FORTH
INSTITUTE OF ASTROPHYSICS

Institute of Astrophysics
FORTH
2023 Annual Report

www.ia.forth.gr

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1. Executive Summary

The current document presents the activities of the members of the Institute of Astrophysics (IA) at the Foundation for Research and Technology – Hellas (FORTH), during the 2023 calendar year.

IA was founded on March 2, 2018 and commenced its independent operations in the summer of 2019. The Institute was established in order to facilitate and further enhance the very successful research activities of the Crete Astrophysics Group, which was operating for nearly 30 years, within the Institute of Electronic Structure and Laser (IESL) of FORTH and the Department of Physics of the University of Crete.

During the past year, members of the IA published **88** papers in refereed journals, that is **4** papers per PhD researcher per year, in the fields of Theoretical and Observational Astrophysics. The research of IA was supported by national and international research grants and the total funding awarded in 2023 was ~**2,1 MEuros.**

A major highlight of the year was the recruitment of two excellent junior scientists, Dr. Maria Charisi and Dr. Ioannis Liodakis, who were awarded the highly competitive ERC Starting Grants in order to build their research groups at IA-FORTH, starting in 2024. Moreover, Dr. Liodakis was also awarded a tenured research position. <u>This brought the total of ERCs awarded to scientists of our Institute to 5, out of the 6 ERCs awarded in the area of Universe Sciences (PE9) in all of Greece.</u> In addition, Dr. Gerry Gilmore, Professor of Experimental Philosophy Emeritus at the University of Cambridge (UK), was elected lifetime honorary fellow of IA and his experience is expected to have strong influence in the science directions of the institute.

Regarding Skinakas Observatory, our major research infrastructure, the upgrades which will enable space telecom with lasers (in the context of ESA's Scylight program) began in January 2023, and its participation in the EU-SST program formally took place in September. Moreover, the construction of the enclosures for the 16 optical telescopes (with 25cm diameter each) of TURBO, the "Total-Coverage Ultra-Fast Response to Binary Mergers Observatory", also began and first light of the facility is expected in the summer of 2024.

This document was prepared in January 2024, based on contributions from all members.

2. Structure

As of March 6, 2019, Director of the Institute is Prof. Vassilis Charmandaris. Since June 18, 2021, the Deputy Director is Prof. Vasiliki Pavlidou.

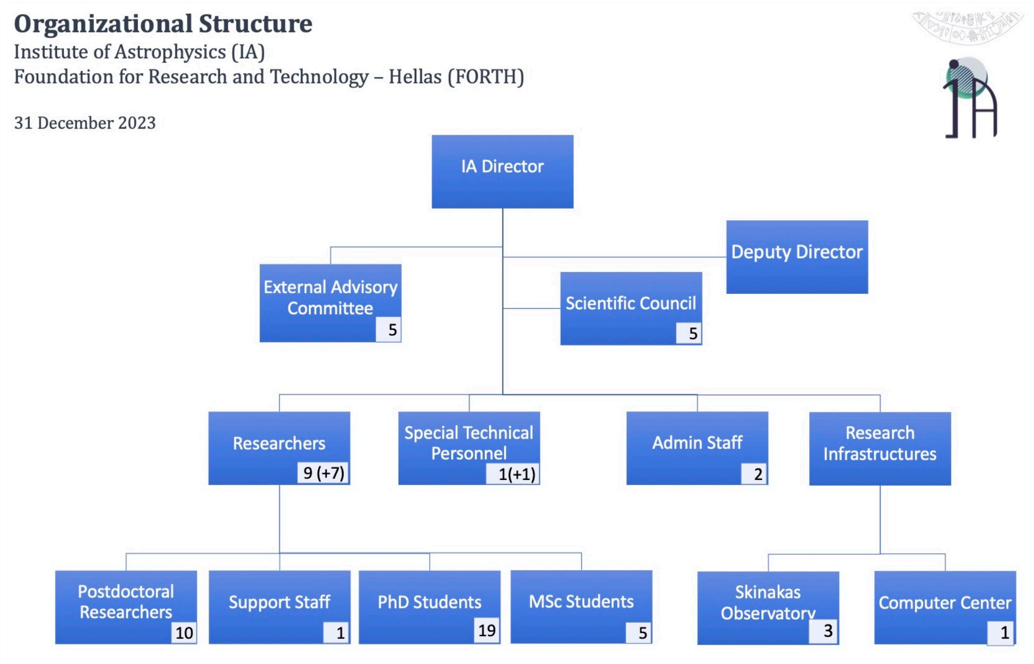
The current Scientific Council of the Institute (SCI) was formed on April 24, 2023 and it consists of:

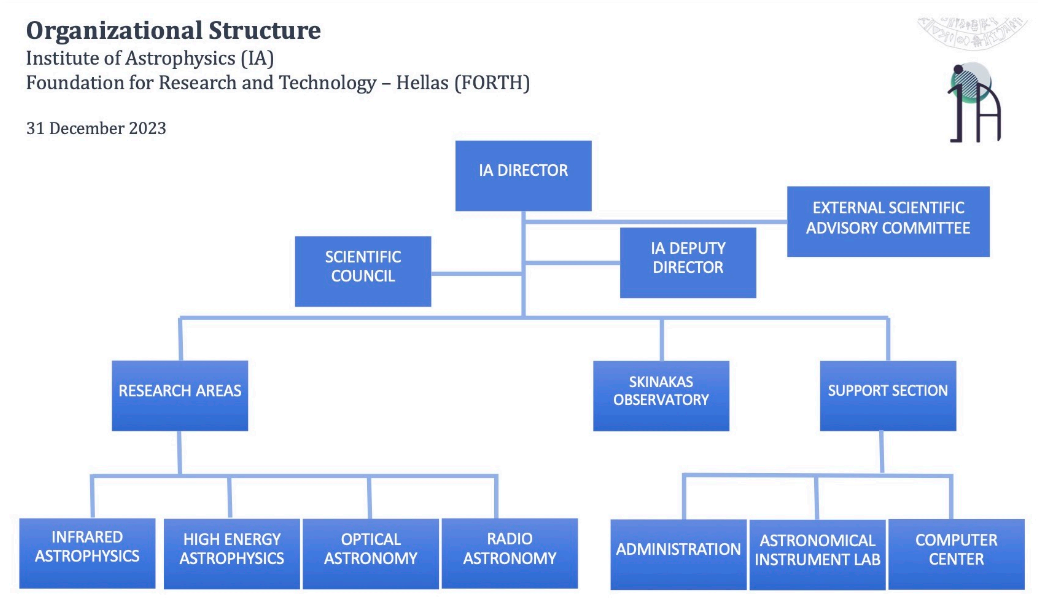
- Ioannis (John) Antoniadis
- Carolina Casadio
- Tanio Diaz Santos
- Pablo Reig, Chair
- Andreas Zezas

The External Scientific Advisory Committee (ESAC) of IA plays a crucial role in the strategic development of the Institute. In 2023 two members of ESAC, Prof. Blandford and Prof. van der Klis, completed their terms and they were replaced. The current members were proposed by the SCI and approved by the Governing Council of FORTH on April 24, 2023:

- Kallia Petraki, Professor of Physics, Ecole Normale Superieure (France)
- Paola Caselli, Director Max-Planck Institute for Extraterrestrial Physics (Germany)
- George Helou, Executive Director IPAC/Caltech (USA)
- Jason Spyromilio, Senior Astronomer, ESO (Germany)
- Serra Markoff, Professor of Astrophysics, Amsterdam University (The Netherlands)

The organizational structure of IA-FORTH is presented in the two flowcharts below:





3. PERSONNEL

3.1. PERSONNEL OF THE INSTITUTE OF ASTROPHYSICS

At the end of the period of this report, December 31, 2023, the core personnel of IA consisted of the Director, 4 permanent researchers, 2 technicians as well as 4 affiliated faculty and one technician from the Department of Physics of the University of Crete. The personnel also includes 2 professors emeriti and 10 post-doctoral researchers, as well as 4 support staff. In addition, 19 PhD students, 5 MSc students, and 8 undergraduate students were trained by members of IA. To the above local members, we should add 4 Affiliated Research Fellows and three Honorary Fellows from institutes outside Greece, who visit IA often and have common projects with the local scientists.

In detail, these individuals are listed below (with those who left during the year marked with gray fonts):

Director of IA-FORTH
- Vassilis Charmandaris (Professor)

Four (4) Permanent Researchers
- Ioannis (John) Antoniadis (Associate Researcher / Researcher C)
- Carolina Casadio (Associate Researcher / Researcher C)
- Tanio Diaz Santos (Senior Researcher / Researcher B)
- Pablo Reig (Research Director / Researcher A)

Two (2) Permanent Support Staff:
- Mr. Giannis Kapetanakis – IT/Network support
- Mr. Anastasios Kougentakis - Special Technical Personnel

One (1) Support Staff of the Univ. of Crete for Skinakas Observatory:
- Mr. George Paterakis - Telescope technical support

Seven (7) Affiliated Univ. of Crete Faculty members:
- Vassilis Charmandaris (Professor, Director of IA)
- Nikolaos D. Kylafis (Emeritus Professor)
- Iossif E. Papadakis (Professor)
- Ioannis Papamastorakis (Emeritus Professor)
- Vasiliki Pavlidou (Professor)
- Kostas Tassis (Professor)
- Andreas Zezas (Professor)

Four (4) IA Affiliated Research Fellows:
- Manos Chatzopoulos (Louisiana State Univ., USA) - since Oct. 2021
- Anamparambu Ramaprakash (IUCAA, India) - since Sep. 2019
- Paul Kalas (U. of California Berkeley, USA) - since Sep. 2019
- Maria Charisi (Washington State University, USA) - since Nov. 2023

Two (2) IA Honorary Fellows:
- Anthony Readhead (California Institute of Technology, USA) - since Jul. 2021
- Gerry Gilmore (The University of Cambridge, UK) – since Mar. 2023

One (1) FORTH (ICS & IA) Honorary Fellow:
- Jean-Luc Starck (CEA-Saclay, France) - since Oct. 2022

Ten (10) postdoctoral researchers in non-tenure track positions:
- Dr. Dmitry Blinov
- Dr. Sebastian Kiehlmann
- Dr. Ioanna Leonidaki
- Dr. Siddharth Maharana – until May. 2023

- Dr. Grigoris Maravelias
- Dr. Valentina Missaglia – since Feb. 2023
- Dr. Georgios Pavlou
- Dr. Vincent Pelgrims – until Aug. 2023
- Dr. Felix Poetzl
- Dr. Maria Sánchez-García
- Dr. Dimitris Souropanis – since Nov. 2023
- Dr. Emmanuel Zapartas – since Sep. 2023

Six (6) Support Staff on soft money:
- Mr. Panagiotis Evangelopoulos – Public Outreach Officer
- Mr. Vangelis Pantoulas - Engineering support
- Mr. Vangelis Vardakis - Engineering support – since Oct. 2023
- Ms. Emmanouela Soultatou - Project support – since Jan. 2023
- Ms. Anna Steiakaki - Engineering support
- Ms. Eleftheria Tsentelierou - Executive Secretary

Nineteen (19) PhD students:
- Mr. Diego Alvarez Ortega (with C. Casadio) - since Dec. 2022
- Mr. Savvas Chanlaridis (with I. Antoniadis) - since Jan. 2021
- Mr. Charalampos Daoutis (with A. Zezas) - since Nov. 2022
- Mr. Román Fernández Aranda (with T. Diaz Santos) - since Jan. 2021
- Ms. Anna Konstantinou (with K. Tassis & E. Ntormousi) - since 2021
- Mr. Georgios Korkidis (with V. Pavlidou) - since Feb. 2020
- Mr. Avinash Kumar (with C. Casadio) - since Apr. 2023
- Mr. Ioannis Kypriotakis (with K. Tassis) - since 2017
- Mr. Elias Kyritsis (with A. Zezas) - since 2020
- Ms. Anna Kyvernitaki-Synani (with K. Tassis & A. Readhead) - since Nov. 2023
- Mr. Arnab Lahiry (with T. Diaz-Santos & J.-L. Starck) – since Oct. 2023
- Ms. Cristina Maria Lofaro (with T. Diaz-Santos) – since Nov. 2022
- Mr. Nikolaos Mandarakas (with K. Tassis) - since 2019
- Ms. Katerina Papadaki (with G. Tzagkarakis & K. Tassis) - since Nov. 2021
- Mr. Marios Papoutsis (with I. Papadakis) - since Nov. 2023
- Mr. Charalampos Politakis (with A. Zezas) - graduated Jul. 2023
- Mr. Stylianos Romanopoulos (with V. Pavlidou) - since Dec. 2019
- Mr. Andreas Tersenov (with V. Pavlidou & J.-L. Starck) - since Aug. 2023
- Mr. Alexandros Tsouros (with V. Pavlidou) - since Sep. 2020
- Ms. Evangelia Vaikousi (with A. Zezas) – since Oct. 2023

Five (5) MSc students:
- Mr. Vasileios Binas-Valavanis (with I. Papadakis) - since Sep. 2023
- Mr. Ioakeim Bourbah (with I. Papadakis) - since Sep. 2023
- Mr. Emmanouil Foukarakis (with V. Pavlidou) - graduated Nov. 2023
- Mr. George Kalaitzidakis (with C. Casadio) - since Sep. 2023
- Ms. Anna Kyvernitaki-Synani (with V. Pavlidou) - graduated Nov. 2023
- Mr. Alkinoos-Dimitrios Langis (with I. Papadakis) - since Sep. 2023
- Mr. Nikos Loudas (with V. Pavlidou & N. Kylafis) - graduated Jul. 2023
- Mr. Ioannis Maragoudakis (with A. Zezas & C. Casadio) - graduated Nov. 2023
- Mr. Michalis Mastorakis (with I. Antoniadis) - graduated Nov. 2023
- Mr. Marios Papoutsis (with I. Papadakis) - graduated Jul. 2023
- Mr. Charalampos Psarakis (with A. Zezas) - graduated Nov. 2023
- Mr. Andreas Tersenov (with V. Pavlidou) - graduated Jul. 2023
- Mr. Nikolaos Triantafyllou (with V. Pavlidou) - graduated Jul. 2023
- Ms. Anastasia Tzouvanou (with P. Reig) - since Sep. 2023
- Mr. Ioannis Volakakis (with I. Antoniadis) – gradualted Nov. 2023
- Ms. Theodora Zacharopoulou (with I. Antoniadis) - graduated Nov. 2023

Ten (10) Undergraduate students:
- Mr. Emmanouil Agianoglou (with K. Tassis)
- Mr. Nikolas Aspradakis (with I. Antoniadis)
- Mr. Vasileios Binas-Valavanis (with I. Papadakis) - graduated Jul. 2023
- Mr. Ioakeim Bourbah (with T. Diaz Santos) - graduated Nov. 2023
- Ms. Eirini Chaniotaki (with I. Antoniadis)
- Mr. Issa Hussein-Bassia (with A. Zezas) - graduated Nov. 2023
- Ms. Anastasia Gourni (with I. Antoniadis)
- Mr. Alkinoos-Dimitrios Langis (with I. Papadakis) - graduated Nov. 2023
- Ms. Myrto Falalaki (with V. Pavlidou, K. Tassis)
- Mr. George Kalaitzidakis (with C. Casadio) - graduated Jul. 2023
- Mr. Evangelos Kontopodis (with P. Reig)
- Mr. Panagiotis Kotoulas (with A. Zezas) - graduated Jul. 2023
- Ms. Chryssi Koukouraki (with K. Tassis)
- Ms. Eleni Koutsiona (with T. Diaz Santos)
- Mr. Giannis Markoudakis (with A. Zezas, C. Casadio) - graduated Jul. 2023
- Mr. Ioannis Orfanos (D. Blinov & C. Casadio) - graduated Nov. 2023
- Ms. Natalia Papagiannopoulou (with P. Reig)
- Ms. Anna Vervelaki (with I. Antoniadis)

3.2. Personnel Changes and Notable Events

During 2023, the following personnel changes took place:

Prof. Pavlidou and Prof. Tassis were promoted to the rank of Full Professor and Prof. Charmandaris was reelected for his second and last 4-year term as the Director of IA.

Dr. Vincent Pelgrims moved as a Marie Curie fellow to the Université Libre de Bruxelles (Belgium) and Dr. Siddharth Maharana moved to a postdoctoral fellowship position at the South African Astronomical Observatory.

Dr. Ioannis Liodakis, postdoctoral fellow at NASA/MSFC (USA) was awarded an ERC starting grant and also obtained tenure as Researcher C’ at IA-FORTH. His grant agreement has been signed and he will commence his ERC in January 2024.

Dr. Maria Charisi, was awarded an ERC starting grant and joined the institute as research fellow, while a faculty at Washington State University (USA). She will commence her ERC in March 2024.

Three new postdoctoral researchers joined IA: in February 2023, Dr. Valentina Missaglia joined the group of Dr. Casadio, Dr. Emmanouil Zapartas was awarded an HFRI postdoctoral fellowship to build a group for his SFERICCS project, which he commenced in September 2023, and he also hired Dr. Dimitris Souropanis to join his group in November 2023.

Five new PhD and five new MSc students joined the Institute and their details are presented in Section 3.1. The following 12 students graduated:

One (1) PhD student defended his thesis:
- Charalambos Politakis - Thesis title: "Demographics of X-ray binary populations in nearby galaxies and connection with the stellar populations and intrinsic properties of their host galaxy" - supervisor A. Zezas.

Eleven (11) MSc students defended their thesis:

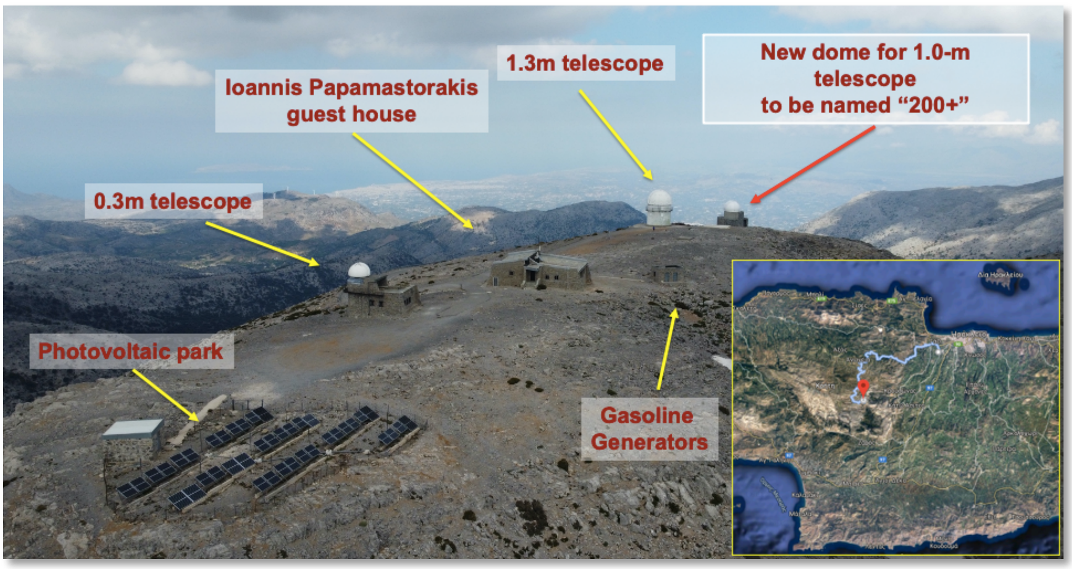
- Emmanouil Foukarakis - Thesis title: "Neutrino radio signatures with ARGOS" – supervisors J. Antoniadis & V. Pavlidou
- Anna Kyvernitaki-Synani - thesis title: "Turnaround density as a probe of the dark energy equation of state" - supervisor V. Pavlidou
- Nikolaos Loudas - Thesis title: "Discriminating power of milli-lensing observations for dark matter models" – supervisors C. Casadio & V. Pavlidou.
- Michalis Mastorakis - Thesis title: "Investigating stellar explosions using stellar evolution models" - supervisor I. Antoniadis.
- Ioannis Orfanos - Thesis title: "Search for AGN jet alignments in the Very Large Array Sky Survey data" – supervisor D. Blinov & C. Casadio
- Marios Papoutsis - Thesis title: "Theoretical model fits to the optical/UV spectral energy distributions of AGN" – supervisor I. Papadakis
- Charalampos Psarakis- Thesis title: "Galaxy cluster detection in the local universe, using machine learning methods" – supervisor A. Zezas
- Andreas Tersenov - Thesis title: " Comparison of mass-mapping techniques using weak gravitational lensing: application to the UNIONS galaxy survey " - supervisor J.L. Starck & V. Pavlidou.
- Nikolaos Triantafyllou - Thesis title: "Searching for a signature of turnaround in velocity profiles of galaxy clusters with machine learning" - supervisor V. Pavlidou
- Ioannis Volakakis - Thesis title: "Pulsars with Gaia counterparts" - supervisor I. Antoniadis.
- Theodora Zacharopoulou - Thesis title: "Interferometric imaging simulations for the ARGOS array" - supervisor I. Antoniadis.

A complete record of all past members of IA, as well as those of the Crete Astrophysics Group of IESL/FORTH & Dept. of Physics, Univ. of Crete, with many relevant information, including their last position, if known, is kept at: https://www.ia.forth.gr/past_members

4. Facilities

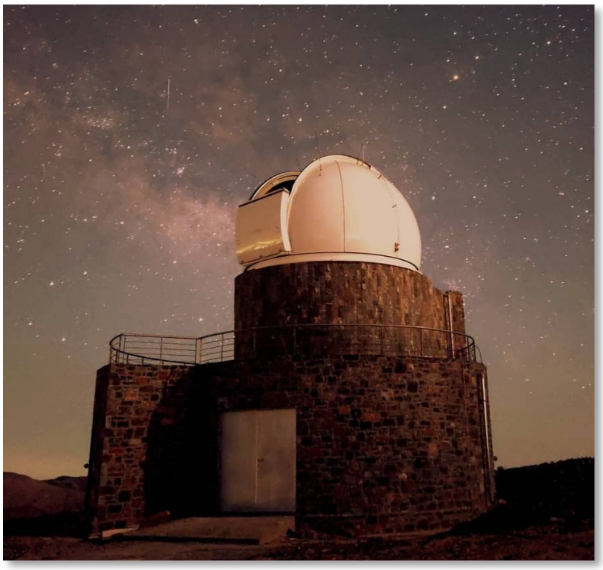
4.1. Skinakas Observatory

Skinakas Observatory is a common research infrastructure of IA-FORTH and the University of Crete.



An aerial view of Skinakas Observatory.

An MoU, signed between FORTH and the University of Crete in 2018, formally assigns the management of Skinakas Observatory[1] to the Director of IA-FORTH, who also acts as the Director of the Observatory.



The new 5.3m dome at Skinakas, currently housing the 60cm telescope.

The 1.3 m telescope was operating full-time at Skinakas Observatory in 2023. This telescope is a modified Ritchey-Chrétien with 1.3 m aperture (focal ratio of f/7.6), which was built by DFM Engineering and Zeiss, and became operational in 1995.

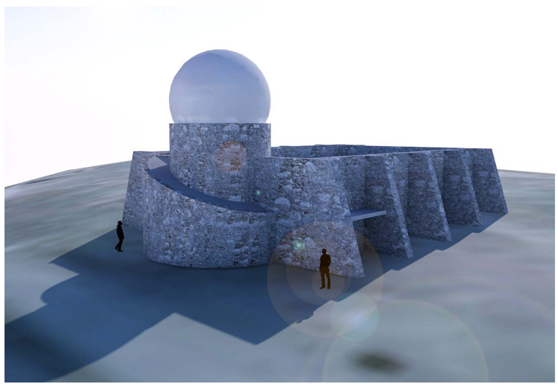
The 60 cm telescope (focal ratio f/8 and f/3) was also used on a regular basis, both from researchers of IA-FORTH for educational and satellite tracking activities, as well as from the amateurs of Capella Observatory (Germany) for wide field imagery (see Appendix).

The 30 cm telescope (f/3.2) was also operating, but for a limited time period on select long term projects on galactic SN remnants.

The RoboPol[2] polarimeter, which saw first light in 2013, continued its nominal operations as the main instrument of the 1.3 m telescope.

The development of the WALOP polarimeter at IUCAA, funded by the Stavros Niarchos Foundation, was affected by the influence of the COVID-19 pandemic to the industry and experienced delays in construction and delivering of its optics. However, rapid progress is taking place and the commissioning at Skinakas is scheduled for the end of 2024.

Moreover, progress was made in six major projects, which are expected to transform the operational capabilities of the facility by the end of 2025.



3D design of the new "Astroschool" bldg.

<u>The first</u> major infrastructure activity was the commencement of the construction, in June 2023, of a new building the "Astroschool", which has an 80 seat multipurpose hall and a 5.3m dome. The building, with a budget of nearly 1MEuro, is expected to be completed in the summer of 2025. During the past year, the order for the dome was placed with the Baader Planetarium GmbH and the construction of the foundations and ground level were completed.

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[1] For more information on Skinakas Observatory visit: https://skinakas.physics.uoc.gr/en/
[2] For more information on RoboPol visit: http://robopol.org/

The second is the 1.0m robotic telescope, which was funded by the Committee "Greece 2021" and the Univ. of Crete. ASA Astrosysteme GmbH is making steady progress and the telescope is expected to be installed at Skinakas during the 3rd quarter of 2024 in the 5.3m dome which currently houses the 60cm telescope.

The 1.0m "200+" ASA telescope

The third project is the construction of the "Total-Coverage Ultra-Fast Response to Binary Mergers Observatory (TURBO)". This project, which commenced in mid 2022, is funded by NSF (Award: 2117236) and it is led by Prof. Patrick Kelly (Univ. of Minnesota, USA). When fully operational in 2025, it will have 16 robotic 25cm telescopes at Skinakas and another 16 in Magdalena Ridge Observatory, New Mexico (USA).

A photo of the four flat concrete bases where the telescope enclosures will be placed (Credit: T. Kougentakis on Dec. 22, 2023).

At the end of 2023, the 4 flat concrete bases (and 8 piers), each of which will house 4 telescopes were completed at Skinakas Observatory (see picture above). The first metal enclosure has also been built and is currently tested at the Univ. of Minnesota. Additional work on the telescope drives and development of the automated pipeline continued during the year. At each site, TURBO will consist of large-format CMOS

The enclosure of four TURBO telescopes at the Univ. of Minnesota campus.

A prototype of a TURBO telescope at the Univ. of Minnesota campus.

detectors mounted on sixteen 0.25-meter diameter optical tube assemblies. Within two seconds of a trigger alert, TURBO will start to obtain continuous, multi-band imaging of over ~100 square degrees. The investment at Skinakas Observatory will be nearly $350,000. By searching more quickly than existing facilities, the telescopes of TURBO will identify new, brightening sources, such as Supernovae or sources of Gravitational Waves, on the sky and obtain early data. The project will also monitor nearby galaxies for very young supernovae. Students from the University of Minnesota, New Mexico, and Crete, as well as the citizen scientists will participate in the project.

An artist's conception of ARGOS.

The fourth project is ARGOS, a concept (TRL2) for a leading-edge, low-cost, sustainable "small-D, big-N" radio interferometer, which will directly address multiple fundamental scientific questions, from the nature of dark matter and dark energy to the origin of fast radio bursts. The 3 year-long project, which commenced in January 2023 and is funded by the European Commission, is led by Dr. John Antoniadis and is a collaborative effort of IA-FORTH, ICS-FORTH and the Univ. of Piraeus in Greece, CEA Saclay in France and the Max-Planck-Institute for Radio Astronomy in Bonn, Germany. The study will culminate with the installation of a prototype radio telescope consisting of 16 parabolic antennas. At the end the prototype will be used to develop and test the innovative technologies required for ARGOS and will also significantly enhance the research and educational work of the Institute.

The fifth project is the connection of Skinakas Observatory with FORTH with an optical fiber; towards this end, 1MEuros was secured via the Hellas Quantum Communication Initiative entitled "Deploying advanced national QCI systems and networks in Greece". The 2.5 year project started in January 2023. Moreover, in December 2022 the Prefecture of Crete confirmed that it will provide the 210,000 Euros necessary in order to connect, in 2024, the Skinakas peak with the electric grid of the island.

Finally, the sixth major development follows the validation, in May 2021, of Skinakas Observatory by the European Union Space Surveillance and Tracking (EU-SST) Campaign #4, as an optical ground station, which can be used in the future to monitor satellites in orbit around the Earth in projects related to space traffic management. To that extent a memorantum of understanding (MoU) between FORTH and the National Observatory of Athens, which is the national central point for the SST activities of Greece, was signed in 2022. In parallel, ESA selected Skinakas Observatory and has scheduled its upgrade in order to be able to participate in projects related to space-to-ground optical communication with lasers, which will increase the data transfer by 5 orders of magnitude, as well as enable quantum cryptography. Two ESA contracts associated with this activity commenced operations in 2023.

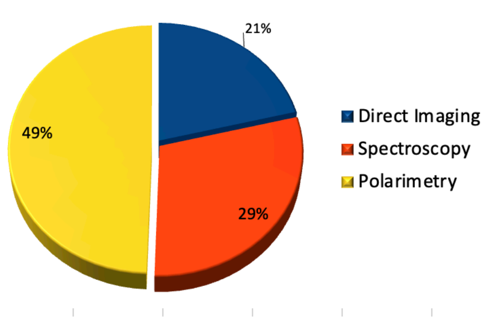
We anticipate that both these new aspects in the usage of the observatory - space traffic management and space telecom with lasers - will provide new opportunities and greatly facilitate both the sustainability of science operations and the future overall growth of the site.

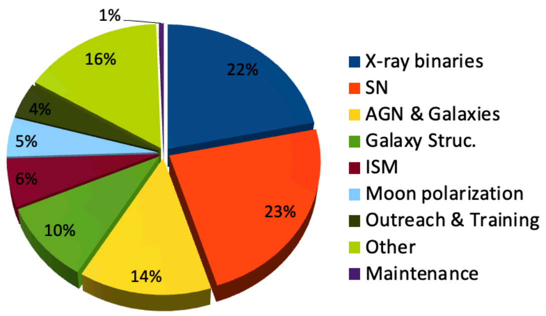
The main science projects during the 2023 observing period were:

- Optical polarization of galaxies
- Target of Opportunity opto-polarimetric follow-up of GRBs, TDEs and SNe
- Polarimetry, Photometry, and Spectroscopy of Binaries with a compact star companion
- Narrow-band imaging and spectroscopy of Galactic Supernova Remnants
- ISM magnetic fields
- The Full Moon as a polarization calibrator
- Follow-up spectroscopy of galaxies detected in the eROSITA survey

In addition, the 1.3 m and the 60 cm telescopes at Skinakas were employed to undergo test observations on satellite tracking. Also, Master students of the Valencian International University had the opportunity to perform on-line observations from the 1.3 m telescope during 6 nights. One night was devoted to the training of Secondary School teachers.

The time distribution of the **184** nights that Skinakas operated during 2023 is presented in the following pie charts.





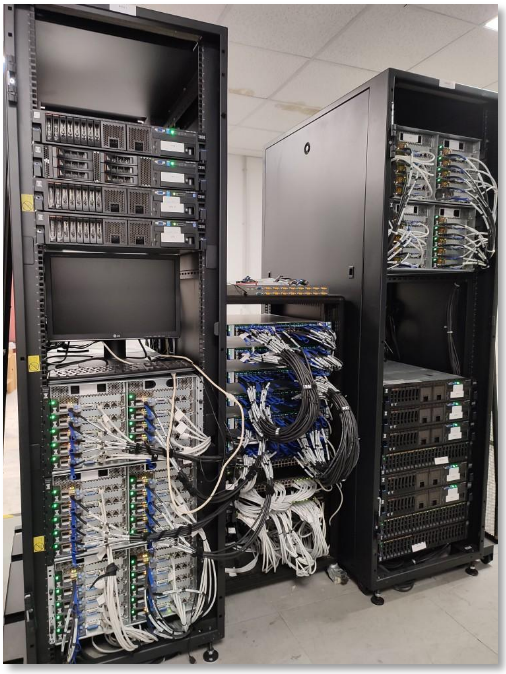
In 2023 a total of **15 refereed papers** were published using data from Skinakas Observatory, **including one in Nature Astronomy and one in Science**.

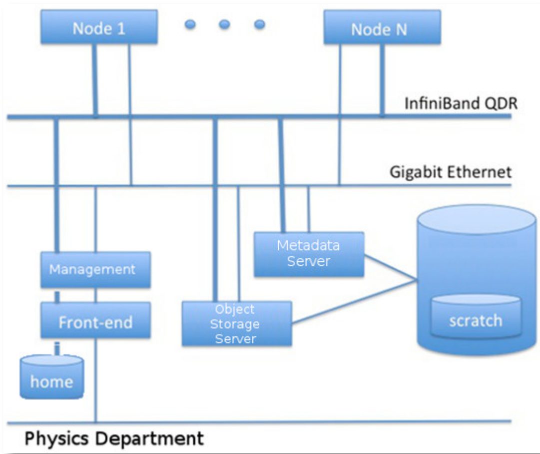
The tradition of open nights resumed in 2023, and five open night events took place at the Observatory, attracting over 2000 visitors.

More details on Skinakas Observatory, the quality of the site, the telescopes, and the available instrumentation can be found in its recently updated web page at: http://skinakas.physics.uoc.gr/en/

4.2. Metropolis HPC Cluster

The IA provides the IT/engineering support for the operation of the "Metropolis" HPC cluster of the Dept. of Physics of the Univ. of Crete since 2015. The cluster has a performance of ~25 Tflops and a storage capacity of 30 TB. It consists of 50 nodes, each with a Dual CPU with 10 cores (1000 cores total) and 96 GB RAM (4.7 TB total RAM) connected with Infiniband 4X QDR running Linux OS.





The Metropolis Cluster

The Metropolis Architecture

Members of the IA have privileged access to "Metropolis" using it extensively mostly for magnetohydrodynamics and ISM chemistry calculations. More information on the technical specifications is available at:

https://qcn.physics.uoc.gr/content/infrastructure/computing-facilities

5. Science Highlights

5.1 How a black hole launches a jet

An international team of scientists have observed both the shadow of a black hole at the center of the Messier 87 (M87) galaxy and the powerful jet ejected from it in the same image for the first time. This breakthrough provides new insight into how black holes can produce powerful relativistic jets. Supermassive black holes are present in most galaxies, and while they typically absorb matter in their vicinity, they can also eject powerful jets of matter that extend beyond the galaxy. The mechanism for producing these jets has long puzzled astronomers.

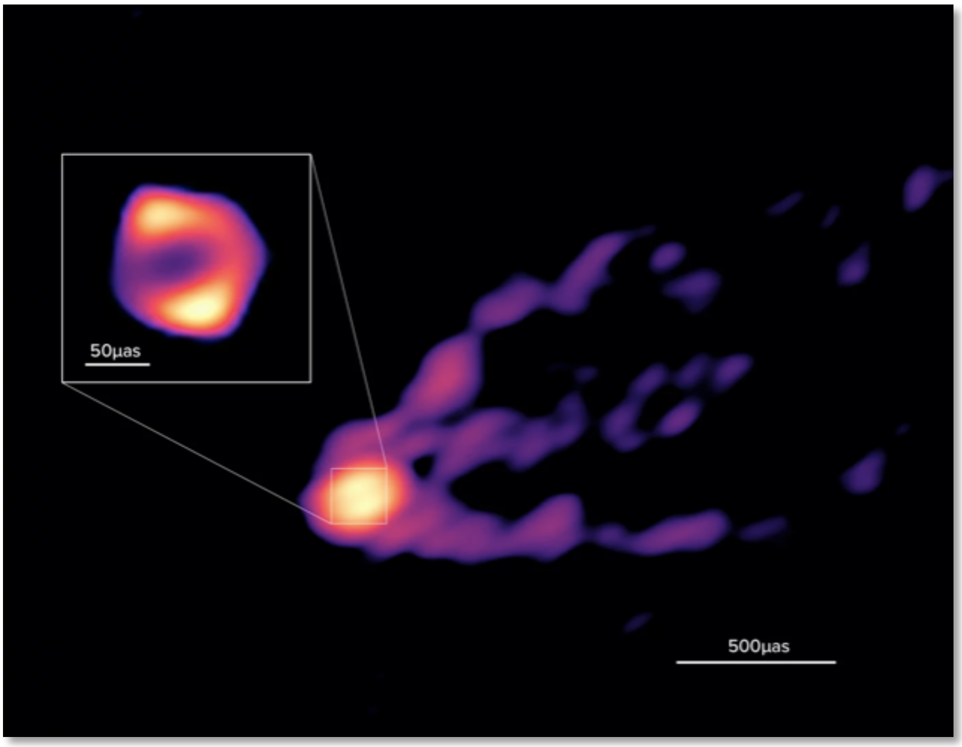


Fig. 1: GMVA+ALMA image of the central black hole region in Messier 87 obtained on April 14-15, 2018 at 3.5 mm wavelength. The large image depicts the jet and central ring as reconstructed by the standard CLEAN method. The inset shows a magnification of the inner region obtained with the super-resolving SMILI method, revealing the ring shape with a diameter of 64 microarcseconds, which corresponds to 8.4 Schwarzschild radii.

Carolina Casadio, a researcher at the IA-FORTH, who participated in the publication, points out that "the mechanism for launching relativistic jets from voracious supermassive black holes, which are at the center of active galaxies, remains a mystery." "The new image of M87," explains Dr. Casadio, "provides an important new element in solving this mystery by revealing the connection between the jet and the emission region surrounding the black hole."
The new image provides a panoramic view of a supermassive black hole that is 6.5 billion times the mass of the Sun, showing how the base of a jet is attached to matter swirling around the black hole. The black hole is located in the M87 galaxy, which is 55 million light-years away. The matter surrounding the black hole is swallowed through accretion, and the new image provides a clearer understanding of the physical processes near the black hole.

Ru-Sen Lu, the first author of the study and leader of a Max Planck Research Group at the Shanghai Astronomical Observatory of the Chinese Academy of

Sciences, is excited by the latest image of the black hole and its jet. "Previously, we had seen both the supermassive black hole and the jet far away from it in separate images, but now with the new image we have taken a panoramic view of the black hole together with its jet in a new observing band." The matter surrounding the black hole is swallowed by a process called accretion. But no one has ever imaged this accretion flow directly. "The bigger and thicker ring we now see shows that the material falling into the black hole contributes significantly to the observed emission in the new image, which allows us to better understand the physical processes near the black hole," adds Dr. Lu.

The observations were made in 2018 with three different groups of telescopes: GMVA located in Europe and North America, ALMA in the Atacama Desert of Chile, and GLT in Greenland. The participation of ALMA in GMVA observations has substantially increased the sensitivity of detecting and imaging radio emissions from M87, providing a clearer understanding of the black hole's structure. Future observations with a network of telescopes distributed across the globe will continue to reveal how supermassive black holes produce powerful jets.

Article: R. Lu (including C. Casadio) et al. "A ring-like accretion structure in M87 connecting its black hole and jet", Nature, Vol. 616, pages 686–690 (2023)

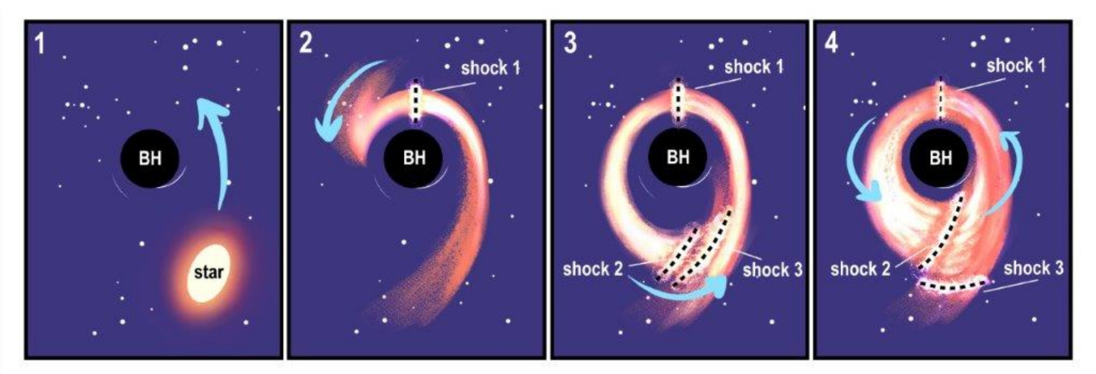
5.2 What happens when a supermassive black hole destroys a star?

The Universe is a violent place, where even a star's life can be cut short. That happens when it finds itself in a "bad" neighborhood, and specifically the neighborhood of a supermassive black hole. These black holes have millions to billions the mass of the Sun and reside in the centers of typically quiet galaxies. As the star moves near the black hole, it starts to experience its ever increasing gravity, until that gravity becomes more powerful than the forces that keep the star together. The star will then be destroyed or disrupted, as it is often called, and its gas will be partially consumed by the black hole.

These "star murders" are called Tidal Disruptions Events (TDE) and are very interesting and energetic phenomena. After the death of the star, its gas will form an accretion disk on its way to the black hole. That results in an outburst that can be seen typically in optical, ultraviolet, and X-rays, but sometimes even in radio wavelengths and gamma-rays as well. Until recently there have been only few TDEs known. Not because they are very rare, but because not a lot of experiments capable of detecting them existed. In recent years, that has changed, giving scientists the necessary tools to start to understand how matter behaves very near a black hole.

Interestingly, that has led to more questions than answers. Observations from large scale experiments with optical telescopes has revealed that a large number of these TDEs does not produce X-rays. This contradicts our basic understanding of TDEs, which suggests the quick formation of an X-ray bright accretion disk as soon as the star is murdered.

Polarization of the light coming from these events might hold the key to solve this mystery. An international team of astronomers that includes members from the Institute of Astrophysics (IA) and the University of Crete, published a study in the journal Science suggesting instead that for the X-ray faint TDEs, the formation of the accretion disk is not fast, but rather tidal shocks form as the gas from the star flows around the black hole. Those shocks are bright in optical and ultraviolet light making up what our telescopes observe as the outburst. The X-ray bright accretion disk comes later.



In a tidal disruption event (TDE), a star finds itself too close to a supermassive black hole whose gravity starts to deform the star (panel 1) until it is destroyed. The gas of the disrupted star follows an elliptical path on its way to the black hole (panel 2). The flowing gas forms shocks near the pericenter of its orbit and the apocenter where it collides with itself (panel 3). The shocks are bright in optical and ultraviolet wavelengths, and make the light polarized. As time passes, the gas slowly circularizes (panel 4) and forms an accretion disk through which the stellar gas can finally be consumed by the black hole. (Image credit: Jenni Jormanainen)

"Polarization of light can provide unique information about the underlying processes in astrophysical systems" said Yannis Liodakis, lead author of the study, astronomer at FINCA and alumnus of the University of Crete. "The polarized light we measured from the TDE could only be explained if we are looking at these tidal shocks."

The team received a public alert in late 2020 from the satellite called Gaia of a TDE in a nearby galaxy designated as AT2020mot. AT2020mot was then observed in a wide range of wavelengths in radio, optical, ultraviolet, and X-rays with many different telescopes. Particularly important were the observations in optical polarization conducted at the Skinakas observatory using the unique RoboPol polarimeter, that made this discovery possible. "The RoboPol polarimeter at the Skinakas observatory has really been the cornerstone of our studies trying to understand supermassive black holes", said Nikos Mandarakas, PhD student at IA and the University of Crete, who led the polarization observations and analysis with RoboPol.

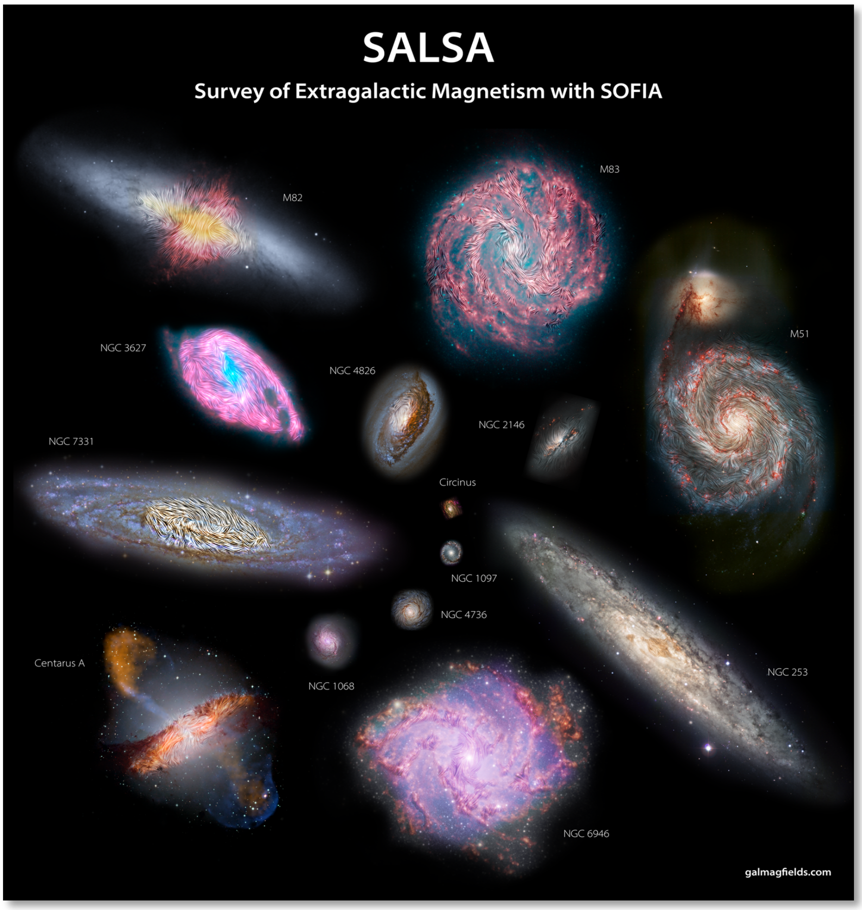
Scientists found that the optical light coming from AT2020mot, was highly polarized, and was varying with time. Despite many attempts, none of the radio or X-ray telescopes were able to detect the event before, during, or even months after the peak of the outburst. "We often observe jets from supermassive black holes that are as polarized as AT2020mot was, but this time there was no evidence for a jet" said Dmitry Blinov, senior postdoctoral scientist at IA.

Putting all this information together, and after comparing their observations to theoretical models, the team of astronomers realized that the data most closely matched a scenario where the stream of stellar gas collides with itself and forms shocks near the pericenter and apocenter of its orbit around the black hole. The shocks then amplify and order the magnetic field in the stellar stream that will naturally lead to highly polarized light. The level of the optical polarization was too high to be explained by most models, and the fact that it was changing over time made it even harder. "We looked at the different models, but only the tidal shock model could explain our observations" said Kostas Kouroumpatzakis, at the time of the observations a PhD student at the University of Crete, now a postdoctoral fellow at the Astronomical Institute of the Czech Academy of Sciences. Scientists will continue to observe the polarized light coming from TDEs, and may soon discover more about what happens after a star is murdered.

Article: I. Liodakis et al. "[Optical polarization from colliding stellar stream shocks in a tidal disruption event]", Science, Vol 380, Issue 6645 pp. 656-658 (2023)

5.3 NASA'S FLYING OBSERVATORY REVEALS MAGNETIC FIELDS OF GALAXIES

Magnetic fields are difficult to detect. For decades, astronomers have studied the factors that shape the interiors of galaxies—gravity, kinetic energy, stellar radiation, gas pressure—but magnetic fields remain largely unknown. Magnetic fields are a fundamental factor in the evolution of any galaxy: they direct interstellar gas toward the supermassive black hole at its center, regulate the rate at which new stars form, influence the formation of molecular clouds of gas, and even influence the motions of disks in spiral galaxies. Magnetic field lines permeate the space between stars and the gas clouds that make up galaxies, but they do not emit light themselves, so magnetic fields are difficult to map.



The 15 neighboring galaxies observed by the HAWC+ polarimeter on NASA's SOFIA flying observatory. The relief pattern shows the magnetic field morphology in the far infrared, which reveals the dense interstellar clouds.

Just like dense clouds in the atmosphere of the Earth bring rain, dense interstellar molecular clouds form stars. Magnetic fields are amplified within these dense star-forming clouds, which optical telescopes (such as the Hubble Space Telescope) cannot penetrate. So astronomers must use specialized telescopes and instruments to detect the magnetic fields.

One of those instruments is the High Resolution Polarimetric Camera (HAWC+) on NASA's Stratospheric Observatory for Infrared Astronomy(SOFIA), a flying observatory. Its sensitivity to the far-infrared region of the electromagnetic spectrum allows HAWC+ to observe the effects of magnetic fields deep in the cold, dark molecular clouds. HAWC+ observed polarized light emitted in the far infrared from magnetically aligned dust grains.

An international team of scientists, including Kostas Tassis, a Professor at the Univ. of Crete and affiliated faculty of IA-FORTH, working on a project called SALSA (Survey on extragALactic magnetiSm with SOFIA), used HAWC+ to observe 15 galaxies in the neighborhood of our own Milky Way galaxy. They mapped the far-infrared magnetic fields and compared their structures to those obtained in radio waves with the Very Large Array in New Mexico and the Effelsberg Telescope in Germany, both of which are sensitive to the galaxies' less dense gas.

SALSA finds that the magnetic fields in the turbulent, dense clouds of star-forming gas are more chaotic and have a more irregular morphology than those in the diffuse interstellar gas detected by radio telescopes. Different spectral regions (far infrared, radio waves) reveal different layers of the structure of magnetic fields. High-resolution observations of galaxy polarization in the far infrared, such as those that were provided by SOFIA/HAWC+ until its final flyby in September 2022, are crucial to our understanding of the role of magnetic fields in the evolution of the Universe.

Article: Borlaff et al. "Extragalactic magnetism with SOFIA (SALSA Legacy Program) -- V: First results on the magnetic field orientation of galaxies", 2023, The Astrophysical Journal, 952, 4

5.4 LOW FREQUENCY GRAVITATIONAL WAVES DETECTED

A collaboration of European astronomers, including Dr. John Antoniadis from IA-FORTH, together with Indian and Japanese colleagues, have published the results of more than 25 years of observations with six of the World's most sensitive radio telescopes. Within these data, the first evidence for ultra-low-frequency gravitational waves has been seen.

In a series of papers published in Astronomy & Astrophysics, European Pulsar Timing Array (EPTA) scientists show that their data are consistent with a “background hum” of low frequency gravitational waves. These elusive waves are ripples in the fabric of space-time, predicted by Albert Einstein's general theory of relativity, and oscillate with timescales of years to decades, much slower than those detected by ground-based interferometers such as LIGO and VIRGO.

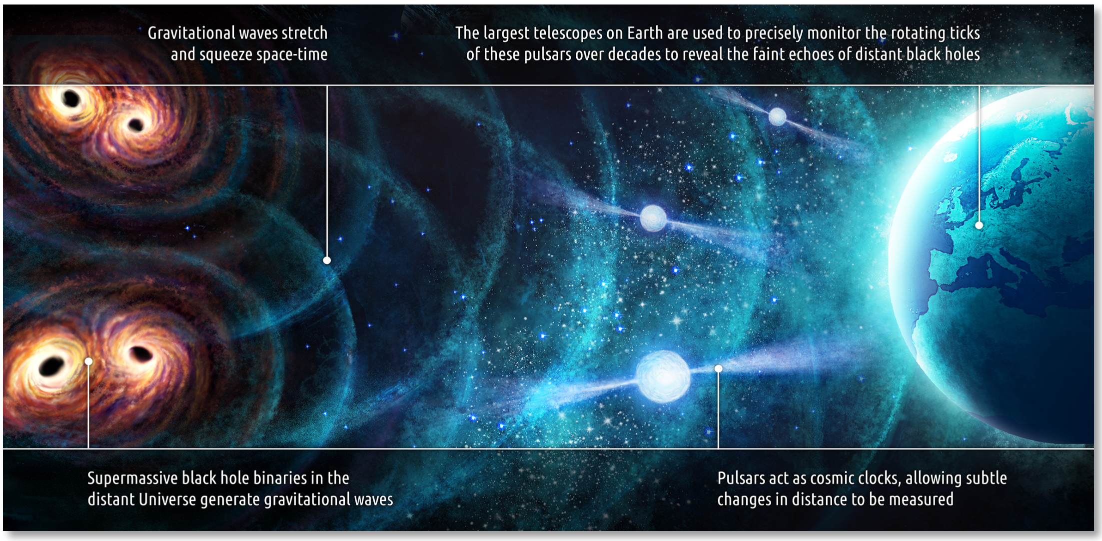
This result is a crucial milestone in opening a new window in the gravitational wave spectrum, which will allow astronomers to study the formation and evolution of supermassive black holes and their host galaxies across cosmic time. It will also provide new tests of gravity and dark matter, potentially also revealing the physical processes that shaped the early Universe.

The collaboration believes that the signal was produced by supermassive black hole binaries - pairs of black holes with masses millions to billions times that of the Sun, orbiting each other due to gravitational attraction. These binaries are expected to form when two galaxies merge, bringing their central black holes closer together.

Gravitational waves produced during this process have wavelengths of millions of kilometres, which are too low to be detected by ground-based interferometers like LIGO or Virgo. However, pulsar timing arrays can detect these waves by using pulsars as natural detectors. Pulsars are highly stable and emit regular pulses of radio waves that reach Earth with clock-like precision. When a gravitational wave passes through the Earth-pulsar system, it causes a slight distortion in space-time that affects the arrival time of the pulses.

"By comparing the observed arrival times with the expected ones, we can measure the effect of the gravitational wave and extract information about its source and amplitude," says John Antoniadis, an Associate Researcher at the FORTH Institute of Astrophysics whose team participated in the data analysis.

Pulsar timing arrays require long-term observations of many pulsars distributed over the sky to achieve sufficient sensitivity and resolution to detect gravitational waves. The dataset analysed by the EPTA contains sensitive data for 25 pulsars collected over the past three decades with Europe's largest telescopes. These are the 100-m Effelsberg Radio in Germany, the Lovell Telescope of the Jodrell Bank Observatory in the United Kingdom, the Nançay Radio Telescope in France, the

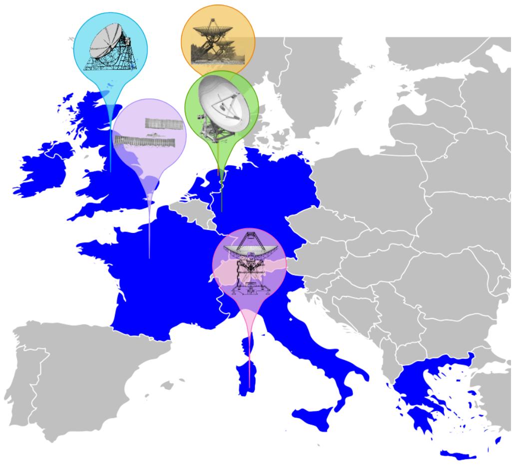


Artist's impression of the measurement of the gravitational wave background using pulsars distributed in the Milky Way. The faint echo of distant binary systems of supermassive black holes alters the precise ticking of the cosmic lighthouses.© Daniëlle Futselaar (artsource.nl) / MPIfR

Sardinia Radio Telescope in Italy and the Westerbork Radio Synthesis Telescope in the Netherlands.

The EPTA is part of a larger international effort, the International Pulsar Timing Array (IPTA), which combines data from similar projects in North America (NANOGrav), Australia (PPTA), India (InPTA) and South Africa (MeerKAT). The same compelling evidence for gravitational waves is seen by NANOGrav and is consistent with results reported by PPTA, and the Chinese Pulsar Timing Array Collaboration.

"This is very exciting," explains Antoniadis. "The odds that the signal we saw in our data occurred by chance is one-in-ten-thousand. However, the golden standard in Science to *claim the detection of a new phenomenon is that the result of the experiment has a probability of occurring by chance less than one in a million.* While the EPTA result does not yet meet this golden standard, the fact that our colleagues worldwide see the same signal gives us great confidence that what we see is the real thing". The IPTA scientists are now keen in combining their independent datasets in the context of the IPTA, to better characterise the signal. "Everyone is confident that the combined dataset will provide the ultimate proof that the signal is genuine", adds Antoniadis.



The EPTA collaboration

In addition, the EPTA plan is already preparing for how to move forward. According to Antoniadis, "One aspect of this is planning for new instruments". "This is why FORTH is leading an international effort supported by European Union funds, to construct a next-generation radio telescope in Crete. The telescope, which we call ARGOS, is specifically designed for dedicated pulsar timing observations. Once built, it will become the most sensitive EPTA instrument. It will allow us to better explore the low-frequency gravitational-wave window, digging deeper for additional signals from the Early Universe".

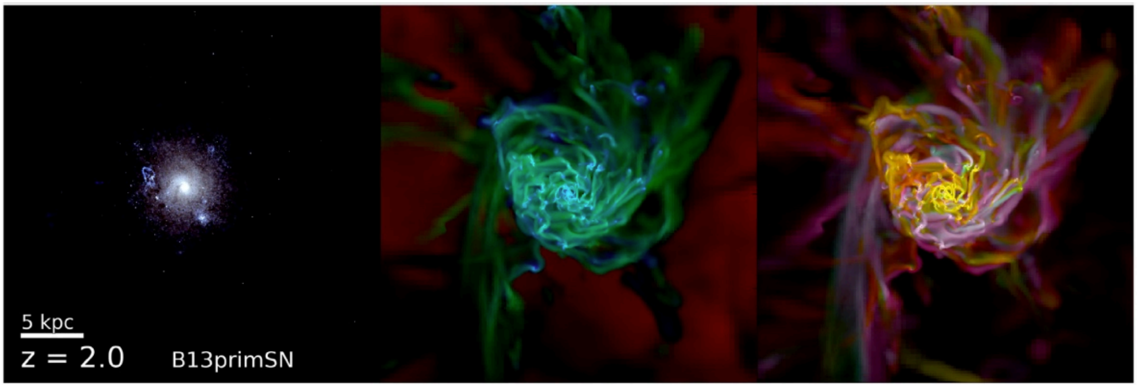
Articles:

1. EPTA Collaboration, "The second data release from the European Pulsar Timing Array I. The dataset and timing analysis", 2023, A&A, 678, 48
2. EPTA Collaboration, "The second data release from the European Pulsar Timing Array II. Customised pulsar noise models for spatially correlated gravitational waves", 2023, A&A, 678, 49
3. EPTA Collaboration, "The second data release from the European Pulsar Timing Array III. Search for gravitational wave signals", 2023, A&A, 678, 50

5.5 UNDERSTANDING GALACTIC DYNAMOS

Spiral galaxies, including ours, have significant large-scale magnetic fields with energy densities comparable to those of turbulent and thermal motions. Therefore, these magnetic fields can play a crucial role in a wide range of internal galactic processes. The dominant theory attributes these magnetic fields to a large-scale dynamo.

A review by Prof. Brandenburg and Dr. Ntormousi, a postdoctoral fellow at IA-FORTH and currently tenured researcher in Scuola Normale Superiore in Pisa (Italy), addresses the current status of dynamo theory and discusses numerical simulations designed to explain either particular aspects of the problem, or to reproduce galactic magnetic fields globally.



Section of Figure 1 from Martin-Alvarez et al. (2021), showing a cosmological galaxy model evolved with two different initial magnetic fields: primordial or "injected" on small scales by stellar feedback. The left panel shows a color-composite mock observation in the optical, the middle panel shows dust absorption along the line of sight, and the one on the right color-codes the total magnetic energy according to its origin: green for the primordial, red for the injected, and blue for the cross-term field.

Their main conclusions can be summarized as follows:

- Contrary to theoretical expectations, idealized direct numerical simulations produce mean magnetic fields, whose saturation energy density tends to decline with increasing magnetic Reynolds number. This problem is still unsolved.
- Large-scale galactic magnetic fields of microgauss strength can probably only be explained if helical magnetic fields of small or moderate length scales can be ejected (by some sort of outflow) or destroyed rapidly.
- Small-scale dynamos are essential throughout a galaxy's life and probably provide strong seed fields at the early stages of galaxy formation.
- The circumgalactic medium (CGM) can play a critical role in driving dynamo action at small and large length scales. The interactions between the galactic disk and the CGM may provide important insights into our understanding of galactic dynamos.

The authors expect future research in galactic dynamos to replace the idealized boundary conditions used so far with the cosmological history of galaxies and their interaction with the CGM.

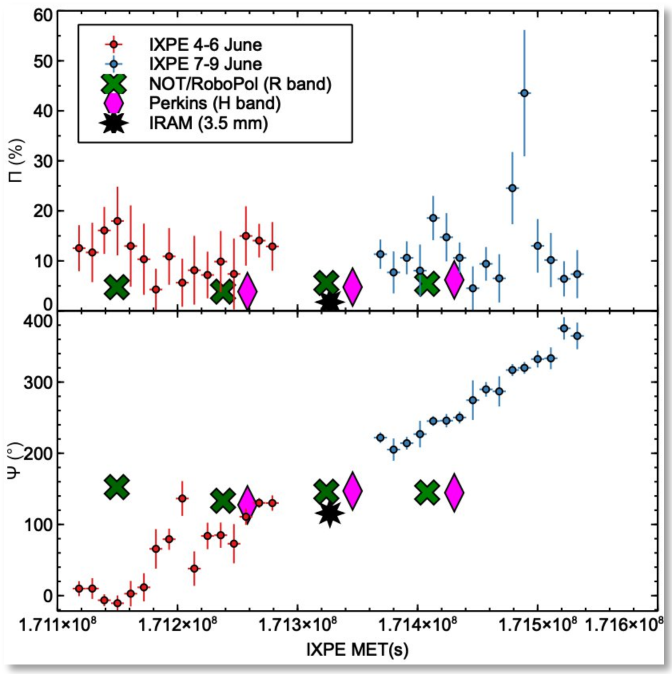
Article: A. Brandenburg & E. Ntormousi "Galactic Dynamos", 2023, Annual Review of Astronomy and Astrophysics, Volume 61, Issue , pp. 561-606

5.6 RoboPol's predictions on black hole jets verified by NASA's IXPE

The universe blazes with energy, not just among stars, nebulae, and teeming galactic nurseries, but also erupting as high-speed jets of ionized matter from some of the most powerful destructive sources ever known – active galactic nuclei known as "blazars."

A blazar is so identified because it expels its powerful beam of ionized matter nearly directly at an observer – in this case, Earth-based ground and space telescopes and satellite imagers. That bright, highly detectable "blaze" of electromagnetic radiation results from the effects of relativistic space-time on the jet's light as the jet hurtles away from the galaxy's center at or near the speed of light, often creating a beam millions of light-years in length. Such jets may be expelled by a variety of powerful, heavy-mass phenomena, including pulsars, neutron stars, or the supermassive black holes to fuel blazars and other active galactic nuclei. Despite decades of study, scientists still don't fully grasp the physical processes that shape the dynamics and emission of relativistic jets expelled by blazars.

RoboPol, a novel polarimeter mounted at the Skinakas observatory's 1.3m telescope has been studying blazars in polarized light for a decade now. The main goal of RoboPol has been to understand a peculiar phenomenon that seems to be unique to blazars called rotations of the polarization angle. That is when the orientation of the polarized light change monotonically for often more than 180°. The origin of those rotations is still not fully understood. However, RoboPol found that not all jets show rotations, but rather a specific subclass of blazars and predicted in a paper published in the Monthly Notices of the Royal Astronomical Society (Angelakis et al., 2016) that another subclass of blazars will show rotations in X-rays.



Radio, infrared, optical and X-ray polarization observations of Mrk 421 for both observations in June 2022. The top panel shows the polarization degree and the bottom panel the polarization angle. The X-ray polarization degree is more than two times the lower energy observations consistent with all other IXPE observations of blazars. The polarization angle is consistent within uncertainties for all wavelengths, but the X-rays that show a roughly 400o rotation. This provides strong evidence that emission regions in astrophysical jets are not co-spatial.

Seven years since that prediction, an international team of astrophysicists, using data from NASA's Imaging X-ray Polarimetry Explorer (IXPE), discovered an X-ray polarization angle rotation in the blazar dubbed Markarian 421, an active galactic nucleus and powerful gamma-ray source in the constellation Ursa Major, roughly 400 million light years from Earth. IXPE was launched Dec. 9, 2021. The new study detailing the IXPE team's findings at Markarian 421 confirming the RoboPol prediction was published in Nature Astronomy (Di Gesu et al., 2023). IXPE's groundbreaking X-ray polarimetry capability gives them an unprecedented view of these targets, their physical geometry, and where their emissions originate. Research models for the typical outflow of the powerful jets typically depict a spiraling helix structure, similar to that of the human DNA chain – but IXPE found unexpected variability during three prolonged observations of Markarian 421 in May and June 2022.

Remarkably, the initial analysis of the polarization data from IXPE appeared to show the polarization dropped to zero between the first and second observations.

It was then found that while the polarization degree remained constant, its direction was changing fast. During the six days of the IXPE observations, the direction of the polarization made slightly over a full 360 degree turn. Sebastian Kiehlmann, a postdoctoral researcher at the Institute of Astrophysics (IA), led the analysis to test the random rotation hypothesis while several students and researchers of IA-FORTH were also involved in the interpretation of the data presented in the paper. It was found that the observed rotation is unlikely to happen by random motions of the polarization angle. This would imply that the rotation is likely caused by real changes in the magnetic field of the jet.

Stranger still was the concurrent optical measurements from RoboPol. Those showed no change in stability or structure at all – even when the polarized X-ray emissions deviated. This is strong evidence that the X-ray emission traces a different region from the optical light. The concept of a shockwave accelerating the jet's particles is consistent with theories about the documented behavior of Markarian 501, the first blazar to be observed by IXPE that led to a published study in late 2022. The new era of multiwavelength polarization with instruments like RoboPol and IXPE make for a very exciting time for studies of astrophysical jets.

Article: Di Gesu et al. "Discovery of X-ray polarization angle rotation in the jet from blazar Mrk 421", 2023, Nature Astronomy, (DOI 10.1038/s41550-023-02032-7)

5.7 The Radio – X-ray correlation in black-hole binaries

From their birth, the stars in our Galaxy are mostly in binaries. Our Sun is an exception. The more massive of the two stars in a binary evolves faster than the less massive one and ends its luminous life as a compact object: a white dwarf, a neutron star, or a black hole. In the last case, a black-hole binary (BHB) is formed. As the normal star in such a binary continues its evolution, matter escapes from its outer layers and it is attracted by the black hole. Because of angular momentum conservation, this attracted matter forms a disk around the black hole, which is called accretion disk. The inner part of this accretion disk (called hot inner flow) is very hot (millions of degrees) and could, in principle, be the source of X-rays.

Naively thinking, since black holes absorb everything, one would expect all the matter in the accretion disk to fall into the black hole because of friction, like the artificial satellites around Earth. However, what actually happens is that a significant fraction of the accreting matter is ejected in the form of a narrow

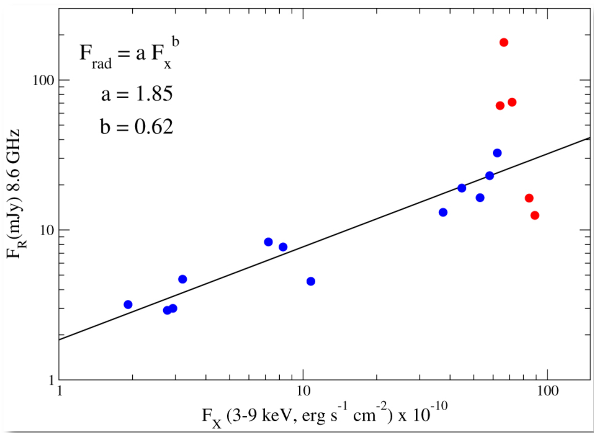


Fig. 1: Radio -- X-ray correlation for the source GX 339-4. The solid line gives the observed correlation. The blue dots are the model results and the red dots are the predictions of the model.

jet or a wide outflow or both. This jet and/or outflow is detected via the radio waves that it emits.

It is known, for about 20 years now, that the observed radio luminosity from BHBs correlates very well with the observed X-ray luminosity (solid line in Fig. 1. The mathematical expression for the correlation is shown in the upper left corner of the Figure). This has puzzled the community, because the X-rays are thought to be emitted from the hot inner flow, the radio from the jet/outflow, and the two "do not talk to each other". One possibility discussed in the community is that both the outflow and the hot inner flow are fed with the matter that is provided by the companion star and this correlates their emissions. When asked about it, Kylafis said: "if you and I fill the tanks of our cars from the same gas station, does this correlate us? Obviously not".

The Group in Crete, consisting of Nick Kylafis, Pablo Reig, and Alexandros Tsouros, followed their intuition and proposed that, in order for the X-rays and the radio emission in BHBs to be correlated, the two emissions must come from the same region. Not that this is a guarantee, but at least there is a good chance. Thus, they assumed that the X-rays come from the outflow, which emits the radio waves and they were able to reproduce the observed correlation (see the blue dots in Fig. 1, which are the results of their model).

Since no model should be taken seriously unless it makes predictions which can be tested, the red dots in Fig. 1 are predictions of the model. The model predicts that, at high luminosity (both radio and X-ray), the correlation will break down (right part of Fig. 1) and the radio luminosity will first increase sharply and then decrease also sharply within a small range of X-ray luminosity (red dots). This sharp increase and decrease of the radio luminosity takes about five days, and no BHB has been caught in this stage so far, because observations of a particular BHB are done typically once a month or at best once a week (radio and X-ray telescopes are too busy). Thus, in order for the prediction to be confirmed or rejected, daily radio and X-ray observations are needed. Such observations are now planned.

Article: N.D. Kylafis, P. Reig, A. Tsouros, "A quantitative explanation of the radio – X-ray correlation in black-hole X-ray binaries", 2023, A&A, 679, A81

6. Research Areas

In the following, we present the research areas in which members of the IA contributed in 2023. The section is organized and sorted by cosmic scales, from largest to smallest; and each scale is structured in research topics. The IA members actively investigating each topic are indicated in parentheses.

A description of the research areas is also presented in the web page of IA, specifically at: https://www.ia.forth.gr/all-research-areas

6.1. Cosmology, Large-scale Structure & the High-z Universe

General Background:
The formation of large-scale structure in the Universe is a cosmic battle between expansion inertia, gravity, and the accelerating influence of dark energy. The properties of the largest structures in the Universe (galaxy clusters and superclusters) respond to the contents of the Universe - dark matter and dark energy. On smaller scales, the evolution of galaxies within those clusters is also subject to radiative processes associated with baryonic matter; processes that give rise to one of the most energetic phenomena in the Universe: quasar activity. Quasars are the most powerful manifestation of accretion of material onto the supermassive black-holes (SMBHs; from several millions to several billion times the mass of the Sun) found at the centers of massive galaxies, a phenomenon producing the so-called active galactic nuclei (AGN). The result of this accretion is the production of intense radiation over the whole electromagnetic spectrum and often the ejection of material in the form of collimated relativist radio jets or larger scale gas outflows.

Cosmology
(Researchers involved: V. Pavlidou, K. Tassis)

Specific Background:
The properties of these largest structures on the largest possible non-expanding scale (the so-called turnaround scale, which is the boundary between a structure and the expanding universe) can be used to obtain information about the contents of the Universe and the relative proportions of its dark constituents. In contrast to other probes of cosmology, such as the cosmic microwave background of the expansion history of the Universe, the turnaround scale of structures probes dark energy locally - here and today - and it maps its result on specific objects (say a galaxy cluster, or a supercluster) rather than on the Universe as a whole.

Current efforts:

<u>The growth of structure and its link to cosmological models</u>: Our group uses analytical and semi-analytical calculations, numerical simulations of cosmological volumes, and observations, to map the turnaround scale and obtain the information it encodes about cosmology. Using analytic and semi-analytic calculations we follow the formation and growth of structure under different cosmologies. In universes with dark energy, the ultimate fate of structure formation is the halting of structure growth – a state which can leave observable imprints in the mass-radius relations of local-universe structures such as groups and clusters of galaxies.

Quasar Activity and Early Galaxy Assembly

(Researchers involved: T. Diaz Santos)

Specific Background:

By studying broad-band images and spectra of quasars from radio to X- and Gamma-rays, we can learn about the physical state of the material surrounding them and which are experiencing extreme physical and dynamical conditions. In addition, quasars are among the most distant sources of radiation in the Universe, and have been found up to redshifts larger than 7, when the Universe was less than 1 billion-year-old. Therefore, by deeply surveying large portions of the sky and collecting multi-wavelength data from large sample of quasars at different epochs, we can study the growth of the supermassive black-holes over cosmic time and investigate how the most massive galaxies are assembled at the center of cosmic over-densities.

Current efforts:

<u>High-redshift dust-obscured quasars</u>: Hot dust-obscured galaxies (Hot DOGs) are a previously unknown population of obscured quasars at z > 1 recently discovered by the NASA's WISE mission, which mapped the entire sky at near/mid-IR wavelengths. The bolometric luminosities of Hot DOGs exceed 10^{13} $L_{\odot}$. This outstanding energy output is thought to be powered by accretion onto supermassive black holes (SMBHs) buried under enormous amounts of gas and dust. Their host galaxies are detected in the near-infrared by Spitzer, but are less massive than expected from such hyper-luminous active galactic nuclei, which implies that either the SMBH has a much larger mass than expected given the stellar mass of its host, or it is radiating well above the limit dictated by the isotropic balance between gravity and radiation pressure. Such luminous nuclei harbored by otherwise normal galaxies are likely at a key stage of their evolution, where feedback from the active nucleus may be quenching star-formation – a "quasar" phase that some theoretical models require in order to explain the star-formation and interstellar medium (ISM) properties of red, compact, and mostly quiescent galaxies already identified at cosmic noon, z ~ 2. Our group uses the Atacama Large Millimeter/submillimeter Array (ALMA), the largest radio telescope in the world, to characterize the impact the central SMBH has on the ISM of its host galaxy and to study the morphology and kinematics of their gas and dust. In addition, the 3D (2D spatial sky-projection + frequency) nature of ALMA's interferometric observations allows us to study the environment of these obscured quasars and search for companion galaxies and signatures of mergers, as Hot DOGs live in over-dense regions likely located at the nodes of the filamentary cosmic web.

Moreover, we have been awarded a GO1 proposal with the James Webb Space Telescope (JWST), the largest mid-IR space telescope ever built, to target the most luminous and distant Hot DOG. With the data obtained with the NIRSpec-IFU and MIRI-MRS instruments, we will study the ISM properties and energy sources in a multiple-merger system only 1.3 Gyr after the Big Bang.

Pulsar Timing Arrays: Pulsars as direct gravitational wave detectors

(Researchers involved: J. Antoniadis)

Specific Background:

Pulsar Timing Array (PTA) experiments rely on the precise measurement of the time-of-arrivals (TOAs) of the pulses for a network ("array") of millisecond pulsars spread over the sky. Changes in the local spacetime metric induced by gravitational waves result in TOA variations that correlate among different pulsars. PTA experiments are mostly sensitive to nanoHz gravitational waves (periods of ~1-50 years). The main *signal in this regime is believed to be a stochastic GW background induced by merging supermassive black holes. The overall effect of the GW signal on the TOAs is expected to be well below 100ns. The measurement accuracy of pulse arrival times is determined by the signal-to-noise of the pulse profile, but also depends on other effects, especially those caused by free electrons in the interstellar medium such as dispersion and scattering. In particular, their low-level variations can induce significant low-frequency power in the timing residuals that must be removed before the putative GW signals can be detected.*

Our PTA activities focus on contributions to the European Pulsar Timing Array (EPTA), a consortium of institutions and universities using European telescopes and resources to directly detect low-frequency GWs. The EPTA utilizes the MPIfR's Effelsberg 100-m Telescope, the Nançay Decimetric Radio Telescope (NRT), the Lovell Telescope at Jodrell Bank, the Westerbork Synthesis RadioTelescope (WSRT), and the Sardinia Radio Telescope (SRT). This range of telescopes give the EPTA a significant advantage over other PTA projects as it provides a larger total number of TOAs, high-cadence time coverage, immediate cross-checks on instrumental effects such as polarization calibration and clock offsets.

Current Efforts:

<u>The IPTA third data release (IPTA DR2):</u> In June 2023 the EPTA, NanoGrav and Parkes PTA collaborations announced the discovery of a signal consistent with a nanohertz gravitational wave background. These results represent the most significant milestone in the field and suggest that a highly significant (>10sigma) detection of the background should be possible with the coherent combination of the international PTA datasets. This will be achieved with the third International Pulsar Timing Array third data release, which will combine data from EPTA, NanoGrav, PPTA and MeerKAT.

<u>Large European Array for Pulsars (LEAP):</u> The Large European Array for Pulsars (LEAP) is a key science project within the EPTA collaboration, which coherently combines the five EPTA radio telescopes to deliver an L-band sensitivity equivalent to a 200-m single dish. LEAP conducts monthly observations of over twenty EPTA pulsars including all high-priority EPTA sources. Current LEAP activities focus on observations, data reduction and analysis (using a dedicated HPC cluster at the University of Manchester), contributions to the EPTA DR2, searches for Fast Radio Bursts (FRBs), and studies of the ISM and Solar Wind.

<u>PTA instrumentation:</u> FORTH is coordinating the ARGOS Conceptual Design Study, a horizon-funded project to design a next-generation radio interferometer. ARGOS will consist of several hundred 6-m antennas, equipped with passively-cooled 1–3GHz feeds. It will combine a wide field of view (~10 square degrees), with high resolution (<1 arcsec) and high sensitivity (equivalent to SKA1-mid near L-band). ARGOS will work as a public survey instrument that will provide science-ready data in near real time. One of these data products will be daily timing observations of all EPTA pulsars. This unique dataset will increase the PTA sensitivity to nanohertz gravitational waves by two orders of magnitude, while also allowing us to probe for the first time, the microhertz GW frequency window. Besides the coordination of the project, FORTH-IA is leading the development of the pulsar timing pipeline. A small-scale 10-dish fully-functional prototype of ARGOS will be installed at FORTH Q4 2024, and begin to participate in PTA experiments by Q2 2025.

6.2. Galaxies and Their Evolution

General background:
Galaxies are the places where stars form and spend their lives. They exhibit a wide variety of morphologies and colors, which in general terms reflect their past history.

Hence studies of galaxies provide information on the formation of stars over the history of the Universe and the growth of the SMBHs residing in their nuclei. Galaxies are very dynamic systems, which often collide and merge to form new structures. These interactions depend on the local environment of each galaxy and therefore studies of galaxies can provide information on the evolution of the Universe as a whole.

Our group has a deep interest in understanding the properties of galaxies and their evolution. In particular we focus on the following topics:

ULTRA-LUMINOUS X-RAY SOURCES

(Researchers involved: P. Reig, A. Zezas)

Specific background:
Ultra-luminous X-ray sources are an intriguing class of objects with luminosities above 10^{39} erg/s and often reaching extreme luminosities of 10^{40} or even 10^{41} erg/s, well above the Eddington limit for a stellar-mass black-hole. The nature and formation pathways of these sources is an open question, and their understanding is particularly important given their significant contribution in the X-ray output of galaxies, which they often dominate. Detailed studies of their X-ray spectra also provide information on the accretion physics at extremely high accretion rates.

Current efforts:

At the IA, researchers are performing systematic studies of ULX populations in individual nearby galaxies, as well as their demographics in large samples of galaxies. Our goal is to constrain the dependence of their populations on the age and metallicity of their parent stellar populations. In addition to studies of ULX populations in individual galaxies, in 2023 we continued our efforts in studying the populations of ULxs in large samples of galaxies by combining Chandra and XMM-Newton catalogues.

ACTIVE GALACTIC NUCLEI

(Researchers involved: D. Blinov, C. Casadio, V. Charmandaris, S. Kiehlmann, V. Missaglia, I. Papadakis, V. Pavlidou, V. Pelgrims, A. Ramaprakash, A. Readhead)

Specific background:
Active Galactic Nuclei (AGNs) are the most luminous, persistent objects in the Universe. They emit an enormous amount of luminosity, from a tiny volume, at the center of their host galaxies. It is quite common that the bolometric luminosity emitted by the active nucleus will surpass that of the host galaxy. Today we believe that an AGN is powered by accretion of matter, in the form of a disc, around the super-massive black hole that resides at the center of galaxies.

The mass of the BHs at the center of galaxies ranges from one hundred thousand to several billion solar masses. As matter accretes on them, it releases gravitational energy with an efficiency far greater than the efficiency of the nuclear reactions at the center of stars. As a result, an AGN emits intense radiation at all wave bands, from radio to gamma-rays. Approximately 10 per cent of AGNs are particularly luminous in radio waves, and they show evidence of collimated relativist jets. The AGN radiation is highly variable, at all wavelengths, with the amplitude and variability rate increasing with increasing frequency.

By studying the broad-band (from radio to optical to X- and Gamma-rays) spectra *and the extreme variability of an AGN we can learn about the physical properties that operate in the vicinity of the super-massive black-holes and in the relativistic outflows. In addition, AGNs are among the most distant sources of radiation in the Universe, and have been found up to "redshift" larger than 7, when the Universe was less than one tenth of its current age. Therefore, by deeply surveying large portions of the sky and collecting multi-wavelength data from large samples of AGN at different "redshift" we can study the growth of the supermassive black-holes over cosmic time and their connection to galaxy formation.*

AGNs are also ideal tools to investigate the matter content in the Universe, through the gravitational lens effect. Most of the known cases of strong gravitational lensing involve multiple images of the nucleus of active galaxies. Studies of gravitationally lensed AGNs have a two-fold function: revealing more and finer details about AGNs, and tell us something about the lens, like for example its mass distribution.

Current efforts:

<u>AGN variability</u>: Our group has long worked on the study of the AGN variability, mainly in the optical/UV and X-rays. We have used optical data from the Skinakas observatory to study the optical variability of both radio quiet and radio-loud AGN, and data from space observatories (like Swift and XMM-Newton) to study the fast, X-ray variability in these objects. The group studies the variations of both high-z and nearby AGN, using sophisticated methods in the frequency domain (like power-spectrum, and time-lags analysis) as well as the use of simple statistics like variance-frequency plots, as well as simple spectral shape variations as a function of time. Recently, a theoretical effort has been initiated to construct a theoretical model for the broad-band emission (from optical to UV and X-rays) and use it to fit the broad-band spectral energy distribution from unobscured AGN, and the correlated optical/UV/X-rays variability that is observed in them.

<u>ROBOPOL blazars</u>: Blazars belong to the fraction of AGN whose supermassive black holes host a relativistic jet which is closely aligned with our line of sight. As a result, their emission is enhanced by relativistic effects, appearing shifted to higher frequencies and significantly boosted to very high observed brightnesses. Blazar jets emit across the electromagnetic spectrum. In optical wavelengths, they radiate optically thin Synchrotron, sampling various emission sites along the jet. This emission is highly polarized, with its polarization variability revealing important information about the location of the emission sites, the strength and degree of disorder of the jet magnetic field, and the relation of synchrotron with high-energy gamma-ray inverse Compton emission. Our group has been monitoring blazar optopolarimetric variability using the RoboPol polarimeter since 2013, conducting some of the most detailed, statistically robust studies to-date of the coherent rotations of the polarization angle observed occasionally in certain blazars.

<u>Search for Milli-lenses (SMILE)</u>: Gravitational lensed images with angular separation on milliarcsecond scales probe gravitational lens systems where the lens is a compact object with mass in the range 10^6 -10^6 $M_{\odot}$. This mass range is particularly critical for the widely accepted cosmological model, which predicts many more DM sub-galactic halos (masses below ~ 10^{11} $M_{\odot}$), than currently observed. The most direct way to explore these small angular scales is through the high-resolution radio Very Long Baseline Interferometry (VLBI). In the SMILE project, we propose to use VLBI data on a complete and large sample of radio loud active galaxies (~ 5000 sources) to search for gravitational lens systems on milliarcsecond scales. Given that no gravitational lenses on milliarcsecond scales have yet been found, if any of the gravitational lens candidates that this search will produce is indeed confirmed as a true gravitational lens system, this would be a first and a major discovery. A null

result instead will allow us to infer a new constraint on the abundance of compact objects in the mass range of interest, with over an order of magnitude better precision than in previous studies. Since the number of DM sub-galactic halos that can be detected through milli-lenses depends both on the mass function and the density profiles of DM halos, with the SMILE project we will be able to discriminate between many currently viable DM models.

Star Formation and Galaxy Mergers in the Local Universe

(Researchers involved: V. Charmandaris, T. Diaz-Santos, M. Sanchez-Garcia, A. Zezas)

Specific background:

Stars are the building blocks of galaxies. The process of star formation, starting from the collapse of rarefied gas and leading up to the ignition of thermonuclear reactions at the center of gravitationally bound molecular clouds is an extremely complex process. Moreover, the feedback from stellar winds and the eventual "death" of the most massive stars in super-novae (SN) explosions inject large amounts of energy and momentum in their surrounding interstellar medium (ISM), setting the stage for the formation of the next generation of stars. This "life cycle" of baryons within galaxies, together with the environmental conditions they are subject to (such as galaxy-galaxy mergers and the accretion of inter-galactic matter), are probably the most important pillars over which current theories of galaxy evolution stand, and therefore they are central to modern astrophysics.

Current efforts:

<u>The most energetic galaxies in the nearby Universe</u>: Luminous and ultra-luminous infrared galaxies ((U)LIRGs) are dust-obscured galaxies powered by star formation and/or AGN activity, with luminosities ten to hundred times larger than our own Galaxy. While they are not very common in the nearby Universe and only represent a modest fraction of the total infrared (IR) emission observed, their importance at earlier cosmic times becomes evident from the fact that they dominate the star formation rate density in the Universe during cosmic noon, from $z \sim 1$ to up to $z \sim 3$. A large fraction of (U)LIRGs are interacting systems. Researchers at the IA are active participants in large, international collaborations that focus on the study of nearby IR galaxies, such as the Great Observatories All-sky LIRG Survey (GOALS) and the Star-formation Reference Survey (SFRS). Multi-wavelength observations across the electromagnetic spectrum, from the radio through the X-rays, obtained with a wide suite of first-class observatories, are used in combination with state-of-the-art stellar evolution synthesis models to fit their spectral energy distributions and characterize their physical properties. In addition, we investigate the connection between galactic activity (star formation and AGN) and galactic parameters such as stellar mass, dust content, and morphology. We have produced a census of AGN activity in local IR galaxies and study of the relation between star-formation and stellar mass and other galaxy-wide scaling relations not only globally but also at sub-galactic scales. On-going projects include Hα and NIR imaging which will be used for the comparison of Hα and other SFR indicators in a variety of star-forming environments. We are also combining spatially resolved mapping and integral field unit observations obtained with the Spitzer Space Telescope and the Herschel Space Observatory to study the ISM properties in the extended regions of LIRGs. This project, called XTREME, aims to investigate the impact of the nuclear activity of these galaxies beyond their central, few kilo-parsec region. Our group is also heavily involved in several recent discoveries made with the James Webb Space Telescope as part of an Early Release Science program, as well as GO1 and GO2 approved programs. Using mid-IR MIRI/MRS 3D observations of three nearby LIRG nuclei, we have shown the critical interplay between the ionized and molecular ISM phases as well as the impact of AGN feedback in their circum-nuclear regions. Further, on-going

studies will deepen our understanding on the physics of these extraordinary objects.

Galaxy interactions and mergers: Galaxy mergers trigger vigorous star-formation and are responsible for activating their central SMBHs. Energetic feedback from these sources can generate high-velocity gas outflows heating up and carrying away a large fraction of the gas mass within the host galaxy, thereby rapidly truncating future star formation. We study galaxy mergers in the IR via the Hubble Space Telescope (HST), the Atacama Large Millimeter/submillimeter Array (ALMA) and the James Webb Space Telescope, which commenced operations in 2022. The IR and sub-mm radiation can penetrate through the dust which is ubiquitous in those galaxies and hence these data can give us a clear picture of the star-forming activity, the activity due to their SMBHs and their connection to the interaction process. Our group is combining datasets from HST, ALMA and JWST to study the connection between the star-formation and the molecular gas content in galaxy mergers on ~100 parsec scales, similar to the typical size of Giant Molecular Clouds (GMCs). Such a connection is described by the Schmidt-Kennicutt law, which is observed to vary depending on intrinsic galaxy properties but also as a function of other parameters, such as merger stage or position on the main sequence of star-forming galaxies. Studying these galaxies also helps us understand the origin of massive outflows and more generally understand galaxy evolution during its most rapid and violent stages. In this effort we also use multi-wavelength data from the Skinakas Observatory. In addition, the NuSTAR observatory gives us an unprecedented view of the hard X-ray emission from nearby galaxies.

Star-formation and AGN activity in normal, Milky-way type, nearby galaxies: Our group is leading studies of the star-forming activity in a representative sample of galaxies in the local Universe. The goals of this project are to: (a) compare different methods for measuring the star-formation rate and address the factors that influence these measurements; (b) measure the connection between recent and past star-forming activity in galaxy-wide as well as sub-galactic scales; (c) study the connection between star-forming activity and AGN activity. During 2023 we published a paper presenting new calibrations for the determination of SFR and stellar mass using WISE photometric data accounting for the contribution of old stellar populations in the dust emission, and a new diagnostic for the characterization of star-forming, passive and AGN-hosting galaxies based on infrared (WISE) photometry. We also continued the development of the Heraklion Extragalactic Catalogue (HECATE). This is the most complete, value-added catalogue of galaxies in the local Universe, including information on their stellar content (star-formation rate, stellar mass), metallicity, AGN activity. Such a catalogue is extremely useful for statistical investigations of nearby galaxies, but also for the fast identification and characterization of the hosts of transient events (e.g., gravitational-wave sources, gamma-ray bursts, tidal disruption events, supernovae etc).

Star-formation and X-ray binary populations in nearby galaxies: X-ray binaries are a key tool for understanding the evolution of binary stellar systems and the formation of their end-points such as sources of gravitational waves and short gamma-ray bursts. Studies of the discrete X-ray source populations (in particular accreting sources) in nearby galaxies allow us to: (a) probe areas of the parameter space that are not present in our neighborhood (e.g., different metallicity or star-formation history), and (b) obtain large statistical samples and explore rare types of systems. We have embarked in a systematic study of the X-ray binary populations and their integrated X-ray emission in nearby galaxies and their connection with their parent stellar populations (star-formation history, metallicity, etc) and star-cluster parameters. In addition, as members of the eROSITA Nearby Galaxies collaboration we are exploring the correlation between the integrated X-ray emission of galaxies and their stellar populations. The first results from this work are very intriguing since they suggest a population of galaxies with X-ray luminosities much larger than expected from the existing correlations between X-ray emission, SFR and stellar mass.

Dynamical signatures of past mergers in early type galaxies: According to the current scheme describing galaxy evolution, elliptical galaxies are the end-points in galaxy evolution, forming when the galaxies have converted most of their gas into stars, often during intense interactions. Recent deep observations of elliptical galaxies show that they exhibit ubiquitous structures that are tell-tale signatures of interactions that took place several billion years ago. The IA is very active in developing methods for the identification of these structures and studying their connection with past merger activity of the galaxy. In particular, we are interested in the determination of the mass function of disks and bulges in the local Universe. In addition, our group has pioneered the use of the spatial distribution of globular clusters as indicators of past merger activity, and more recently it is heavily involved in systematic studies of the identification of non-uniformities in the globular cluster distribution in elliptical galaxies in the Virgo and Fornax clusters. We have also extended this study to an investigation between the fine structure in elliptical galaxies and the stellar-mass deficit in their cores.

6.3. THE CONTENTS OF OUR GALAXY

General background:
Accretion is the dominant physical process of generating high energy radiation in many astrophysical contexts. Accretion of matter onto super massive black holes, located at the centers of nearly all galaxies, produces some of the most violent and energetic electro-magnetic and gravitational processes in extragalactic astrophysics: from giant radio lobes extending over tens of kiloparsec into the intergalactic medium, to relativistic jets of ionized, highly collimated matter (blazars), to X-rays from the interaction of BH binaries, to AGN-powered high-velocity galactic gas outflows.

Whether in isolation or in binary systems, white dwarfs, neutron stars, and black holes —collectively referred to as compact objects— allow the study of a variety of open questions in fundamental physics as they represent excellent laboratories to study matter under extreme conditions of gravity and magnetic field. In our work we use data from all major X-ray and radio telescopes as well as, supporting multiwavelength data from Hubble as well as ground-based telescopes.

Members of our group study individual sources that exhibit interesting or unique characteristics, populations of X-ray binaries, as well as their integrated X-ray emission and their connection to the stellar populations they are associated with.

X-RAY BINARIES
(Researchers involved: N. Kylafis, I. Papadakis, P. Reig, A. Zezas)

Specific background:
X-ray binaries are stellar systems consisting of a star and a stellar remnant such as black-hole, neutron star or a white dwarf. When material from the star (or donor) is falling onto the stellar remnant (or compact object), it is heated to temperatures of several million degrees and produces copious X-ray emission. In this process we may also observe jet-like collimated outflows or wide-angle winds of highly ionized plasma. The properties of this emission depend on the conditions close to the compact object and therefore can be used to study the behavior of matter under the influence of strong gravitational fields. In addition, the properties of a binary stellar system (e.g. parameters of the two objects and their orbit, long-term evolution) depend on the past of the two objects. Therefore, X-ray binaries are very useful laboratories for

studies of the properties of compact objects and stellar evolution.

The vast majority of X-ray binaries with massive companions harbor X-ray pulsars. The detection of pulsations from an accreting X-ray source provides one of the strongest pieces of evidence that the compact object is a neutron star. X-ray pulsations result from the misalignment of the neutron star spin and magnetic axis. Gas is accreted from the stellar companion and is channeled by the magnetic field onto the magnetic poles producing two or more localized X-ray hot spots. As the neutron star rotates, pulses of X-rays are observed as the hotspots move in and out of view. The change in the rotation velocity (spin-up or spin-down) of the neutron star allows measurements of accretion torques, which can provide a measure of the accretion rate and the magnetic field. In addition, we use multi-band (photometry, spectroscopy, and polarimetry) observations of X-ray binaries to study the nature of their donor stars, their orbital parameters and address their long-term variability. We combine these observational data with theoretical models of the emission from the accretion flow and jet outflows in order to obtain a better understanding of the physical processes which take place in those extreme environments.

Current efforts:

Black hole X-ray binaries: At present, the origin of the hard X-rays emitted by black hole binaries is controversial. There is general consensus that the hard X-rays result from inverse Compton of low-energy photons, presumably coming from the accretion disk, by high-energy electrons. However, the physical nature and the geometry of the Comptonization medium is still under debate. Black hole binaries exhibit relativistic jets at low/medium X-ray luminosity. We propose that the Comptonization medium is the entire jet. Our jet model has been able to explain many timing and spectral properties of black hole binaries. Currently, we work to improve the model to explain even more challenging results resulting from X-ray observations. Hard X-ray observations provide a valuable probe of the emission region near the compact object. Another goal of this project is to study the correlation between spectral parameters (X-ray continuum and discrete lines) and timing parameters (power-spectra, time lags) and of those with other observables (mass accretion rate, hardness of the spectrum). These correlations represent the tightest constraints for models.

Accreting pulsars: Members of the IA are working on providing unified characterization of accretion-powered pulsar spectral states during giant outbursts. In the last twenty-five years, the discovery of different "states'' in the X-ray emission of black-hole binaries (BHB) and neutron-star Low-Mass X-ray Binaries (LMXBs) constituted a large step forward in the understanding of the physics of accretion onto compact objects. While there are numerous studies on the timing and spectral variability of BHB and LMXBs, very little work has been done on High-mass X-ray Binaries (HMXBs). The goal of this project is to investigate the current observational evidence and find new one for the existence and identification of the various accretion regimes the pulsars go through during a major X-ray outburst. We have also embarked in a systematic study of the hard X-ray emission of outbursting accreting pulsars in the Small Magellanic Cloud. The goal of this project is to measure their magnetic field strength from the detection of Cyclotron lines, and the study of their phase resolved spectra at these high luminosities in order to constrain the dominant emission mechanisms and the geometry of the emitting region at different energies. Finally we have embarked in a systematic study of the outburst statistics of Be-XRBs in order to explore the connection between outburst characteristics and the orbital parameters of the system.

Variability time scales in Be/X-ray binaries (BeX): BeX consist of a neutron star orbiting a O9e-B2e main-sequence star. The letter "e" stands for emission, as instead of the normal photospheric absorption lines the optical spectra of Be stars display emission lines. Strong infrared emission is another defining characteristic of Be stars. A third observational property is that the light from a Be star is polarized. The origin of these three observational properties (emission lines, infrared excess, and polarization) lies in a gaseous, equatorially concentrated circumstellar disc around the OB star. This disc constitutes the main source of variability in BeX and the fuel that powers the X-ray emission through accretion. The main objective of this project is to characterize the optical/IR variability time scales of Be/X-ray binaries in correlation with their X-ray activity.

<u>X-ray binary characterization and spectral synthesis:</u> The characterization of the compact objects in X-ray binaries is a critical component for understanding their nature and testing binary population synthesis models. In 2023 we continued our efforts to develop methods for the characterization of the compact objects in X-ray binaries based on hard X-ray observations with NuSTAR, Chandra, XMM-Newton and other proposed X-ray missions. We also embarked in an effort to calculate integrated X-ray spectra from X-ray binary populations associated with stellar populations of different ages.

MASSIVE BINARIES AND THEIR COMPACT REMNANTS

(Researchers involved: J. Antoniadis)

Specific background:

Massive stars are among the most influential components of galaxies. They regulate star formation and inject vast amounts of energy and chemically-enriched material into the interstellar medium. Upon death, they often produce extremely energetic transients such as supernovae and gamma ray bursts. Their remnants (black holes and neutron stars) are often strong gravitational-wave emitters, important sources of heavy elements and exquisite tools for probing the properties of fundamental physical laws under extreme conditions. Most massive stars are thought to be members of binary or multiple systems that ultimately interact via mass transfer. Such binary interaction is expected to at least partially remove the hydrogen-rich envelope, creating stripped-envelope helium stars. These objects are thought to be responsible for approximately half of all observed supernovae, as well as for the majority of compact-object binaries. Despite their importance, their properties remain poorly constrained. Understanding their formation and evolution is a fundamental open question in astrophysics, motivating multi-billion-euro facilities such as the LIGO/Virgo/Kagra network, the Vera Rubin Observatory, SKA and the James Webb Space Telescope.

Current Efforts:

<u>Electron Capture Supernovae:</u> An electron-capture supernova (ECSN) is thought to occur when a degenerate ONeMg stellar core reaches the Chandrasekhar mass limit. As the density increases, Ne nuclei start capturing electrons, resulting in a sudden loss of outward pressure. The outcome of an ECSN depends on the competition between gravitational collapse, and the release of energy from explosive burning, and can range from the formation of a low-mass neutron star (NS), to the complete disruption of the star in a thermonuclear explosion. ECSNe are thought to be a crucial source of low-velocity NSs, which are required to explain the population of binary pulsars in the Galaxy, as well as the mergers seen by LIGO/Virgo.
Current Efforts at IA focus on modeling the complex evolution of ECSN progenitors in binary systems and understanding the impact of yet uncertain factors (such as nuclear reaction rates, stellar winds, initial composition, convection, etc.) on determining the final outcome. Recently we were able to demonstrate that a considerable fraction of ECSN progenitors is likely to avoid core collapse. This

happens because they initiate explosive oxygen burning when their central densities are below $\log\rho_c$ (g/cm^3) < 9.6, long before they reach the threshold for e-captures on Ne. The result is a thermonuclear runaway that looks similar to a Type Ia SN (CONe SN Ia). Our models imply that the amount of residual carbon retained after core carbon burning plays a critical role in determining the final outcome: Chandrasekhar-mass cores with residual carbon mass fractions of $X_{min}(^{12}C)> 0.004$ result in (C)ONe SNe Ia, while those with lower carbon mass fractions become ECSNe. (C)ONe SNe Ia are more likely to occur at high metallicities, whereas at low metallicities ECSNe dominate.

<u>Neutron star birth masses and islands of explodability:</u> Despite their importance, the relation between the initial properties of helium stars (e.g., mass, composition, rotation) and the remnants they create remains equivocal. The main reason is related to the complexity and computational cost of detailed core-collapse SN simulations. We have recently developed a toolbox that combines stellar evolution models with rapid semi-analytic neutrino-driven supernova models, to make predictions for the explosions (type, kinetic energy, ejecta mass, nickel mass) and remnants (type, mass, kick velocity). This approach enables parametric studies of thousands of progenitor models, at very small computational cost. Some highlights from the application of this approach to helium star models include: a) Detailed predictions for the mass spectrum of neutron stars and black holes across Cosmic Time (i.e., at different metallicities); b) the identification of low-energy explosions that result from a weak sound pulse that is launched when the initial SN ejecta become subsonic. The latter quickly become spherical, resulting in symmetric core-collapse explosions with *negligible natal kicks.* Such explosions may produce both low- (1.4 Msol) and high-mass (2.0 Msol) neutron stars, as well as stellar-mass black holes in the so-called lower mass gap (2.5 Msol); c) A large number of very massive stars with pre-collapse carbon-oxygen core masses above 10 solar masses, and extending up to at least 30 solar masses, may produce NSs or mass-gap objects, instead of BHs. This explosion landscape would naturally cause a fraction of massive binaries to produce compact object binaries with highly asymmetric masses, instead of symmetric-mass binary BHs. A population of such binaries, i.e. GW190814 and GW200210, has been identified during the third LIGO/Virgo run, in line with the predictions of this model.

<u>Observations of slow transients:</u> We have also been involved in a number of observational studies of stellar explosions, both at radio and optical wavelengths with facilities such as Effelsberg, MeerKAT and the Korean Microlensing Telescope Network (KMTNet). A recent highlight includes the earliest detection of a Type Ia supernova, only ~1 hour after the explosion (Ni et al. 2022). The infant phase of this transient provides strong evidence for radioactive material being present near the surface of the exploding white dwarf, as well as for interaction between the ejecta and a low-mass compact companion. This provides support for the so-called double degenerate scenarios in which a high-mass WD accretes material from a lower-mass WD. This discovery was made possible by the unique capabilities offered by KMNTNet. The latter consists of three, 1.5 m telescopes located in Australia, South Africa, and Chile, equipped with large 3x3 deg CMOS detectors and RVB optical filters.

<u>Pulsar Population studies:</u> The advent of multi-wavelength all-sky surveys in the past decade has created unique opportunities to probe various aspects of the Galactic pulsar population that were previously inaccessible. One important such survey is performed by the GAIA mission, that is delivering precise positions, distances and velocities for several billions of Milky-Way stars. In recent studies led by IA-FORTH members, the second (DR2) and early third (EDR3) GAIA data releases were used to perform a systematic search for optical counterparts to 1534 rotation-powered pulsars with positions known to better than 0.5 arcsec. This search returned 22 matches to known pulsars – thereby providing distance and velocity constraints – as well as 8 new candidate companions to young pulsars. This result was used to place

a stringent constraint on the multiplicity fraction of young pulsars (f_{young} < 5.3% at 95% C.L) and the properties of SN kicks.

Targeted Pulsar Searches: Similarly, the information provided by GAIA can also be used to identify objects that are likely to be orbited by millisecond pulsars. Such objects may include low-mass white dwarfs with high peculiar velocities, ablated stars that are coincident with gamma-ray counterparts, and nearby binary white dwarfs. We performed a pilot radio survey of 10 such white dwarfs with the 100-m Effelsberg and LOFAR telescopes, placing constraints on the fraction of NSs orbiting white dwarfs.

The ISM and Star Formation

(Researchers involved: D. Blinov, S. Kiehlmann, V. Pavlidou, V. Pelgrims, K. Tassis)

Specific background:

Investigating the physics of the interstellar clouds enables us to understand the initial conditions of star formation. In particular, the role of magnetic fields is critical, as it affects the formation of dense molecular clouds from the diffuse atomic clouds (by directing the accumulation of gas), it affects the dynamics of the clouds (by resisting the gravitational collapse as it provides an effective pressure) and together with turbulence regulates star formation. We observe the magnetic field in the optical through the polarization of starlight, induced by dichroic absorption of aspherical interstellar dust grains aligned with the local magnetic field that permeates the clouds. We also use magnetohydrodynamic simulations (both ideal and non-ideal) to explore the dynamical effect of the magnetic field both locally in the clouds and globally in galactic scales.

Current efforts:

The IA hosts a world-class center for polarimetric studies of point sources in the optical, featuring cutting-edge, innovative instruments, international collaborations with world-leading groups in instrumentation, observations, and theory, and a wide variety of applications, including studies of extragalactic jets, the interstellar medium, binaries, transient-follow ups, and study and control of foregrounds in the study of the polarization of the cosmic microwave background. Current opto-polarimetric programs running at Skinakas include PASIPHAE, RoboPol, and CIRCE/PHAESTOS. Our group uses observational data in the Infrared part of the electromagnetic spectrum from space-based (Planck, Herschel) and airborne-based (SOFIA) observatories; in the radio from single dish telescopes (ARO, FCRAO, Arecibo, Effelsberg) and in the optical at Skinakas Observatory (RoboPol).

Magnetic Fields in the Interstellar Medium: After suffering absorption by interstellar cloud dust, starlight may become polarised if the dust grains have a preferential alignment induced by the interstellar magnetic field. Studies of this polarisation with the RoboPol instrument can reveal the magnetic field structure in interstellar clouds.

Origins of molecular clouds: Our group has studied the transition from neutral atomic to molecular hydrogen in a cloud towards Ursa Major using a diverse dataset including HI, CO, C+ and optopolarimetric observations as well as theoretical interpretation efforts. We showed that the magnetic field is dynamically important, and plays an important role in determining where in the cloud the transition takes place.

Tomographic mapping of the interstellar magnetic field: We have developed a novel technique, to be used with PASIPHAE data, for the Bayesian tomographic decomposition of optopolarimetric observations along specific lines of sight. The technique determines the number and locations of different interstellar clouds in the line of sight, with simultaneous determination of the average polarization direction in each cloud, and the dispersion of polarization directions. This is achieved based on optopolarimetry of stars and stellar parallaxes alone, without input from other observables.

Interpretation of extreme turbulence in the Galactic center: We have provided an explanation for the abnormally high levels of turbulence observed in clouds within the central molecular zone of the Milky way, in terms of kinetic output from winds of massive stars. The model reproduces both the levels of turbulence, the scaling of turbulence line widths with cloud size, and the observed cutoff of excess turbulence with Galactocentric distance.

Astrophysics of ultra-high-energy cosmic rays and gamma rays: With energies higher than 10^{18} eV, ultra-high-energy cosmic rays are the most energetic particles known. They pack the energy of an aggressively served tennis ball in a single subatomic particle. Their flux at the highest energies is as low as one particle per square kilometer per century! Their origin remains, to this day, unknown, but they are certain to encode important information about the most extreme processes in the Universe. Our group develops novel approaches to their study, including assessing the possibility of back-tracing of their paths through the Galactic magnetic field to uncover their true arrival directions and thus better constrain their origin; develop tests of a multiple-source-population origin; and use gamma rays resulting from intergalactic cascades to identify the location of their sources. Our group also demonstrated that optopolarimetric observations can be used for development and demonstration of techniques to identify previously unknown members of this class.

Supernovae and Their Remnants

(Researchers involved: I. Leonidaki, I. Papamastorakis, A. Zezas)

Specific background:

Massive stars end their lives with spectacular explosions (supernovae). These explosions enrich the interstellar material with the heavy elements produced in the stars during their lifetime. In addition, the strong shock waves of the explosion heat the surrounding interstellar medium to temperatures ranging from ~10^3 to 10^7 degrees. Therefore, study of these supernova remnants can reveal information about the latest stages of stellar evolution, nucleosynthesis, physics of shock-waves and the properties of the interstellar medium.

Current efforts:

Constraining the distribution of supernova kick velocities. Supernova kicks are a critical parameter in the evolution of binary stellar systems with compact objects. They determine the survival of a system, its orbital parameters and its subsequent evolution. We are performing a multi-faceted study aiming at: (a) constraining the kick velocities of X-ray binaries based on modeling their evolution given their observed parameters, and (b) directly measuring their center-of-mass velocities based on their displacement from their birthplaces.

Narrow-band imaging of Galactic Supernova Remnants: Supernova Remnants (SNRs) are an important tool for understanding the physical processes that take place in the interaction between the shock wave from a supernova explosion and the stellar ejecta and/or the surrounding interstellar material. Narrow band images of SNRs in our Galaxy allow us to study their morphology and map their excitation, important parameters for understanding how the mechanical energy of the shock wave is transferred in the surrounding material.

Supernova Remnants in Nearby Galaxies: Studies of Supernova remnants in nearby galaxies provide a more complete picture of their populations by proving a wider range of supernova progenitors and ISM structures. We have embarked in a systematic study of the supernova remnant populations in nearby galaxies using narrow-band imaging observations from the CTIO and Skinakas Observatory. These observations are supplemented by IFU observations of individual regions of the galaxies.

EXTRASOLAR PLANETARY SYSTEMS

(Researchers involved: P. Kalas)

Specific background:
Over the past 30 years, several thousand planetary systems around other stars have been discovered and characterized around pre-main-sequence and main-sequence stars, encompassing many sub-disciplines such as planet formation, circumstellar disks, dynamics, atmospheric chemistry, demographics, astrobiology, and even the search for techosignatures. Our focus is on observational studies of dusty debris disks, wide-separation gas giant planets, and circumplanetary rings using a variety of resources, such as the Hubble Space Telescope, the Gemini Planet Imager, VLT/SPHERE, ALMA, Gaia, JWST and eventually Roman and HWO. Data from these observatories provide unique and fundamental information, such as:

<u>Physical Properties of Exoplanets</u>: Relying mostly on direct imaging techniques we estimate the masses of exoplanets, by analyzing how bright they appear and the properties of their orbits. Their composition is estimated, by analyzing the color of thermal emission from the planet, or by obtaining a spectrum. Finally, the origin of exoplanets is derived, by comparing their current observed properties with simulations of how planets form in a circumstellar disk and subsequently evolve.
Ultimately, this research provides an empirical notion of how common or rare our own planetary system must be in our own galaxy and throughout the universe.

Current efforts:

<u>Hubble Space Telescope:</u> We are leading multiple concurrent programs to image the morphologies of dusty debris disks and track the orbital motion of exoplanets using the HST/STIS coronagraph. Additionally, we were awarded a Legacy Archive project to add high-level science products in the public archive for all optical coronagraphic observations ever obtained by HST.

<u>James Webb Space Telescope</u>: We are investigating the properties of planetary systems as well as characterizing instrument performance as part of a large Early Release Science program.

<u>Gemini Planet Imager</u>: We are planning debris disk science programs for the upgraded instrument which will be installed on Gemini North on Maunakea in early 2025.

6.4. STATISTICAL METHODS AND SIMULATIONS

(Researchers involved: N. Kylafis, I. Papadakis, V. Pavlidou, P. Reig, K. Tassis, A. Zezas)

General background:
Modeling of complex astrophysical phenomena is an important tool for constraining as well as understanding the physical processes at play and for constraining the underlying physical parameters based on comparisons with observational data. In

addition, the increasing volume and complexity of the astronomical data requires the development of more efficient techniques for their analysis and interpretations, often involving state-of-the-art statistics and machine learning methods.

Specific background:
Our group is active in the development of models for complex astrophysical phenomena with the goal of comparing their predictions with observational results in order to understand the underlying physical processes. These efforts are focused in the fields of radiation transfer, chemistry, and fluid dynamics in the ISM, magnetic fields in the ISM, and X-ray binaries. In addition, we are interested in the development of methods for the analysis and characterization of astrophysical data using a broad range of information based on a wide array of space and ground-based observatories.

Current efforts:
Astrochemistry: Non-equilibrium chemodynamical multi-fluid non-ideal MHD simulations of star-forming molecular cloud cores. Our group developed and made public the non-LTE line radiative transfer code PyRATE.

Monte Carlo simulations of Compton up scattering in accreting neutron-star X-ray binaries: A major issue in High-Energy Astrophysics is where the high-energy, power-law emission occurs in black-hole and neutron-star X-ray binaries. One possibility is the hot, inner, accretion flow and the other is the jet. In a series of papers, we have advocated for the jet and have explained a number of observational constraints using a simple jet model. In a recent paper, we have been able to explain the neutron-star X-ray spectra, using the same simple jet model.

Classification of astrophysical sources: The reliable characterization of sources detected in large astronomical surveys is a major challenge given the growing volume of the available samples and the complexity of the available data. We are working on the development of efficient methods for the classification and characterization of sources employing state-of-the-art statistical and machine learning tools. The project underway includes: the distinction of supernova remnants from HII regions, the characterization of X-ray binaries on the basis of their compact object or accretion state, the characterization of stars according to their spectral types, and the activity classification of galaxies into star-forming, passive galaxies or AGN. In 2023 we published a paper presenting a mid-IR galactic activity diagnostic based on WISE photometric data.

Astrostatistics: In addition to the source classification methods, we have also embarked in an effort to develop methods for the principled analysis of imaging and spectroscopic data affected by source confusion. These methods are particularly relevant for the X-ray and gamma-ray regime. In 2023 we published a paper for the identification of extended sources of arbitrary shape in photon lists. In addition, we are working on methods for the analysis of LogN-LogS distributions at the Poisson limit accounting for source confusion. In this context we published a paper presenting a graph-based method for the identification of extended sources in event lists.

Modeling of X-ray binary populations: Standard methods of modeling the formation and evolution of X-ray binaries rely on a brute force approach and are relatively inefficient. We have introduced a methodology that uses a Markov Chain Monte Carlo technique as a wrapper to an already built and maintained binary evolution code. This way we are able to focus computational power on the region of the parameter space of interest. This approach allows efficient fitting of observed binary populations, while taking into account their spatial distribution and the spatially resolved star-formation history of their parent stellar populations. This method is now applied on the formation of the GW150914 progenitor.

Numerical studies of the Galactic Magnetic Field: Magnetic fields lie at the heart of all the outstanding problems in galactic evolution. We are developing the first simulations to include all the core processes of galactic evolution, such as a multi-phase interstellar medium, time-dependent star formation and stellar feedback, and the realistic non-ideal MHD terms necessary for modeling a realistic magnetic field evolution. The simulations are performed with the RAMSES and FLASH codes.

7. RESEARCH FUNDING

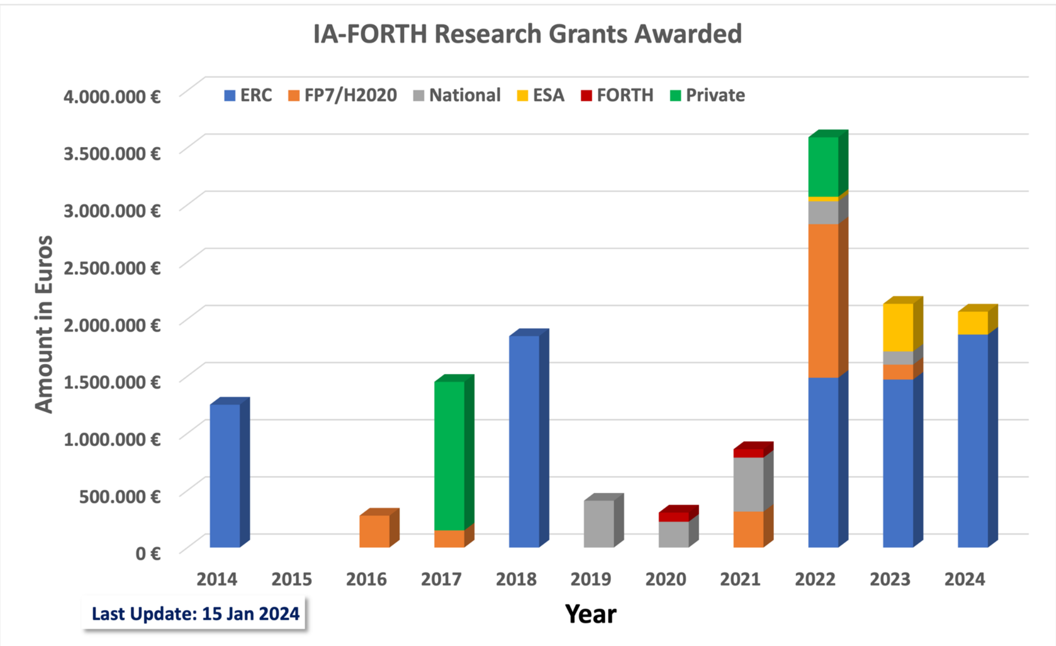
The following projects, funded by national and international agencies, enabled the research activities of the IA during the period of the report.

- Stavros Niarchos Foundation Grant in support of the project "PASIPHAE" (P.I.: K. Tassis, budget: $1,457,000, duration: 2016 – present)
- **ERC Consolidator Grant "PASIPHAE",** entitled "Overcoming the Dominant Foreground of Inflationary B-modes: Tomography of Galactic Magnetic Dust via Measurements of Starlight Polarization", (P.I.: K. Tassis, budget: €1,887,500, duration: 2018 – 2023)
- H2020 RISE, entitled "ASTROSTAT-II: Development of novel statistical tools for the analysis of astronomical data", (P.I.: A. Zezas, budget: €556,800, duration: 2019 – 2025)
- Interreg Greece-Cyprus GEOSTARS, (P.I.: A. Zezas, budget: €410,000, duration: 2019 – 2023)
- HFRI "Cosmic rays at the highest energies", (P.I.: V. Pavlidou, budget: €199,500, duration: 2020 – 2023)
- HFRI "European Pulsar Interior Composition Survey", (P.I.: I. Antoniadis, budget: €194,400, duration: 2020 – 2023)
- FORTH Synergy Grant "Reconstructing the Magnetic field of the Milky way via Astrophysical Techniques and Numerical Simulations", (P.I.: V. Pavlidou, budget: €80,000, duration: 2020 – 2023)
- H2020 INFRAIA, entitled "Opticon-Radionet Pilot", (Local contact: V. Charmandaris, budget: €40,000, duration: 2021 – 2025)
- ERASMUS+, entitled "Large Scientific Infrastructures enriching online and digital Learning", (Local contact: V. Charmandaris, budget: €53,300, duration: 2021 – 2023)
- HFRI "Magnetized galaxies through cosmic time: Simulating the galactic magnetic field across scales and epochs", (P.I.: E. Ntormousi, budget: €194,400, duration: 2021 – 2023)
- HFRI "Discovery Space - Creating an innovative network for teaching astronomy to K-12 via remote access of the telescopes at Skinakas Observatory", (P.I.: V. Charmandaris, budget: €94,500, duration: 2021 – 2024)
- HFRI PhD fellowship "Reconstructing the Magnetic Field of the Milky Way via Astrophysical Techniques and Numerical Simulations", (Fellow.: A. Tsouros, budget: €29,700, duration: 2021 – 2024)
- FORTH Synergy Grant "Computational Intelligence for Multimodal Astrophysical Tomography", (P.I.: K. Tassis, budget: €73,600, duration: 2021 – 2023)
- **ERC Starting Grant "SMILE"**, entitled "Search for Milli-lenses to discriminate between dark matter models", (P.I.: C. Casadio, budget: €1,486,000, duration: 2022 – 2027)
- HFRI "The Extended Interstellar Medium of Extreme Galaxies (XTREME)", (P.I.: T. Diaz Santos, budget: €199,840, duration: 2022 – 2026)

- Committee "Greece 2021", in support of the project "A new 1.0m optical telescope at Skinakas Observatory" (P.I.: V. Charmandaris, budget: $410,000, duration: 2022 – 2024)
- HFRI "Stellar Feedback: Explosive, Radiative, Interacting, and Coalescing Stars in their Surroundings - (SFERICSS)", (P.I.: E. Zapartas, budget: €115,474, duration 2023-2025)
- HORIZON-INFRA-DEV "ARGOS", entitled Designing a next-generation radio facility for multi-messenger astronomy", (P.I.: J. Antoniadis, budget: €3,000,000, duration: 2023 – 2025)
- DIGITAL-SIMPLE, "HellasQCI", entitled "Deploying advanced national QCI systems and networks in Greece", (P.I.: V. Charmandaris, budget: €39,600, duration: 2023 – 2025)
- ESA/EUC-PECS2021-01, entitled "CYprus models for Galaxies and their NUclear Spectra (CYGNUS+)", (P.I.: T. Diaz Santos, budget: €40,500, duration: 2023 – 2024)
- ESA/AO 1-11157/22, entitled "Skinakas Observatory upgrade as an Optical Ground Station", (P.I.: P. Reig, budget: €177,200, duration: 2023 – 2024)
- EU Space Programme, entitled "Financing of the provision of SST services and the upgrade of SST assets by the EU SST Partnership", (P.I.: V. Charmandaris, budget: €21,400, duration: 2023 – 2025)
- HORIZON-CL4-2023-SSA-SST-ART195 entitled "TOP-1: New & improved EUSST Missions and Services", (P.I.: V. Charmandaris, budget: €69,750, duration: 2023 – 2025)
- HORIZON-CL4-2023-SSA-SST-ART195 entitled "TOP-2: SST & STM system architecture and evolutions", (P.I.: V. Charmandaris, budget: €57,250, duration: 2023 – 2025)

Moreover, the following grants were awarded in 2023 but they will commence in 2024:

- **ERC Starting Grant "BOOTES"**, entitled " Black hOle Optical-polarization TimE-domain Survey", (P.I.: I. Liodakis, budget: €1,470,000, duration: 2024 – 2029)
- **ERC Starting Grant "MMMonsters"**, entitled "The first multi-messenger detection of a supermassive black hole binary", (P.I.: M. Charisi, budget: €1,864,000, duration: 2024 – 2029)



It should be notted that <u>at IA-FORTH, an institute of 10 tenure researchers, there are five (5) recipients of the highly competitive ERC grands,</u> of the 6 that have been awarded in the area of Universe Sciences (PE9) in Greece.

In summary of from 2014 until January 2024 the members of the Institute have been awarded a total of ~11 MEuros of new funding. A histogram of all grands received grouped by category is presented below:

8. INSTITUTIONAL COLLABORATIONS

Members of IA have established active long term scientific collaborations, funded by common research proposals and/or supported by institutional MoUs, with the following universities and research institutes:

- GREECE
  - National Observatory of Athens, Athens
  - University of Athens, Dept. of Physics, Athens
  - University of Piraeus

- INTERNATIONAL
  - California Institute of Technology, Pasadena, CA, USA
  - Cambridge University, Institute of Astronomy, Cambridge, UK
  - CEA/Saclay, Service d'Astrophysique, Paris, France
  - Astronomical Institute of the Czech Academy of Sciences, Czech Republic
  - European Southern Observatory, Garching, Germany
  - Geneva Observatory, Geneva, Switzerland
  - Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
  - Imperial College, London, UK
  - Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany
  - Max-Planck-Institut für Radioastronomie, Bonn, Germany
  - NASA/Jet Propulsion Laboratory, Pasadena, CA USA
  - Nicolaus Copernicus Astronomical Center, Warsaw & Torun, Poland
  - Northwestern University, Evanston, IL, USA
  - South African Astronomical Observatories, Sutherland, South Africa
  - Universidad Diego Portales, Santiago, Chile
  - University of California, Davis, Davis, CA, USA
  - University of Valencia, Valencia, Spain

Our polarimetric projects with colleagues at the Institute of Astronomy at Cambridge University are partially supported by The Gianna Angelopoulos Programme for Science Technology and Innovation (GAPSTI) and in particular its "Impact for Greece" initiatives.

9. COMMITTEES AND SERVICE

During the 2023 calendar year period covered by this report, members of the IA served in a number of national and international committees. Specifically:

Dr. J. Antoniadis is a member of the FORTH Gender Equality and Diversity Committee (since 2021), member of the Consortium Board of the Einstein Telescope, coordinator of the Greek Node and Council Board Member of the European Consortium for Astro-pArticle Theory and member of the ORP Sky Protection Working Group management Team and PI of the ARGOS Consortium.

Dr. C. Casadio is a member of the European VLBI Network (EVN) Program Committee since the beginning of 2022.

Prof. V. Charmandaris was a member of the Scientific Council of INSU/CNRS from 1/2019 until 12/2023 as well as of the Scientific Council of IRFU/CEA since 1/2023. He is the representative of Greece to the Board of Directors of the scientific journal “Astronomy & Astrophysics” since 2013 and Vice Chair of the Board since 2021. Since 2020 he has been the elected President of the Hellenic Astronomical Society as well as appointed member of the Section "Natural Sciences & Mathematics" of the National Council for Research & Innovation by the minister of research. In 2023 he was also appointed as member of the Evaluation and Accreditation Council of the Hellenic Authority for Higher Education. In 2023 he also became Chair of the Board of Directors of the Opticon-RadioNet-Pilot H2020 program.

Professor N. Kylafis is a member of the Council of the European Astronomical Society since 2018 and is a Treasurer of the Society since 2019.

Professor I. Papamastorakis is the Scientific Director of the Onassis Foundation Science Lecture Series, that take place every July at FORTH, since 2001.

Professor V. Pavlidou is the Deputy Director of IA, she is serving as the Management Panel Chair of the RoboPol Collaboration, as a National Education Coordinator of the International Astronomical Union for Greece, as the Chair of the “Eureka” creative teaching prize committee, and as a member of the Greek National Committee for Astronomy (since 2022). In 2023 she also commenced her appointment as Associate Editor of the international journal “Astronomy & Astrophysics”.

Dr. P. Reig is the Scientific Operations Manager of Skinakas Observatory and the Chair of the Scientific Council of the Institute of Astrophysics.

Professor K. Tassis is serving as the Management Panel Chair of the PASIPHAE Collaboration, as a National Education Coordinator of the International Astronomical Union for Greece, and is a member of the governing council of the Hellenic Astronomical Society.

Professor A. Zezas is serving as a member of the Athena WFI Instrument and Science Ground Segment team. He is also Chair of the Dept. of Physics of the Univ. of Crete.

10. Conference & Workshop Organization

The following conferences and meetings were organized by members of IA in Crete during the period of this report

- “The 10th Microquasar Workshop: the various facets of extreme gravity”, 22-26 May 2023
- “2023 Astronomy & Astrophysics Board of Directors Meeting”, 31 May-1 June 2023
- “2023 Summer School for Astrostatistics in Crete”, 19-23 June 2023
- “EVN Programme Committee Meeting”, 5-6 July 2023
- "10th Astronomical Data Analysis Summer School", 18-22 September 2023
- “ARGOS: Science Priorities for a European Wide-Field Radio Interferometer”, 24-27 October 2023

A record of all upcoming as well as past conferences/workshops organized is available at: https://www.ia.forth.gr/conferences

In 2019 IA established the "Nick Kylafis Lectureship" in order to honor Nick Kylafis, Professor Emeritus at the Dept. of Physics of the Univ. of Crete, on the occasion of his 70th birthday, for his 35 years of scientific contributions and leadership towards the founding and continuous improvement of the astrophysics group at the University of Crete and FORTH. This lifelong commitment has been instrumental in the international recognition of the research activities of the Crete astrophysics group, which eventually led to the creation of the Institute of Astrophysics at FORTH. Under the auspices of the Lectureship, one distinguished theoretical astrophysicist is invited annually at FORTH for a brief visit. See: https://www.ia.forth.gr/nick-kylafis-lectureship

The 2023 "Nick Kylafis Lectureship" was awarded to Prof. Steven Balbus, Savilian Professor of Astronomy at Oxford University, UK "for his seminal contributions in the field of theoretical astrophysics". Prof. Blabus visited the Institute of Astrophysics from October 17 to 20, 2023. His lecture was entitled "Understanding black holes from stars destroyed by tidal forces".

The formal seminars of IA organized on nearly weekly basis took place on Wednesday, with Dr. C. Casadio being the host. The complete program with recorded videos of most talks is available at: https://www.ia.forth.gr/seminars. It should be mentioned that among the regular astrophysics seminars we also included two seminars with a theme "Careers for astronomers outside academia" where astronomy PhDs who are in the private sector (Airbus, UK and HireVure, UK) presented their experiences on the transition from research to the industry.

Moreover, informal journal club talks organized by graduate students take place every Friday, and their schedule is available at: https://www.ia.forth.gr/journal-club

11. Education And Training

The affiliated faculty members of IA also offer undergraduate and graduate astronomy courses as part of their teaching responsibilities in the Dept. of Physics, of the Univ. of Crete. These are in addition to other physics courses they teach. For the 2023 calendar year these were:

- Spring Semester
  - "Astrophysics II" (Galactic and extragalactic astrophysics) (A. Zezas)

- Fall Semester
  - "Astrophysics I" (stellar structure and evolution) - V. Charmandaris
  - "Observational Cosmology" – I. Papadakis
  - "Astrophysics III" (Advanced radiative processes and radiative transfer) - K. Tassis

IA-FORTH in collaboration with the Dept. of Physics of the Univ. of Crete and the Society of Physicists of Crete organized the **3rd online School of Astrophysics of Crete**. The school took place during the months of March to May 2023 and it was addressed to high school students from Crete who were interested in obtaining a broad overview of modern astrophysics, as well as understanding the basic principles of physics that determine how our Universe works. A total of 146 students from 48 high schools of Crete attended the 8 online lectures.

Since 2001, FORTH also organizes on a yearly basis the "Onassis Foundation Science Lecture Series". The main speakers of these lectures are recipients of the Nobel Prize or of equivalent scientific stature. Support for the lectures is provided by the Onassis Foundation and Scientific Director of the Lectures is Prof. Ioannis Papamastorakis.

12. Public Outreach

Since 2022 the Institute has developed a more vibrant public outreach program having a dedicated person organizing its PO and educational activities which are presented in the dedicated web page of the Institute https://www.ia.forth.gr/public-outreach as well as in our Facebook page.

The tradition of open nights at Skinakas Observatory continued in 2023 with five nights offered to the public. During those, more than 2000 visitors had the opportunity to visit the observatory, peer through our telescopes and discuss with the astronomers. The events were also supported by members of the Astronomy Student Group of the University of Crete and their telescopes.

Moreover, in order to strengthen the ties with the town of Anogeia, a number of additional activities in close collaboration with the municipality were organized at its multipurpose facilities of "Shepher's Land". These included hosting the annual meeting of the amateur astronomers of Crete on July 22, 2023 followed by a dedicated stargazing event, a shadow theater event for kids entitled «Ο Καραγκιόζης στο Φεγγάρι» July 21, 2023, as well as the contemporary "Space Cadet" dance and music event, on August 5, 2023. These were very well received and we expect to continue this type of activities next year.

IA-FORTH, in collaboration with the Center for Open Online Courses Mathesis of the Crete University Press, continued for a third year its support of the "Eureka Prize" which is addressed to the anxious Secondary Education teachers who experiment with more creative forms of teaching and learning, either in the main body of the curriculum program or outside school hours. More specifically, the prize recognizes educational activities that are inspired by the most attractive and at the same time the most dynamic part of fundamental physics today: Astronomy. The 2023 prize was awarded to Ms. Sevasti Malamou from the Music School of Ioannina, on December 2, 2023. Following the award ceremony a public forum discussion on creative teaching of science topics in high schools took place, in which members of the board of the Physics Teachers Union of Crete and the Amateur Astronomer Club of Crete, as well as many highschool teachers participated.

On September 29 2023, the institute participated in the "Researcher Night" showcasing results from Skinakas Observatory. In addition IA sponsored five shows using of a portable planetarium, provided by the "Planetarium of Crete The immersive experience of the planetarium offered to young visitors unique stimuli and a clearer understanding of our cosmos, in particular for concepts related to the motions of the sun and the planets and the vastness of the universe.

On October 22 2023, IA-FORTH also participated in the 3rd puzzle festival which took place at the small and isolated island of Kastelorizo. During this event the few students and the small number of inhabitants of the island, as well as several visiting students from nearby islands, along with visitors and academic guests had the opportunity to observe the sun as well as the night sky with the portable telescopes. These were provided by IA-FORTH and the "PAGKRITION" school which is one of the schools-hubs of the DSPACE project, funded by HFRI.

In the framework of the World Space Week 2023, IA-FORTH in collaboration with the Department of Physics of the University of Crete, organized again this year a public outreach event on Thursday October 5, 2023. The event, which was also supported by members of the Astronomy Student Group of the University of Crete and astronomy PhD students, offered educational activities, hands-on experiments on topics related to space sciences to nearly 90 elementary and highschool students from Crete.

In 2023, FORTH celebrated its 40-years and a number of special events were organized all over Greece. On September 22-23 2023, IA-FORTH, in collaboration with eFantasy.gr and other companies, organized an event entitled "Discover the World of Science through board games". The scope was to demonstrate how often complicated scientific concepts can be understood using games.

The Institute also participated in general exposition of all institutes that took place during the week of December 10-15 at Saint Mark's Basilica in Heraklion displaying the historic first CCD camera of Skinakas Observatory, which in 1986 was the first digital camera to be used for astronomical observations in Greece. Finally, a special event was organized on Friday December 15 2023 entitled "Reading the clock of sky" during which a sundial created by the sculptor Andreas Galanakis was donated for a period of 6 months and was placed at the main entrance of the FORTH bldg. The same evening four dedicated talks on time, sundials, and the well known "Antikythera Mechanism" were presented to the general public during an event in the in the Vikelaia Municipal Library of Heraklion.

Finally an album entitled "Skinakas Observatory: A view to the Universe", which contains pictures of celestial objects taken with the telescopes of Skinakas observatory was produced in 2023 as part of the Interreg project "GEOSTARS". All pictures of the book are also available in the gallery of IA. https://gallery.ia.forth.gr/index.php?/category/65

13. VISITORS

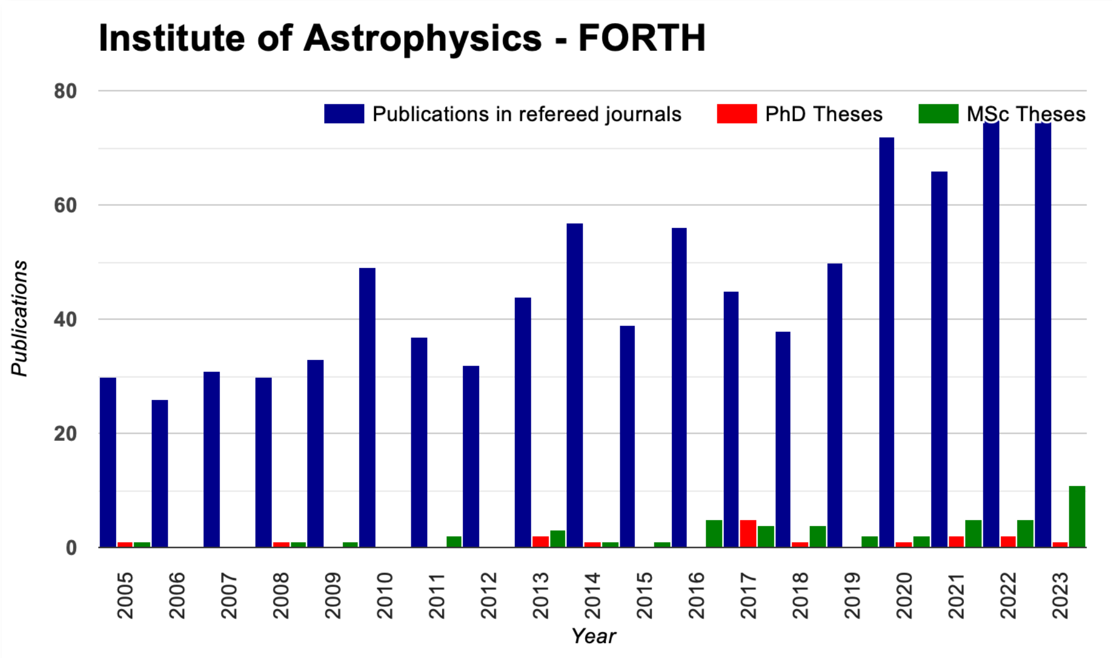
In addition to the IA fellows, Prof. Charisi, Prof. M. Chatzopoulos, Prof. Gilmore, Prof. P. Kalas, and Dr. J.-L. Starck, **a total of 30 scientists visited IA in 2023** in order to collaborate with our staff and/or give seminars. These researchers were:

Dr. Paola Andreani (ESO, Germany), Prof. Steven Balbus (Oxford University, UK), Dr. Lucie Baumont, (CEA/Saclay, France), Mrs. Barbara Cader-Sroka (University of Wrocław, Poland), Prof. Stefano Camera, (Univ. of Torino, Italy), Dr. David Elbaz (CEA/Saclay, France), Dr. Samuel Farrens (CEA/Saclay, France), Dr. Daniel Gilman (University of Toronto, Canada), Prof. Michael Janssen (Radboud University, Germany), Dr. Elias Kammoun (Università Roma Tre, Italy), Prof. Patrick Kelly (University of Minnesota - Twin Cities, USA), Dr. Martin Kilbinger (CEA/Saclay, France), Dr. Johan Knapen (Instituto de Astrofísica de Canarias, Spain), Dr. Maria Kopsachili (IEEC-CSIC, Spain), Dr. François Lanusse (CEA/Saclay, France), Dr. Yannis Liodakis (NASA/MSFC, USA), Dr. Lea Marcotulli (Yale University, USA), Prof. Telemachos Mouschovias (University of Illinois Urbana-Champaign, USA), Prof. Kohta Murase (Penn State University, USA), Dr. Fabrizio Nicastro (Rome Observatory, Italy), Dr. Alessandro Paggi (Univ. of Torino, Italy), Prof. Klea Panayidou (European University Cyprus, Cyprus), Prof. Maurizio Paolillo (University "Federico II" of Naples, Italy), Prof. Kallia Petraki (École Normale Supérieure, France), Dr. Skalidis Raphael (Caltech, USA), Dr. Gudrun Tausch-Pebody (University of Cambridge, UK), Dr. Núria Torres Albà (Clemson University, USA), Dr. Vivian U (Univ. of California - Irvine, USA), Prof. Lukasz Wyrzykowski (Warsaw University, Poland).

Morever, **a total of 7 PhD students visited** IA-FORTH to collaborate with our scientists. These were: Mr. Vincenzo Petrecca (University "Federico II" of Naples, Italy), Ms. Konstantina Dachlythra (Stockholm University, Sweden), Ms. Vilasini Tinnaneri Sreekanth (CEA/Saclay, France), Ms. Namita Uppal (Physical Research Laboratory, India), Mr. Tejal Bhattarai (Constructor University, Germany), Ms. Ruchika Dhaka (IIT Kanpur, India), Ms. Palanimuthu Koushika Vaiyapuri (Univ. of Cantabria, Spain).

14. Publication Statistics

During 2023 the members of IA in Crete produced **76** publications that appeared in print in refereed journals (according to NASA/ADS). This corresponds to ~**4** publications per PhD researcher. An additional **12** refereed papers were published by IA-FORTH research fellows, who spent only a fraction of their research time visiting Crete. The full publication list is available in the Appendix.



The histogram above shows the number of papers published in refereed journals by members of IA-FORTH since 2019. We also include the publications, from 2005 until 2018, of the Crete Astrophysics Group of FORTH and Univ. of Crete, which preceded the creation of IA-FORTH.

15. Contact

All members of the Institute of Astrophysics - FORTH are housed in a dedicated area of ~600 m^2 on the second floor of the Physics Bldg, on the campus of the University of Crete located 8 km south-west of Heraklion, the largest city on the island of Crete, Greece. The postal address of IA is:

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Foundation for Research and Technology – Hellas
Vassilika Vouton
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16. APPENDIX

16.1. SKINAKAS OBSERVATORY

Skinakas Observatory operates as part of a scientific research collaboration between the University of Crete and the Foundation for Research and Technology-Hellas (FORTH). A new MoU, signed between FORTH and the University of Crete in 2018, formally assigns the management of the Observatory to the Director of IA-FORTH, who also acts as the Director of the Observatory. The location of the observatory was chosen in the early 1980’s after an intensive search for a site with clear and dark skies. The site of the Observatory is the Skinakas summit of Mount Ida (Psiloritis) at an altitude of 1750 m and a distance of 60 km from Heraklion (on the island of Crete, Greece). Its geographic coordinates are: Longitude 24º 53' 57'' East and Latitude 35º 12' 43'' North.

Facilities on site

The Observatory hosts three telescopes: a Modified Ritchey-Chrétien telescope with a 1.3 m aperture (f/7.6), which became operational in 1995, a 60 cm Cassegrain robotic telescope (f/8) installed in 2006, and a 30cm Schmidt telescope (f/3.2), the first telescope of the Observatory which had its first light in 1986.

In 2001, a photovoltaic plant was built, making the Observatory independent of external fossil energy sources. Two emergency generators, rated at 45 and 33 kVA, are capable of supporting all Skinakas observatory operations in the event of power failure. A Guest House, formally named “Ioannis Papamastorakis” in 2019, to honor the founding Director of the Observatory, completes the infrastructure of the observatory. The ground floor of the Guest House accommodates three bed-rooms, two bath-rooms, one storage-room, fully-equipped kitchen and a living-room. The basement is used for storage purposes.

Using funds from an Interreg program between Greece and Cyprus, as well as additional support from the University of Crete, as of summer 2022 a new building and a 5.3m dome (made by Baader Planetarium GmbH), hosts again the 60 cm robotic telescope. A new 1.0m robotic optical telescope, which was ordered from ASA Astrosysteme GmbH in September 2022, is expected to be placed in this dome in the summer of 2024.

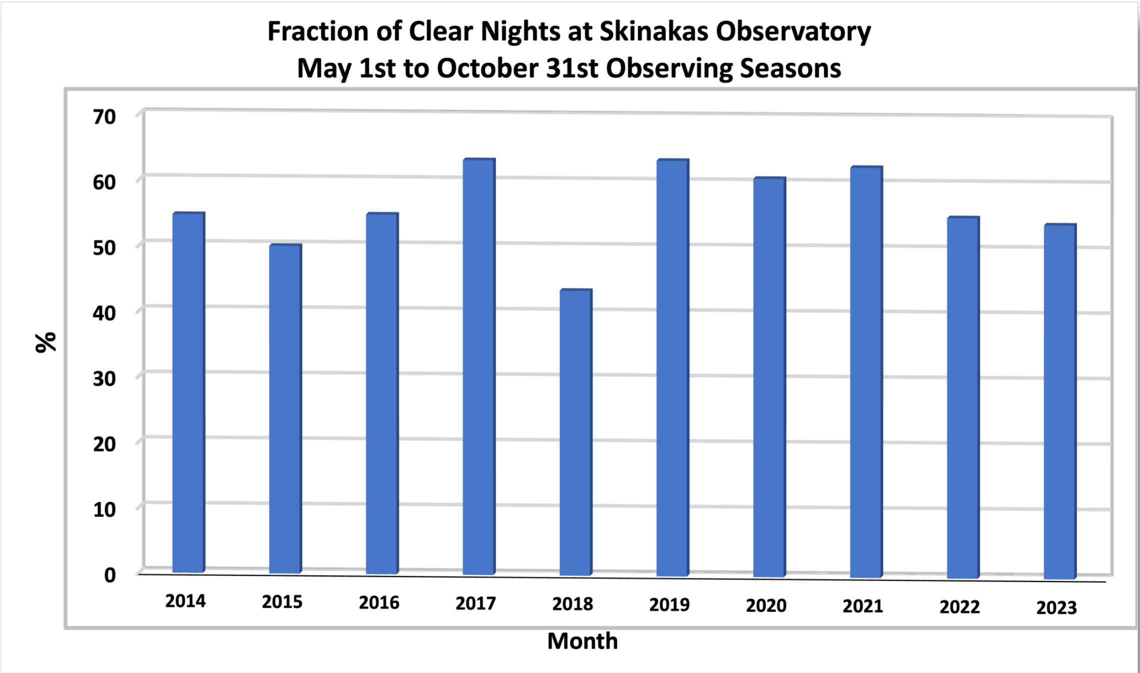
Facilities at sea level

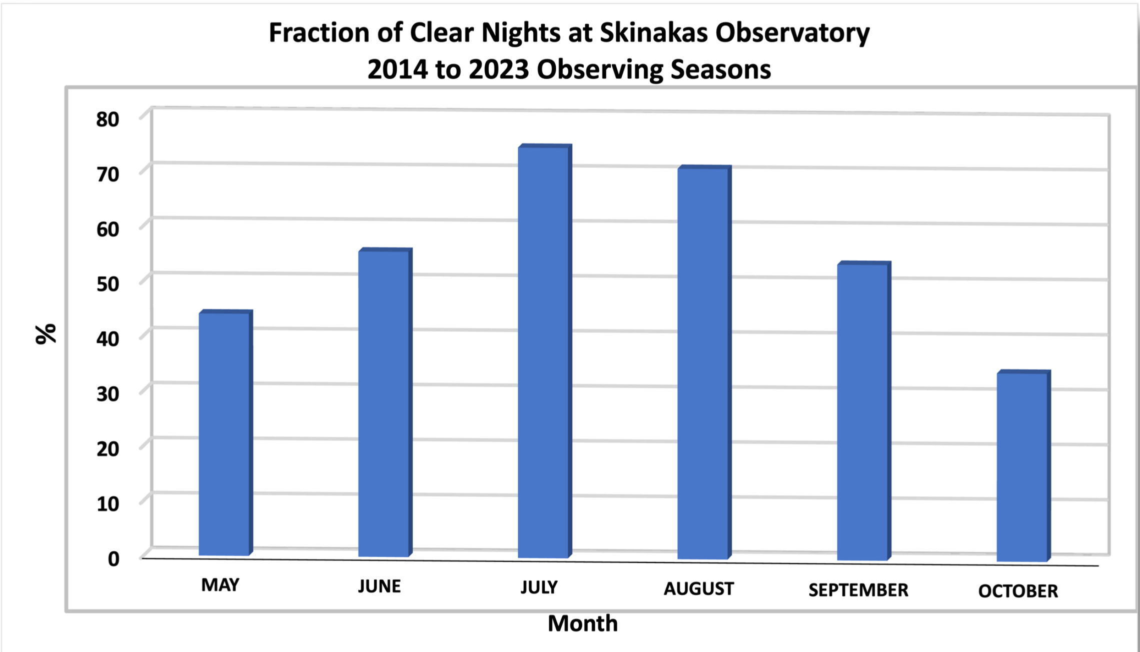
Office space for the staff is located on the premises of the Department of Physics of the University of Crete. An instrumentation lab with an optical table and a computing room are also part of the sea-level facilities. The observatory owns two vehicles used for the transportation of material and personnel. These are a SKODA Rapid (2014) and a TOYOTA HILUX (2008).

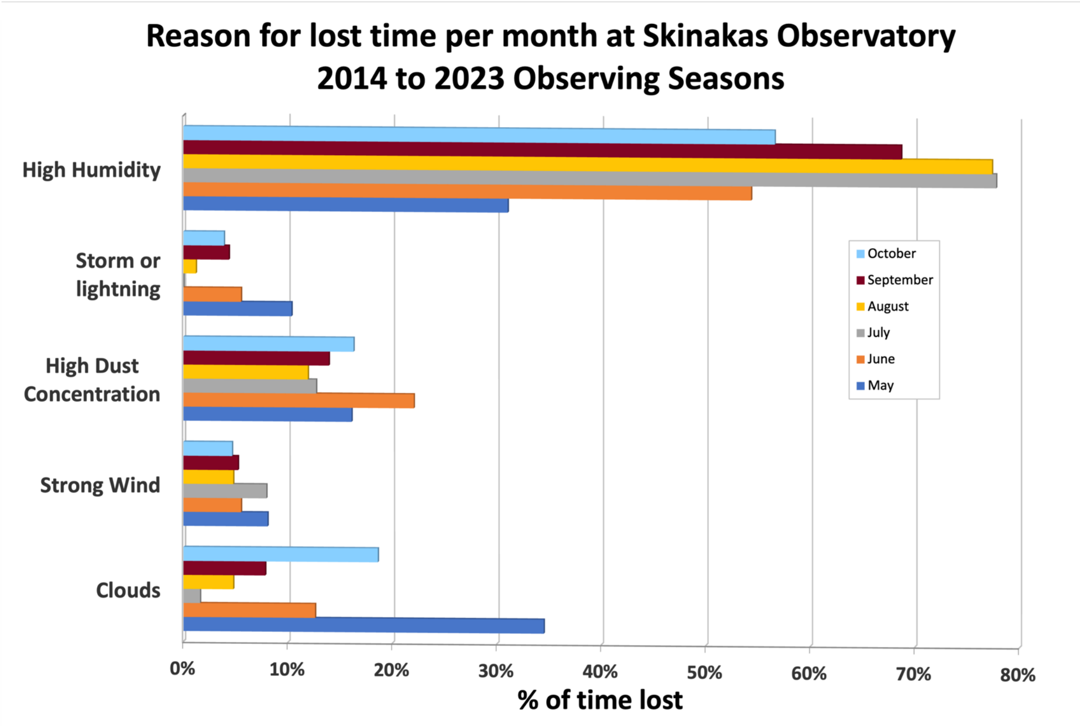
Scientific Operations

Typically, the Observatory operates from late April until early December. The Observatory remains closed for the winter months, mainly because of the cost to keep the road open from snow. However, the emerging possibilities to also perform service operations using the telescopes of Skinakas for satellite tracking and/or support ground to space laser telecommunications, will likely increase the operational window of the facility in the coming years.

In the following we present some statistics on the operations of the facility based on the observers logs over the past ten years (2014 to 2023). The average number of nights the Observatory operates per season is 176 with the average full clear nights to be over 60% the past three years. The best months are July and August, with over 70% of the nights being clear. High humidity is the major reason for not observing (~50% of the cases) with clouds and then dust, due to southern winds, being the other two reasons.







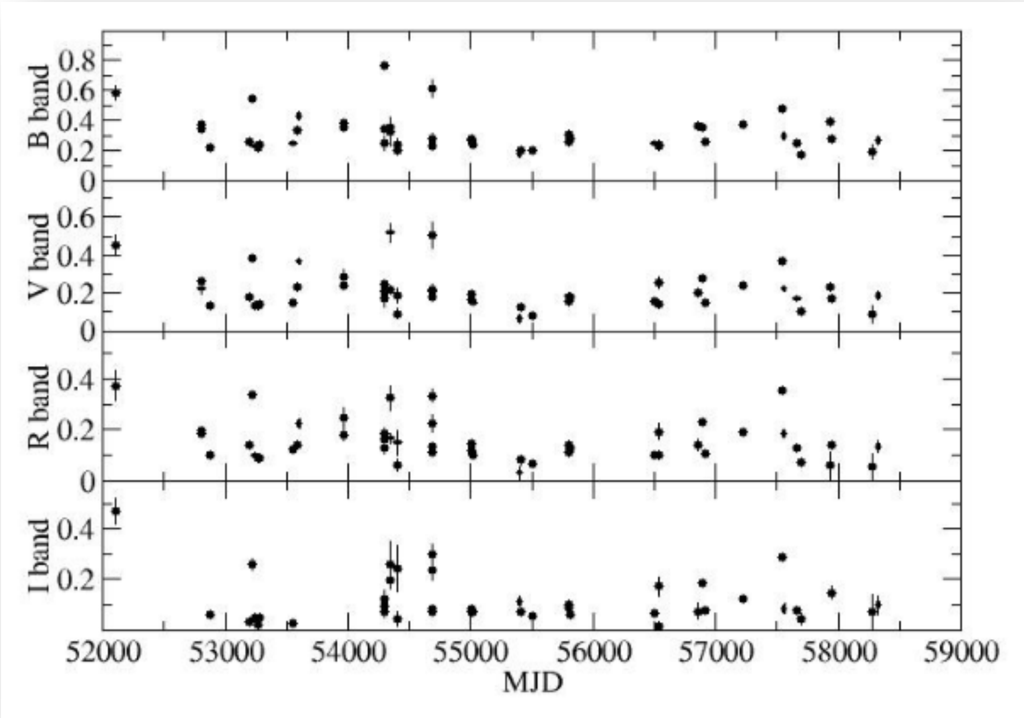
More specifically the reasons the observatory did not operate due to weather were:

- High humidity: It refers to the number of nights during which the dome was closed because the humidity level was higher than the allowed limit of 80%.
- Clouds: These are nights when the clouds prevented normal operation but the humidity was in the allowed range.
- Strong wind: It refers to the number of nights during which the dome was closed because the wind velocity was higher than the operational limit of 70 km/h (or > 50 km/h if pointed directly into the wind).
- High dust concentration: When the dust level was higher than 800 particles per cubic feet.

The number of nights the 1.3m telescope was closed due to technical problems was less than 1%.

Atmospheric Extinction

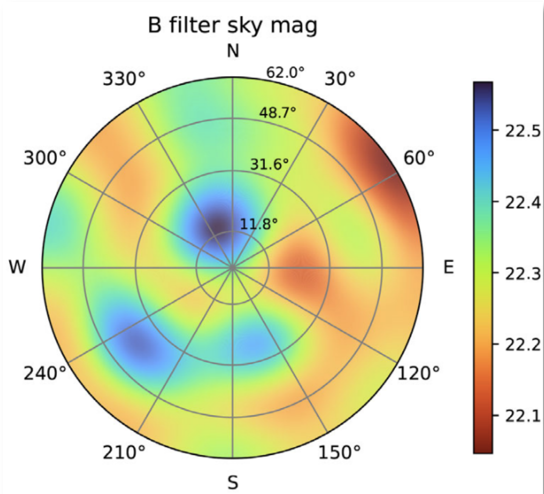
Atmospheric extinction is the astronomical parameter that evaluates sky transparency. Sources causing degradation of the sky transparency are clouds (water vapor) and aerosols (dust particles included). The extinction values and their stability throughout the night are essential for determining the accuracy of astronomical measurements. The nights with low and constant extinction are classified as photometric.

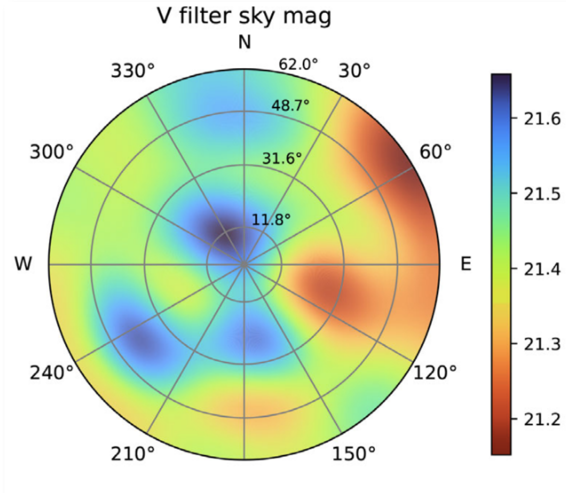


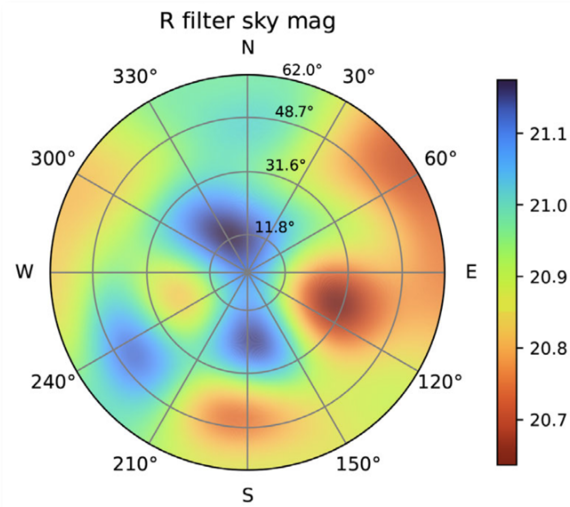
The extinction at the Skinakas Observatory during photometric nights are (in mag/airmass): 0.26 ± 0.06 for B, 0.17 ± 0.03 for V, 0.13 ± 0.04 for R, and 0.09 ± 0.06 for I.

Night Sky Brightness

Night sky BVR brightness observations were conducted during 12 nights from early June to late October 2016 and revealed that Skinakas Observatory is a relative dark site, with the exception of the direction towards the city of Heraklion (North East). The average night sky surface brightness towards zenith was found to be B=22.80±0.10, V=21.92±0.09, R=21.39±0.07 mag/arcsec^2. Comparison with a similar study which was performed in 2008 did not show a statistically significant change. The brightness maps are presented below while the full report is available here.







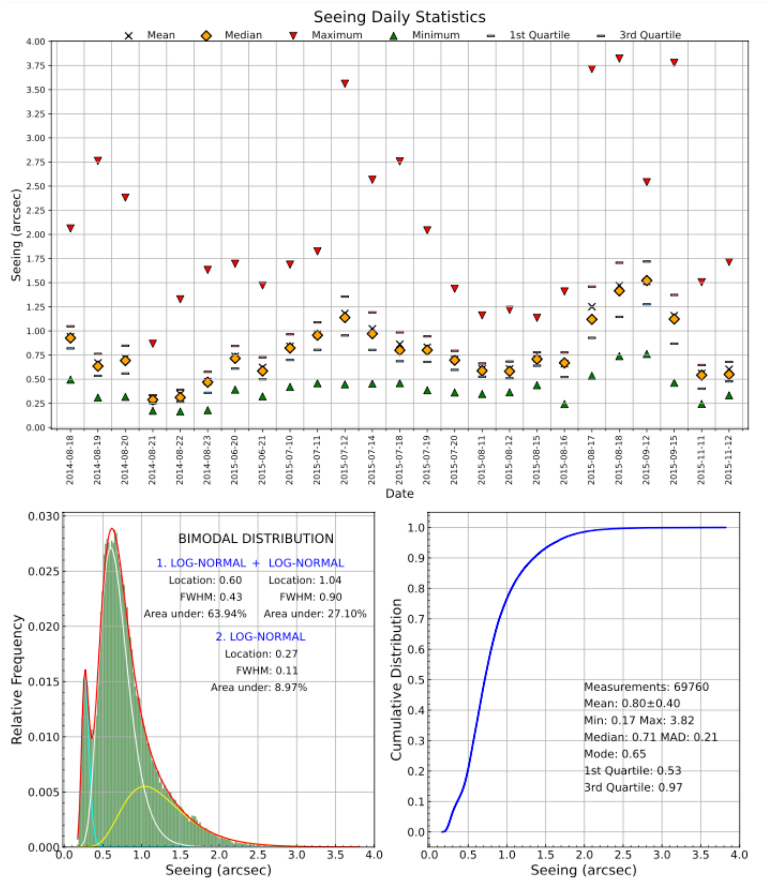
An older internal report on the night sky spectrum at Skinakas, along with an estimate of the contribution of the light pollution lines to the sky brightness can be found here.

Seeing conditions

The Skinakas Summit is an excellent site for astronomical observations. As it can be seen in the satellite photo to the right, showing the island of Crete and Africa in yellow at the bottom of the photo, since the winds are typically from the north and the closest land mass to the north is the island of Santorini, some 150km away, the flow of air reaching the Skinakas peak is laminar. Only when there are strong winds from the south, sometimes including dust from the Sahara Desert, there is turbulence.

Using a two-aperture Differential Image Motion Monitor (DIMM), the seeing over Skinakas was measured in 2000 and 2001. For a total of 45 nights, the median seeing was found to be less than 0.7 arcsec.

Image of Crete from the International Space Station taken on 13 Oct. 2019.



Seeing measurements during 25 nights in 2014 and 2015

Subsequent sporadic measurements of seeing during 25 nights in 2014 and 2015 confirm that the overall seeing conditions have not changed. An analysis of those is available here.

A more detailed analysis on the Skinakas weather conditions is presented in a 2023 internal report by Dr. P. Reig and it is available here.

THE 1.3 M TELESCOPE

The optical system of the 1.3 m telescope was manufactured by Carl Zeiss (Germany), and the mechanical parts by DFM Engineering (USA). It has an f/7.6 focal ratio giving a scale of 0.021 arcsec/μm in direct mode (Table 1). With the use of the focal reducer, the scale is multiplied by 1.87. The telescope works together with an off-axis guiding unit, which provides tracking with an accuracy of 0.2 arcsec.

The main mirror was re-aluminized in 1998, 2004, 2011, and 2019 while some key technical characteristics are presented in the tables below:

PRIMARY MIRROR (M1)	
PHYSICAL DIAMETER	1300 (1290) mm
APERTURE	1230 mm
THICKNESS	200 mm
CURVATURE RADIUS	7380 mm
FOCAL LENGTH	3690 mm
CENTRAL HOLE	350 mm
WEIGHT	5700 N

SECONDARY MIRROR (M2)	
PHYSICAL DIAMETER	456 mm
FREE DIAMETER	446 mm
EFFECTIVE (EF) DIAMETER	412 mm
RADIUS OF CURVATURE	-3953 mm
FOCAL LENGTH	-1976 mm
OUTER "EF" DIAMETER	552.5 mm

SYSTEM	
FOCAL LENGTH	9857.0 mm
FOCAL RATIO	7.64
DISTANCE M1 to M2	2453.4 mm

Instrumentation

General overview:

A number of instruments are permanently available on the 1.3 m telescope. These include an auto-guider, three optical CCD cameras with complete filter sets, a long slit optical spectrograph providing low/intermediate resolution (R=1000-8000), a near-IR wide field camera, and an optical polarimeter. All the digital cameras and the optical elements associated with them are installed and attached to the telescope through the Guiding and Acquisition Module (GAM). Therefore, Skinakas offers the observers the possibility to carry out intermediate-low dispersion spectroscopy, wide-field imaging, and polarimetry. A movable diagonal mirror and the fast-cooling of the CCD cameras allow the observer to switch among the various instrumental configurations in a very short time (~30 minutes). However, changing to the near-IR camera requires daytime engineering work. When the near-IR camera is mounted, no other instrument option is available.

The Tables below summarize the observing capabilities of the 1.3 m telescope.

Optical Imaging				
CCD	**Size (pixel)**	**Scale ("/pixel)**	**Filters**	**Field of view (')**
Andor iKon-L 936	2048x2048	0.28	Jonhson Stromgren interference	9.5 x 9.5

Polarimetry				
CCD	**Size (pixel)**	**Scale (''/pixel)**	**Filters**	**Field of view (')**
Robopol ANDOR DW436	2048x2048	0.435	B, V, R, I SDSS r', g', i'	13 x 13

Spectroscopy					
CCD	**Size (pixel)**	**Scale (''/pixel)**	**Wavelength Range (Å)**	**Resolution**	**Slit width('')**
Andor iKon-L 936	2048x2048	0.529	3500 - 10000	1000 < R R< 8000	2, 4, 13

Infrared Imaging				
Instrument/focal plane array	**Size (pixel)**	**Scale (''/pixel)**	**Filters**	**Field of view (')**
Rockwell Science Center, Inc. HgCdTe	1024x1024	0.38	Broad (J,H,K) Fe,Br-γ,CO,H	6.5 x 6.5

CCD cameras

The observatory has four ANDOR 2048x2048 pixels CCDs with 13.5 μm pixel size. All four CCDs use thermoelectric water cooling (Peltier effect) to achieve an operational temperature of between -70 to -90ºC. Three CCD are used for direct imaging (*Andor iKon L-936, #CCD-20241*), spectroscopy (*Andor iKon L-936, #CCD-20240*), and polarimetry (*Andor DW436*) on the 1.3m and the fourth on the 30 cm telescope (*Andor DZ436*).

With the optical characteristics of the 1.3 m telescope, these values translate into a field of view of 9.5 arcmin x 9.5 arcmin for direct imaging, 13 arcmin x 13 arcmin in the polarimetry mode, and 18 arcmin x 18 arcmin for spectroscopy.

In addition, an SBIG auxiliary CCD with 1536x1024 pixels and 9 μm pixel size is used in the auto-guider.

A near-IR camera, manufactured by Fraunhofer IOF was commissioned in 2006. It is an f/7.7 Offner design with a Rockwell Hawaii Array of 1024x1024 and pixel size 18.5 μm, providing an image resolution of 0.38 arcsecs per pixel, and a 6.5 arcmin x 6.5 arcmin field of view. It covers the spectral range between 1 and 2.4μm. The near-IR camera has not been used during the period of the report.

Filters

The observers can choose among a full set of narrow and broad-band photometric filters. The broad-band filters available are the Johnson-Couisins U, B, V, R, I and the SDSS u', g', r', i', z'. The narrow-band filters are the full Strömgren set u, v, b, y, Hβ(narrow), Hβ(wide) and more than 15 interference filters. In the infrared, the observatory offers three broad-band filters J, H, and K, and five narrow-band filters: FeII (16440 Å), H_2 (21220 Å), H_2 (21440 Å), Br-γ (21660 Å), and CO (22950 Å). The Tables below gives the list of filters together with some technical information.

Standard Johnson-Cousins filters			
Type	**Central Wavelength (Å)**	**FWHM (Å)**	**Peak Transmission (%)**
U	3640	320	63
B	4350	980	72
V	5380	980	88
R	6300	1180	82
I	8940	3370	96

List of Strömgren filters			
Type	**Central Wavelength (Å)**	**FWHM (Å)**	**Peak Transmission (%)**
u	3500	330	57
v	4110	170	67
b	4685	183	83
y	5493	235	84
Hβ wide	4890	145	80
Hβ narrow	4869	32	80

Near-IR Filter Characteristics	
Type	**Central Wavelength / FWHM**
FeII	1644 nm /17 nm
H_2	2122 nm /22 nm
H_2	2144 nm /22 nm
Br-γ	2166 nm /22 nm
CO	2295 nm /231 nm
J-band	1250 nm /160 nm
H-band	1635 nm /290 nm
Ks-band	2150 nm /320 nm

List of interference filters				
Type	**Central Wavelength (Å)**	**FWHM (Å)**	**Peak Trans. (%)**	**Refraction index**
[OII]3727	3727	25	60	2
[OIII]4363	4363	10	35	2
HeII4686	4687	20	46	2
Hβ4861	4864	28	65	2.1
[OIII]5007	5010	28	63	2.1
[OIII]5007	5007 (April 2013)	25	52	2.1
[NII]5755	5755	10	52	2
HeI5876	5877	20	54	2
Hα6563	6563	10	52	2
Hα+[NII]	6575	20	48	2
Hα+[NII]	6570	75	80	2.1
[NII]	6584	20	60	2
[SII]6716	6716	10	47	2
[SII]6720	6720	27	80	2.1
[SII]6731	6731	10	57	2
[SII]6735	6735	30	48	2
[SIII]	9069	20	70	2
Continuum	6096	134	-	-

Spectrograph

For spectroscopic observations, the focal reducer is used as a slit spectrograph with slit widths 80, 160, 320, and 640 μm. A range of gratings results in dispersion from 530 Å/mm to 25 Å/mm.

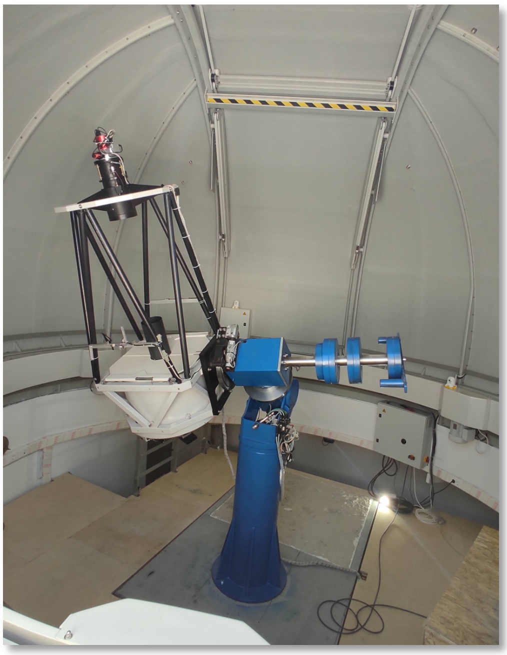
Gratings for the Focal Reducer				
Grating (lines/mm)	**Blaze Wavelength (nm)**	**Wavelength in 1st order for max. intensity**	**Dispersion (Å/mm)**	**Mounted**
3600	250	231	25.41	No
2400	430	397.3	37.8	Yes
1302	550	508.1	70.44	Yes
1302	480	443.5	70.27	Yes
1200	700	646.7	76.39	Yes
651	530	489.7	137.6	Yes
600	750	692.9	150.8	Yes
600	500	461.9	148.4	Yes
325.5	550	508.1	269.0	No
325.5	430	397.3	267.3	Yes
162.75	500	461.9	529.1	No

Polarimeter

RoboPol is a specialized photopolarimeter designed specifically for the 1.3 m telescope at Skinakas and commissioned in the spring of 2013. It was conceived, designed, and developed by the RoboPol Collaboration, which is comprised of the University of Crete and the Foundation for Research and Technology – Hellas in Greece, the California Institute of Technology in the United States, the Max-Planck Institute for Radioastronomy in Bonn, Germany, the Nicolaus Copernicus University in Poland, and the Inter-University Centre for Astronomy and Astrophysics, in Pune, India.

RoboPol was designed with high observing efficiency and automated operation as prime goals. It uses no moving parts other than the filter wheel. Instead, a combination of half-wave plates and Wollaston prisms are used to separate photons with orthogonal linear polarizations, retard them, and simultaneously produce four images on the CCD detector for each source in the focal plane. The photon counts in each "spot" are used to calculate the Stokes parameters of linear polarization. This novel, 4-channel design eliminates the need for multiple exposures with different half-wave plate positions, thus avoiding unmeasurable, dominant systematic errors due to sky changes between measurements. A mask in the focal plane of the telescope prevents unwanted photons from the nearby sky and sources from overlapping with the central target on the CCD, further increasing the sensitivity of the instrument. Its large, 13′x13′ field of view allows relative photometry using standard catalogs and the polarimetric mapping of large regions in the sky.

THE 0.6 M TELESCOPE



The 60 cm Cassegrain telescope, called Ganymede, following an agreement between the Univ. of Crete and the Univ. of Tübingen, was installed at the Observatory in 2006, using an old existing dome. It operated until 2012 when the dome was destroyed by adverse weather conditions. As mentioned in Section 4.1 of this report, the new building and 5.3m Baader dome where the telescope is housed again, was completed in May 2022. The optics and electronics of the telescope were upgraded in 2021 and in June 2022 it commenced again normal operations.

During 2023, the 60 cm telescope was used in primary focus mode (camera placed at the position of the secondary mirror). The camera used was a 6064 x 4040 Omegon veTEC410c with 5.9 μm pixel size. This configuration offers a wide field of view of 0.74º x 1.1º

The telescope is also equipped with a full suite of the standard optical filters.

We anticipate that in addition to standard imaging/monitoring science projects the telescope will be used for EU-SST projects in the future. Its absolute pointing is better than 1 arcmin and the relative (post processing) better than 1 arcsec. Slew rate for changing the pointing direction is 4º/sec and the pointing stability ~1 arcsec in 4 hr with an autoguiding system.

THE 0.3 M TELESCOPE

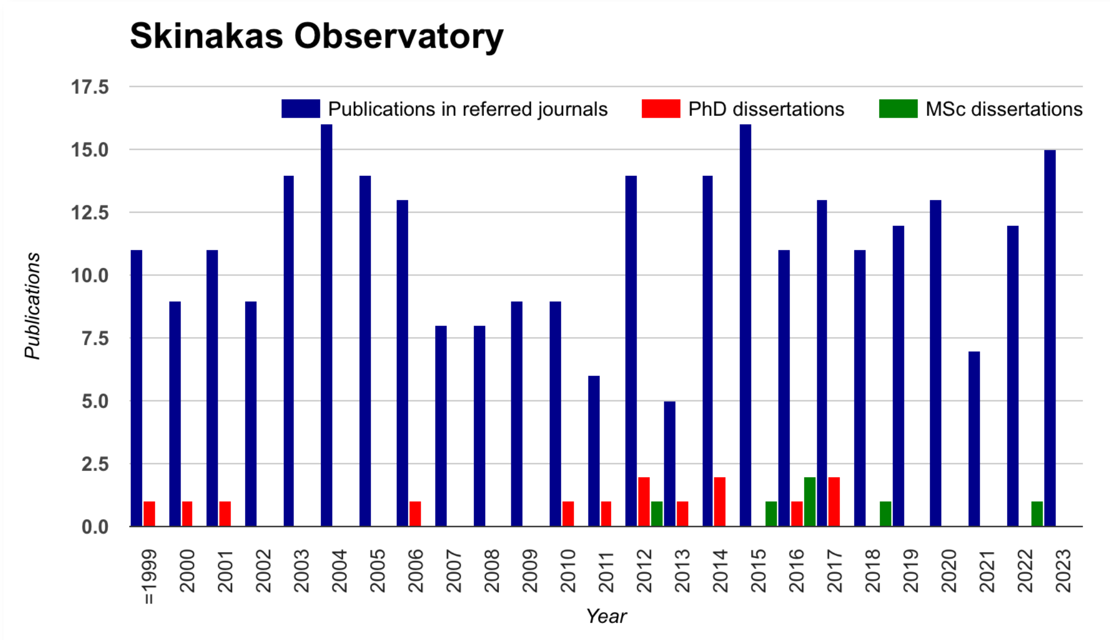
The 30 cm Schmidt-Cassegrain telescope (f/3.2) was the first one installed on Skinakas Observatory in 1986 and it was equipped with the first CCD camera ever used for astronomy in Greece.

It has a computer controlled German mount built by Eckard Alt and an off-axis guiding system. It provides a high-quality wide field of view and has been used extensively in studies requiring monitoring and supernovae remnants as well as for public outreach activities. In its current configuration the telescope is equipped with an ANDOR DZ 436 CCD with a 2048 x 2048 chip and 13.5 μm pixel size, resulting in a pixel scale of 3 arcsec and a field of view of 1.7 square degrees.

The telescope is used in direct imaging mode. A six-slot filter wheel allows the observations in six different photometric bands. It should be noted that the same filters available for the 1.3 m telescope can be used in the 0.3 m telescope. It was used to produce a large fraction of the images of extended objects presented in the book «Αστεροσκοπείο Σκίνακα: Με θέα το Σύμπαν» ("Skinakas Observatory: A view to the Universe") edited by Crete University Press in 2010. A new version of the book, this time is English, was produced in 2023 as part of the Interreg project "GEOSTARS".

SKINAKAS OBSERVATORY PUBLICATIONS

Until the end of 2023 observations from the telescopes at Skinakas Observatory have resulted in a total of 280 publications in refereed journals, which have received ~8000 citations. In addition, 15 PhD and 6 MSc dissertations have been produced using data from Skinakas Observatory. A histogram of those publications as a function of time, follows:



A total of **15 refereed papers** using data from Skinakas Observatory, **including one in Nature Astronomy and 1 in Science**, were published in 2023.

A few select publications using Skinakas data, which have been well cited, follow:

- "Polarized X-rays constrain the disk-jet geometry in the black hole x-ray binary Cygnus X-1", Krawczynski, H. et al., **2022**, Science, 378, 650 [64 citations]
- "Full orbital solution for the binary system in the northern Galactic disc microlensing event Gaia16aye", Wyrzykowski, Ł., et al. **2020**, A&A, 633, 98 [30 citations]
- "RoboPol: first season rotations of optical polarization plane in blazars", Blinov, D., et al. **2015**, MNRAS, 453, 1669 [89 citations]
- "Be/X-ray Binaries", P. Reig, **2011**, ApSS, 332, 1 [429 citations]
- "Very fast optical flaring from a possible new Galactic magnetar" Stefanescu, A., Kanbach, G., Słowikowska, A. et al., **2008** Nature, 455, 503
- "Correlated fast X-ray and optical variability in the black-hole candidate XTE J1118+480", Kanbach, G., Straubmeier, C., Spruit, H. C., Belloni, T., **2001**, Nature, 414, 6860, 180 [125 citations]
- "Optical and radio behaviour of the BL Lacertae object 0716+714", Raiteri, C. M. et al., **2003**, A&A, 402, 151 [192 citations]
- "Are spiral galaxies optically thin or thick?", Xilouris, E.M., Byun, Y.I., Kylafis, N.D., et al. **1999**, A&A, 344, 868 [258 citations]

A complete list of all publications from Skinakas Observatory is available at:

https://skinakas.physics.uoc.gr/en/index.php/research

16.2. The 2023 Refereed Publication List

The **76** refereed publications of the members of IA in Crete during 2023, as well the **12** of the IA-FORTH research fellows are presented below:

1. Abe, H., Abe, S., Acciari, V. A., Agudo, I., Aniello, T., Ansoldi, S., Antonelli, L. A., Arbet-Engels, A., Arcaro, C., Artero, M., Asano, K., Baack, D., Babić, A., Baquero, A., Barres de Almeida, U., Barrio, J. A., Batković, I., Baxter, J., Becerra González, J., Bednarek, W., Bernardini, E., Bernardos, M., Berti, A., Besenrieder, J., Bhattacharyya, W., Bigongiari, C., Biland, A., Blanch, O., Bonnoli, G., Bošnjak, Ž., Burelli, I., Busetto, G., Carosi, R., Carretero-Castrillo, M., Castro-Tirado, A. J., Ceribella, G., Chai, Y., Chilingarian, A., Cikota, S., Colombo, E., Contreras, J. L., Cortina, J., Covino, S., D'Amico, G., D'Elia, V., da Vela, P., Dazzi, F., de Angelis, A., de Lotto, B., Del Popolo, A., Delfino, M., Delgado, J., Delgado Mendez, C., Depaoli, D., di Pierro, F., di Venere, L., Do Souto Espiñeira, E., Dominis Prester, D., Donini, A., Dorner, D., Doro, M., Elsaesser, D., Emery, G., Escudero, J., Fallah Ramazani, V., Fariña, L., Fattorini, A., Foffano, L., Font, L., Fruck, C., Fukami, S., Fukazawa, Y., García López, R. J., Garczarczyk, M., Gasparyan, S., Gaug, M., Giesbrecht Paiva, J. G., Giglietto, N., Giordano, F., Gliwny, P., Godinović, N., Grau, R., Green, D., Green, J. G., Hadasch, D., Hahn, A., Hassan, T., Heckmann, L., Herrera, J., Hrupec, D., Hütten, M., Imazawa, R., Inada, T., Iotov, R., Ishio, K., Jiménez Martínez, I., Jormanainen, J., Kerszberg, D., Kobayashi, Y., Kubo, H., Kushida, J., Lamastra, A., Lelas, D., Leone, F., Lindfors, E., Linhoff, L., Lombardi, S., Longo, F., López-Coto, R., López-Moya, M., López-Oramas, A., Loporchio, S., Lorini, A., Lyard, E., Machado de Oliveira Fraga, B., Majumdar, P., Makariev, M., Maneva, G., Mang, N., Manganaro, M., Mangano, S., Mannheim, K., Mariotti, M., Martínez, M., Mas-Aguilar, A., Mazin, D., Menchiari, S., Mender, S., Mićanović, S., Miceli, D., Miener, T., Miranda, J. M., Mirzoyan, R., Molina, E., Mondal, H. A., Moralejo, A., Morcuende, D., Moreno, V., Nakamori, T., Nanci, C., Nava, L., Neustroev, V., Nievas Rosillo, M., Nigro, C., Nilsson, K., Nishijima, K., Njoh Ekoume, T., Noda, K., Nozaki, S., Ohtani, Y., Oka, T., Okumura, A., Otero-Santos, J., Paiano, S., Palatiello, M., Paneque, D., Paoletti, R., Paredes, J. M., Pavletić, L., Persic, M., Pihet, M., Pirola, G., Podobnik, F., Prada Moroni, P. G., Prandini, E., Principe, G., Priyadarshi, C., Rhode, W., Ribó, M., Rico, J., Righi, C., Rugliancich, A., Sahakyan, N., Saito, T., Sakurai, S., Satalecka, K., Saturni, F. G., Schleicher, B., Schmidt, K., Schmuckermaier, F., Schubert, J. L., Schweizer, T., Sitarek, J., Sliusar, V., Sobczynska, D., Spolon, A., Stamerra, A., Strišković, J., Strom, D., Strzys, M., Suda, Y., Surić, T., Tajima, H., Takahashi, M., Takeishi, R., Tavecchio, F., Temnikov, P., Terauchi, K., Terzić, T., Teshima, M., Tosti, L., Truzzi, S., Tutone, A., Ubach, S., van Scherpenberg, J., Vazquez Acosta, M., Ventura, S., Verguilov, V., Viale, I., Vigorito, C. F., Vitale, V., Vovk, I., Walter, R., Will, M., Wunderlich, C., Yamamoto, T., Zarić, D., MAGIC Collaboration, Cerruti, M., Acosta-Pulido, J. A., Apolonio, G., Bachev, R., Baloković, M., Benítez, E., Björklund, I., Bozhilov, V., Brown, L. F., Bugg, A., Carbonell, W., Carnerero, M. I., Carosati, D., Casadio, C., Chamani, W., Chen, W. P., Chigladze, R. A., Damljanovic, G., Epps, K., Erkenov, A., Feige, M., Finke, J., Fuentes, A., Gazeas, K., Giroletti, M., Grishina, T. S., Gupta, A. C., Gurwell, ., Heidemann, E., Hiriart, D., Hou, W. J., Hovatta, T., Ibryamov, S., Joner, M. D., Jorstad, S. G., Kania, J., Kiehlmann, S., Kimeridze, G. N., Kopatskaya, E. N., Kopp, M., Korte, M., Kotas, B., Koyama, S., Kramer, J. A., Kunkel, L., Kurtanidze, S. O., Kurtanidze, O. M., Lähteenmäki, A., López, J. M., Larionov, V. M., Larionova, E. G., Larionova, L. V., Leto, C., Lorey, C., Mújica, R., Madejski, G. M., Marchili, N., Marscher, A. P., Minev, M., Modaressi, A., Morozova, D. A., Mufakharov, T., Myserlis, I., Nikiforova, A. A., Nikolashvili, M. G., Ovcharov, E., Perri, M., Raiteri, C. M., Readhead, A. C. S., Reimer, A., Reinhart, D., Righini, S., Rosenlehner, K., Sadun, A. C., Savchenko, S. S., Scherbantin, A., Schneider, L., Schoch, K., Seifert, D., Semkov, E., Sigua, L. A., Singh, C., Sola, P., Sotnikova, Y., Spencer, M., Steineke, R., Stojanovic, M., Strigachev, A., Tornikoski, M., Traianou, E., Tramacere, A., Troitskaya, Y. V., Troitskiy, I. S., Trump, J. B., Tsai, A., Valcheva, A., Vasilyev, A. A., Verrecchia, F., Villata, M., Vince, O., Vrontaki, K., Weaver, Z. R., Zaharieva, E., & Zottmann, N., Multimessenger Characterization of Markarian 501 during Historically Low X-Ray and γ-Ray Activity., 2023, The Astrophysical Journal Supplement Series, 266, 37.

2. Acharyya, A., Adams, C. B., Archer, A., Bangale, P., Benbow, W., Brill, A., Christiansen, J. L., Chromey, A. J., Errando, M., Falcone, A., Feng, Q., Finley, J. P., Foote, G. M., Fortson, L., Furniss, A., Gallagher, G., Hanlon, W., Hanna, D., Hervet, O., Hinrichs, C. E., Hoang, J., Holder, J., Jin, W., Johnson, M. N., Kaaret, P., Kertzman, M., Kieda, D., Kleiner, T. K., Korzoun, N., Krennrich, F., Lang, M. J., Lundy, M., Maier, G., McGrath, C. E., Millard, M. J., Millis, J., Mooney, C. L., Moriarty, P., Mukherjee, R., O'Brien, S., Ong, R. A., Pohl, M., Pueschel, E., Quinn, J., Ragan, K., Reynolds, P. T., Ribeiro, D., Roache, E., Sadeh, I., Sadun, A. C., Saha, L., Santander, M., Sembroski, G. H., Shang, R., Splettstoesser, M., Talluri, A. K., Tucci, J. V., Vassiliev, V. V., Williams, D. A., Wong, S. L., VERITAS Collaboration, Hovatta, T., Jorstad, S. G., Kiehlmann, S., Lähteenmäki, A., Liodakis, I., Marscher, A. P., Max-Moerbeck, W., Readhead, A. C. S., Reeves, R., Smith, P. S., & Tornikoski, M., VERITAS Discovery of Very High Energy Gamma-Ray Emission from S3 1227+25 and Multiwavelength Observations., 2023, The Astrophysical Journal, 950, 152.

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