Solar Axion Searches at CERN with the CAST Telescope

for the **CAST Collaboration**

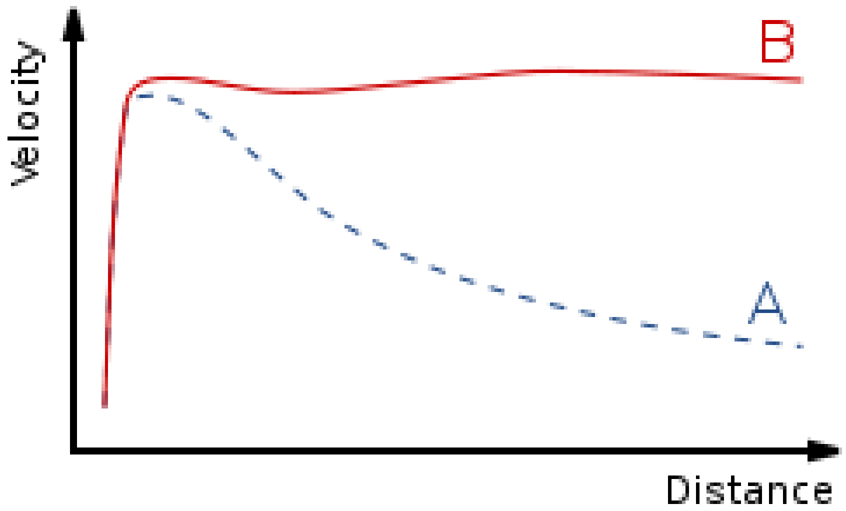
Christos Eleftheriadis

Aristotle University of Thessaloniki

Ioannina, September 5th, 2011

10th Hellenic Astronomical Conference

Dark matter: a lot of candidates



Hot dark matter, like neutrinos

Cold dark matter (this is the strong candidate..)

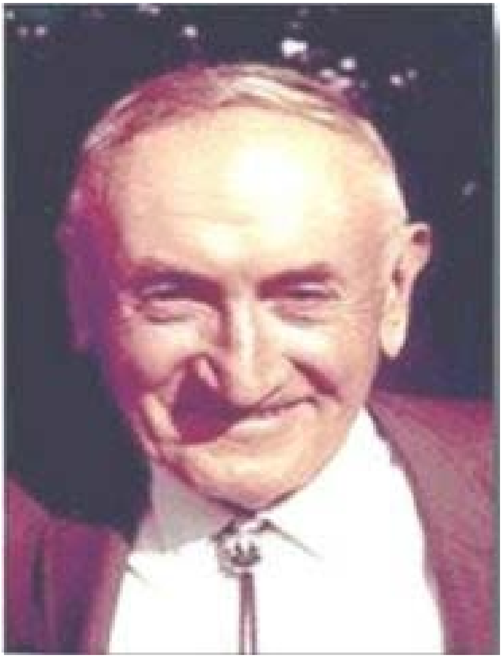
WIMPS (~3 PhDs per parameter… may be more)

Neutralino LSP

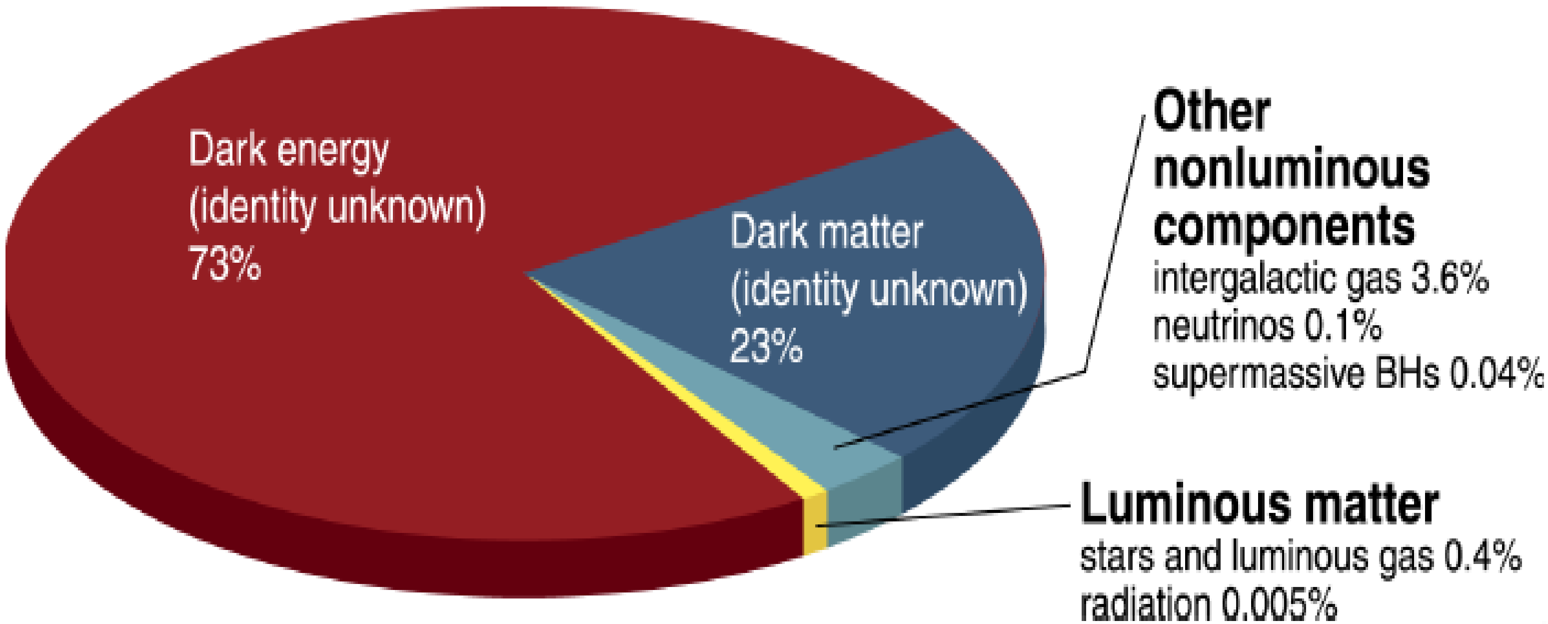
MACHOs… … and last but not least → **Axions**

Relativistic particles cannot be controlled by gravity→ rotation curves cannot be explained in terms of HDM

Fritz Zwicky (1898-1974)



The cosmological inventory:



- But, what is dark energy or dark matter ?

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A brief history of axion…

The strong CP violating term can be suppressed easily!

You just need a massless quark!

→ …no quark is massless..

A solution proposed by Peccei and Quinn:

new global chiral U(1) symmetry spontaneously broken at scale f_{α}

θ is not anymore a constant, but a field → the axion a(x)

→ Broken symmetry → Goldstone theorem

Appearance of a spinless particle → Nambu-Goldstone boson (axion)

If symmetry is perfect → massless …However, for some reason, no symmetry is perfect in this world → axions acquire a small mass

recapitulating...

- Axions are predicted to have
  - **no charge,**
  - **very low mass,**
  - **spin-parity 0^-**
  - **very low interaction cross-sections**

$$m_a = 6\,\mathrm{eV}\,\frac{10^6\,\mathrm{GeV}}{f_a}$$

- They are
  - **nearly invisible to ordinary matter**
  - excellent candidates for **dark matter**
  - a necessary component of **string theory**

Is it worth the search for axions?

Discovery of an axion:

- New elementary particle
- Solution of strong CP problem
- Dark matter particle

New solar physics

answer to solar mysteries, e.g.:

- *Solar corona heating problem,*
- *Flares*
- *Unexpected solar X-rays, …*

Where the Axions come from

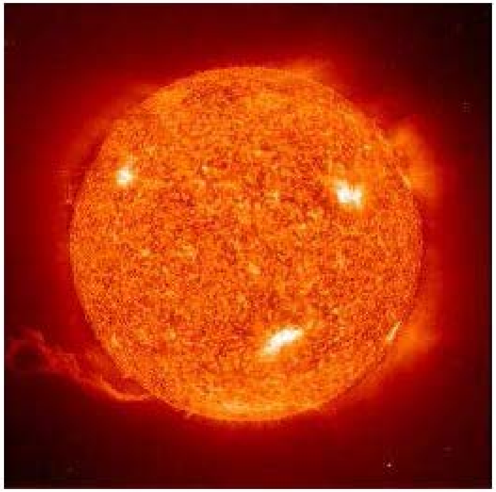
- Cosmological axions (cold dark matter)
- Solar axions

Stellar plasmas may be a powerful source of axions..

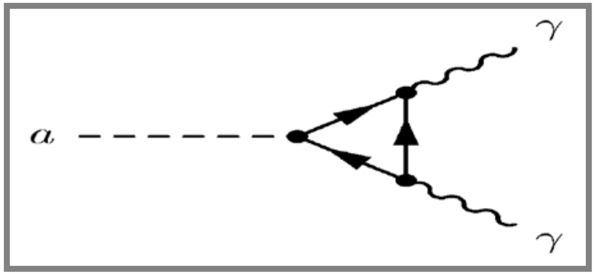
Important notice:

The closest stellar plasma available is:

the Sun

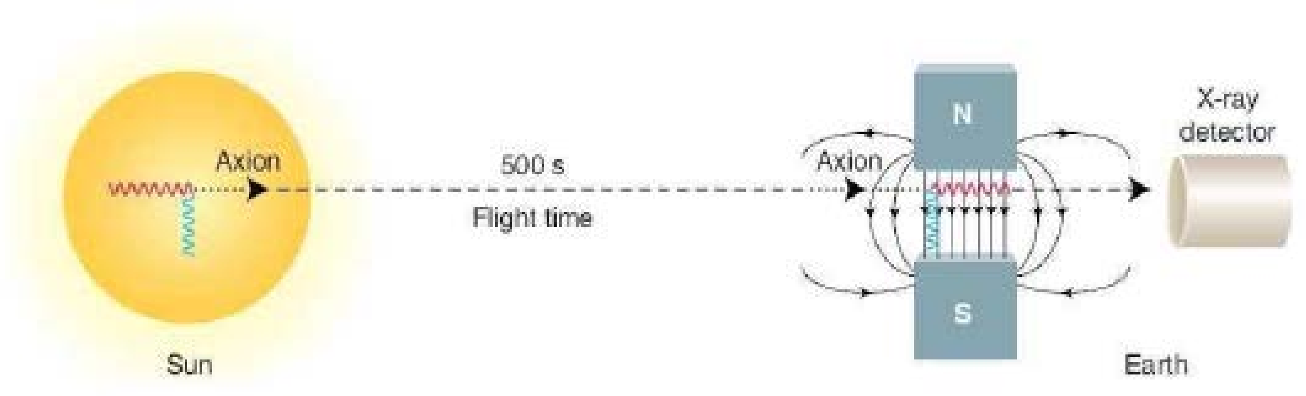


Primakoff effect



Axions are coupled to two photons

This could be done either in the sun interior or in earth…

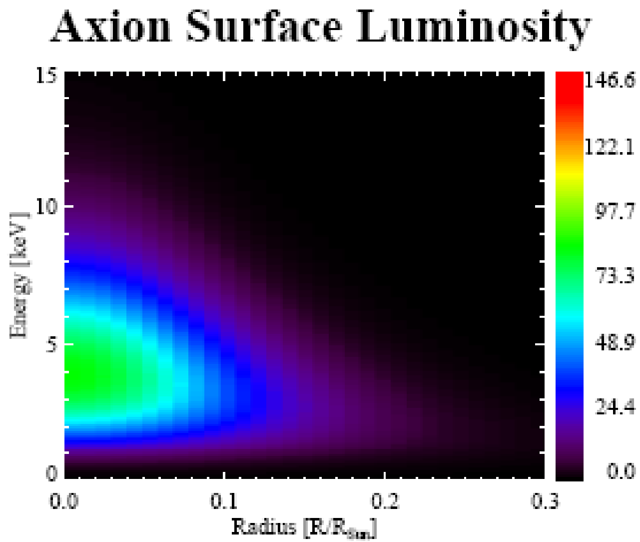


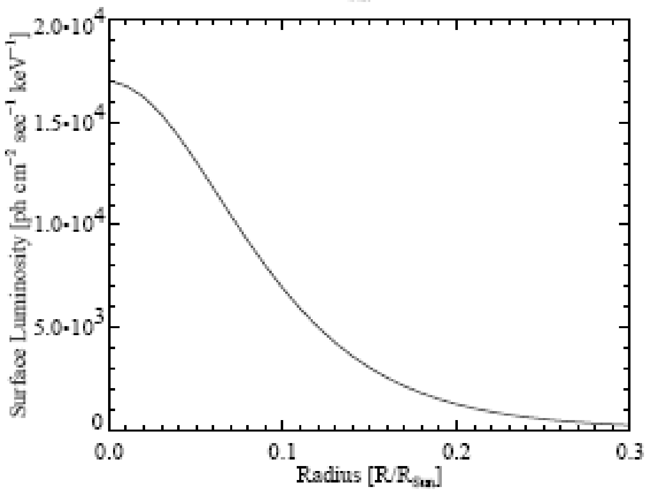
a thermal photon converts into an axion in the Coulomb fields of nuclei and electrons in the solar plasma

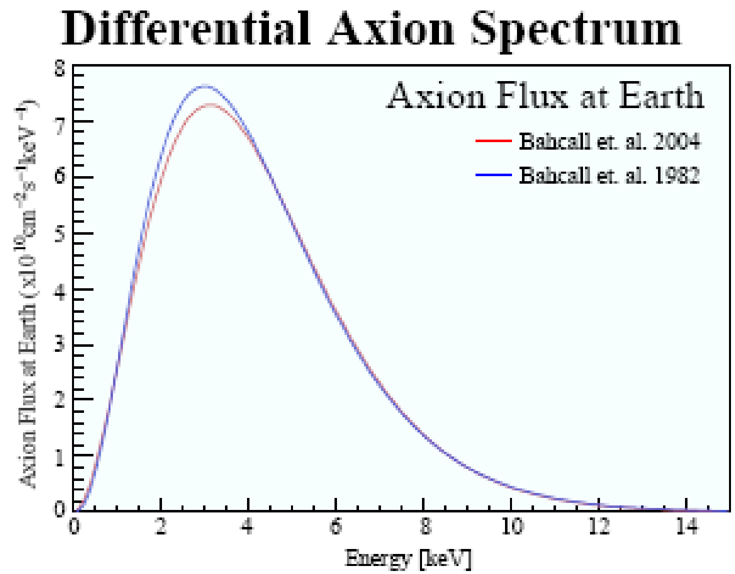
The axion converts into a photon under a strong magnetic field in the laboratory (inverse process, Sikivie 1983)

Solar axion flux

(with new solar model implemented)







Mean energy: $< E >= 4.2\,\mathrm{keV}$

Axion Luminosity:

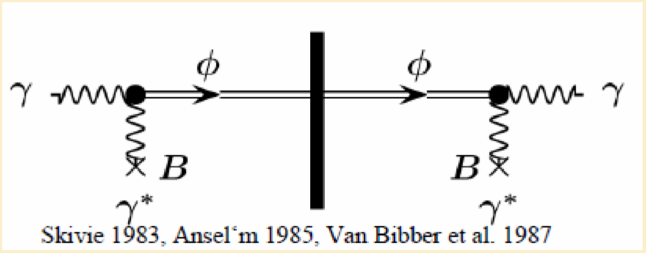
$$L_a = 1.9 \times 10^{-3} L_\odot$$

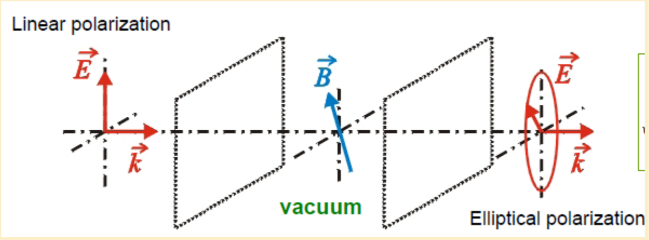
Axion flux: $\Phi_a = 3.8 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

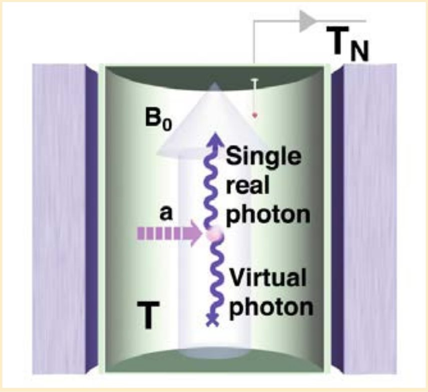
Provided by Serpico & Raffelt
Based on the standard solar model BP2004 (Bahcall et al., 2004)

Experimental axion searches

- **Laser experiments (*laboratory*):**
  - Photon regeneration ("invisible light shining through wall")
  - Polarization experiments (PVLAS)
- **Search for dark matter axions:**
  - Microwave cavity experiments (ADMX)
- **Search for solar axions:**
  - Bragg + crystal (SOLAX, COSME, DAMA)
  - Helioscopes (SUMIKO, **CAST**)







The CAST Collaboration

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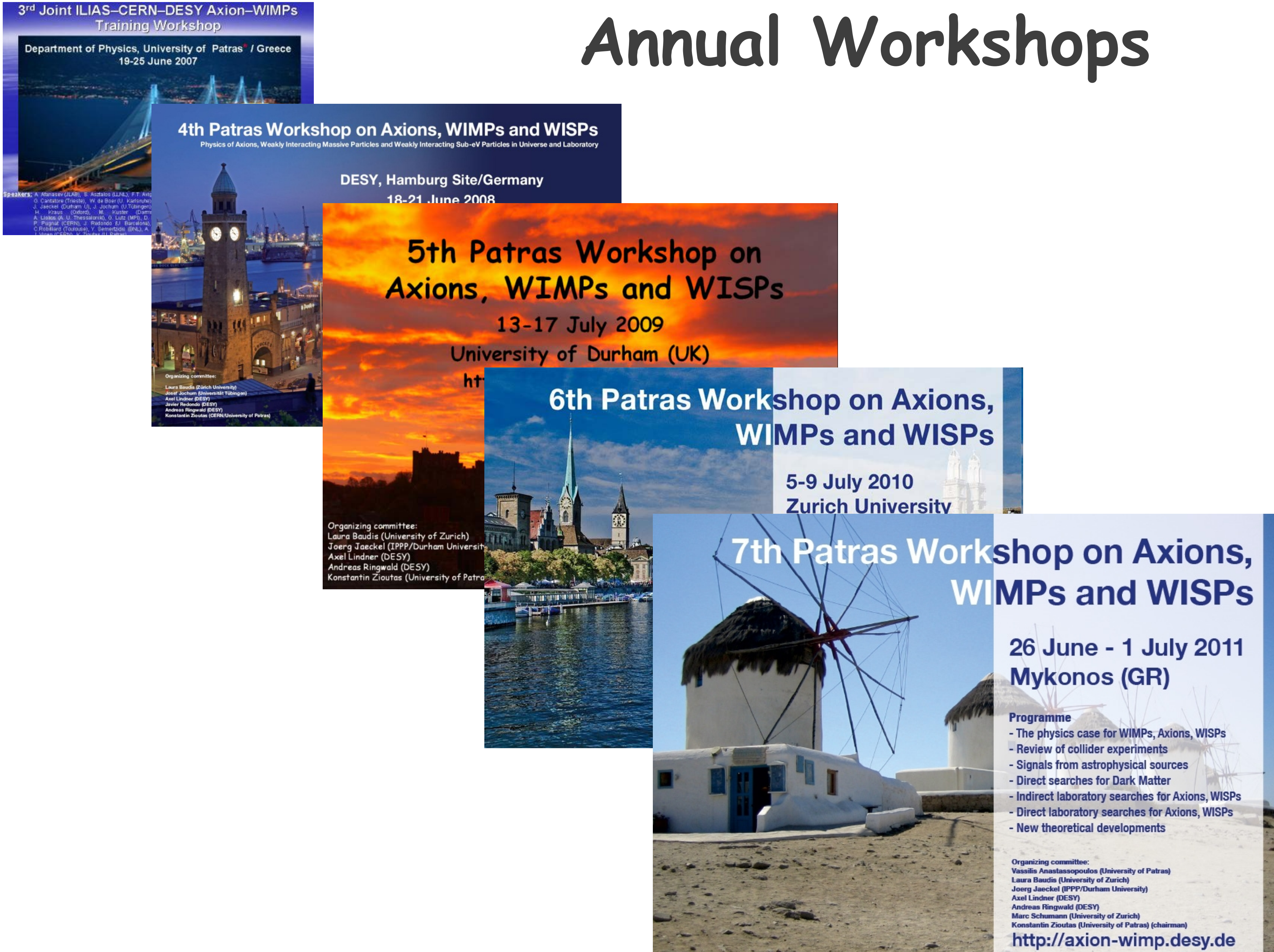
CERN LHC

Annual Workshops



CAST milestones

Proposal approved by CERN (13th April 2000)

Commissioning(2002)

CAST Phase I: vacuum operation (2003 - 2004) *completed*

CAST Phase II: (2005–2011)

4He run, (2005–2006) *completed*

0.02 eV < ma < 0.39 eV

3He run (2007-2011) data taking completed in 20th July 2011

0.39 eV <ma<~1.20 eV

Low energy axions (2007 – 2011) in parallel with the main program

~ few eV range

5th April 2011: Proposal to SPSC for 2012-2014

Start of 2nd solar cycle (!?)

13th April 2011: CAST completed one solar cycle (11 years...)

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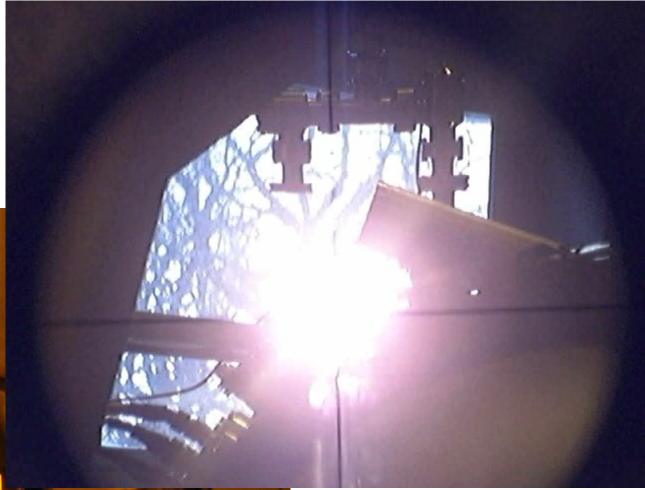
Sun Filming



Twice a year (September and March): filming the Sun through the window
Regular checks by CERN surveyors

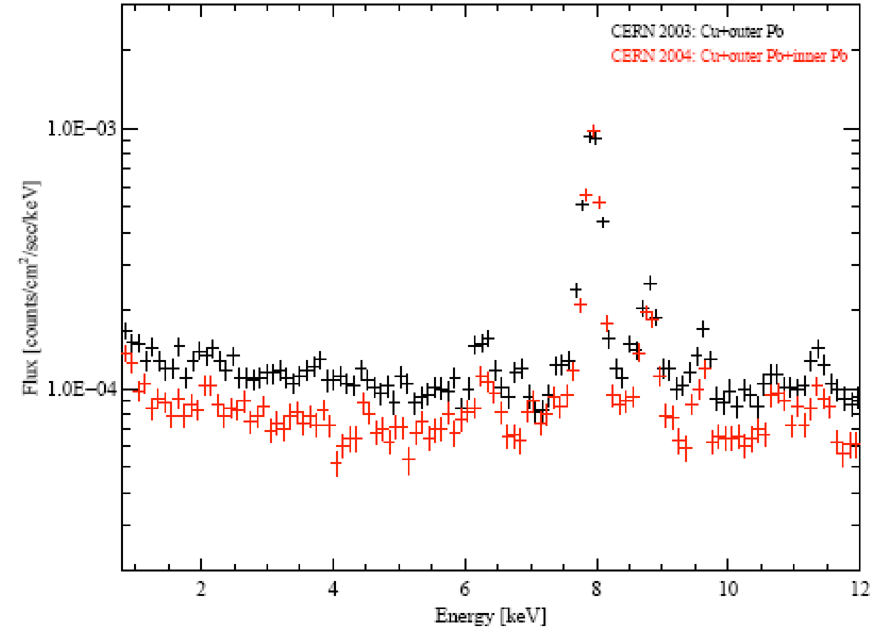
CCD

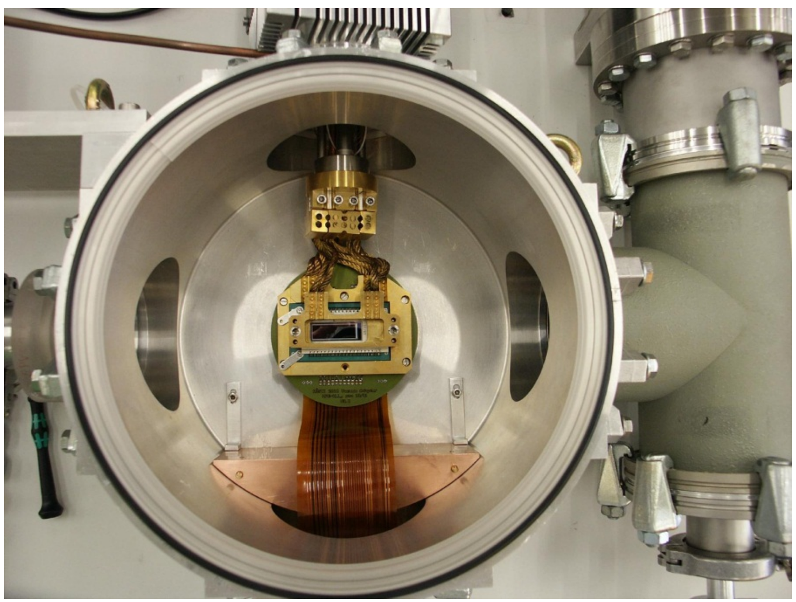
- Excellent Energy Resolution
- Excellent Space Resolution

Pixel size: 150μm x 150μm

Additional shield plus X-ray finger source for continuous monitoring of the spot position

CCD Background





2003: $11.5 \pm 0.2 \times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}

2004: $7.69 \pm 0.07 \times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}

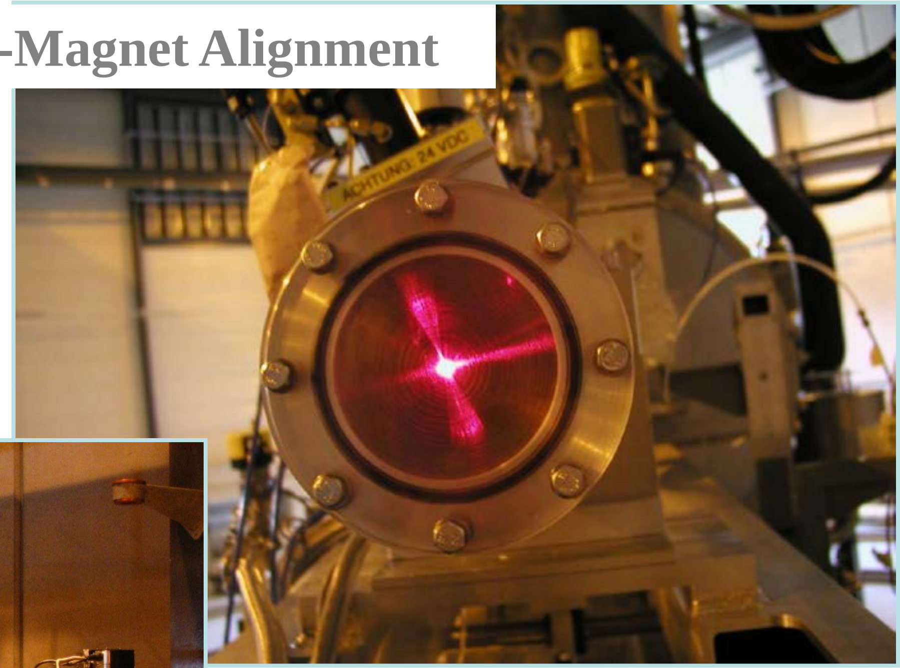
Background reduction by a factor of 1.5

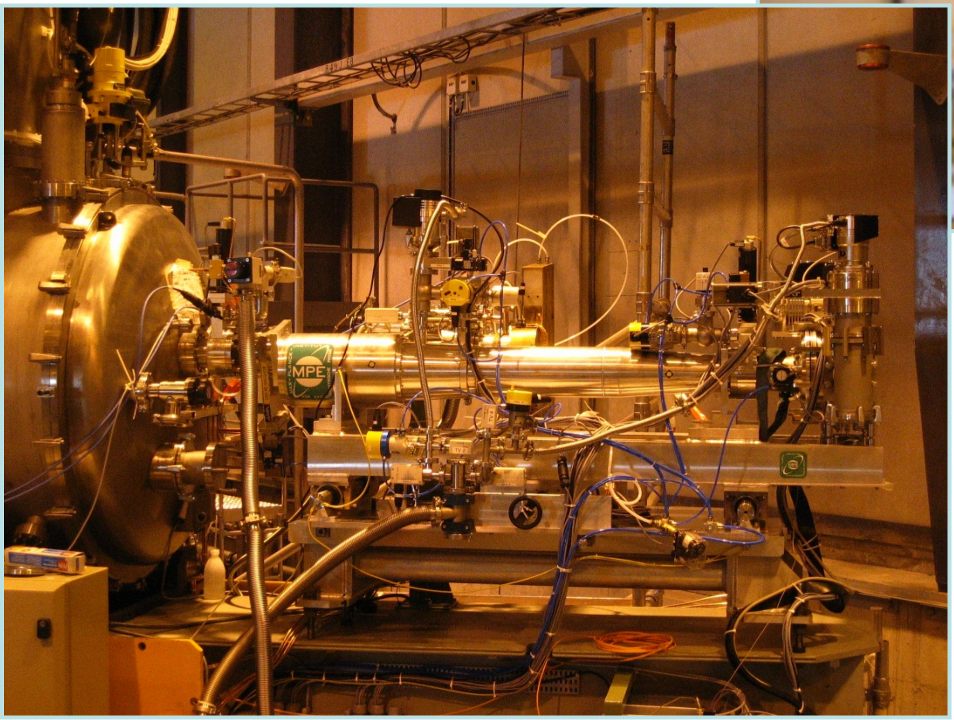
The X-Ray Telescope

<u>Space technology</u>:

Spare part of the ABRIXAS Space mission

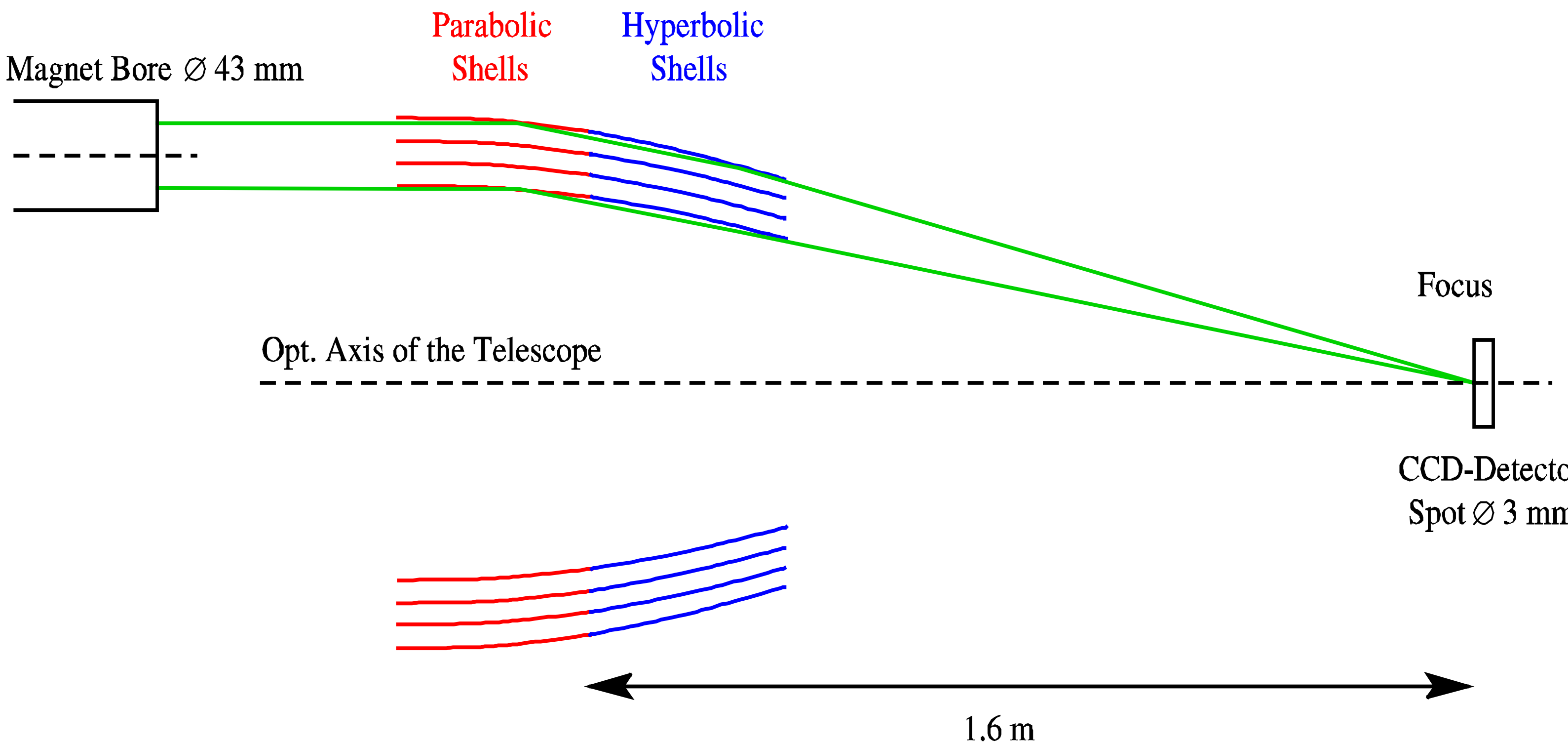
Telescope-Magnet Alignment





The X-Ray Telescope

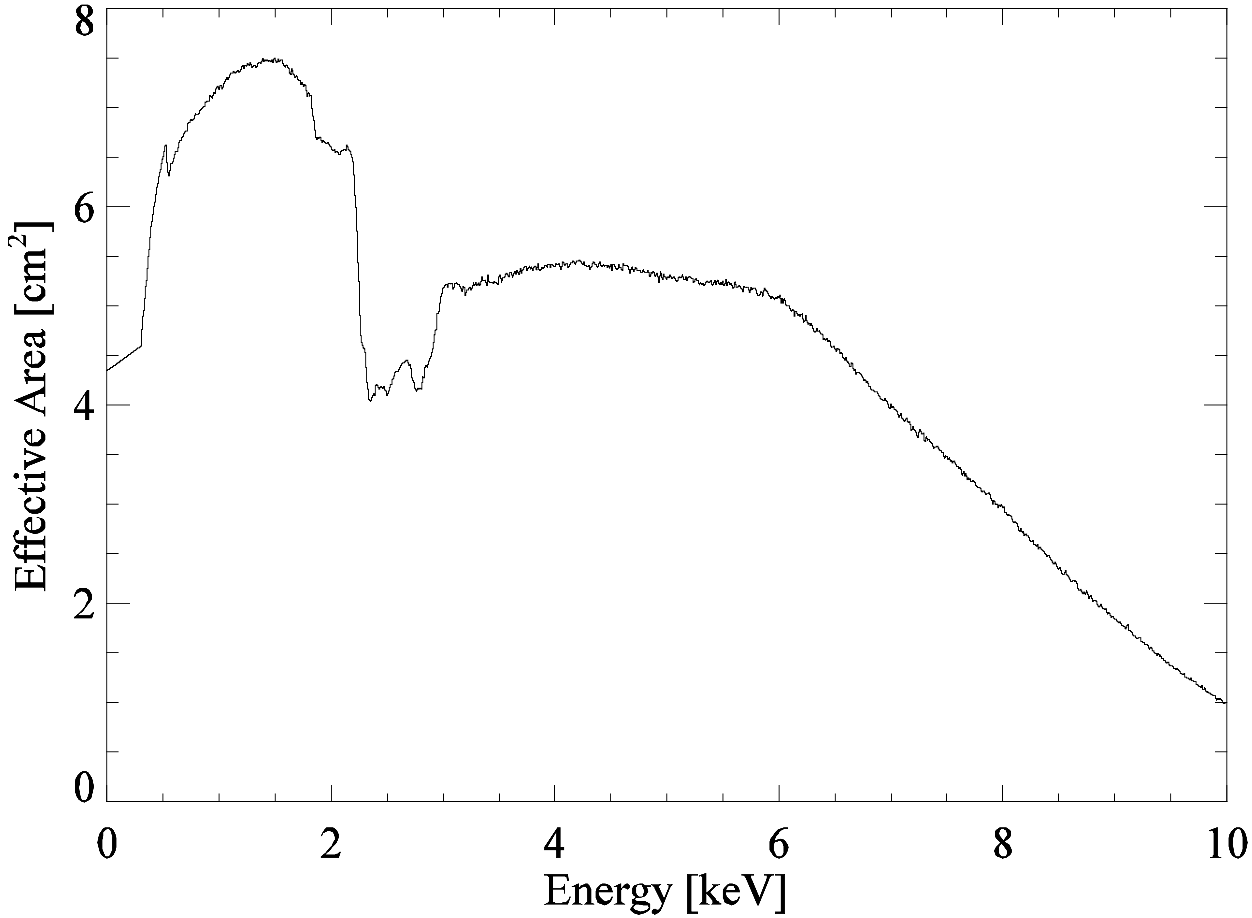
~35% efficiency due to reflections



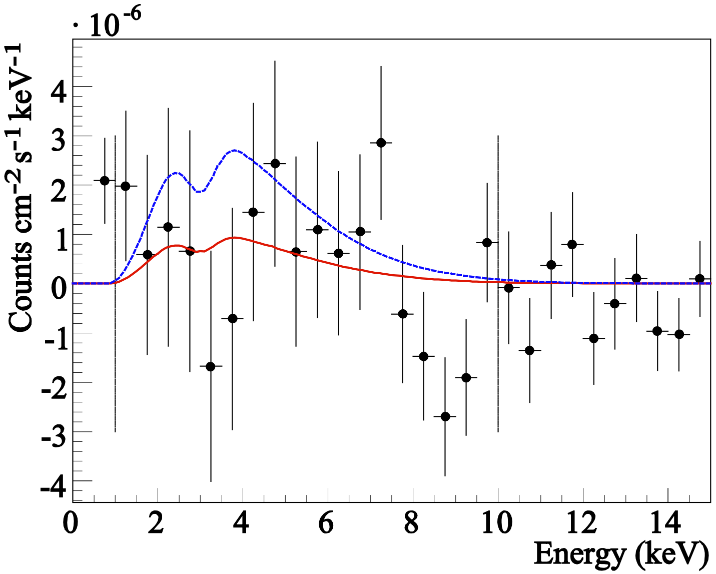
- 27 nested pairs of mirrors
- **very strong signal-to-noise improvement**

Telescope-CCD efficiency

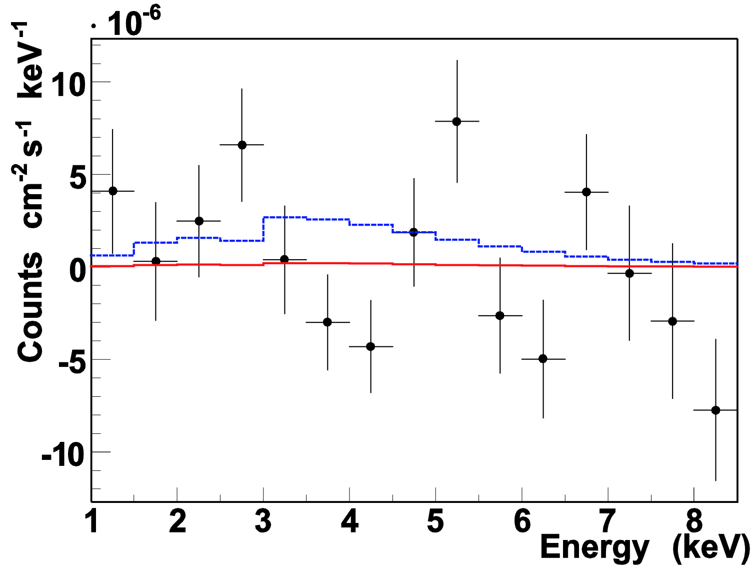
In units of effective area, out of magnet's bore 14.52 cm^2



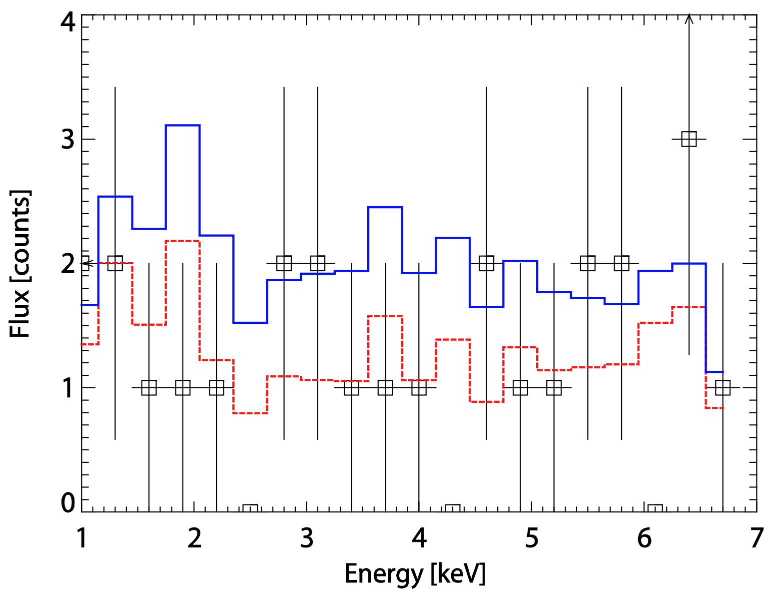
TPC subtracted spectrum



MM subtracted spectrum



CCD spectrum



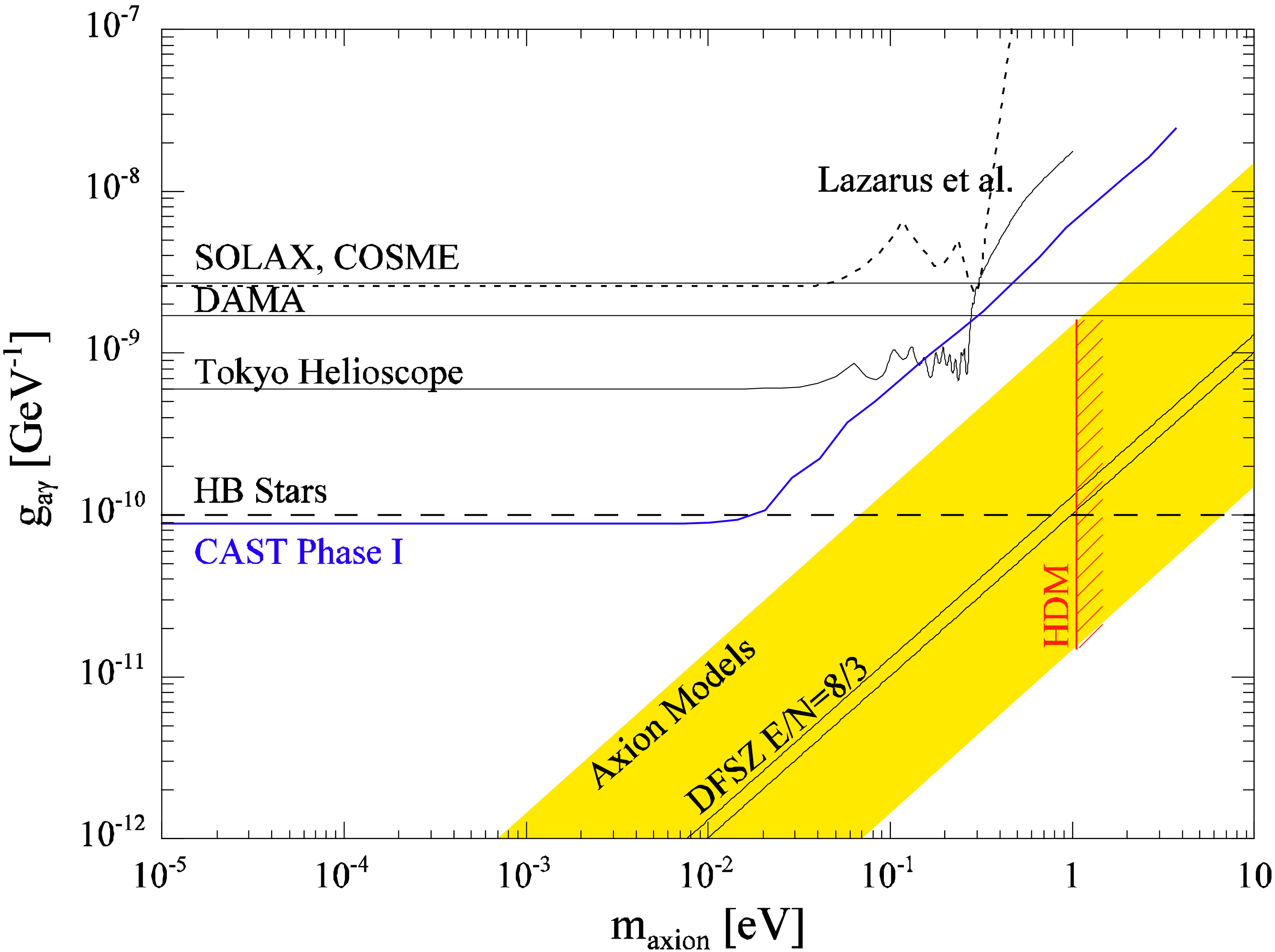
Data taking during 2003 and 2004

In total 12 months

Result from CAST phase I:

$$g_{a\gamma\gamma} < 0.88 \times 10^{-10}\, GeV^{-1}$$

Published in JCAP, hep-ex 0702006 (2007), CAST Collaboration



Published in JCAP, hep-ex 0702006 (2007), CAST Collaboration

CAST phase II

Exploring higher axion masses...

- Coherence for higher masses may be restored by using buffer gas.
- Filling the two magnetic channels with helium
- The photon acquires an effective mass: $m_\gamma > 0$
- Momentum transfer is

$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$ (as opposed to $$|q| = \frac{m_a^2}{2E}$$)

- Coherence condition ($qL << 1$) is recovered for a narrow mass range around m_γ

Extending sensitivity to higher axion masses…

Axion to photon conversion probability:

$$P_{a\to\gamma} = \left(\frac{B \quad a\gamma}{2}\right)^2 \frac{g \;\; 1}{q^2+\Gamma^2/4}\left[1-e^{-\Gamma L/2}-2e^{-\Gamma L/2}\,\mathrm{c} \quad q \;\;)\right]$$

Vacuum:
Γ=0, mγ=0

Coherence condition: $qL < \pi$, $|q| = \frac{m_a^2}{2E}$

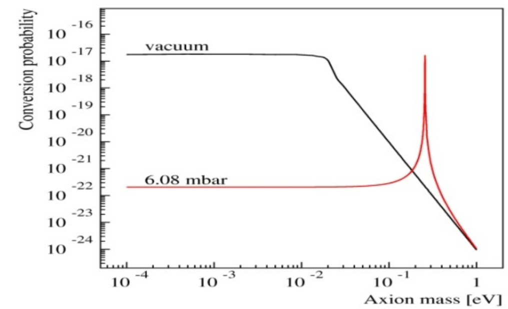
For CAST phase I conditions (vacuum), **coherence is lost for ma > 0.02 eV**.

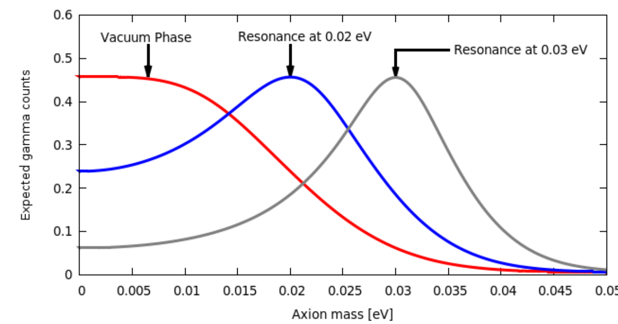
With the presence of a **buffer gas** it can be **restored** for a narrow mass range:

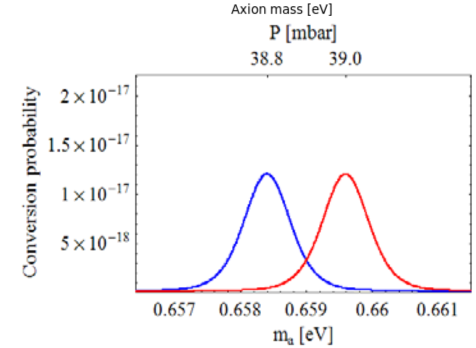
$$q \quad < \pi L \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

with $m_\gamma = \sqrt{\frac{4\pi \quad N_e \alpha}{m_e}} \approx 2 \quad .9 \; 8\sqrt{\frac{Z}{A}\rho} \quad e$

- New discovery potential for each density (pressure) setting







For P~50 mbar Δma ~ 10-3 eV

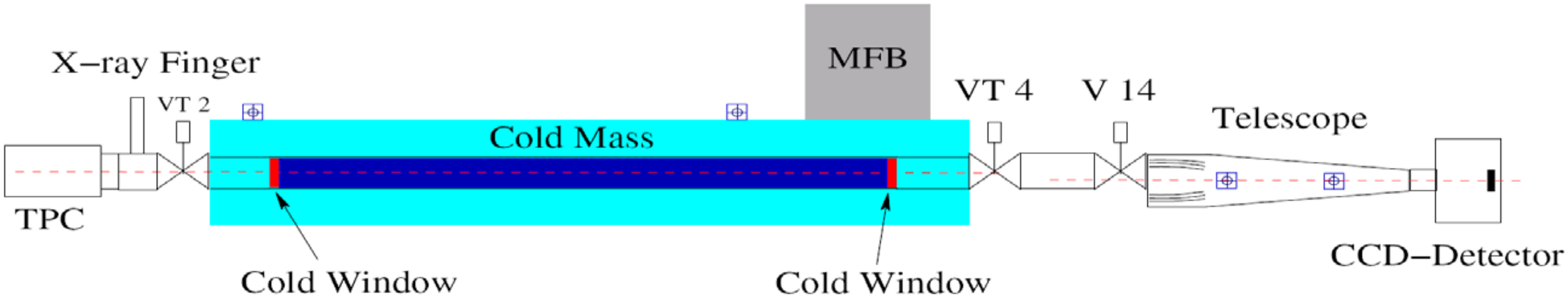
CAST phase II

m_γ can be adjusted by changing the gas pressure:

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \ \ \mathrm{eV}$$

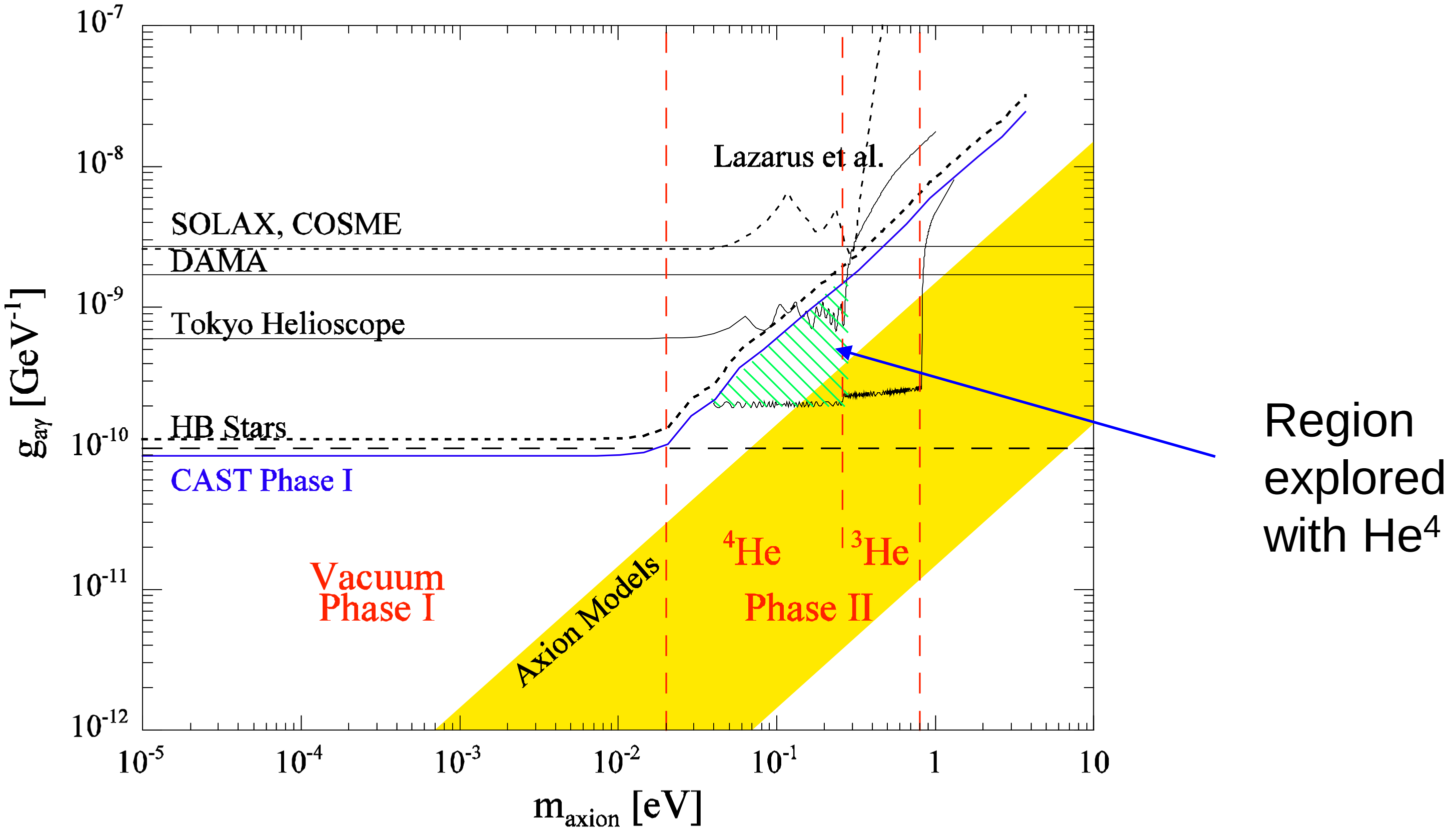
- *Every specific pressure of the gas allows the test of a specific axion mass.*
- *The higher the pressure, the higher the photon effective mass, the higher the axion mass tested.*
- *For every step there is a new discovery potential !*

Transforming to Phase II 2005



- Cold Windows (installed) /He-Gas System
- ^{4}He gas system (in operation in 2005 and 2006)
  - High precision (better than 0.01 mbar)

^{4}He pressure =13.43 mbar $\Rightarrow$ m_a~ 0.39 eV/c^2



First time a helioscope explores the models region

Next step: upgrade to He^3 phase, extending sensitivity up to 1 eV axion mass (135.8 mbar).

Preliminary - 3He result

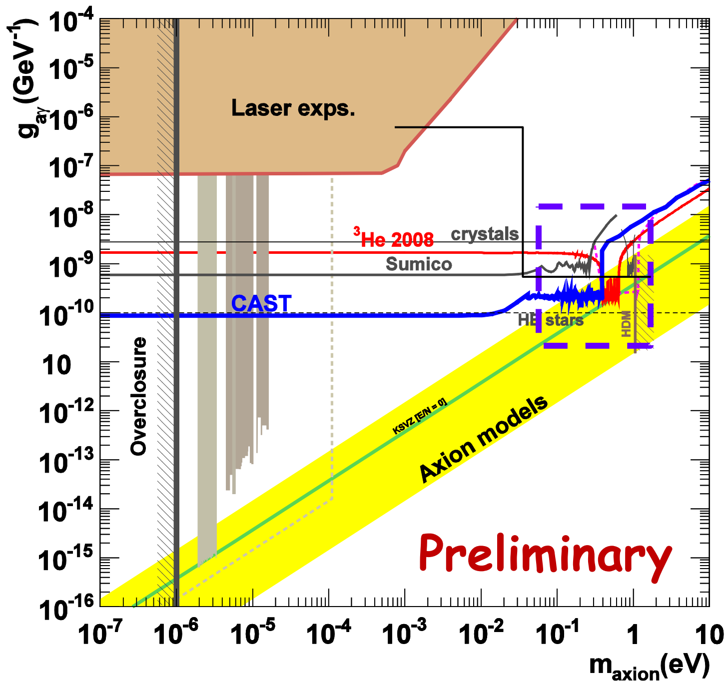
Density variation during a tracking 4He phase analysis not easy to be used.

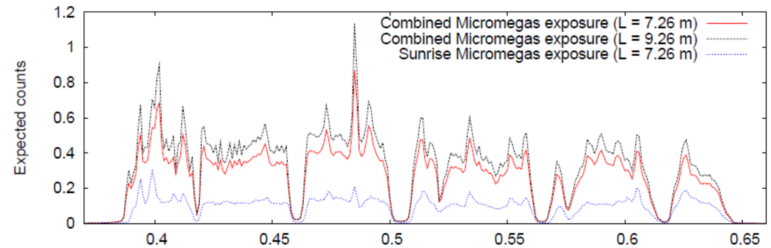
- new formulation of the unbinned likelihood:

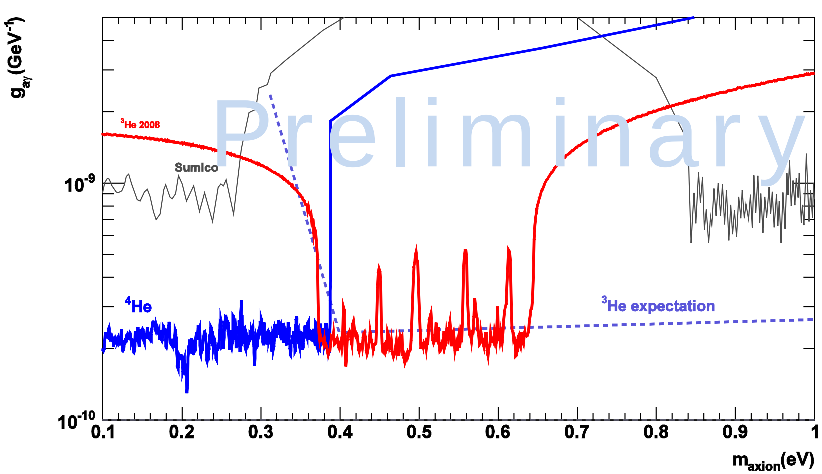
$$Log\left(L_{m_a}(g_{a\gamma})\right) = \underbrace{-g_{a\gamma}^4 \int_E \int_{t_k} \frac{d^2 n_\gamma}{dE \cdot dt_k} dE \cdot dt_k}_{\text{Zero counts detected contribution}} + \sum_{kn_i=1} \underbrace{Log\left(b_{ik} + g_{a\gamma}^4 \int_{E_i}^{E_i+\Delta E} \frac{dn_\gamma^k}{dE}\right) dE}_{\text{One count detected contribution}}$$

1st term: expected number of axions. Depends on exposure time

2nd term: Depends on the gas density at the moment a count occurred







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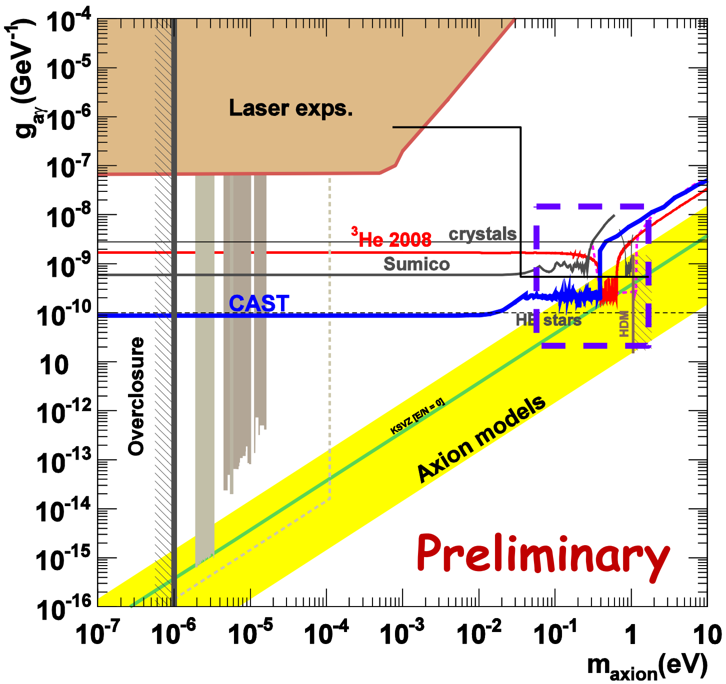
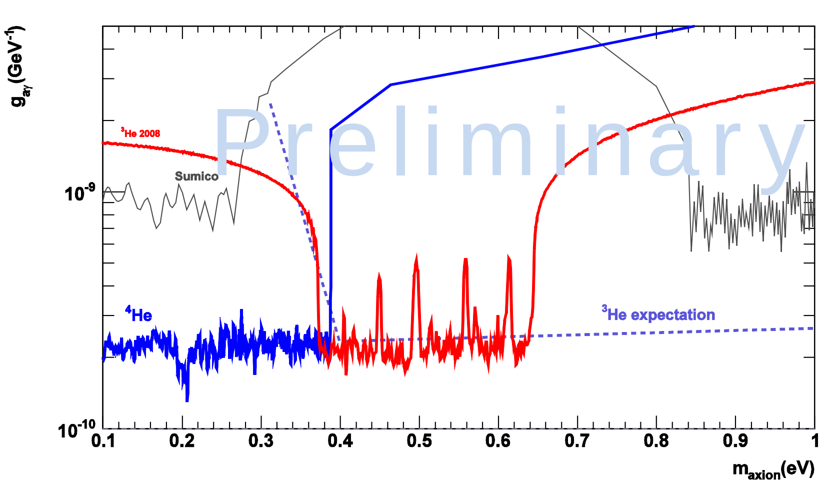


Exceed expectations!
Detector improvements



- *Motivated by new physics cases*
- *Supported by detector improvements*

101st Meeting of the CERN / SPSC

CAST Physics Proposal to SPSC

K. Zioutas *on behalf of* **CAST**

and
in collaboration with

D. Anastassopoulos, O. Baker, M. Betz, P. Brax, F. Caspers, J. Jaeckel,
A. Lindner, Y. Semertzidis, N. Spiliopoulos, S. Troitsky, A. Vradis.

Solar Paraphotons

Hidden Sector particles □ Theoretically motivated

kinetic mixing: γ ↔ γ′ oscillations

□ **NO magnetic field!** □ NO cold bores needed

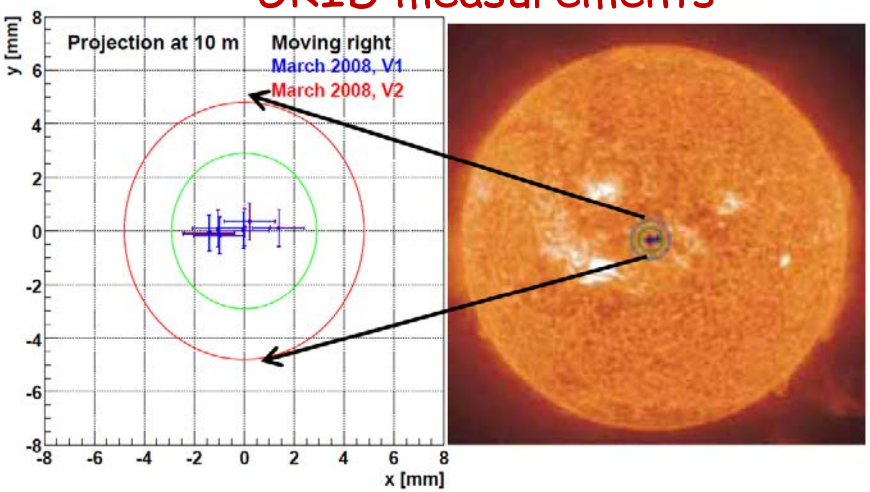
□ Vacuum path length relevant for oscillations

□ upstream in front of the detector

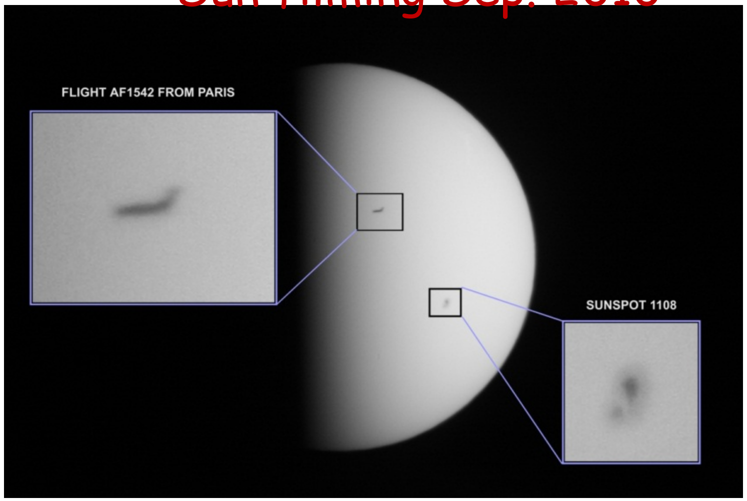
□ a good sensitivity requires: 3 **ULB MMs** **&** FS pn**CCD**

& solar tracking!!!

GRID measurements



Sun filming Sep. 2010



Solar Chameleons

- Chameleons are **DE** candidates to explain the acceleration of the Universe
- Chameleon particles can be created by the **Primakoff effect** in a strong magnetic field. This can happen in the Sun.
- The chameleons created inside the sun eventually reach earth where they are energetic enough to penetrate the CAST experiment. **Like axions**, they can then be back-converted to X-ray photons.
- In vacuum, CAST observations lead to stronger constraints on the chameleon coupling to photons than previous experiments.
- When gas is present in the CAST pipe, the analogue spectrum of regenerated photons shows characteristic oscillations: **ID**

□ **axion helioscope** = **chameleon helioscope,** but @ LE!!

□ ***Low energy threshold: MM + CCD!***

+ ***vacuum***

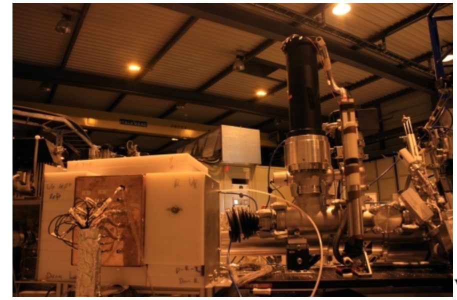
P. Brax, K. Zioutas PRD (2010)

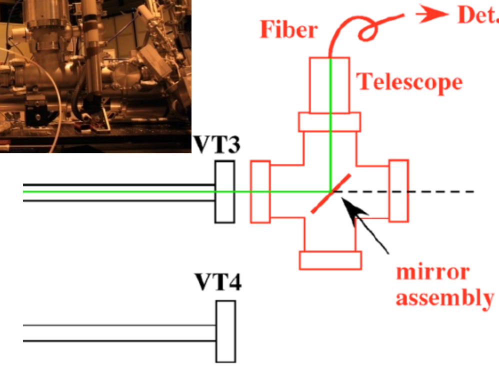
In addition…

Search in the visible:

a, γ′, CH, …

BaRBE & Transition Edge Sensor (TES)





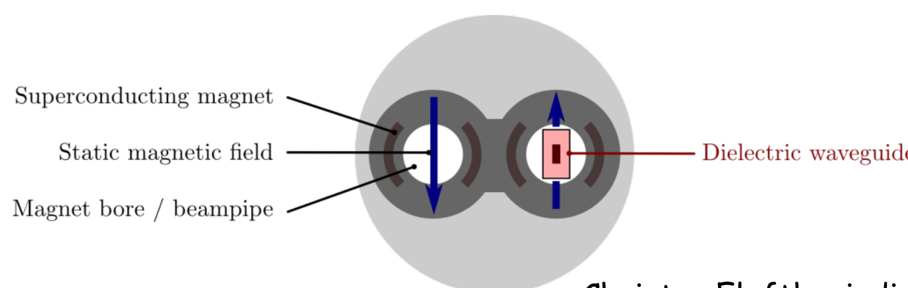
Towards a new relic axion antenna?

Dielectric waveguide inside the CAST magnet may perform as a new kind of "***macroscopic fiber***", being a sensitive detector for relic axions:

- **~ 0.1 - 1 meV** rest mass range (experimentally inaccessible)

- **Feasibility study of the proposed concept is in progress**

>>> theoretical estimates!!



Christos Eleftheriadis

Exploiting QCD axion models

arXiv:1103.5334v2 [hep-ex] 29 Mar 2011

Towards a new generation axion helioscope

> 50 M€ project

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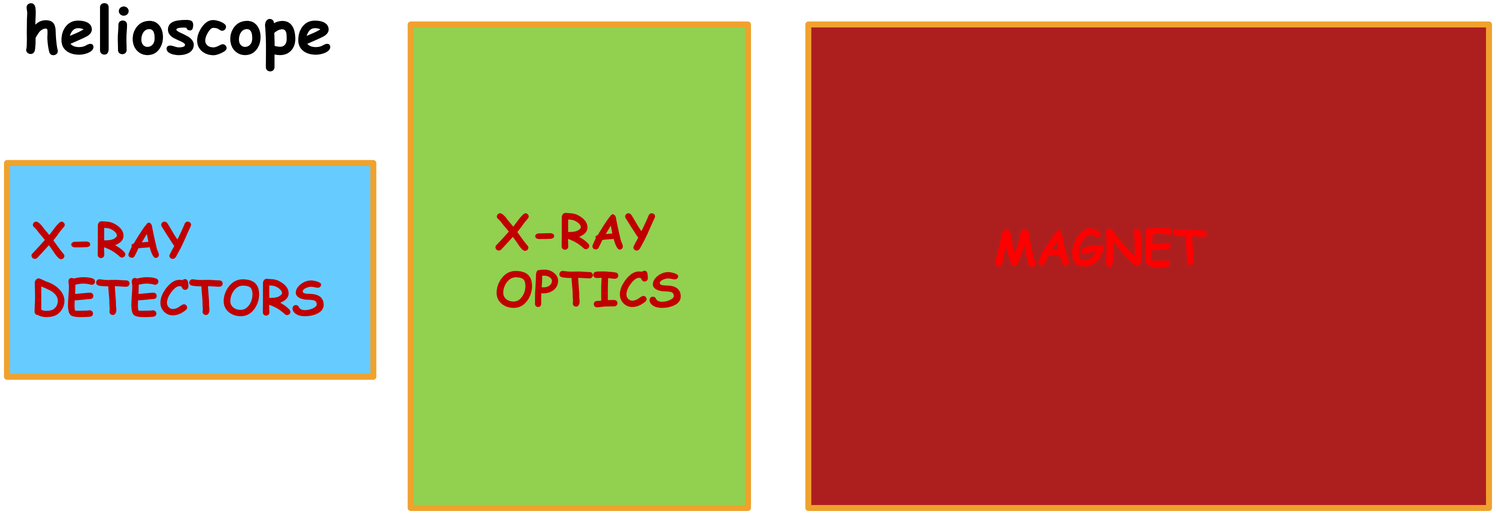
Axion helioscopes FOM

- **3 parts drive the sensitivity of an axion helioscope**



$$\frac{1}{\mathrm{FOM}} \propto g_{a\gamma}^{4} \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

where b is the time- and area-normalized background of the detector, ϵ_d its efficiency; a is the focal spot area of the optics, ϵ_o its througput, B is the magnet field strength, L its length, and A its cross sectional area; t is the exposure time.

Christos Eleftheriadis

Goals for the next 1 - 2 years

- **Magnet**
  - Built a new "magnet", tailored to our needs
  - **Main goal: B2L2A ~ x1000 better than CAST (desirable), x100 (minimum)**
  - Other construction technical issues □ feasibility study, design study.
  - Work in progress

- **Optics**
  - Cost-effective large optics (all magnet instrumented) □ 0.5-1 m2

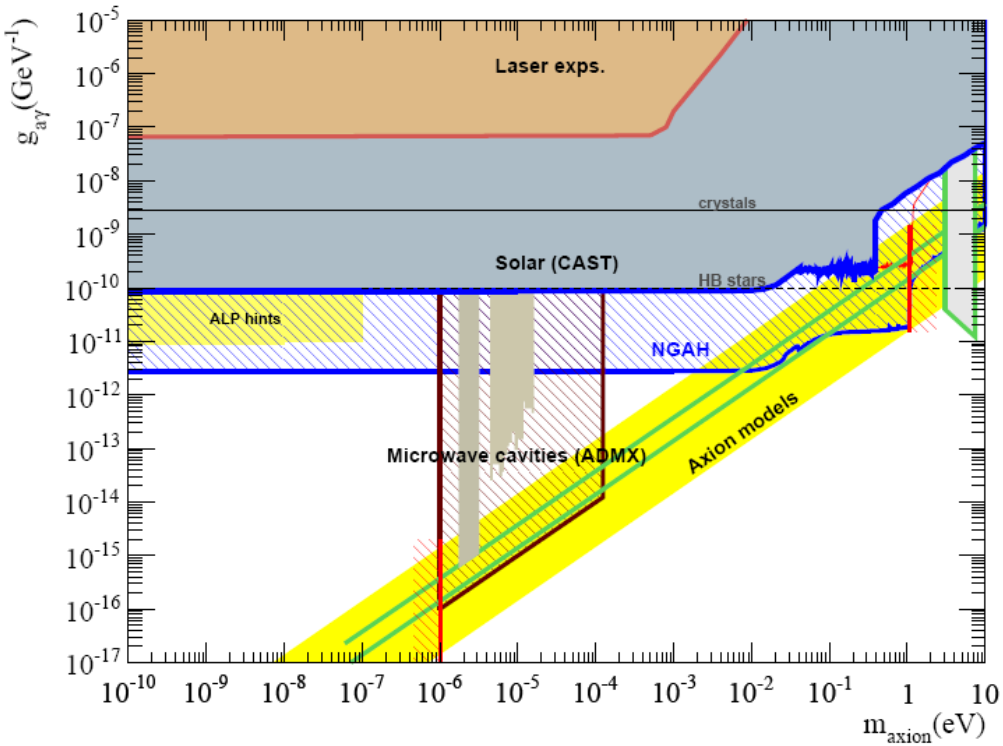
- **Detectors**
  - Main goal: background ~ 10-7 keV-1 cm-2 s-1 >>> **already reached**!?

- **Platform**, general assembly engineering
  - 40-50% Sun coverage?

Conclusions

CAST, during its 11 years of existence:

- has put the strictest experimental limit on axion searches for a wide mass range



In combination with Microwave Cavity experiments (ADMX), a big part of QCD favored model region can be swept up to 2020

Constraints

- Astrophysical
  - Our sun
  - Globular clusters
  - White dwarfs
  - Supernova 1987A
  - all the above related to the energy loss argument
- Cosmological
  - Overclosure of Universe
- Experimental
  - Helioscope experiments with magnets
  - Experiments with crystals

CONCLUSIONS

There are two main problems to be answered (related to axions)…

1. Strong CP problem
2. Dark matter

For the time being, CAST established the most stringent experimental limit on axion coupling constant, exceeding for the first time astrophysical constraints.

CAST phase II checked an experimentally unexplored axion mass - coupling constant region predicted by axion models

SPSC Committee at CERN is expected to decide on the new physics program of CAST