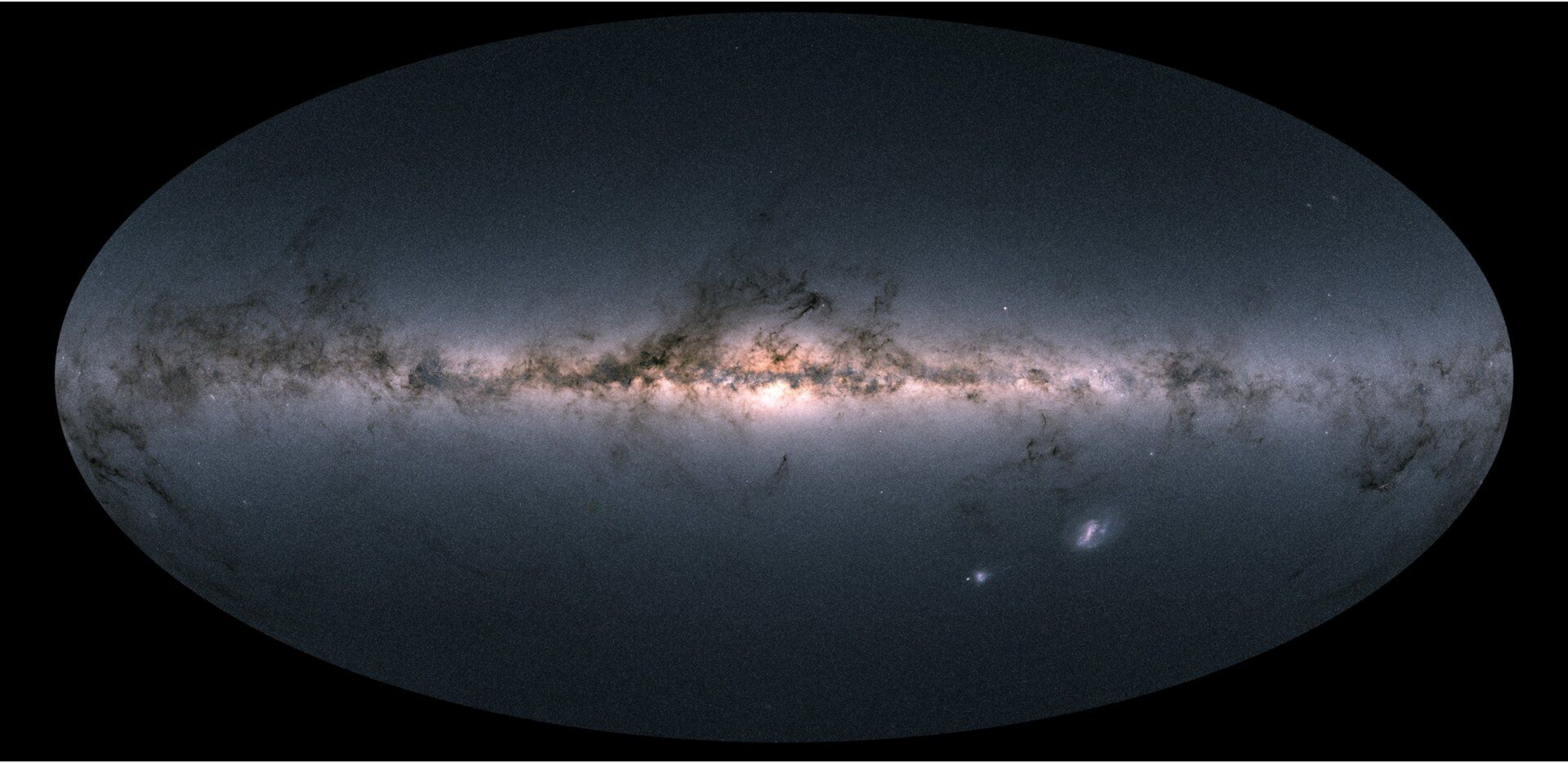
A high energy view of our Galaxy

…With a focus on X-rays and things to come

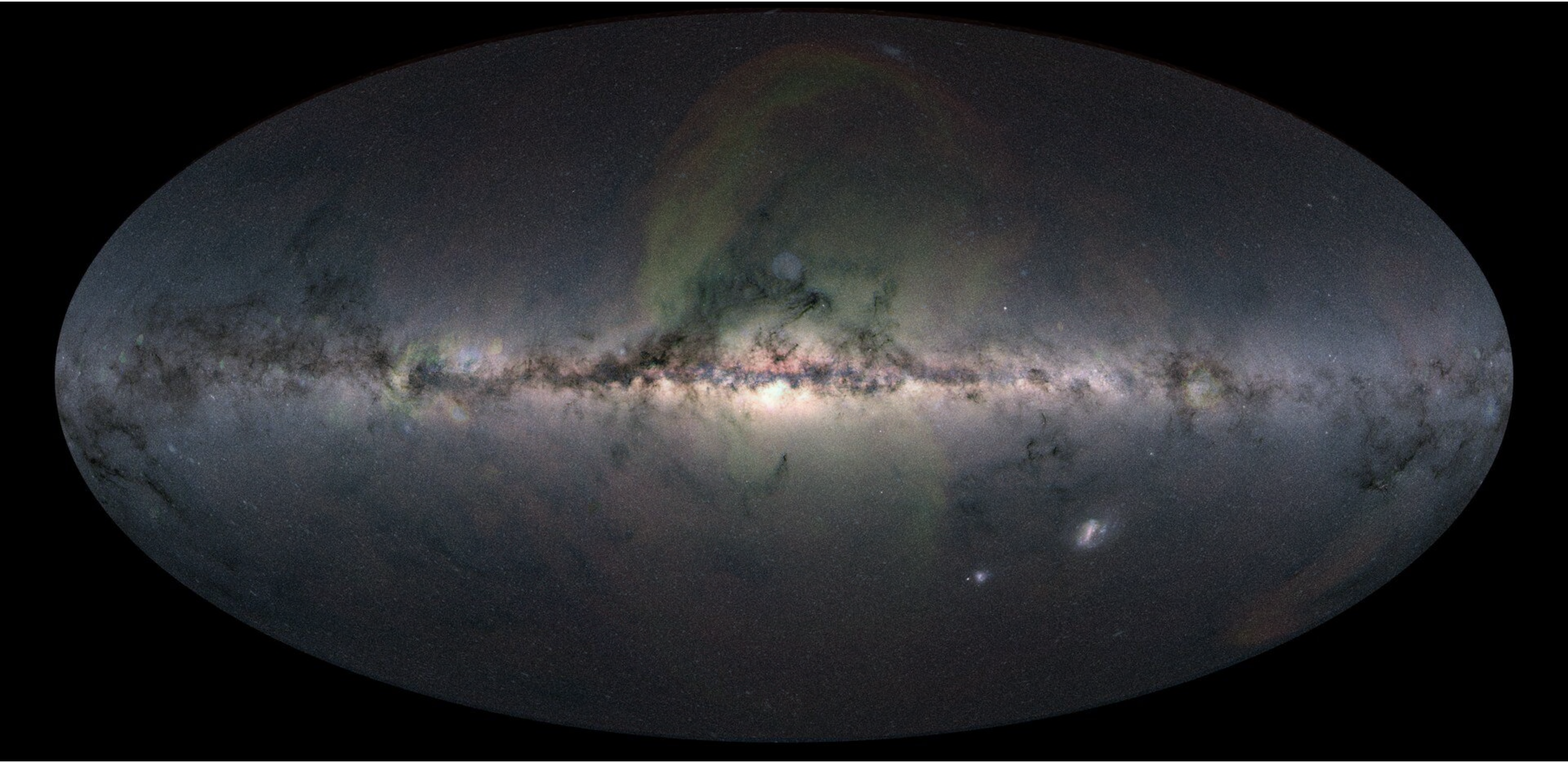
What we will cover

- A view of the sky in high energies
- Let’s focus on the Galactic plane and center
    - Diffuse emission and point sources
    - I discovered a new source now what? (hands-on)
- What to hope for in the next decade or two

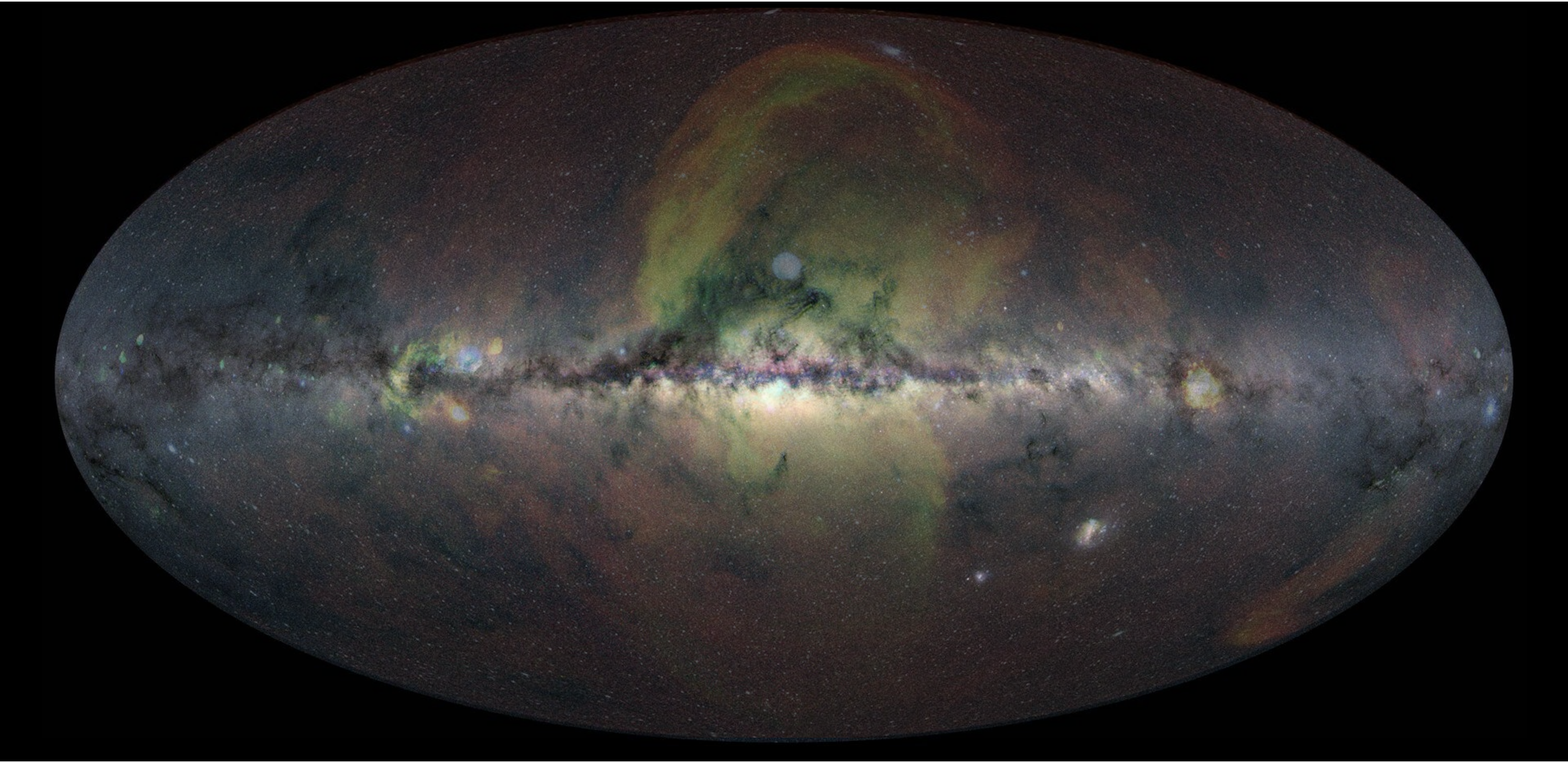
GAIA view of the entire sky.



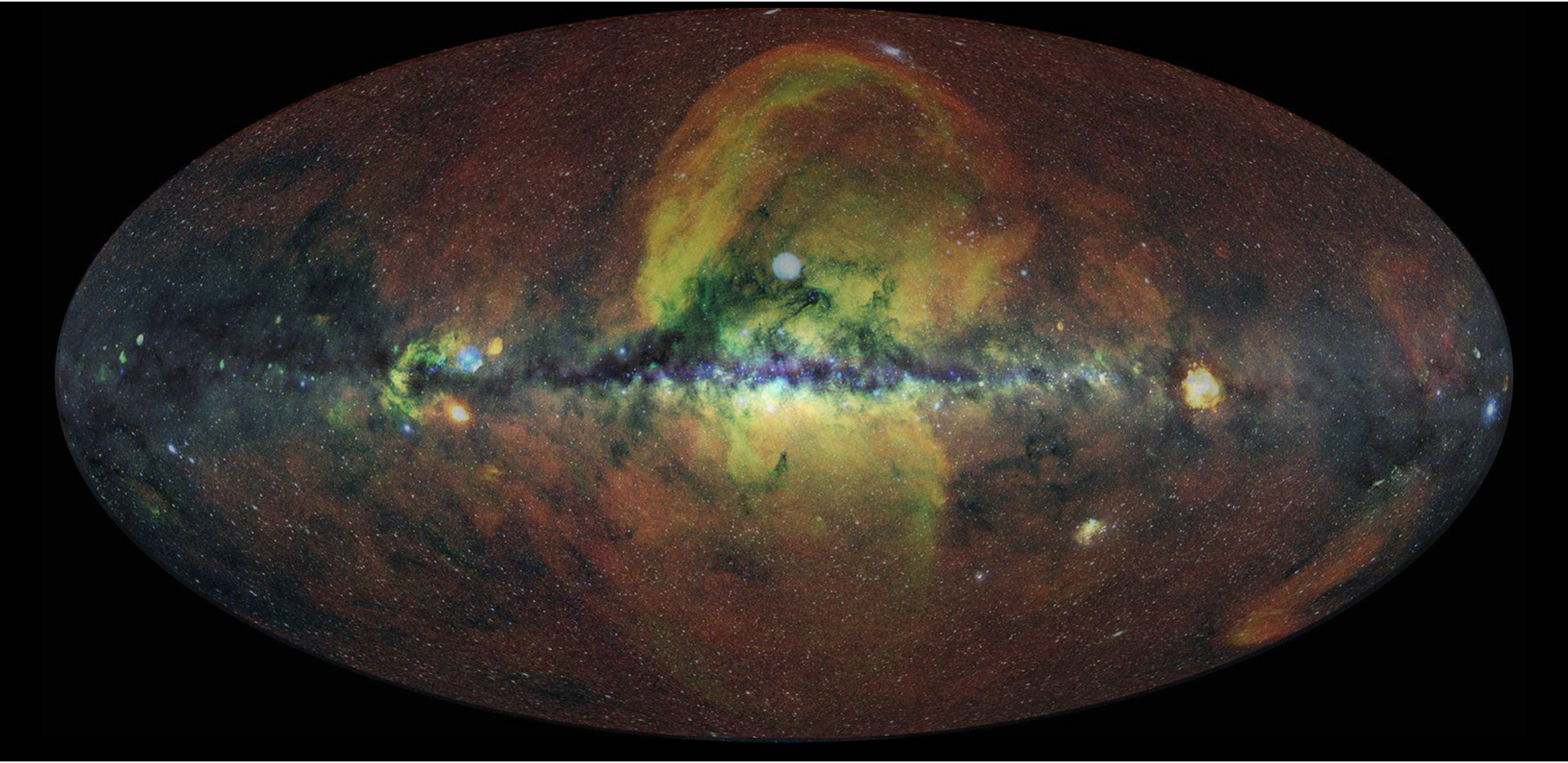
GAIA view of the entire sky… But what can we see in higher energies… so lets go to X-rays



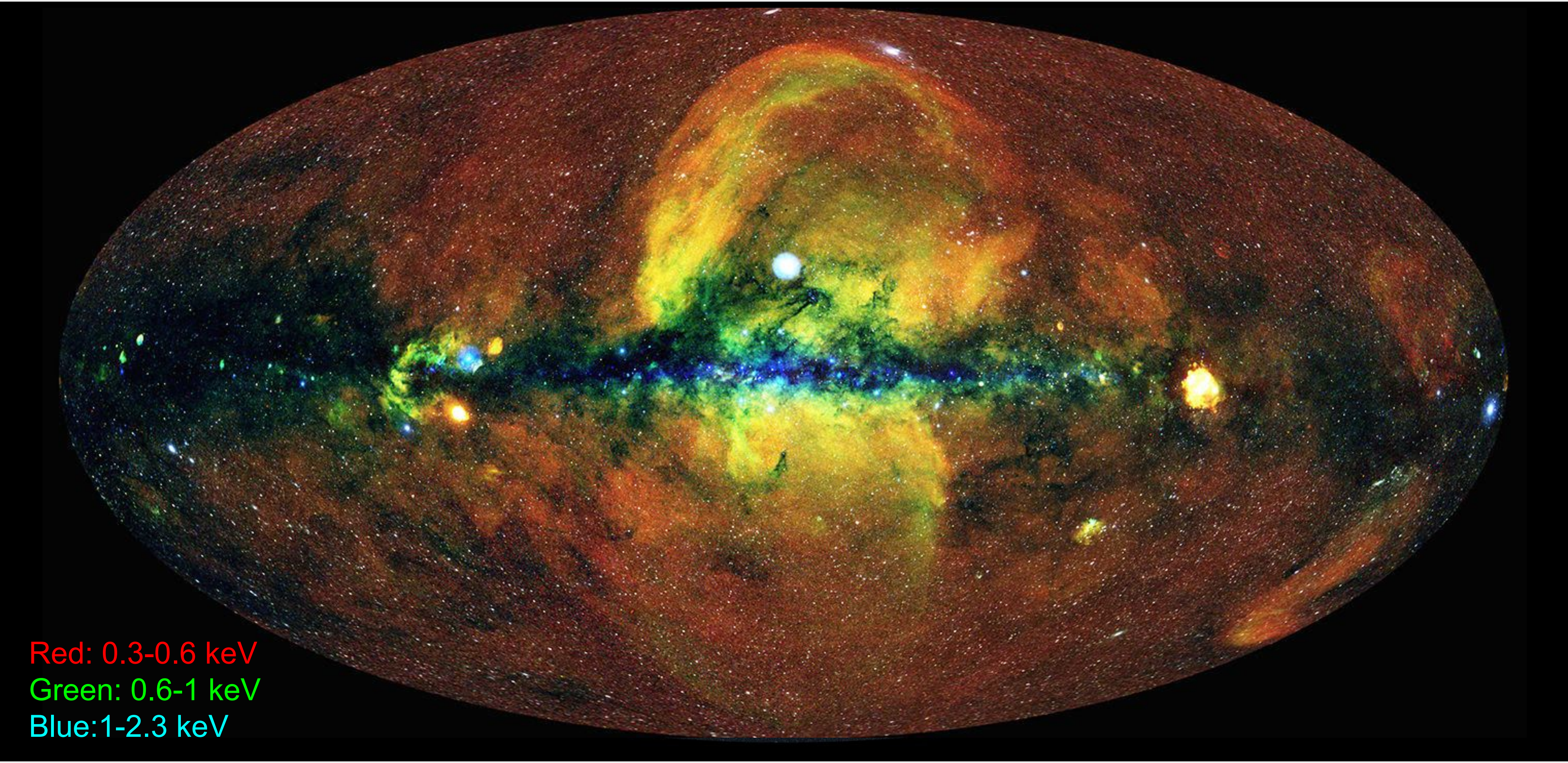
Suspense….



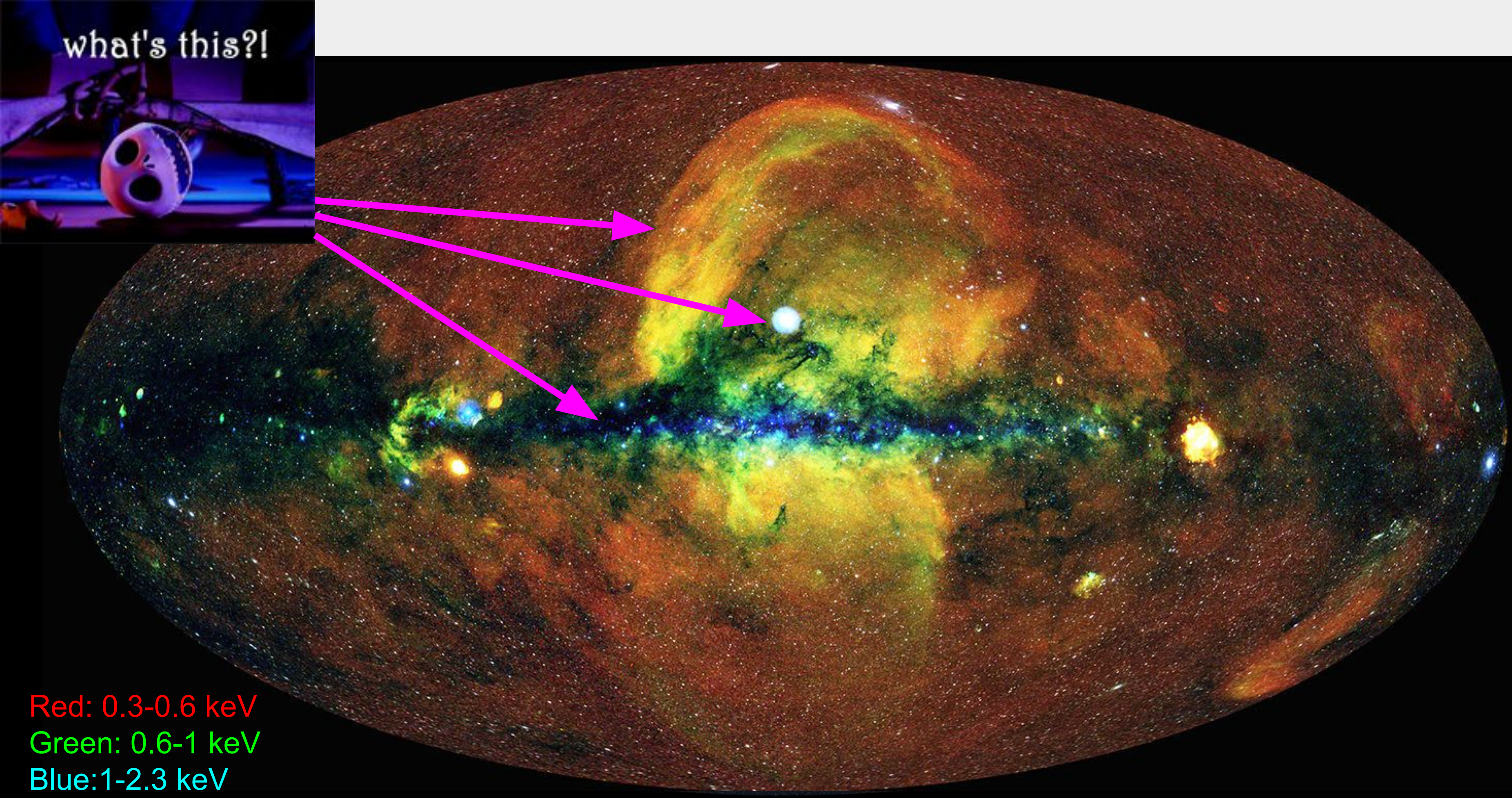
Suspense….



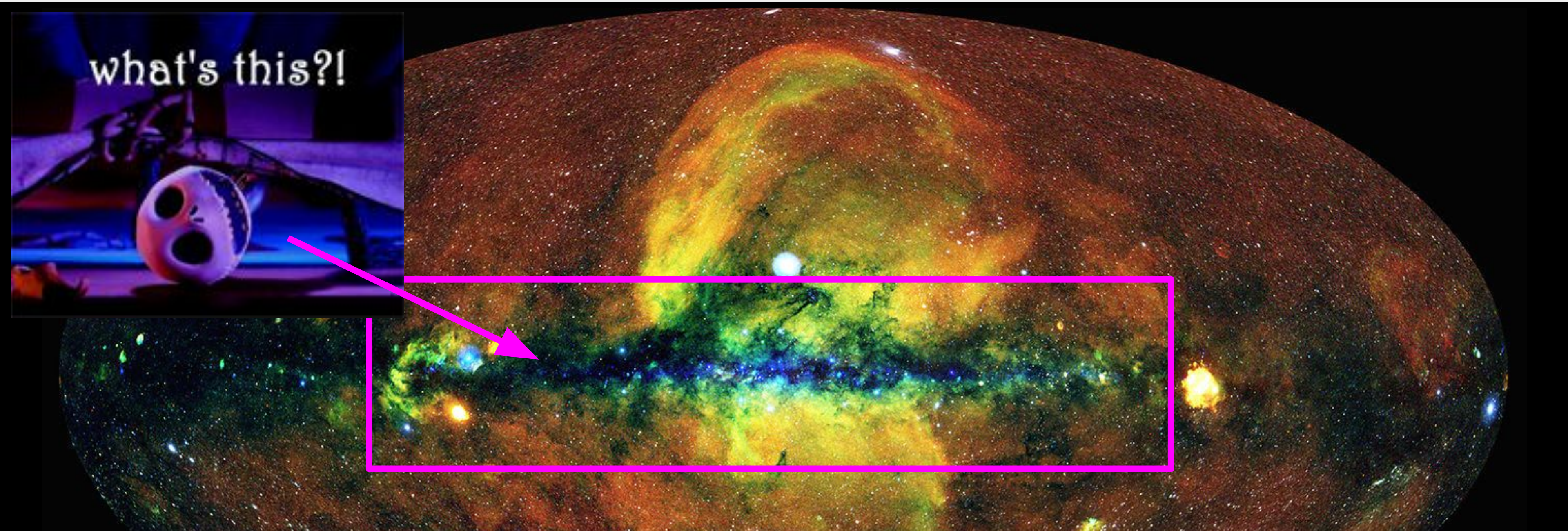
eROSITA View of the entire sky @ 0.3-2.3 keV



https://www.mpe.mpg.de/7461761/news20200619



Red: 0.3-0.6 keV
Green: 0.6-1 keV
Blue:1-2.3 keV



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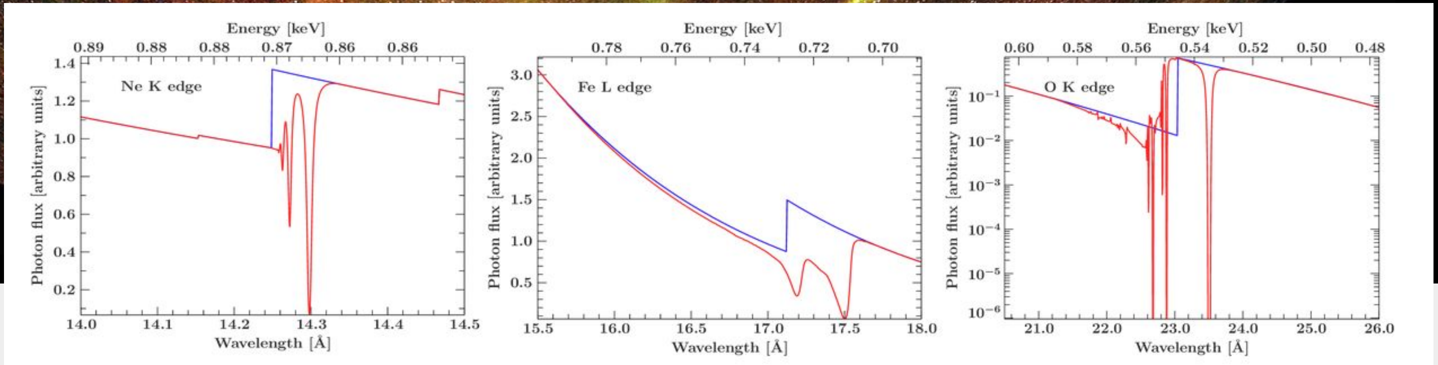
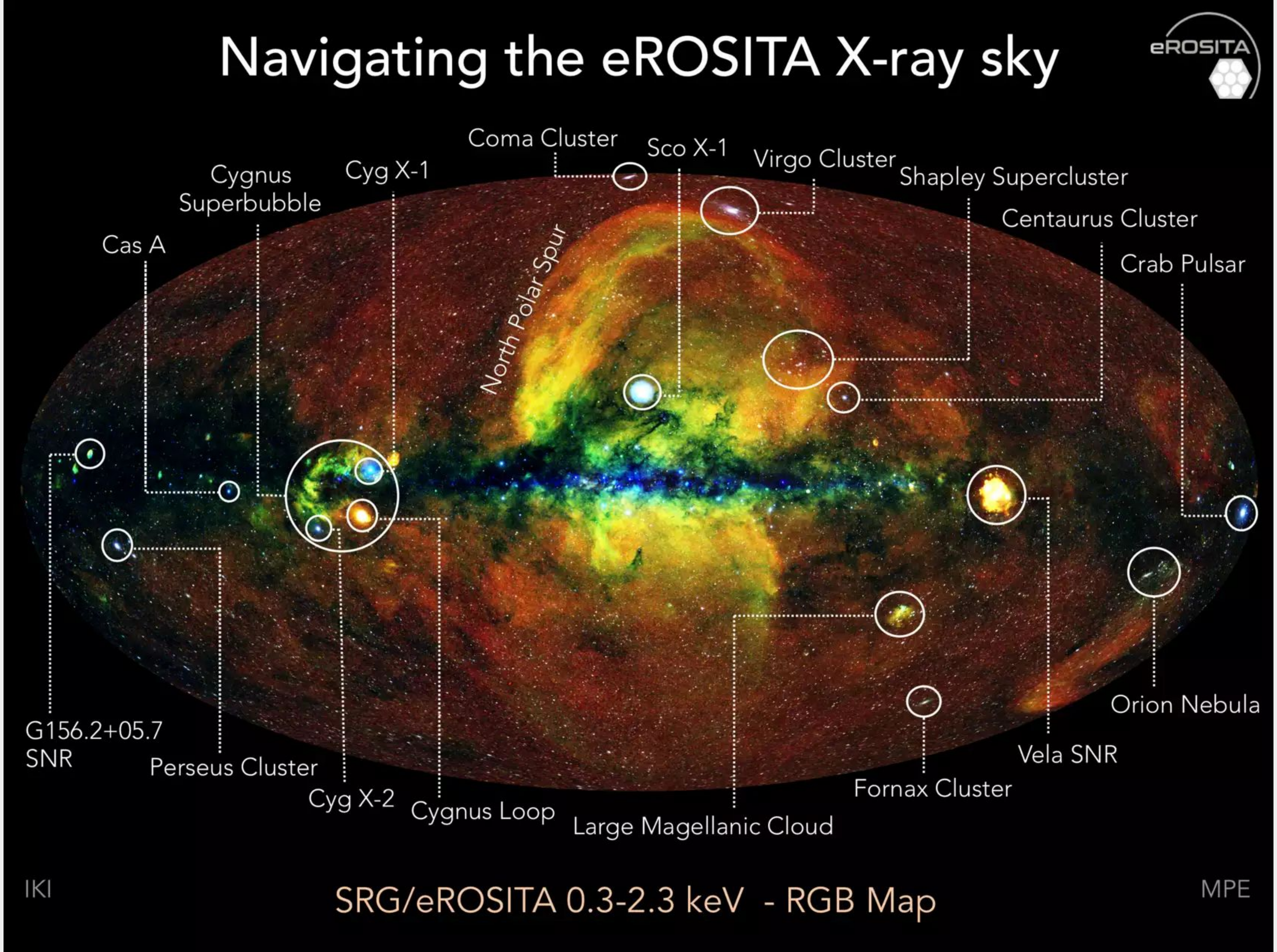




Can you spot your favorite source?

…

XRBs

…

SNRs

…

Pulsars

…

Nebula

…

Clusters

…

Galaxy clusters

…

AGN-Blazars

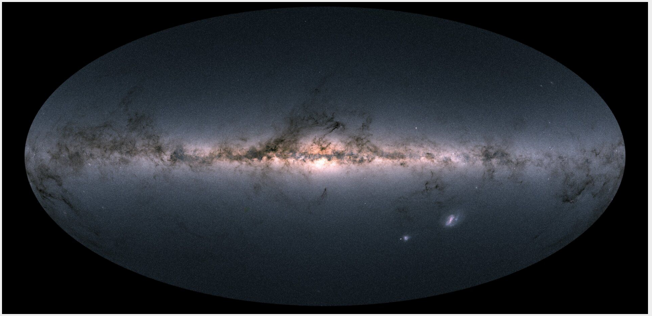
…

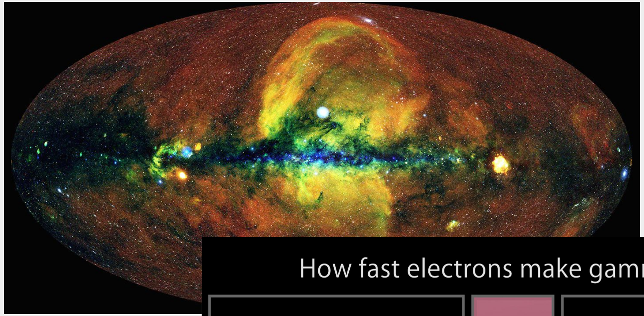
…

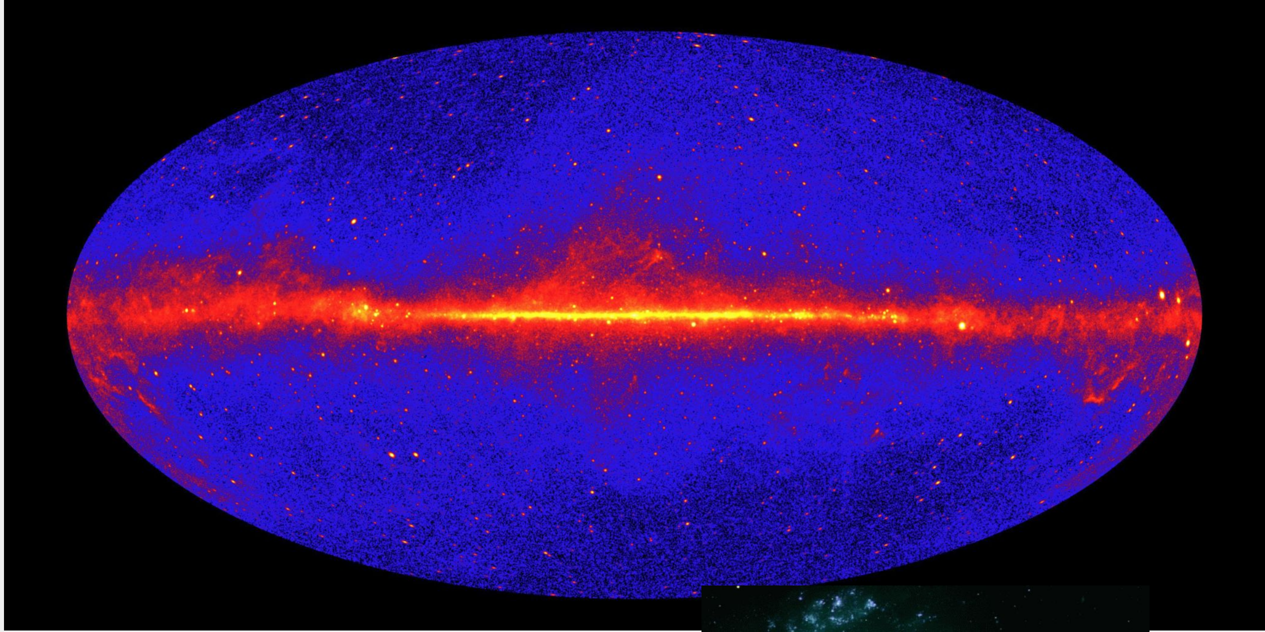
They are all here

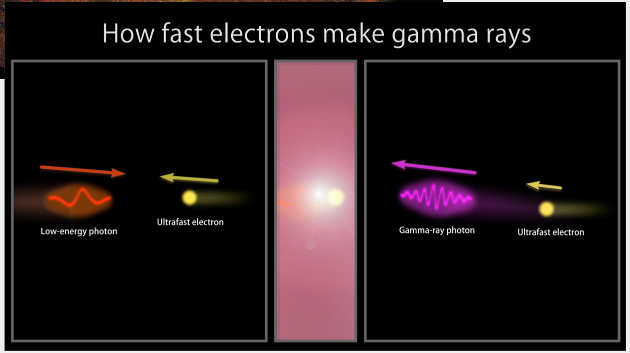
FERMI LAT sky map

~ 100 MeV - 100 GeV





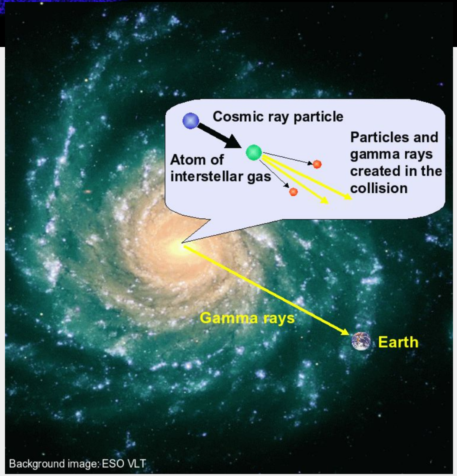


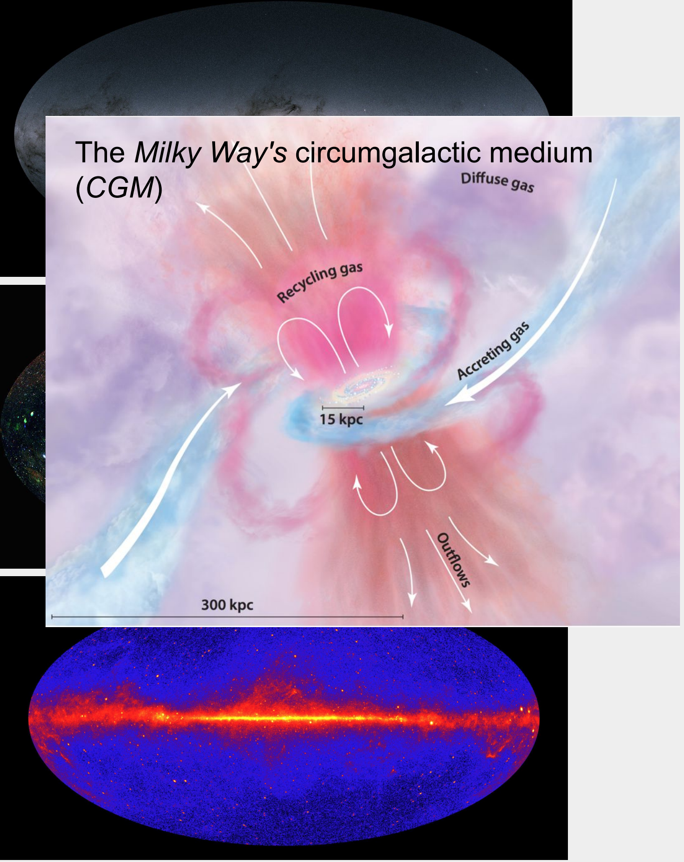


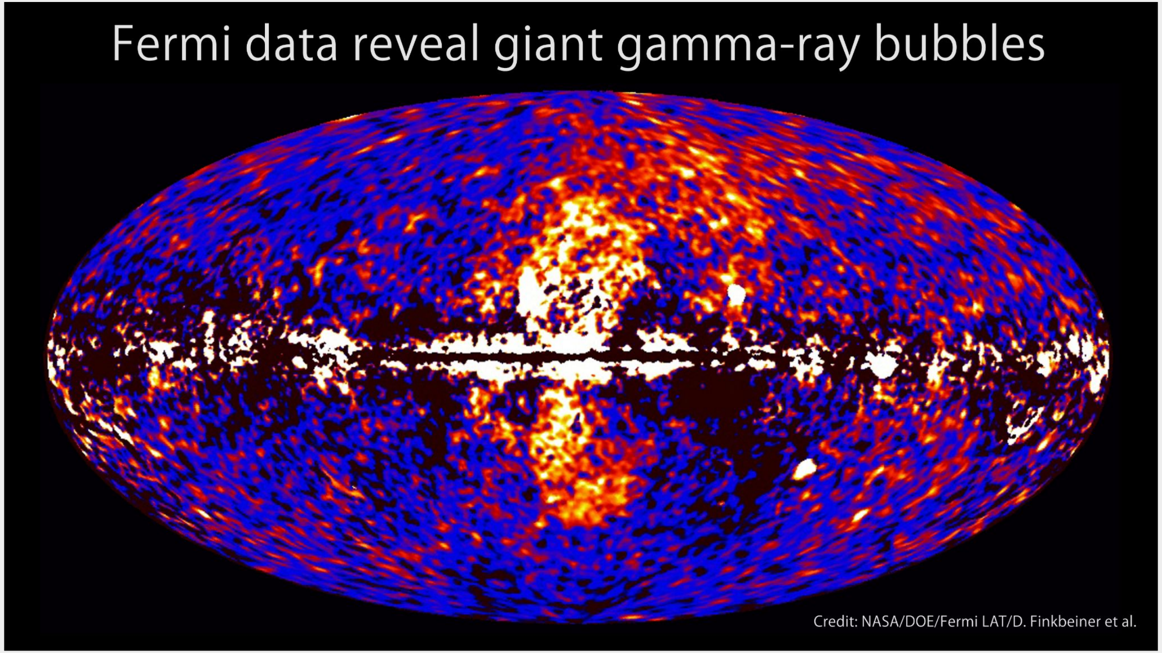
Compton scattering

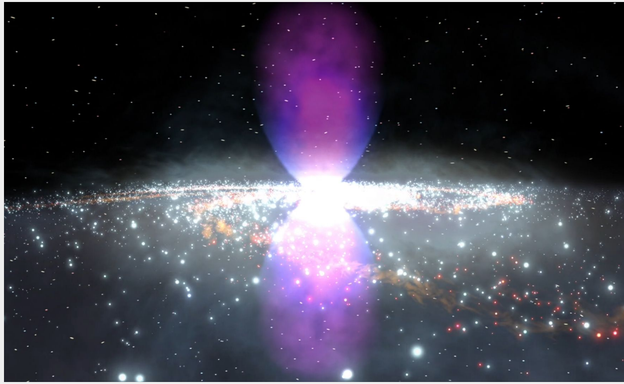
&

Pion Decay



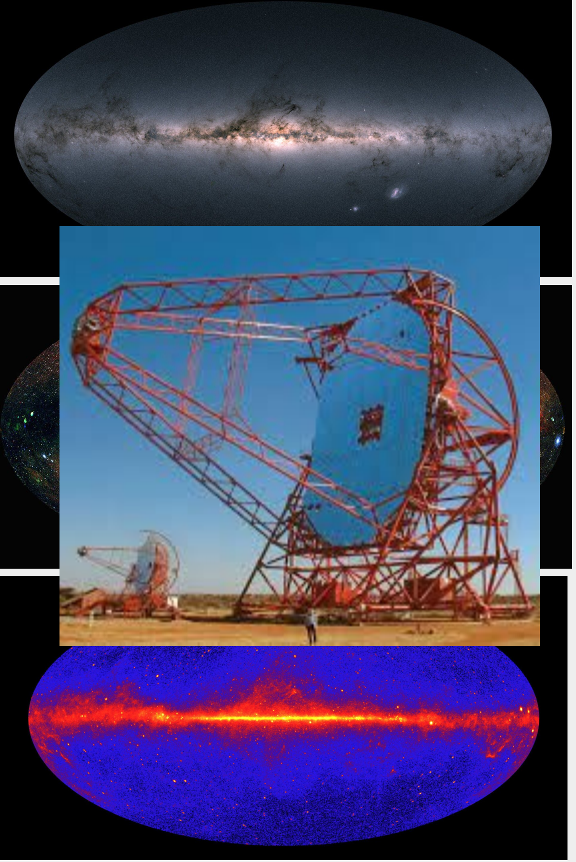


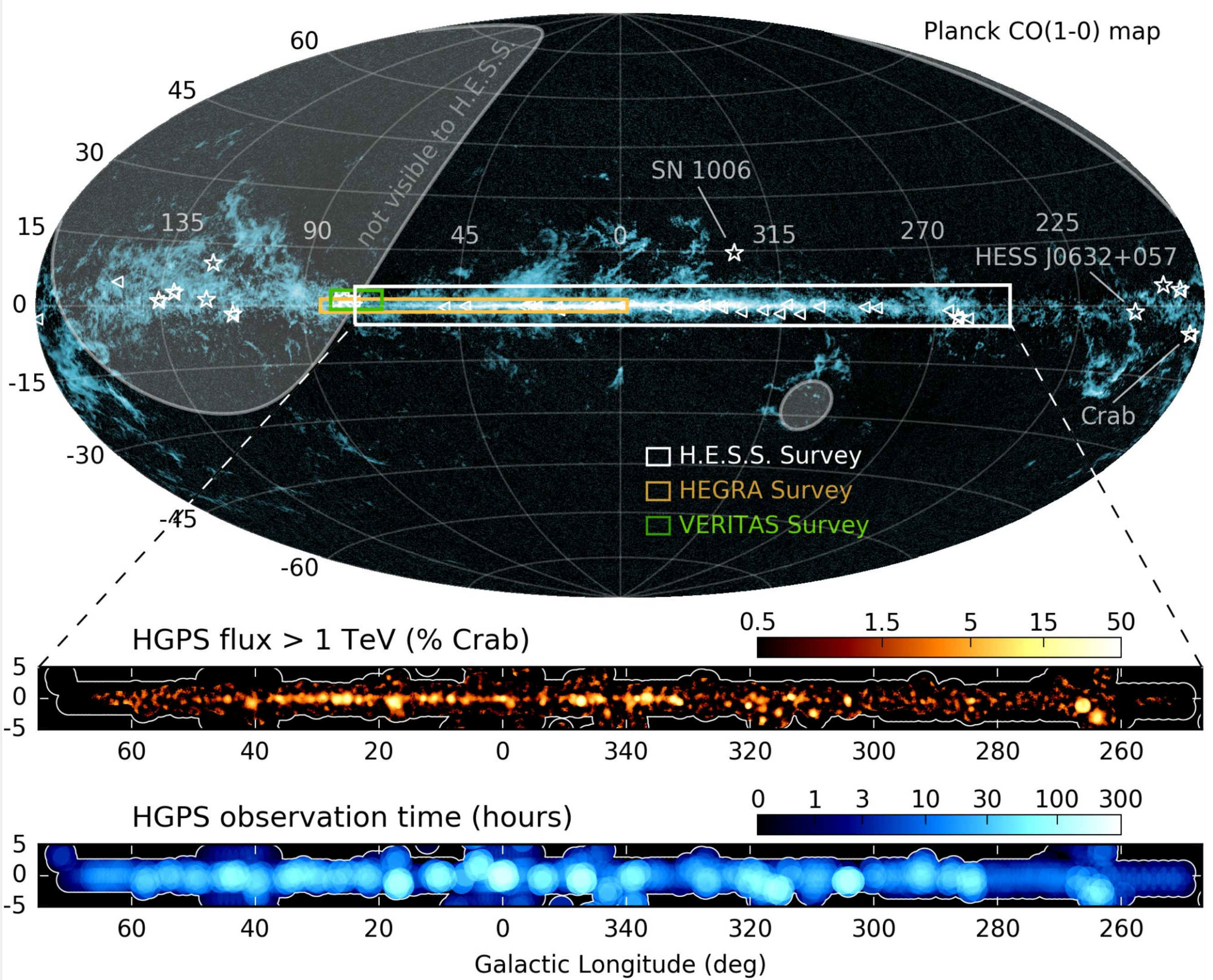




Goals:

- Understand feedback between nuclear activity and CGM
- Does the nuclear activity of quiescent galaxies influence their CGM?

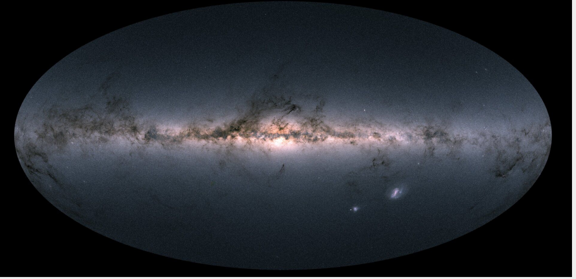


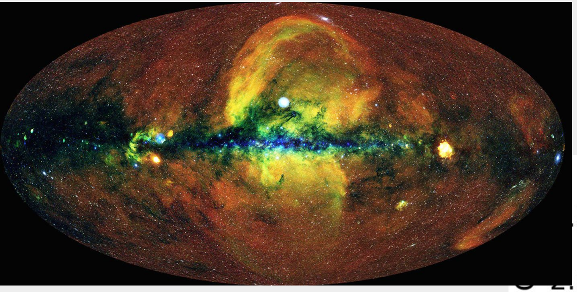


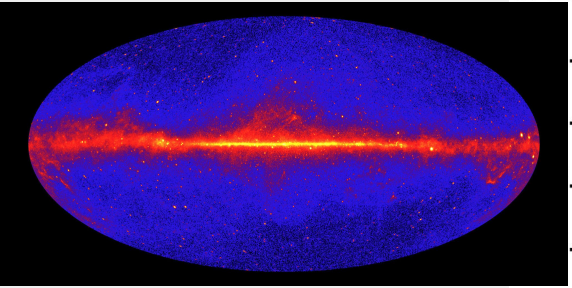
HESS@Namibia

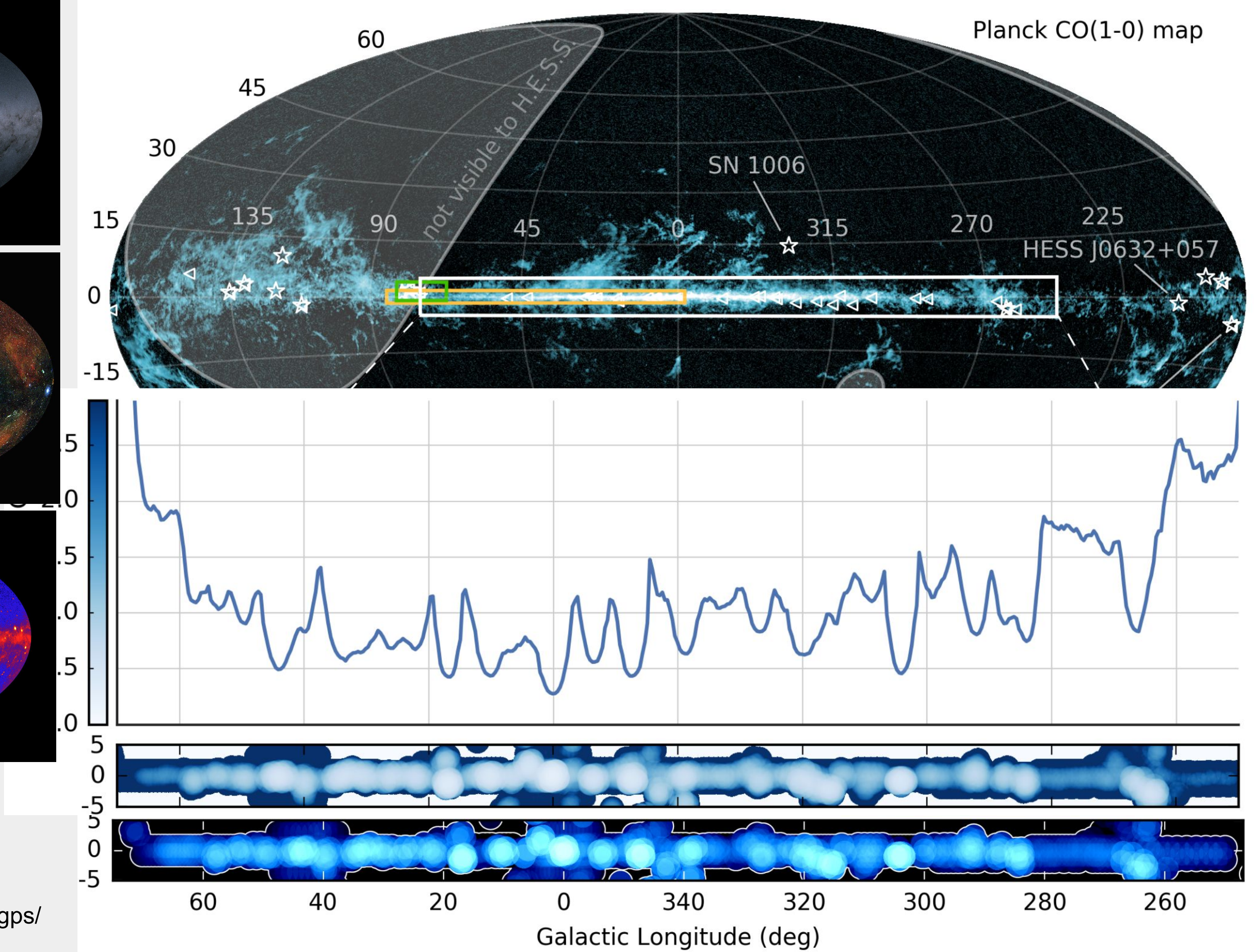
~ 1-10 TeV

https://www.mpi-hd.mpg.de/hfm/HESS/hgps/
https://arxiv.org/abs/2107.01425
https://arxiv.org/abs/2105.00983 (Table 1)

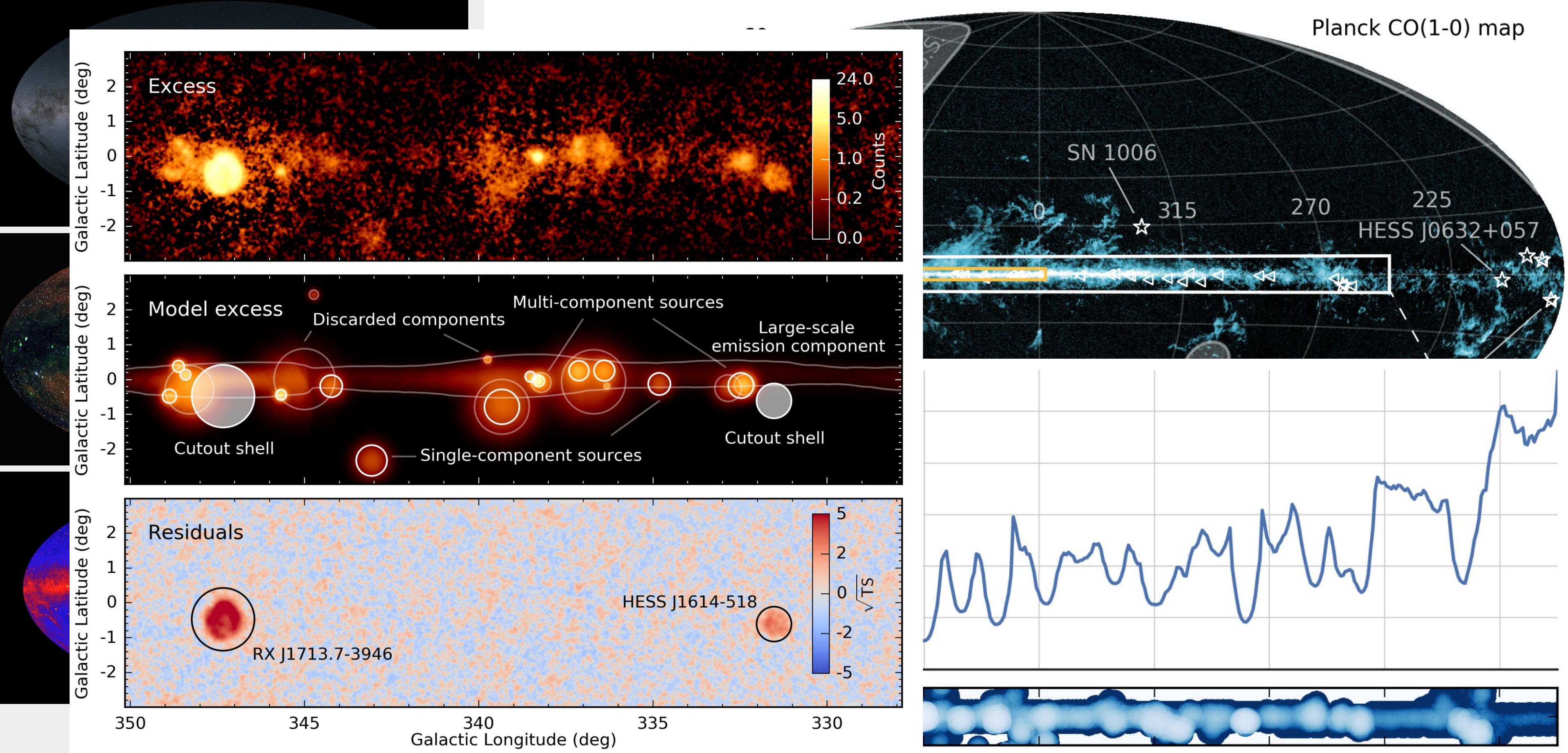


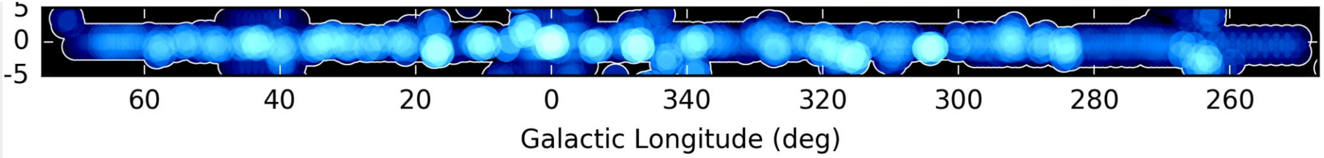






https://www.mpi-hd.mpg.de/hfm/HESS/hgps/





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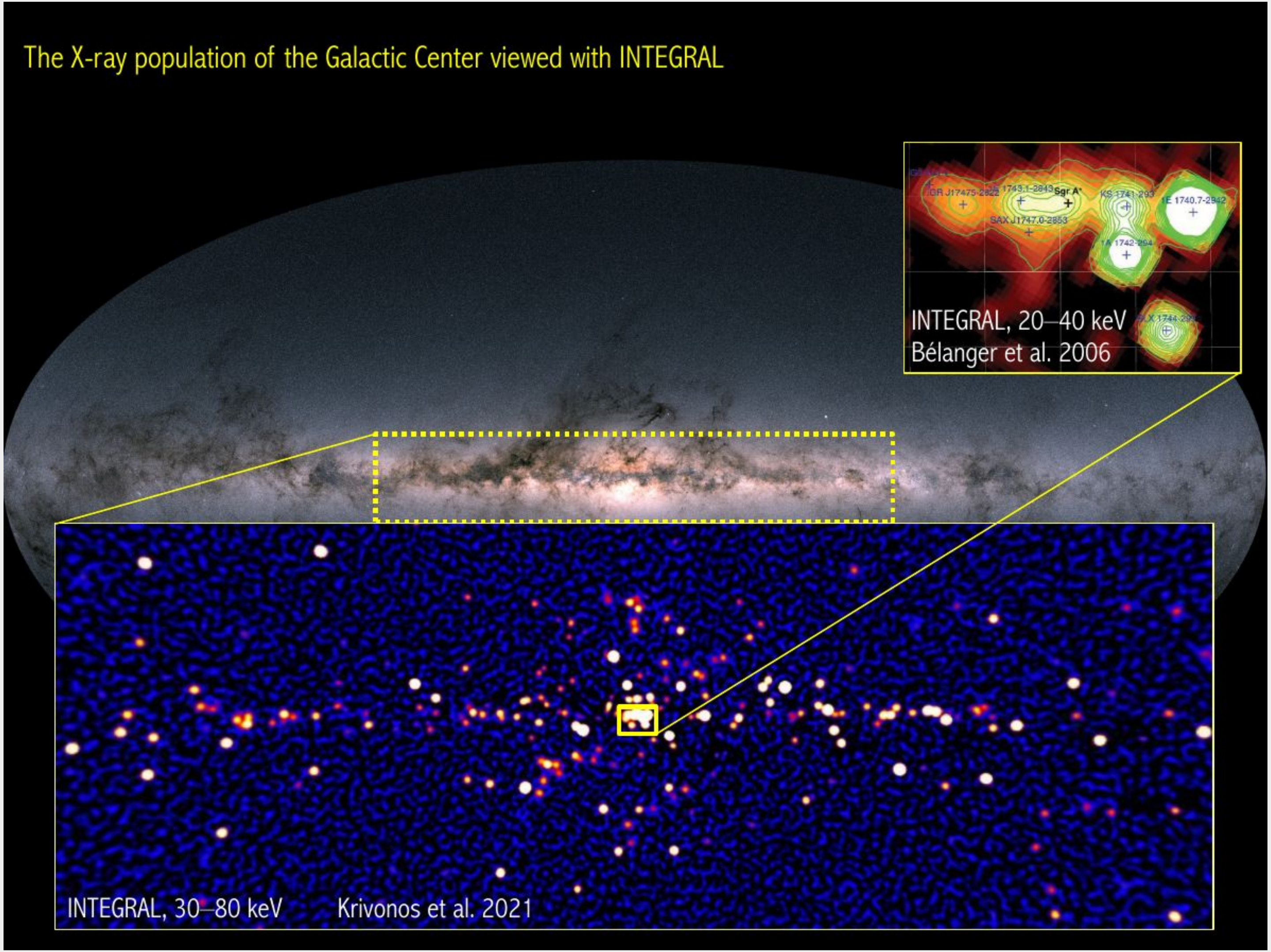
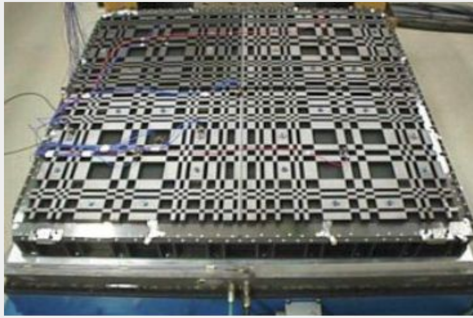
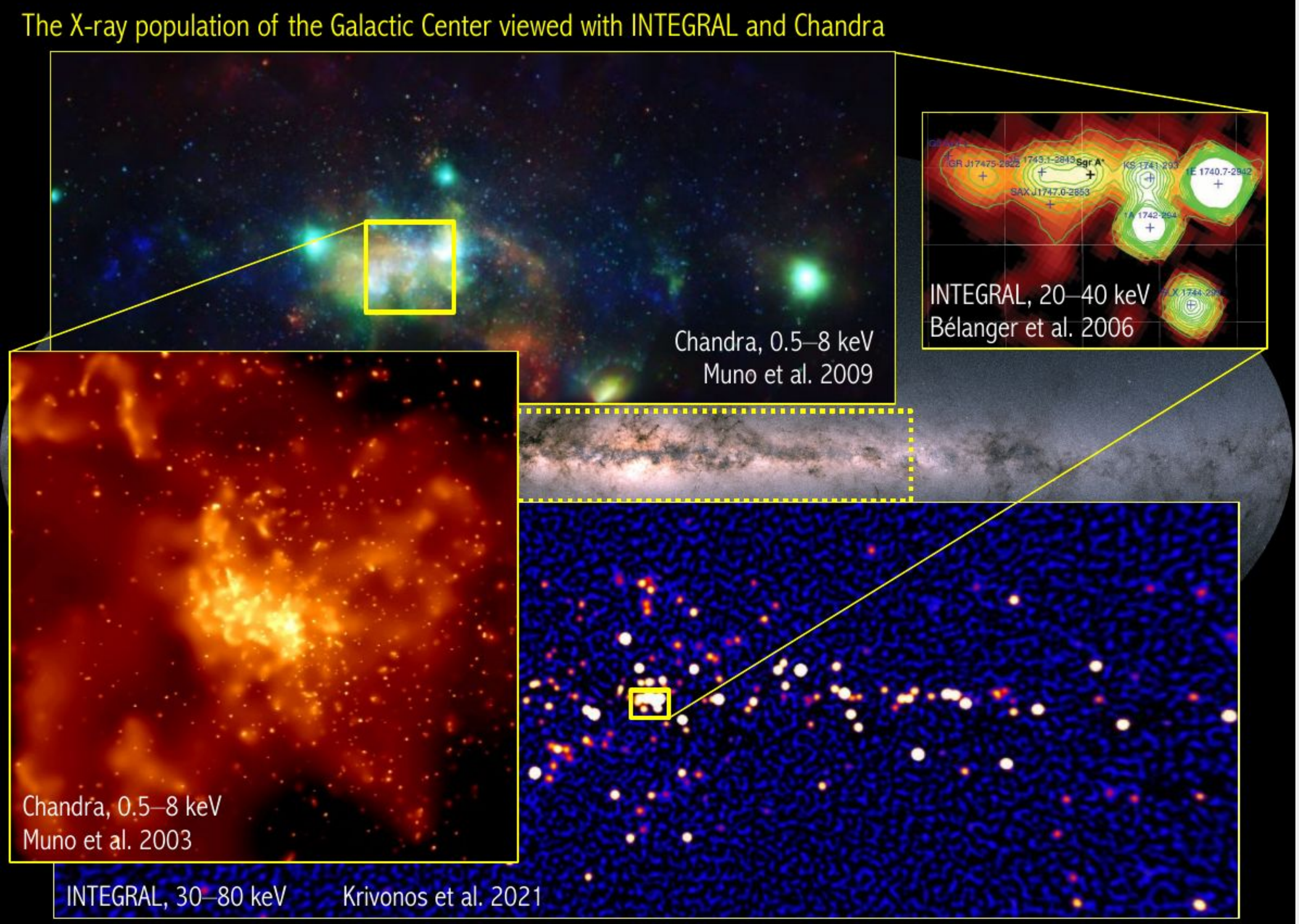
INTEGRAL



The Imager on Board the INTEGRAL Satellite (IBIS)
Coded mask

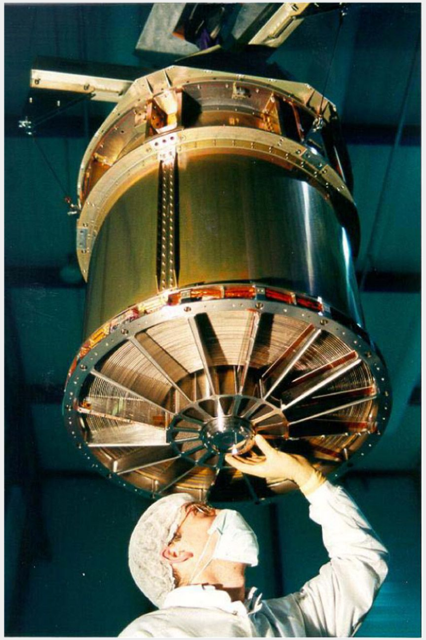


Good for hard sources
But poor resolution

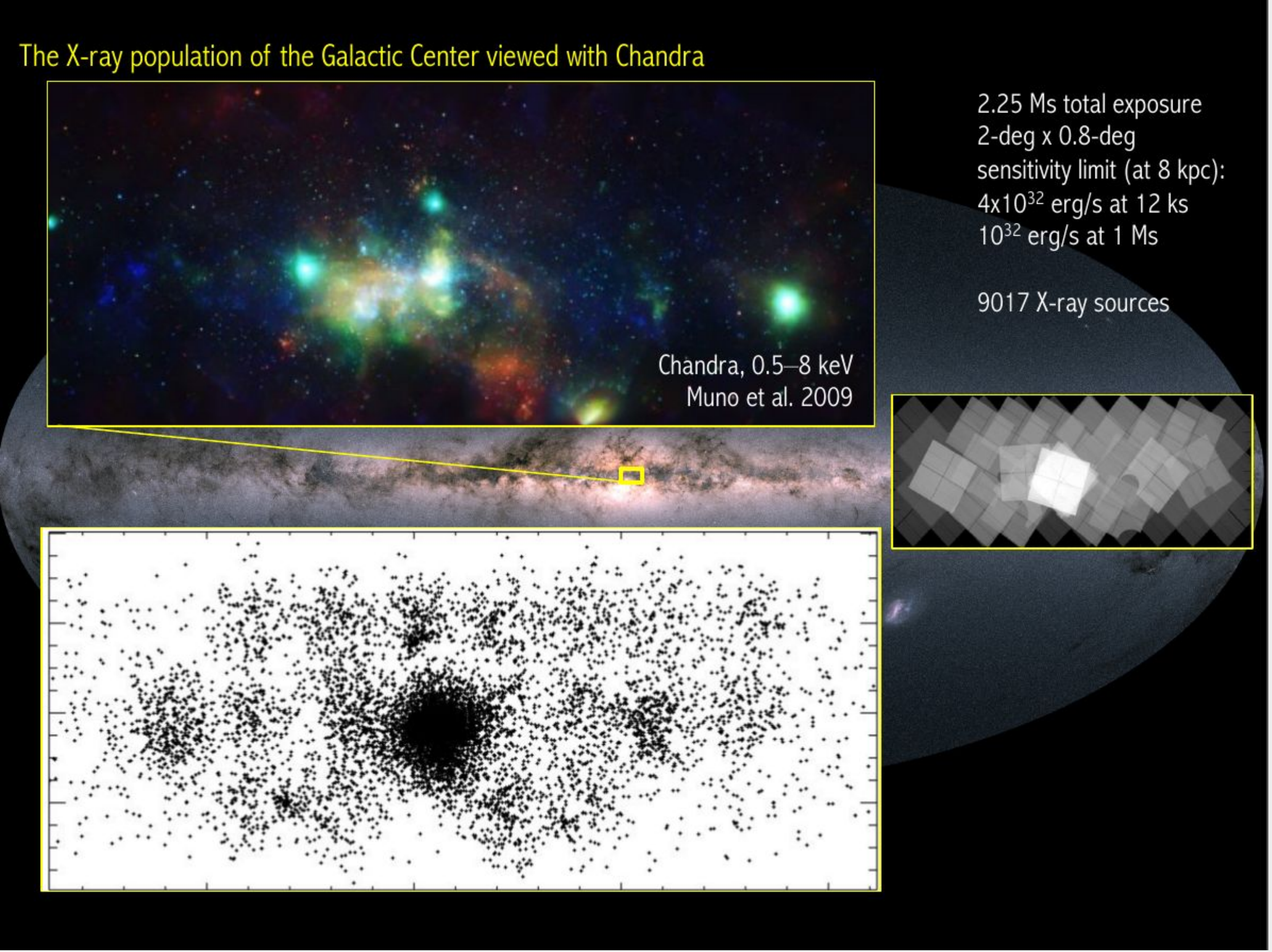


Chandra

Best mirrors available
< 1 arcsec resolution



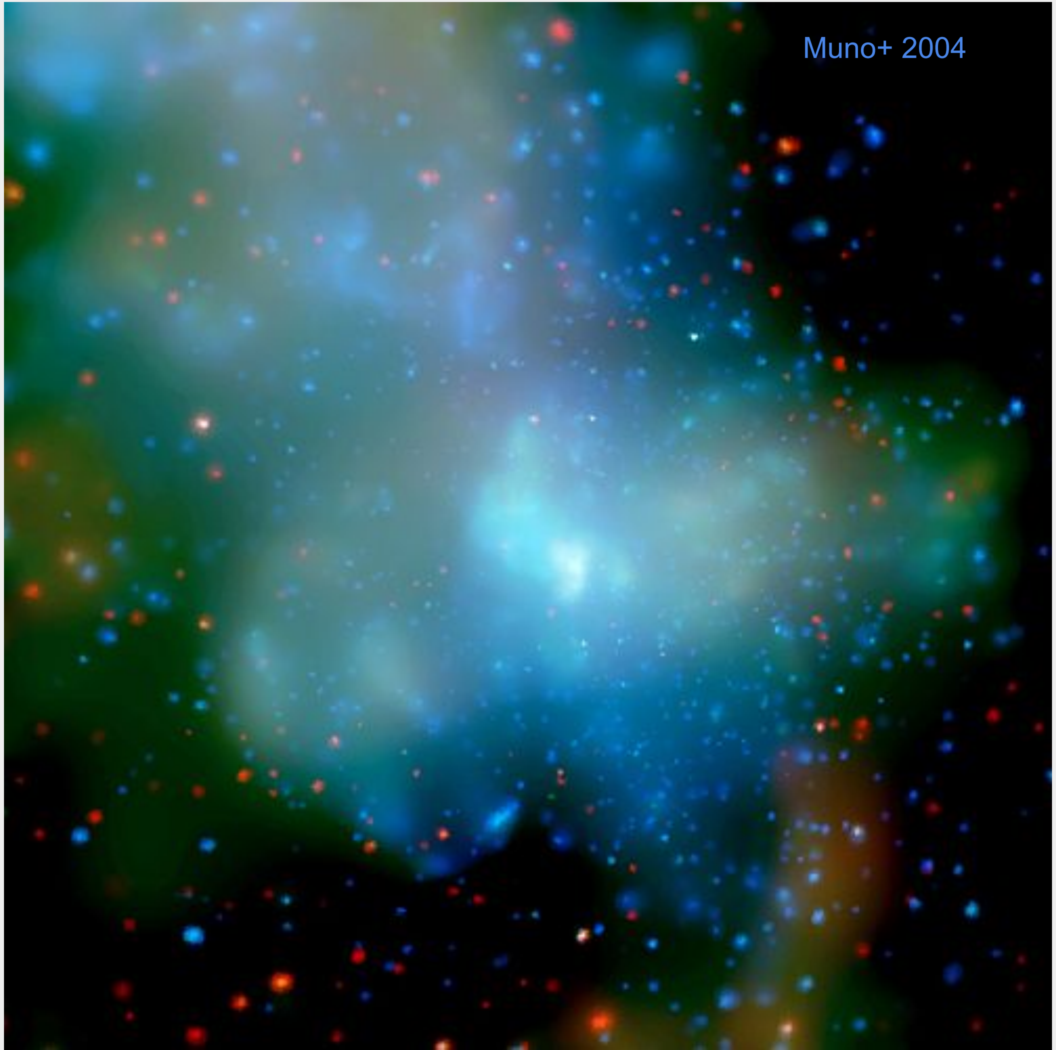
But small field of view
and degrades off-axis



Chandra

If we take many exposures…

Notice the bulk of sources are in areas where exposure is higher



Diffuse emission at GC

Irregular, diffuse glow from a 10-million-degree Celsius gas cloud, embedded in a glow of higher-energy X-rays with a spectrum characteristic of 100-million-degree gas.

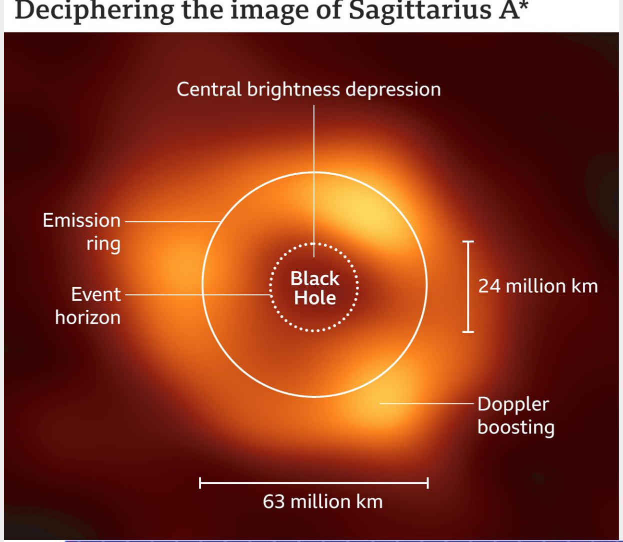
The gas could be replenished by winds from massive stars.

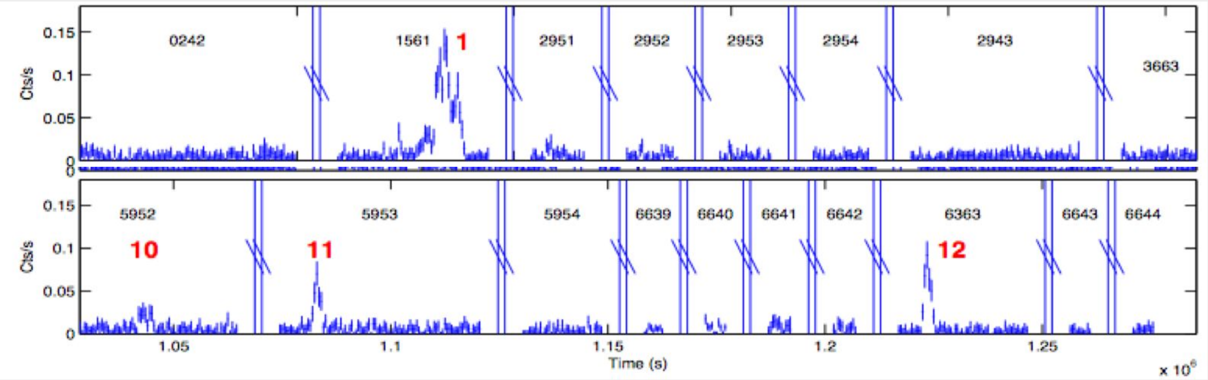
Magnetic turbulence produced by supernova shock waves can heat the gas to 100 million degrees. Alternatively, high-energy protons and electrons produced by supernova shock waves could be the heat source.

We still lack a complete understanding of the heating mechanism.

Sgr A*

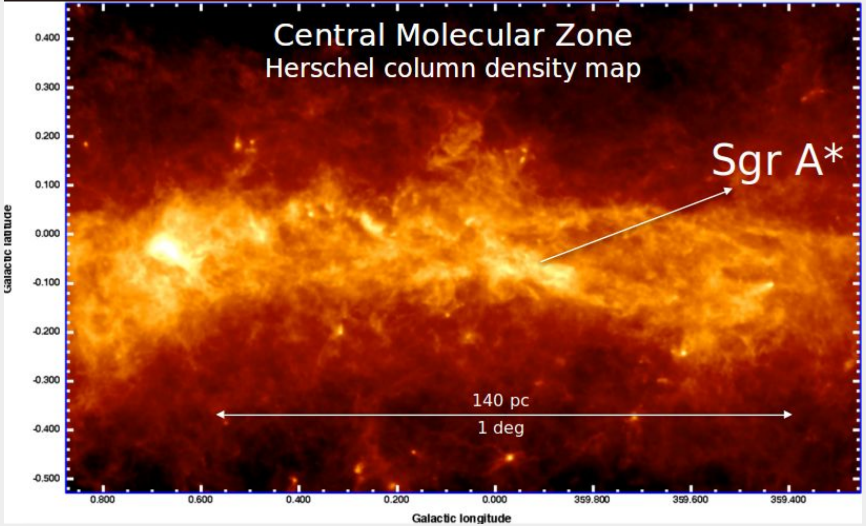
Ponti+ 2015

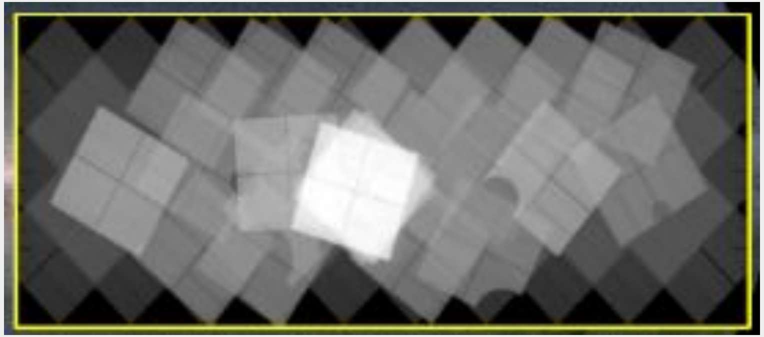


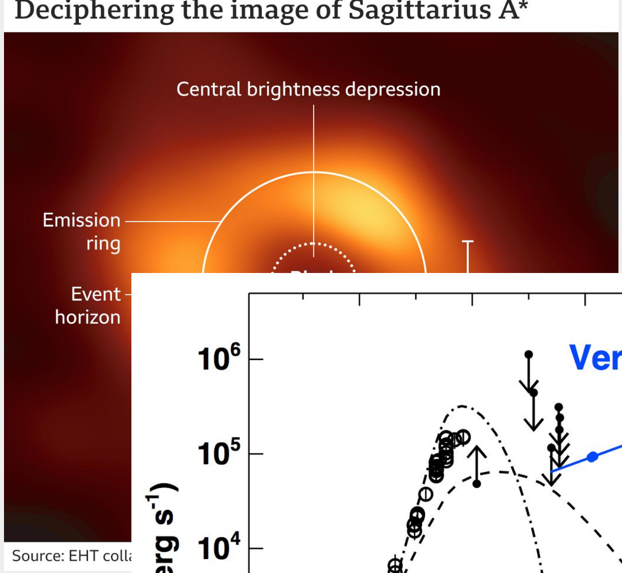


Flaring rate ~ 1 day^{-1}

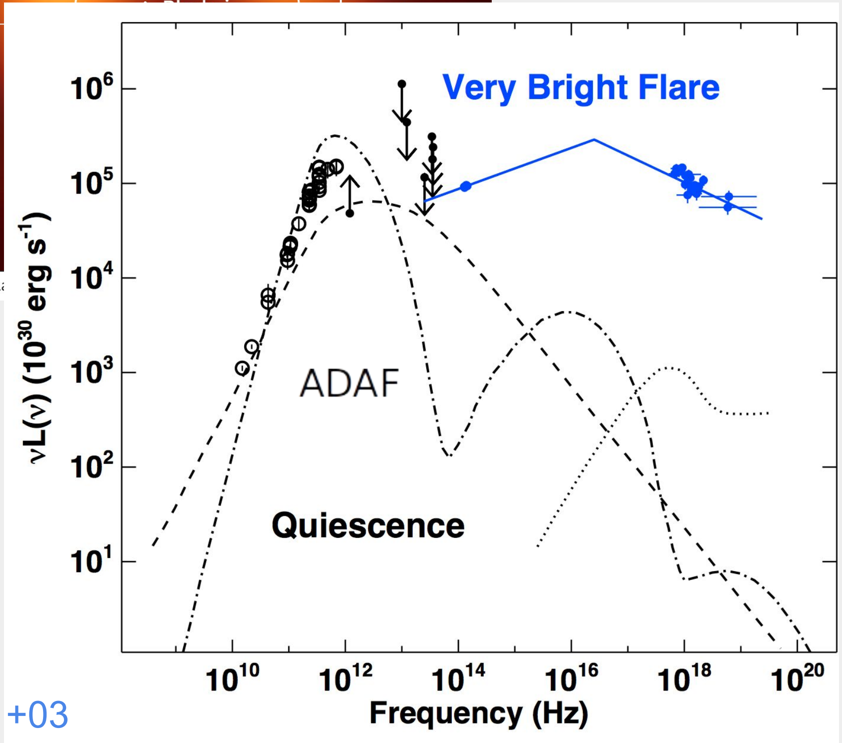
Flares L>10^{35} erg s^{-1} ~ 0.1 day^{-1}

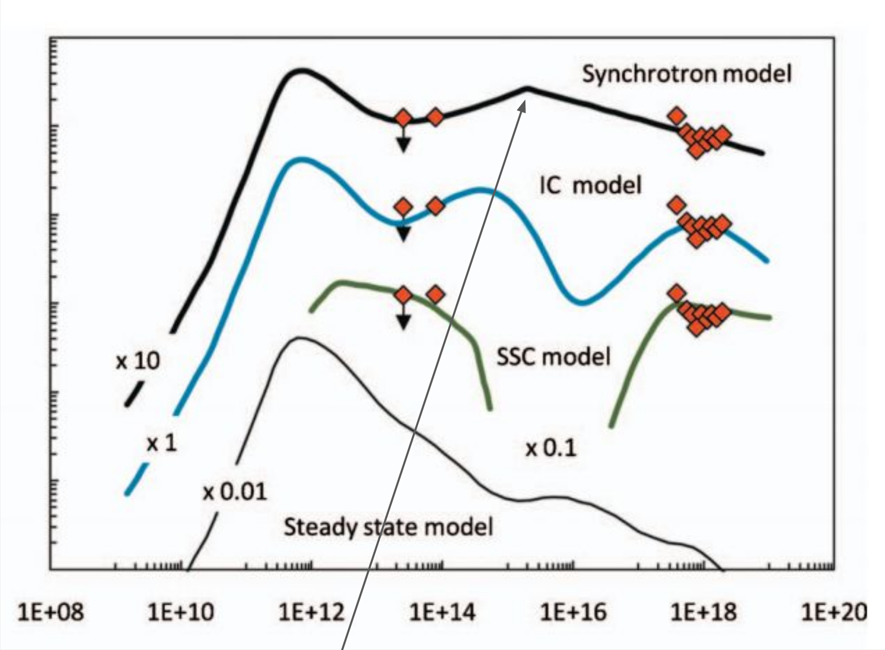






What is the radiative process in X-ray?
Duration -> size of region -> a few Rs
What causes acceleration? -> Perhaps magnetic reconnection close to disk?

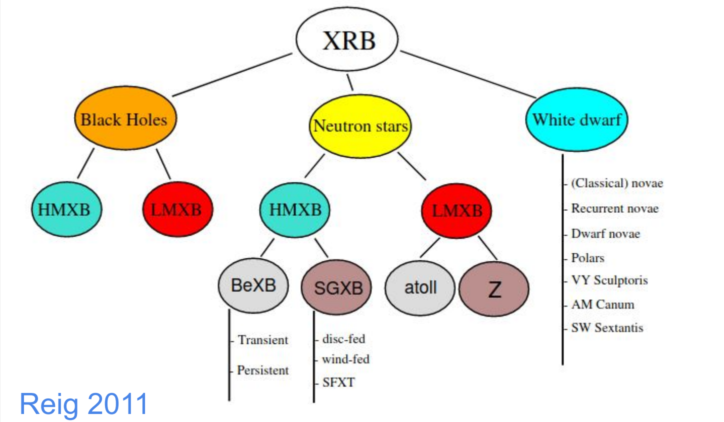




The synchrotron cooling timescale is shorter than the dynamical timescale

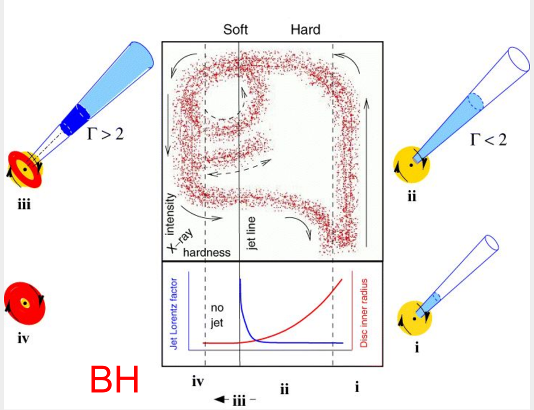
Yuan +03
Ponti +17b

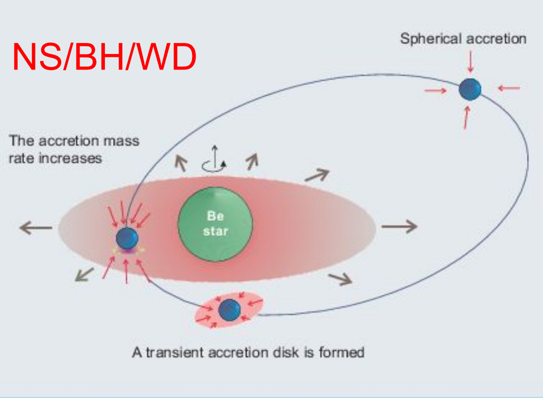
Point sources in the Galactic center: Theory

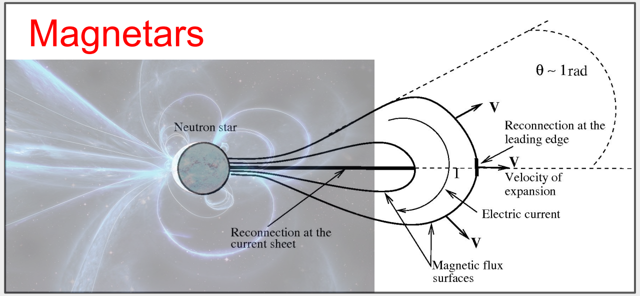


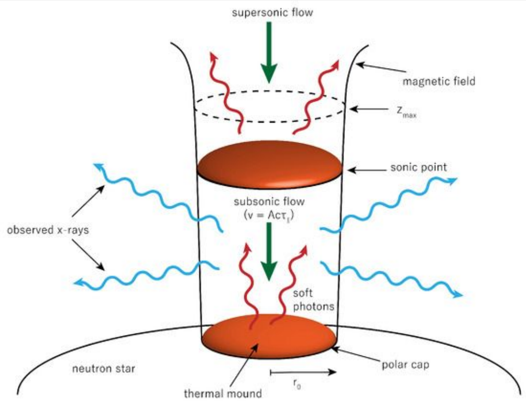
Reig 2011

Fig. 1 Classification of X-ray binaries.

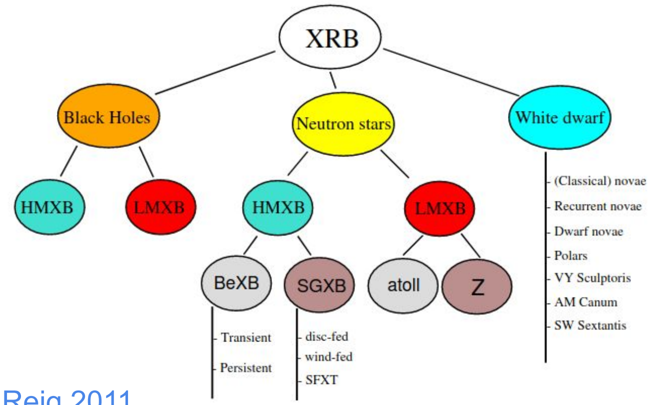






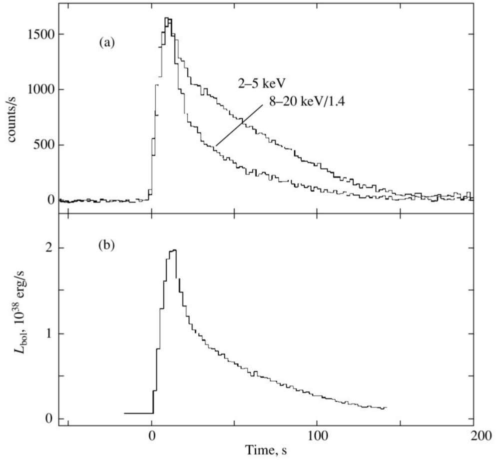


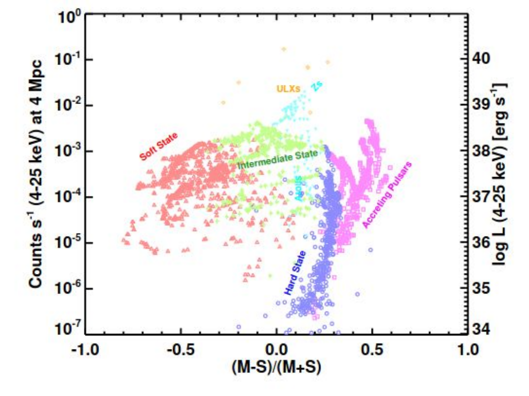
Point sources in the Galactic center: Theory

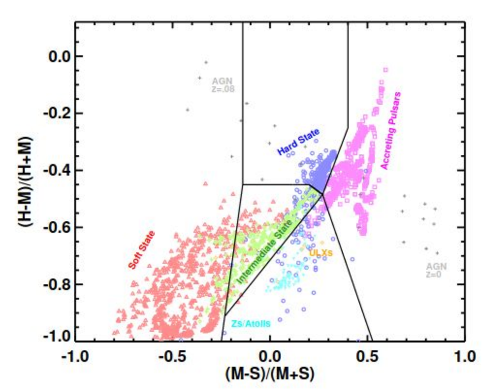


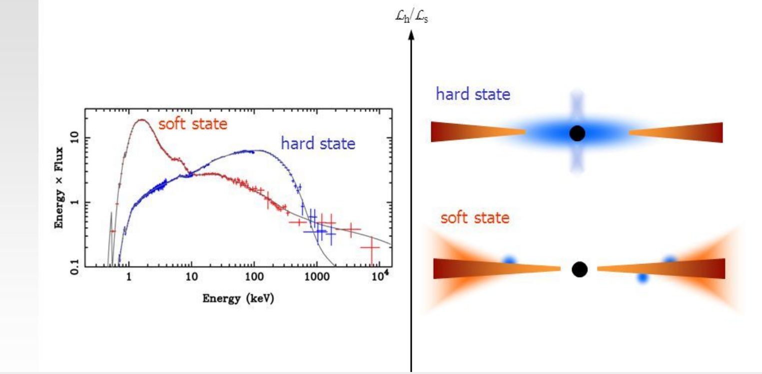
Reig 2011

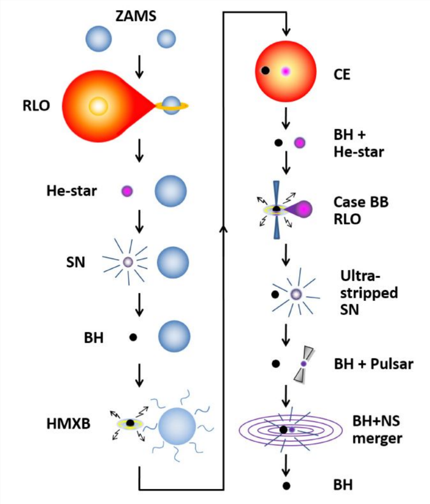
Fig. 1 Classification of X-ray binaries.











S : 4 − 6 keV
M :6 − 12 keV
H: 12 − 25 keV

Point sources in the Galactic center:
simulations

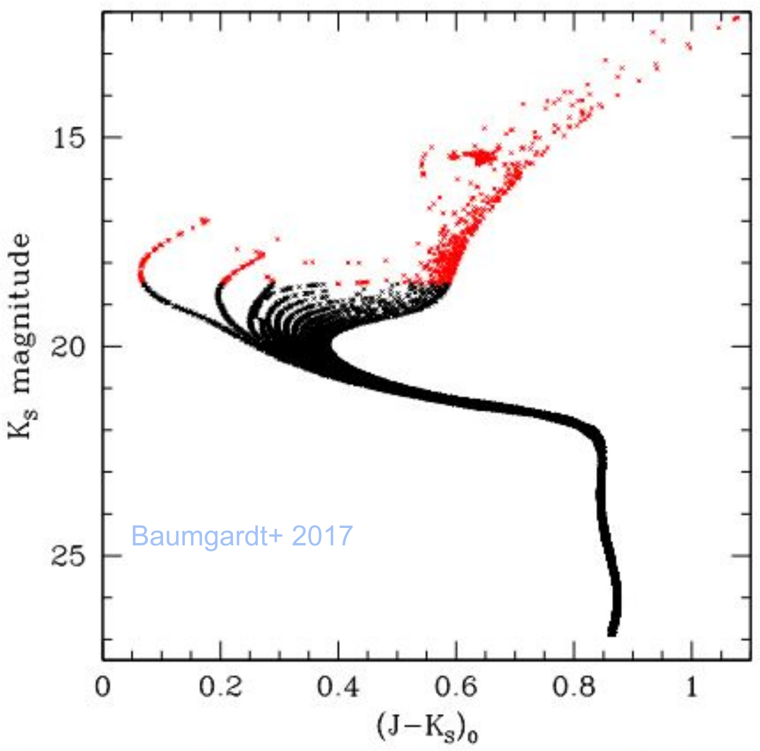
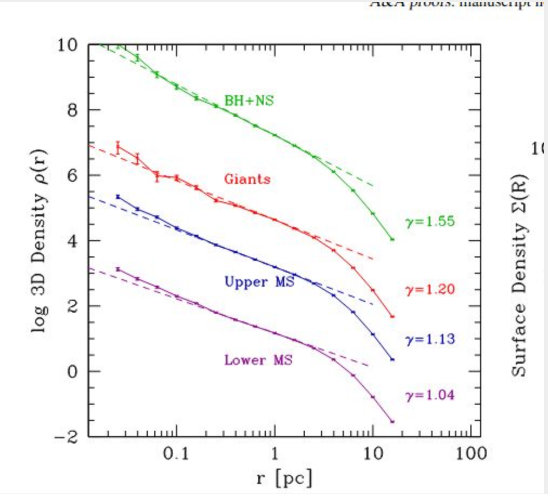


Fig. 1. $J - K_S$ CMD of the simulated nuclear clusters after 13 Gyr of evolution for a distance of 8 kpc to the GC and and an average reddening of $A_{K_S} = 2.54$ mag. The different stellar generations that were added to



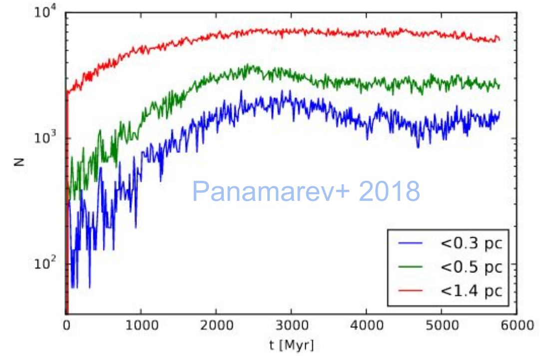


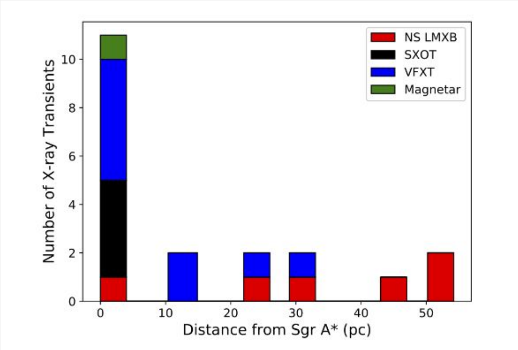
Figure 6. The number of BHs as function of time. The red, green and blue line show the number of stellar mass BHs inside 1.4, 0.5 and 0.3 pc respectively.

Point sources in the Gal. center: observations

Mori+ 2021

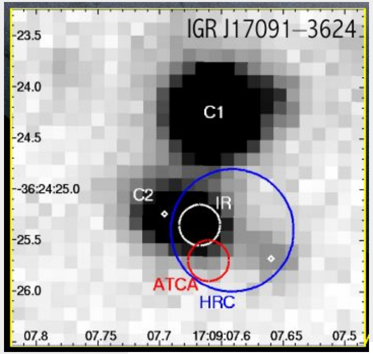
Table 2. Classification of LMXBs in the GC

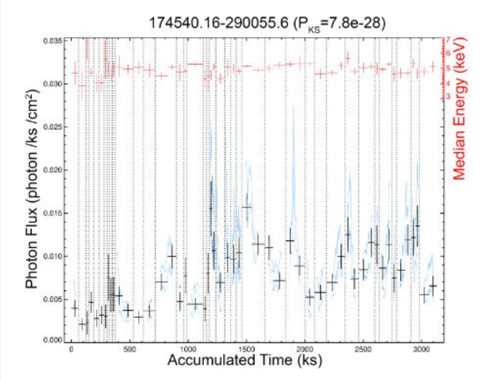
Source	# of sources	Location	Recurrence time	Compact object type	Orbital period range
Non-thermal sources	12	$r \lesssim 1$ pc	$\gtrsim 13$ yrs	BH[a]	$\sim 4 - 12$ hrs[a]
SXOTS (single X-ray outbursters)	4	$r \lesssim 2$ pc	$\gtrsim 13$ yrs	BH[a]	7.9 hrs[c] or $\sim 4 - 12$ hrs[a]
NS-LMXBs	6	$r \gtrsim 3$ pc	$\lesssim 5$ yrs	NS	8.35 hrs[d] otherwise unknown
Recurrent VFXTs	5	$r < 10$ pc	$\lesssim 10$ yrs	Unknown	Unknown
VFXTs with single outbursts	4	$r \gtrsim 10$ pc	$\gtrsim 10$ yrs[b]	Unknown	Unknown

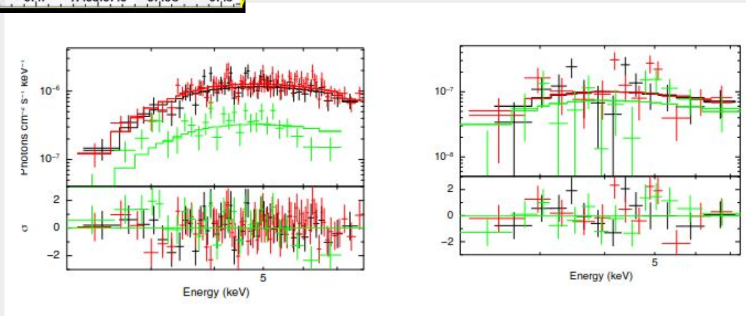


A majority of these sources are undetectable by X-ray telescopes since their dominant soft thermal emission (kT <~ 0.1 keV) and high absorption

Source name	Photon index	L_X [10^{31} erg s^{-1}]	Variability significance [σ][a]
174539.87−290034.2	$2.2^{+0.8}_{-0.7}$	8.1–30	12.8
174540.38−290033.5	$1.7^{+1.5}_{-1.8}$ [c]	0.3–4.9	3.8
174540.40−290024.1	$2.0^{+0.8}_{-0.7}$	7.9–16	4.5
174540.45−290036.3	$1.5^{+0.7}_{-0.8}$ [c]	4.0–6.8	2.5
174540.79−290024.5	$2.8^{+1.2}_{-1.0}$	4.7–18	7.2
174539.40−290040.9	$2.9^{+1.0}_{-0.9}$	8.2–9.8	1.6
174540.95−290031.2	2.1 ± 0.7 [c]	2.0–6.2	3.8
174541.03−290026.8	$1.7^{+0.7}_{-0.8}$ [c]	3.3–5.2	1.6
174540.63−290013.4	$2.1^{+0.9}_{-0.8}$	2.3–15	12.1
174539.48−290045.8	$2.9^{+0.6}_{-0.5}$	6.3–30	19.5
174540.37−290049.9	2.2 ± 0.5 [c]	3.1–4.3	1.4
174540.16−290055.6	2.0 ± 0.4	20–77	24.0





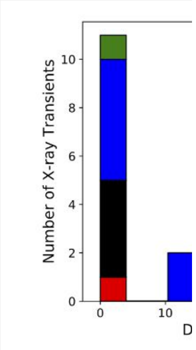


Point sources in the Gal. center: observations

Mori+ 2021

Table 2. Classification of LMXBs in the GC

Orbital period range
12 hrs^a
~ 4 – 12 hrs^a
erwise unknown
nown
nown



Source name			
174539.87−29003			
174540.38−29003			
174540.40−29002			
174540.45−29003			
174540.79−29002			
174539.40−29004			
174540.95−29003			
174541.03−29002			
174540.63−29001			
174539.48−29004			
174540.37−290049.9	2.2 ± 0.5^c	3.1–4.3	1.4
174540.16−290055.6	2.0 ± 0.4	20–77	24.0

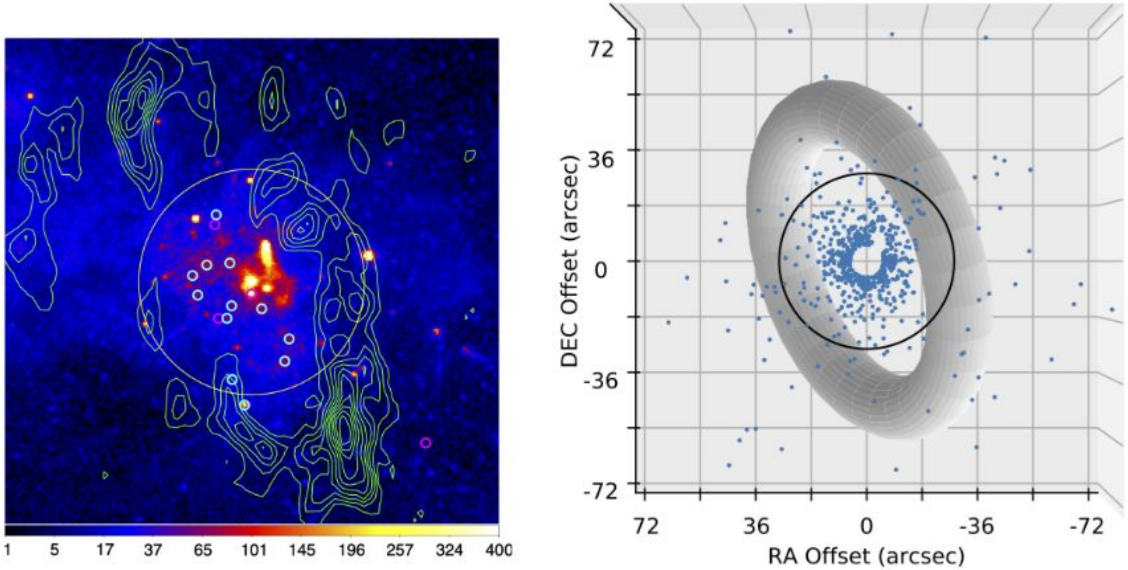
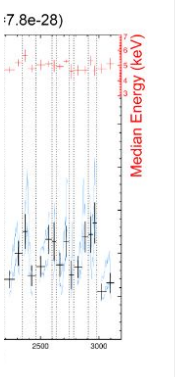
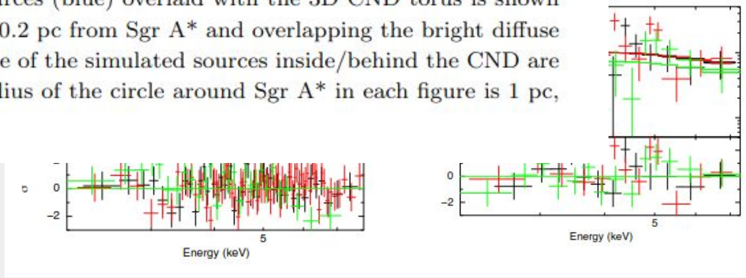


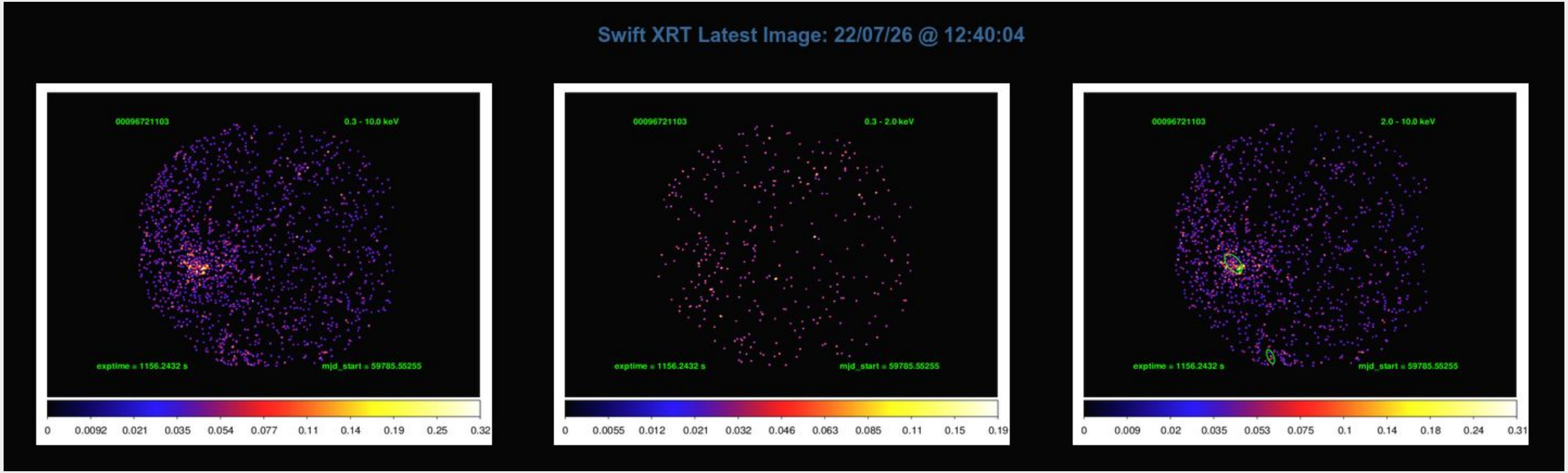
Figure 6. Left: 2–8 keV *Chandra* ACIS-I image centered on Sgr A* of the 12 quiescent BH-LMXBs (cyan) and four BH transients (i.e., SXOTs, magenta) with CND contours (green). Right: A plot of 1,000 simulated sources (blue) overlaid with the 3D CND torus is shown to illustrate their spatial distribution and obscuration. Note that the regions at $r < 0.2$ pc from Sgr A* and overlapping the bright diffuse X-ray sources (as shown in the left panel) are devoid of simulated sources. Also, some of the simulated sources inside/behind the CND are removed as they are not observable due to the significant X-ray absorption. The radius of the circle around Sgr A* in each figure is 1 pc, corresponding to $r = 25''$.

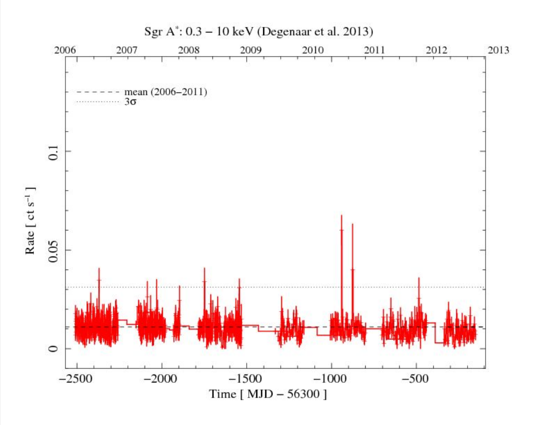




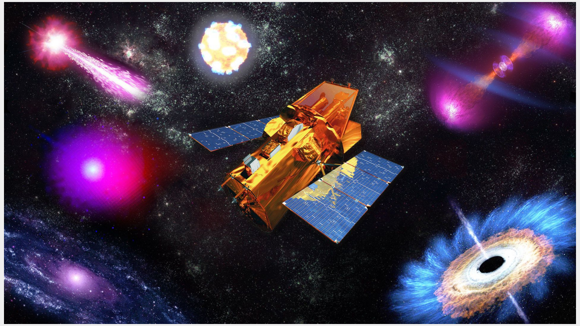
Point sources in the Gal. center: observations II (variability)

http://www.swift-sgra.com/



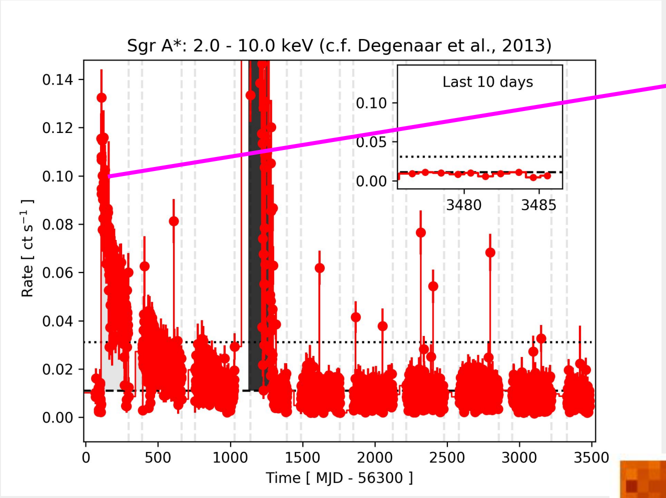


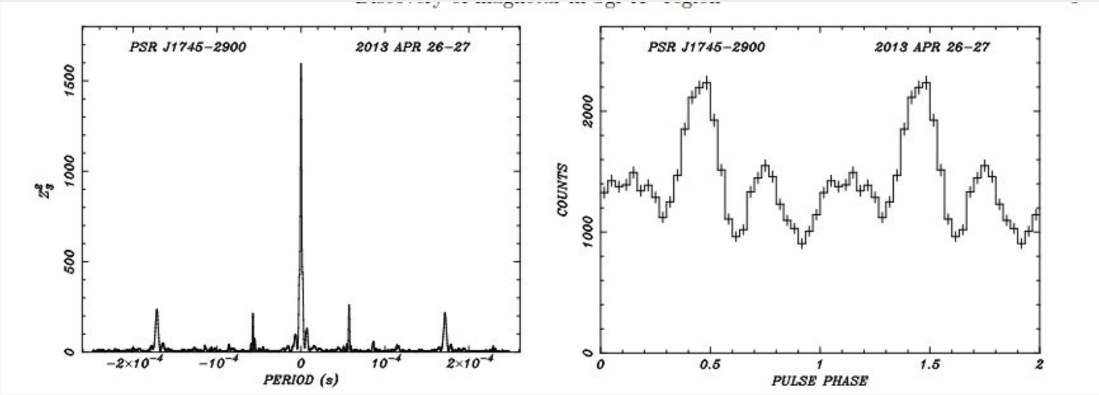
Swift monitoring campaign of the Galactic center. Using almost daily observations since 2006, this program has provided a unique baseline to study the long-term X-ray behavior of the central super-massive black hole Sgr A*

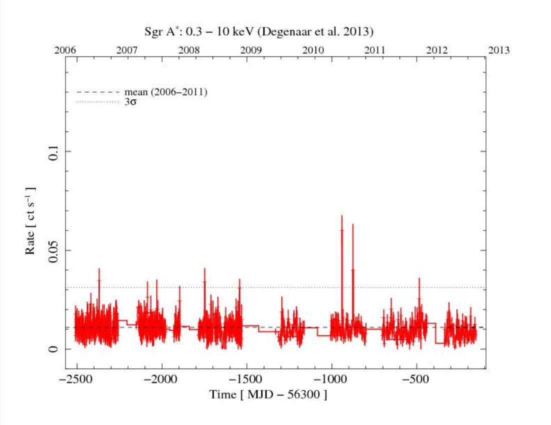


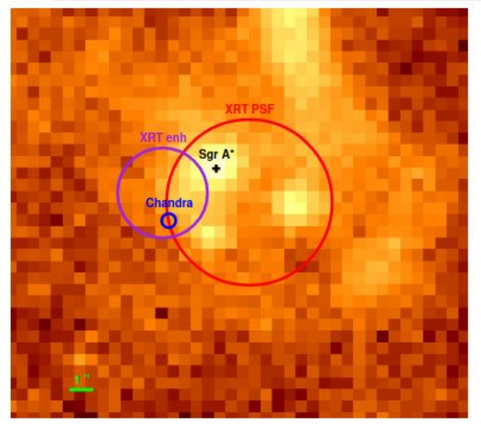
Point sources in the Gal. center: observations II (variability)

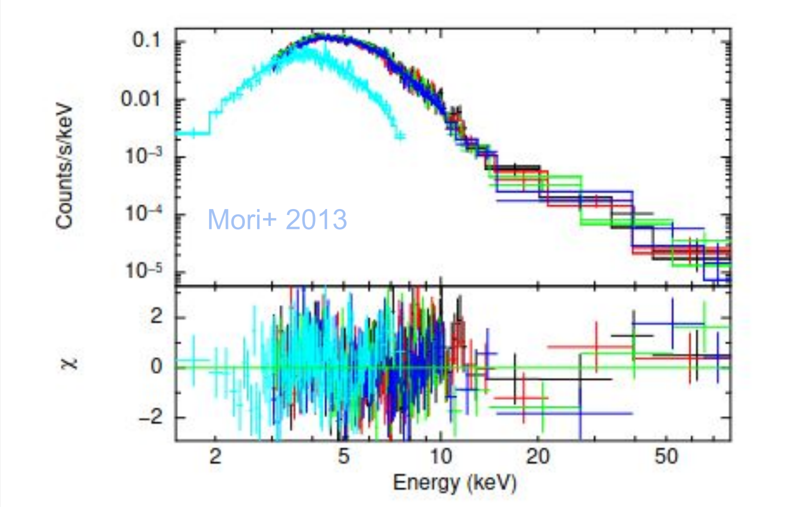
http://www.swift-sgra.com/
https://www.swift.ac.uk/user_objects/tprods/USERPROD_62508/index.php









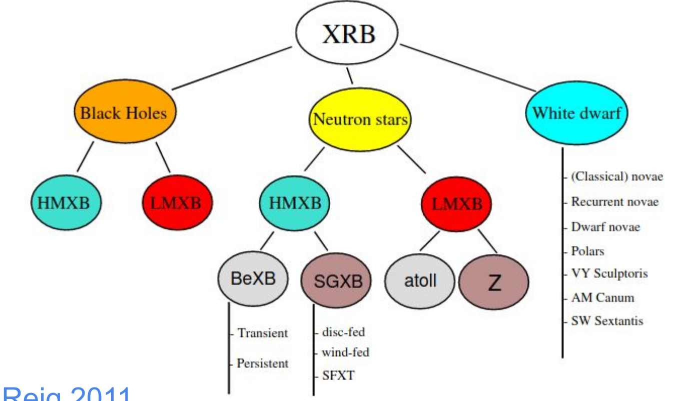


Complete the logN-logS curve for Galactic sources

The logN-logS diagram or luminosity function, traces the evolutionary history and spatial distribution of its constituent object classes.

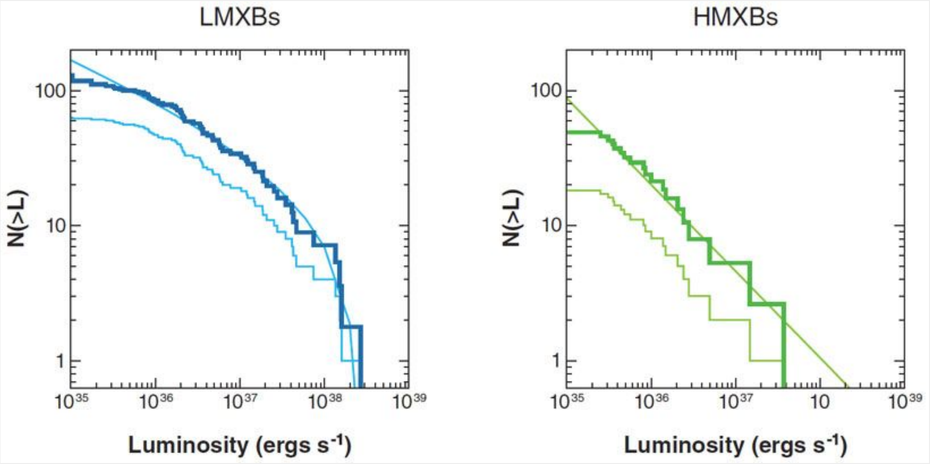
X-ray surveys of the Galactic Plane show that the logN-logS relation turns over at low luminosities which indicates an incomplete tally of the objects that emit below the telescope's sensitivity limit.

Helps us understand early evolution

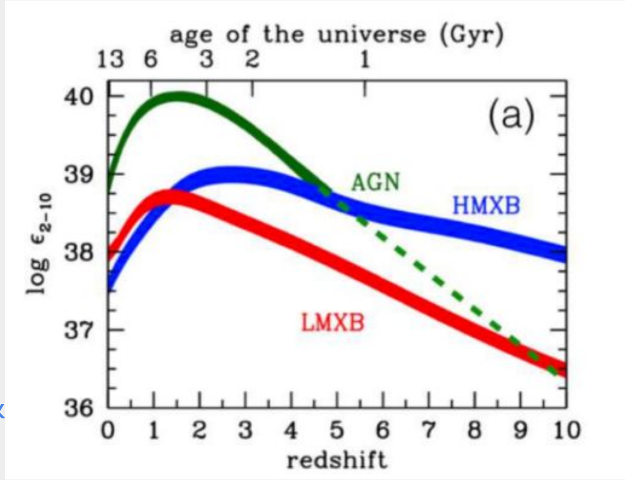


Reig 2011

Fig. 1 Classification of X-ray binaries.

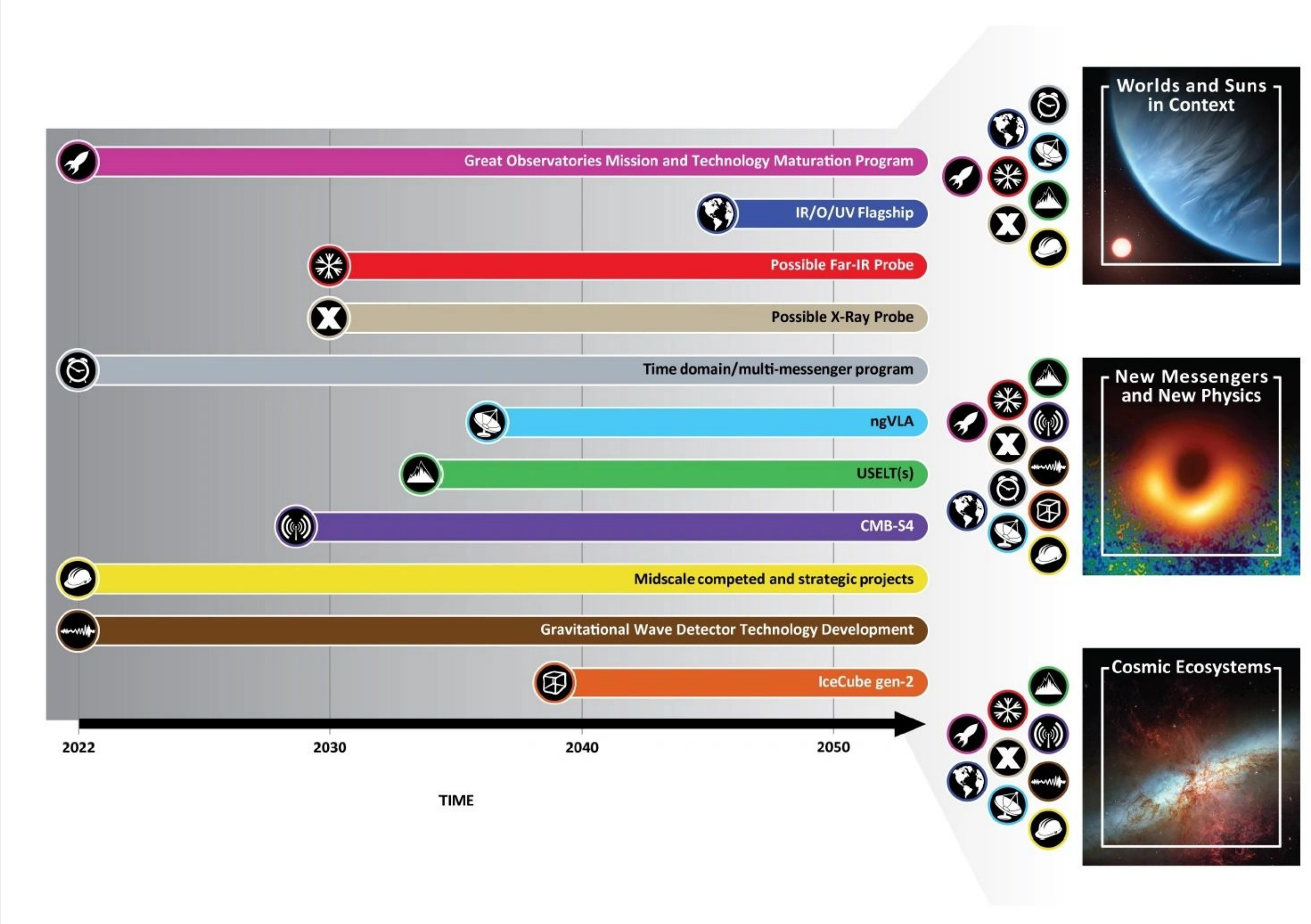


Grimm, Gilfanov & Sunyaev (2002)



Madau & Fragos 2016

- What to hope for in the next decade or two

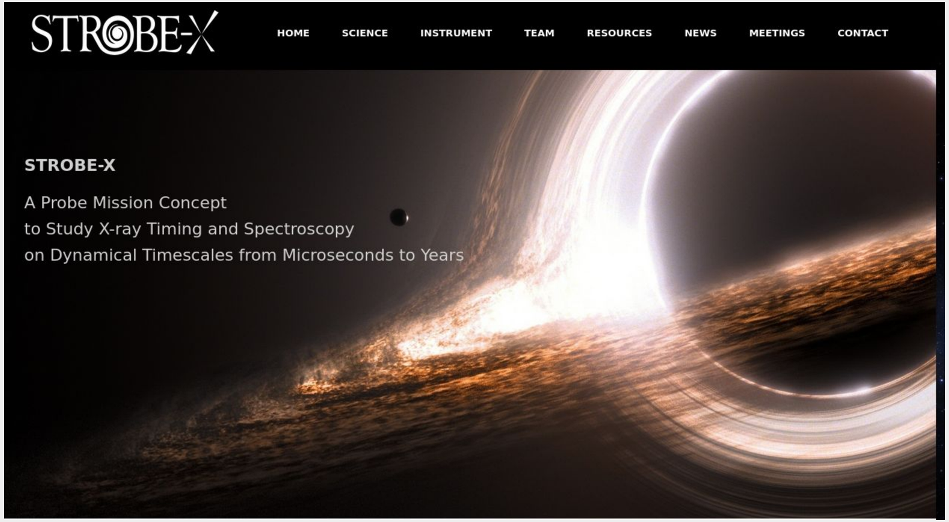


ASTRO 2020

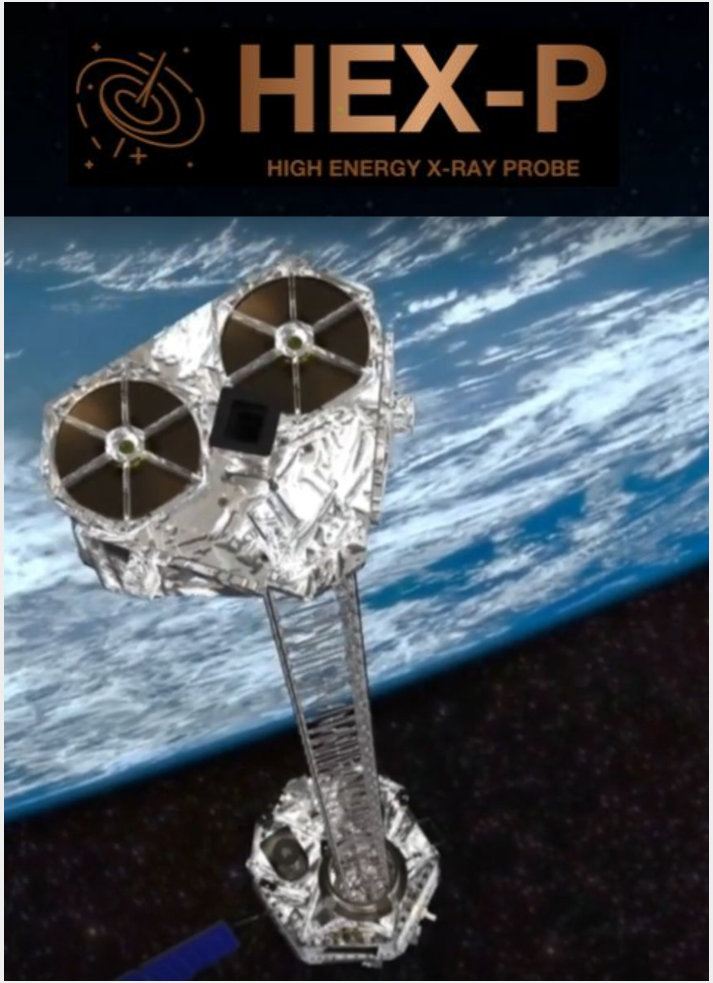
Astronomy needs a combination of space-based and ground-based missions across all wavelengths for new discoveries

Either a next-generation far-infrared observatory (like the proposed Origins) or a next-generation ***X-ray observatory*** (like the proposed Lynx) should proceed.

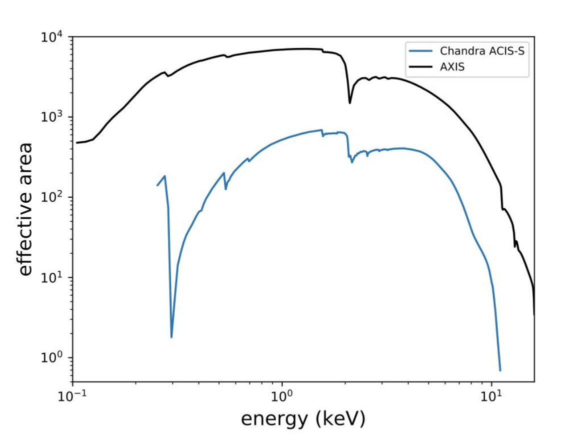
https://axis.astro.umd.edu/

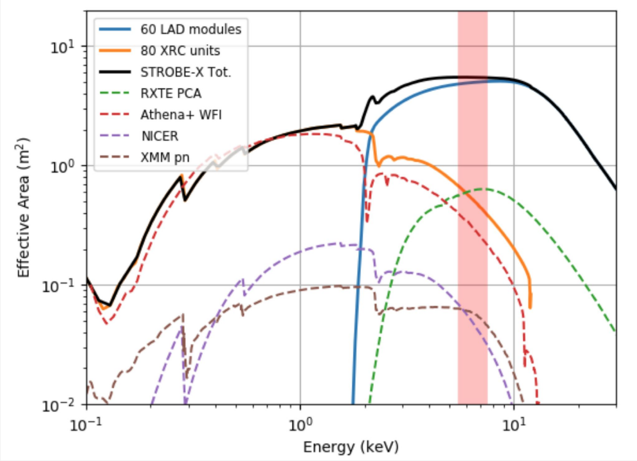


https://gammaray.nsstc.nasa.gov/Strobe-X/



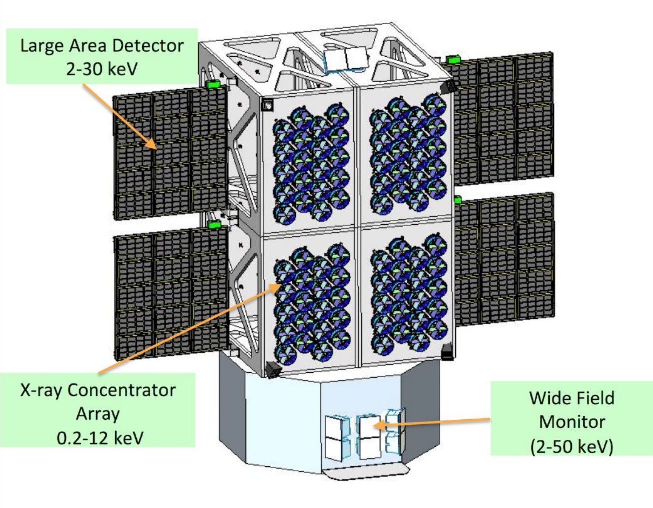
https://hexp.org/





	NuSTAR	Athena/X-IFU	HEX-P
bandpass	3-79 keV	0.2-12 keV	2-200 keV
angular resolution	60″	5″	5″
spectral resolution [FWHM]	600 eV @ 6 keV 1.2 keV @ 60 keV	2.5 eV below 7 keV	200 eV @ 6 keV 0.8 keV @ 60 keV
timing resolution	1 μsec	10 μsec	1 μsec
field of view	13′ × 13′	5′ diameter	13′ × 13′
Effective Area @ 6.4 keV	840 cm²	2400 cm²	5800 cm²

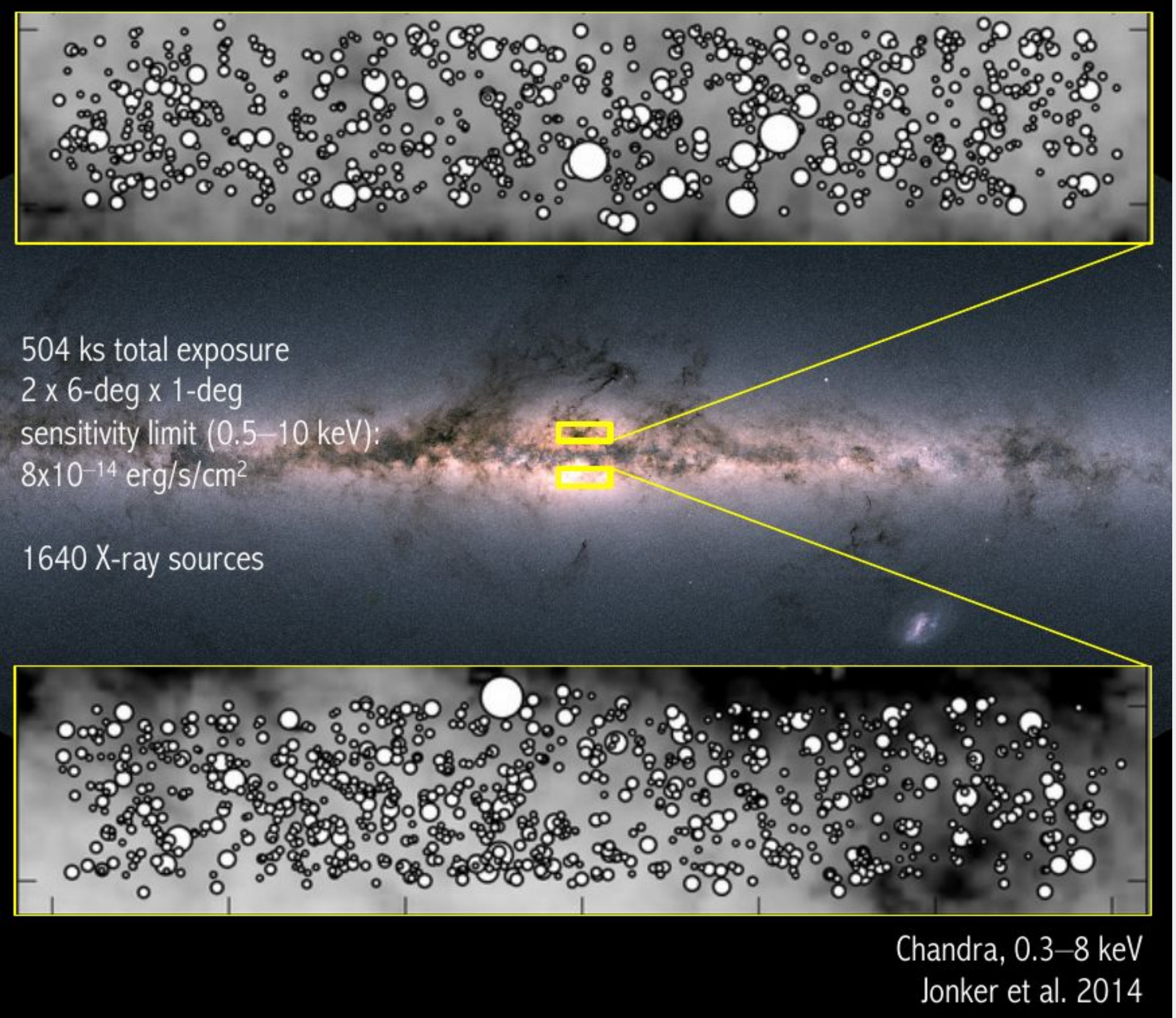
Area	Value	Requirement
Angular Resolution	1 arcsec on-axis 2 arcsec 15′ off-axis	Point source detection, separation, excision
Bandpass	0.2-10 keV	Soft and hard X-ray sensitivity
Effective Area (including detector)	5600 cm² @ 1 keV 1200 cm² @ 6 keV	Faint/low surface brightness source analysis
Energy Resolution	~150 eV @ 6 keV (CCD resolution)	Emission line separation
Readout rate	<50 ms	Variable source analysis
Field of View	24 arcmin (diameter)	Extended source analysis, surveys
Detector Background	4-5x less than Chandra	Sensitivity to low surface brightness
Slew Rate	120 deg / 5 min	Observing efficiency /TOOs

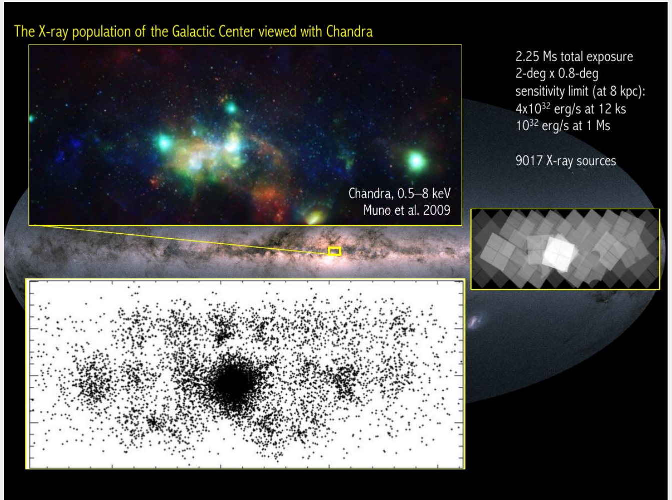


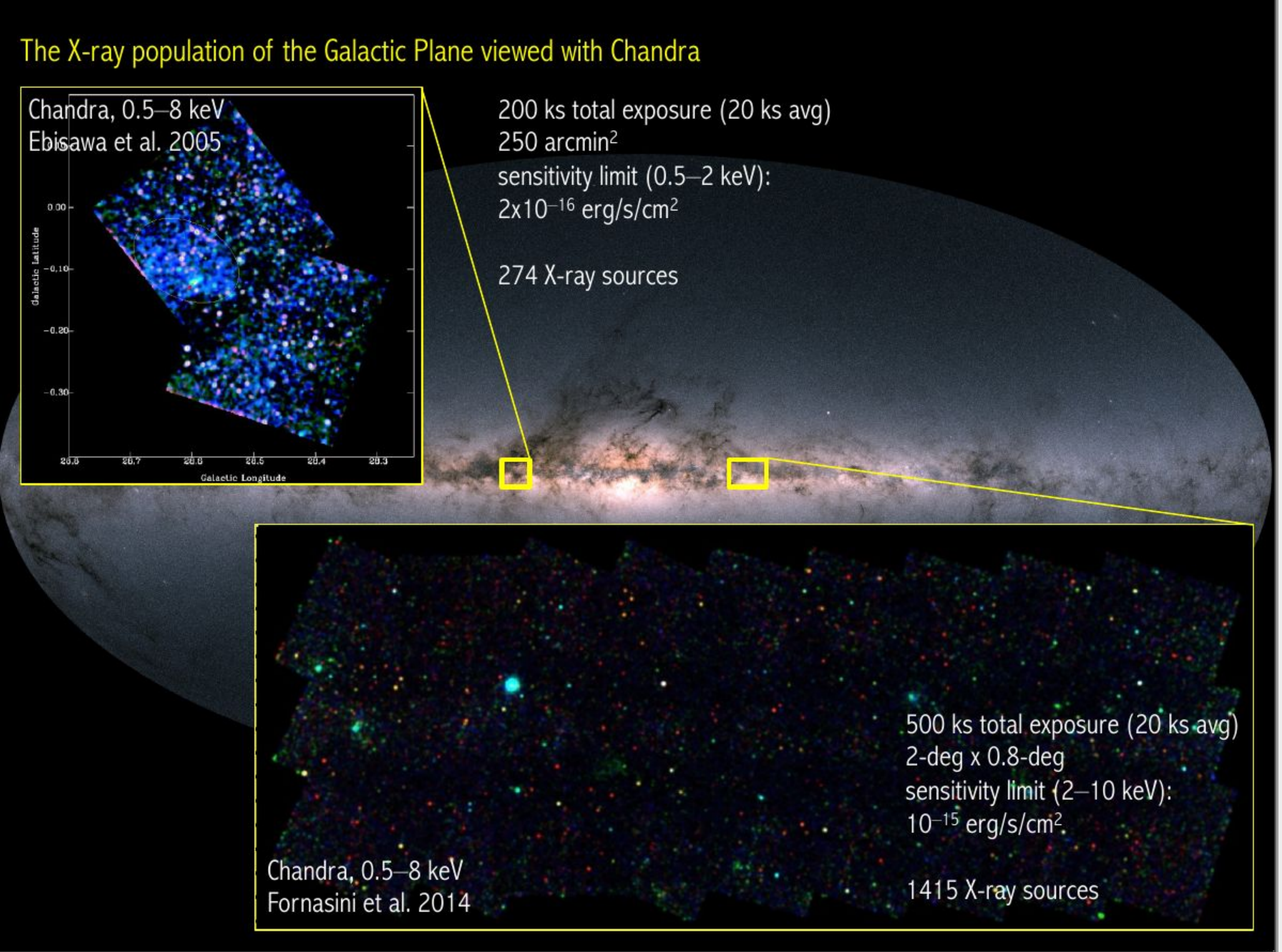
Chandra

We can try to get a bit more area

Just right above and below Sgr A*

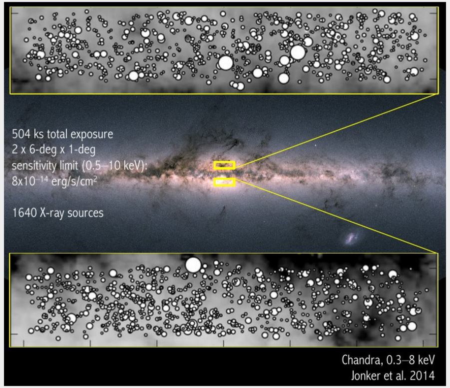


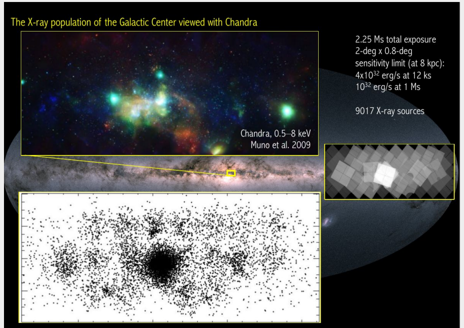




Chandra

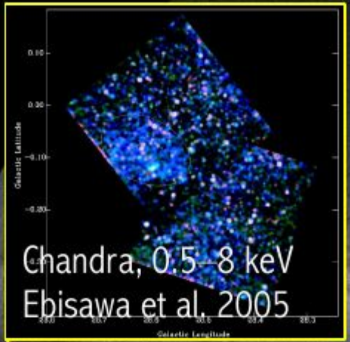
And we can go left and right

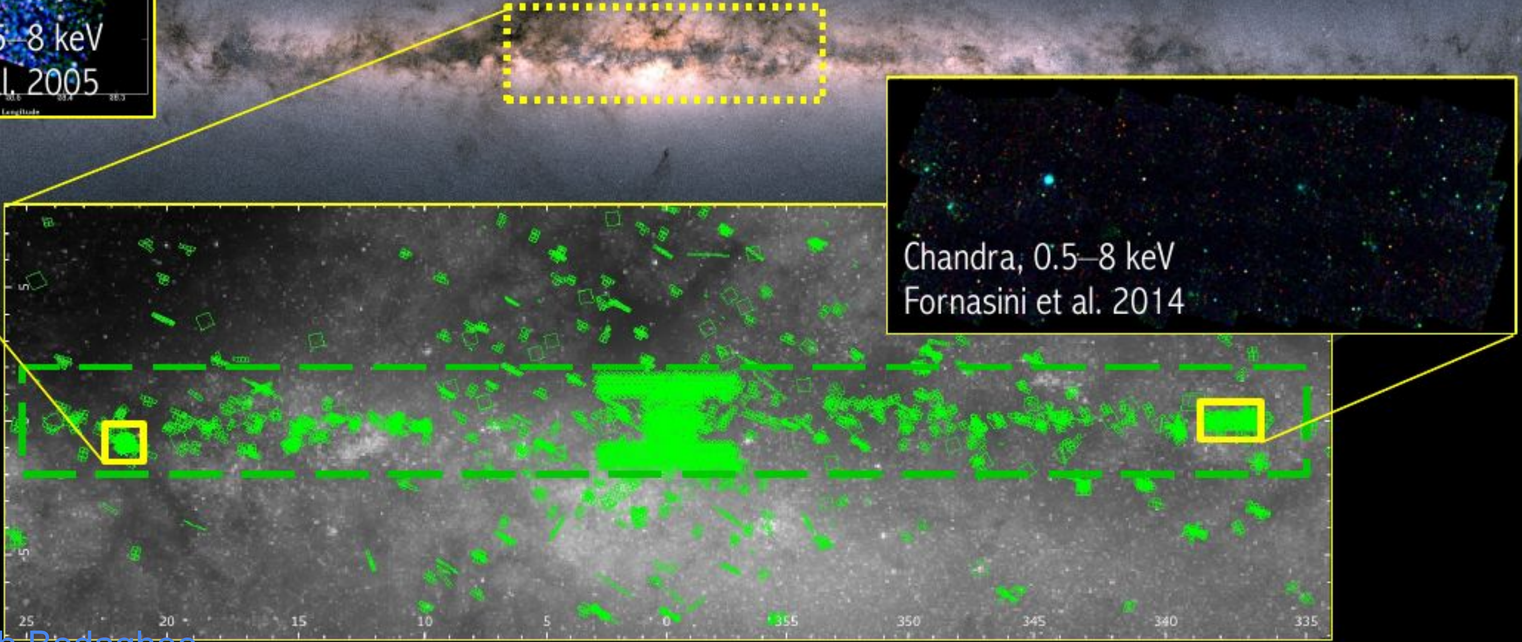




AXIS can obtain sub-arcsecond positions and flux information for all active X-ray sources in the Galactic Plane. Plus, an AXIS survey of regions previously seen by Chandra will permit variability studies for sources therein.

<u>**Requirement**</u>: a consistent, narrow PSF(~1”) across a large FOV (20–30 arcmin);
A 50-deg x 4-deg survey needs 1488 pointings
(24-arcmin FoV with 10% overlap between adjacent tiles).
For 1 ks per pointing (10 ks in select regions), the total exposure time is 1.5 Ms (2.5 Ms).
Compare this with the 3.5 Ms allocated to Chandra surveys.



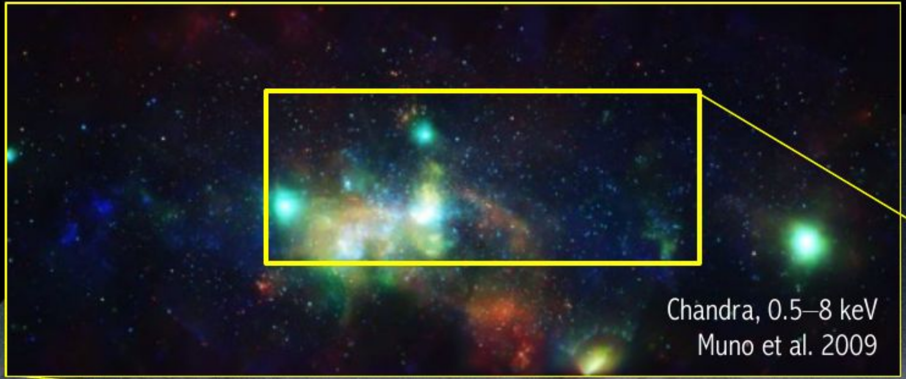


Credit: Arash Bodaghee

green: Chandra observations up to 6/2022

The X-ray population of the Galactic Center viewed with Chandra and NuSTAR

HEX-P
HIGH ENERGY X-RAY PROBE



2.25 Ms total exposure
2-deg x 0.8-deg
sensitivity limit (at 8 kpc):
4×10^{32} erg/s at 12 ks
10^{32} erg/s at 1 Ms

9017 X-ray sources

1.7 Ms total exposure
1.2-deg x 0.5-deg
sensitivity limit (at 8 kpc):
2×10^{33} erg/s at 25 ks
4×10^{32} erg/s at 160 ks

77 X-ray sources