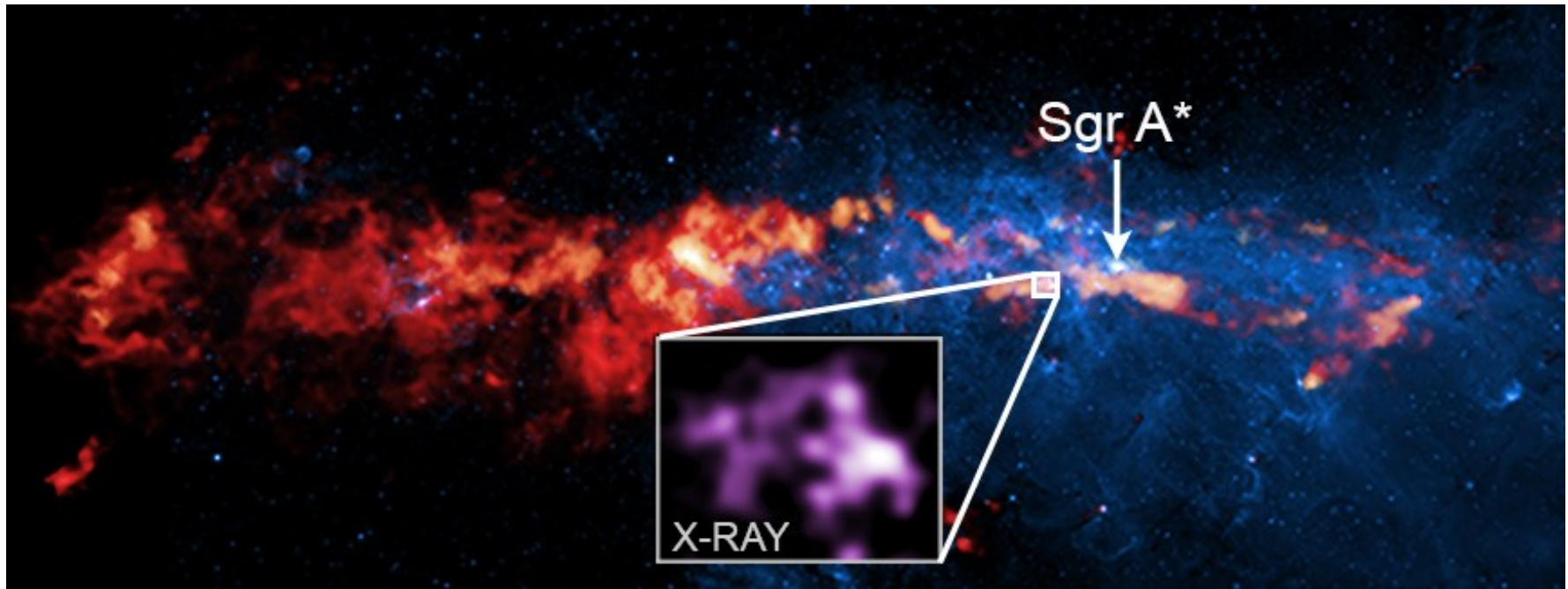
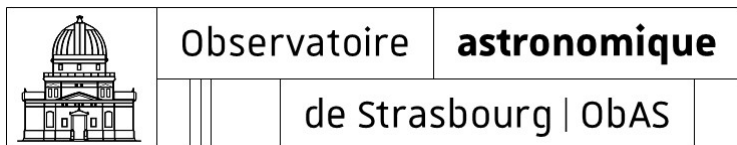


Light echoes from past Sgr A* activity revealed by X-ray polarimetry



Frédéric Marin
on behalf of the IXPE team



An X-ray view of the GC



NASA/UMass/D. Wang et al.

A panoramic X-ray view extending 400 light years by 900 light years of the GC

- even at this distance from the center of the Galaxy (~ 8 kpc), conditions are getting **crowded**
- the **energy level** is **increasing** dramatically

A vast collection of :

- supernova remnants (SNR 0.9-0.1, probably the X-ray Thread, and Sagittarius A East)
- bright binary X-ray sources (containing a black hole or a neutron star, the 1E sources)
- giant molecular clouds (SGR B1, B2, C)
- arc-like structures (pulsar wind nebulae?)
- hundreds of unnamed point-like sources (neutron stars or white dwarfs)

An X-ray view of the GC



NASA/UMass/D. Wang et al.

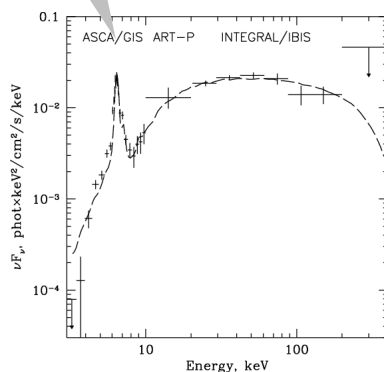
Among the sources are strange signatures in X-rays

An X-ray view of the GC

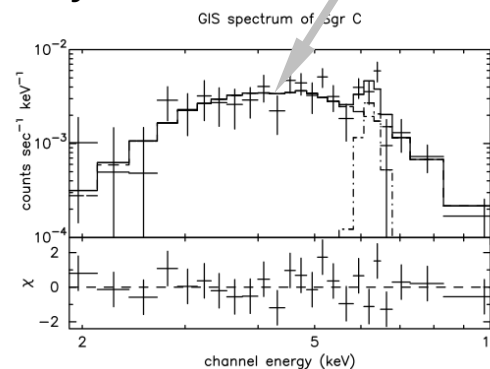


NASA/UMass/D. Wang et al.

Among the sources are strange signatures in X-rays



Koyama et al. (1996)
Terrier et al. (2010)



Murakami et al. (2001)

Pure **reflection spectra** ($L_X \sim 10^{35}$ erg s⁻¹) ... but no nearby sources bright enough ($> 10^{39}$ erg s⁻¹)!

An X-ray view of the GC

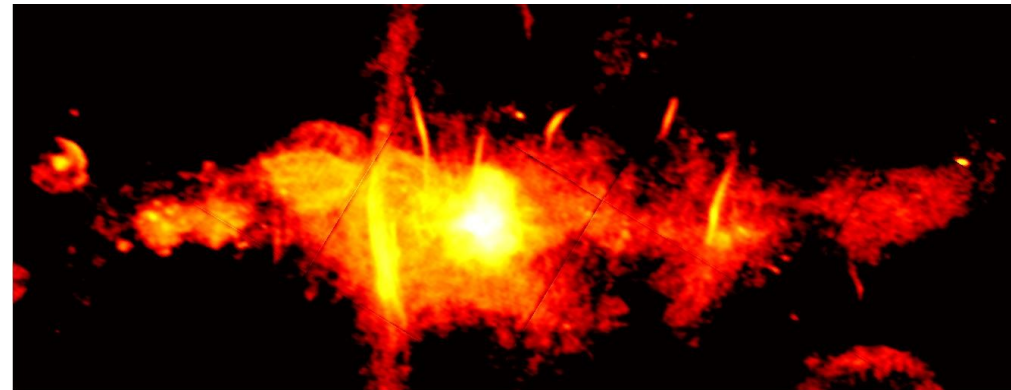


NASA/UMass/D. Wang et al.

Among the sources are strange signatures in X-rays

Spectacular radio filaments
(including the most prominent Radio Arc)
in the Galactic center region

What is the role of **pulsar wind nebulae**
in their appearance? What powers them?



90 cm Galactic center
Credit: VLA/NRL/N. Kassim

A polarized view

Why using (X-ray) polarimetry to scan the GC?

- X-ray polarimetry reveals the **scattering** geometry of light
- Reflected X-ray emission can retain polarization signatures of **ancient activity periods**
- Polarimetry helps **discriminate** between thermal bremsstrahlung, synchrotron or inverse Compton emission (key to understanding the energetic processes in GC sources)
- Polarized X-ray synchrotron emission traces the **orientation and structure of magnetic fields**
- Polarization vectors can help separate **overlapping emissions** (e.g., between Sgr A*, the central cluster, and diffuse hot plasmas) based on differing polarization degrees and angles
- **Discrimination** between **point** and **extended sources** (point sources typically have low P, while reflected or scattered radiation from extended regions can show high P)
- X-ray polarization can help detect **relativistic signatures** (such as rotation of the polarization plane due to frame dragging)

But how to do it?

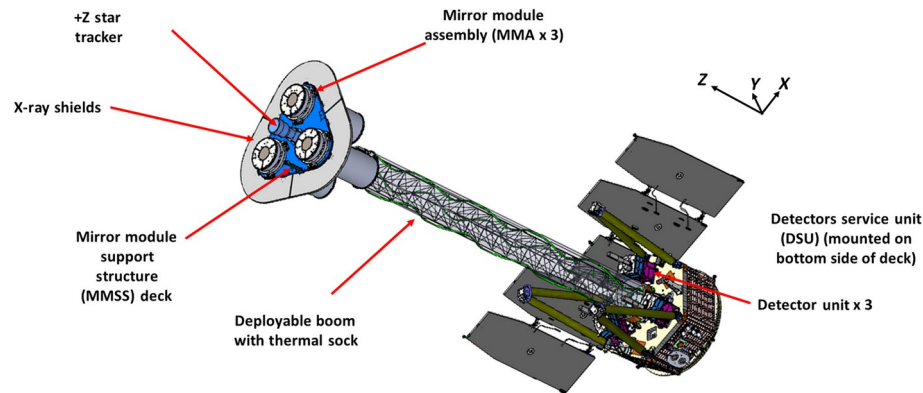
Until 2021, it was not possible (no X-ray polarimeter in space)

But everything changed with the launch of the **Imaging X-ray Polarimetry Explorer**

IXPE

The Imaging X-ray Polarimetry Explorer (IXPE)

(a Small Explorer mission undertaken by NASA in partnership with the Italian Space Agency)



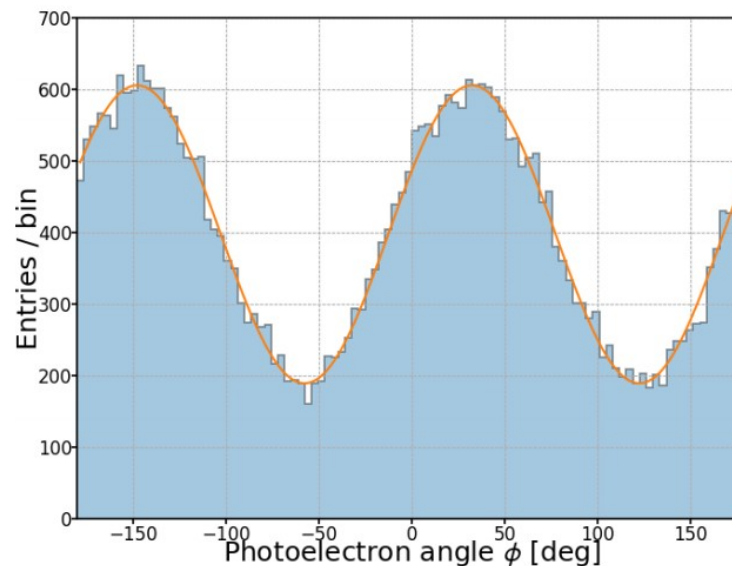
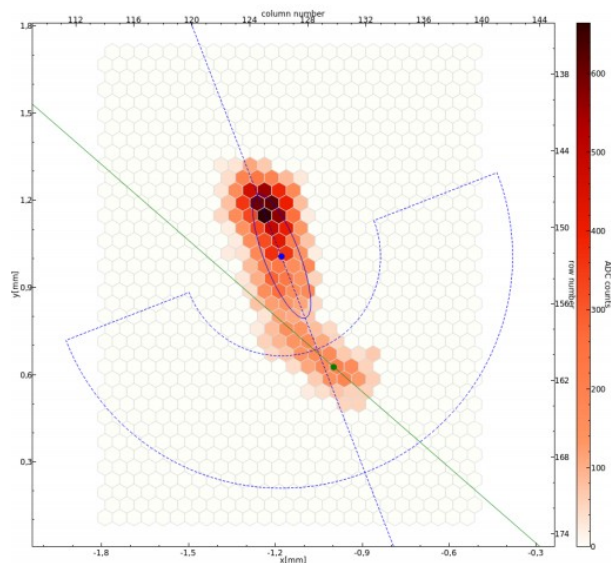
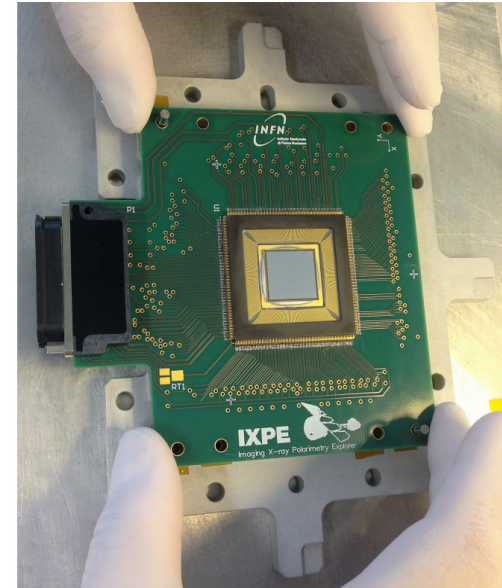
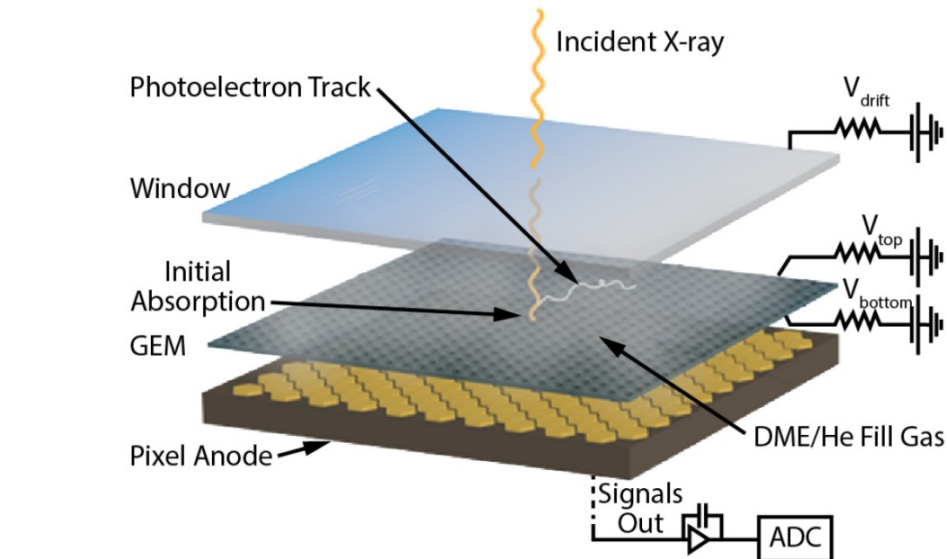
Parameter

Performance

Launch mass	330 kg
Length	5.2 m (deployed)
Nominal lifetime	2 years (no life-limiting consumables)
Energy band	2 to 8 keV
FOV (detector limited)	12.9 arcmin square
half-power diameter	28 arcsec @ 4.5 keV
Effective area per mirror module (x3)	166 cm ² @ 2.3 keV
Energy resolution (FWHM)	0.52 keV @ 2 keV ($\propto \sqrt{E}$)
Timing	1 μ s

The Gas Pixel Detector

To measure the polarization of incoming X-ray photons, IXPE uses the **Gas Pixel Detector** technology (based on the **photoelectric effect**)



Costa et al. (2001)
Bellazzini et al. (2006,2007)
Sgrò et al. (2017)

Imprint of a single photon
on the pixelized anode
(**imaging**)

Modulation of the signal
to measure the polarization
properties of a stream
of X-ray photons

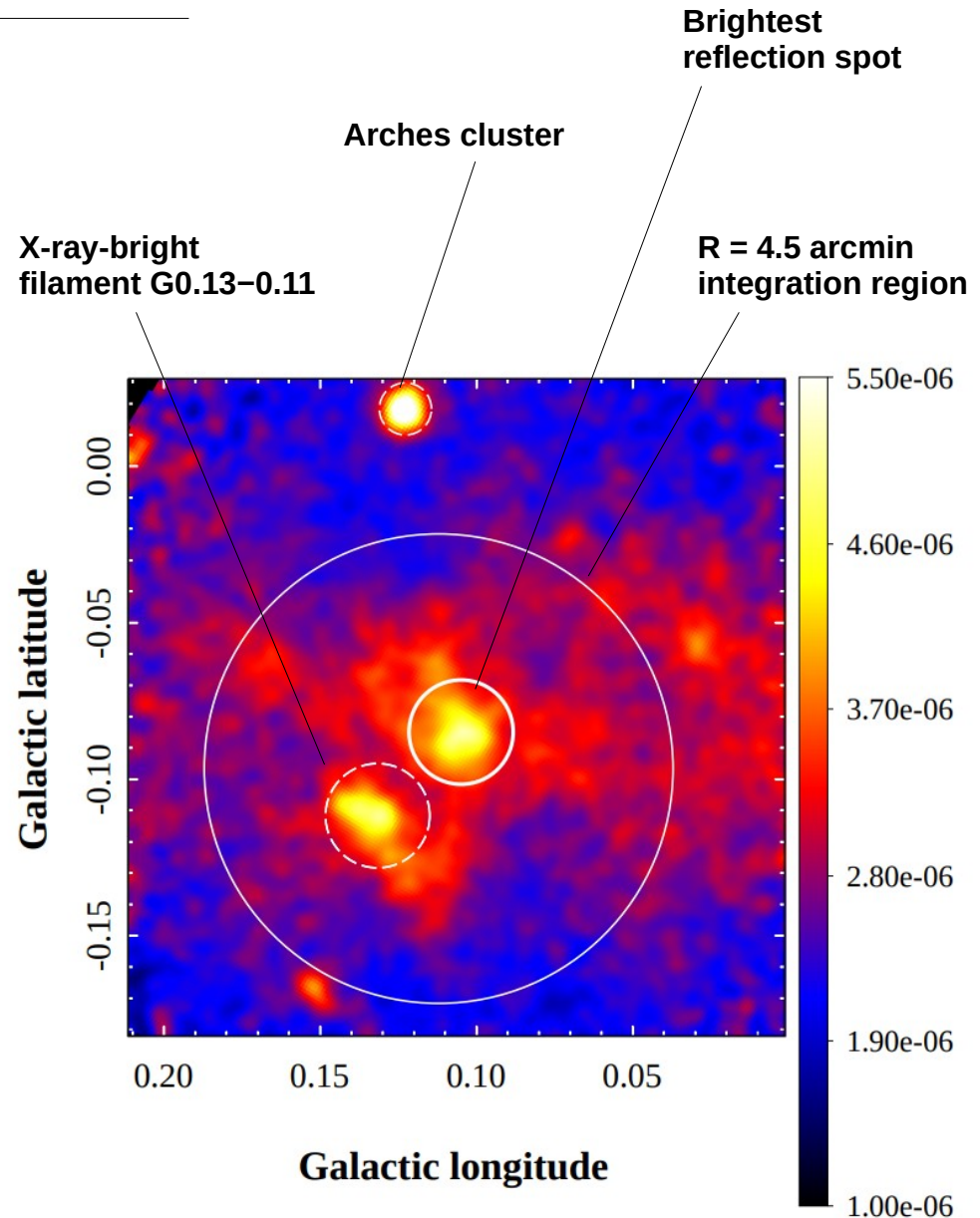
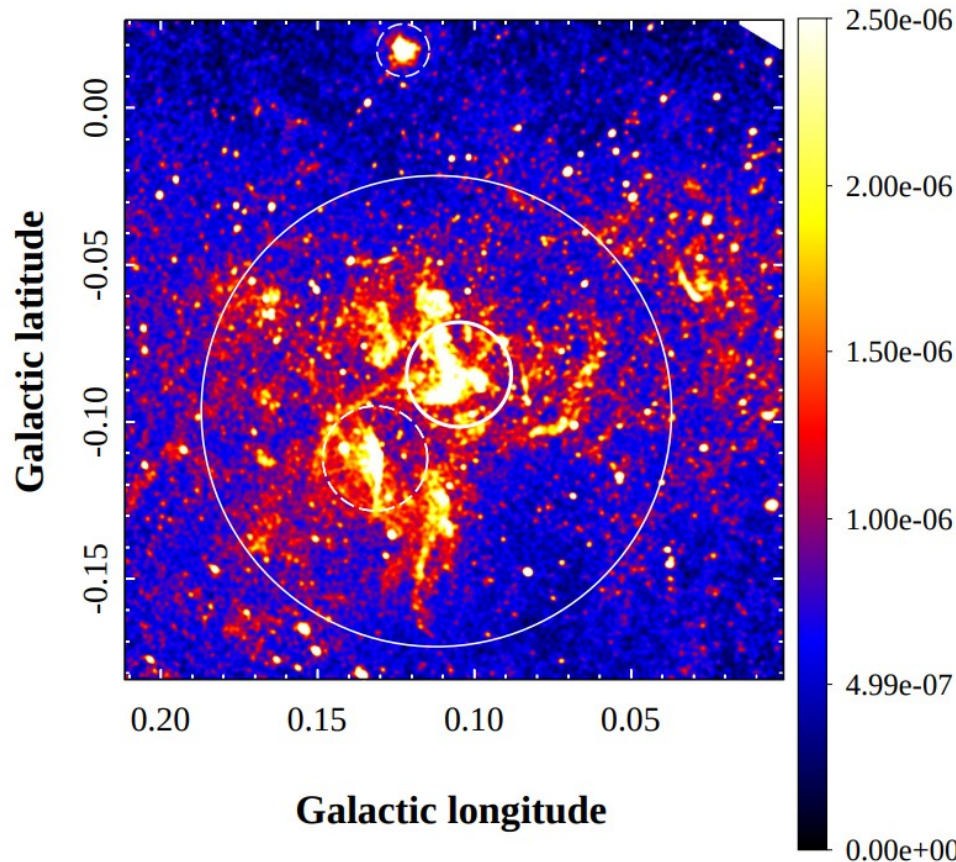
IXPE observation of the GC

Observation: 1.8 Ms (after cleaning)

Target: Sgr A region (several GMCs)

Date: February 2022 + September 2023

P.I. : F. Marin



Comparison of the Chandra (2022, left) and IXPE (combined 2022 and 2023 datasets, right) 3-8 keV images (Khabibullin et al., 2026)

IXPE observation of the GC

What did we find?

Focusing on the reflection signatures

R = 4.5 arcmin

Polarization degree of $37\% \pm 9\%$

Polarization angle of $-43^\circ \pm 7^\circ$

(quoted uncertainties correspond to 1σ confidence interval)

Detection significance = 3.9

Brightest spot

Polarization degree of $44\% \pm 18\%$

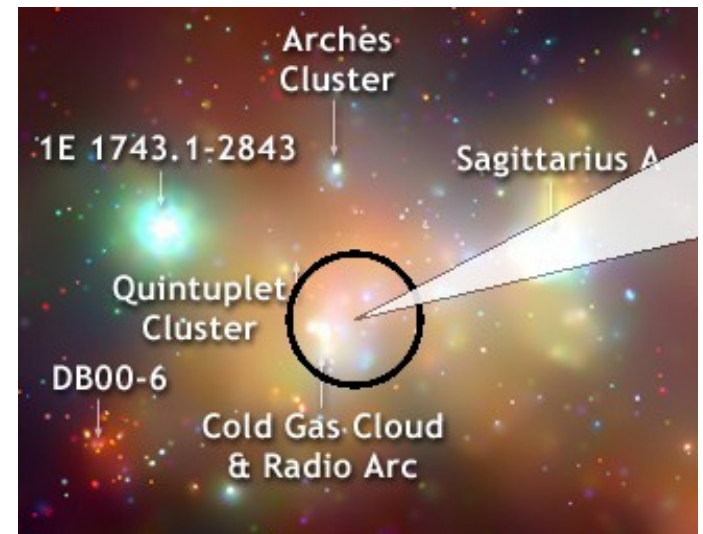
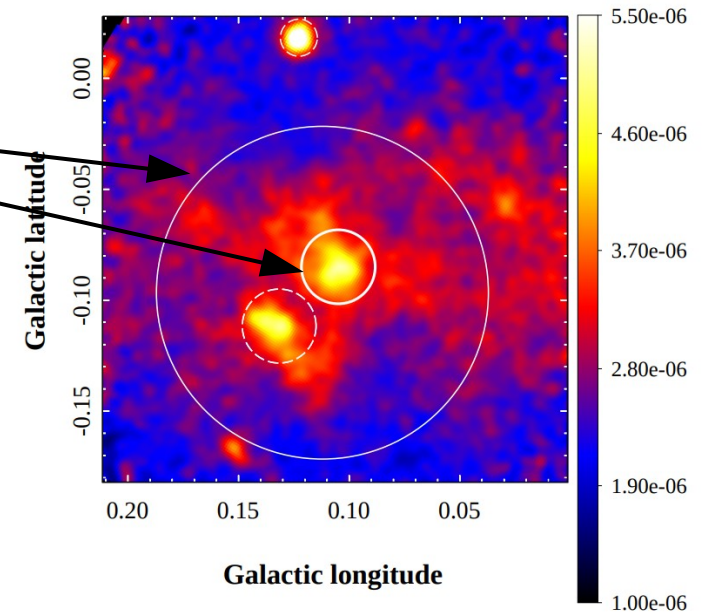
Polarization angle of $35^\circ \pm 12^\circ$

(quoted uncertainties correspond to 1σ confidence interval)

Detection significance = 2.7

The polarization angle of the $R_{4.5'}$ region is fully consistent with **Sgr A* being the primary source of the emission**

The polarization angle of the small, brightest spot is not fully trustable but **deviates** from Sgr A*
→ could be the sign of a **second flare** (from the Arches?)



IXPE observation of the GC

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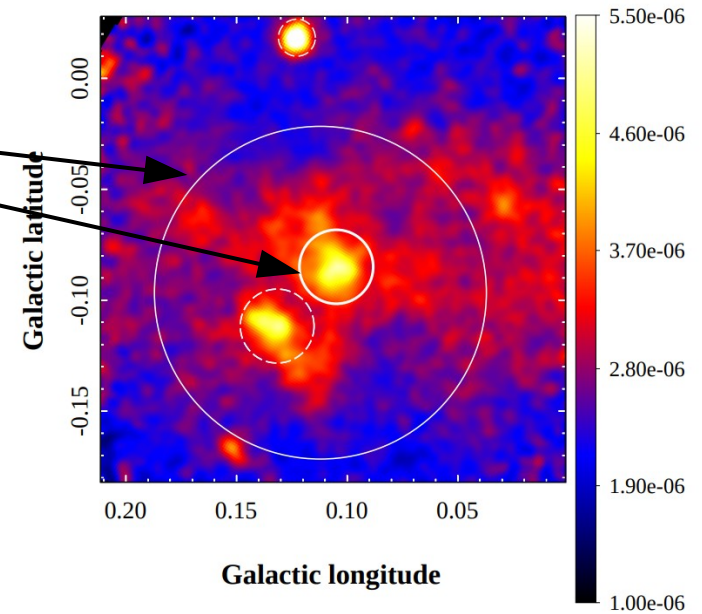
Brightest spot

Polarization degree of $44\% \pm 18\%$

Polarization angle of $35^\circ \pm 12^\circ$

(quoted uncertainties correspond to 1σ confidence interval)

Detection significance = 2.7



From $P_{4.5'}$, we can estimate the 3D position of GMC using $P = (1 - \cos^2(\theta)) / (1 + \cos^2(\theta))$

with $\cos \theta = -z / \sqrt{x^2 + z^2}$

→ for $x = 25$ pc and $\theta = 180^\circ - 43^\circ = 137^\circ$

→ $z \approx 26$ pc

i.e. the illuminated clouds are further away from us than Sgr A* by this distance.

25 years of XMM-Newton observations of the Sgr A complex

3D distribution and internal structure of the clouds

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ABSTRACT

Context. Sgr A*, the supermassive black hole at the center of the Milky Way, is currently very faint. However, X-ray radiation reflected by the Sgr A complex, a group of nearby molecular clouds, suggests that it went through one or more periods of high activity some hundreds of years ago.

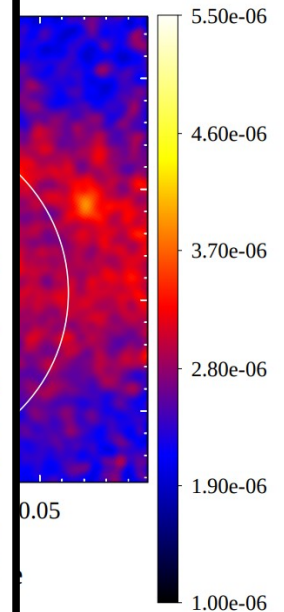
Aims. We aim to determine whether previously proposed physical scenarios are consistent with the observed X-ray variability over the past 25 years. Furthermore, we seek to characterize the spatial distribution, shape, and internal structure of the clouds.

Methods. We exploit the whole set of available *XMM-Newton* observations of the Sgr A complex to date, extending the previously studied dataset on variability by at least 12 years. Starting from the recent *IXPE* result that places the so-called Bridge cloud 26 pc behind Sgr A*, we reconstruct the Line-Of-Sight (LOS) position of the remaining clouds in the molecular complex, assuming that they were illuminated by a single flare. Additionally, we derive the probability density function (PDF) of the molecular density. We also study the 3D geometry of the complex in case two flares illuminate the clouds.

Results. As of spring 2024, the lightfront is still illuminating the Sgr A complex, with the Bridge currently being the brightest cloud. The other clouds in the complex have faded significantly. In the single flare scenario, the Sgr A complex is located ≈ 25 pc behind Sgr A*. In the past 25 years, the illuminated region spans 10–15 pc along the LOS. The derived PDF of the molecular hydrogen exhibits a roughly log-normal distribution, consistent with previous *Chandra* results, with a potential excess at the high-density end.

Conclusions. Both a single and a multiple flares scenario can explain the observed X-ray variability. Previous concerns about the single flare scenario, raised by shorter monitoring, are now overcome in the 25 years of monitoring. If two flares illuminate the clouds, they must be separated by at least ~ 30 years. We speculate that these clouds are closer to Sgr A* than the nuclear molecular ring at $\approx 100 - 200$ pc and possibly drifting from the ring to the inner region of the Galaxy.

Key words. Galaxy: center – ISM: clouds – X-rays: ISM



What did we find

Focusing on the

$R = 4.5$ arcmin

Polarization

Polarization

(quoted uncertainty)

Detection significance

Brightest spot

Polarization

Polarization

(quoted uncertainty)

Detection significance

From $P_{4.5'}$, we can estimate the 3D position of GMC using $P = (1 - \cos^2(\theta)) / (1 + \cos^2(\theta))$

with $\cos \theta = -z / \sqrt{x^2 + z^2}$

→ for $x = 25$ pc and $\theta = 180^\circ - 43^\circ = 137^\circ$

→ $z \approx 26$ pc

i.e. the illuminated clouds are further away from us than Sgr A* by this distance.

IXPE observation of the GC

What did we find?

Focusing on the reflection signatures

R = 4.5 arcmin

Polarization degree of $37\% \pm 9\%$

Polarization angle of $-43^\circ \pm 7^\circ$

(quoted uncertainties correspond to 1σ confidence interval)

Detection significance = 3.9

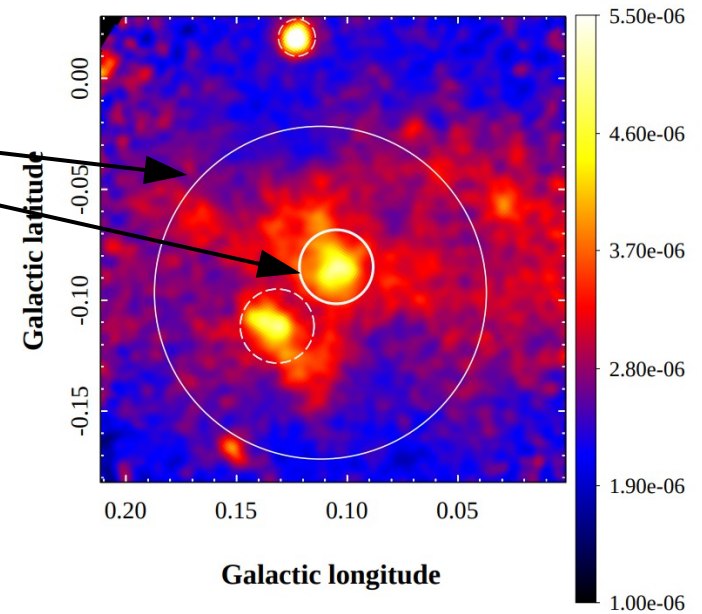
Brightest spot

Polarization degree of $44\% \pm 18\%$

Polarization angle of $35^\circ \pm 12^\circ$

(quoted uncertainties correspond to 1σ confidence interval)

Detection significance = 2.7



Assuming that Sgr A* is the primary source, a detection of the scattered light from a cloud relates the age of the flare and the position of the cloud as $t = \sqrt{x^2 + z^2}/c + z/c$

→ 190 ± 25 yrs

From the fluence, we can estimate the luminosity of the flare (maximal possible albedo of GMC)

→ $L_{4-8 \text{ keV}} > 10^{39} \text{ erg/s}$

Some 200 years ago, the X-ray luminosity of Sgr A* was briefly comparable to that of an AGN

IXPE observation of the GC

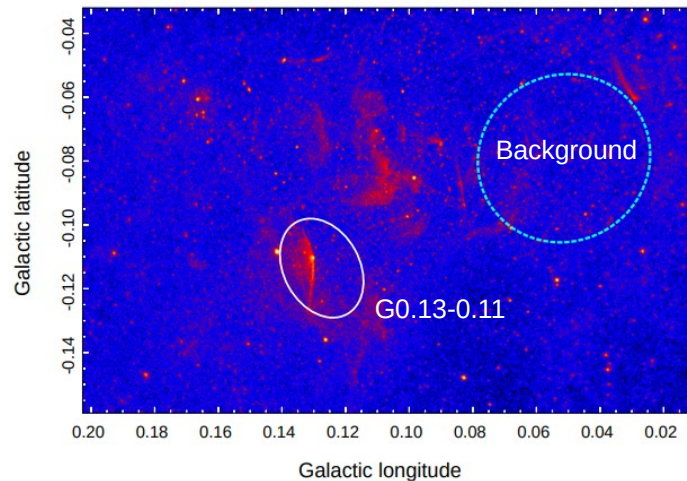
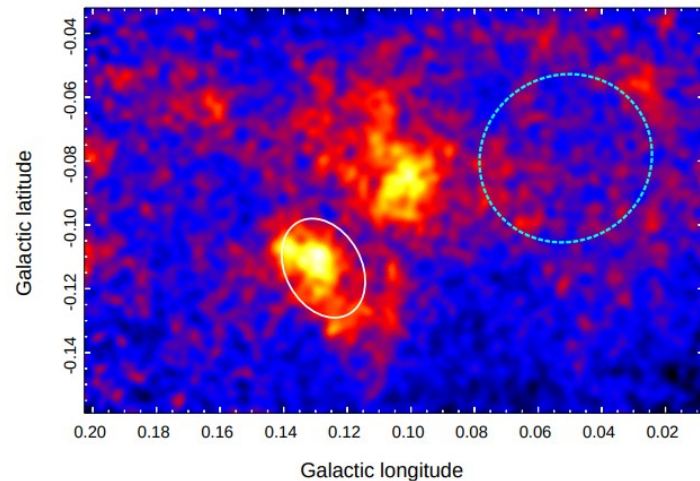
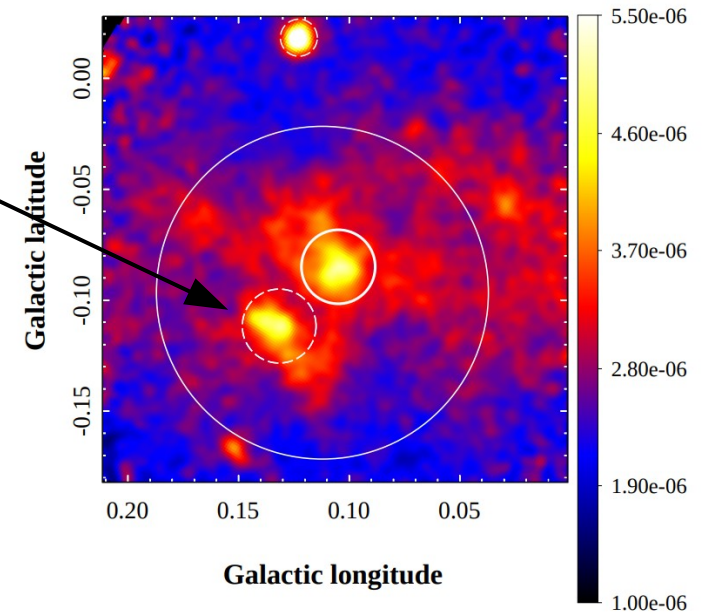
What did we find?

Focusing on the X-ray-bright filament G0.13-0.11

The **origin** of radio filaments in the GC region and the **role of pulsar wind nebulae** in their appearance is an actively debated topic

Many of the observed radio filaments have spectral and (radio) polarization properties suggesting that they are dominated by **non-thermal emission**

G0.13-0.11 = PWN with a filament formed by leptons escaping from the supersonically moving PWN into the ambient magnetic field (Gaensler & Slane 2006; Kargaltsev et al. 2017; Bykov et al. 2017; Olmi & Bucciantini 2023)



3-6 keV IXPE (left panel)
and Chandra (right panel)
X-ray images

Churazov et al. (2024)

IXPE observation of the GC

What did we find?

Focusing on the X-ray-bright filament G0.13–0.11

X-ray emission of G0.13–0.11 is highly polarized:

Polarization degree of $57\% \pm 18\%$

Polarization angle of $21^\circ \pm 9^\circ$

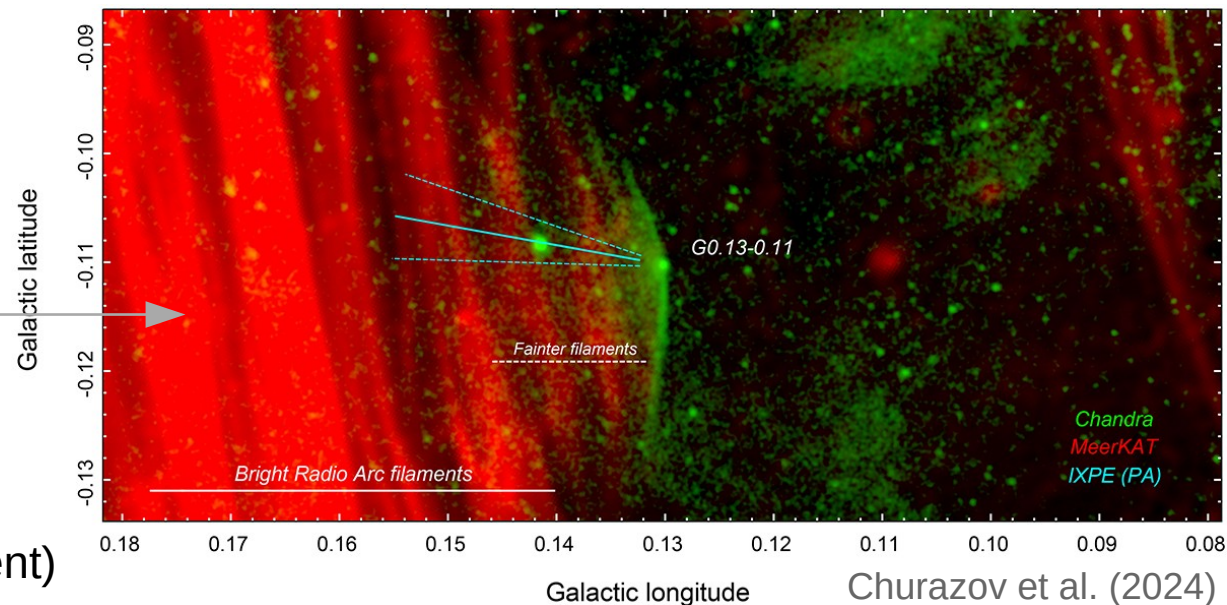
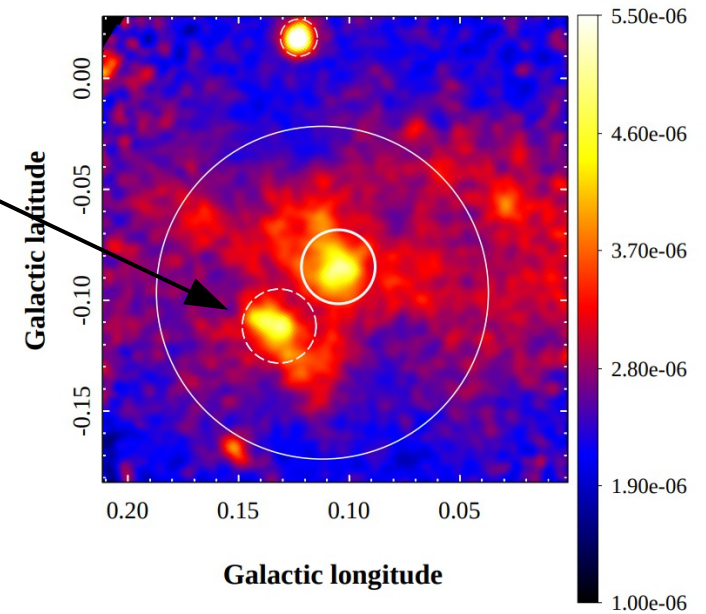
(quoted uncertainties correspond to 1σ confidence interval)

Detection significance = 3.2

This high degree of polarization **proves the synchrotron origin** of the X-ray emission from G0.13–0.11 and that the field is **well ordered**

In turn, the measured polarization angle implies that the X-ray emission is polarized approximately **perpendicular** to a sequence of nonthermal radio filaments that may be part of the GC Radio Arc

The **magnetic field** is on the order of **$100 \mu\text{G}$** and appears to be preferentially ordered along the filaments (fiducial value that makes the model self-consistent)



Conclusions

An X-ray polarimetric exploration of the GC revealed:

- An **AGN-like activity** about **200 years ago** (Sgr A*)
- Giant molecular clouds are X-ray bright because they **reflect the past AGN activity** of Sgr A*
- Hints for several (**repeated**) activity

Deeper (longer) X-ray polarimetric imaging with IXPE can shed light on this question, but a future (more sensitive) instrument would be crucial

→ the case for **EXPO (ESA M8 call)**

- The G0.13–0.11 X-ray emission (and arc structure) is from **synchrotron emission** in a **well ordered magnetic field**
- The G0.13–0.11 magnetic field is on the order of **100 μ G** and preferentially **ordered along the filaments**

The latest finding corroborates the scenario that PWNs power not only the X-ray emission but also radio emission of filaments in the GC region

→ a particularly interesting question would be whether **the entire Radio Arc is powered by the same mechanism**