Results from IXPE

After two years of spatially resolved X-ray polarimetry

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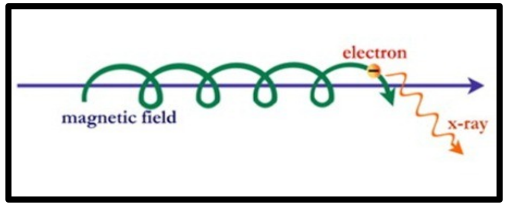
on behalf of the IXPE Science Team
(https://ixpe.msfc.nasa.gov/partners_sci_team.html)

Vulcano Workshop 2024
FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS
Ischia, Campania (Italy), 26 May - 1 June, 2024

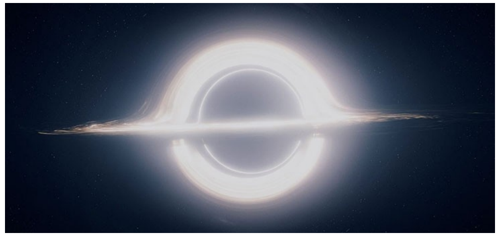
TECHNIQUE		OBSERVABLE		INFORMATION
• **Imaging:**	→	Position	→	Morphology
• **Spectroscopy:**	→	Energy	→	Composition, processes
• **Timing:**	→	Arrival time	→	Variability
• **POLARIMETRY:**	→	**1) Polarization Degree**	→	**Processes / asymmetry**
		2) Polarization Angle	→	**Geometry / B Field**

Polarization arises when there is a **preferred direction**

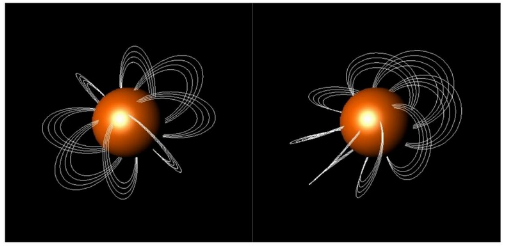
→ **Non-Thermal emission processes**: e.g. synchrotron



→ **Geometrical Asymmetries** e.g. accretion disk, jets, columns, blobs, etc...



→ Radiative transfer in strong **gravitational / magnetic field**



IXPE Imaging X-Ray Polarimetry Explorer

Marshall Space Flight Center

Agenzia Spaziale Italiana

INTRODUCTION

THE IMAGING X-RAY POLARIMETRY EXPLORER (IXPE)

Polarimetry:
$F_{2\text{-}8}$ = 10^{-11} cgs, Δt = 10 d → MDP≤5.5%

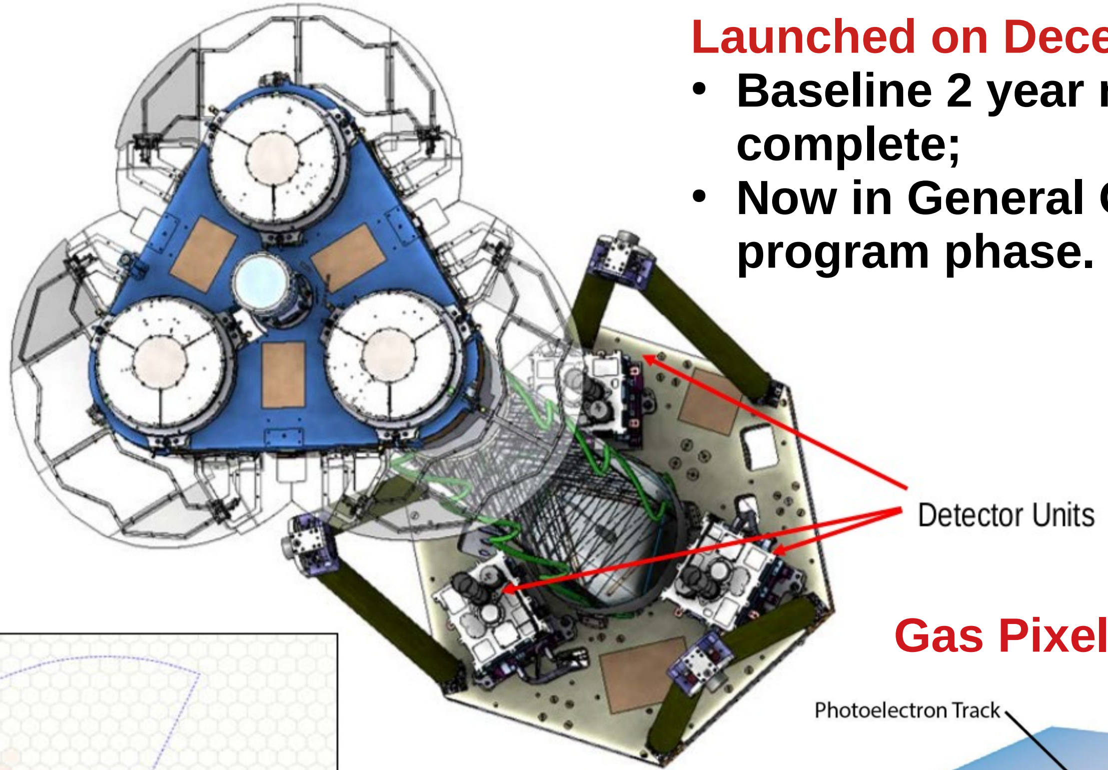
Spectroscopy: moderate capabilities, **≤1.5 keV** energy resolution

Imaging: <30” spatial resolution, **12.8’ x 12.8’** F.O.V.

Timing: ~20 µs (using GPS)

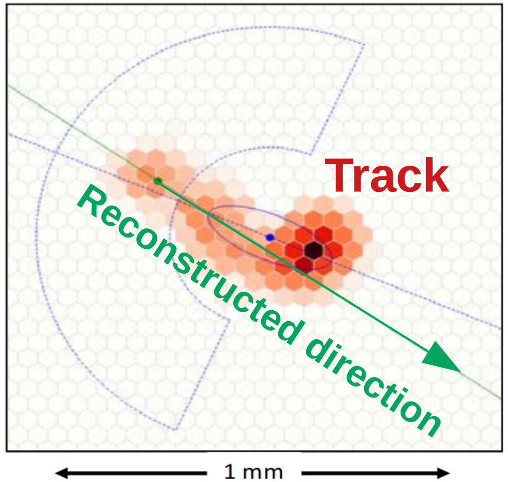
NASA Marshall Space Flight Center	PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving
IAPS, INAF (Istituto Nazionale di Astrofisica – National Institute for Astrophysics), INFN, OAC, OHB Italia	Polarization-sensitive imaging detector systems
CU, LASP	Mission operations
Roma Tre, Stanford University	Scientific theory
ASI (Agenzia Spaziale Italiana)	Detector system funding, ground station
McGill	Co-Investigator
Ball	Spacecraft, payload structure, payload, observatory I&T
Massachusetts Institute of Technology	Co-Investigator

Science Advisory Team

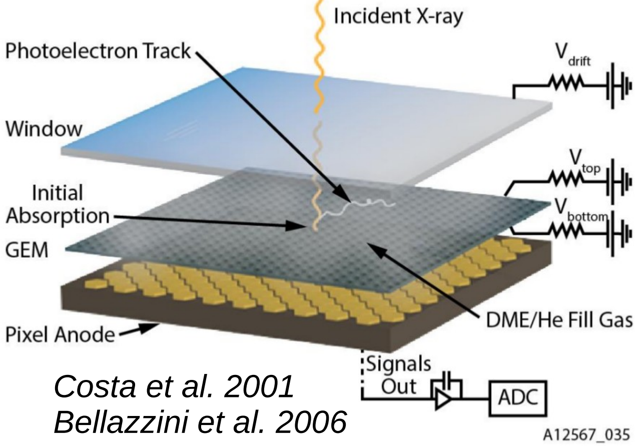


Launched on December 9th 2021

- **Baseline 2 year mission complete;**
- **Now in General Observer program phase.**

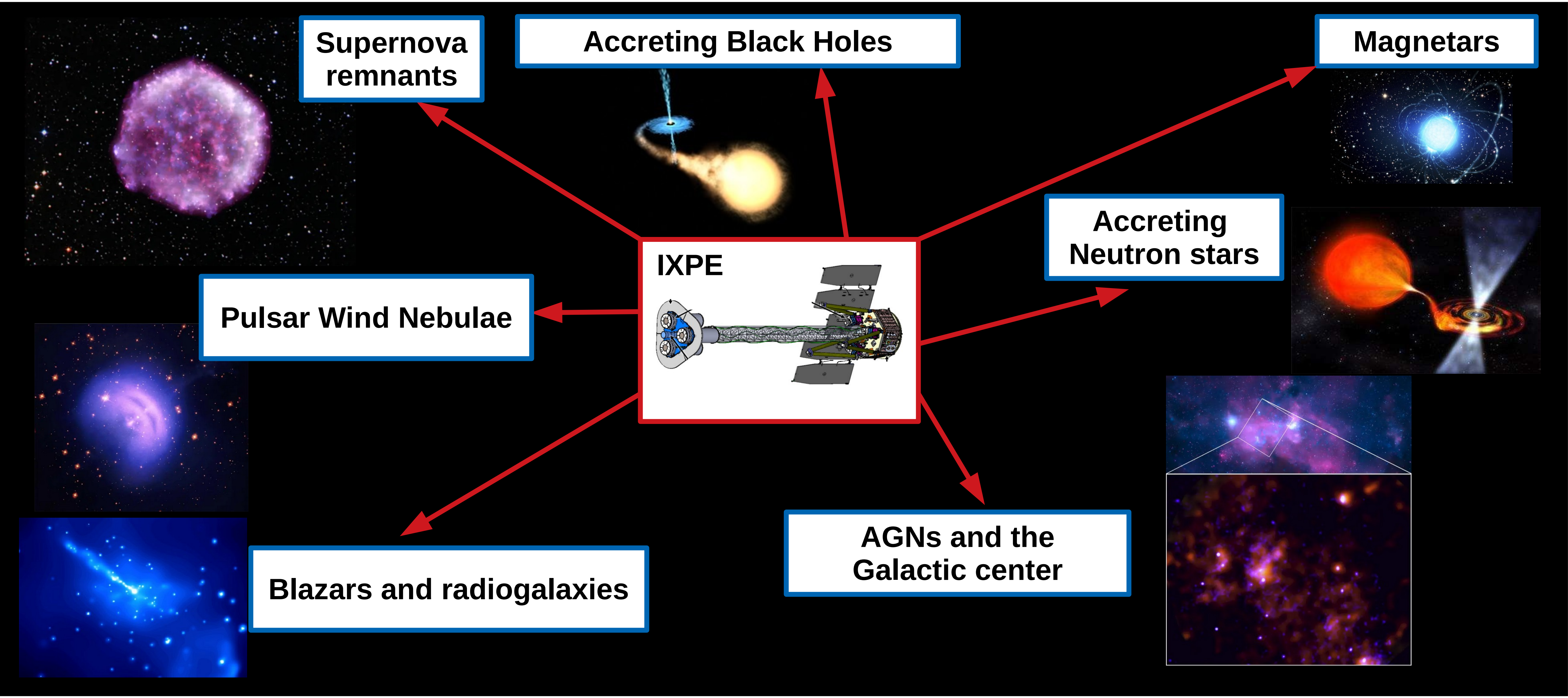


Gas Pixel Detector



Costa et al. 2001
Bellazzini et al. 2006

IXPE TARGET CLASSES
THE COMPLETE PICTURE



IXPE Imaging X-Ray Polarimetry Explorer

IXPE TARGET CLASSES
THE COMPLETE PICTURE

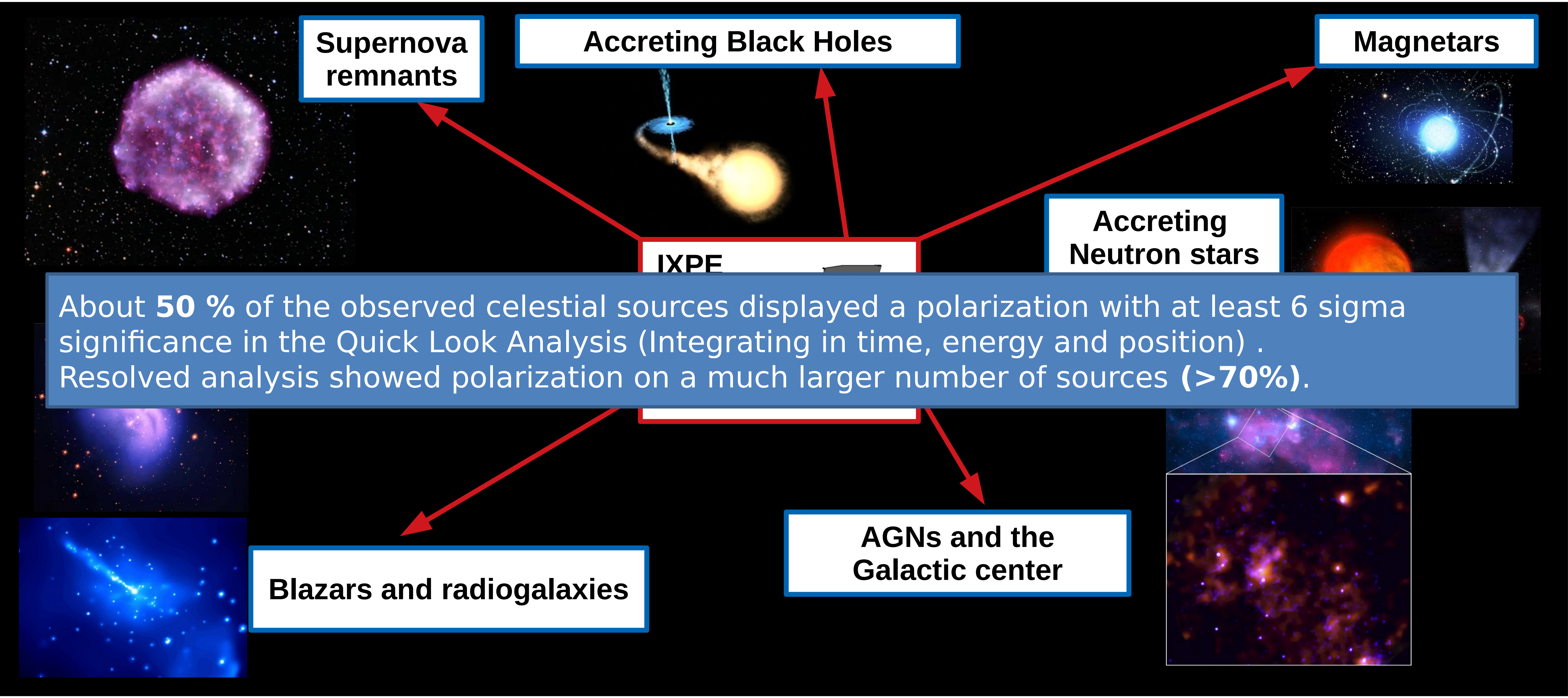
Supernova remnants

Accreting Black Holes

Magnetars

Working Group	Number of observed objects	Objects
PWNe	**5**	Crab PWN, Vela PWN, MSH 15-52, PSR B0540-69, G21.5
SNRs	**6**	Cas A, Tycho's, NE SN 1006,RCW 86, RX J1713.7-3946, Vela Jr.
Accreting stellar-BH	**9**	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, SS433, 4U 1957-115, SS 433 Lobes, LMC X-3, SWIFT J1727.8-1613, 4U 1957+115, Swift J0243.6+6124, Swift J1727.8-1613
Accreting NS	**16**	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, Xpersei, GX 9+9, 4U 1820-30, GRO J1008-57, XTE 1701-46, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X-1, GX13+1, SMC X-1
Magnetars	**4**	4U 0142+61, 1RXS J170849, SGR 1806-20, 1E 2259+586
Radio-quiet AGN & Sgr A*	**4**	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A Sgr A* Complex, NGC 1068
Blazars & radio galaxies	**13**	Cen A, S5-0716-714, 1ES 19-59-650, Mrk 421, BL Lac, 3C 454, 3C 273, 3C 279, Mrk 501,1ES 1959-650, BL-Lac, 1ES 0229-200, PG 1553 -113, S4 0954+65, 1E 2259+586,

IXPE TARGET CLASSES
THE COMPLETE PICTURE



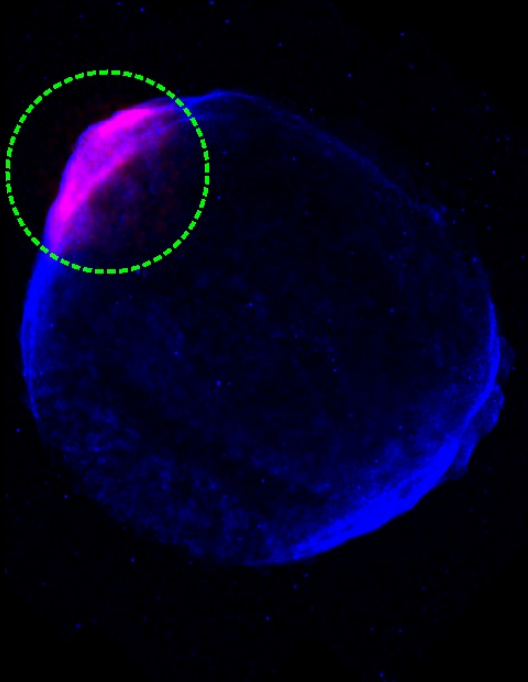
About **50 %** of the observed celestial sources displayed a polarization with at least 6 sigma significance in the Quick Look Analysis (Integrating in time, energy and position) .
Resolved analysis showed polarization on a much larger number of sources **(>70%)**.

SUPERNOVA REMNANTS

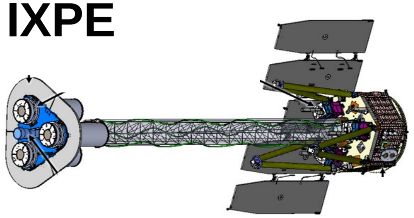
Tycho: Ferrazzoli et al. 2023 ApJ

Supernova remnants

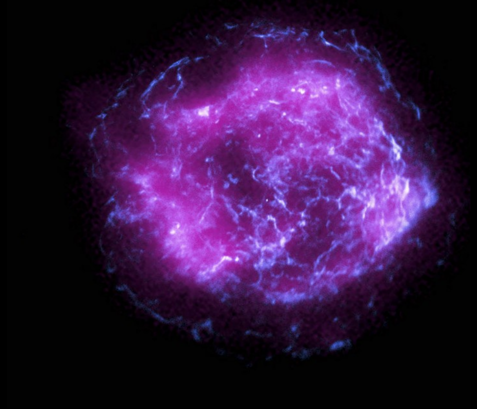
SN 1006 NE:
Zhou et al. 2023 ApJ



IXPE



Cas A: first target of the IXPE scientific campaign in Jan. 2022.
Vink et al. 2022 ApJ

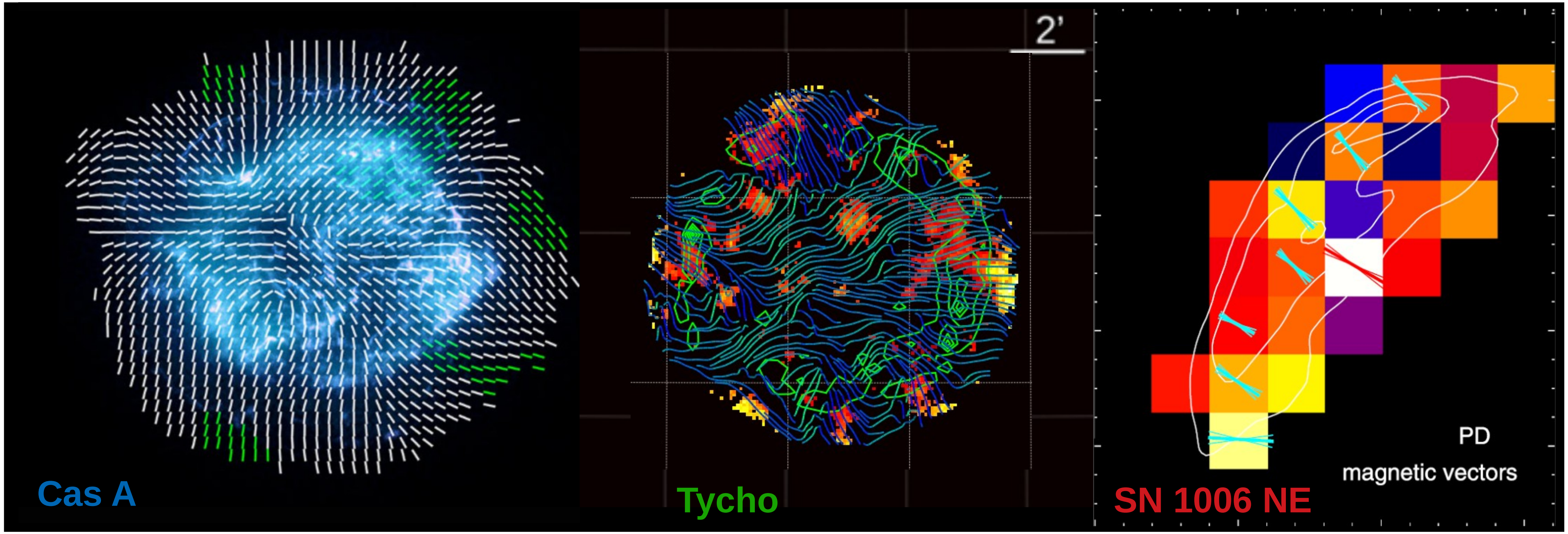


SNRs are the probable source of most of Galactic cosmic rays

X-RAY POLARIMETRY GOALS:

- **Probe magnetic field turbulence (→ PD) and morphology (→ PA) much closer to particle acceleration sites in shocks than radio band;**
- **Investigate magnetic field morphology dichotomy observed in radio band**

SNR WITH IXPE
THE THREE REPORTED 1ST YEAR TARGETS



- Same radial magnetic field morphology
- Different polarization degree (different turbulence levels?)
- Possible dependence of turbulence on ambient medium density

	PD (rim) %	PD (SNR) %	PD (peak) %	Magnetic field morphology
Cas A	4.5 ± 1.0	2.5 ± 0.5	~15	Radial
Tycho	12 ± 2	9 ± 2	23 ± 4	Radial
SN 1006 NE	22.4 ± 3.5	...	31 ± 8	Radial

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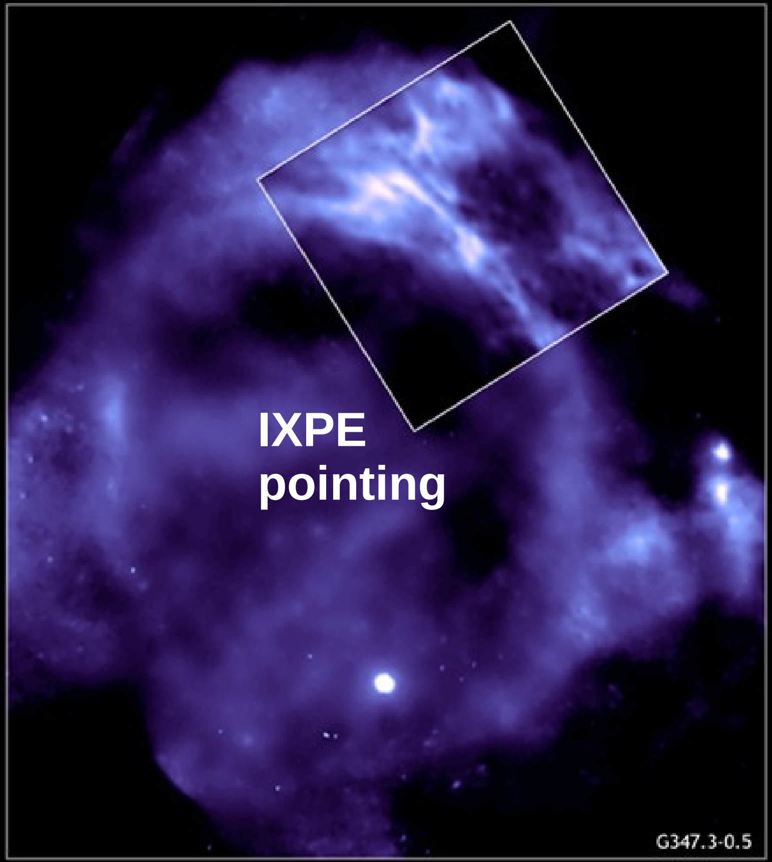
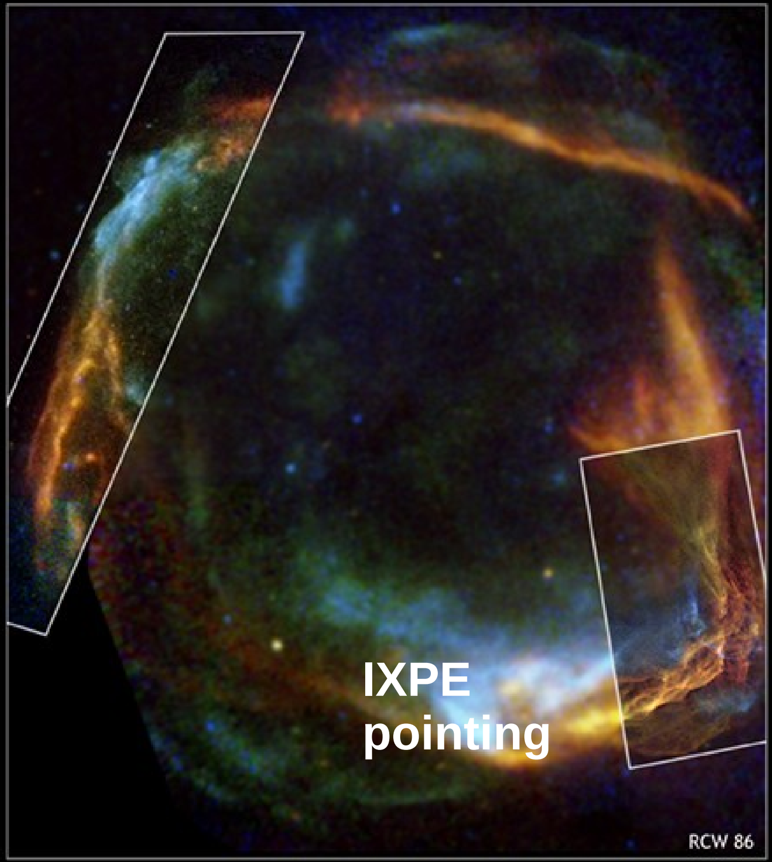
SNR WITH IXPE
PRESENT AND FUTURE

RX J1713.7-3946
- Extended
- Non thermal

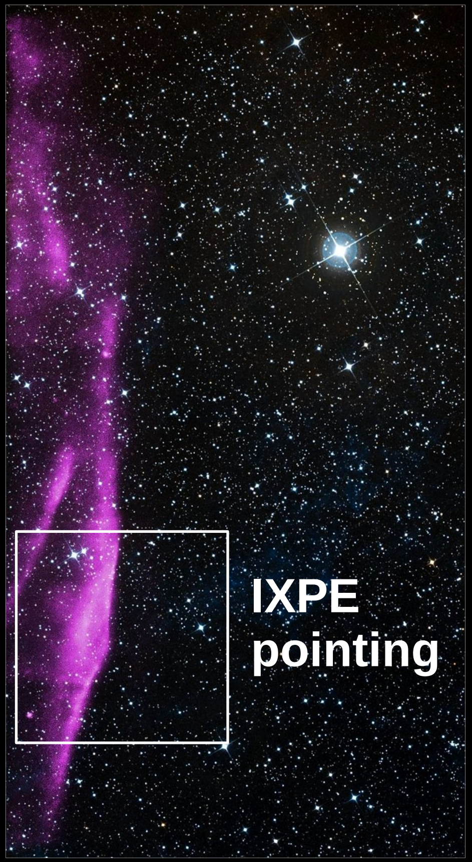
Ferrazzoli et al. accepted by ApJL



RCW 86
- Extended
- Non thermal AND thermal
- Analysis in progress



Vela Jr
- VERY Extended
- Non thermal
- Analysis in progress



SNR WITH IXPE
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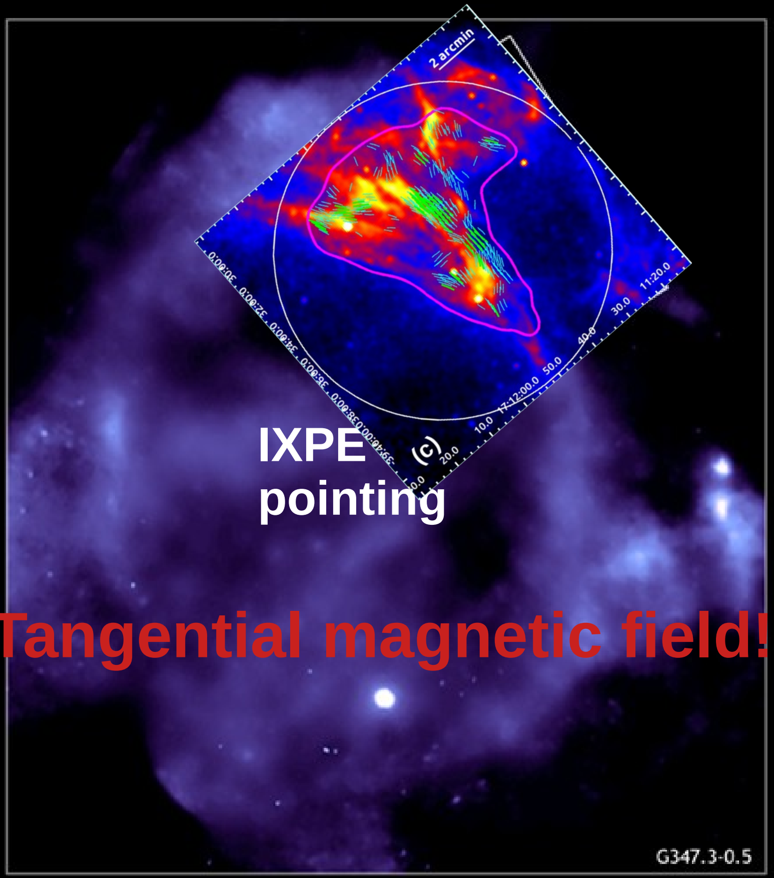

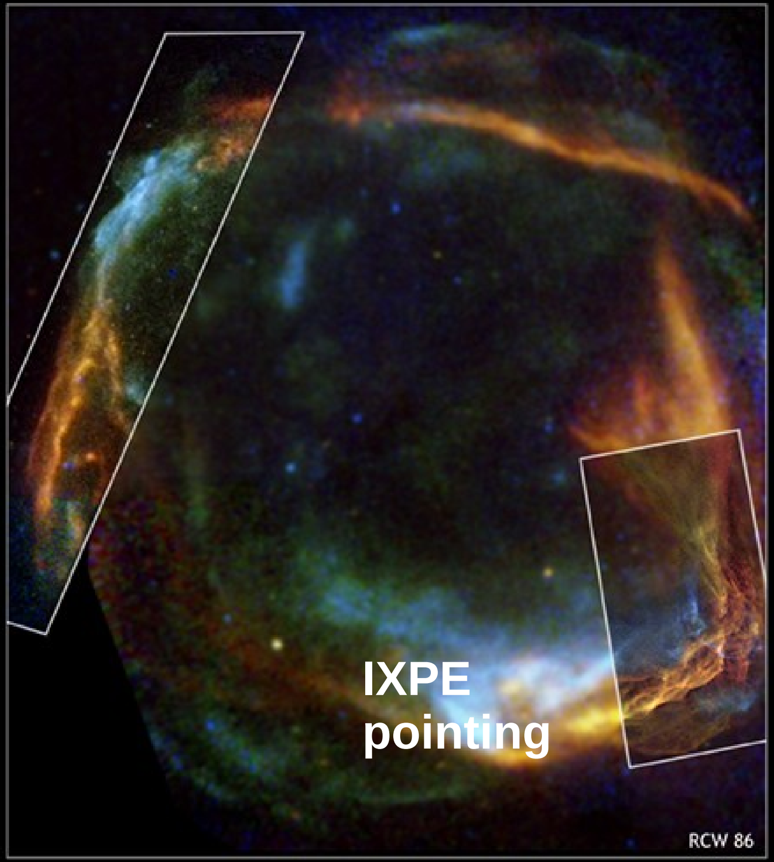

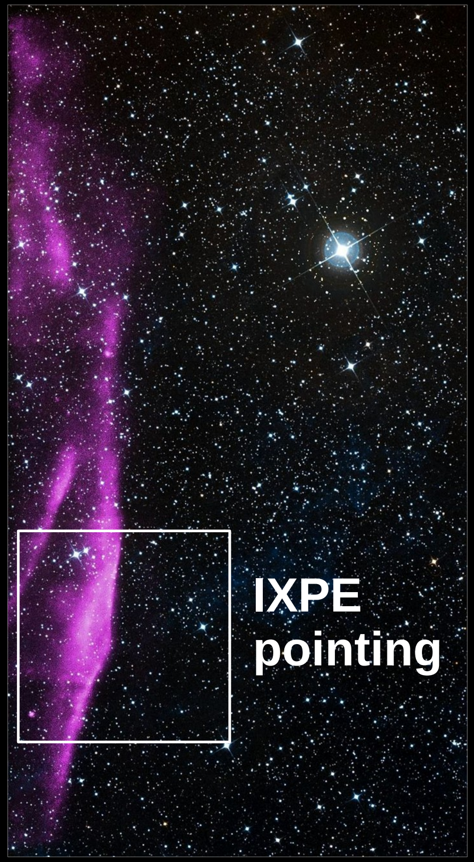

SNR WITH IXPE
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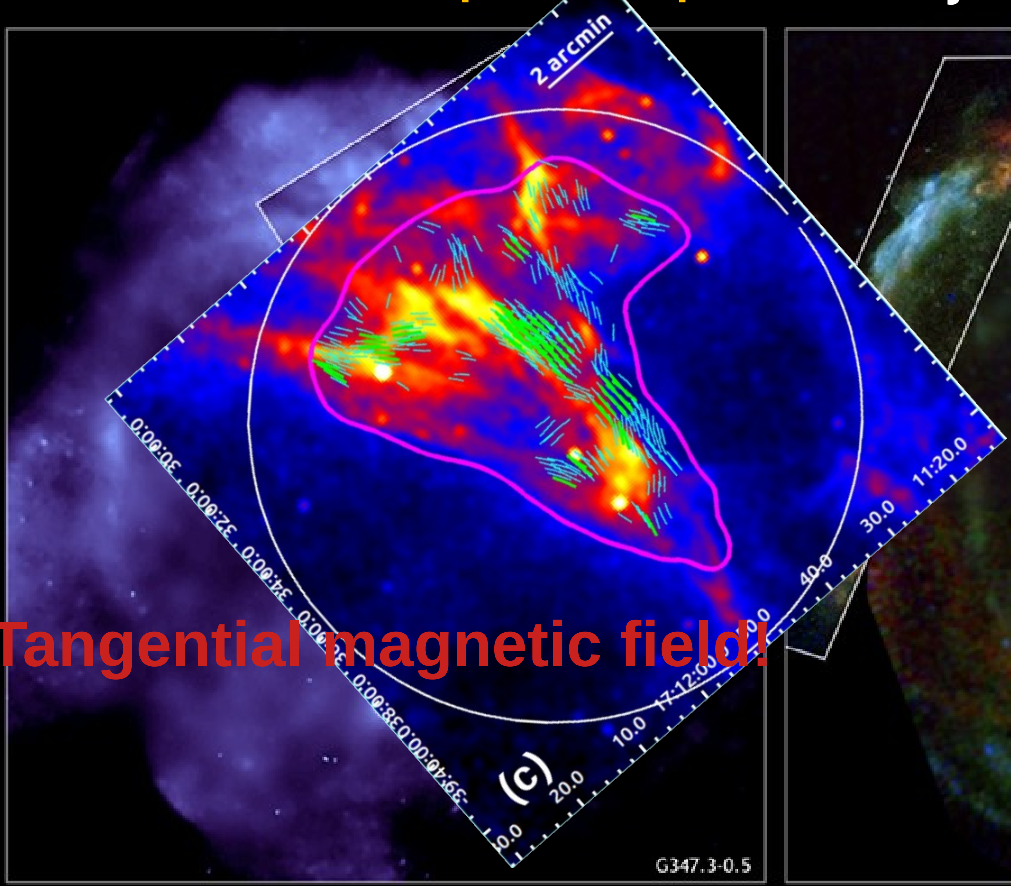

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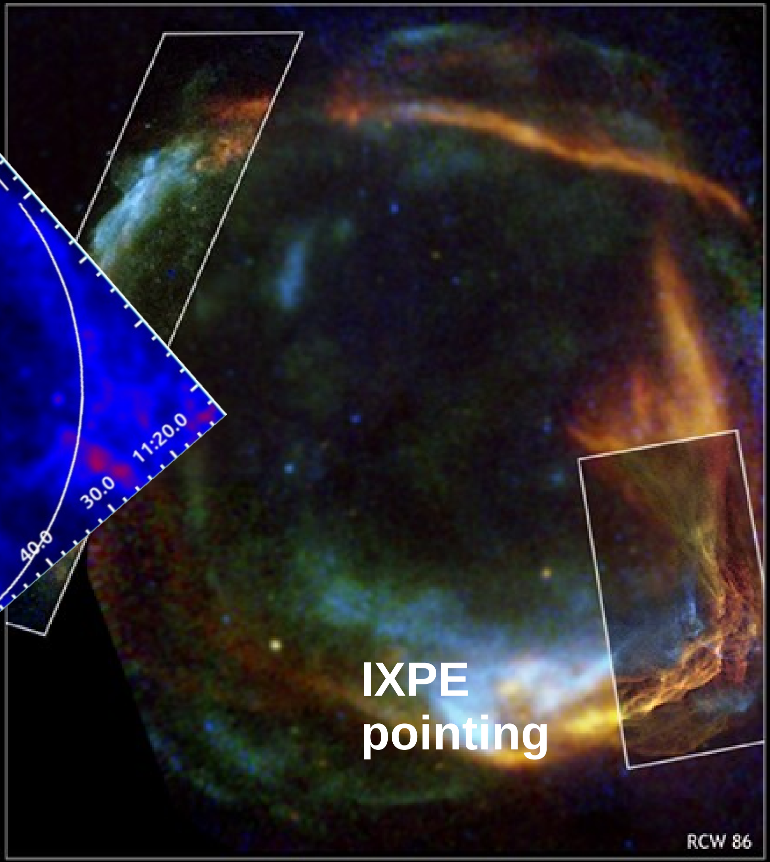

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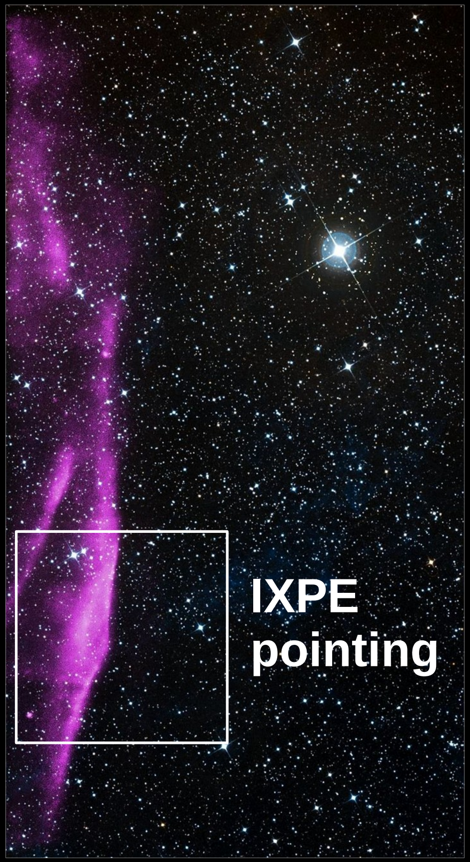
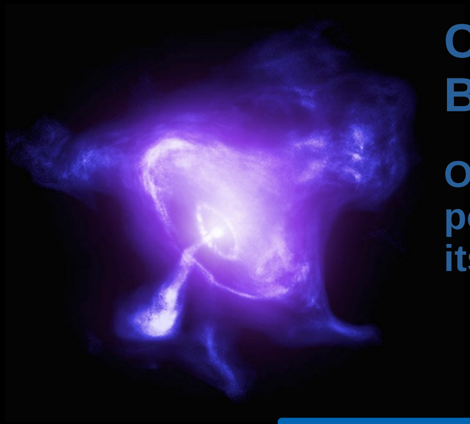


PULSAR WIND NEBULAE



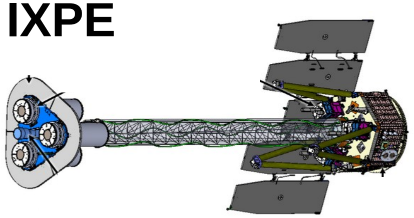
Crab Nebula:
Bucciantini et al. 2022 Nat. Astr.

Only source for which OSO-8 detected polarized radiation in the 1970s thanks to its collimated Bragg diffraction polarimeter

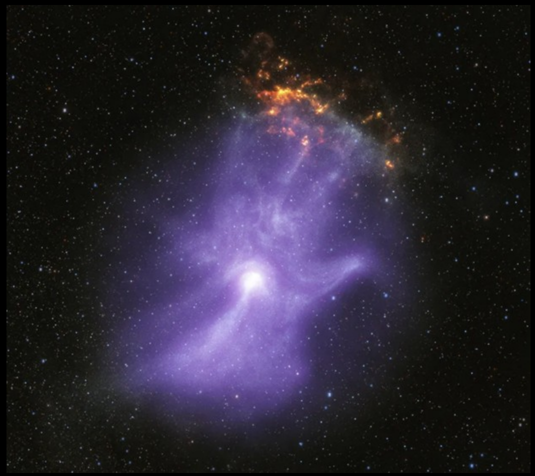
- X-rays emitted via the synchrotron process.
- Bubbles of plasma accelerated up to 10 - 100 TeV and magnetic fields produced by spinning neutron star interact with the interstellar medium → complex morphologies seen in X-rays.

X-RAY POLARIMETRY GOALS:
- constrain the plasma dynamics inside the sub-components of PWNe;
- verify if the relative orientation between rotational and magnetic axes of pulsars correlates with the nebula morphology;
- test MHD models.

Pulsar Wind Nebulae ← **IXPE**



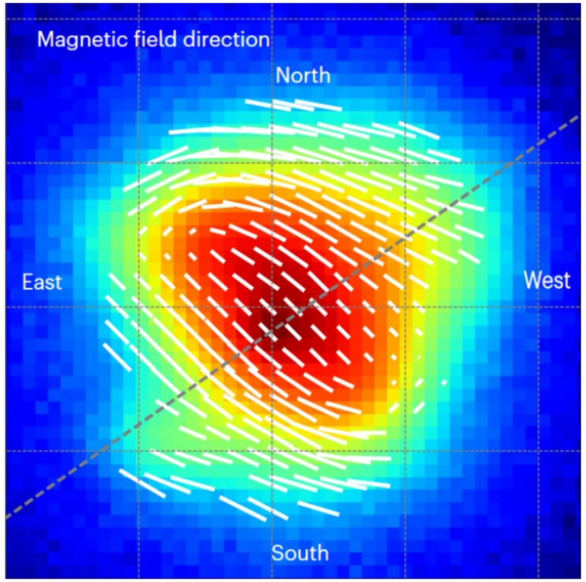
Vela Nebula:
Xie et al. 2022 Nature



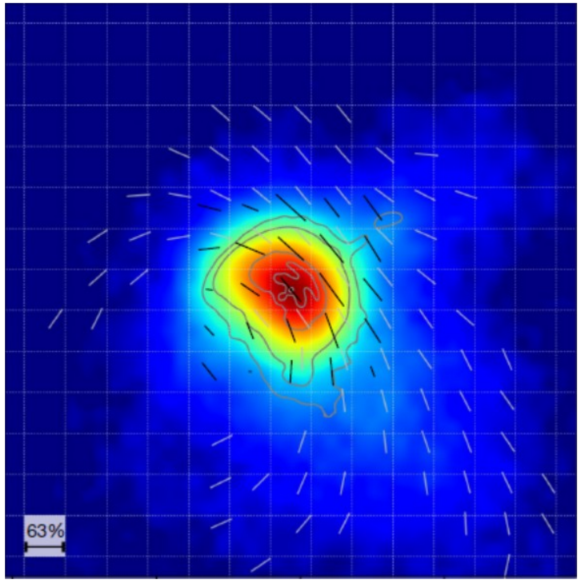
MSH 15-52:
Romani et al. 2023 ApJL

PULSAR WIND NEBULAE IN X-RAY POLARIMETRY
THE THREE REPORTED 1ST YEAR TARGETS

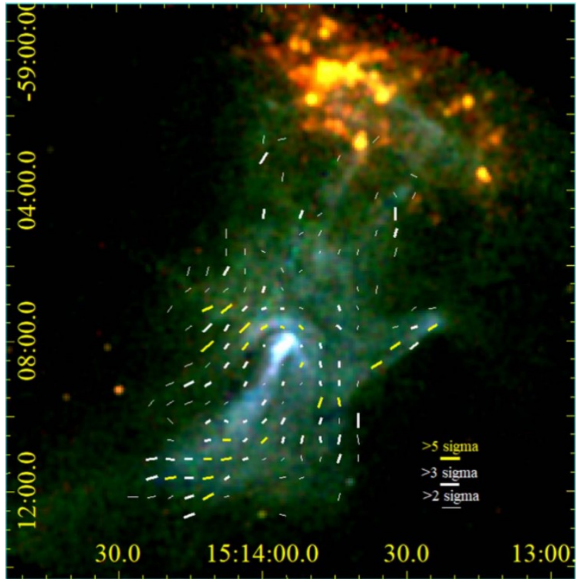
Crab Nebula



Vela Nebula



MSH 15-52



- **High level of polarization degree: Crab PWNe (45–50%), Vela (67–72%), MSH 15-52 (~70%),**
- **Turbulence is much less effective than expected PD close to maximum theoretical limit in Vela and MSH 15-52.**
- **Vela PWN: polarization structure is symmetric about the projected pulsar spin axis, which corresponds to its proper direction of motion.**
- **Crab PWN: integrated PD = 20% PA = 145°.**
- **PD consistent between IXPE and OSO-8, PA has a small but statistically significant difference from the 154° measured by OSO-8.**
- **Difference could be due to a change in the morphology of the inner structure of the Crab Nebula.**
- **MSH 15-52: B follows the thumb, fingers, and other linear structures.**
- **Maximum PD about 70% at the end of the jet, while B is less ordered at the base of the inner jet.**
- **Pulsars studies require longer integration times (pulsar polarization detected in only one phase bin of Crab and MSH 15-52)**

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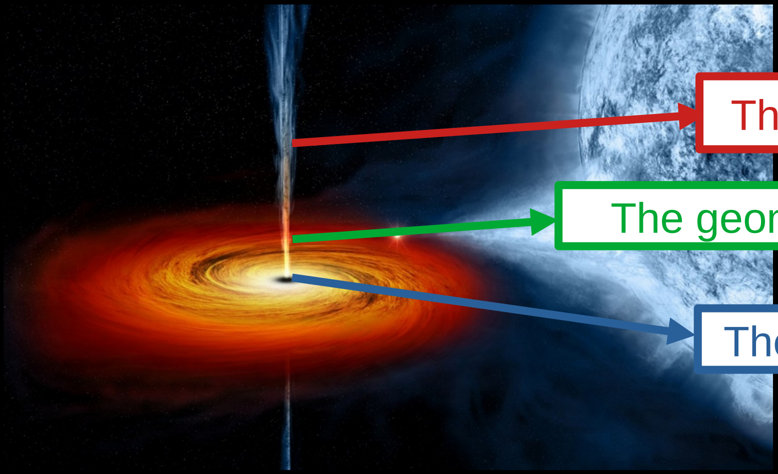
ACCRETING STELLAR-MASS BLACK HOLES

Accreting Black Holes

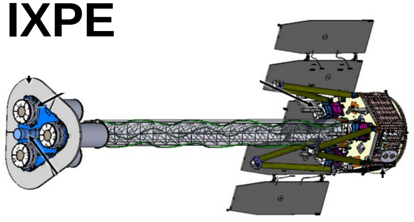


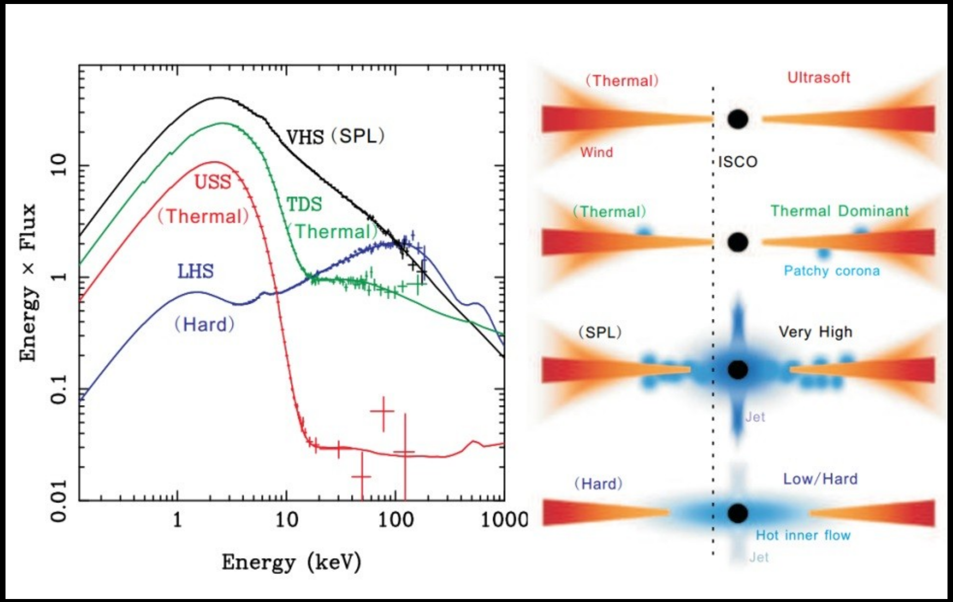
The role of the jet

The geometry of the corona

The BH spin

IXPE





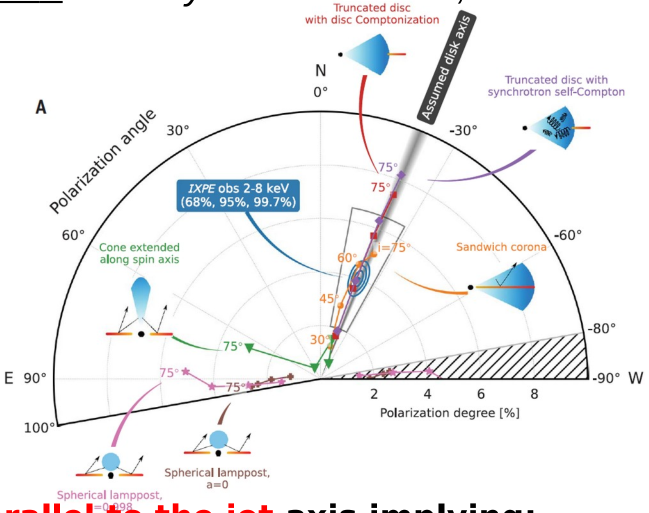
X-RAY POLARIMETRY GOALS:

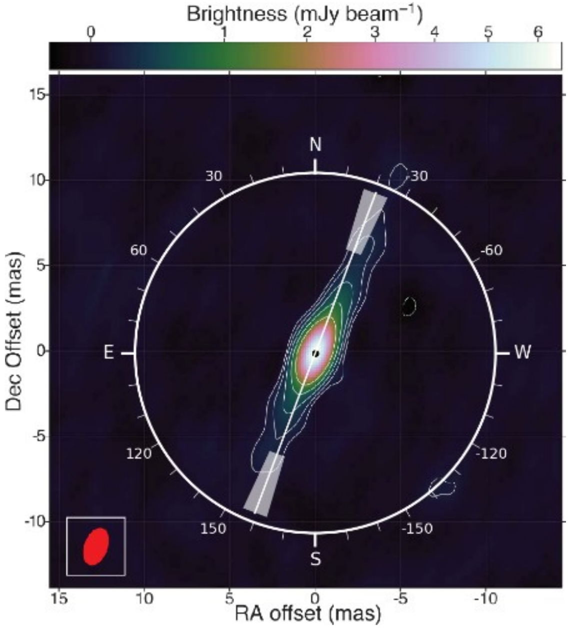
- X-ray Polarimetry of BH binaries in Hard State (jet dominated) can probe the coronal geometry and the Jet-Corona interplay.

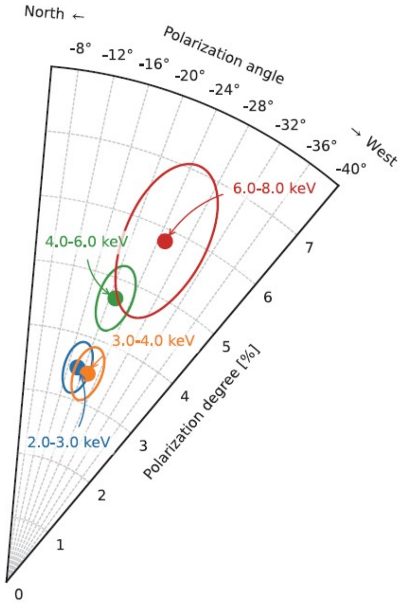
- X-ray Polarimetry of BH binaries in Soft State (disk dominated) can probe the disk geometry and physical status.

ACCRETING STELLAR-MASS BLACK HOLES
CYG X-1

Cyg X-1: *Krawczynski et al. 2022, Science*







Low hard state.

PD = 4.01 ± 0.20%
PA = -20.7 ± 1.4°
i = 28°

PA parallel to the jet axis implying:

- **(1a) the corona is sandwiched to the disk or**
- **(1b) an external cold truncated standard disk + an internal region optically thin geometrically thick.**
- **(2) the jet is launched perpendicularly to the inner flow.**

PD larger than expected for the inclination angle i implying that the disk may be warped.

Other interesting BHB results:

- we got surprises from **4U1630**, from which we had a large PD and increasing with energy, which point to a scattering on the wind (*Ratheesh et al. 2023, Cavero et al. 2023*);
- **Swift J1727:** was the first case in which we monitored the transition of a BHB, which confirmed that the **PD** (and then the accretion geometry) evolved during the transition, with a PA again aligned with the radio jet (*Ingram et al. 2023*).
- **Cyg X-3:** PA perpendicular to the radio ejection, thought to be due to reflection from the circumnuclear material and a PD as high as ~25%, suggesting a scattering in a “funnel” that implies a lower limit on the beamed luminosity exceeding the Eddington value. **Cyg X-3 is viewed as a ULX to an extragalactic observer located along the axis of the funnel!** (*Veledina et al. 2023*)

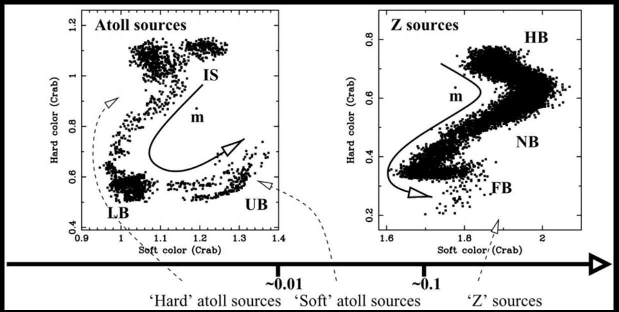
ACCRETING NEUTRON STARS

Low Magnetized NS binaries (LMNSB)

- NS (**B < 10^{10}G**) + companion star (**M < M⊙**)
- Accreting matter via Roche lobe overflow.

Depending on the track drawn on the C-C diagram we distinguish:

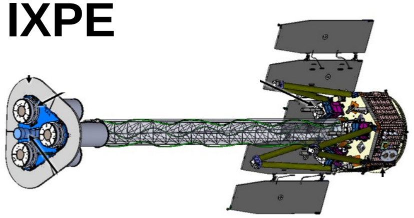
- **"Z"** sources
- **"Atoll"** sources



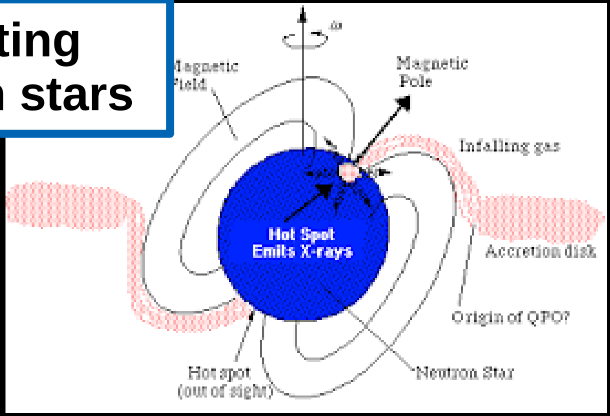
X-ray binary pulsars (XRPs):

- Magnetized NS (**B ~ 10^{12} G**) accreting matter from a normal stellar companion.
- Accreted matter channeled by the NS's magnetic field on to the magnetic poles, producing two or more localized X-ray hot spots.

IXPE



Accreting Neutron stars



X-RAY POLARIMETRY GOALS:

- Study the **boundary/spreading layer geometry** and eventual jet-couplings (similar to BHB);
- Probing between **"fan beam"** or **"pencil beam"** accretion scenarios;
- provide independent tracer of the magnetic field geometry in XRPs;
- constrain the observer's inclination with respect to the rotation axis and the hot spot in AMPs.

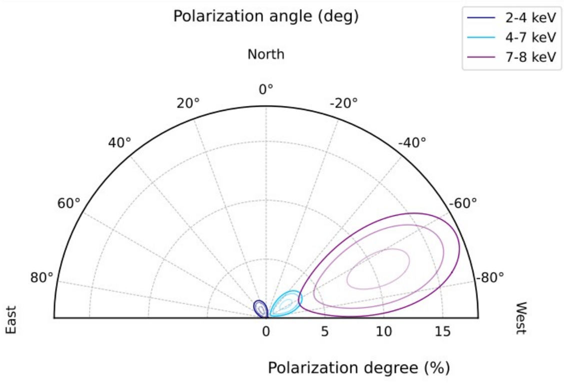
IXPE Imaging X-Ray Polarimetry Explorer

ACCRETING NEUTRON STARS

LOW MAGNETIZED NS BINARIES (LMNSB) & X-RAY BINARY PULSARS (XRPS)

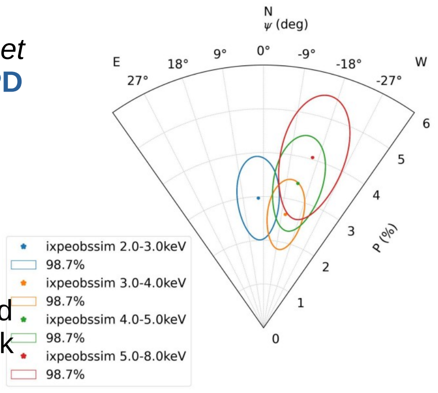
4U 1820–303 (LMNSB - "Atoll"): *Di Marco et al. 2023, ApJL*

- Polarization results to be energy dependent:
  - **PD of Reflection component negligible→ soft disk component not well determined;**
  - **Energy spectrum dominated by Comptonization → from PD we can study corona properties: hard component due to boundary layer shows higher linear-dependent PD, associated with a corona with slab/wedge geometry;**
  - **the two components are rotated by 90°;**
- Energy bin **7–8 keV** highly significant (**99.99%CL**)



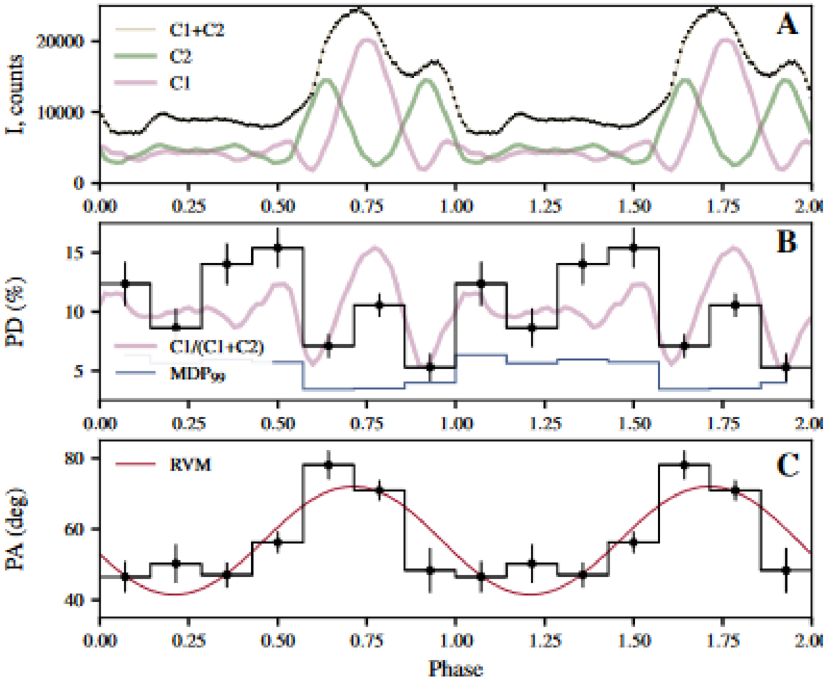
(LMNSB – "Z"):
Both **XTE J1701-462** (*Cocchi et al. 2023*) and **GX 5-1** (*Fabiani et al. 2024*) observed in the horizontal branch (flat top of the Z) (**PD ~ 4%**) and Normal branch (inclined segment of the Z) (**PD ≤ 2%**).
Cyg X-2 (*Farinelli et al. 2022* was observed only in the normal branch of the Z with a low polarization.)

- **PD** varies as a function of the position of the source in the color-color diagram;
- Evidence of a **variation in the PA with energy** likely related to the different, nonorthogonal polarization angles of the disk and Comptonization components, which peak at different energies.
- **The ability to predict the polarization depending on the spectral properties of the source is quite an unicum in the sometimes messy zoology of IXPE sources.**



Her X-1 (XRP), *Doroshenko et al. 2022, Science*

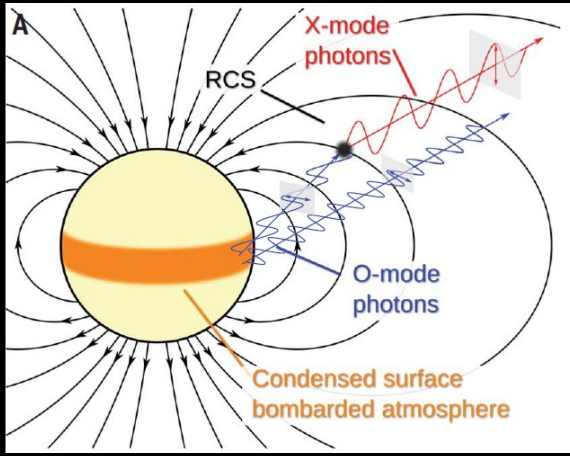
- IXPE detected for the first time polarization resolved in phase;
- Average **PD = (8.6 ± 0.5)%** much smaller than expected **(~60–80%);**
- **Why?** reprocessing geometry is much more complex than the simple **"fan"** or **"pencil"** model, which involves only simple columns and hot spots at the poles;
- **PA** dependence allows to constrain geometry with the **rotating vector model** (**RVM**);
- RVM analysis shows a variation in geometry compatible with **precession** (*Heyl et al. Accepted*).

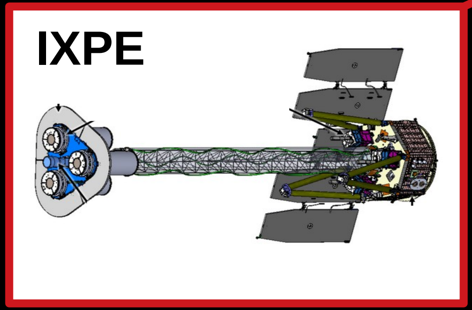


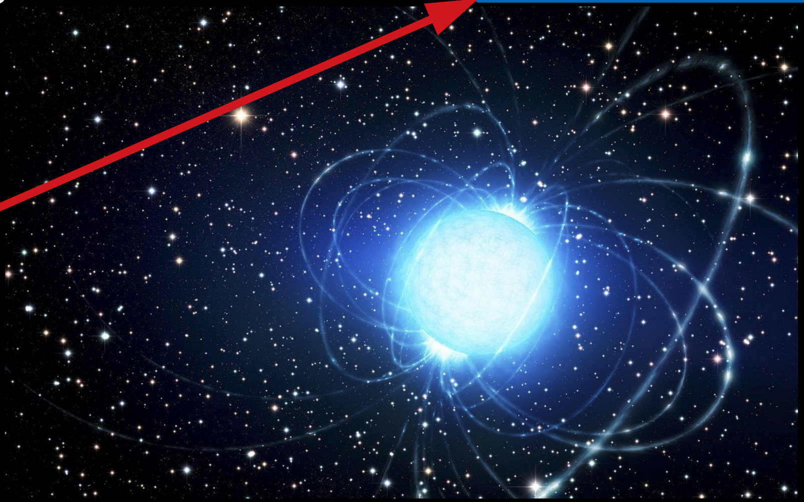
MAGNETARS

Magnetars

Isolated neutron stars powered by an extreme magnetic field, ranging from 10^{14} to 10^{15} Gauss.







X-RAY POLARIMETRY GOALS:

- Uncover the magnetar geometry (inclination of the line of sight and of the magnetic axis with respect to the spin axis). This will give crucial, quantitative information on the magnetosphere of magnetars (magnetic twist, currents) and on the mechanism that triggers their powerful outbursts.

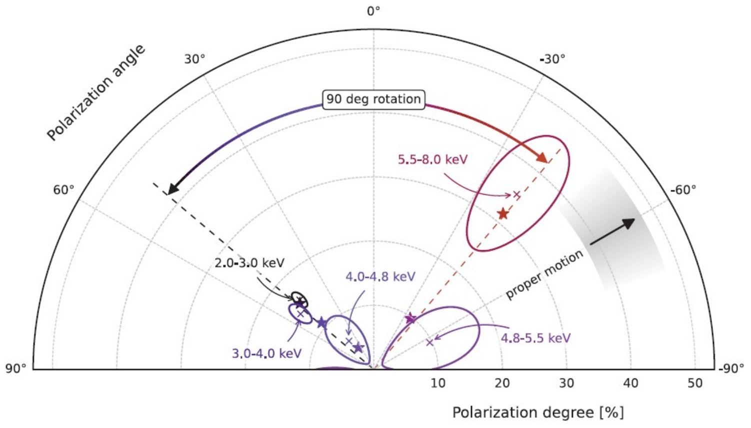
- Study of propagation of radiation through strong magnetic field → Fundamental and new physics (e.g. QED effects such as vacuum birefringence).

MAGNETARS
4U0142 + 61 AND HER SISTERS

IXPE published results from 4 magnetars and no two of them are the same!
Difference explained by different kinds of emitting regions on the surface (i.e. different geometrical and physical status)

4U 0162+61
Taverna et al. 2022, Science

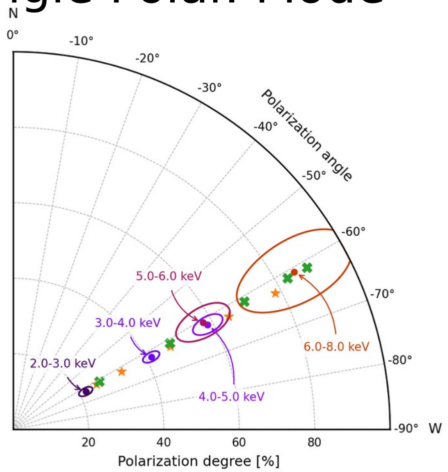
Double Polar. Mode



- **Low energy (O-mode):** Equatorial belt condensed surface
- **High energy (X-mode):** Resonant Compton Scattering

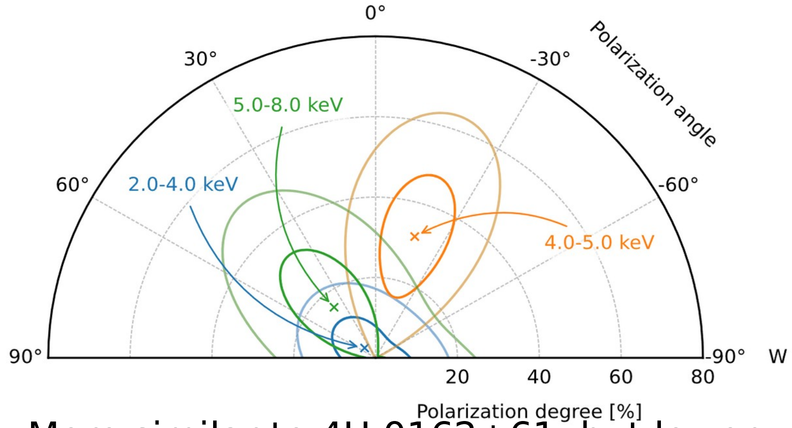
1RXS J170849.0-400910
Zane et al. 2023, ApJL

Single Polar. Mode



Condensed surface warm region **(low-PD)** plus hot regions with on-top an atmosphere **(high PD)**

SGR 1806-20
Turolla et al. 2023, ApJ

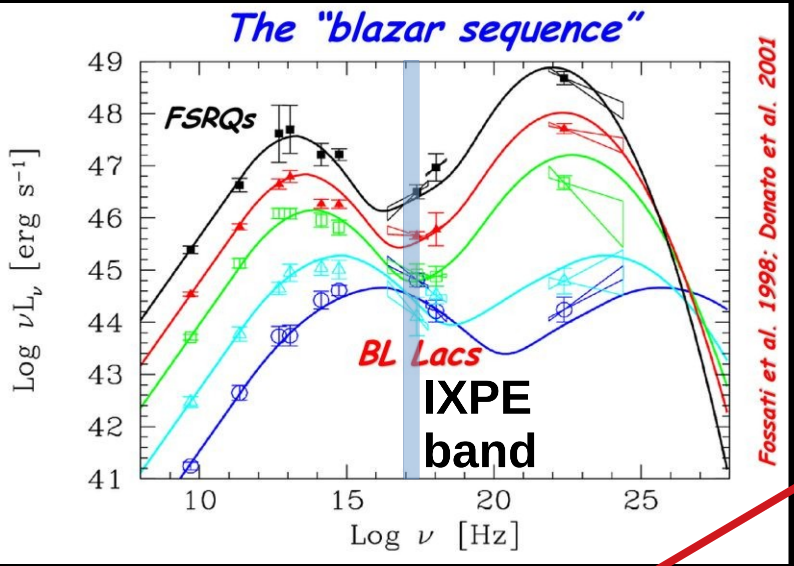


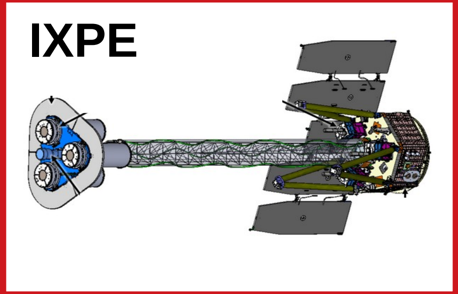
- More similar to 4U 0162+61, but lower significance.
- Modeled with two hot spots placed near the magnetic equator of the bare neutron star's surface.

Vacuum birefringence is considered in the modeling while evaluating polarimetry expectations, **but the size of the emitting region is not yet sufficiently extended to require unambiguously this QED effect.**

BLAZARS AND RADIO GALAXIES

A blazar is an AGN with a relativistic jet directed closely towards the observer. Relativistic beaming from the jet makes blazars appear much brighter than they would be if the jet were pointed in a direction away from Earth.





Blazars and radiogalaxies

X-RAY POLARIMETRY GOALS:

- In Synchrotron dominated (HSP) blazars: determines jet and magnetic field structure and the acceleration mechanism.

- In Inverse Compton dominated (LSP-ISP)blazars: discriminate between leptonic and hadronic models and determines the origin of the seed photons in leptonic jets.

BLAZARS AND RADIO GALAXIES
MRK 501 & MRK 421

Mrk 501 (HSP)
- **PA** directed along the jet;
- **PD = 10%** , twice the Optical one
- Modest (if not null polarization variability)
- **Energy stratified shock acceleration process.**

Liodakis et al. 2022, Nature

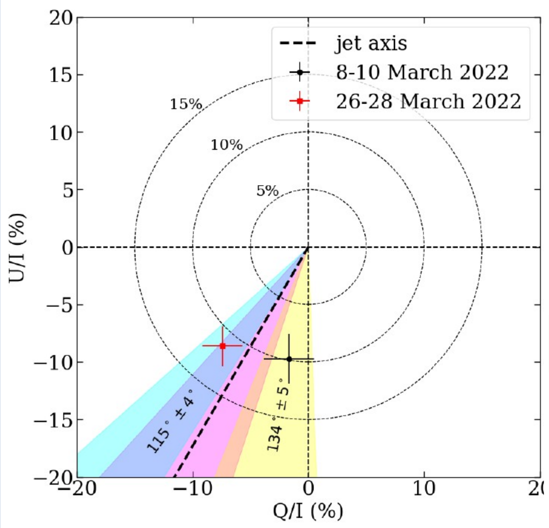
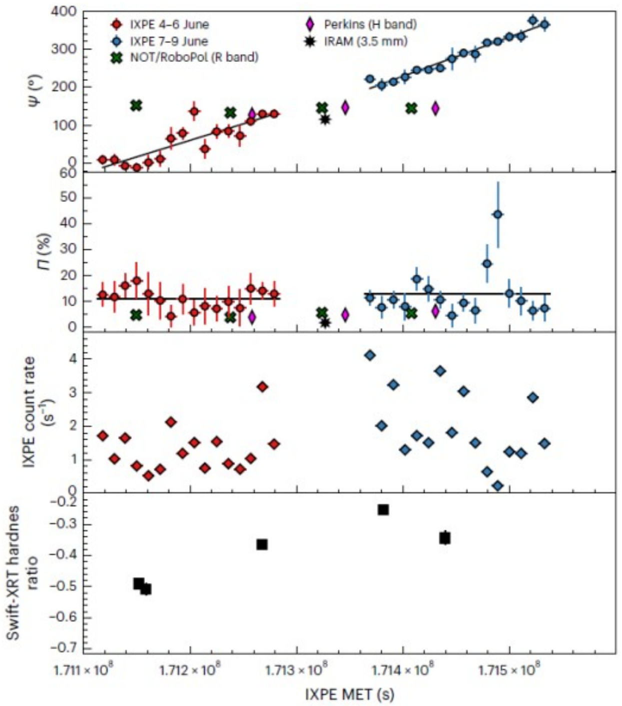


Table 1 | Summary of model properties

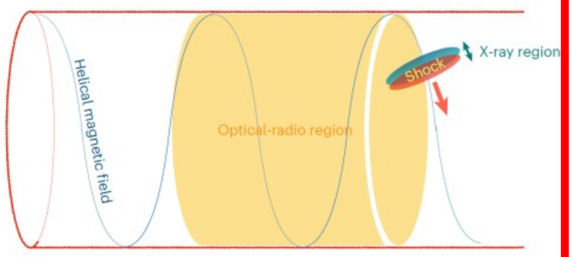
Model	Multiwavelength polarization	X-ray polarization variability[a]	X-ray polarization angle
Single zone	Constant[b]	Slow	Any
Multizone	Mildly chromatic	High	Any
Energy stratified (shock)	Strongly chromatic	Slow	Along the jet axis
Magnetic reconnection (kink instability)	Constant	Moderate	Perpendicular to the jet axis
Observed	Strongly chromatic	Slow	Along the jet axis

First, we find an increasing Π towards higher frequencies. Second, we do not find significant variability during the 2–3-day-long IXPE observations, and finally, we find a rough alignment of ψ with the jet axis from radio to X-rays. Therefore, a shock-accelerated, energy-stratified electron population model satisfies all our multiwavelength polarization observations.
[a]Slow variability, a few days to a week; moderate variability, days; high variability, less than 1 day.
[b]There is a slight dependence on the slope of the emission spectrum.

Mrk 421 (HSP)
- **PA** in X-rays rotates 10 times faster (**80°-90°/day**) than in Optical;
- **PD = 15 ± 2%** → **Energy stratified shock acceleration active in an environment embedded with a helical magnetic field.**

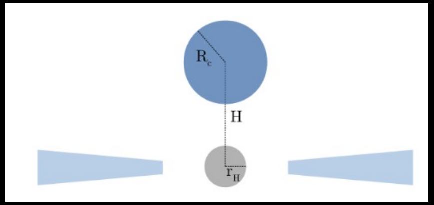


Di Gesu et al. 2022, ApJL;
Di Gesu et al. 2023, Nat. Astr.



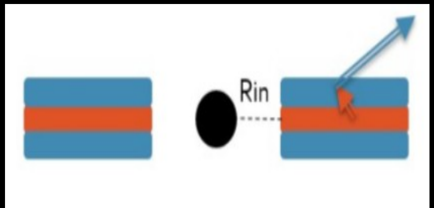
RADIO-QUIET AGNS

Spherical lamppost



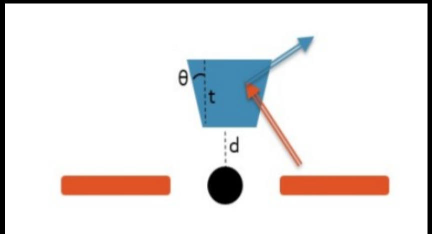
PD: 0-2%
PA: perpendicular to the disc axis;
Phenomenological model

Slab corona

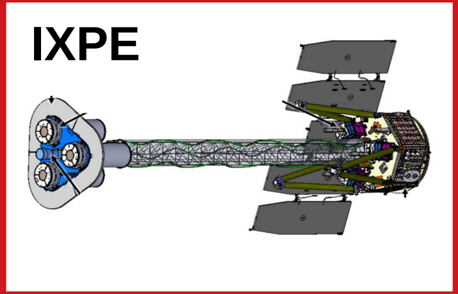


PD: up to 14%;
PA: parallel to the disc axis;
Magnetic loops?

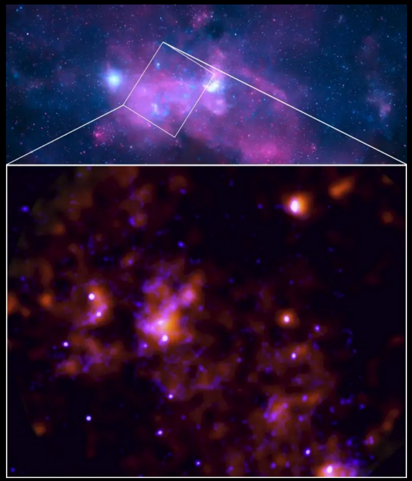
Conical outflow



PD: up to 6%;
PA: perpendicular to the disc axis;
Base of a jet?



AGNs and the Galactic center



X-RAY POLARIMETRY GOALS:

- **break degeneration of physical parameters of the AGN's corona with respect to geometry.**

RADIO-QUIET AGNS

CIRCINUS GALAXY

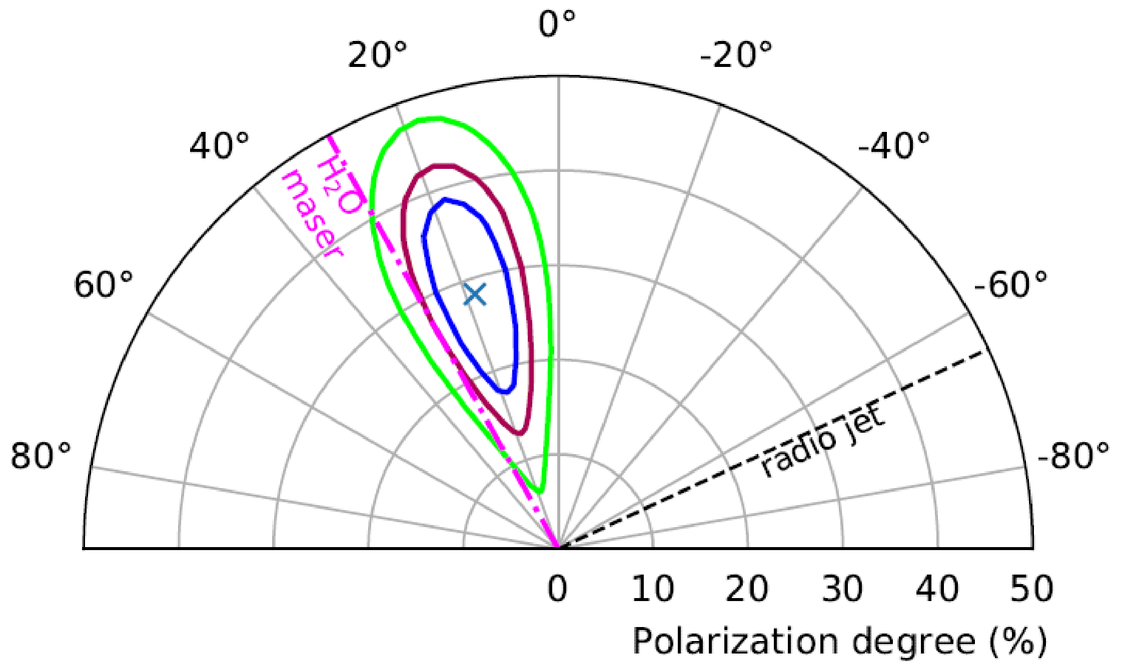
Circinus galaxy is a close (**D = 4.2 Mpc**) Compton Thick (Seyfert 2) AGN.

- X-ray spectropolarimetry in Circinus galaxy showed that **radio jet, ionization cone and torus axis are aligned**

Other sources:

- **NGC 4151** (Seyfert 1, Giannolli et al. 2022 MNRAS): source of the primary emission is not a lamp post but it is sandwiching the accretion disk.
- **IC429A** (Seyfert 1, Ingram et al. 2023 MNRAS) and **MCG-5-2316** (Seyfert 1, Tagliacozzo et al. 2023, MNRAS) hints at low significance the same geometry.

Circinus (Compton thick)
Ursini et al. 2023, MNRAS
Cold reflection



For The cold reflection component IXPE measured a 2-6 keV polarization of:
P = 28 ± 7% and θ = 18 ± 5°

IXPE Imaging X-Ray Polarimetry Explorer

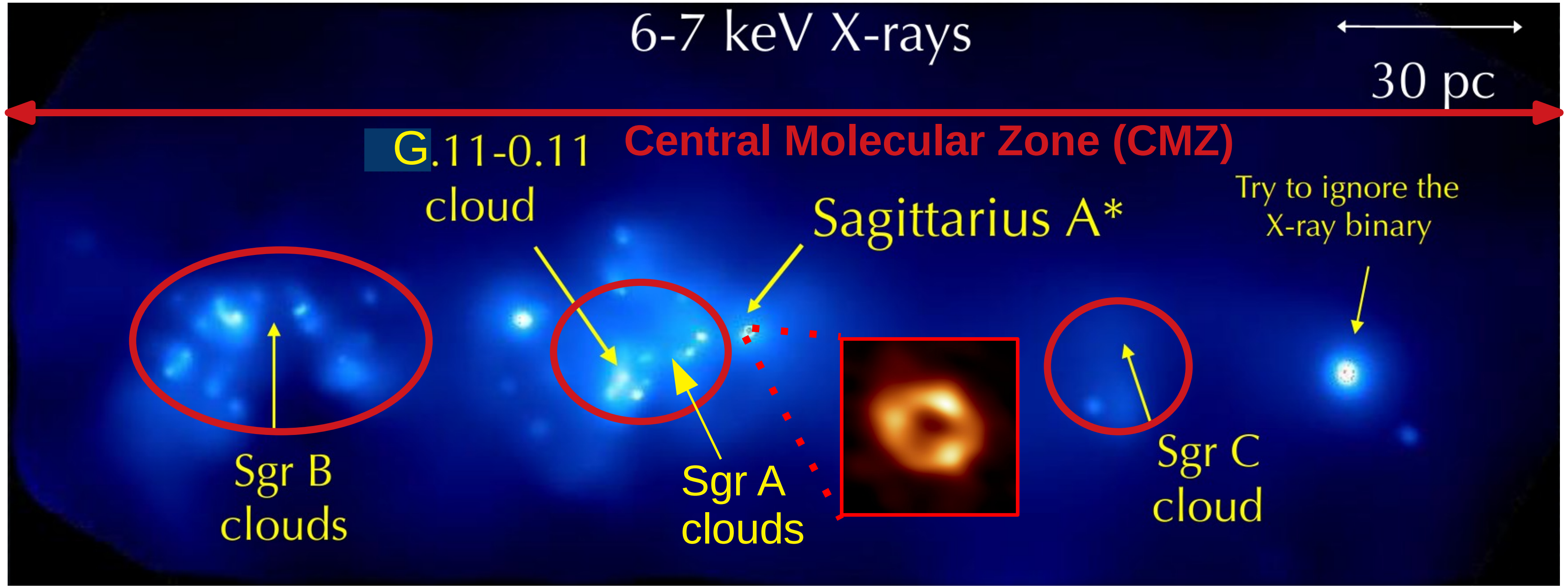
X-RAY POLARIMETRY OF THE GALACTIC CENTER
A GALACTIC ARCHAEOLOGY MYSTERY..

Today Sgr A* is "X-ray dim": **$L_X \sim 2 \times 10^{33}$ erg s^{-1}** .

However, signs of active past:

- Fermi-LAT: gamma-ray bubbles *(Su et al. 2010; Zubovas et al. 2011)*;
- Gas distribution in CMZ reminiscent of AGN torus *(Molinari et al. 2011,)*;
- **X-ray reflection features in Molecular Clouds but no (persistent) source strong enough to have produced them!** *(Sunyaev et al. 1993)*

Was Sgr A* X-ray luminosity 10^6 larger "JUST" ≈300 years ago?



X-RAY POLARIMETRY OF THE GALACTIC CENTER
A GALACTIC ARCHAEOLOGY MYSTERY..

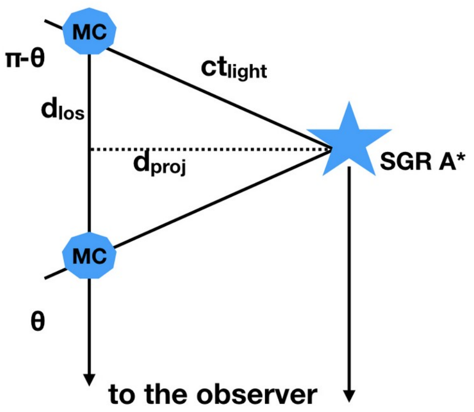
An X-ray polarimetric observation could solve this mystery!

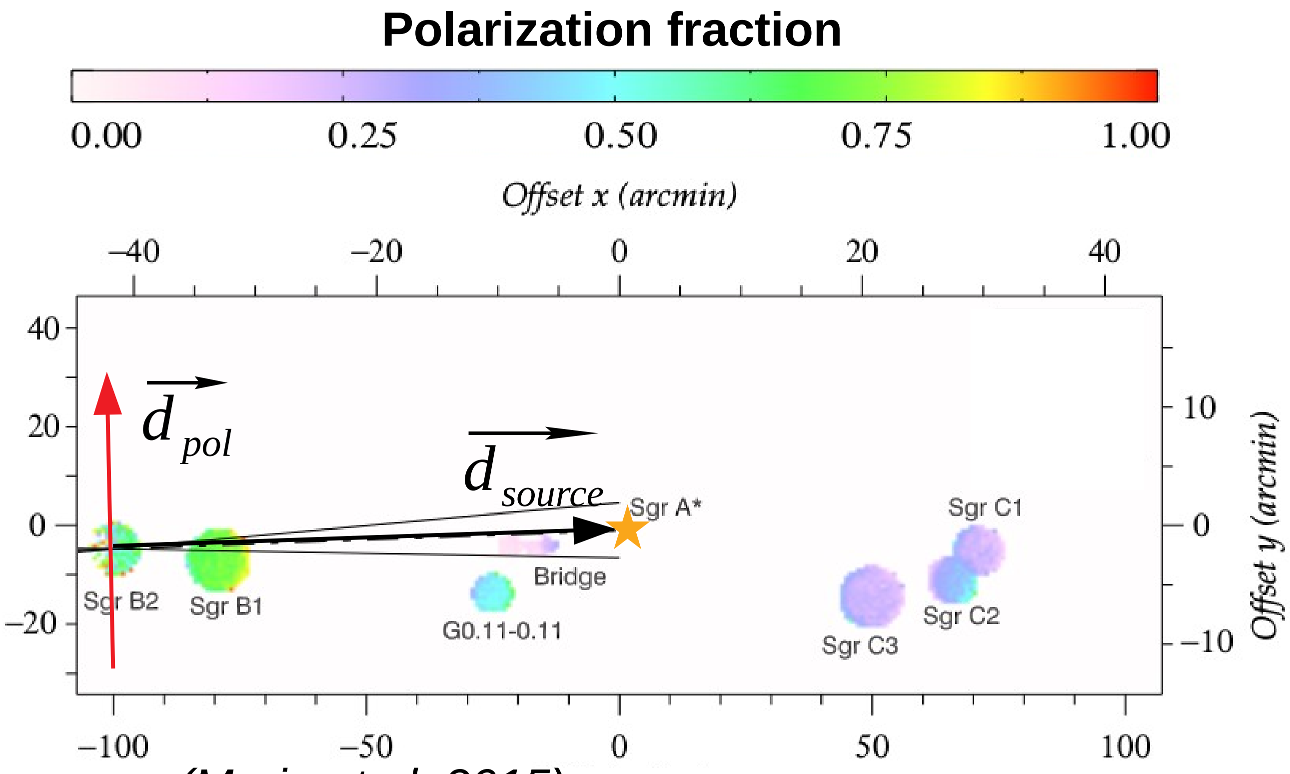
Direction of external illumination source from **polarization angle**

$$\vec{d}_{pol} \perp \vec{d}_{source}$$

Scattering angle **θ** → cloud distance along l.o.s → **polarization degree**

$$P = \frac{1-\cos(\theta)}{1+\cos(\theta)} \Rightarrow d_{los} = d_{proj}\cot(\theta)$$

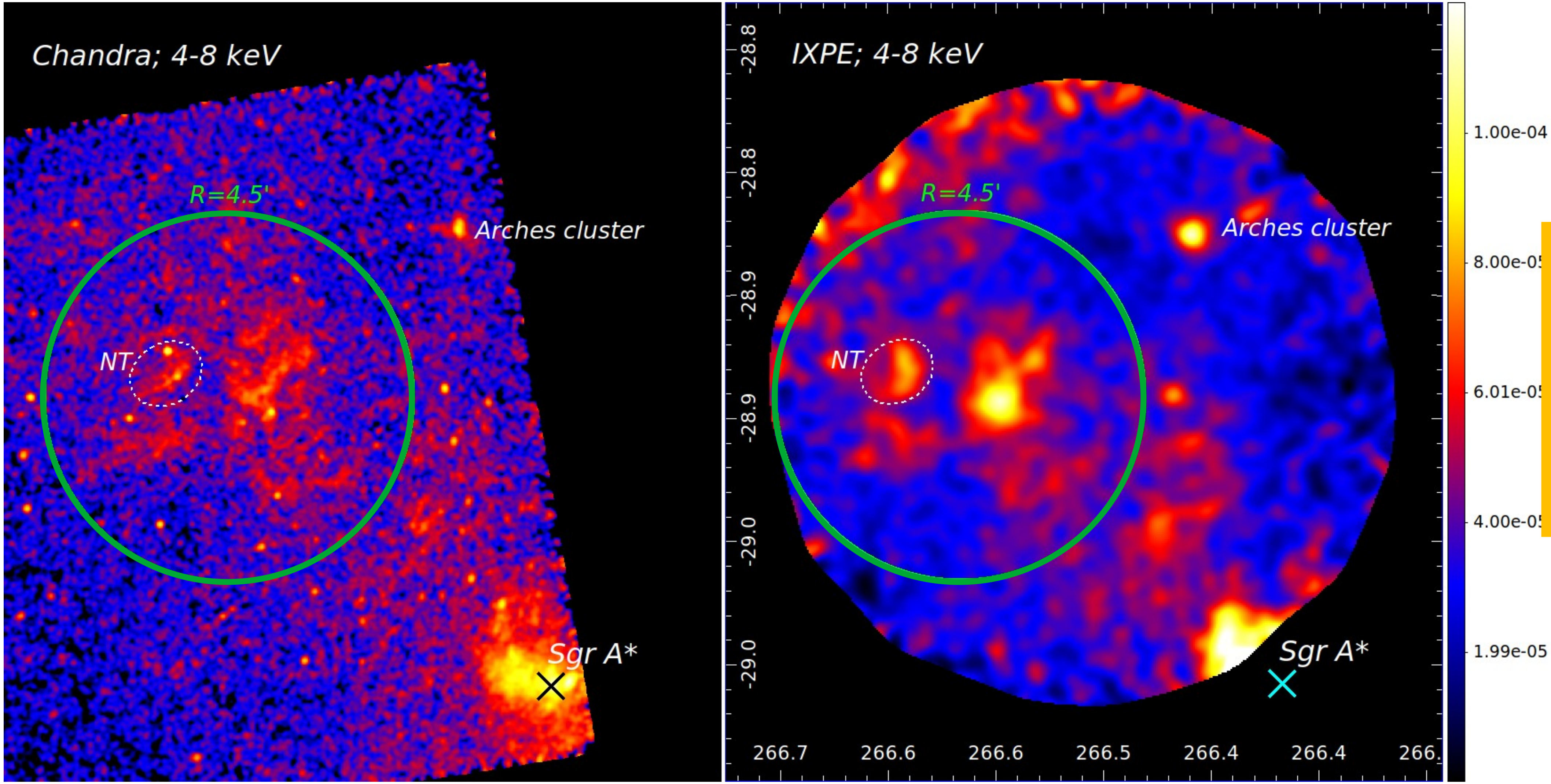




(Marin et al. 2015)

WAS THE GALACTIC CENTER MORE ACTIVE IN THE PAST?

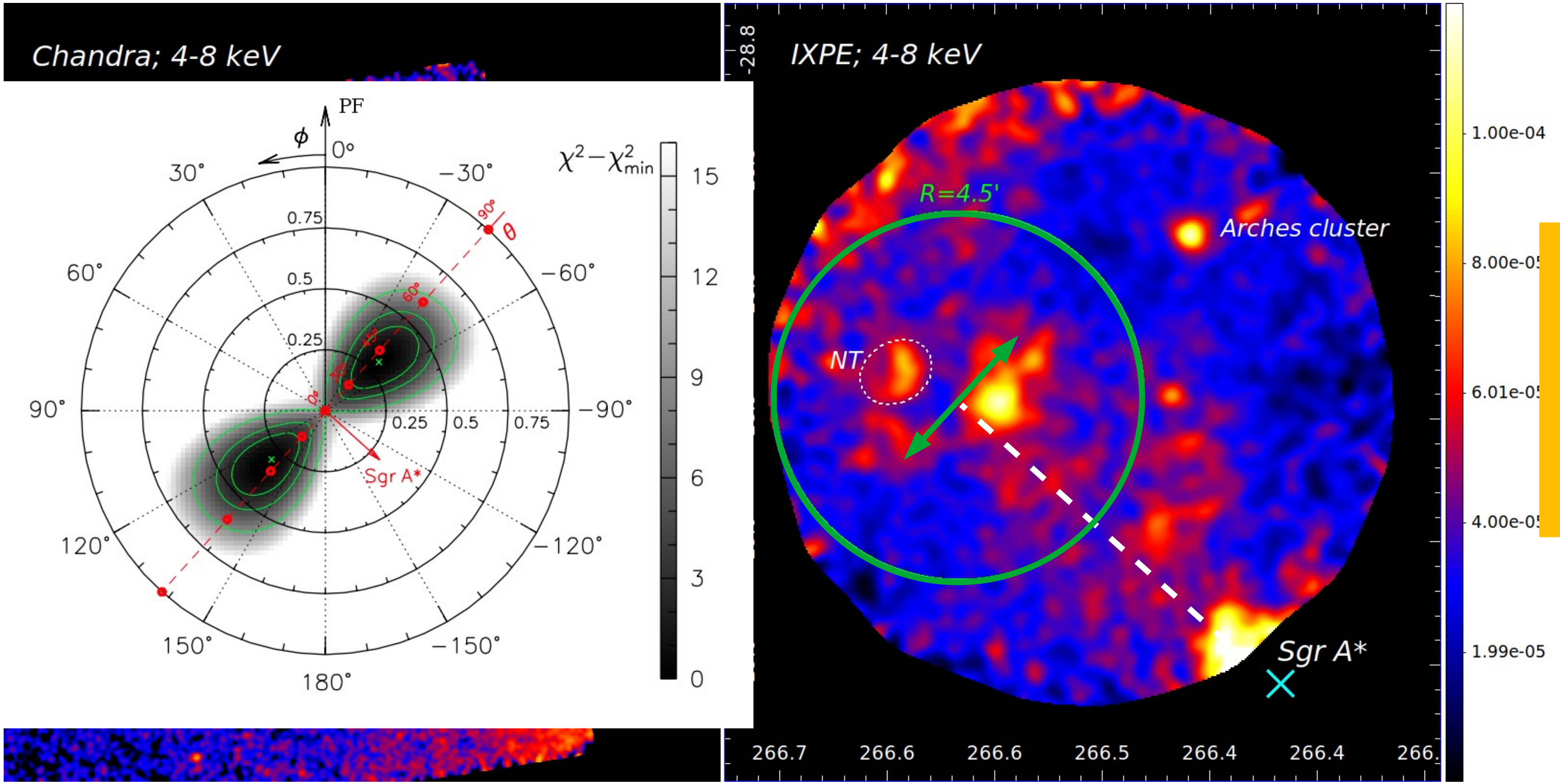
LET’S ASK IXPE…



Marin et al., Nature 2023

WAS THE GALACTIC CENTER MORE ACTIVE IN THE PAST?

LET'S ASK IXPE…



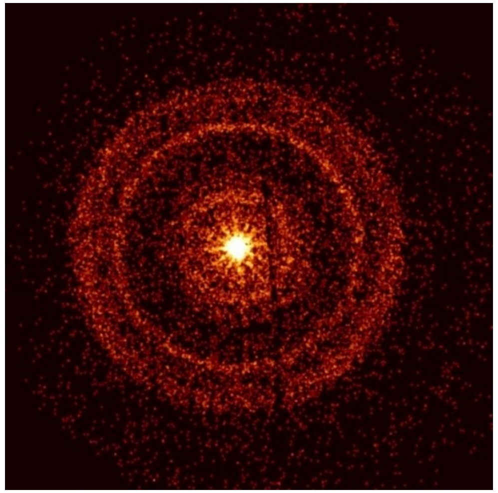
Marin et al., Nature 2023

GRB 221009A
THE “BOAT”

We did not plan to follow-up on GRBs, because of the relatively slow reaction time (**2 - 3 days**).

However, **GRB 221009A** (a.k.a. “the BOAT” GRB) was so exceptional in terms of brightness, that we decided to observe it.

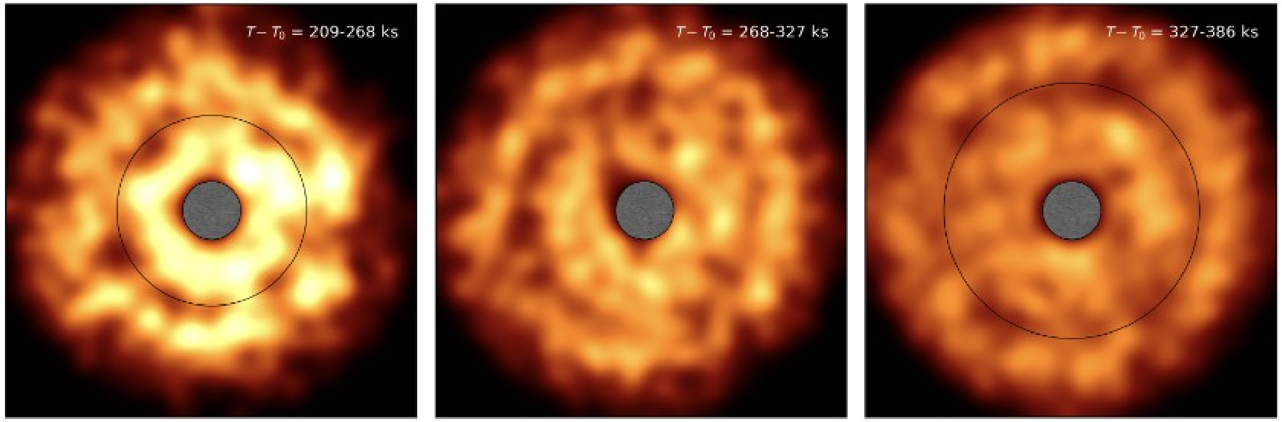
We obtained upper limits on the **PD** of both **prompt and afterglow emission** in the soft X-ray energy band (***Negro et al. 2023***).



Swift/XRT image

Afterglow: **PD<13.8% (99% c.l.)**

Prompt emission: **PD<13.8% (99% c.l.)** thanks to the Dust rings that allows to put constrains on it.



Time evolution of dust rings as seen by IXPE

FUTURE PROSPECTS AND CONCLUSIONS

- **The IXPE baseline program ended on February 2024;**
- **NASA on 6 June 2023 approved an extension of IXPE until September 2025;**
- **The next NASA senior review for mission is foreseen in 2025;**
- **GO program is at the present time foreseen from February 24 to September 2025;**
- **The first GO program call received an oversubscription of 6 times the available observing time;**
- **The new GO program call will end on August 29th 2024**

IXPE
Imaging X-Ray Polarimetry Explorer

CONCLUSIONS
AND FUTURE PROSPECTS

TWG 1 (Pulsar Wind Nebulae): The magnetic field is very ordered even at a large distance from the pulsar.

TWG 2 (Supernova Remnants): The magnetic field is radially directed even in vicinity of the shock (except when it is not!).

TWG 3 (Accreting Black Holes): The corona in hard X-ray sandwiches the accretion disk and the lamp-post is excluded.

TWG 4 (Accreting Neutron Stars): The rotating vector model works in X-rays. The degree of polarization is much smaller with respect to models predictions.

TWG 5 (Magnetars): Magnetars show unexpectedly very different behavior on the polarization degree and angle.

TWG 6 (Radio-Quiet AGN & SgrA clouds): Corona is sandwiching the disk. Lamp-post is excluded. Reflection confirms obscuring torus in Compton-thick AGNs. Molecular clouds points to Sgr A* as origin of their reflected emission.

TWG 7 (Blazars and Radio Galaxies): Energy stratified shock acceleration is confirmed. In X-ray fast rotation of the polarization vector with time is present in High Synchrotron Peak Blazars.

> *"The 2024 Bruno Rossi Prize has been awarded to Dr. Martin Weisskopf, Dr. Paolo Soffitta, and the IXPE team for their development of the Imaging X-ray Polarimetry Explorer whose novel measurements advance our understanding of particle acceleration and emission from astrophysical shocks, black holes and neutron stars."*

THANK YOU FOR THE ATTENTION