IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

agenzia spaziale italiana

IXPE: X-ray Polarization in the Variable Sky

Roger W. Romani

Stanford University

On behalf of the full *IXPE* Science team

(https://ixpe.msfc.nasa.gov/partners_sci_team.html)

[>150 folks from 15 countries]

WHY STUDY X-RAY POLARIZATION?

- **Polarization probes <u>geometry</u>**
  - Scattering-induced PD from planar sources esp. accretion disks
  - Magnetic field-induced PD – emission geometry (e.g. accretion columns), synchrotron emission
- **X-rays probe fresh electrons from accelerators**
  - Thermal X-rays: from inner accretion zone of compact objects
  - Synchrotron emission from high energy (**$5\gamma_7$TeV**) e^+/e^-

$$E_\gamma = 0.5\gamma_7{}^2 B_{mG}\,\mathrm{keV},\quad \tau \approx 2\gamma_7{}^{-1} B_{mG}{}^{-2}\,\mathrm{y}$$

For typical nebula B, 10TeV particles for soft X-rays

  - Compare with other polarization measurements: radio (Faraday depolarization), optical (low γ, absorption)

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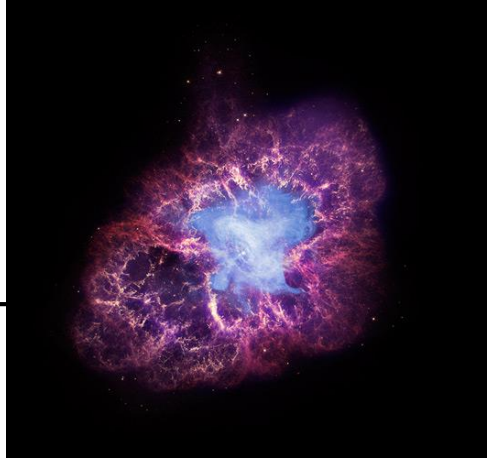
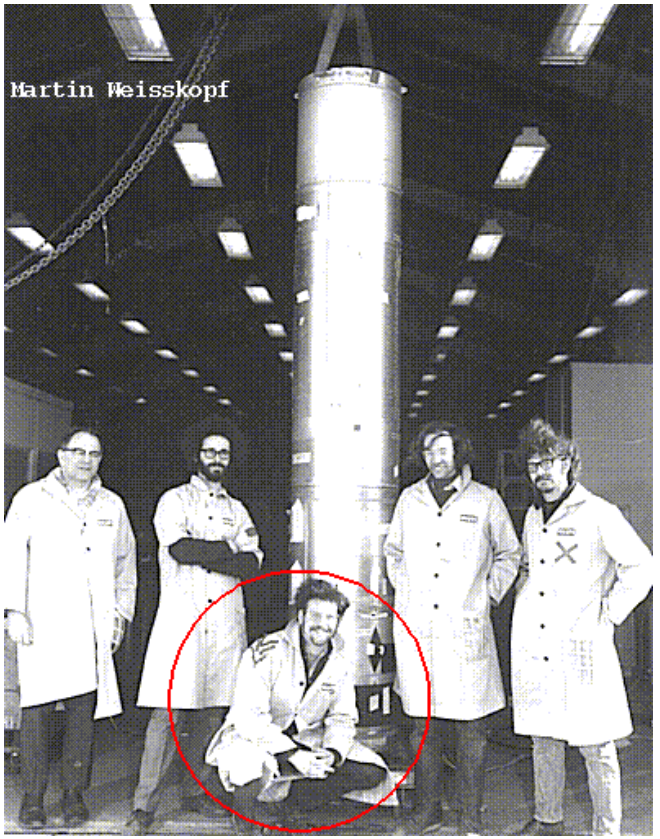
X-RAY POLARIZATION HISTORY



- **It's been a long time coming…**
  - In the classical soft X-rays, only the Crab w/ sounding rockets, then OSO-8: (Novick et al 1972, Weisskopf et al.1976, Weisskopf et al. 1978)

    PD= 19.2 ± 1.0%; PA= 156.4º ± 1.4º
  - Handful of other UL, a recent cubesat confirmation (PolarLite)
  - Harder X-ray allows Compton effect: RHESSI, balloon experiments
- **Why so long? Several large mission concept studies w/ polarizers. Always 1st Inst. to be dropped.**



M.W. prepping for a Wallops Launch in 1971

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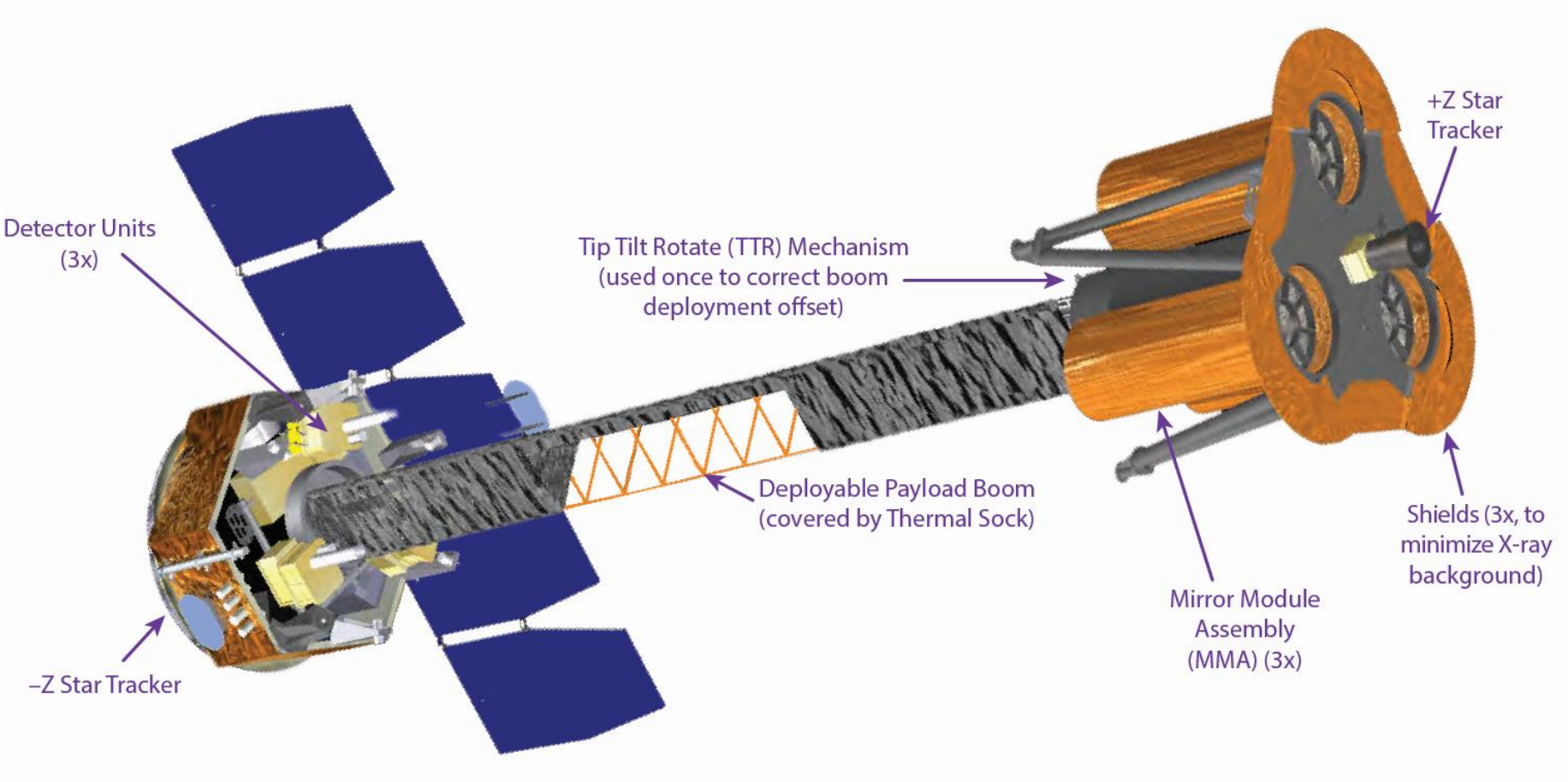
SOLUTION: A DEDICATED (SMEX) MISSION
NEW DETECTORS ALLOW *IMAGING* POLARIMETRY



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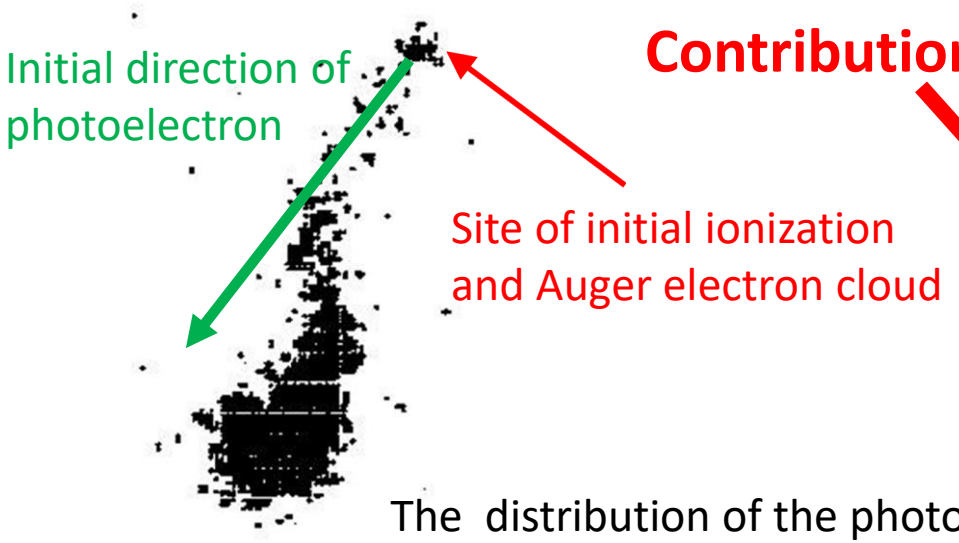
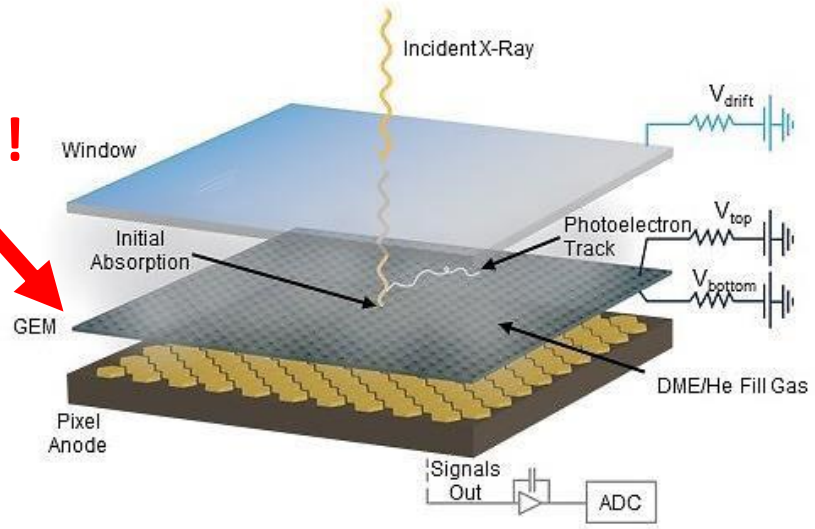
THE POLARIZATION SENSITIVE DETECTORS

- **The initial direction of the K-shell photoelectron is determined by the electric vector**

$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2}\sin^2\theta\cos^2\varphi\,, \text{ where } \beta \equiv \frac{E}{mc^2} = \frac{h\nu}{mc^2}$$





The distribution of the photoelectron directions determines the degree of polarization and the position angle

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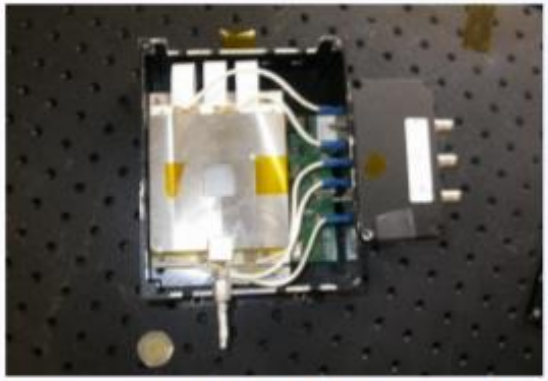
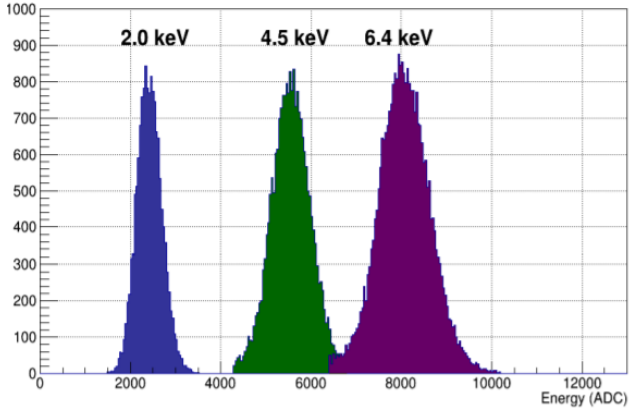
GPD (Bellazzini, Costa, colleagues @ INFN Pisa)

``Everything about Every Photon''

- **Position to ~120μ (~6” at IXPE FP)**
  - IXPE resolution limited by X-ray optics
    - HPD ~20-30”
  - FOV ~13’x13’



- **Energy Resolution – <0.5keV@ 2KeV**
  - Achieved 16% @ 6keV
  - Nominal band 2-8keV (some resp 1-10keV)

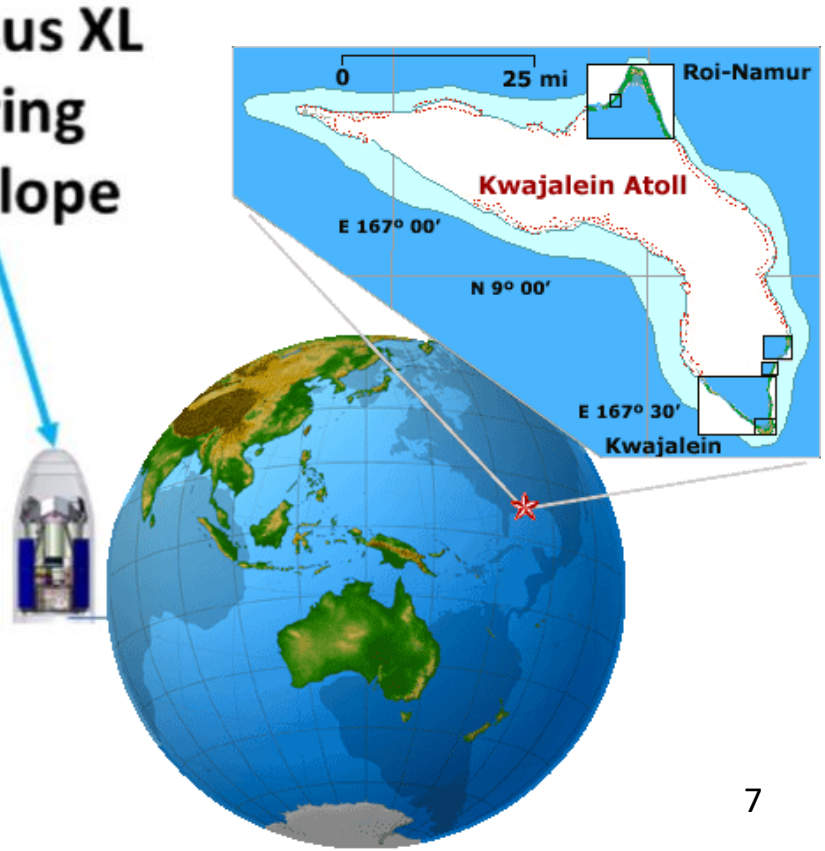


- **Timing <0.1ms**
  - Sufficient for MSP

… & EVPA

IXPE APERTURE AS A VICTIM OF POLITICS

MSFC is in Alabama: *Proposal Required an Equatorial Orbit* →
Of 2017 Launch facilities: Pegasus on L1011 out of Kwajelein (ULA (Alabama!) vehicle)
As for e.g. NuSTAR



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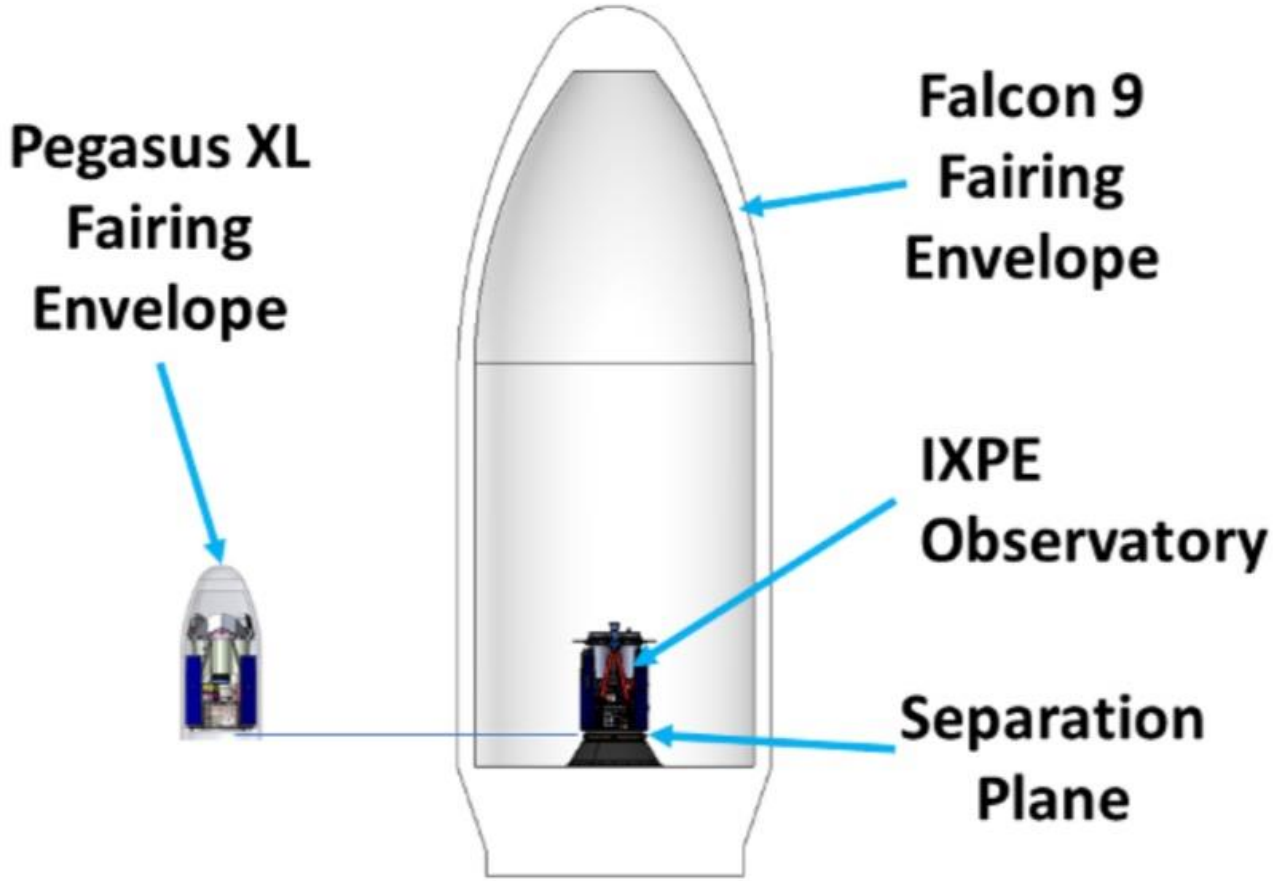
VICTIM OF POLITICS:
TINY IXPE SPACECRAFT IN F9 FAIRING



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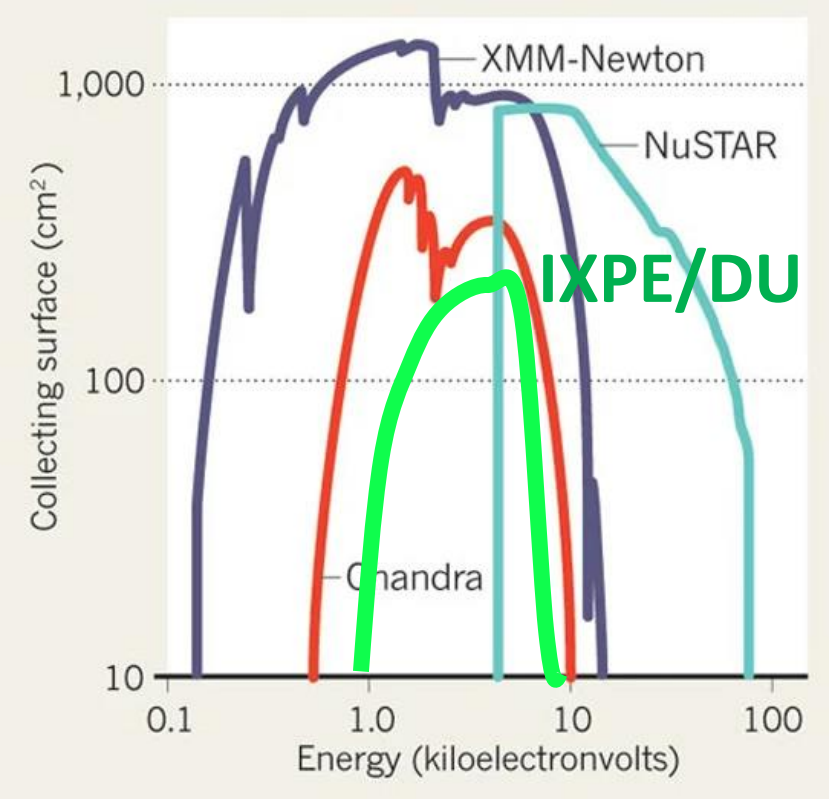
VICTIM OF POLITICS: TINY IXPE SPACECRAFT IN F9 FAIRING

- **Effective Area (3 telescopes)**
  - Total ~500cm^2
  - But need ~10^4-10^5 counts for good precision polarimetry
  - Bright sources and/or long exposures



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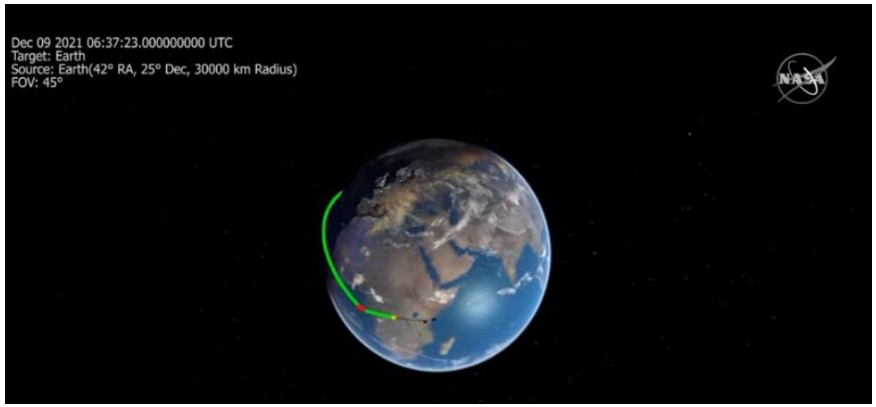
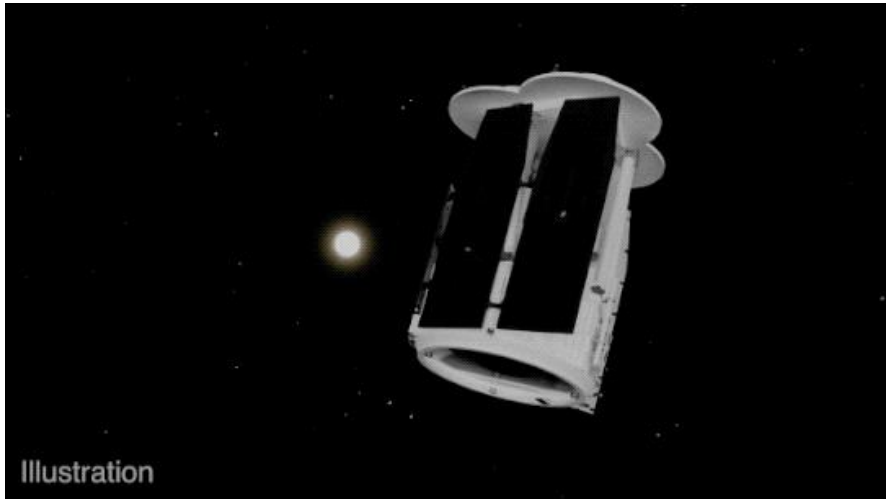
IXPE Launch Dec 9 2021





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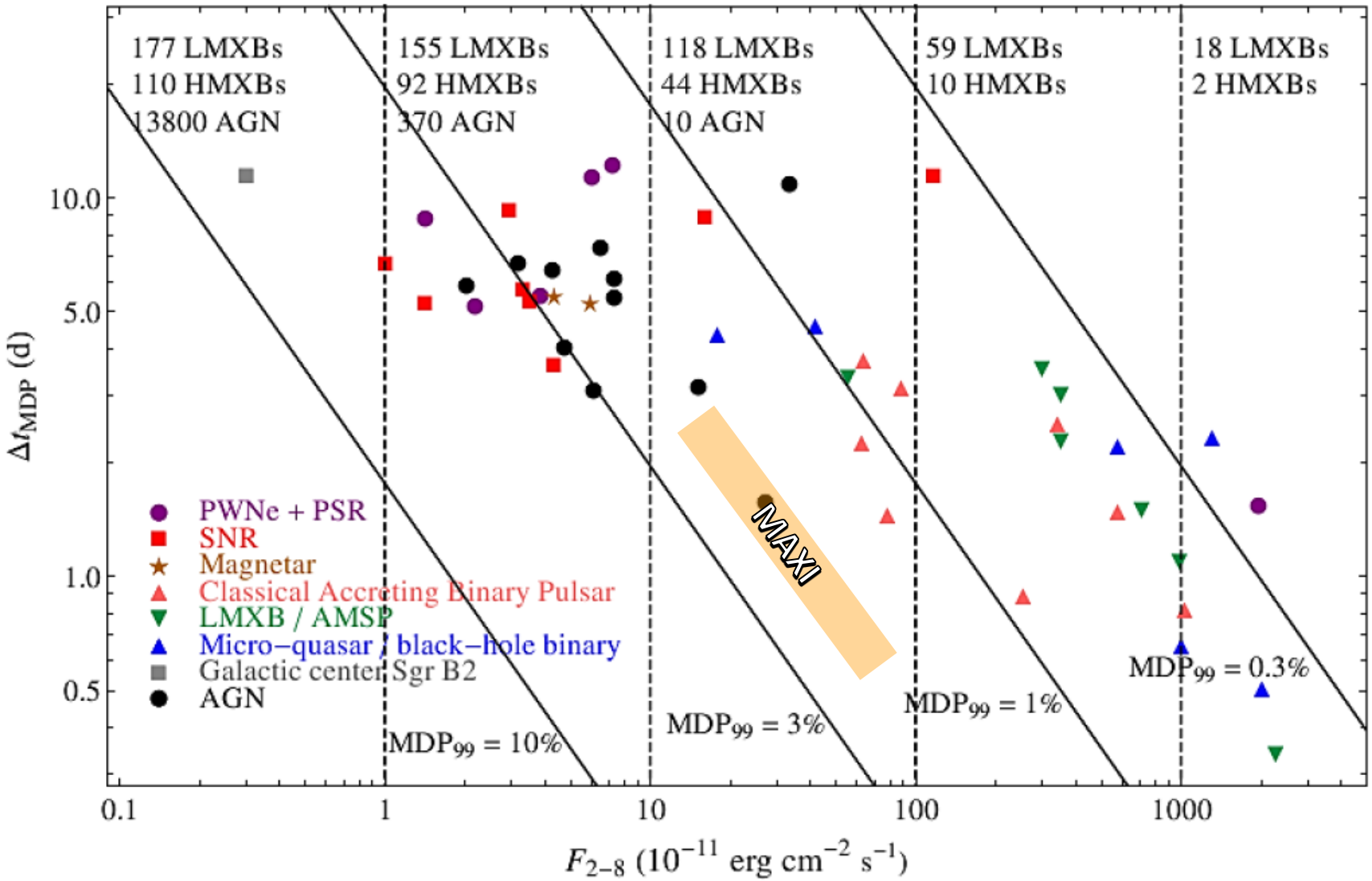
TARGETS NEED TO BE BRIGHT. TRANSIENTS WELL MATCHED TO MAXI ALERTS.



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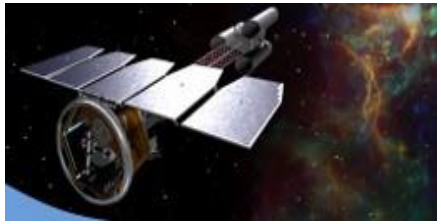
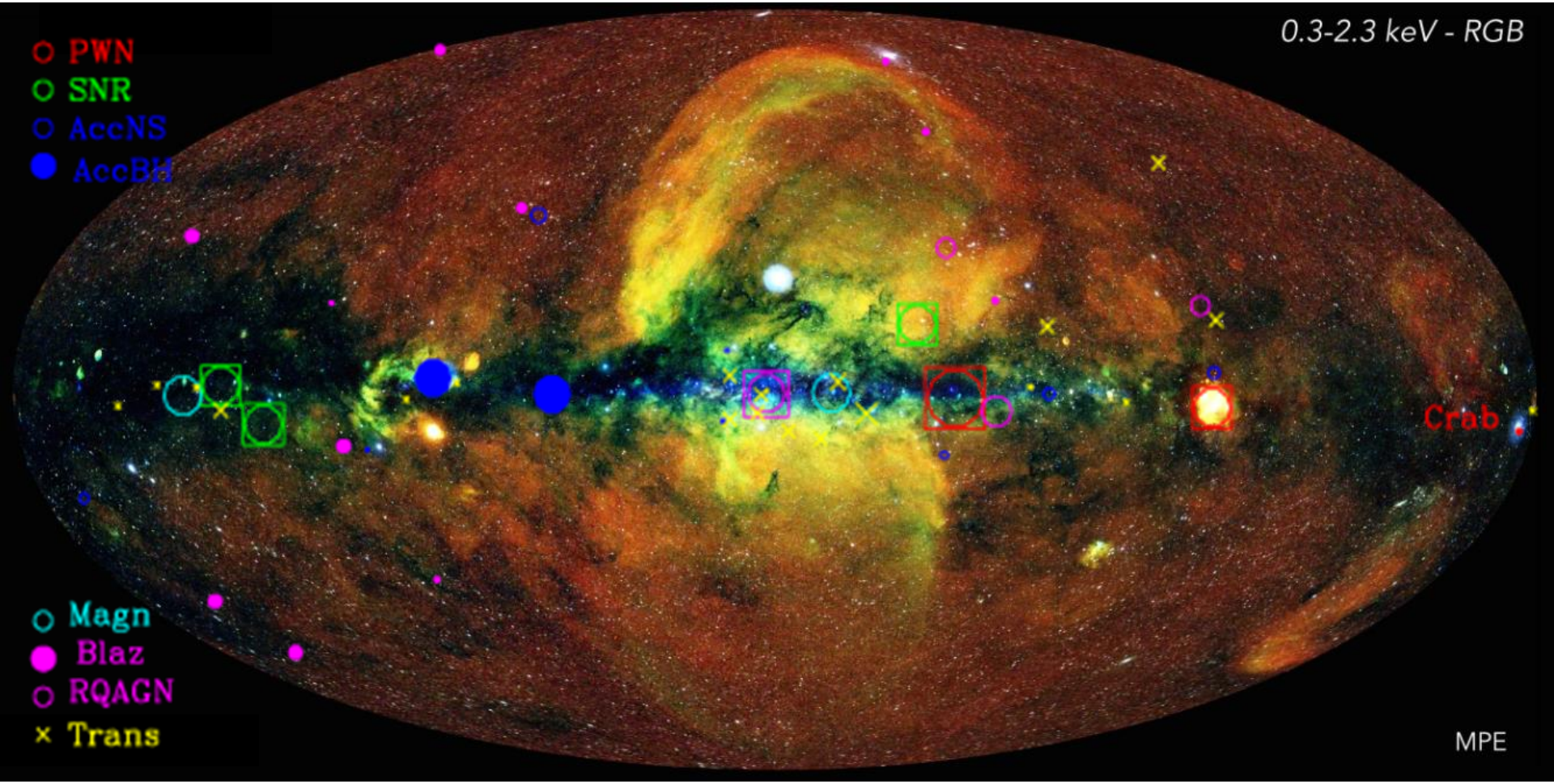
Y1 Targets

Persistent + Transient





Notes: Dot size ~t_{exp}
Dots in squares – polarization images of extended target

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HIGHLIGHTS FROM 2Y PRIME MISSION

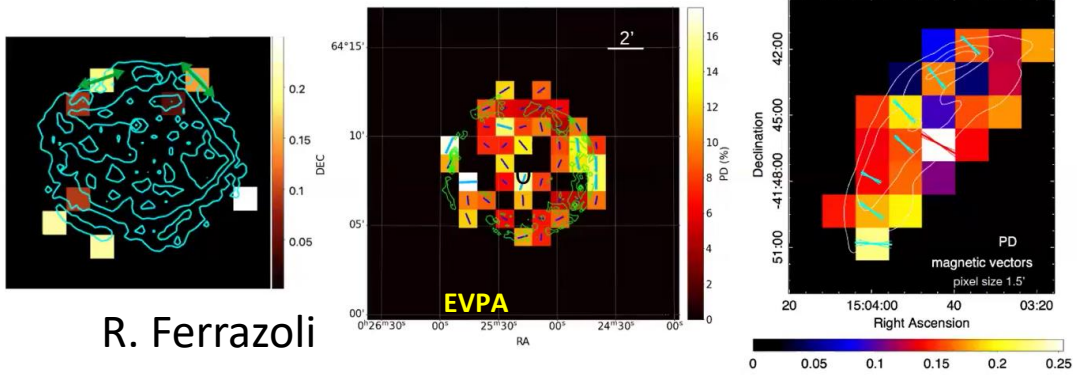
- **115 pointings**
  - 69 individual targets
  - 65+ 'Discovery' papers by our team (+~10 others)
  - 1st detection of X-ray polarization from Blazars, PWN, Pulsars, X-ray binaries, Magnetars, Supernova Remnants, Black hole binaries,…
  - Low polarization where High was expected (e.g. accreting pulsars)
  - Very high (physics-limited) polarization in other sources (pulsar wind nebulae)

+ First X-ray polarization images

The Power of Imaging: Resolved sources

- **Faint ~10^{-11} erg/cm^2/s steady sources, long exposures.**
- **Supernova Remnants**
  - Map fields across remnant, probe diffusive shock acceleration
- **Pulsar Wind Nebula**
  - Coherent structure of fields in relativistic shocks.
- **Complex areas**
  - e.g. Galactic Center Molecular Clouds, SS433 lobes
- **All Sources have a reduced, characterized background**

SUPERNOVA REMNANTS: RESOLVED, RADIAL



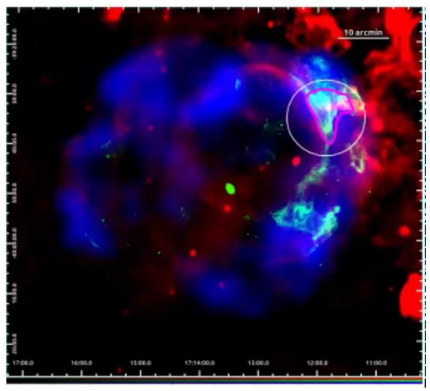
R. Ferrazoli

We found all three remnants **radial magnetic fields.**

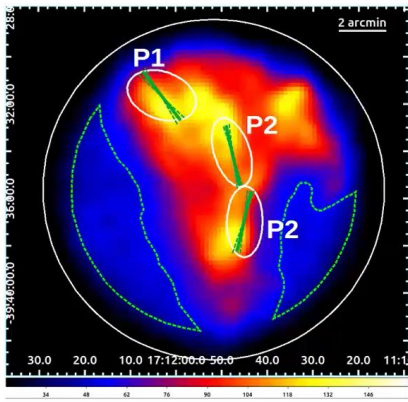
- In Cas A the **PD** was also very low **~5%**, pointing to very high turbulence.
- In Tycho PD somewhat higher **~12%** at the rim.
- Highest PD detected in SN 1006 **~22%.**

Possible dependence of turbulence level with ambient density and/or other environmental factors?

- **Radial in young SNR – low PD (High turbulence)**
- **But(!) concentrated, tangential in RXJ 1713 PD_{max} ~40% (older at ~1600y)** ➔
- **We are starting to probe, turbulence, field generation, dependence on upstream ISM**
- **Other targets (RCW 86, Vela Jr)**



RGB image:
- Radio: 20 cm ATCA,
- X-rays: 0.5 – 7 keV Chandra,
- ɣ-rays:>2 TeV HESS



IXPE 2 – 5 keV image
- Magenta: IXPE contour
- White: IXPE f.o.v.

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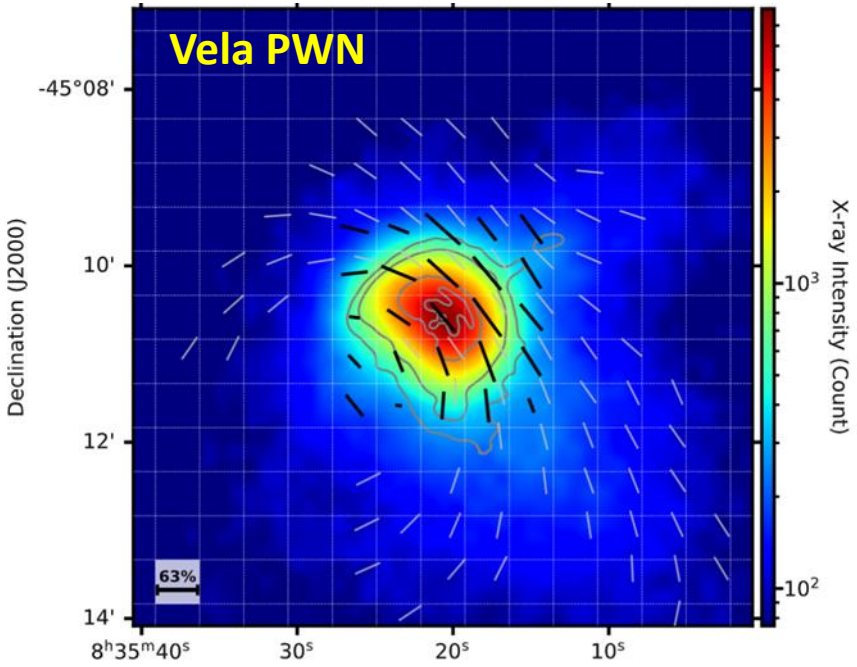
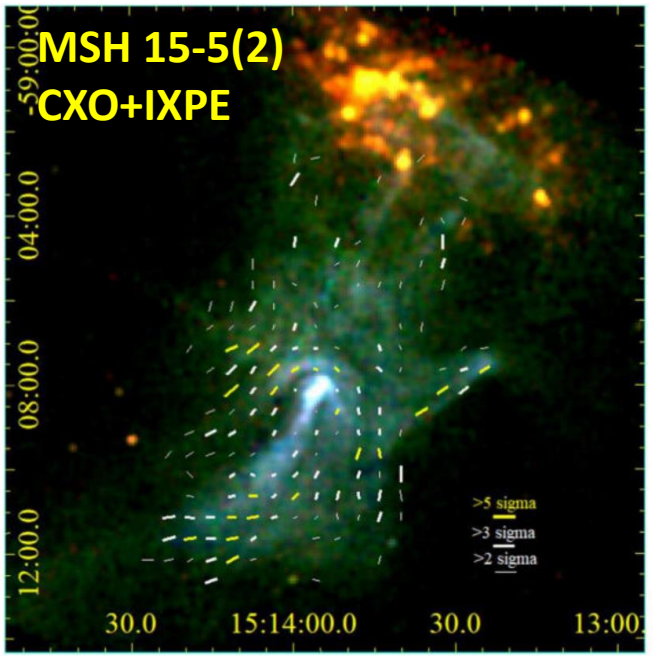
PWNe: Ordered, Polarized

- **PWN Polarization has strong toroidal structure**
- **Reaches the synchrotron limit**
  - Implies low turbulence. Acceleration via **reconnection**?
- **Can separate jet-like structures**
- **Pulsed X-ray polarization detected in 3 PSR. Differs from low E, but more S/N needed to interpret**





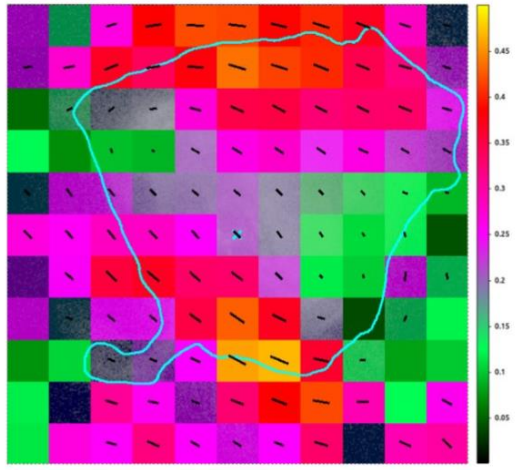
GS Josephine Wong

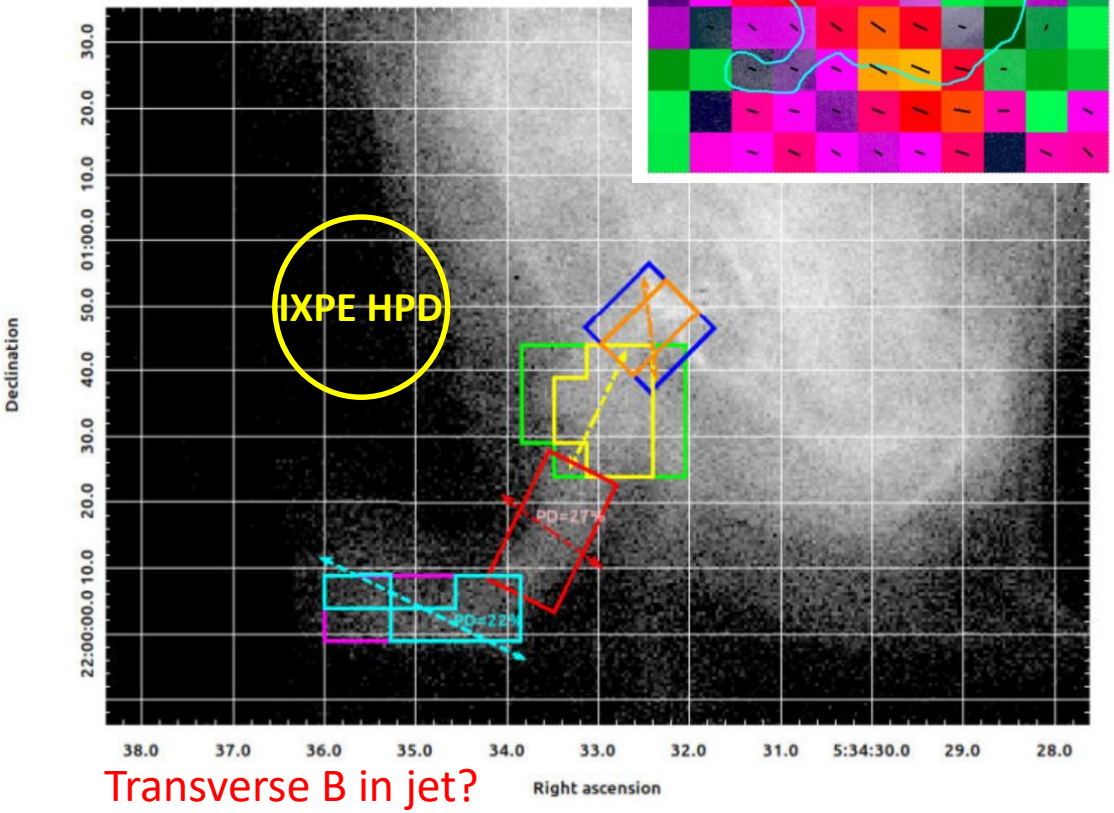
IXPE Crab Results – (barely) resolved nebula and pulsar

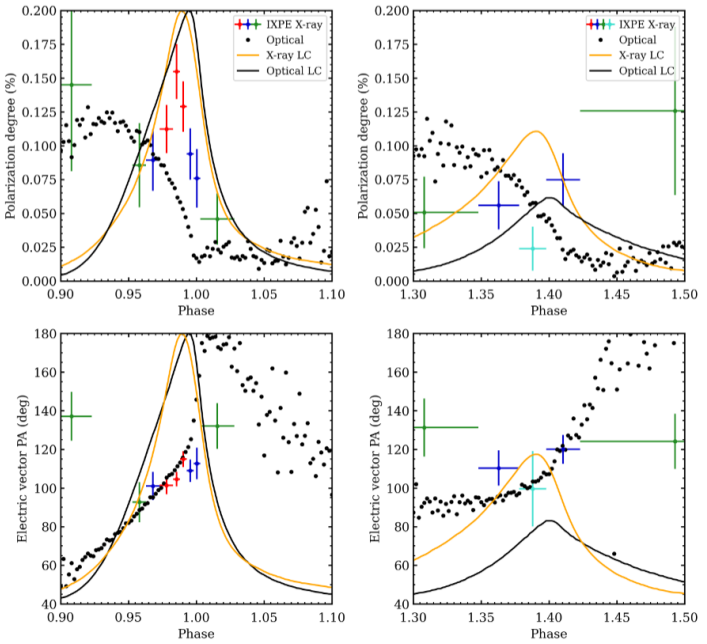
Polarization Degree Map

Toroidal field dominates nebula

300ks of IXPE data





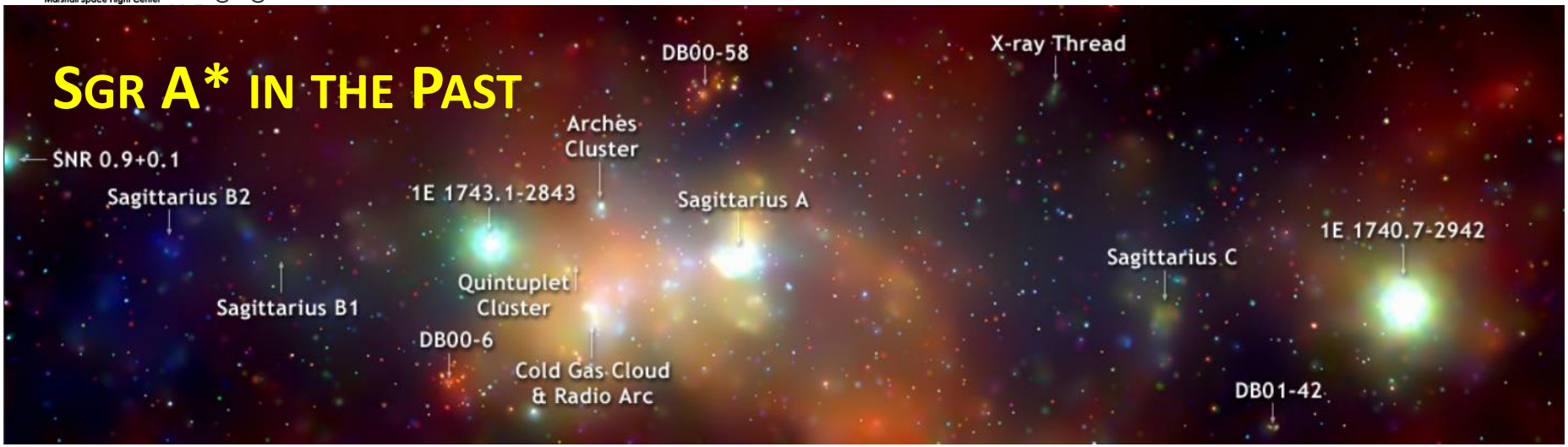


Pulsar X-ray polarization sweep quite different to optical – we will get to push this to ~1.2Ms in AO2

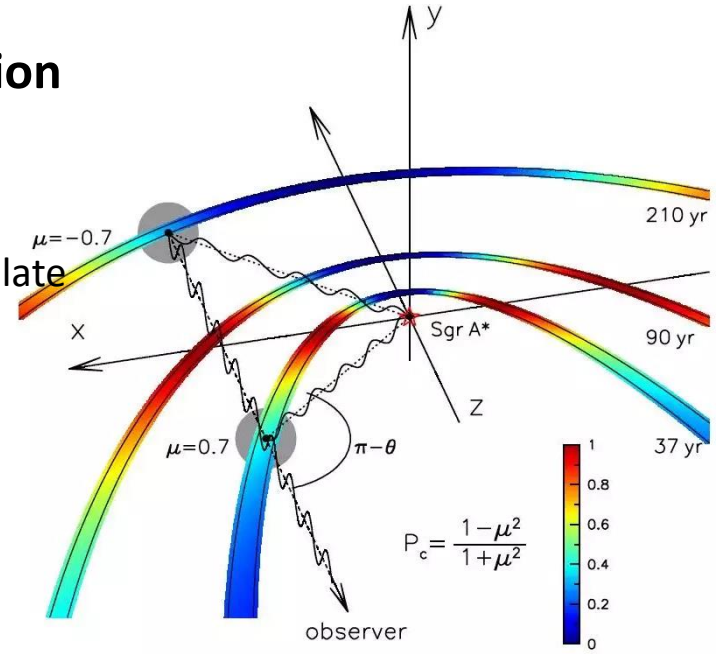
Transverse B in jet?

Imaging for Complex structure

IXPE Imaging



- **Sgr A* accretes at ~$10^{-9} L_{Edd}$ today**
- **Galactic Center molecular clouds (MC) show reflection X-rays, no present source bright enough**
  - If from Sgr A* (in past)
    - *highly polarized* perpendicular to plane of reflection; triangulate to implicate Sgr A*
  - This is a challenging observation –
    - Sgr B (planned target) faded before launch
    - Sgr A 1st Ms gave 3σ detection, 2nd Ms is being analyzed
  - **Polarized flux points back to Sgr A* -- indicates ~10^{-4} L_{Edd} ~200y ago.**



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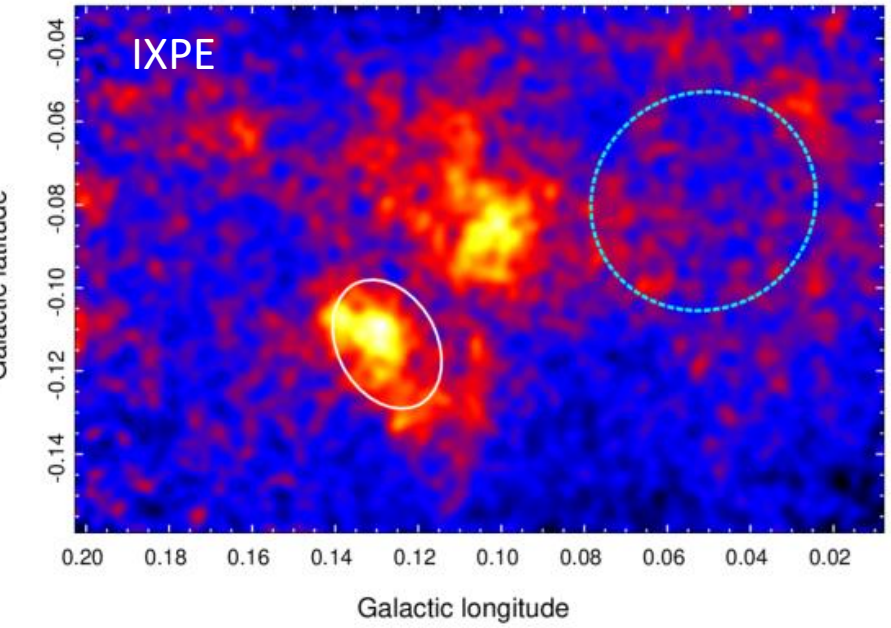
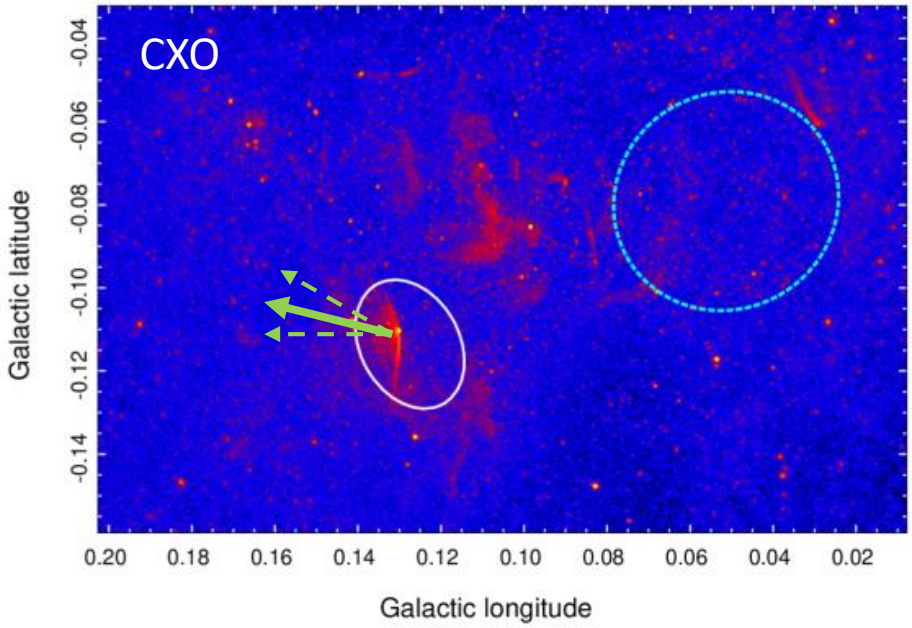
IMAGING FOR SERENDIPITY

- **Galactic Center**
  - Strange radio emitting filaments lie in IXPE FoV
    - one with X-rays
    - shows high polarization – likely PWN-powered – Churuzov et al A&A
- **Also SS433 lobes, etc.**



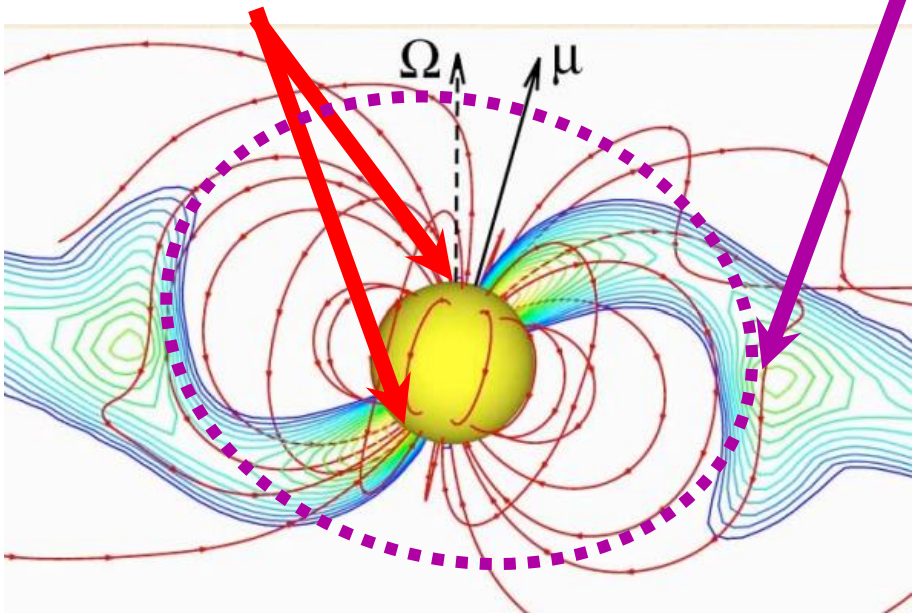


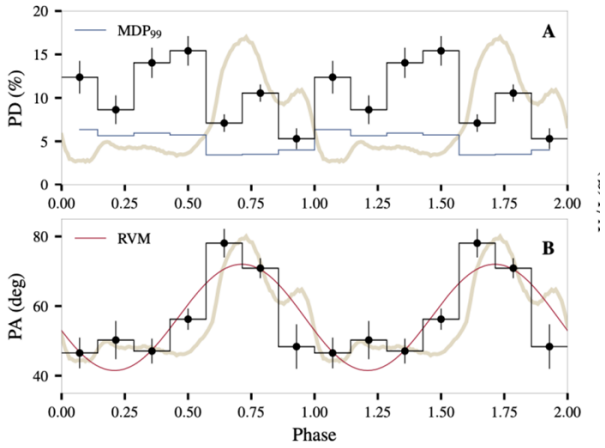
Accretion-powered Sources: Testing the Physics

- NS binaries: Principal Results
- Low 5-15% PD – complex phase structure, highest when one pole dominates
- PA has smooth RV-like swing
- Conclusions:
  - Surface temperature inversion, component mixing
  - EVPA set at polarization limiting radius

PD set here
(Complex Surface B)

PA set here
(B Dipolar)



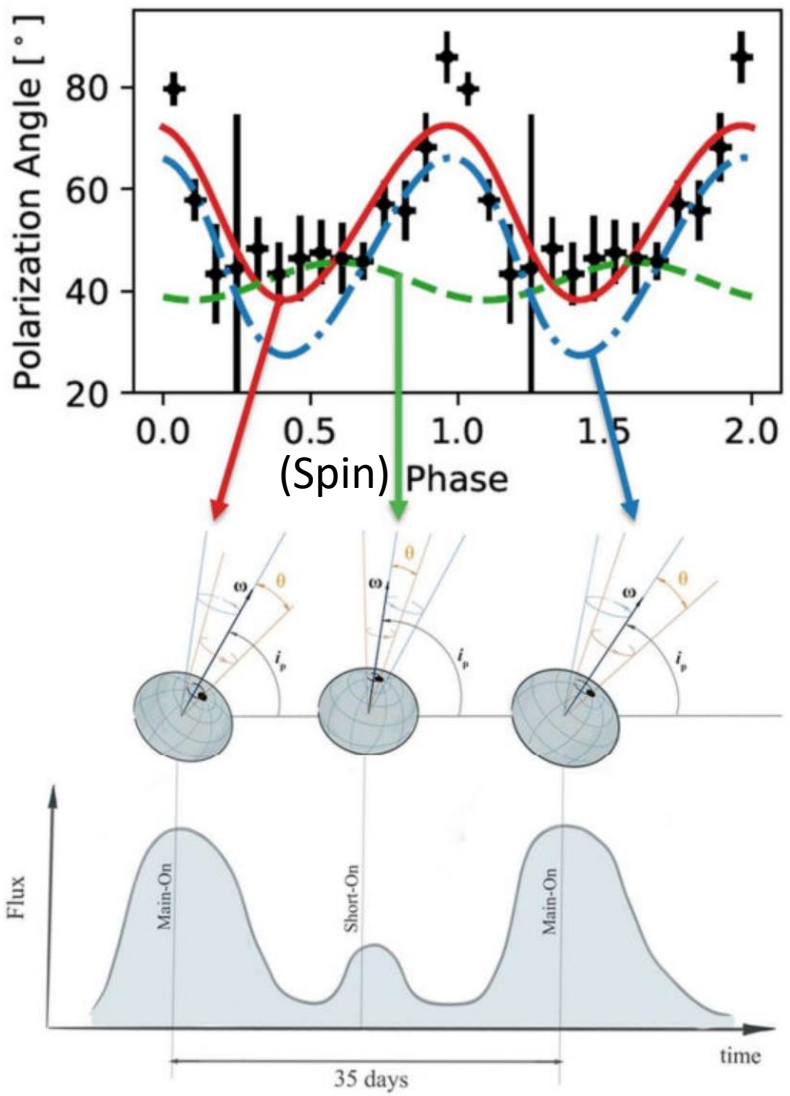


← Her X-1

For ~10 examples, RVM-like swing allows us to measure spin and magnetic axis orientations. More targets to be studied in future AOs

ACCRETION-POWERED SOURCES: TESTING THE PHYSICS

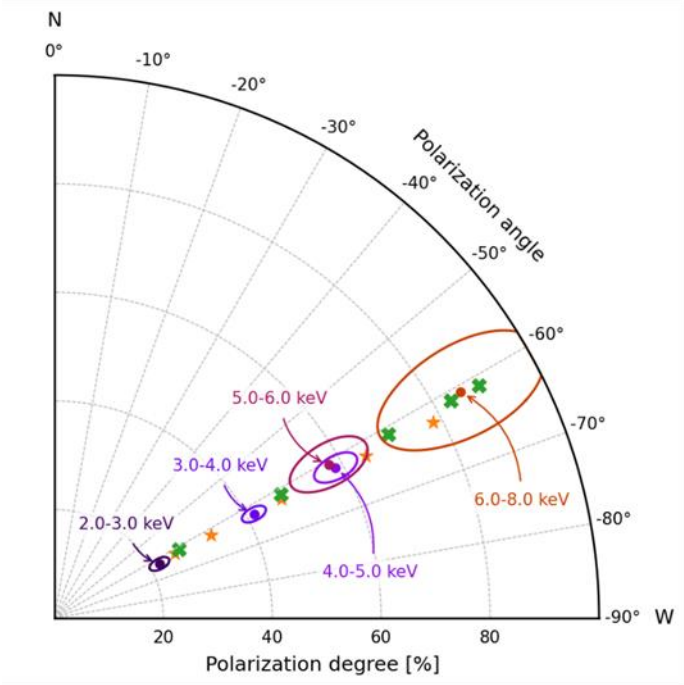
- **Her X-1 – monitor the RVM-type 1.2ms spin period polarization PA over 35d period to measure neutron star precession**
- **Precession appears to be nearly force free, requiring I asymmetry of a few ppm.**
- **Her X-1 (or faster spinners) may be LISA/MAGIS GW targets**



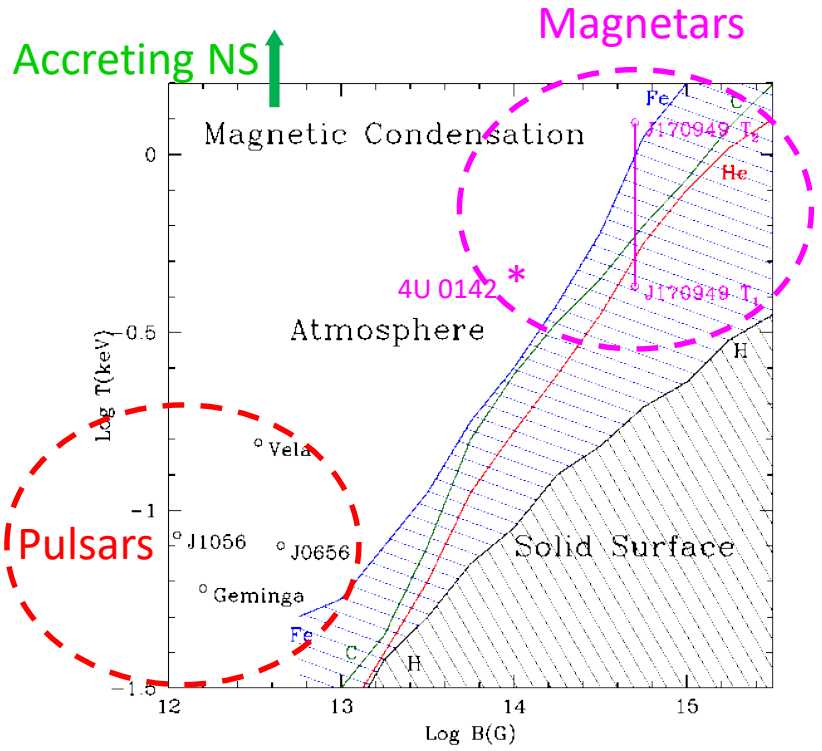
Heyl et al. (2024)

MAGNETARS: TESTING THE PHYSICS

- **Thermal + Magnetosphere results – similar to XRB**
  - Complex thermal surface pulse (in PD), simple magnetospheric dipole (in EVPA)
- **To me the most exciting aspect is possible evidence for a condensed matter surface in 1RXS J170849.0-400910 whose dipole B is ~5x10^{14} G !**



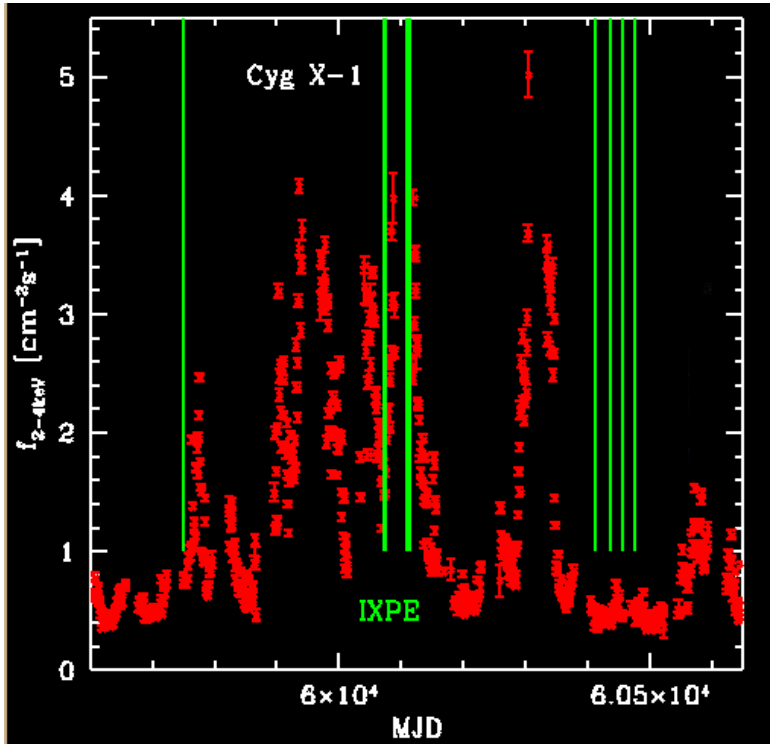
Two Thermal Component Model:
~0.4keV belt, ~1.1keV cap

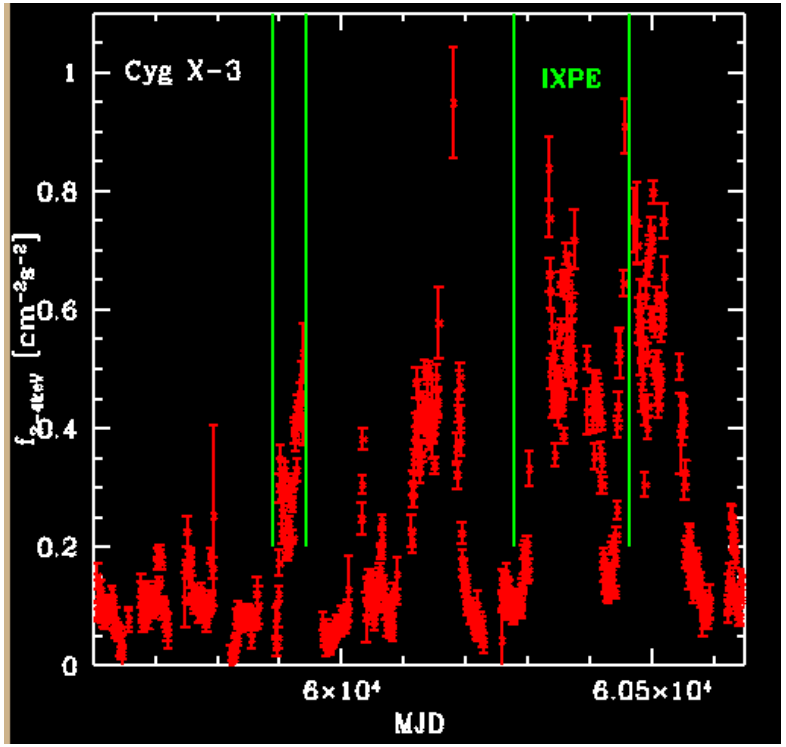


after Turolla 2009

Variable Sources: Binary, Magnetar outBursts, AGN ToOs

- Recall MAXI sensitivity well-matched to useful IXPE triggers.
- IXPE campaigns on a couple of BH Binaries





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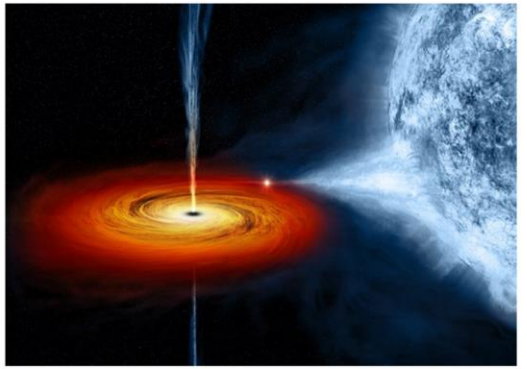
Accretion-powered Sources: Probing the Geometry

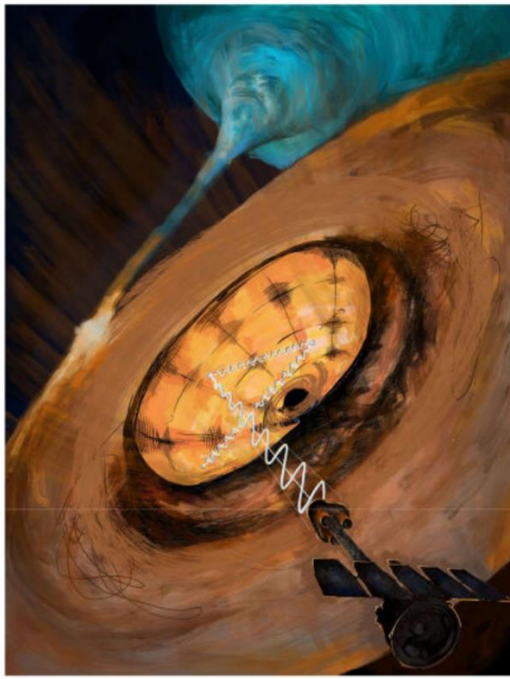


Cyg X-1

- **Black Hole Binaries**
  - -- perhaps the prime result: coronal polarization favors a slab geometry
  - -- some tension with reverberation studies

- **Headliner is Cyg X-1**
  - -- PD ~4% in hard state, increasing with E (increasing coronal domination)
  - -- EVPA normal to the inner disk (parallel to compact jet) → **flat corona**
  - -- IXPE obs. probing the soft state (disk self-reflection dominates?)
  - -- PD still ~2% in soft state.
  - -- these high(!) polarizations are difficult to square with binary i~27^{o} , thus inner disk may be misaligned

Cyg X-3



Other BH Binaries – persistent, transients

- -- Cyg X-3 super-Eddington accretor: 20% PD is evidence for scattering off thick torus (thus, an obscured ULX)
- -- high inclination disk polarization can explain several sources
- -- other sources show evidence for strong winds

BLAZARS: CONSOLIDATING THE MODELS

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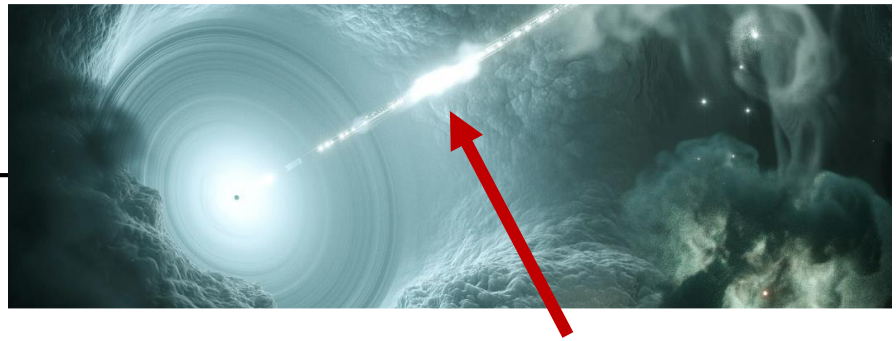
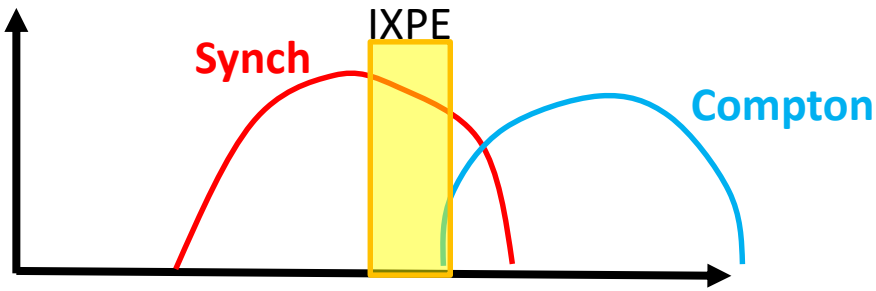
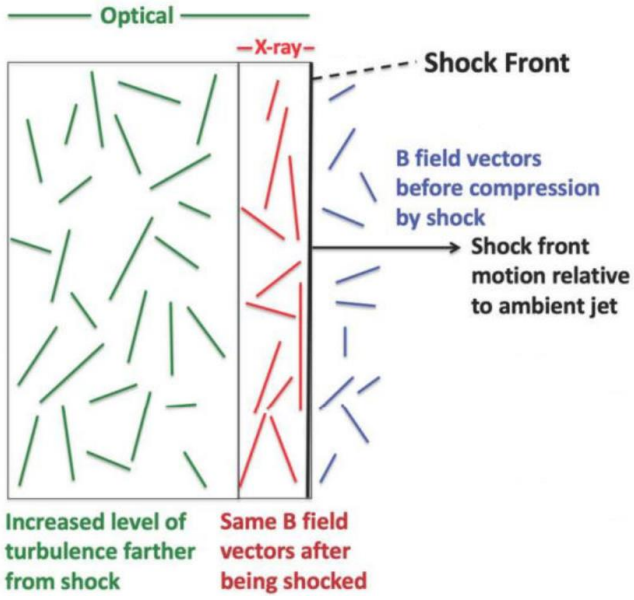


Beamed Emission from Shock

- **Basic Results Mrk 501 Nature paper:**
  - **Stratified shock acceleration**
  - **HBL X-ray synchrotron polarization > optical – radio**
    - **Magnetic field aligned with jet PA**
    - **PD << Single-zone Synch max PD ~ 70% (multiple zones)**
  - **LBL Compton component: no detected polarization**
    - **Expect very low PD for External Compton**
    - **Expect PD < 0.3 of optical polarization for Synch Self-Compton**

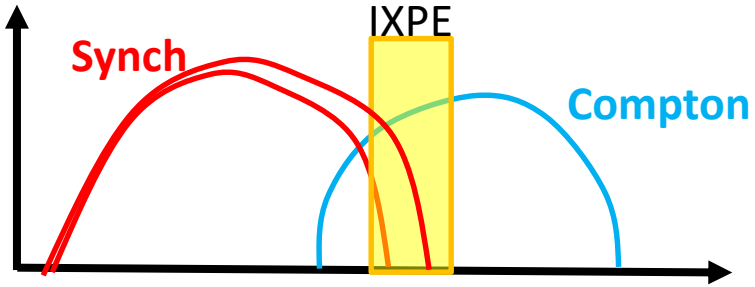




BLAZARS: OTHER INTERESTING PHENOMENA

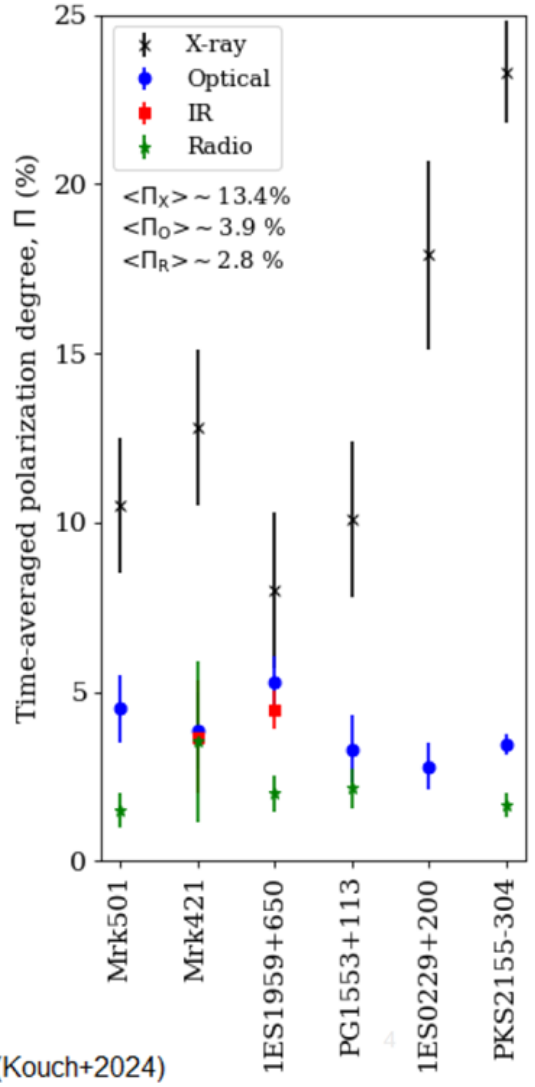
IXPE
Imaging
X-Ray
Polarimetry
Explorer

- BL Lac (IBL) high polarization at lowest IXPE energy as synchrotron pokes into the IXPE band during flares



- PKS 2155-304 PD reaches ~25%. Few ~10 emission zones

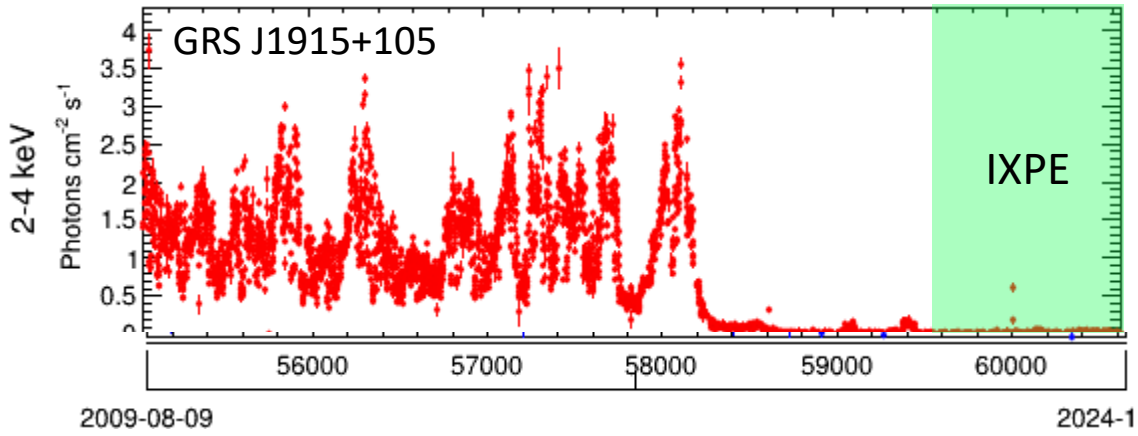
- Much interest for coordinated observations from the multi-ν (esp. radio, mm, optical, TeV) community – X-ray polarization exceeds the radio-optical PD

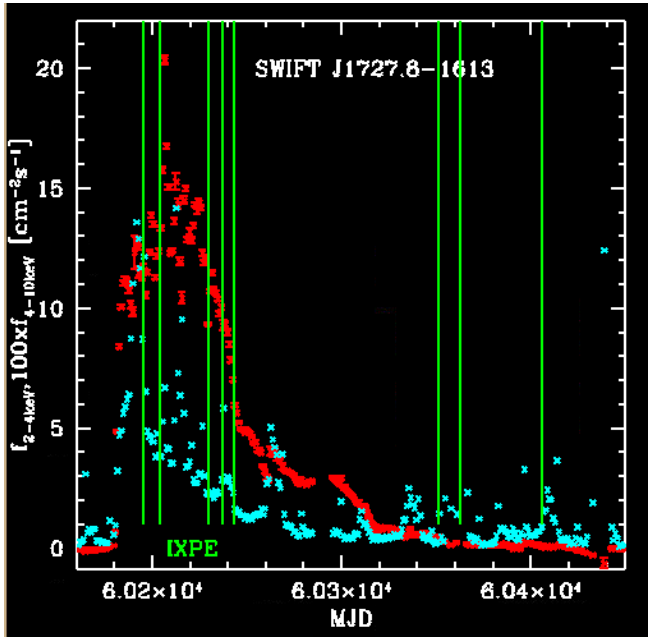


(Kouch+2024)

IXPE AND MAXI-MONITORED TRANSIENTS

- **We receive a good number of Transient Proposals**
  - E.g. Cycle 1: GRS 1915+105, 1ES 1959+650, SAX J1809.4-3658, GX 339-4, IGR J1709.1-3624, 4U 1957+115, SWIFT J1727.8-1613
- **Some, Great success**
  - Eg SWIFT J1727.8
- **Others, still waiting**
  - Eg. GRS 1915+105 …

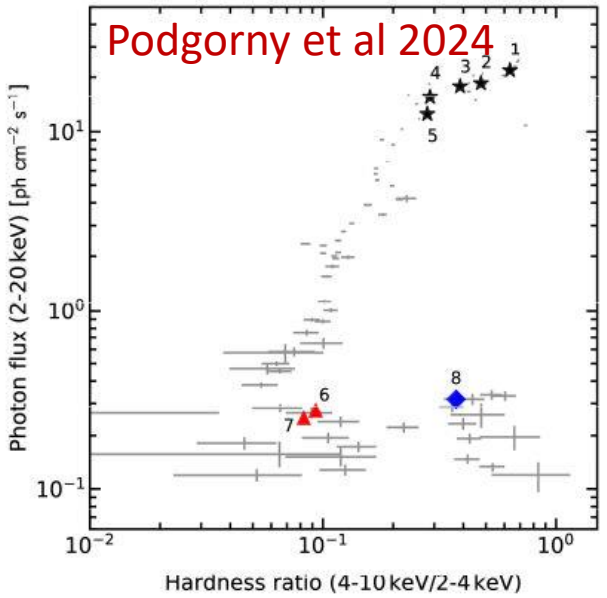


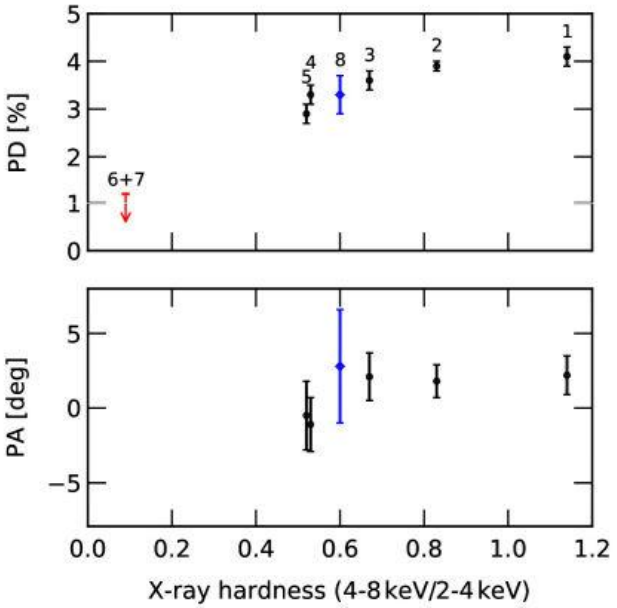


- **16 ToO targets in AO2!**

SWIFT J1727.8-1613 IXPE RESULTS

- **Confirmation of Cyg X-1 pattern**
  - EVPA parallel to radio jet → Corona extended along disk
    - Note NGC 4151 similar EVPA orientation
  - PD relatively high
- **Caught in several flux/hardness states**
  - Last observation recovery into low hard state
  - PD correlates with hardness
  - Hard state EVPA quite stable – extension along disk persists over ~100x in flux
  - Soft state PD low





Rel. to jet axis →

IXPE AND MAXI-MONITORED AGN (MANY FAINT, BUT CONTEXT LIGHT CURVES FOR HBL)

Example: 5 main Mrk 421 IXPE epochs

1 High 15% PD ~ aligned with jet

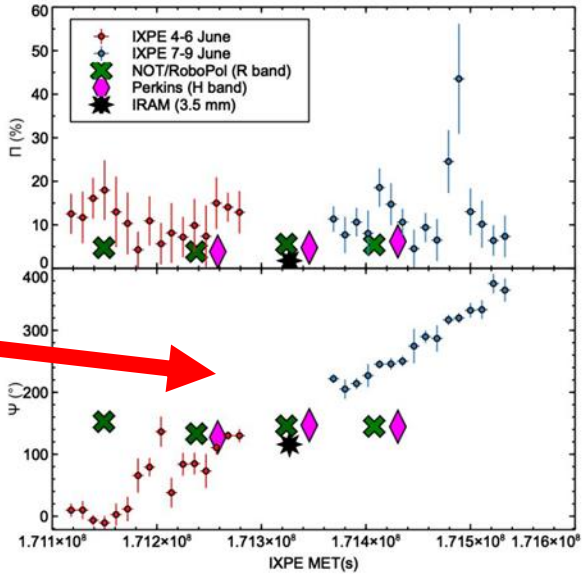
2 dramatic EVPA rotation

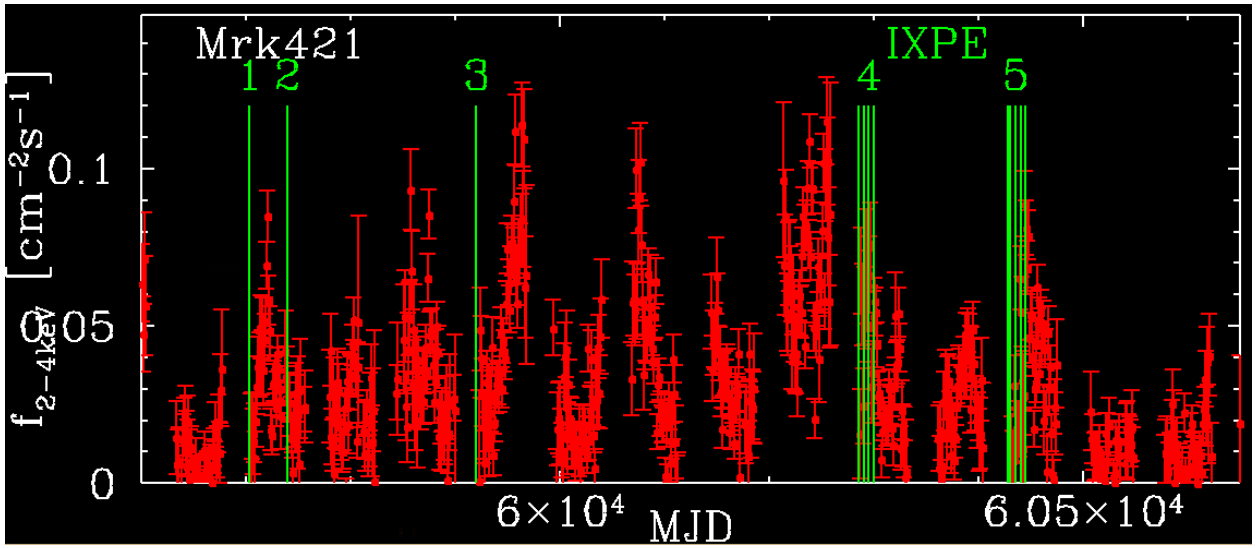
3 EVPA Stable again

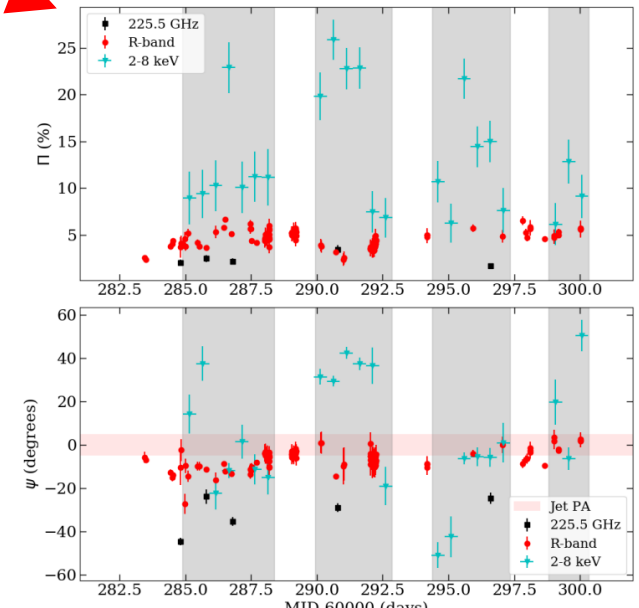
4 15d multi-ν campaign – Big PD flares

5 15d campaign, not yet published

… Next Ao2 ToO campaign







IXPE Imaging X-Ray Polarimetry Explorer

IXPE Early Mission Conclusions

- **Basic job a success: opened field of imaging soft X-ray polarimetry**
  - Several Nature/Science-worthy early discoveries
  - First X-ray polarization images, complex nebular structure
  - Some predicted signals (e.g. BH Kerr PA rotation) not yet seen
  - Some signals stronger than anticipated (esp. non-thermal wind shocks)
  - Complex behavior (esp. NS XRB, SNR) requires follow-up
  - Need to measure in many flux states – MAXI and SWIFT monitoring to trigger
  - ToOs need to be high flux for good sensitivity in few d exposure – well above MAXI threshold
  - Kudos to team for responding to so many transients – tough to schedule!

IXPE Imaging X-Ray Polarimetry Explorer

IXPE Future Prospects

- **W/o expendables continued observations seem promising**
  - GO1 (6.9x oversubscribed), GO2 (more proposals)
  - Transients, XRB in various states. Triggered by MAXI and monitoring
  - Deep integrations, especially on non-thermal sources: PWNe, SNR filaments, etc. – often Ms+ exposures!
  - Improved analysis techniques may eke out some more discoveries

- **Next X-ray Polarization Mission – IXPE highlights the needs**
  - CXO-like resolution, XMM-like effective area
    - Fine structure in PWNe, SNR lost. Some sources vary too fast for 100+ks exp
  - broader energy range (more counts at <1keV), critical spectral features (e.g. cyclotron resonances at >10keV)