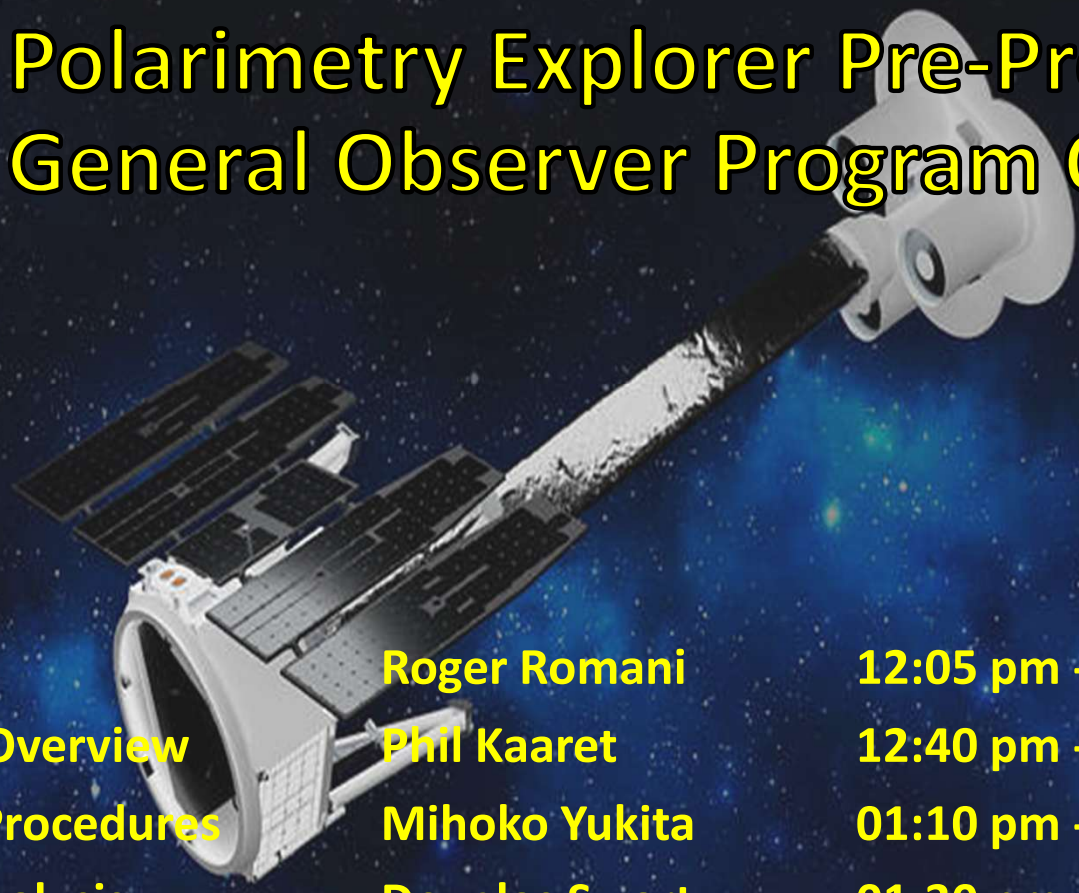
Imaging X-ray Polarimetry Explorer Pre-Proposal Workshop for General Observer Program Cycle 3



IXPE Science Highlights	Roger Romani	12:05 pm - 12:35 pm
IXPE Mission and Cycle 3 Overview	Phil Kaaret	12:40 pm - 01:10 pm
GO Proposal Submission Procedures	Mihoko Yukita	01:10 pm - 01:30 pm
Tools for Proposals and Analysis	Douglas Swartz	01:30 pm - 02:00 pm
Ixpeobssim for Proposals	Niccolo' di Lalla	02:00 pm - 02:30 pm
Questions		02:30 pm - 03:00 pm

IXPE
Imaging
X-Ray
Polarimetry
Explorer

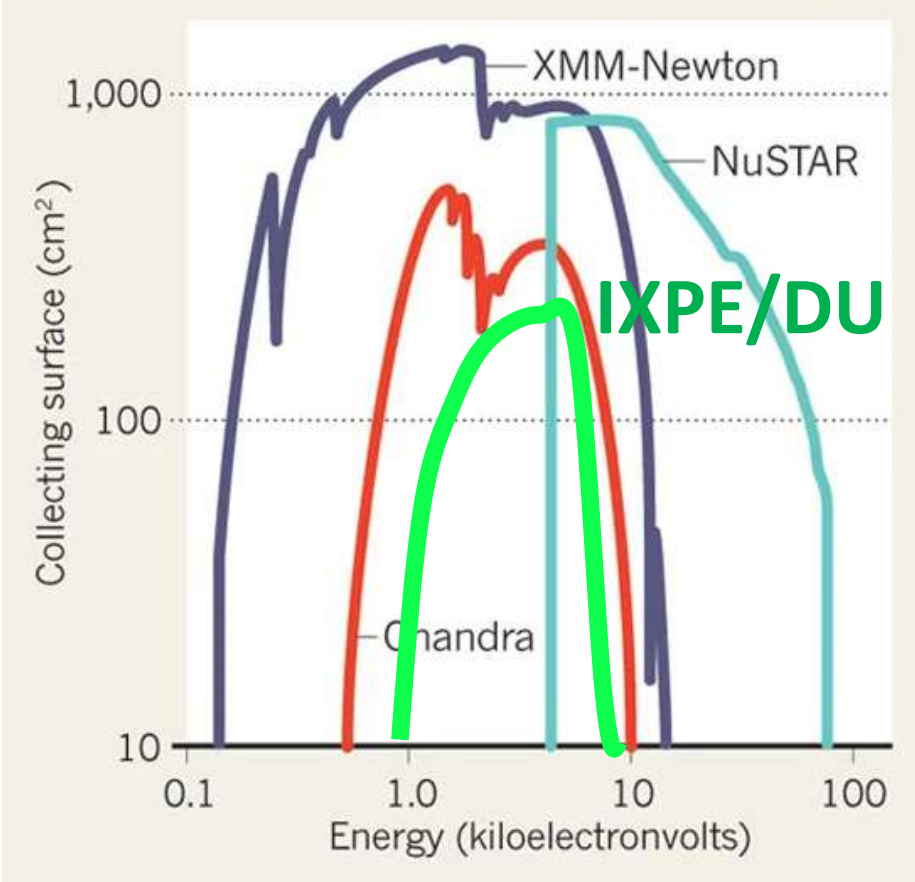
IXPE Science: Results, Trends and Future Propsects

Roger W. Romani

Stanford University

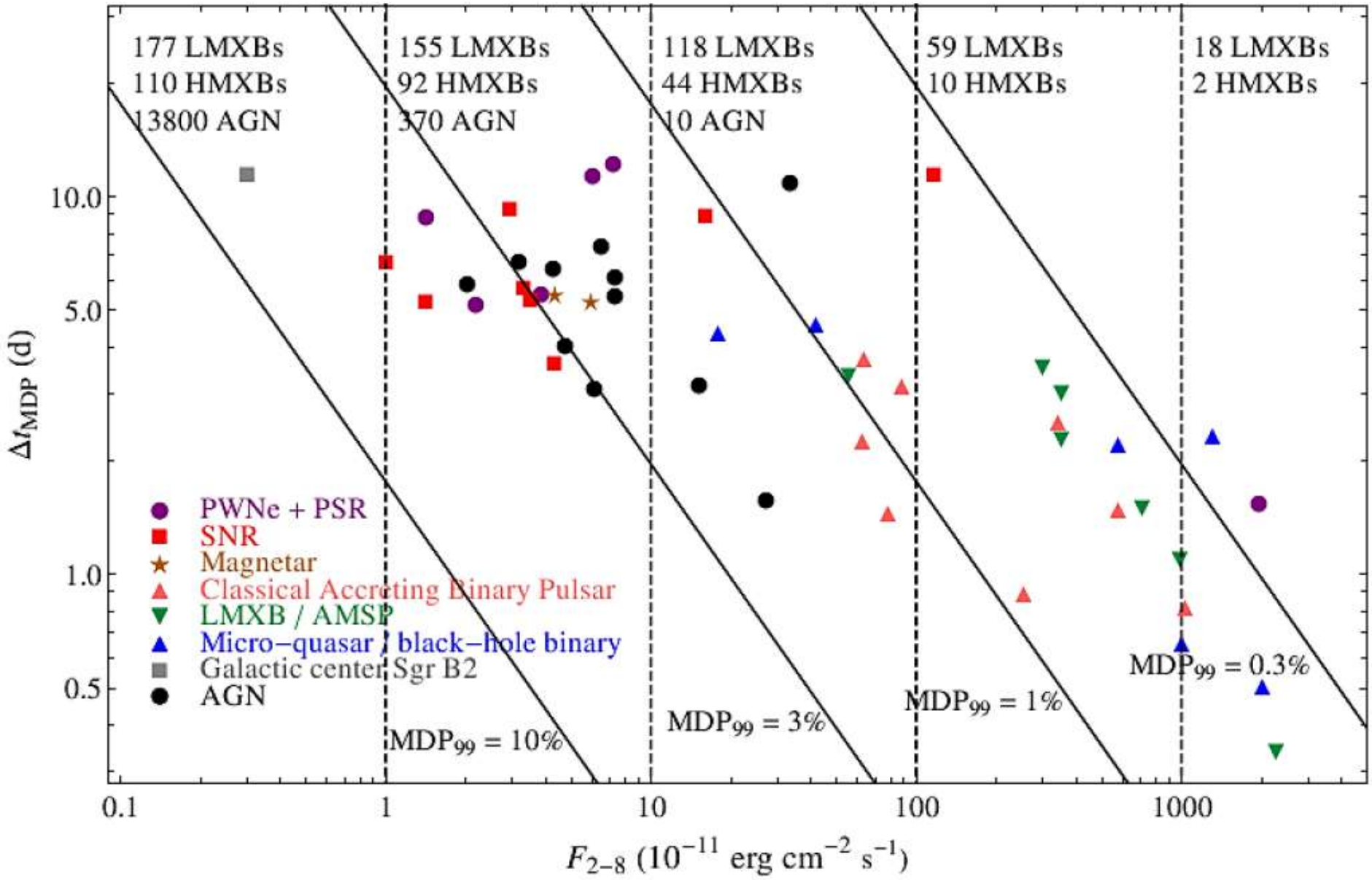
IXPE IS A SMEX: SMALL EXPLORER

- **Unique polarization capability but limited aperture**
- **Effective Area (3 telescopes)**
  - Total ~500cm^2
  - Need ~10^4-10^5 counts for good precision polarimetry
  - Bright sources and/or long exposures
- **use that aperture well!**



IXPE
Imaging X-Ray Polarimetry Explorer

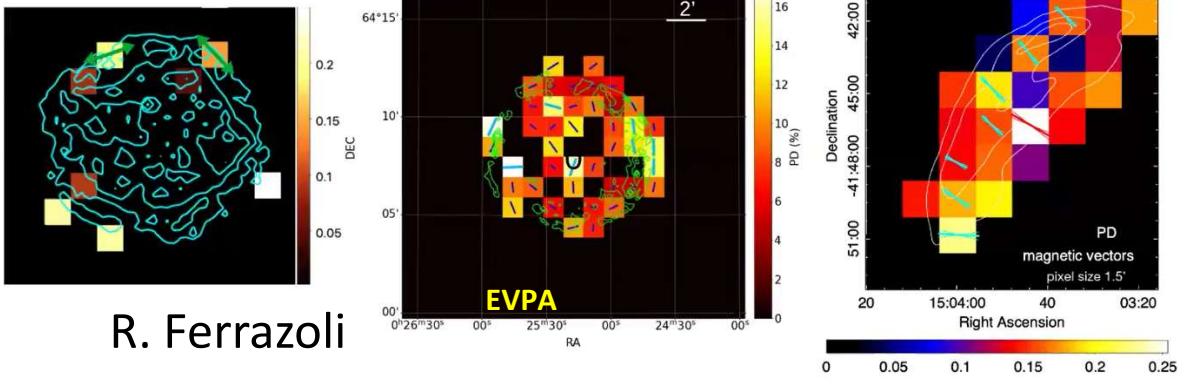
STILL, A WEALTH OF POSSIBLE TARGETS



THE POWER OF IMAGING: RESOLVED SOURCES

- **lets one study faint ~10^{-11} erg/cm^2/s steady sources, but requires 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, simultaneous background**

SUPERNOVA REMNANTS: RESOLVED, RADIAL



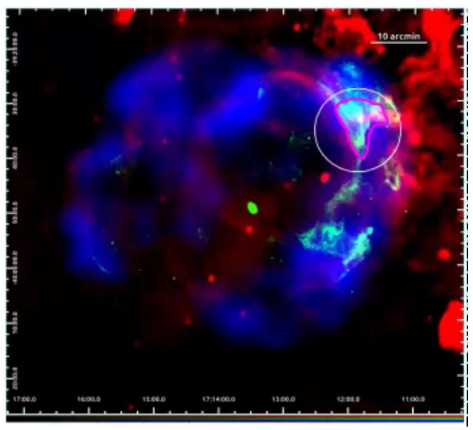
R. Ferrazoli

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

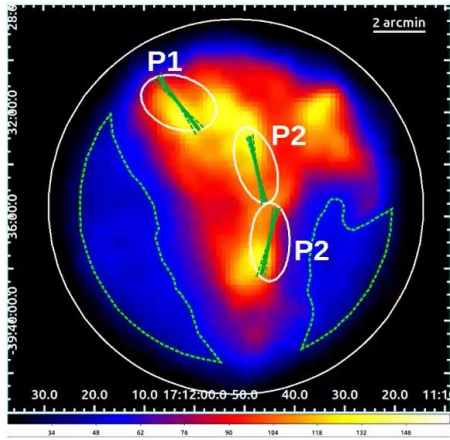
- In Cas A the **PD** was also very low ~5%, pointing to very high turbulence.
- In Tycho PD somewhat higher ~12% at the rim.
- Highest PD detected in SN 1006 ~22%.

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

- **Young SNR – Radial B, low PD (turbulence)**
- **Older SNR -- Tangential B, higher PD**
- **RXJ 1713 (~1600y), PD_{max} ~40%**
- **Vela Jr (~3000y), PD_{max} >50%**
- **We are starting to probe turbulence, field generation, dependence on upstream ISM**



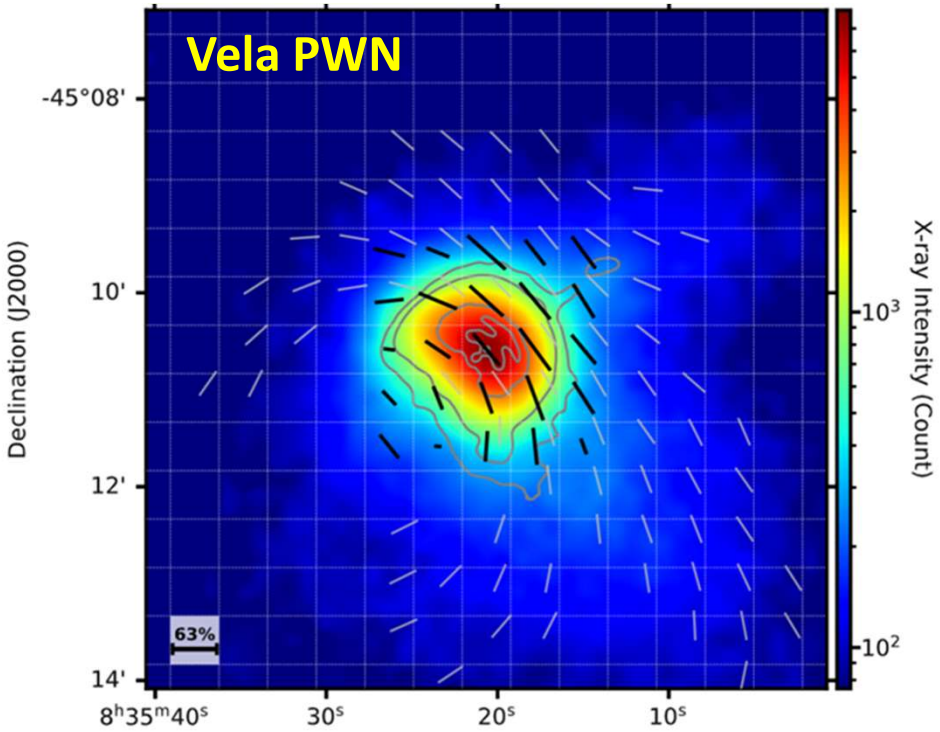
RGB image:
- Radio: 20 cm ATCA,
- X-rays: 0.5 – 7 keV Chandra,
- γ-rays:>2 TeV HESS

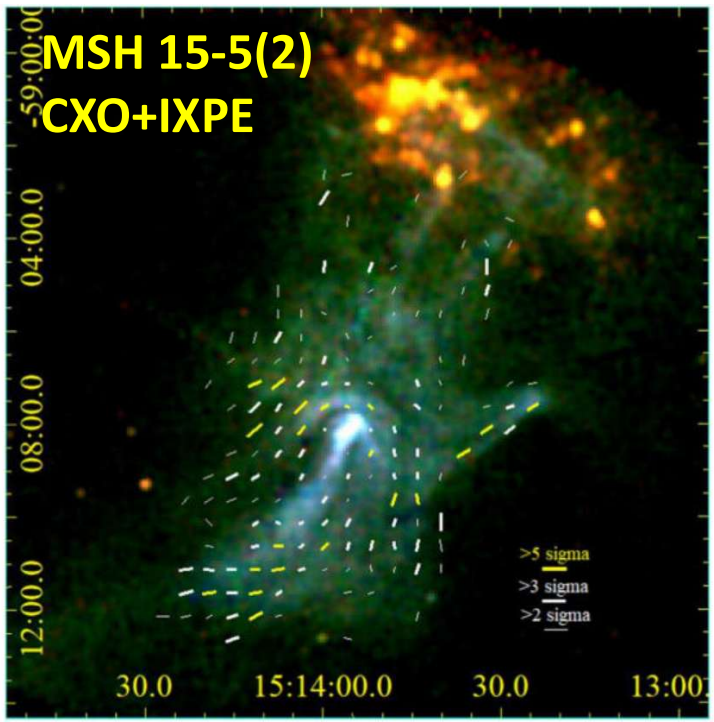


IXPE 2 – 5 keV image
- Magenta: IXPE contour
- White: IXPE f.o.v.

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**





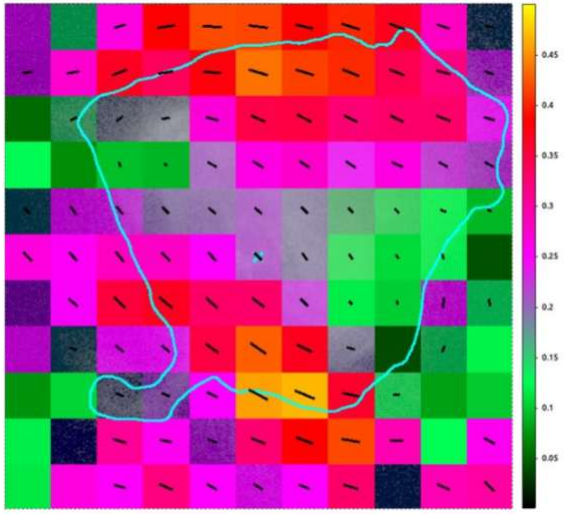
GS Josephine Wong

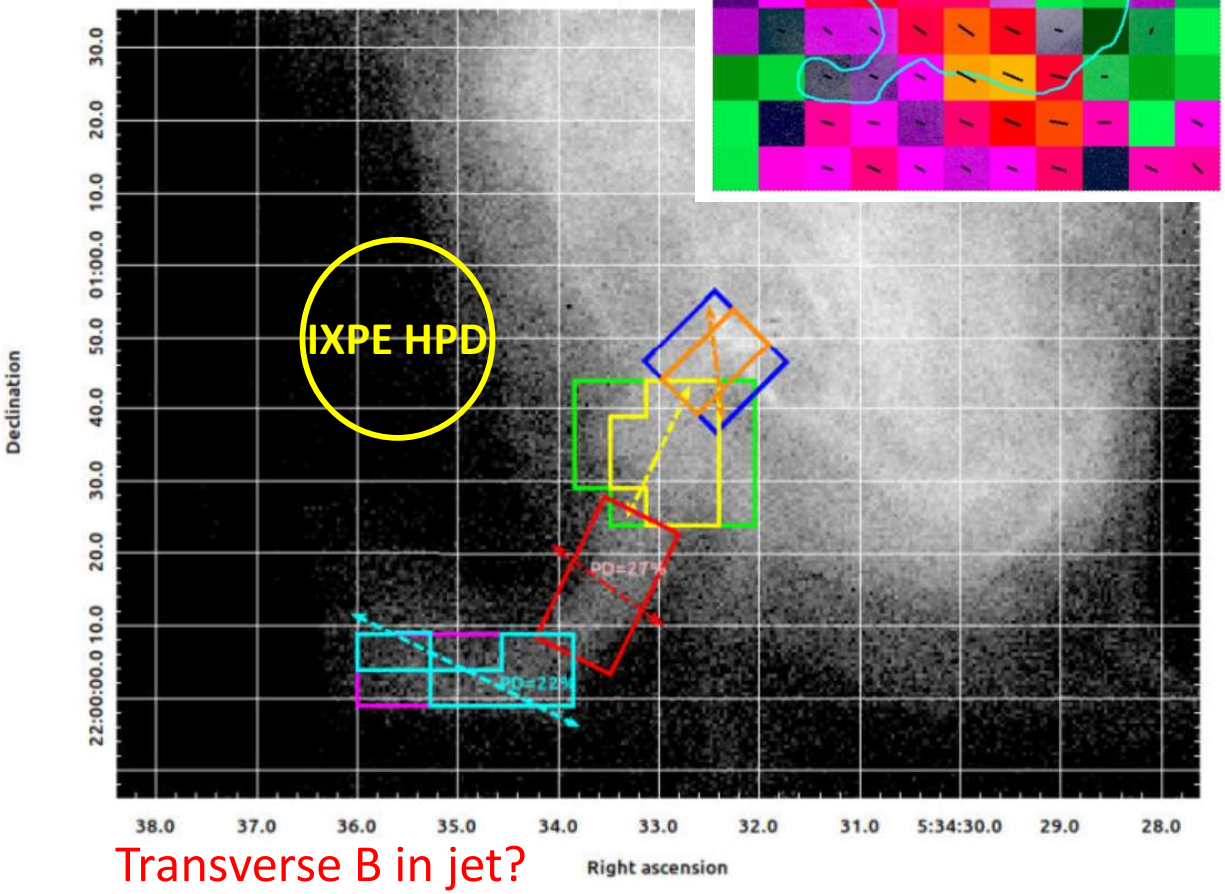
CRAB RESULTS – (BARELY) RESOLVED NEBULA AND PULSAR

Polarization Degree Map

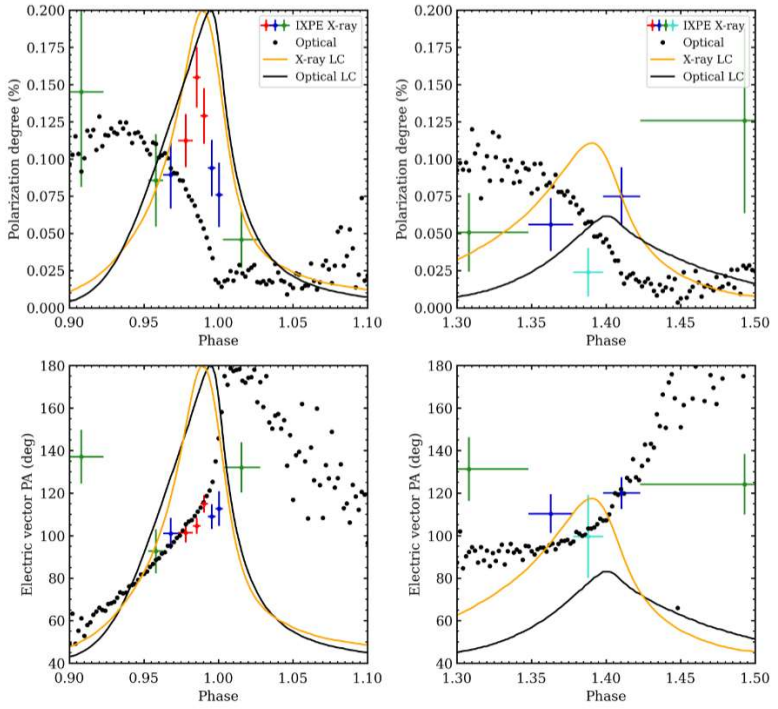
Toroidal field dominates nebula

300ks of IXPE data





Transverse B in jet?

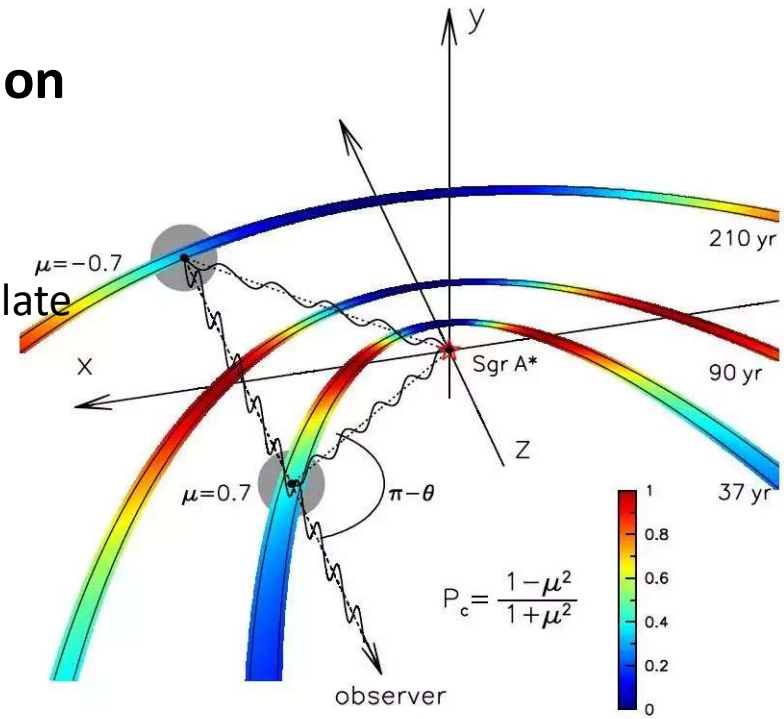


Pulsar X-ray polarization sweep quite different to optical – we hope to push this to ~1.2Ms in AO2

Imaging for Complex structure

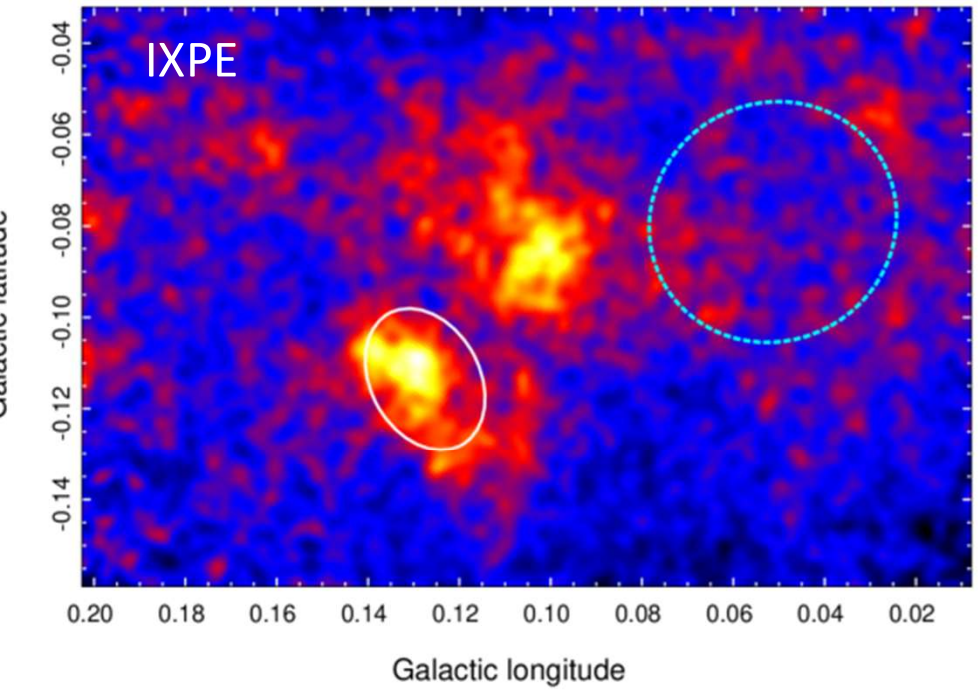
IXPE Imaging

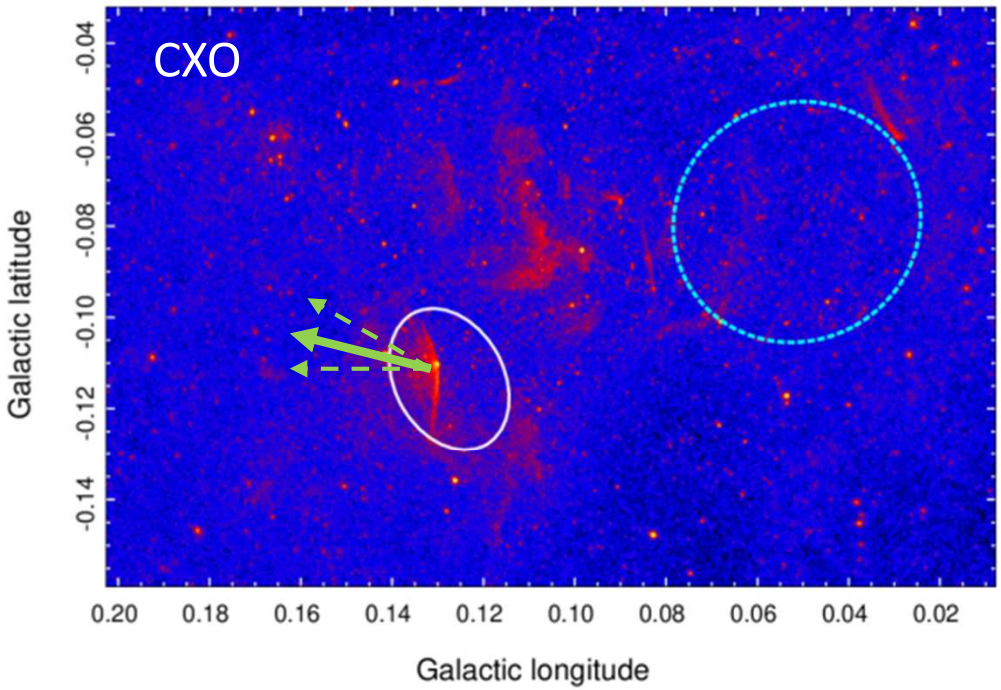
- **Sgr A* accretes at ~$10^{-9} L_{Edd}$ today**
- **Galactic Center molecular clouds (MC) show reflection X-rays, no present source bright enough**
  - If from Sgr A* (in past)
    - *highly polarized* perpendicular to plane of reflection; triangulate to implicate Sgr A*
  - This is a challenging observation –
    - Sgr B (planned target) faded before launch
    - Sgr A 1st Ms gave 3σ detection, 2nd Ms results in prep.
- **Broad Region PA: Sgr A* at ~10^{-4} L_{Edd} ~200y ago**
- **Smaller region PAs vary (multiple sources?)**



IMAGING FOR SERENDIPITY

- **Galactic Center**
  - Strange radio emitting filaments lie in IXPE FoV
    - including G0.13-0.11 with X-rays
    - shows high polarization – likely PWN-powered – Churazov et al A&A (2024)
- **Also SS433 lobes, etc.**



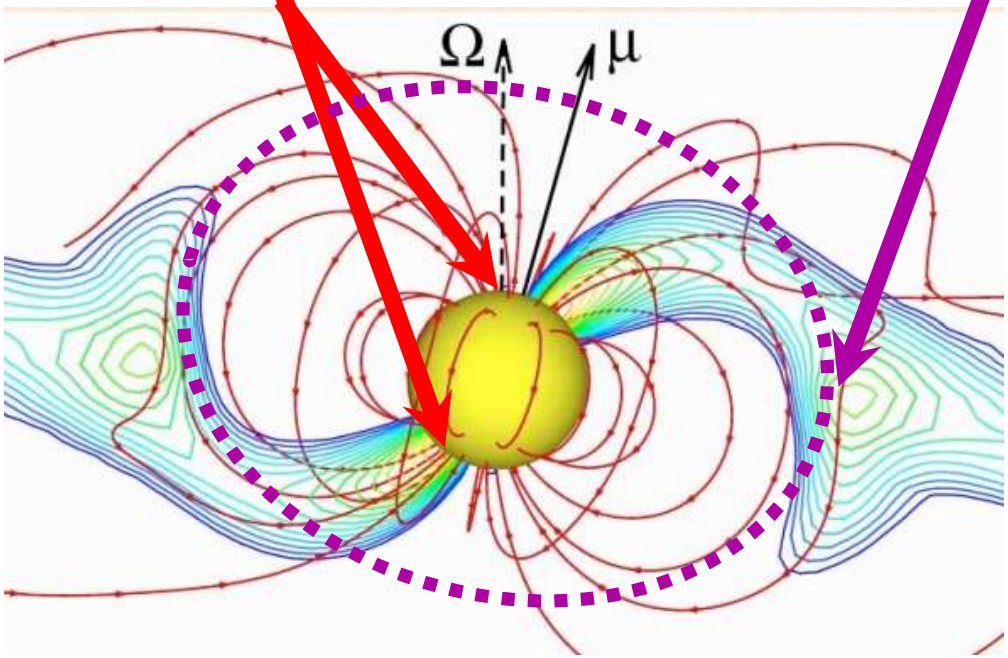


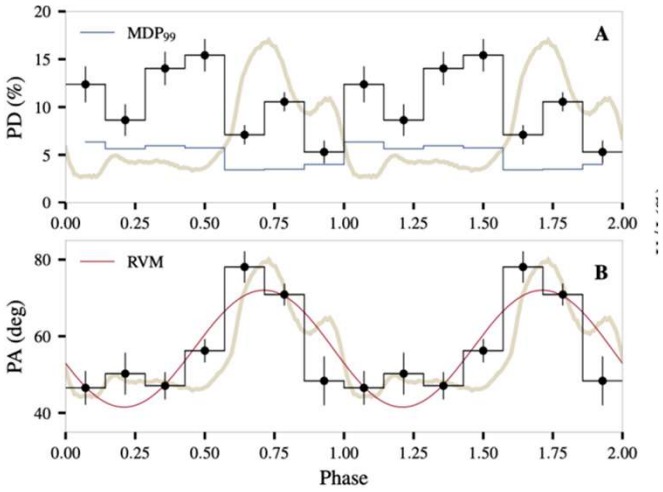
Accretion-powered Sources: Testing the Physics

- 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)



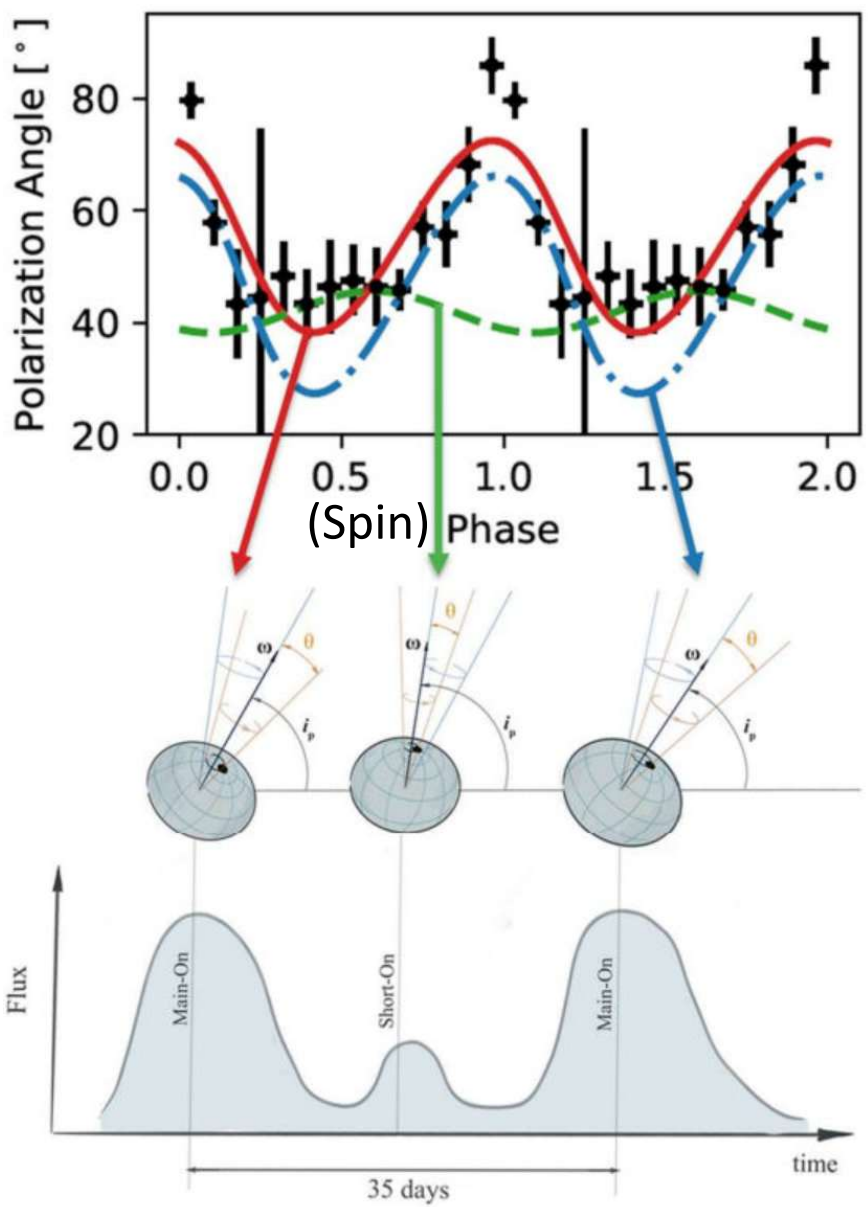


← Her X-1

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

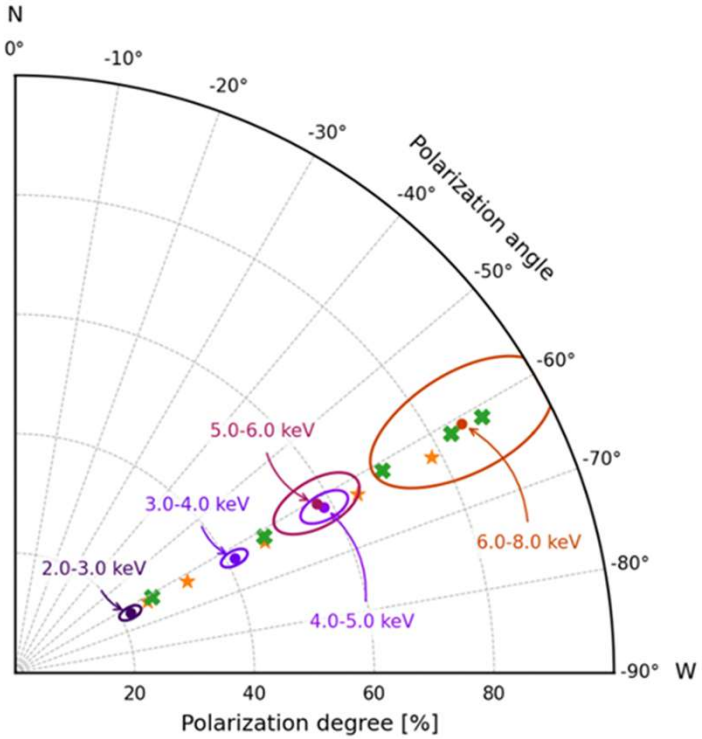
- **Her X-1 – monitor the RVM-type 1.2ms spin period polarization PA over 35d period to measure neutron star precession**
- **Precession appears to be nearly force free, requiring I asymmetry of a few ppm.**
- **Her X-1 (or faster spinners) may be LISA/MAGIS GW targets**



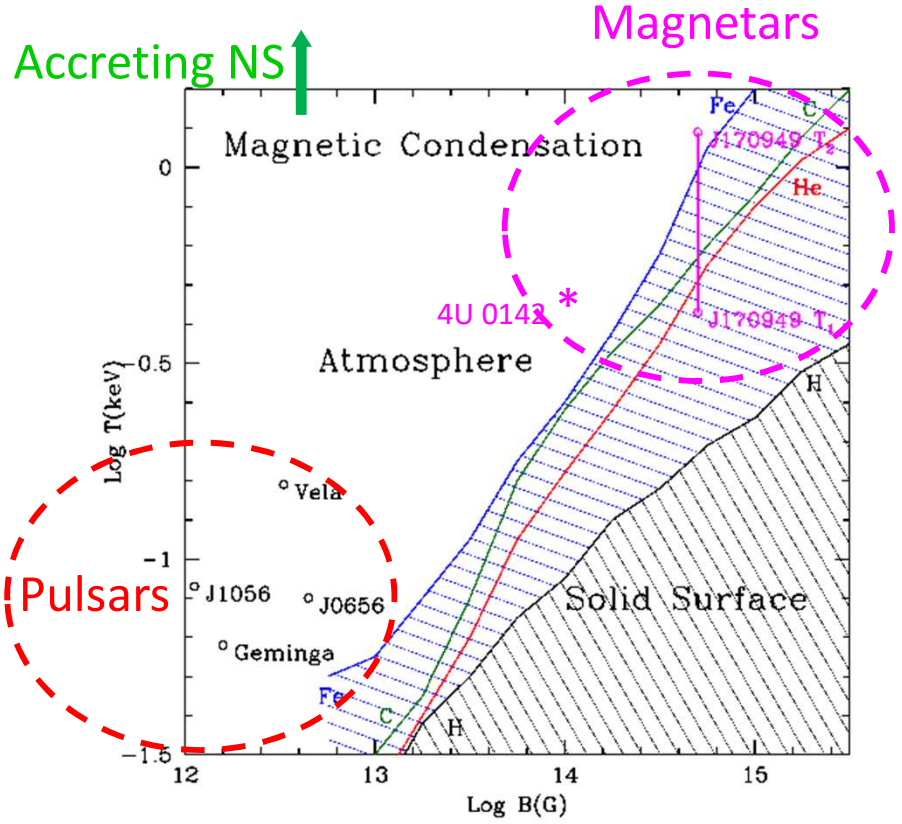
Heyl et al. (2024)

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

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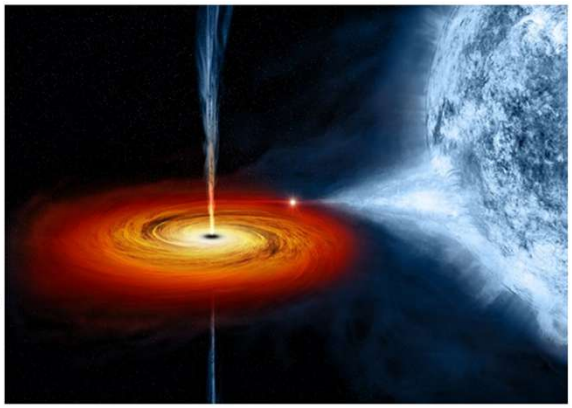
ACCRETION-POWERED SOURCES: PROBING THE GEOMETRY

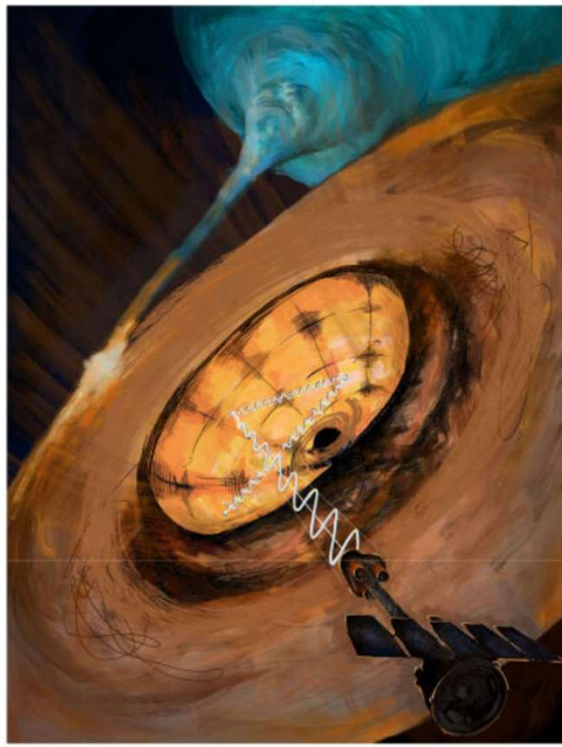


Cyg X-1

- **Black Hole Binaries** **(see Dovciak et al 2024 Review)**
  - -- 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

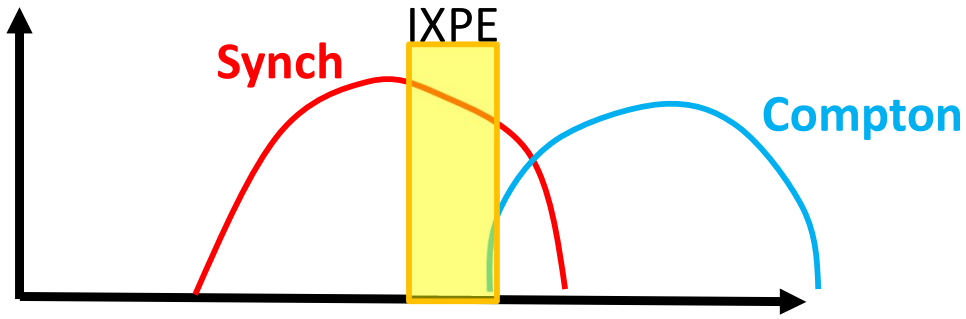
- -- Cyg X-3 super-Eddington accretor: 20% PD is evidence for scattering off thick torus (thus, an obscured ULX)
- -- high inclination disk polarization can explain several sources
- -- other sources show evidence for strong winds

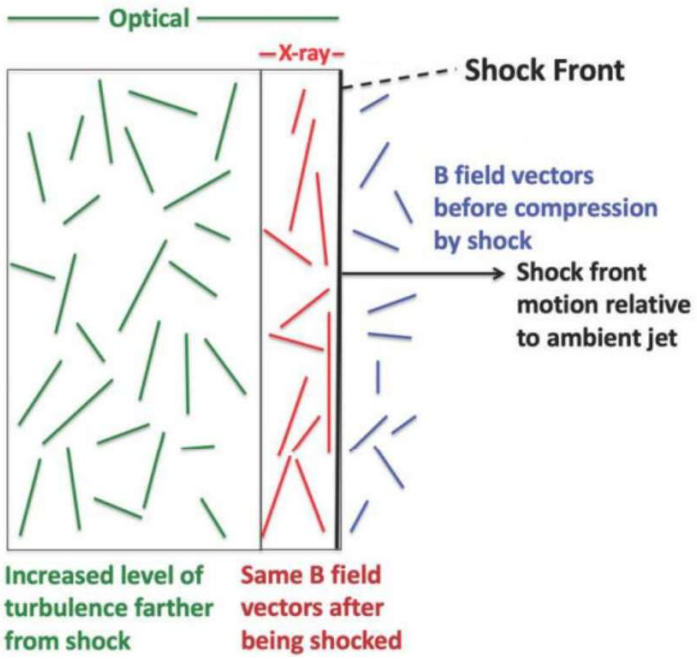
BLAZARS: CONSOLIDATING THE MODELS

IXPE Imaging X-Ray Polarimetry Explorer

Beamed Emission from Shock

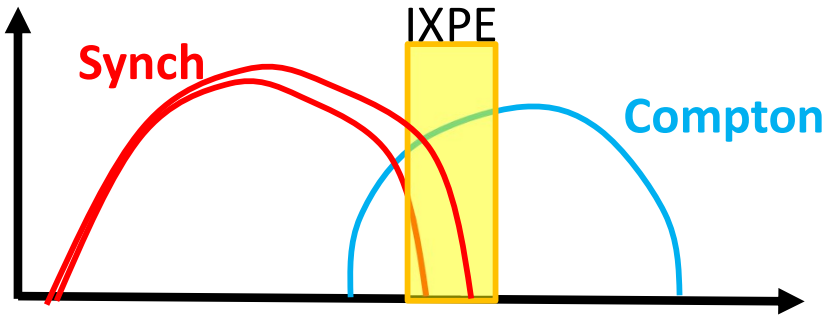
- **Basic Results Mrk 501 Nature paper:**
  - **Stratified shock acceleration**
  - **HBL X-ray synchrotron polarization > optical – radio**
    - **Magnetic field aligned with jet PA**
    - **PD << Single-zone Synch max PD ~ 70% (multiple zones)**
  - **LBL Compton component: no detected polarization**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





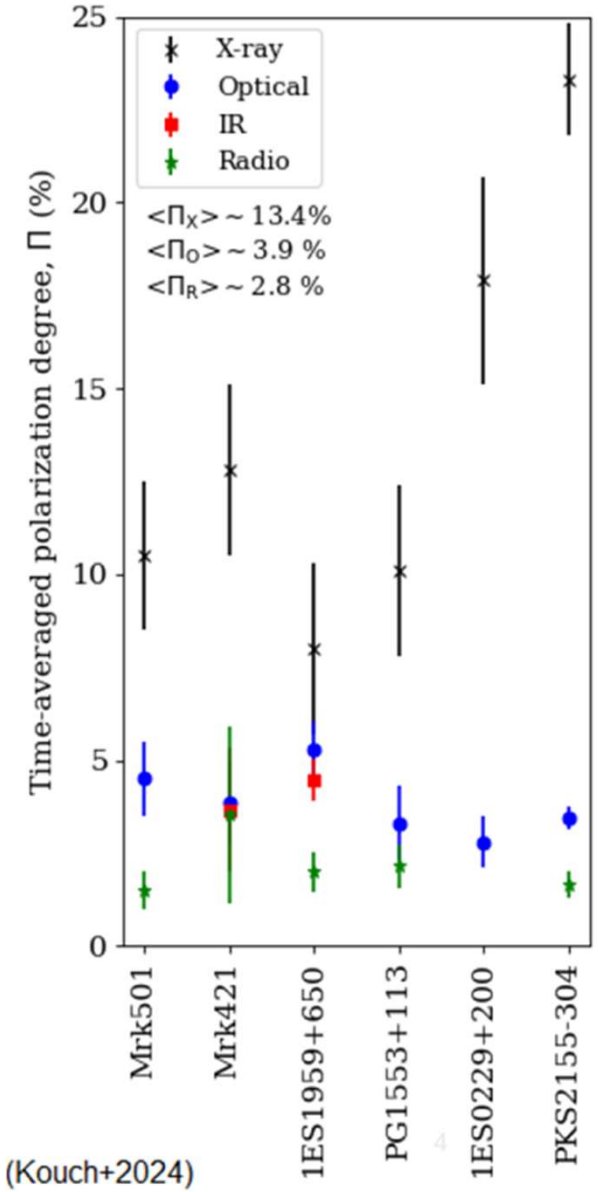
BLAZARS: OTHER INTERESTING PHENOMENA

- BL Lac Extra high optical polarization epoch 47.5% had low <7% X-ray polarization → typically Compton X-rays and not hadronic emission (Agudo 2025)
- BL Lac (IBL) flaring episode high polarization at lowest IXPE energy as synchrotron pokes into the IXPE band



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

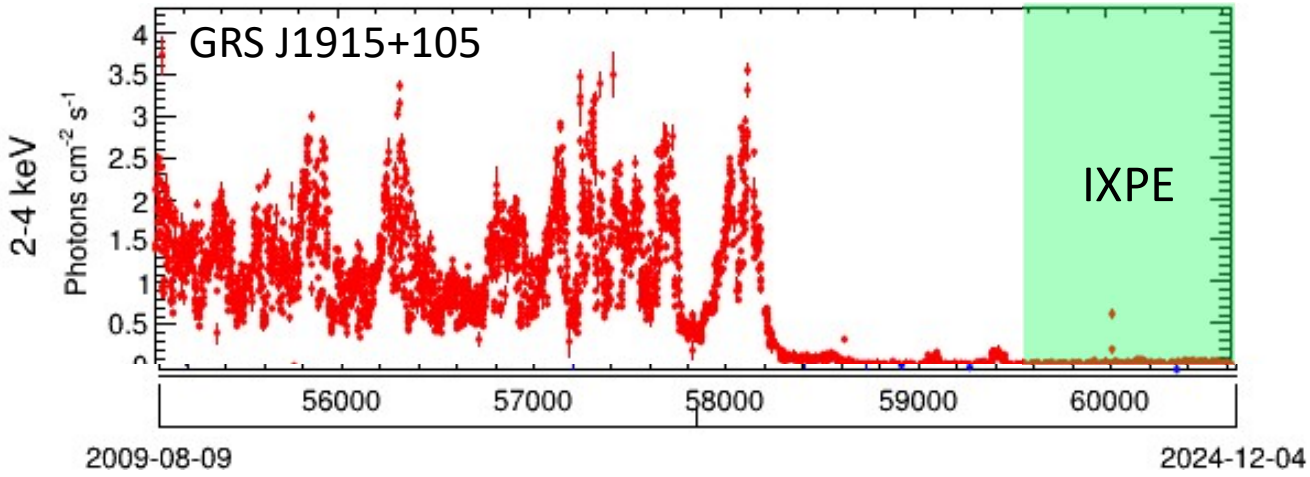
- Much interest for coordinated observations from the multi-ν (esp. radio, mm, optical, TeV) community – X-ray polarization exceeds the radio-optical PD

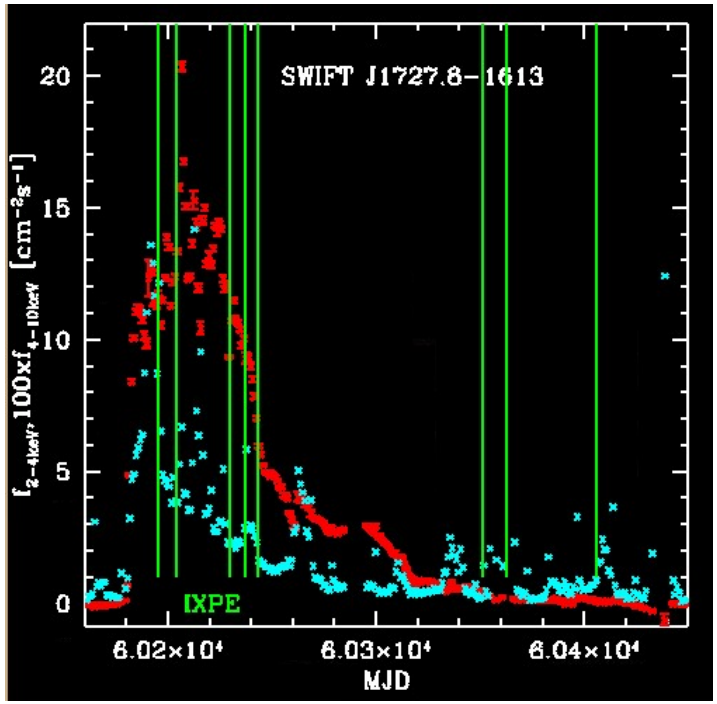


(Kouch+2024)

IXPE OBS OF 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 …

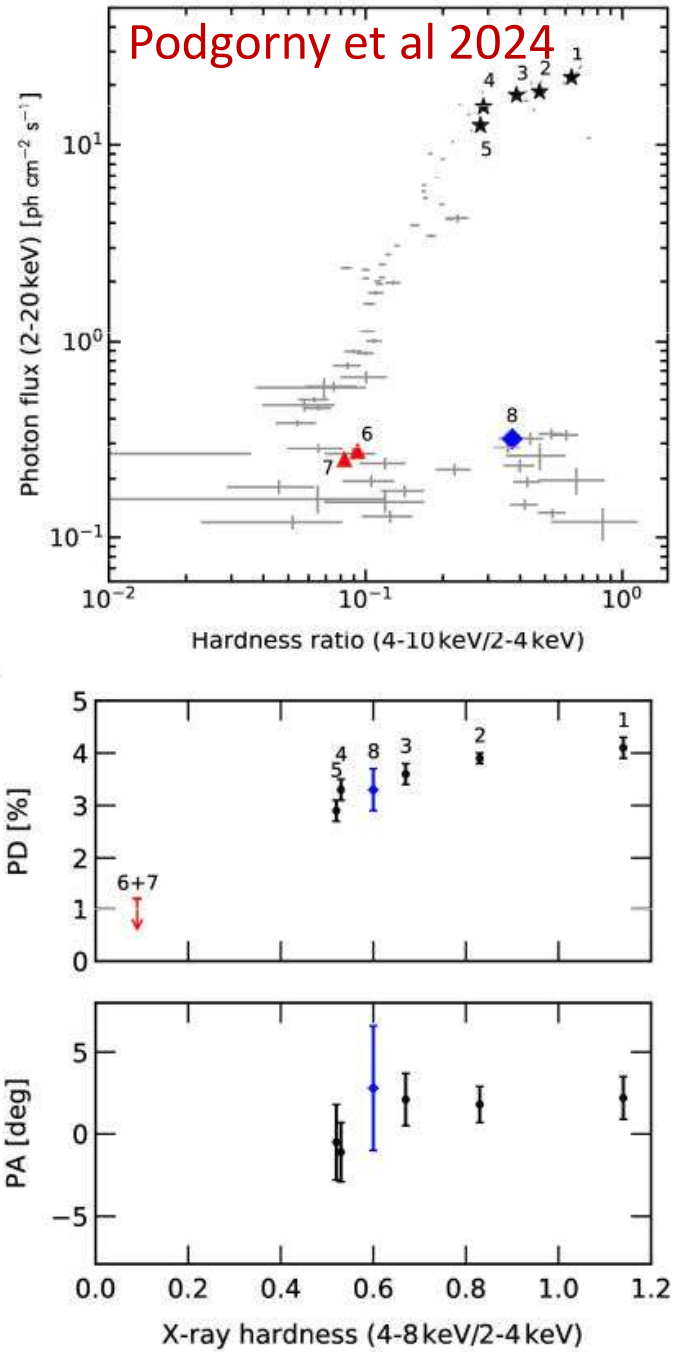




- **16 ToO targets in AO2!**

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 →

Multi Epoch IXPE Campaigns of Monitored AGN

Example: 5 main Mrk 421 IXPE epochs

1 High 15% PD ~ aligned with jet

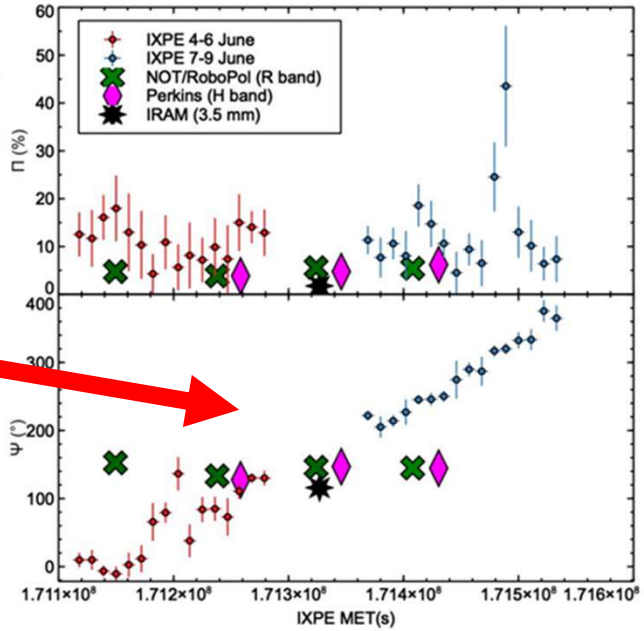
2 dramatic EVPA rotation (Di Gesu et al 2023)

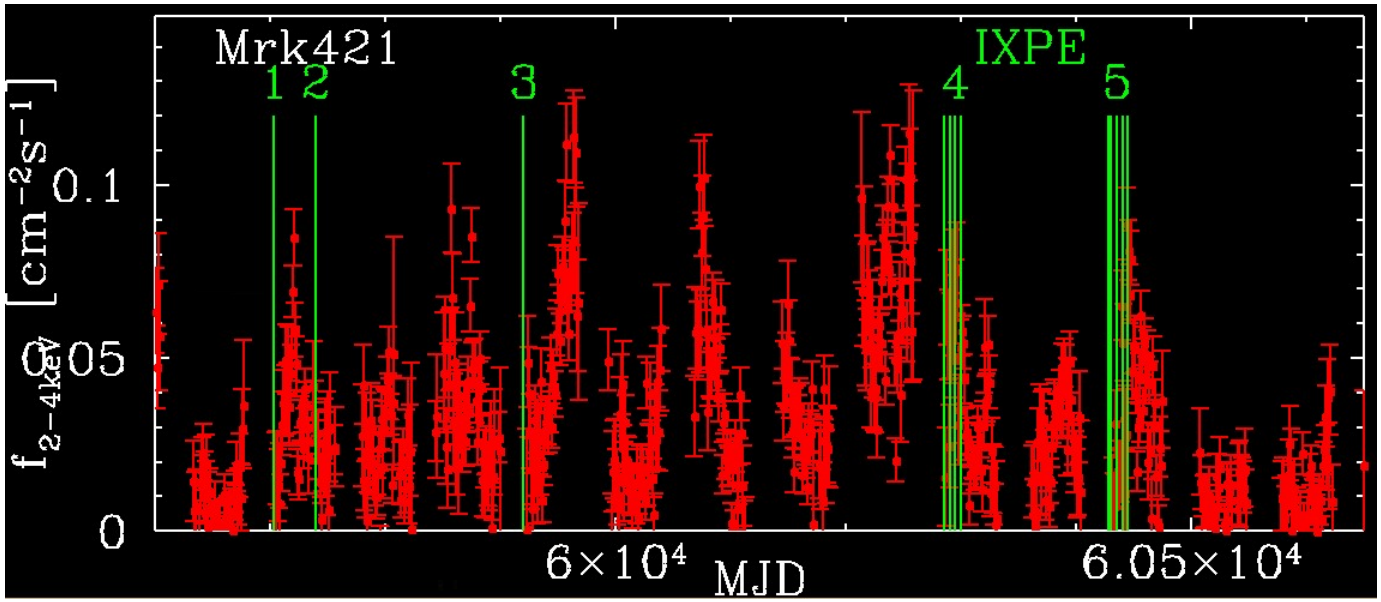
3 EVPA Stable again

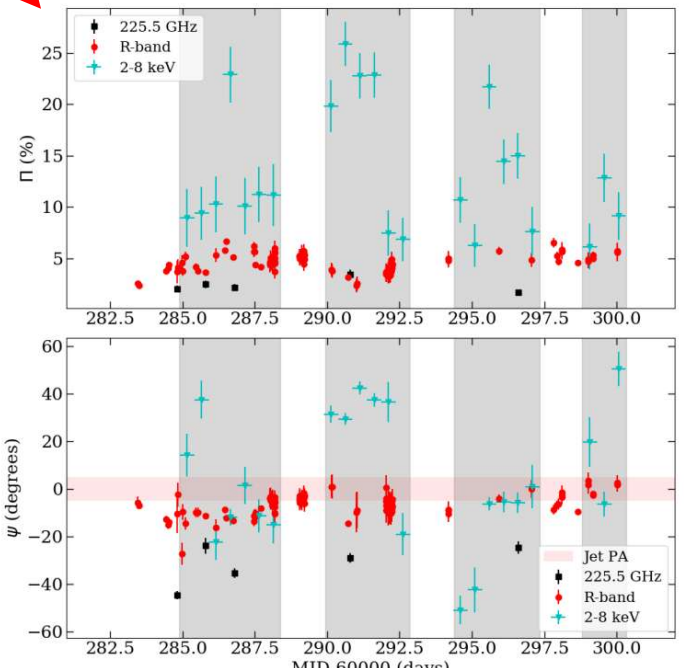
4 15d multi-ν campaign – Big PD flares (Maksym et 2024)

5 15d campaign, not yet published

… Awaiting AO2 ToO campaign results







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 –monitoring (MAXI/SWIFT/EP) to trigger
  - ToOs need to be high flux for good sensitivity in few d exposure – so must be well measured by monitors

  - Kudos to team for responding to so many transients – tough to schedule! If your science *really* requires <3d response, IXPE probably can't do it. Look for projects with ~10+day timescales.

IXPE Future Prospects

- **W/o expendables continued observations seem promising**
  - GO1, GO2 substantially (~7x) over subscribed
  - Small hit from missing rows in DU2
  - Deep integrations, especially on non-thermal sources: PWNe, SNR filaments, etc. – often Ms+ exposures!
  - Synoptic Studies
    - E.g. triggered XRB in various states
    - Scheduled e.g. Her X-1
  - Transients
    - Fast Transients are ***really*** difficult. 10+d durations best. ToOs unlikely to be observed in <5days.
  - Improved analysis techniques can eke out some more discoveries

FAINT, HIGH PD TARGETS

- **Non-Thermal, Magnetically dominated sources**
  - PWN
  - SNR filaments
  - Shocks in Relativistic jets (SS433, AGN)
  - Especially when extended, **need careful treatment of backgrounds**.
    - This is not treated in PIMMS!
      - Proposals for extended sources should address this
    - Particle Background: Can suppress
      - Standard Moments Technique Di Marco et al 2023 -- decreases typical Total BG by ~30%
      - More Advanced NN techniques Dinsmore et al 2025 -- ~50% Total BG decrease, residual largely photons
    - X-ray Background
      - (Steady) Astrophysical Sources – Use XPobssim from CXO imaging to estimate background in your aperture (See Niccola's talk)
      - ***Polarized*** X-ray Background from Solar Flares – see e.g. Buccinatini et al 2025. Some can be removed by cutting high BG rate times. Residual rate varies between DU1-DU3, can have PD~10-20%. Measure w/ large aperture, subtract scaled Q & U from data aperture
      -
  - Don't be shy of Ms+ proposals, but build a strong case!

IXPE Imaging X-Ray Polarimetry Explorer

SYNOPTIC STUDIES

- **Multi-visit campaigns of variable objects**
  - Periodicity (Her X-1)
  - Monitoring (Mrk 421)
  - Triggered Campaigns following known source transient decay
    - Make sure to check the IXPE visibility windows for your targets and ensure that full campaign can be achieved before triggering.
    - Most are bright enough to have archival monitoring (MAXI, SWIFT, etc). Please make realistic, historical assessments of the trigger probability and flare duration!
  - For all of these multi-mission coordination is a big plus
    - At a minimum, SWIFT for supporting imaging and spectral measurements
    - NICER/NuSTAR/XMM/XRISM can be especially helpful for context spectroscopy.
    - Ground-based optical polarization – BU's Program on 1.8m Perkins + others

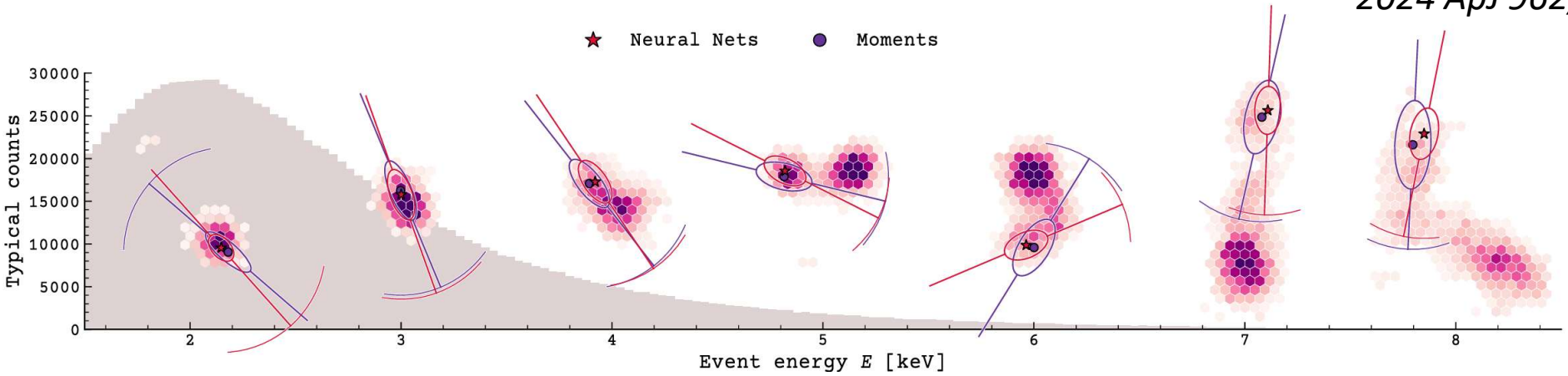
TRANSIENT CAMPAIGNS

- **Re-visits of prior IXPE transients**
- **Flares of known sources**
- **New Transients of Defined Class**

- **Set Flux Threshold High: Aim for MDP < 5% in <300ks**
- **When a completely new class, define trigger criteria strictly and clearly, have plausible models to support claimed (wished for) PD.**
- **Slow is good – example bright, jetted TDE**

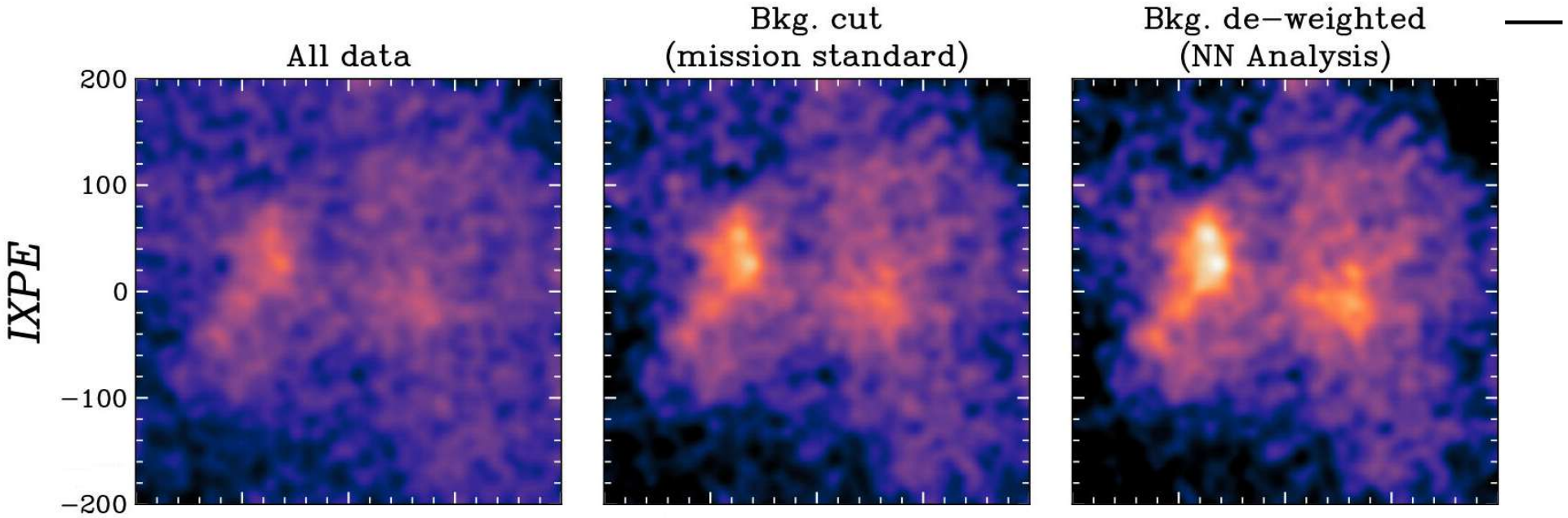
IMPROVED ANALYSIS

- **IXPE Level 1 data are complex – *images of each event*** **Jack Dinsmore GS**
  - Basic pipeline processing is a (surprisingly sensitive) extraction of position, energy and event PA from moments of the event tracks
  - ***BUT*** ML image analysis can get more S/N out of the same data sets. *Dinsmore & Romani 2024 ApJ 962, 183*

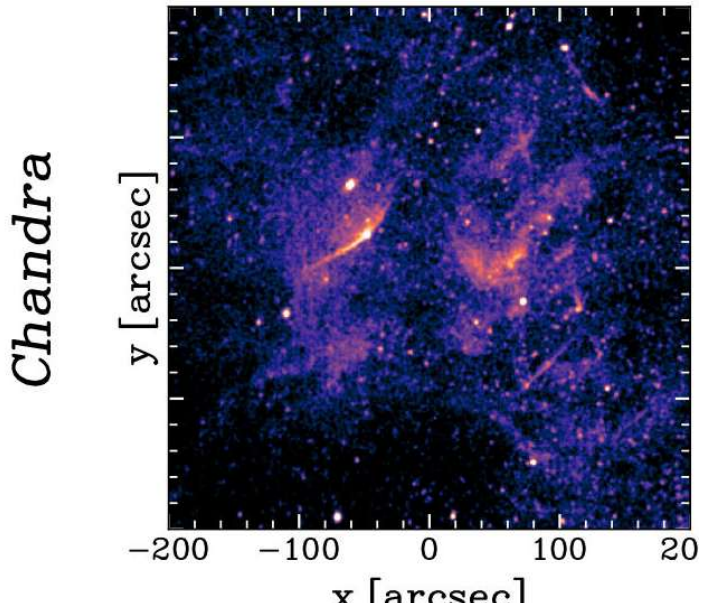


  - We (and more recently, others) developed NN event analysis, including
    - Improved rejection of particle background, poorly contained events
    - Improved photon localization, coupled with detailed on-orbit PSFs allows better extraction of source structures and better correction for polarization leakage
      - Served as **leakagelib** on Github (Dinsmore et al 2024)
    - Improved EVPA measurements that increase the modulation amplitude
      - Served as **IXPEML** on Github (Peirson et al 2020)
    - Weights that allow optimal extraction of broad band polarization signals

IMPROVED ANALYSIS – BACKGROUND SUPPRESSION



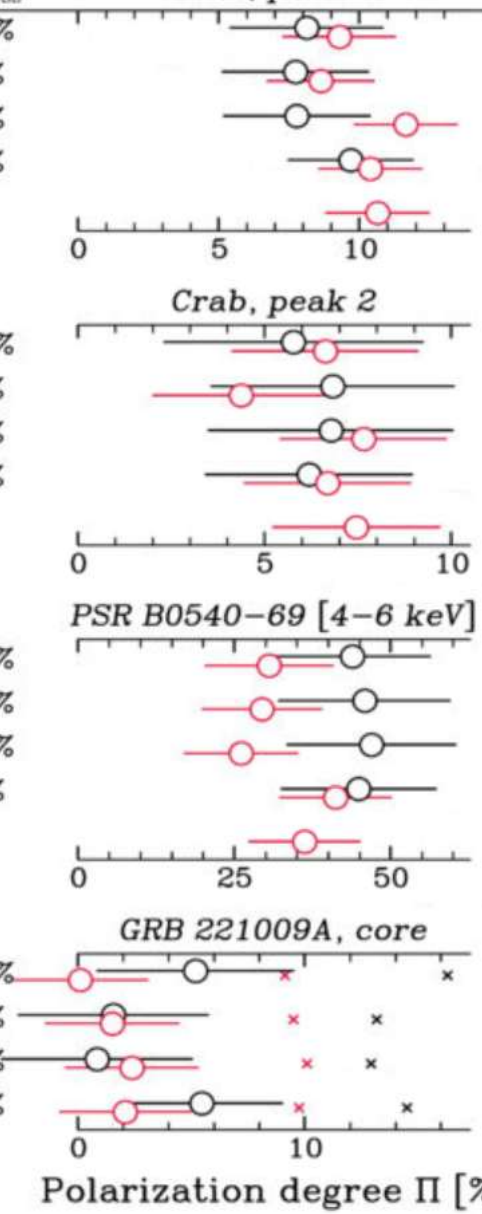
- **Sources and diffuse clouds in the Galactic center 2-8keV ~Ms exposure**



IMPROVED ANALYSIS – WEIGHTS VS. CUTS

Dinsmore & Romani 2025, in prep.

Mission standard	Π	$\frac{\sigma_Q\sigma_U}{(\sigma_Q\sigma_U)_{\rm PCUBE}}$	New method	Π	$\frac{\sigma_Q\sigma_U}{(\sigma_Q\sigma_U)_{\rm PCUBE}}$
Crab, peak 1					
PCUBE, Mom data	8.13 ± 2.75%	100.0%	MLE, NN data	9.29 ± 2.02%	54.0%
+ Mom. evt. wts.	7.73 ± 2.61%	90.0%	+ NN evt. wts	8.63 ± 1.92%	48.7%
+ bkg. cut	7.78 ± 2.62%	91.0%	+ PSF weights	11.66 ± 1.85%	45.4%
MLE + bkg. cut	9.69 ± 2.23%	65.9%	+ bkg. weights	10.39 ± 1.86%	45.5%
			+ phase weights	10.65 ± 1.86%	**45.5%**
Crab, peak 2					
PCUBE, Mom data	5.77 ± 3.49%	100.0%	MLE, NN data	6.62 ± 2.51%	51.7%
+ Mom. evt. wts.	6.82 ± 3.27%	87.8%	+ NN evt. wts	4.36 ± 2.37%	46.1%
+ bkg. cut	6.77 ± 3.29%	88.8%	+ PSF weights	7.65 ± 2.25%	41.5%
MLE + bkg. cut	6.19 ± 2.78%	63.7%	+ bkg. weights	6.68 ± 2.25%	**41.5%**
			+ phase weights	7.46 ± 2.25%	41.7%
PSR B0540−69 [4−6 keV]					
PCUBE, Mom data	43.84 ± 12.59%	100.0%	MLE, NN data	30.58 ± 10.33%	67.2%
+ Mom. evt. wts.	45.85 ± 13.79%	119.8%	+ NN evt. wts	29.42 ± 9.65%	58.6%
+ bkg. cut	46.95 ± 13.54%	115.6%	+ PSF weights	26.08 ± 9.18%	52.9%
MLE + bkg. cut	44.89 ± 12.43%	97.5%	+ bkg. weights	41.20 ± 9.03%	51.4%
			+ phase weights	36.26 ± 8.99%	**50.9%**
GRB 221009A, core					
PCUBE, Mom data	5.18 ± 4.36%	100.0%	MLE, NN data	0.10 ± 3.03%	48.1%
+ Mom. evt. wts.	1.57 ± 4.22%	93.5%	+ NN evt. wts	1.52 ± 2.97%	46.3%
+ bkg. cut	0.85 ± 4.23%	93.8%	+ PSF weights	2.38 ± 2.96%	46.1%
MLE + bkg. cut	5.47 ± 3.60%	68.0%	+ bkg. weights	2.08 ± 2.92%	**44.8%**



IXPE Imaging X-Ray Polarimetry Explorer

CONCLUSIONS

- **Lots of great IXPE science still to be done… but!**

- **If you target bright transients, define clear trigger criteria and ensure that the source will stay in desired state for 10+d**
- **If you target a bright source synoptic campaign, make sure that visibility allows full coverage**
  - **Take advantage of joint programs for supporting spectroscopy, etc.**
- **If you target faint, especially extended, sources**
  - **Be aware of the importance of backgrounds**
  - **Request the required long exposure, with adequate justification, including models or scaling from previously observed IXPE targets**
  - **Consider going beyond standard pipeline analysis; advance level 1 processing gives a modest sensitivity boost**