IXPE
Imaging
X-Ray
Polarimetry
Explorer

Looking at the X-ray sky with polarized lenses

Alberto Manfreda

for the IXPE collaboration

Tenth International Fermi Symposium

Johannesburg 2022

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X-ray Polarimetry

- **Polarimetry** is a powerful diagnostic tools for the physics of celestial objects
- Can reveal the geometry of sources and fields *even when internal structures are unresolved*

Without Polarizer | With Polarizer

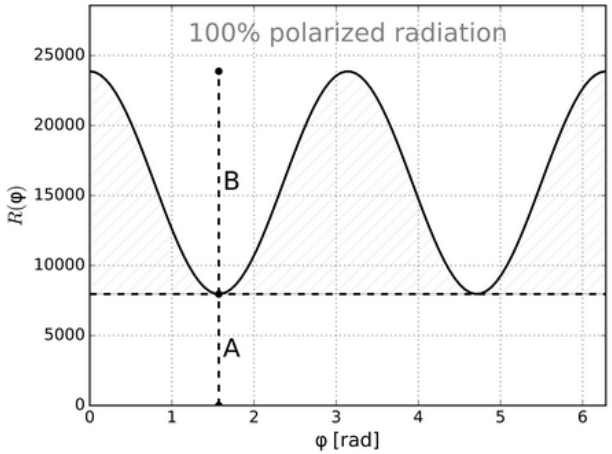
- Unfortunately, no polarized filter exists for X-rays: *polarimetry is challenging*
- For over 40 years significant detection for a single source in the soft X-ray band – the Crab Nebula by OSO-8 (Weisskopf, 1978)
- X-ray emission highly non-thermal: **significant polarization signal expected from many different sources!**

The turning point: Gas Pixel Detector

Costa, 2001 Bellazzini, 2006

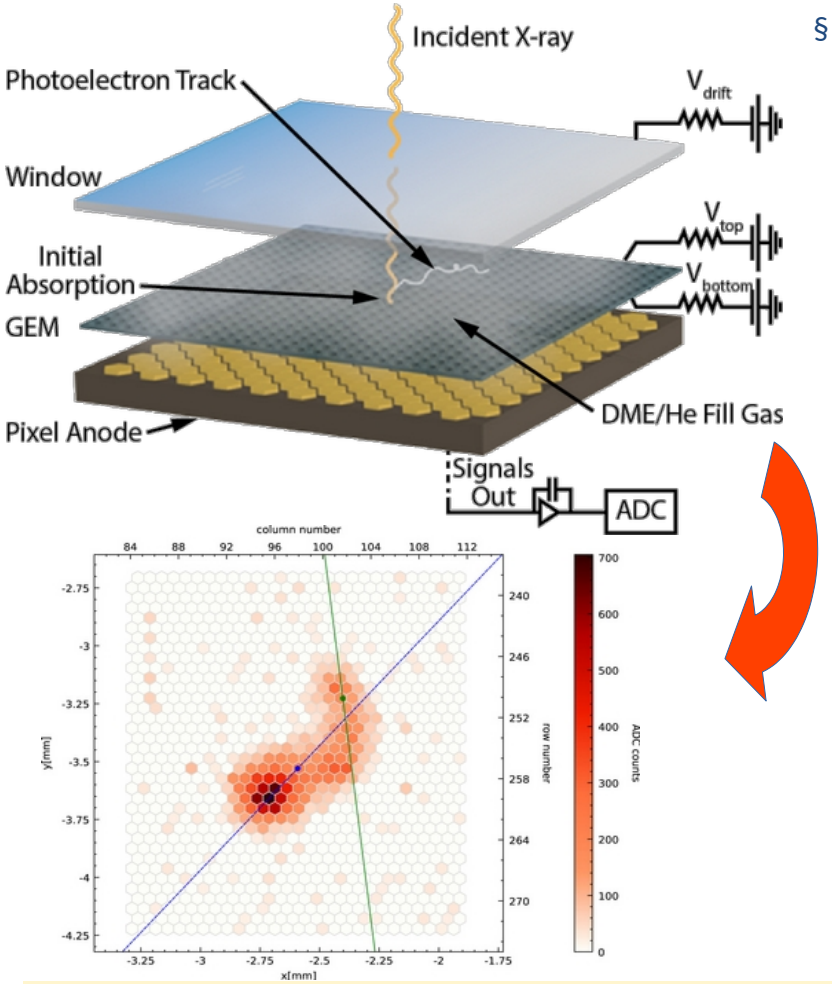
K-shell photo-electron emission **100% modulated** for linearly polarized radiation:

$$\frac{d\sigma_C^K}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$



$$\mu = \frac{R_{max} - R_{min}}{R_{max} + R_{min}} = \frac{B}{B + 2A}$$

$$MDP_{99\%} = \frac{4.29}{\mu R}\sqrt{\frac{R+B}{T}}$$



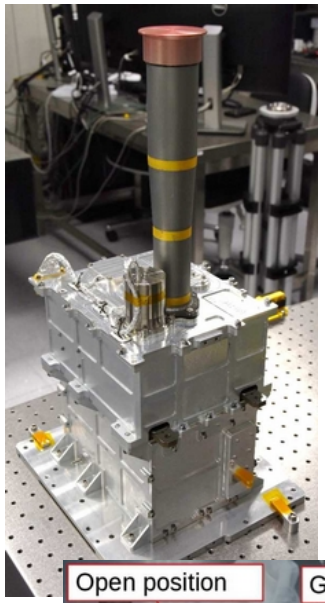
Charge deposition asymmetry allows conversion point identification!

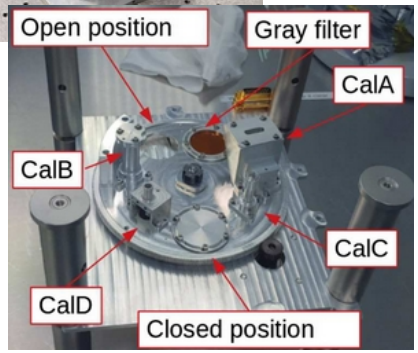
The Imaging X-ray Polarimetry Explorer

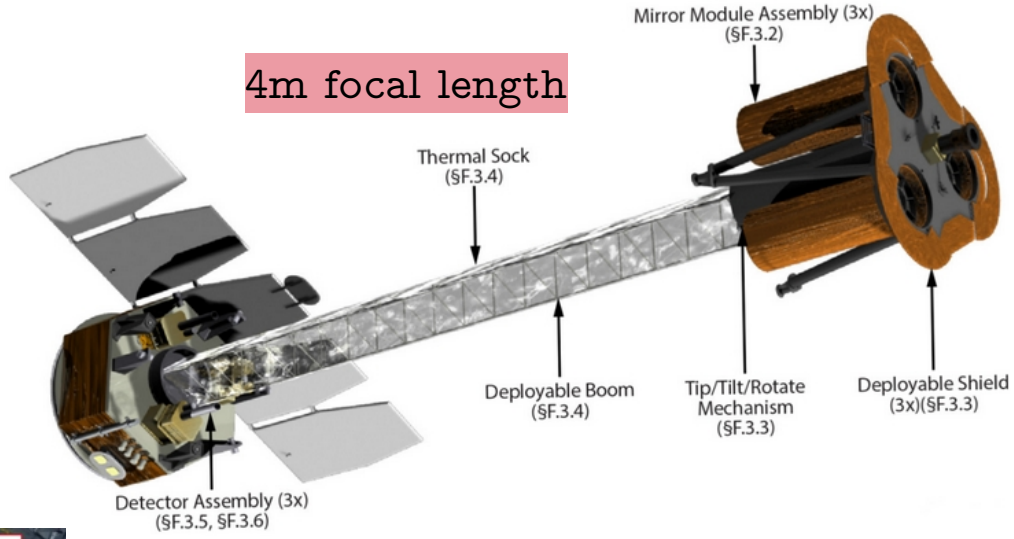
Weisskopf 2021, Soffitta 2021

- NASA-ASI **SM**all **EX**plorer mission
- 3 identical telescopes: X-ray optics + polarization sensitive detectors

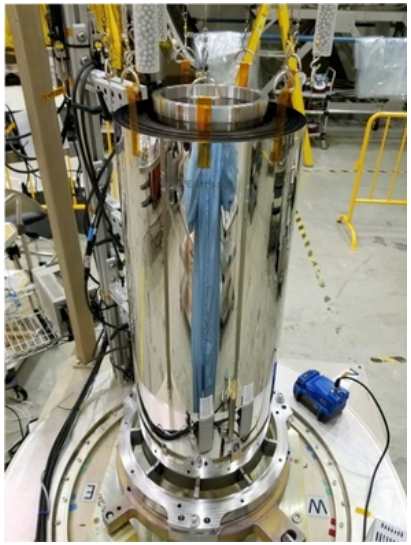
Detector Unit







Mirror Module Assembly



Energy range: 2–8 keV

- **Polarimetry**: MDP>5.5% in 10 days for 10—11 cgs
- **Imaging** (< 30 arcsec)
- **Timing** (~ 10μs)
- **Spectroscopy** (<20% at 5.9 keV)

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IXPE Launch
Cape Canaveral - 9 December 2021

IXPE Imaging X-Ray Polarimetry Explorer

IXPE space operations

Orbit

- LEO 600 km circular orbit
- 96.6-minute period
- ~13% SAA downtime

Observing strategy

- Point-and-stare at known targets (~13' FOV)
- Typical observation time 100 - 1000 ks
- TOO available with a few days notice (https://ixpe.msfc.nasa.gov/for_scientists/too.html)

Data processing

- Science Operation Center at MSFC, Alabama
- Data publicly available on HEASARC one week after the end of an observation
- Analysis tools available through HEASoft or *ixpeobssim* (Baldini, 2022)

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IXPE Science

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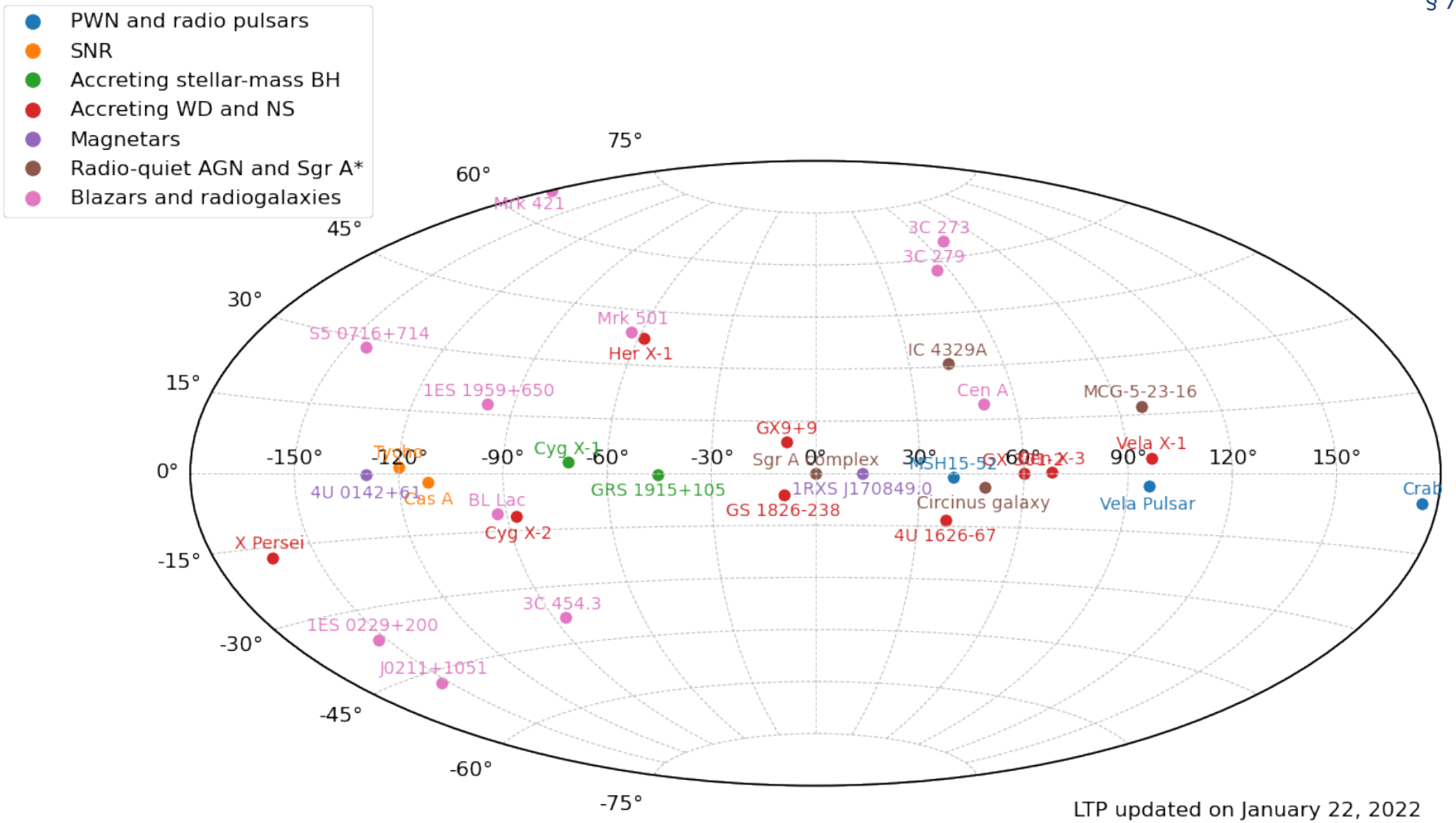


IXPE Imaging X-Ray Polarimetry Explorer

Supernova Remnants

Galactic accelerators, through **DSA**

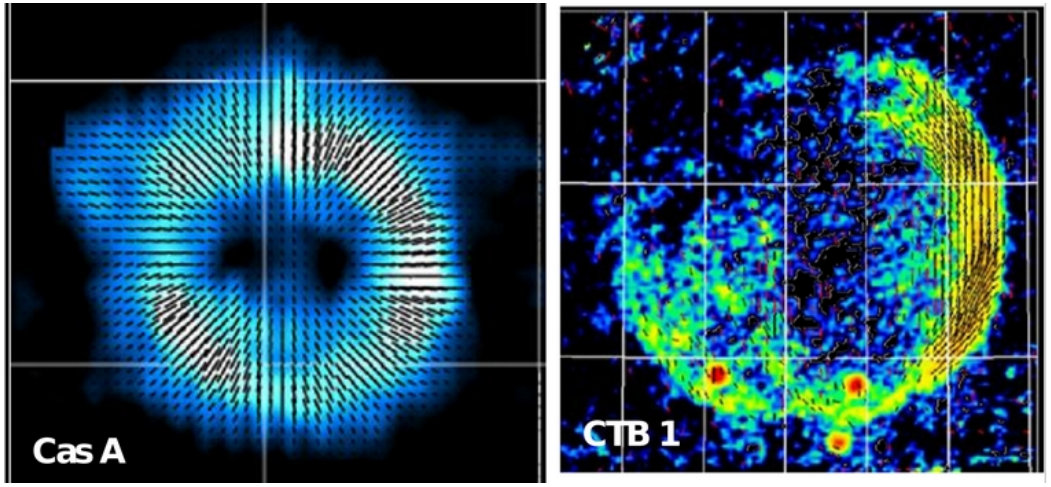
- Requires turbulent magnetic field

Radio observations

- Mature SNRs (≳2500 yr): B-field *tangentially* oriented
  - Shock compression
- Young SNRs (≲2500 yr): *radially* oriented B-fields, low pol. degree
  - Mechanism unclear

X-ray emission

- Thermal lines
- Synchrotron from 10 - 100 TeV electrons: probe 10^{17}cm scale



Dubner&Giacani (2015)

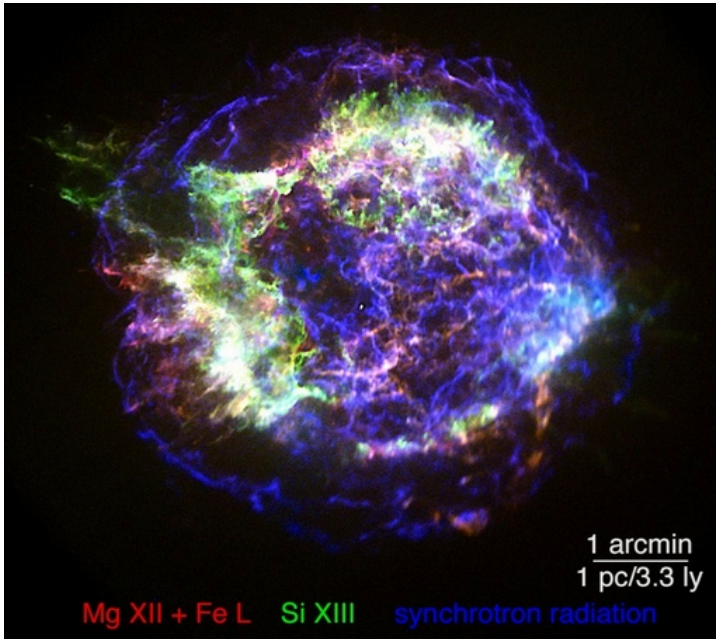
IXPE observed SNRs

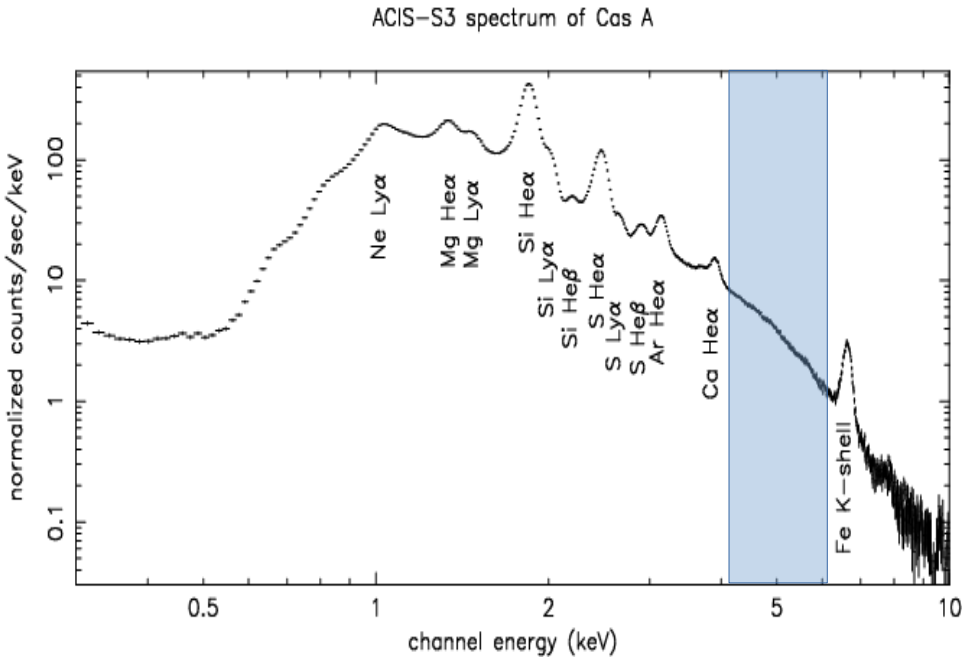
- Cas A (confirmed detection!)
- SN 1006
- Tycho

Supernova Remnants: Cas A

Cas A

- Young (350 yr) Core-collapse SNR
- Synchrotron in front shock filaments
  - *Reverse shock* also present
- Synchrotron emission dominant between 4 and 6 keV



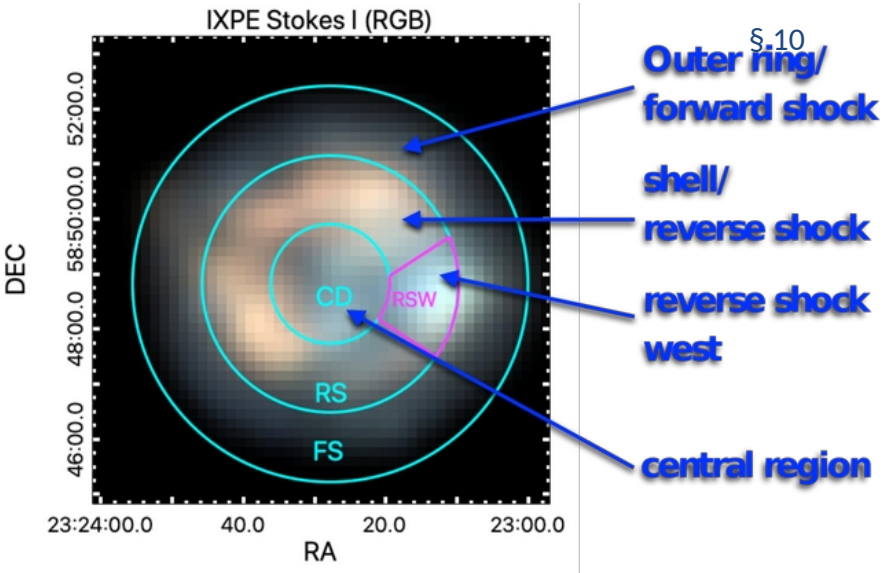


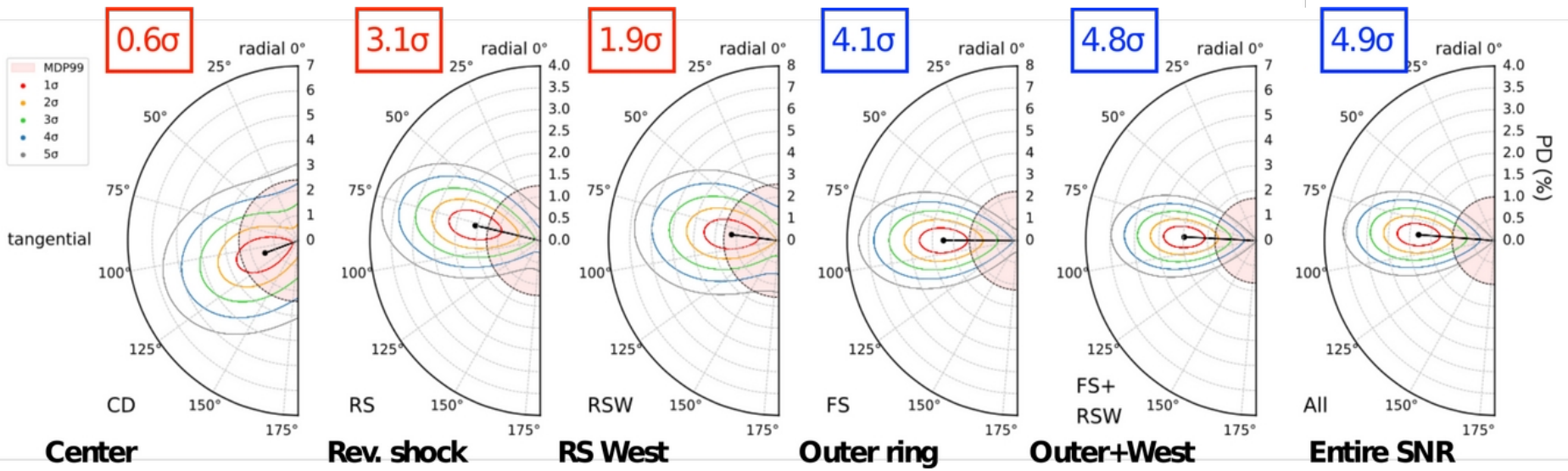
- First IXPE target, 890 ks observation
- Net overall X-ray polarization compatible with zero
- However, *source is spatially resolved:* allows testing different sub-regions

IXPE view of Cas A

Vink, 2022

- **Π = 1.8 ± 0.3% in [3–6] keV band, tangentially oriented**
  - ~5% in the forward shock
- *Magnetic field is radial already 10^{17} cm from the shock*
- Π ≤ than radio
  - High level of MF turbulence





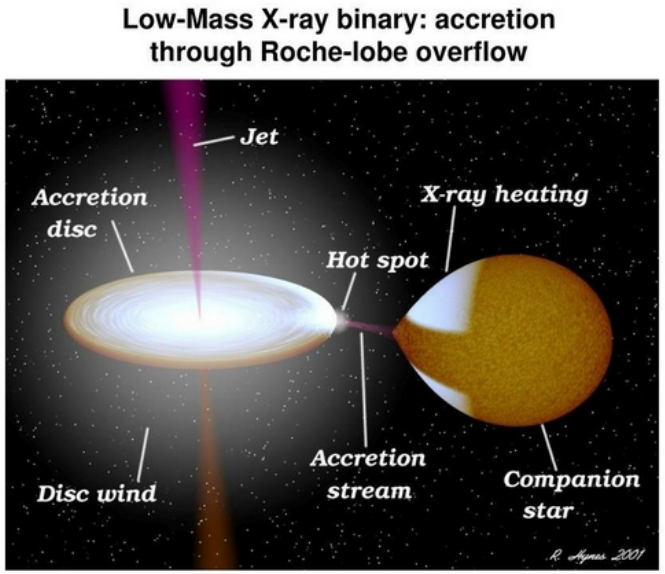
IXPE Imaging X-Ray Polarimetry Explorer

Accreting neutron stars

Weakly magnetized: An accretion disk is able to form

IXPE targets

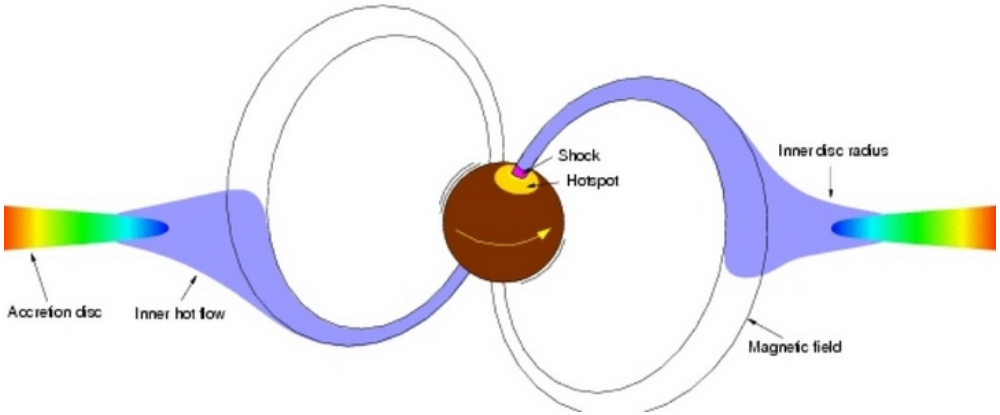
- Cyg X-2
- GS 1826-238
- GX 301-2



Strongly magnetized: Magnetic field drives the accretion flow

IXPE targets

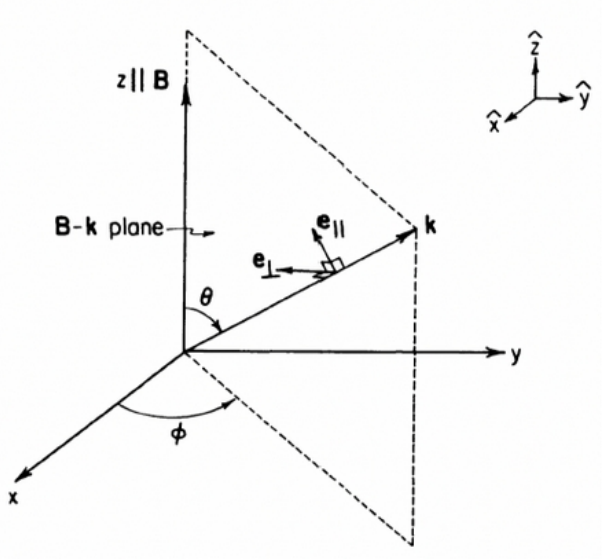
- Cen X-3 (confirmed detection!)
- Her X-1 (confirmed detection!)
- 4U 1626-67 (marginal detection)
- X Persei



Light propagation in strong magnetic field

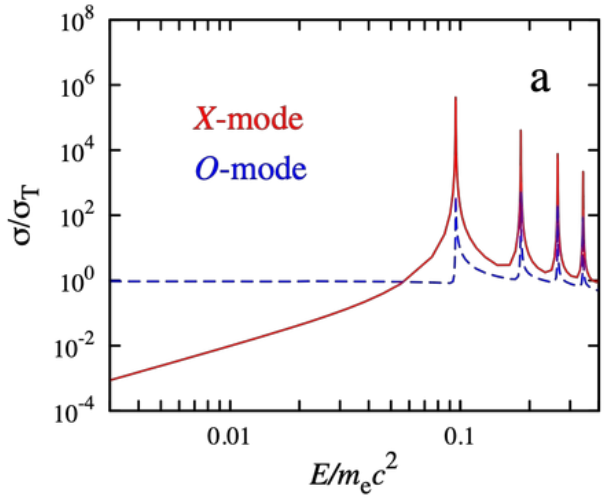
O mode: E lays in the B - k plane

X mode: E orthogonal to that plane



Plasma effects

X-mode and O-mode cross-section drastically different different below cyclotron frequency



QED effects: *Vacuum Birefringence*

$$n_{\parallel} - n_{\perp} = \frac{\alpha_{\rm QED}}{30\pi}\left(\frac{B}{B_{\rm QED}}\right)^2 \sin^2\theta$$

$$B_{\rm QED} = \frac{m_e^2 c^3}{\hbar e} = 4.4 \times 10^{13}\ {\rm G}$$

Strongly magnetized Accreting NS: Her X-1

Doroshenko, 2022

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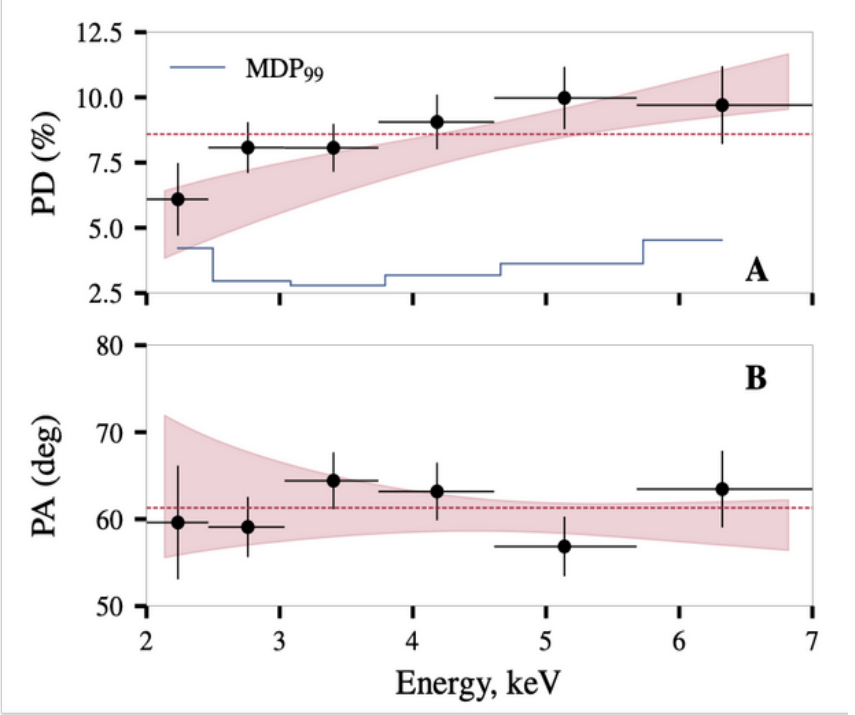
- Persistent, bright accretion powered pulsars
- d = 7 kpc, spin period = ~1.24 s
- B3 ~2.2 solar mass donor star eclipsing the X-ray source every ~1.7 d
- **CRSF detected**, allows magnetic field measure:
  - $B = 4.5 \times 10^{12}$ G
- 35 d cycle not completely understood

- *High X-ray polarization predicted before launch* (due to plasma effects)
- IXPE observation of 150 ks in 'main on' phase (mostly unobscured emission from the pulsar)
- *Average measured polarization is low*: **Π = 8.6 ± 0.5%, PA ~60°**
- Polarization nearly constant in energy

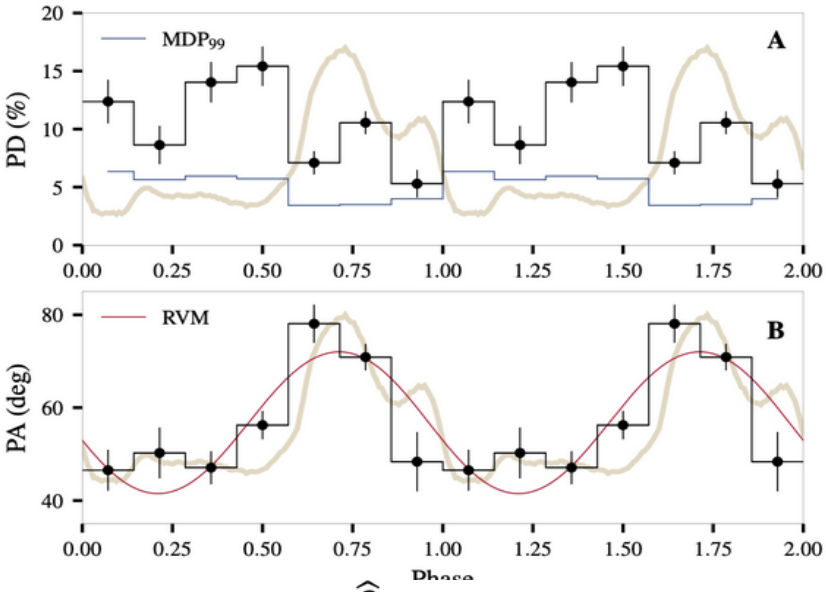


Strongly magnetized Accreting NS: Her X-1

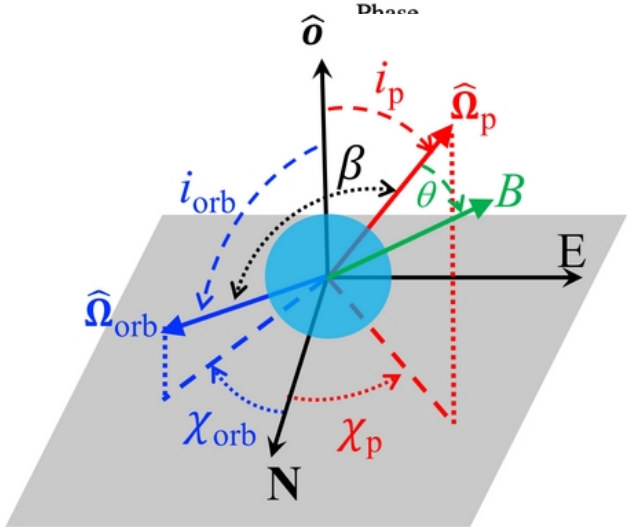
Doroshenko, 2022

Phase resolved polarimetry:

- complex PD behavior
- PA well described by a simple **RVM** model Poutanen, 2020
  - QED effect in play?
  - *Allow resolving the pulsar geometry!*



- Pulsar position angle lays on PA axis (if O mode) or orthogonal to it (if X mode)
- Magnetic colatitude $\theta = 12°.5 \pm 5°.7$
- Pulsar spin axis can be constrained using optical polarization data: $\chi_{orb} = 28°9 \pm 5°.9$
- **Pulsar and orbital angular momentum misaligned!**



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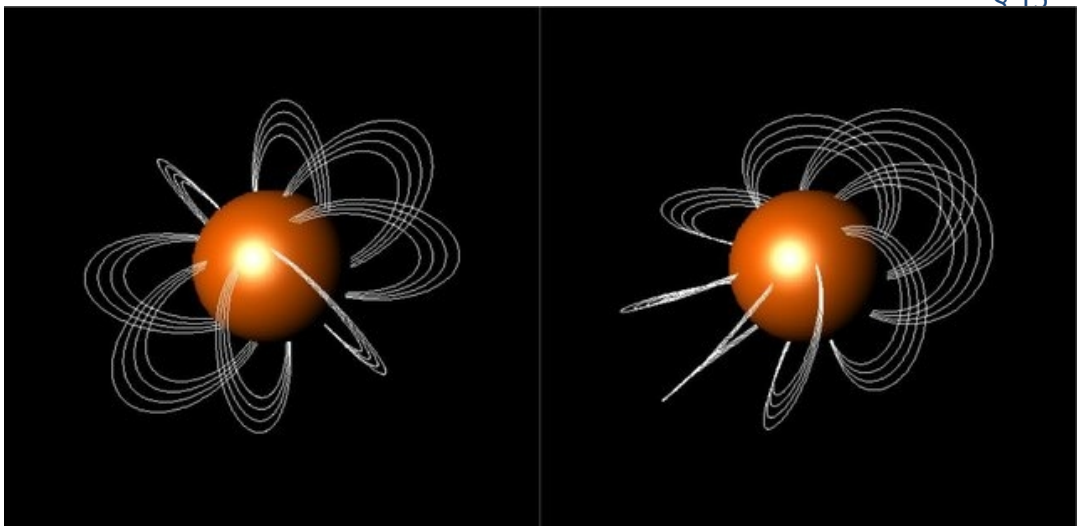
Magnetars

Magnetars are isolated neutron stars powered by huge magnetic fields (**B ≈10^{14} - 10^{15} G**).

Anomalous X-ray Pulsars (AXP) and Soft Gamma-ray Repeaters (SGR) belong to this class.



- Intense X-ray activity (bursts, flares) → rapid magnetic field reconfiguration.
- Highly twisted, non dipolar magnetic field
- *Laboratory for testing QED effects*

IXPE observed mangetars

- 4U 0142+61 (polarization detection!)
- 1RXS J170849 (ongoing)

Magnetar 4U 0142+61

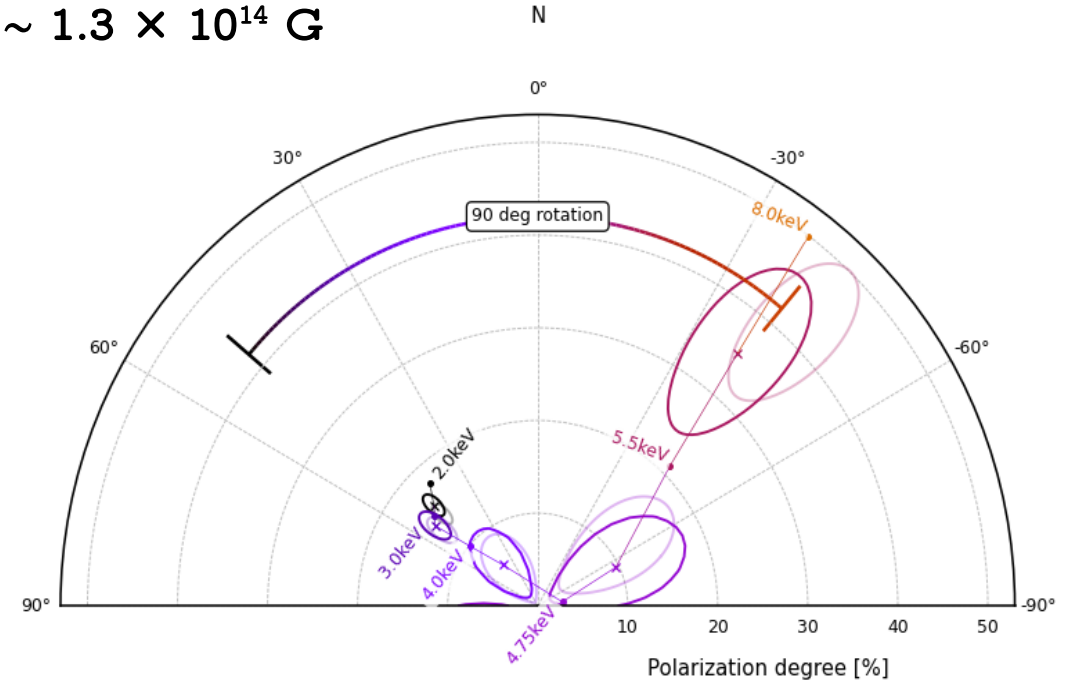
Taverna, 2022

- P = 8.69 s, P' = 2 x 10^{-12} s^{-1}
- Spin-down magnetic field: $B \sim 1.3 \times 10^{14}$ G

IXPE 1Ms observation

- Spectrum: BB + PL tail
- Overall polarization:
  Π = (12 ± 1)%,
  PA = 48° ± 3°

- *Polarization vector variation with energy*, angle swing by 90° between 4 - 5 keV



- **Resonant Compton Scattering**: high-energy photons polarized in the X-mode, with a polarization degree of ~ 30%, almost independently on the production
- Small O-mode polarization at low energy: condensed surface emission? gaseous layer with an "inverted" temperature?

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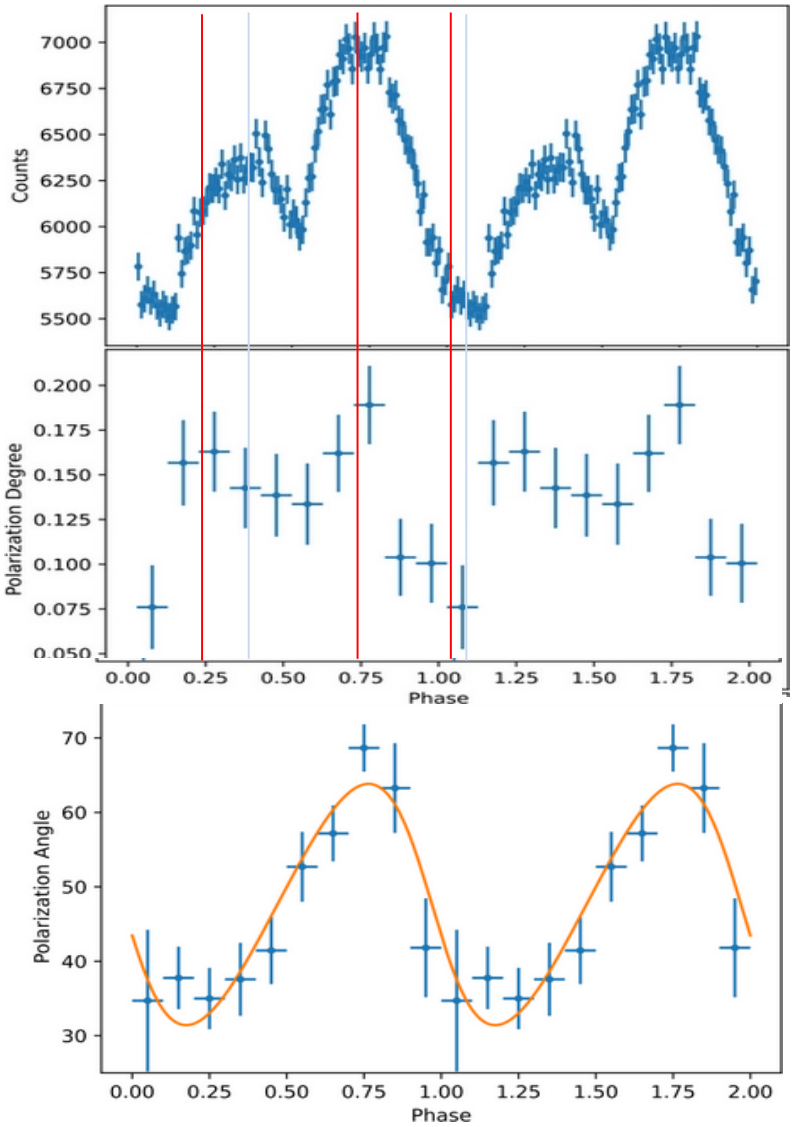
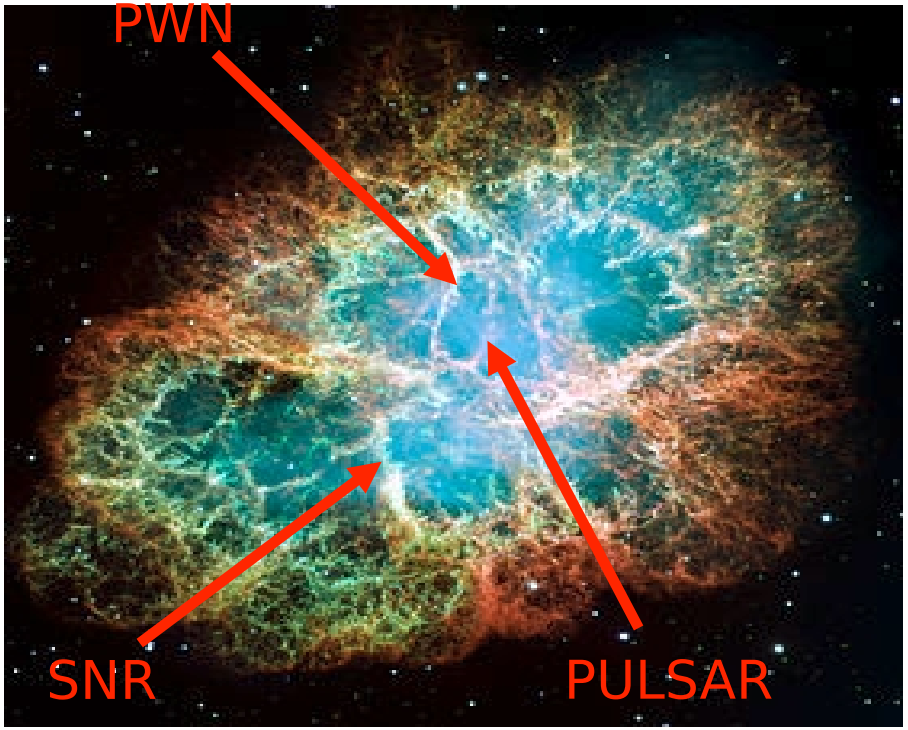
Magnetar 4U 0142+61

Taverna, 2022



- Pulse profile is double-peaked
- Double-peaked profile for PD as well (min and max almost in phase)
- PA profile essentially one-peaked (maximum in phase with the main maximum of the flux)
- **PA well fitted by RVM**:
- QED effects?
  - PD profile depends on emission region
  - PA profile depends on magnetic field geometry far from the source

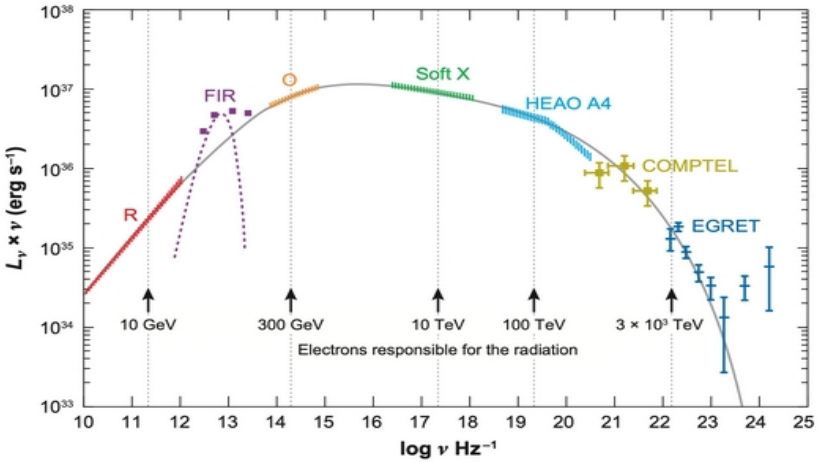
Pulsar Wind Nebulae



- Hot bubbles of relativistic particles and magnetic field: interaction of the magnetized pulsar wind with the expanding SNR (or with the ISM)
- Purely non-thermal spectrum: PWN are extremely efficient accelerators
- MHD models reasonably predict intensity, but magnetic field turbulence is unknown

IXPE observed PWN

- Crab (polarization detection!)
- Vela (polarization detection!)
- MSH 15-52 (analysis ongoing)



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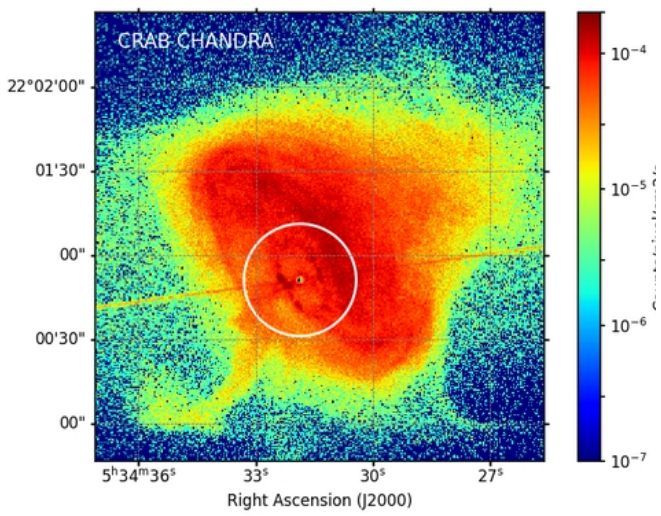
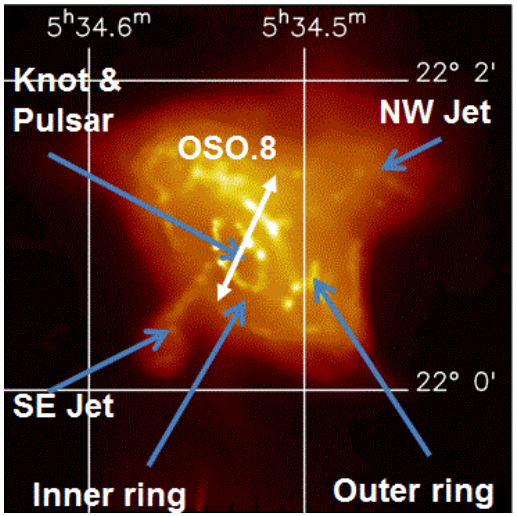
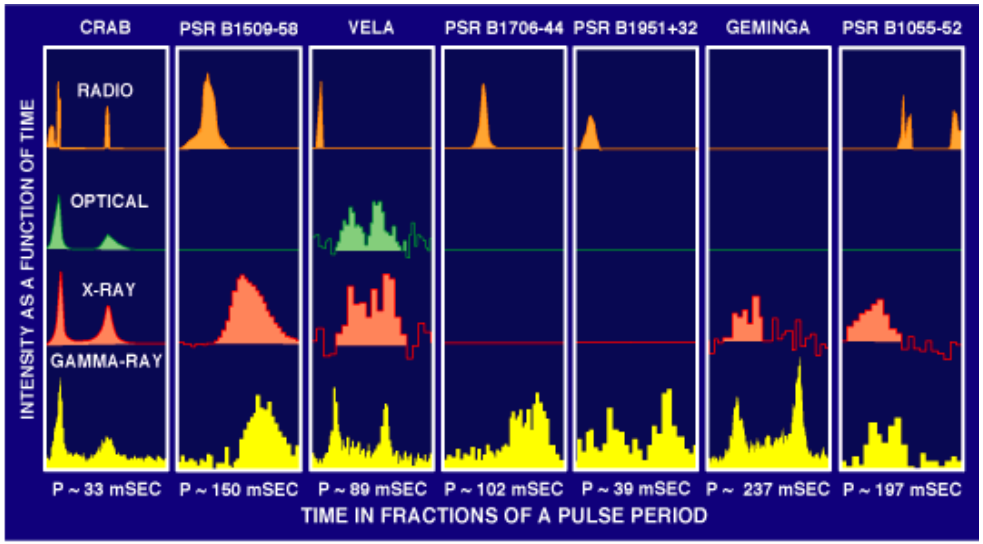
Crab complex







- Complex structures visible in X-rays
- Phase behavior uniquely stable in energy
- Only source with a significant polarization measure in soft X-ray:
  PD ~19%
  PA ~155°
- PolarLight detected a polarization change after a glitch in 2019 (Feng, 2020)

Crab complex polarization

Bucciantini, 2022

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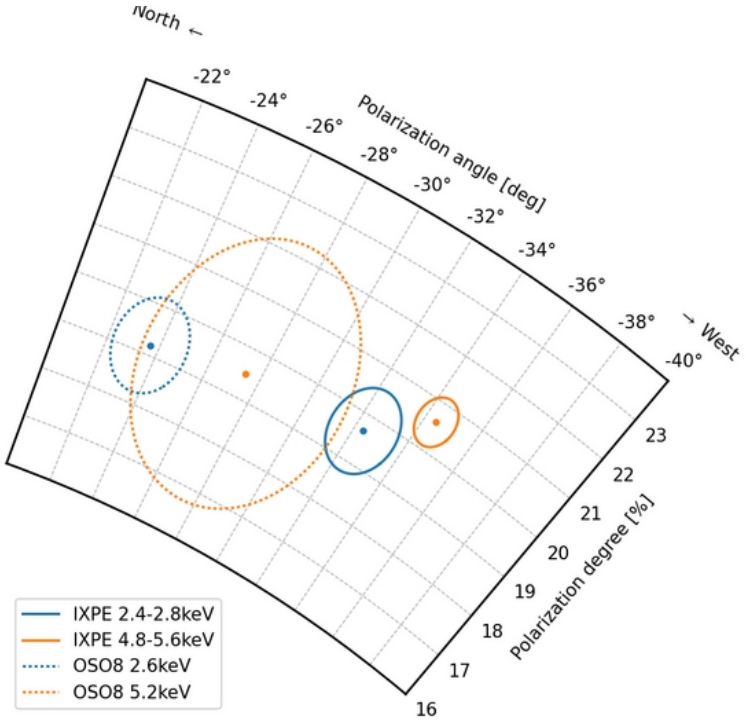

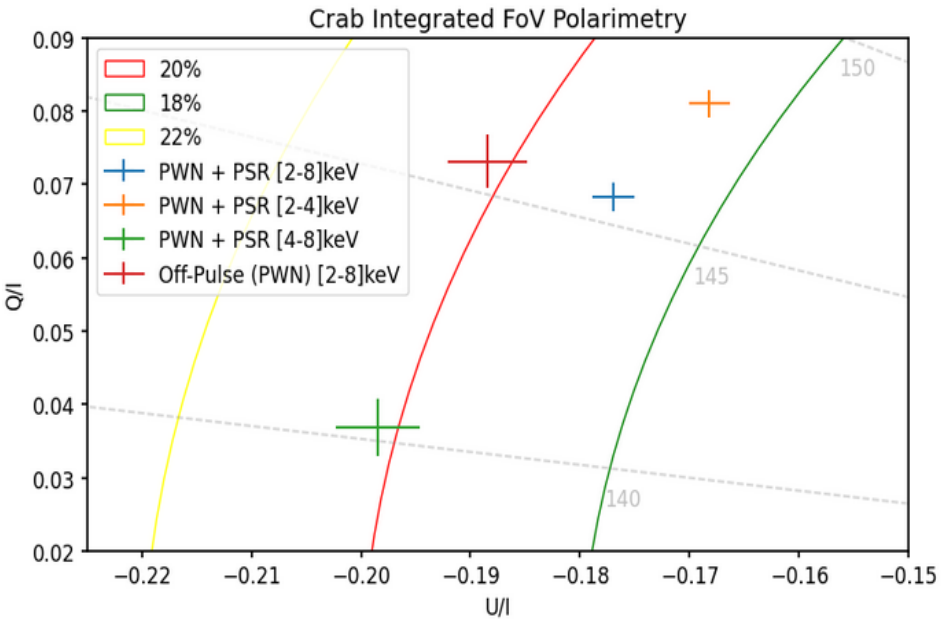

- **Average polarization fraction 20%** (compatible with OSO 8 and Polar Light)
- Polarization angle slightly different from OSO 8
- Modest energy dependence
- Off Pulse polarization is higher (*Nebula more polarized than the Pulsar*)

Space-resolved Crab polarization

Bucciantini, 2022

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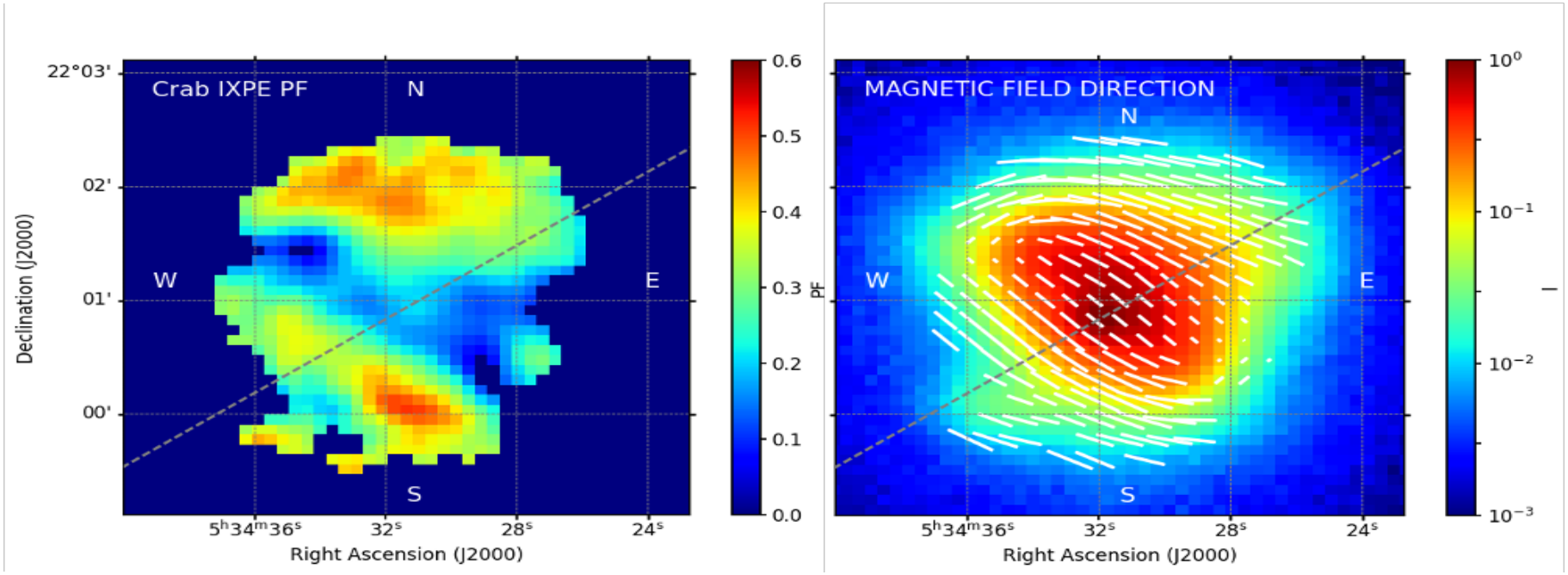

- Magnetic field **mostly toroidal**, in agreement with models
- Polarization reaches 40-50%, high level of MF coherence
- Polarization fraction not symmetric w.r.t. nebular axis, indicates complex turbulence structures

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Crab PSR

Bucciantini, 2022

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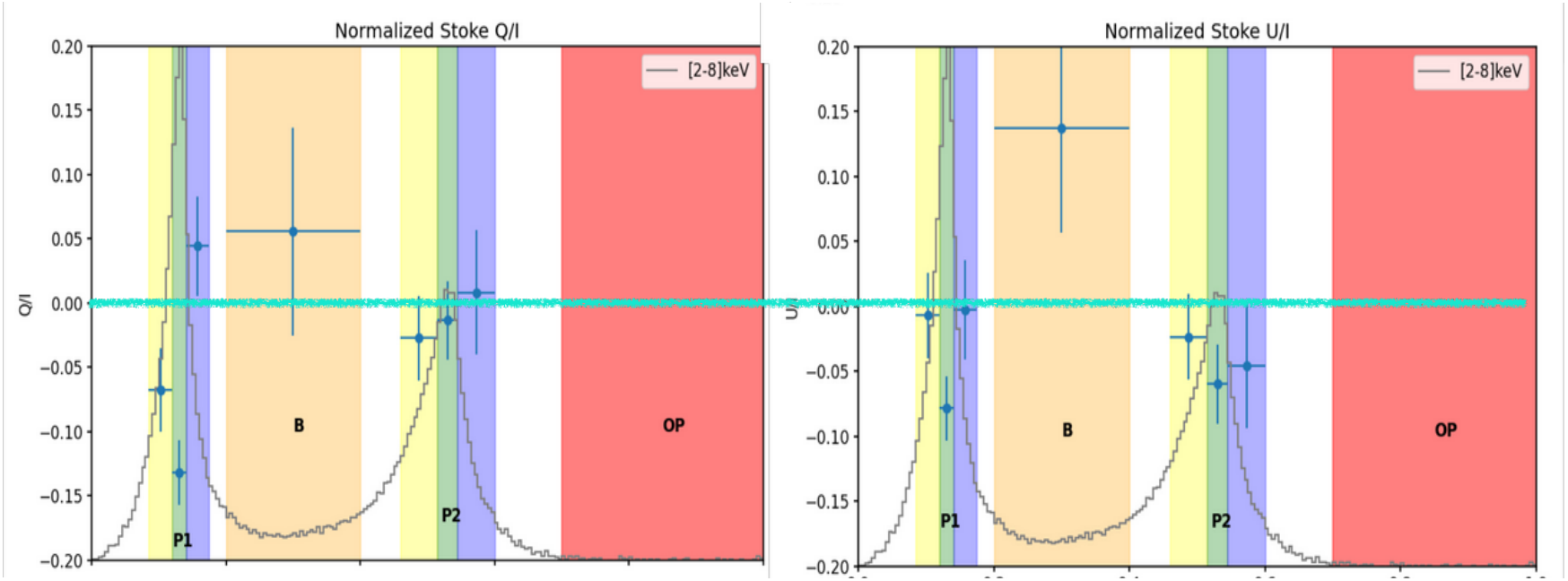

- **Pulsed emission almost unpolarized**
- Marginal detection in P1: $\Pi = 15.4\% \pm 2.5\%$ and $PA = 105° \pm 18°$
- In contrast with optical and hard-X observations
- Not easily explained by current models

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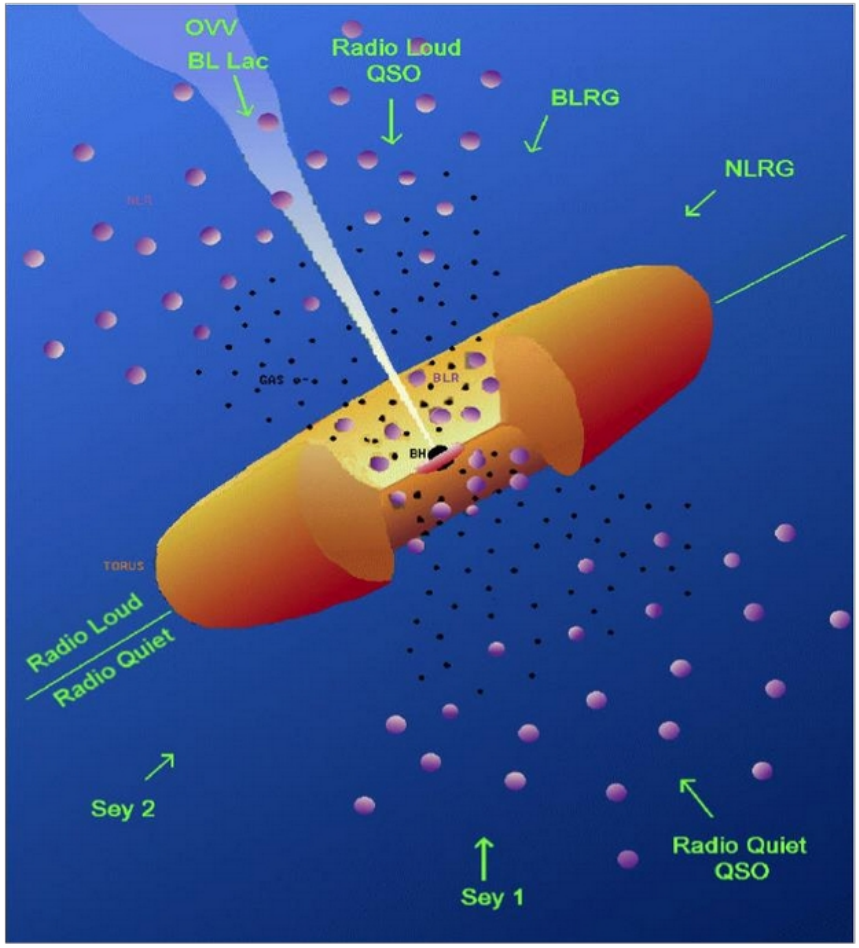
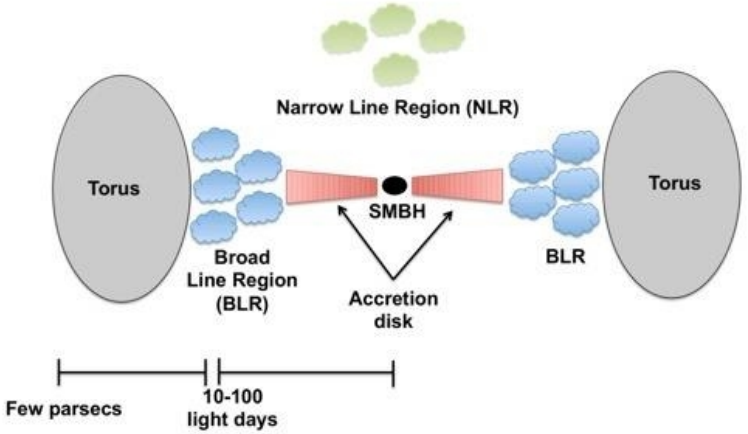
Active Galactic Nuclei





SMBH

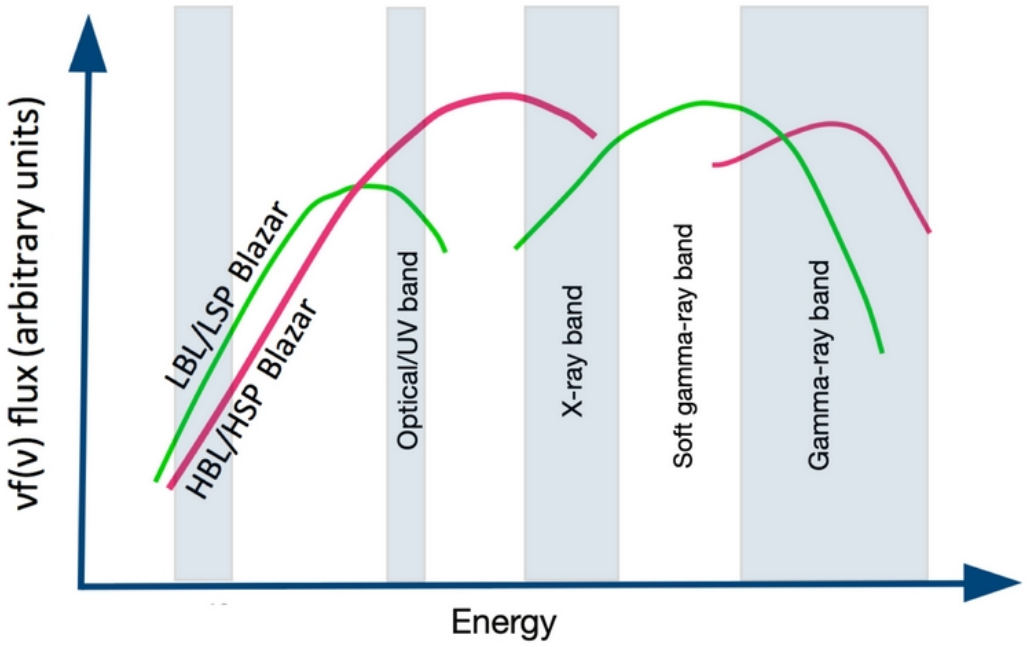
IXPE observed (non blazar) AGNs

- Cen A (upper limit)
- MCG-5-23-16 (upper limit)
- Circinus galaxy

Blazars

Blazars are AGN with the Jet directed towards us

Emission in IXPE energy band can be either **Synchrotron** dominated (HSP) or **inverse Compton** dominated (LSP/FSRQ) or in between (ISP)



IXPE observations:

LSP Blazars
- 3C 454.3
- 3C 273
- 3C 279
- BL Lacertae

ISP Blazars
- S5 0716+71

HSP Blazars
- Mrk 501 (polarization detection!)
- Mrk 421 (polarization detection!)

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Mrk 501

Liodakis, 2022

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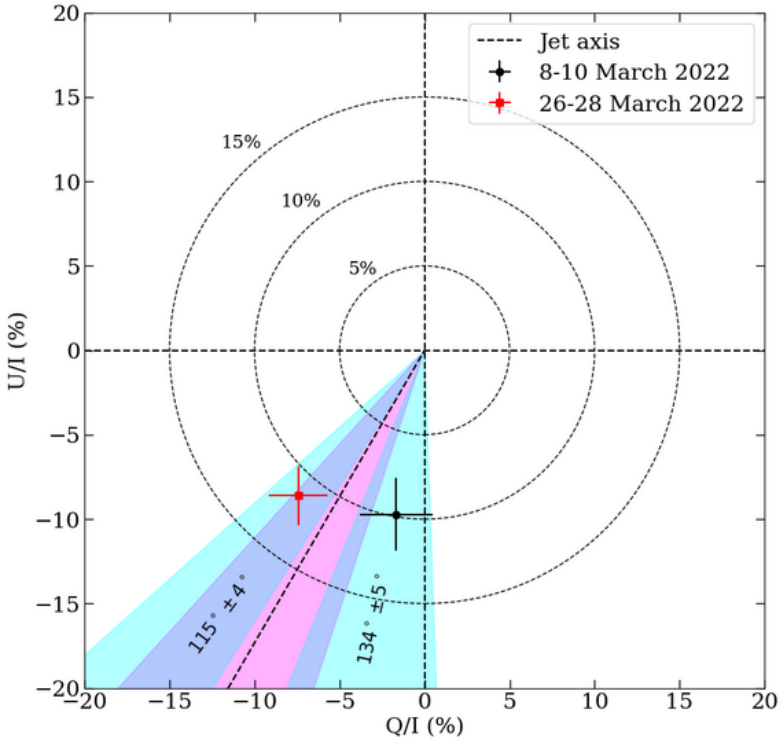

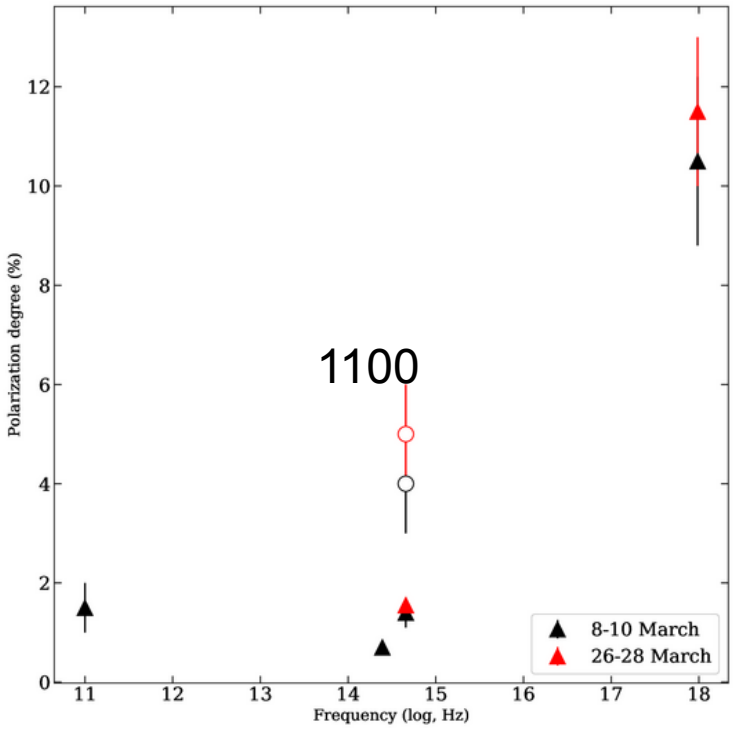

- 2 IXPE observations, source in average state
- X-ray polarization angle *aligned with jet emission*
- MW polarimetric campaign: *PD increases with energy*, PA stays aligned

Mrk 501

Liodakis, 2022

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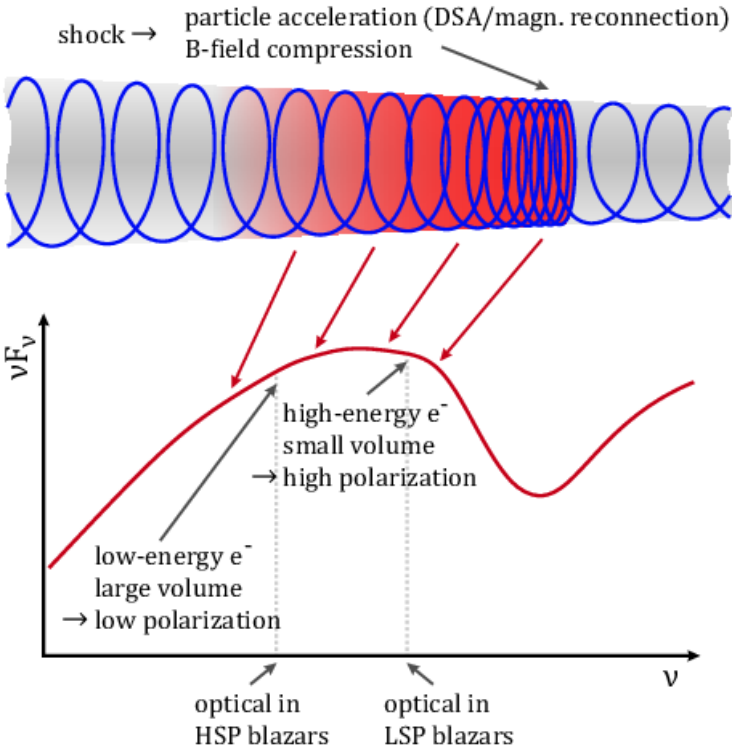
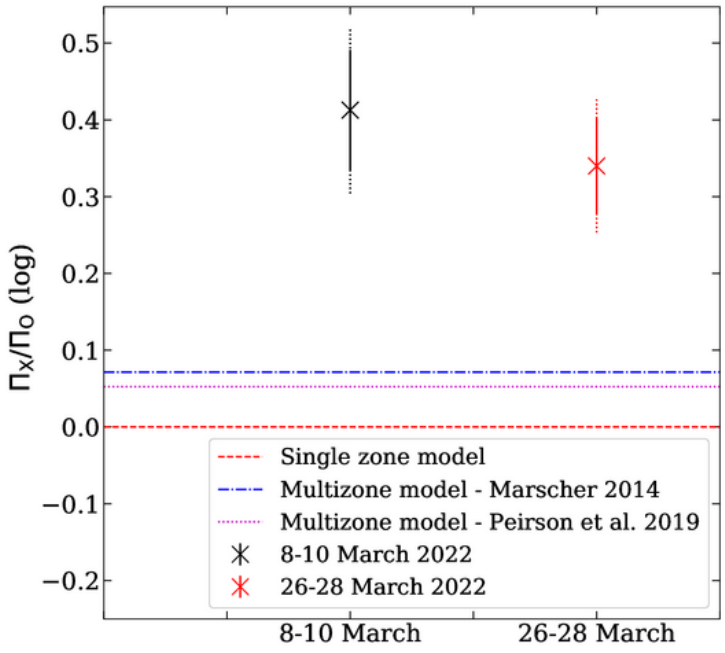


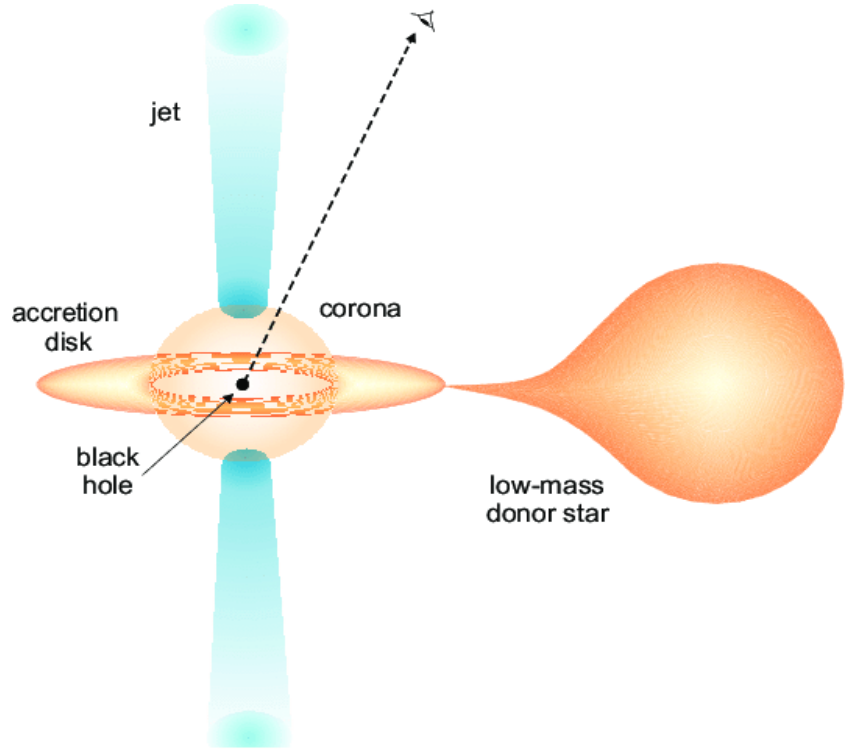


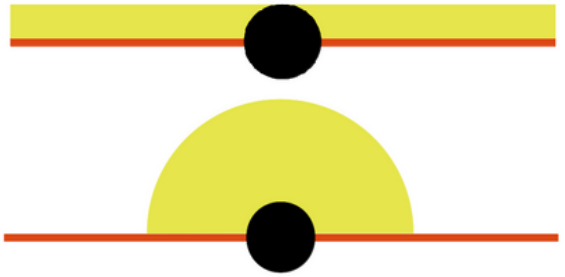
Energy stratified model Marscher, 1985 Tavecchio, 2018

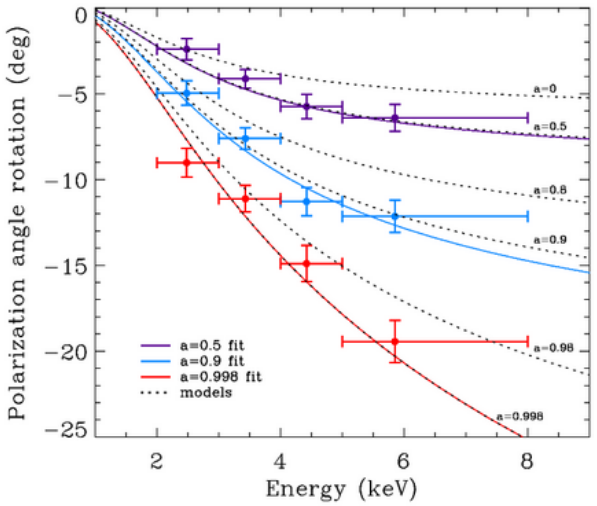
Particles become energized over a limited volume - e.g. at a shock front - and then advect or diffuse away from that region.

In the process, the electrons lose energy to radiation, and so emit at progressively decreasing frequencies

Galactic Black Holes: microquasars







- Miniature version of AGN
- **Hard State**: geometry of the corona, role of the jet
- **Soft State**: geometry of the accretion disk, spin of the Black Hole

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Imaging
X-Ray
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Explorer

Cygnus X-1

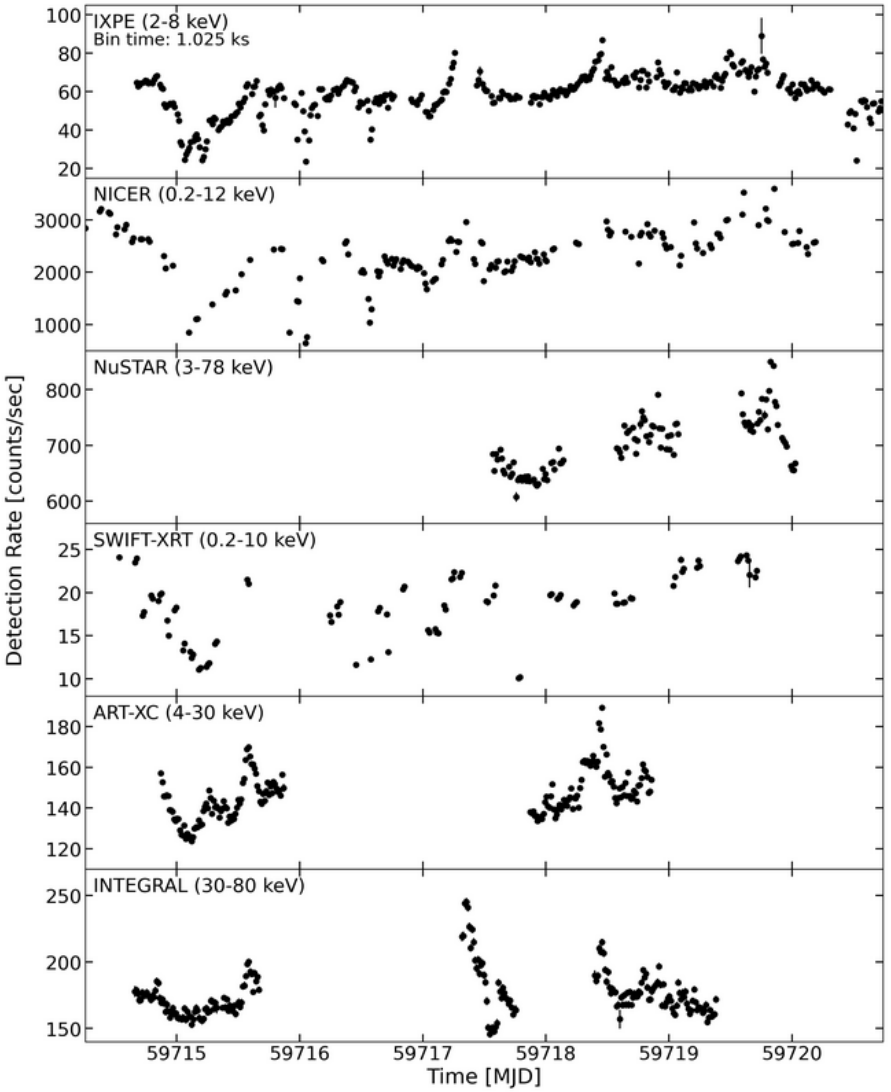
Krawczynski, 2022

Persistent HMXRB

- MBH = 21.2±2.2 M⊙
- M2= 40.6 M⊙
- P = 5.6 days
- d = 2.22 kpc
- i = 27° → *low polarization expected*

MW observation campaign

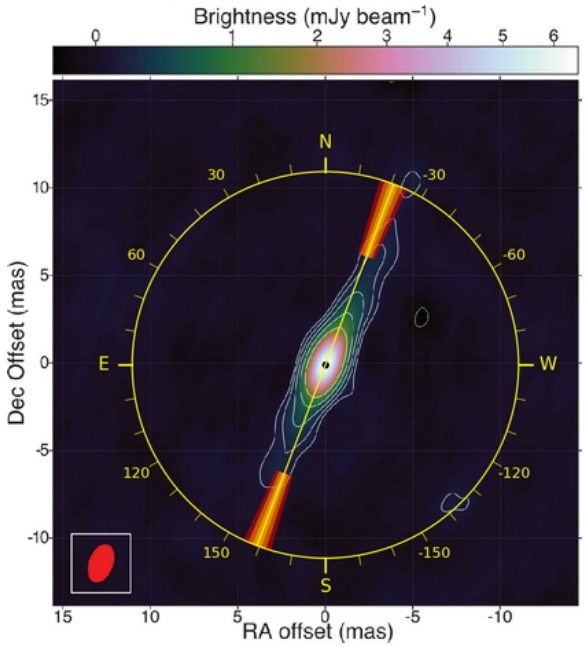
- 242 ksec IXPE observation
- <u>X-ray spectroscopy and timing:</u> NICER, NuSTAR, Swift, ART-XC, INTEGRAL
- <u>Optical polarimetry:</u> Tohoku, Skinakas



IXPE Imaging X-Ray Polarimetry Explorer

Cygnus X-1

Krawczynski, 2022



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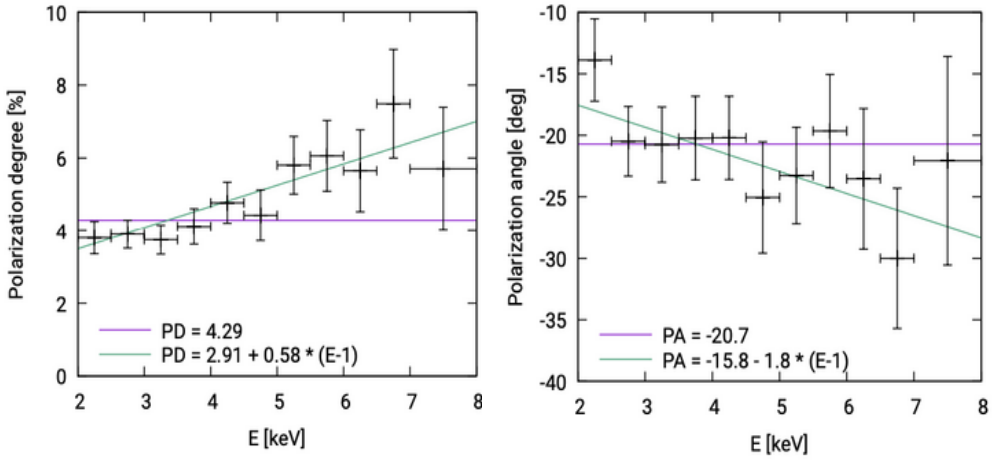
- Emission dominated by Compton scattering in the Corona (90% of the flux in 2-8 keV)
- **Unexpectedly high polarization detected: Π = (4.0 ± 0.2)%, PA aligned with JET axis**
- Optical polarization ~1%, still aligned (with some variability)
- Polarization data exclude popular 'lamp post' models, where the corona is e.g. a plasma column



- *Coronal plasma is laterally extended in the plane of the accretion disk*
- **Requires inclination > 45°**
- *Accretion disk is misaligned with the orbit plane*
  - Warped? Precession?

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Conclusions

IXPE has opened a new window in the X-ray sky, observing for the first time the polarization in the [2-8] keV band of ~30 different sources (with >10 currently confirmed non-null detections).

IXPE has:

- Unveiled the geometry of binary systems with BH or NS
- Shed light on the emission processes in Blazar jets
- Probed the level of turbulence of the magnetic field in galactic accelerators (SNR, PWN)
- Questioned current models of pulsar polarization
- Tested physics of light emission and propagation in presence of extreme magnetic and gravitational fields

Guest Observer program will select future (2024) targets.

Backup

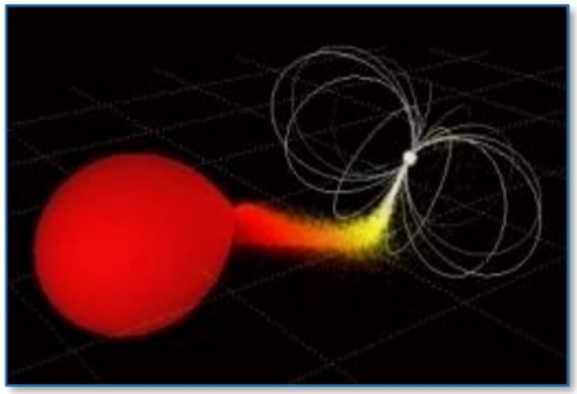
Compact magnetized objects

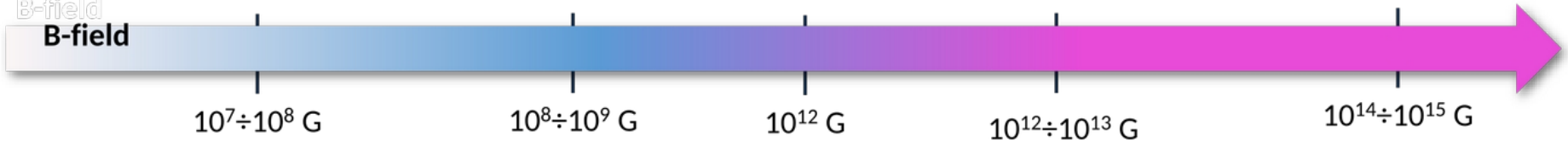
Neutron stars (isolated or in binary systems) are one of the most promising target for IXPE

Magnetic Cataclysmic Variables and Novae

NSs accreting matter from a companion star

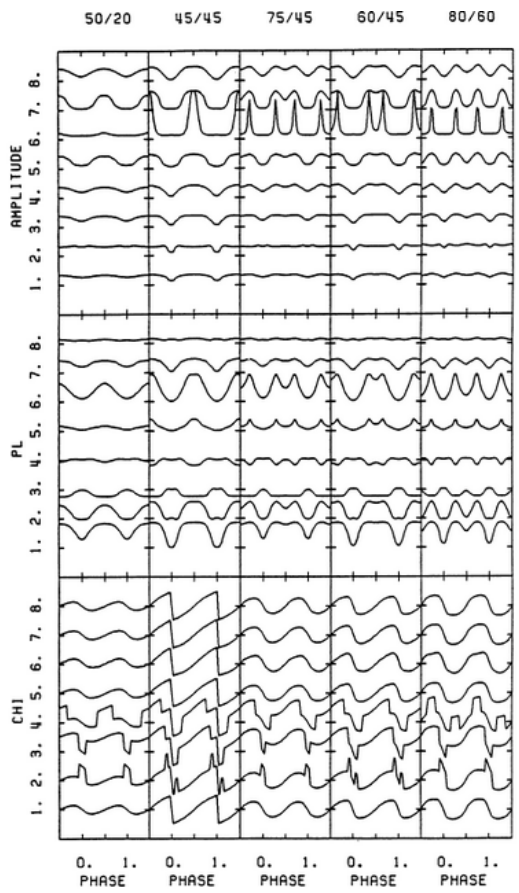
Isolated NSs (rotation powered pulsars, magnetars)

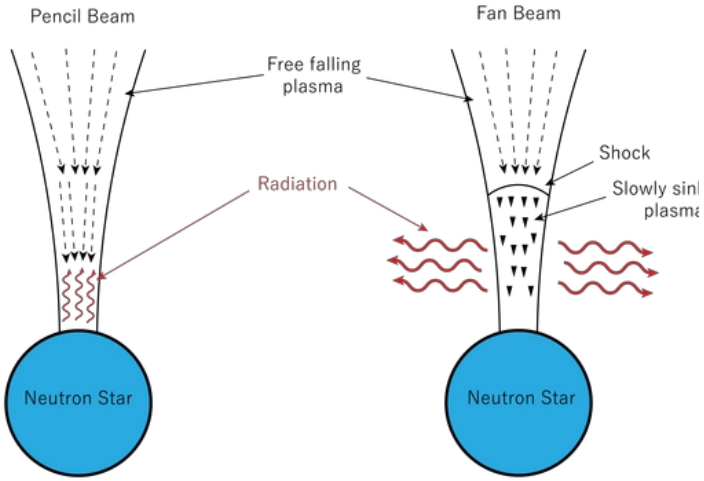




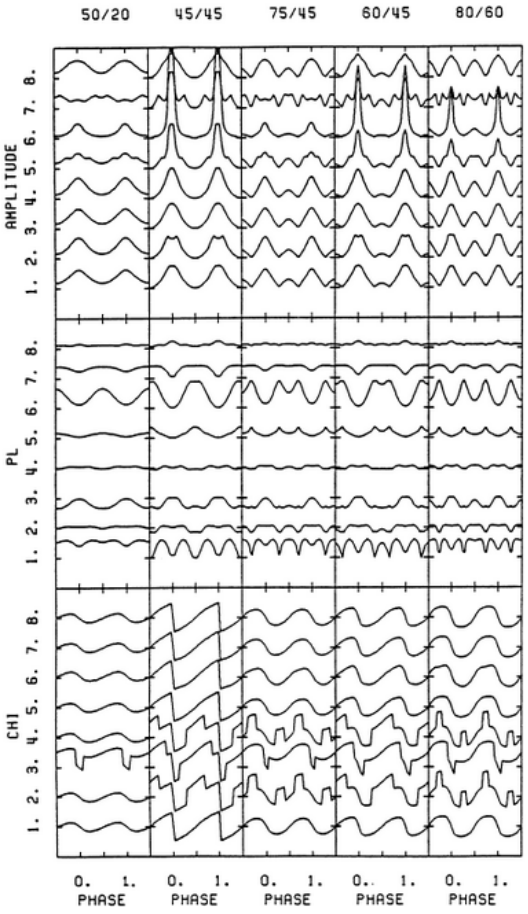
Strongly magnetized Accreting NS

- Very different polarization patterns predicted by different models





Meszaros et al. 1988



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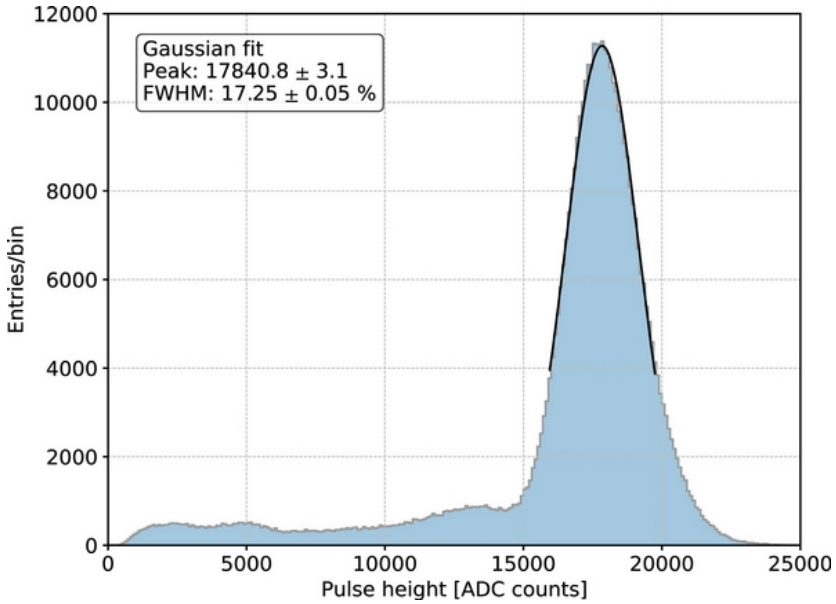
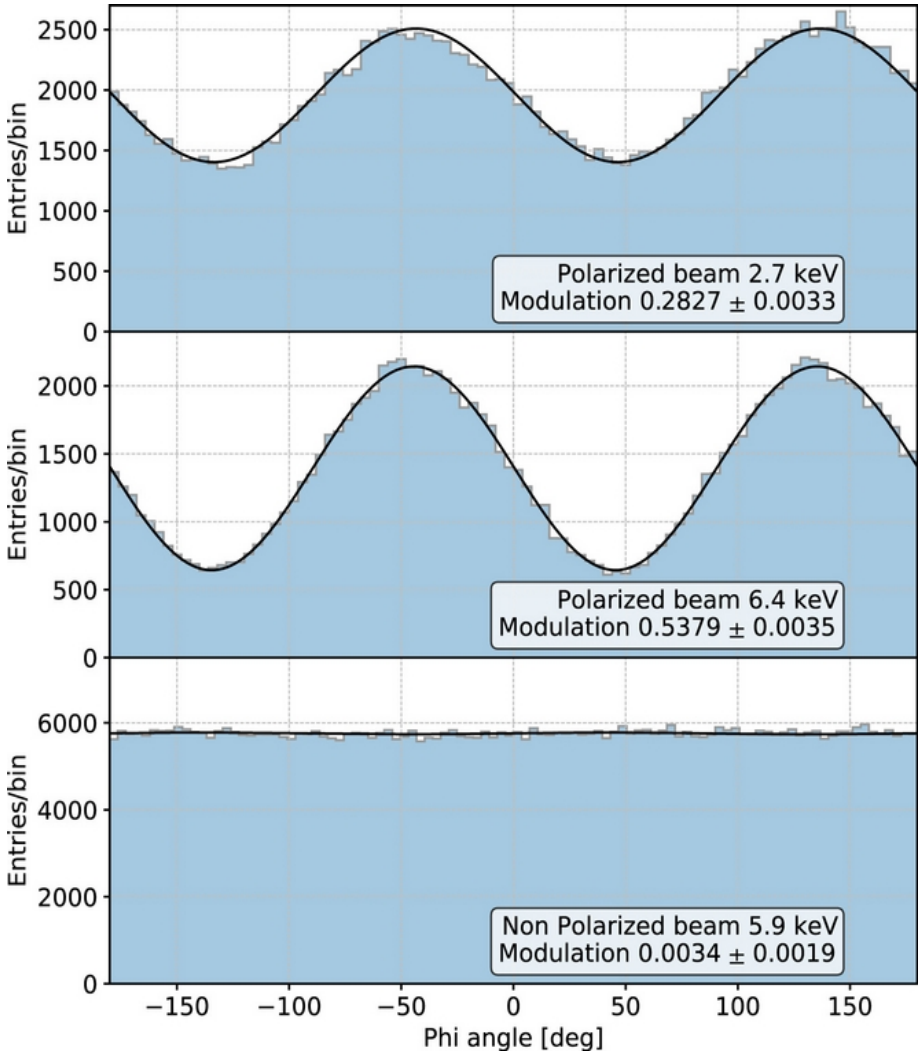
GPD performances





- 17% FWHM @5.9 keV
- μ = 0.54 @6.4 keV
  0.28 @2.7 keV
- ε > 20% @2.0 keV
- ~1 ms dead time