IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

agenzia spaziale italiana

X-ray polarimetry of accreting neutron stars: First results from the Imaging X-ray Polarimetry Explorer

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Helsinki

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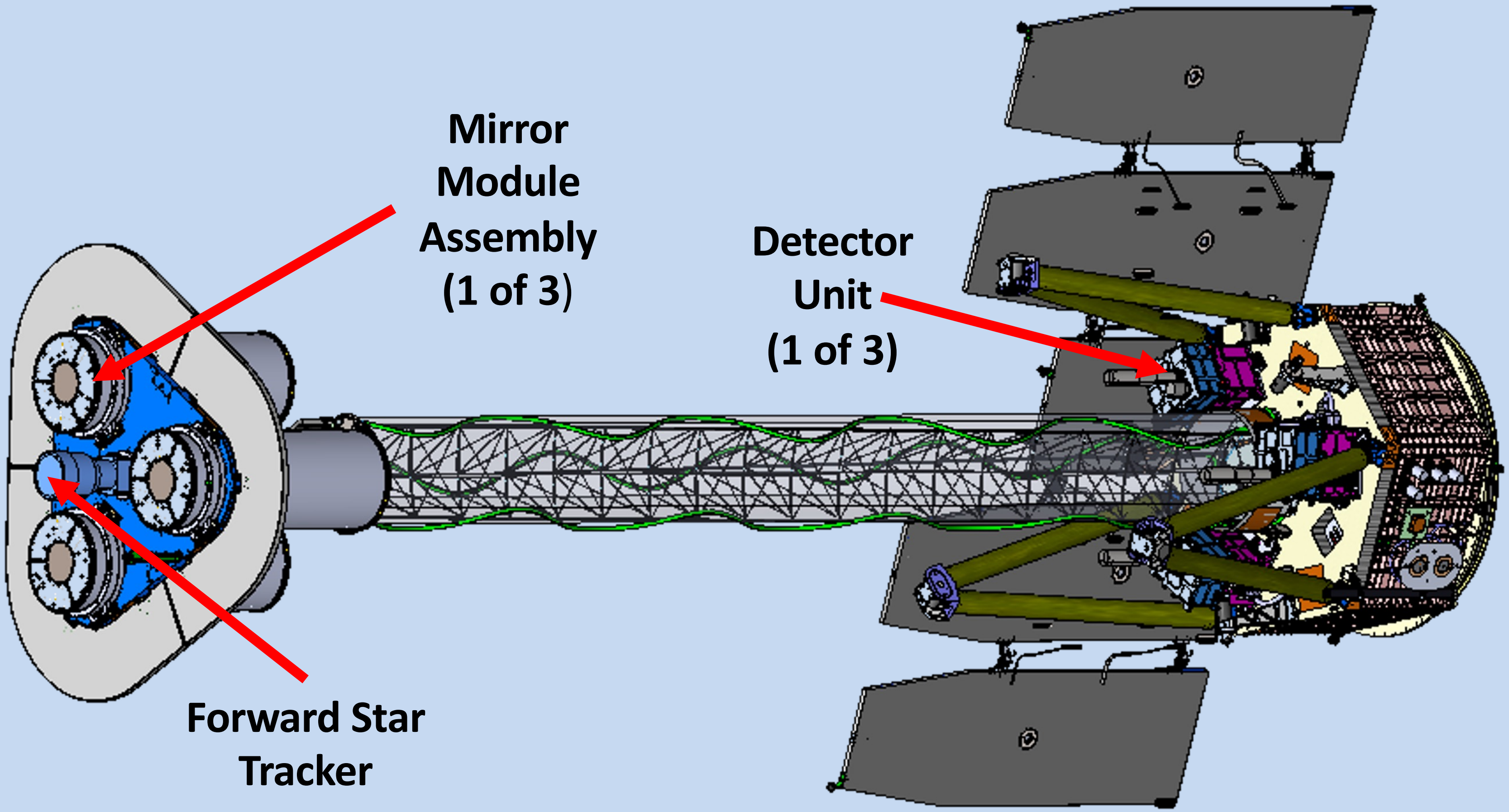
Some of the goals

- **Determining mass and radius of accreting millisecond pulsars which would constrain the equation of state of cold dense matter.**

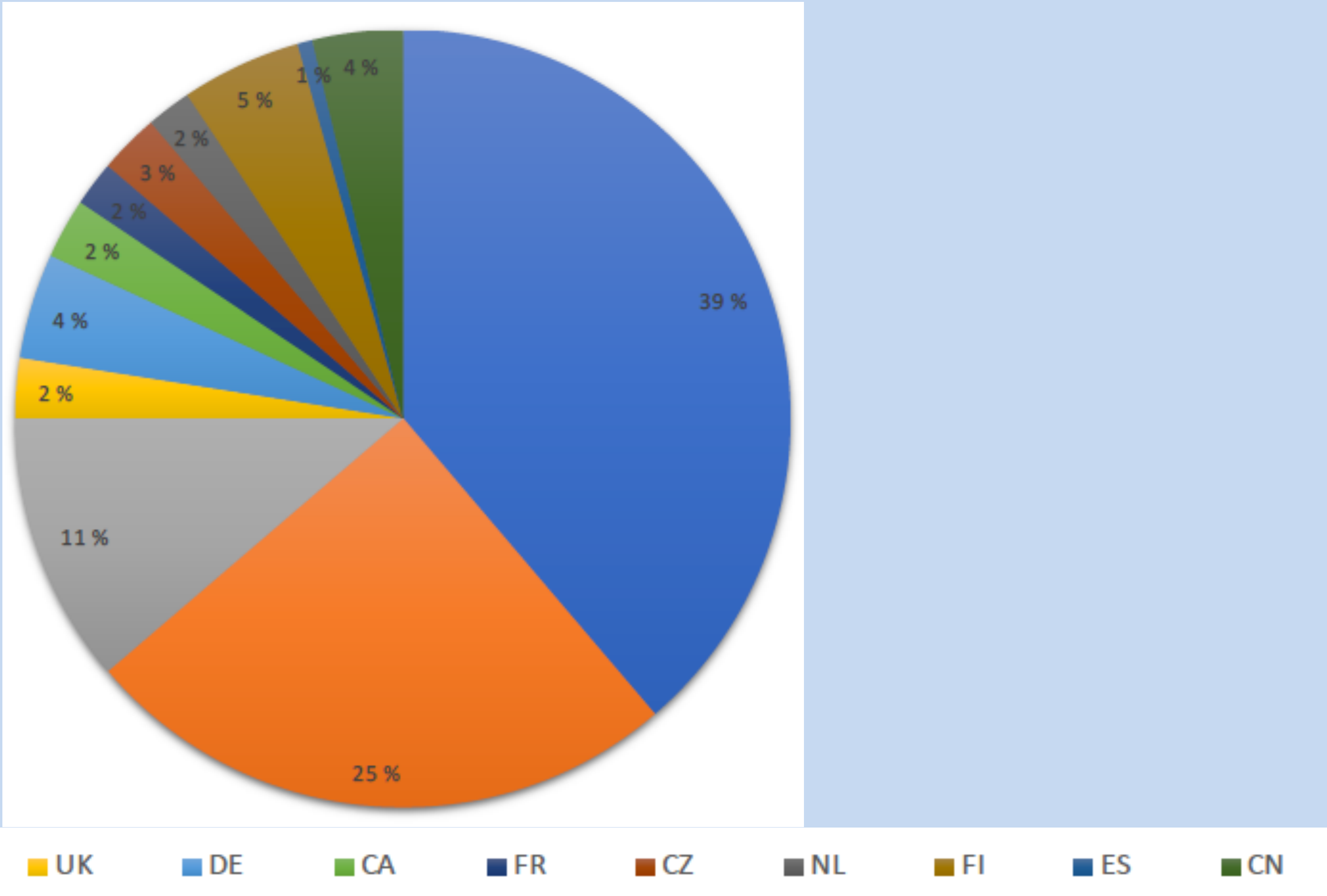
- **Learning about accretion physics in strong magnetic field.**

IXPE launched on 2021 Dec 9



5.2 m total length
4.0 m focal length

The IXPE Team



160 scientists from 12 countries

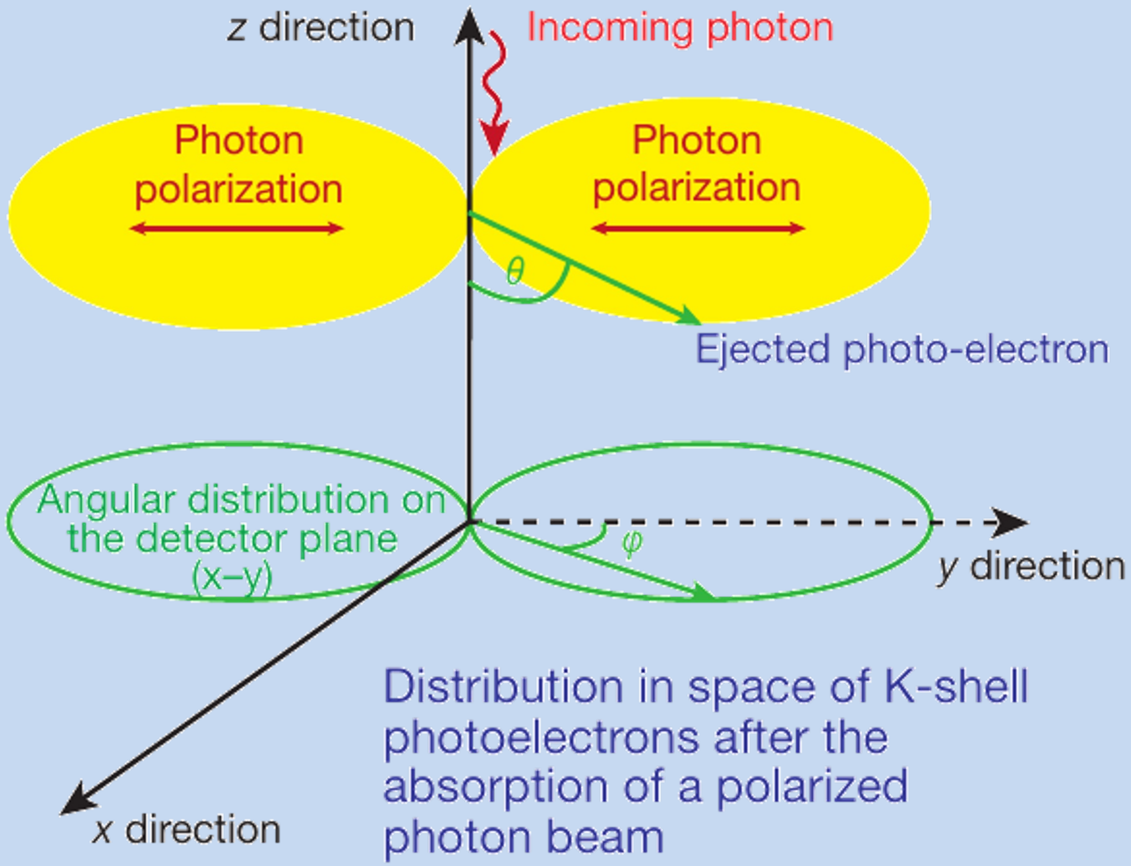
IXPE's former PI

Dr. Martin Weisskopf, former principal investigator for the Imaging X-ray Polarimetry Explorer mission and chief scientist for X-ray astronomy at NASA's Marshall Space Flight Center in Huntsville, Alabama.

Martin Weisskopf and colleagues from Columbia University in 1971 pose with the Aerobee-350 sounding rocket they used to detect X-ray polarization from a celestial object – the Crab Nebula – for the first time. Left to right are Robert Novick, Gabriel Epstein, Weisskopf, Richard Wolff, and Richard Linke.

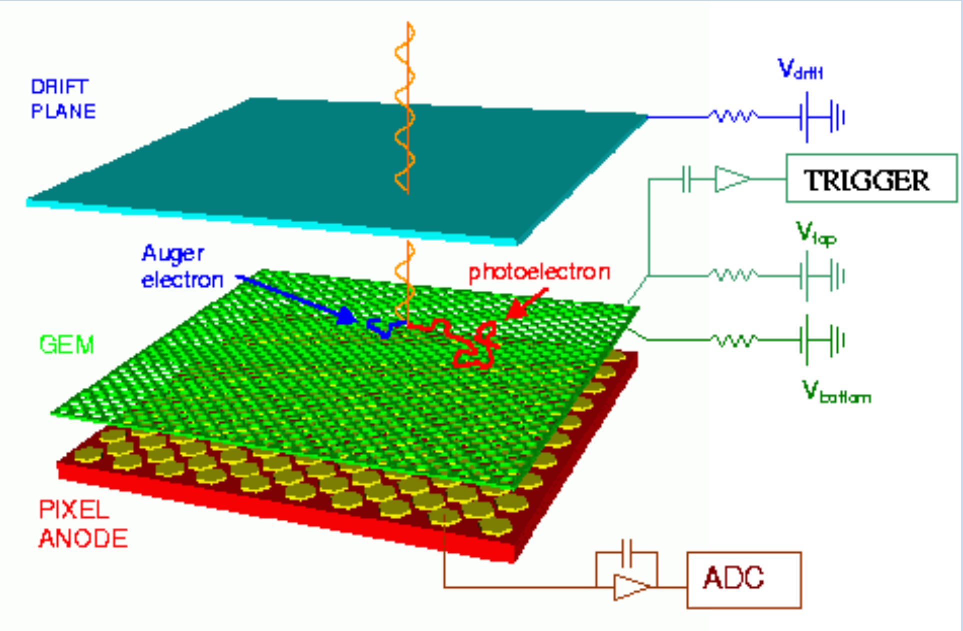
Detection Principle

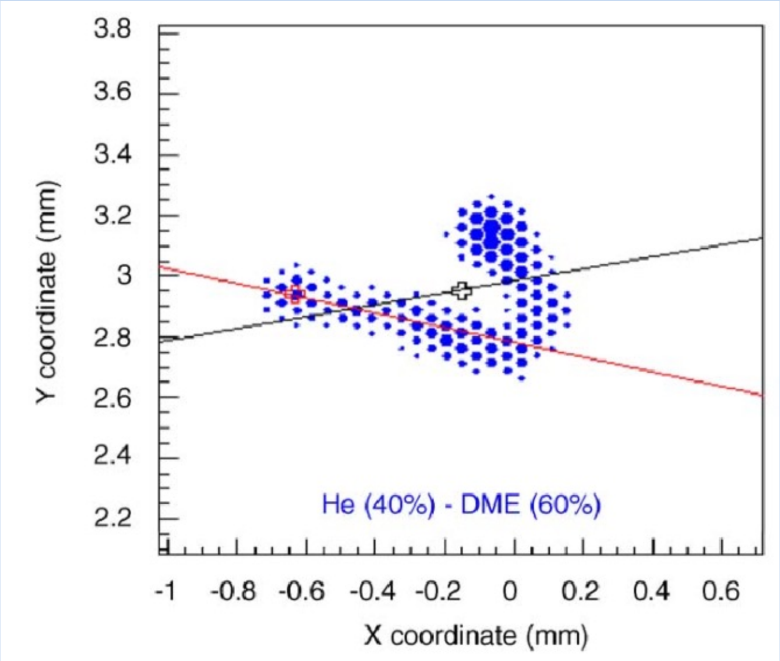
- **The detection principle is based upon the photoelectric effect**



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

Gas Pixel Detector

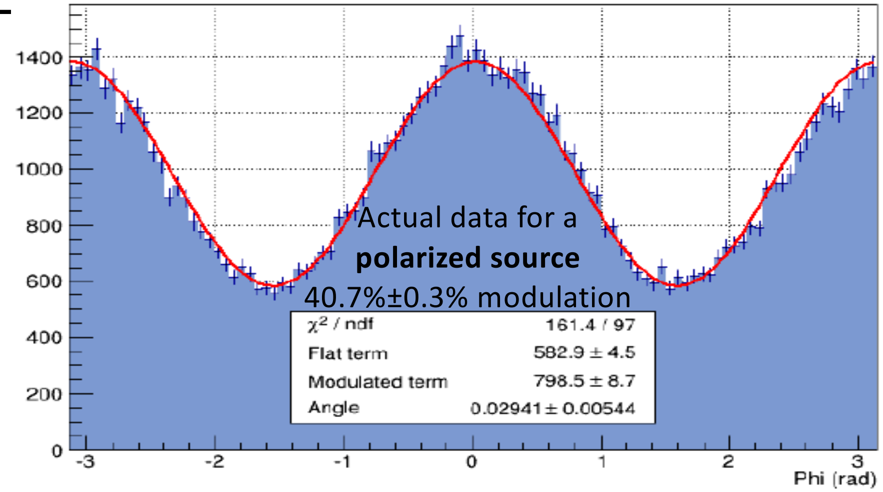


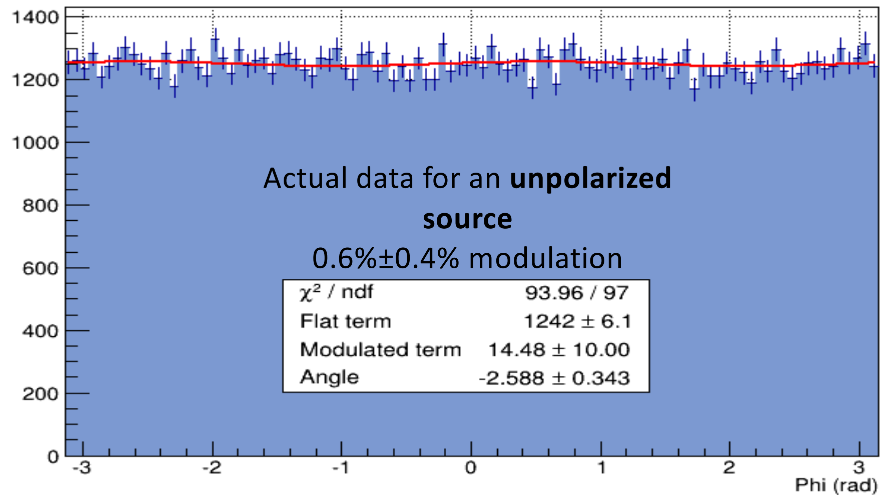


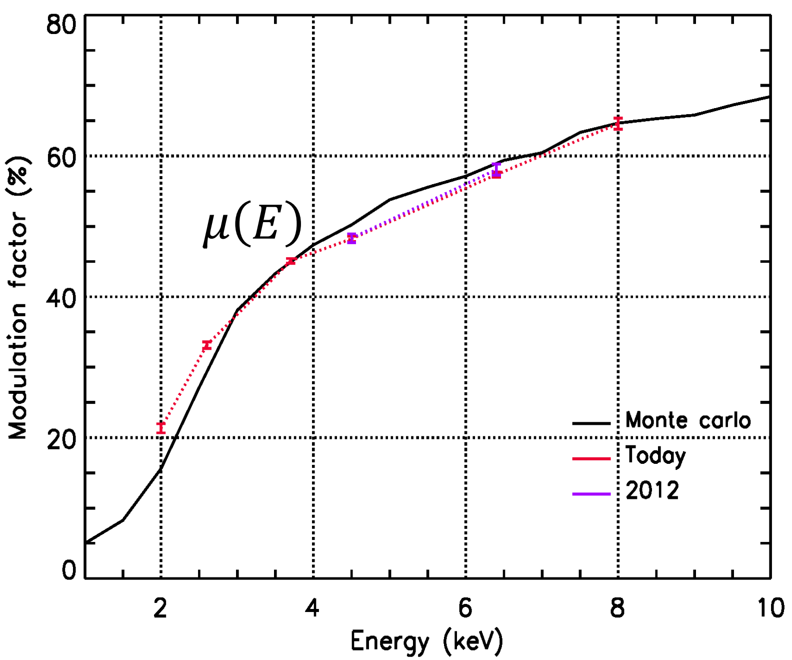
- Include a Filter & Calibration wheel with
  - Filters for specific observations (very bright sources, background)
  - Calibrations sources (polarized and unpolarized, gain)

POLARIZATION FROM MODULATION HISTOGRAM AND CALIBRATED MODULATION FACTOR

- **Polarization degree**
  - $\Pi = \text{Modulation}/\mu(E)$







- **Polarization degree**
  - $\Pi = \text{Modulation}/\mu(E)$

Targets observed by IXPE in first 6 months

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1. **Accreting X-ray pulsars**
   - Her X-1 (Nature Astronomy)
   - Cen X-3 (ApJ Letters)
   - 4U 1626-67 (ApJ)
   - Vela X-1 (ApJ)

2. **Magnetar(s)**
   - 4U 0142+61 (Science)

3. **Accreting non-magnetic neutron stars**
   - GS 1826−238 (ApJ)
   - Cyg X-2 (MNRAS)

4. **Pulsars/Pulsar Wind Nebulae**
   - Crab (Nature Astronomy)
   - Vela (Nature)

5. **Supernova remnant(s)**
   - Cas A (ApJ)

6. **Stellar-mass black holes**
   - Cyg X-1 (Science)

7. **Active galaxies**
   - MCG−5-23-16 (MNRAS)
   - Cen A (ApJ)
   - Mrk 501 (Nature)
   - Mrk 421 (ApJ)
   - 3C 454.3
   - 3C 273
   - 1ES 1959+6520
   - 3C 279

8. **Sgr A* complex**

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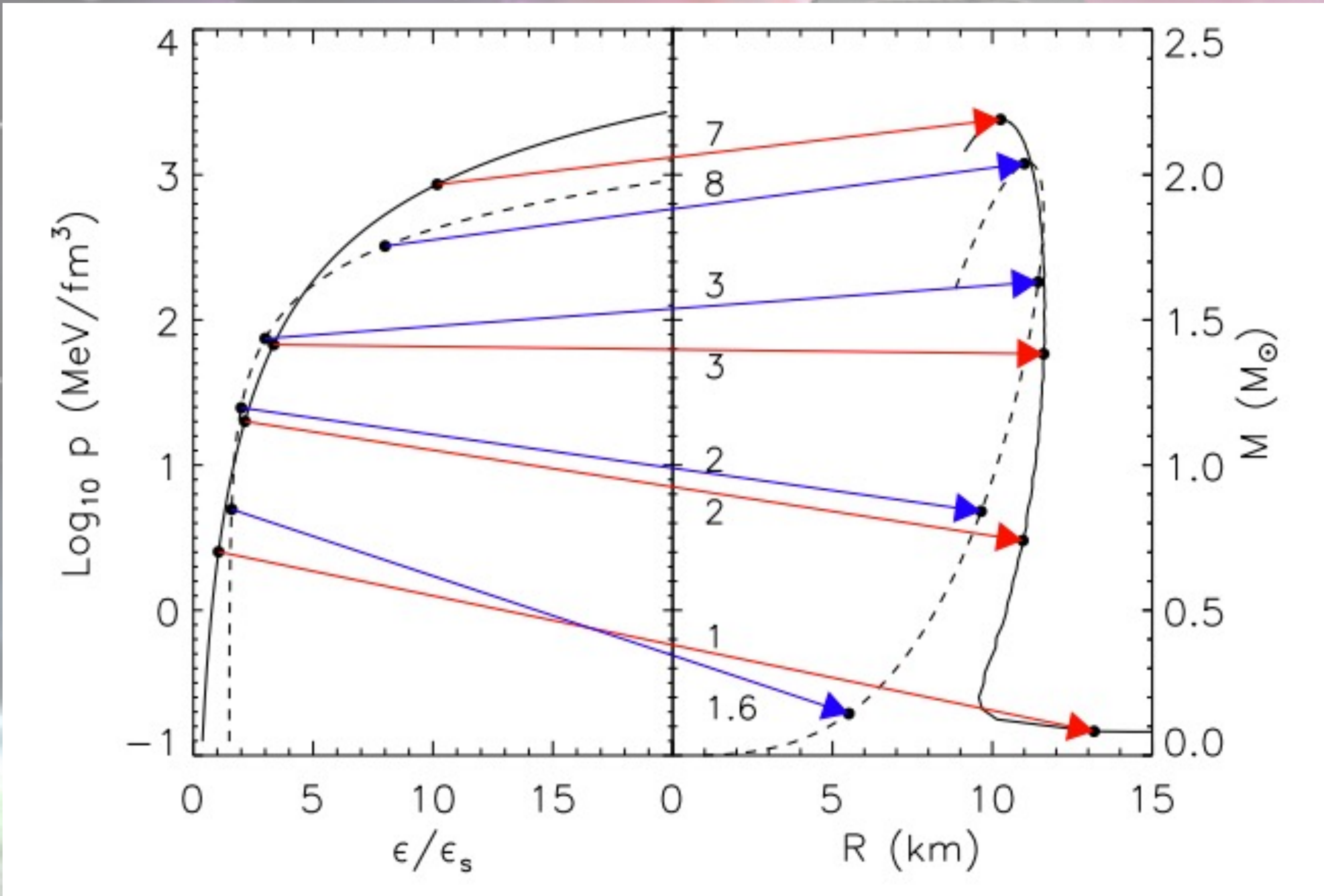
EoS vs neutron star M-R



Lattimer 2012

Neutron star M-R measurements

- **How to measure M?**

  Radio pulsars & X-ray binaries

- **How to measure R?**

  X-ray bursts

  Gravitational wave signal

  Accreting ms pulsars

  Rotation-powered ms pulsars (Salmi's talk)

X-ray bursts from 4U 1702-34

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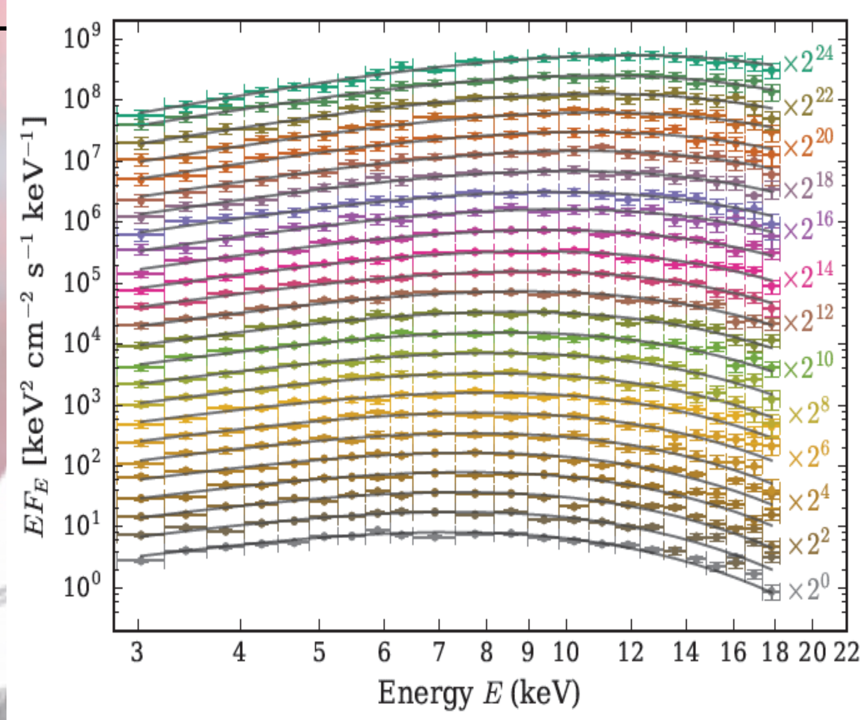
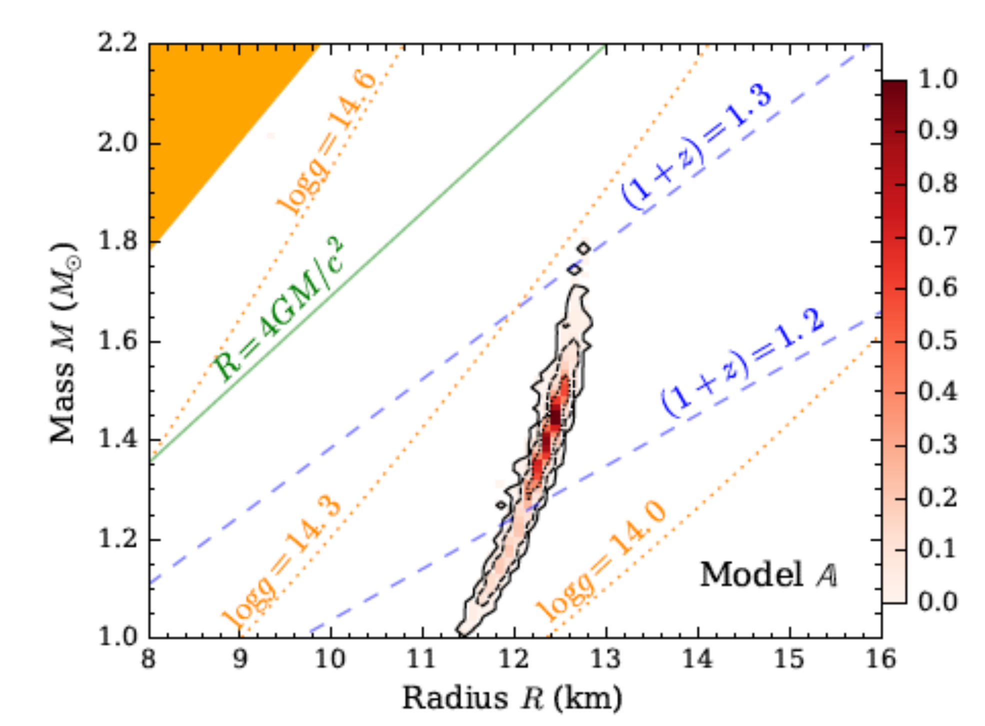
Direct fits to the X-ray burst spectra with the NS atmosphere models.

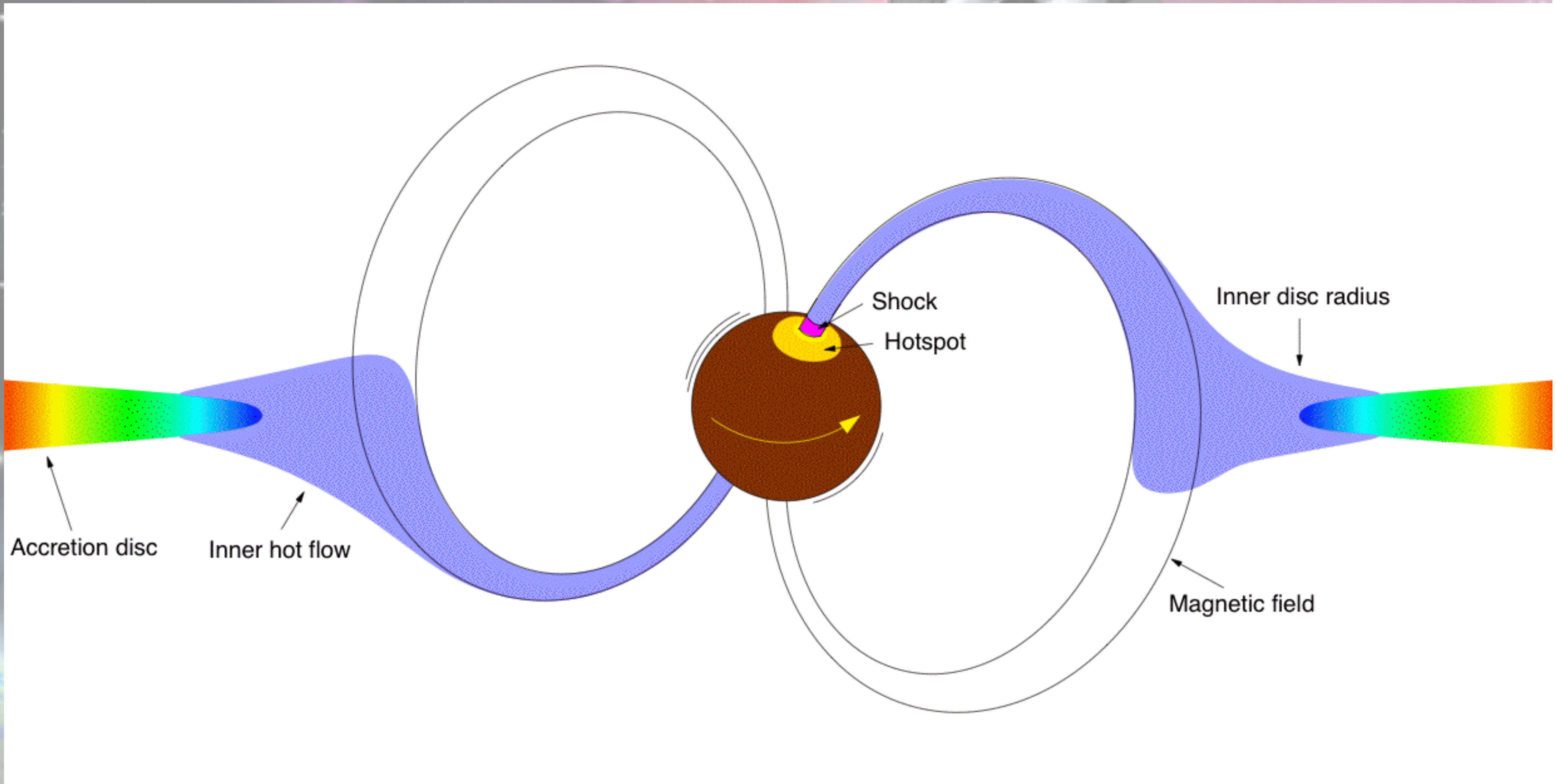




$11.8 < R_{1.4} < 12.4$ km
(pure helium)

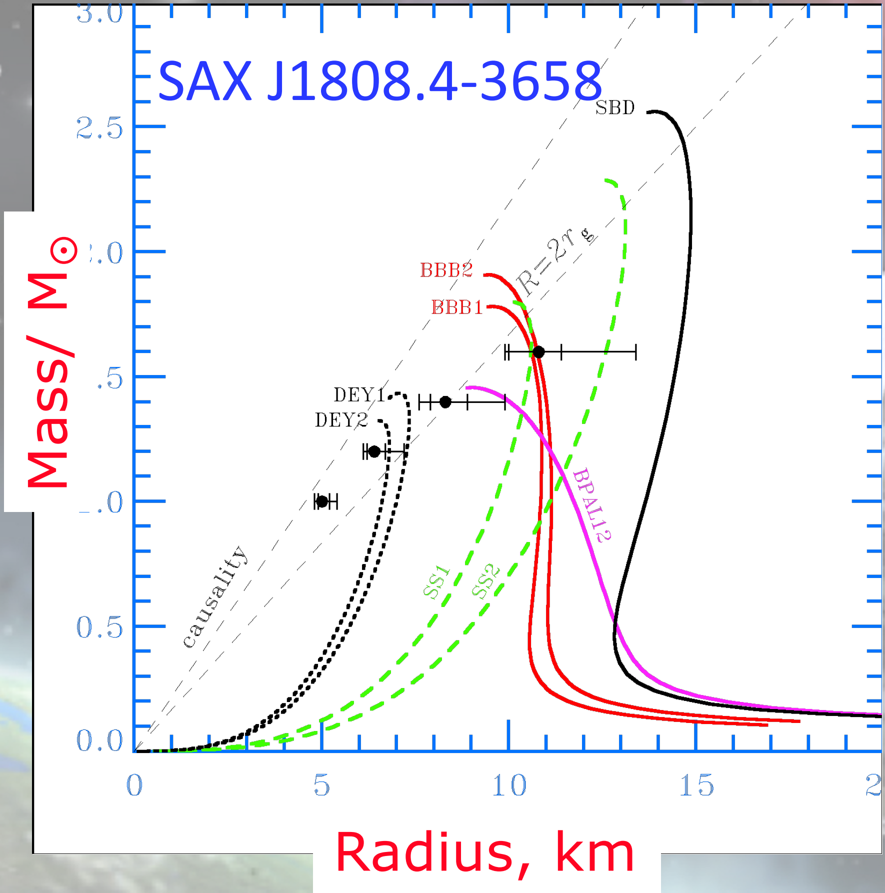
Nättilä et al. 2017

Accreting ms pulsars

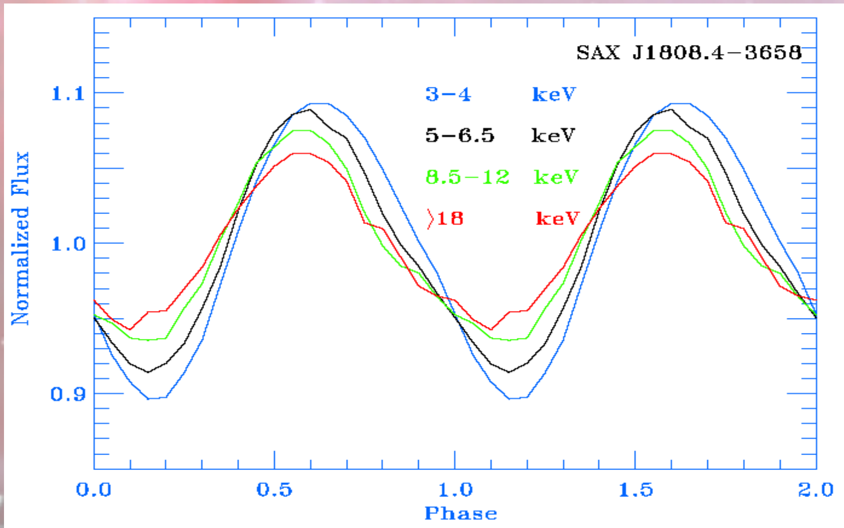


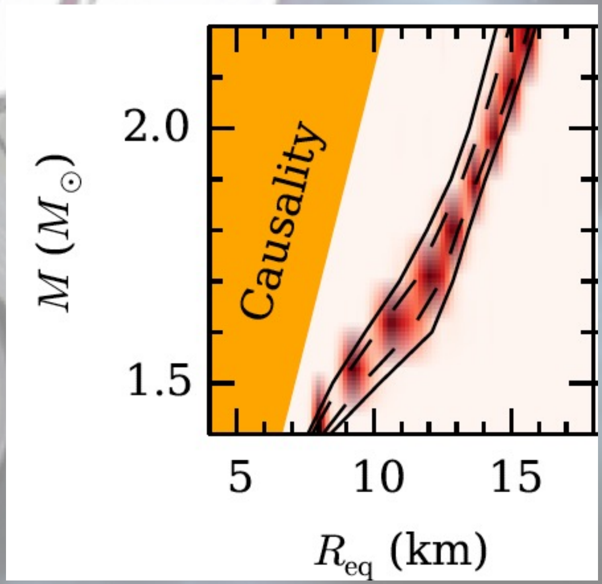
Accreting ms pulsars

Information about M and R is encoded in the pulse profile.



Poutanen & Gierlinski 2003



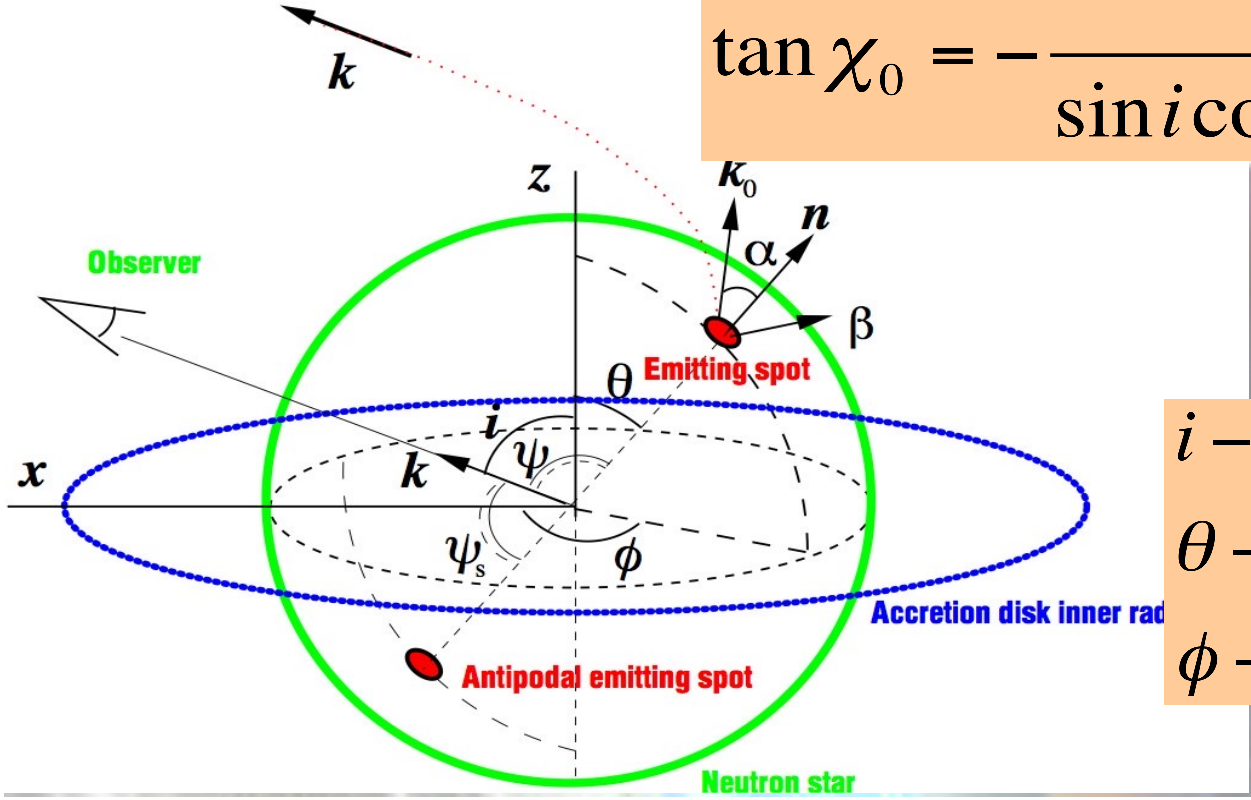


Salmi et al. 2018

X-ray polarization in AMPs

- Radiation coming from hot spots is polarization due to electron scattering
- Polarization provides geometrical information. Apply rotating vector model (RVM) of Radhakrishnan & Cooke (1969) or its relativistic versions (Viironen & Poutanen 2004, Poutanen 2020, Loktev et al. 2020).

$$\tan \chi_0 = -\frac{\sin\theta \sin\phi}{\sin i \cos\theta - \cos i \sin\theta \cos\phi}$$



i – inclination

θ – magnetic inclination

ϕ – pulsar phase

X-ray polarization in AMPs

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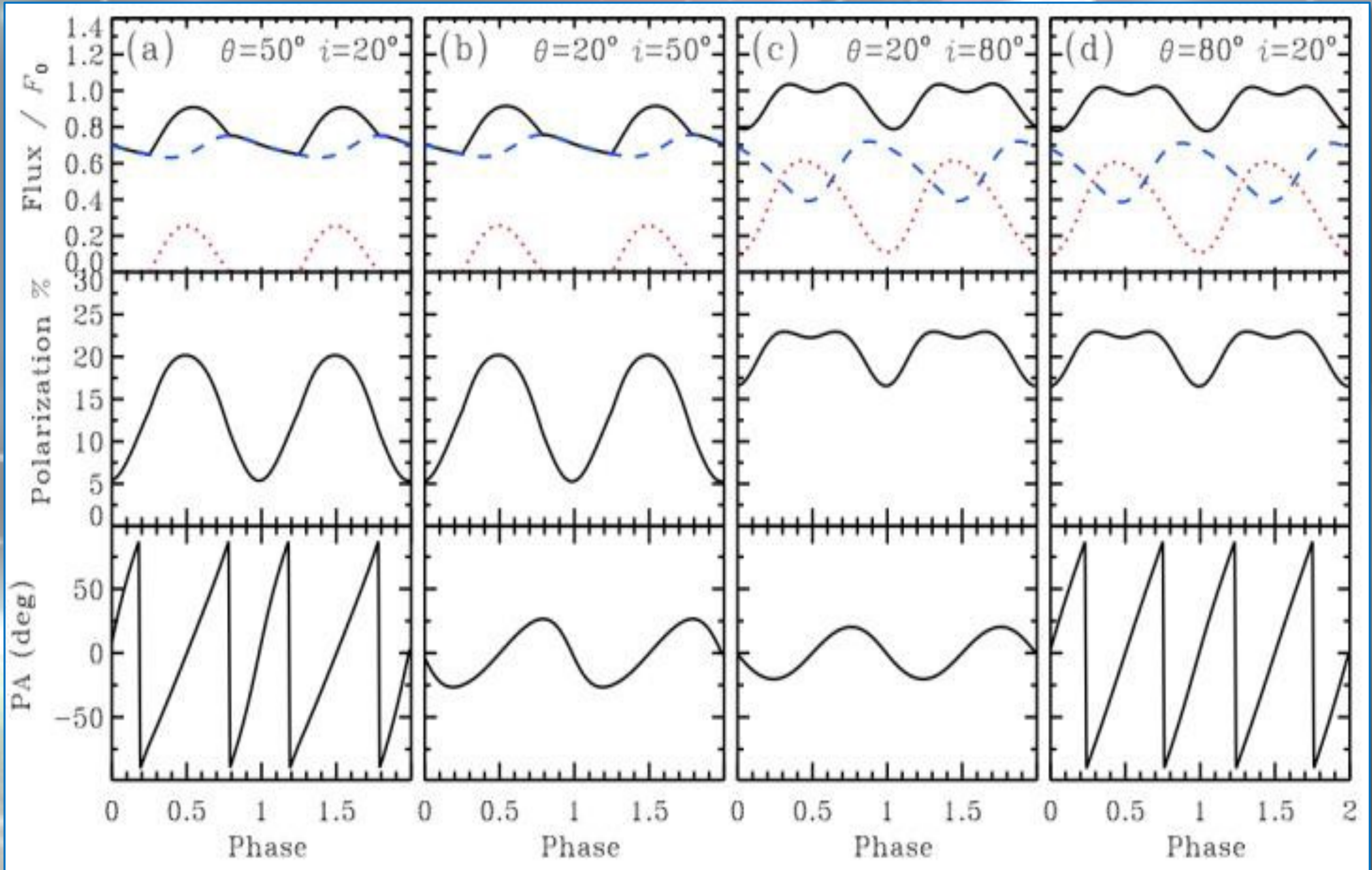

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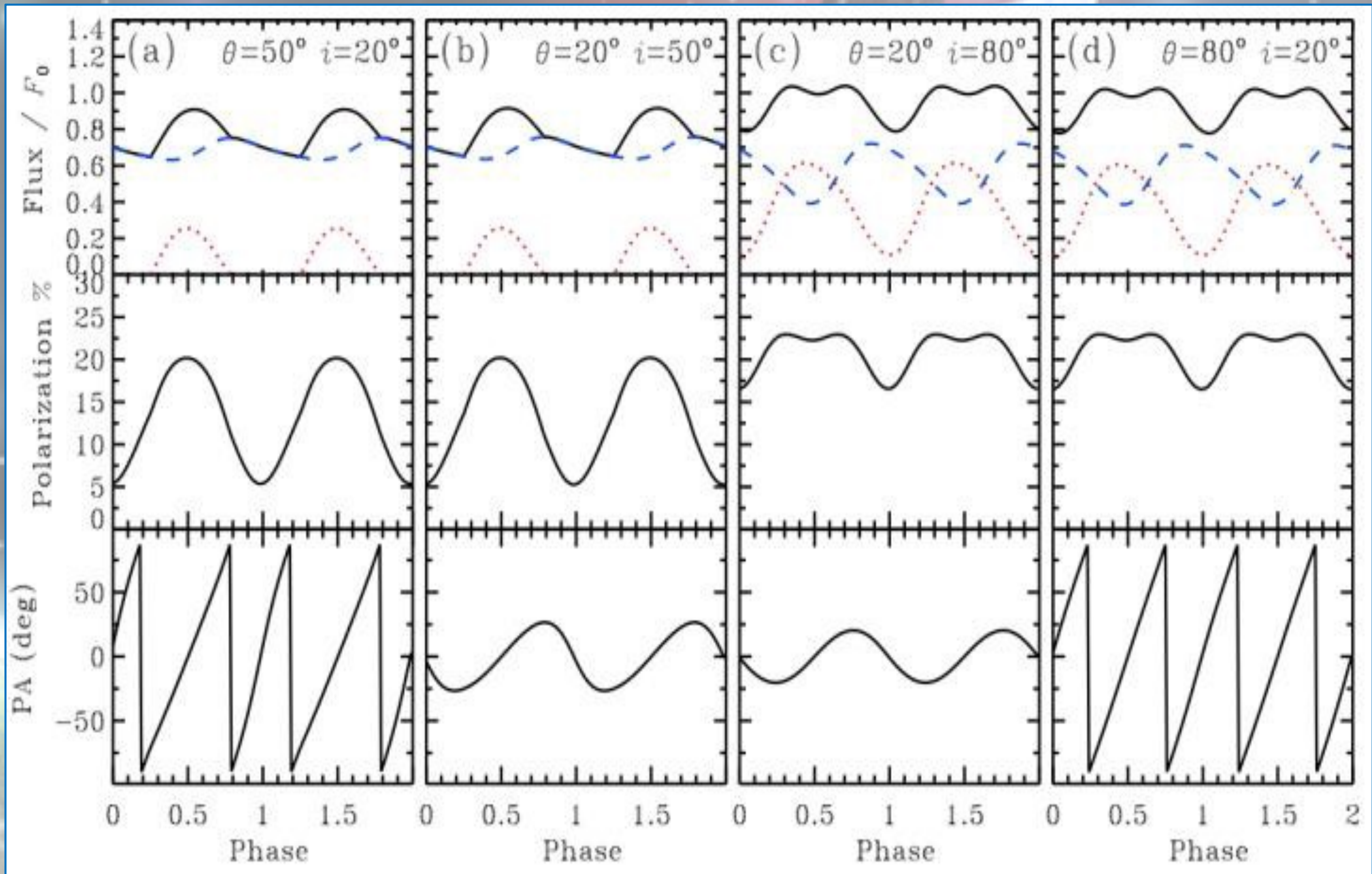
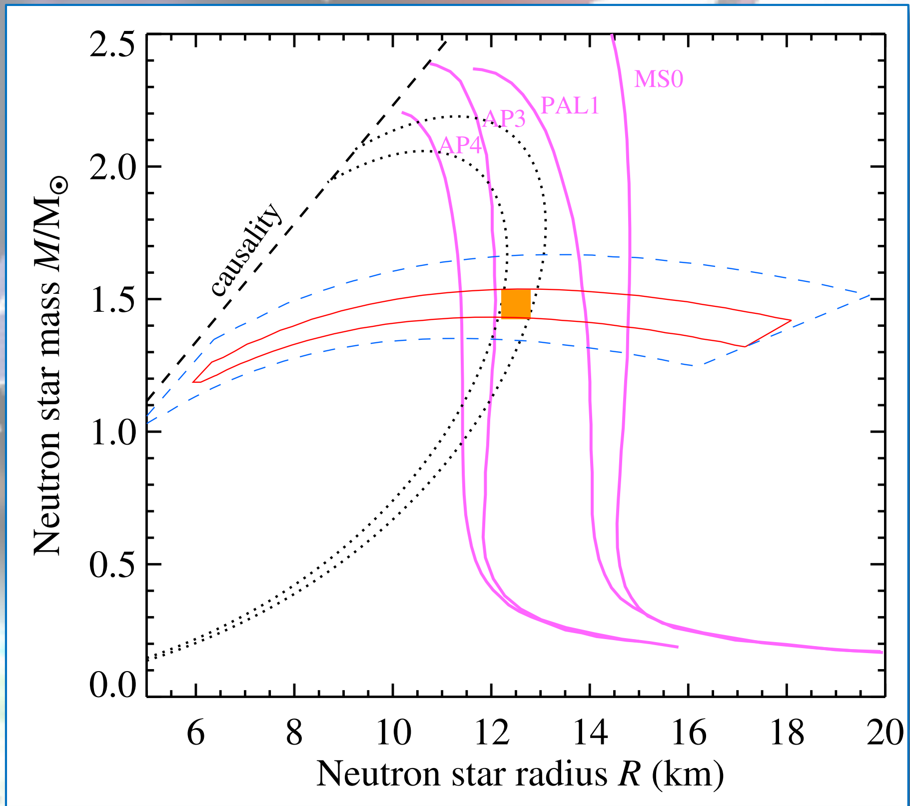


EoS from AMPs

- **Combining data coming from X-ray bursts, pulse profiles and X-ray polarization, we can get improved M-R constraints.**
- **IXPE has not yet observed any AMPs.**



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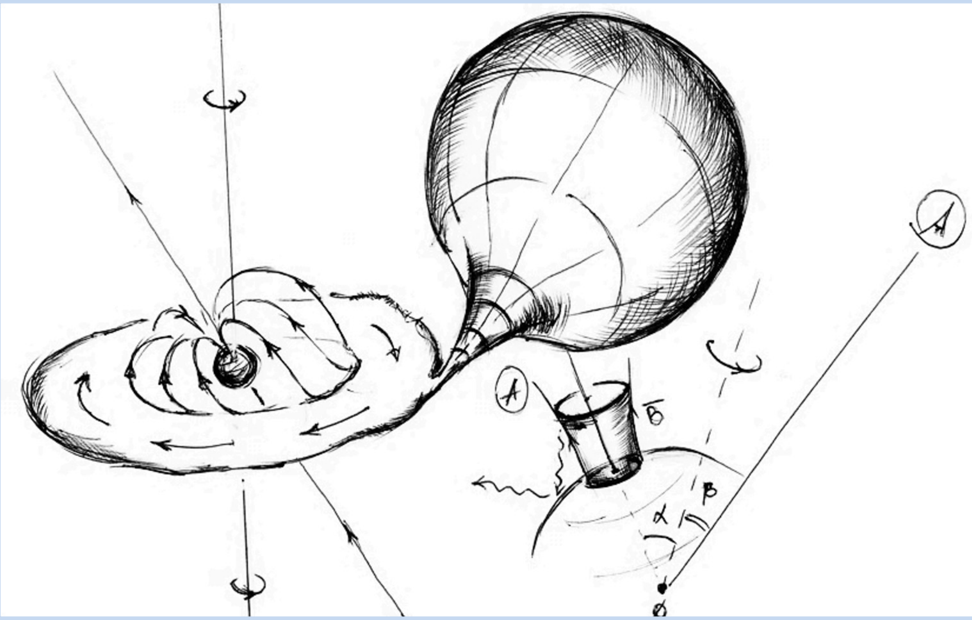
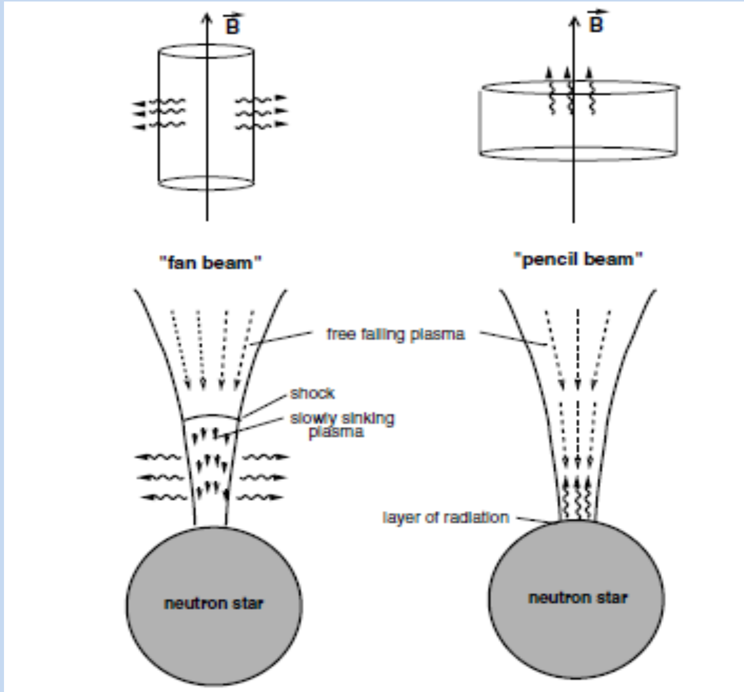
X-ray pulsars

- **Determining geometry of the emitting region (hotspot vs column) and emission pattern (fan vs pencil beam) at different luminosity levels**
- **Revealing evidence for non-dipolar fields**
- **Test free-precession model for Her X-1**





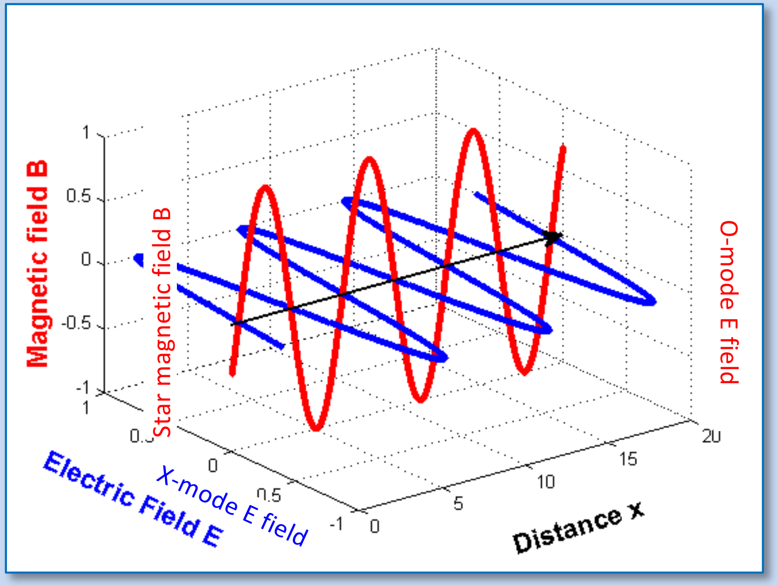
Meszaros et al. 1988

X-ray pulsars

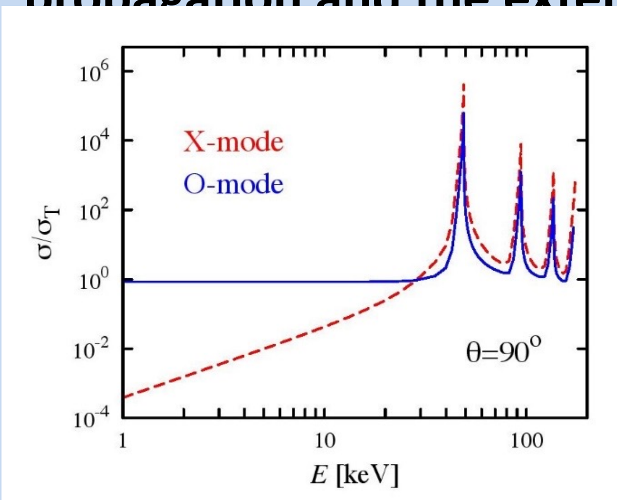
Opacity in highly magnetized plasma:

$k_{\perp} \approx (E/E_B)^2 k_{\parallel}$ $E<E_B = 11.6\ (B_{12})$ keV
(electron cyclotron energy)

where $k_{\perp}$ and ($k_{\parallel}$) are the opacities in the Extraordinary (Ordinary) modes, when the wave electron field is perpendicular (parallel) to the plane defined by the line of propagation and the external magnetic field

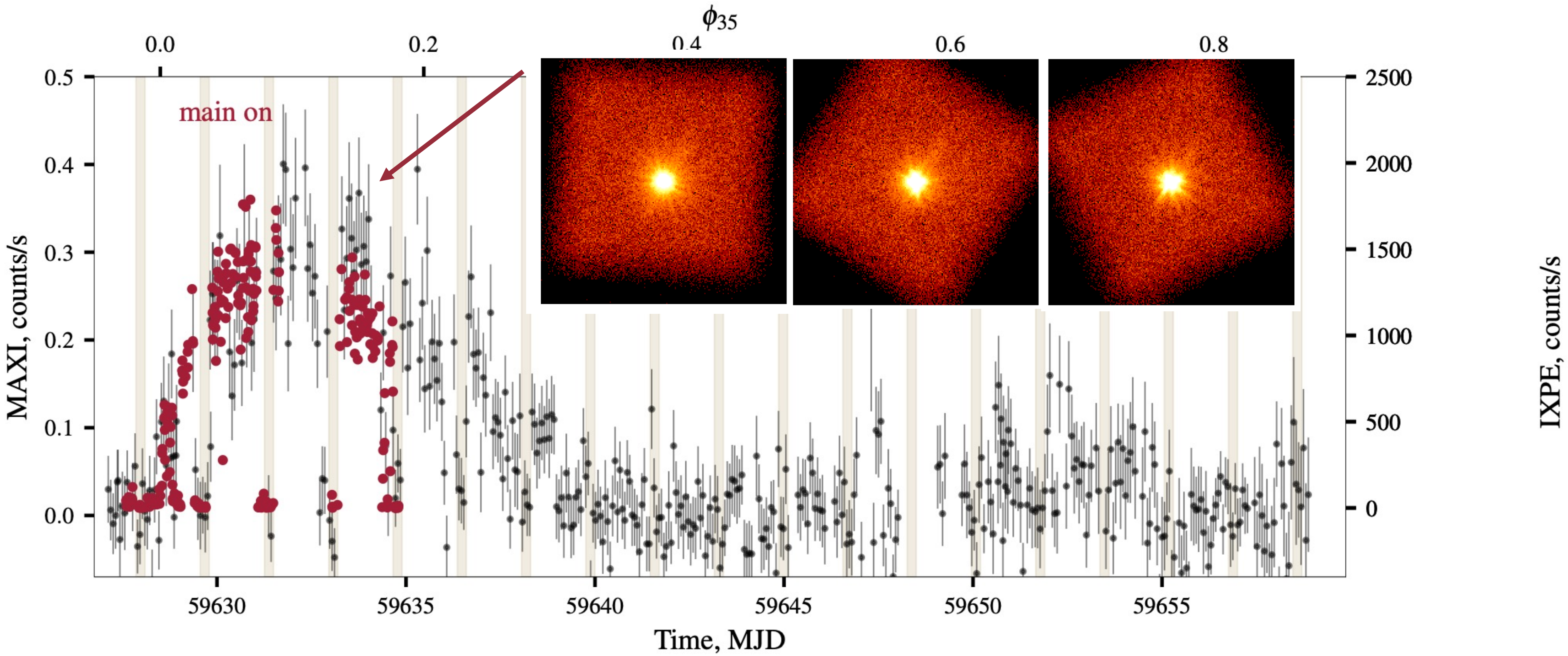


O-mode: the **E**-field oscillates in the **k-B** plane
X-mode: the **E**-field oscillates ⊥ to the **k-B** plane



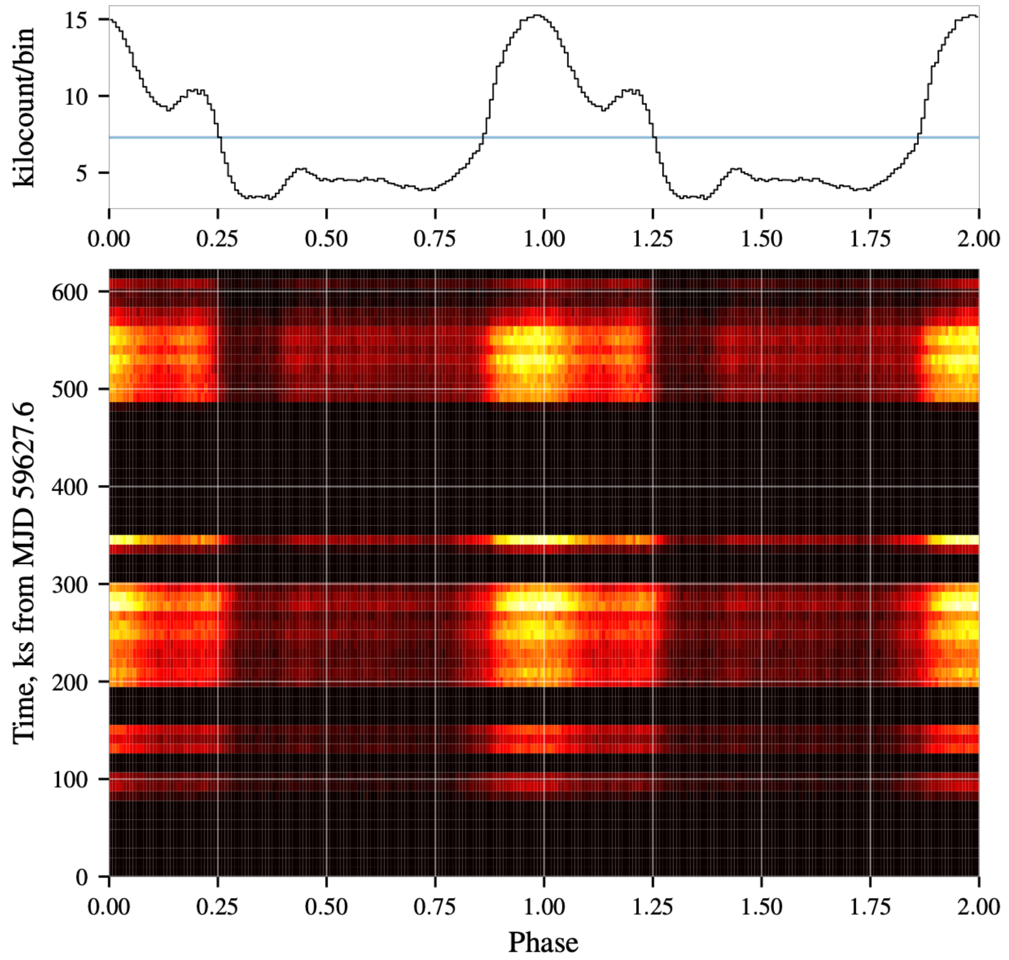
Mushtukov et al. 2016

IXPE observations of Her X-1 - what we actually see?



- Observed beginning of the so-called "main on" or "high on" state (Feb 20-25)
- Total effective exposure (after removing low-flux/eclipse periods) ~150 ks
- Over 900k source photons detected, sufficient for sensitive polarimetry!
- Averaged, time-resolved, energy-resolved, and pulse-phase resolved analysis

IXPE observations of Her X-1 - timing

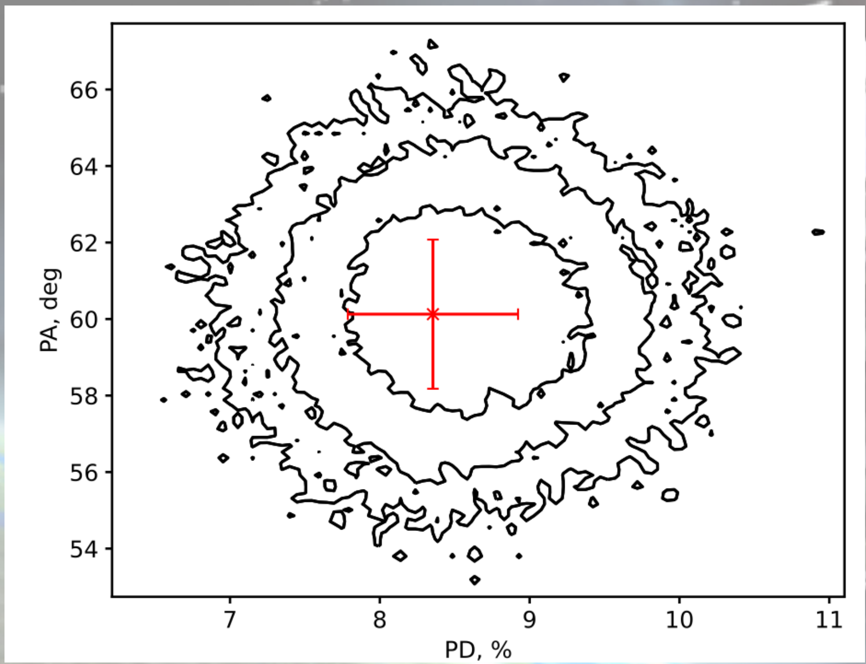


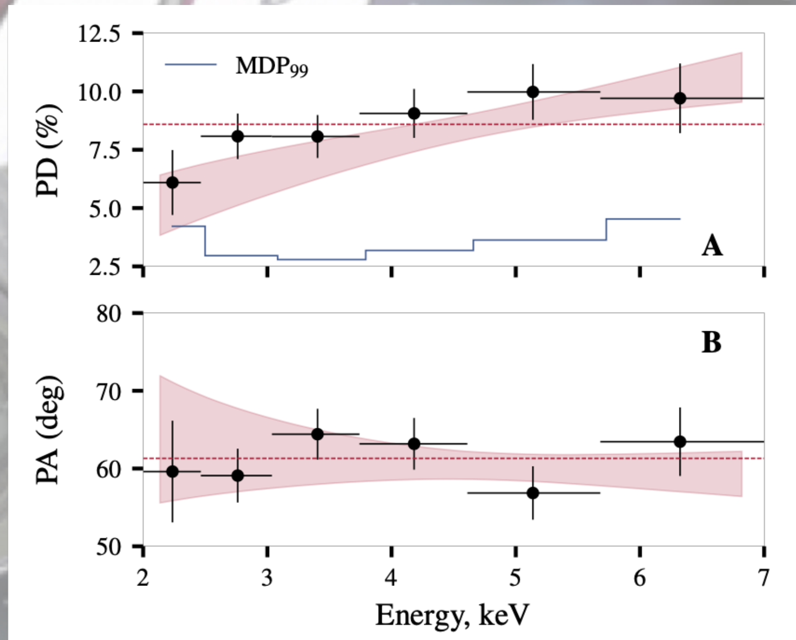
Pulse profile as expected

No issues with timing (after fixing barycorr), spin evolution consistent with constant period 1.2377093(2)s via phase-connection (ephemerides by Staubert et al 2009)

IXPE observations of Her X-1 - spectro-polarimetry

- Baseline for analysis: unweighted spectro-polarimetry
- Phase-averaged polarization degree of 8.6(5)% and polarization angle of 60(2)°; >17σ detection.
- Only weak energy dependence (PA constant, PD increases with energy, ~2-3σ significance)





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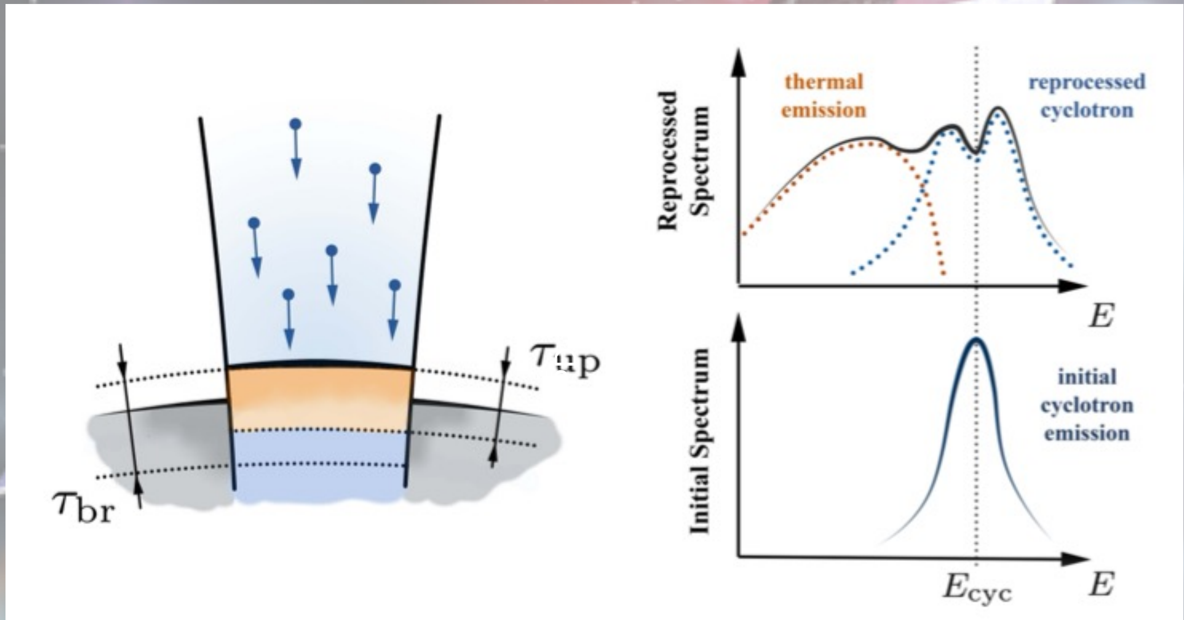
Polarization of Her X-1 - why the polarization is so low?

For instance, Caiazzo, Heyl 2021 assumed emission emerging from accretion column. However, at the given luminosity the column may not have yet started to grow.

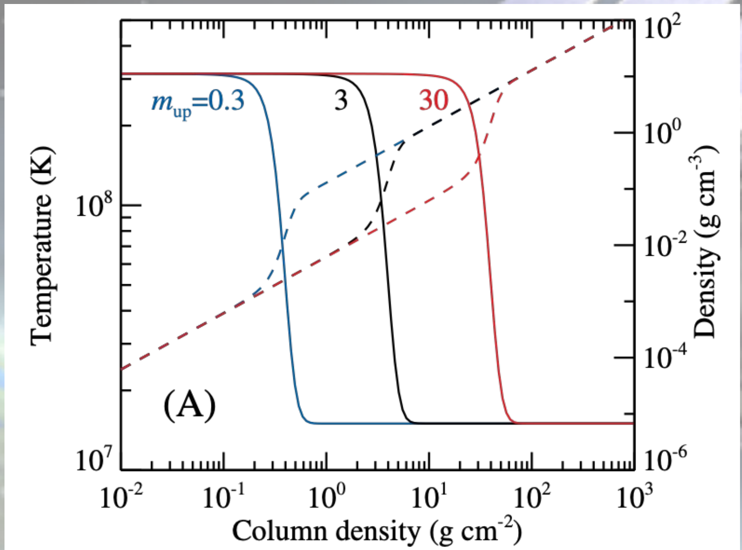


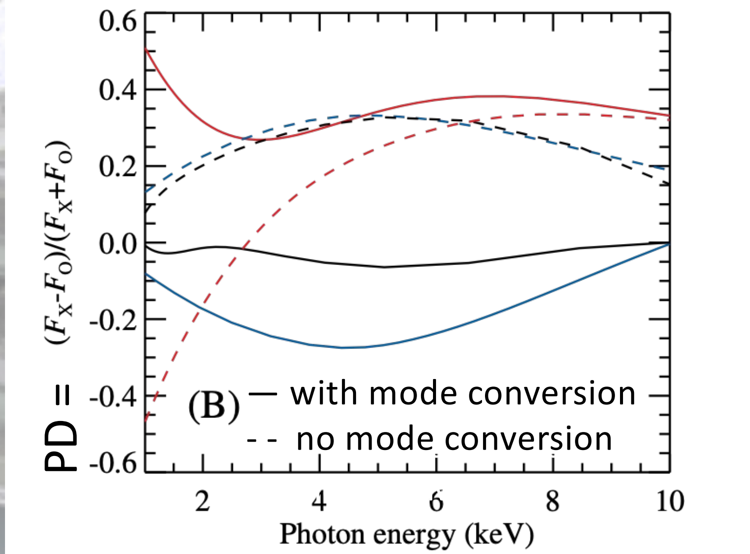
Polarization of Her X-1 - why the polarization is so low?

- **How to produce O-mode photons (and a modest PD)**
  - Emission from a magnetized atmosphere with inverted temperature gradient.
  - Temperature inversion can be produced by particle bombardment.

Polarization of Her X-1 - why the polarization is so low?

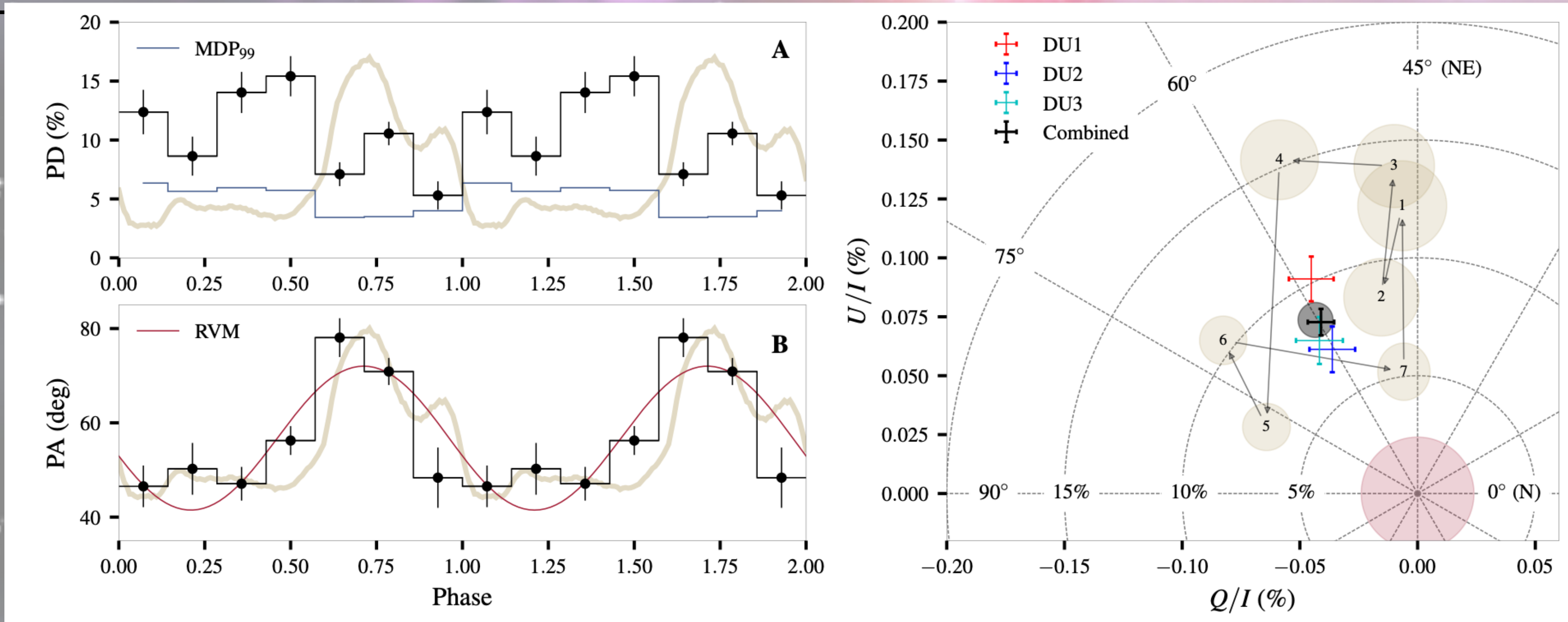
- Normally T decreases going outwards
- X-mode photon photosphere is deeper than the O-mode ⇒
  X-mode dominates flux
- Particle bombardment produces inverted T gradient, O-mode photons escape at a larger temperature, and may dominate the outgoing flux
- Polarization depends on the thickness of the heated layer.





A toy model of heated atmosphere by Valery Suleimanov.

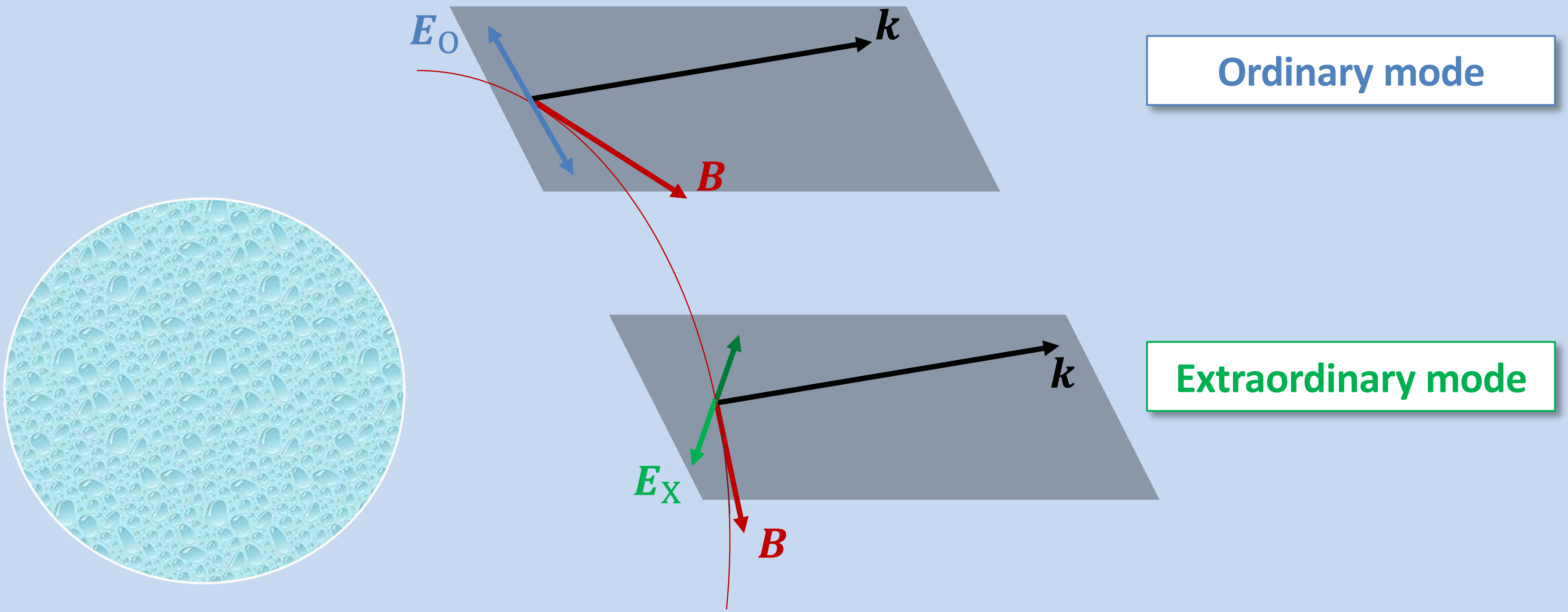
IXPE observations of Her X-1 - phase dependence



- Complex PD dependence on pulse phase, but low PD (5.5-15%) throughout the pulse
- Sine-like PA phase-dependence (with the available statistics)

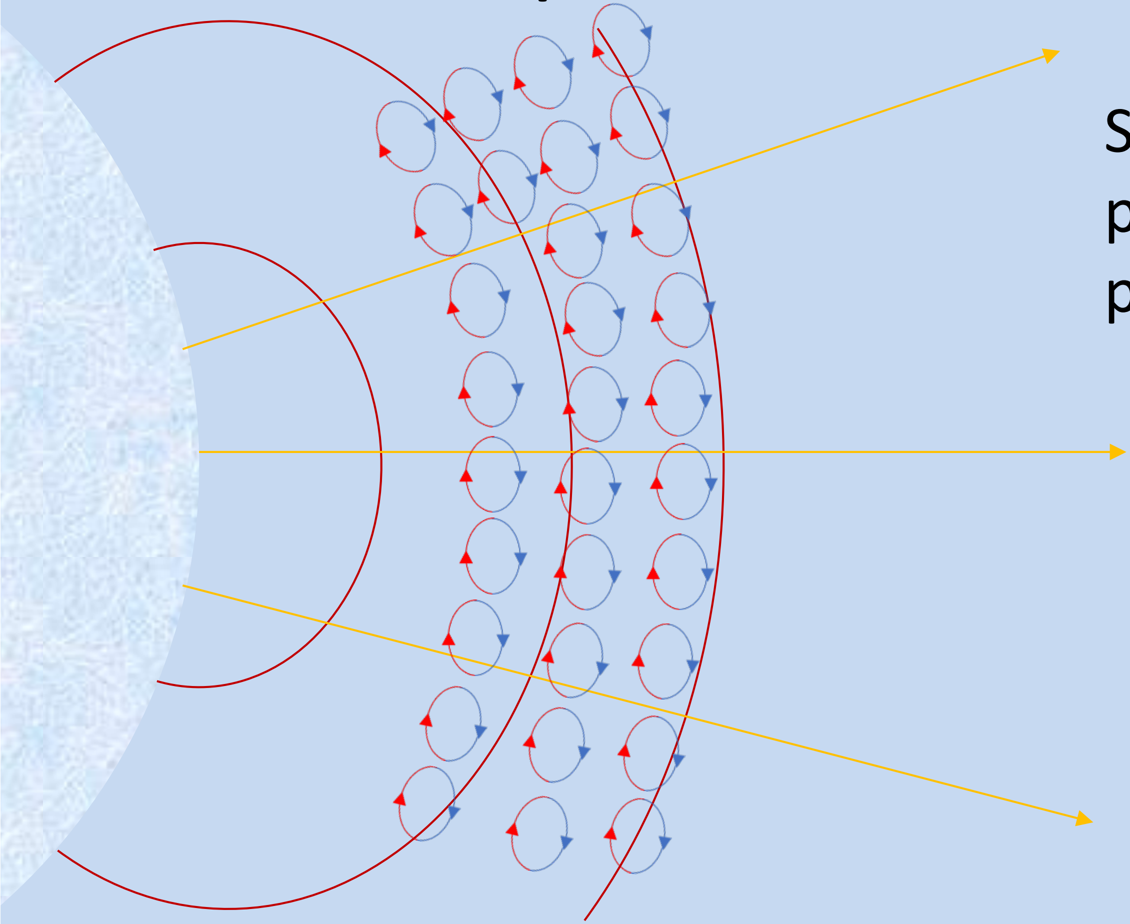
Theoretical interpretation

- **Polarization in strong B-fields (vacuum birefringence)**
  - For $B \sim B_{\mathrm{Q}} = 4.4\times10^{13}$ G photons propagate in vacuo linearly polarized in two normal modes



Theoretical interpretation

- **QED vacuum polarization effects**



Strong magnetic fields polarize the virtual e^{-}-e^{+} pairs around the star

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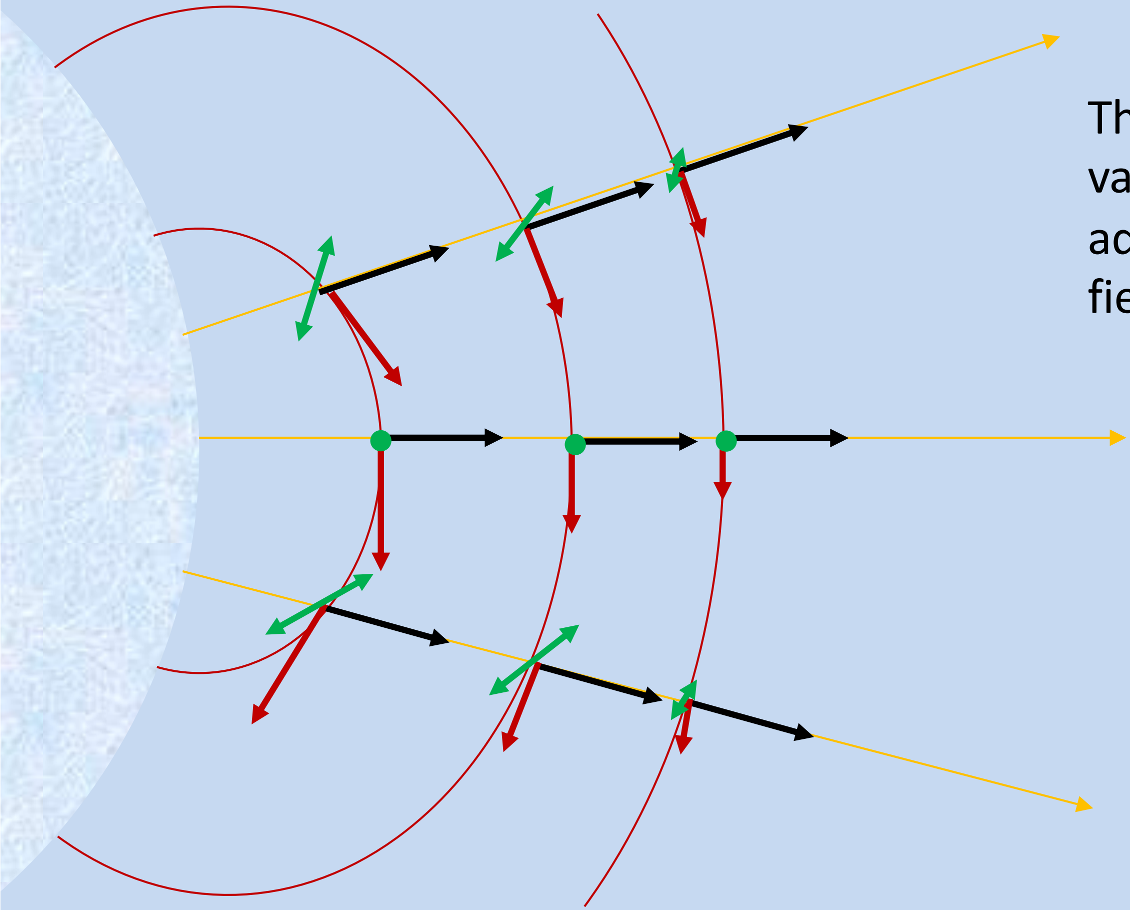
Theoretical interpretation

- **QED vacuum polarization effects**

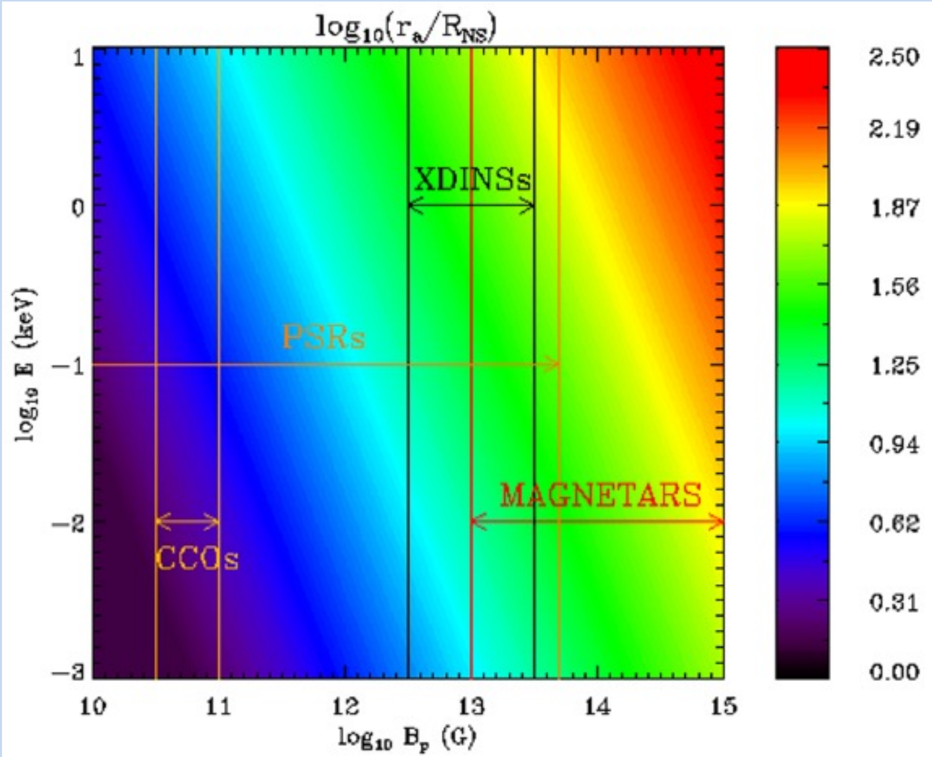


This modifies the ε and μ tensors of the vacuum, forcing the photon E-field to adiabatically follow the star magnetic field along the photon trajectory

Theoretical interpretation

- **QED vacuum polarization effects**
  - The limit within which polarization modes are preserved depends on the star magnetic field strength and photon energy

$$\frac{r_{\rm pl}}{R_{\rm NS}} \simeq 4.8 \left(\frac{\hbar\omega}{1\ {\rm keV}}\right)^{1/5} \left(\frac{B_{\rm p}}{10^{11}\ {\rm G}}\right)^{2/5} \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{1/5}$$



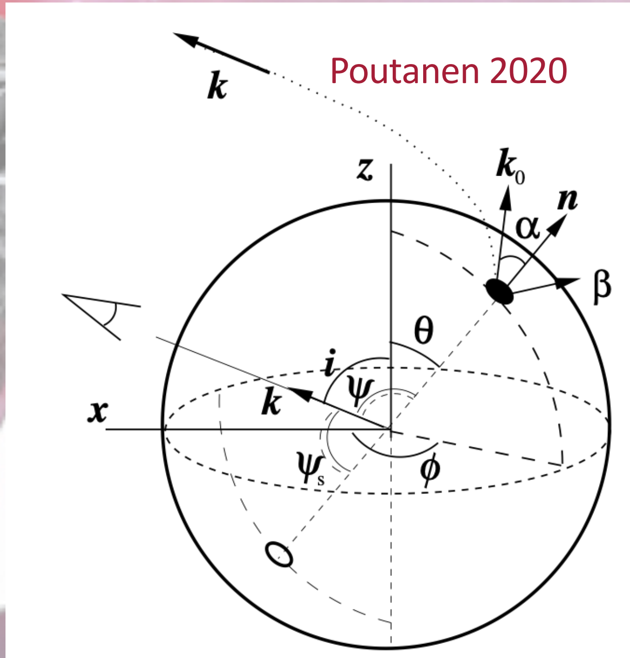
Taverna et al. (2015)

Theoretical interpretation

- **QED effects – Rotating Vector Model**
  - Photon polarization vectors decouple from the B-field at large distances (where the magnetic field is $\approx$ a dipole):
    - PD is still determined by surface emission properties
    - PA is independent of the B-field topology at the surface

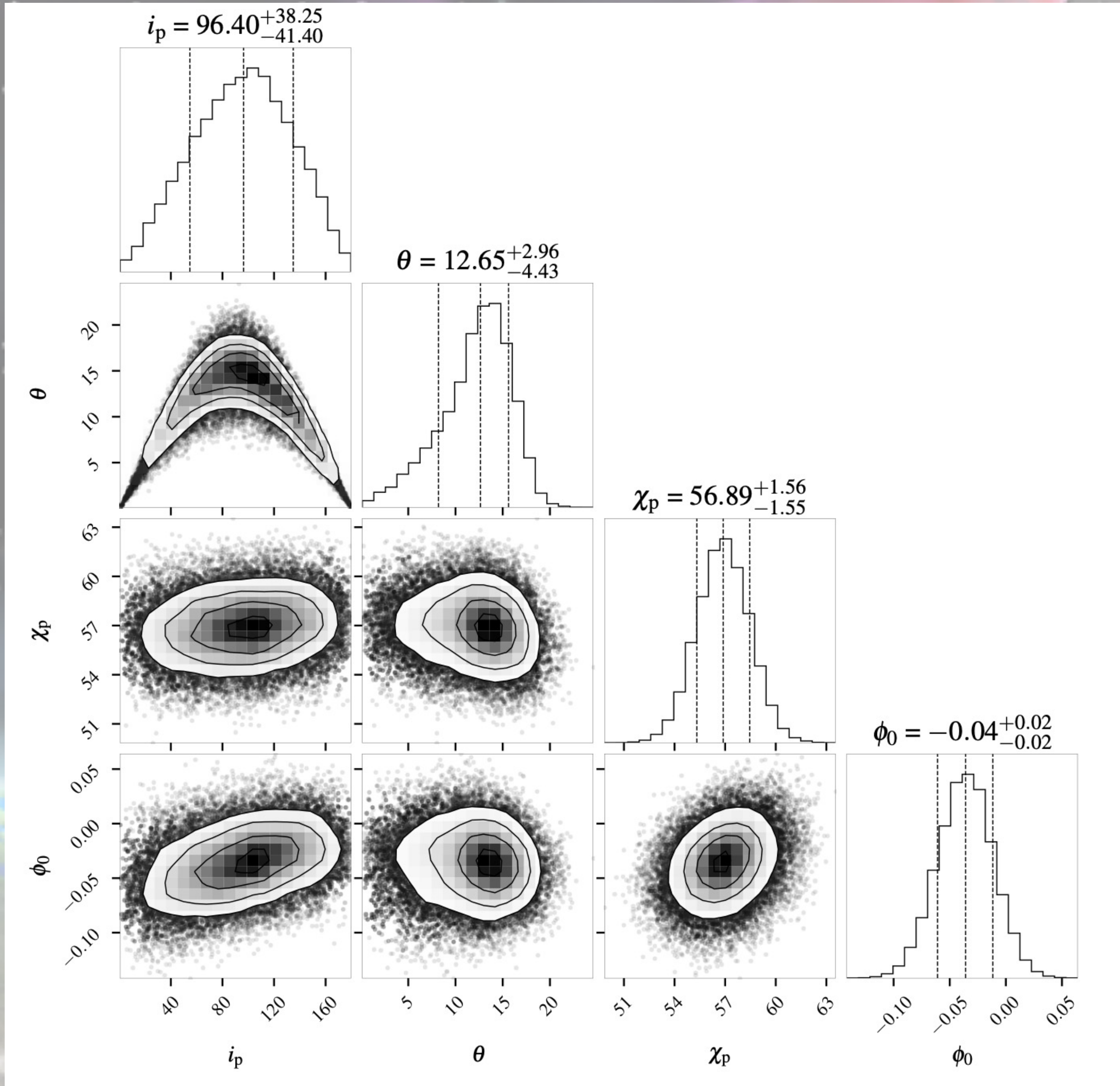
PA phase dependence, QED and RVM

$$\tan(\mathrm{PA} - \chi_\mathrm{p}) = \frac{-\sin\theta\ \sin(\phi-\phi_0)}{\sin i_\mathrm{p}\ \cos\theta - \cos i_\mathrm{p}\ \sin\theta\ \cos(\phi-\phi_0)}$$



- Since PA is expected to be aligned with the magnetic dipole, we expect PA to follow rotating vector model (RVM) (Radhakrishnan & Cooke 1969)
- PA is less sensitive to the details of the radiative transfer close to the surface

PA phase dependence, QED and RVM



Inclination is not constrained by IXPE itself (even if best fit is close to independent measurements of orbital inclination).

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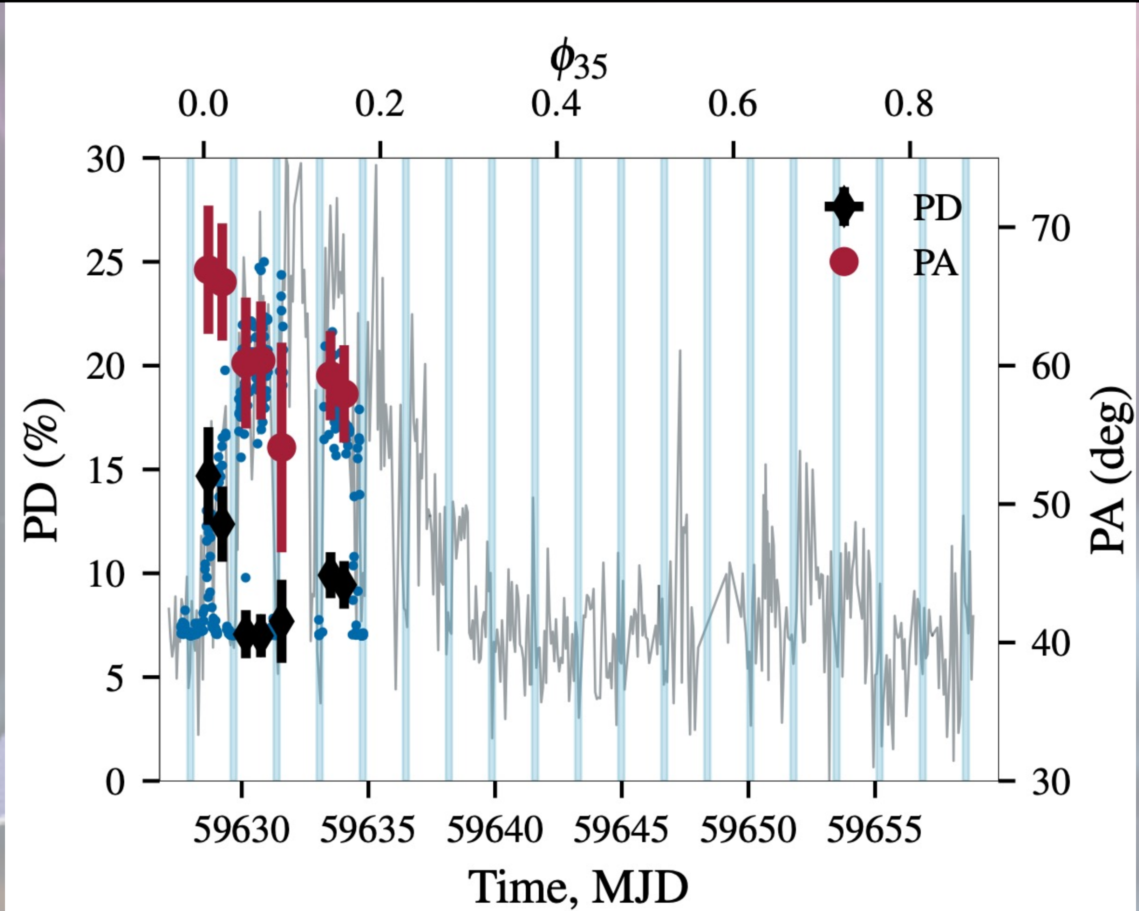
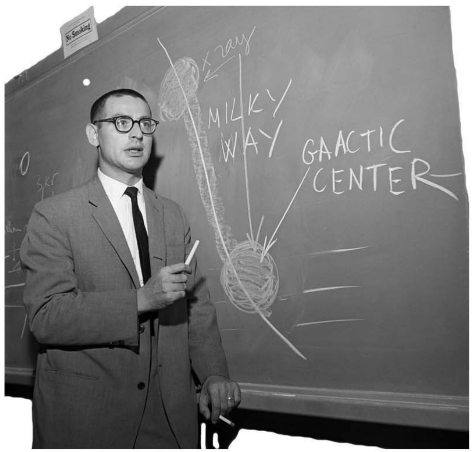
Time dependence of X-ray polarization

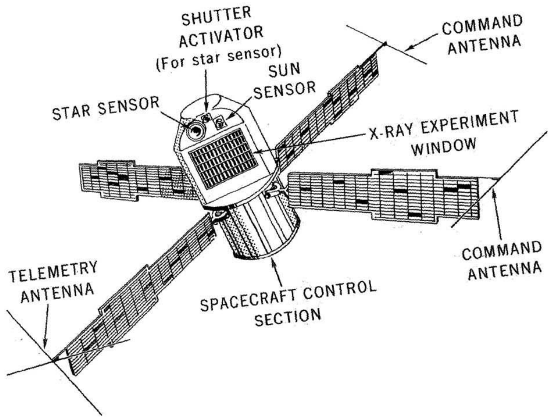


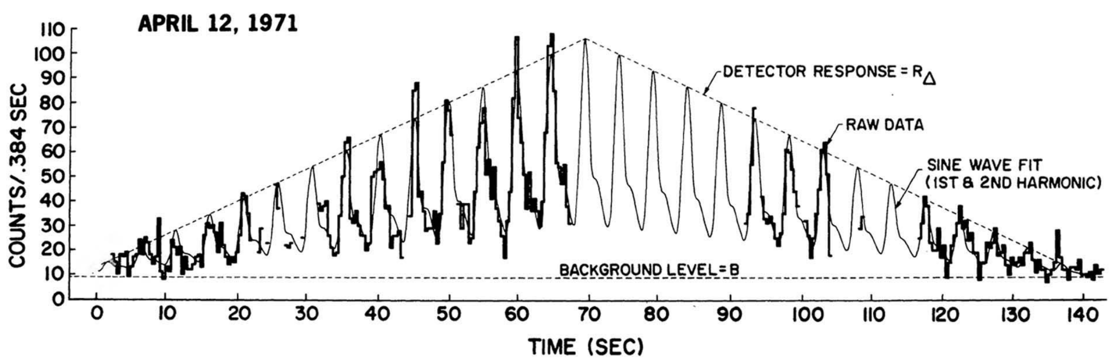
- Variability of both PD/PA with time (not very significant)
- More observations during the short-on are needed to check if those periodic. Evidence for NS precession?

Cen X-3

Persistent X-ray pulsar with almost circular orbit ($e < 0.0016$) around an O6–8 III supergiant V779 Cen of mass and radius of 20.5±0.7 $M_{\odot}$ and 12 $R_{\odot}$, respectively. Ash et al. (1999) determined the inclination of the system to be $70^{\circ}.2 \pm 2^{\circ}.7$.

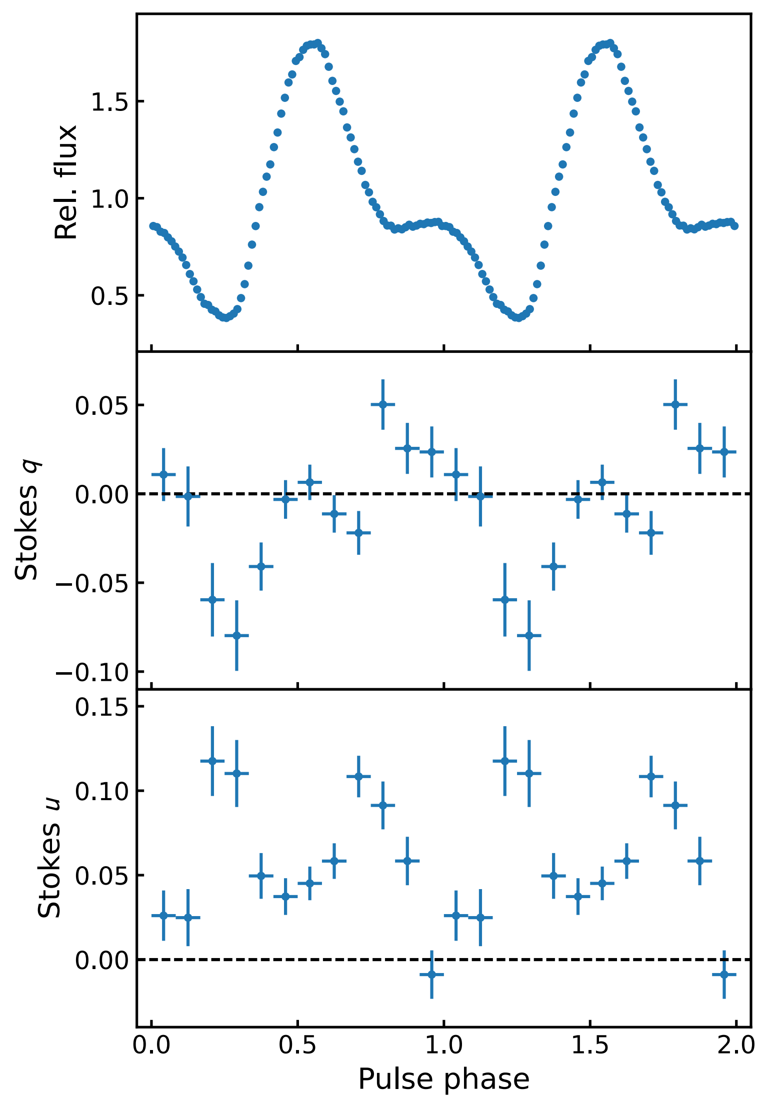


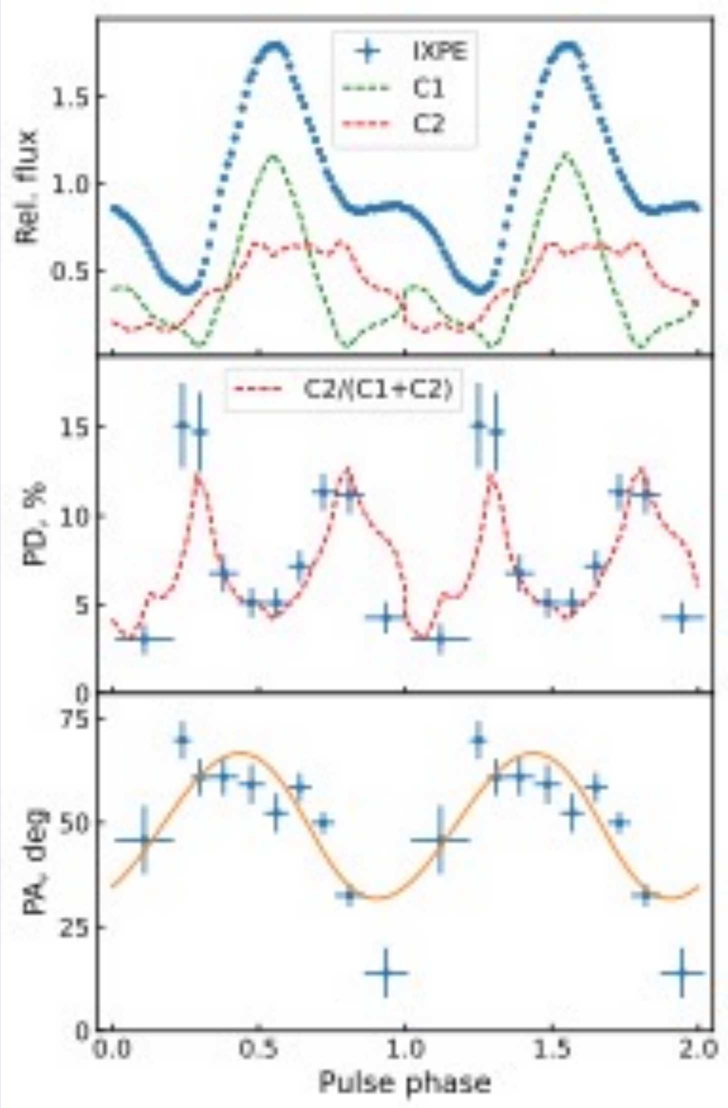




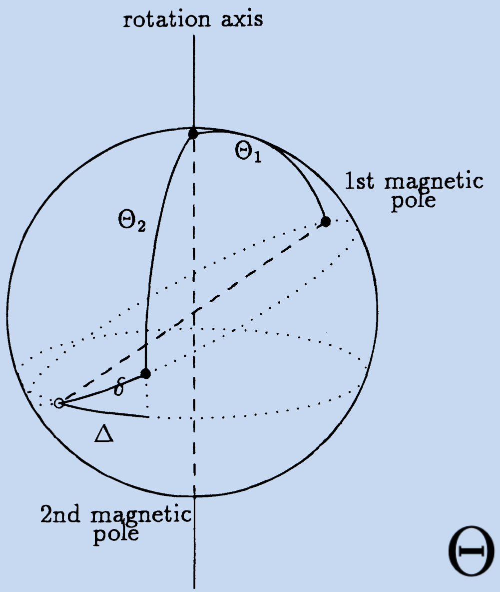
Spin period P_s=4.8 s
Orbital period P_{orb}=2.09 d
Distance d=$6.4^{+1.0}_{-1.4}$ kpc

Pulse phase-resolved polarimetry

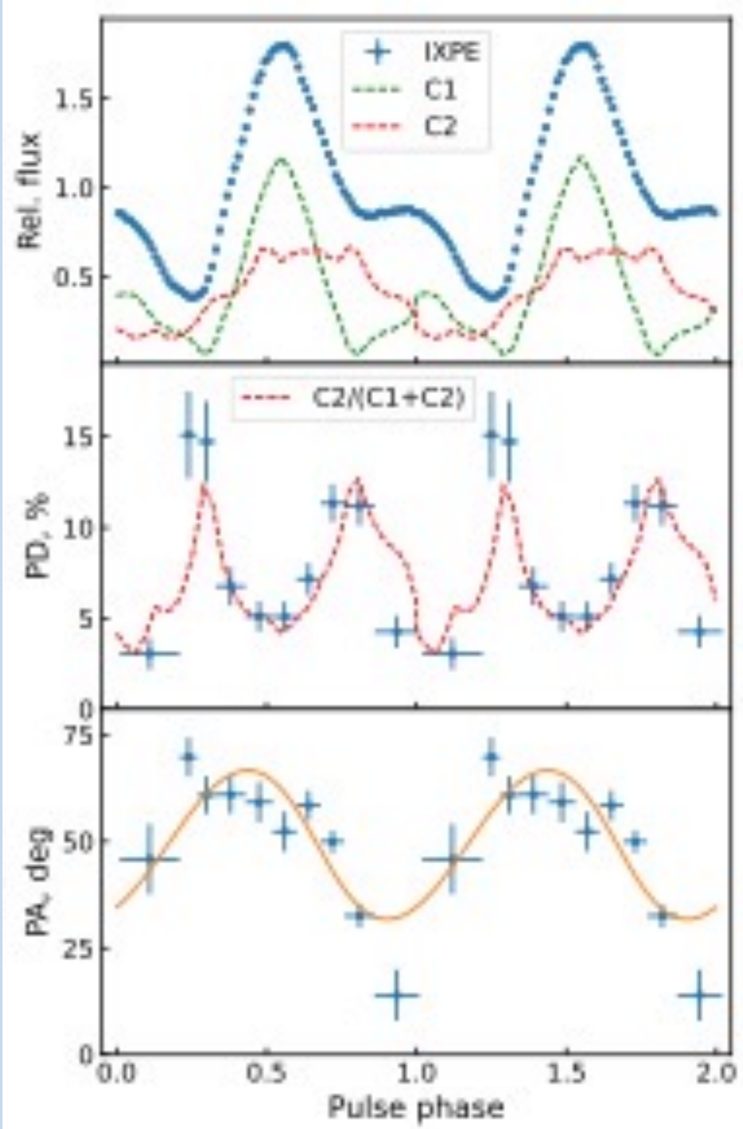




Geometry of the system



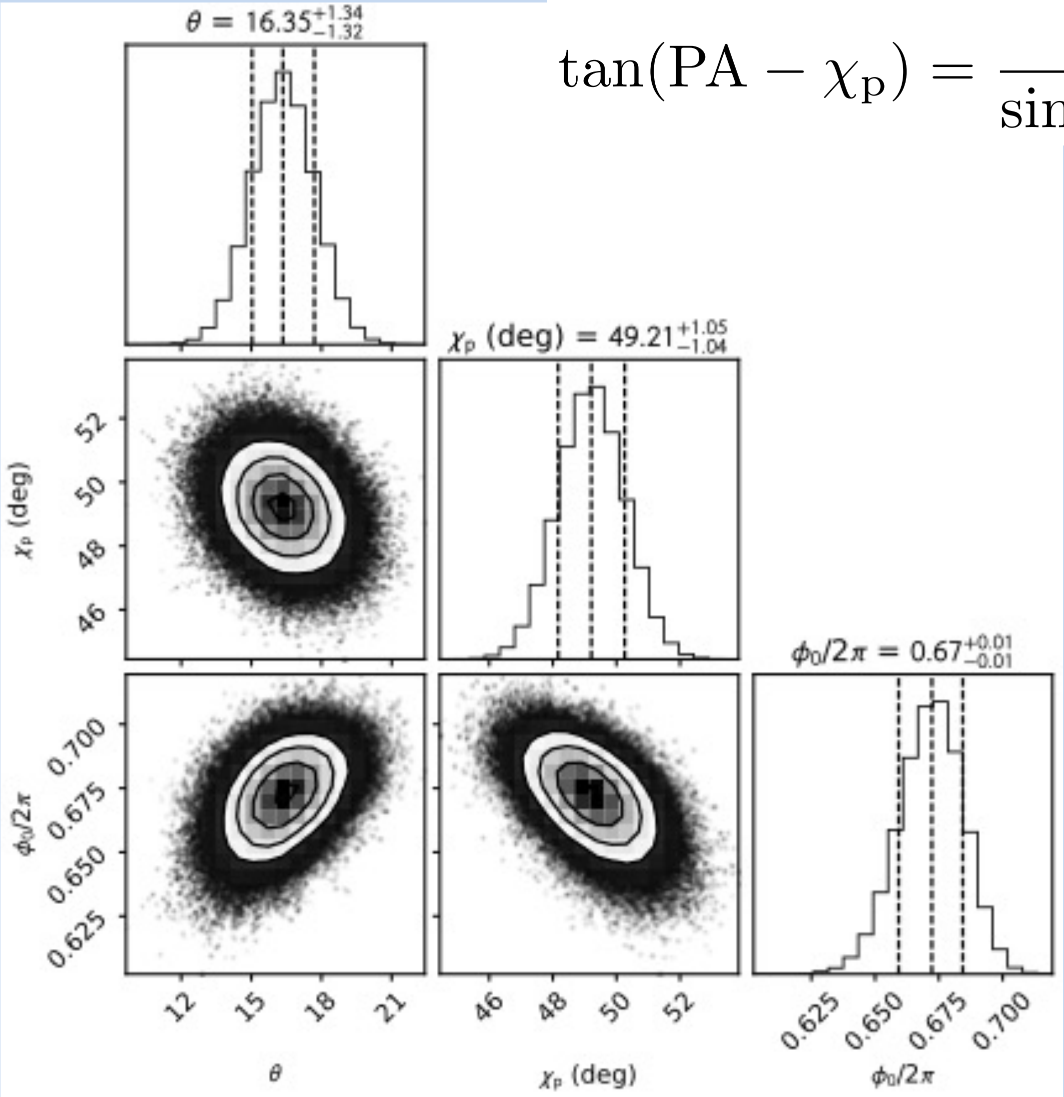
$$\Theta_1 = 18^\circ$$



The PD correlates with the relative contribution of one of the poles (C2) to the total flux. The PD reach minimal values at phases where the main peak (C1) is dominating. This can be understood if this component appears due to pencil beam emission diagram. Indeed, it was shown by Meszaros et al. (1988), that in the case of sub-critical accretion when pencil beam diagram naturally appears, one would expect an anti-correlation between the pulsed flux and PD. In this case the second component of the profile (C2) may correspond to the antipodal hotspot seen at a large angle.

Rotating vector model

$$\tan(\mathrm{PA} - \chi_\mathrm{p}) = \frac{-\sin\theta\ \sin(\phi - \phi_0)}{\sin i_\mathrm{p} \cos\theta - \cos i_\mathrm{p} \sin\theta \cos(\phi - \phi_0)}$$



Conclusion

IXPE has opened a new window to the Universe.

Observations of X-ray polarization are already revolutionizing our understanding of neutron stars.

IXPE allows to measure geometry of emission region.

AMPs – yet to be observed

Low 10% (expected>50%) polarization in accreting X-ray pulsars Her X-1 and Cen X-3. Likely related to inverse temperature gradient in the emitting region.