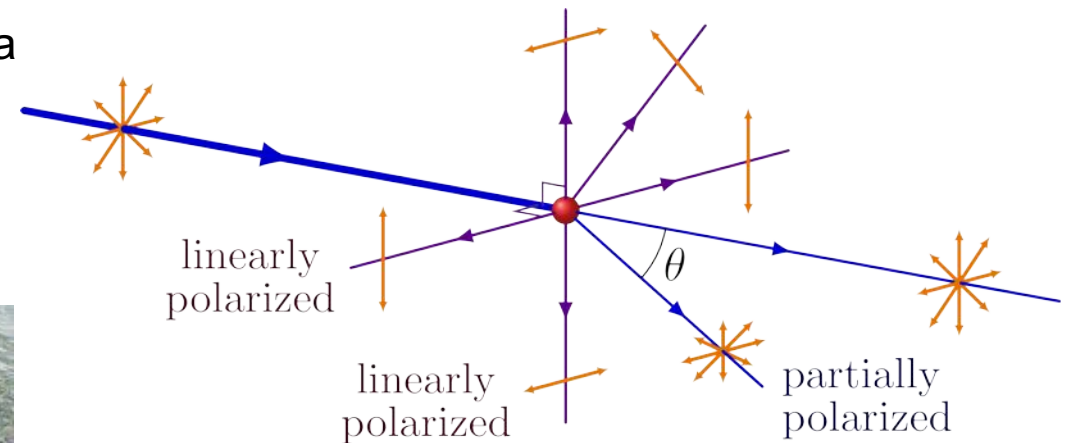
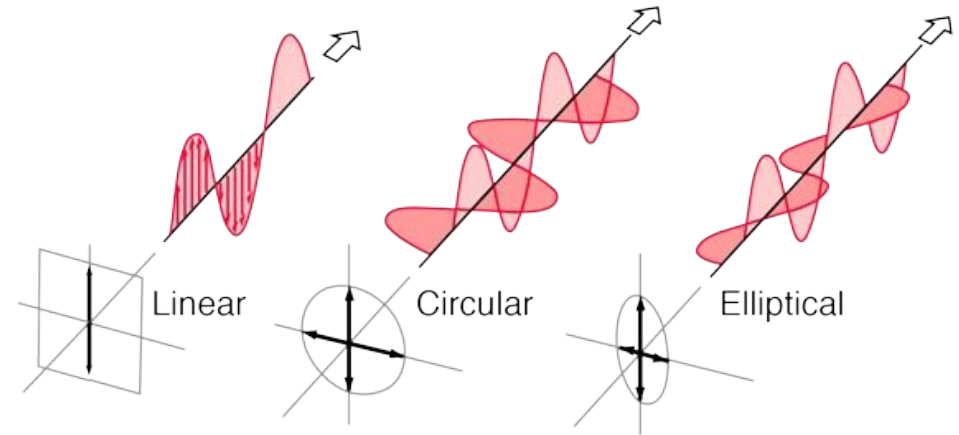


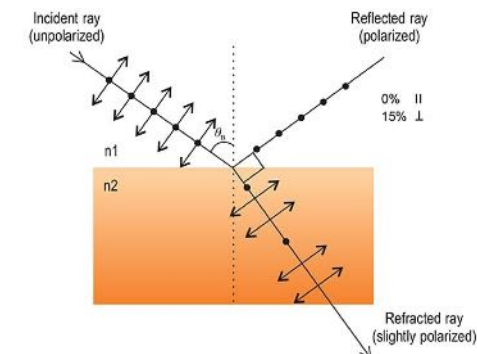
Polarimetric properties of X-ray pulsars

General information on polarization

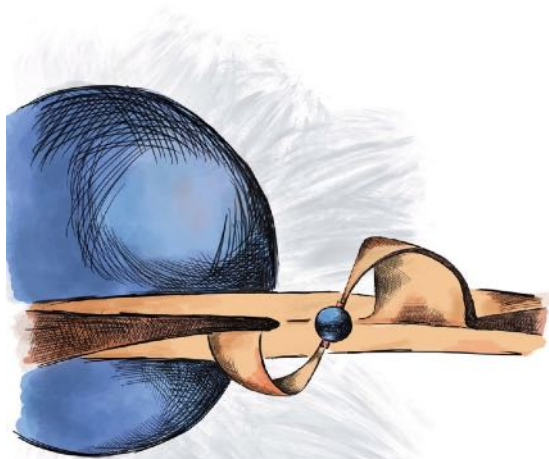
- **Polarization** is a property applying to transverse waves that specifies the geometrical orientation of the oscillations.
- An electromagnetic wave such as light consists of a coupled oscillating electric field and magnetic field which are always perpendicular to each other; by convention, the "polarization" of electromagnetic waves refers to the direction of the *electric field*.
- In linear polarization, the fields oscillate in a single direction. In circular or elliptical polarization, the fields rotate at a constant rate in a plane as the wave travels.



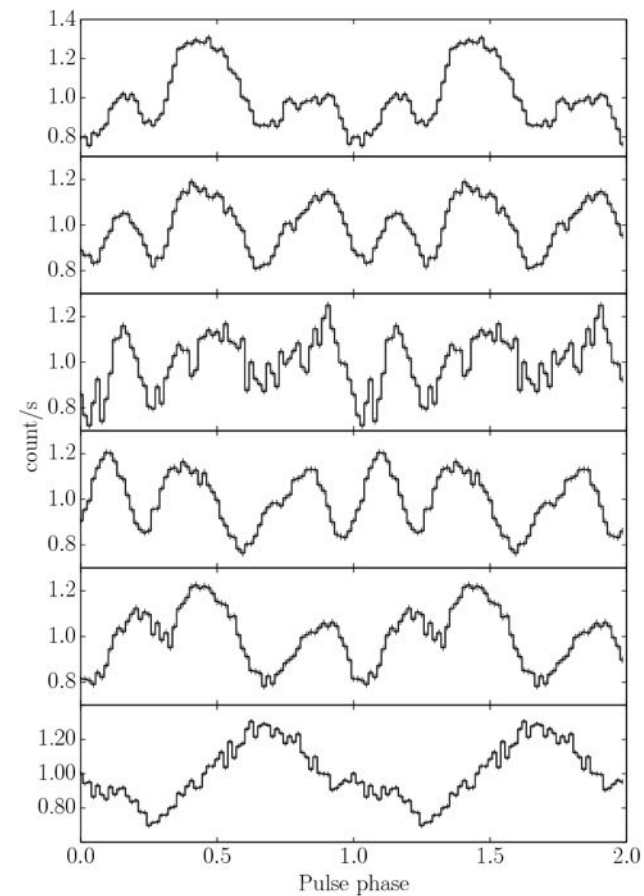
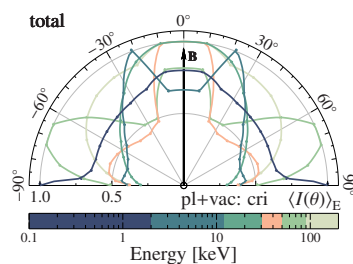
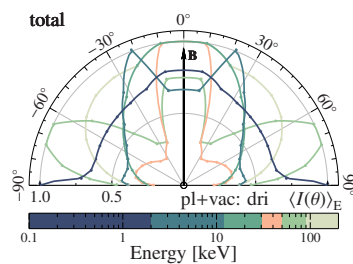
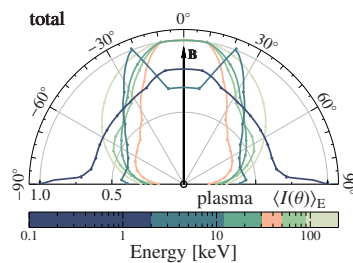
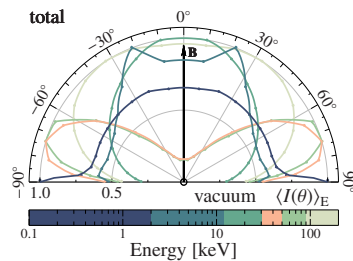
If **light** strikes an interface so that there is a 90° angle between the **reflected** and refracted rays, the **reflected light** will be linearly **polarized**. The direction of **polarization** (the way the electric field vectors point) is parallel to the plane of the interface.



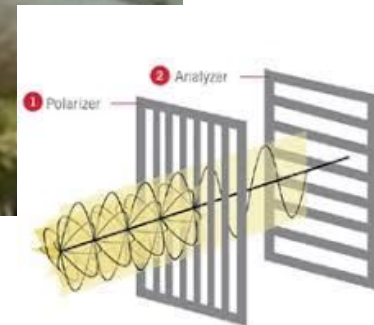
X-ray pulsars



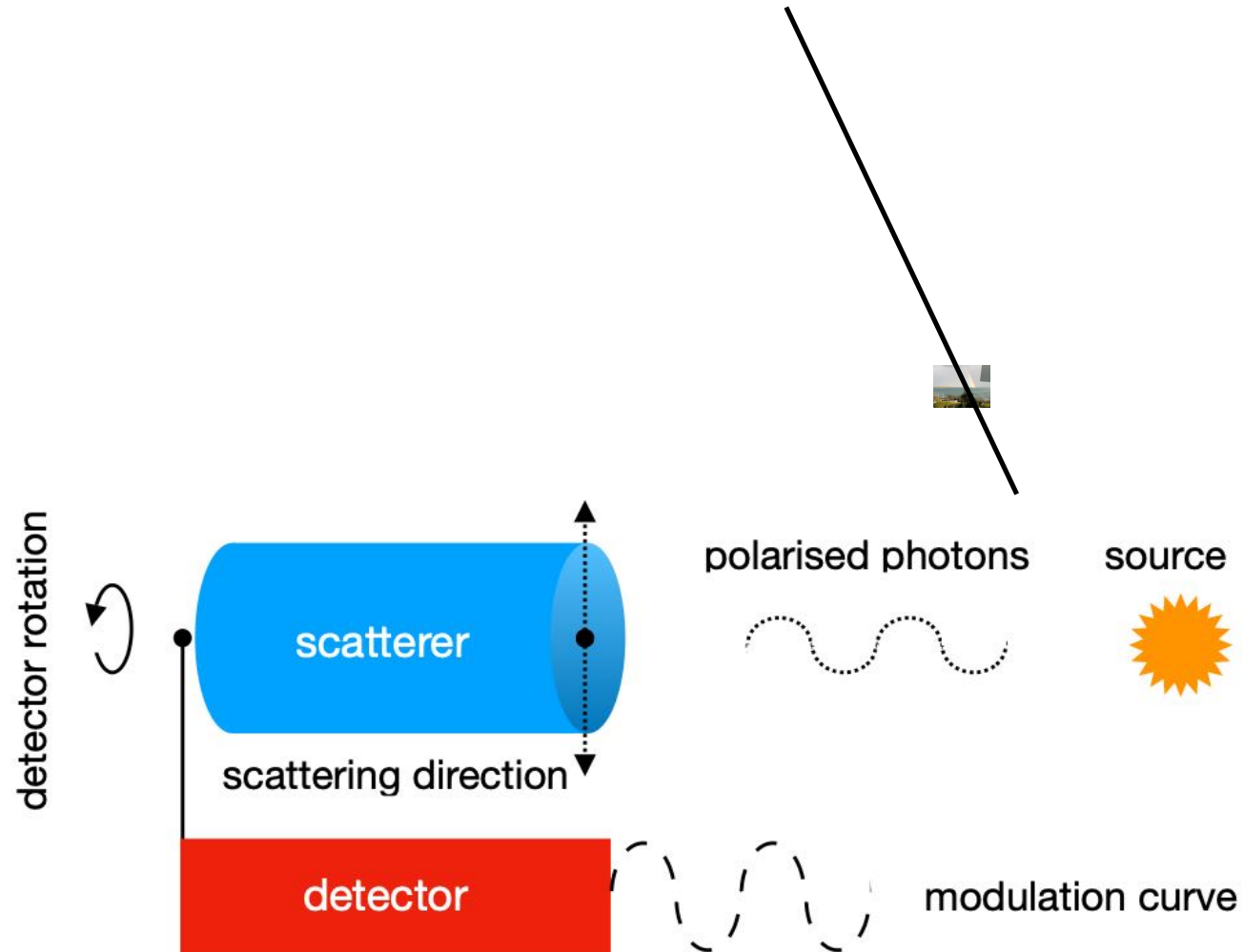
© Alexander Mushtukov



Geometry from polarimetry



Geometry from polarimetry



Polarimetry in X-rays

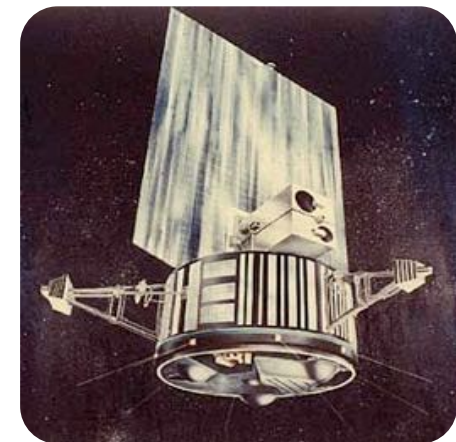
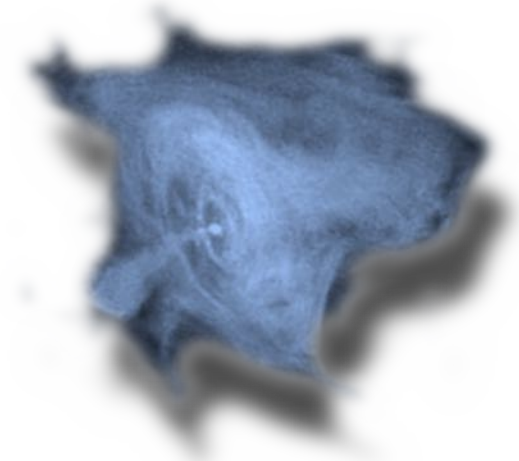
Linear polarization give us information on geometry: the degree depends on the level and kind of symmetry of the system, the angle indicates its orientation.

- First attempt to measure the X-ray polarization of the Crab Nebula back in 1969 with sounding rockets
 - **PD<36%** (Wolff et al. 1970)

- First X-ray nebula polarization measurement:
PD=15.4%±5.2%, PA=156°±10° (5-20 keV)
(Novick et al. 1972)

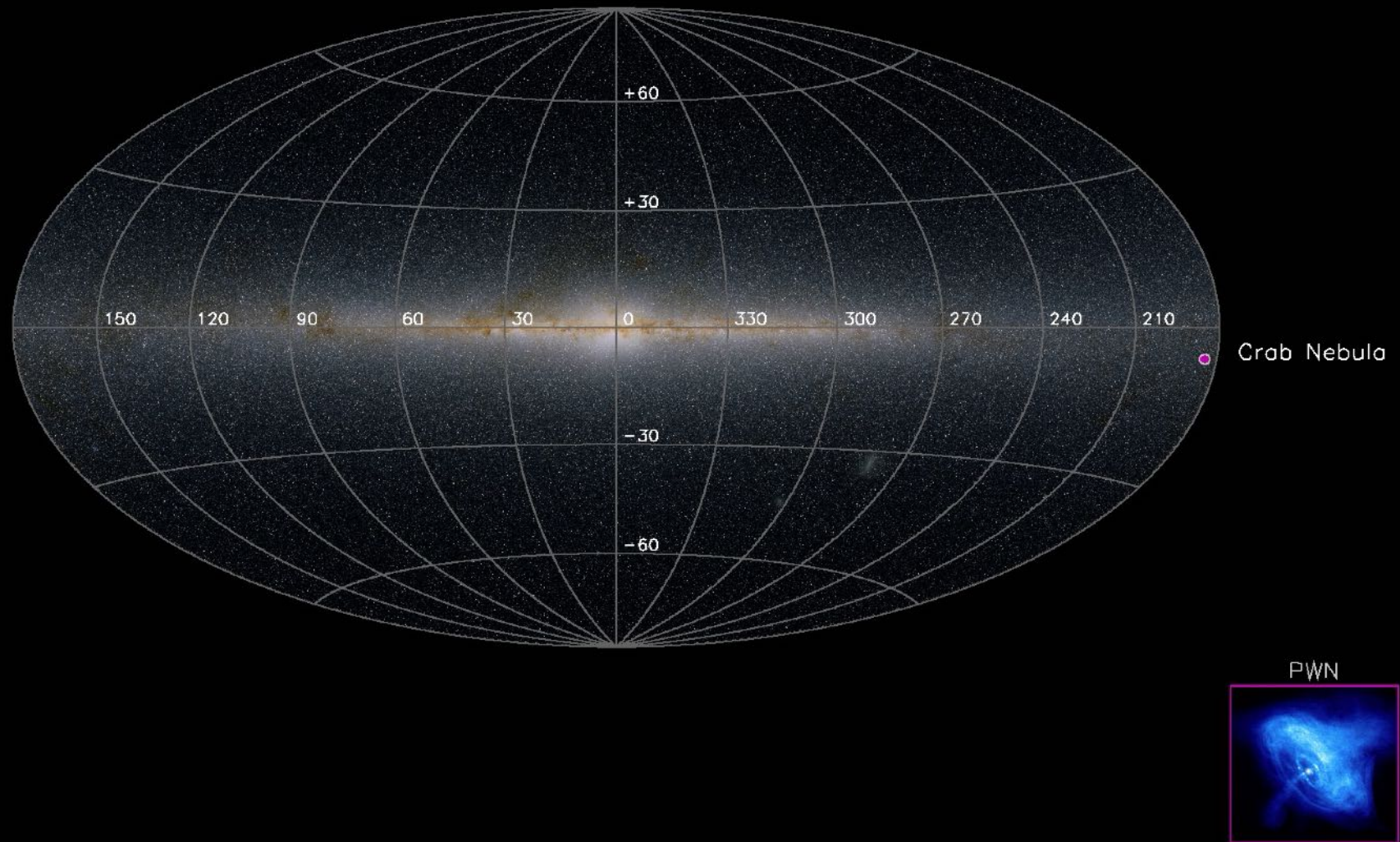
- New nebula polarization by OSO-8 with:
PD=15.7%±1.5%, PA=161.1°±2.8° @2.6 keV
PD=18.3%±4.2%, PA=155.5°±6.6° @5.2 keV
(Weisskopf et al. 1976)

- After Pulsar subtraction (Weisskopf et al. 1978):
PD=19.2%±1.0%, PA=156.4°±1.4° @2.6 keV
PD=19.5%±2.8%, PA=152.6°±4.0° @5.2 keV



OSO-8: based on the "classical" techniques of Bragg reflection

Map of polarized X-ray sources in 2021



IXPE launched on 2021 Dec 9

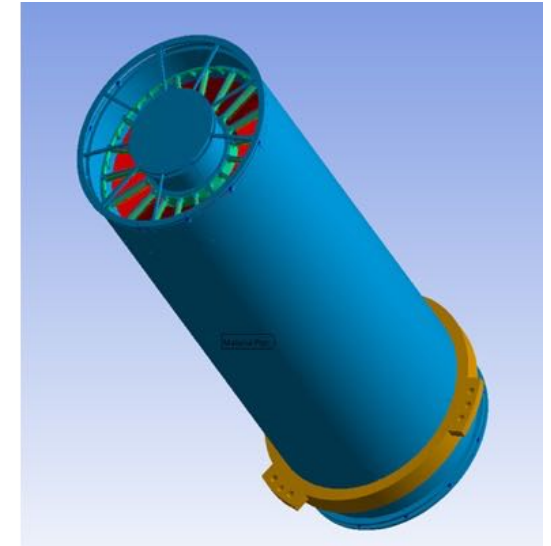


Imaging X-ray Polarimetry Explorer

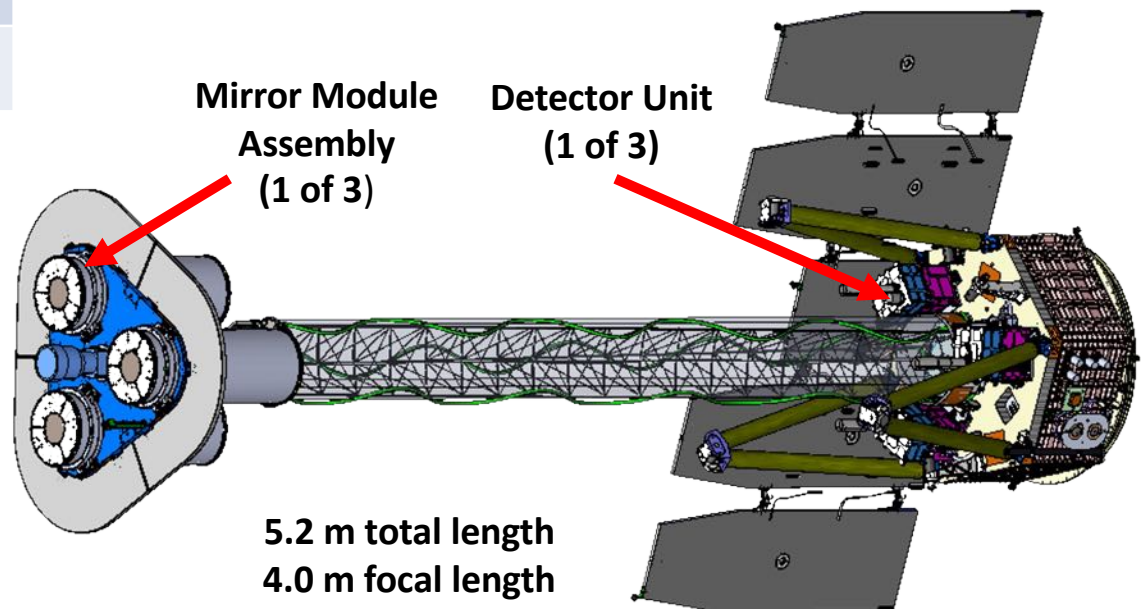
Parameter	Value
Number of mirror modules	3
Number of shells per mirror module	24
Focal length	4 m
Total shell length	600 mm
Range of shell diameters	162–272 mm
Range of shell thicknesses	0.16–0.25 mm
Shell material	Electroformed nickel–cobalt alloy
Effective area per mirror module	166 cm ² (@ 2.3 keV); > 175 cm ² (3–6 keV)
Angular resolution (HPD)	≤ 27 arcsec
Field of view (detector limited)	12.9 arcmin square



MMA, showing 24 shells

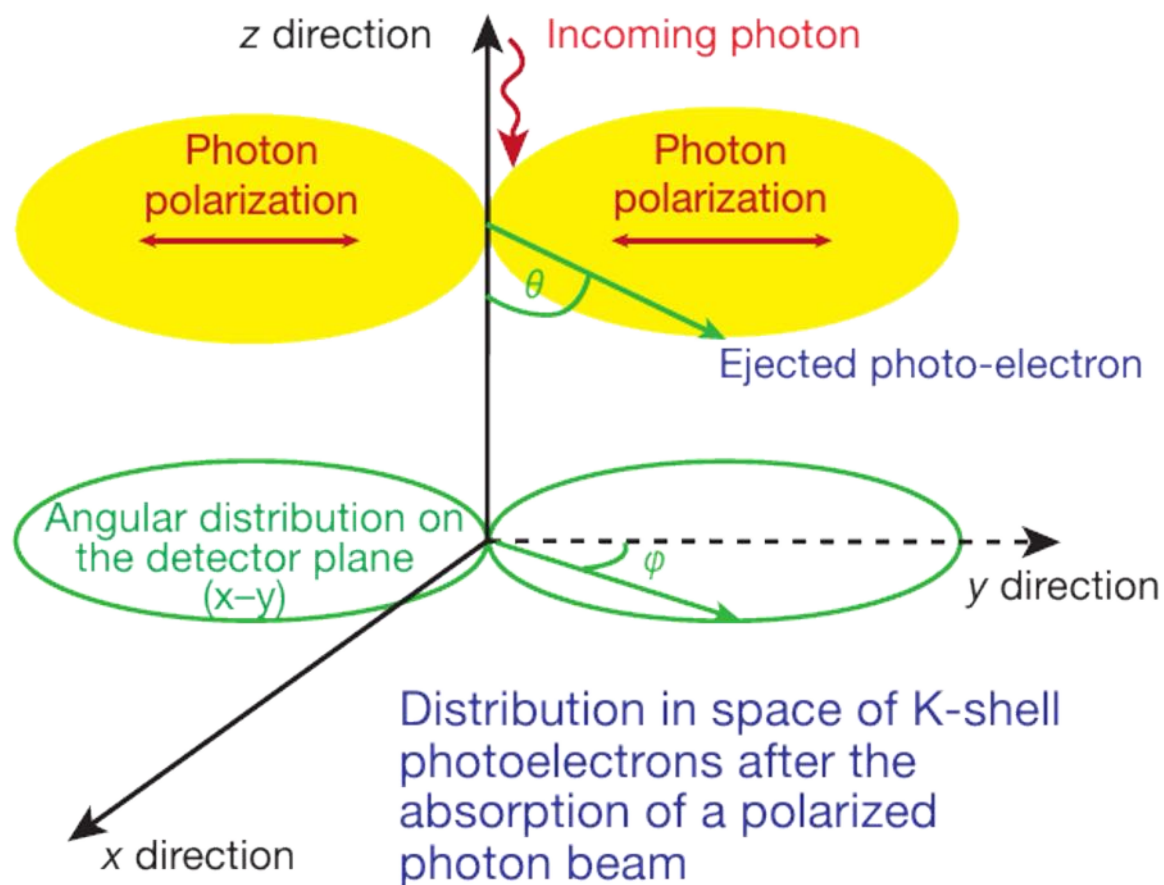


Three IXPE Mirror Module Assemblies



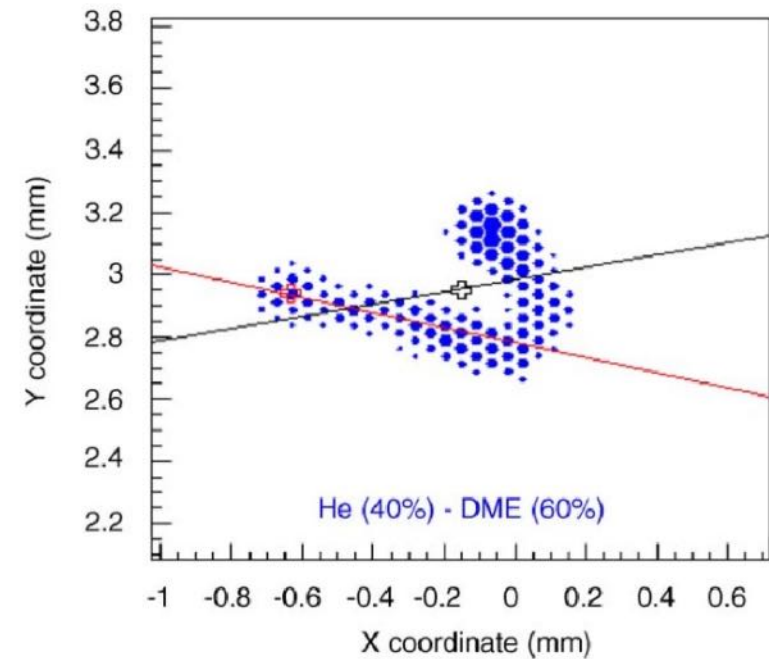
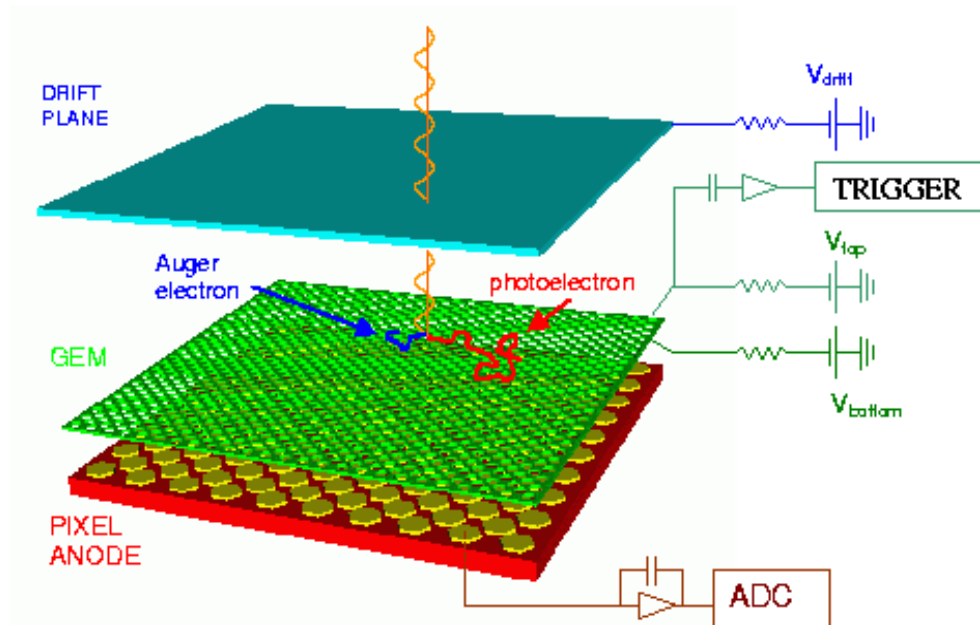
Detection Principle

- The detection principle is based upon the photoelectric effect



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

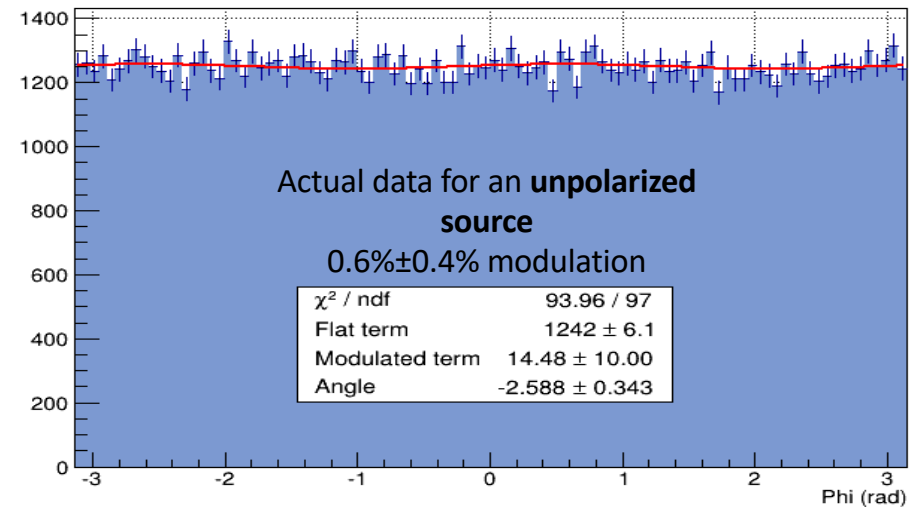
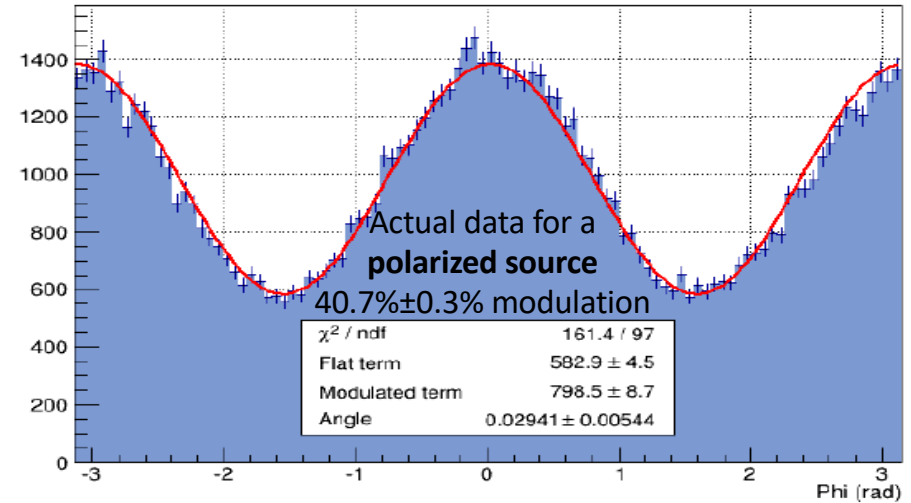
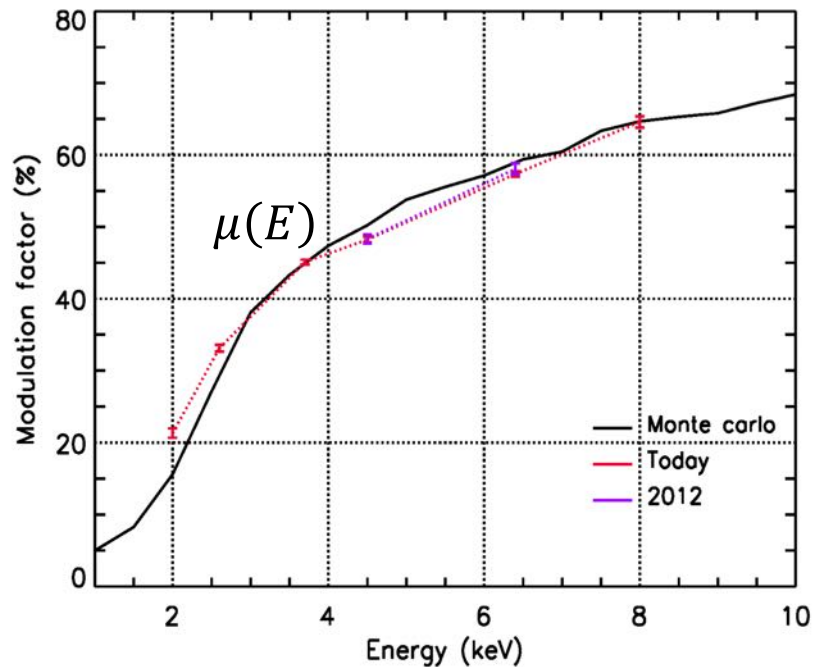
Gas Pixel Detector



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

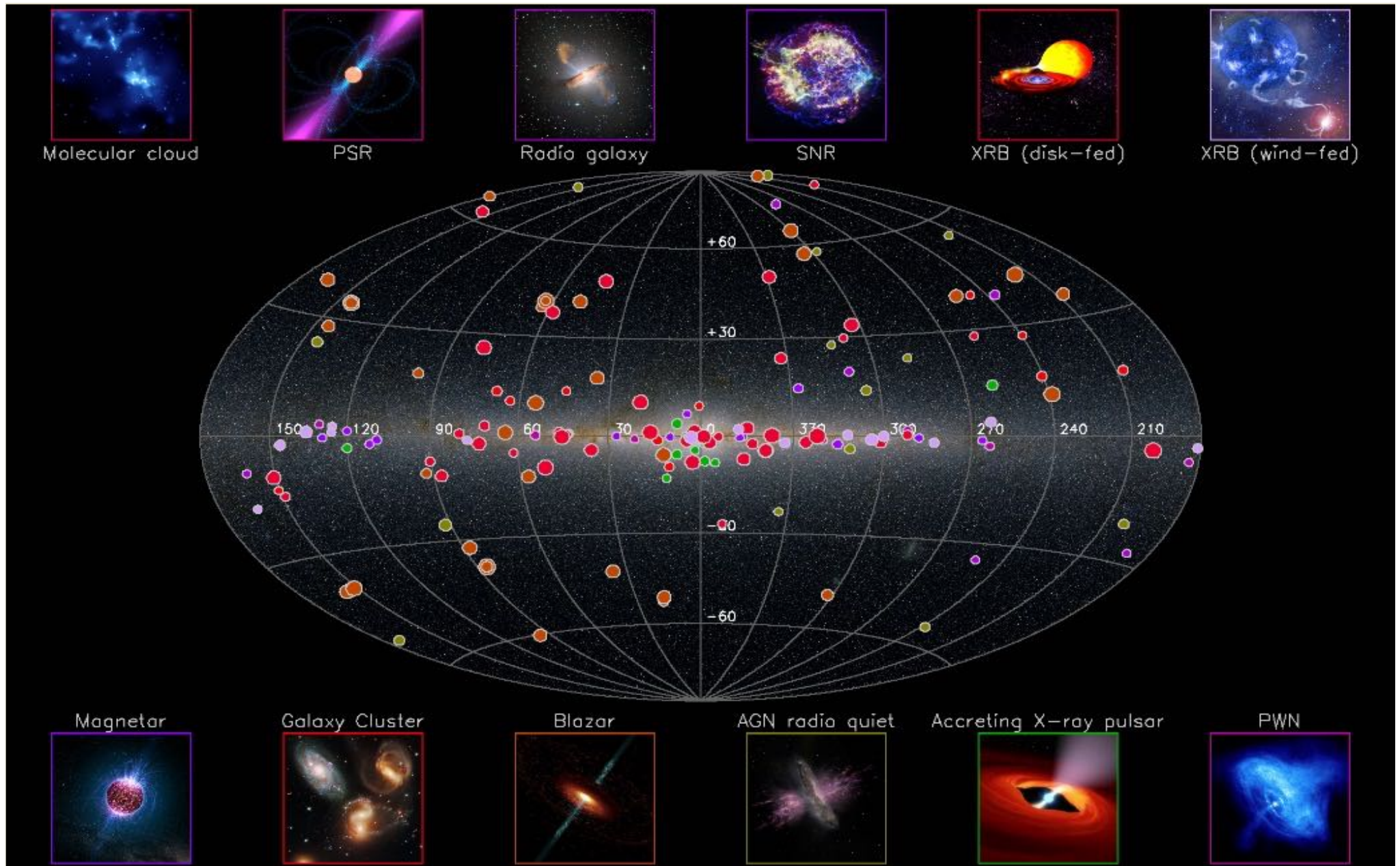


IXPE OBSERVATIONS

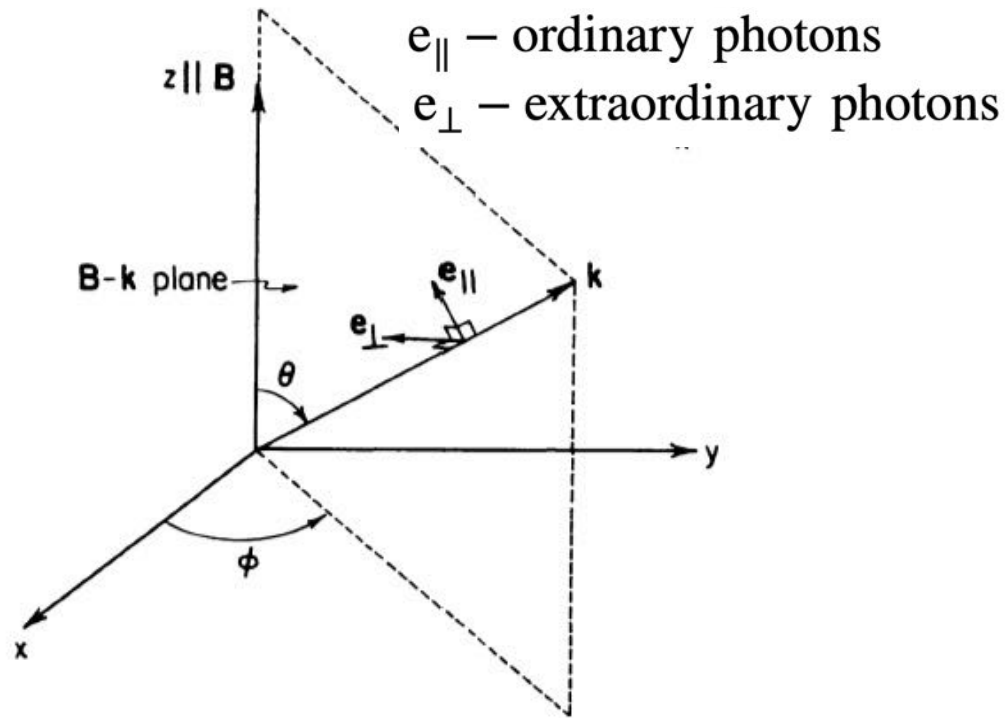
IXPE has made observations of:

- Blazars and radio galaxies
- Neutron star low-mass X-ray binaries
- Accreting X-ray pulsars
- Accreting stellar-mass black holes
- Supernova remnants and pulsar wind nebulae
- Magnetars
- Radio-quiet galactic nuclei
- Center of the Milky Way galaxy
- Gamma-ray burst
- Accreting millisecond pulsar
- Radio galaxy extended jet

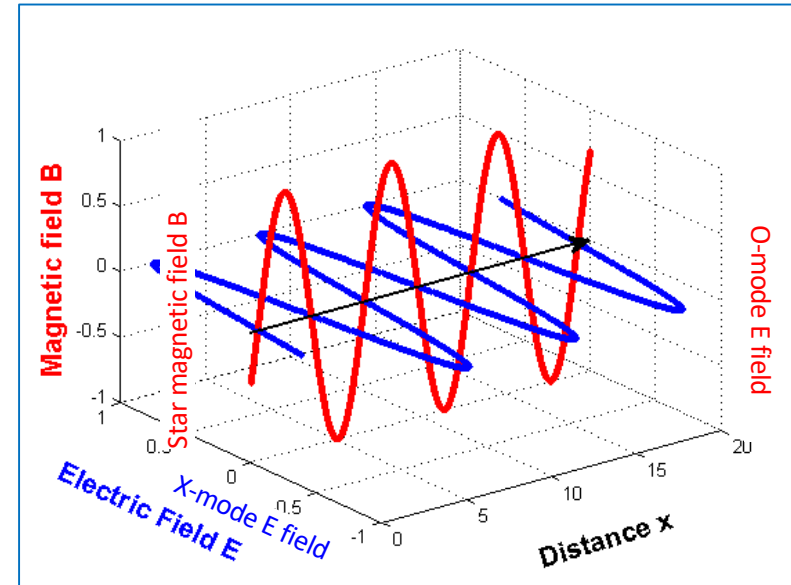
SKY MAP OF X-RAY POLARIZED SOURCES IN 202(6?)



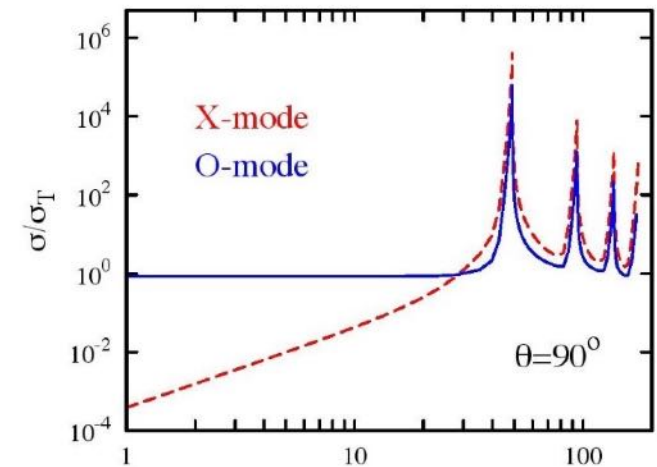
Polarization properties of X-ray pulsars



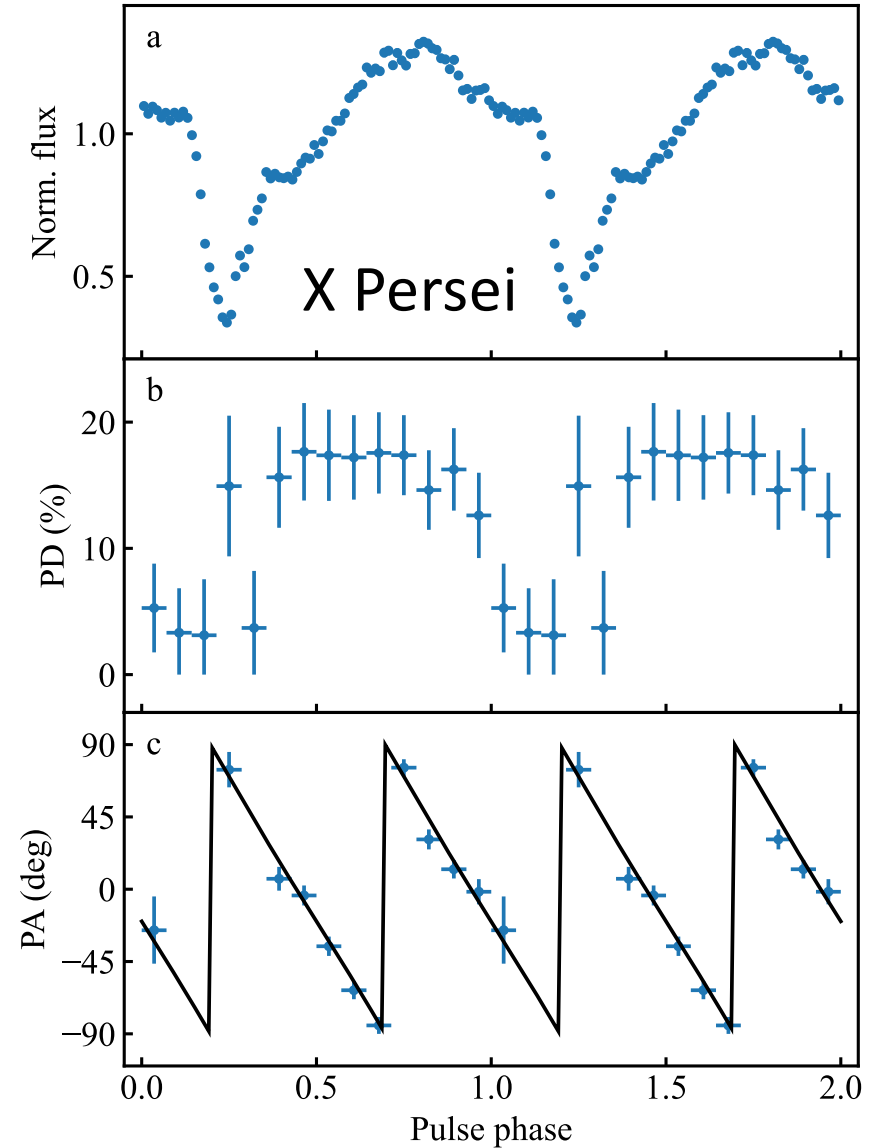
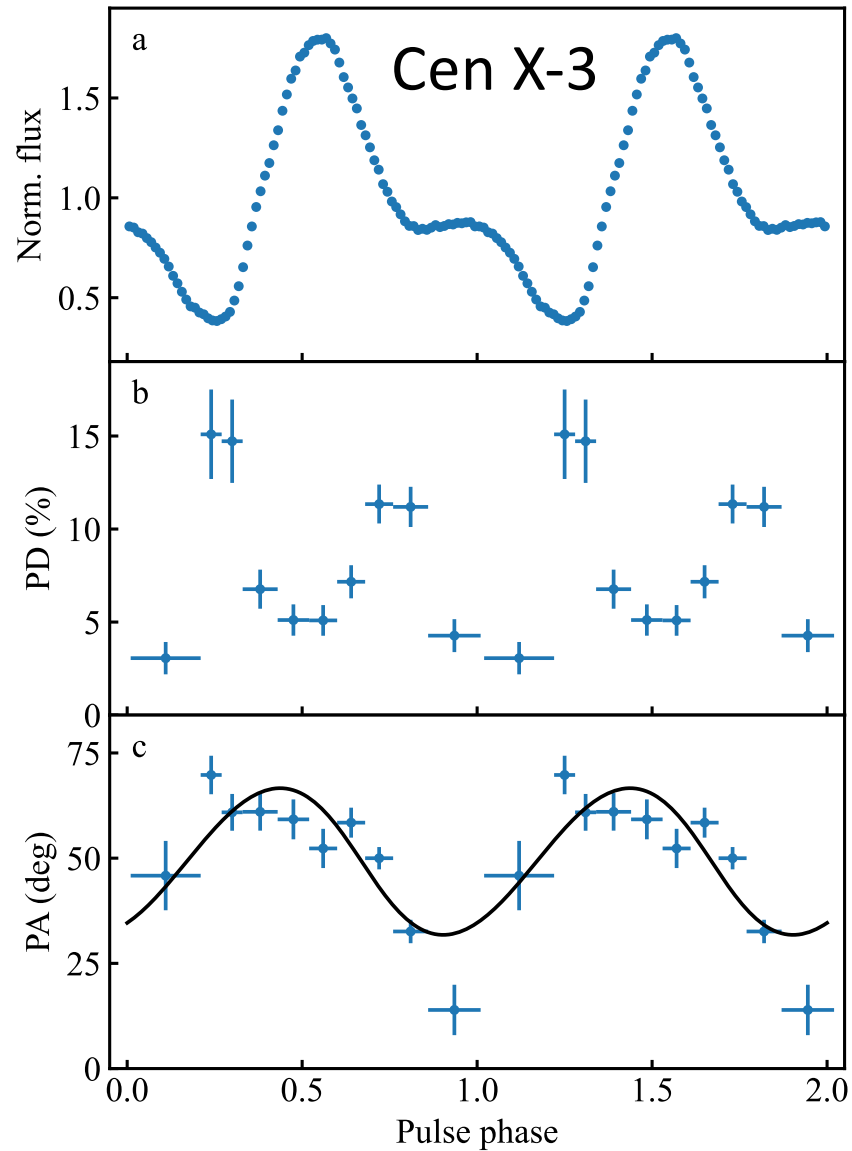
The opacity of the X-mode is drastically reduced compared to that of the opacity of the O-mode. Consequently, the emergent radiation is dominated by the X-mode, which comes from the deeper and hotter layers of plasma, and so is strongly polarized in the direction of the X-mode.



O-mode: the **E**-field oscillates in the **k**-**B** plane
X-mode: the **E**-field oscillates $\perp$ to the **k**-**B** plane

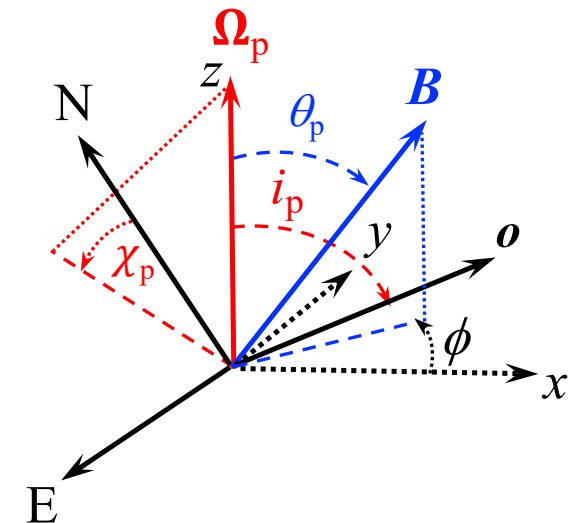
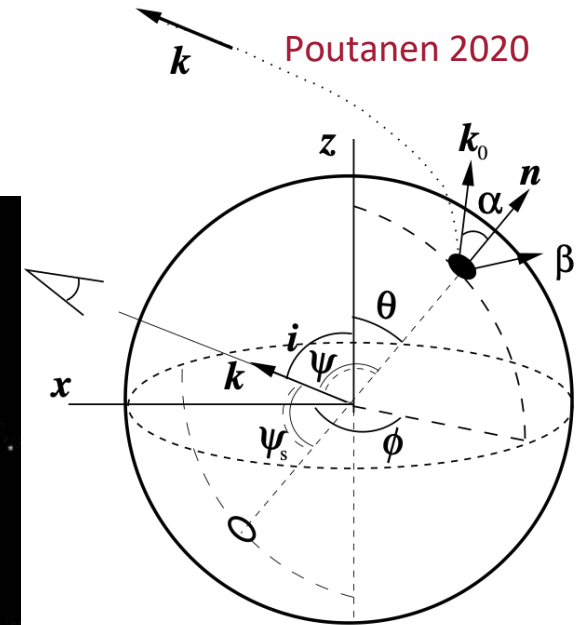
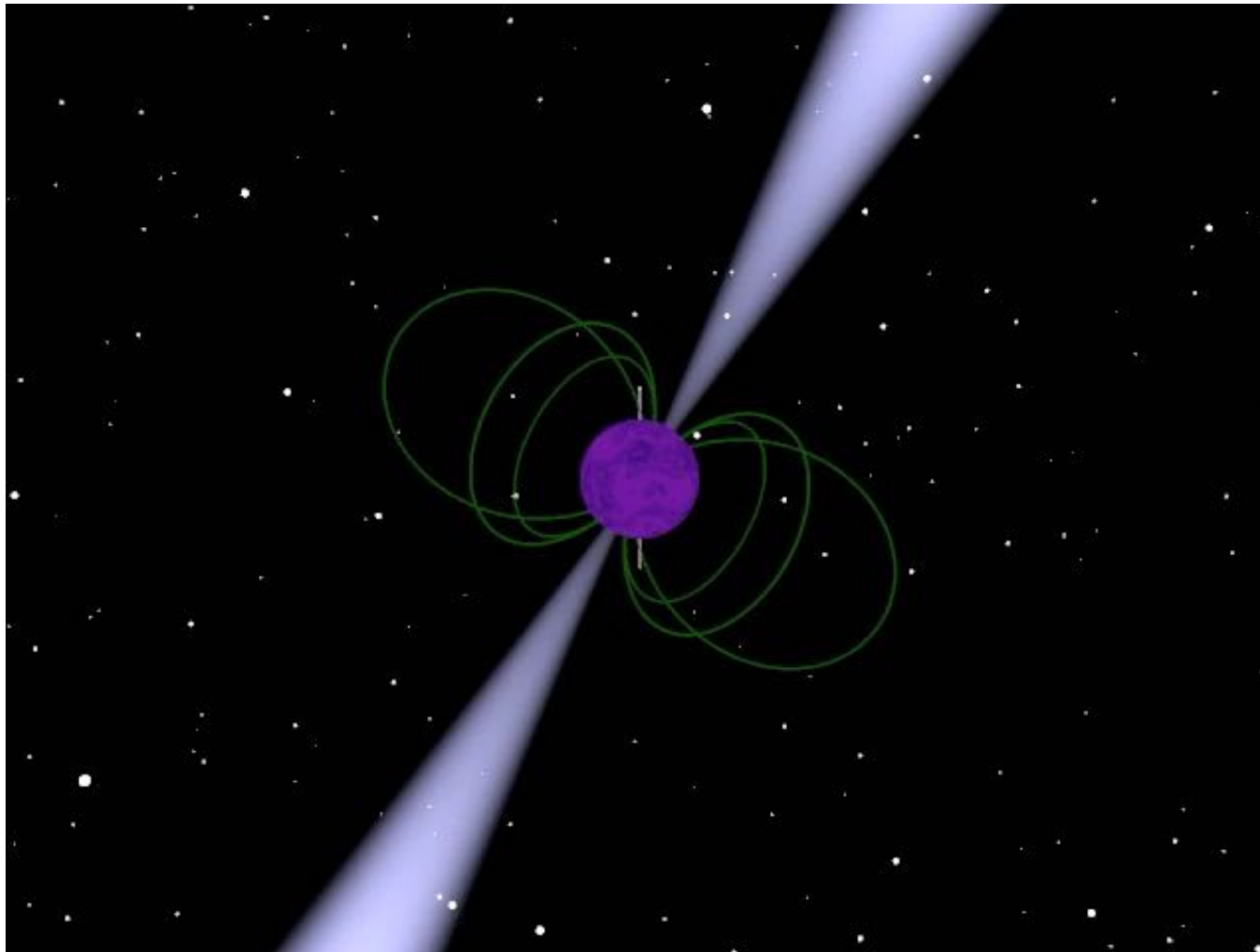


Pulse phase-resolved polarimetry



Geometry of the system

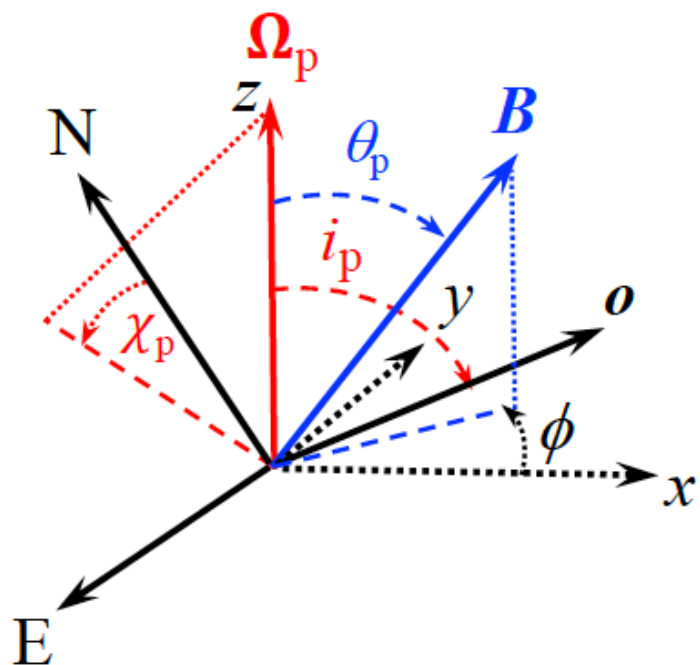
Rotating vector model



Rotating Vector Model (RVM)

- Magnetic dipole misaligned from the rotation axis.
- Pulse phase dependence of the polarization angle (position angle of the dipole).
- Rotating vector model of Radhakrishnan & Cooke (1969), Meszaros et al. (1988), Poutanen (2020)

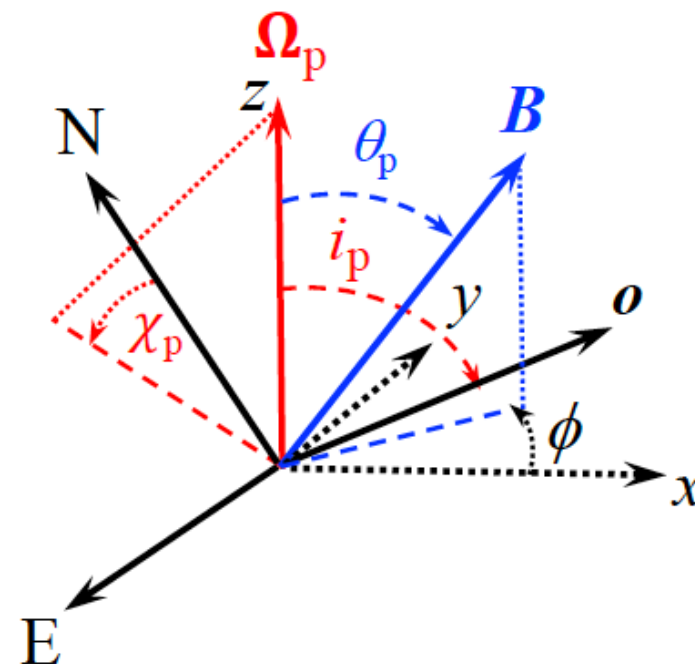
$$\tan(\chi - \chi_p) = \frac{-\sin \theta_p \sin \phi}{\sin i_p \cos \theta_p - \cos i_p \sin \theta_p \cos \phi}$$



χ_p - position angle of the pulsar spin
 i_p - observer inclination relative to the pulsar spin
 θ_p - magnetic obliquity
 ϕ - pulsar phase

Rotating Vector Model (RVM)

- Consider slowly rotating neutron star with the pulsar angular momentum pointing along the z-axis: $\hat{\Omega}_p = (0,0,1)$
- Let the observer be at inclination i_p to that axis in the x-z plane, with the unit vector pointing towards observer being $\hat{k} = (\sin i_p, 0, \cos i_p)$



- Let the magnetic field dipole be misaligned from the rotation axis by angle θ_p so that the unit vector $\hat{b}$ varies with the pulsar phase ϕ as $\hat{b} = (\sin \theta_p \cos \phi, \sin \theta_p \sin \phi, \cos \theta_p)$
- The angle ψ between magnetic dipole $\hat{b}$ and the observer $\hat{k}$ varies with pulsar phase as
$$\cos \psi = \hat{b} \cdot \hat{k} = \cos i_p \cos \theta_p + \sin i_p \sin \theta_p \cos \phi$$

Rotating Vector Model (RVM)

- We can introduce the polarization basis: two unit vectors at the plane of the sky relative to which direction of the electric vector oscillations are measured. The first vector $\hat{e}_1$ is along the projection of the angular momentum vector on the sky (plane $\perp$ to $\hat{k}$), the second $\hat{e}_2$ is perpendicular to that and points to the left

$$\hat{e}_1 = \frac{\hat{\Omega}_p - \cos i_p \hat{k}}{\sin i_p} = (-\cos i_p, 0, \sin i_p); \quad \hat{e}_2 = \frac{\hat{k} \times \hat{\Omega}_p}{\sin i_p} = (0, -1, 0)$$

- The projection of the dipole vector $\hat{b}$ on the sky is $\hat{e}_1^b = \frac{\hat{b} - \cos \psi \hat{k}}{\sin \psi}$ so that the angle this vector makes to $\hat{e}_1$ is

$$\cos \chi_0 = \hat{e}_1 \cdot \hat{e}_1^b = \frac{\sin i_p \cos \theta_p - \cos i_p \sin \theta_p \cos \phi}{\sin \psi}; \quad \sin \chi_0 = \hat{e}_2 \cdot \hat{e}_1^b = -\frac{\sin \theta_p \sin \phi}{\sin \psi}$$

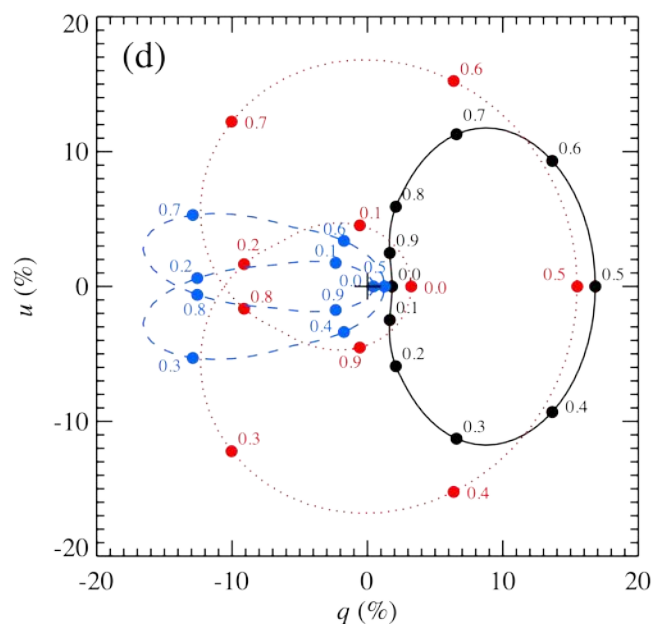
- Thus $\tan \chi_0 = \frac{-\sin \theta_p \sin \phi}{\sin i_p \cos \theta_p - \cos i_p \sin \theta_p \cos \phi}$

- If the projection of vector $\hat{\Omega}_p$ makes angle χ_p with the direction to the North on the sky, the angle $\hat{b}$ make with the North is $\chi = \chi_0 + \chi_p$.
- Substituting $\chi_0 = \chi - \chi_p$ to the formula above, we get the formula at the first slide.

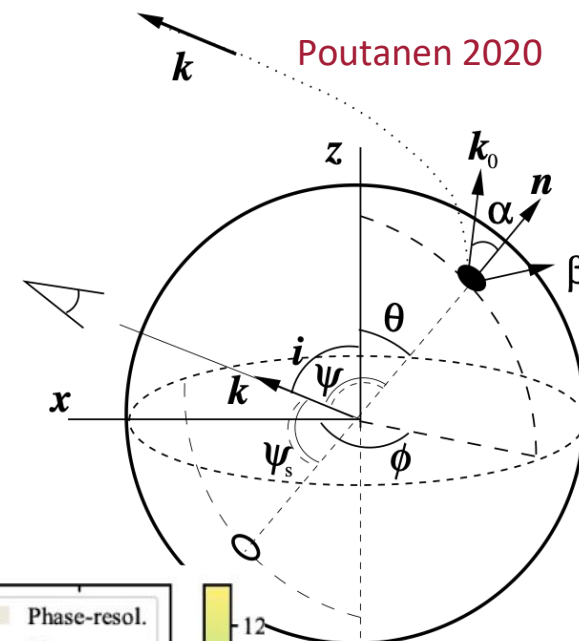
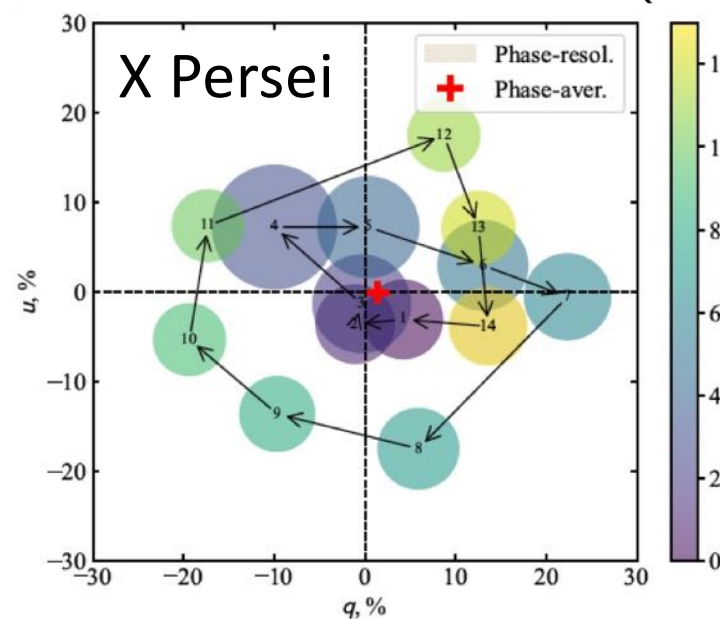
Geometry of the system

Rotating vector model

$$\tan(\text{PA} - \chi_p) = \frac{-\sin \theta \sin(\phi - \phi_0)}{\sin i_p \cos \theta - \cos i_p \sin \theta \cos(\phi - \phi_0)}$$

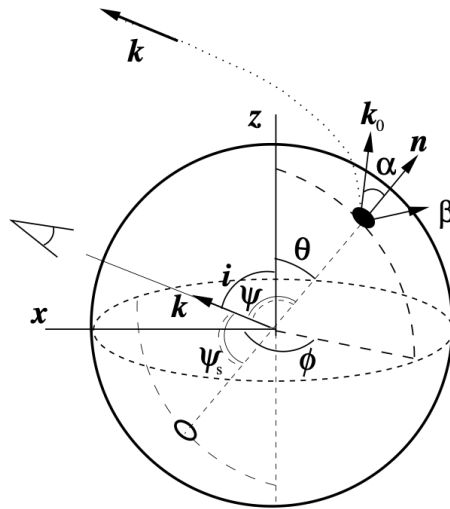


(60°, 30°) (30°, 70°) (70°, 85°)

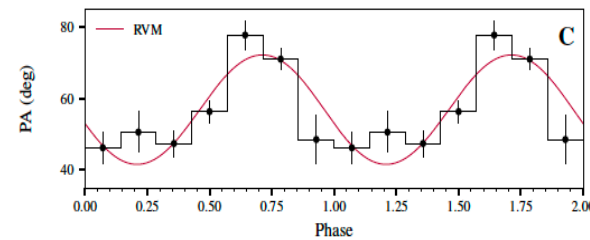


Rotating vector model -> geometry

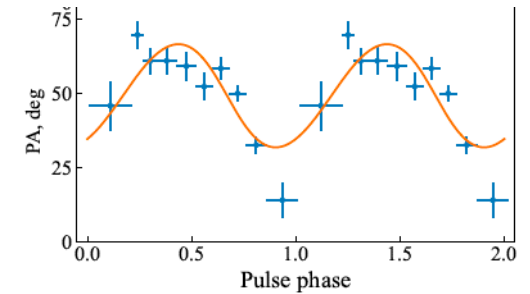
$$\tan(\text{PA} - \chi_p) = \frac{-\sin \theta \sin(\phi - \phi_0)}{\sin i_p \cos \theta - \cos i_p \sin \theta \cos(\phi - \phi_0)}$$



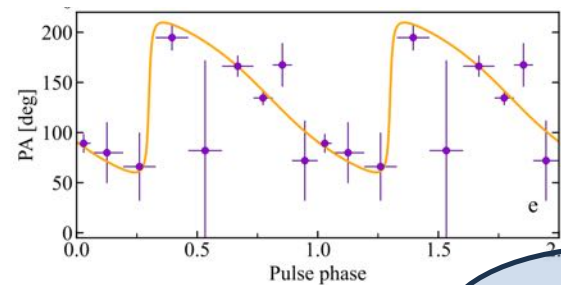
Her X-1



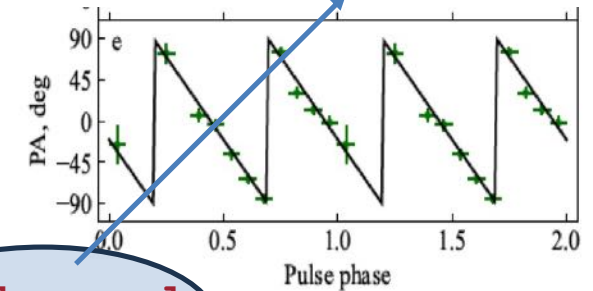
Cen X-3



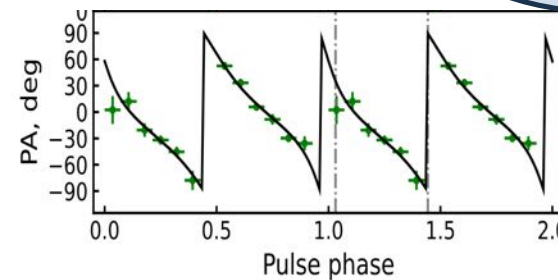
GX 301-2



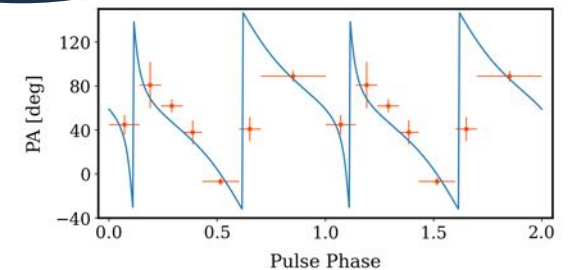
X Persei



GRO J1008-57



EXO 2030+375

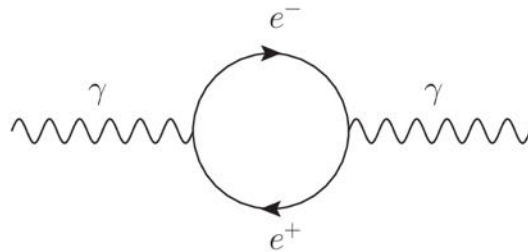


**Orthogonal
rotators**

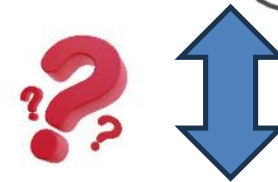
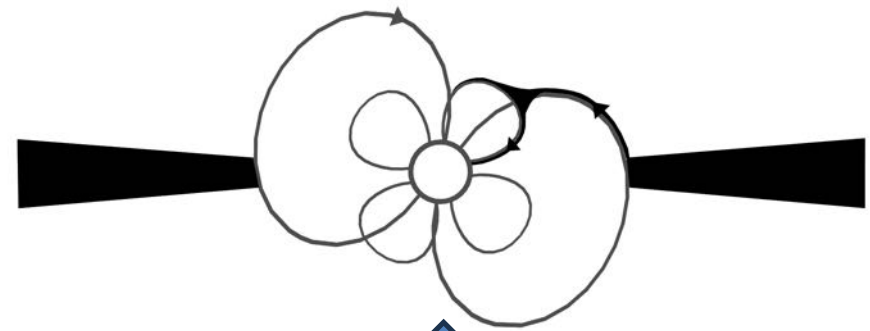
Photon propagation in the magnetosphere

■ QED effects – Rotating Vector Model

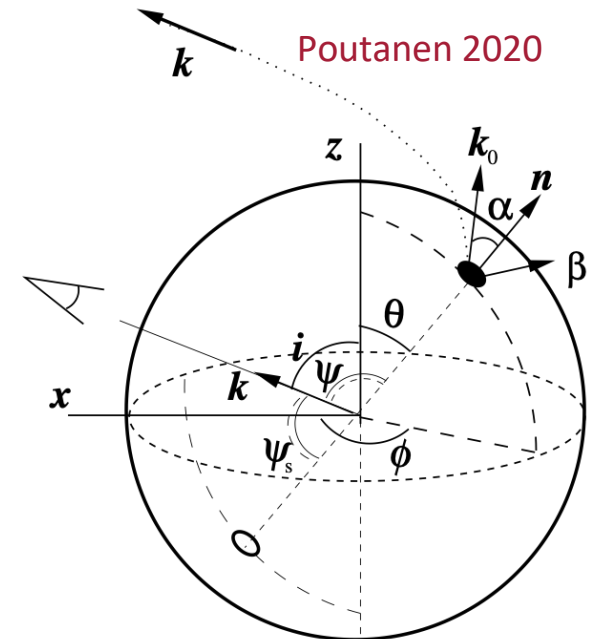
- Strong magnetic fields polarize the virtual e^-e^+ pairs around the star



- The photon E -field is forced to adiabatically follow the star magnetic field along the photon trajectory
- Photon polarization vectors decouple from the B -field at large distances (adiabatic radius; where the magnetic field is $\approx$ a dipole)



Poutanen 2020



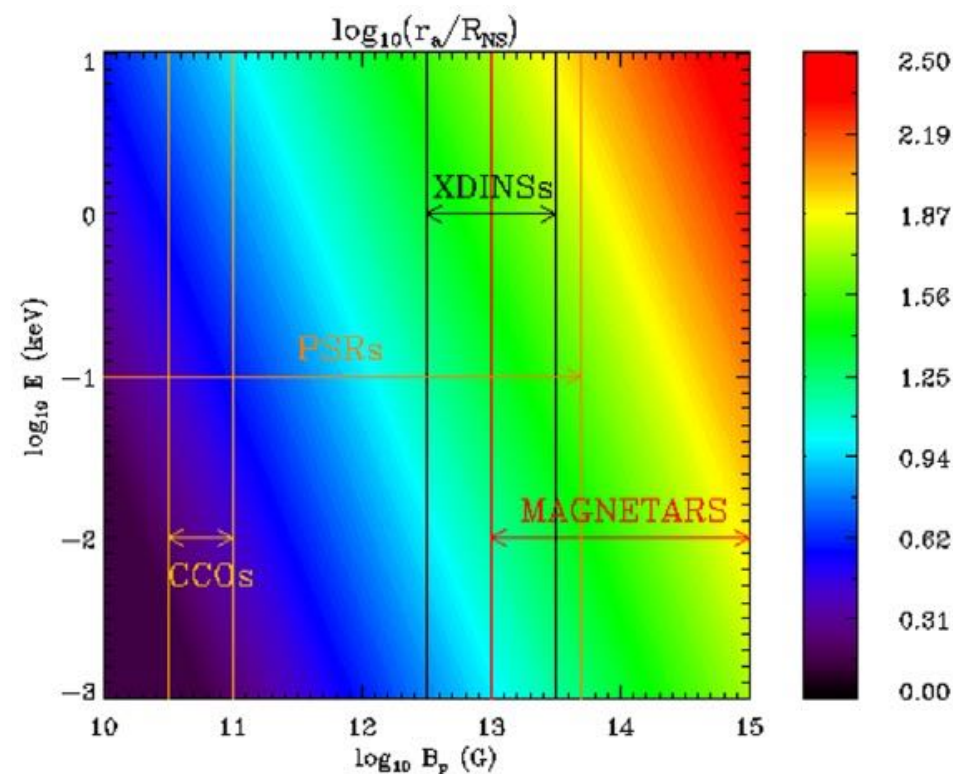
Photon propagation in the magnetosphere

▪ QED vacuum polarization effects

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

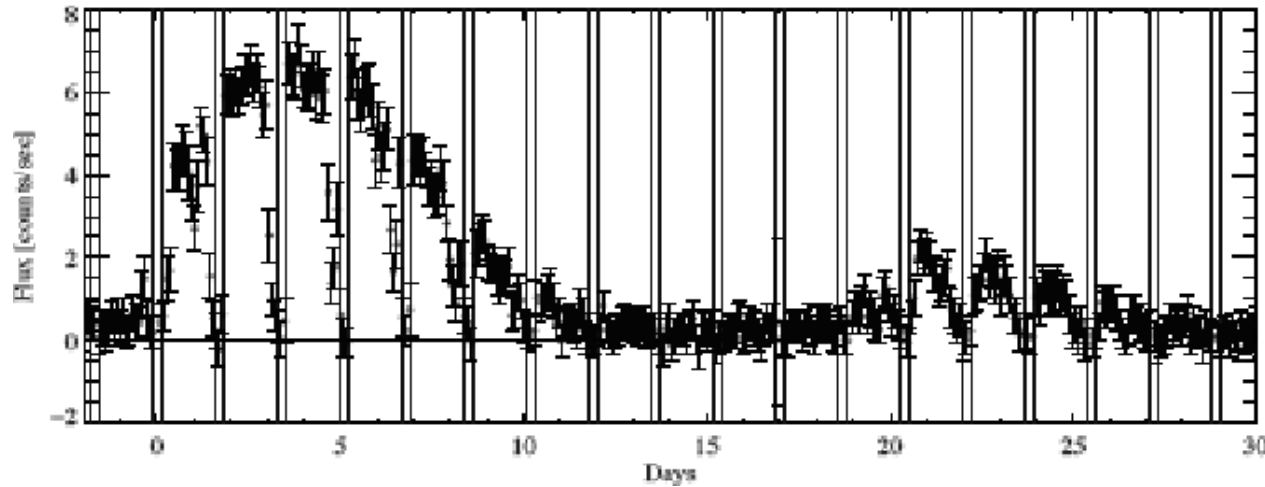
$$\frac{r_{\text{pl}}}{R_{\text{NS}}} \simeq 4.8 \left(\frac{\hbar\omega}{1 \text{ keV}} \right)^{1/5} \left(\frac{B_p}{10^{11} \text{ G}} \right)^{2/5} \left(\frac{R_{\text{NS}}}{10 \text{ km}} \right)^{1/5}$$

- PD is still determined by surface emission properties
- PA is independent of the B -field topology at the surface but reflects the magnetic dipole geometry. We expect PA to follow rotating vector model (RVM) (Radhakrishnan & Cooke 1969)

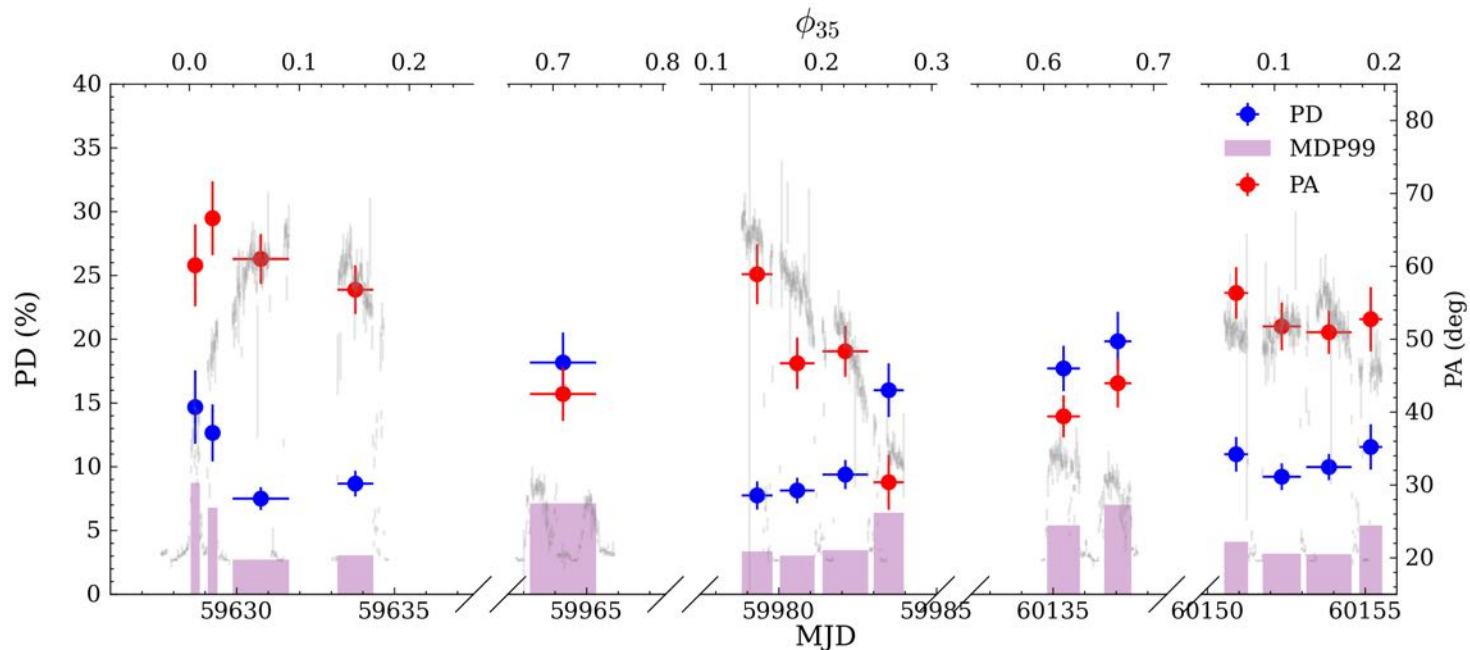


Taverna et al. (2015)

Super-orbital variability: Her X-1



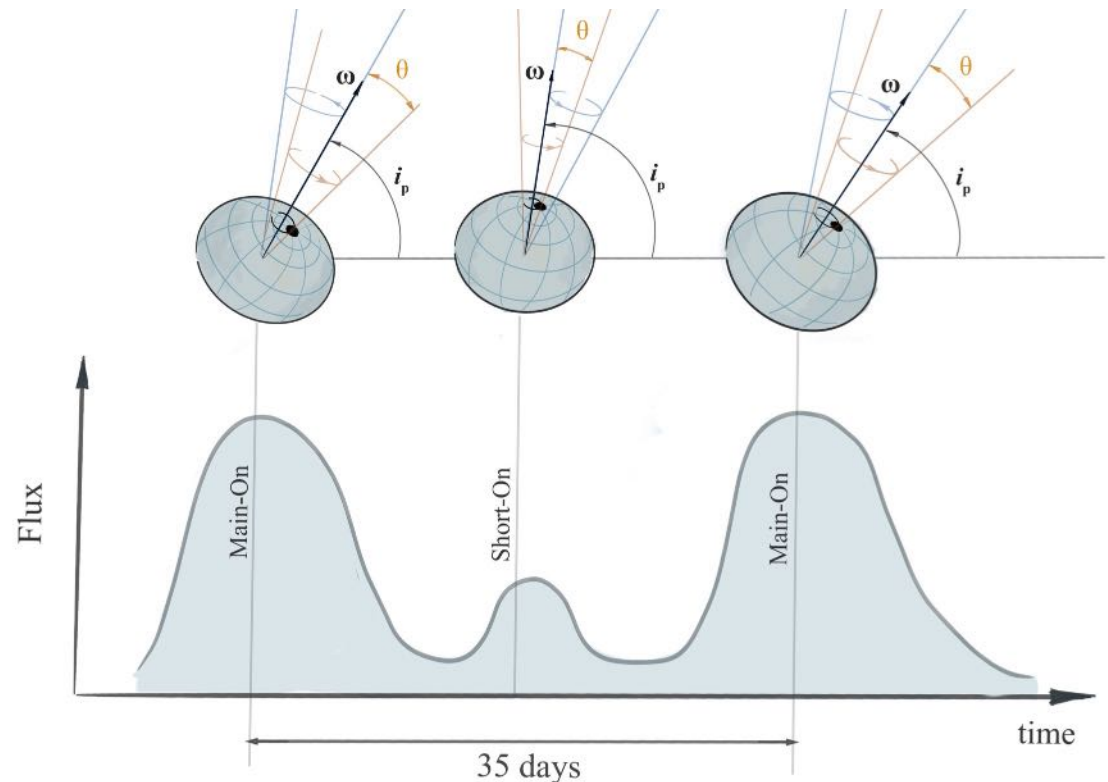
- Spin period: 1.24 s
- Orbital period: 1.7 d
- Super-orbital period: 35 d



Precession of the NS: Her X-1

	Mean PD (%)	i_p (deg)	θ (deg)	χ_p (deg)	ϕ_0 (%)	Prec. Phase (%)
First Main-On	9.5 ± 0.5	58^{+28}_{-22}	$14.5^{+3.0}_{-4.0}$	55.4 ± 1.6	$19.0^{+2.7}_{-2.2}$	8.8
Early	8.6 ± 0.6	64^{+25}_{-22}	$16.3^{+3.5}_{-4.1}$	57.9 ± 2.1	$19.0^{+2.6}_{-2.4}$	7.3
Late	9.3 ± 0.7	85^{+35}_{-37}	$15.9^{+3.6}_{-4.0}$	52.2 ± 2.7	$21.7^{+4.5}_{-5.0}$	16.2
Short-On	17.8 ± 1.4	90^{+30}_{-30}	$3.7^{+2.6}_{-1.9}$	41.9 ± 2.2	85.1^{+18}_{-19}	68.7
Second Main-On	9.1 ± 0.5	56^{+24}_{-20}	$16.0^{+3.1}_{-4.3}$	46.8 ± 1.5	$19.8^{+2.3}_{-2.0}$	15.9

The data allowed to conclude that the observed 35-days period in Her X-1 is set by the free precession of the NS crust, implying that its shape is slightly asymmetric, by a few parts per ten million.



Conclusions on polarimetry of XRPs

IXPE has opened a new window to the Universe. Observations of X-ray polarization are already revolutionizing our understanding of highly magnetized neutron stars. In the first two years of the observatory's operation, we:

- Demonstrated that the degree of polarization is lower than expected even in bright pulsars.
- For the majority of XRPs, we measured the geometry; for all of them, the inclinations of the orbit and the pulsar are in agreement; magnetic inclinations have a wide distribution.
- Observed both correlation and anticorrelation of flux in the profile and degree of polarization.
- Confirmed the precession of the neutron star in Her X-1.

