X-ray polarimetry: science goals *(and synergies with NuSTAR and HEX-P)*

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X-ray polarimetry so far

Polarimetry has proved very important in radio, IR and optical bands (eg. jet emission in blazars, Unification Model of AGN, ...).

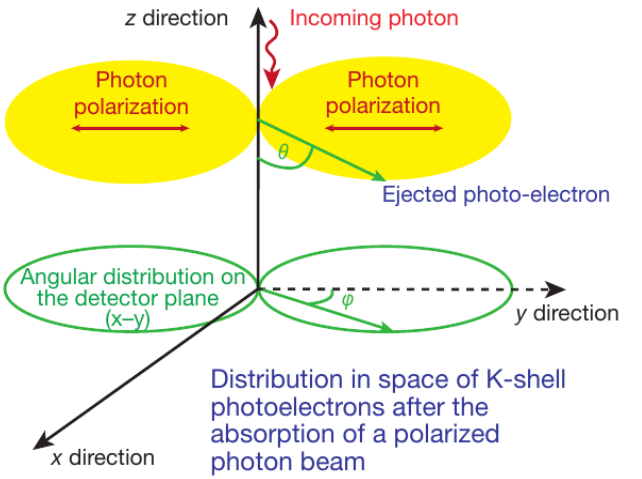
In X-rays, where non-thermal processes and aspherical geometries are likely to be more common than at lower energies, polarimetry is expected to be vital to fully understand emitting sources.

However, only one measurement (P=19% for the Crab Nebula) has been obtained so far, together with a tight upper limit to Sco X-1. These measurements date back to the 70s, for the two brightest sources in the X-ray sky.

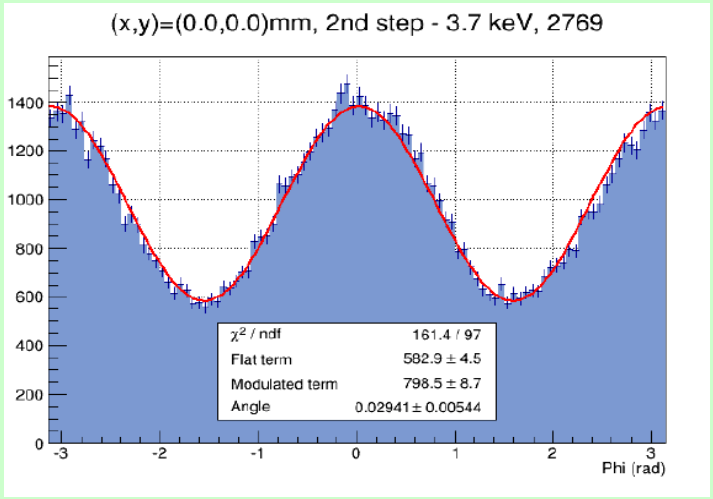
The lack, for many decades, of significant technical improvements implied that no polarimeters were put on board of X-ray satellites. The situation has changed with the advent of polarimeters based on the photoelectric effect. Such detectors, coupled with a X-ray telescope, may provide astrophysically interesting measurements for hundreds of sources (remember that polarimetry is a photon hungry technique...).

The brightest specimens of all major classes of X-ray sources are now accessible!

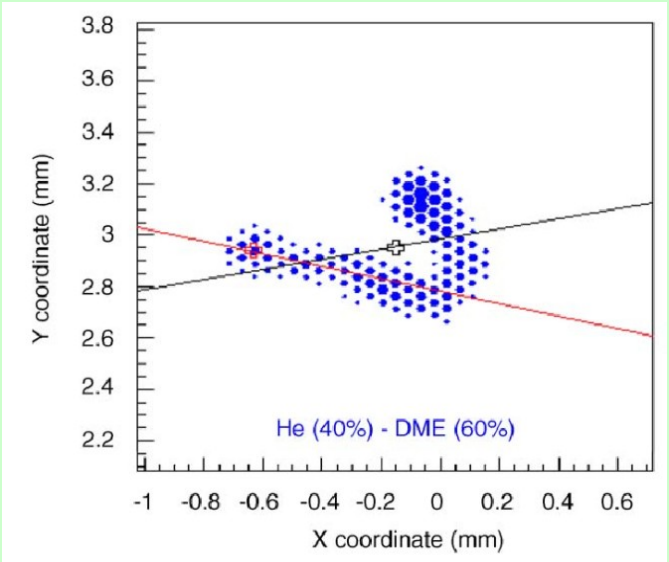
Photoelectric Polarimeters

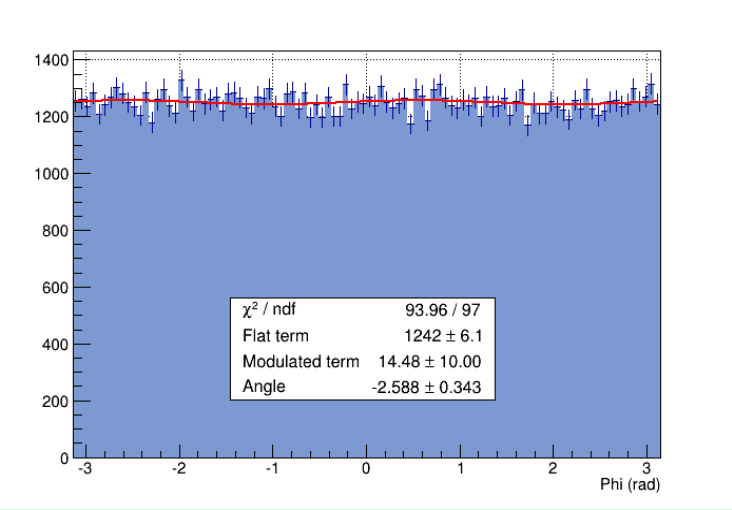


$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



Modulation curve for a fully polarized beam





Residual modulation for unpolarized photons

Missions under competitive studies

XIPE (X-ray Imaging Polarimetry Explorer)

Selected by ESA (M4) for phase A study.
Final selection: May 2017 – Launch: 2026

IXPE (Imaging X-ray Polarimetry Explorer)

Selected by NASA (SMEX) for phase A study.
Final selection: Early 2017 – Launch: 2021

PRAXyS (Polarimeter for Relativistic Astrophysical X-ray sources)

Selected by NASA (SMEX) for phase A study.
Final selection: Early 2017 – Launch: 2021

All these polarimeters work in the ~2-10 keV band

Science Goals

Polarimetry is expected to provide relevant, when not crucial, information for (almost) all classes of X-ray sources. Examples include:

The physics of highly magnetized Neutron Stars
(NuSTAR/HEX-P: B from cyclotron lines)

Acceleration processes in PWN, SNR and jets
(NuSTAR/HEX-P: thermal vs. non thermal, Synchrotron vs IC)

Astroarcheology of the Galactic Center
(NuSTAR/HEX-P: mapping the Galactic Center region)

The geometry of hot coronae in AGN and XRB
(NuSTAR/HEX-P: coronal parameters T and τ)

Strong gravity effects in accreting Black Holes: spin
(NuSTAR/HEX-P: independent spin measurements)

X-ray Pulsars

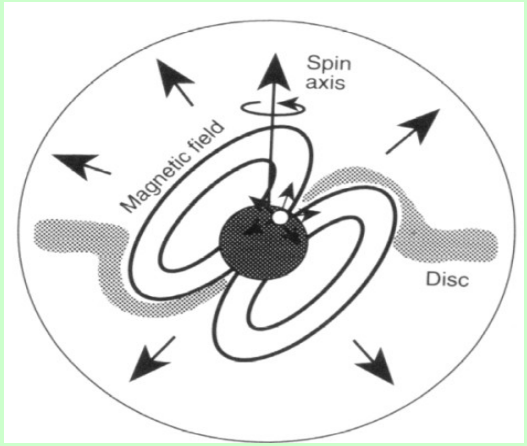
Opacity in highly magnetized plasma

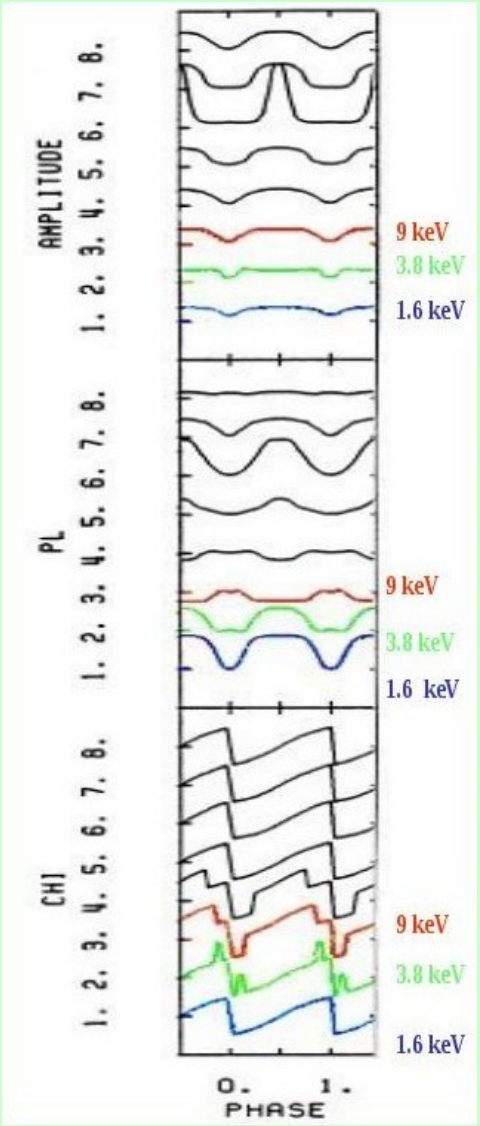
$$\Rightarrow \quad k_{\perp} \neq k_{\parallel}$$

Phase-dependent linear polarization

From the (phase-resolved) swing of the polarisation angle:

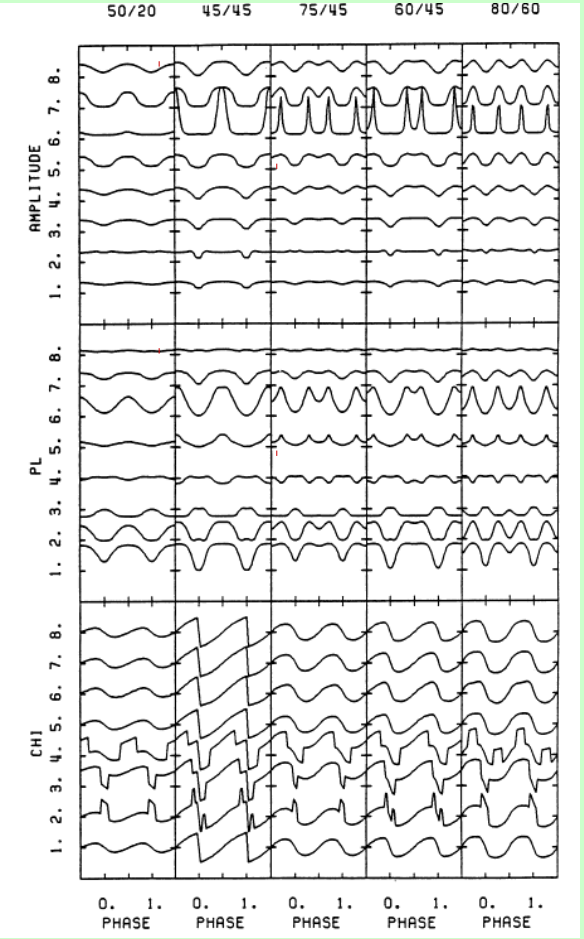
orientation of the rotation axis and inclination of the magnetic field (required for many purposes, e.g. measure of mass/radius relation)



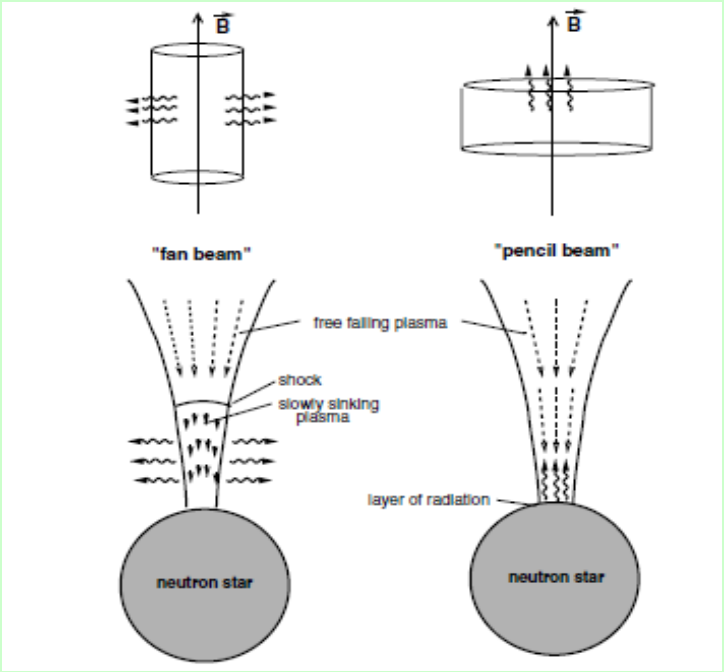


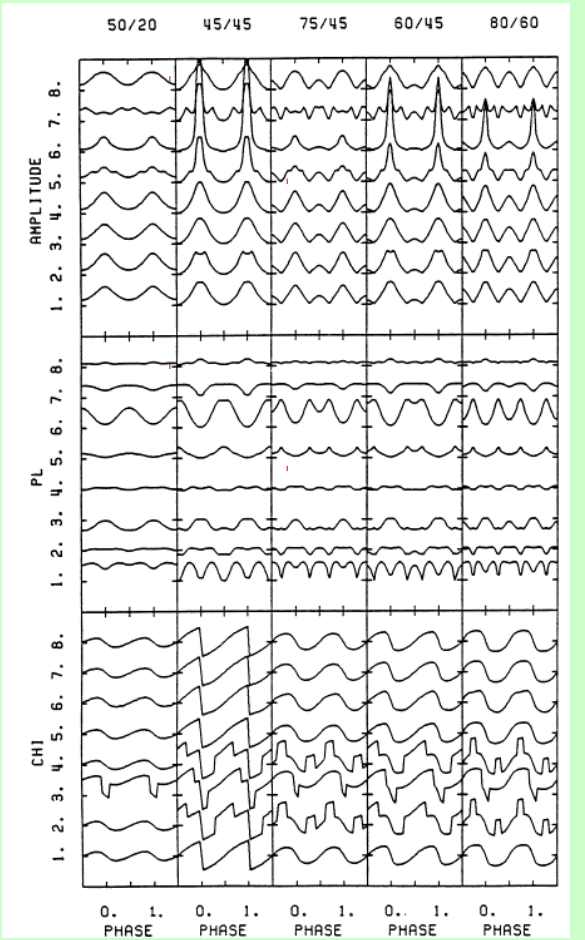
Meszaros et al. 1988

X-ray Pulsars



"Fan" vs. "Pencil" beam





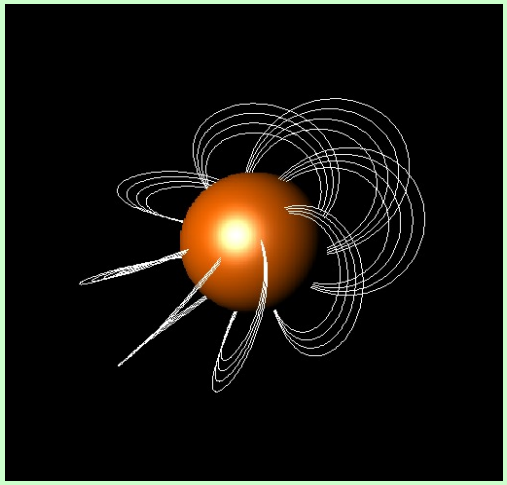
Meszaros et al. 1988

Magnetars

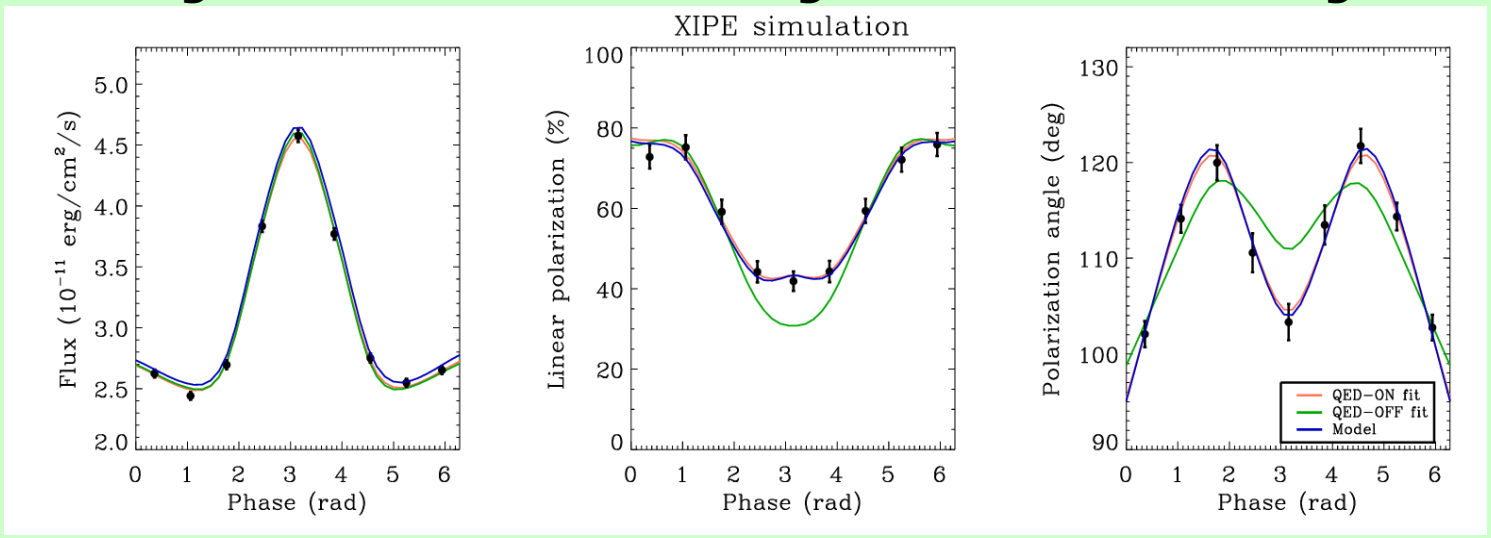
Magnetars are isolated neutron stars with likely a huge magnetic field (B up to 10^{15} Gauss).

It heats the star crust and explains why the X-ray luminosity largely exceeds the spin down energy loss.

QED foresees vacuum birefringence, an effect predicted 80 years ago (Eisenberg & Euler 1936), expected in such a strong magnetic field but not detected yet.

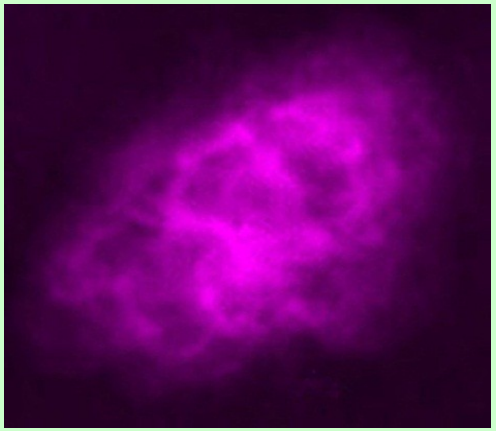


Light curve **Pol. degree** **Pol. angle**



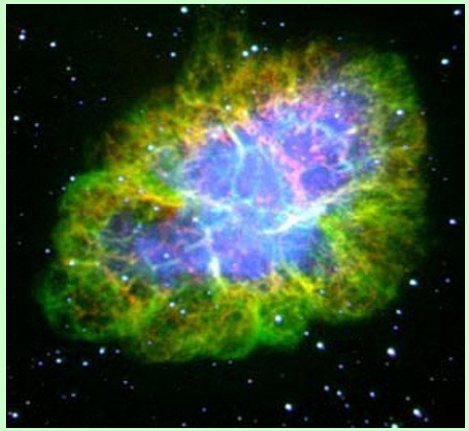
Such an effect is **only** visible in the phase dependent polarization degree and angle.

The Crab Nebula and Pulsar

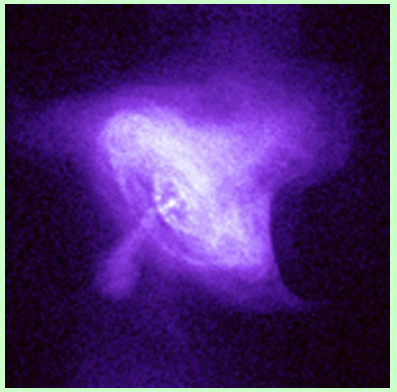


Radio (VLA)

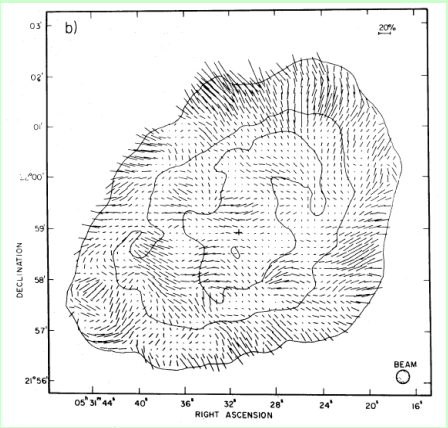
Infrared (Keck)



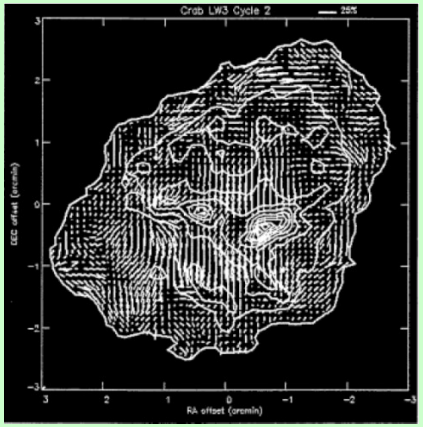
Optical (Palomar)



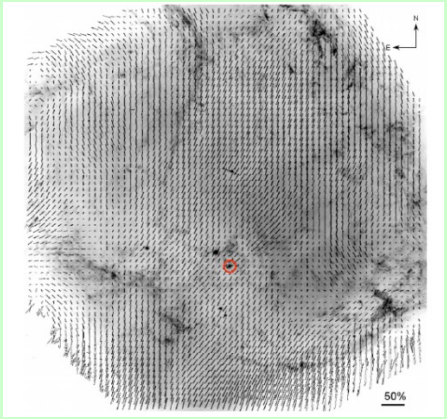
X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

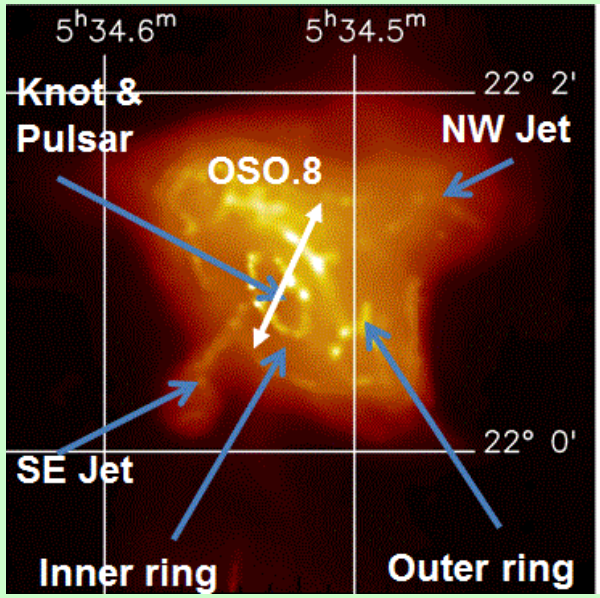
?

P=19% integrated over the entire nebula (Weisskopf et al. 1978)

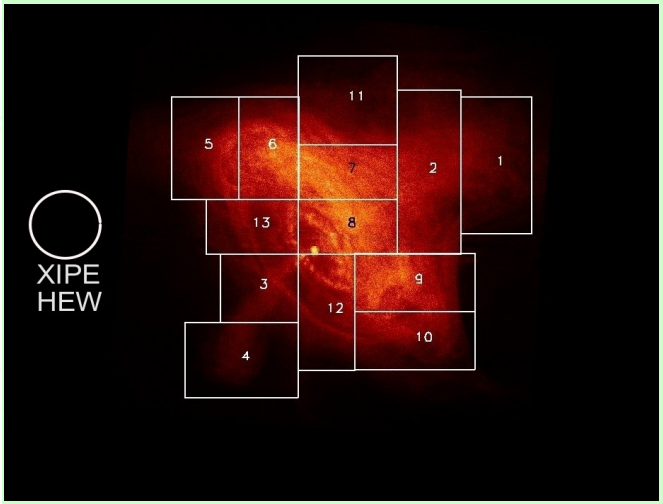
X-ray polarisation

X-rays probe **freshly accelerated** electrons and their acceleration site.

The Crab Nebula and Pulsar



Region	σdegree (%)	σangle (deg)	MDP (%)
1	±0.60	±0.96	1.90
2	±0.41	±0.65	1.30
3	±0.68	±1.10	2.17
4	±0.86	±1.39	2.76
5	±0.61	±0.97	1.93
6	±0.46	±0.75	1.48
7	±0.44	±0.70	1.40
8	±0.44	±0.71	1.41
9	±0.46	±0.74	1.47
10	±0.60	±0.97	1.92
11	±0.52	±0.83	1.65
12	±0.53	±0.85	1.69
13	±0.59	±0.95	1.89



20 ks with XIPE

- The OSO-8 observation, integrated over the entire nebula, measured a position angle that is tilted with respect to both jets and torus axes.
- What is the role of the magnetic field (turbulent or not?) in accelerating particles and forming structures?
- XIPE imaging capabilities will allow us to measure the pulsar polarisation by separating it from the much brighter nebula emission.
- Other PWN, up to 5 or 6, are accessible for larger exposure times (e.g. Vela or the “Hand of God”).

Blazars

In IC dominated Blazars, polarimetry can determine the origin of the seed photons:

- **Synchrotron-Self Compton (SSC) ?**

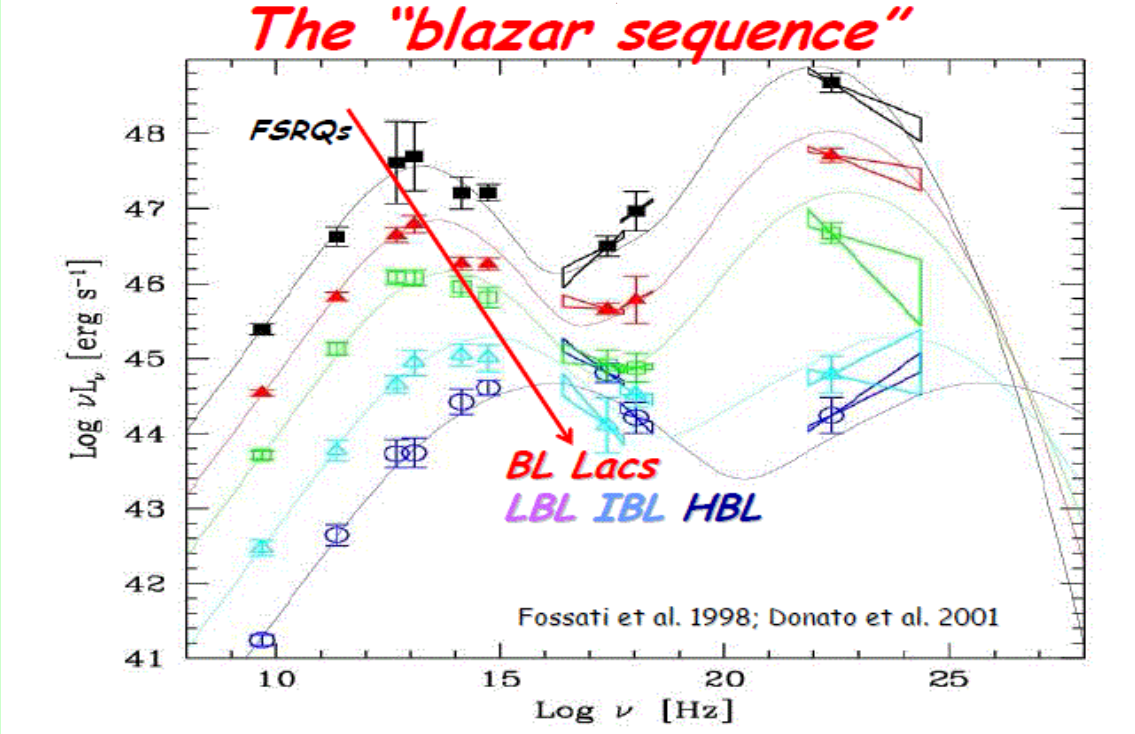
The polarization angle is the same as for the synchrotron peak.

- **External Compton (EC) ?**

The polarization angle may be different.

The polarization degree determines the electron temperature in the jet.

Sync. Peak **IC Peak**



2-10 keV

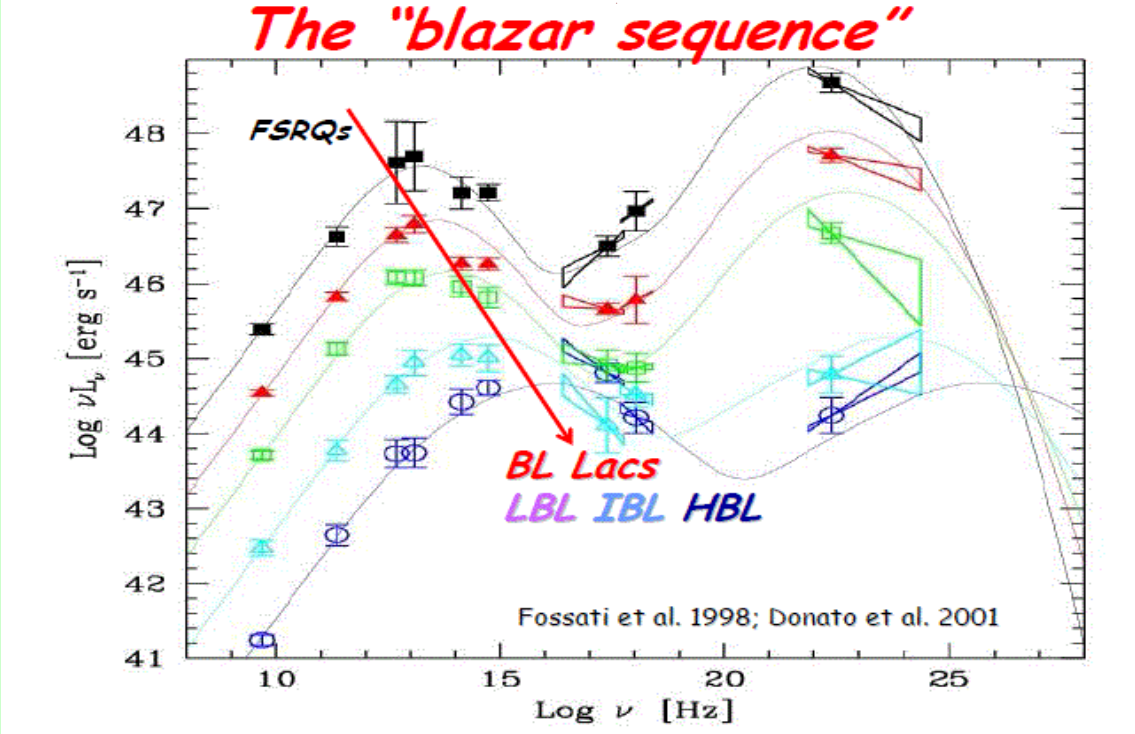
Blazars

In synchrotron-dominated X-ray Blazars, multi-λ polarimetry probes the structure of the magnetic field along the jet.

Models predict a larger and more variable polarisation in X-rays than in the optical.

Coordinated multi-wavelength campaigns are crucial for blazars.

Sync. Peak **IC Peak**

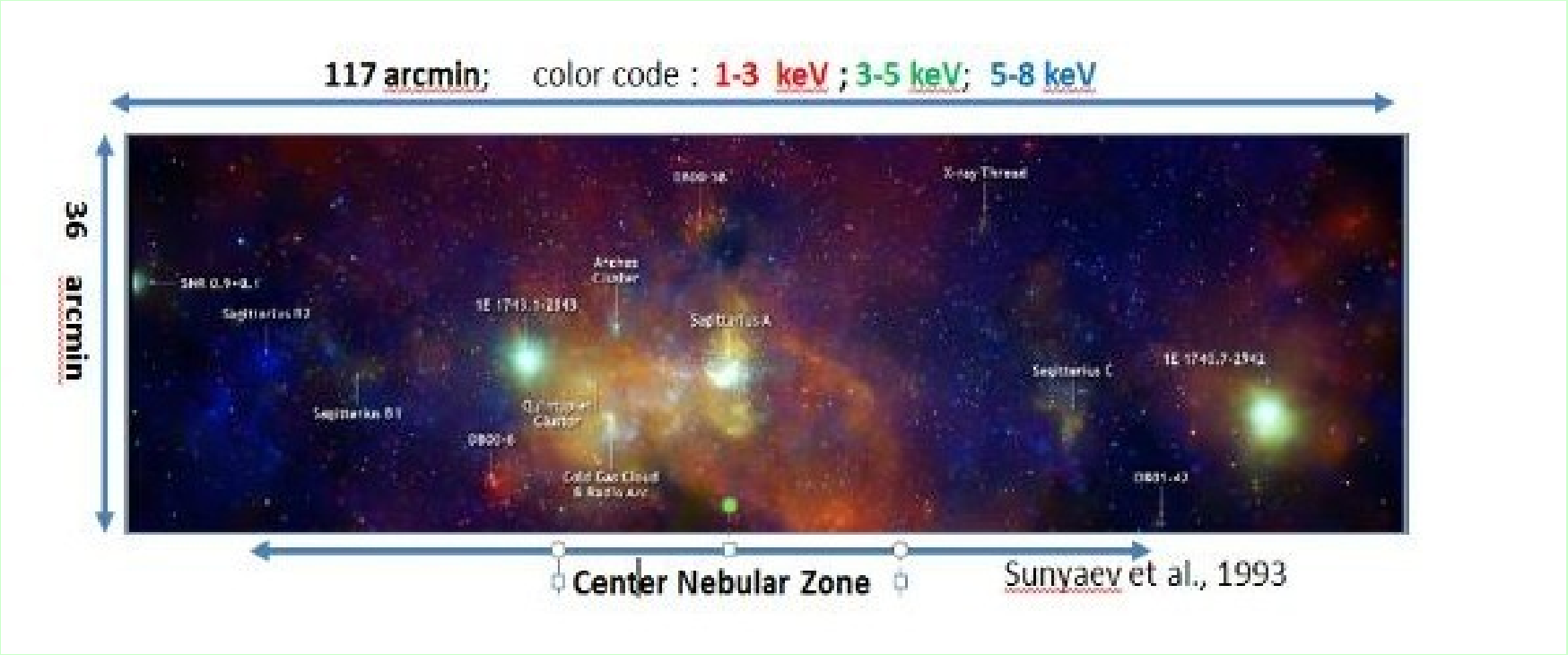


2-10 keV

GC as a low luminosity AGN

Cold molecular clouds around Sgr A* (i.e. the supermassive black hole at the centre of our own Galaxy) show a neutral iron line and a Compton bump → Reflection from an external source!?!

No bright enough sources are in the surroundings. Are they reflecting X-rays from Sgr A*? so, was it one million times brighter a few hundreds years ago? Polarimetry can tell! (Churazov et al. 2002)



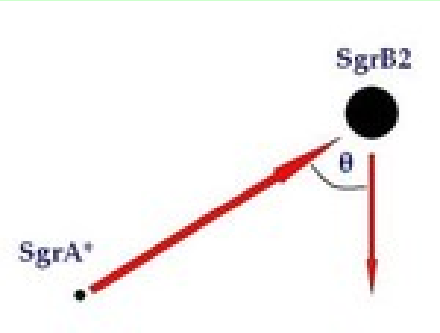
GC as a low luminosity AGN

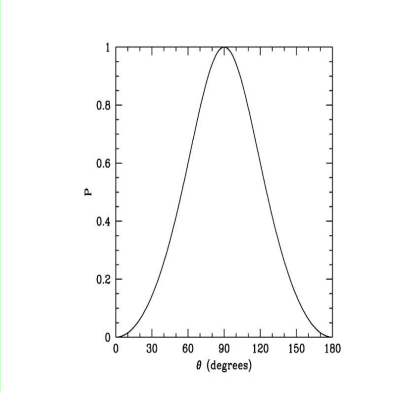
Polarization by scattering from Sgr B complex, Sgr C complex

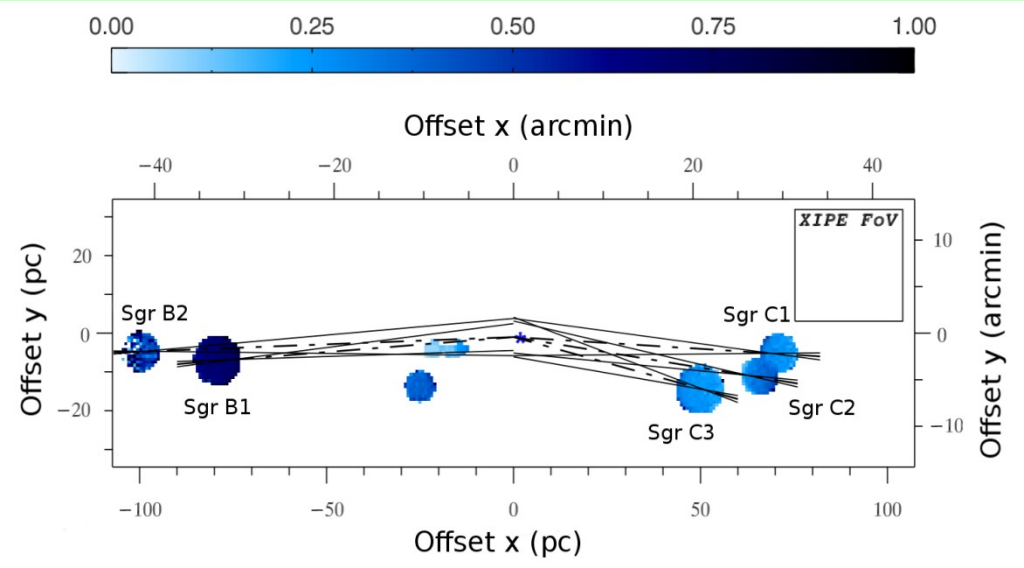
The angle of polarization pinpoints the source of X-rays

The degree of polarization measures the scattering angle and determines the true distance of the clouds from Sgr A*.

Marin et al. 2014

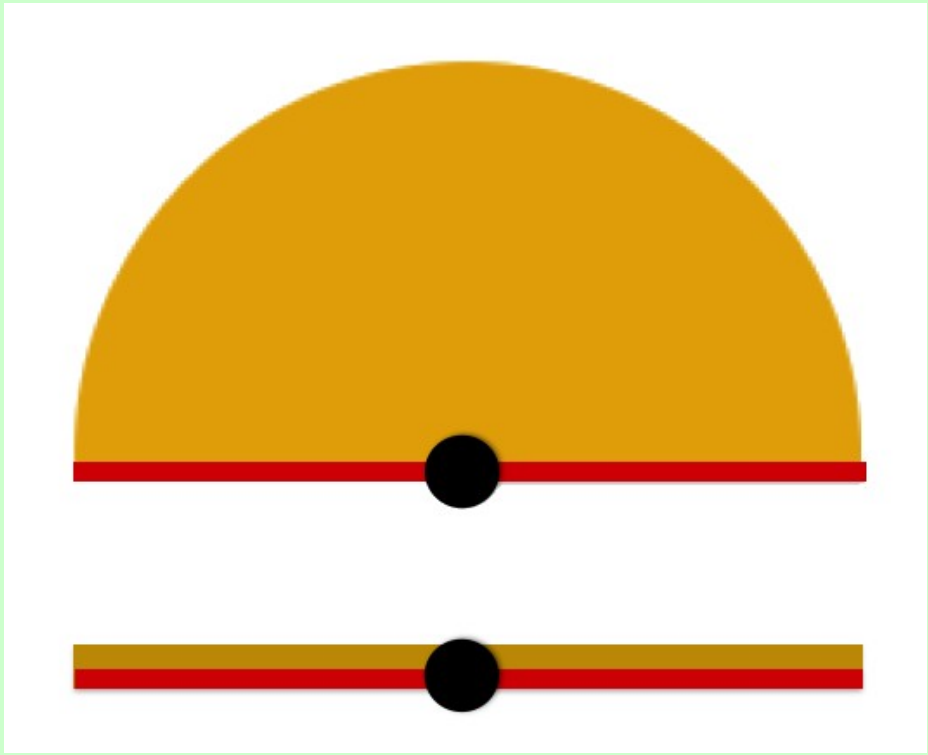




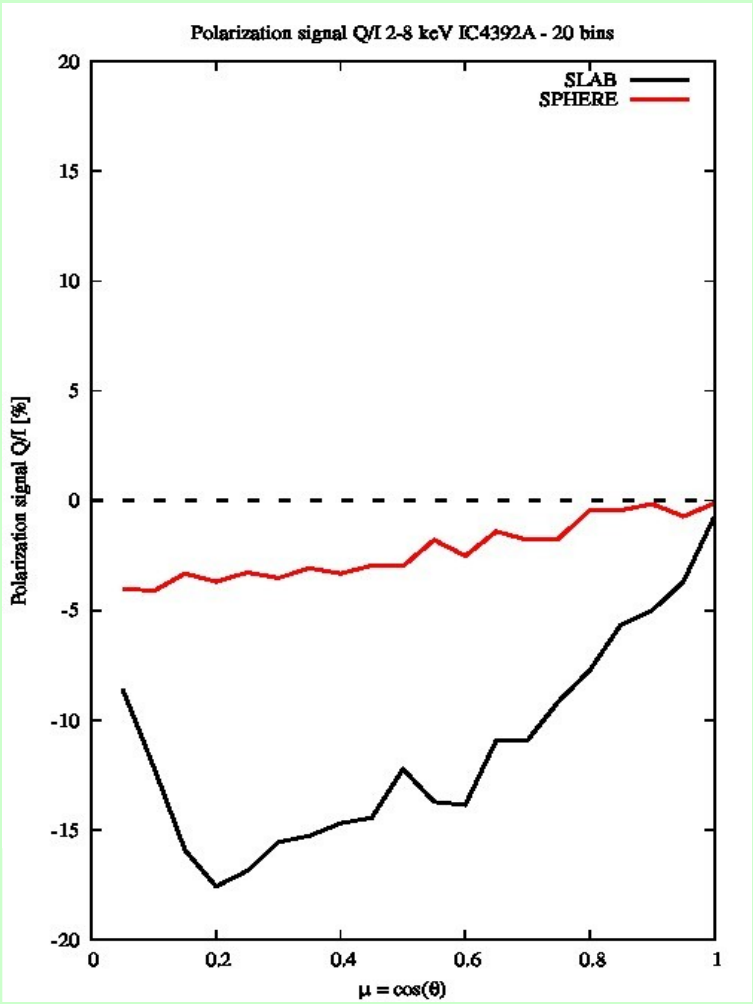


The geometry of the hot corona

The geometry of the hot corona is unknown. Emission is expected to be polarized if the corona OR the radiation field are not spherical



Slab and sphere geometries, temperature and τ as per IC4229A (Brenneman et al. 2014)



Tamborra et al., in prep.

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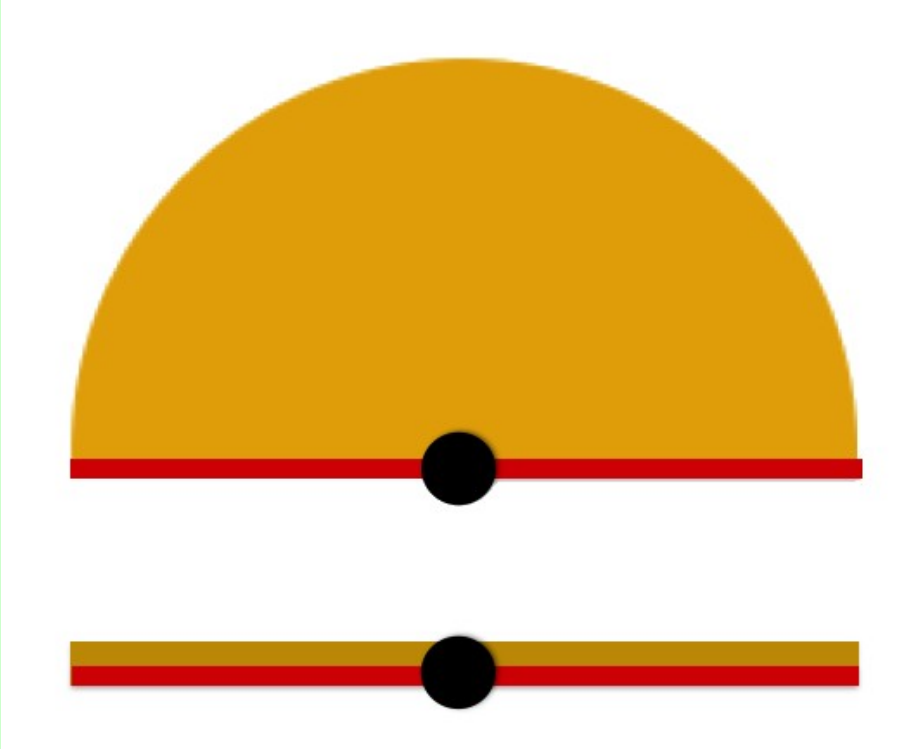
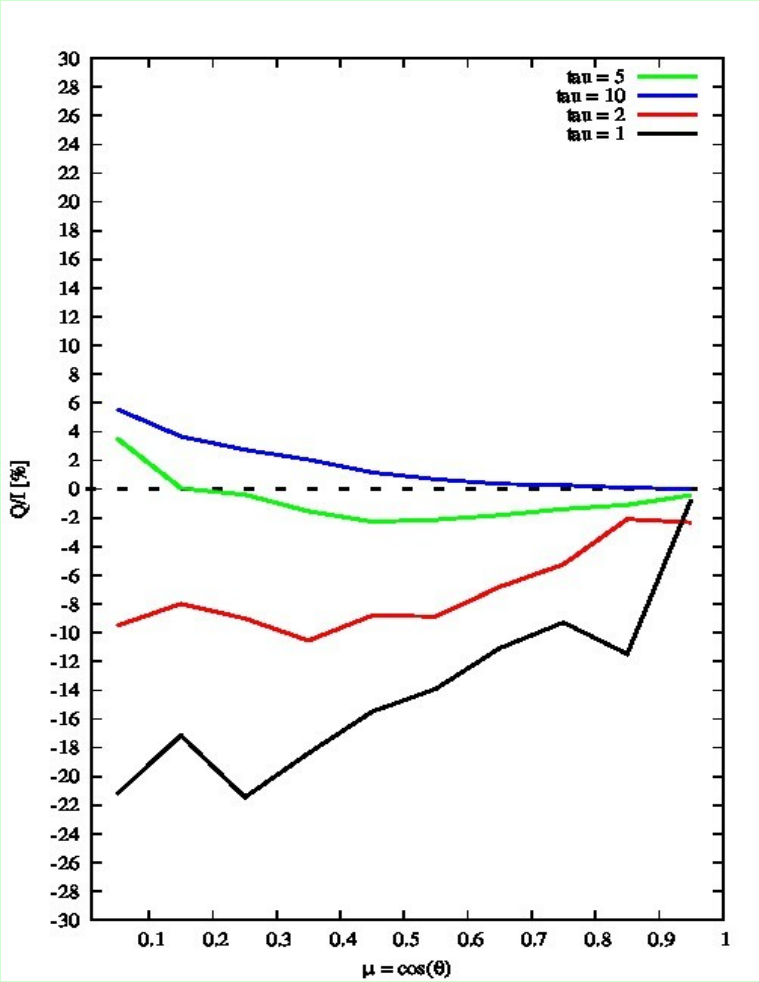
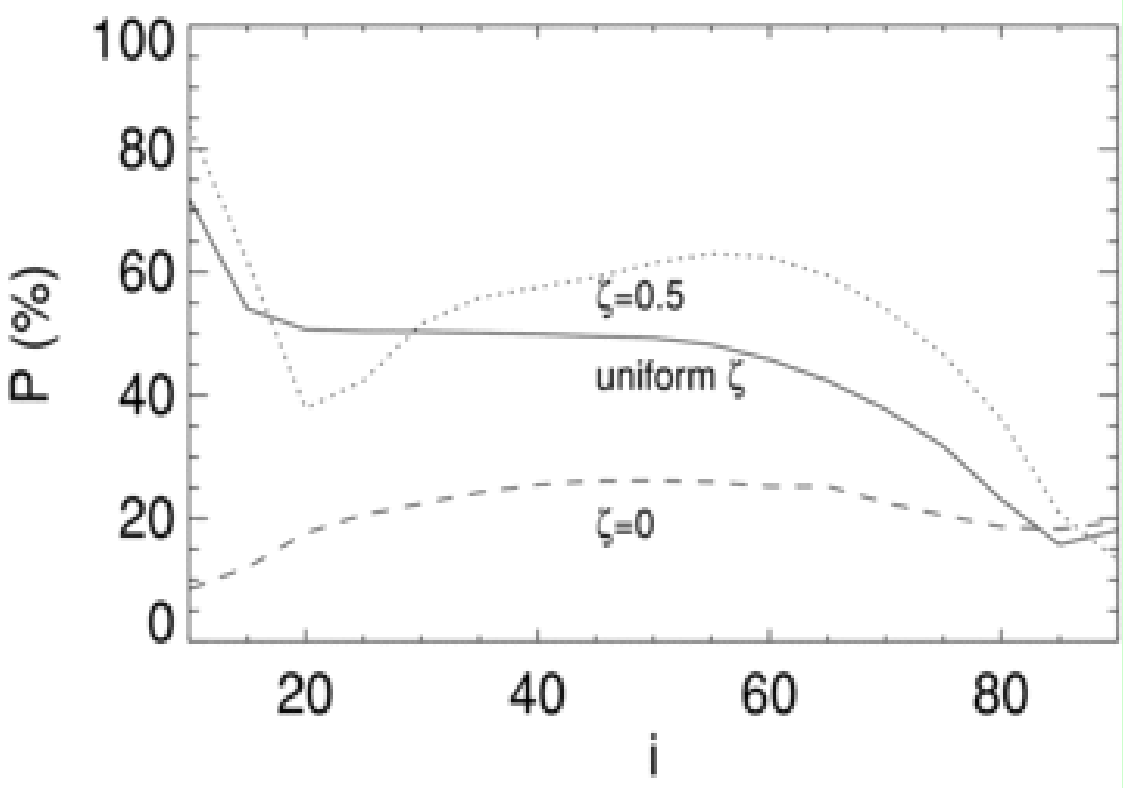


Slab geometry, temperature as per IC4229A (Brenneman et al. 2014), different values of τ



Tamborra et al., in prep.

Corona or jet?

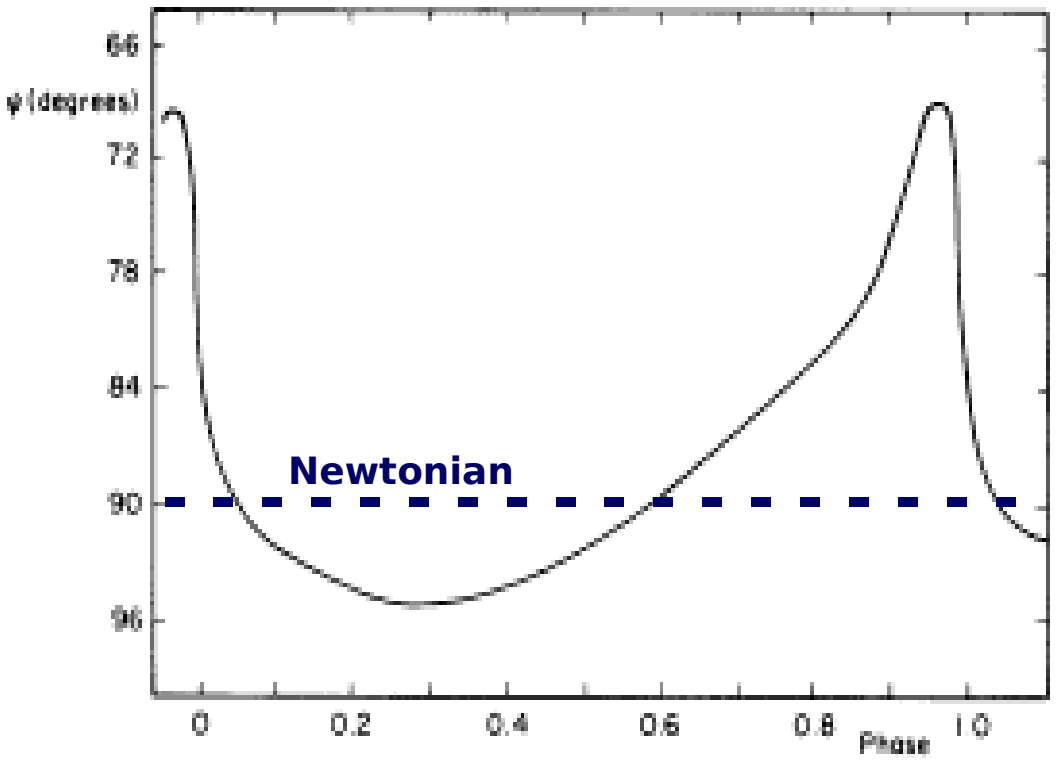


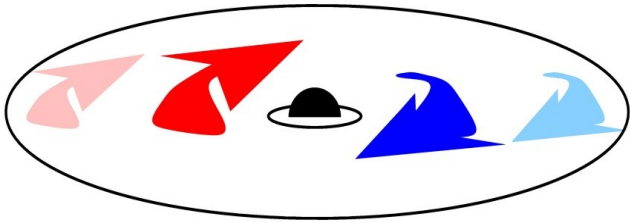
In microquasars, much larger polarization degrees are expected if the X-ray emission is due to SSC in the jet

Mc Namara et al. 2009

Probing strong gravity effects

General and Special Relativity effects around a compact object ("strong gravity effects") significantly modifies the polarization properties of the radiation. In particular, the Polarization Angle (PA) as seen at infinity is rotated due to aberration (SR) and light bending (GR) effects (e.g. Connors & Stark 1977; Pineault 1977).
The rotation is larger for smaller radii and higher inclination angles



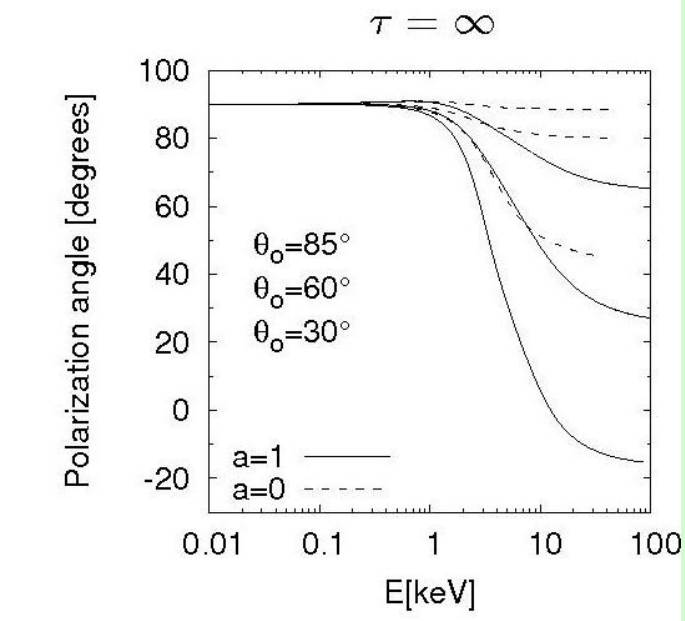


Orbiting spot with:
a=0.998; R=11.1 Rg
i=75.5 deg

(Phase=0 when the spot is behind the BH).

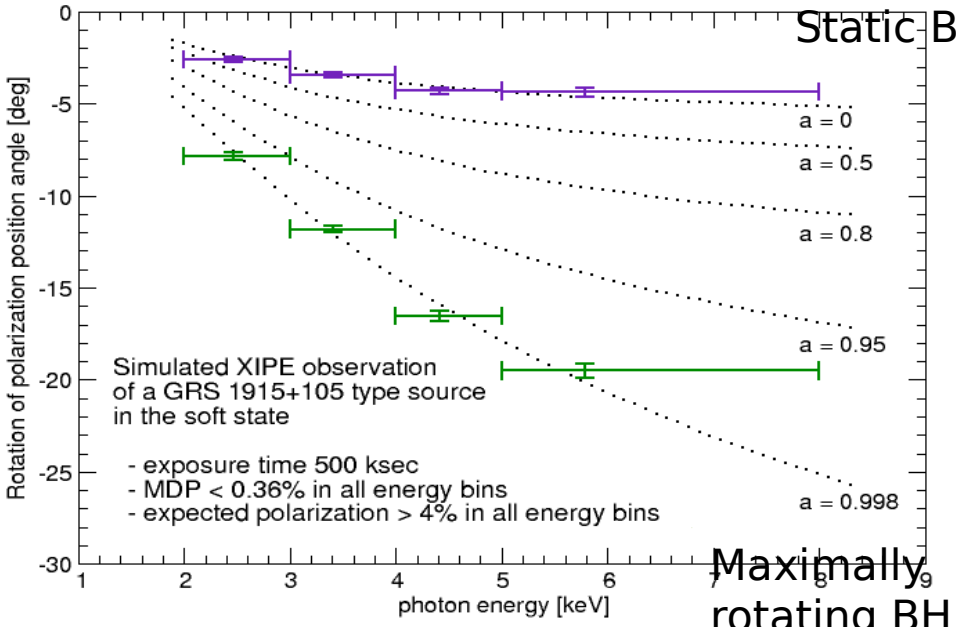
The PA of the net (i.e. phase-averaged) radiation is also rotated!

Measuring the BH spin



Dovciak et al. 2008

This effect provides an independent method to measure the BH spin in Galactic BH systems



Relatively easy to measure with the proposed missions

Summary

Our view of X-ray sources is incomplete without polarimetry

Missions currently under competitive studies have the capability to establish X-ray polarimetry as one of the standard techniques along with imaging, timing and spectroscopy