X-ray polarimetry - A new window to be opened

René W. Goosmann

A review lecture at the theme school

The Universe in X-rays

28th May 2016

Observatoire de Haute Provence, France

OUTLINE

Why should we care about polarization?

Some basics on polarization of electromagnetic radiation

State of the art techniques to measure X-ray polarization

X-ray polarization of neutron stars

X-ray polarization of black hole X-ray binaries

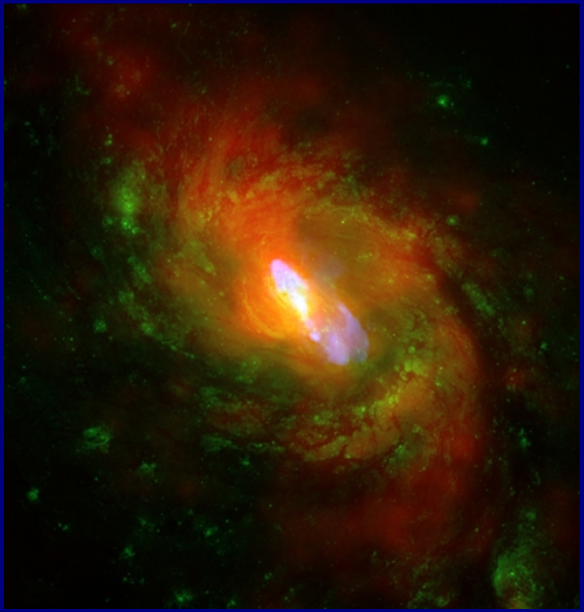
X-ray polarization of active galactic nuclei

René Goosmann
Strasbourg Observatory, France

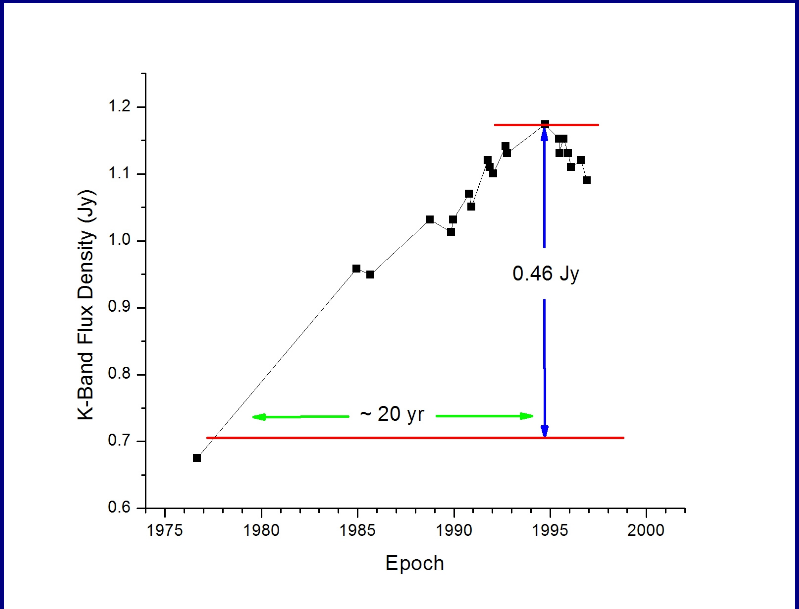
Why should we care about (X-ray) polarization?

We practice observational astronomy *mainly* based on electromagnetic (EM) radiation.
The EM radiation tells us about its emission processes and its interactions with matter.

The information is usually exploited as a function of wavelength, time, and space → **(time-resolved) spectroscopy and imaging**



X-ray (NASA/CXC/MIT/C.Canizares, D.Evans et al), Optical (NASA/STScI), Radio (NSF/NRAO/VLA))

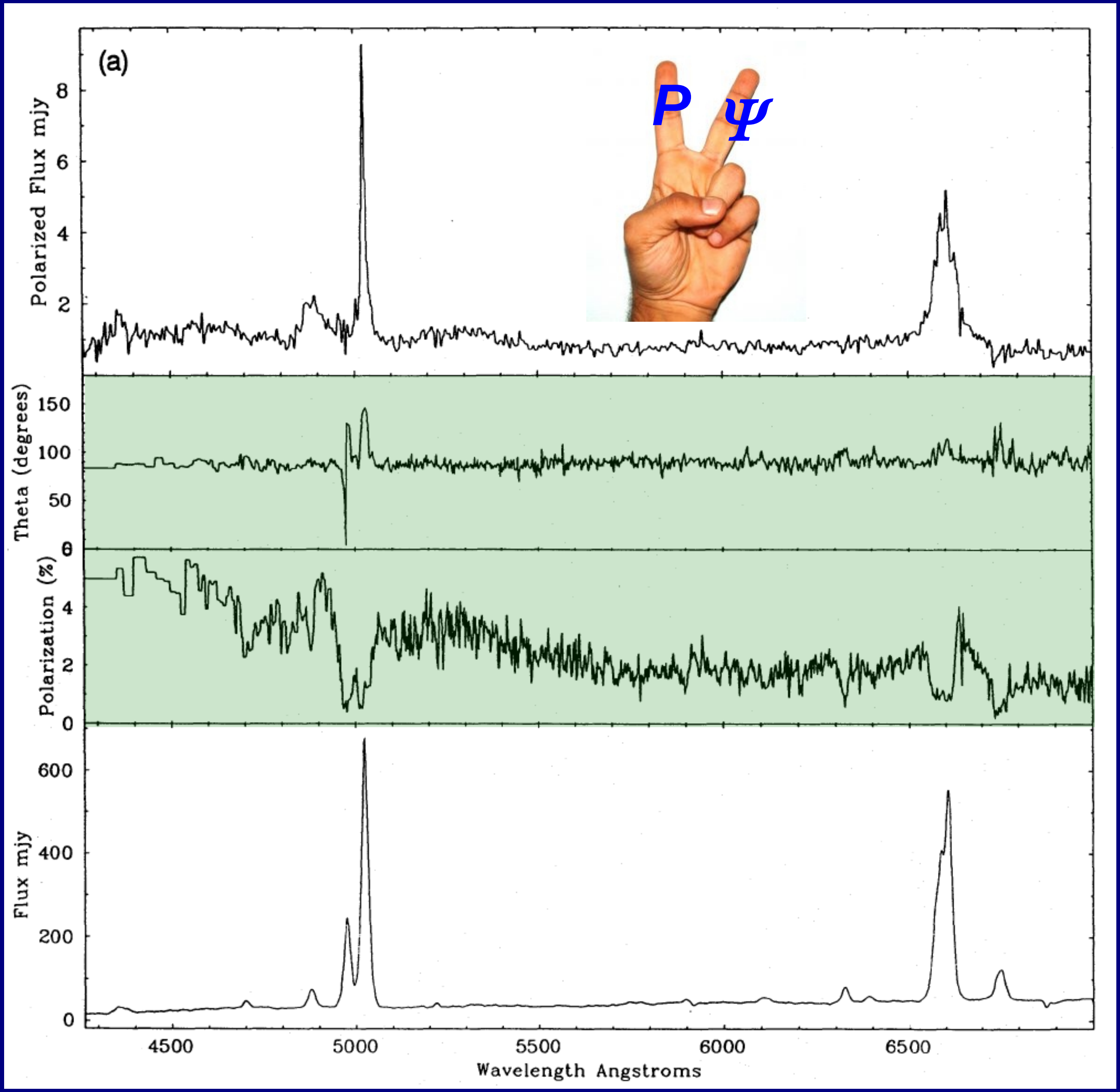


2.2 micron light curve of NGC 1068 (work by I. Glass)

Why should we care about (X-ray) polarization?

BUT: almost any interaction of EM radiation with matter also modifies its polarization state!

ERGO: Considering the polarization state of light gives us a set of **two additional, independent observables** as a function of photon wavelength, time, and space.



Inglis et al. 1995

Why do we need X-ray polarimetry?

Unique contributions of X-ray polarimetry

For a number of present-day and future X-ray observations, timing & spectroscopy alone may provide rather ambiguous and model dependent information.

In X-ray sources it is more common than at other wavelengths to find:

- Aspherical emission/scattering geometries (disc, blobs and columns, coronae);
- Non-thermal processes (synchrotron, cyclotron and non-thermal bremsstrahlung).

What XIPE can do for:

- **Resolved sources**:

Study the emission mechanisms and map the magnetic field:
PWNs, SNR and extragalactic jets,

- **Unresolved sources**:

Inner part geometry of compact sources:
X-ray pulsars, corona in XRBs and AGNs.

Furthermore, fundamental physics effects like, e.g., QED birefringence in strong magnetic fields, can be studied by X-ray polarimetry.

The X-ray Imaging Polarimetry Explorer under phase A study

Scientific objectives: what we want to observe and why

A **large** number of scientific topics and observable sources:

Astrophysics

Acceleration phenomena

Pulsar wind nebulae
SNRs
Jets

Emission in strong magnetic fields

Magnetic cataclysmic variables
Accreting millisecond pulsars
Accreting X-ray pulsars
Magnetars

Scattering in aspherical situations

X-ray binaries and AGN
X-ray reflection nebulae

Fundamental Physics

Matter in Extreme Magnetic Fields:

QED effects

Matter in Strong Gravity Fields:

GR effects close to accreting BHs

Quantum Gravity

Search for axion-like particles

XIPE is going to observe **almost all classes of X-ray sources**.

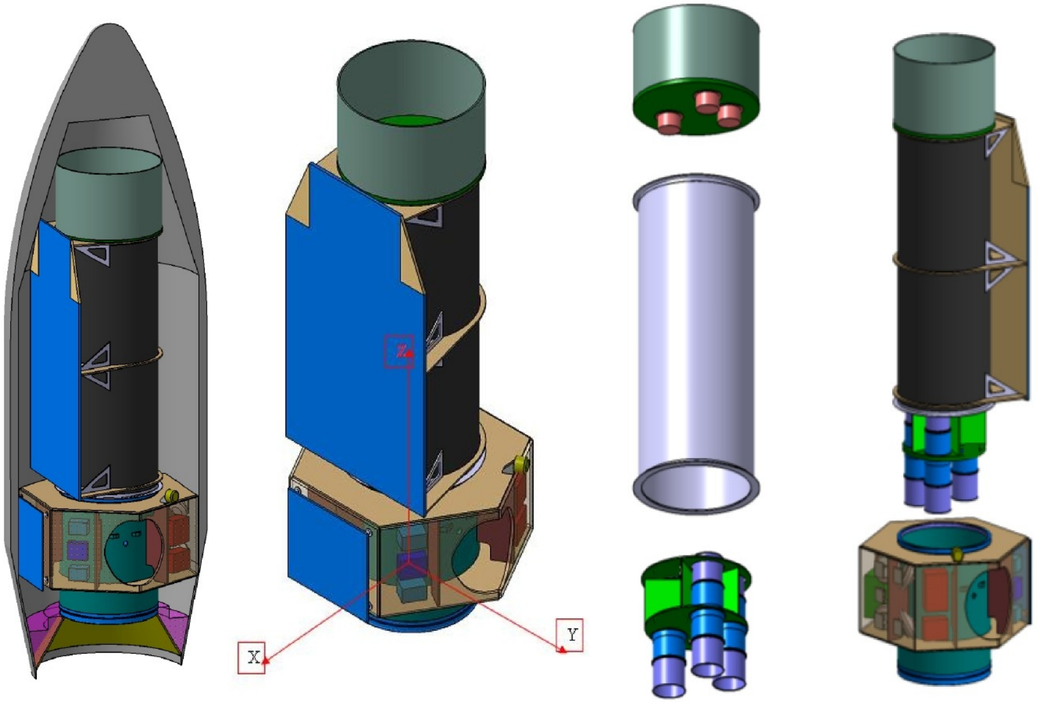
- After peer-review, ESA selected XIPE for a phase A study.
- Next step: refine the science case of XIPE and address the comments of the review committee.
- → We have put a structure of scientific working groups in place

  Goal: the Yellow Book for XIPE
- → More than **300 supporting scientists** signed up to participate in the working groups!

XIPE design guidelines

Basic mission characteristics

- Three telescopes with 3.5 m focal length
- Detectors: conventional proportional counter but with a revolutionary readout
- Mission requirements: 1 mm alignment,
- 1 arcmin pointing
- Three years nominal operation time
- Low Earth equatorial orbit



(a) (b) (c) (d)

- Launch from ESA launch site at Kourou, French Guiana, between 2024 and 2026

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Some basics about linear polarization

In classical physics, the polarization state of an electro-magnetic wave characterizes the behavior of its *E*-vector

In quantum mechanics, the polarization state of a single photon is given by a corresponding hermitian operator. The polarization state characterizes the preferred direction of the photon spin vector.

Most polarization properties that are relevant for the astronomical context can be derived from the classical picture!

The root of all electromagnetism...

Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho/\varepsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

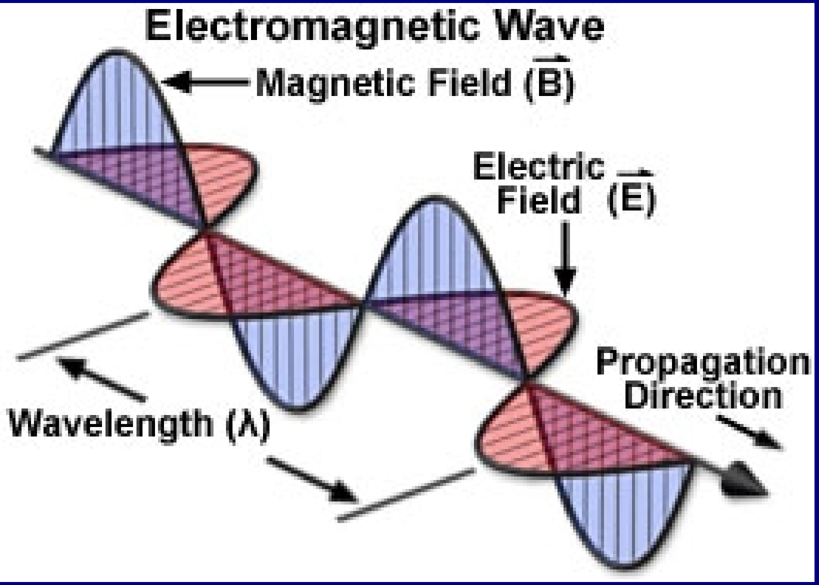
$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \boldsymbol{j}_c$$

where

$$\nabla = \hat{\mathbf{i}} \frac{\partial}{\partial x} + \hat{\mathbf{j}} \frac{\partial}{\partial y} + \hat{\mathbf{k}} \frac{\partial}{\partial z}$$

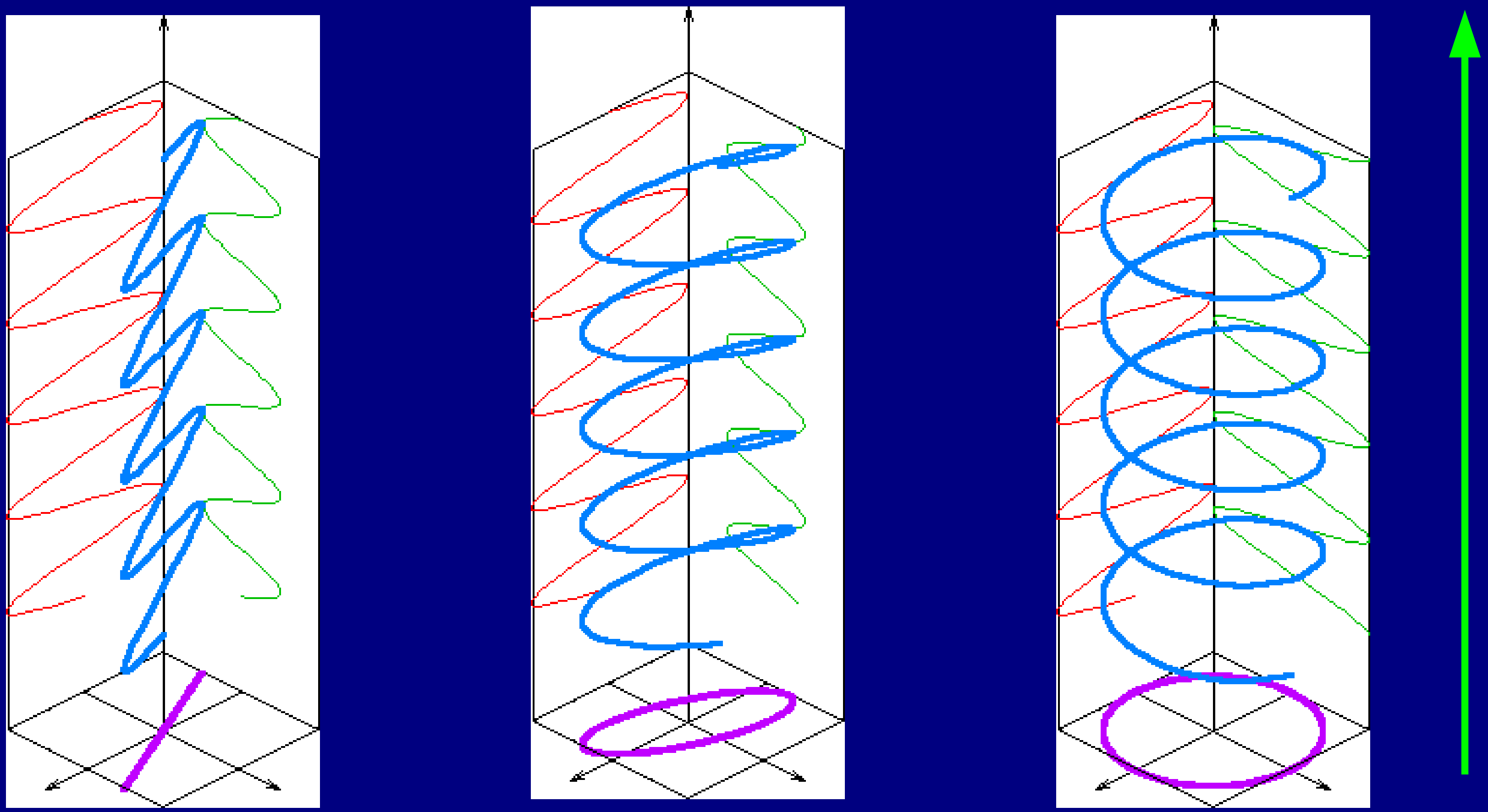
3D wave equation for the electric field

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$



Polarization of coherent light

A **coherent** electromagnetic wave can be decomposed in two perpendicular components with a defined phase relation.



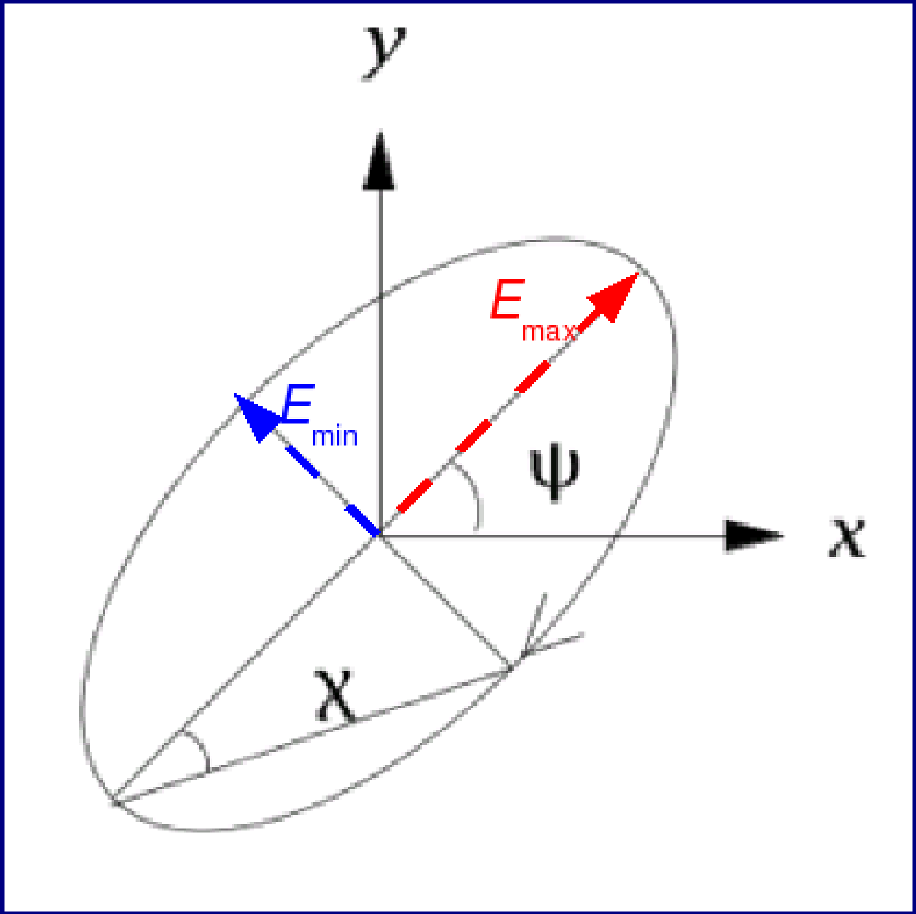
linear elliptical circular

The polarization ellipse

The linear polarization degree P is defined by

$$P = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}.$$

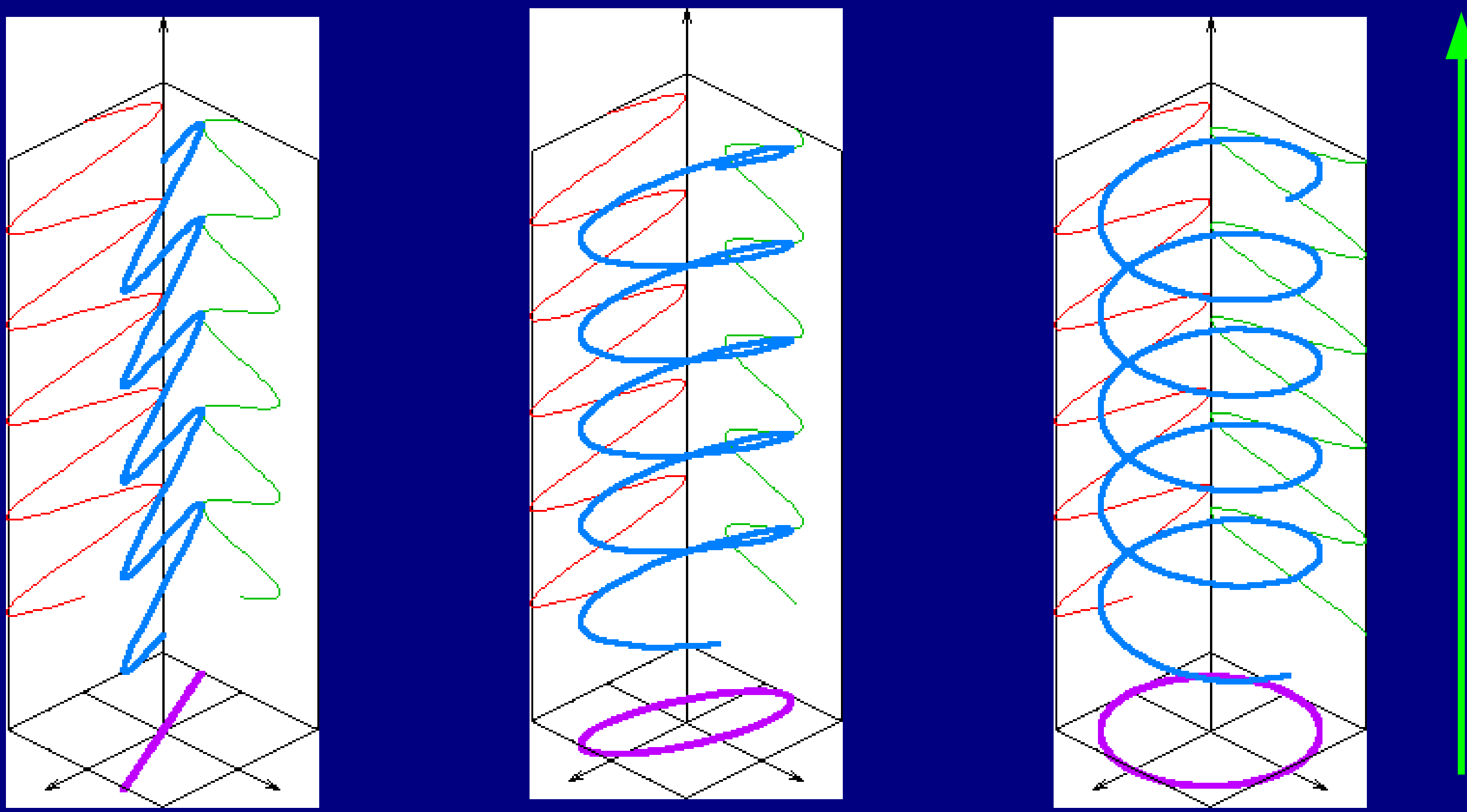
Note: $0 \leq P \leq 1.$



Herein, I_{max} and I_{min} are measured along the directions at which the length of the *E*-vector has a maximum or minimum, respectively.

Polarization of coherent light

100%	~30%	0%	**Linear pol.**
0%	~70%	100%	**Circular pol.**



linear elliptical circular

Astronomical light and (none-)coherence

The light from astronomical sources comes from uncorrelated sub-sources

different parts of a stellar surface,
different layers inside an ionized nebula,
different distances in redshift
...

There is only a statistical coherence of “astronomical light” and a linear polarization degree of 100% is quasi-impossible to observe.

For the remainder of this presentation we only discuss linear polarization that is far more important in the X-ray range than circular polarization.

The Stokes parameters

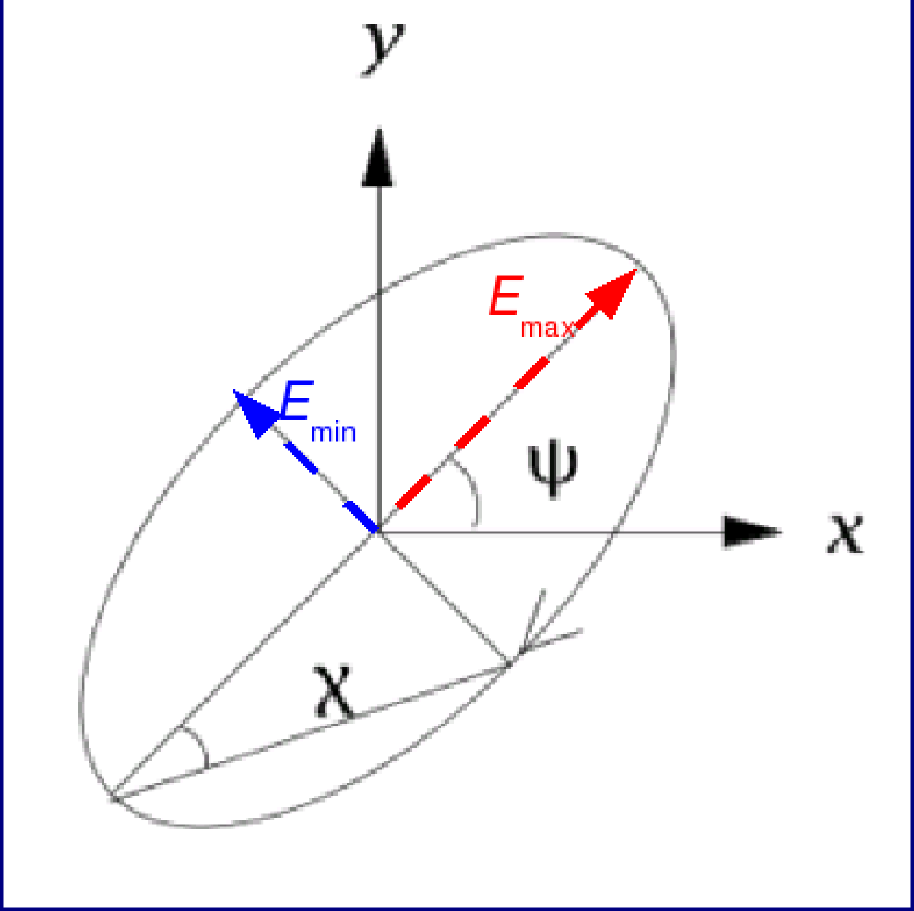
The polarization state is completely described by the Stokes parameters:

$$I = \langle E_{max}^2 + E_{min}^2 \rangle,$$

$$Q = \langle (E_{max}^2 - E_{min}^2) \cos(2\psi) \rangle,$$

$$U = \langle (E_{max}^2 - E_{min}^2) \sin(2\psi) \rangle,$$

$$[V = \langle 2 E_{max} E_{min} \rangle].$$

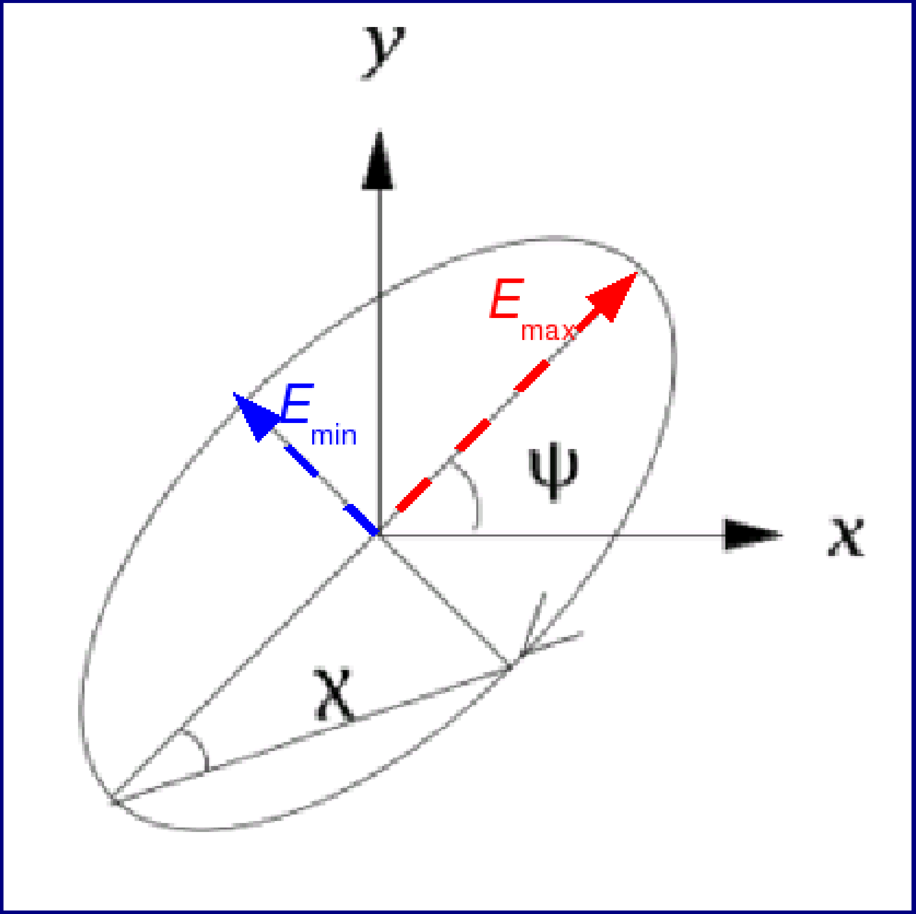


The Stokes parameters

From the Stokes parameters the Linear polarization degree ***P*** and position angle can Ψ easily be recovered:

$$P = \frac{\sqrt{Q^2 + U^2}}{I},$$

$$\psi = \frac{1}{2} \arctan \frac{U}{Q}.$$



Processes producing (de-)polarization

Synchrotron emission

Electron scattering

Dust (Mie) scattering

Resonant line scattering

Dichroic absorption

Faraday rotation

Dilution (by unpolarized radiation)

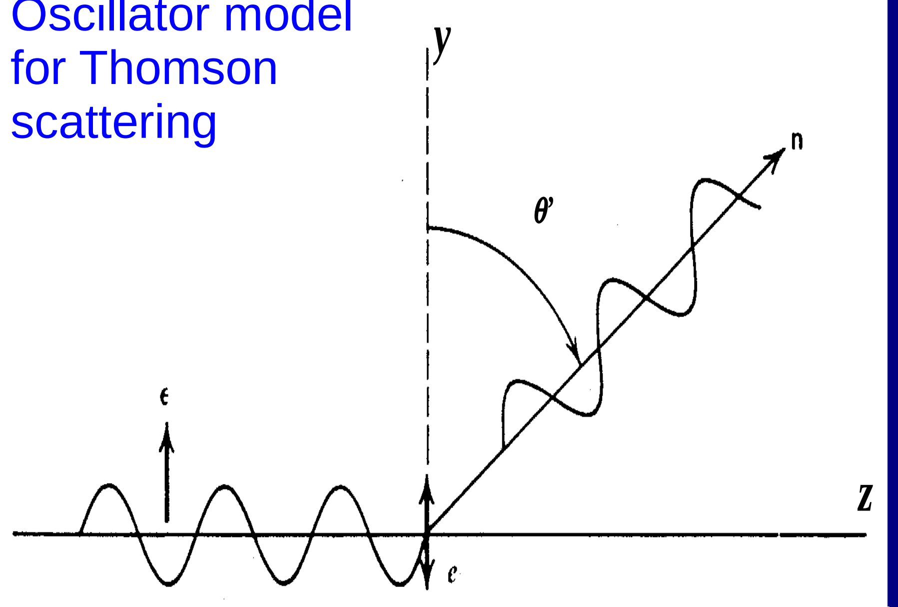
General Relativity

Scattering

Strong polarization: Θ = 90° (Reflection)

Weak polarization: Θ = 0° (Transmission)

Oscillator model for Thomson scattering



$$\frac{\partial\sigma}{\partial\omega}(\alpha)_{tot} = \frac{1}{2} r_0 \left(1 + \cos^2\theta\right).$$

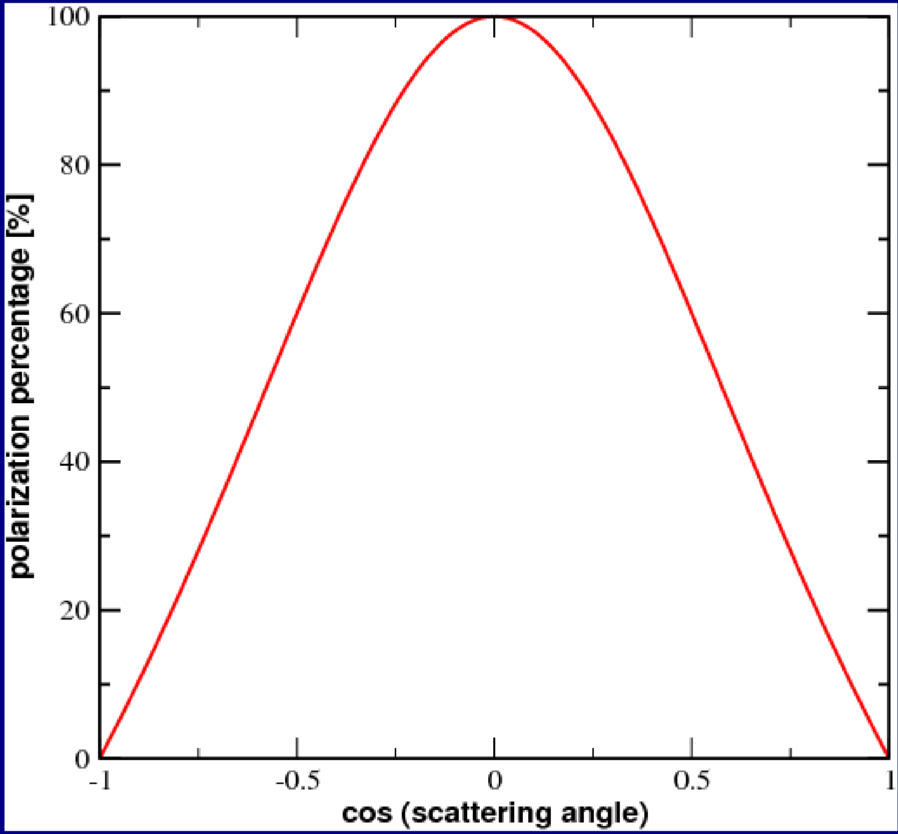
$$P = \frac{1-\cos^2\theta}{1+\cos^2\theta}.$$

$$\sigma_T = \frac{8\pi}{3} r_0^2 = \frac{8\pi e^4}{3m^2c^4}.$$

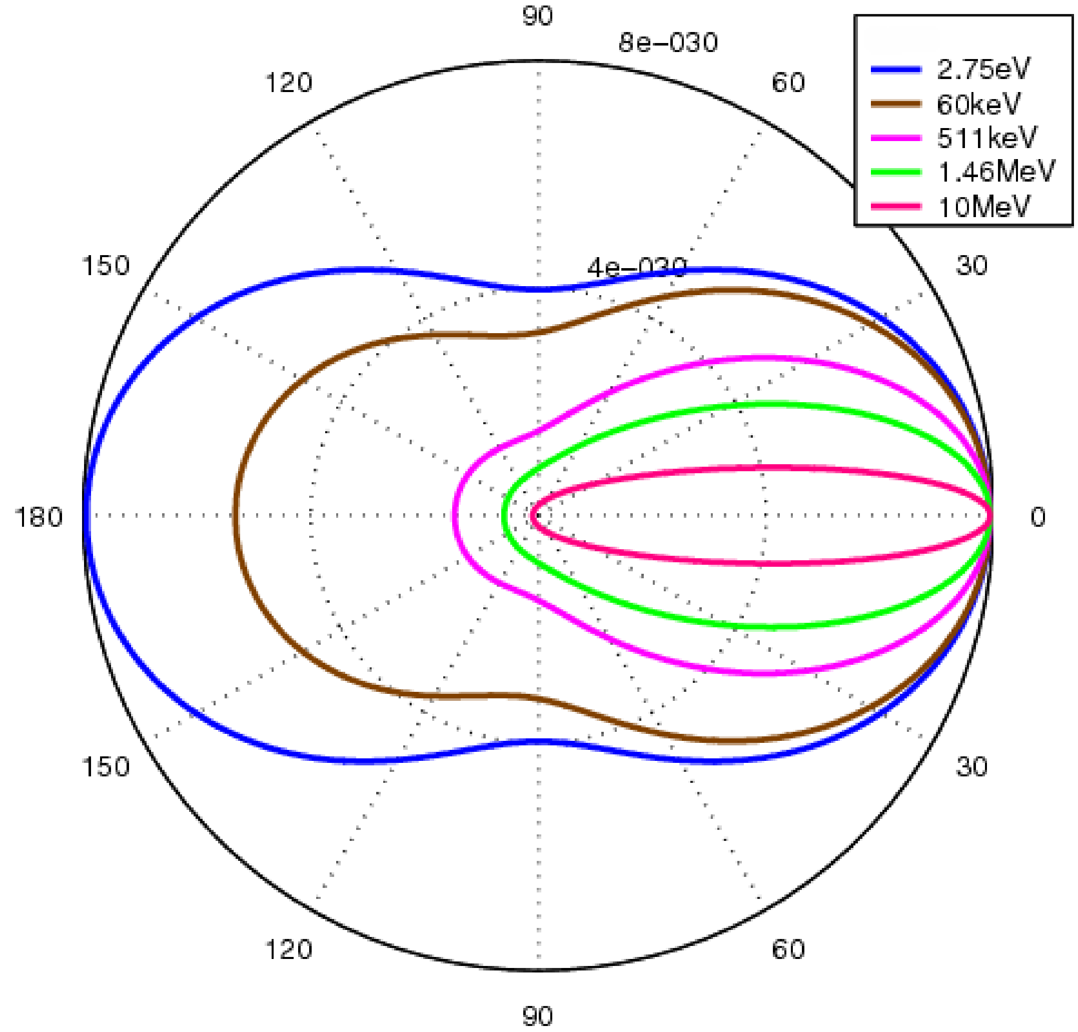
Phase function for scattering-induced polarization

Electron scattering
(Thomson, Compton, Rayleigh scattering)

Polarization phase function:



Differential cross section

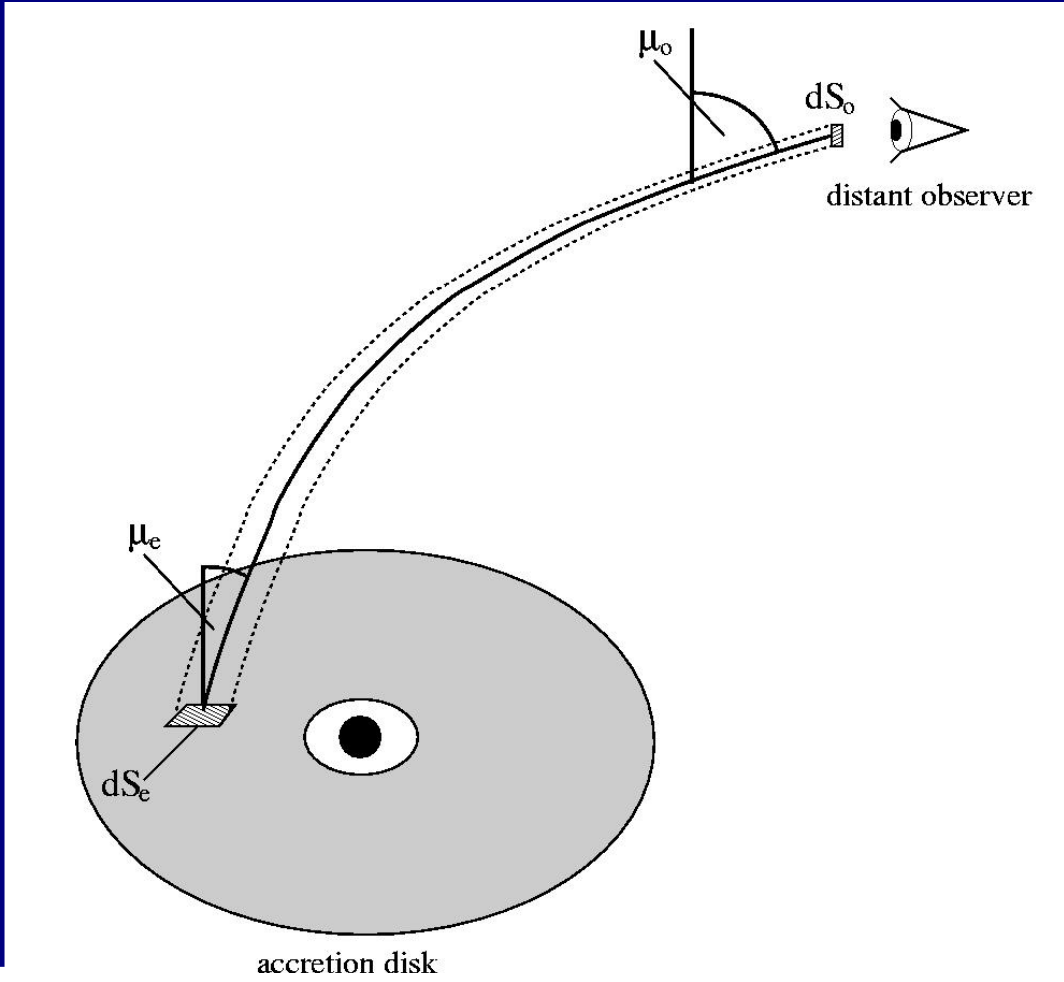


Including relativistic effects

Applying relativistic ray-tracing methods in Kerr metric

Important to know the local polarization

see e.g.
Connors, Piran, Stark (1980)
Dovčiak et al. 2004
Schnittman 2009

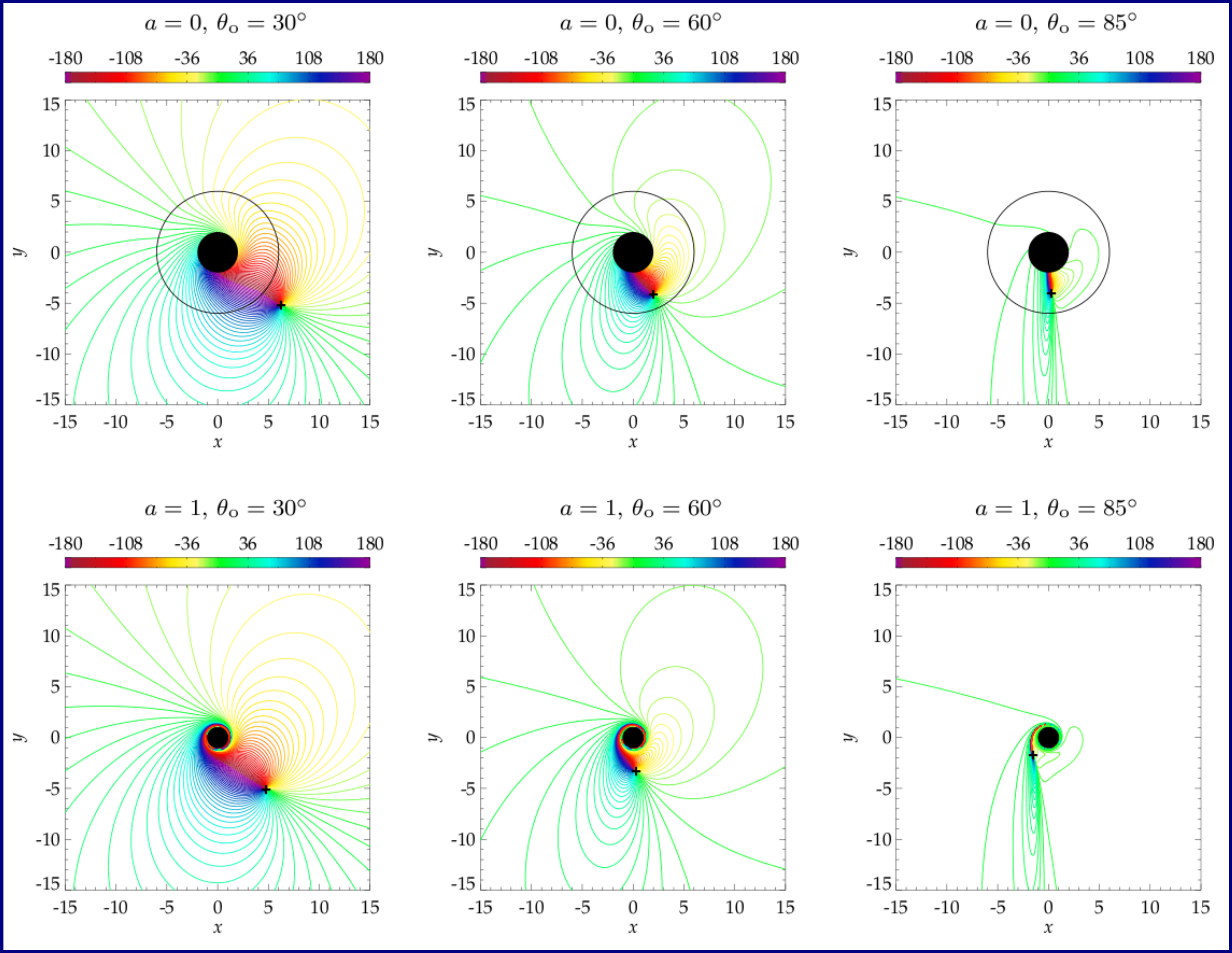


I, Q, U, V

$$\Delta N_o^{\Omega_o}(E,\Delta E,t)=\int_{r_i}^{r_o} dr \int_{\phi}^{\phi+\Delta\phi} d\phi \int_{E/g}^{(E+\Delta E)/g} dE_l N_l(E_l,r,\phi,\mu_e,t-\Delta t)\, g^2 l \mu_e r\,.$$

observed photon flux | **disk integration** | **energy** | **local photon flux** | **transfer**

Integrating the polarization angle



The observed polarization at infinity is obtained by integrating the transferred local polarization.

This gives a vast range in polarization angle...

Dovčiak et al. (2008)

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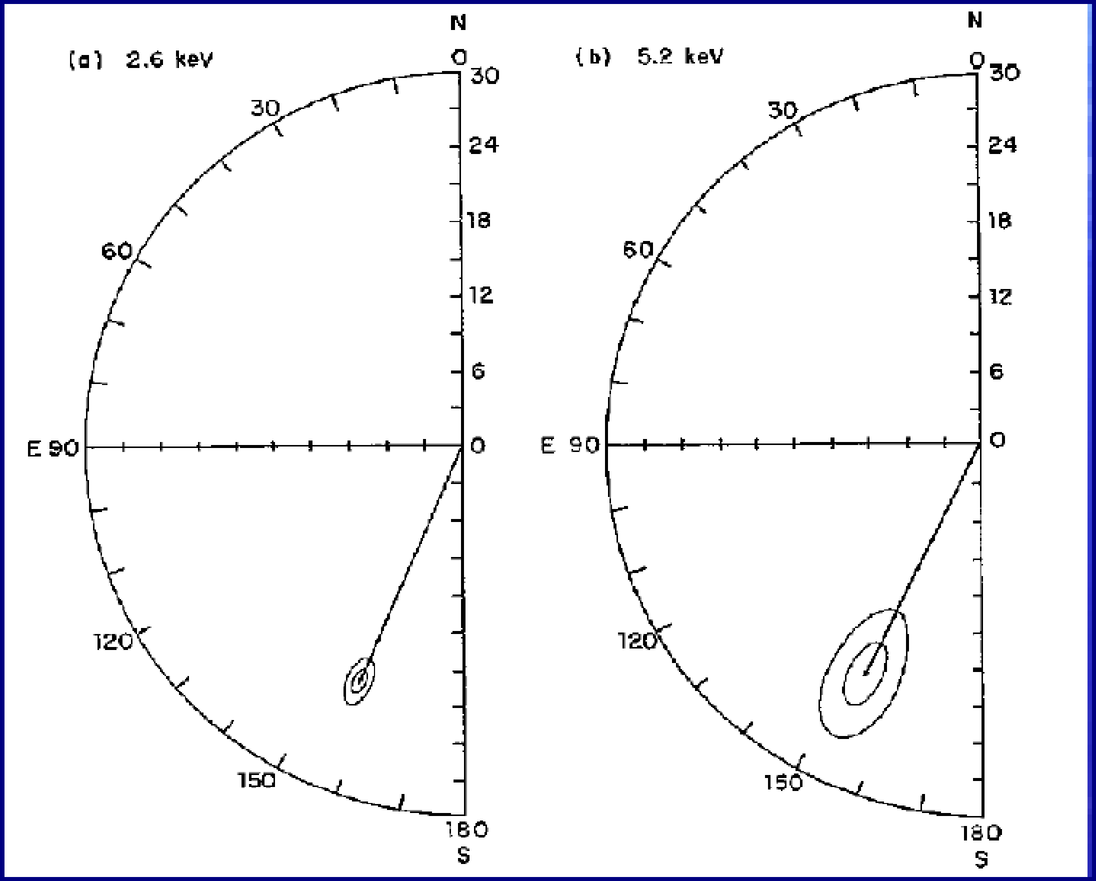
So-far X-ray polarization measurements



Crab Nebula (OSU-7)
Weisskopf et al (1978)

Cygnus-X1
Laurent et al. (2011)

Other (hard X-ray) objects under consideration (including GRBs)

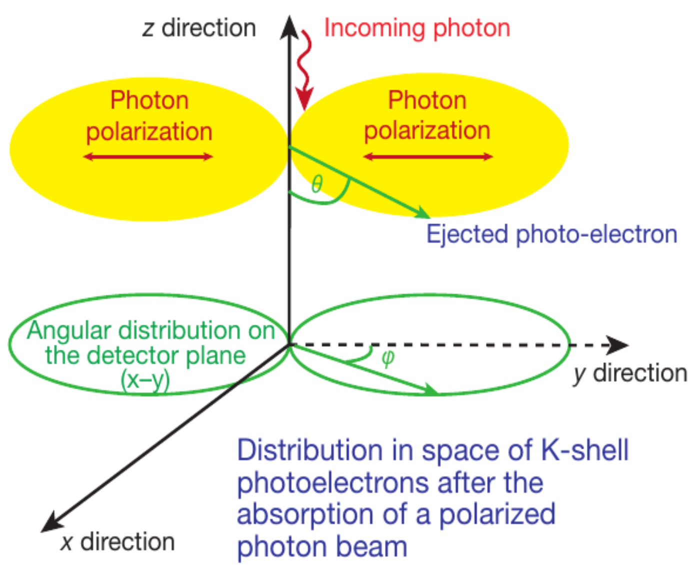
See talk by
J. Rodriguez

The Gas Pixel Detector

We developed at this aim a polarization-sensitive instrument capable of imaging, timing and spectroscopy

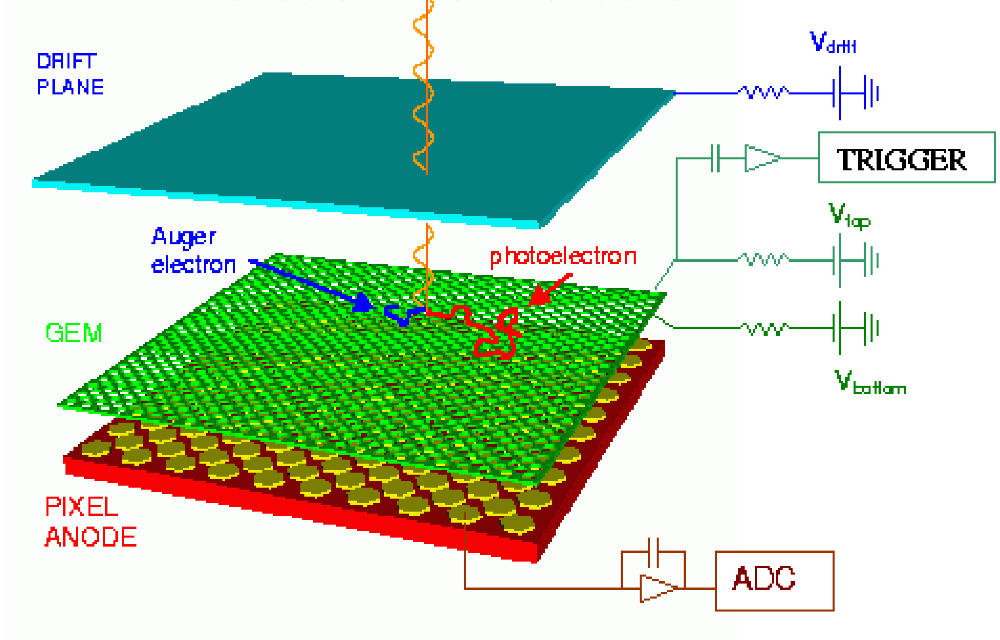
The photoelectric effect

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



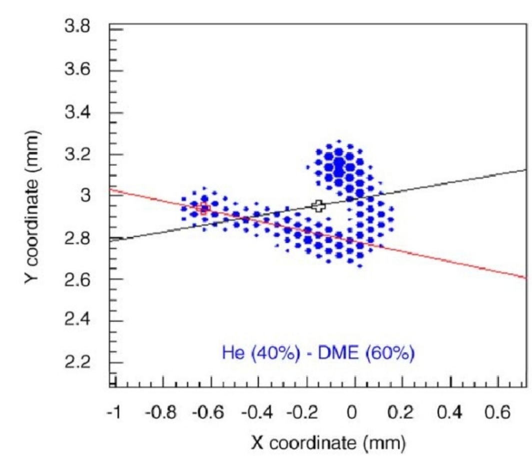
The direction of the ejected photo-electron is statistically related to the polarization of the absorbed photon.

The Gas Pixel Detector



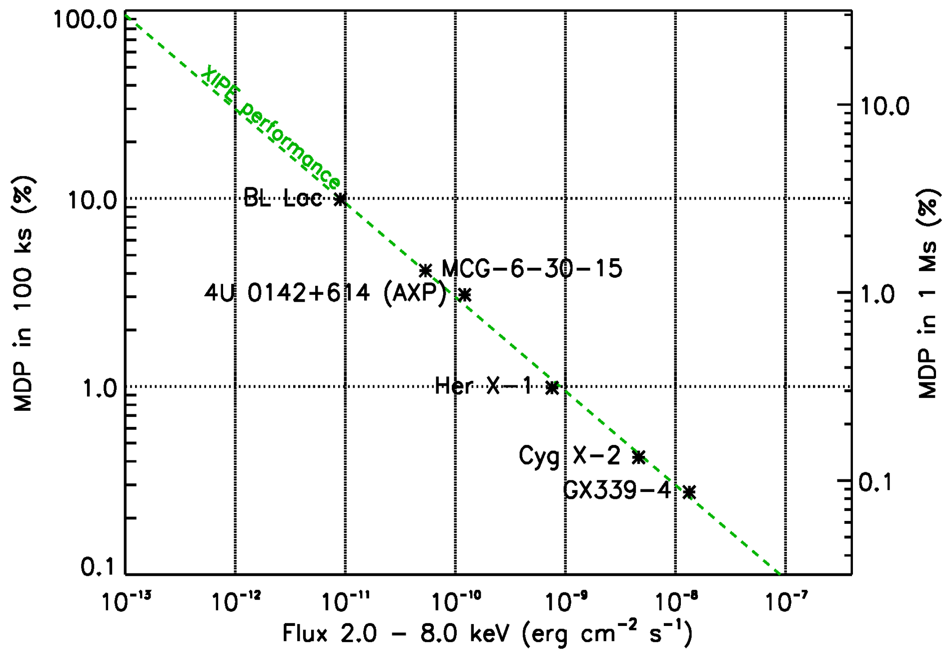
E. Costa et al. 2001

Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.



Computing the minimal detectable polarization

Polarization sensitivity	1.2% MDP for 2x10^{-10} erg/s cm^{2} (10 mCrab) in 300 ks
Energy range	2-8 keV
Angular resolution	<26 arcsec (goal: <24 arcsec)
Field of View	15x15 arcmin^{2}
Spectral resolution	16% @ 5.9 keV
Timing	Resolution <8 µs
Dead time 60 µs	
Stability	>3 yr
Spurious polarization	<0.5 % (goal: <0.1%)
Background	2x10^{-6} c/s or 4 nCrab



$$MDP = \frac{4.29}{\mu\sqrt{S}}\frac{1}{\sqrt{T}}$$

The MDP is the minimum detectable polarization at the 99% confidence level.

μ: modulation factor
S: collecting area
T: observing time

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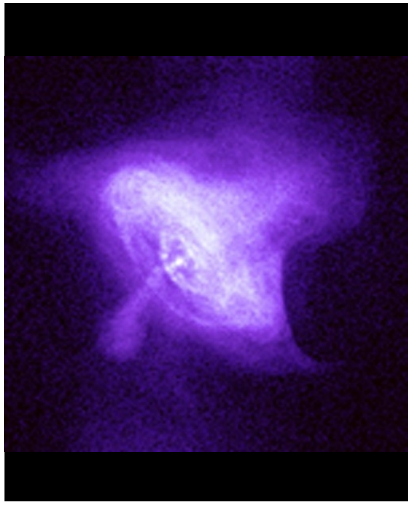
Acceleration phenomena: The Crab Nebula

Unique contributions : polarization mapping of the sub-structure of PWNe

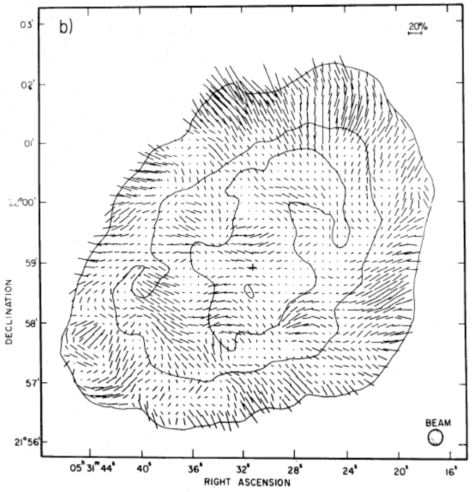
Radio (VLA)

Infrared (Keck)

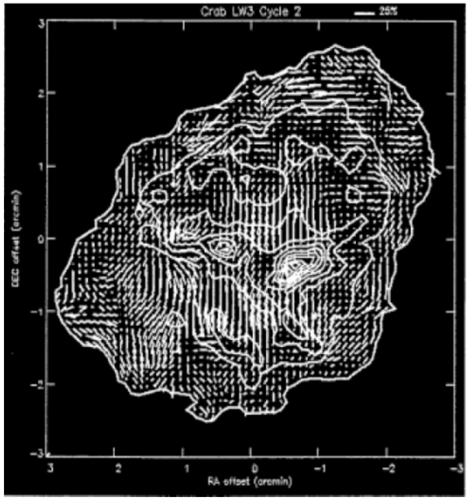
Optical (Palomar)



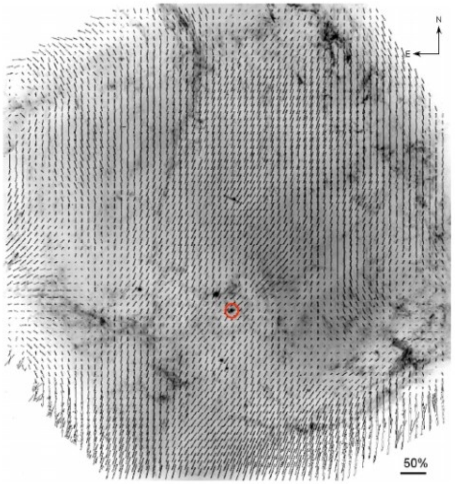
X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

?

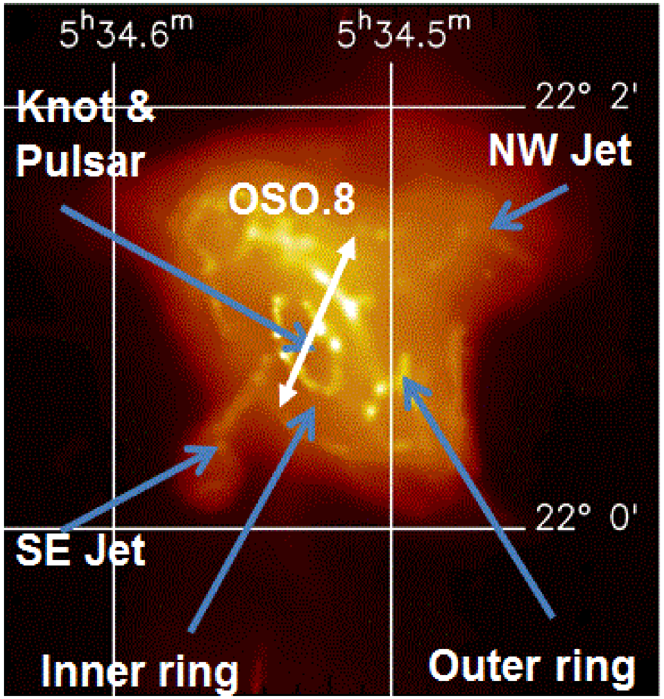
P=19% integrated over the entire nebula (Weisskopf et al. 1978)

X-ray polarisation

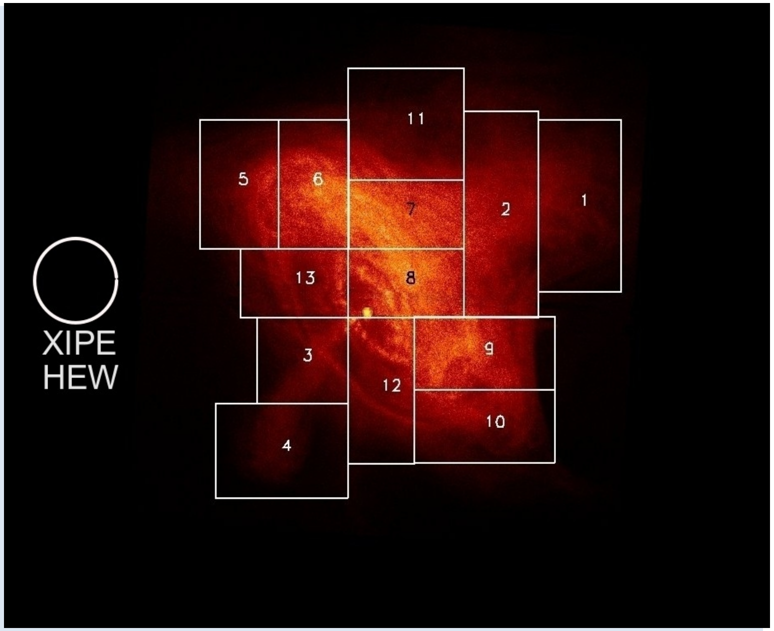
X-rays probe **freshly accelerated** electrons and their acceleration site.

Acceleration phenomena: The Crab Nebula and other PWN

Unique contributions : polarization mapping of the sub-structure of PWNe



Region	σ_{degree} (%)	σ_{angle} (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 the 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 polarization 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”).

Emission in strong magnetic field: X-ray pulsars

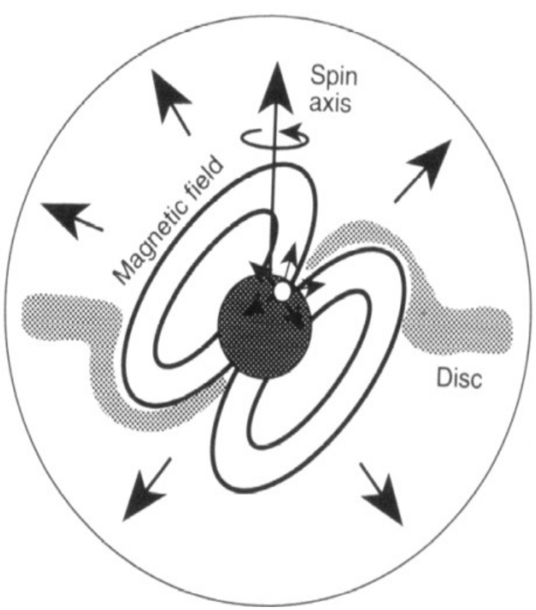
Unique contributions: constraining the accretion geometry in X-ray pulsars

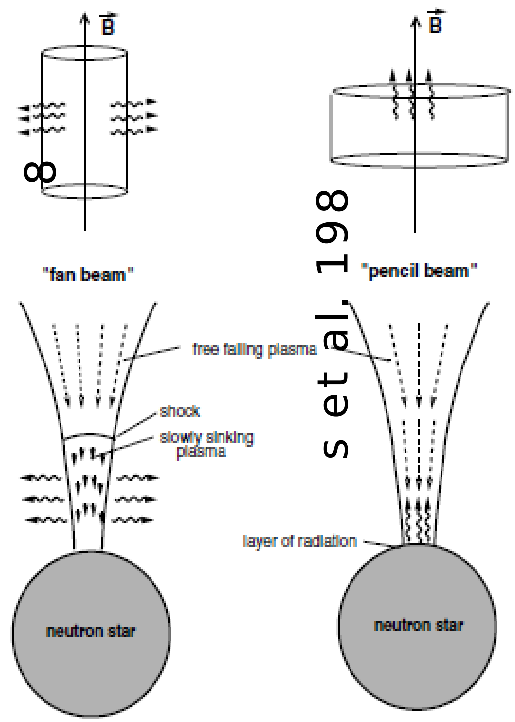
Emission process:
- cyclotron
- opacity on highly magnetized plasma $k_\perp \neq k_\parallel$

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

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

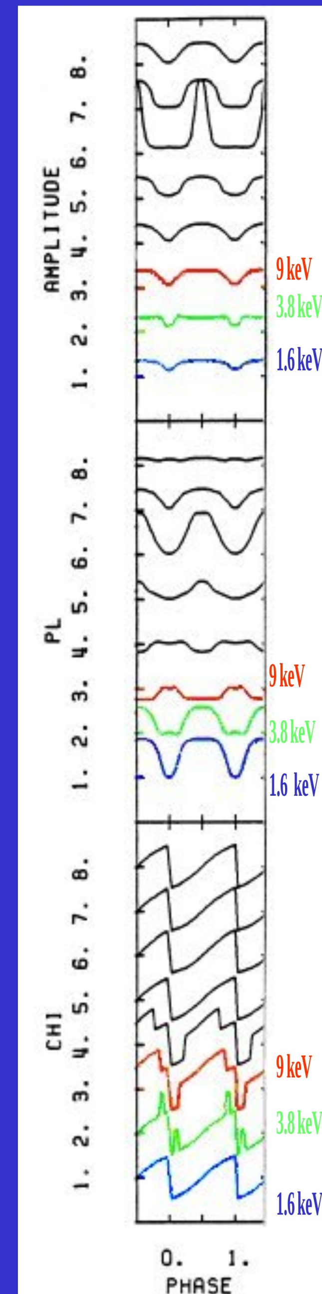
- Geometry of the accretion column: “fan” beam versus “pencil” beam





Meszaros et al. 1988

Accreting X- ray Pulsar

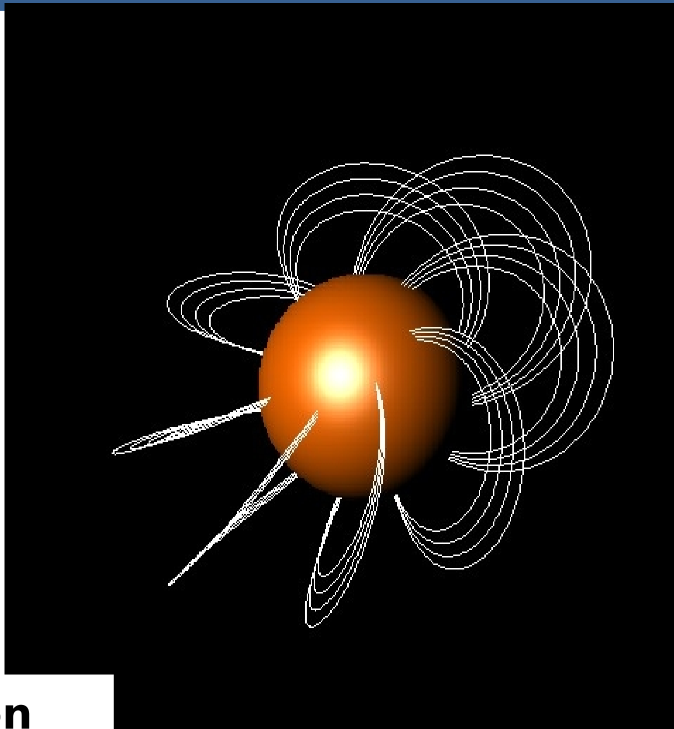


X-ray emission from a binary pulsar will be polarized by:

- Emission process: cyclotron
- Scattering on aspherical (column) accreting plasma
- Scattering on highly magnetized plasma: $\sigma_\parallel \neq \sigma_\perp$
- Vacuum polarization and birefringence through extreme magnetic fields

The swing of the polarization angle with phase directly measure the orientation of the rotation axis on the sky and the inclination of the magnetic field: in the figure the case 45°, 45° (from Meszaros et al. 1988)

A QED birefringence effect in strong magnetic fields and X-ray polarimetry

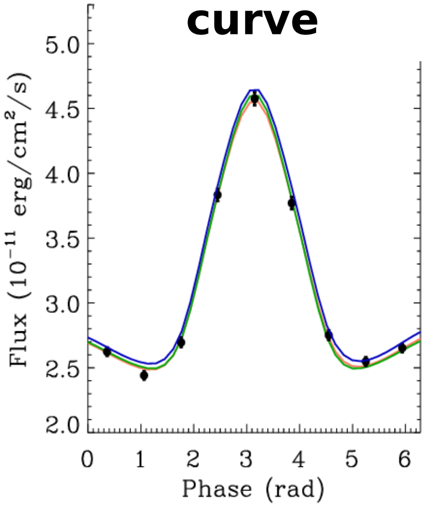


Magnetars are isolated neutron stars with likely a huge magnetic field (B up to 10^{15} Gauss).

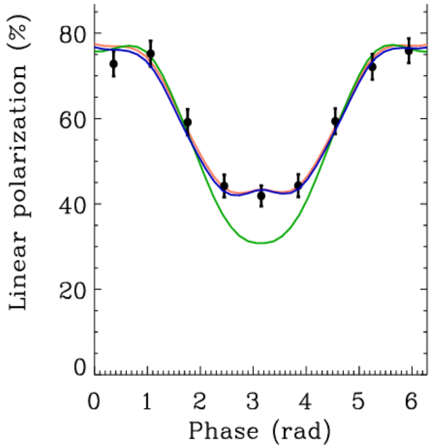
It heats the star crust and explains why the X-ray luminosity largely exceeds the spin down energy loss.

QED foresees vacuum birefringence, an effect predicted 80 years ago, expected in such a strong magnetic field and never detected yet.

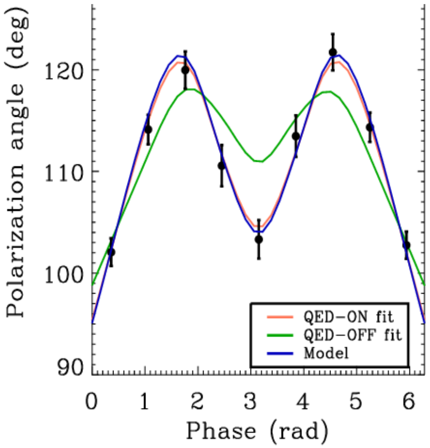
Light curve



Polarisation degree



Polarisation angle



What to do next:

→ Take into account specific properties close to the neutron star surface in the modeling.

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

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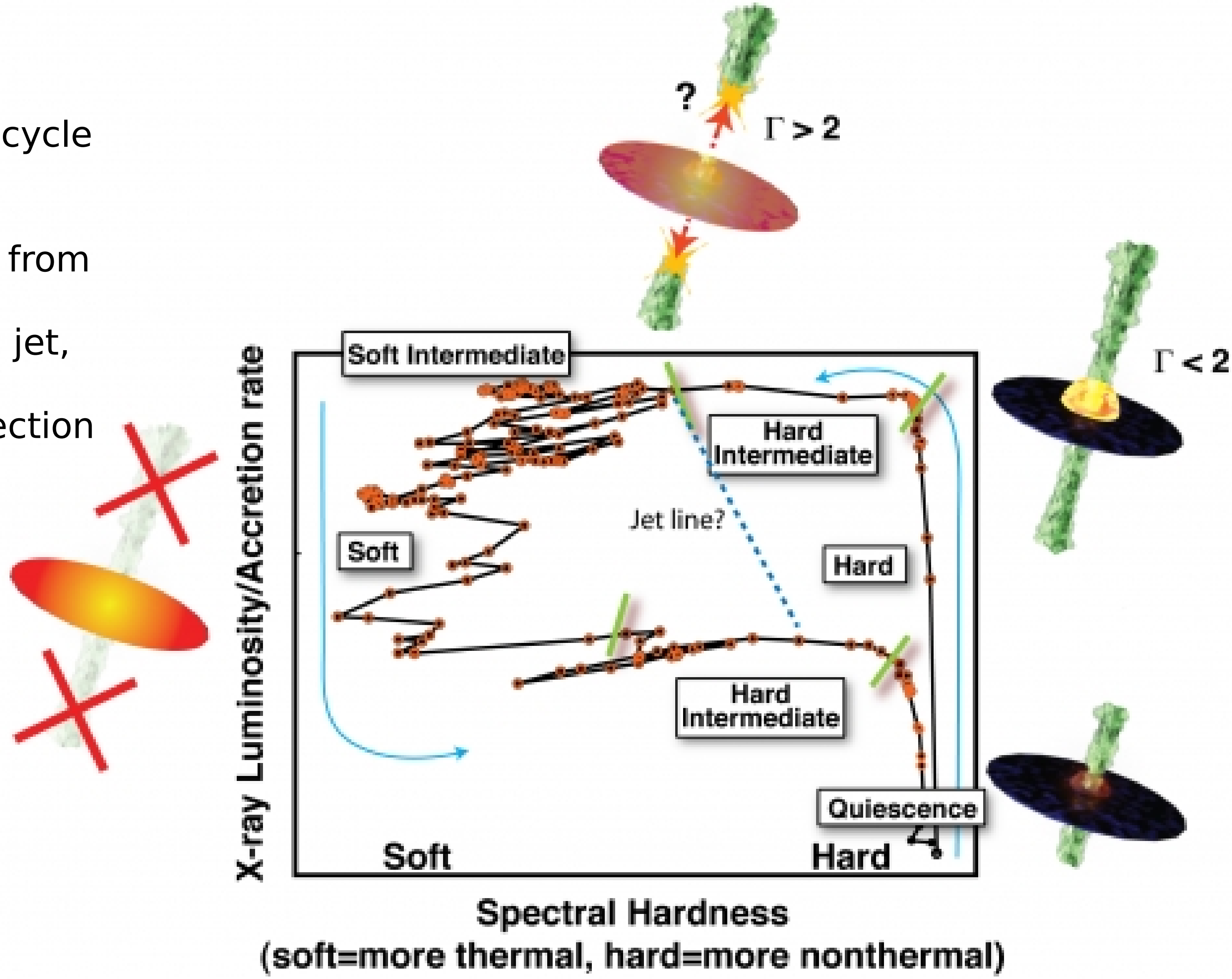
Spectral states and the Q-diagram

GX 339-4 going into outburst and back

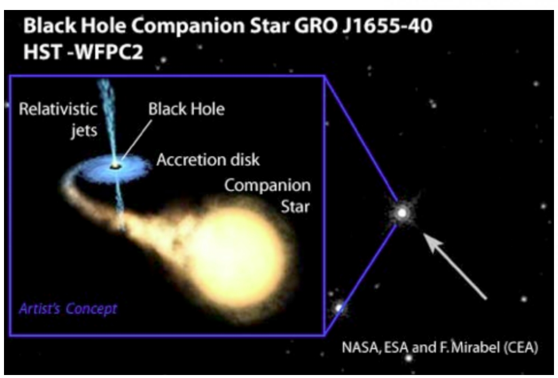
At different phases of the cycle we expect...

– ...different contributions from the thermal disk, the hot corona and the relativistic jet,

– ... different accretion-ejection geometries !



(website Sera Markoff)

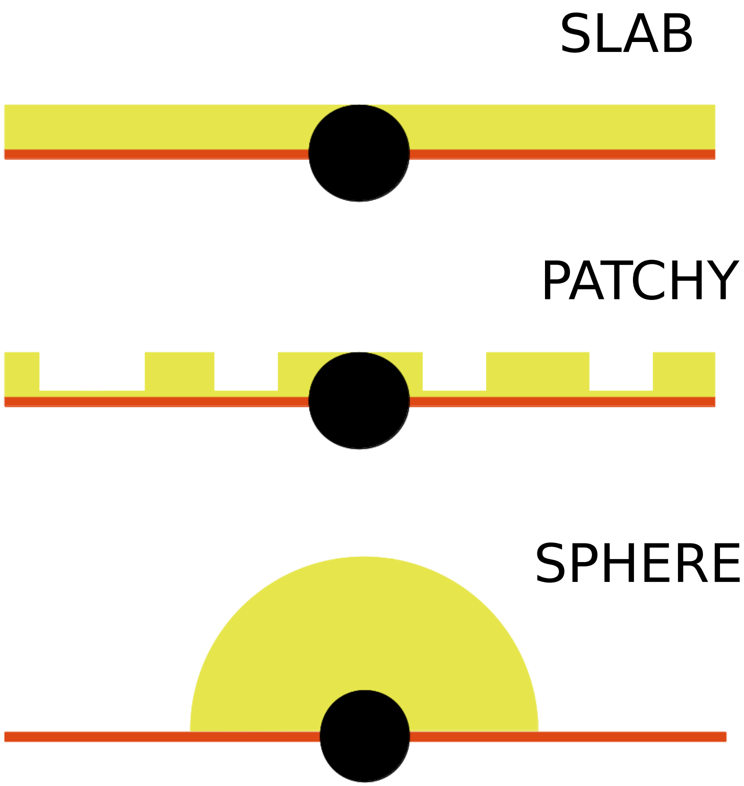


Determine the coronal geometry in X-ray binaries

The geometry of the hot corona, considered to be responsible for the (non-disc) X-ray emission in binaries and AGN, is largely unconstrained.

The geometry is related to the corona origin and heating mechanism:

- (patchy) slab: disc instabilities ?
- sphere: aborted jet ?



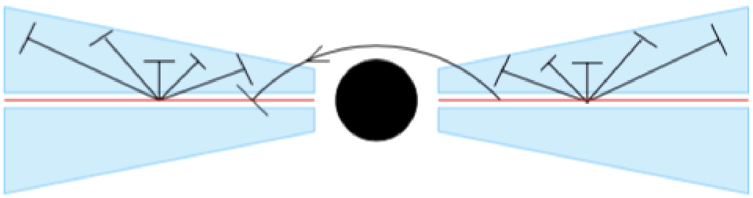
Polarization expected if the X-ray emission of Galactic black hole candidates in the hard state originates in the jet.

Modification of the polarization expected in objects with strong effects of general relativity.

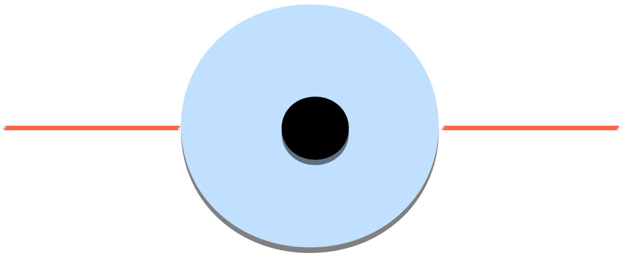
XIPE will allow us to detect the polarization of the corona in a large sample of X-ray binaries (and AGN).

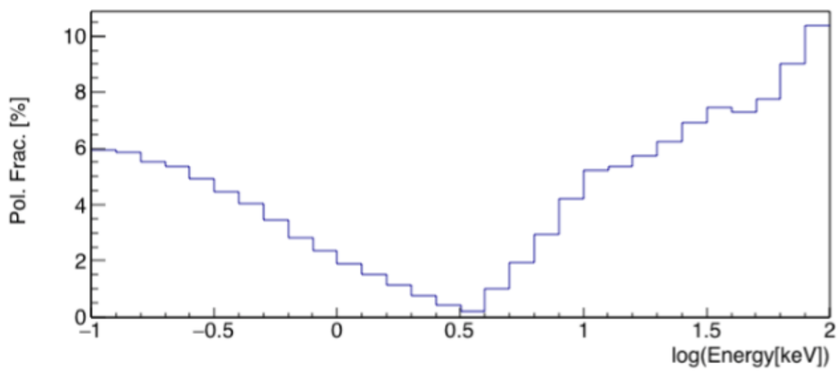
Current state of coronal modeling

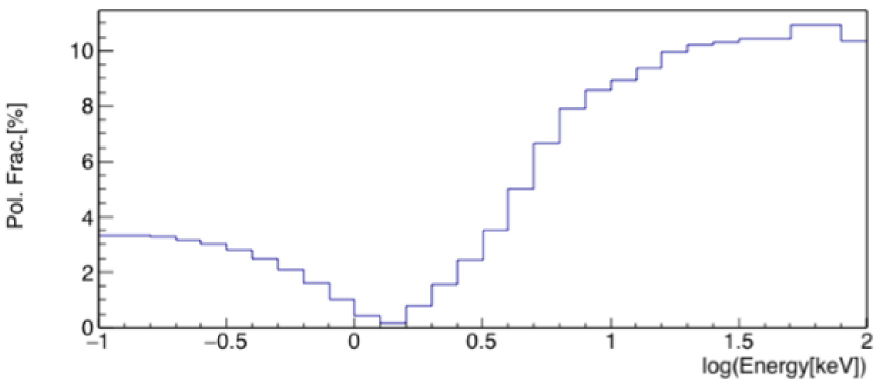
Extended corona above disc

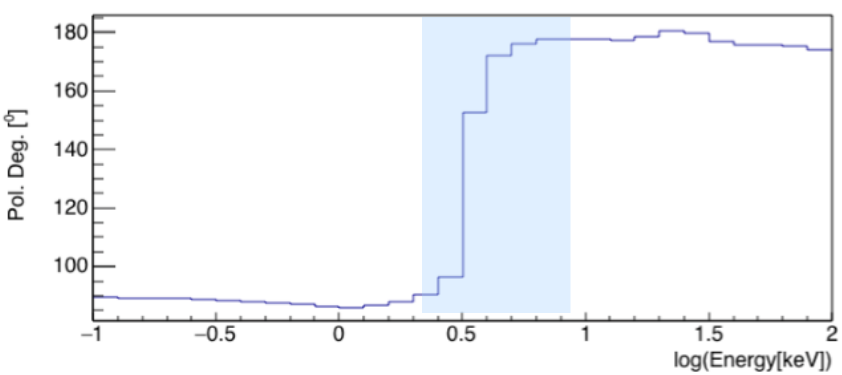


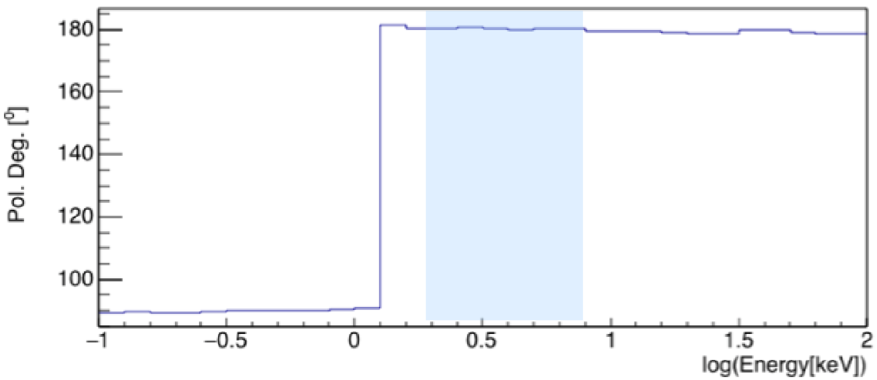
Truncated disc + spherical corona







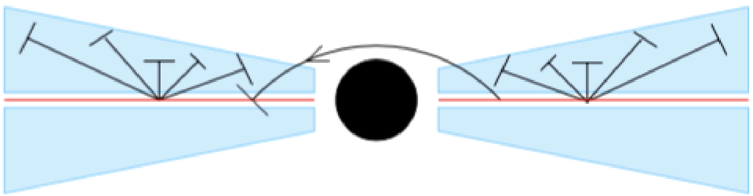


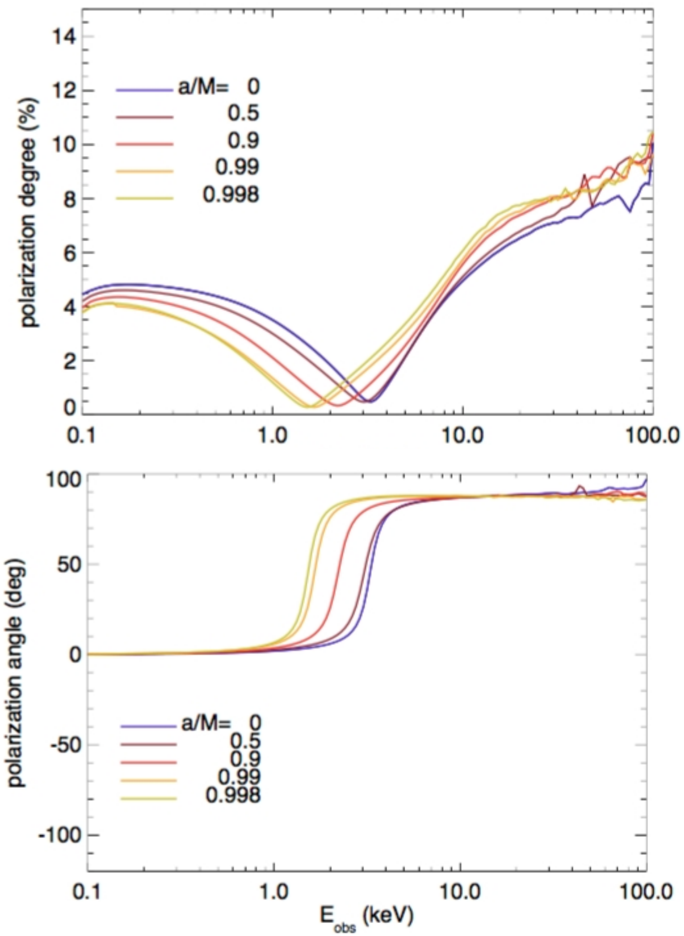


B. Beheshtipour & H. Krawczynski

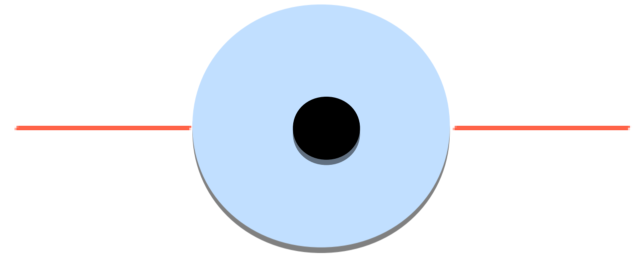
The perturbation by the effects of General Relativity

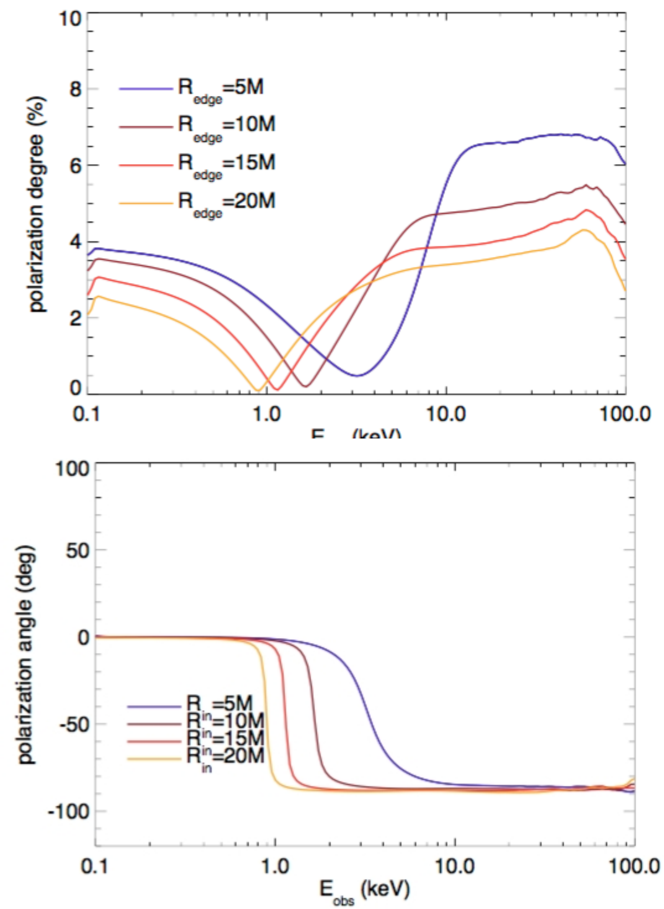
Extended corona above disc





Truncated disc + spherical corona





J. Schnittman & J. Krolik

Disentangling the geometry of the hot corona

Including possible effects of the jet base

Cygnus X-1 model

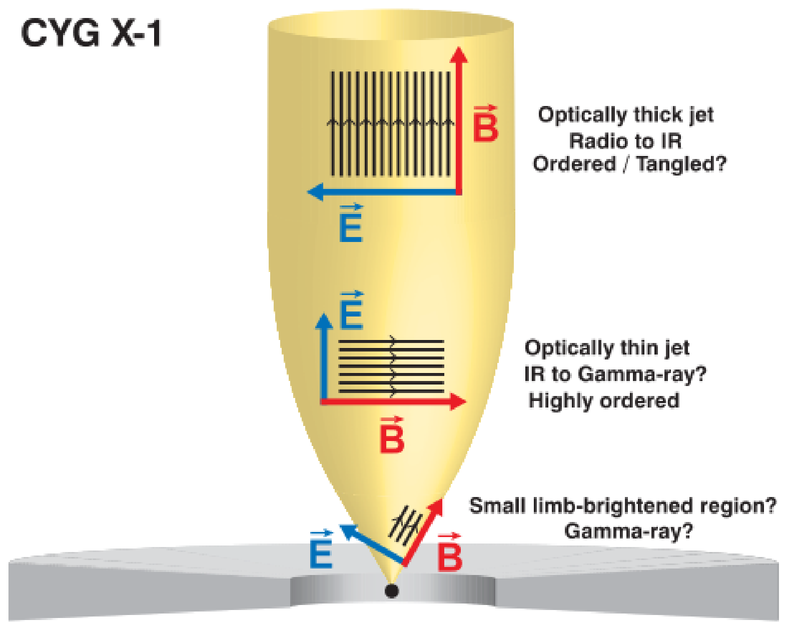
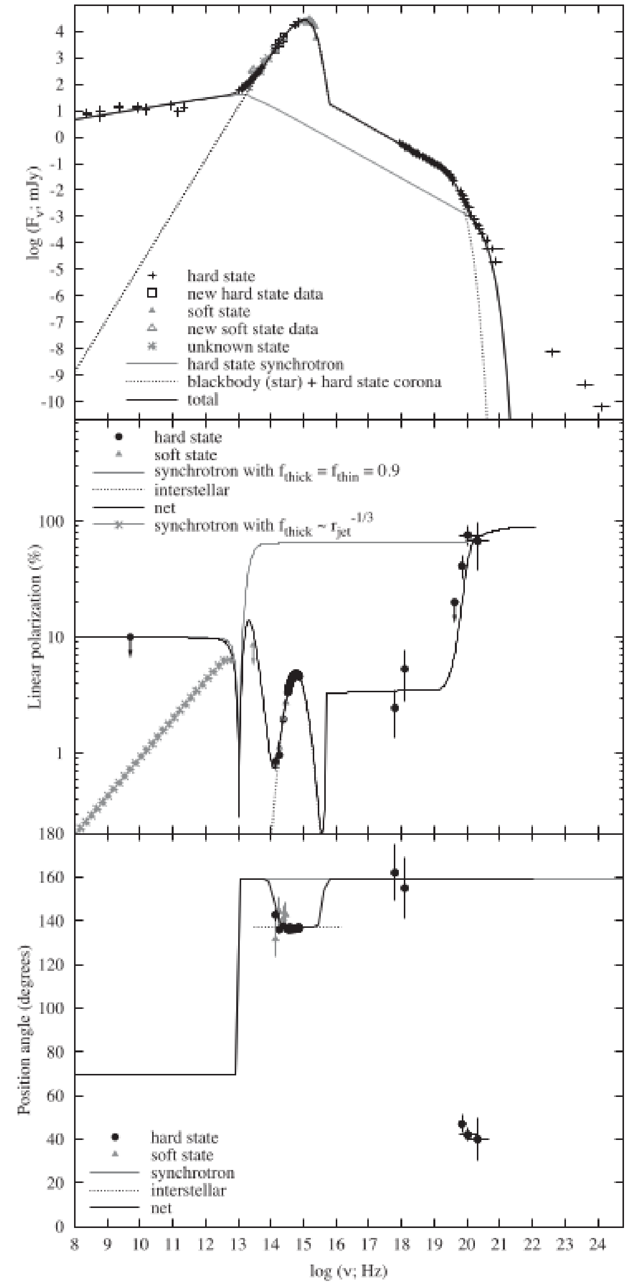


Figure 3. A schematic diagram of the Cyg X–1 jet. This visual illustration assumes (i) a highly ordered magnetic field in the optically thin region near the jet base (as implied by the observations), (ii) an ordered or tangled field in the large-scale jet (this can be tested using radio–mm polarimetry) and (iii) a jet opening angle of 60°, with the highly polarized MeV photons originating in a limb-brightened region with a magnetic field aligned with this angle (but PA rotation due to a steepening spectrum is more likely; see the text).



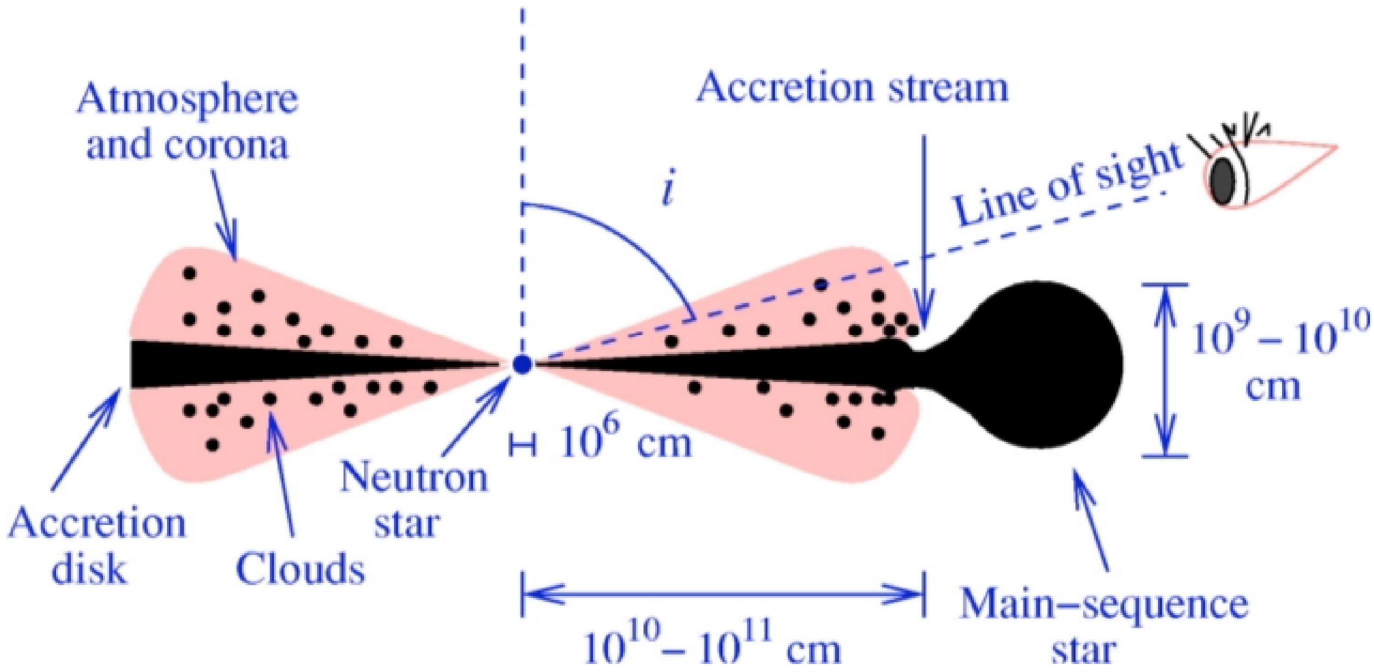
Russell & Shahbaz 2014

Accreting black hole binaries seen edge-on

Polarization due to selected absorption and reprocessing in the extended wind is expected.

Clear feature: for symmetry reasons no rotation/flip of polarization angle with energy is possible!

Polarized flux spectra and spectrum should have the same shape.



Jimenez-Garate et al. 2002

Supporting contributions: constraining black hole spin

So far, three methods have been used to measure the BH spin in XRBs:

1. Relativistic reflection (still debated, requires accurate spectral decomposition);
2. Continuum fitting (requires knowledge of the BH mass, distance and inclination);
3. QPOs (all three QPOs required to completely determine the parameters).

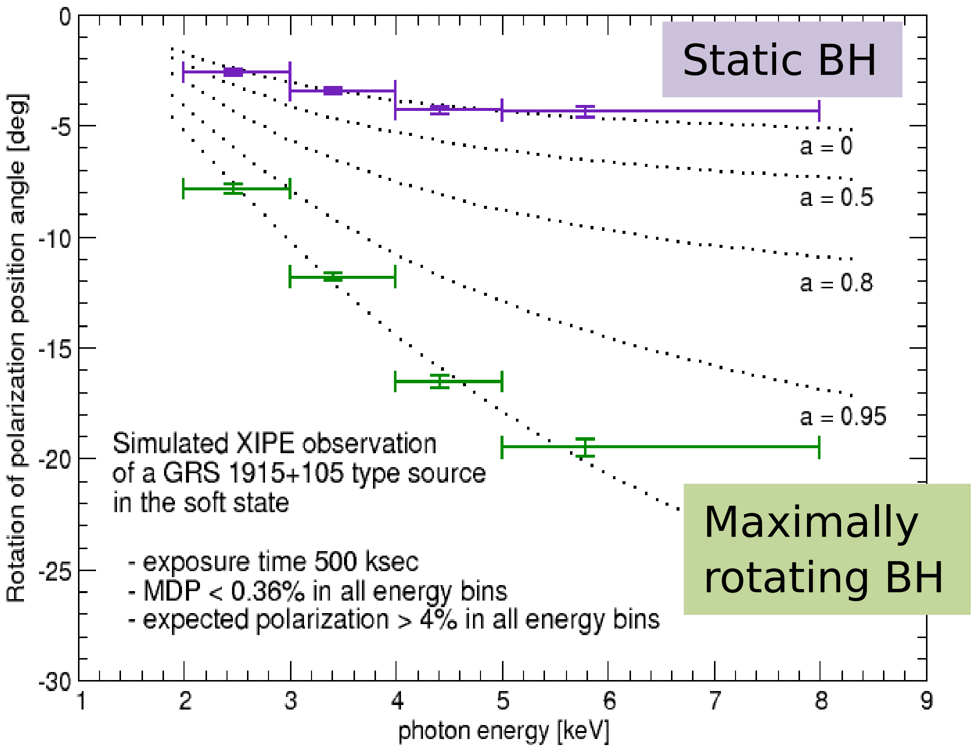
Problem: for a number of XRBs, the methods do not agree!

For GRO J1655-40:

For GRO J1655-40:	QPO:	$a = J/J_{max} = 0.290 \pm 0.003$
	Continuum:	$a = J/J_{max} = 0.7 \pm 0.1$
	Iron line:	$a = J/J_{max} > 0.95$

Energy dependent rotation of the X-ray polarization plane

- Two more observables: polarization degree & angle
- Two parameters: disc inclination & black hole spin



What we plan to do next :

→ check the role of geometrical details of the corona on the *a*-measurement,

→ check the role of returning radiation on the *a*-measurement.

OUTLINE

Why should we care about polarization?

Some basics on polarization of electromagnetic radiation

State of the art techniques to measure X-ray polarization

X-ray polarization of neutron stars

X-ray polarization of black hole X-ray binaries

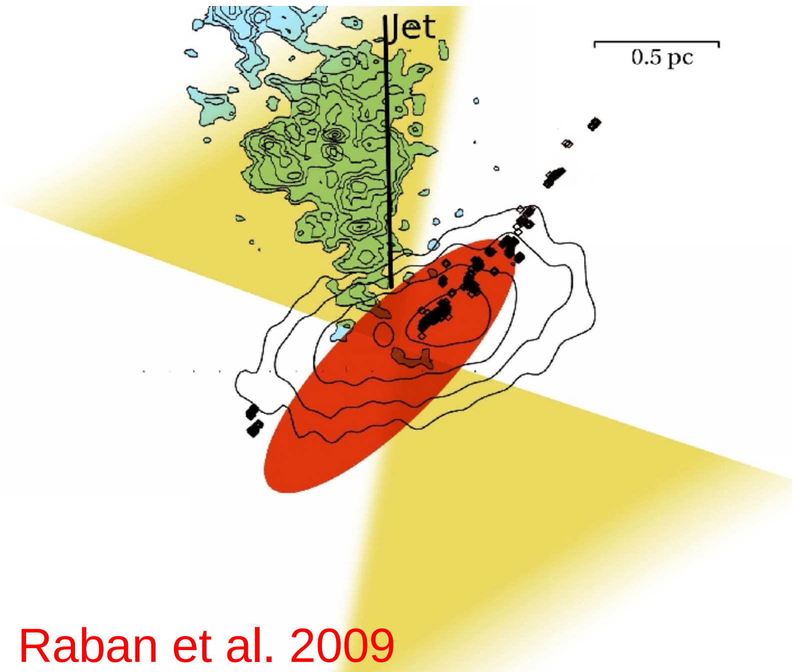
X-ray polarization of active galactic nuclei

René Goosmann
Strasbourg Observatory, France

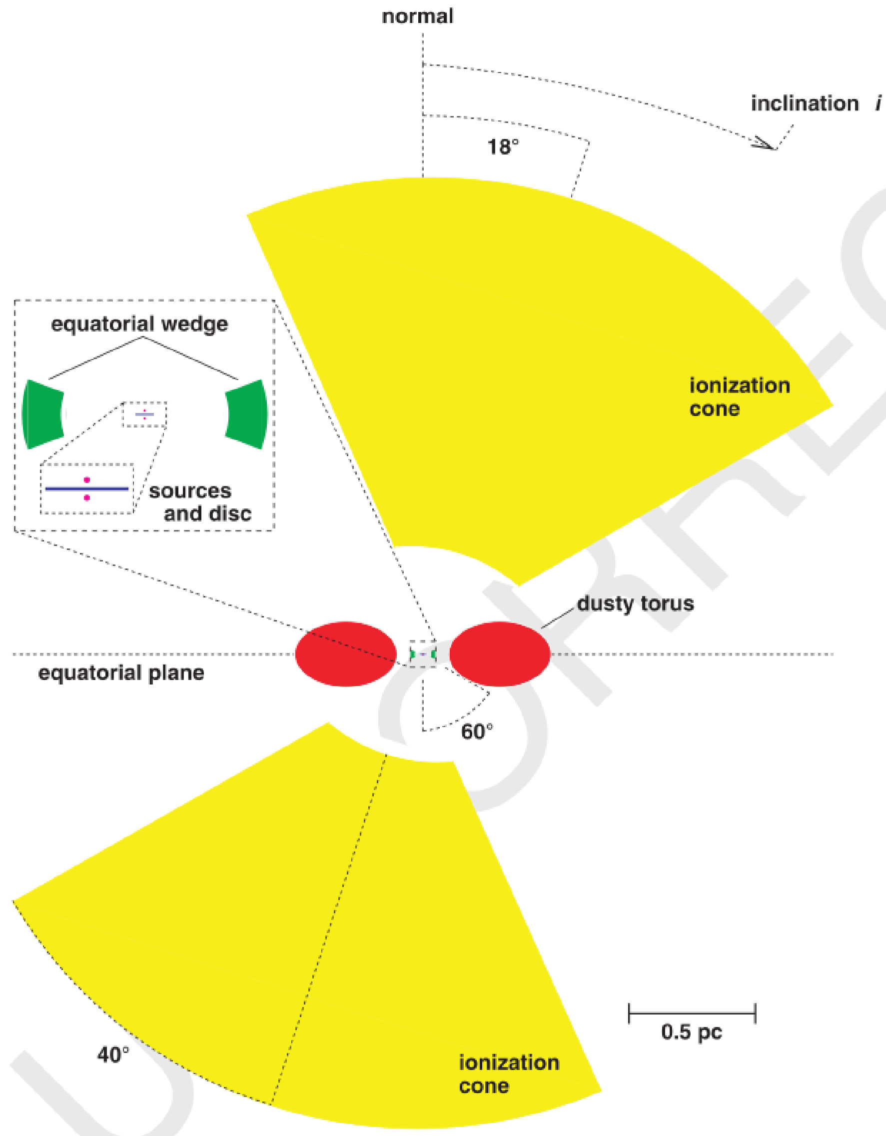
X-ray polarimetry of NGC 1068

Modeling of an irradiated accretion disk, a dusty torus with $\Theta = 60°$, and inclined outflows as suggested by Raban et al. (2009).

Goosmann & Matt 2011

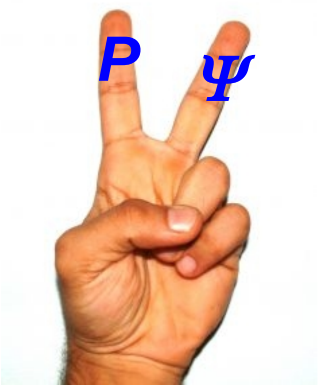


Raban et al. 2009



Possibility to constrain the relative angle between torus and outflows by broad-band polarimetry!

X-ray polarimetry of NGC 1068



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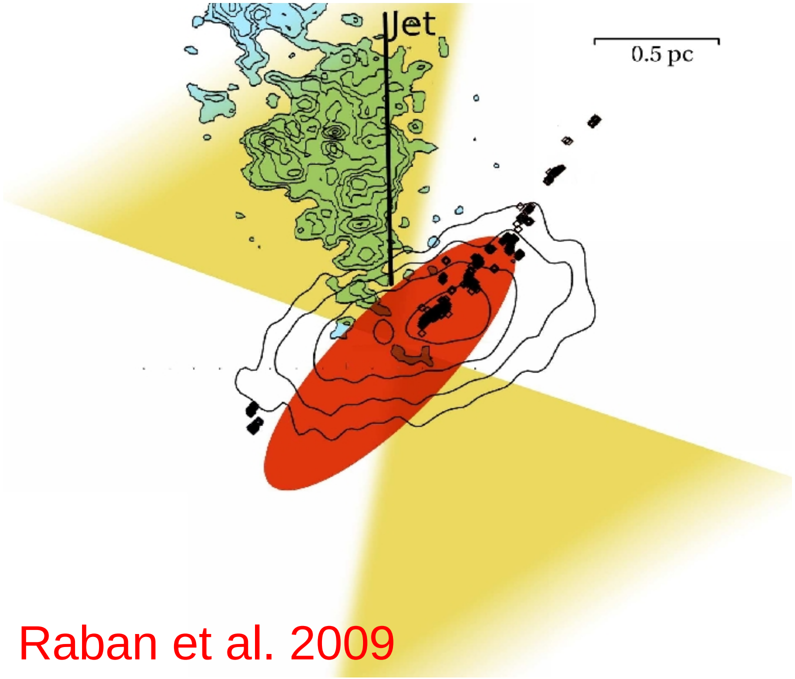
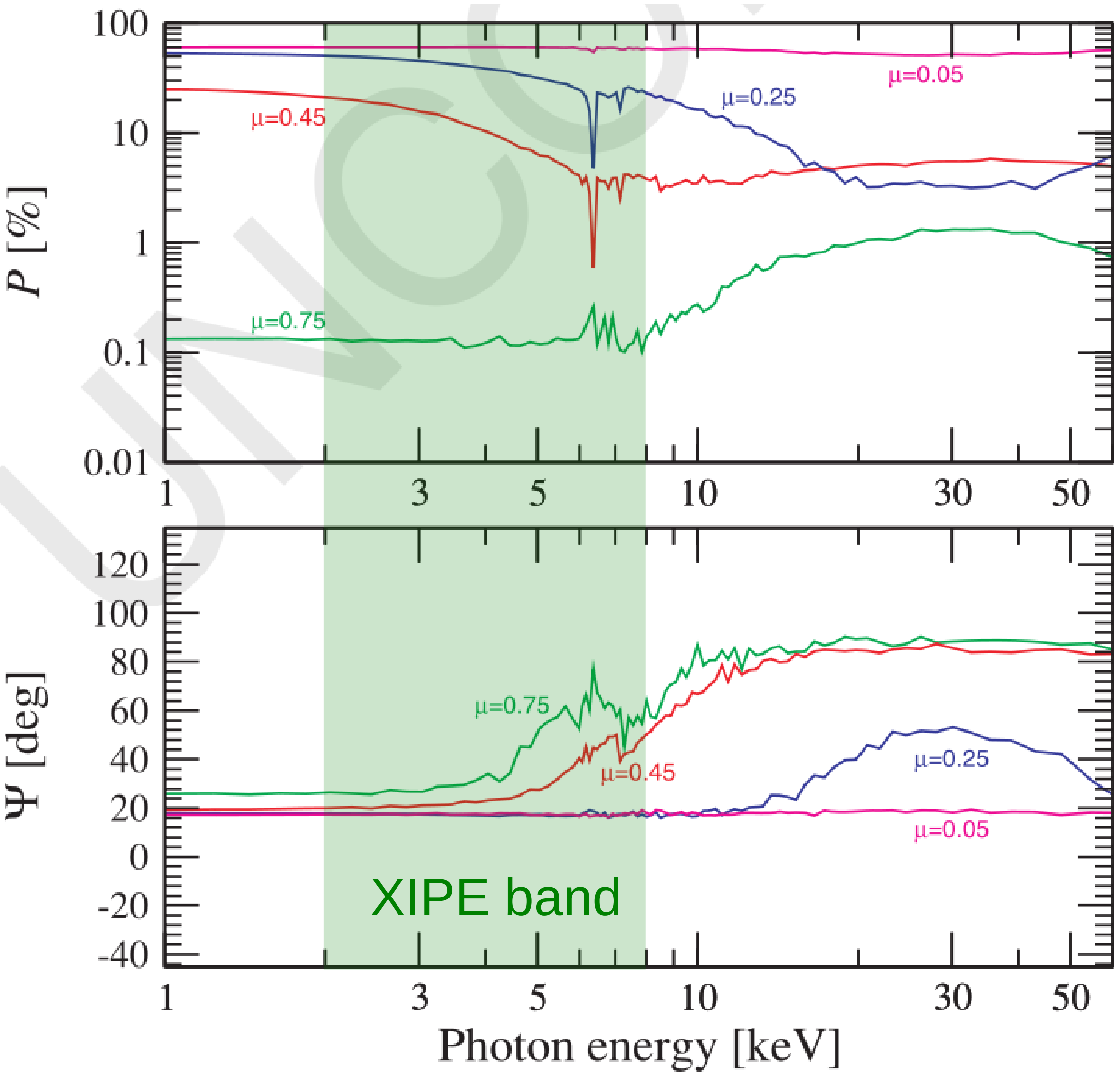


Raban et al. 2009



Possibility to constrain the relative angle between torus and outflows by broad-band polarimetry!

Acceleration phenomena: Unresolved jets

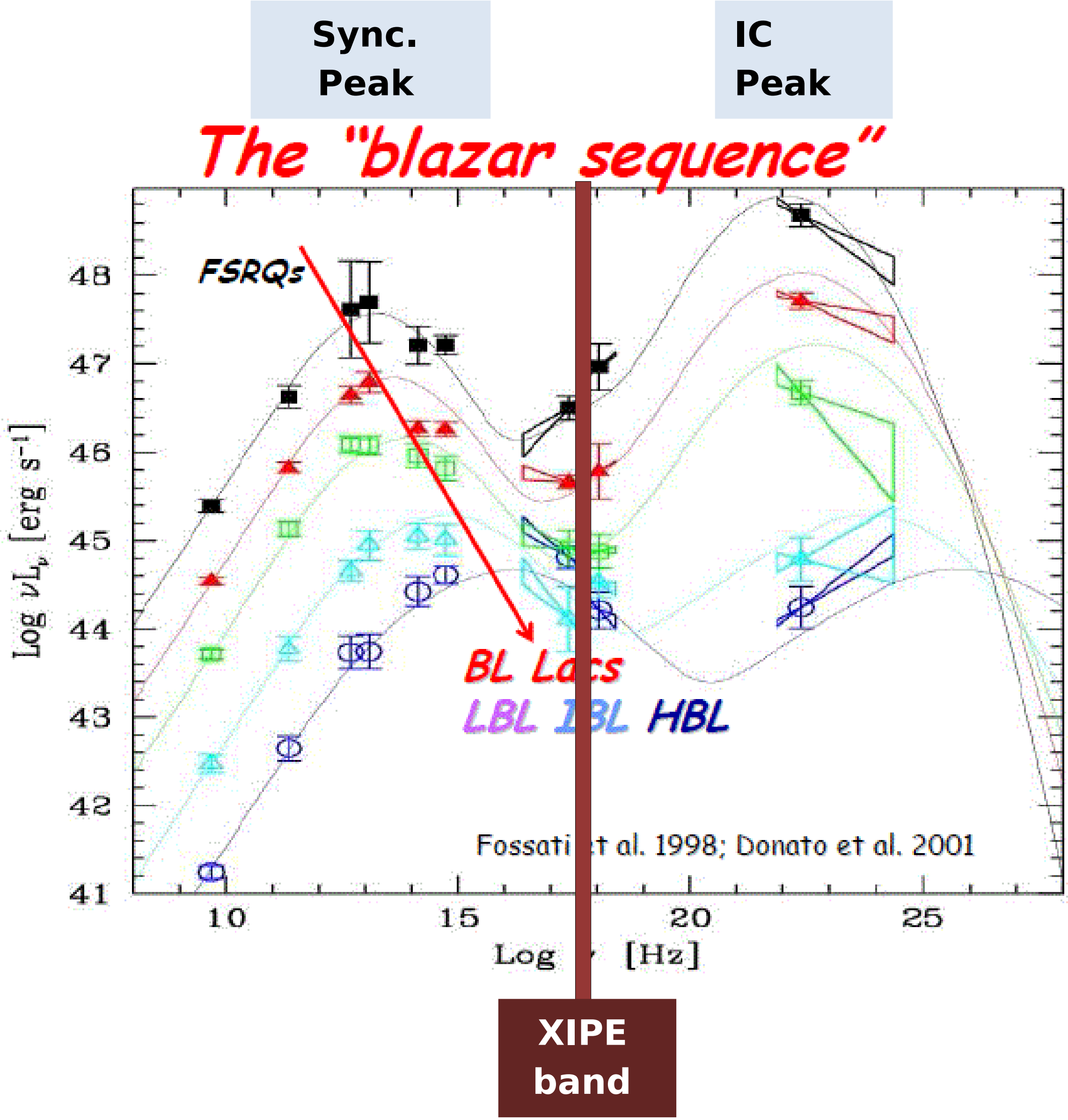
Unique contributions : probing the origin of the seed photons

Blazars are extreme accelerators in the Universe, but the emission mechanism is far from being understood.

In inverse Compton dominated Blazars, a XIPE observation 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.



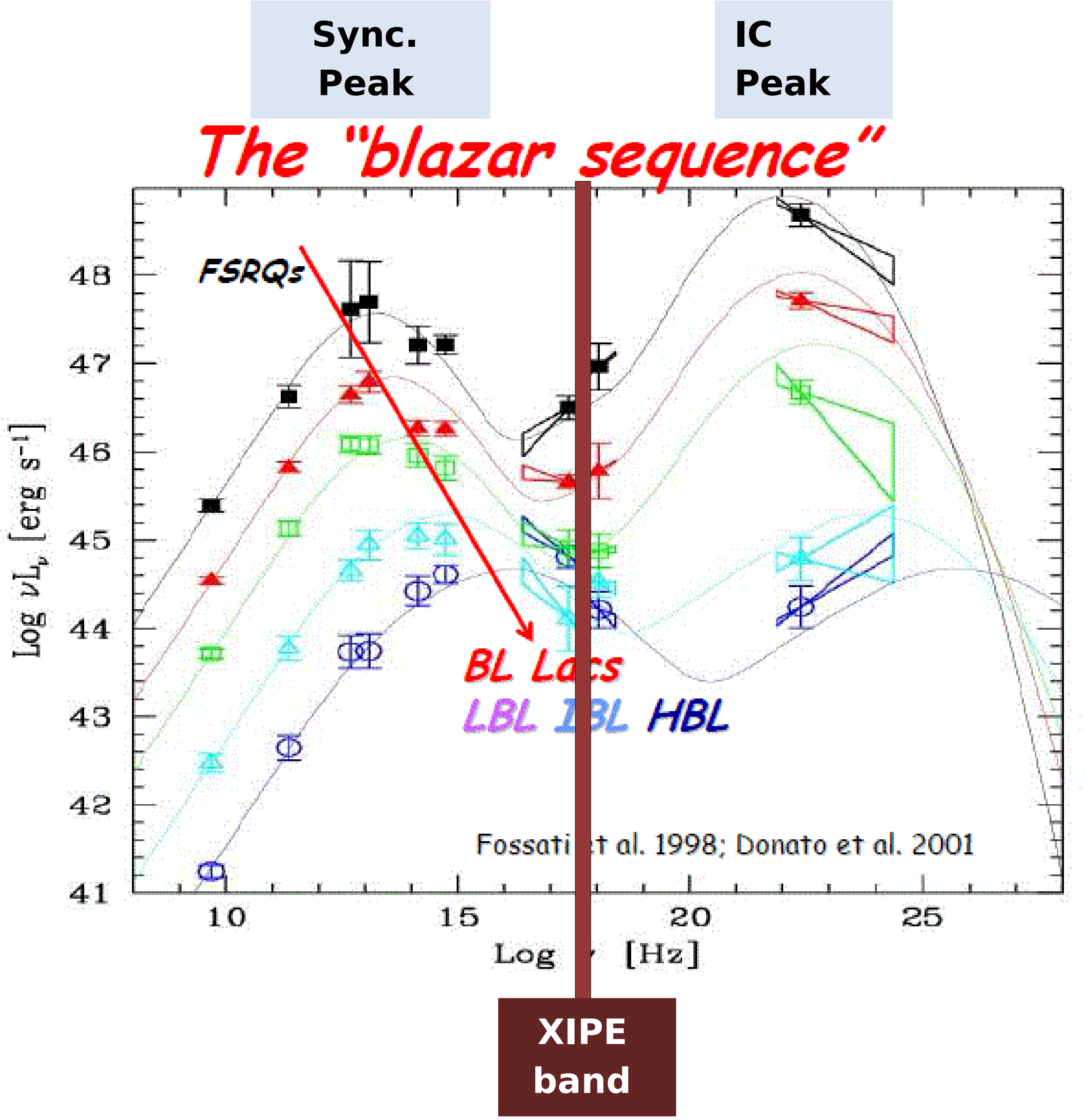
Unique contributions : probing the origin of the seed photons

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

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

Coordinated multi-wavelength campaigns are crucial for blazars.

Such campaigns (including polarimetry) are routinely organized and it will be easy for XIPE to join them.



Was Sgr A* a faint AGN in the past?

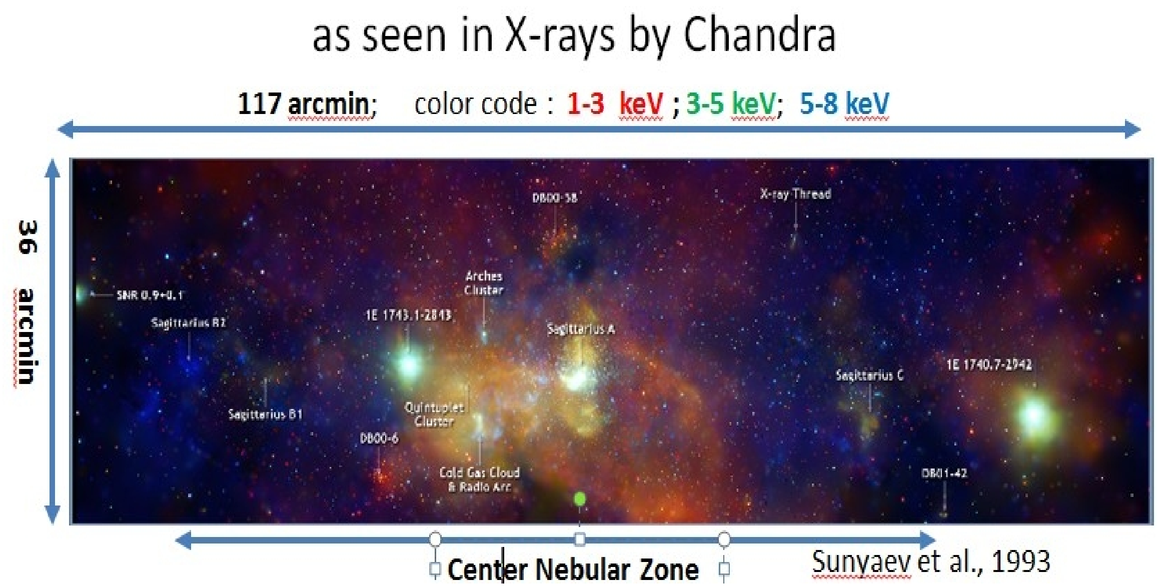
Unique contributions: what lightens up the molecular clouds in Sgr A*?

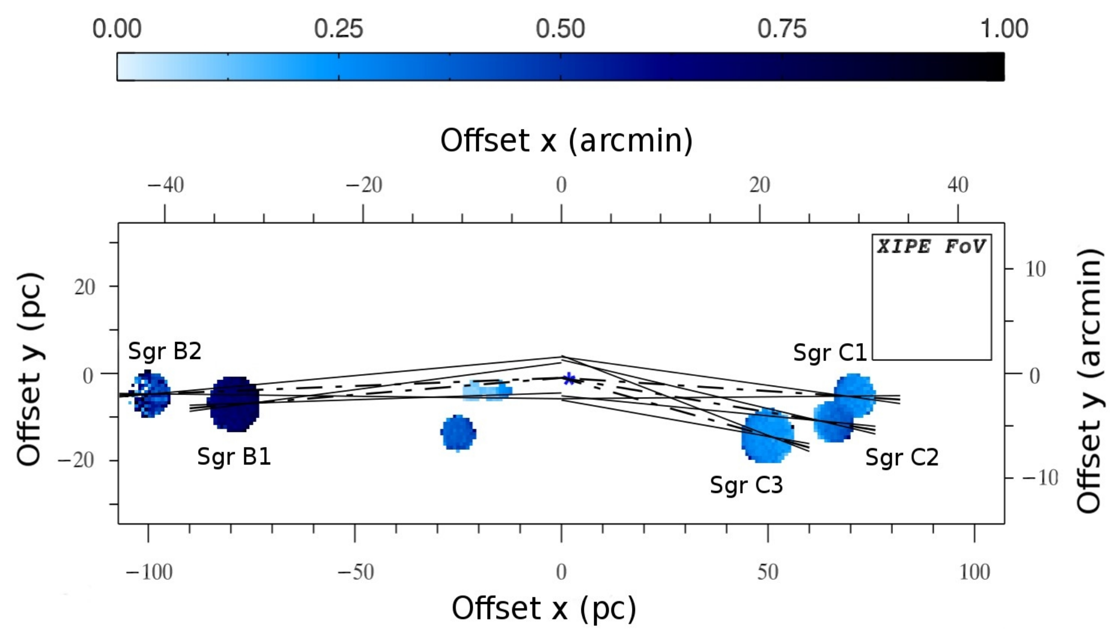
Cold molecular clouds around Sgr A* show a neutral iron line and a Compton bump → Reflection from an external source!?!

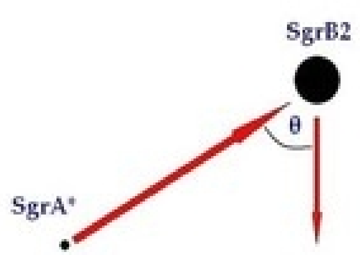
No bright source is there. Are they reflecting X-rays from Sgr A* when it was 10 ⁶ times brighter?

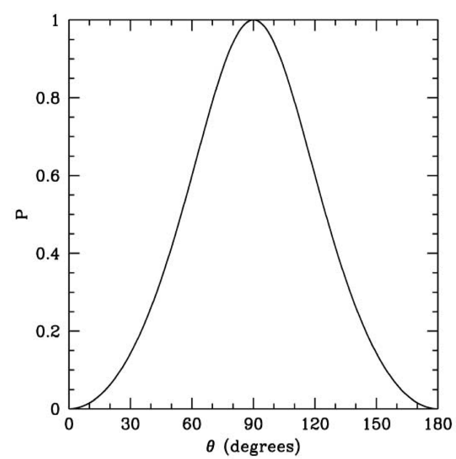
Polarization by scattering from Sgr B complex, Sgr C complex

• The angle of polarization pinpoints the source of X-rays (possibly SgrA*)
• The degree of polarization measures the scattering angle and determines the true distance of the clouds from Sgr A*.









The first XIPE science conference

was held on May 24-26 in Valencia, Spain (hosted by Victor Reglero)

- open to the scientific community with possibility to suggest contributed talks

- invited talks on X-ray polarimetry in general and XIPE science in particular

X-ray polarimetry session planned for COSPAR meeting in July/August in Istanbul.

More information on:

http://www.isdc.unige.ch/xipe/