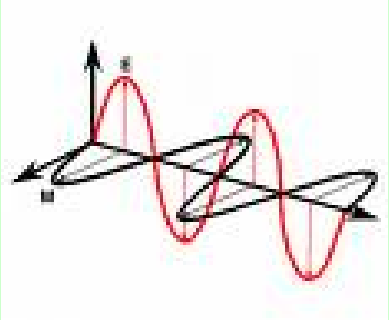


Polarimetry: a new window to the X-ray Universe

Giorgio Matt

(Dip. Fisica, Università Roma Tre, Italy)

Radiation is polarized when it is originated in anisotropic physical situations, as e.g. in *aspherical matter/radiation field distributions* or in *ordered magnetic fields*.

Polarization properties are strongly modified by *GR curvature of space-time*

Many X-ray sources are likely to be strongly polarized !!!

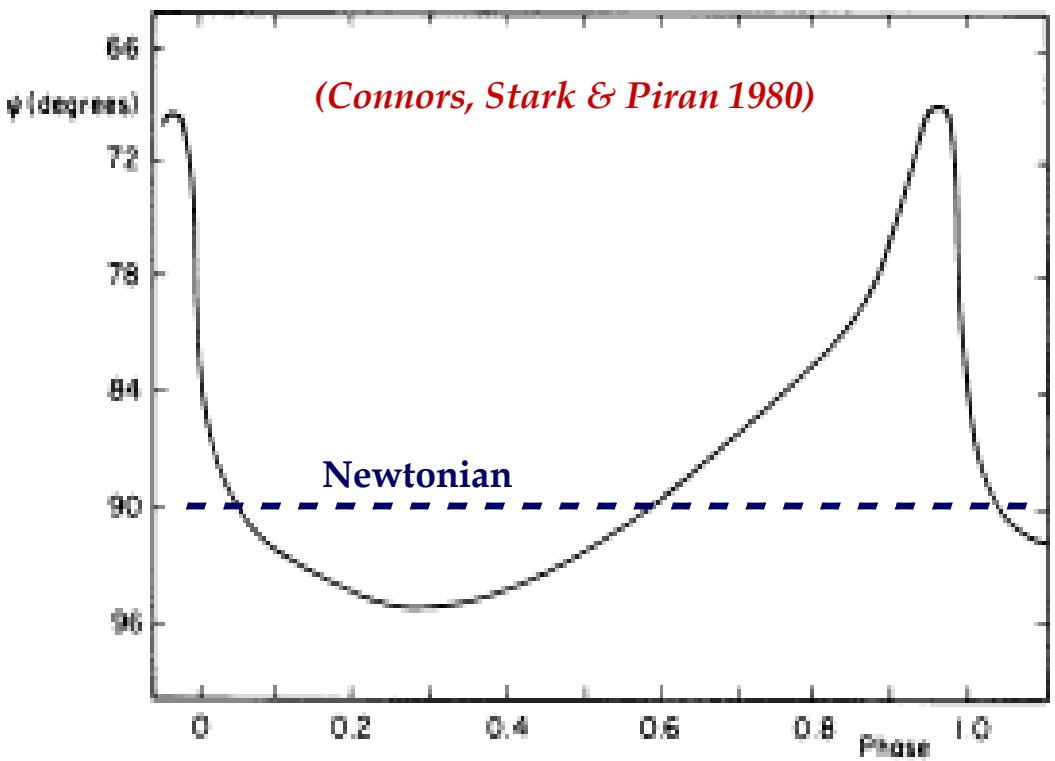
Polarimetry will provide important and often unique informations. Unfortunately, only one positive measurement (the *Crab Nebula*) has been obtained so far.

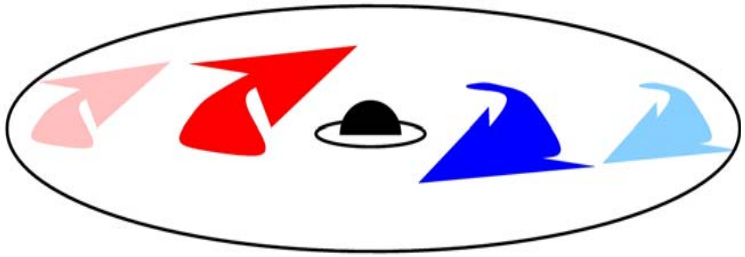
X-ray polarimetry may:

- **Probe strong gravity effects around BHs**
- **Determine the emission mechanism in Blazars**
- **Study strong and extreme magnetic fields in compact sources**
- **Disclose the past activity of the Black Hole in the Galaxy**
- **Map the structure of the magnetic field in PWN and GRB**

+ ... *(SNR, CoG, Fundamental Physics, etc.)*

General and Special Relativity effects around a compact object (here-in-after collectively indicated as "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



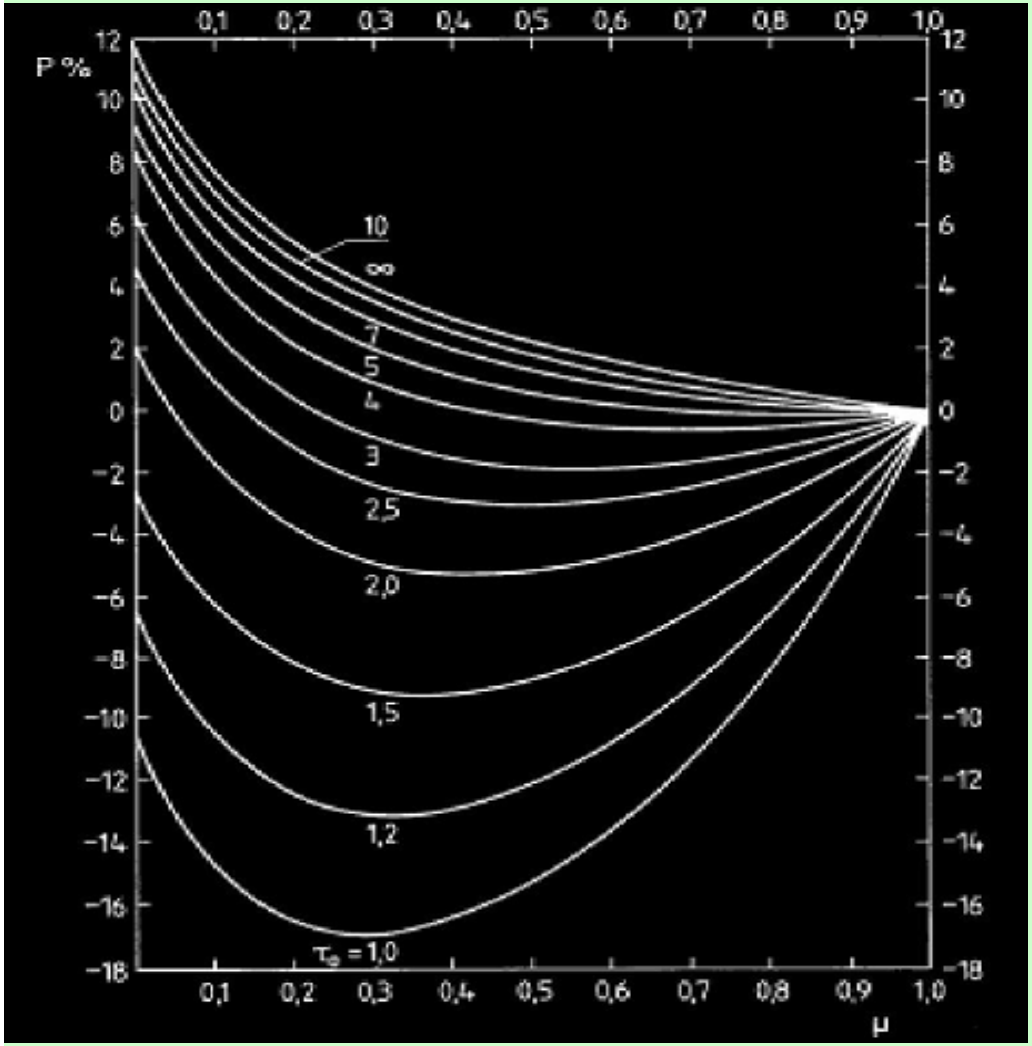


Orbiting spot with:
a=0.998; R=11.1 Rg
i=75.5 deg

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

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

Polarization of disc emission

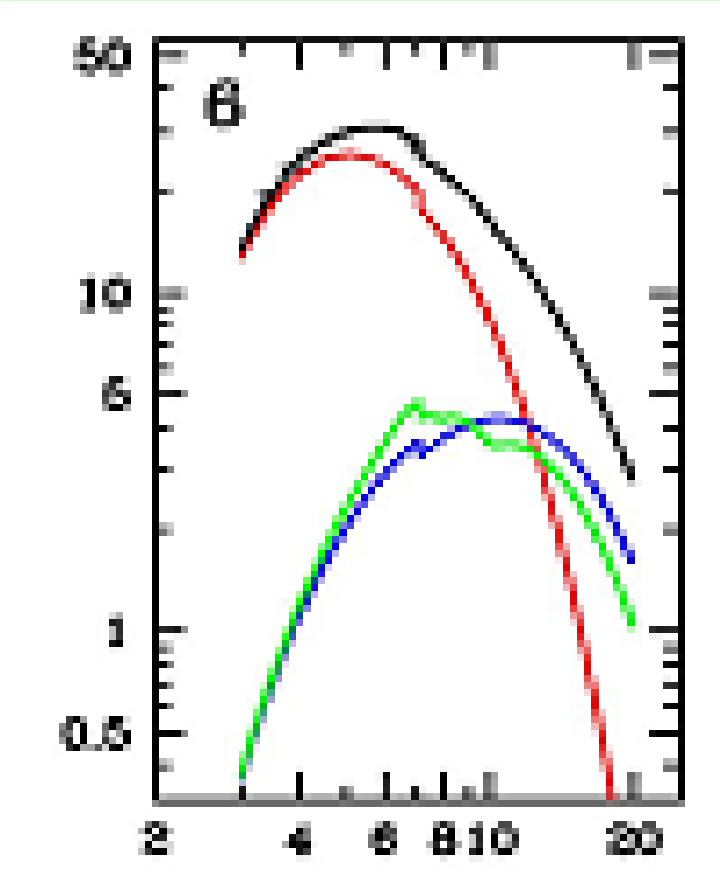


Sunyaev & Titarchuk (1985)

Thermal disc emission, in a pure scattering atmosphere, is polarized up to about 12% (Chandrasekhar 1960), even more if the scattering layer is optically thin (e.g. Sunyaev & Titarchuk 1985, Dovciak et al, 2008)

For symmetry reasons, the polarization is always either parallel or perpendicular to the disc axis.

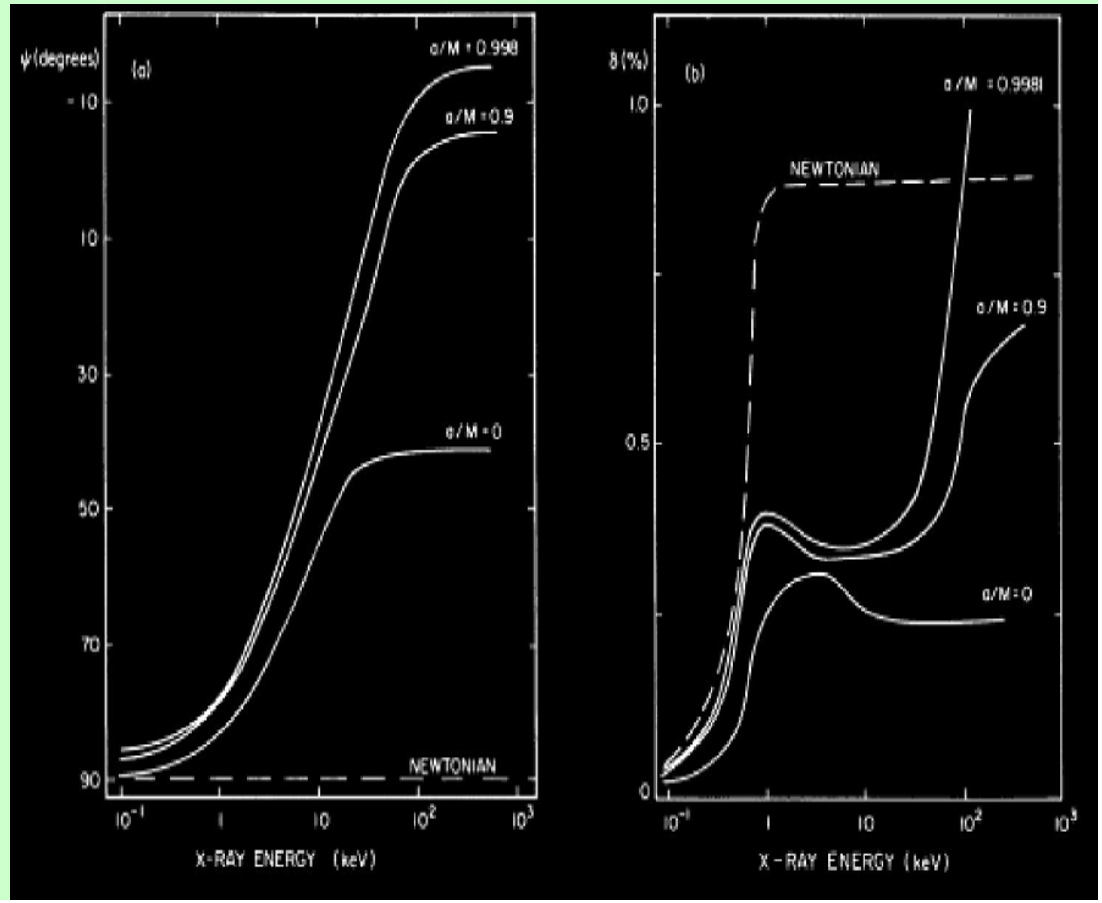
Galactic BH binaries in high state



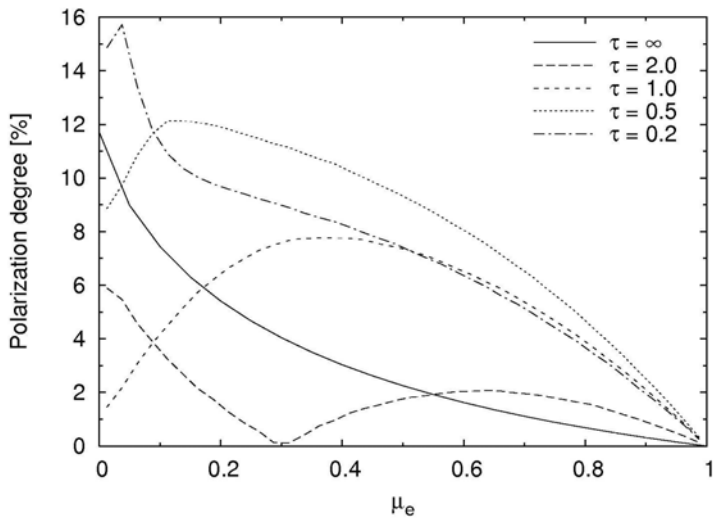
GRS 1915+105
(Done & Gierlinski 2004)

X-ray emission in Galactic BH binaries in soft states is dominated by disc thermal emission, with *T decreasing with radius.*

A rotation of the polarization angle with energy is therefore expected.

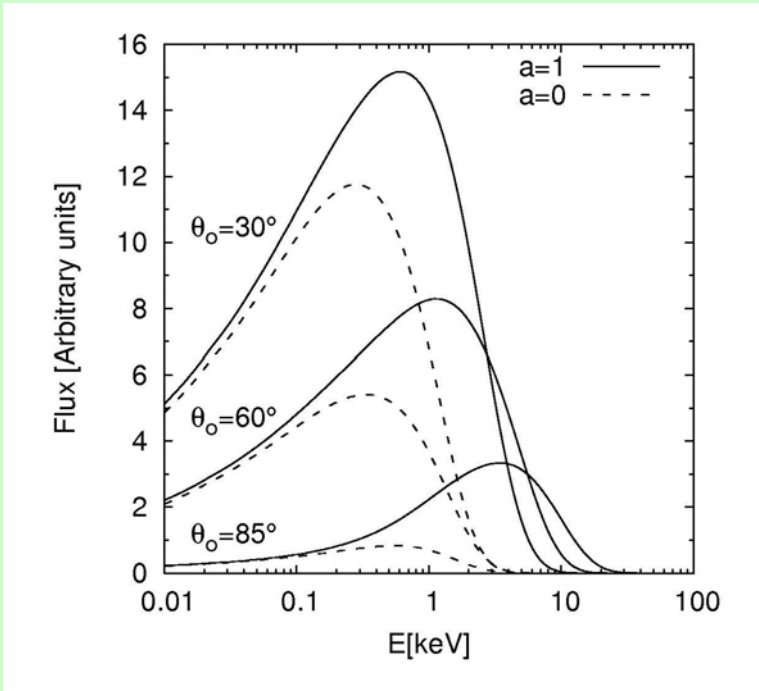


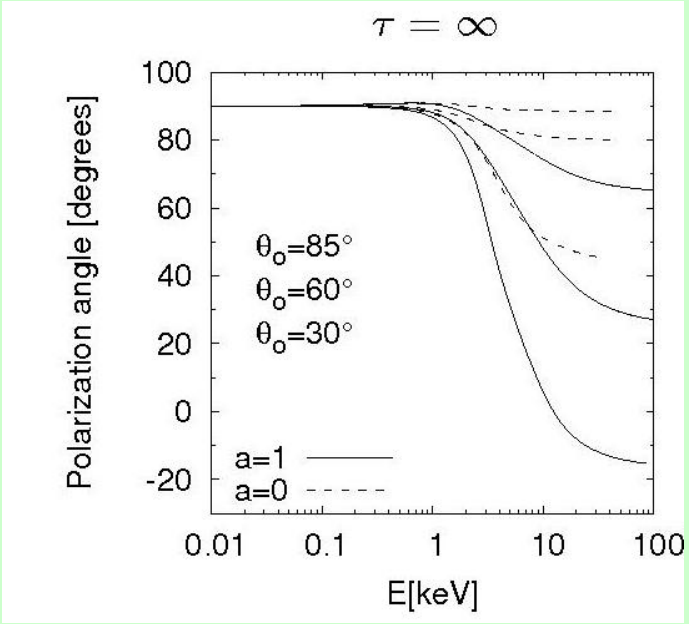
Connors & Stark (1977)



We (Dovciak et al. 2008) revisited and refined these calculations (see also Li et al. 2009 and Schnittman & Krolik 2009).

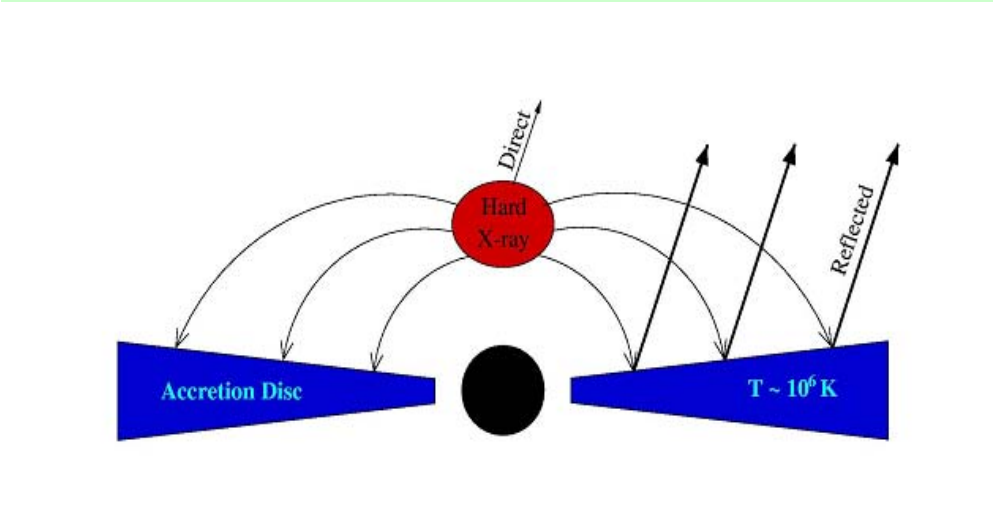
Strongly dependent on the spin of the BH !!





Active Galactic Nuclei

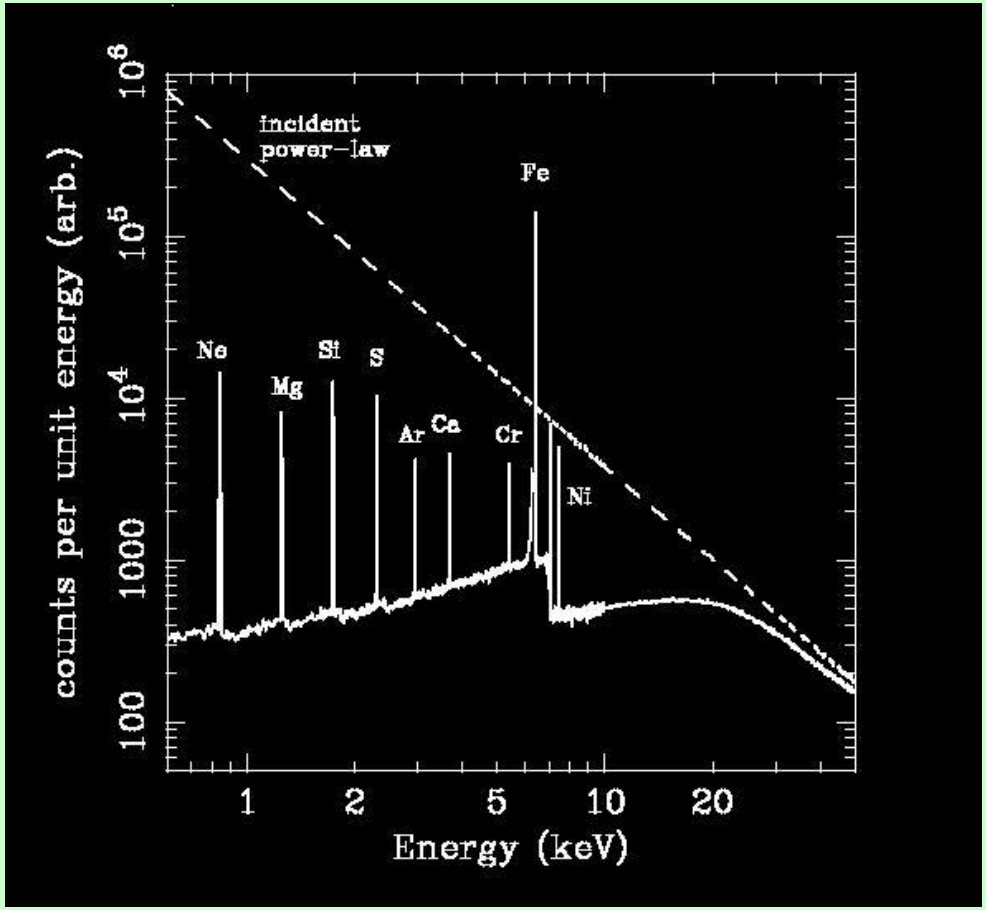
In Active Galactic Nuclei the primary X-ray emission is due to Inverse Compton by electrons in a hot Corona of the UV/Soft X-ray disc photons. It is likely to be significantly polarized (e.g. Haardt & Matt 1993, Poutanen & Vilhu 1993), because the system is unlikely to have a spherical symmetry.



Part of the primary emission illuminates the disc and is reflected (and polarized) via Compton Scattering

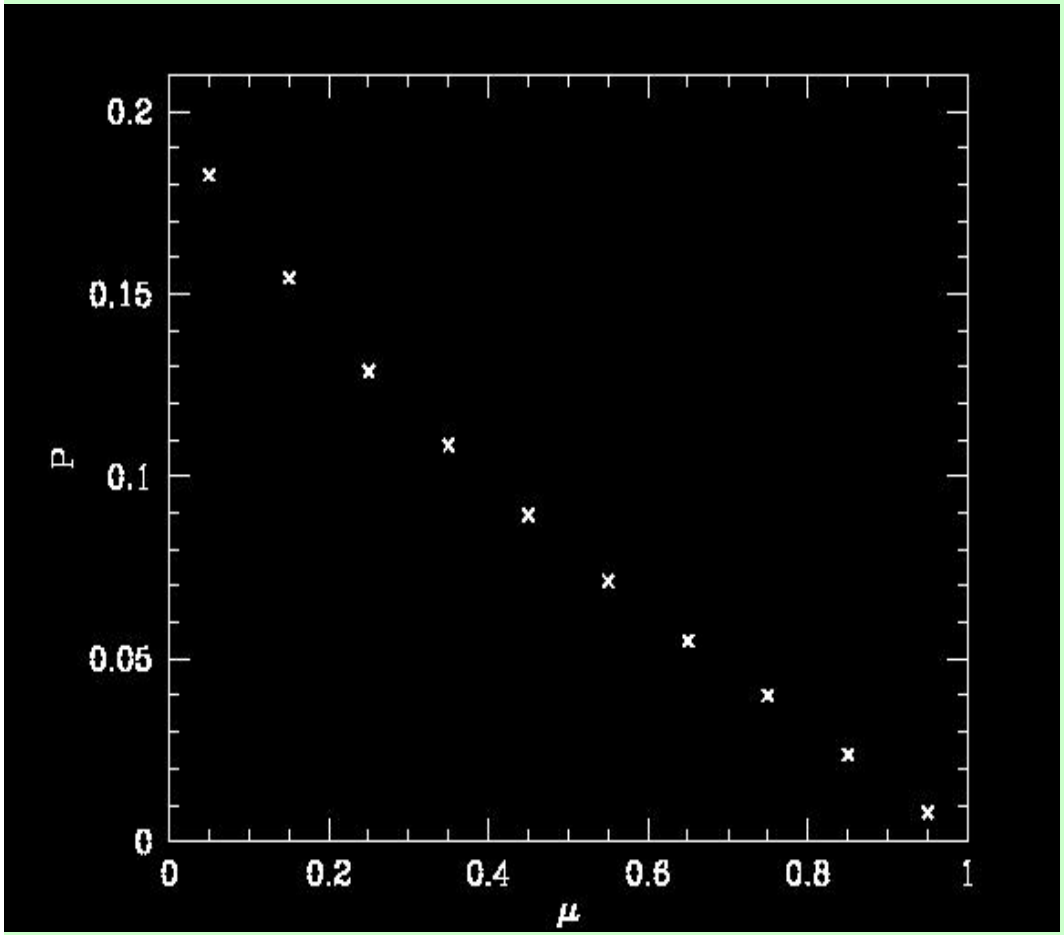
Reflection from cold matter

Reflection from cold matter produces a continuum peaking around 20 keV, due to the combined effects of photoelectric absorption and Compton scattering (plus several fluorescent lines, most prominent of them the Fe Kα line at 6.4 keV).



Reynolds et al. (1995)

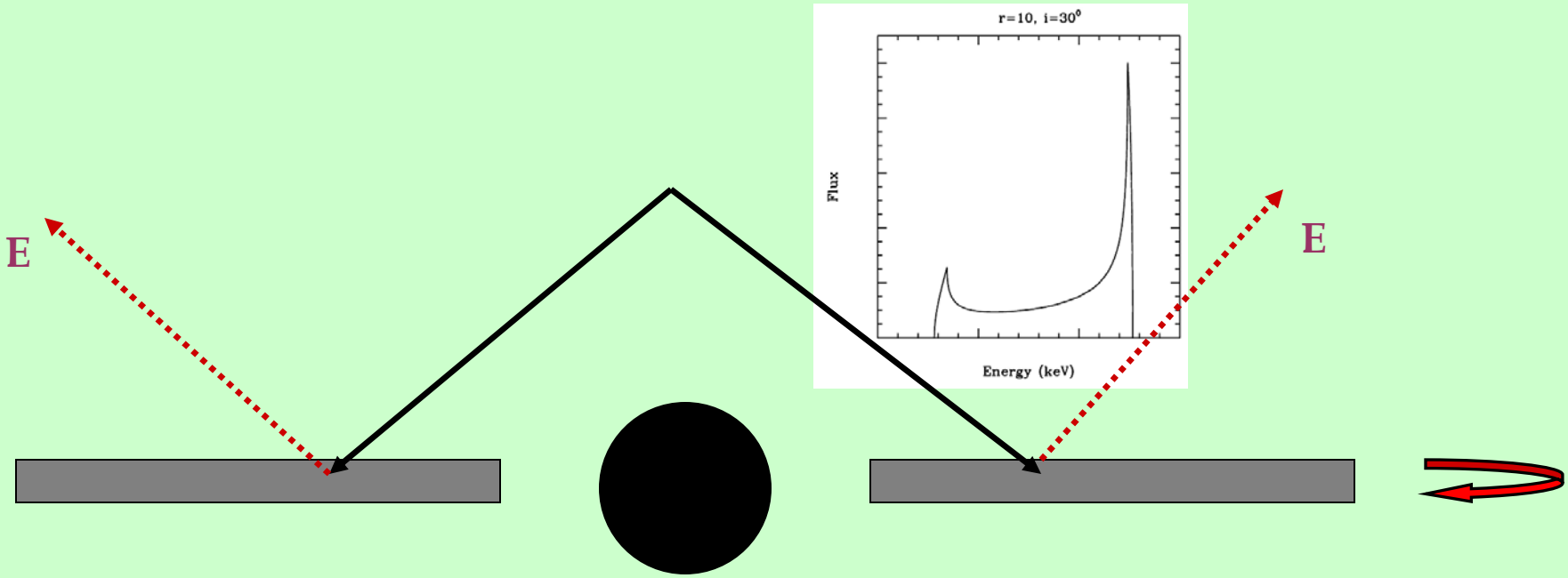
Polarization of reflected flux



Polarization of reflected (continuum) radiation is large. For instance, it is up to 20% (Matt et al. 1989) assuming isotropic illumination, a plane-parallel reflecting slab and unpolarized illuminating radiation.

The exact values depend on the actual geometry of the system and on the polarization degree of the primary radiation

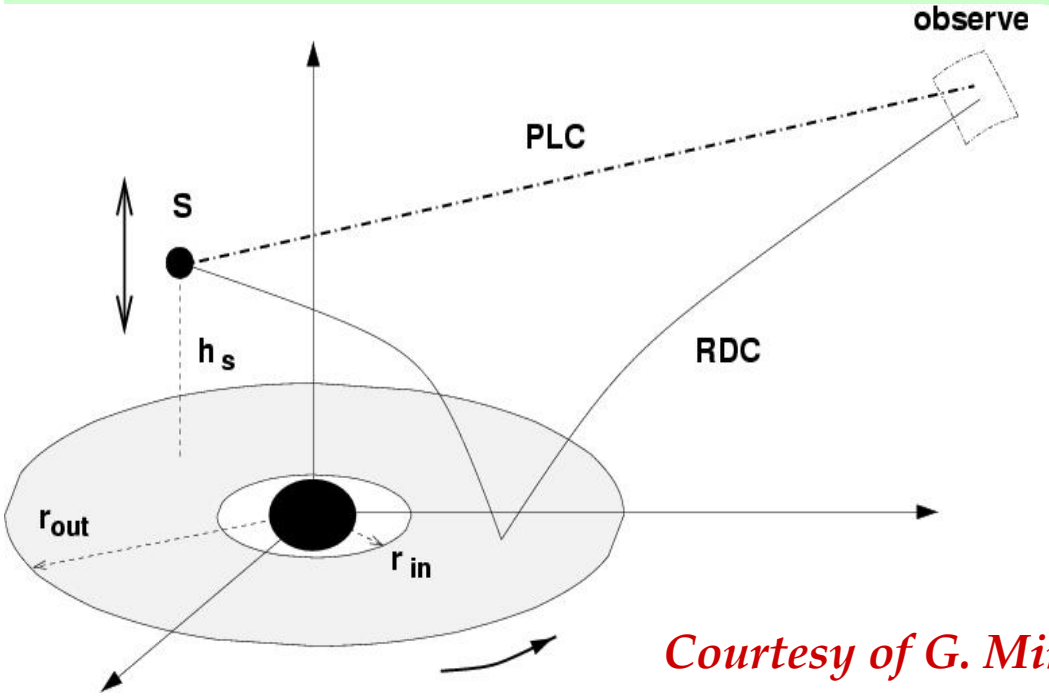
Reflection in Relativistic discs

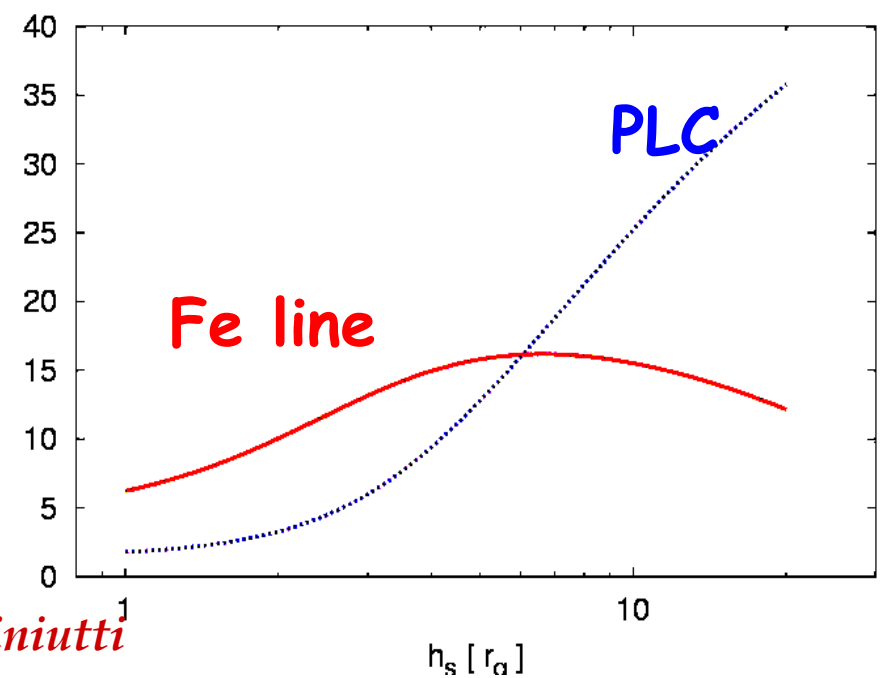


Breaking of the symmetry due to SR (Doppler boosting) adds to the effects already mentioned, causing the rotation of the PA with respect to the Newtonian case. Changes in the illumination properties (e.g. in the height of the lamp-post) will cause changes in the total PA, which is therefore likely to be time dependent (relevant for AGN, timescales too short for GBH).

The case of MCG-6-30-15

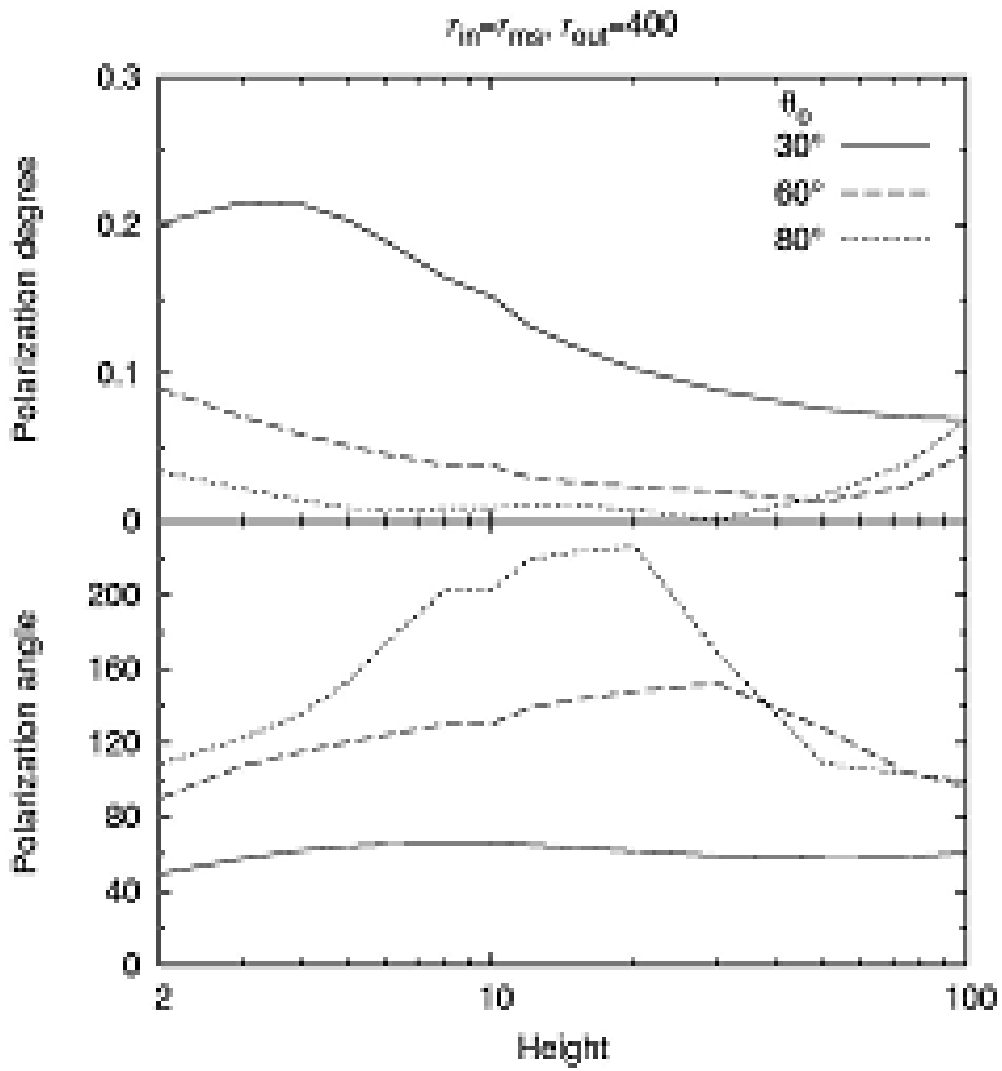
Variations of *h* have been suggested to be the cause of the puzzling temporal behaviour of the iron line in MCG-6-30-15 (Miniutti et al. 2003), where the line flux varies much less than the primary power law flux.





Courtesy of G. Miniutti

Polarization of reflected radiation

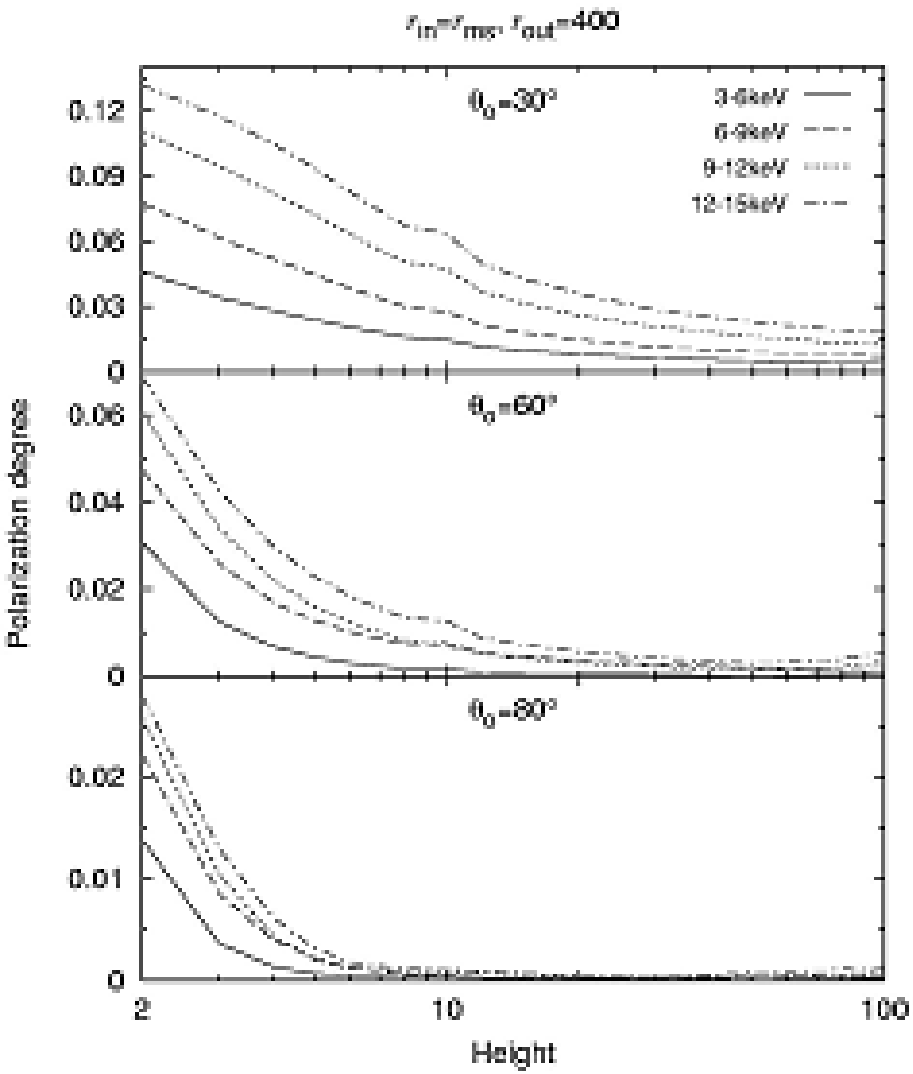


(Dovciak, Karas & Matt 2004)

The polarization degree and angle depend on both *h* and the incl. angle (the latter may be estimated from the line profile; for MCG-6-30-15 is about 30 degrees, Tanaka et al. 1995)

Variation of h with time implies a time variation of the degree and angle of polarization

Net polarization



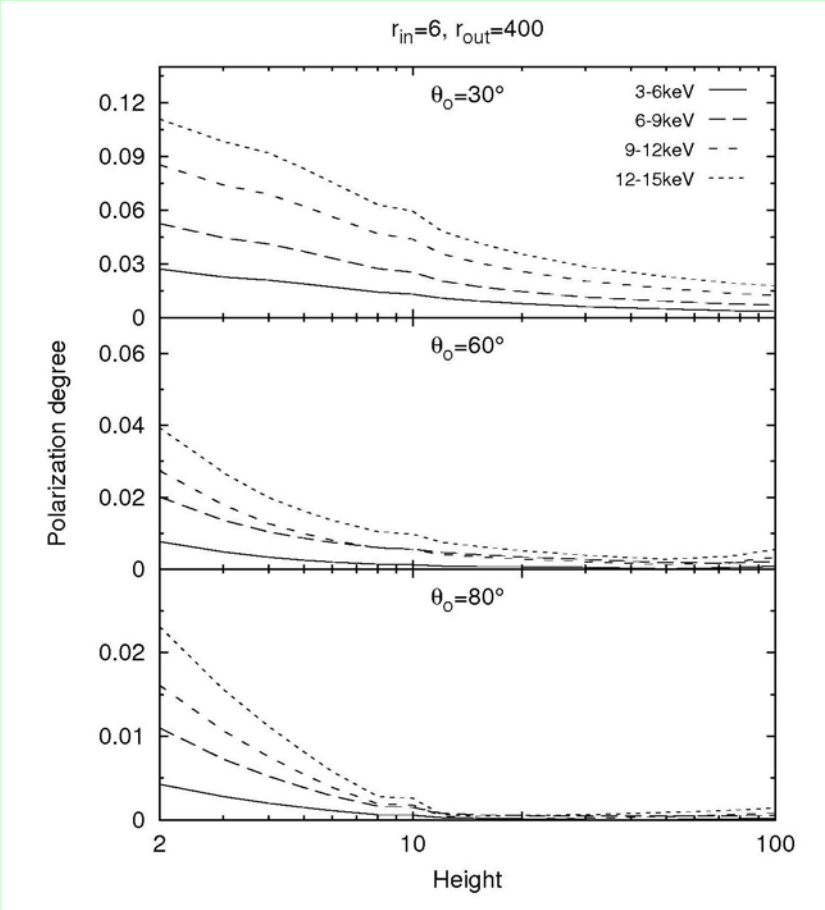
(Dovciak, Karas & Matt 2004)

If the primary emission (supposed unpolarized) is included, the net polarization degree of course decreases, but it is still significant especially for low heigths, where light bending strongly enhances the relative amount of reflection.

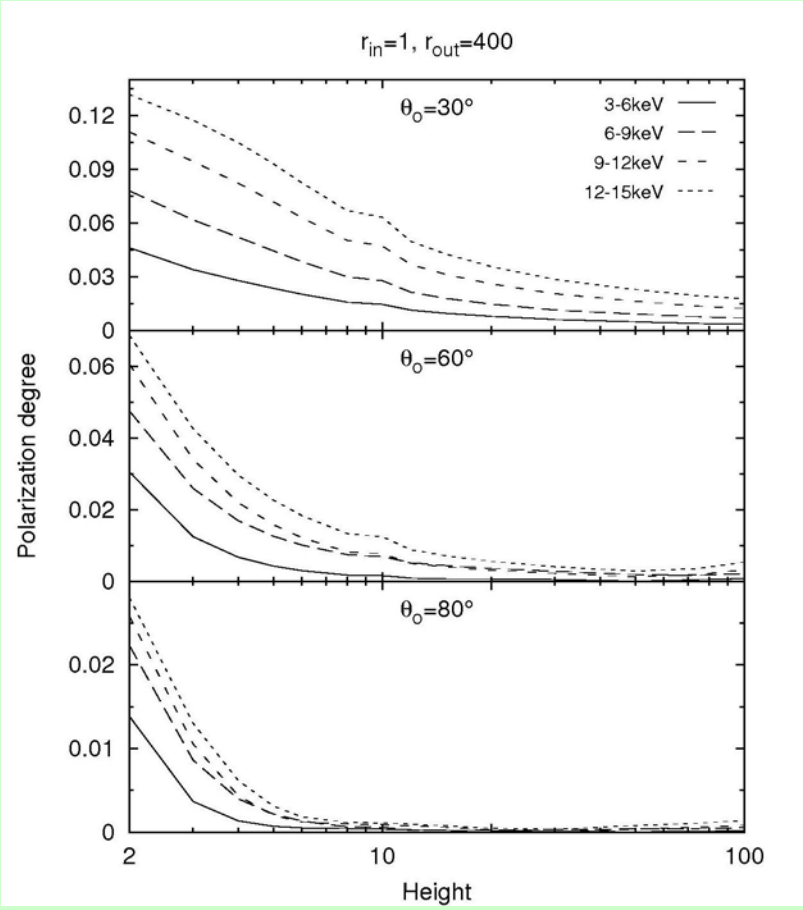
Polarization measurements will provide an independent test of the light bending model

Net Polarization

Courtesy M. Dovciak



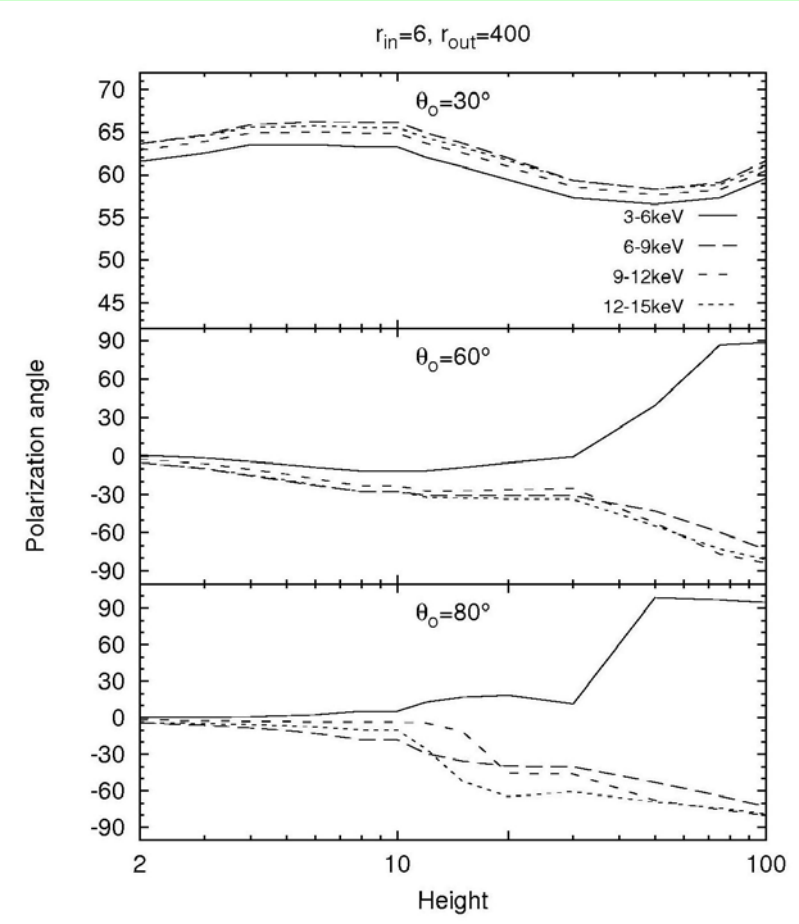
Schwarzschild, a=0



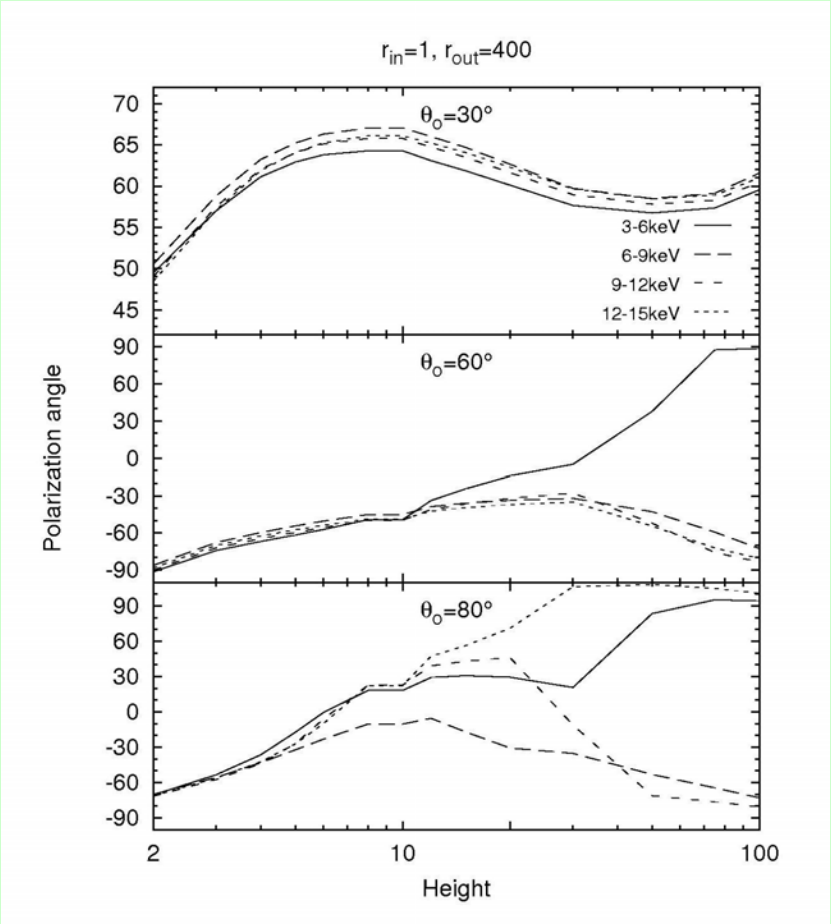
Extreme Kerr, a=1

Net Polarization

Courtesy M. Dovciak



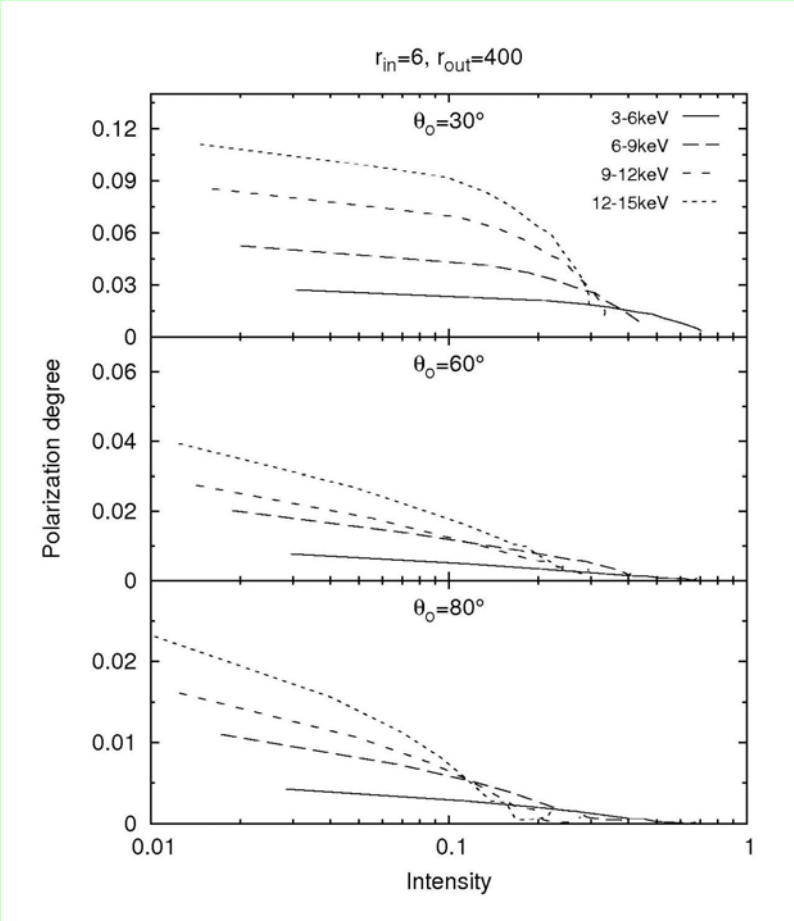
Schwarzschild, a=0



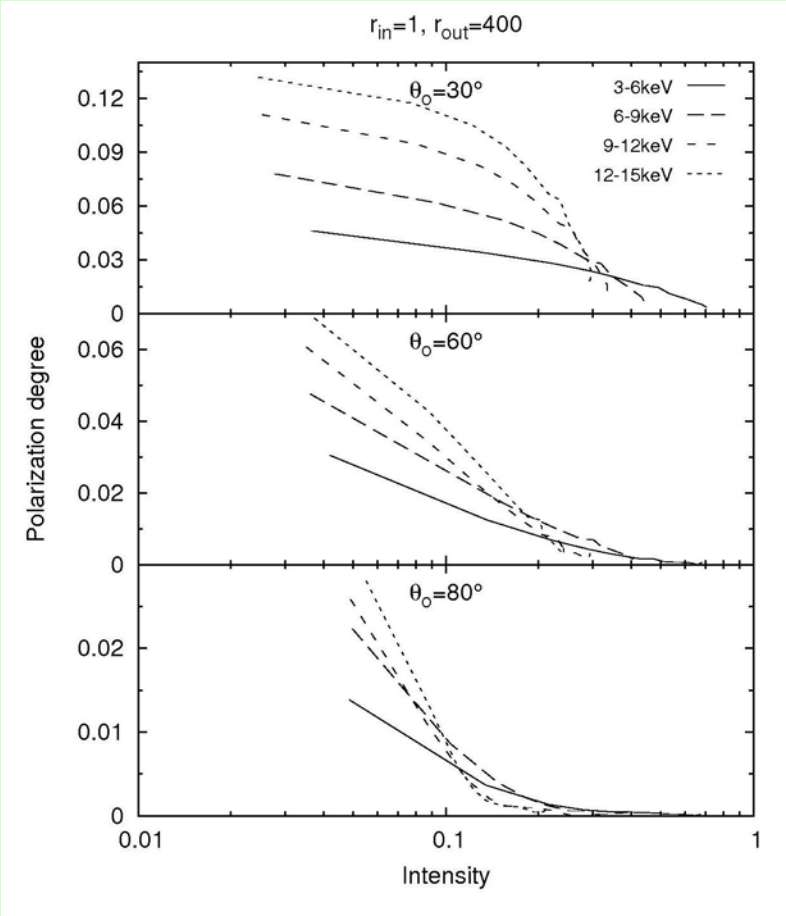
Extreme Kerr, a=1

Net Polarization

Courtesy M. Dovciak



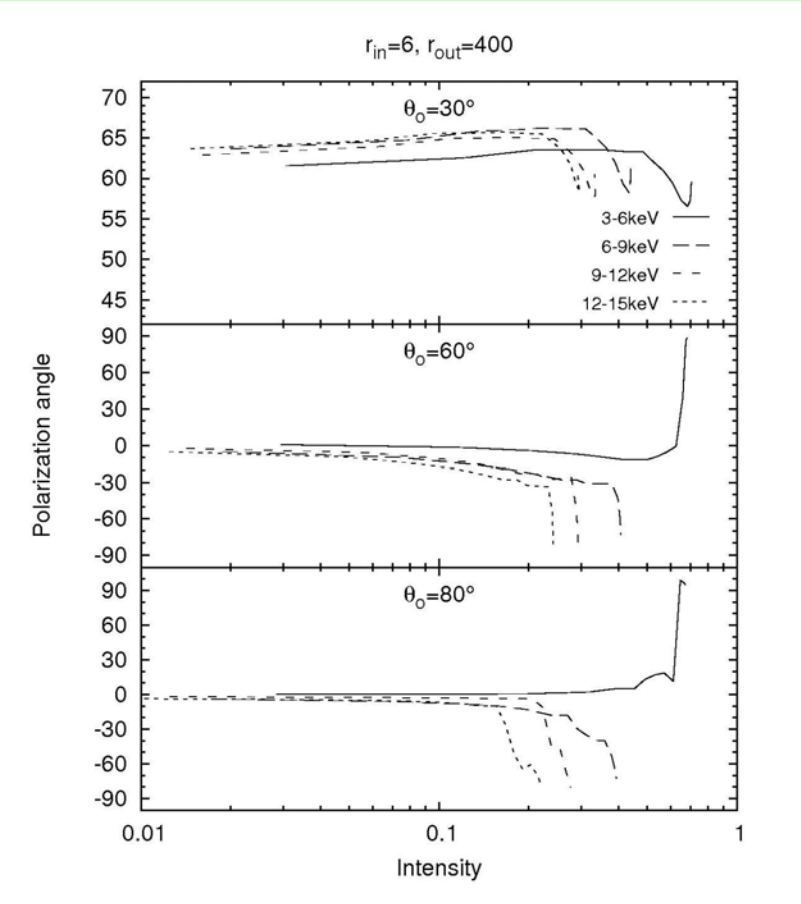
Schwarzschild, a=0

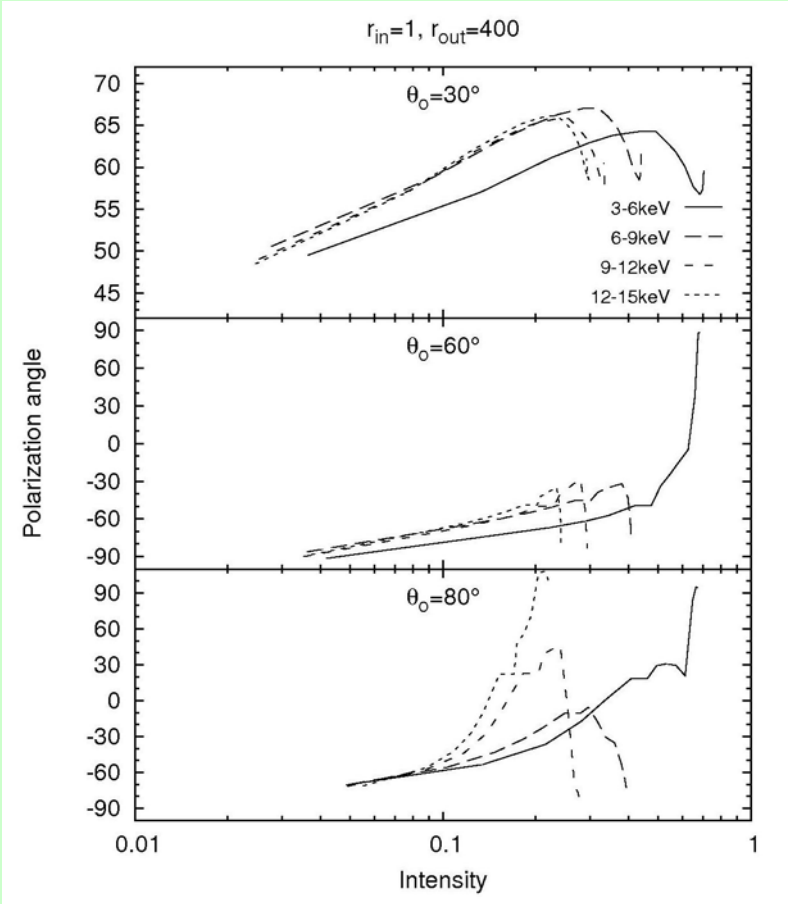


Extreme Kerr, a=1

Net Polarization

Courtesy M. Dovciak



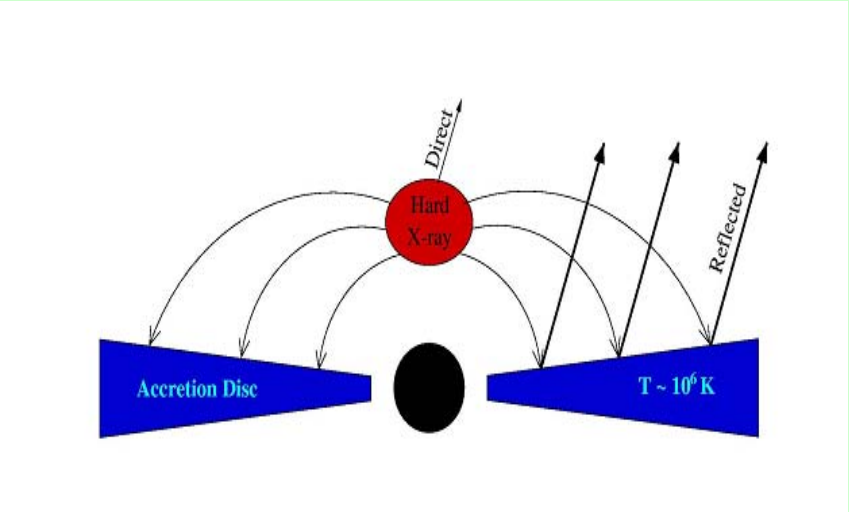


Schwarzschild, a=0

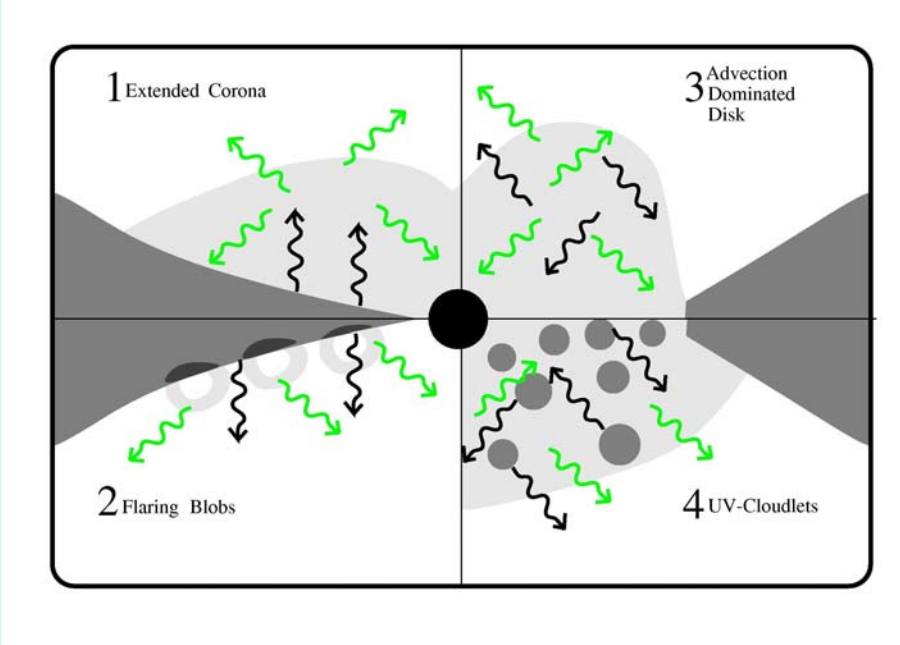
Extreme Kerr, a=1

Primary emission from 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



Polarimetry will help understanding the geometry of the emitting region



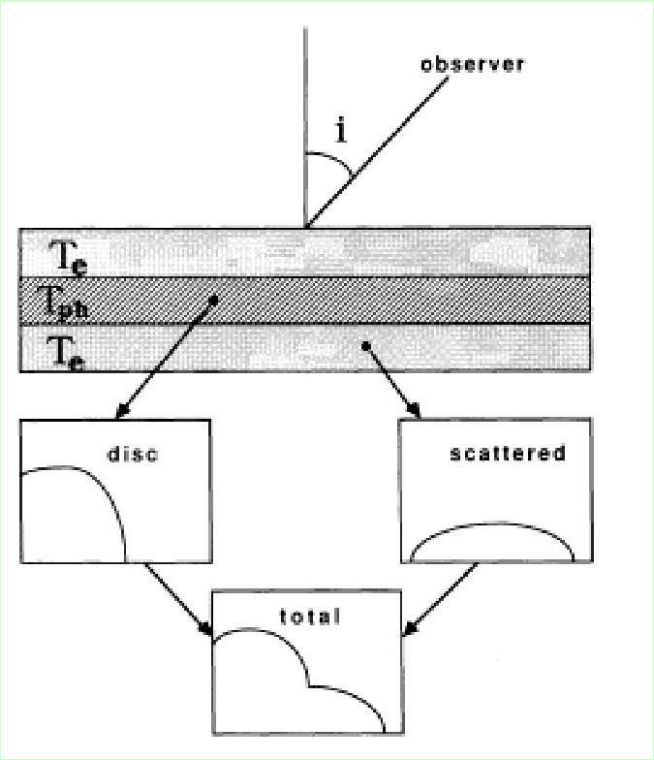
Haardt (1997)

Much work still to do!

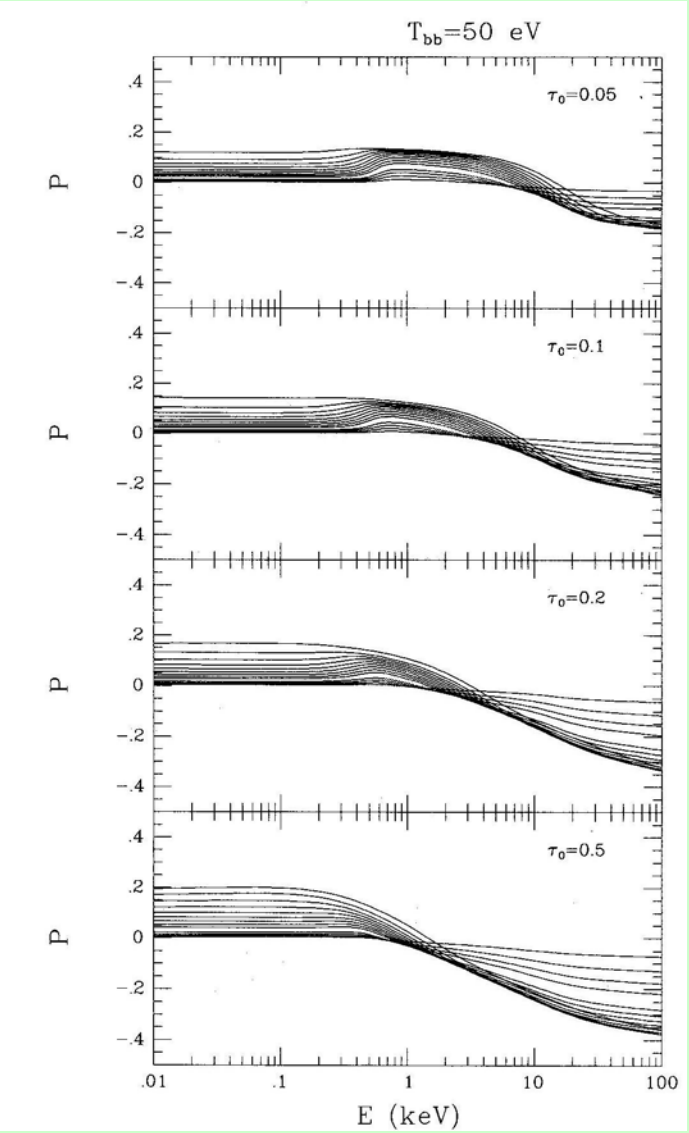
NB: in ADAF models, no significant polarization is expected (LLAGN should be unpolarized)

Primary emission from the hot corona

Example: a two-phase slab ***(Haardt & Matt 1993, Poutanen & Vilhu 1993, see also Sunyaev & Titarchuk 1985)*****.**



Poutanen & Vilhu (1993)

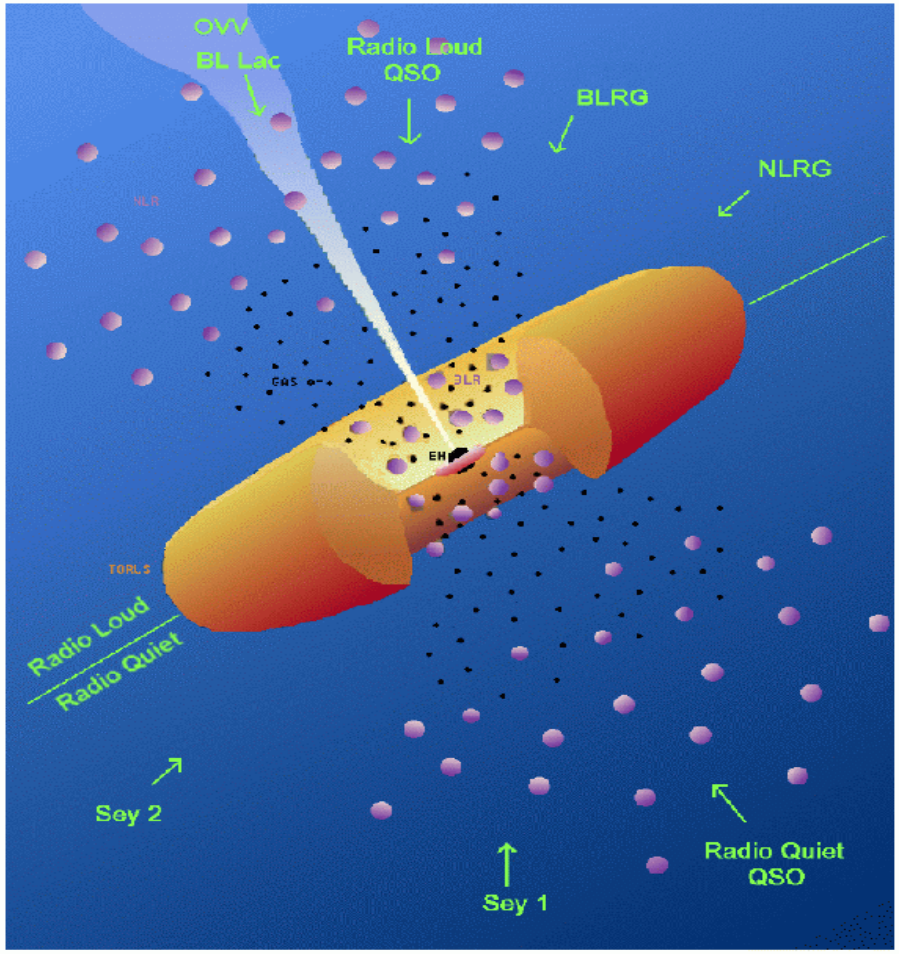


Haardt & Matt (1993)

Reflection from opt. thin matter

Obscured Seyfert galaxies

Soft X-ray emission in X-ray obscured AGN can be due to either reflection from warm matter or Starburst emission. Polarization measurements may provide the answer

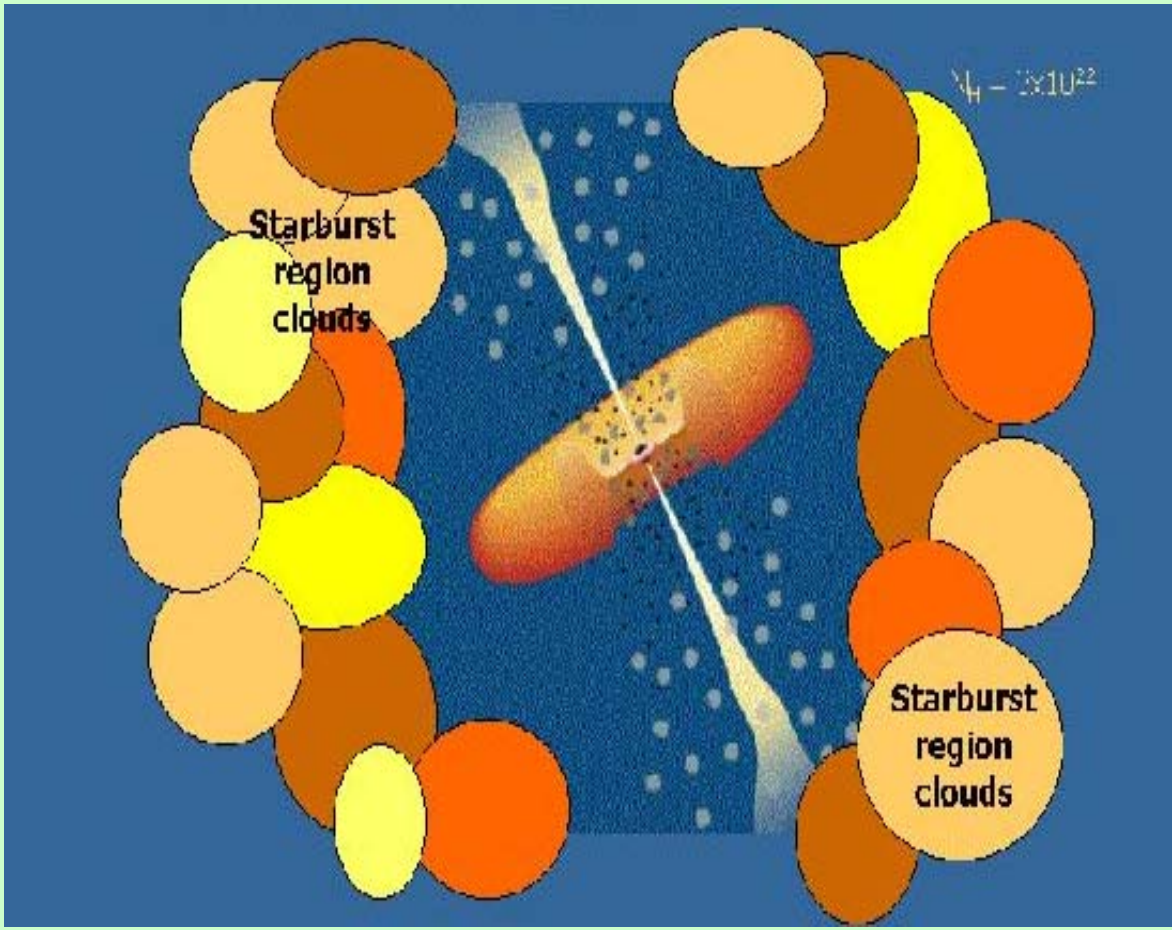


Urry & Padovani (1995)

Reflection from opt. thin matter

Obscured Seyfert galaxies

Soft X-ray emission in X-ray obscured AGN can be due to either reflection from warm matter or Starburst emission. Polarization measurements may provide the answer



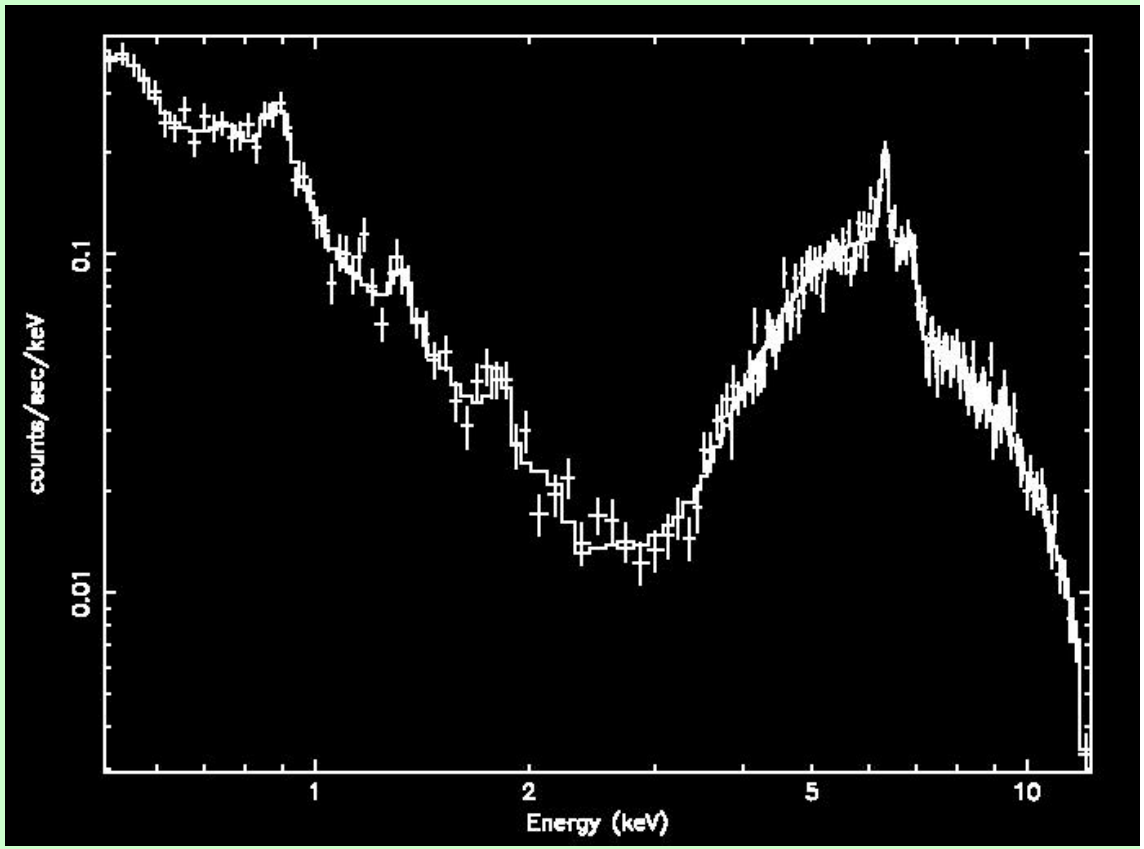
Weaver (2002)

Reflection from opt. thin matter

Obscured Seyfert galaxies

NGC 4507

Soft X-ray emission in X-ray obscured AGN can be due to either reflection from warm matter or Starburst emission. Polarization measurements may provide the answer

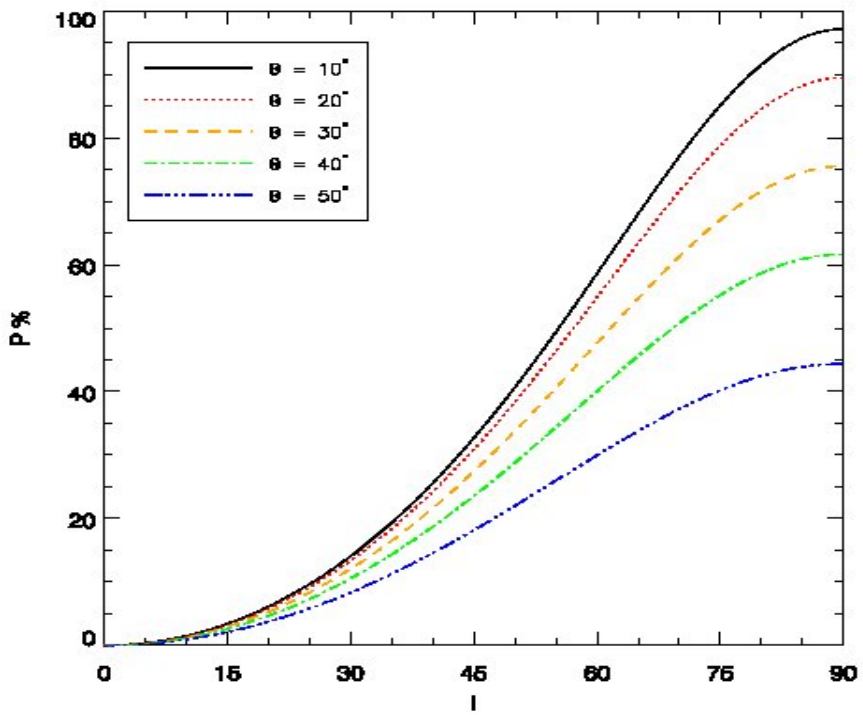


Matt et al. (2004)

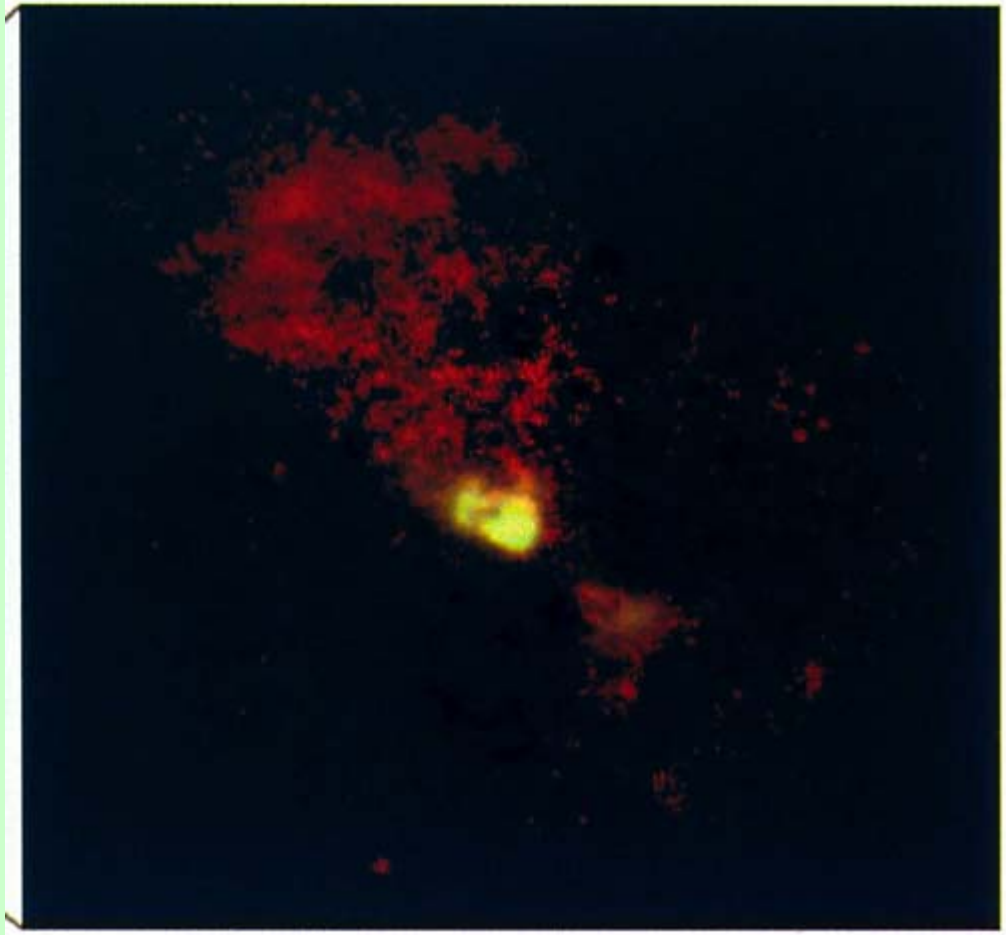
Reflection from opt. thin matter

Reflecting regions are clearly observed in the optical (polarized broad lines, ionization cones). They will reflect soft X-rays too.

Tamborra et al. in prep



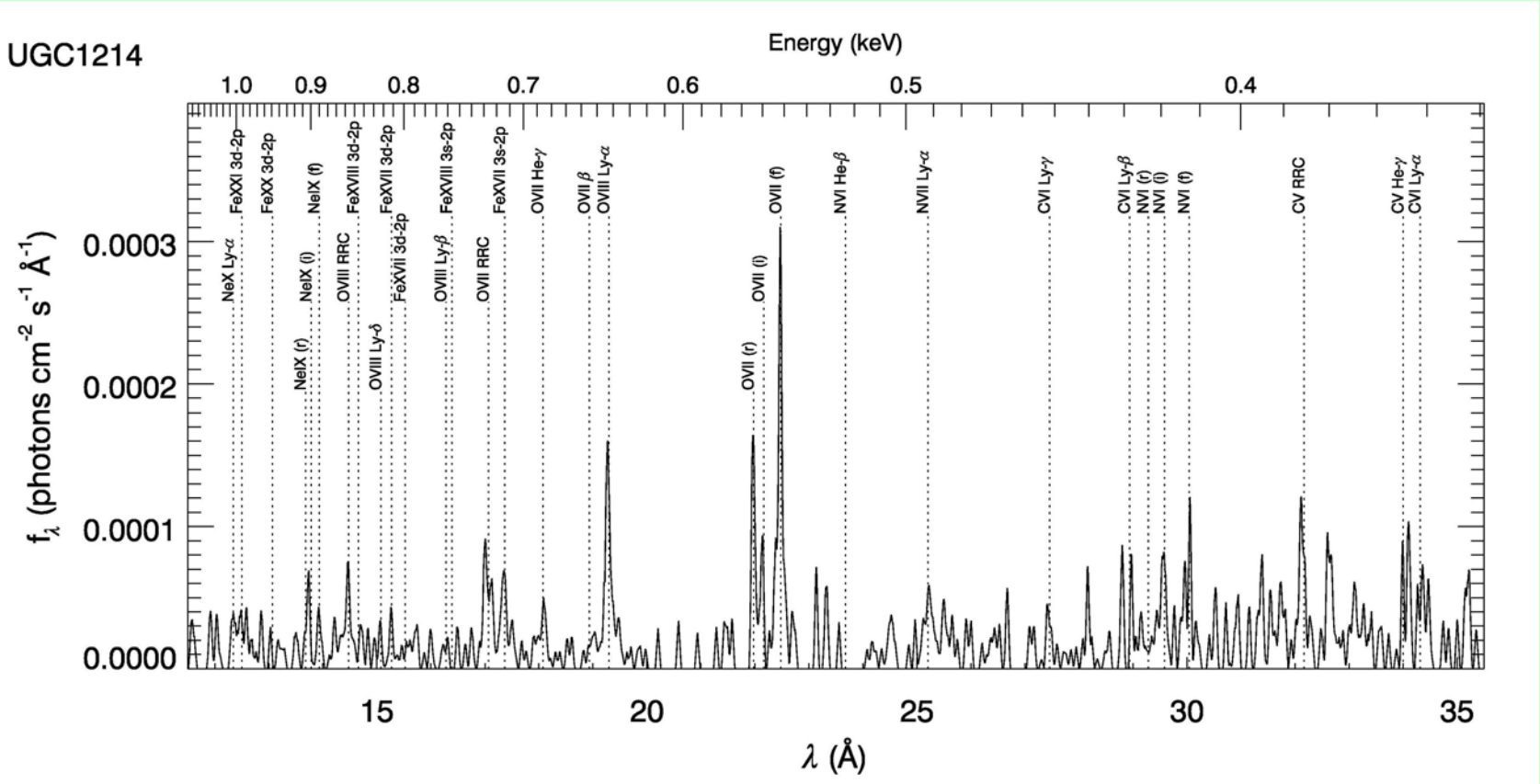
NGC 5738 - HST



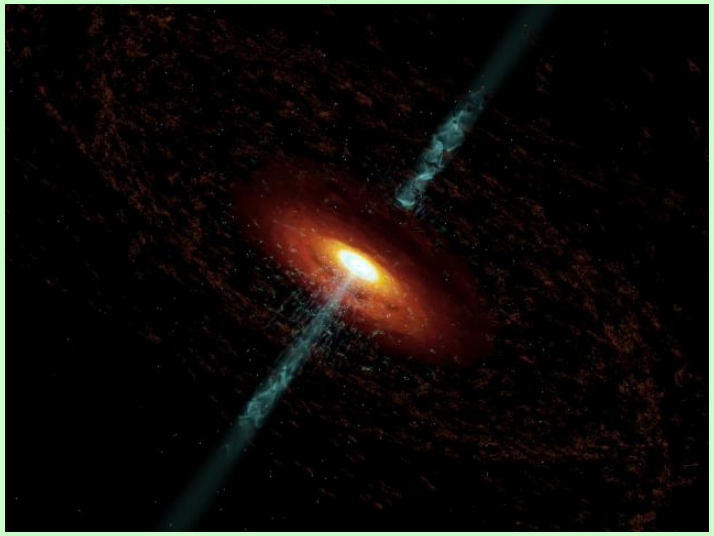
Polarization degrees may be very high !!

Reflection from opt. thin matter

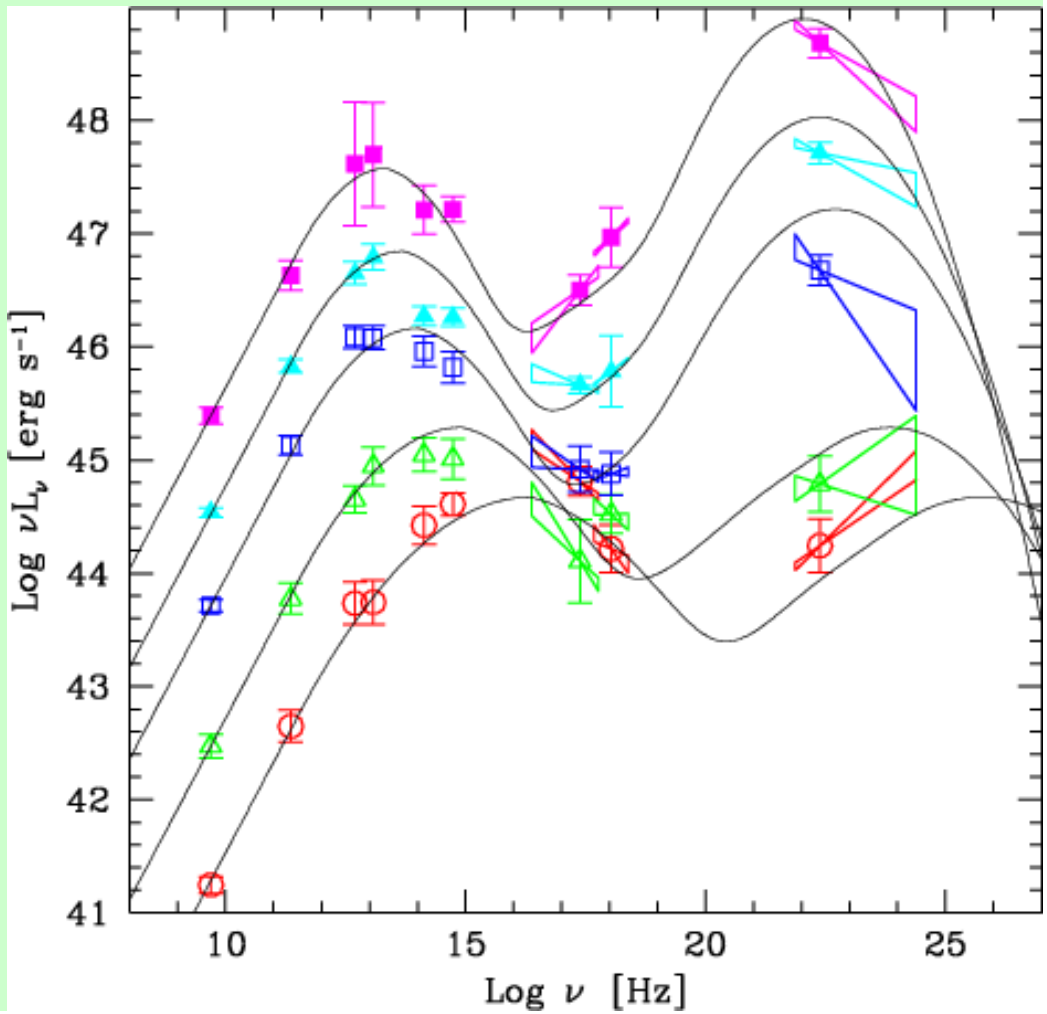
A large fraction of the flux is, however, in lines (Guainazzi & Bianchi 2007), which are usually unpolarized. The continuum accounts for 30-60% of the total flux (e.g. Matt et al. 2009, Marinucci et al., in prep)



The emission mechanism of Blazars



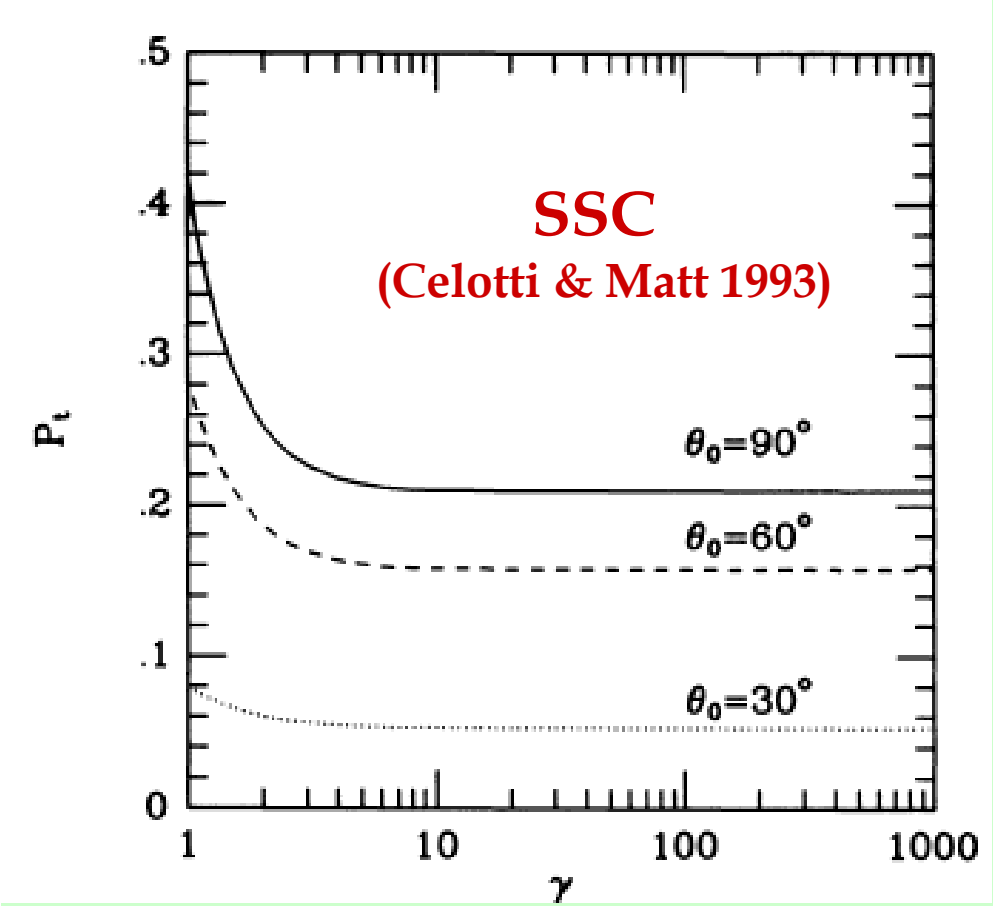
Donato et al. (2001)



X-ray emission in Blazars is due to either synchrotron or Inverse Compton radiation.

In both cases it is expected to be highly polarized.

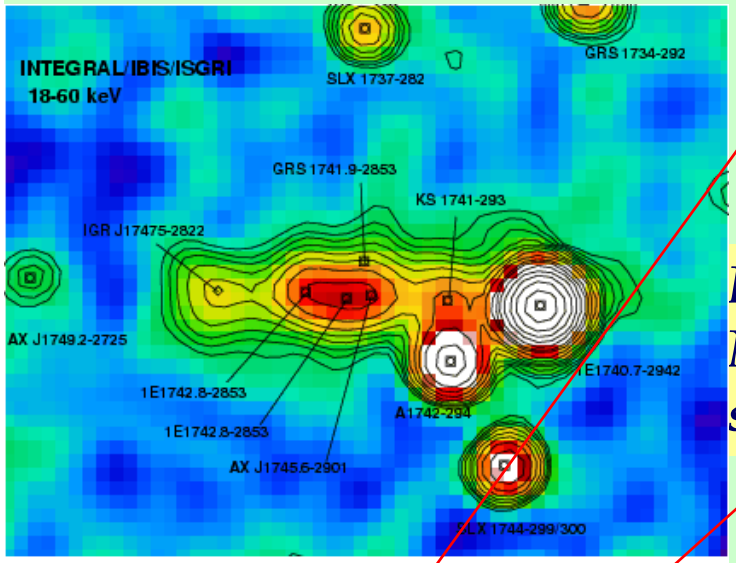
The emission mechanism of Blazars

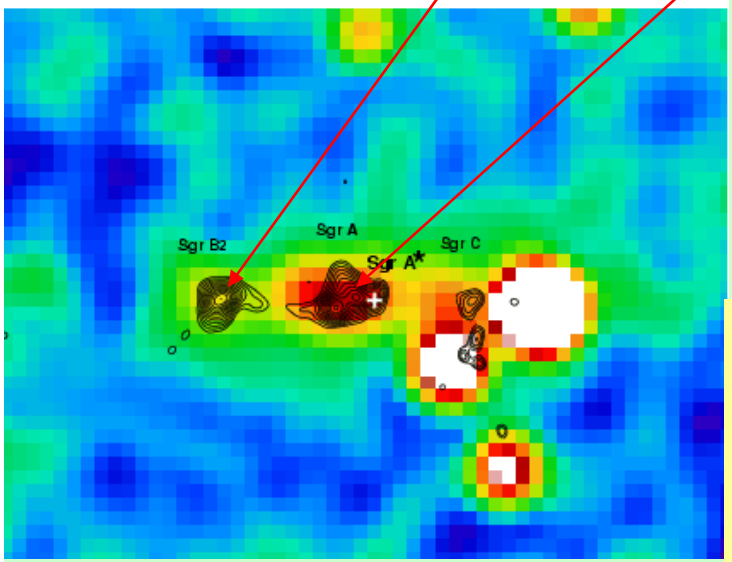


If due to IC, the radiation field may be either the synchrotron emission (SSC) or the thermal emission from the accretion disc (external IC).

The polarization properties are different in the two cases: e.g. while in the SSC the pol. angle of IC and S are the same, in the external IC the two are no longer directly related.

The strange case of Sgr B2



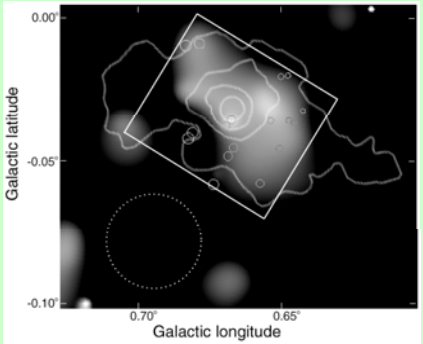


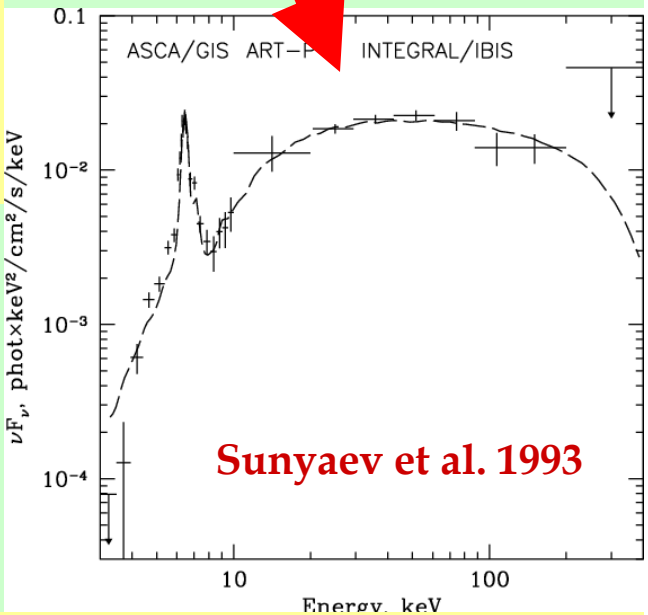
INTEGRAL Image of GC (Revnivtsev 2004)

SgrB2 is a giant molecular cloud at ~100pc projected distance from the Black Hole

The spectrum of SgrB2 is a pure reflection spectrum

Reflection of what? No bright enough source is there !!!





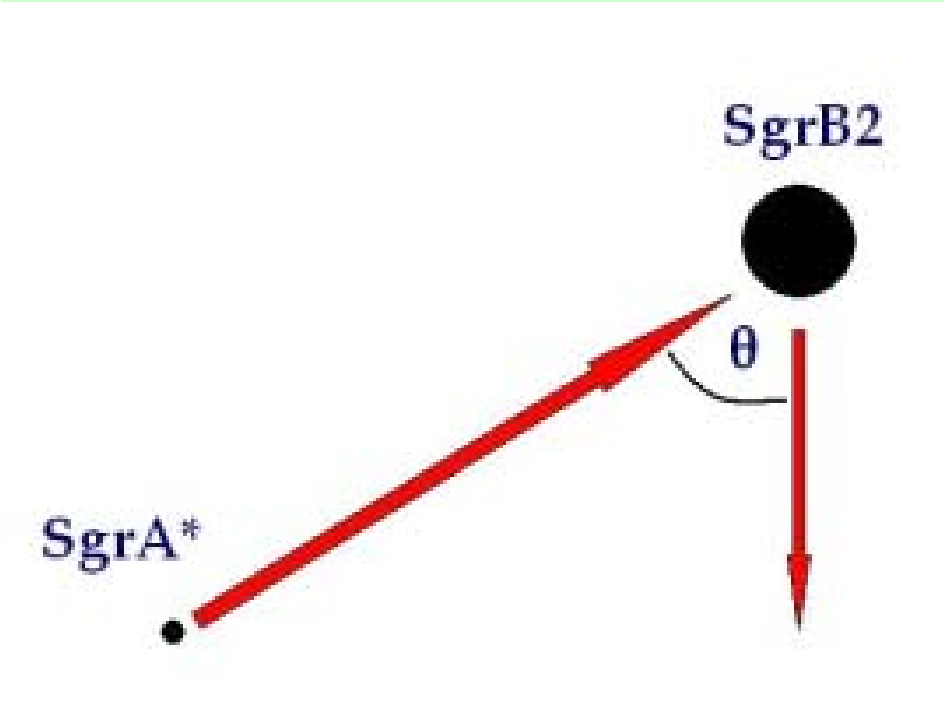
The emission from SgrB2 is extended and brighter in the direction of the BH (Murakami 2001).

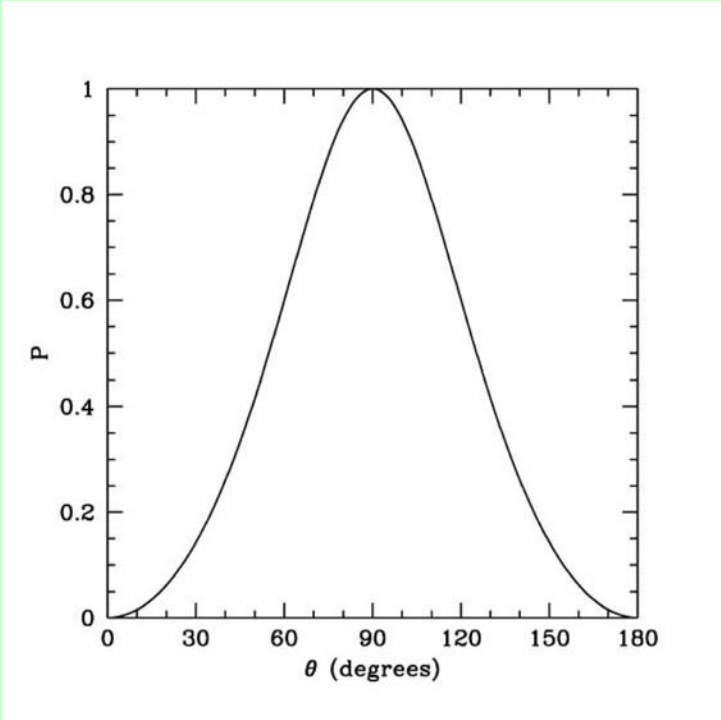
Is SgrB2 echoing past emission from the BH, which was then active in the past (e.g. Koyama et al. 1996) ???

Was the GC an AGN a few hundreds years ago?

X-ray polarimetry can definitively proof or reject this hypothesis.

SgrB2 should be highly polarized with the electric vector perpendicular to the line connecting the two sources.

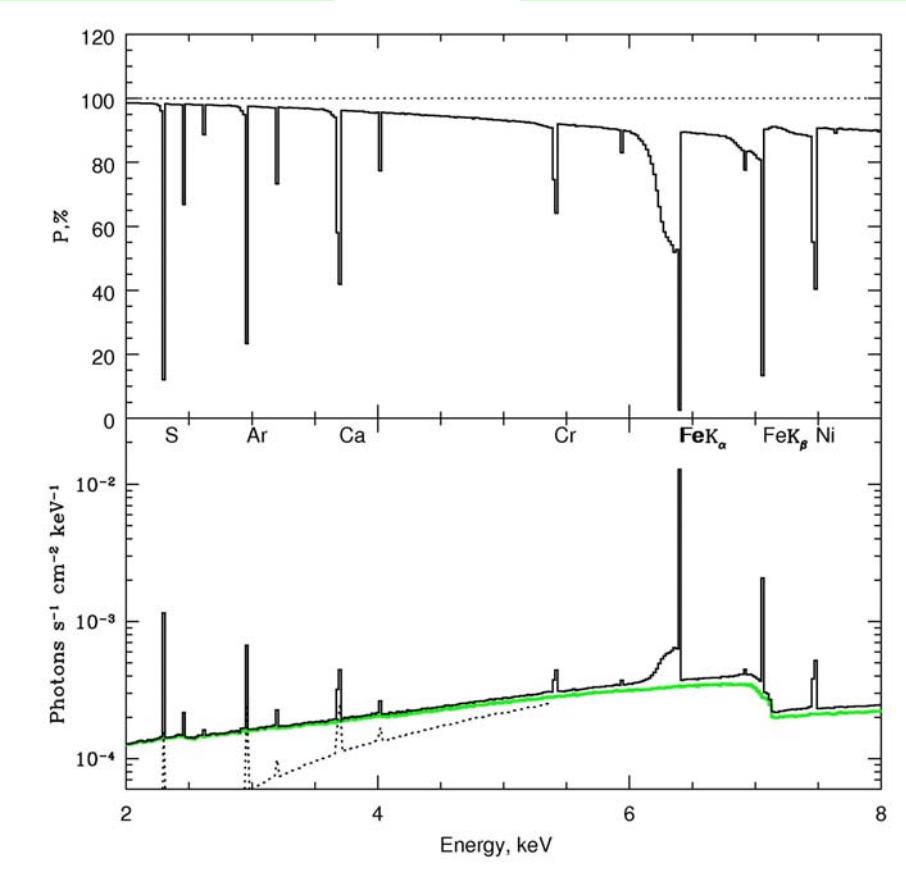




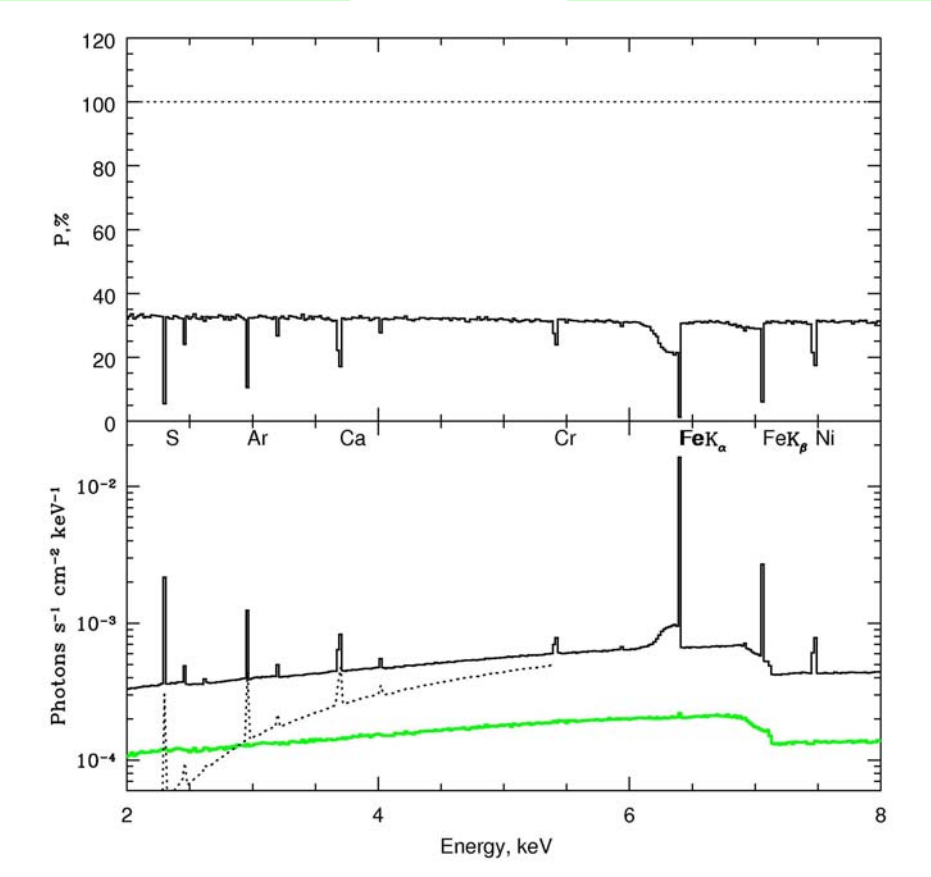
The degree of polarization would measure the angle and provide a full 3-d representation of the clouds (Churazov et al. 2002)

Was the GC an AGN a few hundreds years ago?

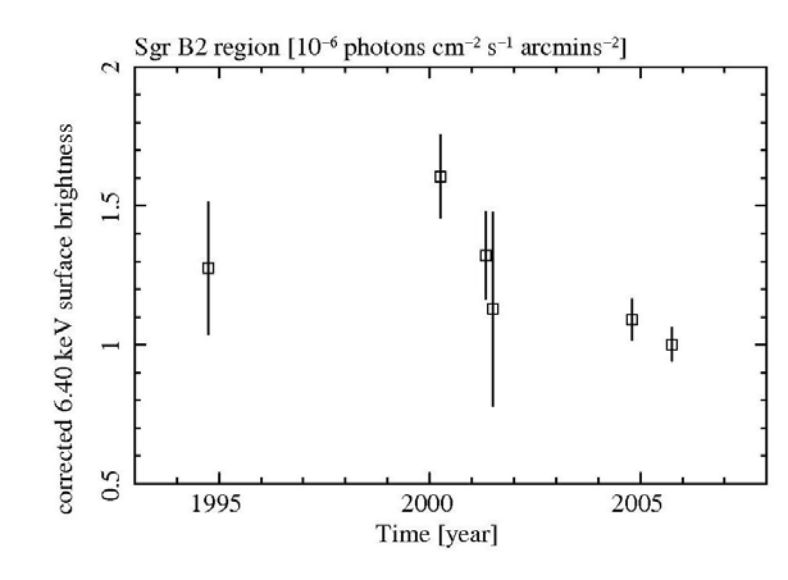
$\theta=90^0$



$\theta=135^0$



The degree of polarization would measure the angle and provide a full 3-d representation of the clouds (Churazov et al. 2002)



Unfortunately, the flux of SgrB2 is decreasing with time ***(Inui et al. 2009)***

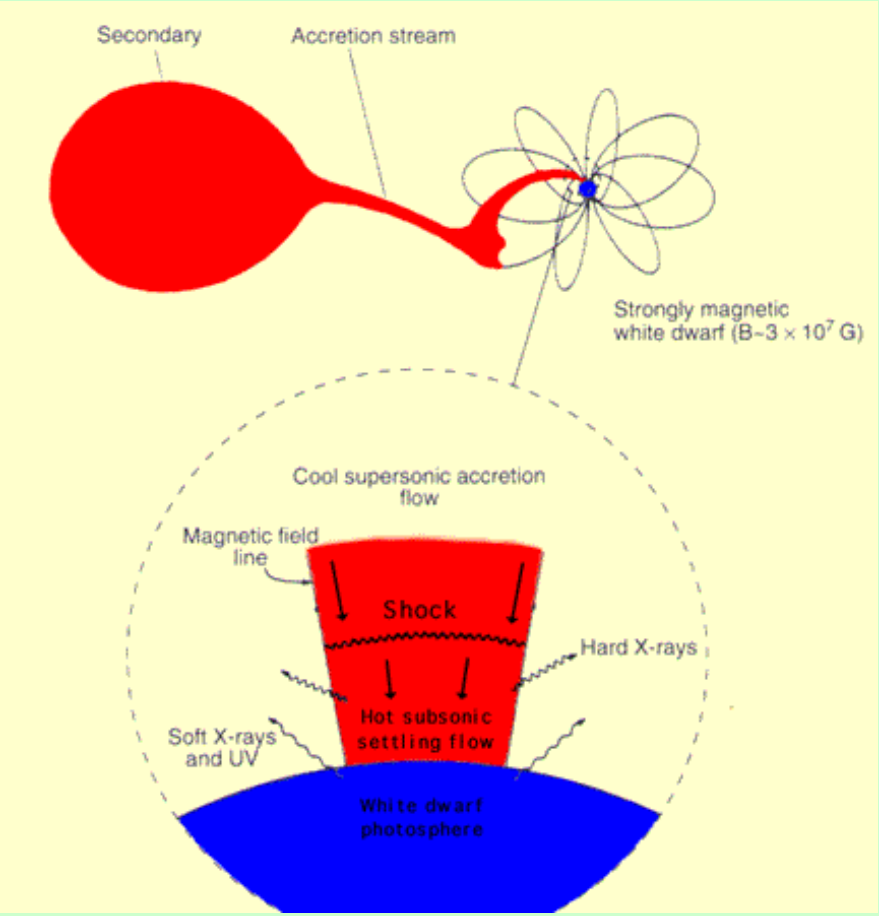
From Chandra web site

But there are many other time-varying molecular clouds, so we can hope that at the time of the first polarimetry mission (soon, hopefully!) there will be at least one bright enough to test the AGN scenario for the GC.

Strong magnetic fields: Polars

Accretion in Magnetic CVs (Polars) occurs via an accretion column; X-rays are produced by opt. thin thermal plasma emission in the post-shock region.

Half of the hard X-rays illuminate the WD surface → Compton reflection

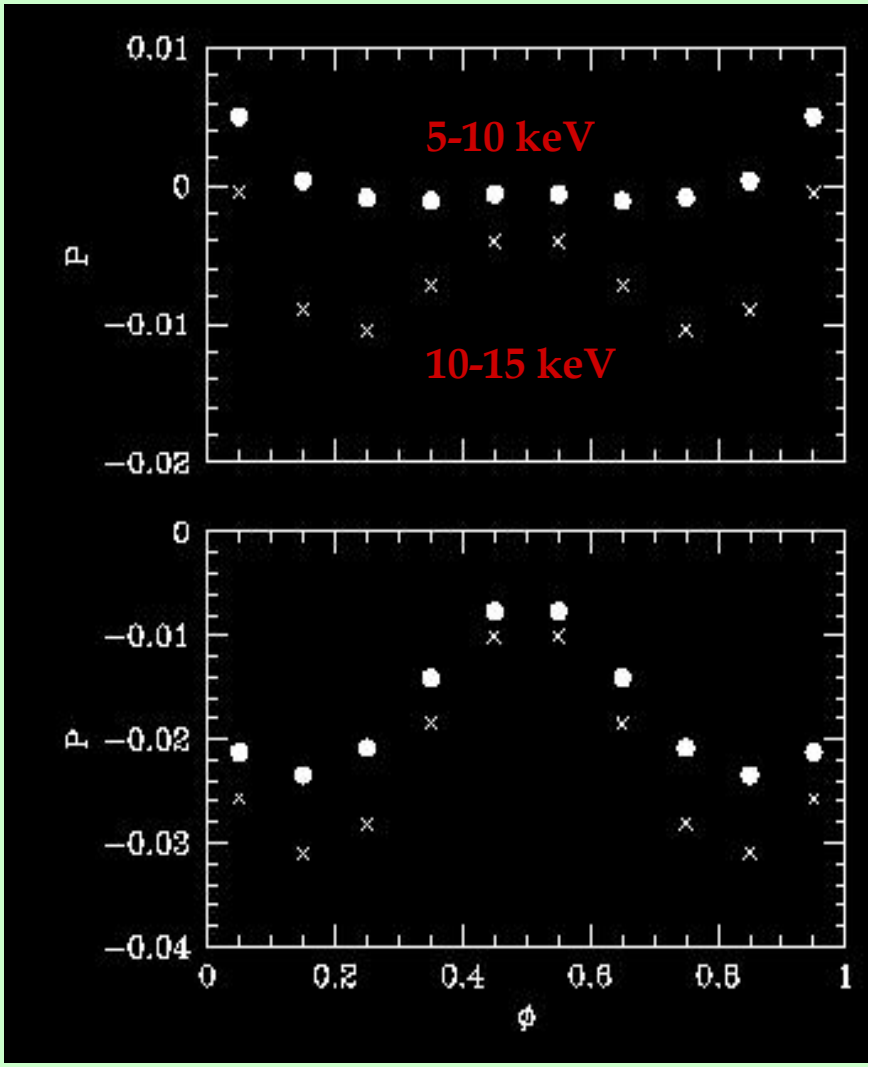


Example: AM Herculis

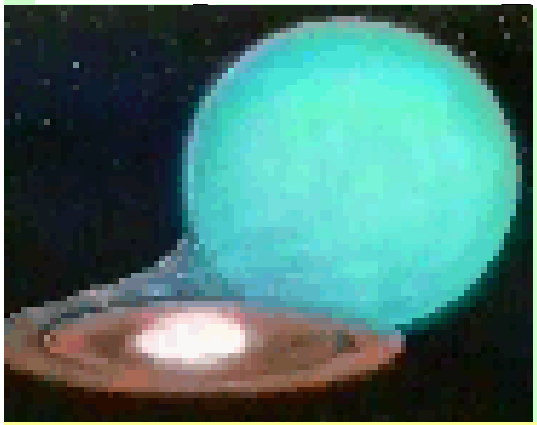
The emission from the accretion column itself may be polarized. In fact, the Thomson depth may be not negligible (τ_{Th}=0.1-1), and a fraction of photons may be scattered (and polarized) before leaving the column.

The degree of polarization of course increases with τ_{Th} (Matt 2004; see also McNamara et al. 2008), which in turn depends on the accretion rate.

Using the geometrical parameters of AM Herculis (Cropper 1988), the expected degree of polarization as a function of the orbital phase can be calculated..
Polarization measurements will yield the parameters of the column, providing a check of accretion models.



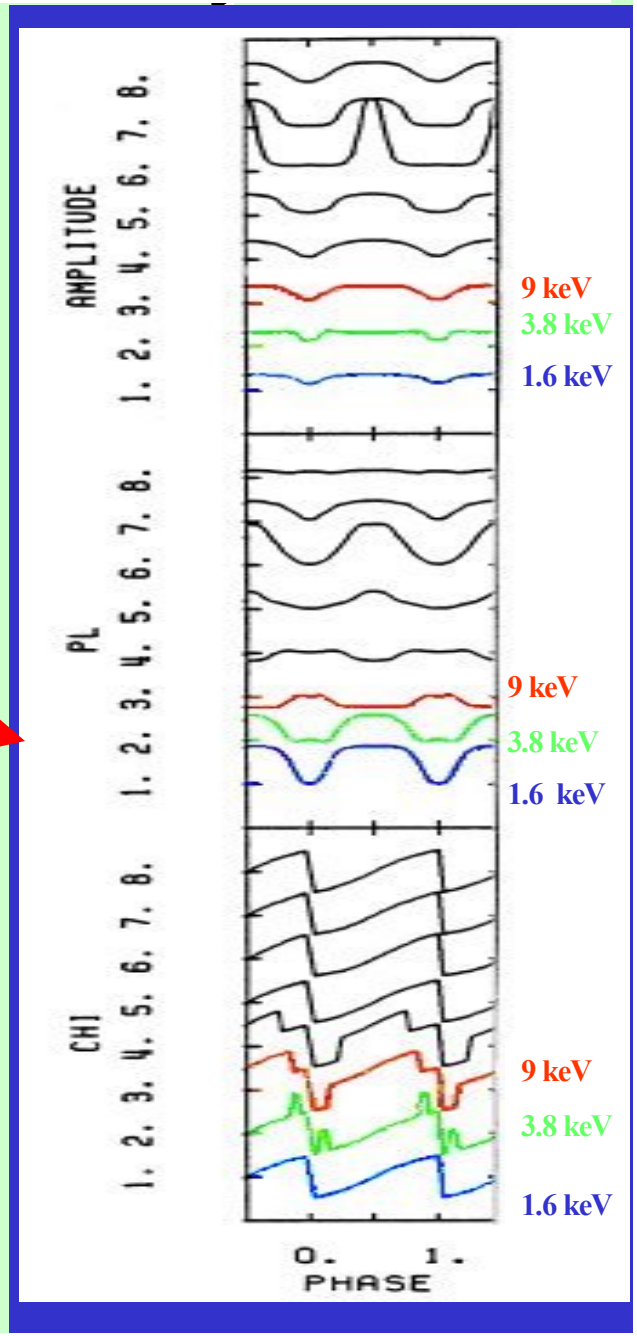
Very strong Magnetic Fields: X-ray Pulsars

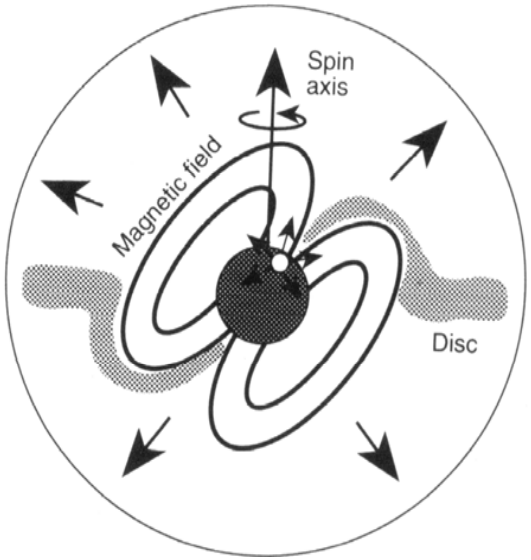


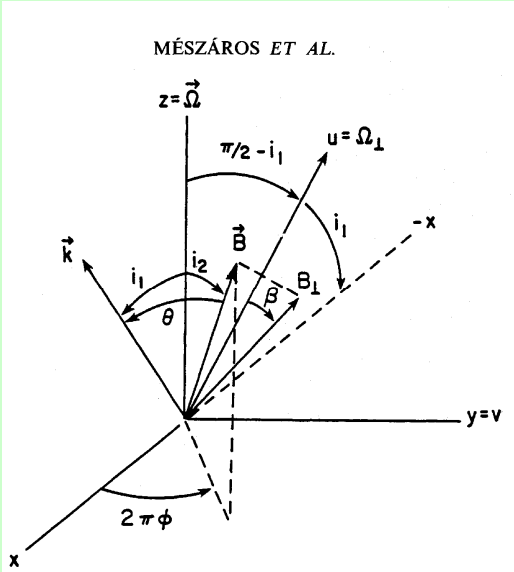
Polarized by:

- Emission process: cyclotron
- Scattering on highly magnetized plasma: $\sigma_{\parallel} \neq \sigma_{\perp}$

Polarization is modulated and the swing of the polarization angle with phase directly measures the orientation of the rotation axis on the sky and the inclination of the magnetic field: in the figure the 45° case is illustrated (from Meszaros et al. 1988)







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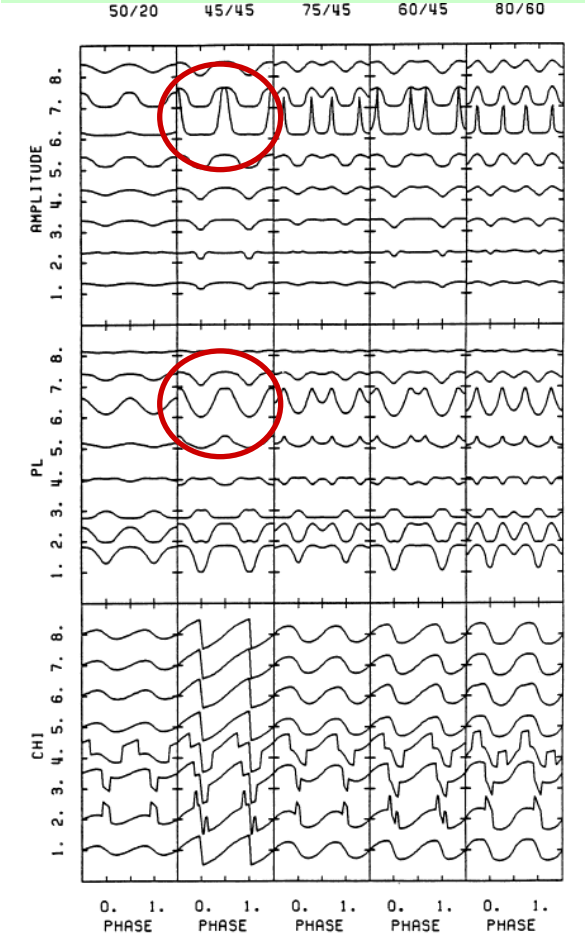
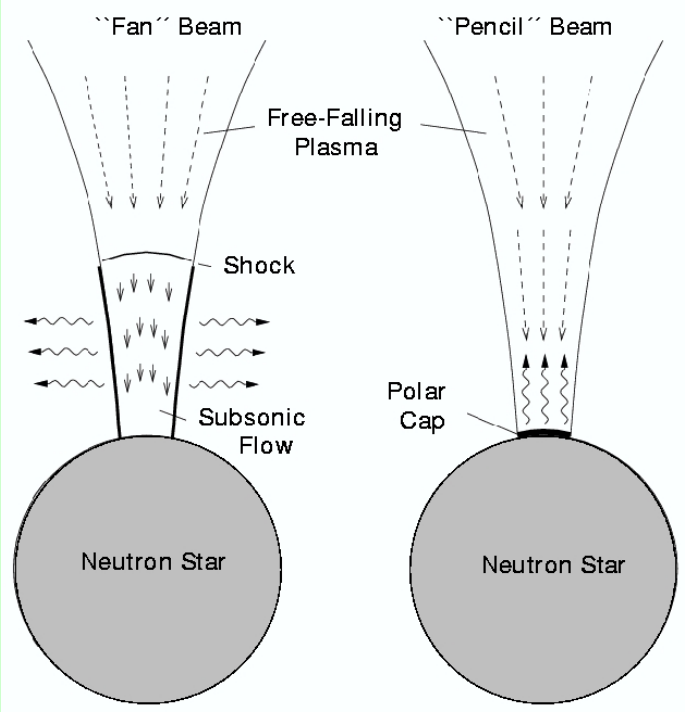
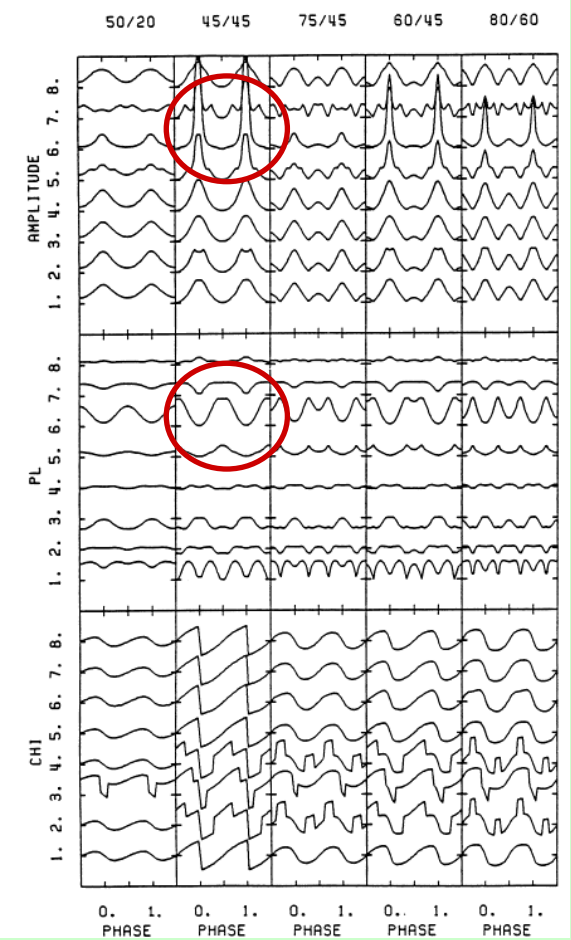
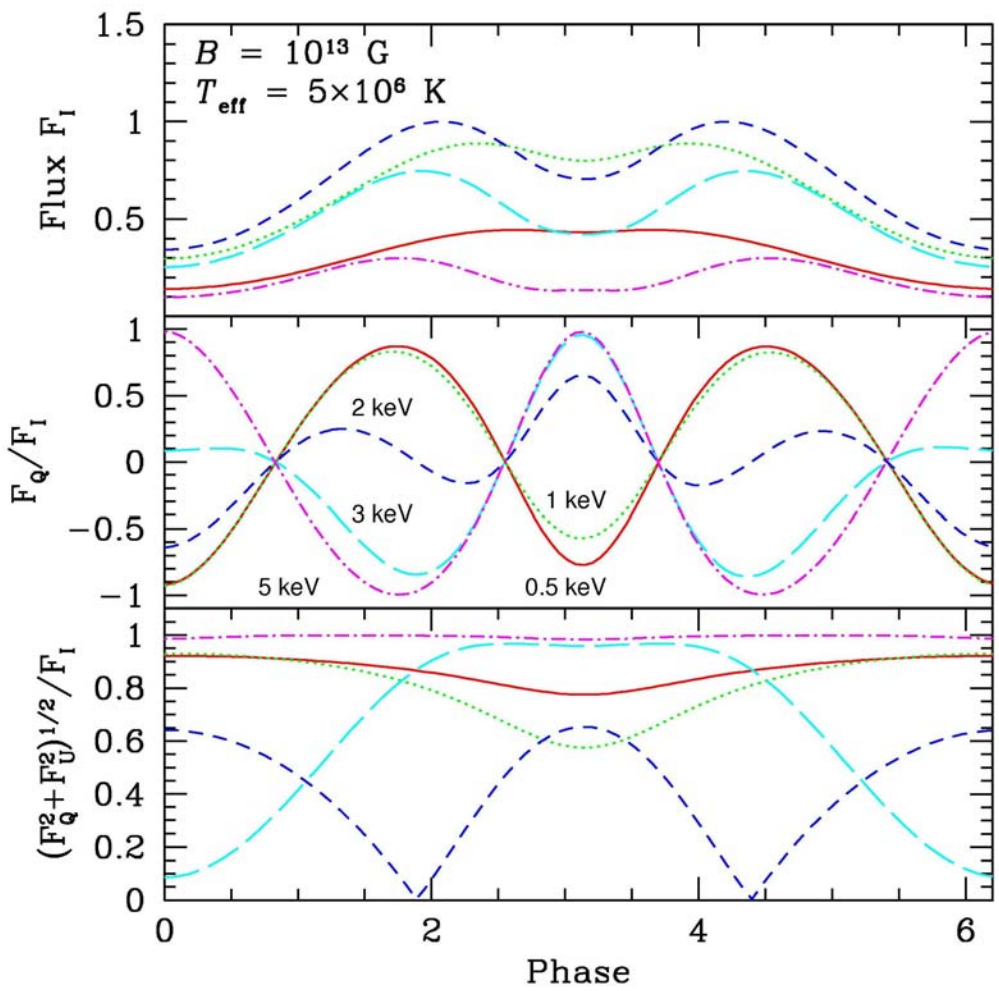






Meszaros et al. 1988

Extreme Magnetic Fields: magnetars

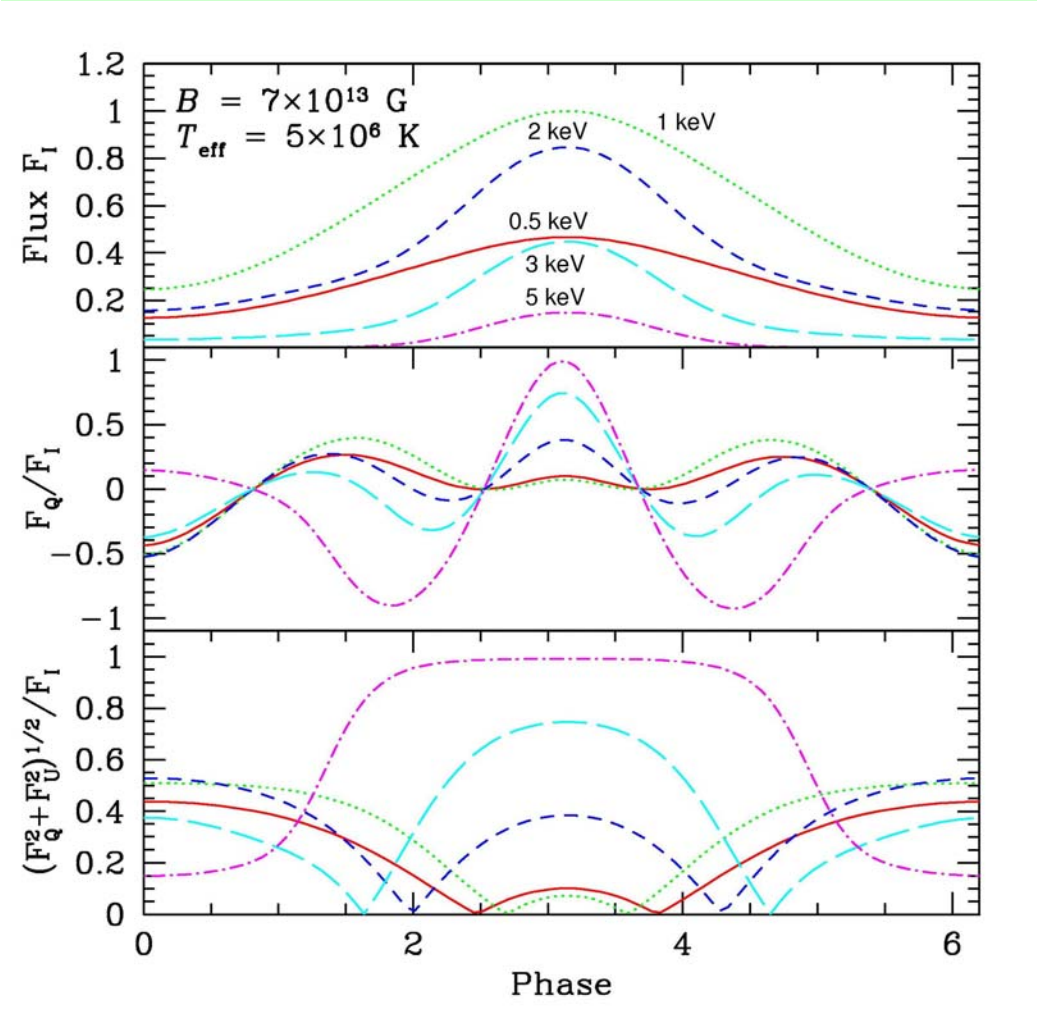


van Adelsberg & Lai 2006

Soft Gamma Repeaters and Anomalous X-ray Pulsars are interpreted in the frame of the Magnetar theory (Thompson & Duncan 1993): neutron stars with extreme magnetic fields.

For $B \geq 7\times10^{13}$ G strong-field QED (vacuum polarization) becomes important, significantly changing the dependence on the phase *and the energy* of the polarization, providing a measurement of B, a test of the magnetar paradigm and a probe of strong-field QED

Extreme Magnetic Fields: magnetars



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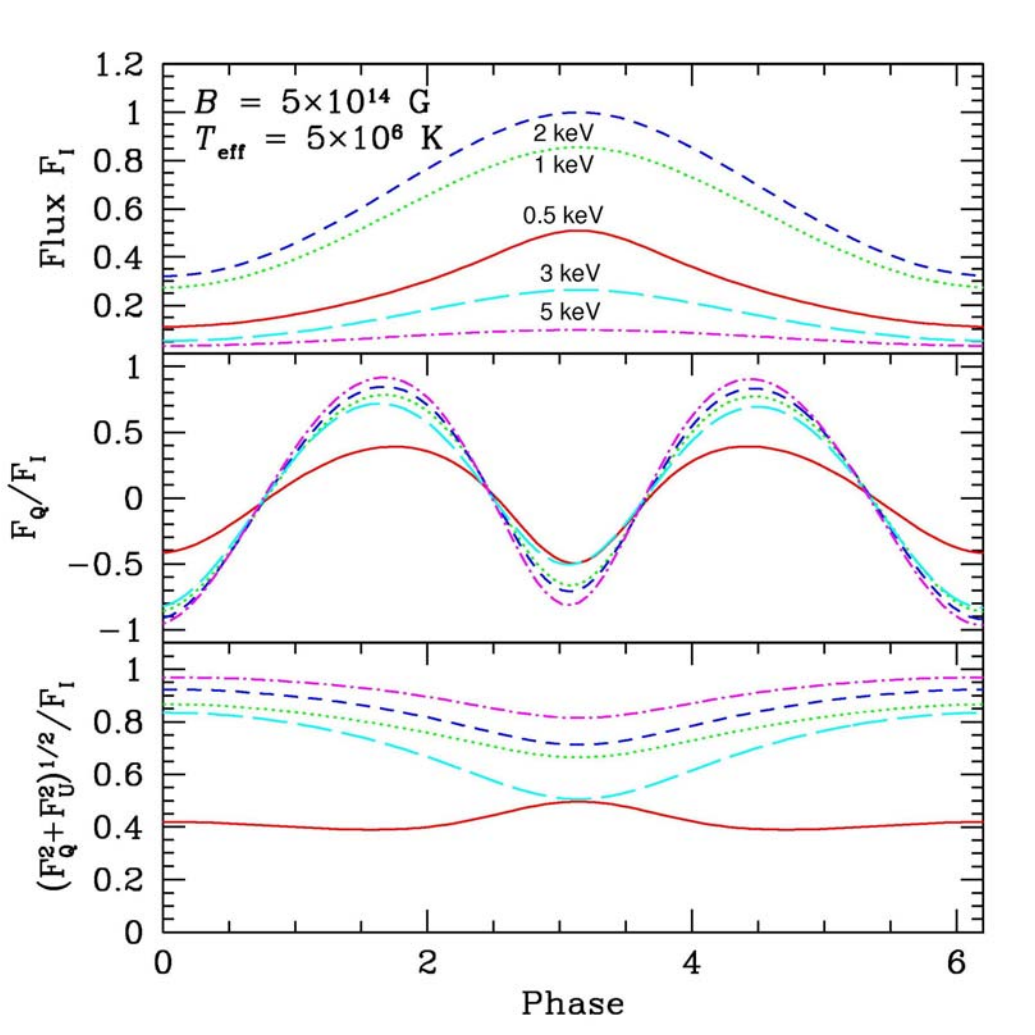

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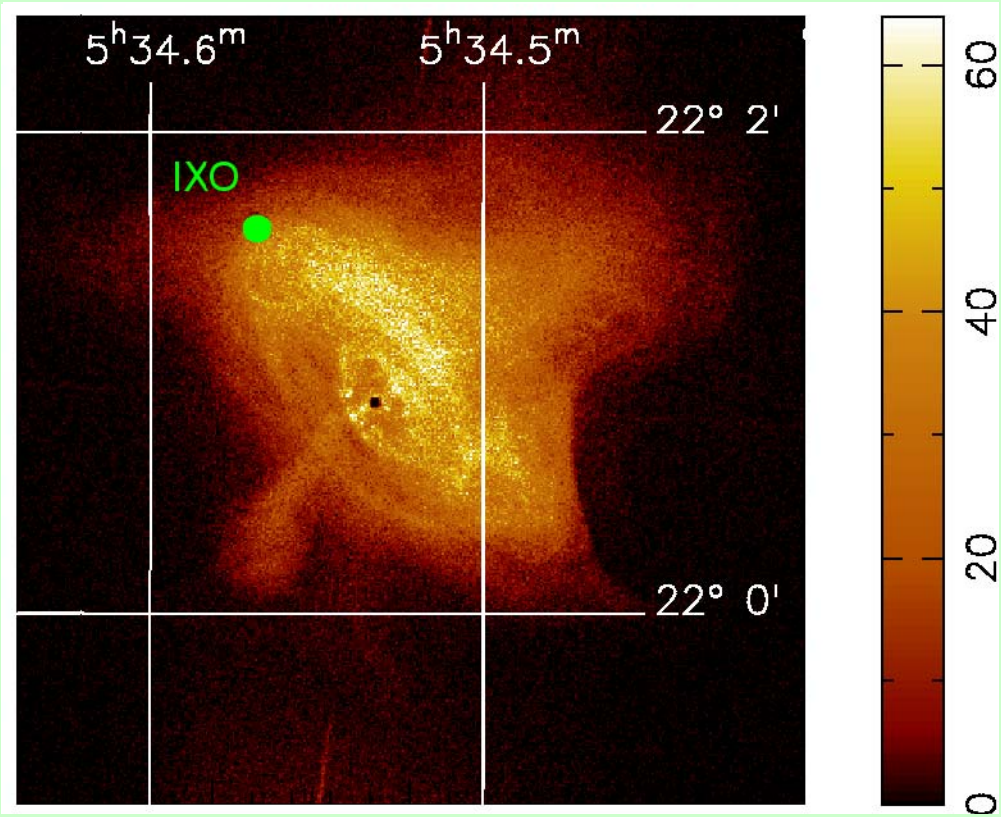
PWN: the Crab



From Weisskopf et al. (2000)

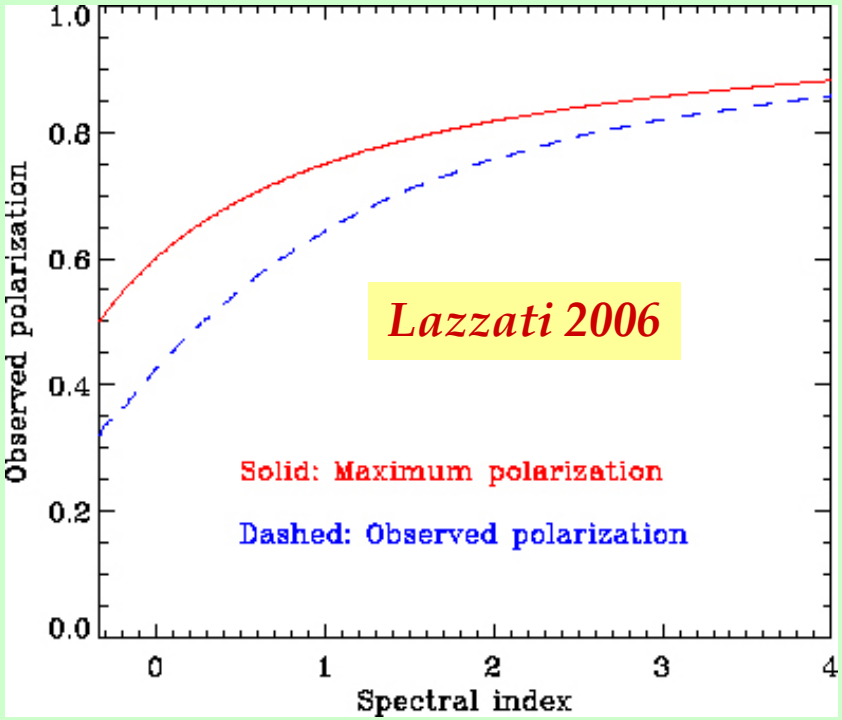
The Crab Nebula is the only source in which the polarization degree has been measured so far (Weisskopf et al. 1978), P=19%.

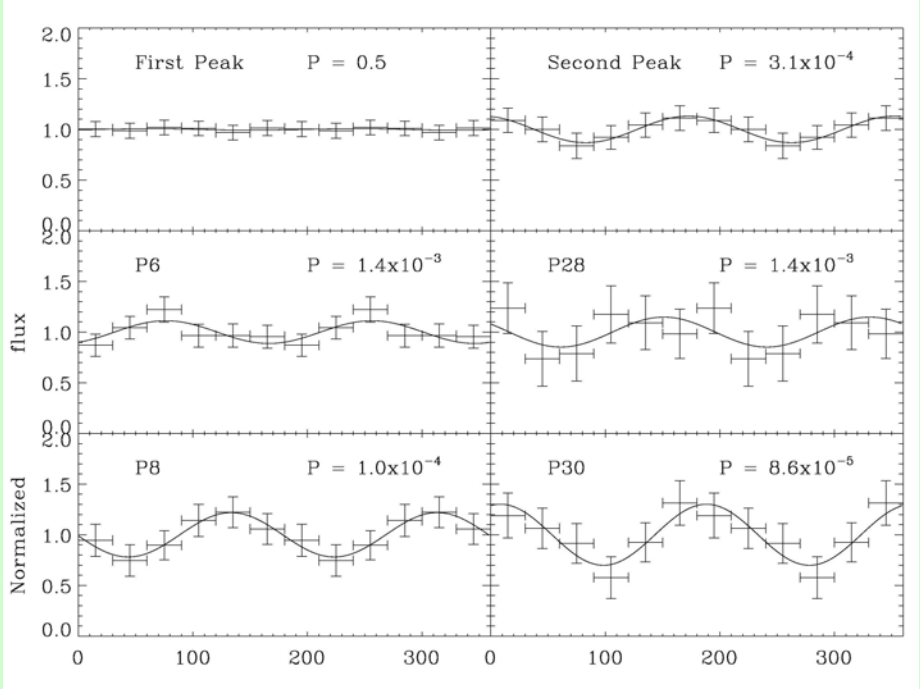
The nebula is highly structured, as shown by Chandra observations, with a jet and a torus.

Imaging polarimetry would be extremely important to map the magnetic field, and to understand the acceleration and emission mechanisms in the Nebula.

Gamma-ray Bursts

Prompt emission: Polarimetry may tell about the emission mechanism (Synchrotron vs IC) and the magnetic field (ordered vs. tangled).



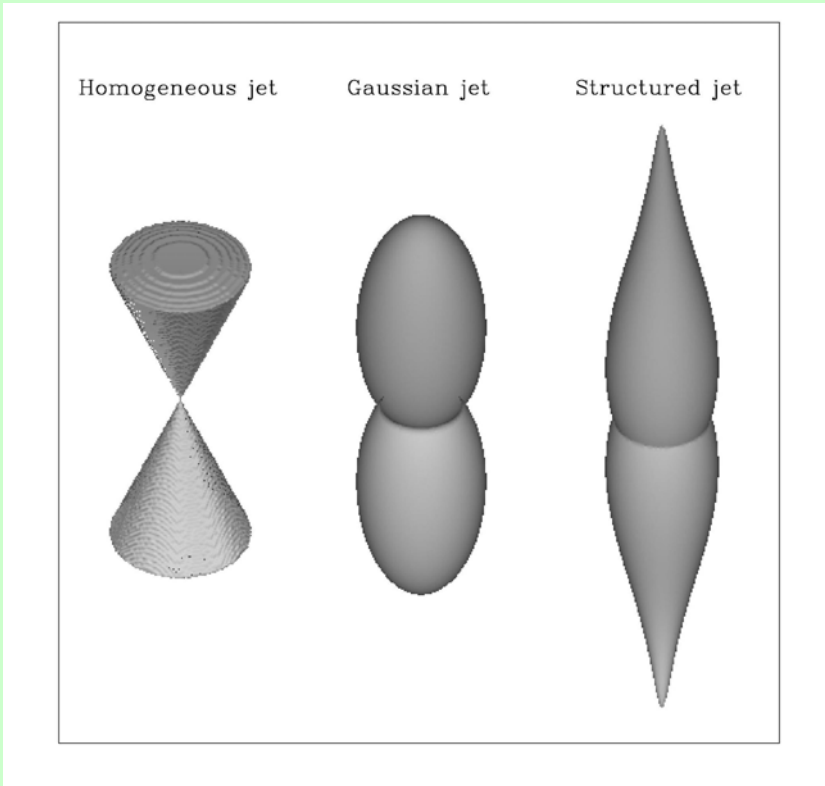


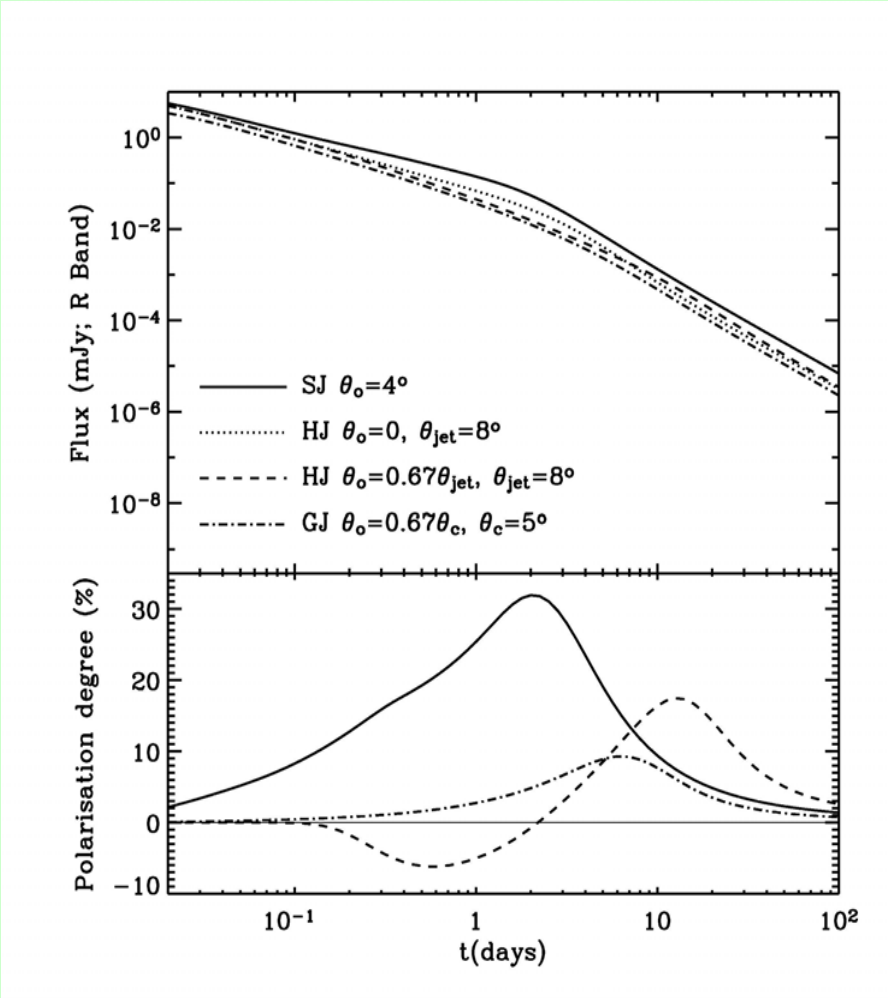
Gotz et al. 2009

INTEGRAL measured a variable polarization in the prompt emission of GRB 041219A, P varying from < 4% up to > 54% (Gotz et al. 2009, McGlynn et al. 2007)

Gamma-ray Bursts

Afterglow: Polarimetry may tell about the structure of the jet





Rossi et al. 2004

Testing Quantum Gravity theories with X-ray polarimetry

Quantum Gravity should be effective on the Planck Energy scale ($E_P=10^{19}$ GeV). But the hypothized existence of space-time foam can produce detectable effects on radiation propagating on very long distance scales.

One of the major approach to quantization of Gravity is the Loop QG that predicts birefringence effects related to Lorentz Invariance Violation,

The result is a difference of light velocity for the two states of circular polarization:

$$V_+ = c\,[1+\eta(E/E_P)^n] \qquad V_- = c\,[1-\eta(E/E_P)^n]$$

→ The plane of linear polarization is subject to a rotation along the path

Testing Quantum Gravity theories with X-ray polarimetry

The rotation of the polarization angle is given by:

$$\Delta\phi(E) = \eta\,(D/hc)\,E^2/E_{QG} \approx 10^4\,\eta\,D\,(E/0.1\ \mathrm{MeV})^2$$

η is already constrained to be less than 10^{-9} (Maccione et al. 2008) by using the recent hard X-ray polarization measurement of the Crab with INTEGRAL (Dean et al. 2008).

Extensive use of distant Blazars with future X-ray polarimeters will further enhance the precision of this measurement.

Measurements in X-ray Astronomy

Photometry: **Timing (Geiger, Proportional Counters, MCA, SDC)**

Rockets, UHURU, Einstein, EXOSAT, ASCA, BeppoSAX, XMM, Chandra

Imaging: **Pseudo-imaging (modulation collimators), grazing incidence optics + Proportional Counters, MCA, CCD**

Rockets, SAS-3, Einstein, EXOSAT, ROSAT, ASCA, BeppoSAX, Chandra, XMM, INTEGRAL, SWIFT

Spectroscopy:

Non dispersive (Proportional Counters, Si/Ge and CCD, Superconducting Junctions, Bolometers)

Dispersive: Bragg, Gratings.

Rockets, Einstein, EXOSAT, HEAO-3, ASCA, BeppoSAX, XMM, Chandra, XMM, INTEGRAL, Suzaku

Polarimetry: **Bragg, Thomson/Compton**

Rockets, Ariel-5, OSO-8

Not many results so far for polarimetry….

In 40 years only one positive detection of X-ray Polarization: the *Crab Nebula* (Novick et al. 1972, Weisskopf et al. 1976, Weisskopf et al. 1978)

$$P = 19.2 \pm 1.0\ \%;\ \ \theta = 156.4^{o} \pm 1.4^{o}$$

Only physically irrelevant upper limits to all other sources

THE TECHNIQUES WERE THE PROBLEM!

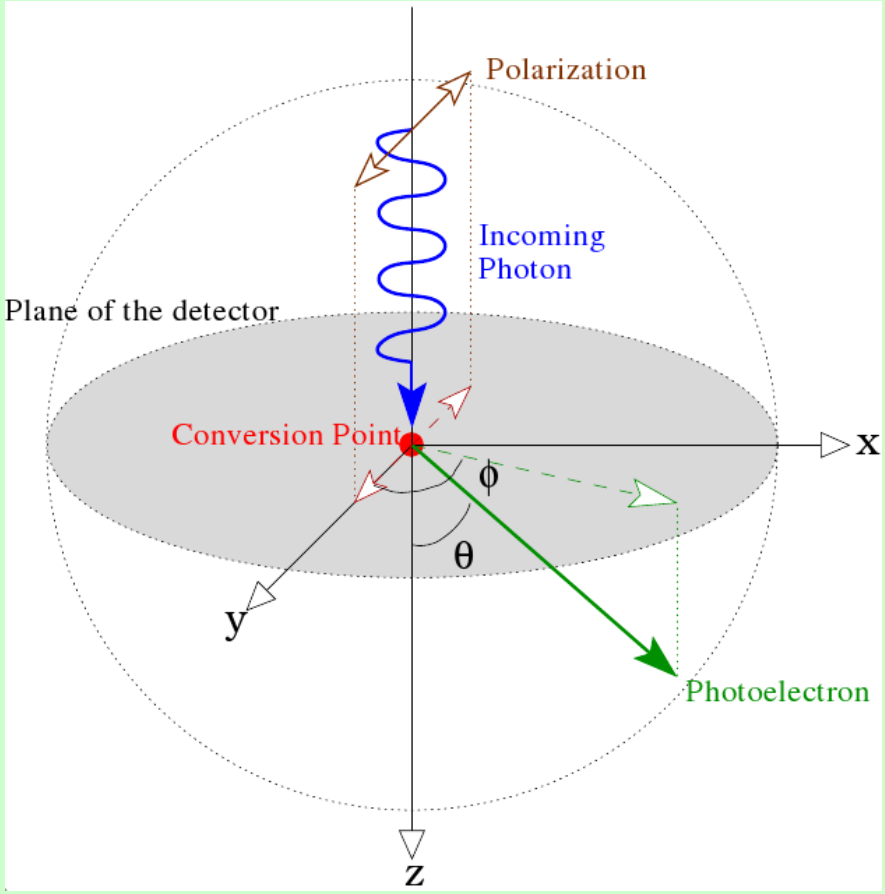
Conventional polarimeters have too low sensitivity (eg Braggs have small energy band, Thomson scattering a very low detection efficiency)

Photoelectric Polarimeters

The direction of the emission of a photoelectron carries memory of the polarization of the absorbed photon.

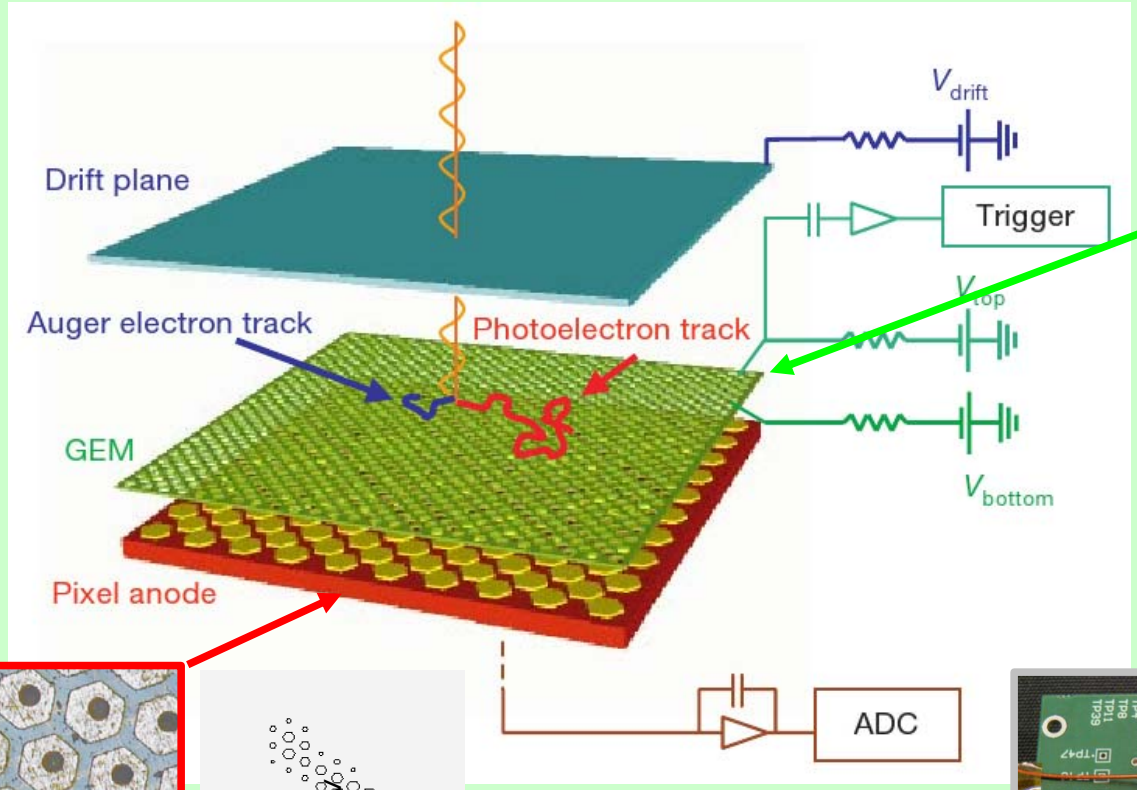
The degree and angle of polarization of a large number (>10^4) of photons can be derived from the modulation of the reconstructed direction of emission.

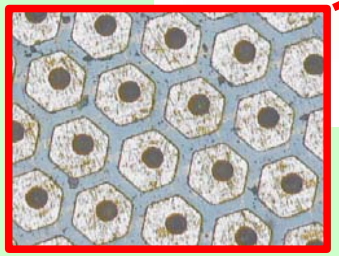
Photoelectric effect can be effective since it provides intrinsically wide-band and efficient response with respect to the classical techniques.

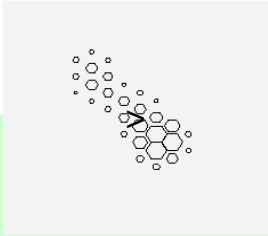


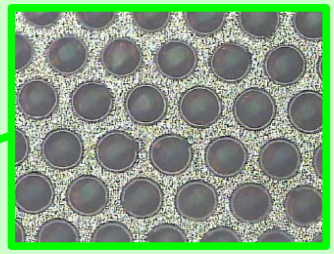
The Gas Pixel Detector

Photons are absorbed in a gas detector, where the path of the photoelectrons is traced by the charges generated by ionization.









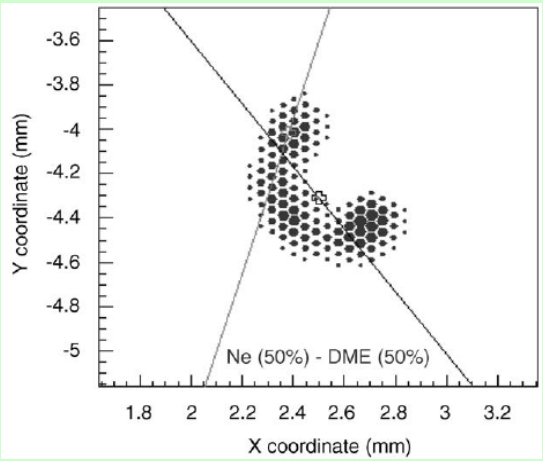
The Gas Pixel Detector

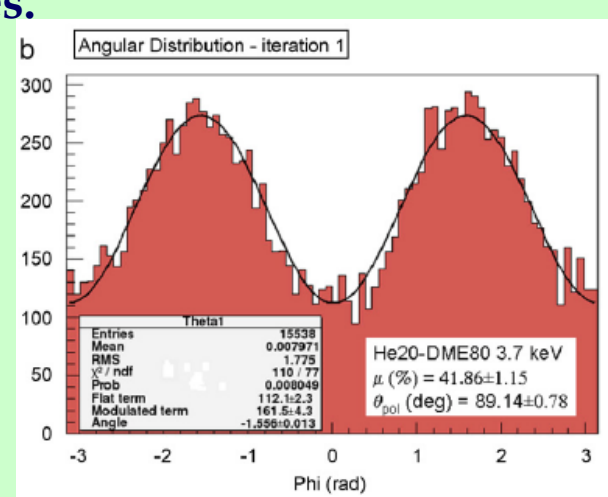
The photoelectrons lose energy by ionization and are randomly scattered by interactions with atoms nuclei.

- The first part of the track must then be spatially resolved to preserve the information on the emission direction and then on the polarization of the absorbed photon.

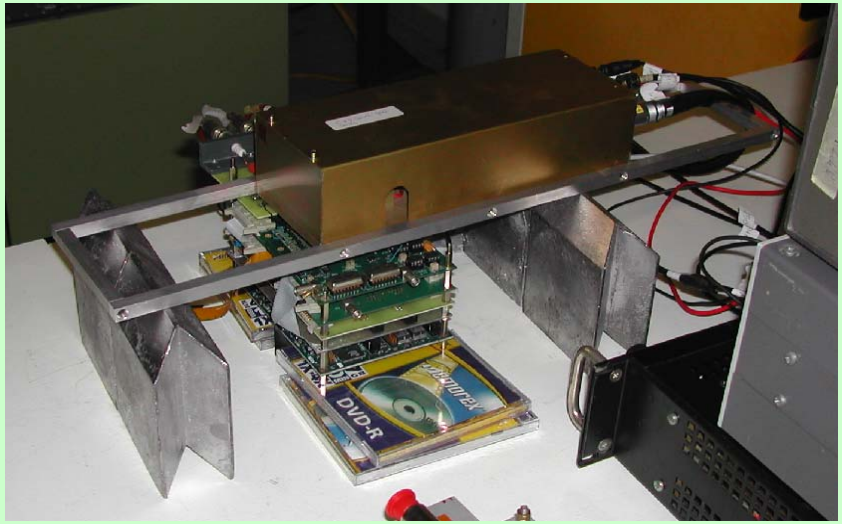
  A detector with pixel-size less than 100 μm is mandatory since the track are less than 1 mm.
- An automatic algorithm has been developed for the identification of
  - the first part of the track;
  - the emission angle;
  - the point where the photon was absorbed.

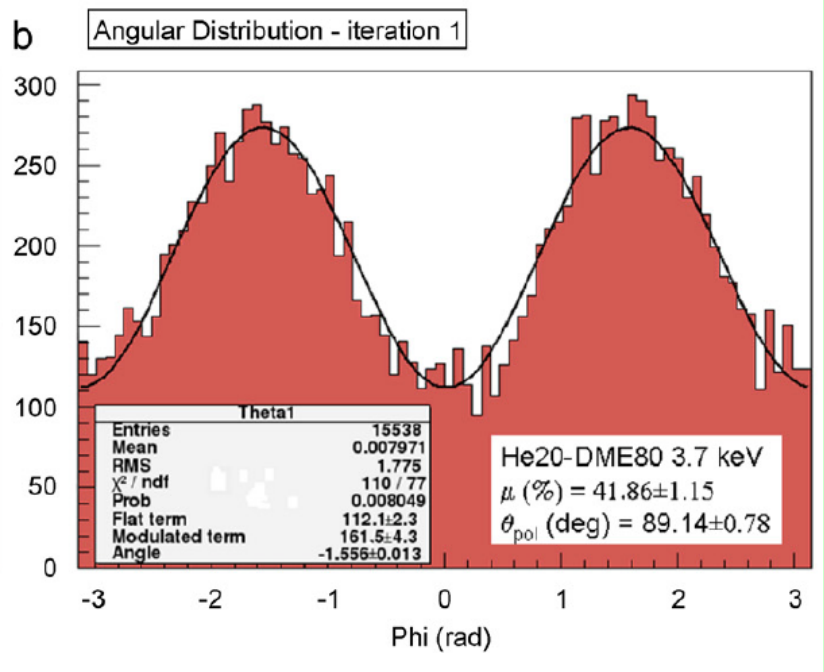
Hence the instrument can provide the polarimetric information together with good imaging, spectral and timing capabilities.

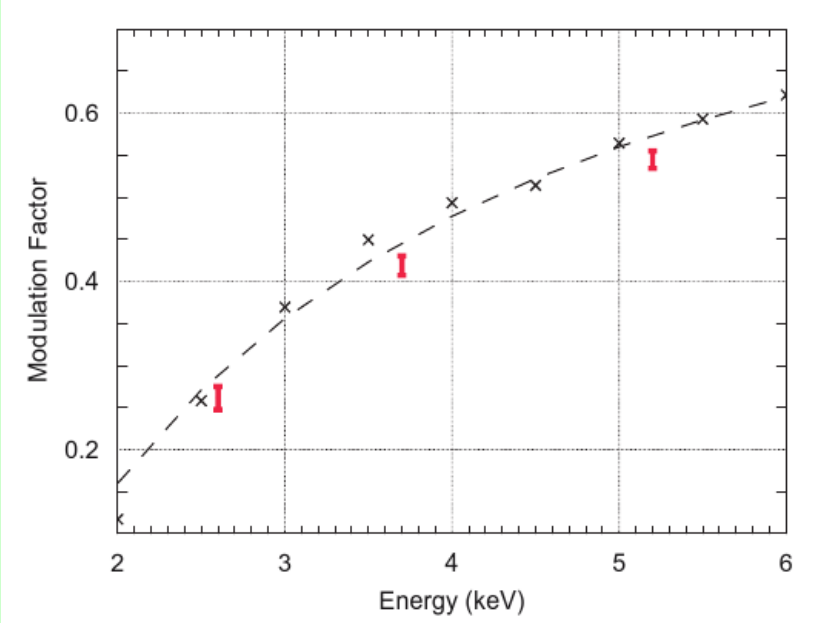




With this calibration source the low energy sensitivity of the GPD has been measured. The sensitivity resulted only slightly less than that predicted by a Monte Carlo software, hence confirming the feasibility of the X-ray Photoelectric polarimeter







Perspectives for X-ray polarimetry

The last mission with a dedicated X-ray polarimeter was OSO-8, launched on 21 June 1975, which discovered polarized X-ray emission from the Crab Nebula.
Since then, and before the advent of photoelectric polarimeters, X-ray polarimeters did not reach enough sensitivity to justify its inclusion in the payload of modern missions, despite the interest for such measurements. Now the situation has changed.

- **ASI has funded the PhaseA study of POLARIX, a dedicated mission to X-ray polarimetry. We are waiting for the final selection**
- **ASI approved the inclusion of an X-ray polarimeter, EXP^2, onboard the chinese HXMT satellite**
- **An X-ray polarimetric mission, GEMS, has been selected for Phase A study within the NASA SMEX program**
  [timeframe for all three: 2012-2014]
- **ESA is funding, within the CV program, the Phase A of IXO, a X-ray observatory which includes in the focal plane a X-ray polarimeter**
  [timeframe ≥2020]

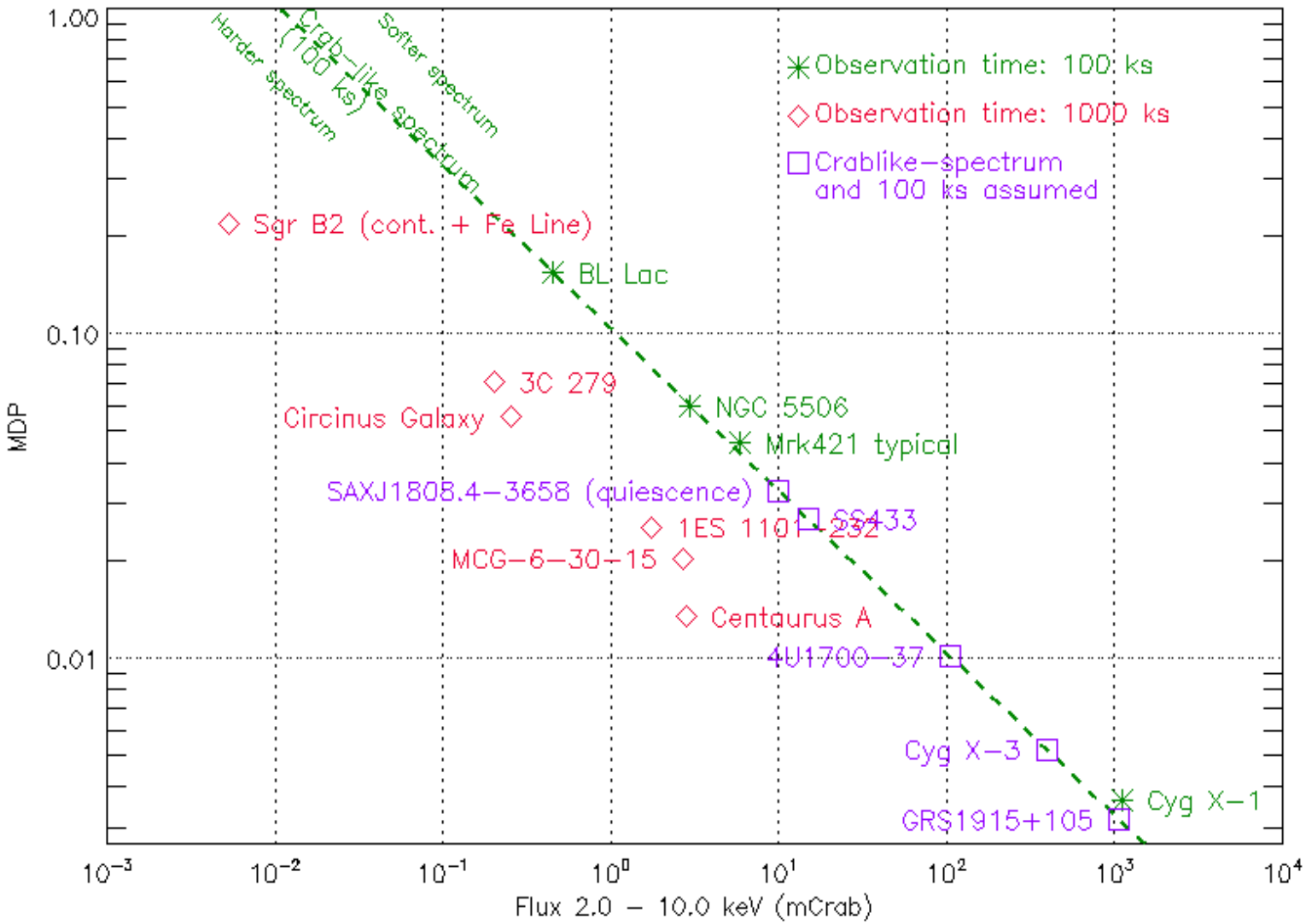
EXP^2 (an Efficient X-ray Photoelectric Polarimeter) and POLARIX

The Institutes currently involved are:

- **IASF/INAF Rome;**
- **INFN Pisa;**
- **OAB/INAF Merate;**
- **Università Roma Tre**

EXP^2 performances

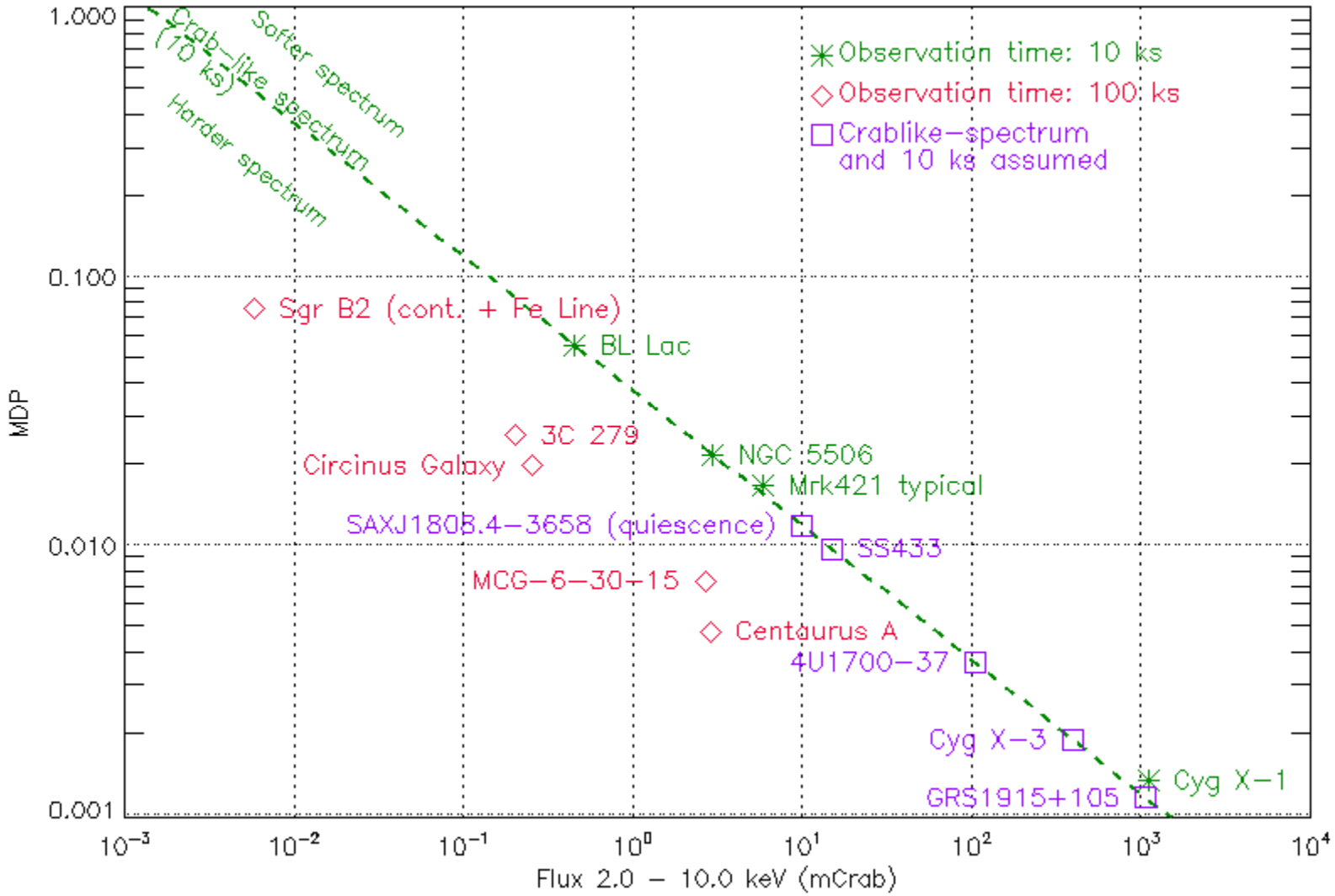
Galactic and bright extragalactic sources are accessible.



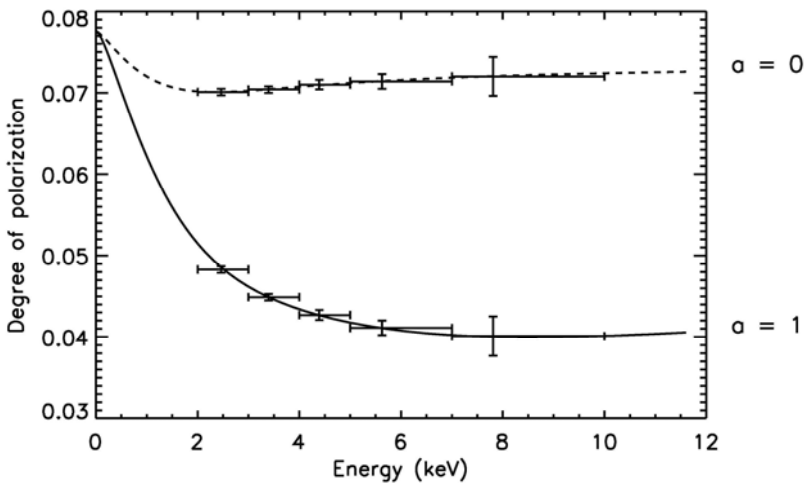
- **Binaries**
- **PWN, Isolated NS**
- **Binaries**
- **Seyfert Galaxies**
- **Blazars**

IXO (XEUS) performances

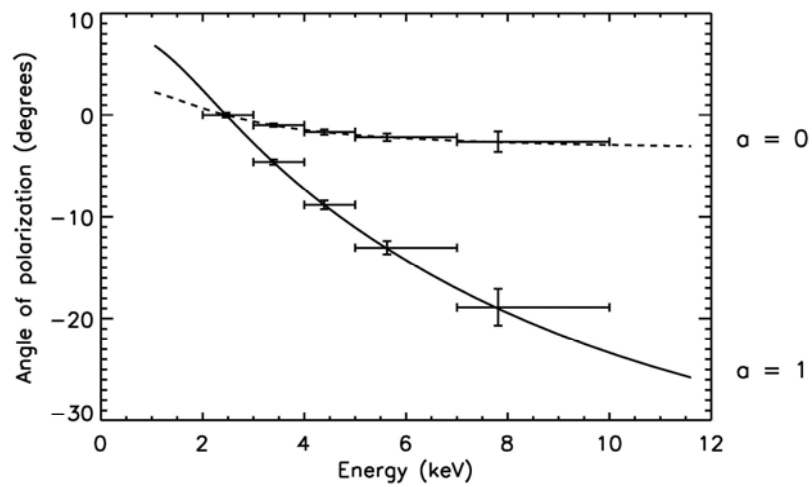
A large sample of AGN are accessible



Observational perspectives with IXO



GRS 1915+105, 200 ks (courtesy F. Muleri)



Summary

X-ray polarization measurements will provide valuable information on the physical conditions and the geometry of the emitting regions in many classes of X-ray sources.

Thanks to novel techniques, X-ray Polarimetry is coming of age!