X-ray polarization studies of black holes

René W. Goosmann

A review lecture at the International School

“Black Holes – Tales of Power and Destruction

19th July 2011

Winchester, United Kingdom

OUTLINE

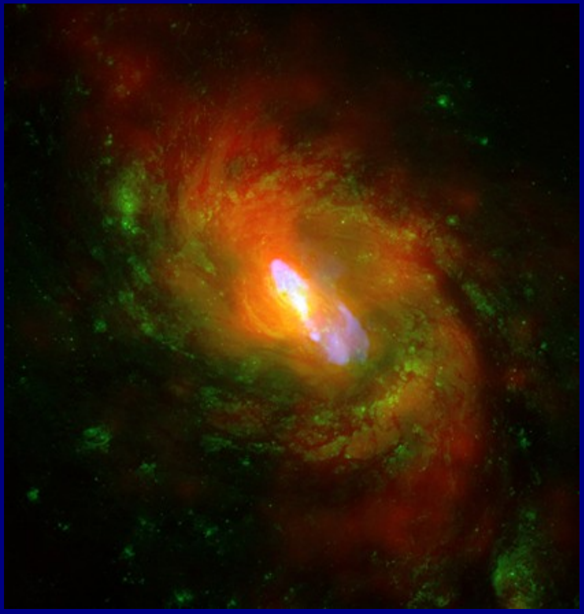
- **Why should we care about polarization?**
- Some basics on polarization of electromagnetic radiation
- Techniques to measure X-ray polarization
- X-ray polarization produced in the vicinity of black holes
- Modeling the X-ray polarization in black hole X-ray binaries
- Modeling the X-ray polarization in AGN
- What to take home from this review

René Goosmann
Strasbourg Observatory, France

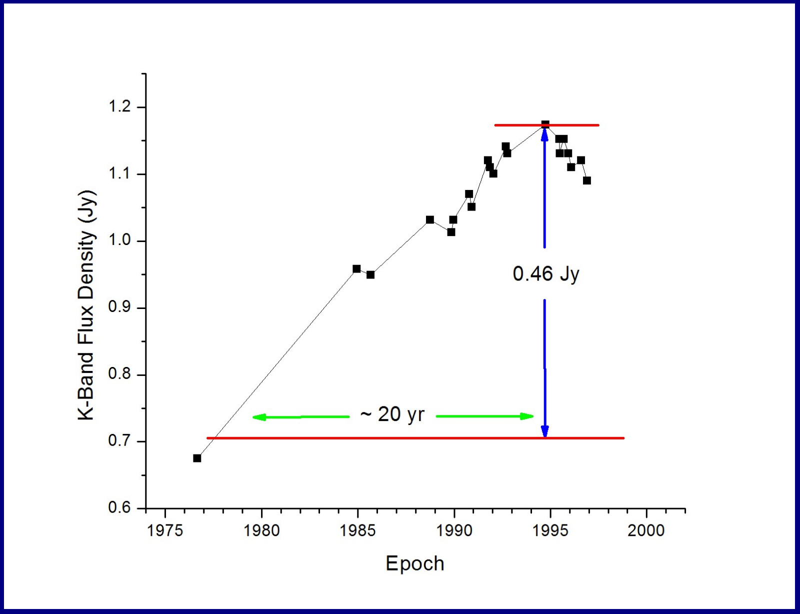
Why should we care about (X-ray) polarization?

- 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))

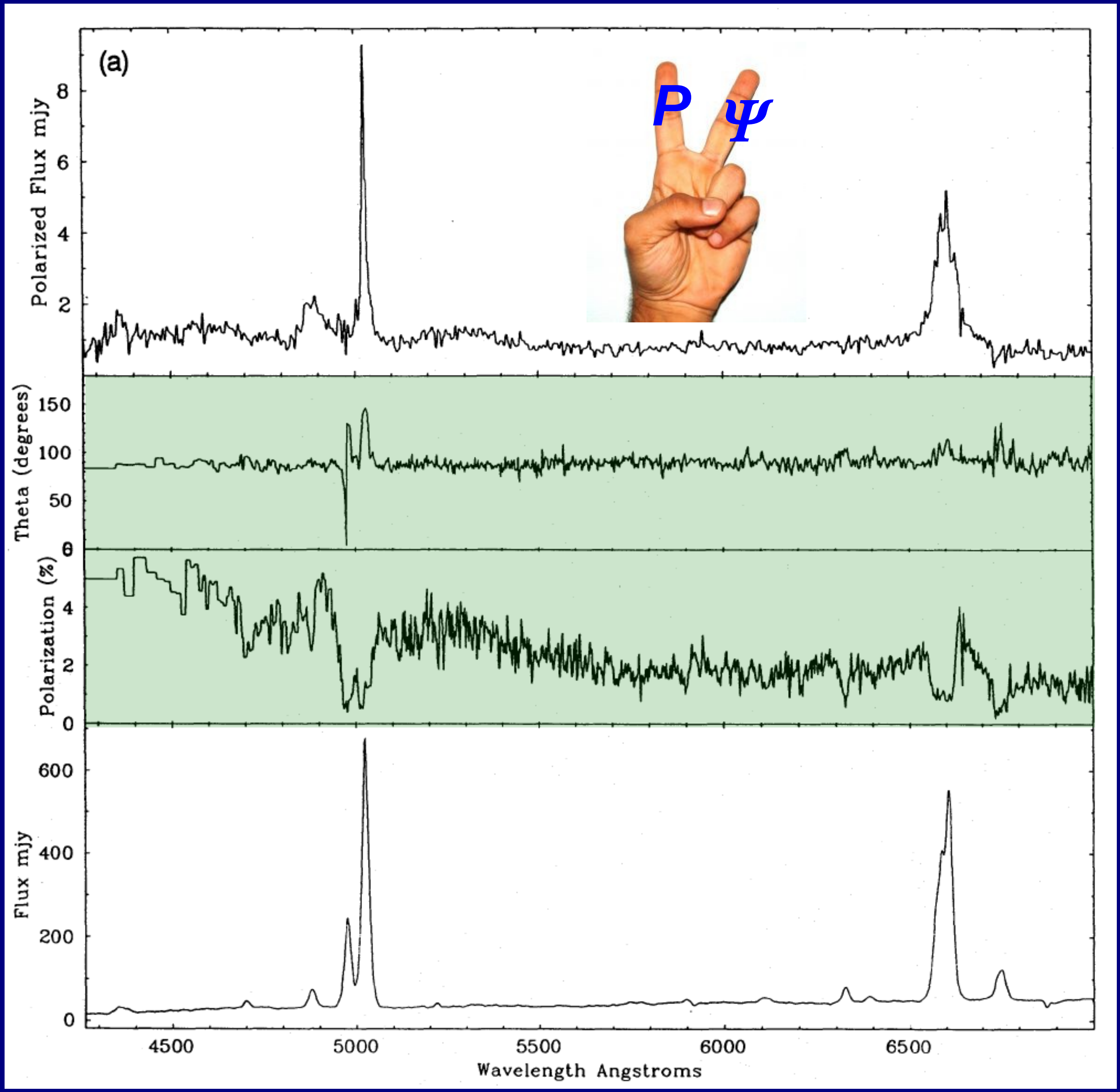


2.2 micron light curve of NGC 1068 (work by I. Glass)

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

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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

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

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

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

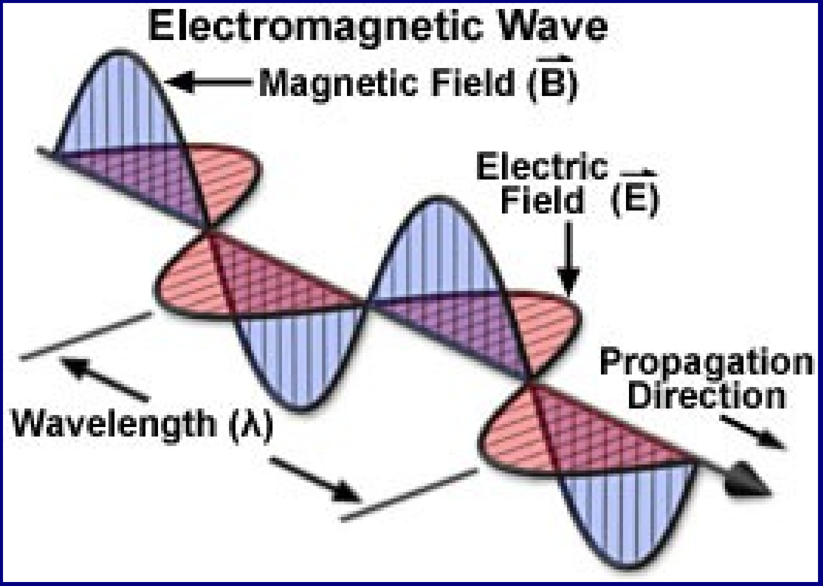
$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \boldsymbol{j}_c$$

where

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

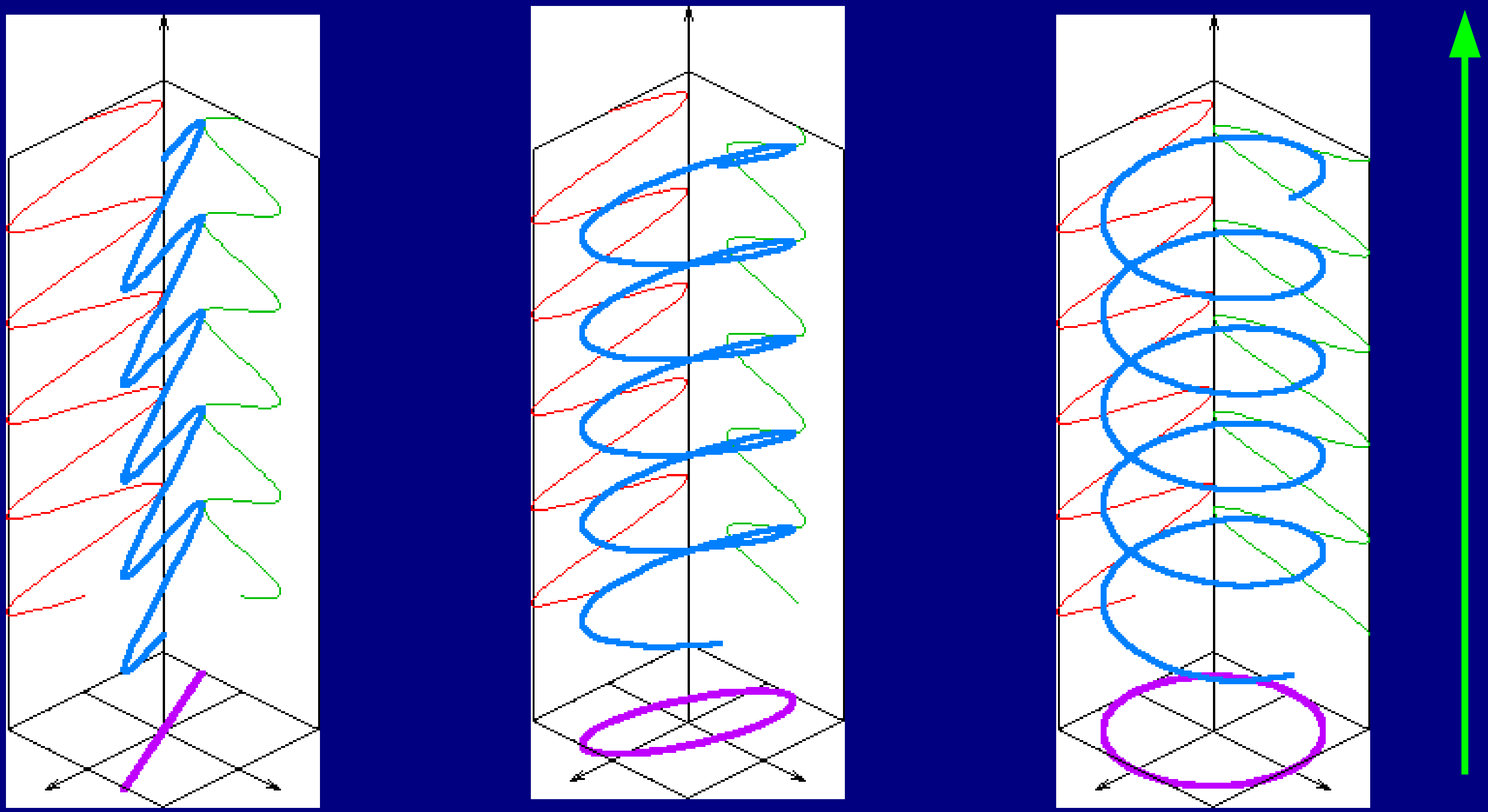
3D wave equation for the electric field

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



Polarization of coherent light

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



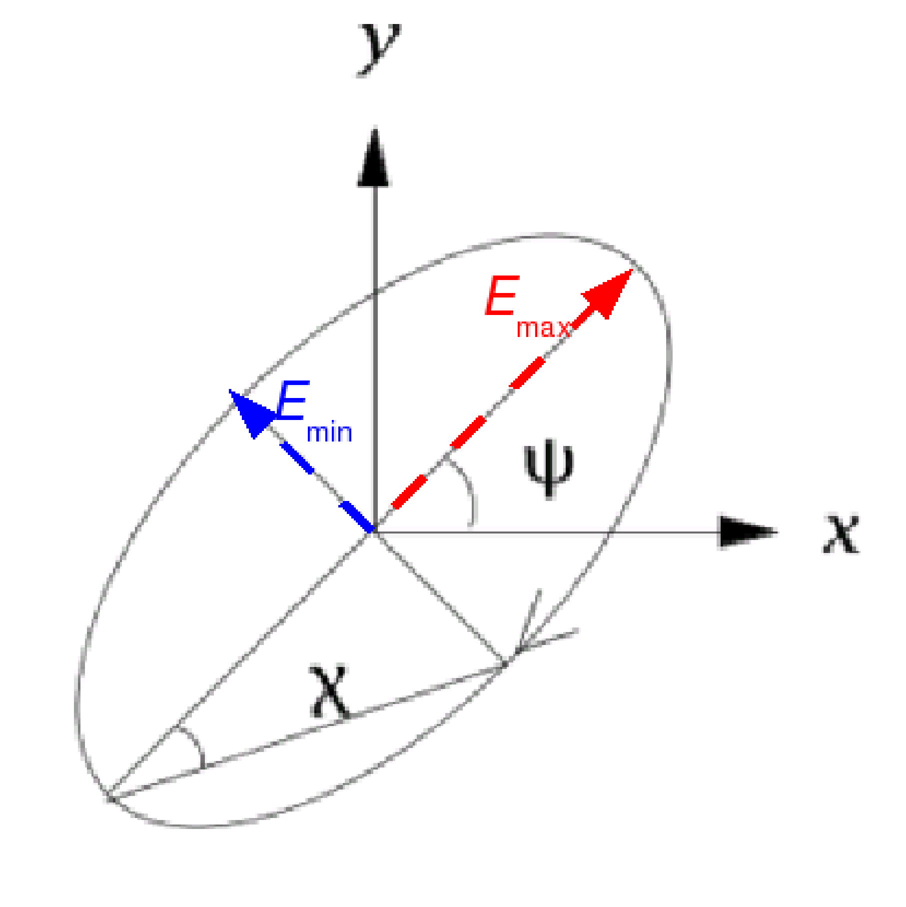
linear elliptical circular

The polarization ellipse

The linear polarization degree P is defined by

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

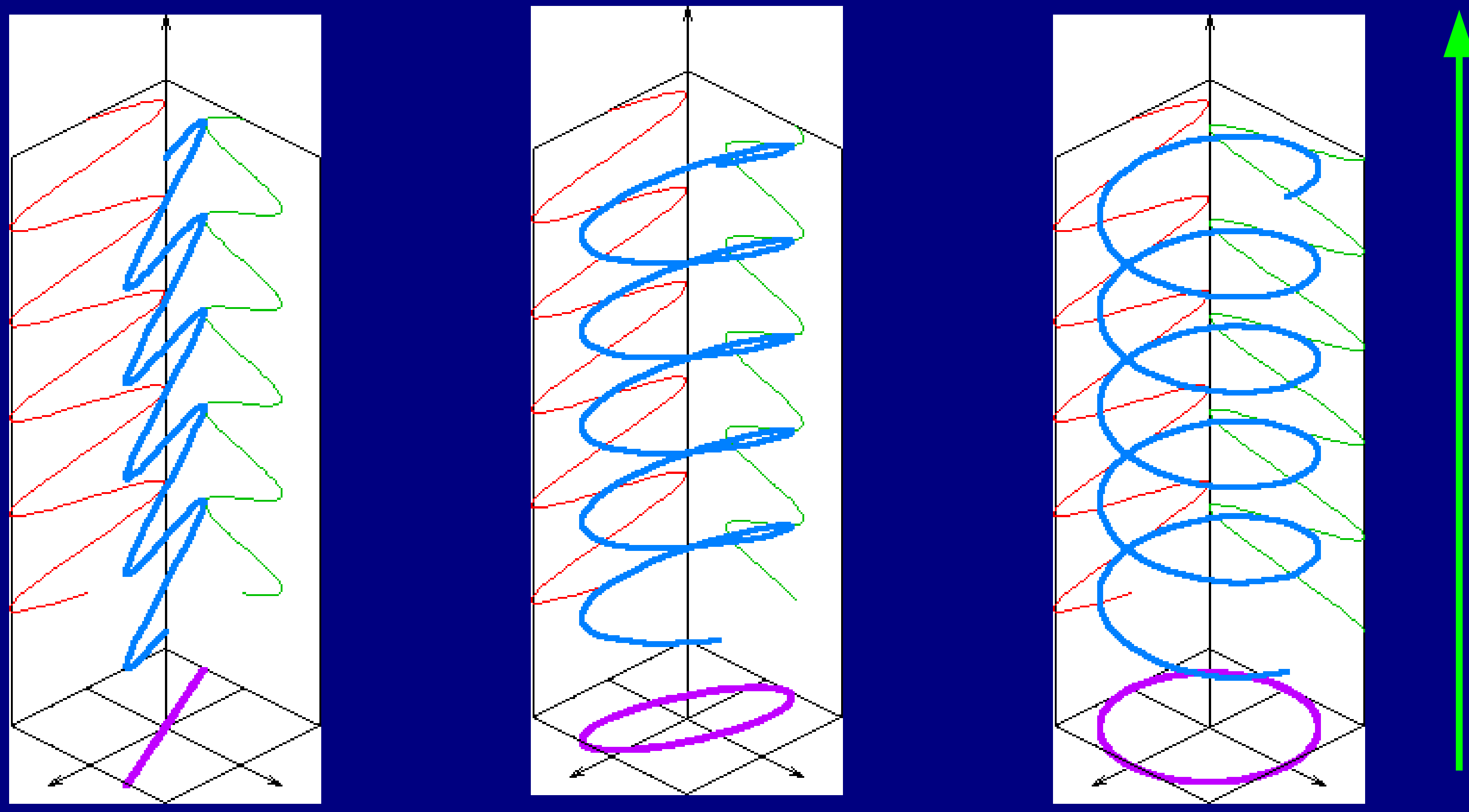
Note: $0 \leq P \leq 1$.



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 <u>we only discuss linear polarization</u> that is far more important in the X-ray range than circular polarization.

The Stokes parameters

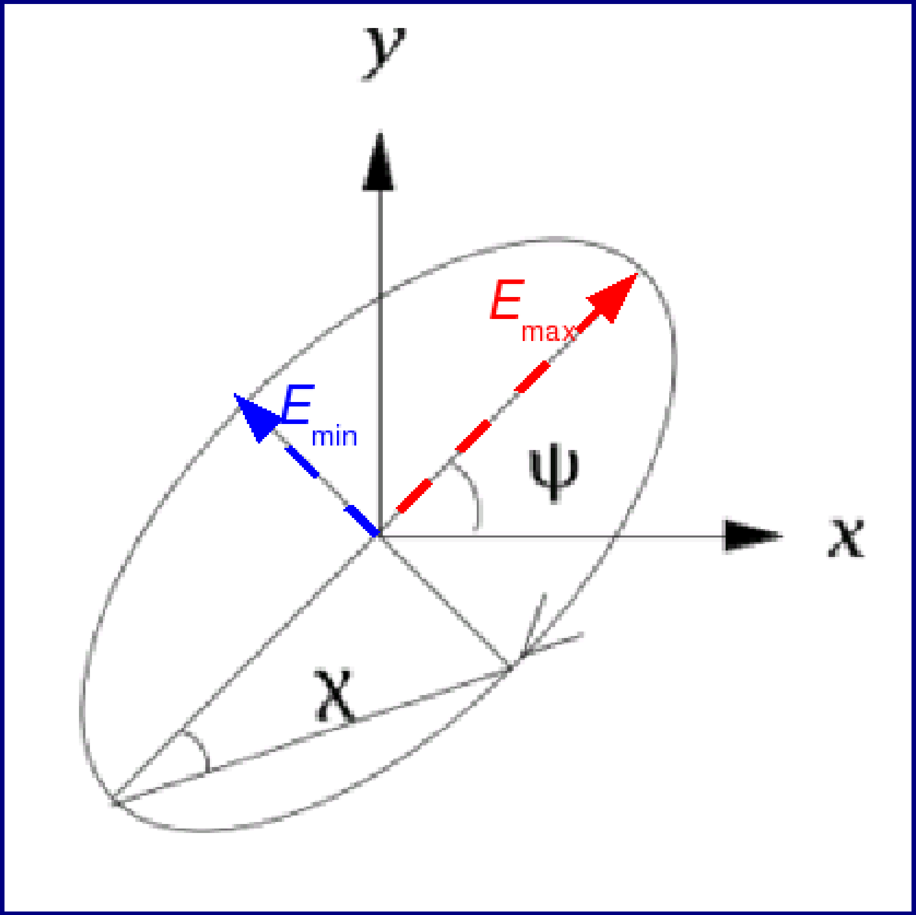
The polarization state is completely described by the Stokes parameters:

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

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

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

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

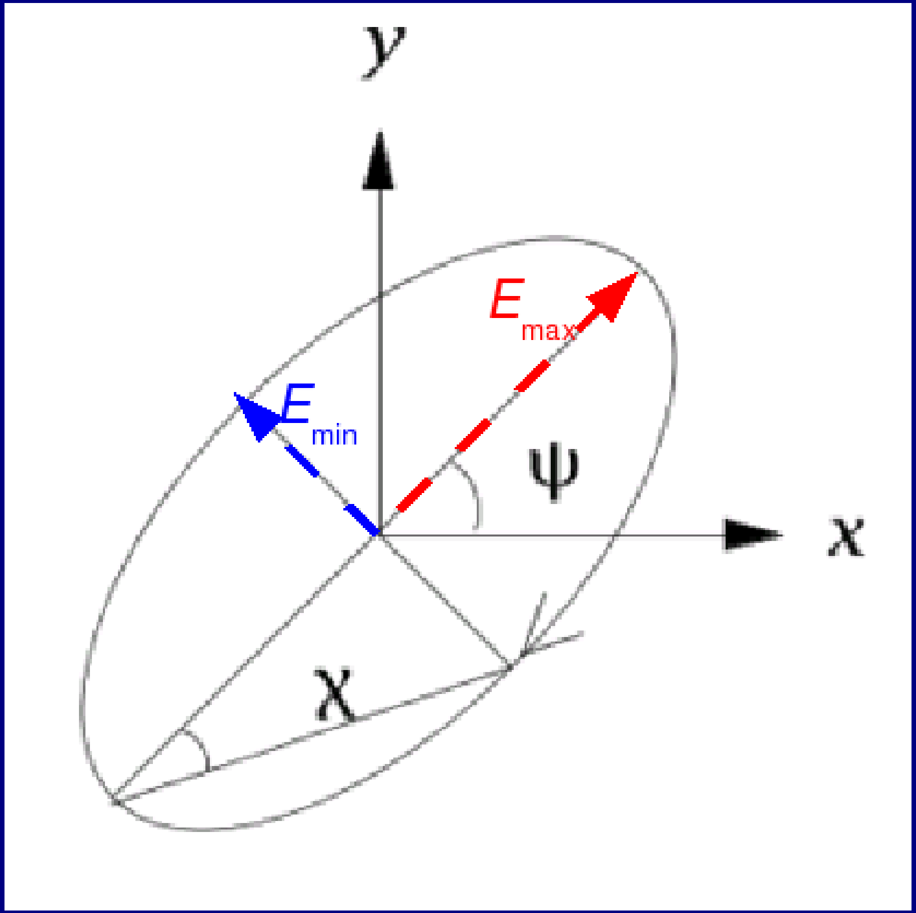


The Stokes parameters

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

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

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



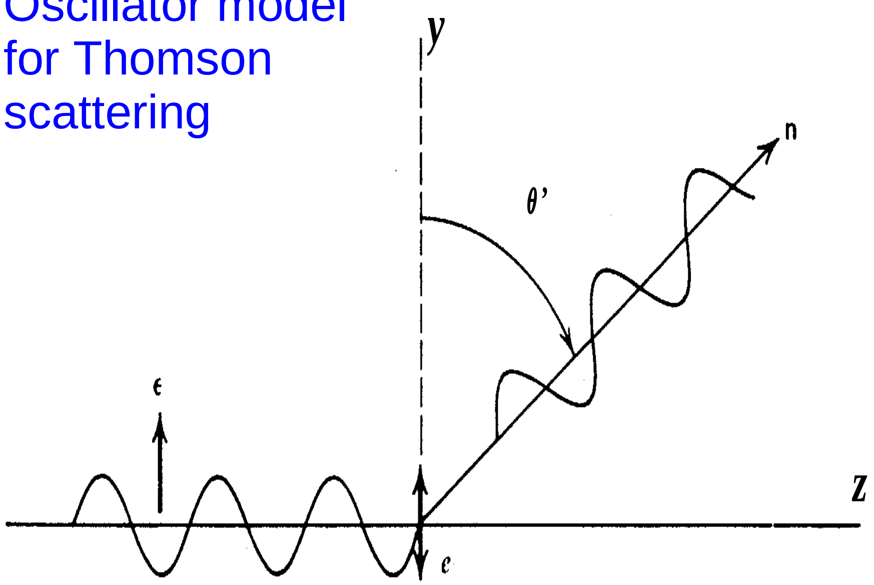
Processes producing (de-)polarization

- Synchrotron emission
- Electron scattering
- Dust (Mie) scattering
- Resonant line scattering
- Dichroic absorption
- Faraday rotation
- Dilution (by unpolarized radiation)
- General Relativity

Scattering

Strong polarization: $\Theta = 90°$ (Reflection)
Weak polarization: $\Theta = 0°$ (Transmission)

Oscillator model for Thomson scattering



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

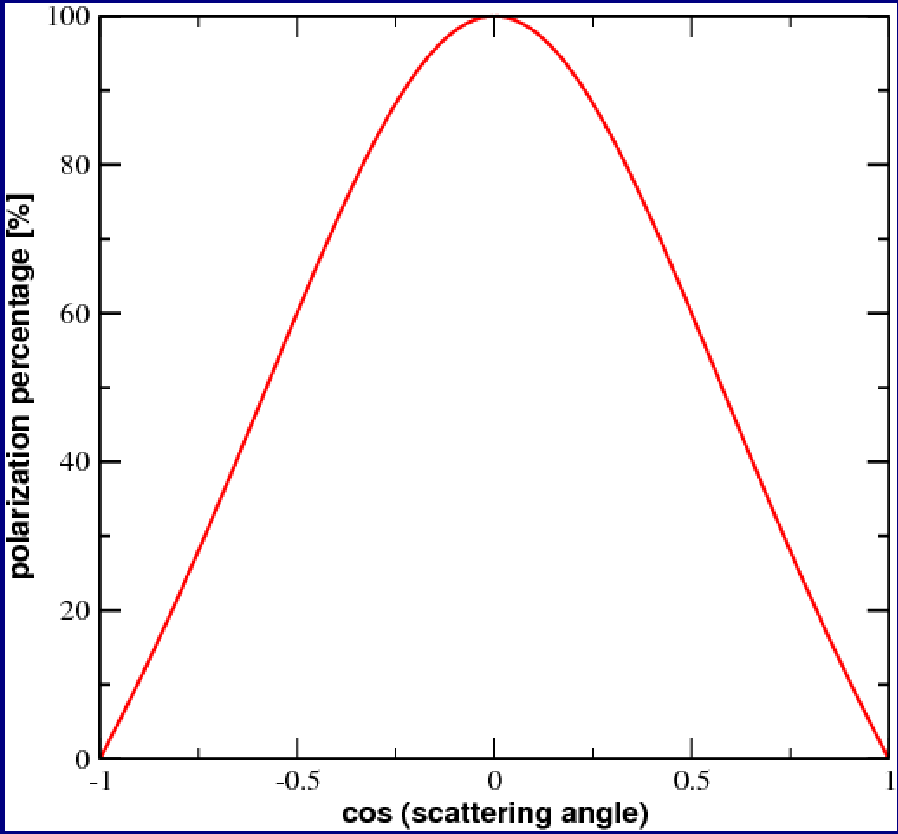
$$P = \frac{1 - \cos^2 \theta}{1 + \cos^2 \theta}.$$

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

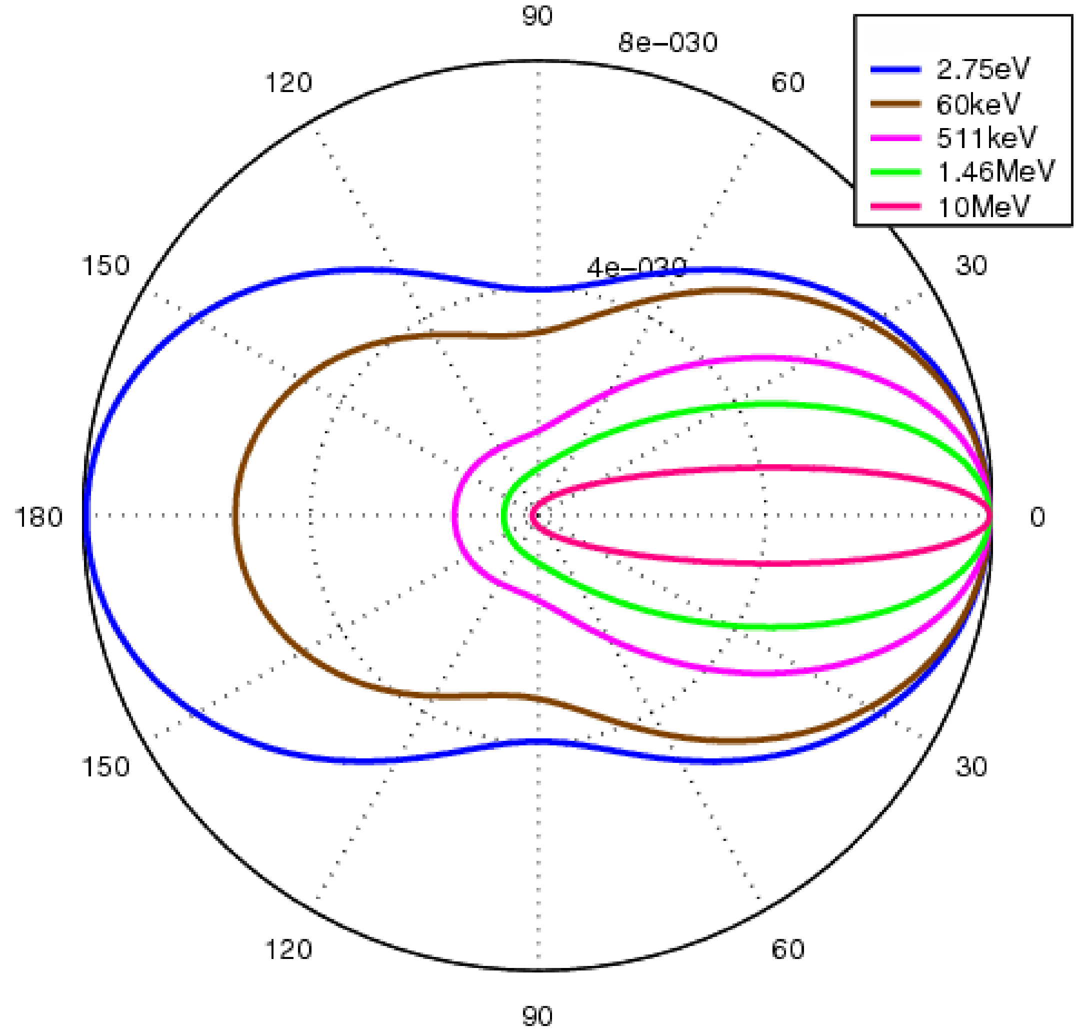
Phase function for scattering-induced polarization

- Electron scattering (Thomson, Compton, Rayleigh scattering)

Polarization phase function:



Differential cross section



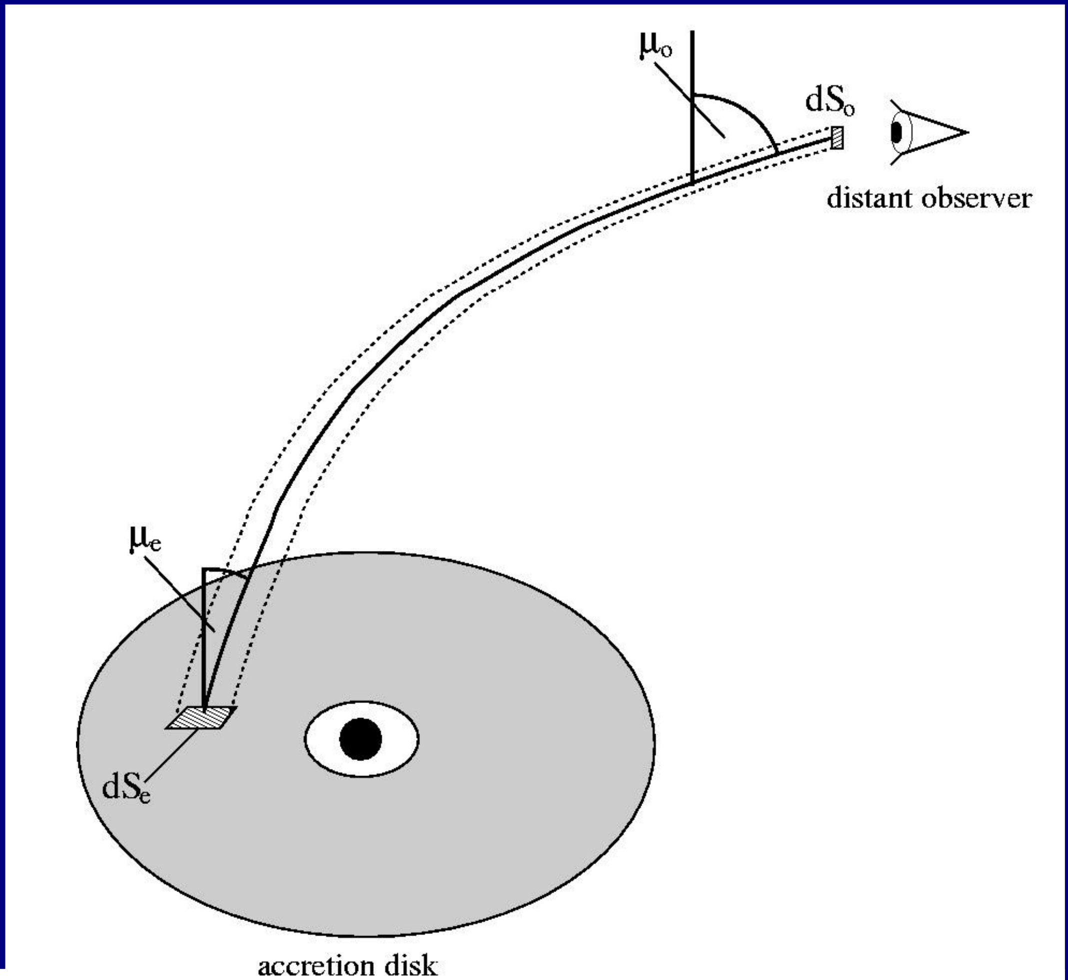
Including relativistic effects

- **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

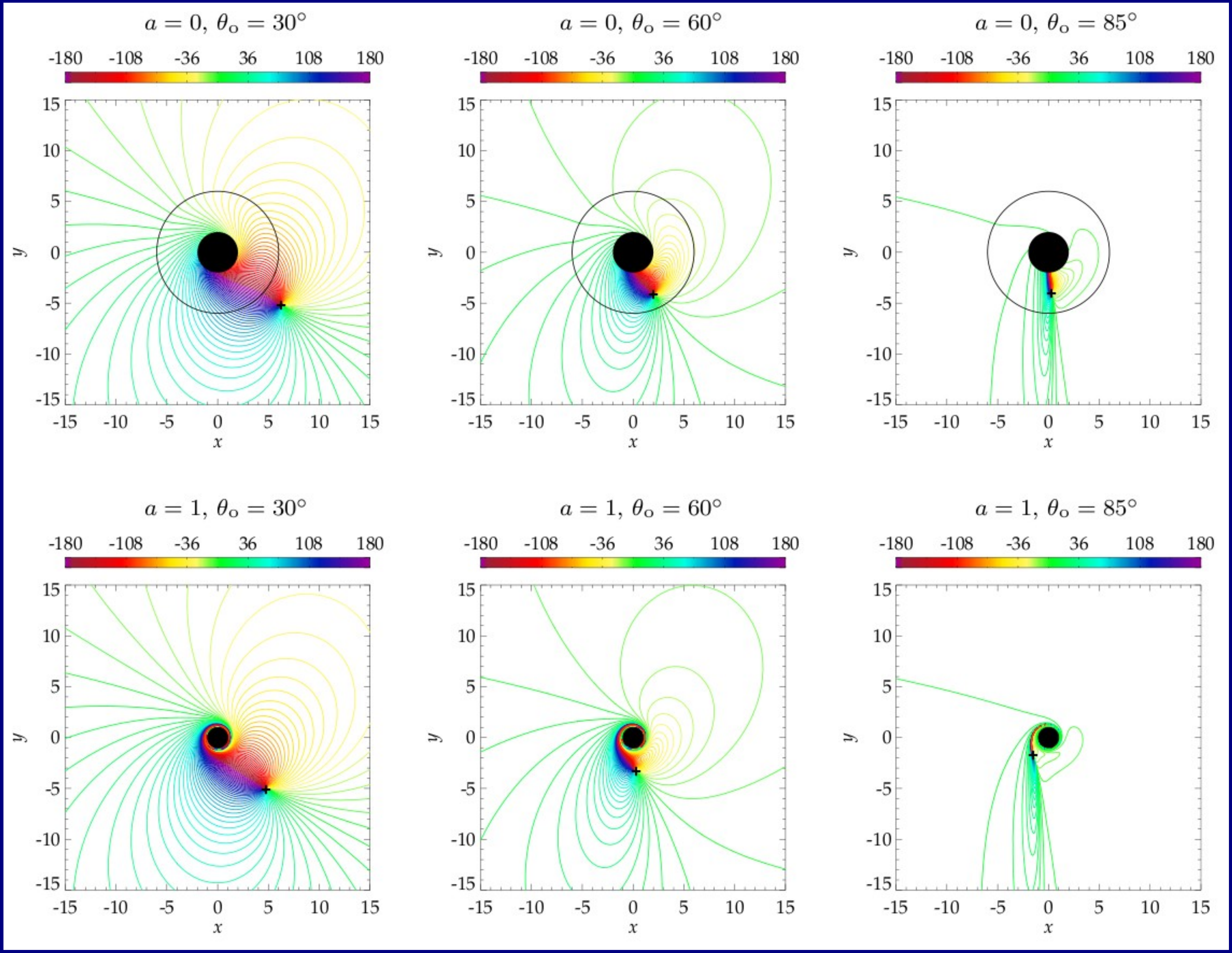
I, Q, U, V



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

observed photon flux | **disk integration** | **ener gy** | **local photon flux** | **transf er**

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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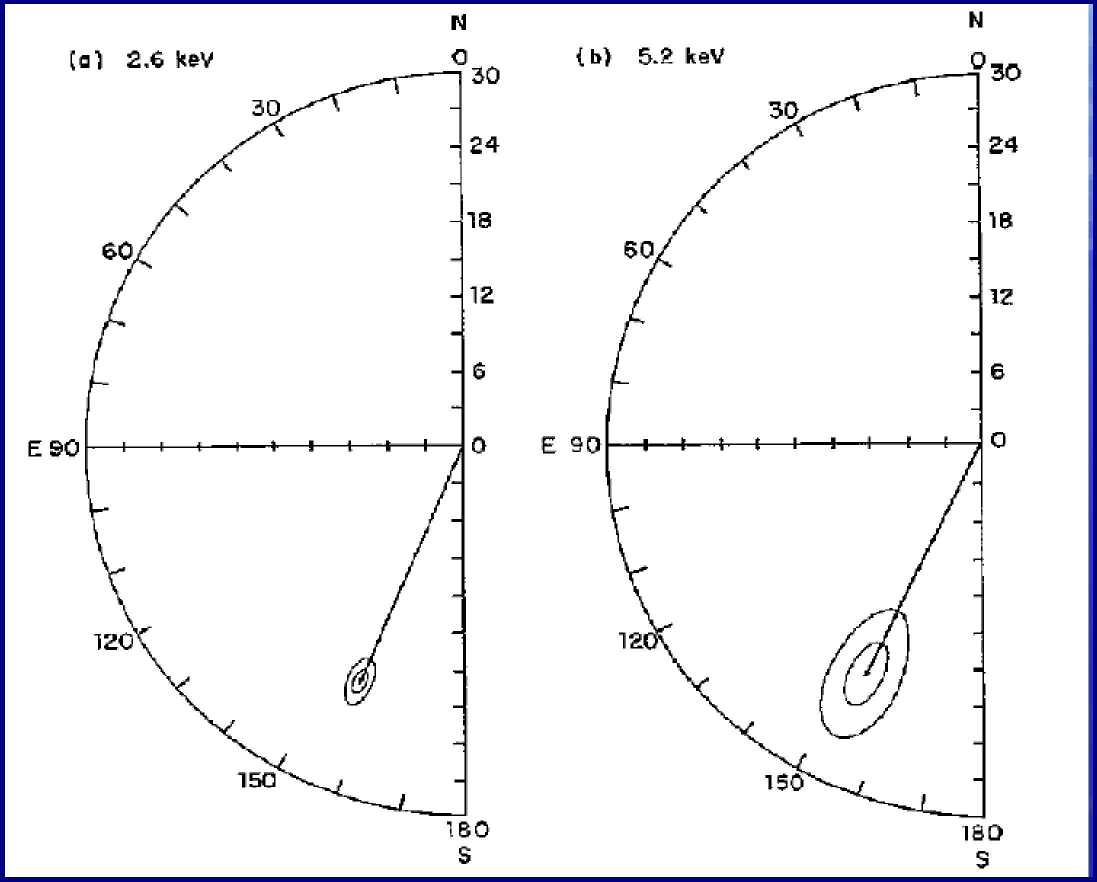
So-far X-ray polarization measurements



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

Observational prospects – ready-to-fly technology

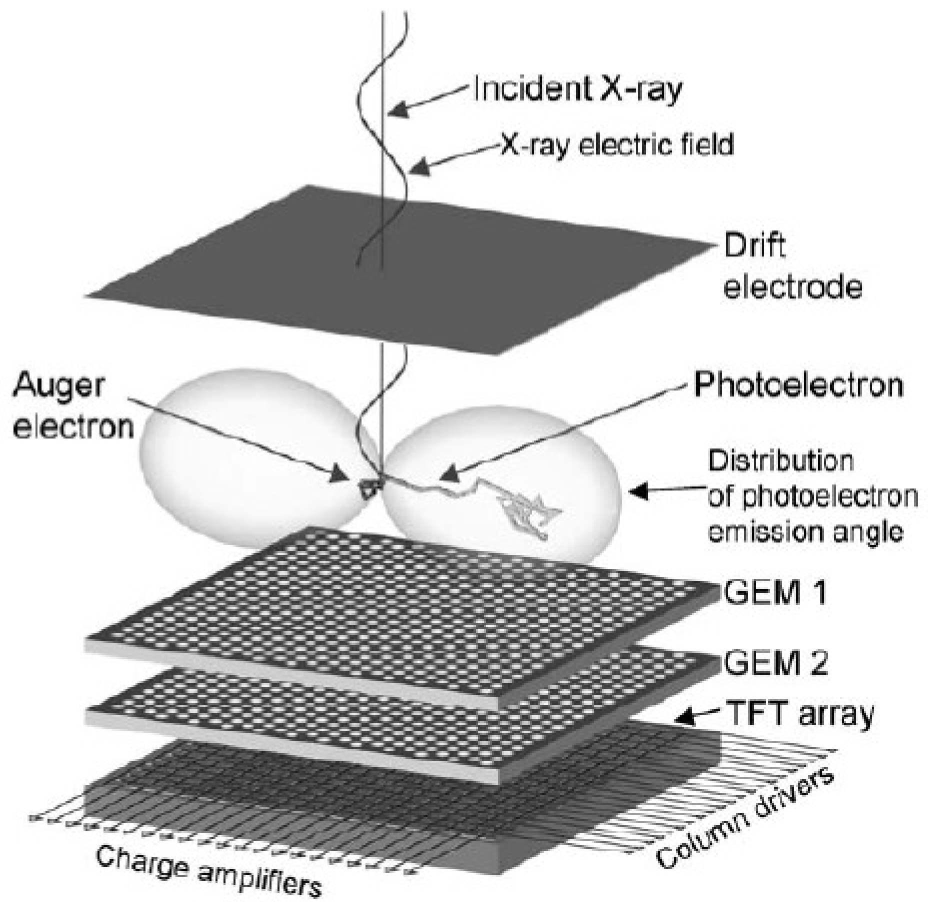


Fig. 1. Schematic diagram of detector geometry used in these measurements. The $\sin^2\theta\cos^2\phi$ distribution of photoelectron emission for normally incident X-rays is projected onto the detector plane and observed as $\cos^2\phi$.

- Photoelectric ionization of and subsequent Auger effect
- Photo electron and Auger electron both <u>know about the initial polarization</u> of the incident photon

Active-matrix pixel prop. counter

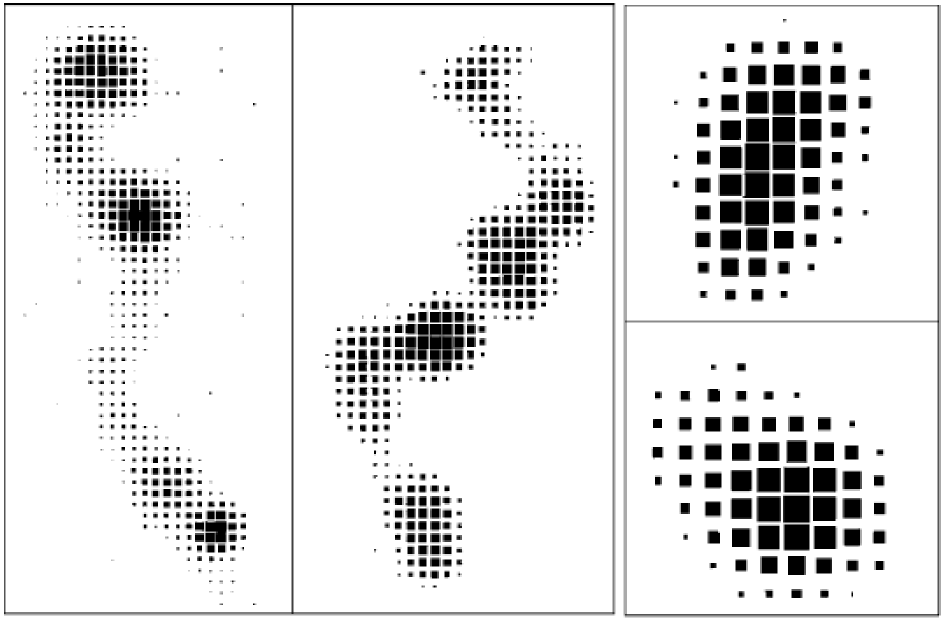
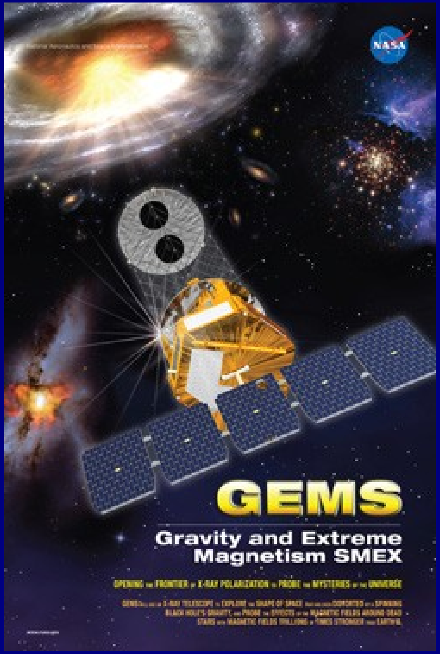


Fig. 3. Track images from 20 keV X-rays (left) and 4.5 keV X-rays (right).

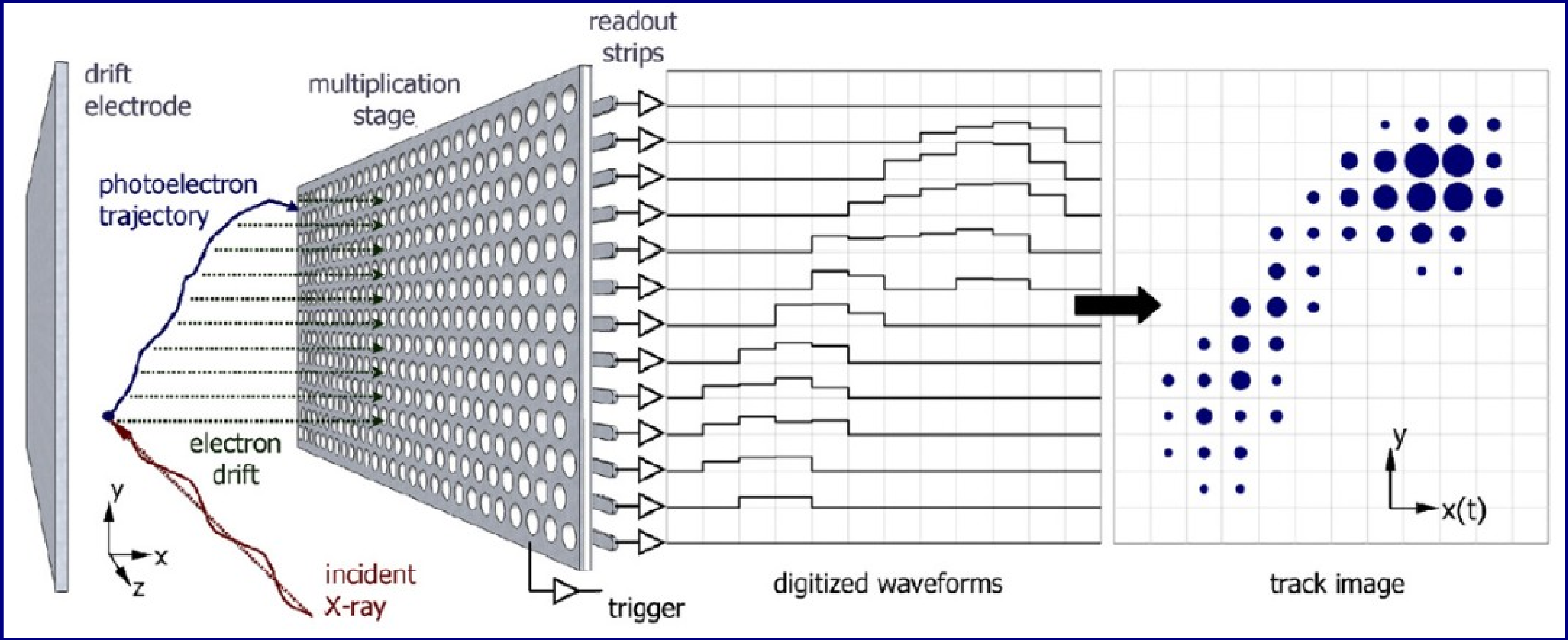
Costa et al. (2001), Bellazzini et al.(2009), Muleri et al. (2009)

Soon observational prospects!

Gravity and Extreme Magnetism SMEX (2014)



- NASA small explorer mission explicitly dedicated to X-ray polarimetry
- Stereo focusing telescope connected to the X-ray Polarimeter Instrument (XPI) operating at



Black et al. 2007

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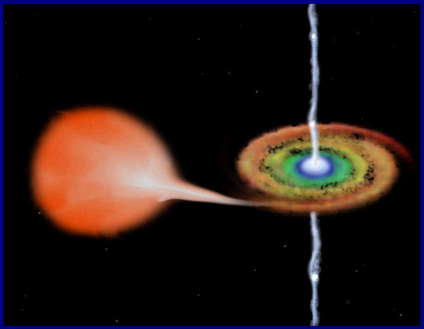
X-ray polarization in black hole X-ray binaries

Determining the local polarization (disk reference frame)

- Intrinsically unpolarized radiation
- multiple Thomson scattering in a disk/corona



Early modeling work done by Angel (1969)

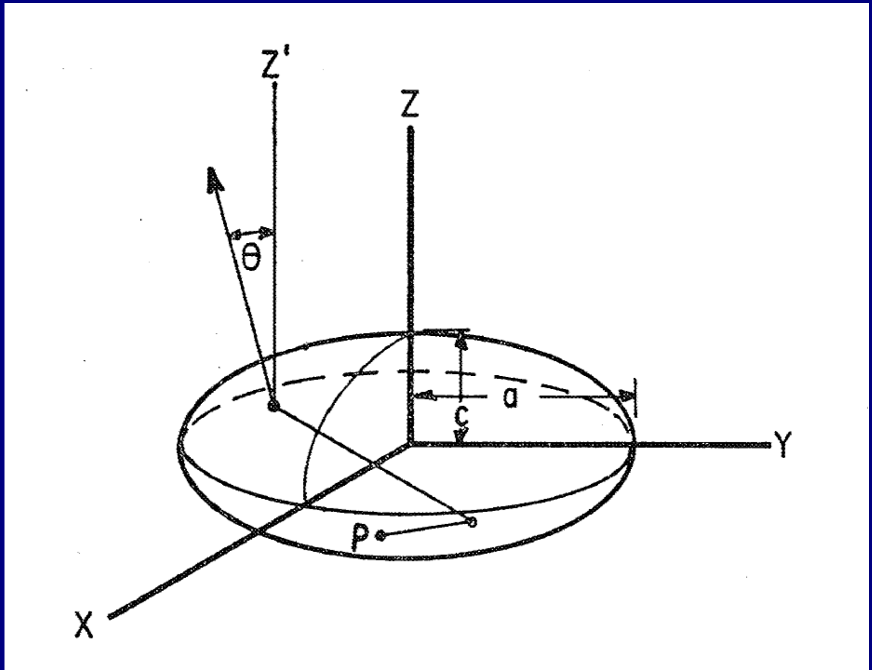
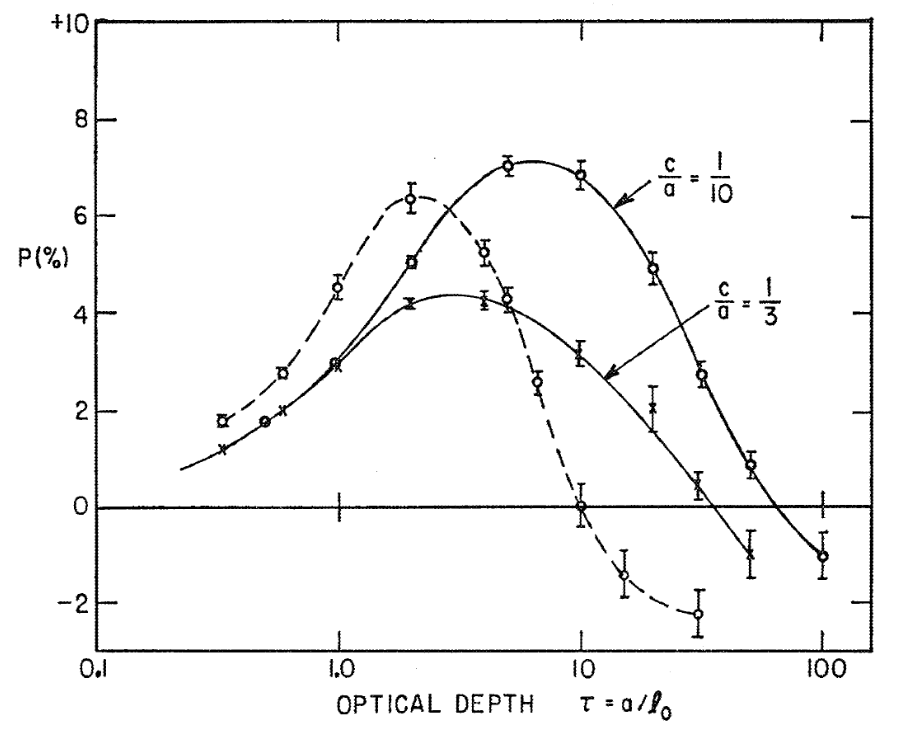
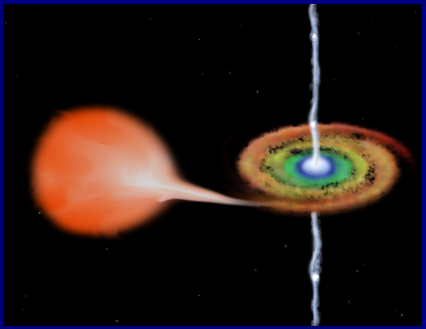


FIG. 1.—Geometry of Monte Carlo calculations



X-ray polarization in black hole X-ray binaries

Determining the local polarization (disk reference frame)

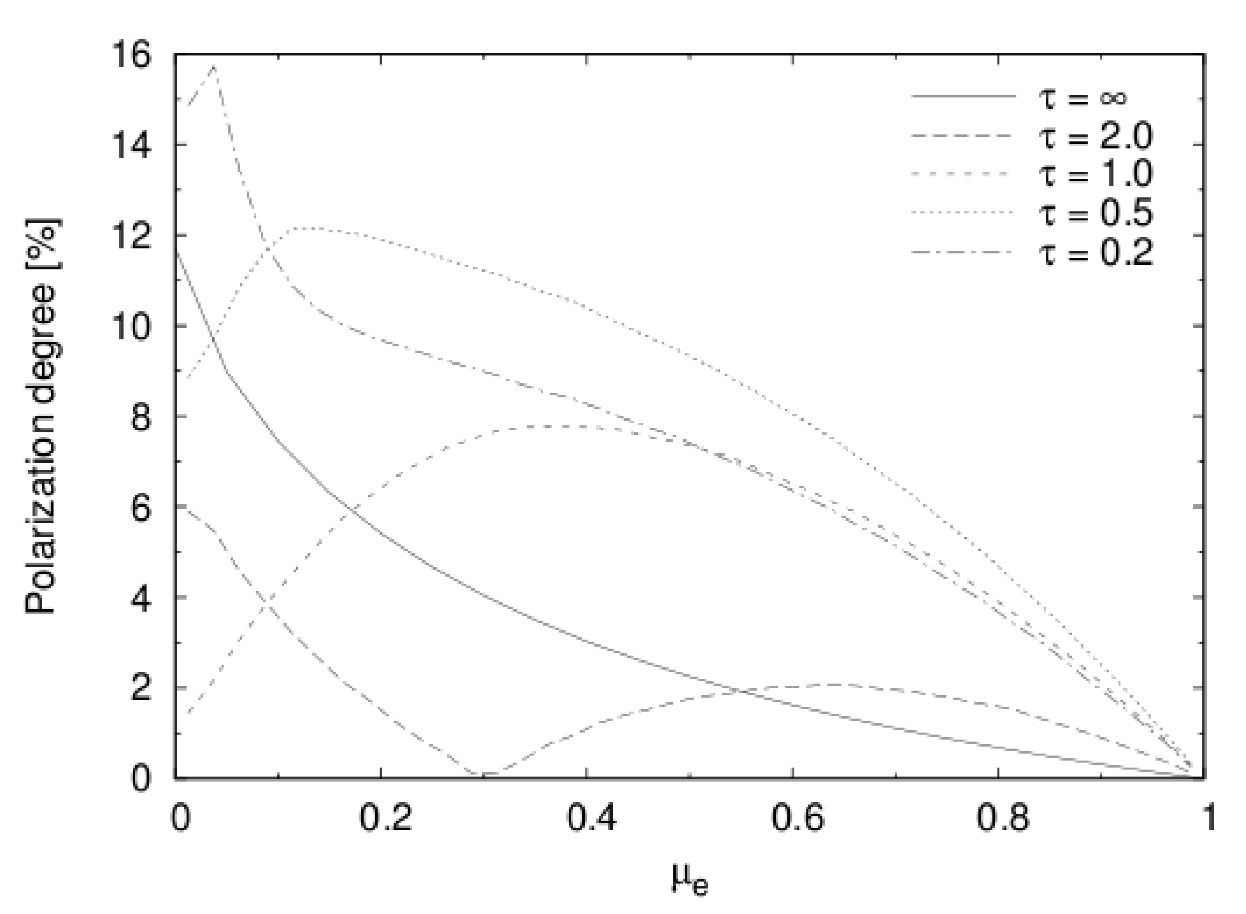


- Intrinsically unpolarized radiation
- multiple Thomson scattering in a disk/corona
- Color correction for Comptonization (Novikov-Thorne)

X-ray radiative transfer modeling that includes polarization

See e.g.

Angel (1969)
Sunyaev & Titarchuk (1985)
Matt et al. (1992)
...



Dovčiak et al. (2008)

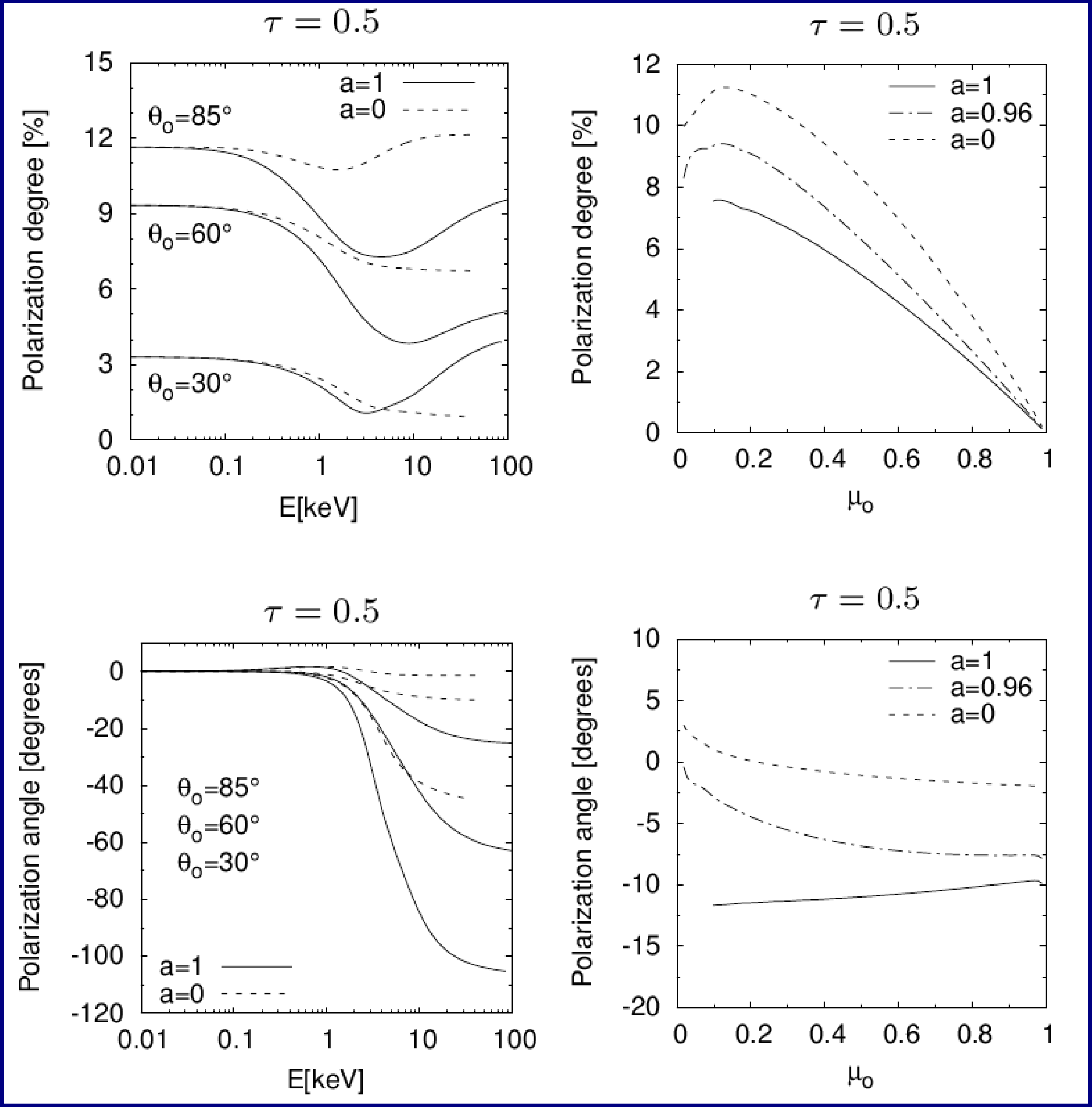
X-ray polarization in black hole X-ray binaries

Polarization observed at infinity

- Integrating the transferred, local polarization across the accretion disk

- Characteristic dependencies of the polarization as a function of energy

- Pioneering modeling of this kind was done already by Connors, Stark, & Piran (1980)



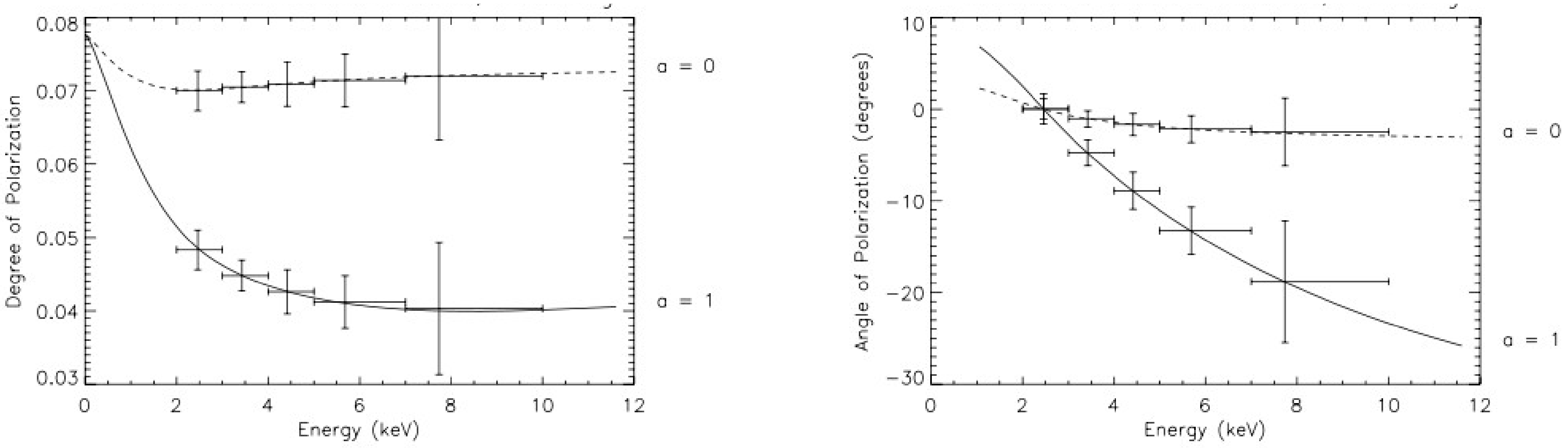
Dovčiak et al. (2008)

Searching for the holy grail

• X-ray polarization as a function of energy is going to put constraints on the black hole spin in X-ray binaries.

• Polarization angle and percentage have a different signature for a Schwarzschild and a Kerr black hole.

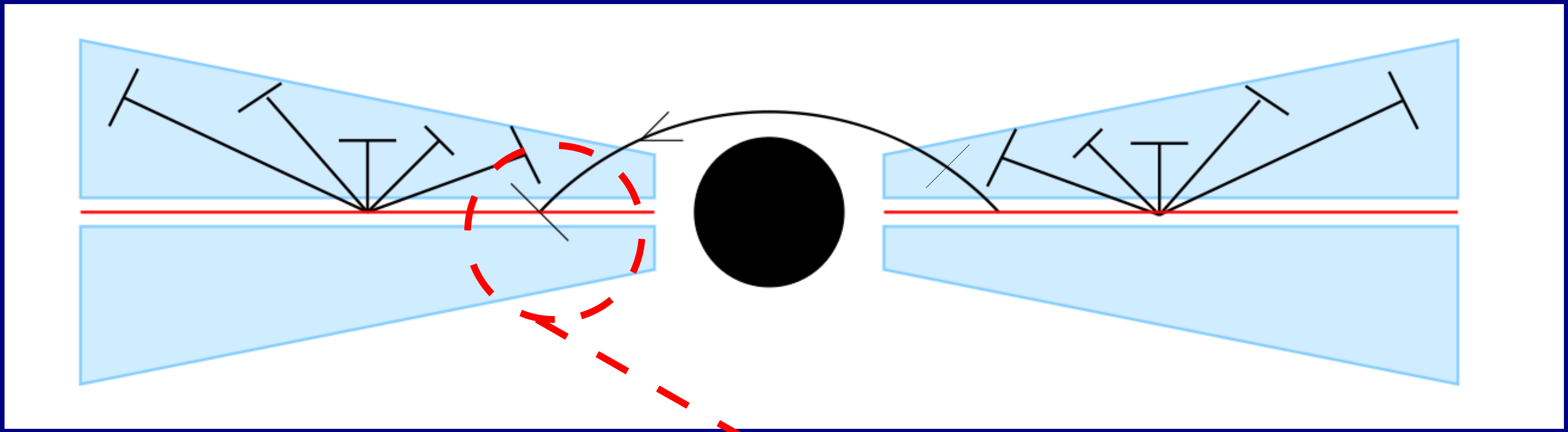
GRS 1915+105 — Pathfinder Mission Scenario, T = 500 ksec, *i* = 70°



Dovčiak, Muleri, Goosmann et al. (2008)

Light-bending and returning radiation

Schnittman & Krolik (2010)



- Compton effects in the disk corona are consistently included with extreme light bending that may lead to <u>secondary reprocessing.</u>

- Different coronal optical depth and electron temperatures are tested

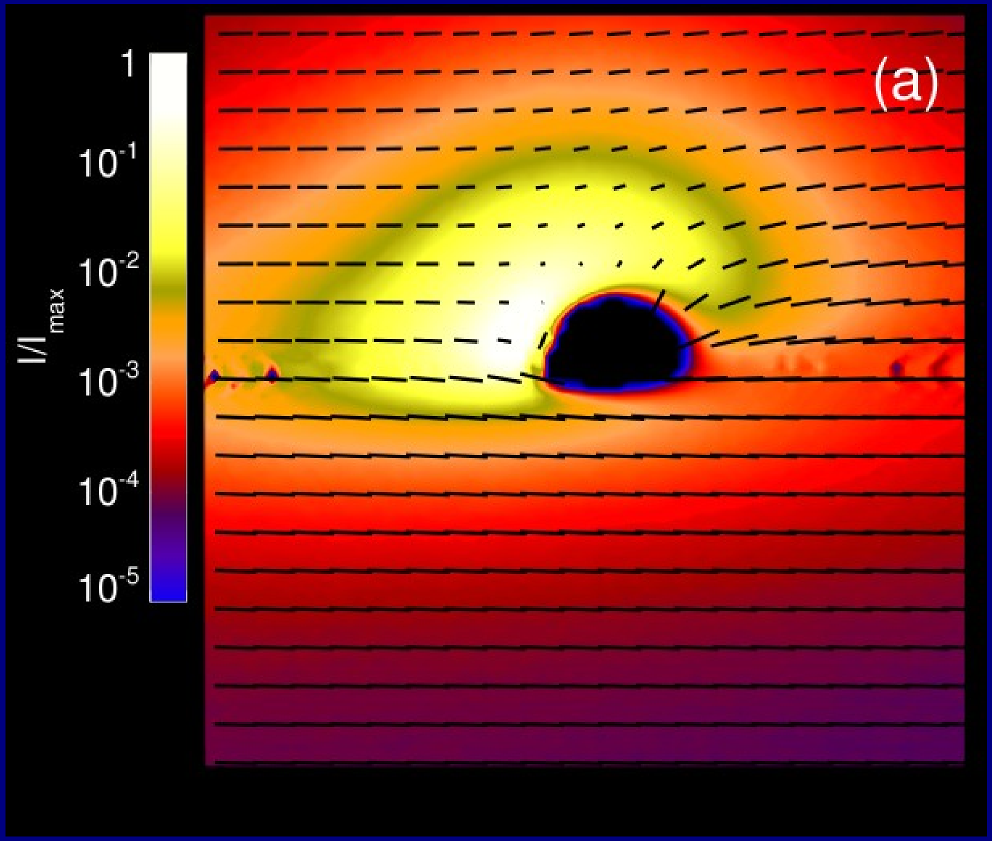
- A wedge-like corona is compared to spherical and patchy geometries

Light-bending and returning radiation

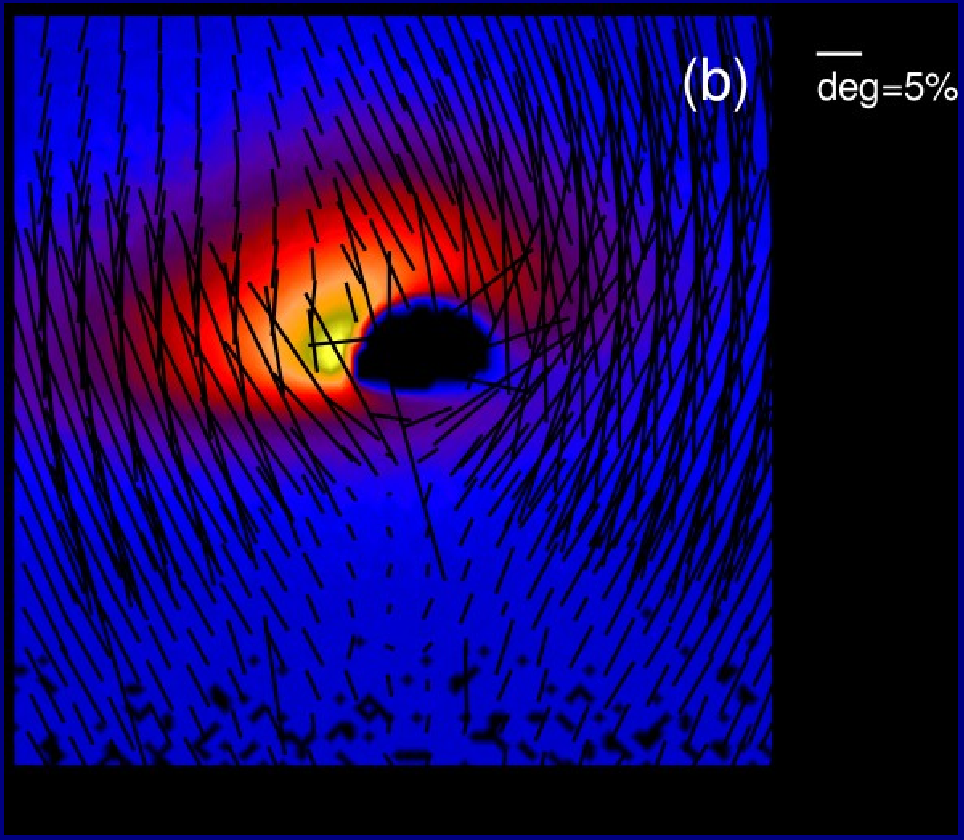
Schnittman & Krolik (2010)

a/M = 0.9
H/R = 0.1
***i* = 75°**

Disk and coronal emission without returning radiation

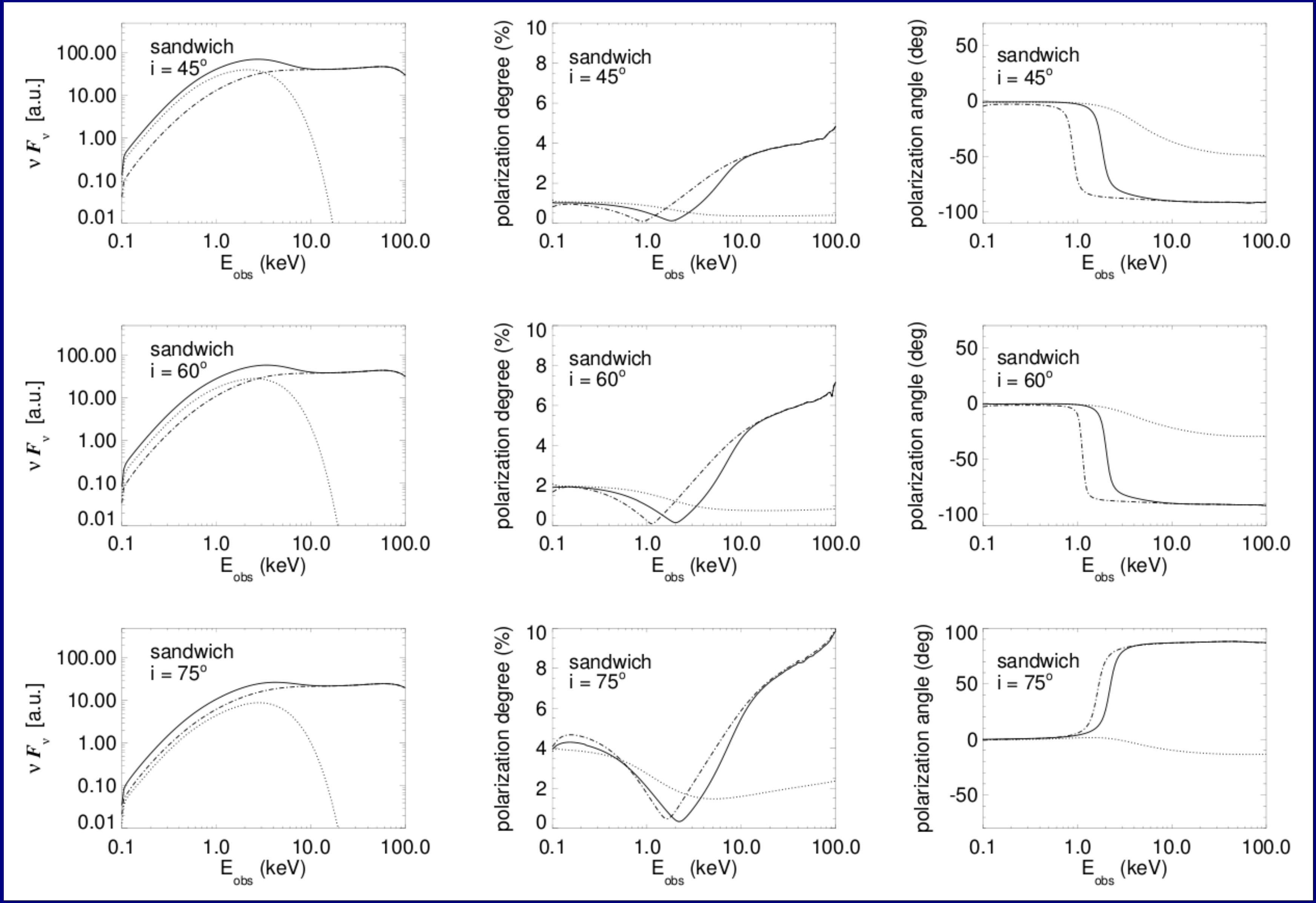


...and including returning radiation



Light-bending and returning radiation

Schnittman & Krolik (2010)



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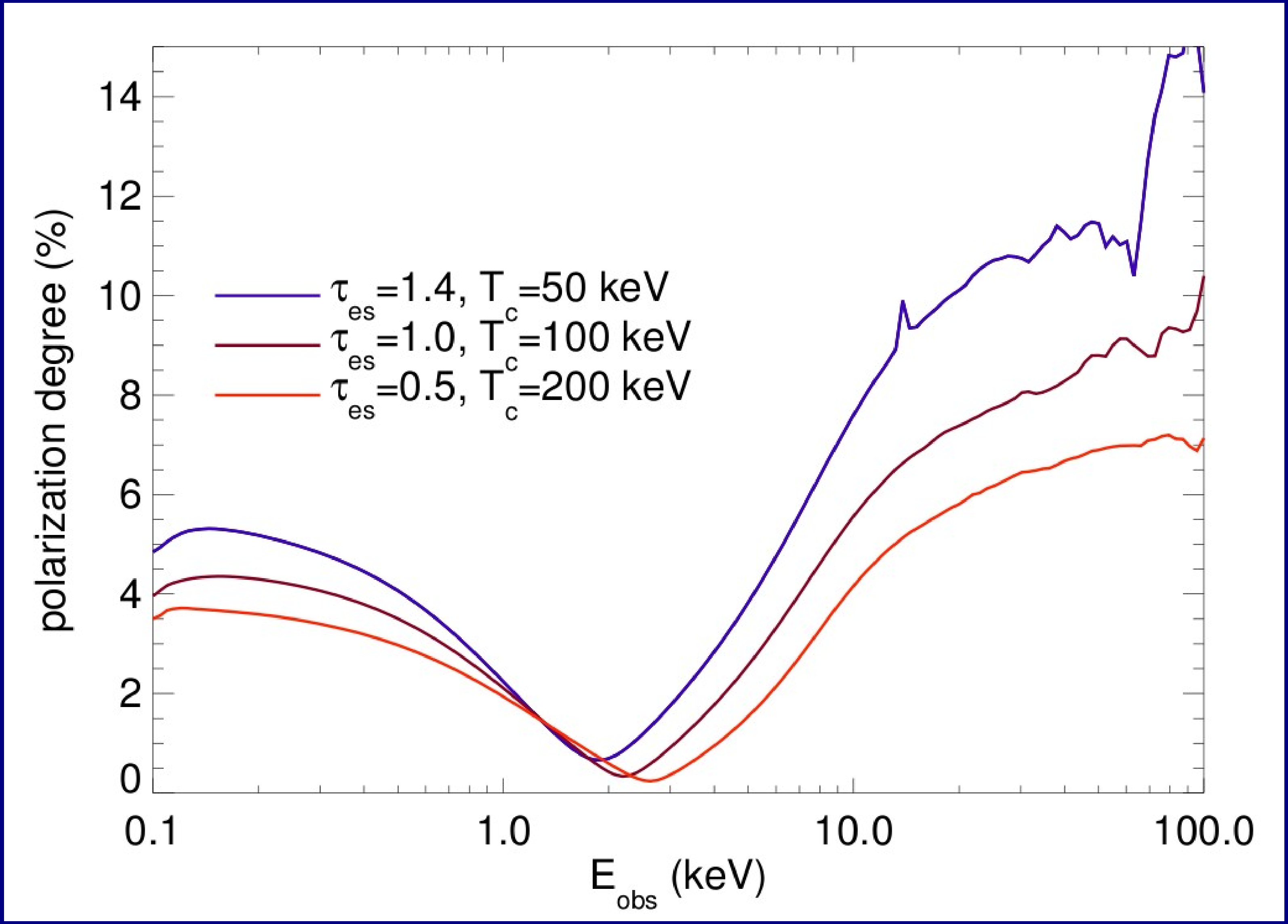
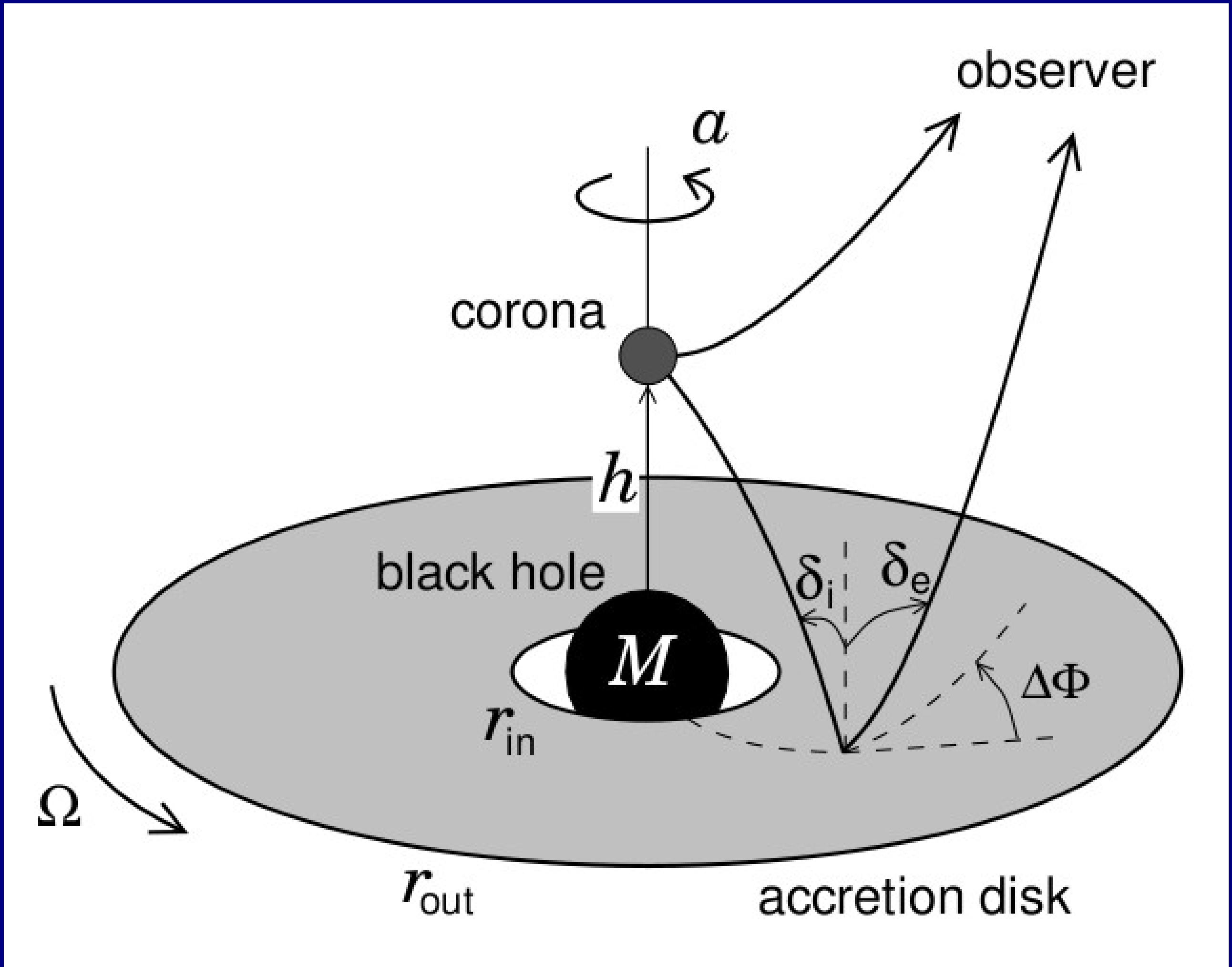


Irradiated disks - the lamp post geometry

Dovčiak et al (2011)

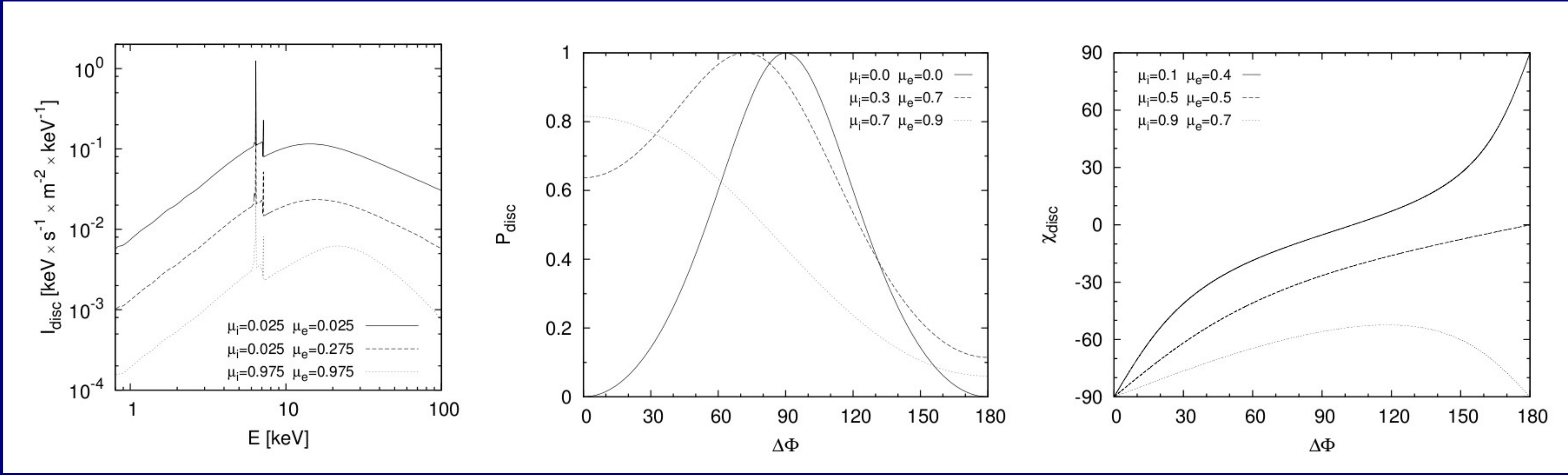
See also

Martocchia & Matt (1996)
Kazanas & Nayakshin (2001)
Miniutti & Fabian (2004)
...



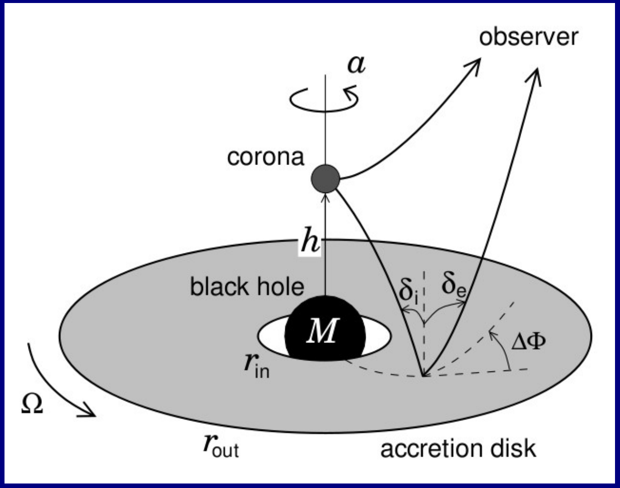
The lamp post geometry

Reprocessed emission in the local disk frame (Dovčiak et al 2011)



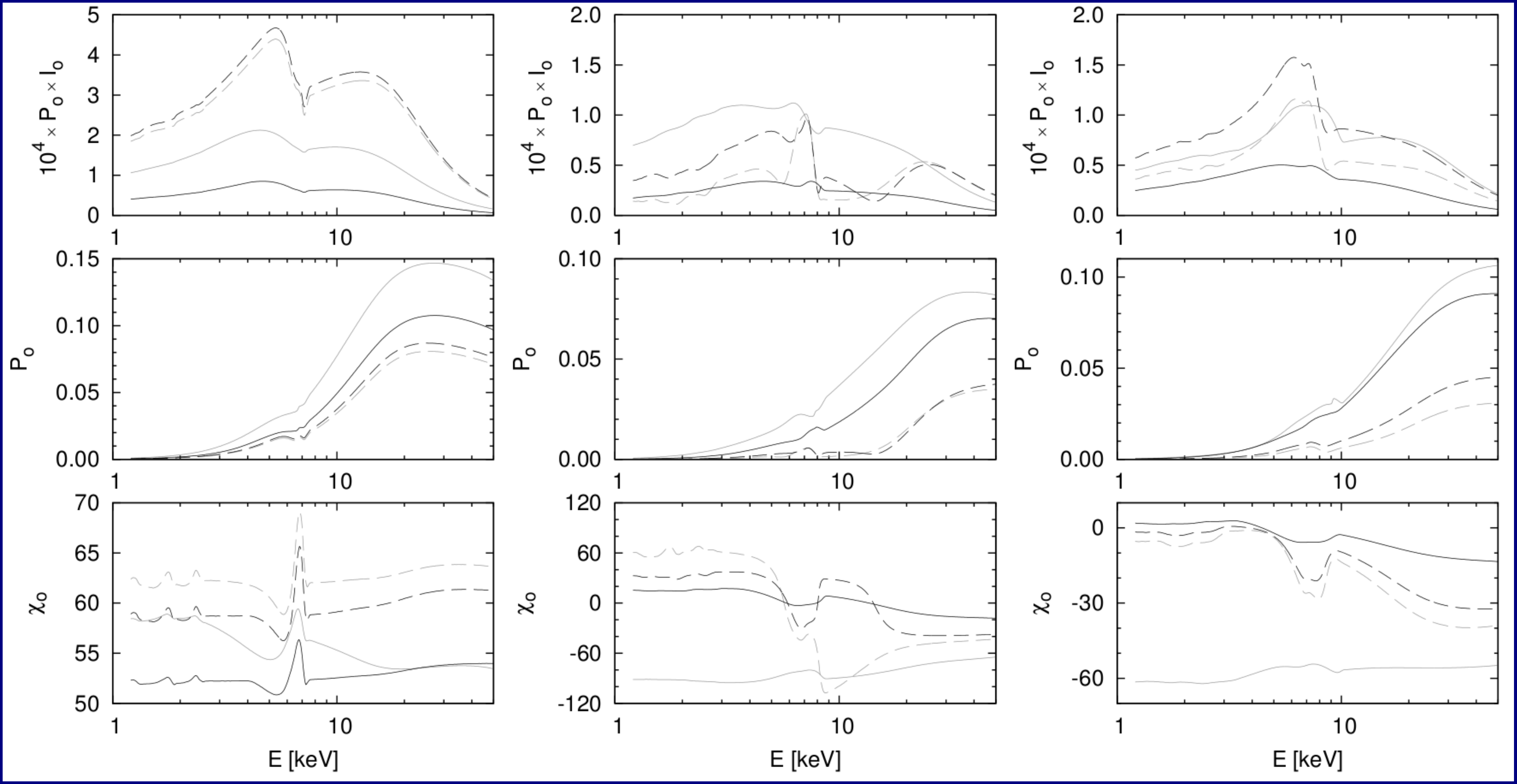
- The shape and polarization of the locally reprocessed radiation depends strongly on the position on the disk.

- Polarization degree and angle cover the whole range of possible values.



The lamp post geometry

Dovčiak et al (2011)

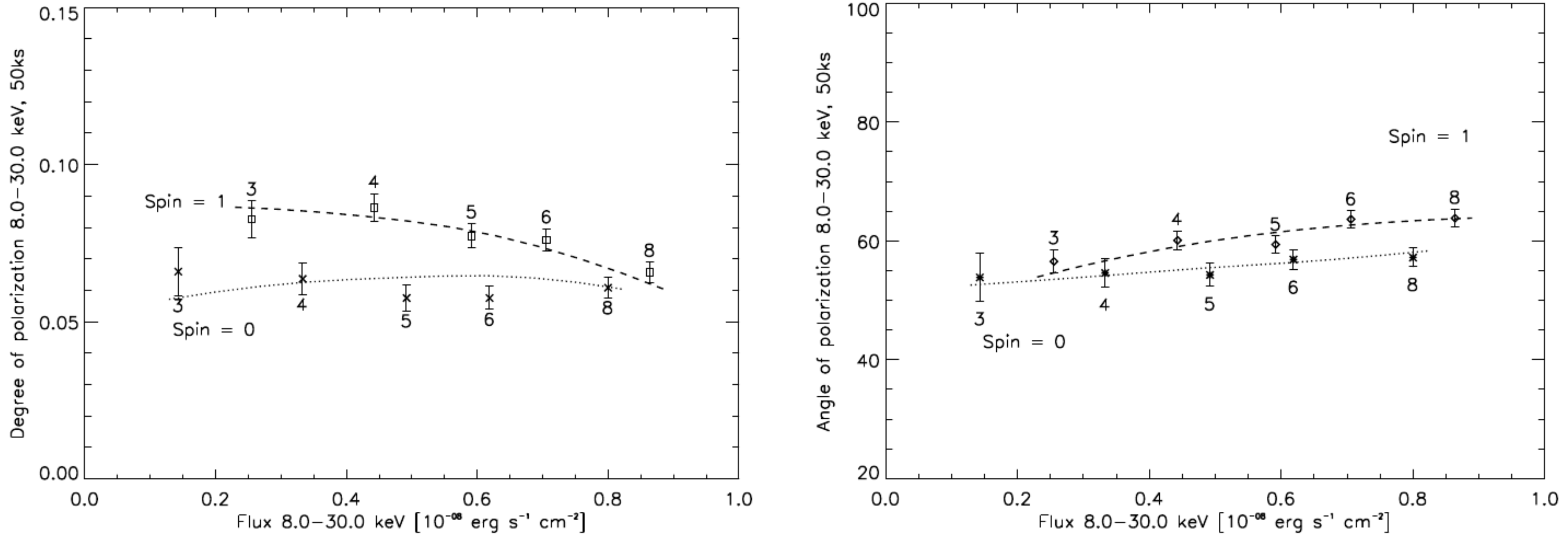


_i_ = 30° **_i_ = 60°** **_i_ = 85°**

Moving the lamp post – polarization variability

- Simulation of a series of snapshots for different heights of the primary source (medium size mission including broad-band polarimetry)
- The two extreme spin states are still distinguishable, but less than for the thermal disk

XTE 1650+500 — NHXM simulation of T = 50 ksec snapshots, *i* = 30°



Dovčiak et al. (2011)

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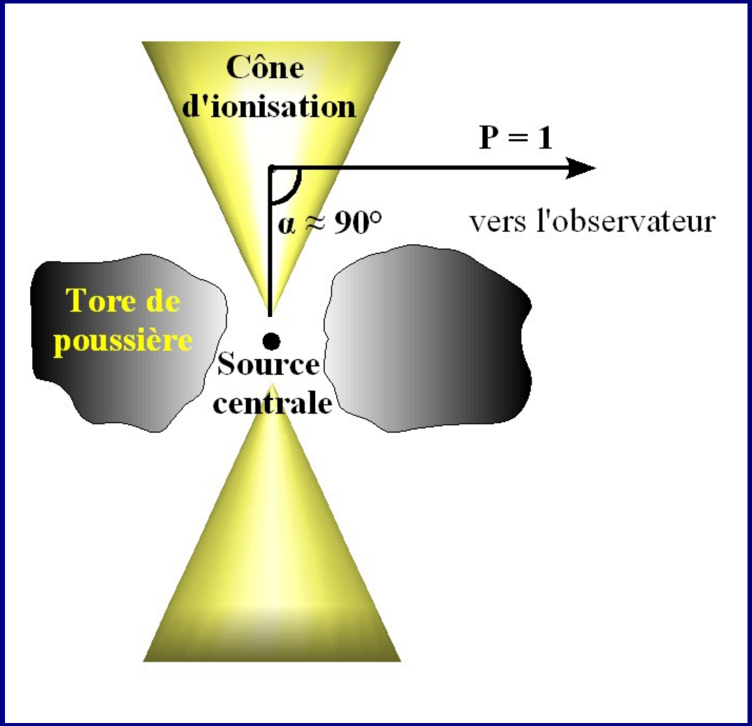
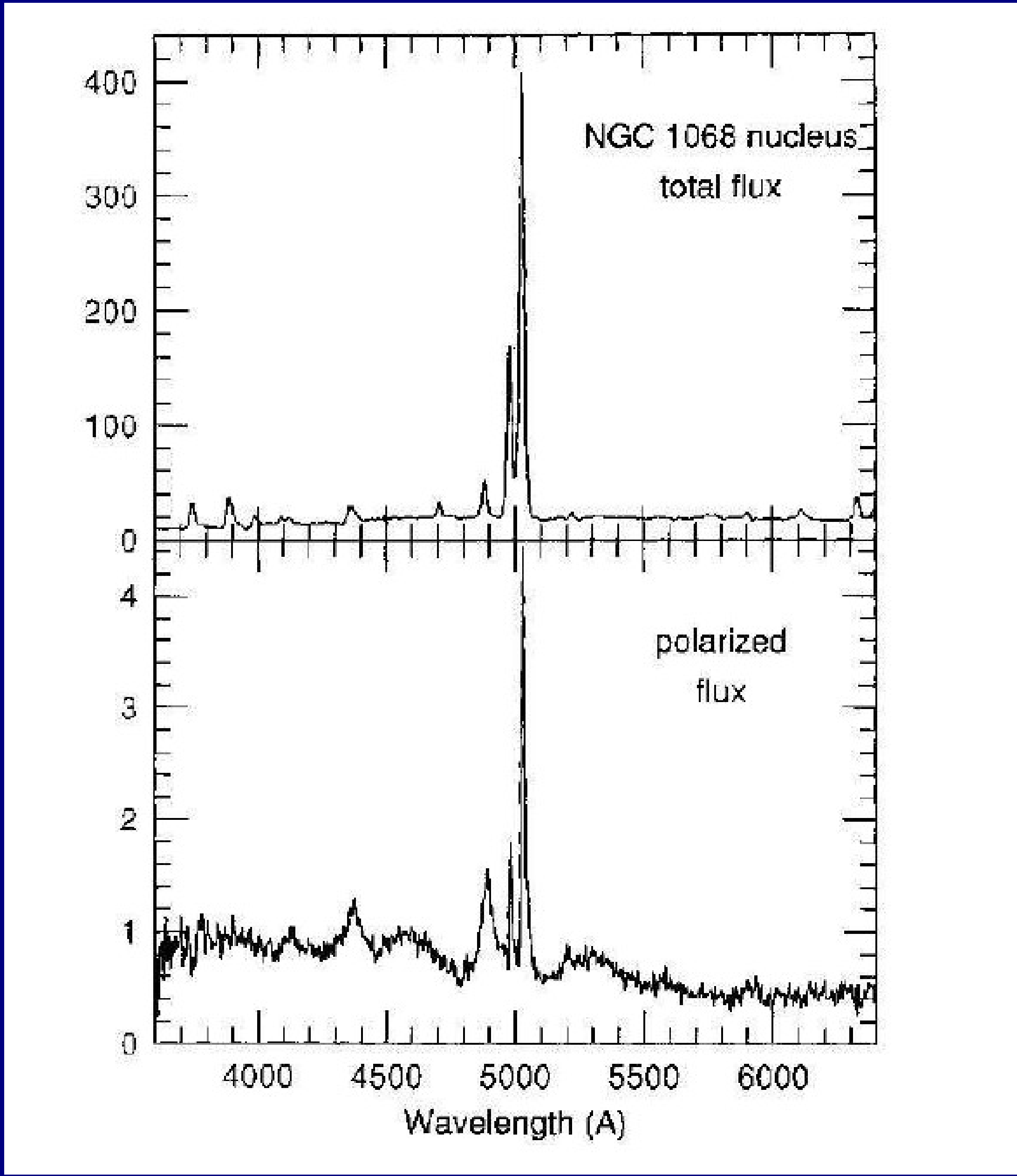
NGC 1068 – the first hidden type-1 AGN

A major break-through for the unified model of NGC 1068 (Antonucci & Miller 1985)

→ **periscope view of AGN in <u>polarised</u> flux**



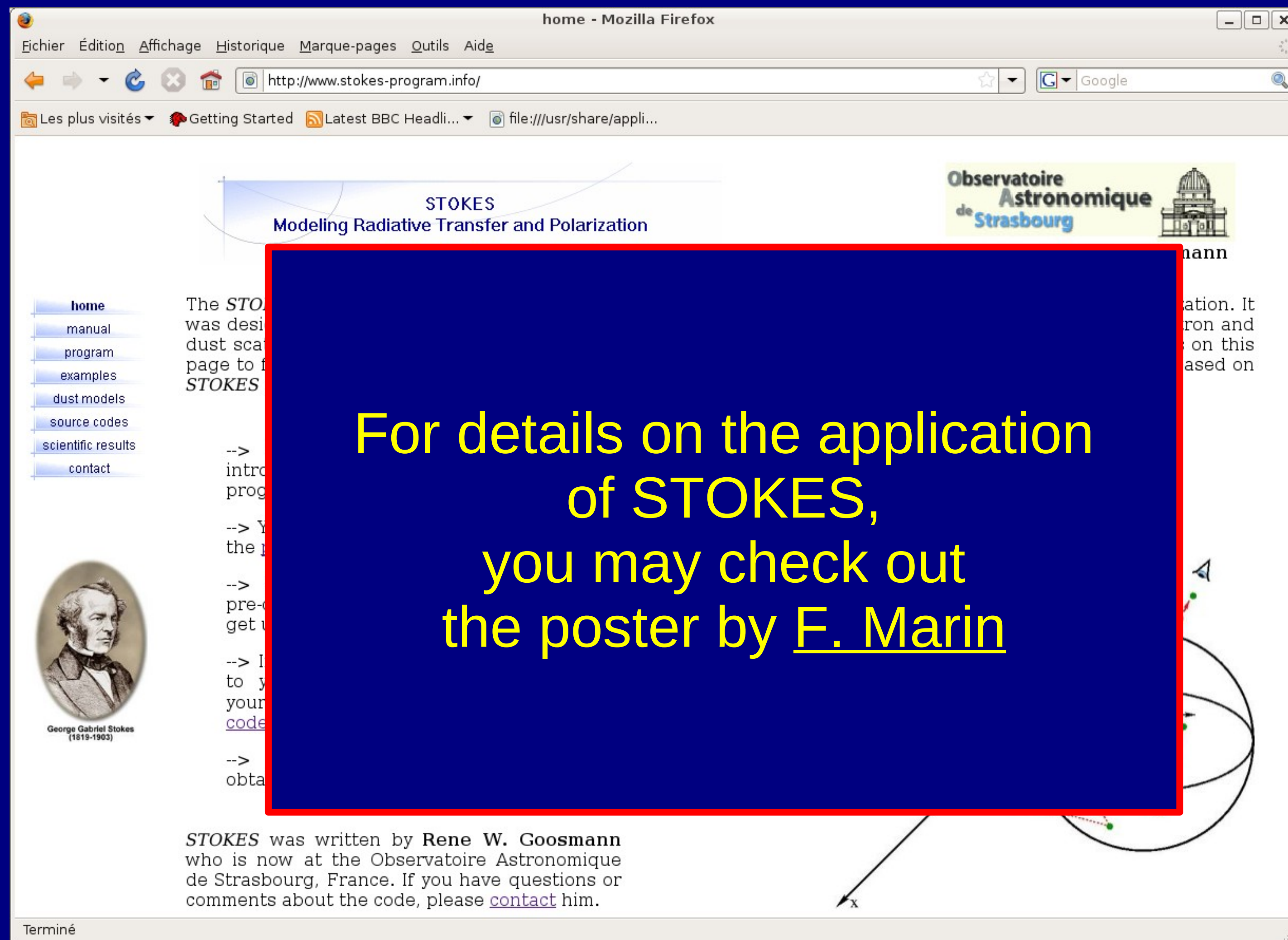


Modeling polarization with STOKES

- Monte-Carlo radiative transfer in 3D
- Various geometries for the emission / scattering regions
- polarisation due to (multi-)electron scattering and dust (Mie-)scattering
- Resonant line scattering routines implemented
- Photo- and K-shell ionization
- variabiliy and evolution of the system

Public access to Version 1.0

http://www.stokes-program.info/

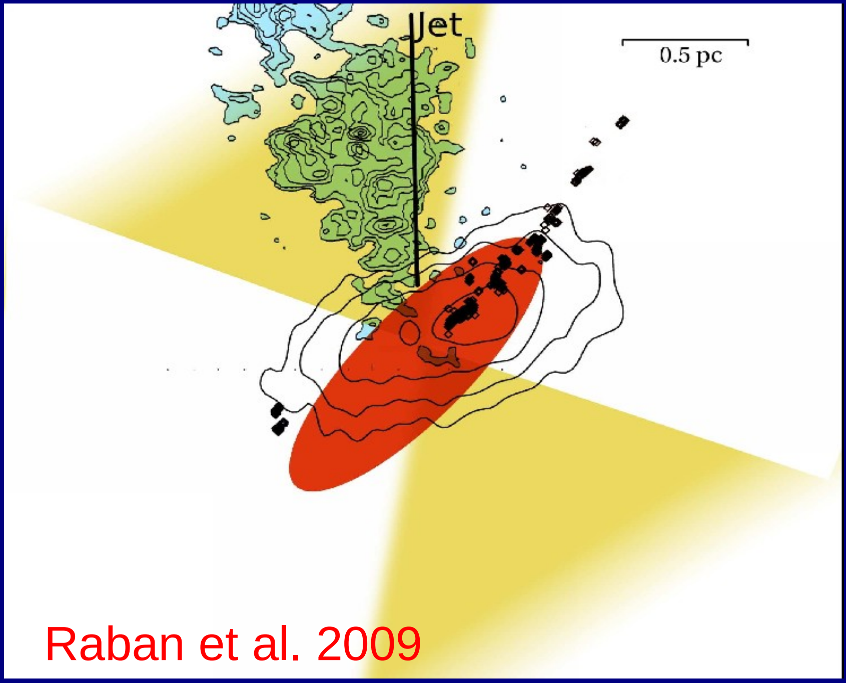


For details on the application of STOKES, you may check out the poster by F. Marin

X-ray polarimetry of NGC 1068

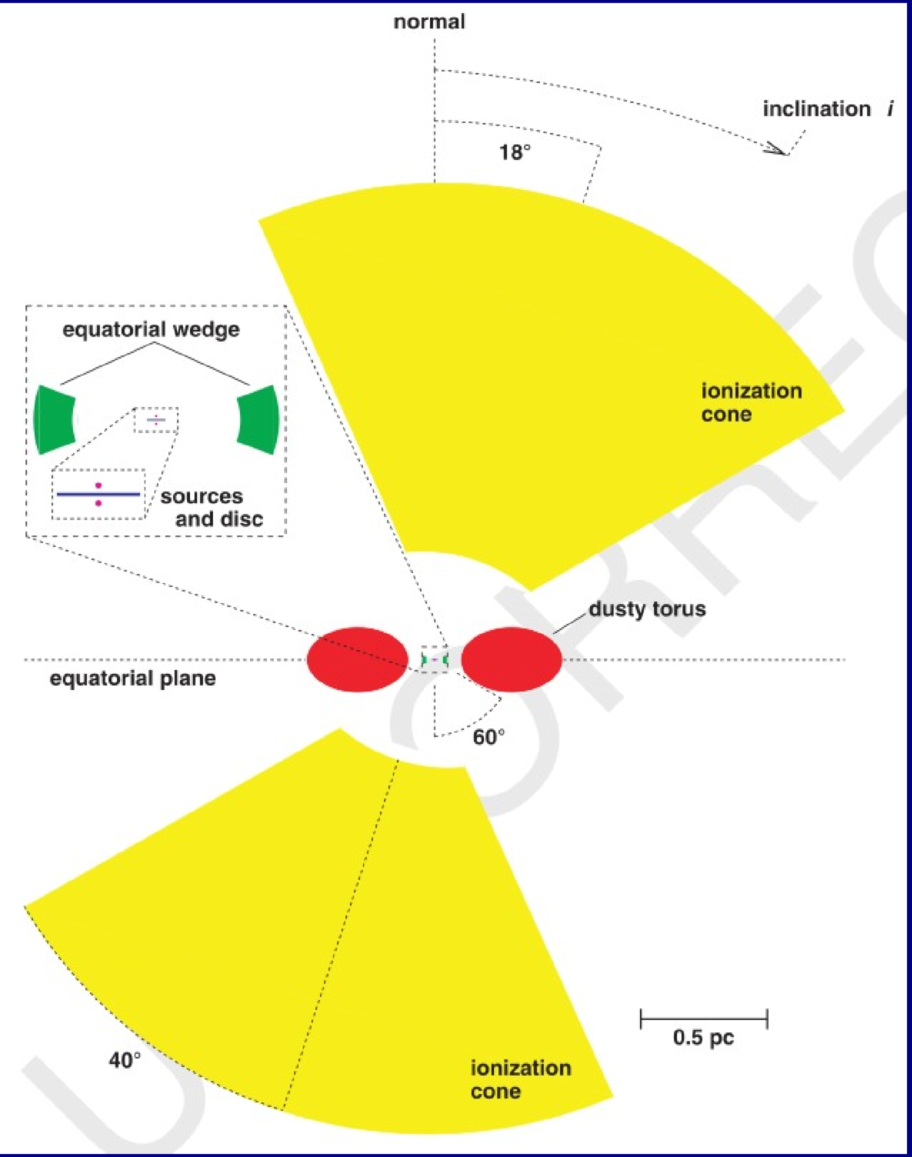
Modeling of an irradiated accretion disk, a dusty torus with Θ=60°, and inclined outflows as suggested by Raban et al. (2009).

Goosmann & Matt 2011



Raban et al. 2009

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



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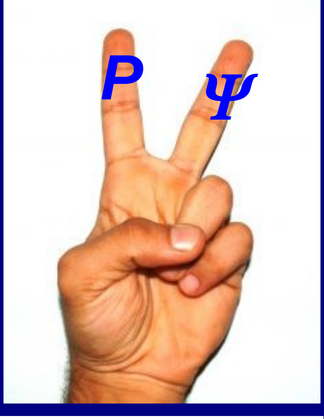

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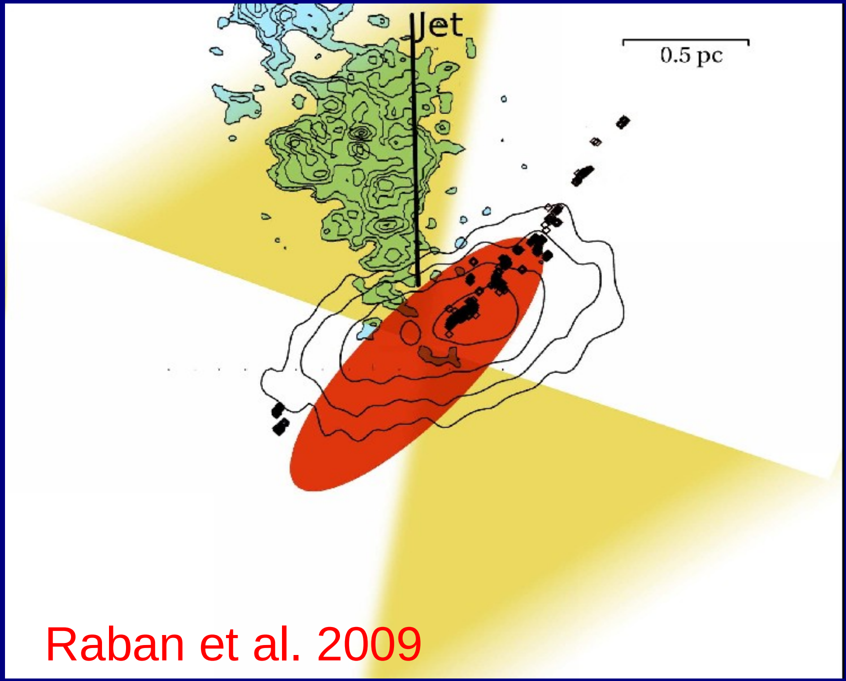
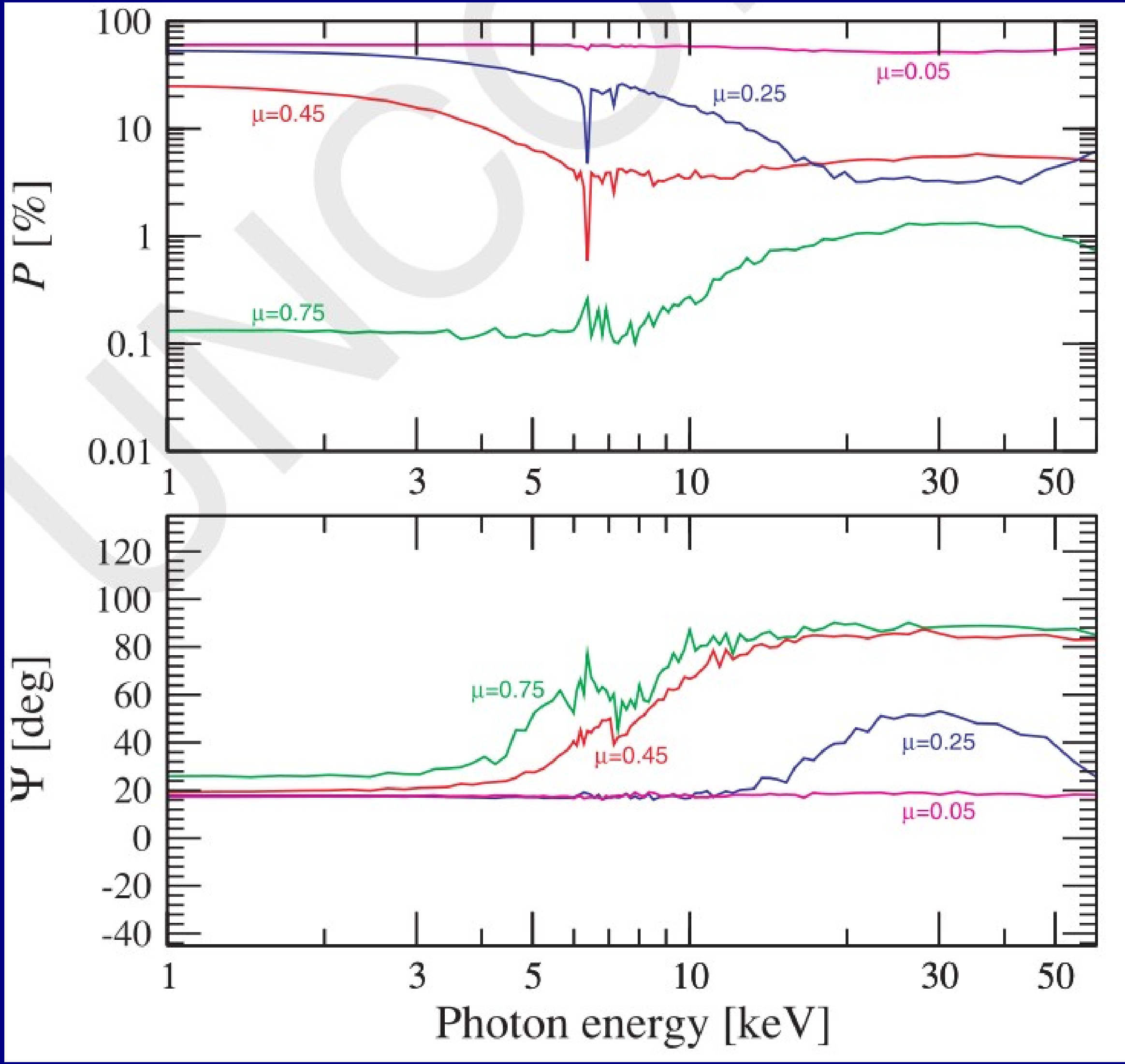
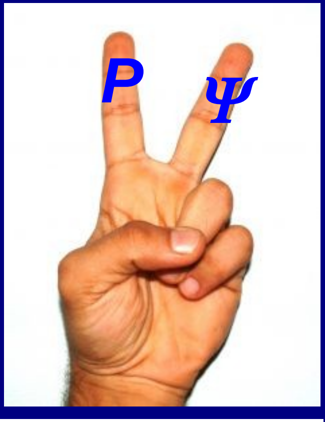


Raban et al. 2009



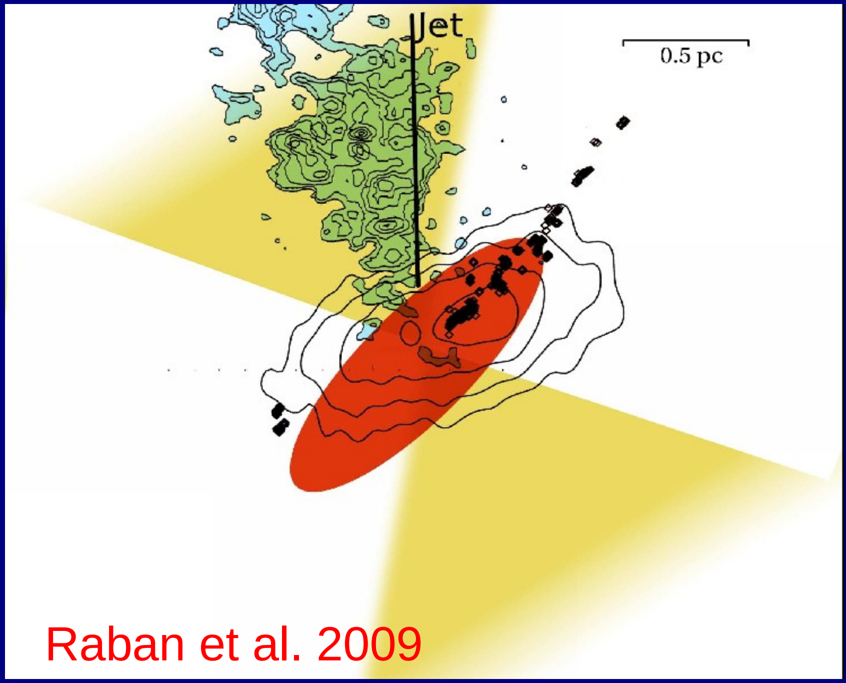
Possibility to constrain the relative angle between torus and outflows by broad-band polarimetry!

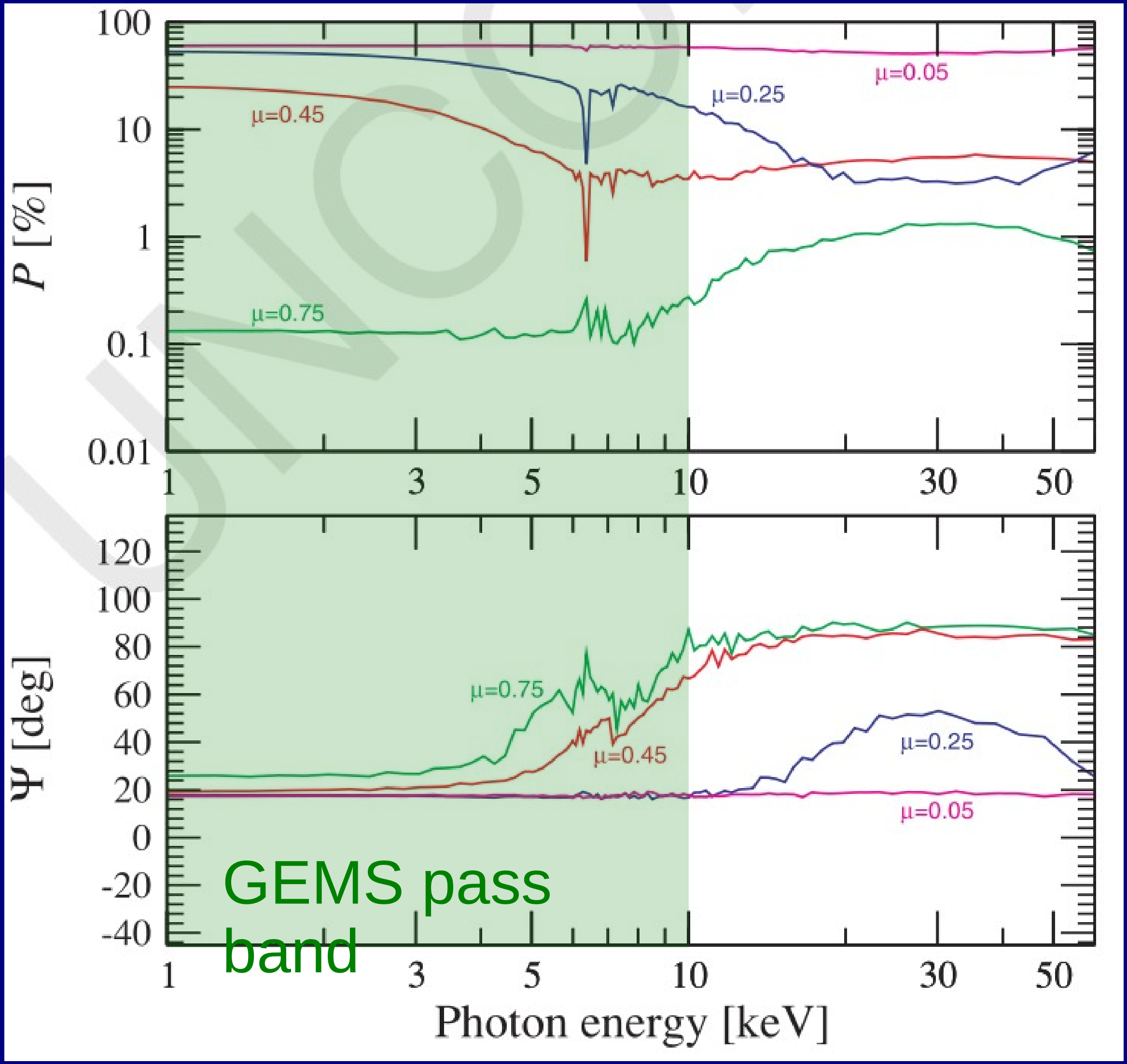
X-ray polarimetry of NGC 1068



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

Goosmann & Matt 2011





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

OUTLINE

- Why should we care about polarization?
- Some basics on polarization of electromagnetic radiation
- Techniques to measure X-ray polarization
- X-ray polarization produced in the vicinity of black holes
- Modeling the X-ray polarization in black hole X-ray binaries
- Modeling the X-ray polarization in AGN
- **What to take home from this review**

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WHAT I NEGLECTED...

For the sake of pedagogy, this 40-minute lecture did not cover all important aspects of X-ray polarimetry. I rather focused on the effects that do not involve strong magnetic fields.

Here are some references to theoretical work on X-ray polarization in magnetized plasma and/or black hole jets (+references therein):

- Davis et al. (2009) – effects of magnetic fields on the X-ray polarization from an accretion disk

- McNamara et al. (2009) – X-ray polarization from jets (see also the talk by D. Russel)

Comprehensive overviews for broad-band X-ray polarimetry and its science drivers can be found in Krawczynski et al. (2011) and Tagliaferri et al. (2011).

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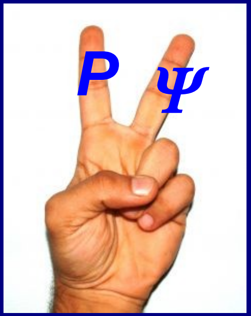
SOME CONCLUSIONS



- X-ray polarimetry is going to reveal details of the accretion and ejection geometry and the metric around the black hole.

- To interpret the upcoming polarization data it is important to construct better models for the local (polarized) emission.

- We need more simulated data for the expected jet X-ray polarization (based on the existing theoretical work).

- I think that the results obtained by GEMS are crucial for the future of all X-ray polarimetry.

- Extension to harder X-ray polarimetry (10-35 keV) would be a very useful, following step. The technology is already available.

- **Stay tuned – there is certainly more to come!**

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