Interpreting spectropolarimetric results across a broad spectral range - 3D radiative transfer with the STOKES code

René W. Goosmann

Astronomical Observatory Strasbourg, France

Observatoire astronomique de Strasbourg

Talk at the 9th Serbian Conference

on Spectroscopic Line Shapes in Astrophysics (SCSLSA)

16th May 2013

Banja Koviljača, Serbia

SEVENTH FRAMEWORK PROGRAMME

AGENCE NATIONALE DE LA RECHERCHE ANR

Credits to our polarization network

Astronomical Institute
Academy of Sciences
of the Czech Republic

Vladimír Karas
Michal Dovčiak

Fabio Muleri

Giorgio Matt

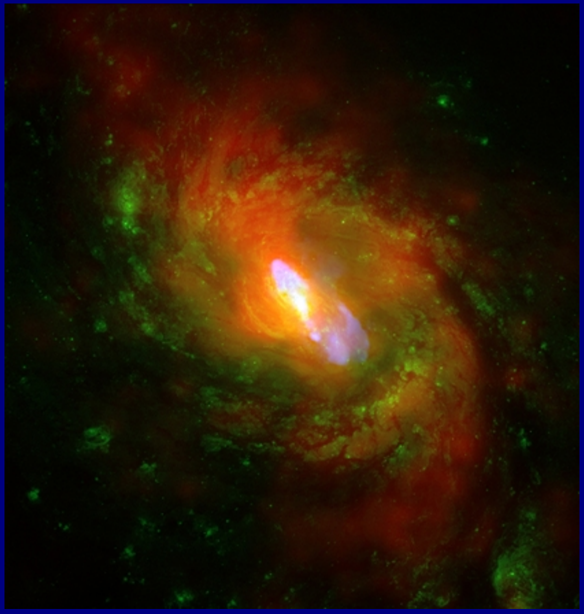
C. Martin Gaskell

Delphine Porquet
Frédéric Marin
Francesco Tamborra
Nicolas Grosso
René W. Goosmann

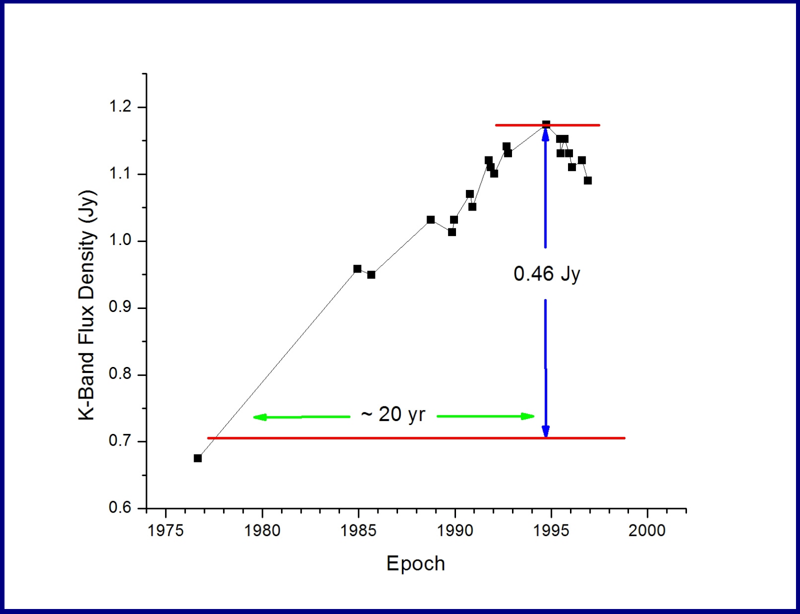
Why should we care about polarization?

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))

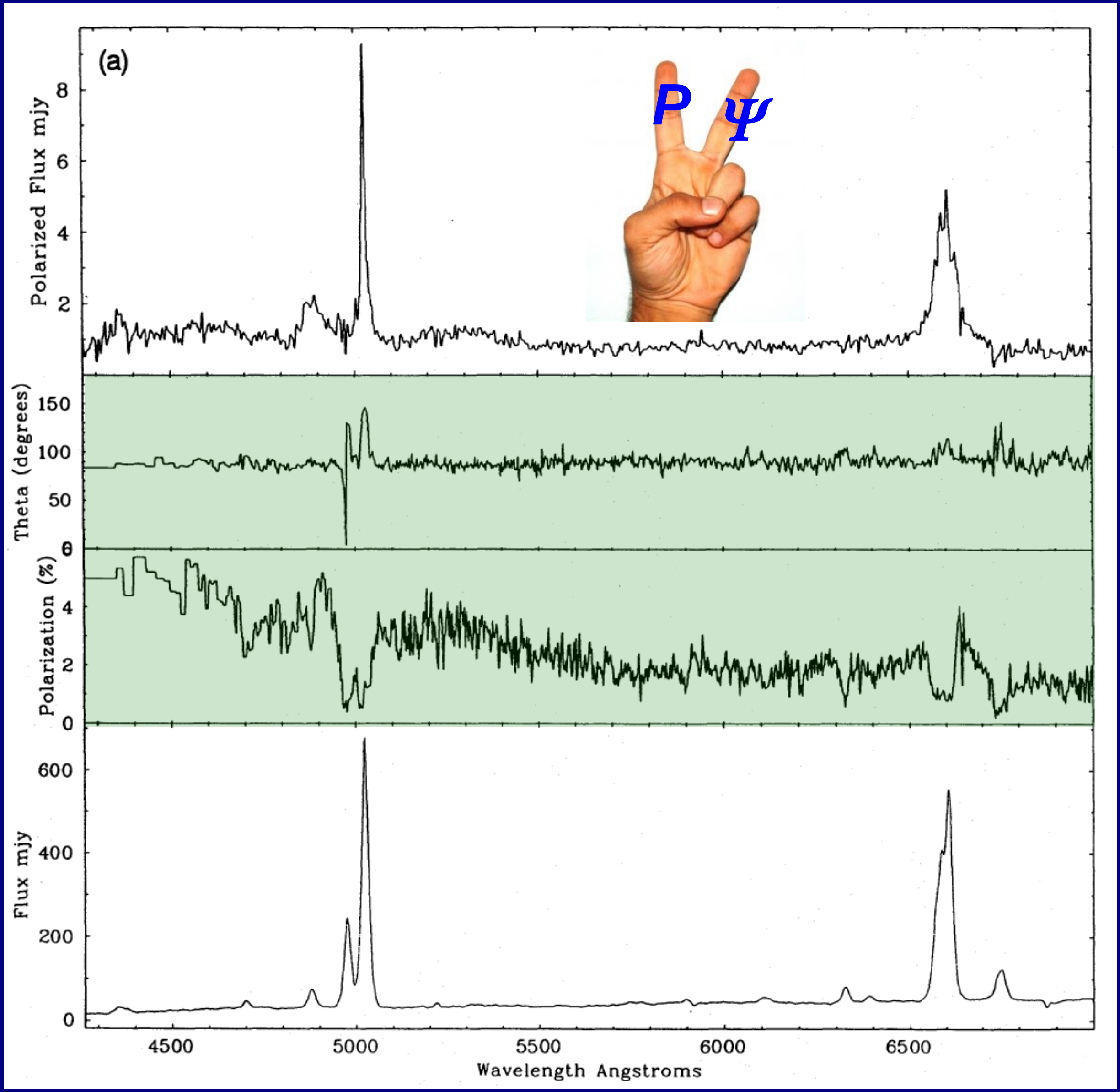


2.2 micron light curve of NGC 1068 (work by I. Glass)

Why should we care about 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.

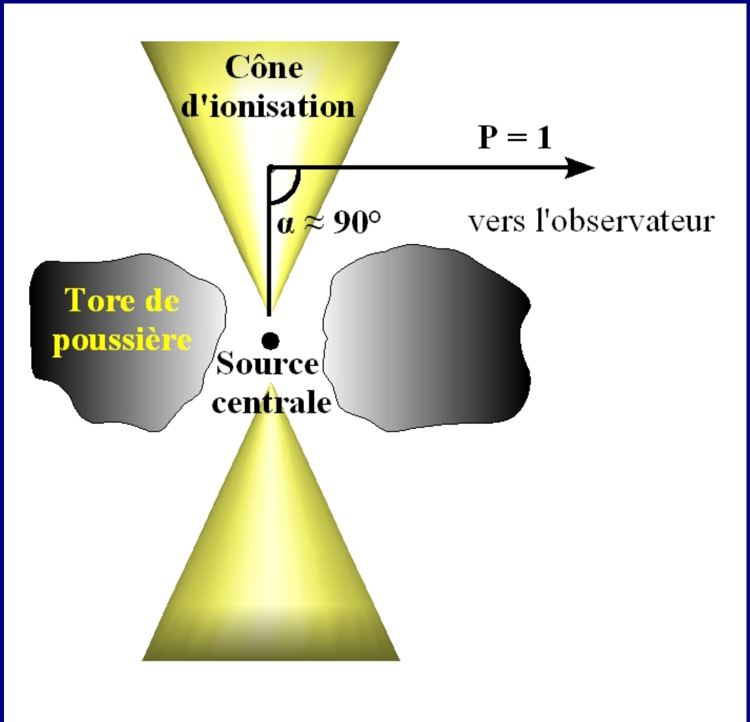


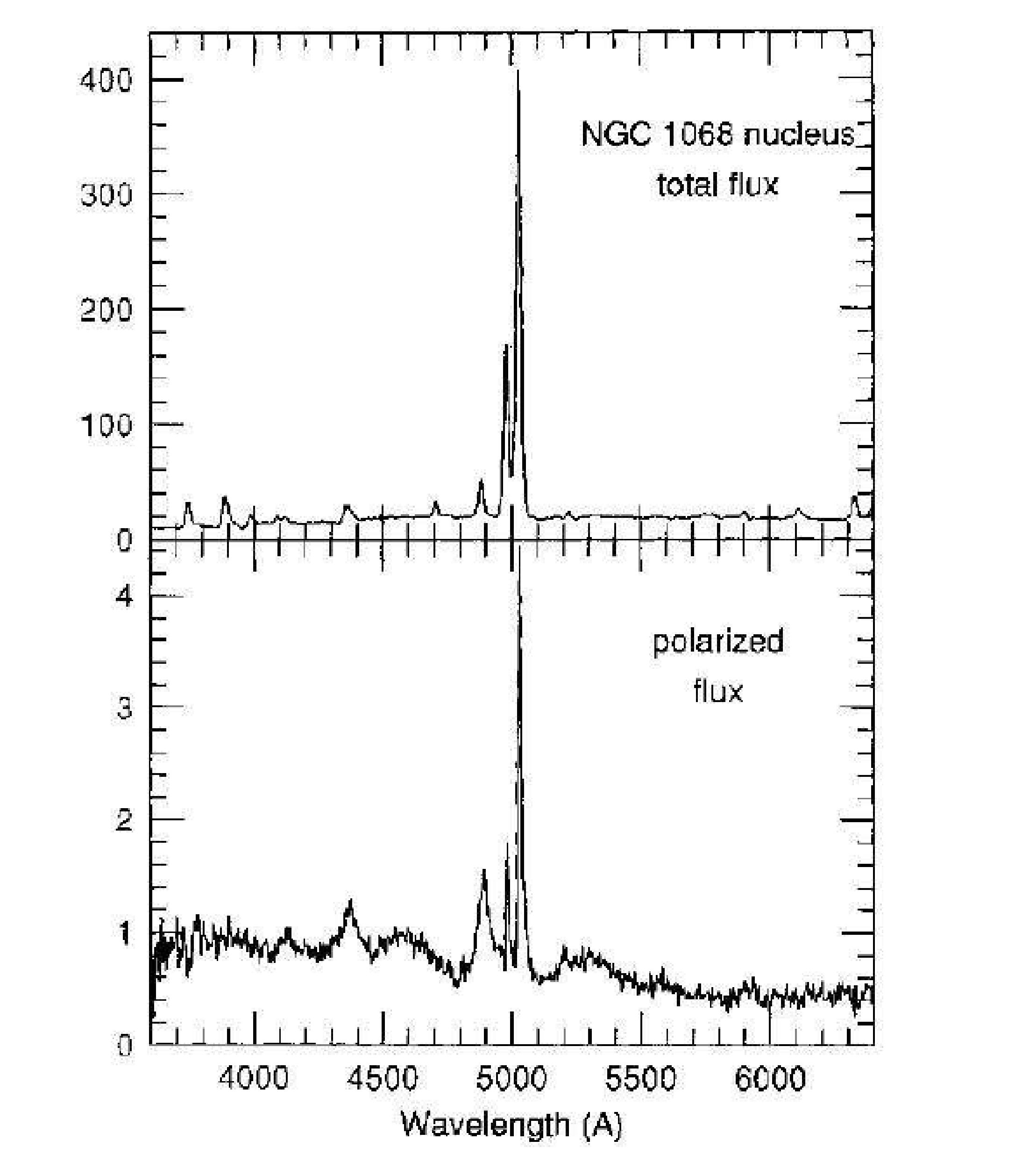
Inglis et al. 1995

Radio-quiet objects Hidden type-1 AGN

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

→ periscope view of AGN in polarized flux





Exploiting and modeling polarization in astrophysics

- The basic concept of (linear) polarization
- Techniques to observe broad-band polarization
- Mechanisms producing polarization
- Modeling scattering-induced polarization with *STOKES*
- Summary and conclusions

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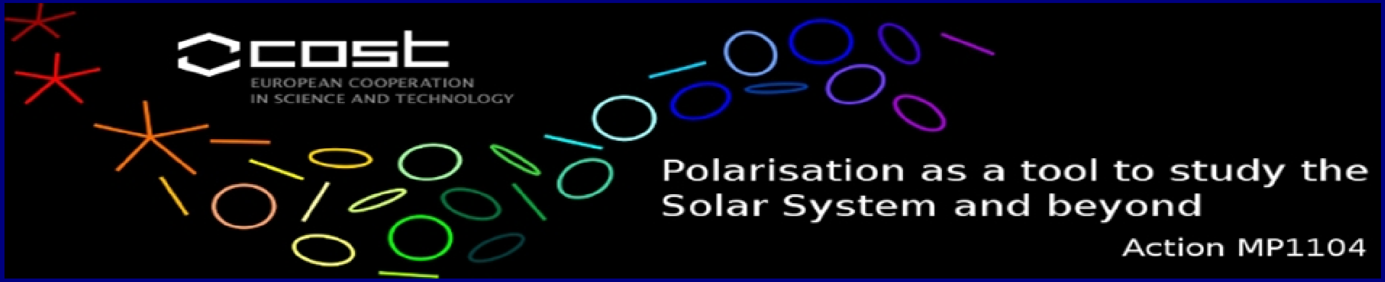

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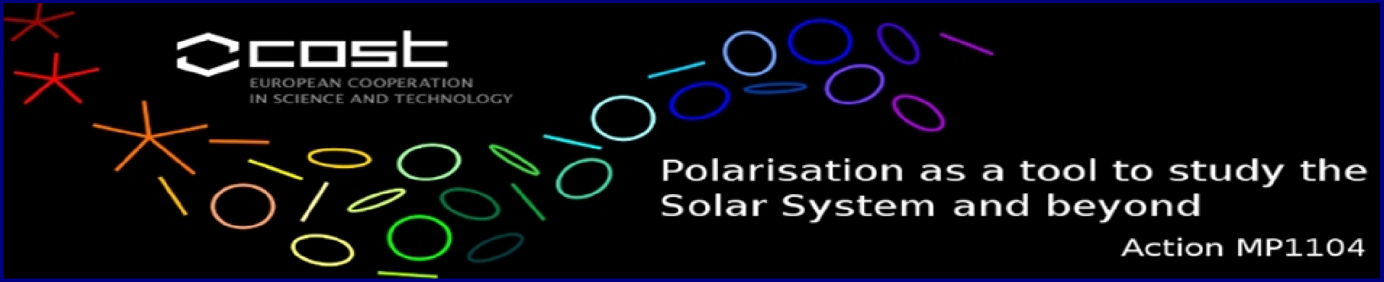


The root of all electromagnetism...

Maxwell's equations

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

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

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

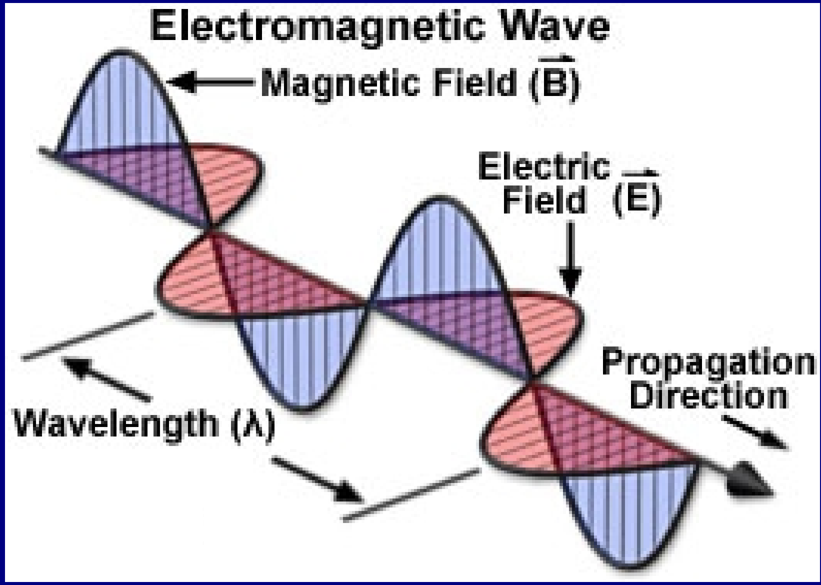
$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \boldsymbol{j}_c$$

where

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

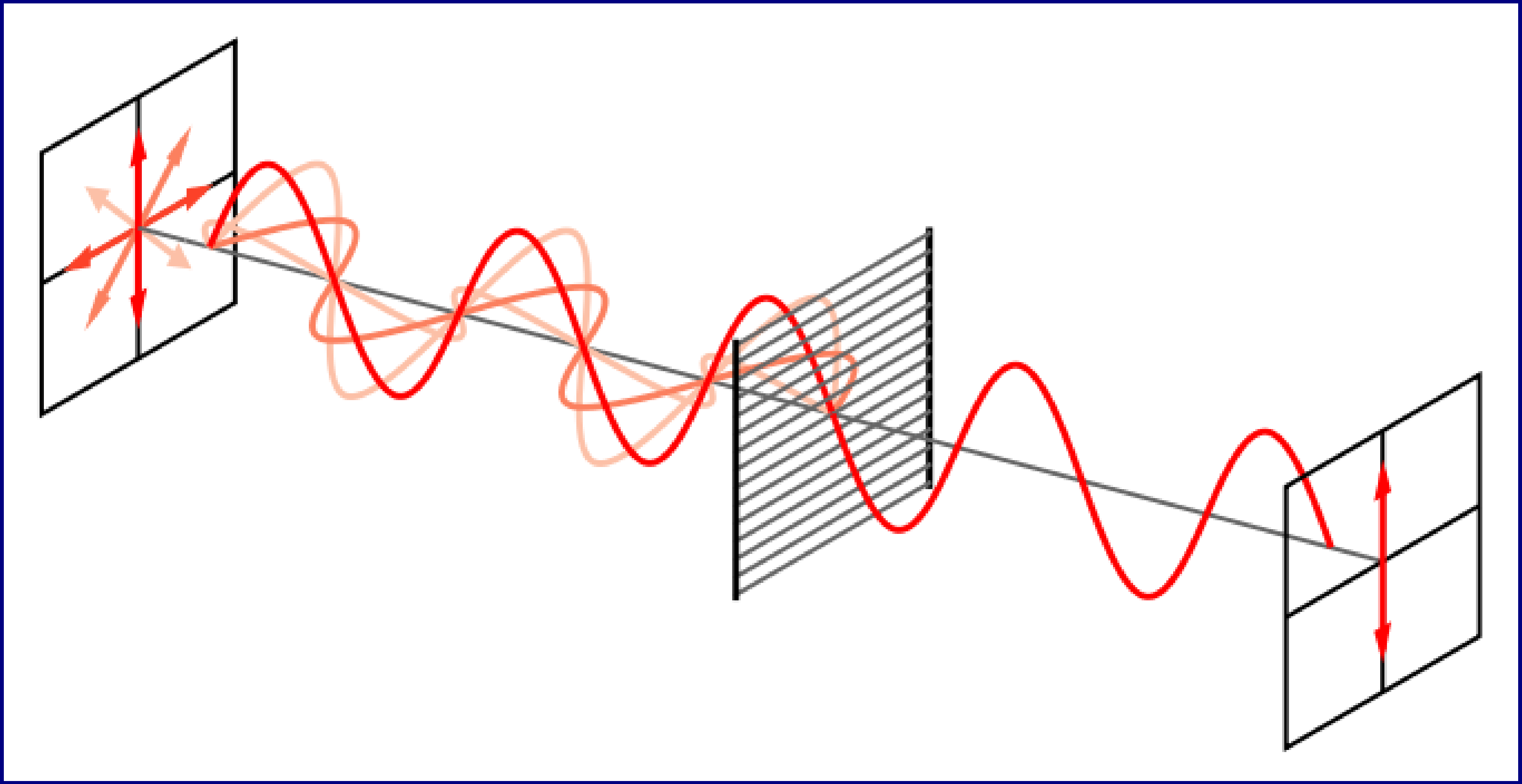
3D wave equation for the electric field

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



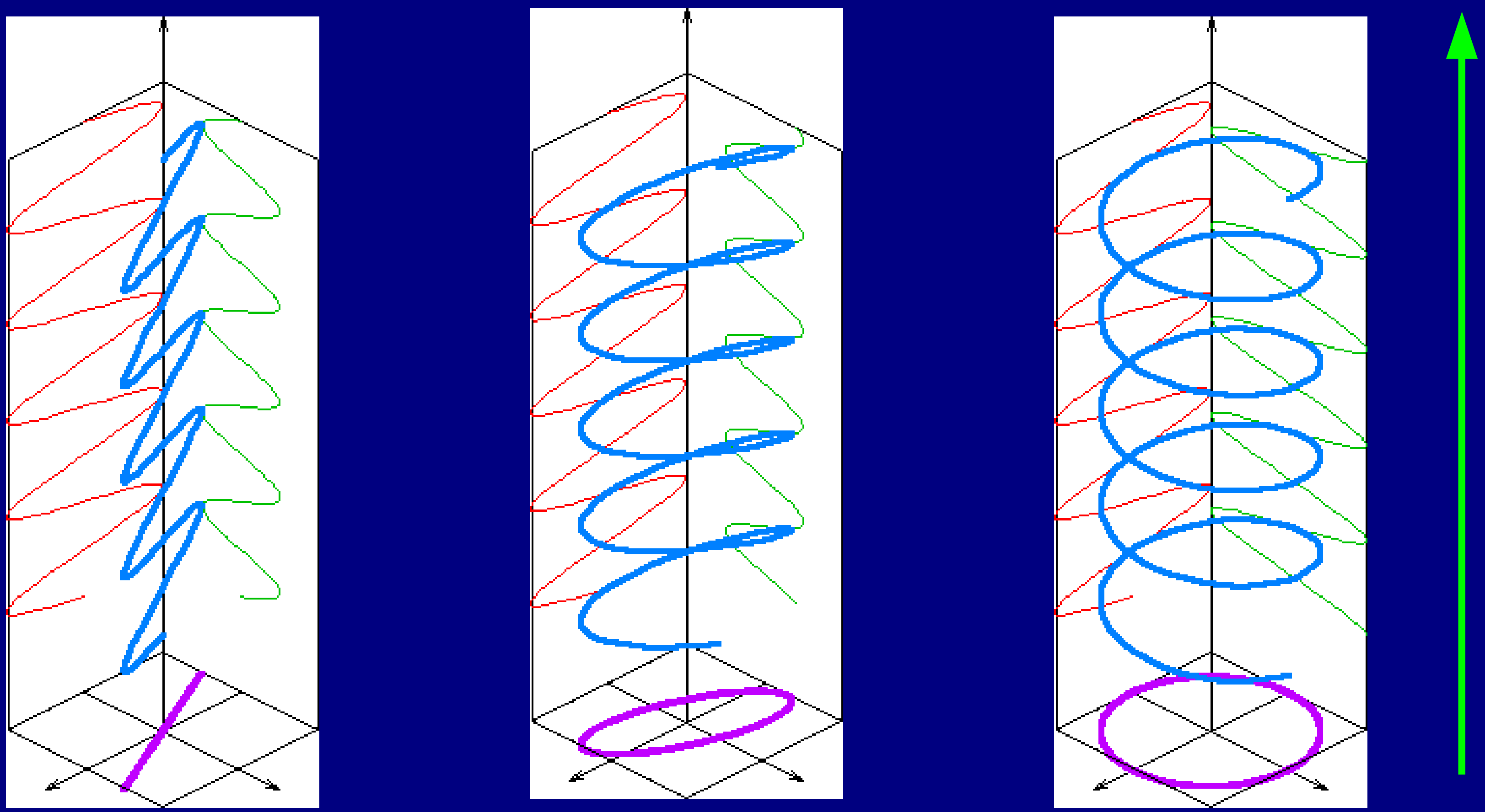
Linear polarization of light

The polarization state of an electromagnetic wave denotes the direction of the electric field vector (classical picture)



Polarization of coherent light

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



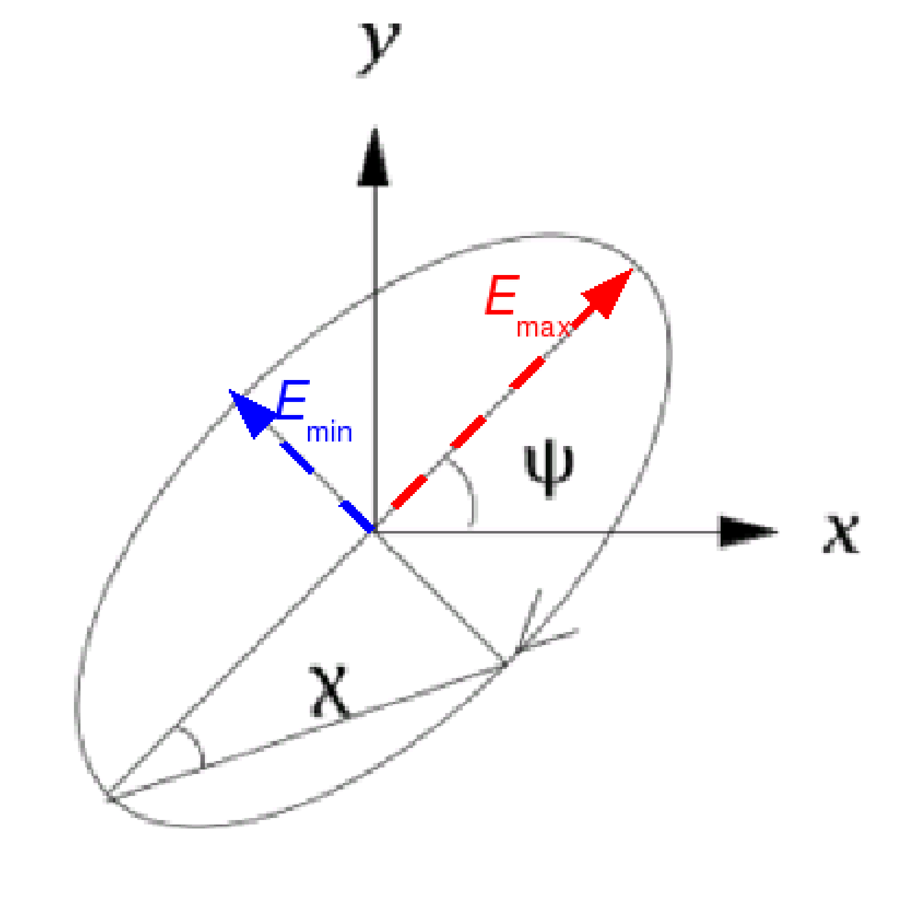
linear elliptical circular

The polarization ellipse

The linear polarization degree *P* is defined by

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

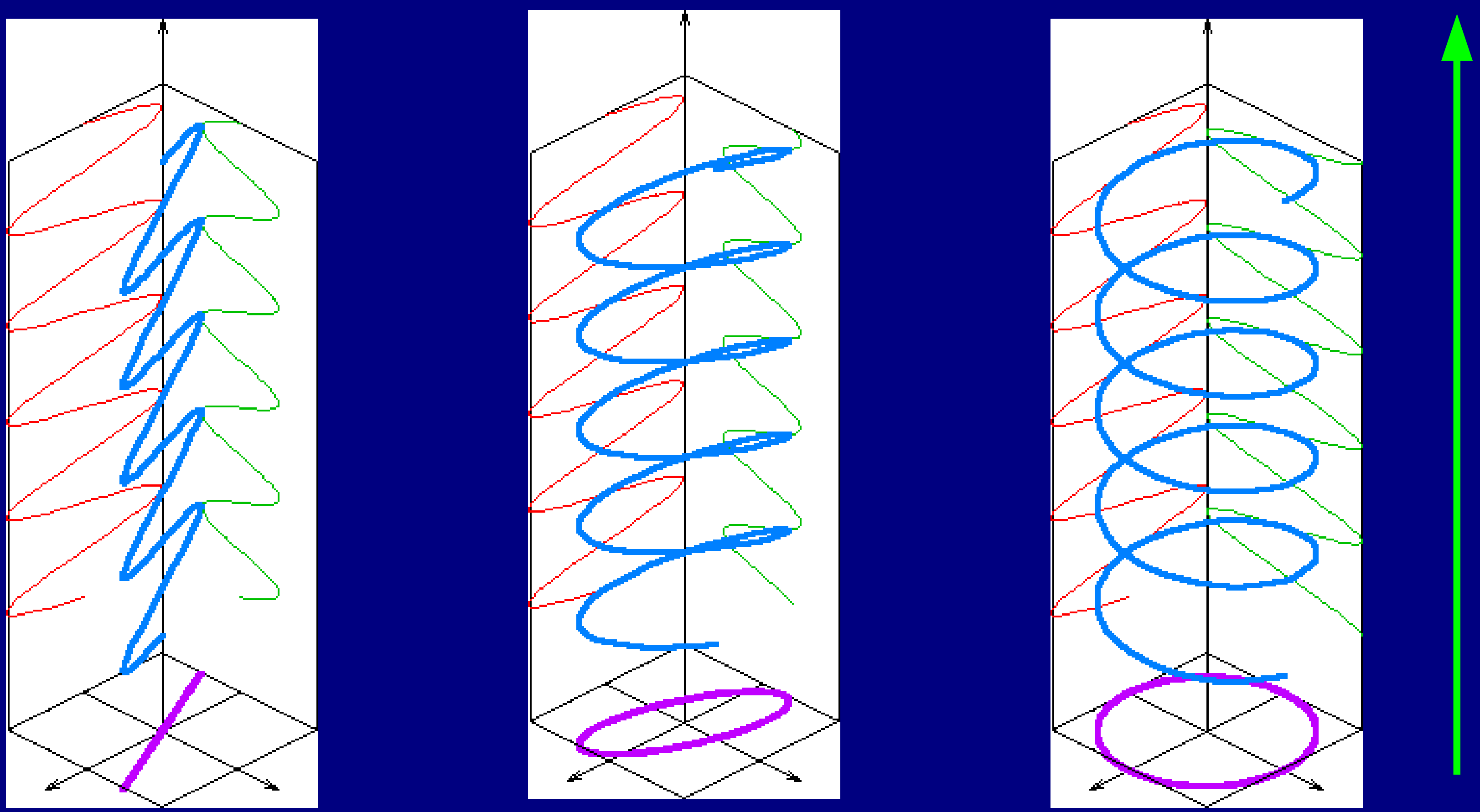
Note: $0 \leq P \leq 1$.



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 more important in most wave bands than circular polarization.

The Stokes parameters

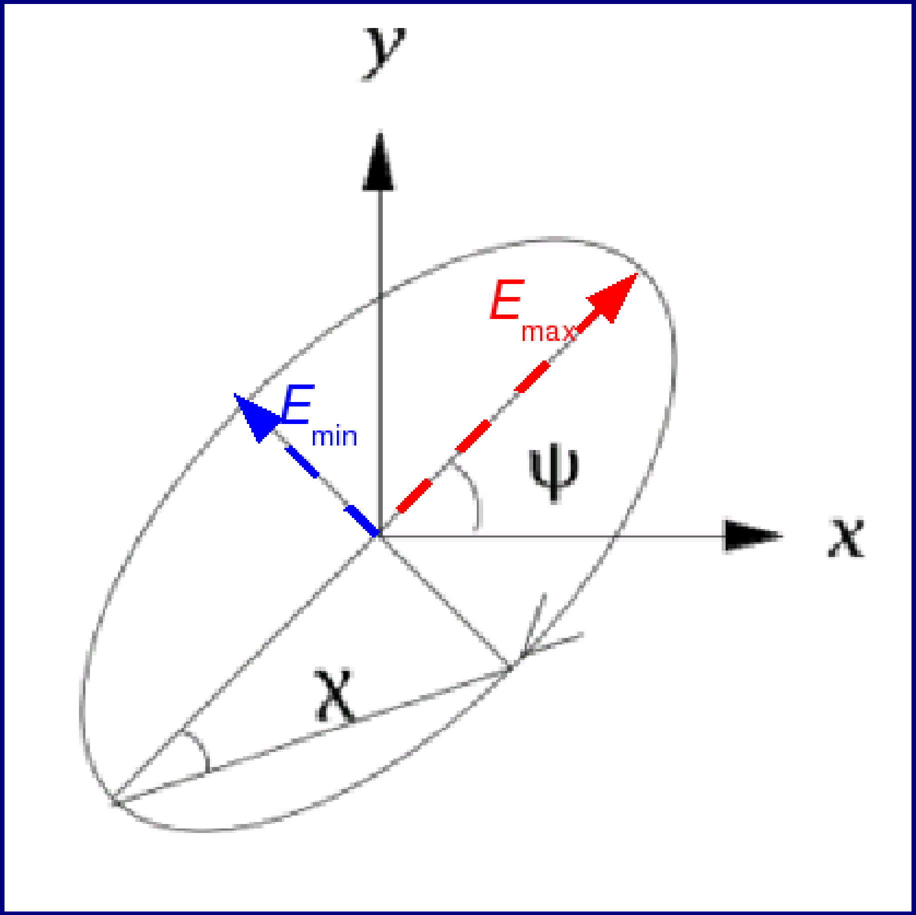
The polarization state is completely described by the Stokes parameters:

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

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

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

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

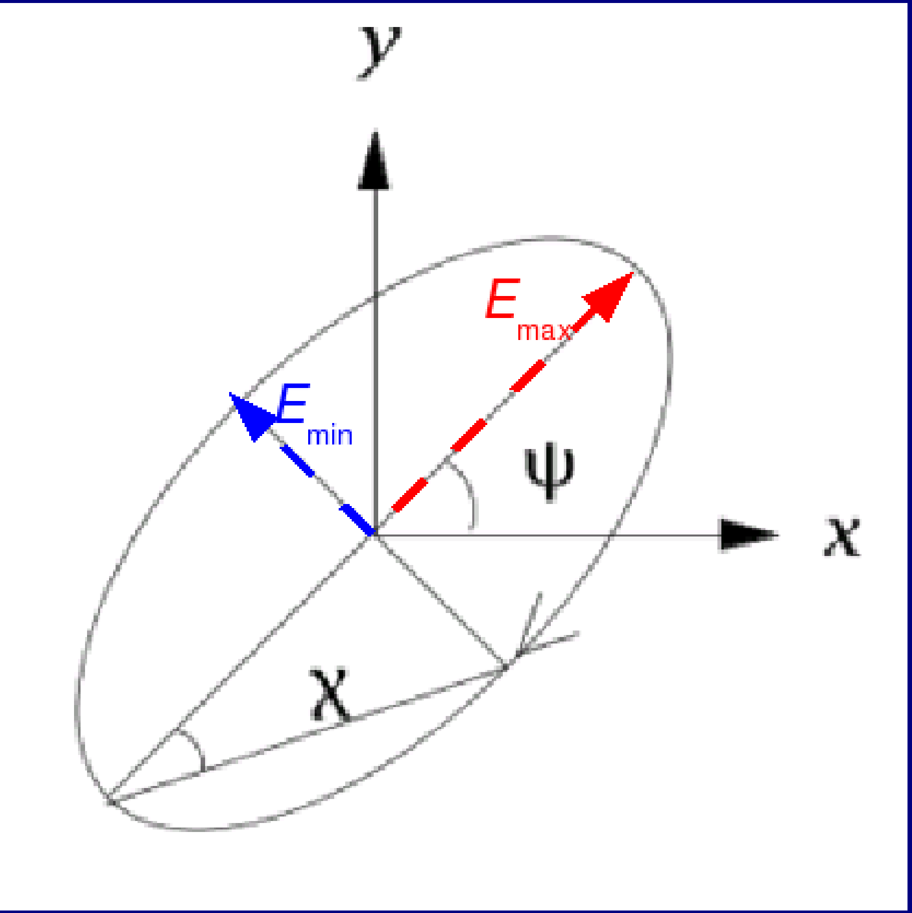


The Stokes parameters

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

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

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



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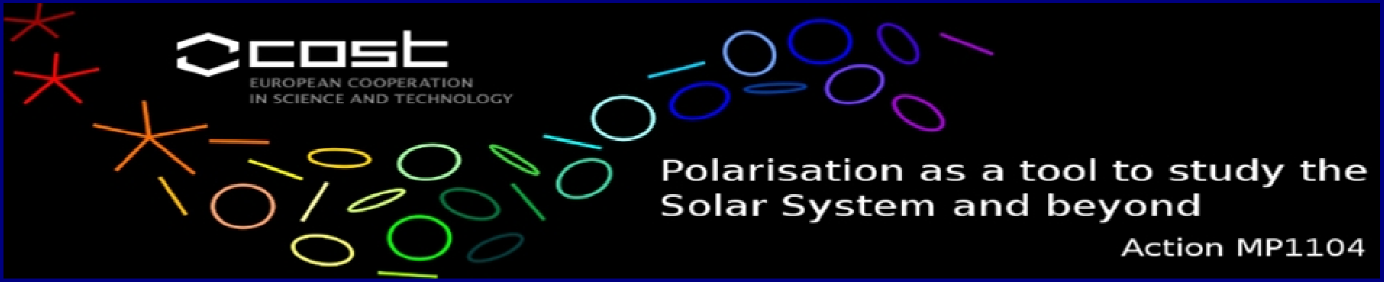
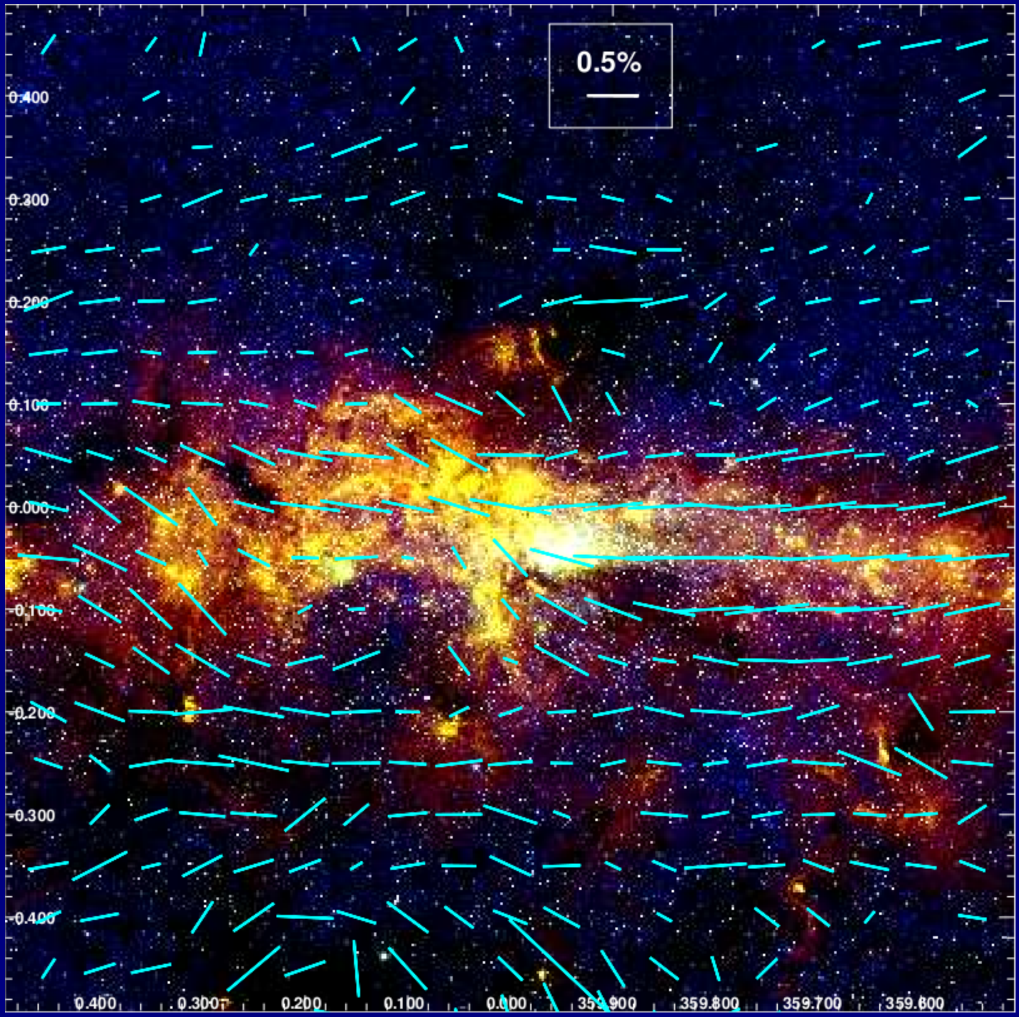


Observing multi-wavelength polarization

In the radio band, polarimetry comes automatically and for free (position of the antenna)

Infrared polarimetry using rotating wave-plates

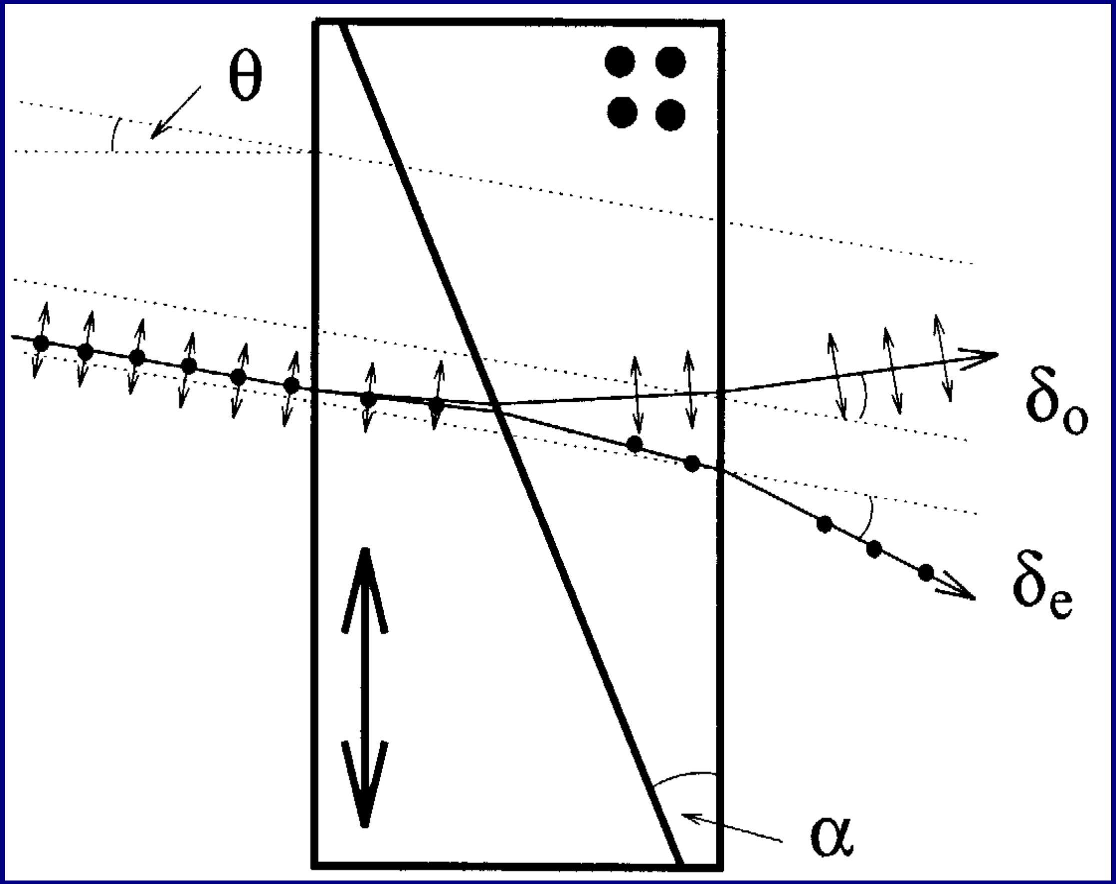


Observing multi-wavelength polarization

- In the optical wave band It is key to separate the two perpendicular polarization components of the light beam.

- This is done using two blocks of ***birefringent*** material.

- In a birefringent block the speed of light and the refraction properties depend on the polarization orientation.



Wollaston prism (Olivia et al. 1997)

Observing multi-wavelength polarization

X-ray polarimetry relies on micro gas pixel detectors (and future X-ray missions...)

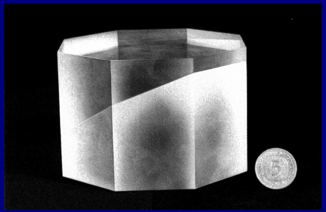
In the optical/UV, birefringent beam-splitters are used to separate the ordinary from the extra-ordinary beam

Polarimetry capabilities at the VLT

ISAAC mounted on UT3
J, H, K polarimetry

NACO mounted on UT4
1-5 micron imaging polarimetry
Wollaston prism

FORS2 mounted
on the VLT
310 nm – 1100 nm
spectropolarimetry
Wollaston prism



Observational prospects – ready-to-fly technology

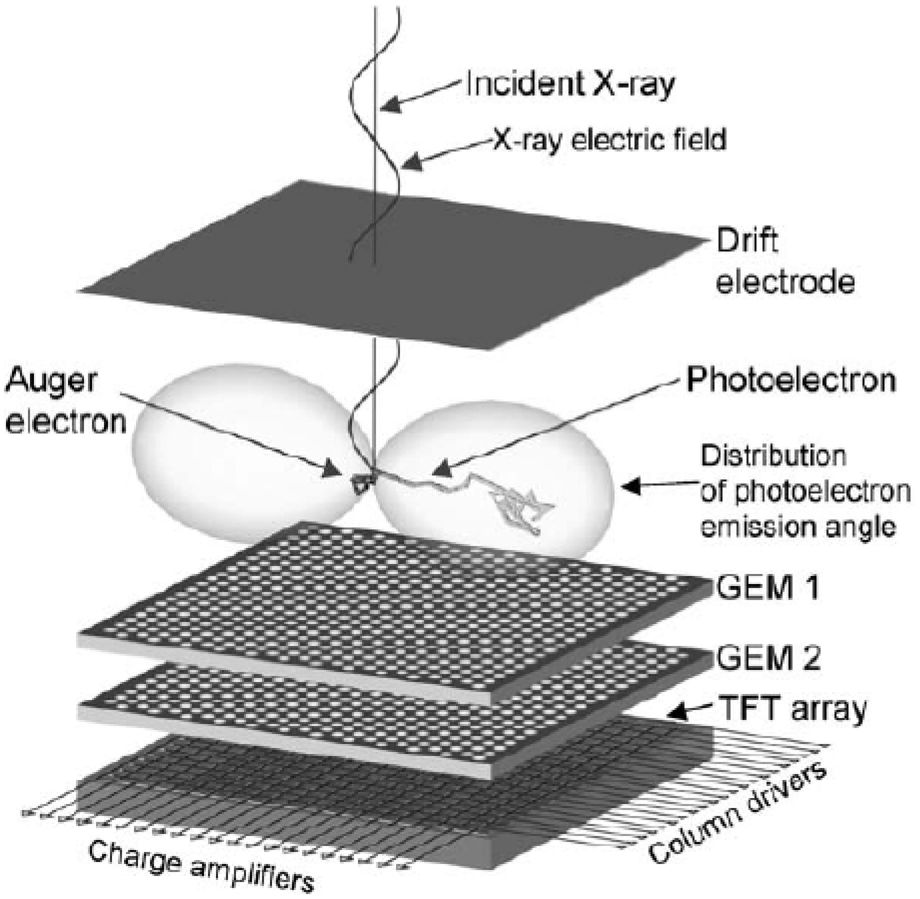


Fig. 1. Schematic diagram of detector geometry used in these measurements. The $\sin^2\theta\cos^2\phi$ distribution of photoelectron emission for normally incident X-rays is projected onto the detector plane and observed as $\cos^2\phi$.

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

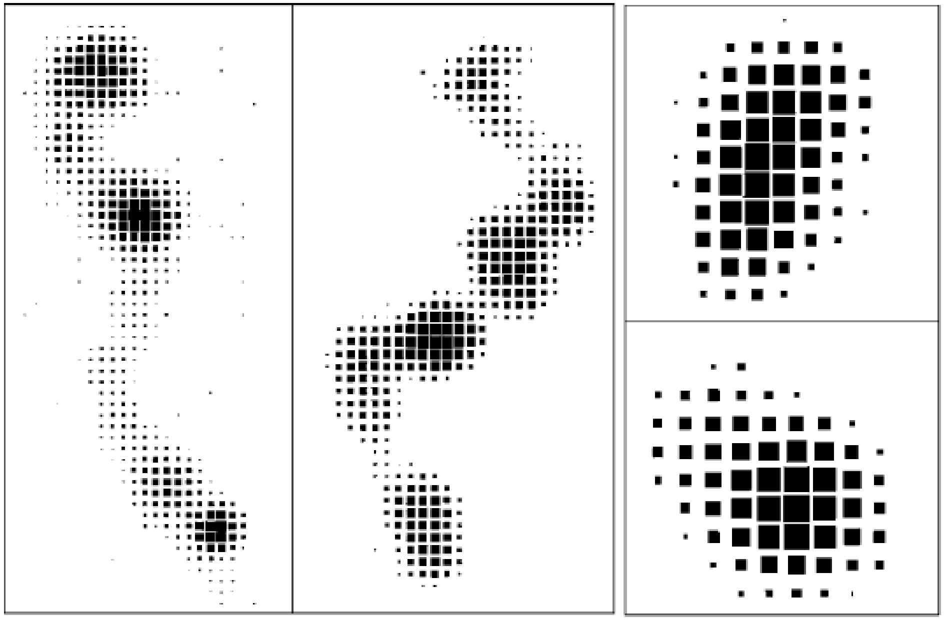
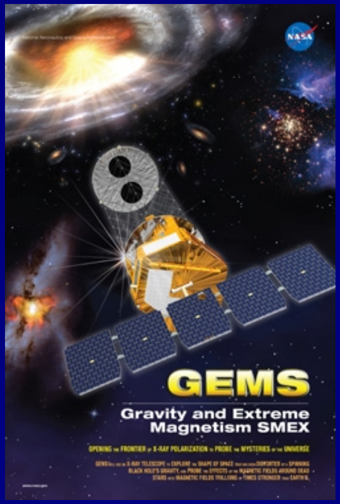


Fig. 3. Track images from 20 keV X-rays (left) and 4.5 keV X-rays (right).

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

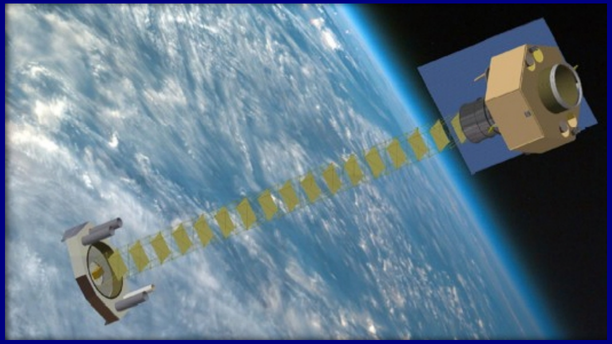
The X-ray polarimetry dilemma : the so-far missing observational perspective

IXO+XPOL (†2011)



GEM SMEX (†2012)

→ ?



NHXM (†2012)

XIPE (†2012)

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Polarisation as a tool to study the Solar System and beyond
Action MP1104

Processes producing (de-)polarization

Synchrotron emission

Electron scattering

Dust (Mie) scattering

Resonant line scattering

Dichroic absorption

Faraday rotation

Zeeman lilne splitting

Dilution (by unpolarized radiation)

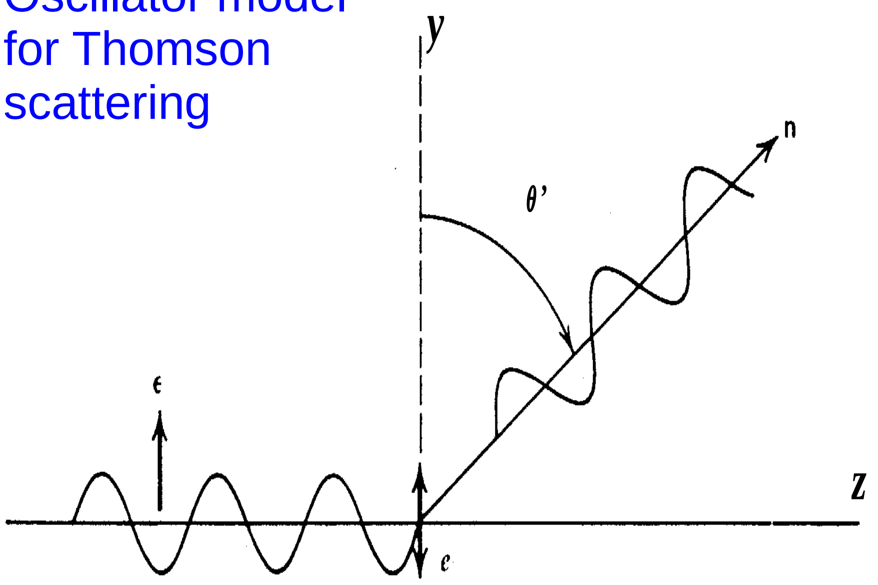
General Relativity

Scattering

Strong polarization: Θ = 90° (Reflection)

Weak polarization: Θ = 0° (Transmission)

Oscillator model for Thomson scattering



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

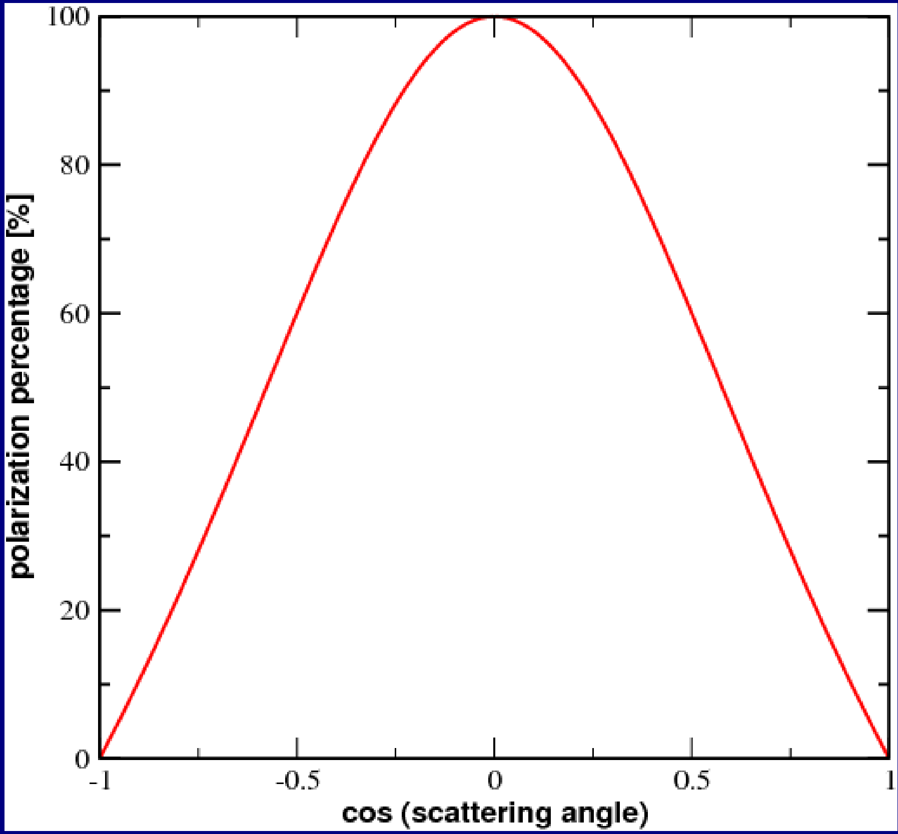
$$P = \frac{1 - \cos^2 \theta}{1 + \cos^2 \theta}.$$

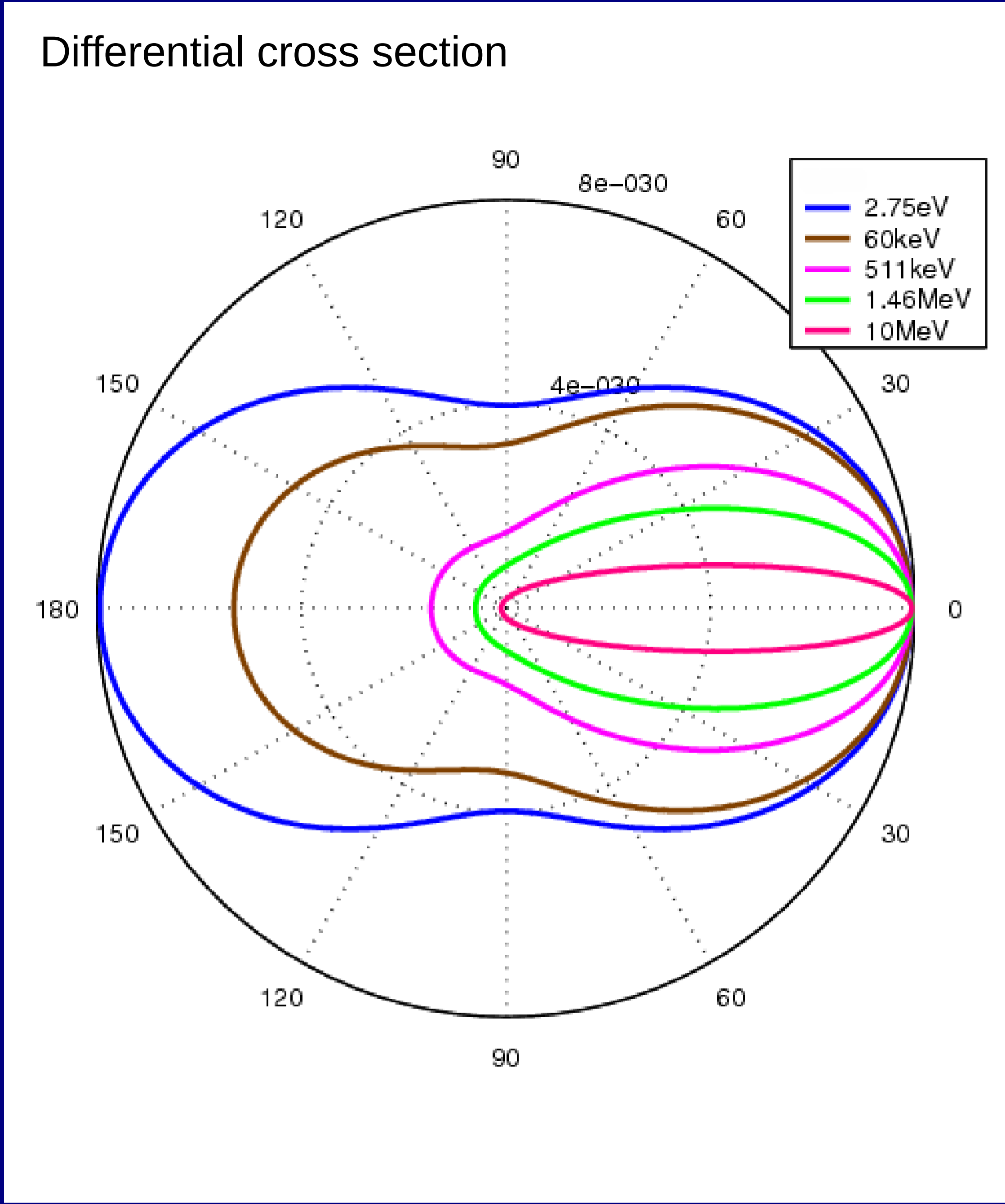
$$\sigma_T = \frac{8\pi}{3} r_0^2 = \frac{8\pi e^4}{3m^2 c^4}.$$

Phase function for scattering-induced polarization

Electron scattering
(Thomson, Compton,
Rayleigh scattering)

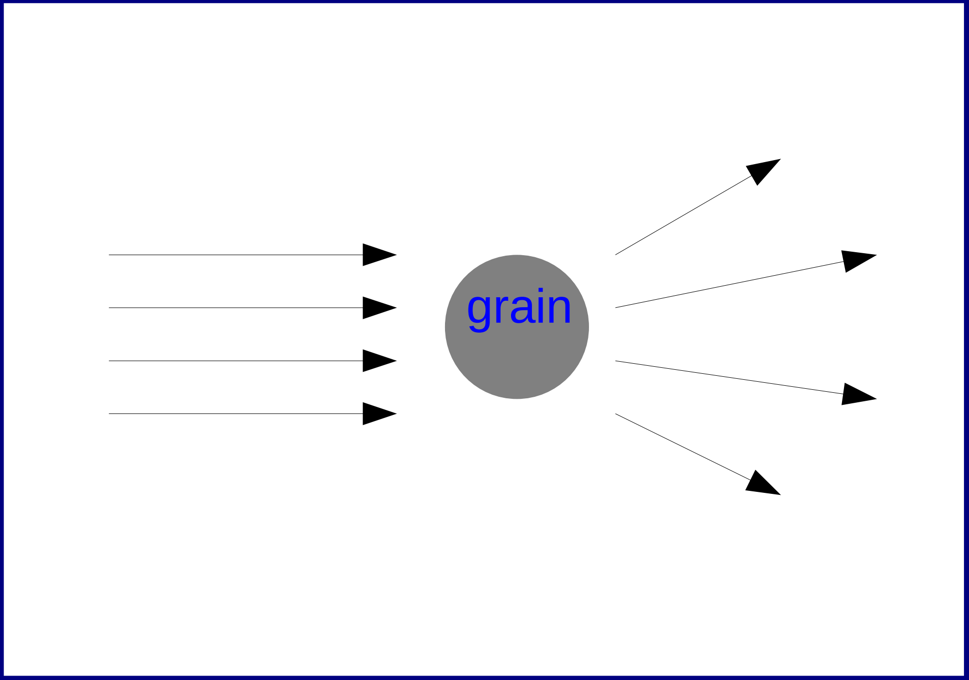
Polarization phase function:





Polarization by dust scattering

- A plane wave passes by a spherical dust grain.
- The electromagnetic field around the grain is computed by solving the Maxwell equations (Mie theory)
- A complete solution for the scattered radiation including polarization is obtained.

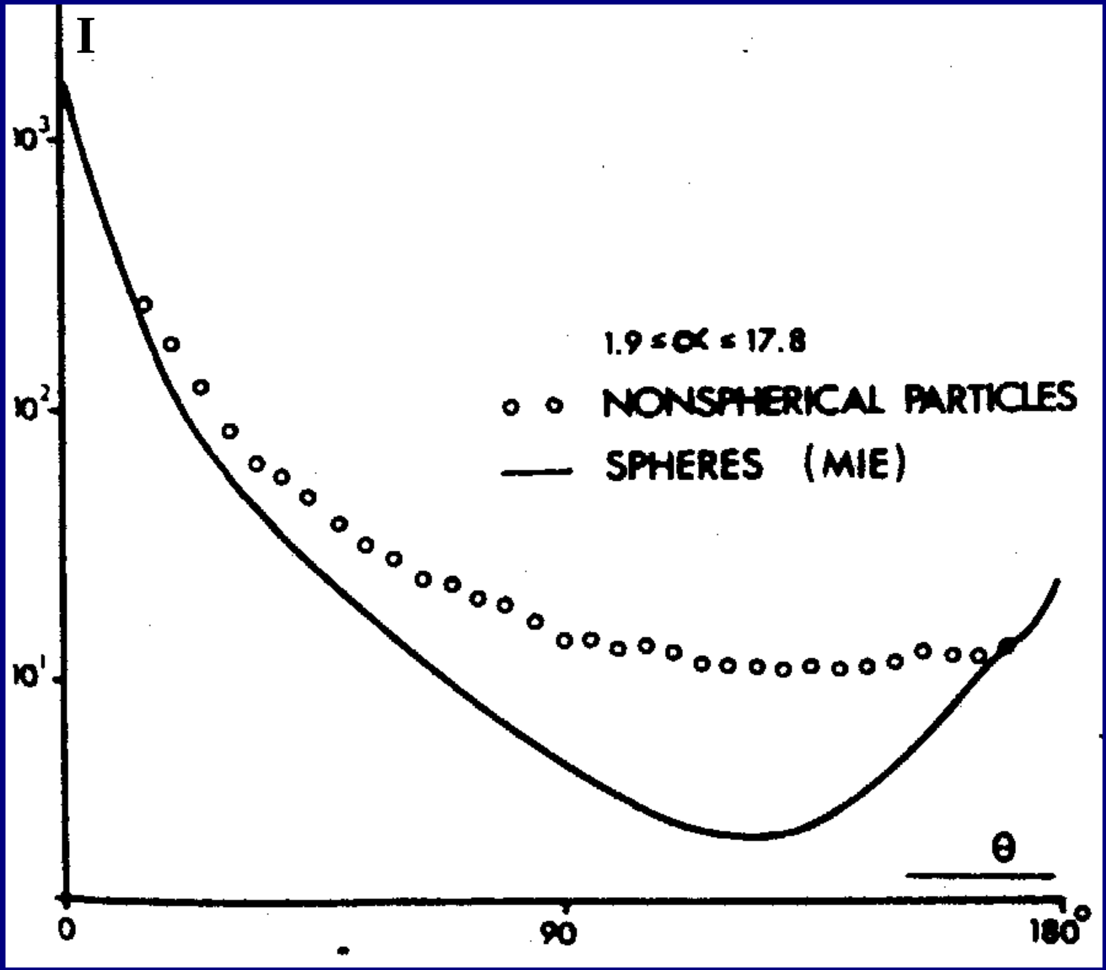


Polarization by dust scattering

It turns out that...

- ...the intensity phase function favors forward-scattering over back-scattering.

- ...as for electron scattering, the resulting polarization is stronger for perpendicular scattering angles.



Reflection-induced polarization

Reflection-induced polarization

Radio-quiet objects, hidden type-1 AGN

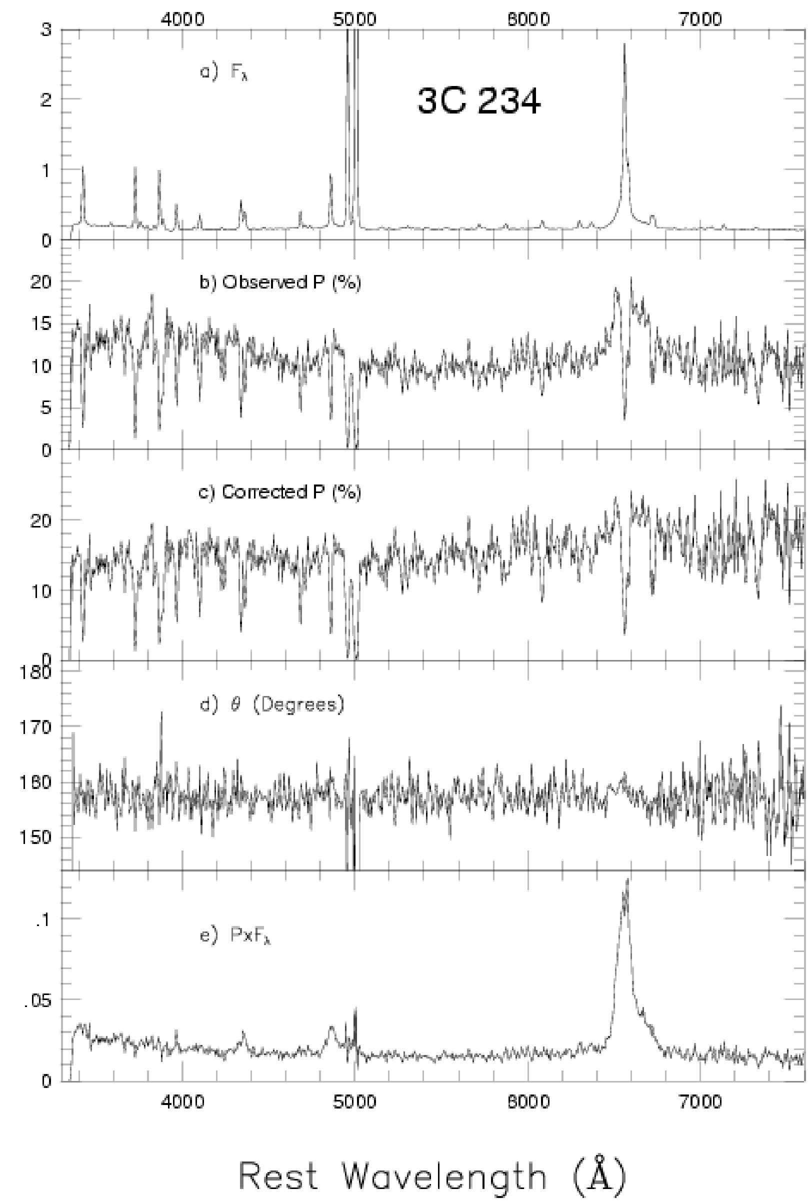
In the following of Antonucci & Miller (1985), more and more hidden type-1 nuclei were found in Seyfert 2 galaxies.

The polarization dichotomy of AGN was established:

Type-2 → *P.A.* ⊥ jet axis

Type-1 → *P.A.* ∥ jet axis,
except for dominant polar scattering

See Antonucci (1993) and Smith et al. (2002) and references therein for summary



Tran et al. (1995)

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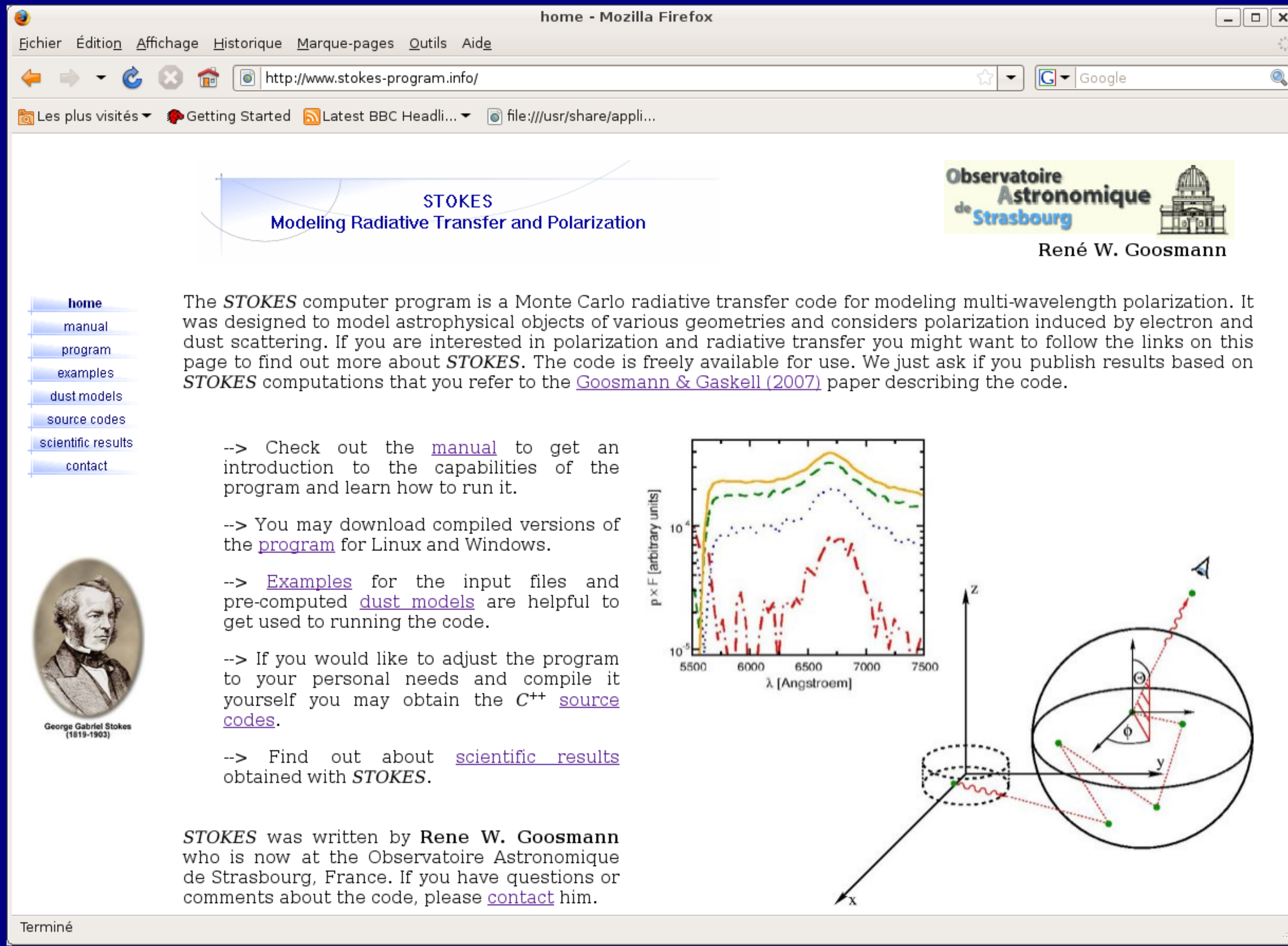
Modeling (scattering-induced) polarization with STOKES

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

Public access to version 1.0 (and soon 1.3)

http://www.stokes-program.info/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STOKES
Modeling Radiative Transfer and Polarization

Observatoire Astronomique de Strasbourg

René W. Goosmann

home
manual
program
examples
dust models
source codes
scientific results
contact

The *STOKES* computer program is a Monte Carlo radiative transfer code for modeling multi-wavelength polarization. It was designed to model astrophysical objects of various geometries and considers polarization induced by electron and dust scattering. If you are interested in polarization and radiative transfer you might want to follow the links on this page to find out more about *STOKES*. The code is freely available for use. We just ask if you publish results based on *STOKES* computations that you refer to the Goosmann & Gaskell (2007) paper describing the code.

--> Check out the manual to get an introduction to the capabilities of the program and learn how to run it.

--> You may download compiled versions of the program for Linux and Windows.

--> Examples for the input files and pre-computed dust models are helpful to get used to running the code.

--> If you would like to adjust the program to your personal needs and compile it yourself you may obtain the C^{++} source codes.

--> Find out about scientific results obtained with *STOKES*.

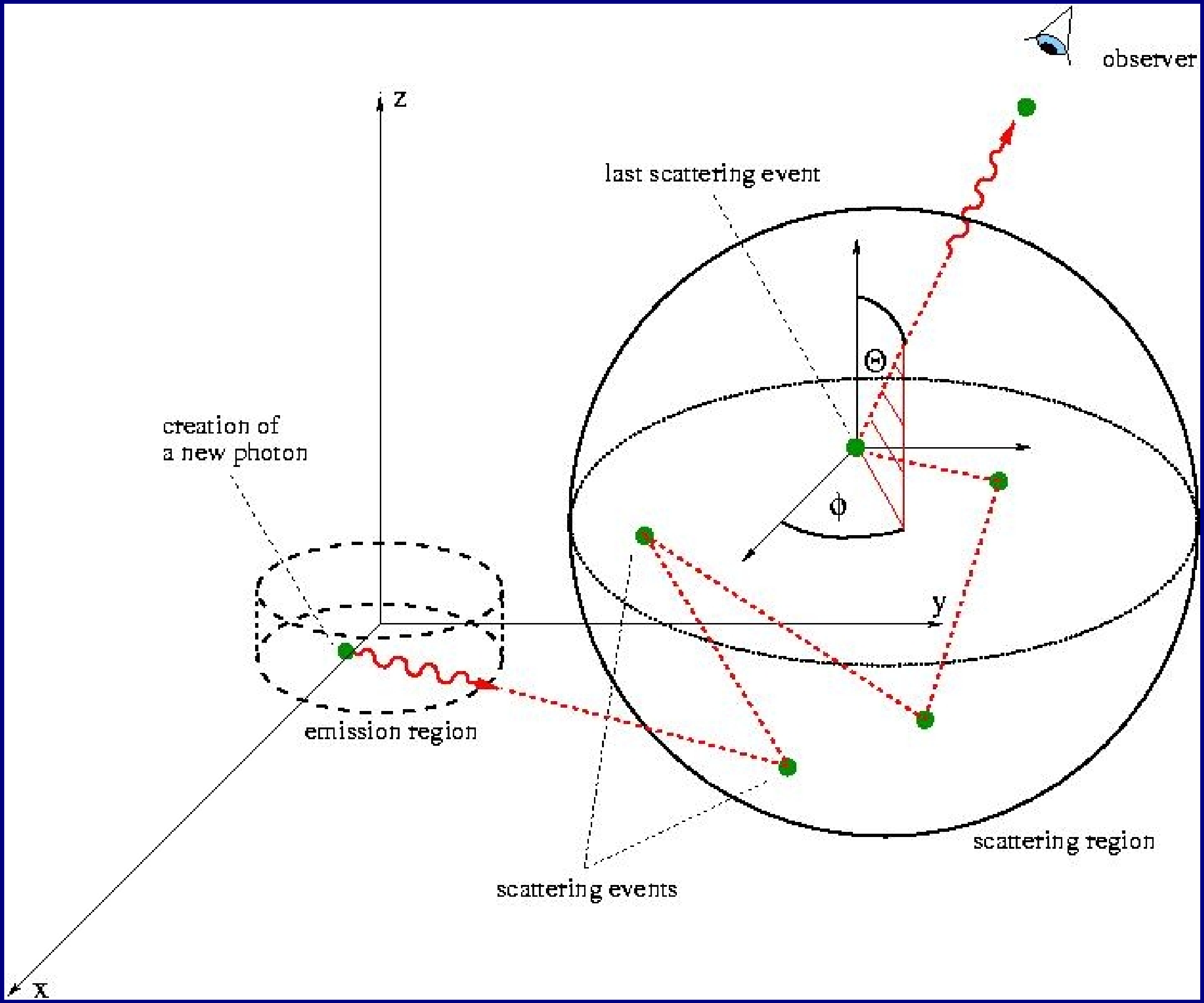
STOKES was written by **Rene W. Goosmann** who is now at the Observatoire Astronomique de Strasbourg, France. If you have questions or comments about the code, please contact him.

Terminé

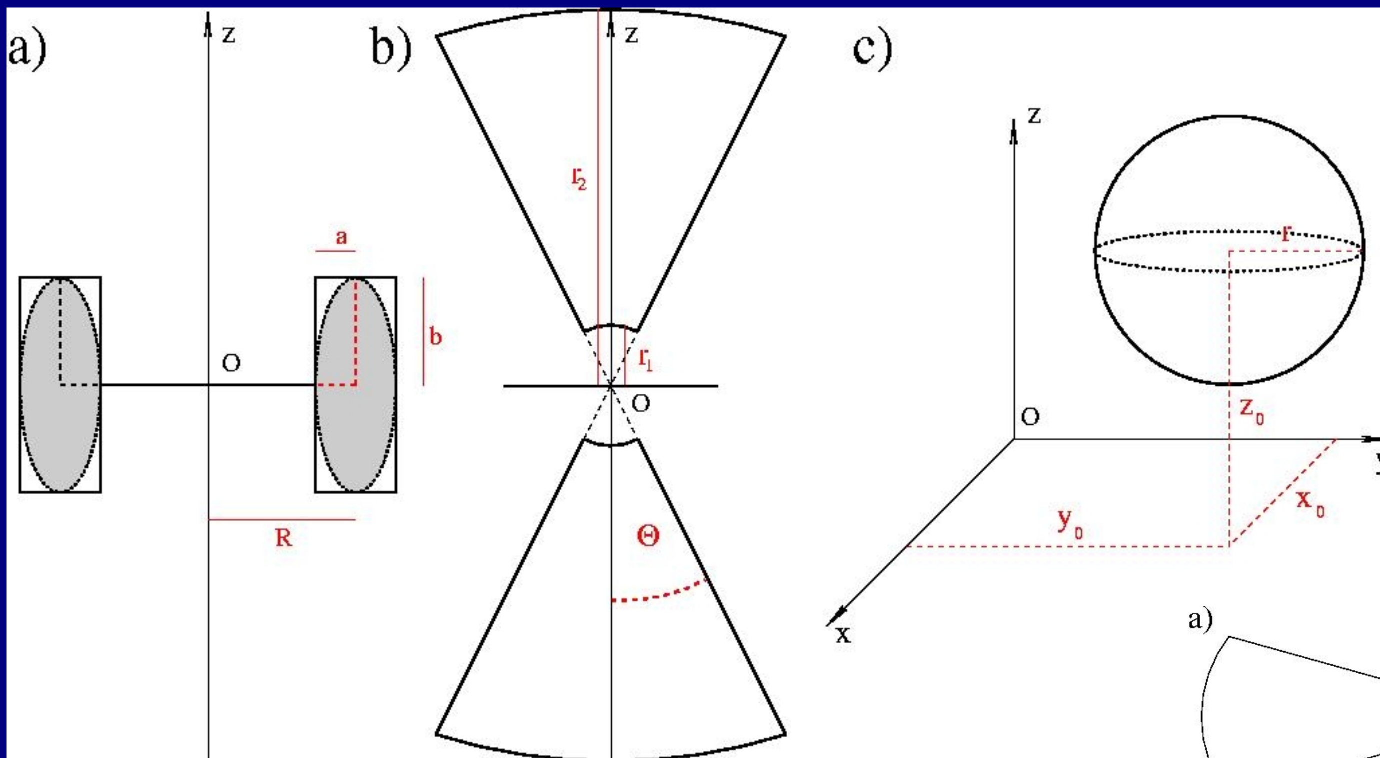
Take a photon for a (random) walk...

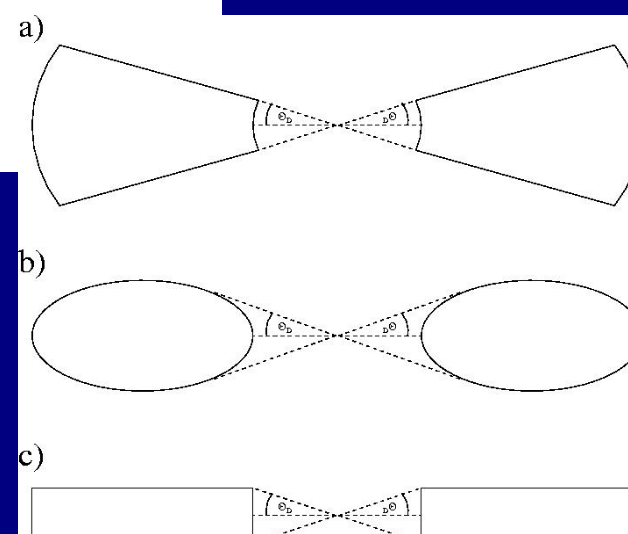
Throw the dice for...

- Photon wavelength
- Emission direction
- Free path length
- Absorption by dust
- Scattering angles



Let it encounter scattering clouds...

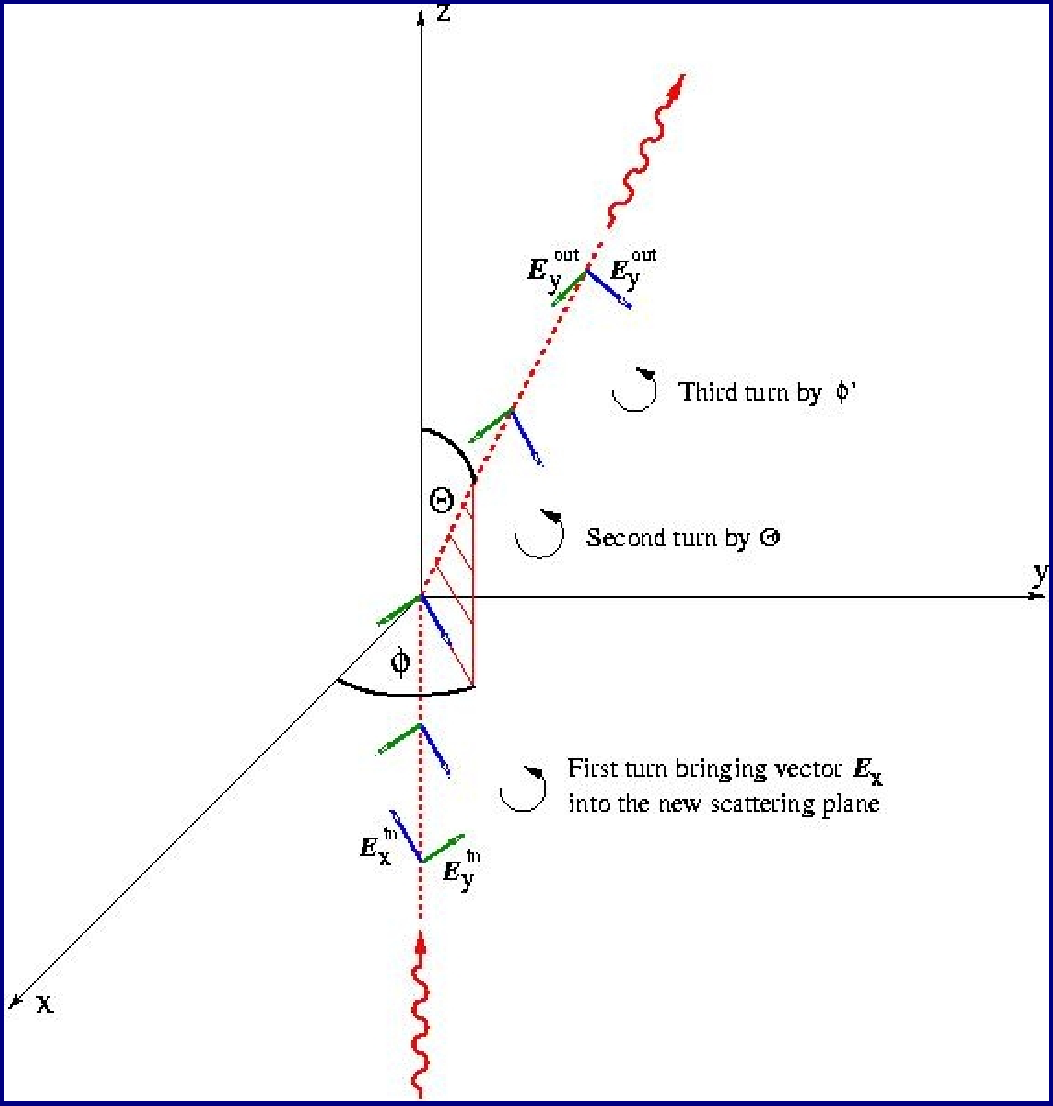




It is possible to define several scattering regions in the model space...

Have the photon scatter accurately...

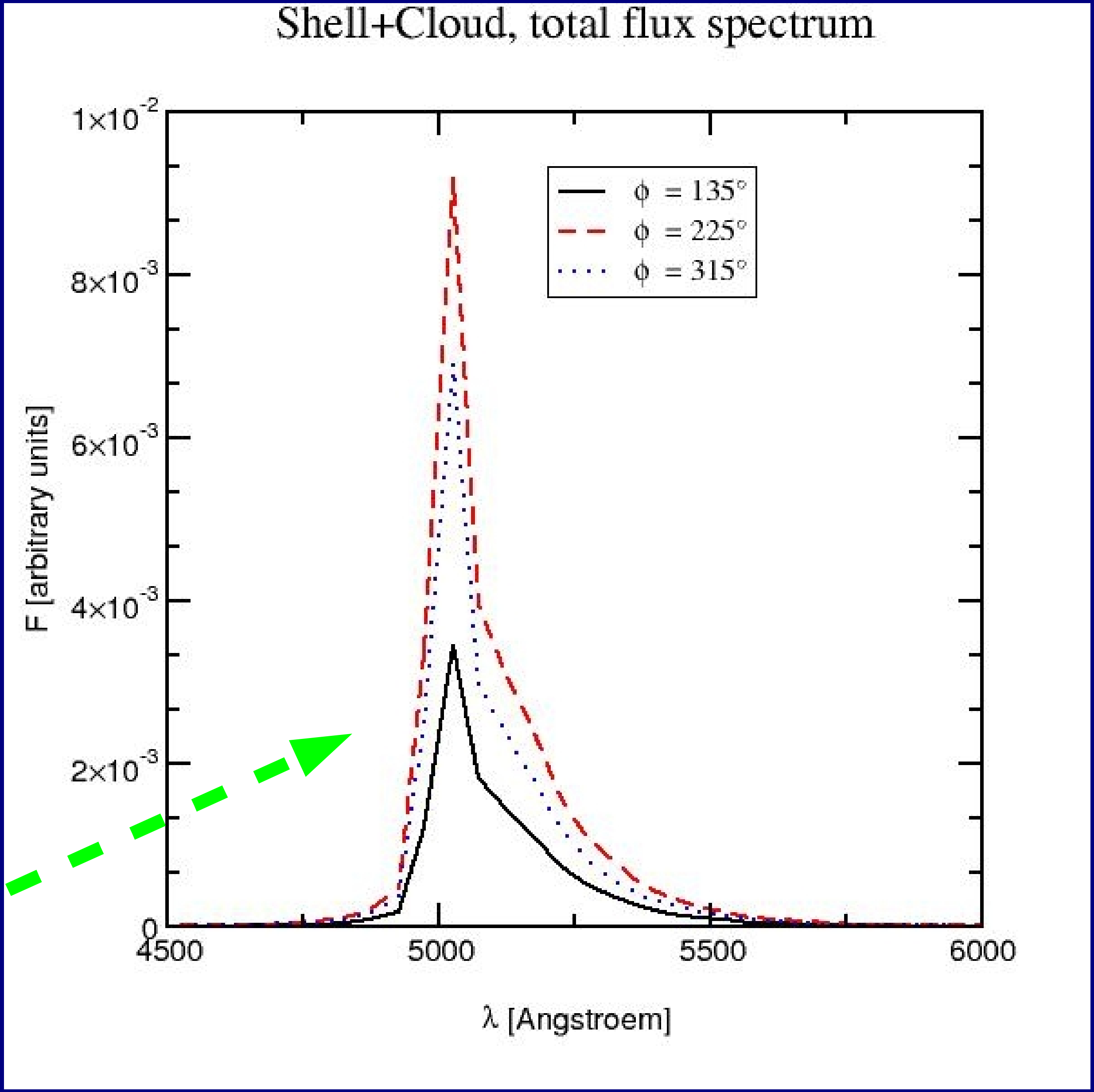
- scattering events are 3D, i.e. they involve two angles
- the sampling of the scattering angle depends on the initial polarization state
- multiple scattering is automatically included
- for dust grains, absorption is considered according to the albedo
- The correct polarization matrices for resonant line scattering are taken into account



Count the photons that manage to escape...

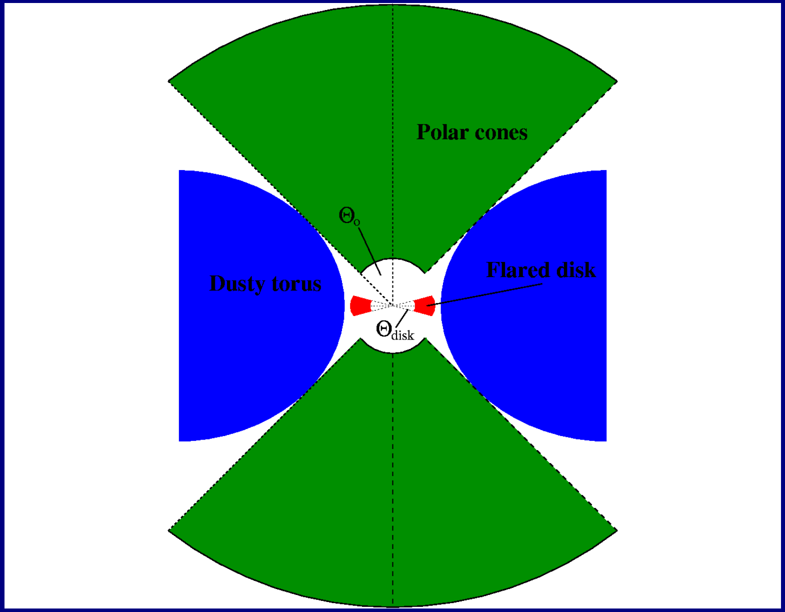
- Stokes parameters are added up for each viewing direction
- number of scatterings are counted
- flight time of the photons is registered

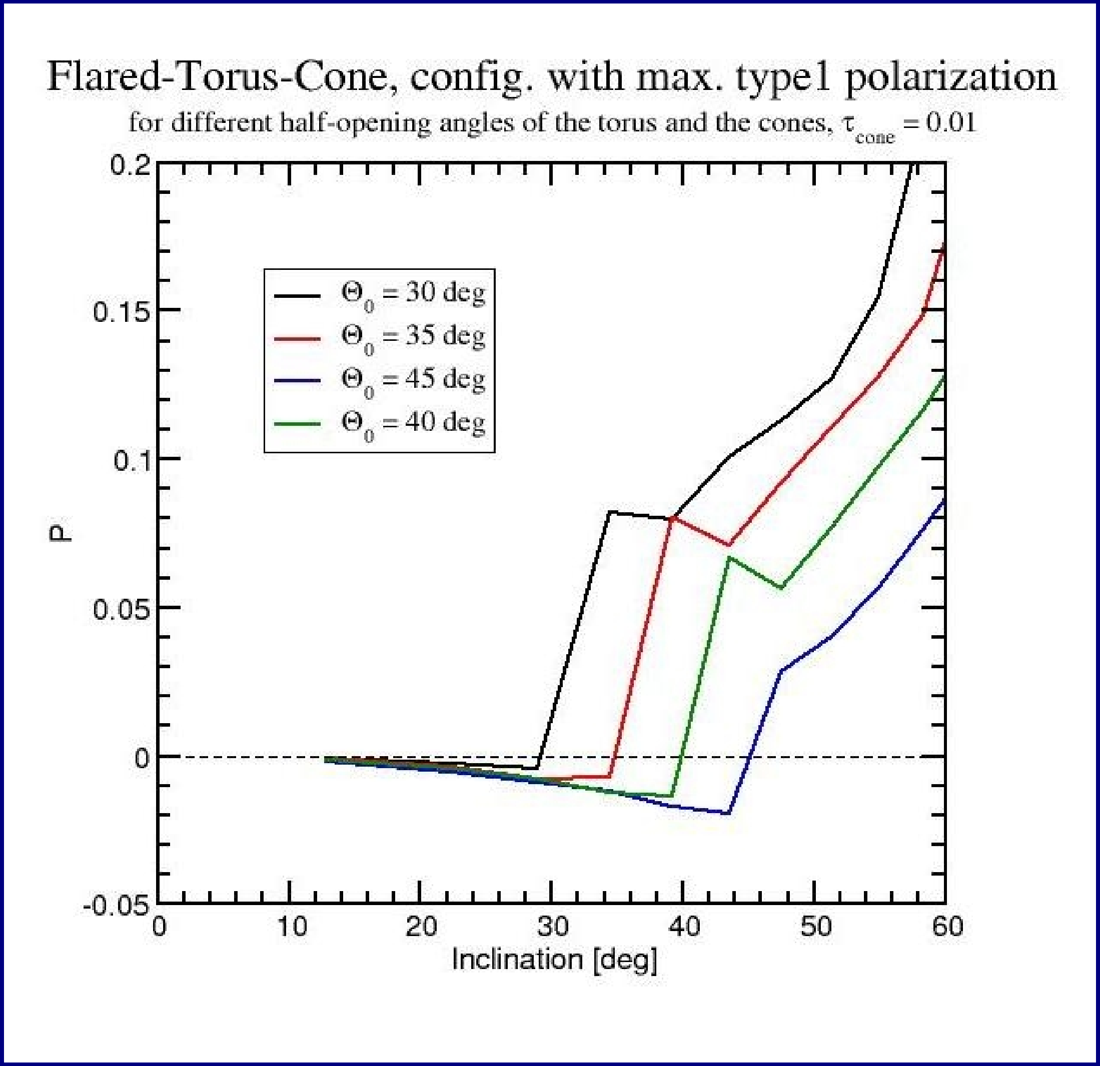
Total flux spectrum of an [OIII] λ5007 line for a centrally illuminated, expanding shell with a few dust clouds further out



Toward the unified model...

Modeling a composition of **flared electron disk**, **dusty torus**, and **polar electron cones**.

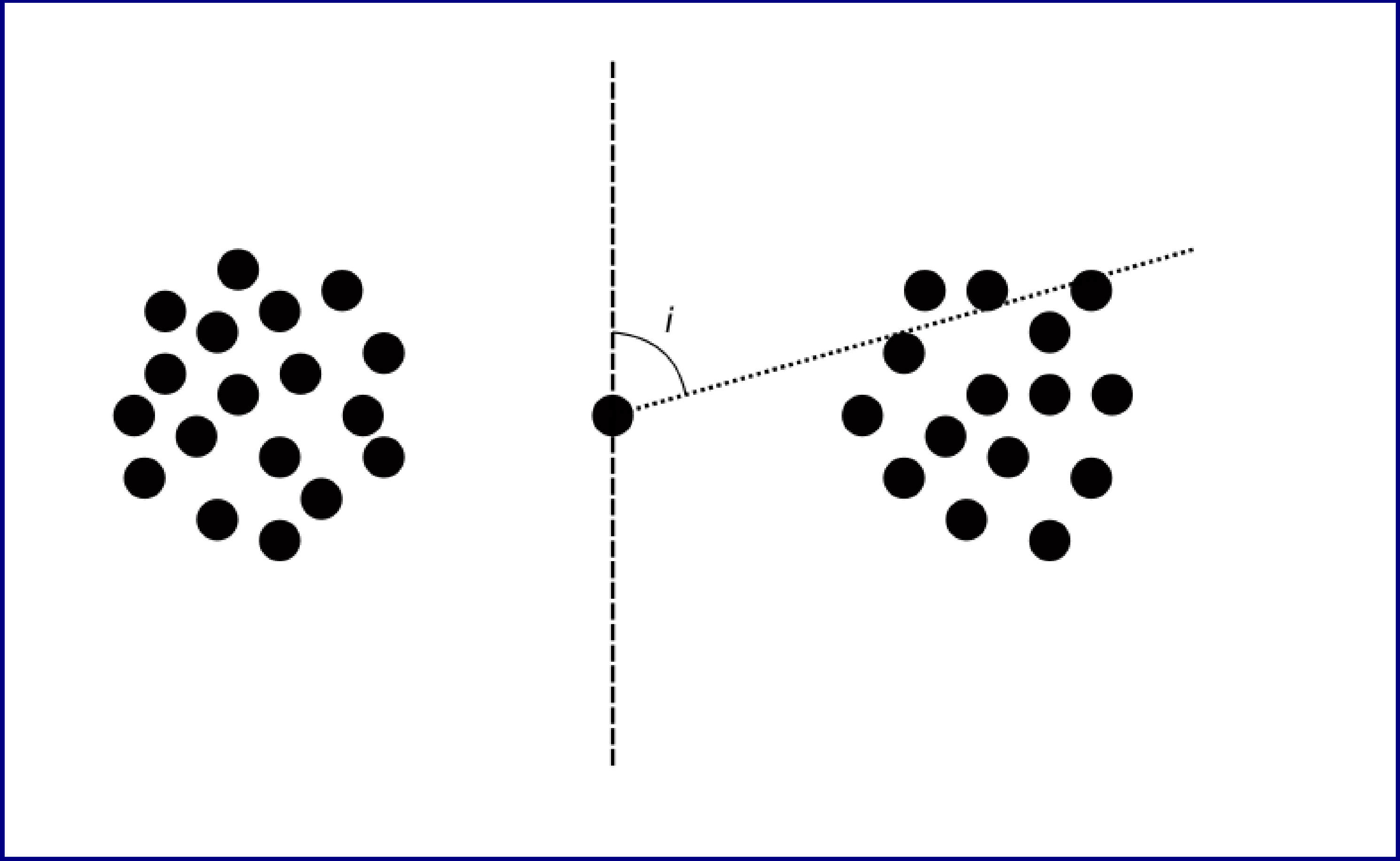




Goosmann 2009, Marin et al. (2012)

Towards more sophisticated torus models for AGN

- Polarization models of clumpy tori (e. g. Nenkova et al. 2008, Heymann & Siebenmorgen 2012, Hönig & Kishismoto 2010)
- To be explored in the light of the work by M. Stalevski, L. Popovic and collaborators...!



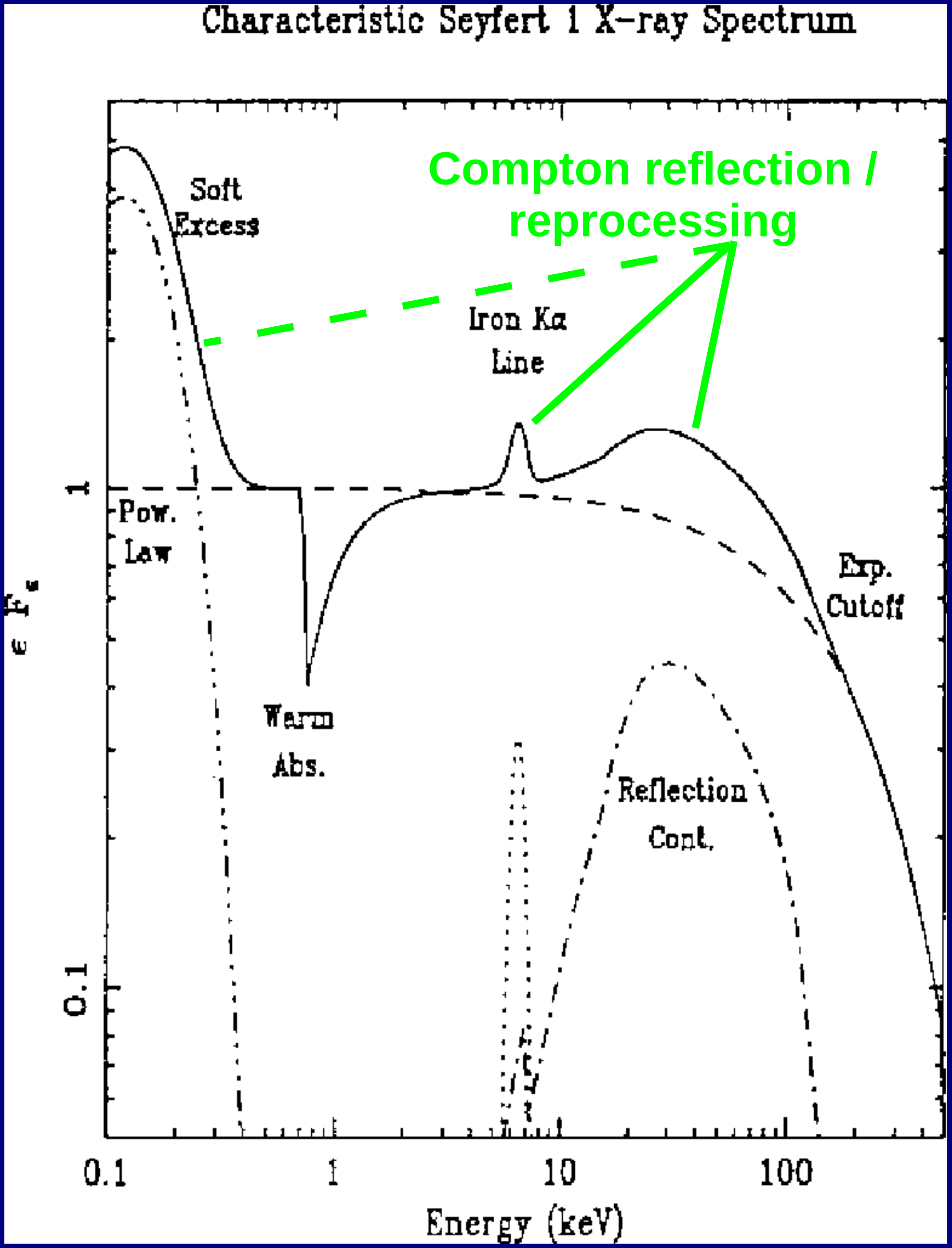
Thesis work by
Frédéric Marin

The X-ray spectrum of (nearby, radio-quiet) AGN

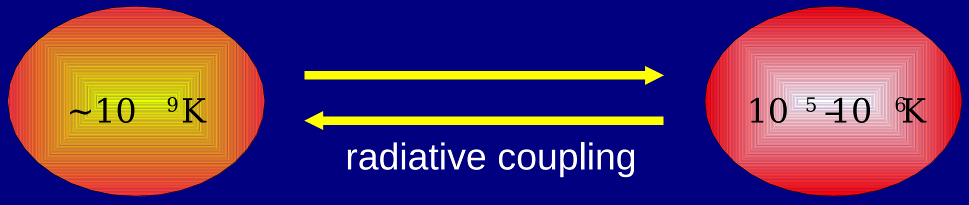
- Primary power-law component
- High-energy cut-off
- Iron Ka-line complex
- Compton hump
- Soft X-ray absorption
- Soft-Excess (Crummy et al. 2006)

but: Gierlinski & Done 2004, Chevallier et al. 2005

Fabian (2000)



Two media are required...



hot, optically thin medium

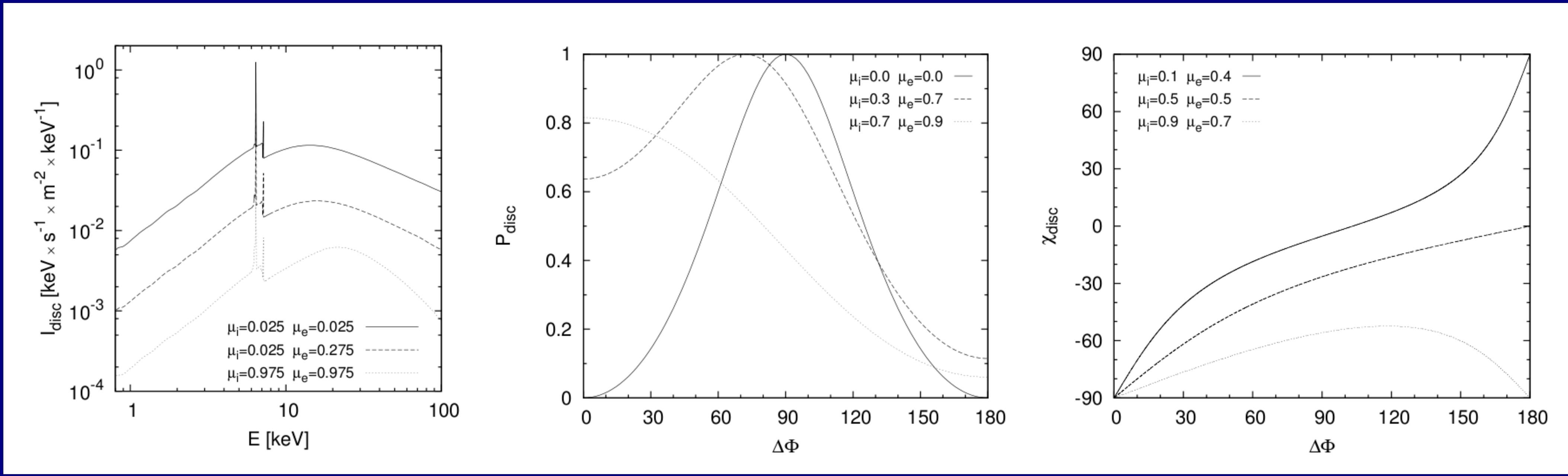
corona

cold, optically thick medium

accretion disk

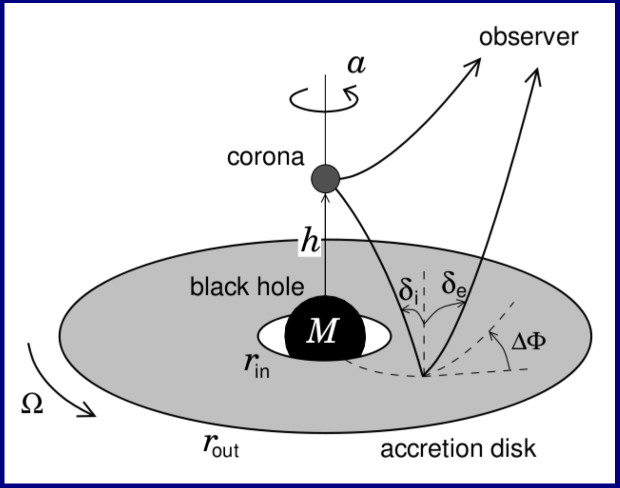
The lamp post geometry

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.

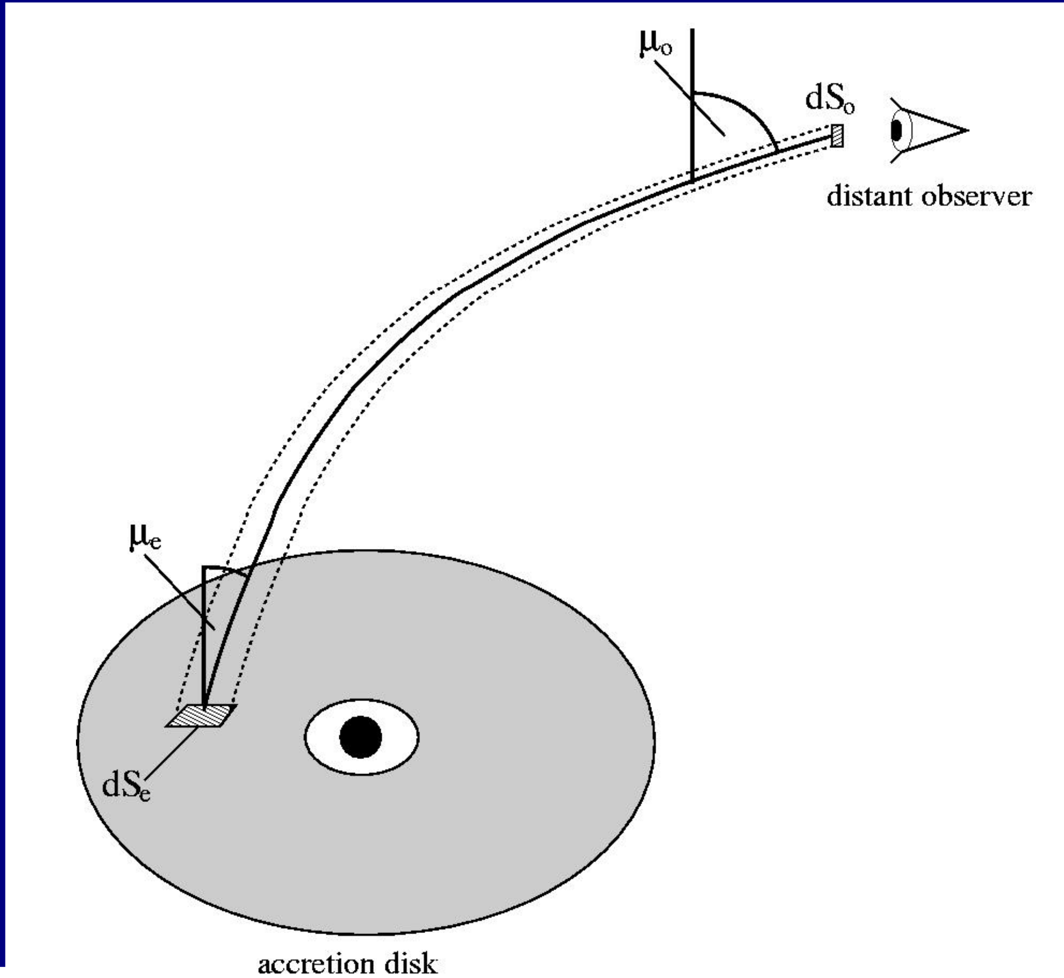


Including relativistic effects

- **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

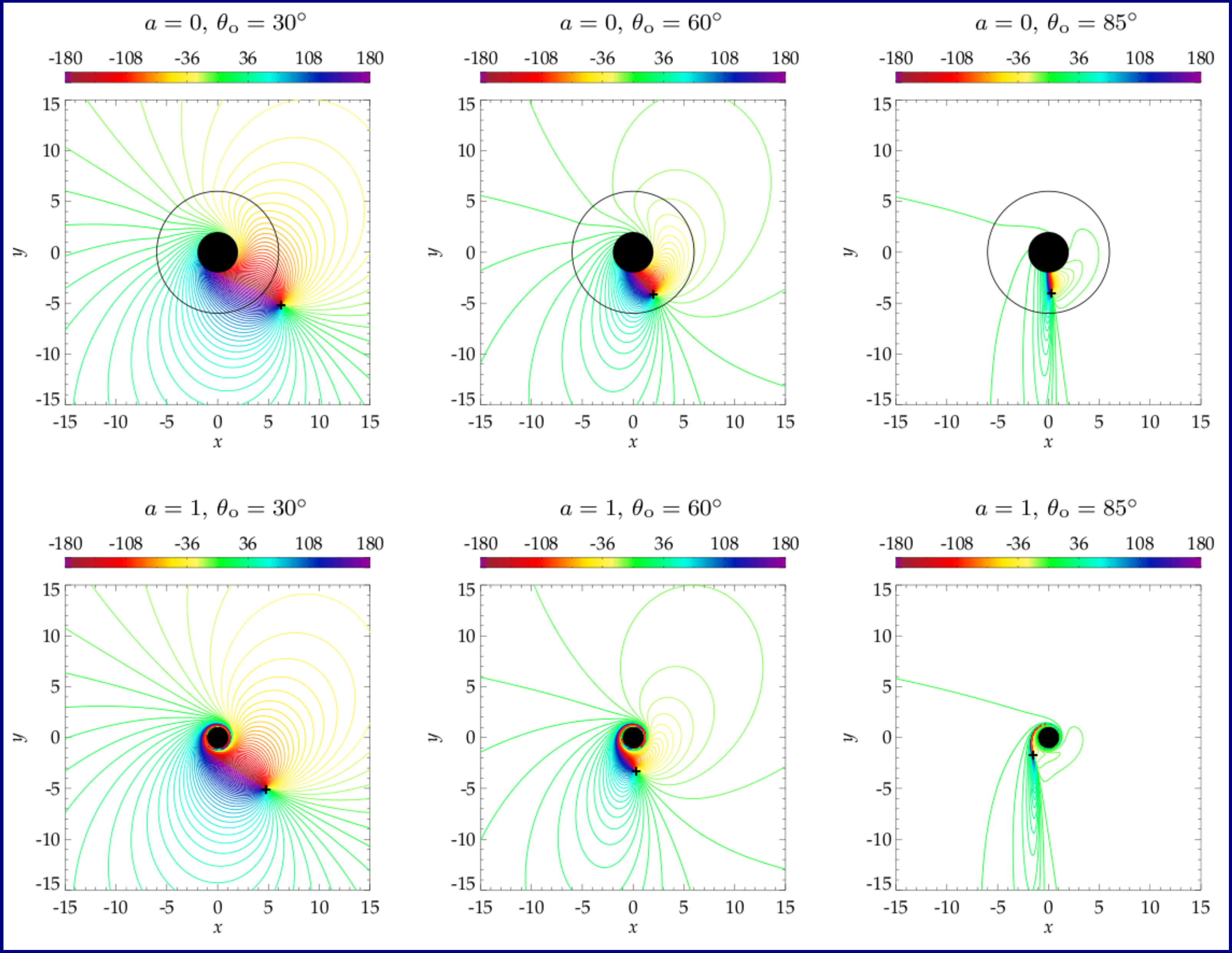
I, Q, U, V



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

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...

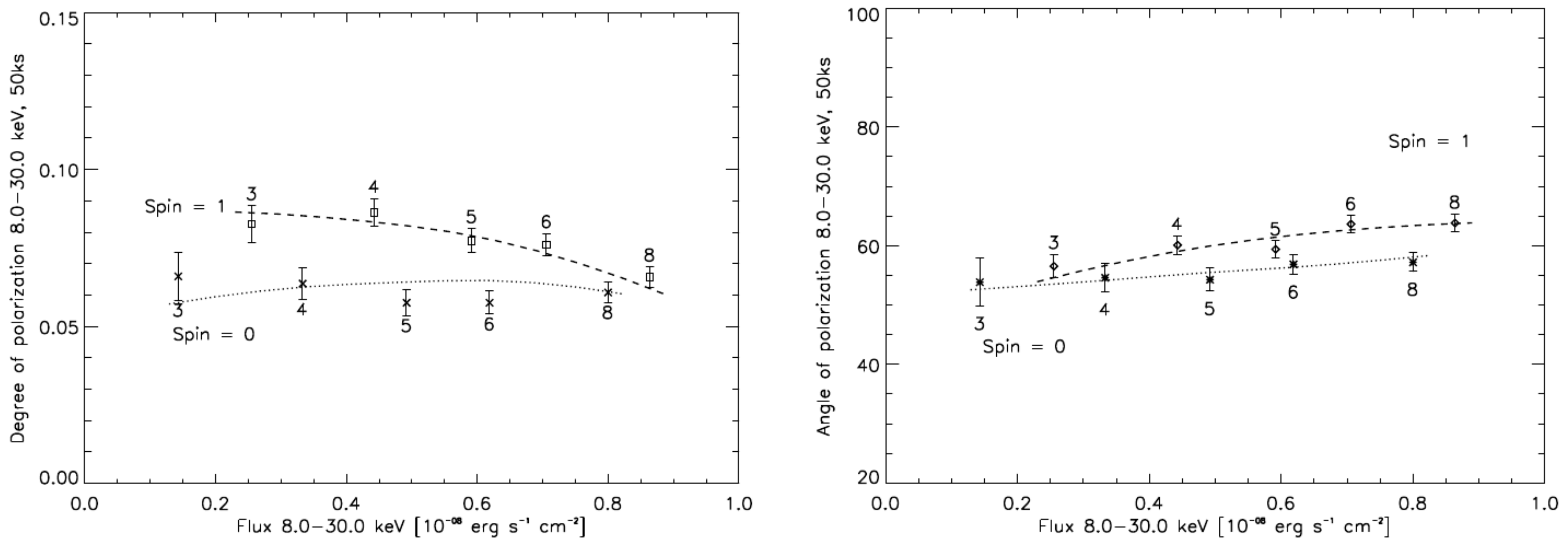
Dovčiak et al. (2008)

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)

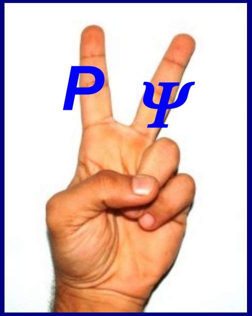
Exploiting and modeling polarization in astrophysics

- The basic concept of (linear) polarization
- Techniques to observe broad-band polarization
- Mechanisms producing polarization
- Modeling scattering-induced polarization with *STOKES*
- **Summary and conclusions**

Talk by René W. Goosmann at the
9th Serbian Conference on Spectral Line Shapes in Astrophysics
16th May 2013

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Polarisation as a tool to study the Solar System and beyond
Action MP1104

SOME CONCLUSIONS...



- Scattering-induced polarization as a function of wavelength reveals details of the interaction between radiation and matter!

- In my opinion, spectropolarimetry still is a neglected source of information about unresolved objects.

- The development of the STOKES code is ongoing and guided by the input of the user – feel free to try it out!

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

- Some more STOKES results on spectral lines are going to come in our talks of tomorrow morning:
  - Line and continuum polarization variability in the optical/UV
  - Absorption, reflection, relativistic effects, and Compton scattering of Kα lines in different geometries