STOKES - a Publicly Available Radiative Transfer Code for Polarization Modeling in the Optical/UV

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Magneto-Hydrodynamical Seminar
at the Astronomical Institue

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Outline of the talk

- Recalling some basics about polarization
- Polarization modeling using the code Stokes
- Introduction to Active Galactic Nuclei (AGN)
- Investigating individual scattering regions of AGN

Recalling some basics about polarization

- What is polarization?
- Quantification and measurement of polarization
- Polarization by electron and dust scattering

Some basics about linear polarization

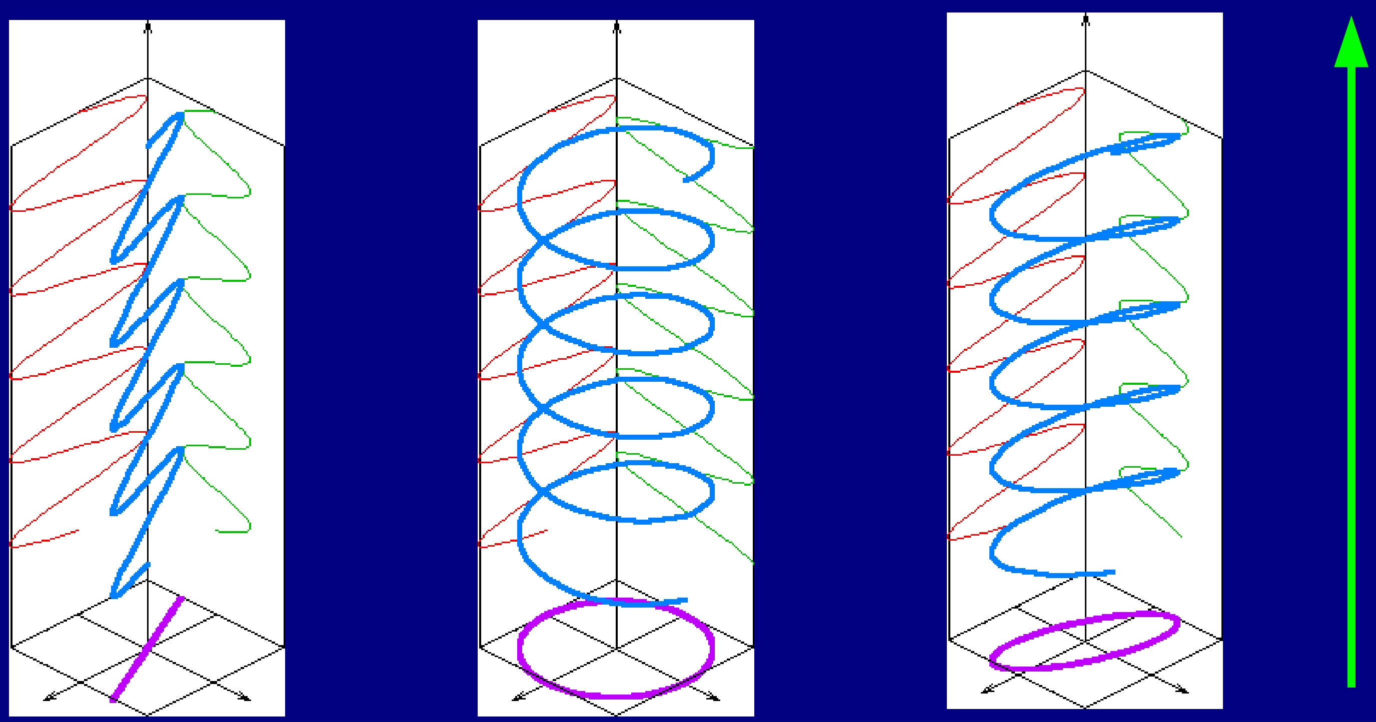
- In classical physics, the polarization state of an electro-magnetic wave characterizes the behavior of its *E*-vector

- In quantum mechanics, the polarization state of a single photon is given by a hermitian operator, which is similar to the classical description.

Most properties relevant for the polarization of light in the astronomical context can be derived from the classical picture!

Polarization of coherent light

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



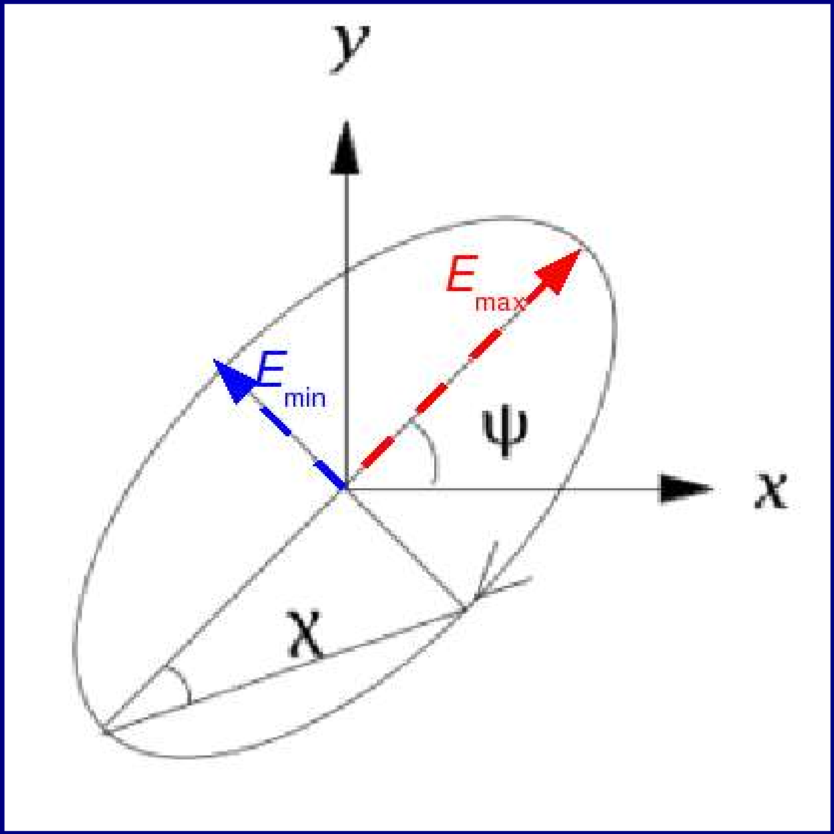
linear circular elliptical

The polarization ellipse

The linear polarization degree *P* is defined by

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

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



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

The Stokes parameters

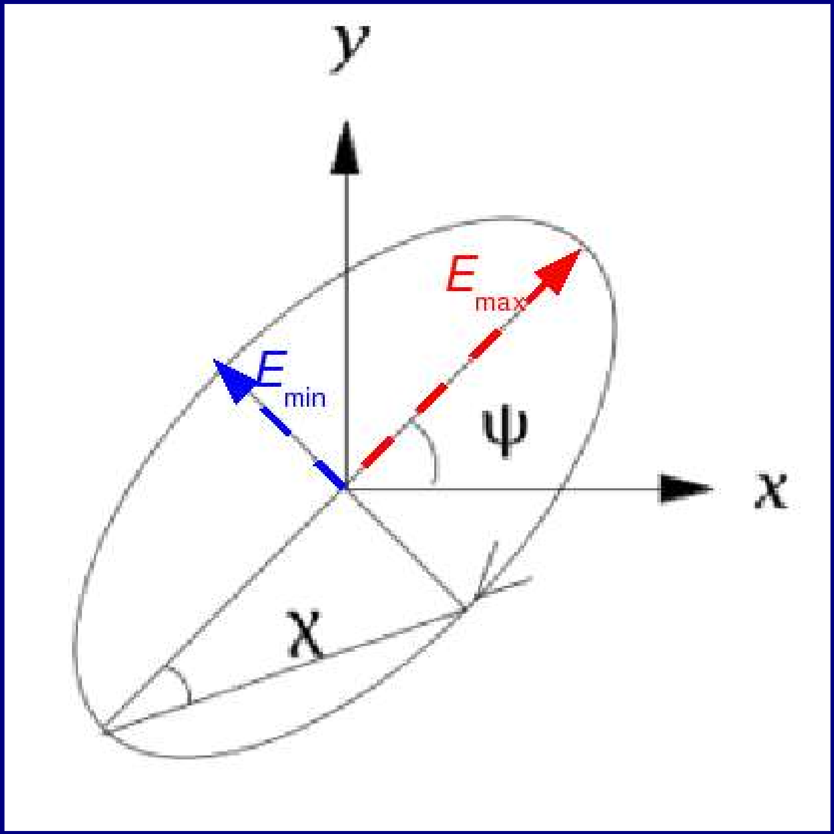
The polarization state is completely described by the Stokes parameters:

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

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

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

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



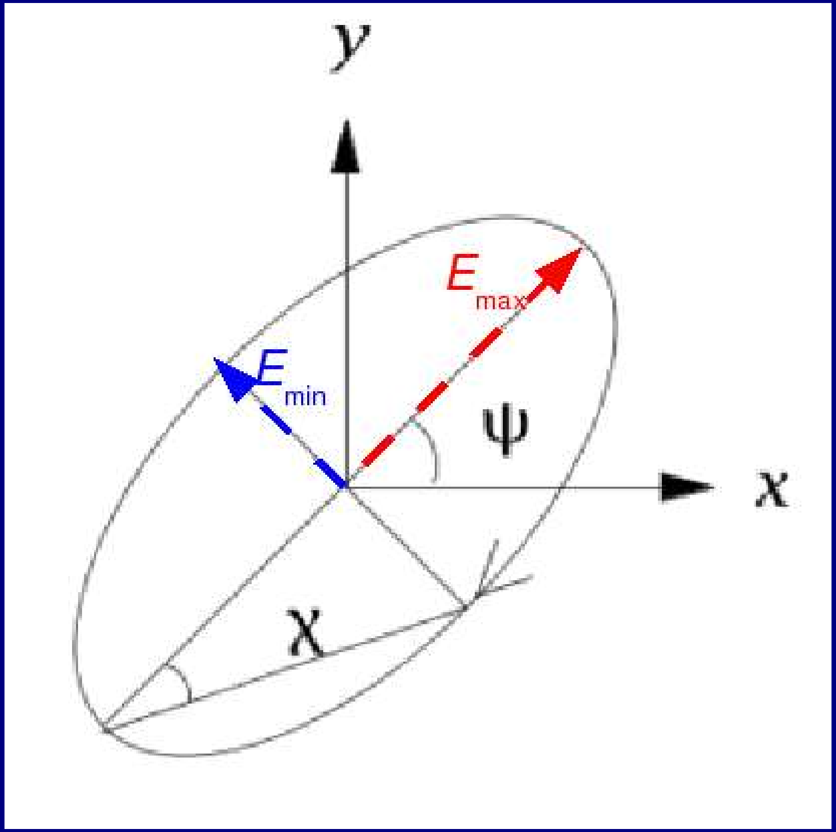
These parameters are convenient for measurements, because the geometry of the polarization ellipse can be constraint using a polarimeter.

The Stokes parameters

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

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

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



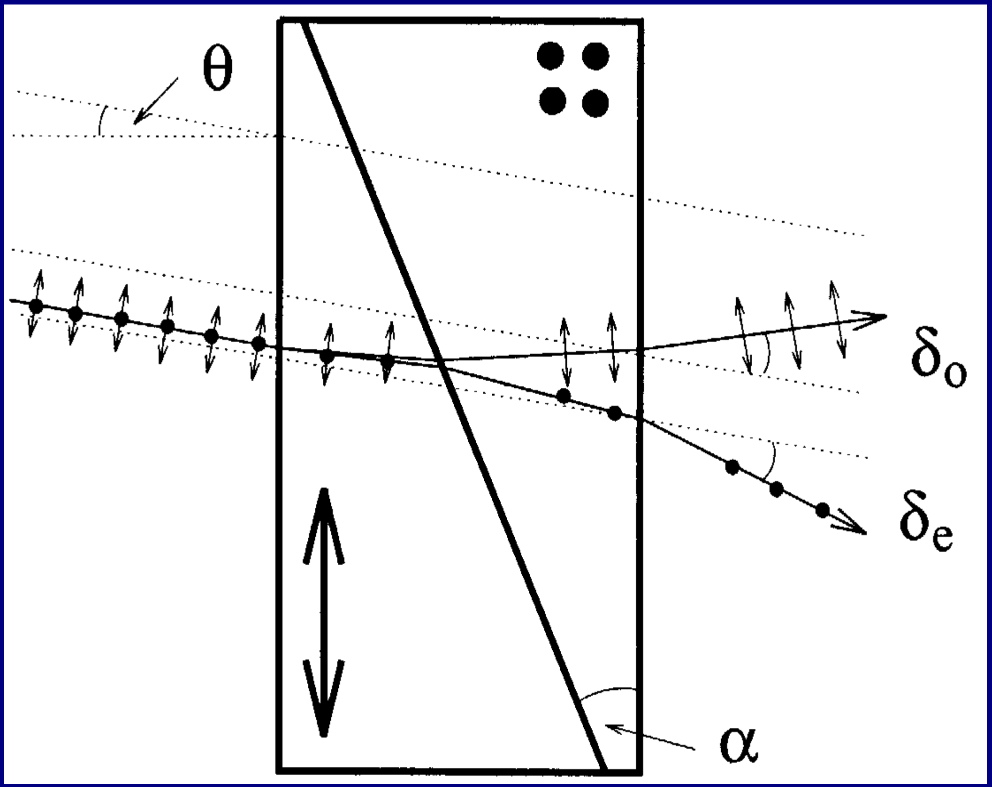
Measuring linear polarization is about mapping out the polarization ellipse!

Measuring the Stokes parameters

- It is key to seperate 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)

"Astronomical light" is hardly coherent...

- An experimental approximation to coherent light are Lasers.

- The light from astronomical sources comes from uncorrelated sub-sources, such as:

  - different parts of a stellar surface,
  - different layers inside an ionized nebula,
  - ...

Only a statistical coherence of "astronomical light" exists and a polarization degree of 1 (=100%) is never observed.

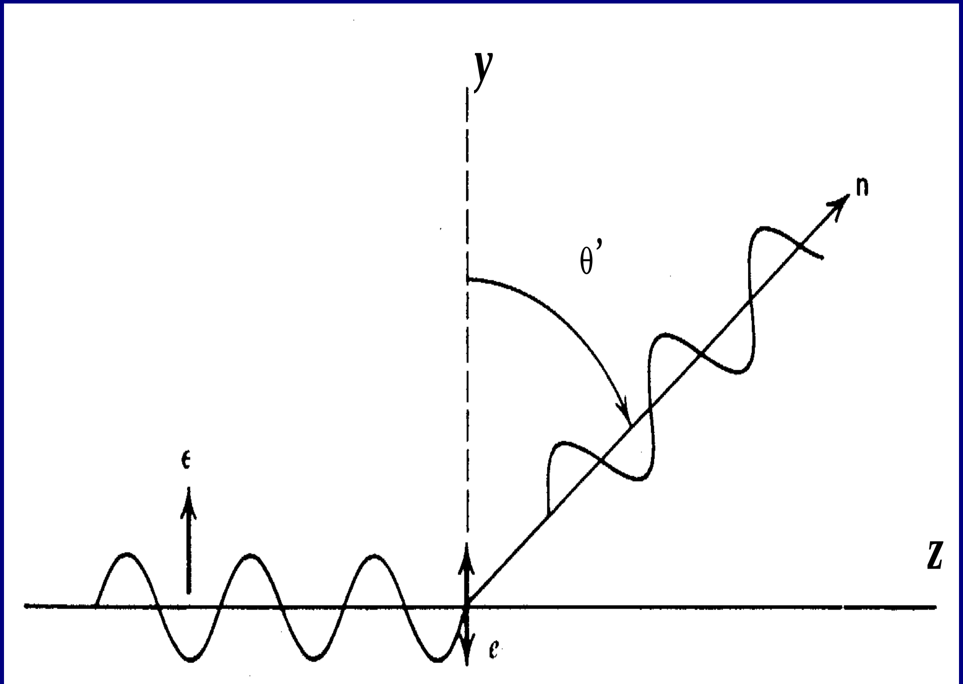
Polarization by electron scattering

- A plane wave passes by an electron inducing linear oscillations.

- The oscillations can be decomposed along two polarization directions:

  parallel and
  perpendicular

  to the scattring plane.



- The parallel component becomes projected.

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

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

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

- The parallel component becomes projected.

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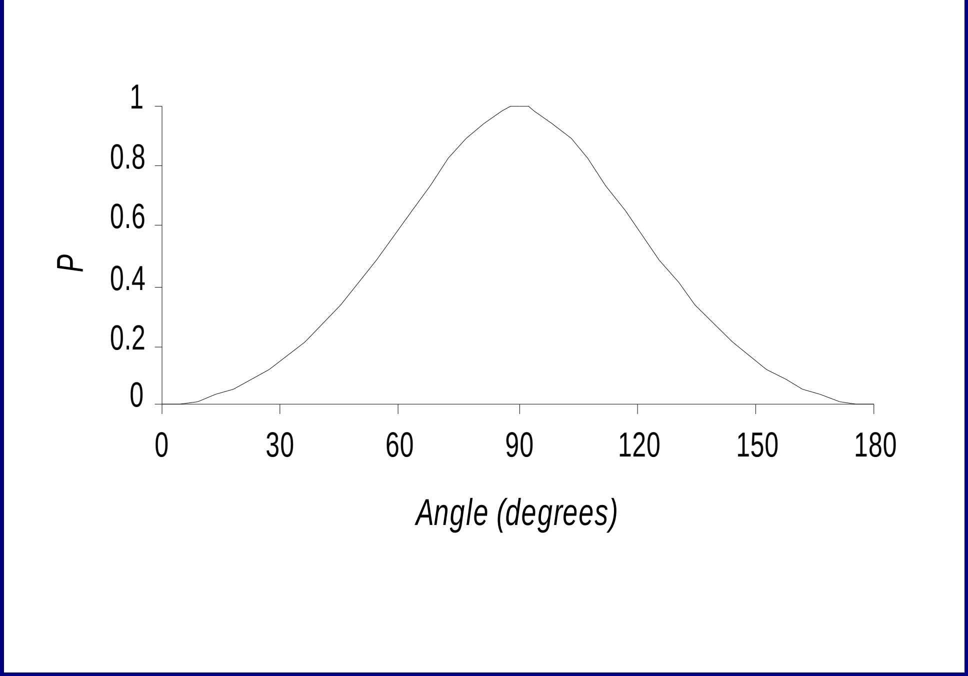
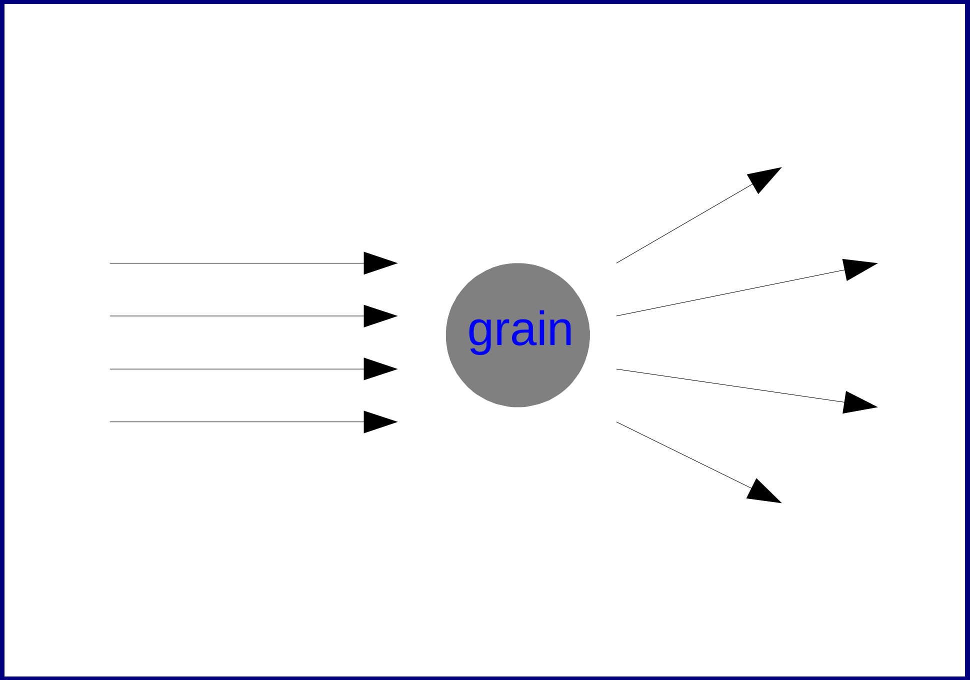


- The parallel component becomes projected.

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.

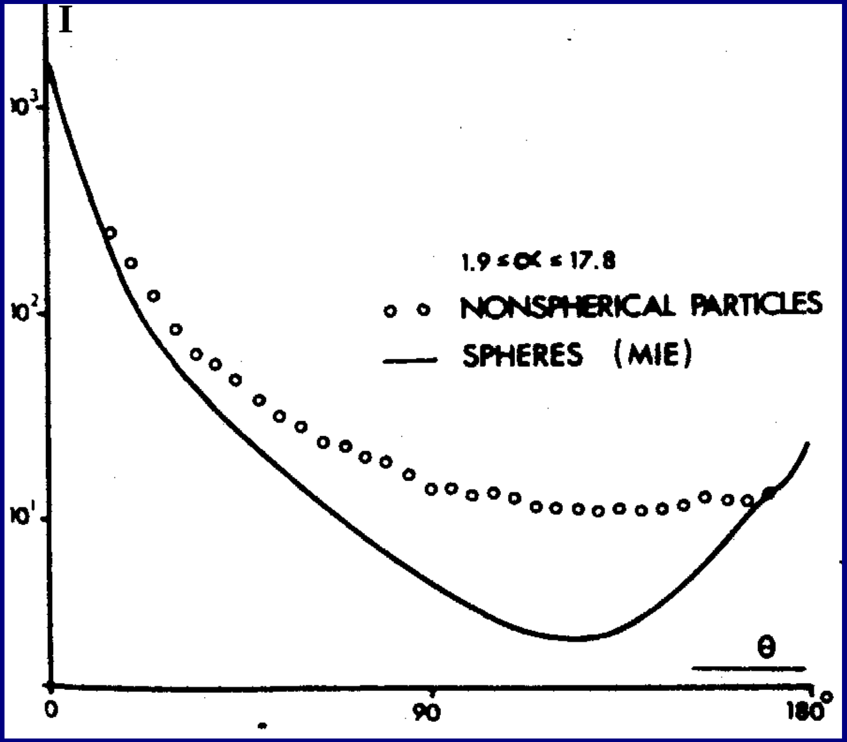


Polarization by dust scattering

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.



Monte-carlo technique for radiative transfer

- Introducing the Stokes code
- Take a photon for a random walk
- Possible configurations of the model space
- Accurate scattering
- Output data

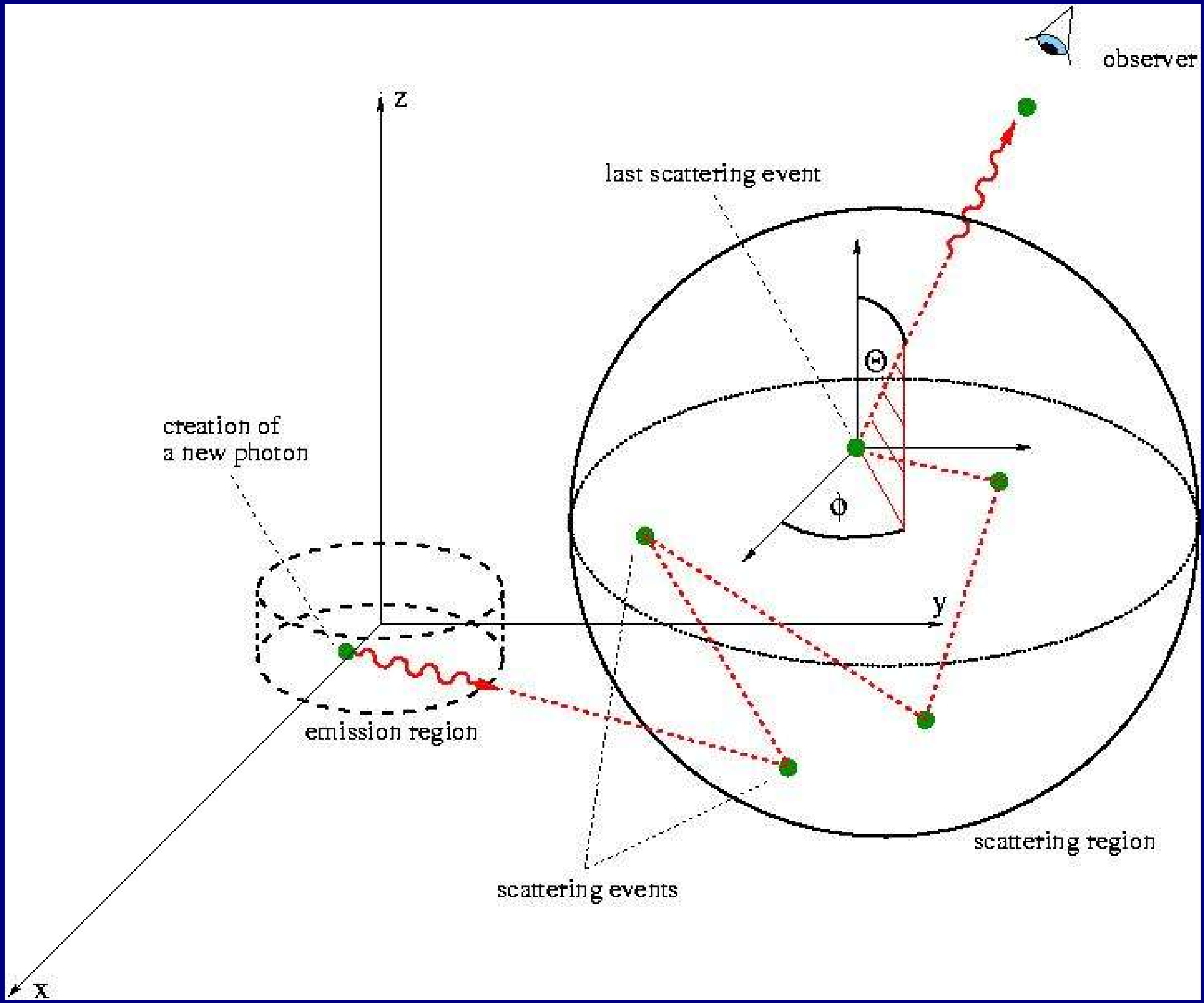
Introducing Stokes

- 3D radiative transfer code for polarization
- valid between 1400 Å and 10000 Å
- based on the Monte-Carlo method
- allows various geometries for emission/scattering regions (spheres, tori, cones, etc...)
- includes polarization by Thomson and Mie scattering
- dust grain composition and size distribution can be adjusted
- available on the web (**www.stokes-program.info**) and for free

Take a photon for a random walk...

Throw the dice for...

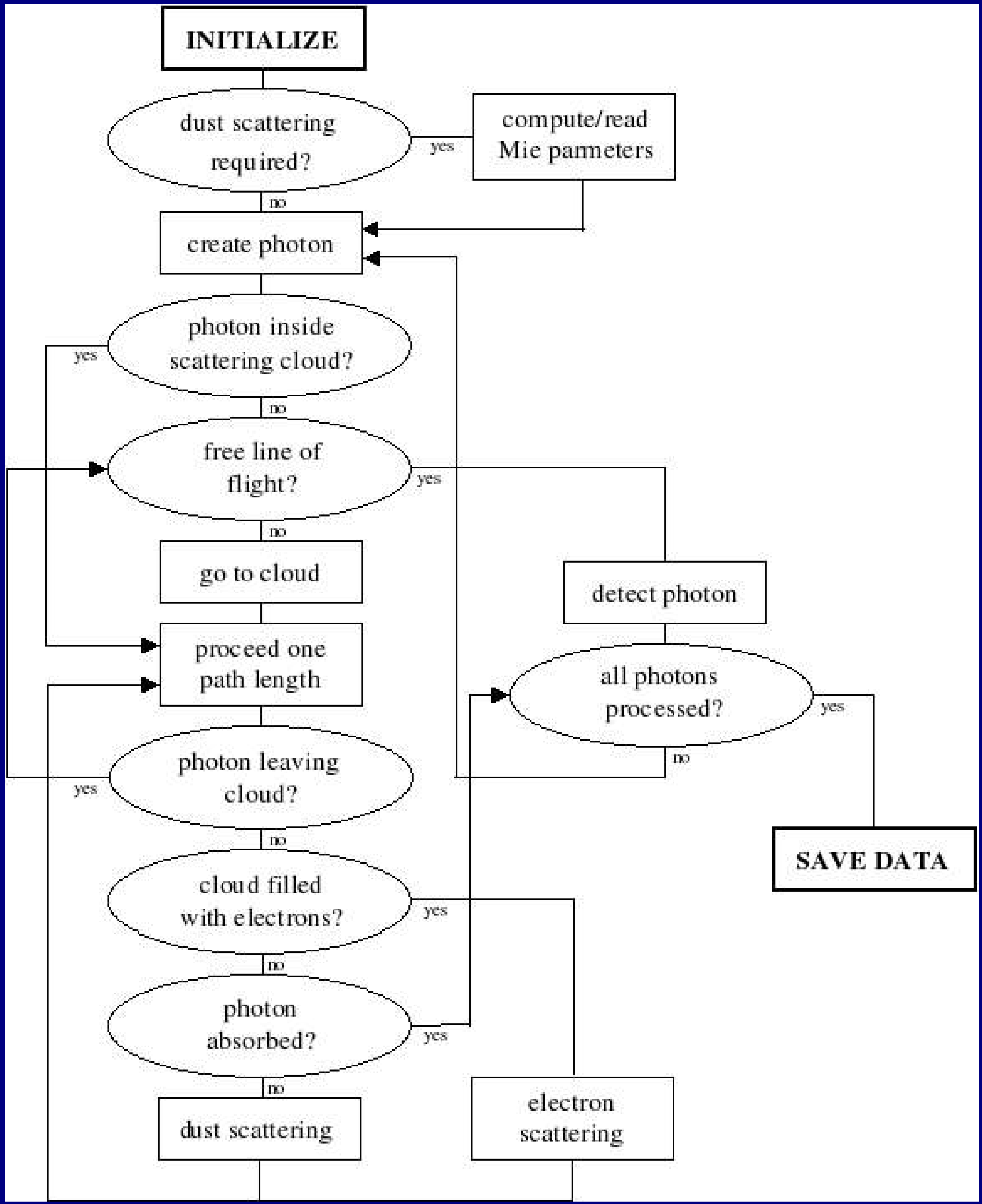
- Photon wavelength
- Emission direction
- Free path lengh
- Absorption by dust
- Scattering angles



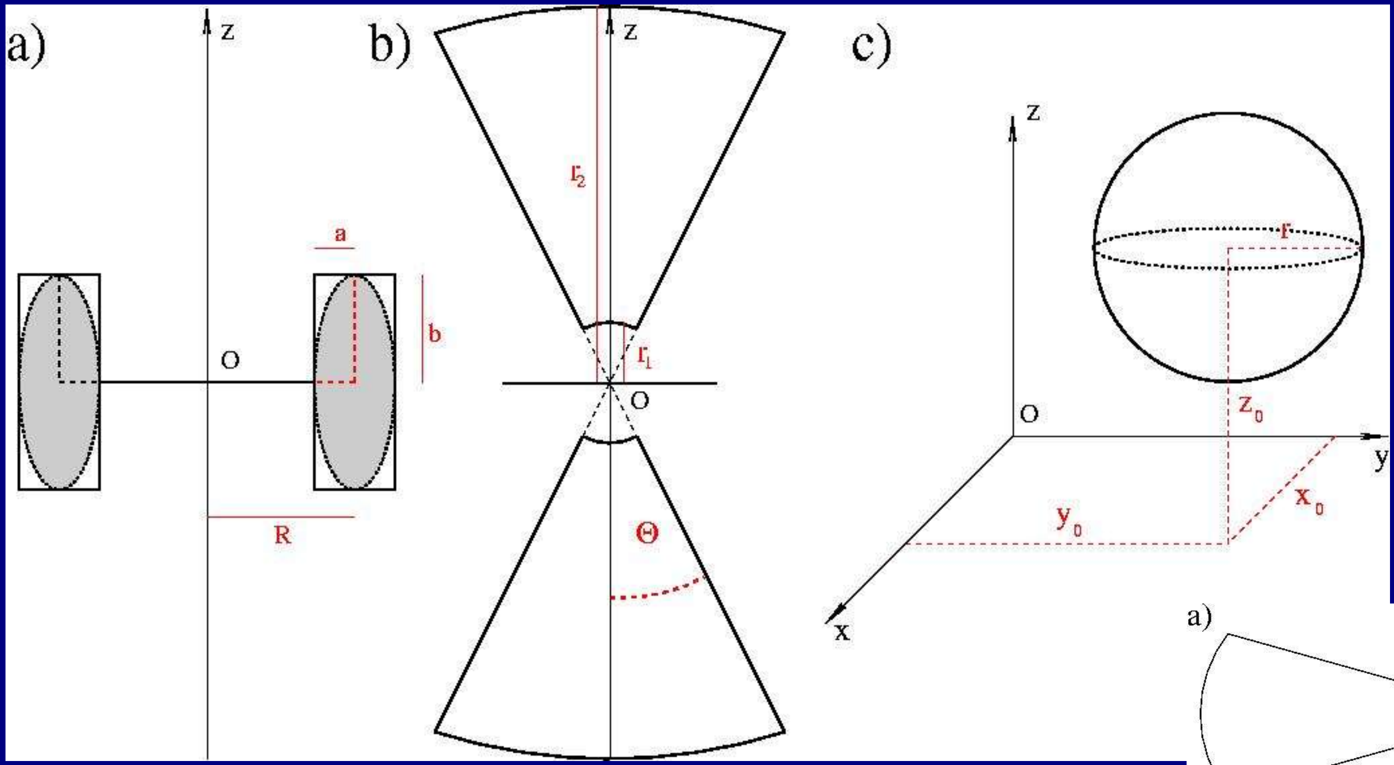
Go with the flow...

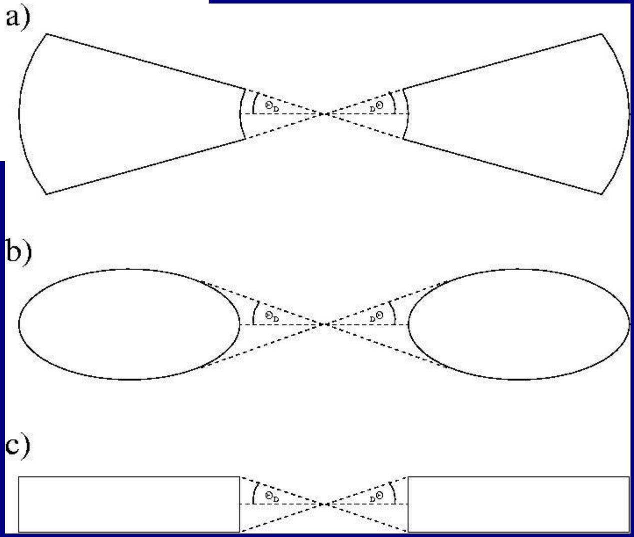
Throw the dice for...

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



Let it encounter scattering clouds...

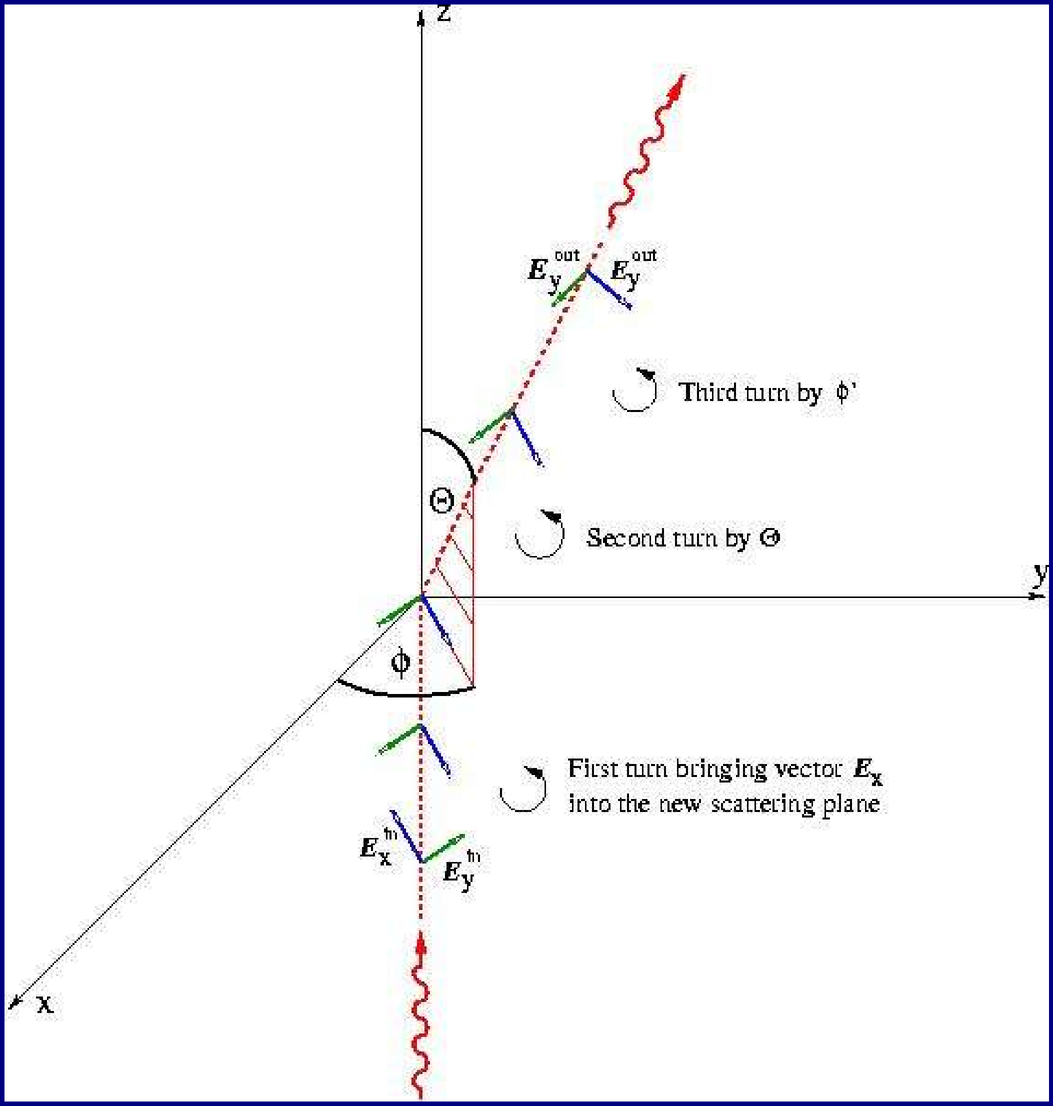




It is possible to define several scattering regions in the model space...

Have the photon scatter accurately...

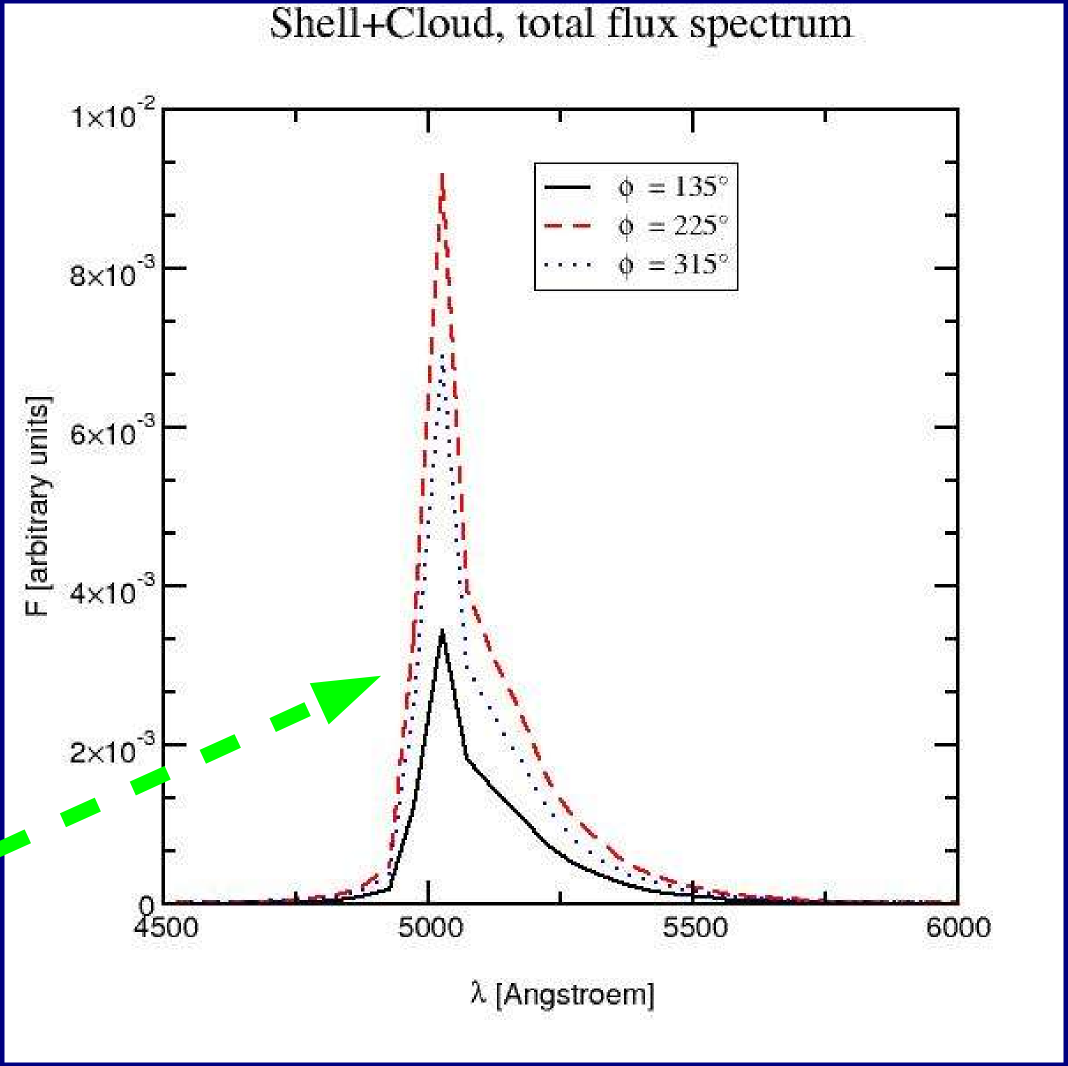
- scattering events are 3D, i.e. around two angles
- the sampling of the scattering angle depends on the initial polarization state
- multiple scattering is automatically included
- for dust grains, absorption is considrered according to the albedo



Count them if they 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



Introduction to Active Galactic Nuclei (AGN)

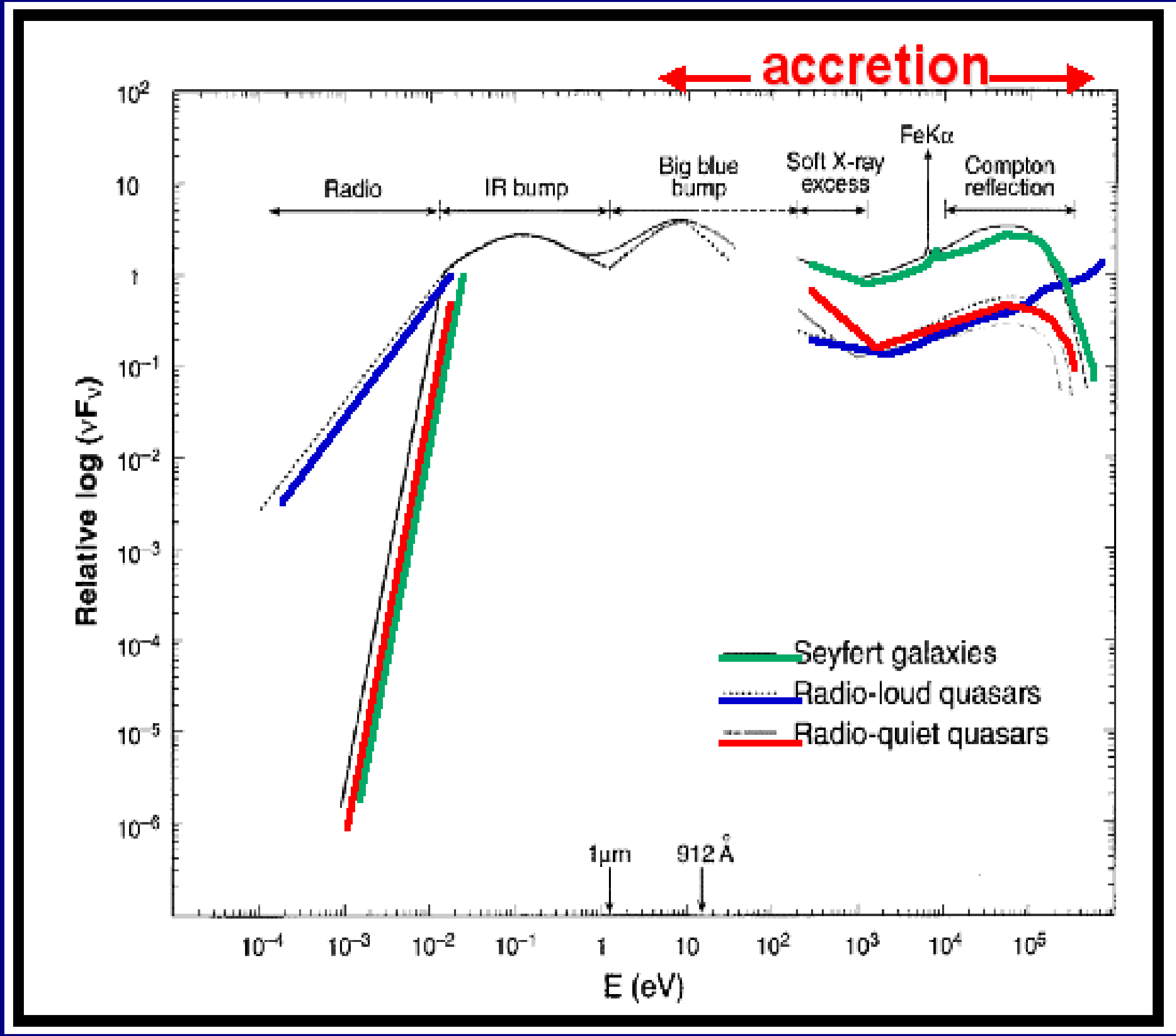
- Spectral appearance and standard model
- Production of the optical-UV radiation
- Polarizing mechanisms relevant to the optical-UV

The AGN phenomenon

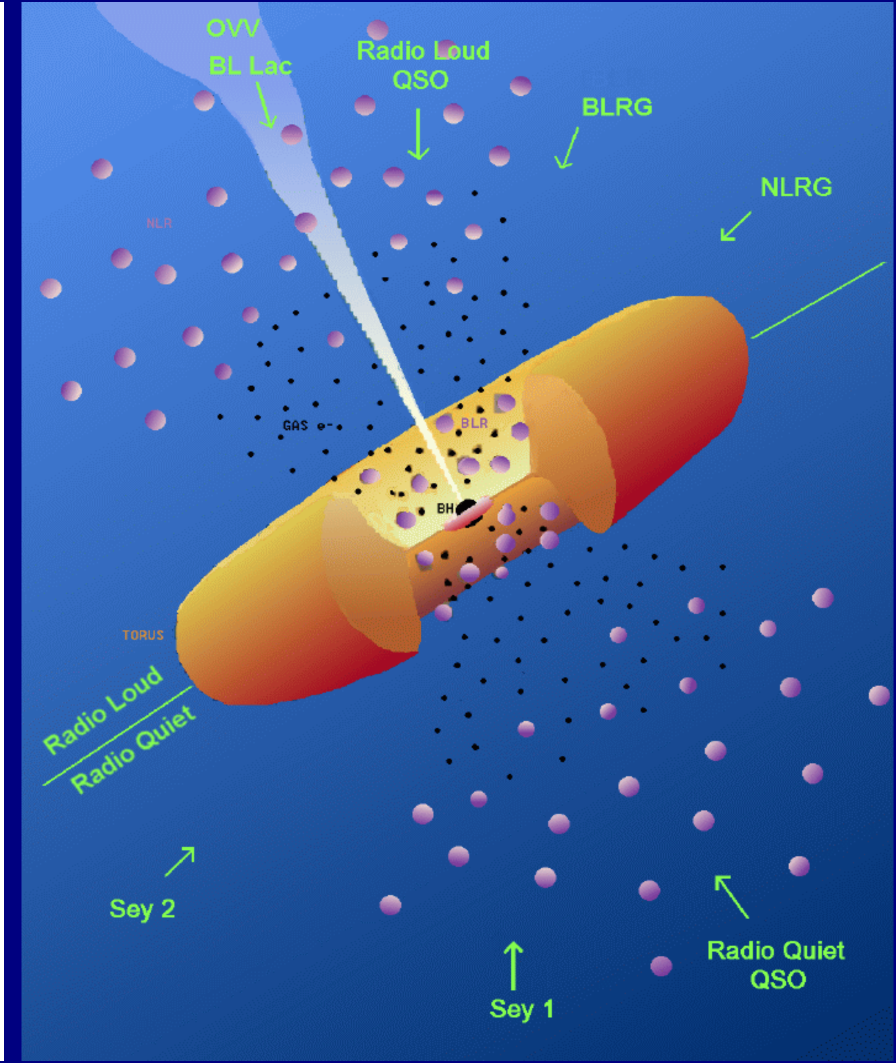
- Most luminous, steady sources observed
- Sources are at the center of galaxies
- Extremely high energy output within relatively small volumes
- Broad spectrum reaching from the radio band to the X-rays or even γ-rays
- Variability in all spectral bands and on all observable time-scales

Ayub, Soinski, & Tyndall, 2003

The AGN spectrum and the standard model



Collin (2001)



(Urry & Godfrey 1995)

So how do AGN work?

- Central supermassive black hole of 10^6—10^9 solar masses
- Accretion of material from the environment and transformation of gravitational energy into radiation

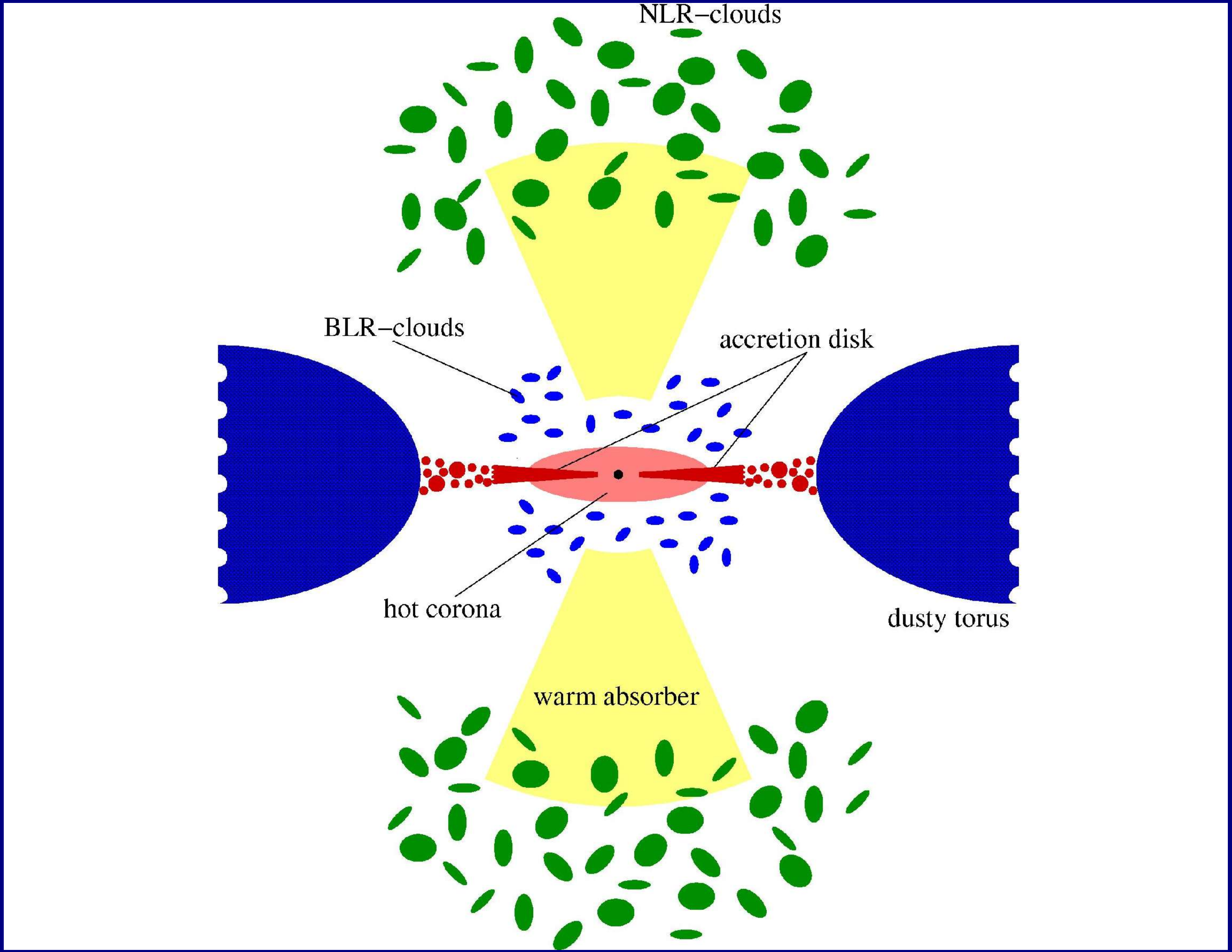
---> α-disk model

- Equatorial obscuration of the central engine
- Eventually, jets directed along the polar axis

Ayub, Soinski, & Tyndall, 2003

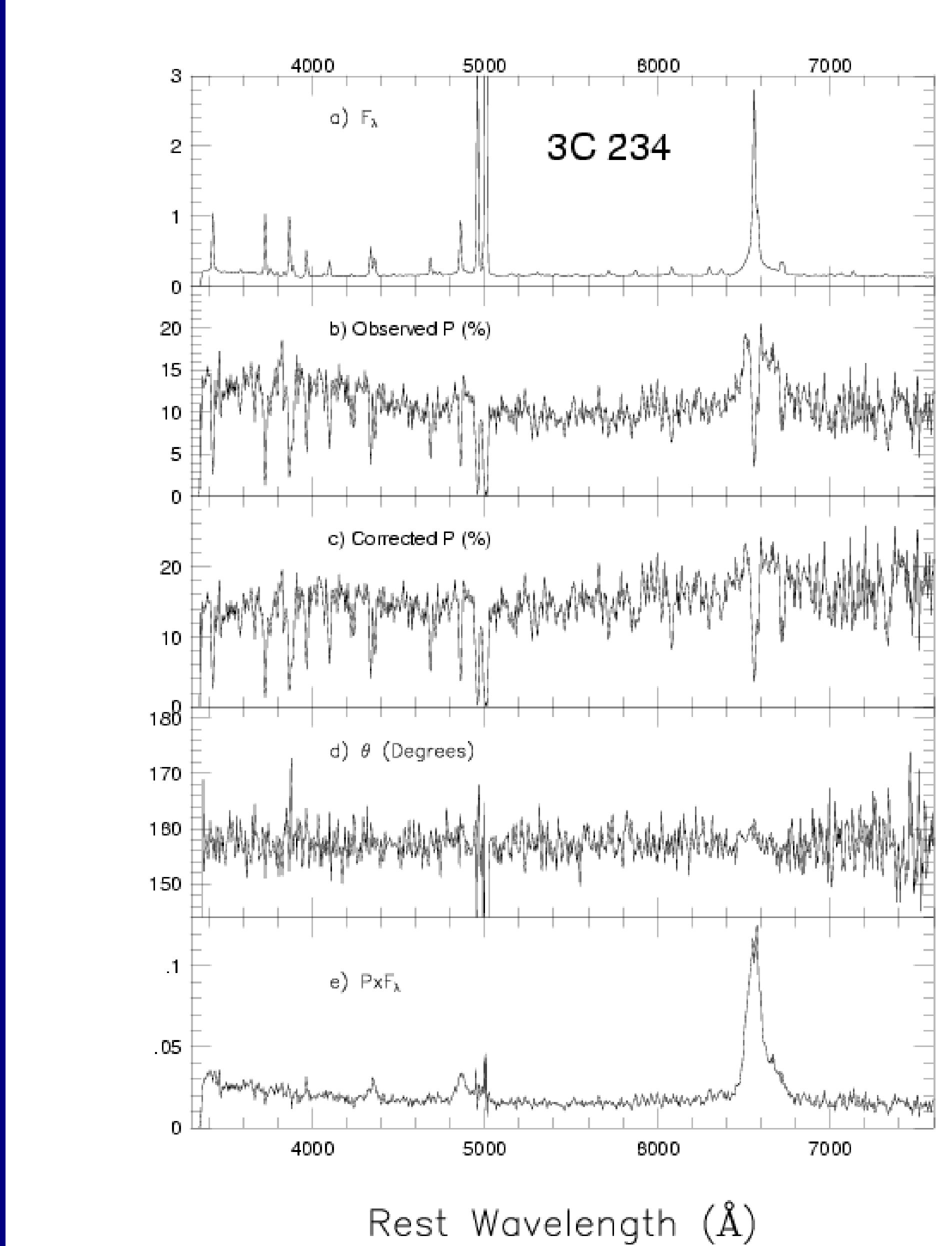
Polarizing mirrors for the optical/UV

All AGN components induce polarization – but some are more important than others.



Hidden type-1 AGN

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



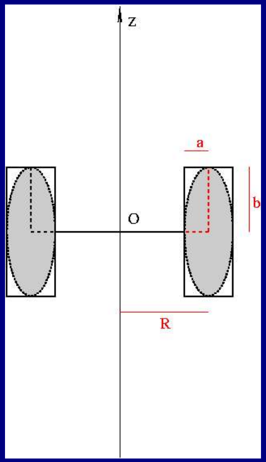
Spectropolarimetric data for 3C 234 from Tran et al. (1995)

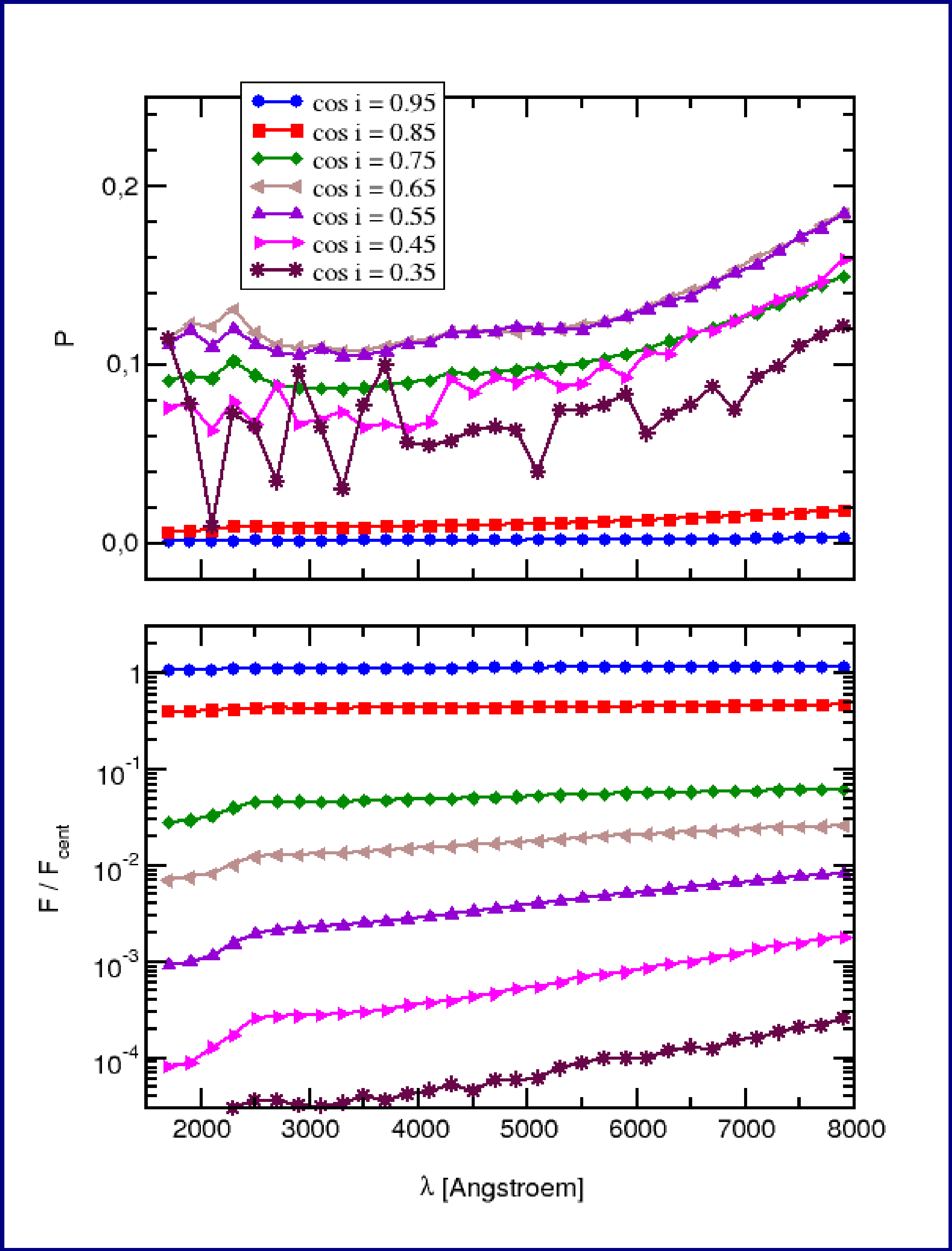
Modeling the polarization of individual AGN scattering components

- The obscuring dusty torus
- Polar scattering regions
- Equatorial electron scattering

The obscuring torus

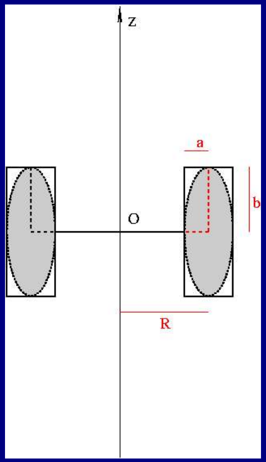
- dust composition and grain size distrubution as for Galactic dust
- half-opening angle of the torus: **30 deg**
- Polarization vector **perpendicular** to symmetry axis

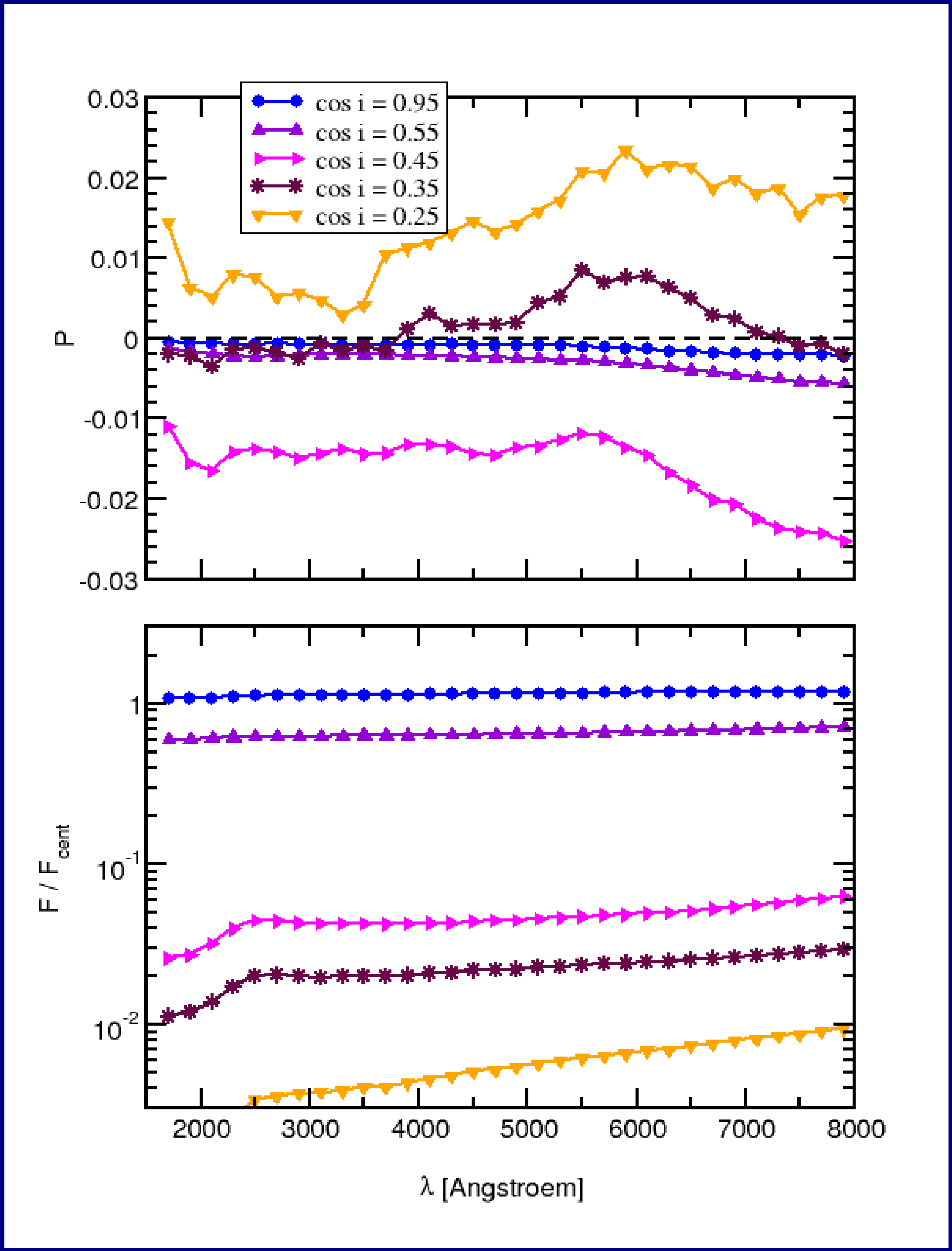




The obscuring torus

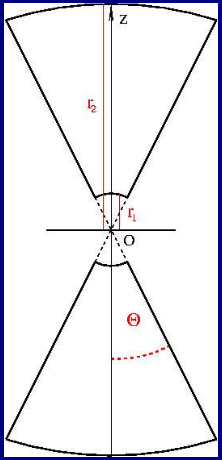
- dust composition and grain size distrubution as for Galactic dust
- half-opening angle of the torus: **57 deg**
- Polarization vector **perpendicular** and **parallel** to symmetry axis

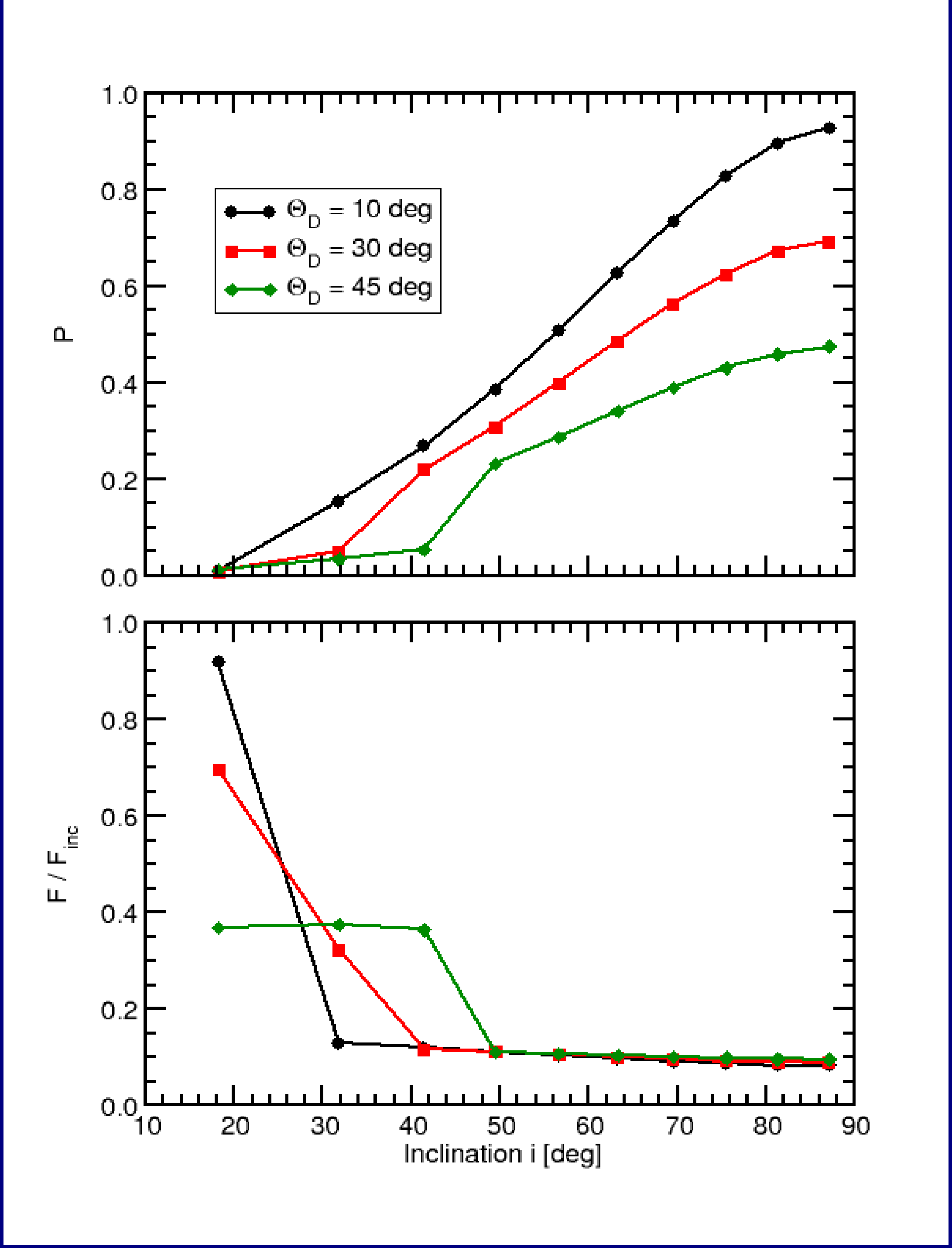




Polar electron cones

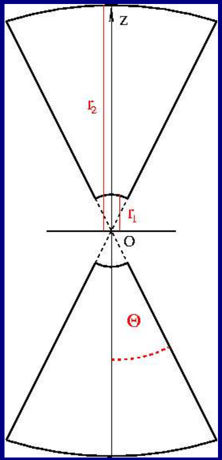
- Optical depth of the cone equals $\tau = 1$.
- Polarization decreases with increasing half-opening angle
- For perpendicular scattering the polarization is most strong

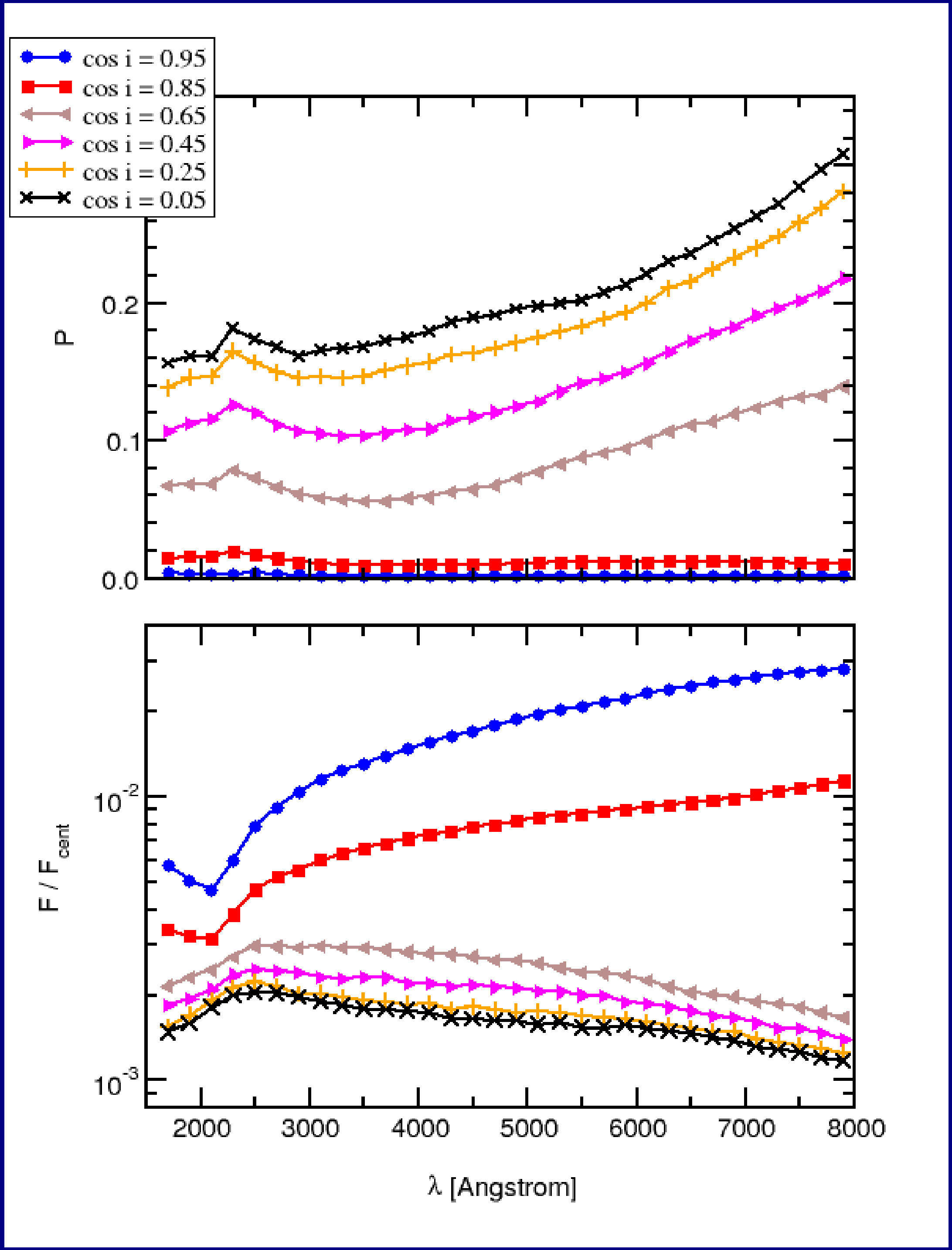




Polar dust cones

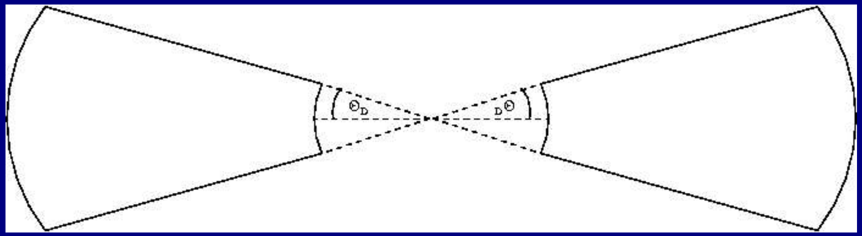
- dust composition and grain size distrubution as for Galactic dust
- half-opening angle of the double-cone: **30 deg**
- Optical depth at 5500 Å equals τ = **0.3** .

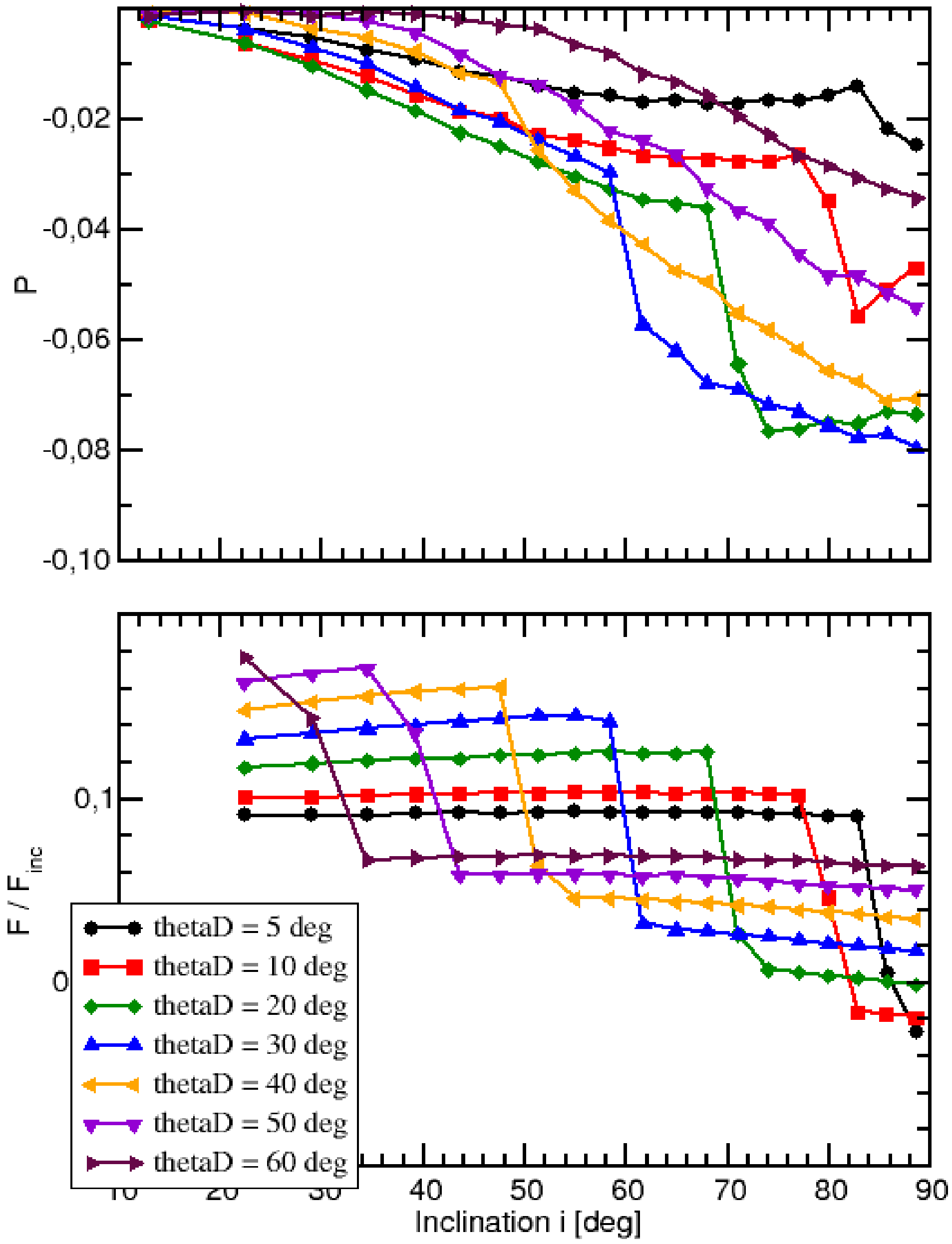




Equatorial wedges

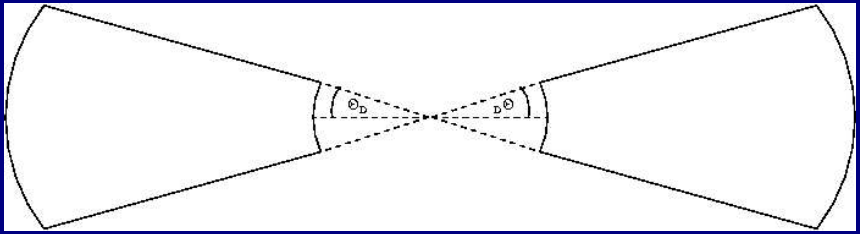
- Wedge filled with electrons of optical depth **τ = 1** .
- Maximum polarization is obtained for half-opening angles around **30 deg** .

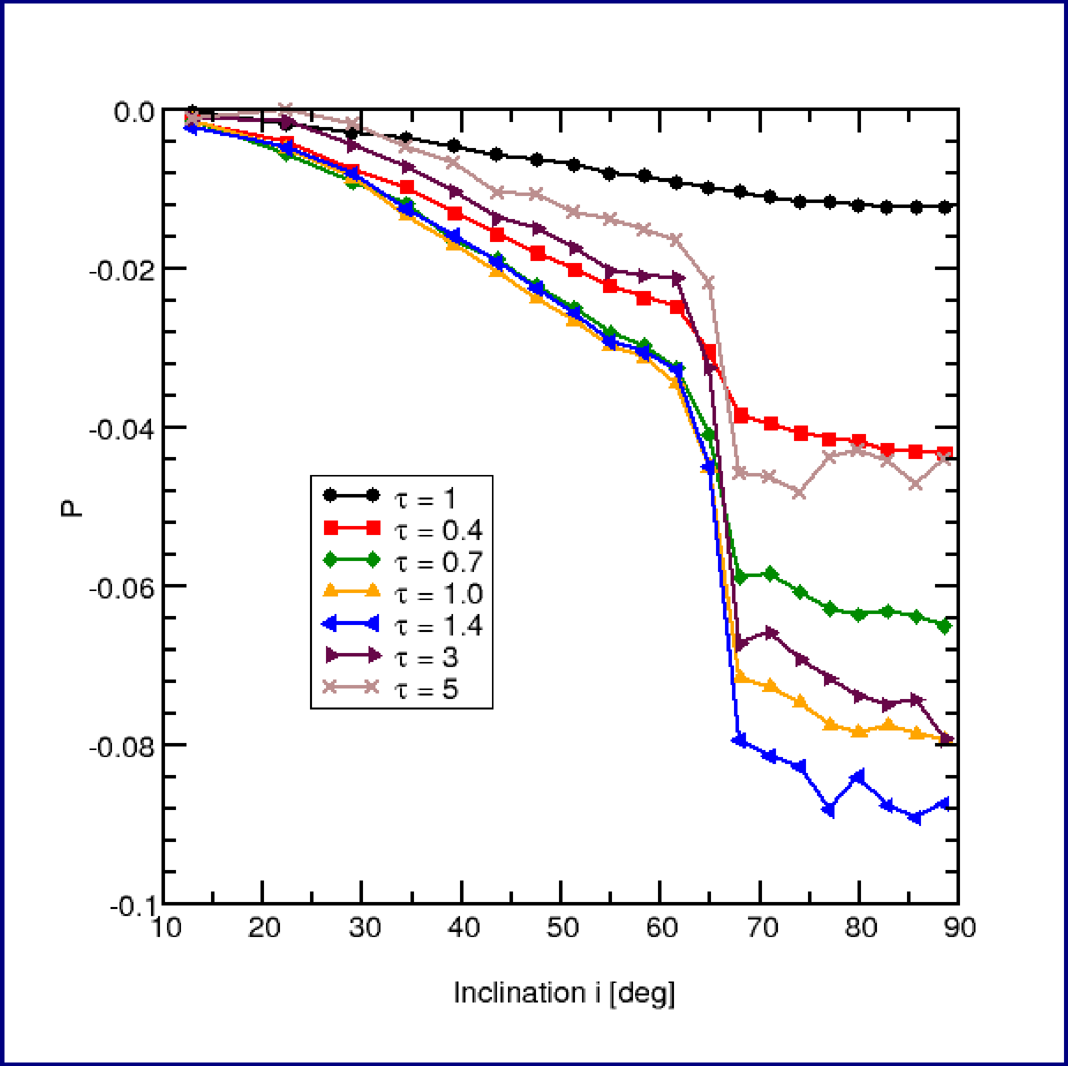




Equatorial wedges

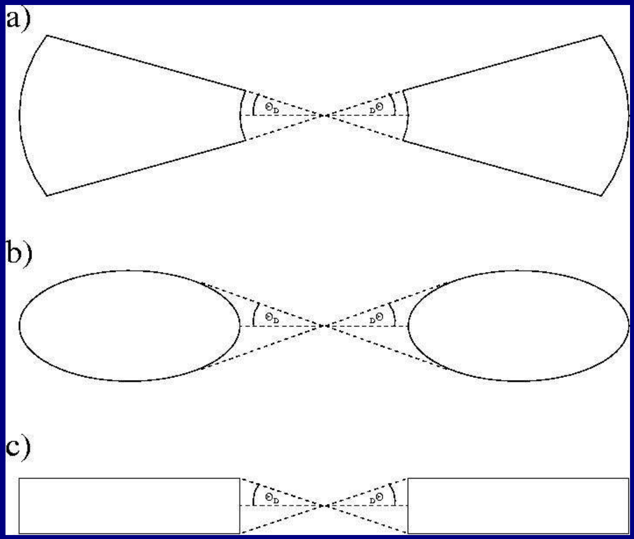
- Wedge filled with electrons of various optical depths.
- Opening angle of the flared-disk equals **25 deg**

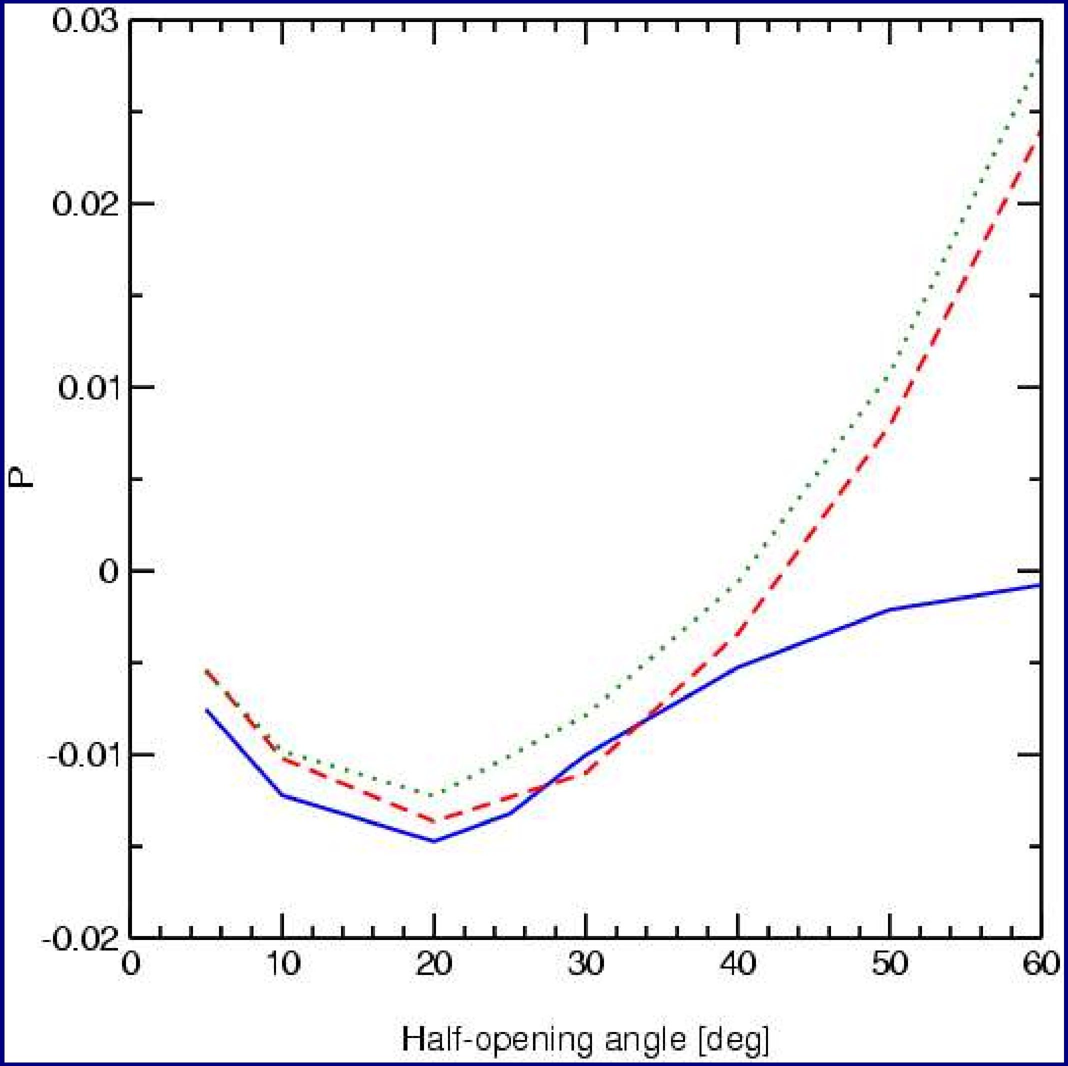




Equatorial wedges

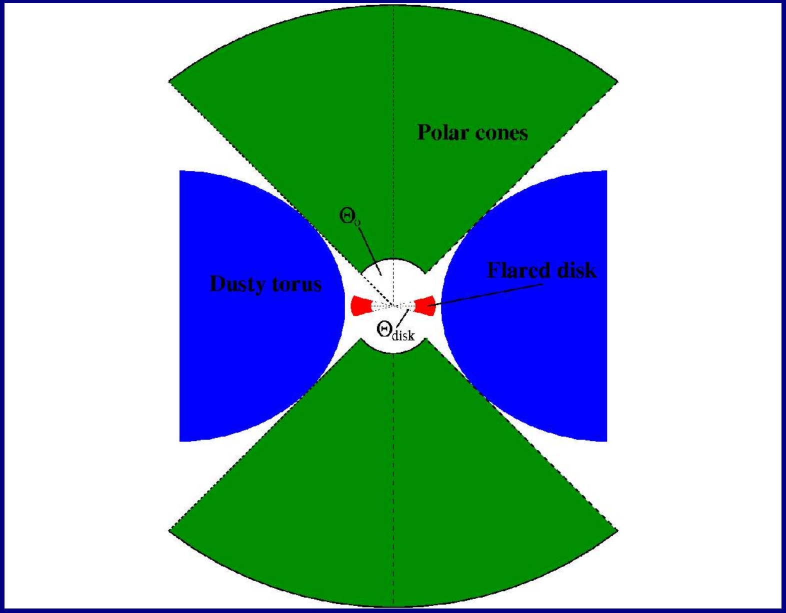
- Influence of different geometries of the equatorial disk.
- Wedge filled with electrons of optical depth $\tau = 1$.

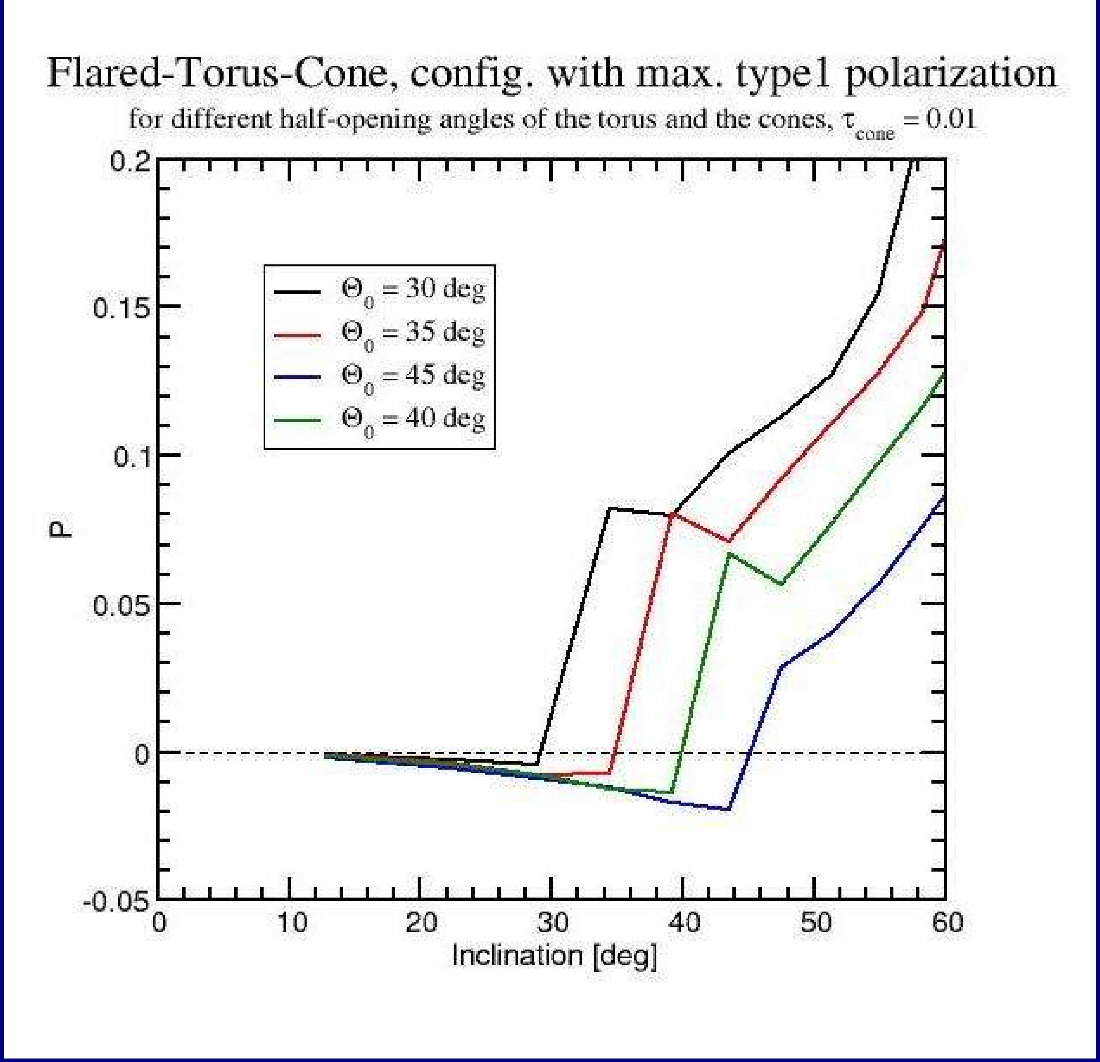




Toward the unified model...

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





Conclusions

- Stokes is a flexible, publicly available code delivering consistent results.
- Although designed for polarization modeling of AGN it can be applied to other astrophysical problems.
- The wavelength-dependent polarization of individual and radiatively connected components of the standard AGN scheme is modeled accurately.
- If you are interested: www.stokes-program.info