Polarization of Active Galactic Nuclei

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Lecture at the COST School

Polarization in Astrophysics

6th June 2013

Centre Paul Langevin

Aussois, France

Observatoire astronomique de Strasbourg

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Polarisation as a tool to study the Solar System and beyond

Action MP1104

Polarization and Active Galactic Nuclei

Outline

- A quick introduction to active galactic nuclei (AGN)
- Polarimetric appearance of radio-quiet AGN in the optical
  - The dichotomy of the continuum polarization
  - The polarization of broad lines
  - The polarization signature of a hidden accretion disk
- A short note on radio-loud AGN
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- Summary and conclusions

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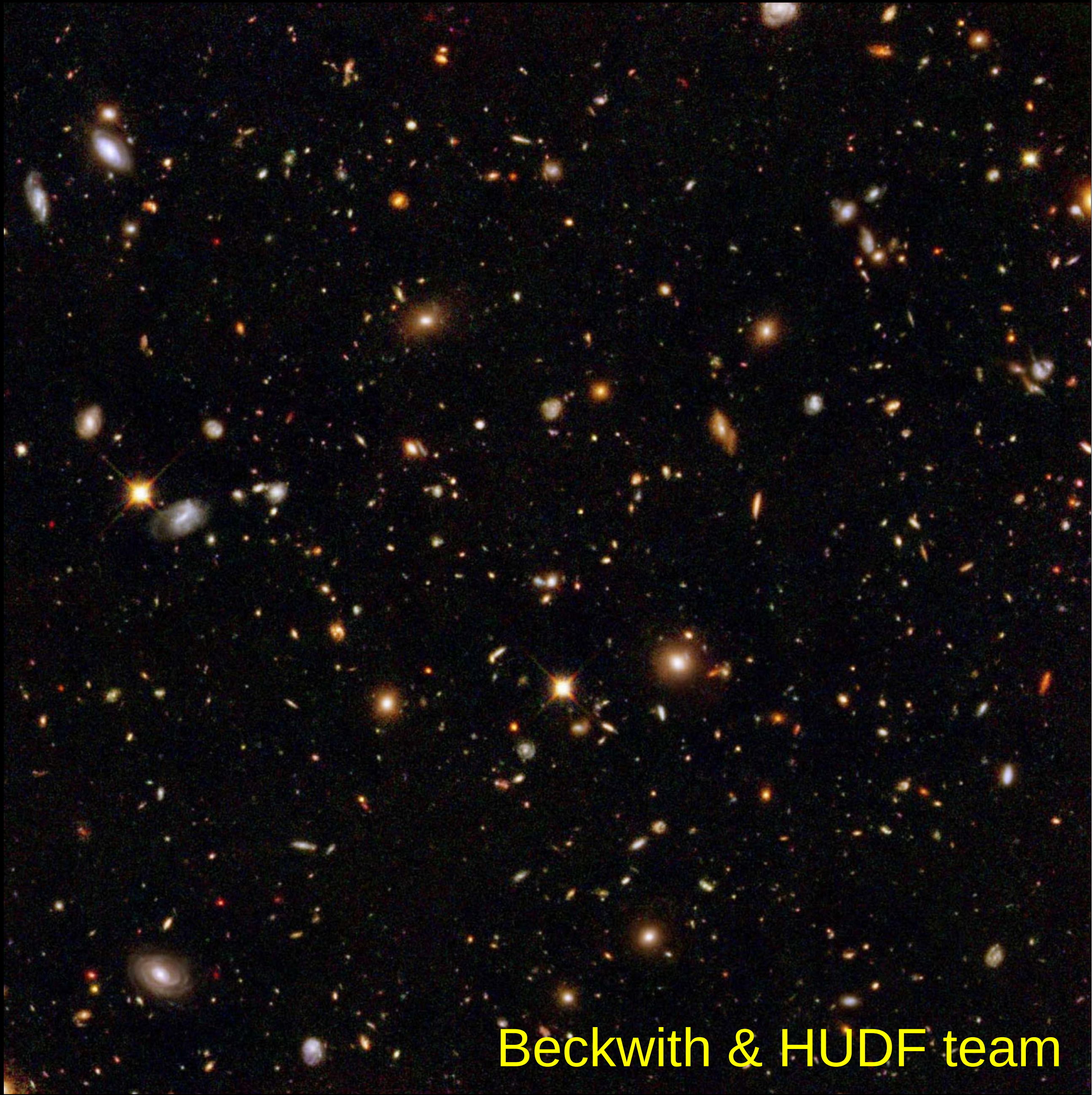
The role of Active Galactic Nuclei in Astrophysics

• *very luminous* from the X-ray to the radio band
--> tracers of baryonic matter in far-away the universe
--> contribution to the re-ionization of the universe
--> connection to the evolution of galaxies

• contain a *supermassive black hole* at the center
--> application of General Relativity in strong fields



Radio-loud AGN have extended jets

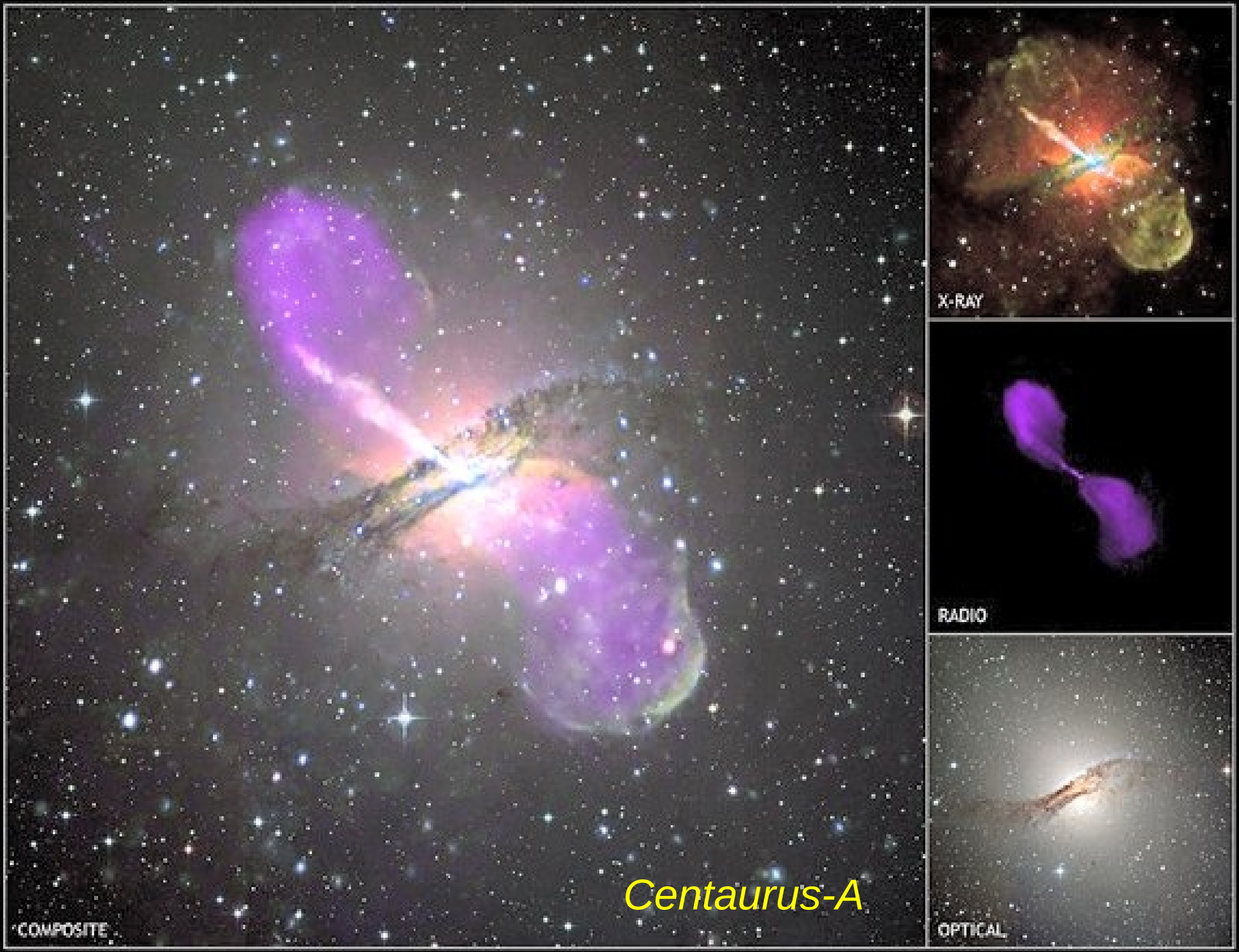
• Ballistic jets of kilo-parsec size, launched from the very center of the AGN

• Launch mechanism not entirely understood

• Collimation effective over several parsecs, until interactions with interstellar medium.

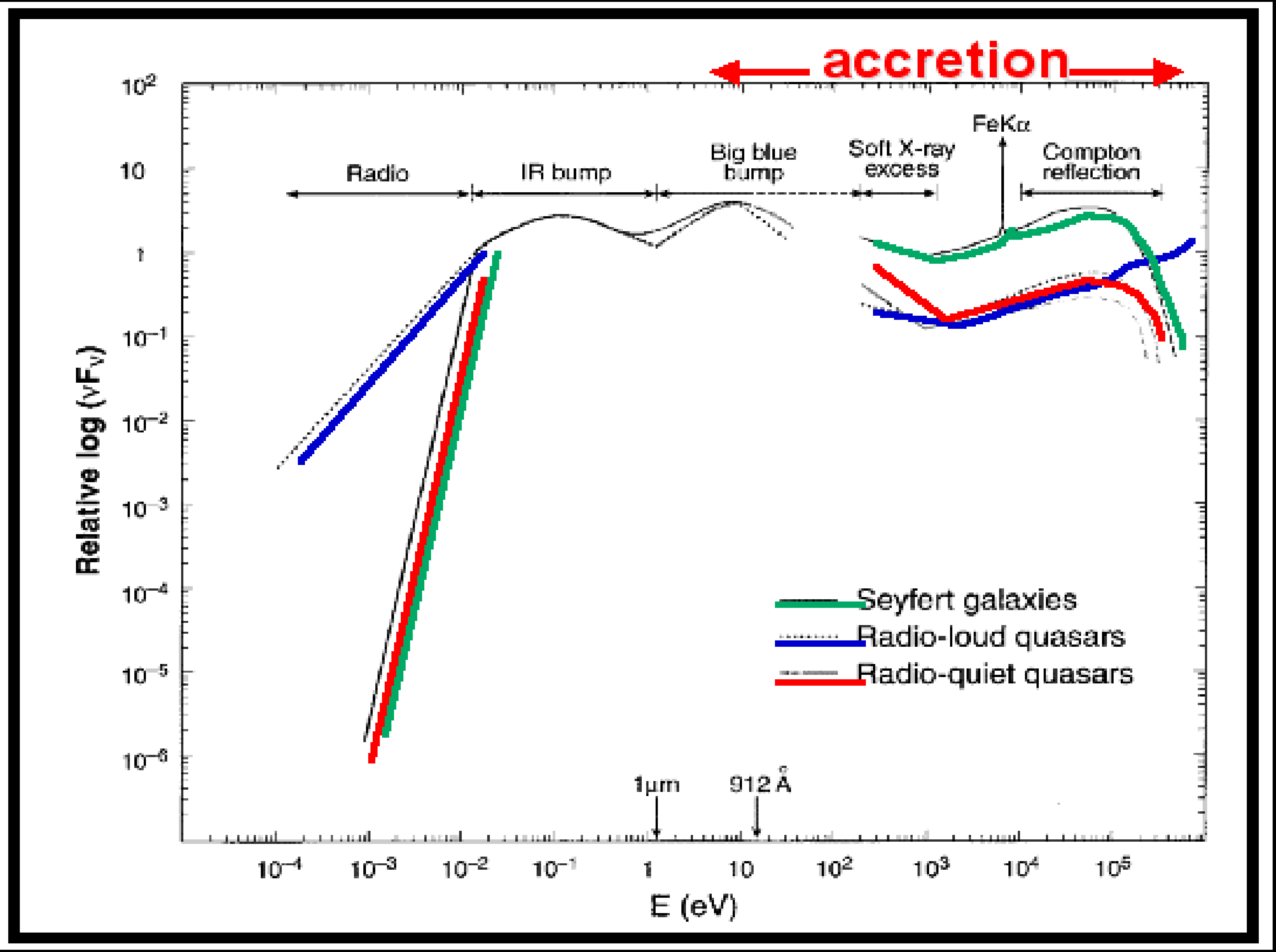
• Possible redirection of the jets in subsequent ejection episodes.

• Interaction between jet and interstellar medium



Kraft et al. (CfA)

The broad spectrum of AGN



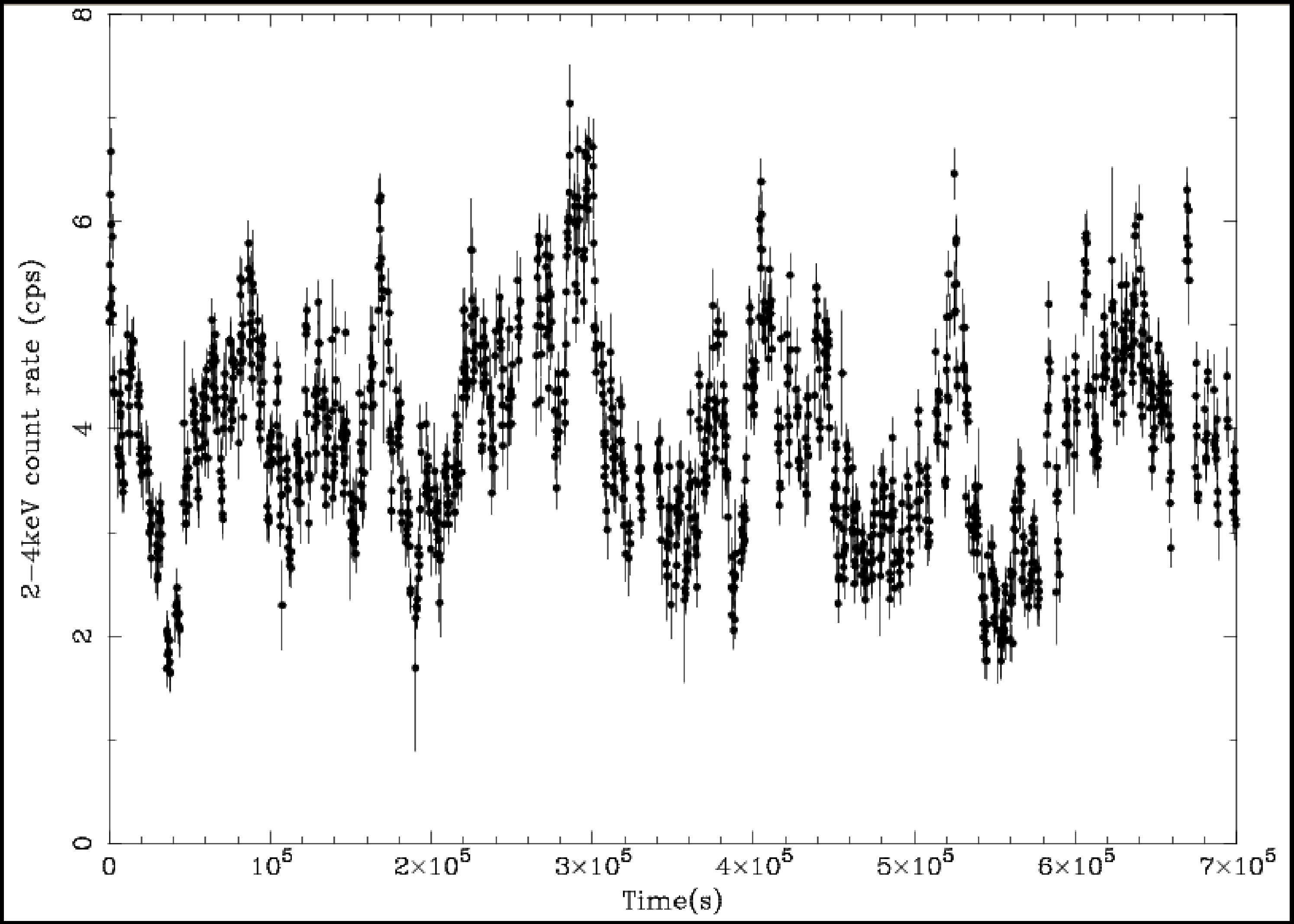
Collin (2001), Sanders et al. 1989

The X-ray variability of AGN: MCG-6-30-15

Active galactic nuclei vary strongly and rapidly in X-ray brightness.

This constrains the size of the emission site to a very compact region.

→ suggests accretion by a supermassive black hole

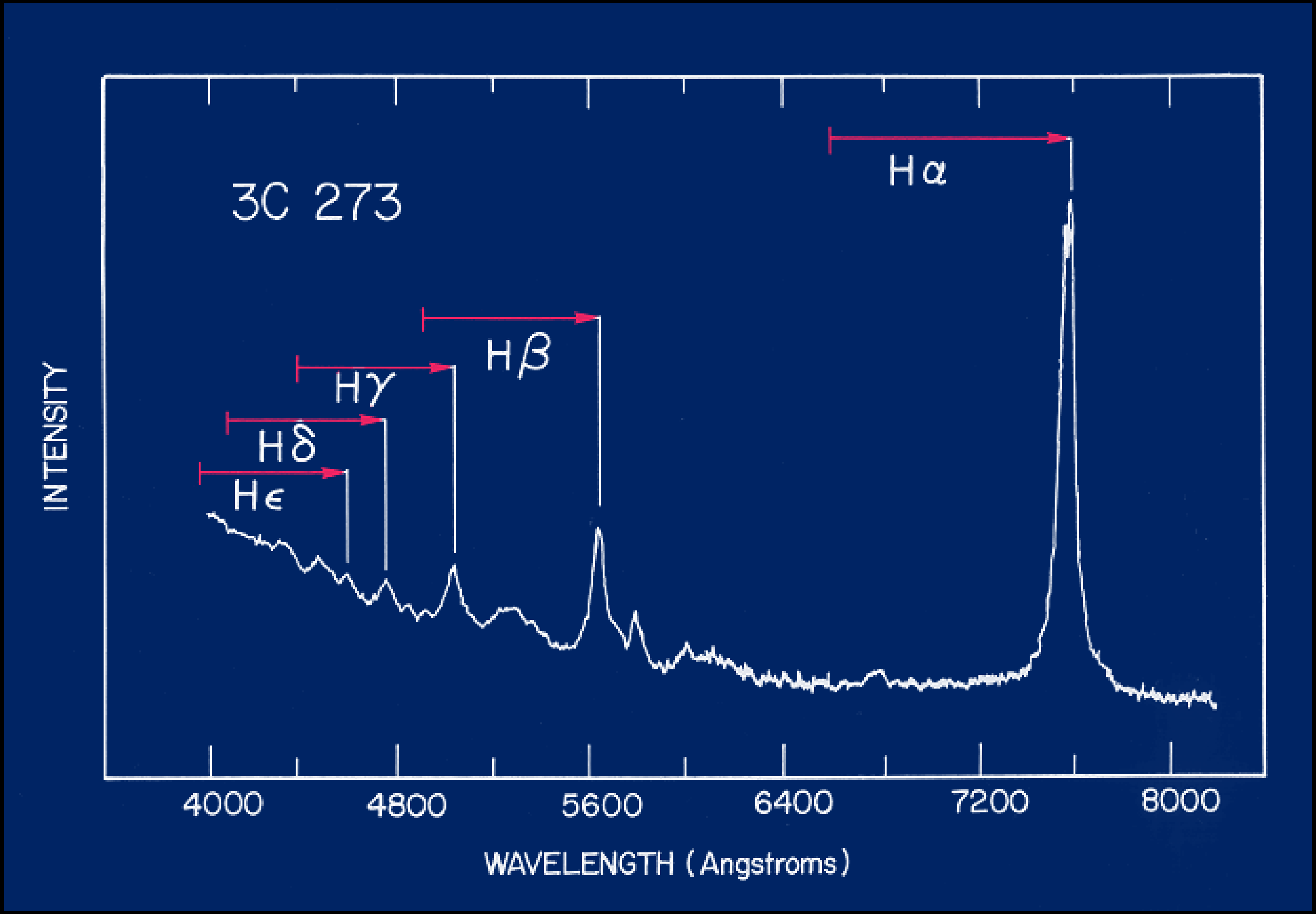


Reynolds 2000

The optical spectrum of AGN: 3C 273

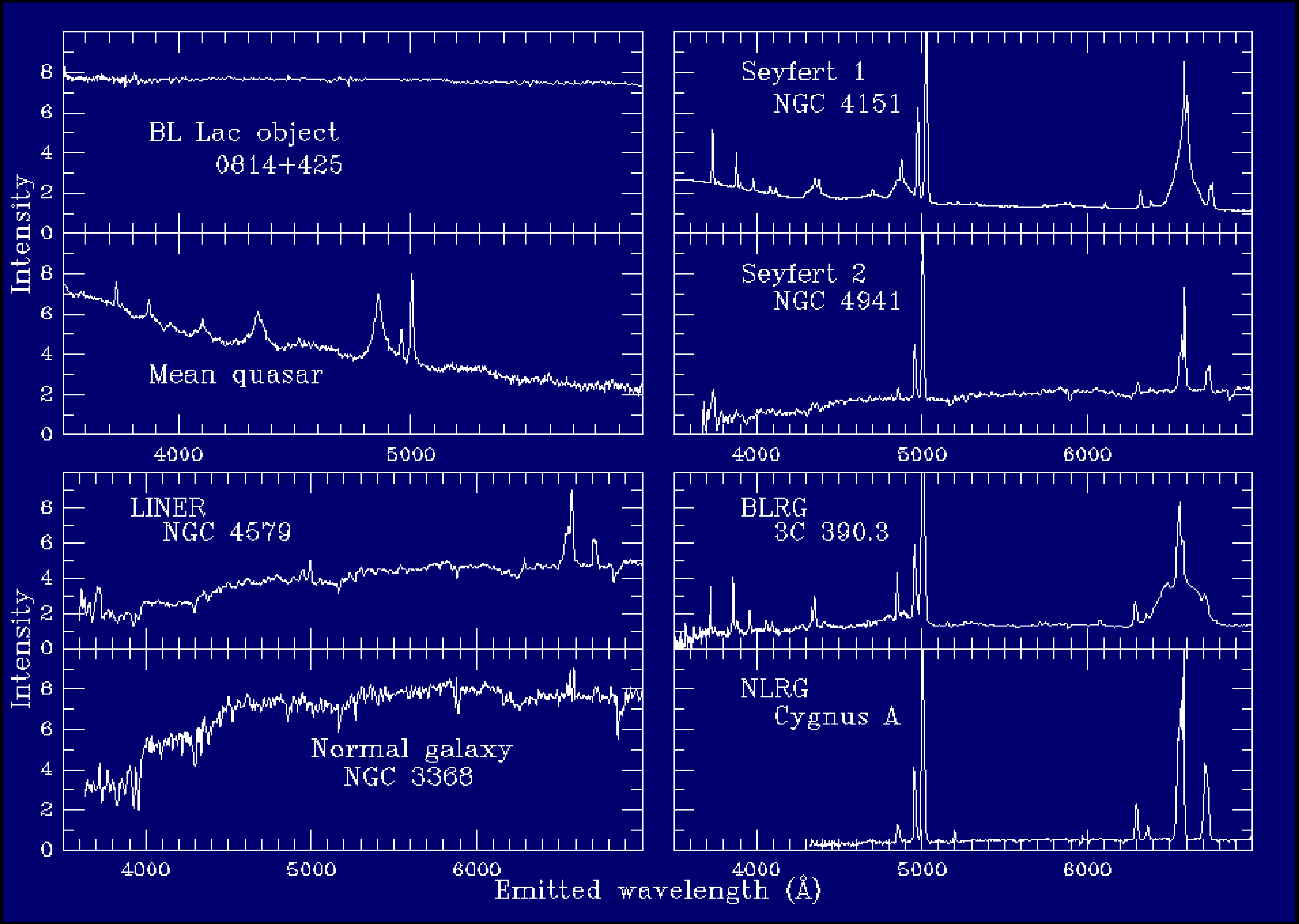
The optical spectrum of the quasar 3C 273 exhibits broadened, redshifted, Balmer emission lines.

The brodening is due to a large differential velocity distribution of the reprocessing medium (several 1000 km/s).



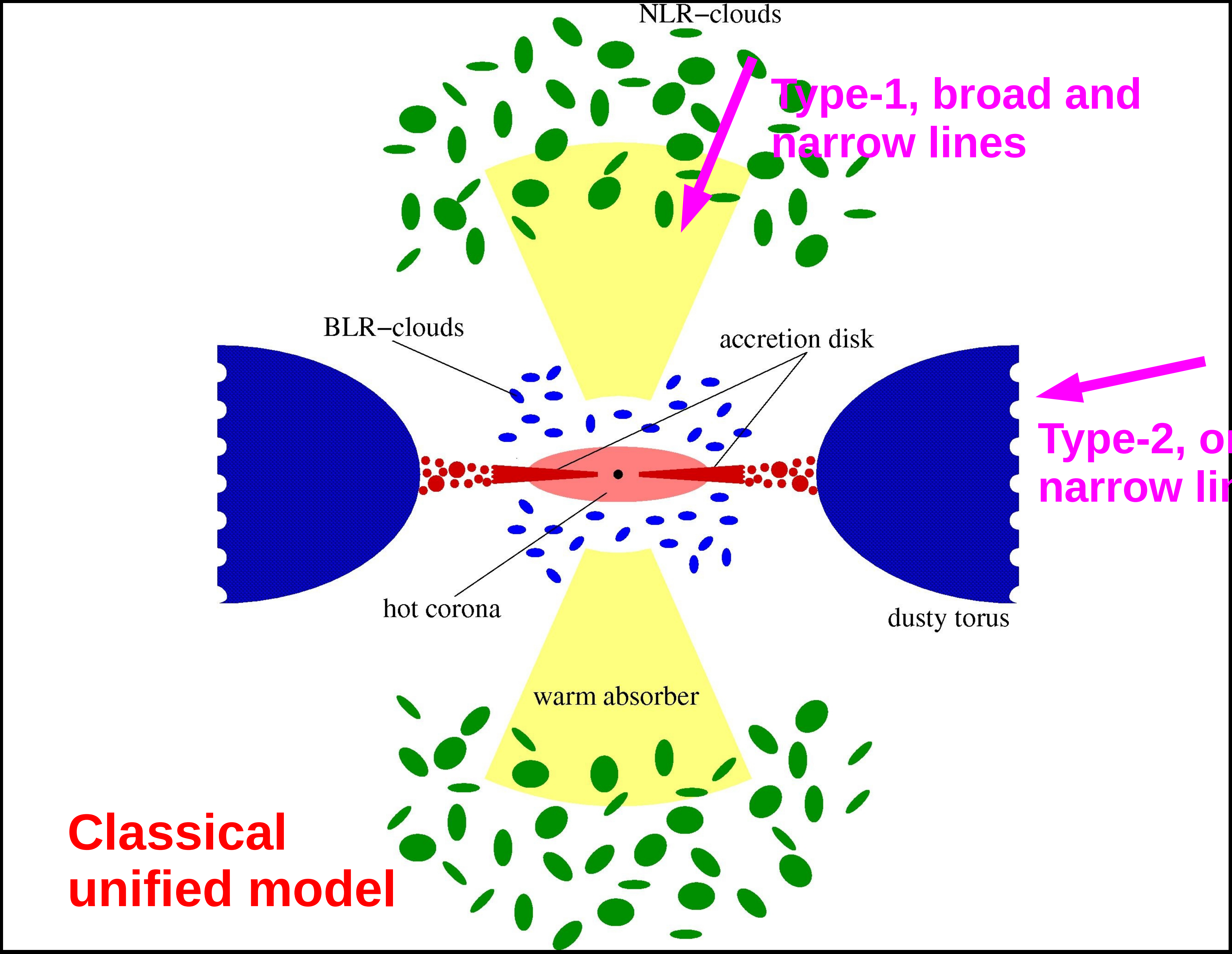
Maarten Schmidt (1963)

The AGN zoo : optical properties of different sub-types



(Bill Keel)

Unifying broad and narrow line objects



Optical fact sheet for the unified model of AGN

- Strong energy release in a limited spatial region due to accretion onto a central supermassive black hole (10^6—10^9 solar masses)
- In radio-quiet objects, the bulk continuum emission comes from an accretion disk.
- In radio-loud objects (~10% of all AGN), strong continuum emission also comes from the jets.
- Around the accretion disk, high velocity clouds reprocess the continuum producing broad emission lines.
- The broad lines are seen at lines of sight not going through the equatorial dust lanes (type-1 AGN).
- At viewing angles blocked by the dust, only narrow lines are seen (type-2 AGN), which are produced in more distant, polar regions.

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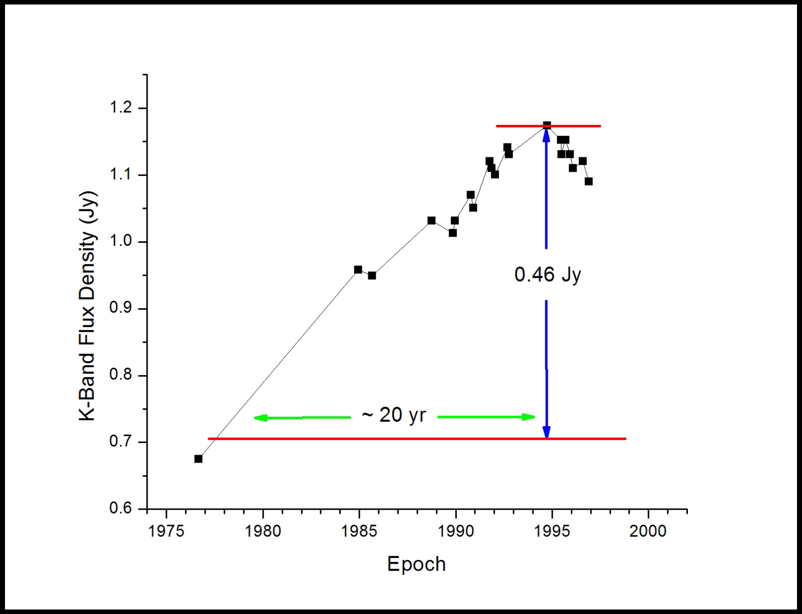
Why should we care about polarization?

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))

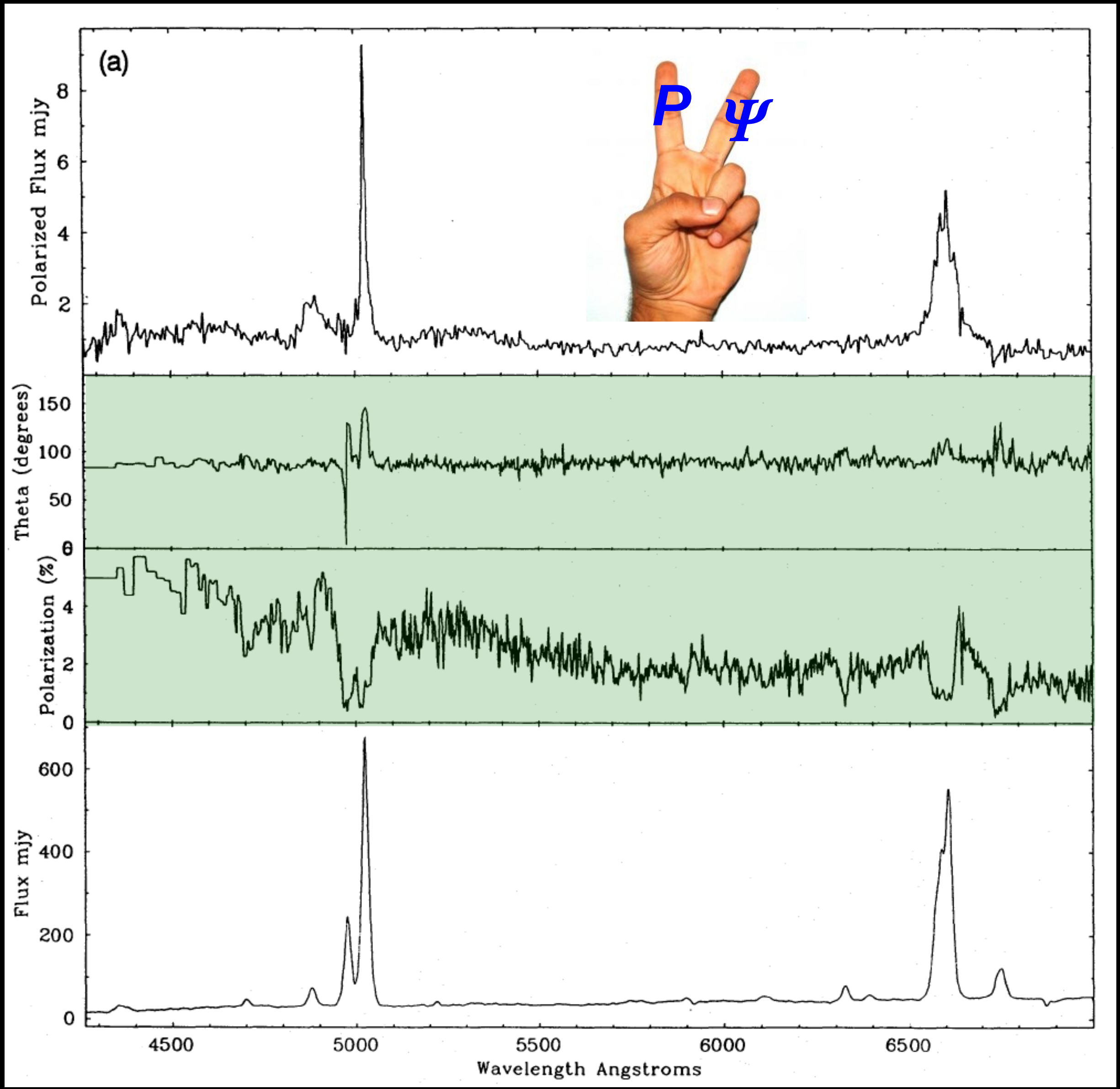


2.2 micron light curve of NGC 1068 (work by I. Glass)

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

Processes producing (de-)polarization

Synchrotron emission

Electron and Rayleigh scattering

Dust (Mie) scattering

Resonant line scattering

Dichroic absorption

Faraday rotation

Dilution (by unpolarized radiation)

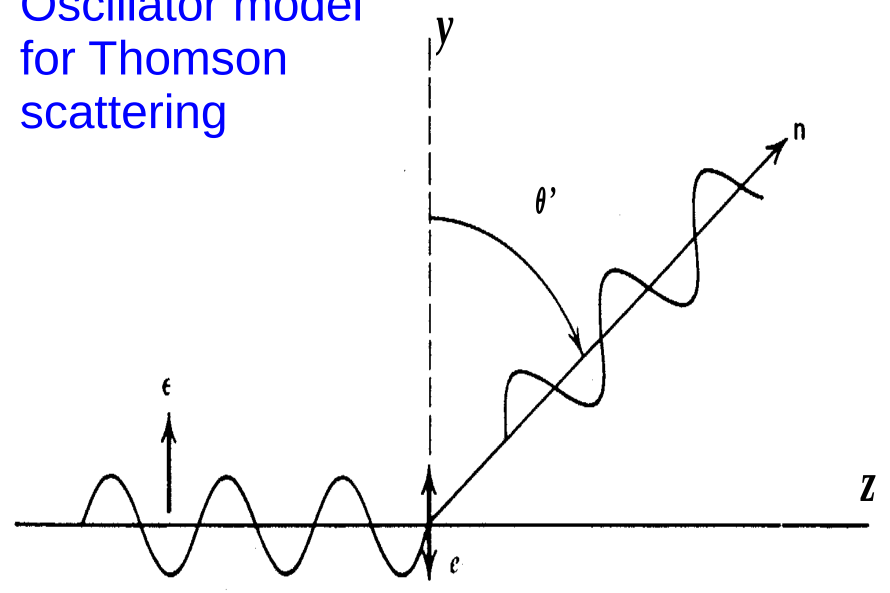
General Relativity

Scattering

Strong polarization: Θ = 90° (Reflection)

Weak polarization: Θ = 0° (Transmission)

Oscillator model for Thomson scattering



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

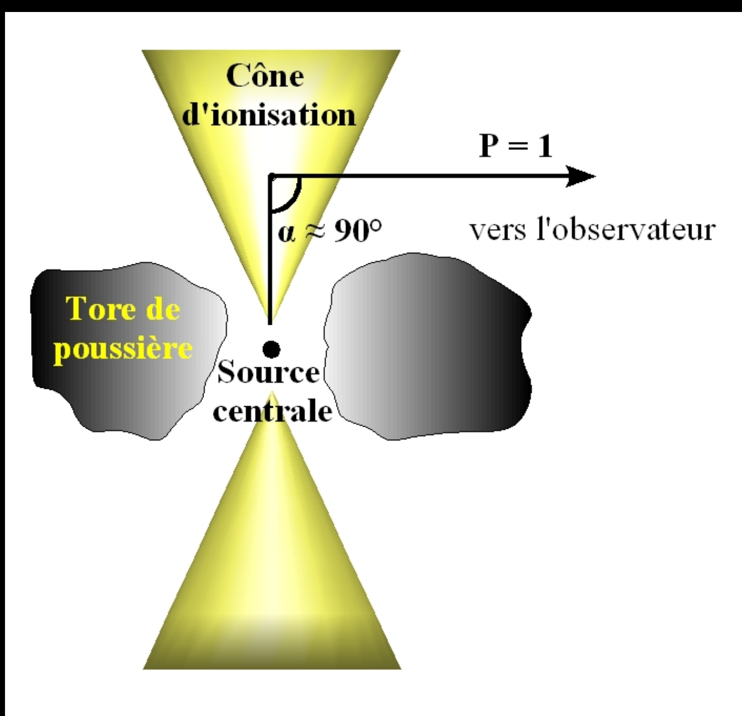
$$P = \frac{1-\cos^2\theta}{1+\cos^2\theta}.$$

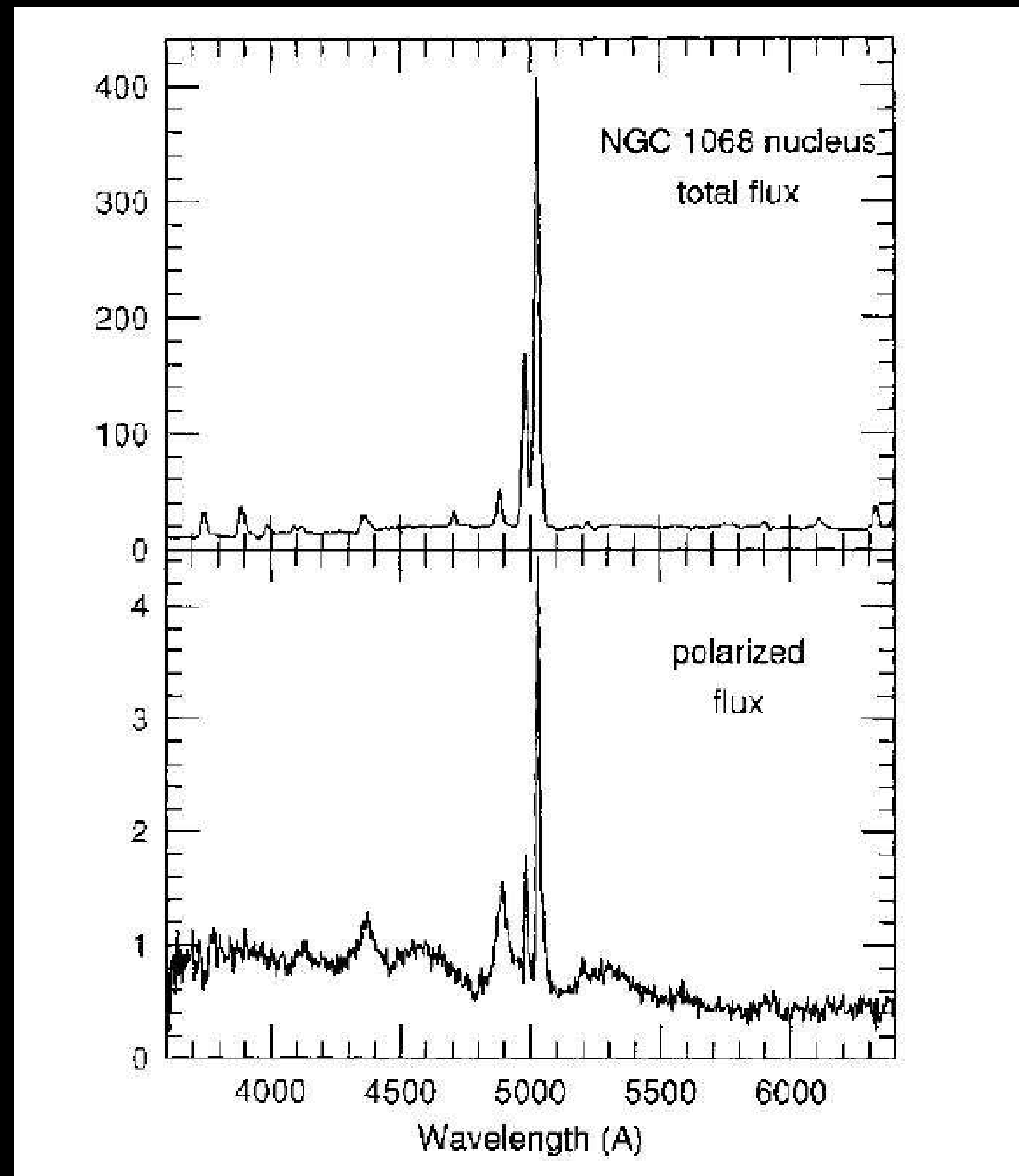
$$\sigma_T = \frac{8\pi}{3} r_0^2 = \frac{8\pi e^4}{3m^2c^4}.$$

Radio-quiet objects Hidden type-1 AGN

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

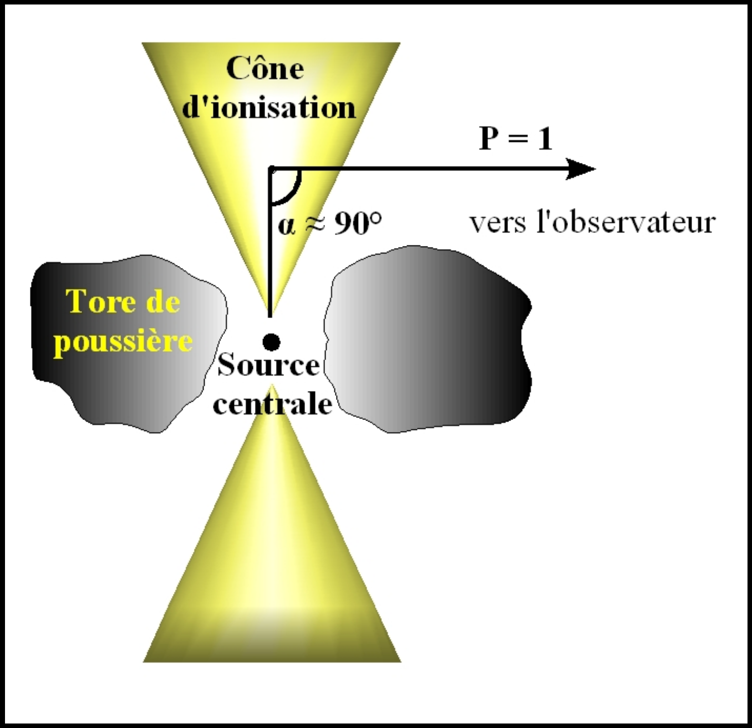
→ periscope view of AGN in polarized flux

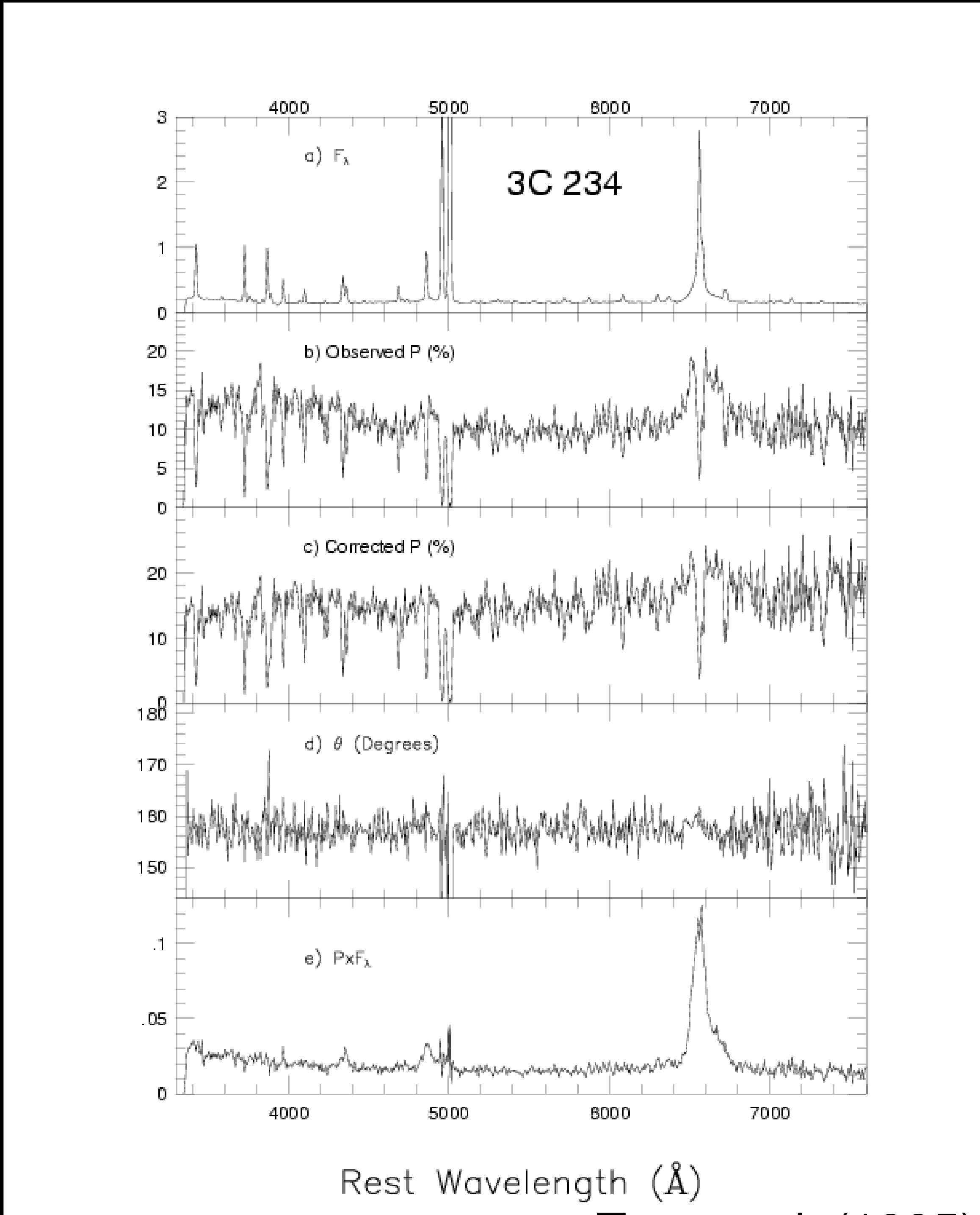




Hidden type-1 AGN

In the following, more and more hidden type-1 nuclei were found in Seyfert 2 galaxies.



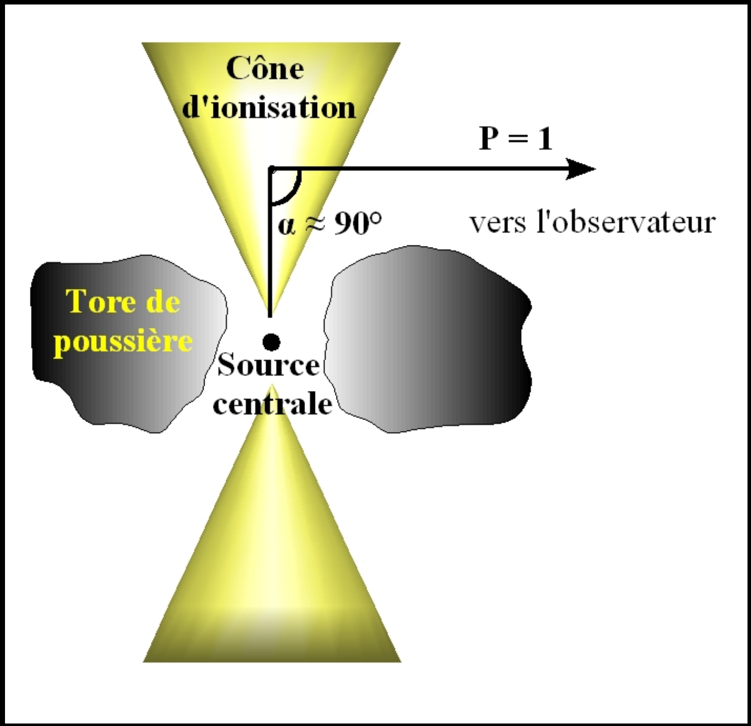


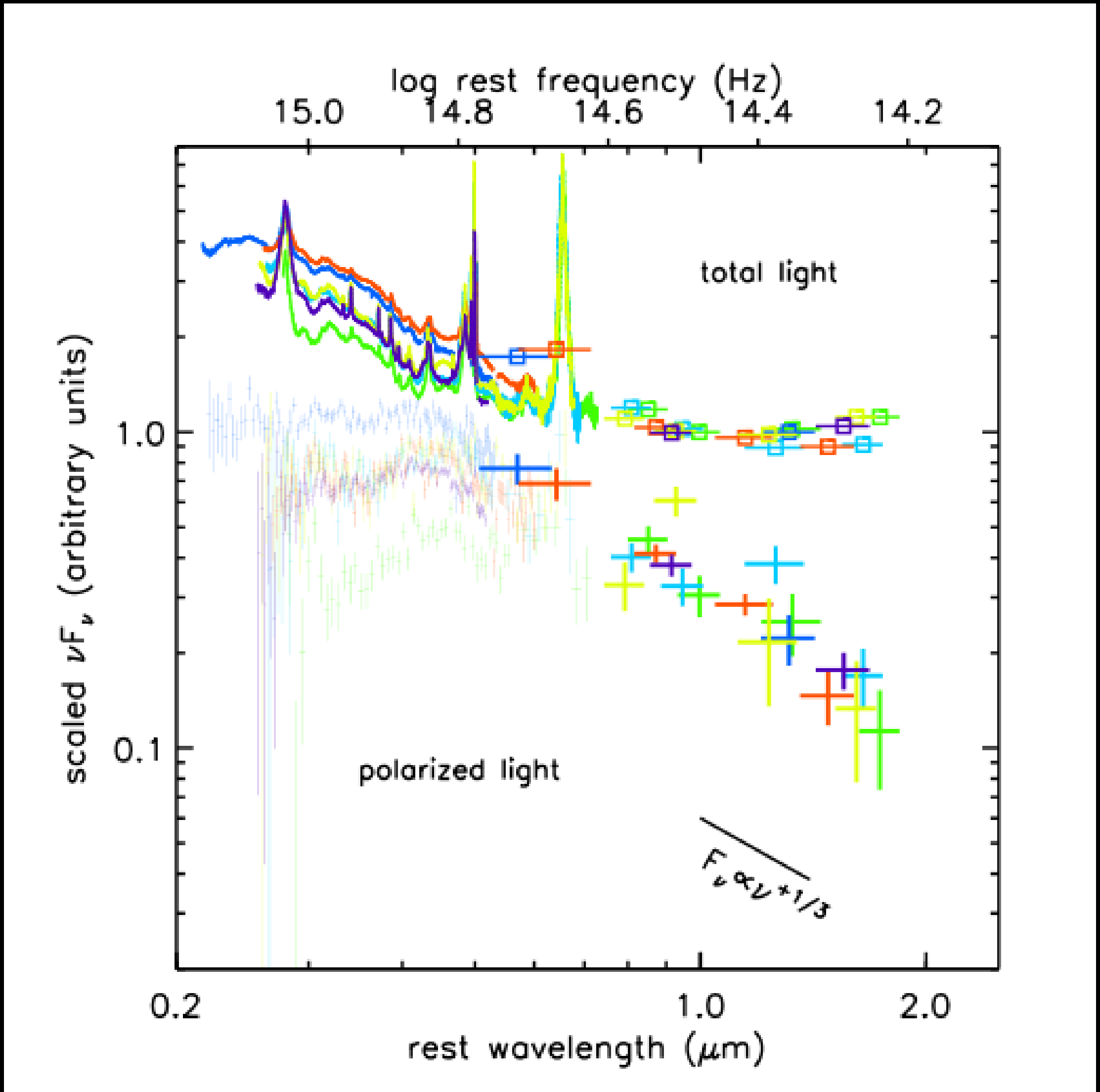
Tran et al. (1995)

Recovering the hidden accretion disk spectrum

Through the periscope, the continuum spectrum of the disk can be revealed.

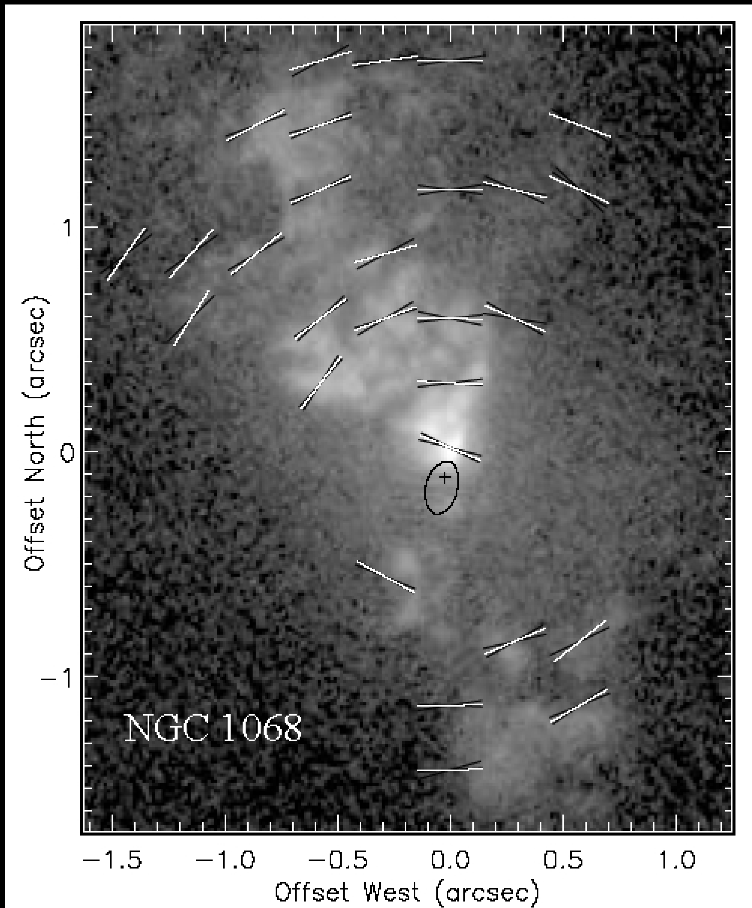
It follows a multiple-blackbody shape with power-law slope of $\nu^{-1/3}$



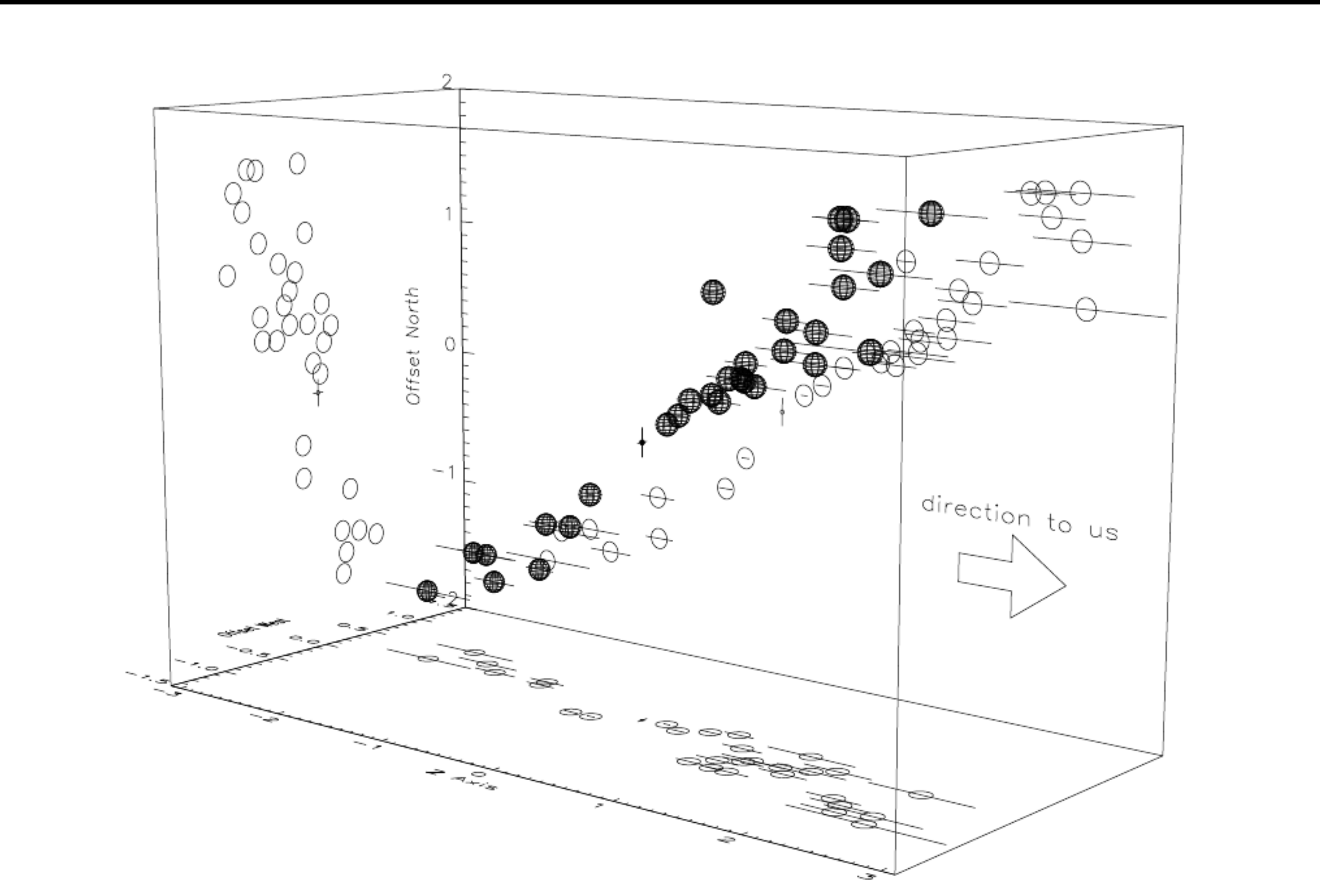


Kishimoto et al. 2008

A 3D image of the scattering clouds in NGC 1068



Capetti et al. 1995



Kishimoto et al. 1999

Phase function of Thomson scattering
Spatial distribution of polarized flux → 3D image of the scattering clouds
Assuming optically thin matter

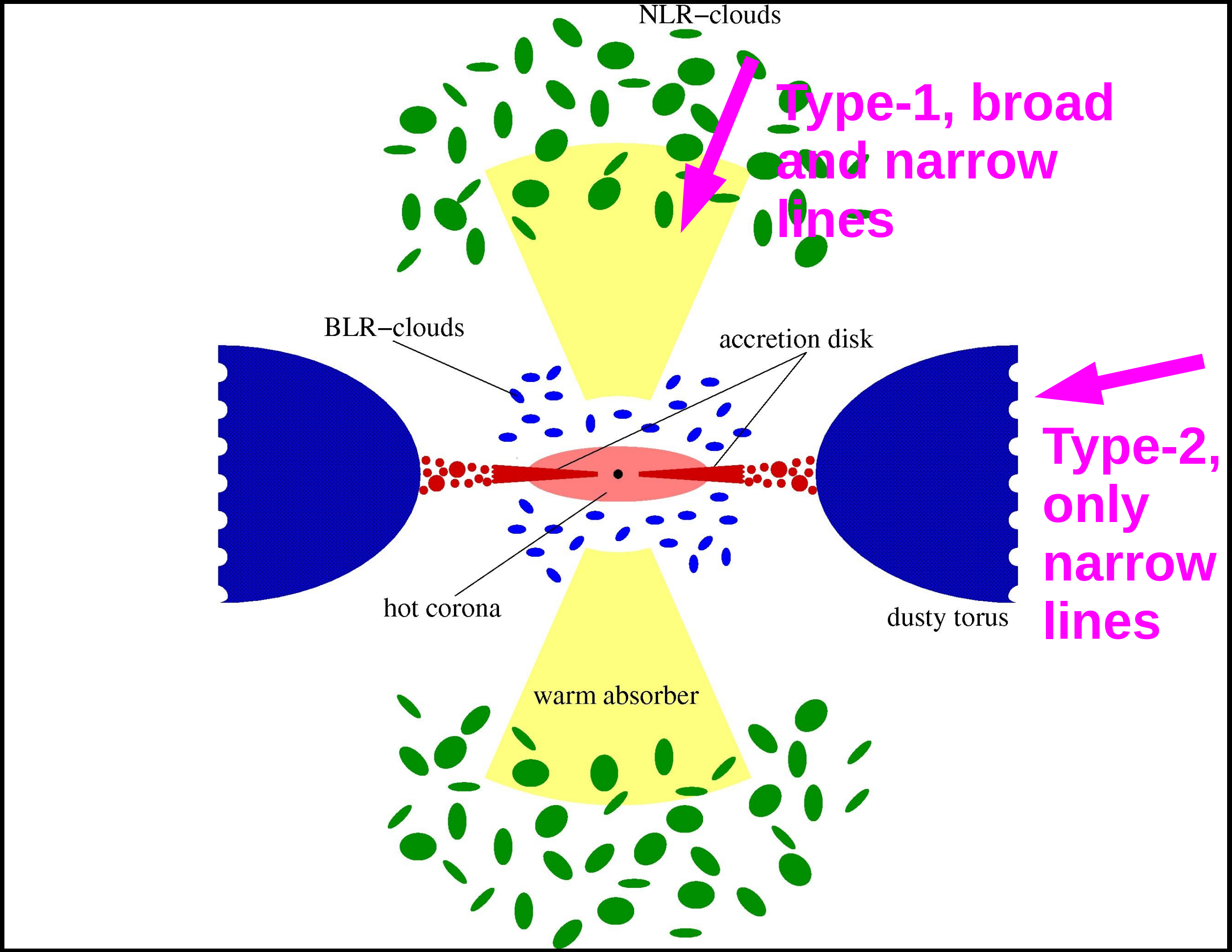
Hidden type-1 AGN and polarization dichotomy

The polarization dichotomy of AGN was established:

Type-2 → *P.A.* $\perp$ jet axis

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

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

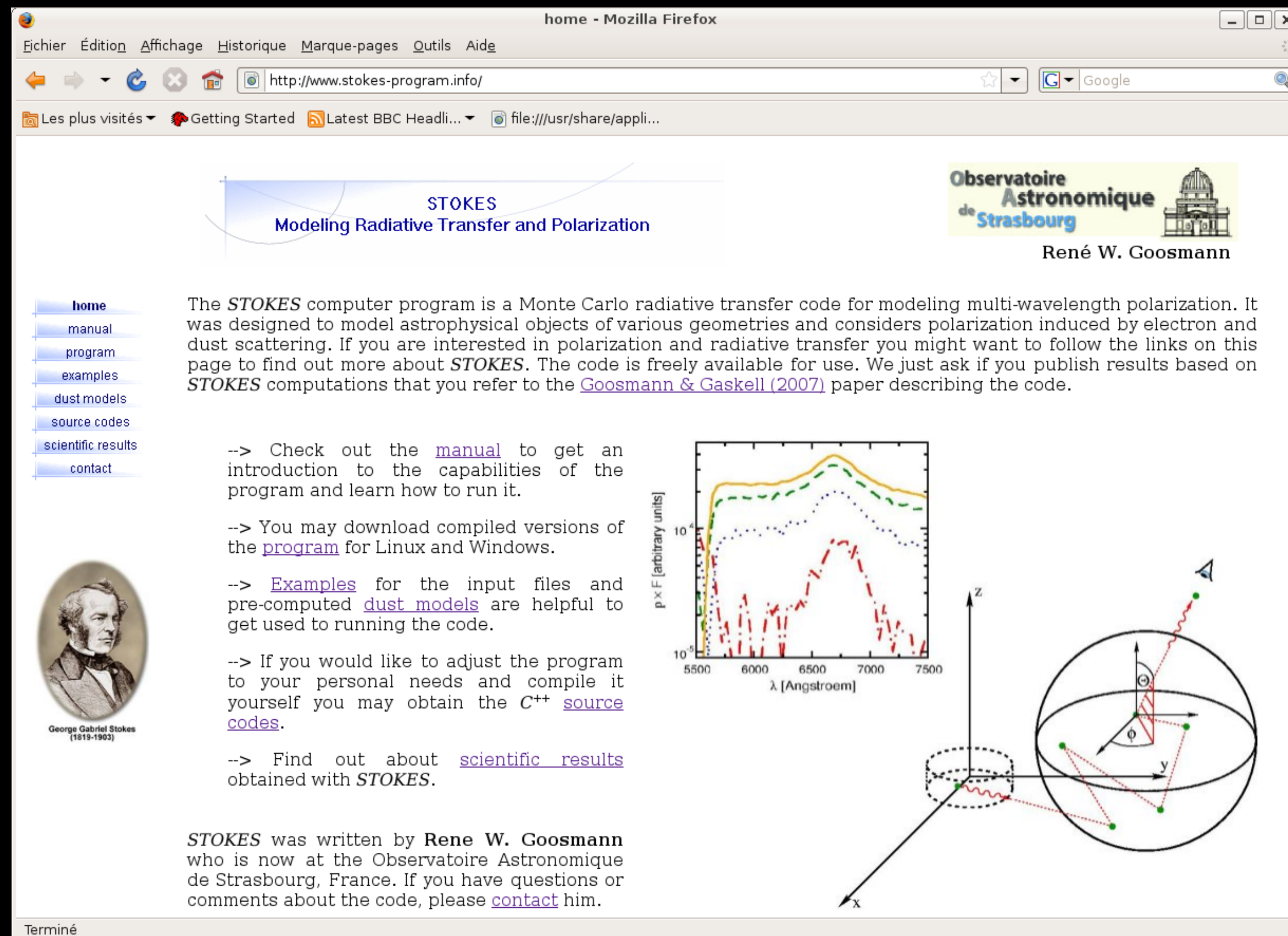


Modeling polarization with the STOKES code

- 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 routines implemented
- Photo- and K-shell ionization / recombination
- variability and evolution of the incident spectrum

Public access

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

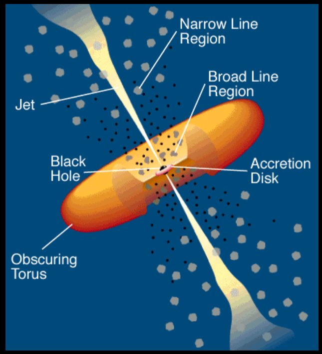


Modeling the polarization dichotomy of AGN

AGN type-1 : view « face-on »
polarisation angle
parallel with respect to the axis

AGN type-2 : view « edge-on »
polarisation angle
perpendicular with respect to the axis

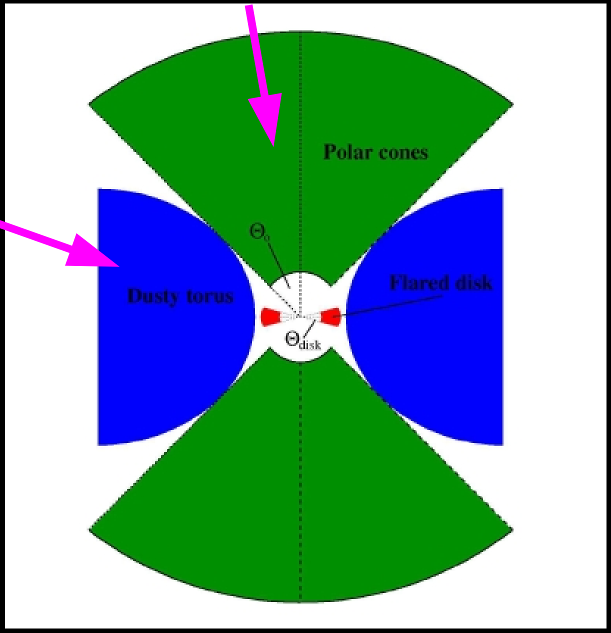
Modeling the unified scheme

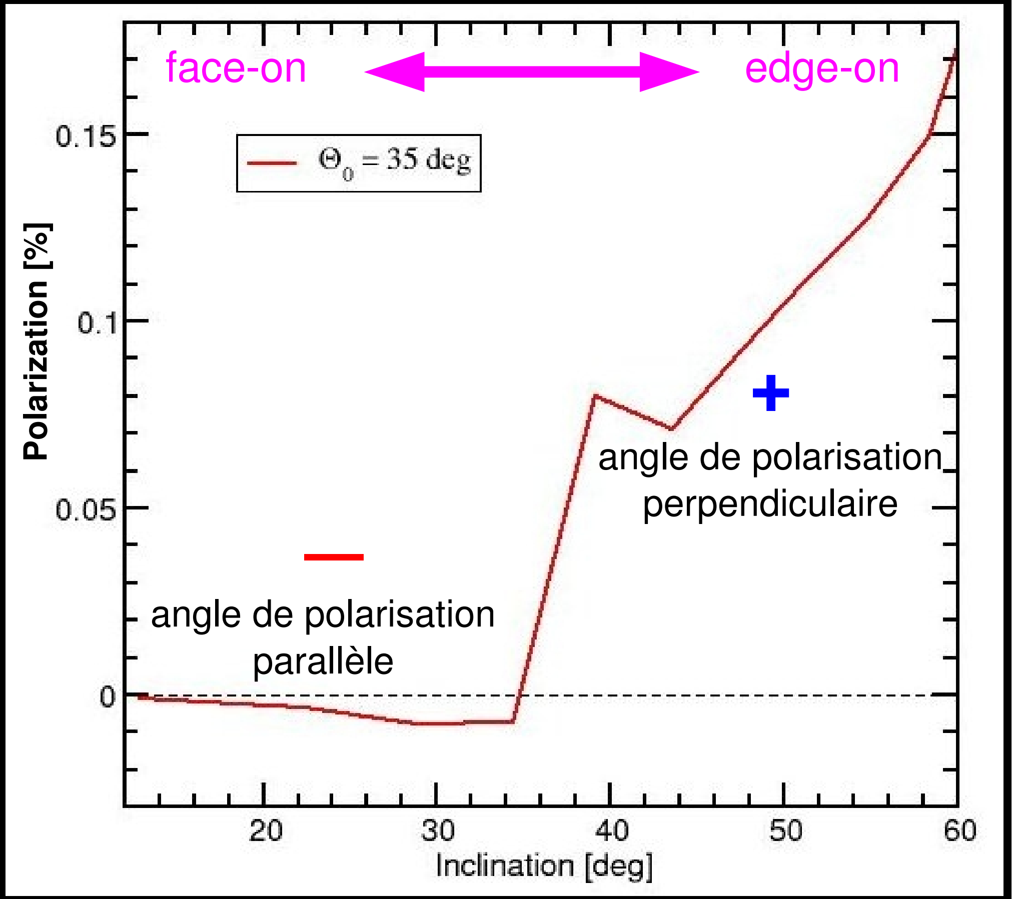


Urry & Padovani (1995)

face-on

edge-on





Goosmann et al. (2006)
Marin et al. (2012)

→ Reproduction of the observed polarization dichotomy

See also Smith et al. 2004, 2005

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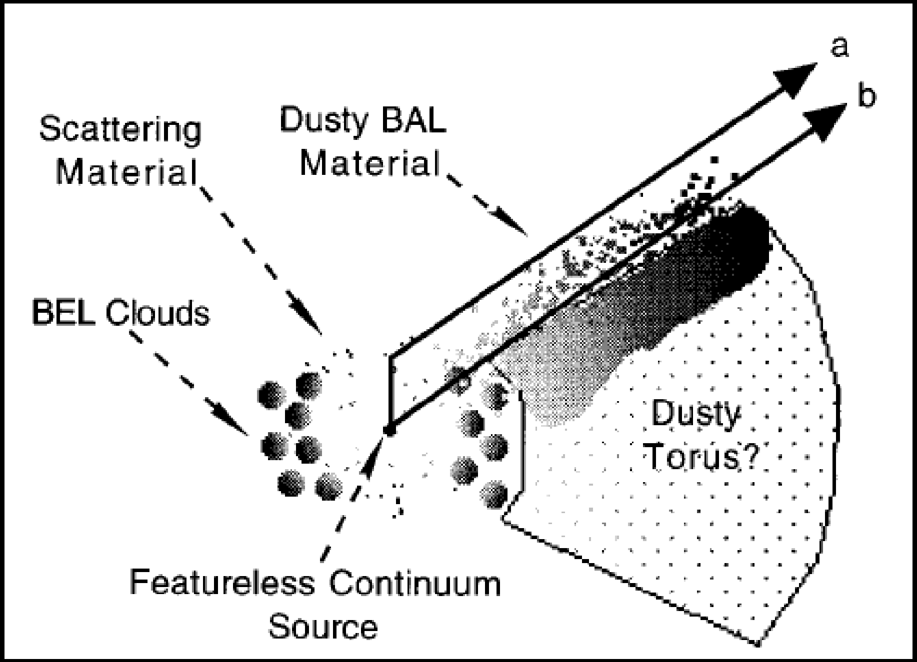
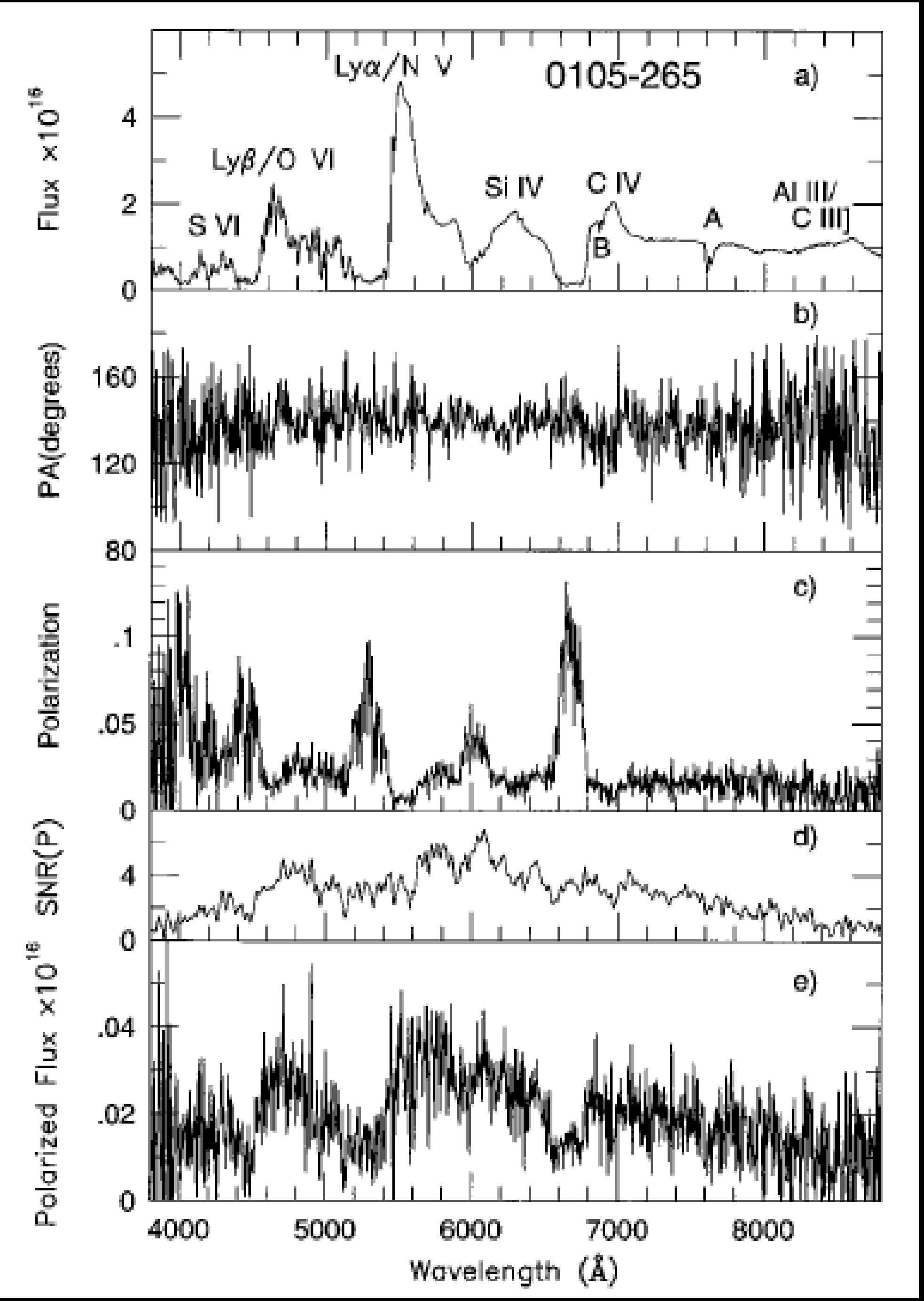
Polarization in broad absorption lines

Strong variation of *P* across a BAL (Cohen et al. 1995)

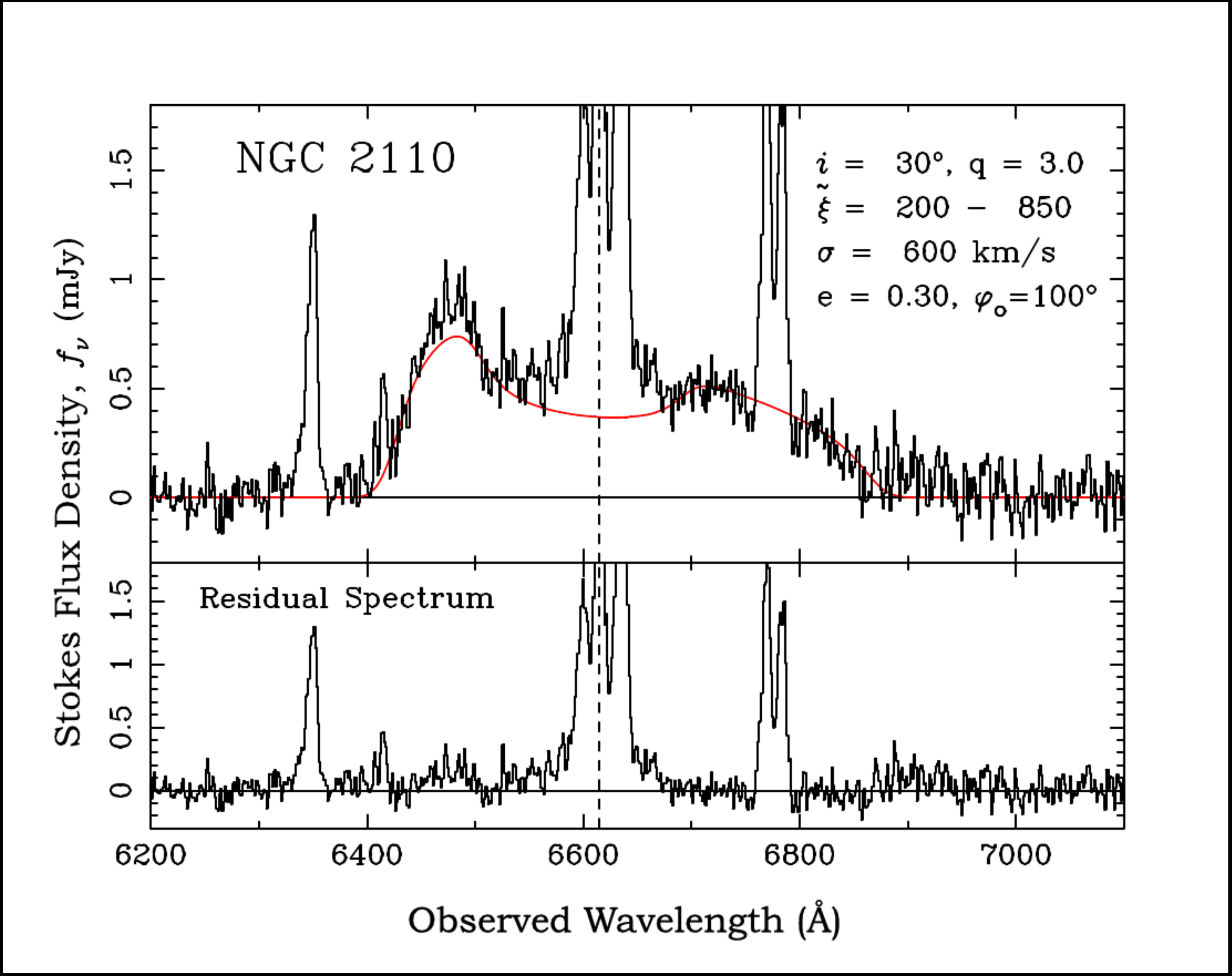




The hidden disk-like BLR in NGC 2110

Spectropolarimetry reveals a double-peaked Hα-line in polarized flux (Moran et al. 2007)

Modeling of the broad line profile by an elliptical, turbulent disk (Eraculous et al. 1995)



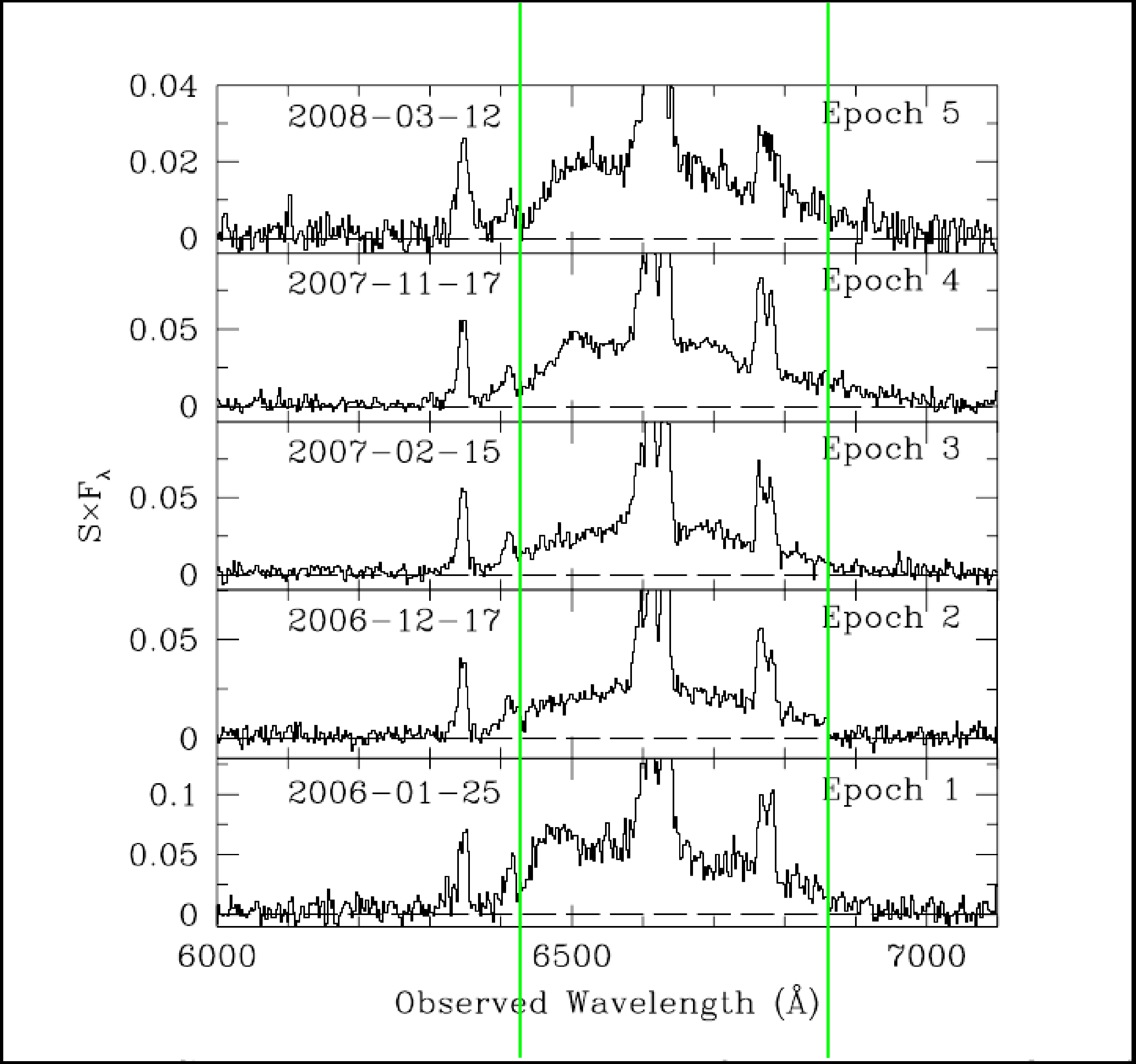
The hidden, disk-like BLR in NGC 2110 and others

Strong variability of the hidden, polarized, double-peaked Hα-line (Tran et al. 2010)

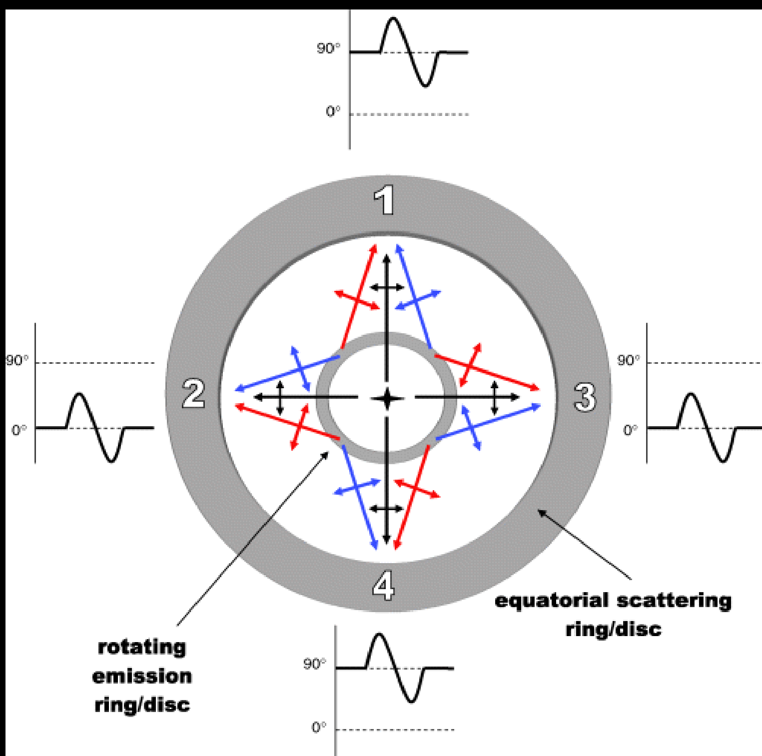
→ scattering medium should be spatially compact

Type-1/type-2 correspondence for double-peaked BLRs:

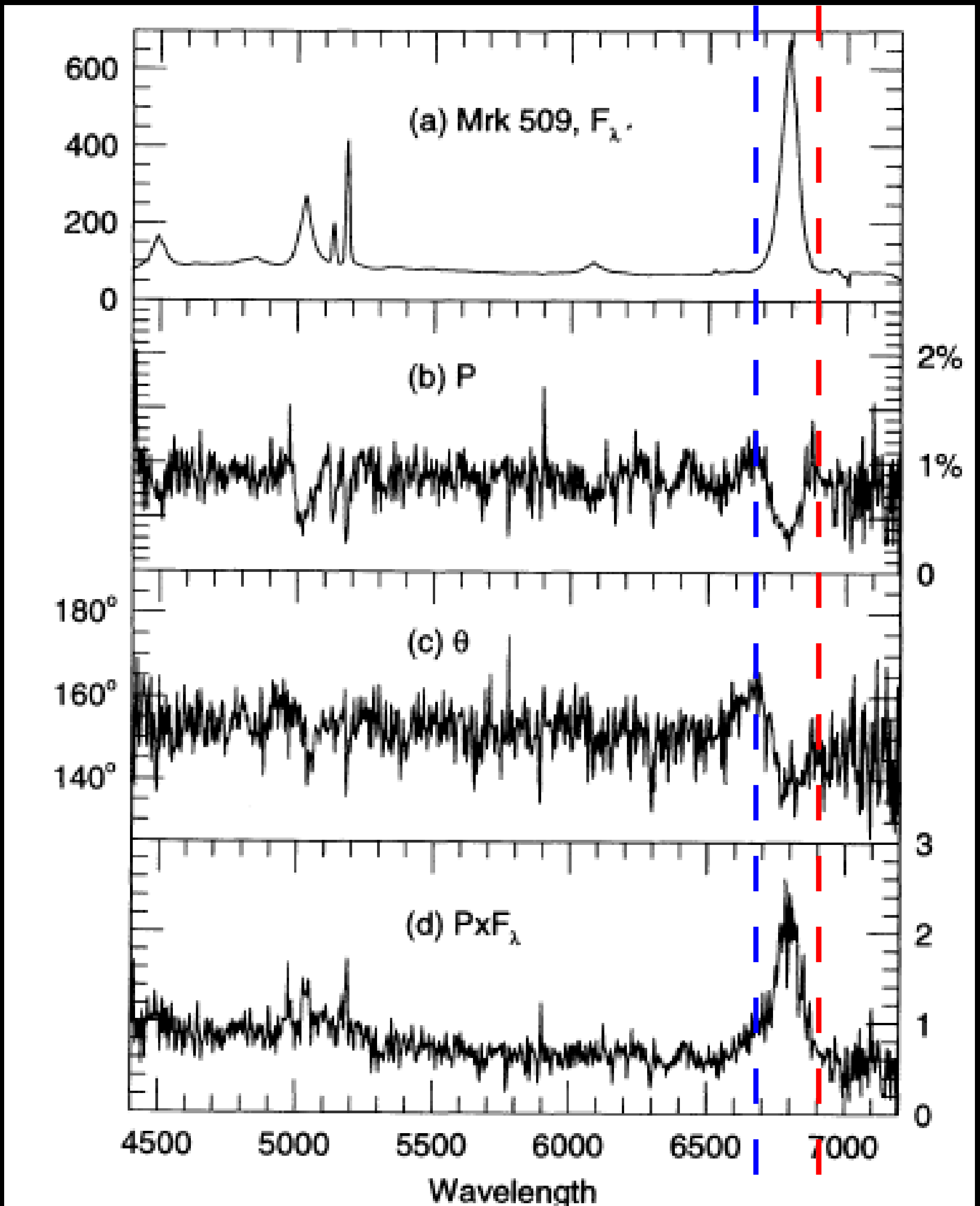
Type-1	Type-2
3C 332	NGC 2110
Arp 102B	NGC 5252



Rotation of polarization angle across emission line

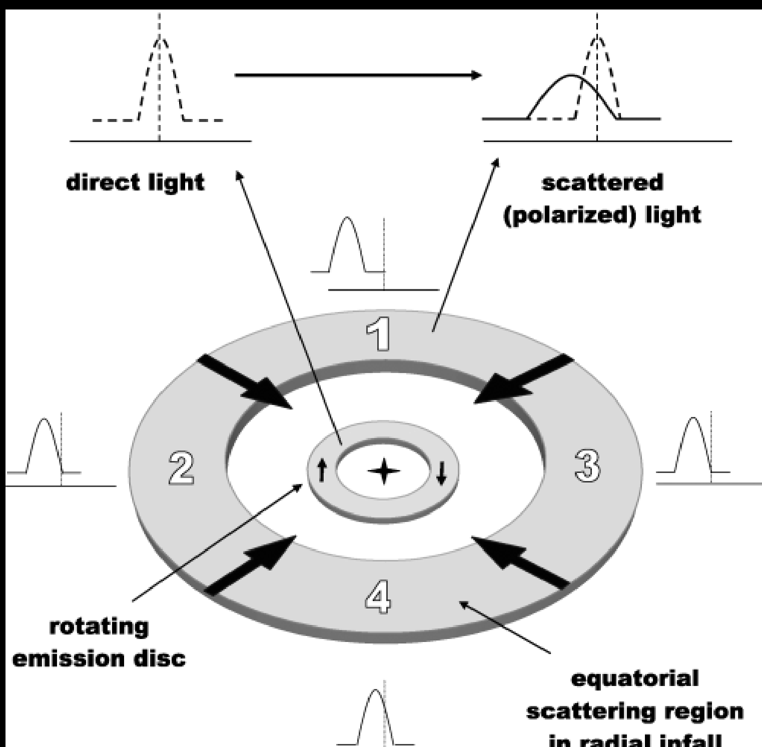


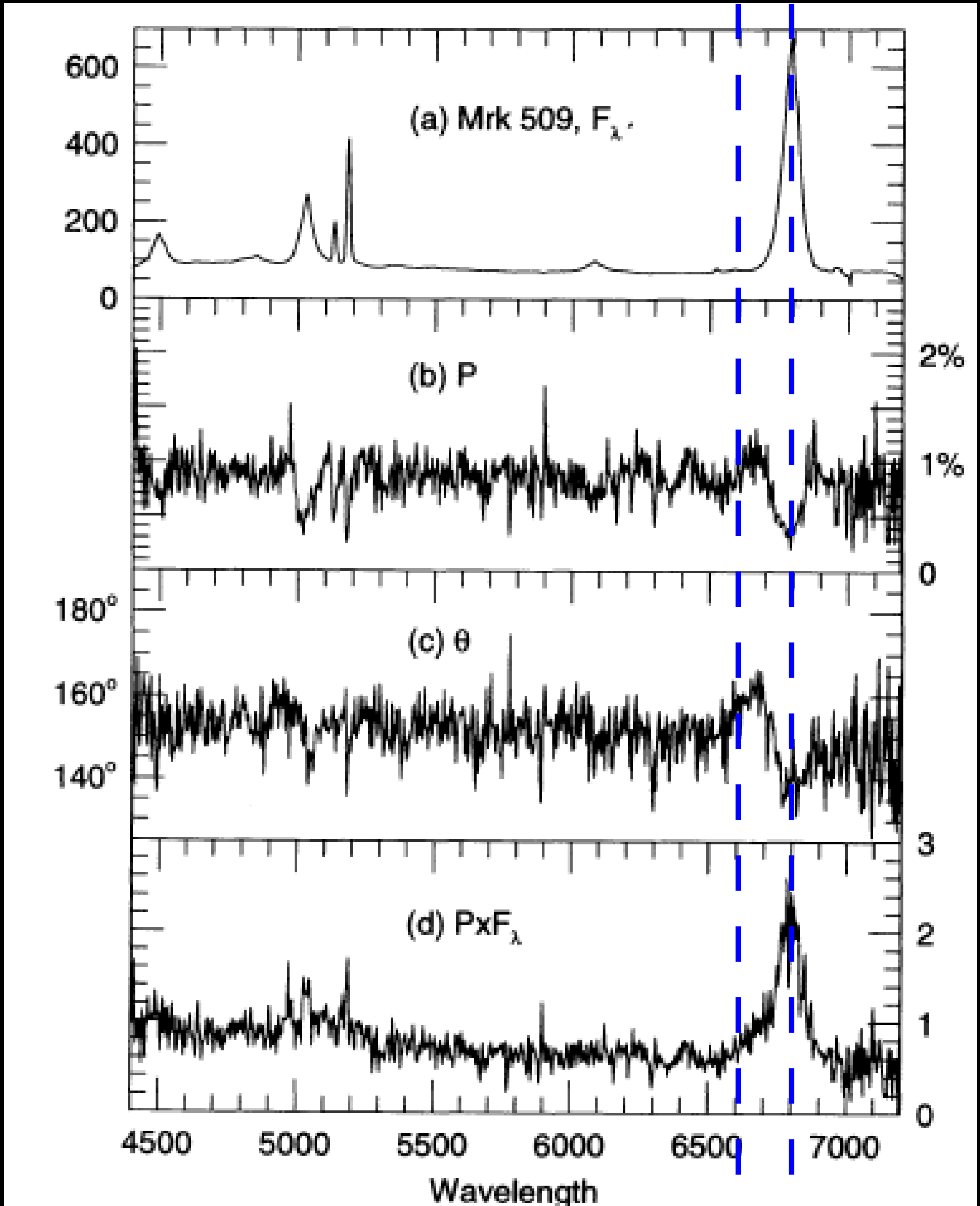
Interpretation and modeling by Smith et al. (2005)



Spectropolarimetric data for Mrk 509 from Goodrich & Miller (1994)

Blue polarization wing of the emission line





Interpretation and modeling by Smith et al. (2005)

Spectropolarimetric data for Mrk 509 from Goodrich & Miller (1994)

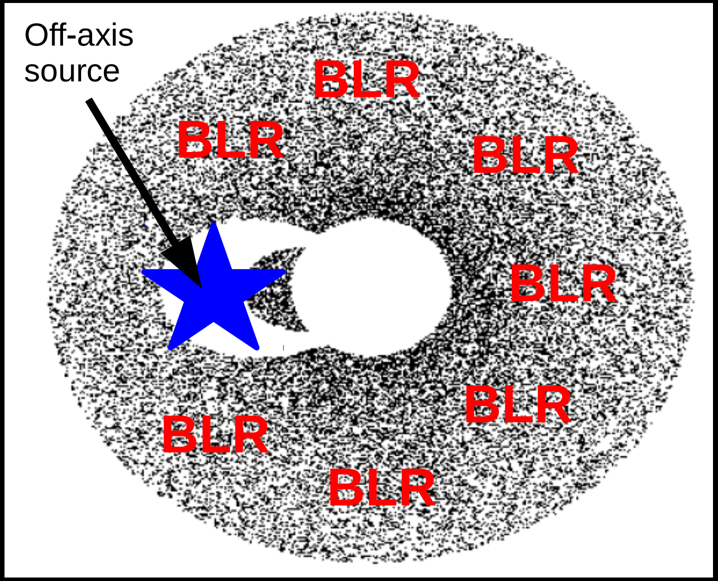
Similar work on NGC 3783 (Lira et al. 2007)

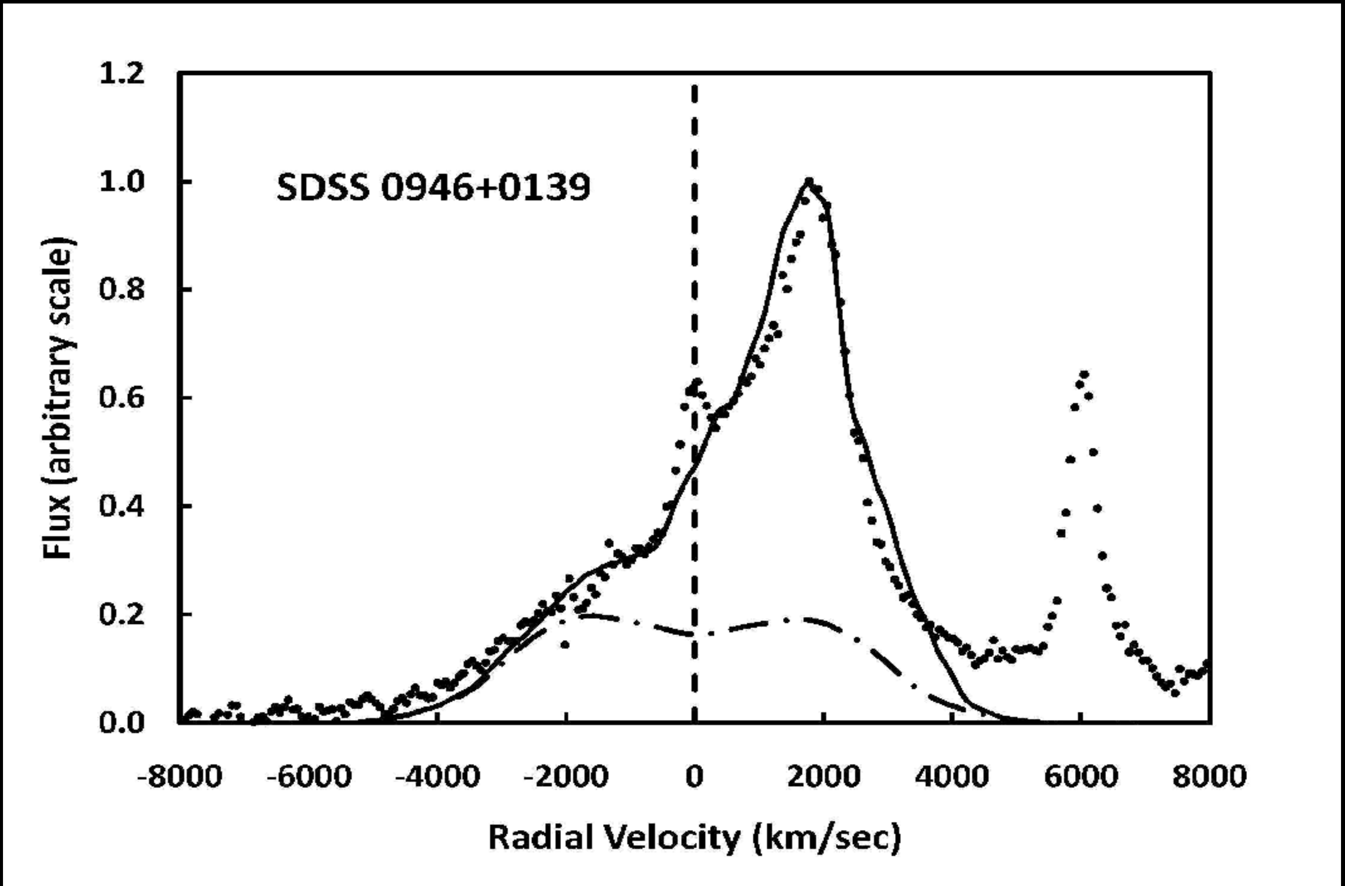
A different approach: off-axis emission

The off-axis scattering model as it is worked out by Gaskell (2011).

See also Jovanovic et al. 2010.

RESEARCH IN PROGRESS !

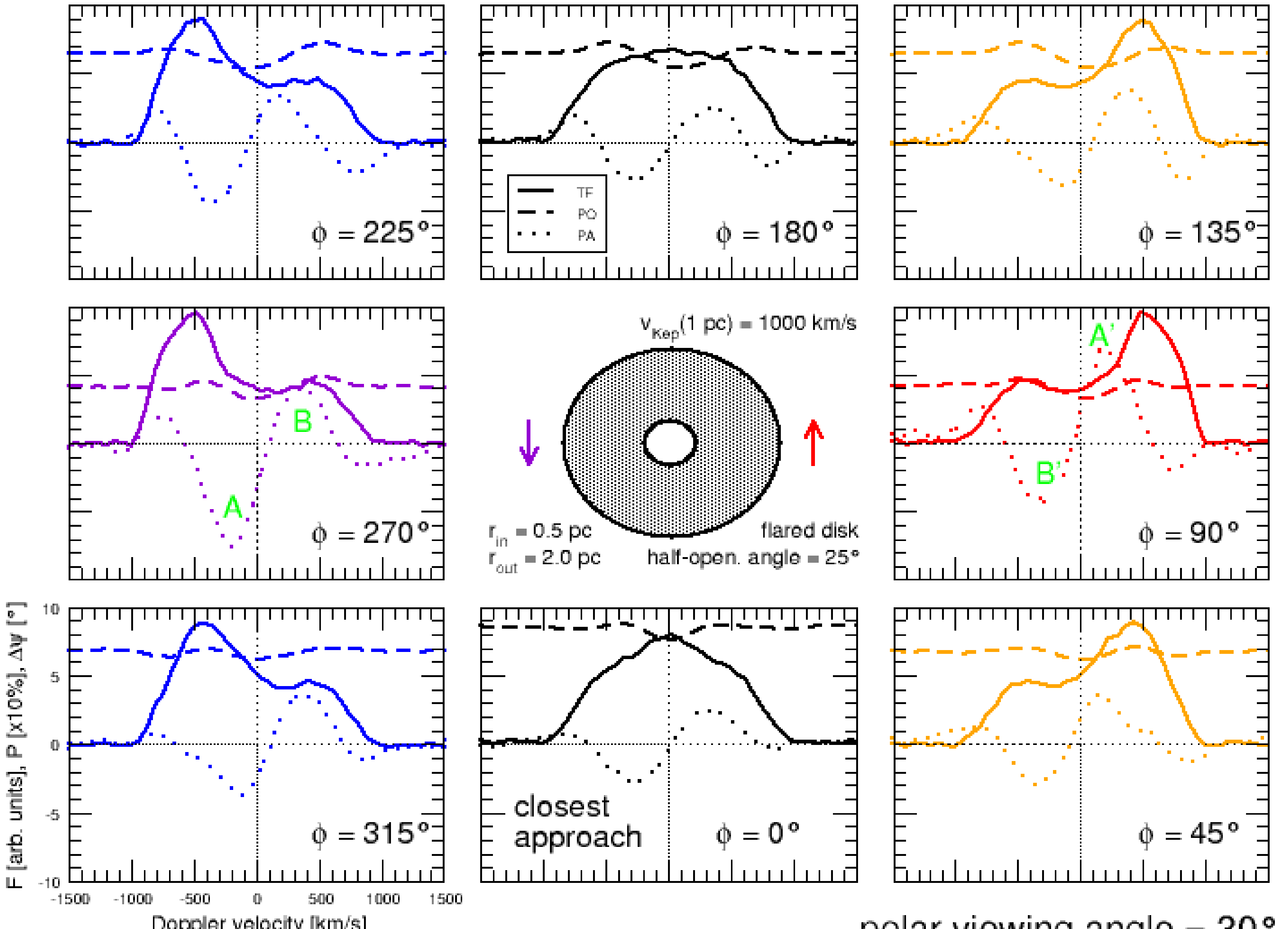




The off-axis model focuses rather on the source than on the scattering regions. The asymmetry lies more in the irradiation pattern and less in the geometry of the different media.

Off-axis irradiation of the BLR as a function of source phase

off-axis source (50% of continuum flux) at inner edge of BLR, Keplerian orbits



polar viewing angle = 30°

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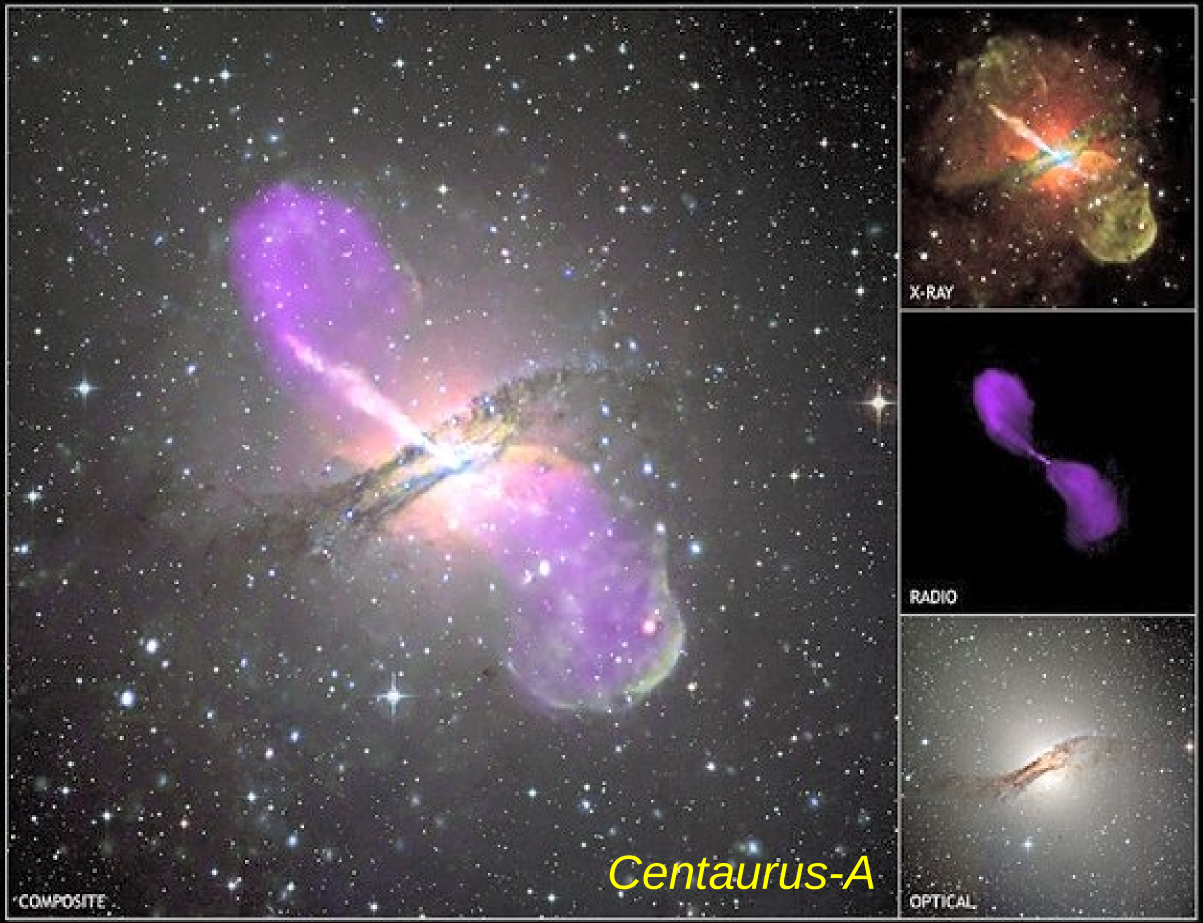
Polarization of radio-loud AGN

• broad-band polarization in radio-lobes or -jets due to synchrotron mechanism (Angel & Stockman 1980)

• in the inner regions of radio galaxies other mechanisms (electron scattering, dichroic absorption, etc.) are possible but less likely (Capetti et al. 2007)

• synchrotron polarization can be highly variable (~4h) clearly indicating a jet origin (Villforth et al. 2008)



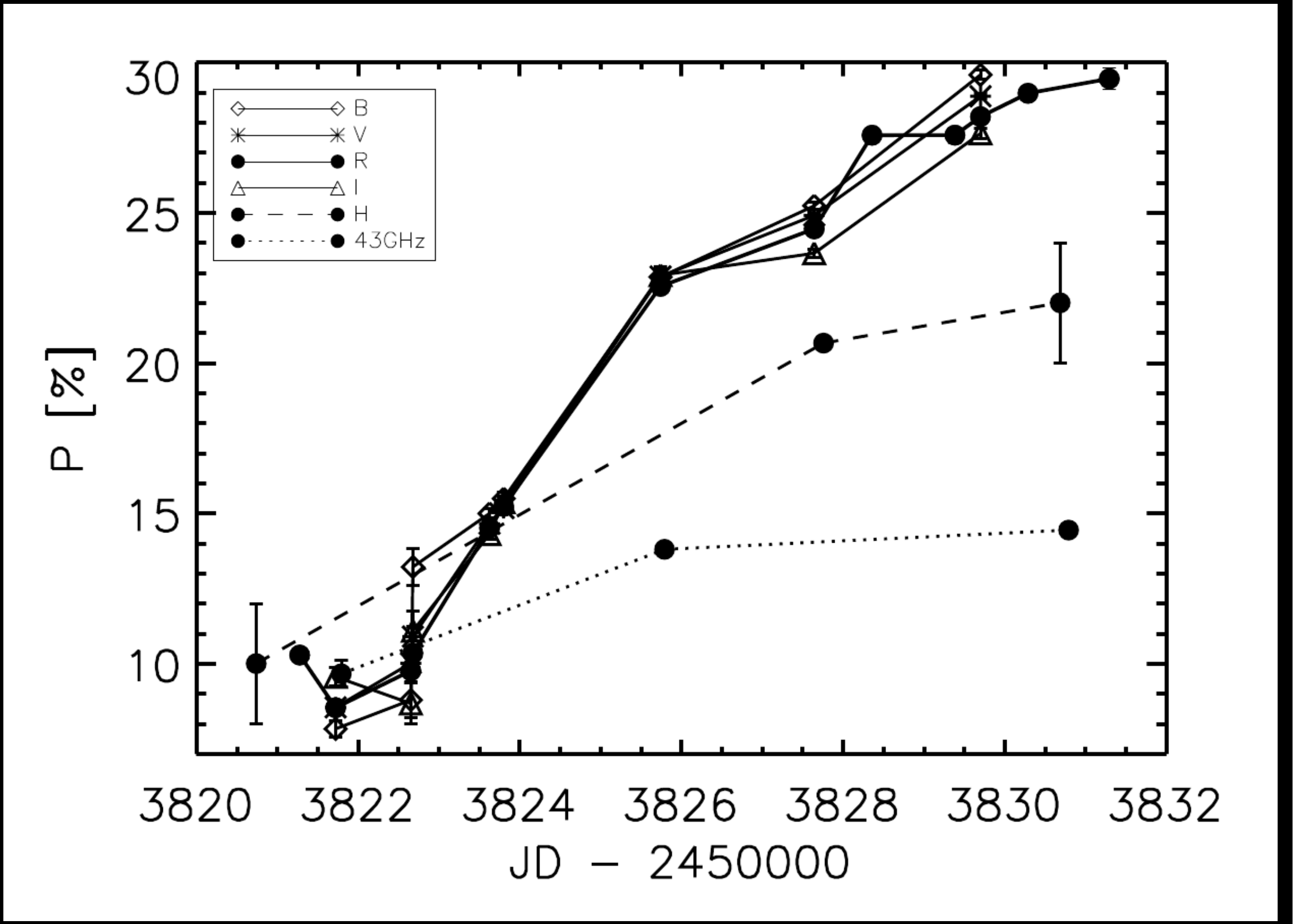
Kraft et al. (CfA)

Multi-wavelength polarization of the Blazar OJ287

- Simultaneous rise of polarization degree in the *B*, *V*, *R*, *I*, *H* bands and the 43 GHz band

- Conclusion : optical and radio emitting regions must be (partly) co-spatial (D'Arcangelo et al. 2009)

→ **High resolution of radio-image can indirectly resolve optical emission region**



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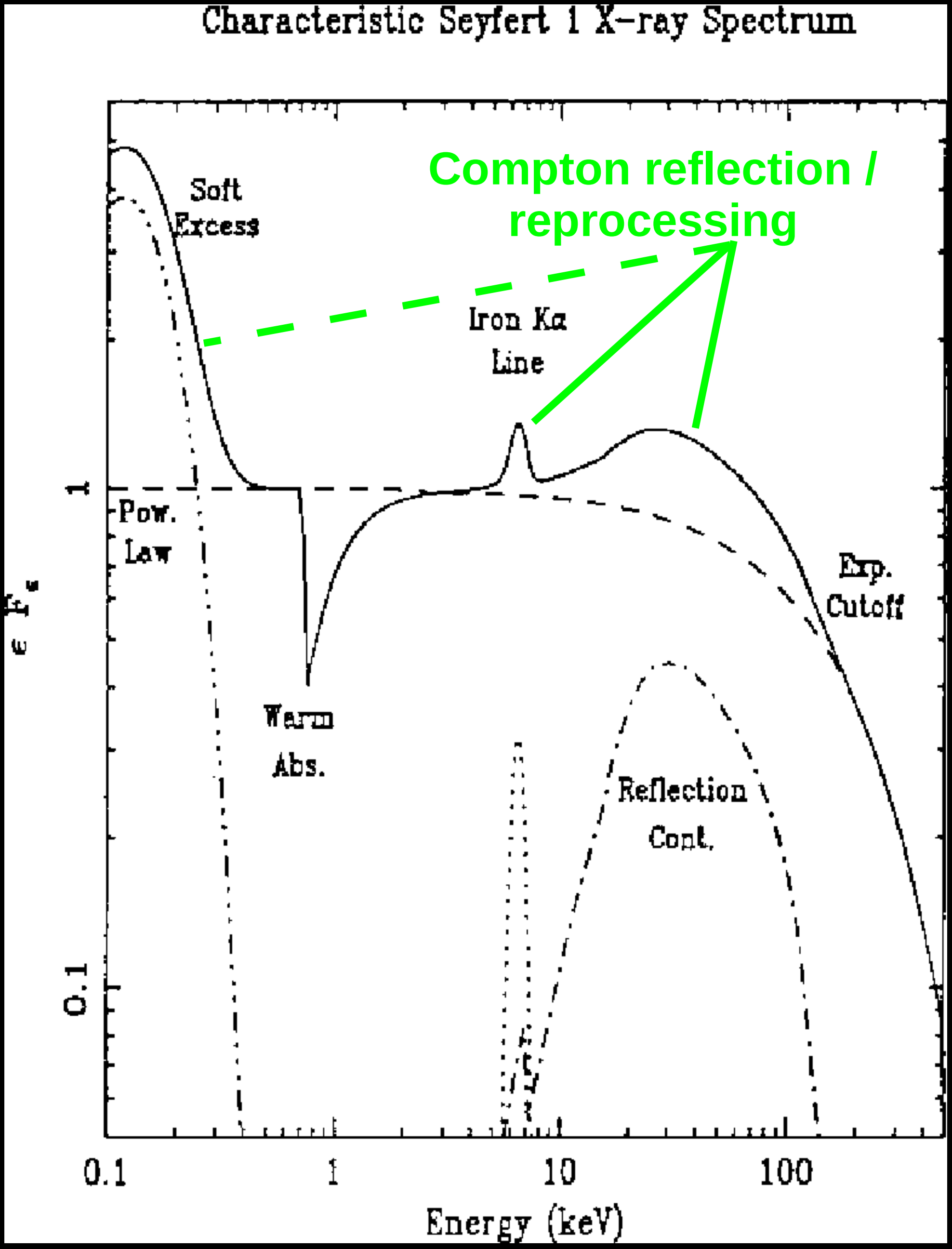
The X-ray spectrum of radio-quiet AGN

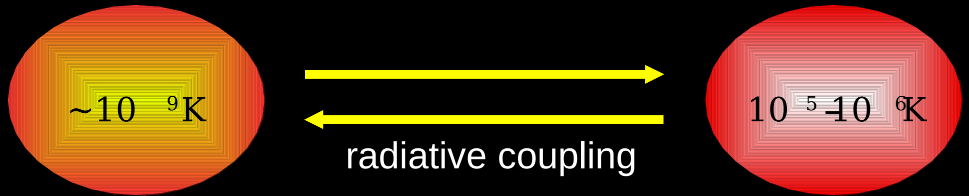
- Primary power-law component
- High-energy cut-off
- Iron Ka-line complex
- Compton hump
- Soft X-ray absorption
- Soft-Excess (Crummy et al. 2006)

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

Fabian (2000)



Two media are required...



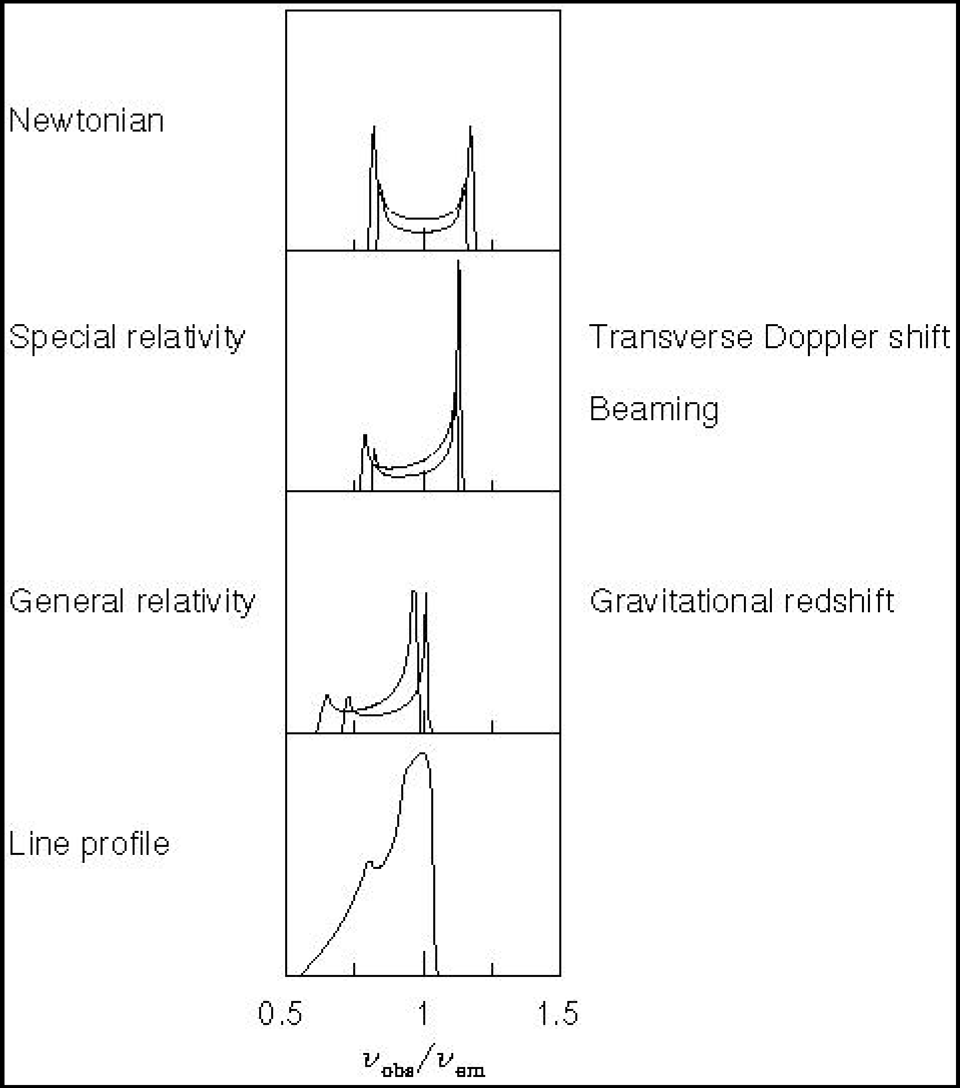
hot, optically thin medium

corona

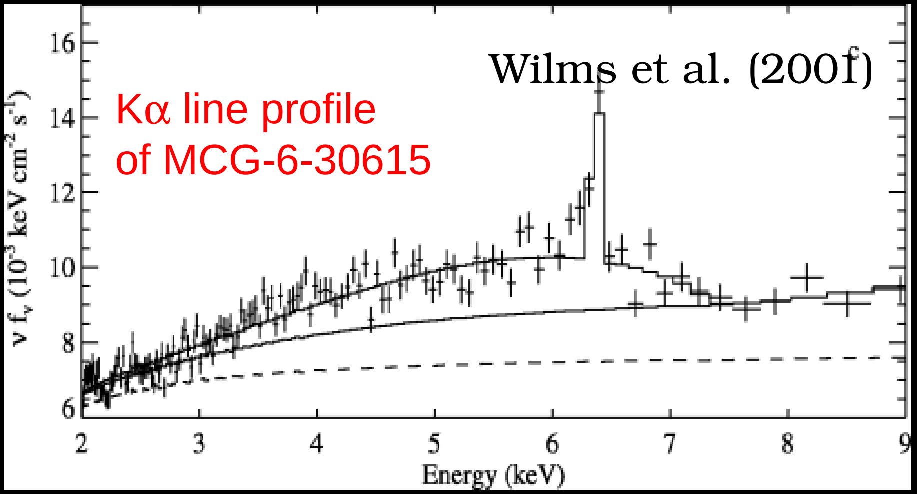
cold, optically thick medium

accretion disk

Probing general relativity close to the black hole



Fabian (2000)

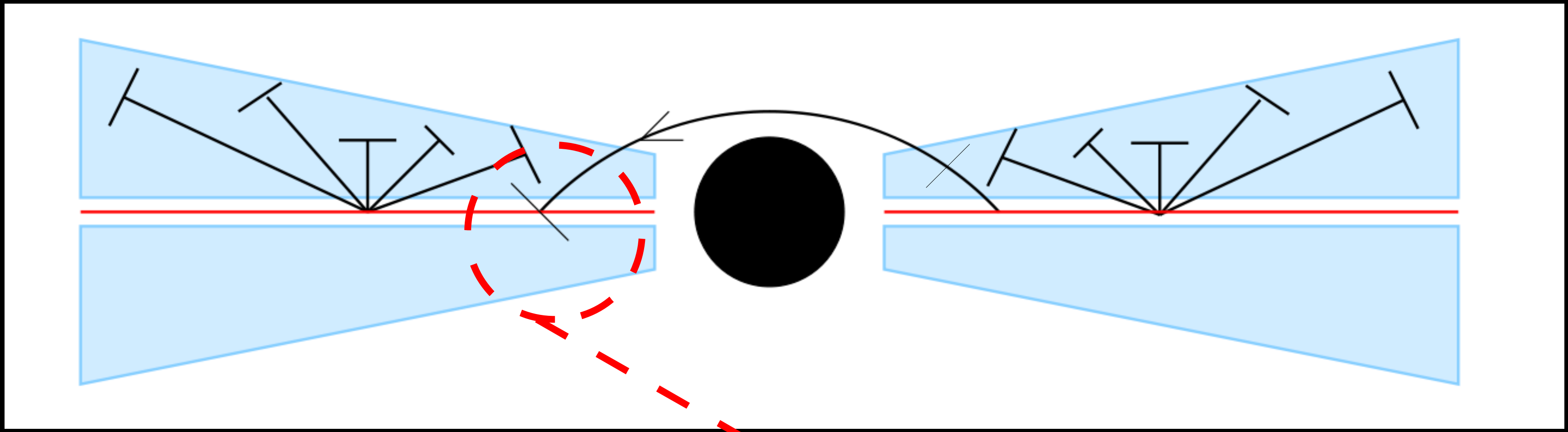


Doppler and general relativistic effects produce a very broad red wing of the reprocessed iron line emission.

Martocchia & Matt (1996)
Kazanas & Nayakshin (2001)
Dovciak et al. (2004)
Miniutti & Fabian (2004)
Dauser et al. (2010)
Wilkens & Fabian (2011)
...

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.

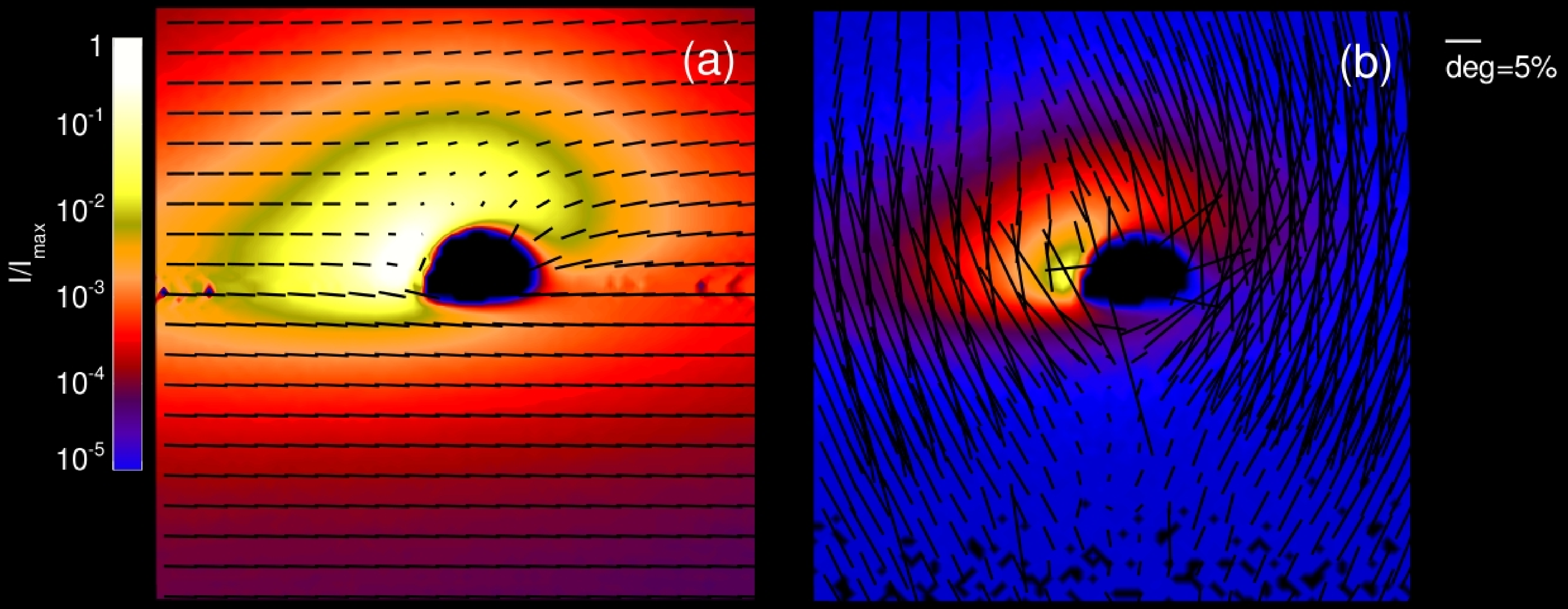
Light-bending and returning radiation

Schnittman & Krolik (2010)

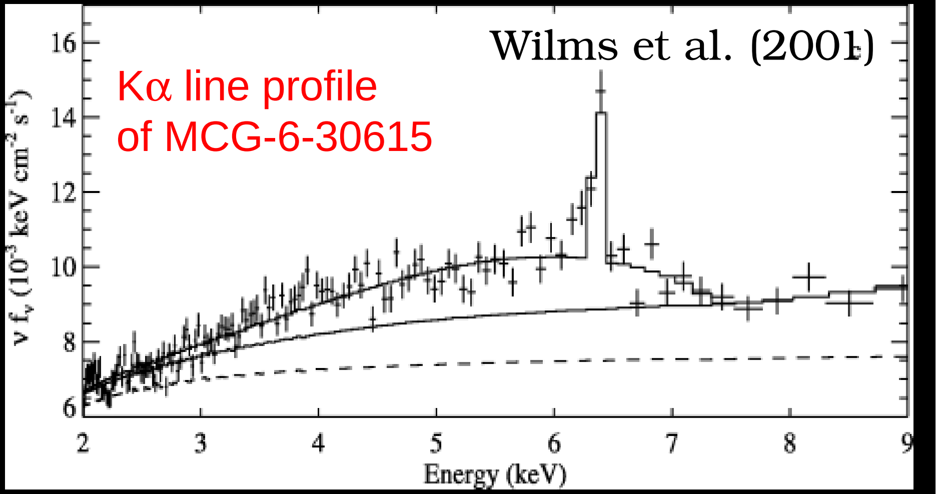
a/M = 0.9
H/R = 0.1
***i* = 75°**

Disk and coronal emission without returning radiation

...and including returning radiation



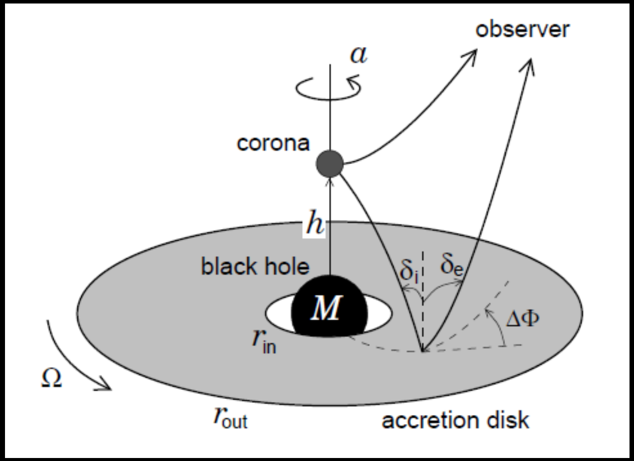
Unravel the nature of broad iron Kα lines



Marin et al. (2012)

Relativistic case

Re-emitted radiation from a rotating accretion disc and relativistic ray-tracing



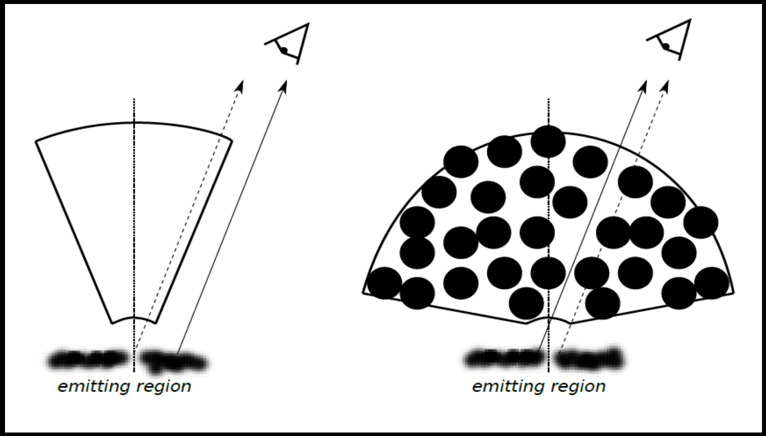
$h = 2.5GM/c^2$

$a = 1$ (Kerr)

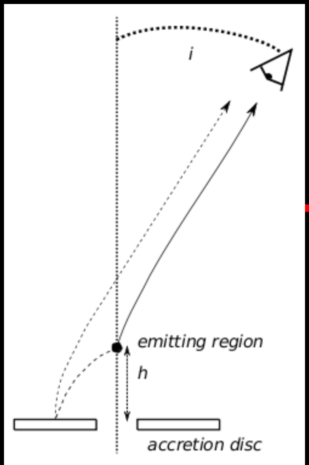
(Miniutti & Fabian 2004)

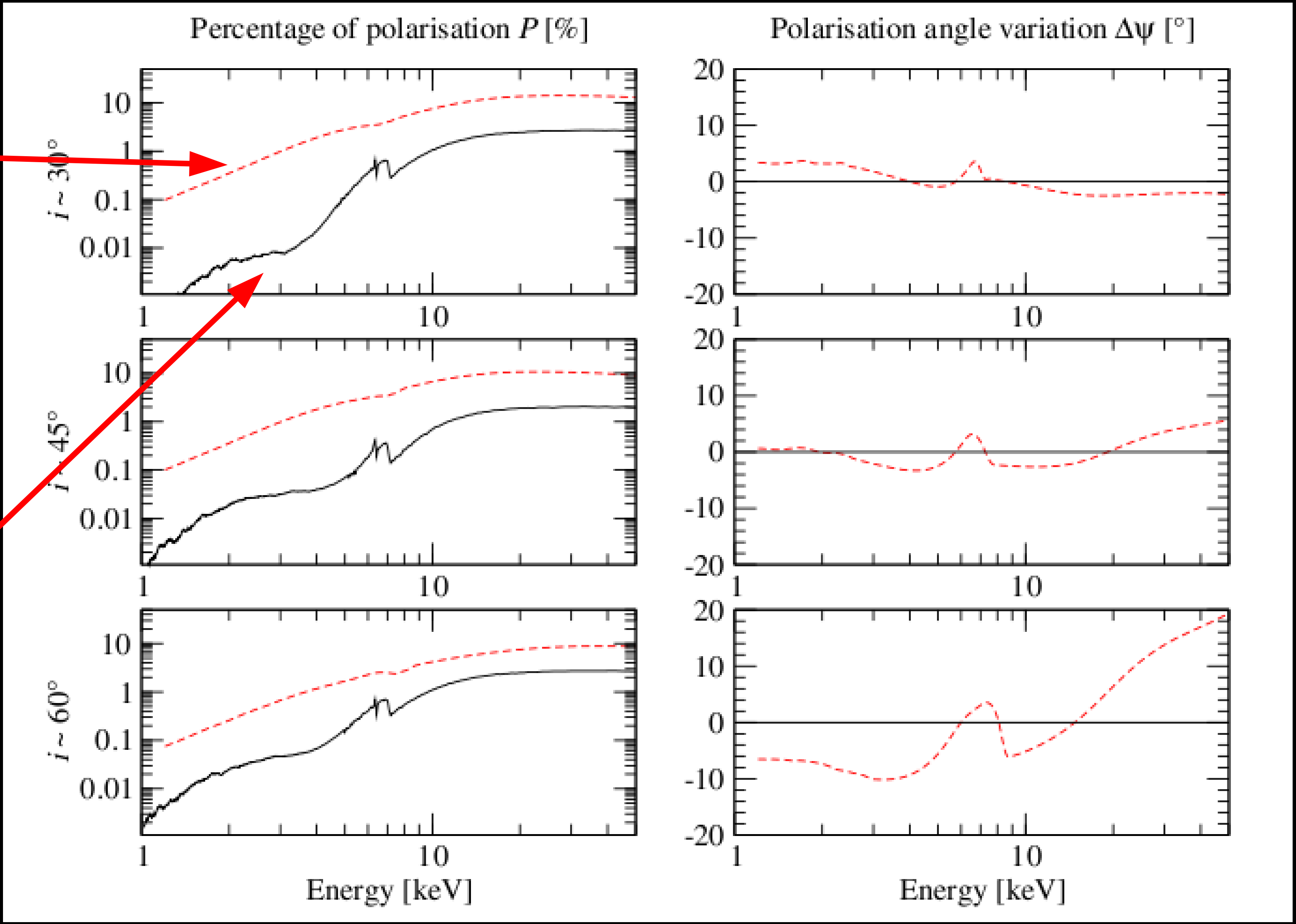
Absorption case

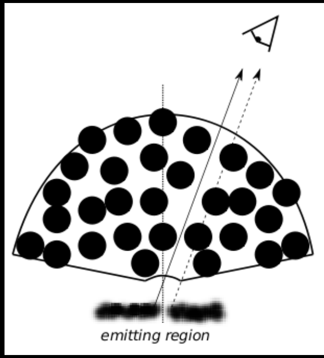
Optically thick, low ionized absorber partially covering the emission region (Miller et al. 2008/2009)



Unravel the nature of broad iron Kα lines







Marin et al. (2012)

Polarization and Active Galactic Nuclei

Outline

- A quick introduction to active galactic nuclei (AGN)
- Polarimetric appearance of radio-quiet AGN in the optical
  - The dichotomy of the continuum polarization
  - The polarization of broad lines
  - The polarization signature of a hidden accretion disk
- A short note on radio-loud AGN
- The innermost parts of AGN, relativistic effects and polarization
- Summary and conclusions

Lecture by René Goosmann
at the COST School Polarization in Astrophysics
Centre Paul Langevin, Aussois, France, 6th June 2013

Polarization and Active Galactic Nuclei

What to take away...

- Polarimetry continues to give us profound insights into astronomical objects that are not spatially resolved.

- Polarization is useful in particular when connected to the *more common* observation modes : spectroscopy, imaging and timing and when considered over a broad waveband range.

- Polarimetry gave the strongest proof for the unified model of AGN and now allows us to probe the geometry and dynamics of the broad line region.

Lecture by René Goosmann
at the COST School Polarization in Astrophysics
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Polarization and Active Galactic Nuclei

What to take away...

- Pushing the analysis of polarized lines in AGN somewhat further, we start to even probe the emission pattern of the accretion disk.

- In the X-ray range, future polarization measurements can be related to the effects of General Relativity and thus help to probe the Kerr metric around accreting supermassive black holes

→ see Fabio Muleri's lecture for more on X-ray polarimetry