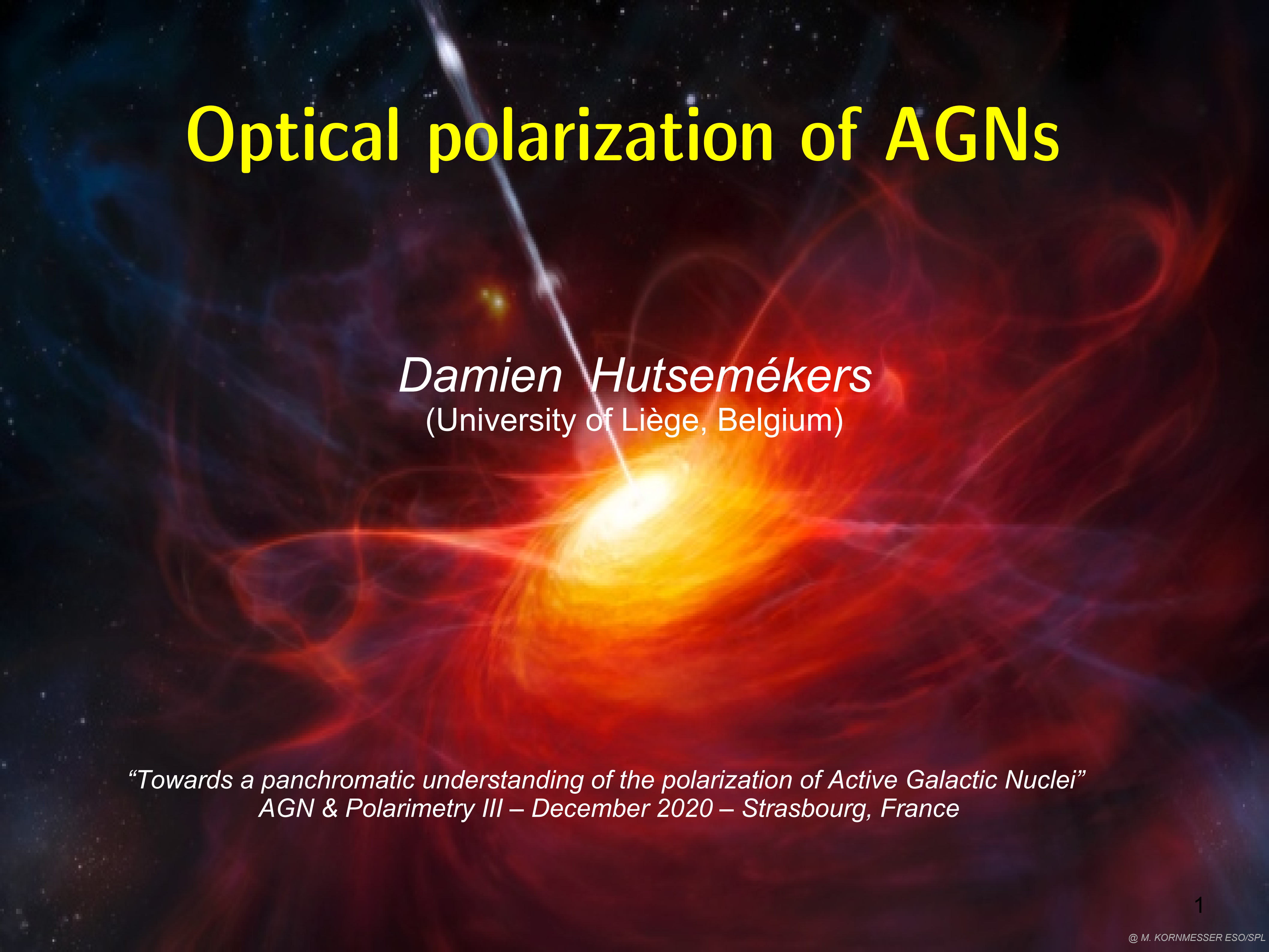

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Optical polarization of AGNs

Damien Hutsemékers
(University of Liège, Belgium)

"Towards a panchromatic understanding of the polarization of Active Galactic Nuclei"
AGN & Polarimetry III – December 2020 – Strasbourg, France

Outline

Focus: polarization properties of radio-quiet AGNs, including some low-polarization radio-loud objects, excluding blazars

Polarization properties : toward a global view

- ➔ Polarization of Seyferts (type 1 & 2)
- ➔ Polarization of quasars (type 1 & 2)
- ➔ Broad Absorption Line quasars

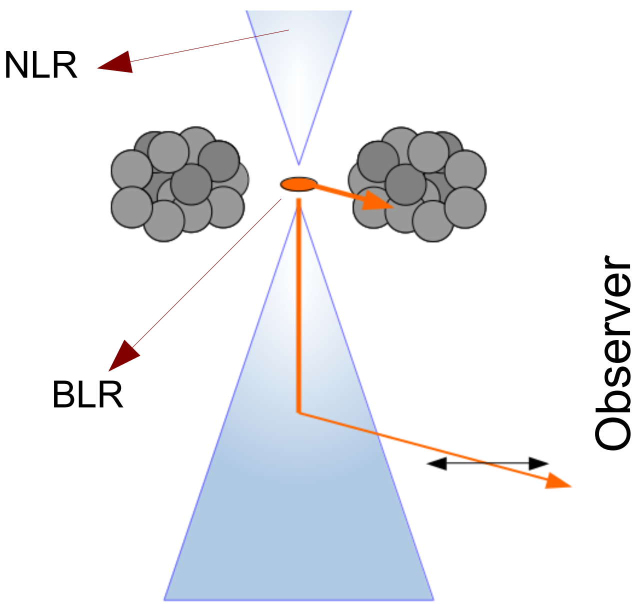
New directions and challenges

- ➔ State-of-the-art modeling
- ➔ Polarization microlensing
- ➔ Polarization reverberation
- ➔ Polarization of changing-look AGNs

Seyfert 2 : NGC 1068

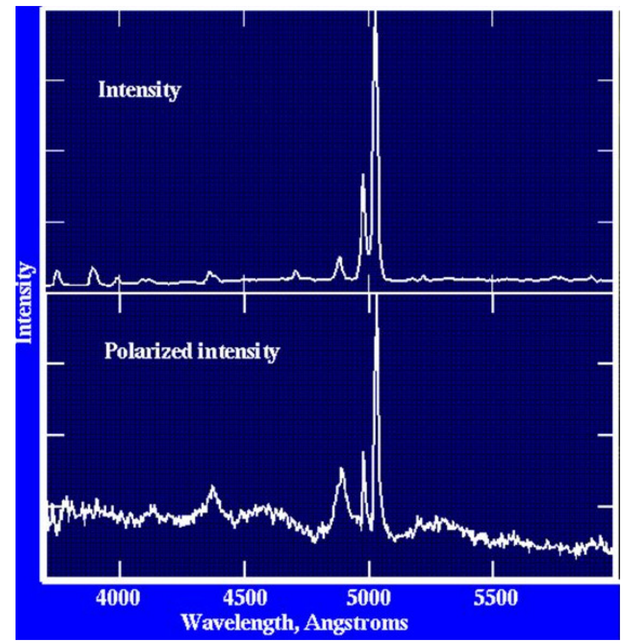
- NGC 1068 : one of the nearest and brightest type 2 Seyfert galaxy (narrow-line only Seyfert)
- Optical spectropolarimetry (Angel et al. 1976, Antonucci & Miller 1985):
  - p ~ 16% wavelength independent but diluted by stellar light from the host galaxy
  - polarization angle perpendicular to the radio jet axis
  - broad Balmer lines typical of Seyfert 1 are observed in the polarized flux and polarized as the continuum (in p and θ)
  - narrow lines have low polarization (~1%) and different θ
- Lines and continuum similarly polarized → not synchrotron but scattering in a region outside the BLR and inside the NLR
- Wavelength-independent scattering over the X-ray / optical range → not dust but electron scattering in the nucleus (see also Marin 2018)

Hidden BLR in type 2 AGNs



The direct light is obscured and only NELs are seen: type 2 AGN classification

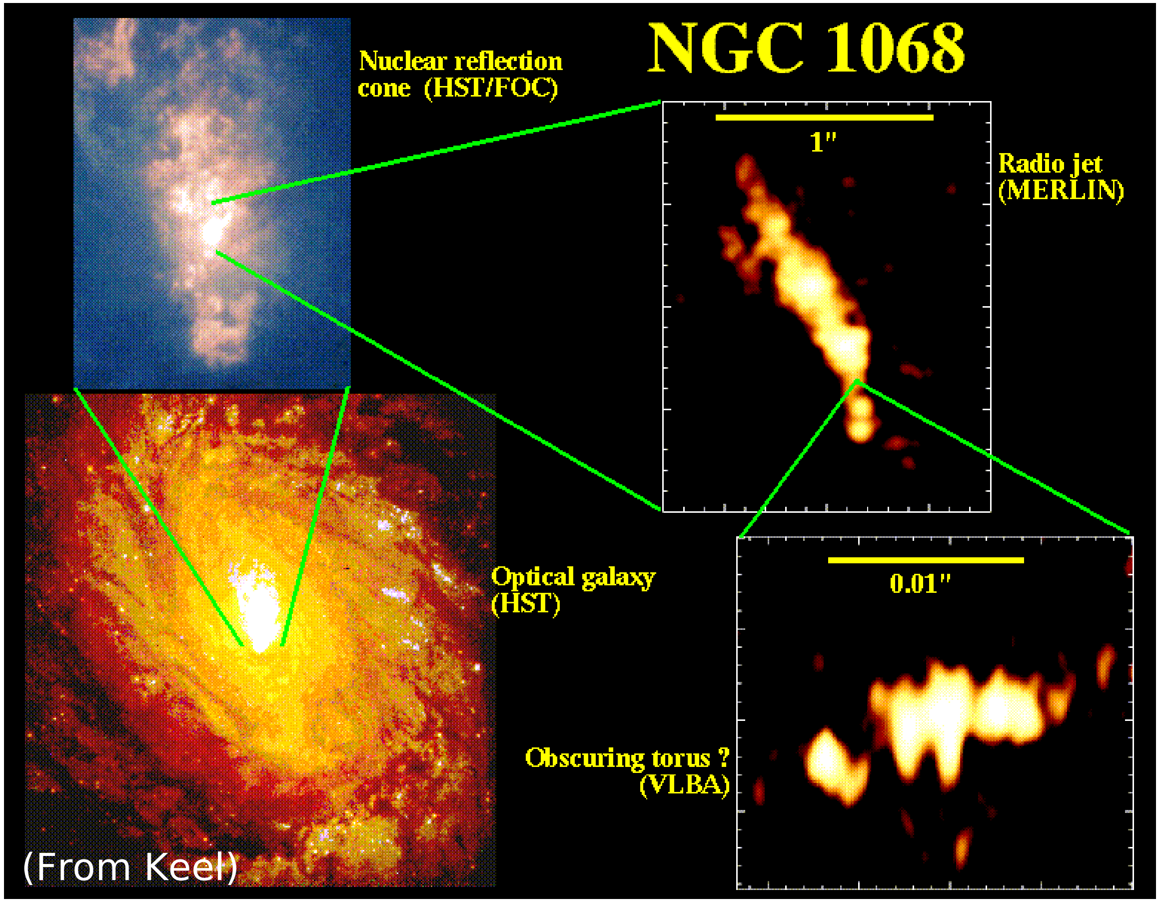
The polarized scattered light shows BELs: hidden type 1 AGN core (periscopic view)

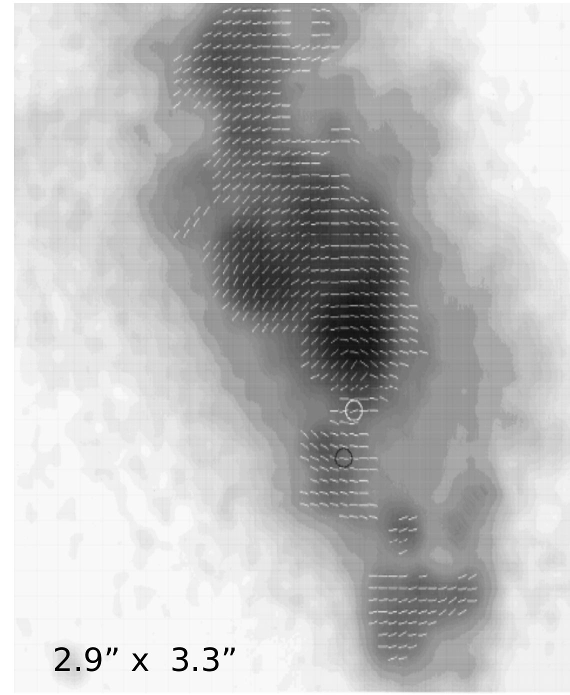


Polarimetry provides strong support to the Unification Model: type 1 and type 2 AGNs only differ by their inclination w.r.t. the line of sight (Antonucci 1983, Antonucci & Miller 1985)

(Not all type 2 AGNs show BELs in their polarized spectra!)

NGC 1068

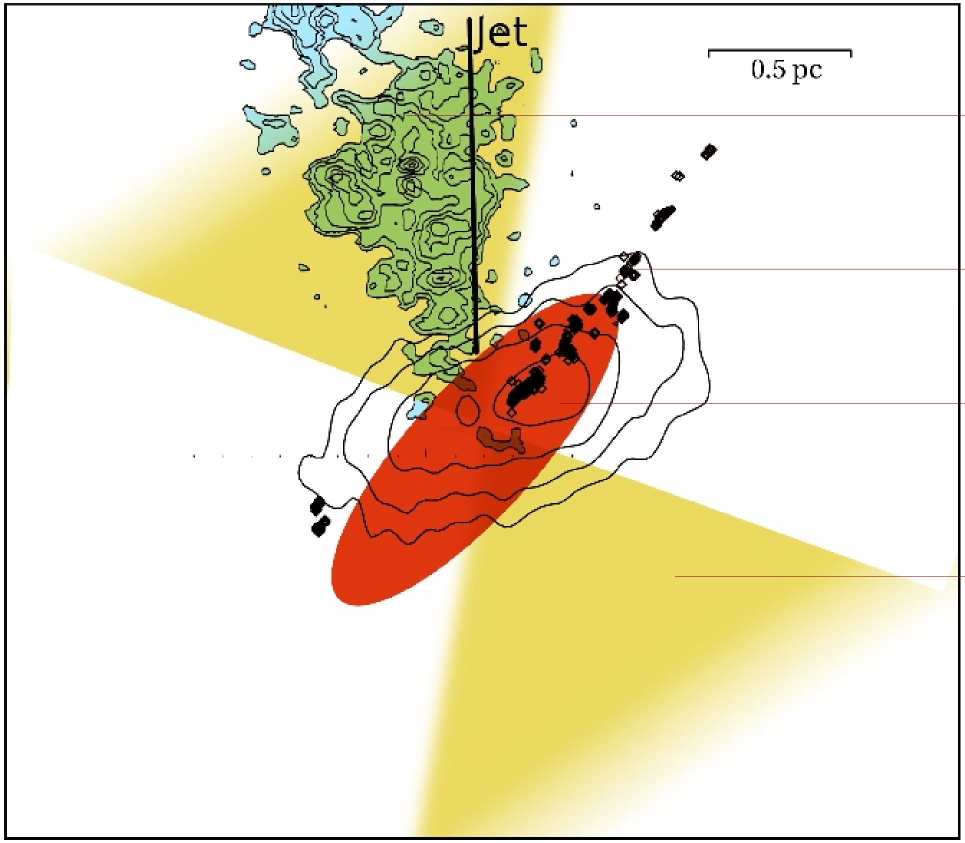




Centrosymmetric polarization indicates scattering
(HST UV observations, Capetti et al. 1995)

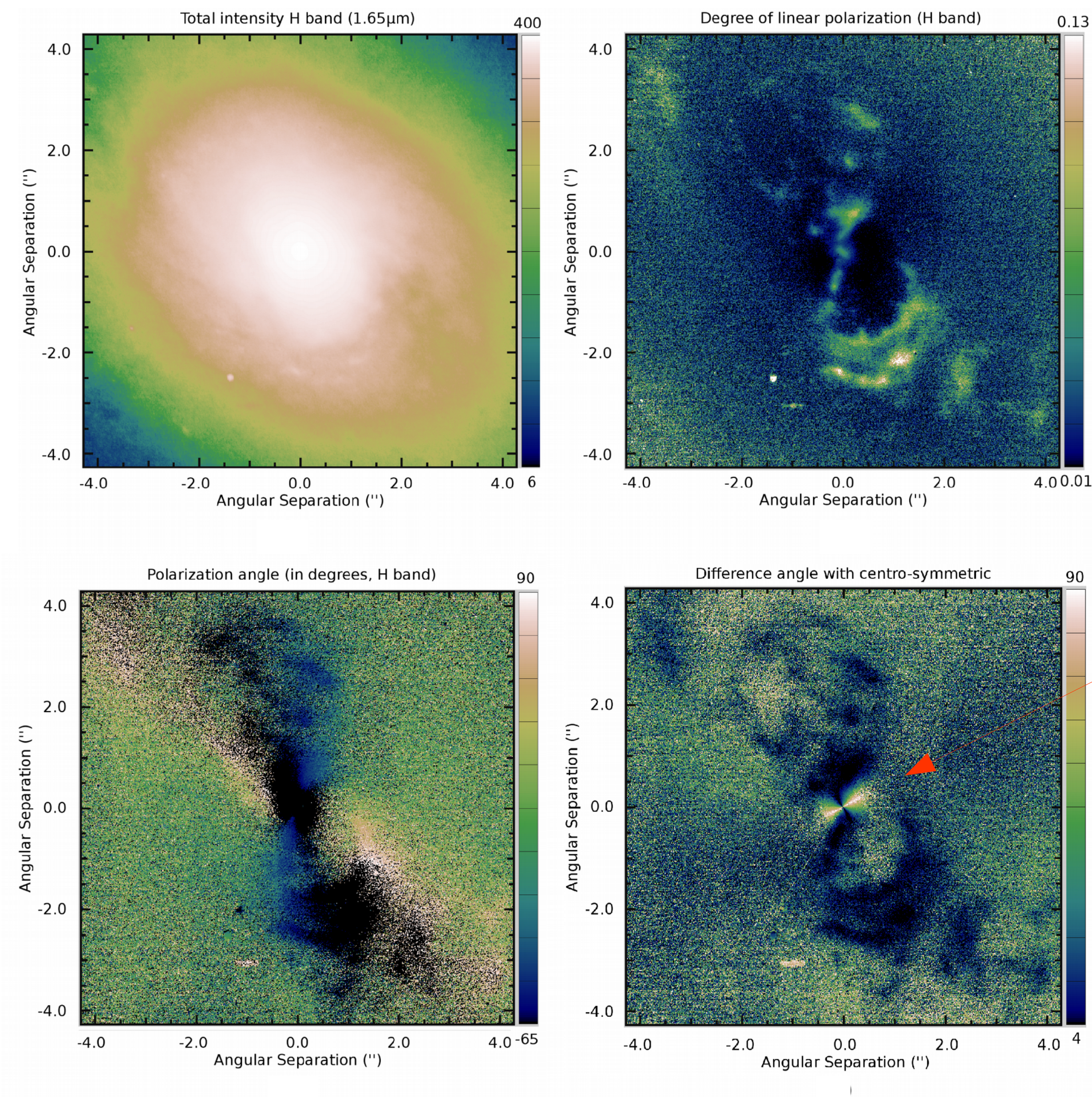
- continuum polarization (> 10%) due to scattering of nuclear light
- caused by electrons inside the NLR and dust in more external regions
- resultant polarization is perpendicular to the radio jet / ionization cones

Infrared interferometry of NGC 1068



(From Raban et al. 2009)

High-resolution polarimetry of NGC 1068



Highly polarized bicone with centro-symmetric pattern seen in the near-IR (edge-brightened)

Compact (1") central region with polarization perpendicular to the bicone axis
→ evidence of a torus

(From Gratadour et al. 2015)

Polarization of Seyfert 2 AGNs

- Observations of other highly polarized Seyfert 2 confirm the scenario proposed for NGC 1068, revealing other hidden Seyfert 1 nuclei
- Electron scattering is likely the main polarization mechanism in the nucleus, although a firm conclusion requires proper disentangling of various contributions to the continuum light
- In most objects, the polarization of the continuum is perpendicular to the radio axis and/or to the ionization cones (polar scattering)
- However, most Seyfert 2 galaxies have little polarization and high polarization objects are rare → dilution by an additional continuum source is needed (host galaxy + partly unobscured continuum, emission from the scattering region itself, starburst)

(Martin et al. 1983, Miller & Goodrich 1990, Tran 1995, Heckman et al. 1995)

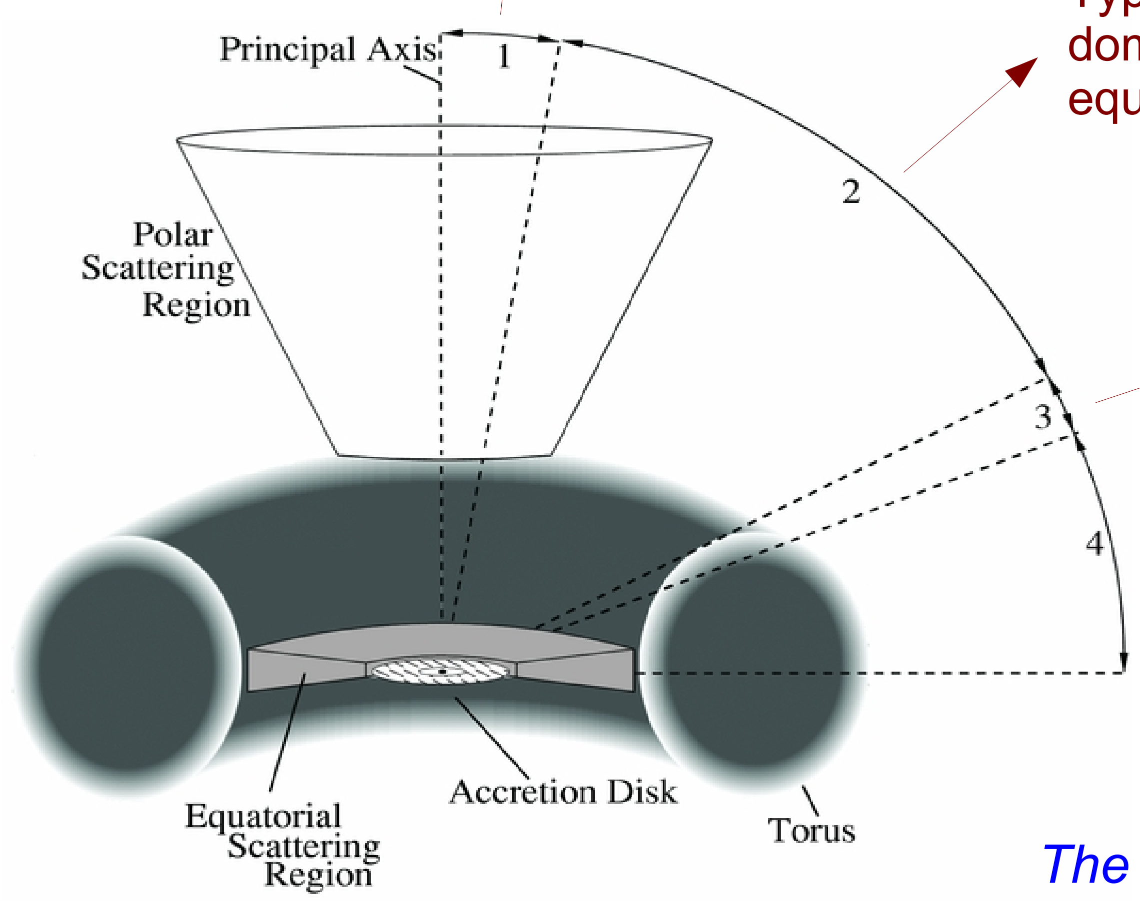
Polarization of Seyfert 1 AGNs

- Most Seyfert 1 have little continuum polarization, some rare objects showing p ~ 5% (Martin et al. 1983, Goodrich & Miller 1994)
- Optical spectropolarimetry of Seyfert 1 nuclei reveals great diversity (Goodrich & Miller 1994, Smith et al. 2002)
  - polarization is most often parallel to the radio axis / ionization cones but perpendicular polarization is also observed (~1/5)
    → equatorial and polar scattering regions are needed
    (the accretion disk only produces perpendicular polarization)
  - diversity of wavelength dependence of p and line broadening
    → both electron and dust scattering contribute
  - broad line polarization shows typical structures in p and θ across the line profile
    → the BLR is resolved in velocity by the equatorial scattering region

Polarization in AGNs : a unified view

Type 1 with null polarization

Type 1 with polarization dominated by equatorial scattering



Type 1 with polarization dominated by polar scattering

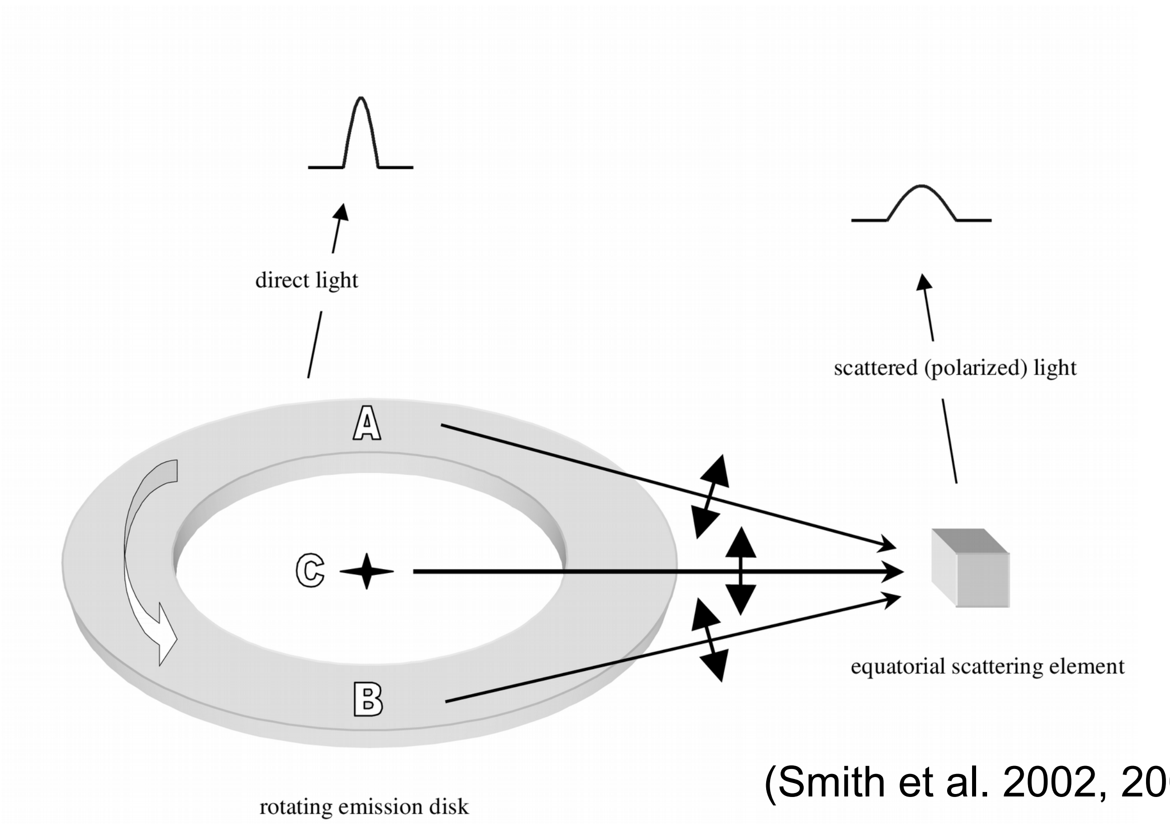
Type 2 with polarization from polar scattering

The relative importance of polar scattering (extended region) and equatorial scattering (compact region) is determined by inclination

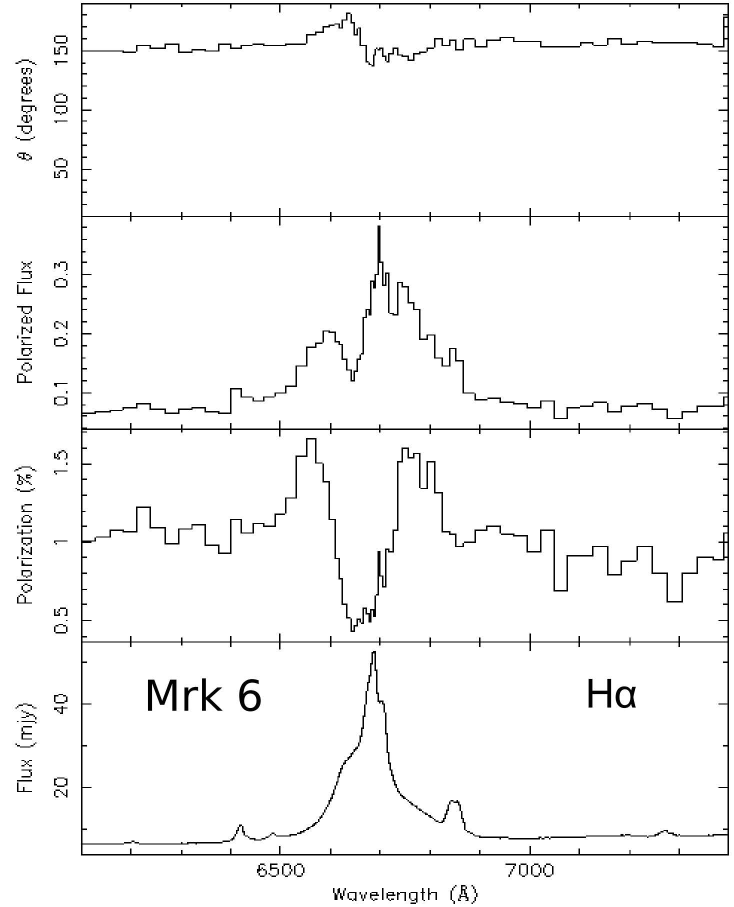
(Smith et al. 2004, Batcheldor et al. 2011)

Polarization across the Hα line profile

Equatorial scattering in Seyfert 1



(Smith et al. 2002, 2005)



→ Polarization dilution in the line core + rotation across the profile symmetric around the continuum PA: signature that BELs come from a rotating disk

→ The PA rotation profile through the emission line can be used to measure the black hole mass (Afanasiev and Popovic 2015, Savic et al. 2018, Afanasiev et al. 2019)

Radio-quiet quasars : type 1

- High-redshift objects :
  - rest-frame ultraviolet continuum and high-ionization lines
  - host galaxies : barely resolved and less contaminating
- Broad-band polarization surveys found p_{mean} ~ 0.6%, a small minority (~ 1/100) showing p > 3% (Stockman et al. 1984, Berriman et al. 1990)
- As for radio-loud quasars (Stockman et al. 1979, Rusk and Seaquist 1985), the optical polarization PA of radio-quiet objects is apparently aligned with the radio structure suggesting equatorial scattering (Berriman et al. 1990)
- Spectropolarimetry of quasars reveals unpolarized narrow lines and polarized broad emission lines with sometimes structure in p and θ (Smith et al. 2003). Other low-polarization quasars (*mostly radio-loud)* show polarization only in the continuum, the broad lines being essentially unpolarized (Kishimoto et al. 2004, 2008).

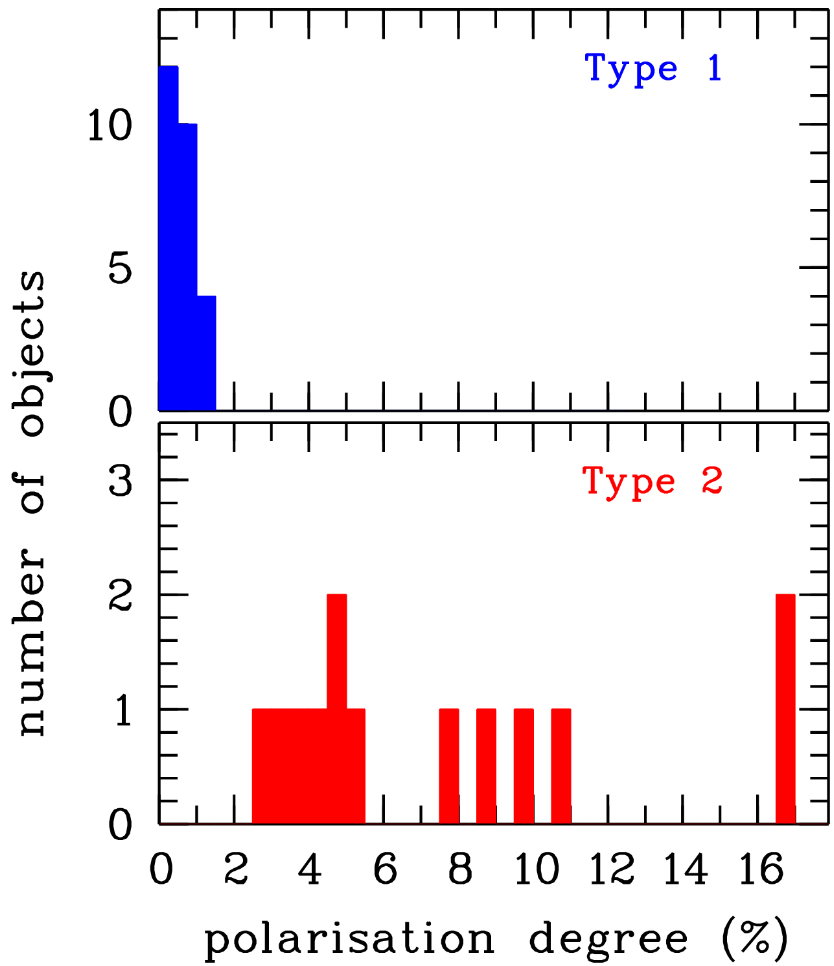
  ⟶ *This suggests that the equatorial scattering region can be located outside or inside the BLR*

Radio-quiet quasars : type 2

- About 150 type 2 quasars in the redshift range $0.3 < z < 0.8$ were found in the SDSS by selecting narrow-line AGN with high [OIII] luminosities (out of $\sim 10^5$ objects) (Zakamska et al. 2003)
- Spectropolarimetry reveals (Zakamska et al. 2005)
  - high polarization often > 3% and up to 17%
  - type 1 broad emission lines are detected in the polarized flux

This supports the extension of the type 1 / type 2 unification by orientation model to at least some high-luminosity AGN

Type 1 / Type 2 polarization dichotomy



Rest-frame UV-blue linear polarization in type 1 and type 2 quasars at 0.2 < z < 0.7 (From Hutsemékers et al. 2017)

- Type 1 quasars have p < 2% and Type 2 quasars have p > 2%

  (Type 2 quasar polarization measurements are still scarce !)

- Similar dichotomy in Seyferts but less clear due to stronger dilution of the polarization by the host starlight (e.g. Marin 2014)

Polarization angles : a type 1 / type 2 dichotomy

- The polarization of type 2 quasars is perpendicular to the extended UV continuum (Zakamska et al. 2005)
- The polarization of type 1 quasars appears mostly parallel to the extended UV continuum
  (after deconvolution, Borguet et al. 2008)

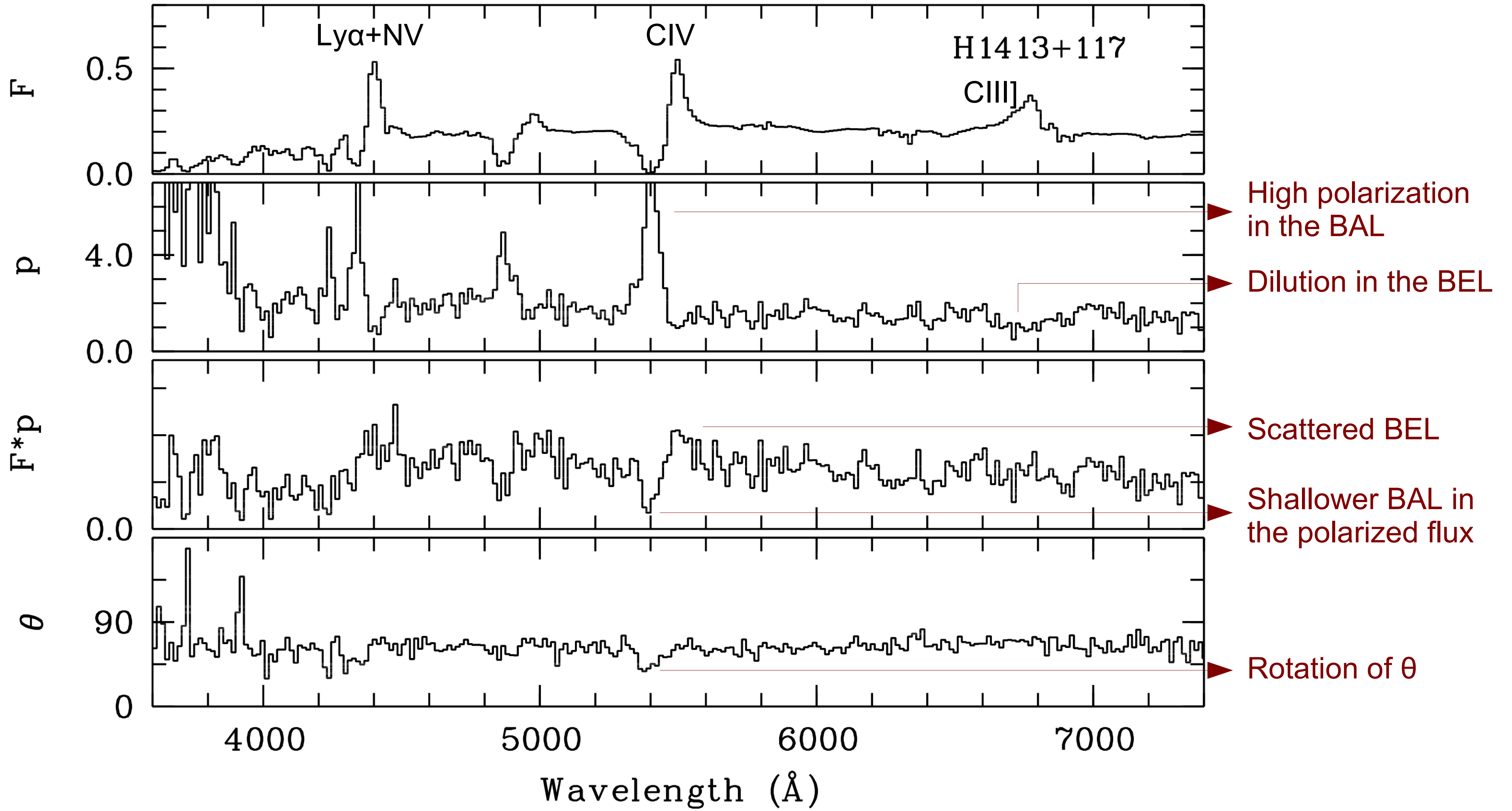
The two-component polar + equatorial scattering model may also prevail in high luminosity AGNs

Three-band HST color-composite images of type 2 quasars. The irregularly shaped blue spot is identified as a one-sided scattering region (top) or as a fairly symmetric biconical region (bottom).
(From Zakamska et al. 2005)

Broad Absorption Line Quasars

- Broad absorption lines are present in ~20% of high redshift ($z > 1.5$) radio-quiet quasars. BALs are blueshifted w.r.t. the emission lines, sometimes detached, revealing ionized outflowing material
- BAL flows may be present in all radio-quiet quasars, BALs being only observed along peculiar lines of sight (intermediate between type 1 and type 2 lines of sight?)
- BAL QSOs are essentially radio-quiet but a significant number of radio-loud objects exists (1/10) (Shankar et al. 2008)
- BAL QSOs as a class are more polarized than non-BAL QSOs (p ~1-2% vs 0.6%) (Moore & Stockman 1984, Hutsemékers et al. 1998)

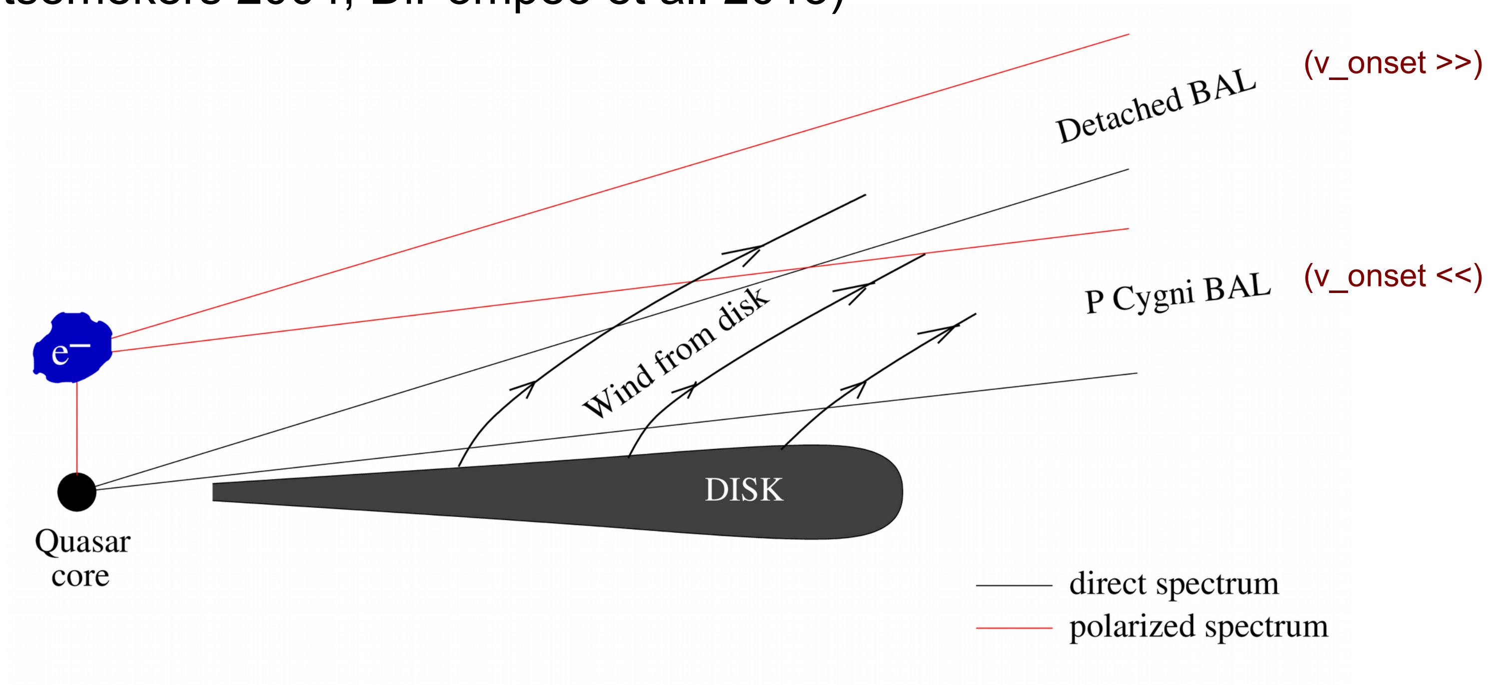
Spectropolarimetry of BAL quasars



(e.g. Goodrich & Miller 1995, Ogle et al. 1999, Lamy & Hutsemékers 2004, DiPompeo et al. 2013)

Polarization in BAL quasars

- BELs are usually less polarized than the continuum → the scattering region is (only slightly?) outside the BLR
- The BAL is shallower in the polarized flux → the scattered light passes through the BALR but it is less absorbed than the direct light
- Statistical analyses of various observables reveal a correlation between polarization and the BAL onset velocity (Lamy & Hutsemékers 2004, DiPompeo et al. 2013)



A two-component BAL wind model?

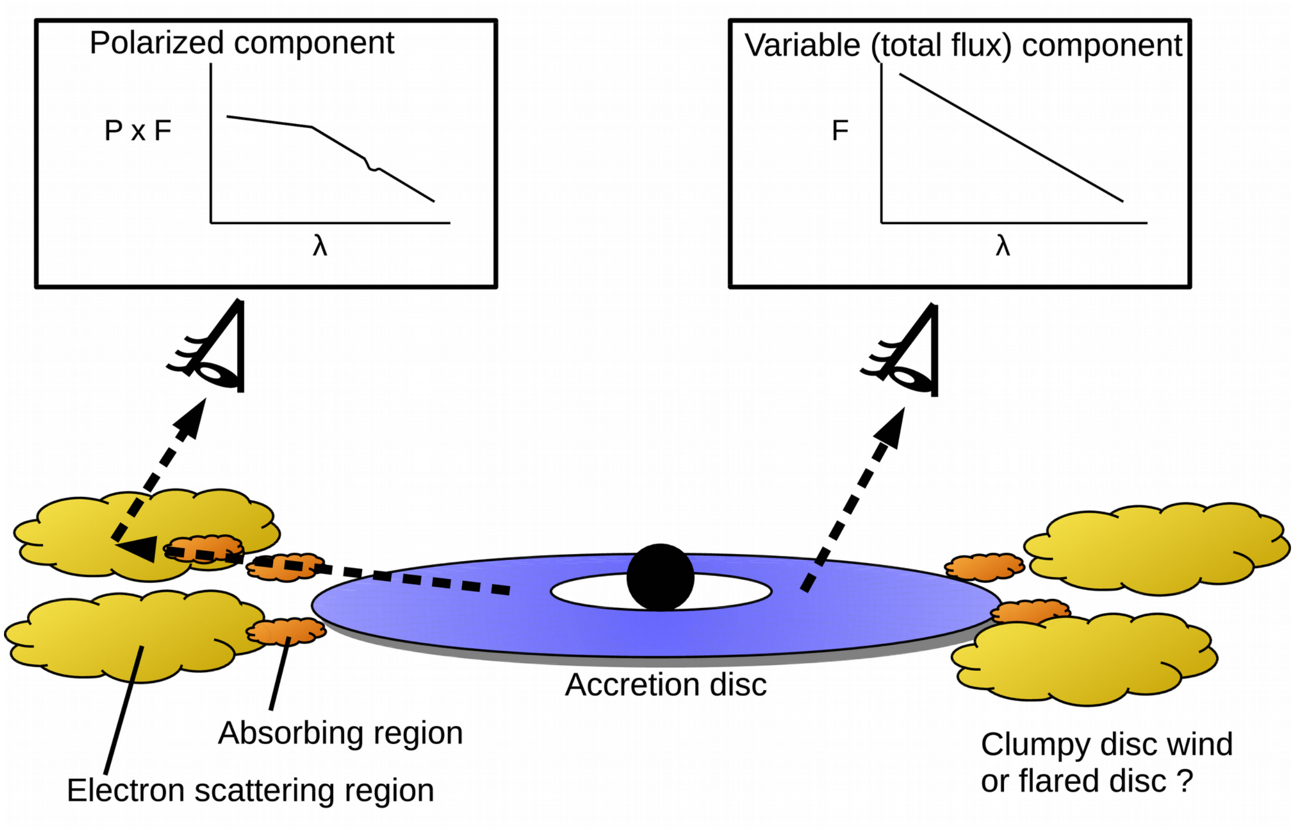
- Rotation of the polarization in the lines → more than one scattering region is needed or contribution from resonance scattering
- Radio observations of radio-loud BAL QSOs suggest that BAL flows are seen at various inclinations w.r.t. the line of sight, and various orientations w.r.t. the jet axis (Zhou et al. 2006, DiPompeo et al. 2013, Bruni et al. 2013) → equatorial and polar outflows do exist

A two-component polar + equatorial wind can qualitatively explain most observations. Continuum polarization can be due to electron scattering in the BEL / BAL winds (Wang et al. 2005, 2007)

Misaligned BAL quasars?

In quasars with continuum-confined polarization

BLR is outside



(From Kokubo 2017)

A coherent view of polarization from radio-quiet AGN ?

Most observations seem to require two scattering regions, polar and equatorial w.r.t. the radio jet / accretion disk axis.
In the framework of unification models their relative importance in terms of polarization is driven by inclination.
The model established for low-luminosity AGNs apparently extends to (at least some) higher luminosity quasars.

The polar scattering region can be resolved and identified, but the nature of the equatorial electron scattering region inside the torus is more elusive.

- What is the nature of the equatorial scattering region?
- Is the equatorial scattering region outside, inside, or within the BLR?
- Are all scattering regions always simultaneously present in all AGNs?
- Is scattering in winds important (in BAL, normal, low-L quasars)?

New directions / challenges

- Modeling and detailed comparison to observations
- Polarization microlensing
- Polarization reverberation
- Polarization of changing-look AGNs

State-of-the-art modeling

- Monte-carlo radiative transfer models allow to consider various geometries, scatterer species, and multiple scattering, further extending previous models
(e.g., STOKES, Goosmann & Gaskell 2007, Marin et al. 2012, 2014)
- Models including a torus, equatorial and polar scattering regions can reproduce the continuum polarization properties of type 1 / type 2 AGNs and the dependence on inclination. The torus should have a large half-opening angle.
- Wavelength independent near-UV to optical polarization does not necessarily imply electron scattering.
- Confirmation that the standard Shakura-Sunyaev geometrically thin / optically thick accretion disk cannot produce the type 1 AGN continuum polarization. An equatorial electron scattering region is necessary, not only to explain the BEL polarization.

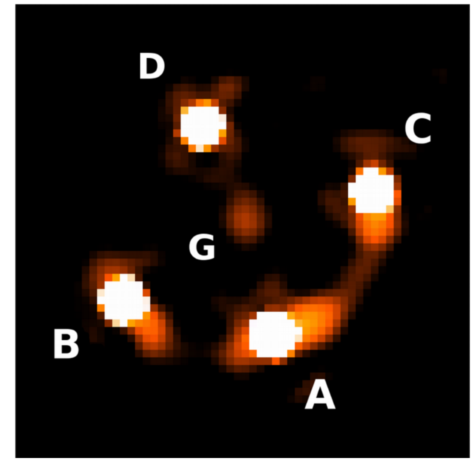
State-of-the-art modeling

- Further developments include clumpiness of the scattering regions, dilution by the host stellar light, continuum polarization timing ("reverberation")
  (Marin et al. 2015, Marin 2018, Rojas Lobos et al. 2018, 2020)
- Simulations of BEL polarization profiles ("PPA swings") in type 1 AGNs have been revisited, including equatorial scattering disks, outflows, binary supermassive black holes
  (Savic et al. 2018, 2019, Lira et al. 2020)

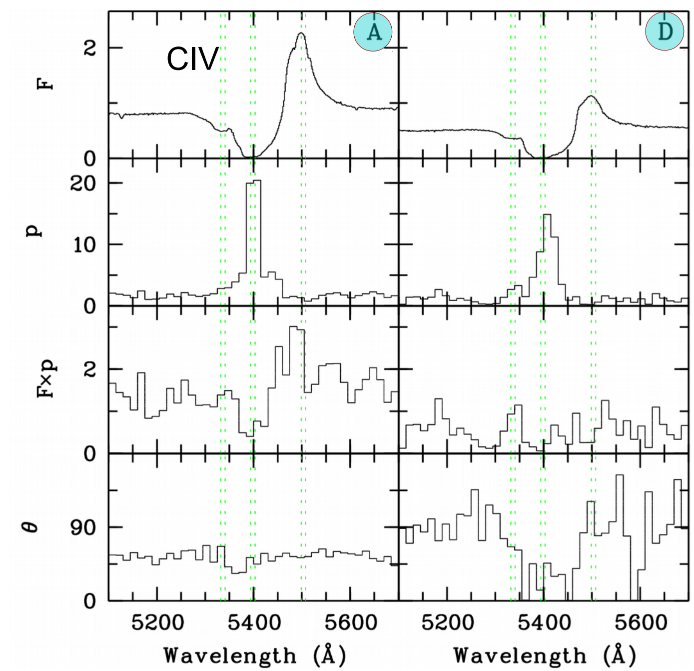
Simulation tools are available for a detailed comparison with high-quality data

Polarization microlensing

- Microlensing can magnify the inner regions of lensed quasars, in particular the continuum source, and induce variability
- H1413+117 is a quadruple BAL quasar (z = 2.55) with a polarization degree around 2%
- In H1413+117, image D is magnified w.r.t. image A
- The continuum polarization of image D differs from the continuum polarization of image A, in both degree and angle. It also changes with time (Chae et al. 2001, Hutsemékers et al. 2015)
- The polarization profile of the CIV BAL is also different in image D

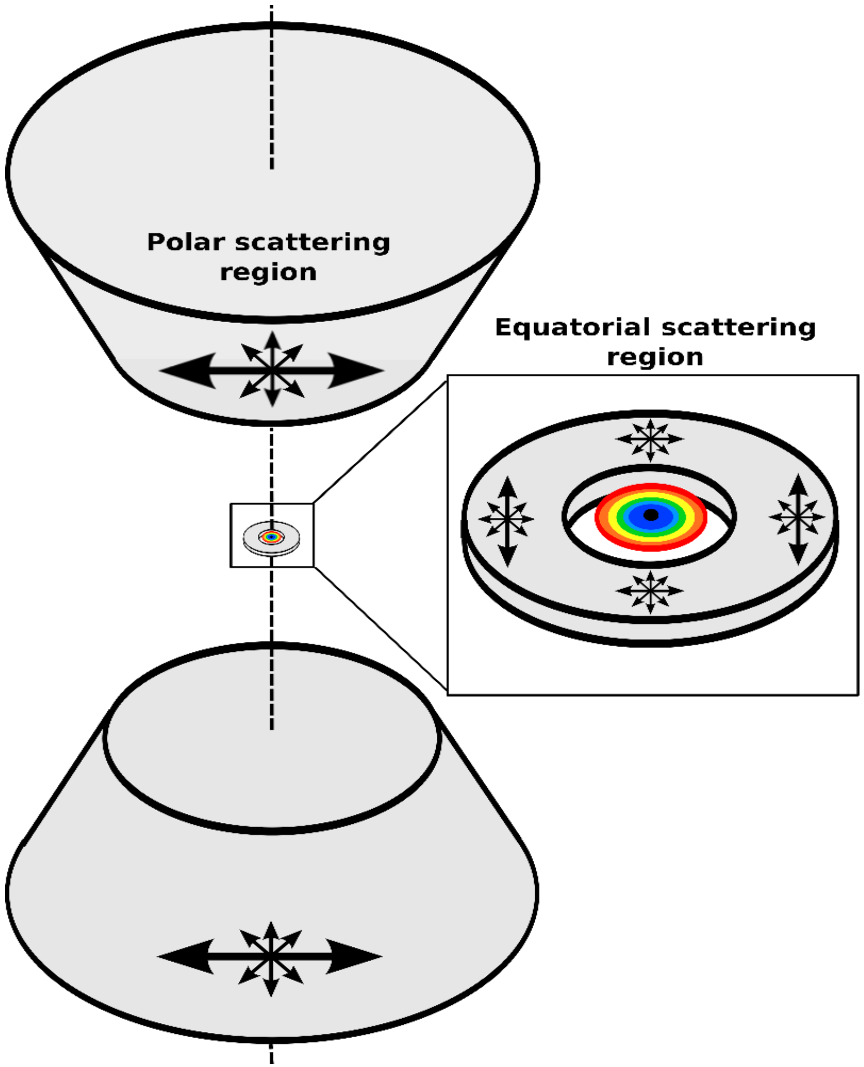


H1413+117 BALQSO at z=2.55



[N.B. Polarization microlensing is also possibly present in the lensed BAL quasar J0818+0601 (Hutsemékers et al. 2020)]

Polarization microlensing



A two-component polar + equatorial BAL flow has been proposed for interpreting the H1413+117 spectrum

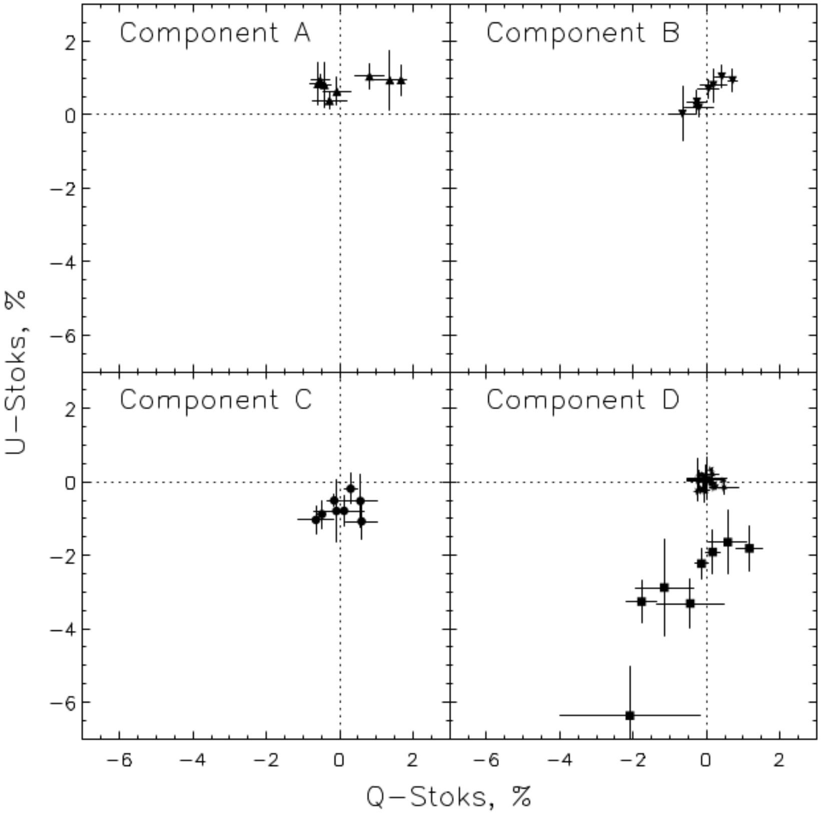
Two differently sources of polarized continuum can explain the polarization variations in image D, assuming that only the compact source is magnified

The size of the compact scattering region must be smaller than the BLR which is not magnified

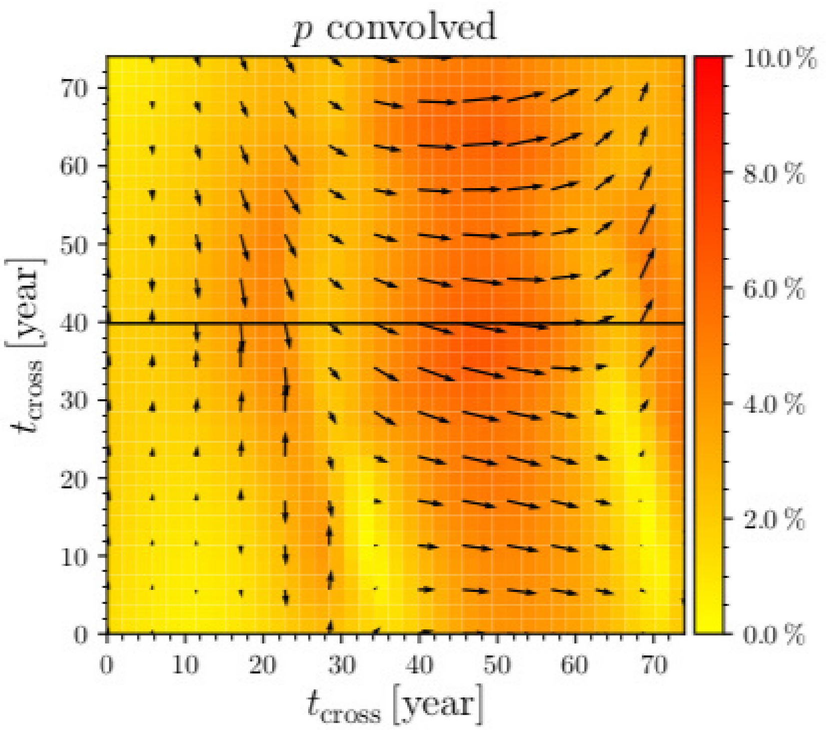
[N.B. The need for two sources of continuum with different spatial extensions in (at least some) quasars has been suggested independently from microlensing in BAL quasars and from reverberation mapping (Korista & Goad 2001, Lawrence 2012, Sluse et al. 2015, Chelouche 2019, Hutsemékers et al. 2020)]

Polarization microlensing

The polarization in image D of J1004+4112 (z=1.73) is strongly variable due to microlensing



Microlensing of an electron scattering region located in the inner part of the torus can explain the observations (simulation with STOKES)



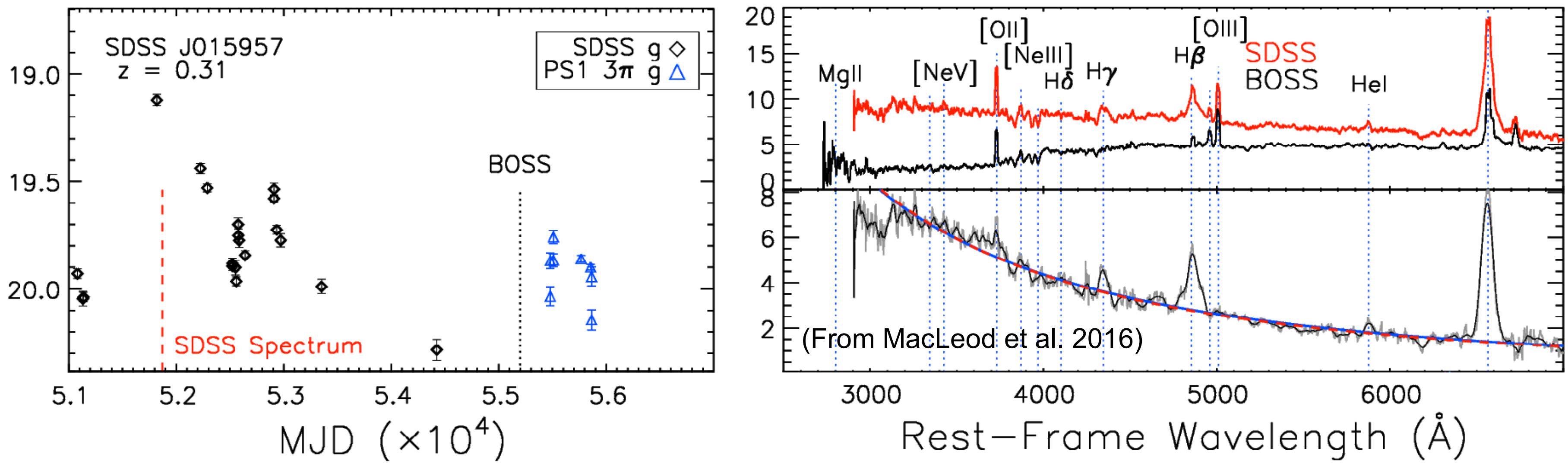
(Popovic et al. 2020)

Polarization reverberation

- In NGC 4151 (Seyfert 1), there is an 8-day time lag between the total and polarized continuum flux (Gaskell et al. 2012).
  STOKES modeling indicates that
  → dust scattering in the torus is ruled out (delay too long)
  → electron scattering in a disk-like region reproduces the delay (the outer edge of the BLR has the right size ~ 6 lt-days)
- In Mrk 6 (Seyfert 1.5), there is a 2-day time lag between the unpolarized and polarized continuum flux while the BLR size is around 20 lt-days (Afanasiev et al. 2014)
  → two components dominate the polarized continuum, the most compact one, much smaller than the BLR, being variable (jet?)
  → a larger equatorial scattering region is still needed to explain the polarization of the BELs
  → Similar conclusions for the Seyfert 1 3C390.3: two sources of polarized continuum are needed, including a very compact one (Afanasiev et al. 2015)

Changing-look quasars

At optical wavelength



Quasars that change from type 1 to type 2 or vice-versa, together with 1-2 mag variations on timescales of years.

Some of them show cycles (e.g., T1-T2-T1)

(LaMassa et al. 2015, Runnoe et al. 2016, Ruan et al. 2016, MacLeod et al. 2016)

→ Challenge for the Unification Model

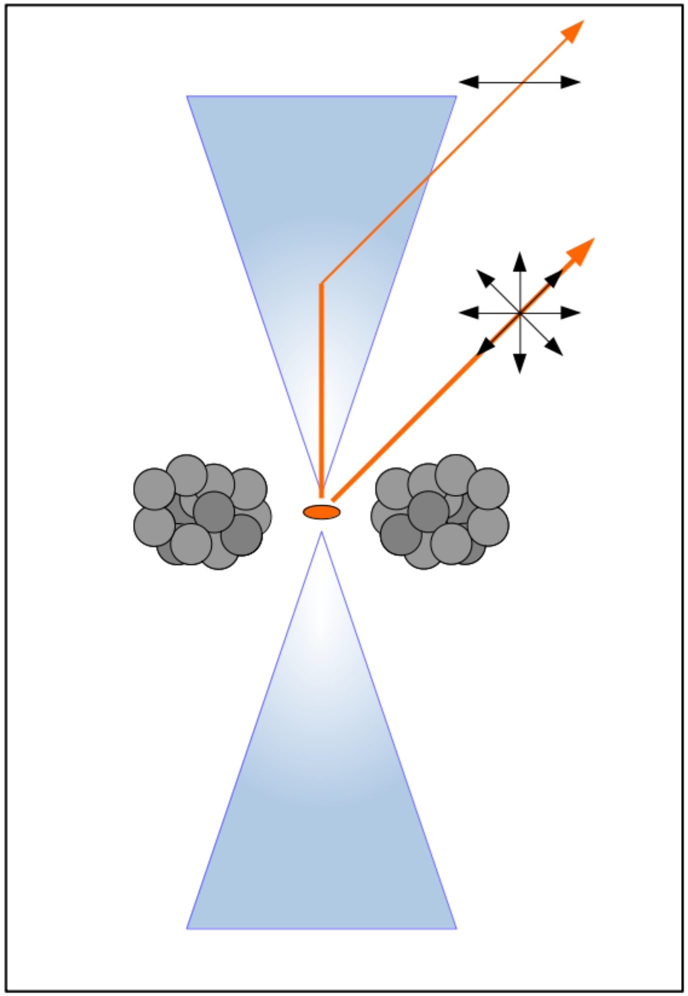
Changing-look quasars

- Possible mechanisms:
  variable obscuration (moving dusty clouds in the torus) or
  dimming / brightening of the ionization source (variable accretion rate)

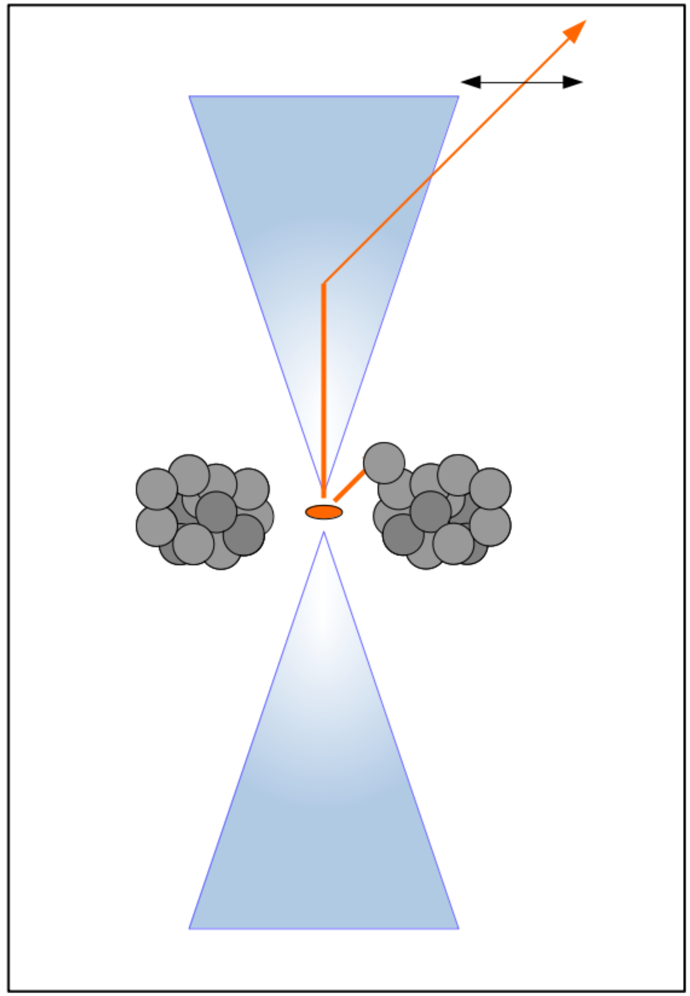
- Variable obscuration is disfavored :
  - no X-ray obscuration
  - optical luminosity variations are followed by mid-IR variations
  - the time needed by a torus cloud to eclipse the BLR is too long, especially in quasars ($R_{BLR} \sim L^{1/2}$)

(see LaMassa et al. 2015, MacLeod et al. 2016, Sheng et al. 2017)

Expected polarization in changing-look quasars



Type 1 AGN

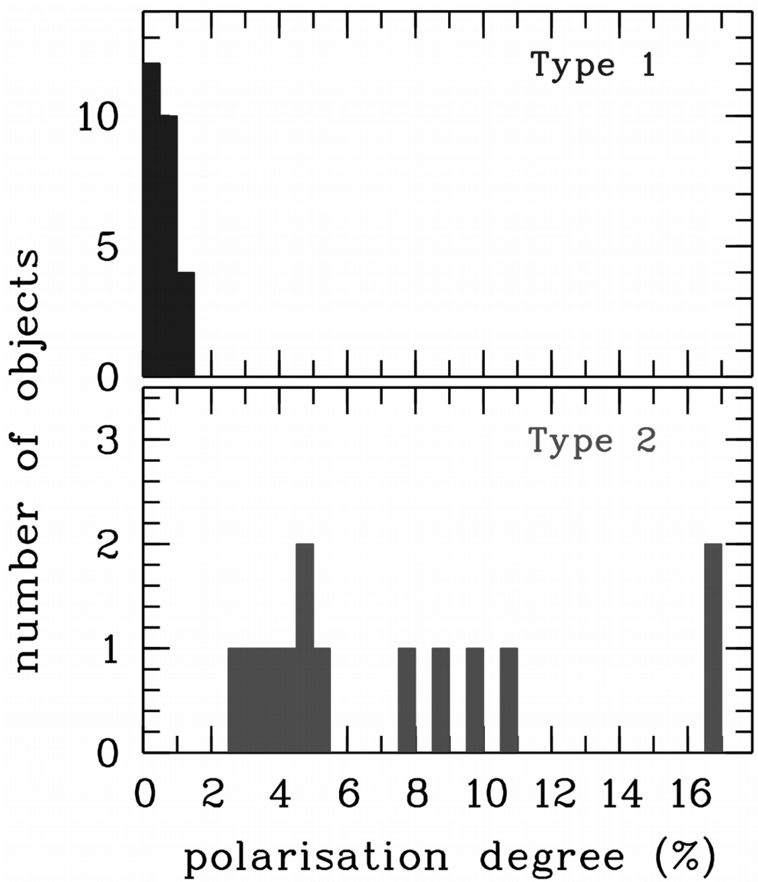


Type 1 → Type 2
due to obscuration

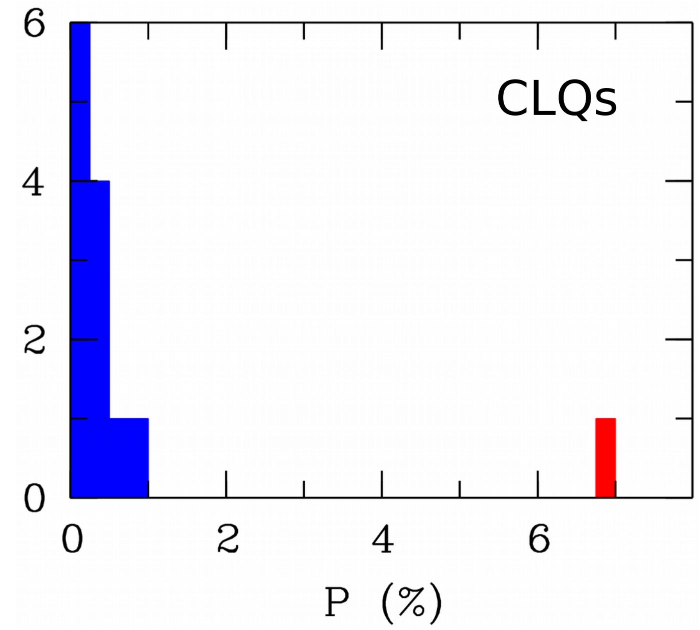
High polarization typical of obscured type 2 quasars is expected if the change of look type 1 → type 2 is due to variable obscuration

Requires intermediate inclinations.
Essentially compatible with the UM

Polarimetry of changing-look quasars



Rest-frame UV-blue linear polarization in quasars at 0.2 < z < 0.7

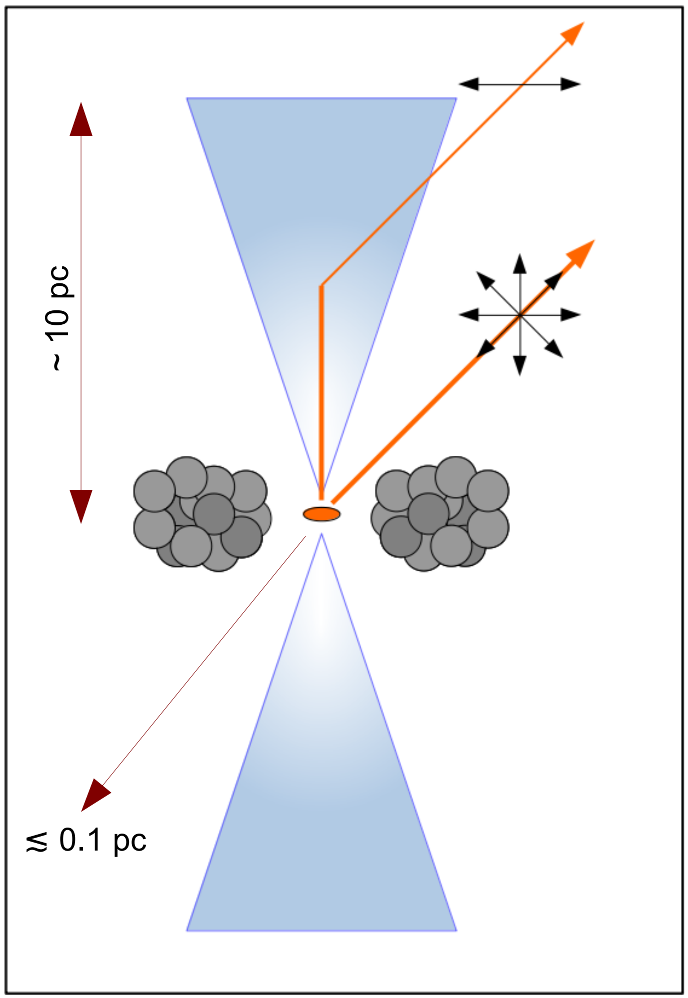


All CLQs but one have a polarization degree < 1% (Hutsemékers et al. 2019)

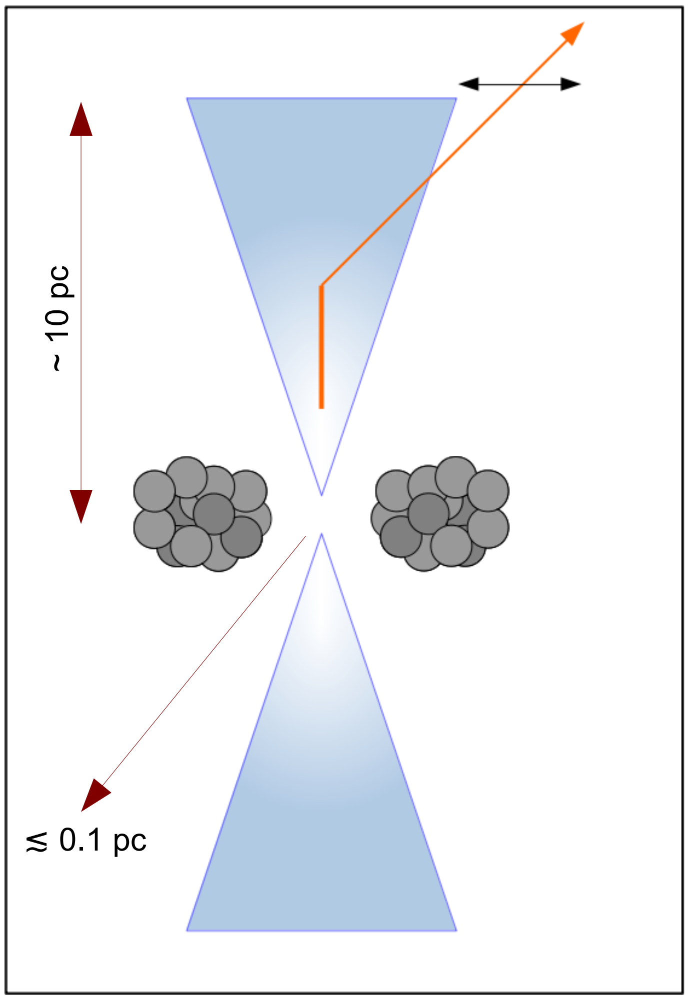
Polarization of changing-look quasars

- All quasars but one, including six in type 2 state, have low polarization $p < 1\%$ => no evidence that dust obscuration causes type 1 → type 2
- Quasars with $p < 1\%$ should be seen at inclinations $< 15^o$ according to simulations with STOKES (Marin 2017)
- One quasar in a type 2 state has a high polarization $p \sim 7\%$. This can be due to obscuration but this is unlikely. Indeed, in that object, the time for a dust cloud from the torus to eclipse the BLR is 80 years, more than one order of magnitude the timescale of the change of look (6 years)
- Alternatively we could see the polarization echo of a switched off type 1 quasar seen at intermediate inclination

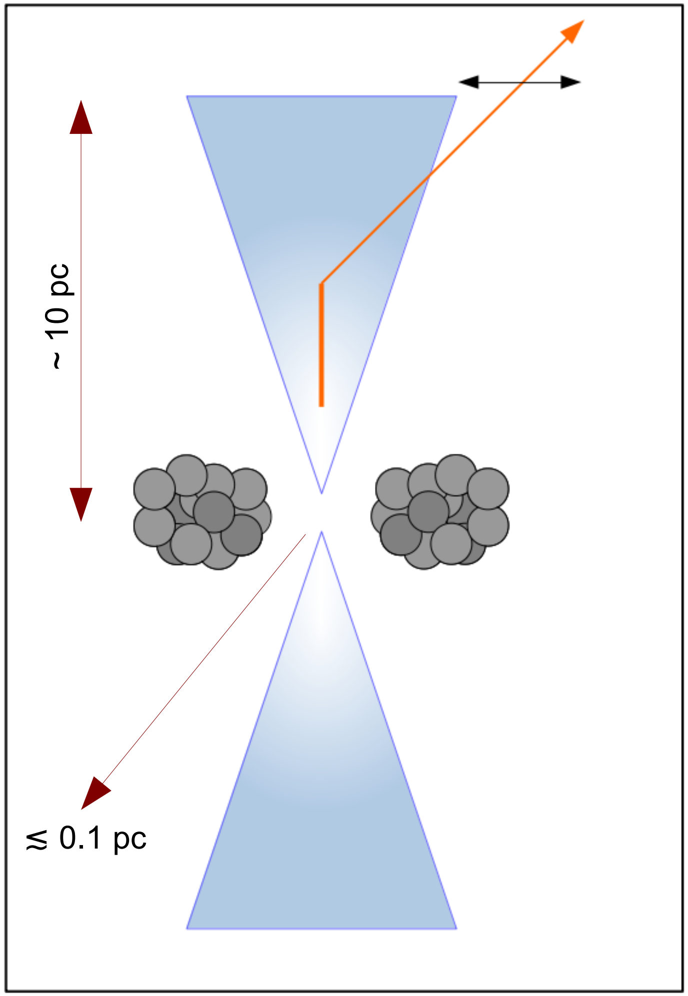
Polarization echo in a switched off quasar

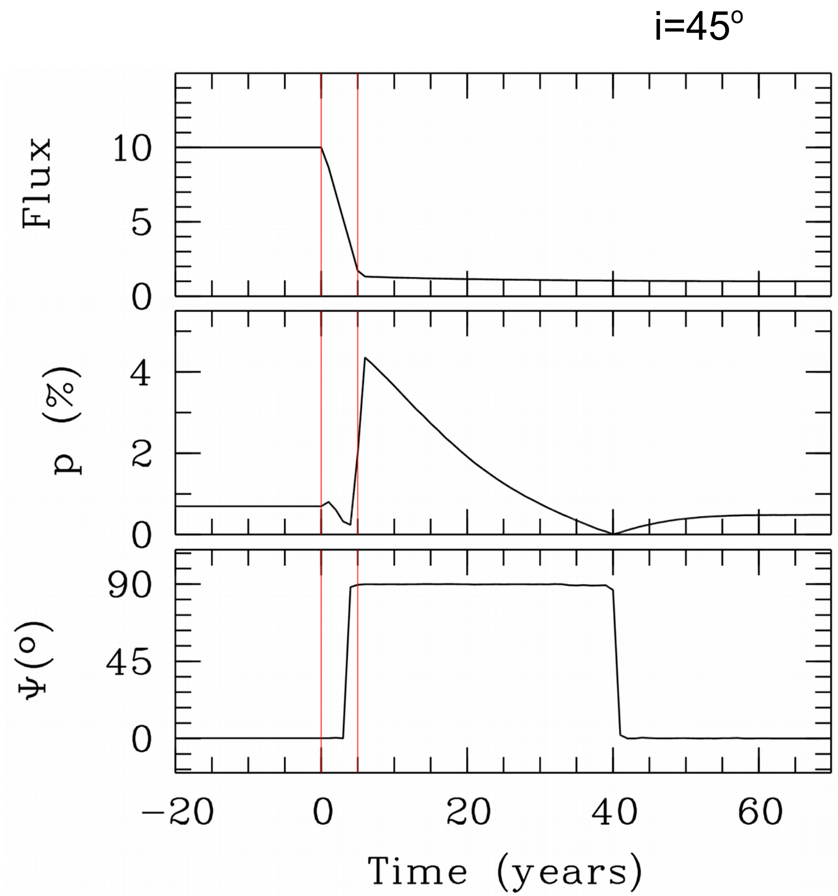


Polarization echo in a switched off quasar



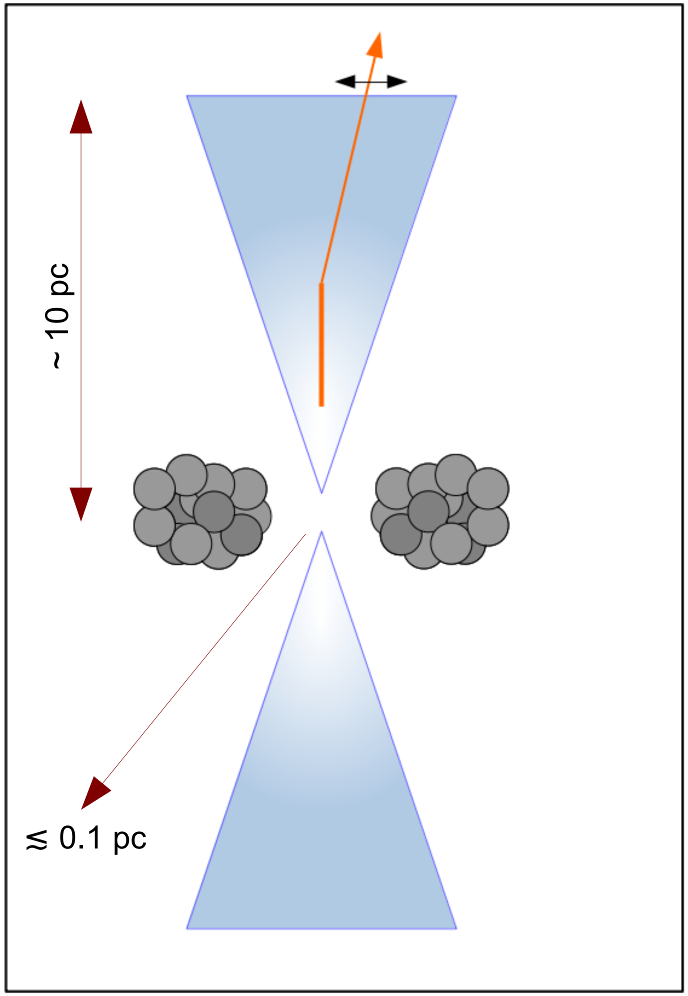
Polarization echo in a switched off quasar



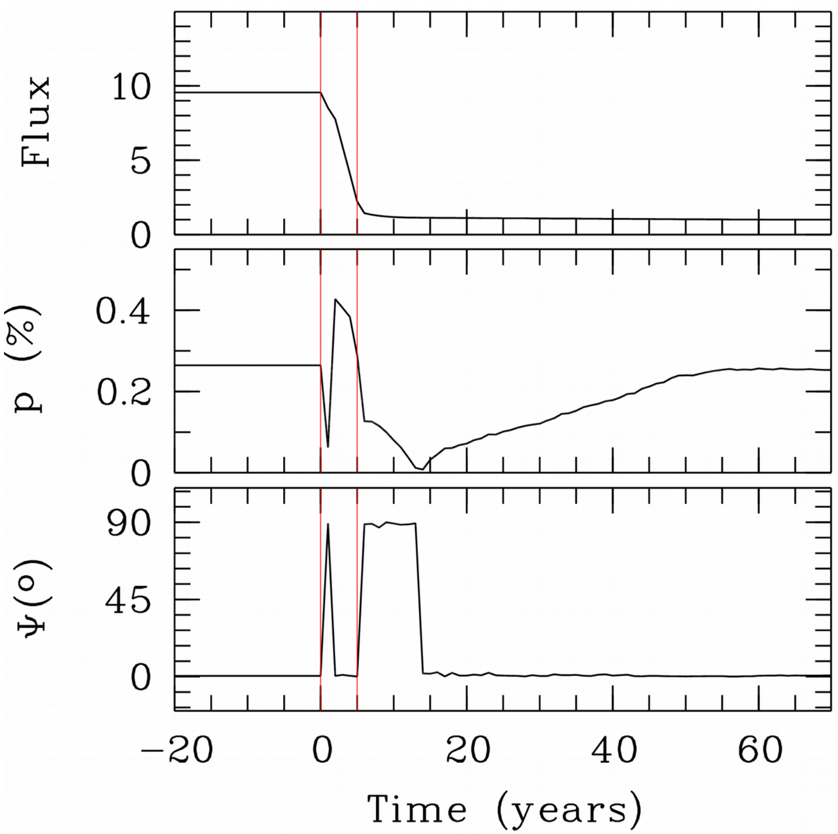


Simulation with STOKES of a Type 1 quasar fading out in five years and the subsequent polarization echo (Hutsemékers et al. 2019, Marin & Hutsemékers 2020)

Polarization echo in a switched off quasar

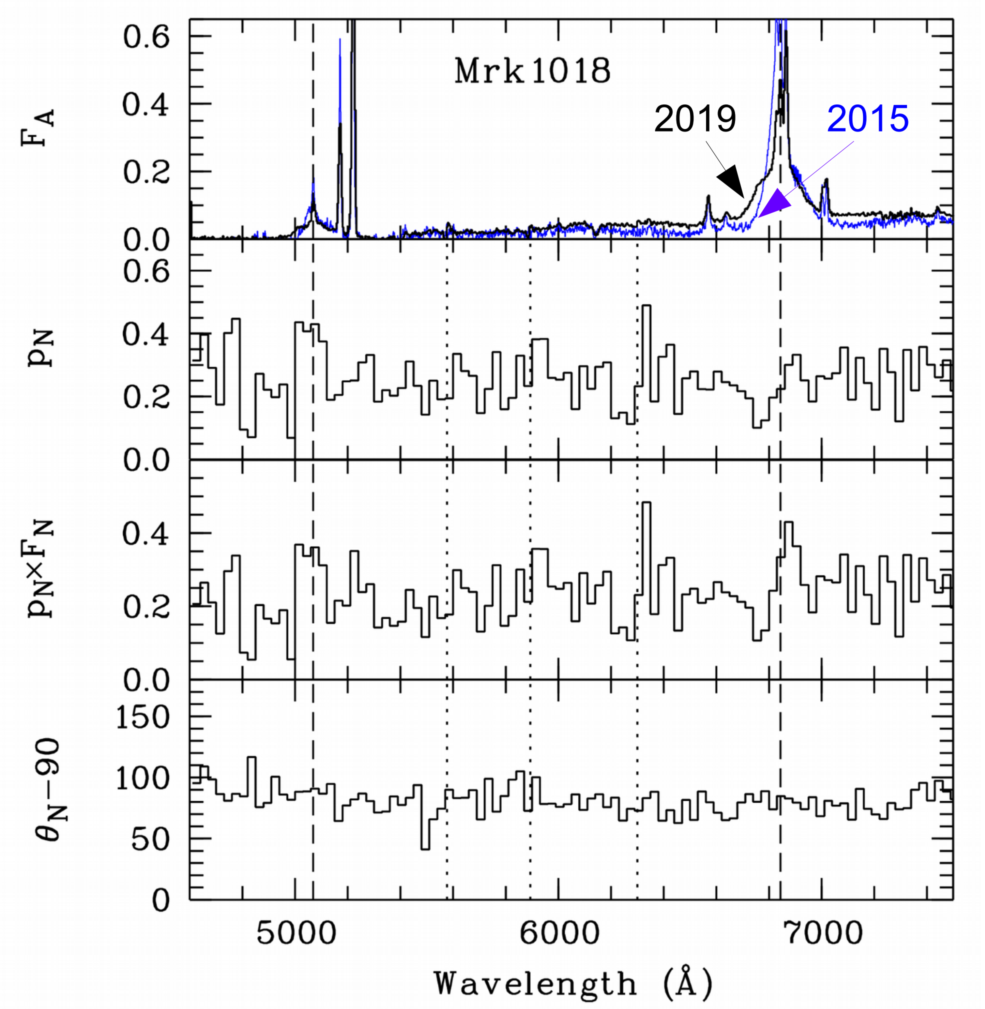


i=10°



Simulation with STOKES of a Type 1 quasar fading out in five years and the subsequent polarization echo (low inclination)

Polarization of changing-look quasars



Spectropolarimetry of Mrk1018
(Hutsemékers et al, 2020)

T2 in 1979, T1 in 1984, T2 in 2015

Continuum polarization remains very low in the faint state as in other CLQs

Delay between direct and polarized light in the Hα blue wing ?

Polarization monitoring of changing-look AGNs could provide key information on the scattering regions
(simulations with STOKES in Marin & Hutsemékers 2020)

In a nutshell

The standard model with equatorial and polar scattering regions still provides a coherent framework to interpret the polarization properties of most type 1 and type 2 AGNs, but

- Where is the equatorial scattering region exactly located w.r.t. the BLR?
- Keplerian disk and/or outflow?
- Where does the continuum polarization really come from?
  Accretion disk? Jet? Wind? Multiple sources?
  New mechanisms (e..g. Silant'ev et al. 2016)?

Polarization monitoring is definitely needed