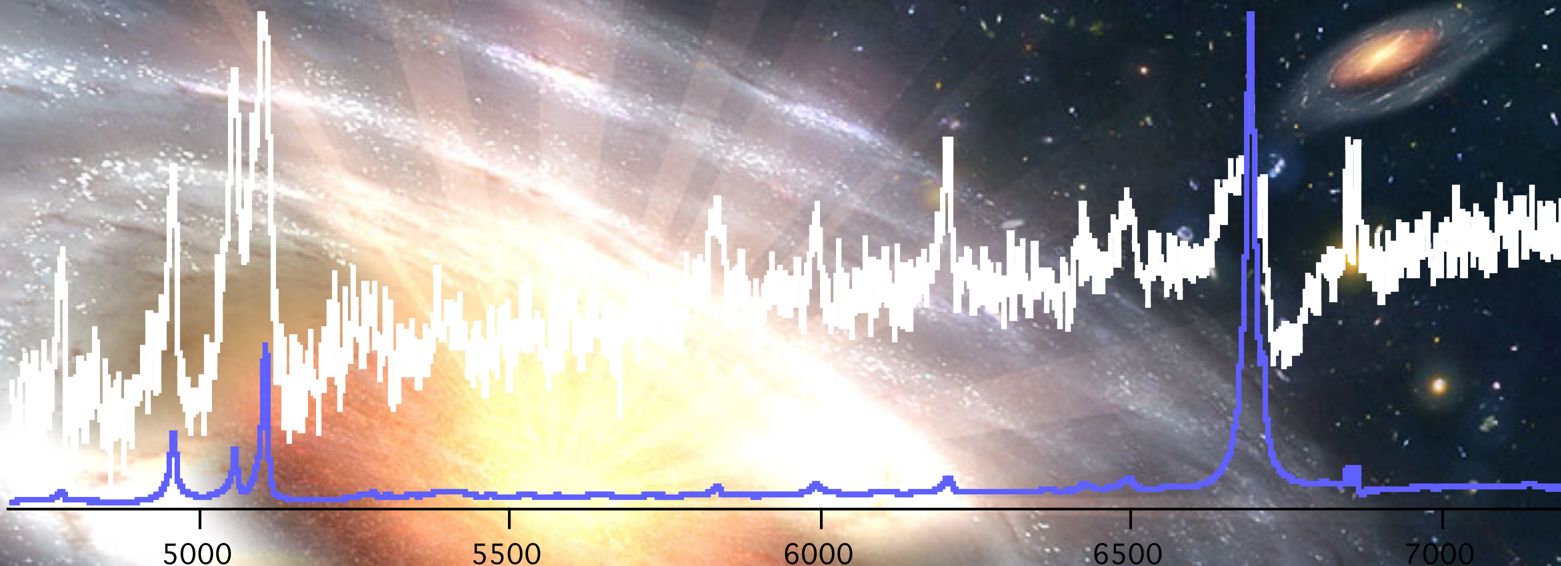
Exploring inner regions of active galactic nuclei with Spectropolarimetry



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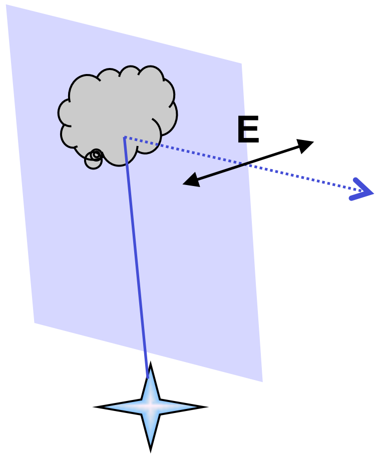
Outline

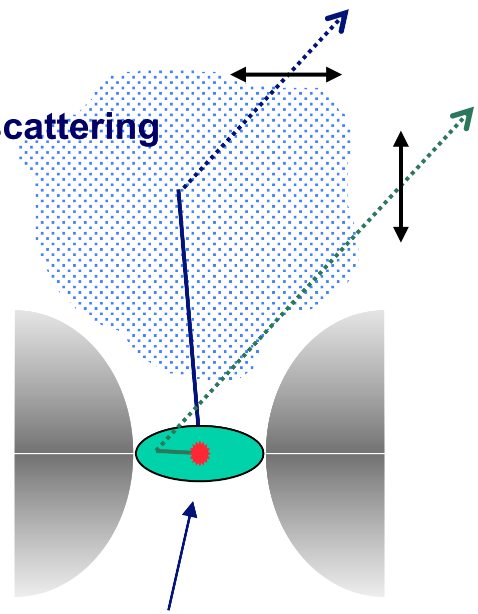
- Astrophysical Motivation
- A refined AGN scattering geometry
- Case studies
  - Equatorial scattering/sub-pc inflows – NGC4151
  - Polar scattering outflow – Mrk231
  - Rotating outflow – PG1700+583
- Polarization of Narrow Line Seyfert 1's
  - (if time)

Seyfert scattering geometries



- The E-vector is perpendicular to scattering plane
  - an important clue to the scattering geometry
- For polar scattering, expect polarization PA to be perpendicular to system axis (traced by radio jet, sometimes…)
  - Usually the case in polarized BL Sy2's

- But Sy1's tend to have pol PA parallel to radio axis ➔ scattering in equatorial plane of torus



Smith et al. 2002
Brindle et al. 1990
Antonnuci 1983

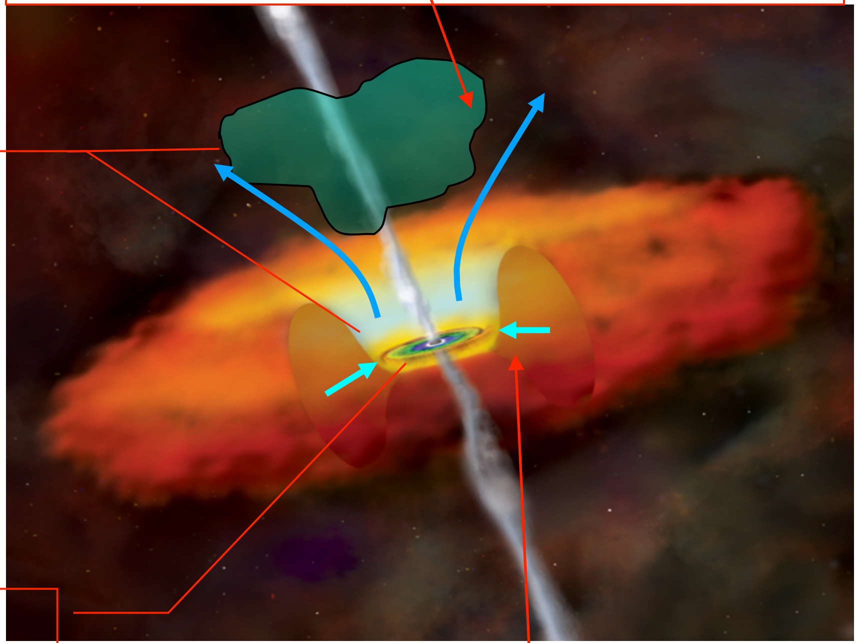
➔ Two scattering routes: compact equatorial scattering region also present

Goals: new insights into the structure of AGN

- Geometry and kinematics of source + scattering regions are imprinted on the polarization spectrum

Establish general structure of the scattering regions, inside and outside torus

What is the nature of gas outflows from the disk, or torus?



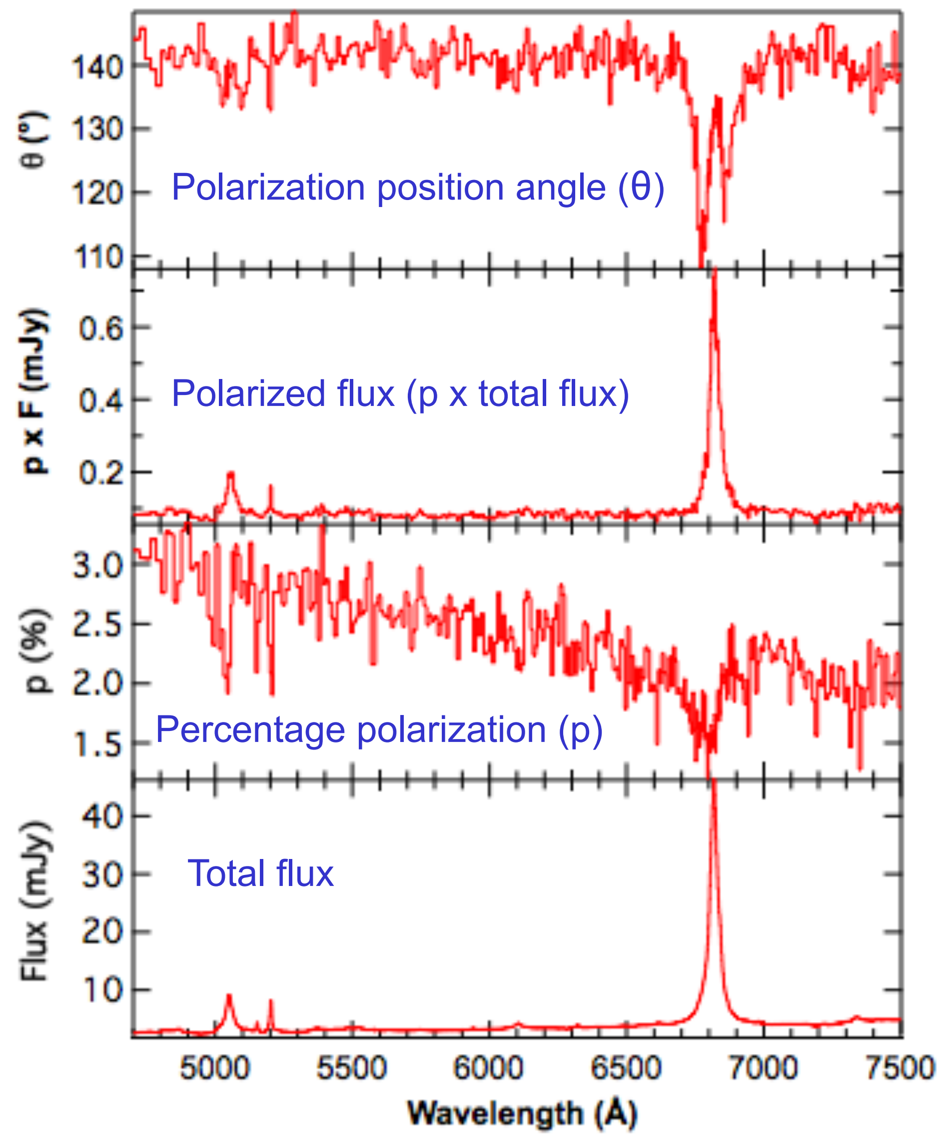
What is the structure of the broad emission line region? Is it part of the accretion disk?

Map accretion flows on sub-torus (sub-pc) scales?

Spectropolarimetry of broad-line AGN

- Optical spectropolarimetry of ≈90 BL AGN to date
- Mostly $z < 0.3$
- Mostly radio quiet
- Seyfert types 1 ➔ 1.9; NLS1
- Weak Seyferts to luminous QSOs
  - ~4 orders of magnitude in luminosity

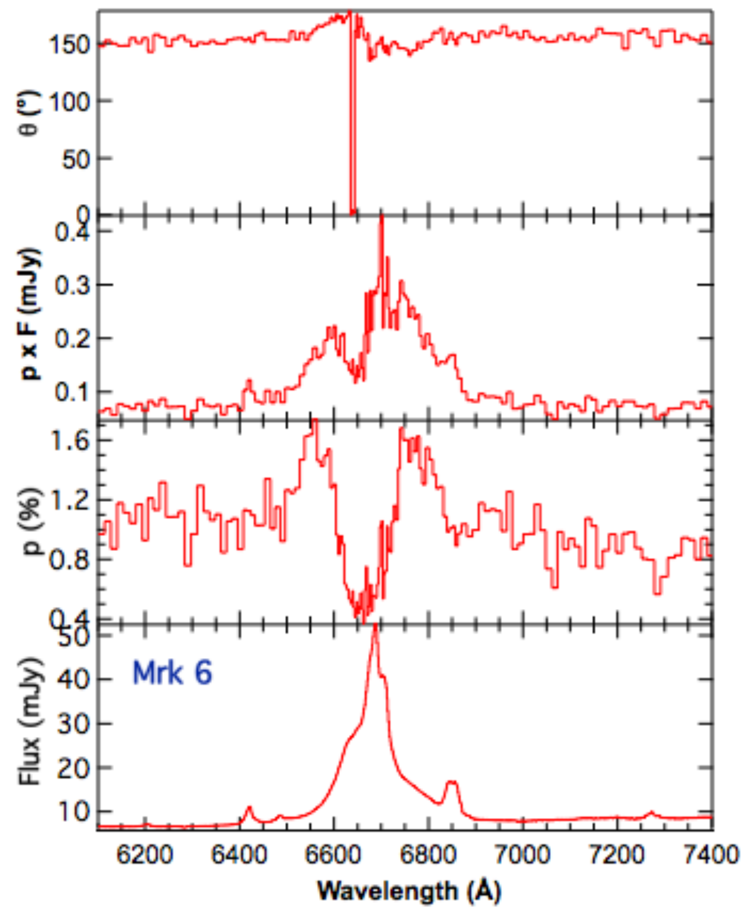
Interstellar polarization (dichroic absorption by aligned dust grains) arising in our ISM or host galaxy dominates in many objects…
But here we are concerned only with polarization by scattering



Seyfert 1 polarization properties

Three broad categories

- Null polarization
  - p < 0.3% (detection limit)
- Equatorial scattering
  - p ~ 0.5–1 %
  - Distinctive variations in p, θ across broad Hα line
- Polar scattering (~30% of S1)
  - p ~1–5%
  - Exhibit "Seyfert 2-like" polarization spectra



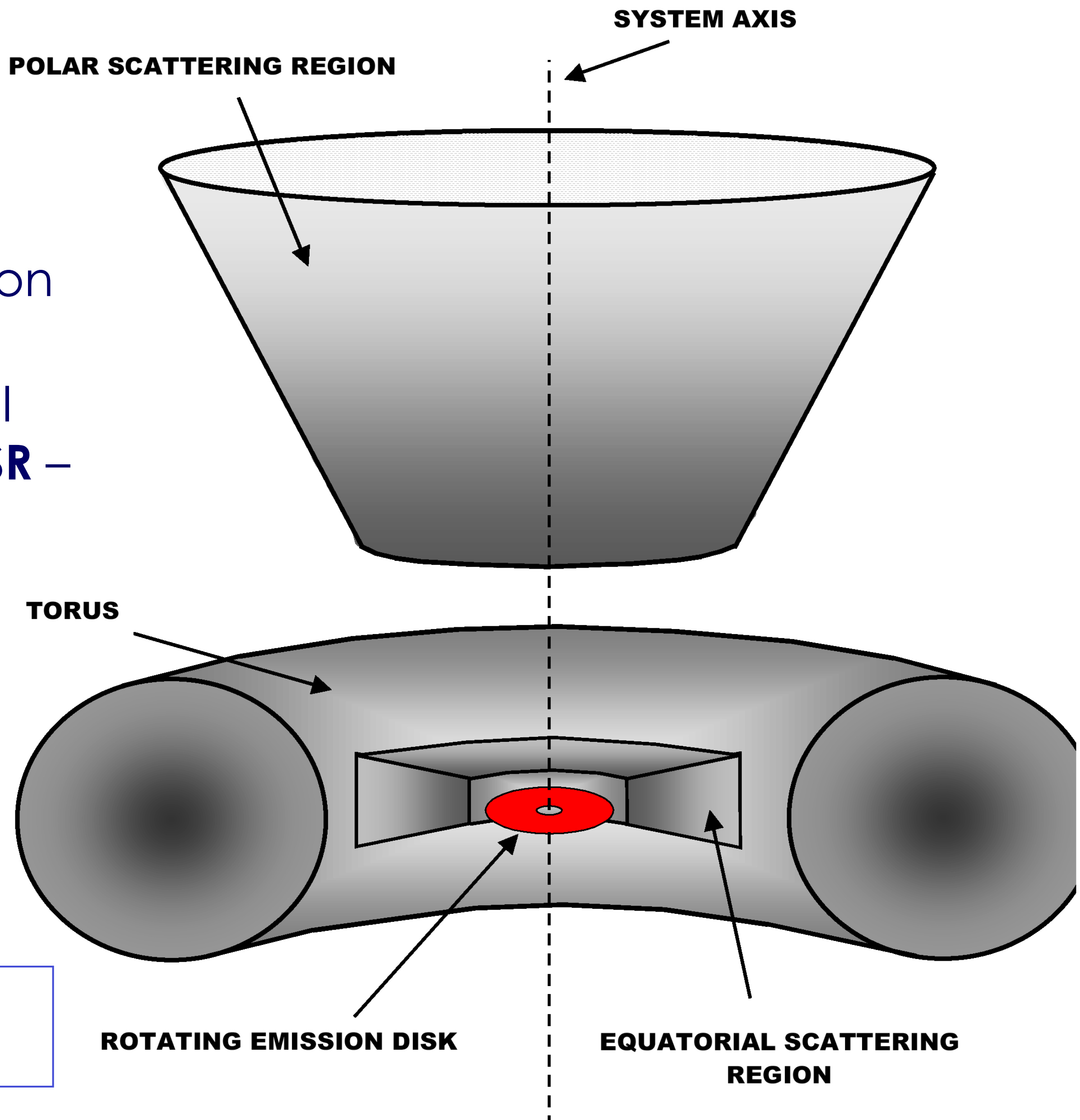
Smith et al. 2002; 2004; 2005 & refs therein

Generic scattering model for Seyferts

All Seyferts (non-Blazar AGN?) contain

- Polar scattering region (**PSR** – outside torus)
- Compact equatorial scattering region (**ESR** – within torus)

observed polarization properties determined by orientation



Young 2000, MNRAS 312, 567

Smith et al 2005, MNRAS, 359, 846

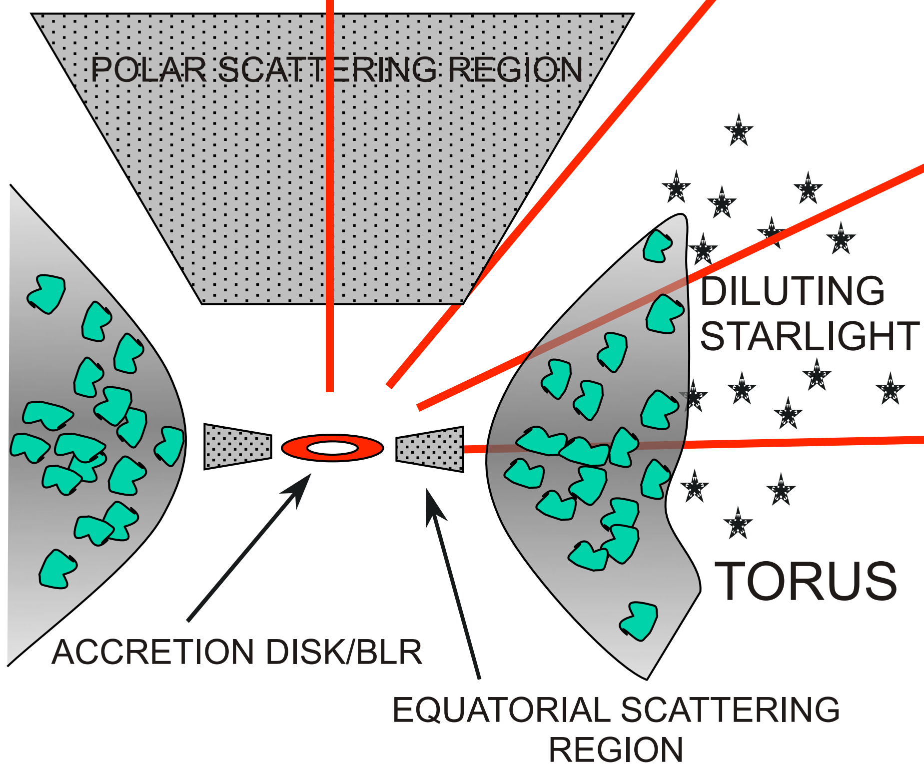
Unification of Seyfert Polarization Properties

i≈0°: null pol Sy1
circular symmetry
➔cancellation

0<i<45°: most Sy1
equatorial scattering dominates
PA || radio axis

i~45°: 30% of Sy 1
polar scattering dominates
PA ^ radio axis; direct l-o-s
subject to A_V~1

i>45°: Sy2
polar scattering dominates
PA ^ radio axis



Smith et al. 2004, MNRAS, 350, 140

NGC4151

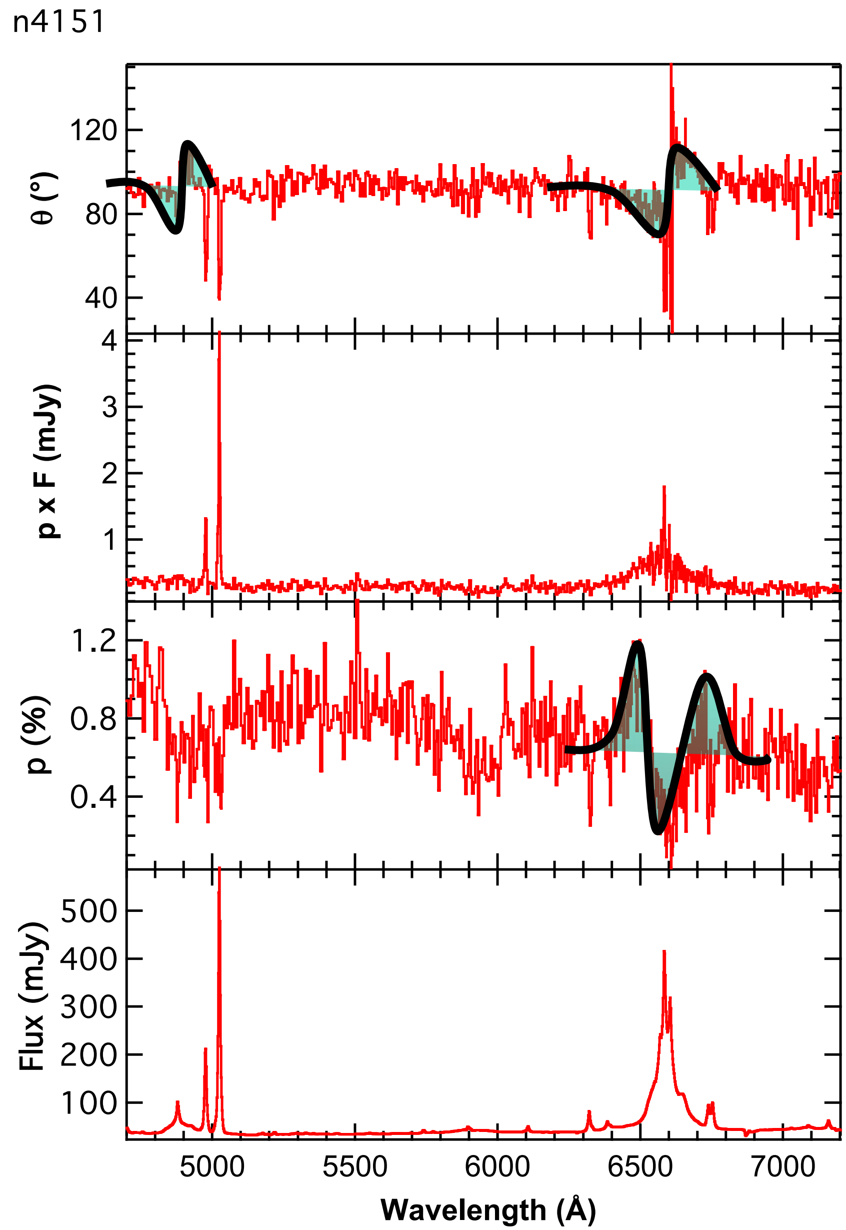
Equatorial scattering dominated
Evidence for polarization reverberation

Spectropolarimetry of NGC4151
S. Young, A. Robinson & D. J. Axon, in preparation

Signatures of equatorial scattering + rotation

Double PA rotation across broad Hα, Hβ

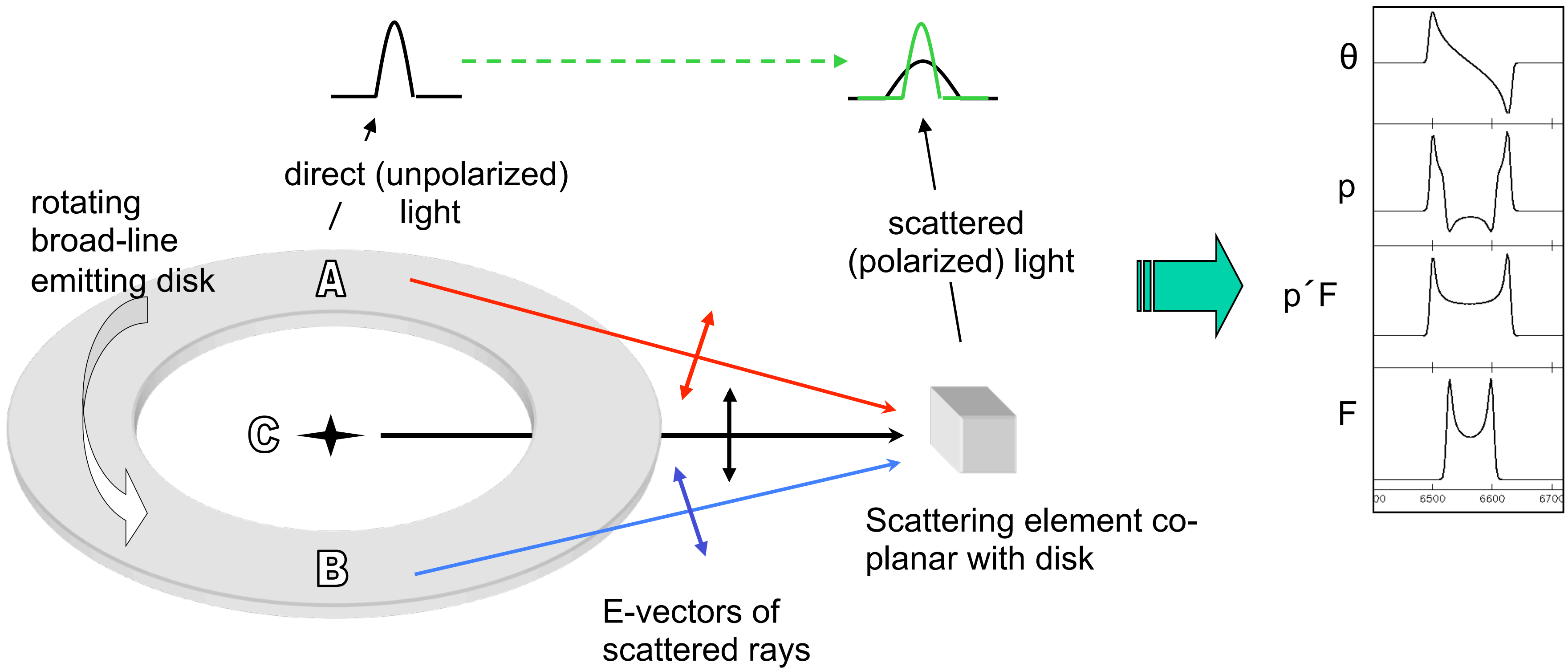
Peak-trough-peak variation in p



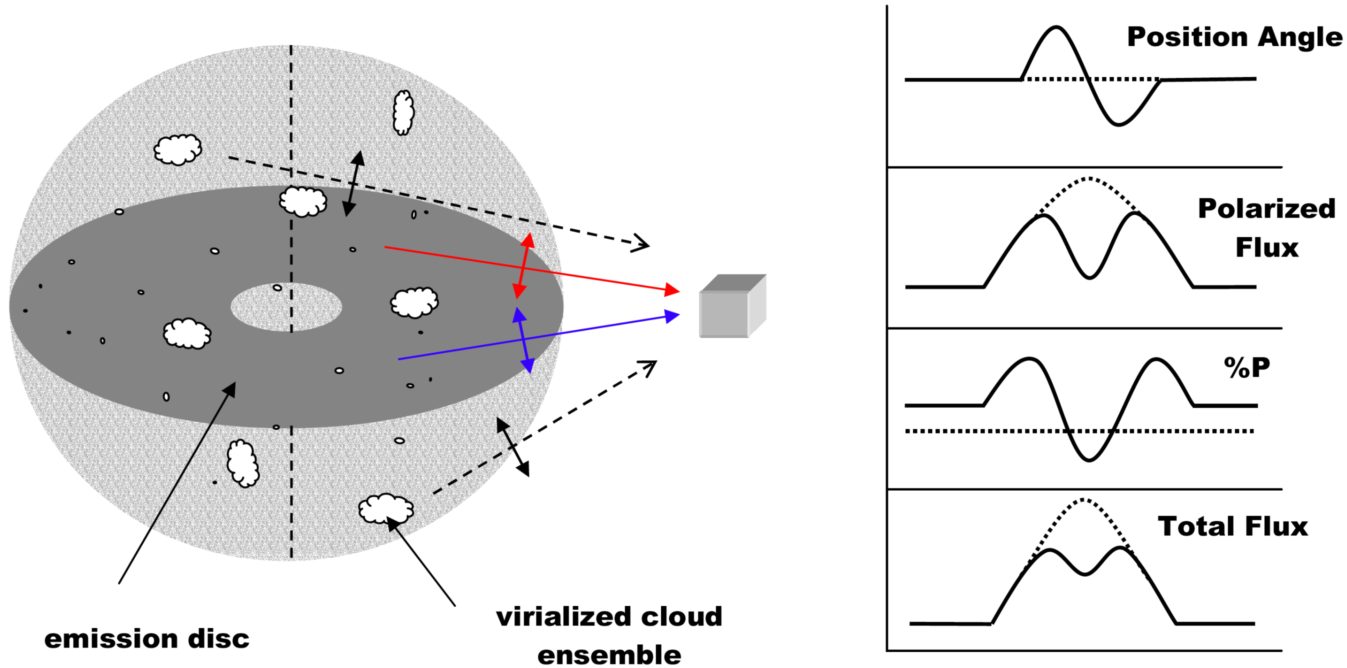
Emission Disk with near-field Equatorial Scattering

Explains variations in both p & θ

- Narrower directly viewed profile dilutes polarized profile
- Redshifted & blueshifted rays subtend different angles at scattering element



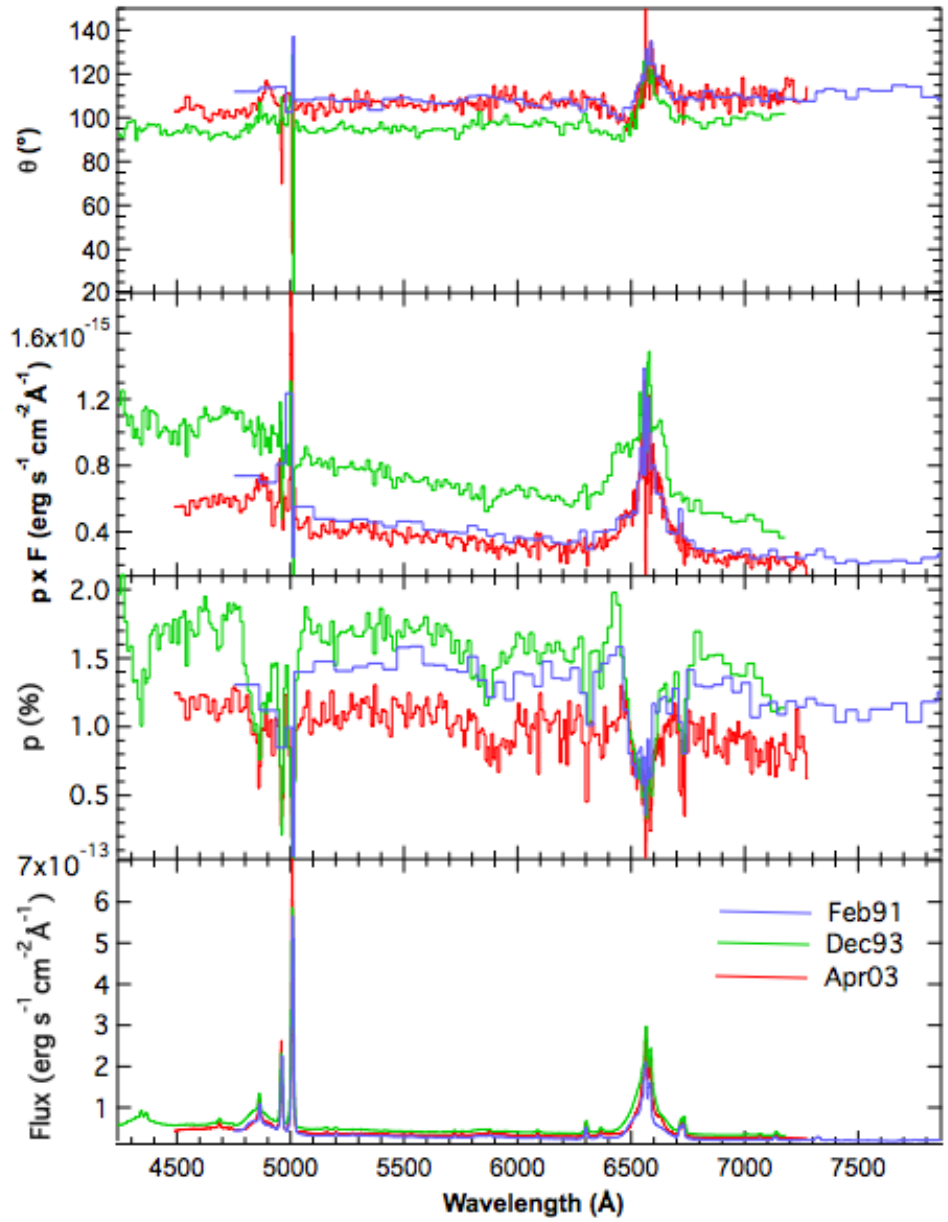
Question 1 : Why don't we see double-peaked lines?



- Balmer line emission does not come <u>only</u> from the disc – there is a second Balmer-line producing component of the BLR
- Example: spherical cloud ensemble with isotropic velocity distribution.
- No spatial discrimination between red- and blue-shifted emission ⇒ adds polarized flux at constant PA (dashed line) to characteristic spectra produced by equatorial scattering of emission disc (solid line).

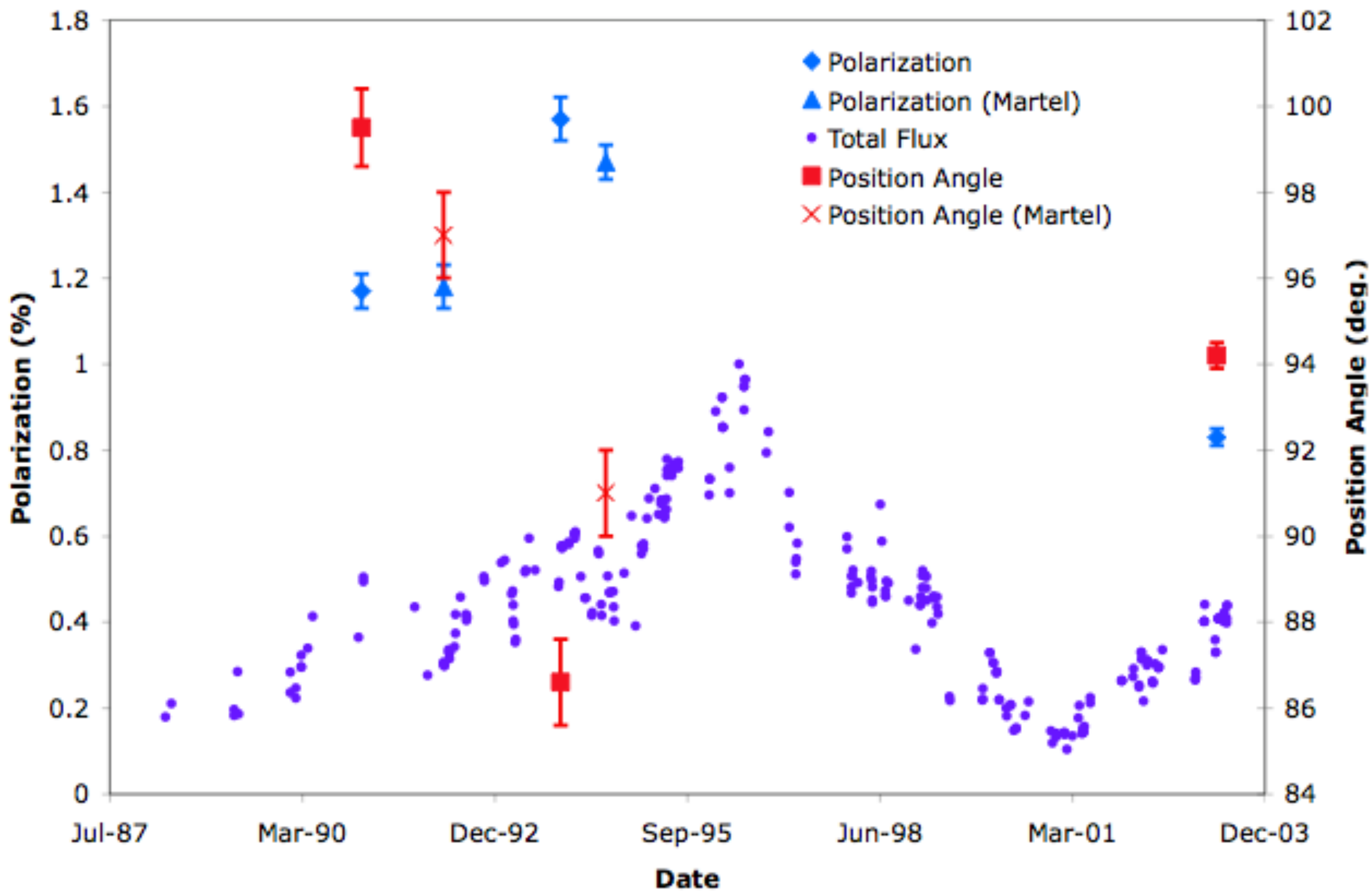
Observations

- Observed at 3 epochs
  - Feb 91
  - Dec 93
  - Apr 03
- Strong variability
  - Continuum
  - Broad-line fluxes & profiles
  - Percentage pol (p) and pol PA (θ)
- Shows features characteristic of equatorial scattering
- But…PA is
  - not parallel to system (radio) axis
  - variable



p, θ and continuum variability

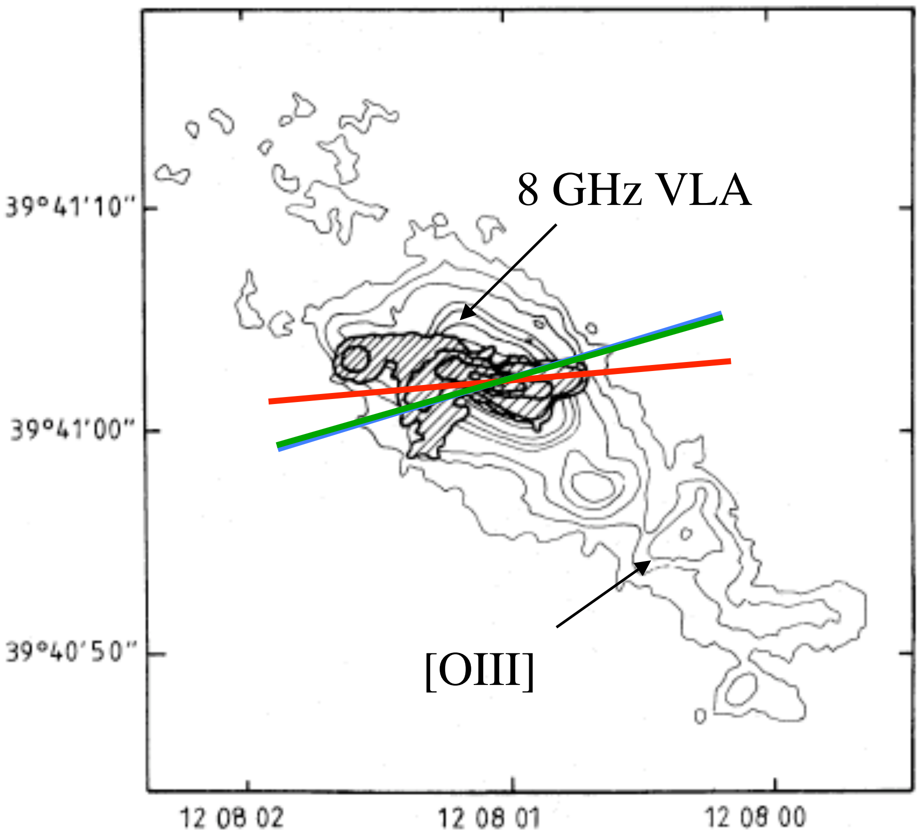
Young et al 2011
Martel 1998
Sergeev etal. 2001
Shapovalova et al. 2008

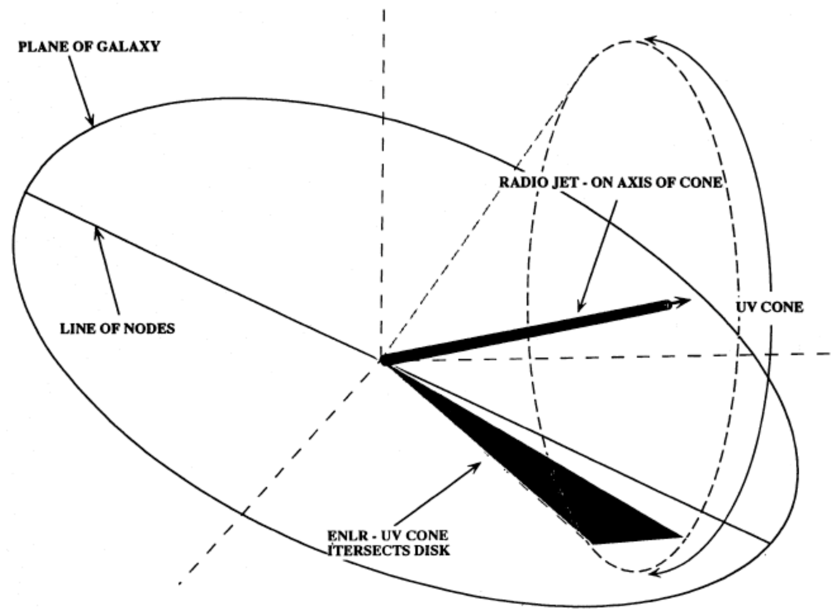


- Variability in average (p, θ)
  - p variations ➔ variations in flux incident on scattering region
  - θ variations ➔relative variations of 2 scattering regions

Polarization PA & AGN axis

- Polarization PA; radio axis and extended [OIII] emission all mislaligned



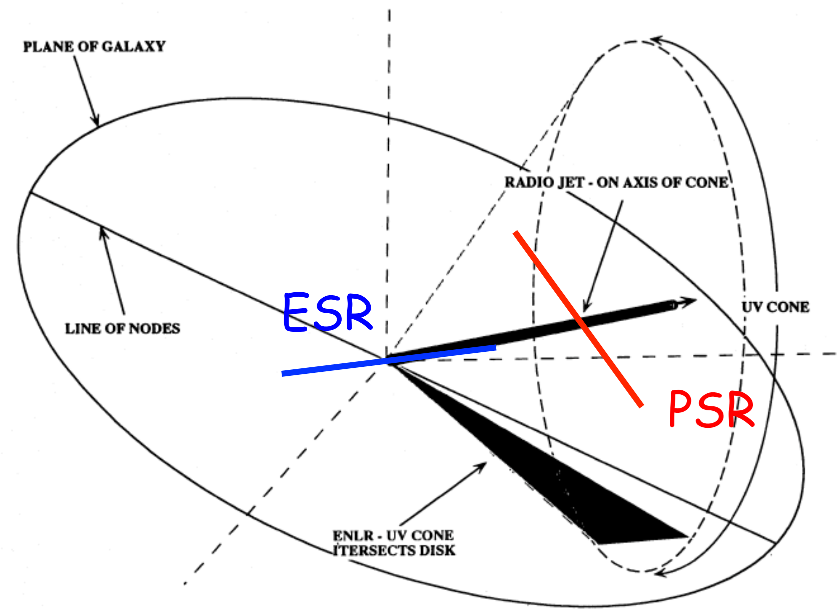


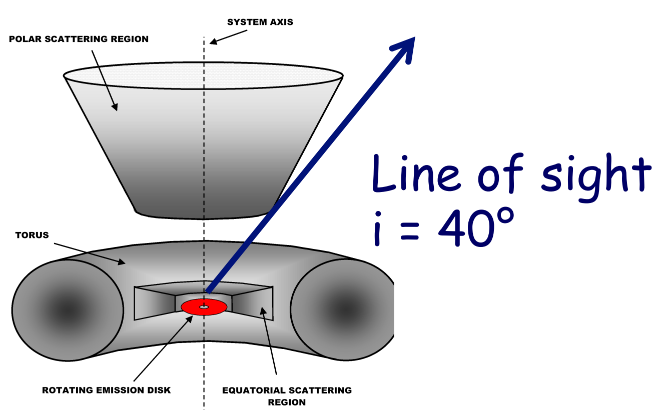
- Radio – [OIII] misaligment explained if torus tilted relative to galactic disk
- Pol PA misalignment (and variability) requires **additional** polarization component ➔ PSR

Pedlar et al 1993

Scattering model for NGC4151

- Equatorial + polar scattering
  - Electron scattering
  - PSR cone 1/2 angle ≈ 60°
- Two component BLR
  - "disk" ➔ Hα wings
  - "isotropic" ➔ Hα core
- AGN Continuum
  - Consistent with $f_\nu \propto \nu^{1/3}$



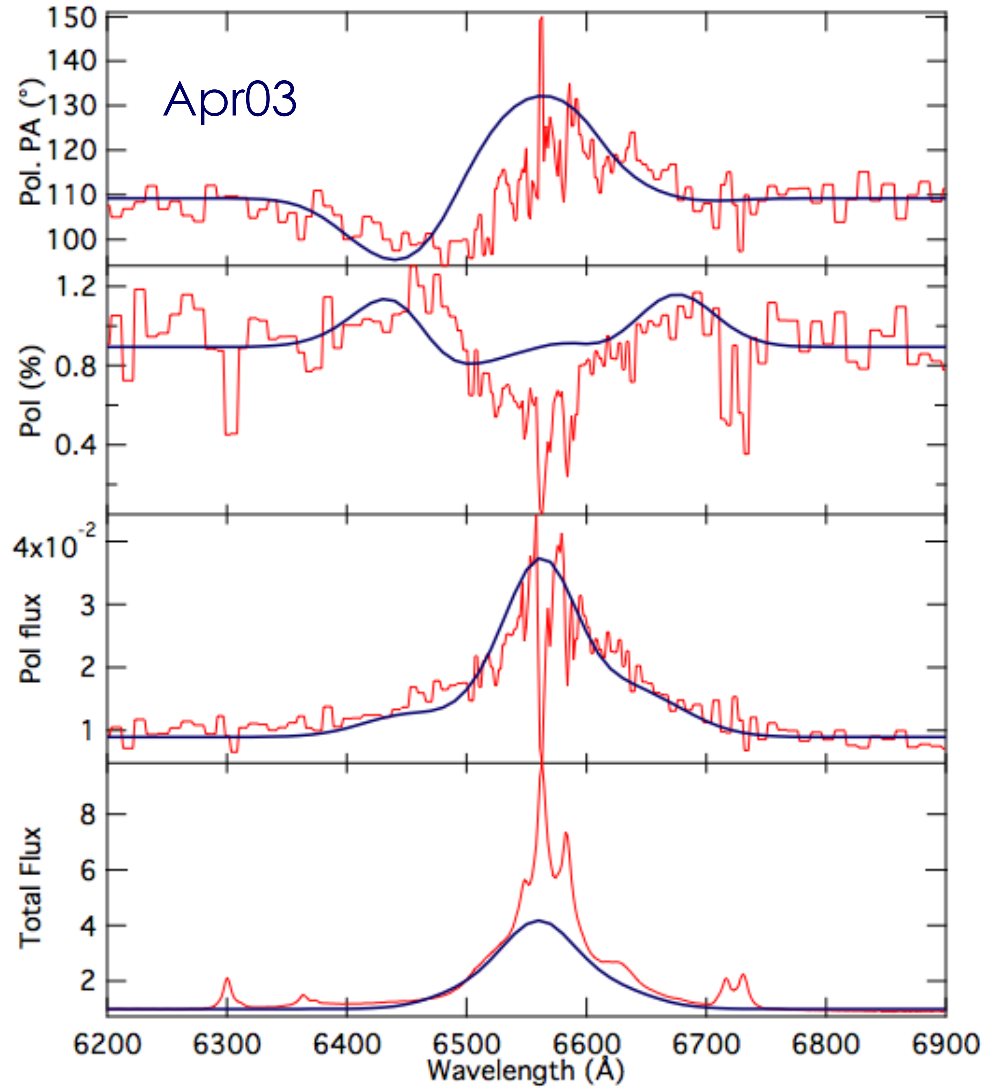


Note: PSR & ESR/disk axes mis-aligned by ≈30°

- Incident spectrum different for ESR & PSR:
  - Different viewing angle
  - Different temporal response (PSR extended ≥ 1 pc; ESR compact 0.01 – 0.03 pc)
- Relative strength of source components varied independently

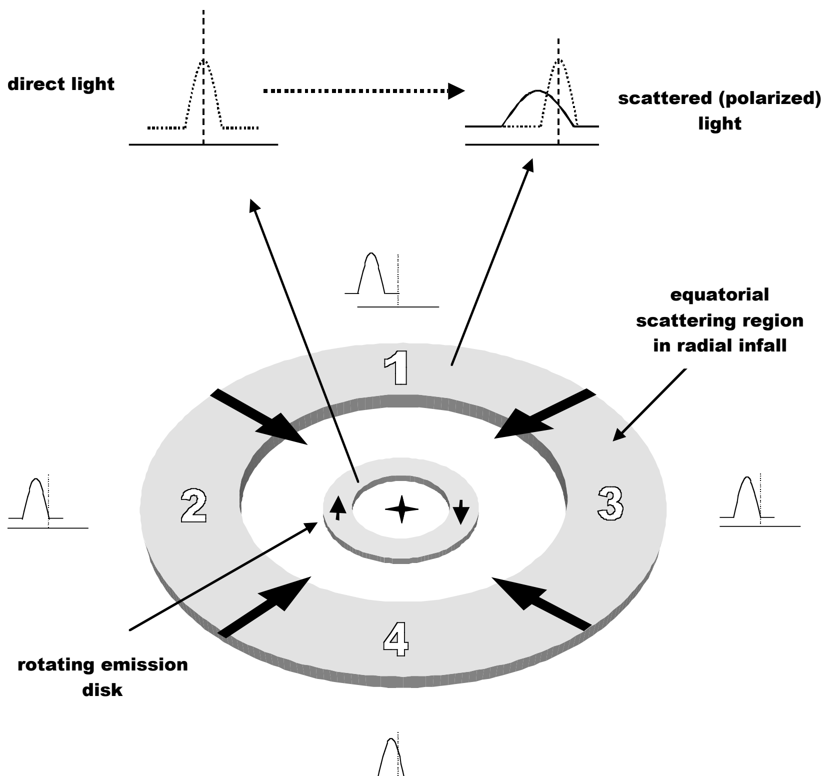
Scattering models – results

- Scattering geometry consistent with system axis & ionization cone orientation deduced from radio/extended line emission
- PSR "sees" little change in continuum, "disk" component, systematic increase in core component
- ESR "sees" large changes in continuum, "disk" component; not sensitive to core component
- ESR requires inflow velocity ≈ 900 km s^{-1}

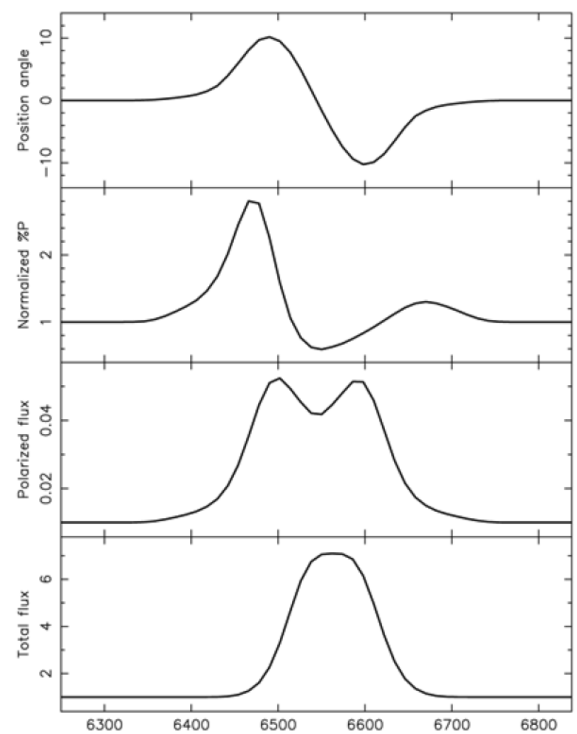


Kinematics of the Equatorial Scattering Region

- Bulk radial motions appear as asymmetries in polarization spectrum
  - inflow produces blue asymmetry

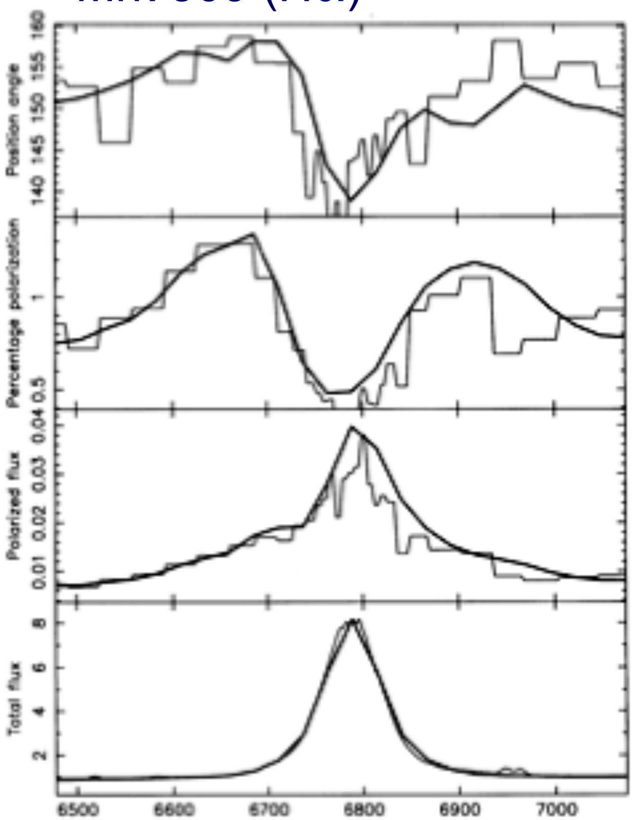


- Blue asymmetries are common in objects with equatorial scattering signatures

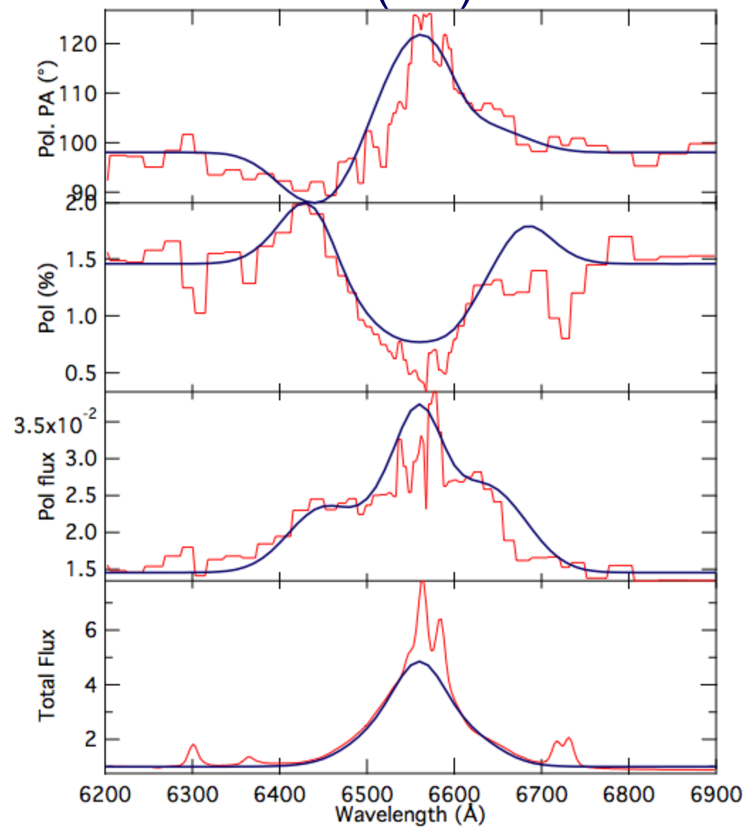


Accretion flows in Mrk 509 & NGC4151?

Mrk 509 (Hα)



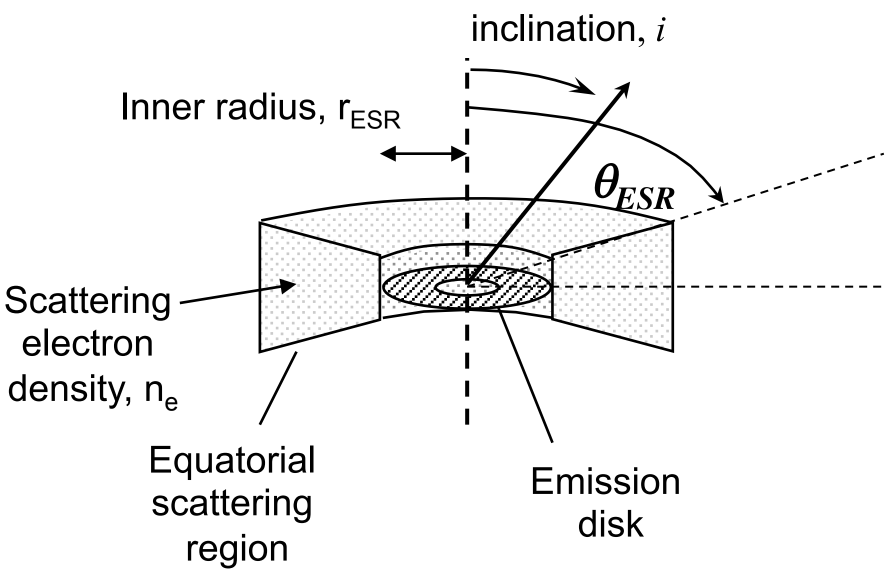
NGC 4151 (Hα)



Scattering models ➔ equatorial scattering region has bulk inward radial velocity ~ 900 km s^{-1}

Scattering electrons part of accretion flow?

Estimating mass inflow rates



Observed pol spectrum also constrains scatterer density, geometrical parameters

mass inflow rates	~ 0.7 $M_\odot$ yr^{-1} for Mrk 509
(ionized gas)	~ 0.2 $M_\odot$ yr^{-1} for NGC 4151

- Mass inflow through ESR exceeds accretion rate in both objects $\dot{m}_{acc} \sim \frac{L_{Bol}}{\eta c^2}$

  Most of mass accreted through ESR gets "blown out" again by disk wind

  NGC4151: mass outflow rate through NLR ~ 0.2 M⊙ yr-1 (Crenshaw & Kraemer 2007)

MRK 231

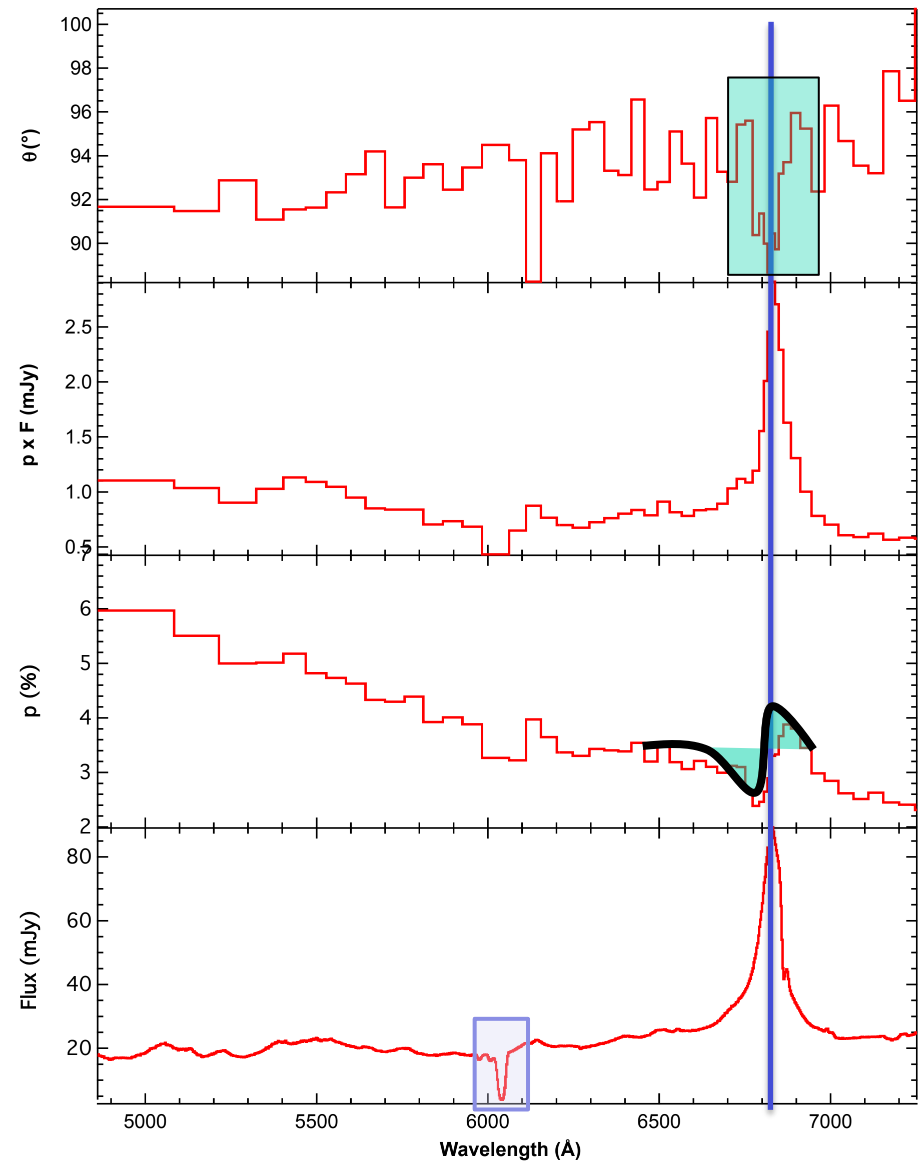
Polar scattering dominated
Evidence for outflow

Spectropolarimetry of Mrk231
S. Young, A. Robinson & D. J. Axon, in preparation

Mrk 231 observations

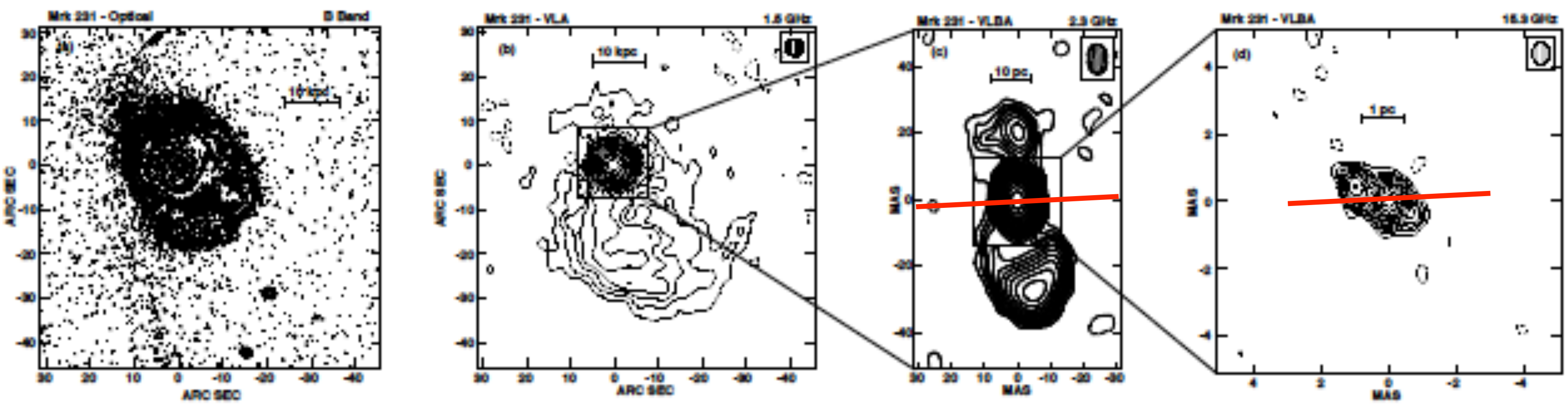
- Well known ULIRG with Sy1/LoBAL nucleus
  - Blueshifted Na I (or He I?) absorbtion ➔ BAL outflow ~ 5-8000 km/s
- Optical polarization generally characteristic of polar scattering
  - Hα redshifted in polarized flux ➔ outflow
- But…
  - weak wavelength dependence of continuum PA
  - PA dip at Hα

indicates second source of polarization



Polarization PA & radio axis

Average polarization PA ≈ 93°

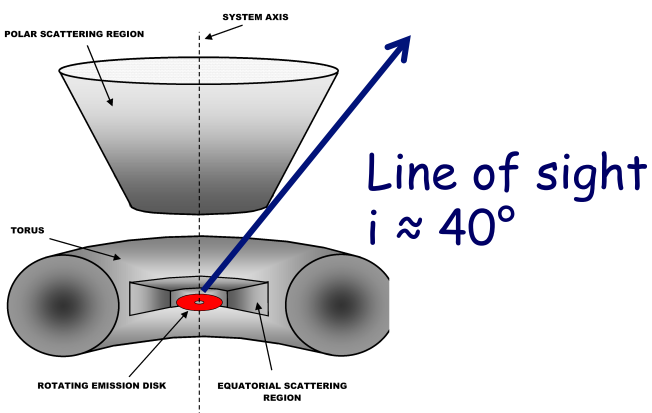


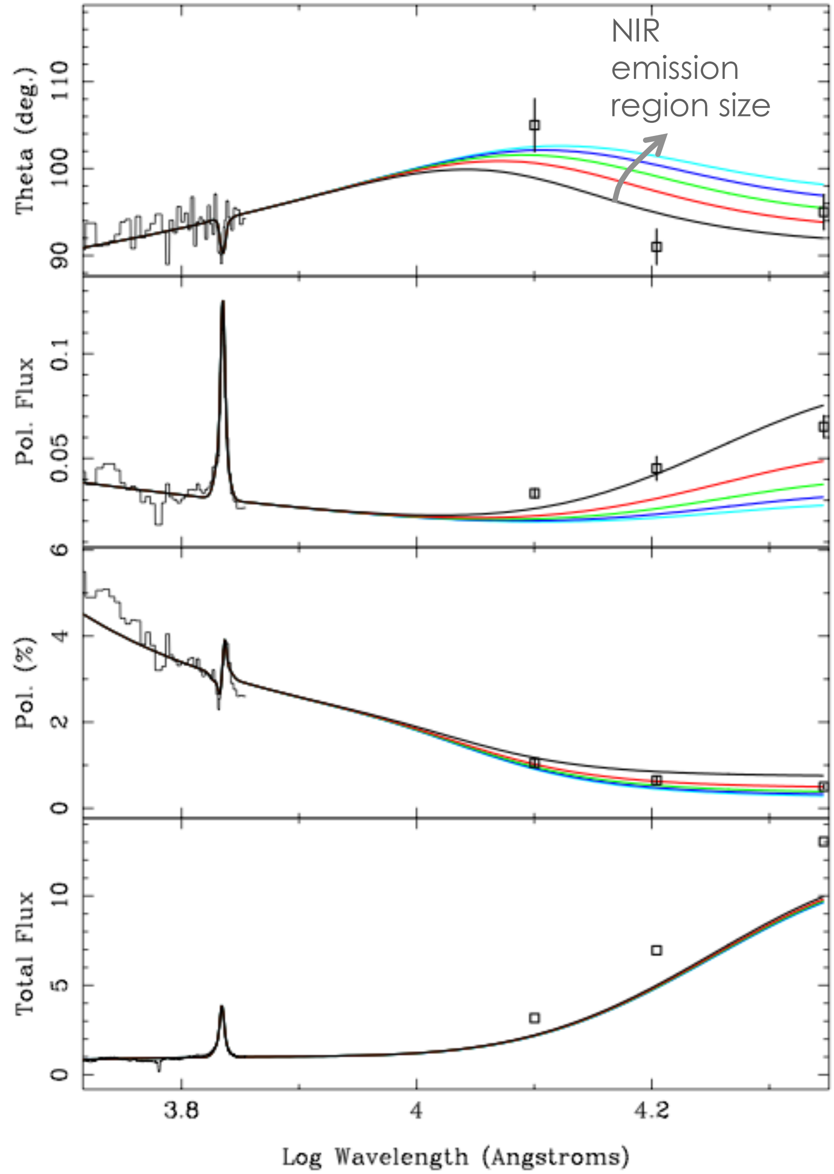
Ulvestad et al. 1989

- VLBA observations:
  - ~40 pc triple oriented N-S
  - Core component resolves into ~2 pc "triple" in PA ≈ 60°
- Average polarization PA orthogonal to 40 pc radio axis
  - As expected if PSR cone aligned with <u>this</u> axis
  - But contribution from reddened ESR also needed to explain PA variations

Mrk 231 scattering model

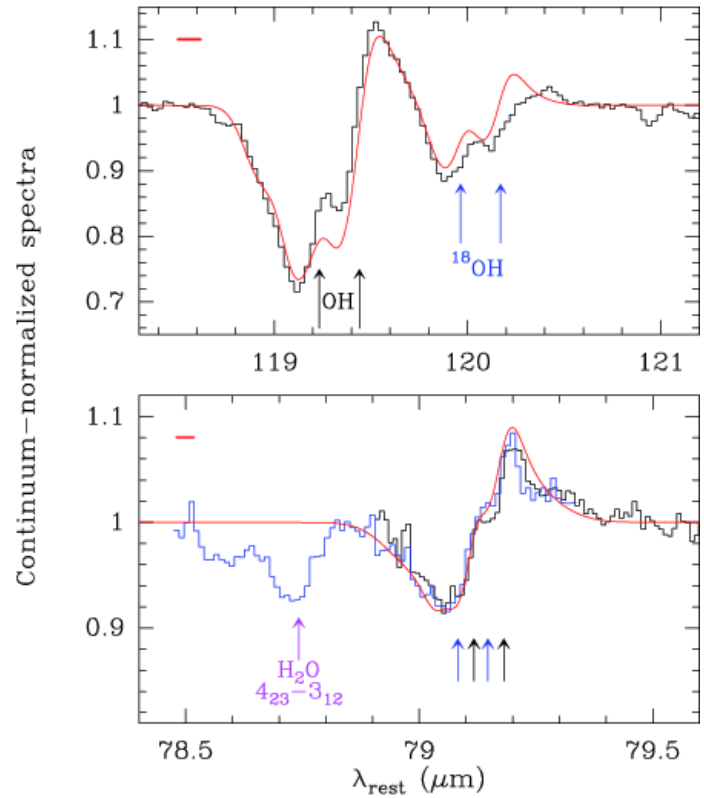
- Two component BLR:
  - "disk" ➔ Ha wings
  - "isotropic" ➔ Ha core
- Toroidal dust emission T≈1200 K
- Instrinsic AGN continuum with $f_\nu \propto \nu^{1/3}$
- Equatorial + polar scattering
  - PSR cone with 1/2 angle ≈ 40° & outflow velocity ≈1100 km s^{-1}
  - ESR & direct view reddened by A_V ~ 1.3 mag





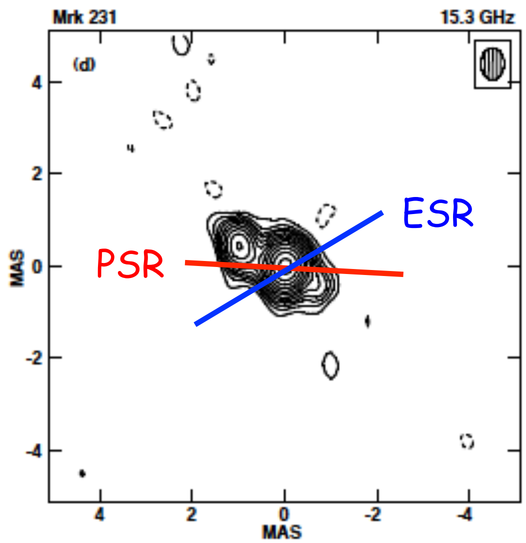
Mass outflow rate

- Redshifted Hα in polarized flux ➔ PSR outflow speed ~1100 km/s
- For inferred geometry & number density, mass o/f rate ~10 $M_\odot$/yr
- PSR outflow speed < BAL speed
- …but consistent with recently detected ~1400 km/s molecular outflow



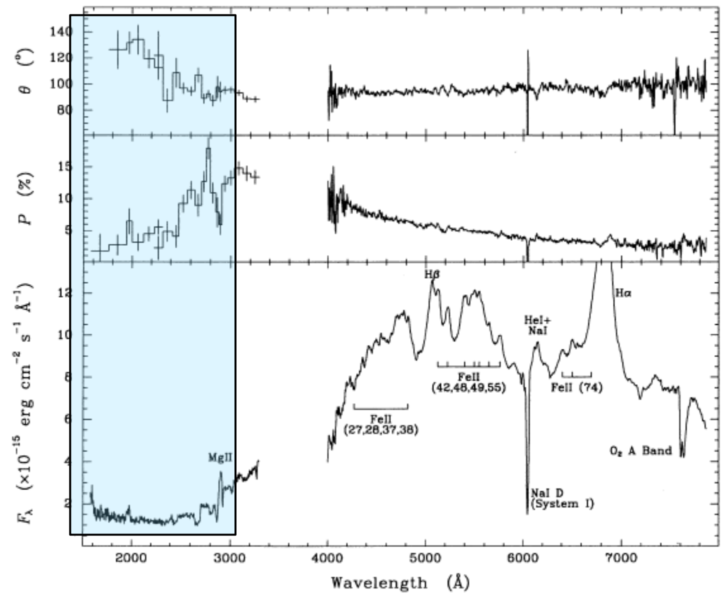
Fischer et al. 2010

Unresolved problems



- Parsec-scale radio source
  - Misaligned with 40 pc axis & PSR pol. PA
  - …but orthogonal to ESR polarization PA
- If this is current system axis, requires different geometry for ESR
  - could be a disk wind (see PG1700+643)

Smith et al. 1987



- UV polarization
  - Polarization peaks at p ≈15% but then drops for λ<3000Å
  - Accompanied by change in PA
- Requires onset of new polarization component in UV
  - Hot stars? But must still be polarized.
  - Intrinsic polarization of accretion disk?

PG 1700+643

BAL Quasar

Evidence for rotation & outflow

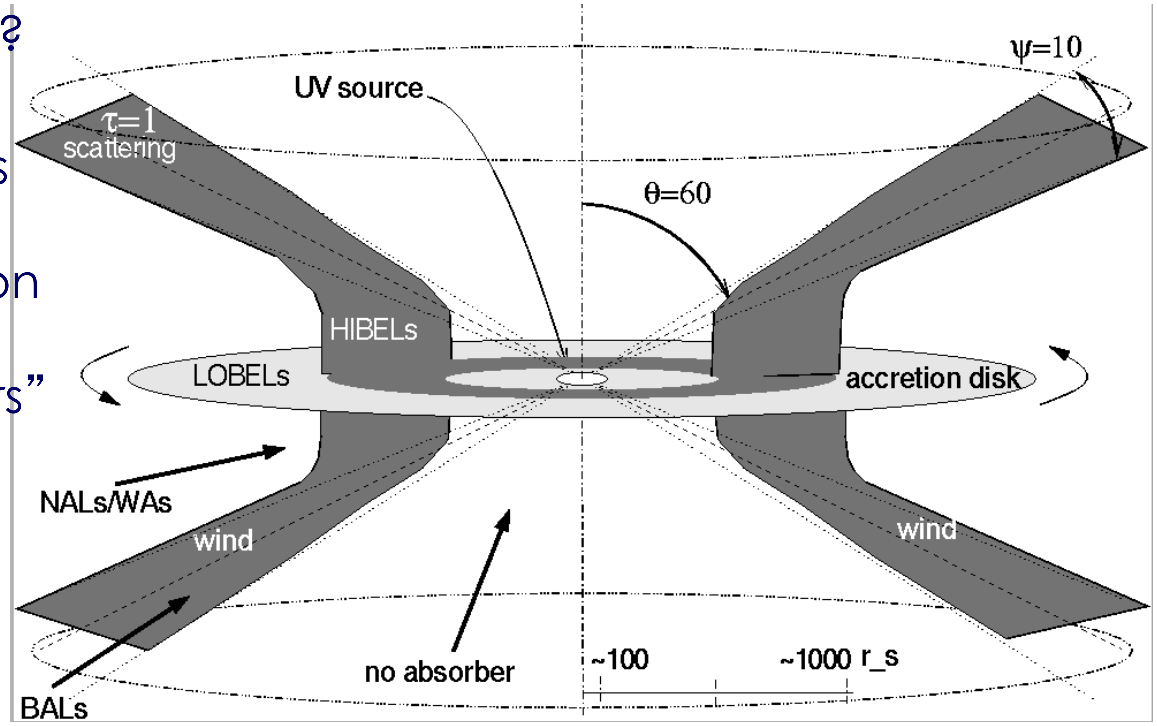
The rotating wind of the quasar PG 1700+518

S. Young[1,2], D. J. Axon[1,2], A. Robinson[1,2], J. H. Hough[2] & J. E. Smith[2]

Nature, Sept 2007

Quasar disk winds

- ***Winds*** launched from accretion disk thought to be key components of AGN
- Physics
  - Carry away disk angular momentum?
  - Significant mechanical luminosity?
  - Feedback to host ISM?
- Phenomenology
  - Broad absorption lines (BAL's)
  - Narrow (UV) absorption lines
  - X-ray "warm absorbers"
  - High ionization broad emission lines?
  - Torus?



e.g. Elvis 2000, 2003

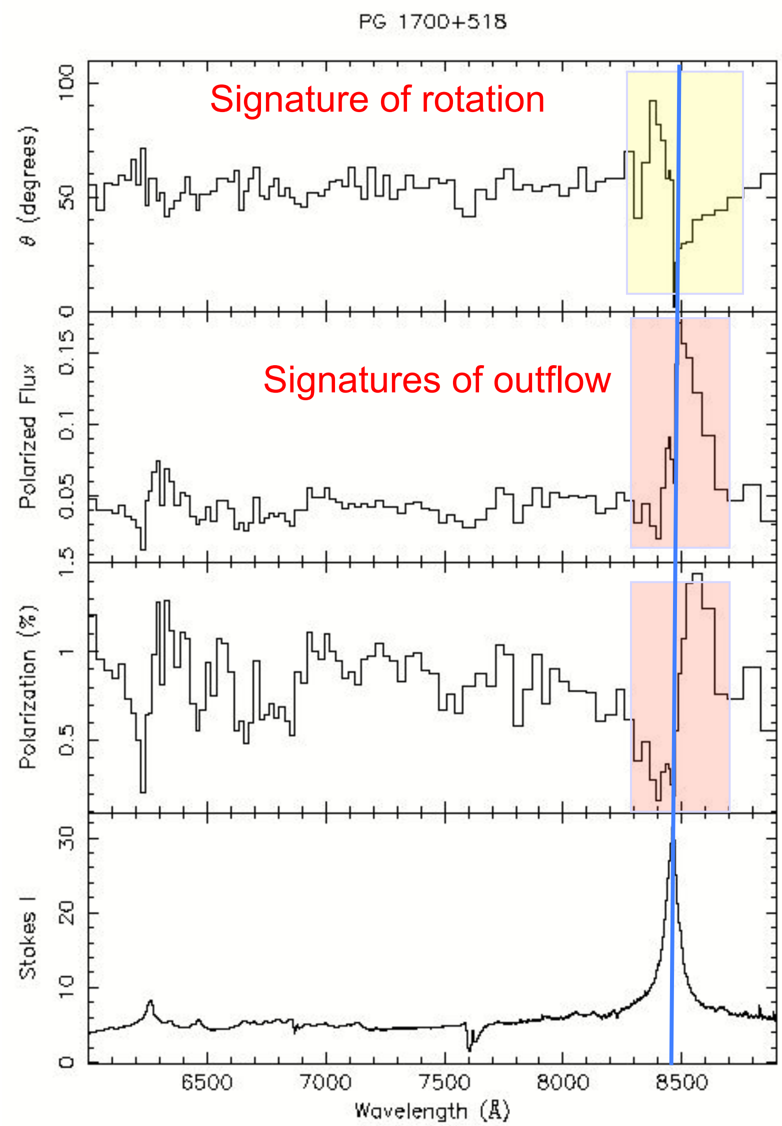
Broad Absorption Line QS0 1700+518

- Low redshift (z=0.292), so Hα accessible in optical

polarization PA exhibits behavior similar to that seen in Seyfert 1 galaxies in which equatorial scattering dominates polarization

however, scattered line profile, seen in polarized flux, redshifted by ~4000 km s^{-1} relative to its total flux counterpart

- Implication: velocity field of scattering medium includes both rotational and outflow components ➔ outflow from a rotating disk — a disk wind.



First detection of a quasar disk-wind

- Polarization spectrum shows signatures of **both outflow and rotation** at speeds expected for gas orbiting a $10^9\ M_\odot$ black hole at the inferred wind launch radius

$$v_{W,z} \sim v_{W,\phi} \sim v_K \sim 4000\ \mathrm{km\ s^{-1}}$$

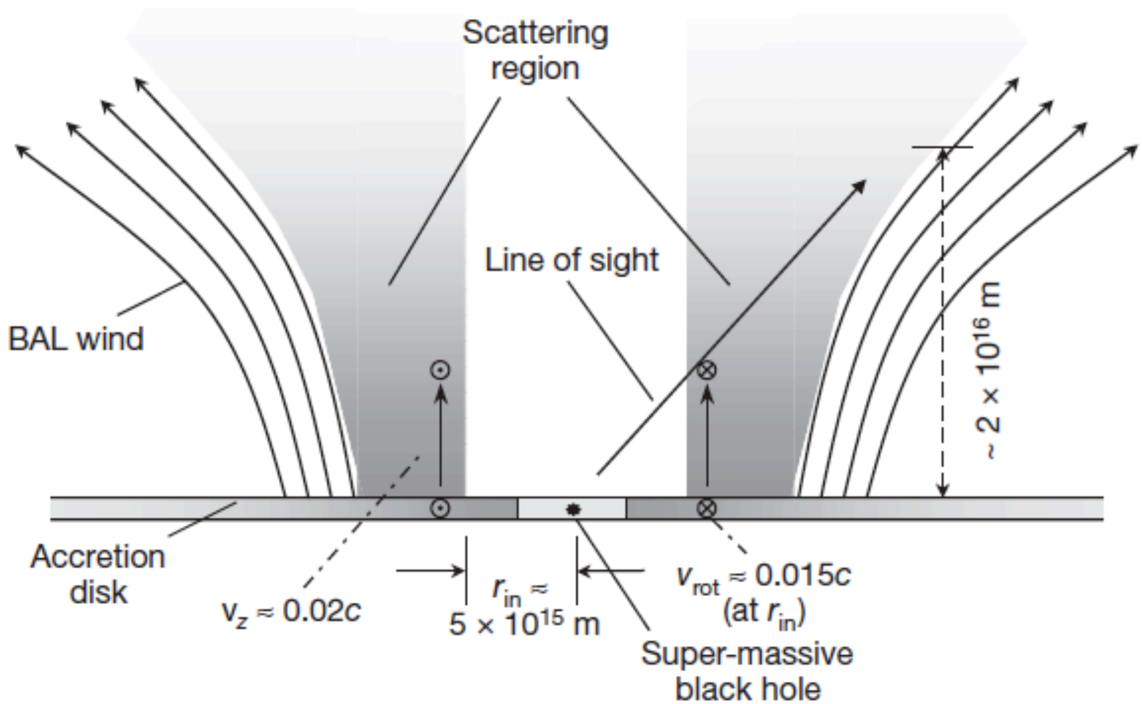
Mass outflow rate (scattering region only)

$$\dot{m}_W \sim 10\ \ M_\odot/\mathrm{yr}$$

Accretion rate

$$\dot{m}(L_{Bol}) \sim 7\ \ M_\odot/\mathrm{yr}$$

- First **direct observational evidence** that quasar winds are launched from the accretion disk



The rotating wind of the quasar PG 1700+518

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Nature, Sept 2007

NARROW LINE SEYFERT 1'S

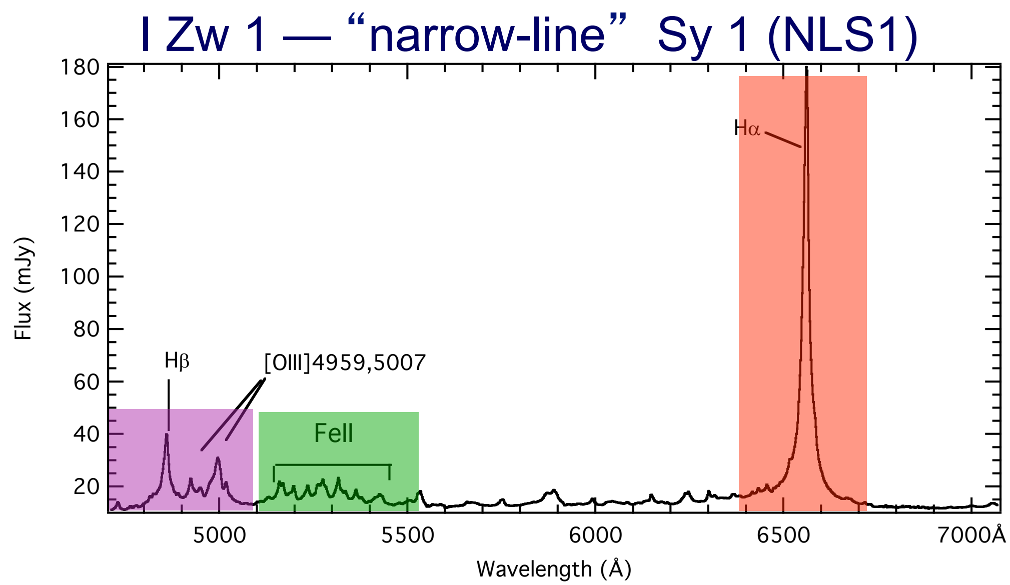
No preferred orientation

Spectropolarimetry of Narrow-Line Seyfert 1 Galaxies a question of orientation?

A. Robinson, S. Young, D. J. Axon & J. E. Smith
In preparation

Narrow Line Seyfert 1's (NLS1)

- Hα, Hβ FWHM < 2000 km/s
- Strong FeII emission
- Relatively weak narrow lines ([OIII]/Hβ < 5)
- Steep soft X-ray spectra
  - Often with blueshifted "warm absorbers" ➔ gas outflowing at speeds ~1000 km/s



Small FWHM but "normal" luminosity suggests NLS1 are physically defined by:

- Low black hole mass (factor ~10 lower than BLS1)
- L_{AGN}/L_E ➔ 1

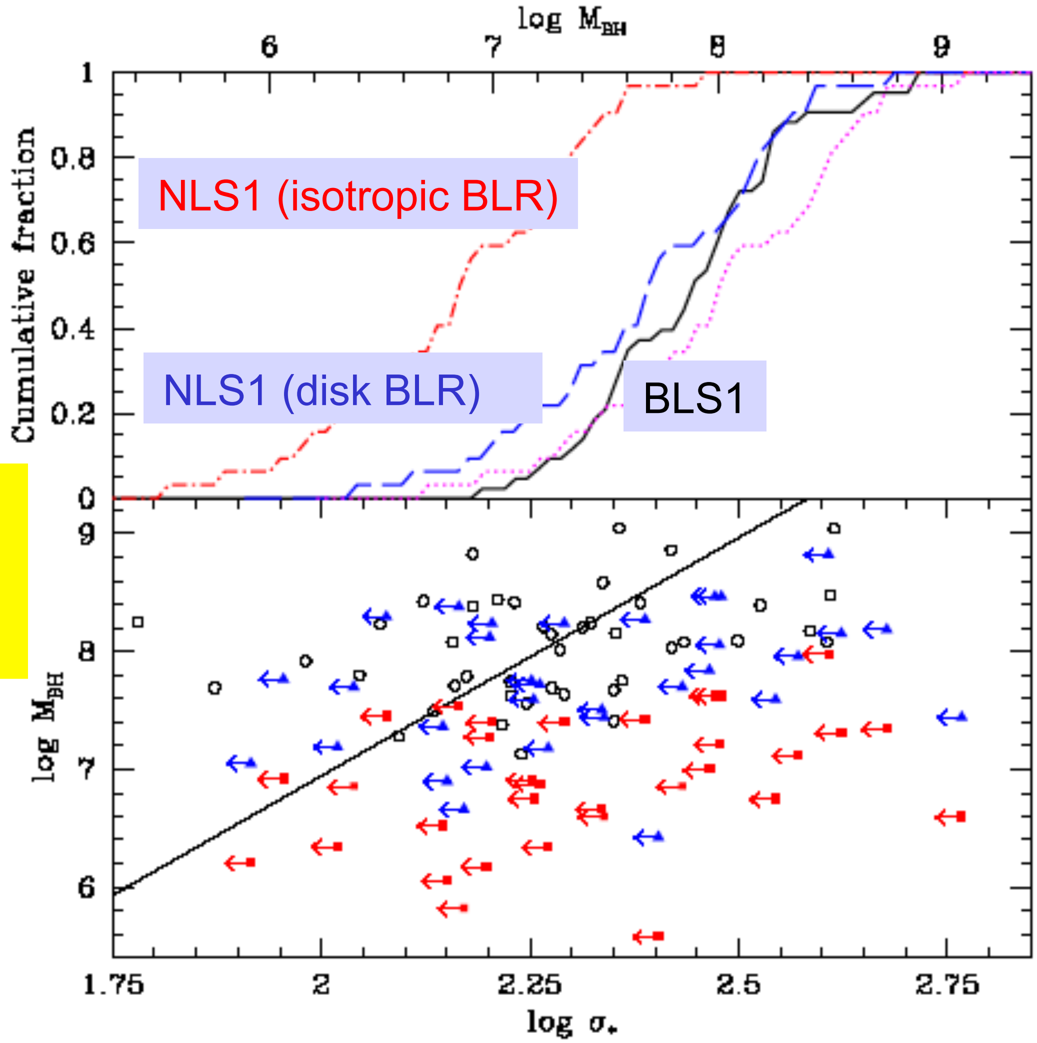
➔ rapid SMBH growth & radiation pressure driven winds

Or are NLS1 merely viewed "face on"?

- What if BLR has a disk geometry?
- Are NLS1 simply "normal" Sy 1's viewed close to the disk axis?

If so, observed FWHM underestimates BH mass

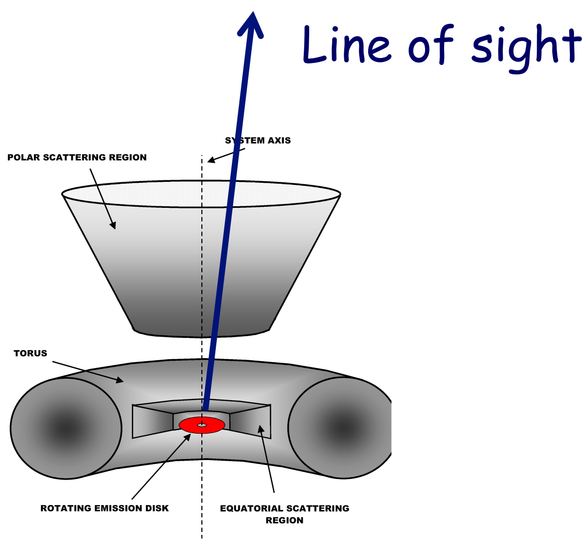
- Anomalous NLS1 SMBH masses & Eddington ratios can be explained if average inclination is ~ 15°
  - Decarli et al. 2008

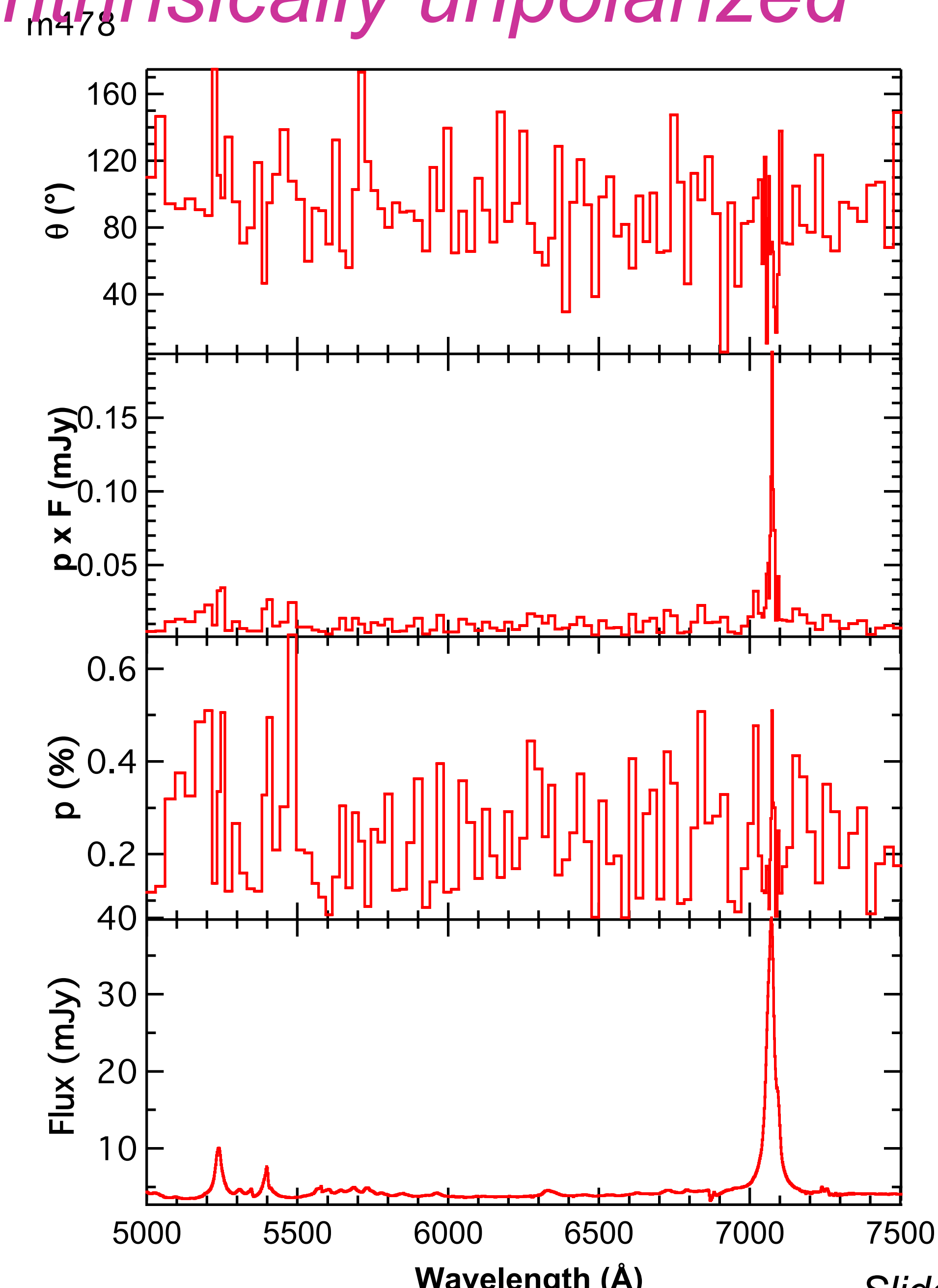


Decarli et al. 2008, MNRAS, 386, L15

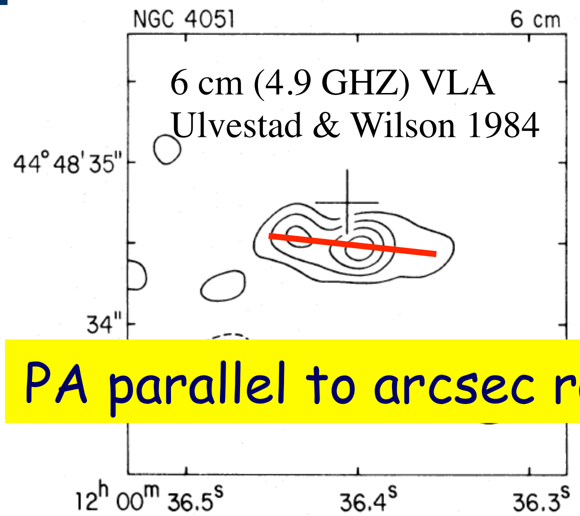
Mrk 478 – intrinsically unpolarized

- Low measured polarization Consistent with zero intrinsic polarization
- ➔ Viewed close to system axis





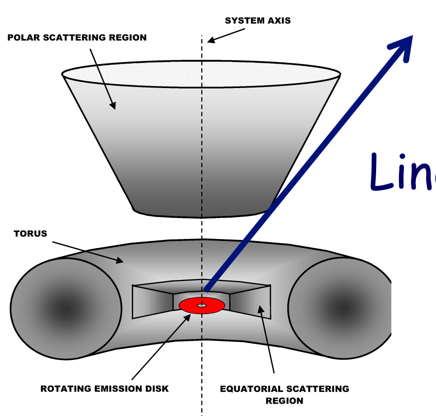
NGC4051 — equatorial scattering

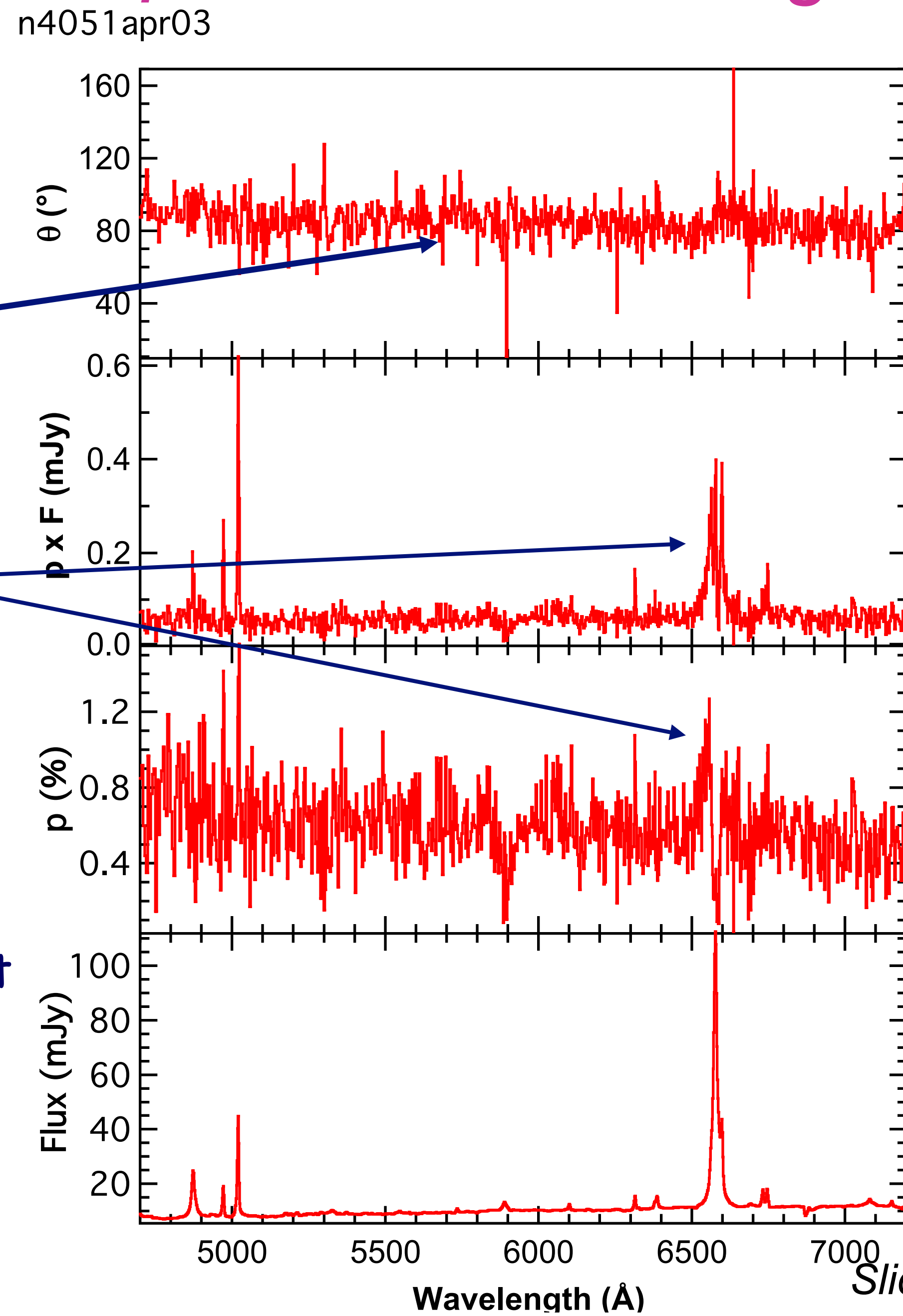


PA parallel to arcsec radio jet

Hα broader in polarized flux

- If equatorial scattering, viewed at intermediate angle



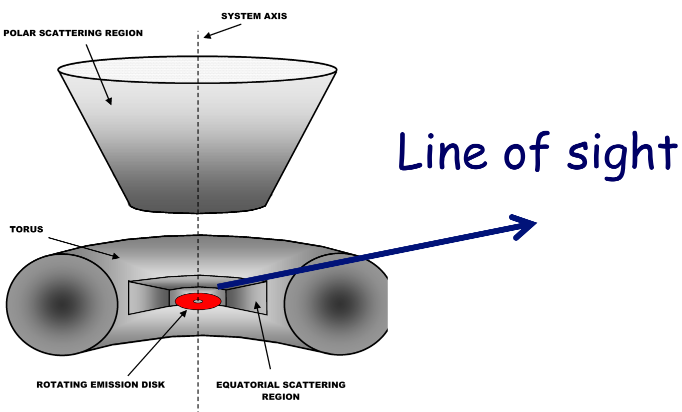


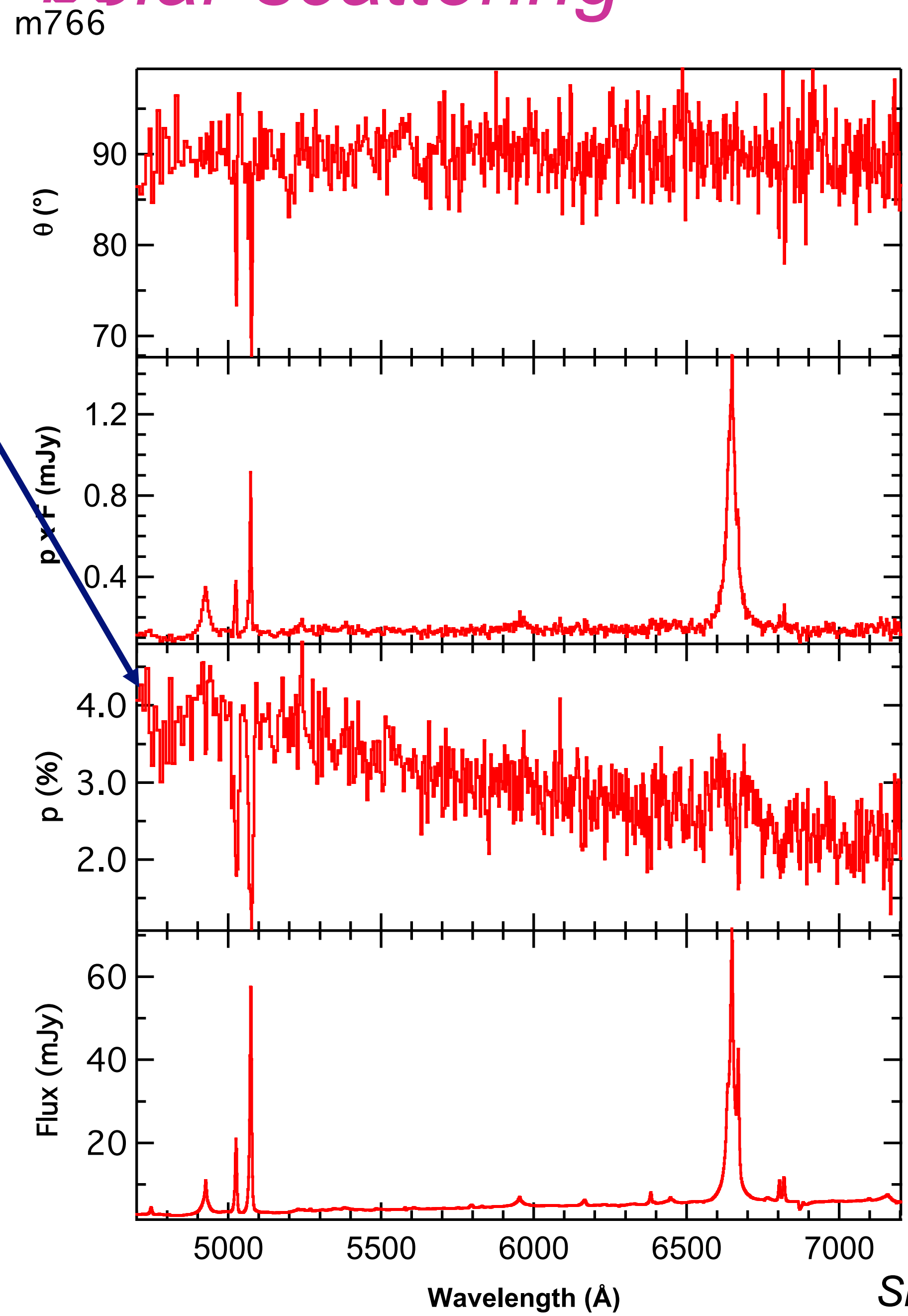
Mrk 766 — polar scattering

Cont. pol. increases to blue; local peaks at broad lines

4/16 NLS1 show polar scattering characteristics, same fraction as in general Sy 1 sample

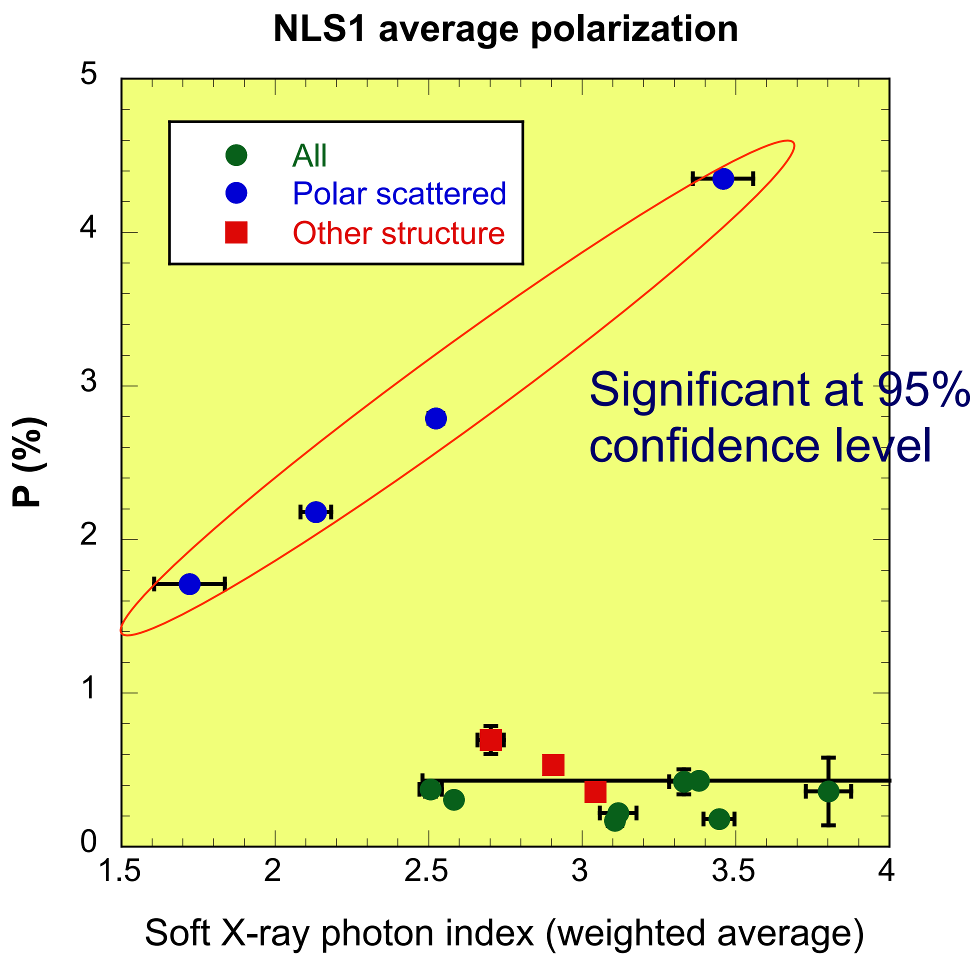
Viewed at large inclination to torus axis





Average Polarization vs X-ray slope

- In polar scattered NLS1 <P> seems to be related to slope of soft X-ray (0.1–2 keV) spectrum
- But origin of soft X-ray excess in Seyferts is disputed…
- Trend suggests that X-ray slope steepens as density/ covering fraction of (cold) scattering material increases
- Favours “reprocessing” models for soft X-ray excess



Summary

Spectropolarimetry of broad-line AGN provides a unique probe of the kinematics of circum-nuclear gas flows, even inside the torus

- Observations indicate 2 major scattering regions
  - Extended polar region
  - Compact (within torus) equatorial region
- Direct evidence that BLR has a **rotating disk-like component**
- Objects with dominant equatorial (NGC4151) or polar (Mrk231) scattering also require the "other" component
- Blue shifted Doppler ghosts in ESR polarized light probe **accretion on sub-pc (torus→BLR) scales**
- Red shifted Doppler ghosts in PSR polarized light probe **outflows**
- Rotating outflow detected in low-z BAL QSO — **direct observational evidence for winds launched from accretion disks**
- NLS1 are **not** viewed at preferred orientation (ie pole-on)