Active Galactic Nuclei in polarized light

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Special Astrophysical Observatory of RAS

12SCSLSA June 4, 2019
Special session

Supported by the Russian Science Foundation: project no. 17-12-01335.

Polarization!

Why?

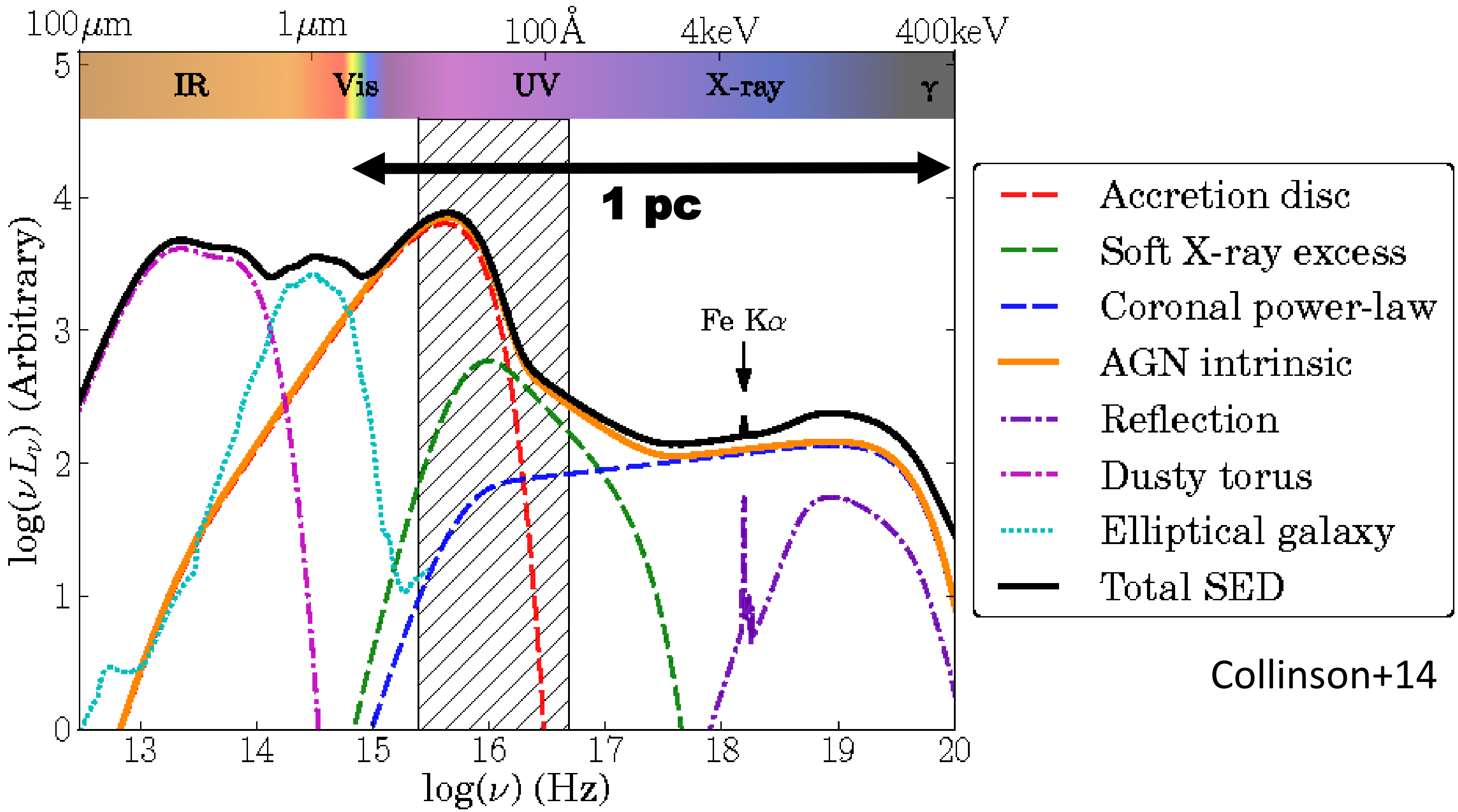
How to?

What?

Observational properties of AGN

1. Non-thermal emission with radio, IR, UV and X-ray excess.

The emission is concentrated in <1 pc region and contains up to 90% of the galaxy luminosity

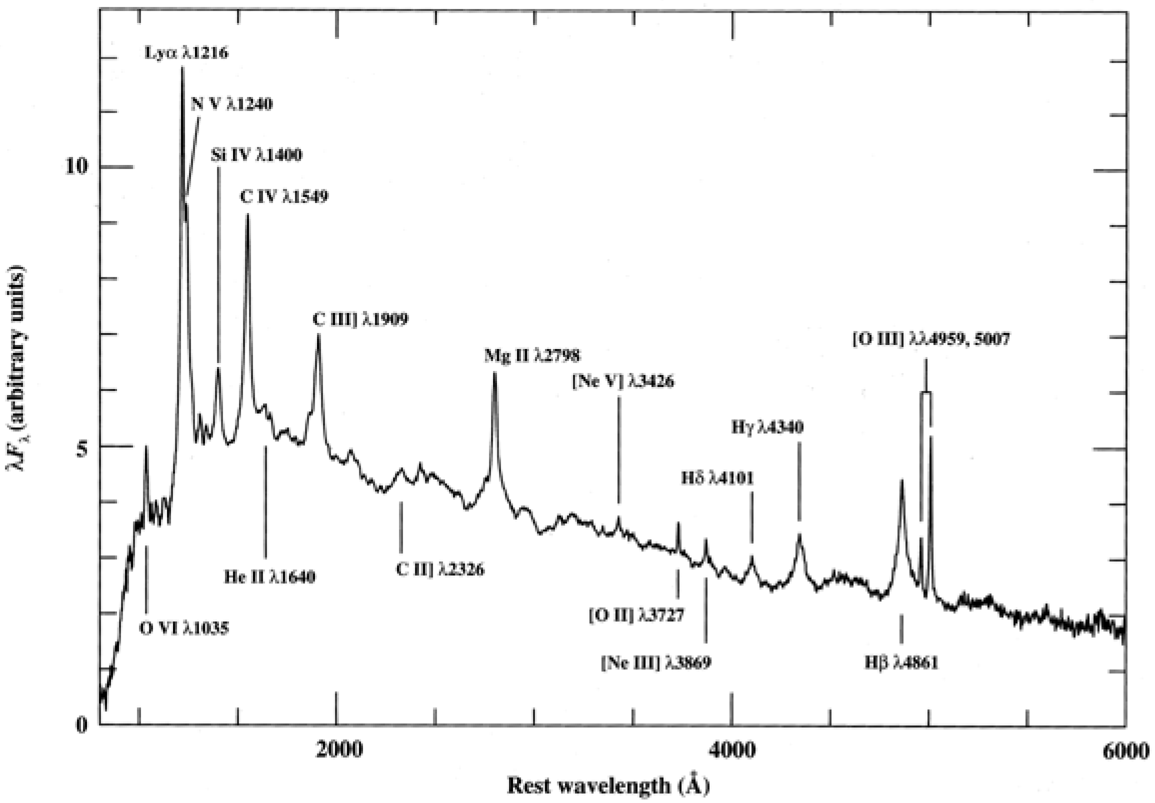


Collinson+14

Observational properties of AGN

2. Emission lines.

Broad emission lines – up to 10.000 km/s (Balmer, MgII, OI, NII…) + highly ionized narrow lines – up to 1000 km/s ([OII], [OIII]…)



Observational properties of AGN

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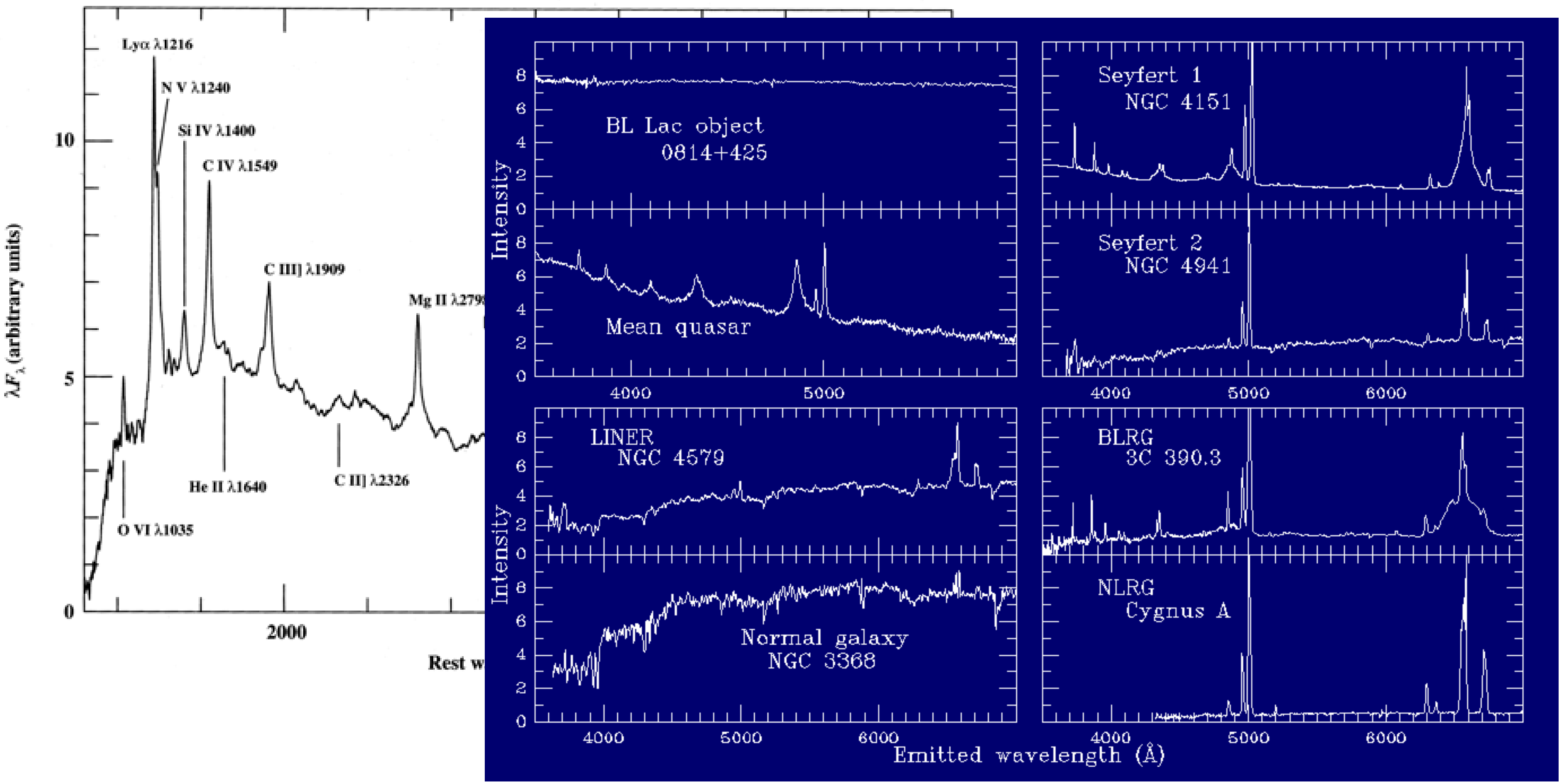
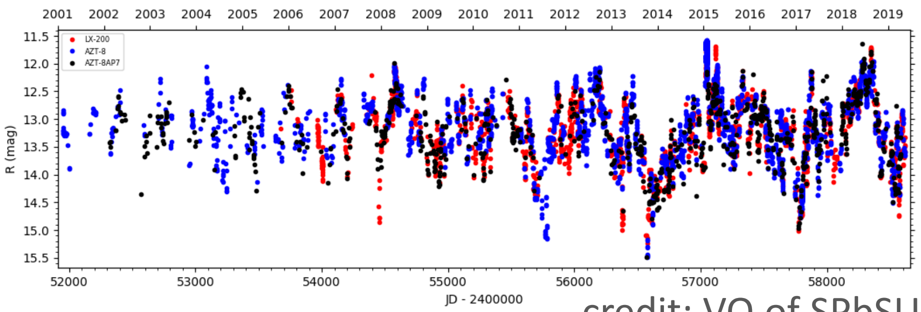


Observational properties of AGN

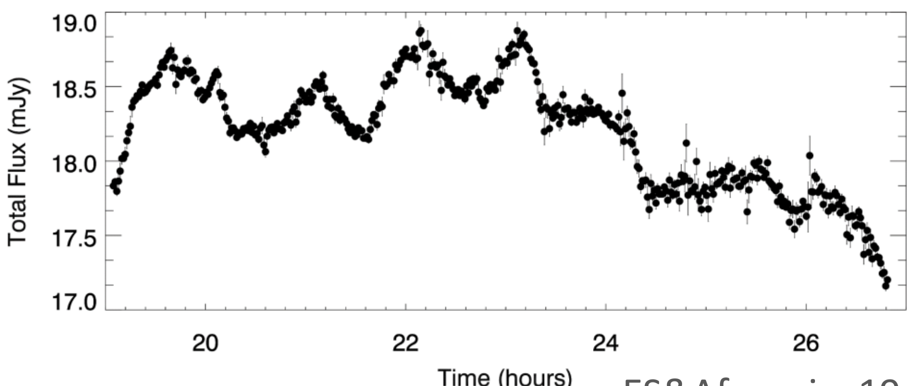
3. Rapid variability

Long-term (years+), short-term (hours!), spectral. The key point – small sizes.

e.g. S5 0716+714:



credit: VO of SPbSU



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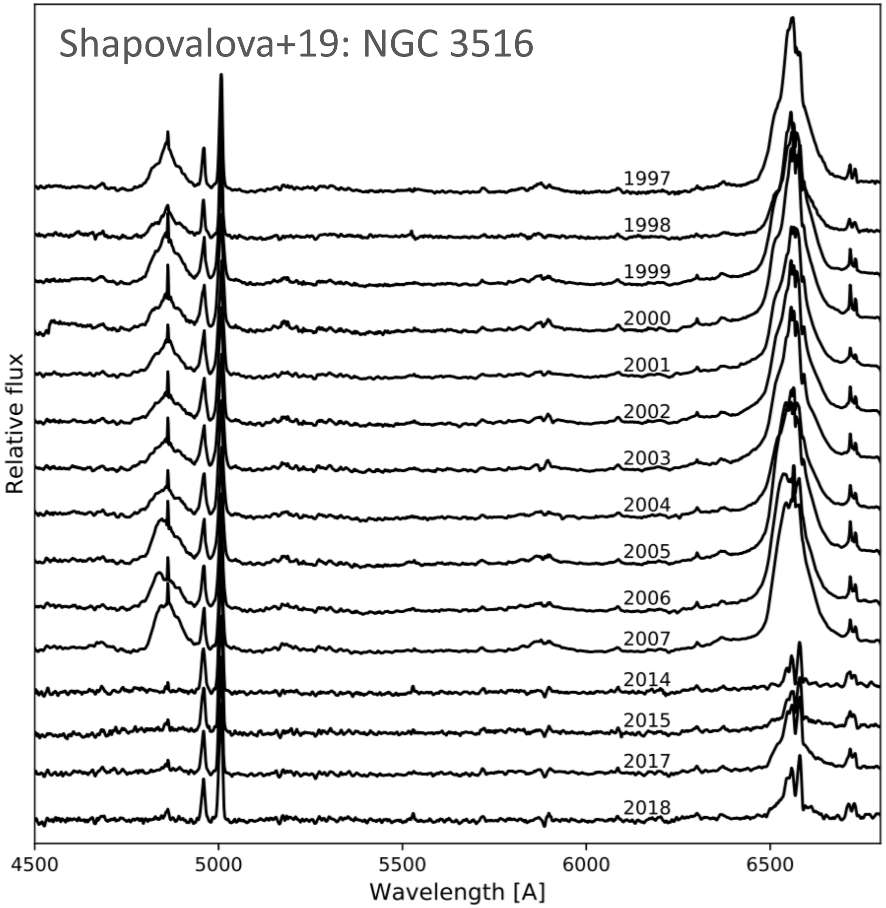
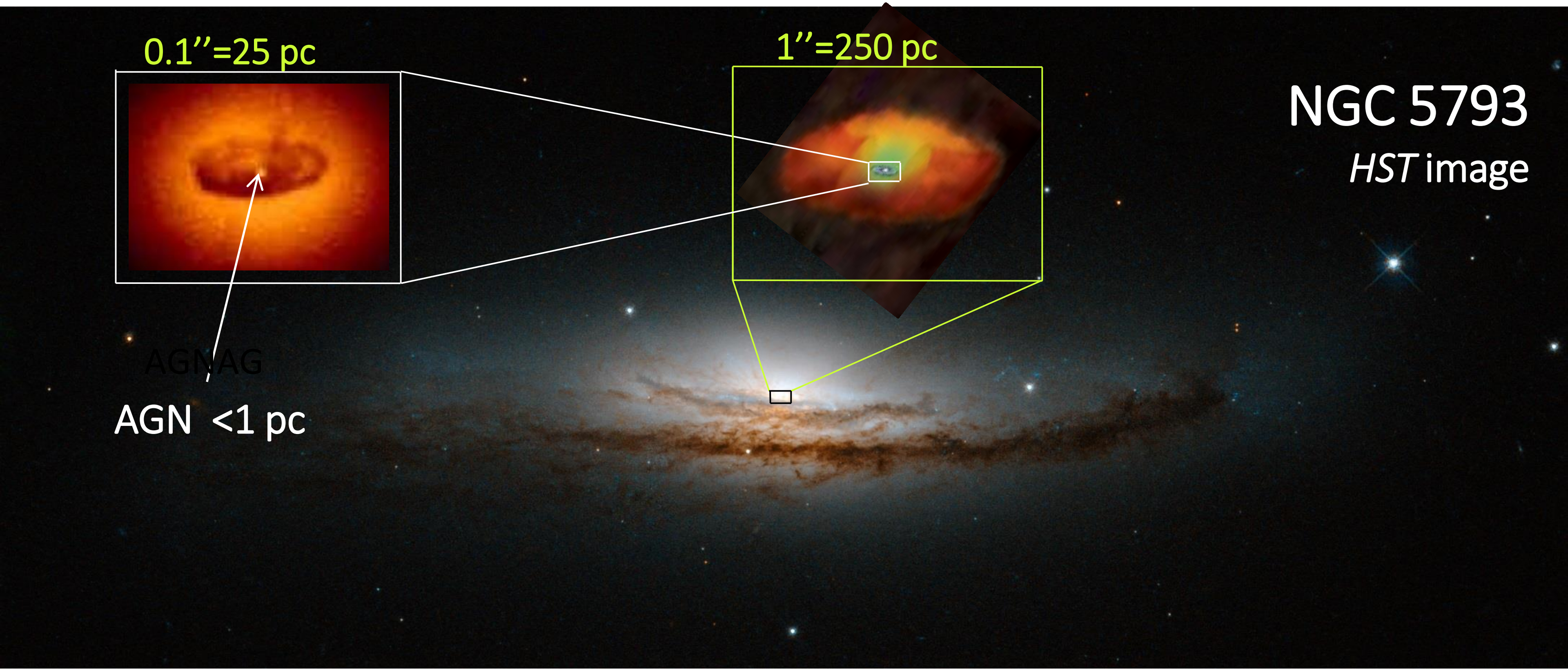
Shapovalova+19: NGC 3516



Observational properties of AGN

4. Polarization

Polarization is an additional parameter of the radiation helping to resolve the structure.



Observational properties of AGN

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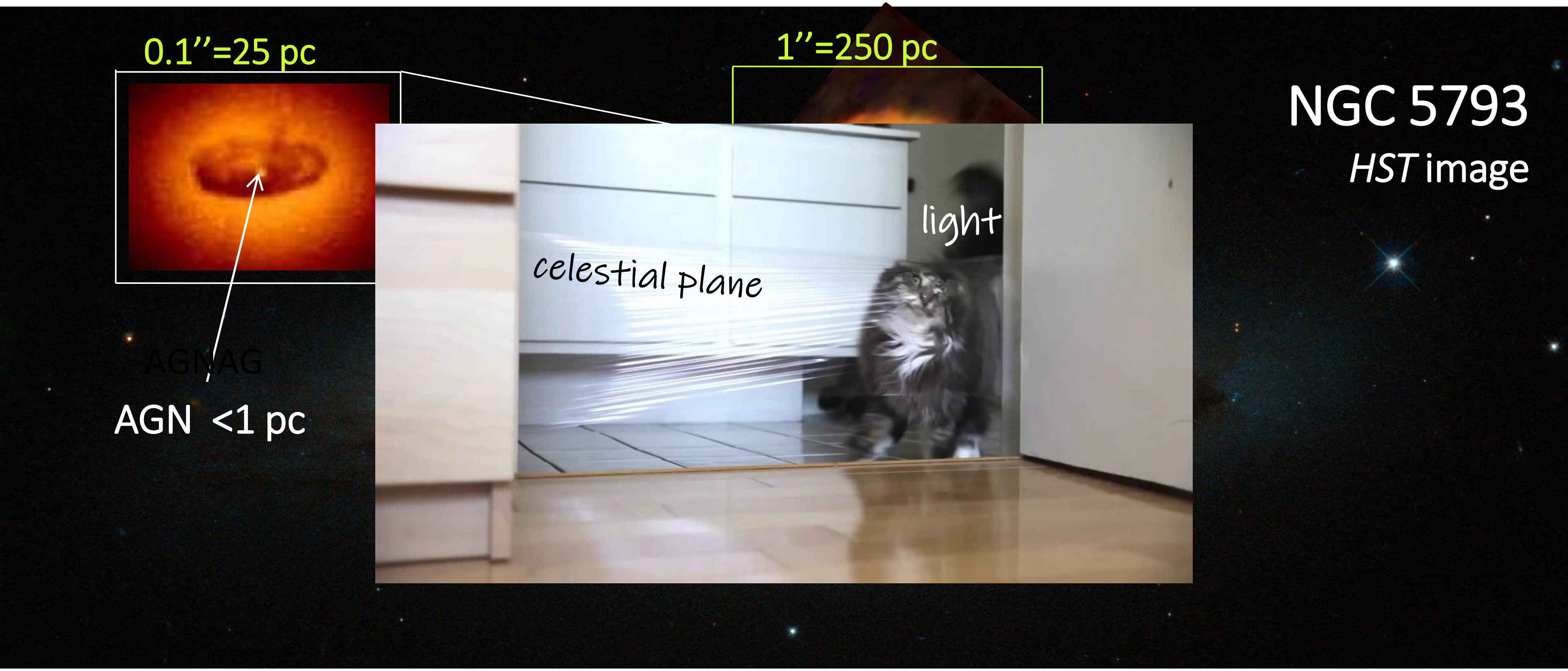
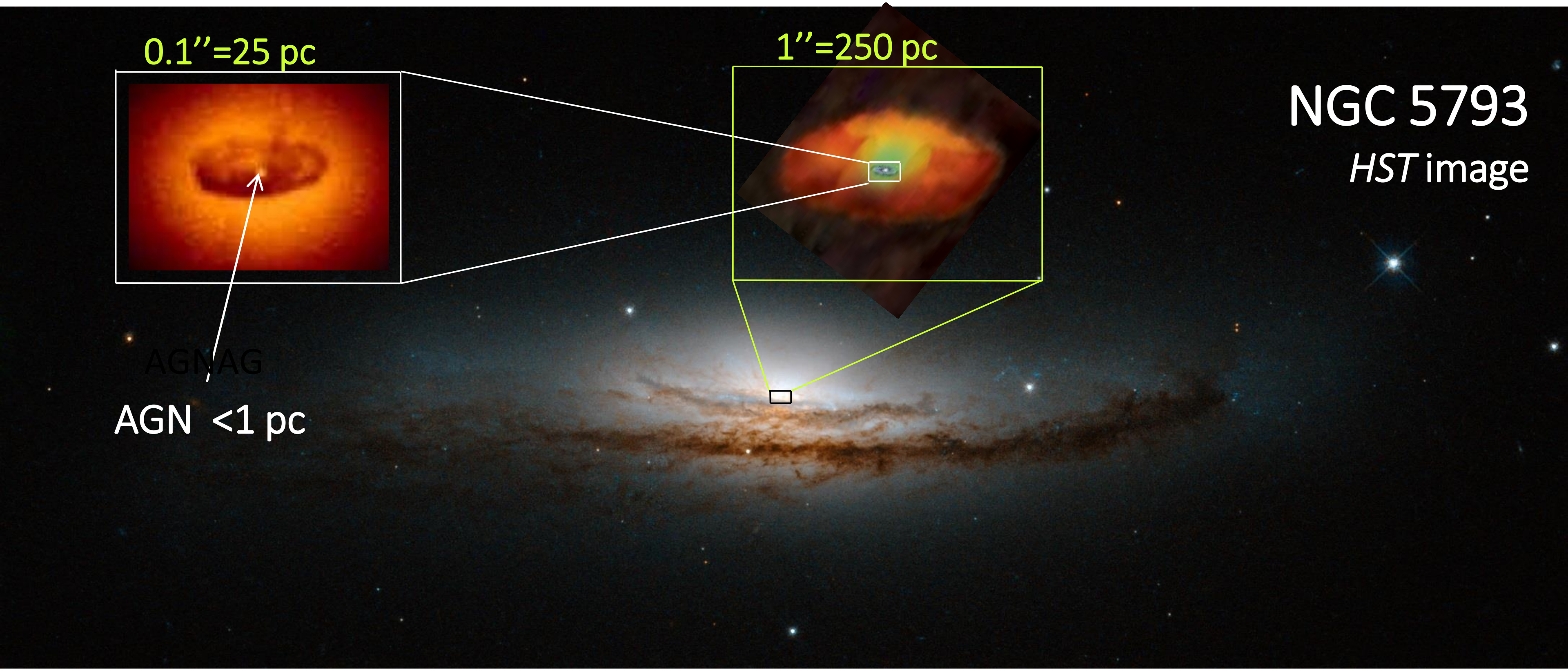


Observational properties of AGN

4. Polarization

Polarization is an additional parameter of the radiation helping to resolve the structure.

physical state — kinematics — volume distribution



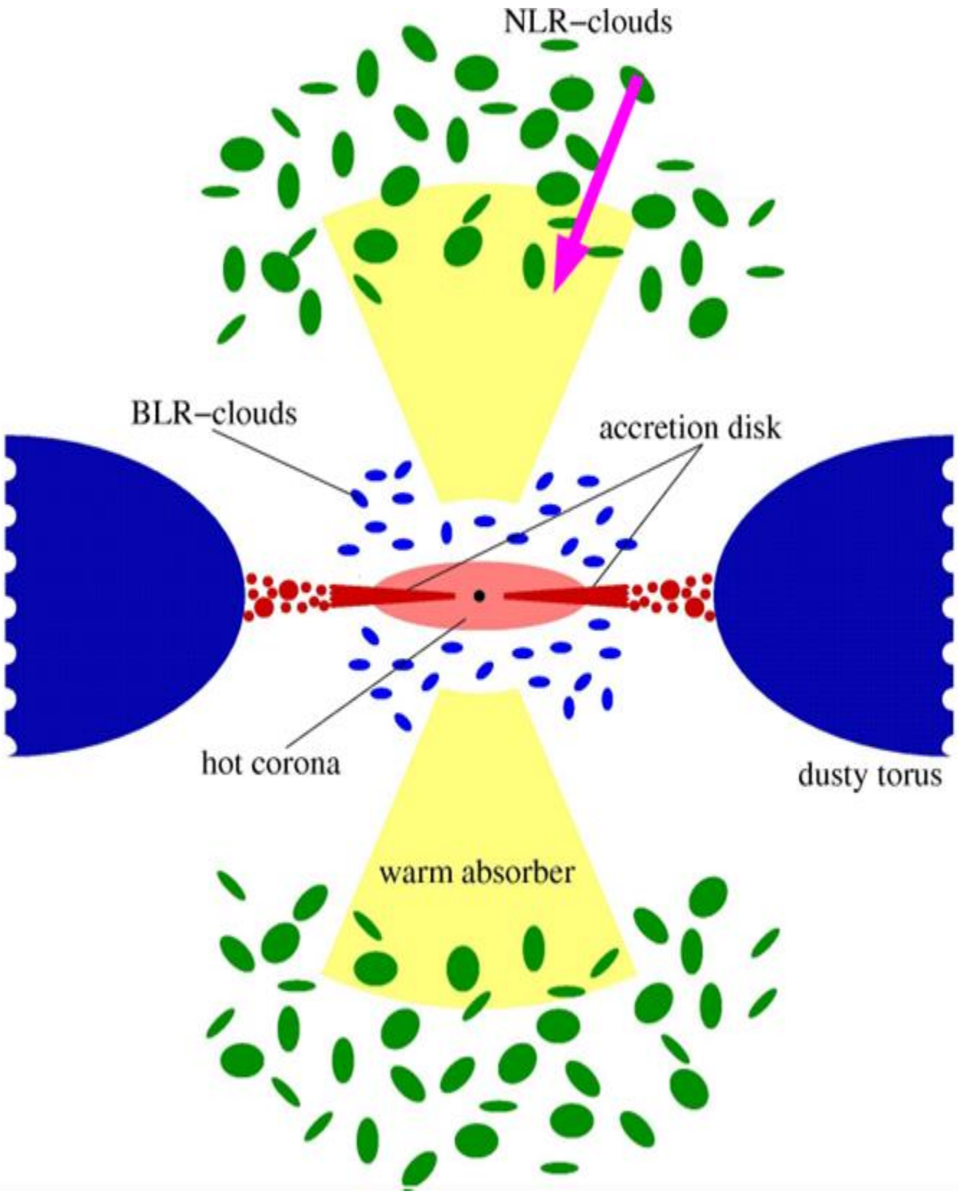
Polarization mechanisms

INSIDE

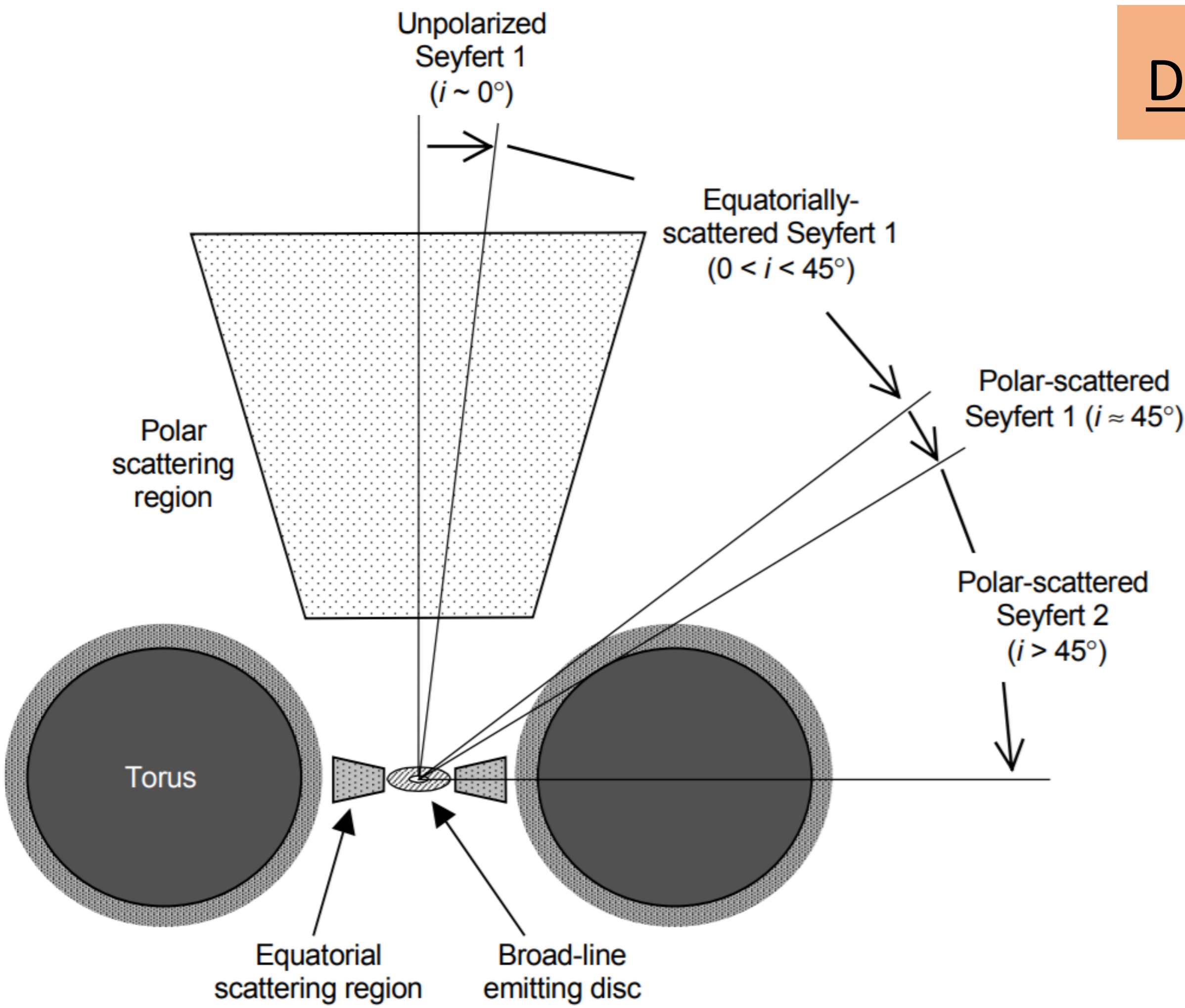
- GR effects near spinning SMBH
- Thomson scattering in AD
- Scattering in hot corona
- Jet synchrotron radiation
- Faraday rotation

OUTSIDE

- Polar scattering by ionization cone
- Equatorial scattering by dusty torus

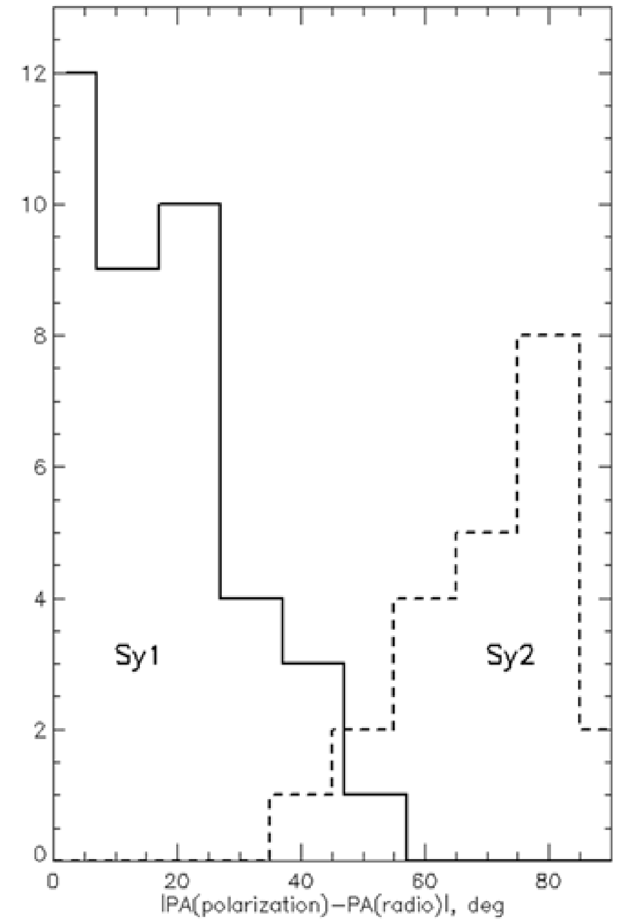


Polarization in Sy

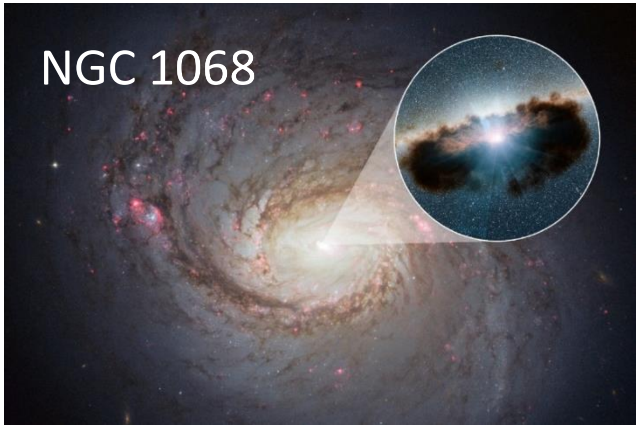


Smith+14

<u>Depends on orientation!</u>

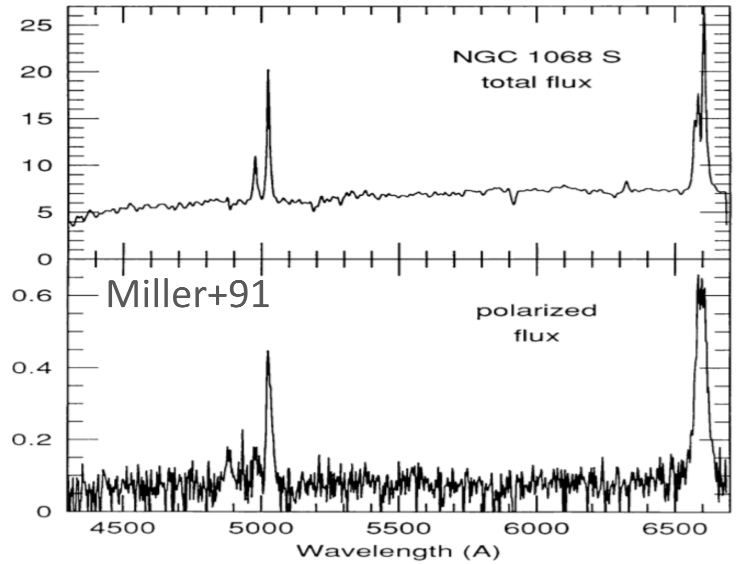


Polarization in Sy

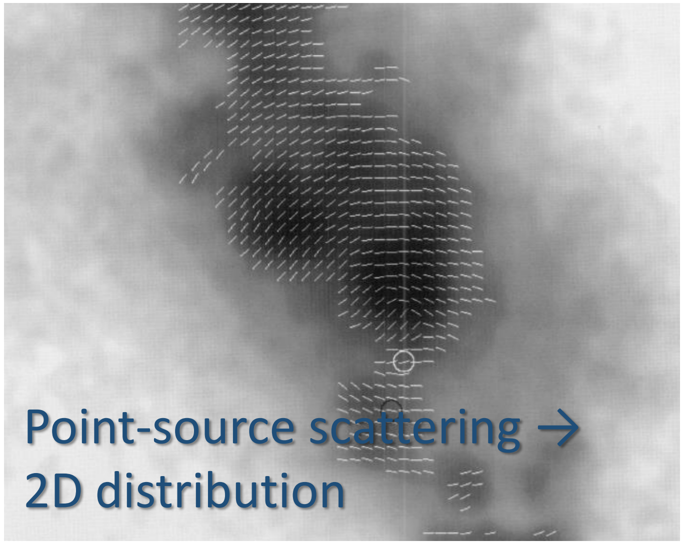


Hidden broad lines

Optically thin cone

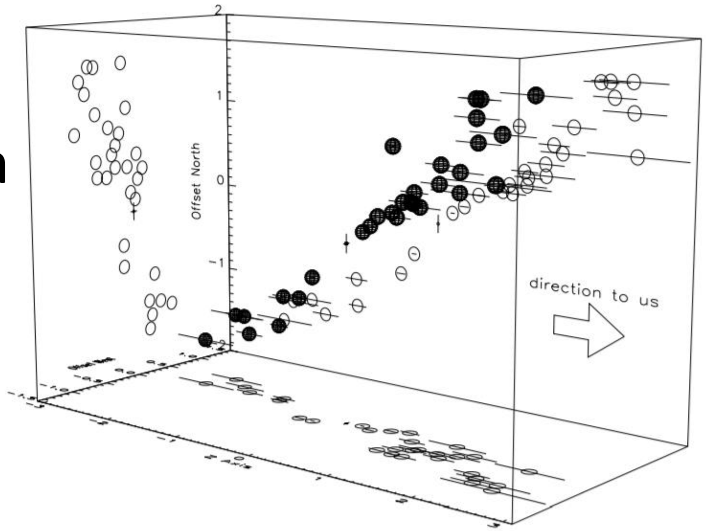


Miller+91



Point-source scattering → 2D distribution

3D clouds distribution



Kishimoto+99

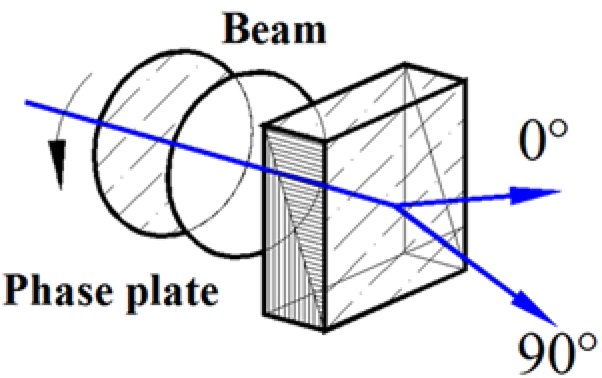
Polarization in AGNs

<u>«Why» conclusions</u>:

- Polarization is a marker of inner physics
- Polarization is a unique tool to resolve the structure and kinematics
- Polarization helps to reconstruct 3D image

Observational techniques

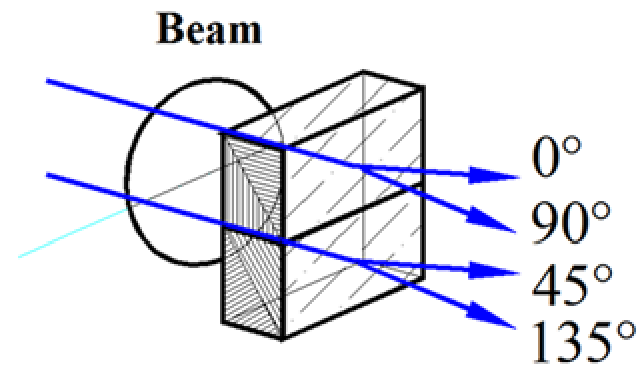
Wollaston prism	Double Wollaston prism



$$Q(\lambda) = \frac{1}{2}\left(\frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)}\right)_{\phi=0} - \frac{1}{2}\left(\frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)}\right)_{\phi=22.5},$$

$$U(\lambda) = \frac{1}{2}\left(\frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)}\right)_{\phi=0} - \frac{1}{2}\left(\frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)}\right)_{\phi=67.5},$$

$$I(\lambda) = \sum_{\phi}[I_0(\lambda) + I_{90}(\lambda)]_{\phi}, \qquad \phi = 0, 45, 22.5, 67.5$$



$$Q(\lambda) = \frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)},$$

$$U(\lambda) = \frac{I_{45}(\lambda) - I_{135}(\lambda)}{I_{45}(\lambda) + I_{135}(\lambda)},$$

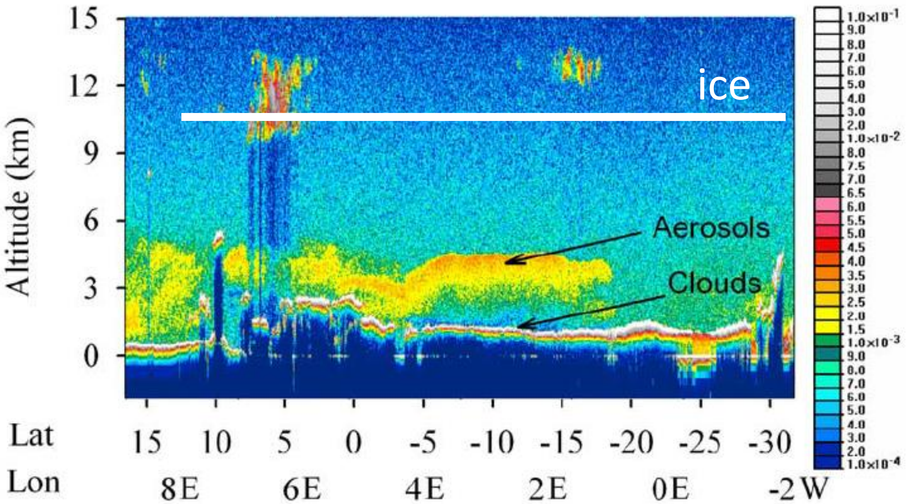
$$I(\lambda) = I_0(\lambda) + I_{90}(\lambda) + I_{45}(\lambda) + I_{135}(\lambda)$$

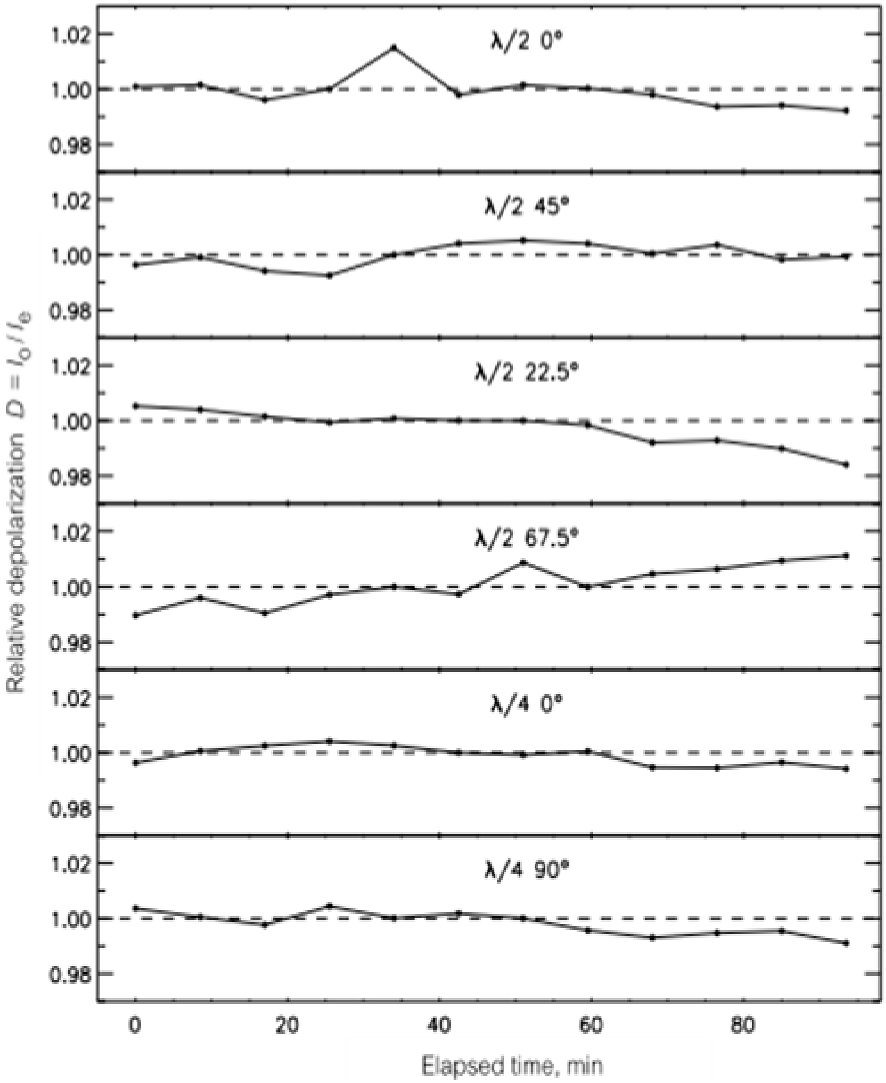
$$\boxed{P(\lambda) = \sqrt{Q(\lambda)^2 + U(\lambda)^2} \qquad \varphi(\lambda) = \frac{1}{2}\mathrm{arctg}[U(\lambda)/Q(\lambda)]}$$

Afanasiev&Amirkhanyan12

Observational techniques

1. Depolarization in atmosphere



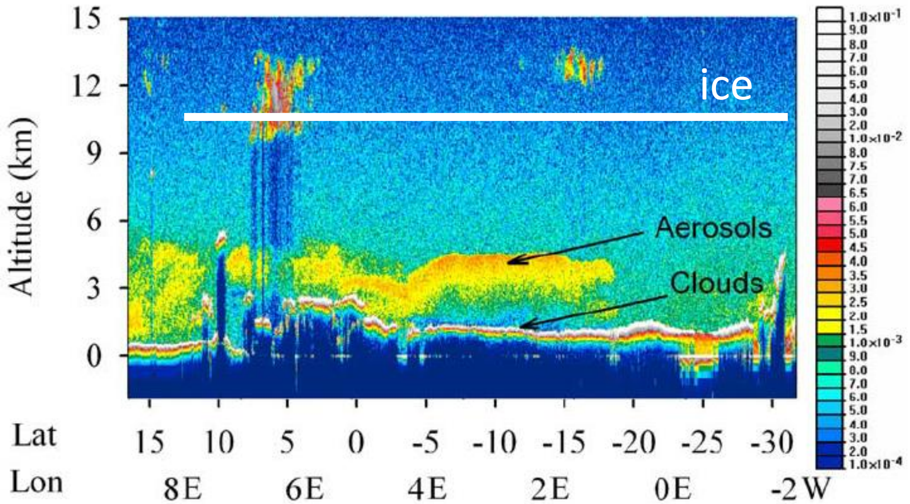


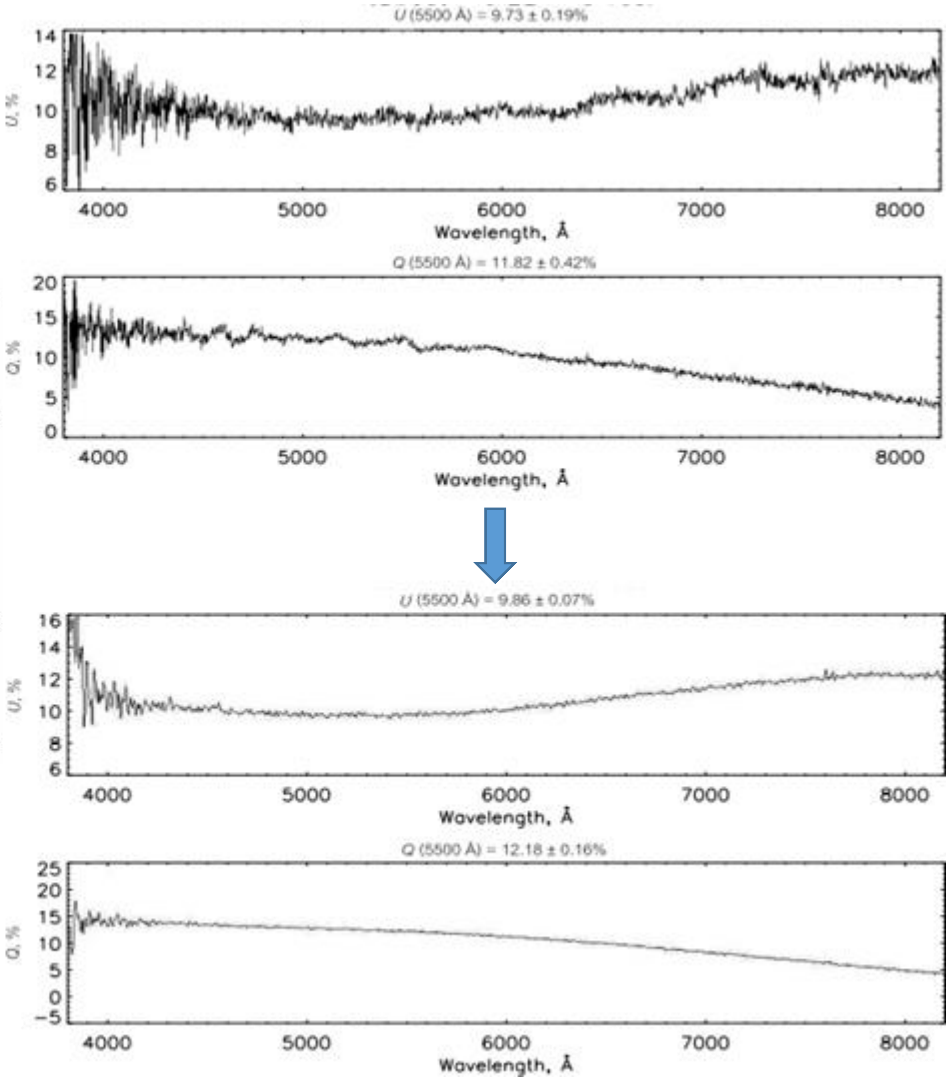
Rayleigh – $p = \frac{\sin^2\theta}{1+\cos^2\theta}$

Ice crystals – 20-30%

Observational techniques

1. Depolarization in atmosphere





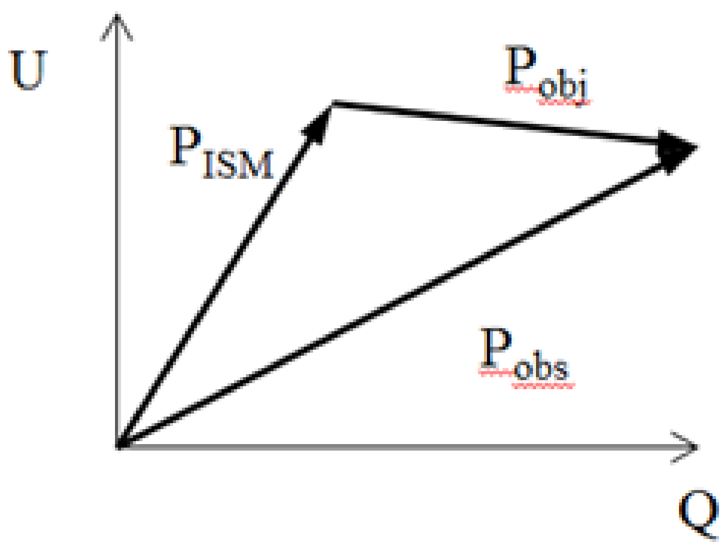
Rayleigh – $p = \frac{\sin^2\theta}{1+\cos^2\theta}$

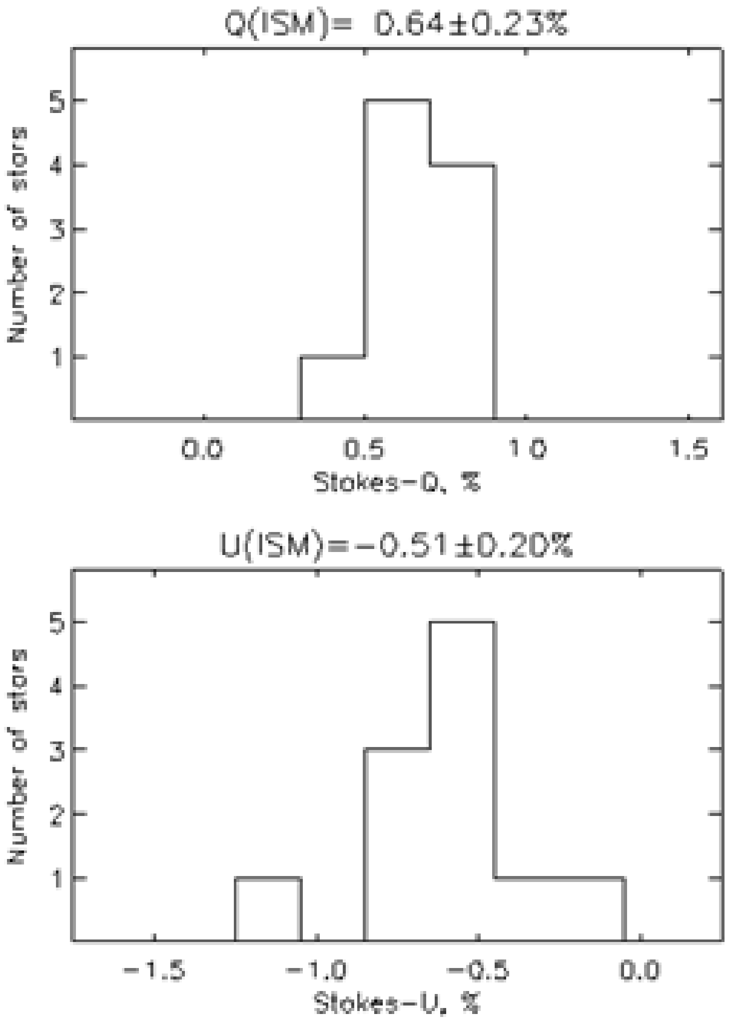
Ice crystals – 20-30%

Observational techniques

2. ISM

$$\vec{P}_{obs} = \vec{P}_{obj} + \vec{P}_{ISM}$$

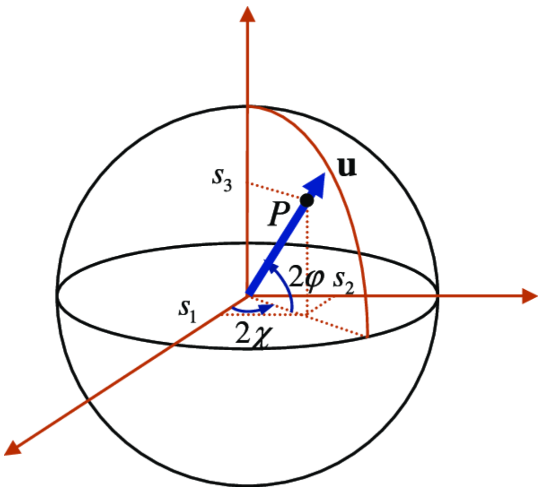




Observational techniques

«How to» conclusions:

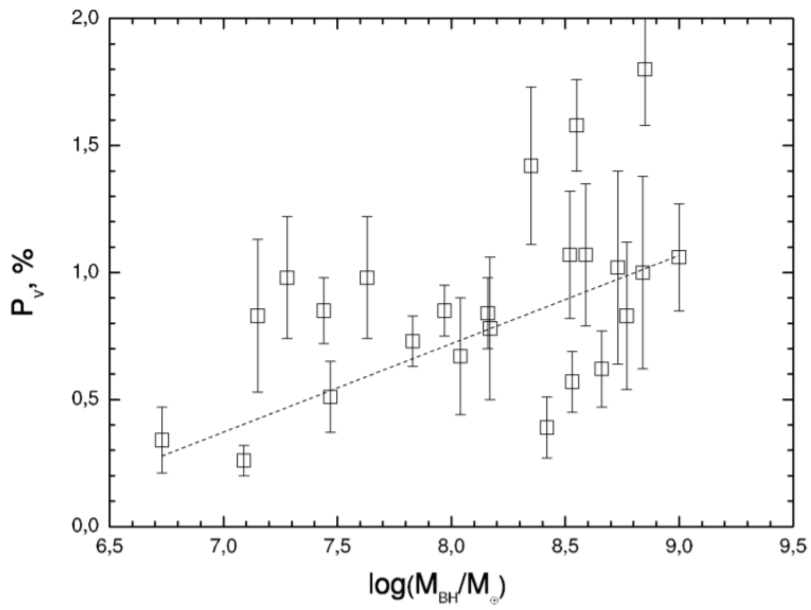
- ISM and atmosphere are the sources of depolarization
- *Polarization is a vector*

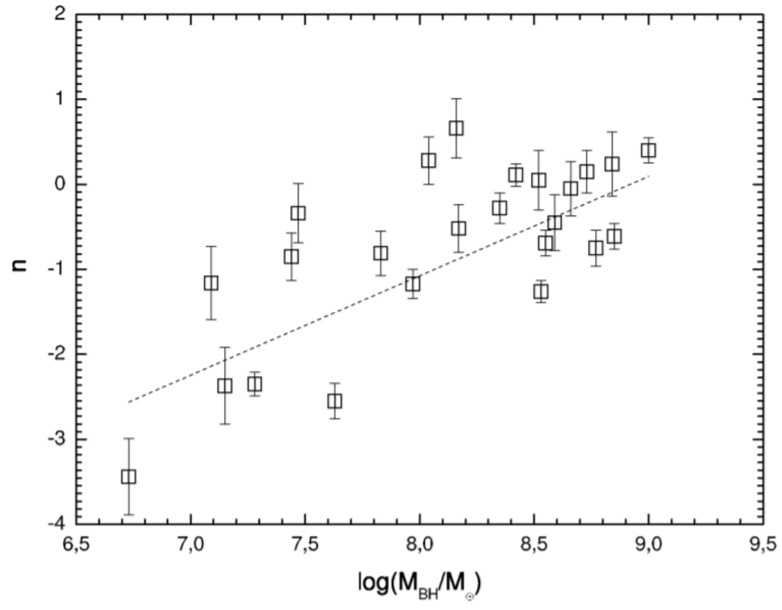


Polarization in continuum

Afanasiev+11: *if the Faraday rotation on the photon mean free path in the process of scattering by electrons is taken into account, then the polarization and its dependences on the wavelength are completely determined by the magnetic field.*

$$\boldsymbol{P}(\lambda) \sim \lambda^{n}$$





$$T_e(R) \sim R^{-p}$$
$$B(R) \sim B_H(R_H/R)^s$$

Silant'ev+07

$$\Rightarrow \quad \boldsymbol{P}_l \sim \frac{\boldsymbol{P}_l(0,\mu)}{B_{z,\perp}\lambda^2} \sim \lambda^{(s/p-2)} \quad \Rightarrow$$

Magnetic field $B(R)$

Polarization in continuum

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Object	p	s	$B(R_\lambda)$[G]
PG 0007+106	1/2	1	2.43
PG 0026+129	3/4	5/4	1
PG 0049+171	3/4	5/4	13
PG 0157+001	3/4	5/4	98
PG 0804+761	3/4	3/2	3.4
PG 0844+349	3/4	1	37
PG 0953+414	3/4	1	300
PG 1116+215	3/4	3/4	100
PG 2112+059	3/4	2	14.4
PG 2130+099	1/2	1	27
PG 2209+184	1/2	3/4	16
PG 2214+139	1/2	5/4	2.8
PG 2233+134	3/4	3/2	0.37
3C 390.3	3/4	1	6.4

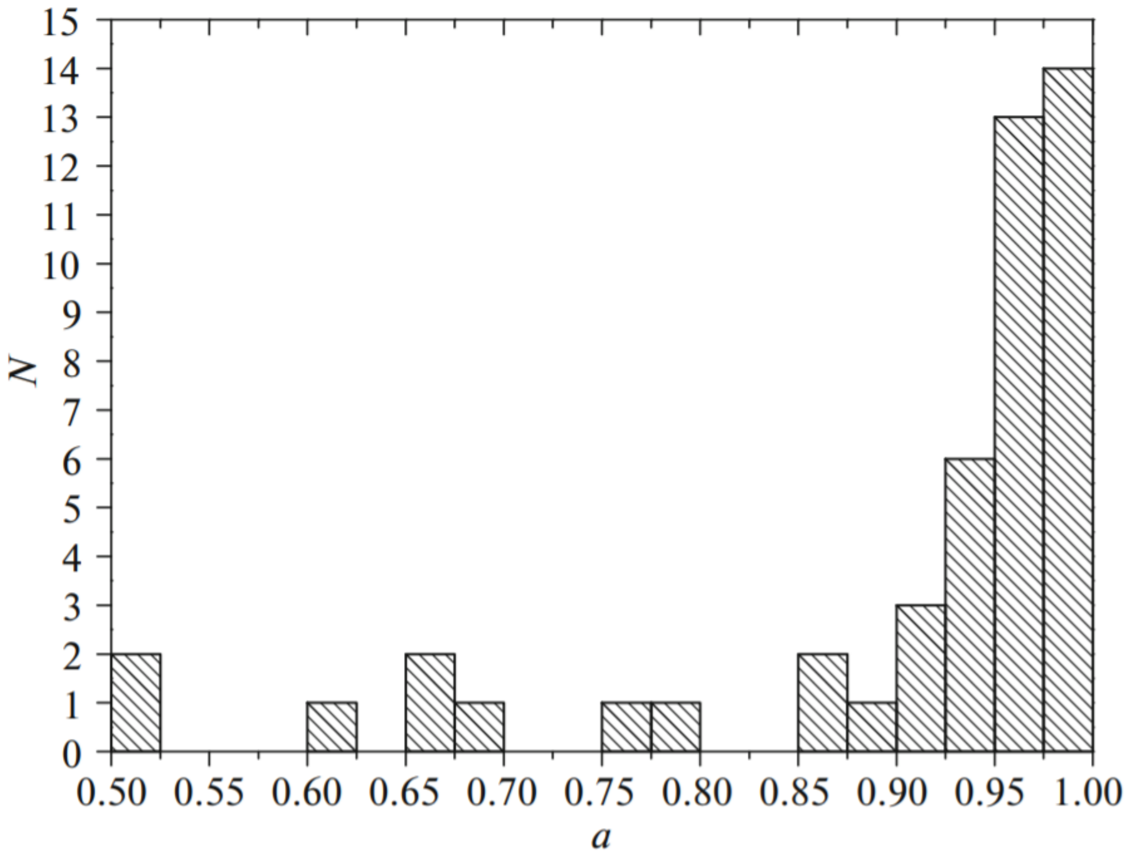
Polarization in continuum

Afanasiev+18: SMBH spins

$$\mu^{3/2} l_E = 0.201 \left(\frac{L_{5100}}{10^{44} erg\ s^{-1}}\right)^{3/2} \frac{\varepsilon(\boldsymbol{a})}{M_8^2}$$

P_l: observations vs. Sobolev-Chandrasekhar theory $\Rightarrow \mu = \cos(i)$

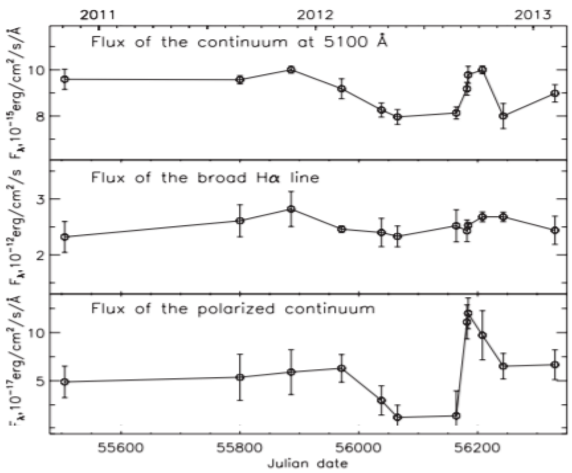
$\Big\}\ \varepsilon(a) \Rightarrow a$

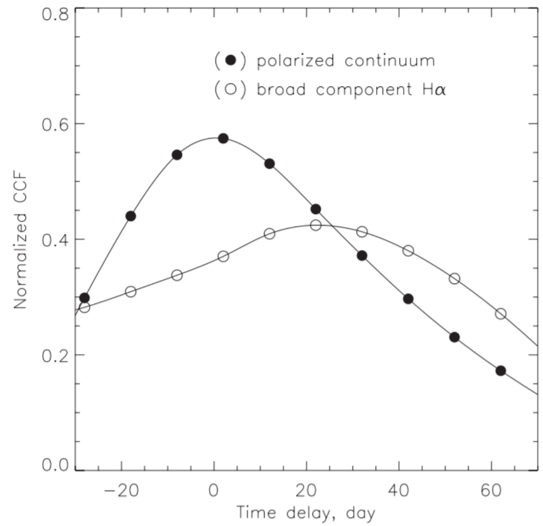


47 type 1 active galaxies

Kerr supermassive black holes

Polarization in continuum: variability

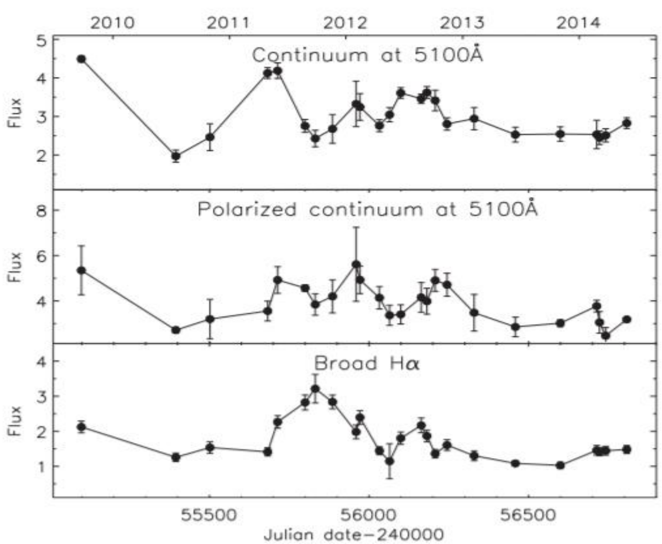


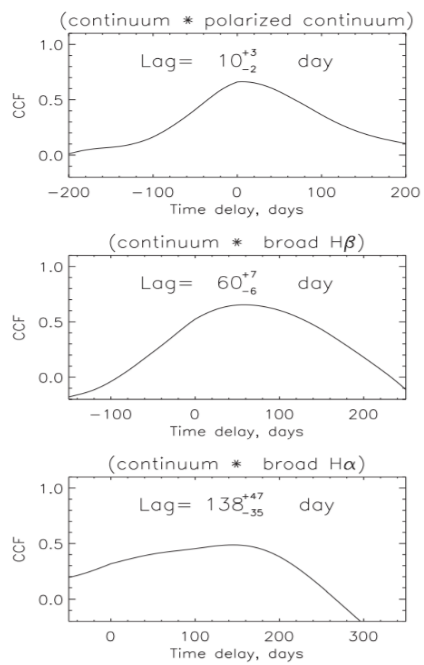


Sy1.5 Mrk 6

- Spectropolarimetric monitoring in 12 epochs 2010-2014;
- Polarized continuum region - 2 days (0.002 pc);
- BLR Hα - 22 days (0.02 pc)

Afanasiev+14





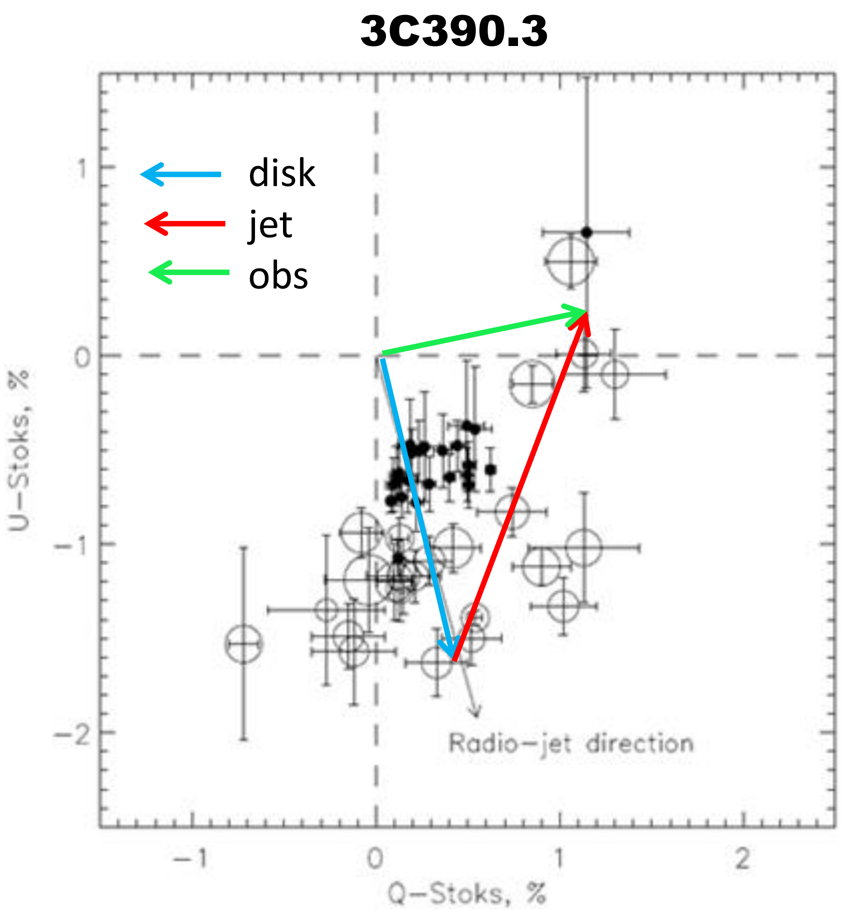
Sy1 3C390.3

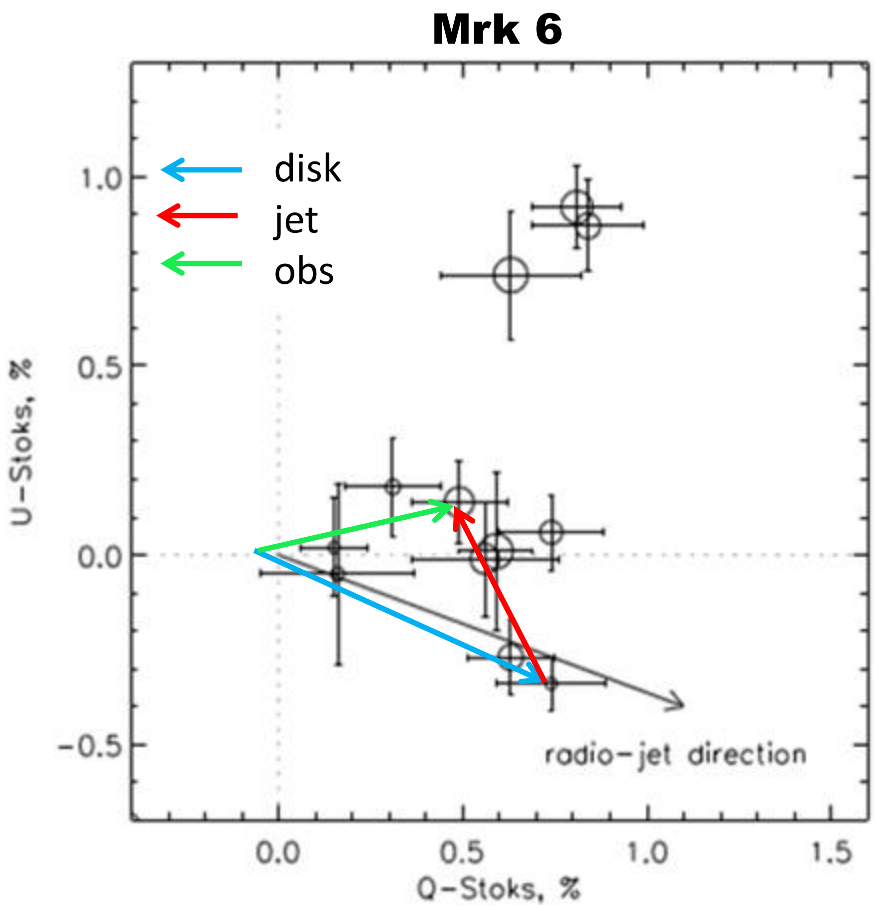
- Spectropolarimetric monitoring in 23 epochs 2009-2015;
- Polarized continuum region - 10 days (0.01 pc);
- BLR Hβ - 60 days (0.06 pc), BLR Hα - 120 days (0.1 pc)

Afanasiev+15

The polarized continuum region is 10 times smaller than BLR.

Polarization in continuum: variability

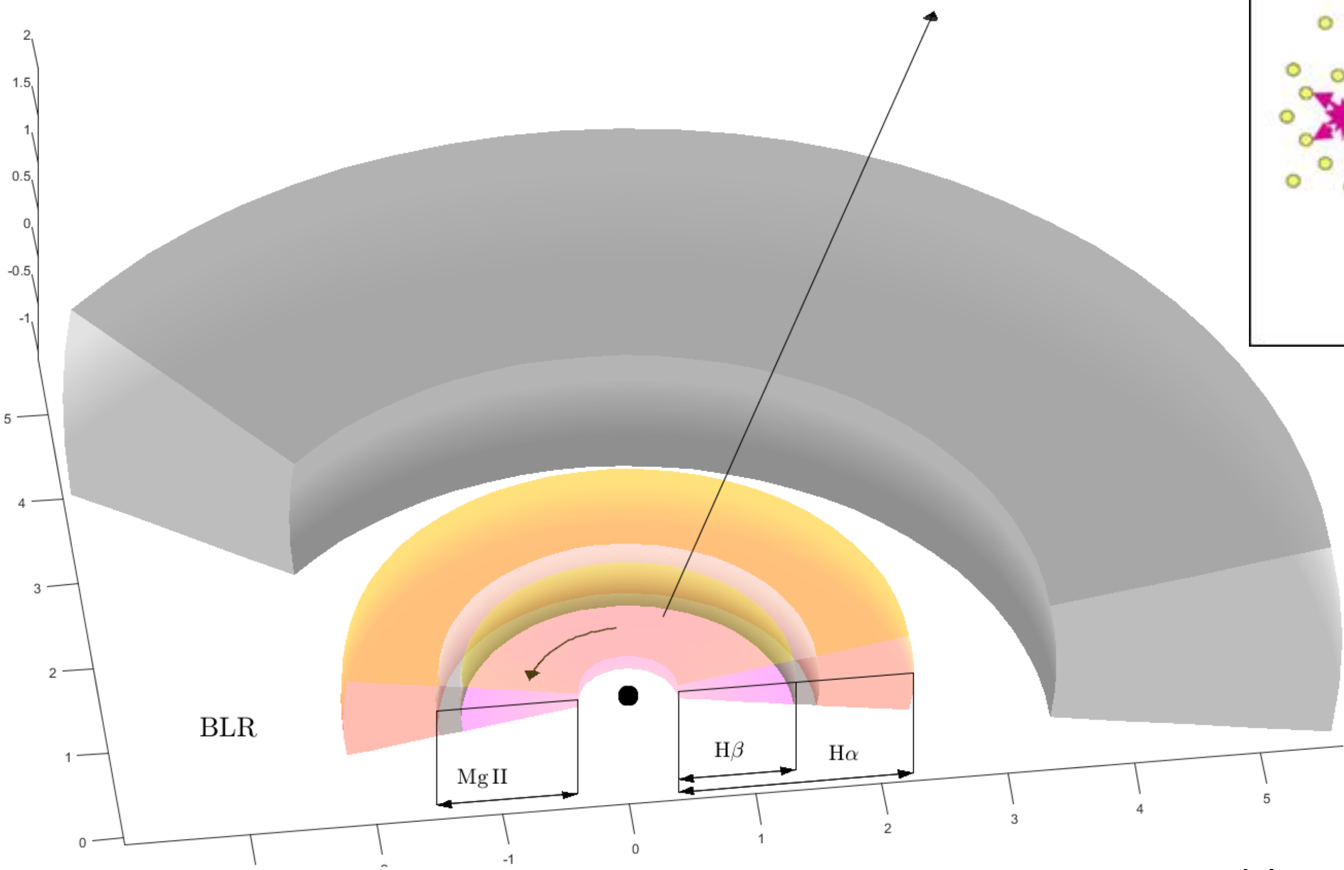


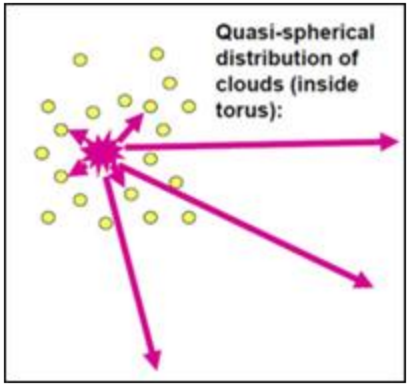


The observed polarization in continuum is the vector sum of the disk and jet polarization.

Polarization in broad lines

Savic+19, in print

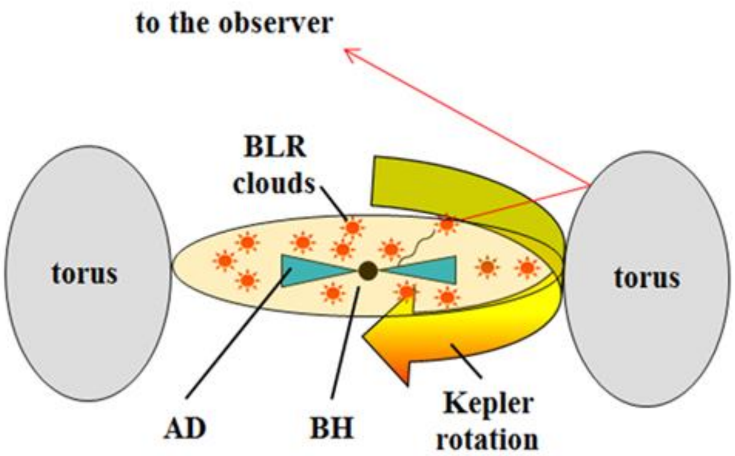




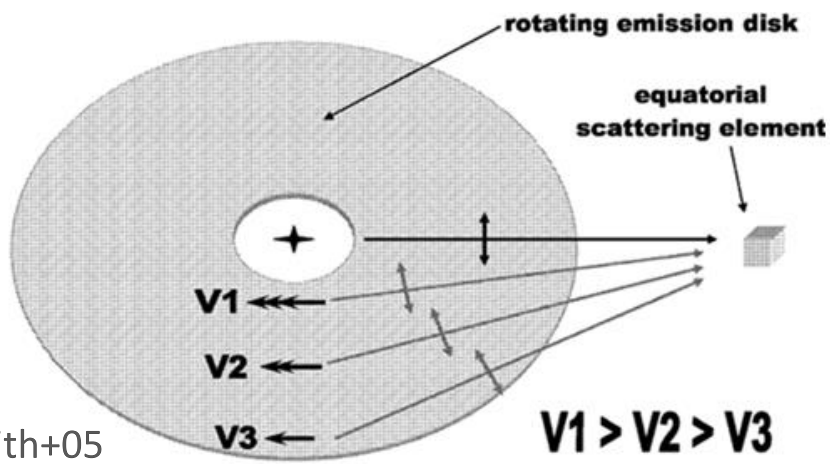
Broad-line region (BLR):

- $n \sim 10^8 \div 10^{12}\ \mathrm{cm}^{-3}$
- 0.1 pc
- clumpy structure

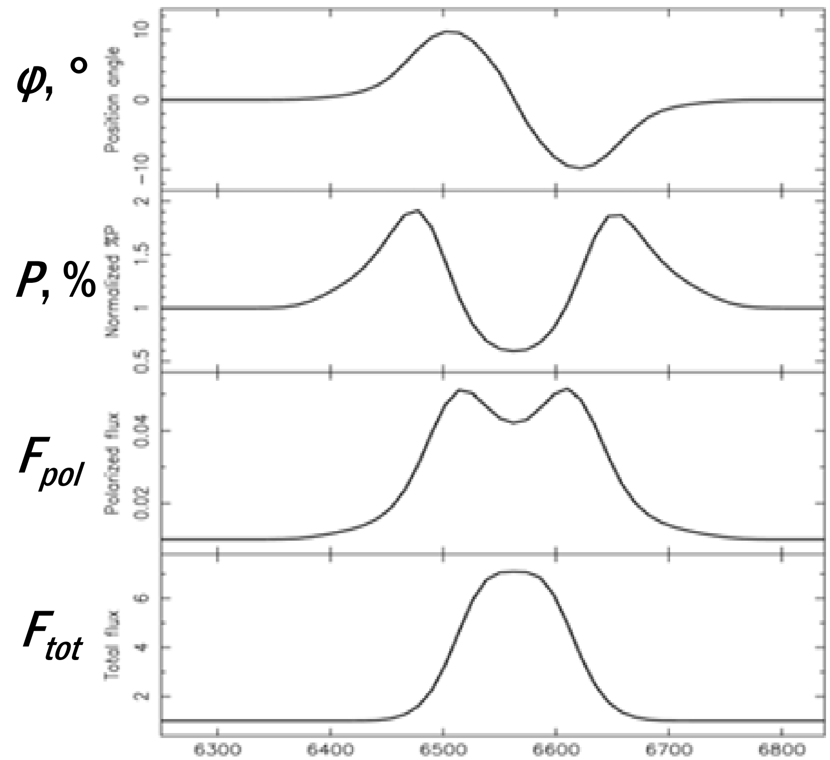
Polarization in broad lines



Broad lines are originally unpolarized.
The polarization is produced by equatorial scattering.



Smith+05



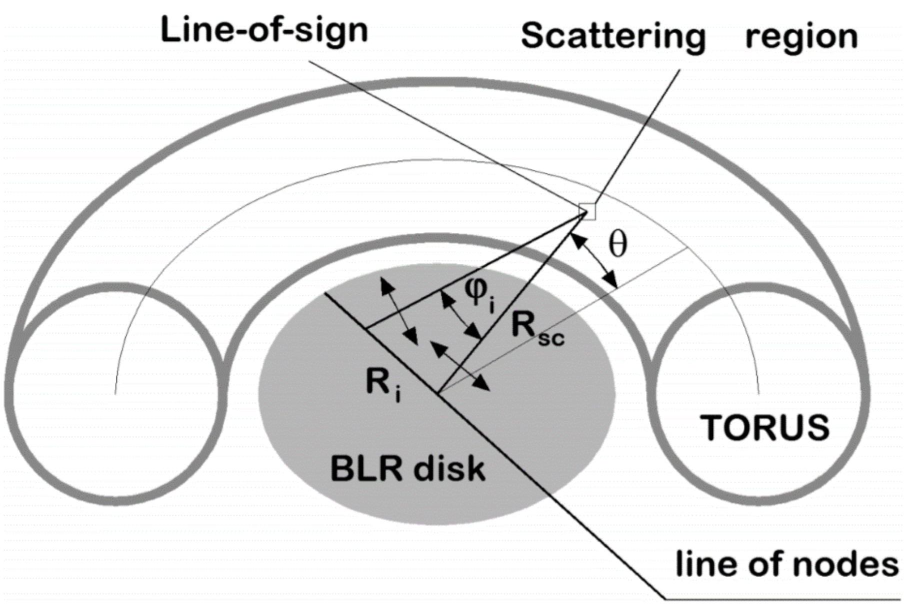
STOKES modelling
(Marin18)

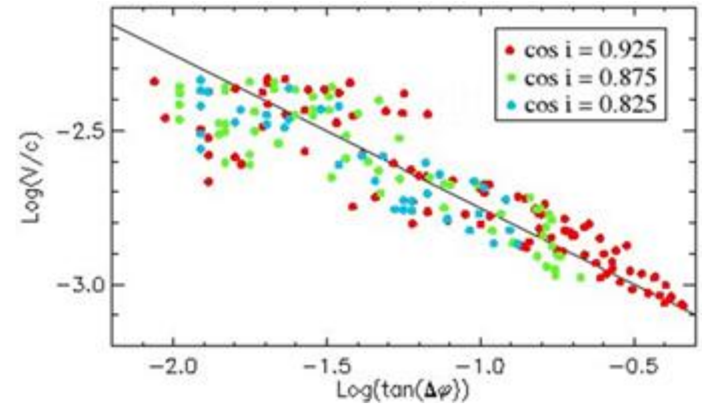
Polarization in broad lines

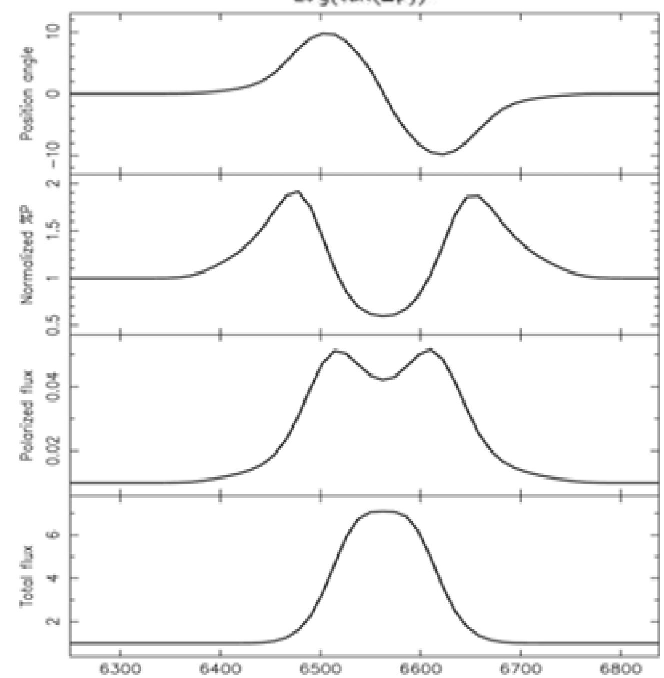
In case of Keplerian-like motion:

$$V_i = V_i^{rot}\cos(\theta) = \sqrt{\frac{G\,M_{BH}}{R_i}}\cos(\theta)\ , \qquad R_i = R_{sc}\tan(\varphi_i)$$

$$log\left(\frac{V_i}{c}\right) = a - b\cdot log(tan(\varphi_i)), a = 0.5log\left(\frac{G\,M_{BH}\cos^2(\theta)}{c^2 R_{sc}}\right)$$







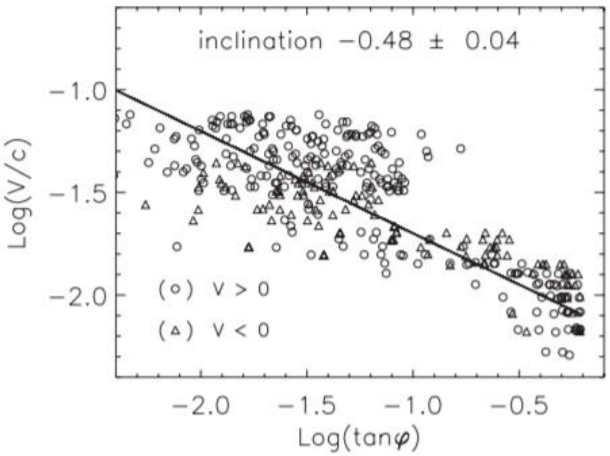
STOKES modelling
(Marin18)

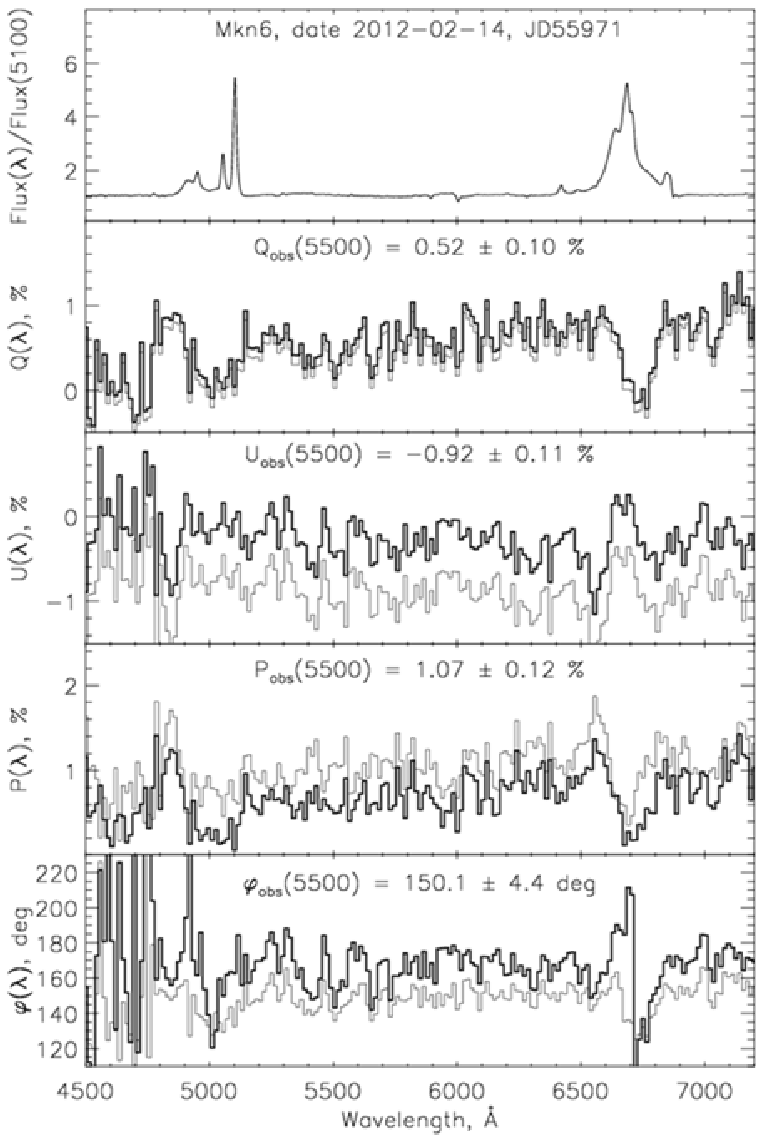
Polarization in broad lines

Mrk 6 (IC 450)

Sy 1.5, $z = 0.0185$
$m(B) = 14.29, M(B) = -20.41$

- observations with SCORPIO-2 at 6-m BTA in 2010-2013;
- 12 spectra (Hα + Hβ) with 2800-3600 sec exposures and 7-8Å resolution;
- Stokes parameters accuracy ~0.2%.





Afanasiev+14

Polarization in broad lines

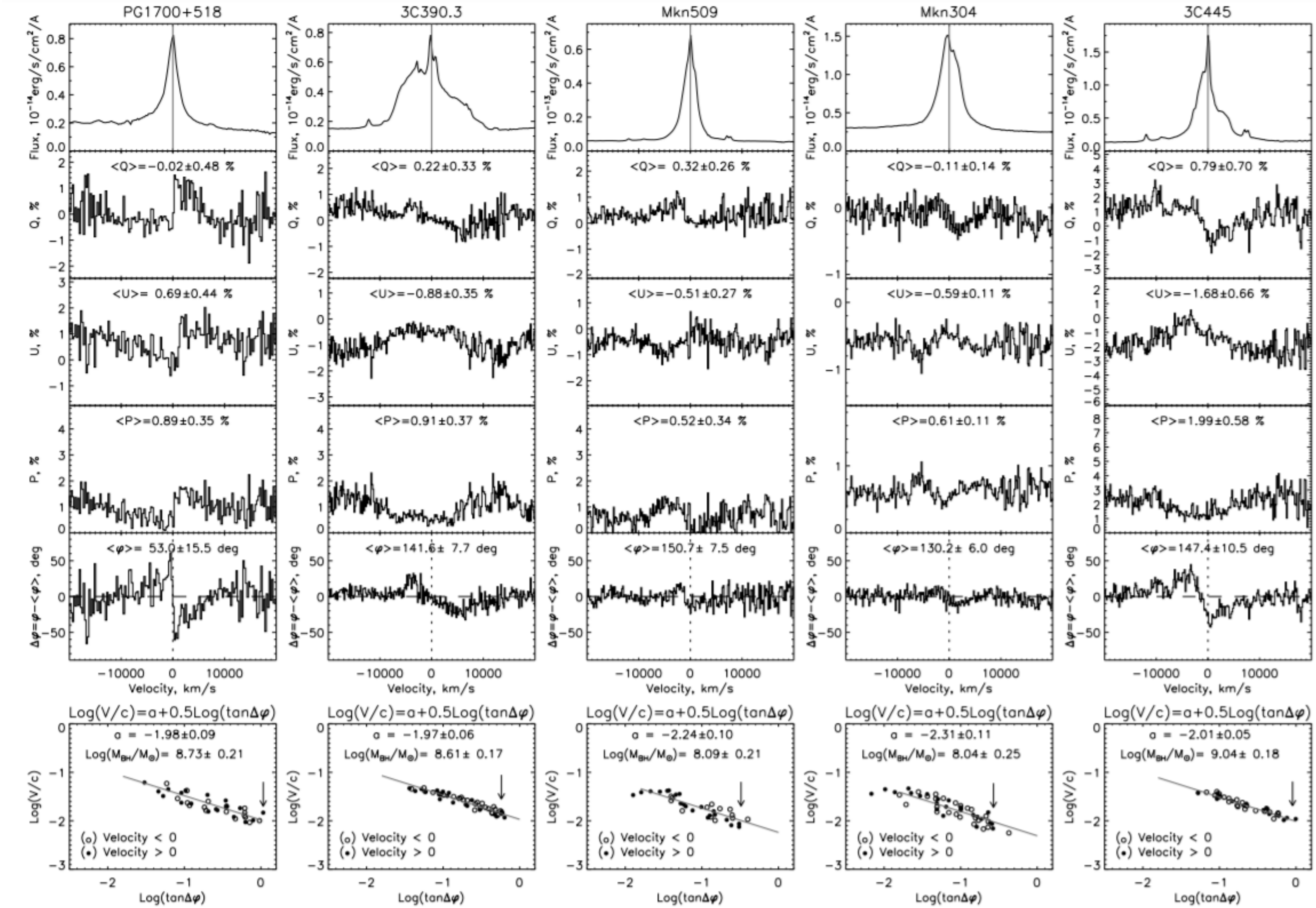


Figure 9. The same as in Fig. 4, but for PG 1700+518, 3C 390.3, Mkn 509, Mkn 304 and 3C 445.

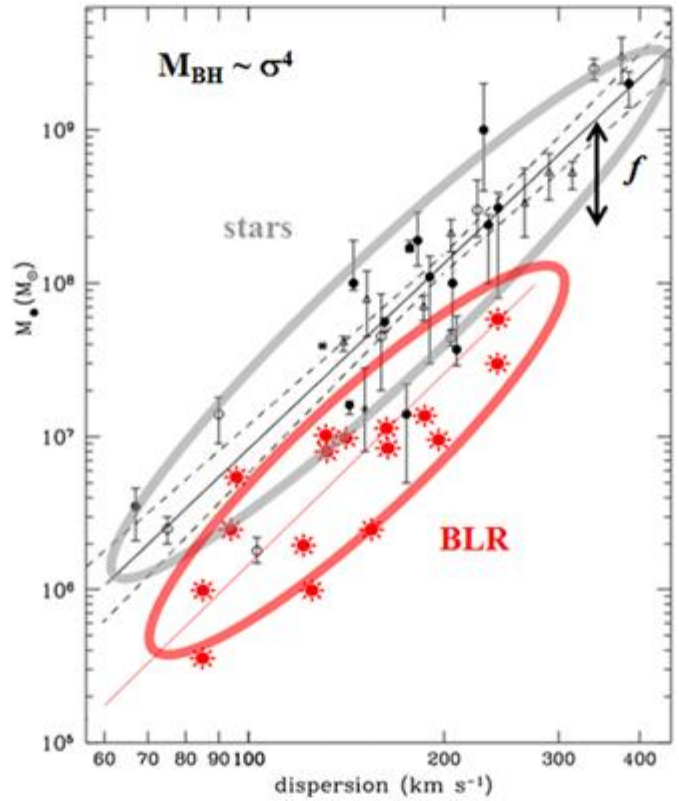
Afanasiev+19: 35 Sy galaxies

Polarization in broad lines: mass estimation

SMBH mass – *reverberation mapping*

- Gas is virialized.
- BLR size as a time-delay in Balmer line: $R_{BLR} = c\tau$.
- v is obtained from the line width: $v = v_{obs}/\sin(i)$ - i is unknown.
- f is totally unknown.

$$M_{SMBH} = f\,\frac{v^2 R_{BLR}}{G}$$



Too many parameters are unknown and unobserved.

Polarization in broad lines: mass estimation

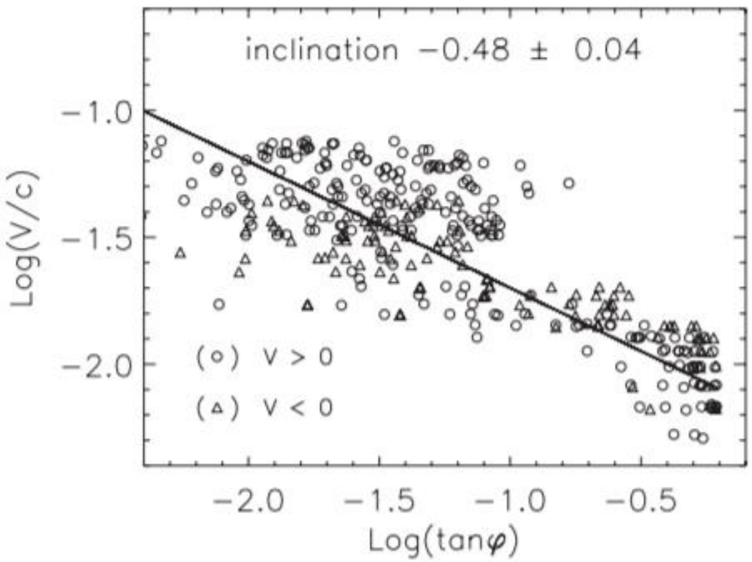
SMBH mass – *spectropolarimetry*

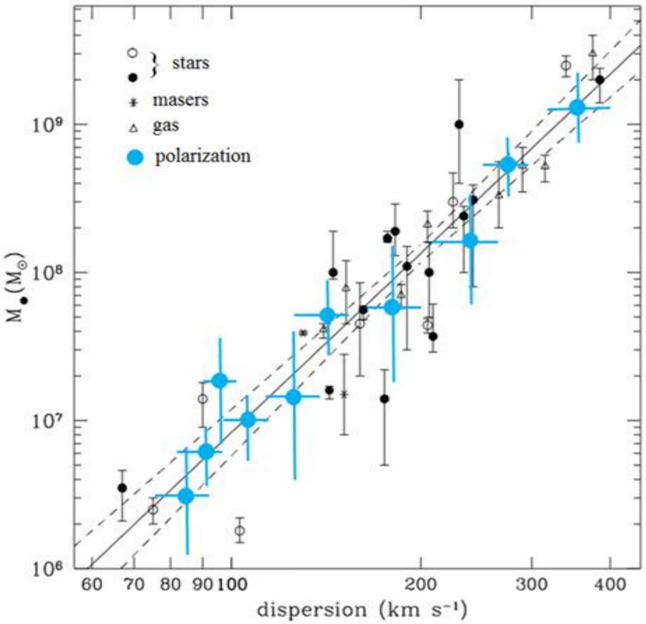
- Gas is virialized.
- Only geometrical effects.

$$a = 0.5 \lg\left(\frac{GM_{SMBH}\cos^2(\theta)}{c^2 R_{sc}}\right)$$

- Direct and indirect measurements of R_{sc}.
- Only 1 epoch is needed.

Independent from the inclination!





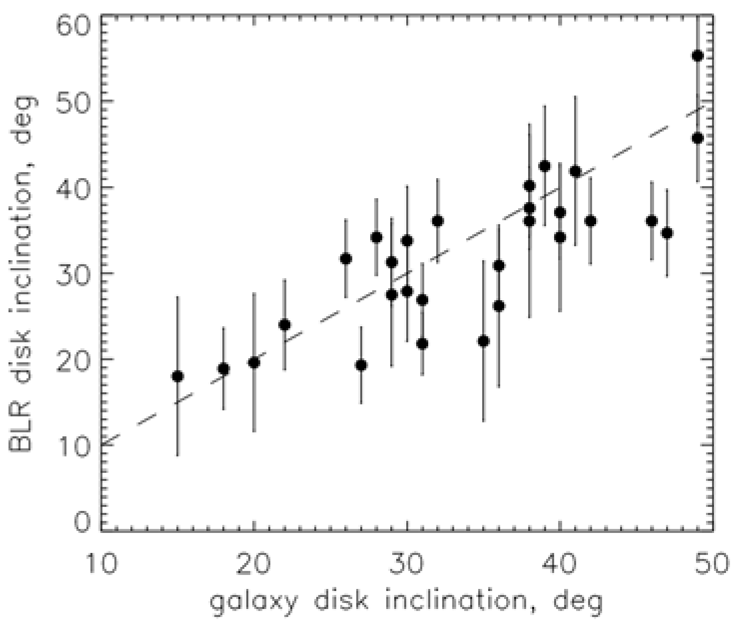
Polarization in broad lines: disk inclination

Afanasiev+19

As the mass is estimated, the inclination angle could be found:

$$\sin^2(i) = \frac{R_{BLR} v^2}{G M_{SMBH}^{pol}}$$

The dependence between BLR inclination angle and galaxy inclination

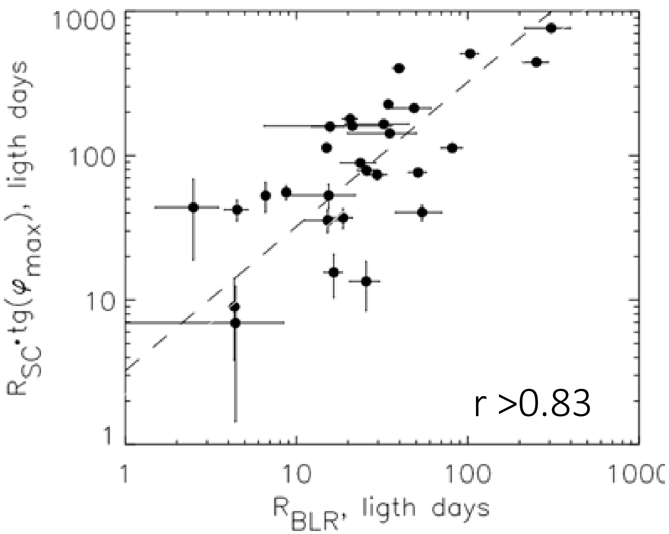


In the frame of equatorial scattering model:

$R_{max} = R_{sc}\tan(\varphi_{max})$; $R_{max} \propto R_{BLR} \rightarrow$

$$R_{BLR} = c\tau = \langle R \rangle = \int_{R_{min}}^{R_{max}} I(R) R dr \,/\, \int_{R_{min}}^{R_{max}} I(R) dr$$

$$\langle R \rangle \cong \frac{(1+\alpha)}{(2+\alpha)} R_{max} \qquad I(R) \propto R^{\alpha}$$



Constant luminosity disk ($\alpha = 0$) $R_{BLR} = 0.5\, R_{max}$
Shakura-Sunyaev disk ($\alpha = -3/4$) $R_{BLR} = 0.2 R_{max}$

Observations $\boldsymbol{R_{BLR} = (0.31 \pm 0.17) R_{max}}$, $\boldsymbol{\alpha \approx -0.57}$

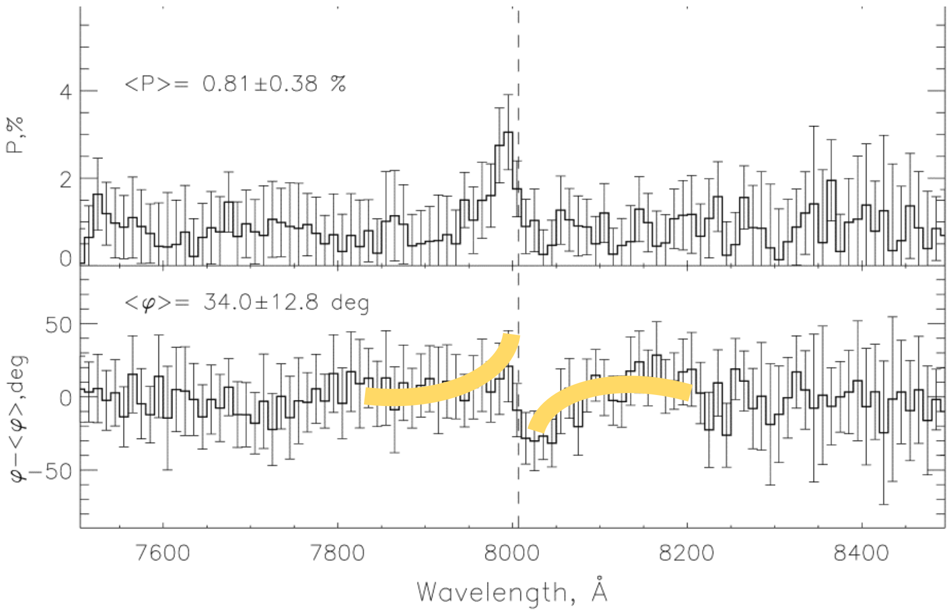
Polarization in broad lines: mass estimation

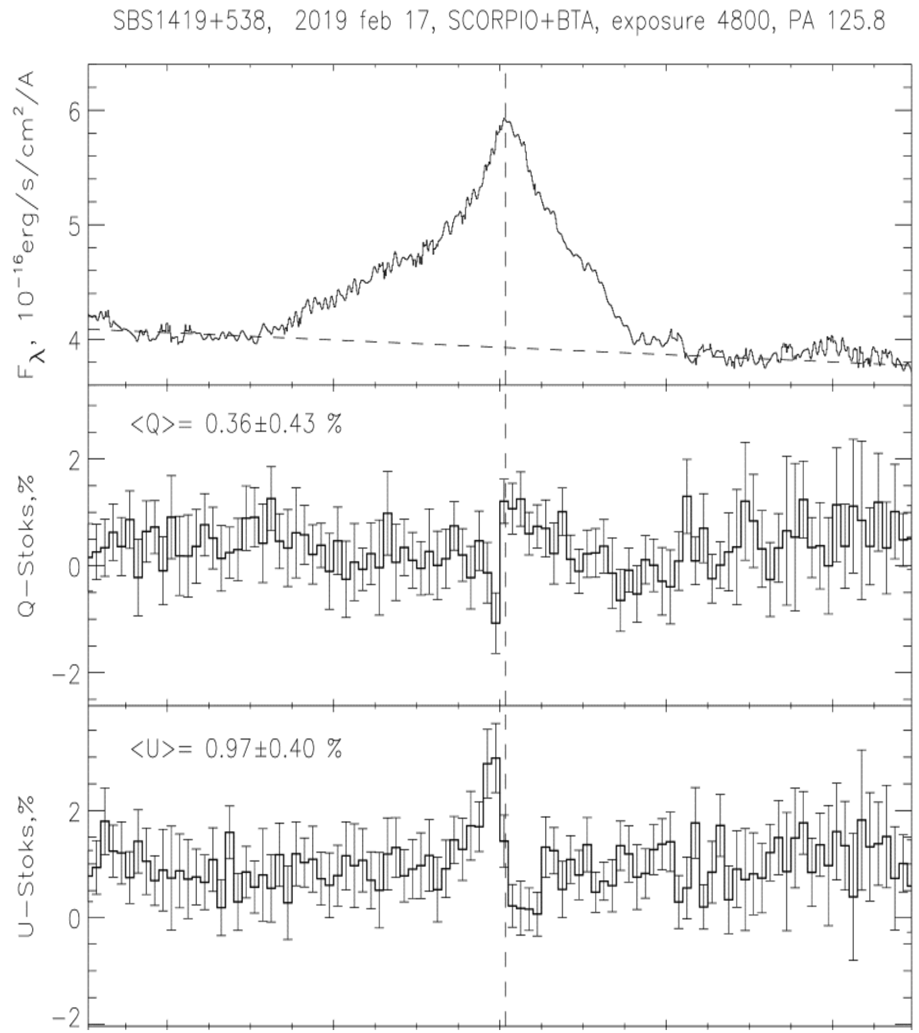
Type 1 AGN SBS 1419+538

$z = 1.862$

- Spectropolarimetry with SCORPIO-2 at 6-m BTA
- Double Wollaston prism
- Exposures: 16 x 300^s

$$\log\left(\frac{M_{BH}}{M_\odot}\right) = 9.59 \pm 0.29$$





Short-term polarization variability

Blazars

The observer looks into the jet, where polarization has the synchrotron origin.

The polarization vector is connected with the plasma trajectory and thus with the magnetic field structure.

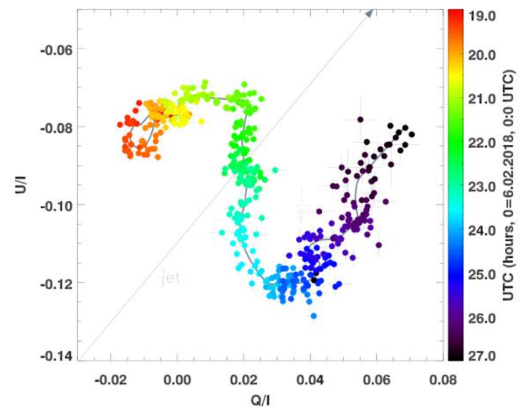
↓

<u>The rotation of the polarization vector</u>

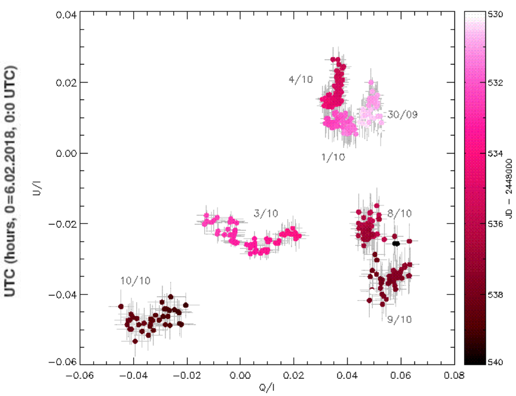
=

<u>The plasma rotation in the magnetic field inside the jet</u>

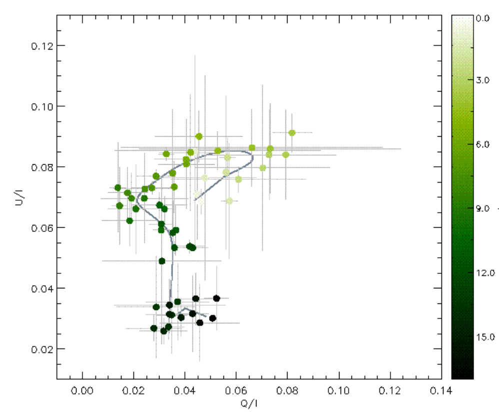
ES&Afanasiev19



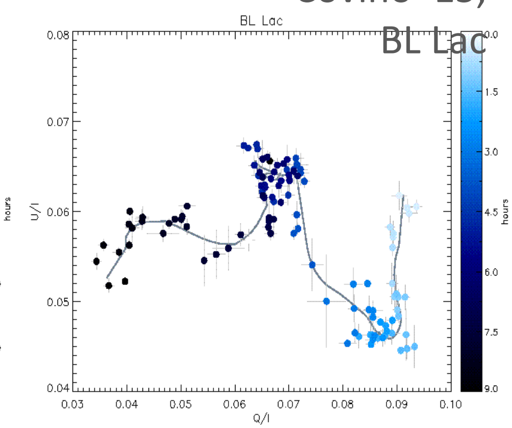
Impey+00



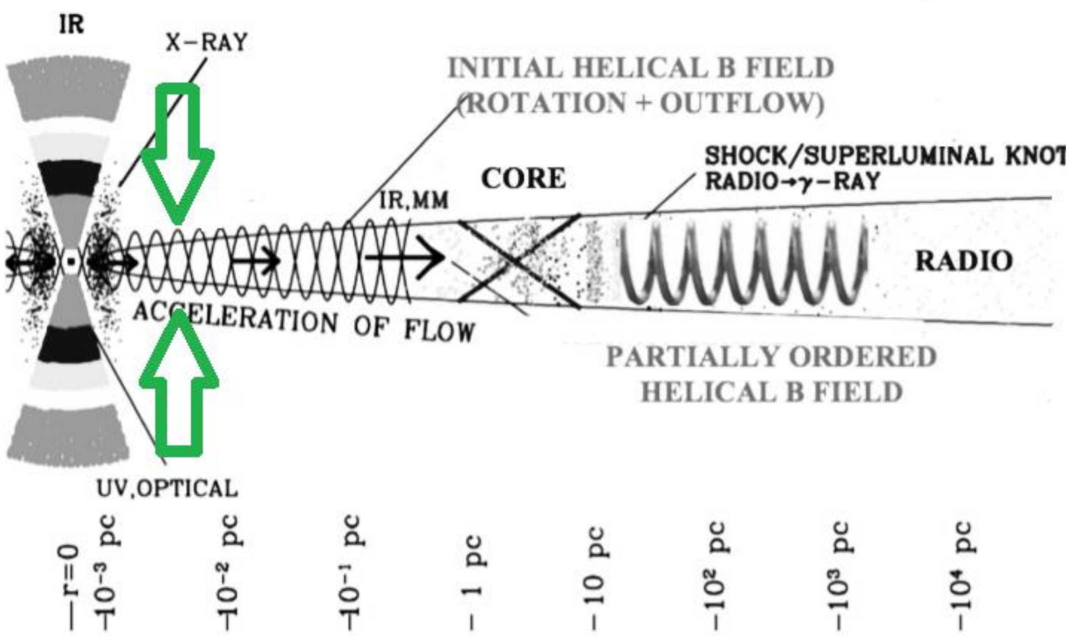
Bhatta+15,16



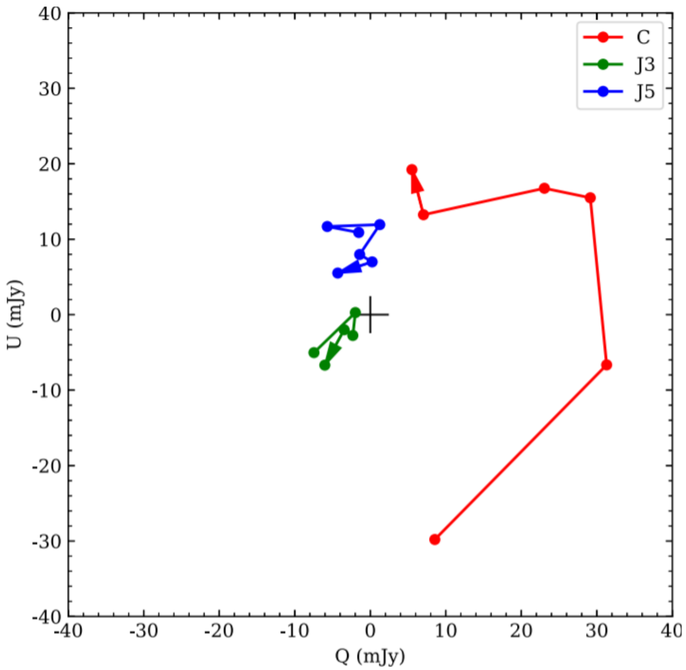
Covino+15, BL Lac



Short-term polarization variability



Li+18: CTA 102



(Marscher05)

Helical magnetic field structure at $< 10^{-2}$ pc from the core.

Conclusions

- The polarization in *continuum* is produced in magnetized AD (0.001-0.01 pc) and depends on:
  - MF in AD $B(R)$;
  - M_{SMBH} and BH spin.
- The polarization in *continuum* consists of the constant $\overrightarrow{disk}$ and the variable $\overrightarrow{jet}$.
- The polarization in *broad lines* resolves the gas kinematics in BLR ($\sim$0.1 pc) $\Rightarrow$ more accurate SMBH mass estimation, independent from the inclination angle.
- *Short-term variability* of the polarization vector in BL Lac type objects marks the plasma kinematics inside the jet $\Rightarrow$ the jet magnetic field structure.