INSTITUTO DE ESTUDIOS ASTROFÍSICOS udp
FACULTAD DE INGENIERÍA Y CIENCIAS

Optical polarimetry of AGN: insights on accretion disk, BLR and dust sublimation

Elena Shablovinskaya

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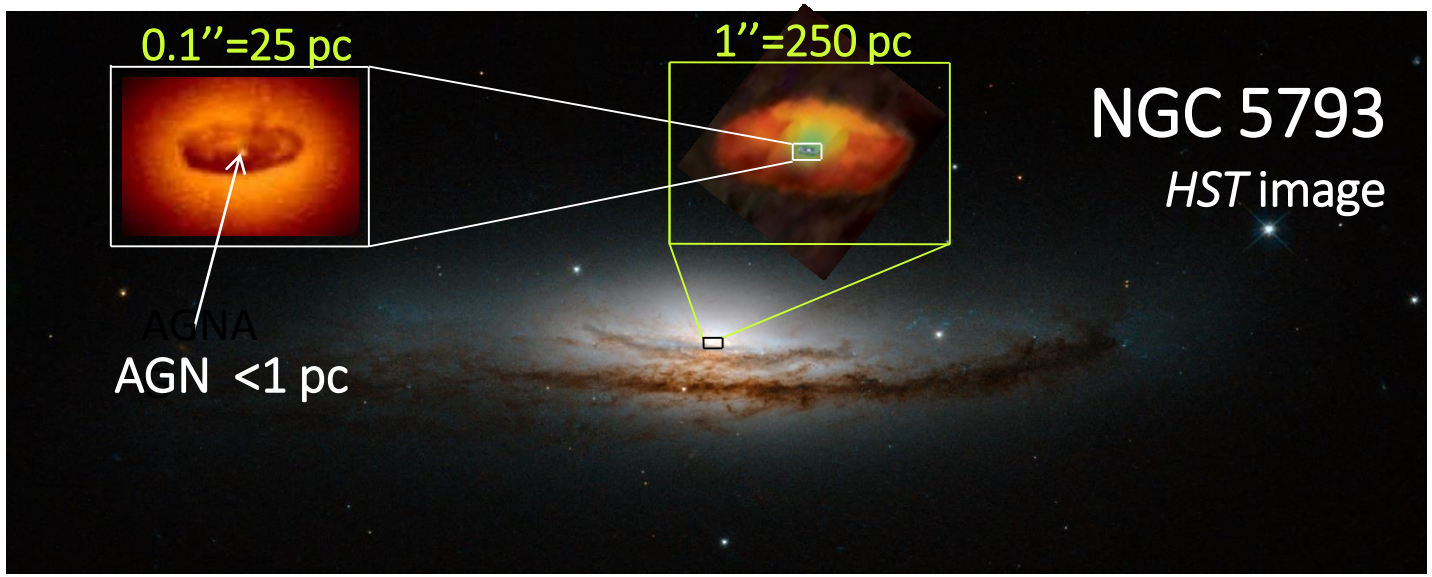
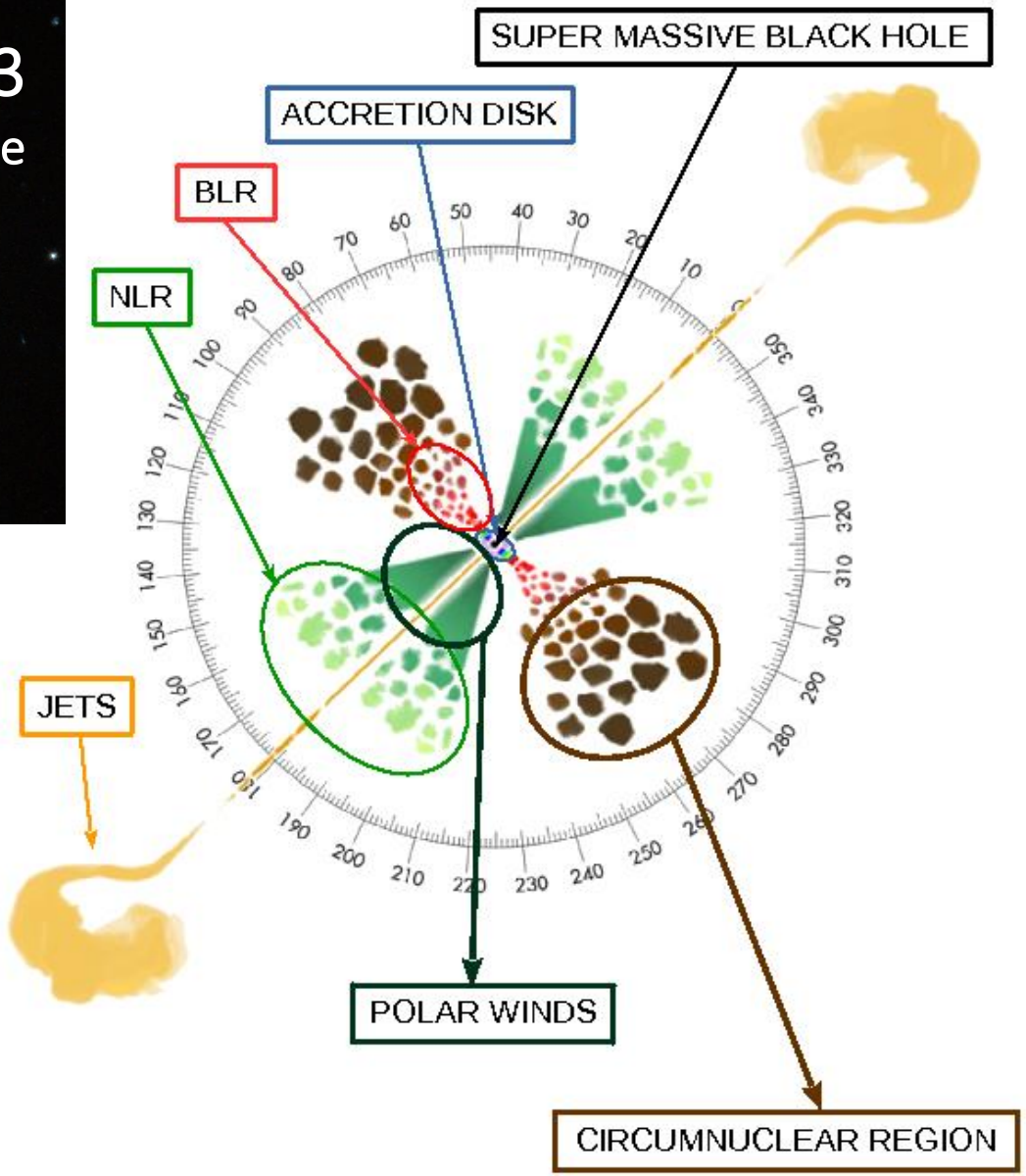
OMNIA IN NUMERO ET MENSURA 1887

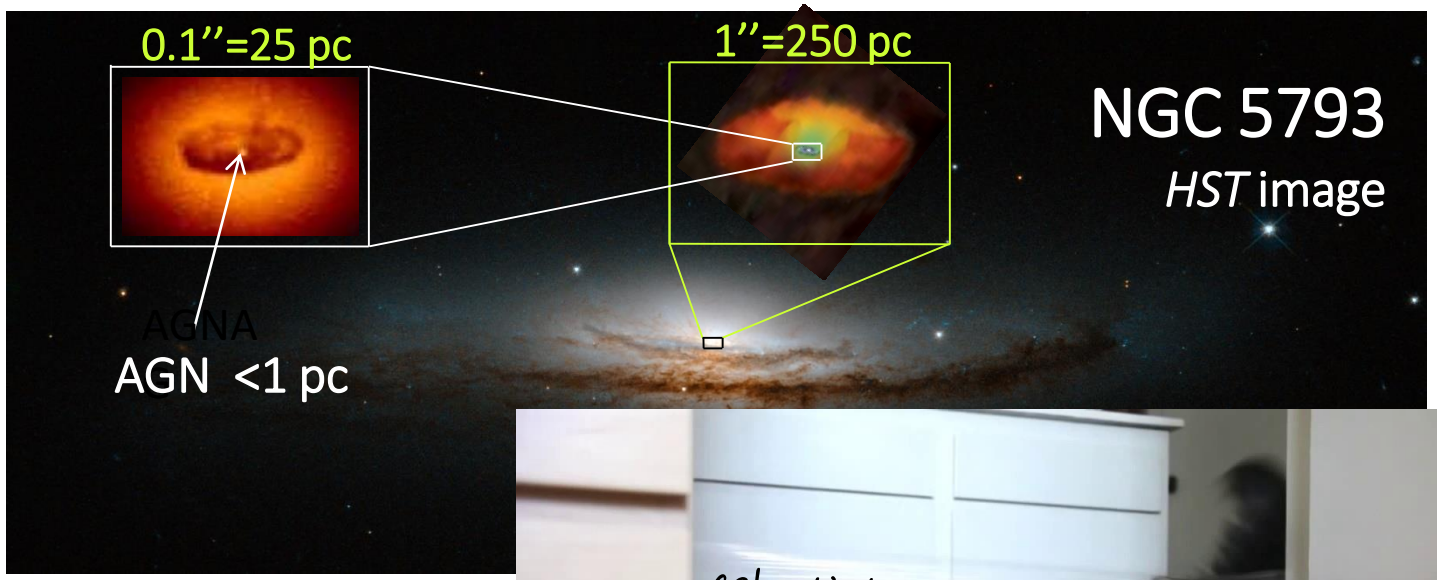
Главная (Пулковская) астрономическая обсерватория РАН

AGN – general

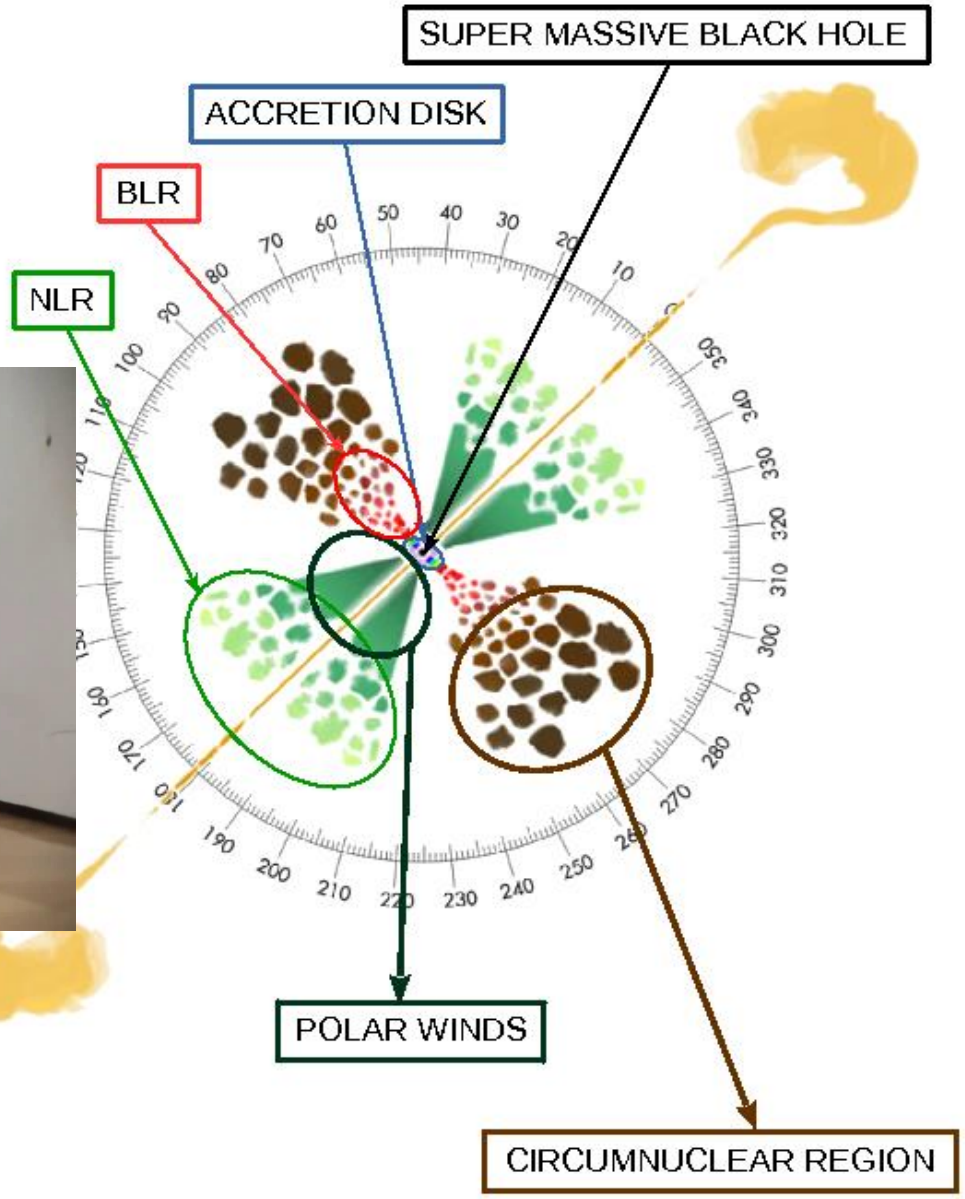

0.1''=25 pc
1''=250 pc
NGC 5793
HST image
AGNA
AGN <1 pc


SUPER MASSIVE BLACK HOLE
ACCRETION DISK
BLR
NLR
JETS
POLAR WINDS
CIRCUMNUCLEAR REGION

AGN – general


0.1''=25 pc
1''=250 pc
NGC 5793
HST image
AGNA
AGN <1 pc


celestial plane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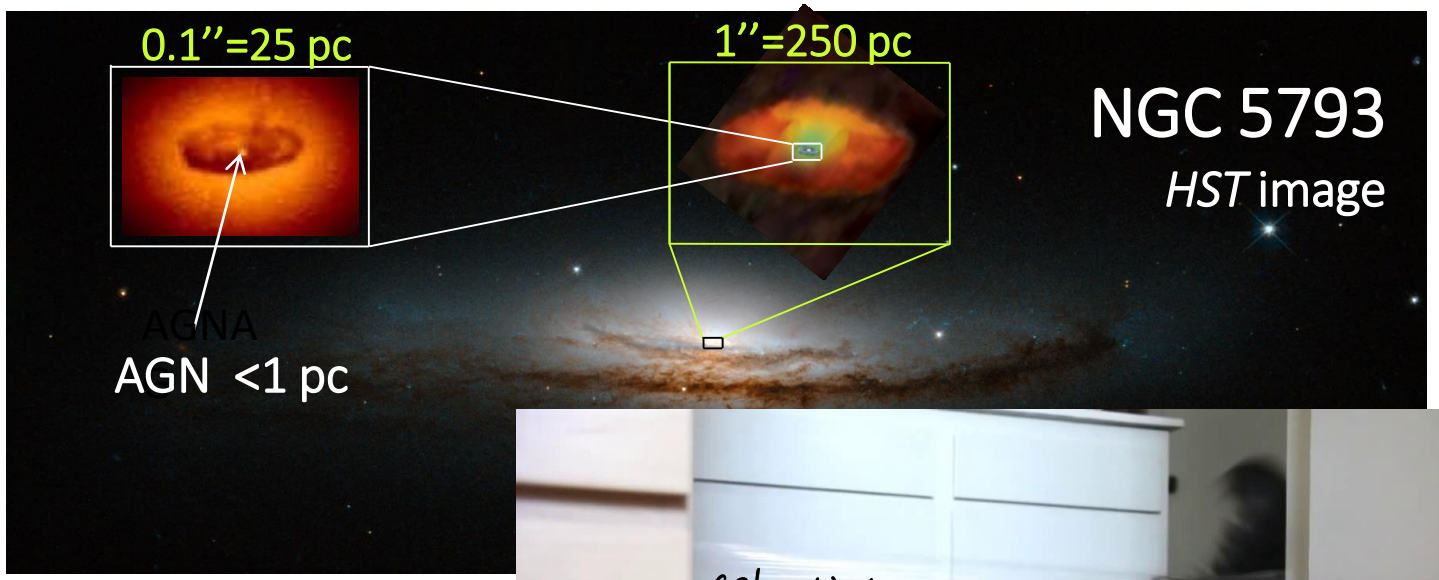
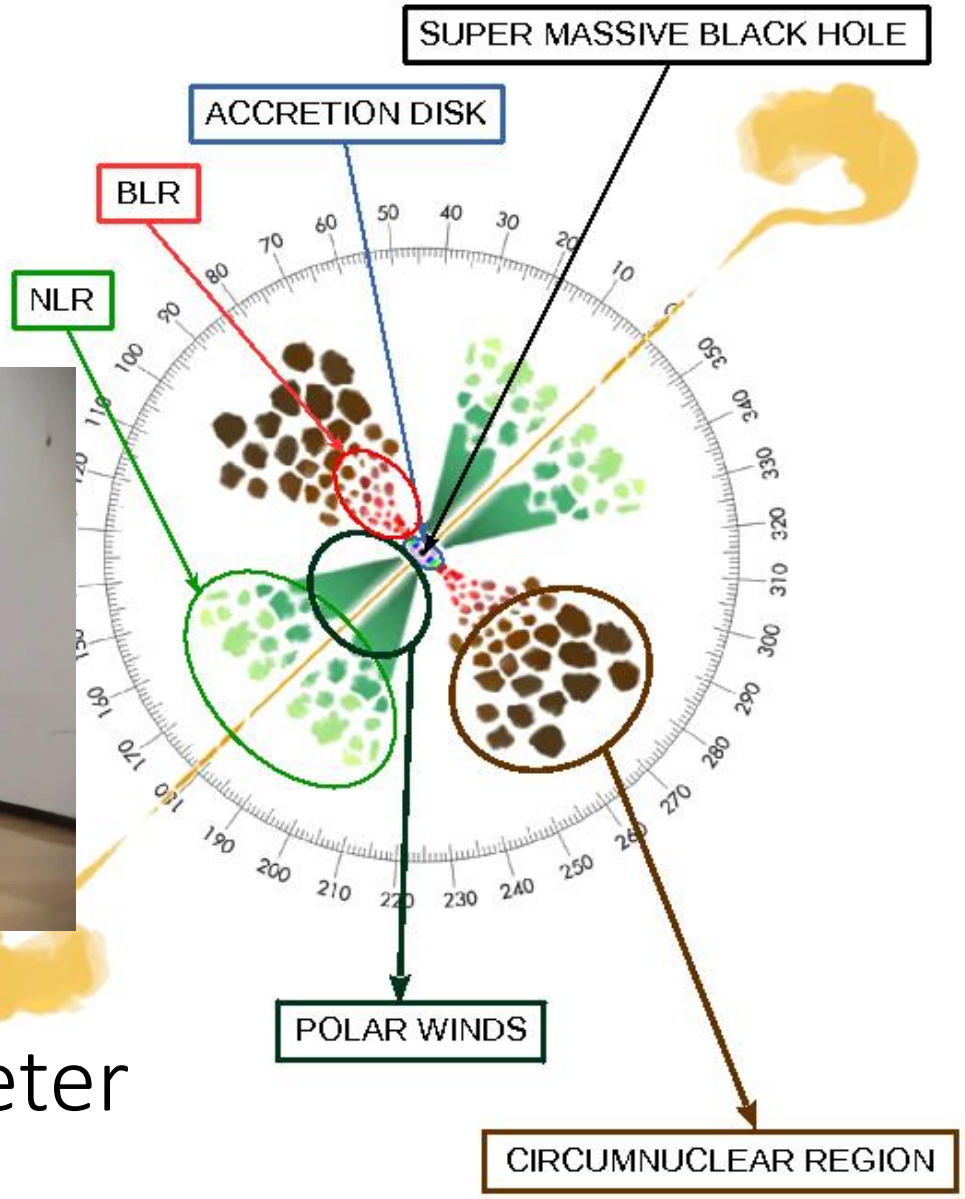
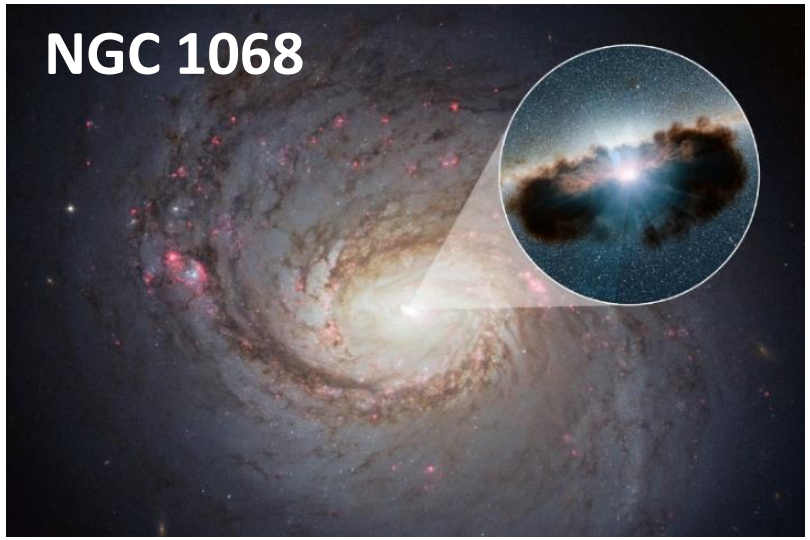
AGN – general

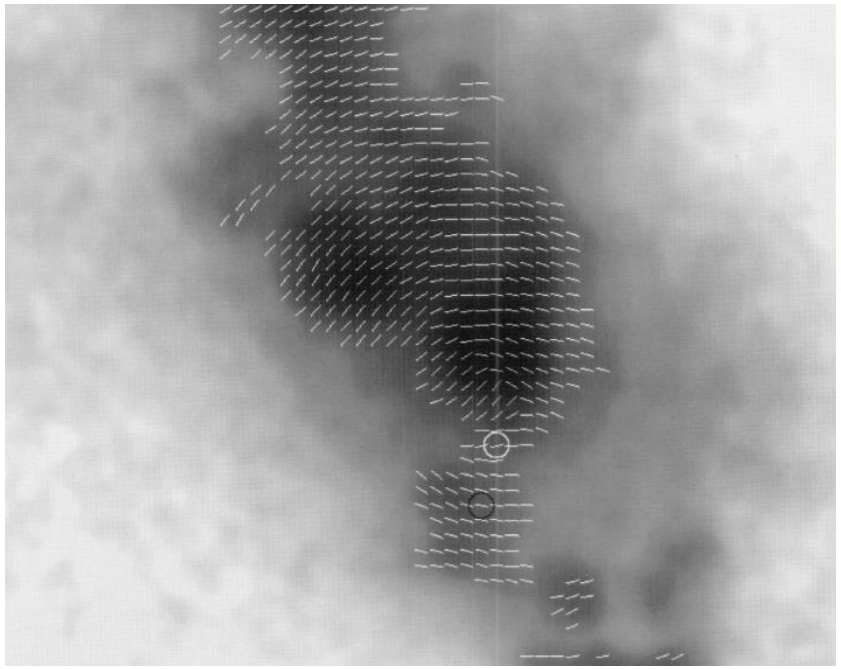




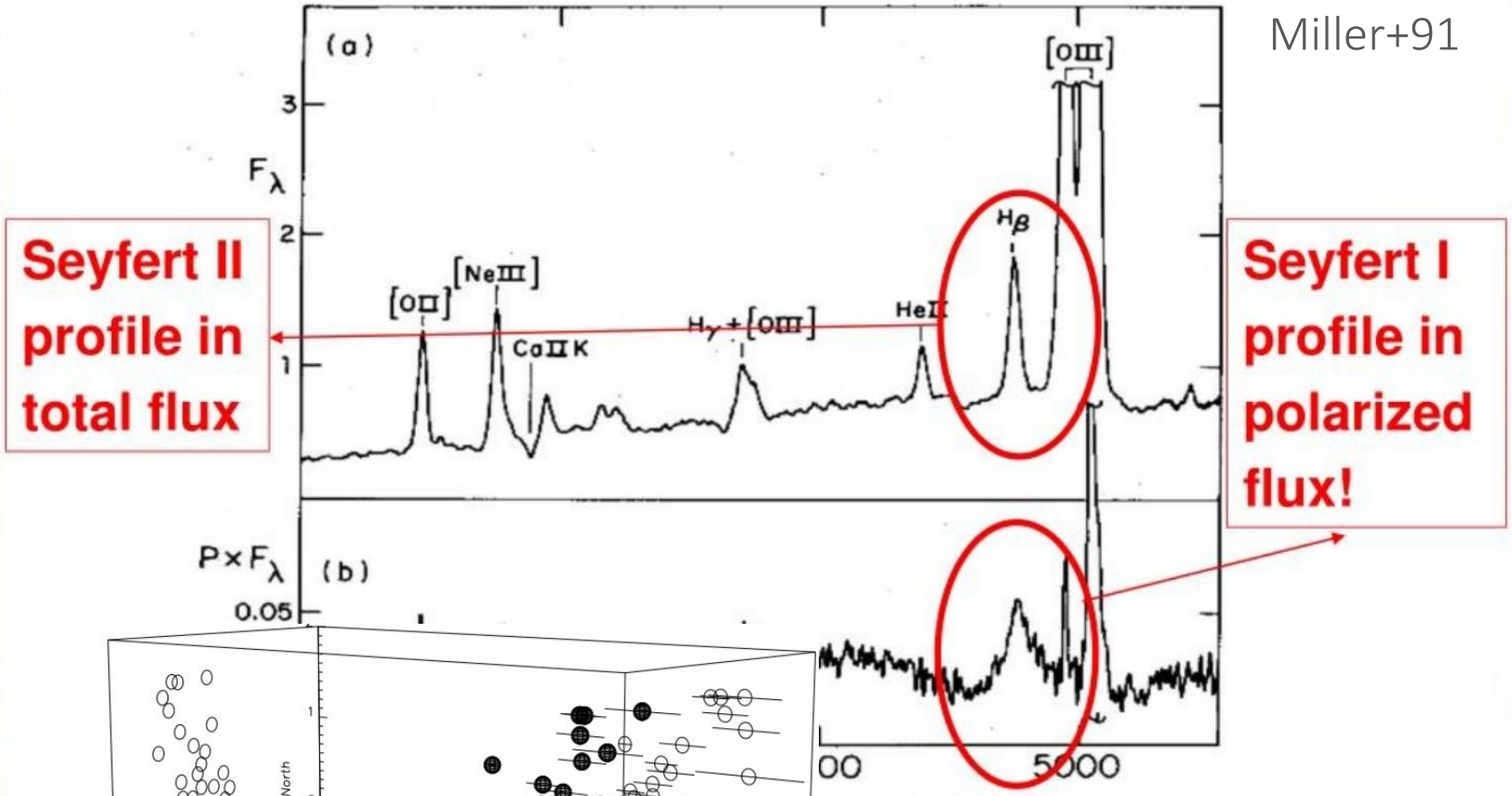
Polarization is an additional parameter

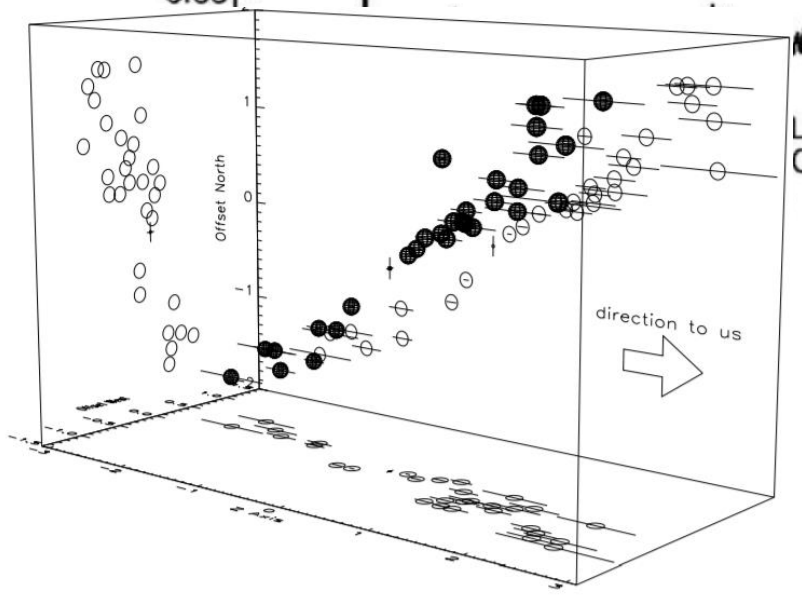
AGN in polarized light





Miller+91



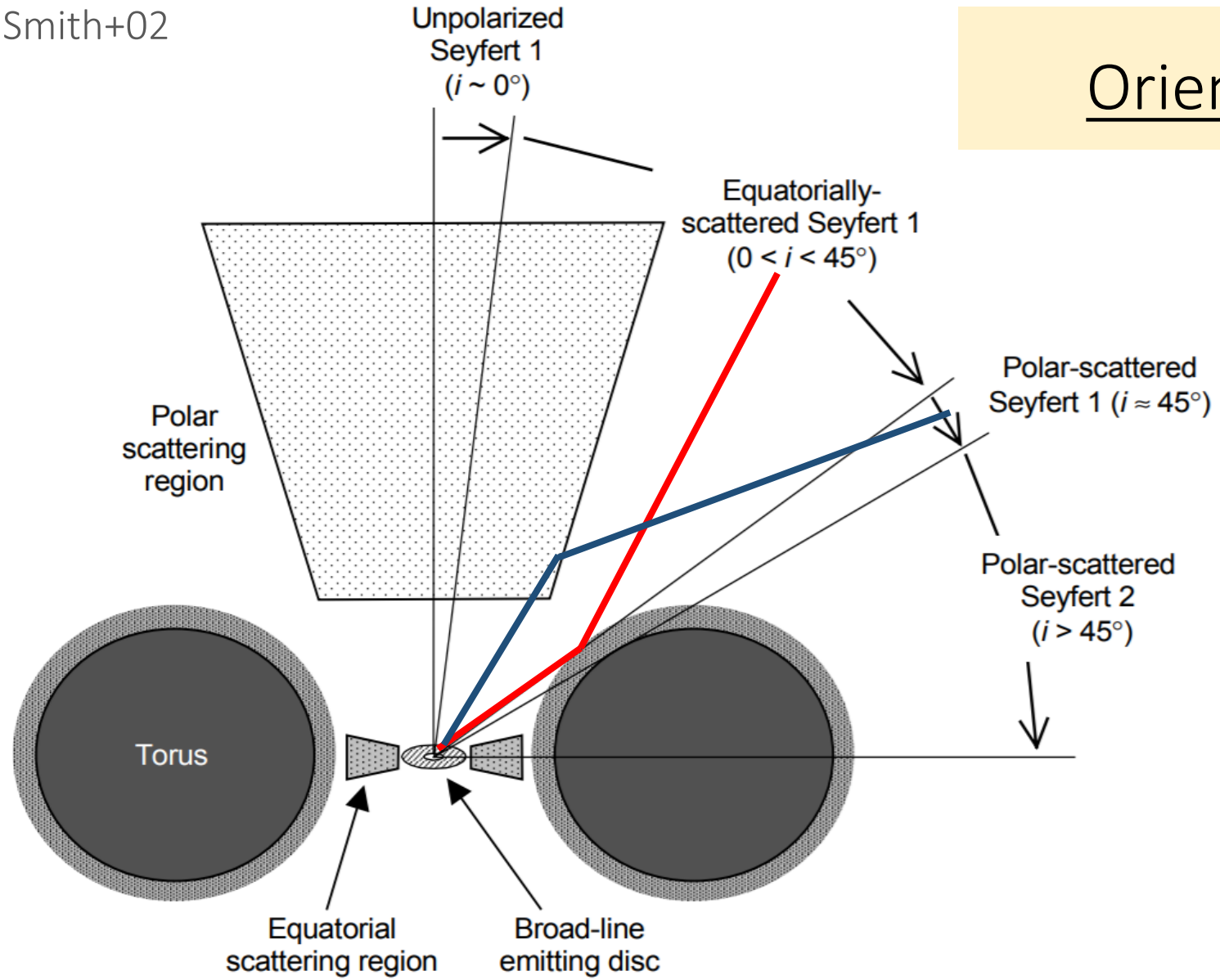


Point-source scattering
2D distribution →
3D clouds distribution

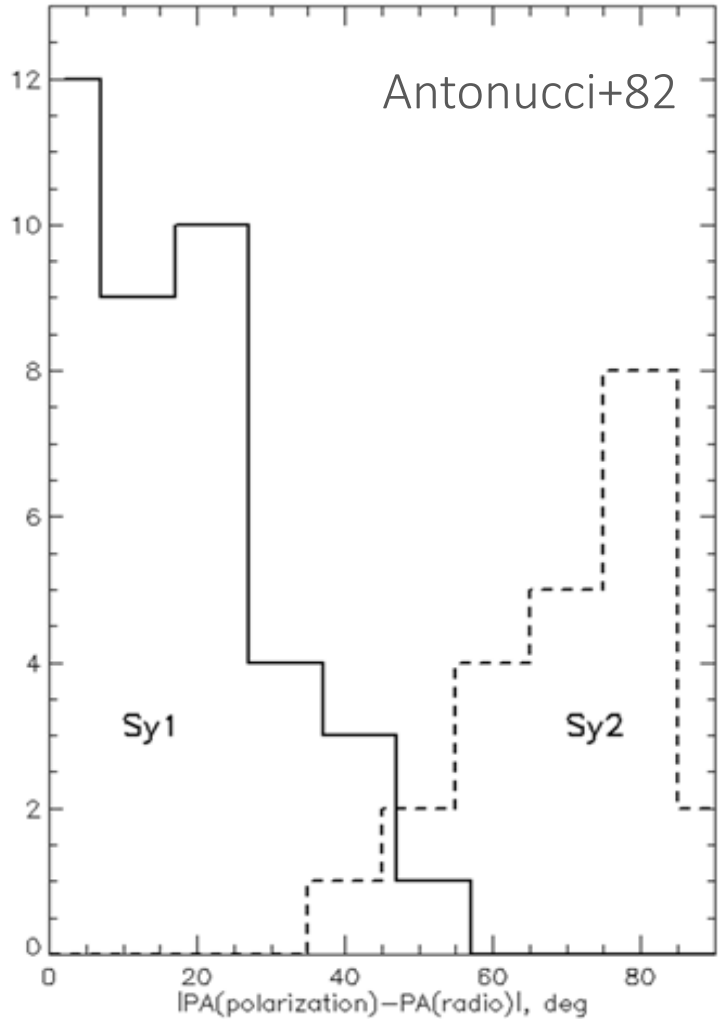
Kishimoto+99

AGN in polarized light

Smith+02



Orientation dependent



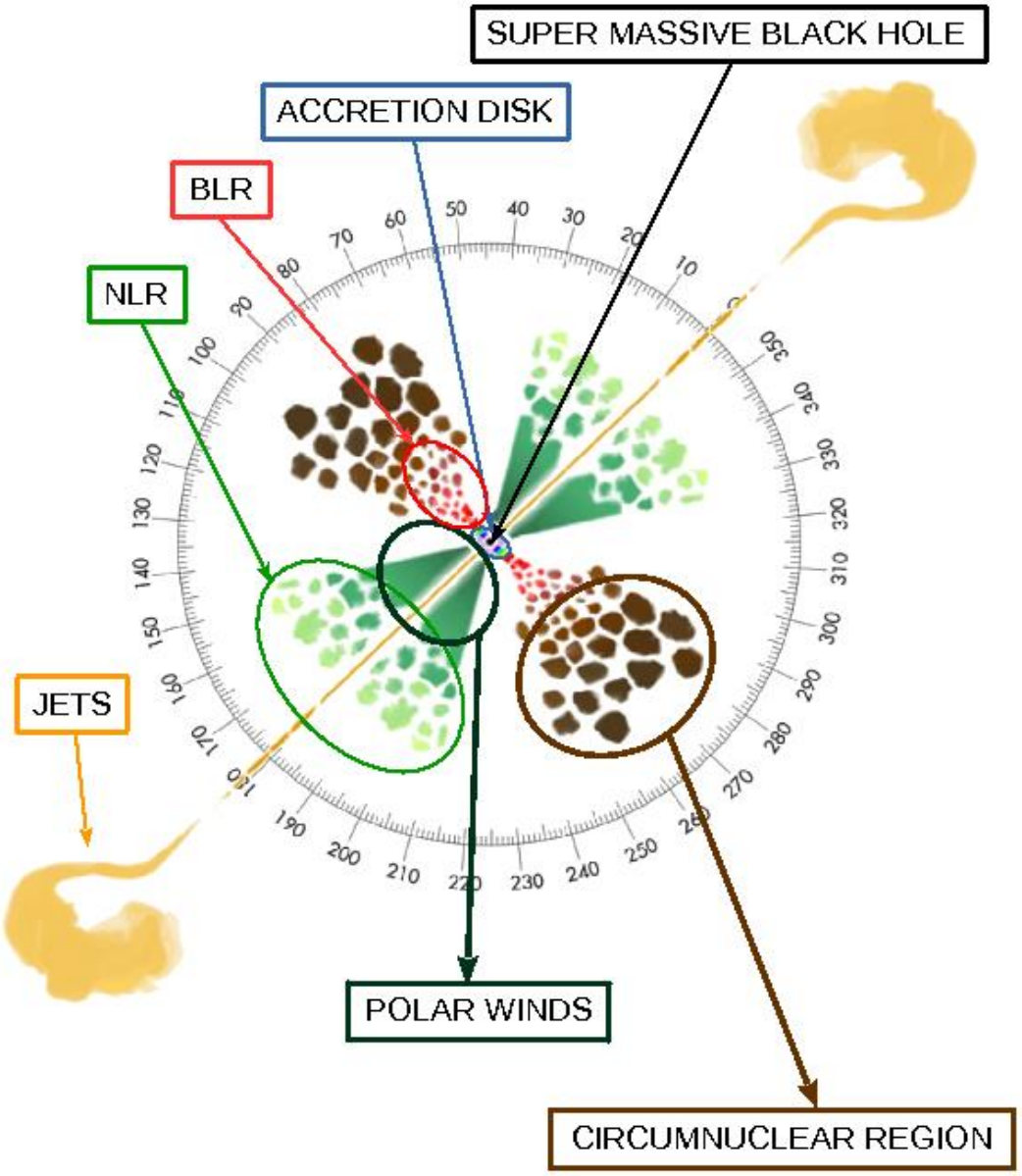
Polarization mechanisms

INSIDE

- Scattering – Thomson, Rayleigh, etc.
- Jet synchrotron radiation
- Faraday rotation

OUTSIDE

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



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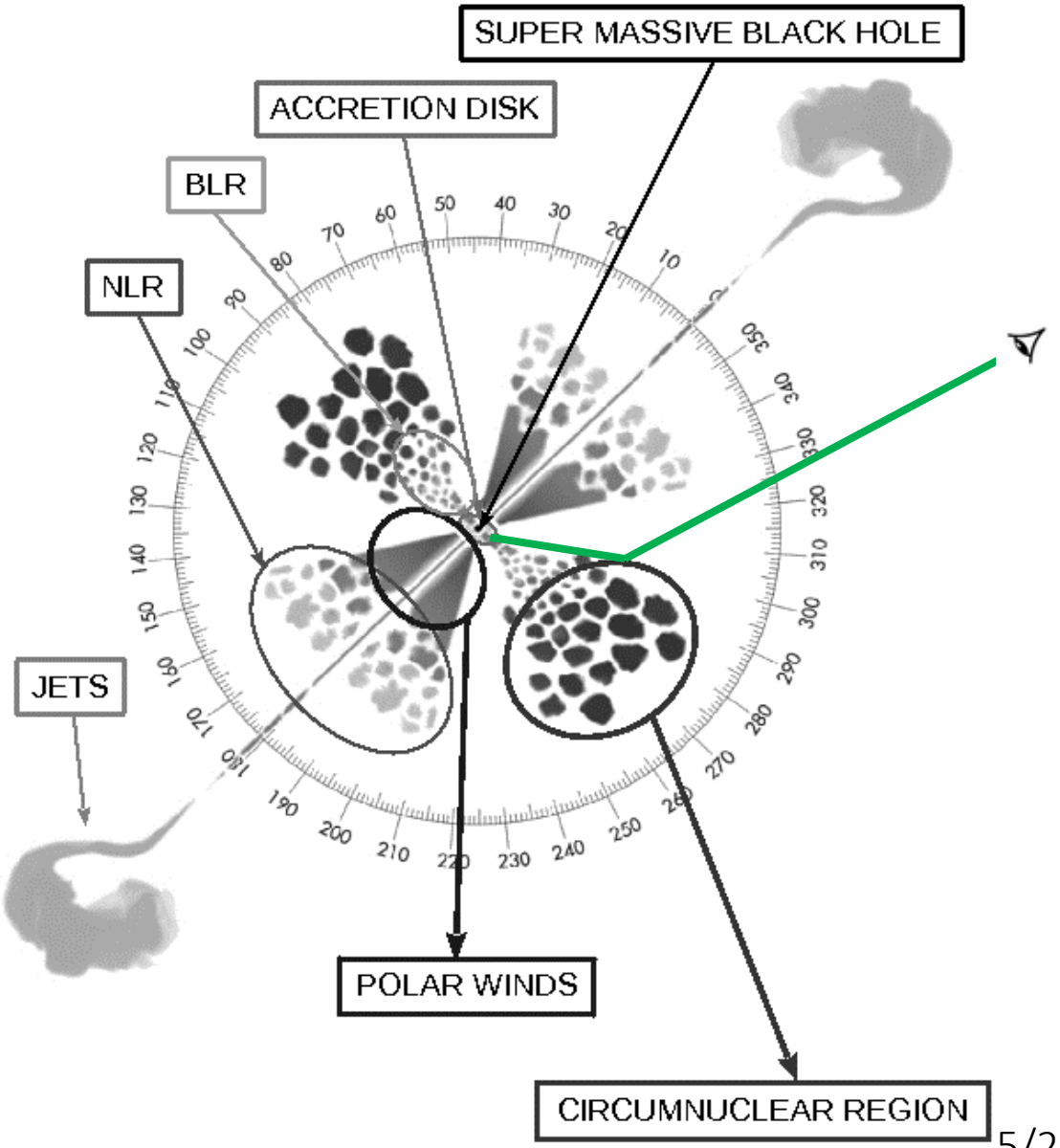


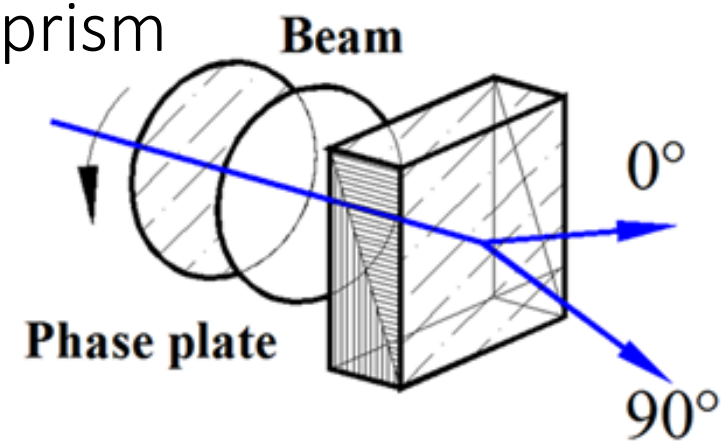
Observational technique

AGN spectropolarimetry:

- 6m BTA/SCORPIO-2
- 8.2m VLT/FORS2
- 8.2m Subaru/FOCAS
- 10m SALT/RSS

Observational technique – basics

Wollaston prism

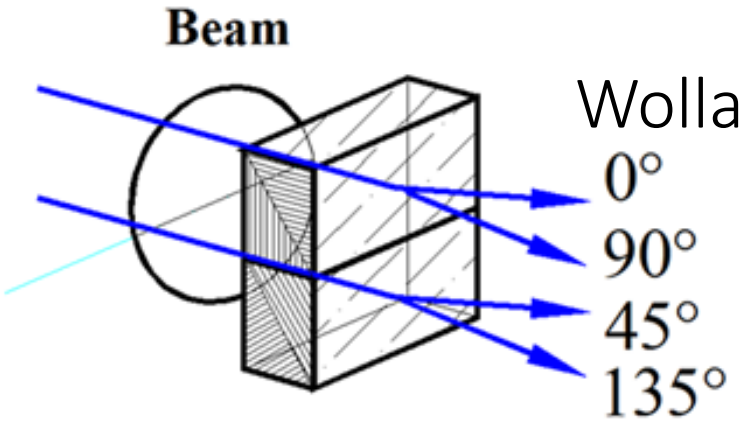


$$Q(\lambda) = \frac{1}{2}\left(\frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)}\right)_{\phi=0} - \frac{1}{2}\left(\frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)}\right)_{\phi=22.5},$$

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

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

Double Wollaston prism



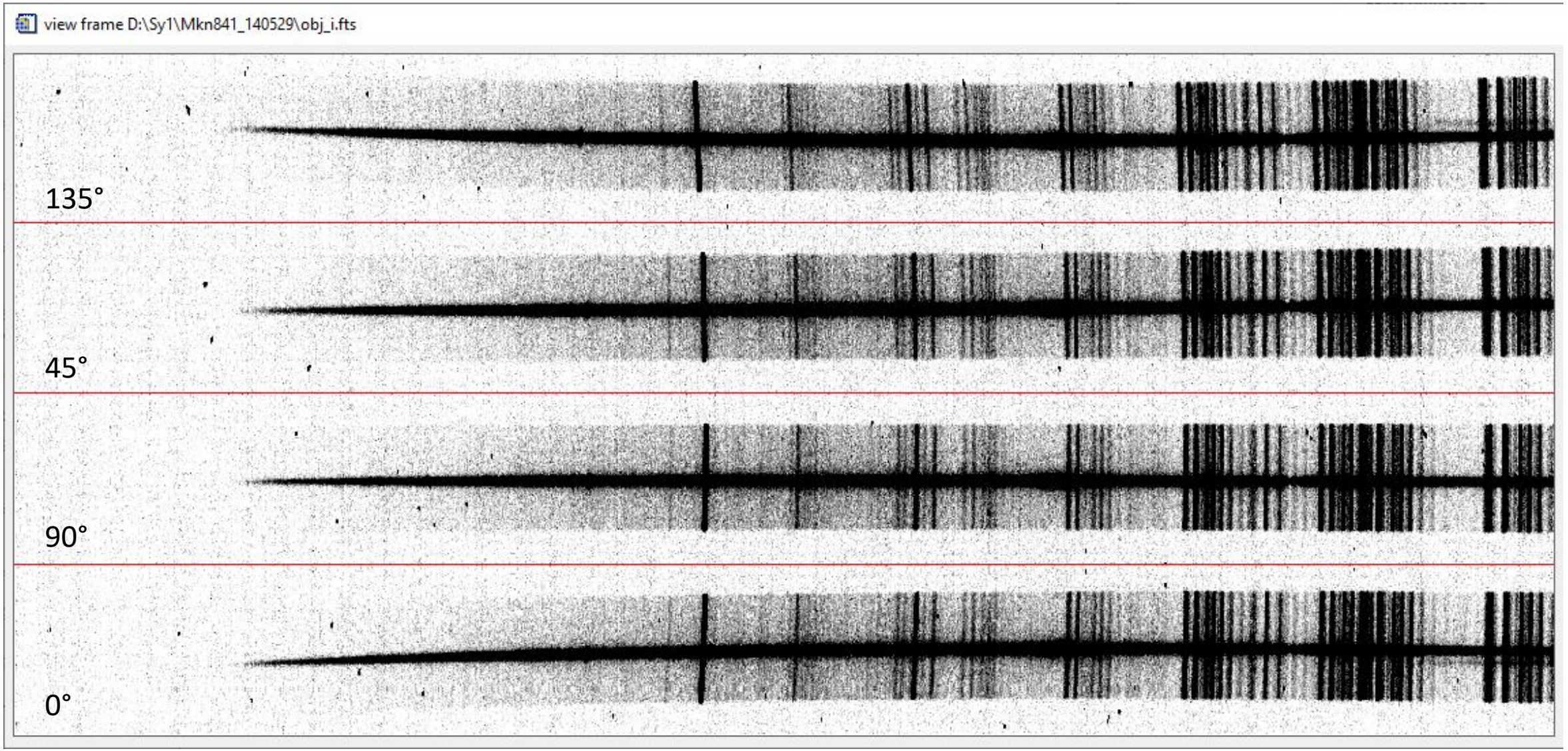
$$Q(\lambda) = \frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)},$$

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

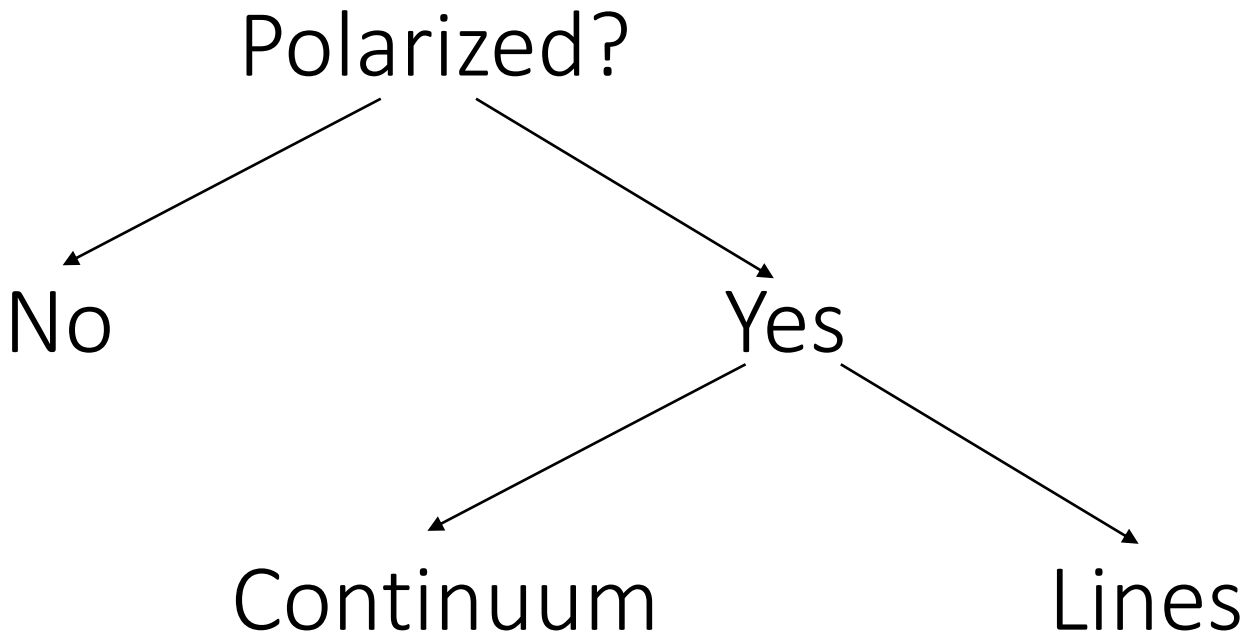
$$I(\lambda) = I_0(\lambda) + I_{90}(\lambda) + I_{45}(\lambda) + I_{135}(\lambda)$$

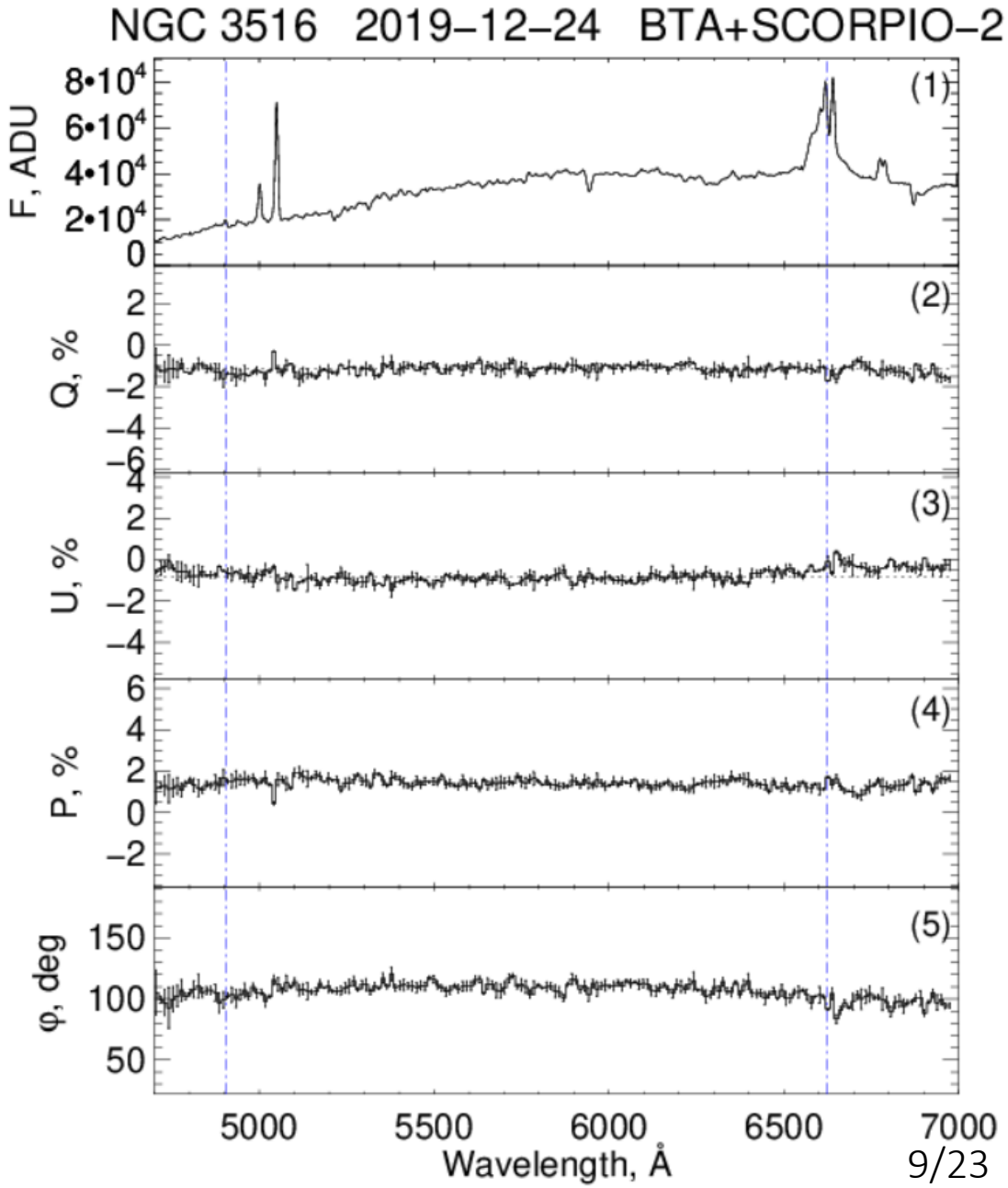
$$P(\lambda) = \sqrt{Q(\lambda)^2 + U(\lambda)^2} \qquad \varphi(\lambda) = \frac{1}{2}\mathrm{arctg}[U(\lambda)/Q(\lambda)]$$

Observational technique



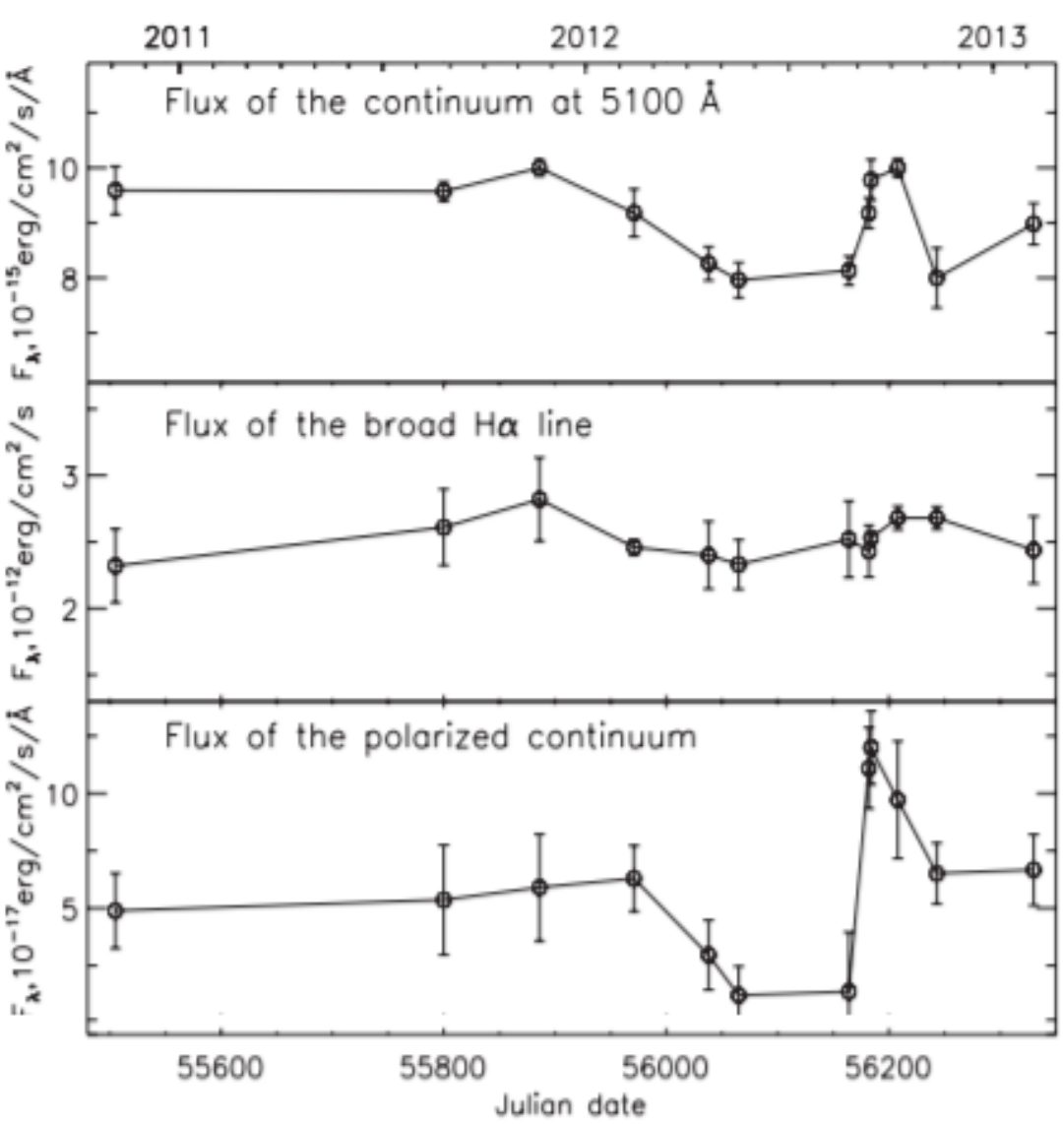
Polarization – how to interpret

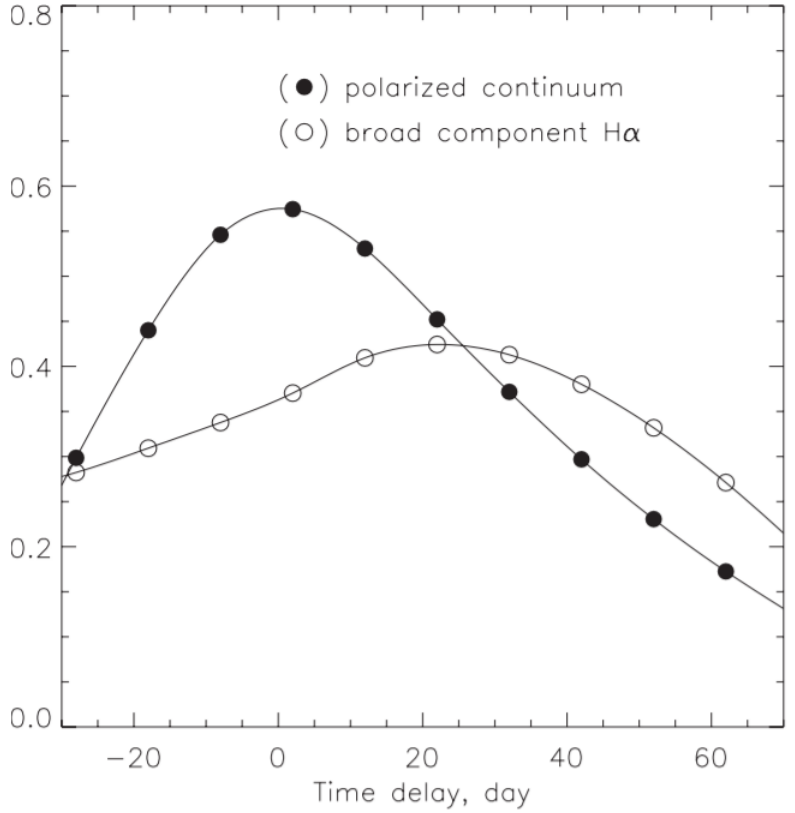




Polarization in continuum: variability

Afanasiev+14,15

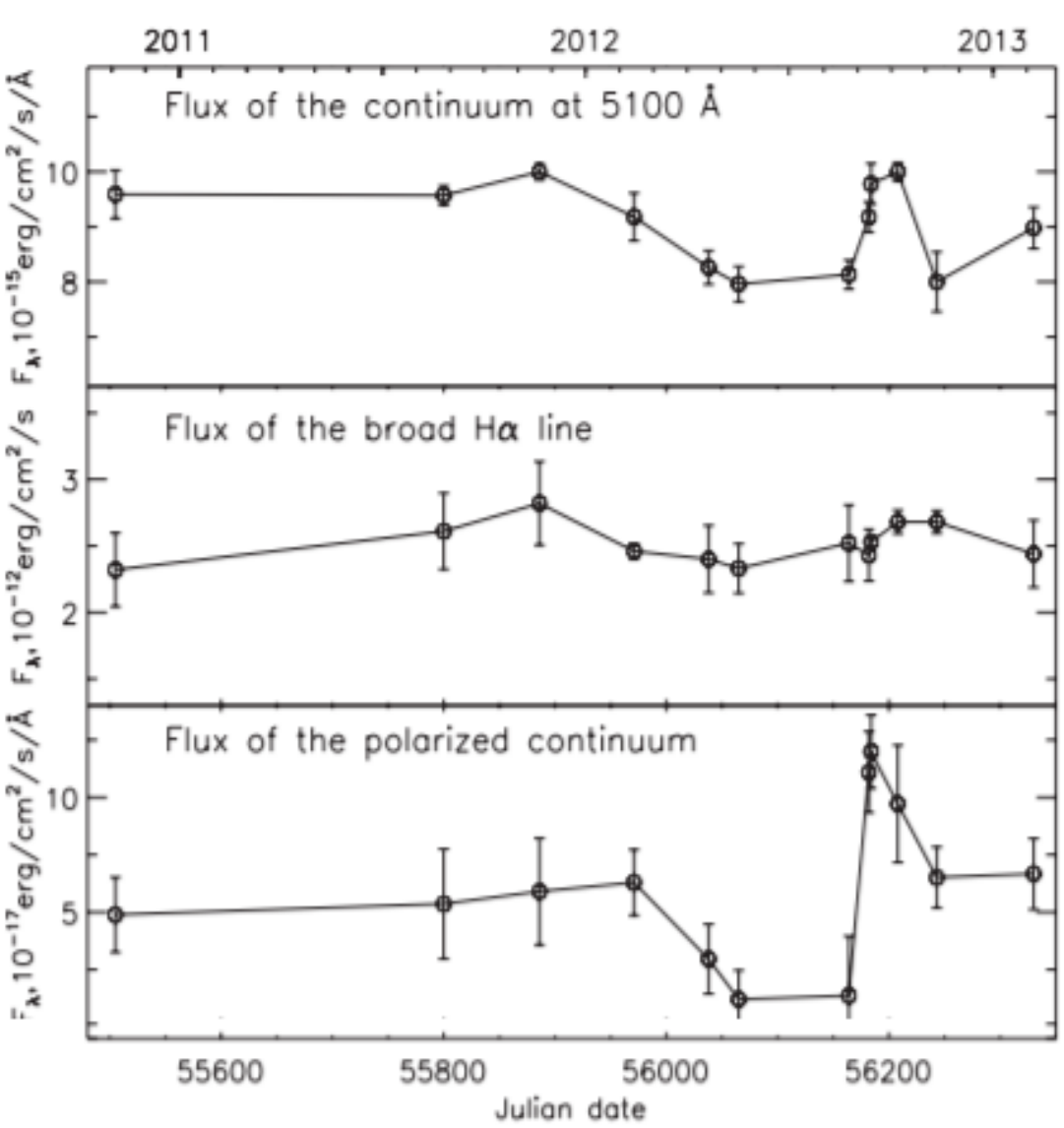




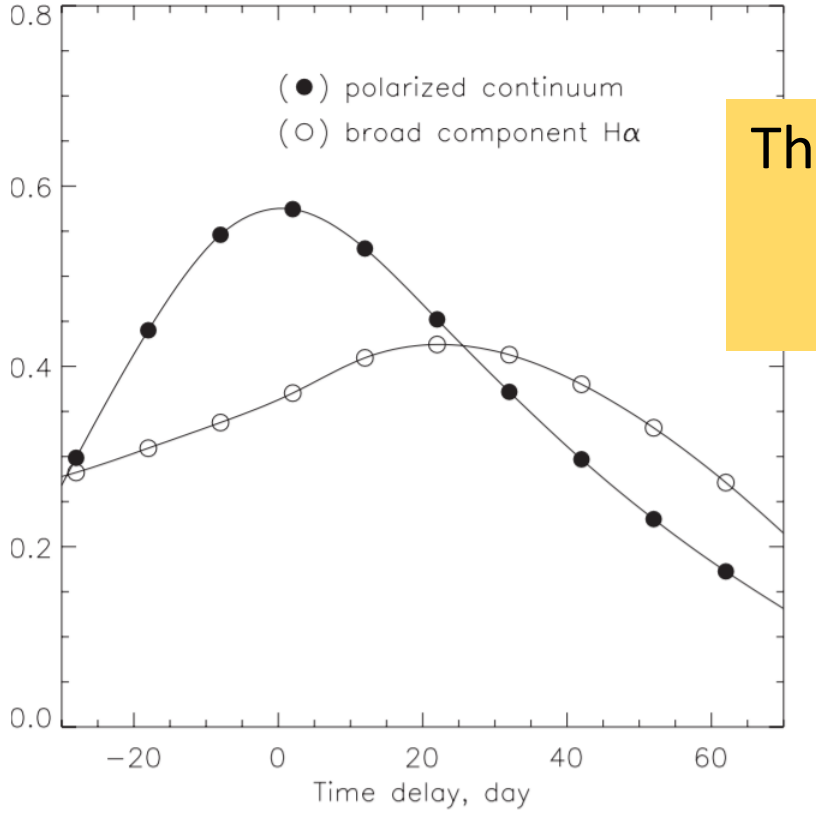
Mrk 6 (Sy 1.5)

- Pol. cont. region – 2 lt days
- BLR Hα – 22 lt days

Polarization in continuum: variability



Afanasiev+14,15



The polarized continuum region is **10 times smaller** than BLR.

Accretion disk

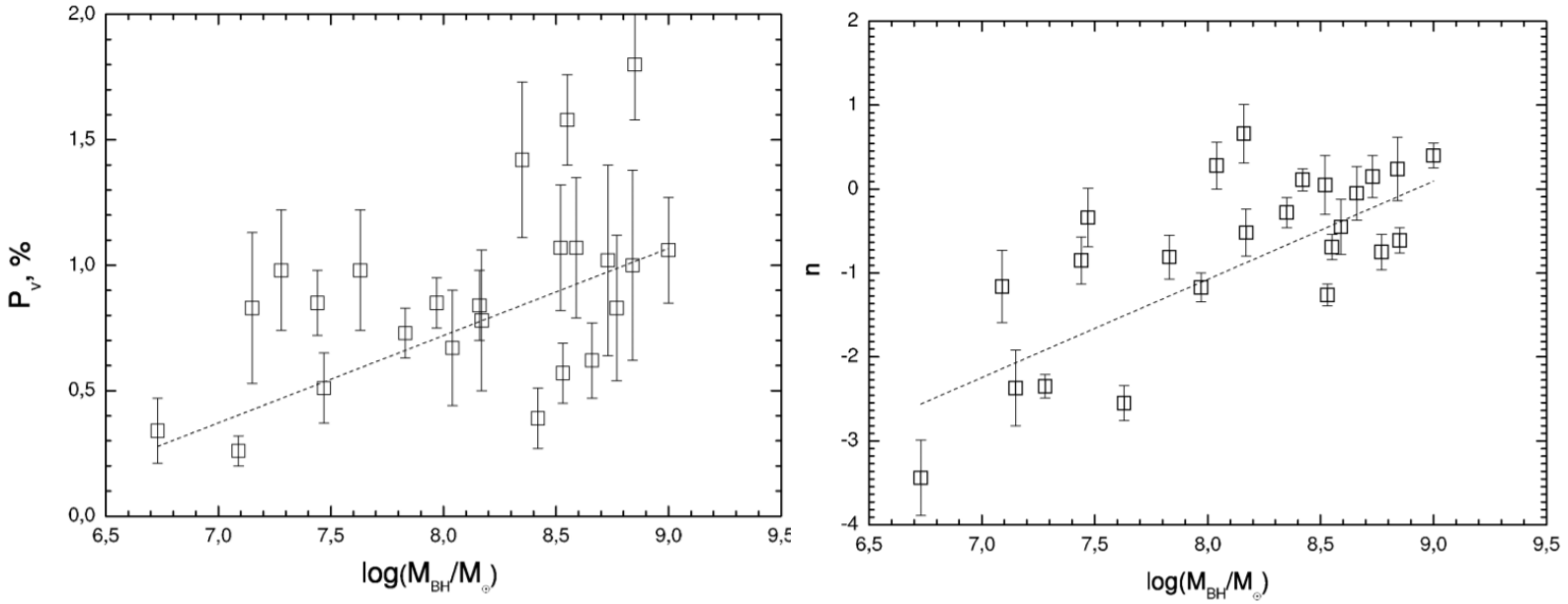
Mrk 6 (Sy 1.5)

- Pol. cont. region – 2 lt days
- BLR Hα – 22 lt days

Polarization in continuum: accretion disk

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.*

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



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

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

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

Magnetic field $B(R)$

Silant'ev+07

Polarization in continuum: SMBH spin

Afanasiev+18: SMBH spins

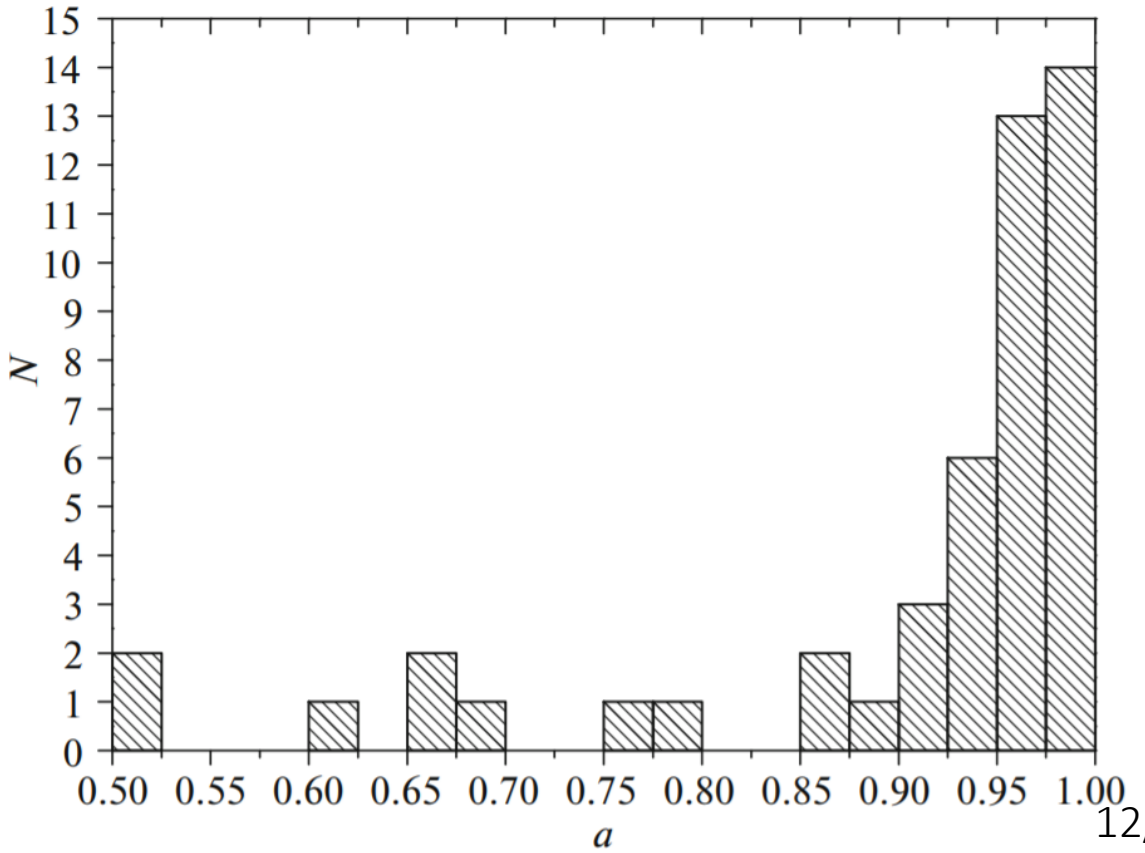
$$\mu^{3/2} l_E = 0.201 \left(\frac{L_{5100}}{10^{44} erg\ s^{-1}} \right)^{3/2} \frac{\varepsilon(\boldsymbol{a})}{M_8^2}$$

$$\left. \begin{array}{l} \\ \\ \end{array} \right\} \varepsilon(a) \Rightarrow a$$

P_l: observations vs. Sobolev-Chandrasekhar theory $\Rightarrow \mu = \cos^2(i)$

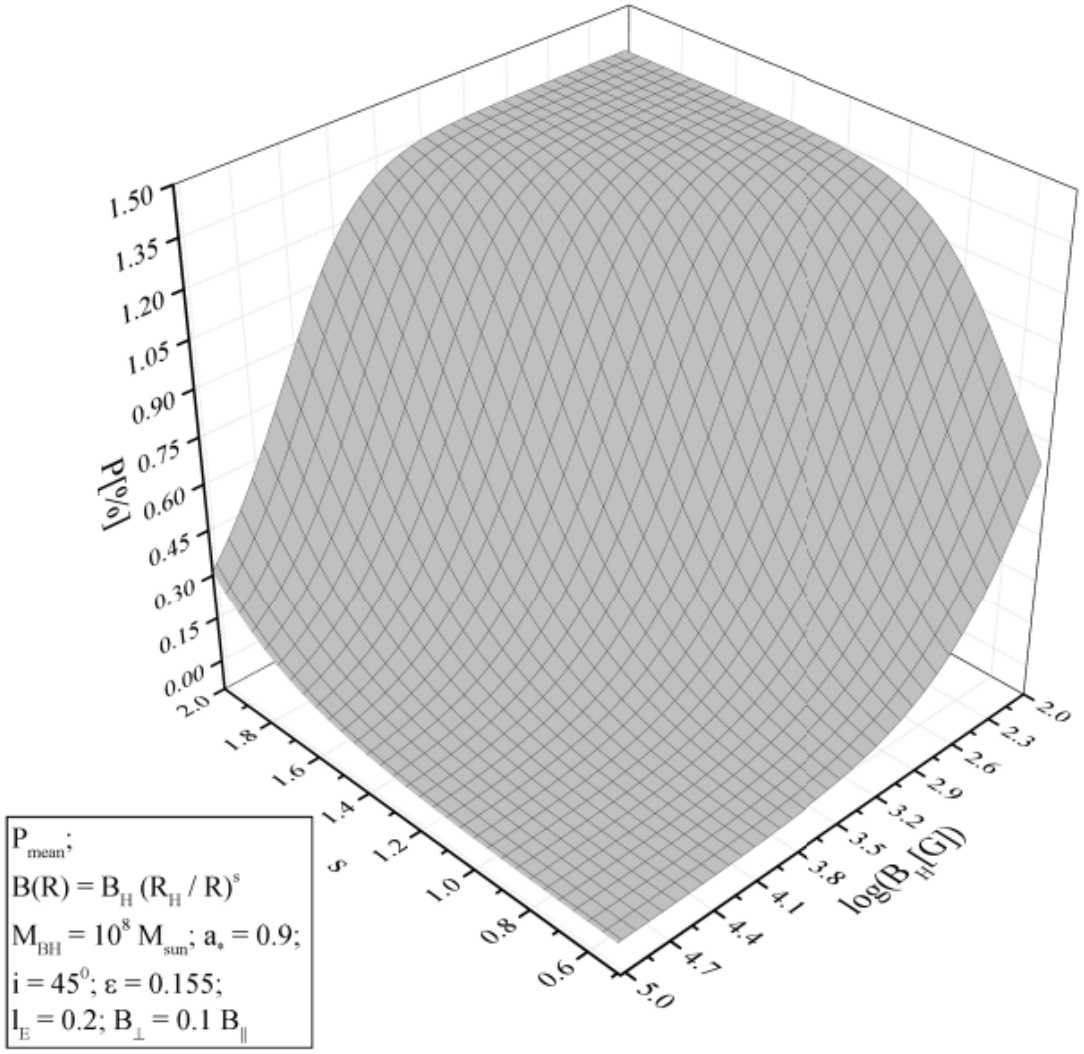
47 type 1 active galaxies

Kerr supermassive black holes

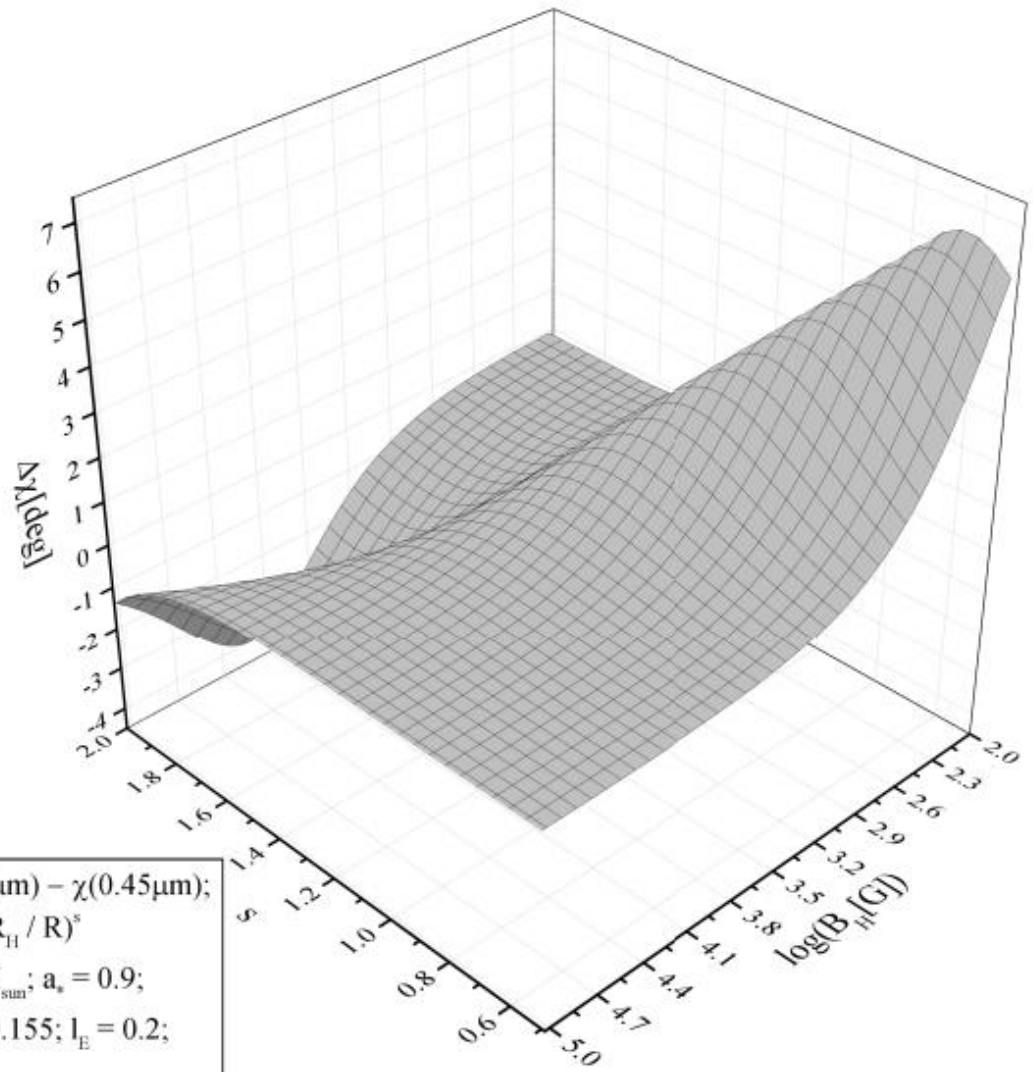


Polarization in continuum

Piotrovich+21



P_{mean};
$B(R) = B_H (R_H / R)^s$
$M_{BH} = 10^8 M_{sun}$; $a_* = 0.9$;
$i = 45^0$; $\varepsilon = 0.155$;
$l_E = 0.2$; $B_\perp = 0.1 B_\parallel$

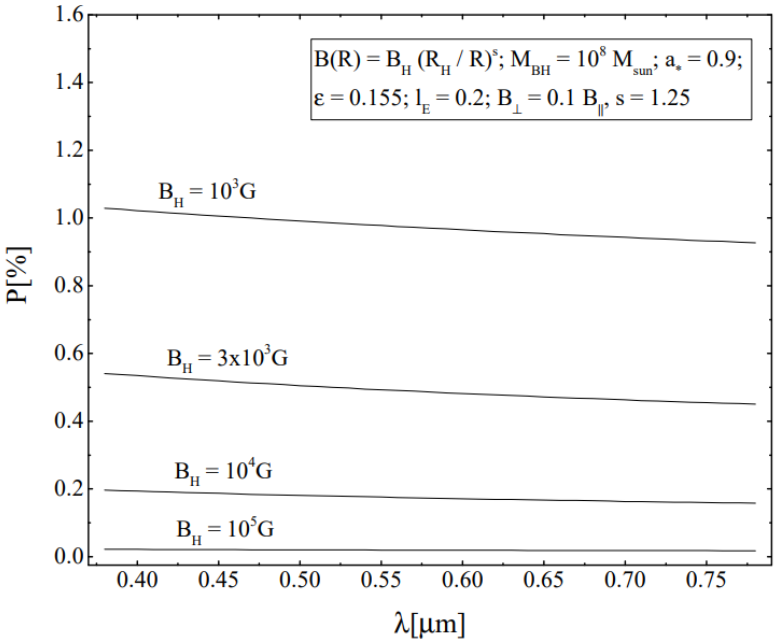


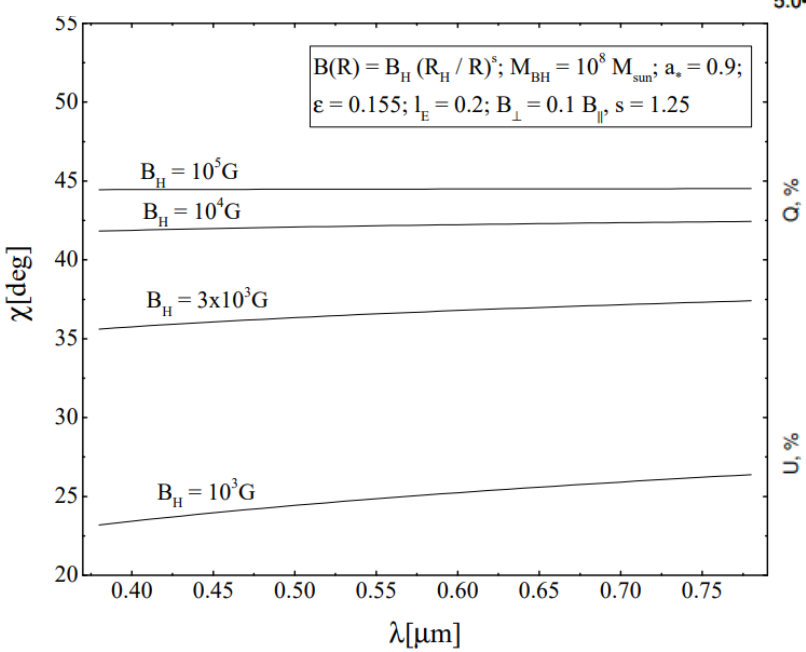
$\Delta\chi = \chi(0.70\mu m) - \chi(0.45\mu m)$;
$B(R) = B_H (R_H / R)^s$
$M_{BH} = 10^8 M_{sun}$; $a_* = 0.9$;
$i = 45^0$; $\varepsilon = 0.155$; $l_E = 0.2$;
$B_\perp = 0.1 B_\parallel$

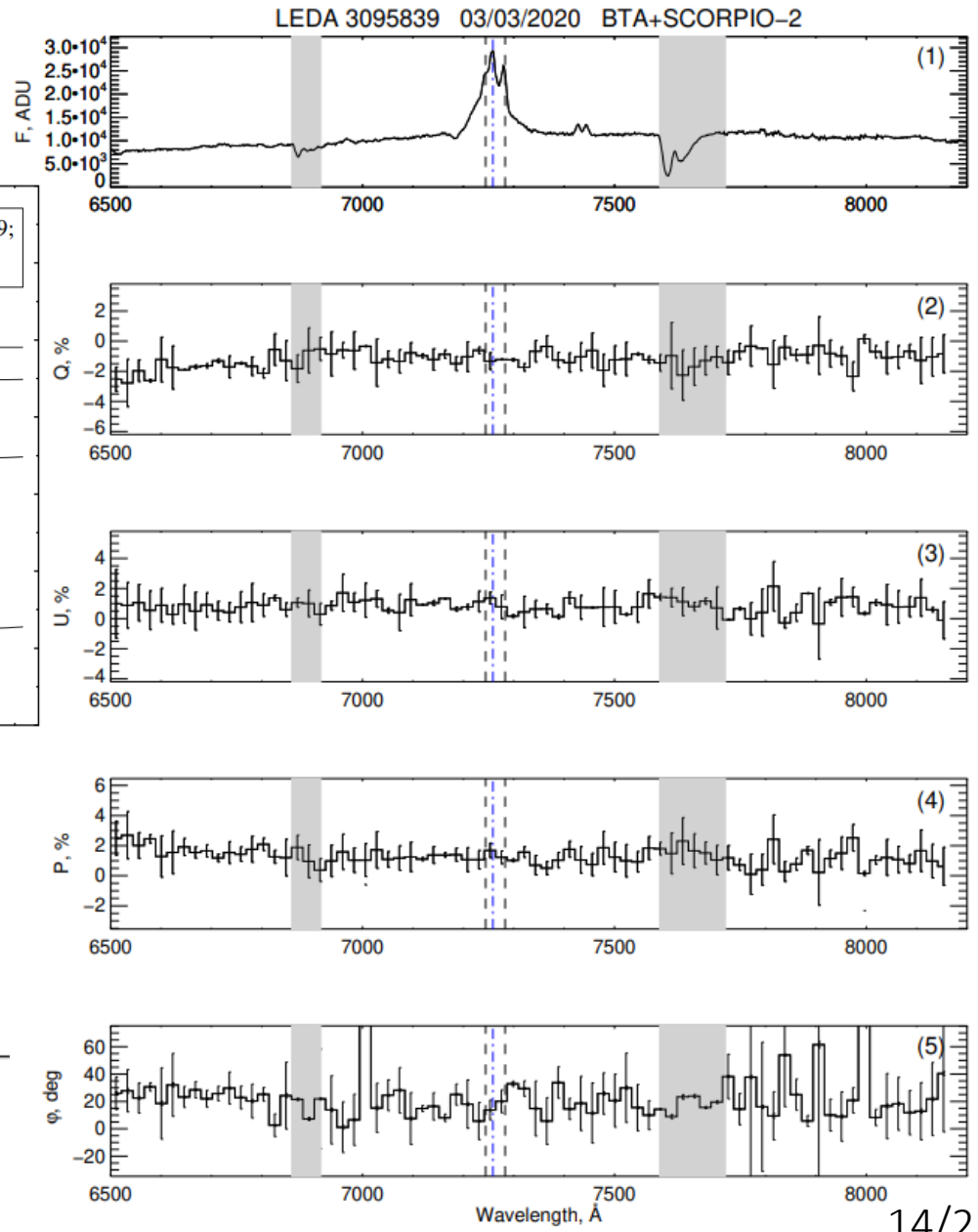
Polarization in continuum

J0853+77 = LEDA 3095839

$< P > = 0.9 \pm 0.4\%$



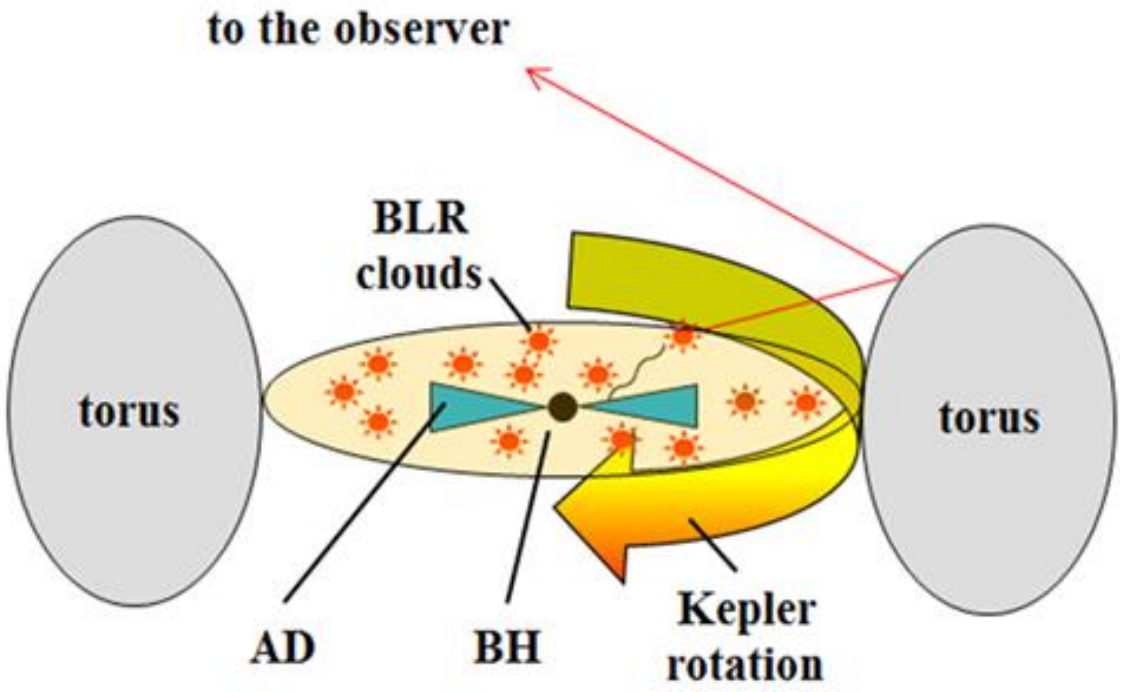


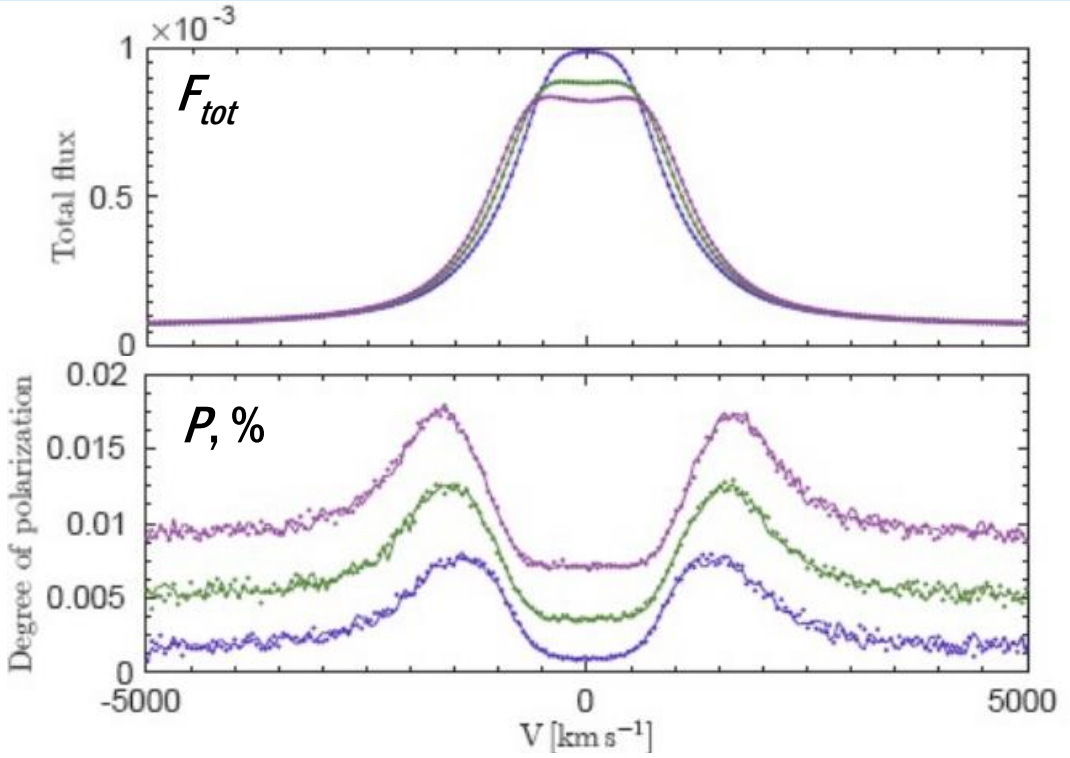


$$\varepsilon(a) = 0.105 \left(\frac{L_{\rm bol}}{10^{46}{\rm erg/s}} \right) \left(\frac{L_{5100}}{10^{45}{\rm erg/s}} \right)^{-1.5} M_8 \mu^{1.5}.$$

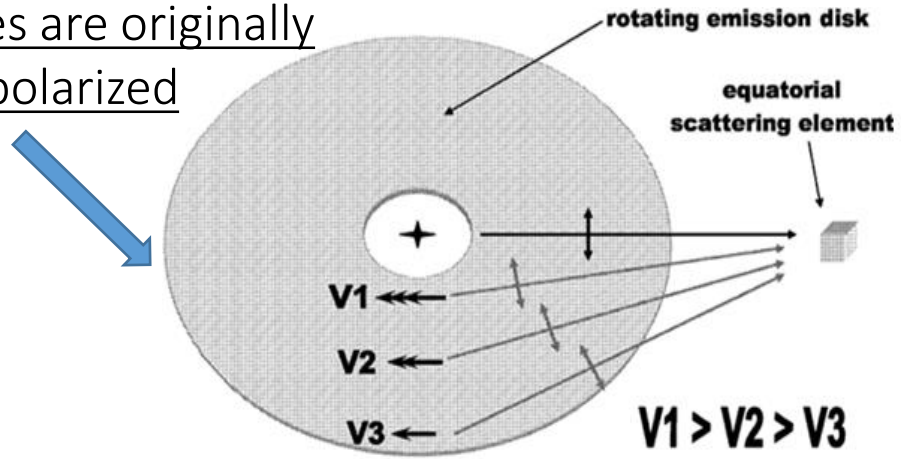
$log(M_{\rm BH}/M_\odot)$	$\log(L_{\rm bol})$	i	a	$log(B_{\rm H})$	$log(B^*_{\rm H})$	s
$7.881^{+0.153}_{-0.171}$	44.95	35	$0.966^{+0.030}_{-0.106}$	$4.06^{+0.24}_{-0.24}$	$3.53^{+0.26}_{-0.53}$	1.77 ± 0.18
$7.699^{+0.153}_{-0.171}$	44.95	45	$0.736^{+0.226}_{-0.368}$	$4.00^{+0.56}_{-0.34}$	$4.08^{+0.30}_{-1.08}$	1.63 ± 0.23

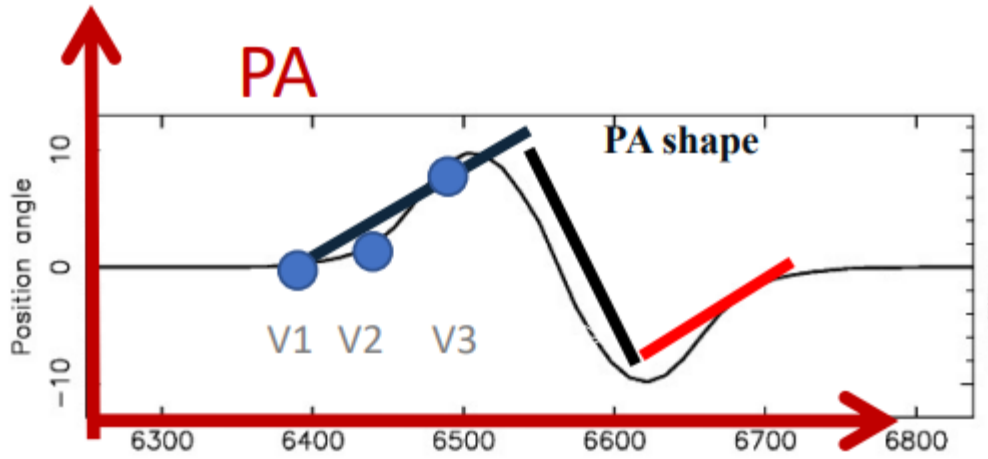
Polarization in broad lines





Broad lines are originally unpolarized





Smith+05

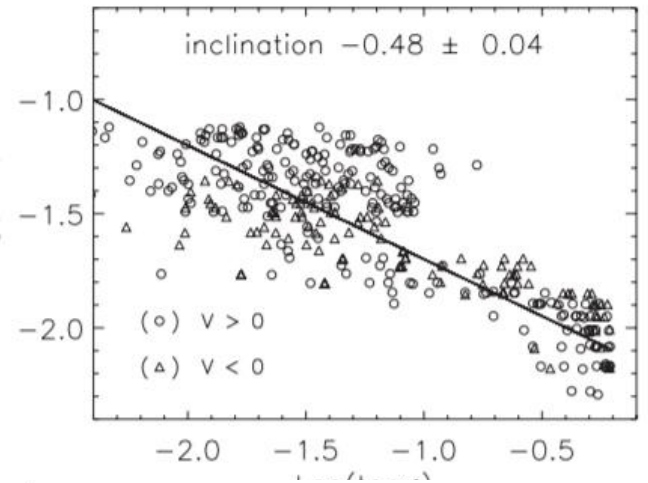
Polarization in broad lines

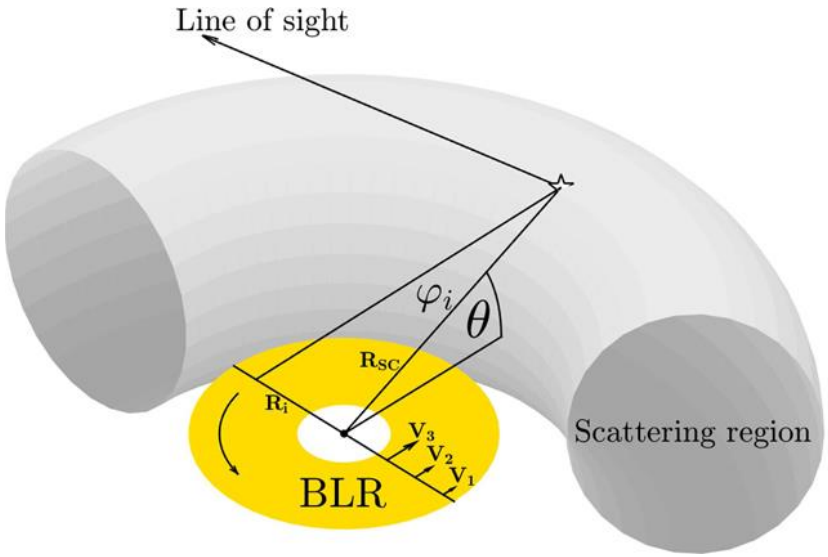
In case of Keplerian-like motion:

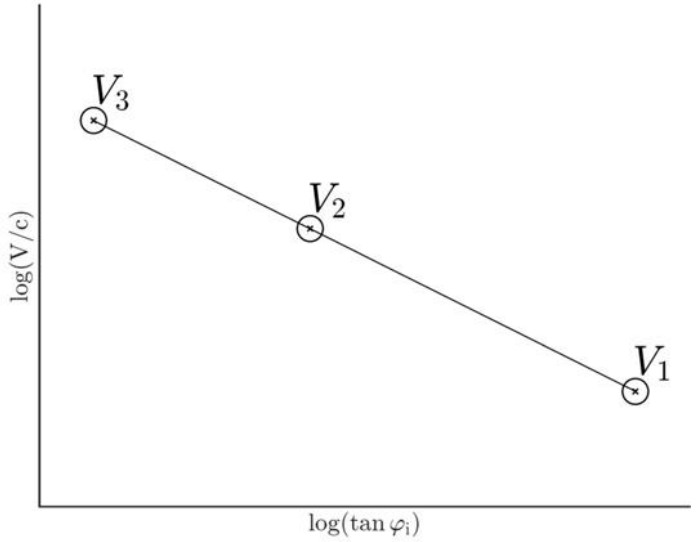
$$V_i = V_i^{rot}\cos(\theta) = \sqrt{\frac{G\,M_{BH}}{R_i}}\cos(\theta)\,, \qquad R_i = R_{sc}\tan(\varphi_i)$$

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

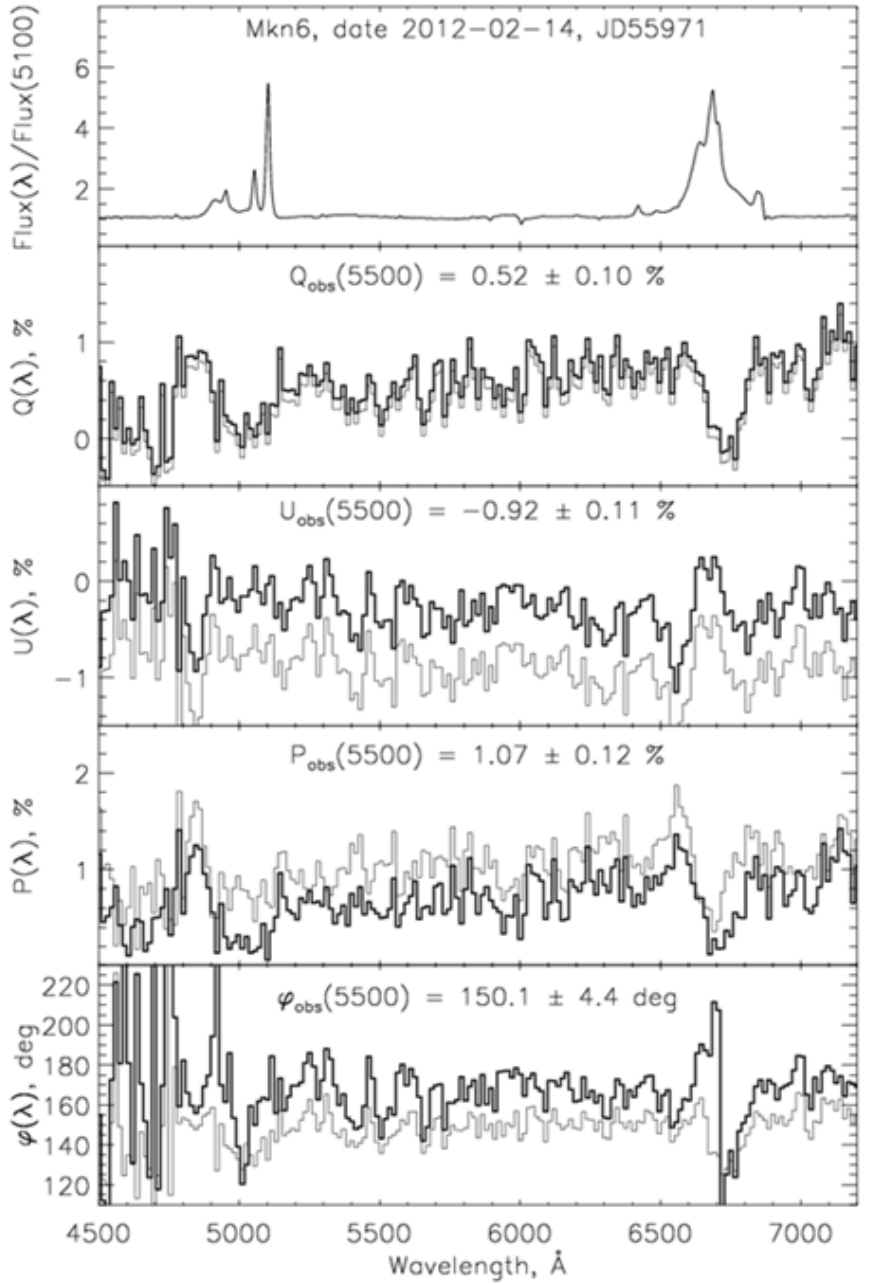
Afanasiev&Popovic15
Afanasiev,Popovic&Shapovalova19





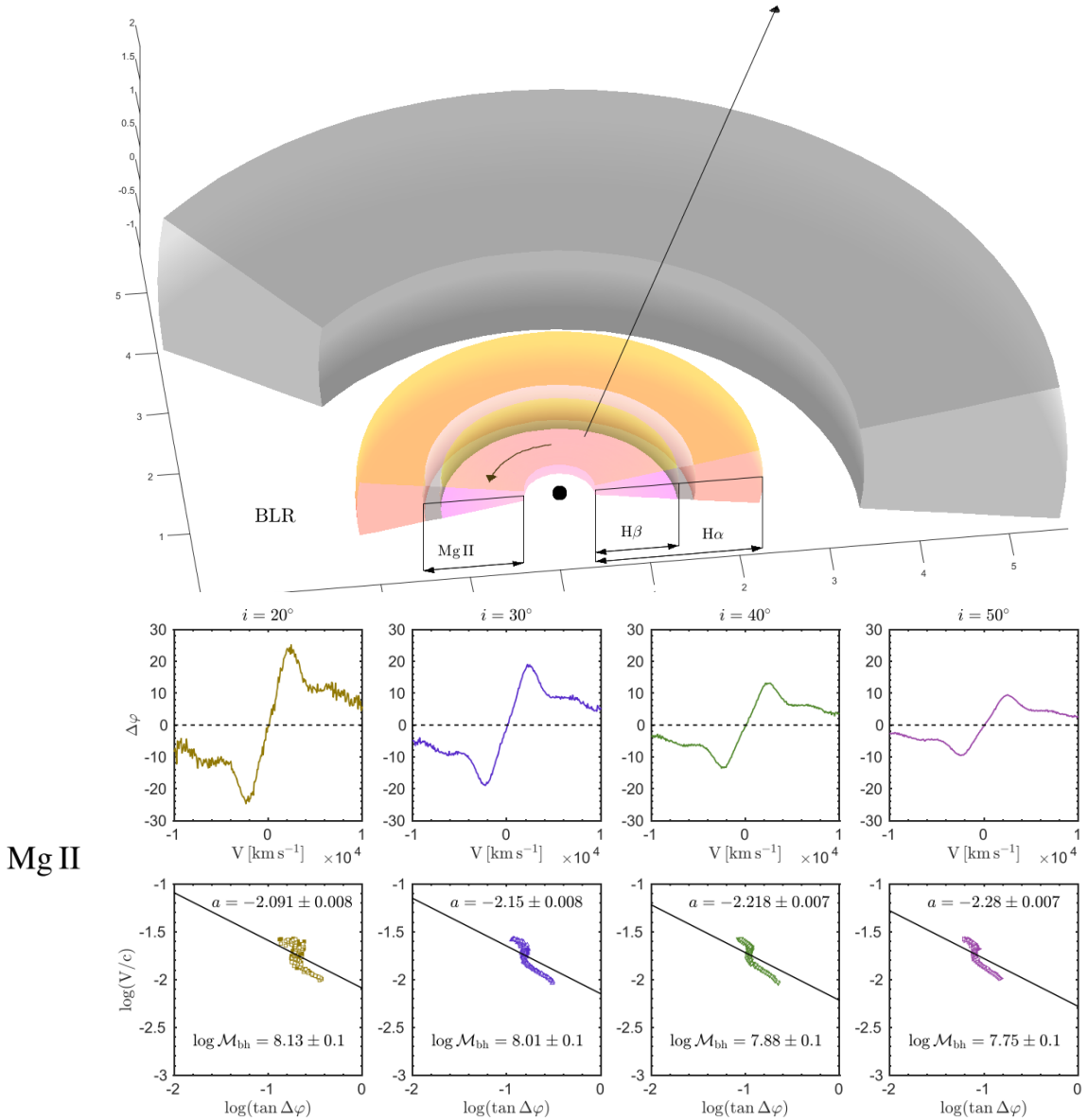


$$M_{BH-kep} = 10^{2a}\frac{c^2 R_{sc}}{G\cdot\cos^2(\theta)} = 1.78\cdot 10^{2a+10}\frac{R_{sc}}{cos^2(\theta)}M_\odot,$$



Polarization in broad lines: SBS 1419+538

Savic+20



Mg II

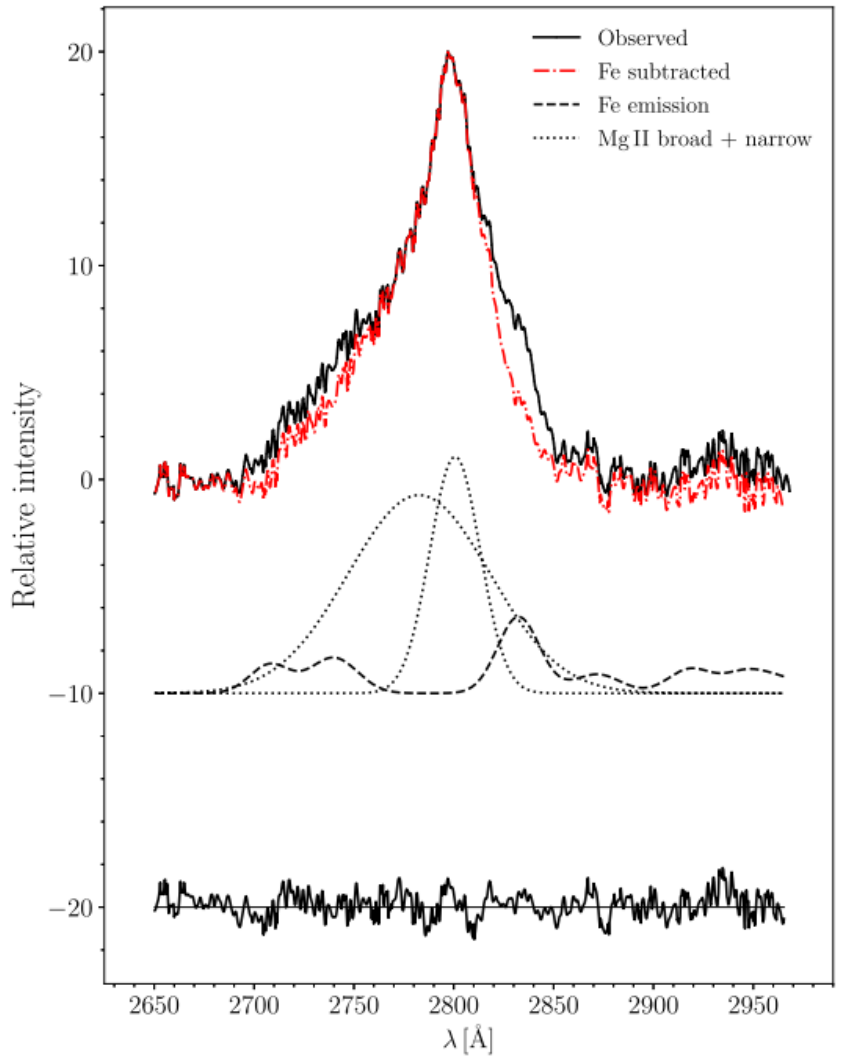
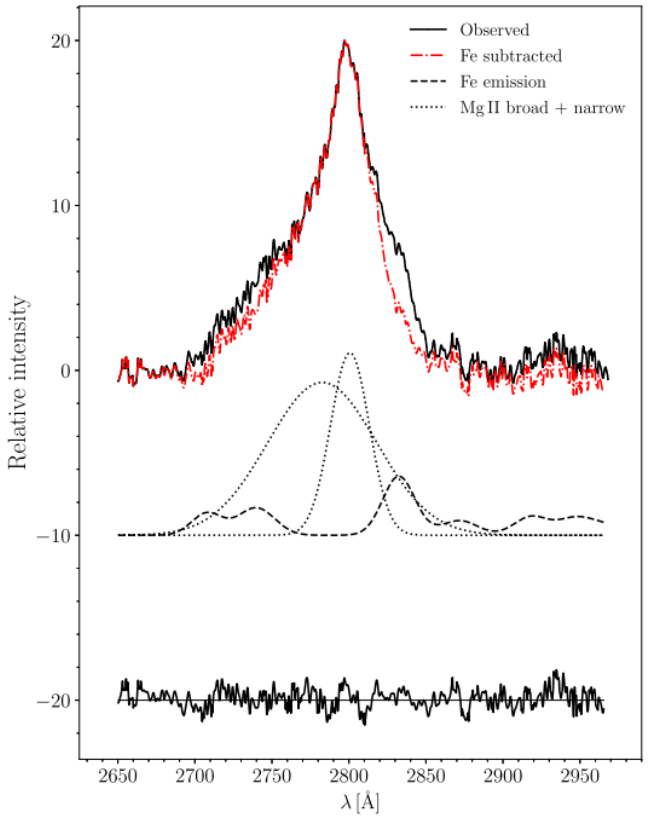


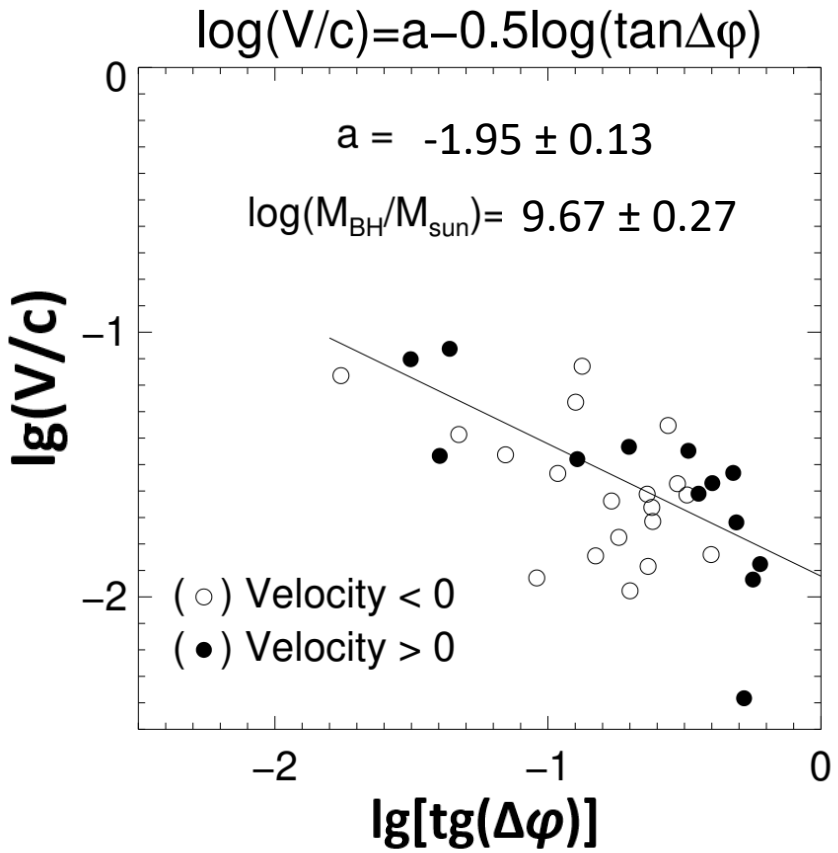
Figure 2. Decomposition of Mg II line emission. Top: solid black line denotes the observed spectrum; dashed red line is the Mg II profile after Fe II subtraction. Middle: broad and narrow Gaussian components of the Mg II line (dotted line) with the contribution of the total UV Fe II emission (dashed black line). Residuals are shown on the bottom.

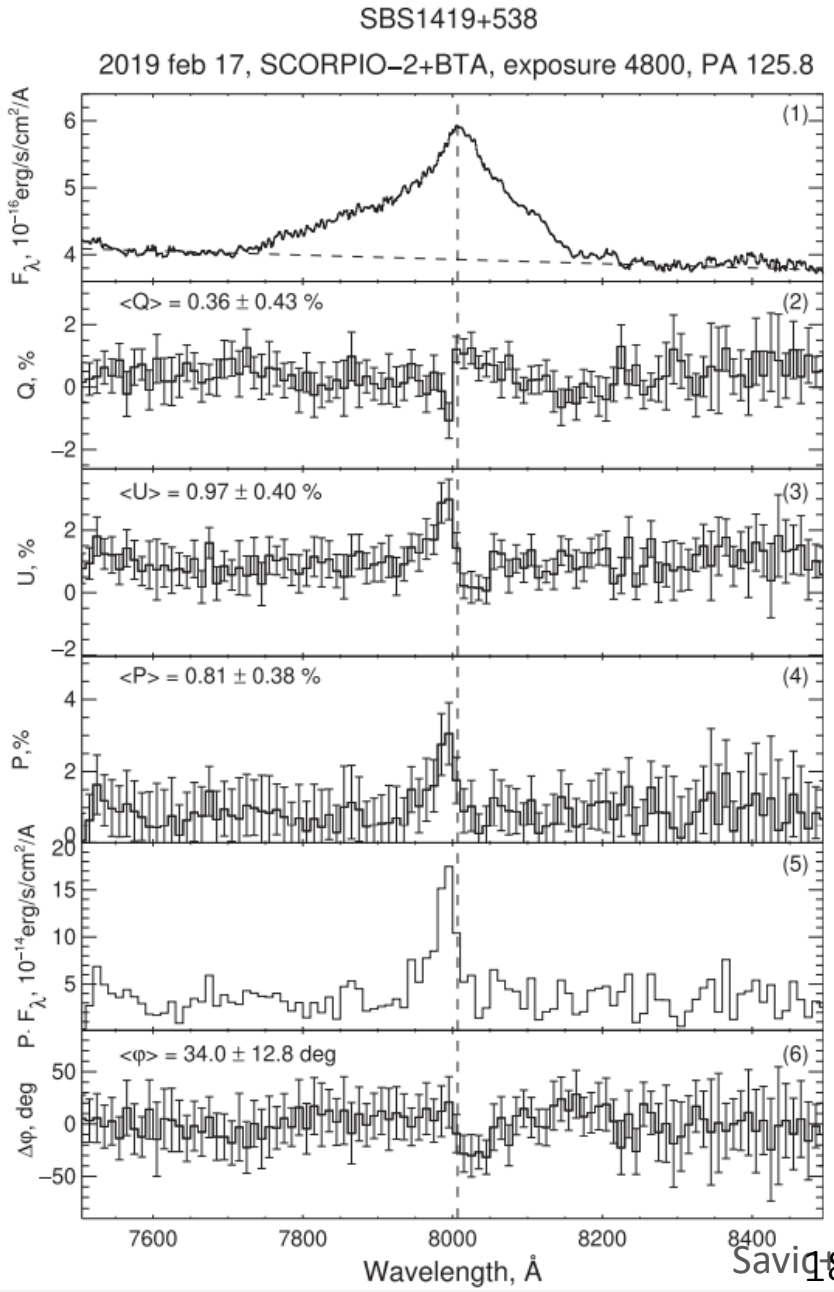
Polarization in broad lines: SBS 1419+538

$z = 1.862$

$R_{sc} = 2041 \pm 683$ lt days







Polarization in broad lines: SMBH mass & inclination

SMBH mass – *spectropolarimetry*

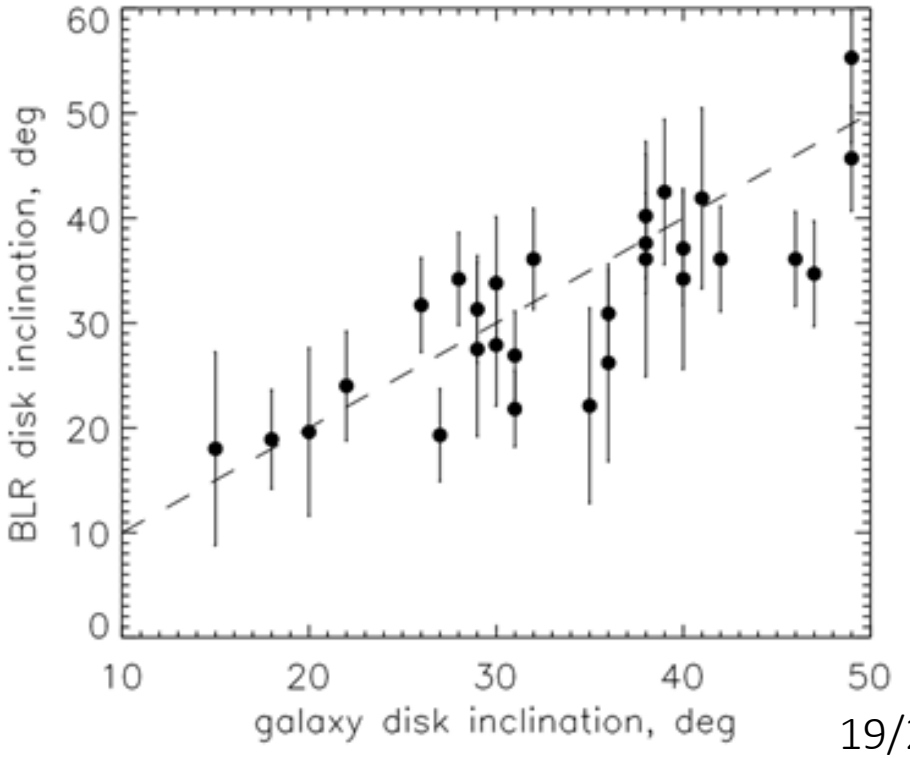
- Only geometrical effects
- Only 1 epoch is needed

Independent from the inclination!

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

The dependence between BLR inclination angle and galaxy inclination

Afanasiev+19



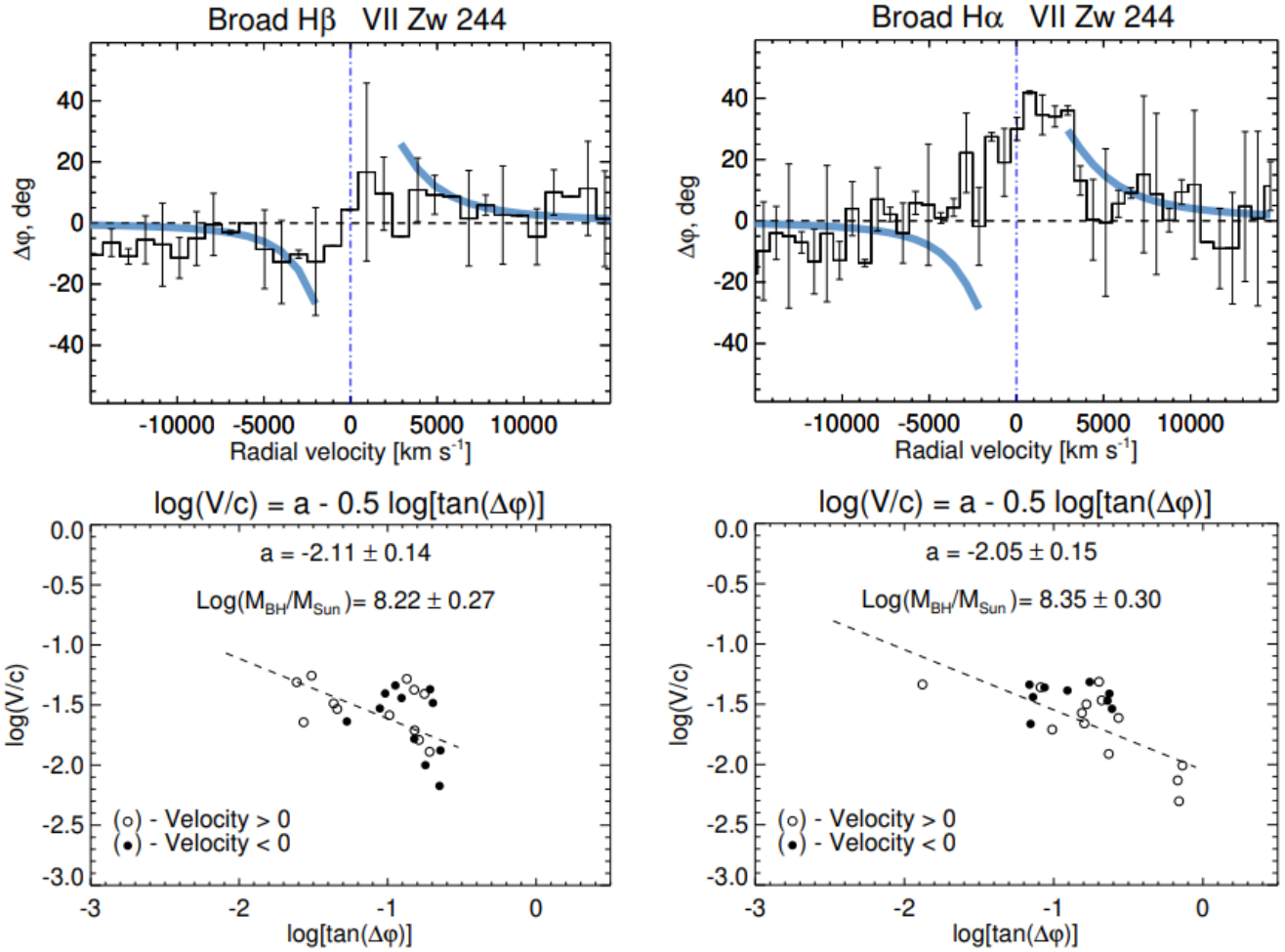
Polarization in broad lines: VII Zw 244

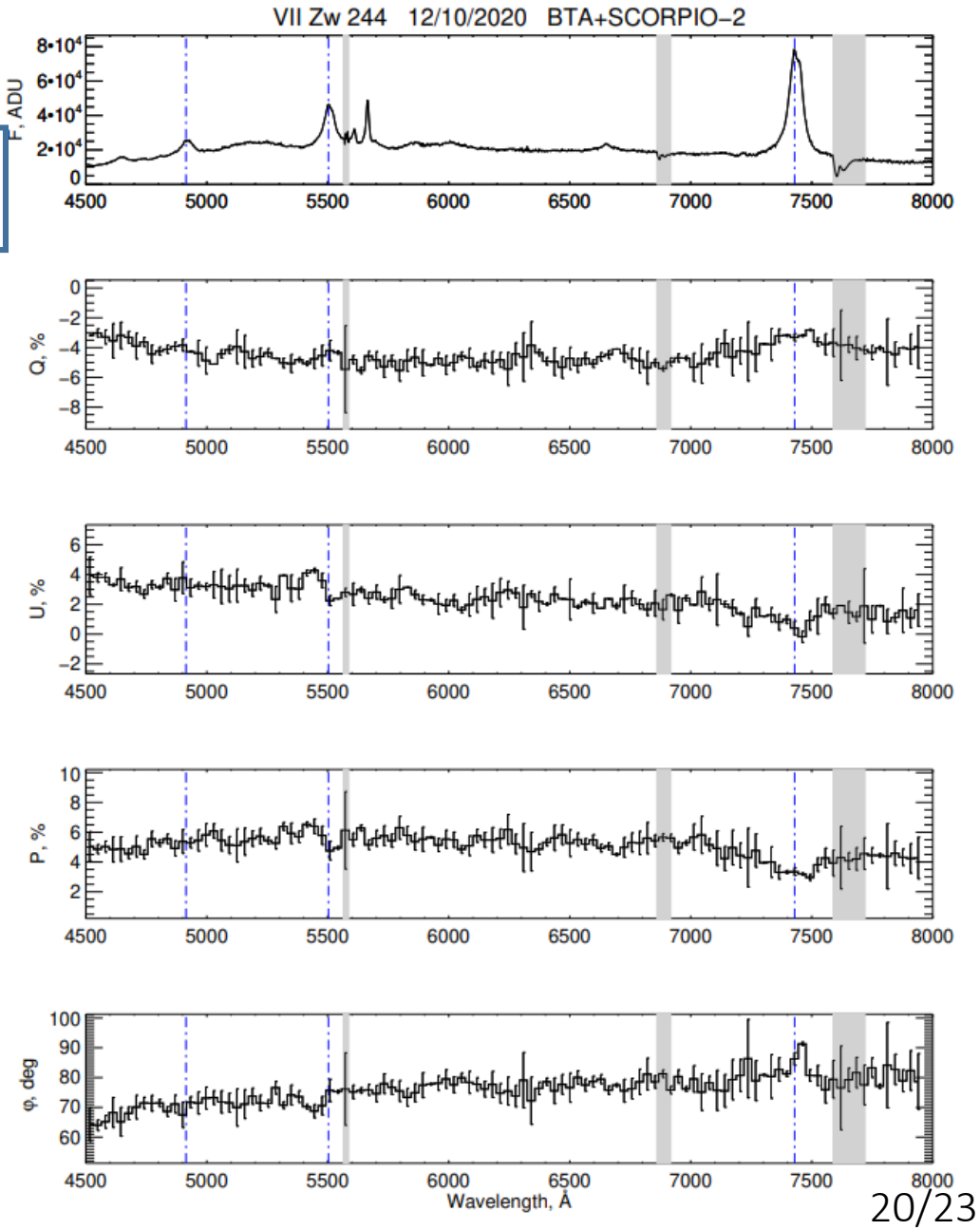
Equatorial scattering in both(!) Hα and Hβ lines, but not in Hγ line.

$R_{sc} = 157$ lt days

$i = 14.3 \pm 3.6°$

$$M_{BH-kep} = 10^{2a} \frac{c^2 R_{sc}}{G \cdot \cos^2(\theta)} = 1.78 \cdot 10^{2a+10} \frac{R_{sc}}{cos^2(\theta)} M_{\odot},$$





Polarization in broad lines: SMBH mass

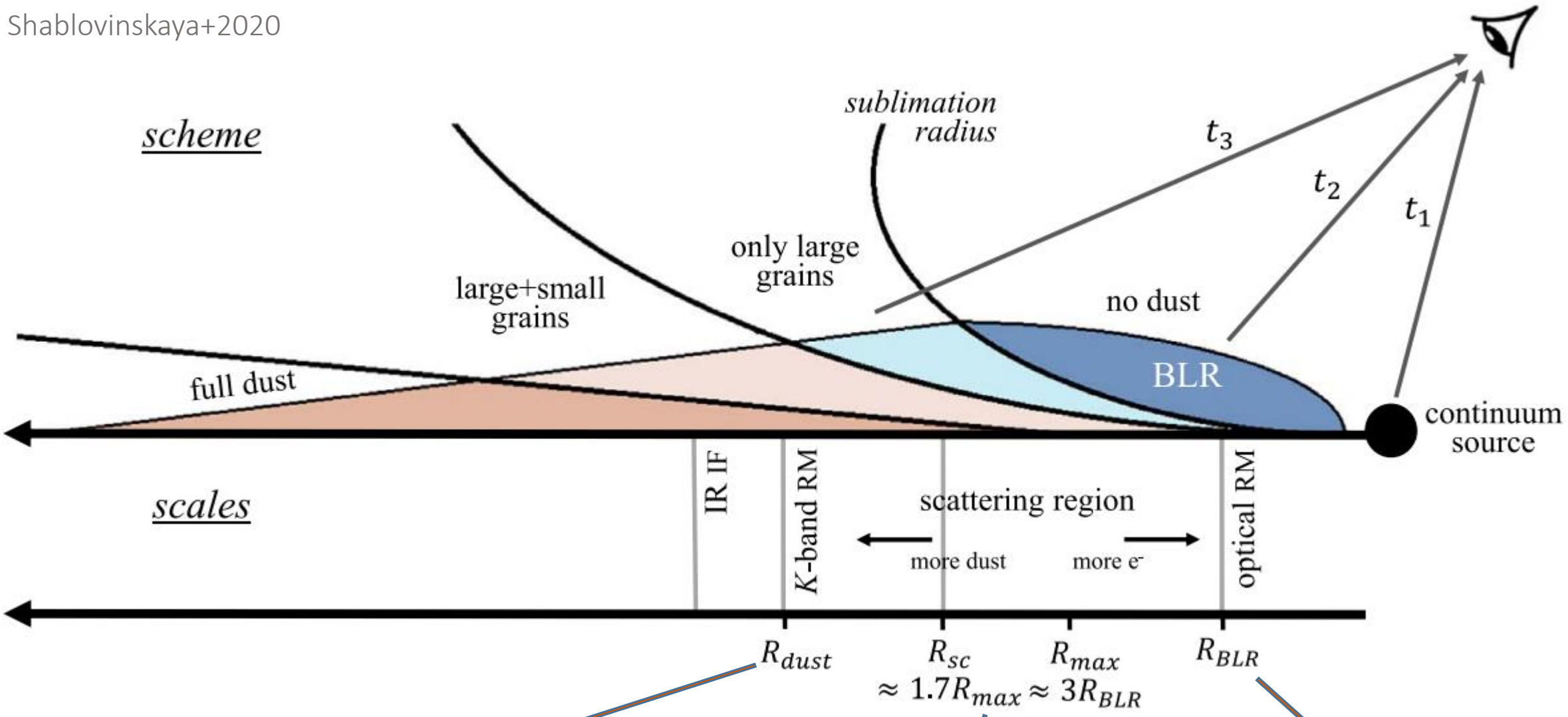
$$M_{BH-kep} = 10^{2a} \frac{c^2 R_{sc}}{G \cdot \cos^2(\theta)} = 1.78 \cdot 10^{2a+10} \frac{R_{sc}}{cos^2(\theta)} M_{\odot},$$

Polarization in broad lines: SMBH mass

$$M_{BH-kep} = 10^{2a} \frac{c^2 R_{sc}}{G \cdot \cos^2(\theta)} = 1.78 \cdot 10^{2a+10} \frac{R_{sc}}{\cos^2(\theta)} M_{\odot},$$

Polarization in broad lines: R_{sc}

Shablovinskaya+2020



VII Zw 244:

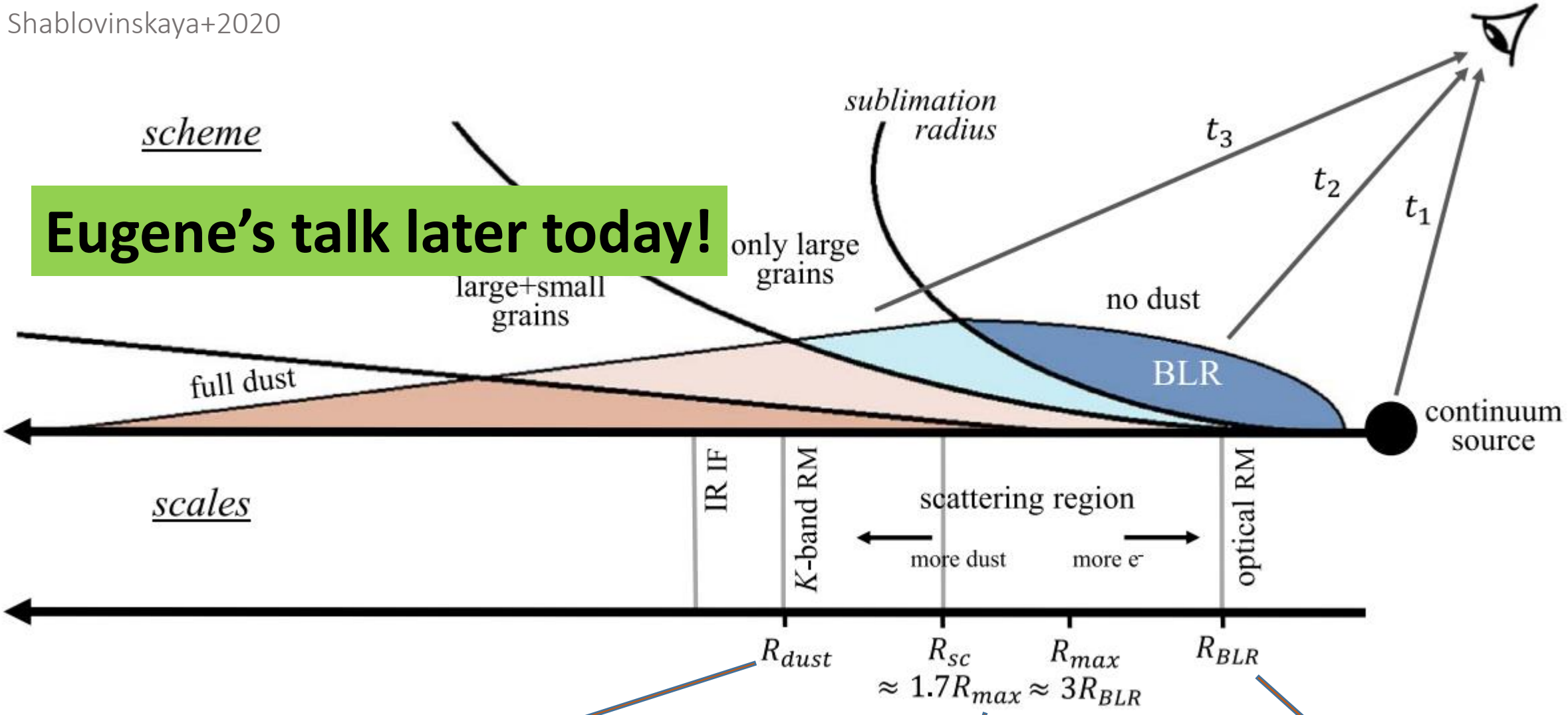
$R_{dust} \approx 350$ ld (Lyu+2019)

$R_{sc} \approx 157$ ld (Afanasiev+19)

$R_{BLR} \approx 30.7$ ld (Malygin+2020)

Polarization in broad lines: R_{sc}

Shablovinskaya+2020



Eugene's talk later today!

VII Zw 244:

$R_{dust} \approx 350$ ld (Lyu+2019)

$R_{sc} \approx 157$ ld (Afanasiev+19)

$R_{BLR} \approx 30.7$ ld (Malygin+2020)

Summary

1. Polarization in continuum → MF in AD $B(R)$, BH spin and AD size
   Silant'ev+07, Afanasiev+11, Afanasiev+18, Piotrovich+21, Shablovinskaya+22
2. Spectropolarimetry in lines → gas kinematics and M_{SMBH} independent from the inclination angle
   Smith+05; Afanasiev&Popovic+15; Afanasiev+19; Savic+19 etc.
3. RM in polarized light → inner radius of the scattering region R_{sc}
   Shablovinskaya+20, Shablovinskaya+22

Eugene's talk later today!

4. Rapid polarization variability in BL Lac objects → jet MF configuration and size
   Shablovinskaya&Afanasiev19, Shablovinskaya+23

My talk on Thursday!

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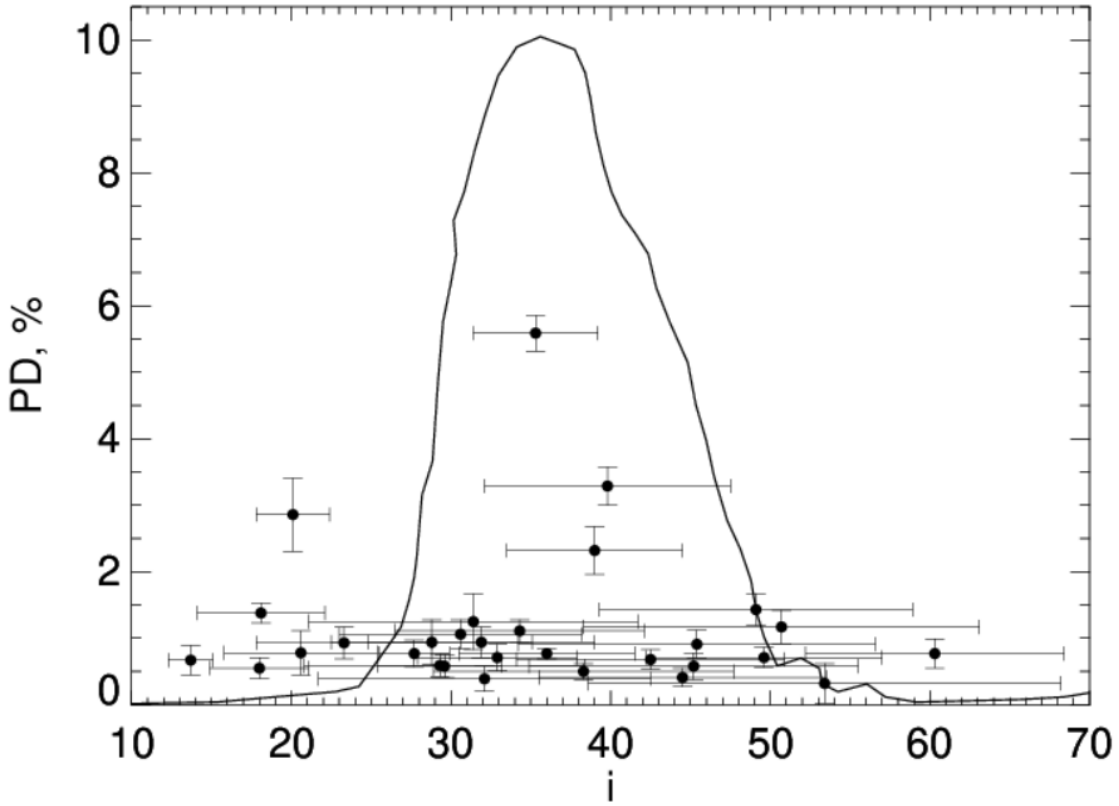
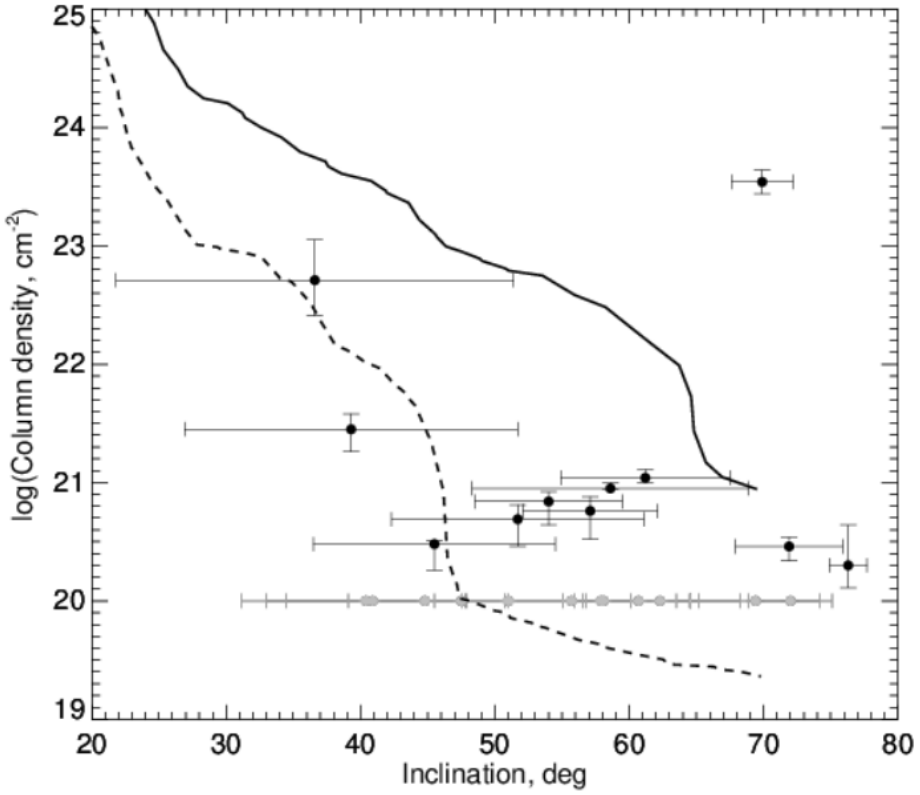
Shablovinskaya, Afanasiev, Popović *Measuring the AGN Sublimation Radius with a New Approach: Reverberation Mapping of Broad Line Polarization*, 2020, ApJ, 10.3847/1538-4357/ab7849
Popović, Afanasiev, Shablovinskaya, Ardilanov, Savić Spectroscopy and polarimetry of the gravitationally lensed quasar Q0957+561, 2021, A&A, 10.1051/0004-6361/202039914
Savić, Popović, Shablovinskaya The First Supermassive Black Hole Mass Measurement in Active Galactic Nuclei Using the Polarization of Broad Emission Line Mg II, 2021, ApJL, 10.3847/2041-8213/ac2d30
Shablovinskaya, Piotrovich, Malygin, Buliga, Natsvlishvili Determination of the physical parameters of AGNs in Seyfert 1 galaxies LEDA 3095839 and VII Zw 244 based on spectropolarimetric observations, 2022, Universe, 10.3390/universe8070383

Future perspectives

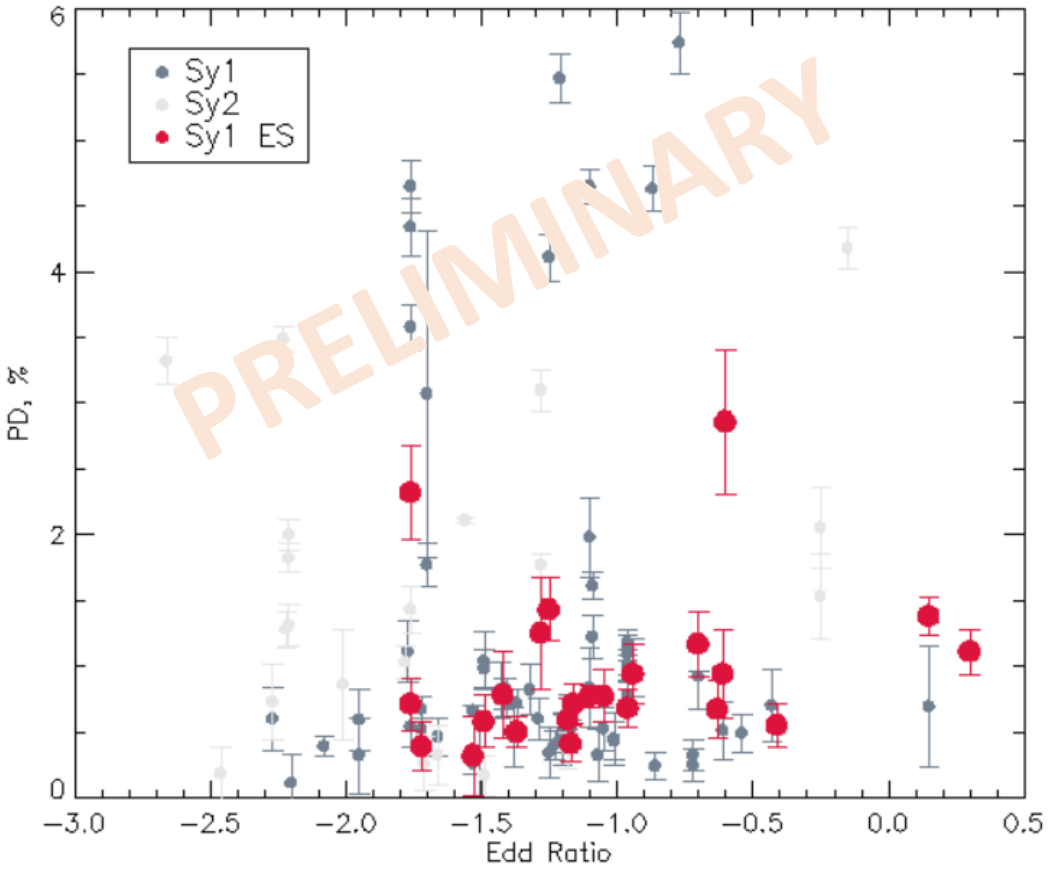


(Marin & Stalevski 2015)



(Kudoh et al. 2023)

Future perspectives



The BAT AGN Spectroscopic Survey

An all-sky study of the brightest and most powerful hard X-ray detected AGN