Supported by RSF grant no. 20-12-00030 "Investigation of geometry and kinematics of ionized gas in active galactic nuclei by polarimetry methods"

New capabilities of AGN polarimetry

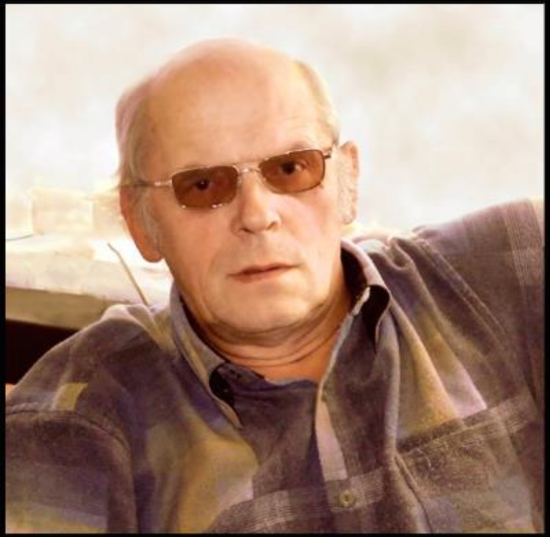
Elena Shablovinskaya[1], Luka Č. Popović[2]

[1]Special Astrophysical Observatory of RAS
[2]Astronomical Observatory of Belgrade

In memory of life and work

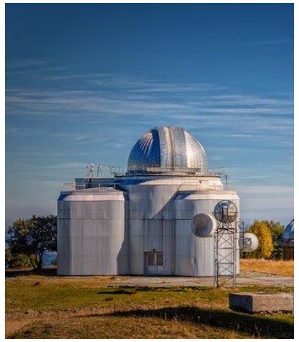
Alla I. Shapovalova started the AGN monitoring in SAO

Victor L. Afanasiev was a founder of the polarimetric investigations of AGN



MAGIC (Monitoring of Active Galaxies by Investigation of their Cores)

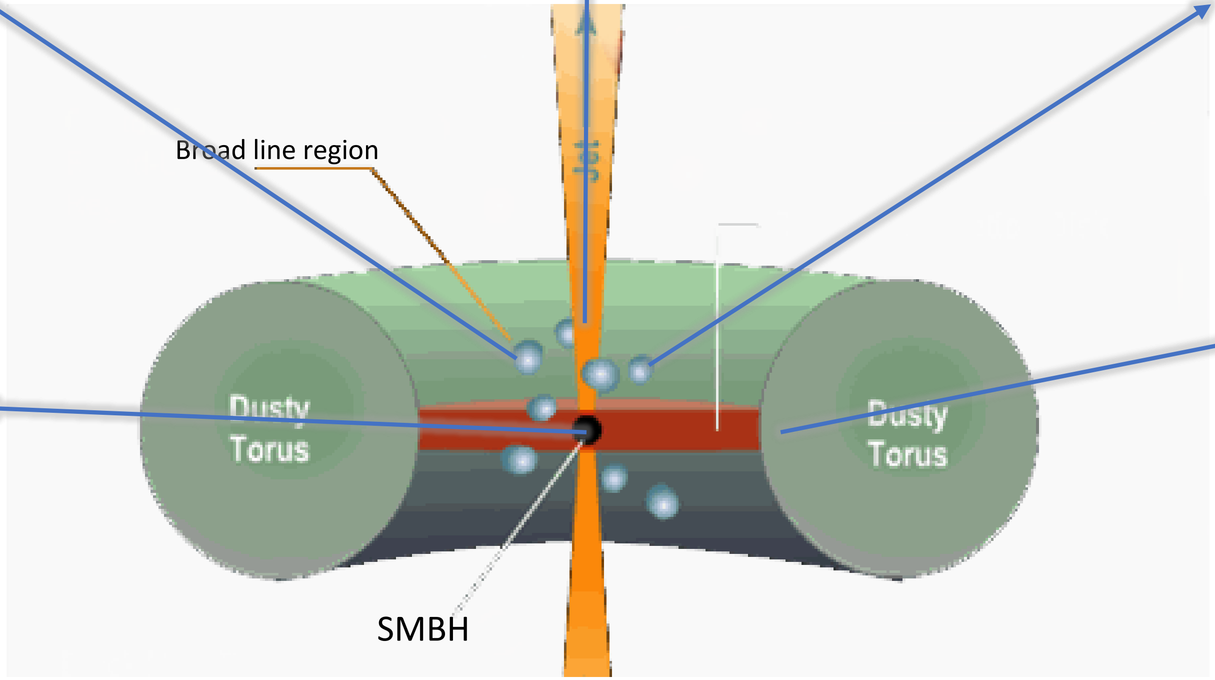
More than 30 years ago Alla I. Shapovalova started the AGN monitoring in SAO (Russia) at 6-m BTA and 1-m Zeiss-1000 telescopes + in collaboration with Serbia, Mexico…



variations of polarization directions in blazars

spectral monitoring of broad line profiles in Sy1 and CL-AGN

photometric reverberation mapping of BLR in broad- and medium-bands

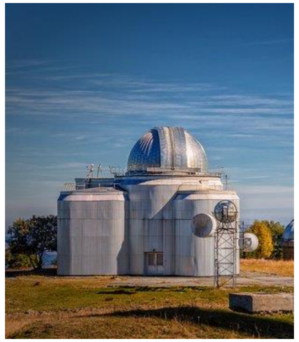


spectropolarimetry of Type 1 AGN

reverberation mapping of the dusty torus in polarized light

MAGIC (Monitoring of Active Galaxies by Investigation of their Cores)

More than 30 years ago Alla I. Shapovalova started the AGN monitoring in SAO (Russia) at 6-m BTA and 1-m Zeiss-1000 telescopes + in collaboration with Serbia, Mexico…



variations of polarization directions in blazars

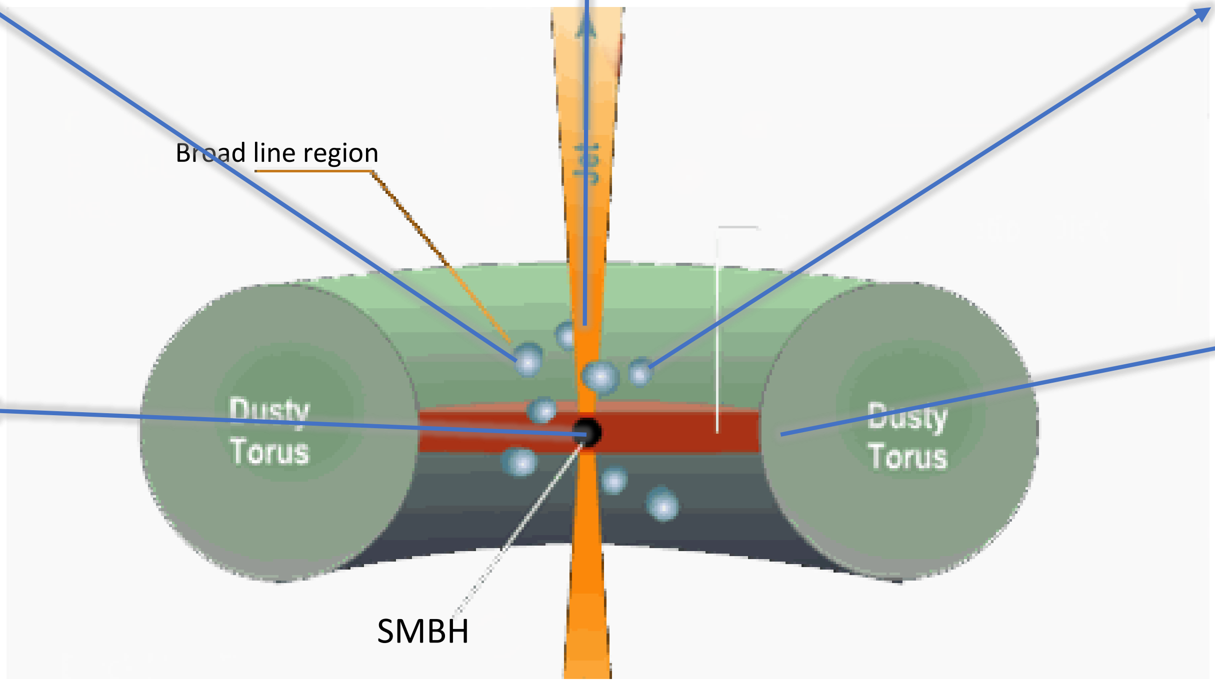
synchrotron

spectral monitoring of broad line profiles in Sy1 and CL-AGN

Alexander Burenkov later today!

photometric reverberation mapping of BLR in broad- and medium-bands

Eugene Malygin earlier today!



spectropolarimetry of Type 1 AGN

equatorial scattering

Luka Popović earlier today!

reverberation mapping of the dusty torus in polarized light

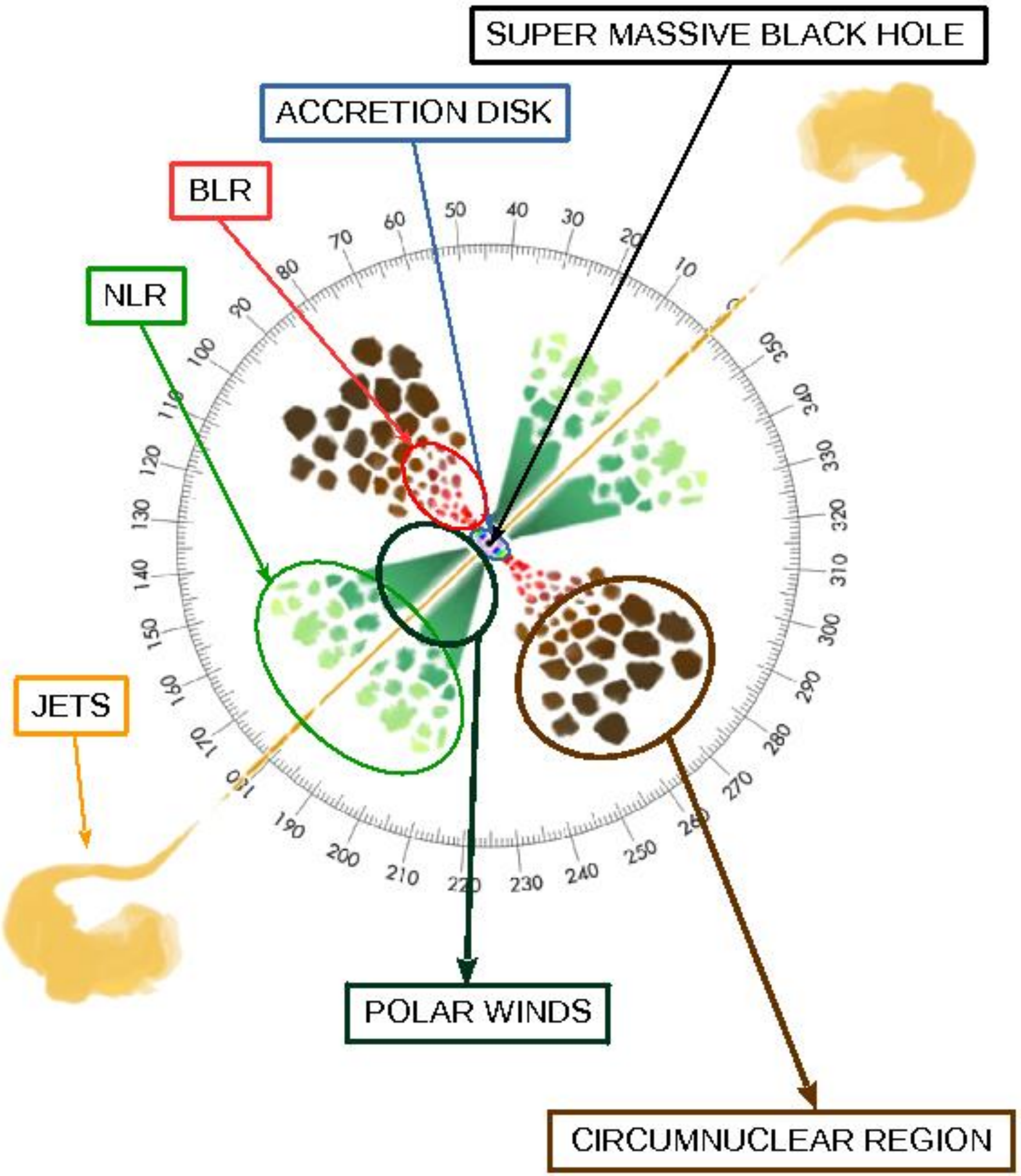
equatorial scattering

INSIDE

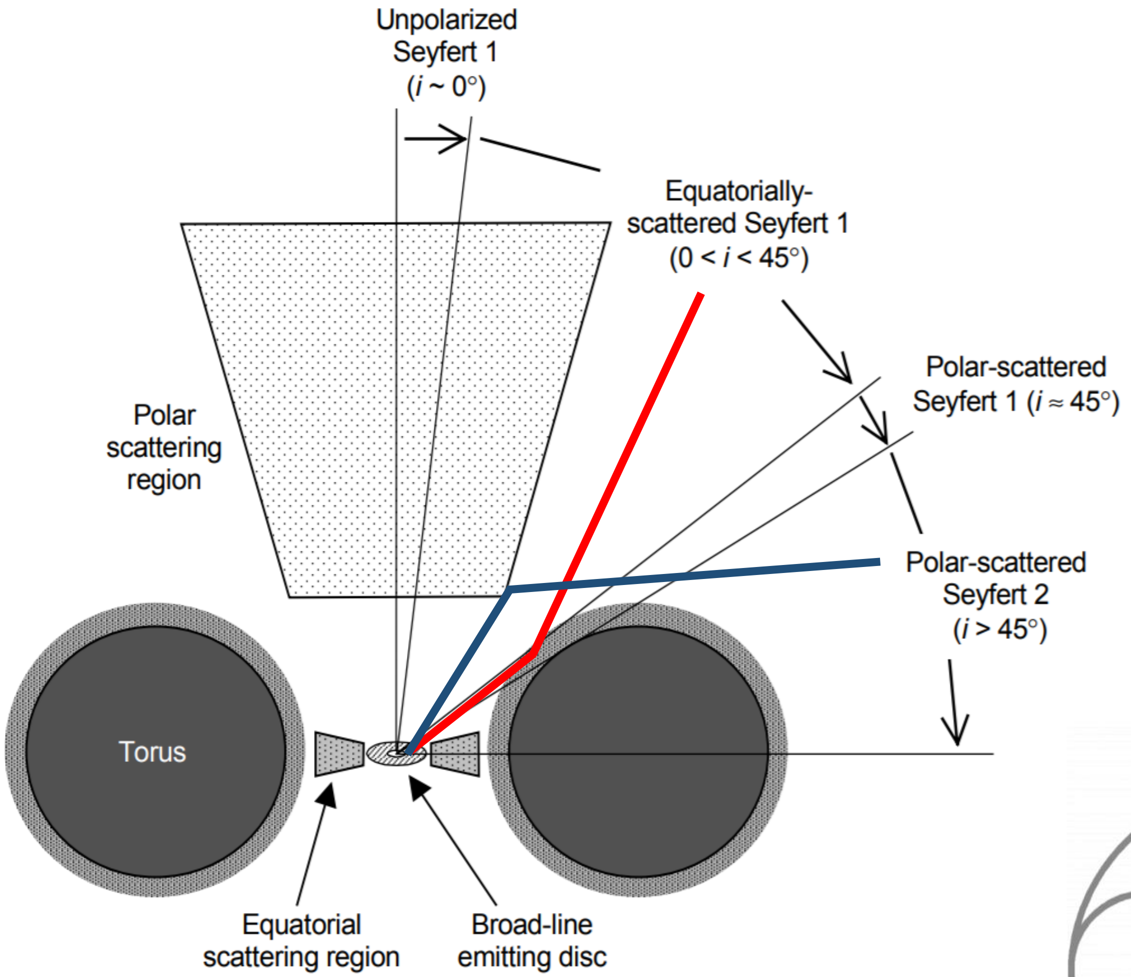
- GR effects near spinning SMBH
- Thomson scattering in AD
- Scattering in hot corona
- Jet synchrotron radiation
- Faraday rotation

OUTSIDE

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



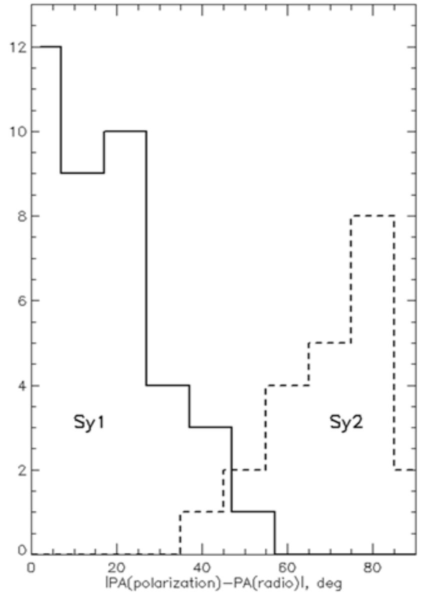
Polarization on the dusty ~~torus~~ region

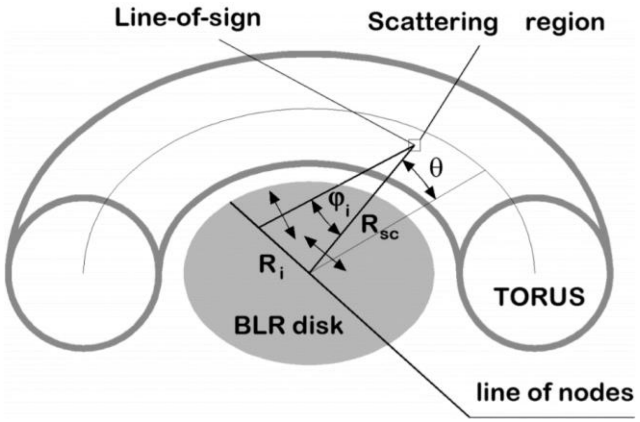


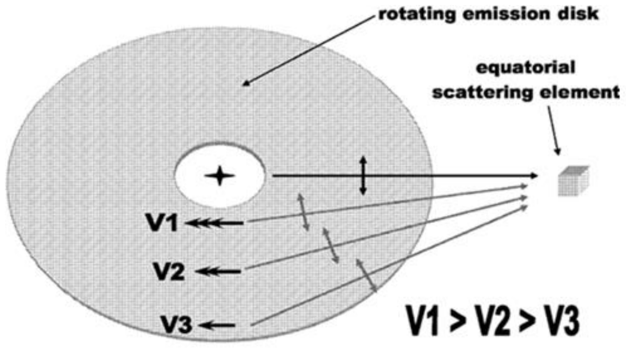
Smith+14

The equatorial / polar scattering dichotomy repeats the Sy 1 / 2 classification.

The torus provides scattering of radiation from the central parts, which is called in this case the equatorial scattering.







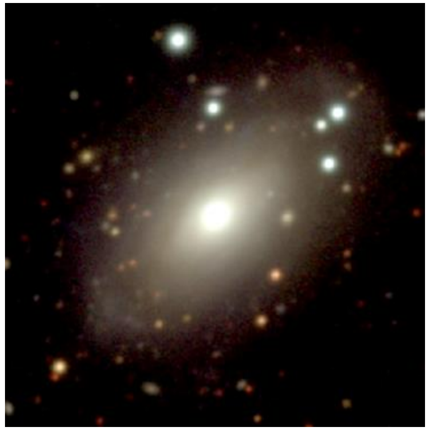
Sy1 polarization in broad lines

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

Afanasiev+14, Afanasiev&Popovic15

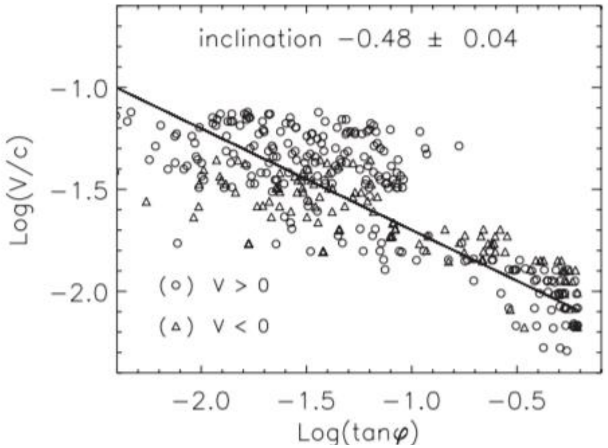
Equatorial scattered Sy 1 AGN *Mrk 6*

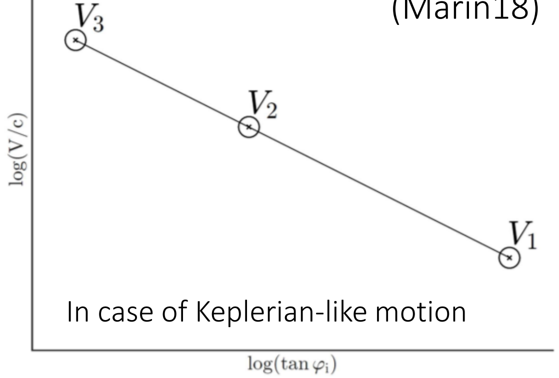
- Observations with SCORPIO-2 at 6-m BTA in 2010-2013;
- 12 spectra (Hα + Hβ) with 2800-3600 sec exposures and 7-8Å resolution;
- Woll-1 + λ/2 plate; Stokes parameters accuracy ~0.2%.

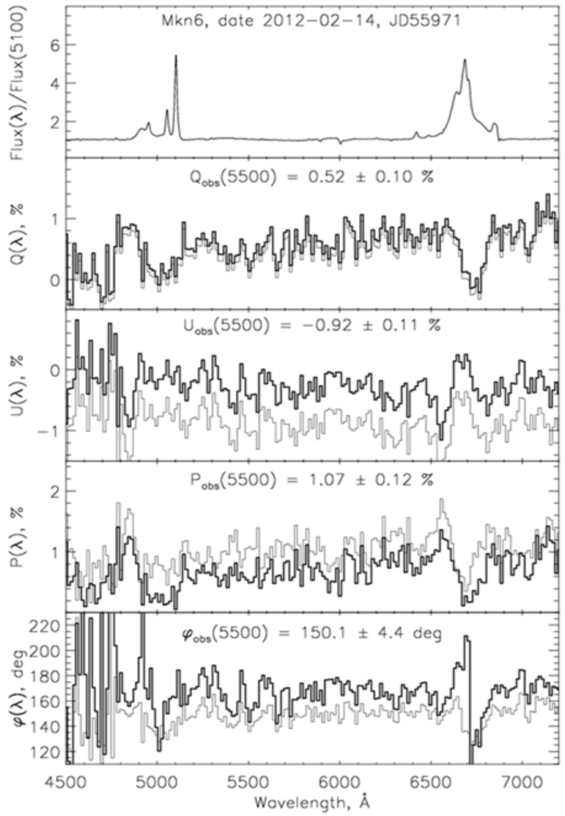


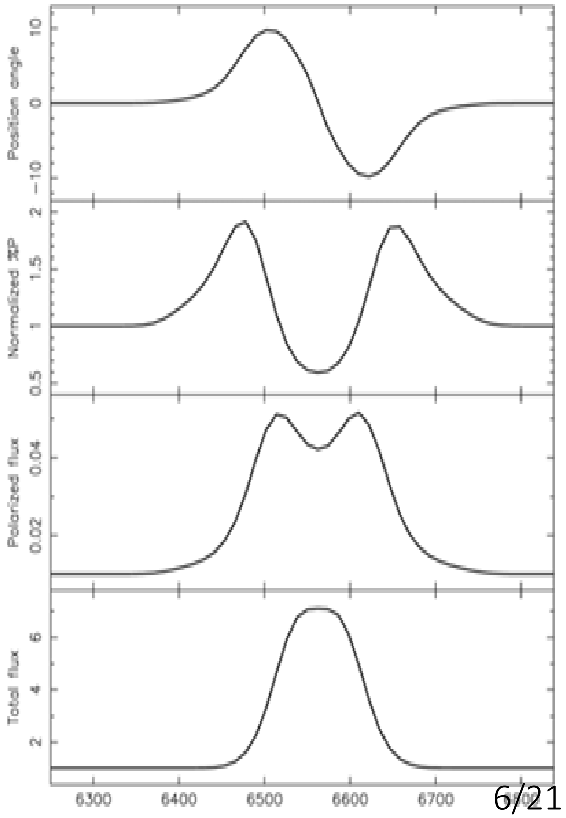
$$M = 1.5 \cdot 10^8 M_\odot$$

$R_{sc} \approx 0.18 \pm 0.05$ pc or $R_{sc} \approx 220 \pm 60$ light days
(estimated using radiation at 2.2 microns, see Kishimoto et al. 2011)









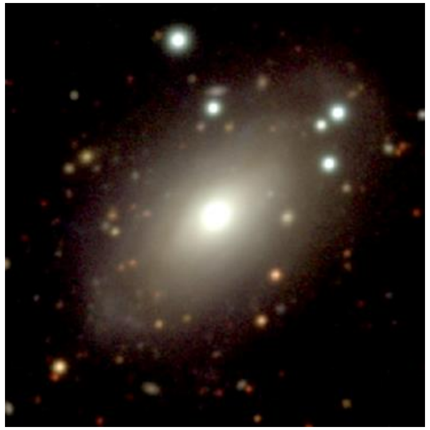
Sy1 polarization in broad lines

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

Afanasiev+14, Afanasiev&Popovic15

Equatorial scattered Sy 1 AGN *Mrk 6*

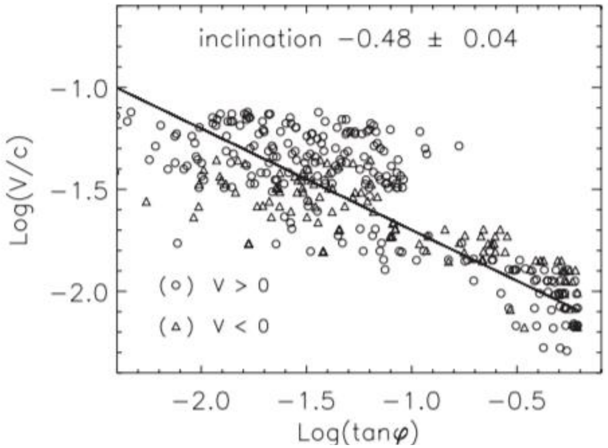
- Observations with SCORPIO-2 at 6-m BTA in 2010-2013;
- 12 spectra (Hα + Hβ) with 2800-3600 sec exposures and 7-8Å resolution;
- Woll-1 + λ/2 plate; Stokes parameters accuracy ~0.2%.

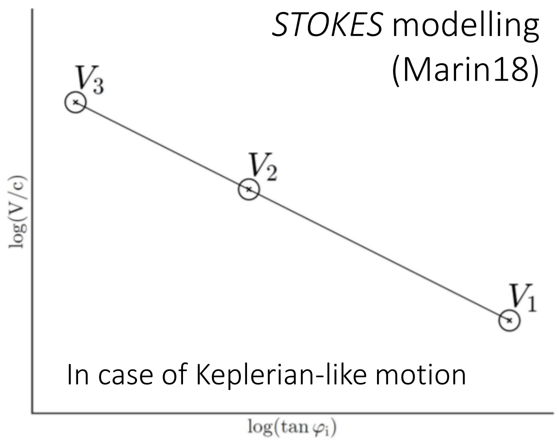


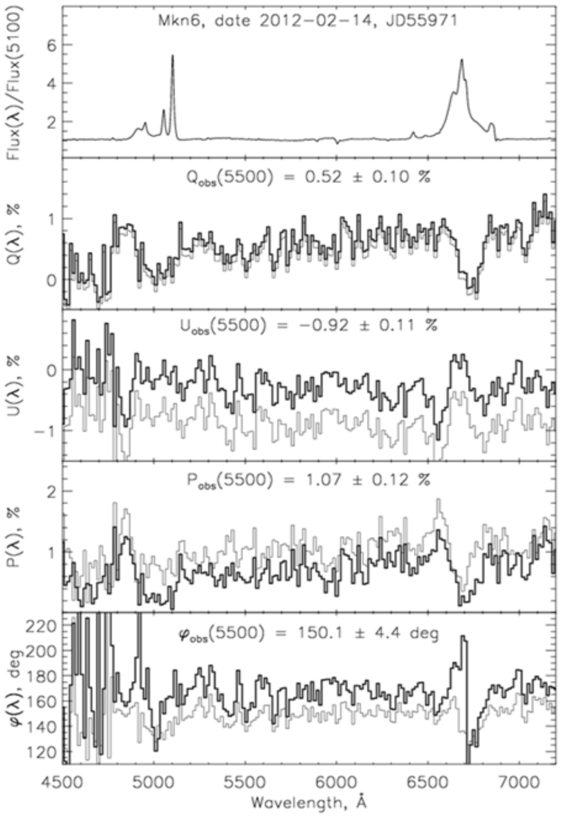
$$M = 1.5 \cdot 10^8 M_{\odot}$$

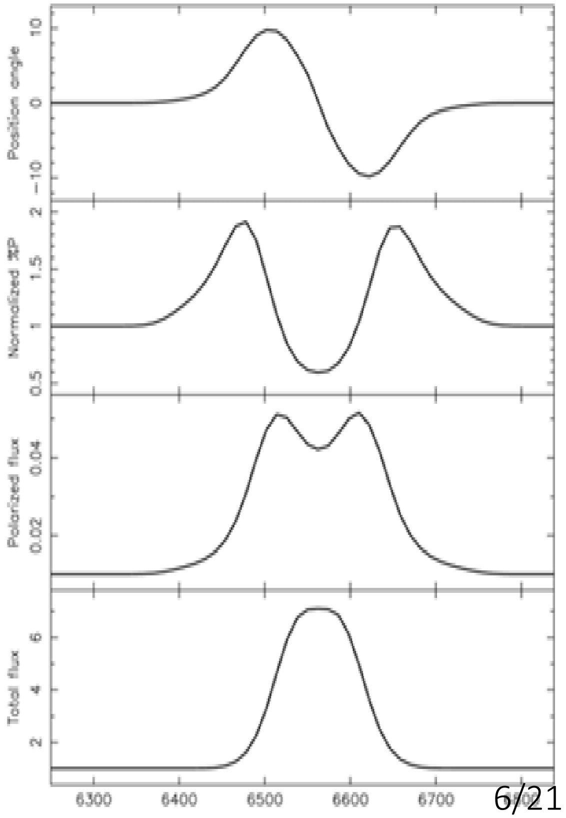
Is $\boldsymbol{R_{sc}}$ assumed correctly?

$R_{sc} \approx 0.18 \pm 0.05$ pc or $R_{sc} \approx 220 \pm 60$ light days
(estimated using radiation at 2.2 microns, see Kishimoto et al. 2011)









Determination of the torus size

1. Reverberation mapping in IR and optics

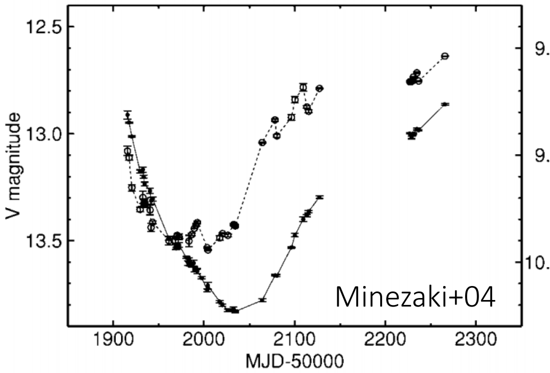
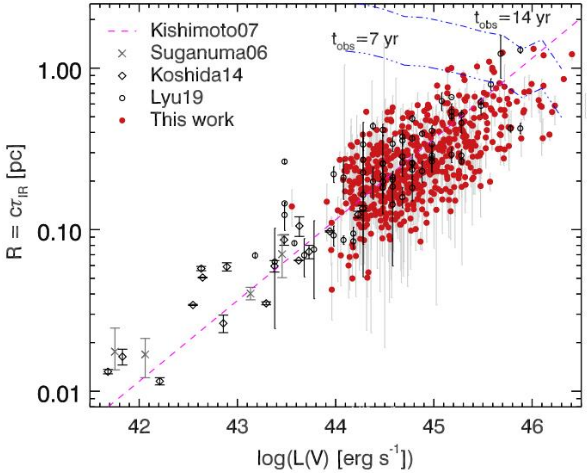


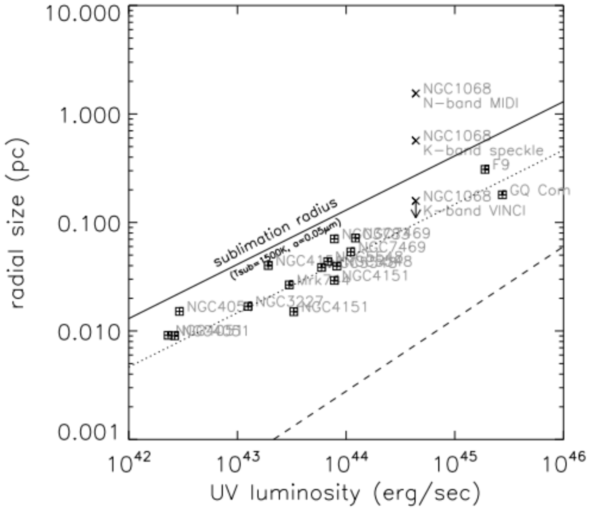
FIG. 1.—*V* (*open circles connected with dashed lines*) and *K* (*filled circles connected with solid lines*) light curves of NGC 4151 nucleus in 2001. The flux from the host galaxy is subtracted. The flux minimum of the *K* light curve is clearly delayed behind that of the *V* light curve. The monitoring observation was interrupted because of the solar conjunction at MJD = 52,130–52,220.



Yang+20: +587 quasars at 0.3 ≤ z ≤ 2

+ Around 20 **+587** AGNs are measured

- The simultaneous observations in IR and optical bands are needed
  - Very long time series



2. NIR and mid-IR interferometry

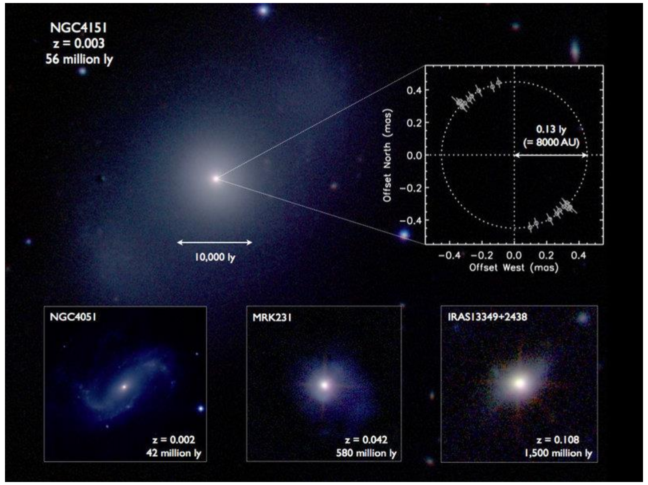


Table 1. Properties of our targets and summary of the results of our KI observations on 15 May 2009 (UT).

Kishimoto+09,11

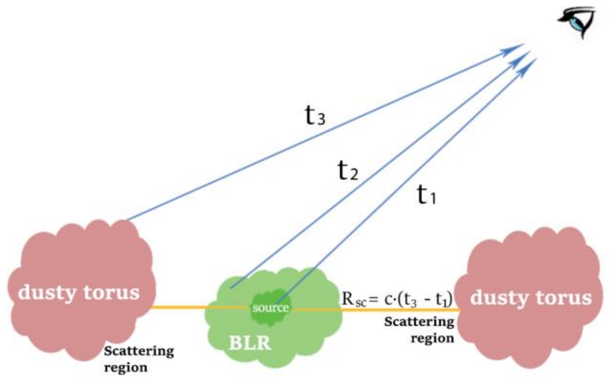
Name	z^a corr.	Scale^b (pc mas^{-1})	$E_{B-V}{}^c$ (mag)	$B_p{}^d$ (m)	PA (°)	V^{2e}	$R_{ring}{}^f$ (mas)	$R_{ring}{}^f$ (pc)	$R_{\tau_K}{}^g$ (pc)	A_V (mag)
NGC 4151	0.00414	0.086	0.028	85.0	12.3	0.862 ± 0.018	0.45 ± 0.04	0.039 ± 0.003	~0.044 ± 0.011	
NGC 4051	0.00309	0.064	0.013	79.4	41.9	0.861 ± 0.026	0.51 ± 0.05	0.032 ± 0.003	~0.011 ± 0.004	
	'	0.84	0.010	74.4	44.3	0.923 ± 0.028	0.38 ± 0.07	0.32 ± 0.06		1.3^h
		2.0	0.012	85.0	34.5	0.869 ± 0.016	0.44 ± 0.03	0.88 ± 0.05		0.93^i

+ Around 20 AGNs are measured

- AGNs for very low-z AGNs
- Limited angular resolution

Reverberation mapping in polarized light

The idea is to observe polarization only in line not to be confused with extra polarization mechanisms.



$$R_{BLR} = c\Delta\tau_{12} = c\cdot(t_2 - t_1)$$

$$R_{sc} = c\Delta\tau_{13} = c\cdot(t_3 - t_1)$$

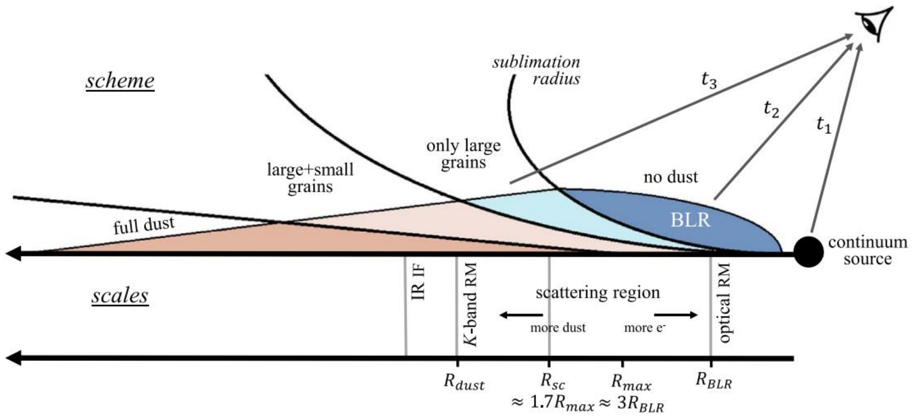
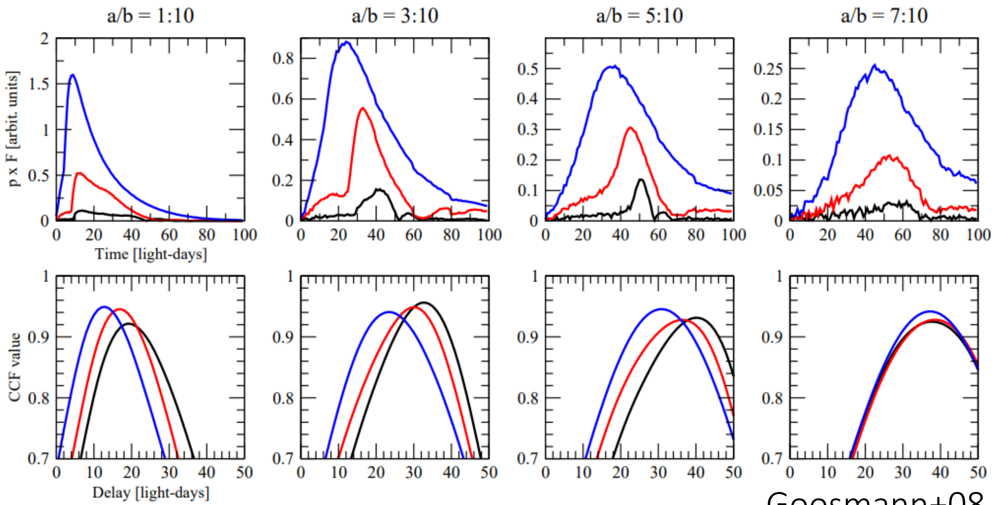
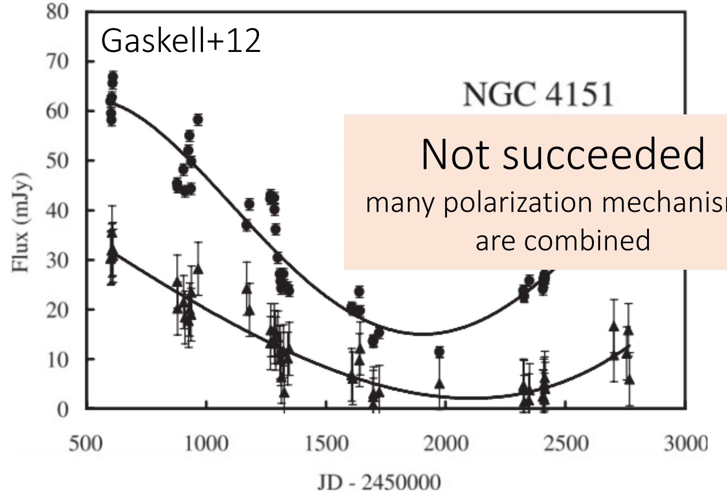


Figure 1. The scheme of the inner AGN sizes. The upper part of the figure illustrates the scheme of the dust distribution inside the AGN introduced by Baskin & Laor (2018). t_1, t_2, and t_3 correspond to the moment when a signal comes from the central ionizing source, the BLR, and the scattering region, respectively. The lower part marks the approximate size scale connecting the photometric BLR radius $R_{\rm BLR}$ observed with the reverberation mapping technique ("optical RM"), the maximal radius of the BLR $R_{\rm max}$, the size of the scattering region, and the radius of the inner part of the dusty region $R_{\rm dust}$ measured by the IR reverberation mapping technique ("K-band RM") and by the near-IR interferometry ("IR IF"). The scale relations are from Afanasiev et al. (2019).



Goosmann+08

Fig. 1. Top: lightcurves for the polarized flux of a light flash emitted at the center of a spheroidal scattering region with aspect ratio a/b. The viewing angles $i = 10°$ (black), $30°$ (red), and $60°$ (blue) are evaluated. Bottom: cross-correlation functions between the total flux and the polarized flux echo when the intensity of the central source varies.



Not succeeded

many polarization mechanisms are combined

Figure 1. Variations in total U-band flux (top curve) and B-band polarized flux (lower curve). The polarized flux has been multiplied by a factor of 30 for plotting convenience. The polarization position angles in both wave bands are consistent with each other and remained nearly constant at $92° \pm 1.6°$ during the whole observational campaign. The two curves are fourth-order polynomial fits through the data.

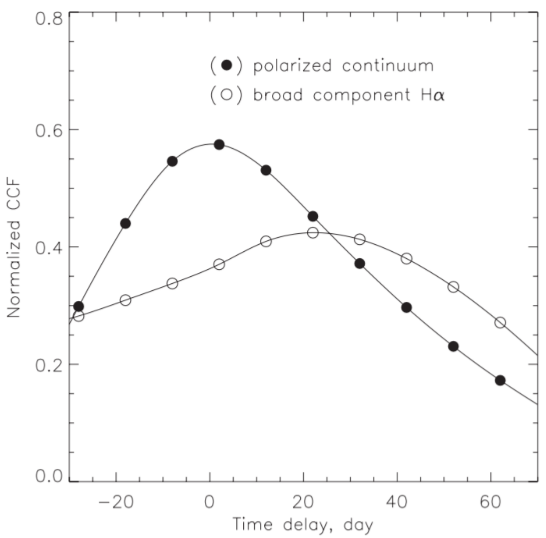
Observational test

Equatorial scattered Sy 1 AGN *Mrk 6* (again!)

SCORPIO-2 + 6-m BTA → 12 epochs of spectropolarimetric observations in 2010-2013

Afanasiev+14:

- Polarized continuum region - **2 days** (0.002 pc);
- BLR Hα - **22 days** (0.02 pc)

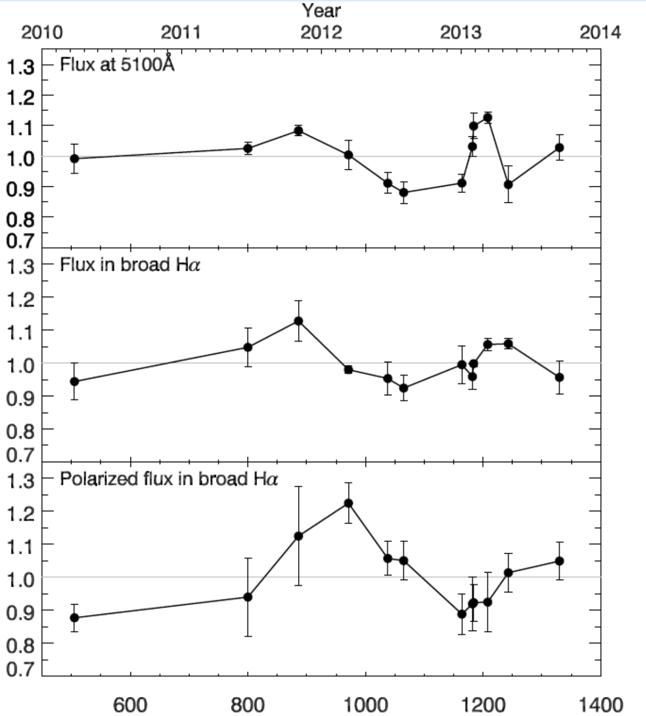


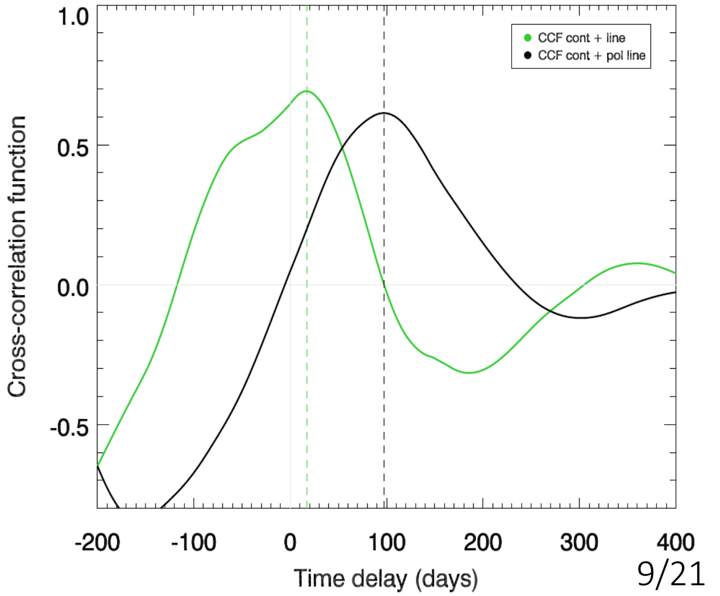
The time delay in polarized line:

- CCF: 94.7 ± 6.9 lt days
- JAVELIN (Mudd+18): 99.5 ± 3.6 lt days

Kishimoto+11, IR IF: 214 ± 59 lt days
Suganuma+06, theory: ≈ 115 lt days

Difference:
(i) Region is not resolved by NIR interferometric observations;
(ii) NIR maximum ≠ sublimation radius





Polarimetric RM at small telescopes

The scattering radius of the torus indicates the radius of sublimation, that may differ from the region of the IR maximum dust temperature.

Like the photometric RM, polarimetric RM in filters could be moved to small telescopes → more time for monitoring

Advantages:

- independent from the inclination
- spectropolarimetric observations could be replaced with *photopolarimetry in narrow/medium-band filters*

Disadvantages:

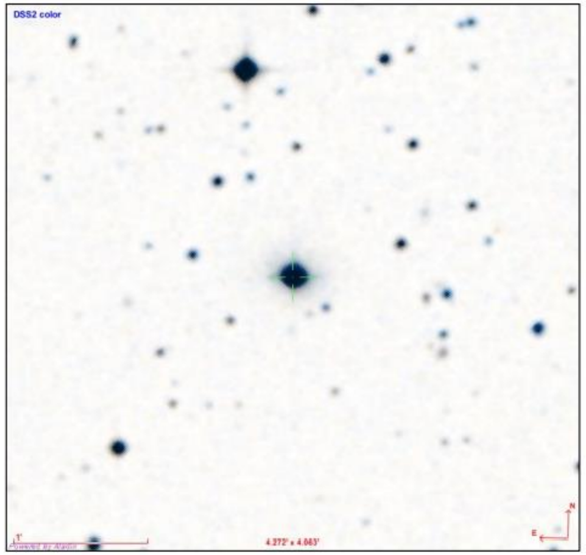
- contribution of polar scattering?
- needs to be carefully modelled

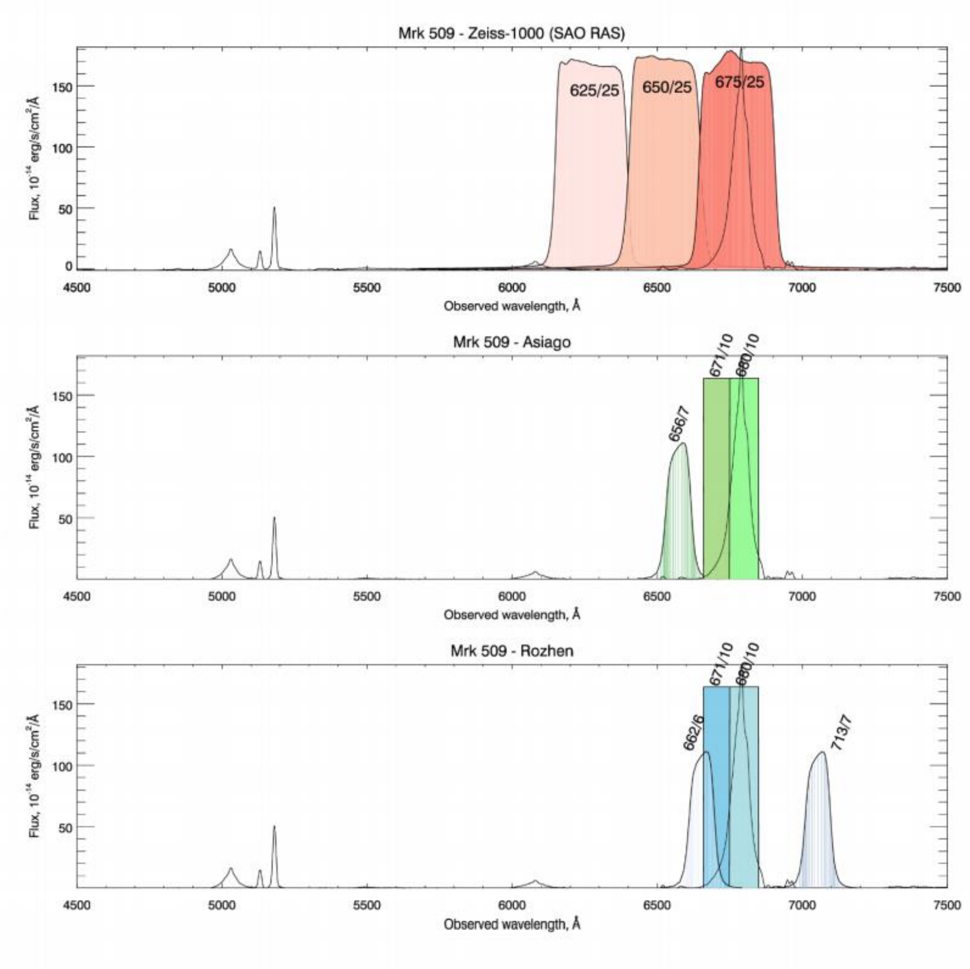
Photopolarimetry of Sy1 AGNs was started in 2019:
SAO (Russia) – 1-m,
Asiago (Italy) – 1.8-m,
Rozhen (Bulgaria) – 2 m,
Vidojevica (Serbia) – 1.4-m.

Mrk 509

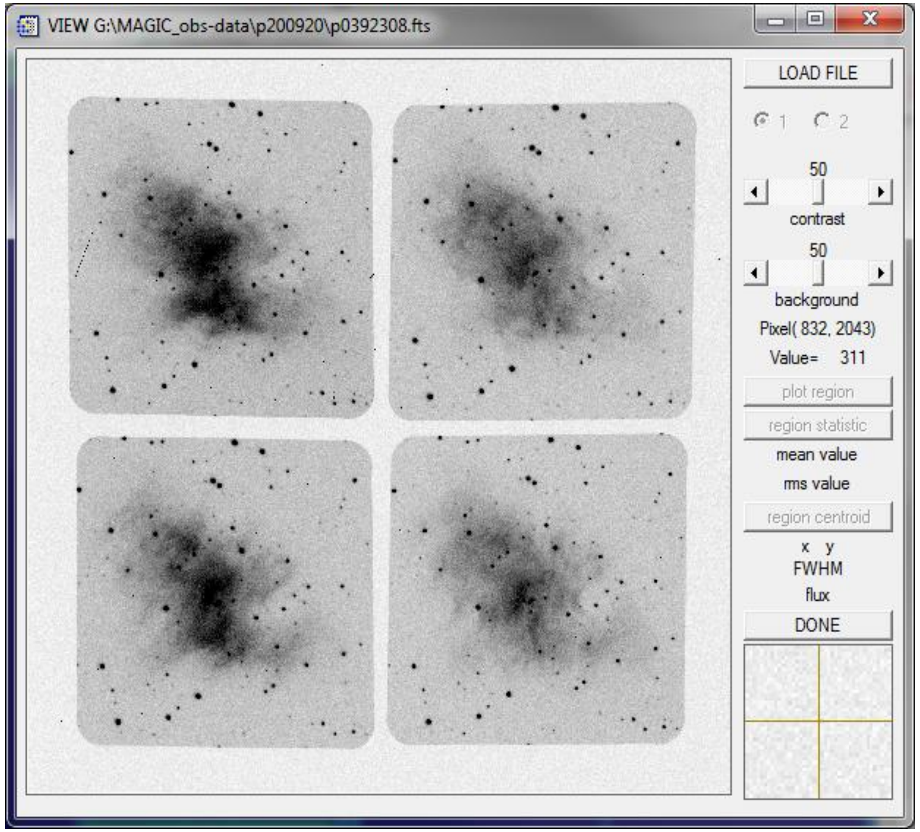
J2000: 20 44 09.75 -10 43 24.7
Gal: 36.0 -29.9
V=13.12
z=0.034

$R_{BLR} = 56$
$R_{sc} = 208$

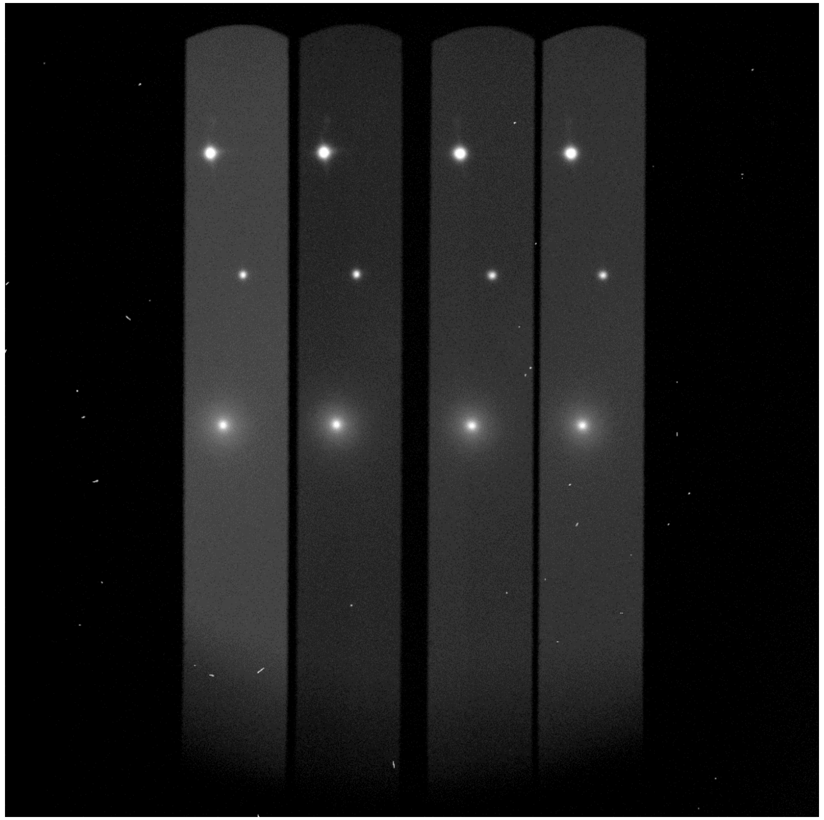




Polarimetric RM at small telescopes



Quadrupole double Wollaston prism in MAGIC

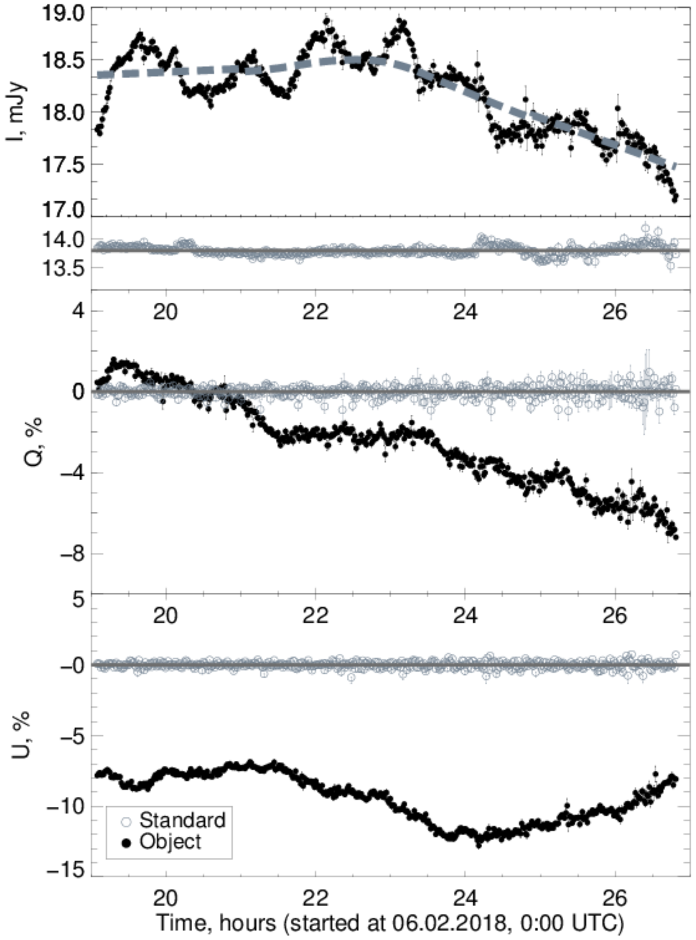


Wedged double Wollaston prism in StoP

Double Wollaston prism (=one shot polarimetry) + differential measurements allow us to achieve 0.1% accuracy of polarimetry (Afanasiev+Amirkhanyan12)

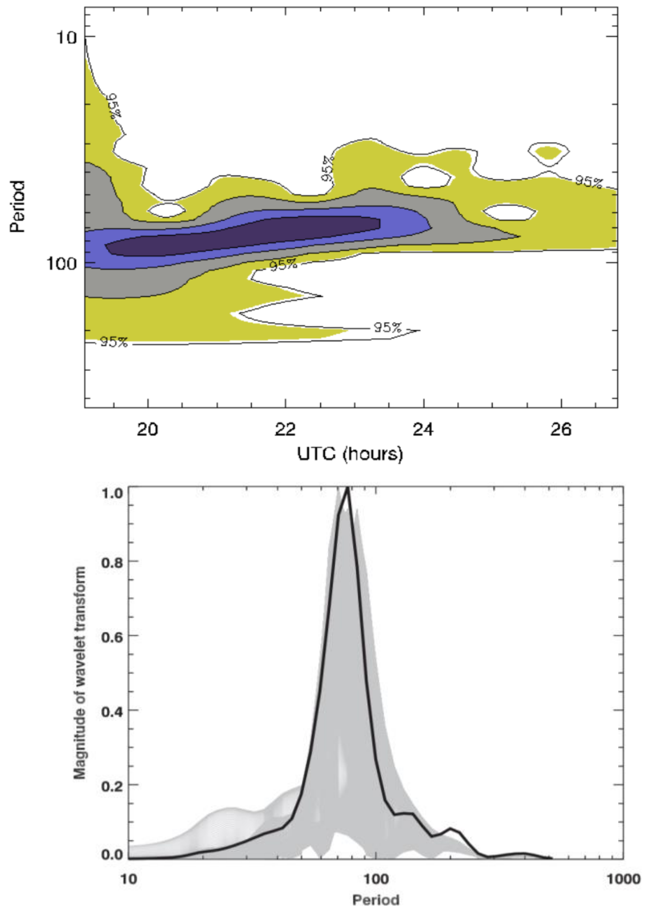
The intraday variations of the polarization vector direction in blazars

Everything started with S5 0716+714 – the bright BL Lac type object without redshift.



9-hour monitoring at 6-m BTA+SCORPIO-2

1. The brightness variability: variation period in total flux $\sim 77 \pm 10$ min.
2. The polarization variability.



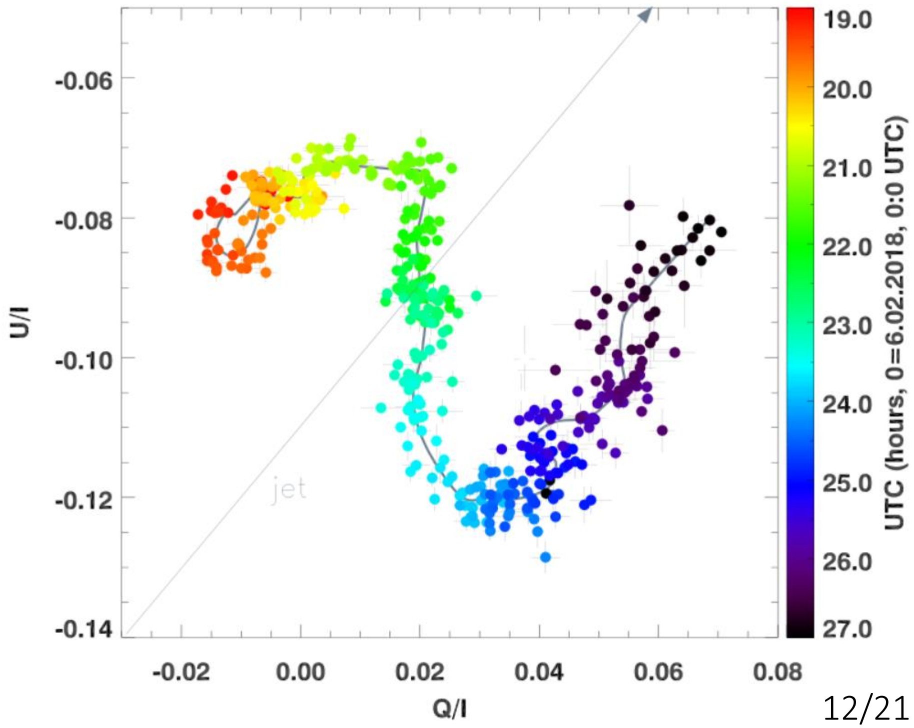
Wavelet-analysis of flux variations

The polarization vector direction switch – 1.5-3 hours.

Polarimetric accuracy – 0.1%.

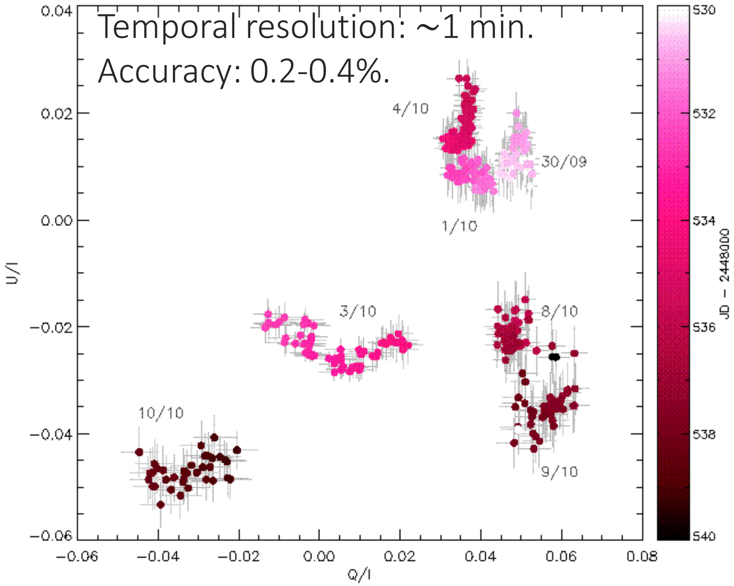
↓

The linear size of the region – $1.5 \cdot 10^{-5}$ pc, or 10 a.u.



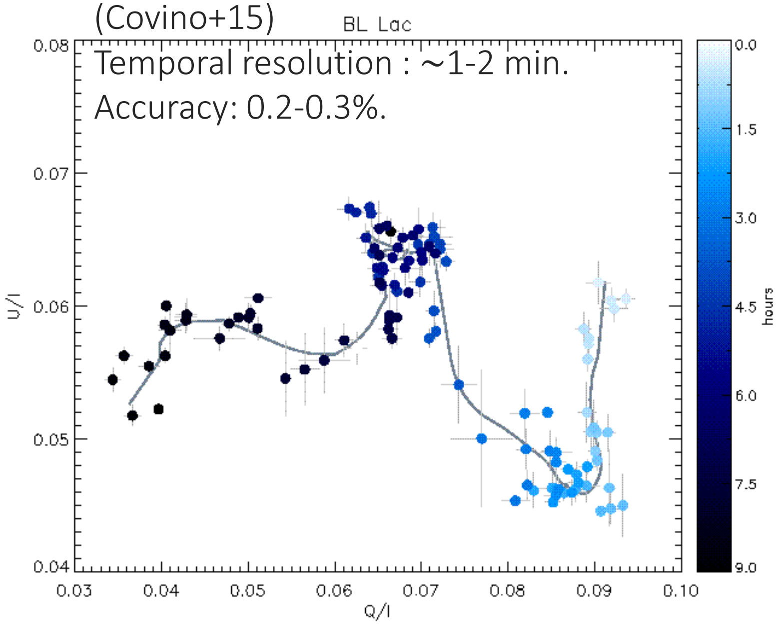
The intraday variations of the polarization vector direction in blazars

(Impey+00), S5 0716+716

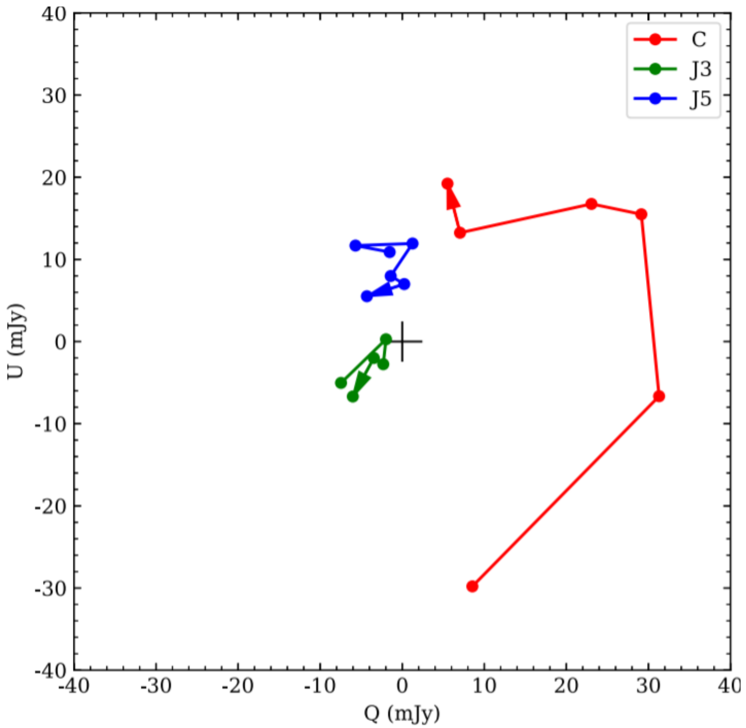


Temporal resolution: ~1 min.
Accuracy: 0.2-0.4%.

(Covino+15)

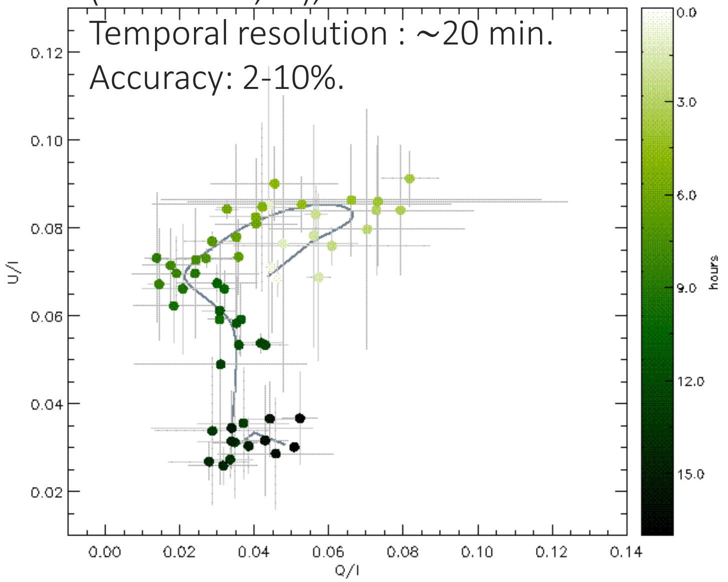


Temporal resolution : ~1-2 min.
Accuracy: 0.2-0.3%.



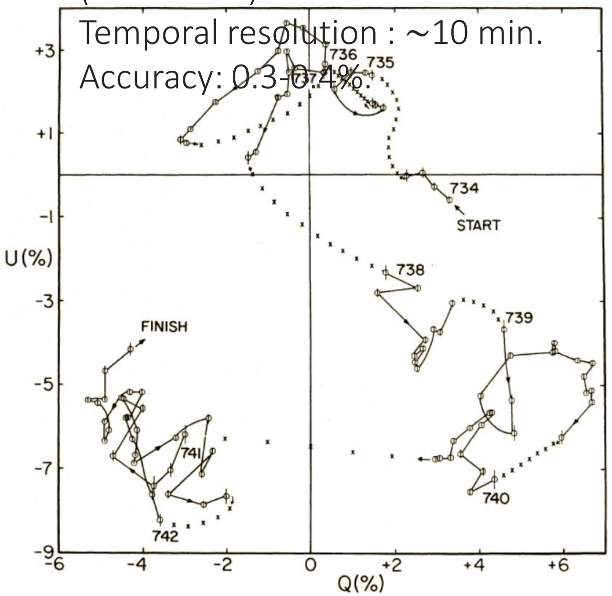
(Li et al. 2018)
Radio observations of CTA 102 in polarized light →
Suggestion of the helical plasma trajectory in jet.

(Bhatta+15,16), S5 0716+716

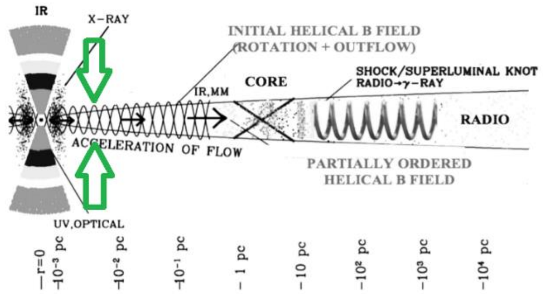


Temporal resolution : ~20 min.
Accuracy: 2-10%.

(Moore+82)



Temporal resolution : ~10 min.
Accuracy: 0.3-0.4%.

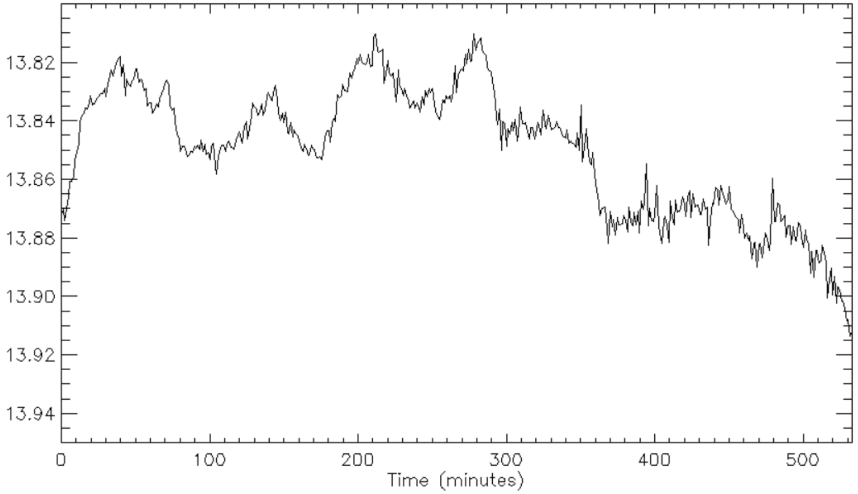


(Marscher 2005): Helical magnetic field at <10^{-2} pc from the core.

Geometrical model

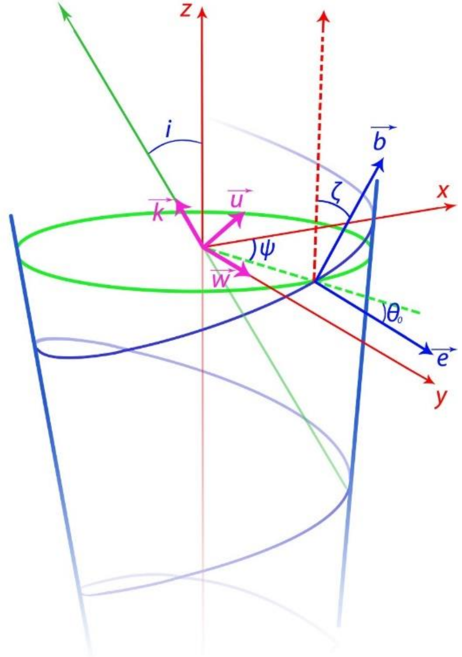
(Butuzova 2018,2020): magnitude variation due to the Doppler factor changes:

$$\Delta m = -2.5(3+\alpha)\log\frac{\delta_1}{\delta_2}$$



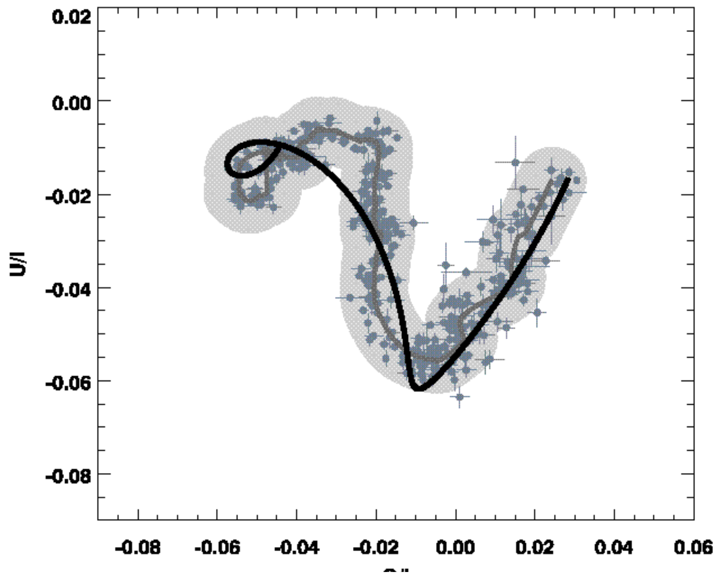
Both polarimetric and photometric variations could be explained with plasma rotation in helical magnetic field

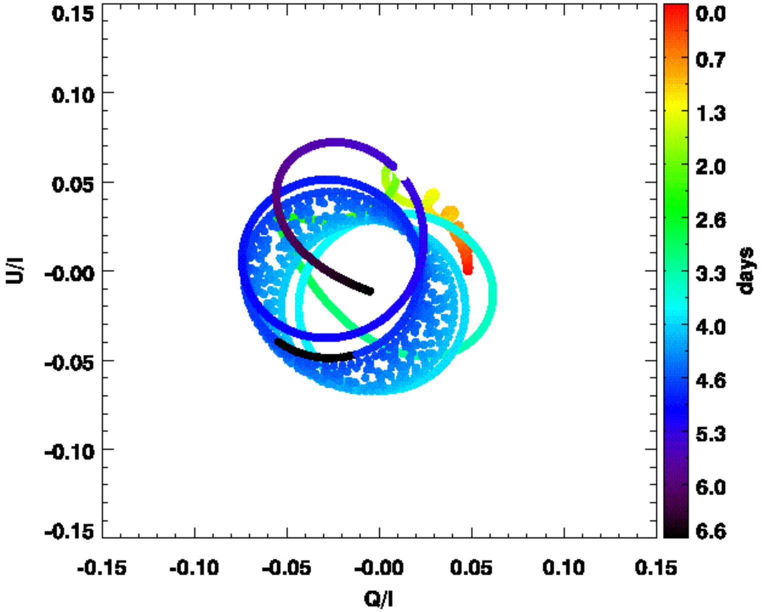
(Steffan+95, Li+18):



+ precession

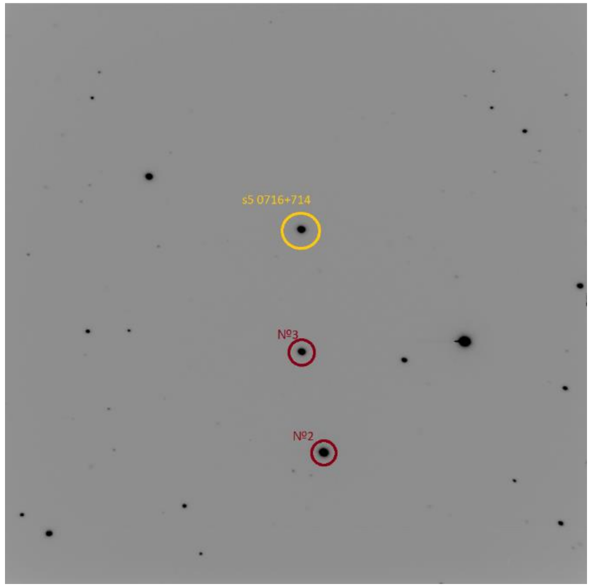
Kinematic parameters	Value
Distance from the precession axis	$0.7 \cdot 10^{-3}$pc
Precession period	15 days

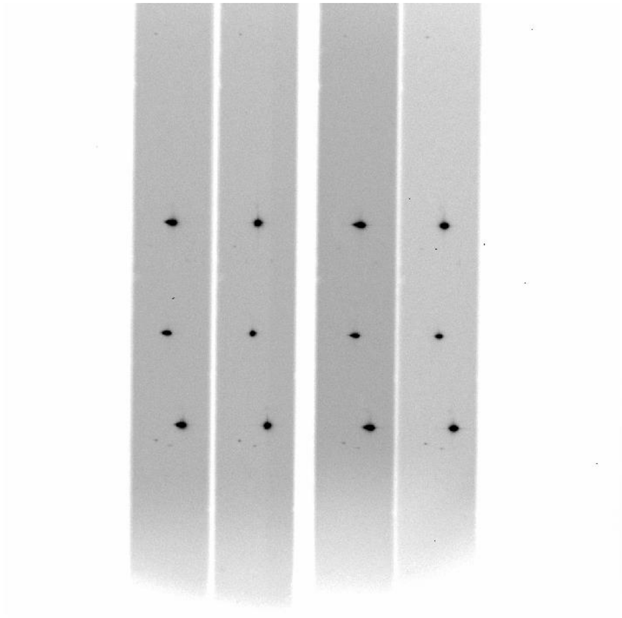


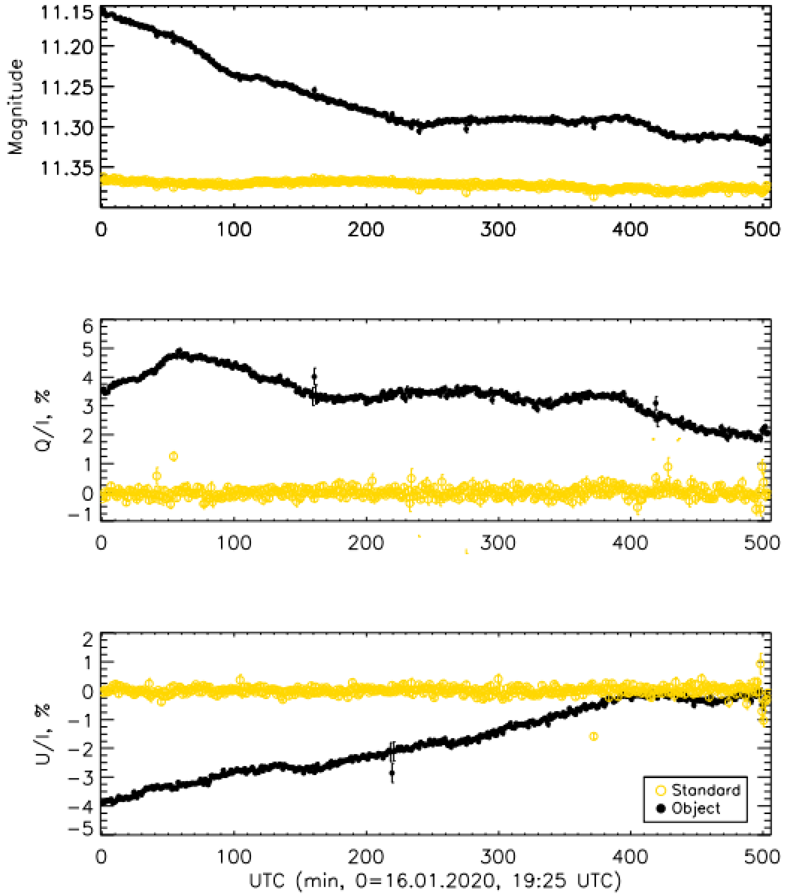


On January 16, 2020, an 8.5-hour monitoring of the S5 0716+714 blazar in polarized light was conducted with **Zeiss-1000 + StoP** – a repeat of the 2019 observations at the BTA.

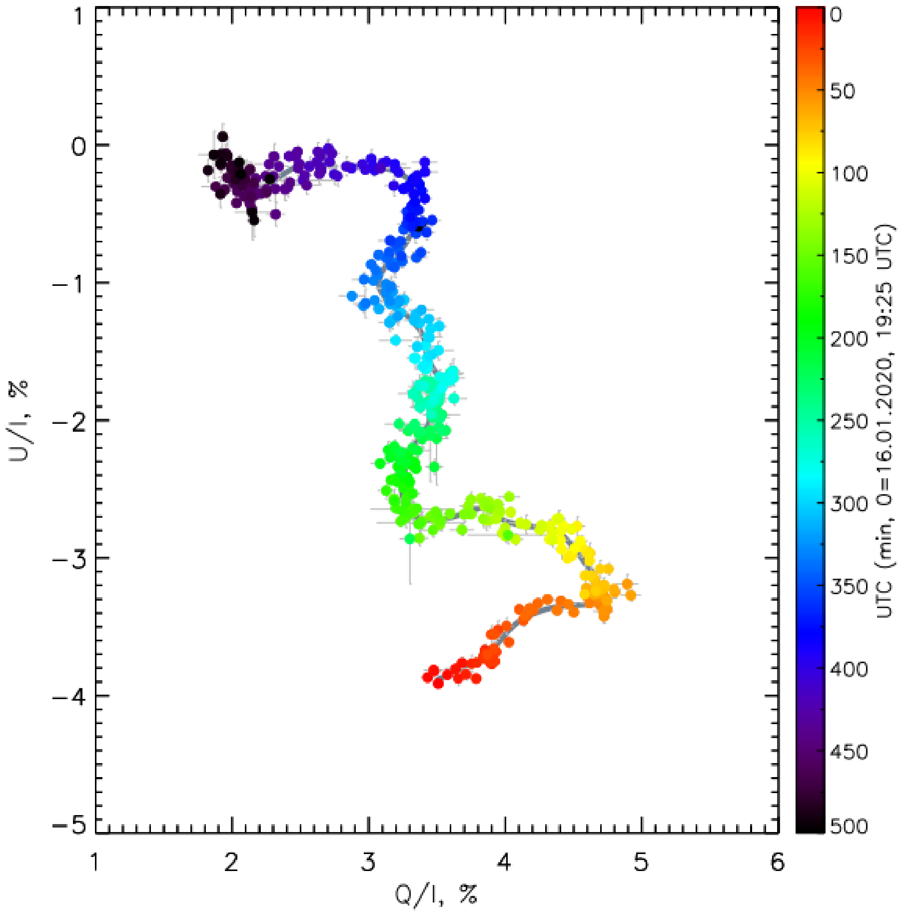
- Exp = 440*60s, white light.
- the photometry accuracy is 0.005 mag.
- the polarimetric accuracy is 0.05%.







S5 0716+714 – two years after



The variations of the normalized Stokes parameters Q and U during the night on the QU-diagram.

The data obtained for S5 0716+714 on Zeiss-1000 confirmed the results obtained earlier with BTA:

- ✓ switching the direction of the polarization vector at times of ~75 minutes;
- ✓ flux variation period 76±10 minutes

Earlier at BTA:

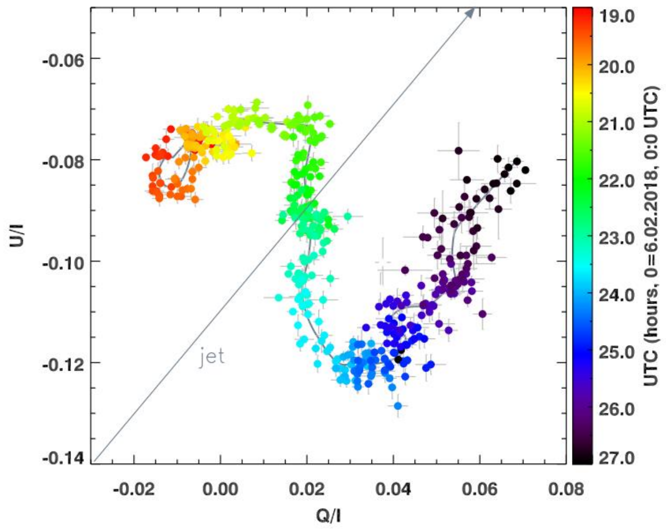
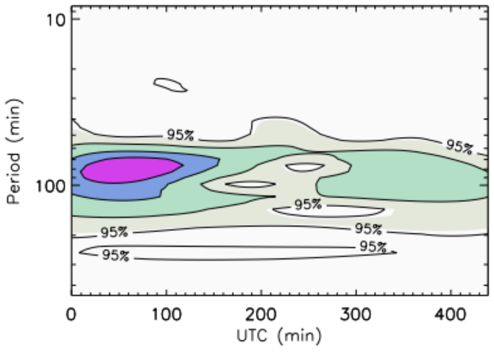
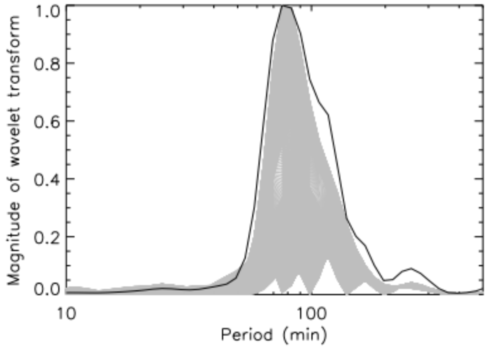
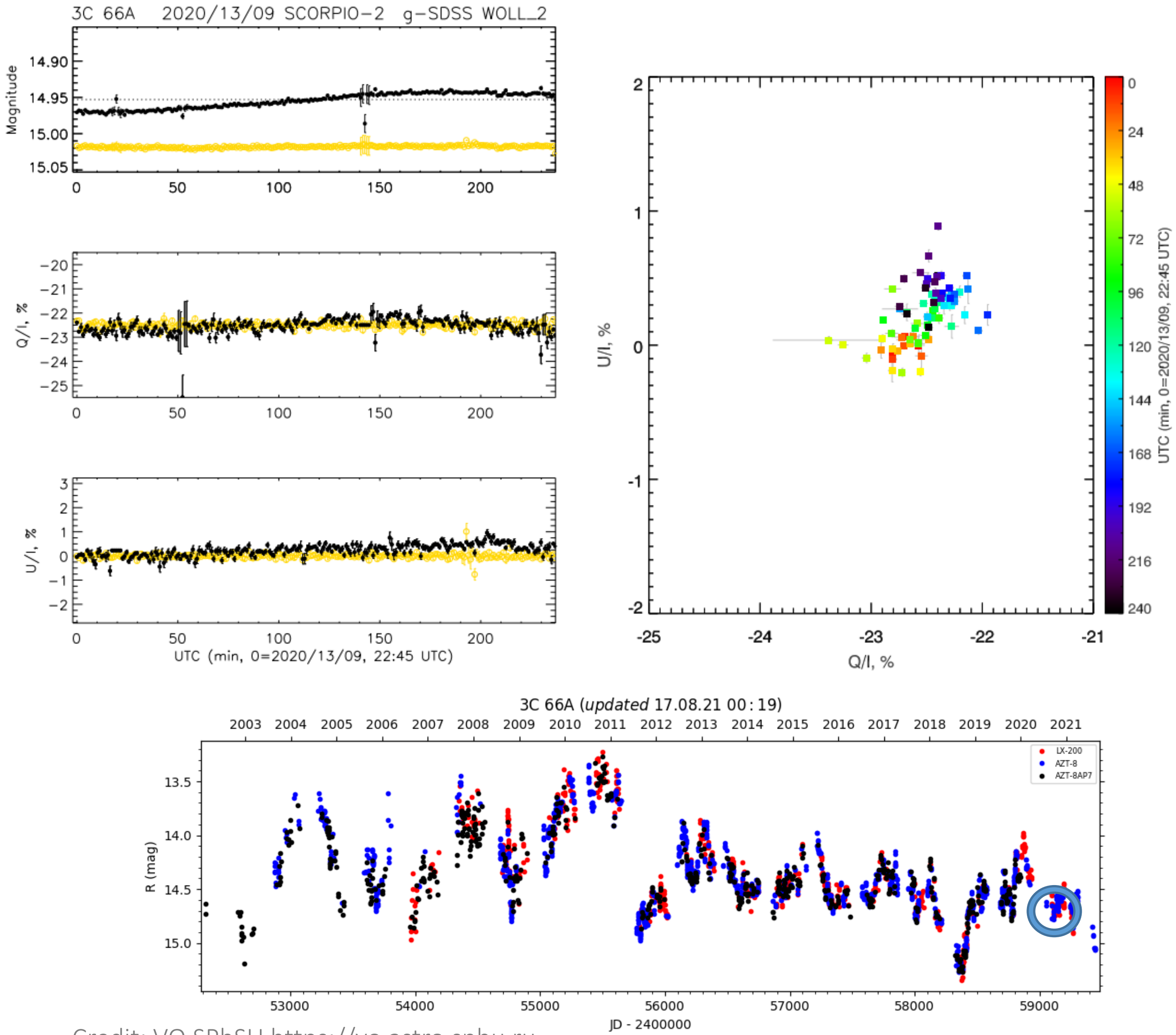


Figure 5. The variations of the normalized Stokes parameters Q and U during the night on the QU-diagram.





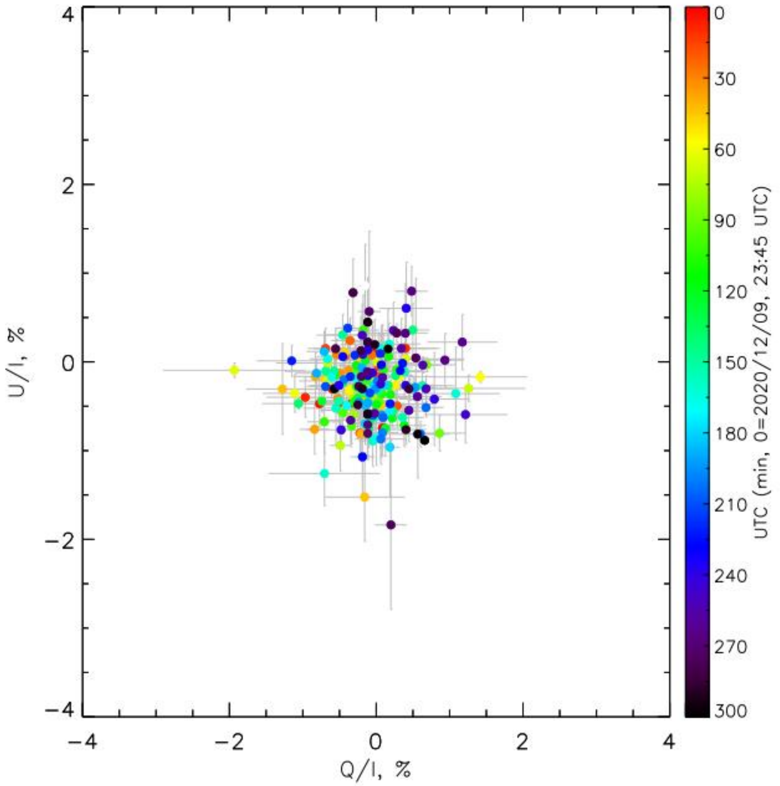
The result of wavelet analysis of the light curve of the blazar S5 0716+714. The maximum of the wavelet transform profile corresponds to a brightness change period of 76 minutes.



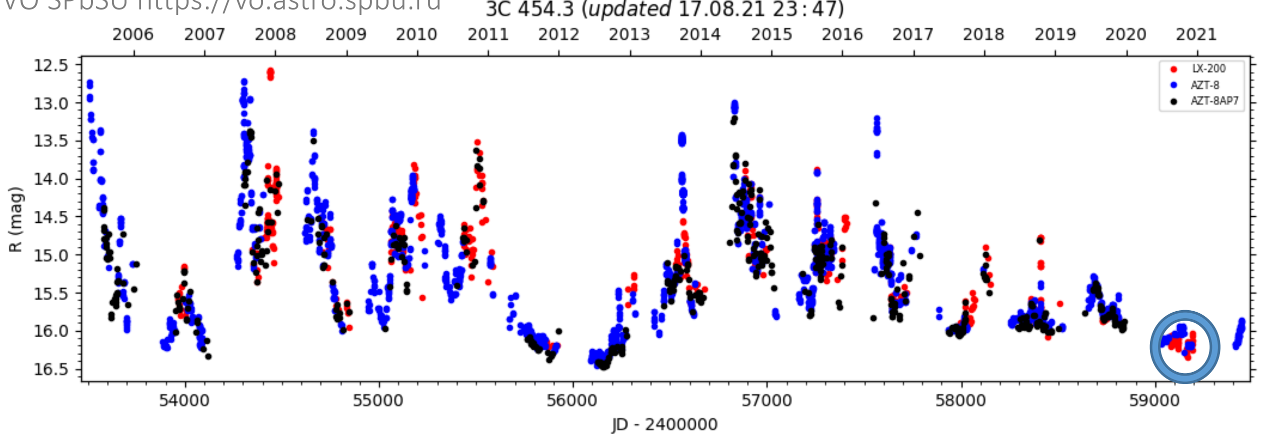
BTA+SCORPIO-2

Only about 2 hours of observations, but the polarization changes are detected. Blazar was in relatively low state.

Credit: VO SPbSU https://vo.astro.spbu.ru



Credit: VO SPbSU https://vo.astro.spbu.ru



BTA+SCORPIO-2

5 hours of monitoring, but **no significant changes at all**! Very low state.

The global question: does IDV depend on the state? More observations for statistics are needed!

Observations of blazars

- IDV on time-scales of hours;
- The estimation of the linear size of the field identifying with the emitting region at ~10^{-3} pc from the central BH;
- The polarization vector rotations marks the magnetic field precessing;
- The similar pattern was found in other papers and also for BL Lac.

The search of IDV of polarization vector direction is not only a key to estimate the size of the optical jet, but also provides a critical test for the jet models.

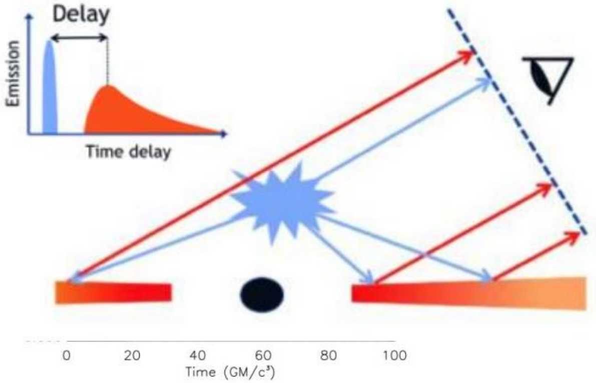
Needs:

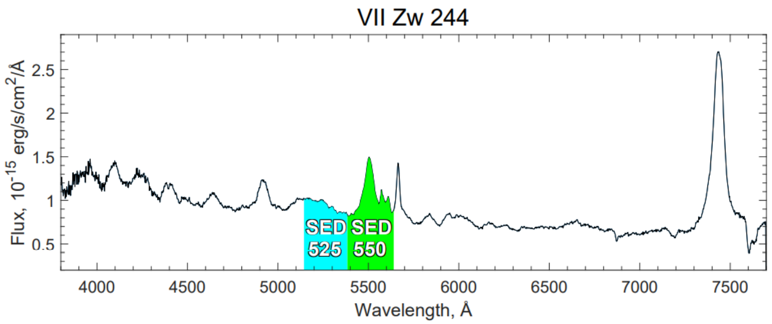
- high polarimetric accuracy
- really A LOT OF telescope time

Tasks for a new device at Zeiss-1000 of SAO

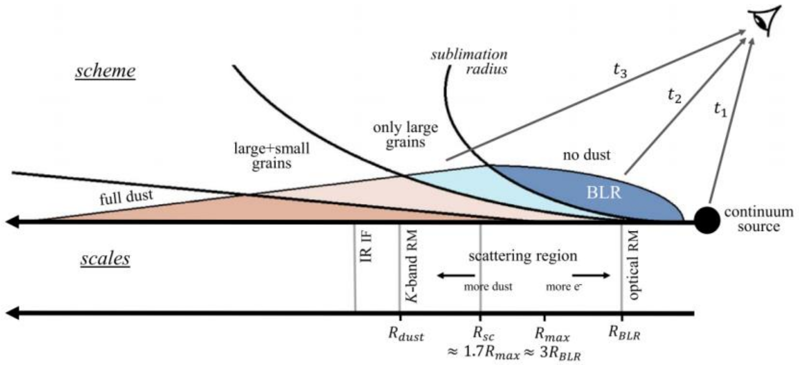
AGN monitoring:

- Reverberation mapping of AGNs in broad lines with medium-band filters (Haas+11, Uklein+2019, Malygin+2020)

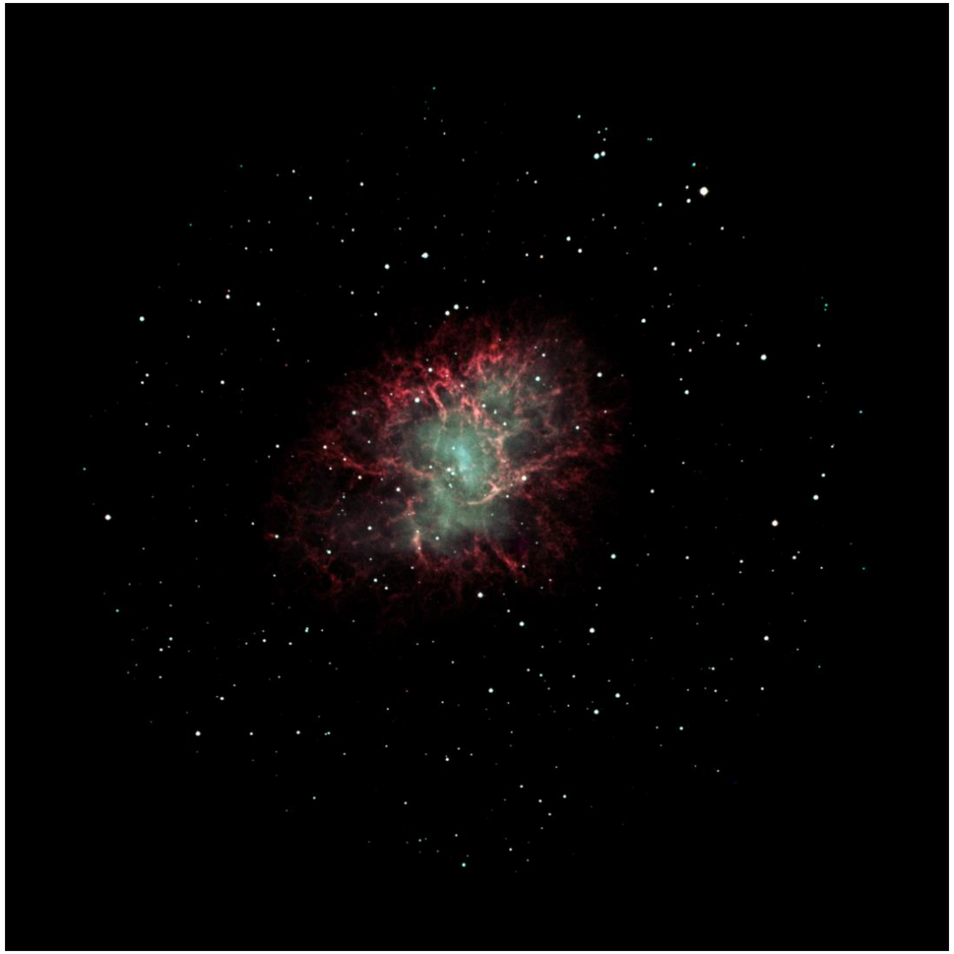




- The intraday variations of the polarization vector direction in BL Lac type objects (Shablovinskaya+Afanasiev 2019)
- Reverberation mapping of AGNs in broad lines in polarized light (Shablovinskaya, Afanasiev & Popovic 2020)



MAGIC



e.shablie@yandex.com

Shablovinskaya & Afanasiev *The intraday variations of the polarization vector direction in radio source S5 0716+714*, 2019, MNRAS, 10.1093/mnras/sty2943

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

Afanasiev, Shablovinskaya, Uklein, Malygin *Stokes-Polarimeter for 1-meter telescope*, 2021, Astr.Bull., in print

Thank you for your attention!