

Blazar Optical Sky Survey –BOSS Project (2013-2016) and the long-term optical variability monitoring

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Blazar Optical Sky Survey (BOSS) project

Blazar Optical Sky Survey (BOSS) project is a dedicated observational survey which aims to the long-term monitoring of known blazars in optical wavelengths.

The project started at the **University of Athens Observatory (UOAO)** in March 2013 under the coordination of Dr. Kosmas Gazeas.

In the frame of **BOSS Project**, ground-based optical photometric observations are performed, in parallel with orbital (SWIFT/XRT, FERMI/LAT) X-ray observatories, as well as ground-based radio observatories (CARMA, OVRO).

Blazar Optical Sky Survey (BOSS) project

BOSS project has immediately met international attention, attracting the interest of several collaborators worldwide, such as:

- Purdue University (USA)
- Max Planck Institut - MPIfA (Germany)
- University of Turku (Finland)
- Jagiellonian University of Krakow (Poland)
- Würzburg University (Germany)

It is currently running as an international collaboration of the University of Athens, utilizing the robotic and remotely controlled telescope at the UOAO.

Blazar Optical Sky Survey (BOSS) project

The blazar **Mrk421** was the first target to be observed in the frame of **BOSS project** and soon after, several blazars were added in the list of monitoring targets.

Mrk421	OJ287
Mrk501	3C279
Mrk180	PKS 1510-089
BL Lac	1ES 1959+650

The targets are continuously observed on a daily basis, with the aim to achieve dense temporal coverage in optical wavelengths.

In parallel, simultaneous observations in high and low energy bands are cross-correlated with BOSS database.

Main contribution of BOSS project

BOSS project can contribute in High Energy Astrophysics, in the field where:

- there is lack of low energy (optical) follow-up observations
- there is a need for cross-correlation studies
- multi-wavelength studies are essential for modeling purposes
- rapid flux variability is “missed” in non-frequent monitoring campaigns

The robotic telescope at the University of Athens Observatory



Dome: 5 m (Observadome Inc, 1994)
Telescope: 0.4 m f/8 Cassegrain (DFM Engineering Group, 1997)

Operations since 2000 (first light in 1999)

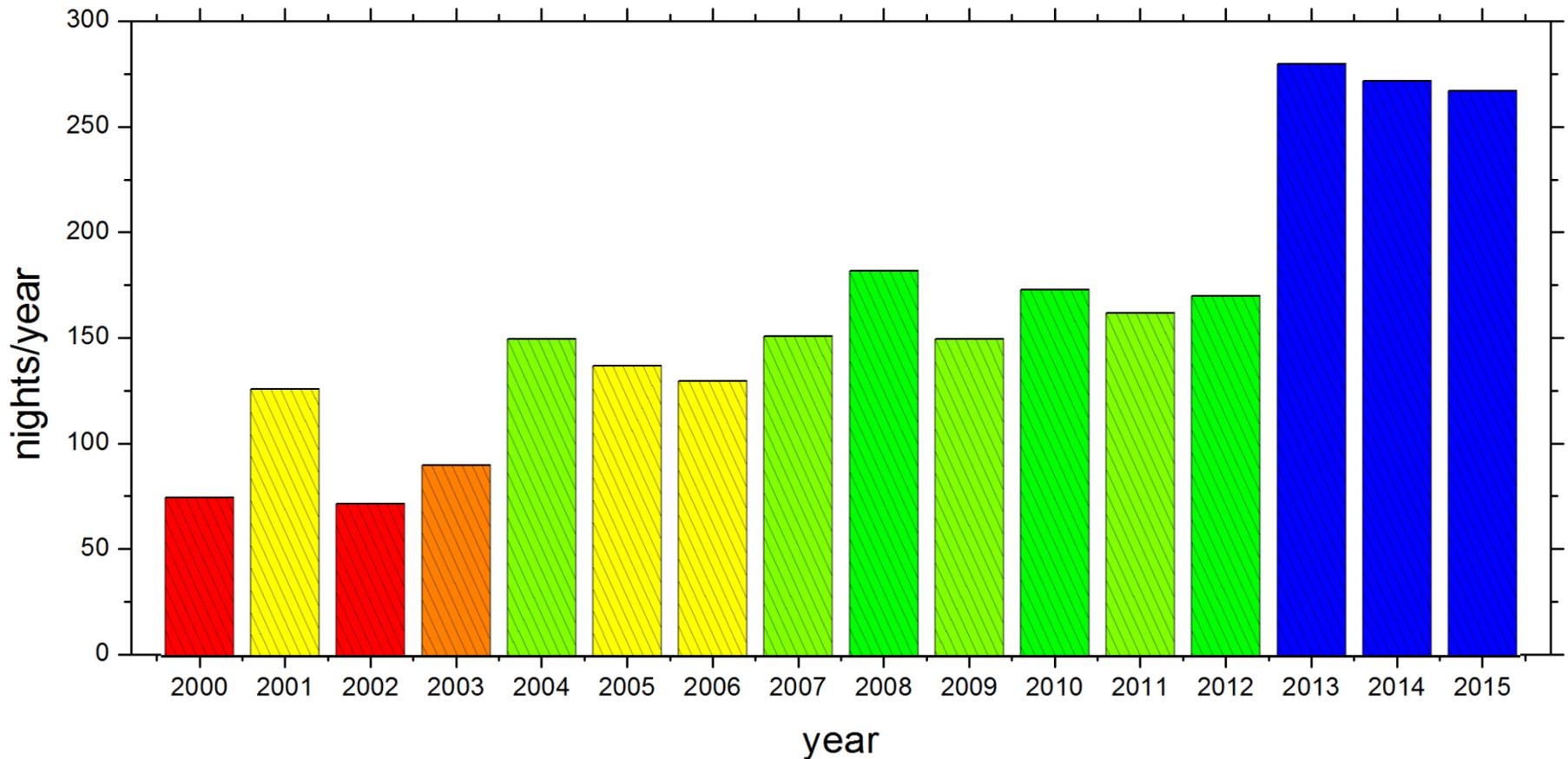
Robotic and remotely controlled



Since August 2012 the telescope and dome became robotic and remotely controlled. Photometric observations can be performed entirely remotely, utilizing the network connection between the telescope control room and the user.

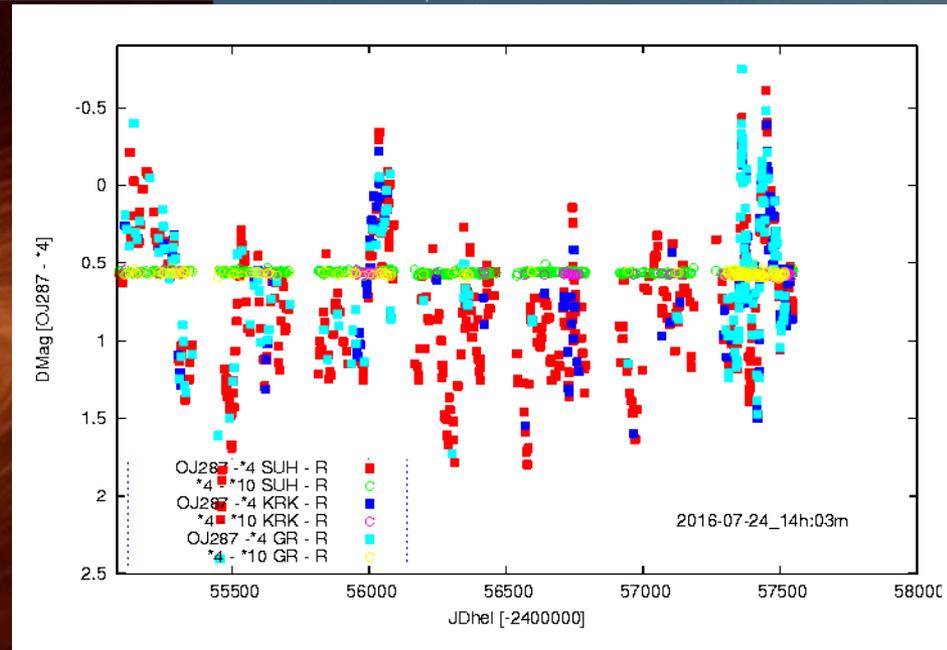
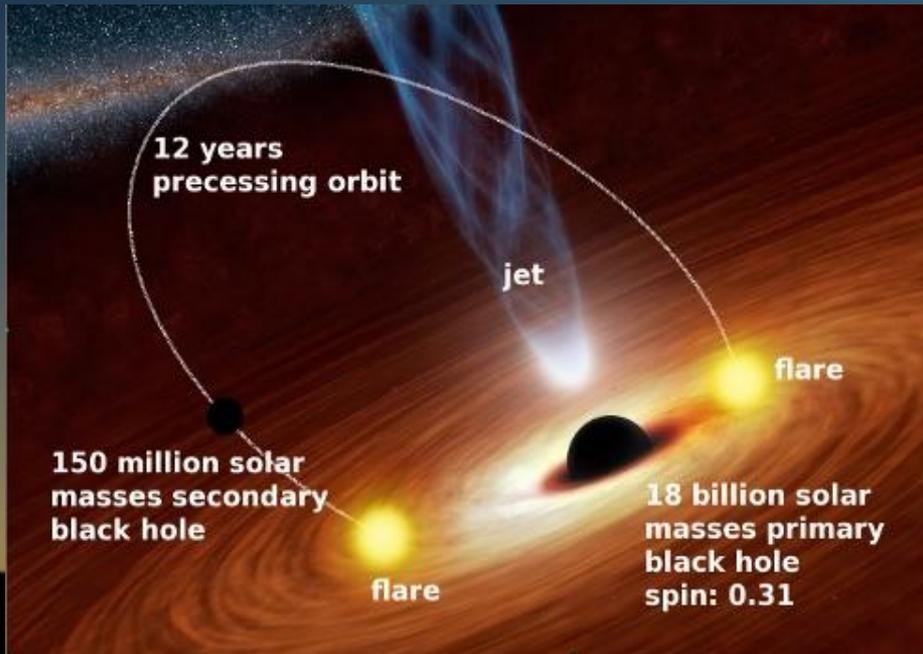
Results after the installation of the Auto Dome Remote Control Board in 2012

- ✓ Since 2012 the annual observing nights have dramatically increased (almost doubled)



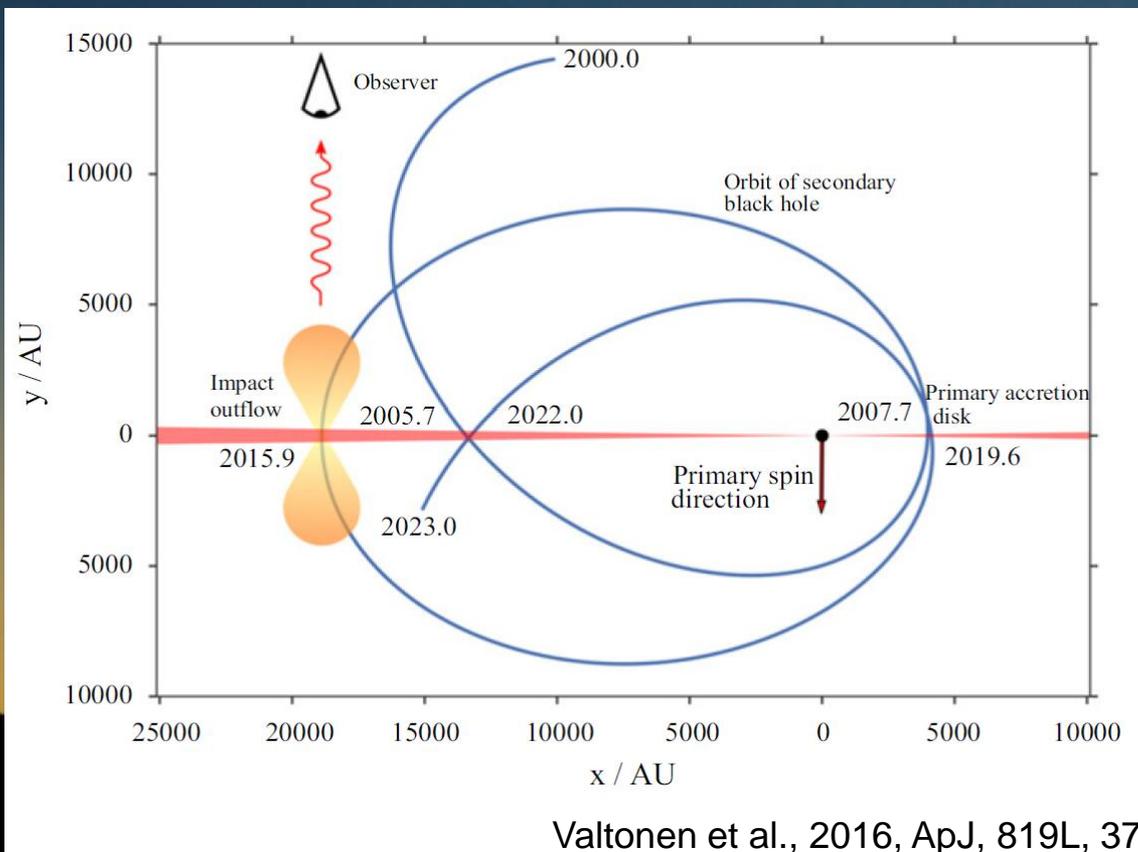
The super massive binary black hole OJ 287

- ✓ Continuous monitoring of the supermassive black hole binary.

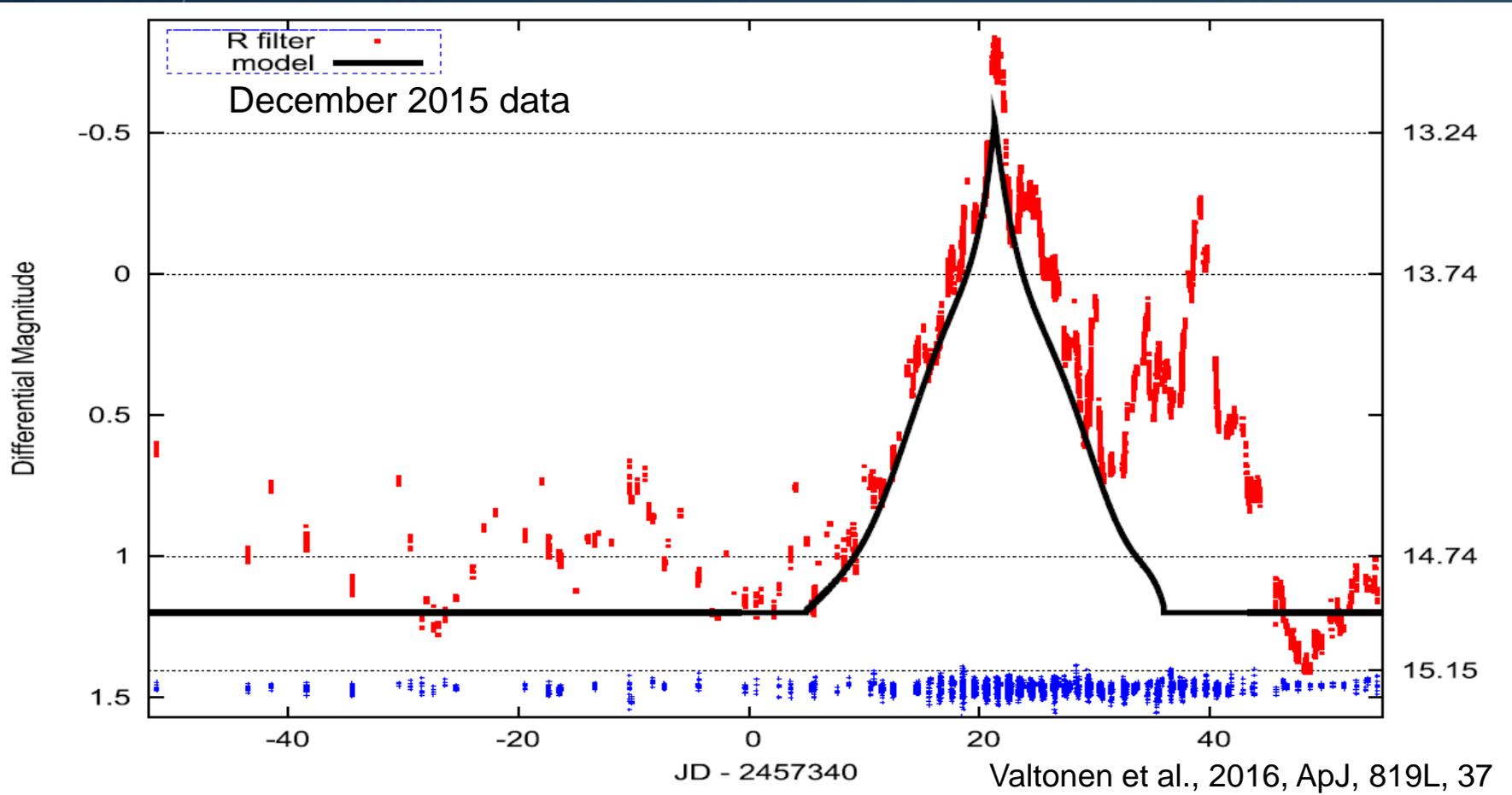


The super massive binary black hole OJ 287

- ✓ Orbital precession of OJ287 binary black hole and the predicted flare events between 2005-2023.



The super massive binary black hole OJ 287



The super massive binary black hole OJ 287

PRIMARY BLACK HOLE SPIN IN OJ 287 AS DETERMINED BY THE GENERAL RELATIVITY CENTENARY FLARE

CrossMark

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K. NILSSON¹, A. BERDYUGIN², V. PIROLA^{1,2}, H. JERMAK¹¹, K. S. BALIYAN¹², E. ALICAVUS^{13,14}, D. BOYD¹⁵, M. CAMPAS TORRENT¹⁶,

2016, ApJ, 819L, 37

DETECTION OF POSSIBLE QUASI-PERIODIC OSCILLATIONS IN THE LONG-TERM OPTICAL LIGHT CURVE OF THE BL LAC OBJECT OJ 287

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A. LIAKOS³, D. KOZIEŁ-WIERZBOWSKA¹, K. GAZEAS⁴, B. DEBSKI¹, T. KUNDERA¹, G. STACHOWSKI², AND V. S. PALIYA⁵

2016, ApJ, 832, 47

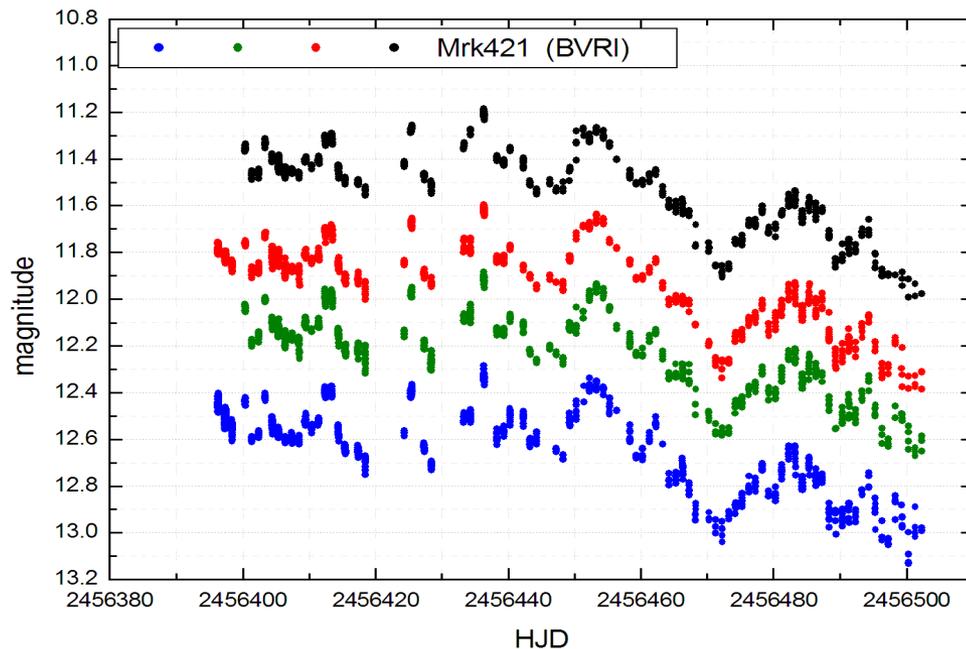
Search for QPOs in the light curve of the blazar OJ287: preliminary results from 2015/16 observing campaign

S. Zola^{1,2}, M. Valtonen^{3,4}, G. Bhatta¹, A. Goyal¹, Debski¹, A. Baran², J. Krzesinski², M. Siwak²,
S. Ciprini^{5,6}, A. Gopakumar⁷, H. Jermak⁸, K. Nilsson⁴, D. Reichart⁹, K. Matsumoto¹⁰,
K. Sadakane¹⁰, K. Gazeas¹¹, M. Kidger¹², V. Piirola^{3,4}, E. Alicavus^{13,14}, K.S. Baliyan¹⁵, D. Boyd¹⁶,

2016, Galaxies, 4, 41

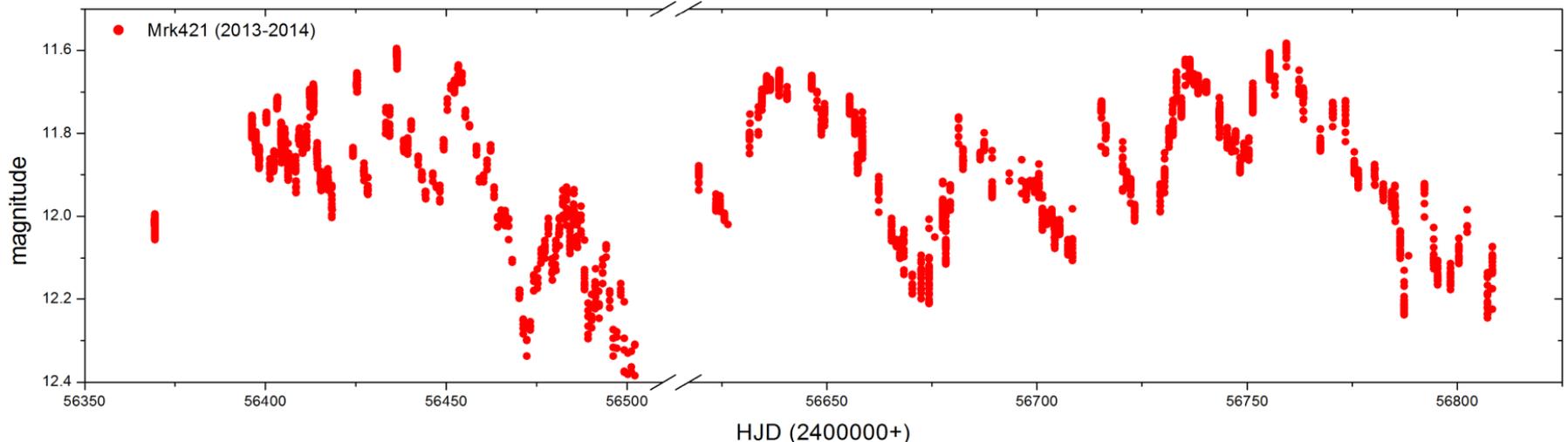
The highly active blazar Mrk421

- ✓ In 2013 the continuous monitoring of Mrk421 started, covering ~ 120 days in BVRI optical bands.
- ✓ Luminosity variations in all bands are cross-correlated with each other and other monitoring campaigns.



The highly active blazar Mrk421

- ✓ Continuous monitoring of Mrk421 for a total of 370 days (2013-2014) in R-band.
- ✓ Luminosity variations of this highly active blazar can be cross-correlated with orbital data and/or other monitoring campaigns in a wider range of energies.
- ✓ Over 98% of these observations were obtained remotely, using automated scripts.

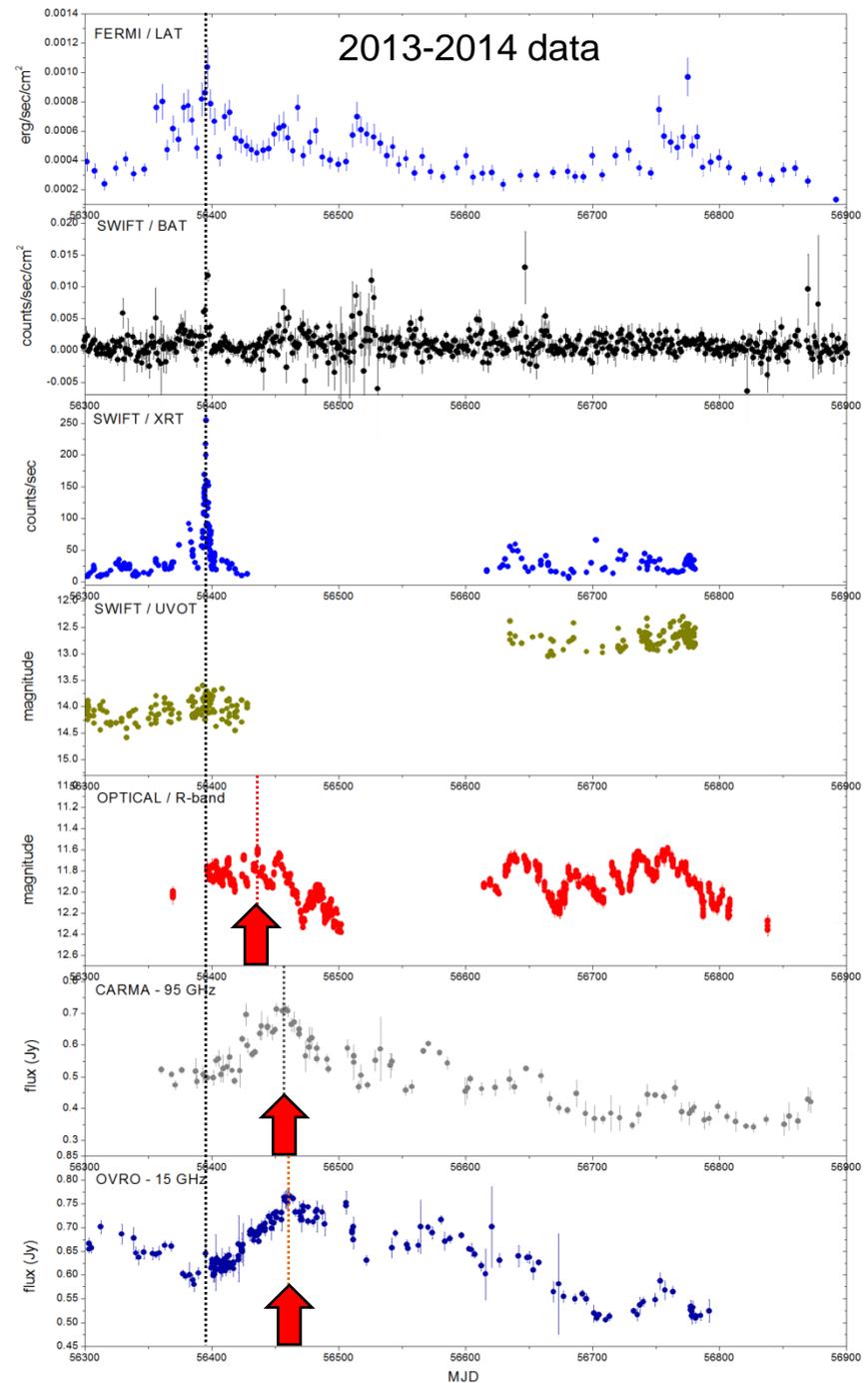


Mrk 421

Multiband sample of Mrk421 data, spreading from γ -rays (top) to radio signal (bottom).

Vertical lines represent the high energy flare occurred on **12 April 2013** (MJD 56394) and the corresponding signals detected a few days later in lower energies.

A ~ 60 day time lag is detected, as a result of electron cooling mechanism.



Continuous optical monitoring of the highly active blazar Mrk421

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Abstract. We present the recent photometric monitoring of blazar Mrk421, obtained from the Gerostathopoulos Observatory at University of Athens. Follow-up observations have been performed on this source after a highly energetic flare which occurred on 12 April, 2013. The flare was observed in X-rays by *Nustar* & *Swift* and in GeV - TeV gamma-rays by the Fermi satellite and MAGIC/VERITAS telescopes respectively. Continuous photometric monitoring in the optical BVRI bands during 3 months after the flaring activity reveals a quasi-periodic light variation. This is one of the few times that Mrk421 was observed for such a long period with large observational gaps in four different filters. We find a strong correlation between the different optical bands. Although we did not detect any signs of intra-day variability, the optical flux is variable in longer time scales (days/weeks) with the relative amplitude of variations being approximately the same in all four bands.

Observations or Mrk 421

Mrk 421 is one of the closest to earth blazars at redshift $z=0.031$ (Punch et al. 1992) and it is classified as a high-peaked BL Lac object since the low-energy bump peaks in the UV/soft X-rays energy band. It has been detected in all energies of the electromagnetic spectrum, i.e. from radio wavelengths (e.g. Rebillot et al. 2006) up to Very High Energy (VHE) gamma-rays (Punch et al. 1992) and it has been a target of simultaneous multi-wavelength (MW) observing campaigns, e.g. Takahashi et al. 2000, Gupta et al. 2008, Fossati et al. 2008.

Photometric observations were obtained with the 0.40 m f/8 Cassegrain reflector at the University of Athens Observatory (located in Athens, Greece), and a SBIG ST-10 XME CCD camera, equipped with a set of U, B, V, R, I (Bessel) filters. The data span over a period of 135 days between March - July 2013, covering the variability in all optical bands. During this period Mrk 421 exhibited bright flaring activity in the X-rays up to the VHE gamma-rays, which motivated our long-term optical monitoring of the blazar. Our optical data set is one of the longest optical photometric observing run obtained for Mrk421, resulting in a dense and homogeneous data sample, since only one telescope was used.

Differential aperture photometry was performed on all images, using the AIP4WIN software (Berry & Burnell, 2000). The comparison and check stars were chosen according to Villata et al. (1998). However, since these stars are quite faint in comparison to the high optical emission of Mrk421 during this period, the stars GSC 3010.0688 and GSC 3010.0762 were used as comparison and check stars respectively.

Photometric uncertainty was typically 0.03 mag in all filters. The light contribution from the nearby host galaxy was excluded from the overall magnitude estimation, since the photometric aperture was chosen to be as small as 8 arcsec in radius, while the host galaxy is 10 arcsec away from Mrk421. The resulting photometric light curves, which are shown in Fig. 1, have been obtained after calibration to the standard system and converted into flux units (erg cm⁻²sec⁻¹Hz⁻¹).

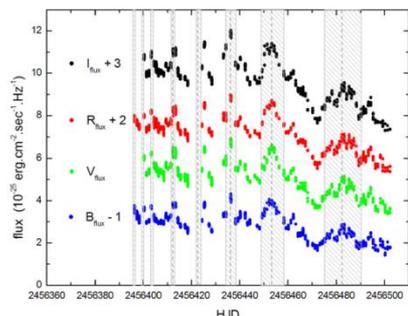


Figure 1: The photometric light curves in all optical bands. Gray areas mark the periods of brightness peak, while the width of each box represents the duration of each peak and the dashed line the day of maximum brightness. Note that the (assumed) peak at HJD=2456423.0 is absent, due to bad weather conditions. The observed maximum at HJD=2456425.5 seems to be the secondary peak, following the non-observed one.

Optical Flux Variability

Blazar variability timescales are often divided into three categories: the intra-day variability (IDV) which ranges between a few minutes up to one day (Wagner & Witzel 1995), the short-term variability (STV) which ranges between a few days to a few months and the long-term variability (LTV), which covers all variations longer than a few months, up to several years (Gupta et al. 2004). With the data spanning over 3 months and with a high-density coverage, IDV and STV can be studied in detail, in comparison to the flare activity in X-ray and γ -ray region.

Fig. 1 clearly show STV with a strong correlation between all four optical bands. The data do not show a clear IDV. A very weak IDV of 0.08 mag might be a weak indication of possible short-scale flare events. On the other hand, STV is much more obvious. Several flares with amplitude of ~ 0.3 mag (even 0.5 mag in some cases) are resolved during the entire observing period. These flares are visible in all filter bands. Among the most prominent features, the most important are the following:

- 1) all four optical bands are highly correlated with each other
- 2) the overall brightness is getting lower with time (LTV)
- 3) no IDV is observed within a 2-3 hour run, or it is very weak
- 4) time interval between peaks is getting progressively longer, and each peak lasts longer than the previous one
- 5) each individual peak is followed by a secondary one of lower amplitude and shorter duration

Another feature of the presented light curves, which cannot be directly deduced from Fig. 1, is the achromaticity of the flux variability, i.e. the amplitude of variations relative to the average flux does not differ among the optical filters. This is in contrast to previous works, where the amplitude of variations increases with decreasing wavelength (e.g. Hovatta et al. 2009).

In order to quantify the variability amplitude in different wavelengths we calculated the fractional rms flux variability (F_{var}), which is defined as:

$$F_{var} = \sqrt{\frac{\overline{(x_i - \bar{x})^2}}{\bar{x}^2}} \quad \text{where } \bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad \text{and } s^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2$$

are the average flux and the variance of our sample light curve. Finally, $\overline{(x_i - \bar{x})^2} = \sigma^2$ is the mean error squared with σ being the errors associated with each flux measurement. Our results show that the F_{var} for each filter band is: B=0.136, V=0.139, R=0.131, I=0.137.

Data analysis

The almost uninterrupted photometric monitoring in the optical BVRI bands during 3.5 months after the flaring activity in mid-April 2013 reveals a quasi-periodic light variation, gradually fading down towards the nominal optical flux of Mrk421.

Due to the tight correlation between different filters, in what follows, we will restrict our analysis on the B-filter.

• **Autocorrelation function (ACF):** The autocorrelation coefficients as a function of the lag are shown in Fig. 2. Their slow decrease implies that the optical light curve is non-stationary and there is an underlying trend in the time-series.

• **Lag-Plot:** If $X(t)$ denotes B-mag at time t , then the lag-plot is simply a graph of $X(t) \times X(t-l)$ (see Fig. 3). Our data points are clustered along the diagonal (red line), i.e. the value at time t can be predicted if a value at the previous time is known. Thus, our optical data are highly auto-correlated.

• **Autoregressive modeling (AR):** Due to the high degree of autocorrelation we assume that the optical light curve is described by a 2nd order AR process, which is best described by: $X_t = a_0 + a_1 X_{t-1} + a_2 X_{t-2} + \epsilon_t$ where $a_0=12.615 \pm 0.056$, $a_1=0.750 \pm 0.029$, $a_2=0.230 \pm 0.029$

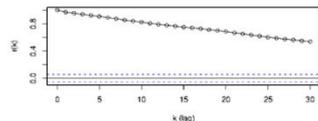


Fig. 2: Autocorrelation coefficients (k) as a function of the time lag k of the corresponding time-series in B filter.

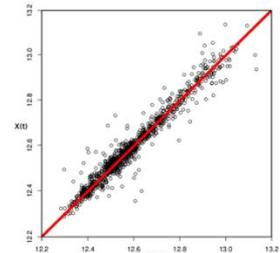


Fig. 3: Lag-plot for the optical (B-filter) light curve (points). Red line is plotted for guiding the eye.

Summary

This study presents one of the most comprehensive observing campaign, in terms of duration (temporal coverage), temporal density (observations were obtained almost daily), wavelength range and consistency/homogeneity of data.

The observing campaign was obtained with the opportunity of the very recent strong flare activity which occurred on 12 April 2013, in order to follow and study the optical behavior of Mrk421, as an active high-energy emitting source.

No X-ray and VHE gamma-ray data were available for our observing period. Therefore, no direct link between optical and X-ray flux was found during these days. A similar result was also extracted by Rebillot et al. 2006.

Time-series analysis revealed a high degree of auto-correlation in all optical filters. This means that flux measurements at a certain time strongly depend on their past values.

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Multi-wavelength monitoring of the highly active blazar Mrk421

Investigating the high vs. low energy correlated variability

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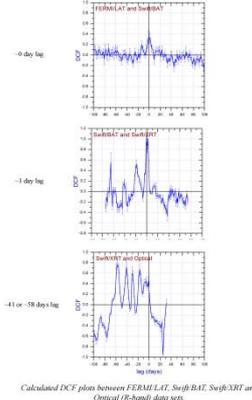
Abstract. We present a long-term multi-wavelength monitoring of blazar Mrk421, obtained simultaneously with orbital and ground-based instruments. Daily optical observations from the University of Athens Observatory started as a follow-up monitoring of the major γ -ray flare of 12 April, 2013. This data set is compared with the γ -rays, X-ray and UV observations obtained with Fermi/LAT and SWIFT satellite telescopes respectively, as well as with the 95 GHz and 15 GHz data from the CARMA and OVRO 40-m radio telescope. We investigate the existence of correlated variations among the different wavebands using the discrete correlation function (DCF) technique.

Introduction

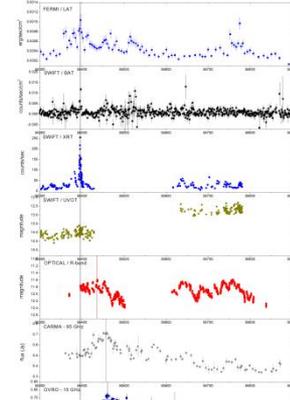
Mrk421 is one of the closest blazars to Earth ($z=0.03$) exhibiting large amplitude, rapid variations across the electromagnetic spectrum. It is extensively monitored in various wavelengths (e.g. Rebillot et al. 2006, Fossati et al. 2008, Gupta et al. 2008, Hovatta et al. 2009, Aleksić et al. 2012). Temporal correlations between two energy bands have been detected in the past (e.g. Giabetti et al. 2007, Fossati et al. 2008, Hovatta et al. 2015). This behavior along with the fact that most campaigns with wide spectral coverage have shorter temporal coverage has motivated our long-term optical monitoring of Mrk 421.

Multi-wavelength sample

Our sample consists of contemporary data in seven different energy bands: γ -rays (FERMILAT), hard X-rays (Swift/BAT), soft X-rays (Swift/XRT), UV (Swift/UVOT), optical (LOA), millimeter (CARMA) and radio (OVRO) wavelengths. The data sets extend over the period of about 600 days (MJD 56300-56900). The optical observations (R-band) were performed from the University of Athens Observatory in a daily basis. It is one of the most comprehensive optical observing campaigns, in terms of duration (temporal coverage). Density of data (most observations were obtained on a daily basis and homogeneity (data have been obtained with a single instrument). The CARMA 95 GHz data were obtained as part of the *Monitoring of Rapid Active Galactic nuclei with Radio, Millimeter and Optical Telescopes (MARMOOT)* program (<http://www.astro.caltech.edu/marmot>), while the OVRO 40-m 15 GHz data were obtained as part of an on-going blazar monitoring program where ~ 1800 blazars are observed with twice per week cadence (Richards et al. 2011).



Calculated DCF plots between FERMILAT, Swift/BAT, Swift/XRT and Optical (R-band) data sets.



Calculated DCF plots between Optical (R-band), CARMA (95 GHz) and OVRO (15 GHz) data sets.

The observed time lags

Setting the peak time of the γ -ray flare (MJD 56394) as zero time we detect corresponding flares in lower energies (optical, millimeter and radio) a few days later (see table below).

Brightness Peak	Energy band
MJD 56394.1	FERMILAT
MJD 56394.1	Swift/BAT
MJD 56395.1	Swift/XRT
MJD 56436.2 or 56453.2	Optical
MJD 56463.2	CARMA
MJD 56463.2	OVRO

Subtracting the brightness peak time of each data set from the γ -ray flare time we get:

- 0 day lag between FERMILAT and Swift/BAT (MJD 56394.1)
 - 1 day lag between Swift/BAT and Swift/XRT (MJD 56395.1)
 - 41-58 day lag between Swift/XRT and Optical (MJD 56453.2)
 - 25 day lag between Optical and CARMA (MJD 56463.2)
 - 2 day lag between CARMA and OVRO (MJD 56463.2)
- As a consequence we see (also shown on last DCF plot):
- 65-50 day lag between FERMILAT and OVRO.

The sample of all data sets used in this study, spreading over the entire electromagnetic spectrum from high energies (top: FERMILAT, GeV) to very low ones (bottom: OVRO 15 GHz data sets). Vertical dashed lines represents the moment when the high energy flare occurred on 12 April 2013 (MJD 56394.1) and the reciprocal signals detected a few days later in lower energies.

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BOSS Project

current status

3C279, PKS1510-089, 1ES 1959+650

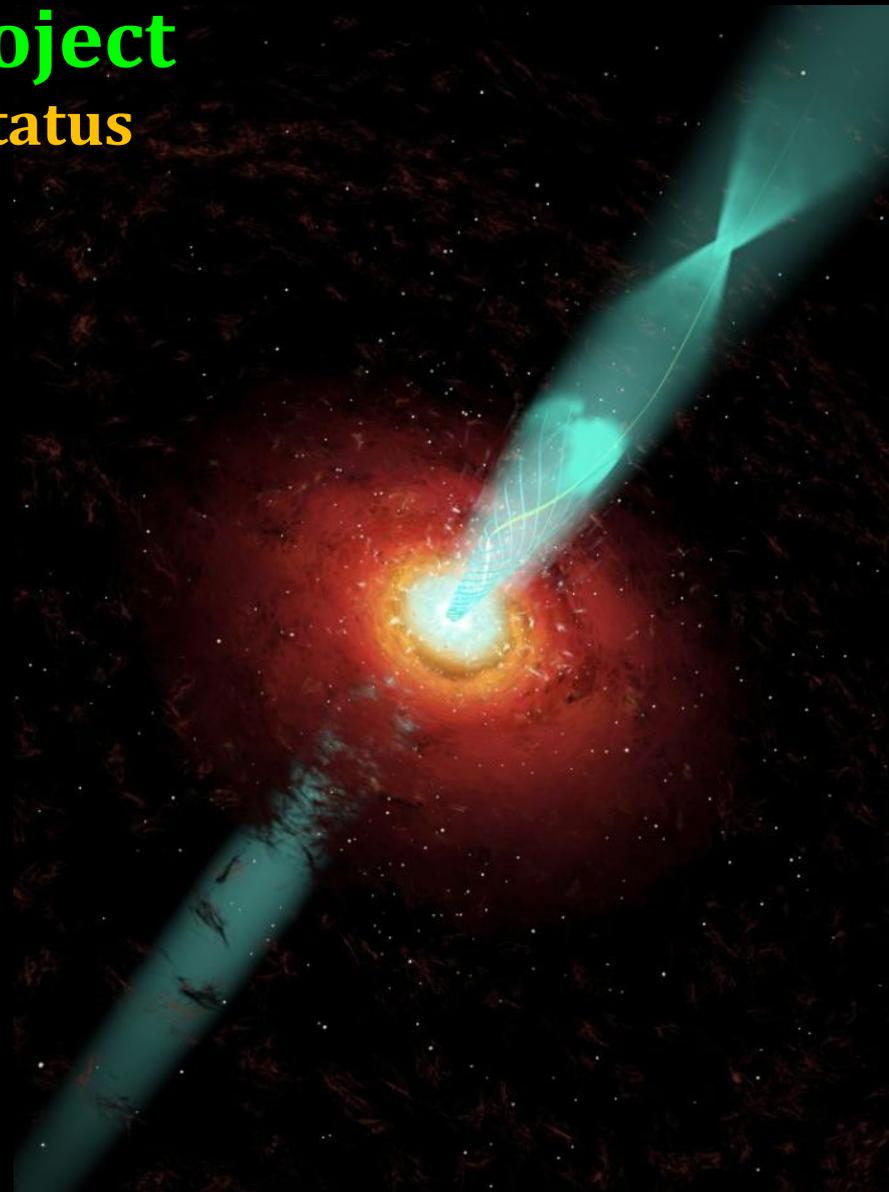
...observations started recently...

Mrk501

Collaboration initiated with:
Jagiellonian University of Krakow, Poland
Würzburg University, Germany

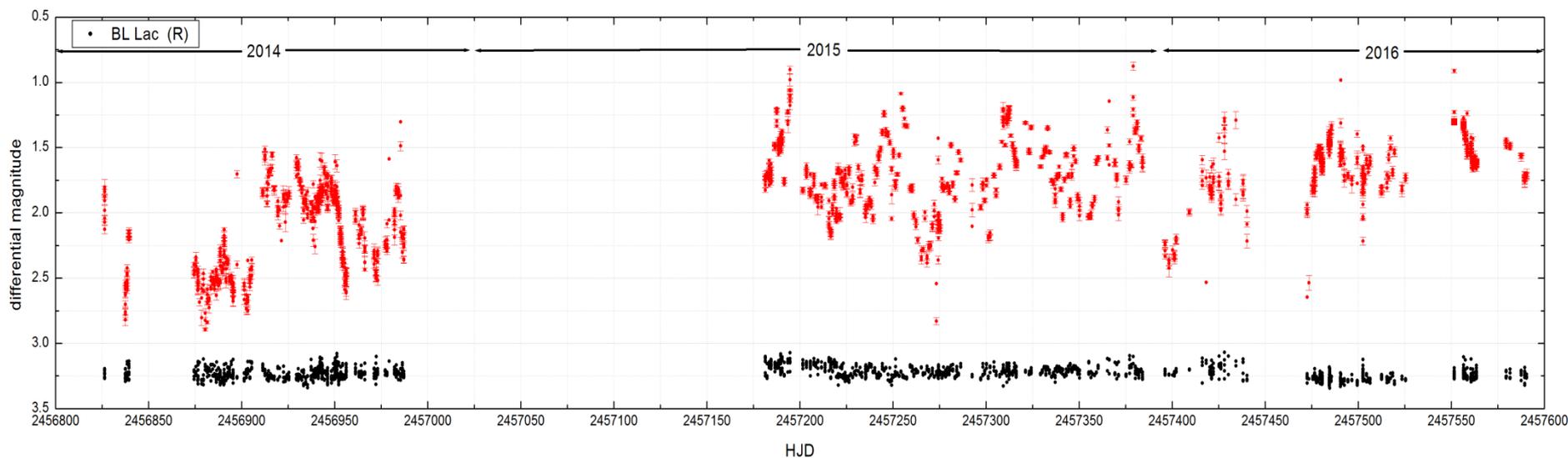
BL Lac, Mrk180

...waiting to be “adopted”...

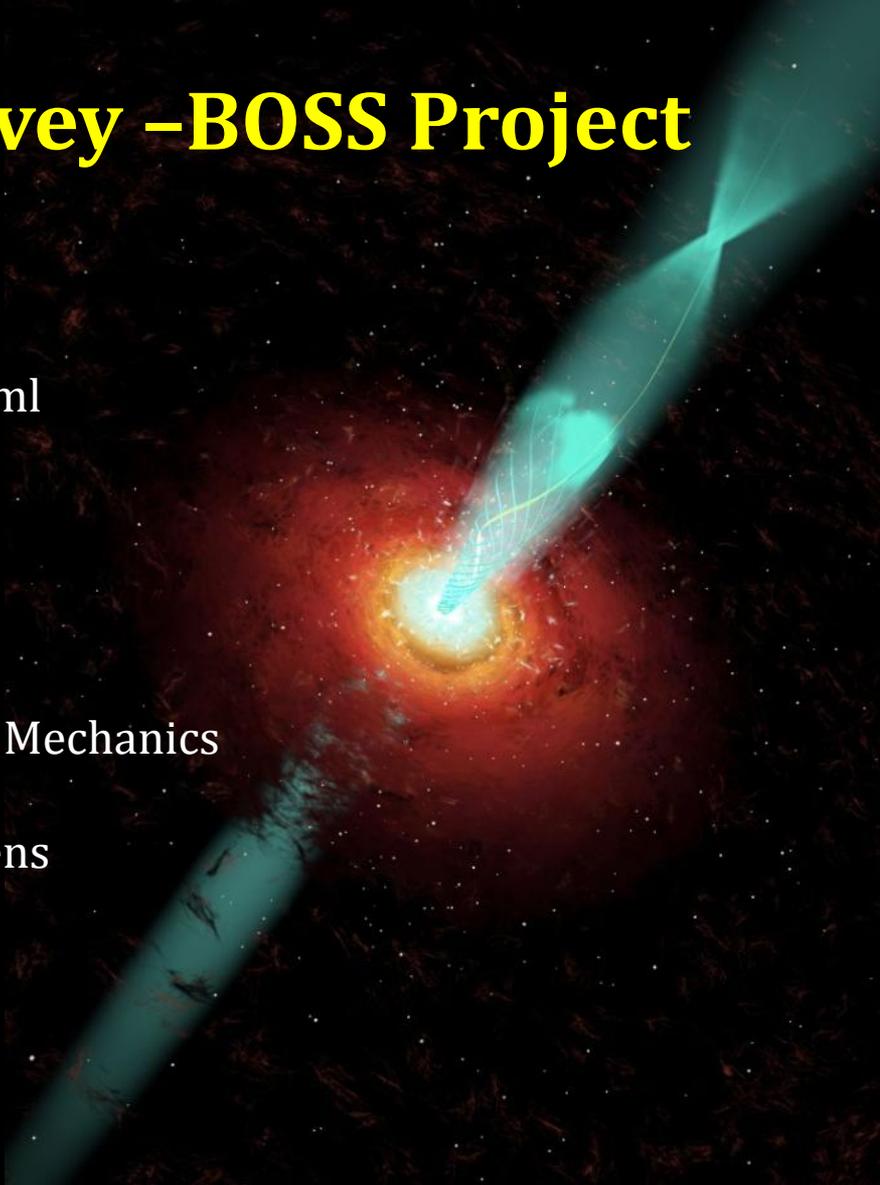


BL Lac – the prototype

- ✓ Continuous monitoring of BL Lac for a total of ~325 days (2014-2016) in R-band.



Blazar Optical Sky Survey –BOSS Project



BOSS Project Link:

http://users.uoa.gr/~kgaze/boss_project.html

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