Optical variability modelling of newly identified blazars and blazar candidates behind Magellanic Clouds

Natalia Żywucka-Hejzner
In collaboration with
Mariusz Tarnopolski, Volodymyr Marchenko, Łukasz Stawarz, Markus Boettcher, Szymon Kozłowski, and Andrzej Udalski

Nort-West University and Astronomical Observatory of Jagiellonian University

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Credit: imgur.com/JADDgSL

Table of Contents

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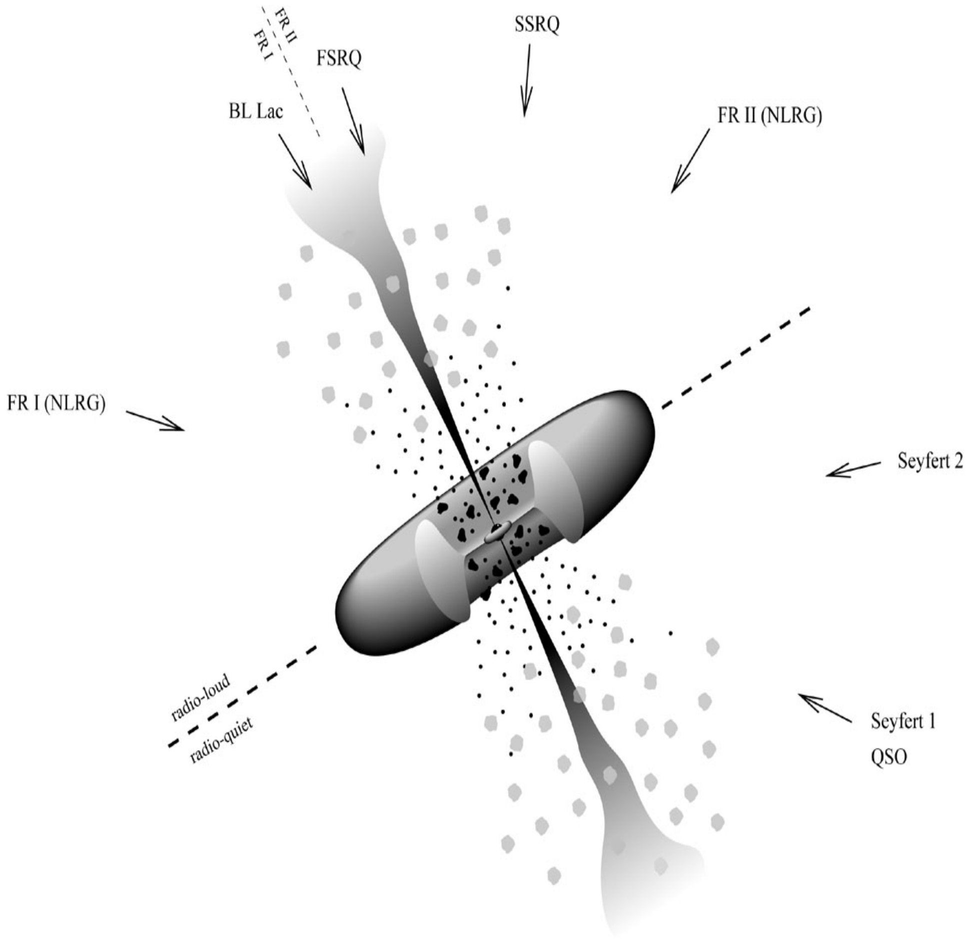
Blazars



- Unification model: jets of blazars are close to line of sight
- Broad-band and non-thermal continuum of electromagnetic radiation (radio to γ-rays)
- Flat spectrum radio emission with:

$$S(\nu) \propto \nu^{-\alpha}$$
$$\alpha < 0.5$$

- Significant optical polarization

$$P_o > 3\%$$

- Significant flux variability

BL Lacertae (BL Lac)
→ no/weak emission lines

Flat Spectrum Radio Quasar (FSRQ)
→ narrow and broad emission lines

Credit: The unification model of AGNs; Urry & Padovani 1995

OGLE
The Optical Gravitational Lensing Experiment

OGLE project: since 1992;
Andrzej Udalski

Main scientific goals:

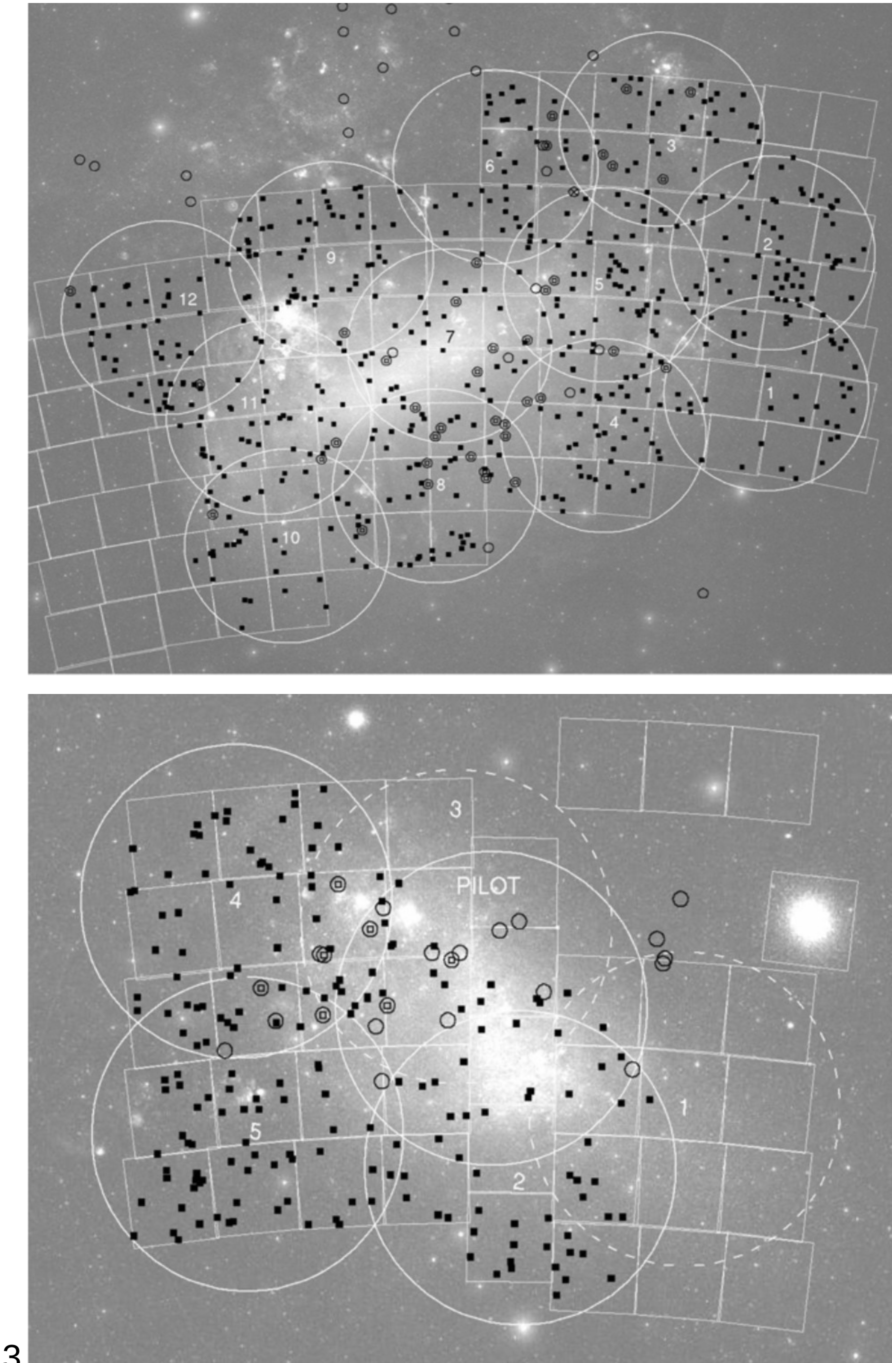
- MCs and Galactic Bulge monitoring,
- dark matter study with microlensing phenomena,
- extrasolar planets' searching,
- galactic structure study,
- analysis of different time scale variability of hundred millions regularly observed objects.

Location: Las Campanas, Chile.

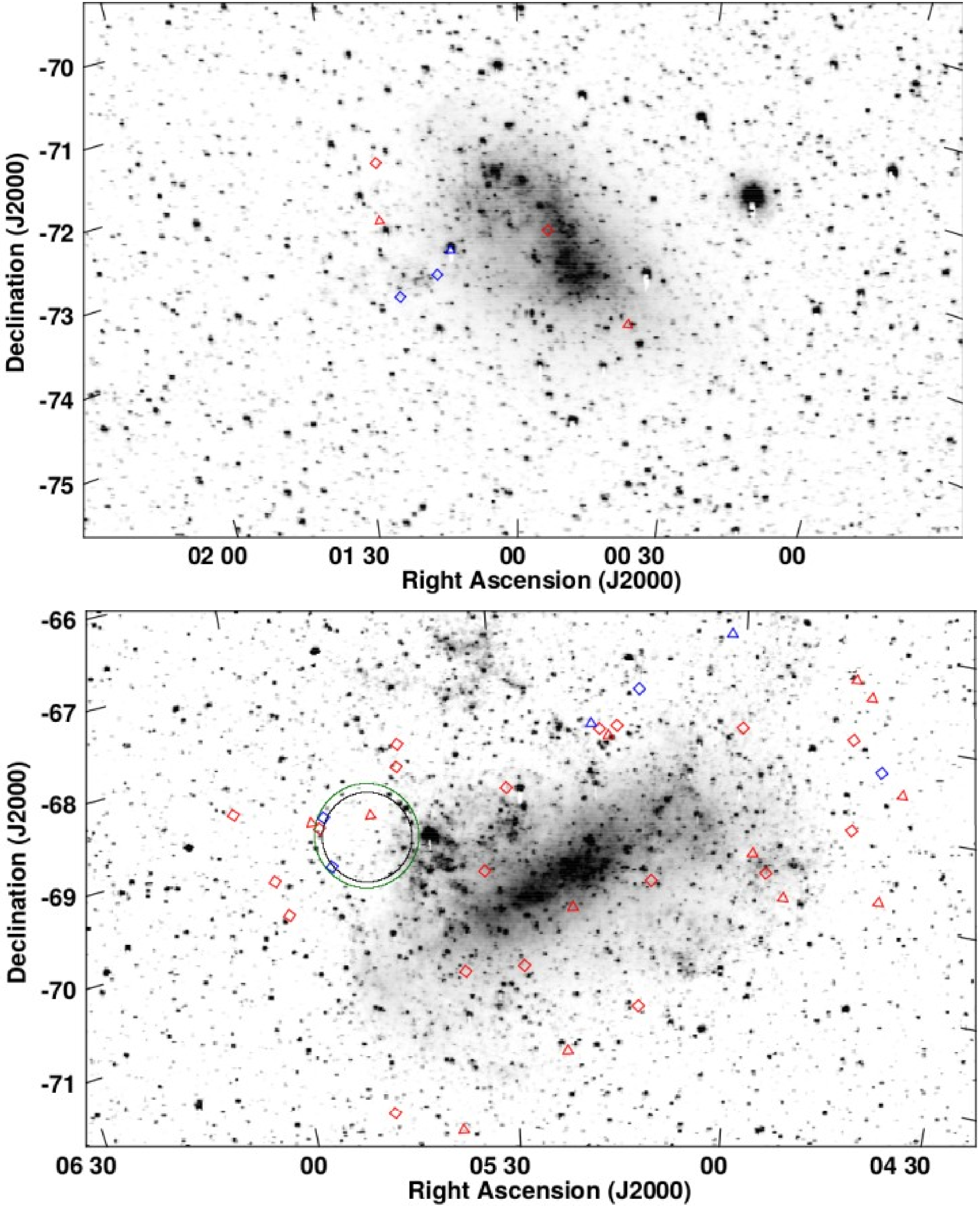
Credit: Prof. I. Soszyński

Magellanic Quasars Survey

- Sky coverage of the MQS: 100% of the LMC and 70% of the SMC
- Targets from OGLE-III and OGLE-IV
- Selection based on mid-IR and optical colours, optical variability, X-ray properties, and optical spectroscopy
- Confirmation of 758 quasars (565 in the LMC and 193 in the SMC)
- 94% quasars from the MQS catalogue (527 in the LMC and 186 in the SMC) are newly identified objects



Credit: Kozłowski et al. 2013



Optical image: Bothun & Thompson (1988)

- 44 sources selected:
  27 FSRQs
  17 BL Lacs
- faint sources with 16 – 21 mag_I
- distant sources with z = 0.3 – 3.3
- radio-loudness:
  FSRQs: 12 – 4 450
  BL Lacs: 171 – 7 020
- radio spectral index:
  from -0.57 up to 1.37
- IR spectral index:
  from -0.44 up to 3.07
- average polarization of $PD_{r,4.8}$ ~ 6.8% at 4.8 GHz
- possible association with flarying source detected by Fermi-LAT

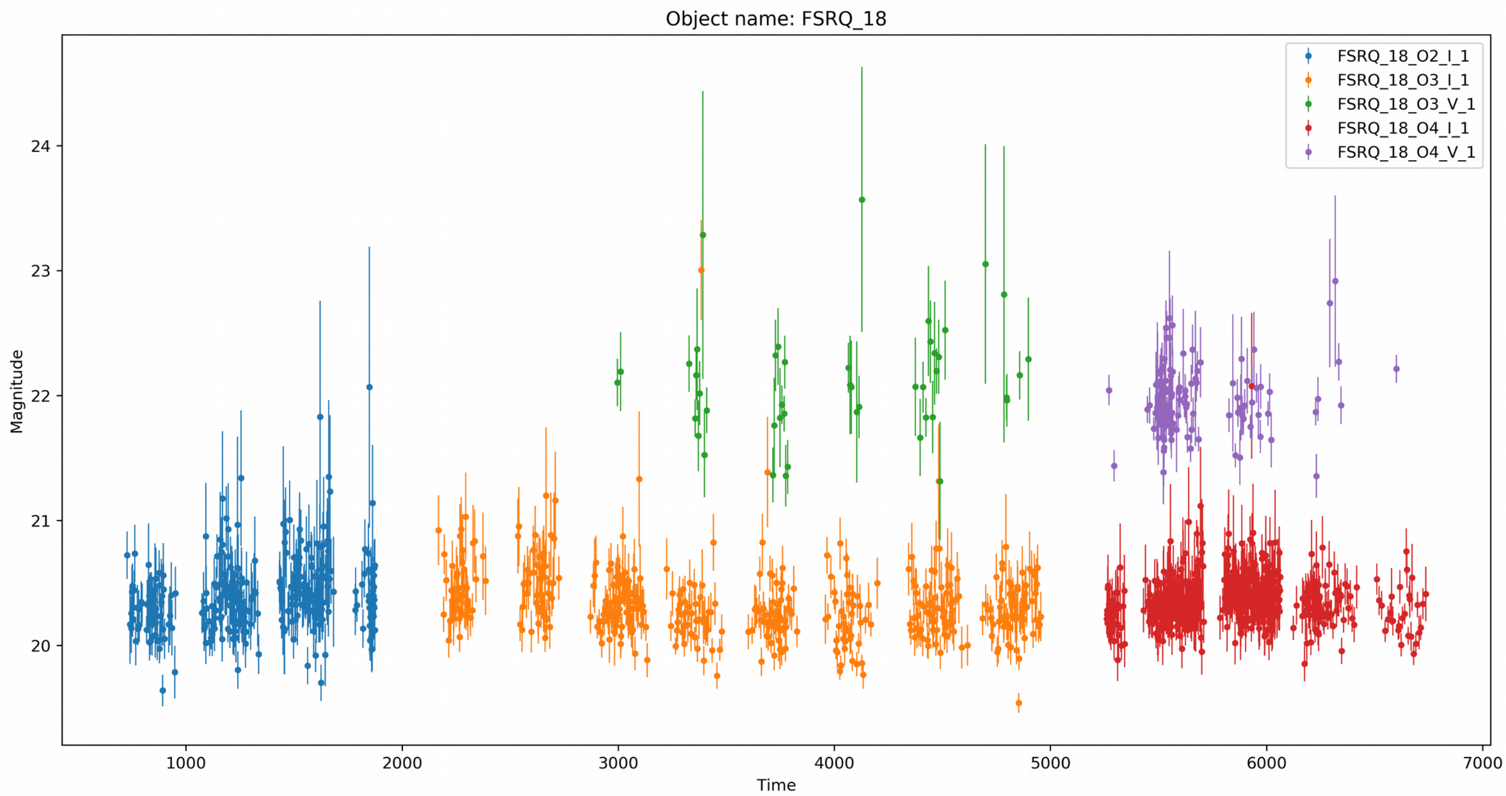
Optical variability study of all blazar candidates

- Motivation

→ to look for blazar-like characteristics
→ to analyse the long-term behaviour
→ to search for the quasi-periodic oscillations.

- Data

Optical variability study in filters I and V of both blazar candidates based on OGLE-II (1996-2000), OGLE-III (2001-2009), and -IV (2010-now) data
→ temporal coverage of > 20 years.



Optical variability study of all blazar candidates
methodology

- Lomb-Scargle periodograms
  power spectral density (PSD) for unevenly sampled time series:

$$P_{LS}(\omega) = \frac{1}{2\sigma^2}\left[\frac{\left(\sum_{k=1}^{N}(x_k-\bar{x})\cos[\omega(t_k-\tau)]\right)^2}{\sum_{k=1}^{N}\cos^2[\omega(t_k-\tau)]} + \frac{\left(\sum_{k=1}^{N}(x_k-\bar{x})\sin[\omega(t_k-\tau)]\right)^2}{\sum_{k=1}^{N}\sin^2[\omega(t_k-\tau)]}\right]$$

PL + Poisson noise: $P(f) = \frac{P_{\rm norm}}{f^{\beta}} + C$

smoothly broken PL (SBPL) plus Poisson noise:

$$P(f) = \frac{P_{\rm norm} f^{-\beta_1}}{1+\left(\frac{f}{f_{\rm break}}\right)^{\beta_2-\beta_1}} + C$$

- zero-mean Continuous-time Auto-Regressive Moving Average (CARMA) modelling

differential equation of stochastic processes:

$$\frac{{\rm d}^p x(t)}{{\rm d}t^p} + \alpha_{p-1}\frac{{\rm d}^{p-1}x(t)}{{\rm d}t^{p-1}} + \ldots + \alpha_0 x(t) = \beta_q\frac{{\rm d}^q\varepsilon(t)}{{\rm d}t^q} + \beta_{q-1}\frac{{\rm d}^{q-1}\varepsilon(t)}{{\rm d}t^{q-1}} + \ldots + \varepsilon(t)$$

PSD:

$$P_{\rm CARMA}(f) = \sigma^2\frac{\left|\sum_{j=0}^{q}\beta_j(2\pi{\rm i}f)^j\right|^2}{\left|\sum_{k=0}^{p}\alpha_k(2\pi{\rm i}f)^k\right|^2}$$

Ornstein-Uhlenbeck process for CARMA(1,0)
Lorentzian with a break frequency at $\alpha_0/(2\pi)$

$$P_{\rm OU}(f) = \frac{\sigma^2}{\alpha_0^2 + (2\pi f)^2}$$

Optical variability study of all blazar candidates
methodology

- Hurst exponent
  measures the statistical self similarity of a time series x(t): $x(t) \doteq \lambda^{-H} x(\lambda t)$

  autocorrelation function: $\rho(k) = \frac{1}{2}\left[(k+1)^{2H} - 2k^{2H} + (k-1)^{2H}\right]$

  Properties of Hurst exponent:

→ $0 < H < 1$,
→ H = 1/2 for an uncorrelated process (e.g. white noise or Brownian motion),
→ H > 1/2 for a persistent (long-term memory, correlated) process,
→ H < 1/2 for an anti-persistent (short-term memory, anti-correlated) process.

- A-T Plane
  Abbe value, which quantifies the smoothness of a time serie $$\mathcal{A} = \frac{\frac{1}{N-1}\sum_{i=1}^{N-1}(x_{i+1}-x_i)^2}{\frac{2}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2}$$

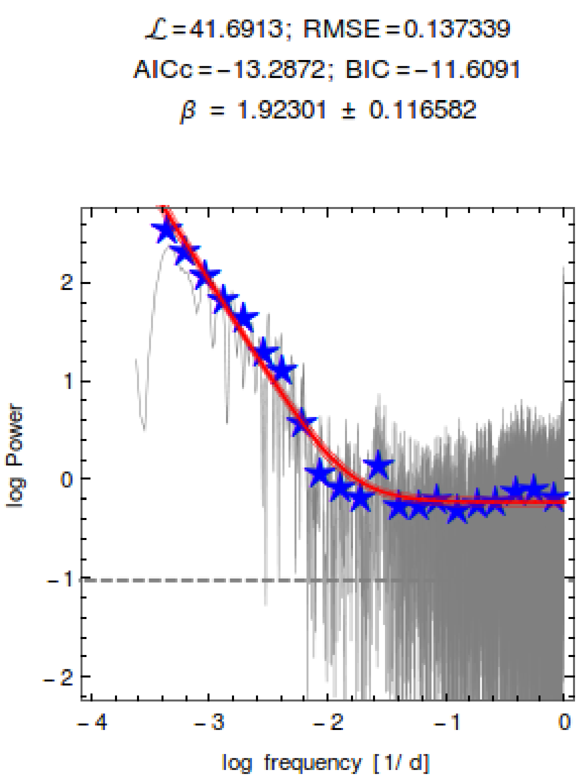
  frequency relative to number of observations: $\mathcal{T} = T/N$
  where T is number of turning points in a time series

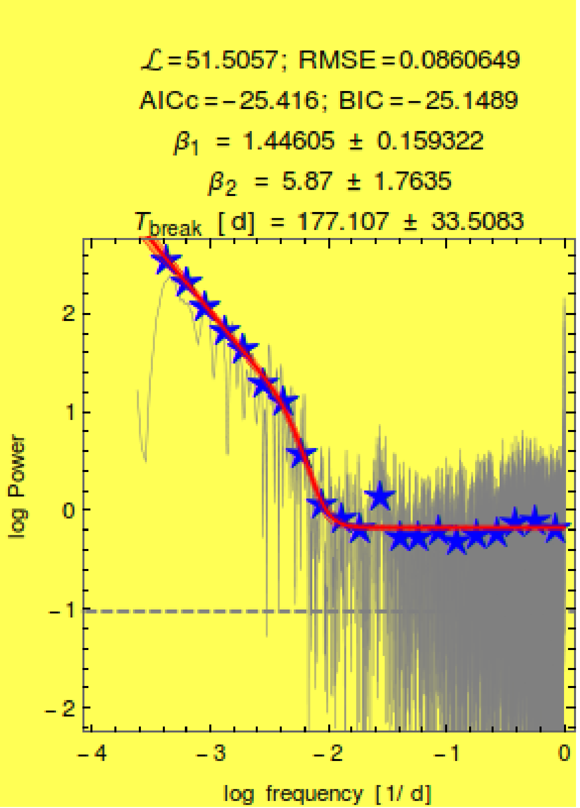
→ to provide a fast and simple estimate of the Hurst exponent
→ to differentiate between different types of colored noise, $P(f) \propto 1/f^{\beta}$, characterized by different values of β

Optical variability study of all blazar candidates
fitted models

- 23 sources with PL model, i.e. 10 FSRQs and 13 BL Lacs
- 15 sources with SBPL model, i.e. 13 FSRQs and 2 BL Lacs
- 6 sources with PL and SBPL models, i.e. 4 FSRQs and 2 BL Lacs

FSRQ 20

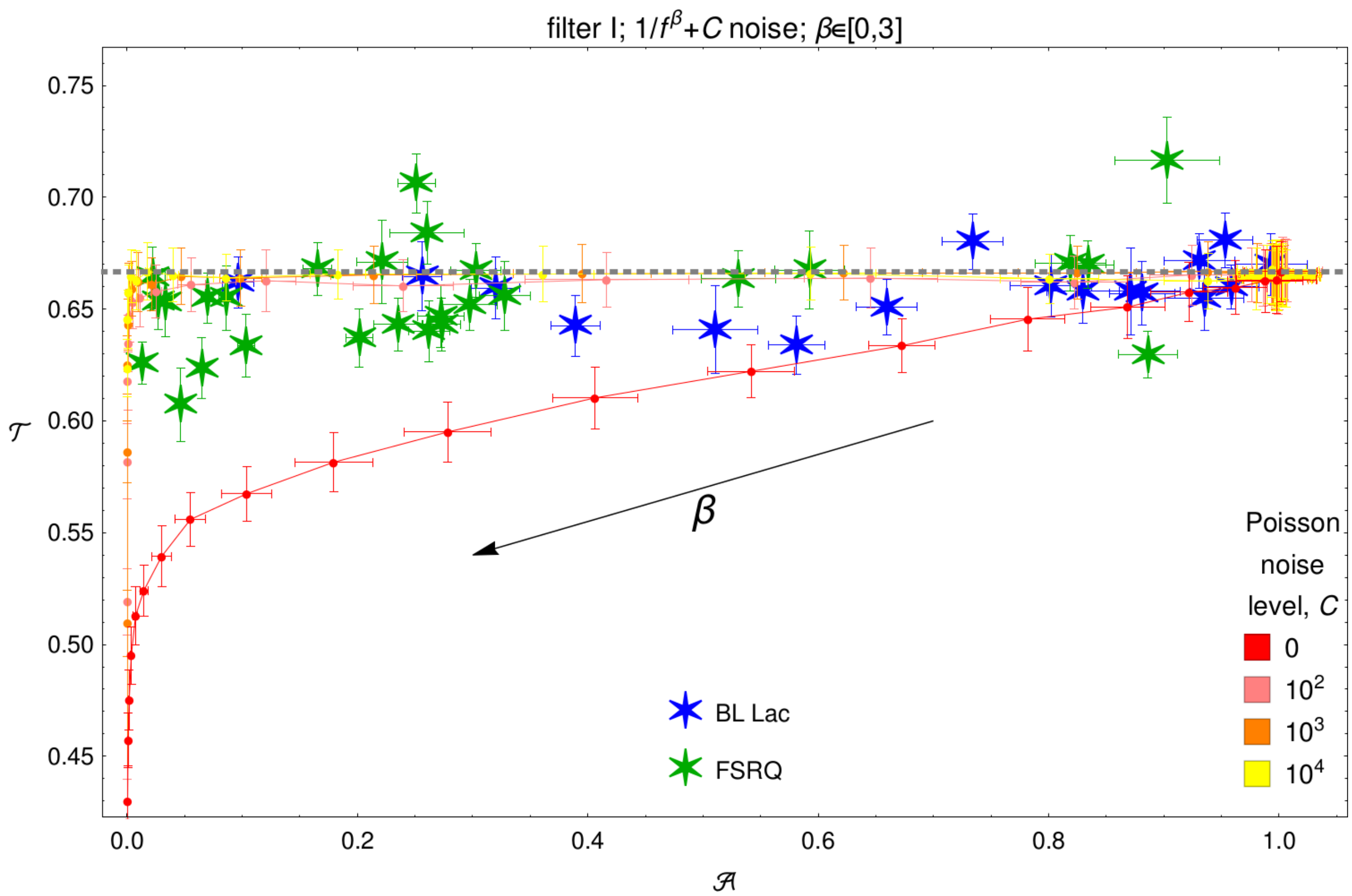




→ FSRQs' PL exponent β mostly lies in the range (1, 2)
→ one object has a flat PSD, β ≈ 0
→ BL Lacs are slightly flatter, spanning mostly the range (1, 1.8)
→ one BL Lac has a flat PSD
→ three BL Lacs have steeper PSDs, with β ∼ 3 − 4

Optical variability study of all blazar candidates

A-T plane and Hurst exponents

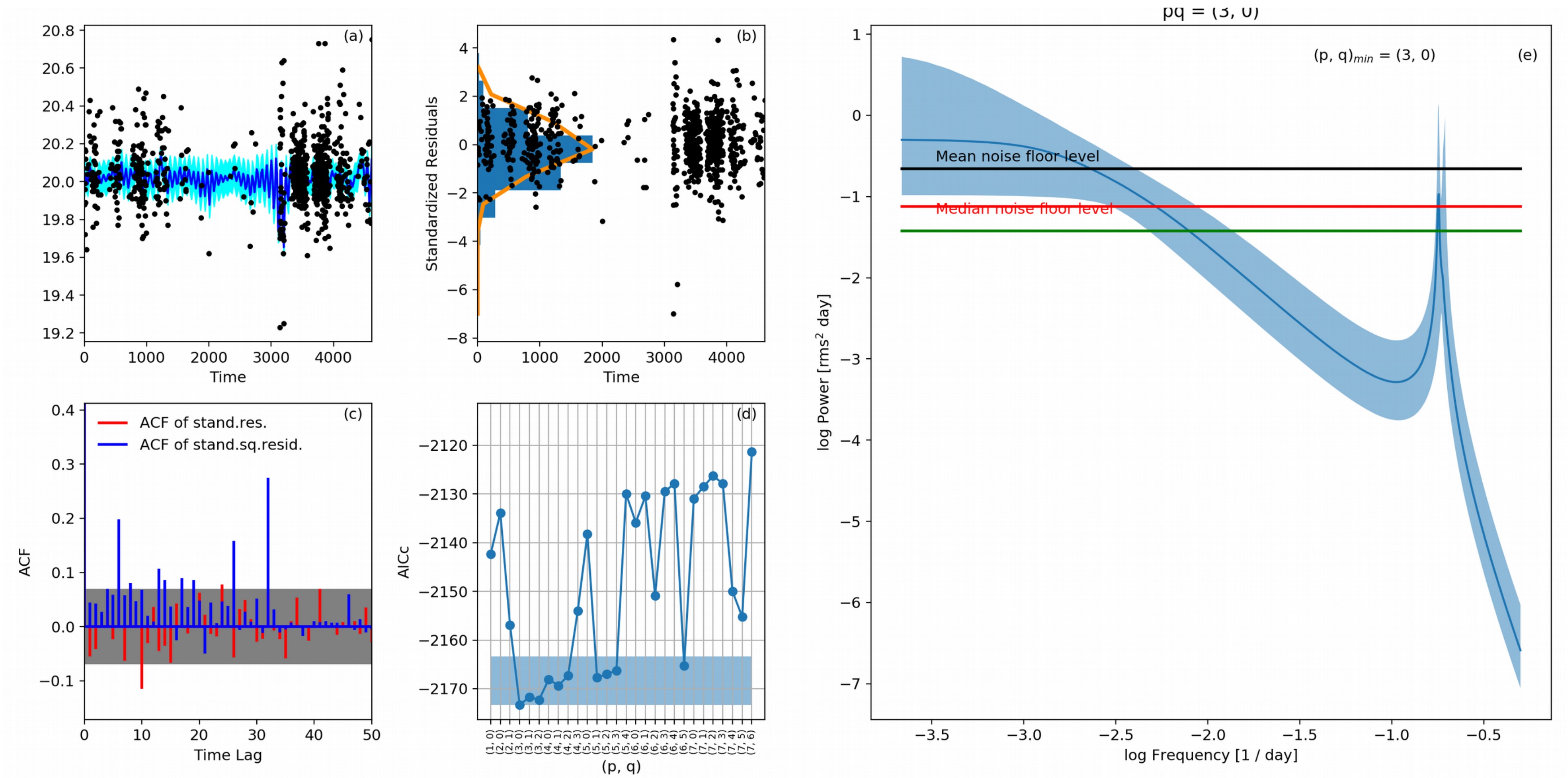


PL plus Poisson noise PSD of the form $P(f) \propto 1/f^{\beta} + C$ with $\beta \in \{0, 0.1, . . . , 3\}$

→ most objects have H ≤ 0.5 → short-term memory
→ 4 BL Lacs and 2 FSRQs have H > 0.5 → long-term memory

Optical variability study of all blazar candidates

Carma modelling



→ most of the examined objects, i.e. 18/27 FSRQs and 13/17 BL Lacs, are well described by a CARMA(2, 1) process

→ This simplest model, with a single-Lorentzian PSD, is in turn the best fit for only 3/27 FSRQs and 2/17 BL Lacs

Conclusions

- jet domination should be visible in the PSD as a PL, without a flattening at low frequencies at all, or with a break at time scales >1000 d;

- The secure blazar candidates (5 FSRQs and 2 BL Lacs) have an LSP best described by the SBPL, with break time scales at 200–300 days; 1 FSRQ and 1 BL Lac are consistent with the PL PSD;

- For FSRQs such a break is not really surprising, i.e. they can be interpreted as disk dominated. But the two BL Lacs with a broken PSD are interesting, as BL Lacs are believed to be jet dominated;

- the steepness of the high frequency component of the SBPL is intriguing: it can indicate a new class of AGNs, or it can be a sign of a double BH system, where the shorter time scale variability from the disk is wiped out - the accretion disk surrounds both BHs, outside their orbit.

Further directions

Possible Fermi-LAT coincidences