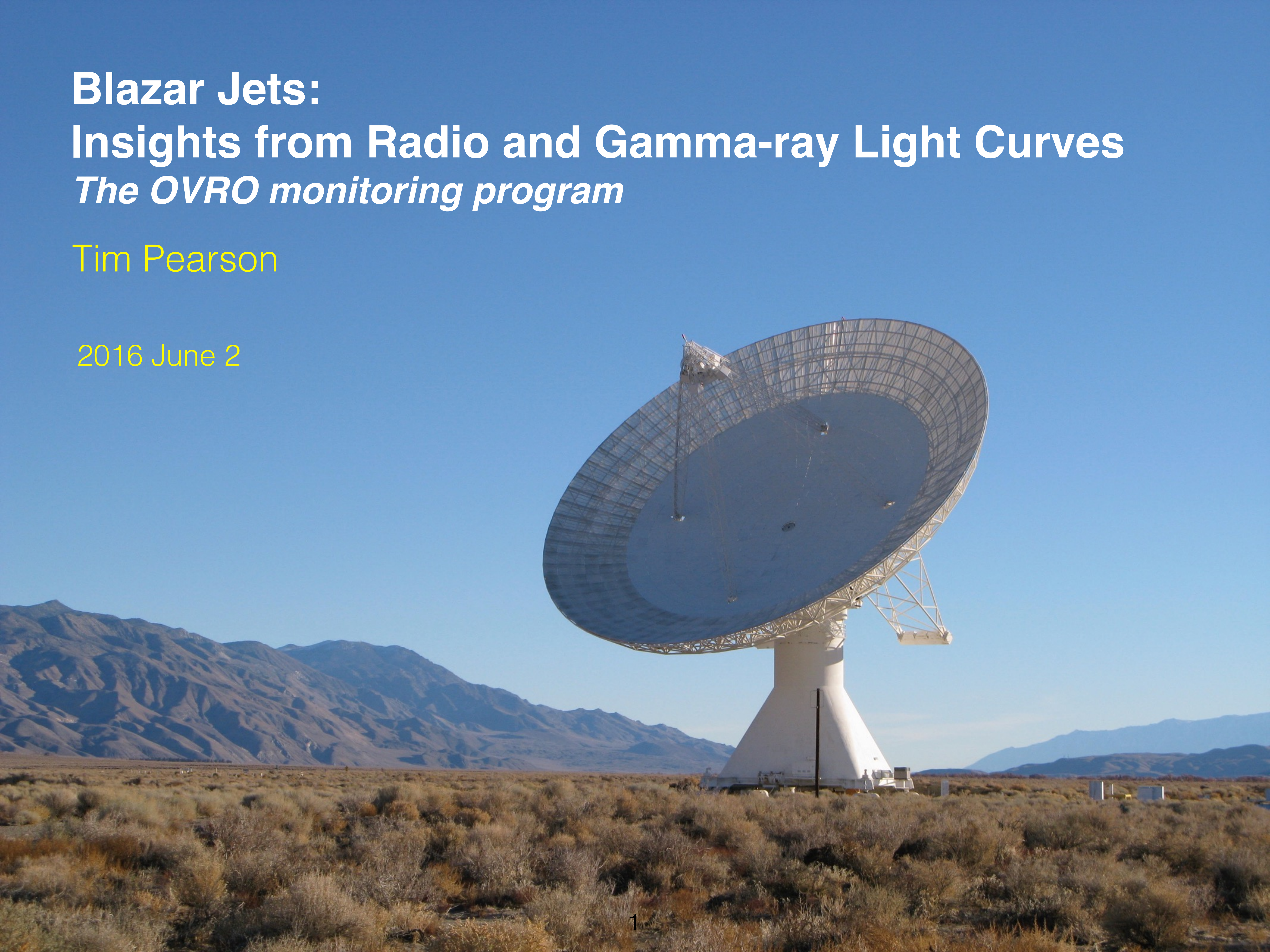
Blazar Jets:
Insights from Radio and Gamma-ray Light Curves

The OVRO monitoring program

Tim Pearson

2016 June 2



Looking back

- Discovery in 1965 – Bill Dent (U Michigan)
  Kellermann & Pauliny-Toth ARAA1968
- Short timescales imply small sizes
- High brightness temperatures
- Relativistic expansion (Rees)
- VLBI and discovery of superluminal motion
- Relativistic jets and beaming

- Long term monitoring programs:
  especially Aller & Aller (University of Michigan)

The OVRO 15 GHz program

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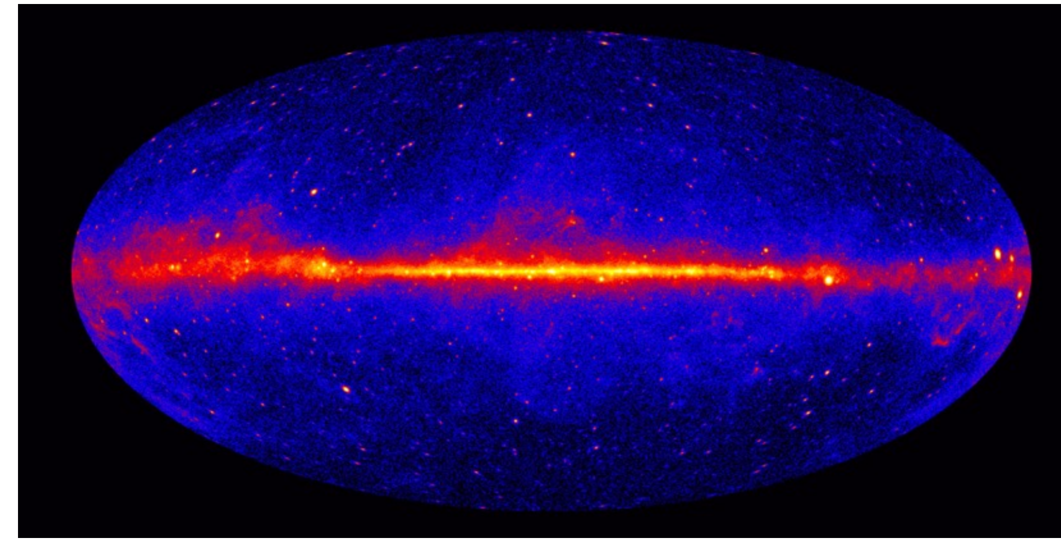
Mark Hodges, Oliver King *(Caltech OVRO)*
Talvikki Hovatta *(Aalto University)*
Walter Max-Moerbeck *(MPIfR Bonn)*
Rodrigo Reeves *(Universidad de Concepción)*
Jennifer Richards *(Purdue University)*



- Motivated to support ***Fermi LAT***
- Enabled by availability of 40m telescope: modest costs
- Started in 2007, a year before the start of LAT
- Core sample of 1158 northern ($\delta > -20°$) sources from the Candidate Gamma-ray Blazar Survey (CGRABS)
- Added all 1LAC and 2LAC (and soon 3LAC) detections
- Added TeV detections and other objects of interest
- Now more than 1800 sources
- Each observed ~ twice per week
  - ~ 4 mJy and 3% uncertainty
- 15 GHz flux density and (soon) polarization

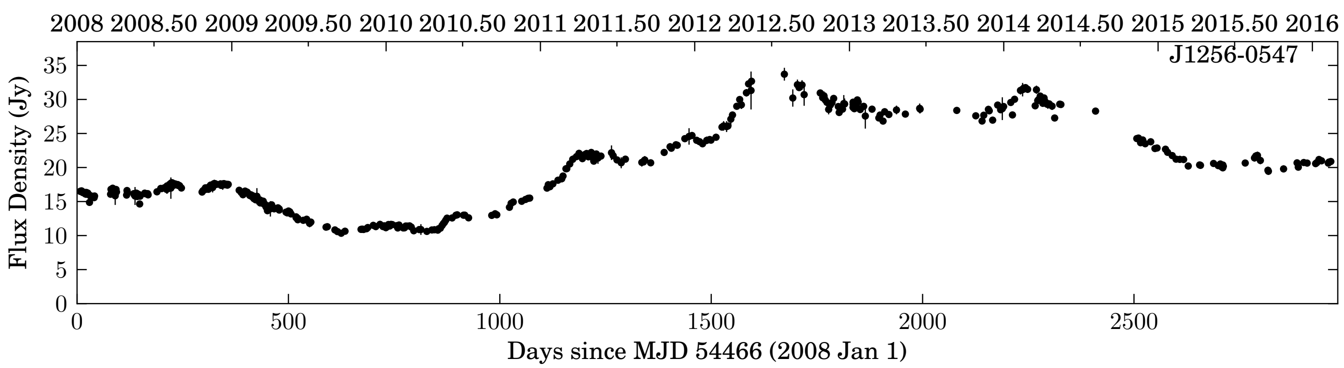
Goals

- Individual objects
  - Understanding flare emission mechanisms in radio, gamma-ray, …
  - Support SED modeling
  - Supplement VLBI imaging

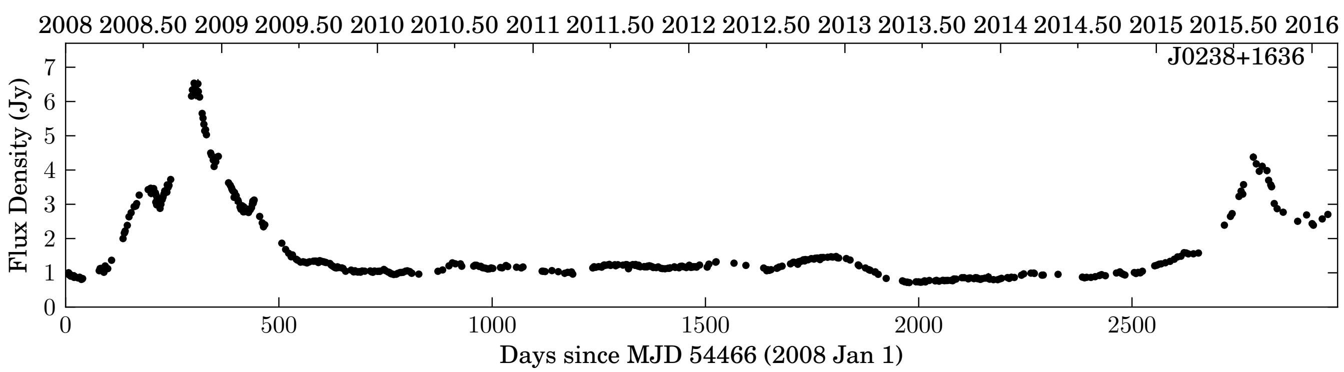
- Statistical studies
  - Occurrence and characteristics of flares in e.g. FSRQ, BL Lacs, HSP, LSP …
  - Relationship of radio and gamma-ray
  - Tie down location of gamma-ray emission?

- Support external programs
  - Data available on web or on request
    - `http://www.astro.caltech.edu/ovroblazars/`
  - More than 70 published papers using OVRO data

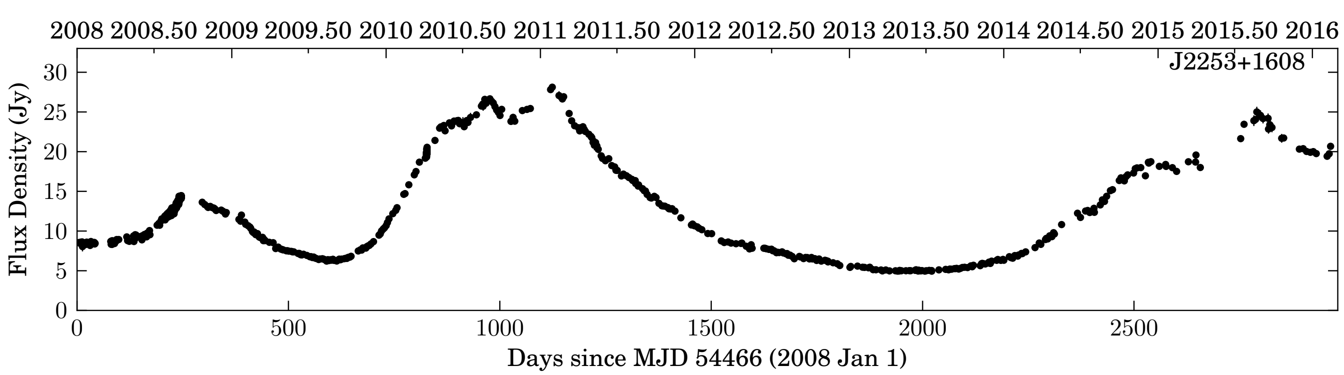
Example 8-year light curves (2008–2016)



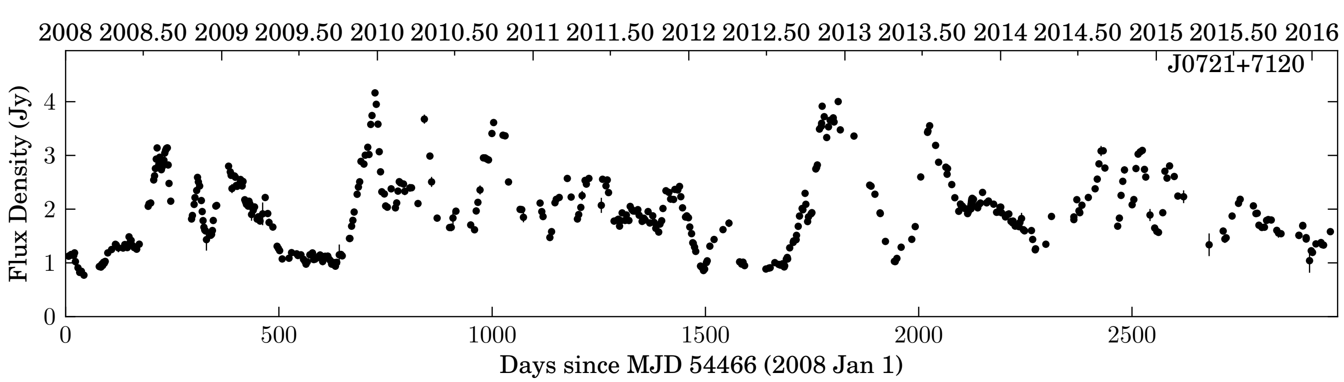
3C279 QSO z=0.536



AO 0235+164 QSO z=0.94

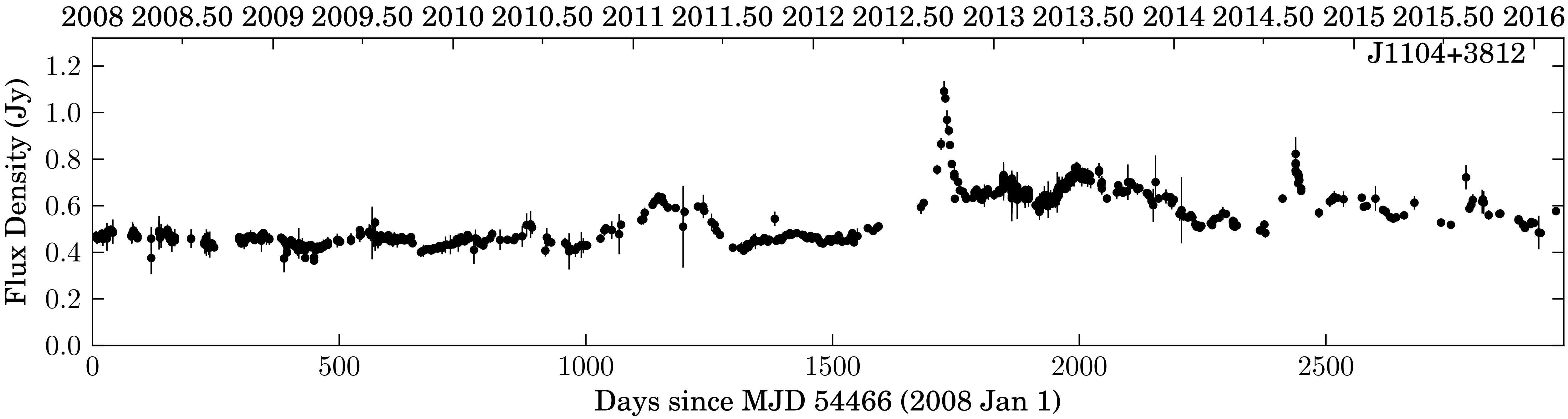


3C454.3 QSO z=0.859

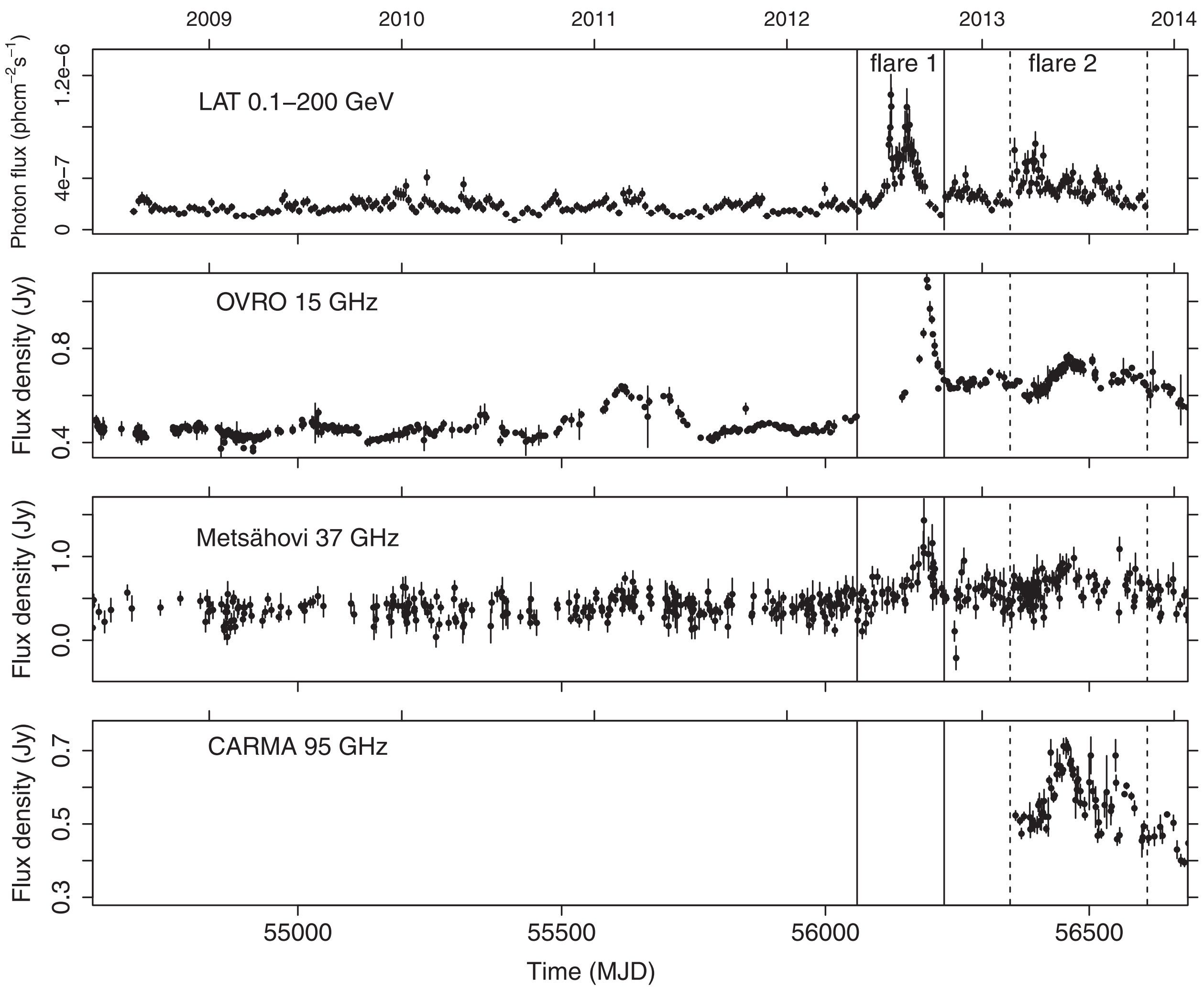


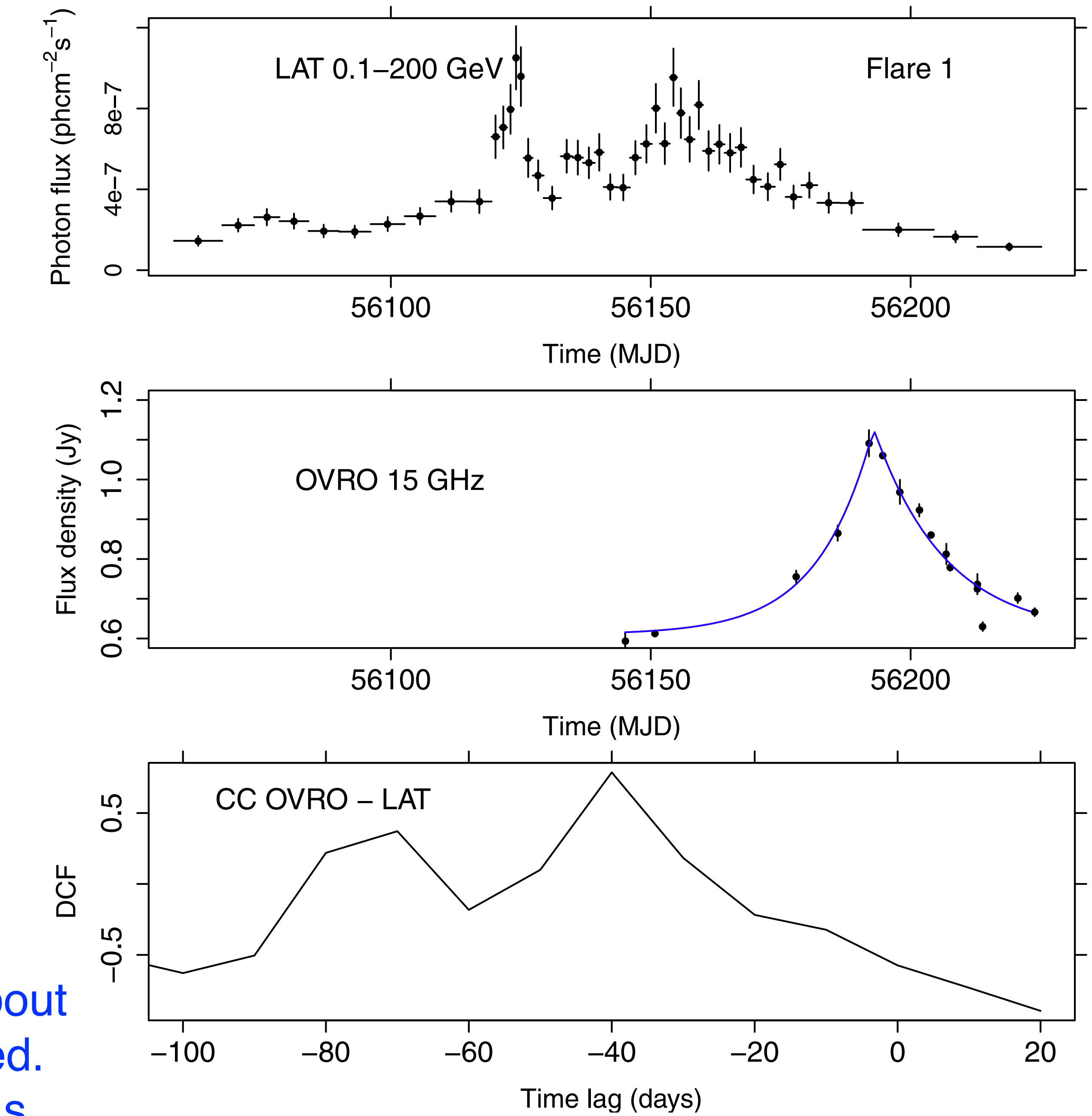
S5 0716+714 BL Lac object

Mrk 421 (J1104+3812) galaxy z=0.03



Mrk 421 flares





In 2012 July, Mrk 421 exhibited the largest γ -ray flare observed by *Fermi* since the beginning of its mission. About 40–70 d later, the largest ever 15 GHz flare was observed. The flare rise time determined from an exponential fit was just 10.6 ± 0.5 d, which is extreme compared to previous radio flares observed in the source.

Hovatta+ 2015 MNRAS 448 3121

Statistics

- For statistical studies, we need
  - Large, well-defined samples
  - Robust statistical methods

- Richards et al. (2011, 2014)
  - ML estimate of “intrinsic modulation indices”
    - a measure of the true amplitude of variations in the source, rather than a convolution of true variability, observational uncertainties, and effects of finite sampling.

$$\overline{m} = \frac{\sigma_0}{S_0}.$$

  - gamma-ray detected blazars (LAT) vary more than gamma-ray quiet blazars
  - BL Lacs have higher variability than FSRQs in radio-selected samples
  - but not in gamma-ray selected samples

Statistics

Table 5. Population variability comparison results.

Parent pop.	Subpop. A	Subpop. B	Δm_0	Signif.
CGRaBS	Gamma-ray loud	Gamma-ray quiet	$0.075^{+0.013}_{-0.012}$	6σ
CGRaBS	BL Lac	FSRQ	$0.050^{+0.017}_{-0.015}$	4σ
1LAC	BL Lac	FSRQ	-0.031 ± 0.020	$<2\sigma$
BL Lac	CGRaBS	1LAC	0.013 ± 0.021	$<1\sigma$
FSRQ	CGRaBS	1LAC	$-0.068^{+0.014}_{-0.015}$	6σ
1LAC	HSP	ISP	$-0.136^{+0.027}_{-0.032}$	5σ
1LAC	HSP	LSP	-0.139 ± 0.017	5σ
1LAC	ISP	LSP	$-0.002^{+0.033}_{-0.029}$	$<1\sigma$
1LAC	HSP BL Lac	ISP BL Lac	$-0.139^{+0.028}_{-0.034}$	4σ
1LAC	HSP BL Lac	LSP BL Lac	$-0.116^{+0.029}_{-0.037}$	4σ
1LAC	ISP BL Lac	LSP BL Lac	$0.022^{+0.044}_{-0.045}$	$<1\sigma$
CGRaBS	FSRQ ($z \geq 1$)	FSRQ ($z < 1$)	-0.018 ± 0.009	$<2\sigma$

The Δm_0 column tabulates the most-likely value of $m_{0,\,\mathrm{A}} - m_{0,\,\mathrm{B}}$. A source is included in the gamma-ray-loud subpopulation if it has a clean association in the 2LAC catalogue (Ackermann et al. 2011b).

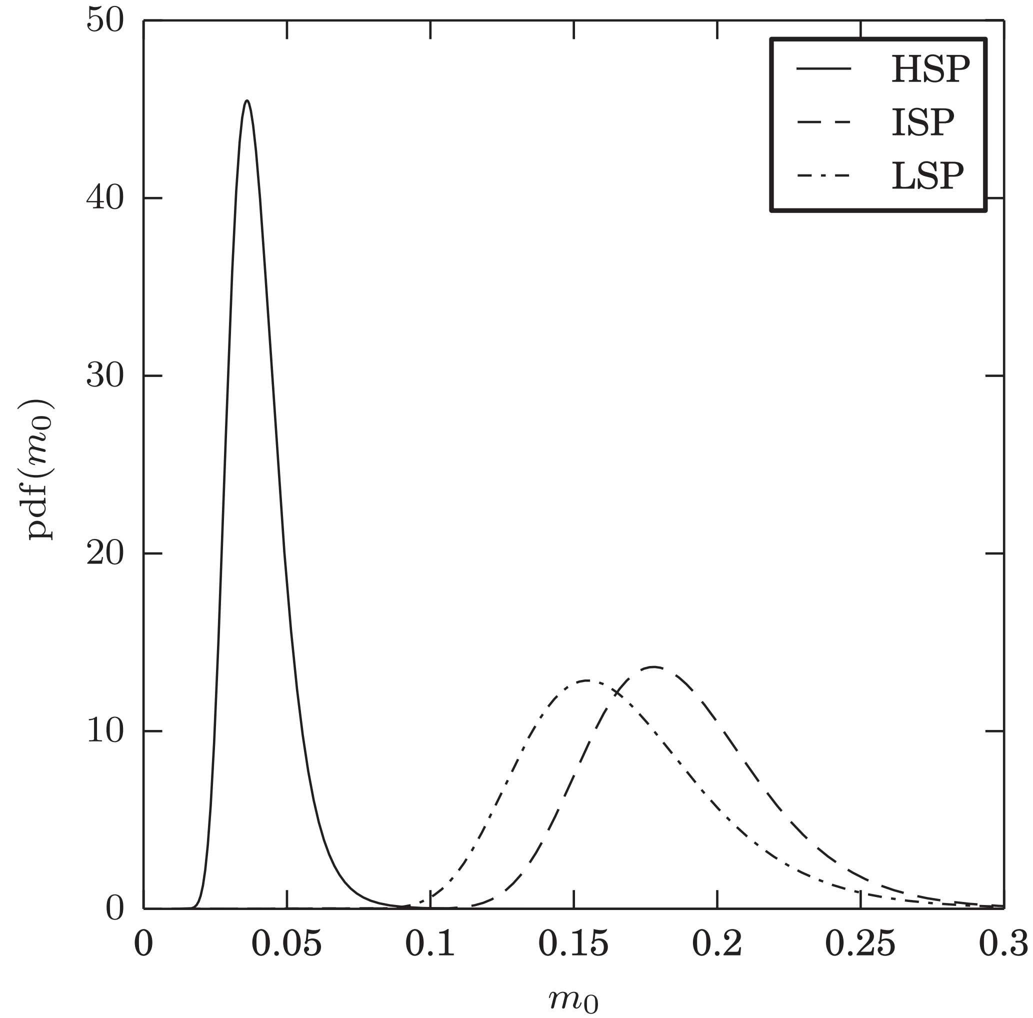


Figure 12. Likelihood distributions for m_0 for 1LAC BL Lac sources classified as HSP, (solid line), ISP (dashed line) and LSP (dot–dashed line). The most-likely values for the mean modulation index for each distribution and for the differences between the pairs are listed in Tables 4 and 5. The ISP and LSP distributions *are* consistent with having the same mean modulation index at the 1σ level. The HSP distribution *is not* consistent with either of the others with about 4σ significance.

Cross-correlations

- Max-Moerbeck et al. (2014a,b)
  - A method of estimating significance in correlations between radio and gamma-ray light curves
  - *Difficult because the underlying statistics are unknown and not stationary*
  - Monte-Carlo method based on assuming Gaussian processes with power-law PSD (power spectral density)
  - Estimate the PSD slope from the time-series, either
  - individual sources or ensembles
  - "Red" PSDs with a lot of power at low frequencies (month-to-year variations) can show apparent correlations that are not significant
- Only 3 out of 41 sources with good data show even 2.5σ significant correlations
- Radio lags gamma-ray

AO 0235: 150 day delay

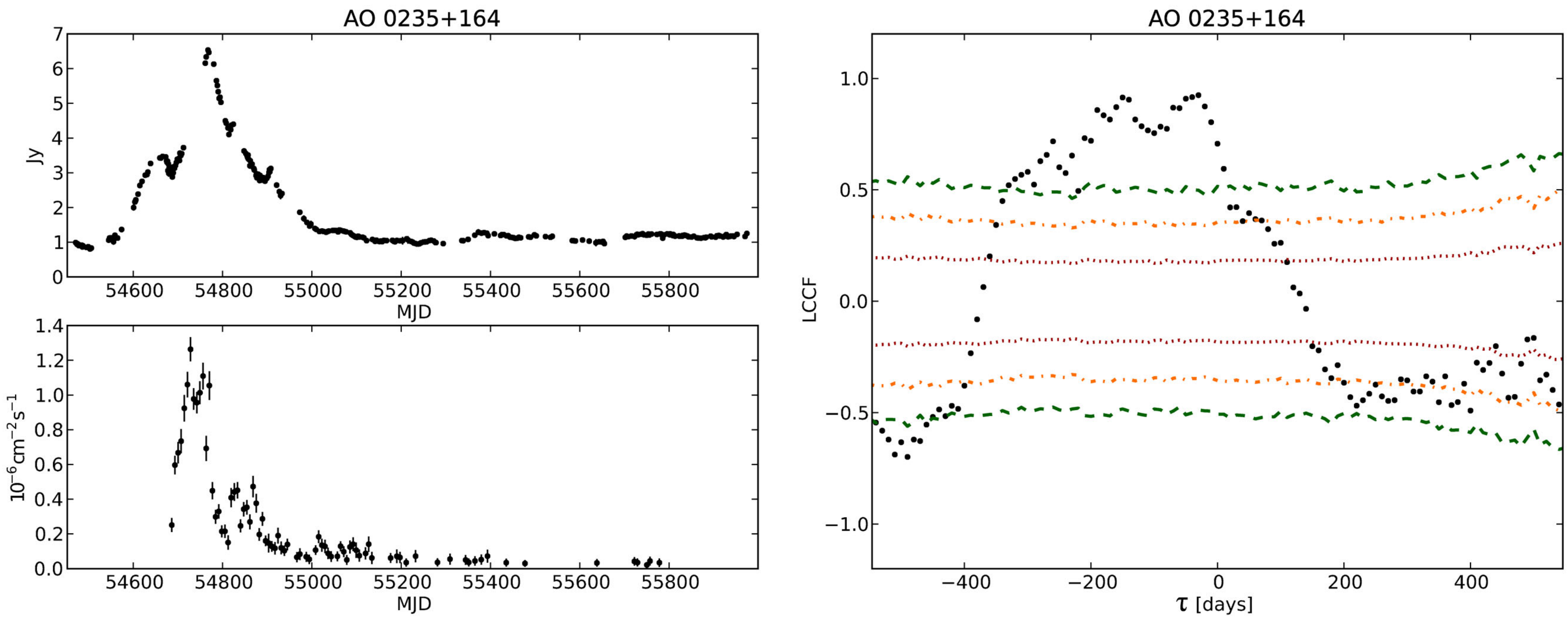
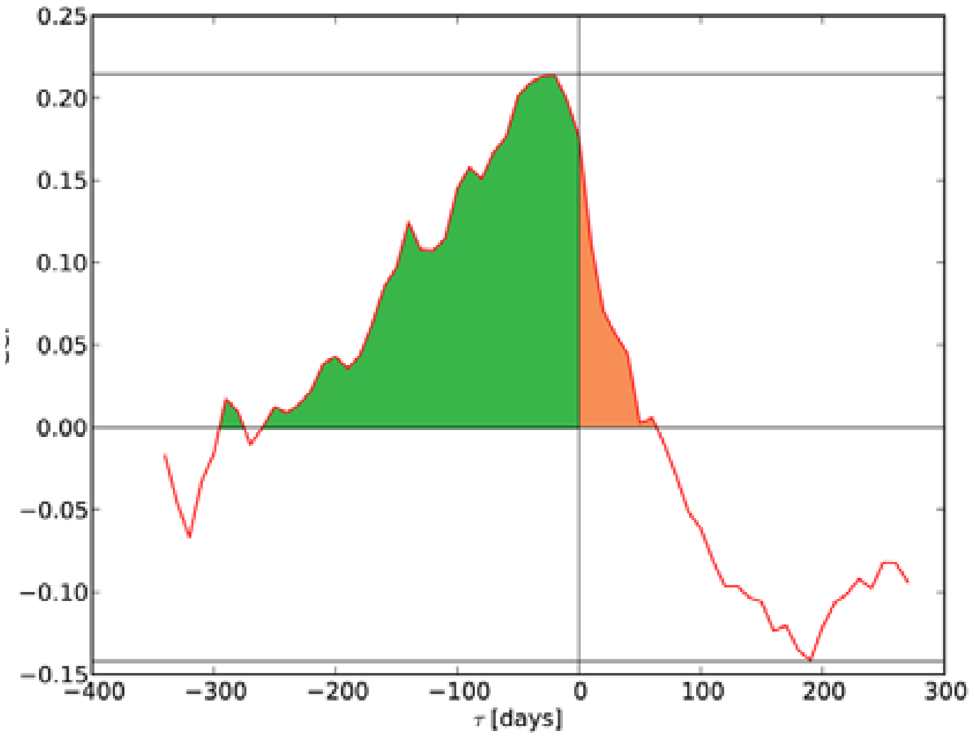


Figure 1. Light curves (left) and cross-correlation (right) for sources with significant cross-correlation. Contours indicate the cross-correlations significances (red dotted line: 1σ; orange dash–dotted line: 2σ; green dashed line: 3σ). The most significant peak for AO 0235+164 is at -150 ± 8 d with 99.99 per cent significance, for PKS 1502+106 it is at -40 ± 13 d with 98.09 per cent significance for the best-fitting PSD model and 97.54 per cent for the lower limit, and for B2 2308+34 it is at -120 ± 14 d with 99.99 per cent significance for the best-fitting PSD model and 99.33 per cent for the lower limit. The significance lower limit for PKS 1502+106 is above the 97.56 per cent threshold within the error (see Table 1).

Stacked cross-correlations



Stacked cross-correlation coefficients for 41 blazars after correcting to the cosmological reference frame.

- The radio variations lag behind the γ-ray variations (green vs. orange).
- Lag at 15 GHz is ~ 30–100 days.
- For Lorentz factor of 10 this implies a delay in the object rest frame of ~ 300–1000 days.

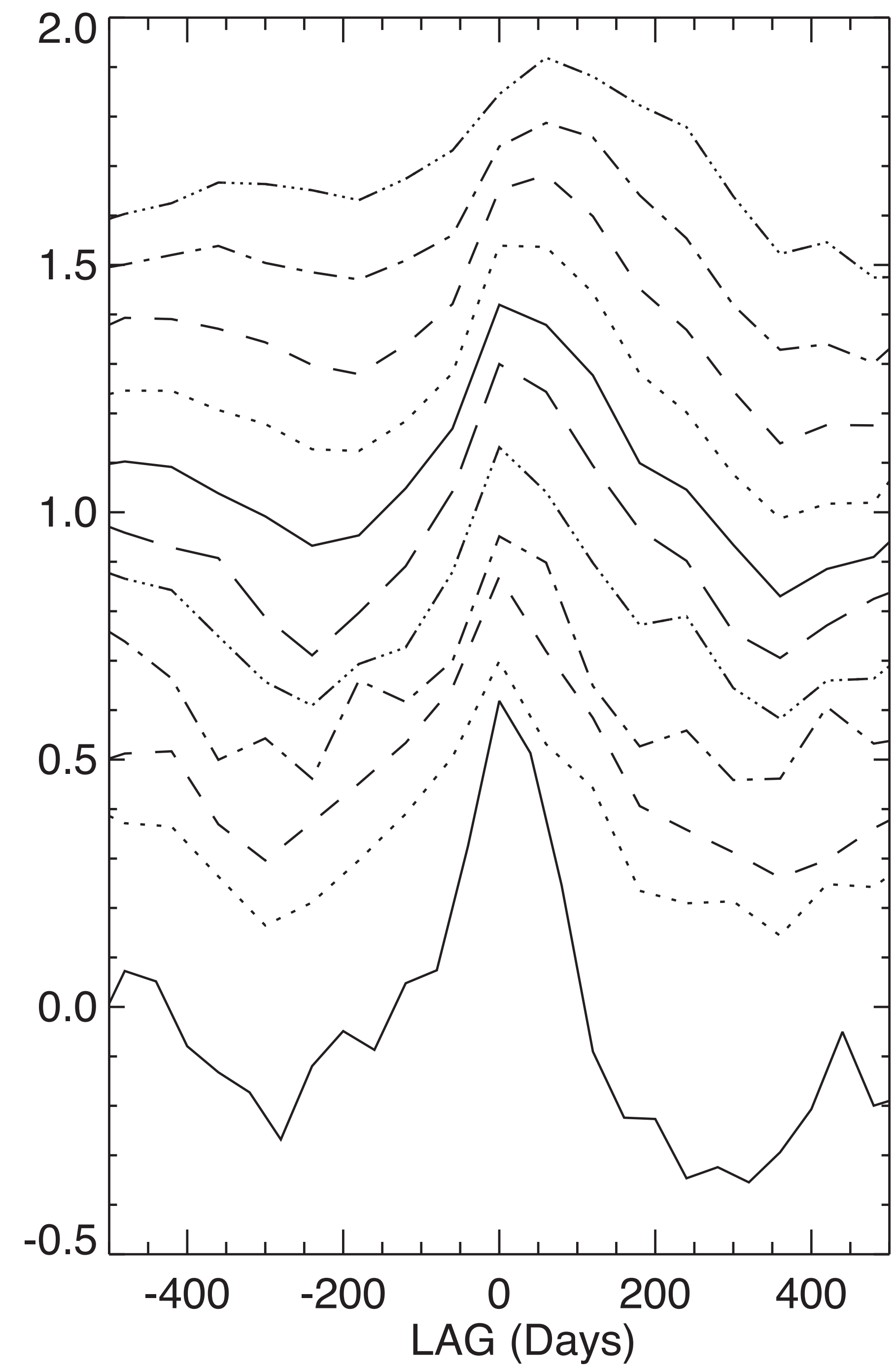
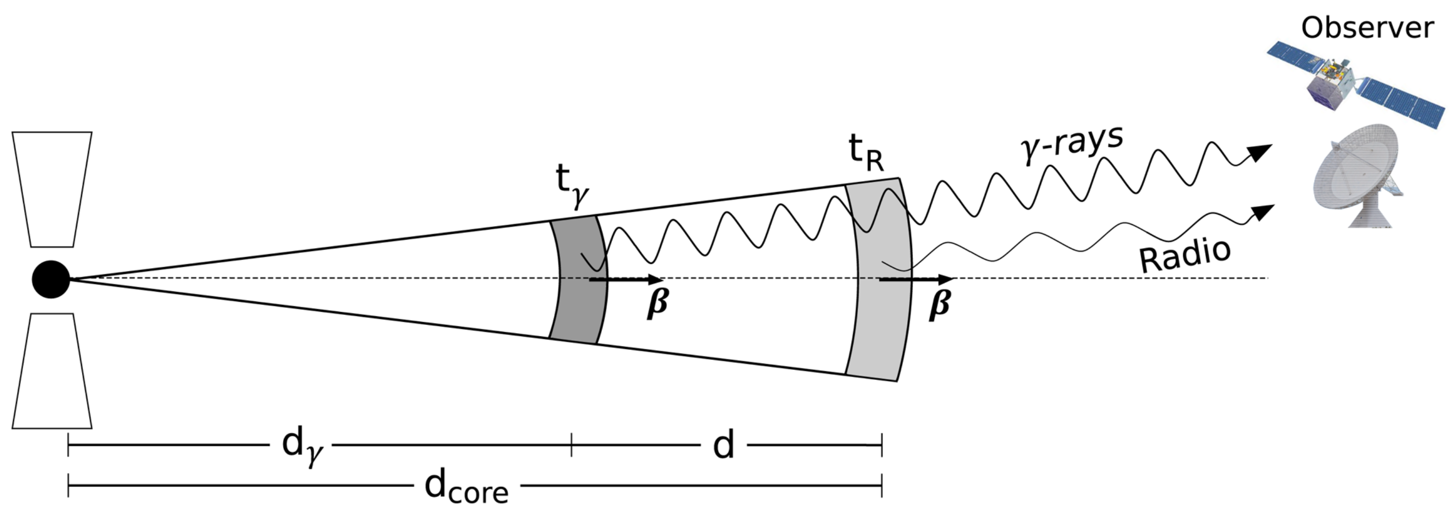


Figure 4. Stacked radio/γ-ray DCCFs (source frame) across all radio bands. From top to bottom are shown: γ-ray versus 110, 60, 36, 28, 20, 13, 9, 7, 3, 2 and 0.8 mm wavelength. For better illustration, the 2 mm/γ-ray

F-GAMMA program
Fuhrmann++ 2014 MNRAS

Interpretation of time delays

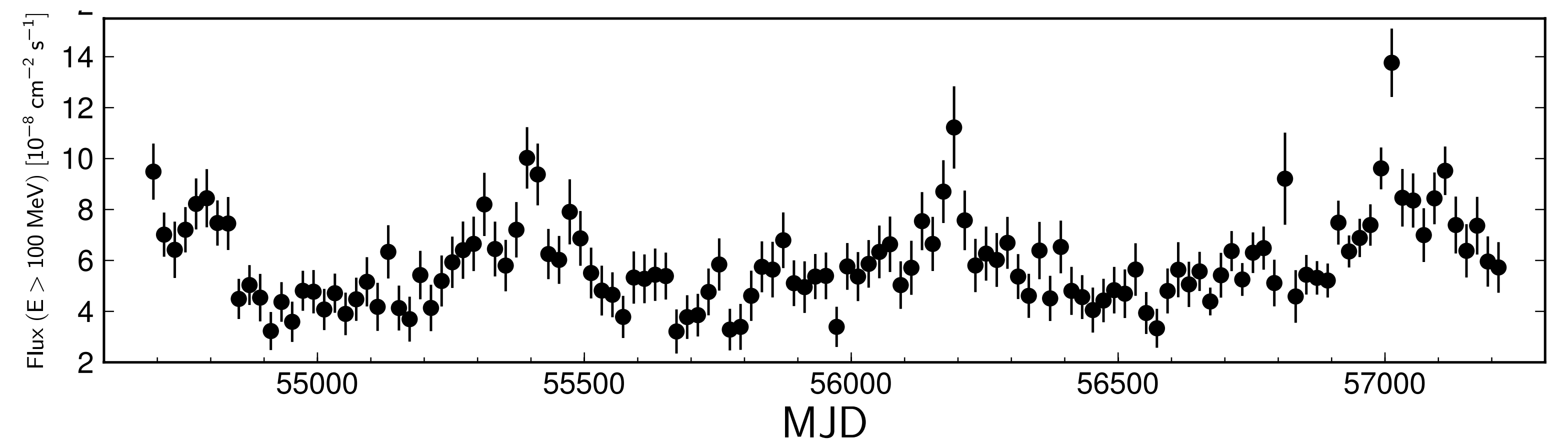


Max-Moerbeck (2014)

- Cross-correlation delay is a measure of *d*
- VLBI modeling can give estimates of d_{core}
- Hence infer d_γ
- AO 0235: d = 37±23 pc, d_γ > 15 pc

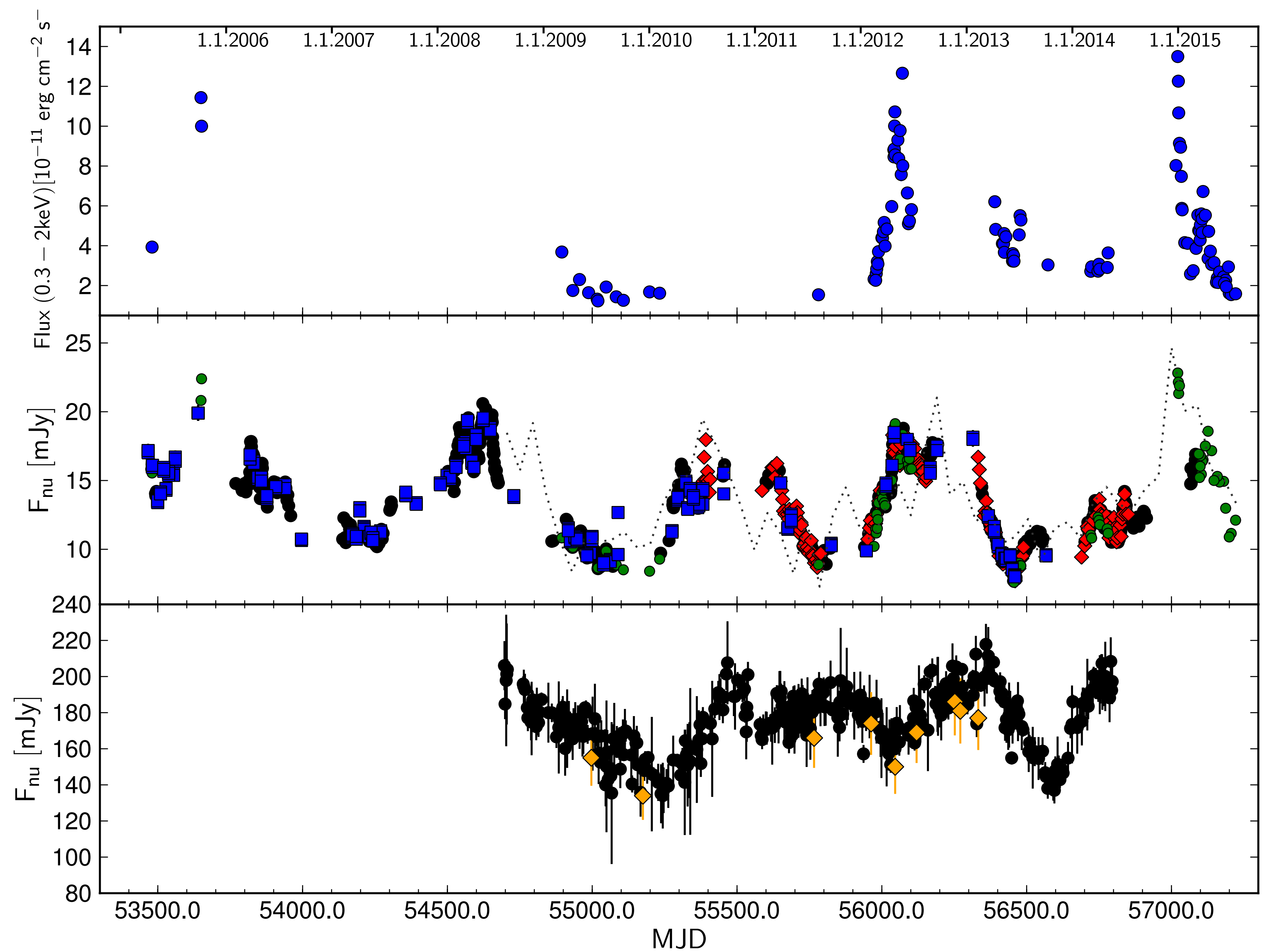
Quasi-periodic oscillations

FSRQ **J1359+4011** shows a strong and persistent quasi-periodic oscillation. The time-scale of the oscillation varies between 120 and 150 d over a ~4 year time span. This is not a gamma-ray source. *King et al. 2013 MNRAS 436 L114*.



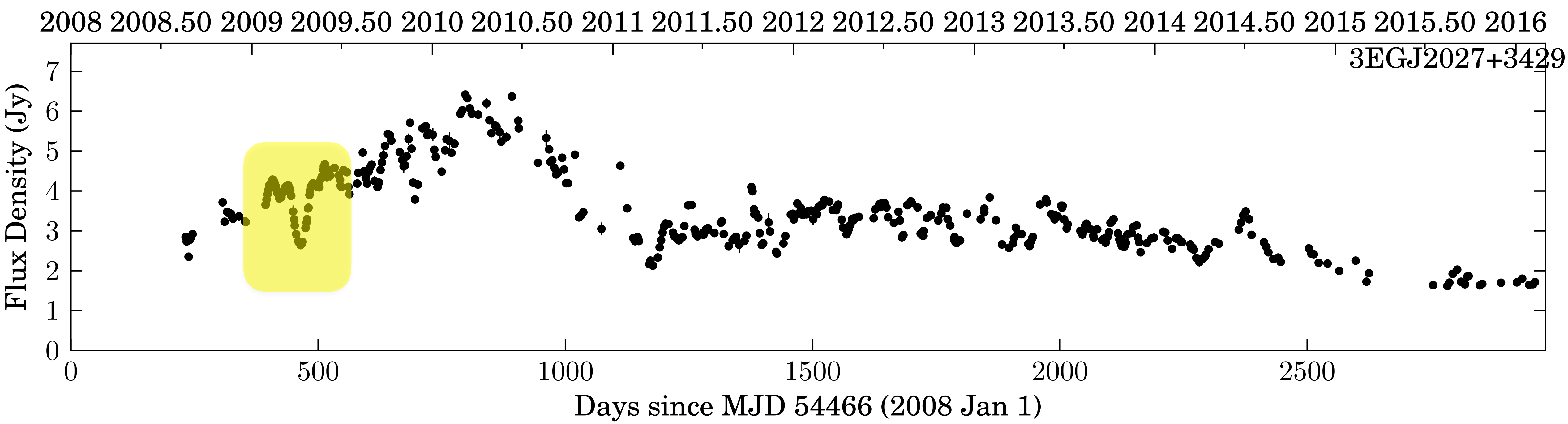
BL Lac object **PG 1553+113** has a 2.18 ± 0.08 year-period gamma-ray cycle with correlated oscillations observed in radio and optical fluxes. Is the periodic modulation real and coherent, as would be expected for a binary black hole, or is it a QPO like J1359, which might be due to instabilities in the jet or accretion flow.

2015ApJ...813L..41A

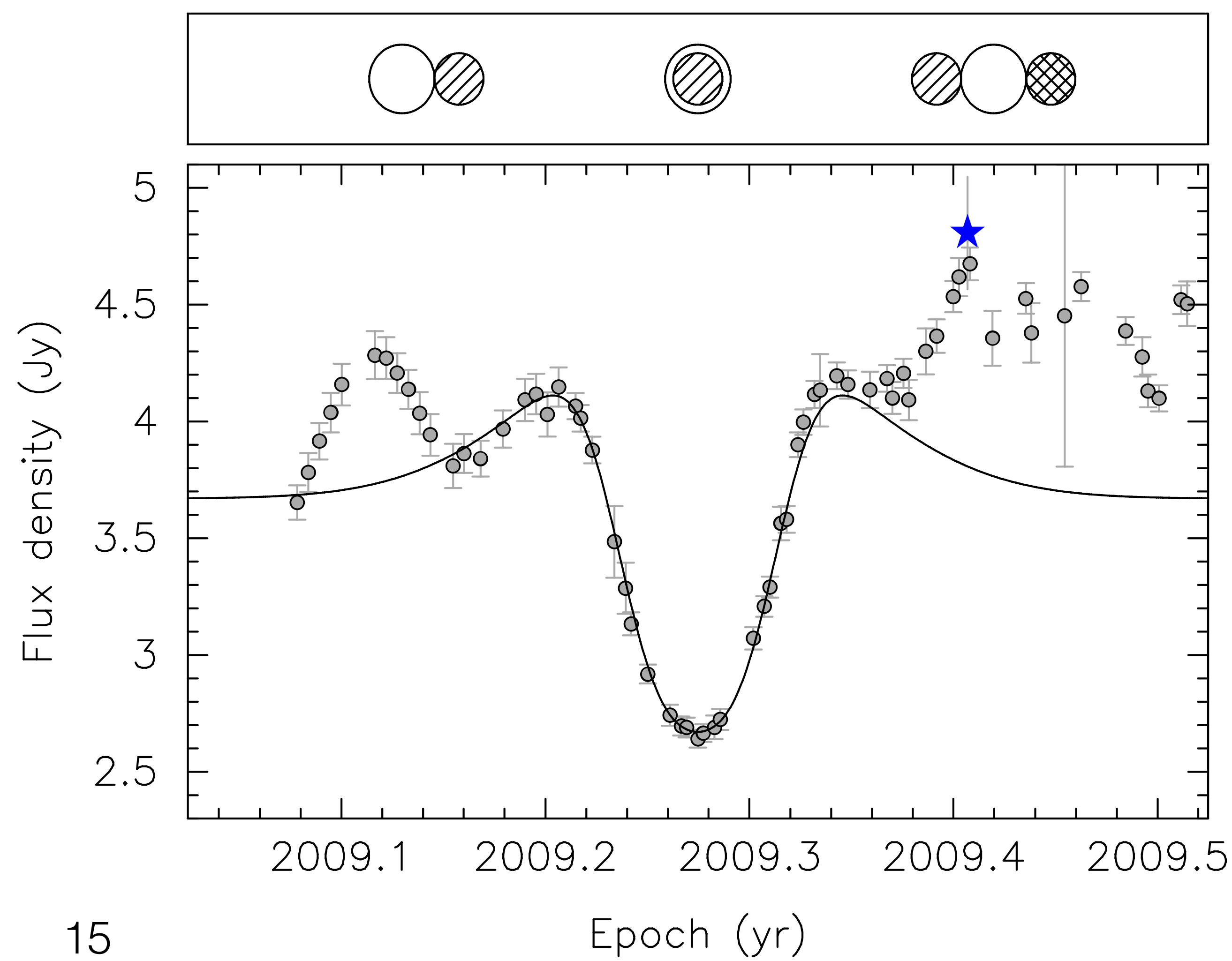


Multifrequency lightcurves of PG 1553+113 at gamma-ray, x-ray, optical and radio bands. *Bottom panel:* 15 GHz flux density from OVRO 40m (black filled circle points) and parsec-scale 15 GHz flux density by VLBA.

‘Extreme Scattering’ B2023+335 (J2025+3343)



Pushkarev A&A 555, A80 (2013) detected multiple imaging in a VLBA observation, and modeled the light curve with a plasma lensing event.



Looking forward

- Understanding flaring and light curves needs comparison with GRMHD simulations
- Simulations need to be carried through radiative transfer to simulated light curves
- Need ensembles of simulations to see how physical parameters can be constrained from the light curves
- Multiwavelength light curves are needed

Future at OVRO

- Polarization! at 15 GHz
  - New digital receiver is working
  - Checking polarization calibration…
- Starburst single baseline interferometer
  - *Gregg Hallinan: stellar flares*
  - New instrument on the old 90ft (27m antennas)
  - Continuous 2-18 GHz, spectropolarimeter
  - *but antennas are almost as old as Alan Marscher*

- 3mm and 1mm polarization monitoring?
  - Using old CARMA 10m dishes, relocated to OVRO
  - Extension of the MARMOT program on CARMA (Talvikki Hovatta) http://www.astro.caltech.edu/marmot/
  - *Unfunded*

http://www.astro.caltech.edu/ovroblazars/

OVRO 40m Telescope

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Monitoring of *Fermi* Blazars

In 2007, the 40 M Telescope at the Owens Valley Radio Observatory (OVRO) embarked on a new research campaign. In support of the *Fermi* Gamma-ray Space Telescope, launched in 2008, the OVRO 40 M Telescope is monitoring more than 1800 blazars about twice per week.

Our paper, Blazars in the *Fermi* Era: The OVRO 40-Meter Telescope Monitoring Program, describes our observing program in detail and presents results from 2008 and 2009. Extended analysis on the differencies of radio and gamma-ray selected samples using data between 2008 and 2011 is presented in Connecting radio variability to the characteristics of gamma-ray blazars. Other OVRO publications are listed on the OVRO 40m Papers page.

The 40 M measurements at 15 GHz are being compared to the Fermi gamma-ray measurements of the same sources. By looking for correlations in the variability, we are gaining a new understanding of the emission mechanisms at the hearts of Active Galactic Nuclei.

Reduced data for our core sample, the 1158 CGRaBS (Healey et al. 2008) north of -20° declination, are available to the public. The data can be obtained here. Use the user name *guest* and a blank password for access.

List of all AGN monitored at OVRO can be found here. If you wish to obtain data for a source not listed on our data page, please contact us via email.

The OVRO 40 M Telescope *Fermi* Blazar Monitoring Program is supported by NASA under awards NNX08AW31G and NNX11A043G, and by the NSF under awards AST-0808050 and AST-1109911.