The location of the gamma-ray emission site in blazars from radio and gamma-ray monitoring

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Monitoring the non-thermal Universe
Cochem, Germany
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Collaborators

OVRO blazar monitoring program:

A. Readhead, T. Pearson *(Caltech OVRO)*

T. Hovatta *(Aalto U.)*

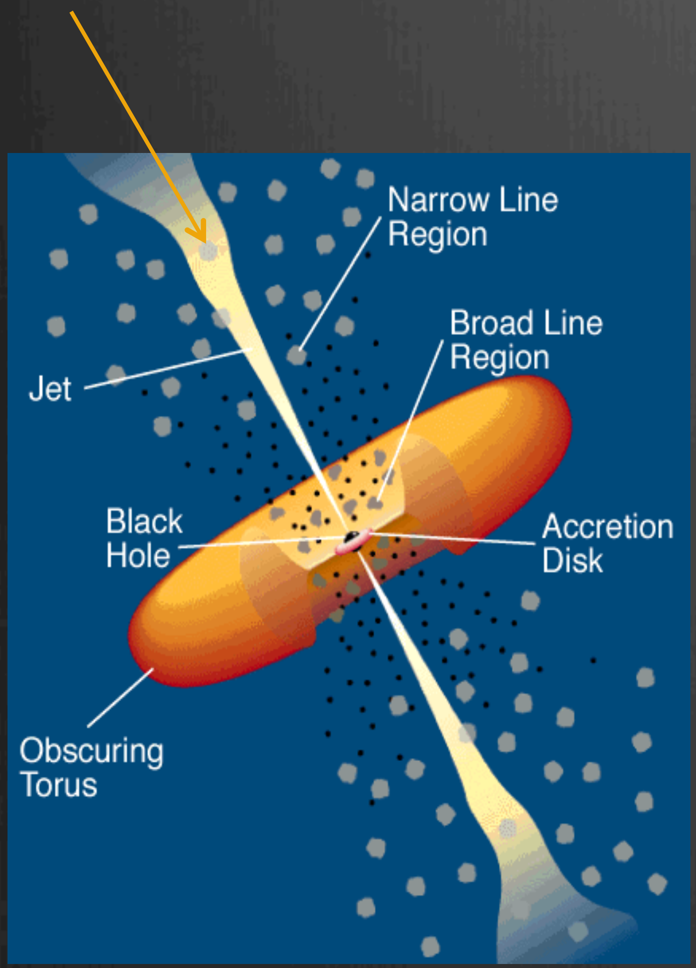
R. Reeves *(U. de Concepción)*

J. Richards

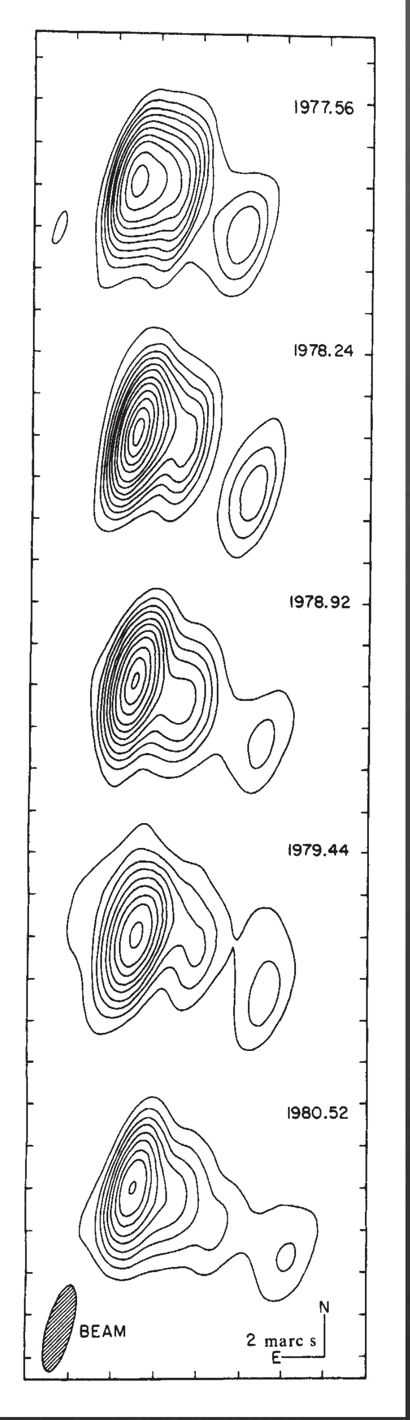
J. A. Zensus *(MPIfR)*

and many others

Blazars



Urry and Padovani 1995

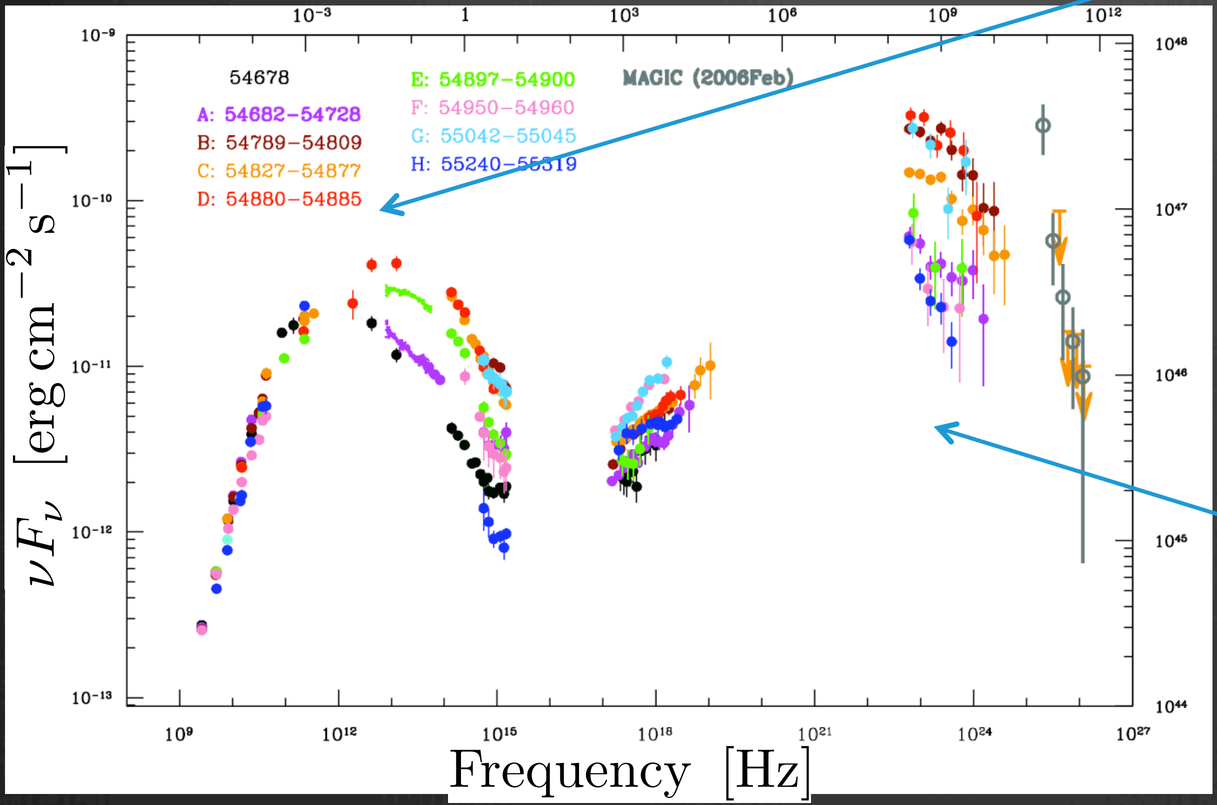


VLBI can resolve these objects

- Radio loud
- Small angular size
- Single sided jet
- Superluminal expansion

3C 273, Pearson et al. 1981

Blazars: Spectral Energy Distribution



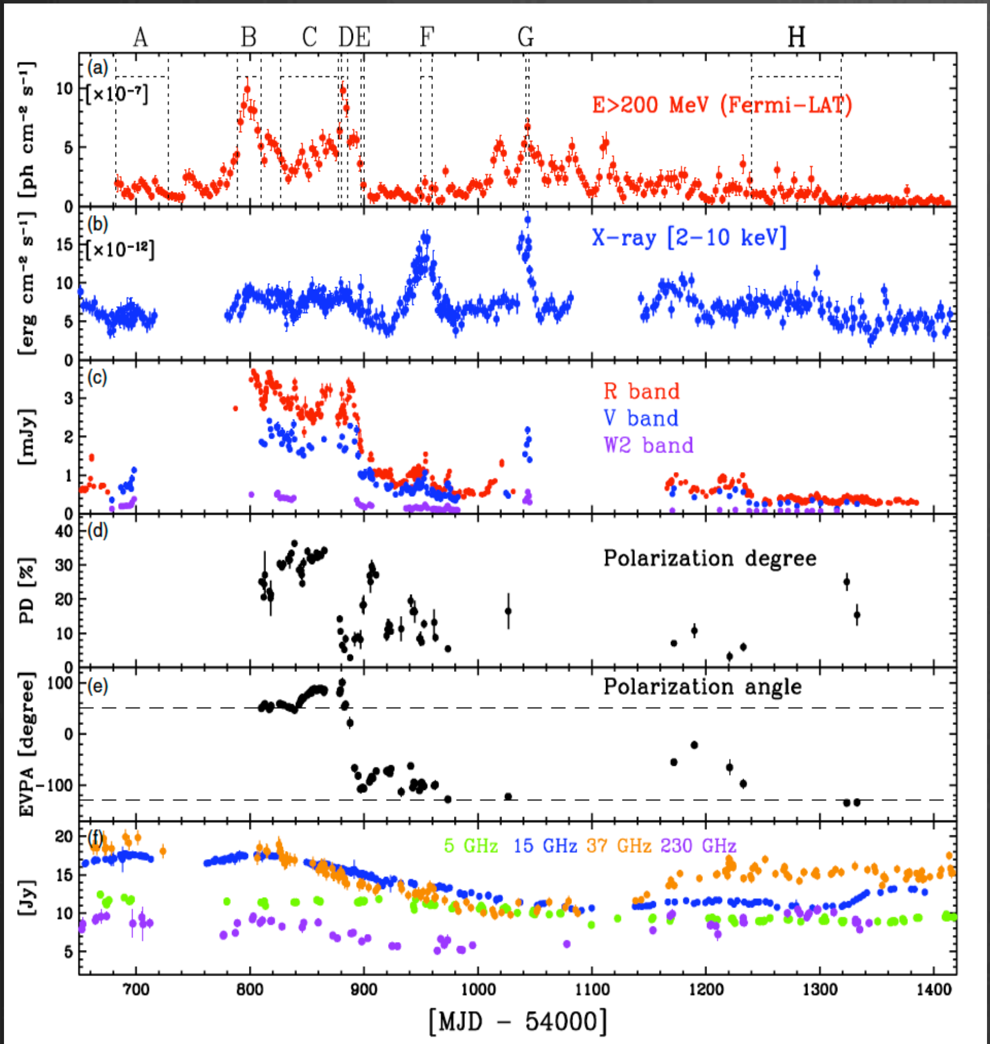
Broadband spectral energy distribution
3C 279 from Hayashida et al. 2012

Synchrotron emission

Inverse Compton
- **Synchrotron self Compton**
- **External Compton**
  - Accretion disk, corona
  - Broad line region
  - Dust torus

Hadronic models

Blazars are extremely variable



γ -ray

X-ray

optical/UV

optical polarization degree

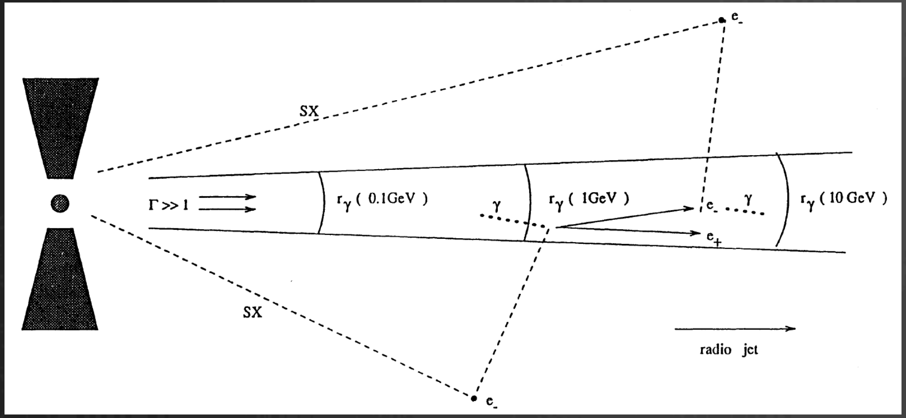
optical polarization angle

radio mm and cm

Variability in 3C 279 from Hayashida et al 2012

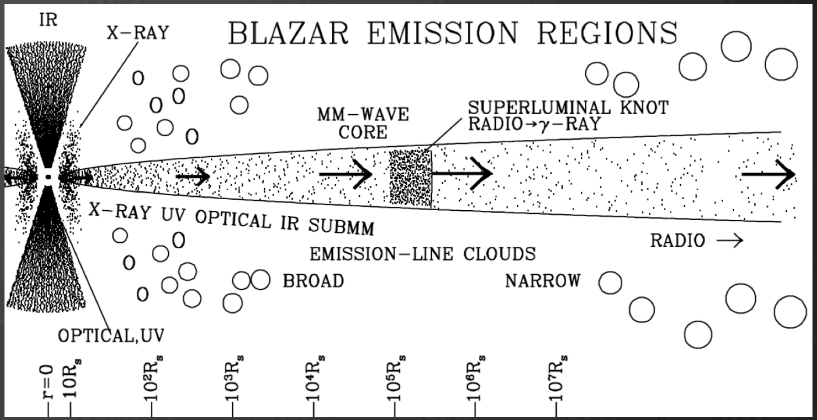
Uncertain location of the gamma-ray emission site

Close to the central engine < 1 pc



Blandford and Levinson 1995

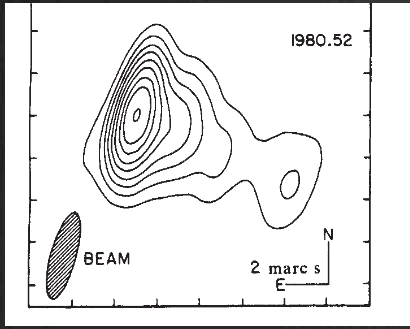
Few parsecs down the jet

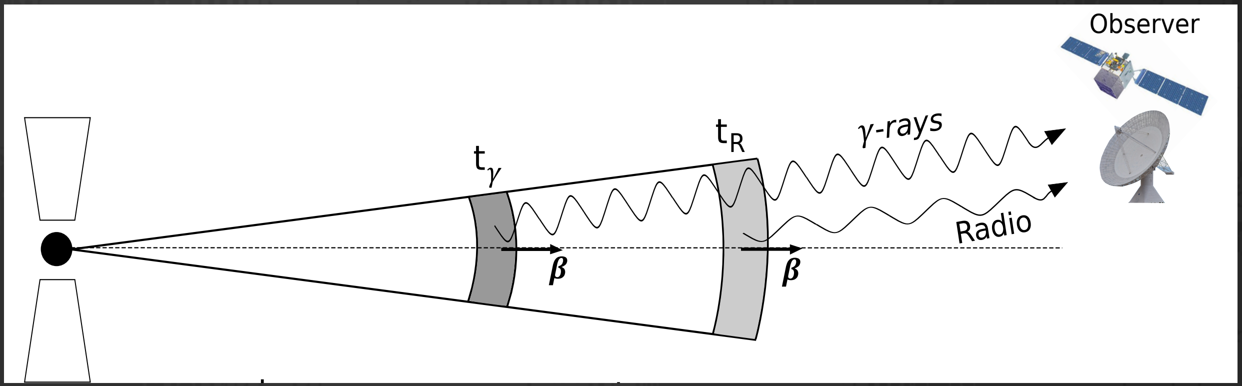


Jorstad et al. 2001, Marscher 2006

Observational constraints on the gamma-ray emission site

- Direct imaging is not possible
  - VLBI observations have submilliarcsecond resolution
  - Gamma-ray telescopes have ~0.2^{o} at E ~10 GeV
- One alternative is to use the variability
- Correlated variations expected if the emission regions are related

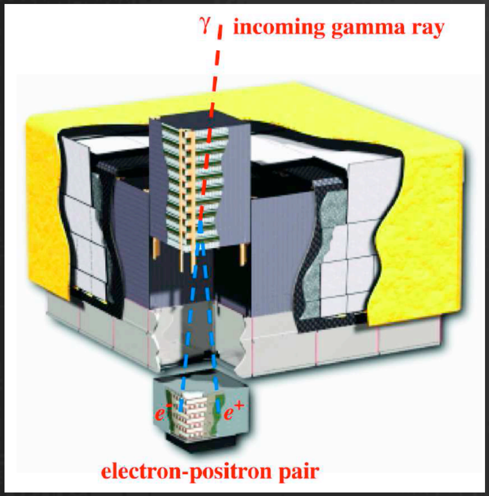


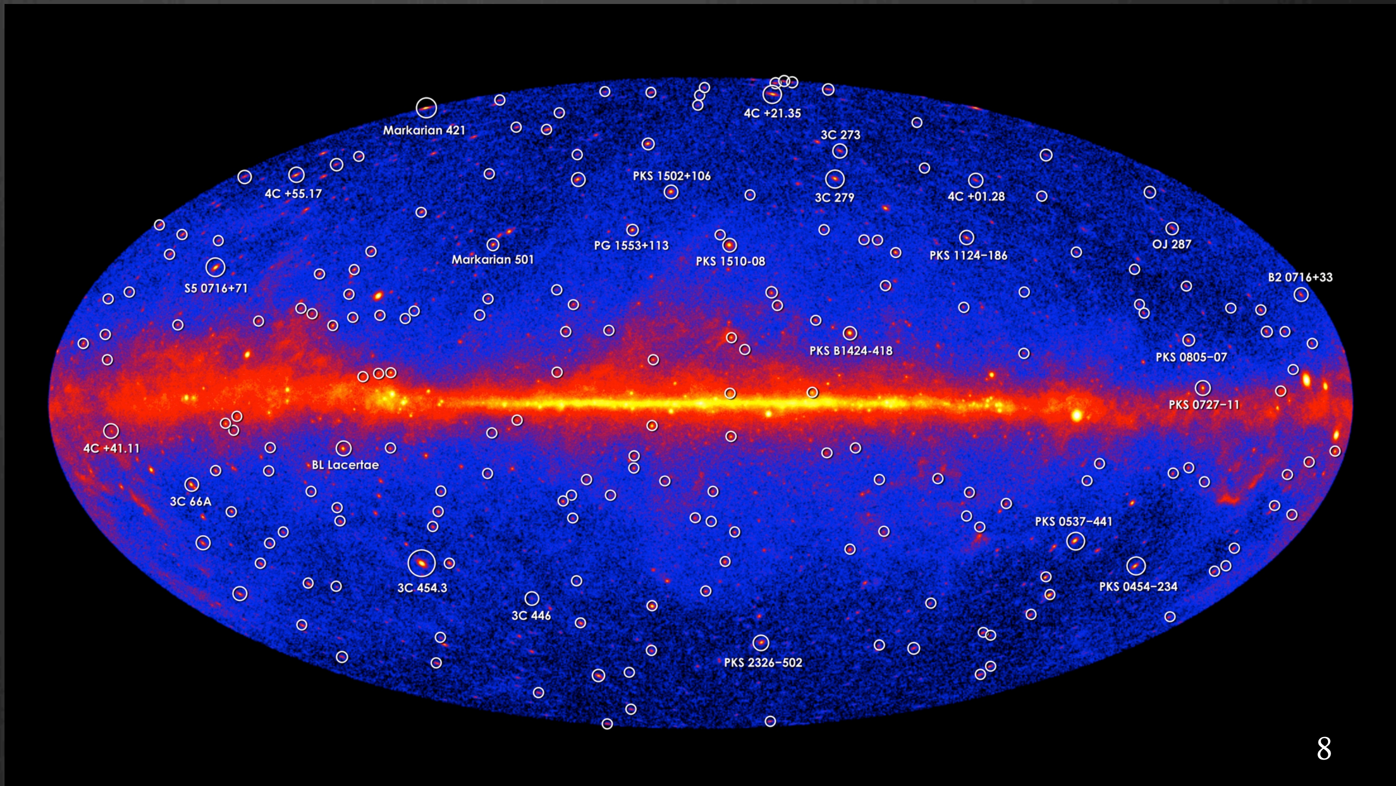


Max-Moerbeck et al. 2014a

Gamma-ray monitoring: The Fermi Gamma-ray Space Telescope

- Fermi monitors the sky continuously at high energies
  - Energies from 20 MeV to 300 GeV
- A full sky map every 3 hours





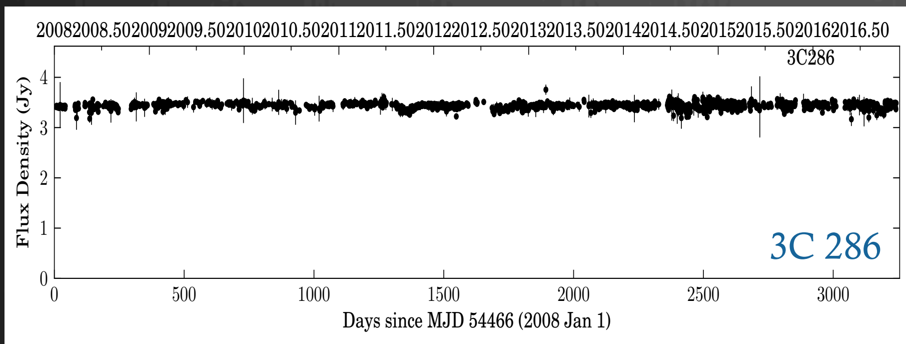
Radio Monitoring:
The OVRO 40 m Telescope Blazar Monitoring Program

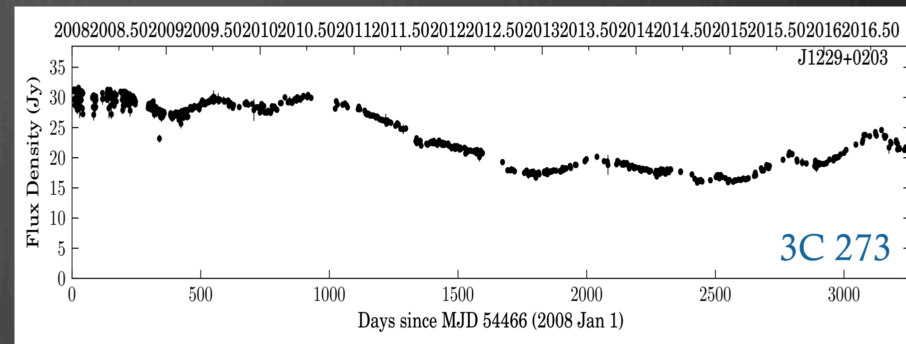
- Monitoring ~1800 sources
- Radio continuum observations
  - 15 GHz with 3 GHz bandwidth
  - ~4 mJy thermal noise
    3% typical error
- Two observations per week since 2008
- Richards et al. 2011 for details

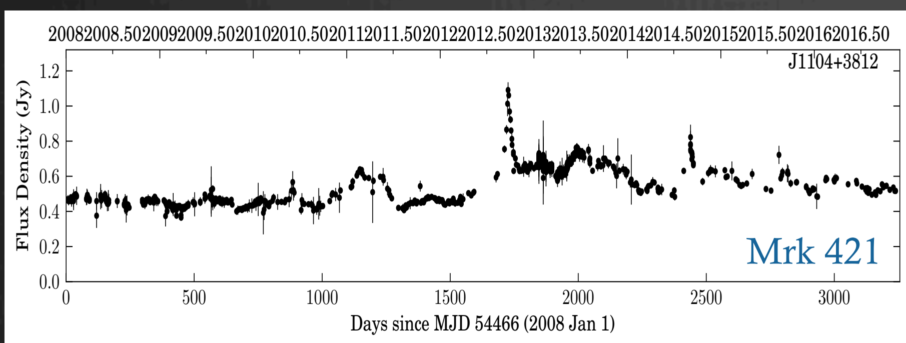
The OVRO 40 m telescope at night
by J. L. Richards

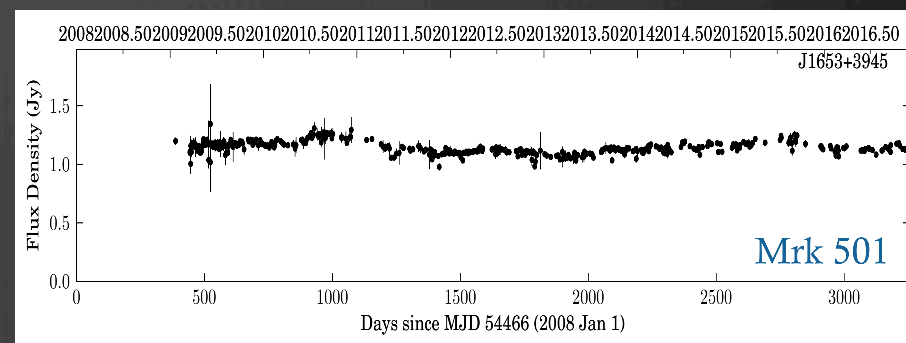
More details in our website
www.astro.caltech.edu/ovroblazars

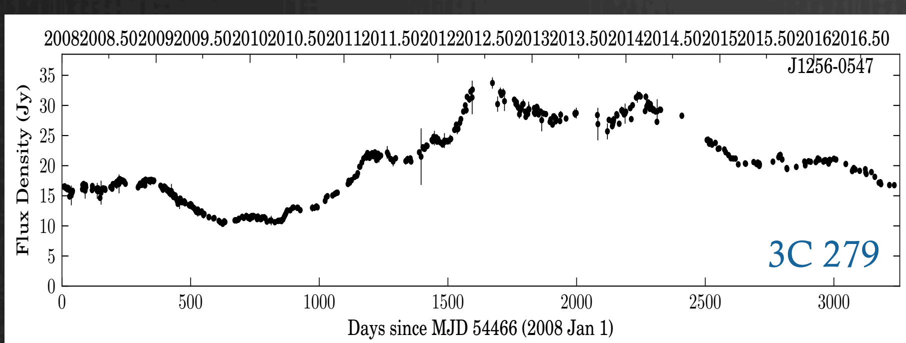
Example of 15 GHz light curves (2008-2016)

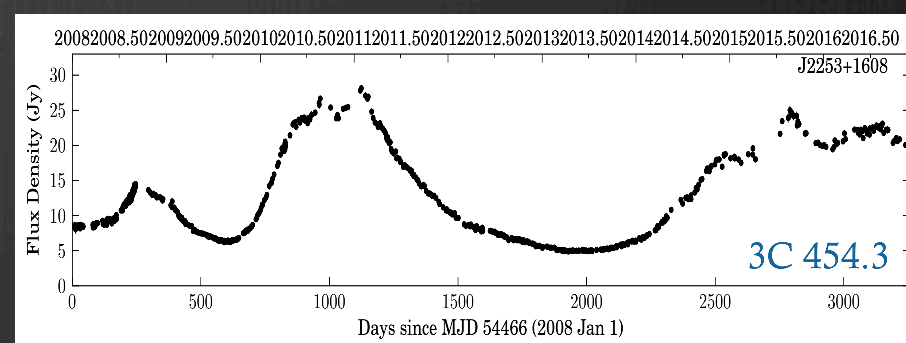






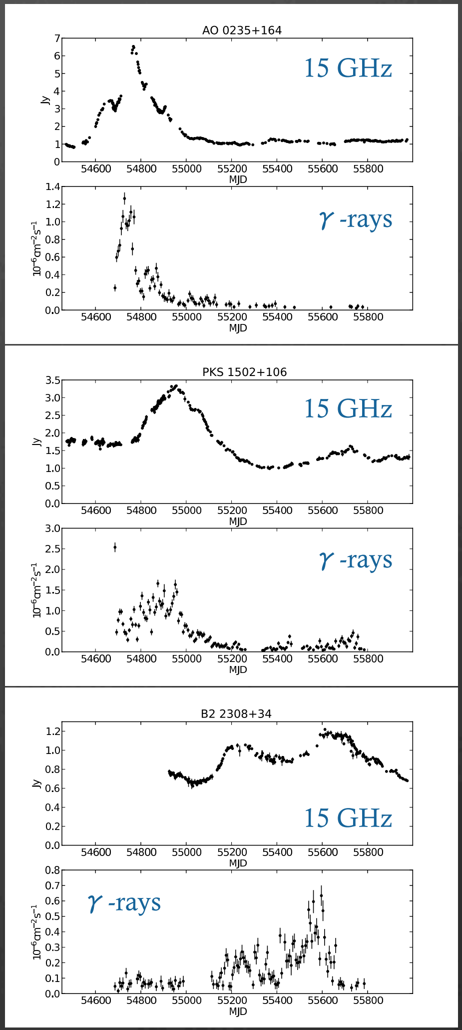






OVRO/Fermi-LAT results: Relation between the radio and gamma-ray bands

- 4 years of radio and 3 years of gamma-ray data
- 3 out of 41 sources significant correlation
- In all cases radio lags gamma-ray emission
  - => gamma-rays are produced inside the radio core
- Consistent signature in multiwavelength radio data using source stacking (Fuhrmann et al. 2014)



Max-Moerbeck et al. 2014a

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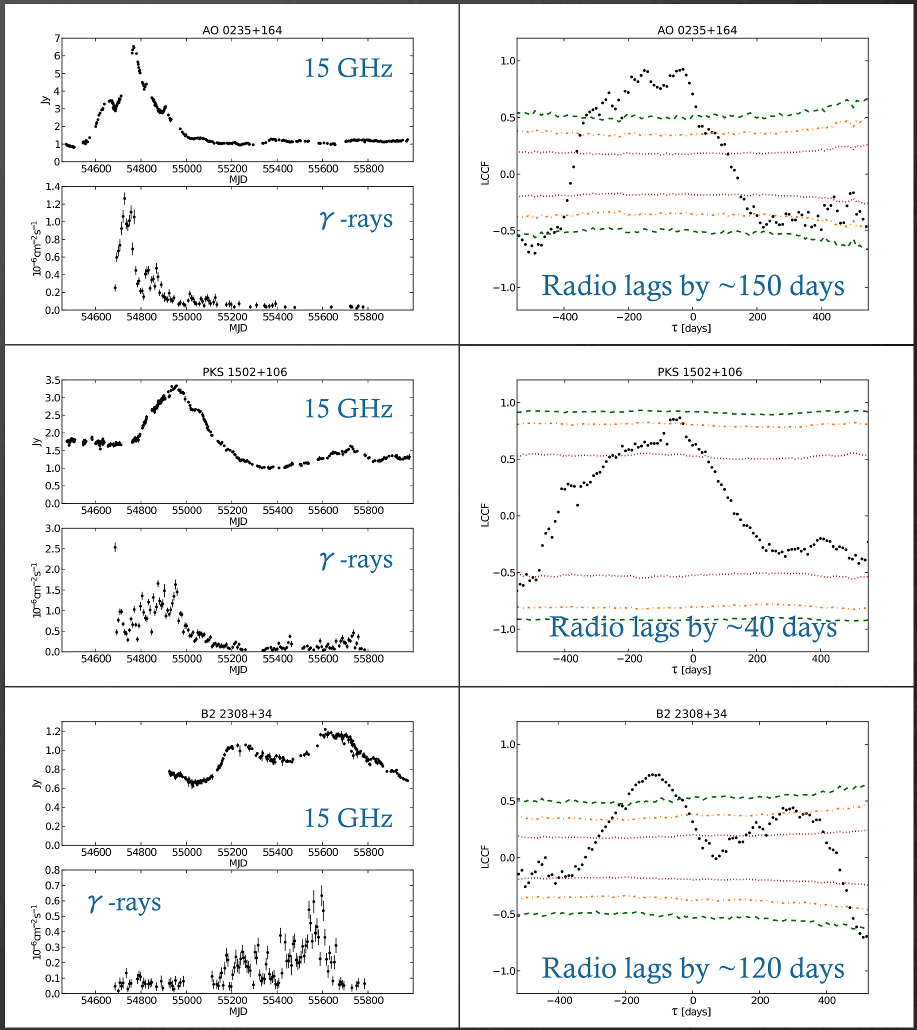
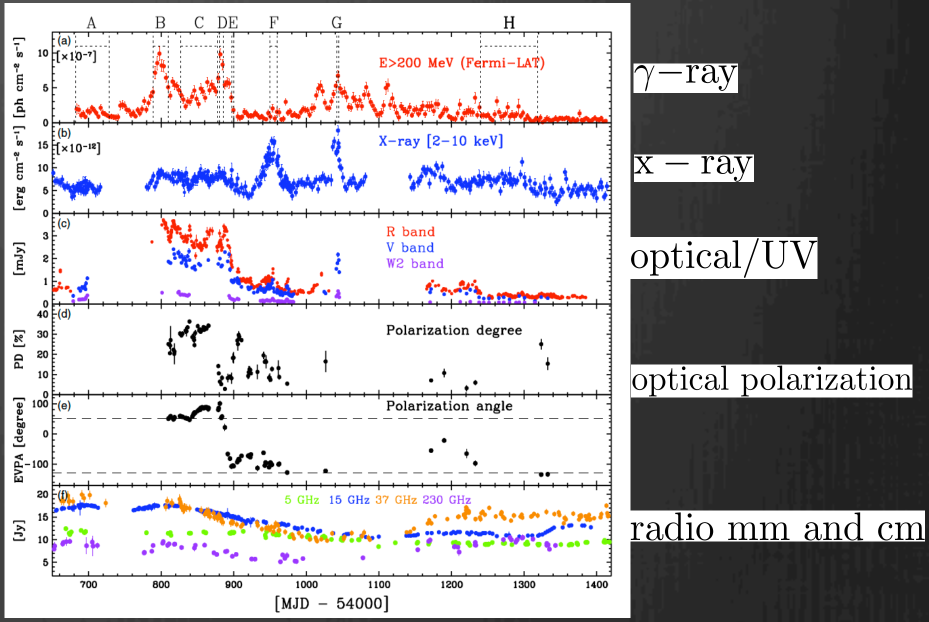


Max-Moerbeck et al. 2014a

Characterization of the Power Spectral Density

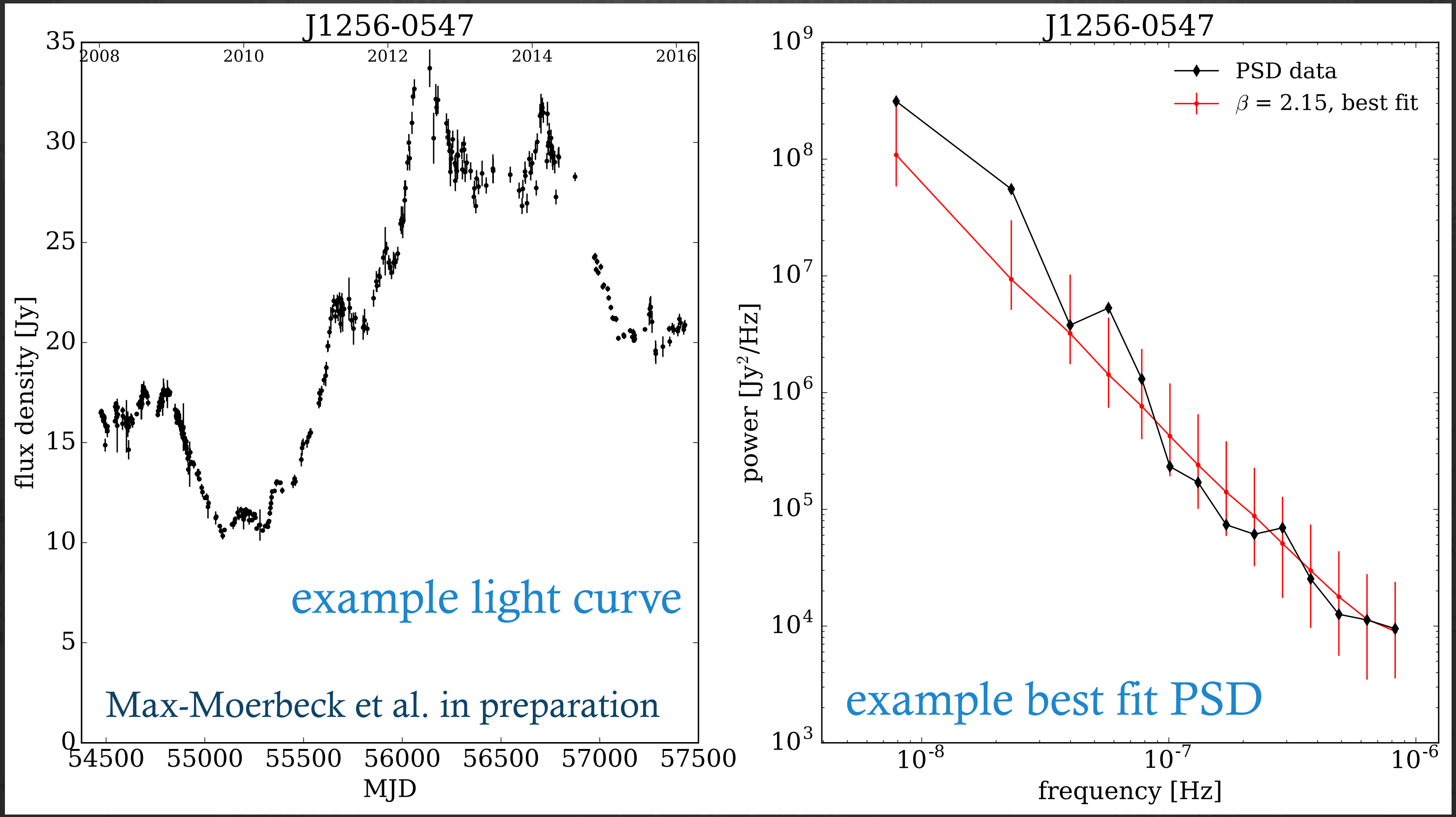
- Variability is one the main characteristics of blazars
- Essential ingredient for cross-correlation significances
- Several models are available
  - Power spectral density (PSD)
  - Stochastic models
- Characterization of the PSDs is complicated by the uneven sampling of the light curves
  - Max-Moerbeck et al 2014b based on PSRESP (Uttley et al. 2002)



Variability in all wavebands
3C 279 from Hayashida et al. 2012

Characterization of the radio variability:

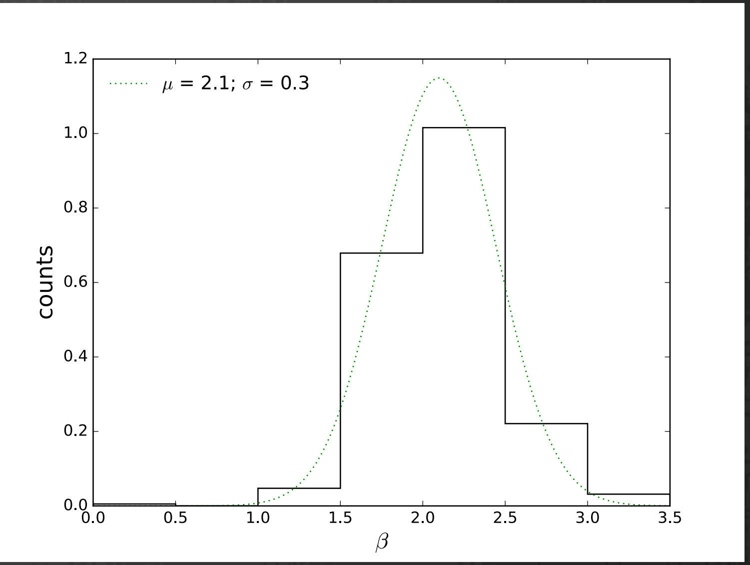
- We use a simple $PSD \propto 1/f^{\beta}$
- 8 years of radio data
- 1,722 sources, 421 with high quality PSD fits



PSD results:

No difference between different blazar classes

- The values cluster around $\beta \sim 2.1$

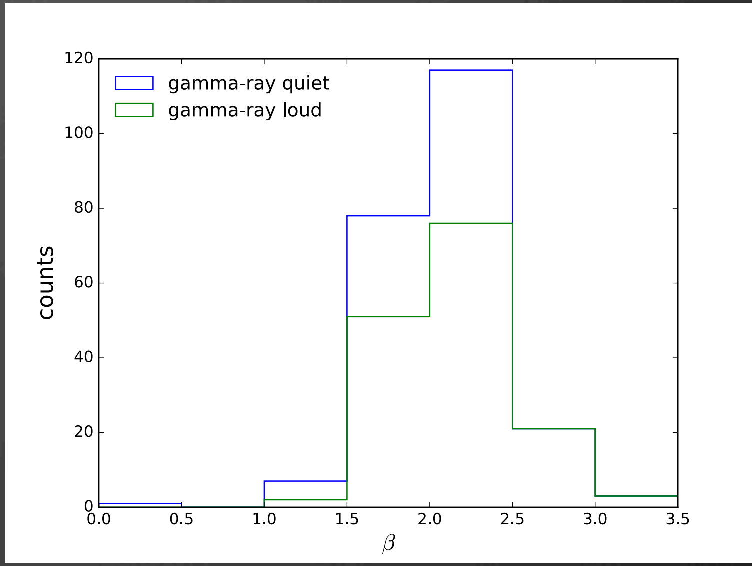


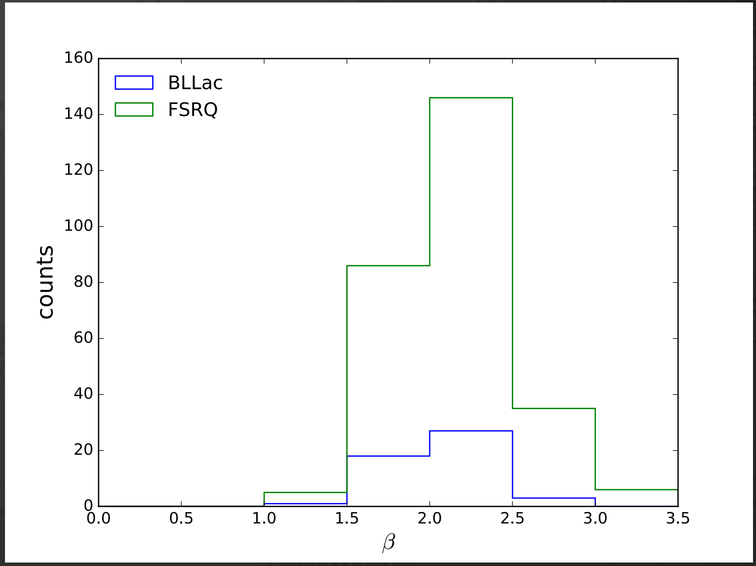
Max-Moerbeck et al. in preparation

PSD results:

No difference between different blazar classes

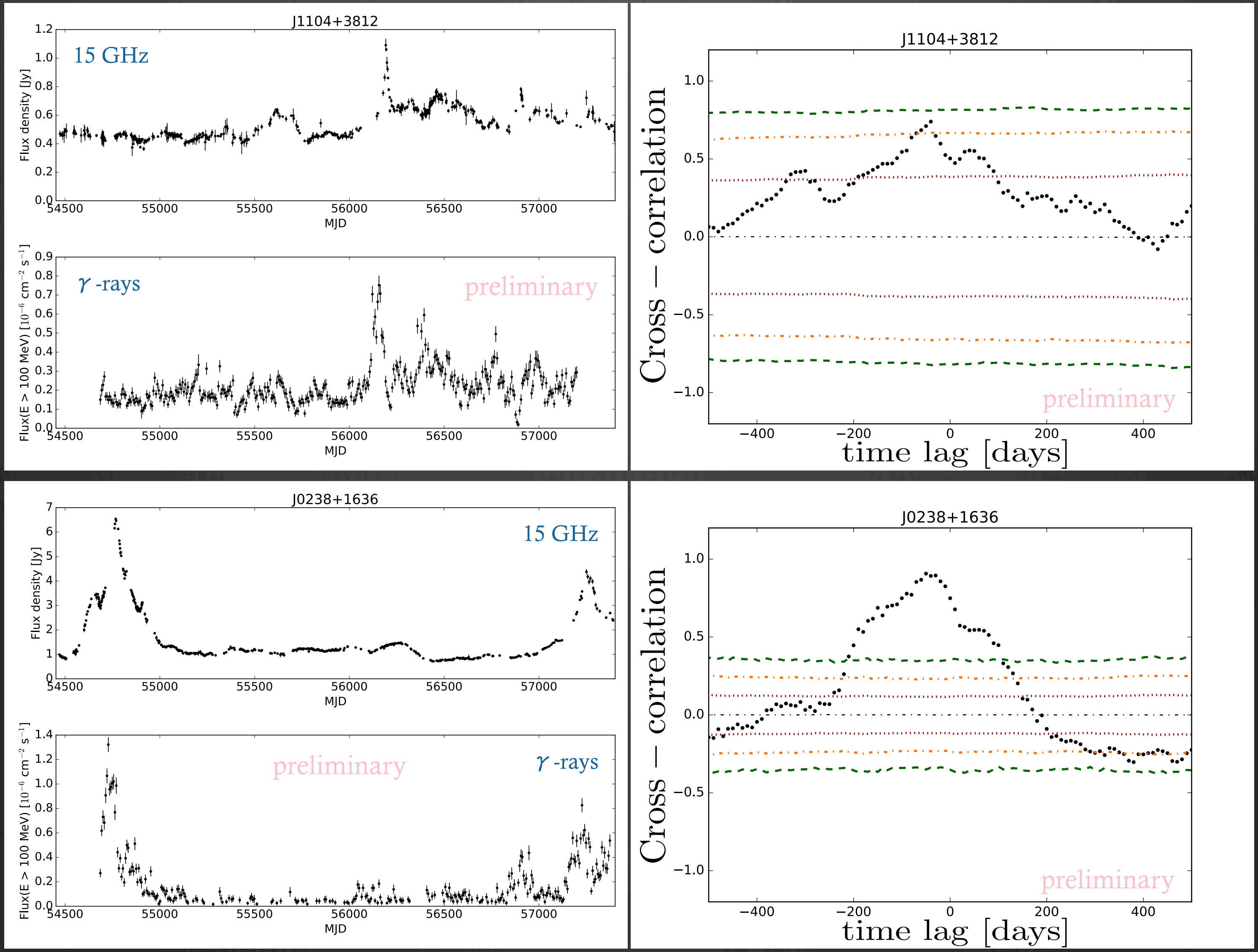
- The values cluster around $\beta \sim 2.1$
- Consistent distributions for different source populations
  - Gamma-ray loud v. gamma-ray quiet: KS-test p-value=0.23
  - BL Lac v. FSRQ: KS-test p-value=0.24





Max-Moerbeck et al. in preparation

Radio/gamma-ray correlation now:
8 years of radio and 7 years of gamma-ray data



Max-Moerbeck et al. in preparation

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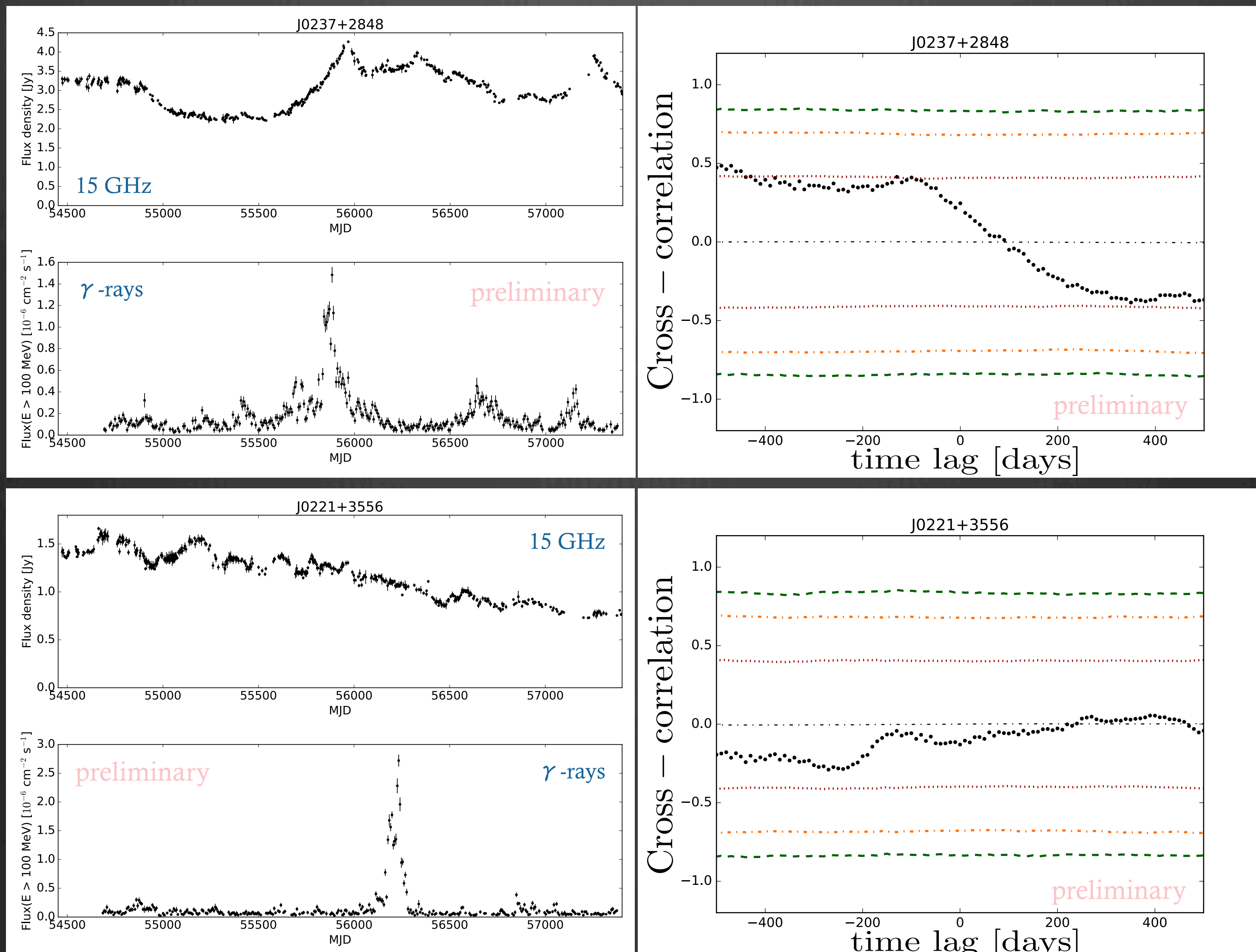
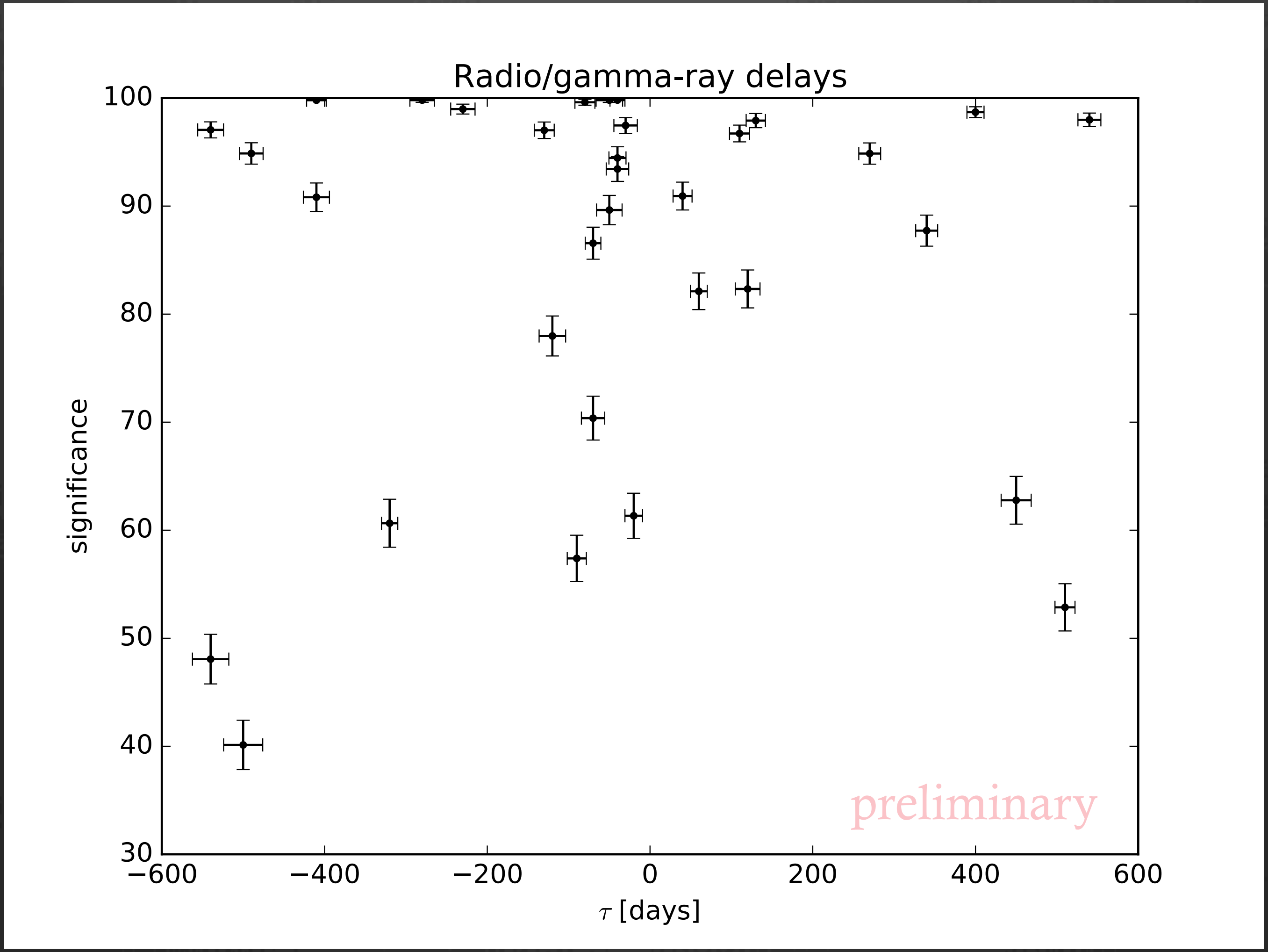


Max-Moerbeck et al. in preparation

Radio/gamma-ray correlation now:

8 years of radio and gamma-ray monitoring



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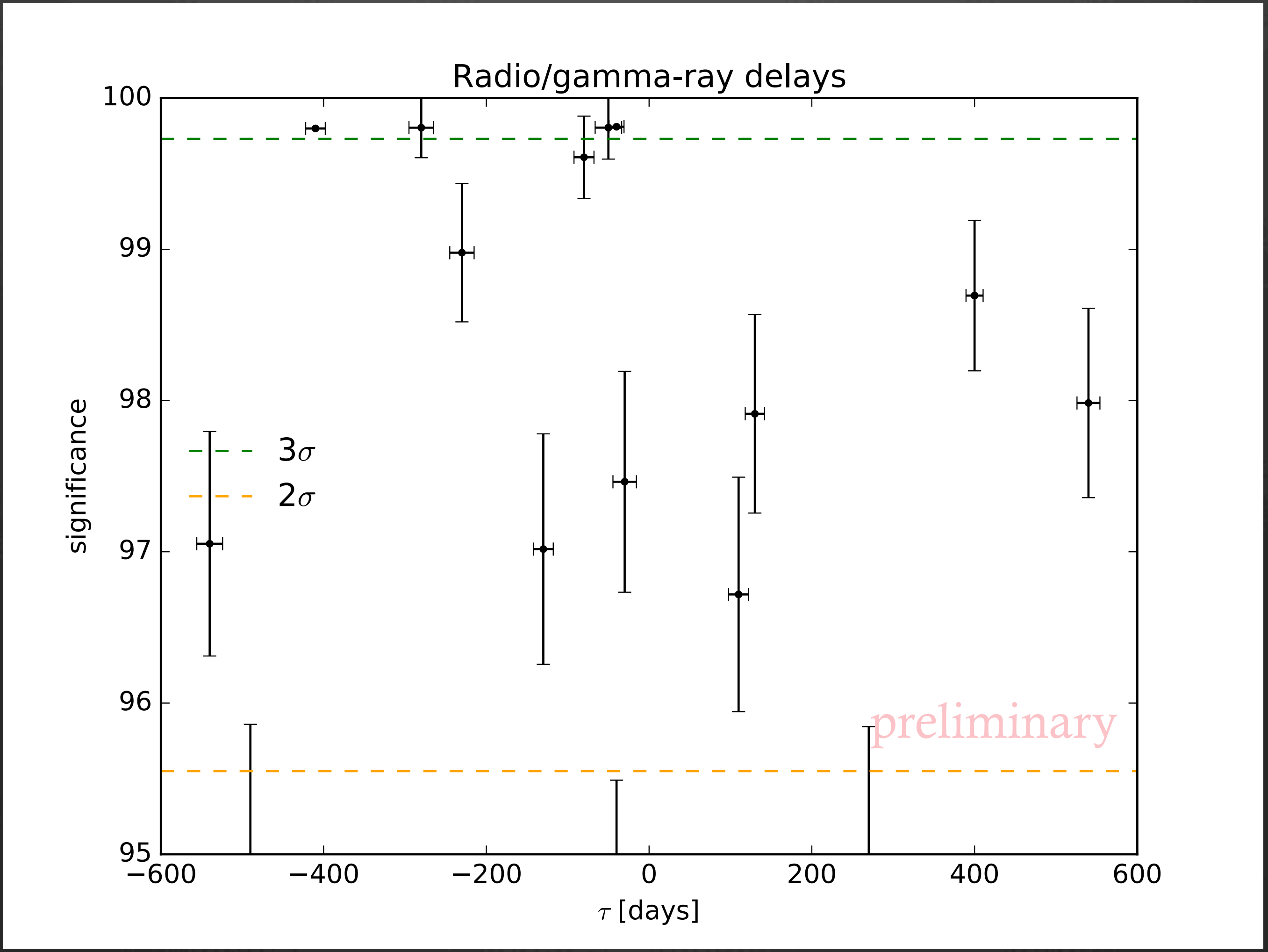


Radio/gamma-ray correlation now:

8 years of radio and gamma-ray monitoring

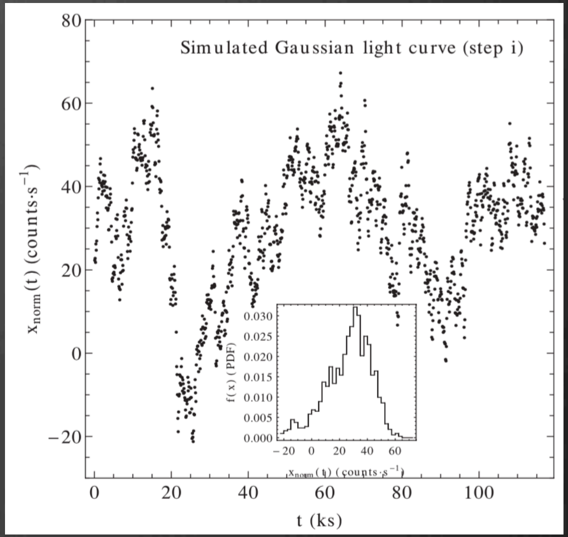
- Preliminary results for 33 sources
  - 4 with 3sigma significant time lags
  - Radio lags gamma-ray emission as seen before

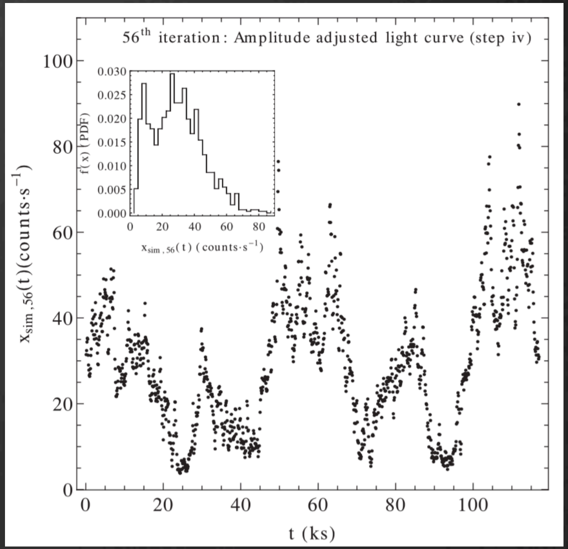
- Results in preparation for more (> 100)

Some comments on methodology:

Simulating light curves

- A light curve can be characterized by its
  - Power Spectral Density
  - Probability Density Function
- Methods to simulate light curves
  - Timmer and König 1995
    - PSD and Gaussian PDF
  - Emmanoulopoulos et al 2013
    - PSD and arbitrary PDF
- Don't forget aliasing and red-noise leakage
  - Aliasing -> include high frequencies, finely sampled data
  - Red-noise leakage -> include low frequencies, longer light curves

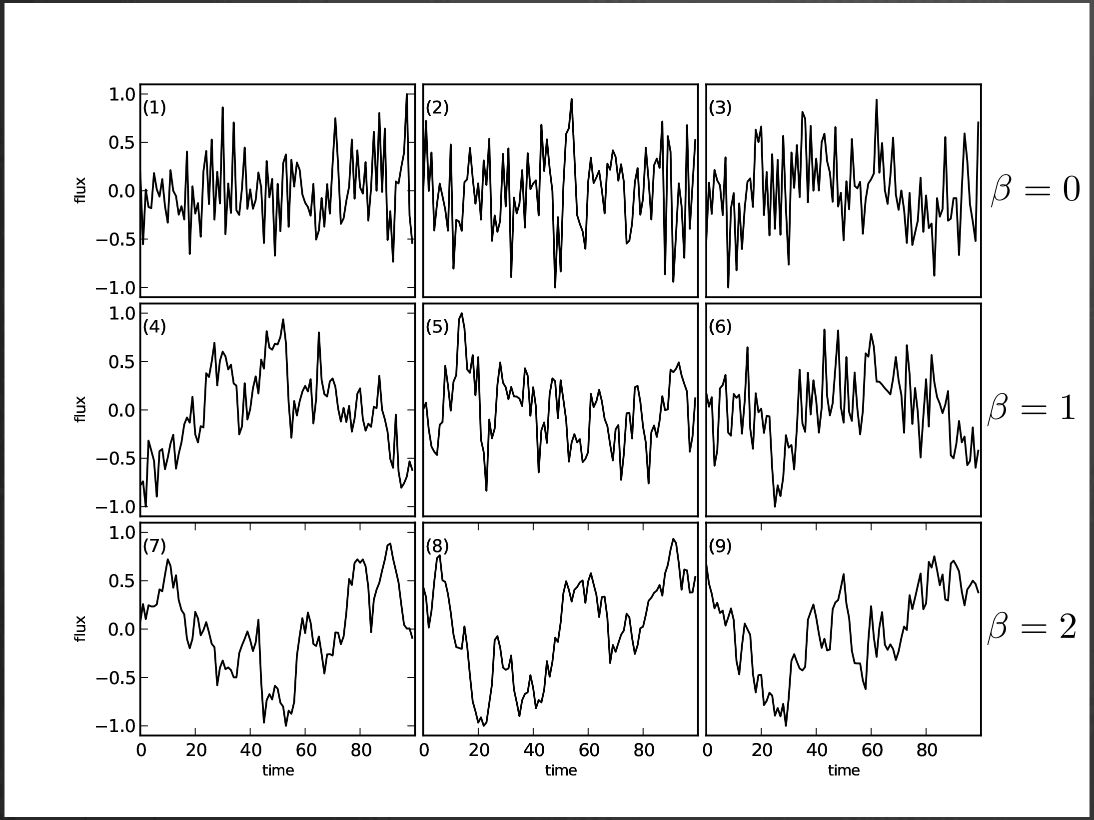


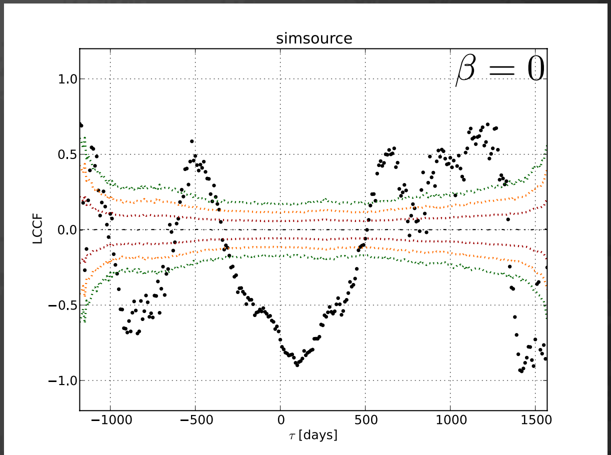


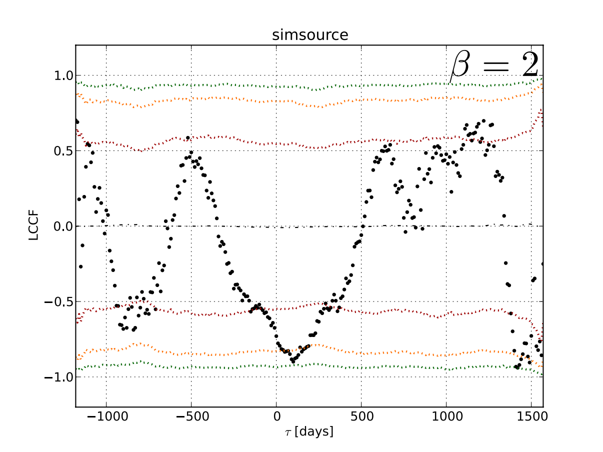
Some comments on methodology:

The significance depends on PSD

Simulated light curves with different $PSD \propto 1/f^{\beta}$



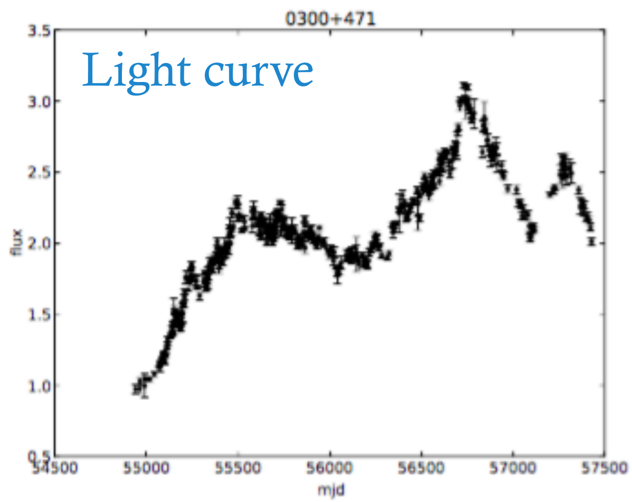


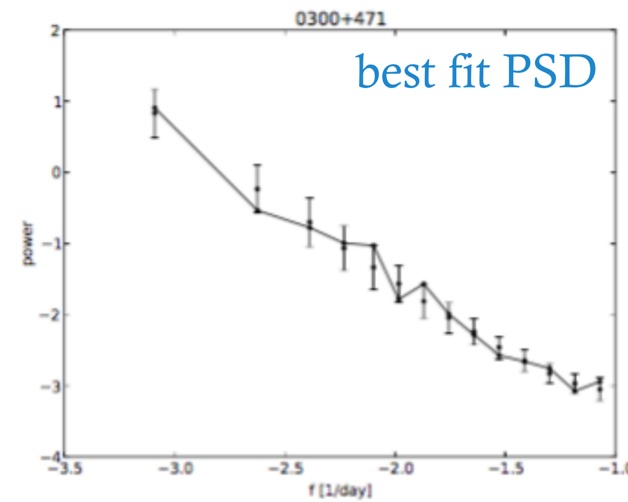


Figures from Max-Moerbeck et al. 2014b

Some comments on methodology:

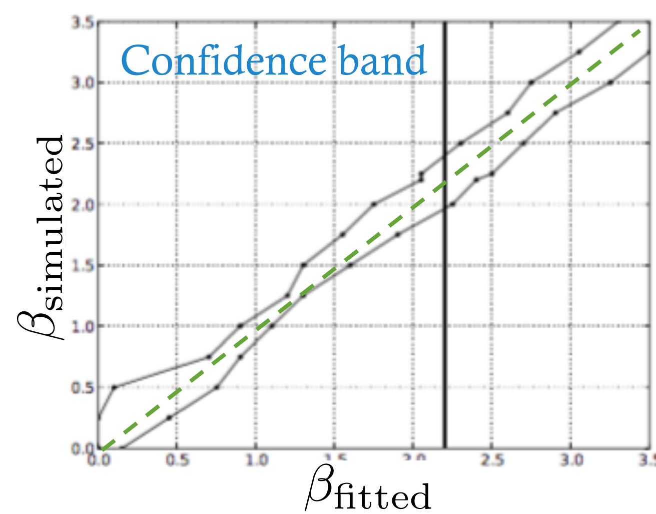
Error on the slope of the PSD and limits of the method





Good sampling
Low noise

⇒ well constrained PSD exponent



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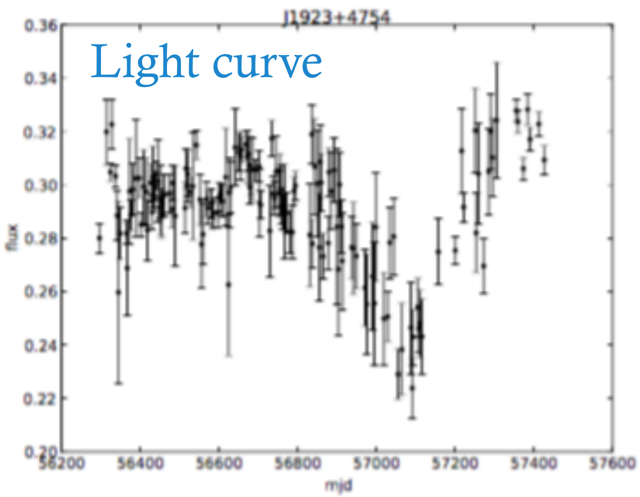
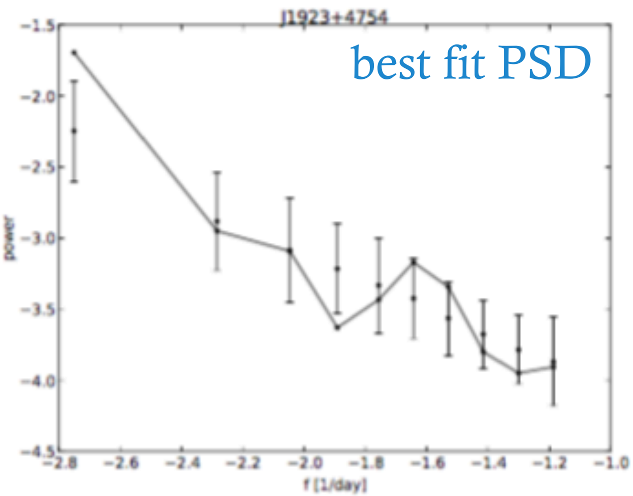
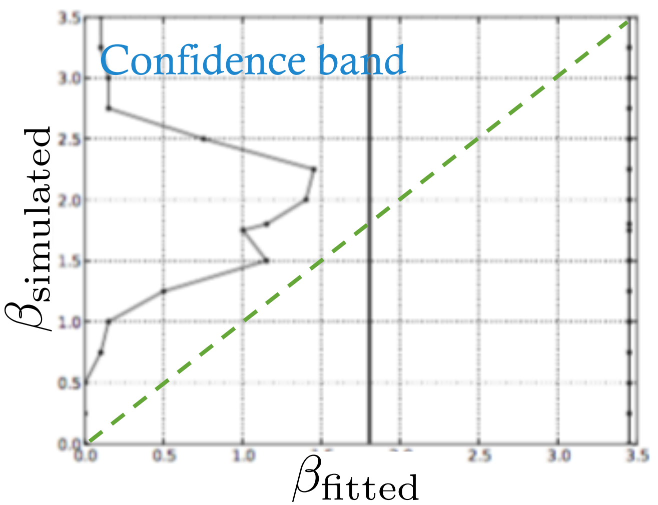




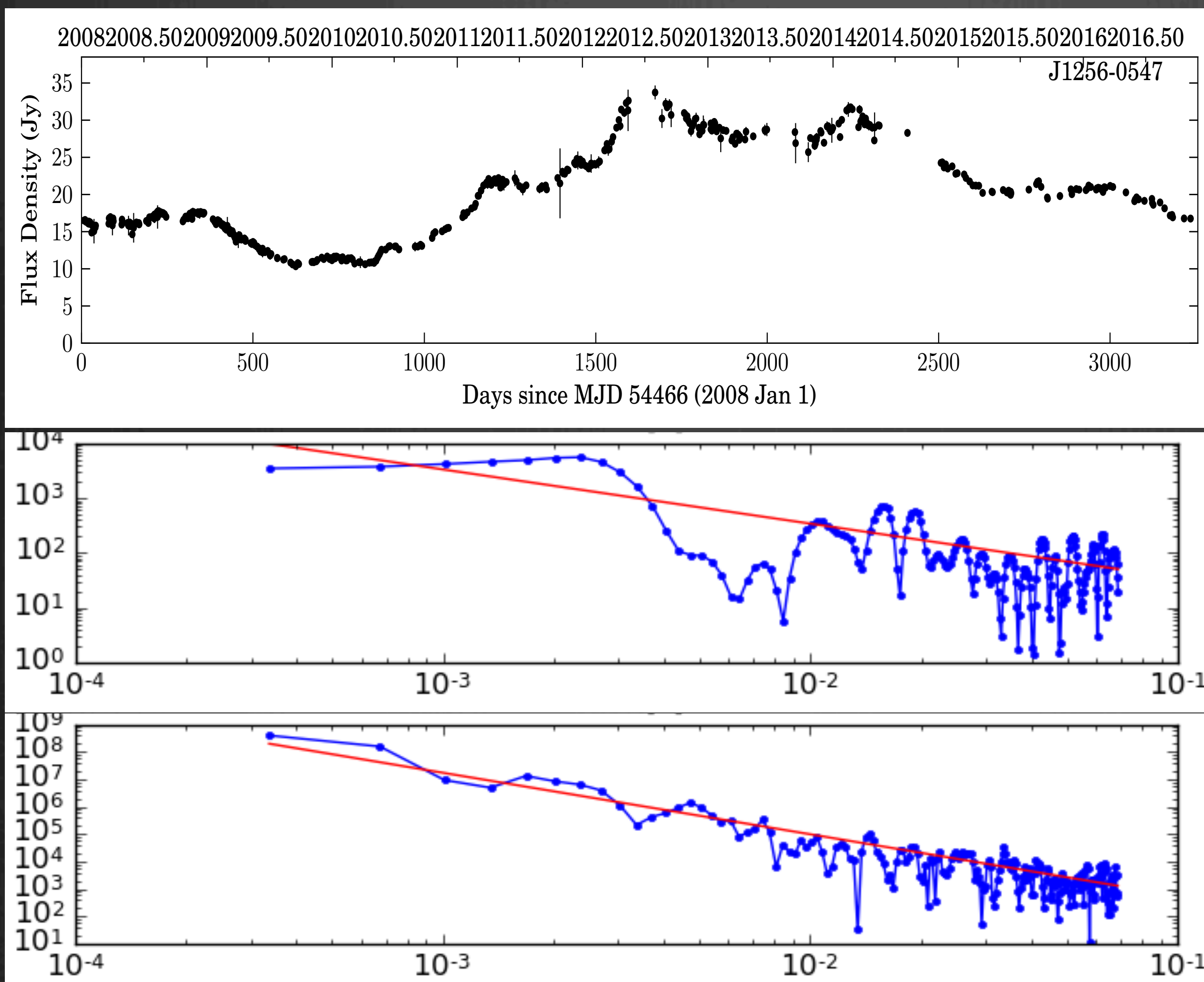
Good sampling
but high noise

⇒ non-constrained PSD exponent



Some comments on methodology:

An example of a systematic problems with a simple methods



Example case where we directly fit a slope to log(P)-log(f)

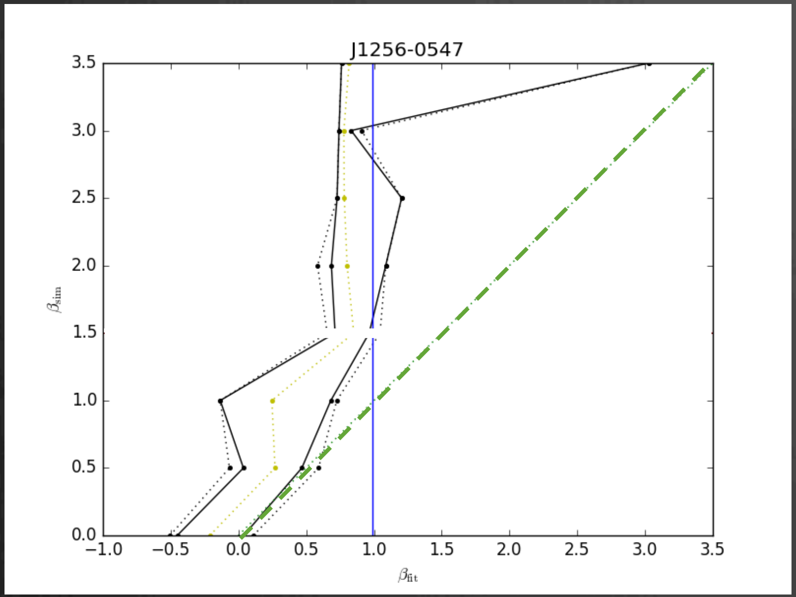
Only for the purpose of the example, don't do it a home

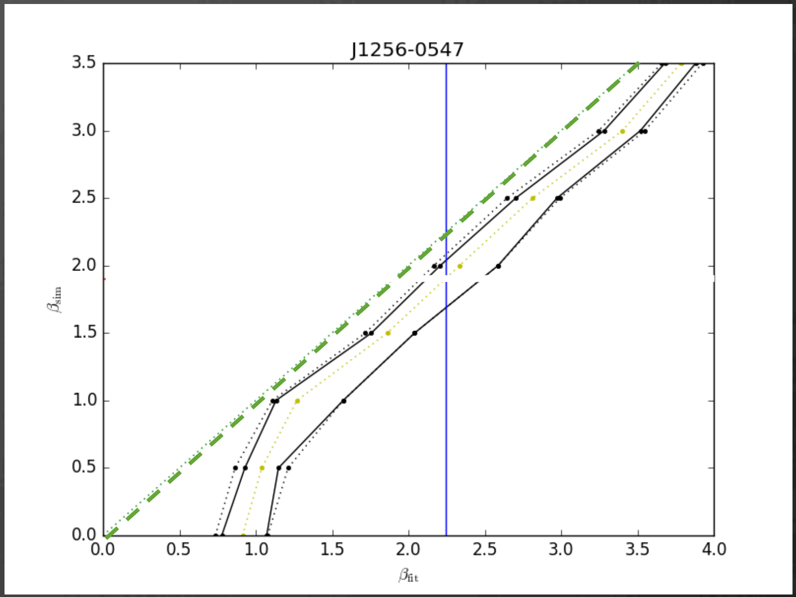
Lomb-Scargle periodogram

Evenly sampled with interpolation + DFT

Some comments on methodology:

An extreme example of a systematic problem





Lomb-Scargle periodogram

No spectra steeper than 1 can be fit

Evenly sampled with interpolation + DFT

No problems fitting stepper spectra
BUT the slopes are biased to higher values.

We can see how simply fitting a slope to log(P)-log(f) produces problems

It is a good idea to validate any method with signals of known properties

Summary

- OVRO blazar monitoring program
  - Monitoring of ~1800 blazars at 15 GHz, twice per week since 2008
- Blazar variability is essential for their study
  - Access to small scales and help us understand their multiband behavior
- Correlated radio/gamma-ray variability for uniform sample
  - Only a minority of the sources show significant correlations, always with radio lagging gamma-ray variations
  - We are currently looking at 8 years of radio data and gamma-ray monitoring
- Progress in methodology but there are still some problems
  - Simulations are a powerful tool that should be use with care