Assessing AGN Variability and Cross-waveband Correlations in the Era of High Quality Monitoring Data at Low and High Energies

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JD-6 The Connection Between Radio Properties and High-Energy Emission in AGN

MOTIVATION

- Where is the high-energy emission coming from?
  - close to the BH within the BLR?
  - further down in the parsec-scale jet?
  - Is it External Compton or Synchrotron Self-Compton?
- We know the location of the radio emission

➡ Correlations can be used to locate the unresolved gamma-ray emission site

HIGH-QUALITY DATA (a biased list)

- Fermi LAT:
  - > 1000 gamma-ray sources associated with AGN
  - continuous all-sky coverage between 0.1 and 300 GeV

- OVRO:
  - twice per week monitoring of ~1700 sources
  - 15 GHz with the 40-m telescope

- F-GAMMA:
  - monthly monitoring of 60 sources
  - 10 frequencies between 2 and 150 GHz with Effelsberg 100m / IRAM 30-m telescope

- UMRAO:
  - weekly monitoring of ~ 30 sources
  - 4.8, 8, 14.5 GHz in total intensity and polarization

- Metsähovi:
  - weekly monitoring of ~ 100 sources (total sample much larger)
  - 37 GHz with the 14-m telescope
  - See talk by E. Valtaoja

+ Many more, e.g. SMA, APEX, CARMA + VLBA programs (talk by M. Lister)

OVERVIEW

	Amplitude domain	Time domain
Goal	Flux-flux correlation	Light curve cross-correlation
Common caveats / biases	• sample selection • common redshift dependence • non-simultaneous data • averaging time	• uneven sampling • short time series • significance
Methods	• parametric / non-parametric correlation coefficients (e.g. Pearson's, Spearman's, Kendall's tau) • censored data (e.g. ASURV)	• Discrete correlation function and its variants (e.g. local DCF, Z-DCF)
Significance estimates	Monte-Carlo simulations to account for common redshift dependence and limited dynamic range in luminosity / redshift space	Monte-Carlo simulations to estimate the significance of the correlation amplitude / time lag

EXAMPLES OF FLUX-FLUX CORRELATIONS

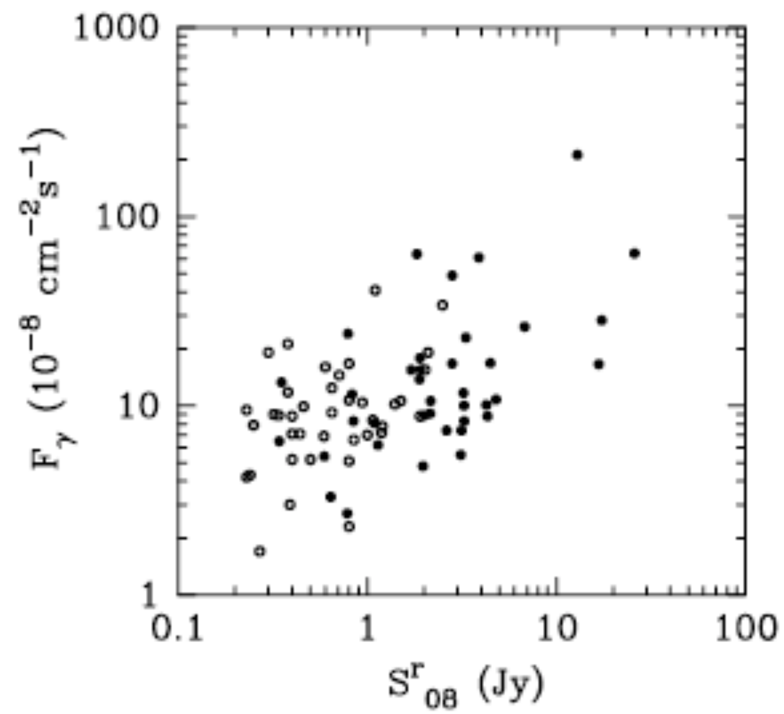


Figure 1. Average *Fermi* LAT 100 MeV–1 GeV photon flux (Abdo et al. 2009b) vs. quasi-simultaneous 15 GHz flux density. The filled circles represent total VLBI flux density while open ones—single-dish flux density. The single-dish flux densities are representative of the parsec-scale emission in these objects as described in Section 2.

15 GHz VLBA
Kovalev et al.
2009

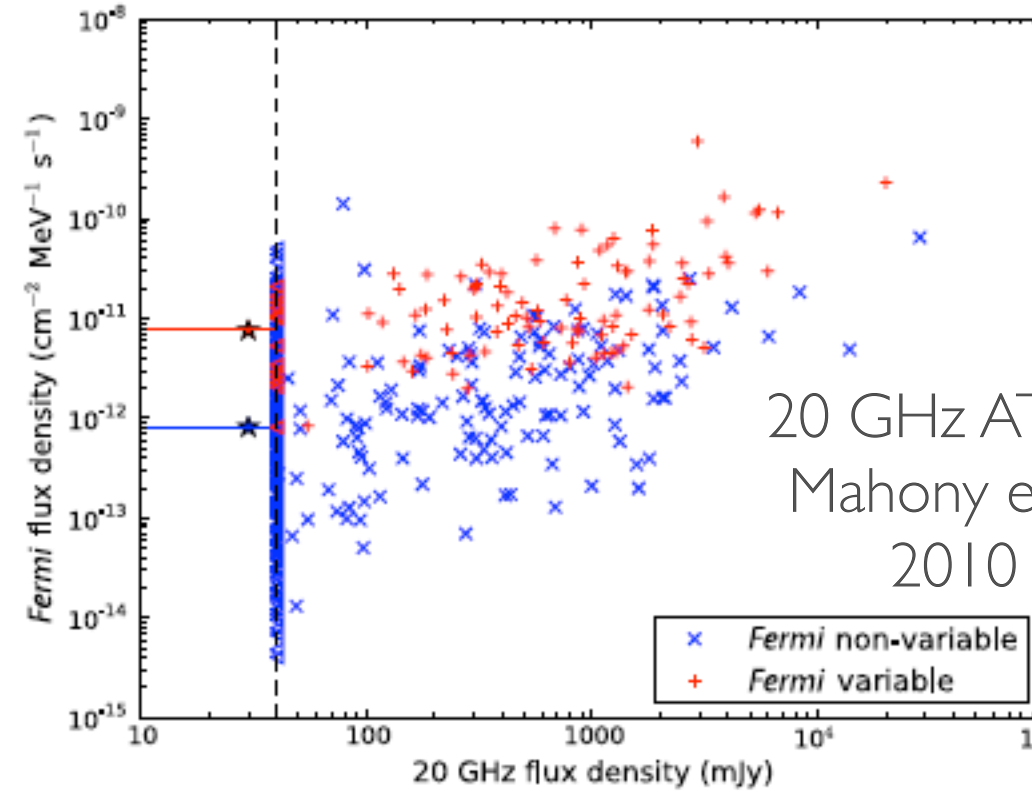
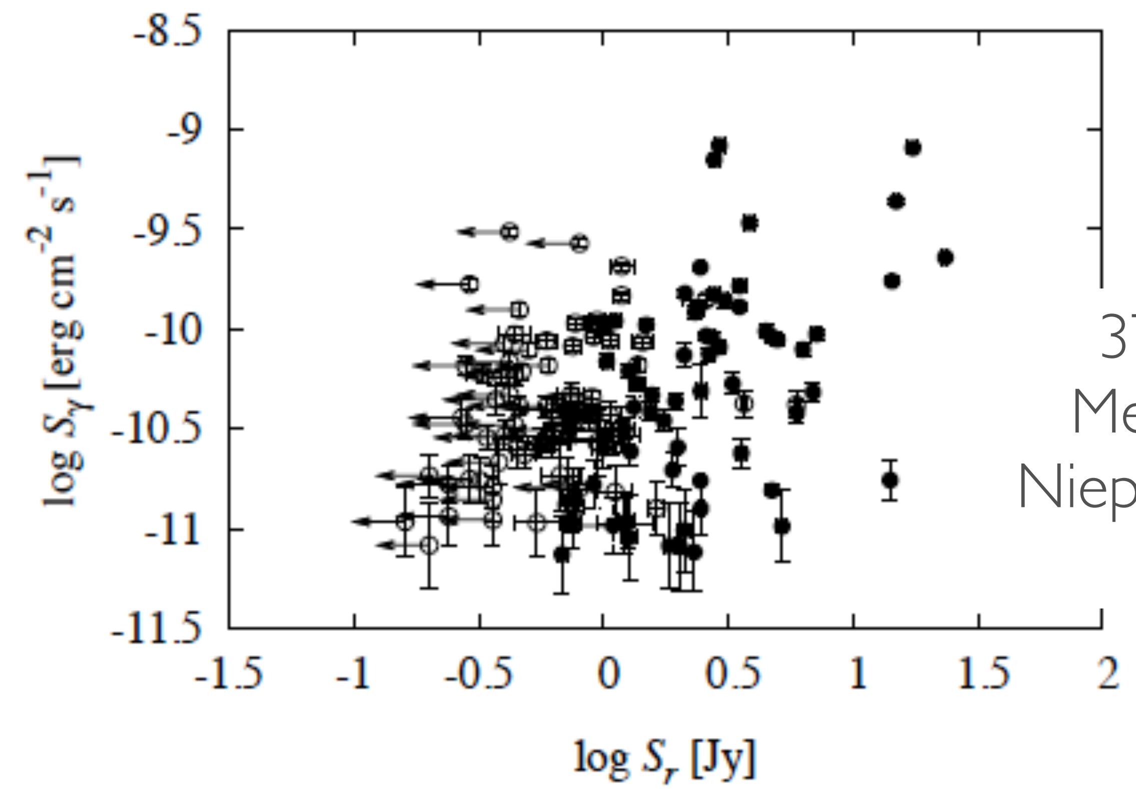


Figure 8. 20 GHz flux against *Fermi* flux density for sources classified as variable in 1FGL (red "+") and those not classified as variable (blue "×"). ...or the non-variable sources. The *Fermi* sources not ...hown as triangles at the 40 mJy flux limit of the survey ...ed line). The median gamma-ray fluxes for the upper ...e stars, but it should be noted that these upper limits ...ulations and are not limited to AGN.

20 GHz ATCA
Mahony et al.
2010

See also talks by Lister & Valtaoja



37 GHz
Metsähovi
Nieppola et al.
2011

POSSIBLE CAVEATS

1. Sample selection and redshift bias

    - Narrow luminosity range and a flux-limited sample with common redshift bias

    → can result in significant correlation with traditional correlation methods

2. Flux averaging time

    - Using peak fluxes only narrows the luminosity range

    - Too long averaging period including many flares correlates general activity, not necessarily individual events

    - Too short averaging period might not take intrinsic time delays between wavelength bands into account

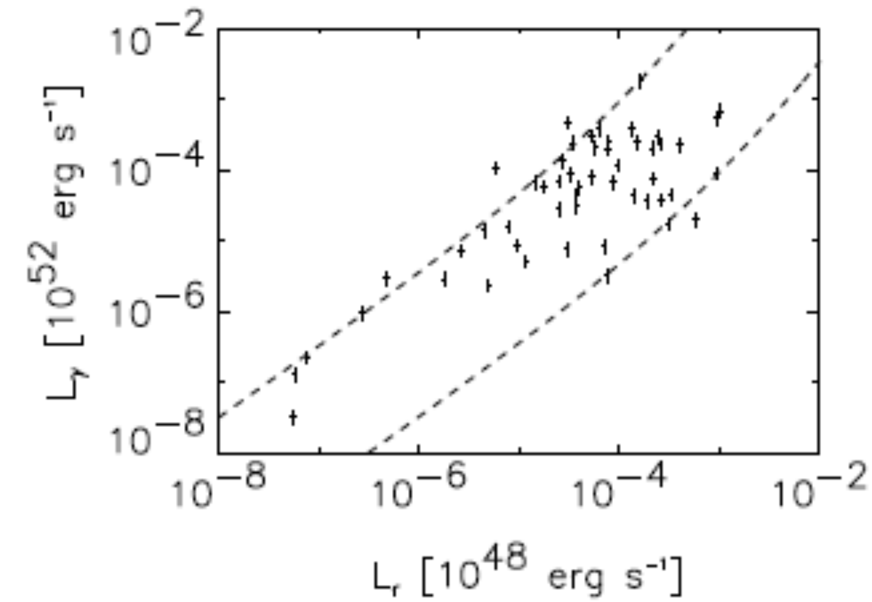


Fig. 1. Typical distribution of a **flux-limited** sample of objects which possesses **no correlation** between the radio and γ-ray luminosity. The dashed lines follow the sensitivity limits of the sample.

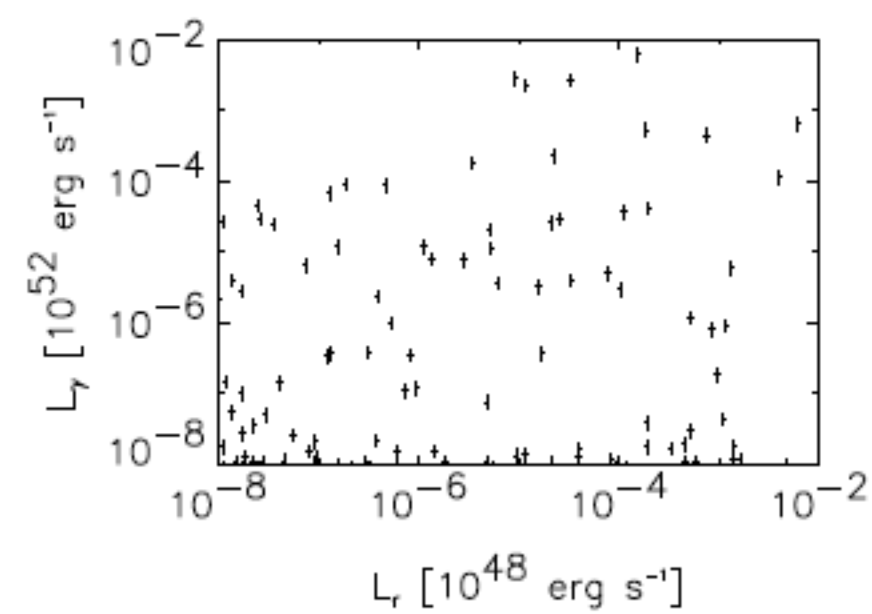


Fig. 2. Typical distribution of a **complete** sample of objects which possesses **no correlation** between the radio and γ-ray luminosity.

Mucke et al. 1997

SIGNIFICANCE OF FLUX-FLUX CORRELATION

- Monte Carlo Simulations using data scrambling
- Scrambling in luminosity space to account for redshift bias
- Accept same redshift / flux range as in the original data
- Repeat N=many times to obtain a distribution of correlation values for the scrambled data
- Valid for small subjective samples and best with larger samples that can be divided into redshift bins

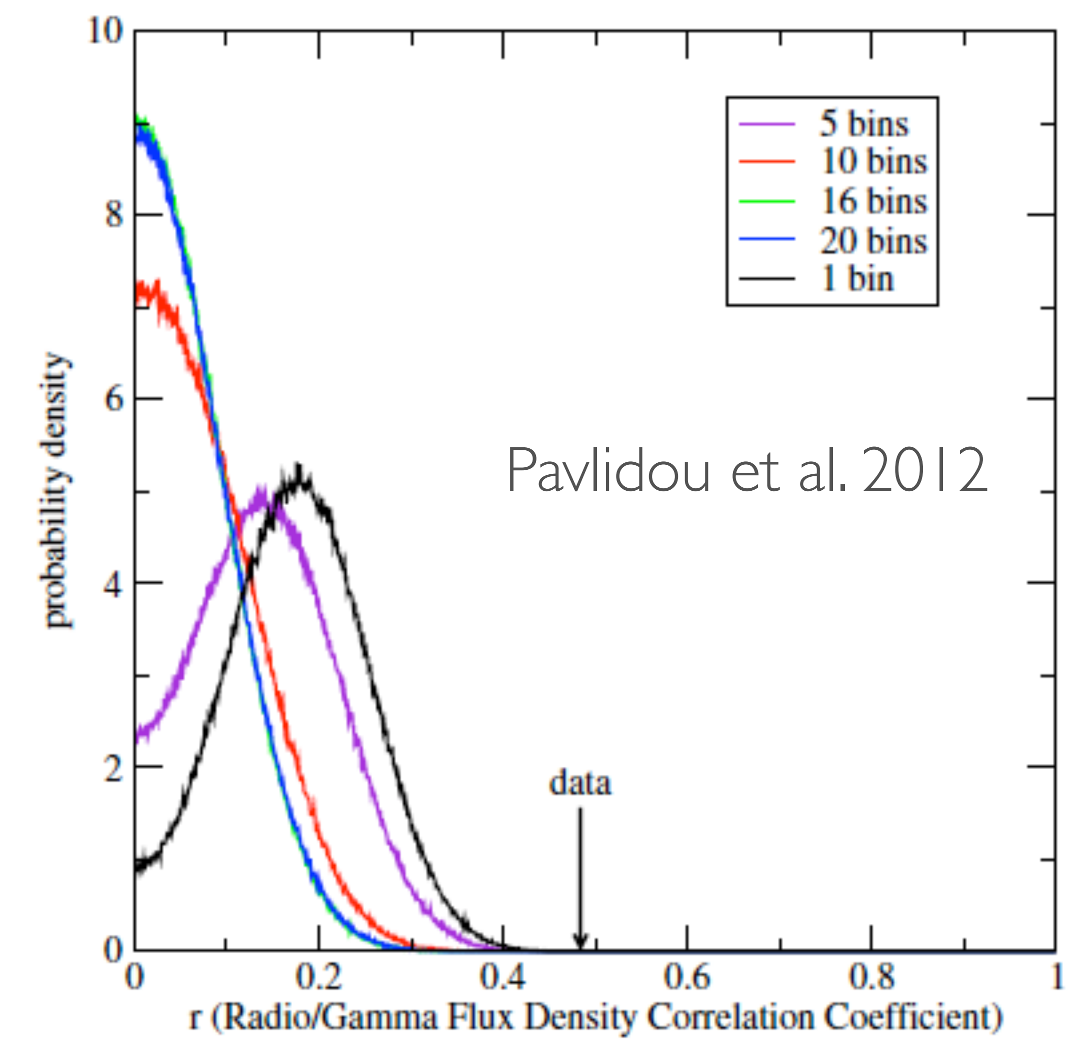


Figure 7. Distribution of $|r|$-values for randomly selected 160 blazar sets picked from the ensemble of accepted pairs generated through data scrambling. The vertical arrow indicates the r-value ($r = 0.48$) for the actual observations. Different colors correspond to different numbers of redshift bins, as in the legend.

EXAMPLE WITH SIMULTANEOUS DATA

Simultaneous OVRO 15 GHz and LAT data integrated over 11 month period. Ackermann et al. 2011

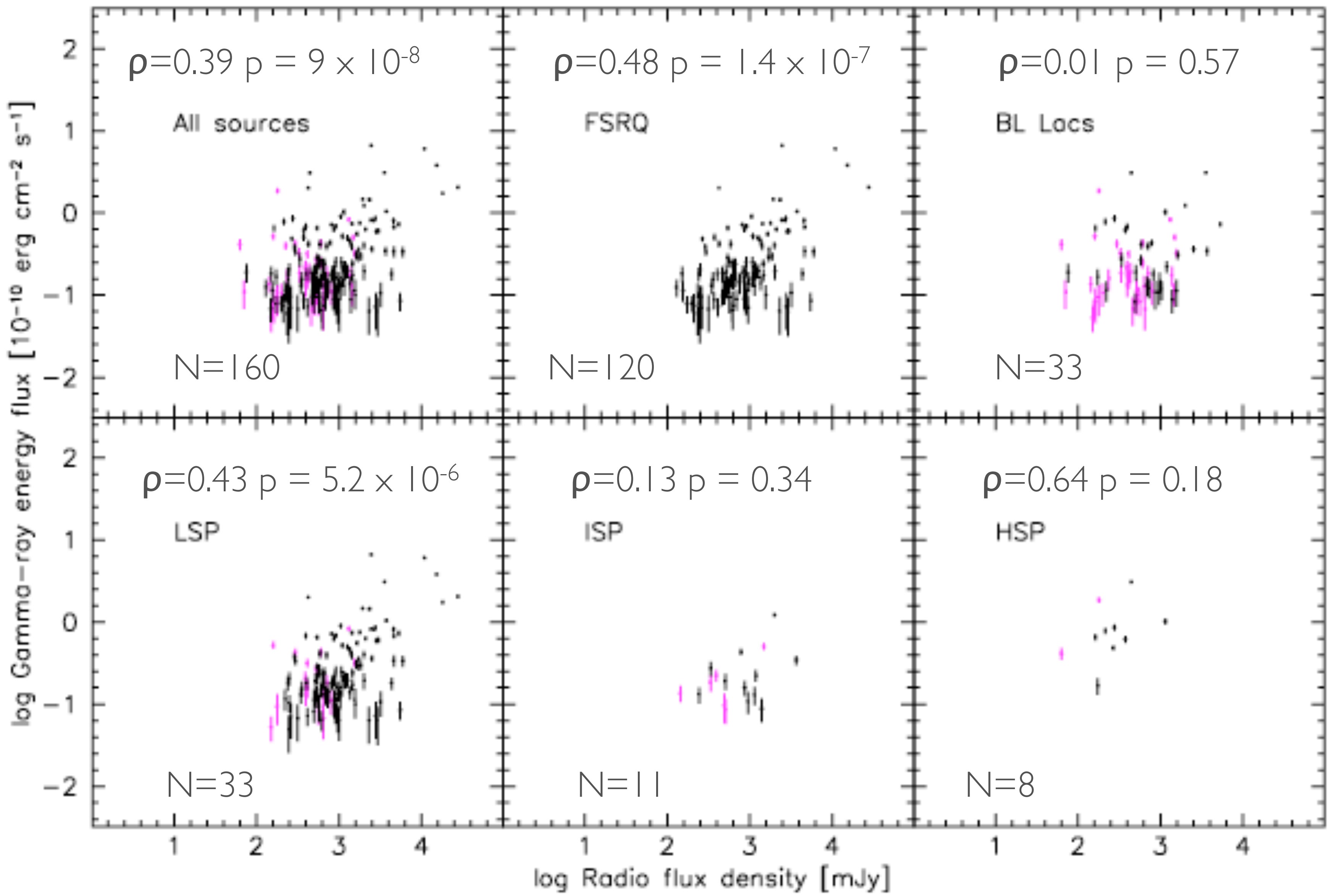


Figure 7. Broadband gamma-ray energy flux vs. concurrent 15 GHz mean radio flux density for OVRO sources, divided by the source type. Top, from right to left: all AGNs, FSRQ, BL Lacs; bottom, from right to left: LSP, ISP, and HSP blazars. Sources with unknown redshift are shown in gray.

- Intrinsic radio / gamma-ray correlation confirmed
- FSRQs and BL Lac show different behavior (selection effect?)

EXAMPLE WITH ARCHIVAL DATA

Archival 8 GHz data and LAT data integrated over 11 month period. Ackermann et al. 2011

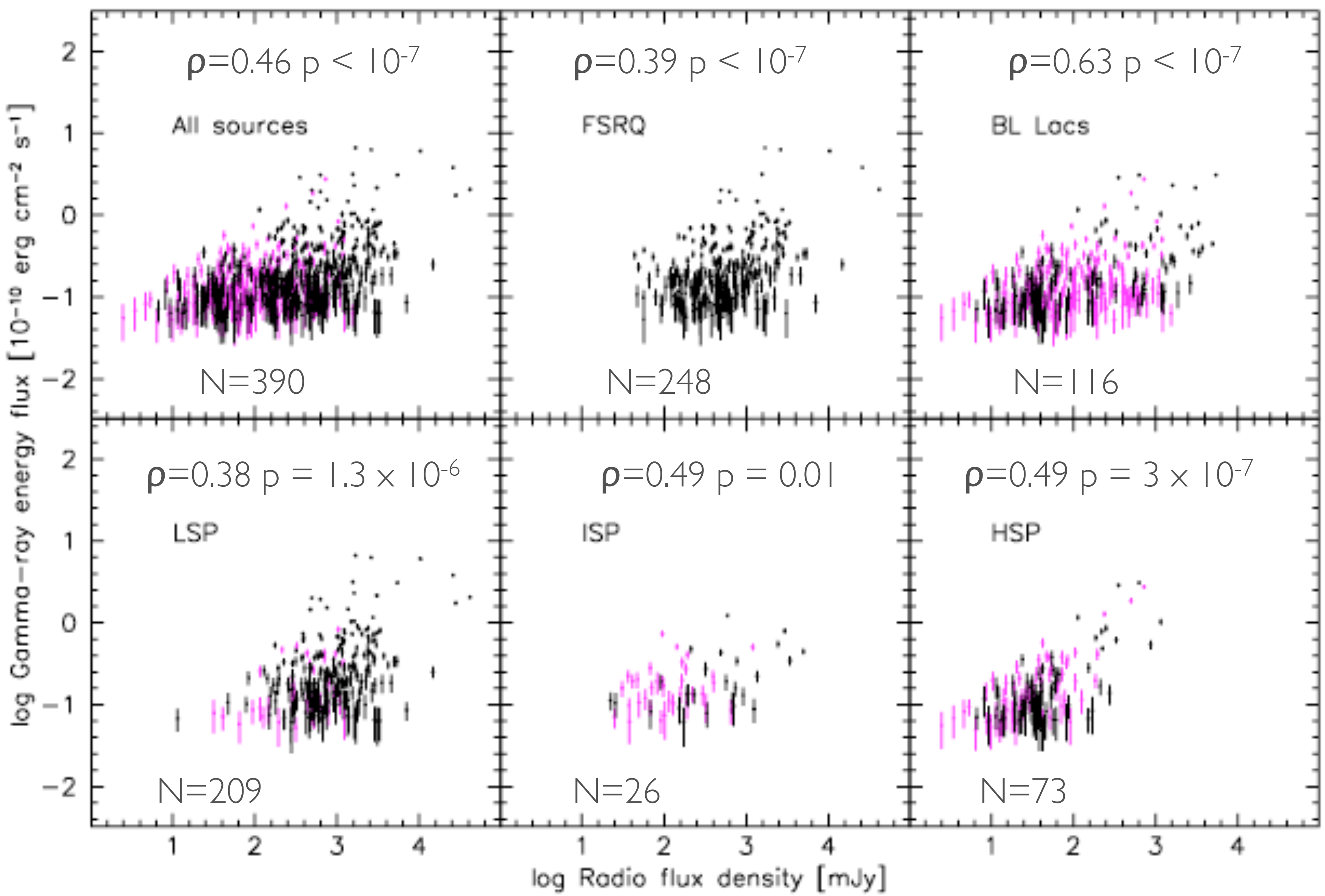


Figure 3. Broadband gamma-ray energy flux vs. 8 GHz archival radio flux density for the 1LAC sample, divided by the source type. Top, from right to left: all AGNs, FSRQ, BL Lacs; bottom, from right to left: LSP, ISP, and HSP blazars. Sources with unknown redshift are shown in gray.

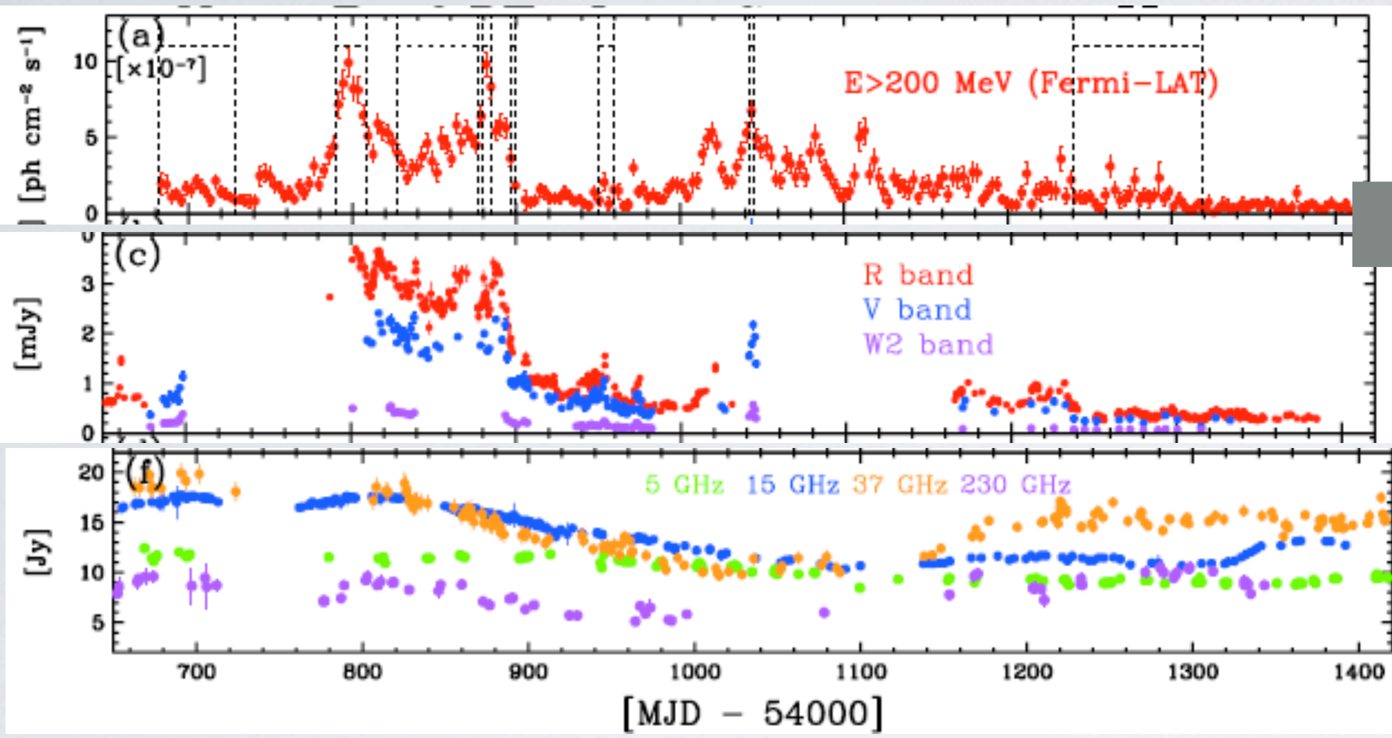
- Correlation persists with archival data
- Stronger than in simultaneous case for BL Lacs because more sources

IMPLICATIONS

- Sample selection is important!
  - flux-limited radio samples bias against HSP sources
- Simultaneous data
  - methods cannot account for non-simultaneous data
- Averaging period
  - introduce adaptive binning (Lott et al. 2012) / Bayesian blocks (Scargle et al. 2012)
  - possible time lags -> see next slides

LIGHT CURVE CROSS CORRELATION EXAMPLES

3C 279 Hayashida et al. 2012



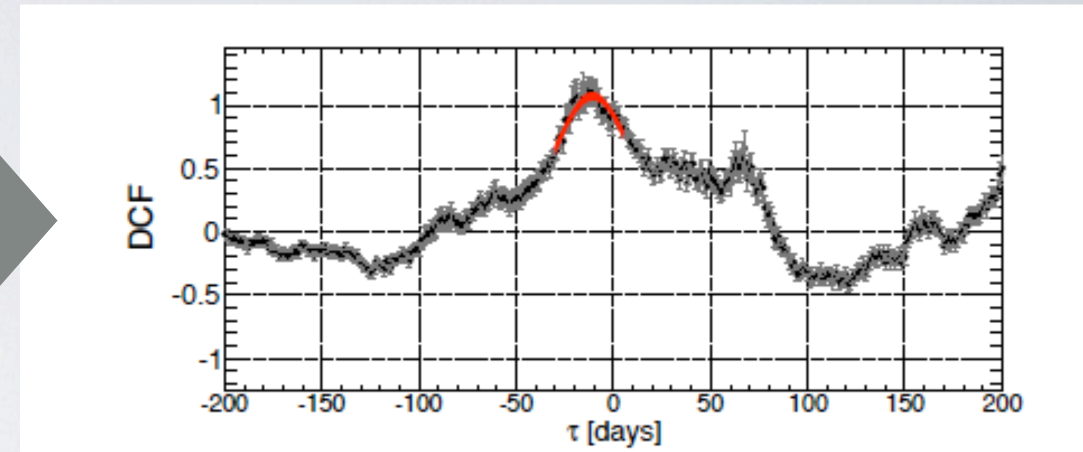
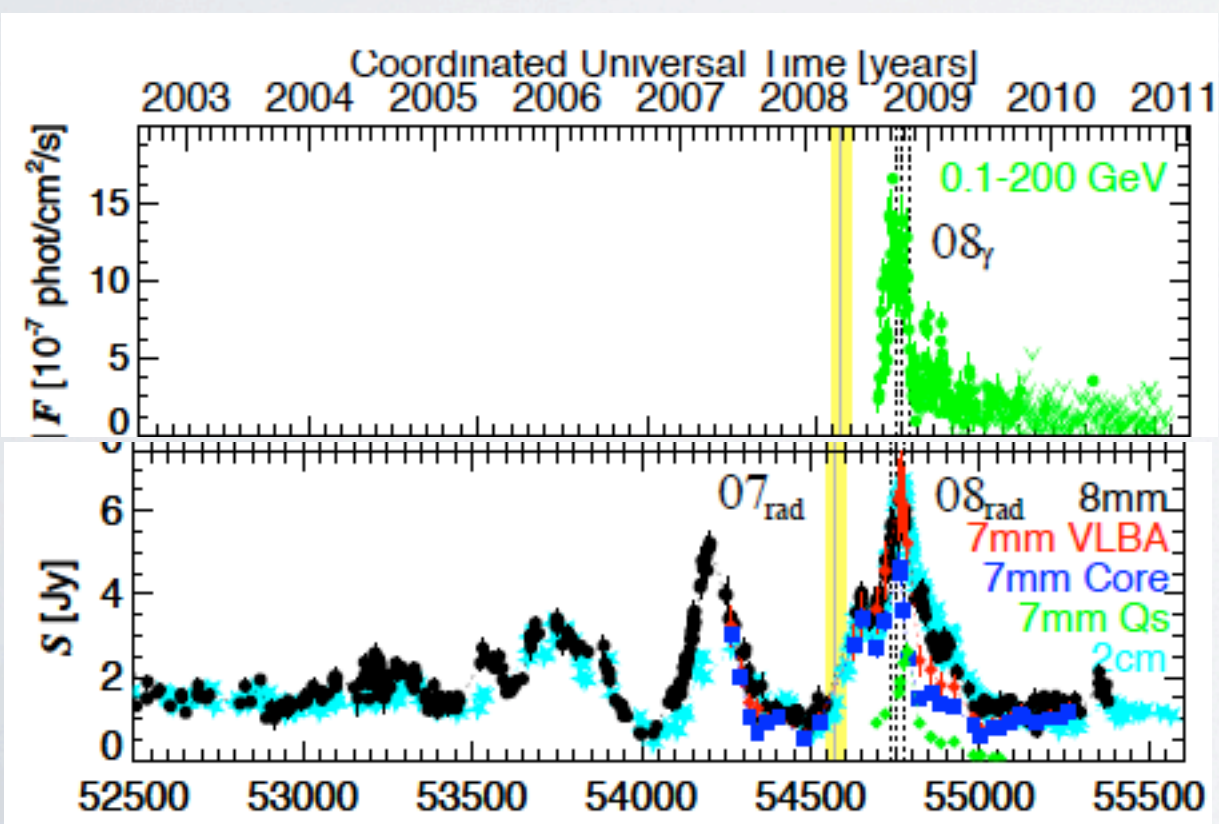
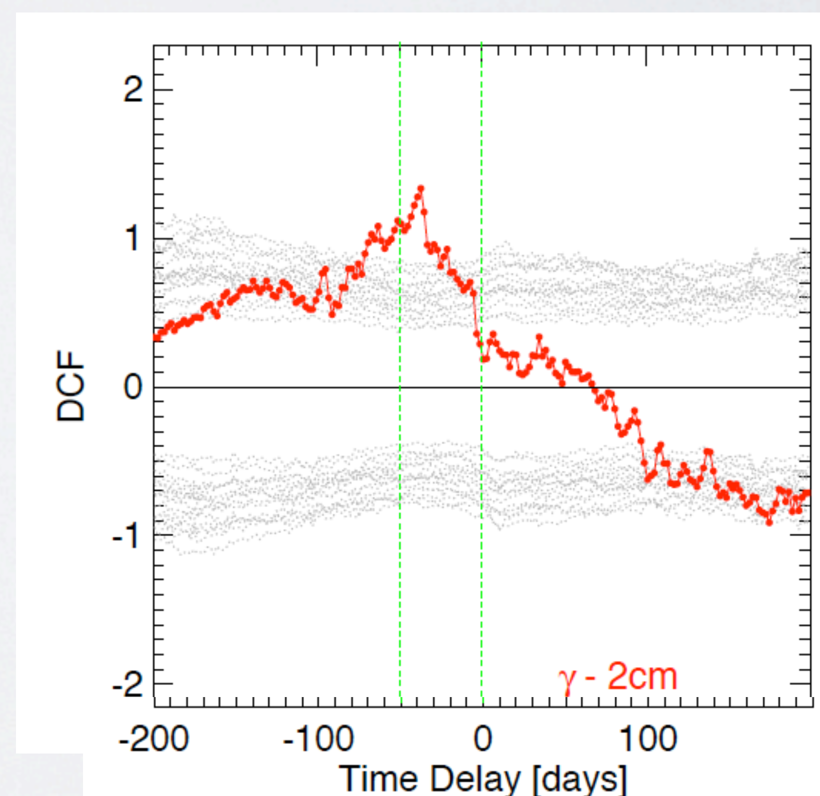


Figure 13. Discrete Correlation Function (DCF) derived for the γ-ray and optical R bands. Positive values of 'τ' correspond to flux variations in the γ-ray band lagging flux variation in the optical band. The red curve represents a Gaussian fit to the data between -30 and 5 days. See the text for the fitting results.

0235+164 Agudo et al. 2011





SIGNIFICANCE OF CROSS CORRELATIONS

Mixed source method:

- Take the radio light curve of one source and correlate it with the gamma-ray light curve of another source

+ No need to know the underlying power spectral density

- Limited by the number of available sources

Simulated light curve method:

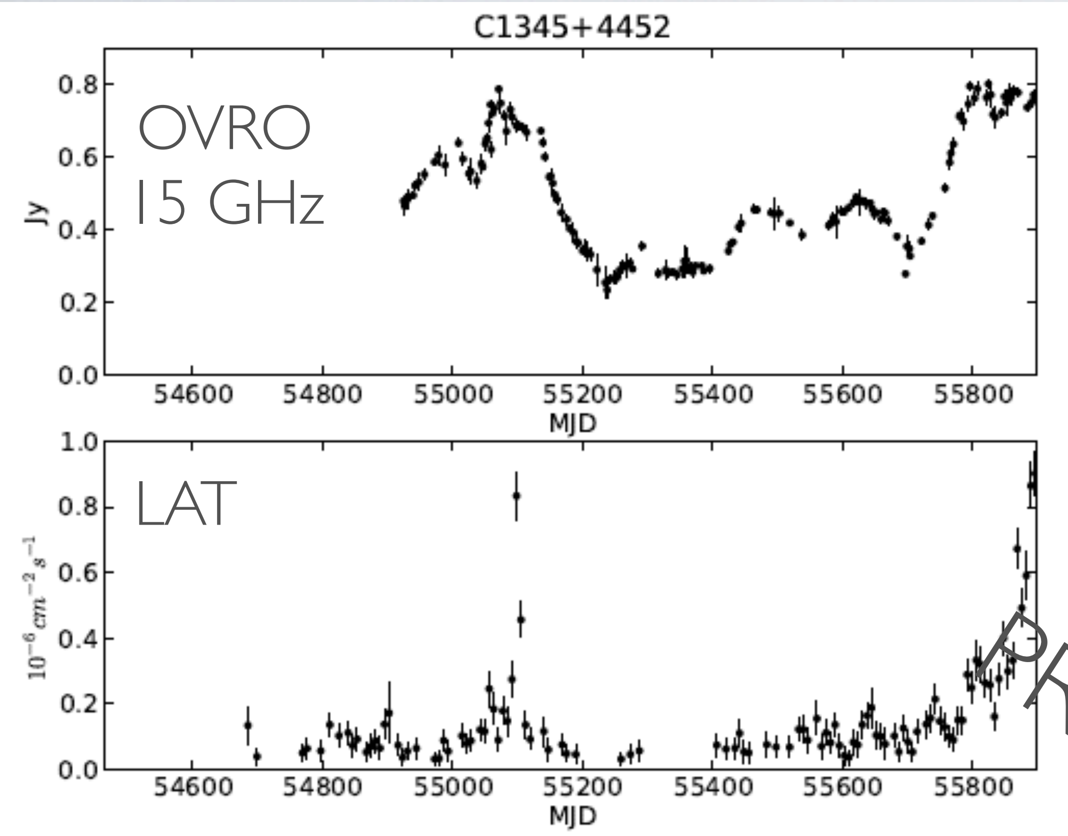
- Simulate light curves of known power spectral density shape similar to the light curves to be correlated

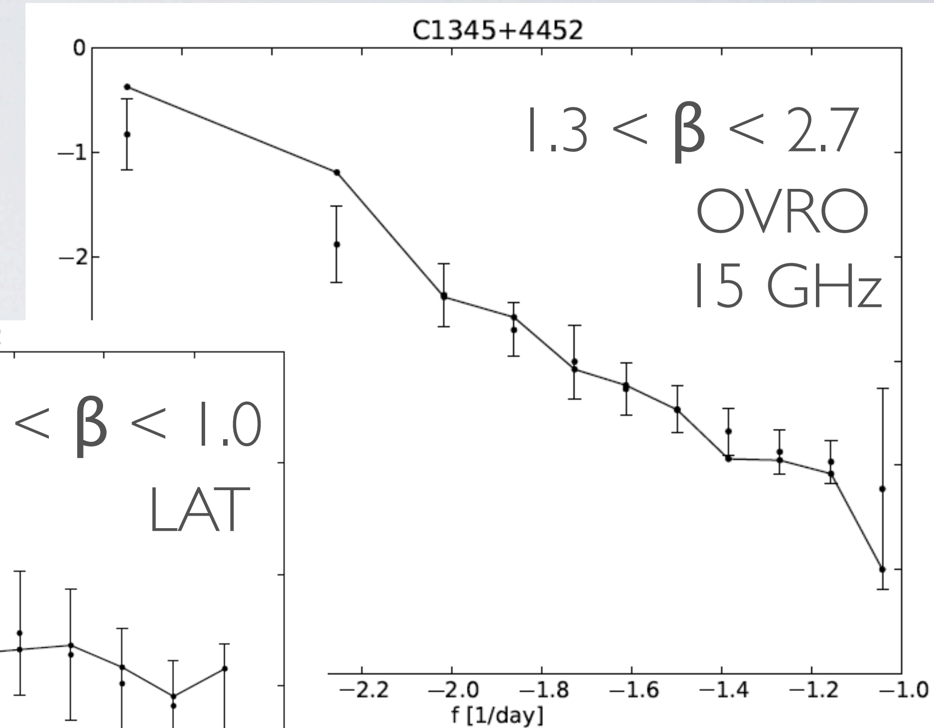
+ Valid for individual sources or small samples

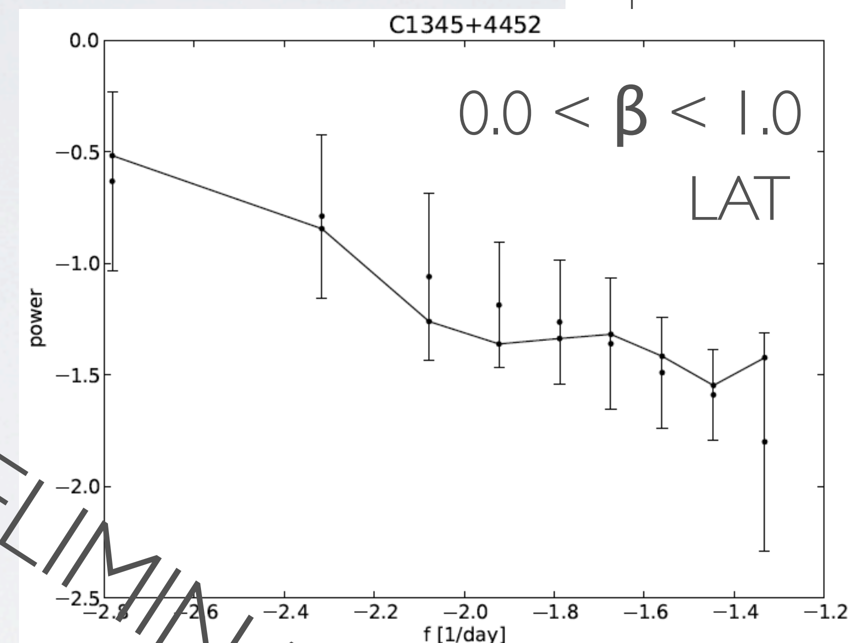
- Need to know the PSD shape

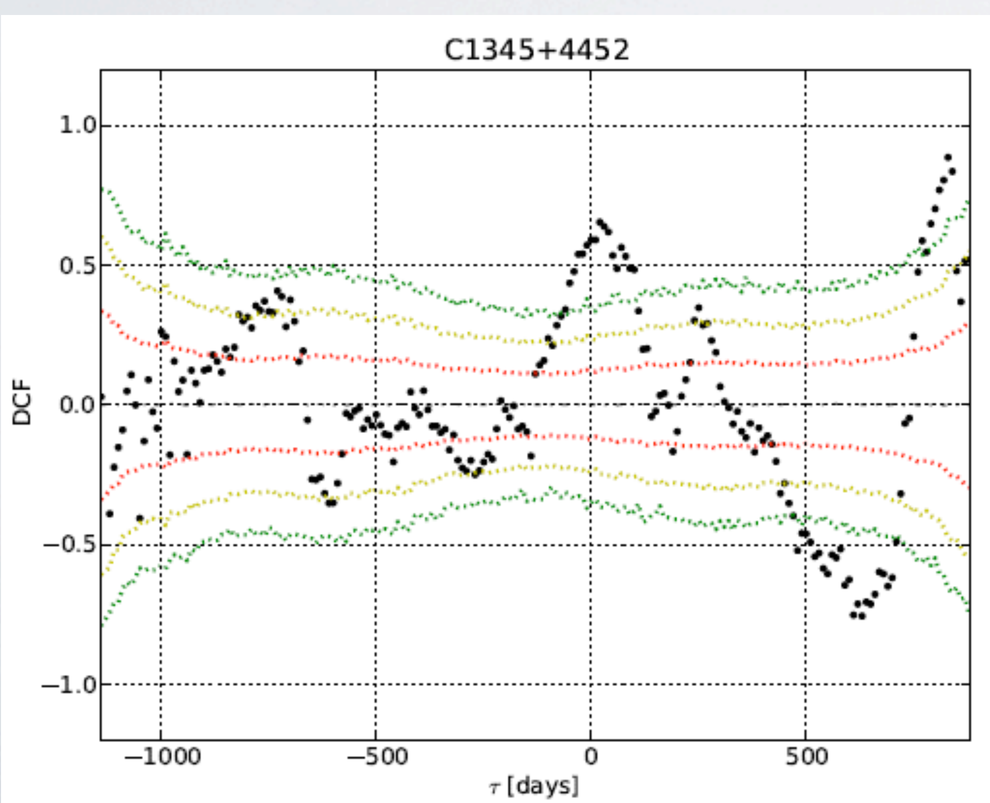
MC SIMULATIONS USING PSD OF THE SOURCE

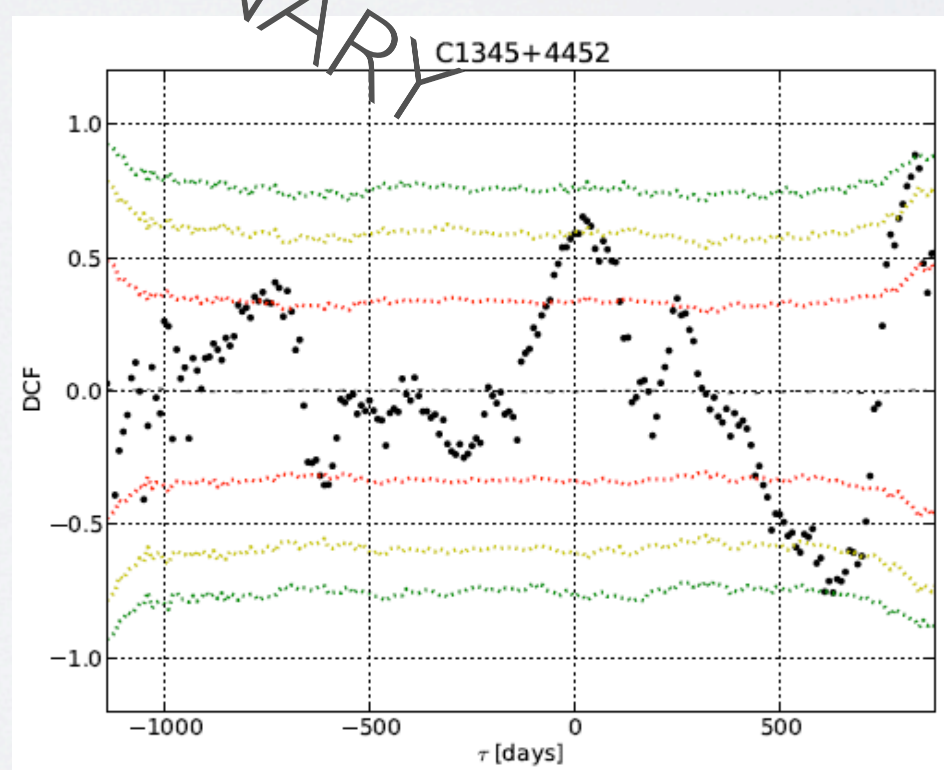
CRATES J1345+4452







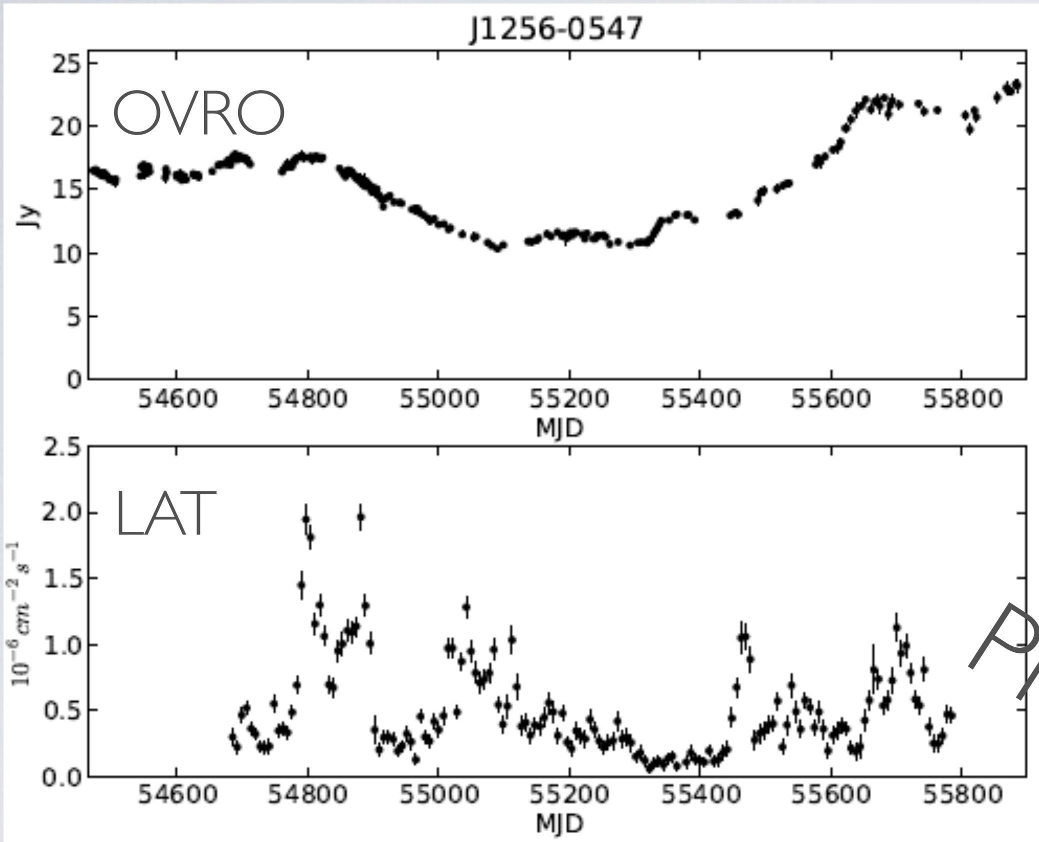


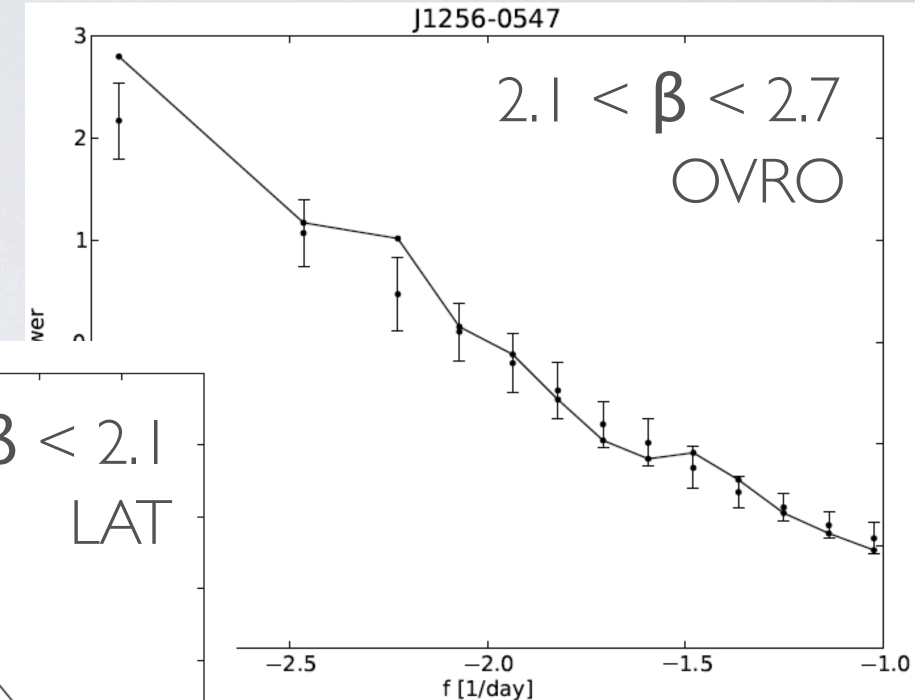


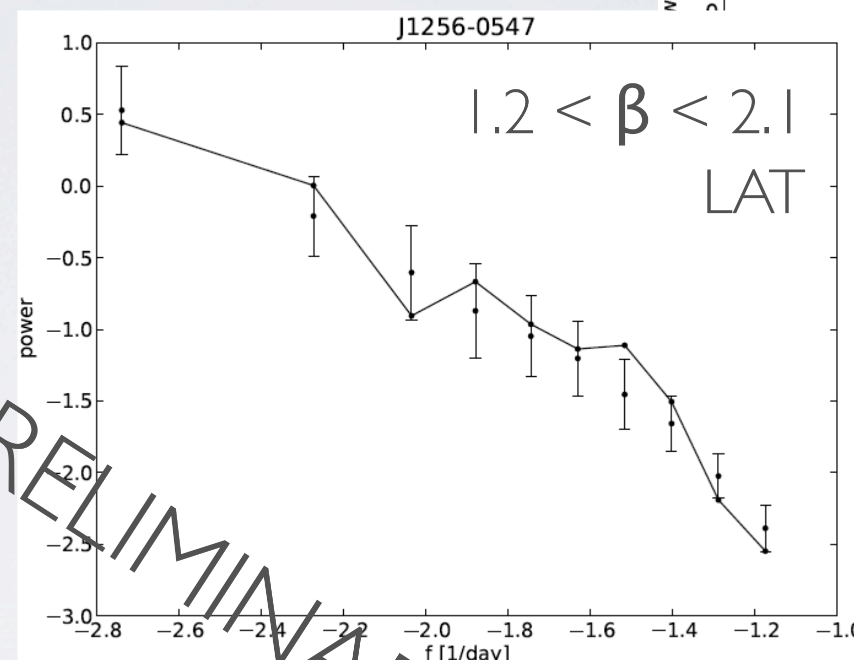
W. Max-Moerbeck et al. 2012 in preparation

MC SIMULATIONS USING PSD OF THE SOURCE

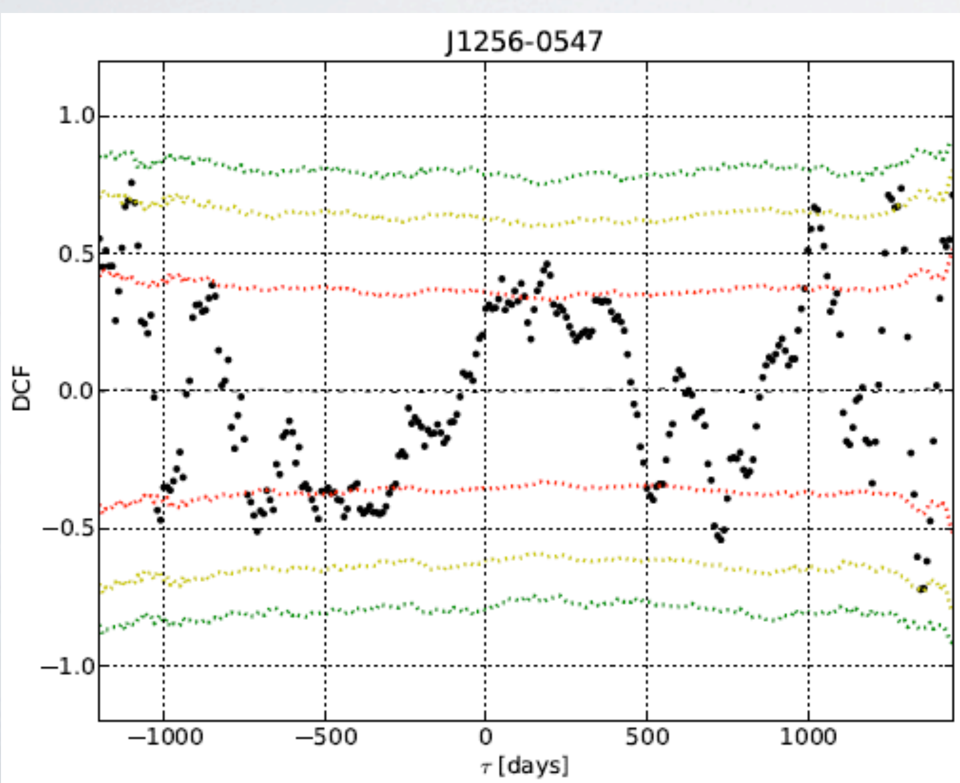
3C 279

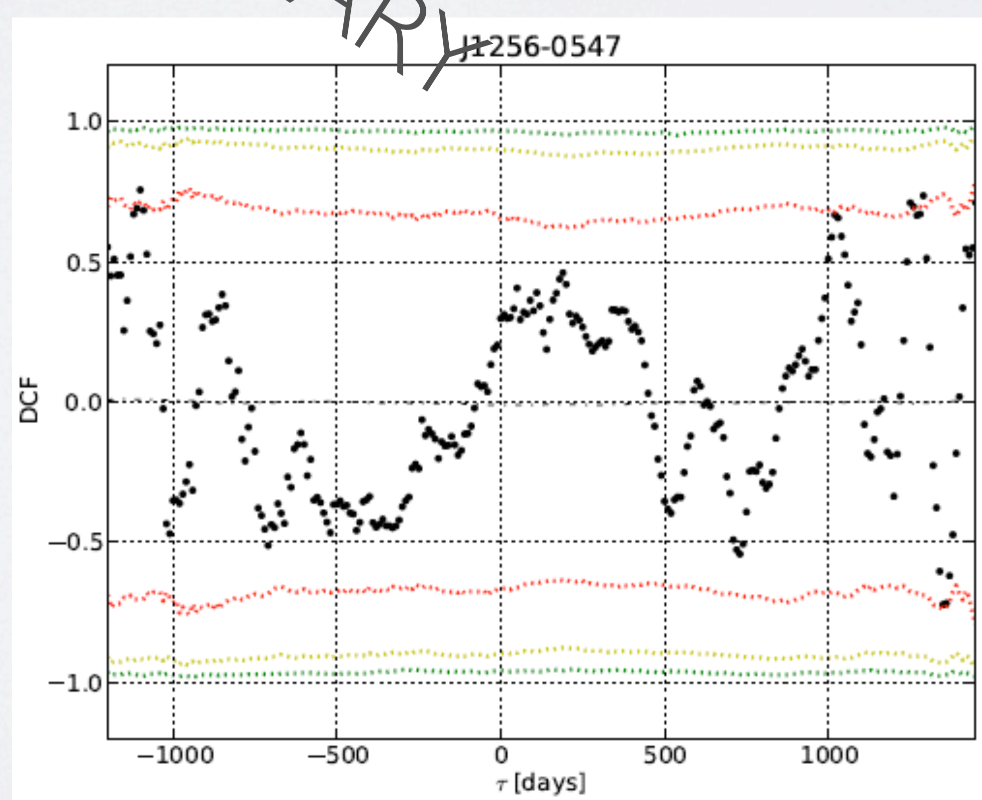






PRELIMINARY

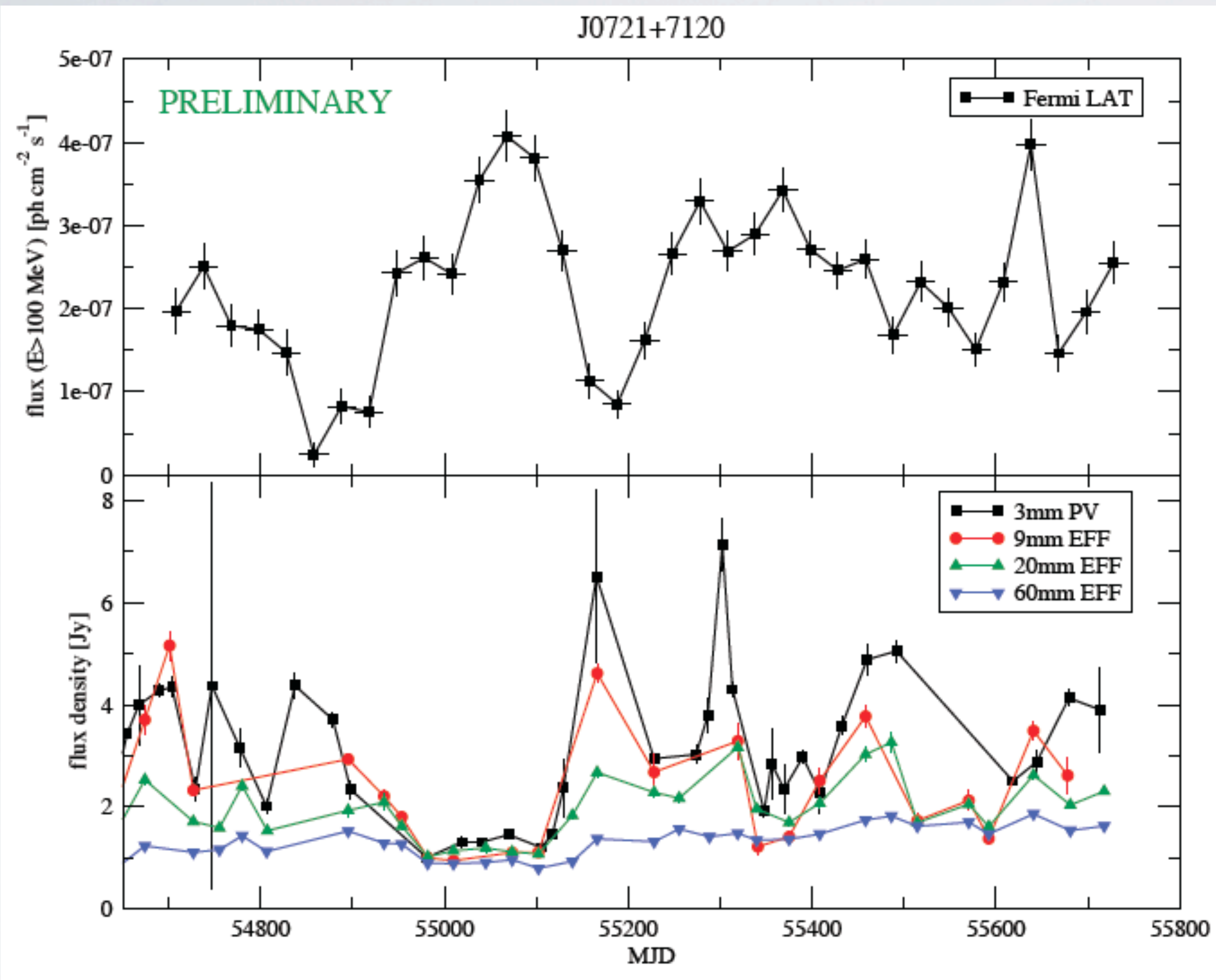




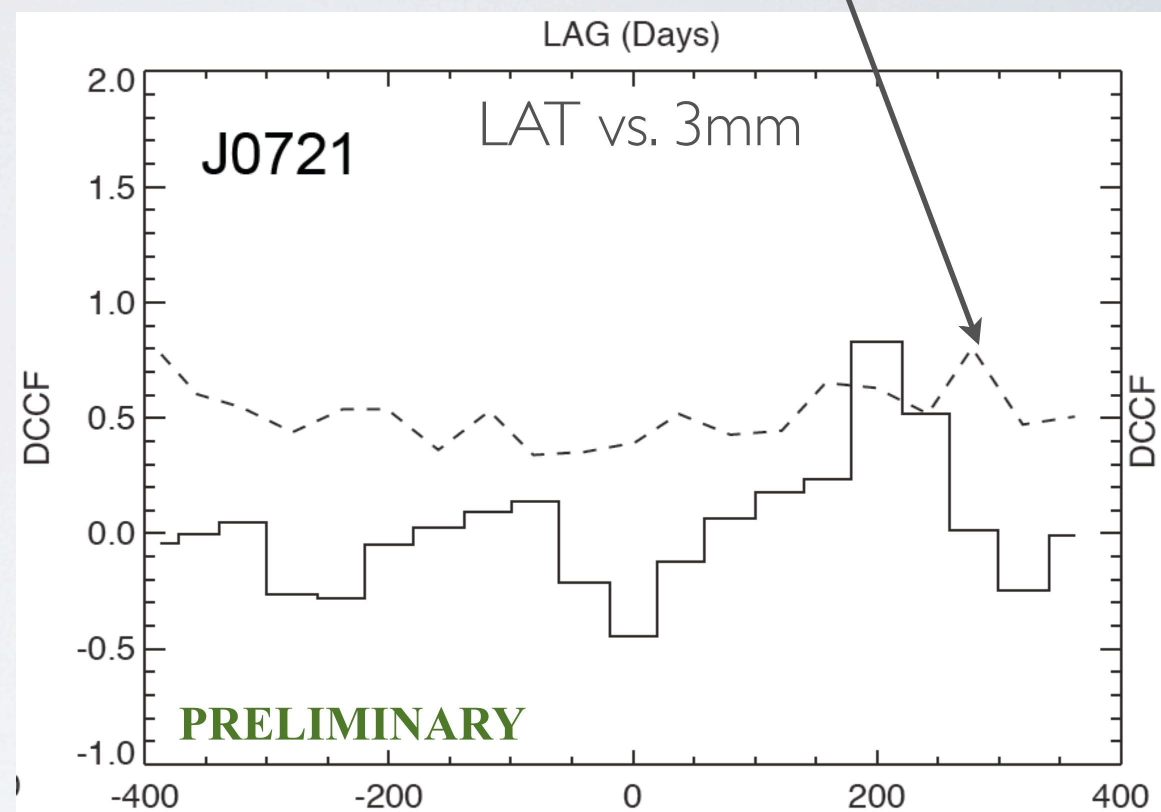
W. Max-Moerbeck et al. 2012 in preparation

MIXED SOURCE METHOD

F-GAMMA data between 60 and 3 mm
58 sources in total



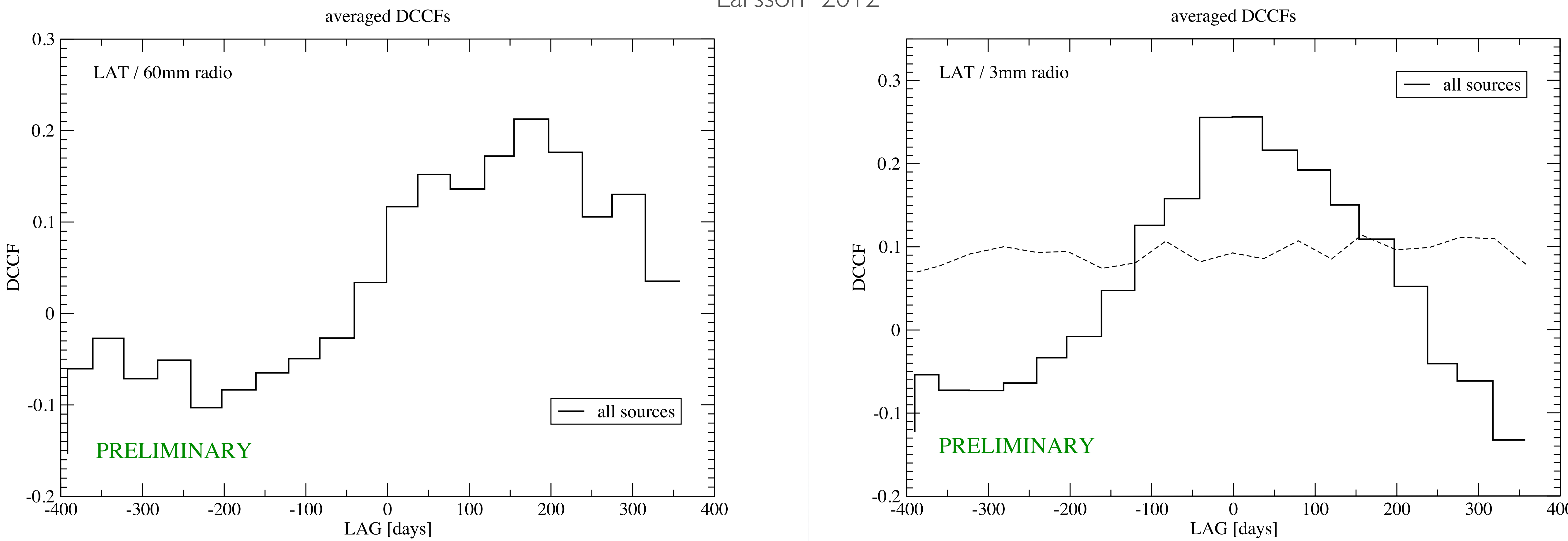
Significance envelope from
mixed source analysis



L. Fuhrmann et al. 2012, in preparation
Larsson 2012

STACKED CORRELATIONS

L. Fuhrmann et al. 2012, in preparation
Larsson 2012



- Stacked correlation of all 58 sources to improve the statistics
- Time lags are shorter at higher frequencies
  - expected for opacity effects (e.g. Pushkarev et al. 2010)

IMPLICATIONS

- Simple 1:1 correlation difficult to establish in individual sources
  - ~5/80 significant correlations at 2cm vs. 18/58 at 3mm
  - opacity effect play a role in the radio bands
  - still "too short" time series?
- Stacked correlations show statistically significant time delays with increasing delays for longer wavelengths
  - need multiwavelength coverage

CONCLUSIONS

- General flux-flux radio / gamma-ray correlation is evident
- More difficult to tell if individual events are correlated and what are the time delays
    - Opacity effects play a significant role in the radio bands
- Well-sampled long time series -> Any method will work
    - When this is not the case, care needs to be taken on selecting the method and assessing the significance