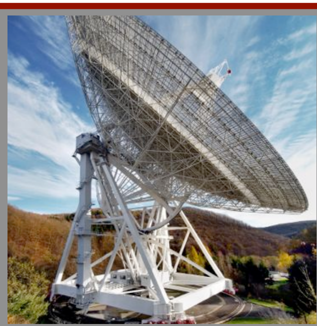
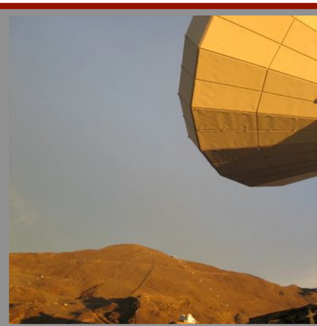
The radio/gamma connection:

cm to short-mm band radio and gamma-ray correlated variability in *Fermi* bright blazars



100-m Effelsberg covers the band 2.64 - 43 GHz with a precision of a few percent for monthly sampling of 60 sources



30-m IRAM covers the band 86 - 250 GHz monthly also for roughly 60 sources

12-m APEX 345 GHz, located in Atacama desert in Chile at an altitude of 5100 m

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on behalf of the

F-GAMMA and *Fermi*/LAT collaborations

Fuhrmann et al. 2007, Angelakis et al. 2008, Fuhrmann et al. in prep.

Fermi-GST γ-ray blazars:
broad band monitoring of
variability and spectral evolution
at cm/mm/sub-mm wavelengths

F-GAMMA program

The radio/gamma-ray connection

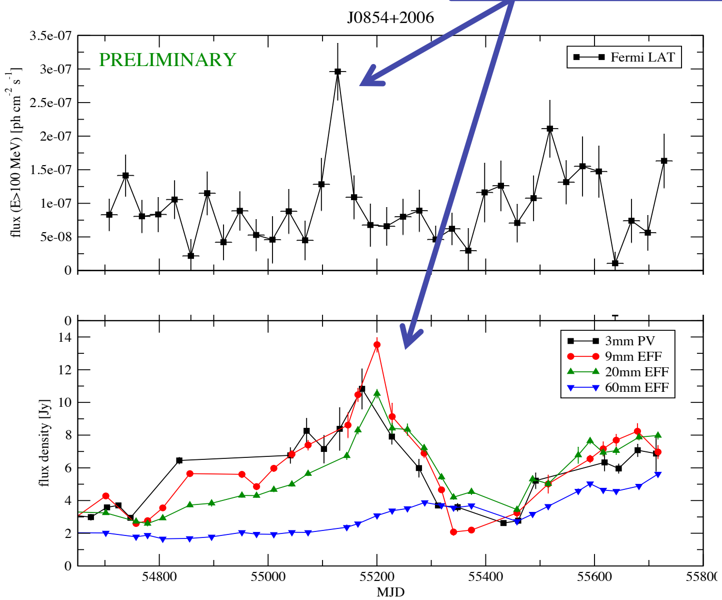
Where in the jets are the gamma-rays produced? Timing analysis

Aim: study focusing on the possible connection between radio and gamma-ray flares/activity periods in the ~ 3.5 yr long-term light curves of about 60 *Fermi*-GST detected blazars through a detailed cross-band analysis

Main question: where in the jets are the gamma-rays produced (very close to BH or on pc-scales) ? (e.g. Blandford & Levinson 1995, Valtaoja et al. 1992, Jorstad et al. 2001, Agudo et al. 2011, Leon-Tavares et al. 2011)

⇨ **radio cm/mm (F-GAMMA program) vs. *Fermi*-LAT 3.5 yr light curves:**

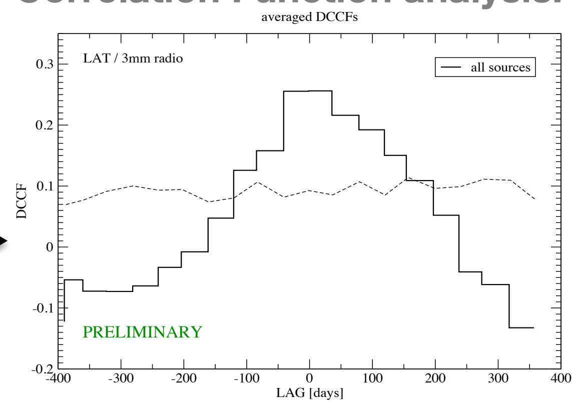
relative timing of flares



Fermi-GST

100-m Effelsberg & IRAM 30-m

statistical Discrete Cross-Correlation Function analysis:



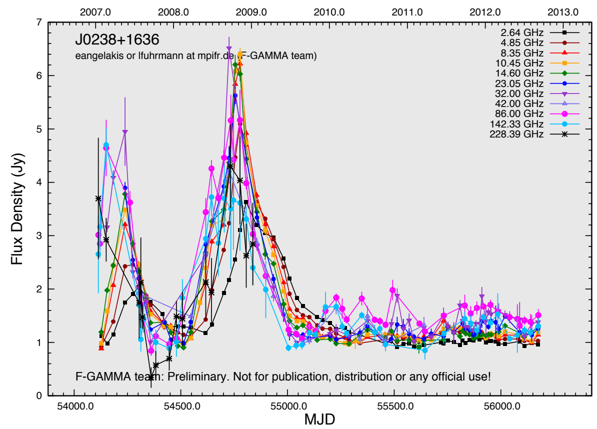
stacking analysis: averaging over whole sample (58 sources)

Project overview

The sample and data sets

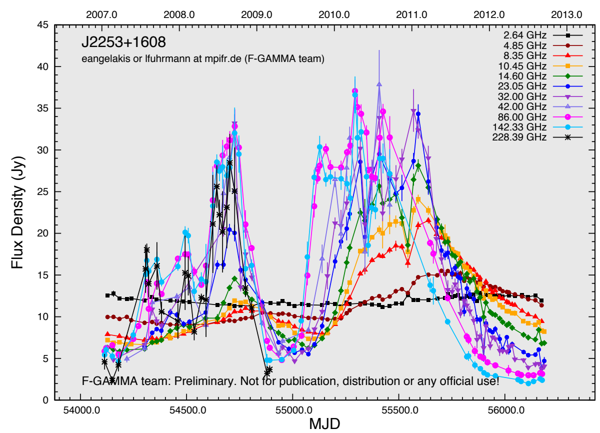
1) radio bands: F-GAMMA program since Jan. 2007:

3-4.5 yrs of Effelsberg 100-m/IRAM 30-m monthly monitoring data at 10 different frequencies (110, 60, 36, 28, 20, 13, 9, 7, 3, 2 mm) + APEX (0.8 mm)



⇨ “the best suitable” 58 1FGL sources (best sampl., frequency & time coverage)
sample statistics:

Type	#
FSRQ	33
BL Lac	17
RG	2
Blazar	5
NLSy1	1



2) Fermi/LAT 3.5 yr monthly light curves: Aug. 2008 – Dec. 2011

specific time boundaries to best match the radio light curves – start Aug. 15, 2008

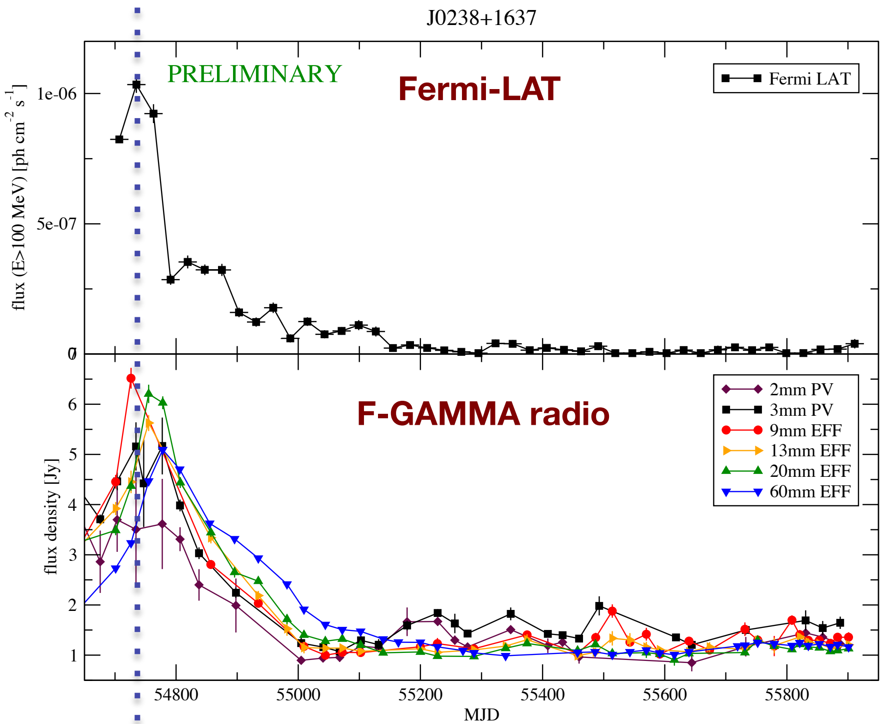
RSP pipeline, energy range 0.1 – 300 GeV using power law over that energy range

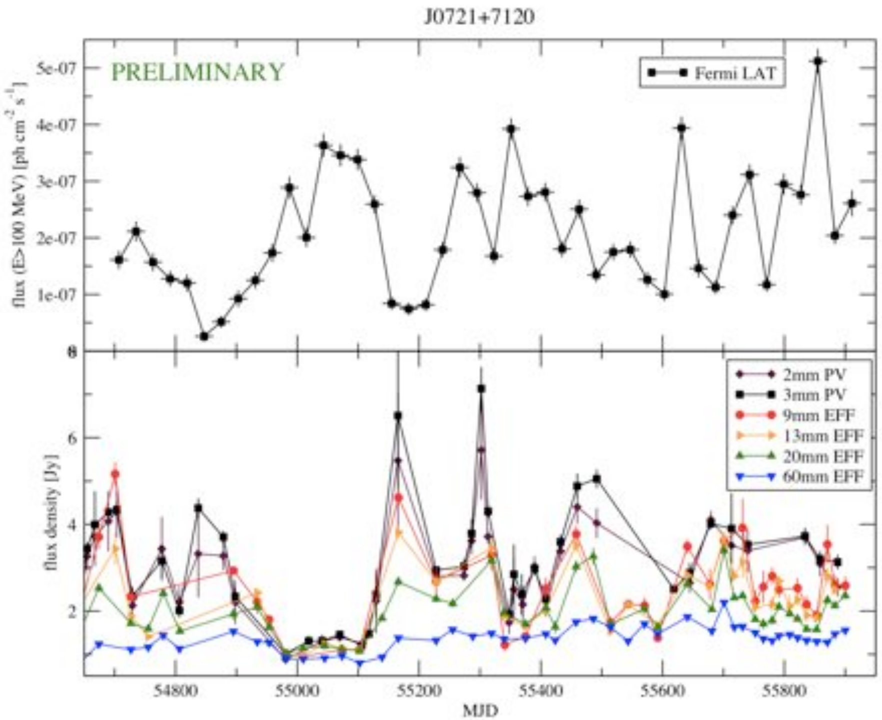
2FGL sources for ROI, ROI size etc.

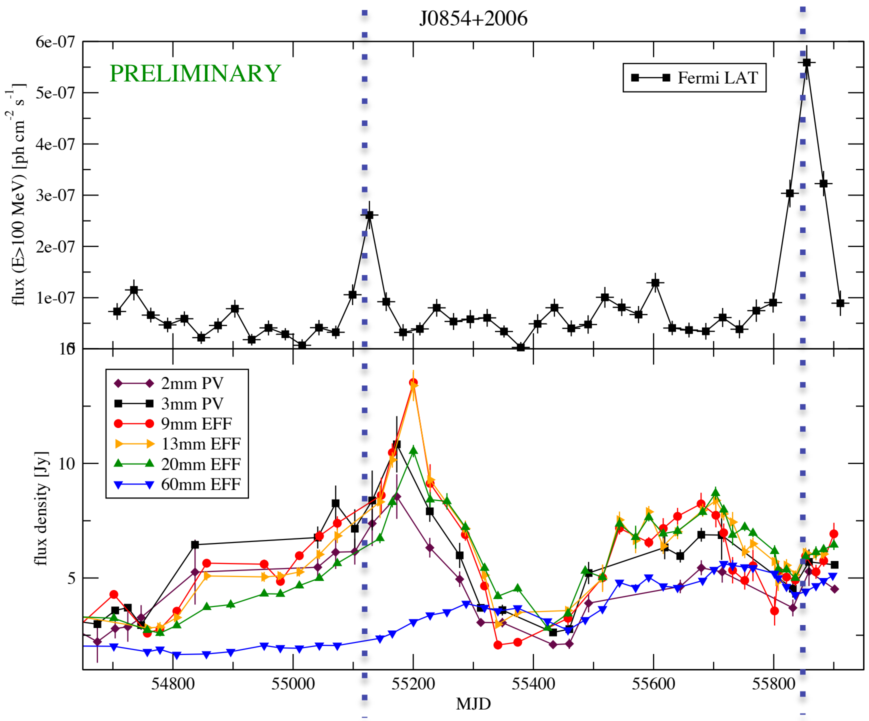
Cross-band analysis

The light curves

Examples:

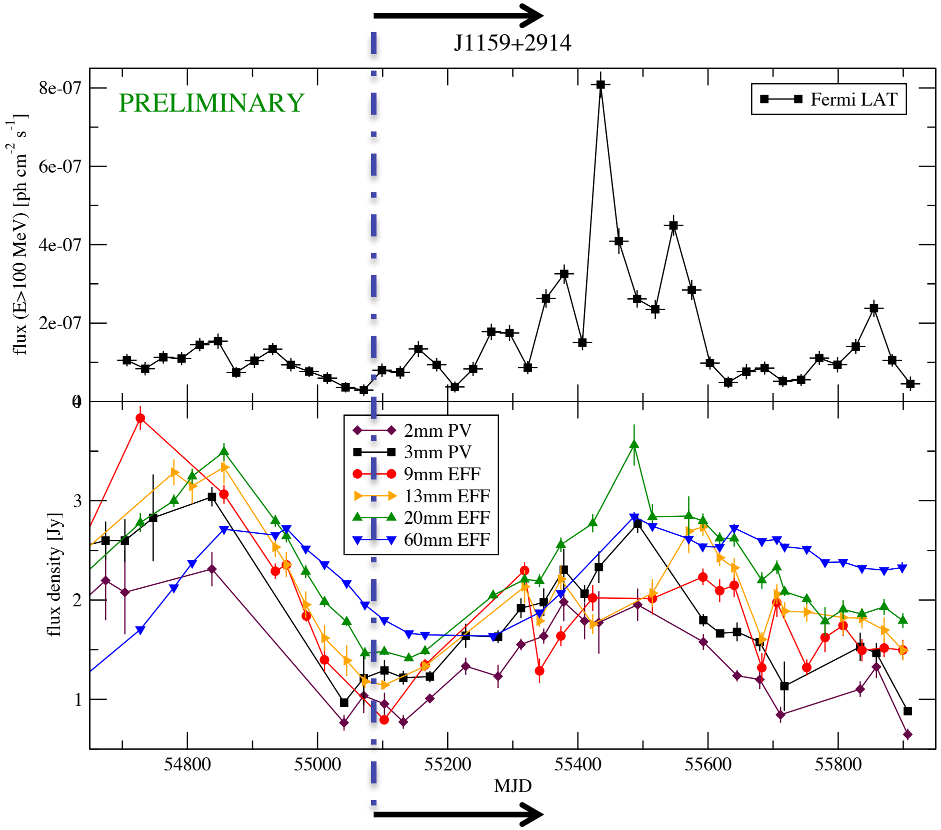


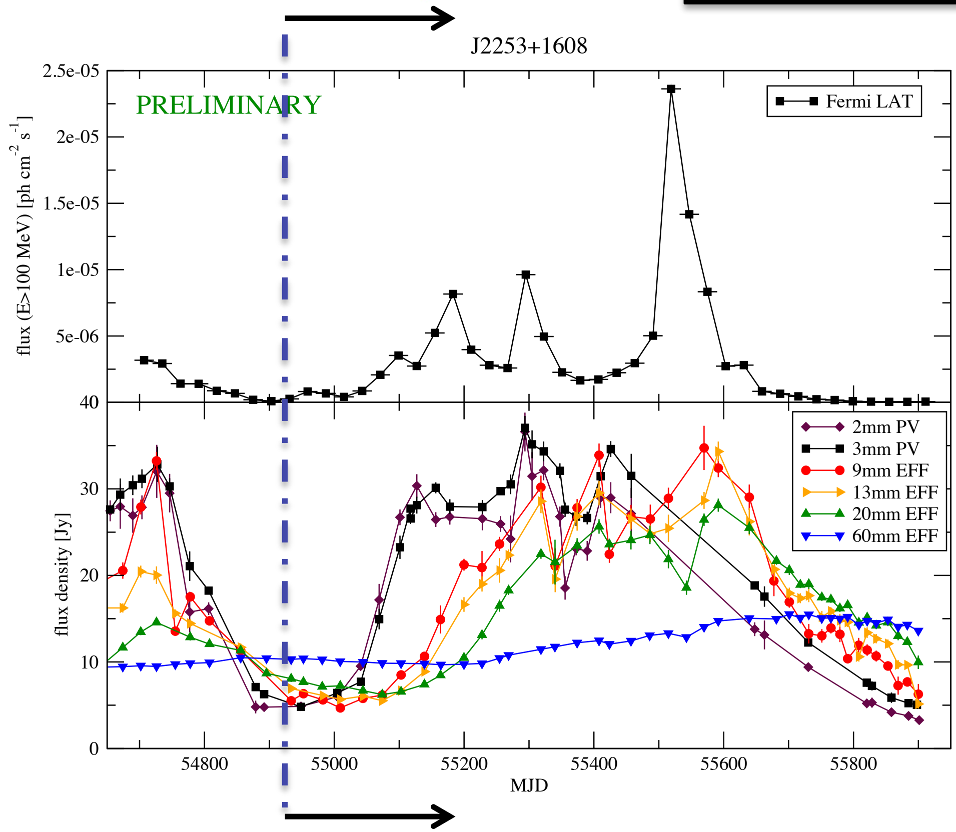




Project overview

Three different approaches





1) statistical Discrete Cross-Correlation Function (DCCF analysis)

[2) direct LC analysis: relative timing of flare onsets]

[3) $flux_r$ – $flux_\gamma$ analysis using simultaneous, monthly fluxes]

DCCF analysis

The setup

compute DCCFs for each source: for all gamma-ray – radio (ν, ν = 142, 86….2.6 GHz) combinations following Edelson & Krolik (1988)

caveats: 3.5 yrs – still limited number of events, complicated flare structures (multiple sub-flares), “broad DCCFs”, what correlates?, “monthly smoothing” etc.

determine significances of correlations: test of chance correlations by mixing source’ gamma-ray LCs: e.g. source 1 (radio) with source 2 to N (gamma-ray), find “upper envelop” confidence levels

time lags with uncertainties are estimated by Monte Carlo simulations (Peterson et al. 1998)

apply method to the whole sample plus sub-dividing according to FSRQs, BL Lacs, spectral type, physical parameters etc.

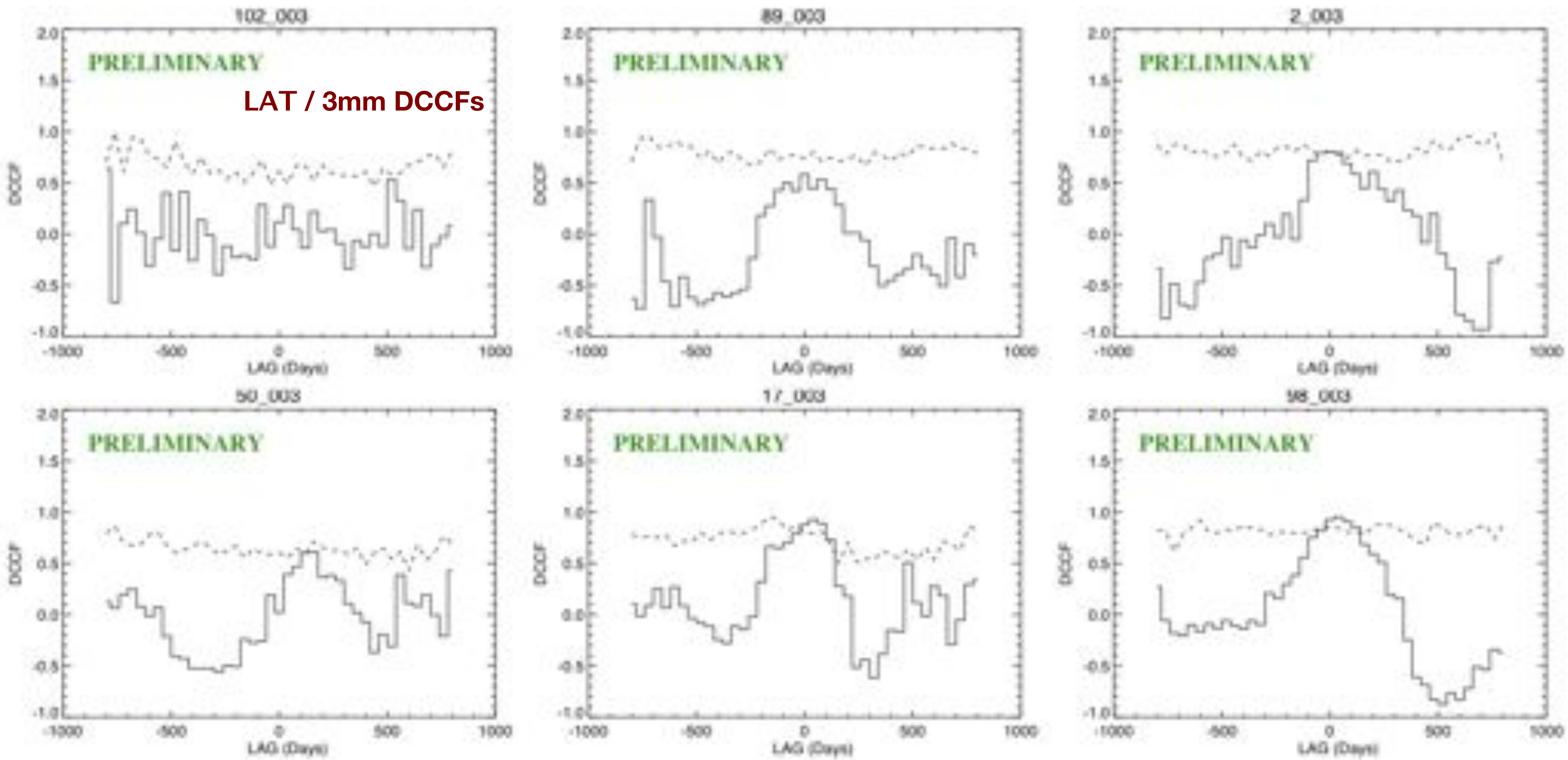
stacking of DCCFs: increasing the significance, study of averaged behavior of the sample

DCCF analysis

First results

3 mm vs Fermi/LAT: examples of single source' DCCFs

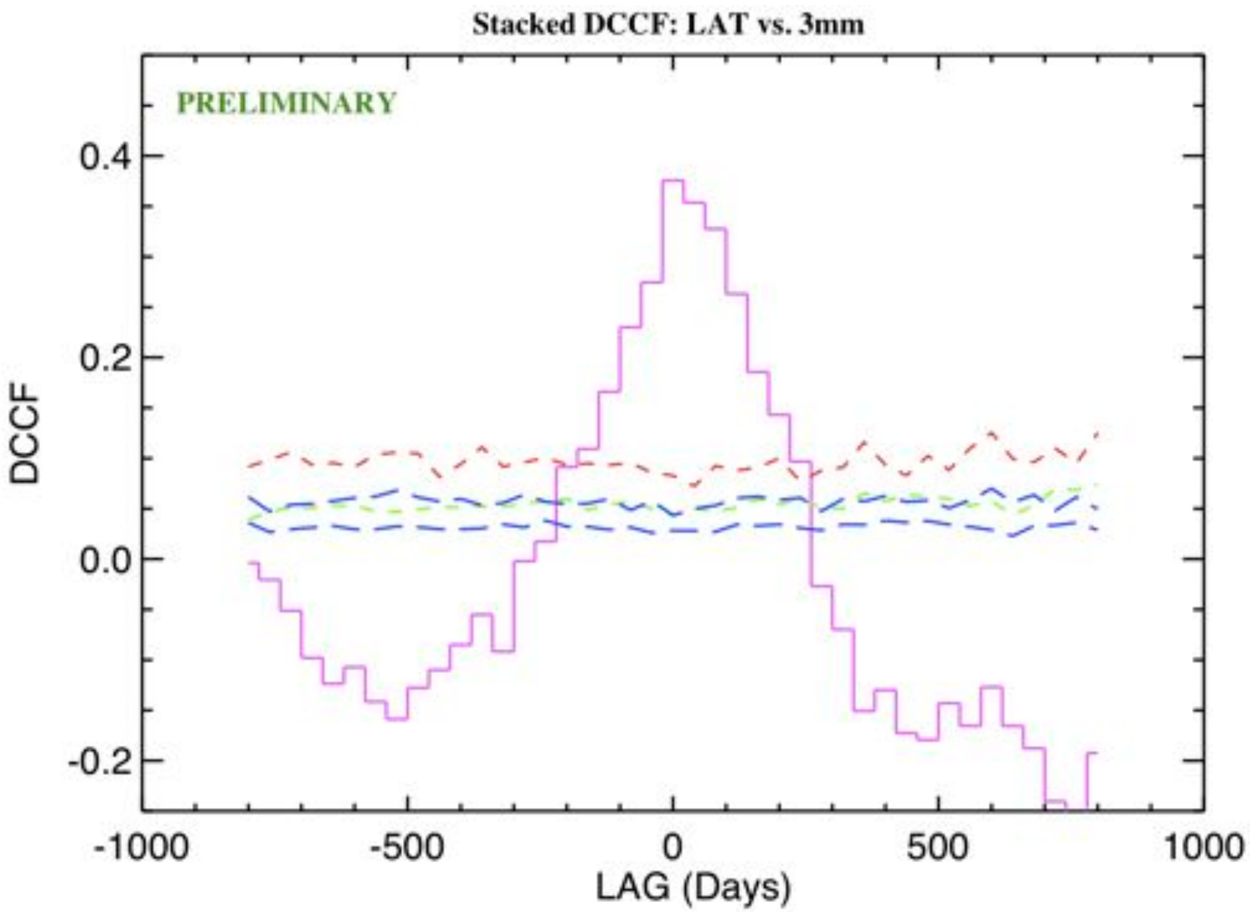
-single source cases often not significant: just a few so far!
-often no obvious, simple 1:1 correlation
-not yet long enough data trains
-conservative upper envelops - dashed lines: significance levels



DCCF analysis

First results

3 mm vs. Fermi/LAT: stacking of DCCFs



dashed lines: different confidence levels

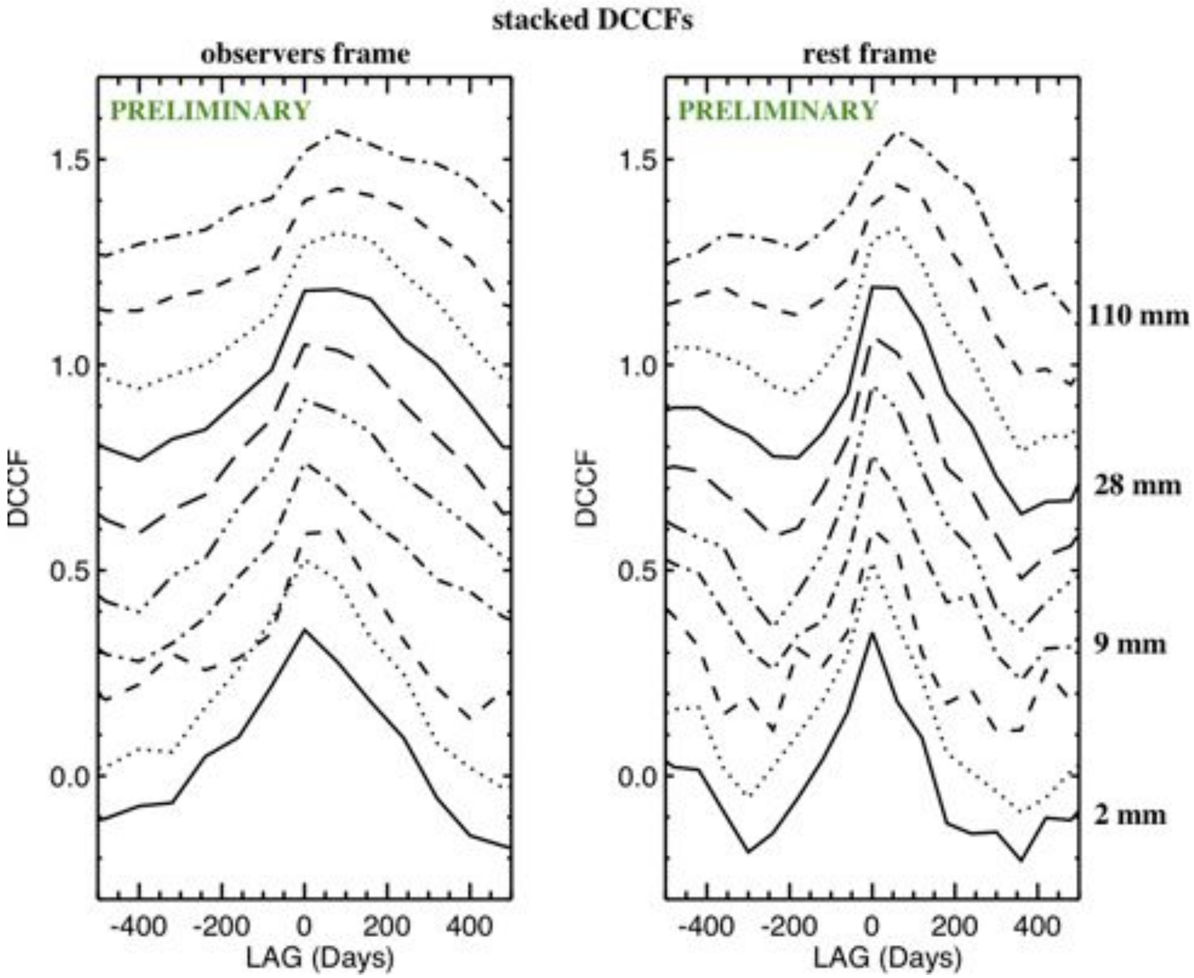
DCCF peak > than our confidence levels

⇨ averaged over whole sample: we obtain highly significant correlations !

DCCF analysis

First results

radio vs. Fermi/LAT: stacking of DCCFs



all LAT/radio (110 to 2 mm) combinations

DCCF peaks all > than our confidence levels

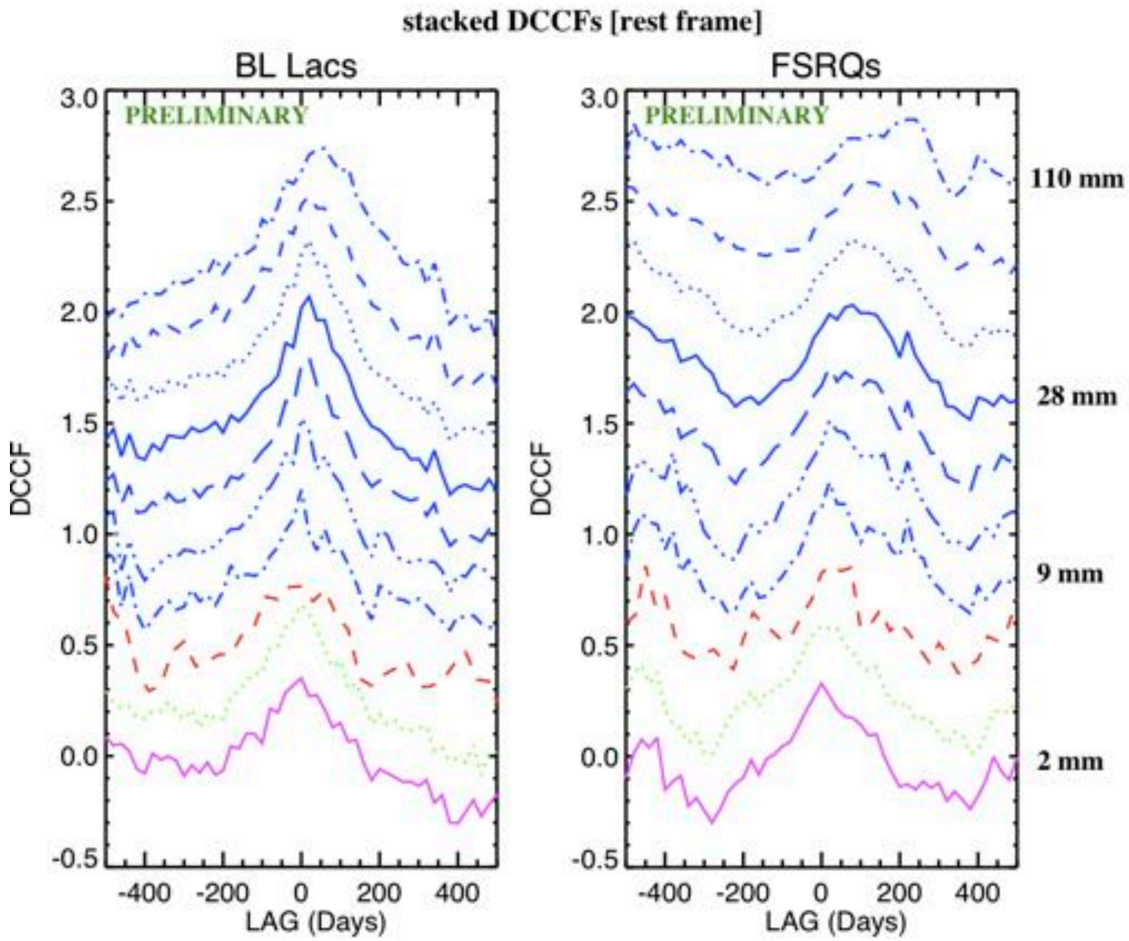
observers frame ➔ rest frame

asymmetry

DCCF analysis

First results

sub-grouping: FSRQs vs. BL Lacs



different behavior ?

Dependence on physical parameters?
e.g. BH masses (M_{BH}):

- M_{BH} estimates for 33 sources
- low mass range: < $10^{8.9}$
- high mass range: > $10^{8.9}$

⇨ stronger DCCF peaks & lower lags for high M_{BH}, e.g. FSRQs:

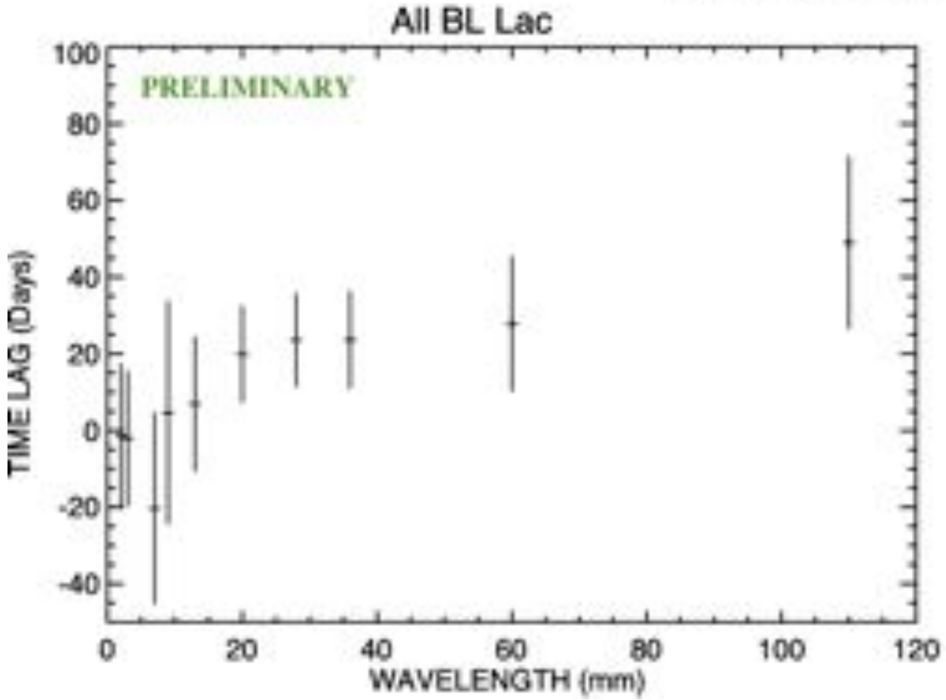
$\langle lag \rangle_{3mm}$ low M_{BH} : 44 +/- 19 days
$\langle lag \rangle_{3mm}$ high M_{BH}: 1 +/- 20 days

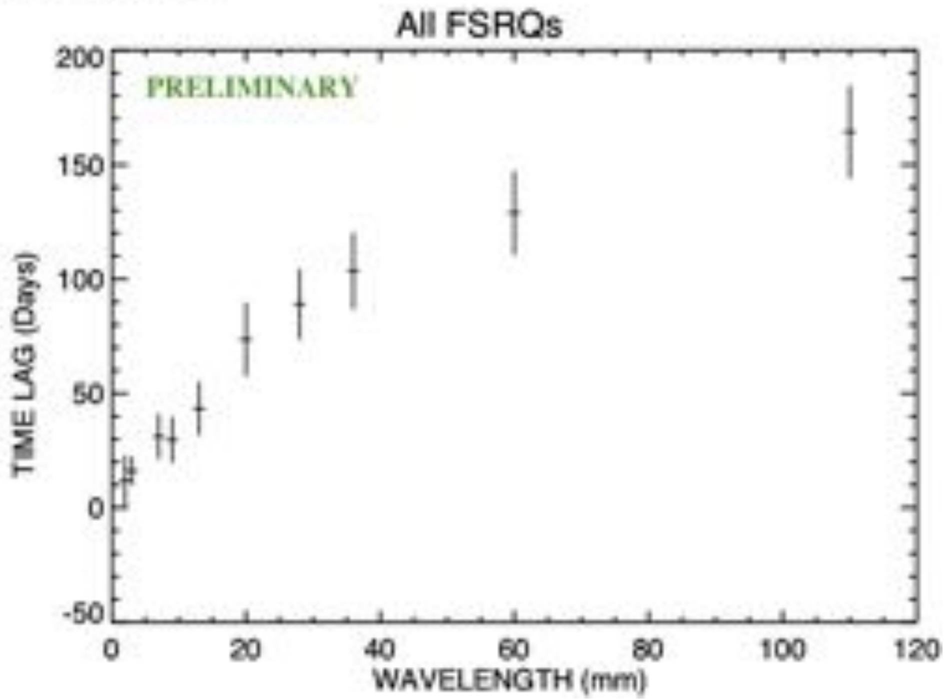
$\langle lag \rangle_{28mm}$ low M_{BH} : 118 +/- 31 days
$\langle lag \rangle_{28mm}$ high M_{BH}: 46 +/- 13 days

DCCF analysis

First results

time lag [rest frame] vs. wavelength





delay origin: synchrotron self-absorption/opacity
(e.g. Pushkarev et al. 2010)

Fuhrmann et al. in prep.

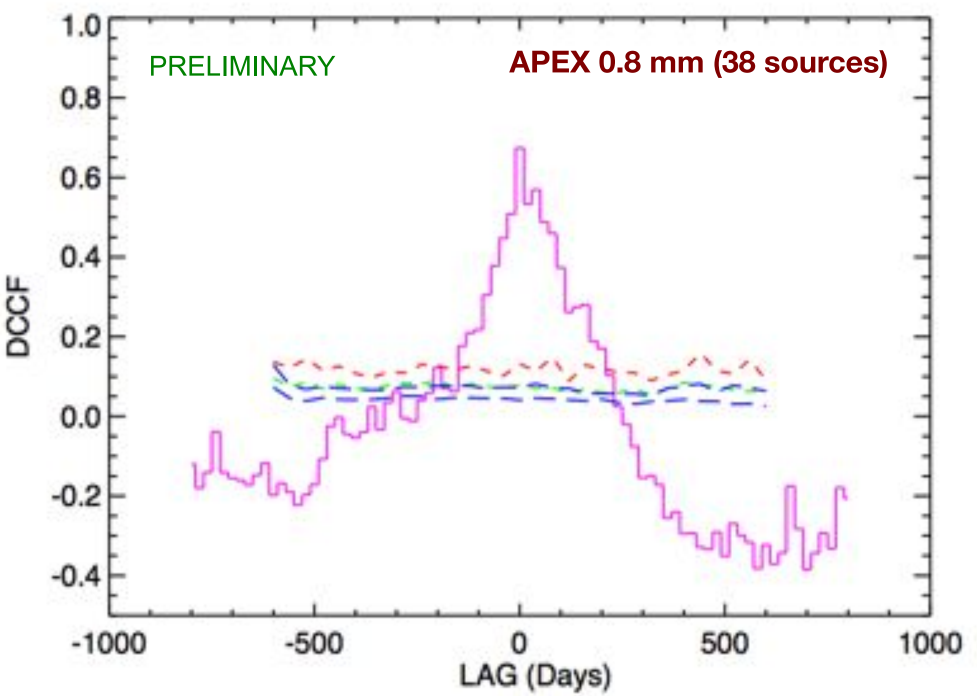
1) pos. delay: gamma from inside “mm-core”

2) distance between “gamma-origin” and radio τ=1 surface (VLBI jet speeds, var. Doppler factors, viewing angles): Δr ~ 0 - 0.4 pc (3, 2 mm), ~ 8 pc (cm)

DCCF analysis

First results

APEX sub-mm vs. Fermi/LAT (see poster by Larsson et al.)



Larsson et al. in prep.

<lag>$_{\text{sub-mm}}$: 7 +/- 7 days
<lag>$_{\text{sub-mm}}$ BL Lacs: -12 +/- 12 days
<lag>$_{\text{sub-mm}}$ FSRQs: 13 +/- 9 days

⇨ mm/sub-mm and gamma-ray emission regions co-spatial (within the given uncertainties)

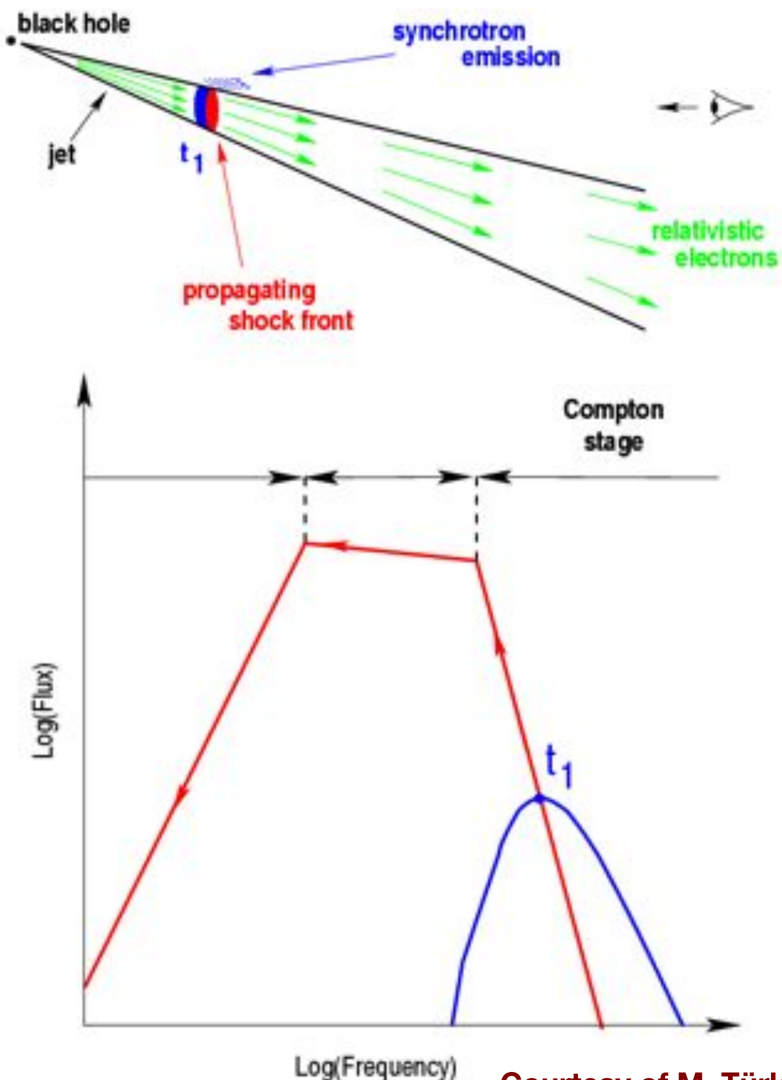
⇨ SED modeling:

including the mm/sub-mm bands should be considered!

Radio variability

Is the overall flaring behavior in agreement with shocks on pc-scales?

Shock-in-jet model

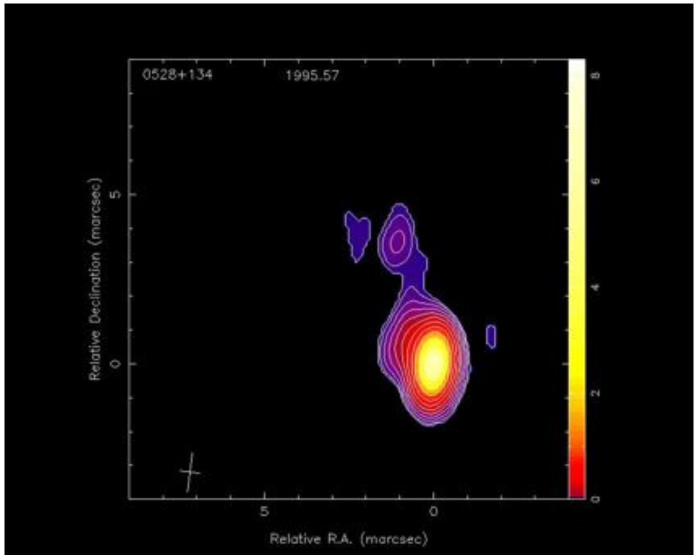


Courtesy of M. Türler

-each variability model: characteristic signatures in the time and spectral domain

-e.g. shock scenario (Marscher & Gear 1985, Türler et al. 2000)

-seen as standing/moving VLBI components/features in the core region and downstream on pc-scales



Courtesy: MOJAVE program

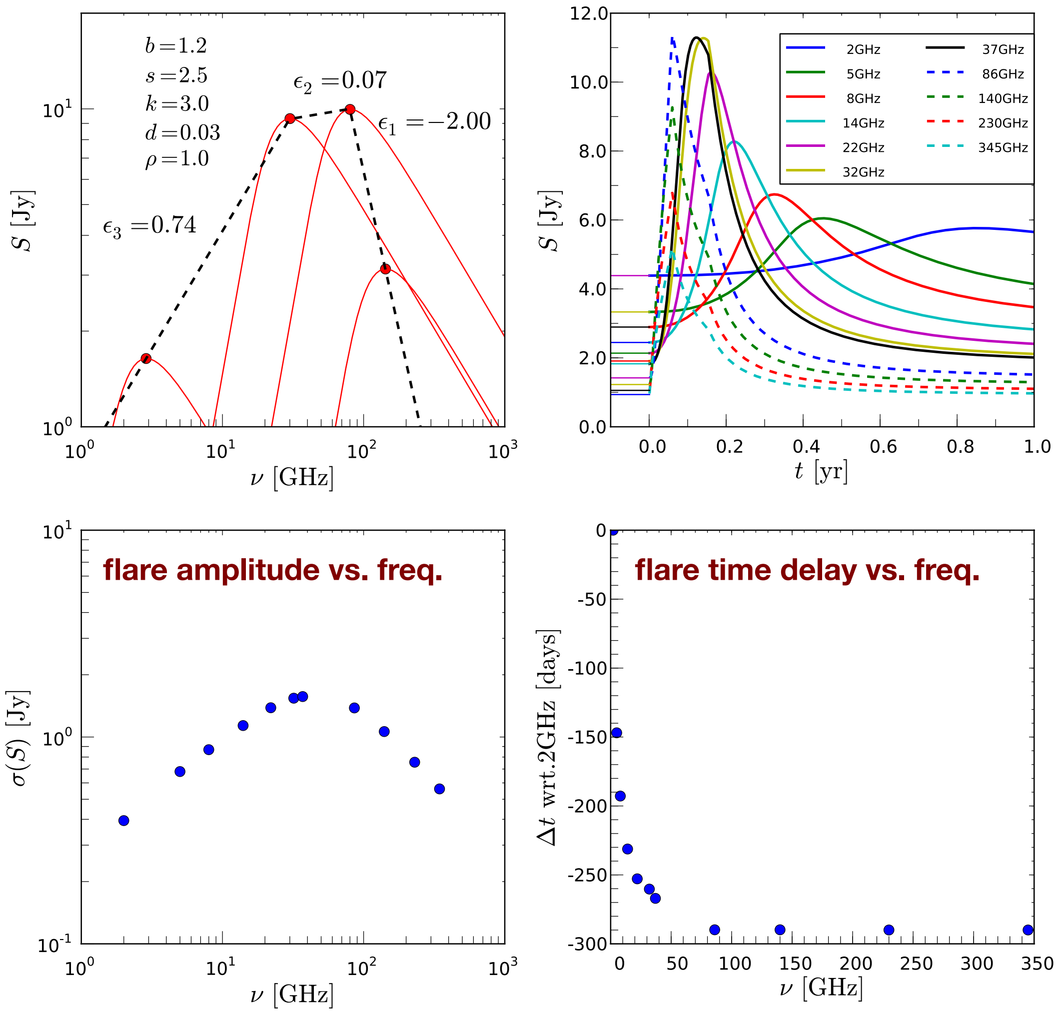
Radio variability

Is the overall flaring behavior in agreement with shocks on pc-scales?

Fermi Gamma-ray Space Telescope

F-GAMMA PROGRAM — Fermi-GST AGN Multi-frequency Monitoring Alliance

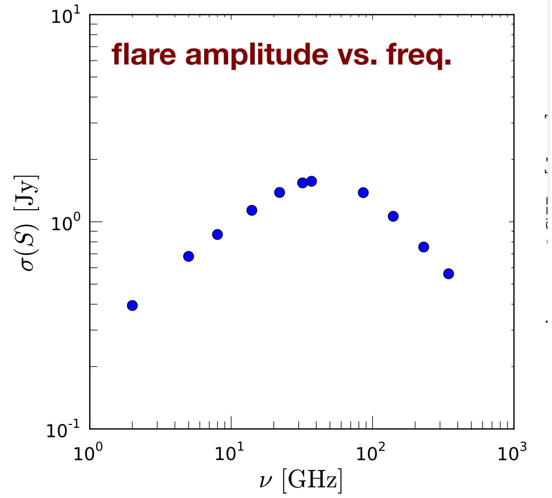
semi-analytical model calculations:



- standard shock model (Marscher & Gear 1985)
- Fromm et al. (2011): calculations for (a typical) blazar (CTA 102)
- a conical jet (p = 1)
- a toroidal magnetic field (b = 1.2)
- a constant Doppler factor
- predictions for variability amplitude and time delays

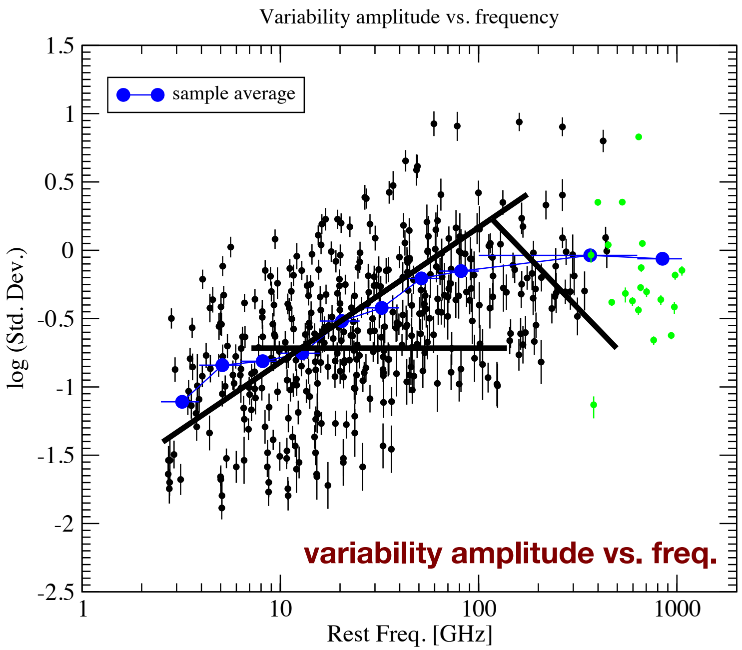
Radio variability

Is the overall flaring behavior in agreement with shocks on pc-scales?



Time domain - F-GAMMA radio vs. model:

a) Variability amplitude:



-quantity: light curve standard deviations: "intrinsic values" using a likelihood method (Richards et al. 2011)

-sample averages: clear overall increase, max: ~ 60-80 GHz, then plateau/decreasing trend?

-individual source patterns:

a) increase up to mm bands

b) peak and subsequent decrease

c) "flat behavior"

-a) + b): good agreement with growth/plateau/decay phase of shocks, c) different mechanism?

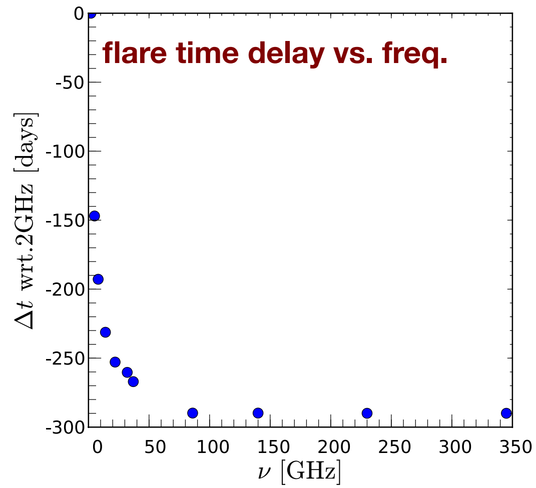
-F-GAMMA covers all stages of shock evolution!

-individual source studies/modeling (single flares, max., slopes): constrain model parameters (B-Field, non-conical geometry, shock-shock interaction etc.)

-growth: APEX band important ! optical bands?

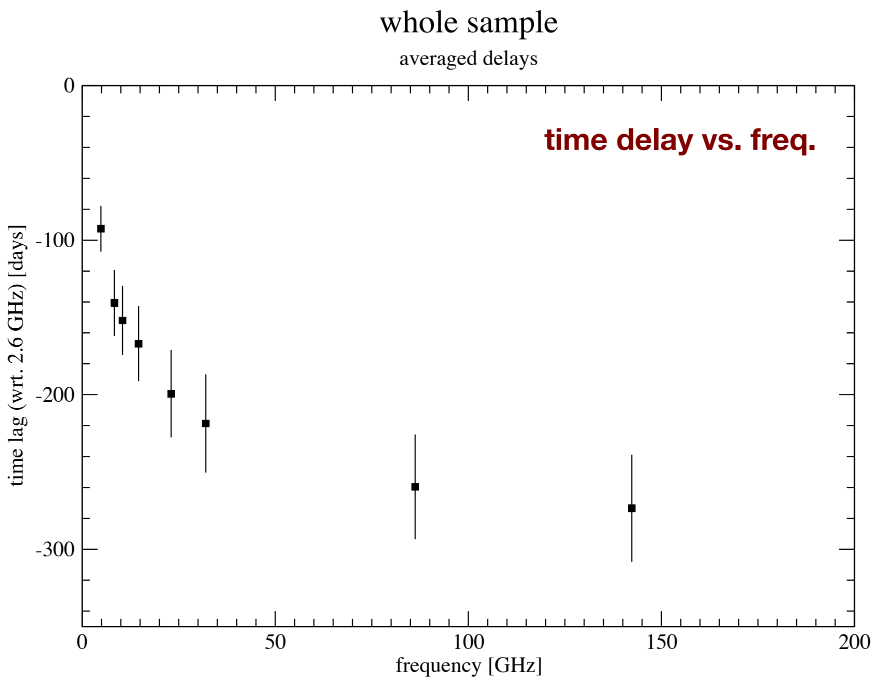
Radio variability

Is the overall flaring behavior in agreement with shocks on pc-scales?



Time domain - F-GAMMA radio vs. model:

b) sample averaged time delays:



-detailed Discrete Cross-Correlation Function analysis (DCCF) between 2.6 and 140 GHz (110 - 2 mm)

-~ no lags at high frequencies

-increasing lags towards lower frequencies

-overall good agreement with model predictions

⇨ most of the radio variability/flares produced in shocks on pc scales !

⇨ together with previous (DCCF) findings: gamma-rays likely produced in shocks on pc scales !

Conclusions

–*Fermi*–LAT & F–GAMMA synergy:

- timing analysis of flares/events
- constraining the location of the gamma–ray emitting region

–DCCF and stacking analysis using 3.5 yrs *Fermi* LCs:

- first significant radio/gamma–ray correlations
- strongly decreasing lags towards mm/sub–mm bands (lags → 0)

⇨ ~ 0–0.4 pc: emitting regions co–spatial!

- possible differences for FSRQs/BL Lacs and for physical parameters like BH mass

–radio variability in overall good agreement with shocks on pc–scales

⇨ gamma–rays likely produced in shocks on pc–scales!