Correlations of the multiwavelength emission in the blazar CTA 102 during 2016-2018

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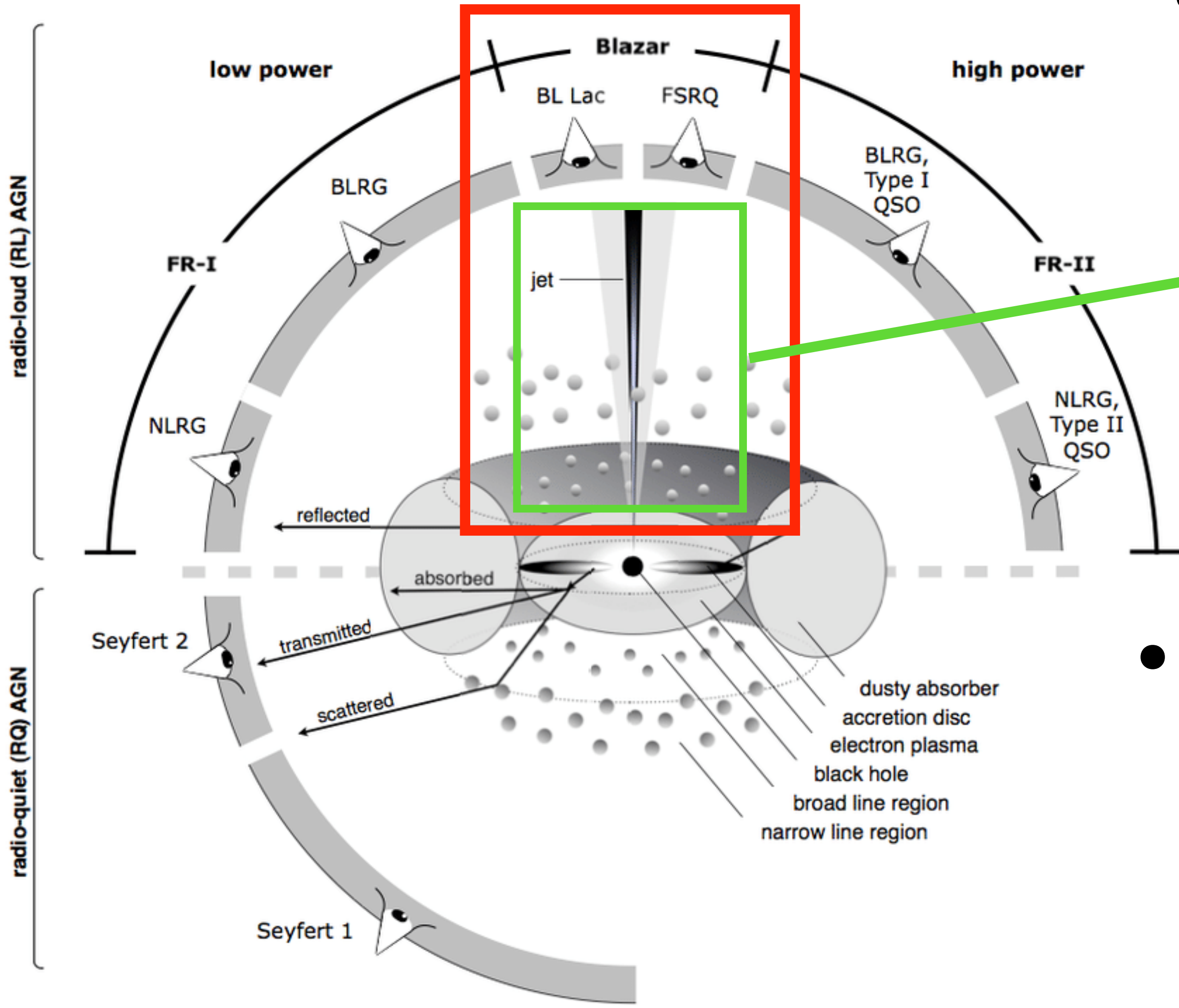
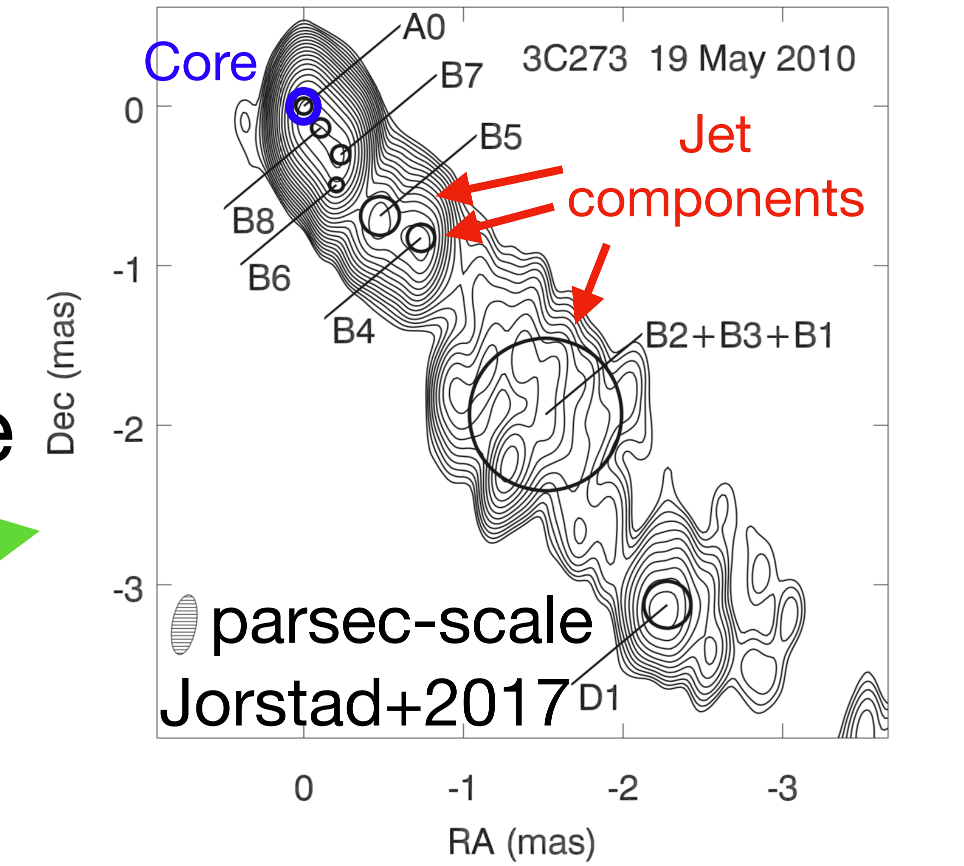
Active Galactic Nuclei (AGNs)?

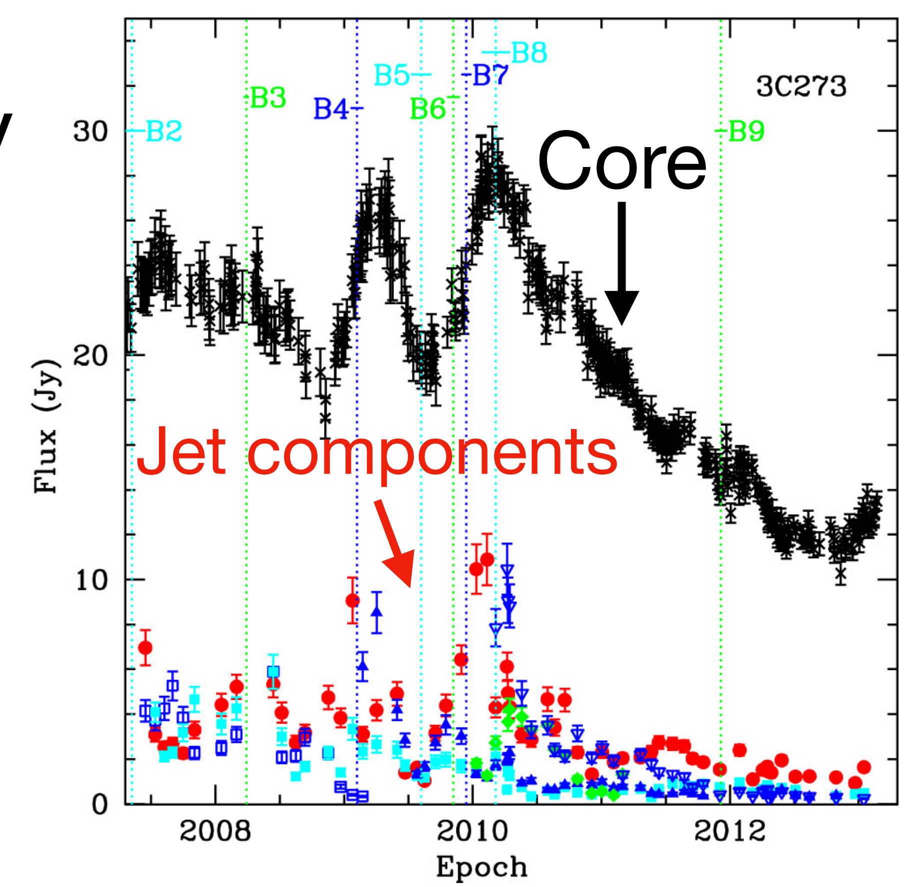


Beckmann+2012

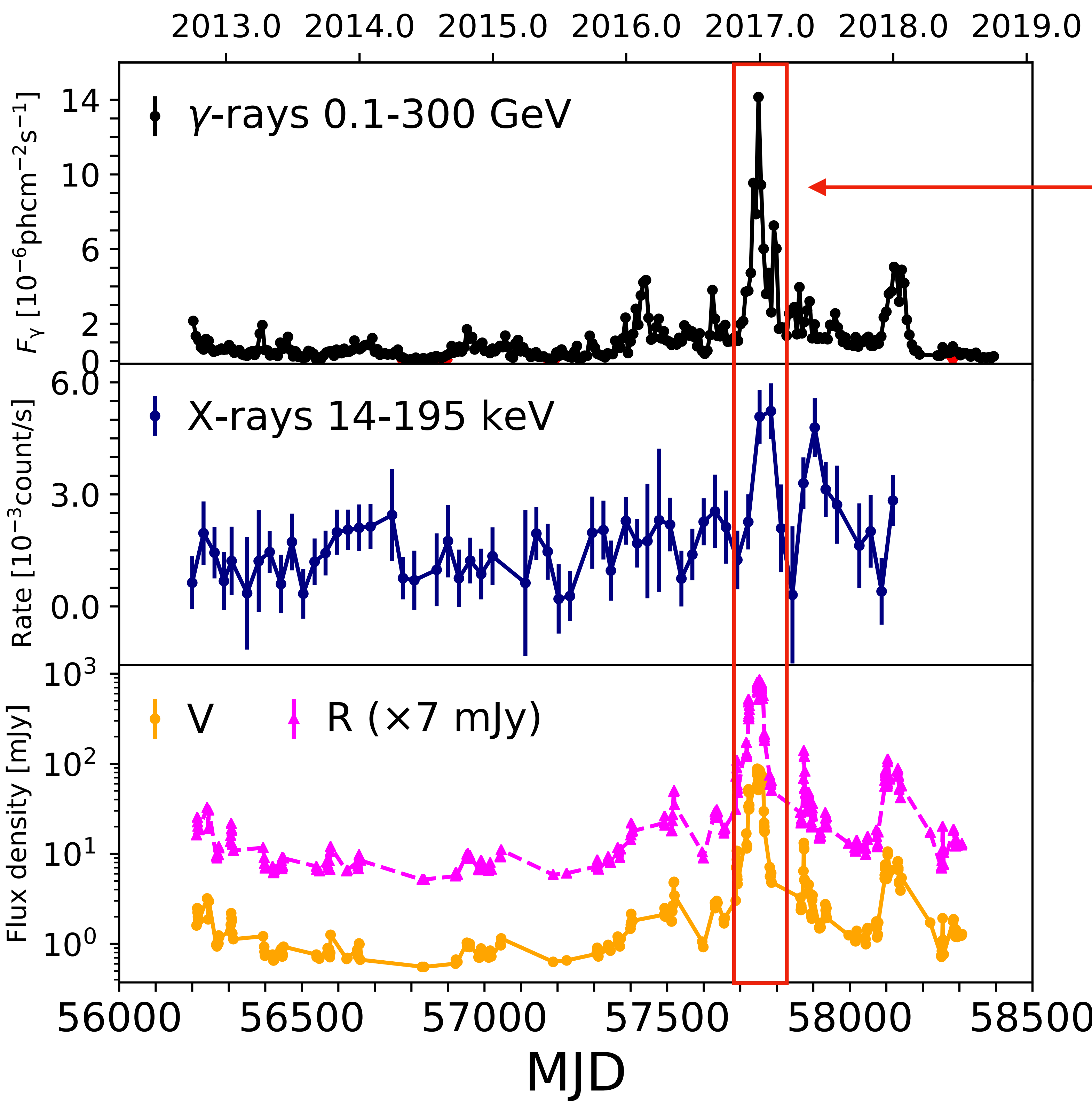
- Core-jet structure



- Variability

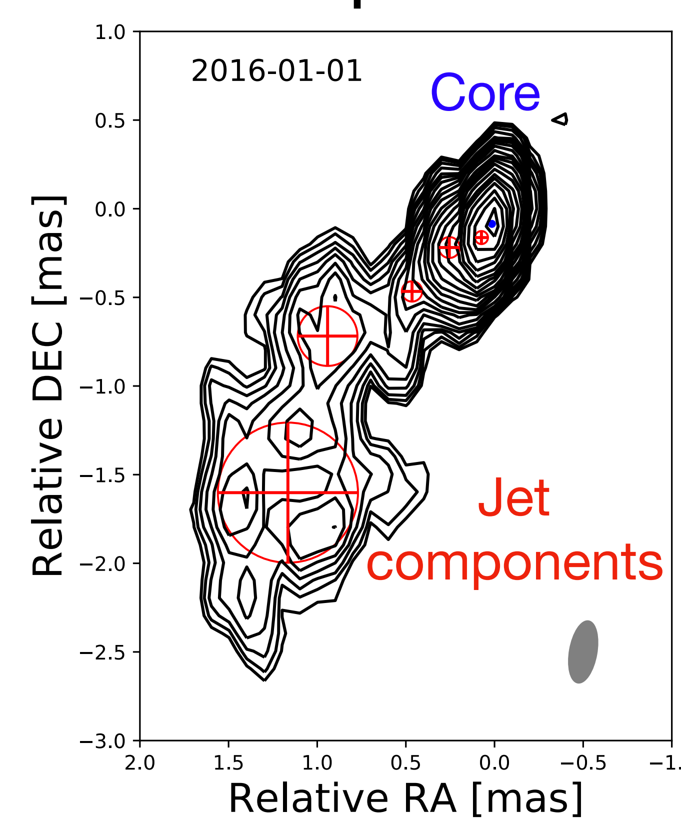


What is interesting about **CTA 102**?

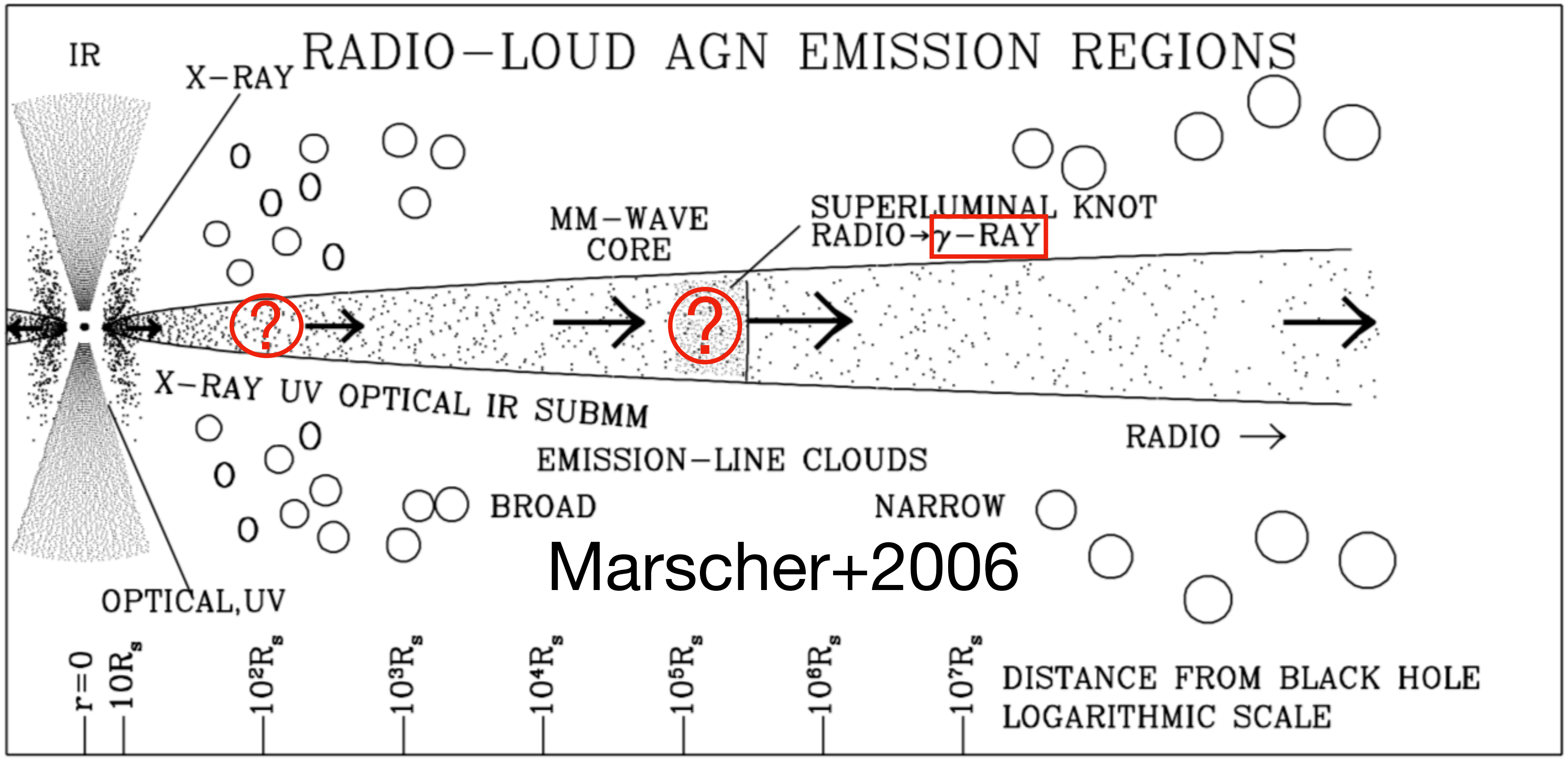


Very strong γ-ray flares among the blazars!

VLBA Map 43 GHz

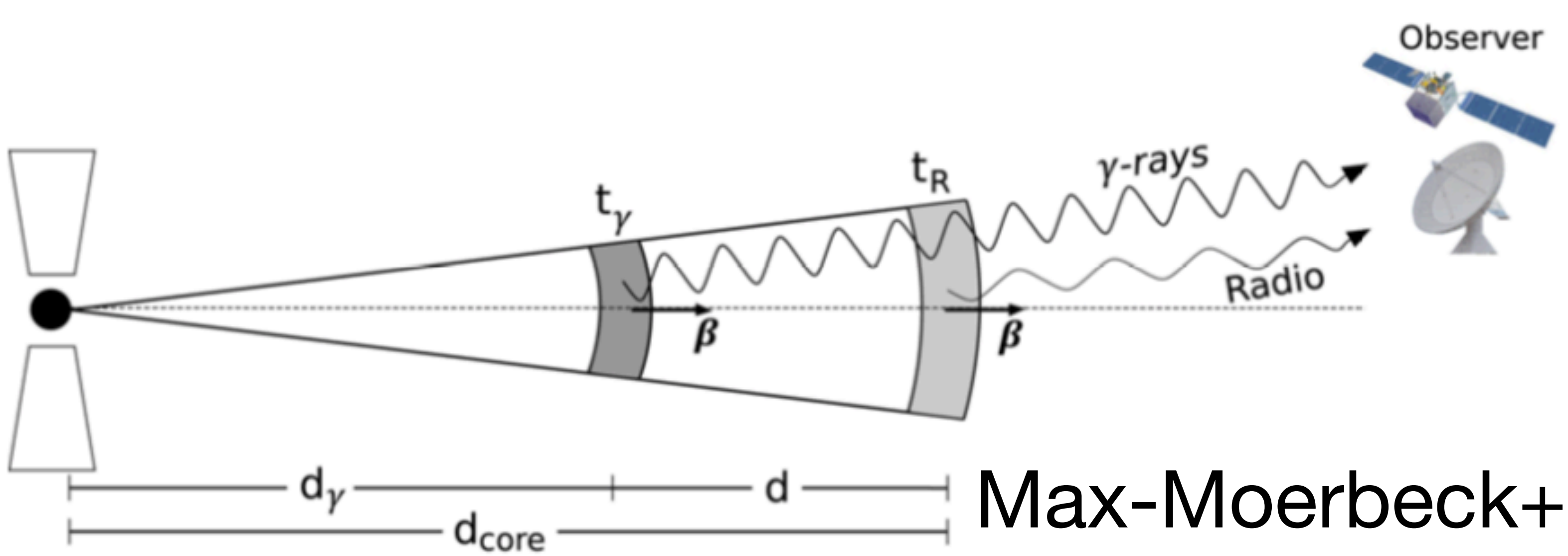


Q1. Location of the γ-ray emission region?



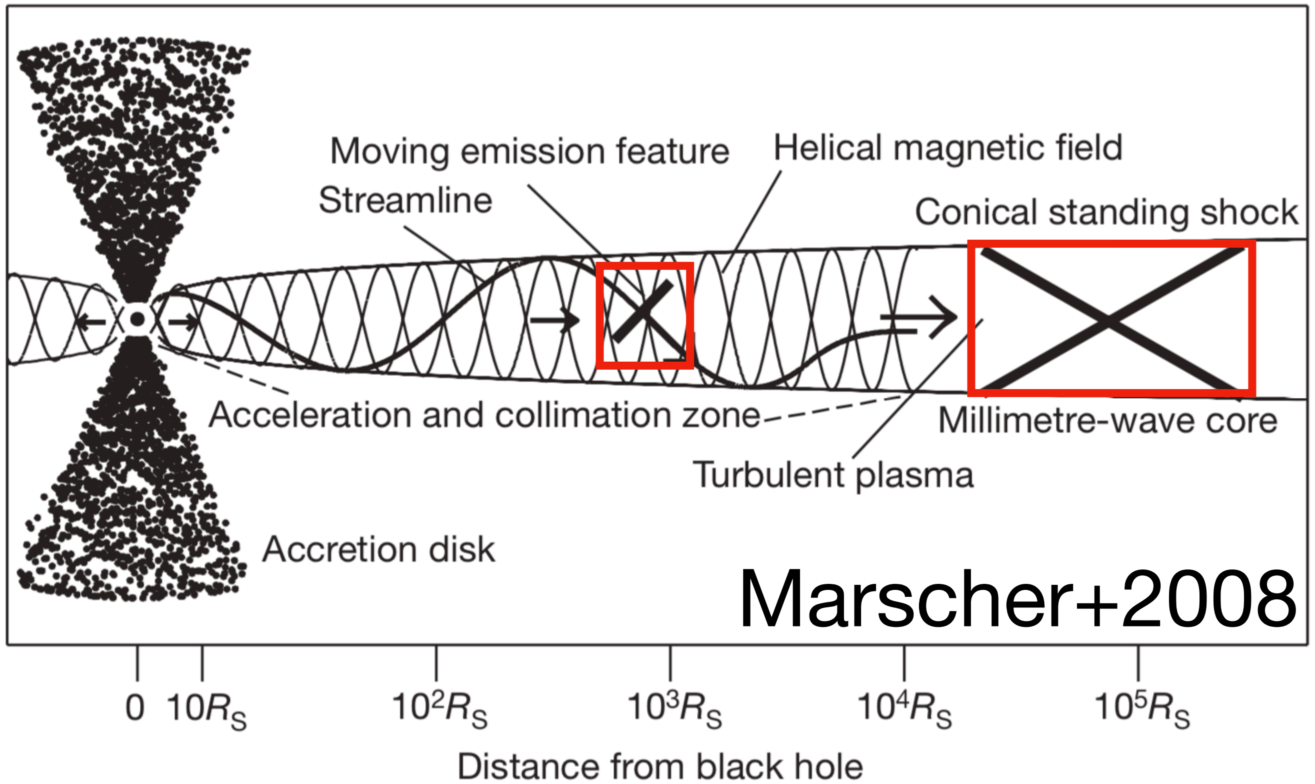
Marscher+2006

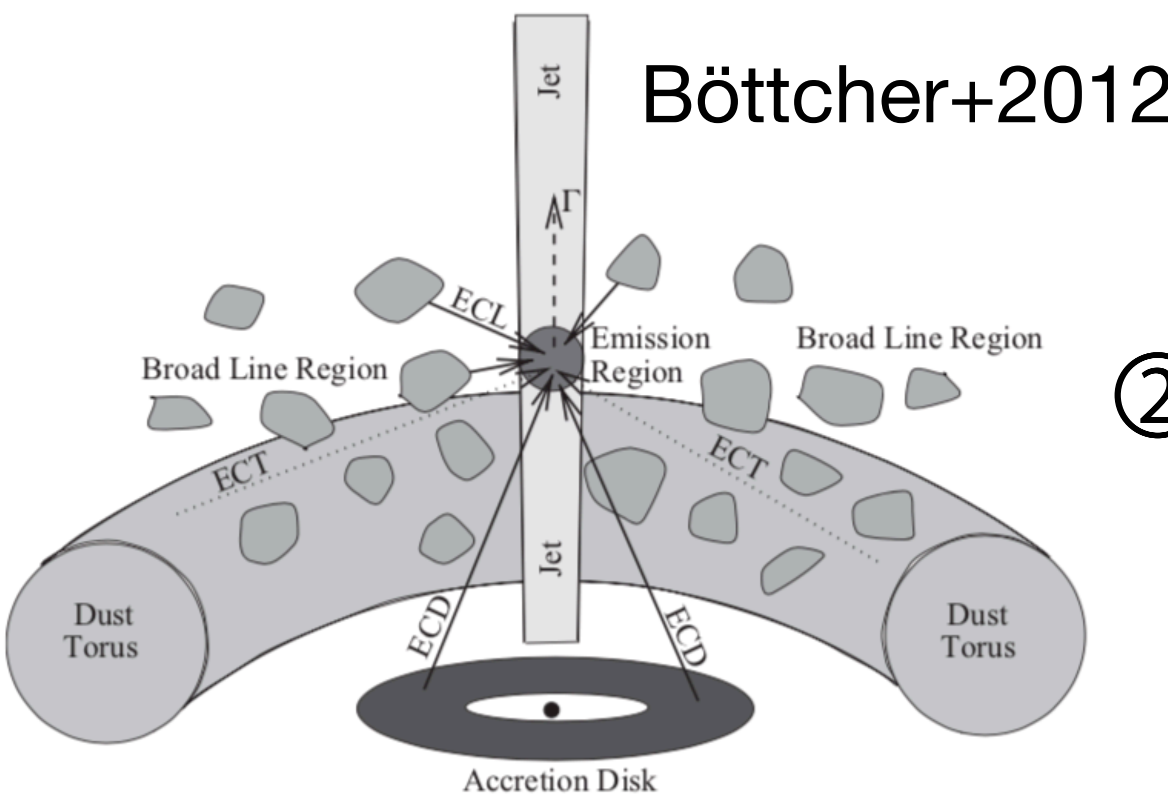
"Cross-correlation analysis" reveals the location of the γ-ray emission site



Max-Moerbeck+2014a

Q2. Physical mechanisms responsible for the γ-ray emission?





Possible scenarios

① Shock-shock interaction

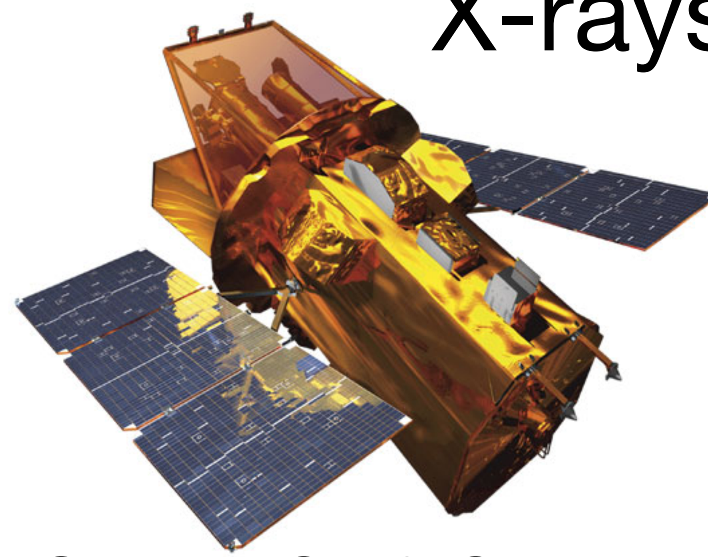
② External Compton scattering

γ-rays

Fermi Large Area Telescope

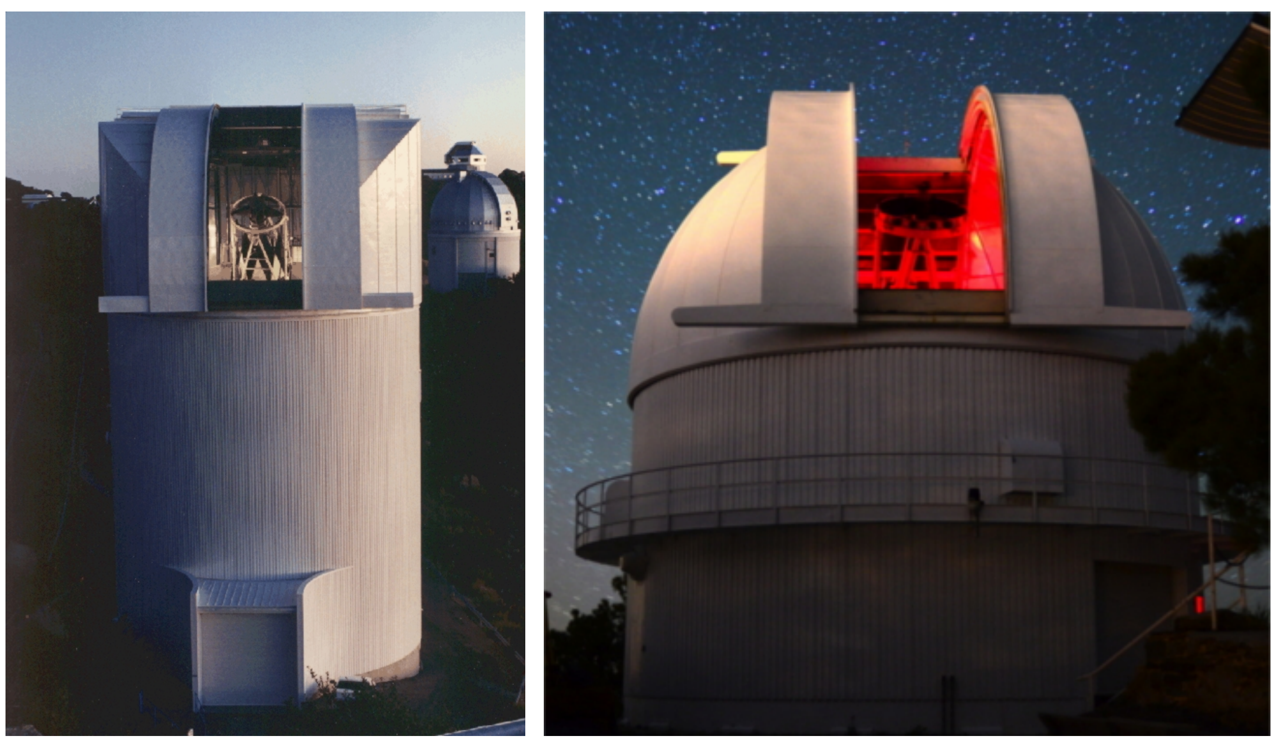
Credits: NASA

X-rays



Neil Gehrels Swift Observatory

Credits: NASA E/PO, Sonoma State University, Aurore Simonnet



Optical

(Left) Bok Telescope
(Right) Kuiper Telescope

Credits: Steward Observatory of the University of Arizona

OVRO 40m

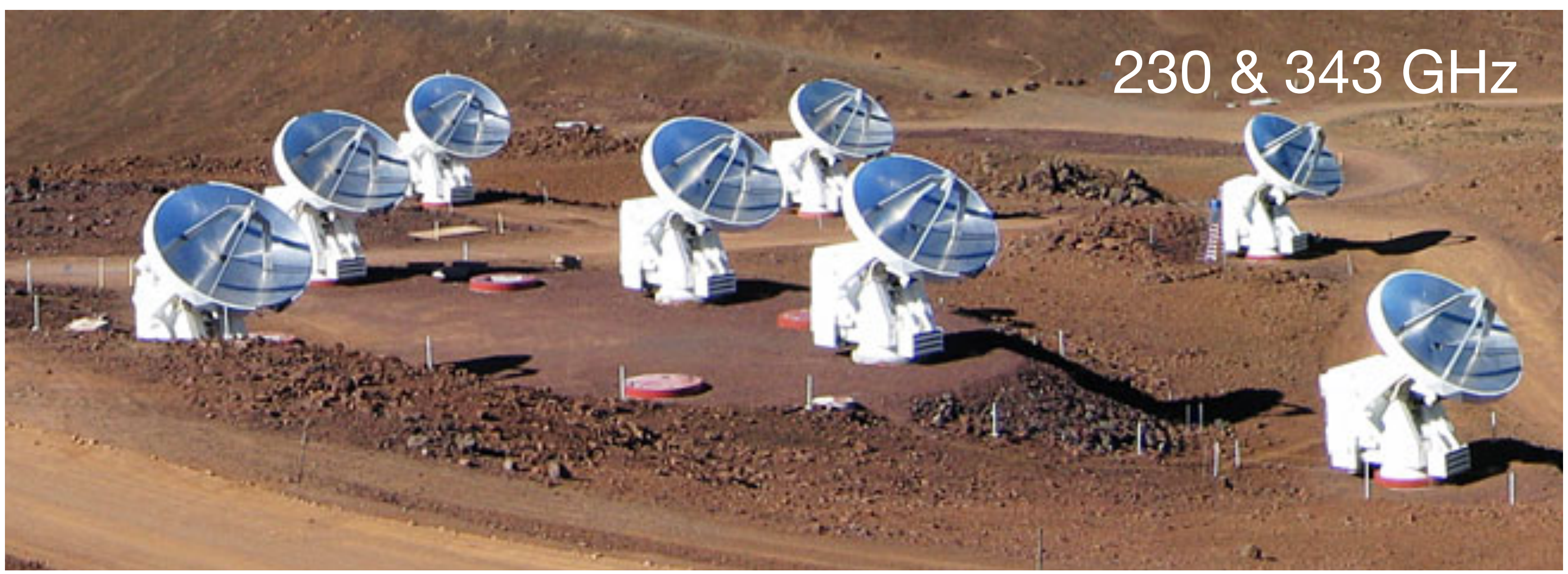
Credits: NRAO/AUI/NSF

Metsähovi 14m

Credits: Aalto University

IRAM 30m

Credits: DiVertiCimes

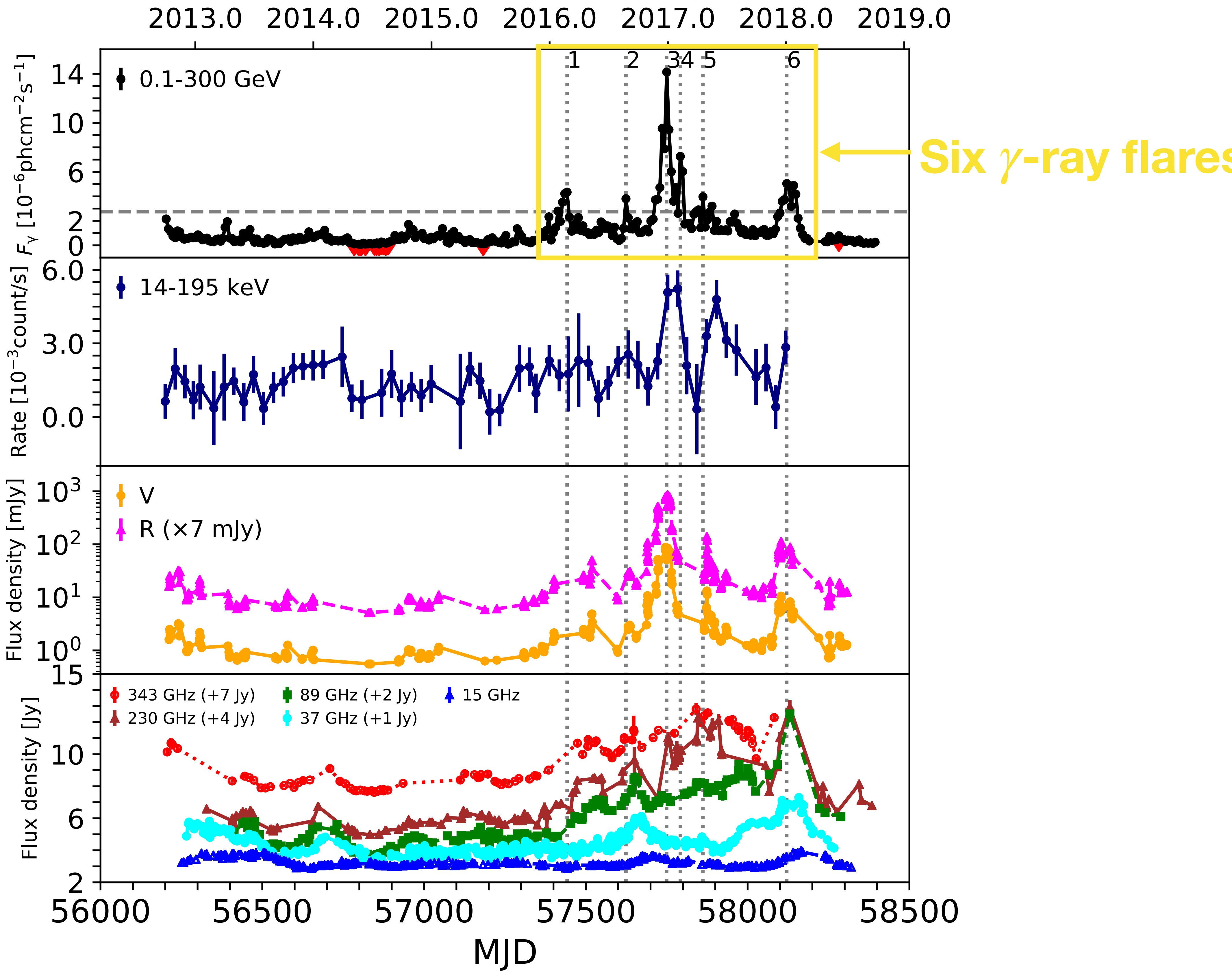


SMA

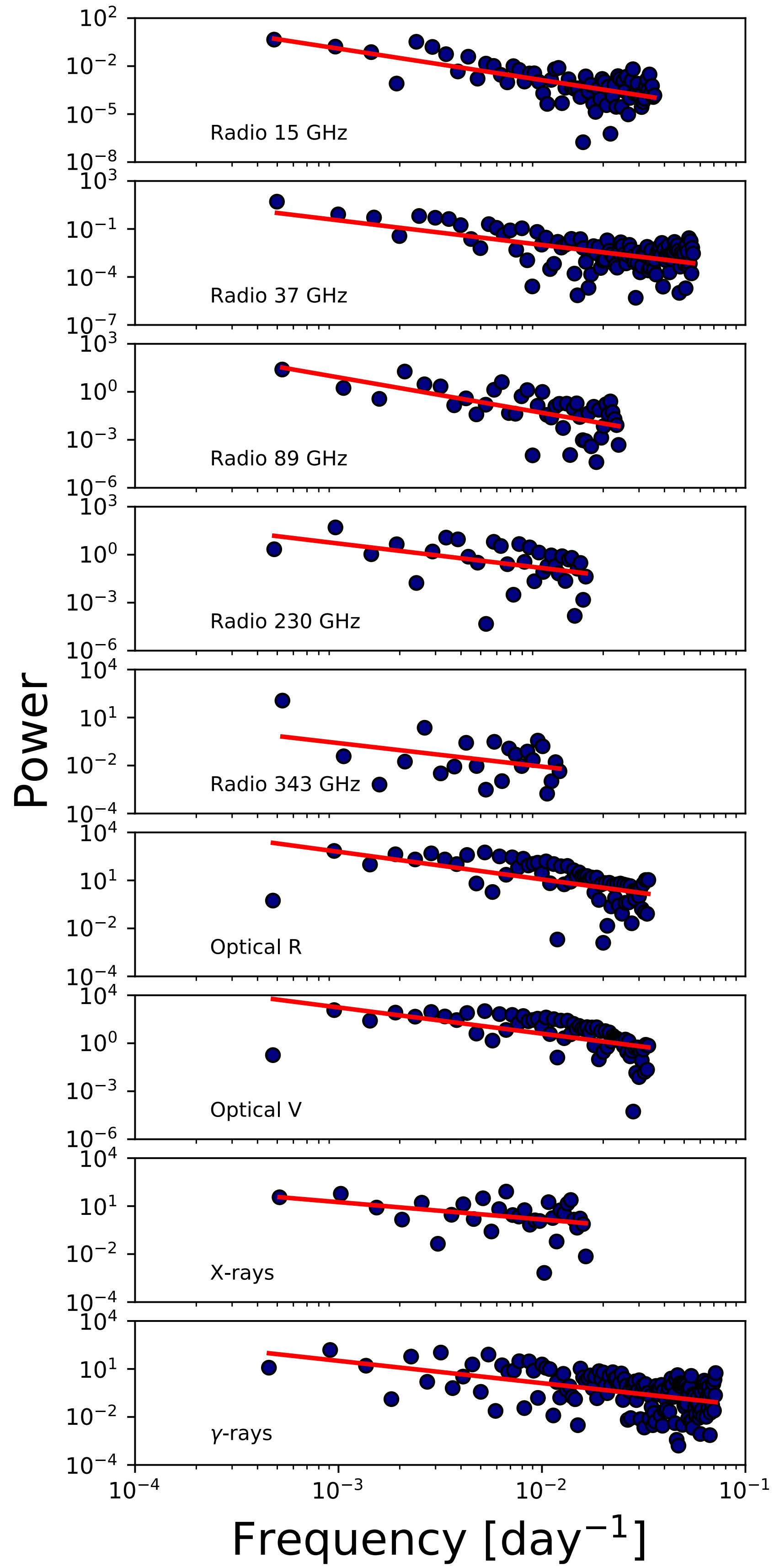
Credit: J. Weintroub

ALMA

Credits: ESO/C. Malin



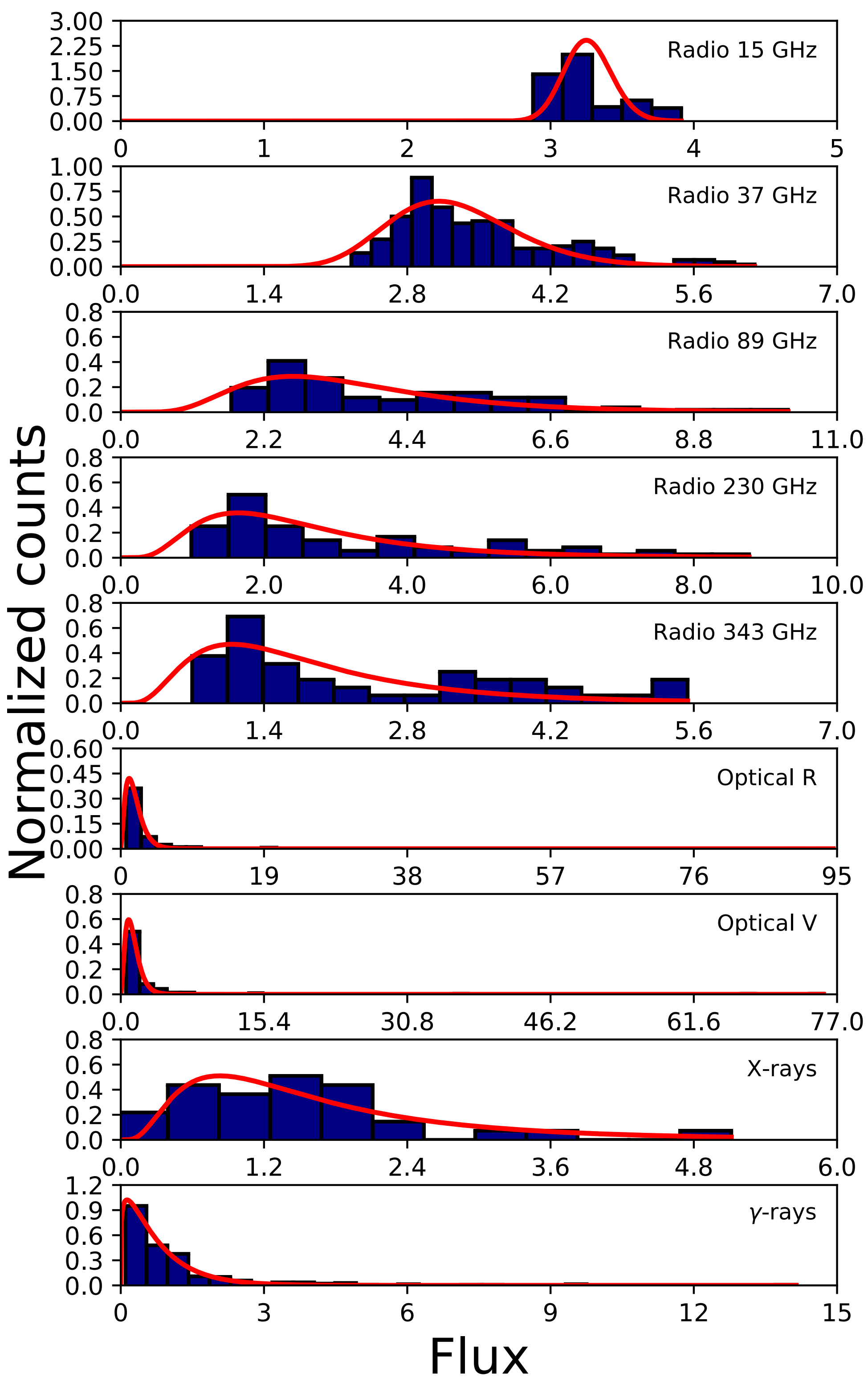
* A dashed line in the γ-ray light curve means the criteria for a flare.



Power Spectral Density (PSD)

- PSD(ν) $\propto \nu^{-\beta}$
- $\beta \geq 1$ at all ν

Frequency band	PSD β	PDF κ	PDF θ	PDF σ	PDF μ
(1)	(2)	(3)	(4)	(5)	(6)
Radio 15 GHz	$2.18^{+0.29}_{-0.26}$			0.05 ± 0.01	$3.26^{+0.09}_{-0.04}$
Radio 37 GHz	$1.73^{+0.24}_{-0.20}$			0.19 ± 0.02	3.23 ± 0.06
Radio 89 GHz	$2.24^{+0.42}_{-0.38}$			$0.47^{+0.05}_{-0.06}$	$3.31^{+0.21}_{-0.23}$
Radio 230 GHz	$1.52^{+0.62}_{-0.50}$			$0.59^{+0.07}_{-0.08}$	2.29 ± 0.22
Radio 343 GHz	$1.33^{+0.63}_{-0.61}$			$0.64^{+0.09}_{-0.11}$	1.63 ± 0.23
Optical R	$1.53^{+0.30}_{-0.28}$	$2.55^{+0.02}_{-0.15}$	$0.72^{+0.04}_{-0.02}$		
Optical V	$1.86^{+0.35}_{-0.30}$	$2.77^{+0.01}_{-0.20}$	0.48 ± 0.02		
X-rays	$0.96^{+0.44}_{-0.41}$			0.72 ± 0.10	$1.40^{+0.17}_{-0.18}$
γ-rays	1.24 ± 0.17	$1.21^{+0.04}_{-0.06}$	0.63 ± 0.03		



Probability Density Function (PDF)

- Gamma Distribution - Optical & γ-rays
- Log-Normal Distribution - Radio & X-rays

		Gamma		Log-Normal	
Frequency band	PSD β	PDF κ	PDF θ	PDF σ	PDF μ
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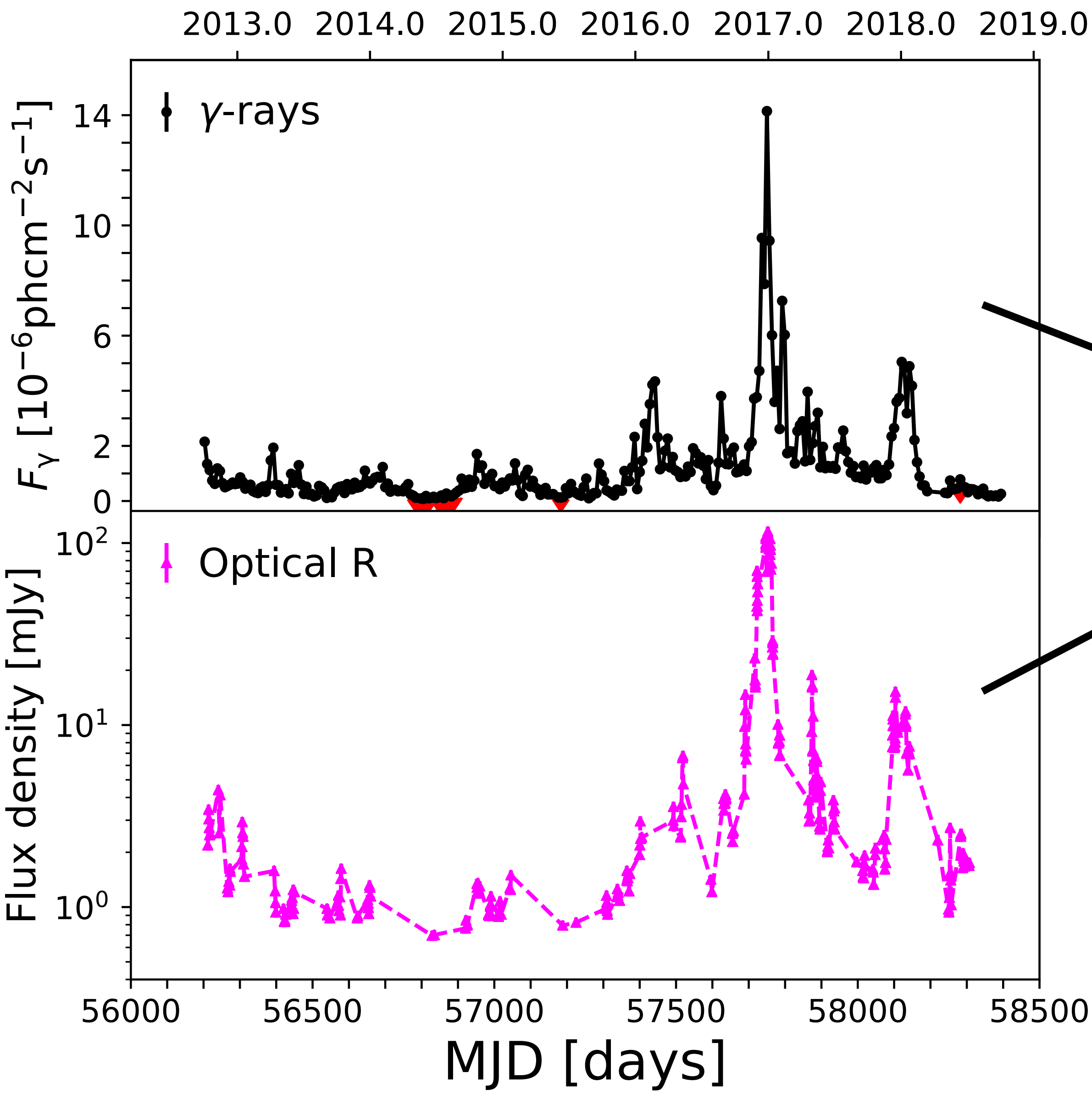
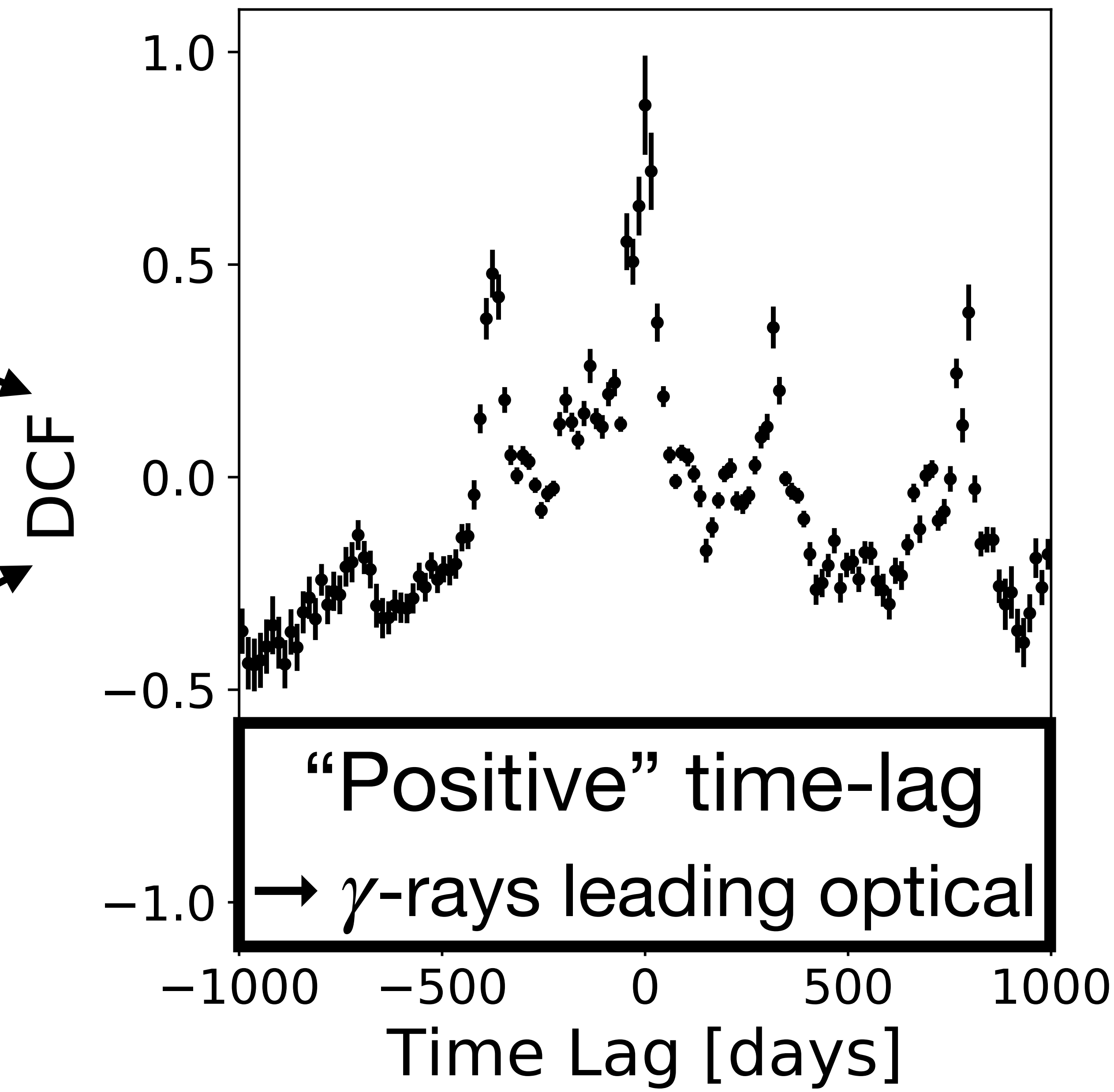
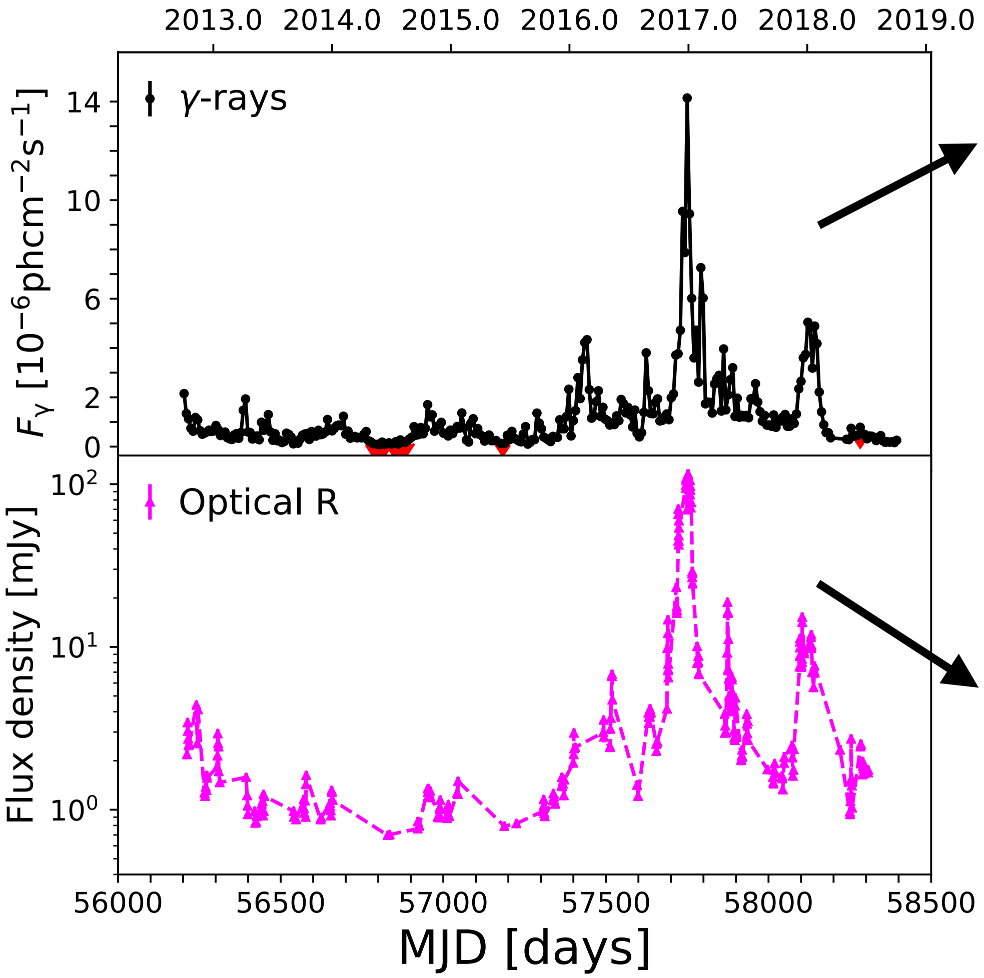
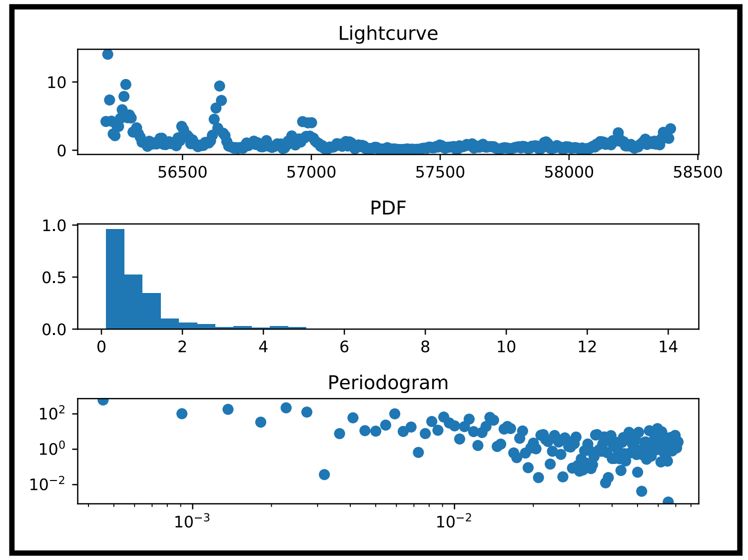
Discrete Cross-correlation Function (DCF)



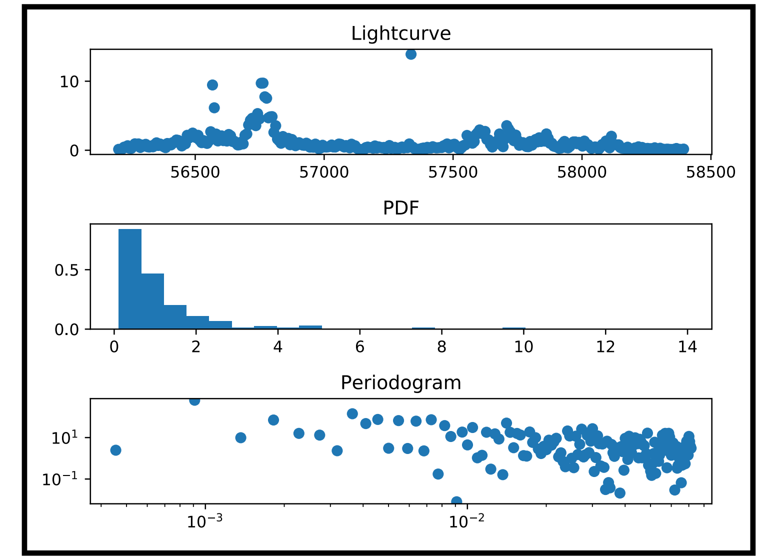




1st

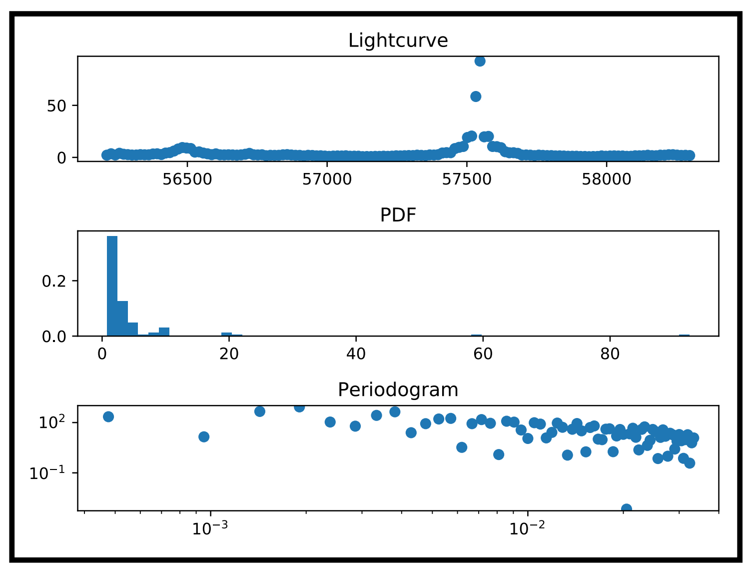


10,000th

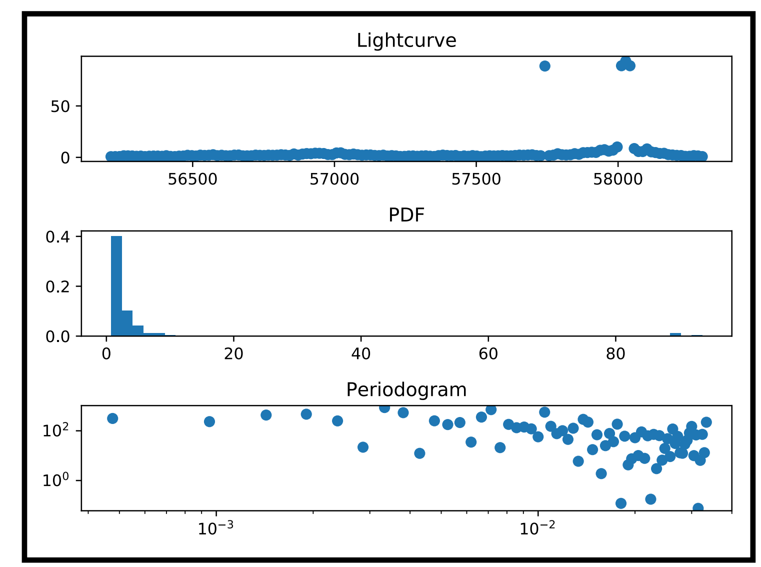


Generate 10,000 DCFs

1st



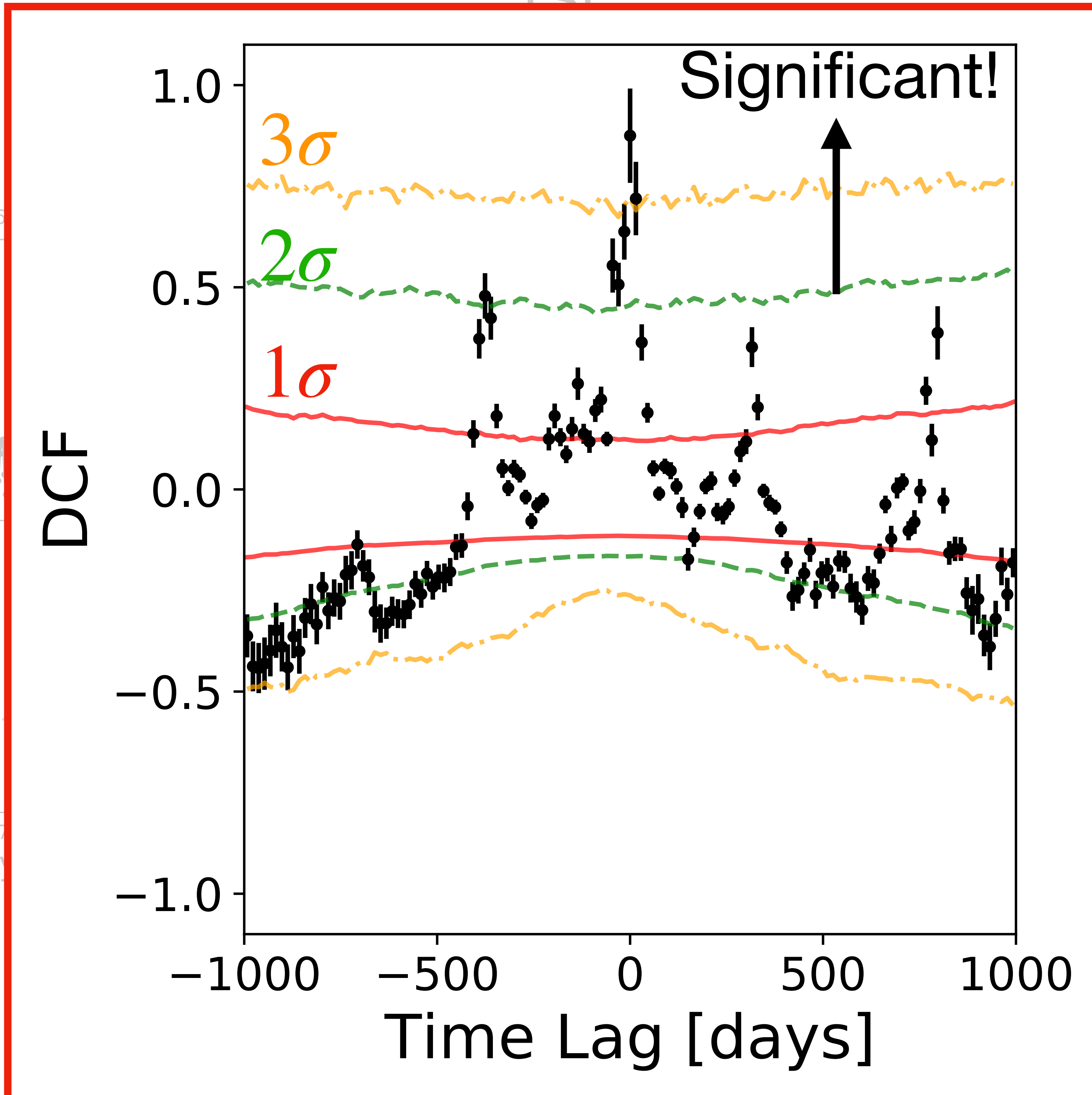
10,000th



Model implementation is described in Emmanoulopoulos+2013

1st

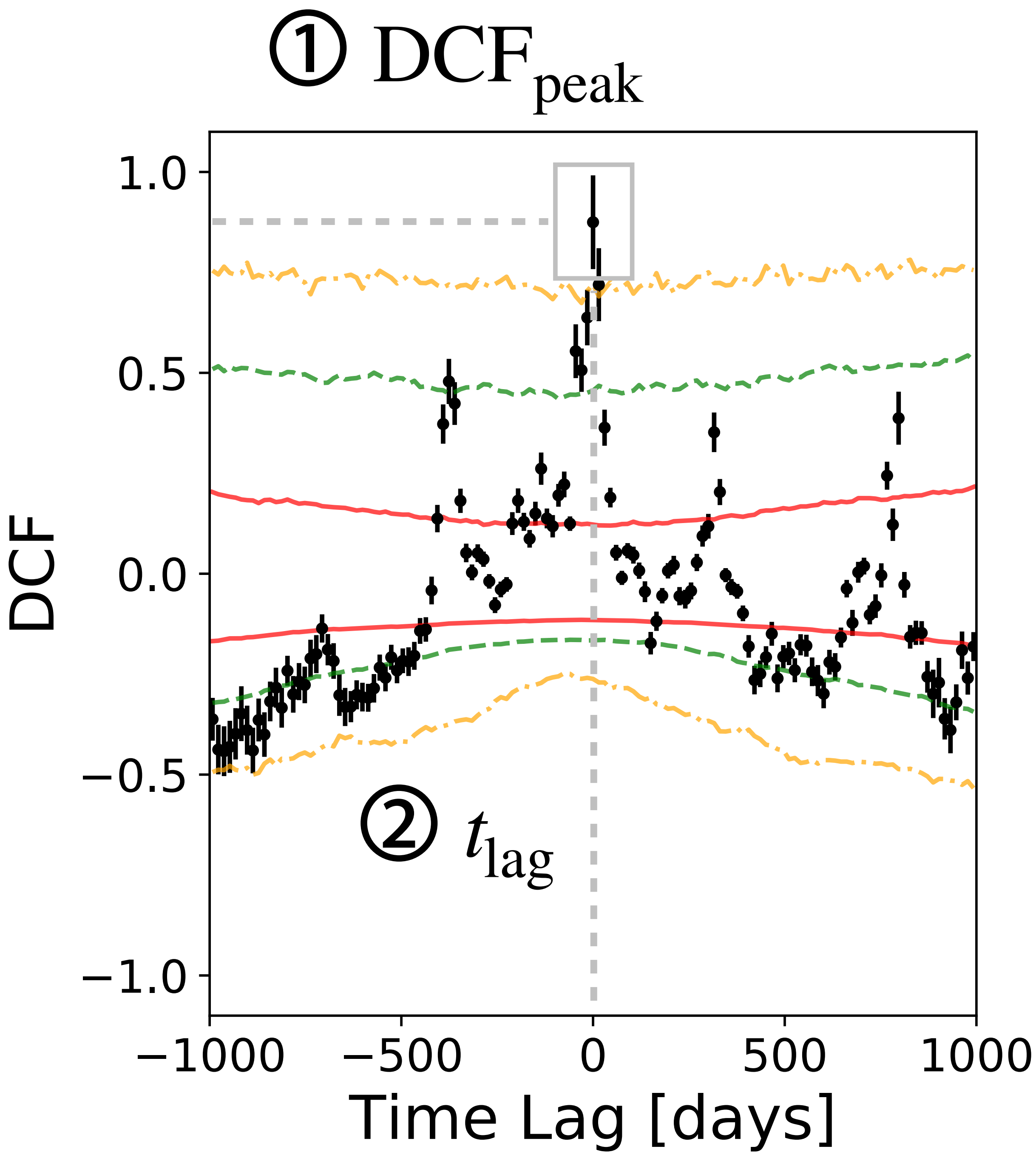
10,000th

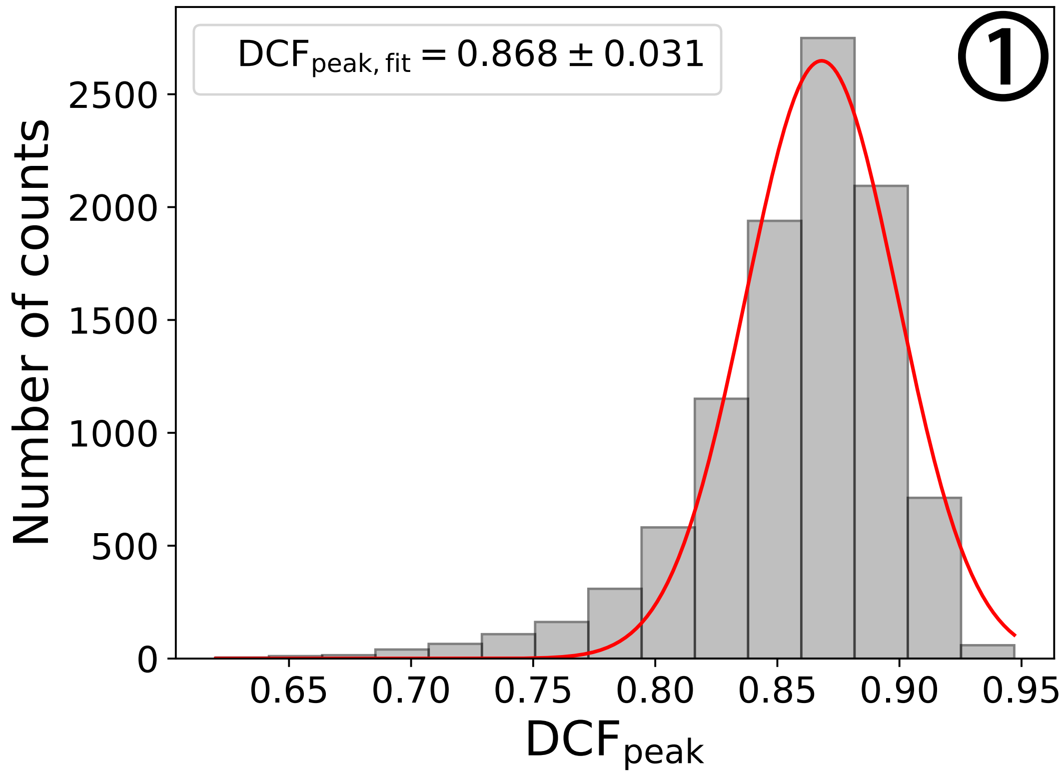


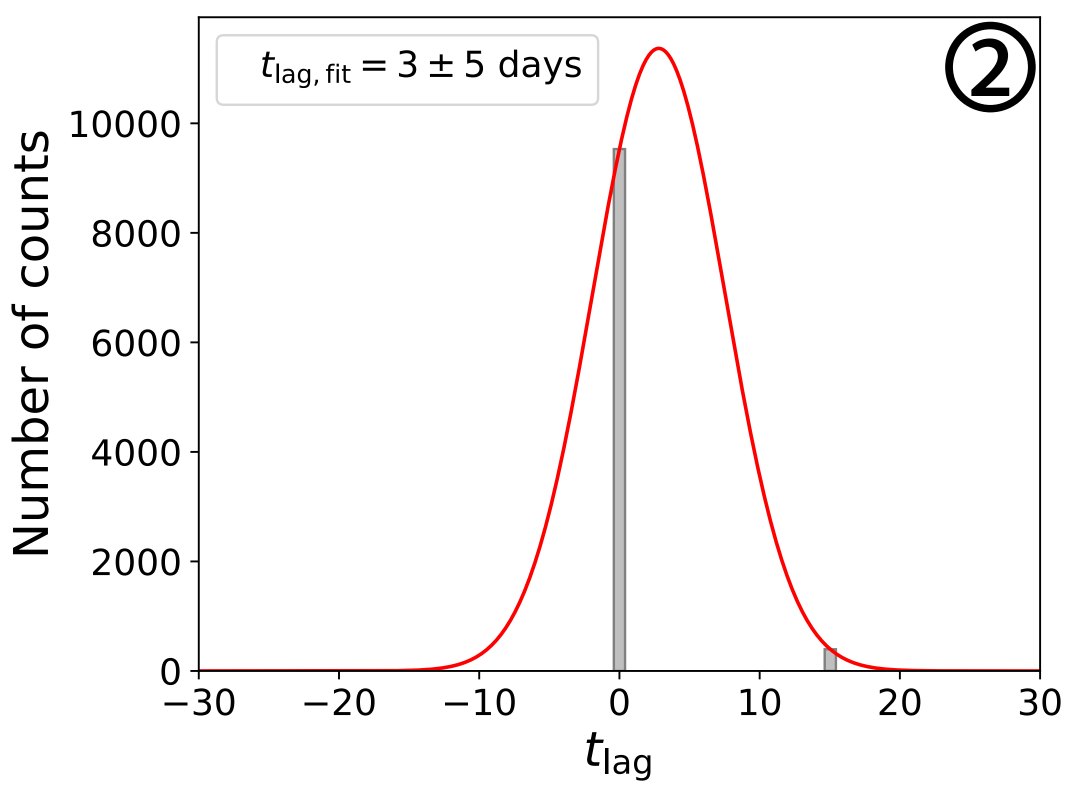
0,000th

Model implementation is described in Emmanoulopoulos+2013

FRRSS Method by Peterson+1994

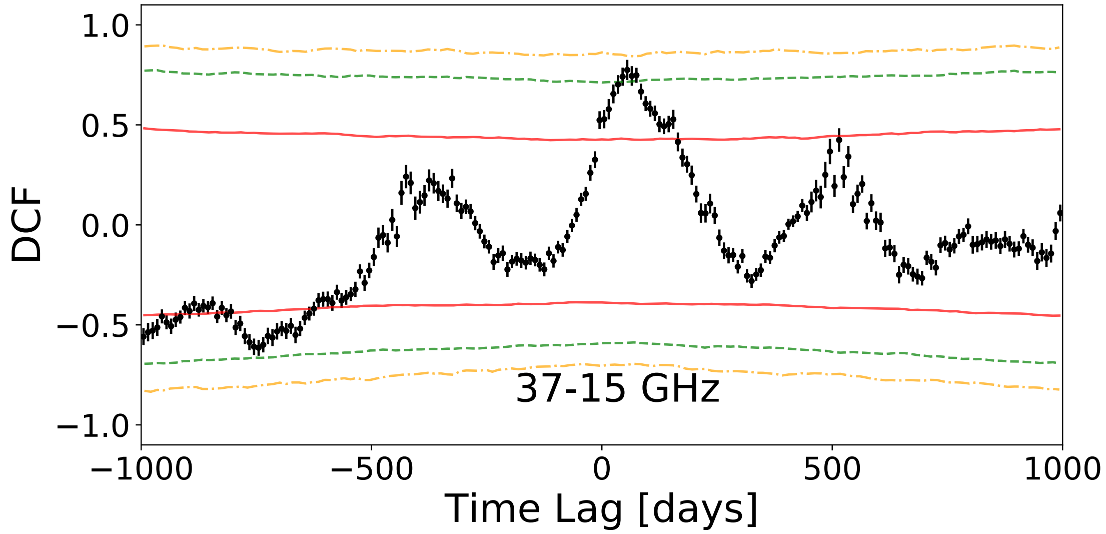


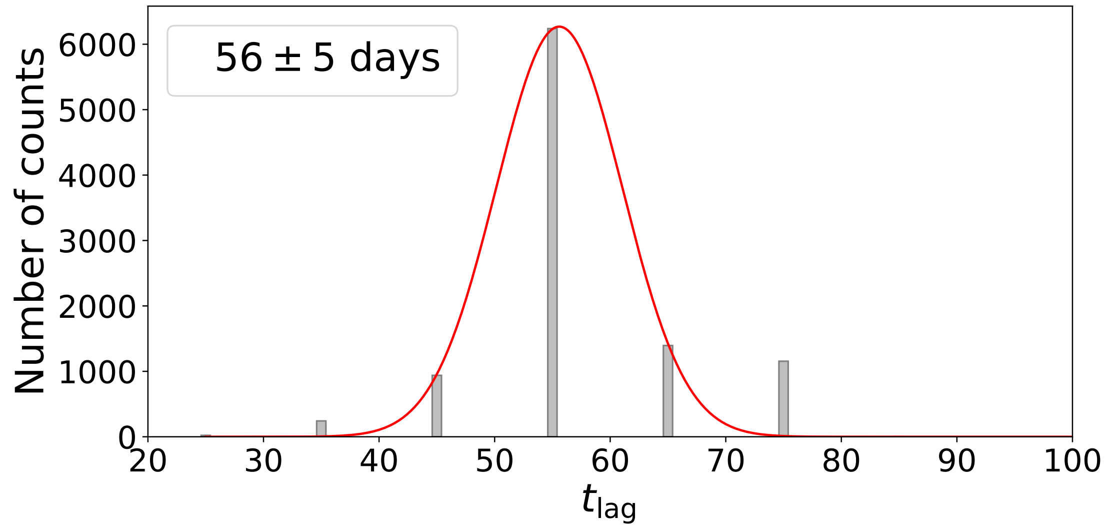


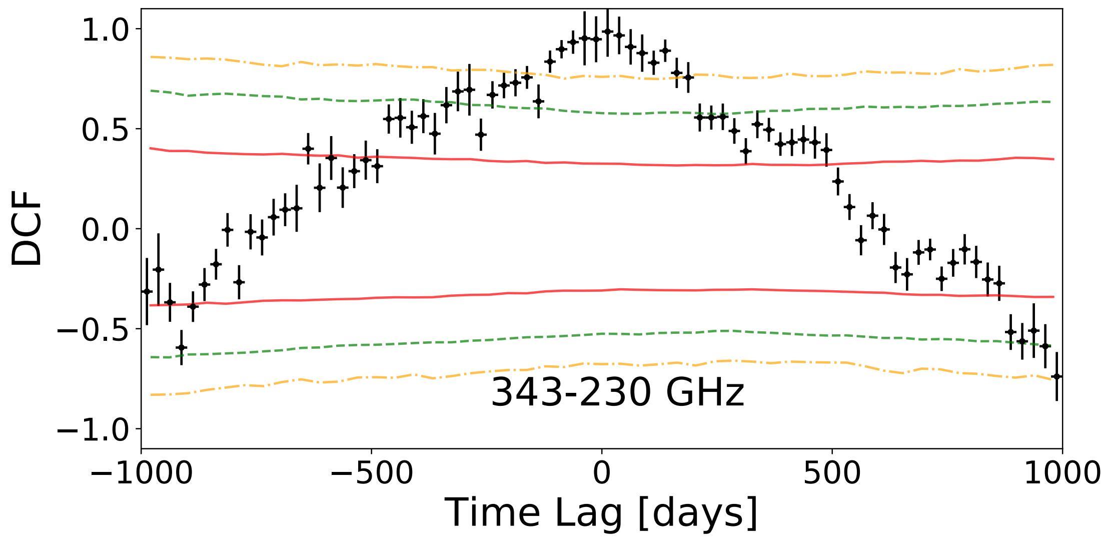


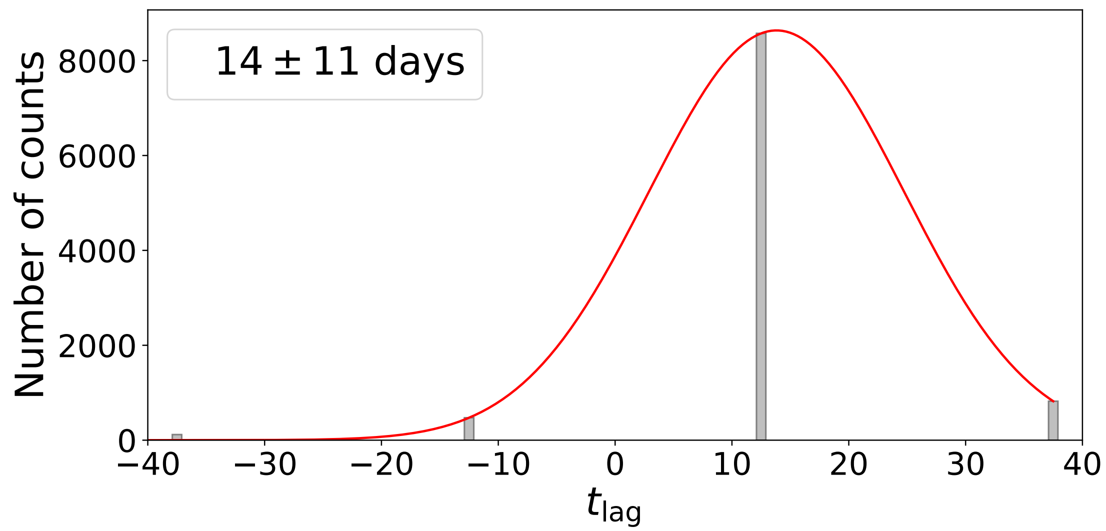
* **FR - Flux Randomization**
RSS - Random Subset Selection

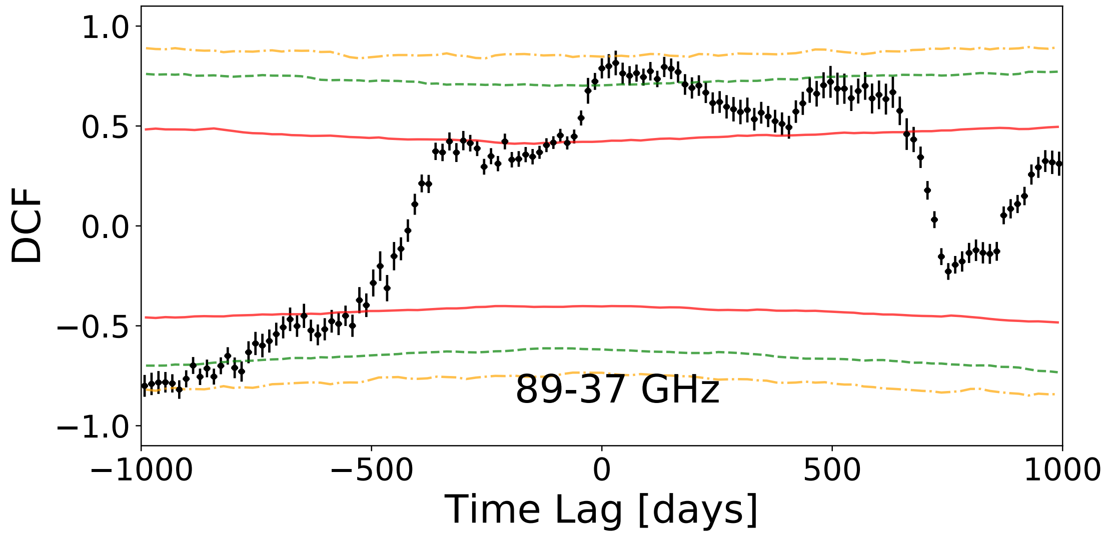
Radio - Radio Correlations

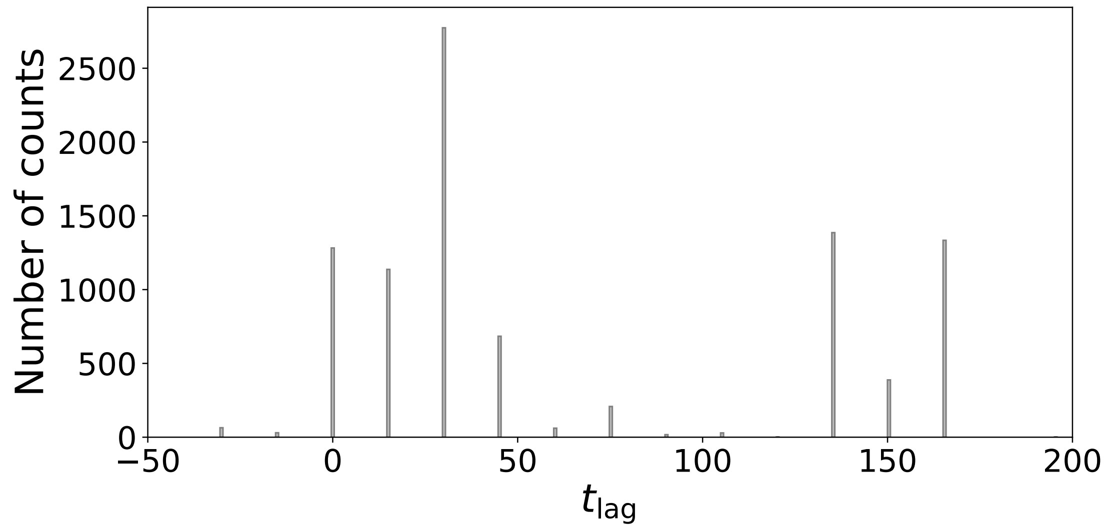




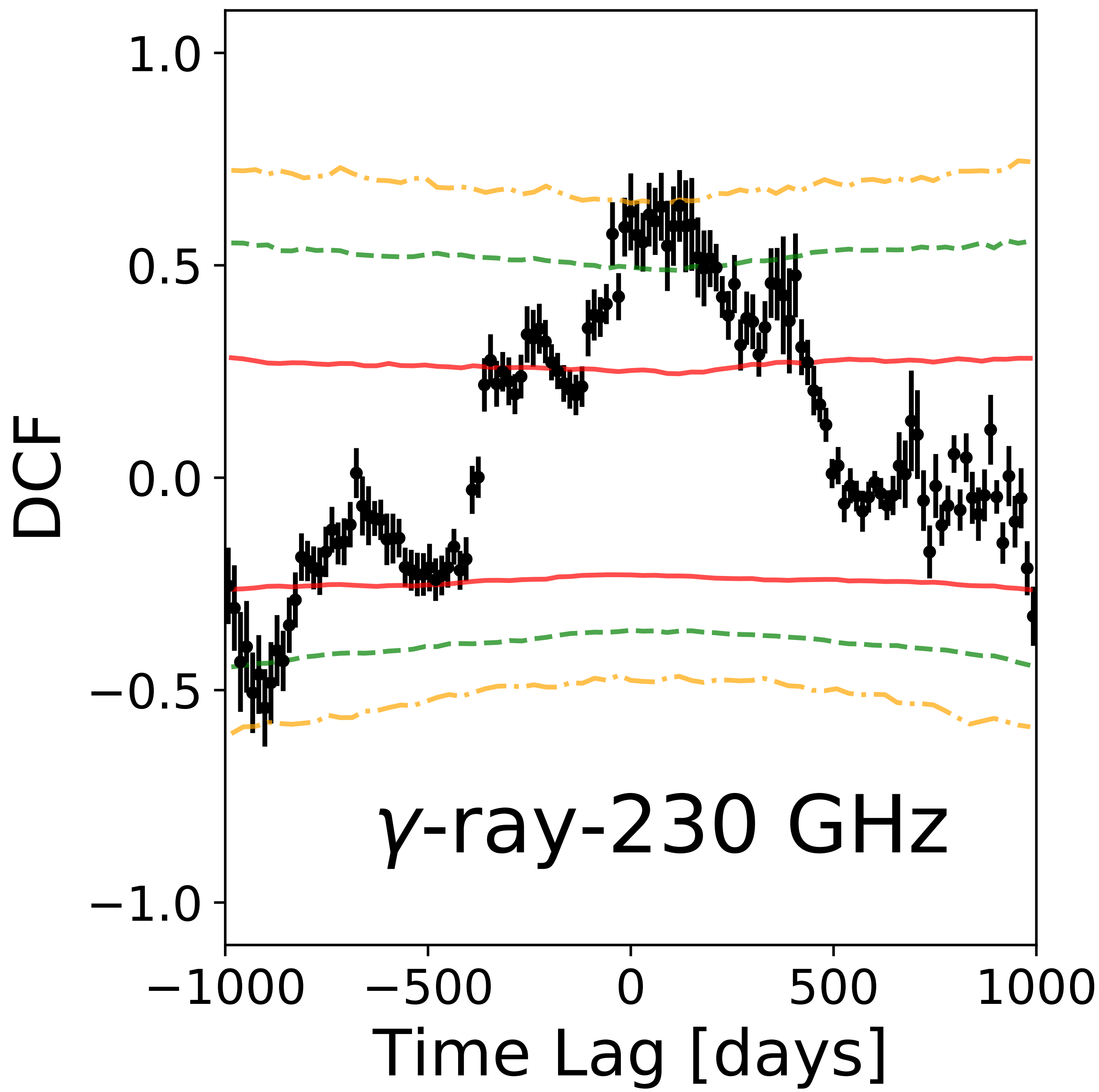


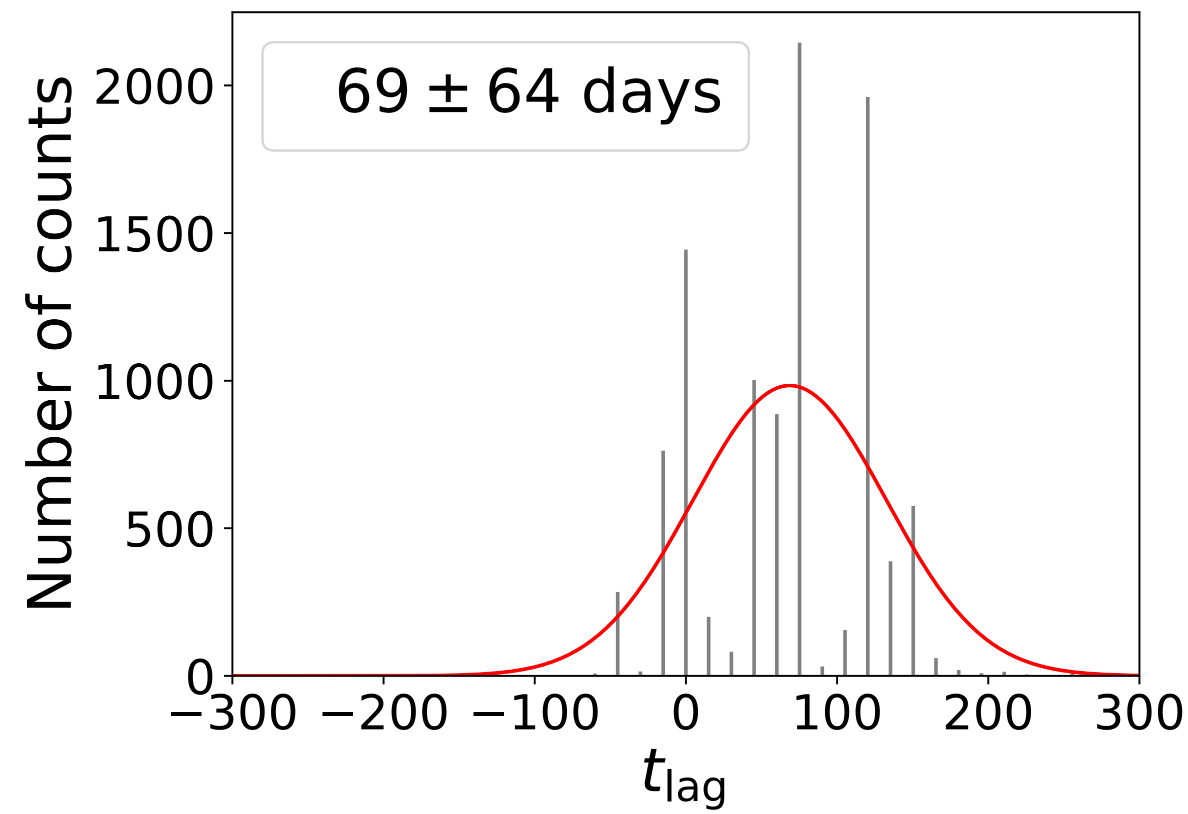




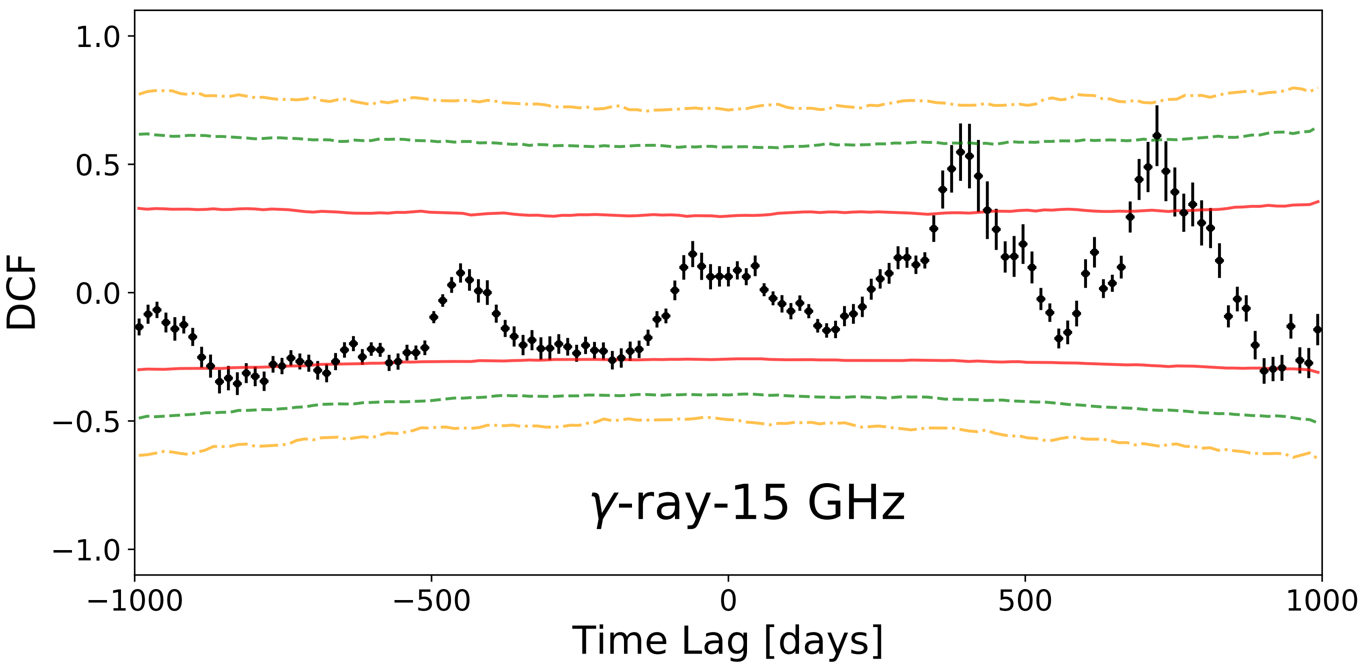


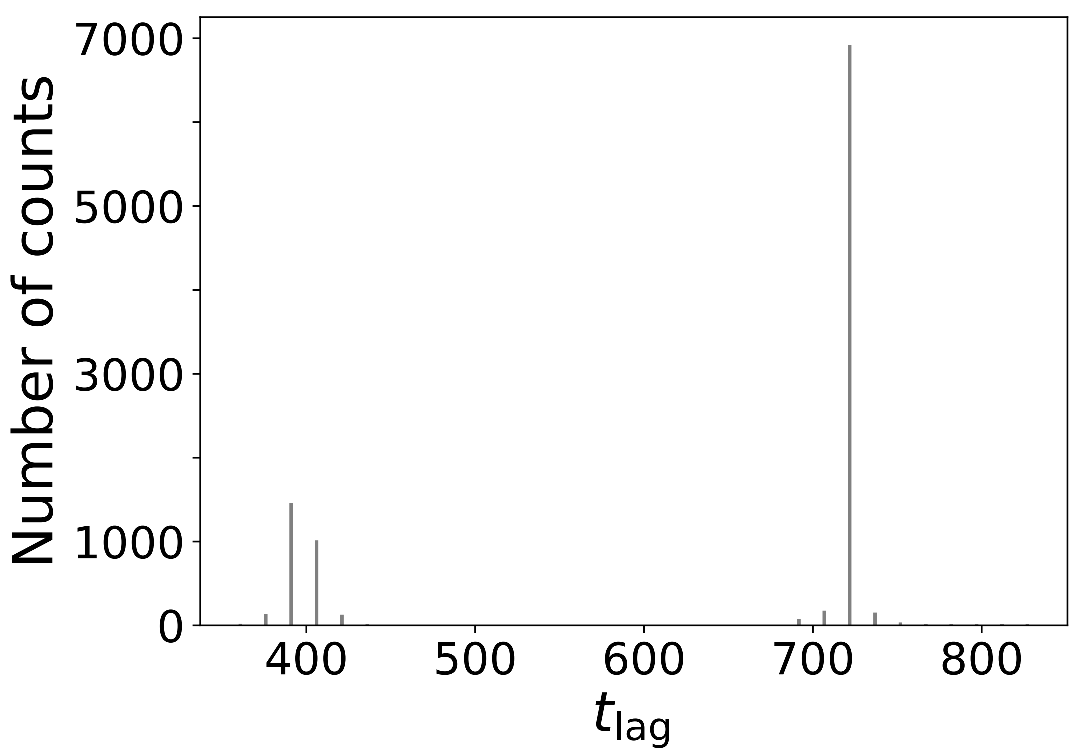
Radio - γ-ray Correlations

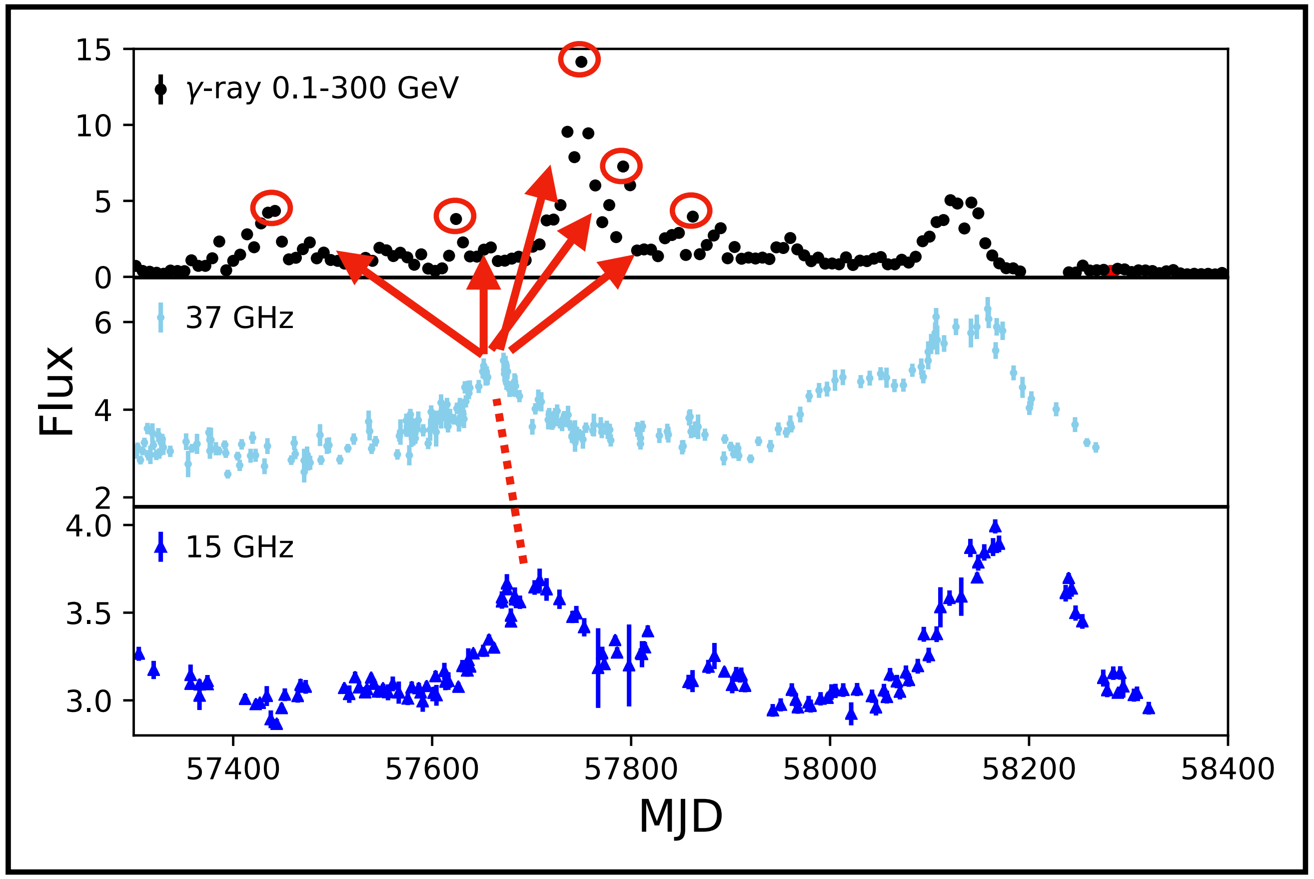




Radio - γ-ray Correlations

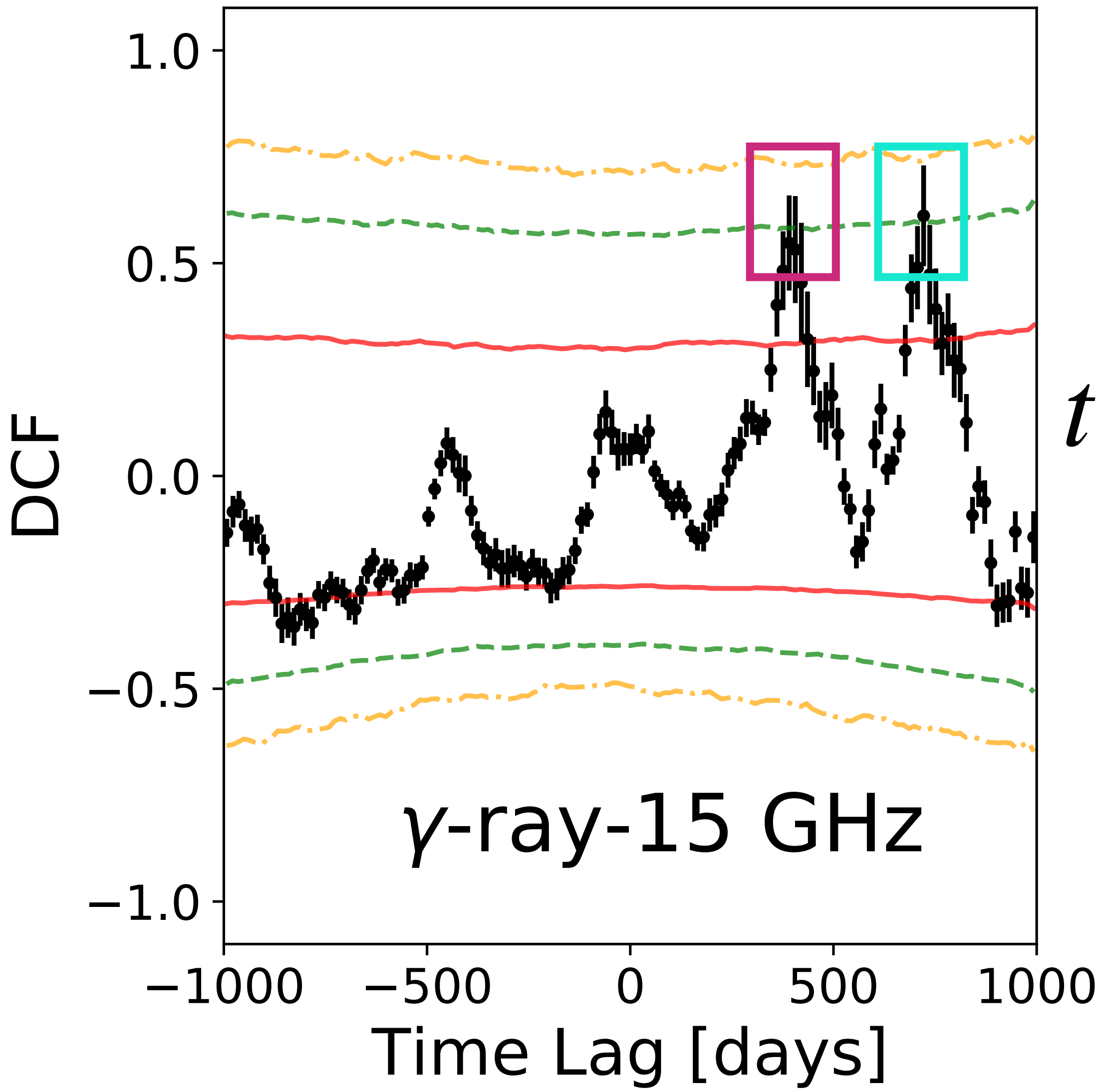




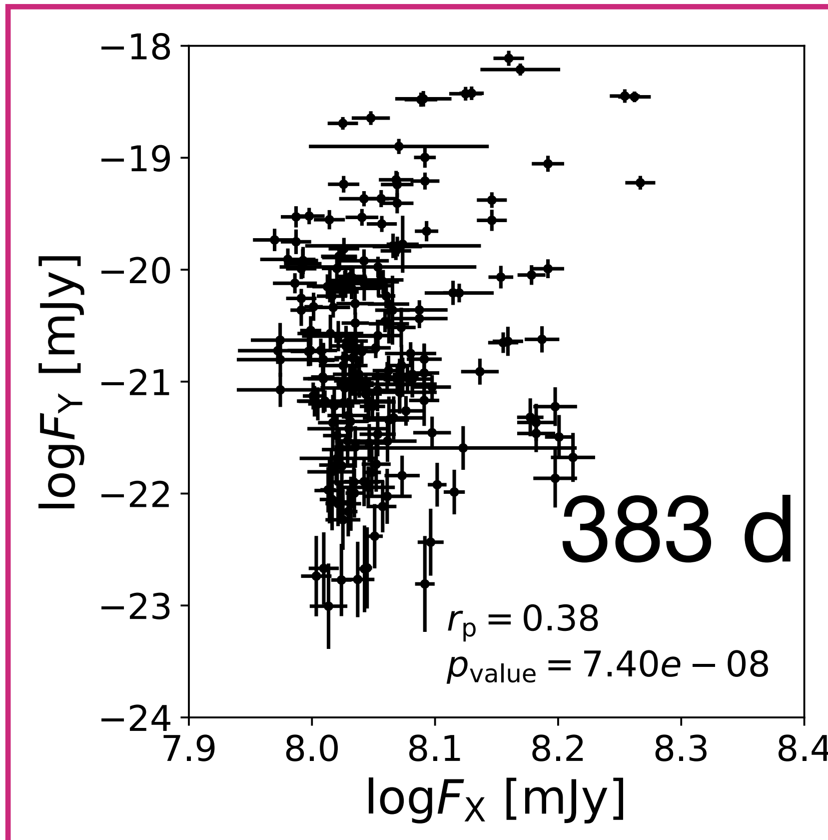


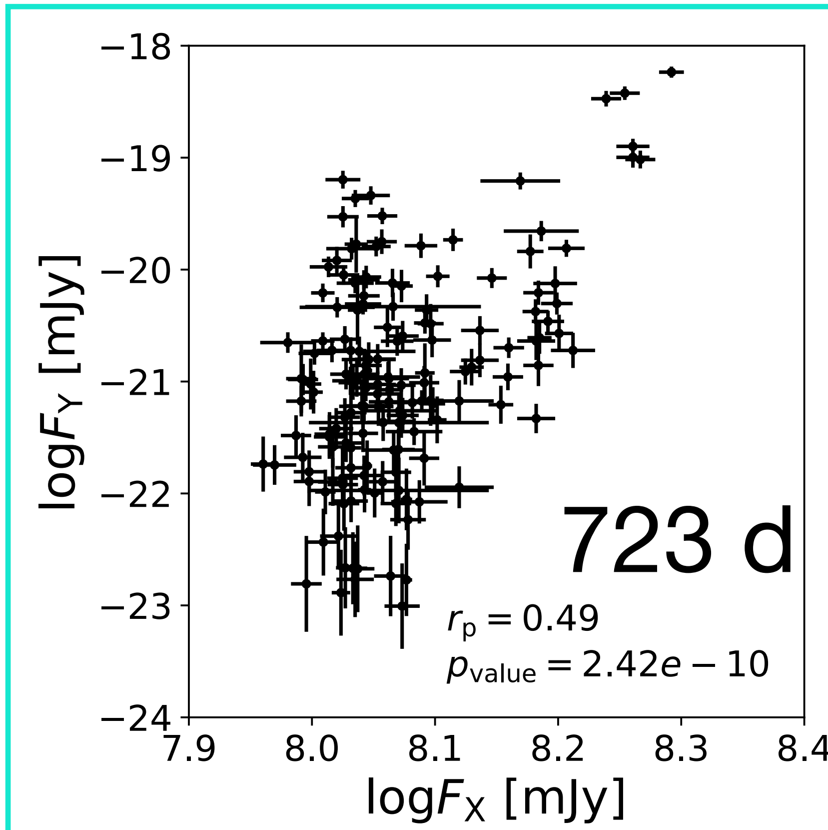
To "cross-check" the consistency of DCF results …

Not sure the correlation between the radio($\nu \leq 37$ GHz) - γ-ray



t shifted by t_{lag}





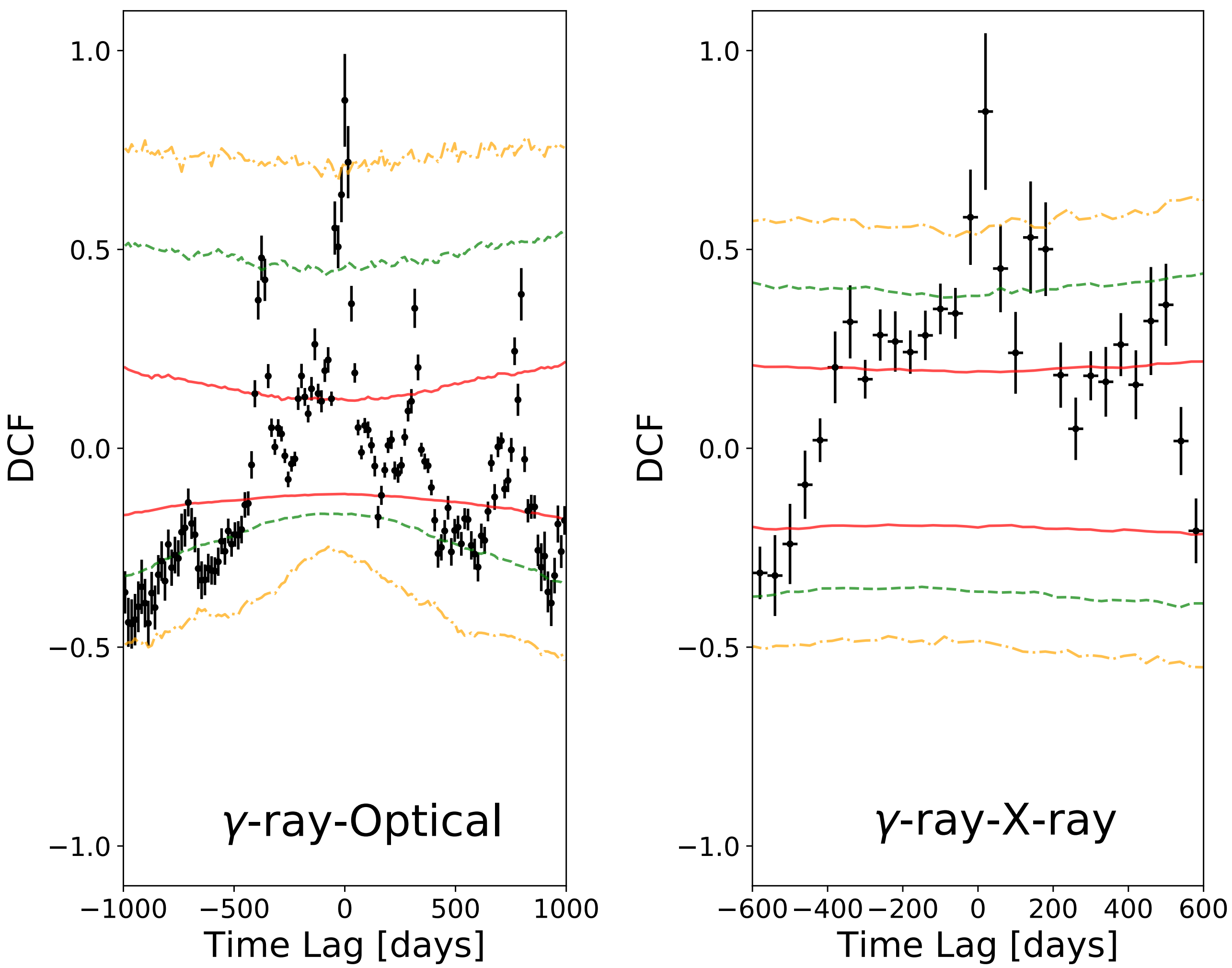
* r_{p}: Linear Pearson correlation coefficient

Confidence level = $1 - p_{\mathrm{value}}$

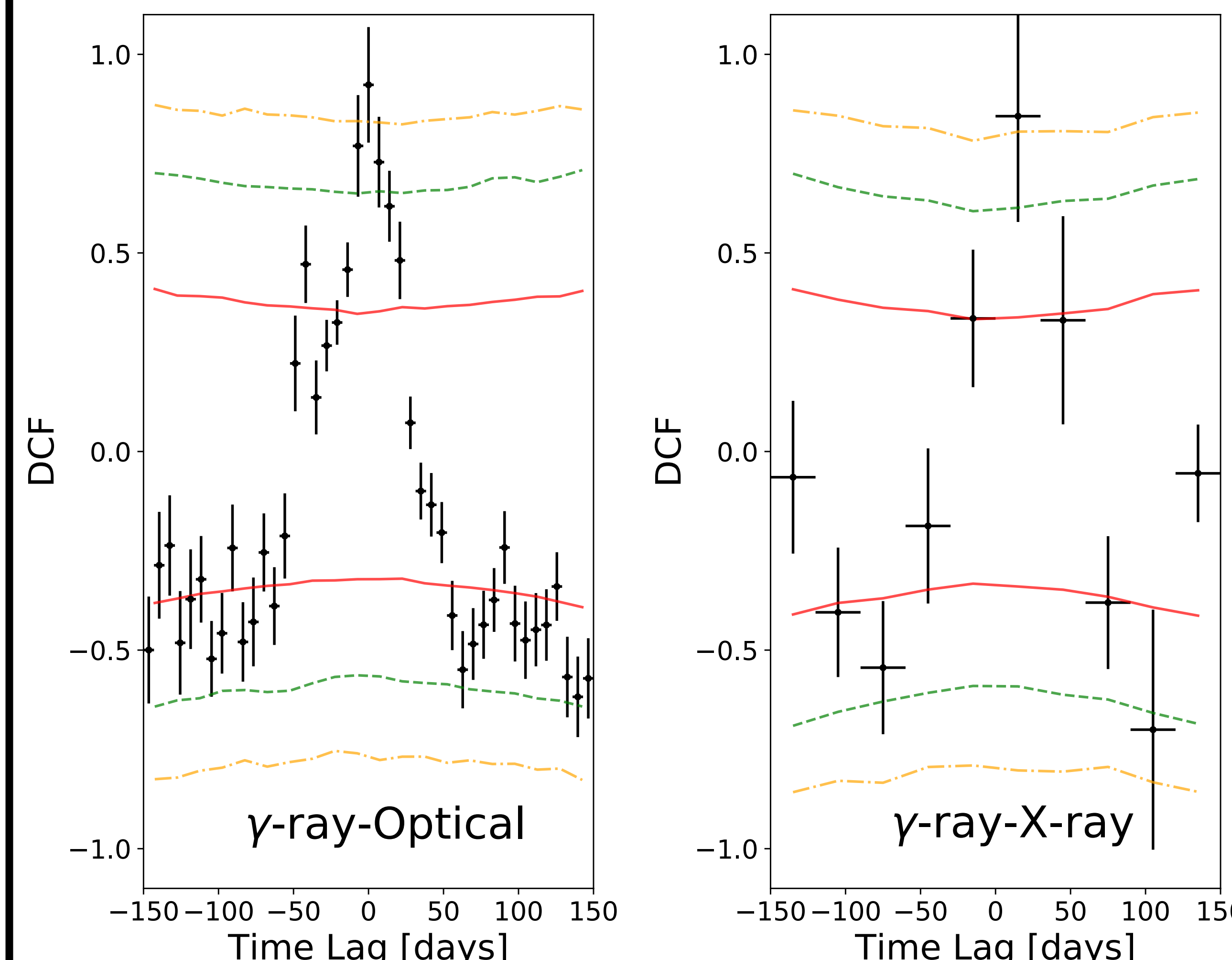
Optical/X-ray - γ-ray Correlations

Around “**zero**” time lag for the γ-ray - Optical emission!

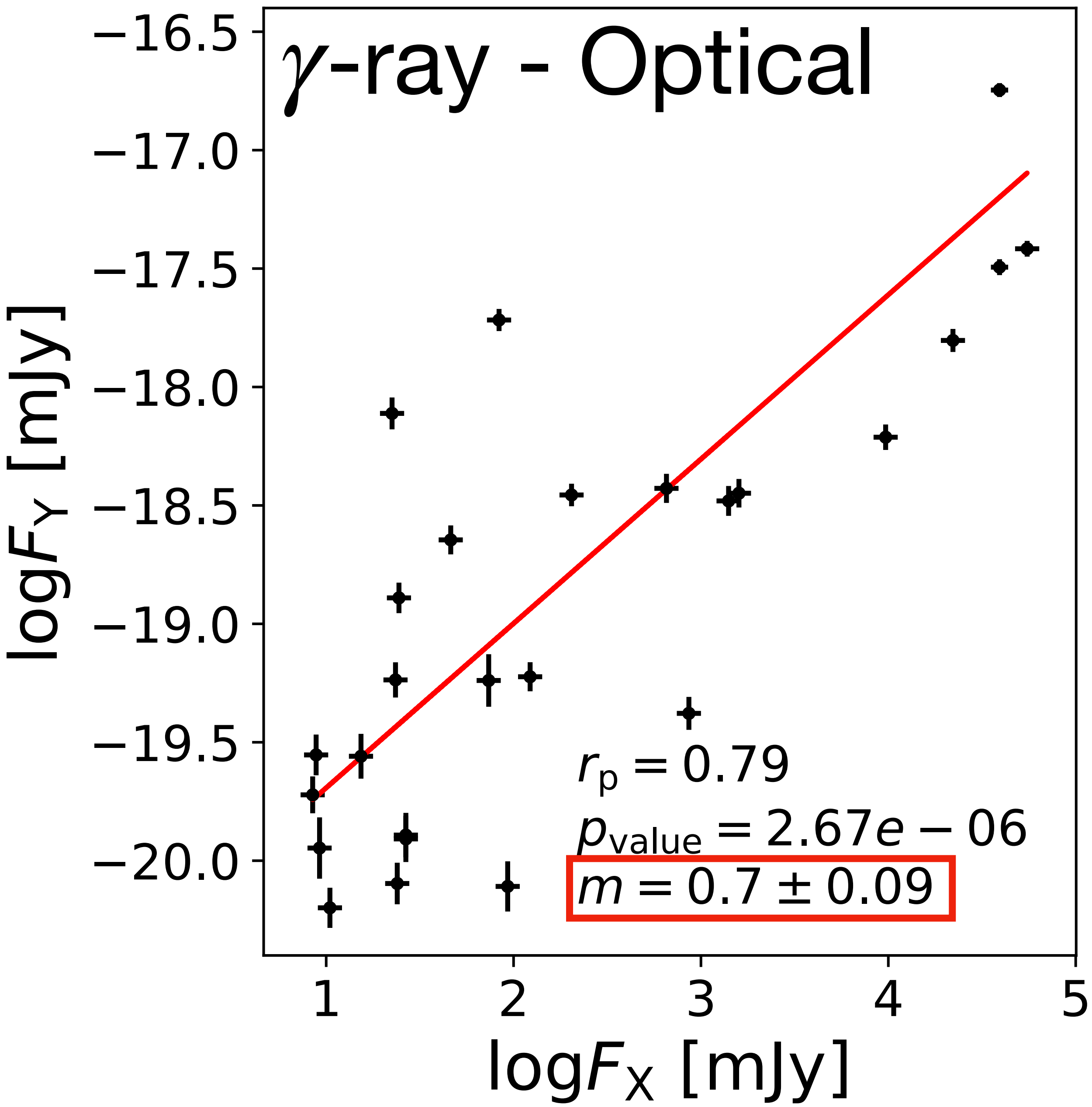
Whole period
Dec 2012 - Oct 2018



Flare 3



External Compton scattering - Flare 3's mechanism

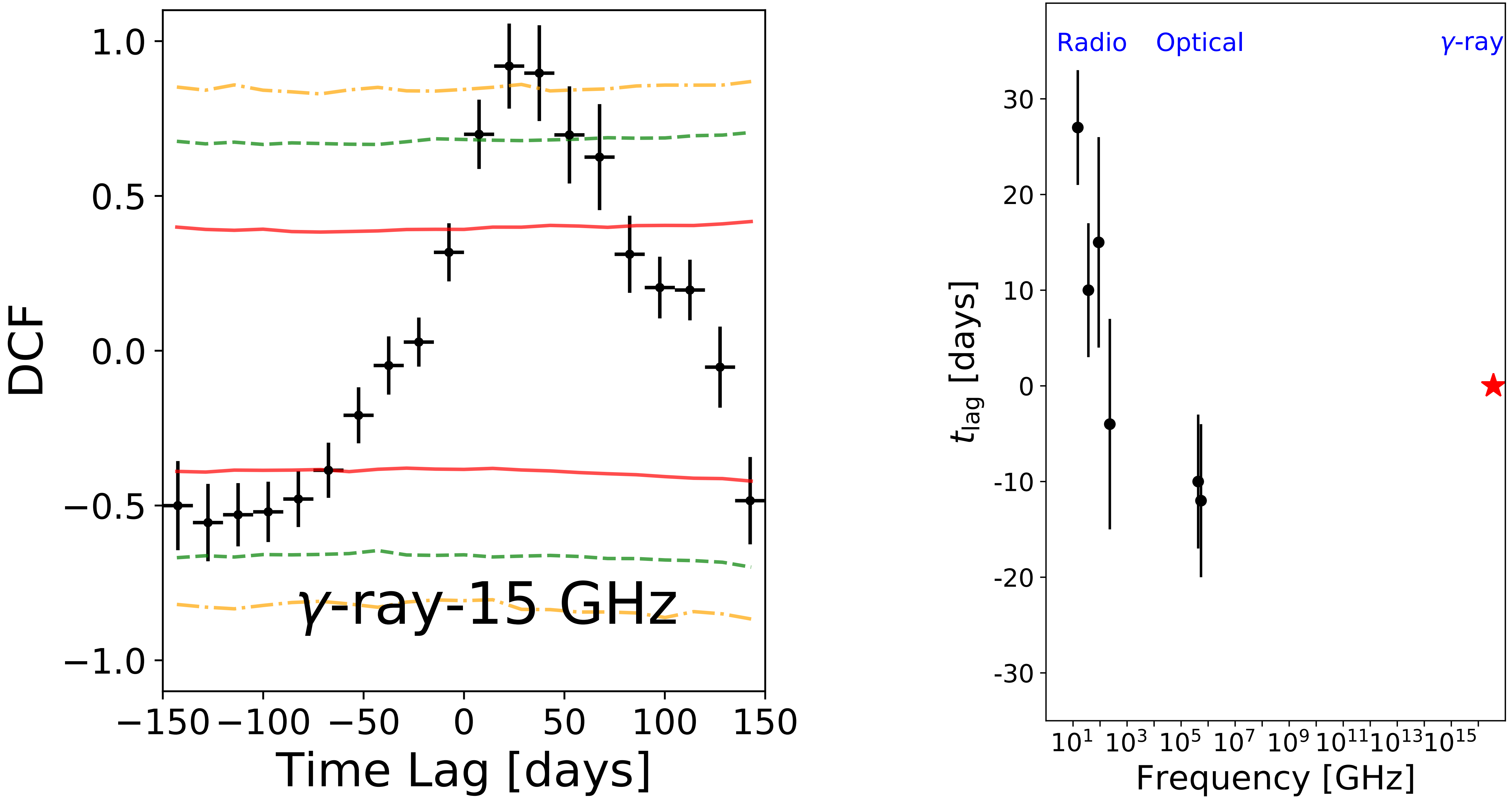


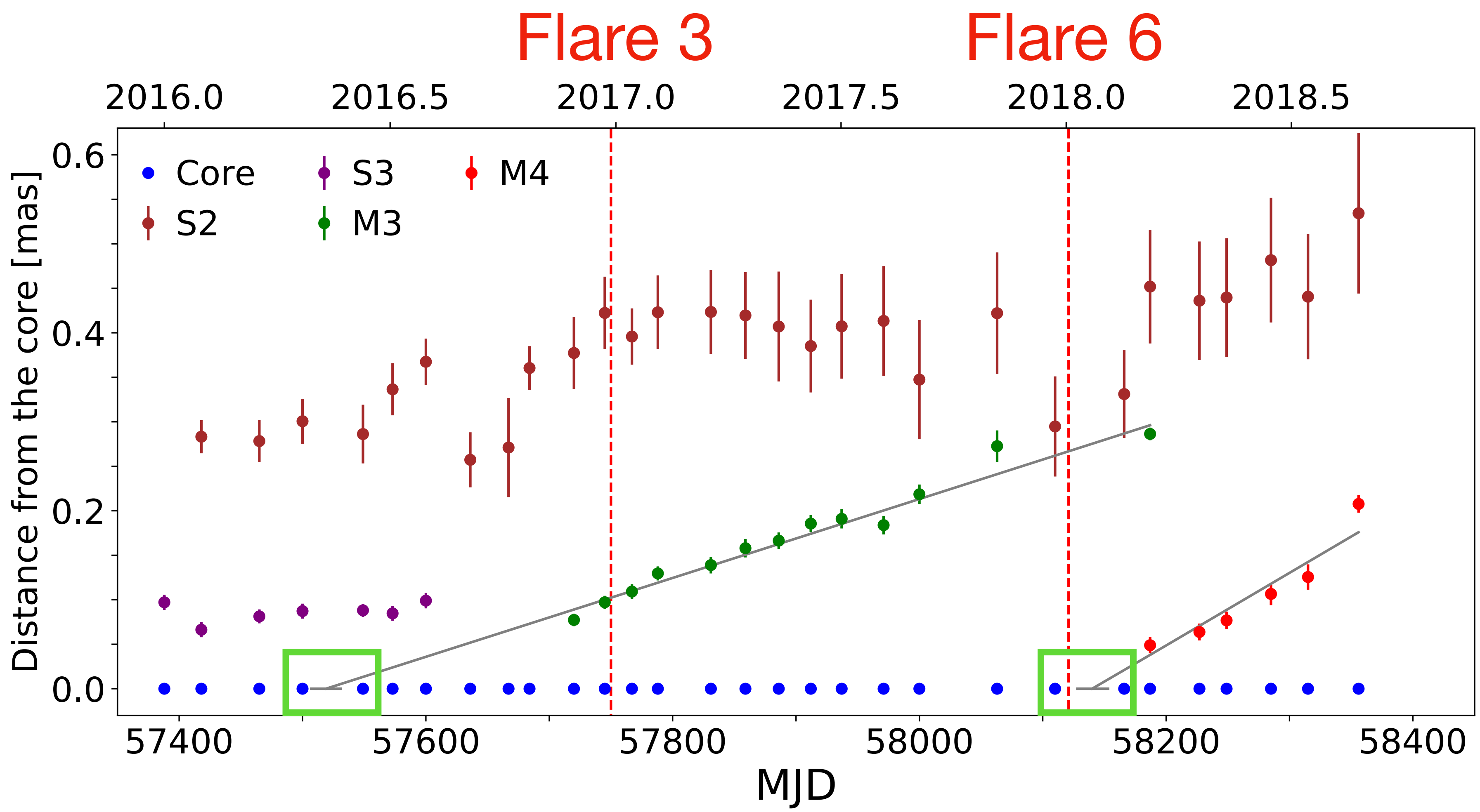
Flux-Flux Relation $F_{IC} \propto F_{syn}^m$

$F_{IC} \propto F_{syn}^m \Rightarrow \log F_{IC} \sim 1 \times \log F_{syn}$

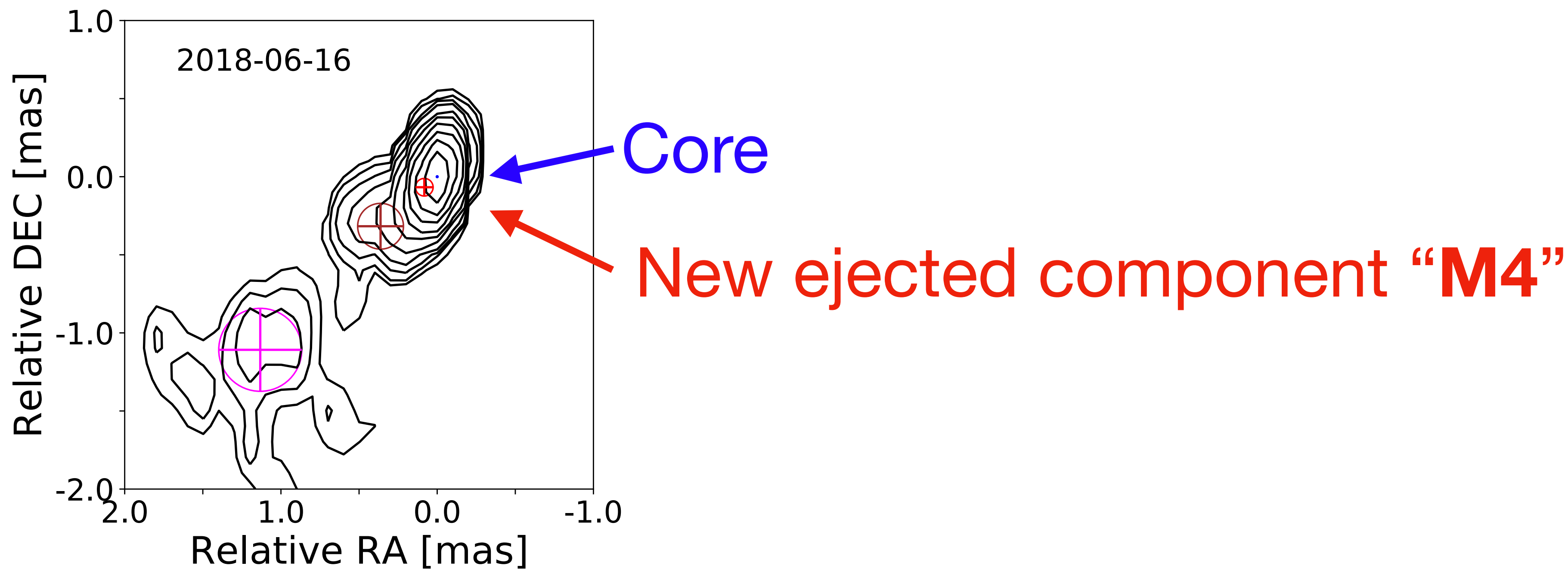
γ-ray Correlations: Flare 6

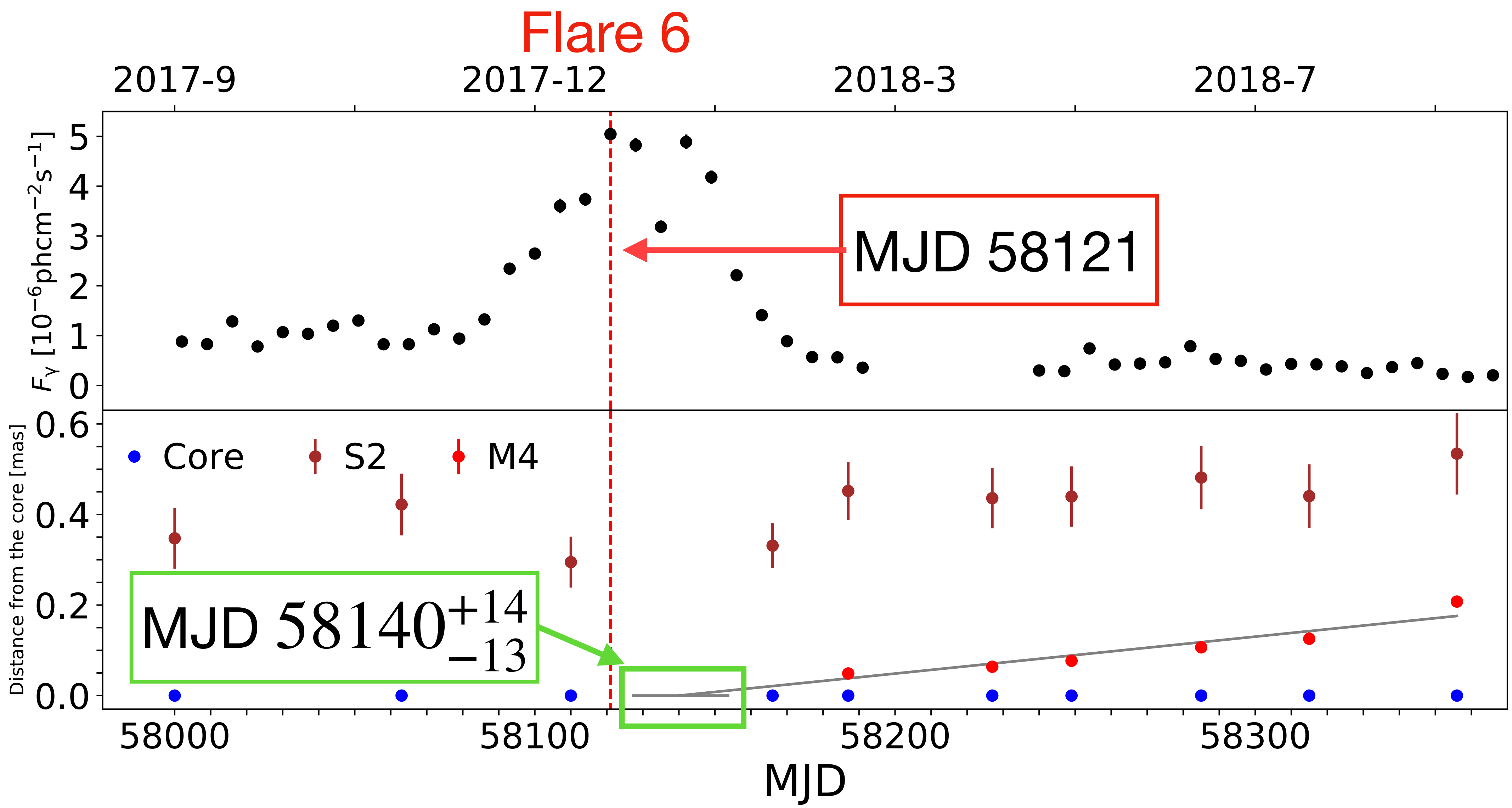
γ-ray shows significant correlations with other frequencies!





Ejection of "new" jet components





$t_{\text{lag,37-gamma}} = 10 \pm 7$ days

Method is adopted from Pushkarev+2010

MJD 58140^{+14}_{-13} - MJD 58121 $\approx t_{\text{lag,37-gamma}}$ ⇨ $d_{\text{radio}-\gamma-\text{ray}} \sim 3.29$ pc

d_{radio} ~ 8-11 pc from the SMBH, based on the core-shift analysis (e.g., Kudryavtseva+2011)

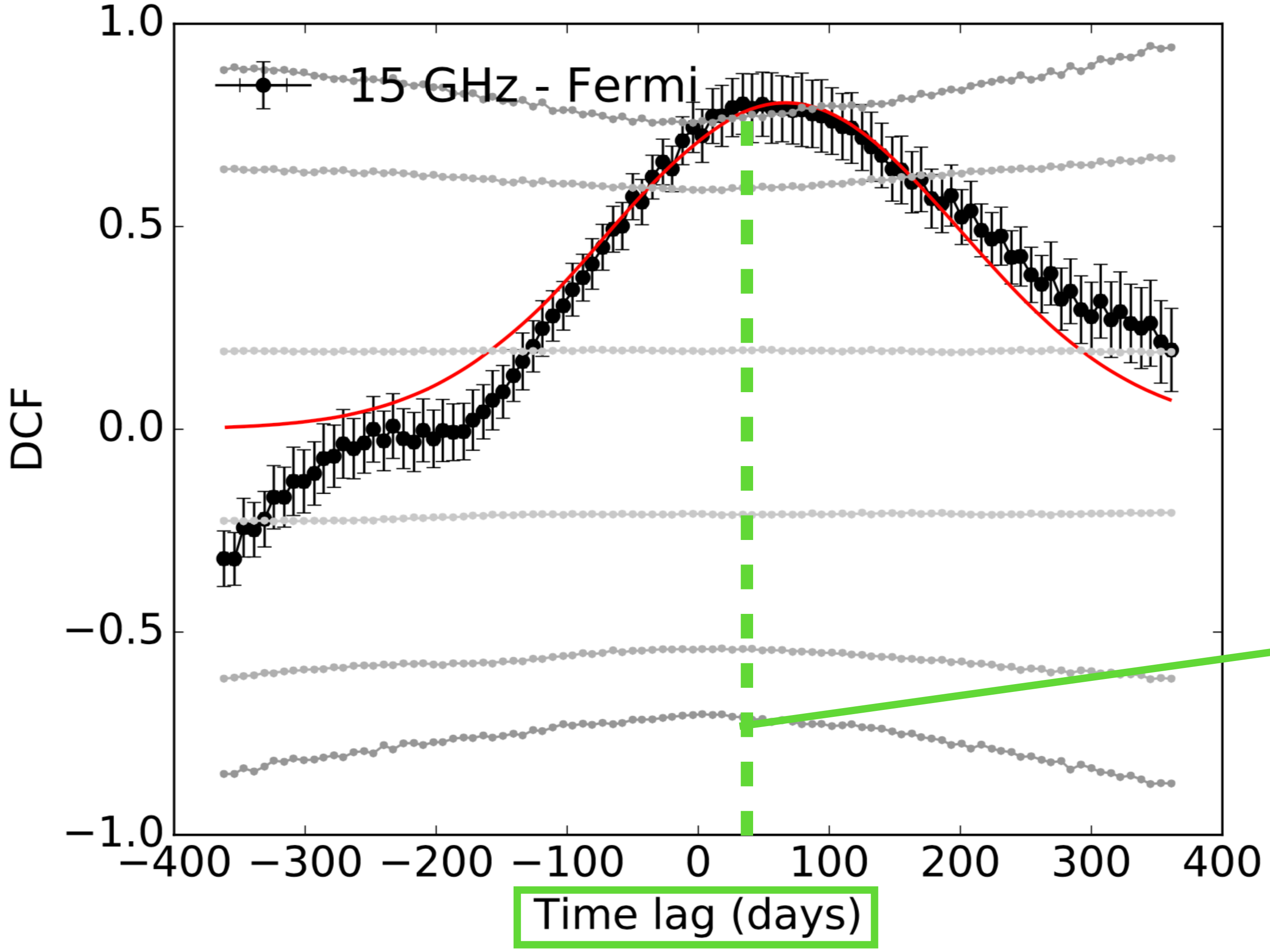
$d_{\gamma-\text{ray}}$ ~ **4-7 pc** from the SMBH

* SMBH: **S**uper**m**assive **B**lack **H**ole

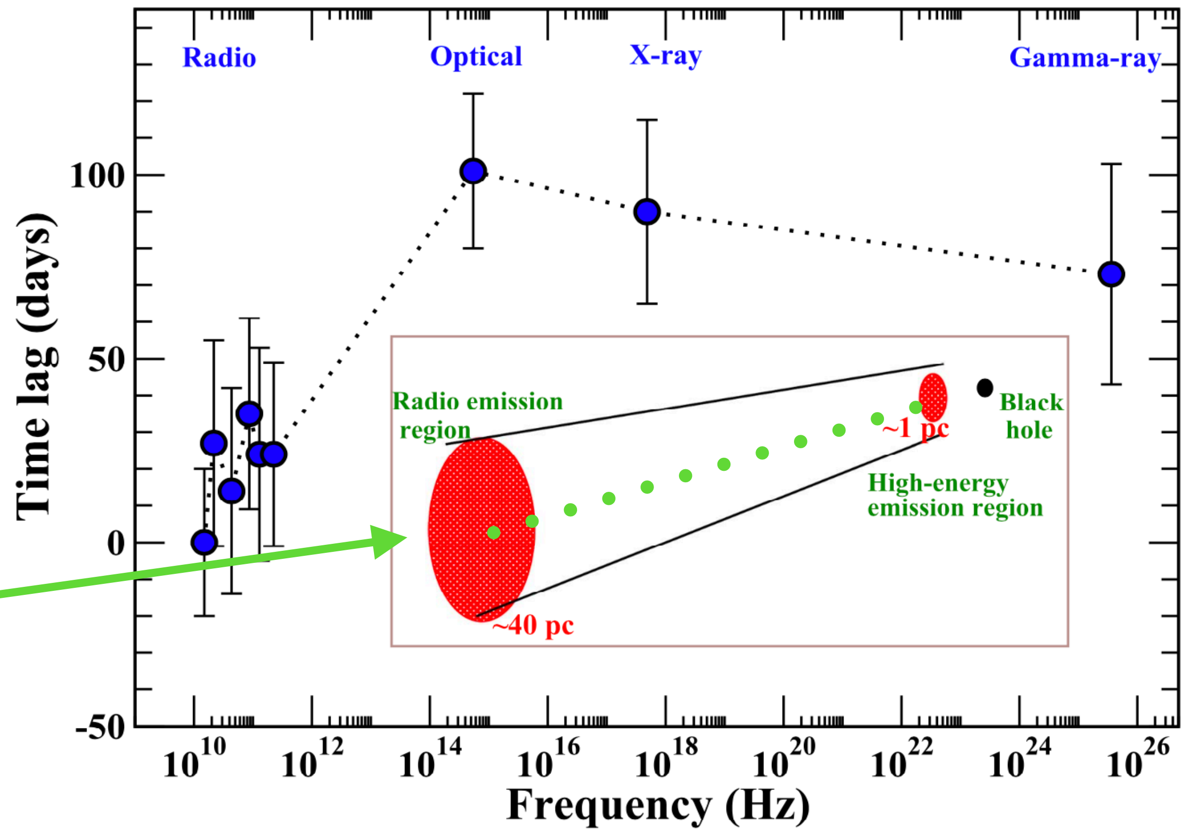
Summary

- The γ-ray emission from CTA 102 is "**significantly**" correlated with the emission at X-ray, optical, and mm-wavelengths during the period of Dec 2012 - Oct 2018.
- We are not sure that Flare 3 has radio counterparts, but infer a co-spatial origin of Flare 3 and the optical emission, indicating the external Compton scattering origin for this flare.
- Flare 6 precedes ejection of a new jet component, suggesting that this flare is produced near the radio core.

Thank you for your attention!

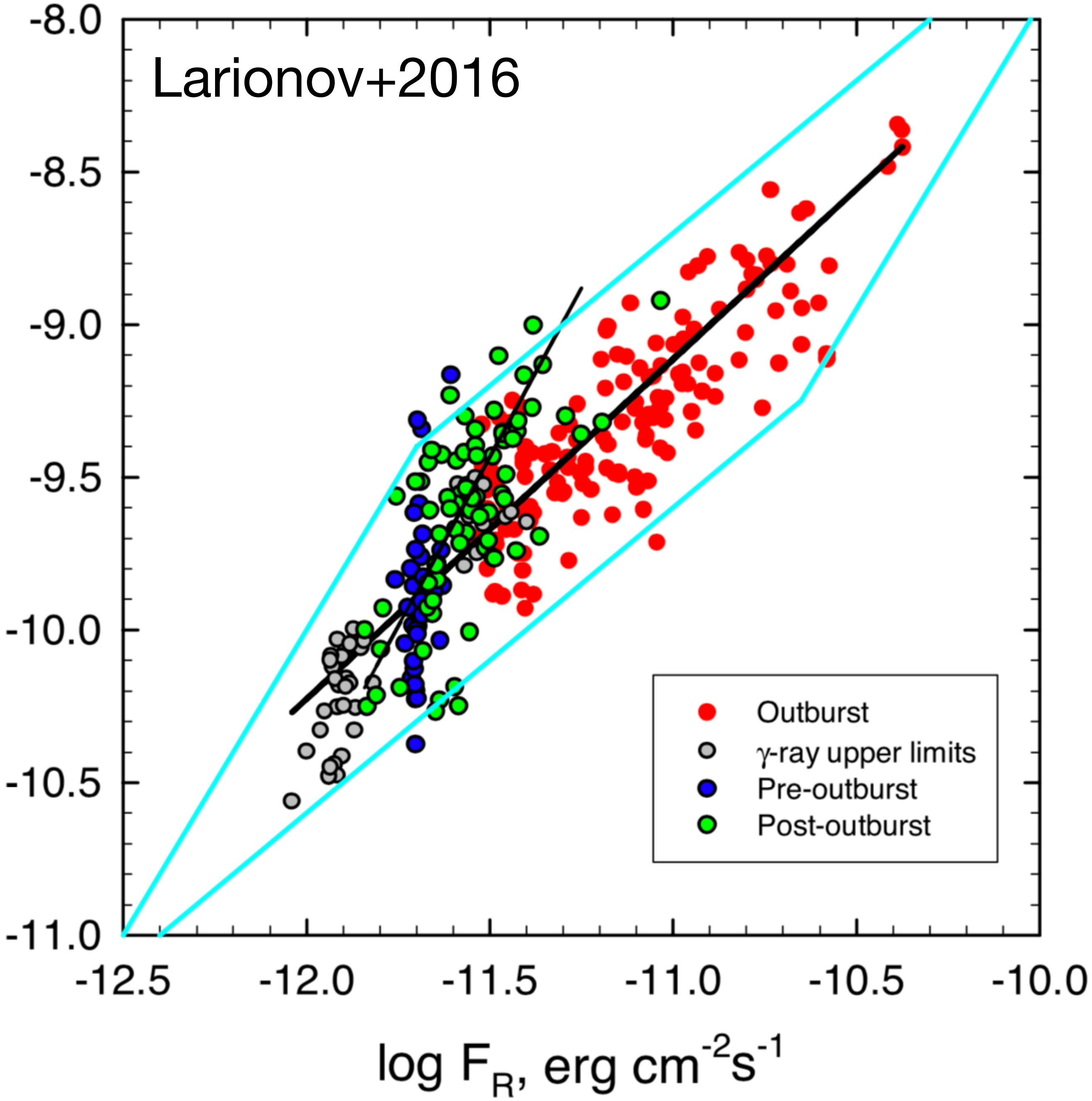


1633+382



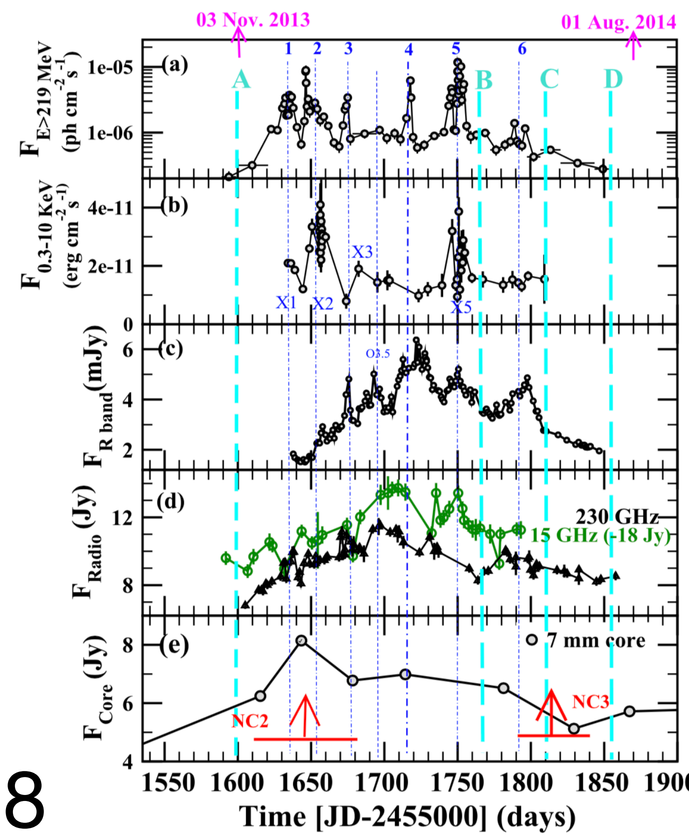
Algaba+2018a

Variability analysis

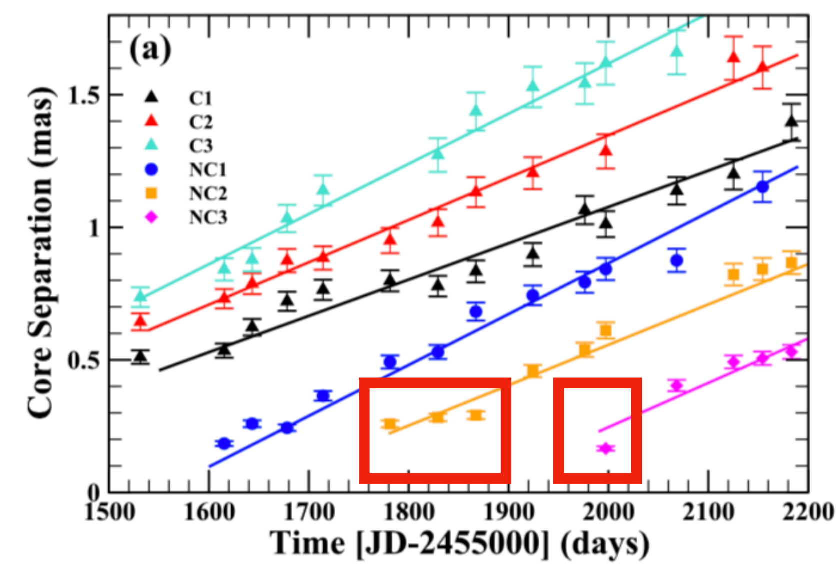


Jet kinematics

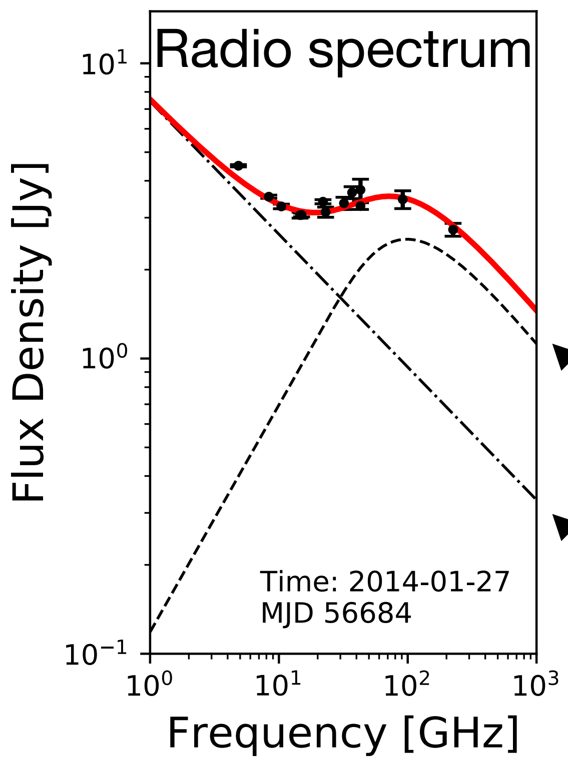
3C 279



Rani+2018



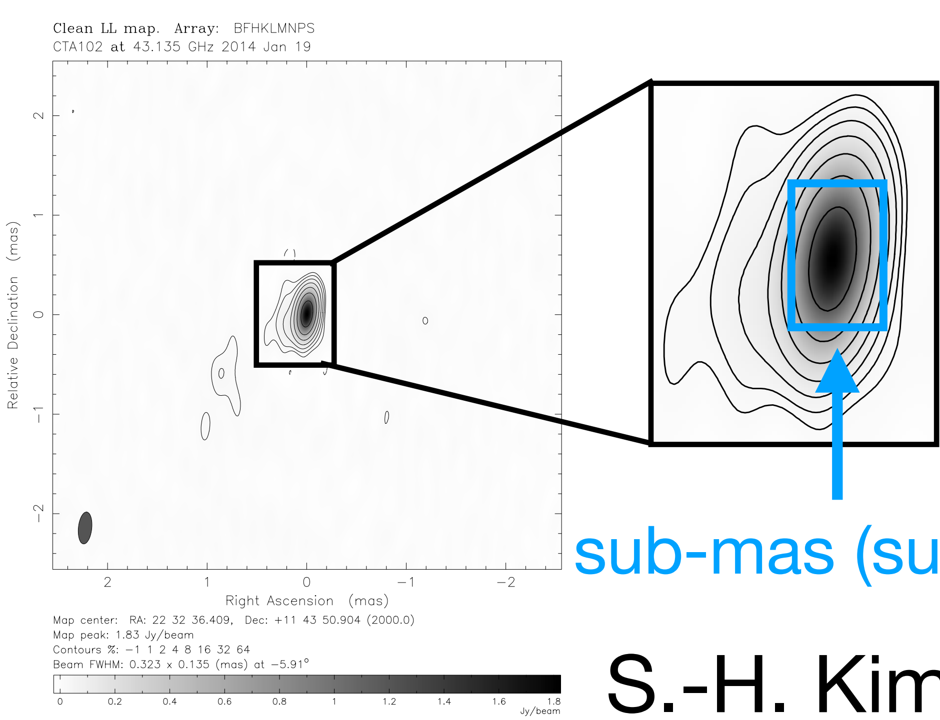
The blazar CTA 102 - Our previous study



Flaring Spectrum

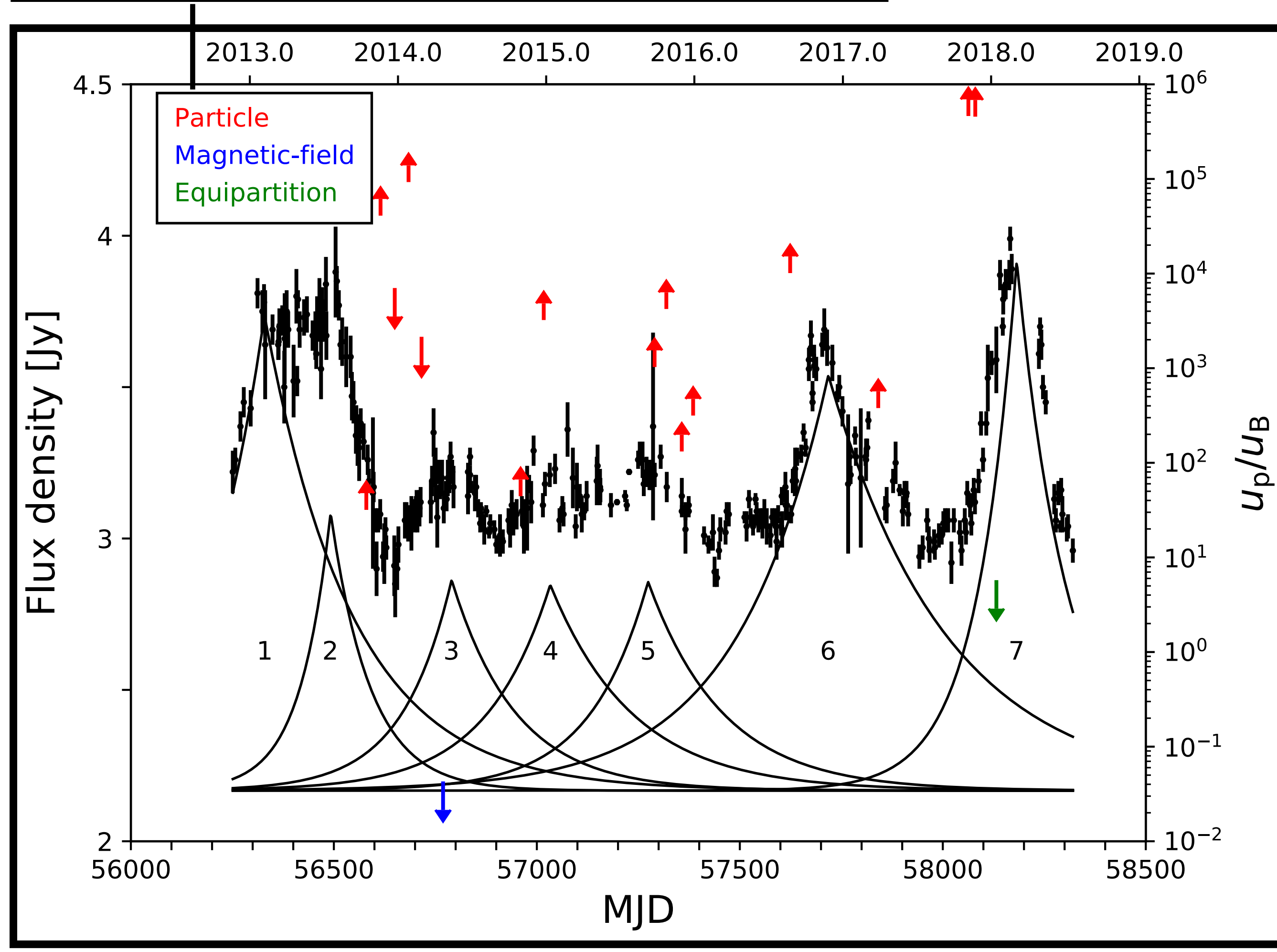
Quiescent Spectrum

⊕



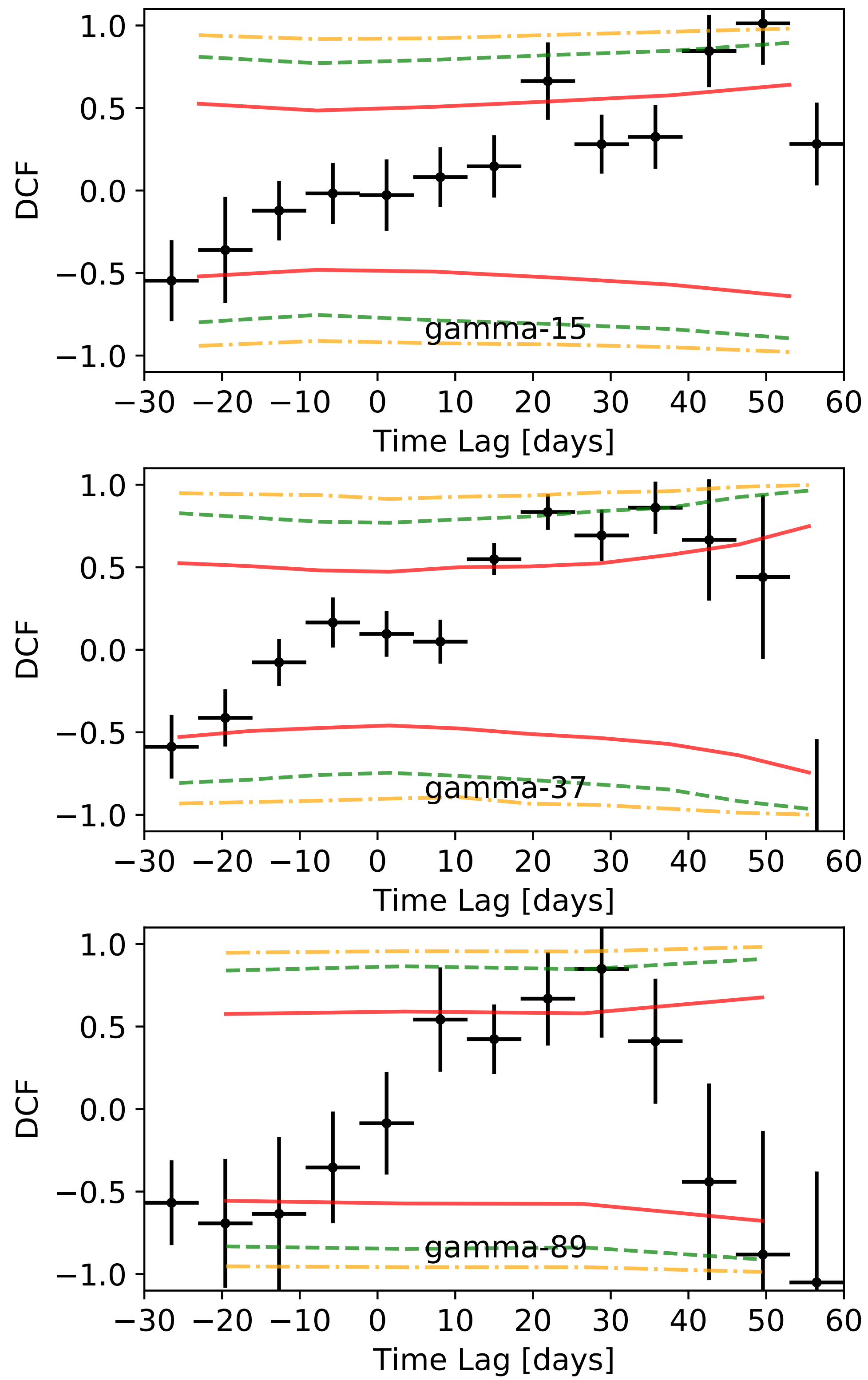
sub-mas (sub-pc)

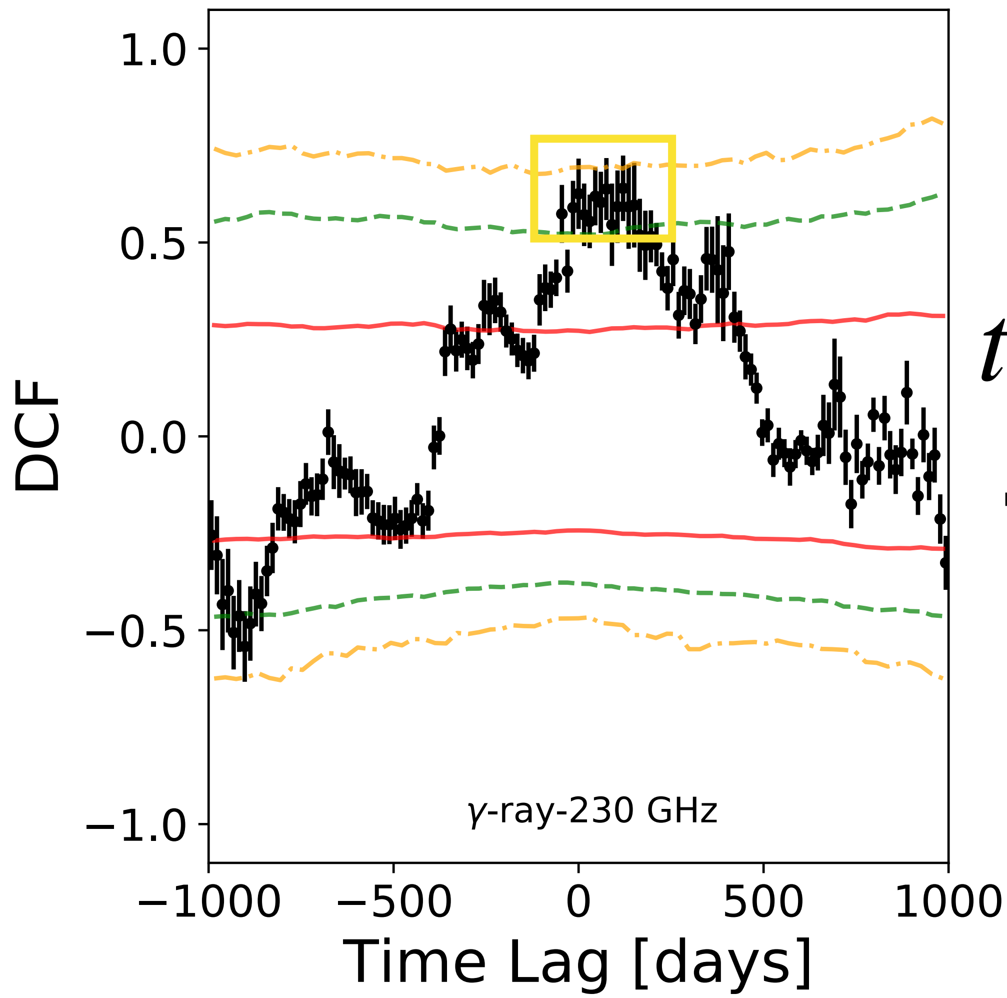
Dominant Energy Source



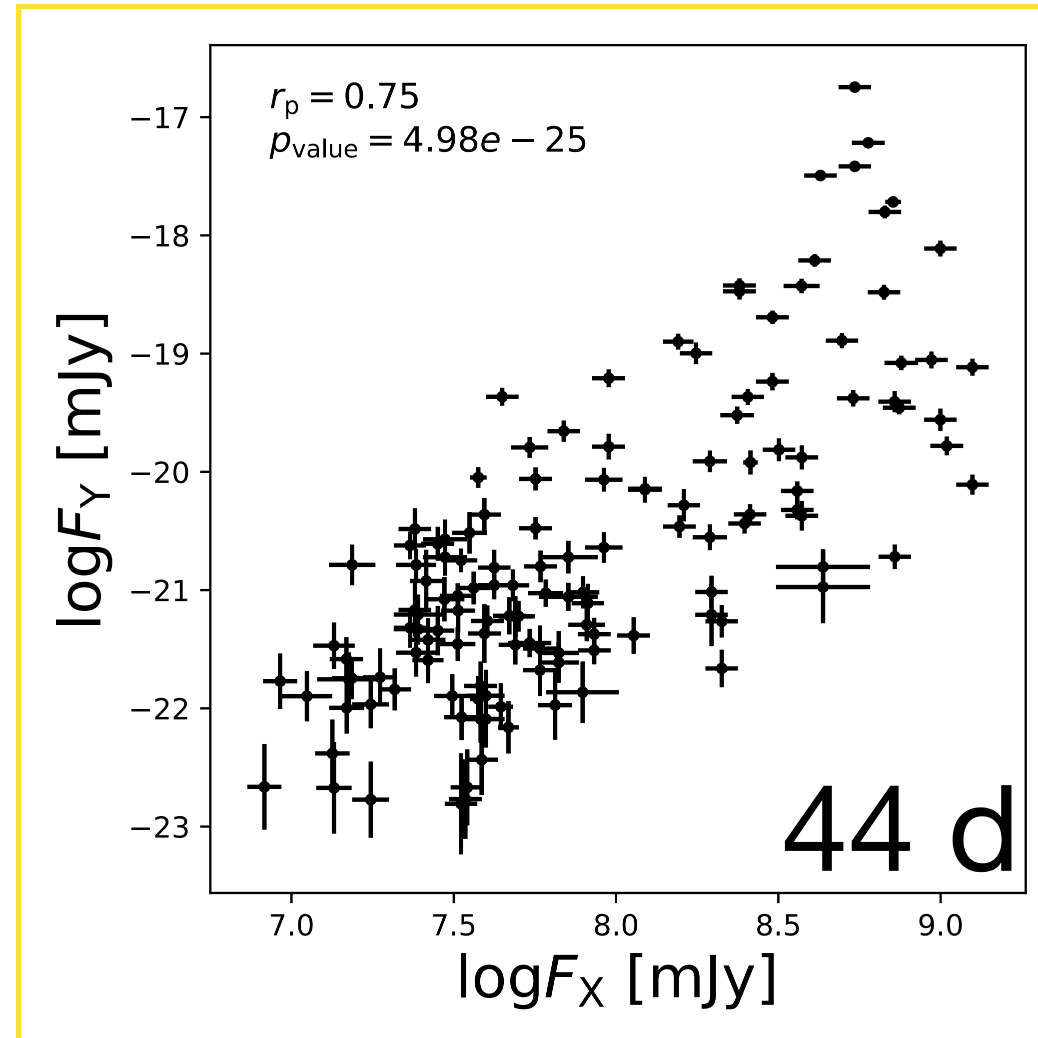
S.-H. Kim+2022

Radio - γ-ray Correlations: Flare 2





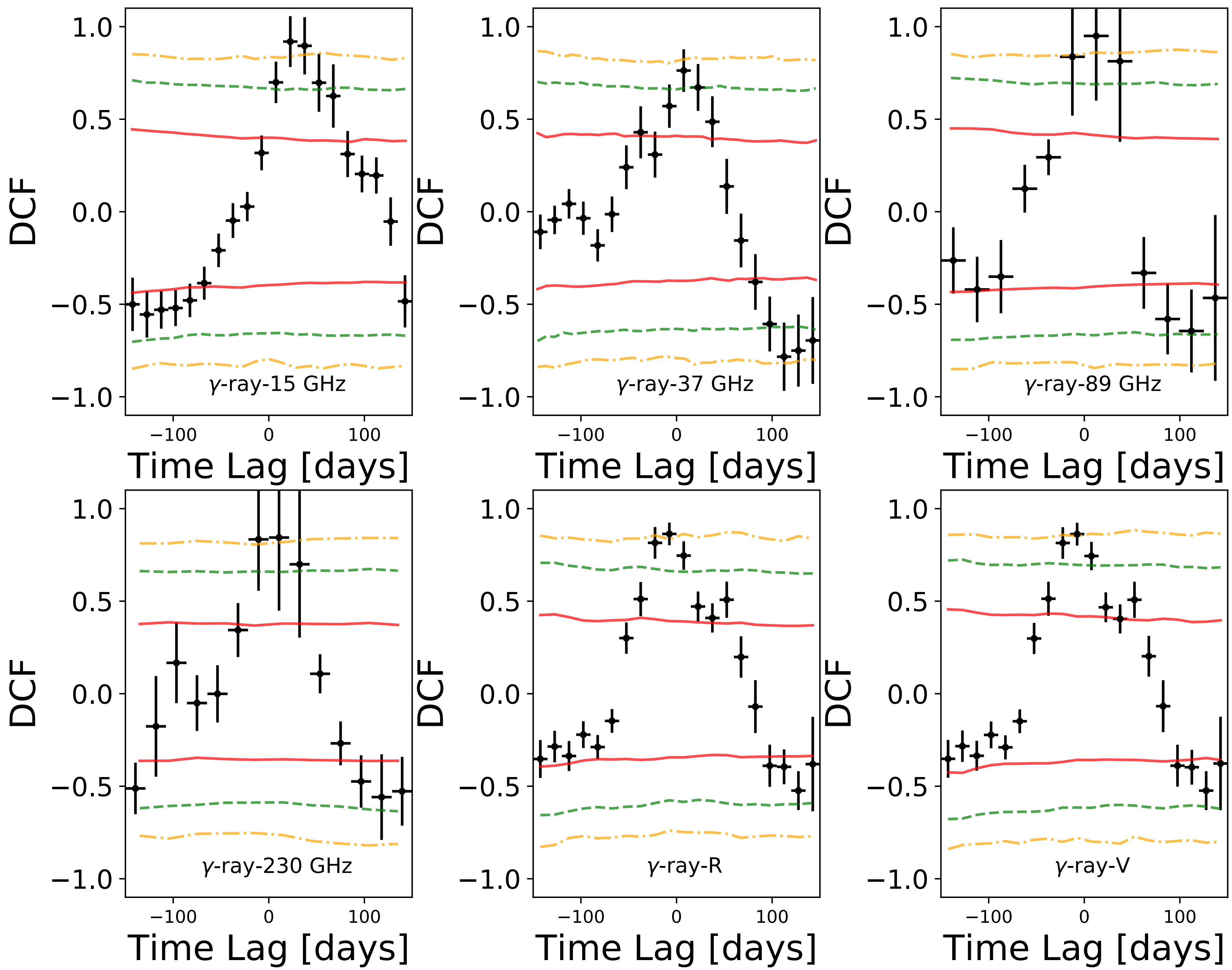
t shifted by t_{lag}



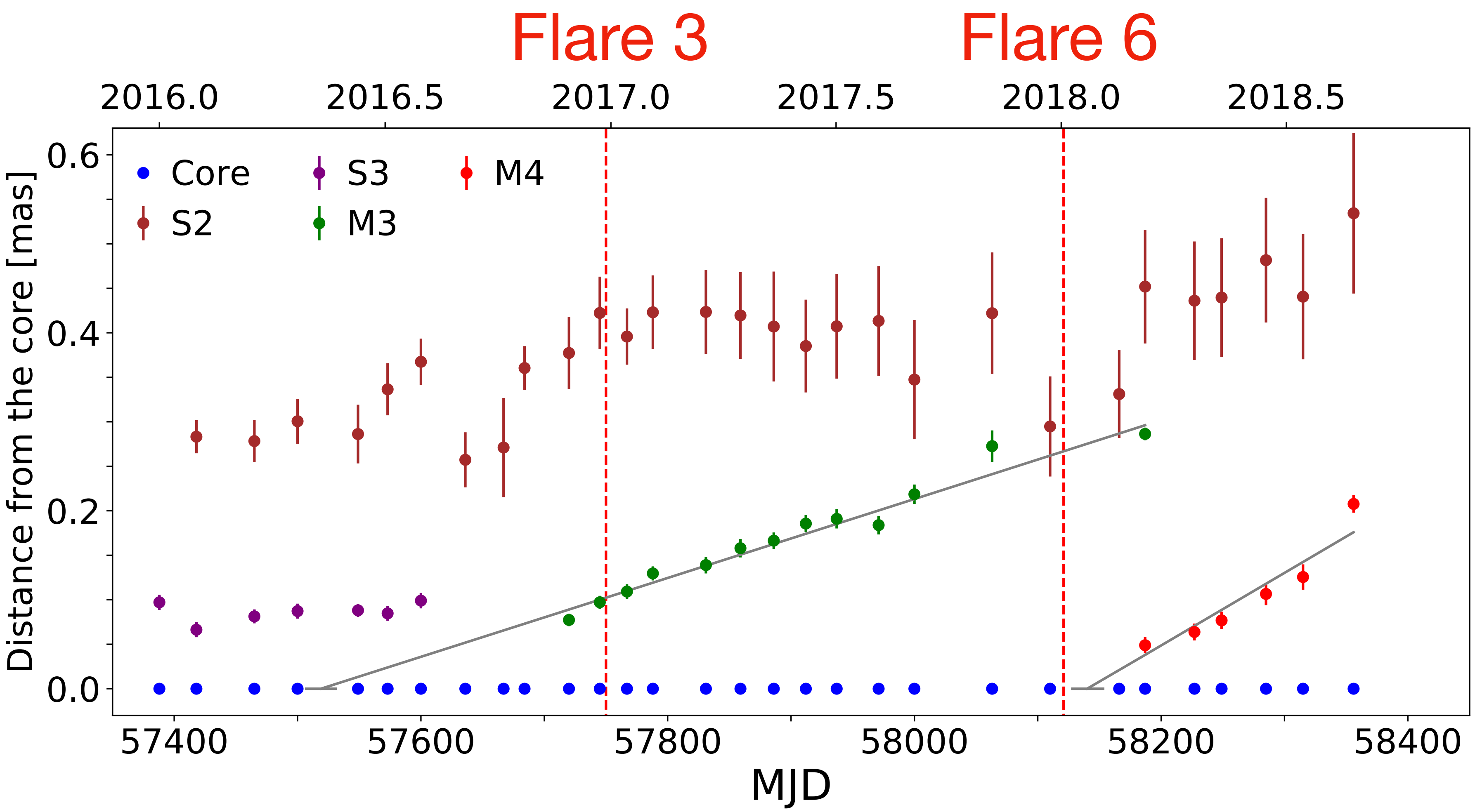
* r_p: Linear Pearson correlation coefficient

Confidence level = $1 - p_{\text{value}}$

γ-ray Correlations: Flare 6



15th EVN Symposium & Users Meeting - Backup Slides



Jet component's name	t_{var} [d]	δ_{var}	β_{app} [c]	Γ	θ [deg]
M3	186^{+27}_{-26}	$11.48^{+1.79}_{-1.73}$	$8.57^{+0.42}_{-0.37}$	$8.98^{+0.50}_{-0.47}$	$4.80^{+0.96}_{-0.93}$
M4	104^{+22}_{-24}	$30.76^{+6.65}_{-7.36}$	$15.76^{+2.33}_{-2.80}$	$19.43^{+2.72}_{-3.07}$	$1.51^{+0.53}_{-0.59}$