Stanford University

SLAC

Fermi Gamma-ray Space Telescope

CHARACTERIZING THE BRIGHTEST GAMMA-RAY FLARES OF FLAT SPECTRUM RADIO QUASARS

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ROGER BLANDFORD, JEFF SCARGLE,
ON BEHALF OF THE FERMI-LAT COLLABORATION
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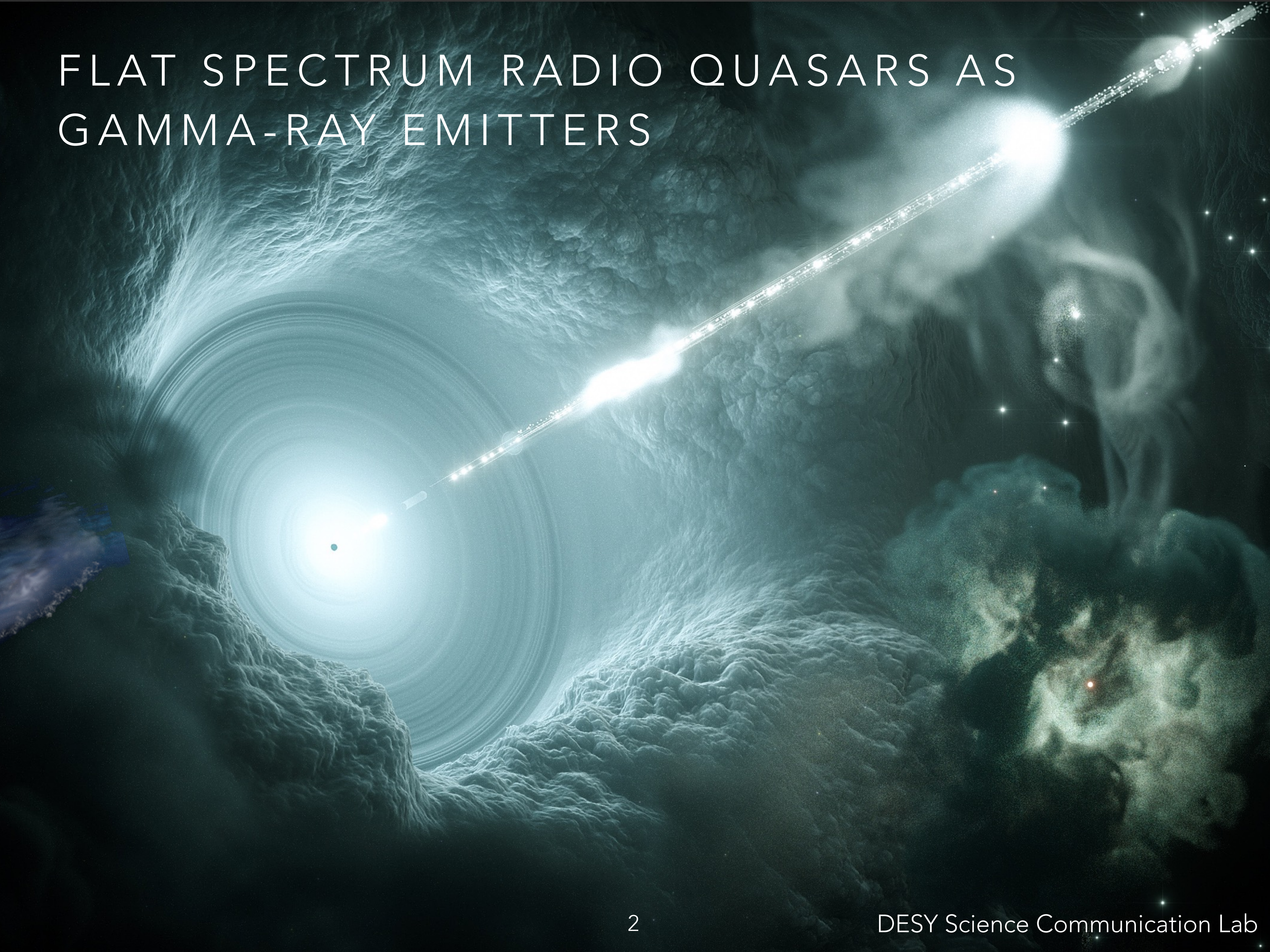
FLAT SPECTRUM RADIO QUASARS AS GAMMA-RAY EMITTERS



DESY Science Communication Lab

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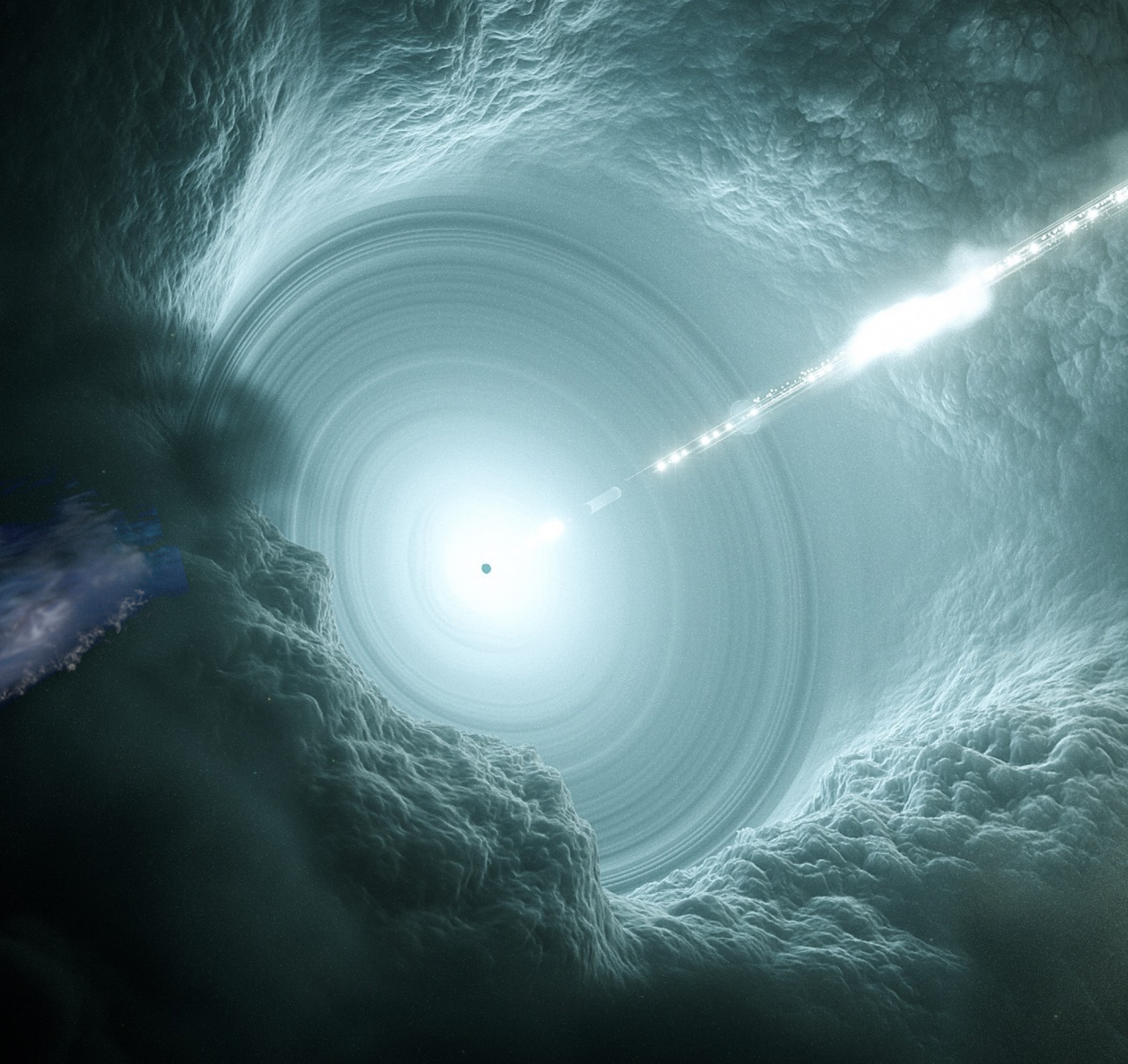

- Blazars with flat radio spectra and broad optical emission lines
- Bright ɣ-ray emitters with extreme flares, 1/3 of Fermi observed AGNs
  [3LAC, Ackermann+ 2015]
- Variability on time scales of minutes observed above100 MeV (100 GeV) for 2 (1) sources
  [e.g., Aleksic+ 2012, Ackermann+ 2015, Shukla+ 2018, and talks this session]
- Location and mechanism of ɣ-ray emission still unclear: lepto-hadronic / synchrotron self Compton / external Compton
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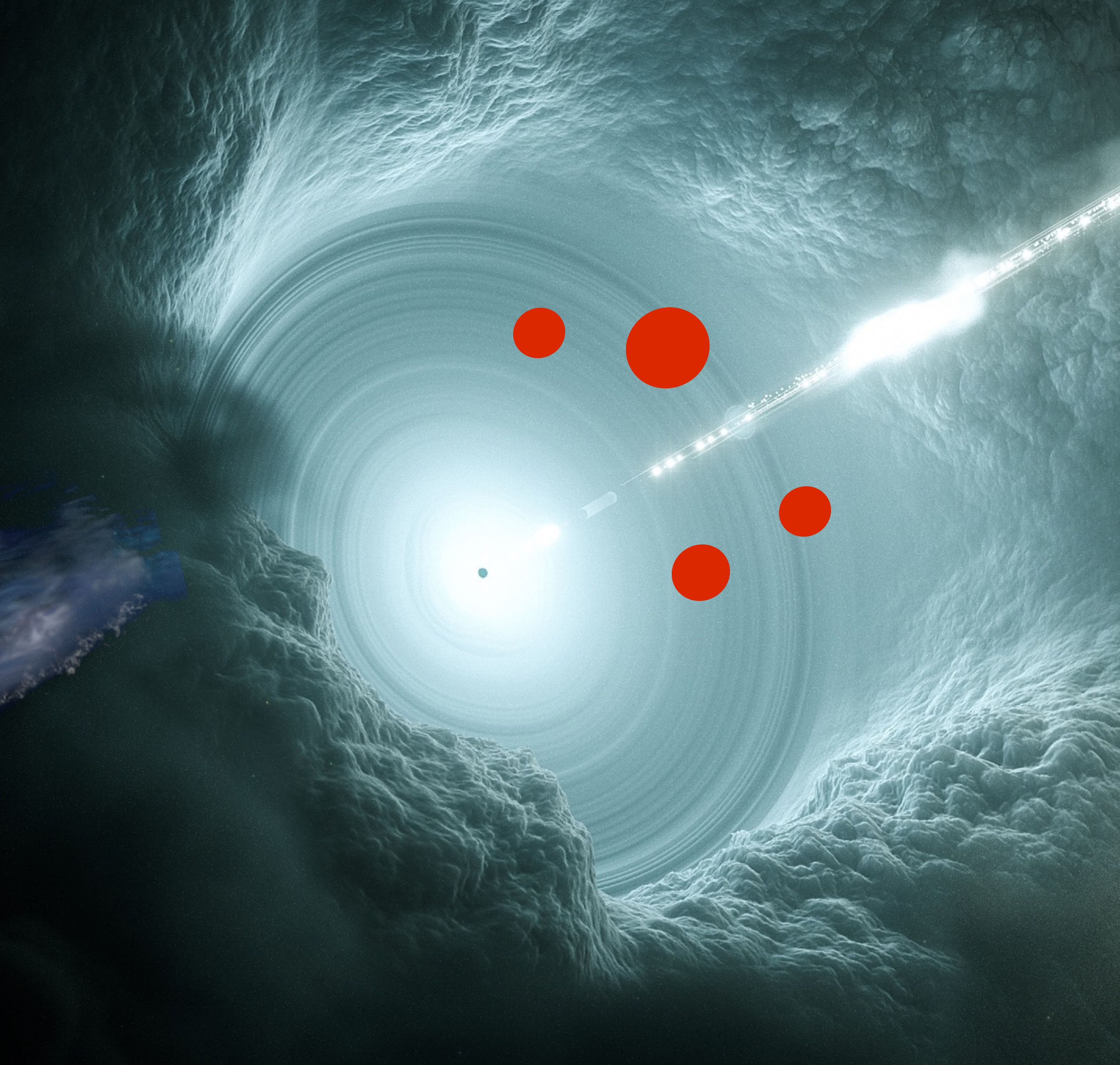

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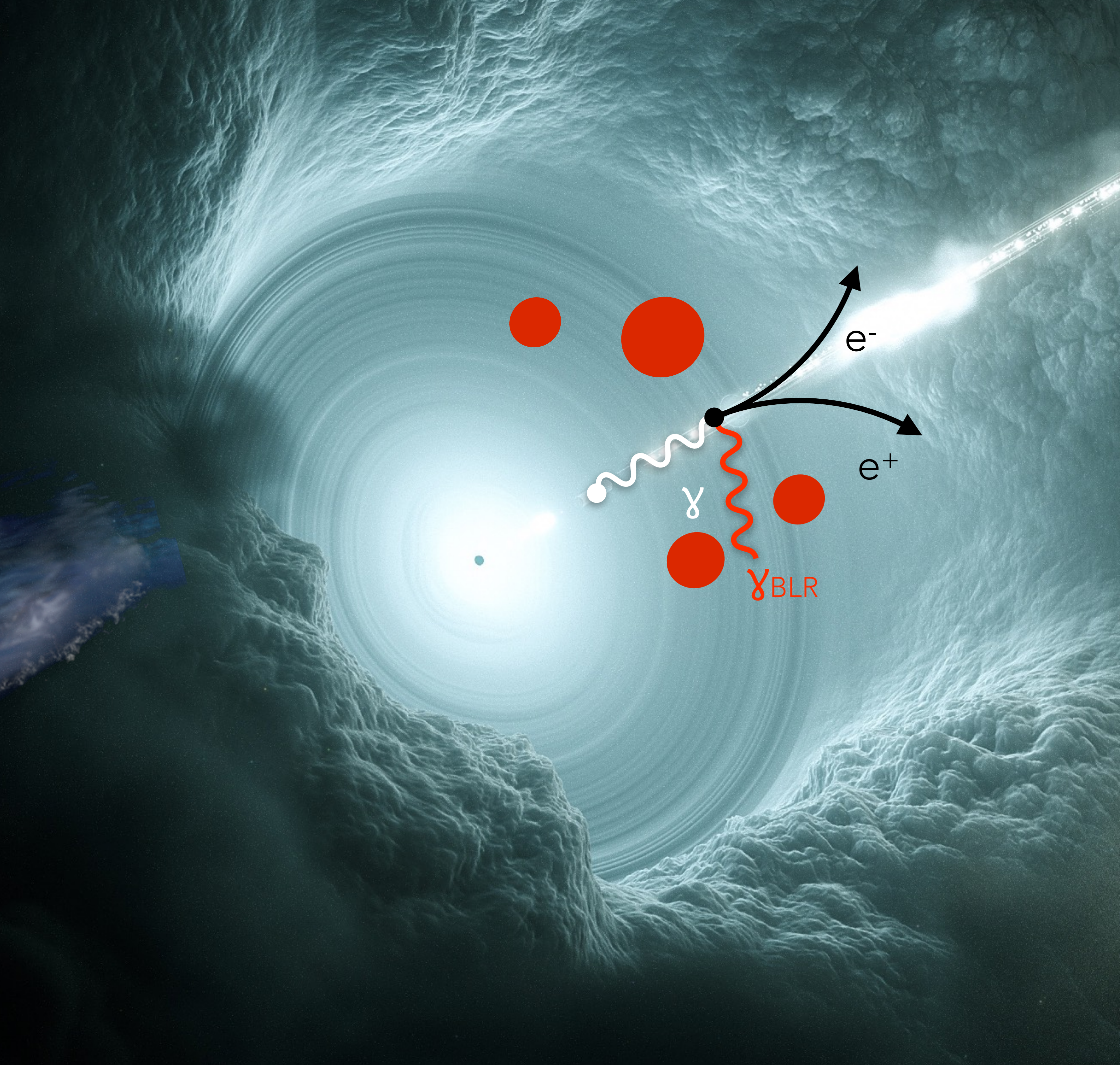

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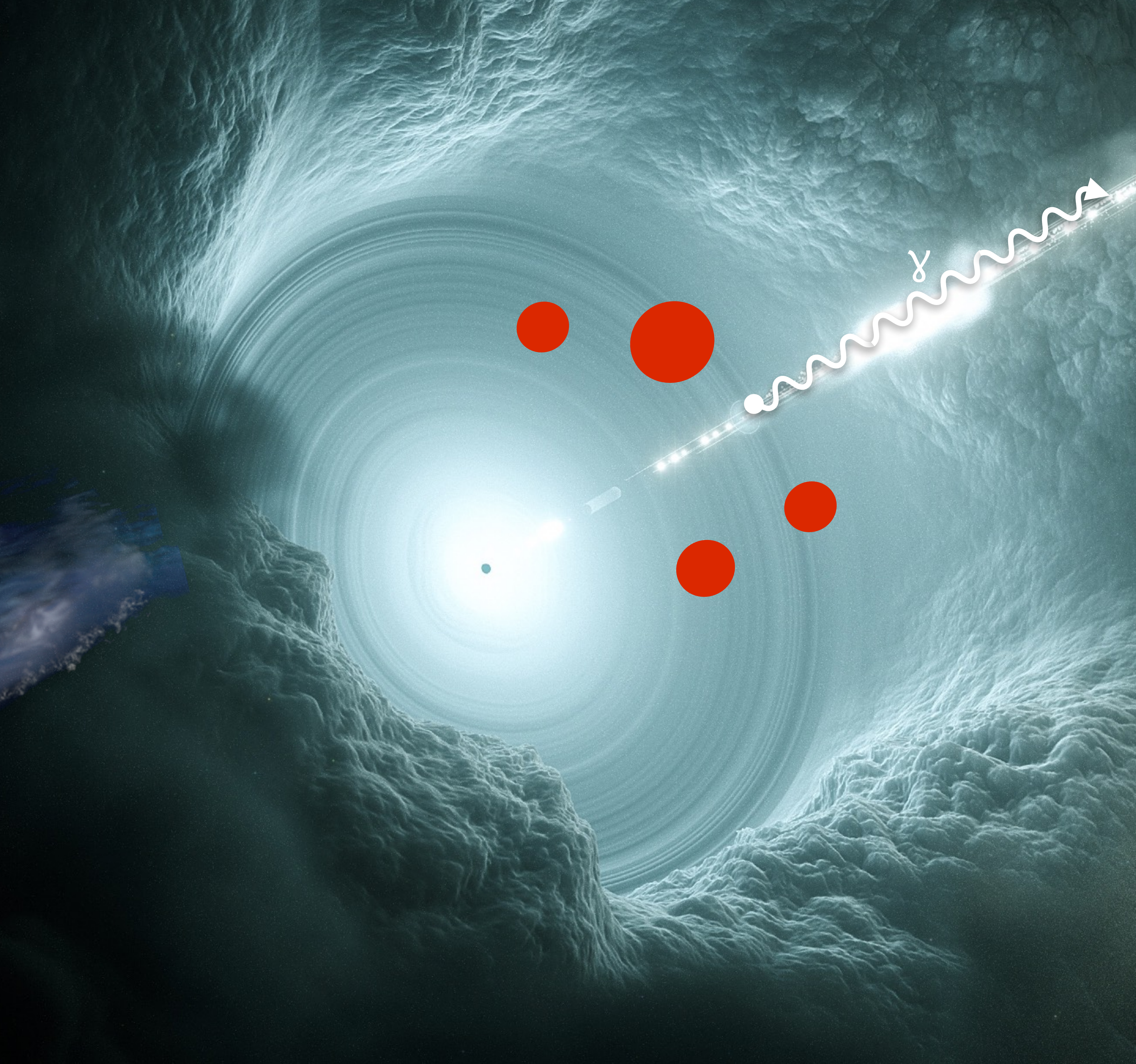

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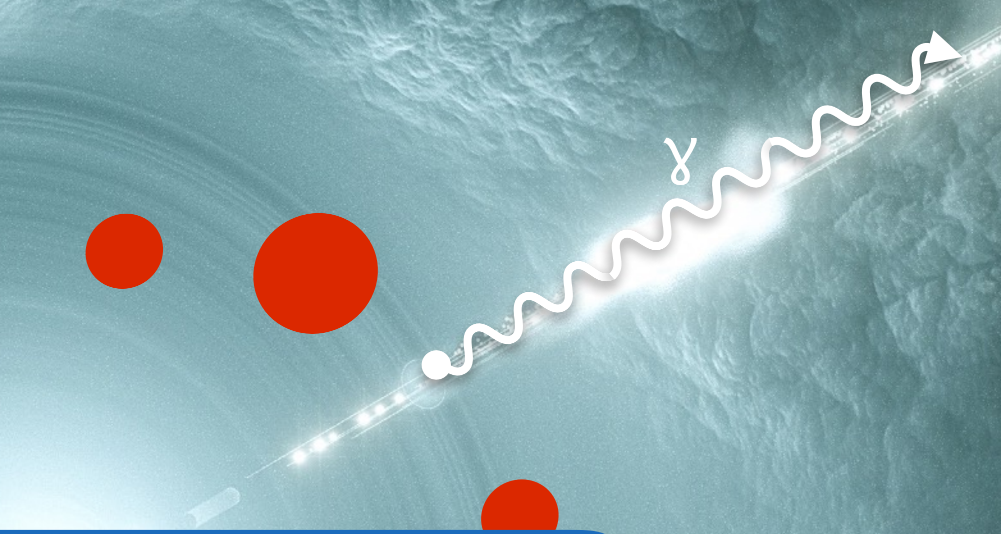

Goals:

- Systematic characterization of **global** and **local** temporal ɣ-ray behaviour of brightest FSRQs using ***Fermi*-LAT observations**
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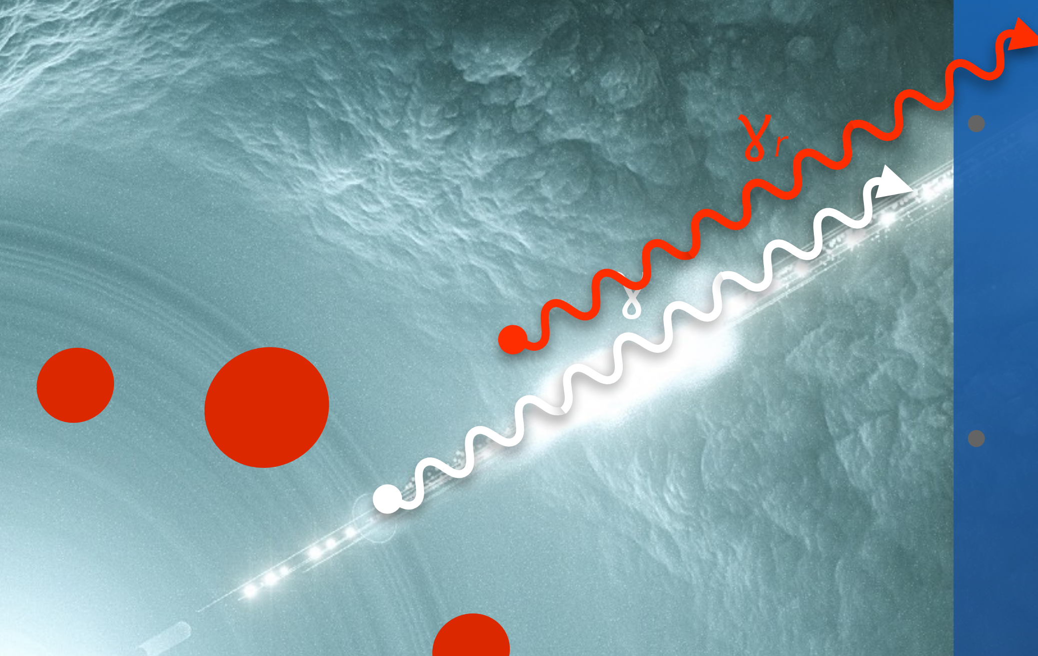

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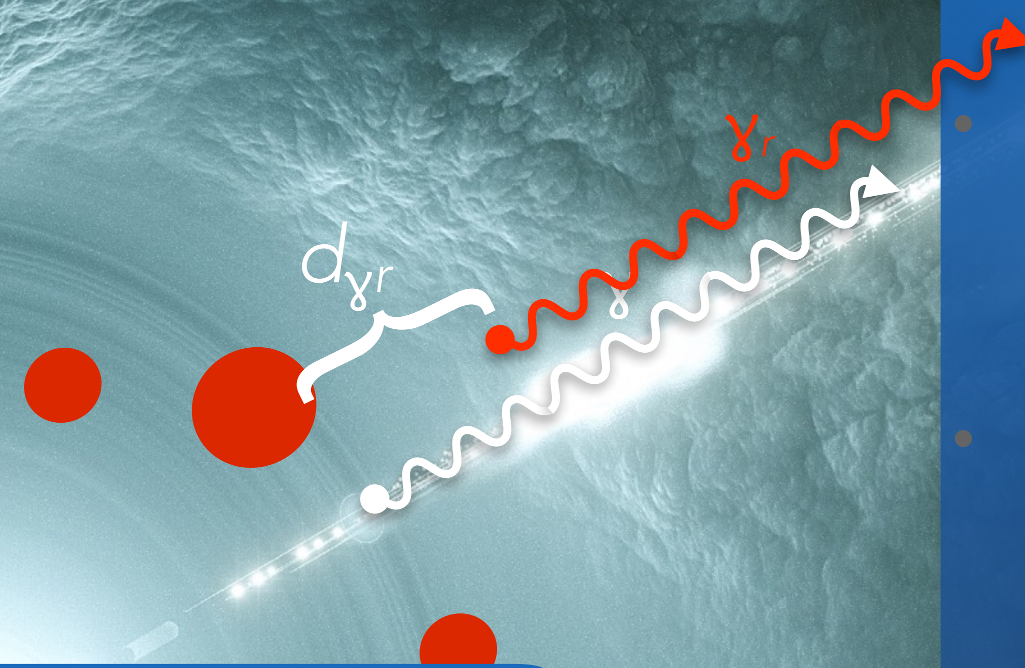

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SOURCE SELECTION AND ANALYSIS

- Goal: select brightest flares to guarantee high S/N spectra and ability to search for variability within one *Fermi*-LAT orbit

- Requirement: daily flux > 10^{-5} ph cm^{-2} s^{-1} within 1σ uncertainty in weekly monitored light curves

- Perform Fermi-LAT analysis above 100MeV with 9.5 years of Pass 8 data

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

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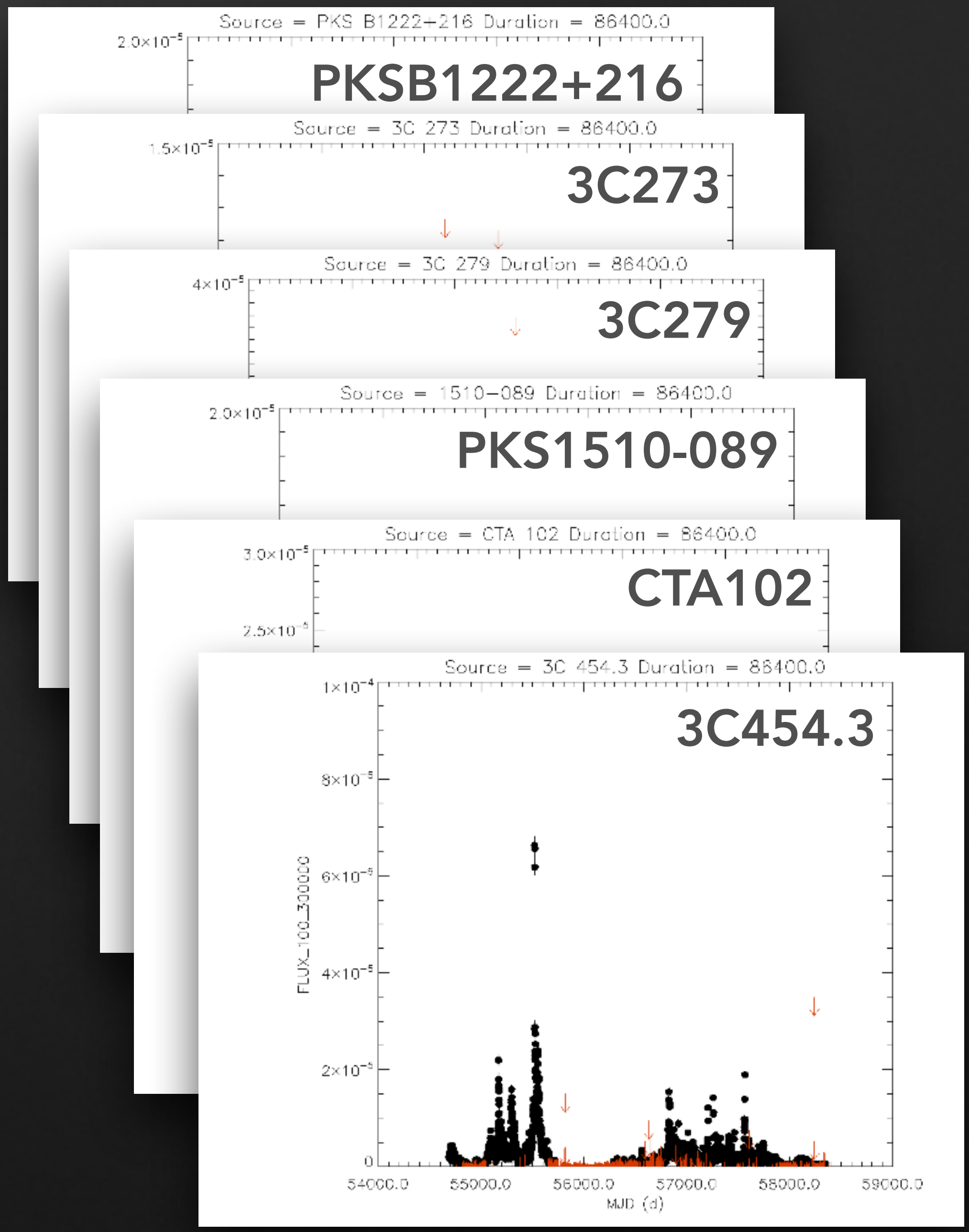

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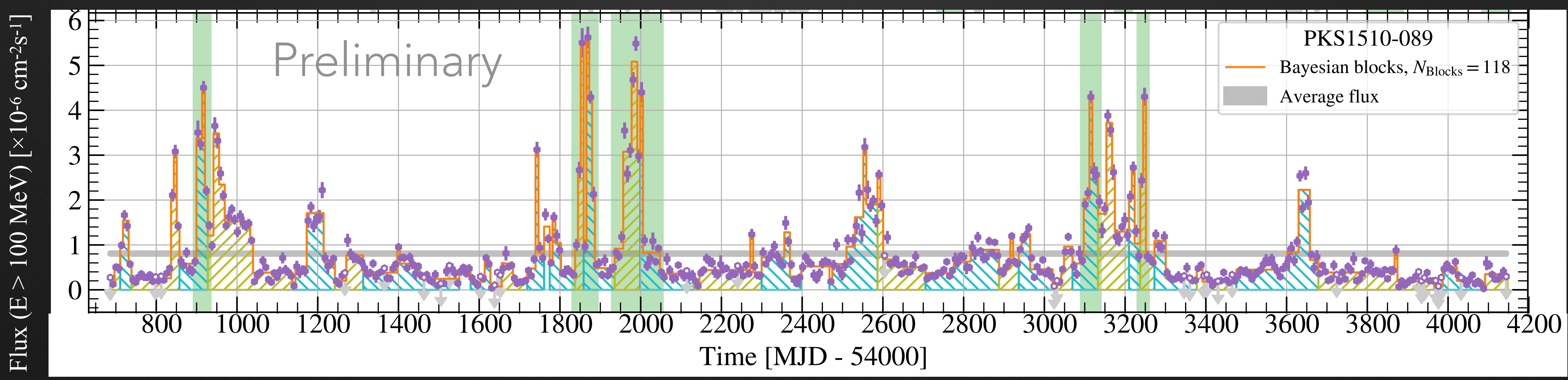
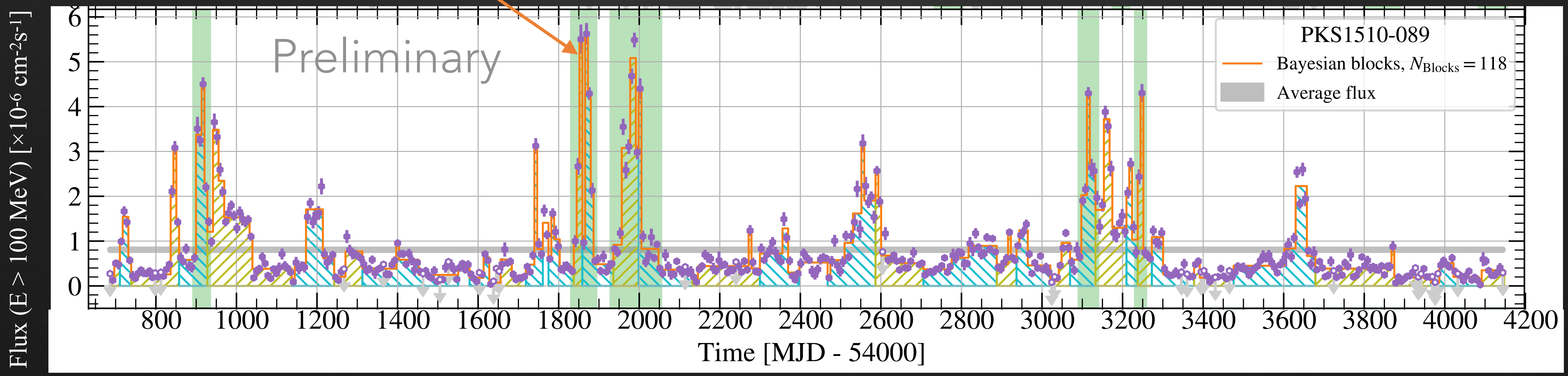
WEEKLY LIGHT CURVES



WEEKLY LIGHT CURVES

BAYESIAN BLOCKS TO DETECT SIGNIFICANT VARIATIONS [SCARGLE+ 2012]



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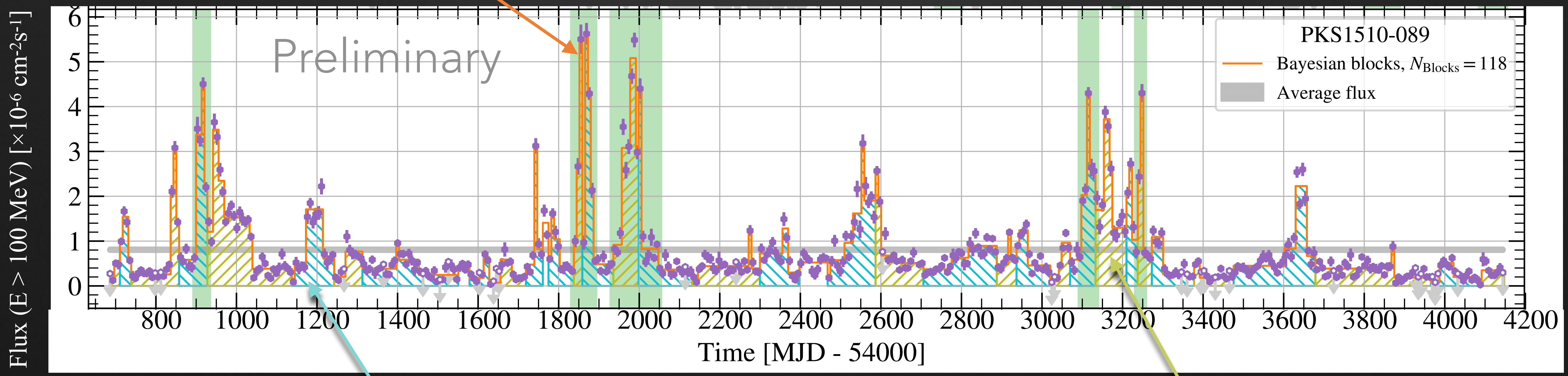

IMPLEMENTATION OF HOP ALGORITHM / HILL CLIMBING [EISENSTEIN & HUT 1998] TO GROUP BAYESIAN BLOCKS

WEEKLY LIGHT CURVES

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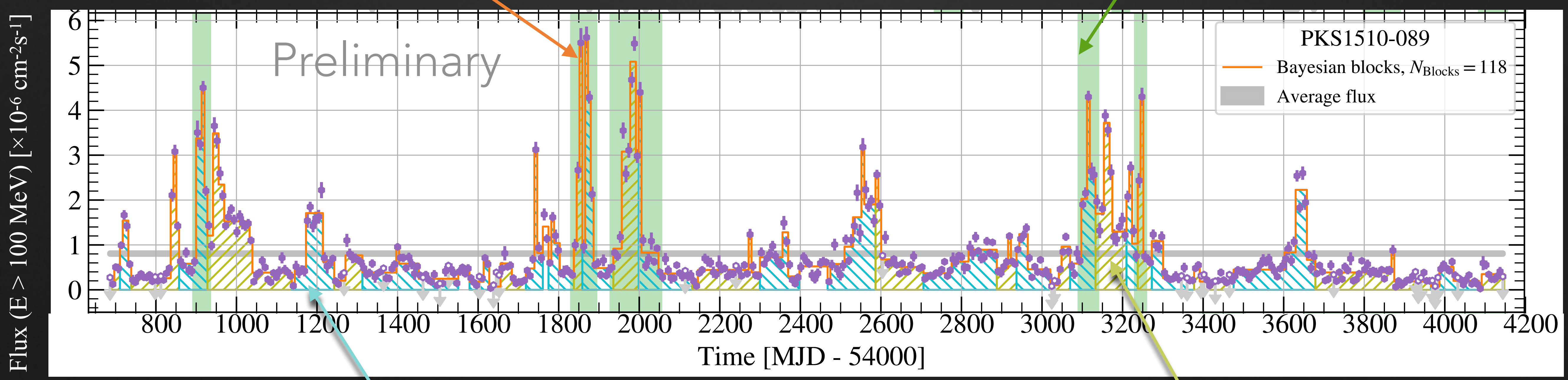
SELECT BRIGHT HOP GROUPS TO ZOOM IN ON SHORTER TIME SCALES (DAYS, ORBITS)



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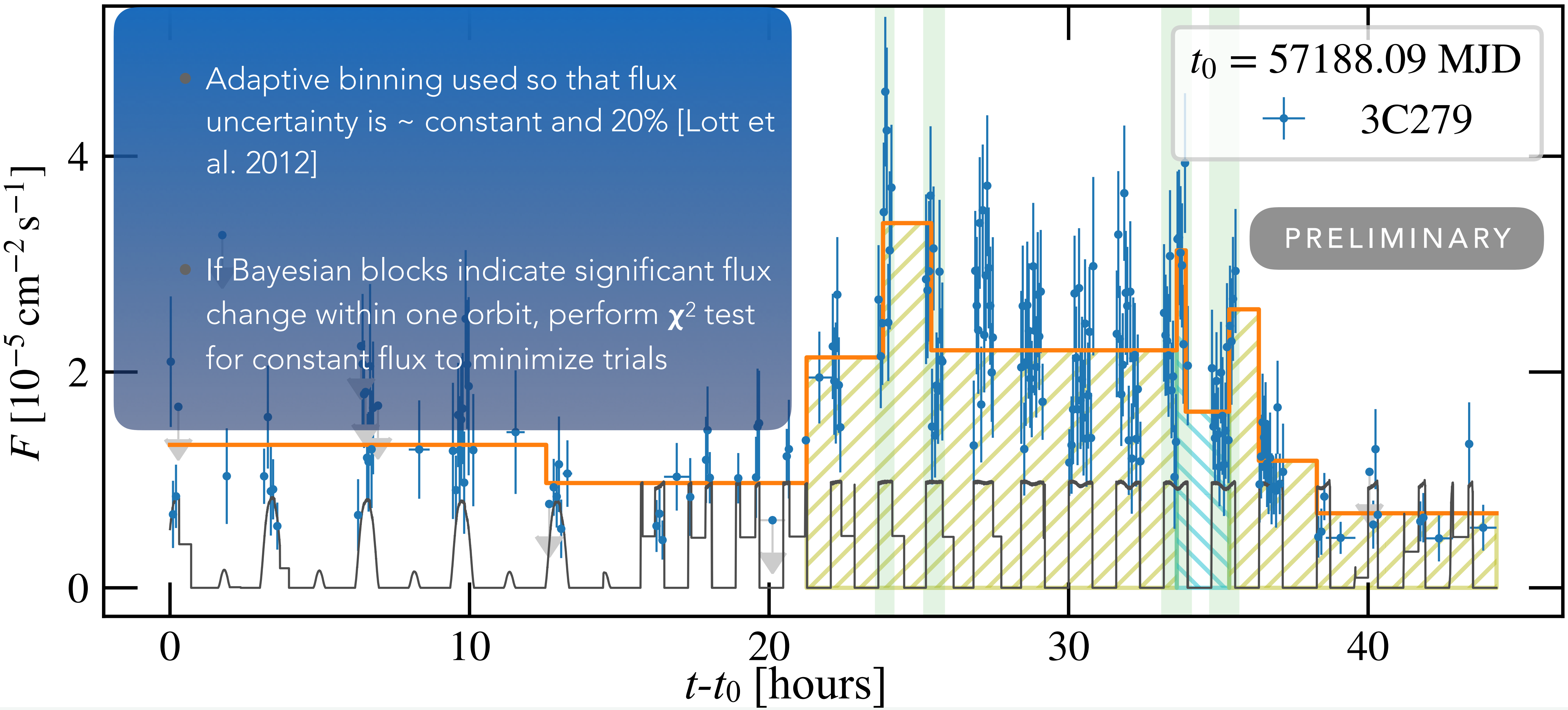
SUB-ORBITAL LIGHT CURVES: SEARCH FOR VARIABILITY ON MINUTE TIME SCALES



- Adaptive binning used so that flux uncertainty is ~ constant and 20% [Lott et al. 2012]
- If Bayesian blocks indicate significant flux change within one orbit, perform χ^2 test for constant flux to minimize trials

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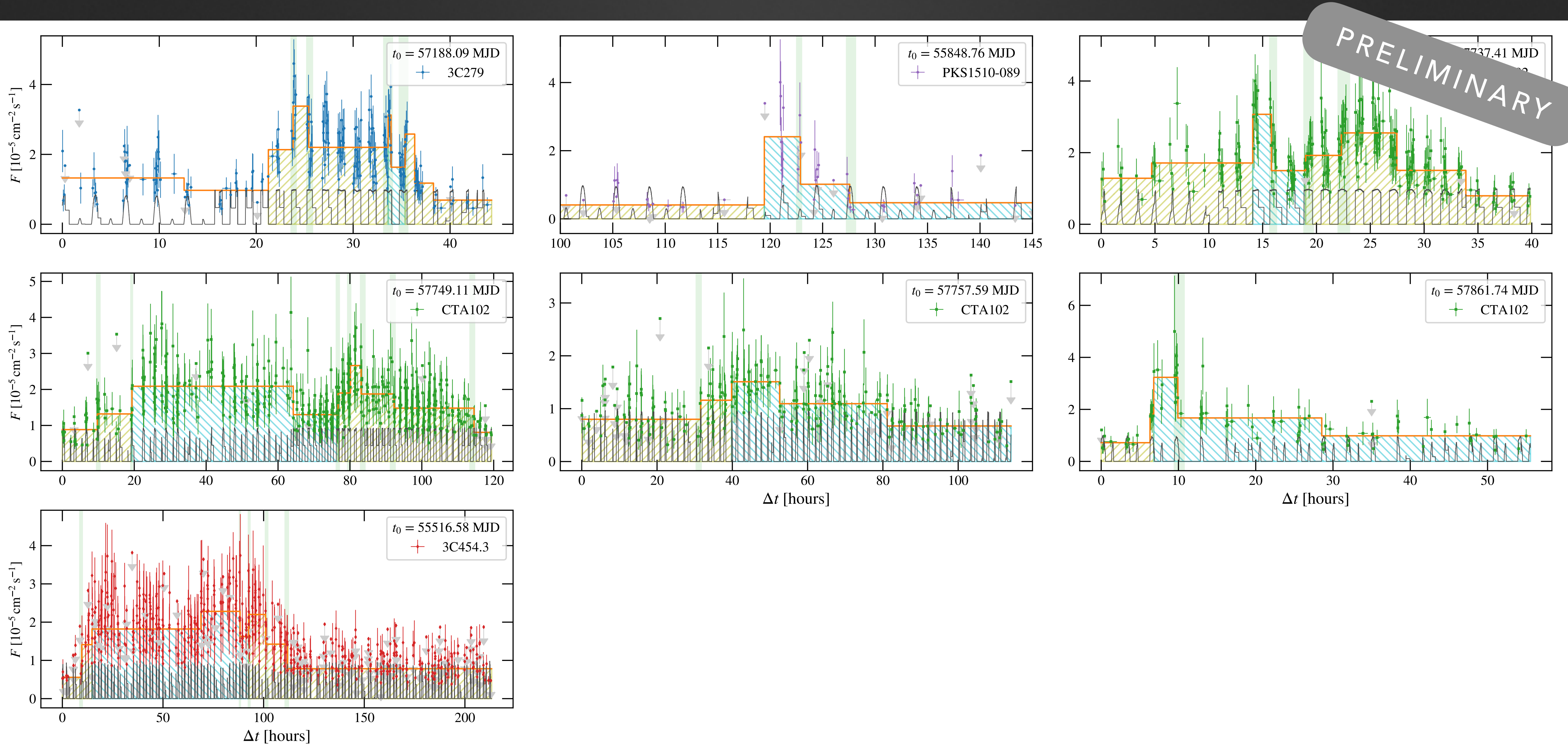

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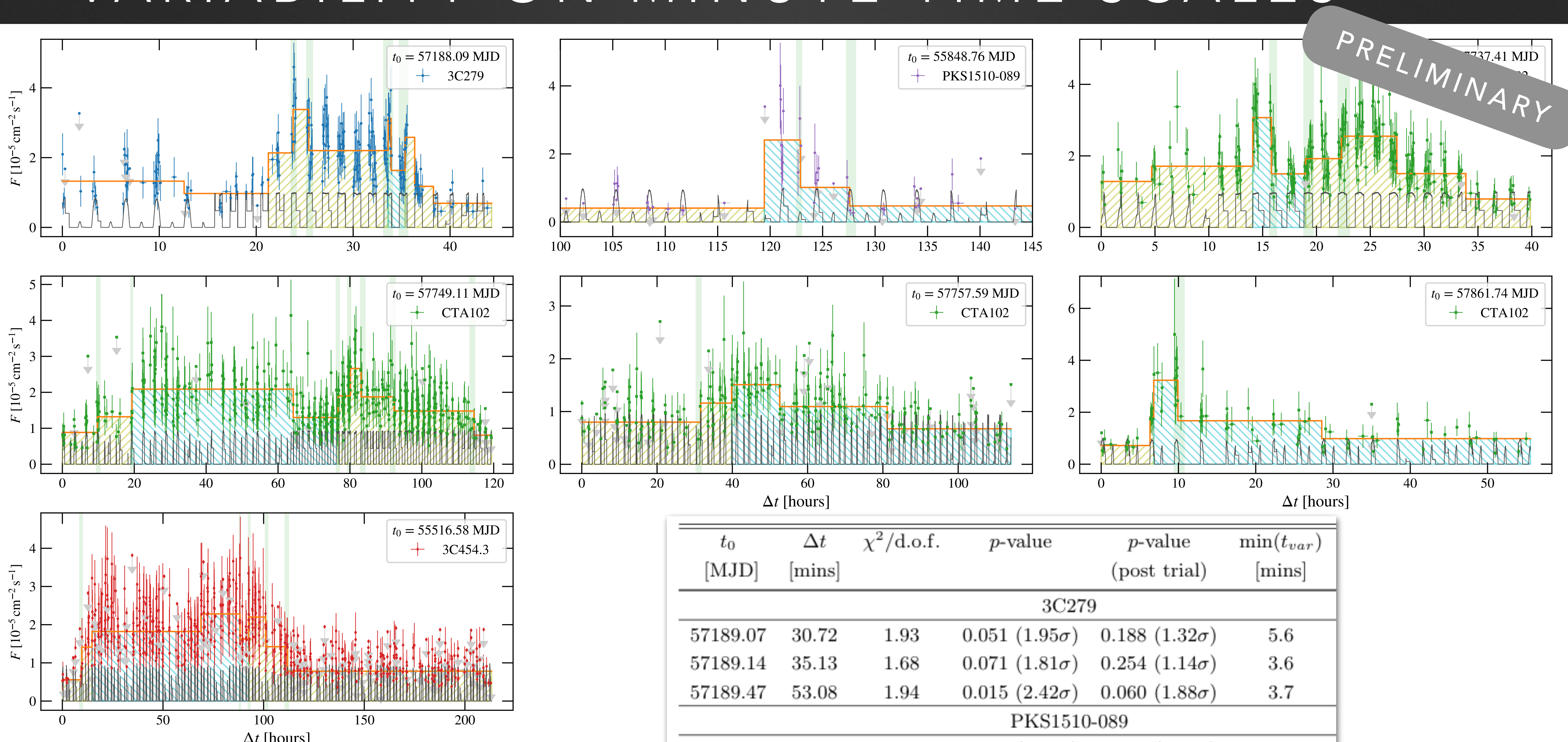
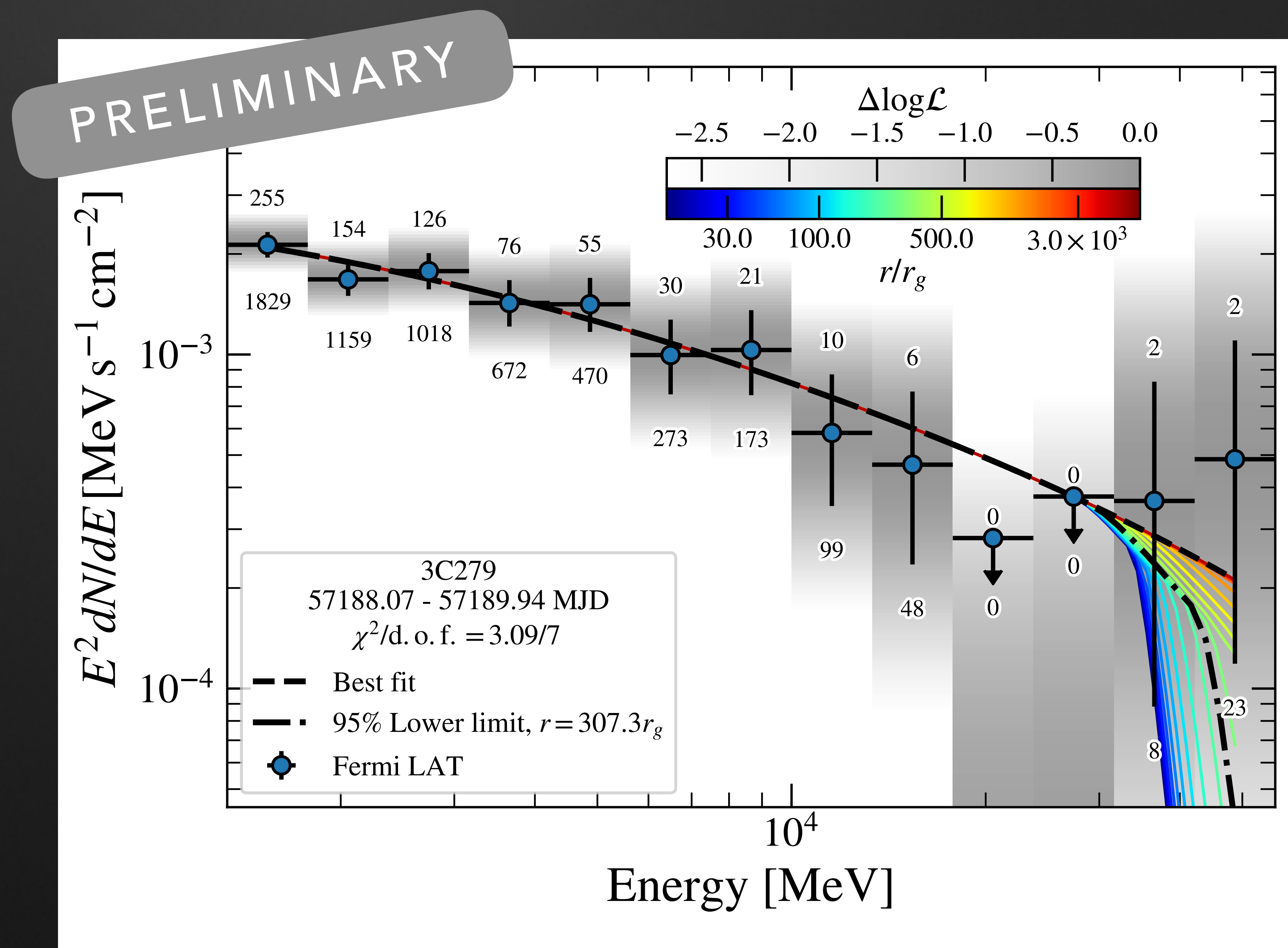


t_0 [MJD]	Δt [mins]	χ^2/d.o.f.	p-value	p-value (post trial)	min(t_{var}) [mins]
			3C279		
57189.07	30.72	1.93	0.051 (1.95σ)	0.188 (1.32σ)	5.6
57189.14	35.13	1.68	0.071 (1.81σ)	0.254 (1.14σ)	3.6
57189.47	53.08	1.94	0.015 (2.42σ)	0.060 (1.88σ)	3.7
			PKS1510-089		
55854.07	50.80	2.01	0.091 (1.69σ)	0.173 (1.36σ)	7.9
			CTA102		
57738.07	37.04	2.30	0.011 (2.55σ)	0.032 (2.14σ)	2.8
57758.86	78.00	2.62	0.049 (1.97σ)	0.049 (1.97σ)	7.8
			3C454.3		
55520.25	25.83	1.96	0.048 (1.98σ)	0.216 (1.24σ)	3.2

SEARCH FOR ABSORPTION FEATURES IN SPECTRA

- Stratified BLR model with flattened geometry: emission lines emitted from rings perpendicular to jet [Finke 2016]
- Ring radii and line luminosities from reverberation mapping [Liu+ 2006; Torrealba+ 2012]
- Only free parameter: distance of ɣ-ray emission region to BH



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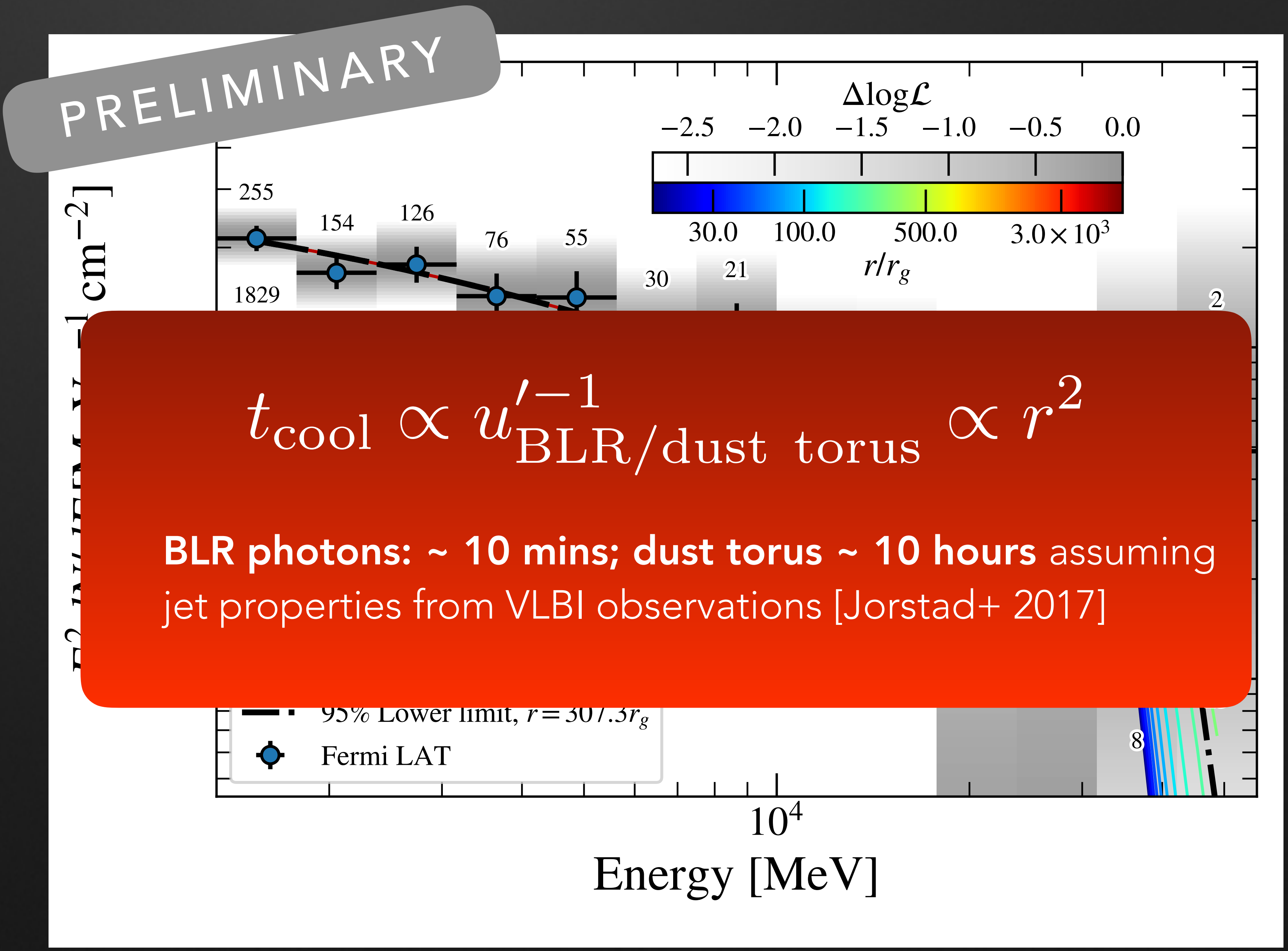
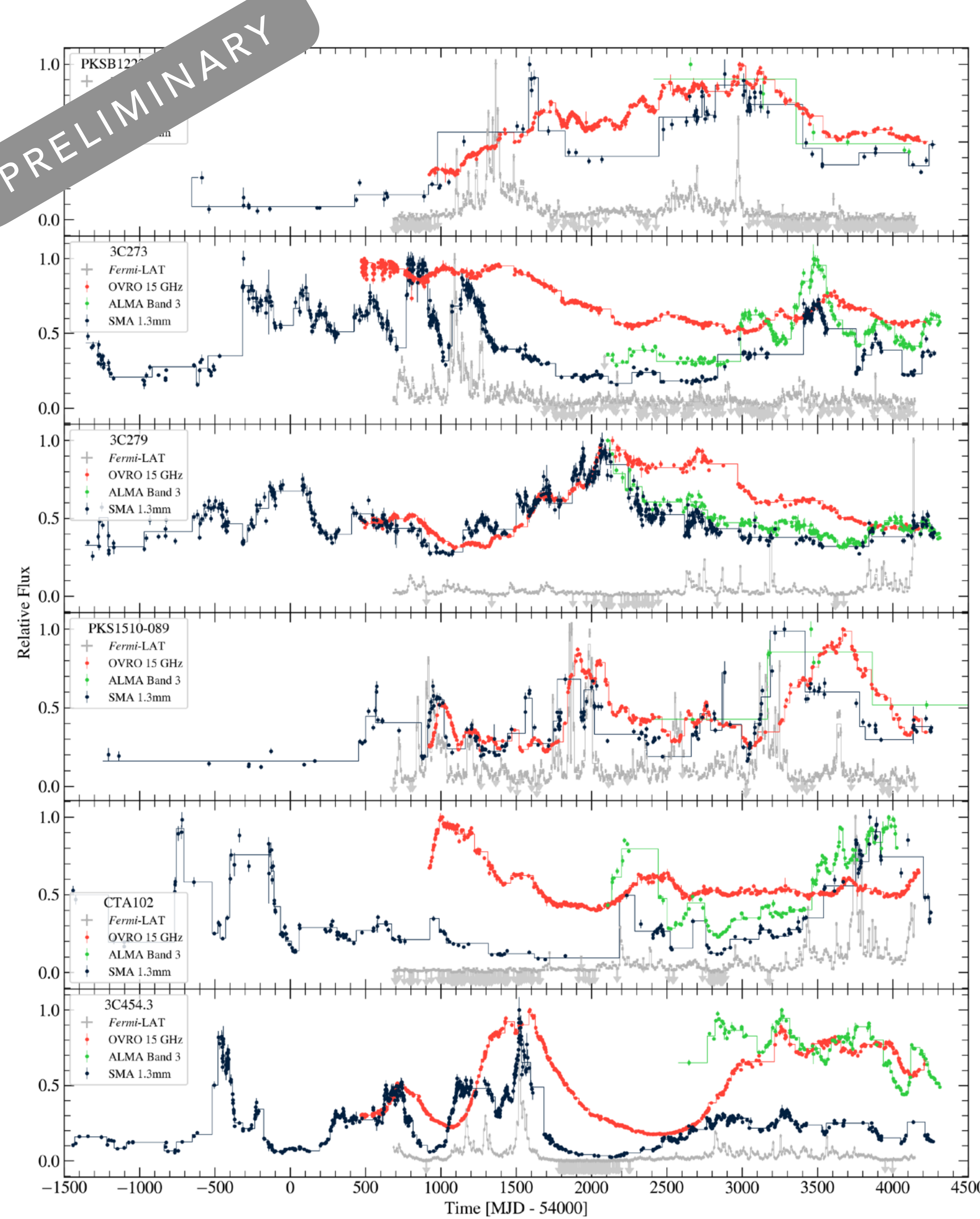


$$t_{\rm cool} \propto u'^{-1}_{\rm BLR/dust\ \ torus} \propto r^2$$

BLR photons: ~ 10 mins; dust torus ~ 10 hours assuming jet properties from VLBI observations [Jorstad+ 2017]

CORRELATION ANALYSIS BETWEEN GAMMA-RAY AND RADIO LIGHT CURVES

- Search for time lags with local cross correlation function [Max-Moerbeck+ 2014]
- Radio observations:
  - SMA (1.3 mm / 230 GHz)
  - ALMA Band 3 (~3 mm / 100 GHz)
  - OVRO (15 GHz)



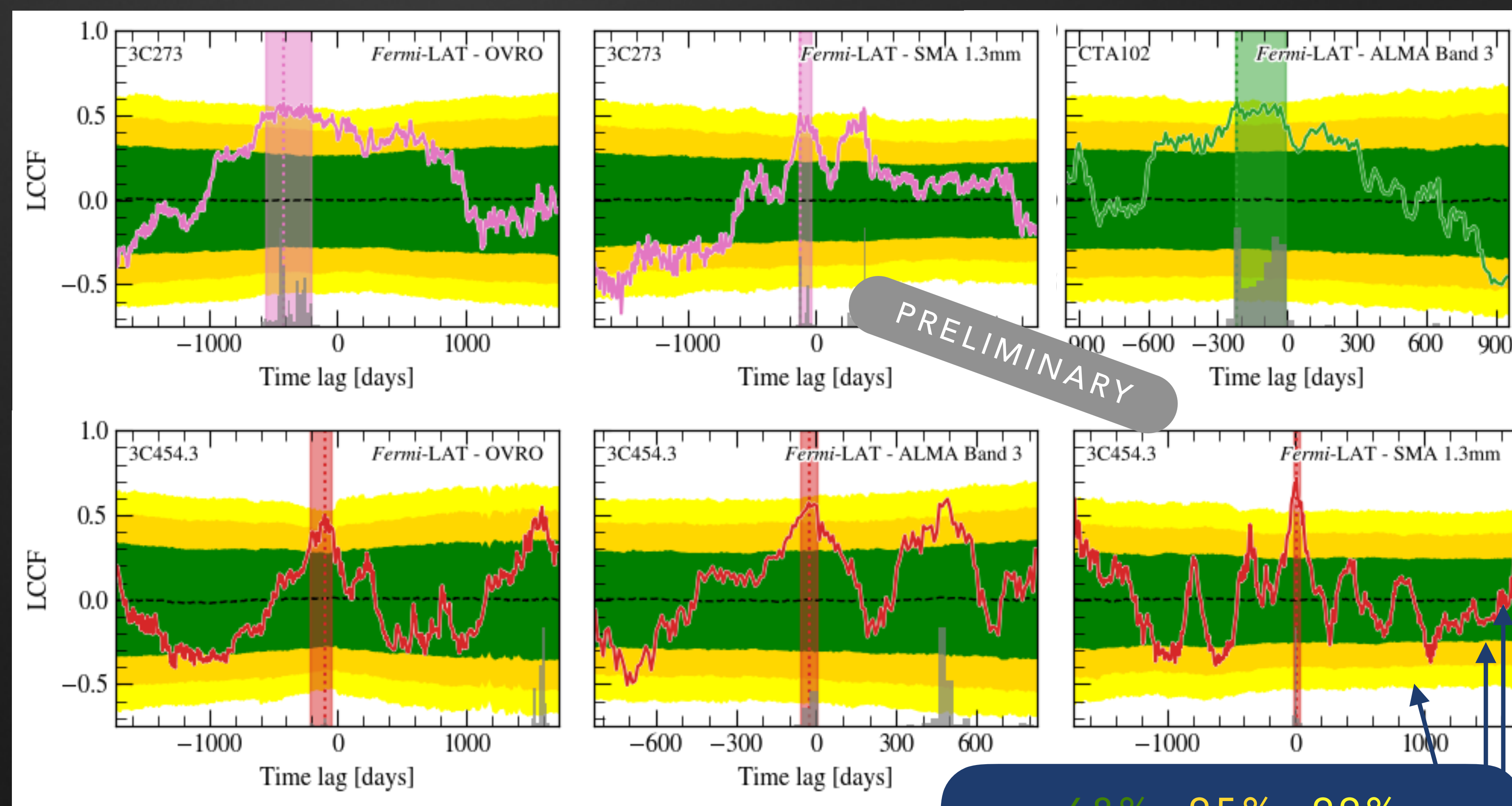
RESULTS FOR CROSS CORRELATION STUDY

- Correlations with significance > 2σ found for 3C273 (OVRO, SMA), CTA102 (ALMA), and 3C454.3 (OVRO, ALMA, SMA)
- ɣ-ray leads radio emission
- Distance between ɣ-ray and radio emitting zones:

$$d_{\gamma,r} = \frac{\Gamma \delta \beta c \tau_{\rm peak}}{1+z}$$

[jet parameters from Jorstad+ 2017]

- Core position from VLBI observations [Lister+ 2016 and following Fuhrmann+ 2014]
- For 3C454.3 and CTA102: **ɣ-ray emission consistent with mm emission produced at distances ≳ pc, however would drastically increase cooling time!**



68%, 95%, 99% ENVELOPES FROM 5000 PAIRS OF SIMULATED LIGHT CURVES

CONCLUSIONS

- Carried out systematic study of brightest ɣ-ray emitting FSRQs with **9.5 years of LAT data**
- Flaring episodes determined using **Bayesian blocks and implementation of HOP algorithm**
- Sources show **complex flaring behaviour and flicker noise** on longer time scales
- Evidence for **variability on minute time scales** found for 4 sources
- Absence of spectral **BLR absorption features places ɣ-ray emitting region close to Lyα emitting BLR ring** [see other talks this session]
- Evidence for **correlation between ɣ-ray and radio emission found for 3 sources**, consistent with co-spatial production of ɣ rays and mm emission, however, might **conflict with short cooling times**

BACK UP

WEEKLY, DAILY, ORBITAL LIGHT CURVES

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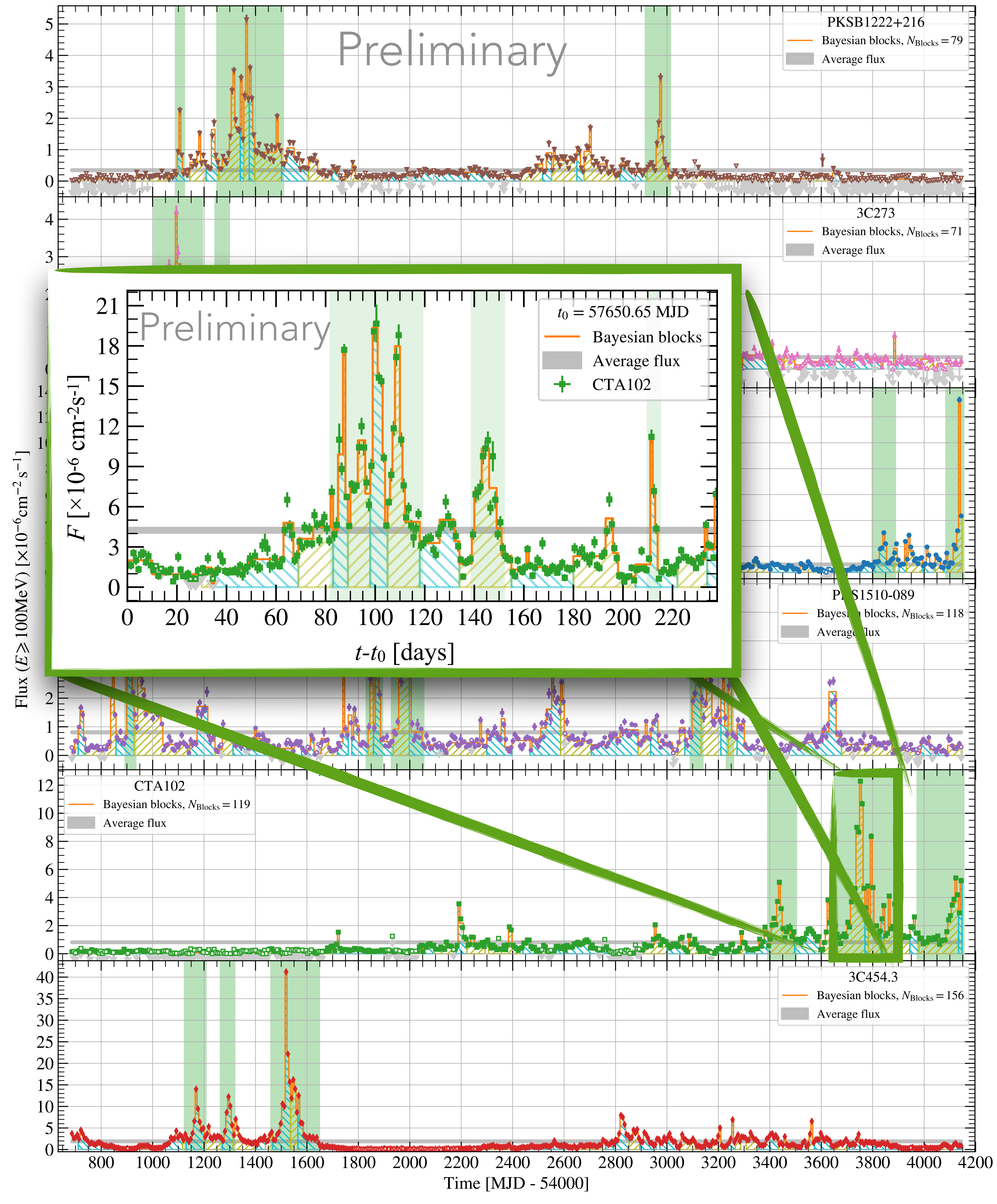

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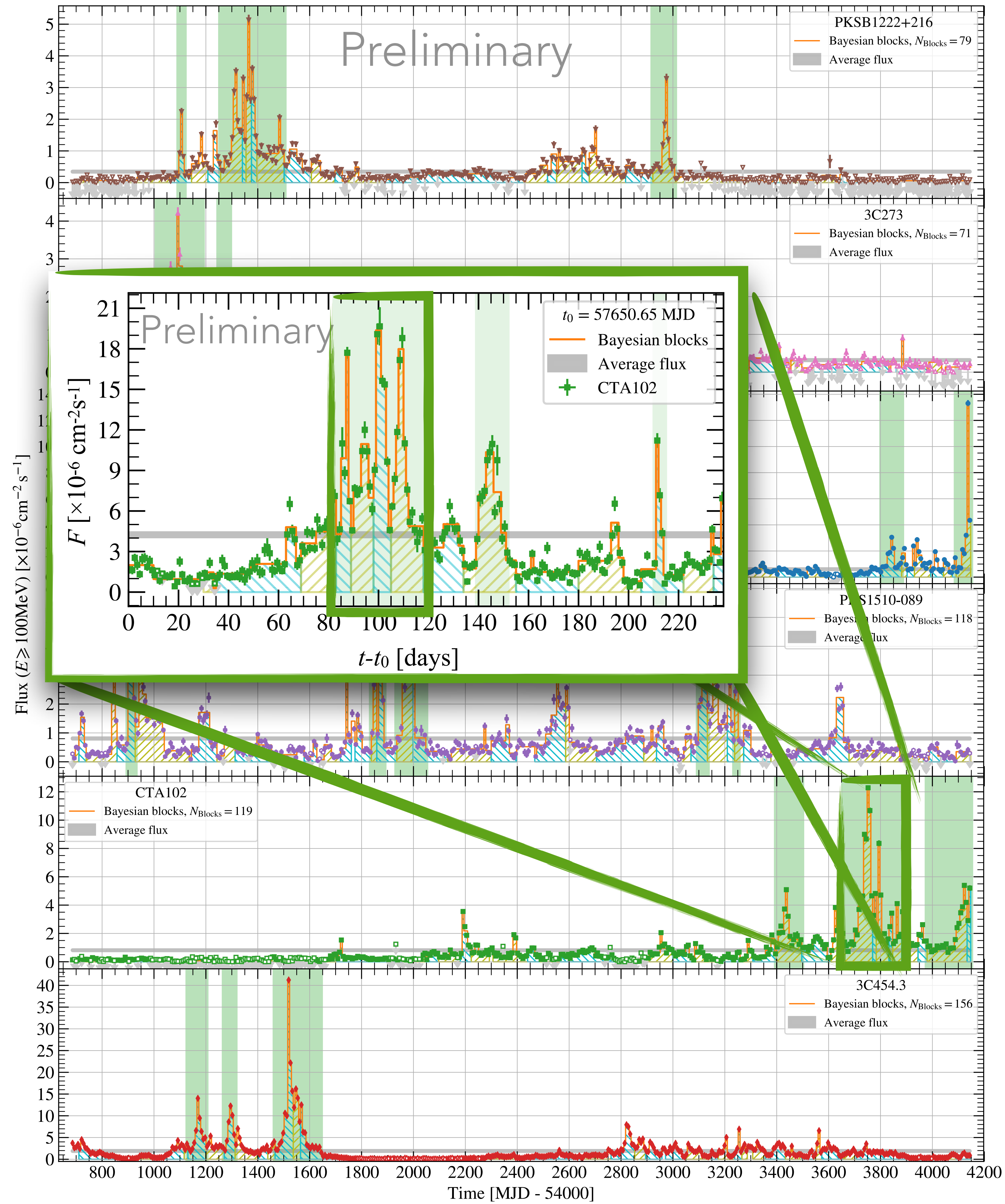

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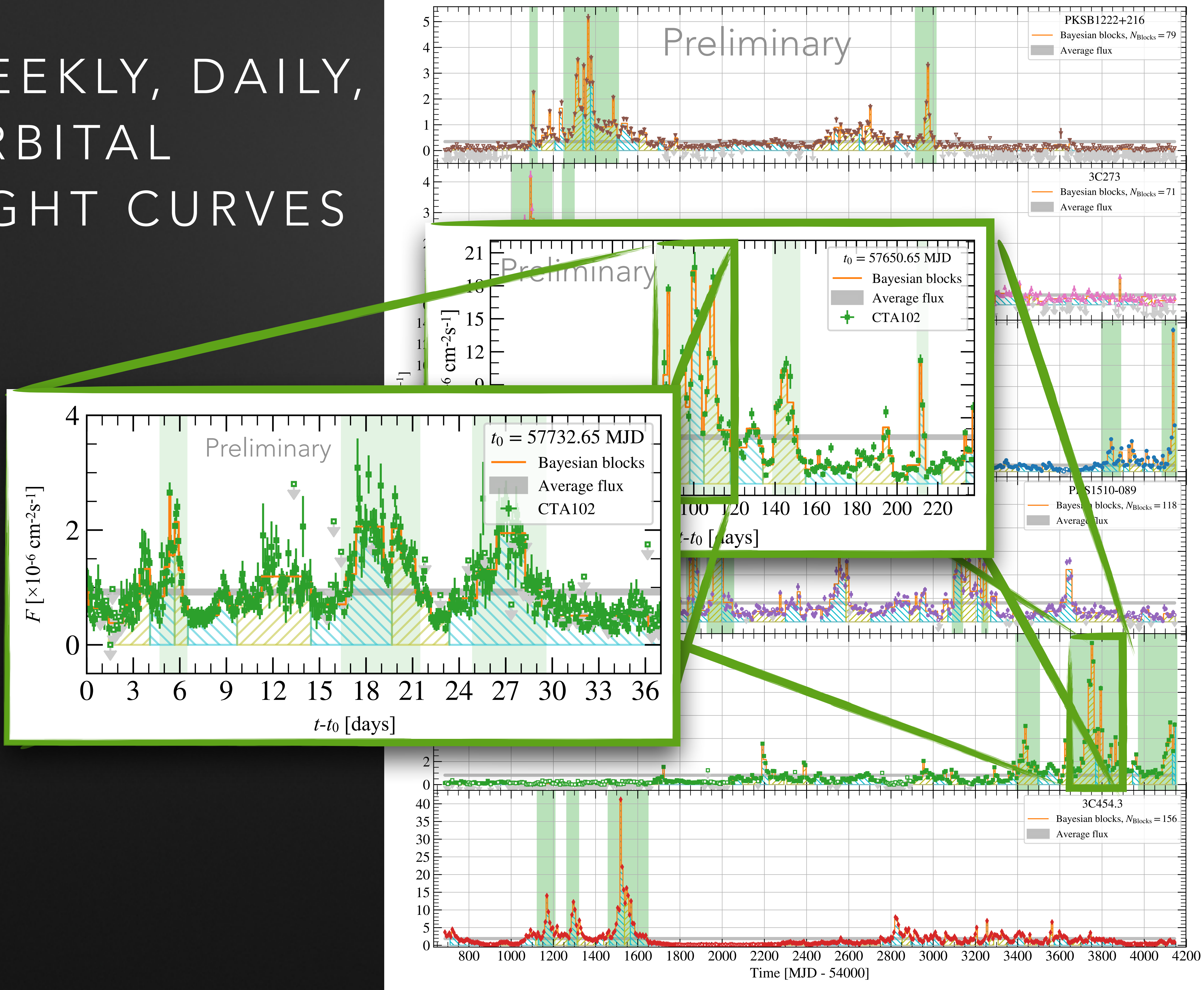
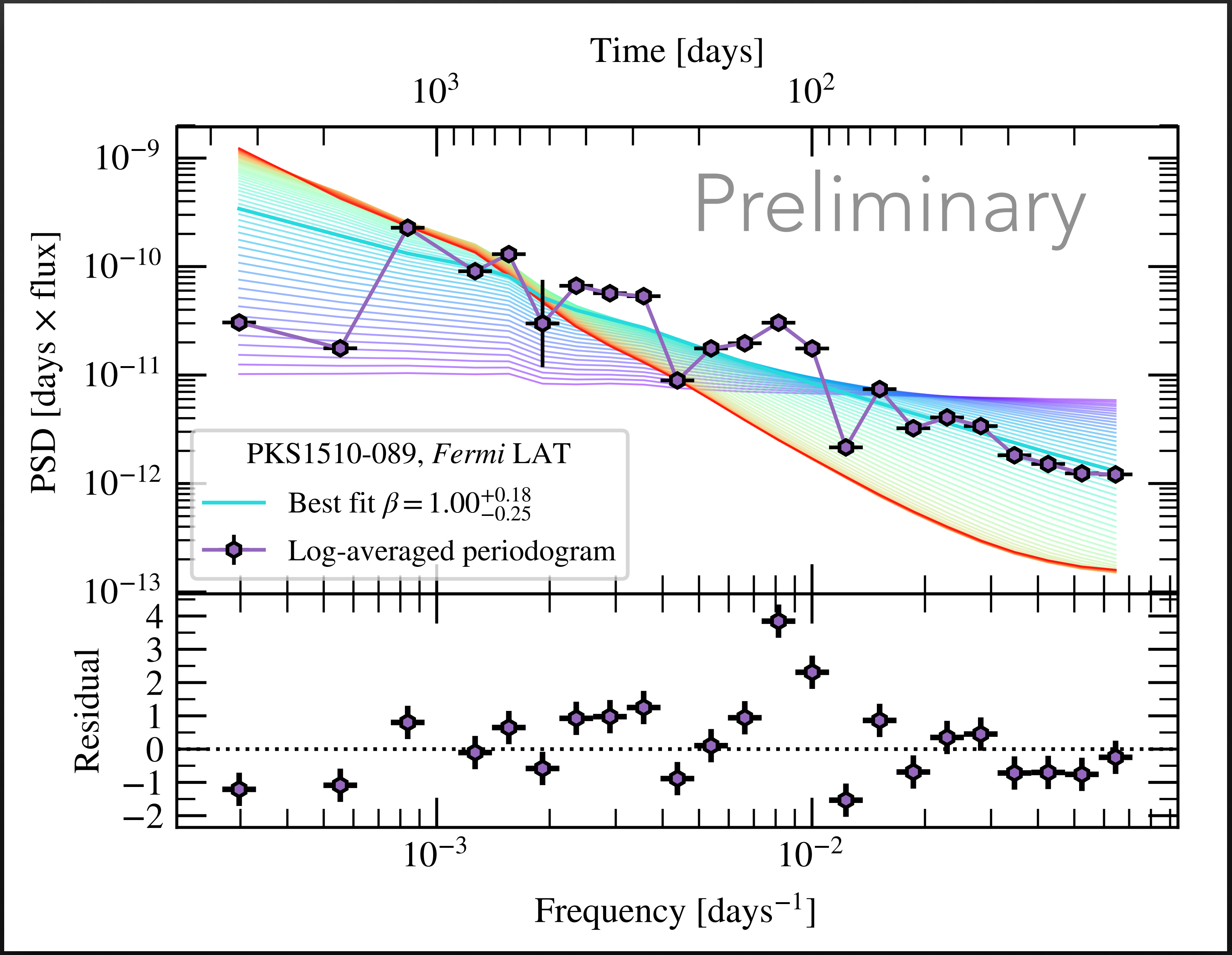


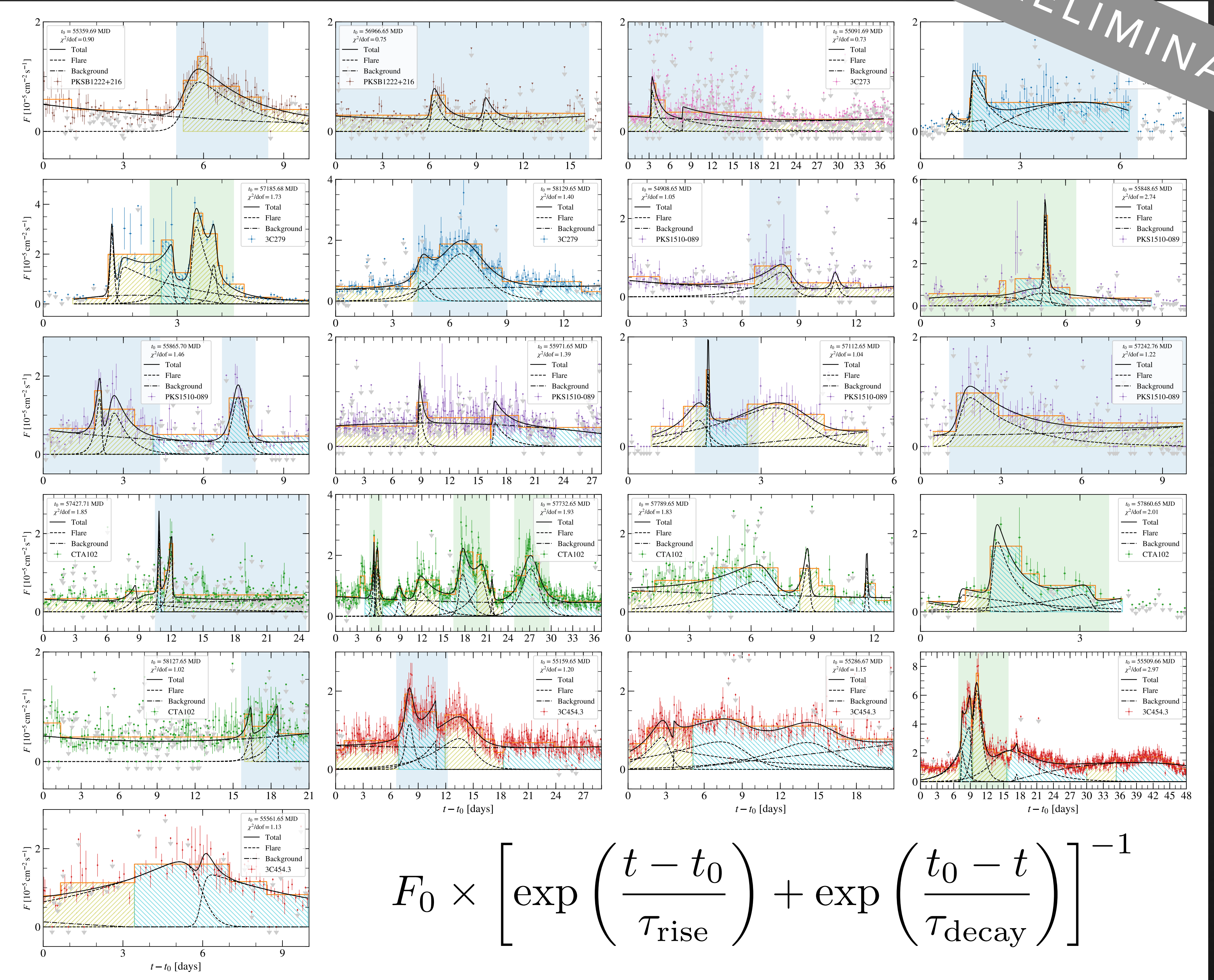
DETERMINING THE POWER SPECTRUM

- Best-fit periodogram derived from simulated light curves [following method of Max-Moerbeck+ 2014 and Emmanoupoulos+ 2013]
- Best-fit power spectral density with power law with index ~ 1, **flicker noise**



FIT TO ORBITAL LIGHT CURVES

PRELIMINARY



$$F_0 \times \left[\exp\left(\frac{t - t_0}{\tau_{\rm rise}}\right) + \exp\left(\frac{t_0 - t}{\tau_{\rm decay}}\right)\right]^{-1}$$

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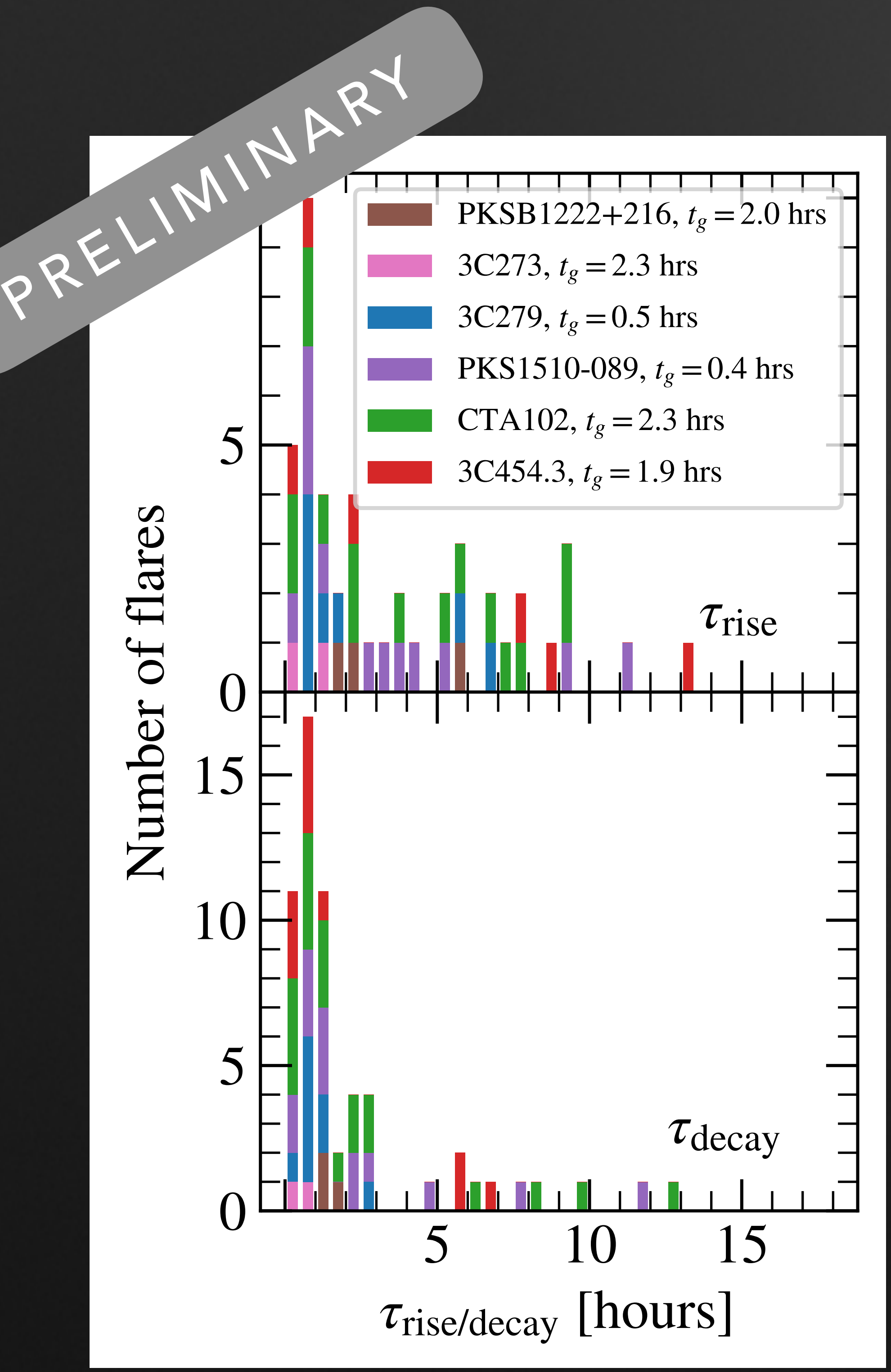

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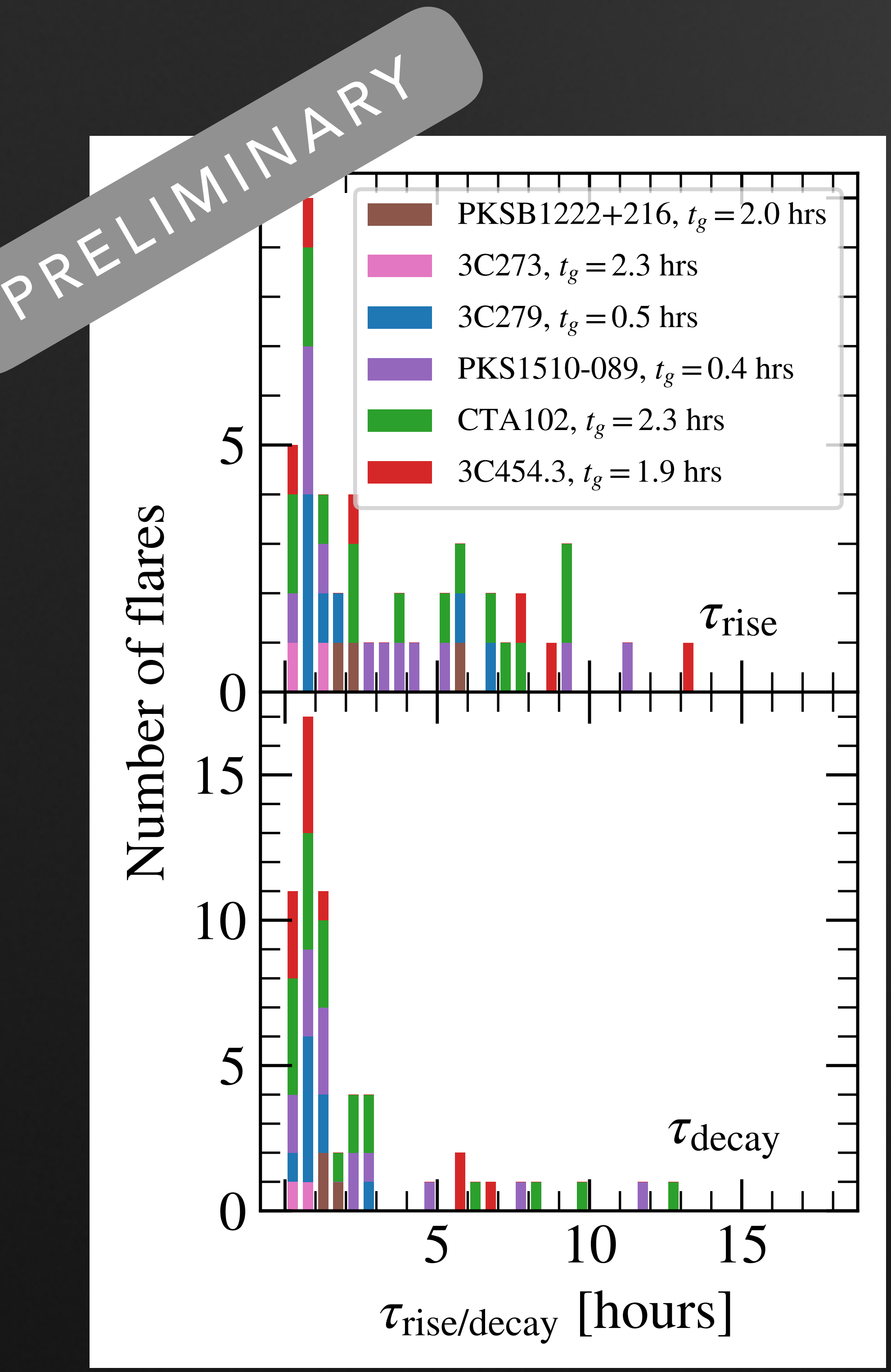
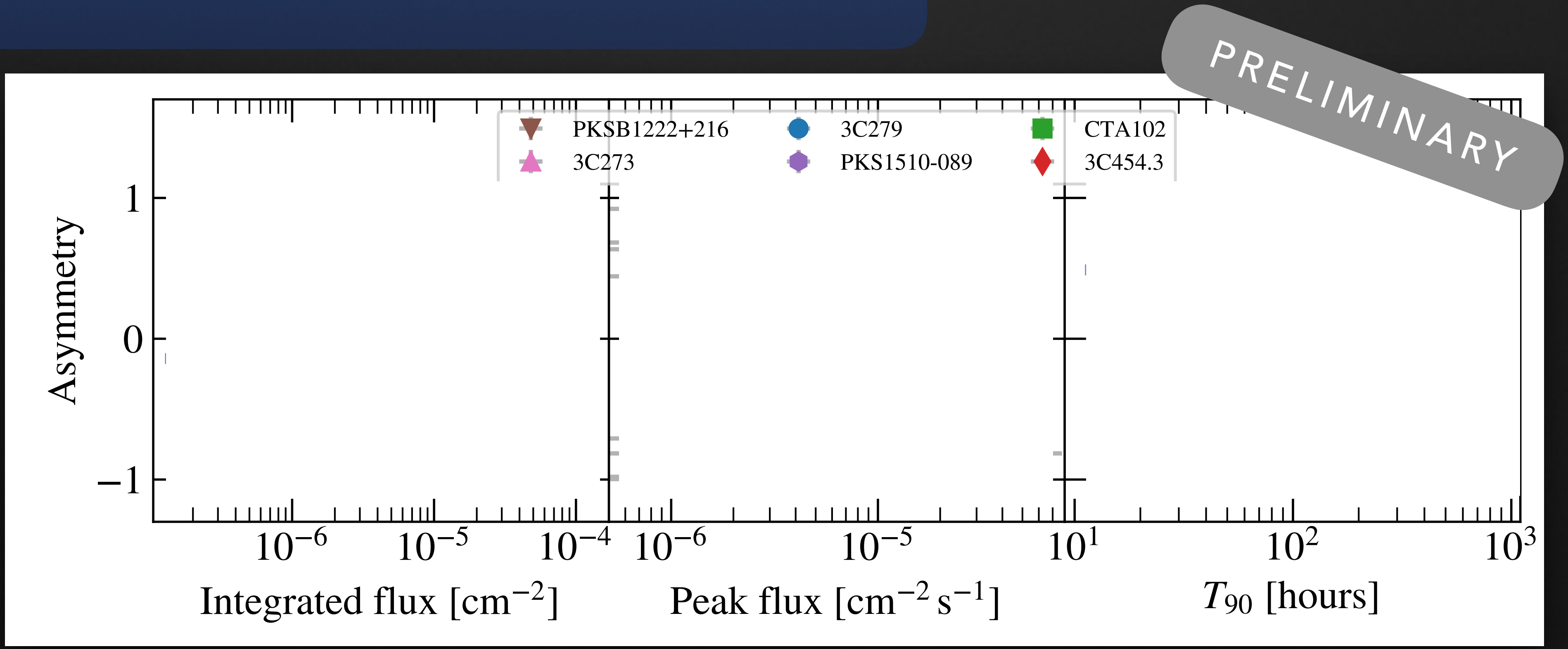


All sources show rise and decay times shorter than horizon crossing time (in observer's frame)

FIT TO ORBITAL LIGHT CURVES: ASYMMETRY

- A < 0: fast rise exponential decay (FRED), could indicate particle injection and cooling
- A ~ 0: symmetric flares, could indicate beam sweeping through line of sight, or superposition of flares
- A > 0: exponential rise fast decay (ERFD)

$$A = \frac{\tau_{\rm rise} - \tau_{\rm decay}}{\tau_{\rm rise} + \tau_{\rm decay}}$$



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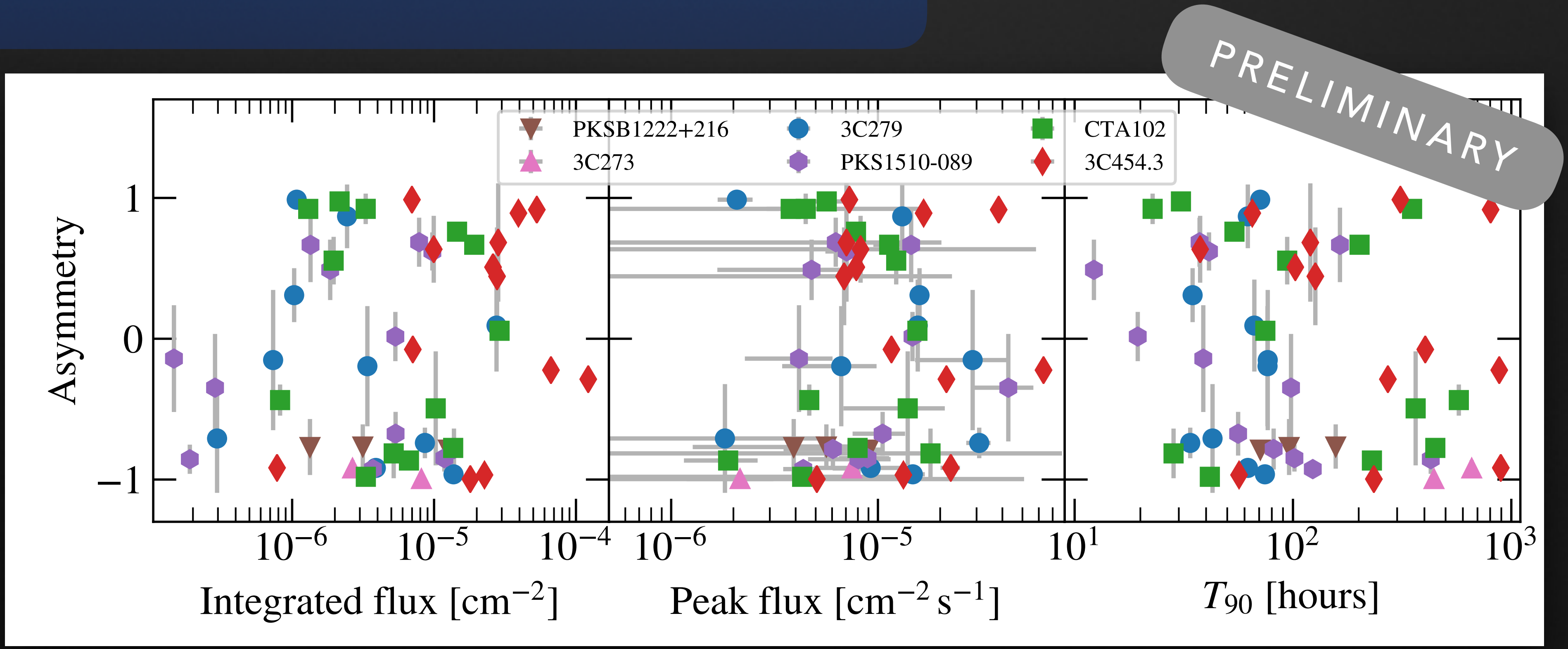
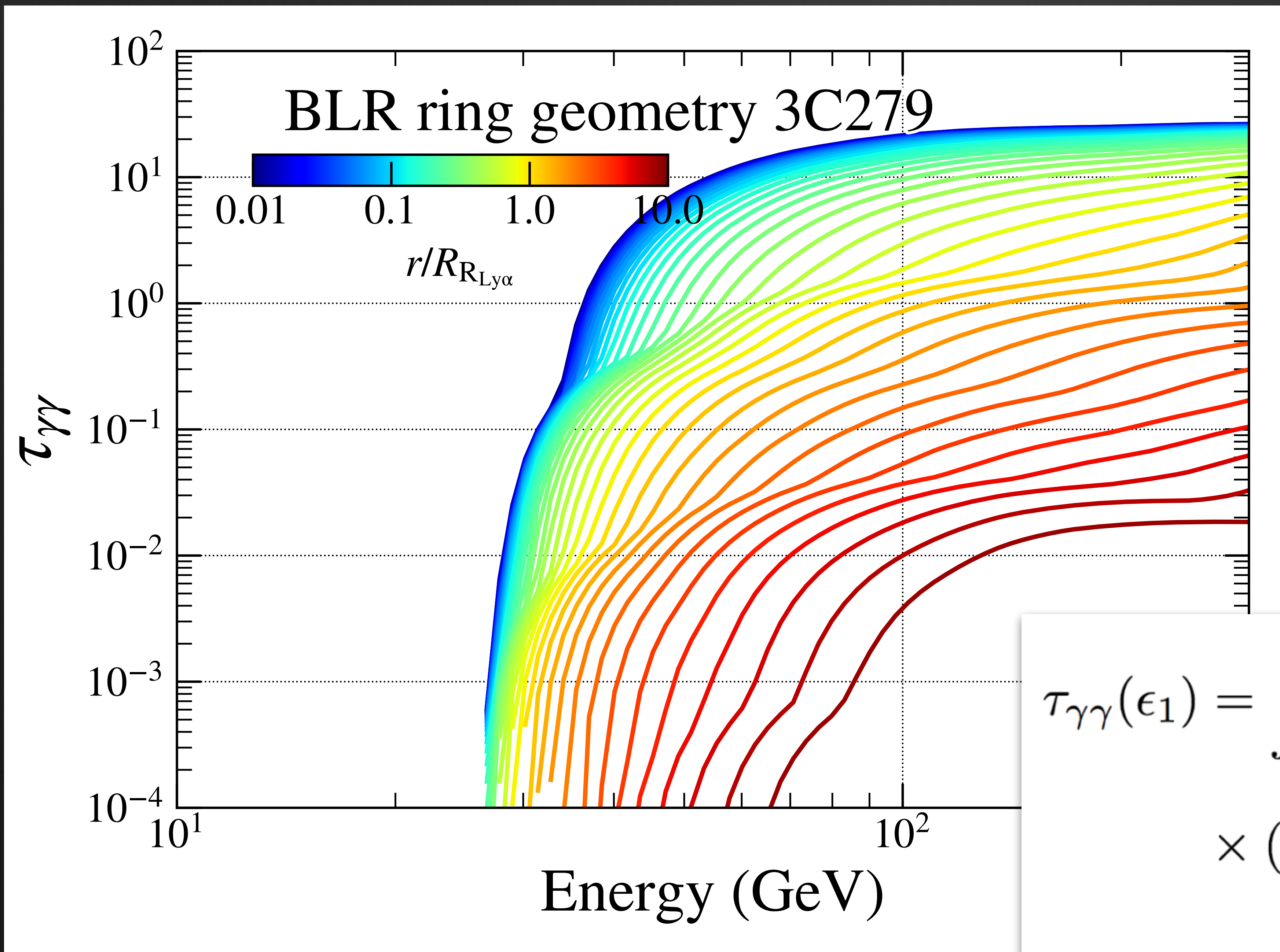


GAMMA-RAY OPACITY DUE PAIR PRODUCTION WITH BLR PHOTONS

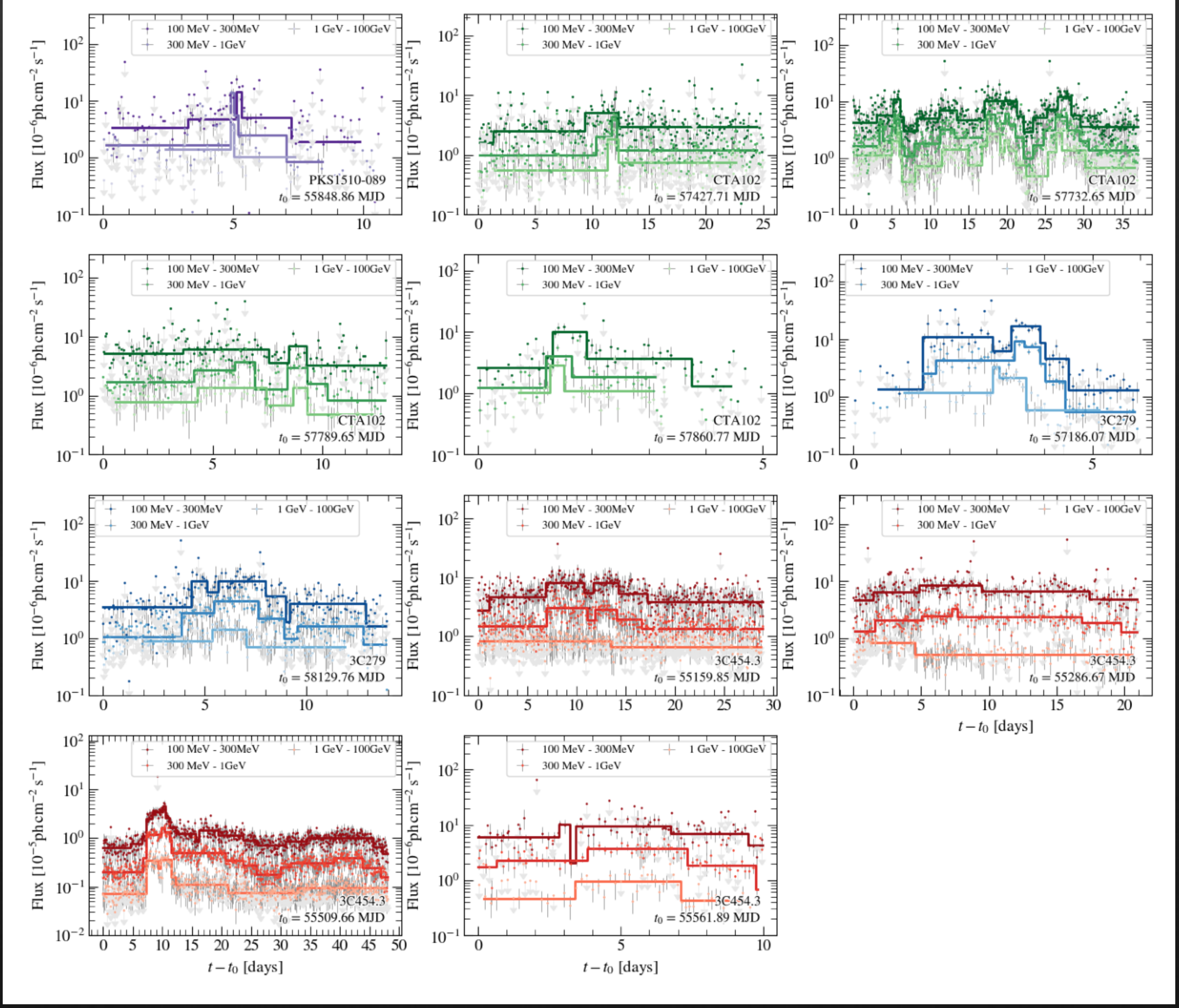


$$\tau_{\gamma\gamma}(\epsilon_1) = \int_r^\infty d\ell \int_0^{2\pi} d\phi \int_{-1}^{1} d\mu \times (1-\cos\psi) \int_0^\infty d\epsilon \, \frac{u(\epsilon,\Omega;\ell)}{\epsilon m_e c^2} \times \sigma_{\gamma\gamma}\left[\frac{\epsilon\epsilon_1(1+z)}{2}(1-\cos\psi)\right]$$

[Model adapted from Finke 2016]

ENERGY DEPENDENT ORBITAL LIGHT CURVES

- Light curves only shown if at least 2 bayesian blocks per energy bin detected
- Time delay searched with ZDCF method [Alexander 1997, 2013]
- Positive and negative time lags are found, peak width of ZDCF consistent with zero lag



RESULTS FOR SEARCH FOR GAMMA-RAY RADIO CORRELATION

PRELIMINARY

Source	$\hat{\beta}$	p_β	$\tau_{\rm peak}$ [days]	p_τ	$d_{\gamma,r}$ [pc]
			OVRO		
PKSB1222+216	$1.92^{+0.39}_{-0.59}$	0.59	—	—	—
3C273	$2.38^{+0.30}_{-0.97}$	0.94	$-416.5^{+217.0}_{-140.0}$	0.0068	10.96 [5.2, 14.6] ± 4.4
3C279	$2.29^{+0.32}_{-0.94}$	0.71	—	—	—
PKS1510-089	$1.89^{+0.45}_{-0.84}$	0.34	—	—	—
CTA102	$2.23^{+0.26}_{-0.92}$	0.84	—	—	—
3C454.3	$2.20^{+0.36}_{-2.20}$	0.40	$-101.5^{+49.0}_{-112.0}$	0.0156	15.39 [8.0, 32.4] ± 2.8
			ALMA Band 3		
3C273	$2.12^{+0.40}_{-2.12}$	0.73	—	—	—
3C279	$1.82^{+0.38}_{-0.45}$	0.89	—	—	—
CTA102	$1.94^{+0.42}_{-1.33}$	0.45	$-216.0^{+209.0}_{-11.0}$	0.0092	58.85 [1.9, 61.8] ± 7.3
3C454.3	$1.73^{+0.36}_{-0.30}$	0.25	$-27.0^{+30.0}_{-30.0}$	0.0164	4.09 [−0.5, 8.6] ± 0.7
			SMA 1.3mm		
3C273	$1.48^{+0.40}_{-0.33}$	0.17	$-122.5^{+84.0}_{-7.0}$	0.0088	3.22 [1.0, 3.4] ± 1.3
3C279	$1.61^{+0.16}_{-0.28}$	0.97	—	—	—
3C454.3	$1.64^{+0.31}_{-1.64}$	0.21	$10.5^{+21.0}_{-28.0}$	0.0002	−1.59 [−4.8, 2.7] ± 0.3

CALCULATING THE COOLING TIME FOR EXTERNAL COMPTON SCATTERING

$$t_{\mathrm{cool,BLR/dt}} = \frac{1+z}{\delta_D} \frac{3 m_e c^2}{4 c \sigma_{\mathrm{T}} u'_{\mathrm{BLR/dt}} \gamma'_{\mathrm{BLR/dt}}}$$

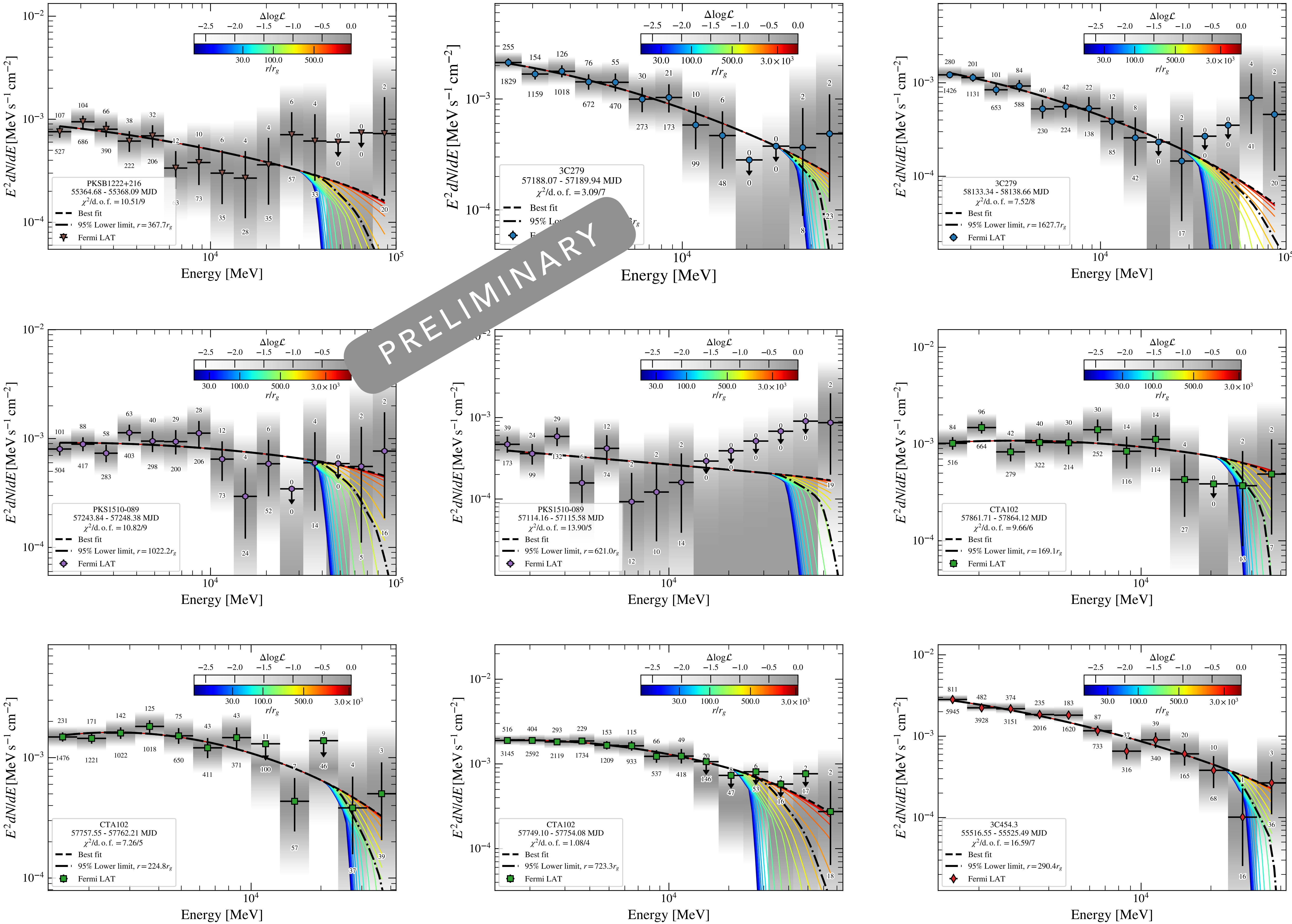
$$u_{\mathrm{BLR/dt,ring}} = \frac{\xi_{\mathrm{li}} L_{\mathrm{disk}}}{4\pi c (R_{\mathrm{li}}^2 + r^2)}$$

$$u'_{\mathrm{BLR/dt,ring}} = \frac{4}{3} \Gamma^2 u_{\mathrm{BLR/dt,ring}}$$

$$\gamma'_{\mathrm{BLR/dt}} = \frac{1}{\delta_{\mathrm{D}}} \sqrt{\frac{\epsilon_s^{\mathrm{obs}}(1+z)}{2\epsilon_{\mathrm{BLR/dt,0}}}}$$

[E.g., Dermer & Schlickeiser 2002; Dermer & Menon 2009; Finke 2016]

SEARCH FOR ABSORPTION



RESULTS FOR SEARCH FOR ABSORPTION

PRELIMINARY

t_0 [MJD]	Δt [days]	$r_{\rm lim}$ [10^{17}cm]	$r_{\rm lim}$ [$R_{{\rm Ly}\alpha}$]	$r_{\rm lim}$ [r_g]	$E_{\rm HEP}$ [GeV]	$E_{\tau_{\gamma\gamma}=1}$ [GeV]	$t_{\rm cool,\ BLR}$ [mins]	$t_{\rm cool,\ dt}$ [hours]	$\tau_{\rm decay}$ [hours]
				PKSB1222+216					
55364.68	3.42	1.33	1.40	609	75.39	69.69	8.2	26.8	47.4 ± 8.3
				3C279					
57188.07	1.87	0.49	0.64	867	56.03	42.91	2.7	19.0	0.5 ± 0.9
58133.34	5.32	1.45	1.91	2580	92.56	107.91	9.0	19.0	8.2 ± 6.3
				PKS1510-089					
57114.16	1.42	0.51	0.66	1088	66.54	54.99	0.6	4.5	0.4 ± 0.3
57243.84	4.53	0.74	0.97	1591	75.93	65.39	0.8	4.5	44.4 ± 9.4
				CTA102					
57737.41	1.67	1.41	0.86	562	36.25	21.23	1.0	6.4	0.3 ± 0.5
57749.10	4.99	3.20	1.95	1275	73.80	37.94	2.8	6.4	8.7 ± 1.2
57757.55	4.66	2.76	1.67	1096	39.19	32.38	2.2	6.4	24.6 ± 2.3
57861.71	2.42	1.95	1.18	776	34.73	24.94	1.4	6.4	1.2 ± 0.7
				3C454.3					
55516.55	8.93	3.19	1.36	1598	41.19	28.73	4.2	16.8	2.6 ± 1.0