Recent highlights from the Fermi LAT

Disclaimer: this will be a biased talk focusing on transient phenomena

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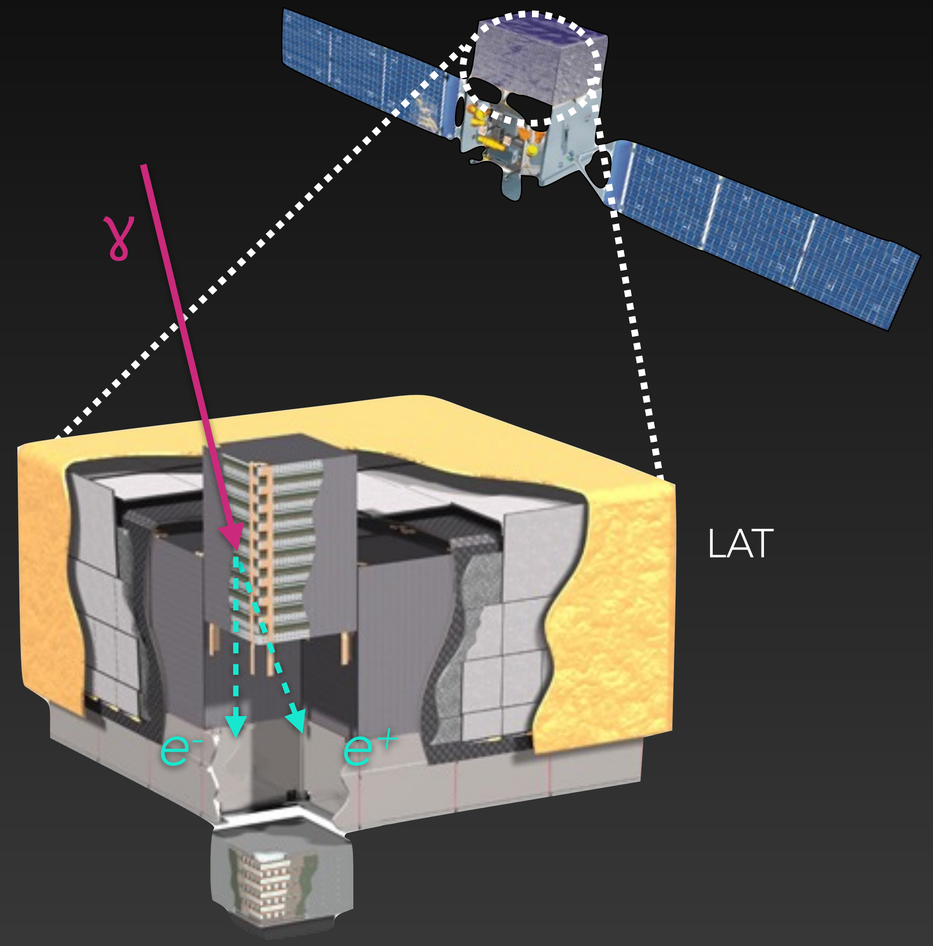
Epiphany Conference Cracow 01/10/2022

The *Fermi* Large Area Telescope (LAT)

Observing the gamma-ray sky since June 11, 2008

Energy range	20 MeV - over 300 GeV
Effective Area (E > 1 GeV)	~ 1 m^2
Point spread function (PSF)	0.8° @ 1 GeV
Field of view	2.4 sr (~20% of the sky)
Orbital period	91 minutes
Altitude	565 km

- **Survey mode**: full sky observed every 3 hours
- **Public data**, available within 12 hours

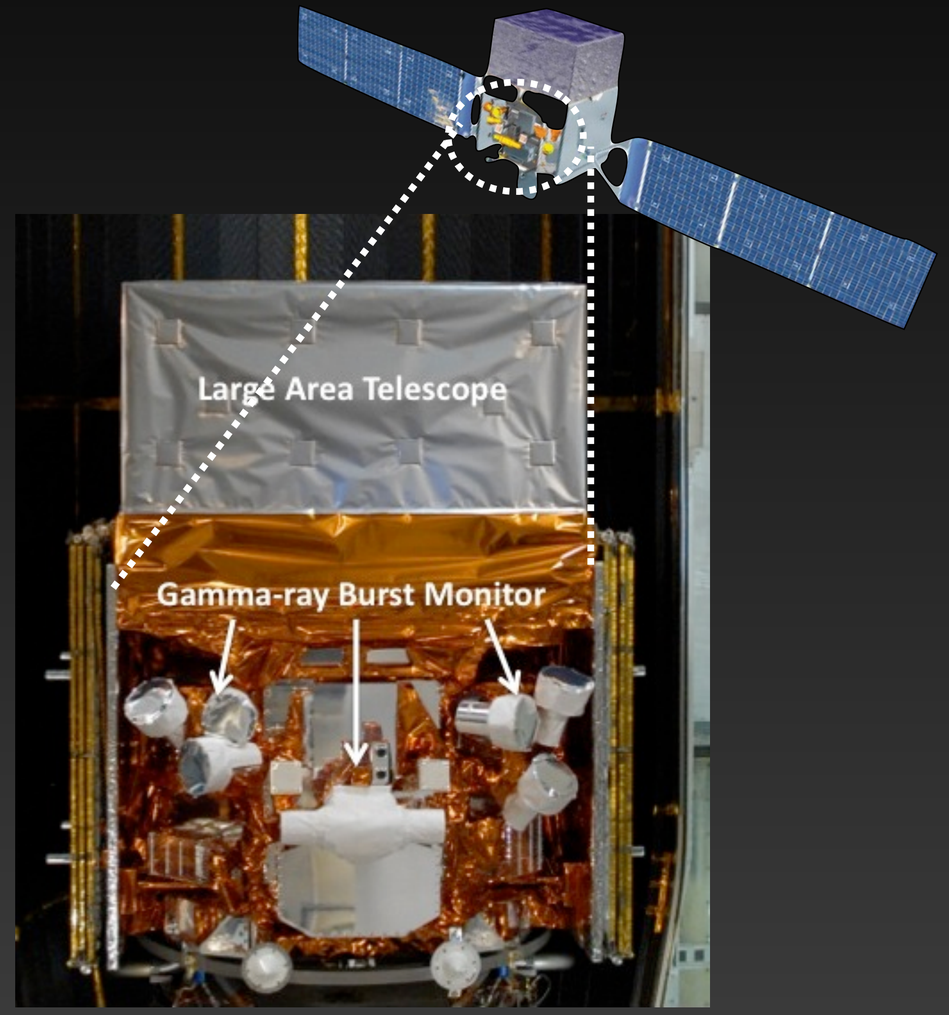


The *Fermi* Gamma-ray Burst Monitor (GBM)

Observing the gamma-ray sky since June 11, 2008

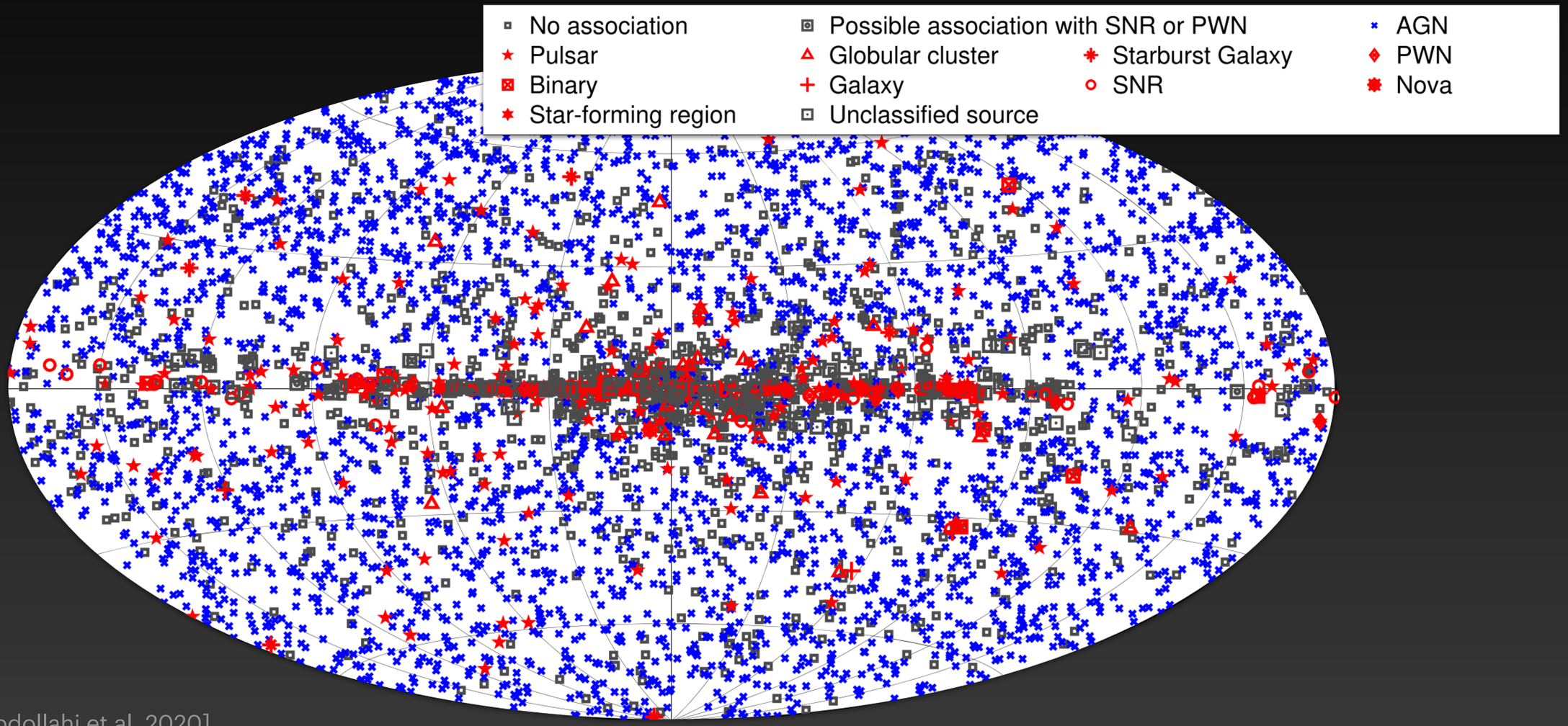
Energy range	8 keV - 40 MeV
Gamma-rat burst localization	~3˚
Field of view	9.5 sr (~75% of the sky)
Timing accuracy	2 μs

- 12 NaI and 2 BGO Scintillators



More than 5,000 sources detected in first 10 years

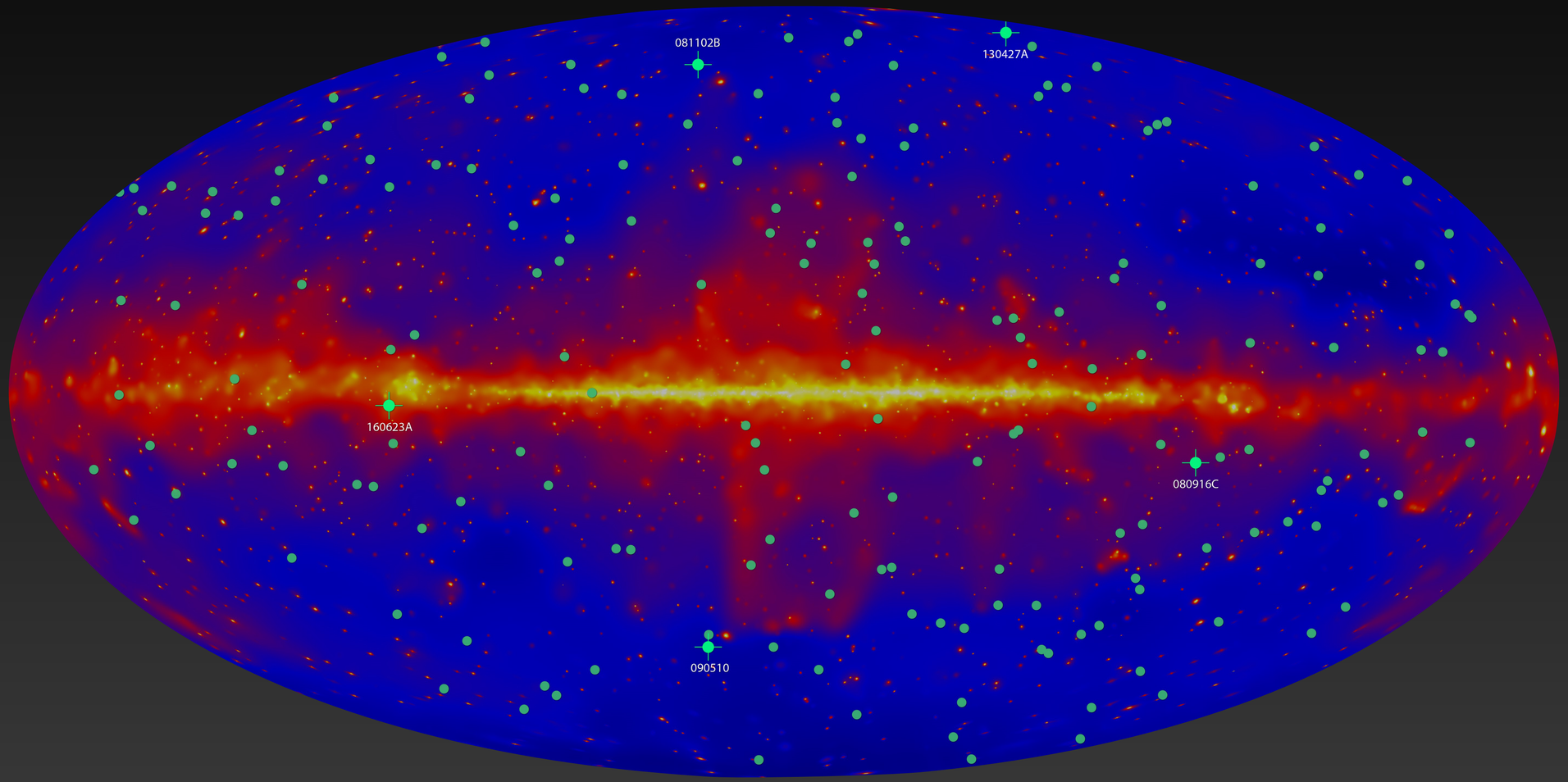
Between 50 MeV and 1 TeV



4FGL-DR2 catalog [Abdollahi et al. 2020]
DR3 with 12 years of data coming soon

Second Gamma-Ray Burst (GRB) catalog released

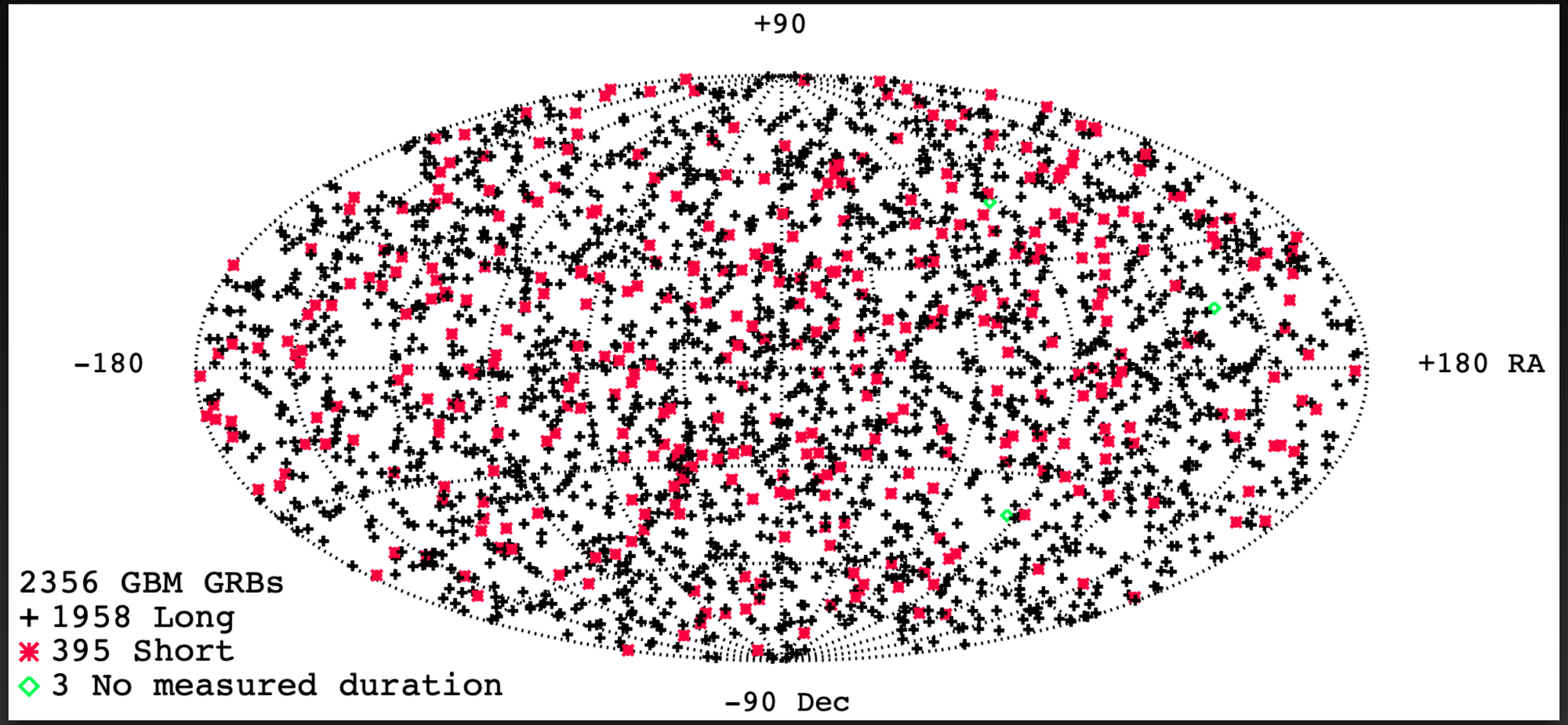
17 short GRBs, 169 long GRBs detected in 10 years with the LAT



2FLGC, Ajello et al. (2019)

4th *Fermi*-GBM catalog of GRBs released

395 short GRBs, 1958 long GRBs detected in 10 years with the GBM

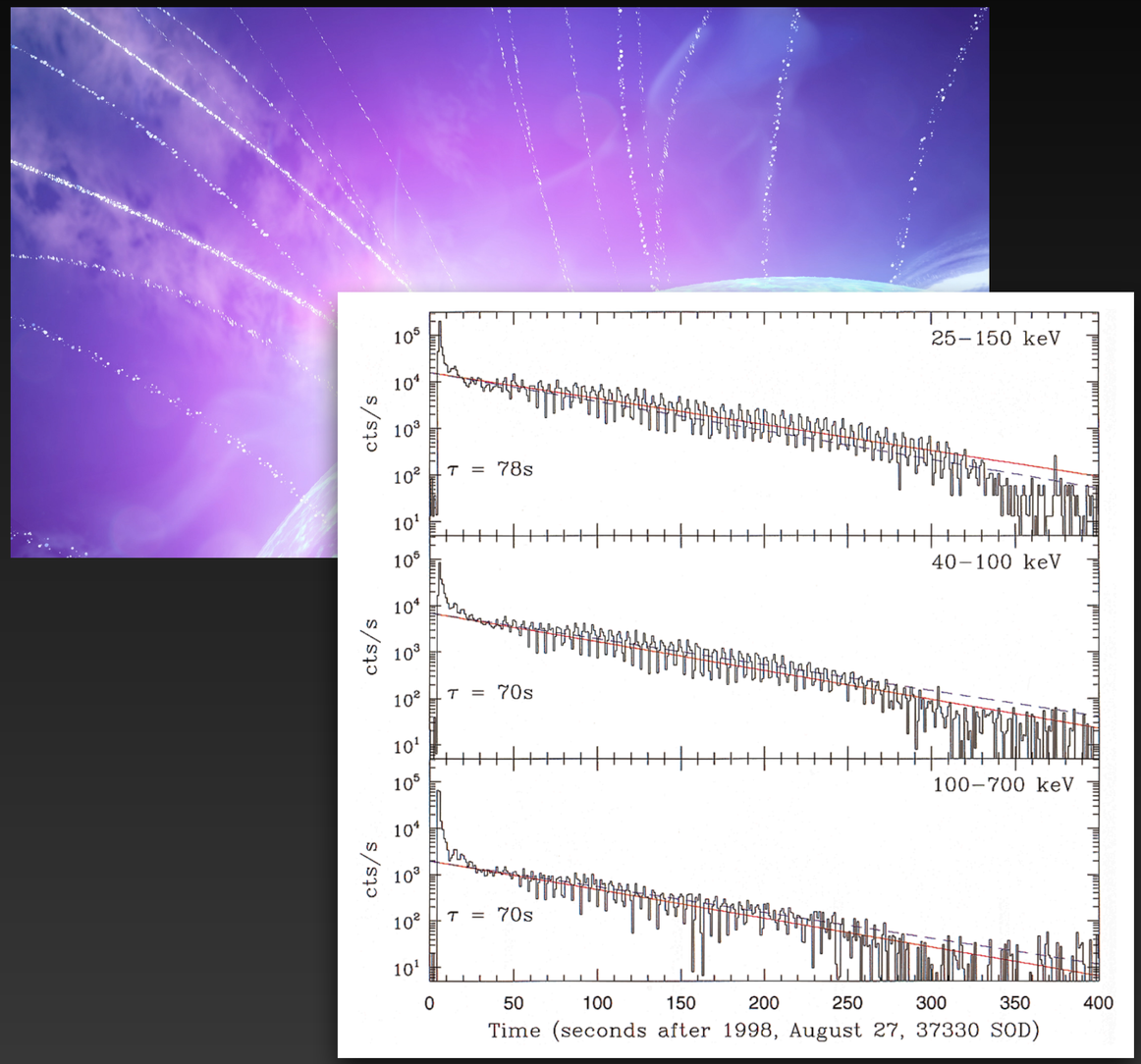


Von Kienlin et al. (2020)

Detection of a Magnetar Giant Flare

Magnetar Giant Flares (MGF)

- Magnetars: strongly magnetized neutron stars with magnetic fields $\sim 10^{13-15}$ G and periods of 0.1-10 s
- Can show rare outbursts in X-rays and soft gamma-rays with luminosities around 10^{44-47} erg s^{-1}
- Bright initial flare, followed by pulsating tail
- Likely caused by crustquakes induced by high magnetic fields

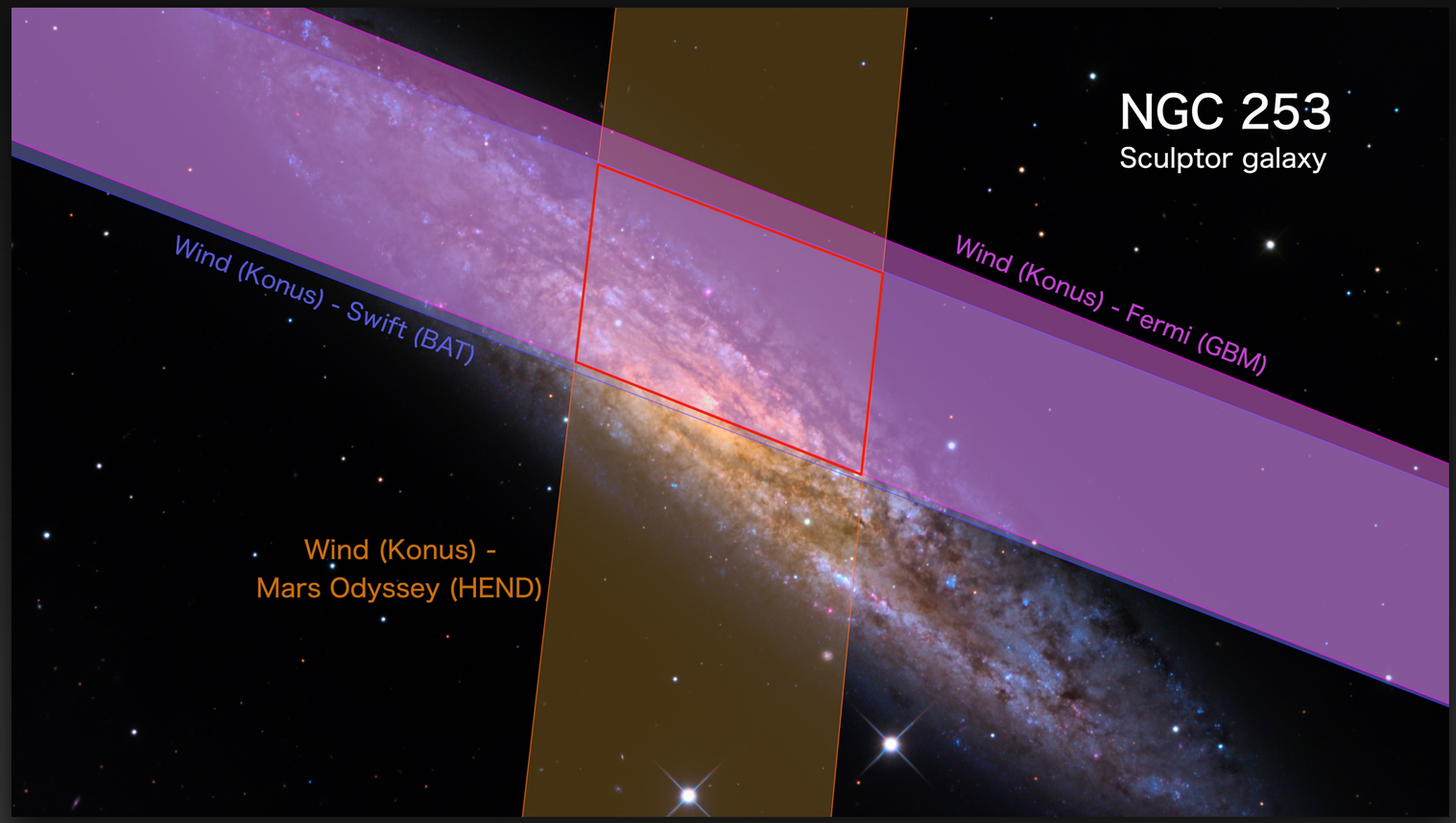


[Feroci et al. 2001]

GRB 200415A

Transient on April 15th 2020

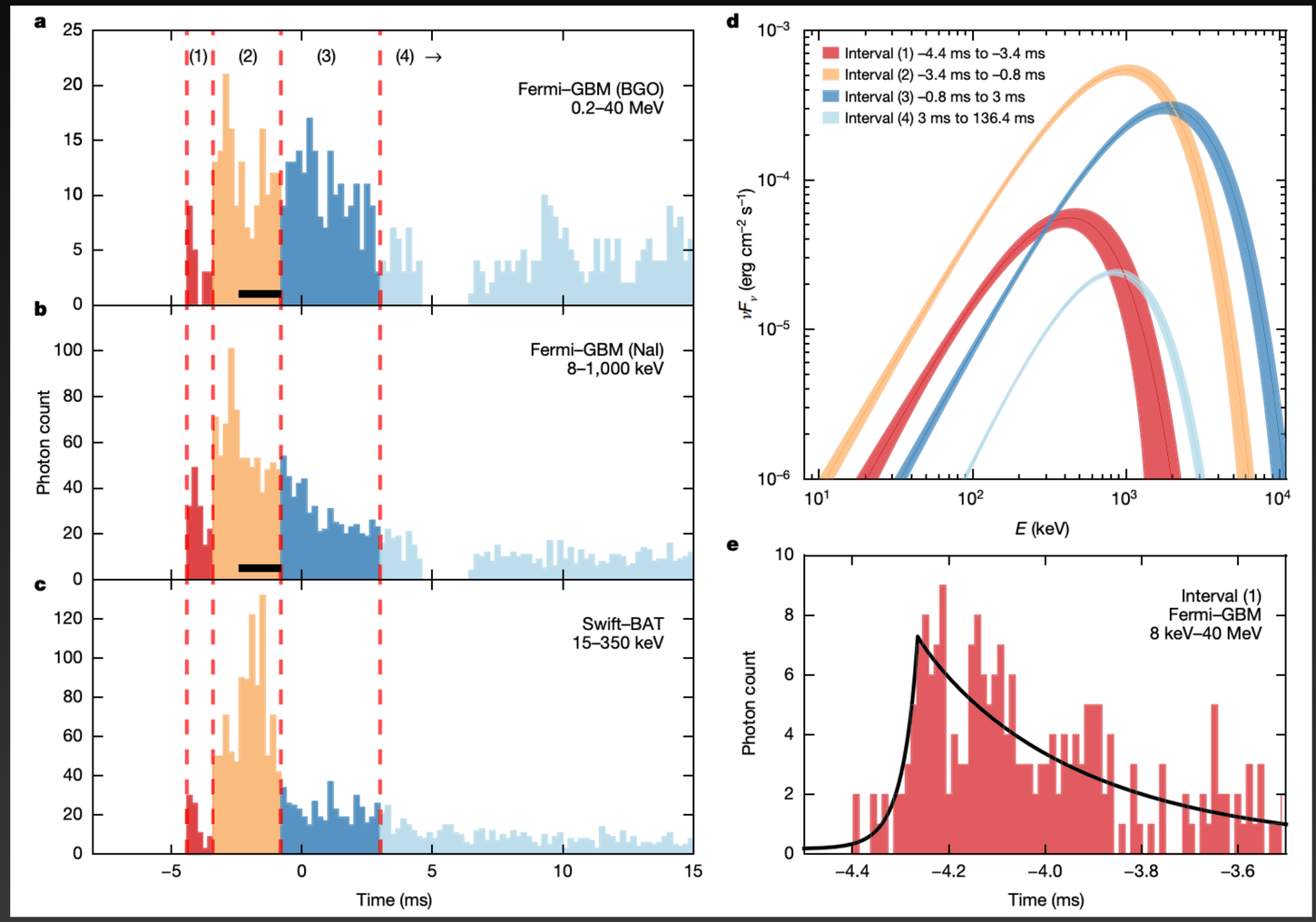
- GBM triggered at 08:48:05.56 UTC
  [Roberts et al. Nature, 589, 207, 2021]
- Localized with 20 square-arcmin precision through interplanetary Network of gamma-ray detectors
  [Svinkin et al. Nature, 589, 211, 2021]
- Burst most likely originated in star-forming Sculptor Galaxy, $D_L \approx 3.5$ Mpc



Fermi GBM observation

Unusual properties for short GRB — giant magnetar flare better explanation

- High peak energy: ~ MeV
- Hard spectral shape: ~0
- Short rise time: 77 μs
- Sub-ms spectral evolution
- 2.5σ Evidence for QPO @ 180 Hz
  - QPO significantly detected at 2,132 Hz and 4,250 Hz in main peak with Atmosphere-Space Interactions Monitor [Castro-Tirado et al. Nature 600, 621, 2021]
- Very bright burst:
  - $L_{\rm iso} \approx 10^{47}$ erg s^{-1}
  - $E_{\rm iso} \approx 1.5 \times 10^{46}$ erg
- No radio counterpart (VLA)
- No GW emission (KAGRA)

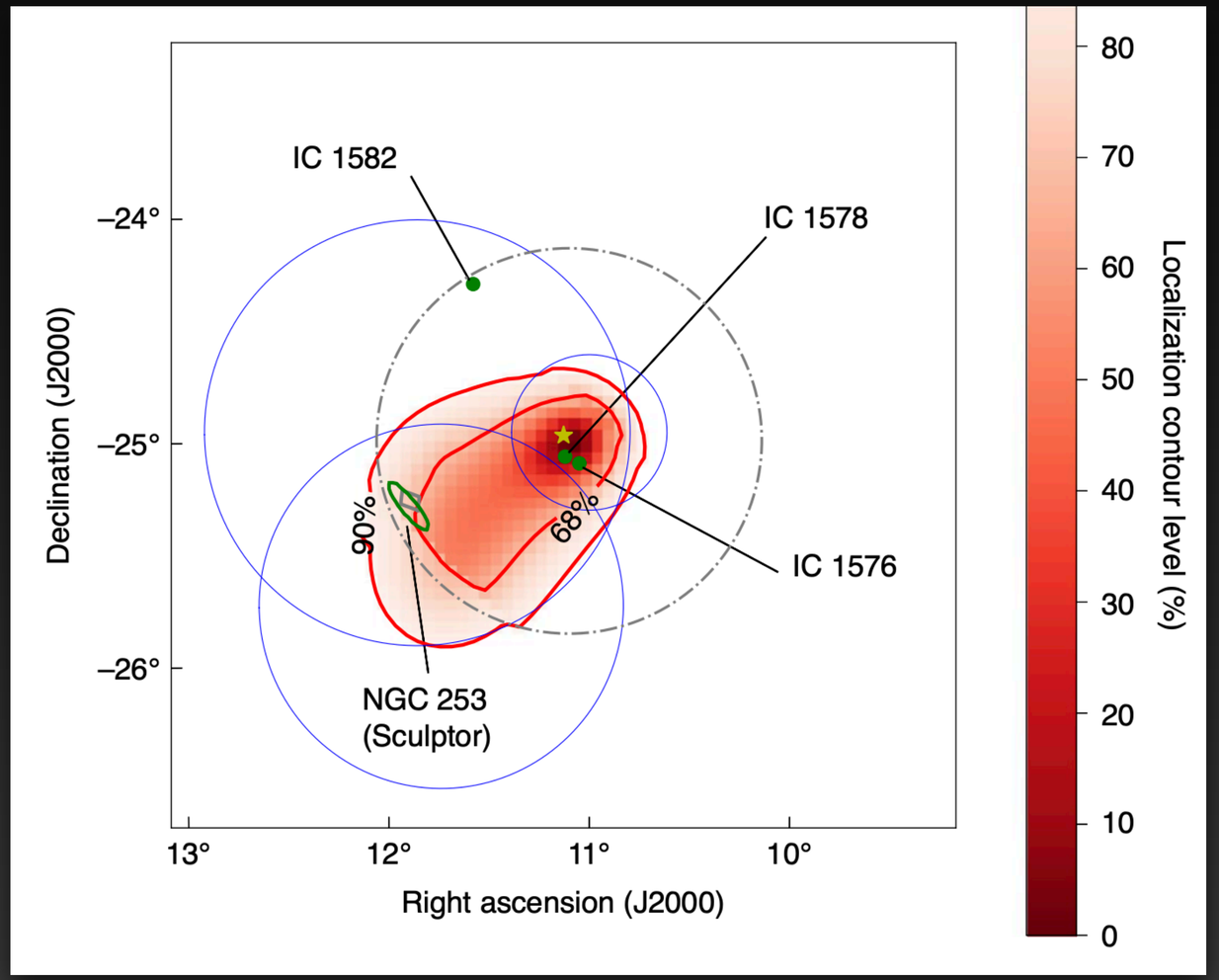


[Roberts et al. Nature, 589, 207, 2021]

LAT detection of GRB 200415A

- LAT detected 3 photons
- Maximum test statistic TS $= 29$
- NGC 253 at 72% localization CL
- Probability of chance coincidence: $< 2.9 \times 10^{-3}$
- Long delay of first photon to T_0 atypical for sGRB

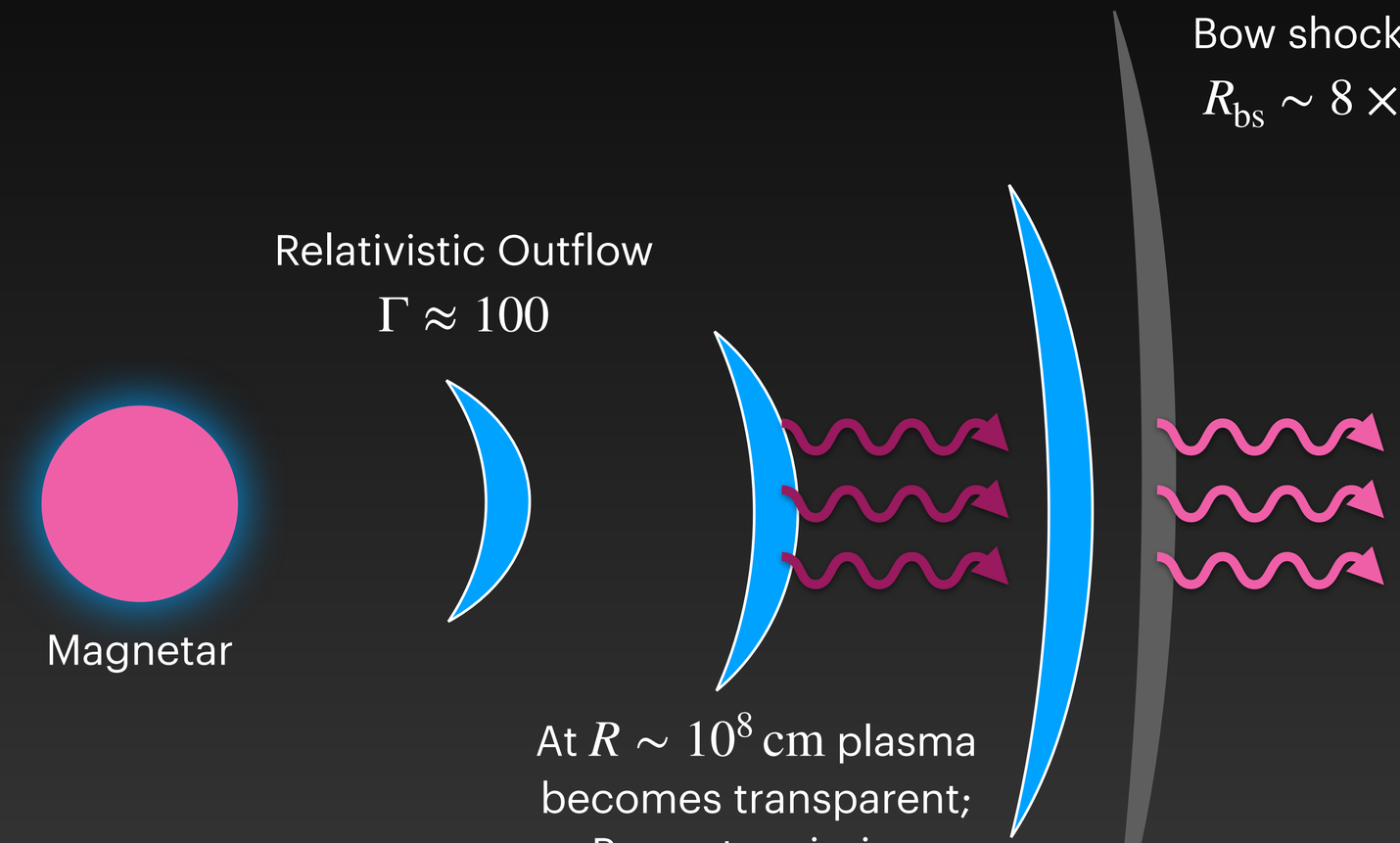
Time since T_0 (s)	Energy (MeV)	Distance to NGC 253 (°)	Assoc. Prob.
19.18	480	0.3	0.990
180.22	1300	0.5	0.988
284.05	1700	0.9	0.999



[Ajello et al. NatAs, 5, 385, 2021]

Model for the MGF emission

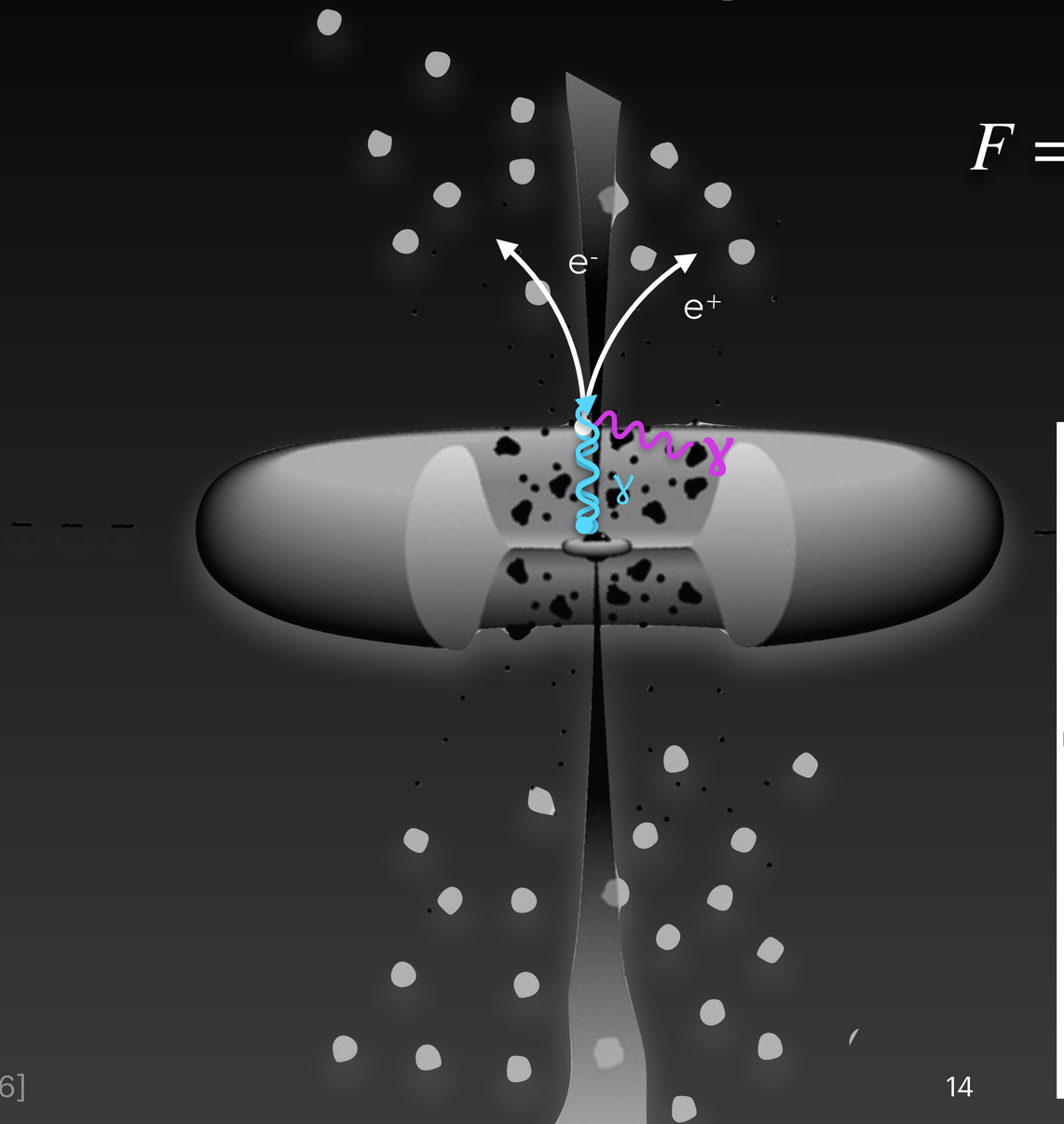
See Ajello et al. NatAs, 5, 385, 2021 for details



[Slide adapted from N. Di Lalla]

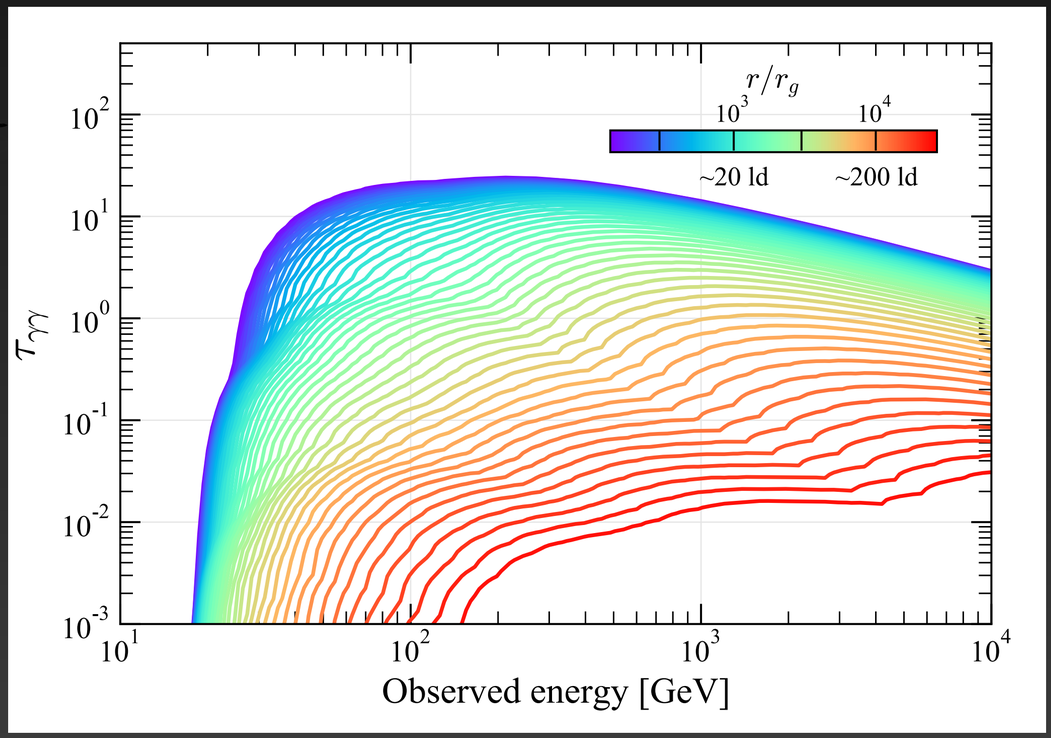

Blazar Variability
Highlights on the detection of minute-scale variability, evidence for magnetic reconnection, gamma-ray-neutrino connection

Probing the location of the gamma-ray emission region
in Flat Spectrum Radio Quasars



$$F = F_0 \exp(-\tau_{\gamma\gamma}) \qquad E_\gamma \epsilon_{\rm thresh} \geqslant (m_e c^2)^2$$

$$\Rightarrow \frac{E_\gamma}{30\,\mathrm{GeV}} \geqslant \frac{10\,\mathrm{eV}}{\epsilon_{\rm thresh}}$$

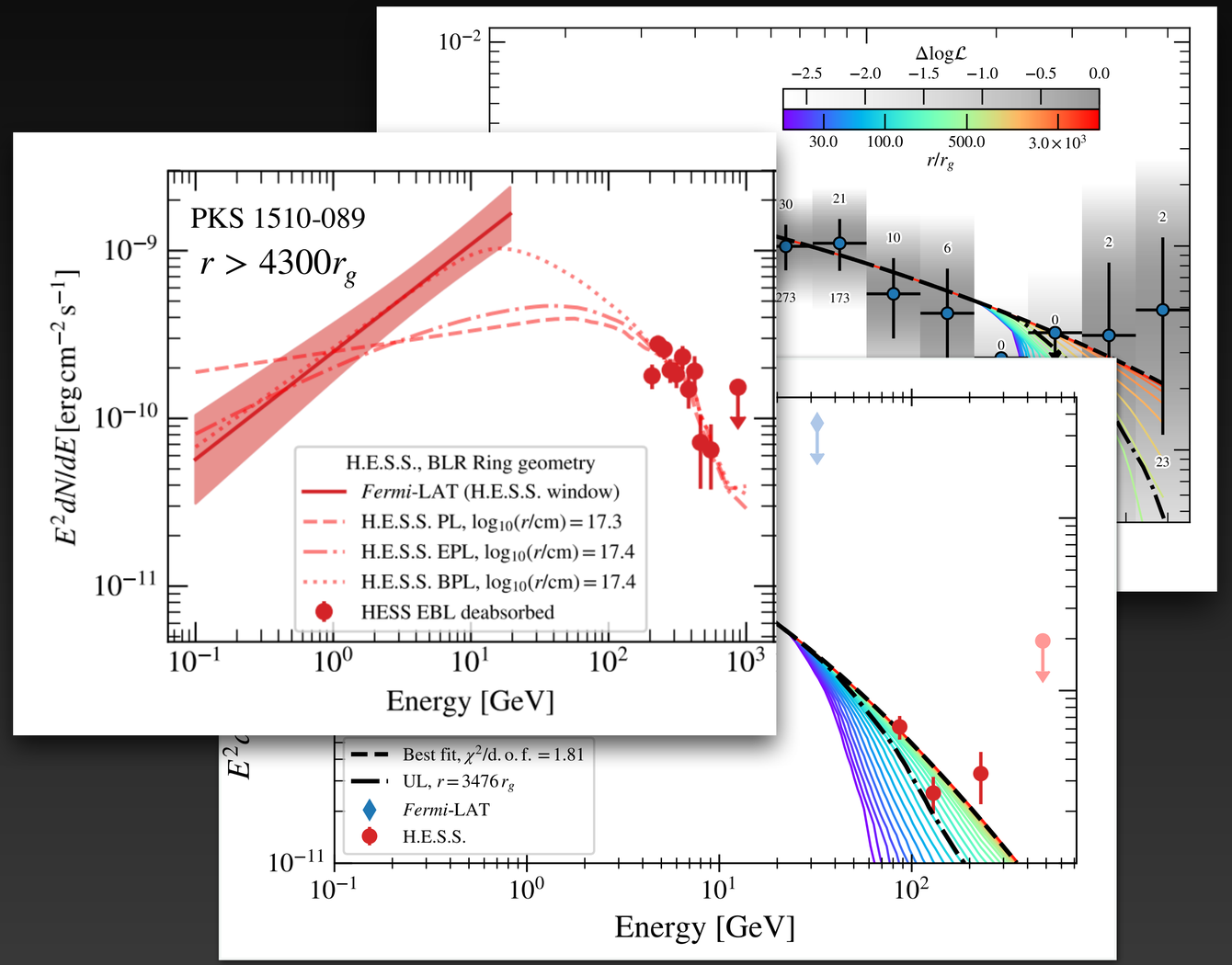


[e.g., Finke 2016]

Bright flares in FSRQs do not show signs of absorption

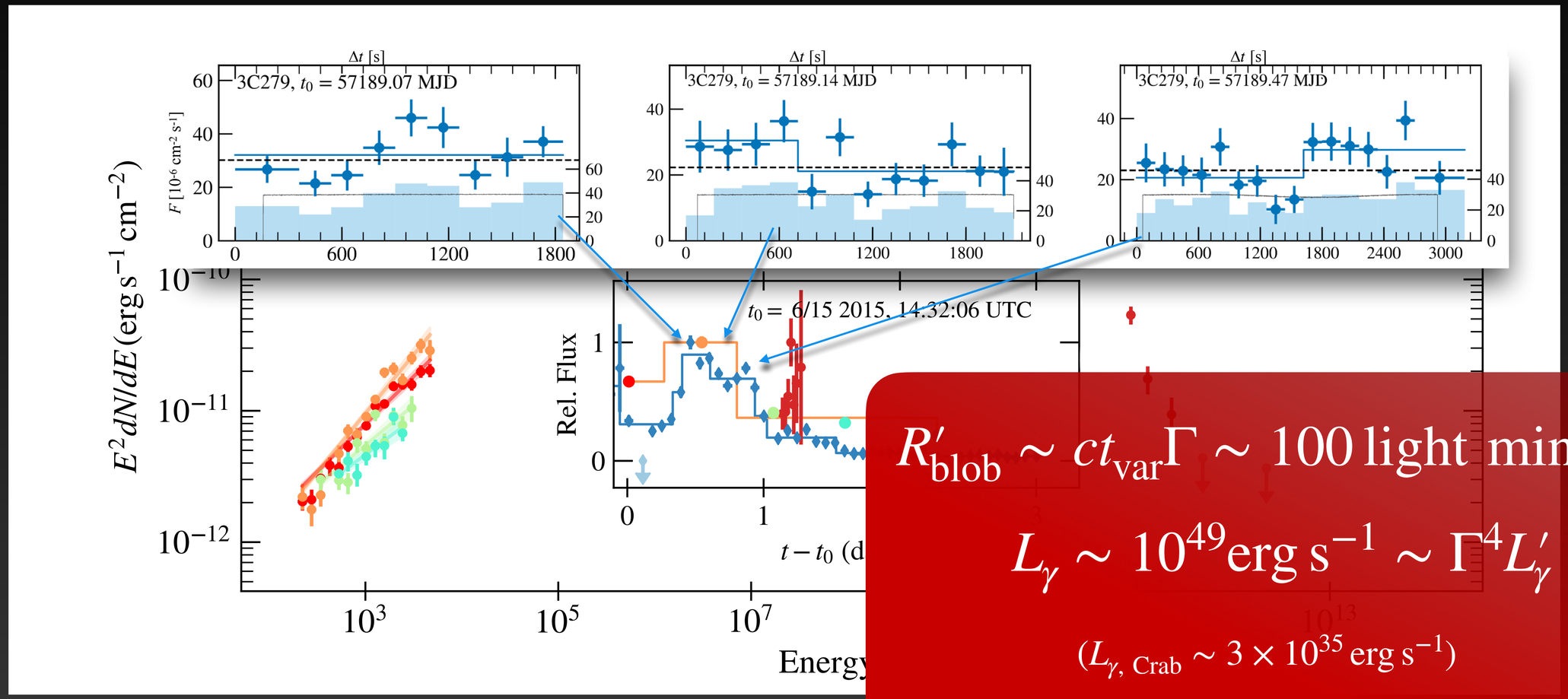
Further supported by recent observations / analyses

- Absence of clear absorption features: emission must occur $\gtrsim 10^3 r_g$ away from central engine
- Combination of LAT and Cherenkov telescope data can provide strong constraints



[e.g., MM, Scargle, Blandford 2019;
H.E.S.S. Collaboration 2019;
H.E.S.S., MAGIC, ATOM, LAT, Boston VLBI Collaborations 2021;
Acharyya, Chadwick, Brown 2021]

Short time variability in 3C 279



$$R'_{\rm blob} \sim c t_{\rm var} \Gamma \sim 100 \text{ light minutes}$$

$$L_\gamma \sim 10^{49} \text{erg s}^{-1} \sim \Gamma^4 L'_\gamma$$

$$(L_{\gamma,\,\rm Crab} \sim 3 \times 10^{35} \text{ erg s}^{-1})$$

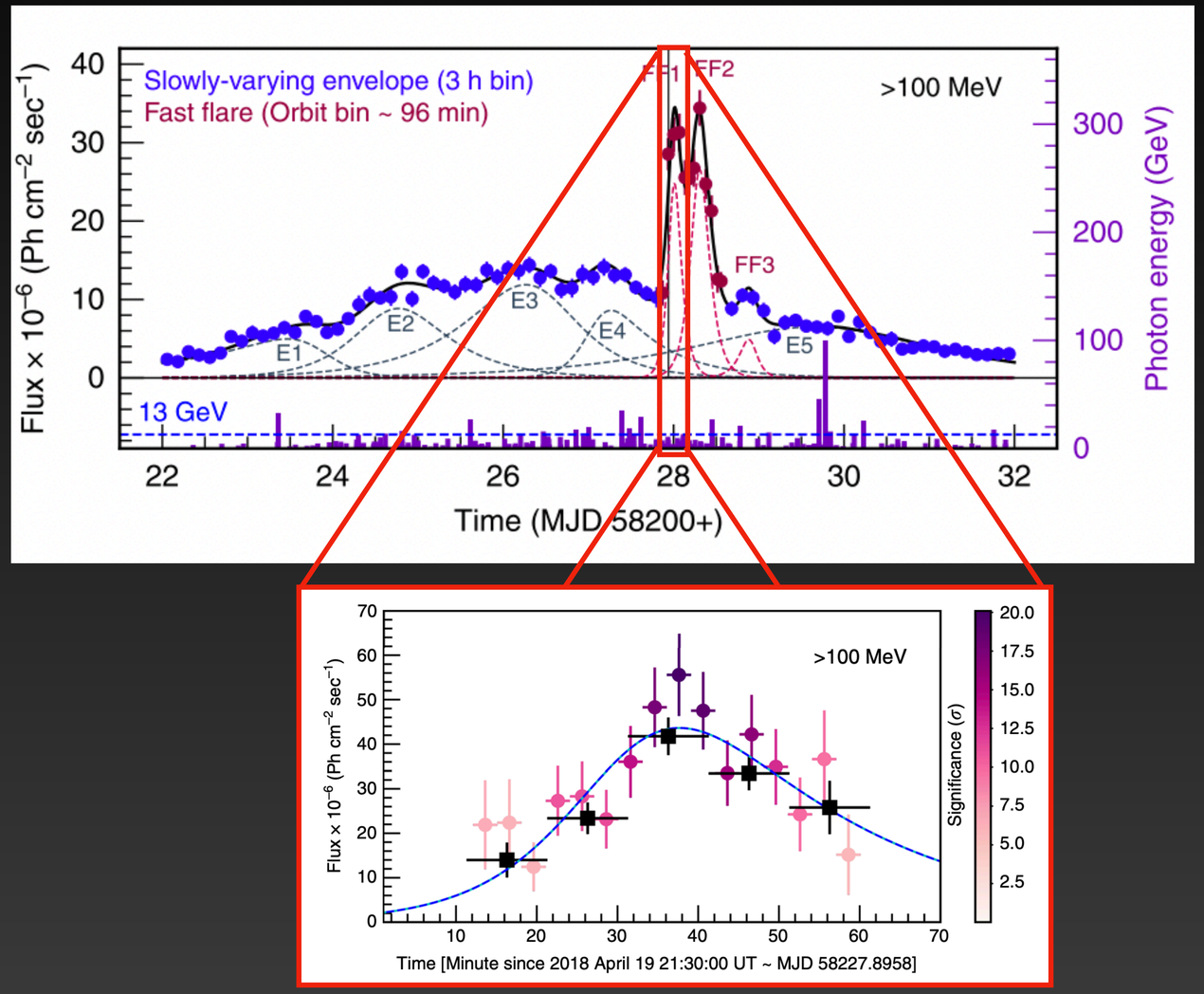
$$r \gtrsim 3500 r_g \sim 10^5 \text{ light minutes}$$

[MM, Scargle, Blandford 2019]

Fast variability in 3C 279 in 2018

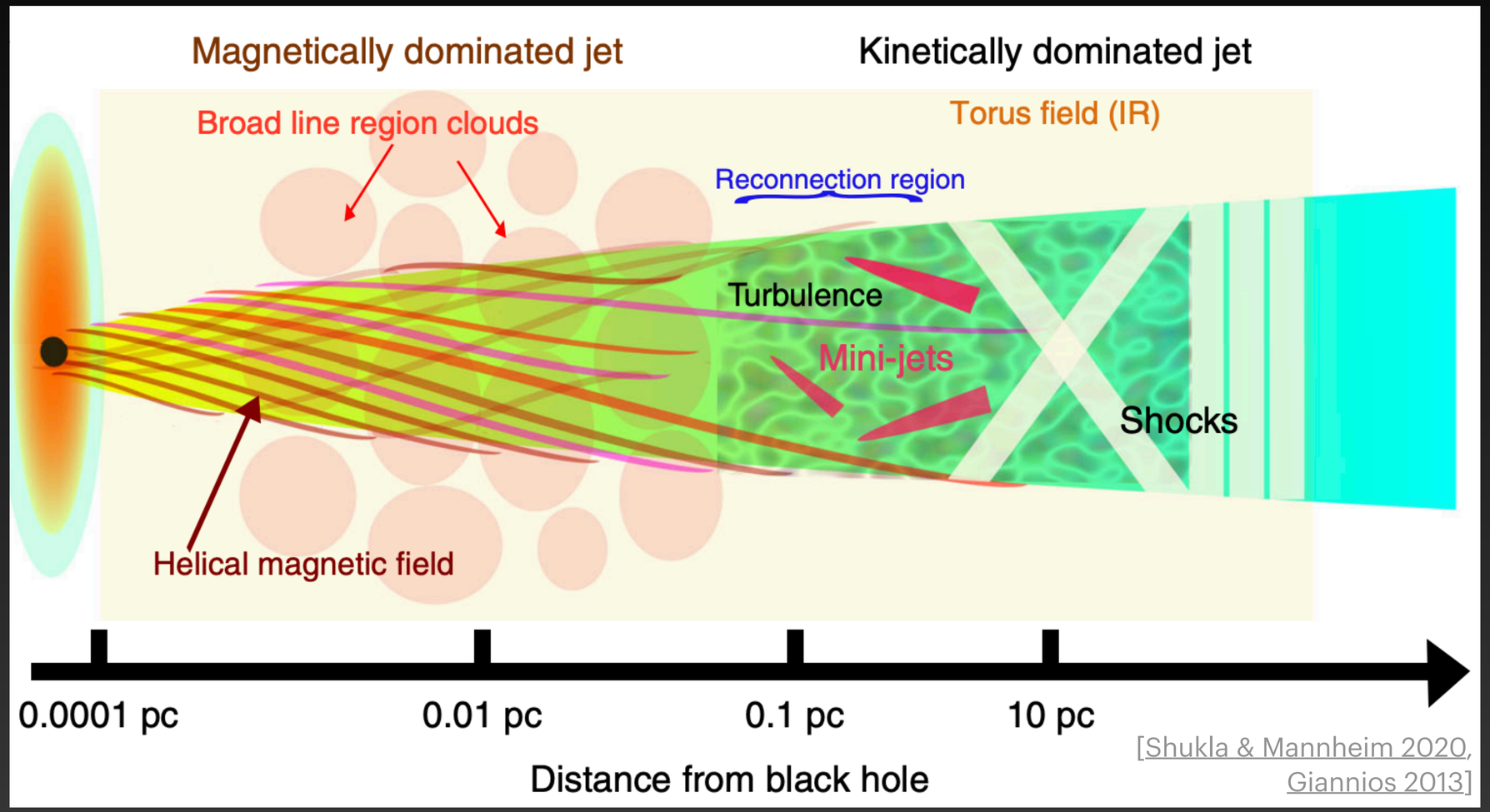
Evidence for magnetic reconnection event?

- Fast variation on top of slowly varying component
- Both components have curved spectra
- Gamma-rays with $E > 13$ GeV observed → no attenuation in BLR
- Minute-scale variability
- Suggested explanation: jet-in-jet scenario with particle acceleration through magnetic reconnection



[Shukla & Mannheim, Nature Communications 2020]

Jet-in-jet scenario and magnetic reconnection



[Shukla & Mannheim 2020, Giannios 2013]

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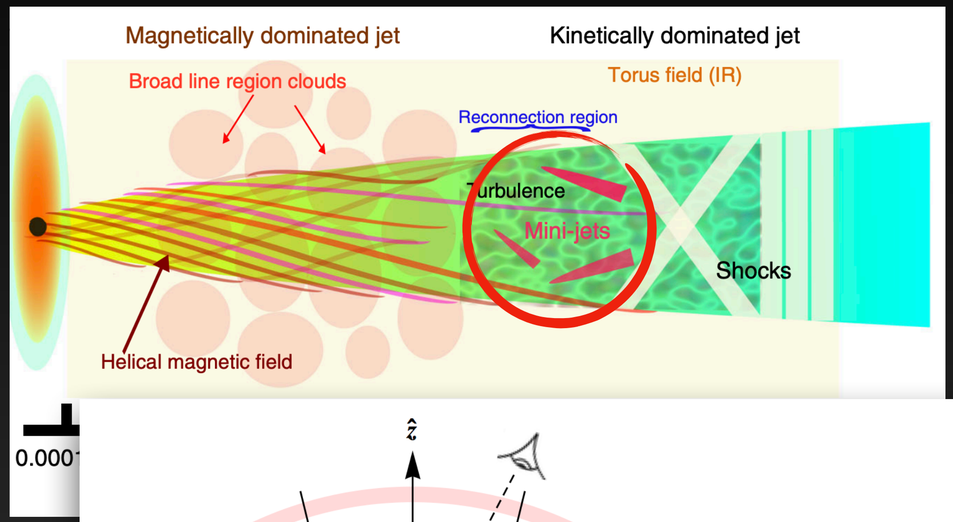
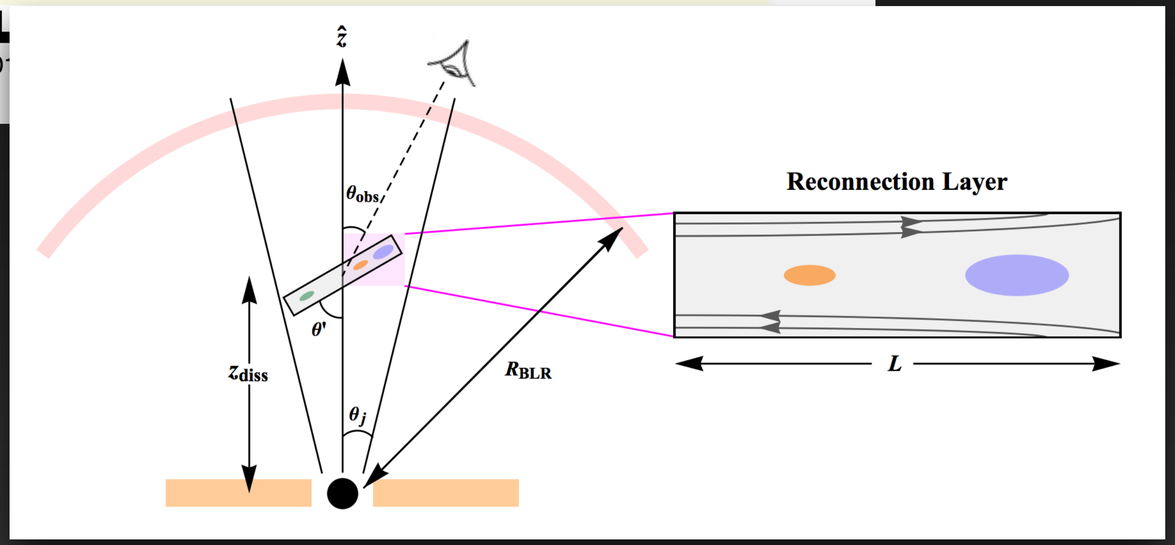
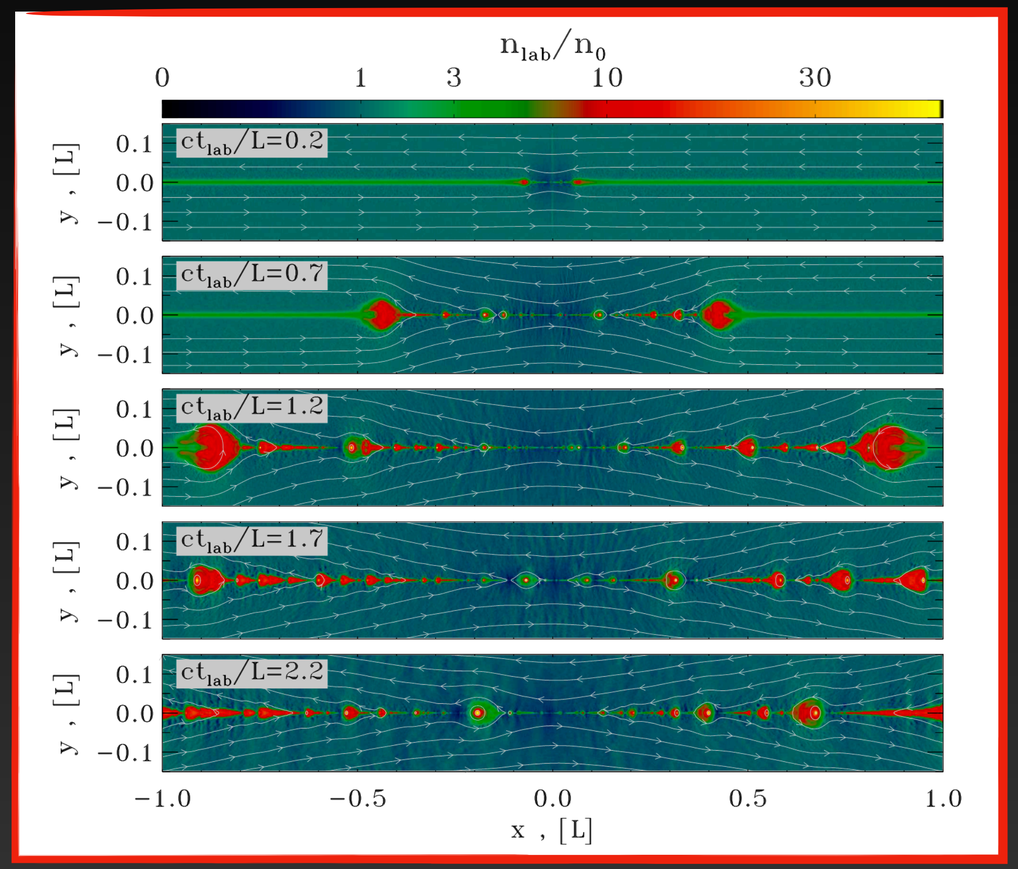




[Giannios et al. 2010; Petropoulou et al. 2016; Christie et al. 2019]

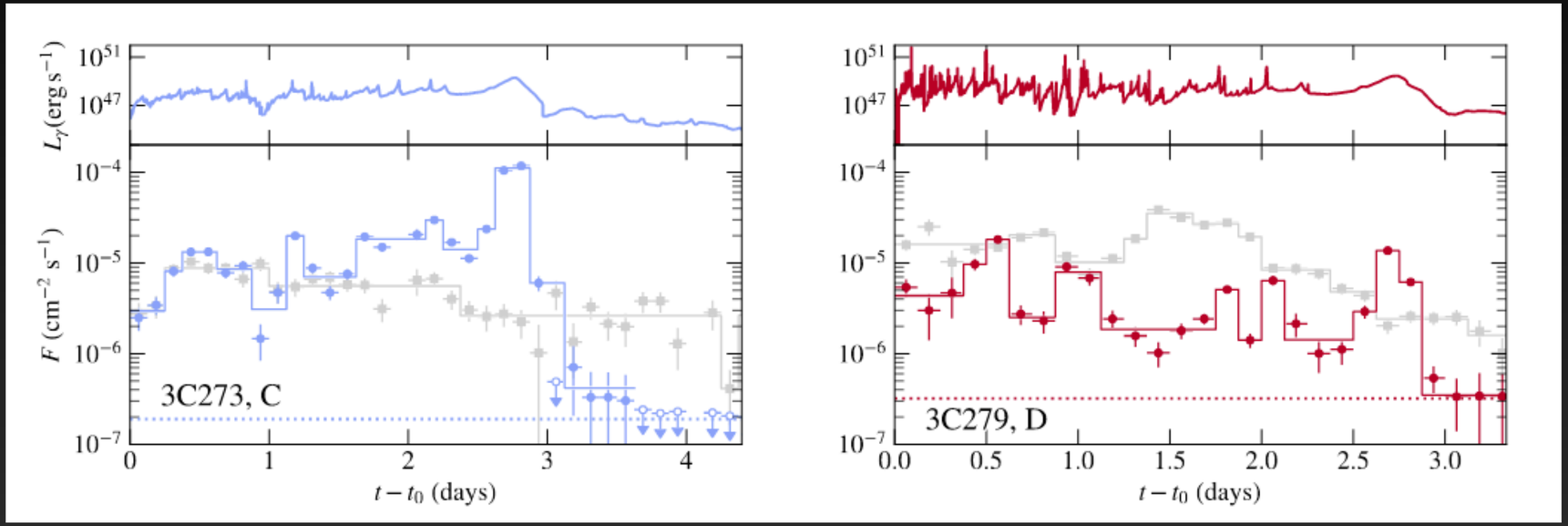


[Sironi, Giannios, Petropoulou 2016]

See also session "particle acceleration II" on Wednesday at 5pm

Can magnetic reconnection explain observed time variation?

- 2D PIC simulations provide theoretical light curves
- From theoretical light curves: fake light curves of flares created as would be observed by LAT
- Fake light curves can reproduce flux, variability time scales, power spectra
- Minute-scale variability could be explained by plasmoids moving towards the observer



[MM, Petropoulou, Christie 2021]

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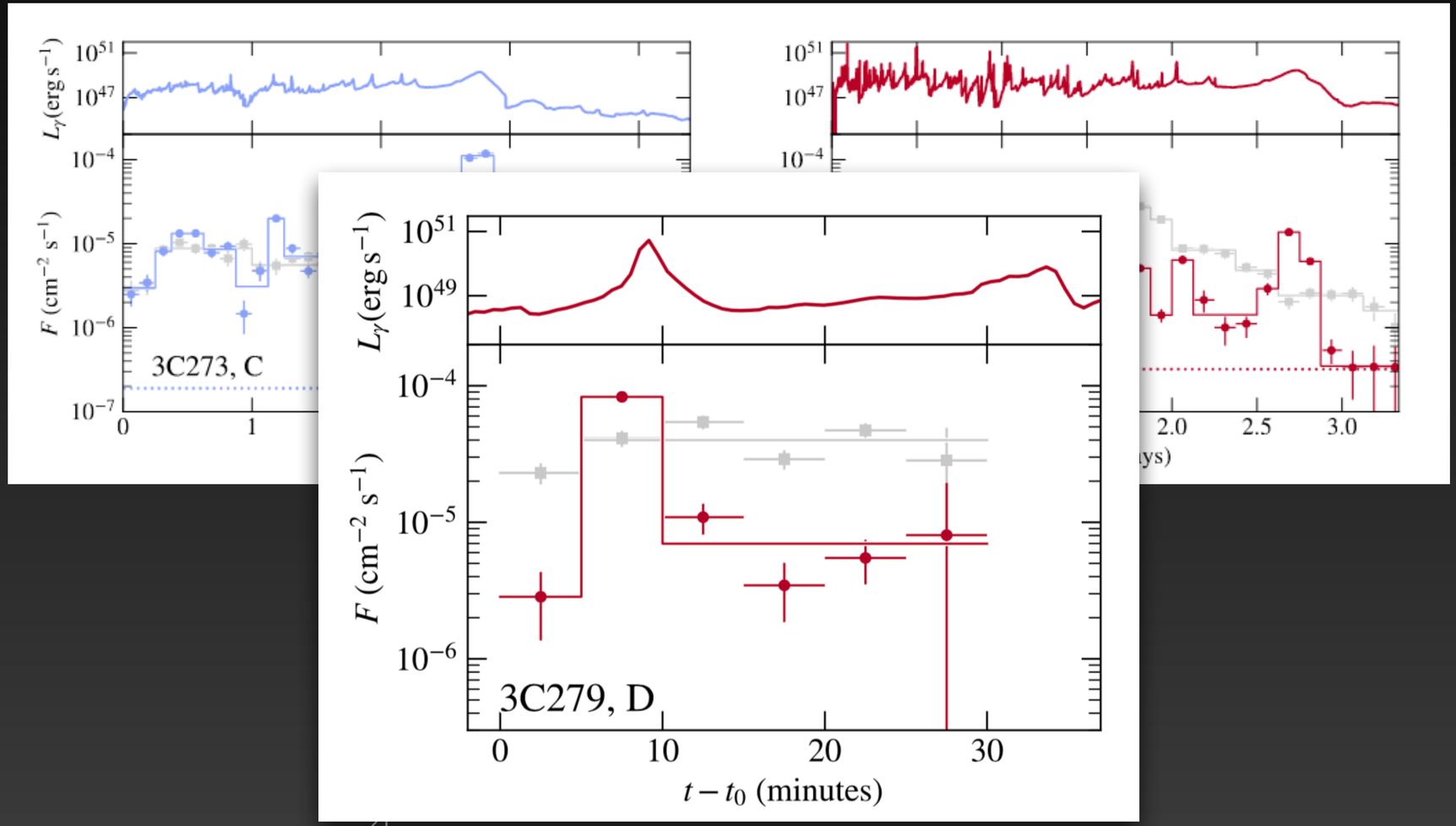
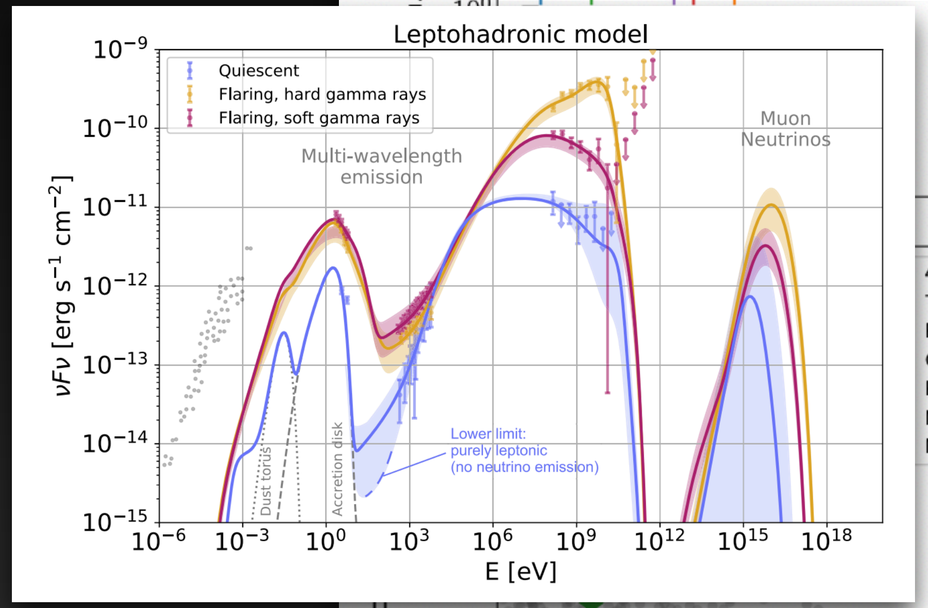


[MM, Petropoulou, Christie 2021]

News on neutrino - gamma-ray connection

- Association of neutrino with flaring blazar TXS0506+056 sparked interest to identify further counterparts
- So far, no other counterpart has been unambiguously identified
- One source of interest: PKS 1502+106; bright FSRQ located at redshift $z = 1.84$



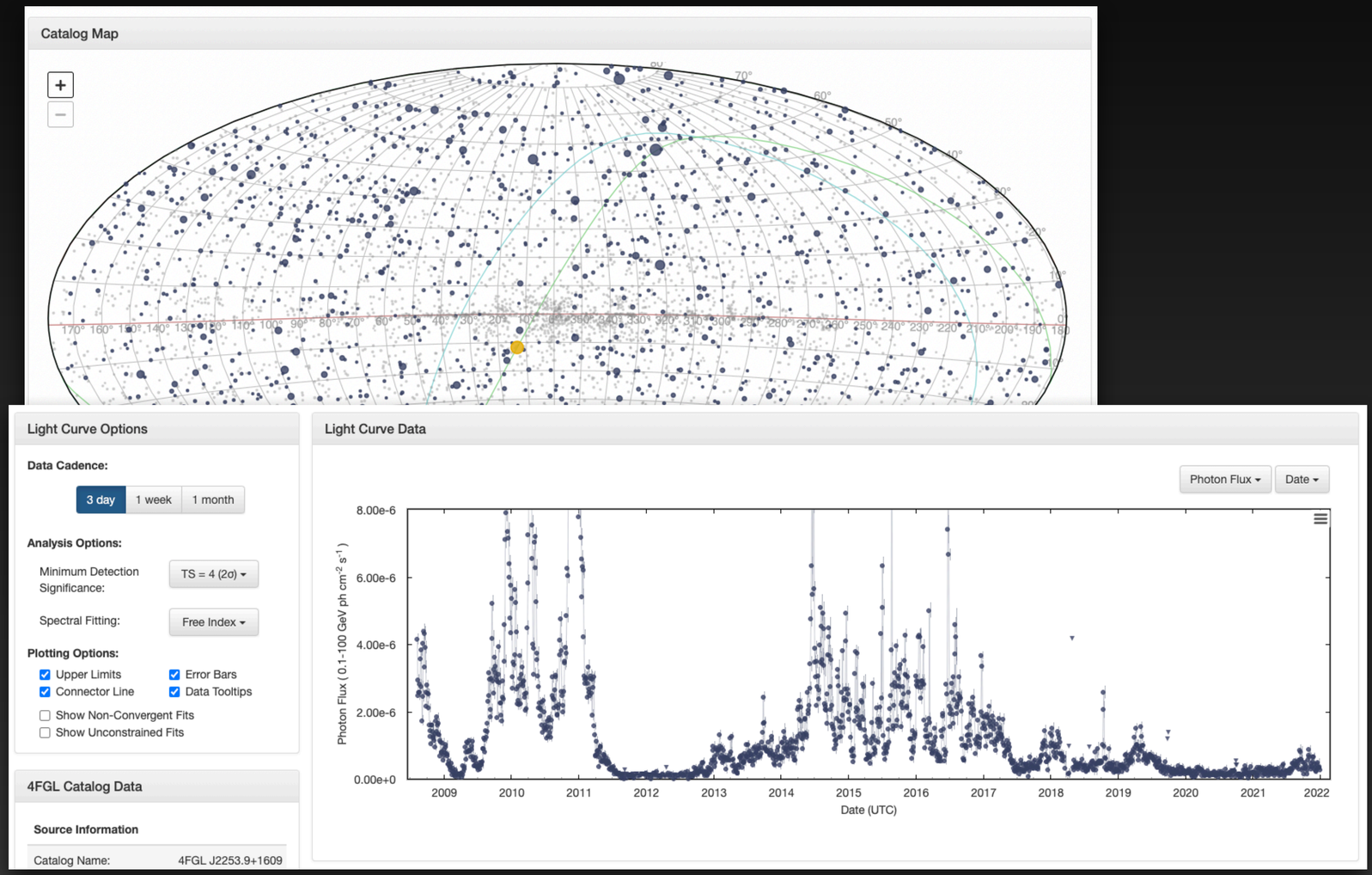
See also Francis Halzen's talk on IceCube & multi-messenger astronomy, Tuesday, 4.15pm

[Garrappa et al. 2019, 2021; Franckowiak et al. 2020, Rodrigues et al. 2021]

Light curve repository is online!

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

- Provides 3 day, 1 week and 1 month light curves for many 4FGL sources
- Light curves derived from full likelihood fit
- Facilitates, e.g., search for gamma-ray flare counterparts of neutrino events



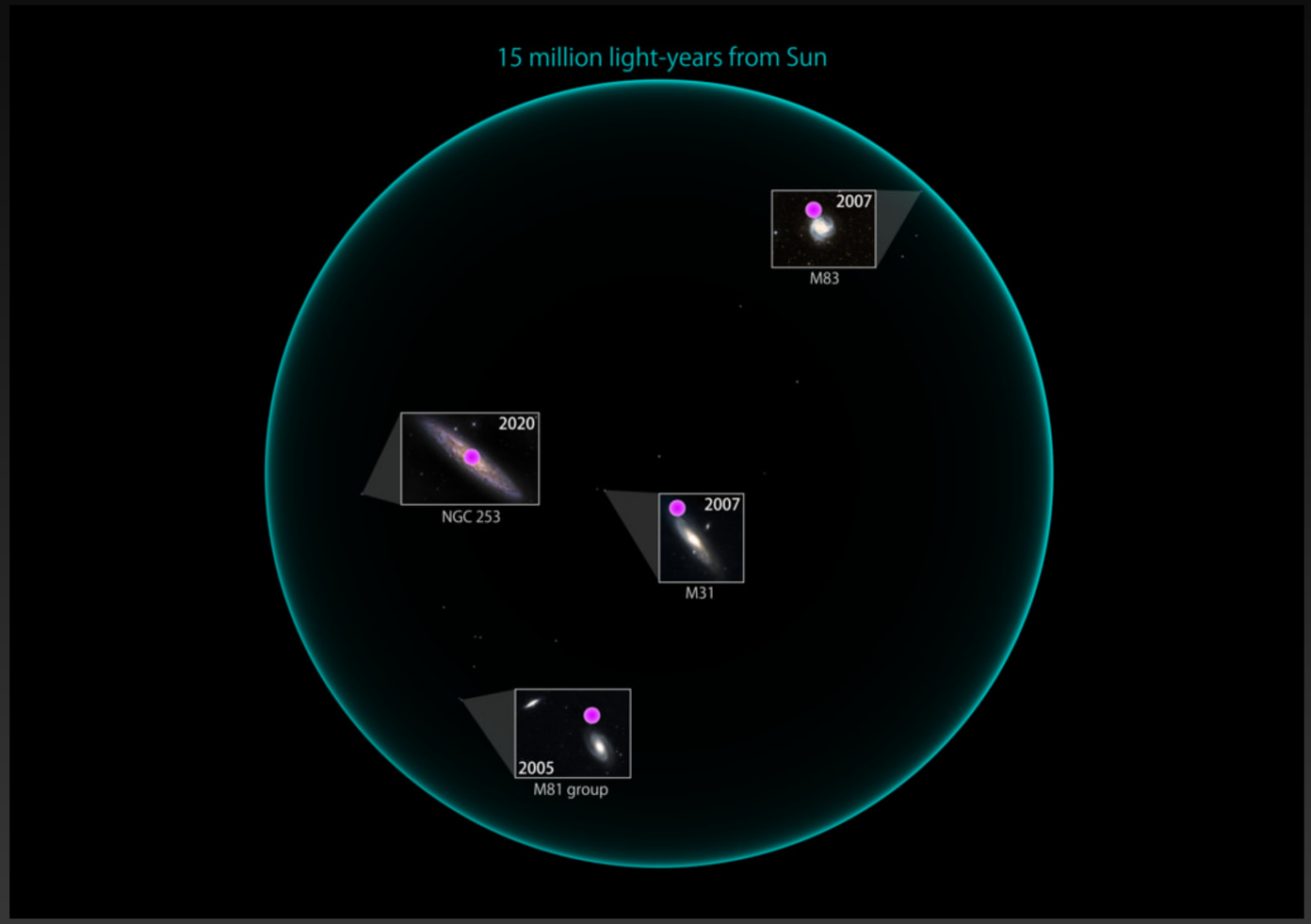
Summary & Conclusions

- *Fermi* LAT and GBM are working without major problems and continue to deliver exciting science results
- After 13.5 years of data taking, discovery of (new) transient phenomena are particularly exciting
- 2020 marked the year of the detection of a magnetar giant flare: LAT and GBM observations help to determine emission process
- Observations of FSRQs suggest fast variability and gamma-ray production at large distances from central engine: evidence for magnetic reconnection?
- *Fermi* observations remain indispensable for multi-messenger counterpart searches

Back up

4 Local GRBs are consistent with MGF interpretation

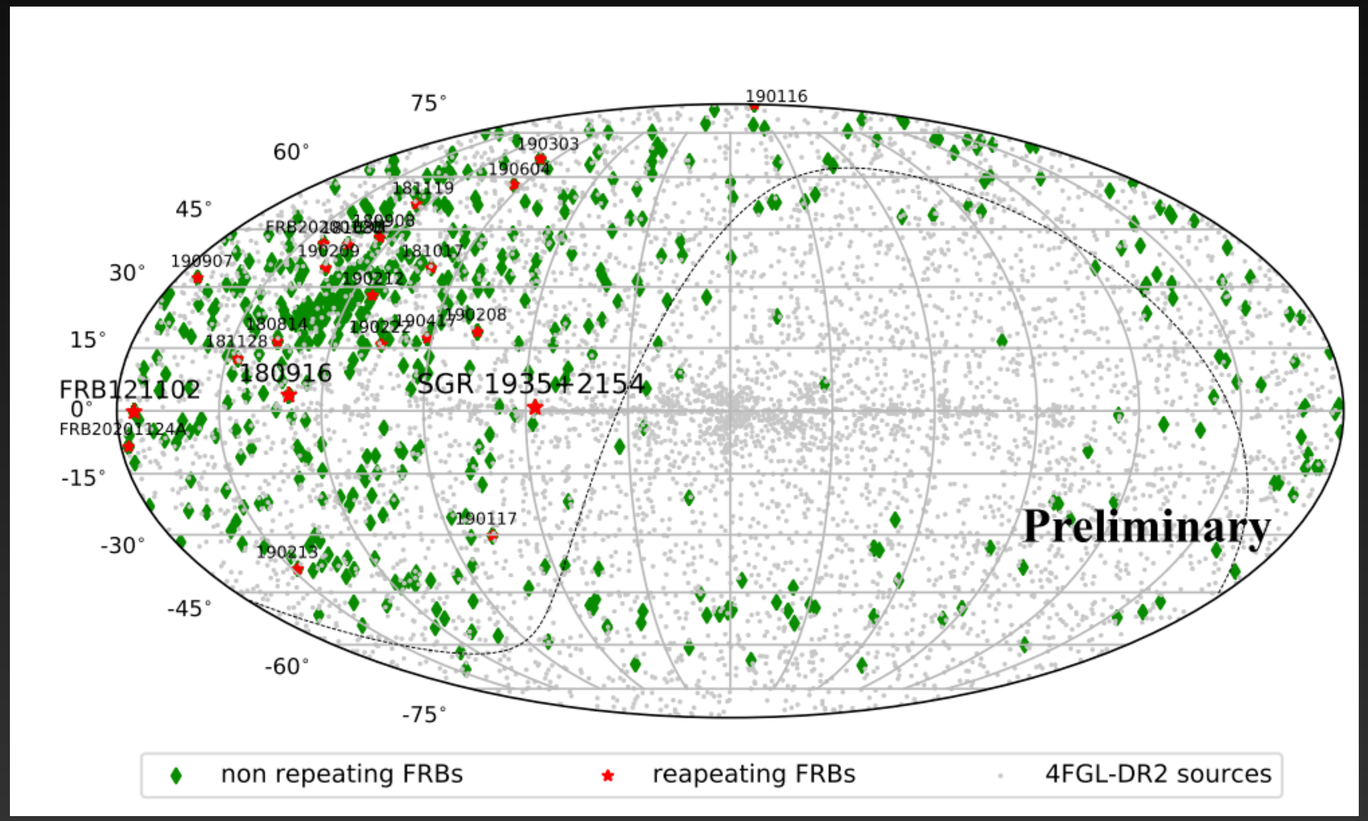
- 4 most nearby GRBs occurred within 5 Mpc
- Associated with star-forming galaxies
- Prompt emission is inconsistent with that of cosmological short GRBs
- Inferred MGF rate:
  $3.8^{+4.0}_{-3.1} \times 10^5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



[Burns et al. 2021]

Gamma-ray / FRB connection?

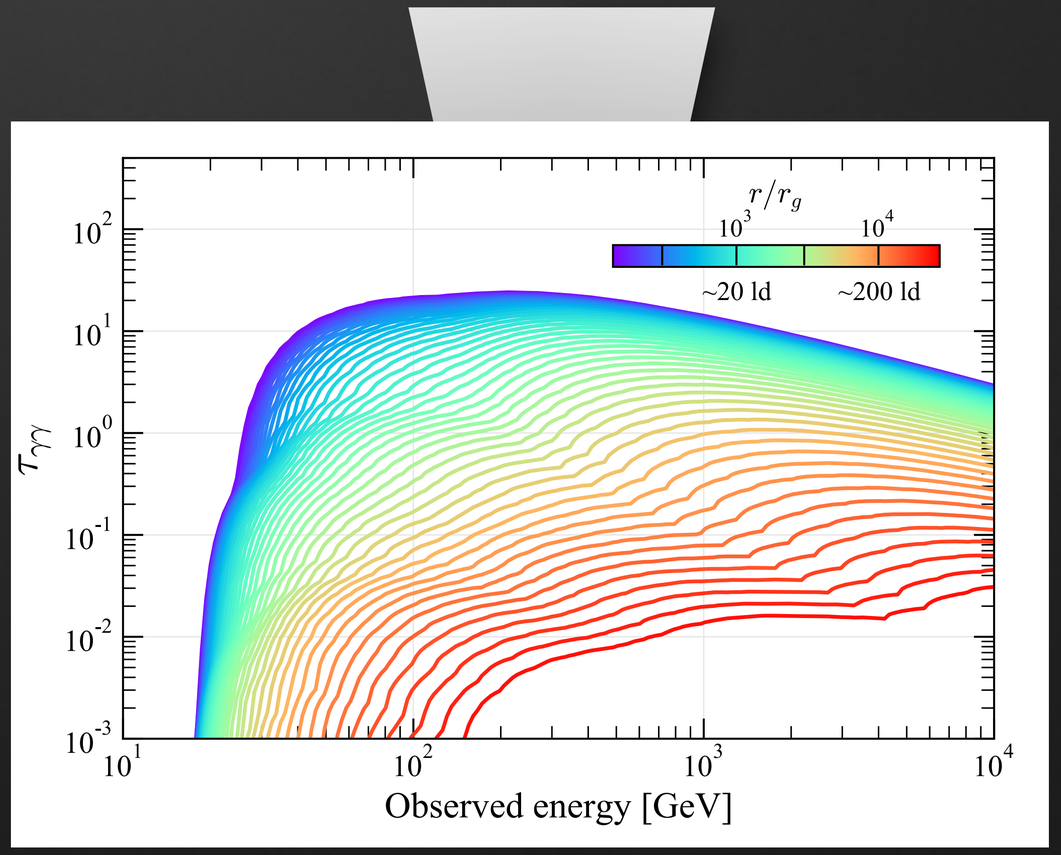
- Magnetars are leading candidates to explain FRBs
- One MGF detected with LAT
- Preliminary search for gamma-rays from ~1000 observed FRBs does not show any detection



[Principe et al. 2021]

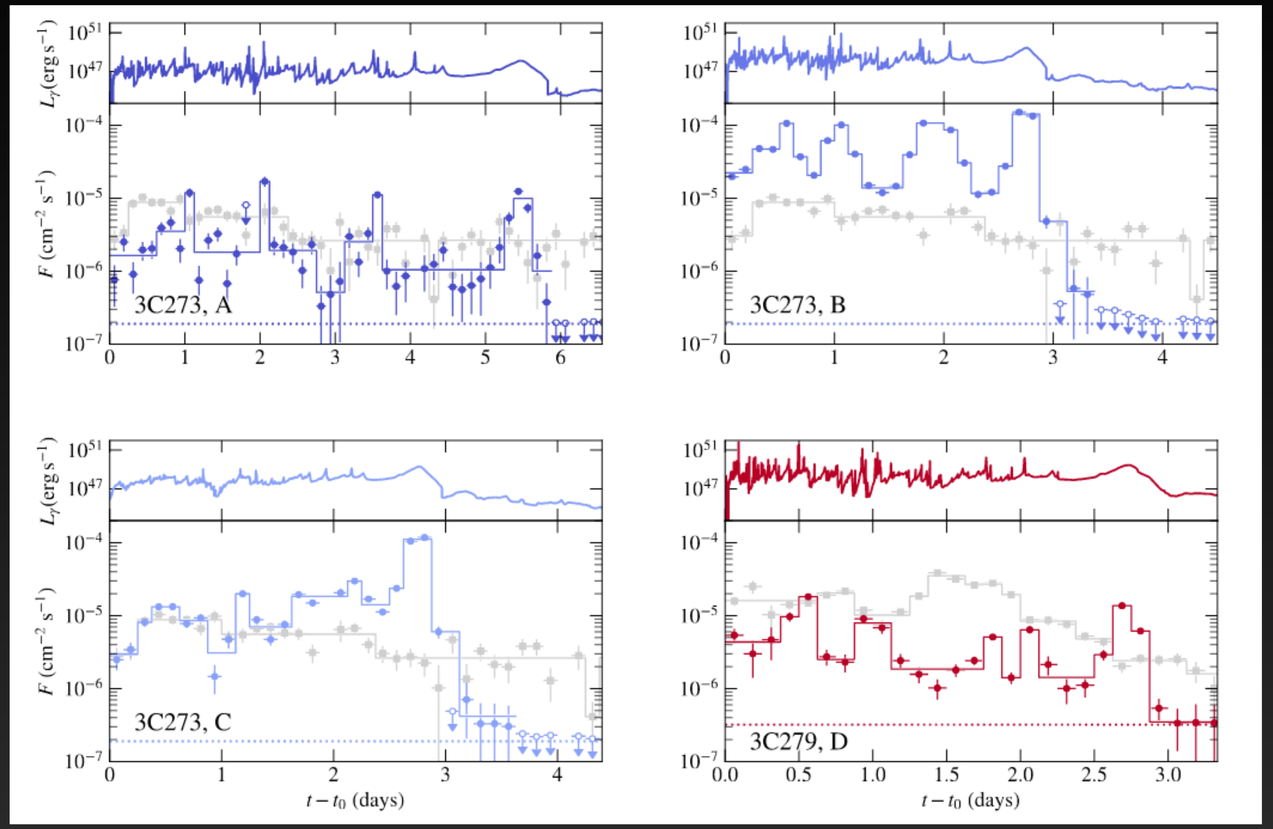
BLR MODEL

- Flattened BLR model from Finke 2016 [supported by observations of 3C273 with GRAVITY]
- Collection of infinitesimally thick rings
- Each ring emits one mono-energetic emission line
- Radius and ring luminosity taken from reverberation mapping



Fake Fermi Light Curves — General Observations

- Much of fast **variability washed out** due to chosen binning
- Possible to **reproduce average flux levels** for 3C273, more difficult for 3C279
- Models with **slight misalignment appear to better reproduce observed light curves (bottom left panel)**
- **Minimum variability time scales agree** between fake and observed light curves

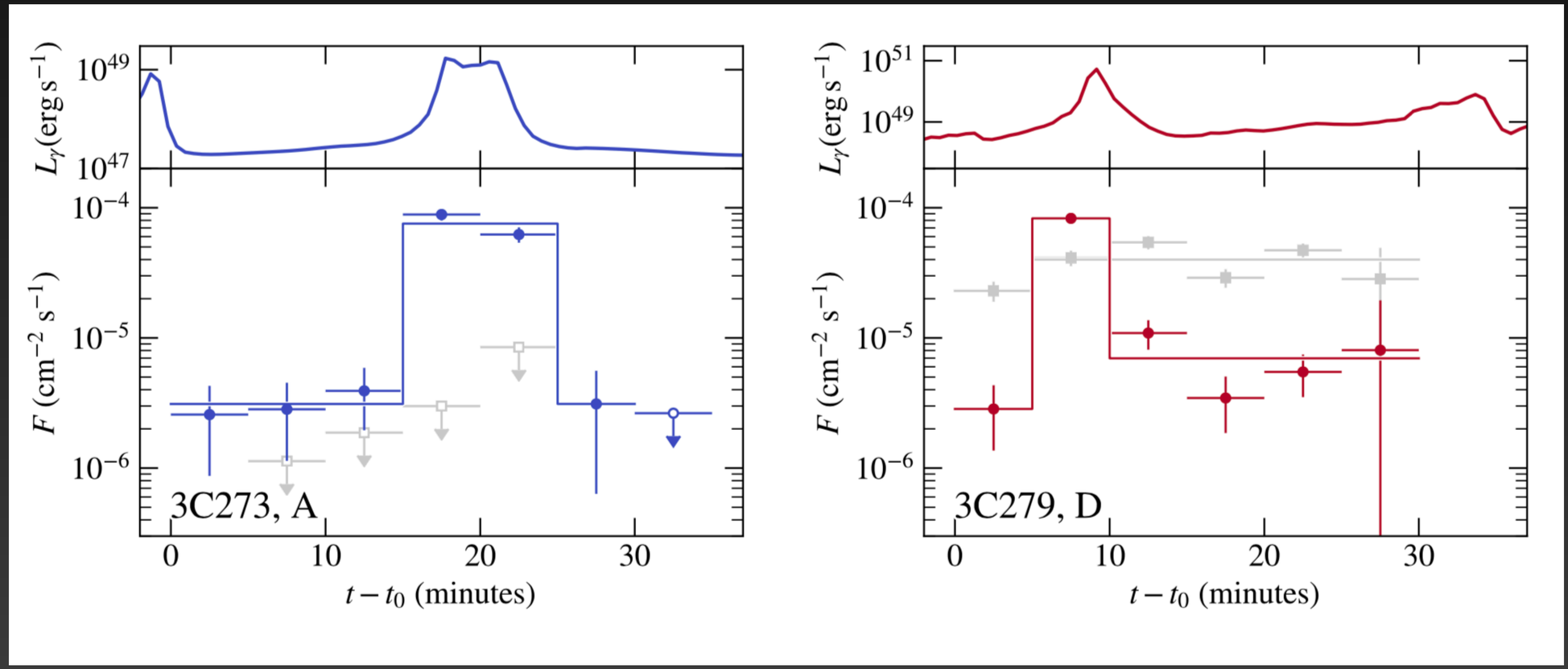


$$\min(t_{\rm var}) = \min_{i,j}\left(\frac{F_i + F_j}{2}\left|\frac{t_i - t_j}{F_i - F_j}\right|\right)$$

Model	Source	$\min(t_{\rm var})$ (min) Fake	$\min(t_{\rm var})$ (min) Obs.
A	3C 273	102.1 ± 16.5	140.4 ± 75.8
B	3C 273	96.7 ± 3.3	140.4 ± 75.8
C	3C 273	99.7 ± 3.7	140.4 ± 75.8
D	3C 279	107.2 ± 10.8	215.9 ± 91.4

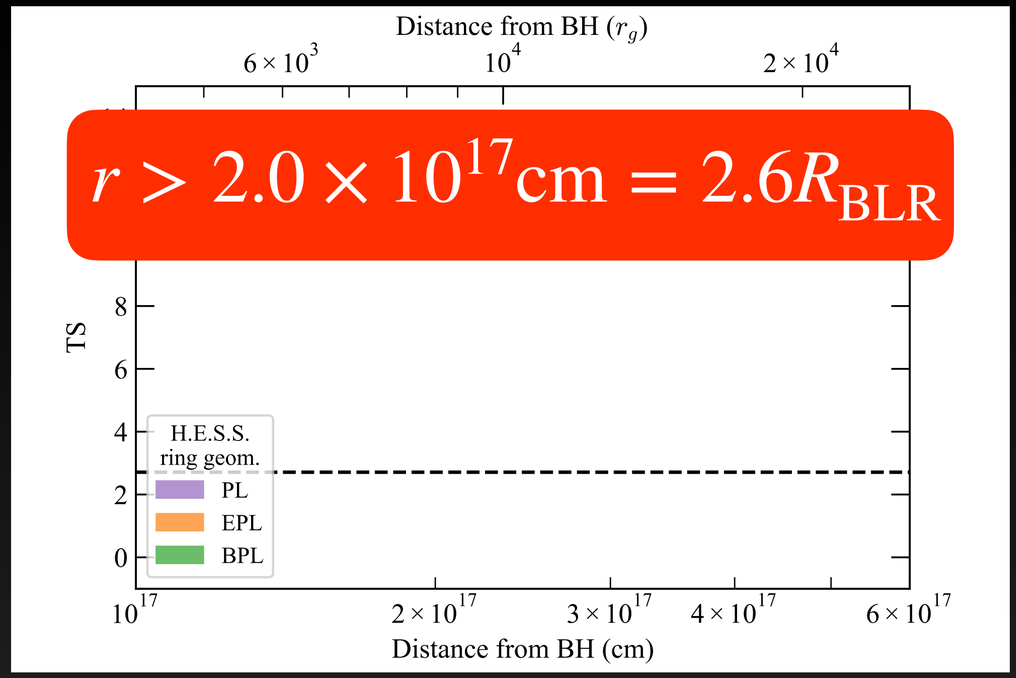
Fake Fermi Light Curves — Fast Variability

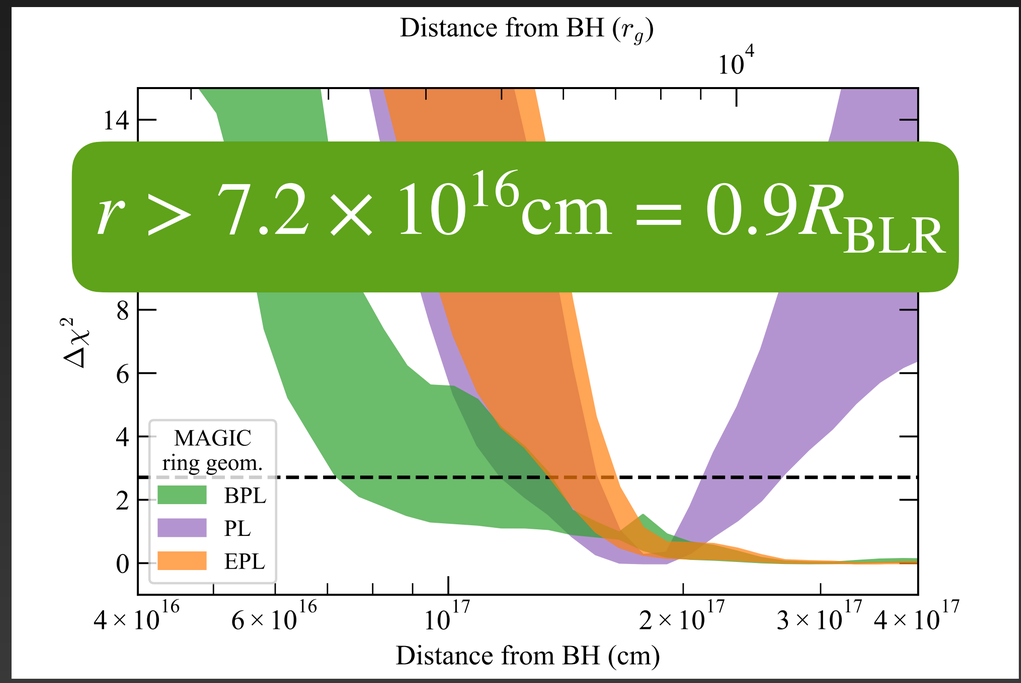
- Shifted one of the fast plasmoids peaks of model light curves to coincide with a good time interval (GTI)
- Repeated analysis for one GTI using five minute binning
- Result: **fast moving plasmoids could explain evidence for fast variability observed in FSRQs**



Likelihood profiles vs distance in PKS1510-089
is absorption significantly detected?

- Significantly detected for PL intrinsic function
- However, no intrinsic spectrum significantly preferred
- Impossible to disentangle intrinsic cut-off and absorption
- Derive lower limits on distance

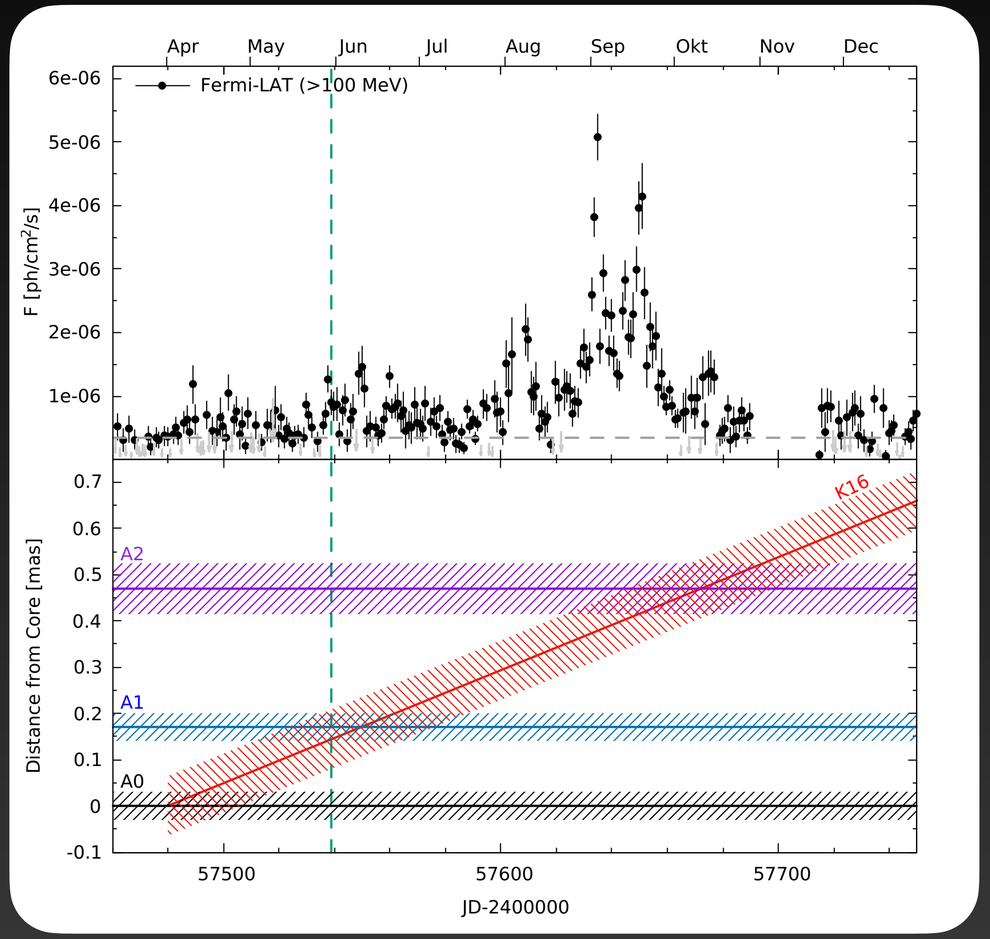




[H.E.S.S., MAGIC, Fermi-LAT, ATOM, Boston U. VLBI group, in prep.]

Suggestive coincidence of knot crossing standing features
During gamma-ray flare in PKS1510-089

- From VLBI: knot (K16) crosses standing features (A0-2)
- A1 located 40pc away from radio core
- Would suggest VHE emission produced far away from central black hole
- Would imply shock acceleration far down in jet

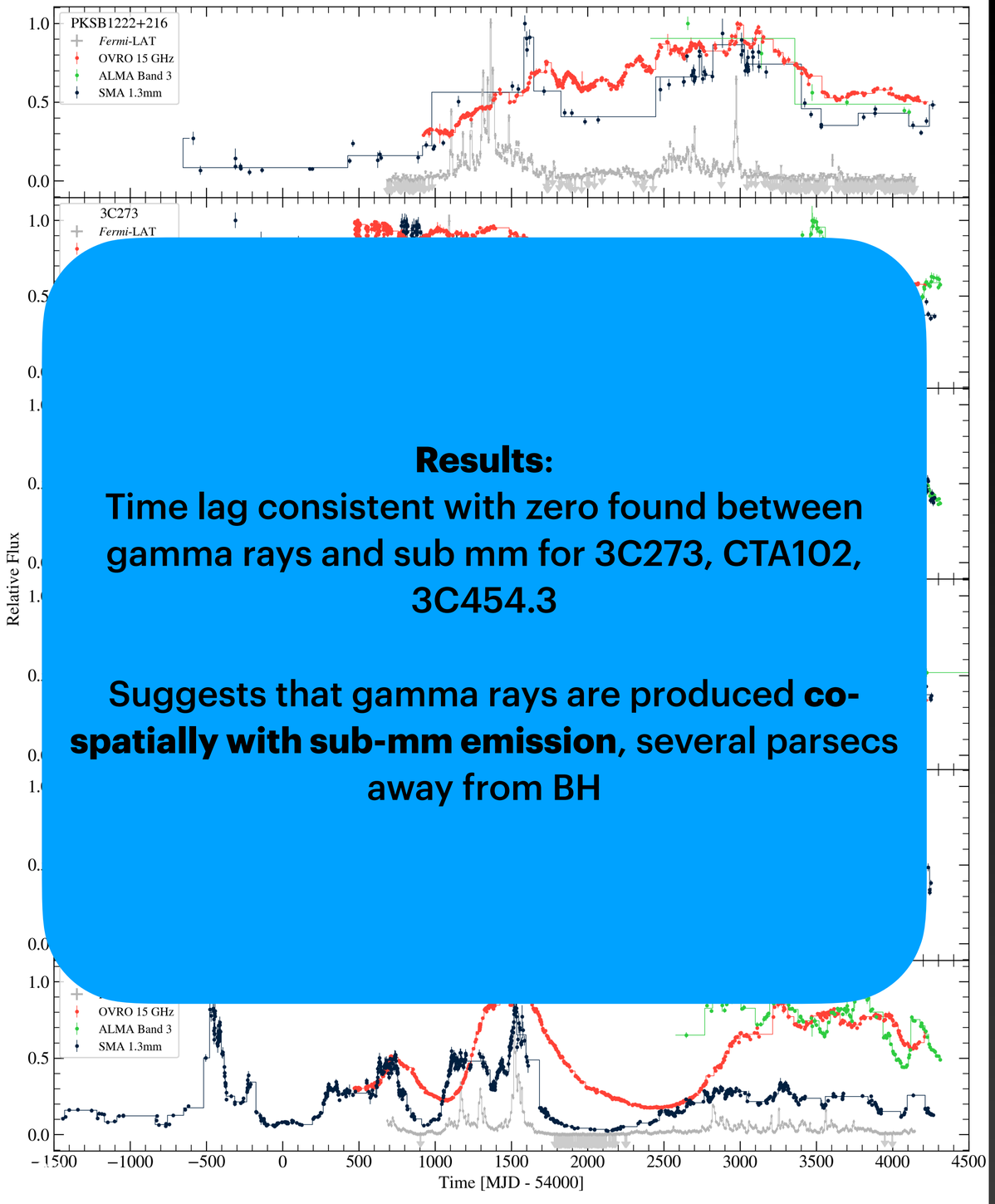


[H.E.S.S., MAGIC, Fermi-LAT, ATOM, Boston U. VLBI group, in prep.]

Correlation analysis between gamma-ray and radio light curves

- Search for time lags with local cross correlation function
- Radio observations:
  - **OVRO** (14 GHz)
  - **ALMA Band 3** (1 mm)
  - **SMA** (1.3 mm)

[MM, Scargle, Blandford 2019,
See also Max Moerbeck et al. 2014,
Fuhrmann et al. 2014, Liodakis et al. 2018]



Results:
Time lag consistent with zero found between gamma rays and sub mm for 3C273, CTA102, 3C454.3

Suggests that gamma rays are produced **co-spatially with sub-mm emission**, several parsecs away from BH