Bright blazar flares and their lagging neutrino counterparts

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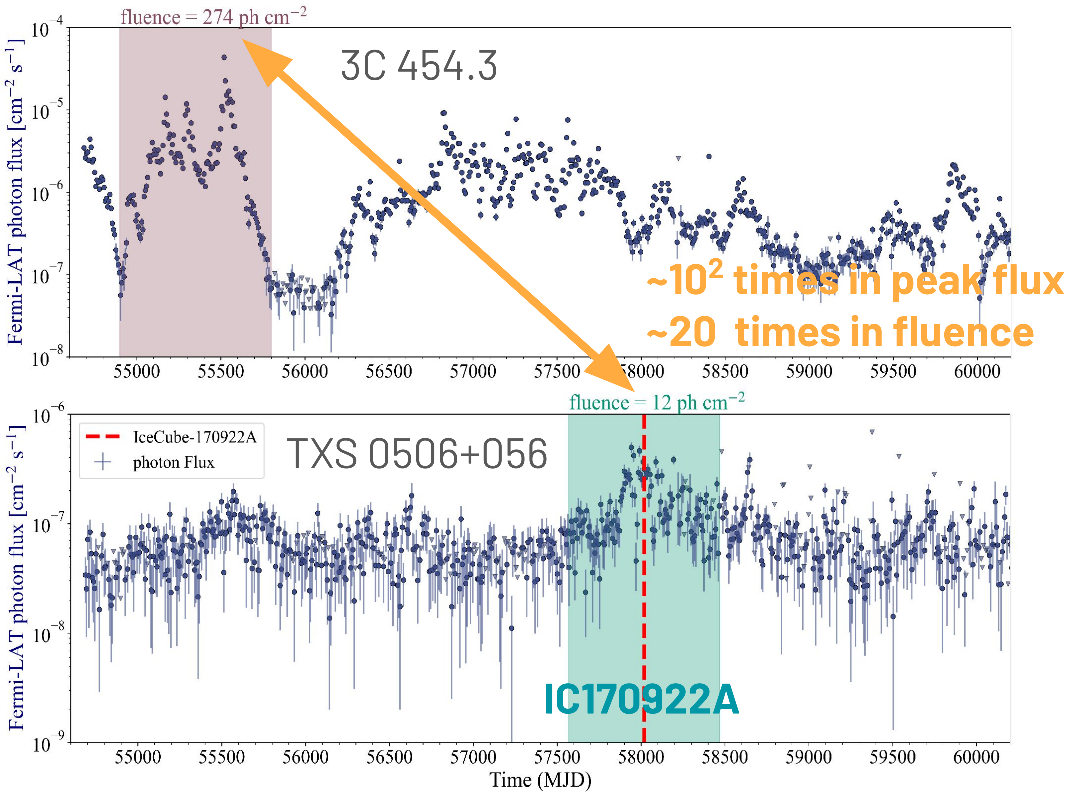
Based on
arXiv 2502.12111 (in print in MNRAS)
and arXiv 2511.01361 (submitted)

Motivation

- γ-ray fluence in the 2009-2010 3C 454.3 outburst was **~20 times higher** than the fluence around IceCube-170922A!
- **~20 times more** neutrinos?

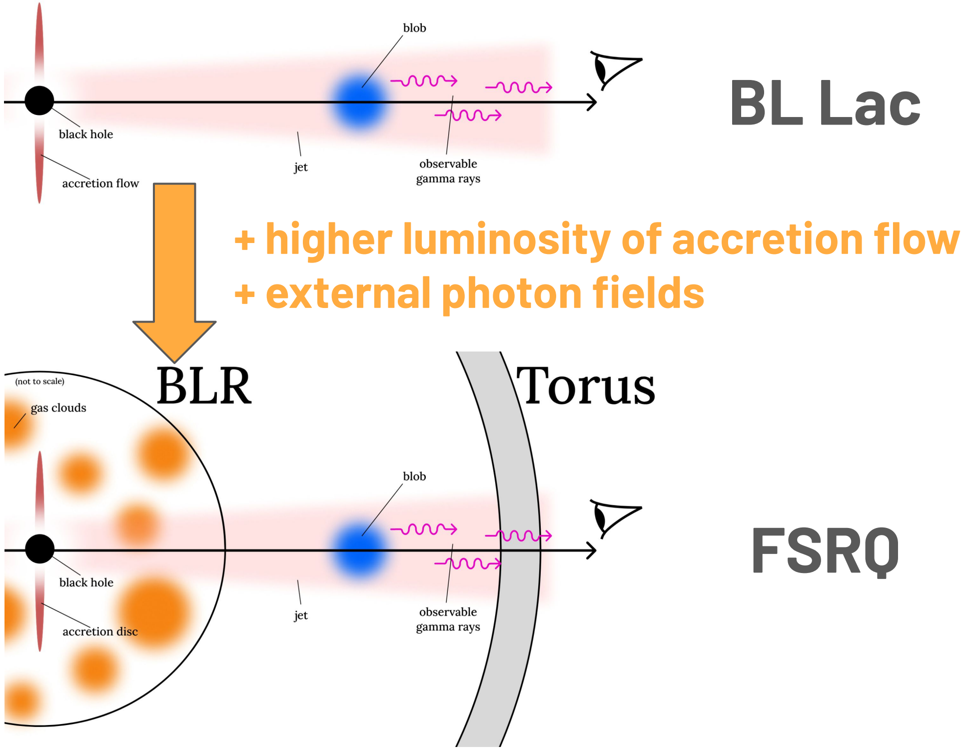


IceCube Coll.+ (2018, Science, 361, eaat1378)

Fermi-LAT light curve repository by Abdollahi+ (2023, ApJS, 265, 31)

Why flat-spectrum radio quasars?

- 3C 454.3 – **brightest** *Fermi*-LAT FSRQ
- FSRQs host **strong photon fields** from broad-line regions according to the canonical model
- During flares – **enhanced luminosity** and/or **Doppler factor**

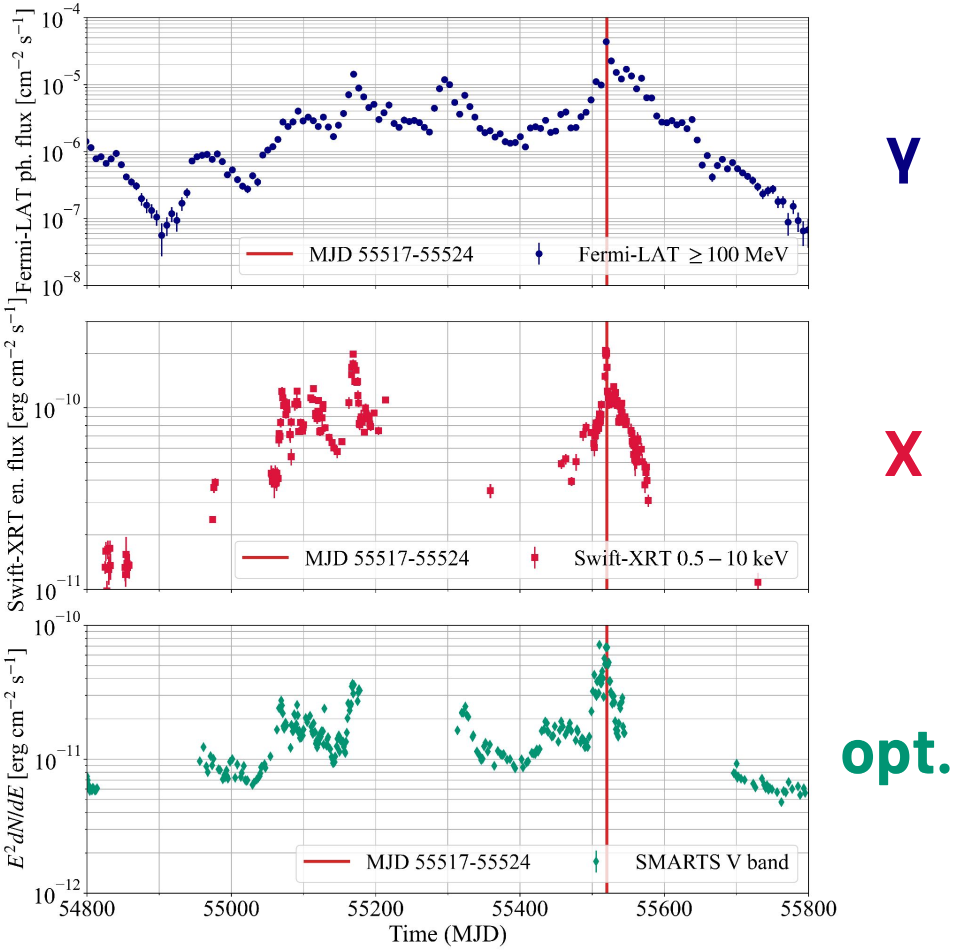


Ghisellini & Tavecchio (2009, MNRAS, 397, 985)

Adapted from Dzhatdoev+ (2022, MNRAS, 515, 5242)

Data analysis

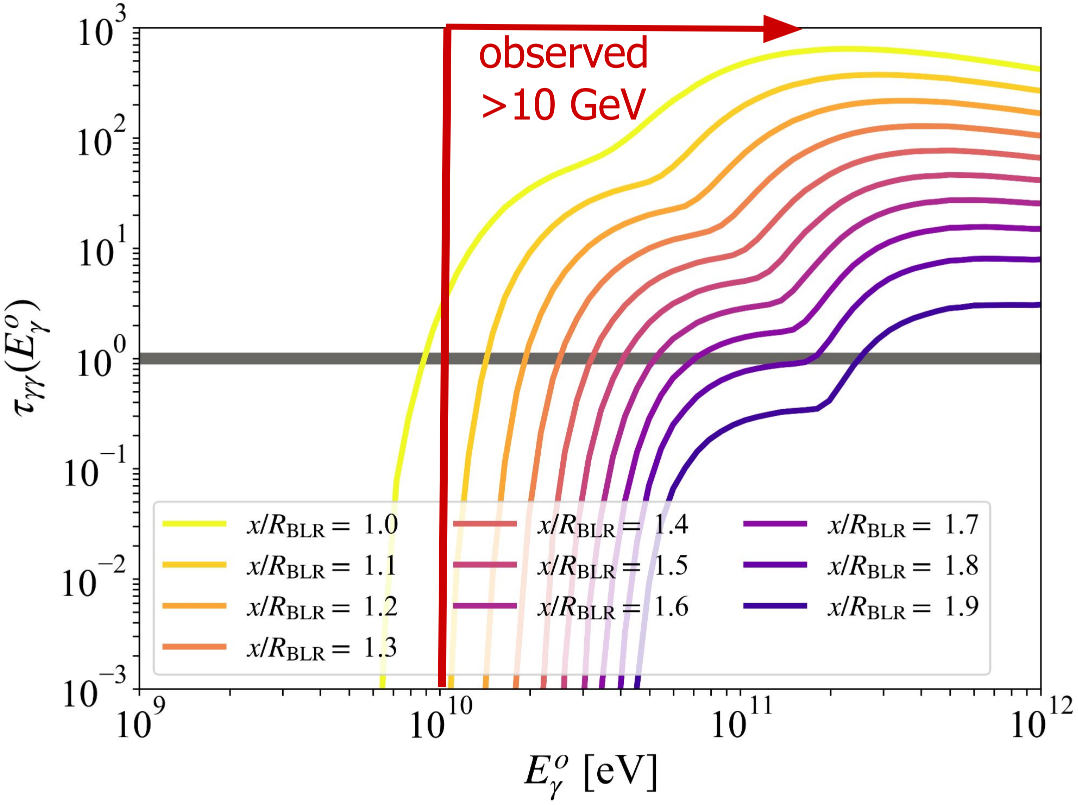
- ➢ **Quasi-simultaneous analysis** of γ-ray, X-ray, UV/optical/IR data around peak of Nov. 2010 flare of 3C 454.3
- ➢ **Time-dependent modelling** of the observed SEDs with AM^3



Klinger+ (2024, ApJSS, 275, 4)

Location of the emitting region

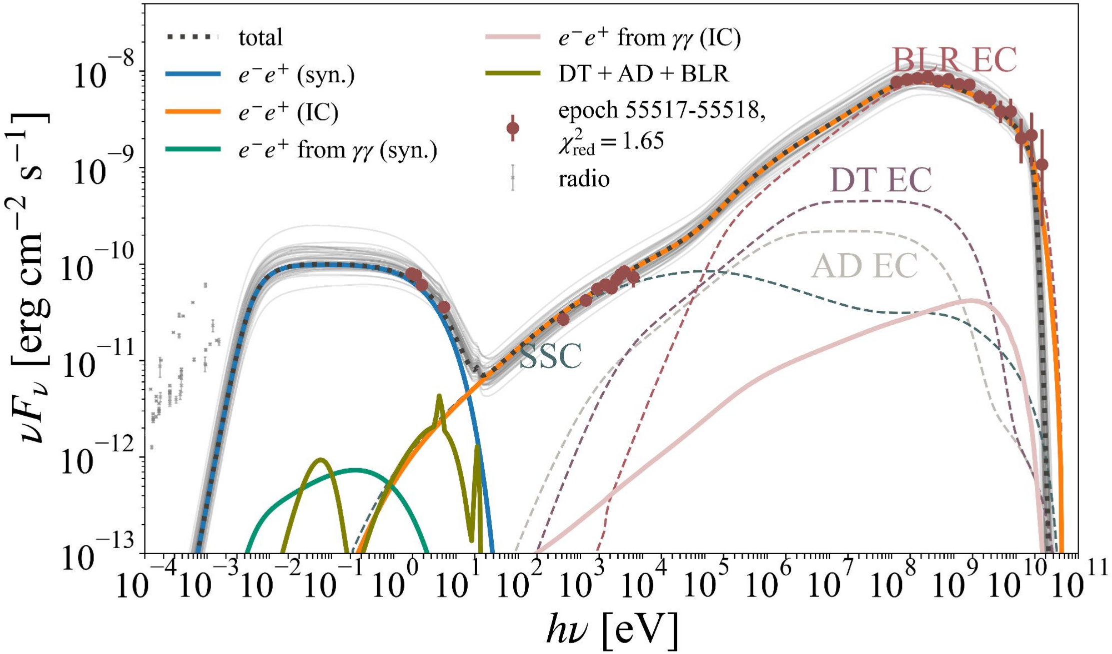
- For all days of the flare, *Fermi*-LAT observes **>10 GeV** photons
- The blob is **outside the broad-line region**, hence the dissipation radius $x > R_{BLR}$
- This **limits** the efficiency of neutrino production



Using the BLR model implemented by Rodrigues+ (2024, A&A, 681, A119)

Leptonic model

- Fast changes of the SEDs require the **emitting region to be small and close** to the SMBH, hence **continuous injection of new blobs** ~every day in the Earth frame
- Radiation zone is **outside the BLR** to avoid γγ absorption



Data analysis and model by E. Podlesnyi & F. Oikonomou, arXiv 2502.12111

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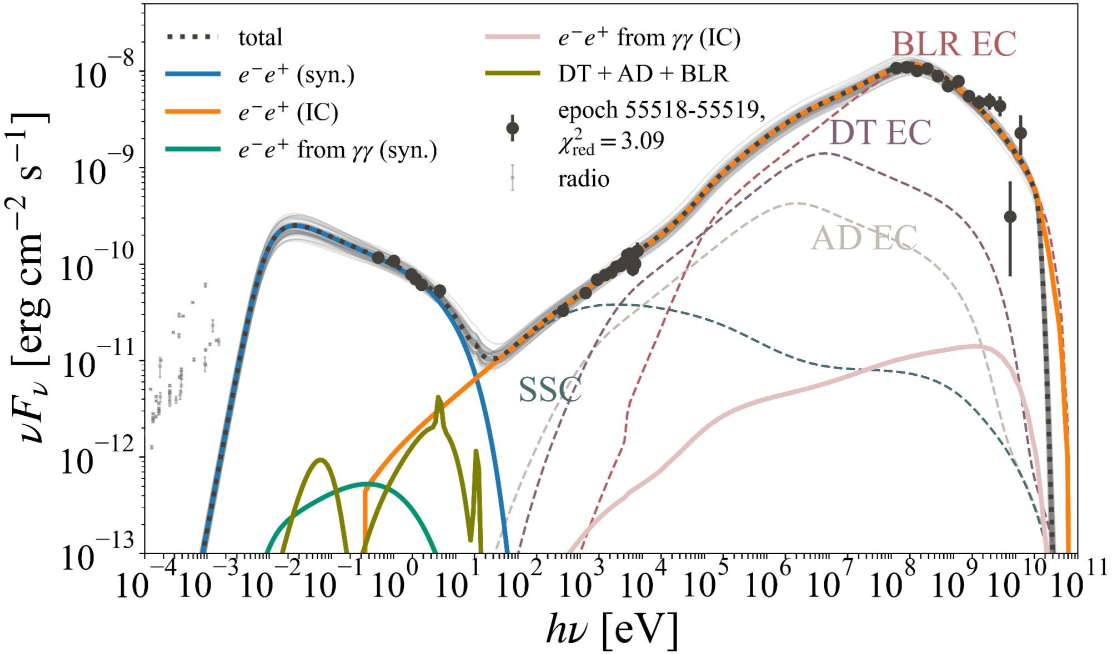

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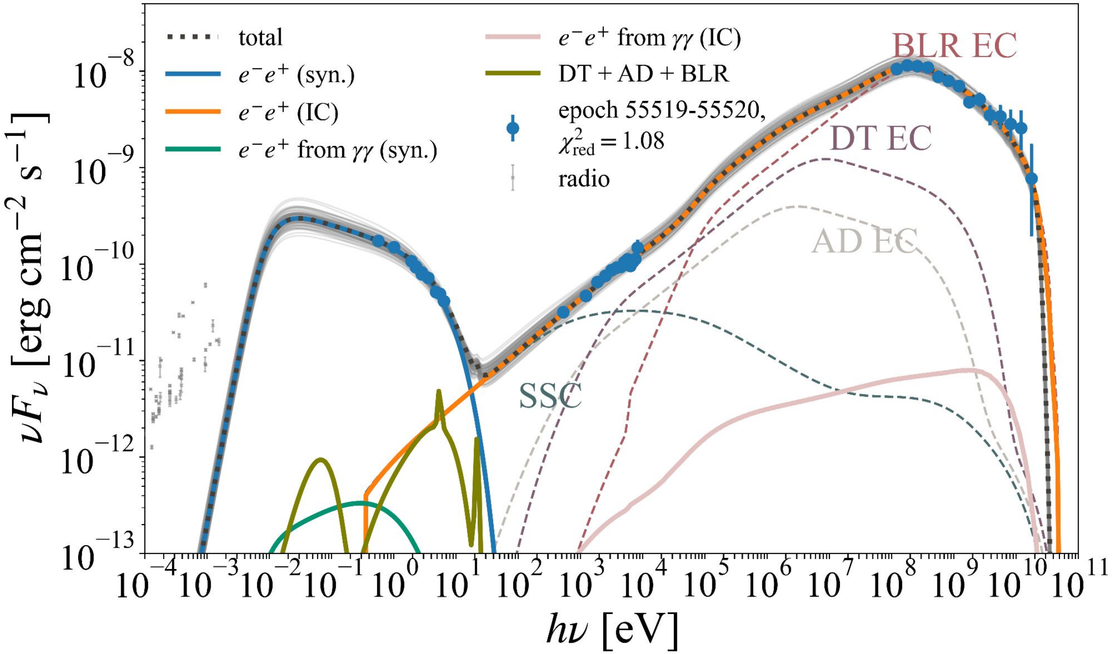

Data analysis and model by E. Podlesnyi & F. Oikonomou, arXiv [2502.12111](https://arxiv.org/abs/2502.12111)

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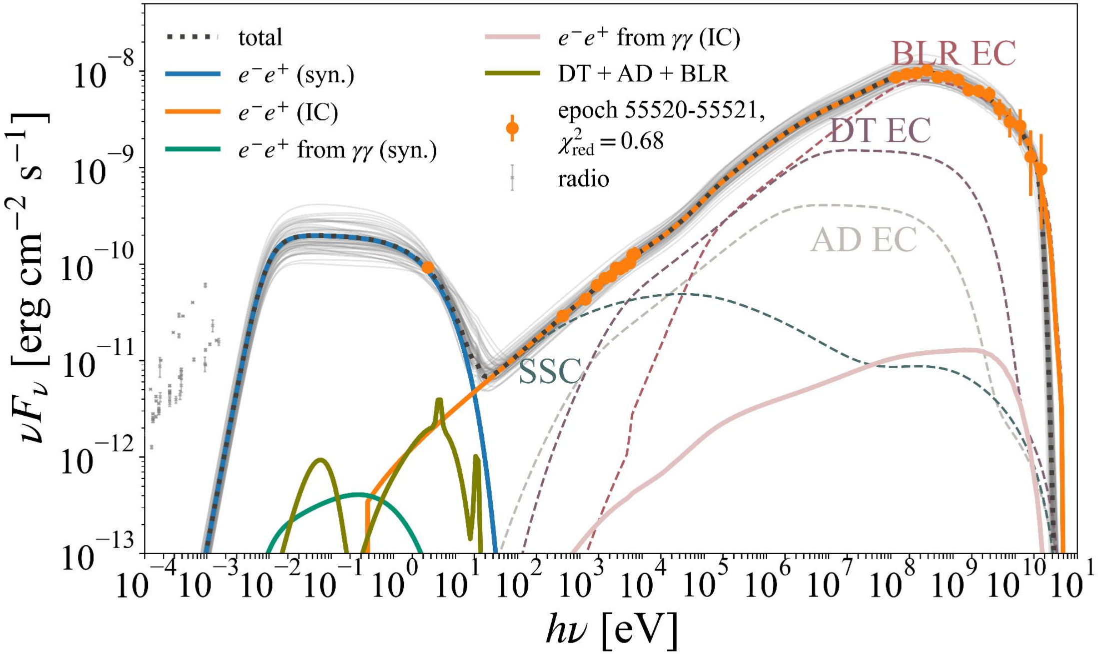

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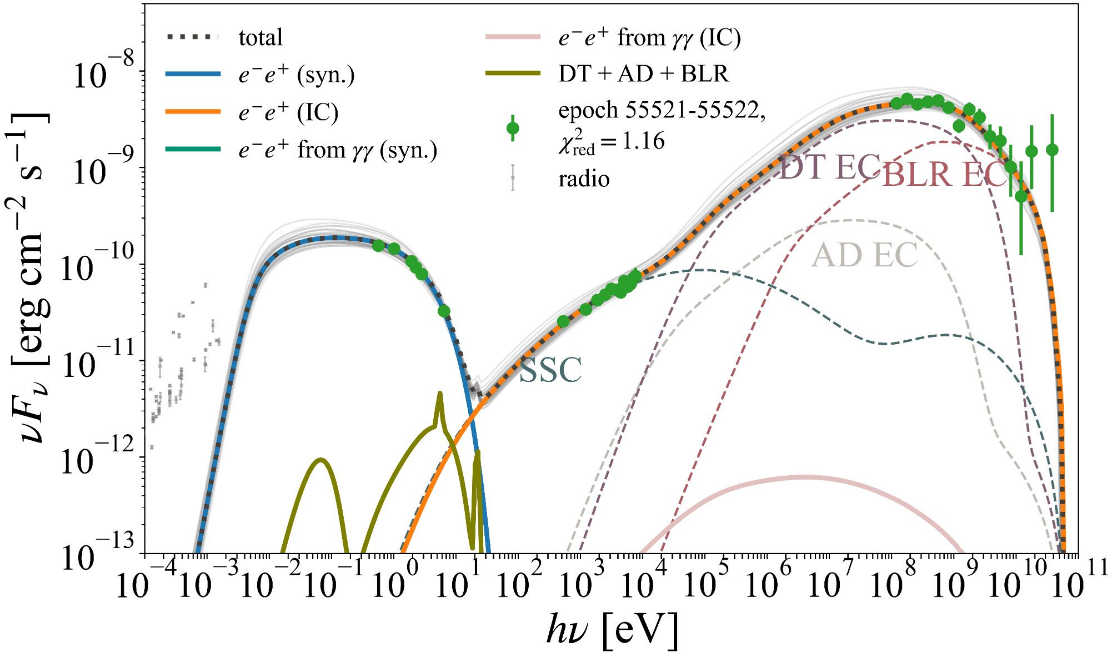

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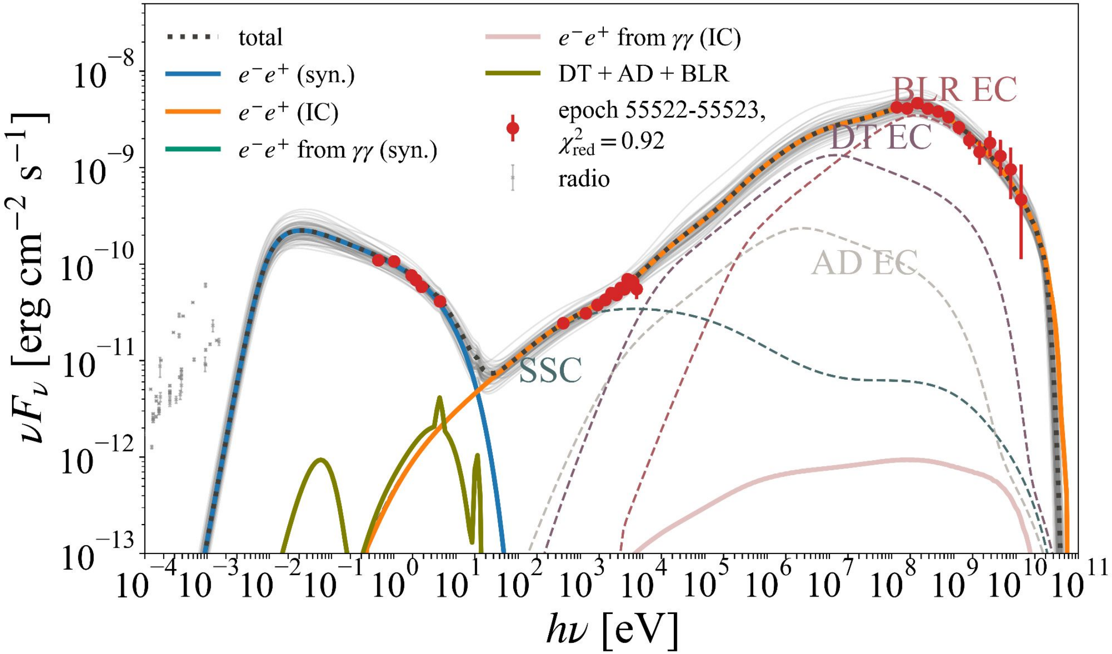

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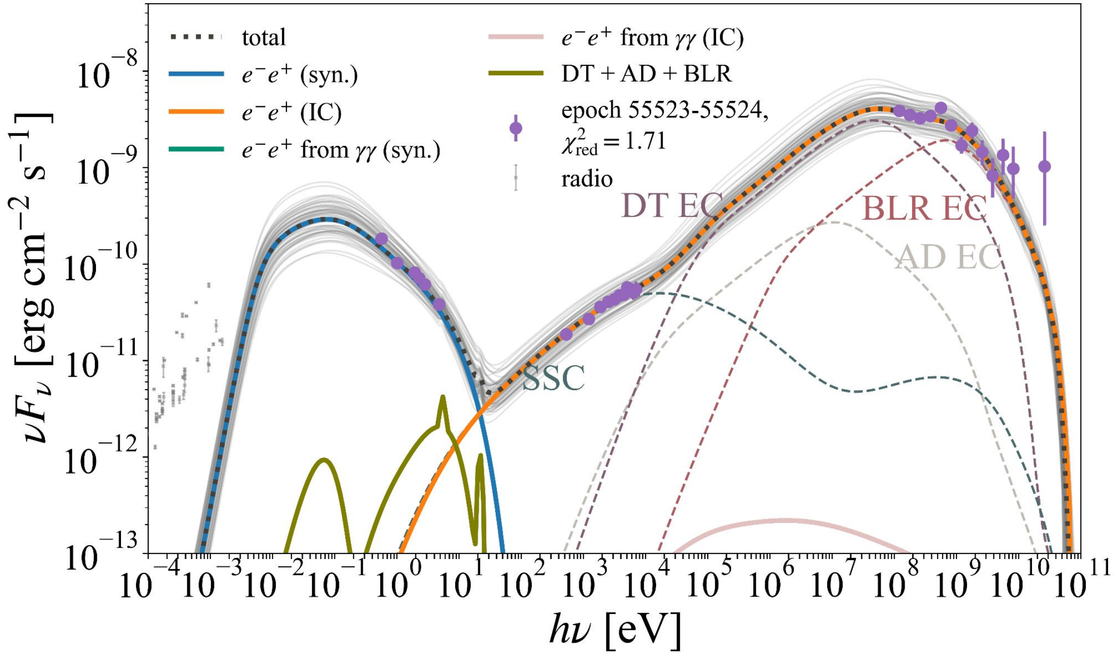
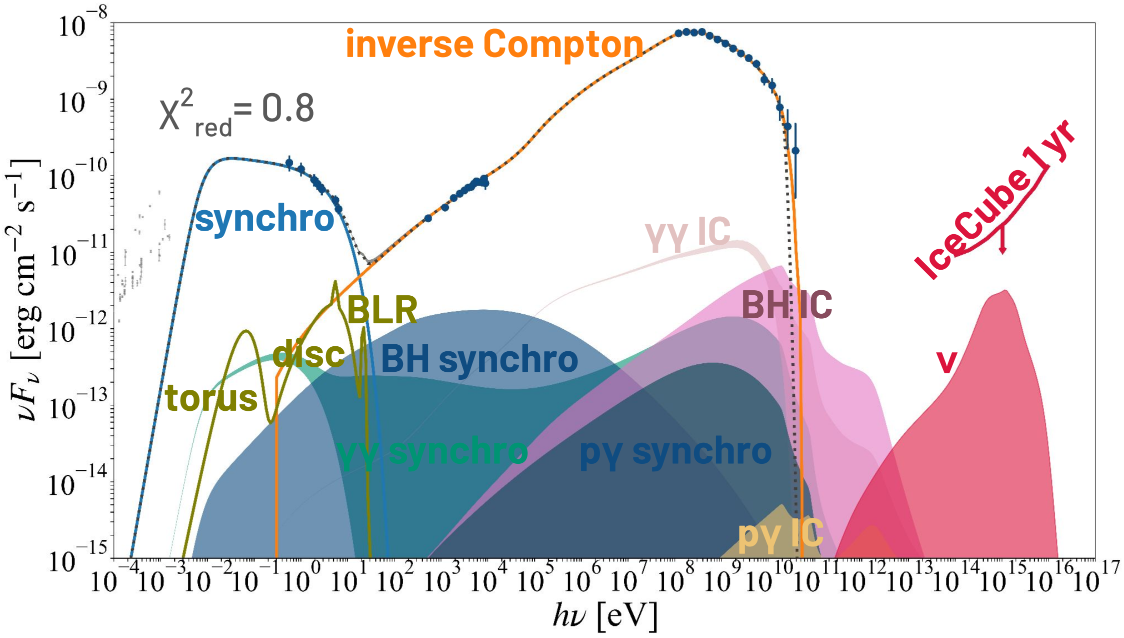


Data analysis and model by E. Podlesnyi & F. Oikonomou, arXiv [2502.12111](2502.12111)

Leptohadronic model

- Pure leptonic model **describes the data well**
- Proton contribution is constrained by the X-ray data: **proton to electron energy density ratio** $\rho_{p/e} \lesssim$ **130** (when the likelihood worsens by 10^2)



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Method similar to Keivani+ (2018, ApJ, 864, 84)

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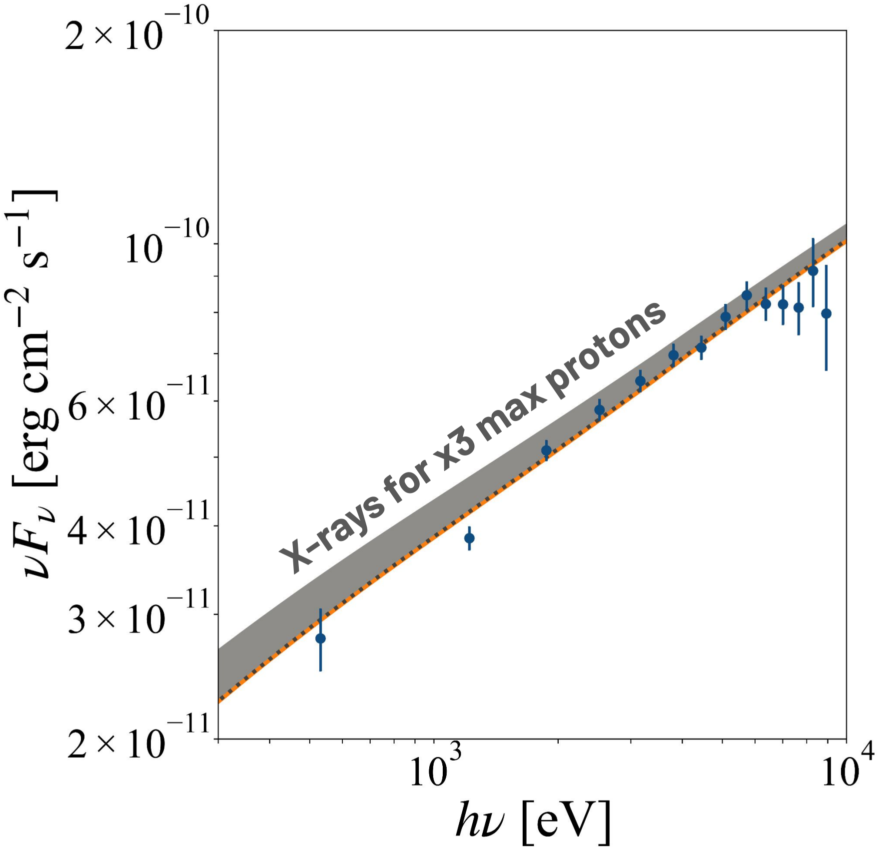

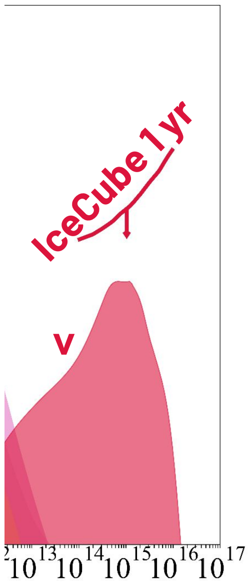

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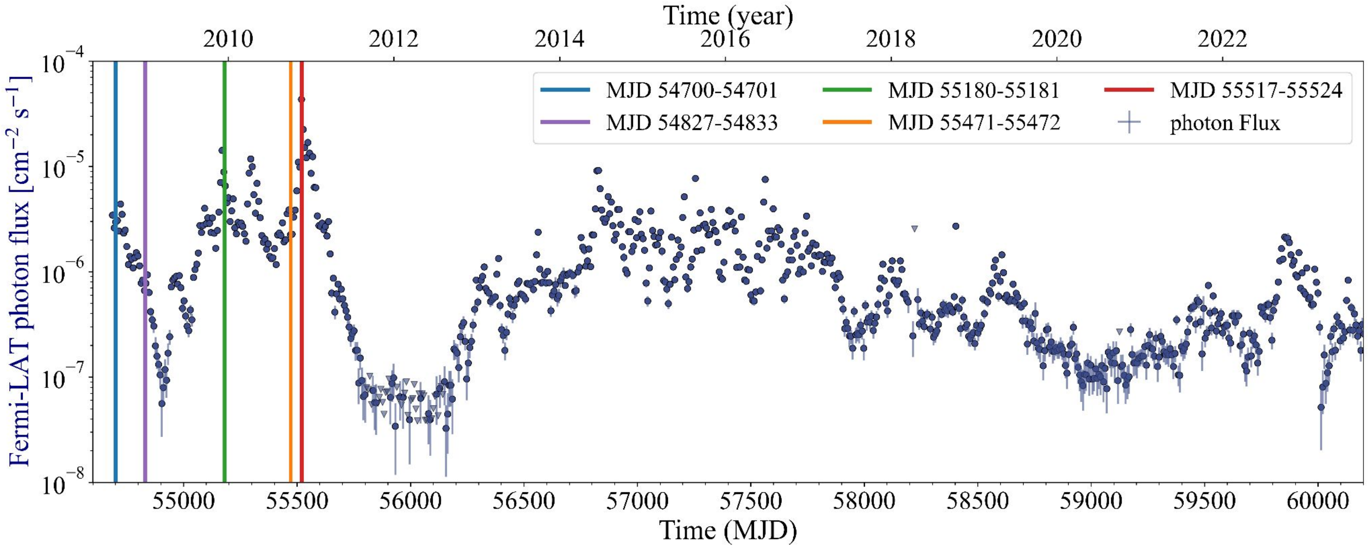
Fermi-LAT light curve from repository

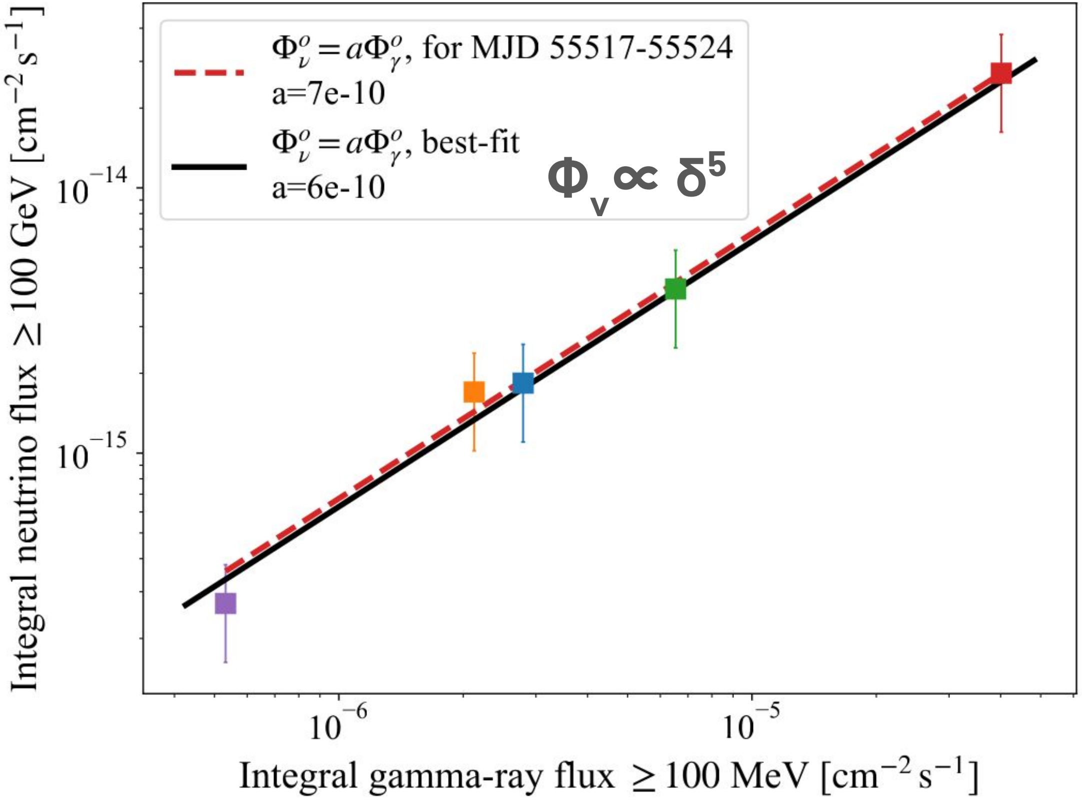
➢ To predict the neutrino flux for any time period and obtain a ν–γ flux scaling, we repeat the analysis for four other periods covering various flux levels



Fermi-LAT light curve repository by Abdollahi+ (2023, ApJS, 265, 31)

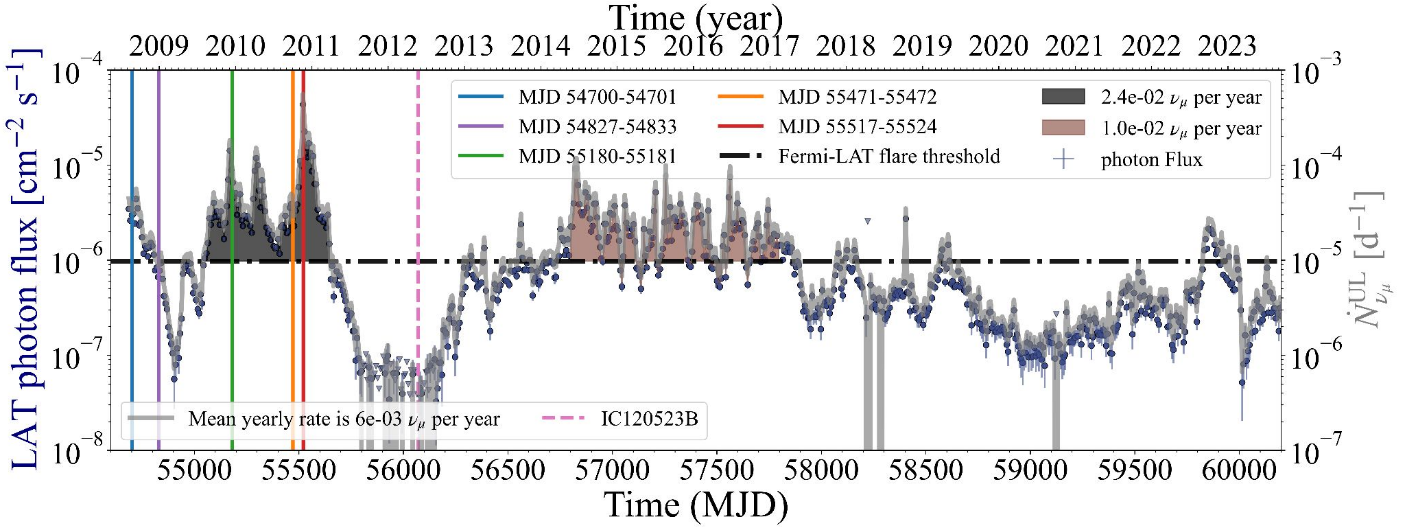
Linear relation of ν-γ integral fluxes

- ➢ Approximately **linear relation** between integral neutrino and gamma-ray fluxes
- ➢ Neutrinos produced on **external Compton γ rays** (lower energies) and **BLR photons** (energies ≥ 100 TeV)



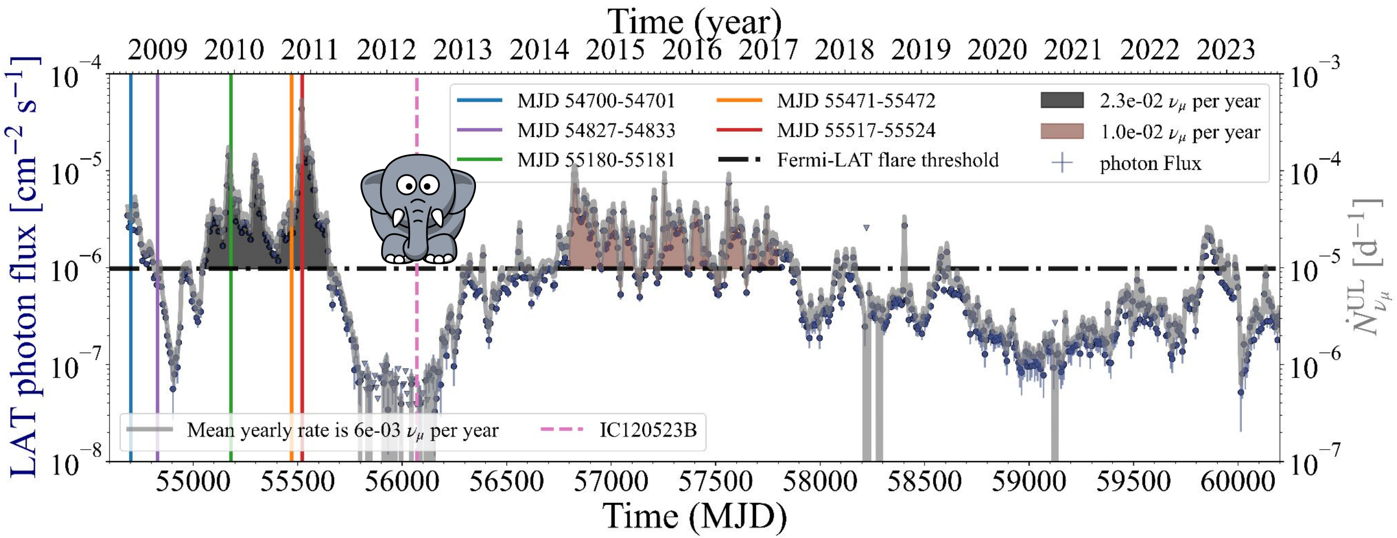
Neutrino production yield (≥ 100 TeV)

- ~6x10^{-3} ν_μ per yr in *IceCube* on average from 3C 454.3
- ~6x10^{-2} ν_μ per yr in *IceCube* on average from 820 *Fermi*-LAT FSRQs
- ~0.5% contribution of all *Fermi*-LAT FSRQs to *IceCube* neutrinos



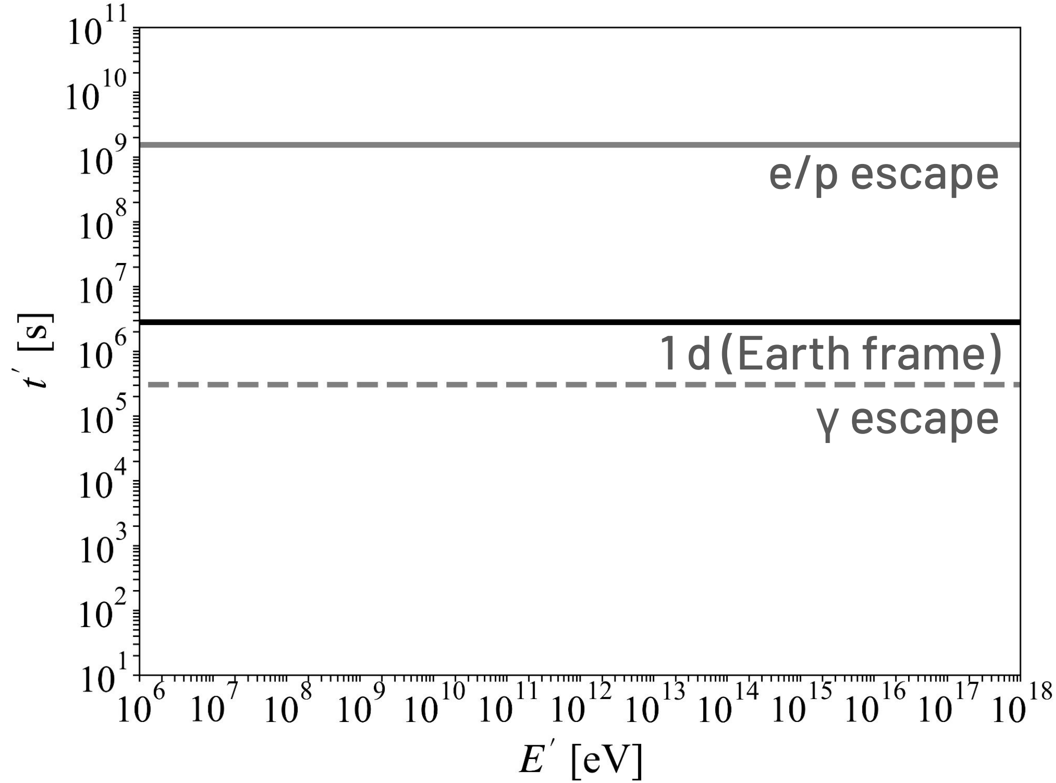
The elephant in the room

- In 10 yr of IceCat-1, there was one 168-TeV neutrino from 3C 454.3
- Probability to observe one or more ν_μ in ~10 yr in our model ≃ 0.06
- But the neutrino came 551 d after the flare!



Possibility of the neutrino delay

- *Slow* **proton acceleration** and **energy-loss timescales** of months to years (in the Earth frame) may imply a long delay for neutrino emission



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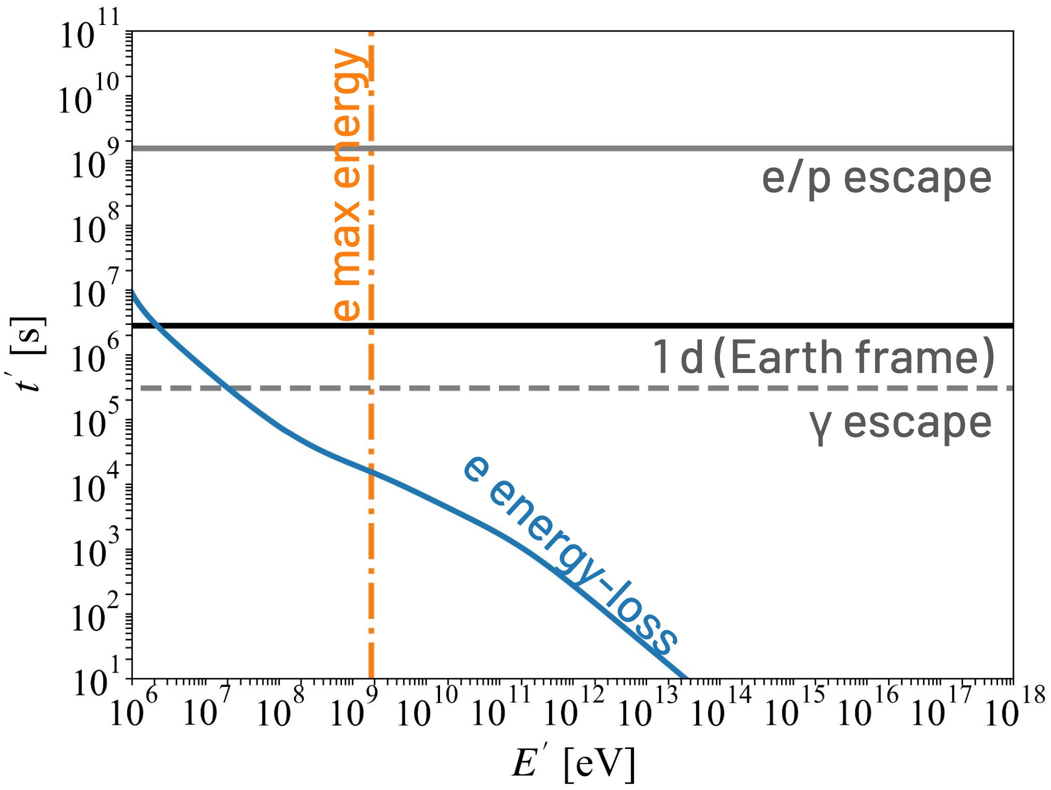

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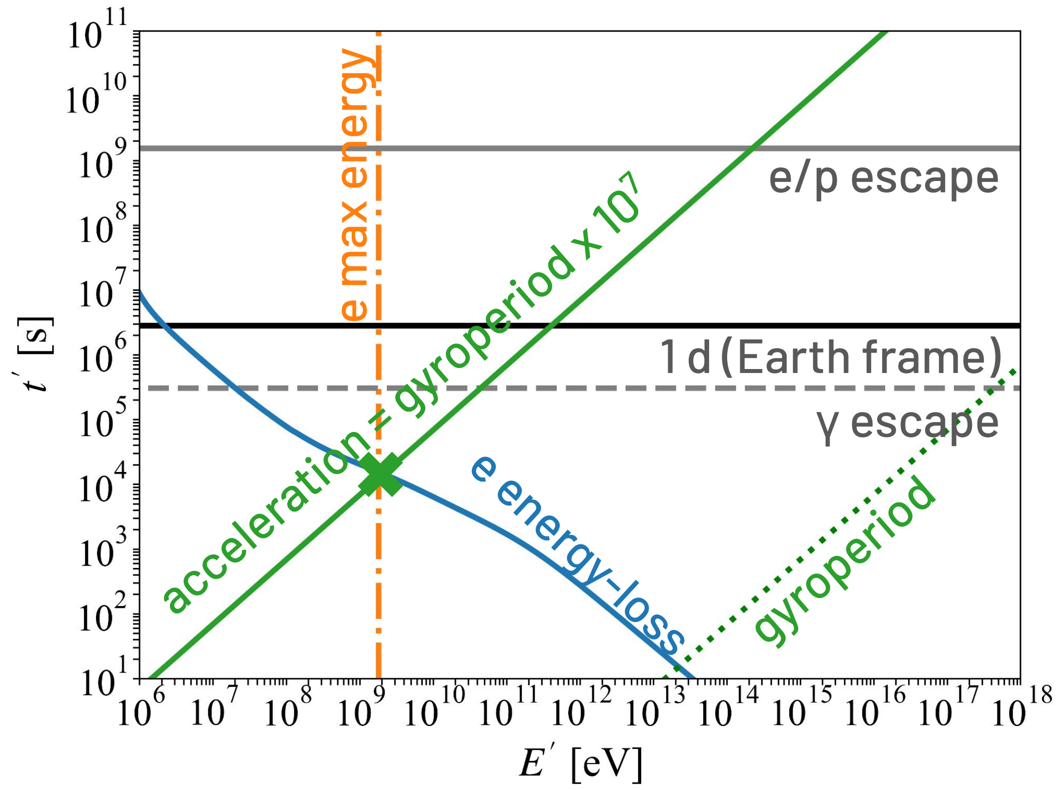

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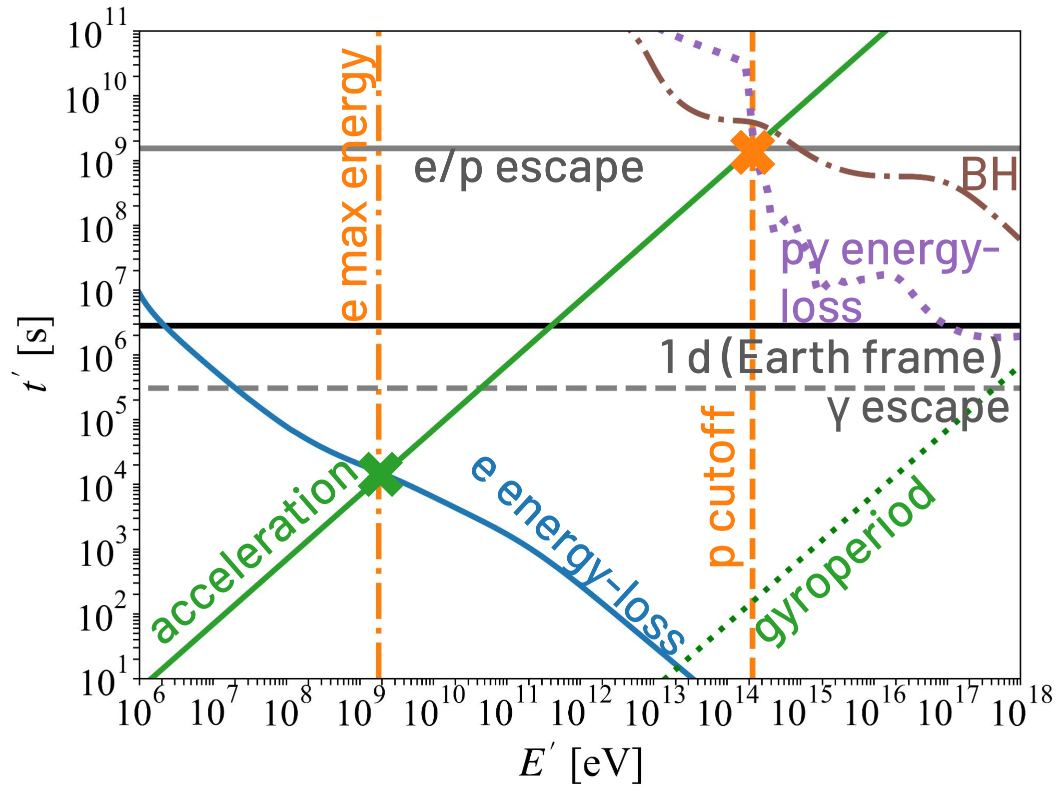

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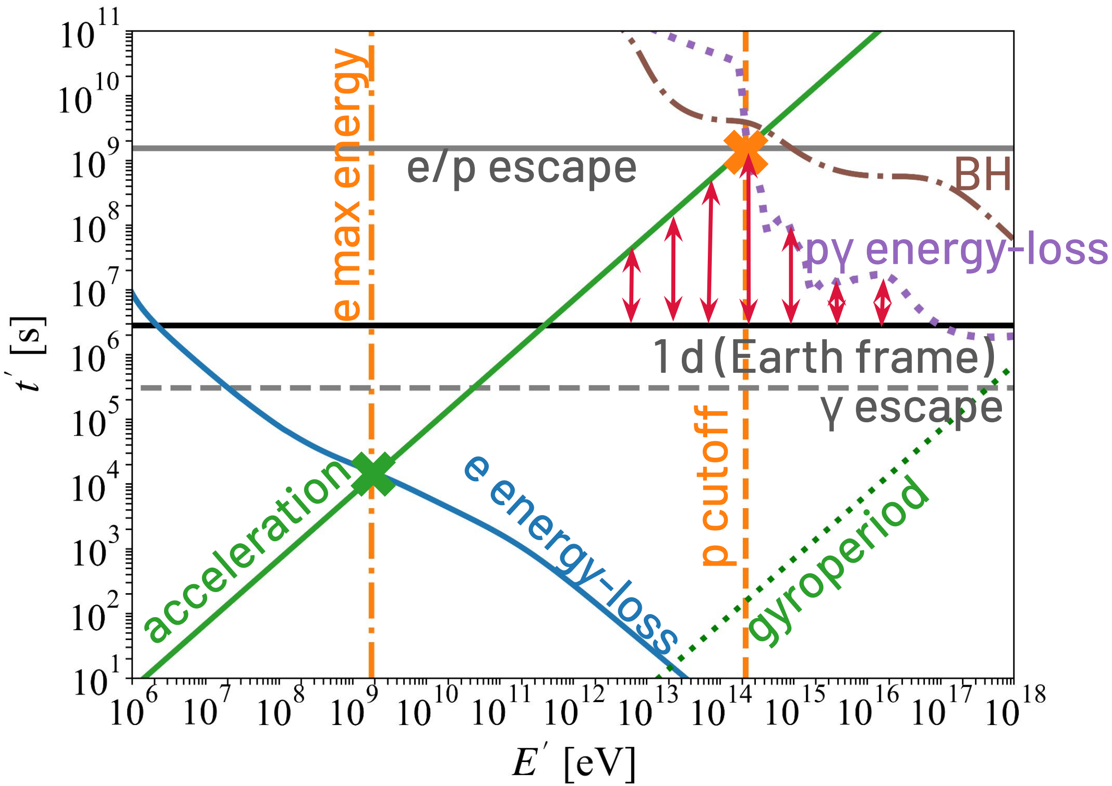
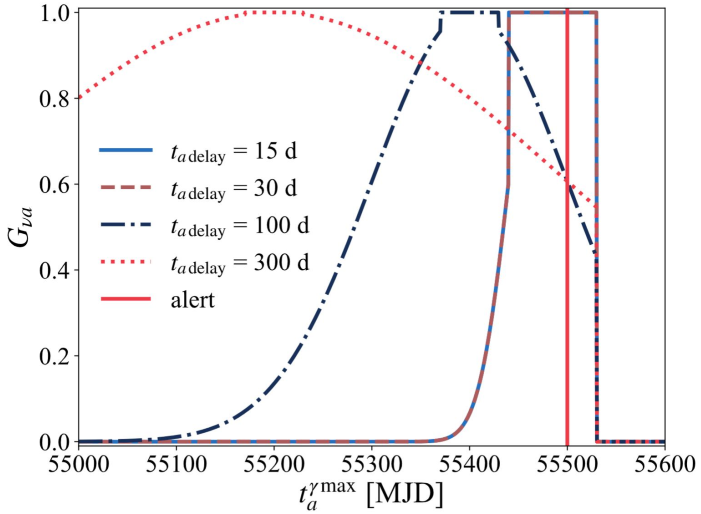


Search for delayed neutrinos with IceCat-1

- ➢ Gaussian temporal weights with the centre at the **anticipated prior maximum of the flare** based on the neutrino arrival time and jet-frame delay

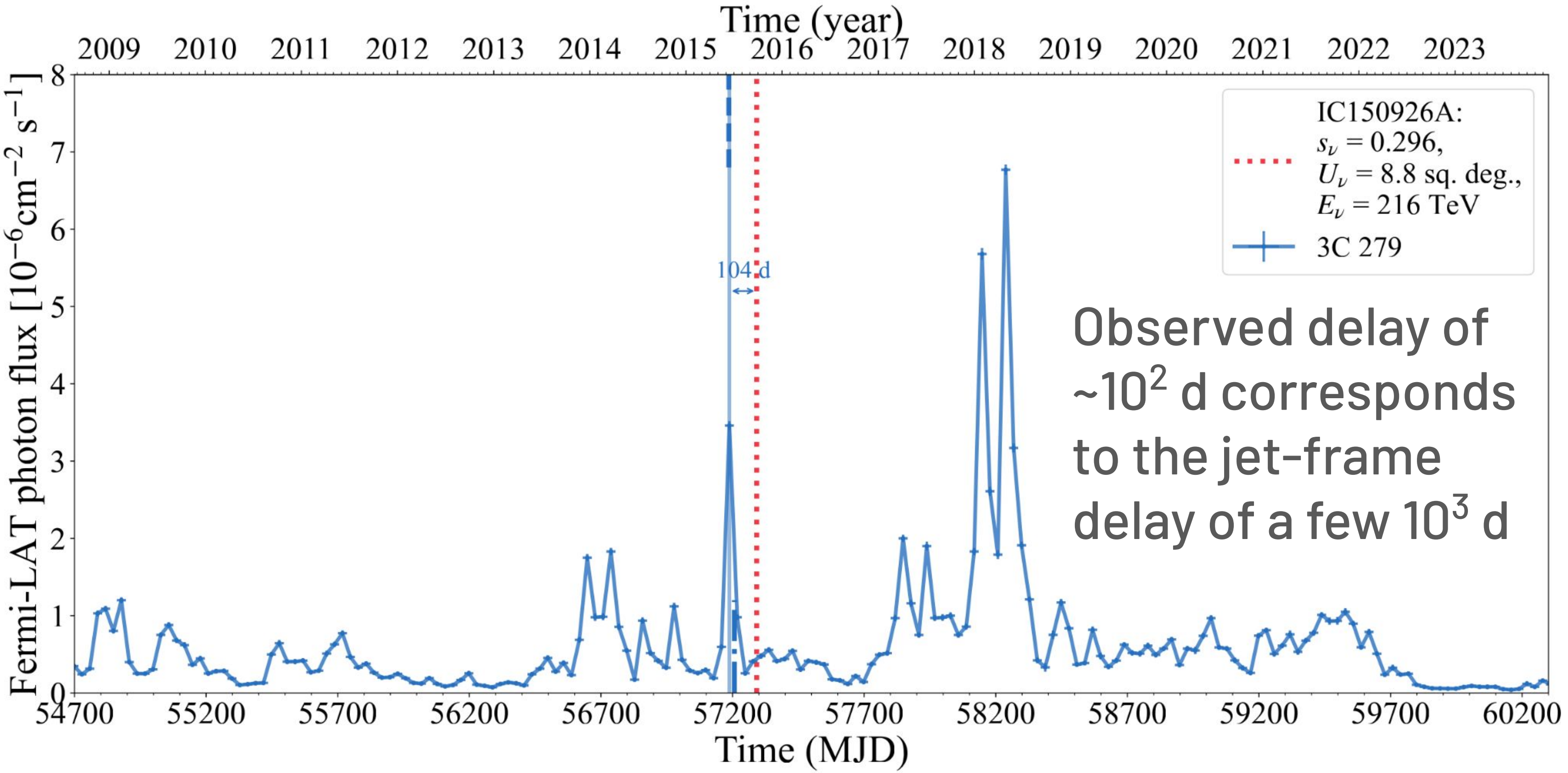
$$w_\nu(t'_{\rm delay}) \propto G_{\nu a}(t_a^{\gamma\,\rm max}, t_\nu; t'_{\rm delay}, D_a, z_a) F_a^\gamma(t_a^{\gamma\,\rm max})$$

$$t_{a\,\rm delay}(t'_{\rm delay}, D_a, z_a) = \frac{1+z_a}{D_a} t'_{\rm delay}$$



1) *Fermi*-LAT **light curves** from the repository *Fermi*-LAT Coll. (2023, ApJS, 265, 31)
2) **Neutrino alerts** from IceCat-1 IceCube Coll. (2023, ApJS, 269, 25)
3) **Doppler factors** from Rodrigues+ (2024, A&A, 681, A119) or Homan+ (ApJ, 2021, 923, 67)

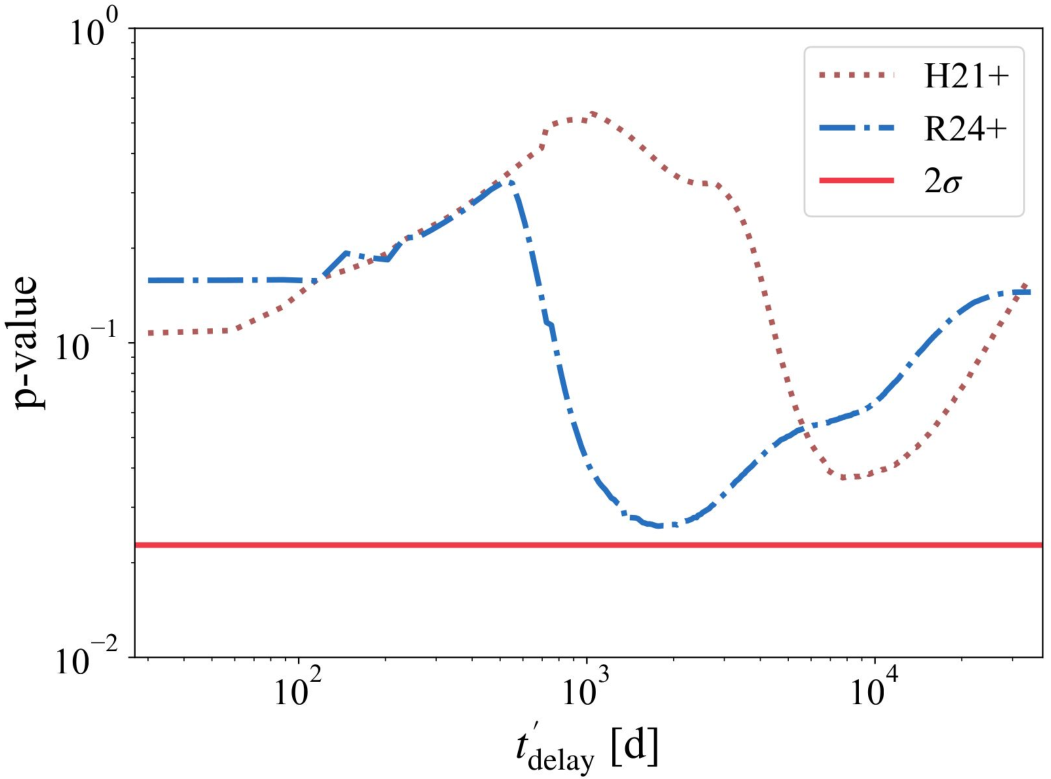
Light curve of 3C 279 with a delayed



Observed delay of ~10^2 d corresponds to the jet-frame delay of a few 10^3 d

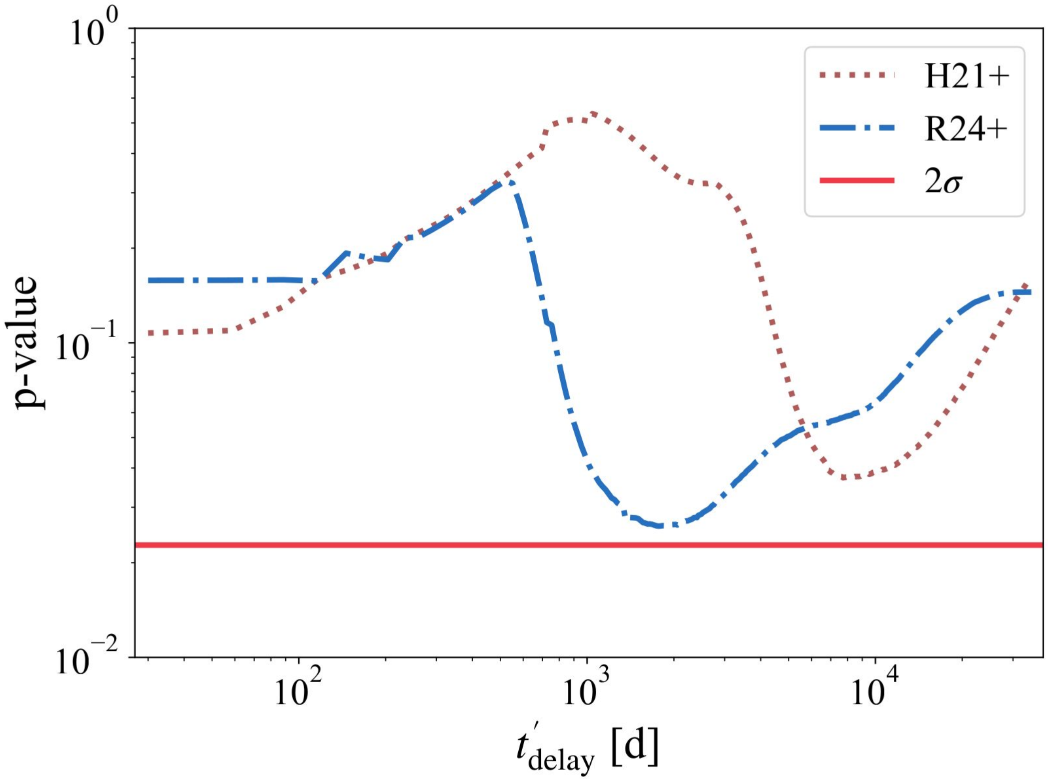
Search for lagging ν_μ from blazars

- **Scanning** over the jet-frame delay
- ~2σ **pre-trial** correlation at a few x 10^3 d
- **~10% post-trial chance** of a similar signal with mock catalogues with random RAs and t_ν



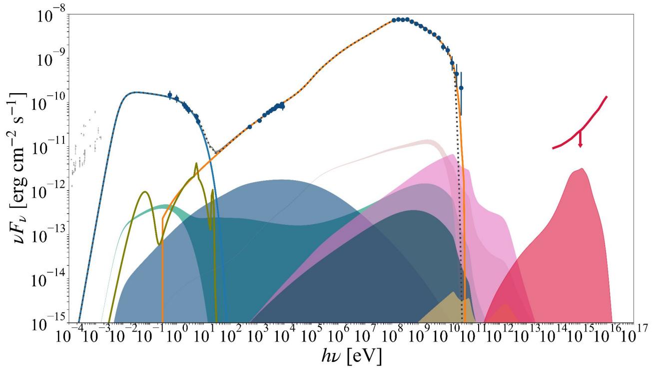
Why no evidence for delayed neutrinos?

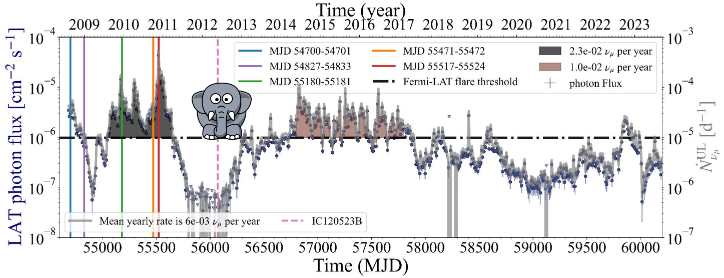
- ➢ **Too few ~100 TeV neutrinos** from the studied AGNs
- ➢ **No universal** jet-frame time delay among various sources
- ➢ **Too large uncertainty** of the Doppler factors
- ➢ **Electrons and protons** get accelerated and/or dissipated in **different regions of the jet**

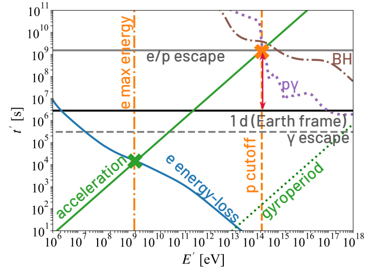


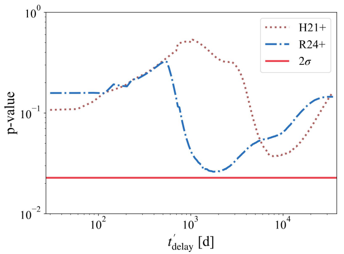
Summary

- The **brightest** *Fermi*-LAT blazar **flare** of 3C 454.3 modelled with time-dependent program **AM^3** in a **single-zone** approach
- Model estimates that **all *Fermi*-LAT FSRQs give ~0.5%** contribution to the ***IceCat-1* neutrinos at E ≥ 100 TeV**
- Search for **delayed** IceCat-1 neutrinos with *Fermi*-LAT **prior major flares** reveals **no significant correlation**









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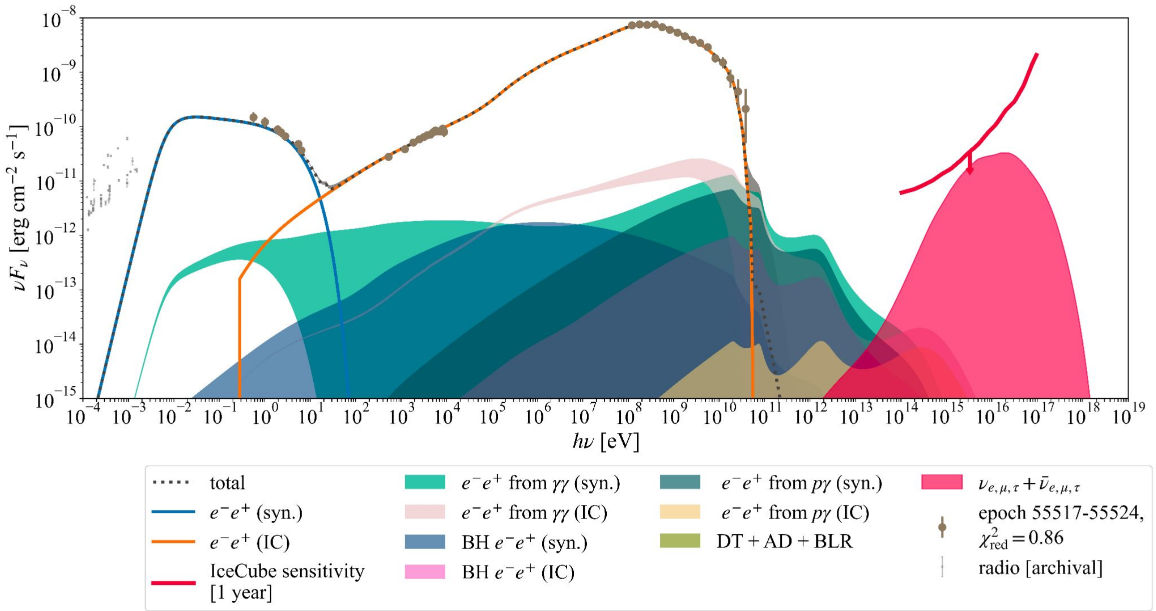
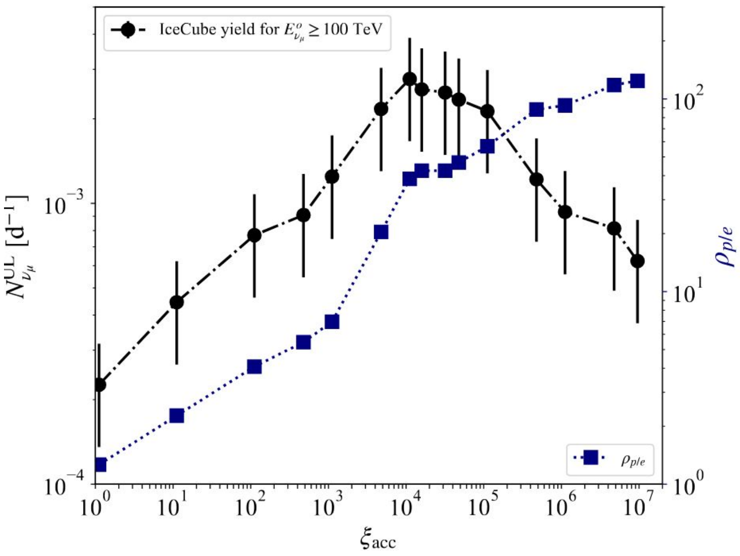
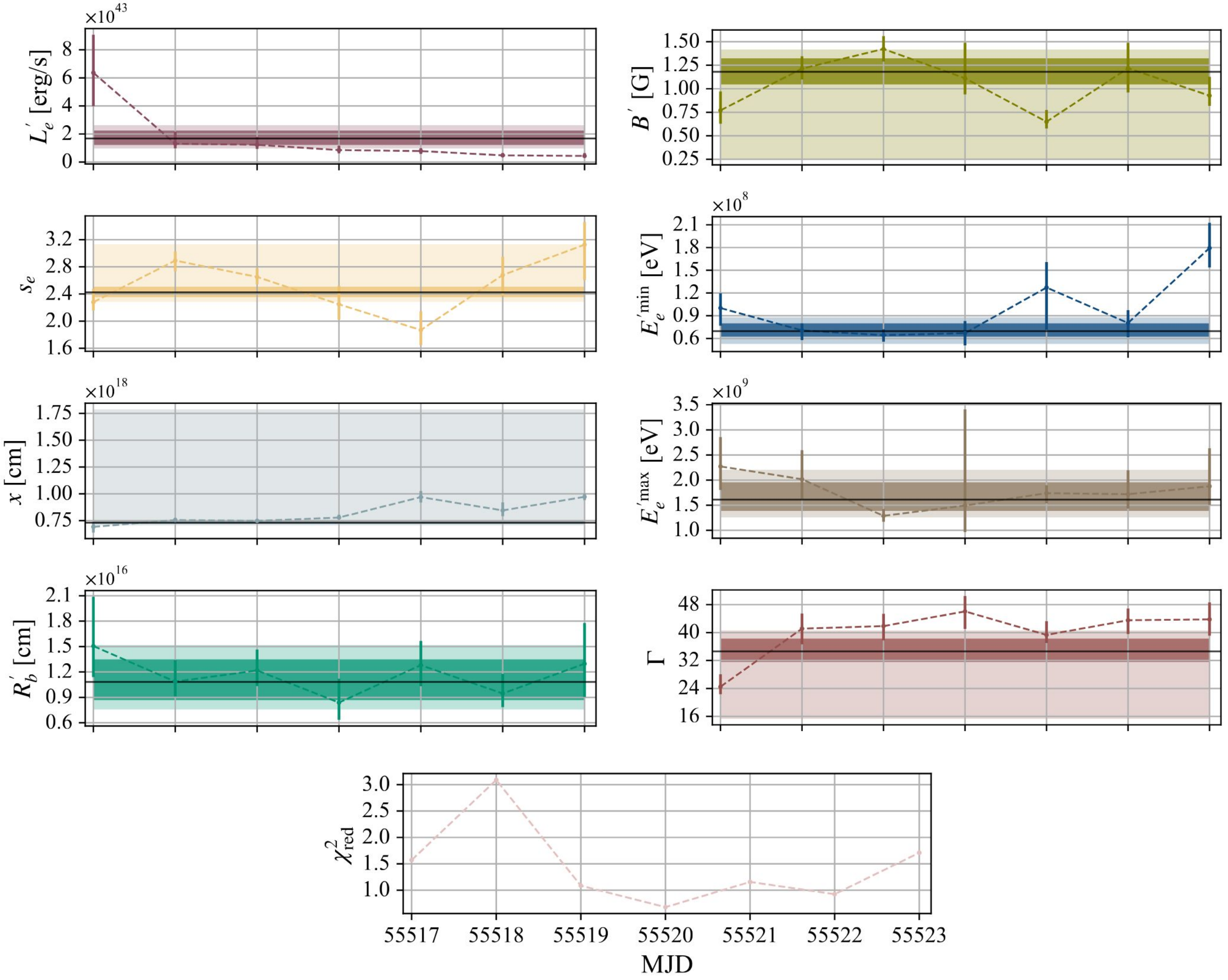




40% uncertainty of the neutrino SED from Cerruti et al. (2024), arXiv 2411.14218

Values $\xi_{acc} \lesssim 10^3$ are required to produce neutrinos with energies similar to the energy of the recently discovered >100 PeV neutrino KM3-230213A


L_e' [erg/s]
$\times10^{43}$
B' [G]
s_e
$E_e'^{\rm min}$ [eV]
$\times10^{8}$
x [cm]
$\times10^{18}$
$E_e'^{\rm max}$ [eV]
$\times10^{9}$
R_b' [cm]
$\times10^{16}$
Γ
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55517
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55522
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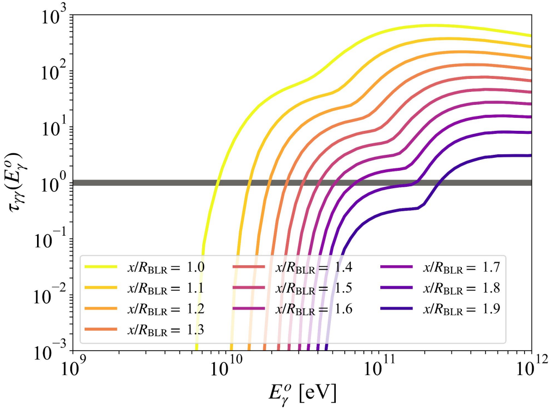
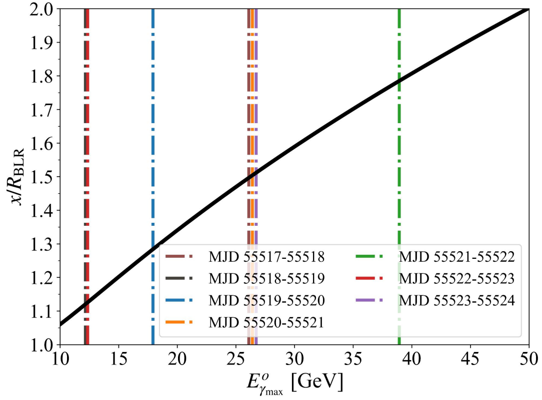
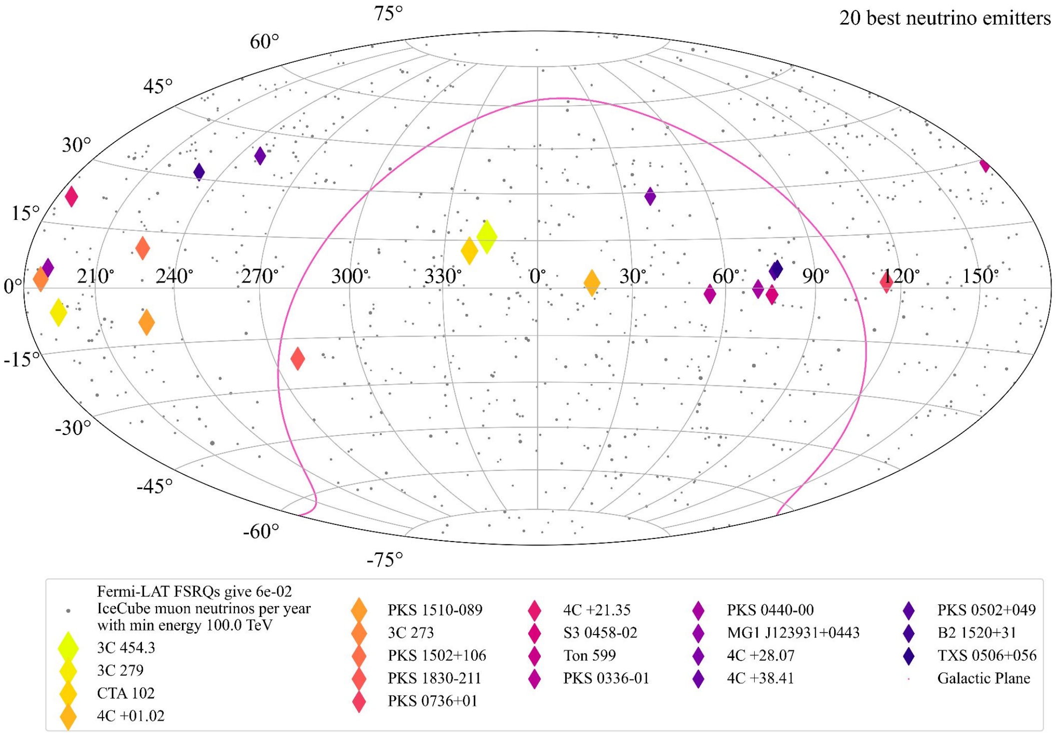
MJD


$\tau_{\gamma\gamma}(E^o_\gamma)$
E^o_γ [eV]
$x/R_{\rm BLR} = 1.0$
$x/R_{\rm BLR} = 1.1$
$x/R_{\rm BLR} = 1.2$
$x/R_{\rm BLR} = 1.3$
$x/R_{\rm BLR} = 1.4$
$x/R_{\rm BLR} = 1.5$
$x/R_{\rm BLR} = 1.6$
$x/R_{\rm BLR} = 1.7$
$x/R_{\rm BLR} = 1.8$
$x/R_{\rm BLR} = 1.9$


$x/R_{\rm BLR}$
$E^o_{\gamma_{\rm max}}$ [GeV]
MJD 55517-55518
MJD 55518-55519
MJD 55519-55520
MJD 55520-55521
MJD 55521-55522
MJD 55522-55523
MJD 55523-55524

Extrapolating to all Fermi-LAT FSRQs

- ~0.5% of *IceCat-1* from Fermi-LAT FSRQs **is in line with the result** of [Abbasi et al. (2023), ApJ, 954, 75](#) that <1% of the *Fermi*-LAT AGNs emit neutrinos that pass the alert criteria



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