Calorimetric neutrino expectations from bright blazars

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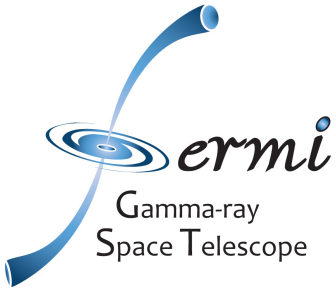
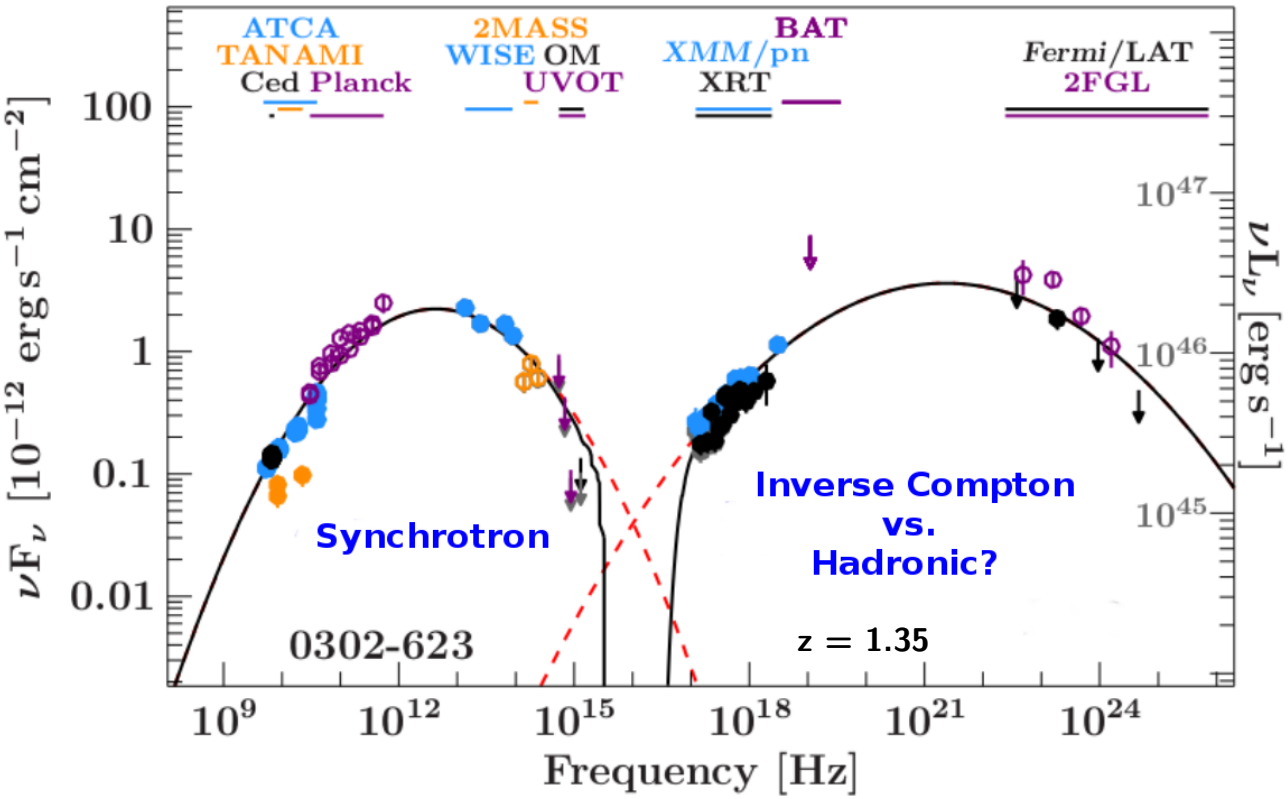


Motivation
Short Blazar Flares
Track-like events
Summary

MWL emission behavior of blazars



Credit: Krauss et al. 2014, A&A 566, L7

Expect correlation between ν and γ from $\pi^{0,\pm}$ decays

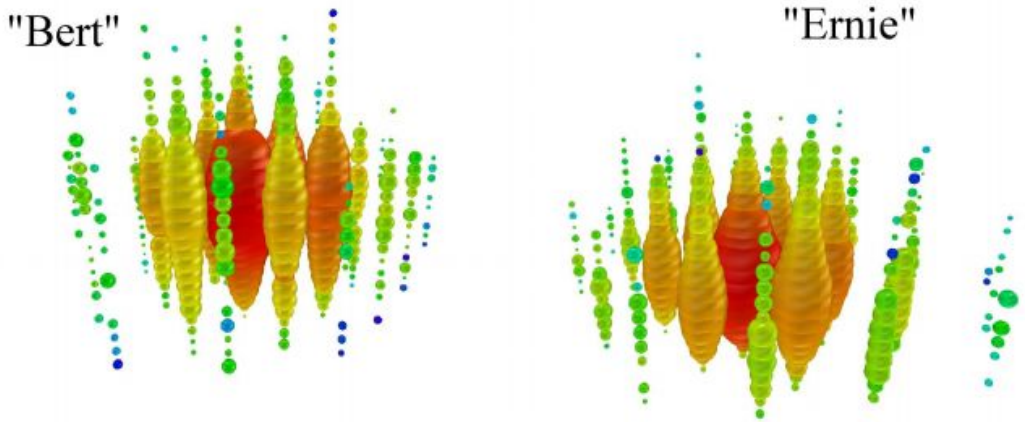
Blazars as promising neutrino sources

In Krauss et al. 2014 we showed:

- Blazars as a class are capable of explaining IceCube PeV neutrino events
- High-fluence blazars are best candidates for individual source associations

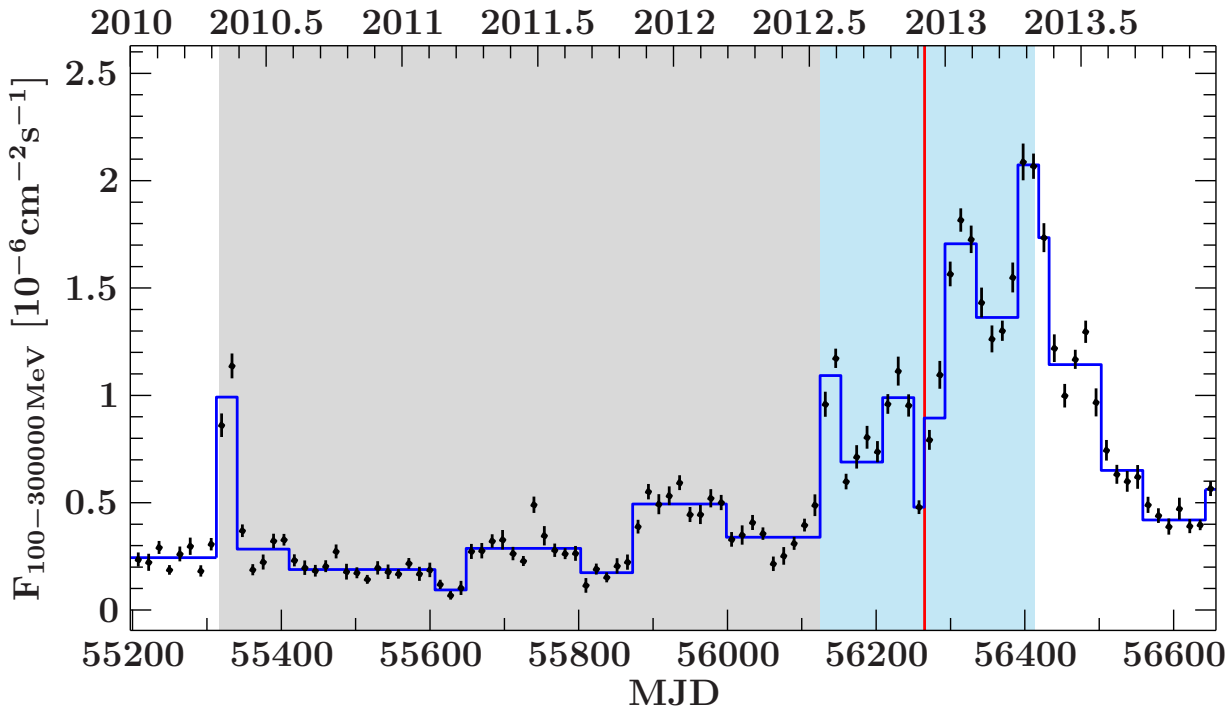
Source	F_γ(erg cm^{-2} s^{-1})	events
0235−618	$\left(1.0^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.19^{+0.04}_{-0.04}$
0302−623	$\left(3.4^{+0.7}_{-0.7}\right) \times 10^{-11}$	$0.06^{+0.01}_{-0.01}$
0308−611	$\left(7.5^{+2.9}_{-2.9}\right) \times 10^{-11}$	$0.14^{+0.05}_{-0.05}$
1653−329	$\left(4.5^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.86^{+0.10}_{-0.10}$
1714−336	$\left(2.4^{+0.5}_{-0.6}\right) \times 10^{-10}$	$0.46^{+0.10}_{-0.12}$
1759−396	$\left(1.2^{+0.3}_{-0.2}\right) \times 10^{-10}$	$0.23^{+0.50}_{-0.40}$
Total		1.9 ± 0.4

Credit: Krauss et al. 2014, **A&A** 566, L7



Blazars as promising neutrino sources

Followed by Kadler et al. 2016:



Credit: Kadler et al. 2016, **Nat Phys** 12, 807

$\Rightarrow$ Calorimetric output in BigBird field dominated by PKS B1424-418

But: Chance Coincidence $\approx 5\%$

Calorimetric neutrino expectations from bright blazars

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Blazars as promising neutrino sources

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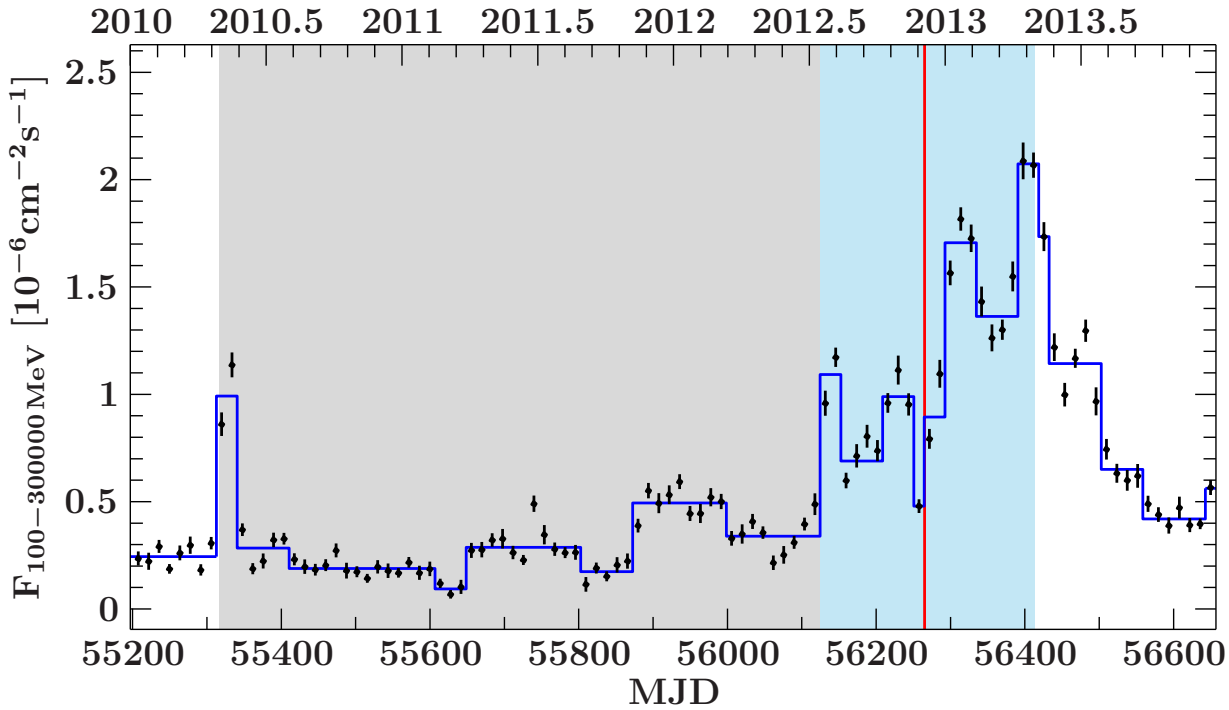

Credit: Kadler et al. 2016, **Nat Phys** 12, 807

How to estimate the neutrino prediction from individual sources/flares?

How can we improve with shorter flares or track-like events?

Calorimetric neutrino expectations from bright blazars

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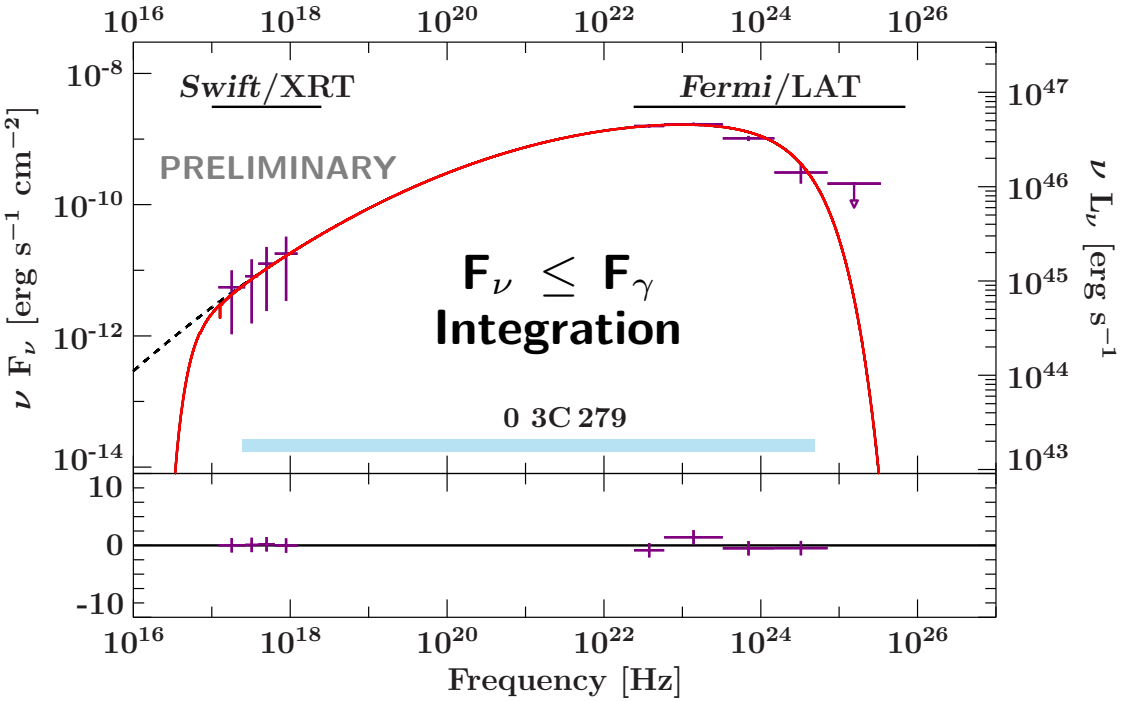
Estimate maximum neutrino output

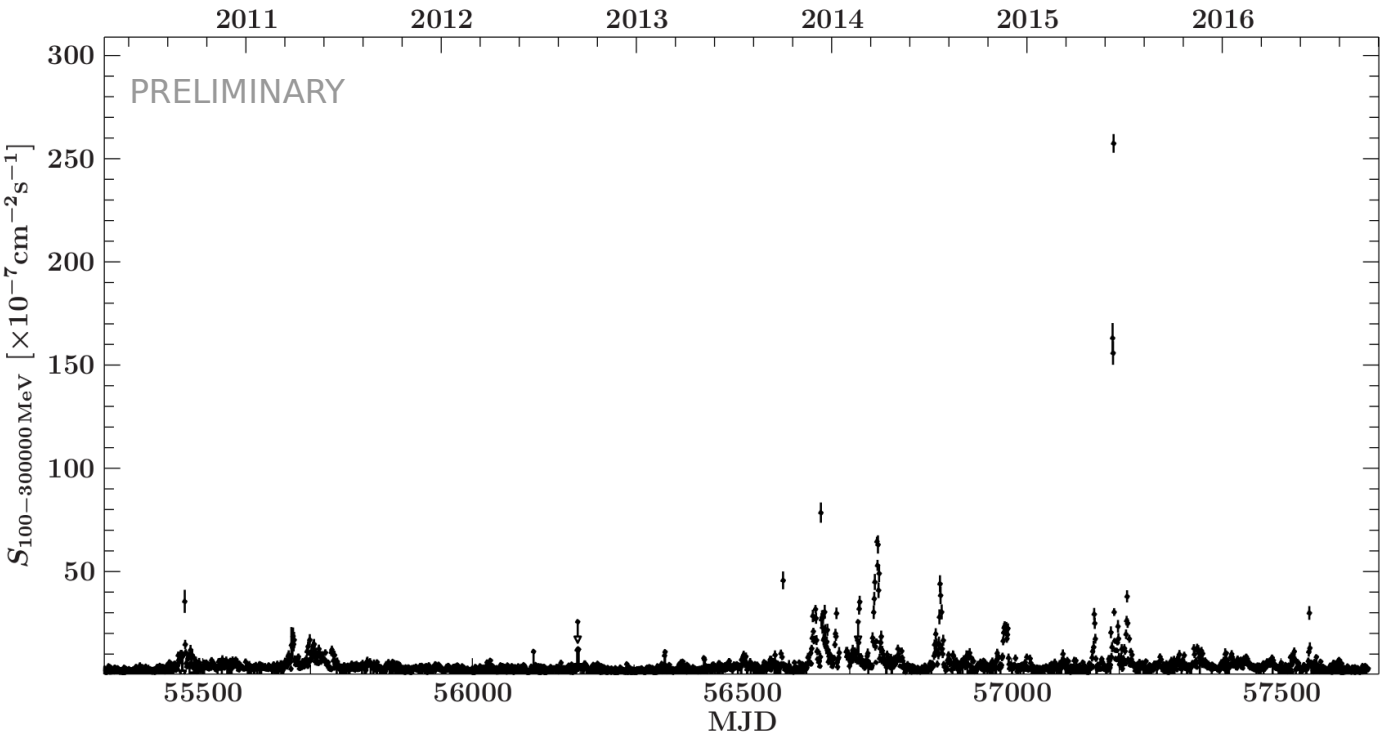
3C 279 June 2015 flare:



$$N_\nu^{max} = A_{eff,\nu} \times \left(\frac{F_\gamma}{E_\nu}\right) \times \Delta t$$

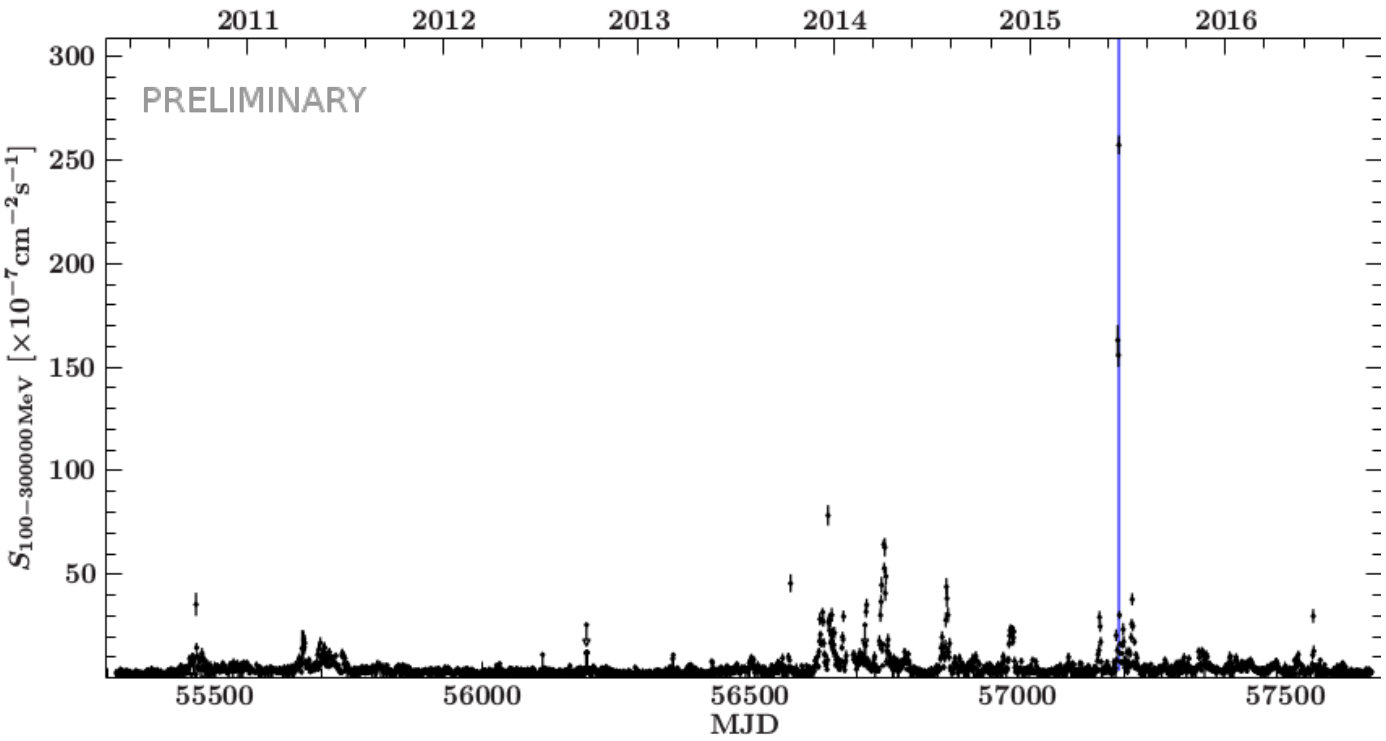
$\Rightarrow$ Actual predicted neutrino number is smaller, due to several additional factors

3C279



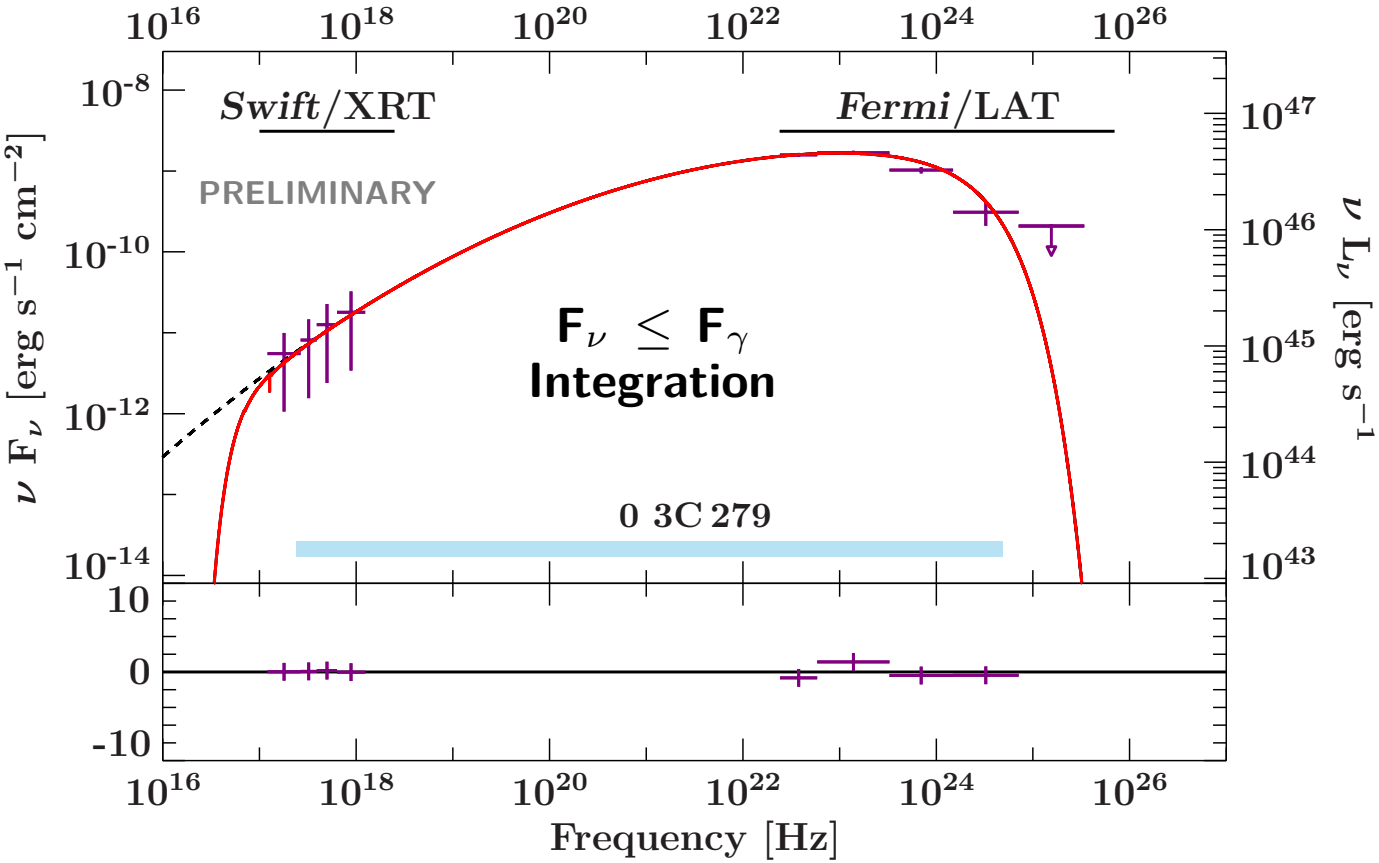
- Halzen & Kheirandish 2016, ApJ. 831,12
- Suggestion of promising neutrino candidate

3C279



- Halzen & Kheirandish 2016, ApJ. 831,12
- Suggestion of promising neutrino candidate
- Identify flare duration of 6 days

3C279



- $N^{pred}_{\nu,PeV} \approx 0.02$
- $\approx$ 5 months of non flaring activity

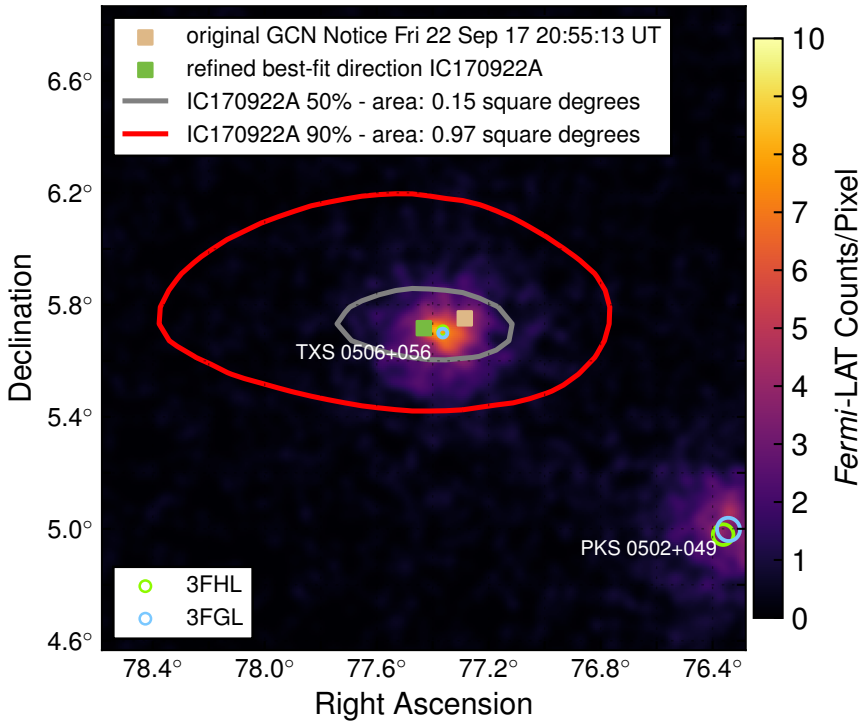
Flare sample

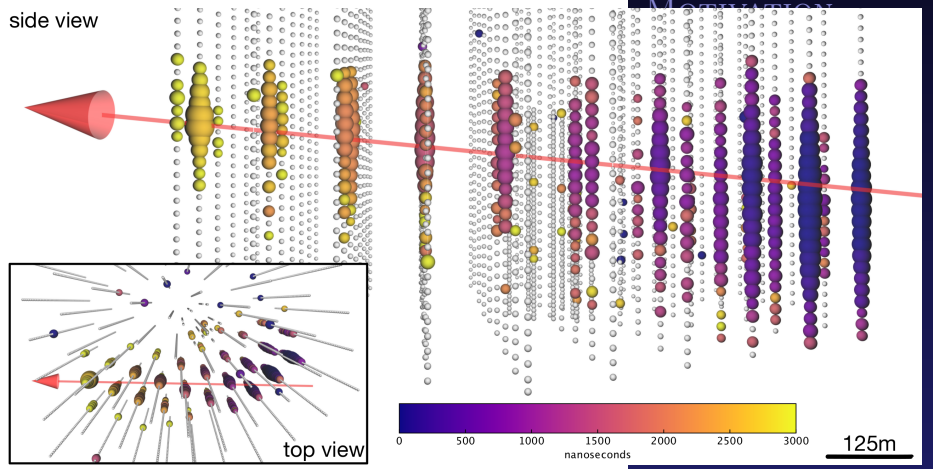
Source	Duration in Days	N_ν^{max}	$N_\nu^{pred} \times 10^{-2}$
3C 279	6	0.797	1.99
PKS 1510-089	5	0.306	0.764
PKS 1510-089	11	0.586	1.46
PKS 1510-089	1	0.0405	0.101
3C 279	1	0.0272	0.0681
3C 279	5	0.214	0.535
PKS 1510-089	10	0.393	0.982
3C 279	2	0.0993	0.248
PKS 1510-089	4	0.159	0.398
PKS 1510-089	2	0.0605	0.151
⋮	⋮	⋮	⋮
3C 454.3	240	11.71	29.28

- More then 500 flares studied from 140 bright blazars
- Detection probability of short flares $\sim$ days is small
- 3C 279 and PKS 1510−089 account for the majority of flares

Short flares ($\sim$ days) provide only a marginal neutrino prediction.

Blazars as promising neutrino sources



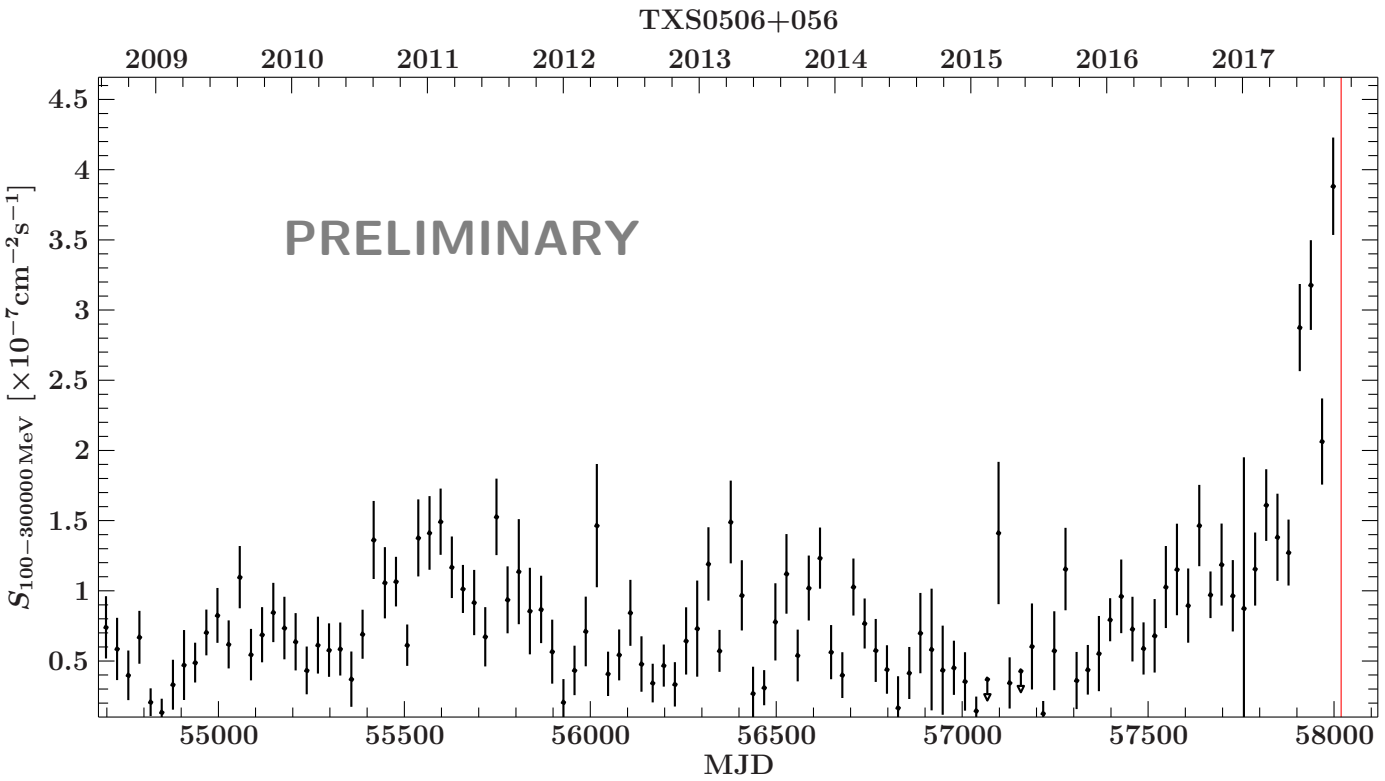


Credit: IceCube Collaboration et al. 2018, **Science** 361, 6398

- First track-like IceCube event consistent with a *Fermi*-LAT source in an active state
- Chance Coincidence $\approx 3.5\,\sigma$ level

How can we improve with track-like events?

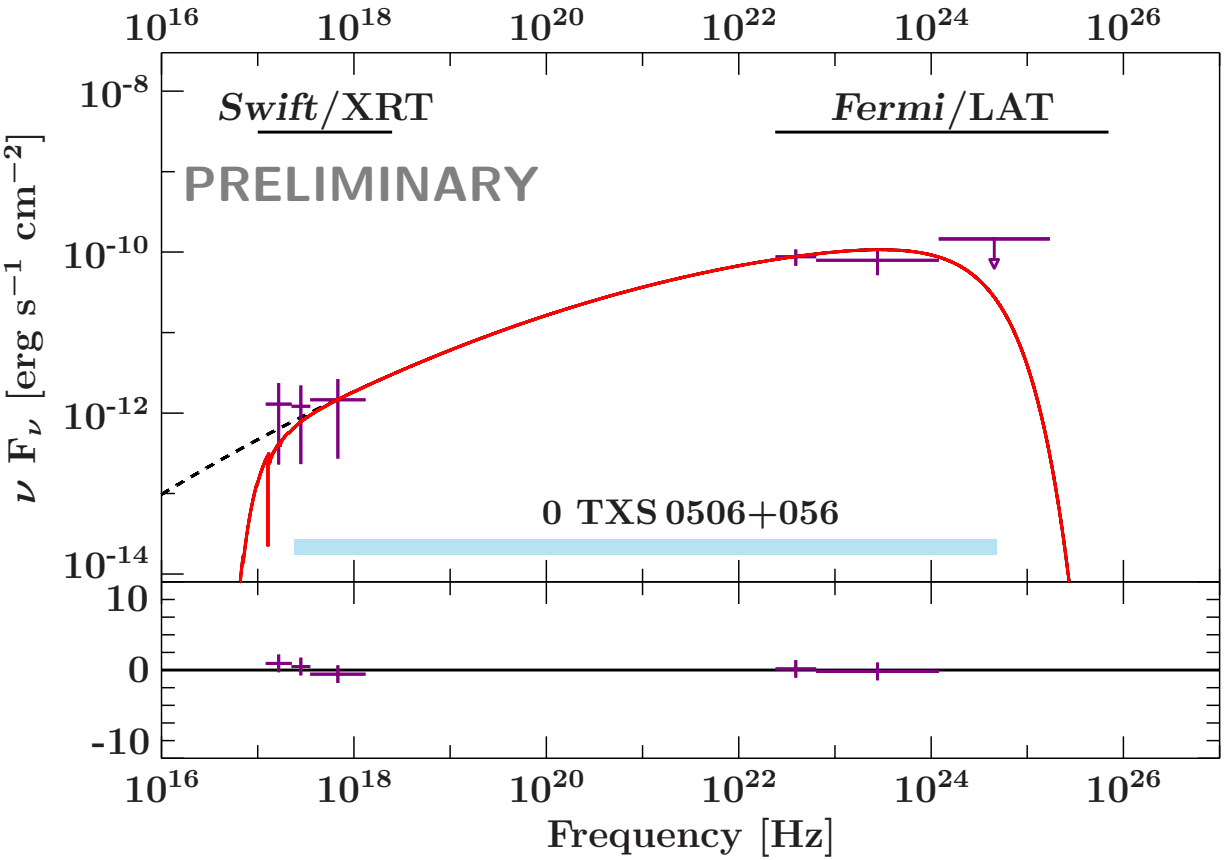
γ-ray light curve of TXS 0506+056



- Outburst already going on since early 2016

Calculate neutrino expectation for IC-170922A arrival time

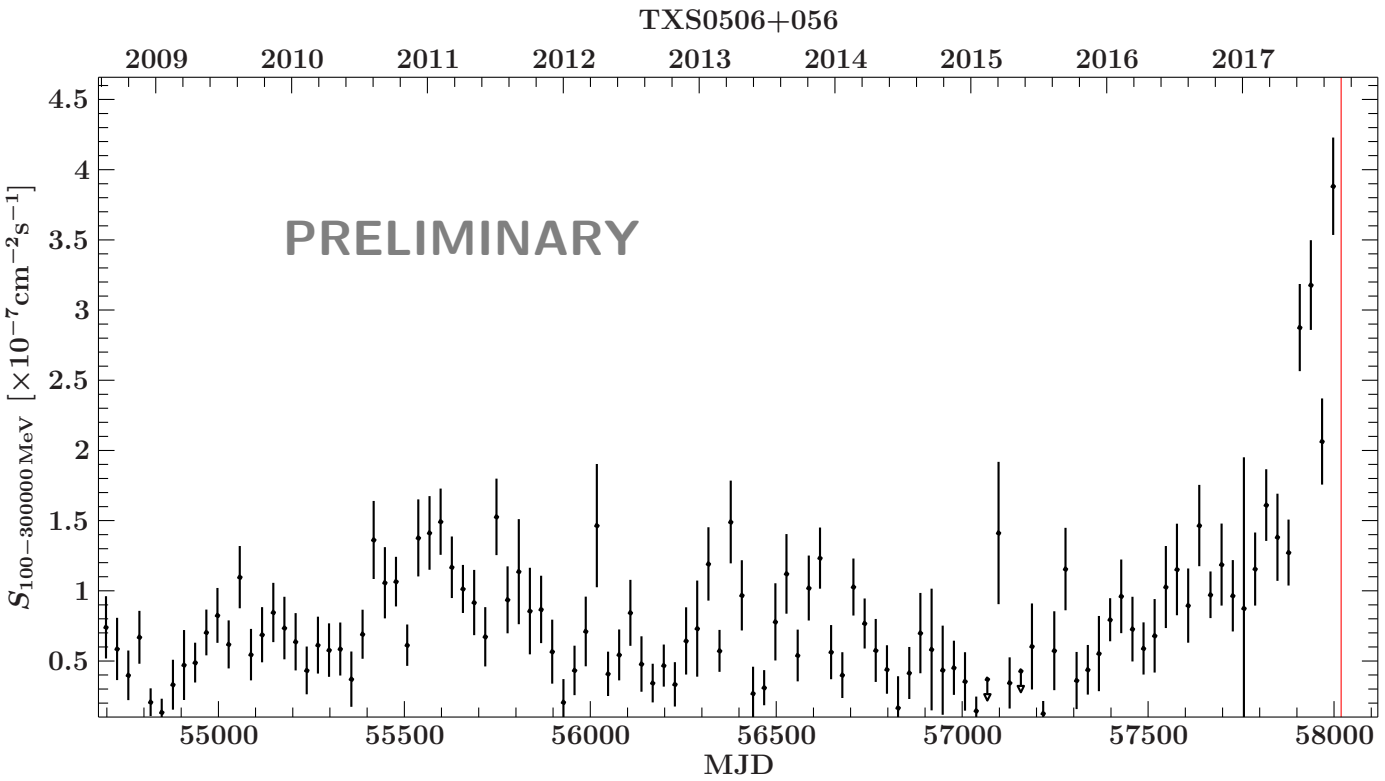
Short-flare SED of TXS 0506+056



- Select 3-days period around neutrino arrival
- $N_\nu^{pred} \approx 9 \times 10^{-5}$

Neutrino expectation from short-flare period is negligible

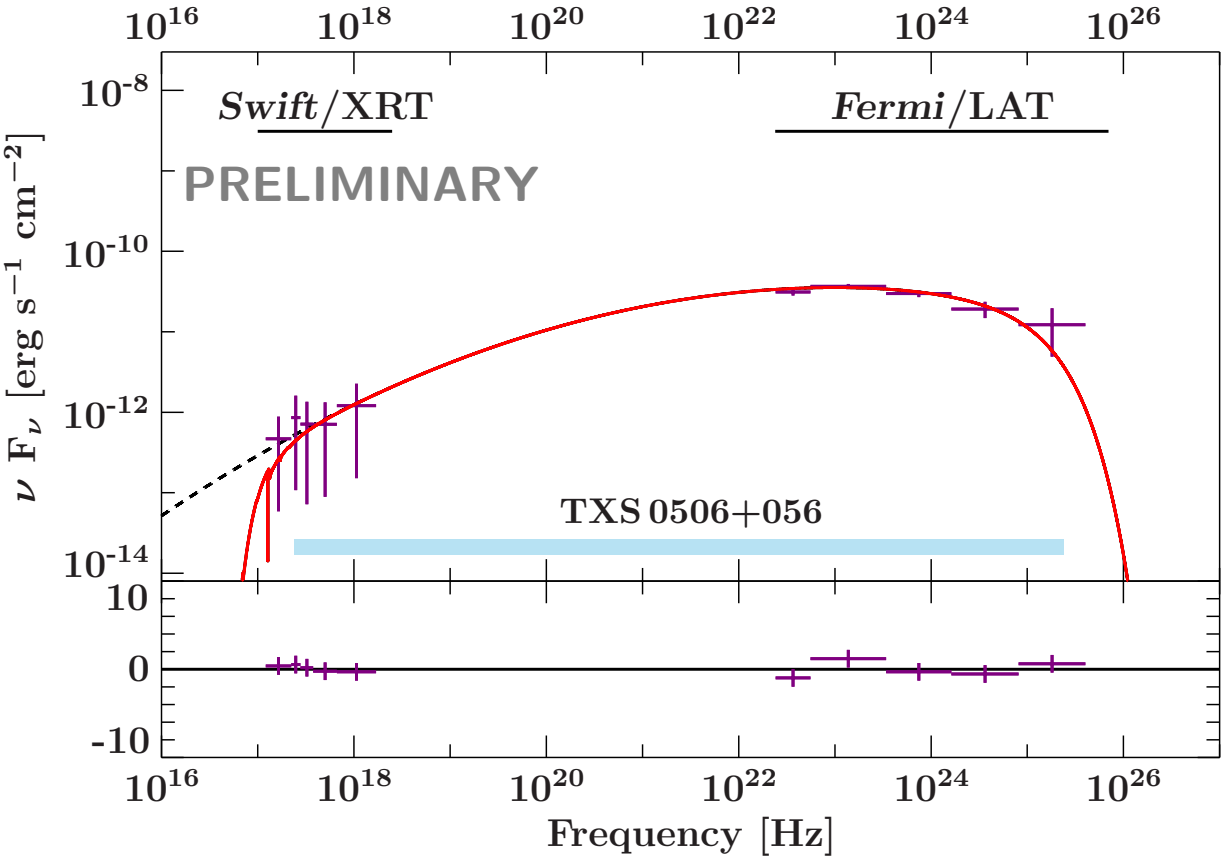
γ-ray light curve of TXS 0506+056



- Outburst already going on since early 2016

Calculate neutrino expectation for long-term outburst

Long-term SED of TXS 0506+056



- Select time range from early 2016 through Sep 2017
- $N_\nu^{\text{pred}} \approx 0.029$

Long-term association is calorimetrically (more) plausible

Summary

- Short blazar flares ($\sim$ days) yield only a small (calorimetric) neutrino detection probability
- Long-term outbursts ($\sim$ weeks - months) neutrino expectation of TXS 0506+056 seems (calorimetric) reasonable

Summary

- Short blazar flares yield only a small (calorimetric) neutrino detection probability
- Long-term neutrino expectation of TXS 0506+056 seems (calorimetric) reasonable

Future neutrino point source searches should concentrate on longer outburst / track-like neutrino events
Consider different ν emission models

Possible correlation between ν's and X-ray/optical emission

Backup

Rank	Source	Energy Flux in erg cm^{-2} s^{-1}	Integrated γ-ray Fluence in erg cm^{-2}	Energy Flux × Effective Area in erg s^{-1}	N_ν^{max}
1	3C 454.3	1.36×10^{-4}	$3.25 \pm 0.15 \times 10^{-9}$	5.48	13.10
2	CTA 102	5.25×10^{-4}	$3.11 \pm 0.15 \times 10^{-9}$	21.18	11.67
3	3C 279	9.95×10^{-5}	$1.44 \pm 0.07 \times 10^{-9}$	4.85	7.20
4	PKS 1510-08	6.17×10^{-5}	$1.05 \pm 0.05 \times 10^{-9}$	3.01	5.19
5	4C +01.02	5.59×10^{-5}	$8.5 \pm 0.5 \times 10^{-10}$	2.80	4.36
6	PKS B1424-418	8.48×10^{-5}	$7.5 \pm 0.4 \times 10^{-10}$	4.07	3.65
7	NGC 1275	1.71×10^{-4}	$1.22 \pm 0.07 \times 10^{-9}$	4.17	3.02
8	PKS 0426-380	1.03×10^{-4}	$4.74 \pm 0.27 \times 10^{-10}$	4.95	2.32
9	PKS 1502+106	6.06×10^{-5}	$4.45 \pm 0.26 \times 10^{-10}$	2.76	2.06
10	PKS 2023-07	3.48×10^{-5}	$3.49 \pm 0.21 \times 10^{-10}$	1.69	1.73
11	BL Lacertae	1.02×10^{-4}	$6.2 \pm 0.4 \times 10^{-10}$	2.48	1.55
12	PKS 0447-439	1.05×10^{-4}	$3.03 \pm 0.20 \times 10^{-10}$	5.05	1.48
13	PKS 2155-304	1.46×10^{-4}	$2.66 \pm 0.17 \times 10^{-10}$	6.89	1.27
14	**TXS 0506+056**	5.81×10^{-5}	$\mathbf{2.63 \pm 0.18 \times 10^{-10}}$	**2.92**	**1.19**
15	PKS 0208-512	1.82×10^{-5}	$2.57 \pm 0.24 \times 10^{-10}$	0.85	1.18
			...		
			...		

P-VALUE CALCULATION BASED ON A-PRIORI DEFINED MODEL

Krauß et al. 2014 and Kadler et al. 2016:

- Highest probability for a neutrino-blazar association is given for highest-fluence sources

$\Rightarrow$ Produce ranked list of high-fluence blazars from early 2016 through Sep 2017

P-VALUE CALCULATION BASED ON A-PRIORI DEFINED MODEL

- Use *Fermi*/LAT measured GeV flux as a first proxy of F_γ

$\Rightarrow$ **TXS 0506+056 is the 19 th brightest GeV source in the entire sky**

- Sorting sources according to their sensitivity for IC-170922A in the IceCube detector by $F_\gamma \times A_{\mathrm{Eff}}^{\nu_\mu;290\ TeV}$
- Calculate SEDs for top-70 sources and derive N_ν^{pred}

$\Rightarrow$ **TXS 0506+056 is the 14 th best ranked source**

Pre trial corrected p-value calculation based on a-priori defined model

$$p_{pre} = N_{\text{Alert}} \cdot \frac{\Omega_\nu}{4\pi} \cdot N_{\text{rank}}$$

- $N_{\text{Alert}} = 10$ (number of similar IceCube events)
- $N_{\text{rank}} = 14$ (ranking based on pγ correlation)
- $\Omega_\nu = 0.0314\,\text{deg}^2$ (positional uncertainty)

$\Rightarrow p_{pre} = 1.1 \cdot 10^{-4} \sim 3.9\,\sigma$

$\Rightarrow$ **How to compare this with other studies?**

Post trial corrected p-value calculation

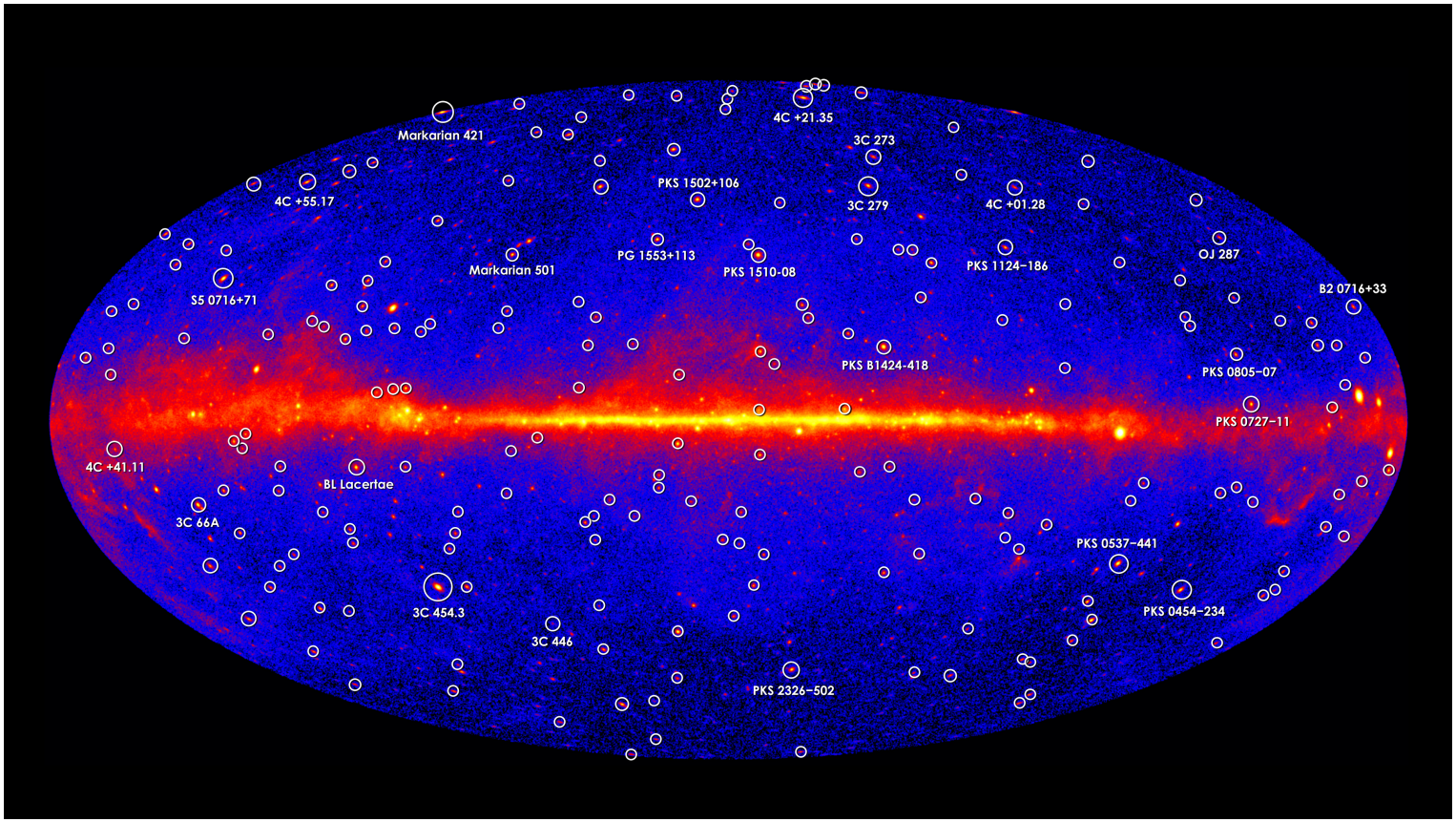
$$p_{post} = 1 - (1 - p_{pre})^N$$

- $N = 51$ (considering additional 41 EHE events that have not been published)

$$\Rightarrow p_{post} = 5.4 \cdot 10^{-4} \sim 3.5\,\sigma$$

Association of IC-170922A and TXS 0506+056 is significant independent of flare-counting arguments and consistent with predictions of our pre-defined model

The *Fermi*-LAT γ-Ray Sky



Credit: NASA, DOE; Fermi/LAT Collaboration

- Five-years all-sky map observed by the Large Area Telescope
- Blazars dominate the high-energy sky

Study systematic flaring behavior of bright blazars