γ-ray lightcurve correlation search for IceCube neutrinos from TXS 0506+056 & other blazars

Christoph Raab & Juan Antonio Aguilar Sánchez
for the IceCube collaboration

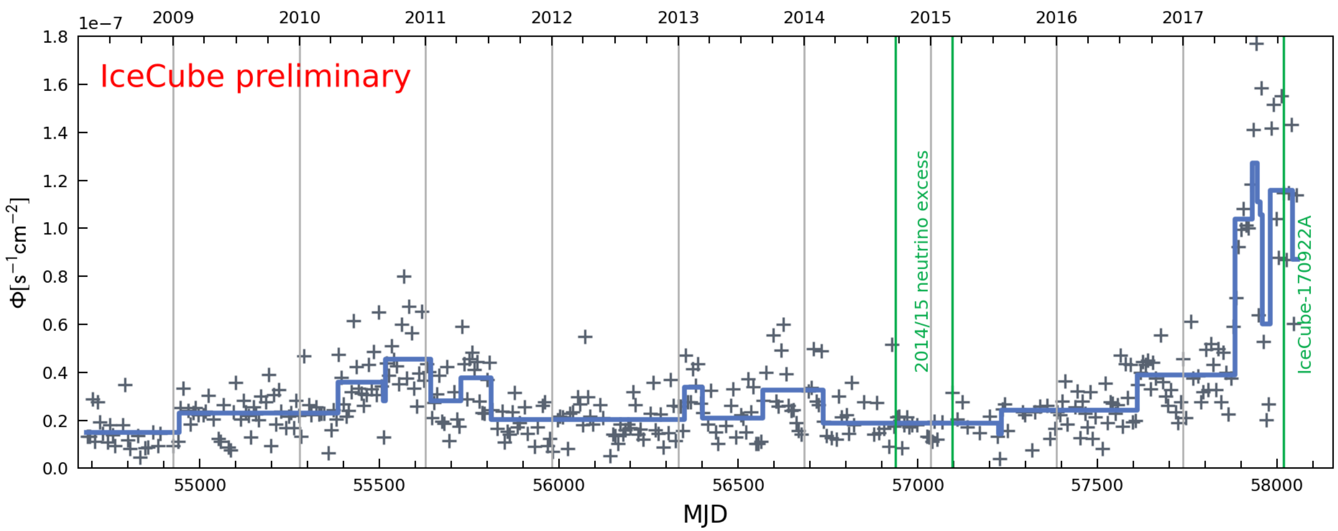
Context

- IceCube-170922A in coincidence with 2017 flare of TXS 0506+056 *(talk by Anna Franckowiak)*
- No additional neutrinos in ± 7 days (fast response)
- 3 searches for more neutrinos from TXS in 9.5 years of archival data:

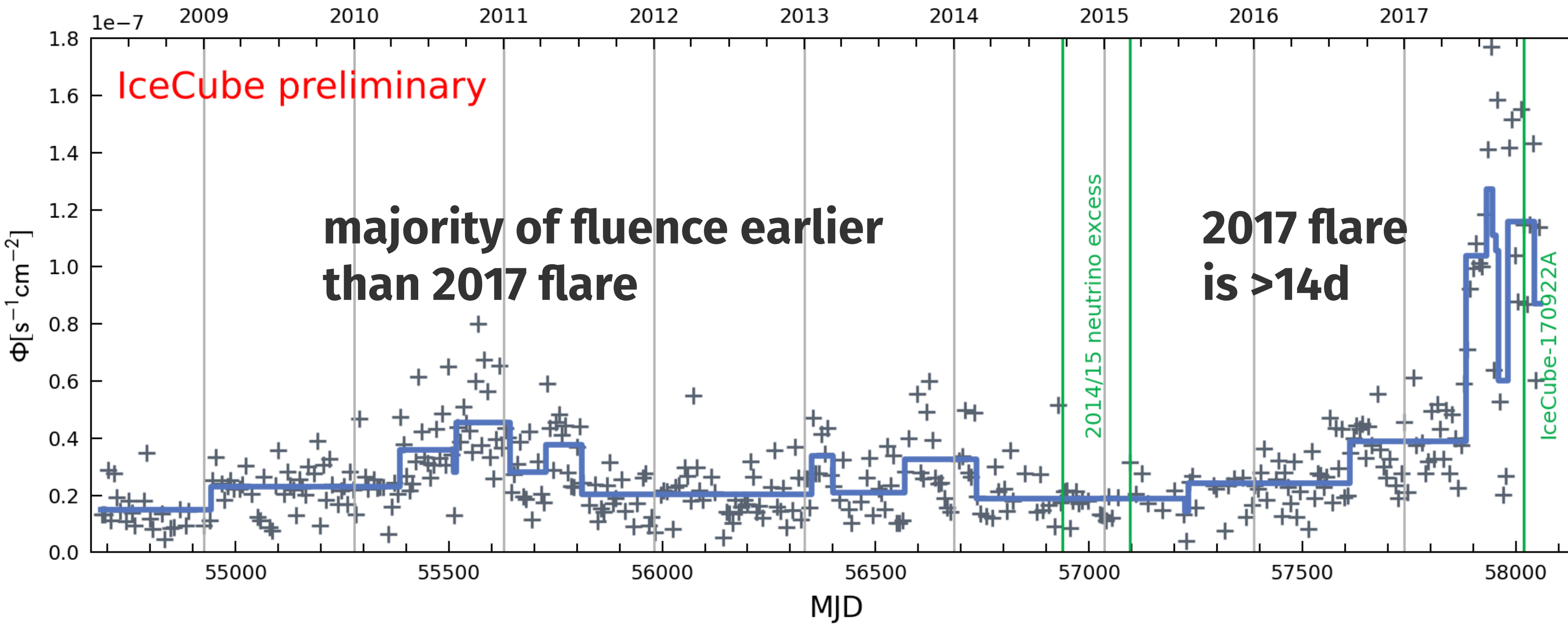
1) integrated over time → find excess *(talk by Chad Finley)*

2) clustered anytime → mostly during 2014/15

3) correlated to γ-rays → set limits **(this analysis)**



Why correlated to γ-rays?

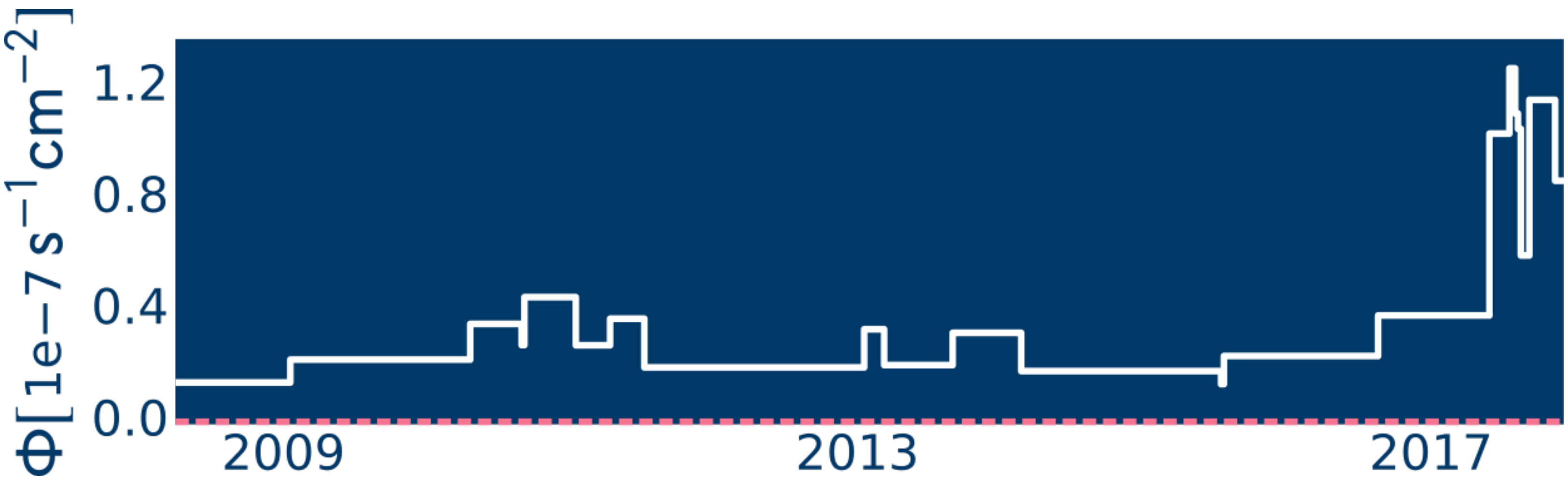


TXS 056+056 γ-ray lightcurve from Fermi-LAT >300 MeV
+ weekly flux LLH fits — Bayesian Blocks (used for analysis)
Thanks to: S. Buson, A. Franckowiak, Y. Tanaka, K. Bechtol, E. Cavazzuti, M. Wood

Hypothesis & method

- E.g. p-γ in blazar jets → ν∝γ
- Our hypothesis: only Φ>threshold ("flare") adds ν

→ time p.d.f. : truncate light curve at flux threshold, normalize



← ν from flare (high threshold)

← ν∝γ (threshold=0)

→ extend standard *(forward-folding, unbinned)* point source LLH

$$TS = 2\log L(\text{best fit})/L(\mathrm{H}_0)$$

$$= 2\log\Big[\sum_{i\in\text{events}} 1 + \Big[\frac{n_S}{N_{obs}}\frac{\mathrm{S}}{\mathrm{B}}(\mathrm{RA}_i,\delta_i)\times\frac{\mathrm{S}}{\mathrm{B}}(\mathrm{E}_i;\gamma)\times\frac{\mathrm{S}}{\mathrm{B}}(\mathrm{t}_i;\text{thres}) - 1\Big]\Big]$$

→ maximize over **n_S, γ, threshold**

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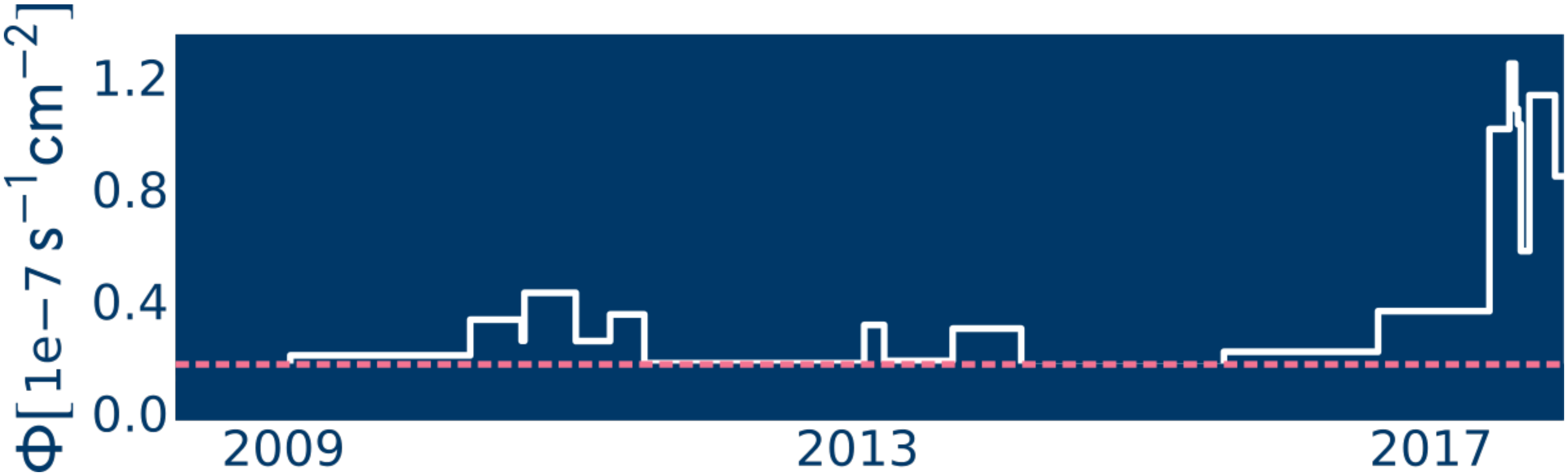

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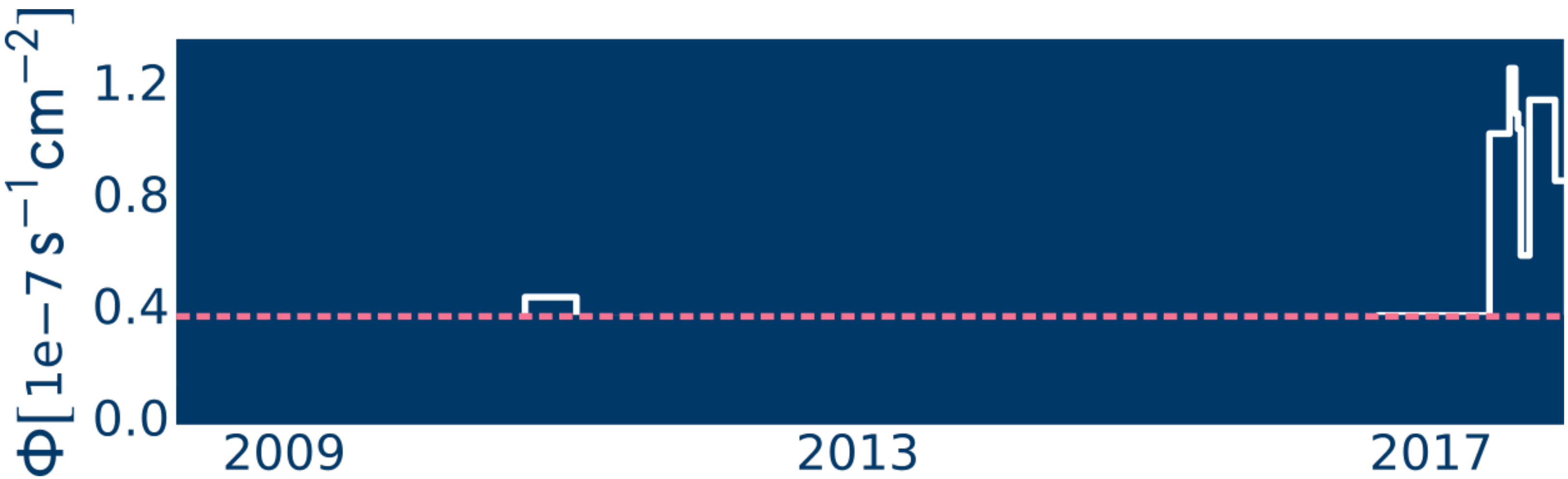

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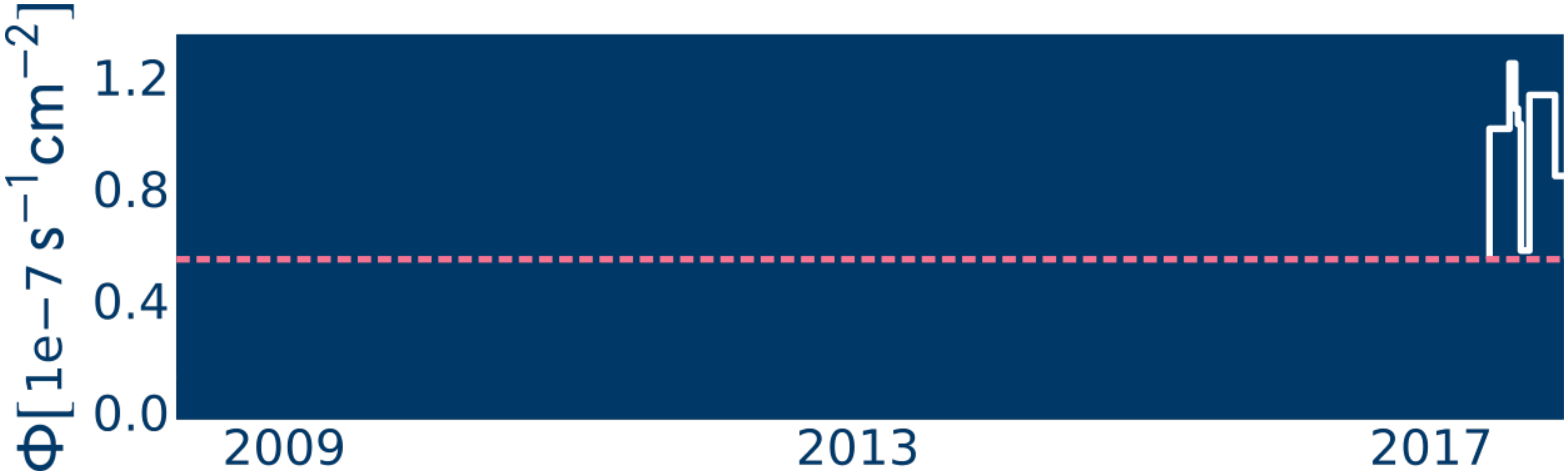

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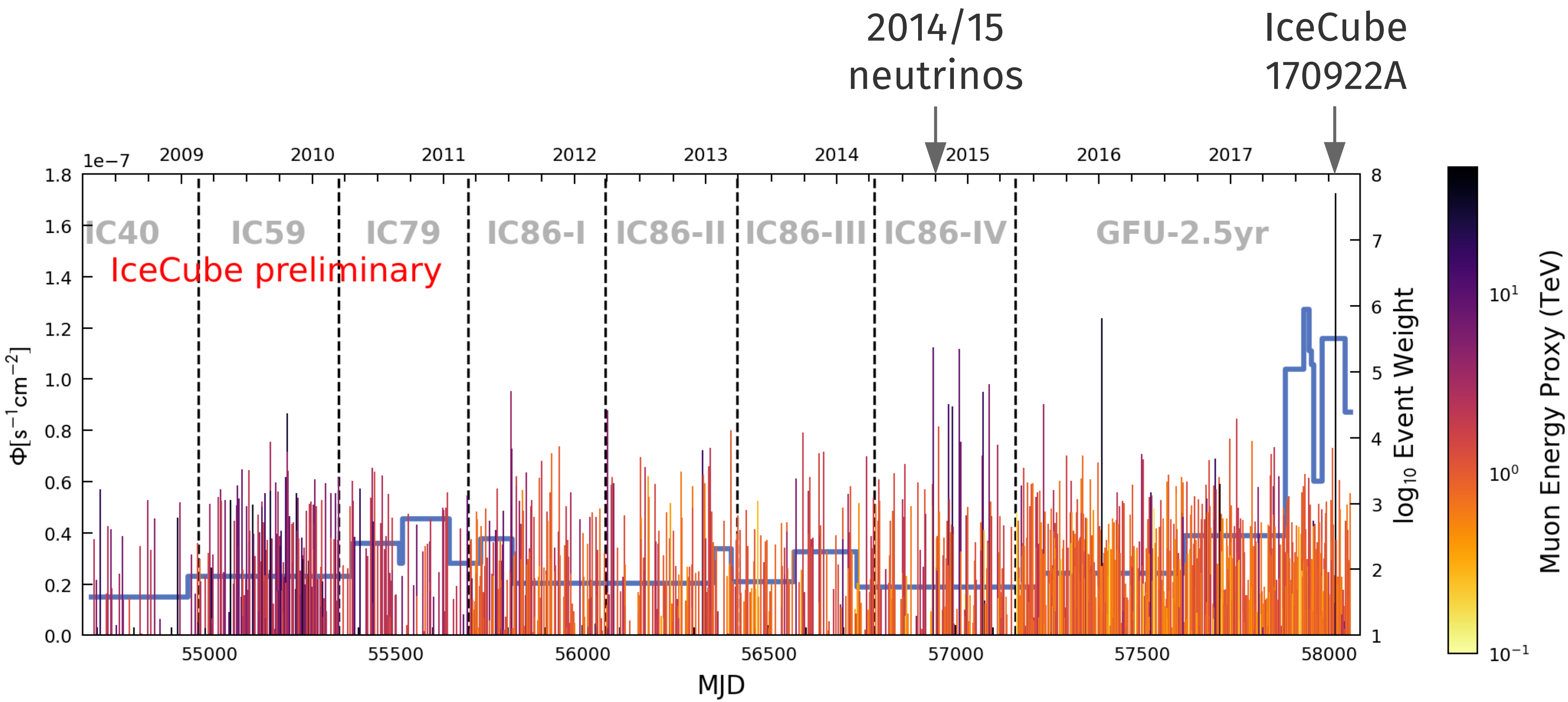
Neutrino events near TXS 0506+056

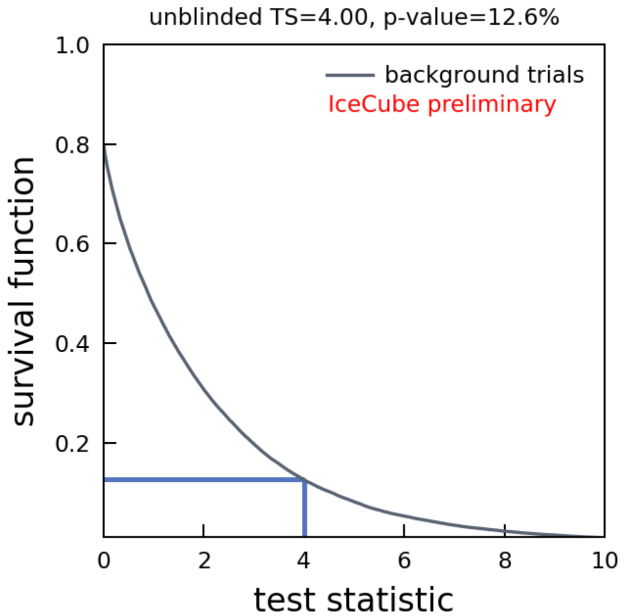


- Events where signal weight (spatial, energy) > 1
  and energy proxy E_{μ} > 100 GeV
- Transitions between datasets change **rate**, angular resolution, mean energy

Results & significance

maximize TS on unblinded data & compare to background TS distribution

- without IceCube-170922A



p = 12.6% (1.1 σ)

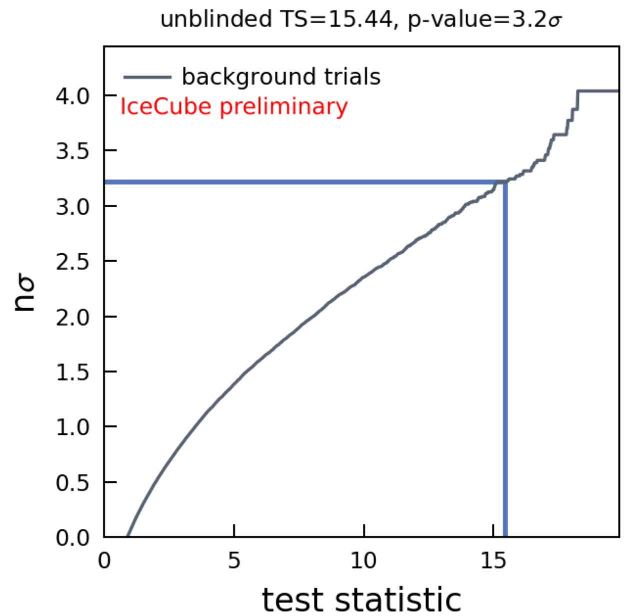
$\hat{n}_s$ = 7.02

$\hat{\gamma}$ = 4.00 (parameter bound)

$\hat{t}$hres. = 1.14 10^{-7}/cm²/s

→ **no evidence** for additional ν produced in correlation with γ-rays observed by Fermi-LAT

- with IceCube-170922A



p = 3.2 σ

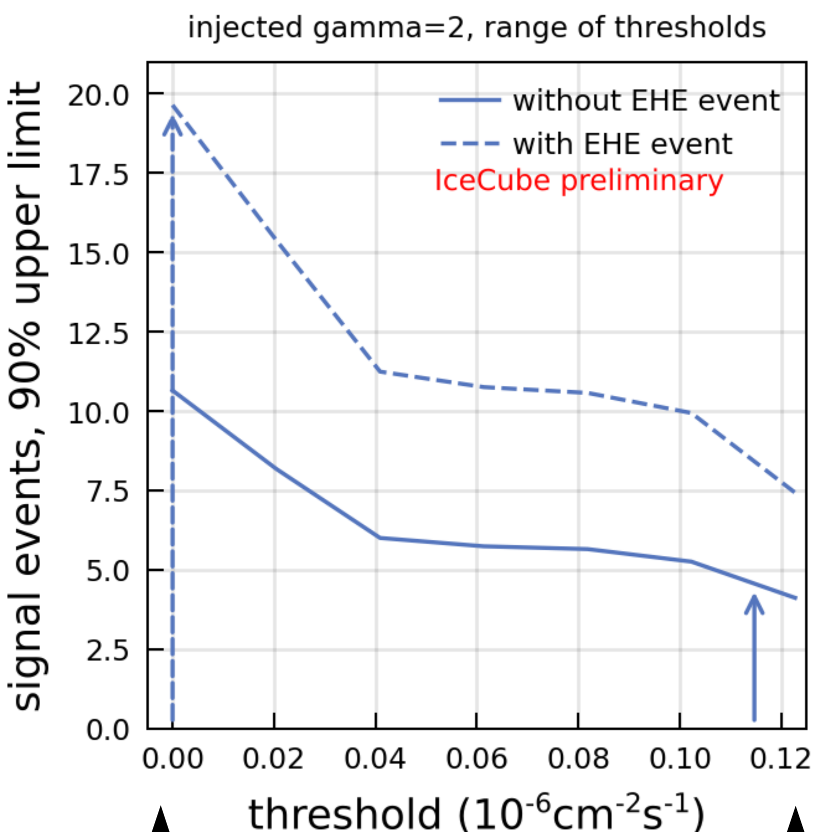
$\hat{n}_s$ = 10.15

$\hat{\gamma}$ = 2.06

$\hat{t}$hres. = 0/cm²/s

→ **evidence** from this analysis is mostly due to the EHE event (although this was the trigger)

Upper limits



low threshold
high background

high threshold
low background

Determine 90% upper limits:

- same hypothesis as in LLH
- γ=2, threshold∈ [0,max]

→ limits in terms of events

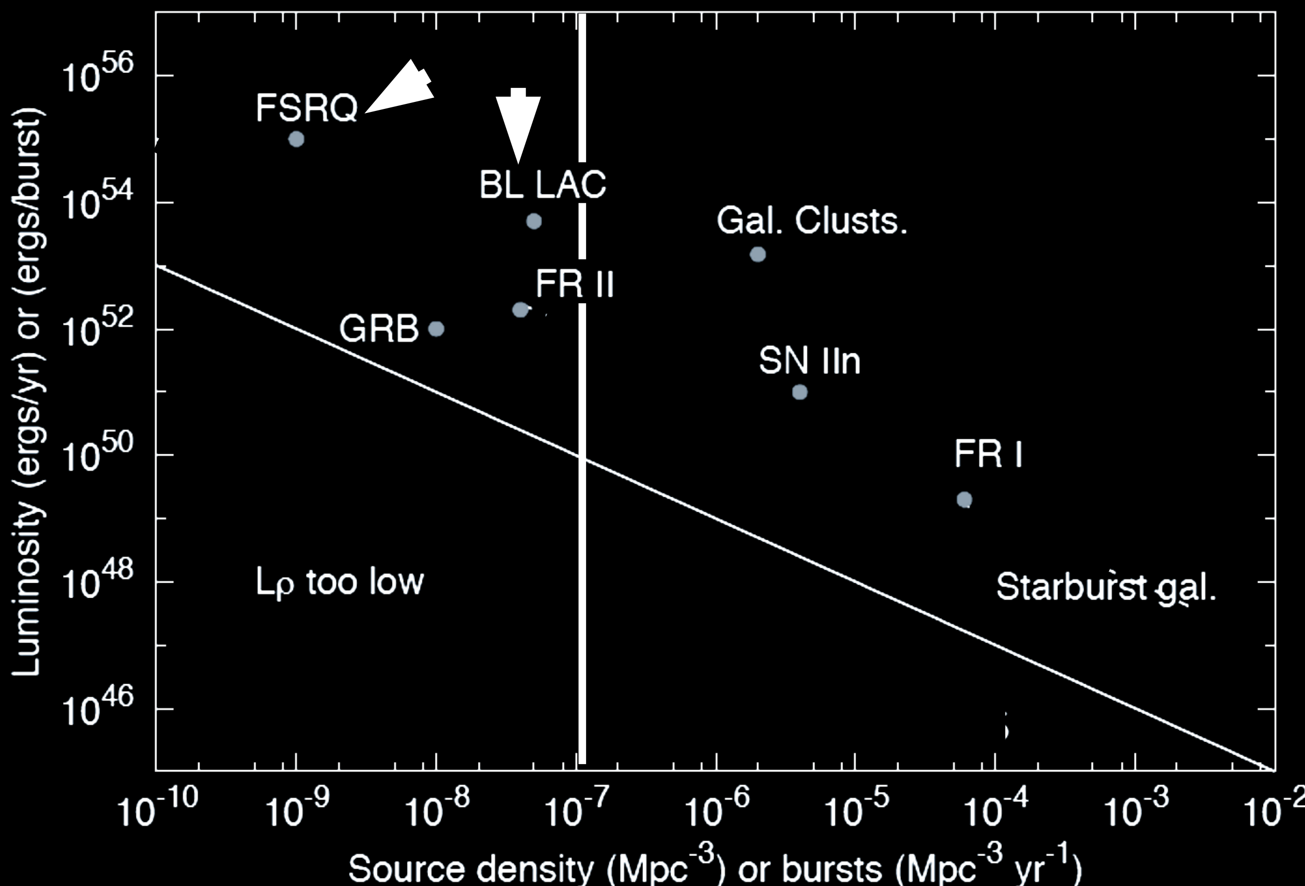
We find a constraint to <11 events (apart from IceCube-170922A) directly correlated in time to γ-rays detected by Fermi-LAT.

This doesn't mean that there can't be neutrinos matching other time templates! (As we know now there are).

Blazar Flare Stacking

Flare stacking motivation

- Stacking limits (signal=$\Sigma_{sources}$) constrain the contribution of (resolved, un-obscured) blazars to the diffuse ν flux



plot after M. Kowalski, arXiv:1411.4385

- But these limits don't exploit the variability of blazars
- → stronger limits or discovery could come from a **stacking analysis** that is also **time-dependent**

Flare stacking approach

- Problem: can not use the same threshold for each lightcurve

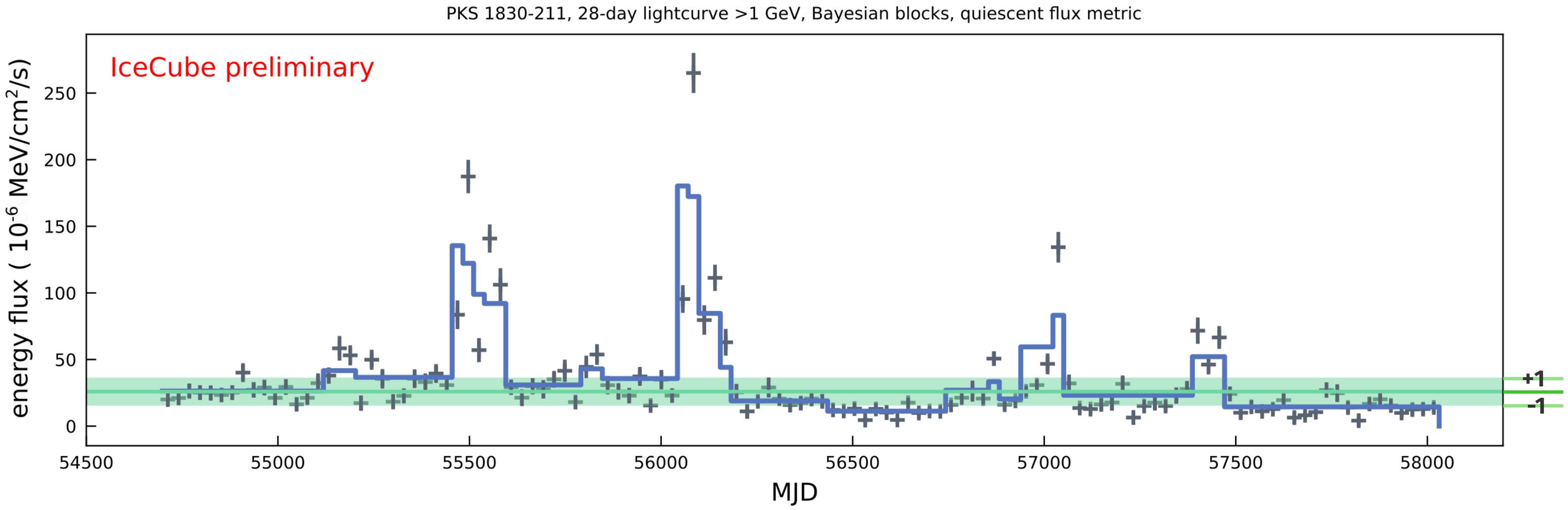
→ for N=O(100) sources, need to minimize over $\mathbf{n_s}$, **γ**, {$\mathbf{thres_k}$ }k=1...N

- First idea: estimate “separating flux level” for each source

→ easiest but restricts the hypothesis space a lot

- Instead: define common threshold parameter **τ**

→thres(k) = max{0, quiescent flux (k) + **τ** x quiescent rms (k) }



Flare stacking likelihood anatomy

events **signal** **background**

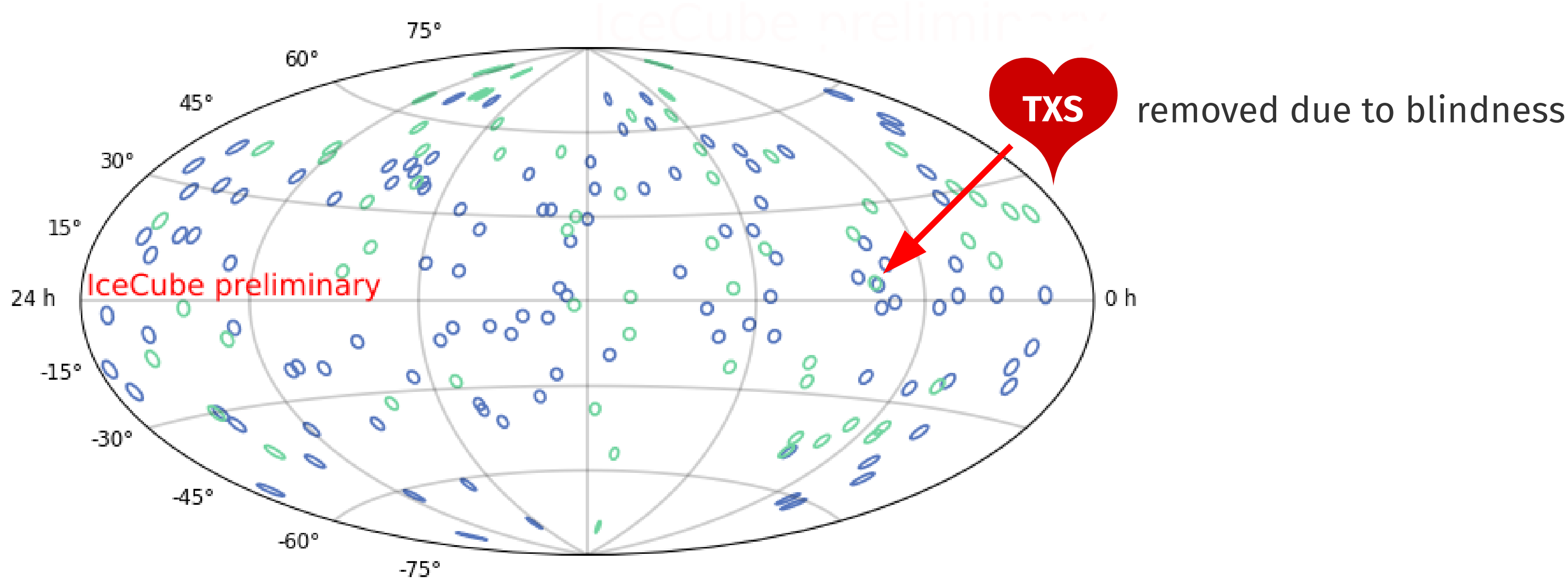
$$L(n_S, \gamma, \tau) = \prod_{i \in \text{events}} \left[\frac{n_S}{N_{\text{obs}}} \sum_{k \in \text{sources}} w_k(\gamma, \tau) S_i^k(x_i, E_i, t_i | \gamma, \tau) + \left(1 - \frac{n_S}{N_{\text{obs}}}\right) B_i(x_i, E_i | \delta_i) \right]$$

fraction **sources** **weight** **signal PDF** **fraction** **BG PDF**

Sources

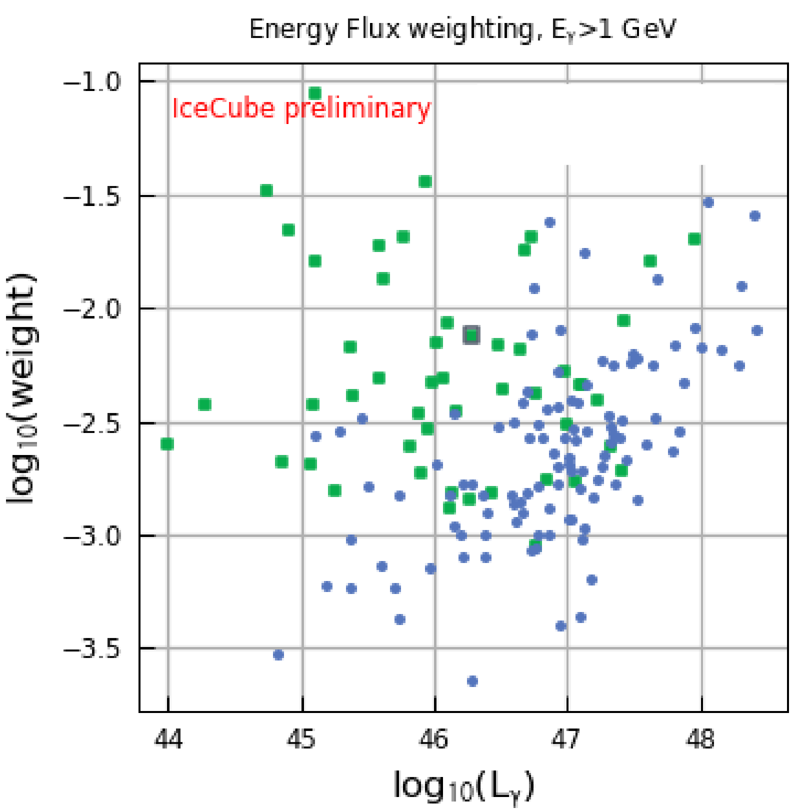
- Starting point: 2254 extragalactic sources from 3FGL, 3FHL
- Variability & quality cut using monthly LCs
- Associated to BL Lac or FSRQ

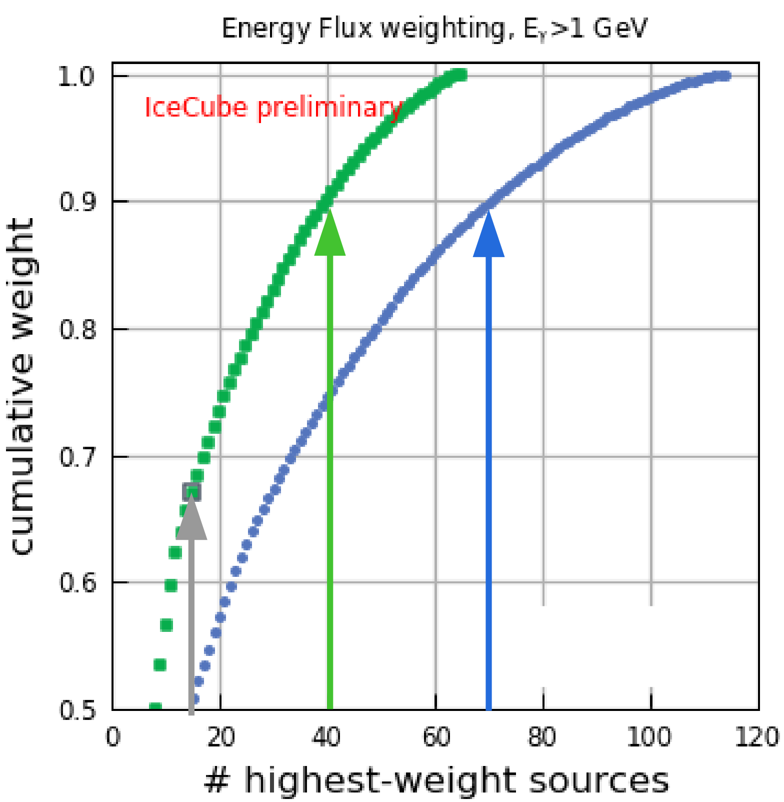
→ 179 blazars: ○ BL Lac (65), ○ FSRQ (114)



Weighting schemes 1) Energy flux

- $L_\nu \propto L_\gamma \rightarrow w \propto L_\gamma / 4\pi d_L^2$ = energy flux
- for models dominated by $\pi^0 \rightarrow \gamma\gamma$
- also used in previous analyses
  - reflected in LLH construction



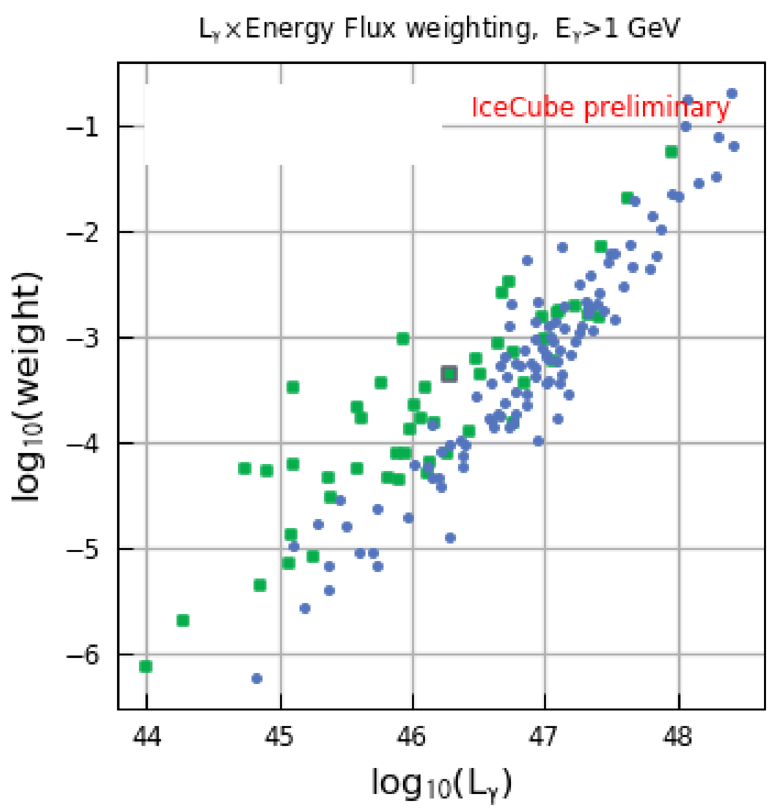


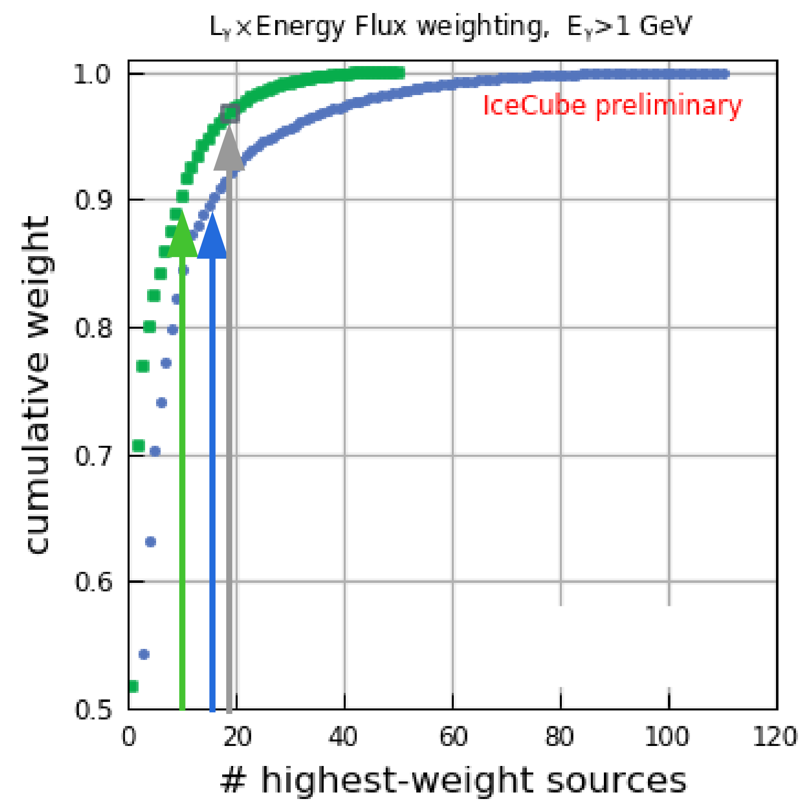
Weighting schemes 2) Luminosity²

- $L_\nu \propto L_\gamma^2 \rightarrow \quad w \propto L_\gamma^2/4\pi d_L^2 = L_\gamma$ x energy flux

→ remove 19 sources without redshift from list)
- from p-γ models where $\varepsilon_\nu \propto L_\gamma$ & constant baryonic loading

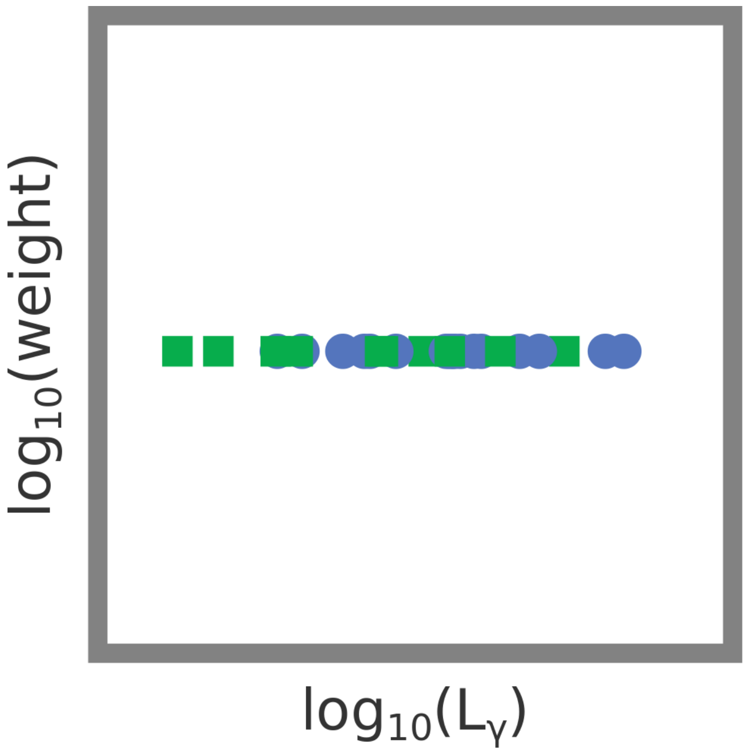
e.g. one case in Palladino et al. [1806.04769]

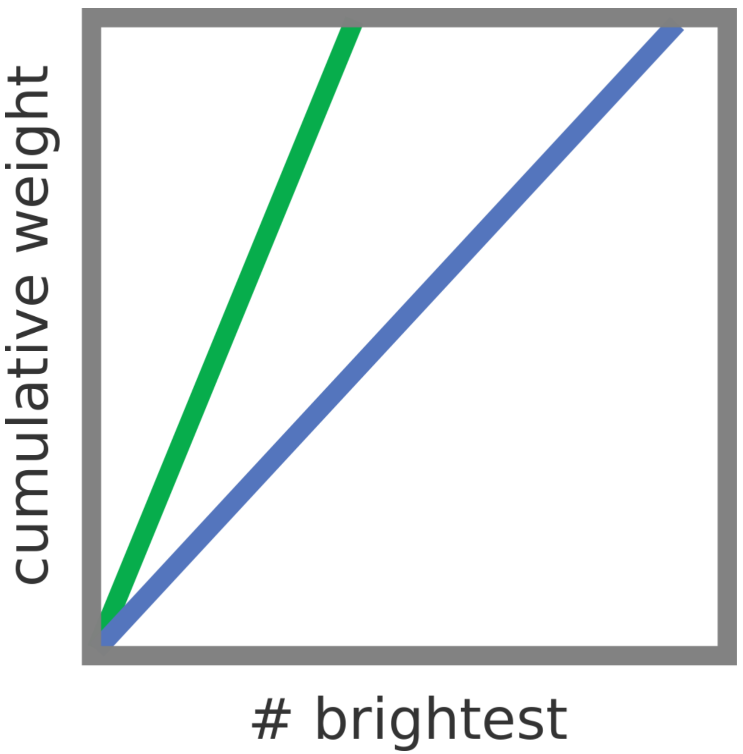




Weighting schemes 3) Equal

- $w \propto 1$
- to catch hypotheses not anticipated





Unblinding plan

- Combined p-value from {3 weighting schemes} x {FSRQ, BL Lac}
- Post-unblinding check: results affected by inserting TXS?
- Compute limits & discovery potentials for all combinations with $\gamma=2$ (classic benchmark), threshold=0 (conservative)
- Current 90% sensitivities 90% (number of signal events):

weighting	**BL Lac (all)**	**FSRQ (brighest 64)**
1. EF	26.1	21.6
2. LxEF	17.6	24.7
3. equal	20.5	17.5

Conclusions & Outlook

- We look for neutrinos correlated to γ-ray lightcurves (thanks to collaboration Fermi-LAT ↔ IceCube)

→ No such signature from TXS 0506+056 beyond the initial alert (but consistent with other analyses on this blazar)

- Method extended to stack 179 blazars in a novel type of multimessenger analysis

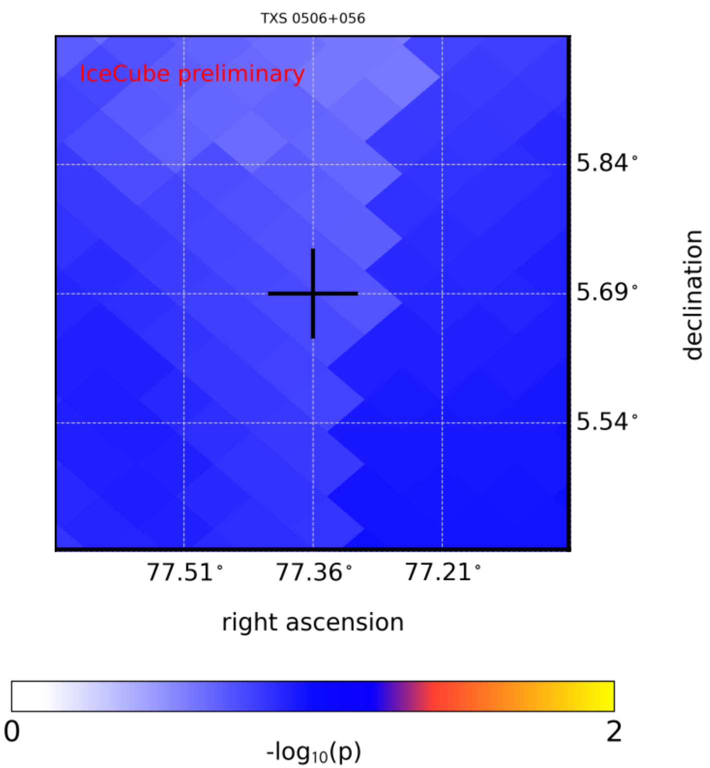
→ unblinding soon

Thanks!

Backup

Additional checks

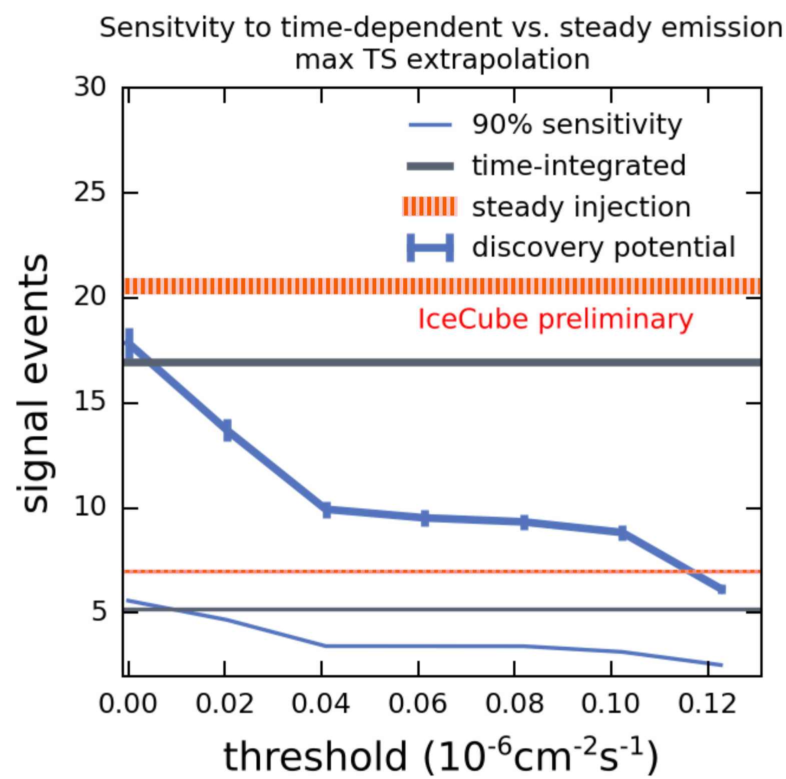
local scan of the significance



10% - 28% within **±0.3°**

→ Did not miss any excess due to pointing systematics

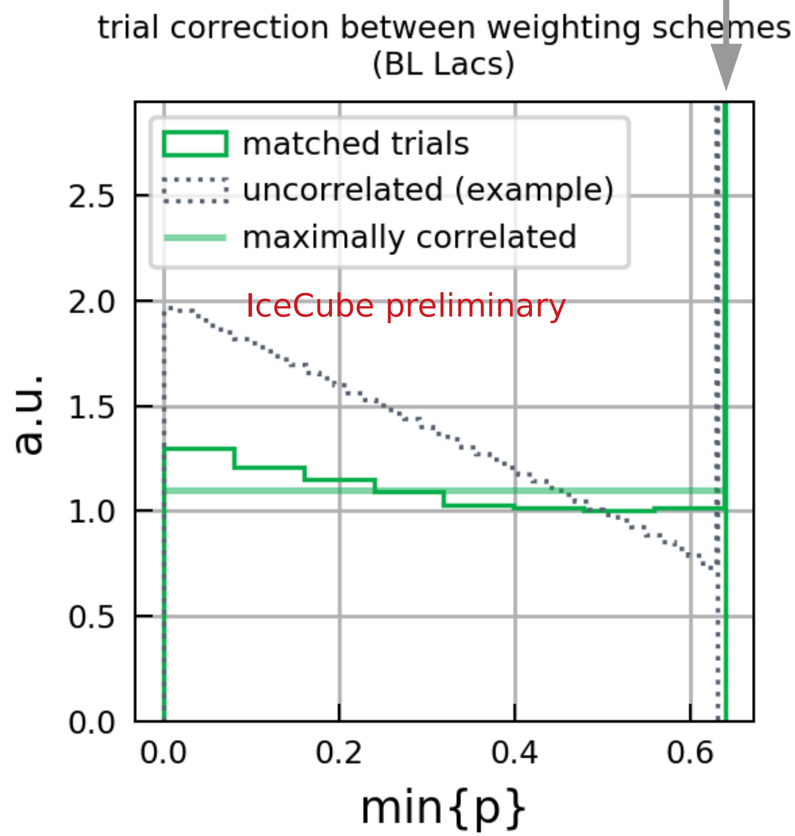
sensitivity to steady emission



→ need **15-25%** more events if flux is steady instead

Trial correction

underfluctuations



- 2 source lists → factor x2
- 3 weighting schemes → best p-value
  $p_{pre} = \min\{p_i\}_{i \in \{1,2,3\}}$
  → compare identical scrambles
  → get p_{post}
- Distributions in this plot, compare:
  - totally uncorrelated p_i
    (grey dotted line)
  - maximally correlated p_i
    (faint horizontal lines)

→ weighting schemes more correlated than expected, but not maximally ✔
(so the correction scheme **is** useful)

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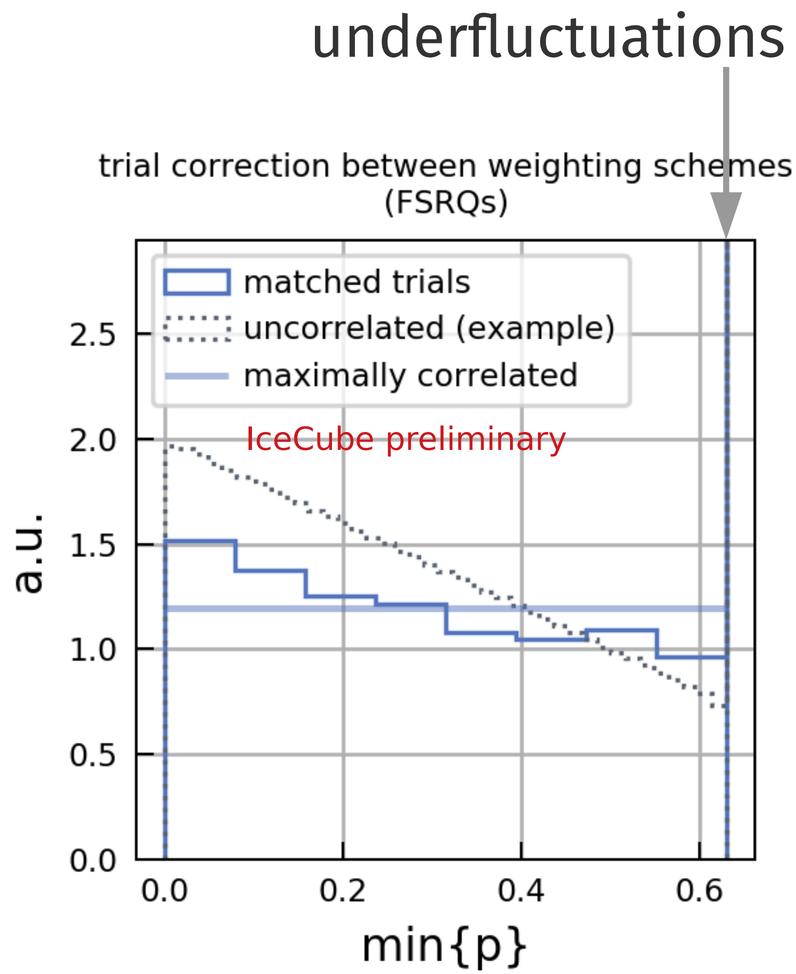

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