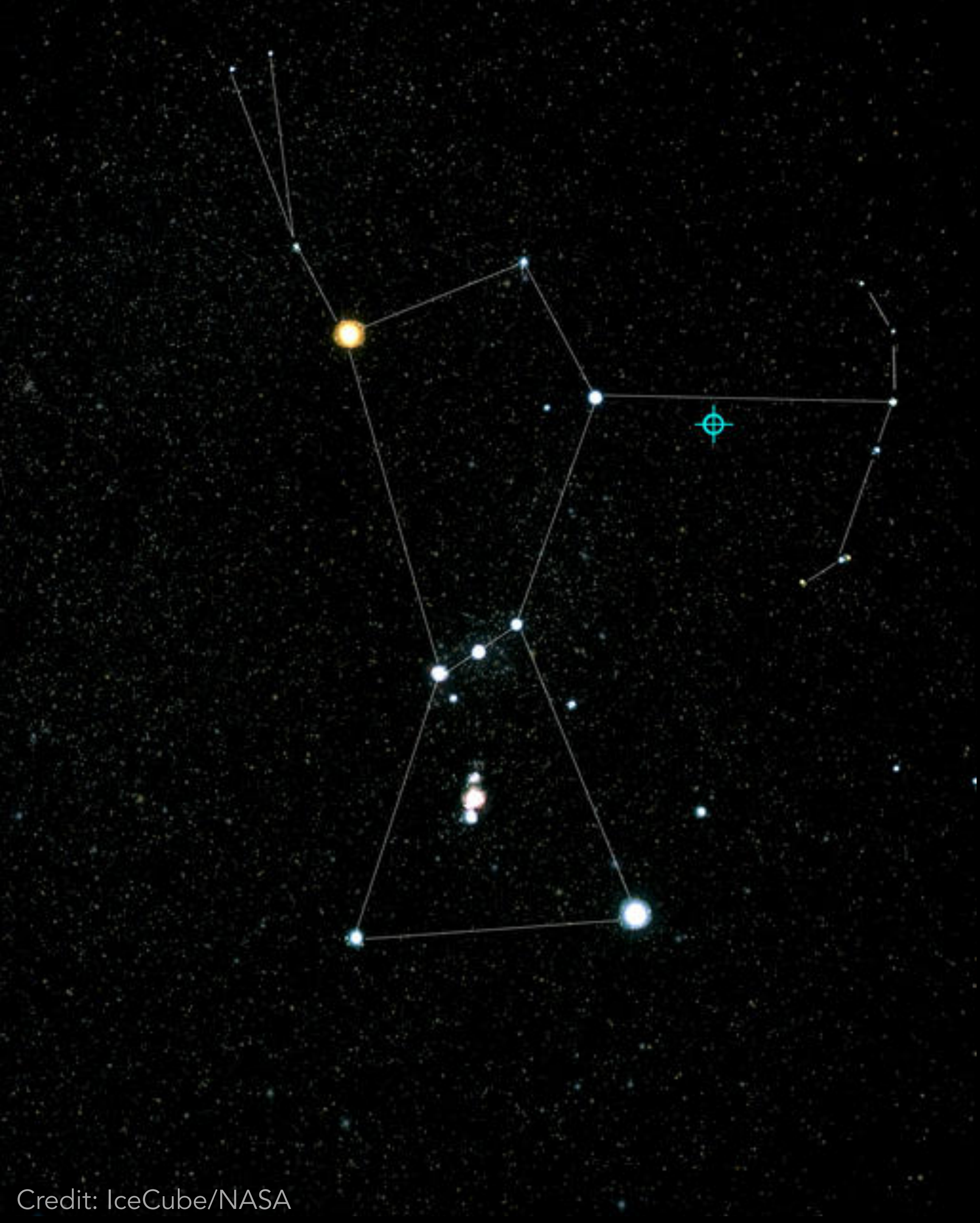

Neutrinos From TXS 0506+056

Chad Finley
Oskar Klein Centre
Stockholm University

Berlin, 2018 August 26

Credit: IceCube/NASA

This talk will give my perspective on how well we can characterize the neutrino flux from the direction of TXS 0506+056

Main message:

Combination of independent pieces of evidence =>

Likely identification of a blazar as a source of high-energy neutrinos

But, precise characterization of the neutrino emission is uncertain

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Main message:

Combination of independent pieces of evidence =>

Likely identification of a blazar as a source of high-energy neutrinos

But, precise characterization of the neutrino emission is uncertain

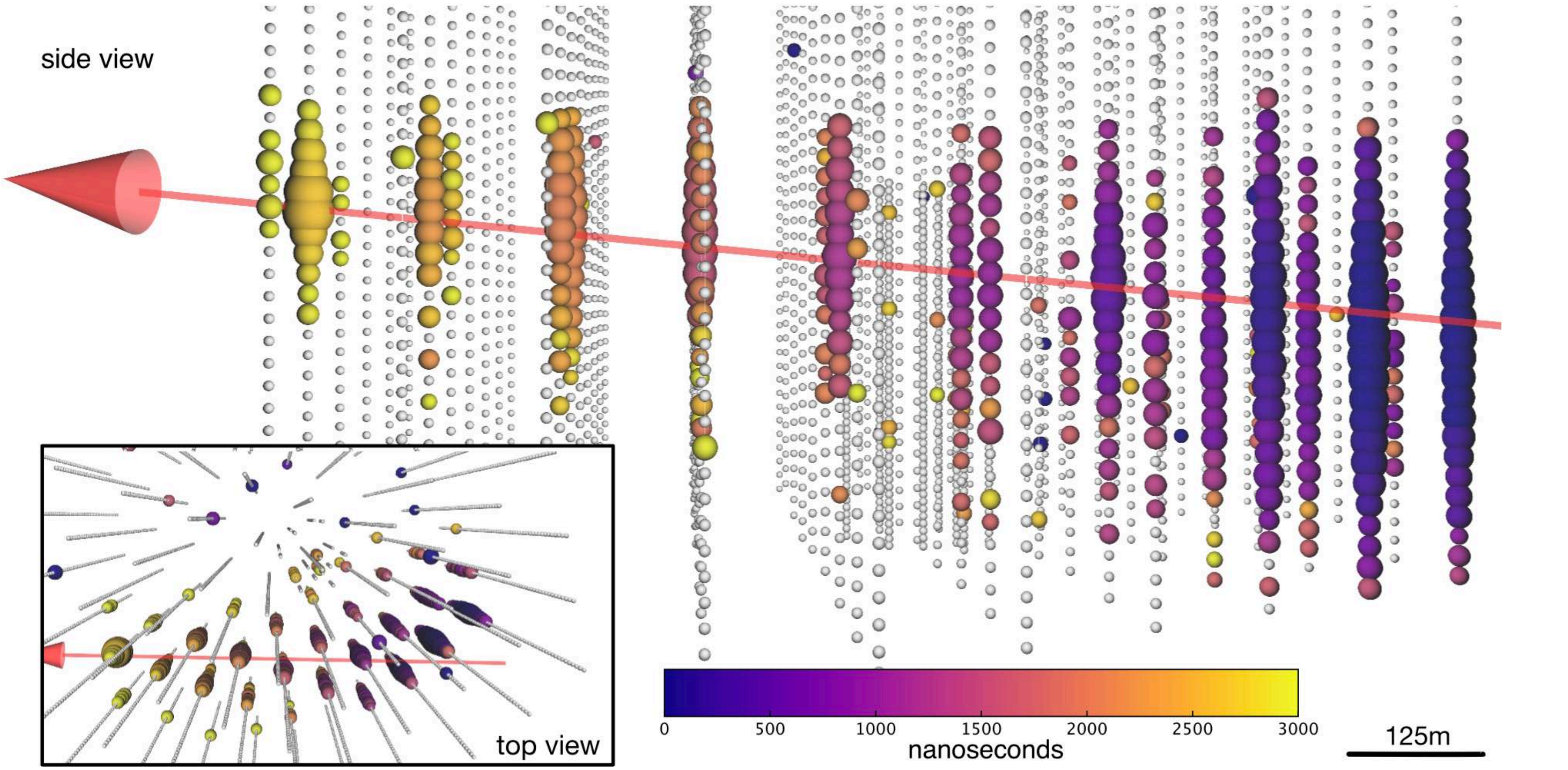
Poisson Statistics Rules!

=> Even for high significance signal, there are large uncertainties on Flux, Energy, Time Window

=> Additional uncertainty for a population of weak sources: First source observed may be the one that fluctuates upward

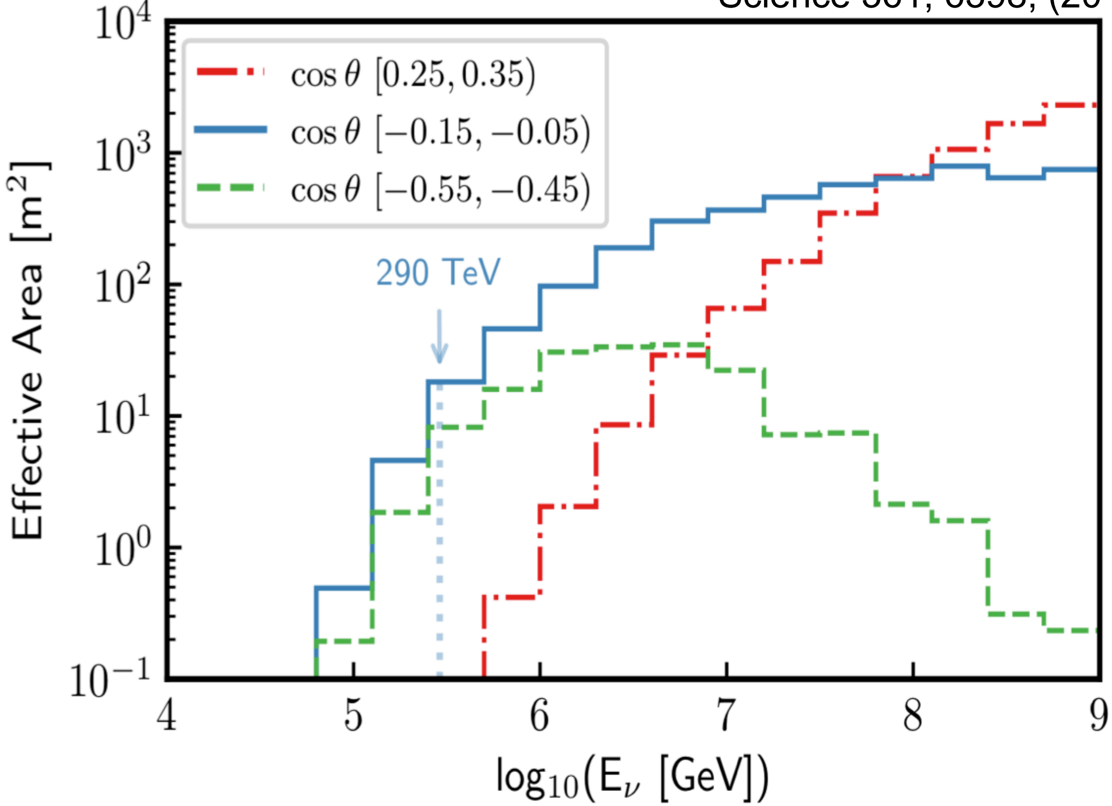
The EHE-Alert that started it all:

Science 361, 6398, (2018) eaat1378



Neutrino Effective Areas:

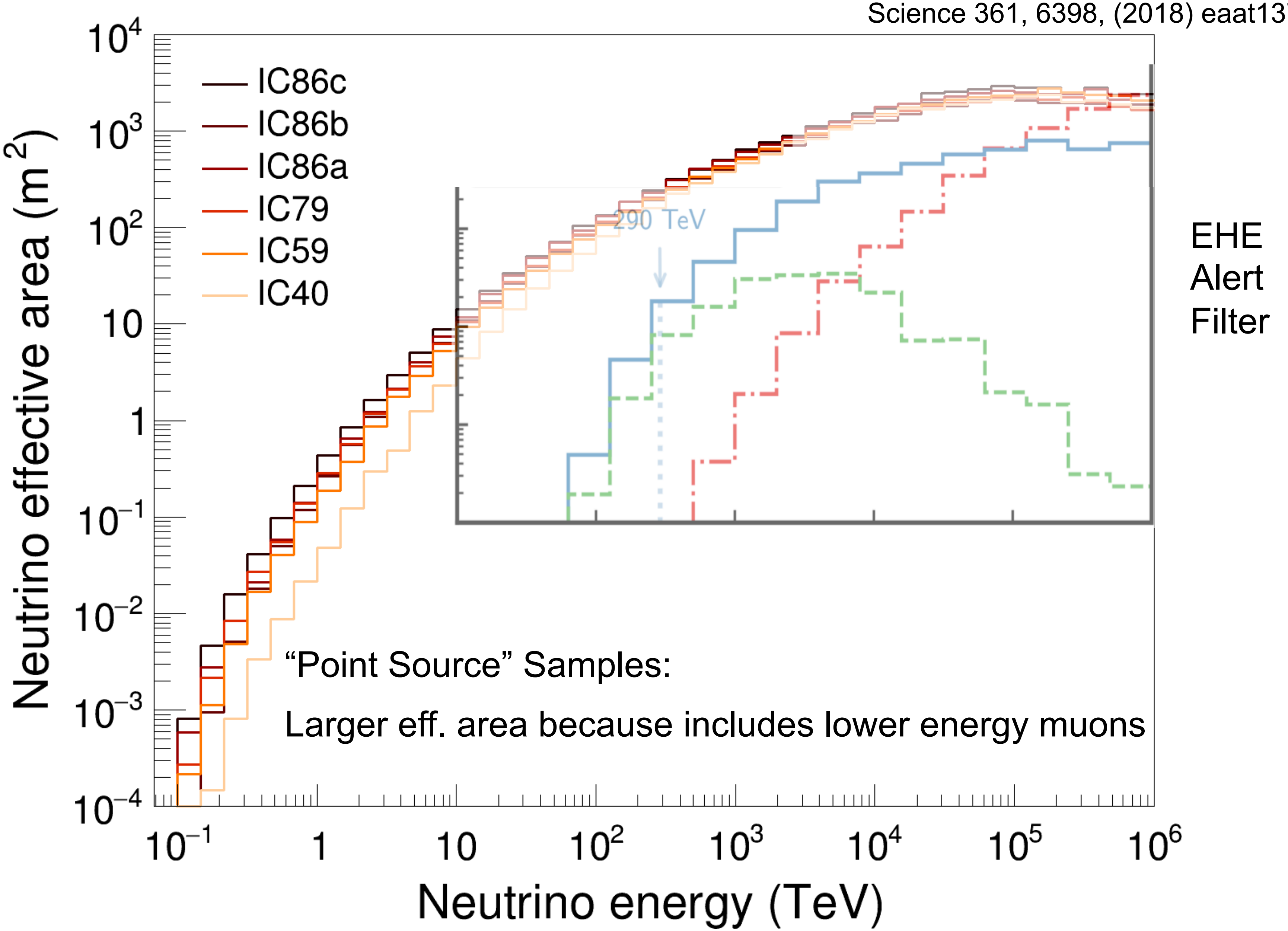
Science 361, 6398, (2018) eaat1378



EHE
Alert
Filter

Neutrino Effective Areas:

Science 361, 6398, (2018) 147
Science 361, 6398, (2018) eaat1378



- How do we estimate flux of neutrino emission related to EHE event?
  - conventional low E events were not seen in full point source sample during +/- 1 week around alert
  - lack of low E events is informative: flux is lower than from EHE eff. area only
  - Note: does not call into question significance. Just suggests it is the fortunate case where the one detected event was also high E. This is by construction of the alert system. Most cases of similar flux would typically lead to one event but below EHE threshold.

What time window to use?

“Untriggered” Time-Dependent Likelihood

Braun et al. Astropart.
33, 175 (2010)

Generic Time Window can be Gaussian (here) or Box (“Top Hat”)

$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_s|^2/2\sigma_i^2} \cdot P(E_i|\gamma) \cdot \boxed{\frac{1}{\sqrt{2\pi}\sigma_T} e^{-(t_i - T_0)^2/2\sigma_T^2}}$$

$$\mathcal{L}(n_s, \gamma, \underline{\sigma_T, T_0}) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \underline{\sigma_T, T_0}) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

For “untriggered” search, consider **all** possible time windows and durations:

$$TS = 2 \log \left(\boxed{\frac{\hat{\sigma}_T}{T_{\mathrm{tot}}}} \times \frac{\mathcal{L}(\hat{n}_s, \hat{\gamma}, \hat{\sigma}_T, \hat{T}_0)}{\mathcal{L}(n_s = 0)} \right)$$

Penalty for choosing a short-time window duration σ_T
(corresponds to the fact that there are many more short than long windows)

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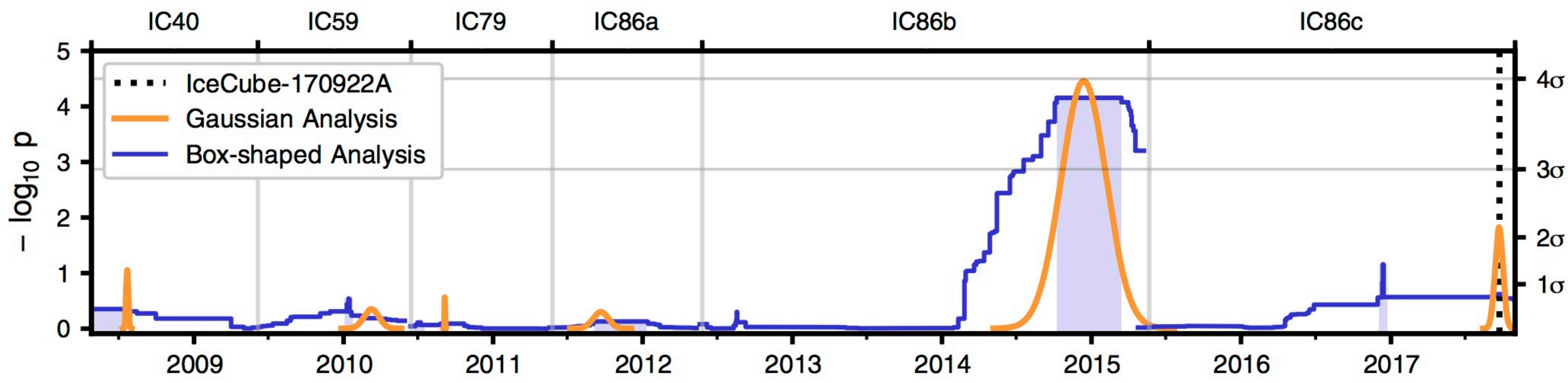
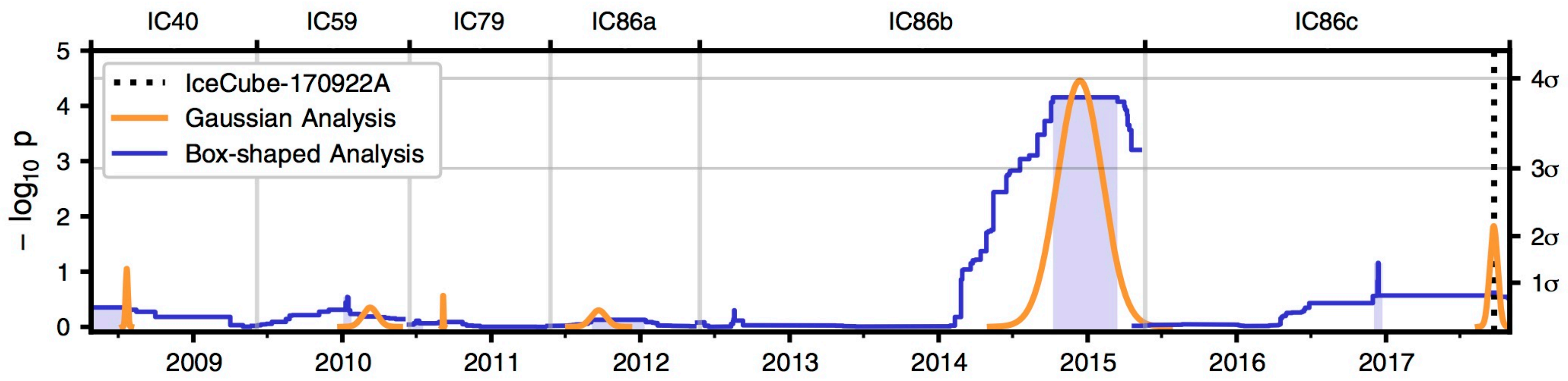


EHE flare not as significant in this analysis

Because: **untriggered analysis** is a search for **self-clustering** of events **in time** => need **two** or more events

Gaussian Time Window accepts one other event weakly nearby… but any duration is acceptable. Box Time Window includes EHE in a much longer window.

⇒ Time-window for neutrino emission related to EHE-event is not well constrained. Can use anything, e.g. gamma-enhanced period



Significance of “Big” flare:

Scramble 2012-2015 data

Repeat analysis (search for any time window) at TXS location

Such a high TS value as found by Gaussian (for **any** time window) occurs at a rate of 3 times per 100 000 scrambled data sets.

Two final trial corrections were applied after this:

6 different data periods, each analyzed separately

two analyses (Gaussian and box) (this is overkill, as they are correlated)

Final significance cited: 2 in 10 000, or 3.5 sigma

UNIVERSITÉ DE GENÈVE ICECUBE

Time Dependent Searches – All sky scan

Lets start with generic search:

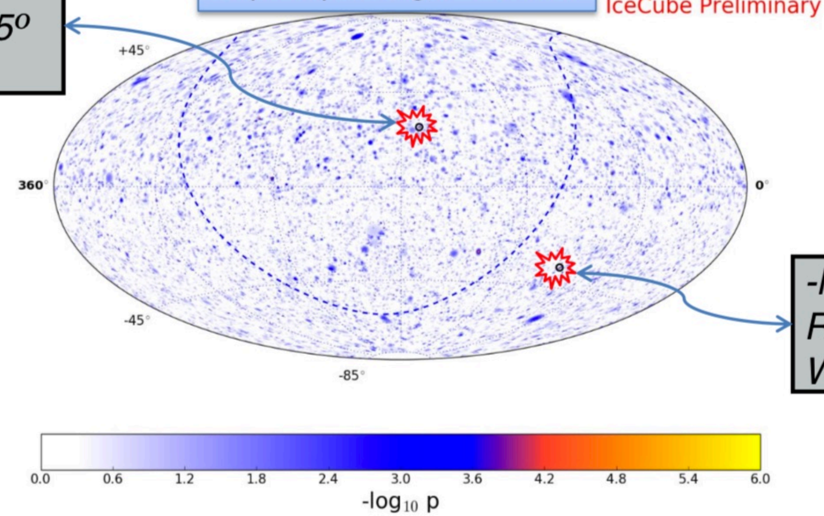
Gaussian in time

Signal PDF: $S_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma) \quad \frac{1}{\sqrt{(2\pi)}\sigma_T} exp\left(-\frac{(t_i - T_0)^2}{2\sigma_T^2}\right)$

T_{sig}

Sky map of significances

-log10(p) = 6 (pre-trial)
Ra: 170.35°, Dec: 27.95°
Width: 40 days



-log10(p) = 5.8 (pre-trial)
Ra: 89.45°, Dec: -35.95°
Width: 4 days

Only samples IC86-II, III, and IV + MESE

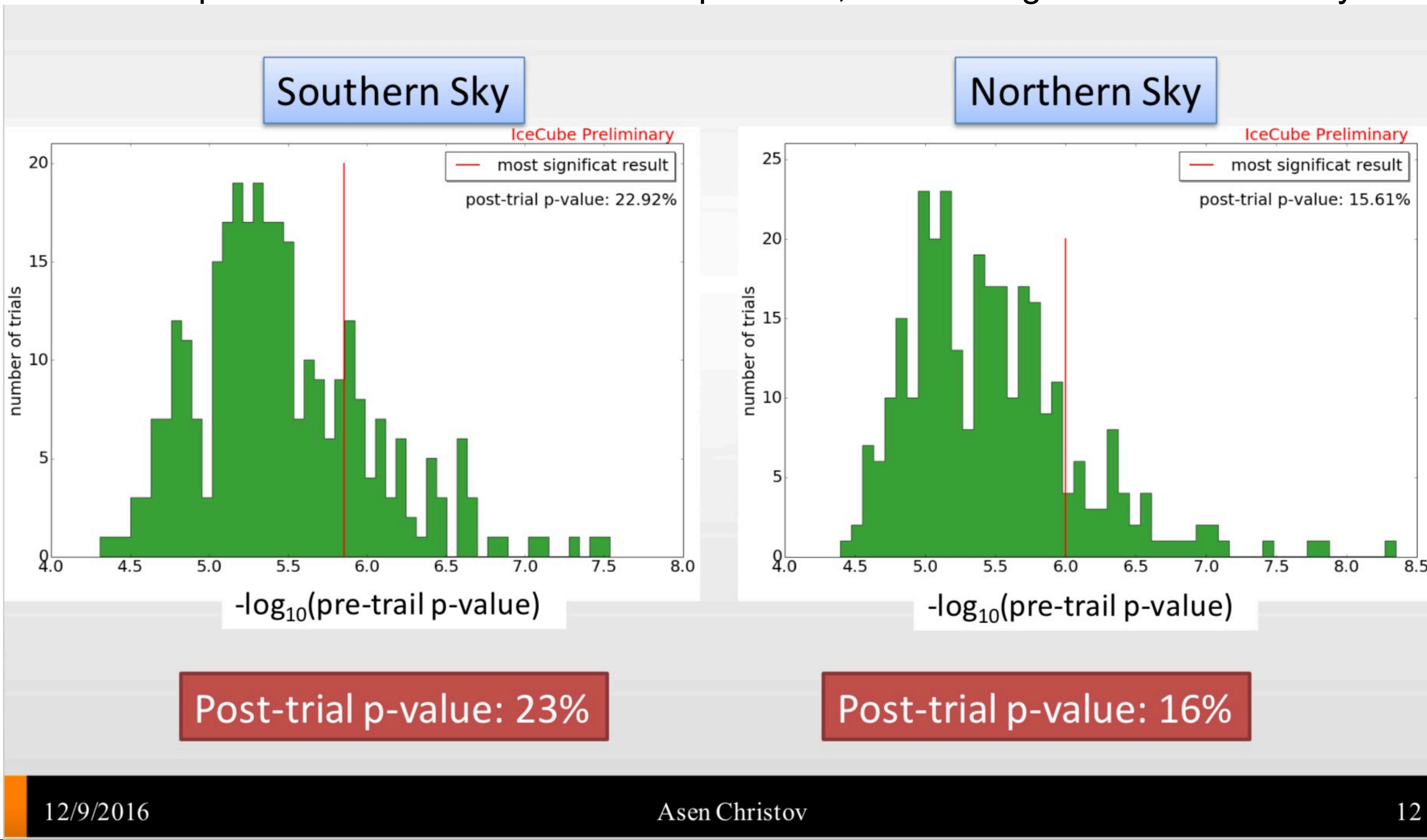
12/9/2016 Asen Christov 11

TeVPA 2016 – Presentation by Asen Christov:

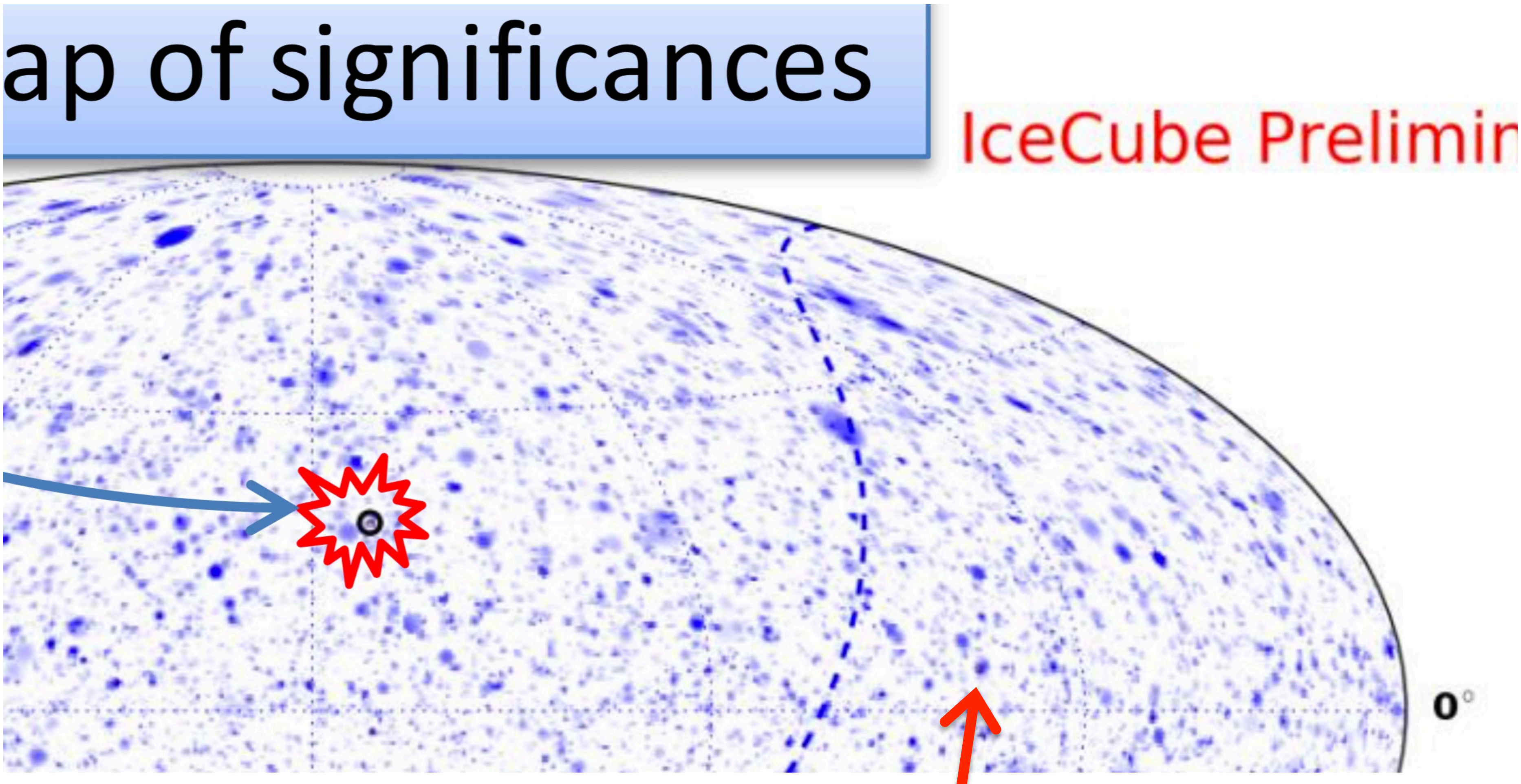
<u>Look-elsewhere effect:</u>

All-sky scan for untriggered time-dep flare has **large** trial factor, ~ 10^5

i.e. local p-value of 10^{-6} becomes ~10% post-trial, considering whole northern sky



Zoom in on Asen Christov's presentation



2nd hottest spot in the northern sky

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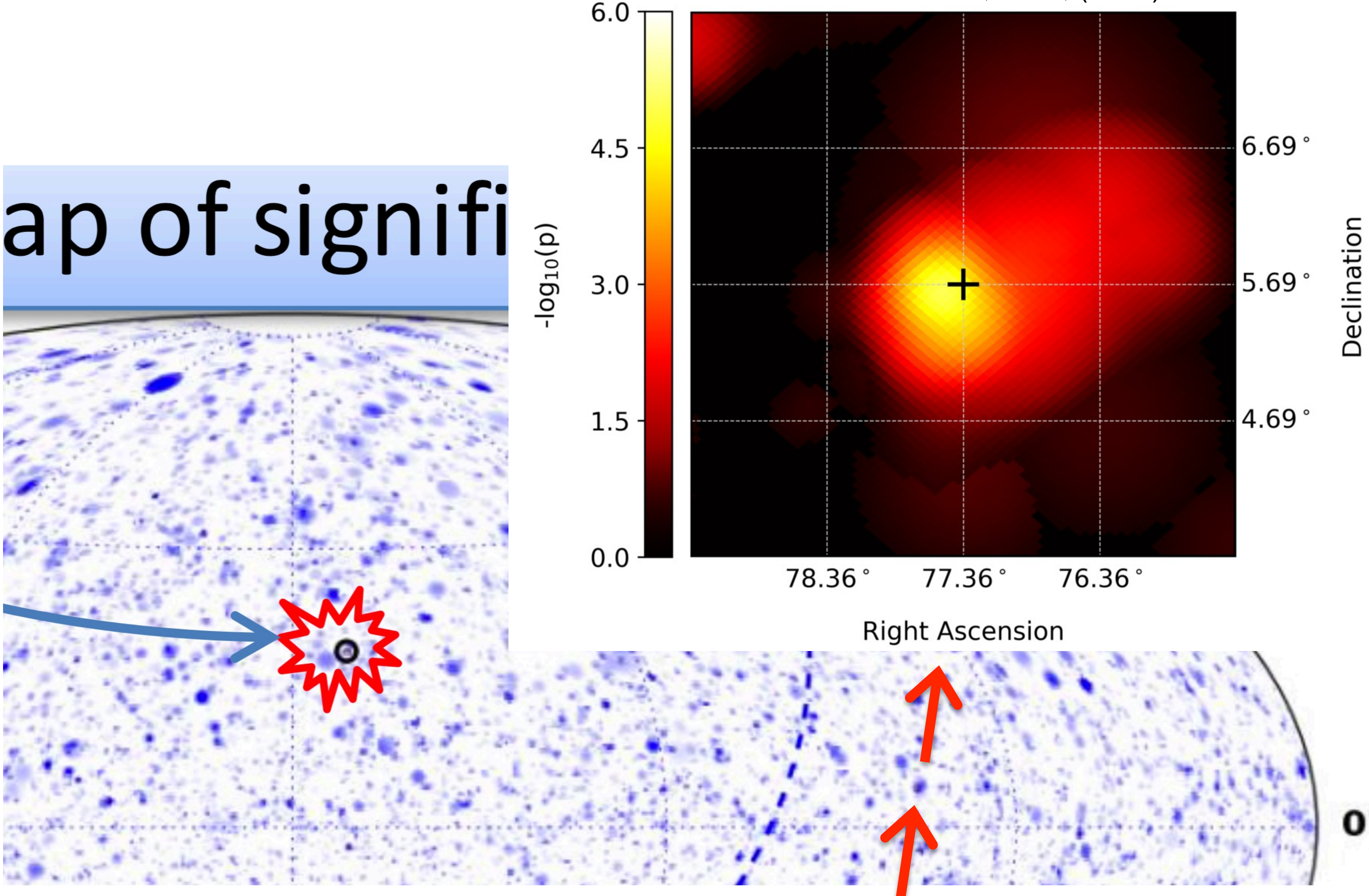
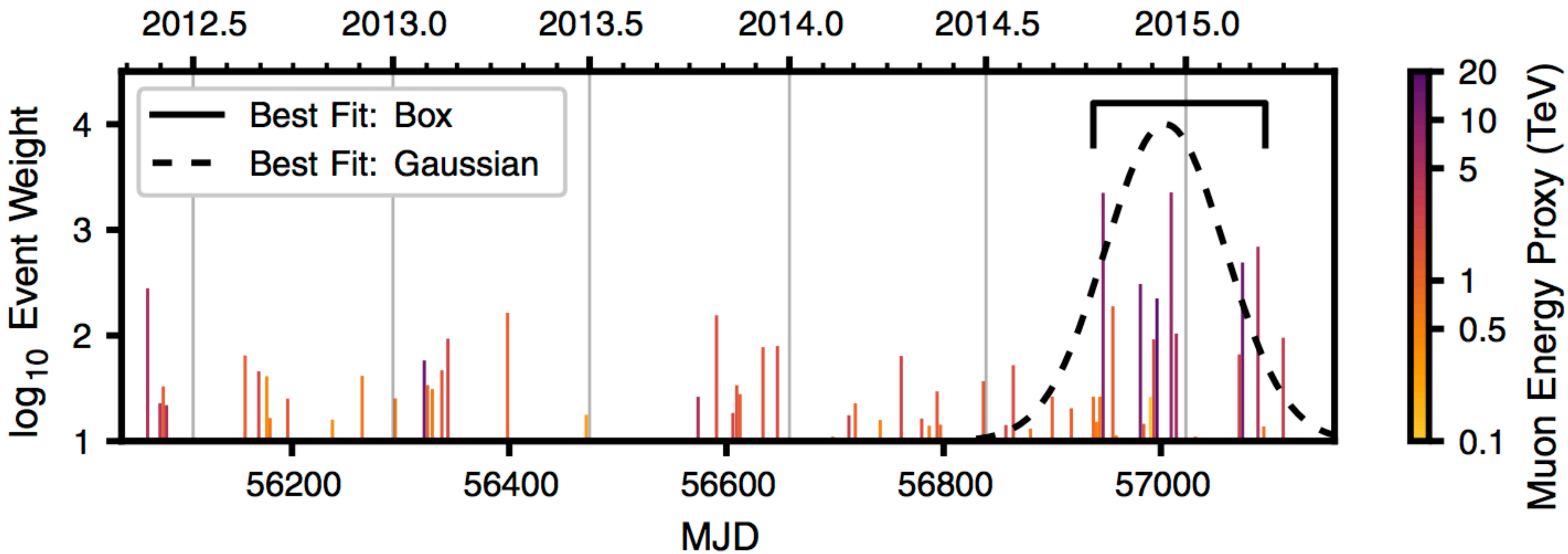


2nd hottest spot in the northern sky

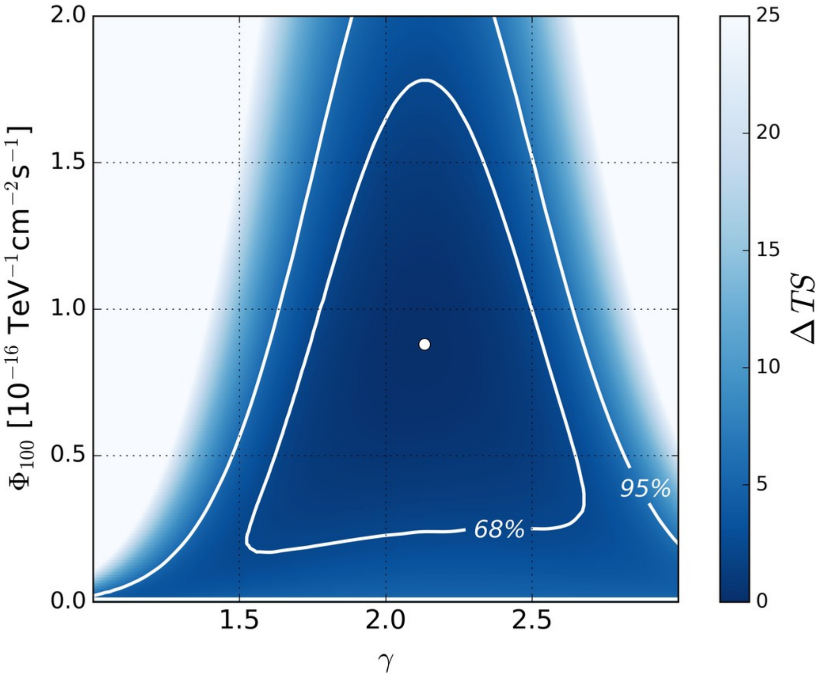


Note: Significance of the Time-Dep. analysis is w.r.t. a null hypothesis of **no signal,** not **constant signal**

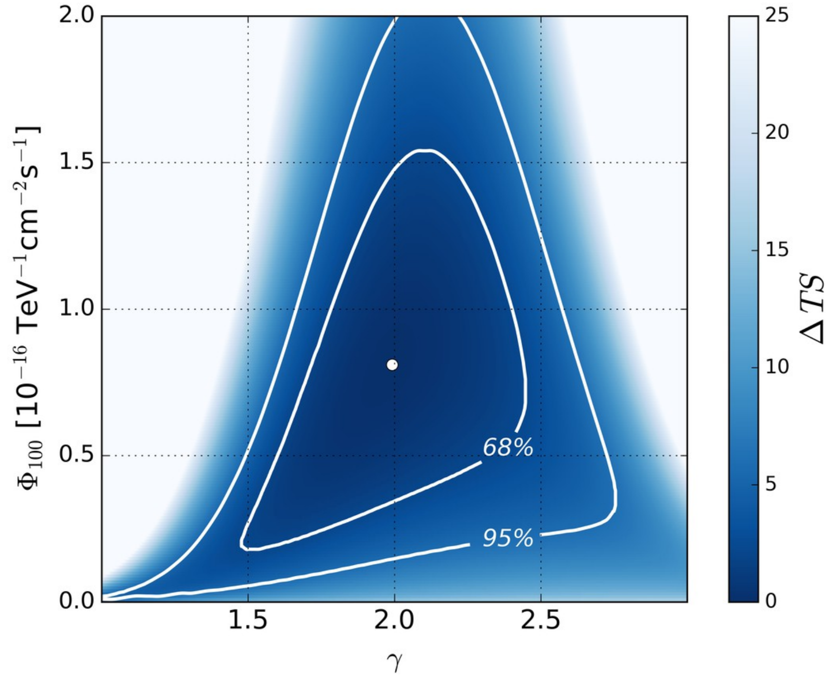
A strong, <u>constant</u> neutrino signal would also get picked up by the time-dep analysis

But, for constant signal, the time-integrated result is usually more significant

Time-Integrated Analysis



2008-2015 (7yr)

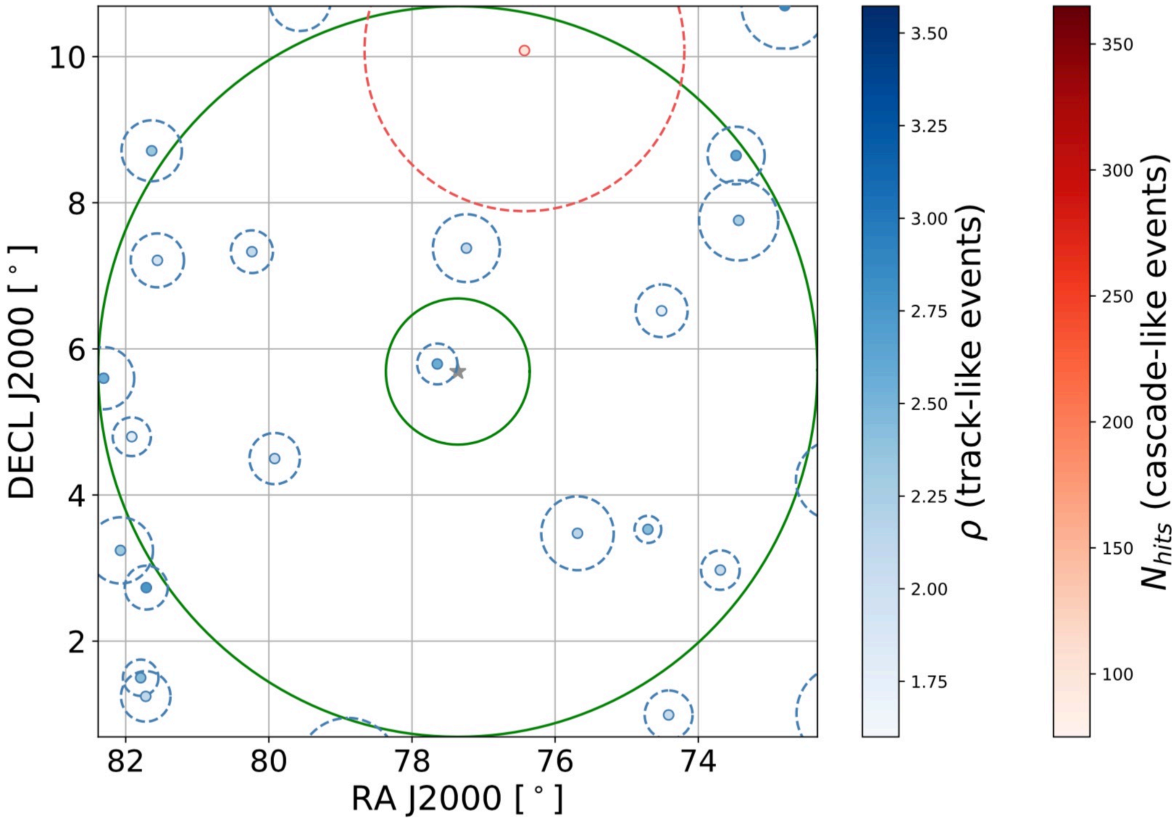


2008-2017 (9.5yr)

The time-averaged result for first 7-years of data is similar to the 2014-15 flare result (fluence, spectral index). Significance 2.1 σ

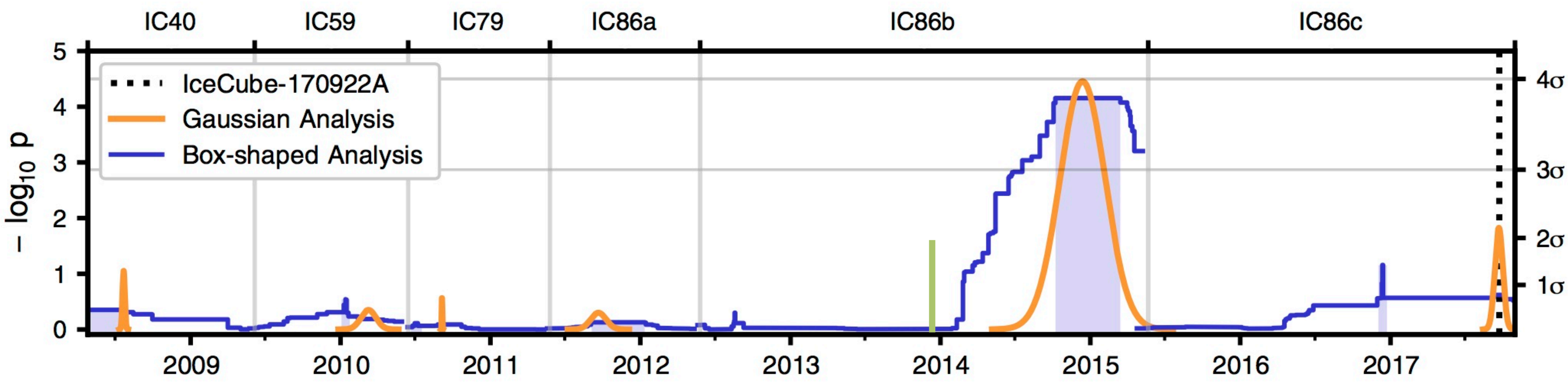
With the extension to 9.5 years, the EHE event is included. This drives the significance to 4.1 σ Interestingly, fit parameters (flux, index) stay nearly the same when the EHE event is included.

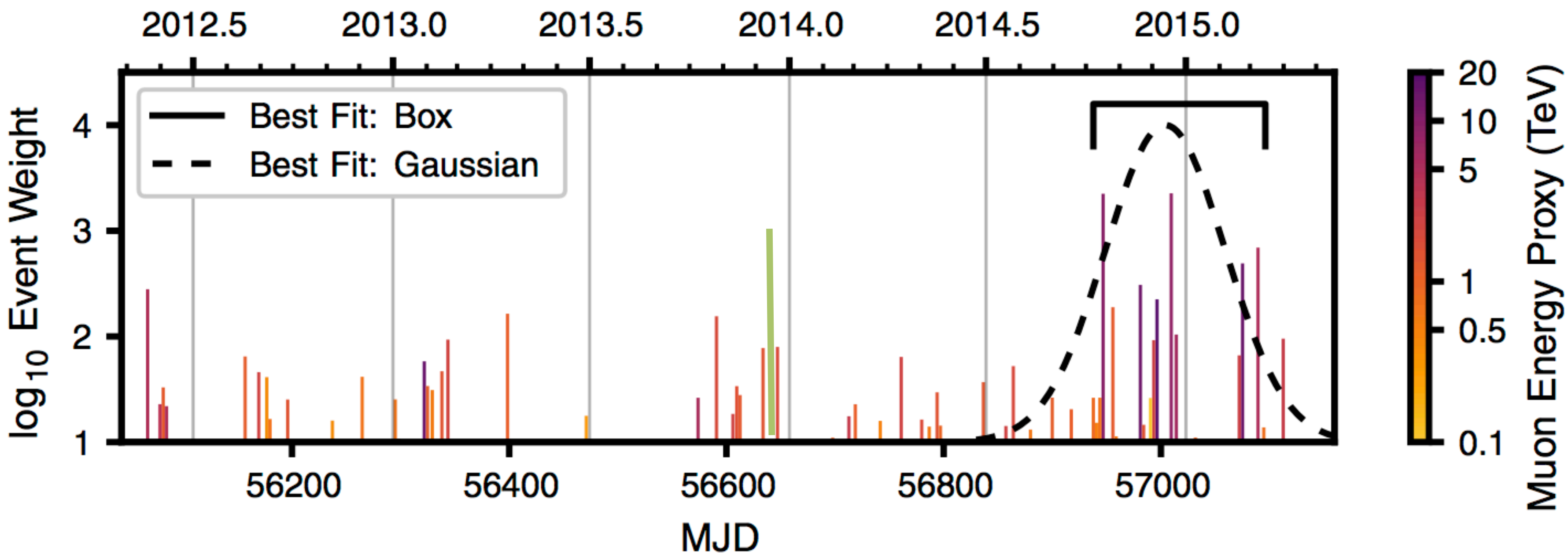
ANTARES Analysis of TXS 0506+056



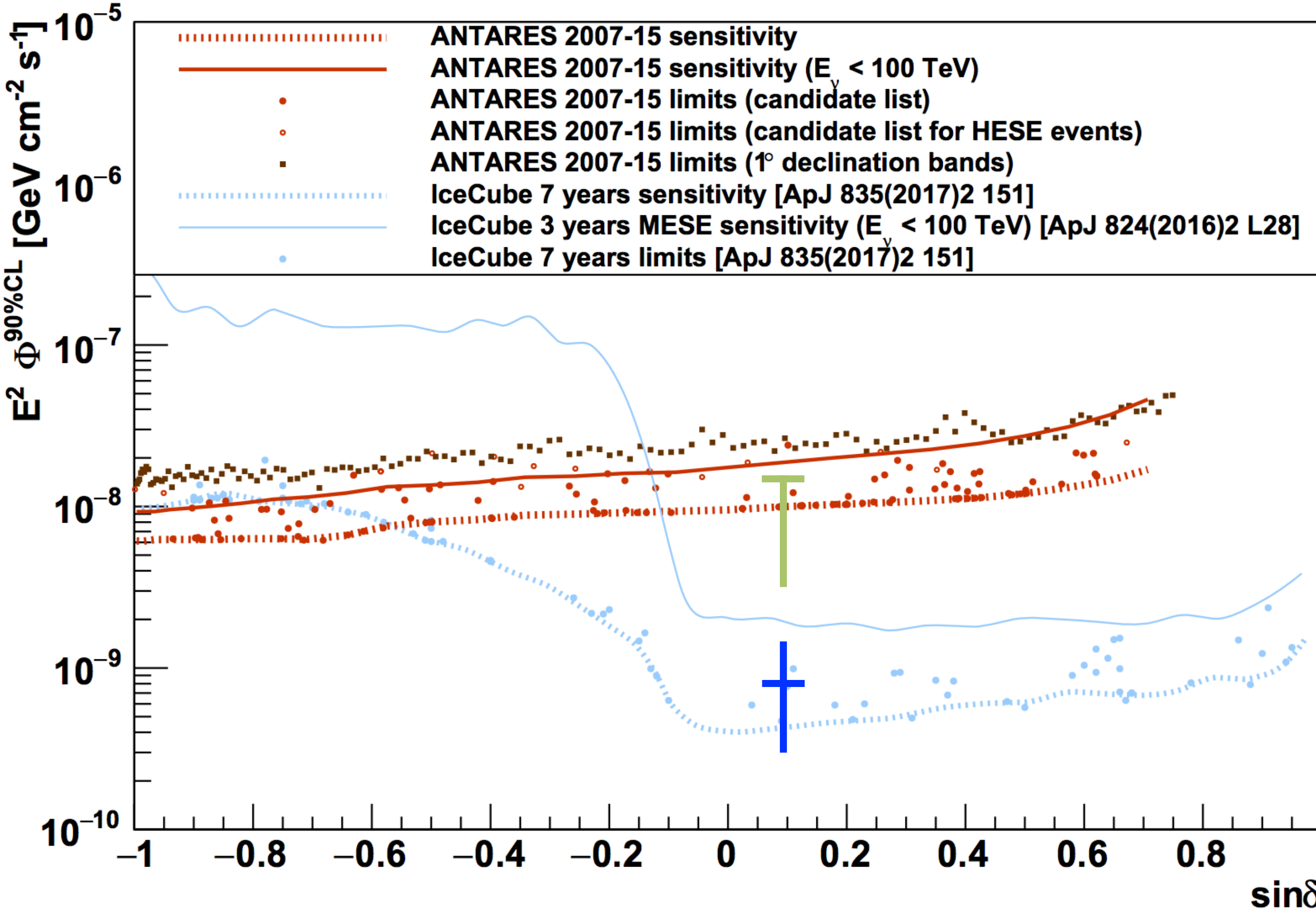
ANTARES, arXiv:1807.04309

2007-17 Time-integrated analysis: best-fit number of signal events: 1.03
Significance (p-value) 3.4%





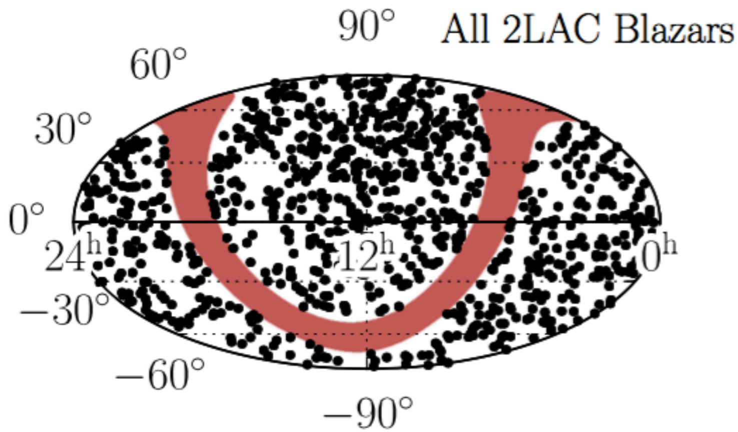
ANTARES event 2013.12.12 1 year earlier … so, not related to flare?

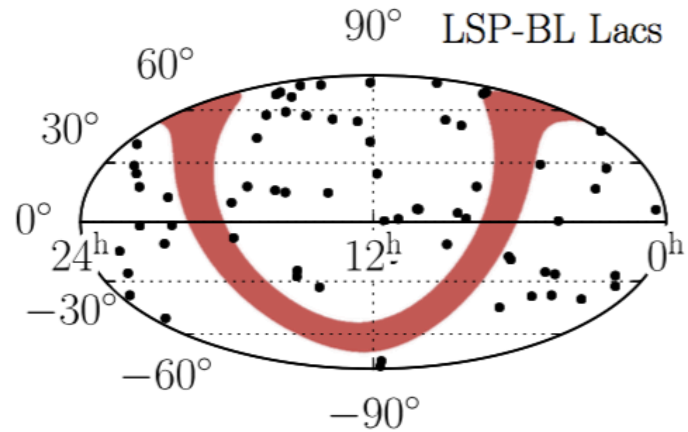


ANTARES, Phys. Rev. D 96, 082001 (2017)

Population Study: Blazars

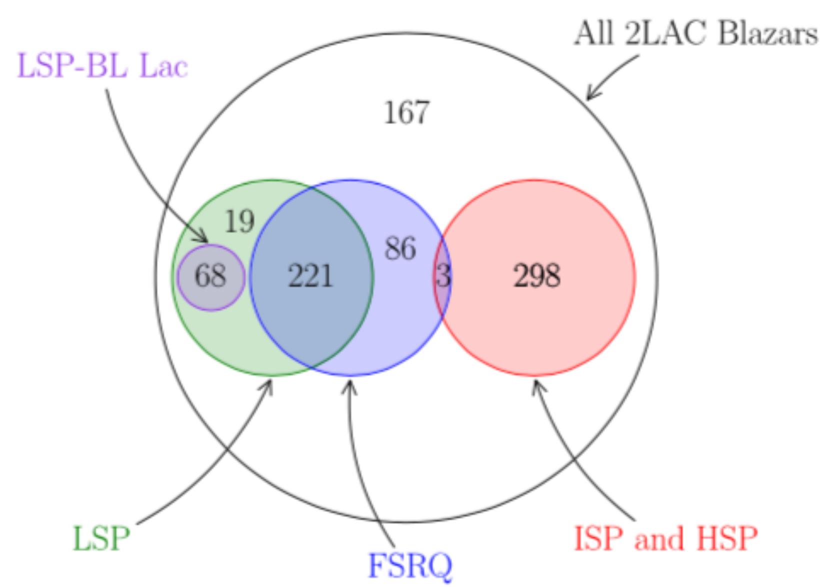
ApJ vol. 835, no. 1, p. 45 (2017)





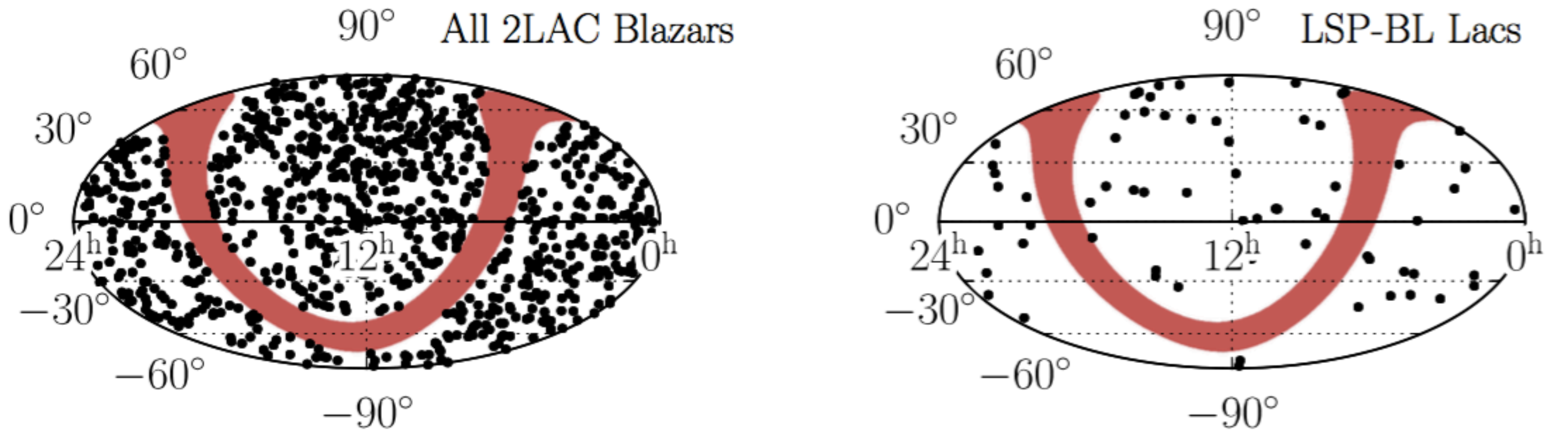
Stacked Source Analysis - Fermi 2LAC

Catalog	# objects
All blazars	- 862
FSRQs	- 310
LSPs	- 308
ISP / HSPs	- 301
LSP-BL Lacs	- 68



Population Study: Blazars

ApJ vol. 835, no. 1, p. 45 (2017)



One assumption: ν luminosity of each blazar is prop. to its γ-ray luminosity

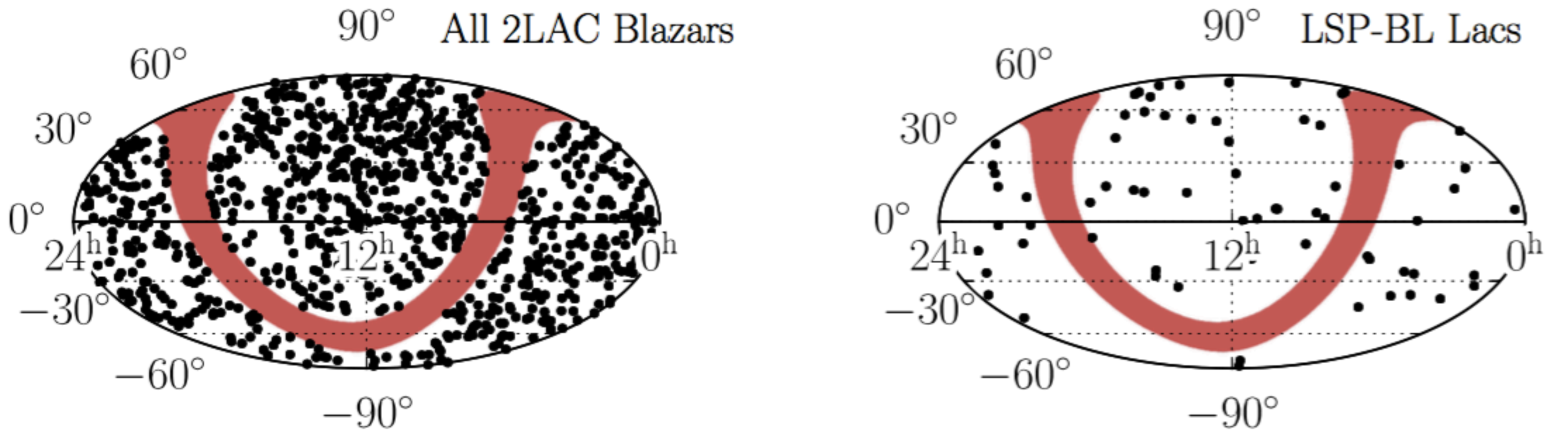
Alternative assumption: no particular correlation between γ and ν luminosity

Population	*p*-value	
	γ-weighting	Equal Weighting
All 2LAC blazars	36% ($+0.4\sigma$)	6% ($+1.6\sigma$)
FSRQs	34% ($+0.4\sigma$)	34% ($+0.4\sigma$)
LSPs	36% ($+0.4\sigma$)	28% ($+0.6\sigma$)
ISP/HSPs	>50%	11% ($+1.2\sigma$)
LSP-BL Lacs	13% ($+1.1\sigma$)	7% ($+1.5\sigma$)

Excess is found for different sub-catalogs and assumptions, but not significant.

Population Study: Blazars

ApJ vol. 835, no. 1, p. 45 (2017)



Limits strictly apply only to **objects (and models) tested in catalog**.

Extrapolation from a catalog to a source class would require further assumptions.

Spectrum: $\Phi_0 \cdot (E/\text{GeV})^{-2.0}$

Blazar Class	$\Phi_0^{90\%}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]	
	γ-weighting	Equal Weighting
All 2LAC Blazars	1.5×10^{-9}	$4.7\ (3.9–5.4) \times 10^{-9}$
FSRQs	0.9×10^{-9}	$1.7\ (0.8–2.6) \times 10^{-9}$
LSPs	0.9×10^{-9}	$2.2\ (1.4–3.0) \times 10^{-9}$
ISPs/HSPs	1.3×10^{-9}	$2.5\ (1.9–3.1) \times 10^{-9}$
LSP-BL Lacs	1.2×10^{-9}	$1.5\ (0.5–2.4) \times 10^{-9}$

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Relative to diffuse ν flux, the ν upper limit from 2LAC catalog objects is:

~ 27% for $E^{-2.5}$

~ 40%-80% for $E^{-2.0}$

Main message:

Combination of independent pieces of evidence =>

Likely identification of a blazar as a source of high-energy neutrinos

But, precise characterization of the neutrino emission is uncertain

Poisson Statistics Rules!

=> Even for high significance signal:

large uncertainties on Flux, Energy, Time Window

=> Additional uncertainty for a population of weak sources:

First source observed may be the one that fluctuates upward