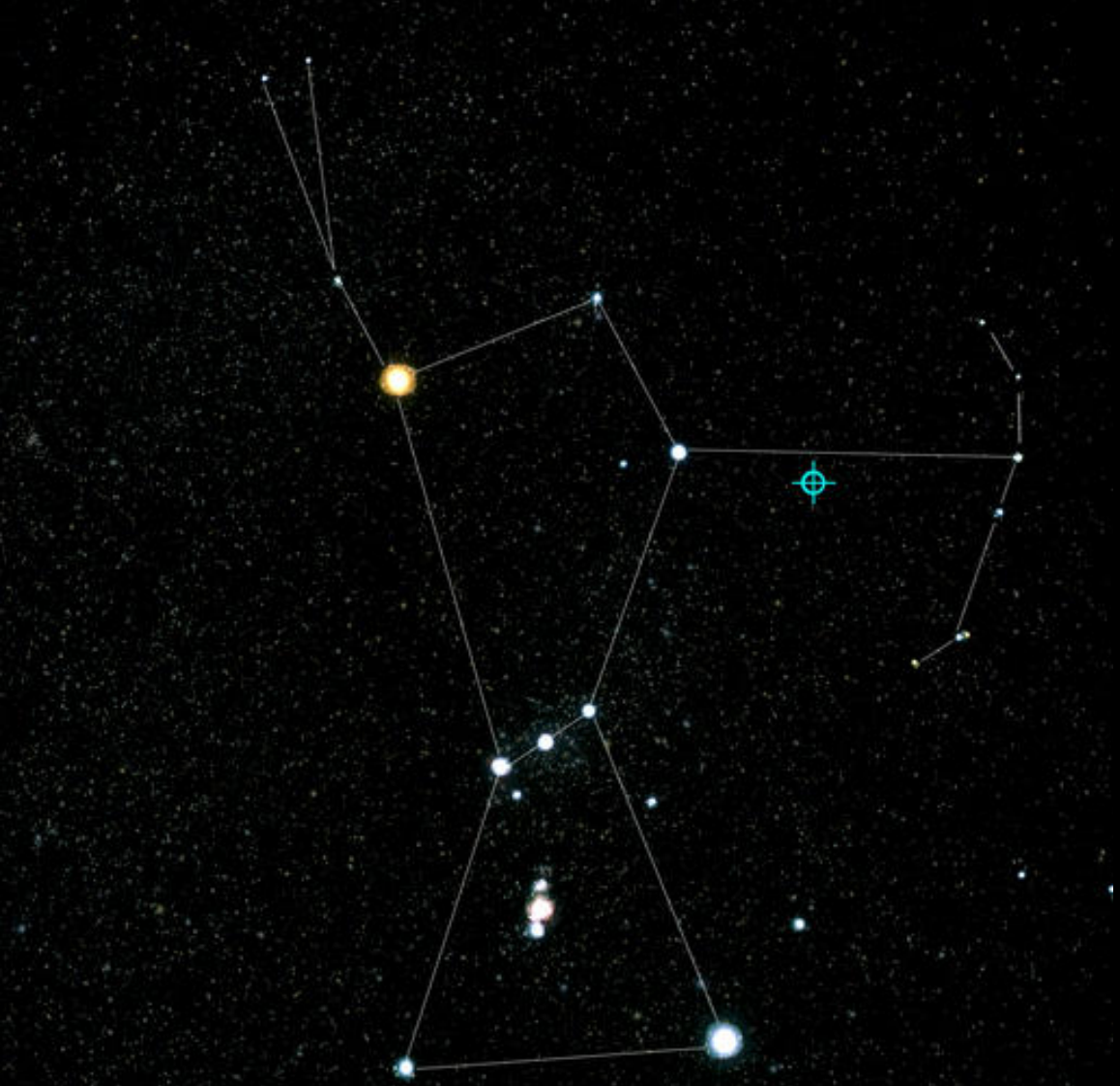


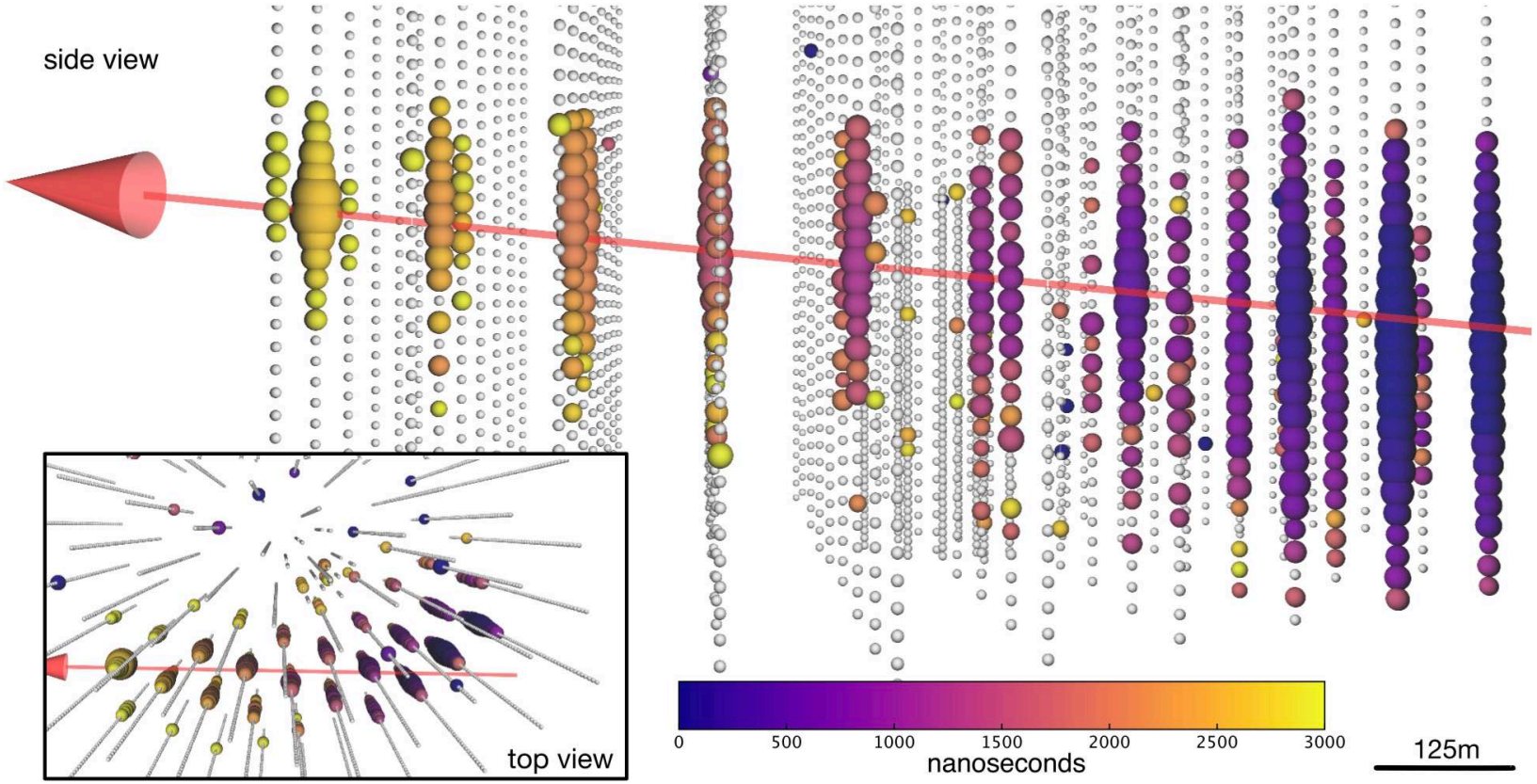
Credit: IceCube/NASA

Neutrinos From TXS 0506+056

Chad Finley
on Behalf of the IceCube Collaboration

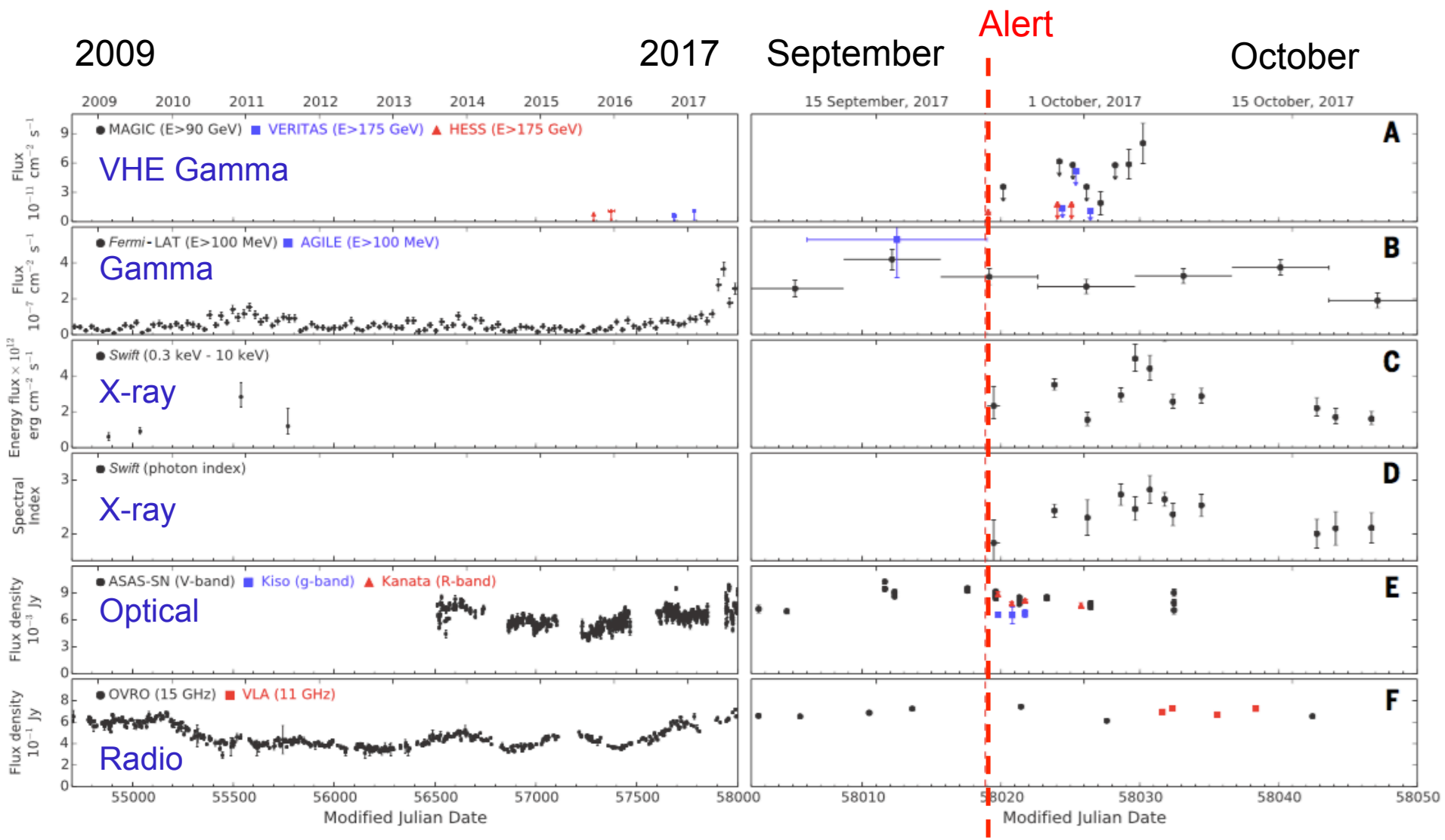
VLVnT 2018
Dubna, 2018 October 2

The EHE alert: IceCube-170922A



Science 361, 6398, (2018) eaat1378

Time-dependent multi-wavelength observations of TXS 0506+056 before and after IceCube-170922A



Science 361, 6398, (2018) eaat1378

"Untriggered" Time-Dependent Likelihood

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

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

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

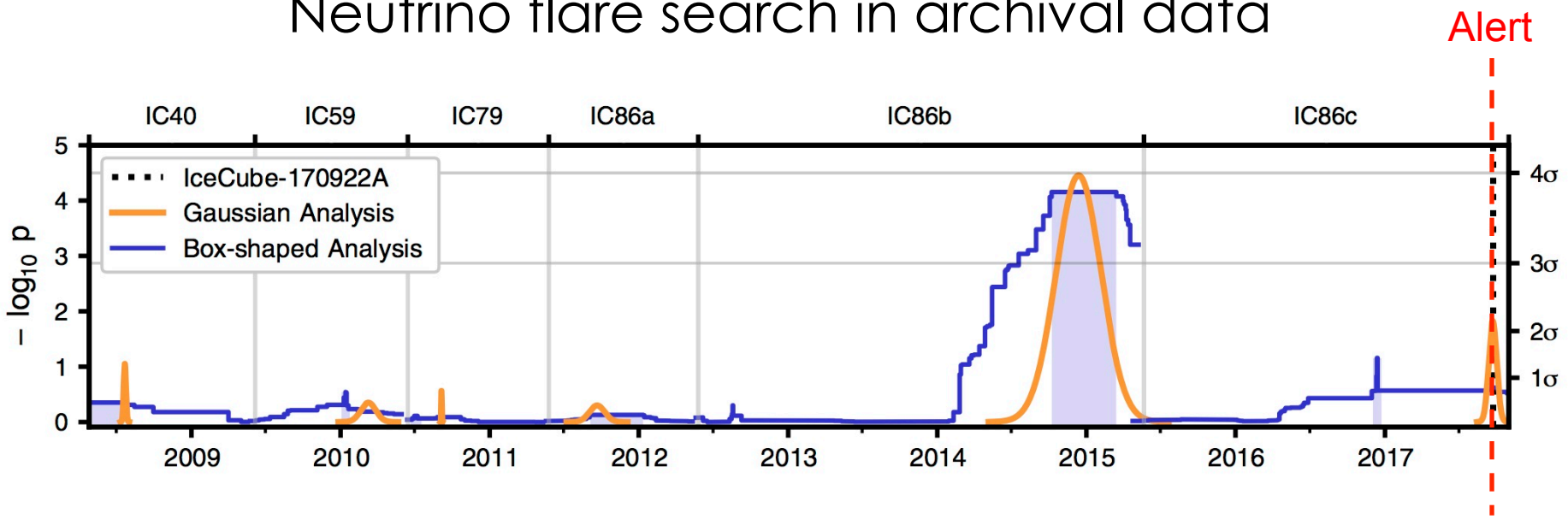
$$\mathcal{L}(n_s, \gamma, \sigma_T, T_0) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \sigma_T, T_0) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

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

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

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

Neutrino flare search in archival data



Analysis is performed at coordinates of TXS 0506+056

Six data periods analyzed separately

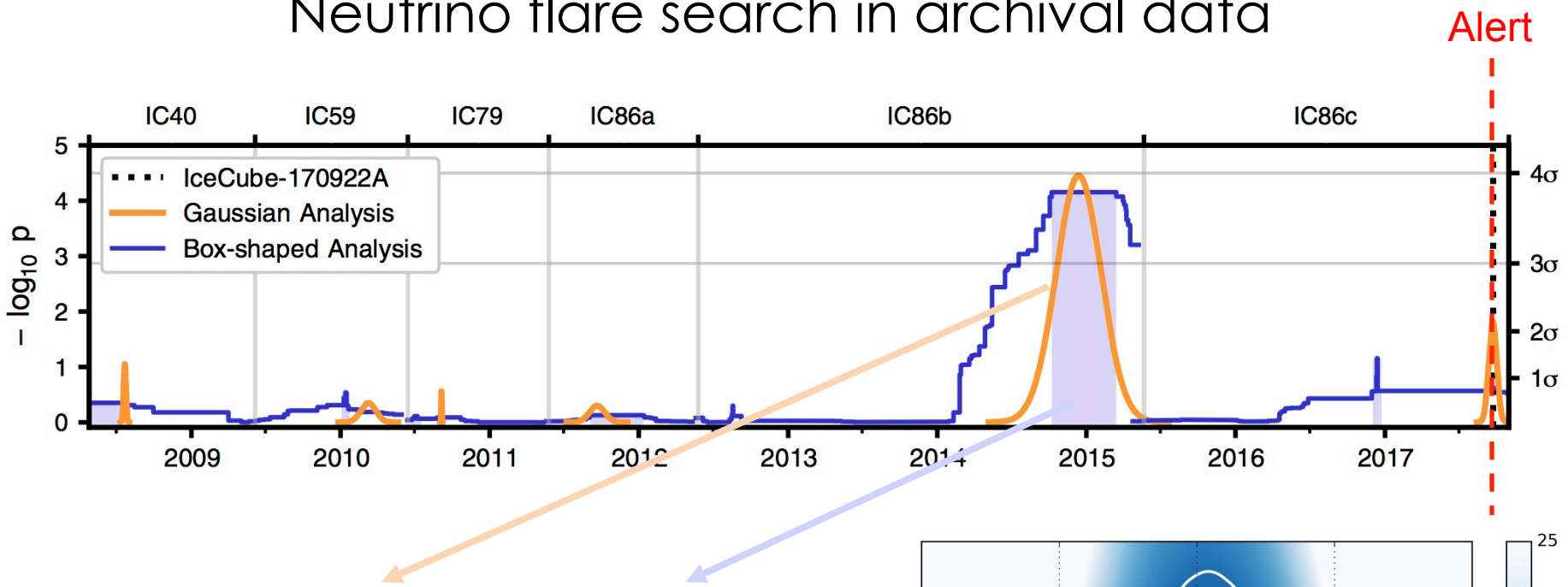
Report most significant **Gaussian-shaped** and **Box-shaped** time window for each period

(For the Box-shape analysis, the **outer blue curve** also shows less significant time windows)

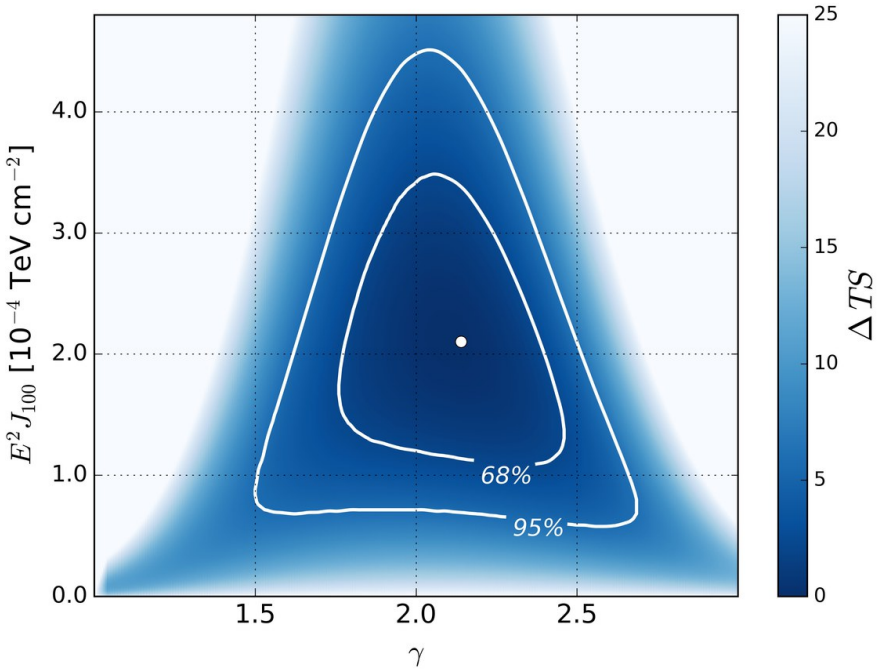
Same excess isfound by both analyses centered in December 2014.

Science 361, 6398, (2018) 147

Neutrino flare search in archival data

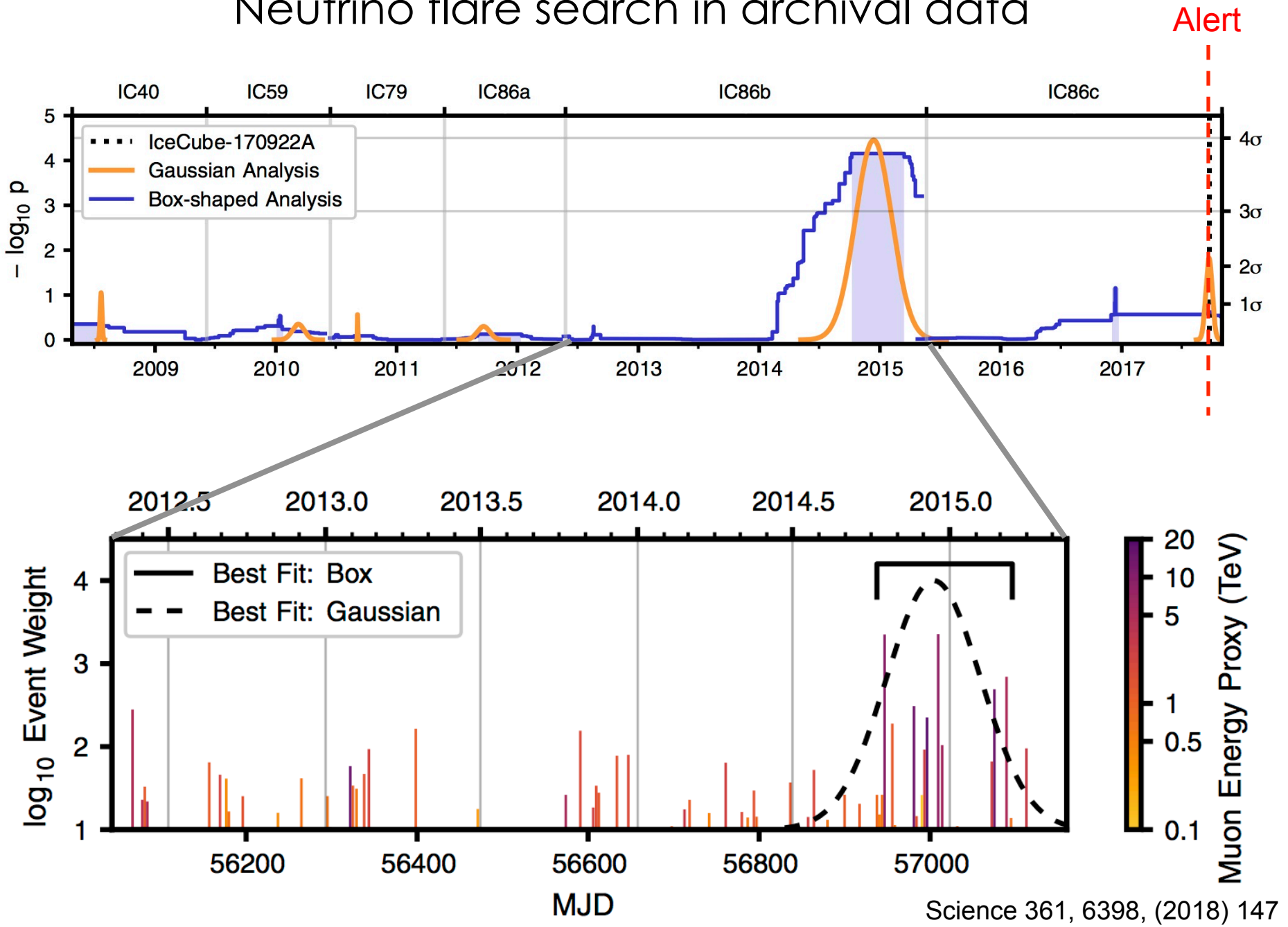


Best-fit values	Gaussian	Box
Central Date	2014 Dec. 13	2014 Dec. 26
Width	110 days (-1σ to +1σ)	158 days
$\nu_\mu+\bar{\nu}_\mu$ fluence	2.1×10^{-4} TeV cm^{-2}	2.2×10^{-4} TeV cm^{-2}
spectral index	2.1	2.2



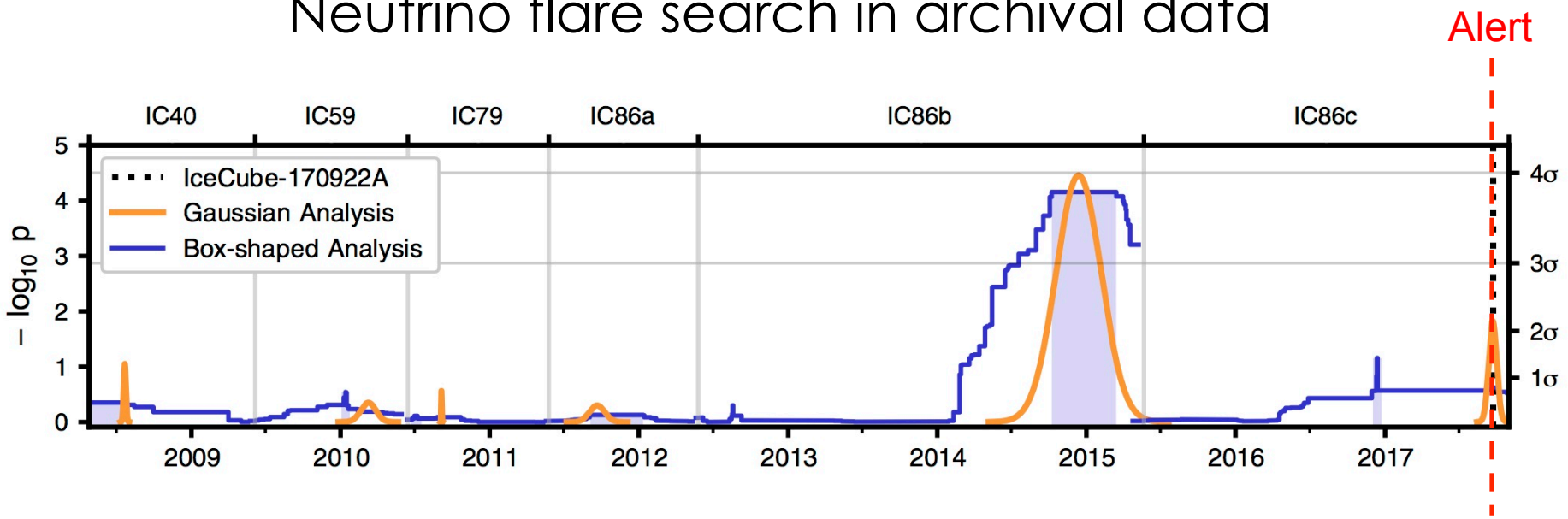
Joint uncertainty on fluence and index for Gaussian time window

Neutrino flare search in archival data



Science 361, 6398, (2018) 147

Neutrino flare search in archival data



Significance Estimation:

Scramble 2012-2015 data in right ascension
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

Why wasn't this excess seen before?

TeVPA 2016 – Presentation by Asen Christov:

Time Dependent Searches – All sky scan

Lets start with generic search:

Gaussian in time

Signal PDF:

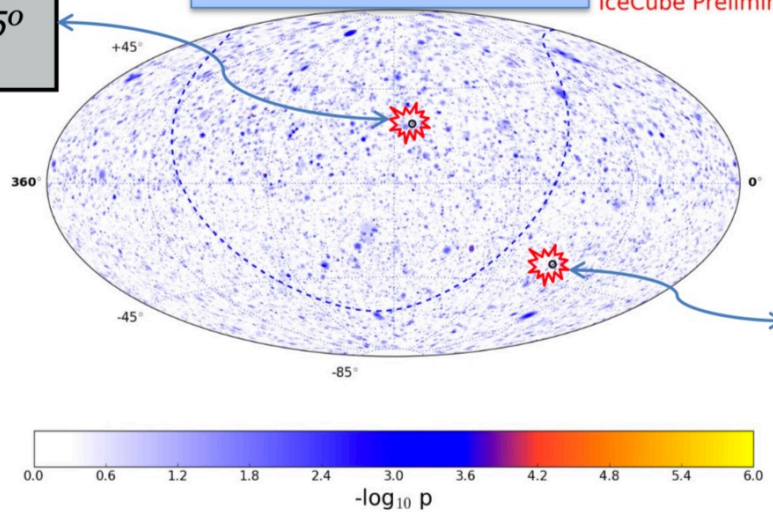
$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma) \qquad \frac{1}{\sqrt{(2\pi)}\sigma_T} exp\left(-\frac{(t_i - T_0)^2}{2\sigma_T^2}\right)$$

T_{sig}

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

Sky map of significances

IceCube Preliminary



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

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

12/9/2016 Asen Christov 11

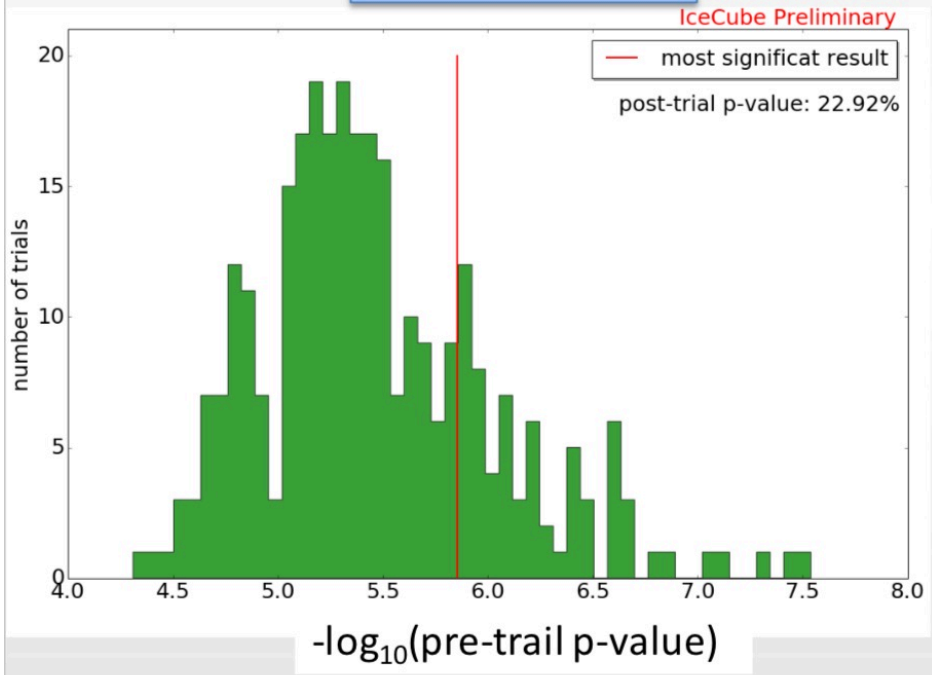
TeVPA 2016 – Presentation by Asen Christov:

Look-elsewhere effect:

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

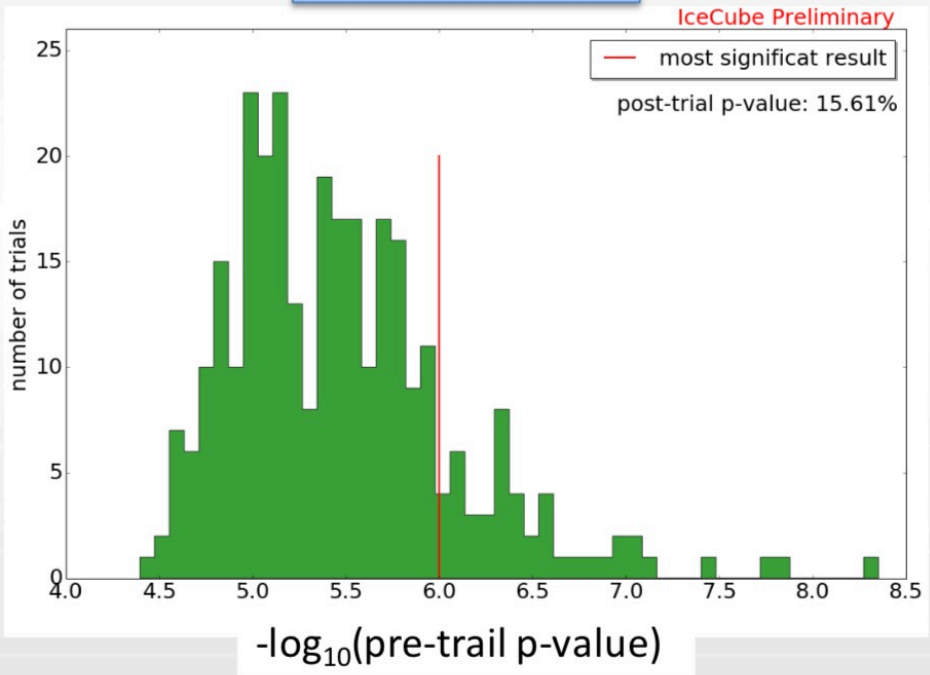
i.e. local p-value of 10^{-6} becomes ~10% post-trial, considering whole northern sky

Southern Sky



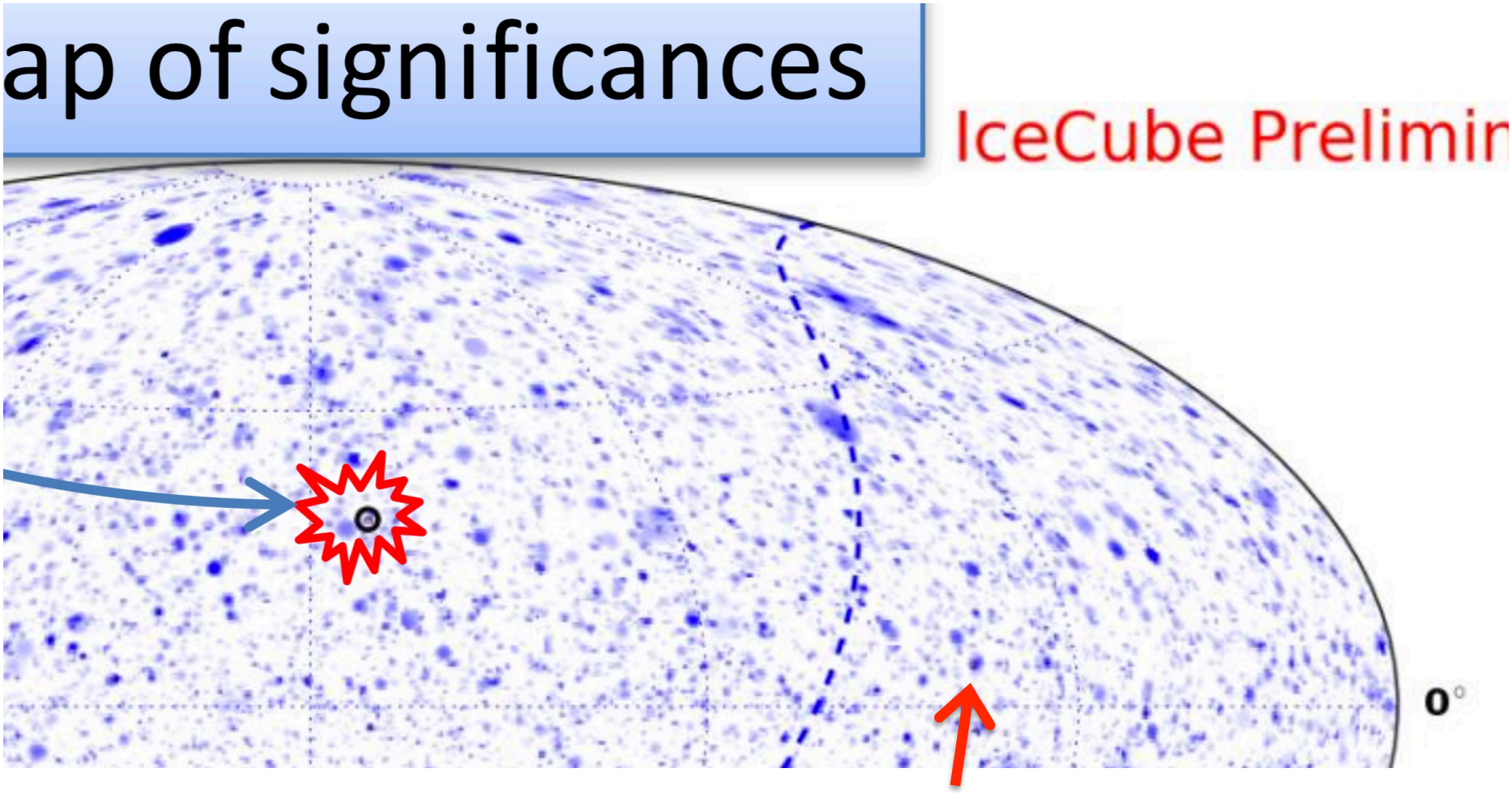
Post-trial p-value: 23%

Northern Sky



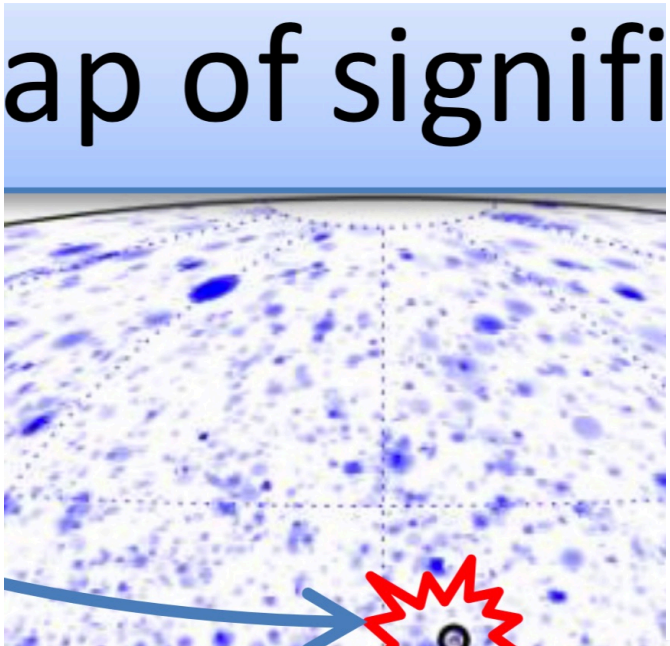
Post-trial p-value: 16%

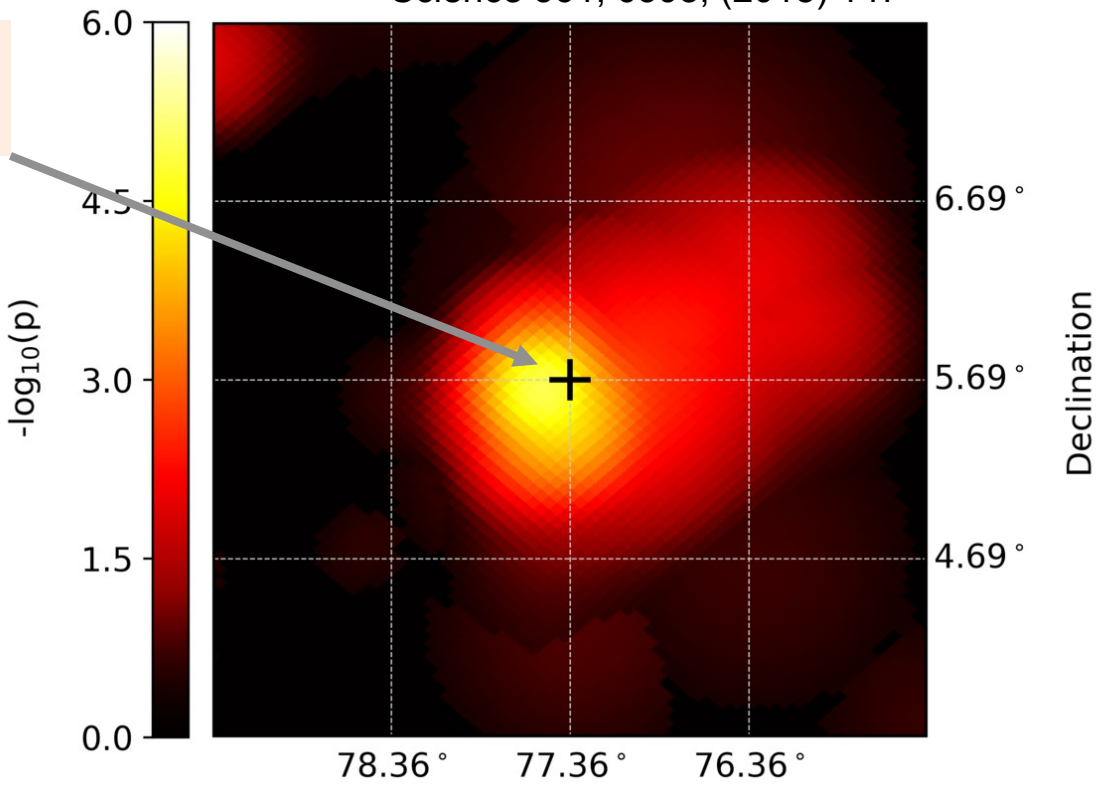
Zoom in on Asen Christov's presentation:

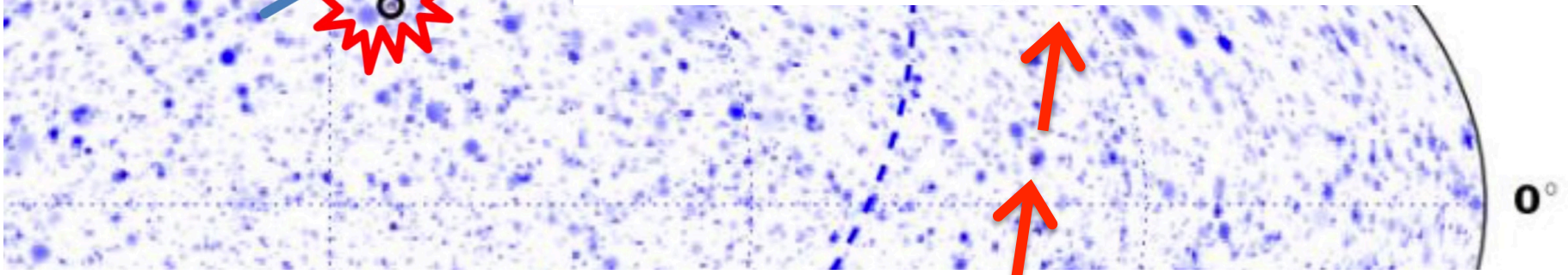


Science 361, 6398, (2018) 147

Archival analysis performed at coordinates of TXS 0506+056

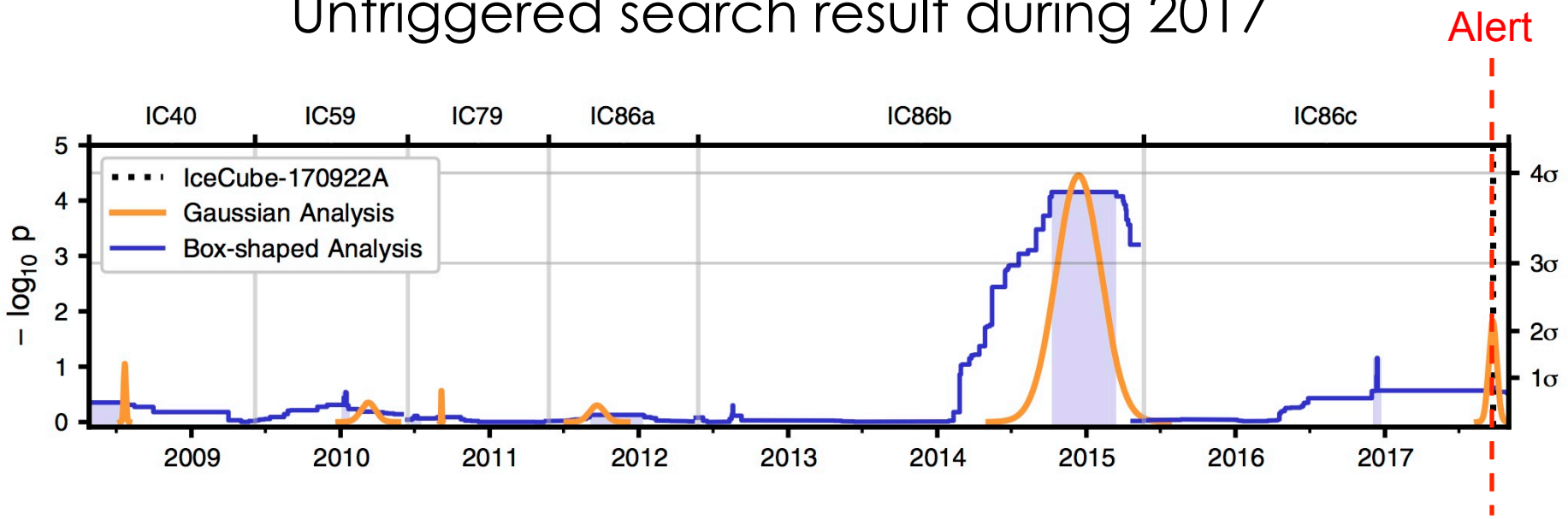






2nd hottest spot in the northern sky

Untriggered search result during 2017

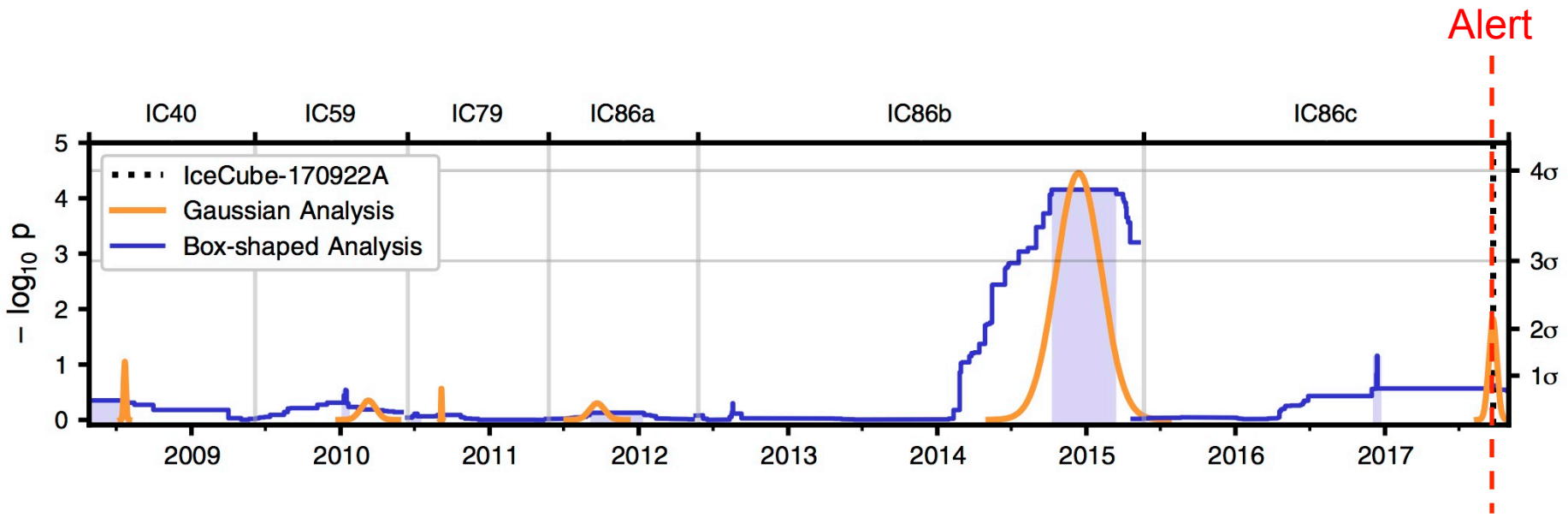


EHE flare is not as significant in this analysis

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

Gaussian Time Window connects weakly with one other event 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.



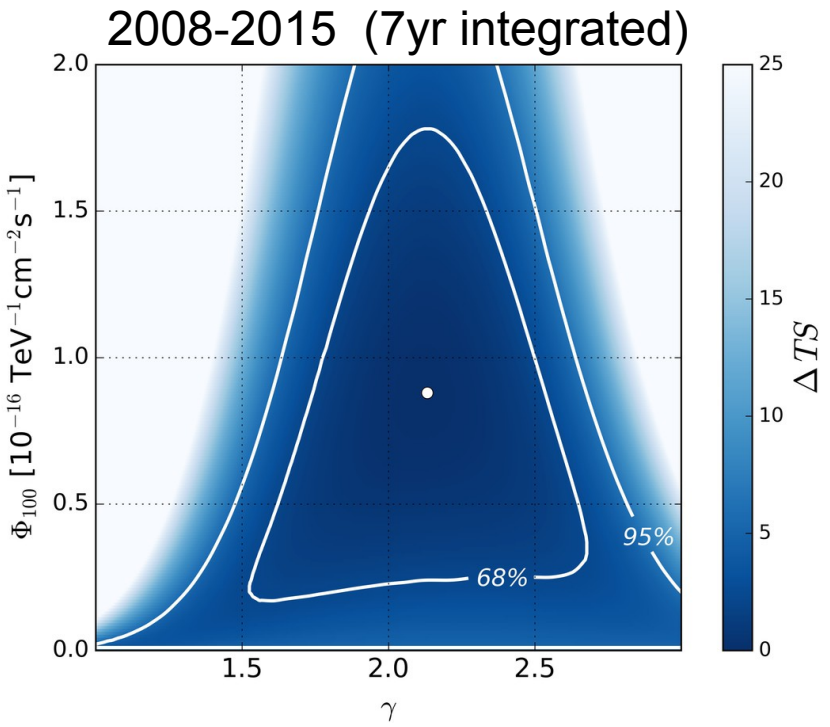
Note:

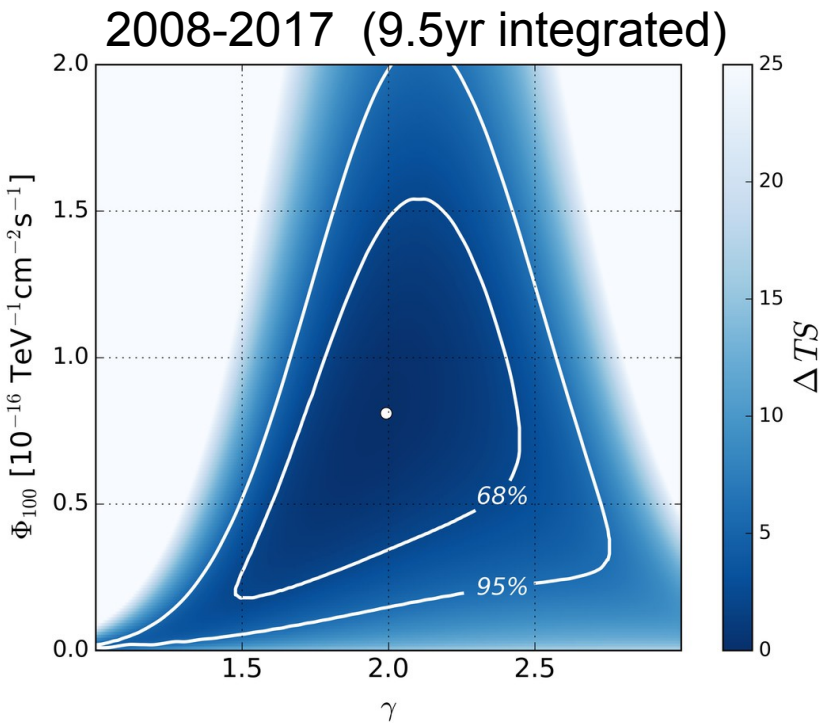
The significance of the untriggered time dependent analysis is w.r.t.
a null hypothesis of **no signal.**
Not a null hypothesis of **constant signal.**

A strong, constant neutrino signal will also be significant in the time-dep analysis

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

Time-Integrated Analysis

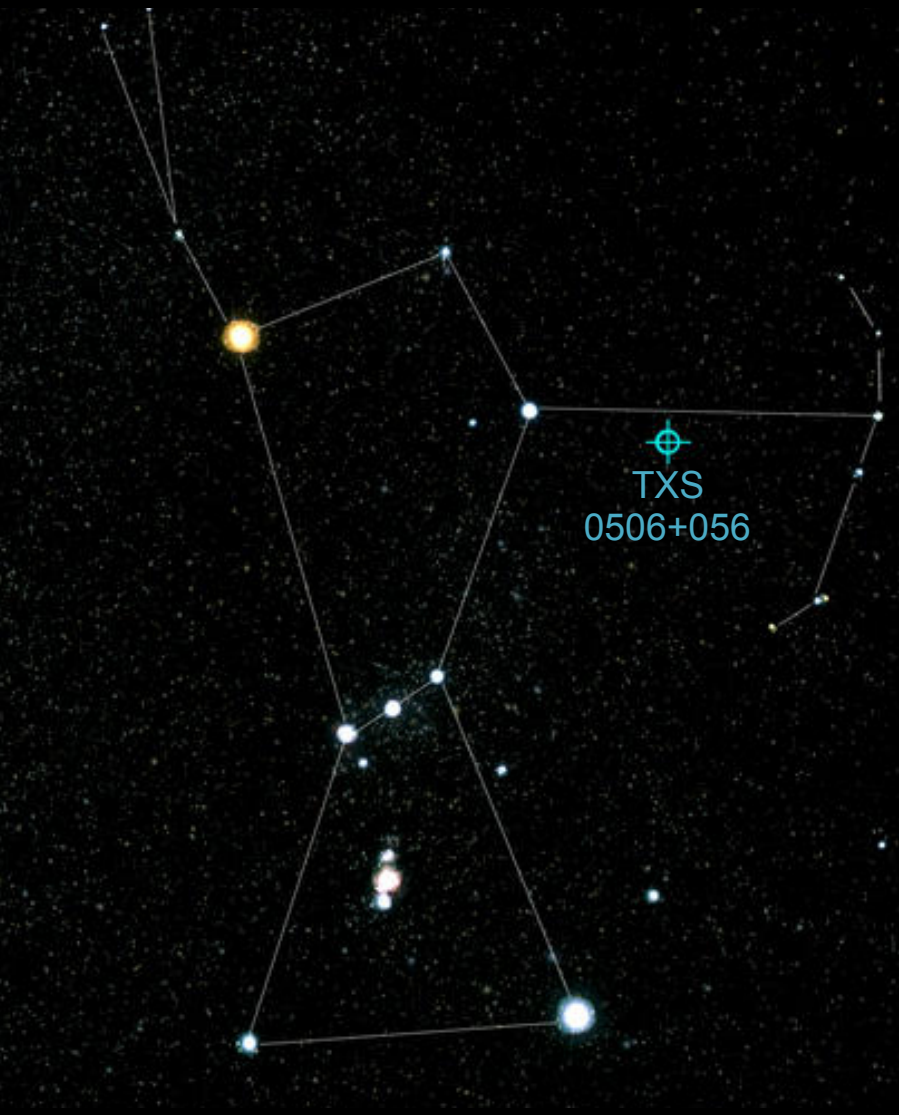




Time-averaged result for first 7-years of data is similar to the 2014-15 flare result (fluence 2.0×10^{-4} TeV cm^{-2}, index 2.1). Significance: 2.1σ

With the extension to 9.5 years, the EHE event is included. This drives significance to 4.1σ (a posteriori)

Fit parameters (flux, index) stay nearly the same when the EHE event is included.



Blazars were one of earliest sources to be predicted as nu sources

Combination of independent pieces of evidence =>

Likely identification of a blazar as a source of high-energy neutrinos and cosmic rays

But, not clear yet how all pieces of evidence fit together

Data will now start to drive models

Isolated instance, or major source of HE cosmic rays? What about UHE cosmic rays? *Not yet known…*