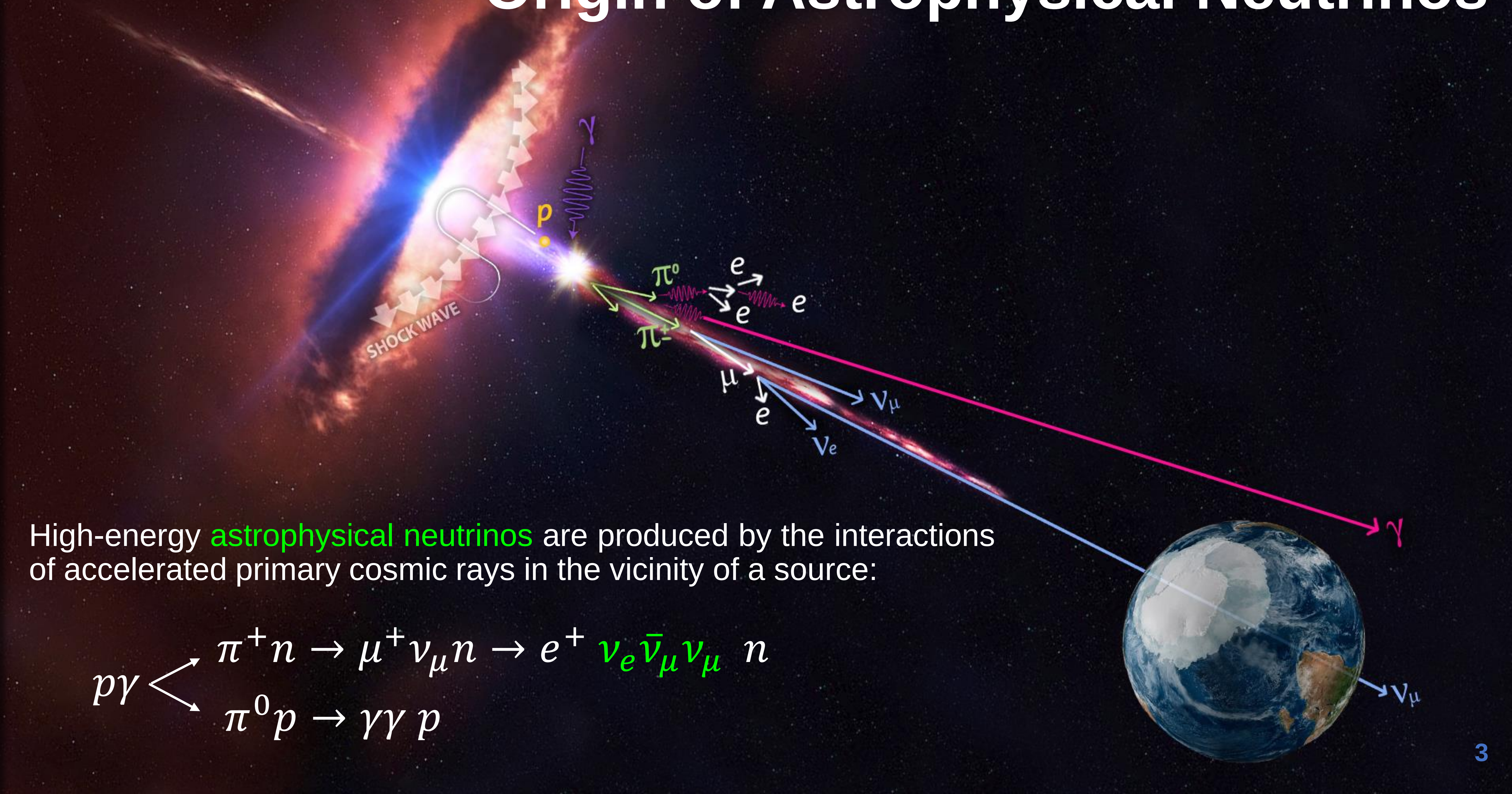
Innsbruck, 30 August - 3 September

Search for transient sources of astrophysical neutrinos with 10 years of IceCube data

F. Lucarelli, T. Montaruli

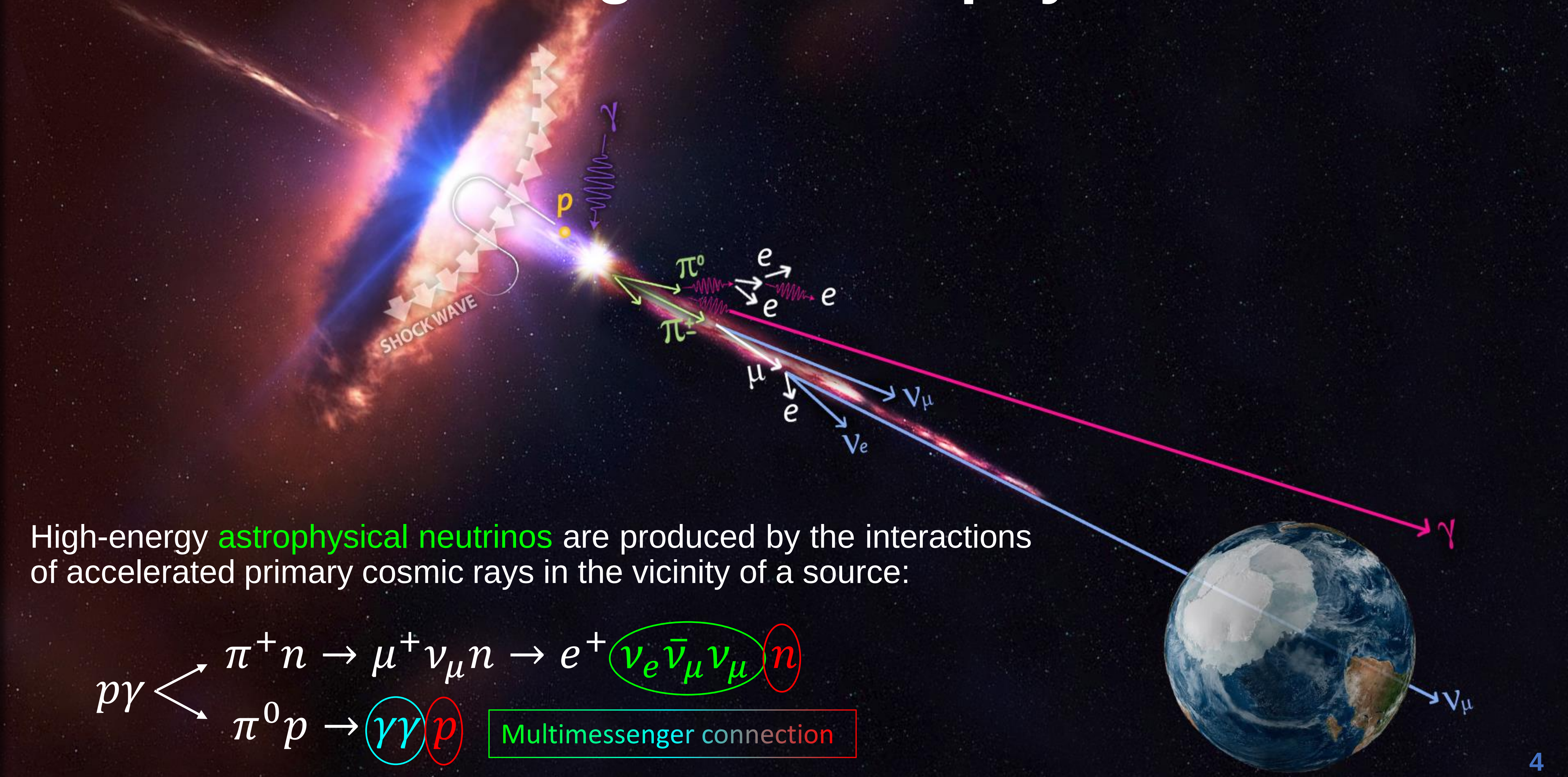
Origin of Astrophysical Neutrinos



High-energy astrophysical neutrinos are produced by the interactions of accelerated primary cosmic rays in the vicinity of a source:

$$p\gamma \begin{cases} \pi^+ n \rightarrow \mu^+ \nu_\mu n \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \; n \\ \pi^0 p \rightarrow \gamma\gamma \; p \end{cases}$$

Origin of Astrophysical Neutrinos



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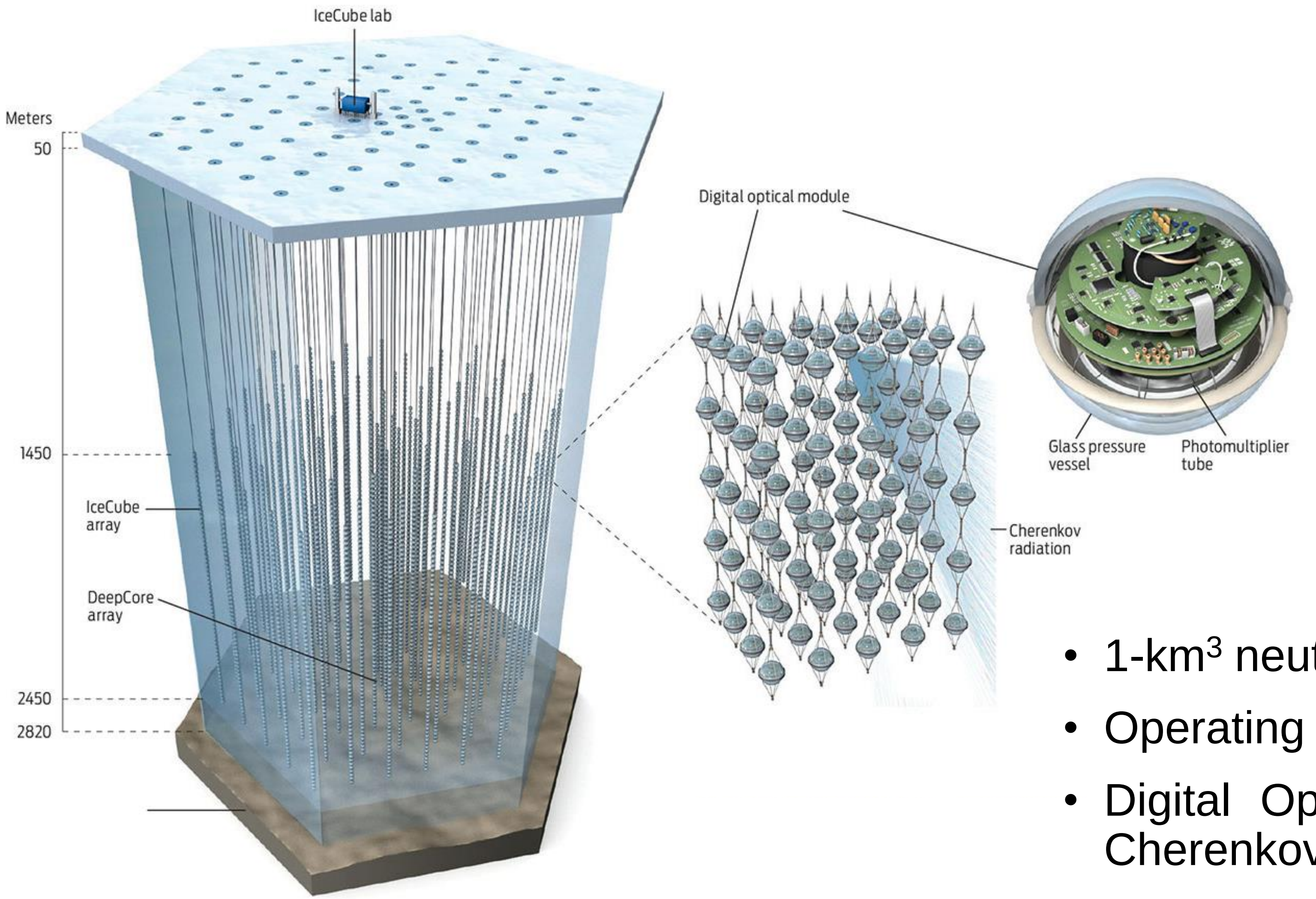
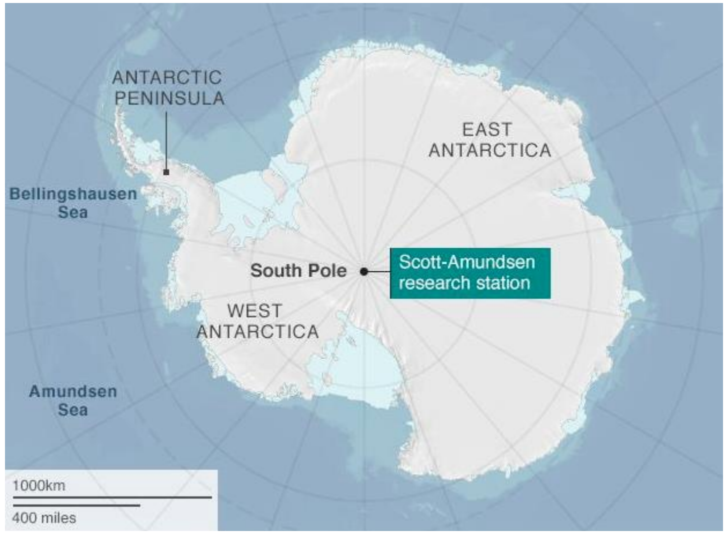
Multimessenger connection

IceCube Neutrino Observatory





- 1-km^3 neutrino telescope at the South Pole
- Operating in full configuration since May 2011
- Digital Optical Modules designed to collect Cherenkov light
- $> 99\%$ uptime, 4π survey

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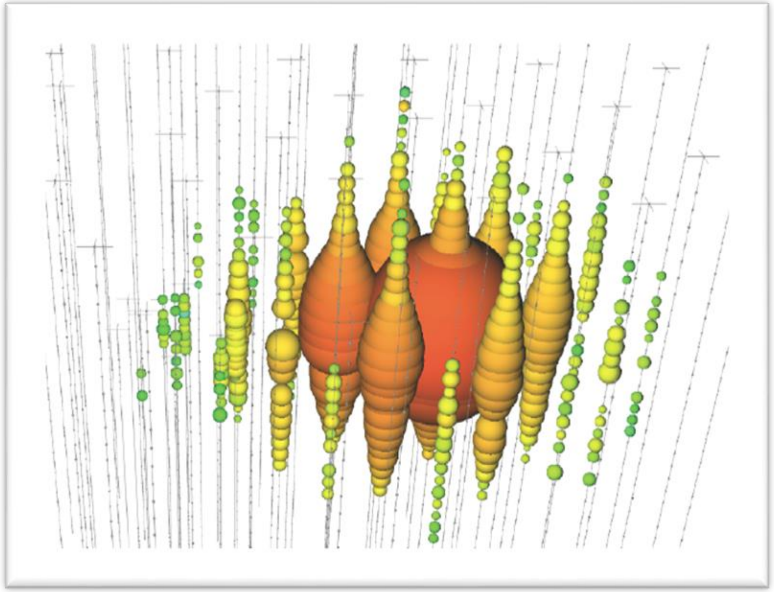
Neutrino Signature

Tracks and cascades

Cascade event

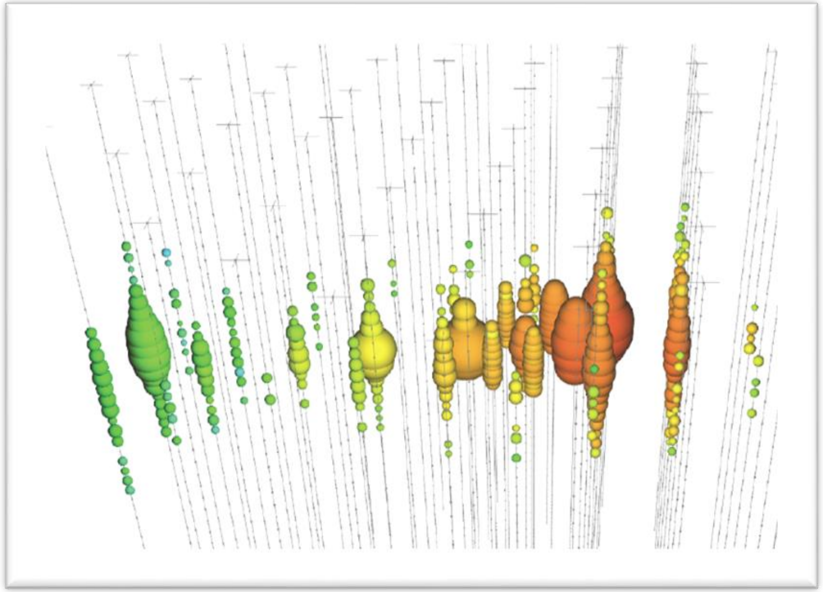


ν_e, ν_τ CC; All-flavour NC

Bad angular resolution: $\sim 10^\circ$ (> 100 TeV)

Good energy resolution: $\sim 15\%$

Track-like event



ν_μ CC (dominant)

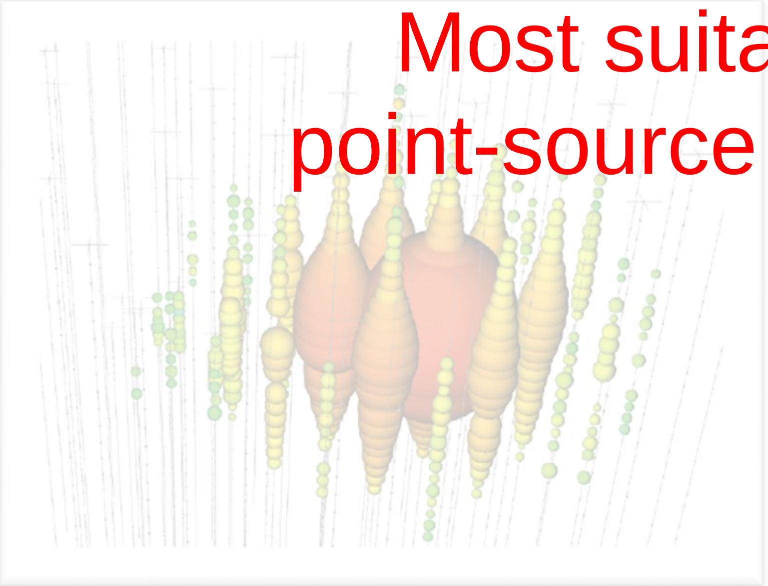
Good angular resolution: $< 0.3^\circ$ (> 100 TeV)

Bad energy resolution: $\sim 2\times$

Neutrino Signature

Tracks and cascades

Cascade event



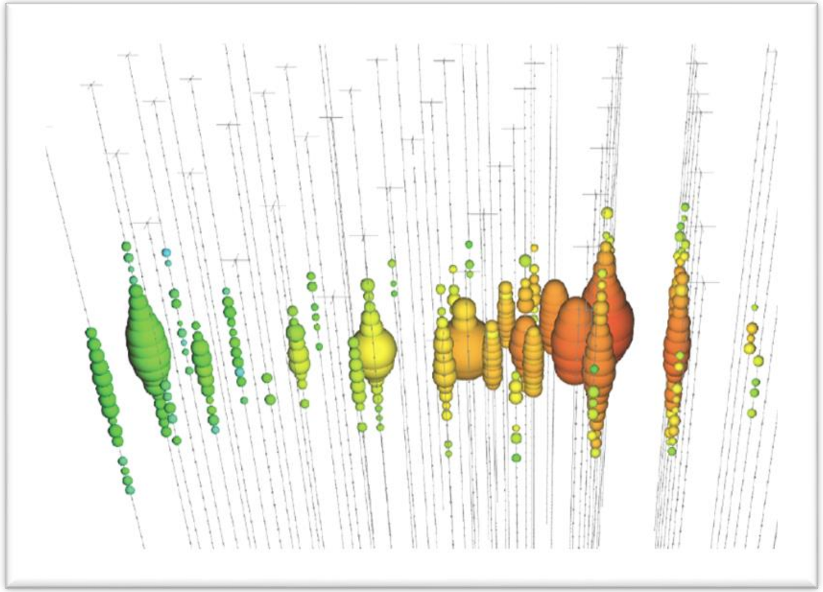
Most suitable for point-source searches

ν_e, ν_τ CC; All-flavour NC

Bad angular resolution: $\sim 10^\circ$ (> 100 TeV)

Good energy resolution: $\sim 15\%$

Track-like event



ν_μ CC (dominant)

Good angular resolution: $< 0.3^\circ$ (> 100 TeV)

Bad energy resolution: $\sim 2\times$

Signal and Background

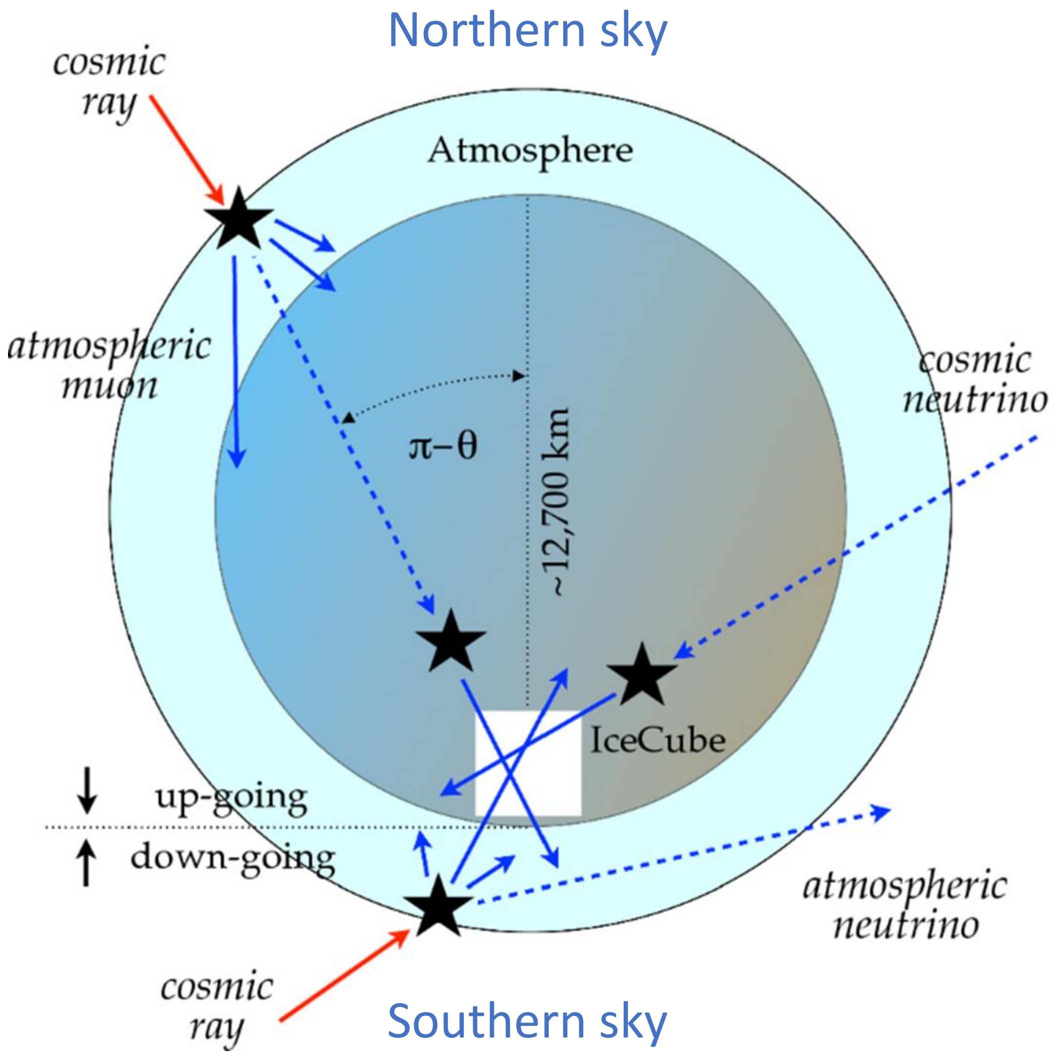
Signal

- **Astrophysical muon neutrinos**

Background

- **Atmospheric muons**
  Dominant in Southern sky
- **Atmospheric muon neutrinos**
  Dominant in Northern sky

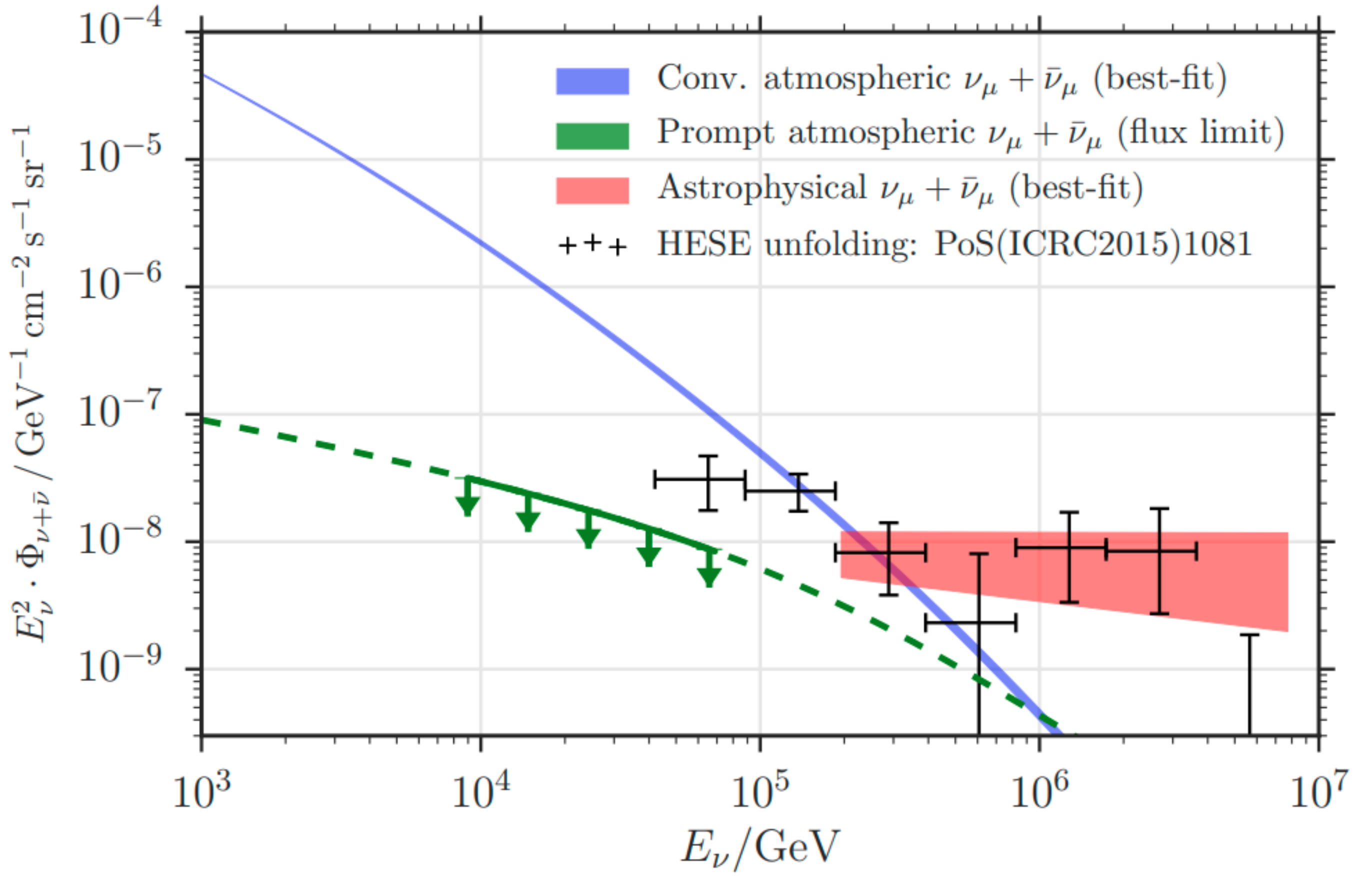
Astro ν_μ : Atm ν_μ : Atm μ = 10 : 10^5 : 10^{11} evts/yr



IceCube Results

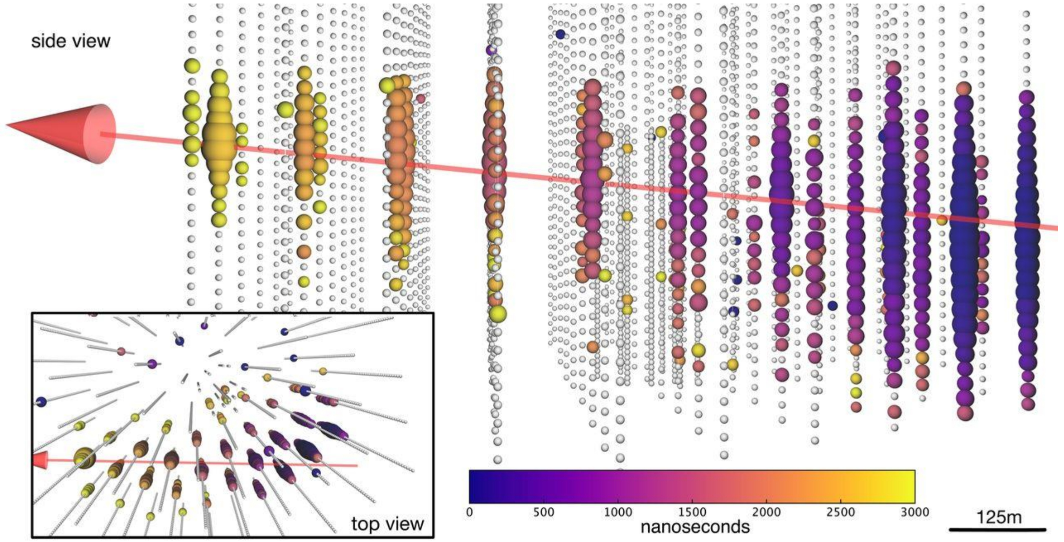
Astrophysical Diffuse Flux

- In 2014 IceCube observed a diffuse flux of astrophysical neutrinos at $> 5\sigma$
- Expected spectrum:
  - Main background: $\propto E^{-3.7}$
  - Astrophysical signal: $\propto E^{-2}$
- Astrophysical component dominant above $O(100\text{ TeV})$



IceCube Results

Evidence of Point-Like Sources: TXS 0506+056



- On 22 September 2017 IceCube detected a track event with reconstructed neutrino energy of 290 TeV
- Its arrival direction was compatible with the location of a known blazar TXS 0506+056

IceCube Results

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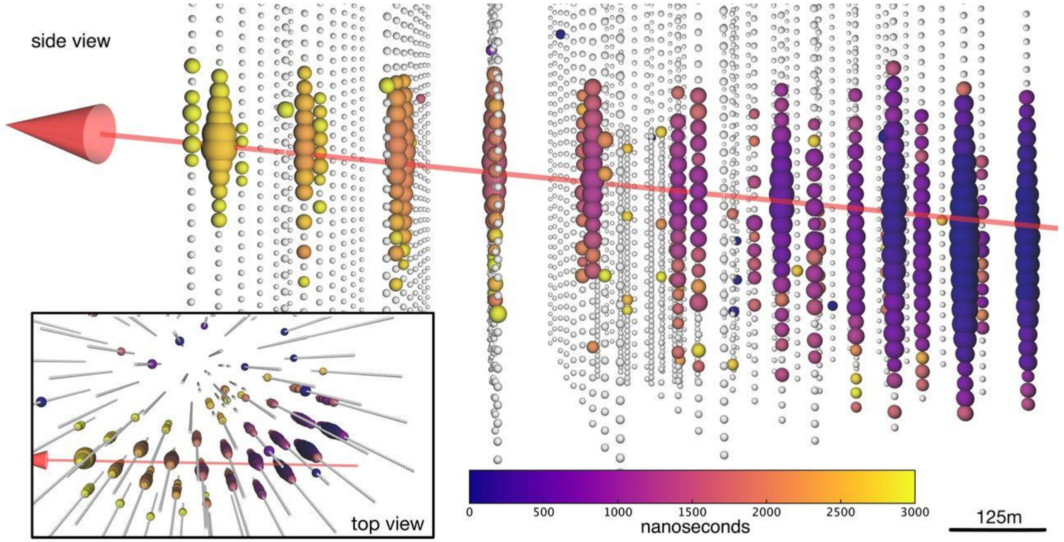

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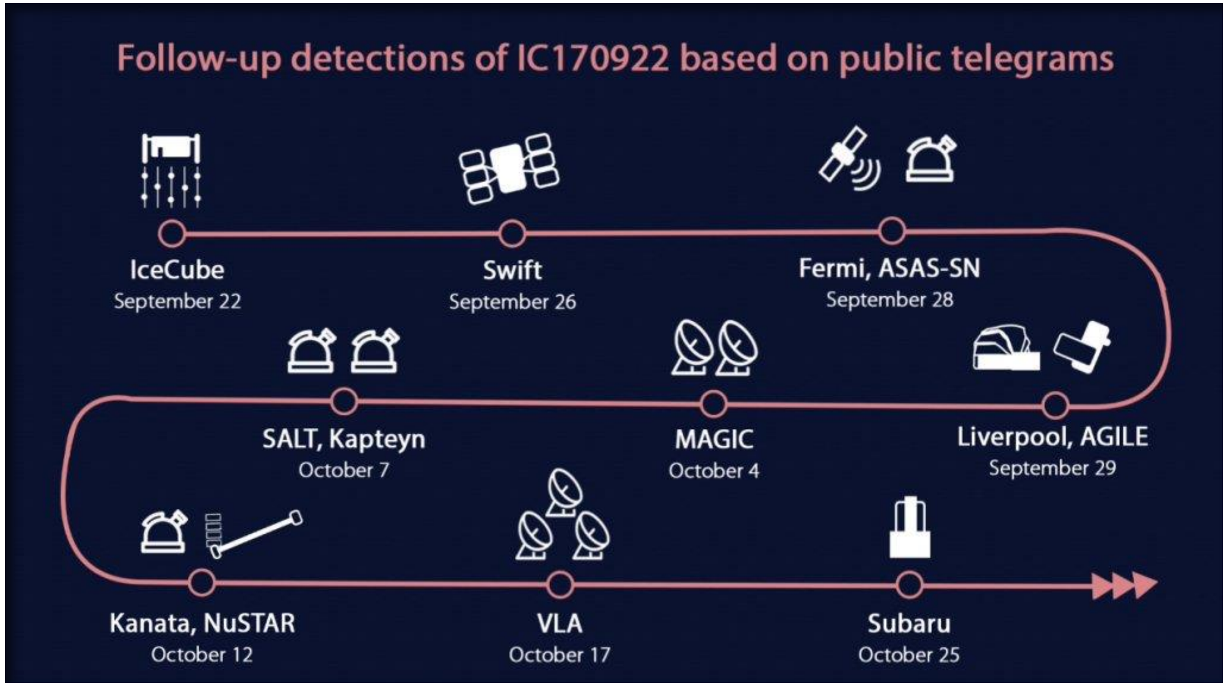
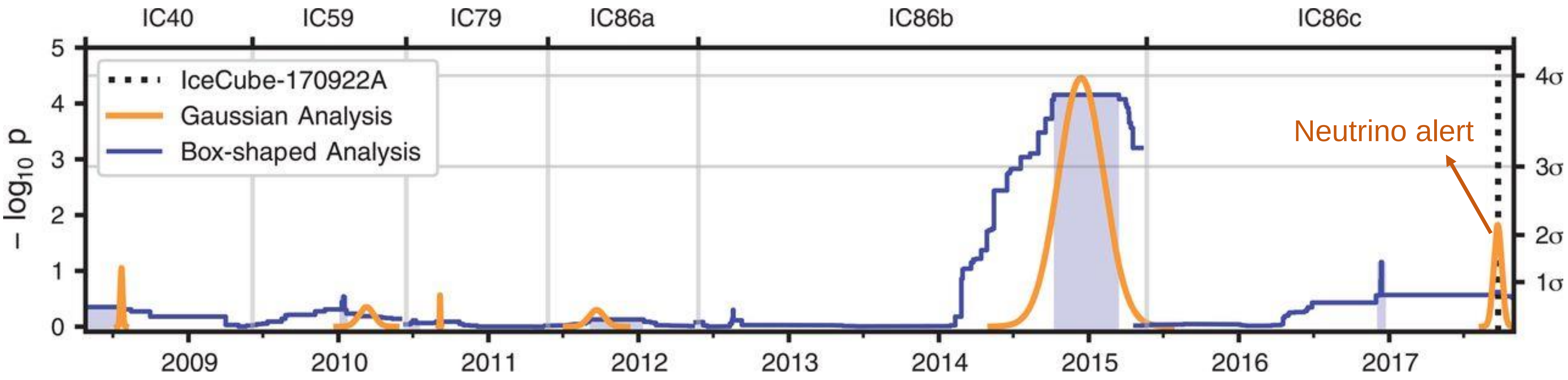


- An increased flux was observed from a compatible direction in the following days

It was the first common observation of the two messengers, indicating TXS 0506+056 as a potential source of cosmic rays

IceCube Results

Evidence of Point-Like Sources: TXS 0506+056



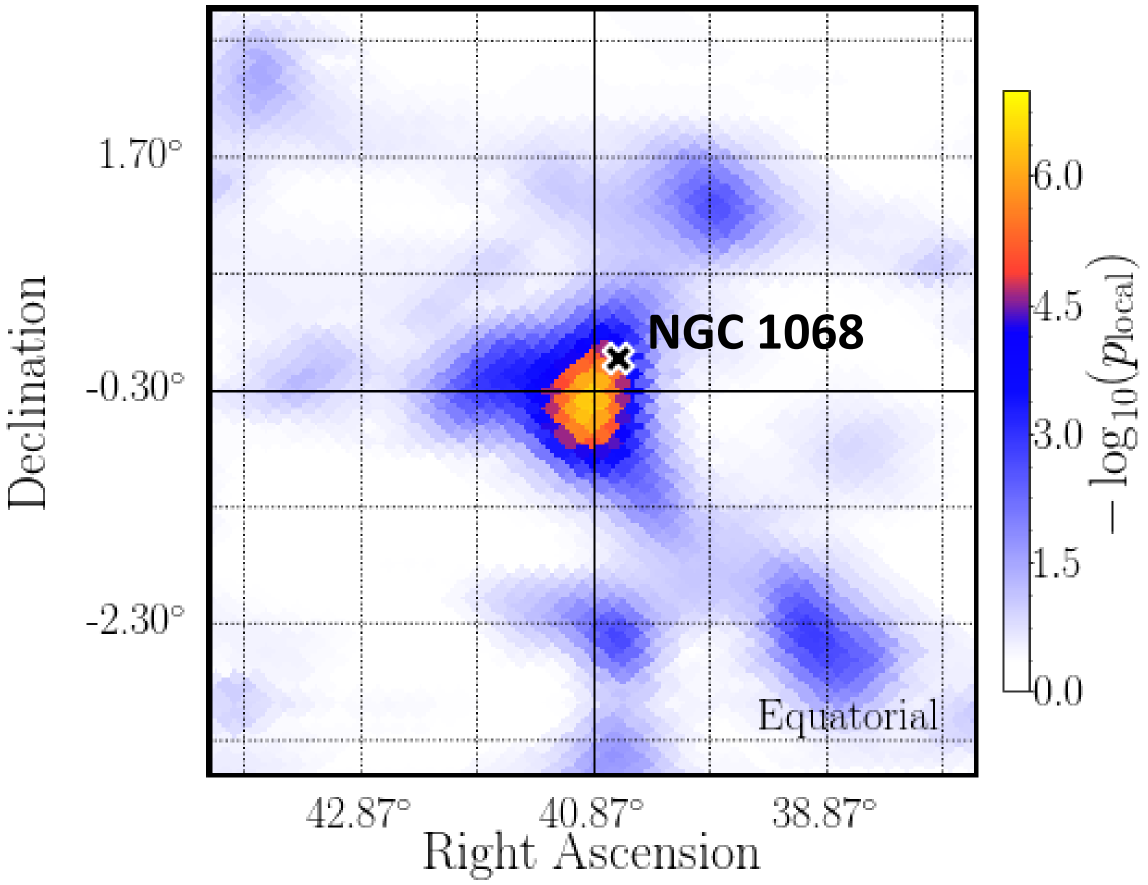
- Looking back at the data from the direction of TXS 0506+056, IceCube observed a neutrino flare prior to the alert time with a significance level of 3.5σ

No gamma-ray counterpart was observed for this flare

IceCube Results

Hints of Point-Like Sources: NGC 1068

- To exploit the multi-messenger connection, in 2019 another analysis looked for point-like sources from a catalogue of gamma-ray emitters
- This analysis identified NGC 1068 as the hottest source at a significance level of 2.9σ
- Intriguingly, this source is also close to the hottest spot in the Norther hemisphere in an all-sky search



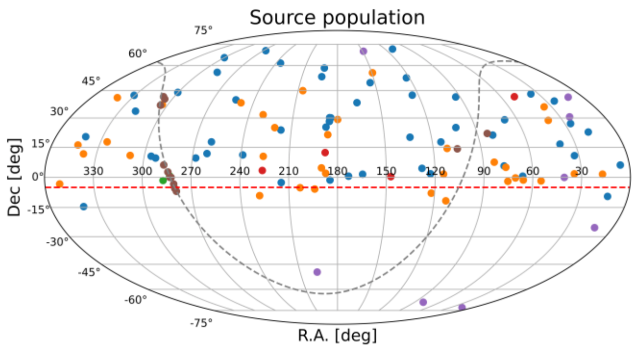
Analysis Outline

The following time-dependent analysis:

- Looks for transient sources with 10 years of IC data
- Can reconstruct multiple neutrino flares from one single direction
- Is based on an **unbinned maximum-likelihood method**

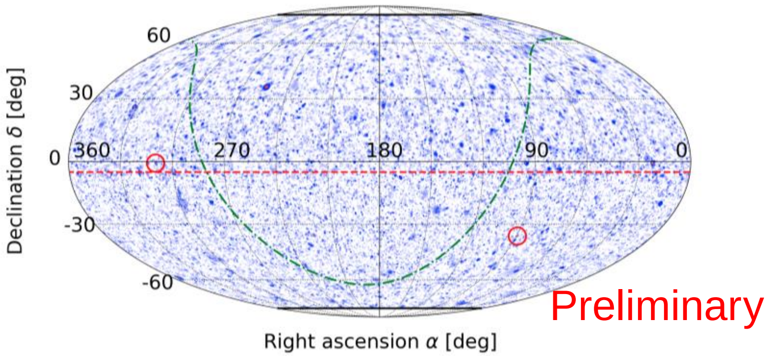
Catalogue search

- Tests the directions of 110 gamma-ray emitters
- Exploits the multi-messenger correlations
- Looks only at specific directions



All-sky search

- Looks at the full sky in an unbiased way
- Identifies the hottest spot in the full sky
- Strong penalisation for “look elsewhere” effect



Time-Dependent Likelihood

Single-event probability

$$\mathcal{L} = \prod_{i=1}^{N} \left[\left(\sum_{f=\text{flares}} \frac{n_s^f}{N} \mathcal{S}_i^f \right) + \left(1 - \frac{\sum_f n_s^f}{N} \right) \mathcal{B}_i \right]$$

Signal term

Background term

Time-Dependent Likelihood

$$\mathcal{L} = \prod_{i=1}^{N} \left[\left(\sum_{f=\text{flares}} \frac{n_s^f}{N} \mathcal{S}_i^f \right) + \left(1 - \frac{\sum_f n_s^f}{N} \right) \mathcal{B}_i \right]$$

Total events

Signal-like events in flare *f*

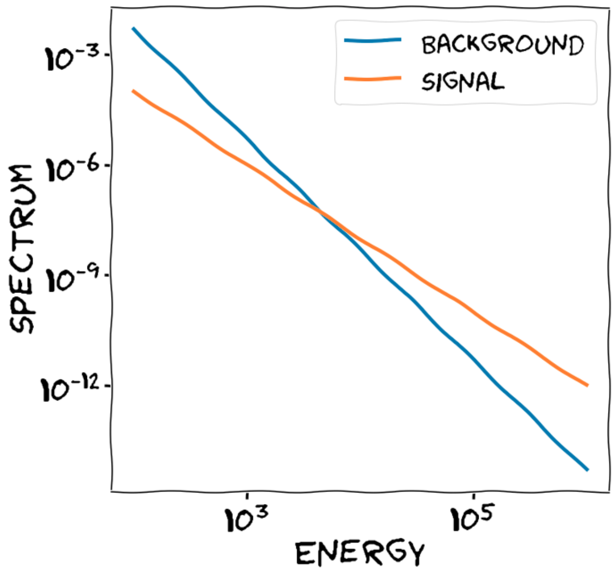
Single-flare signal PDF

Background PDF

Time-Dependent Likelihood

$$\mathcal{L} = \prod_{i=1}^{N} \left[\left(\sum_{f=\text{flares}} \frac{n_s^f}{N} \mathcal{S}_i^f \right) + \left(1 - \frac{\sum_f n_s^f}{N} \right) \mathcal{B}_i \right]$$

Signal/background PDF = Energy PDF X

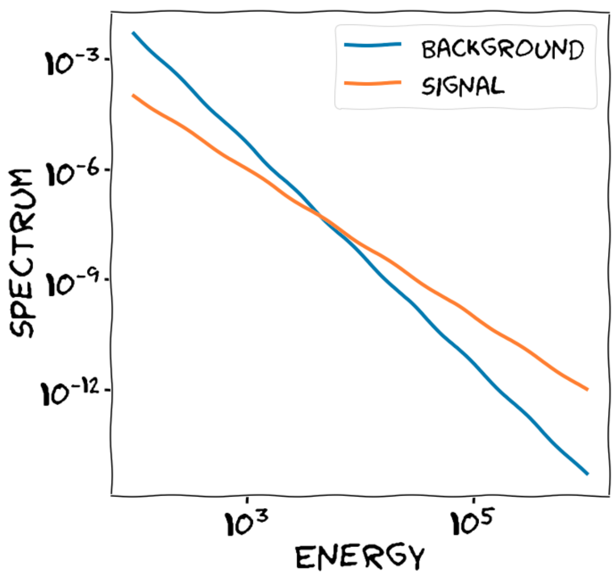


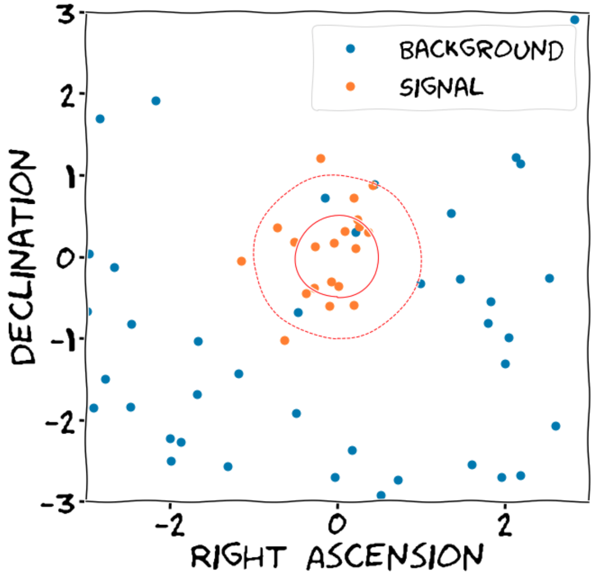
Signal: power-law $E^{-\gamma}$
Background: data-driven

Time-Dependent Likelihood

$$\mathcal{L} = \prod_{i=1}^{N} \left[\left(\sum_{f=\text{flares}} \frac{n_s^f}{N} \mathcal{S}_i^f \right) + \left(1 - \frac{\sum_f n_s^f}{N} \right) \mathcal{B}_i \right]$$

Signal/background PDF = Energy PDF X Spatial PDF X





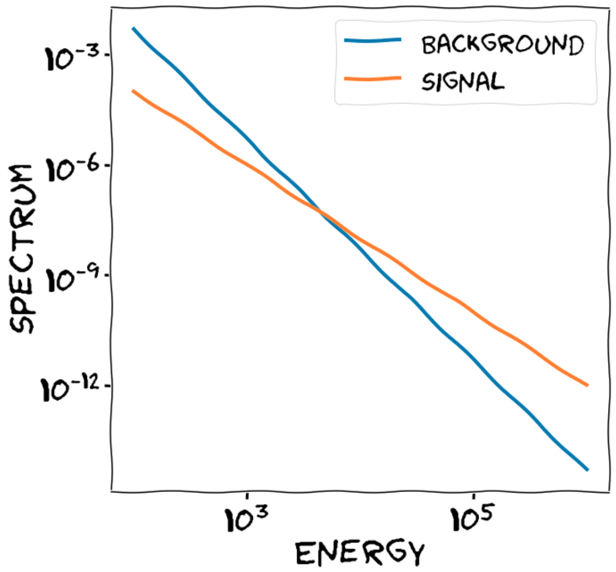
Signal: power-law $E^{-\gamma}$
Background: data-driven

Signal: 2D Gaussian
Background: data-driven

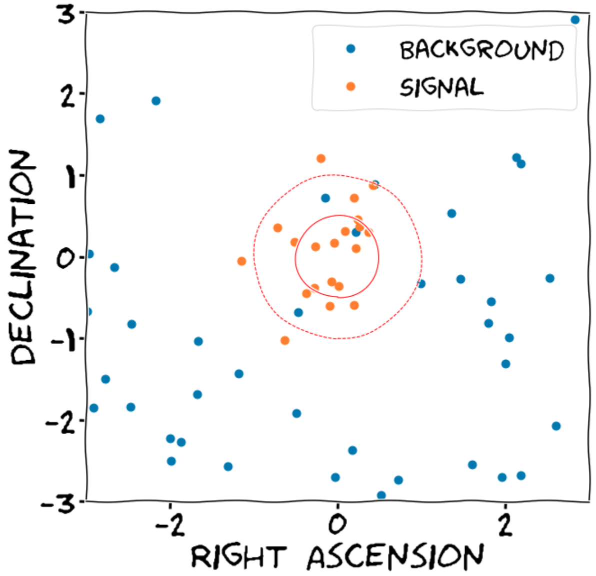
Time-Dependent Likelihood

$$\mathcal{L} = \prod_{i=1}^{N} \left[\left(\sum_{f=\text{flares}} \frac{n_s^f}{N} \mathcal{S}_i^f \right) + \left(1 - \frac{\sum_f n_s^f}{N} \right) \mathcal{B}_i \right]$$

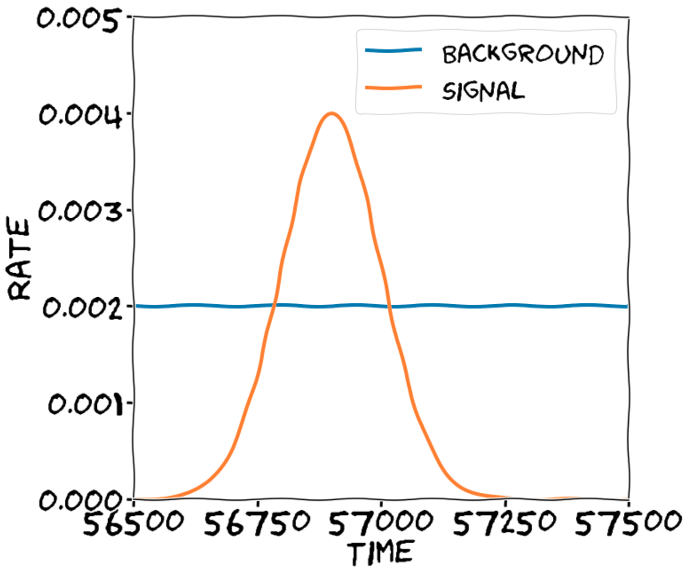
Signal/background PDF = Energy PDF X Spatial PDF X Temporal PDF



Signal: power-law $E^{-\gamma}$
Background: data-driven



Signal: 2D Gaussian
Background: data-driven



Signal: Gaussian $G(t_i|t_0^f, \sigma_T^f)$
Background: uniform

Test Statistic

Background likelihood

Full data livetime

$$\mathrm{TS} = -2\log\left[\frac{1}{2}\left(\prod_{f=\mathrm{flares}} \frac{T_{live}}{\sigma_T^f \int G(t|t_0^f, \sigma_T^f)dt}\right) \times \frac{\mathcal{L}(\vec{n}_s = \vec{0})}{\mathcal{L}(\hat{\vec{n}}_s, \hat{\vec{\gamma}}, \hat{\vec{t}}_0, \hat{\vec{\sigma}}_T)}\right]$$

Gaussian time PDF

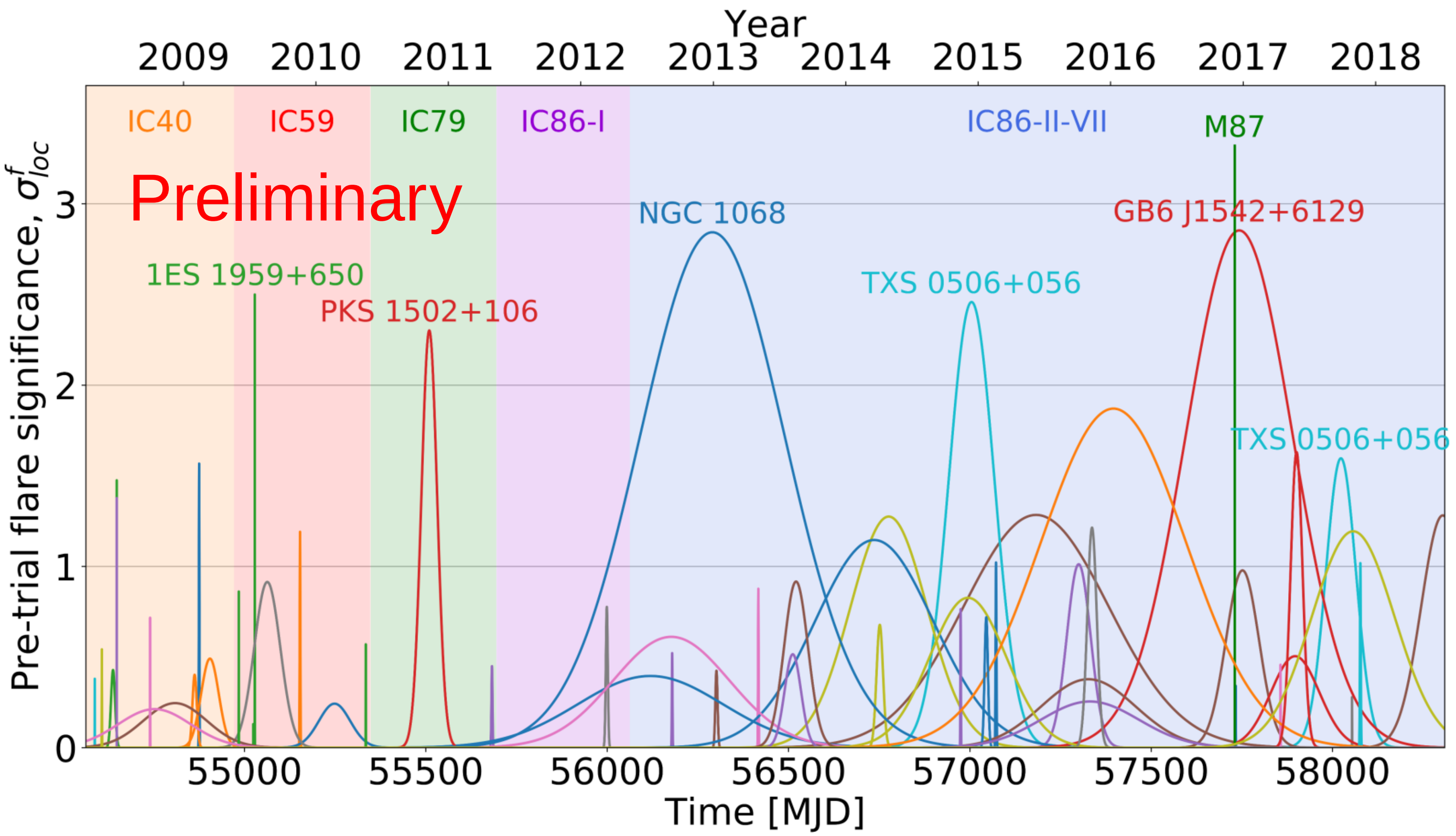
Marginalization term

Maximum likelihood

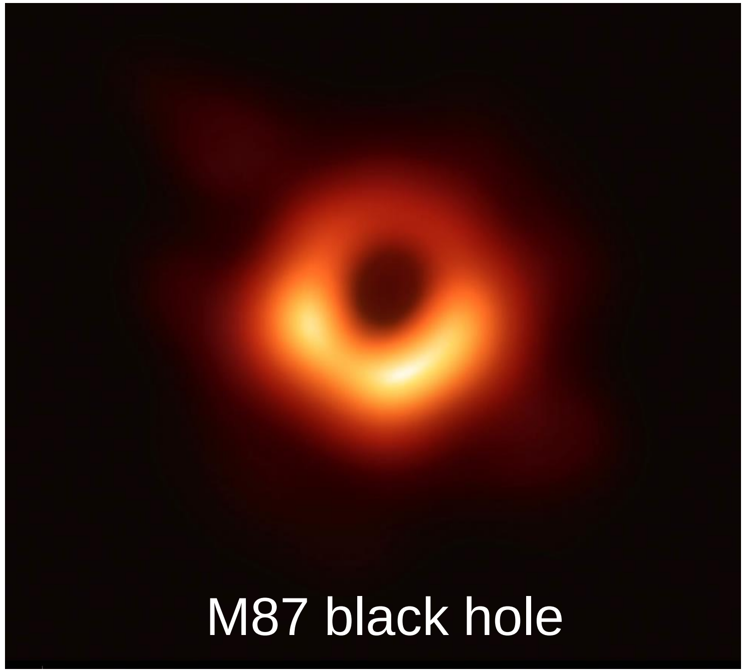
- For any tested direction, the TS is used to evaluate a p-value
- When needed, the p-value is further penalised for the “look else-where” effect

Catalogue Search

Individual source results



- Hottest source: M87, 1.7σ
- TXS 0506+056 only multi-flare source
- No hints of time-dependency from NGC 1068



Catalogue Search

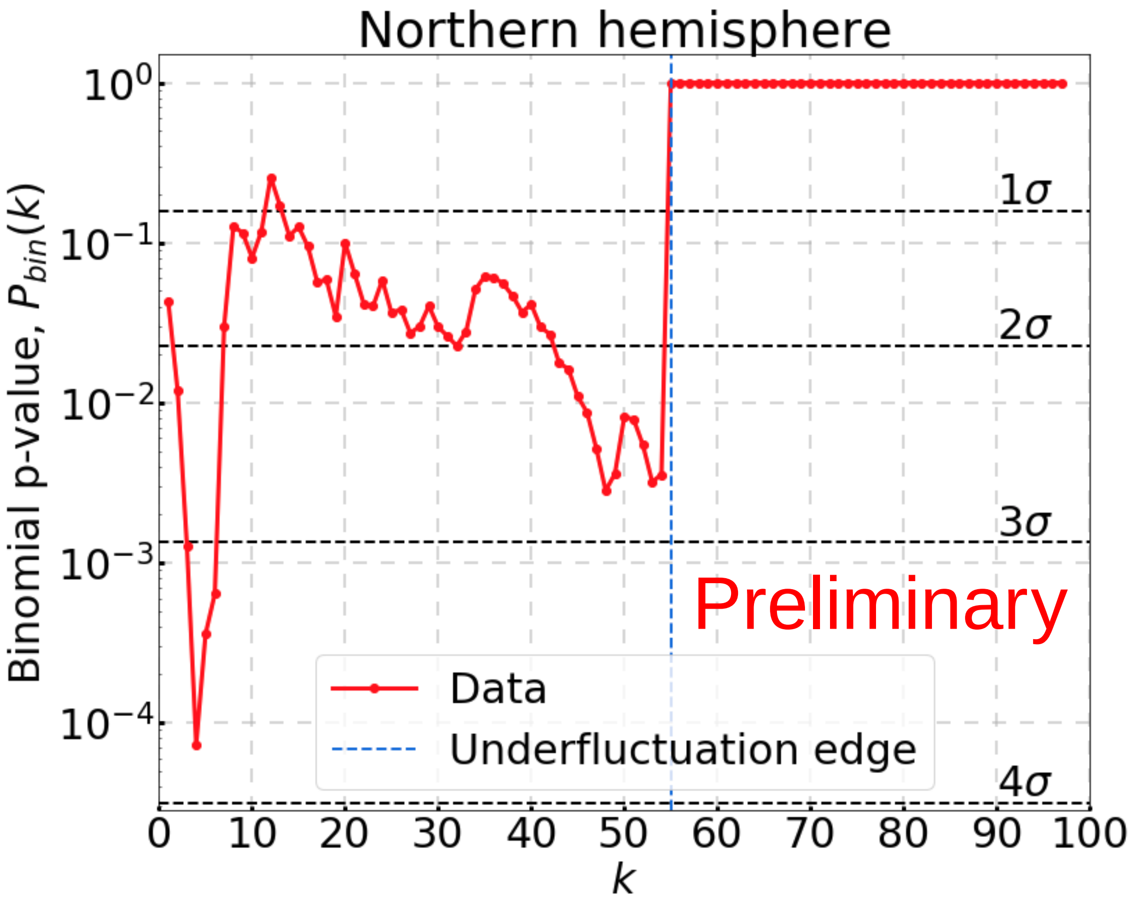
Population Test

Looks for a cumulative excess of neutrinos from a subset of sub-threshold sources

Source p-values are sorted and a binomial p-value is evaluated for each source index k:

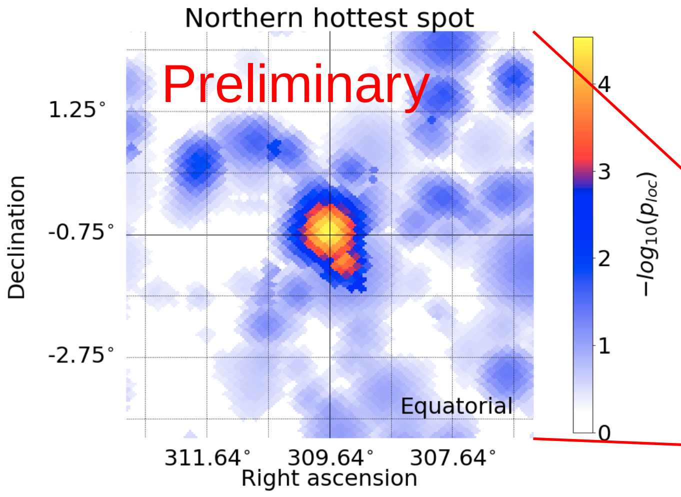
$$P_{bin}(k) = \sum_{m=k}^{N_{src}} \binom{N}{m} p_k^m (1 - p_k)^{N-m}$$

Result: Excess in Northern sky at 3.0σ when $k = 4$ sources are considered (M87, TXS 0506+056, NGC 1068, GB6 J1542+6129)

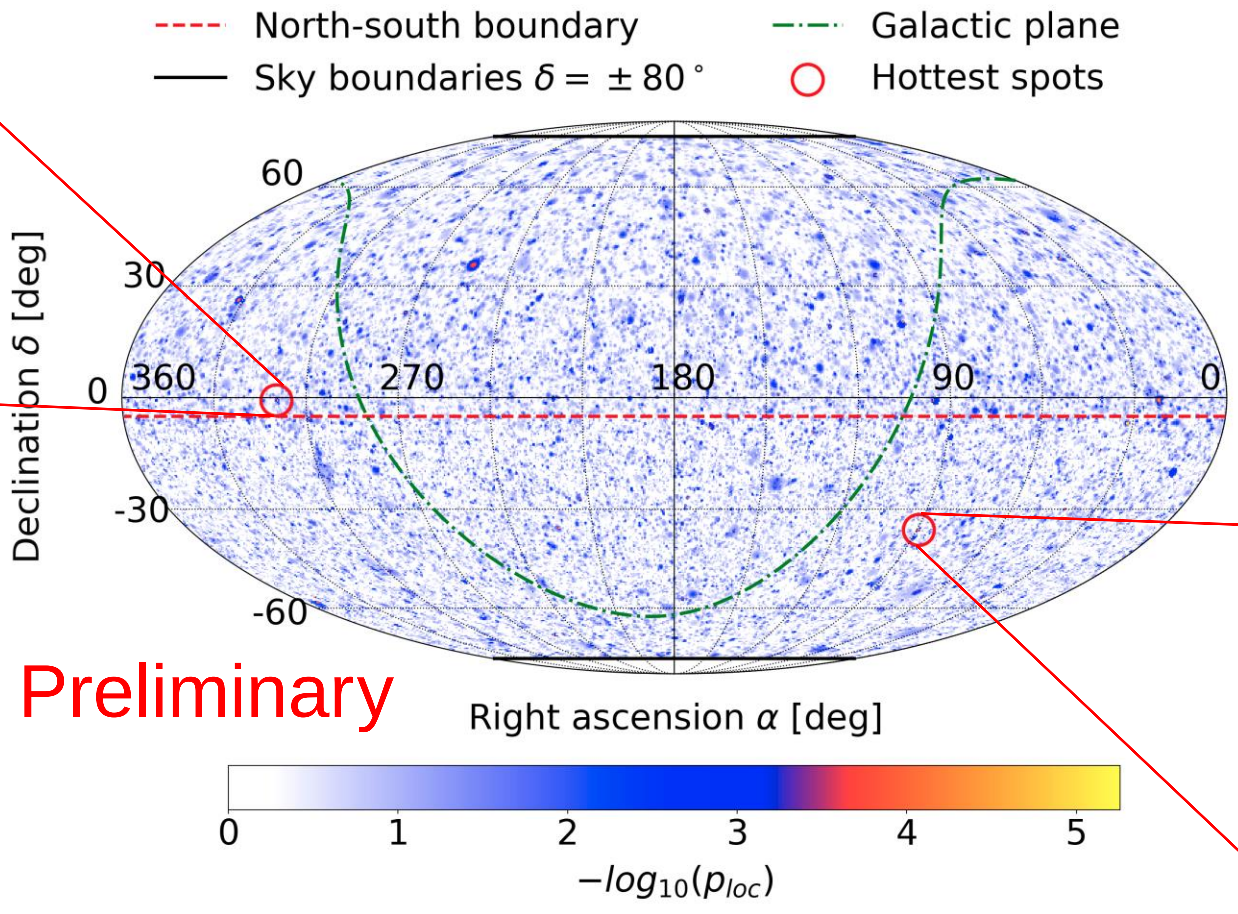


All-Sky Search

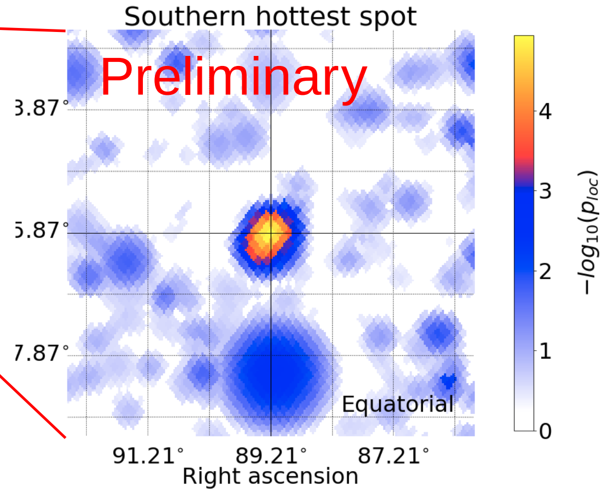
Hottest Spot



R. A. = 309.64°
dec = −0.75°
p_{val} = 0.98



R. A. = 89.21°
dec = −35.87°
p_{val} = 0.90



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All-Sky Search

Population Test

Looks for a cumulative excess from sub-threshold hot spots in the sky.

Based on Poissonian statistics:

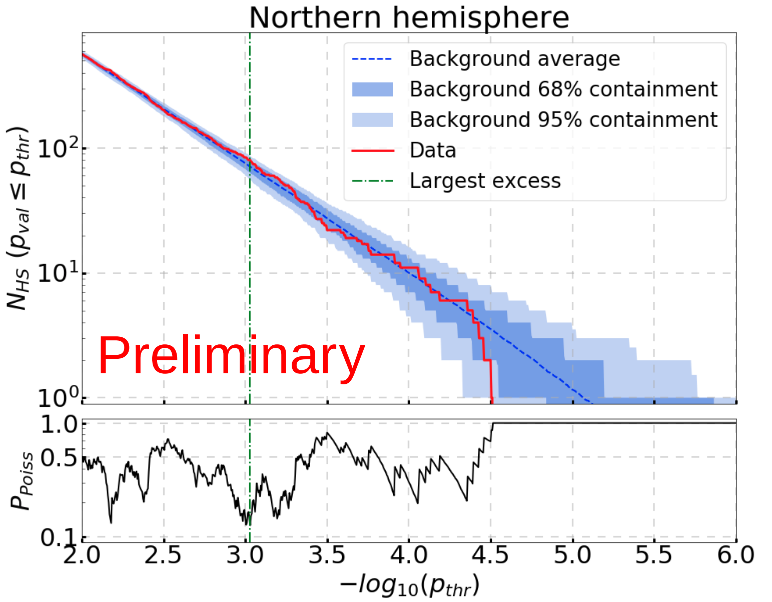
$$P_{Poiss}(p_{thr}) = e^{-\lambda(p_{thr})} \sum_{m=k(p_{thr})}^{\infty} \frac{\lambda(p_{thr})^m}{m!}$$

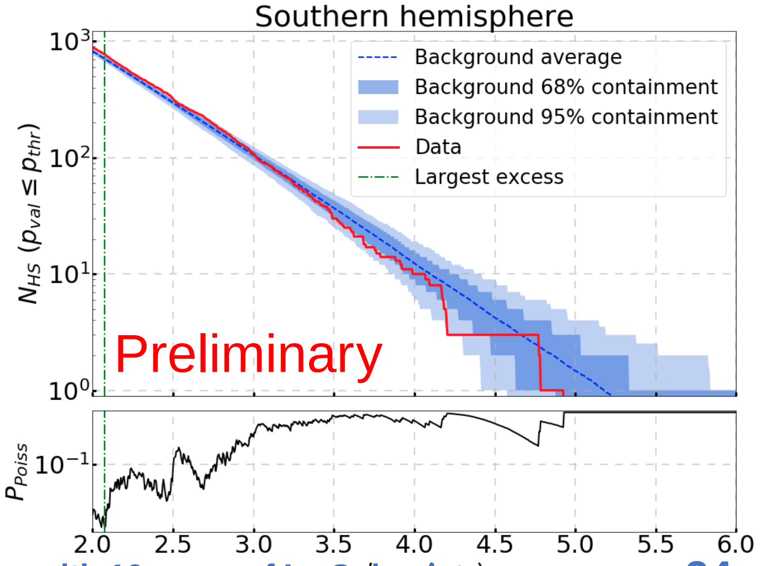
Expected hot spots (↑ $\lambda(p_{thr})$)

Observed hot spots (↓ $k(p_{thr})$)

After scanning some p_{thr}, the smallest $P_{Poiss}(p_{thr})$ is selected and corrected for the "look else-where" effect

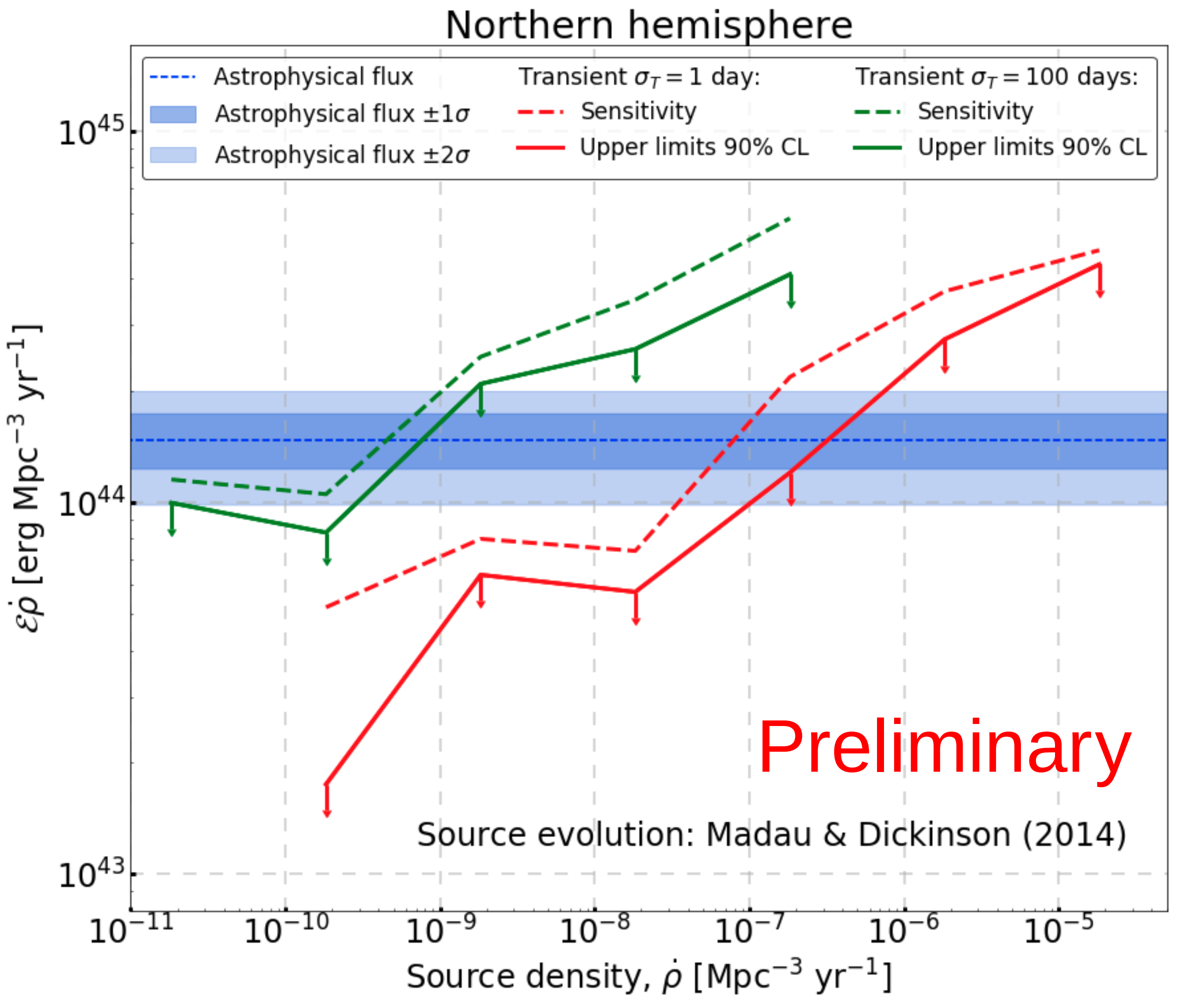
Hemisphere	Corrected P_{Poiss}
North	0.85
South	0.22





All-Sky Search

Population Test



The population test is used to constrain the luminosity and density of a population of transient sources assuming:

- Single-flare emission
- Isotropic source distribution
- Source spectrum $dN/dE \propto E^{-2.28}$
- Time scales of 1 and 100 days
- Source evolution: Madau & Dickinson (2014)

Simulations of flare intensities and source distributions are based on FIRESONG

Conclusions

- A multi-flare method has been implemented in the IceCube likelihood
- No significant transient sources are observed, although promising hints come from the catalogue search
- The all-sky results are used to constrain the parameters of an hypothetical all-sky population of transient sources
- In the near future, improvements of the analysis and additional data can bring interesting results. Stay tuned!

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FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

We wish to acknowledge the Swiss National Science Foundation for its support in this and other IceCube ananlyses

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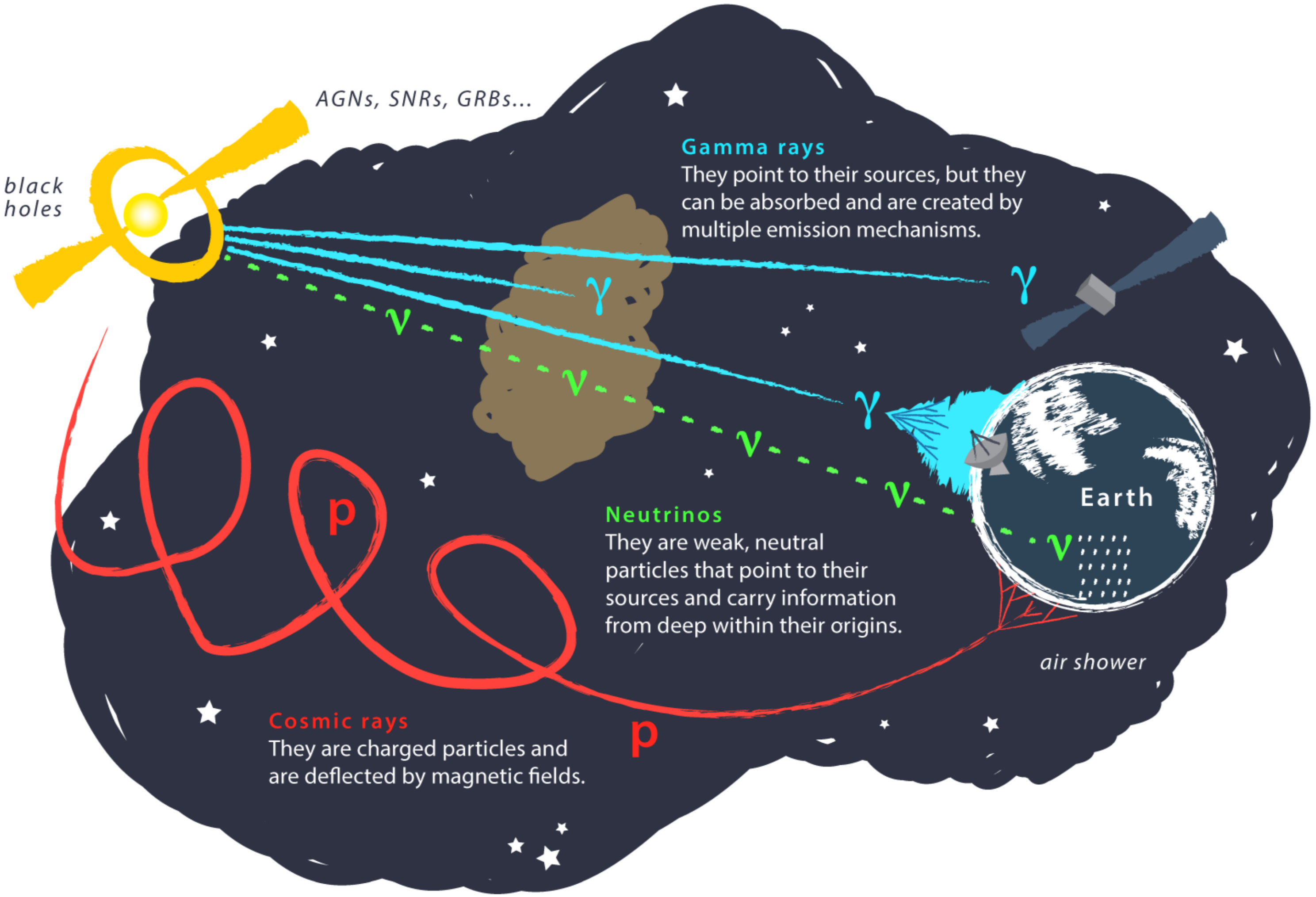
BACKUP

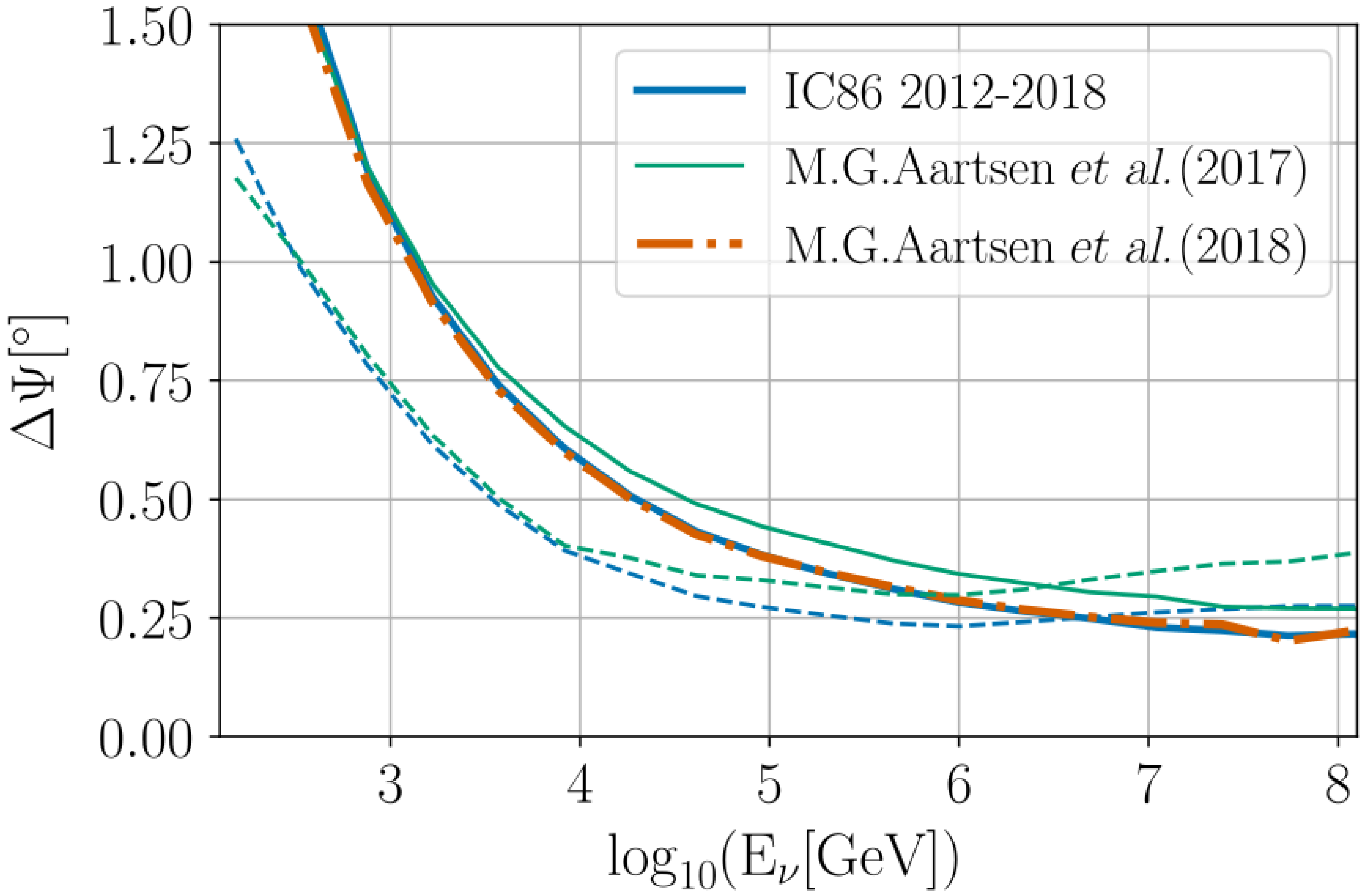
Why Neutrino Astronomy?



Astroparticles in the multi-messenger era:

- Cosmic rays
  - Easy to detect
  - Deflected by magnetic fields
  - Interact during travel
- Gamma rays
  - Easy to detect
  - Point back to the source
  - Absorbed during travel
- Neutrinos
  - Difficult to detect
  - Point back to the source
  - Travel unaffected through the Universe

Angular Resolution

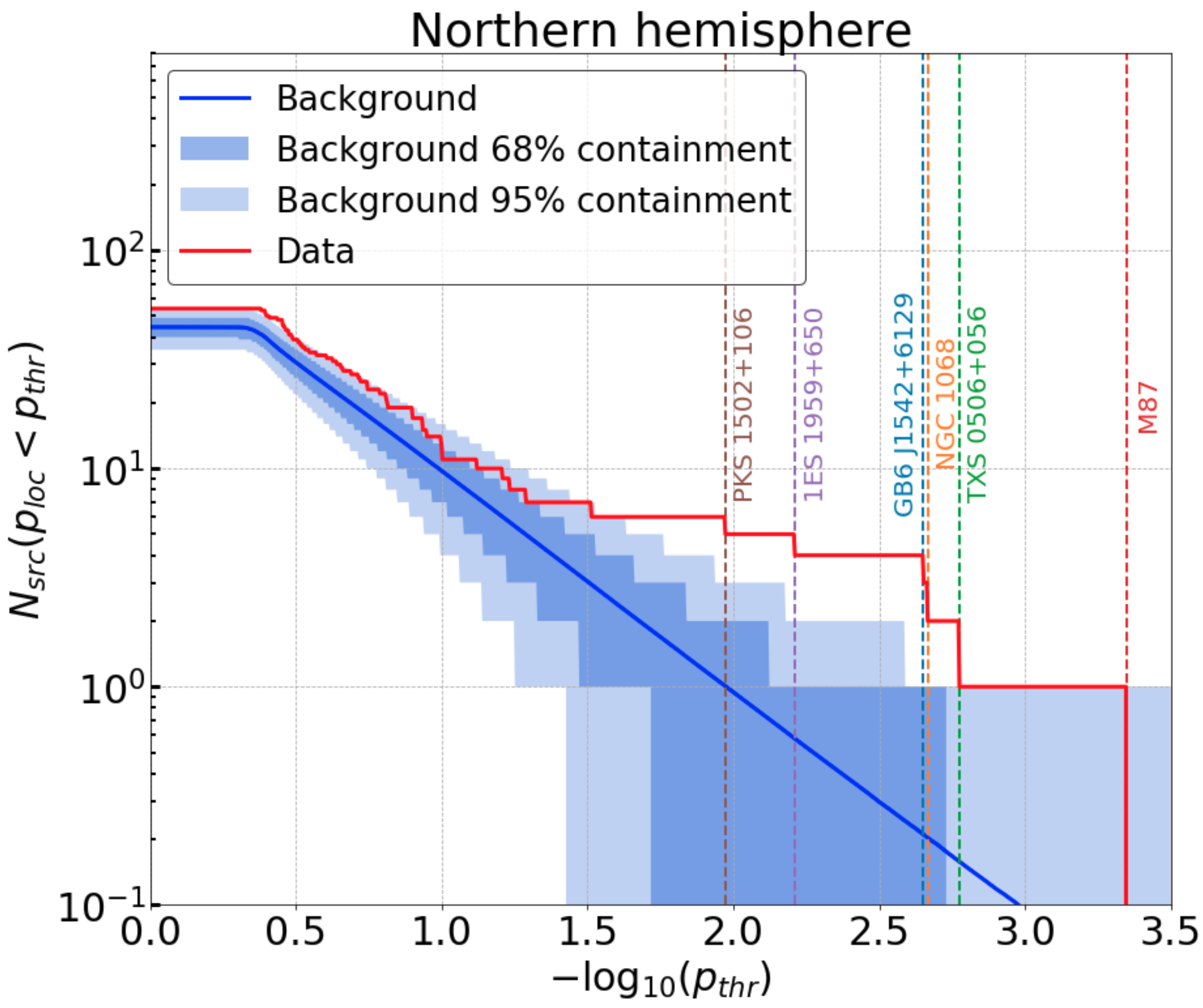


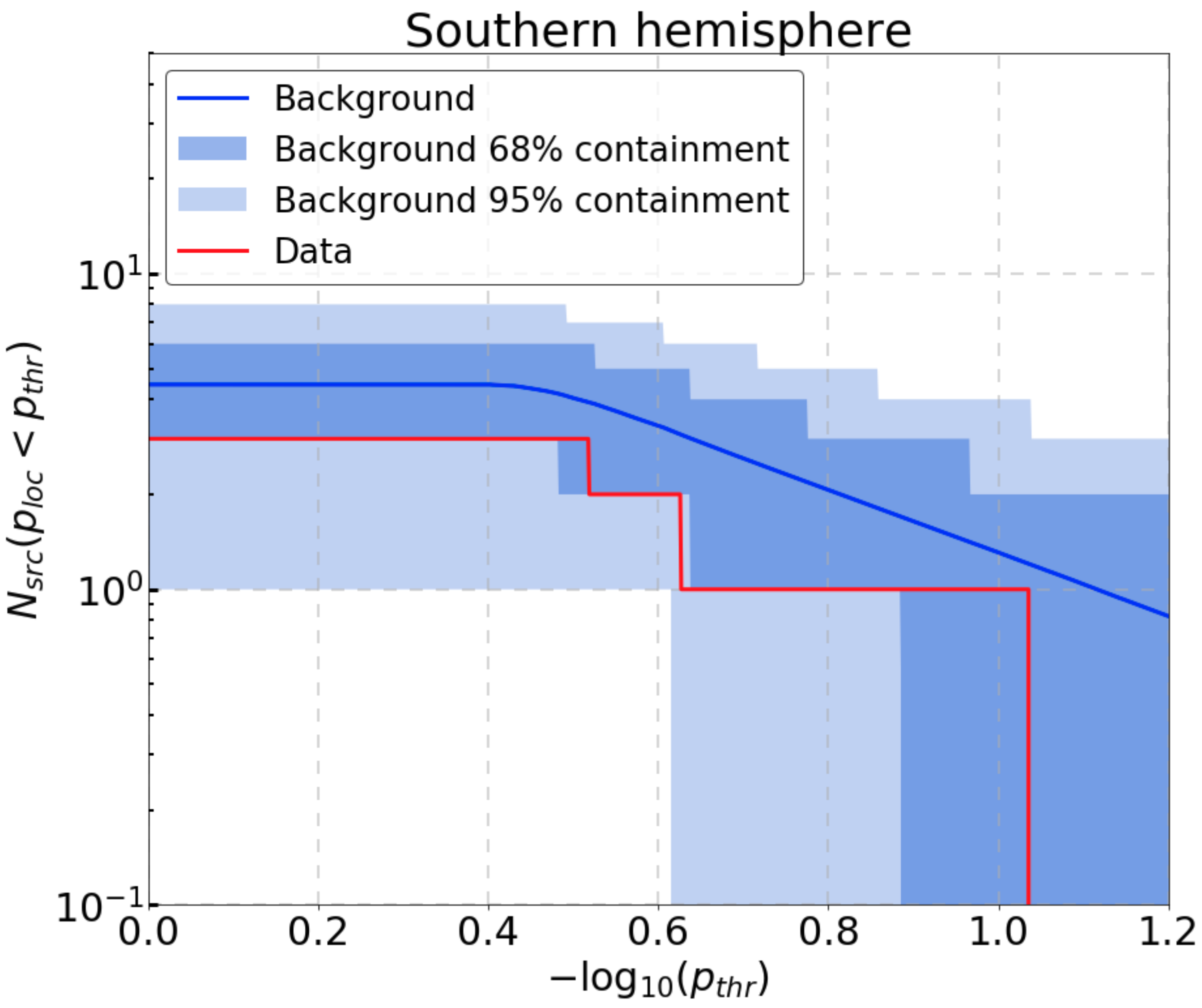
Solid lines: Northern hemisphere

Dashed lines: Southern hemisphere

Catalog Search

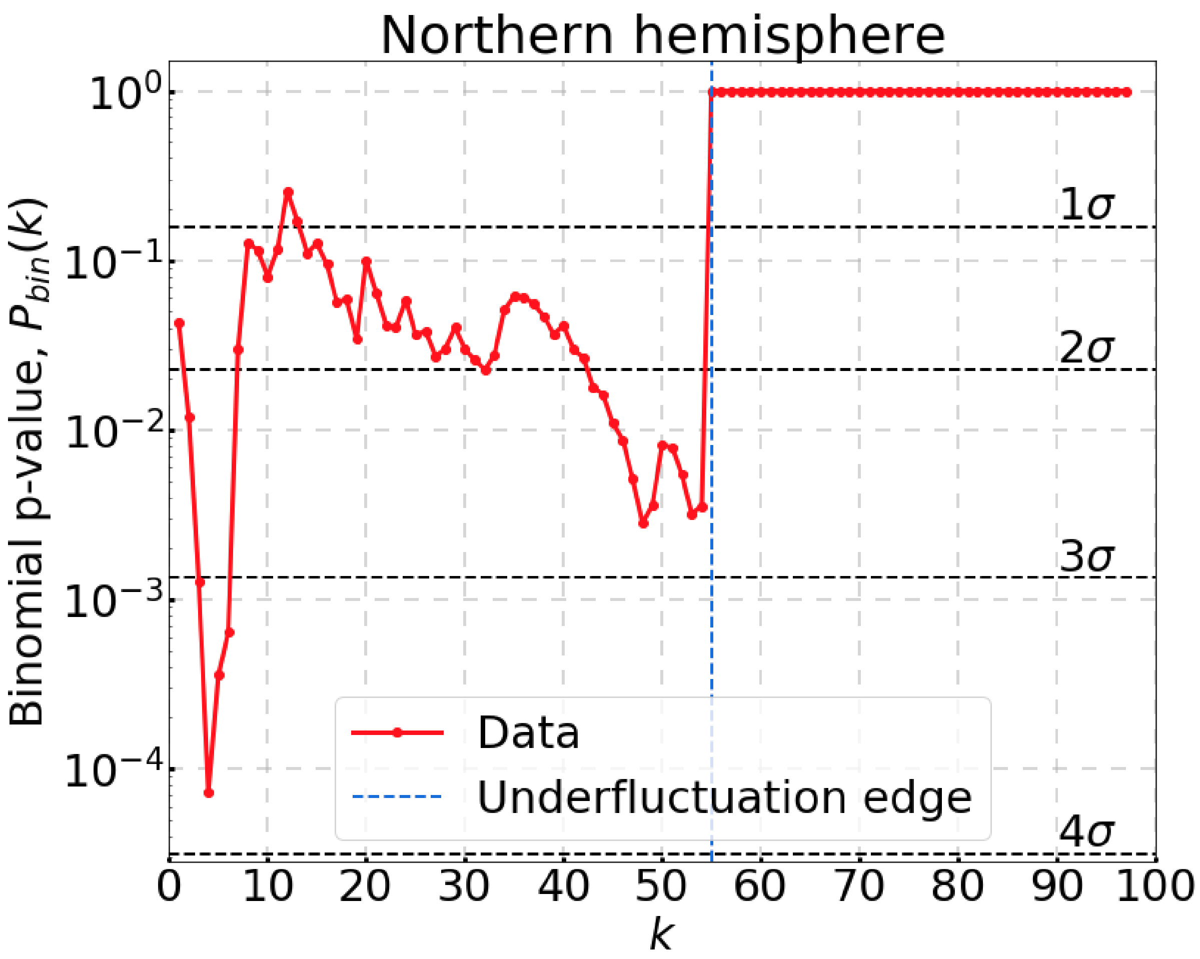
Source p-values

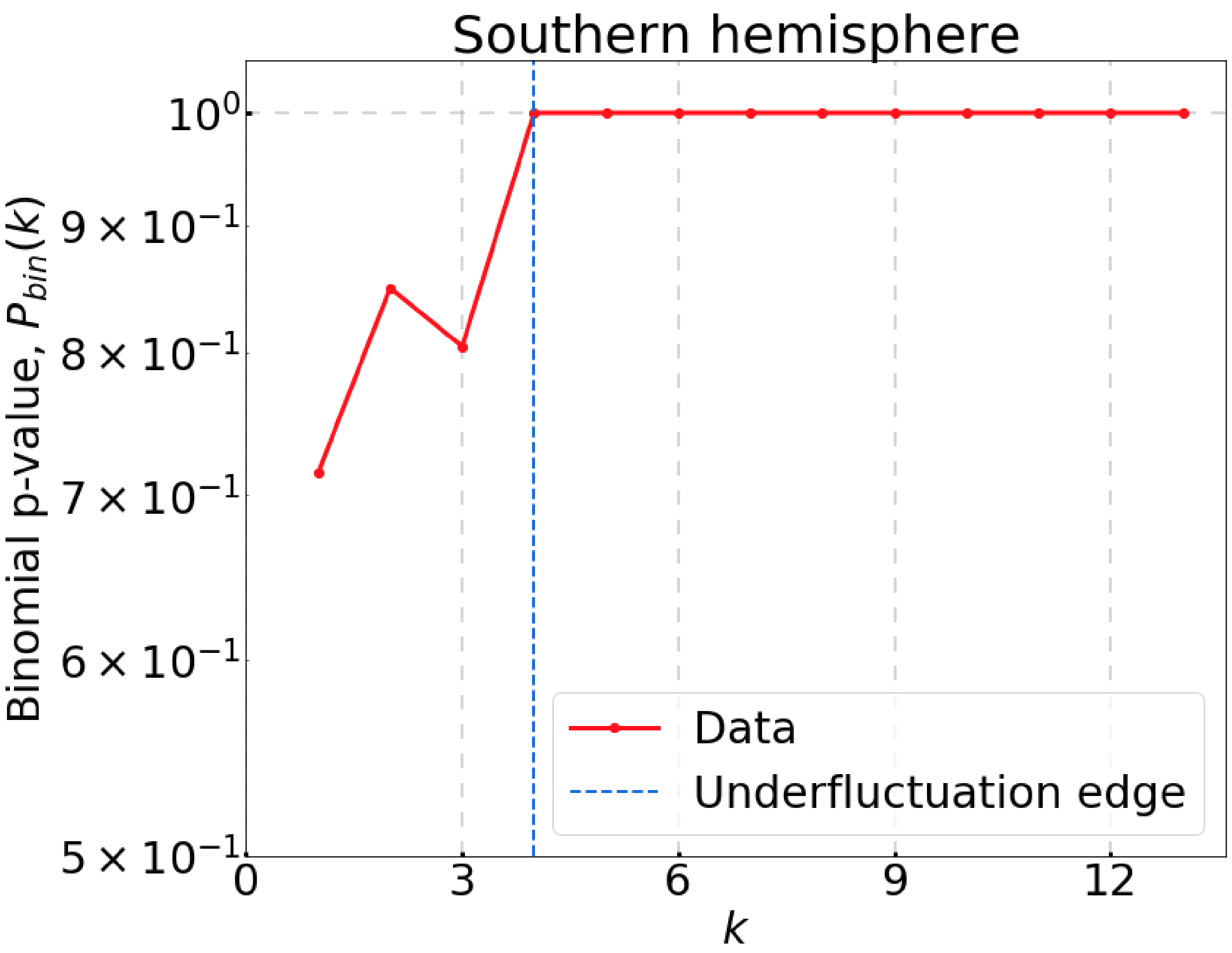




Catalog Search Population Test

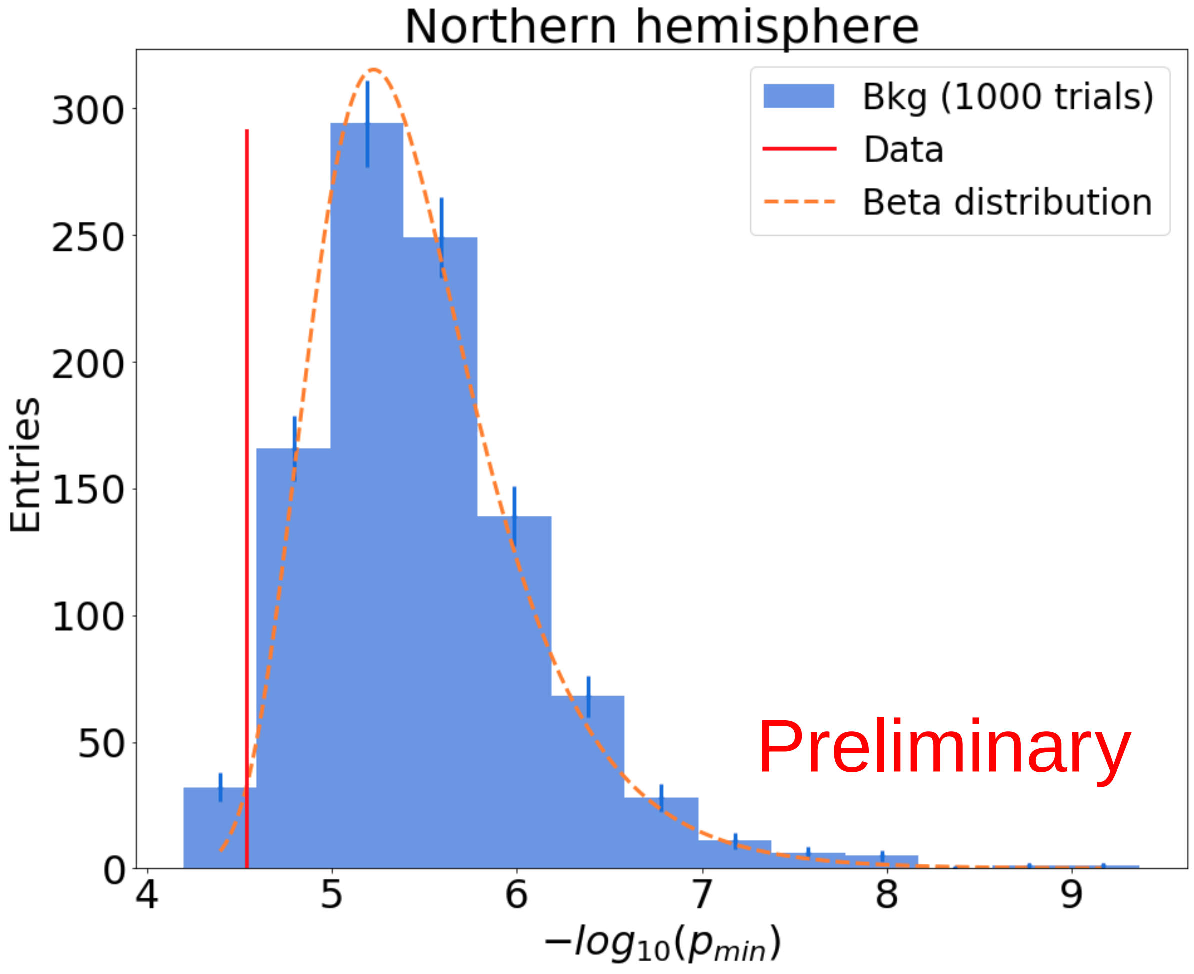
Binomial p-value

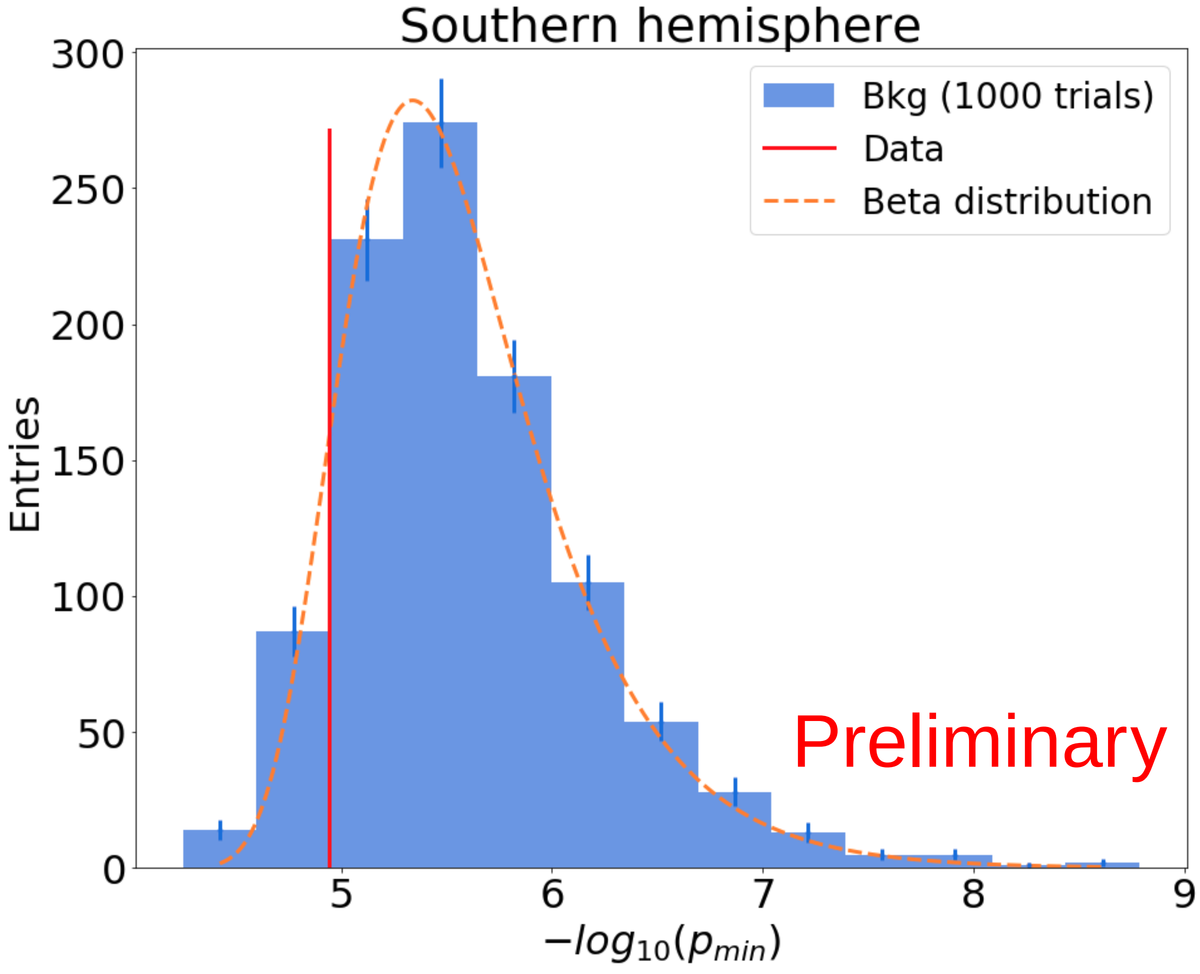




All-Sky Hottest Spot

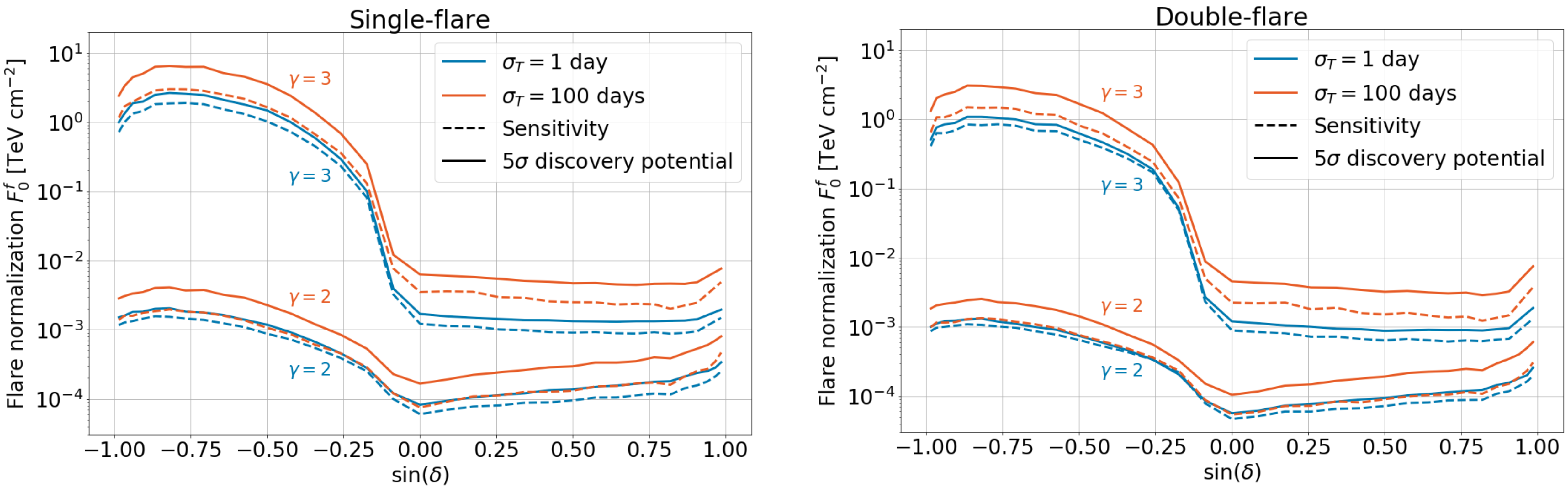
Post-trial p-value





All-Sky Sensitivity

$$\Phi(E,t) = \sum_{f=\text{flares}} \frac{F_0^f}{\sqrt{2\pi}\sigma_T^f}\left(\frac{E}{\text{TeV}}\right)^{-\gamma^f} G(t|t_0^f,\sigma_T^f)$$



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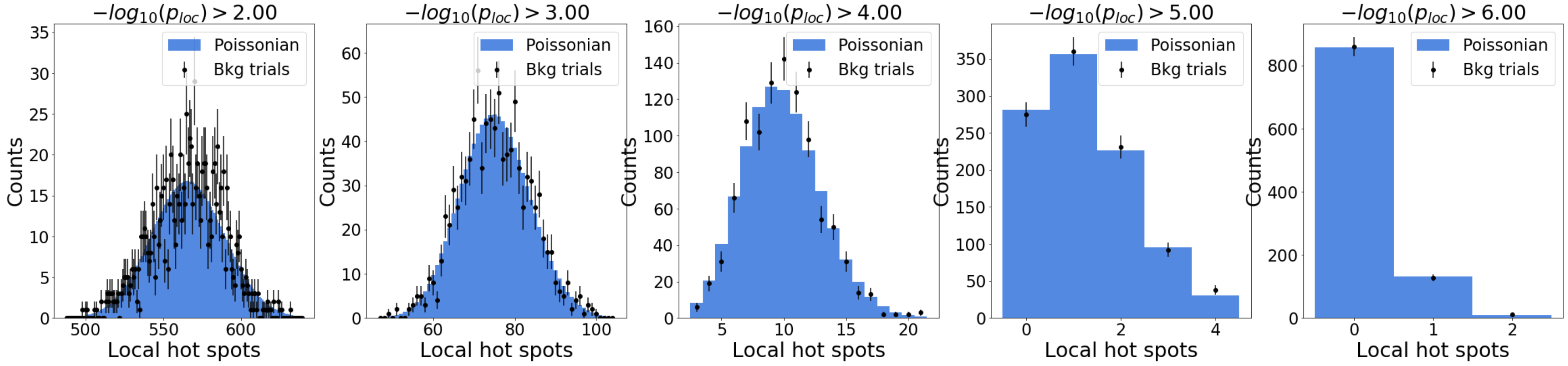
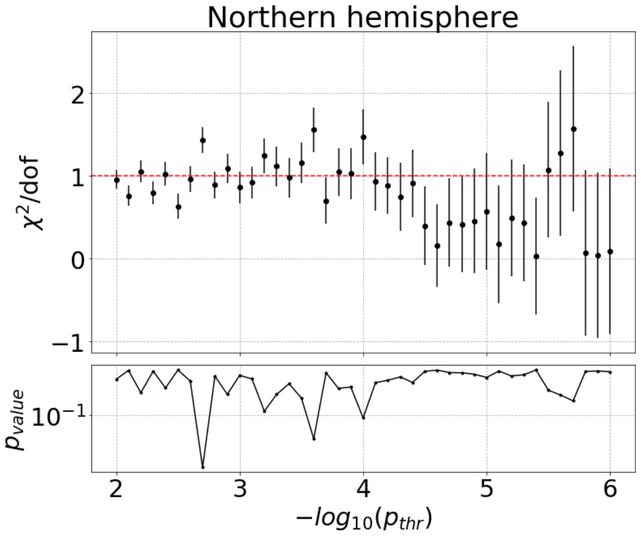
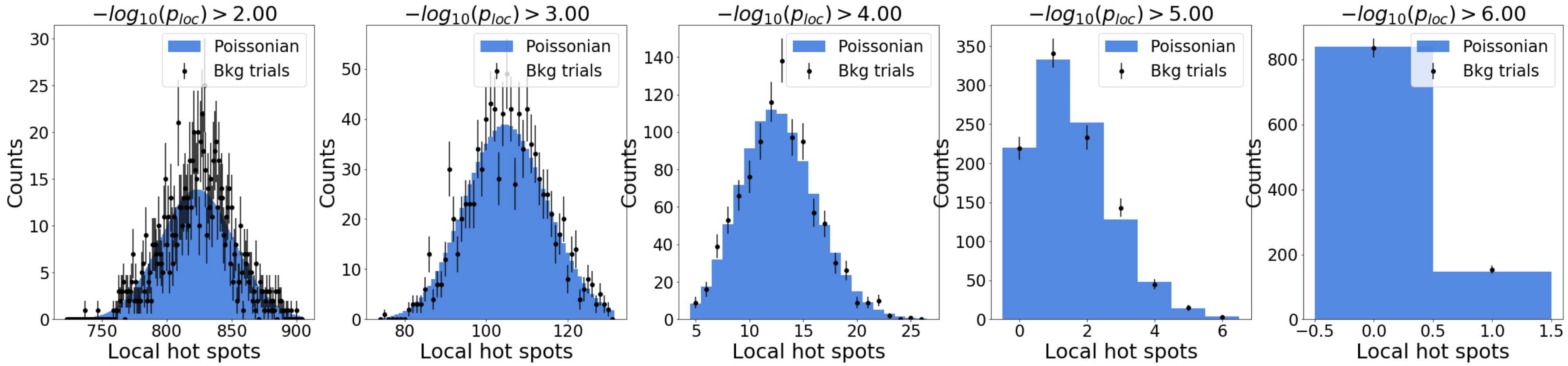
Hot Spot Distribution

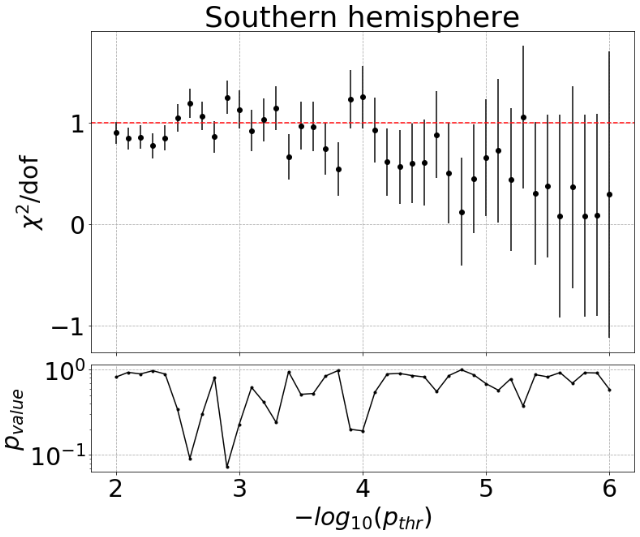
Northern hemisphere





Southern hemisphere





All-Sky Population Test

Post-trial p-value