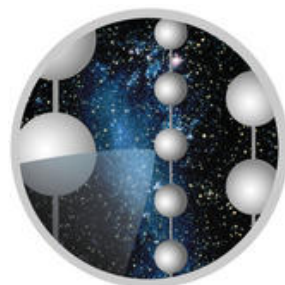


The Search for High Energy Neutrinos

A TDE Stacking Analysis

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ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



Overview

01 Overview of Neutrino Astronomy

02 Diffuse High-Energy Neutrino Flux

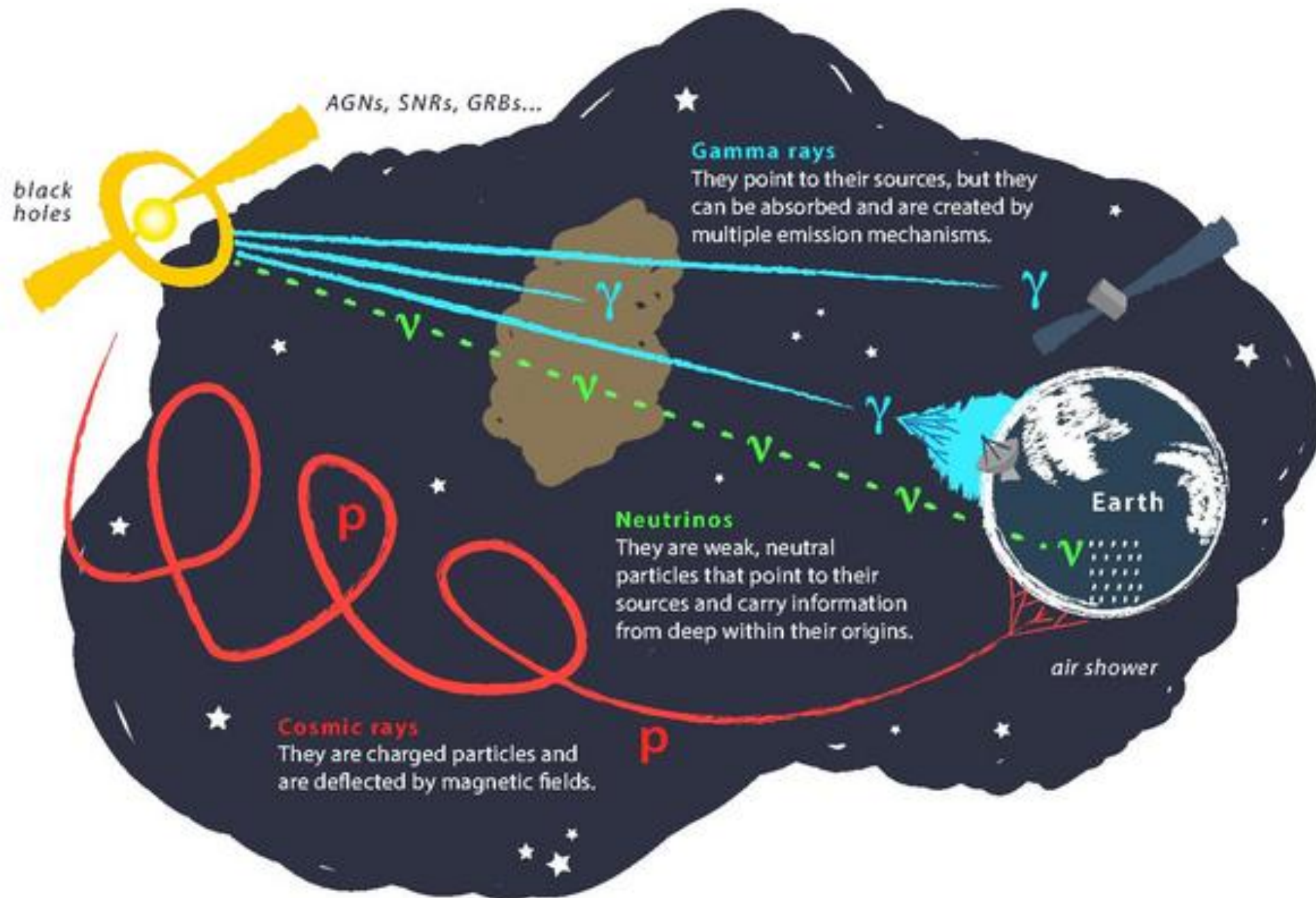
03 Why TDEs?

04 Analysis Plan

05 Outlook



The dawn of Multi-messenger Astronomy



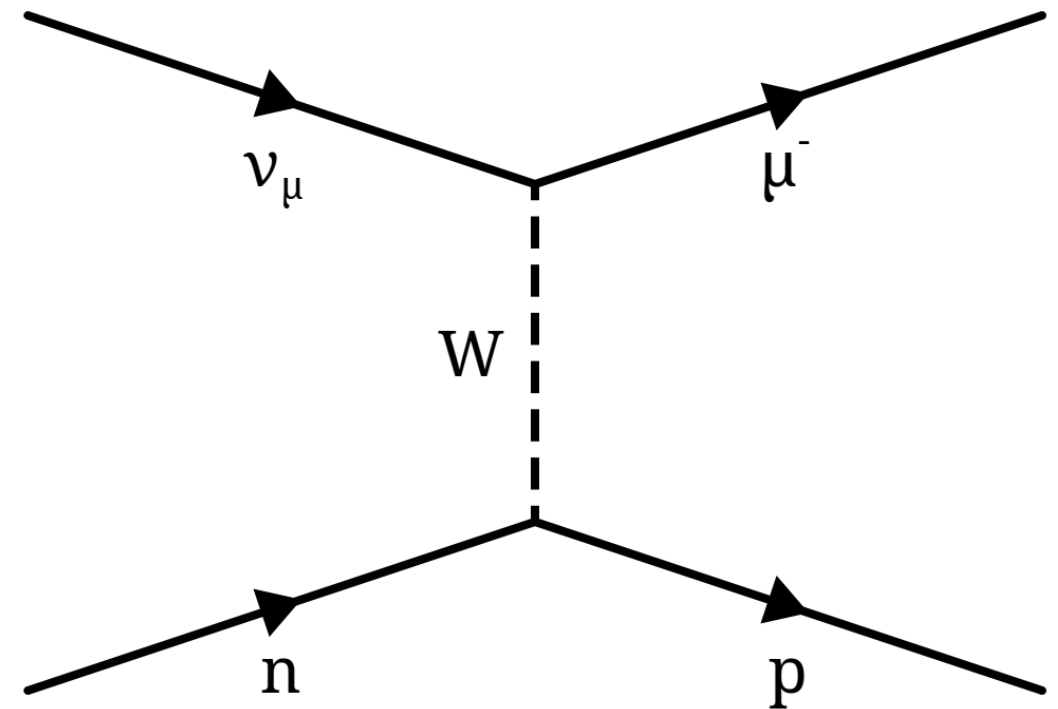
How to detect astrophysical neutrinos...

What to do

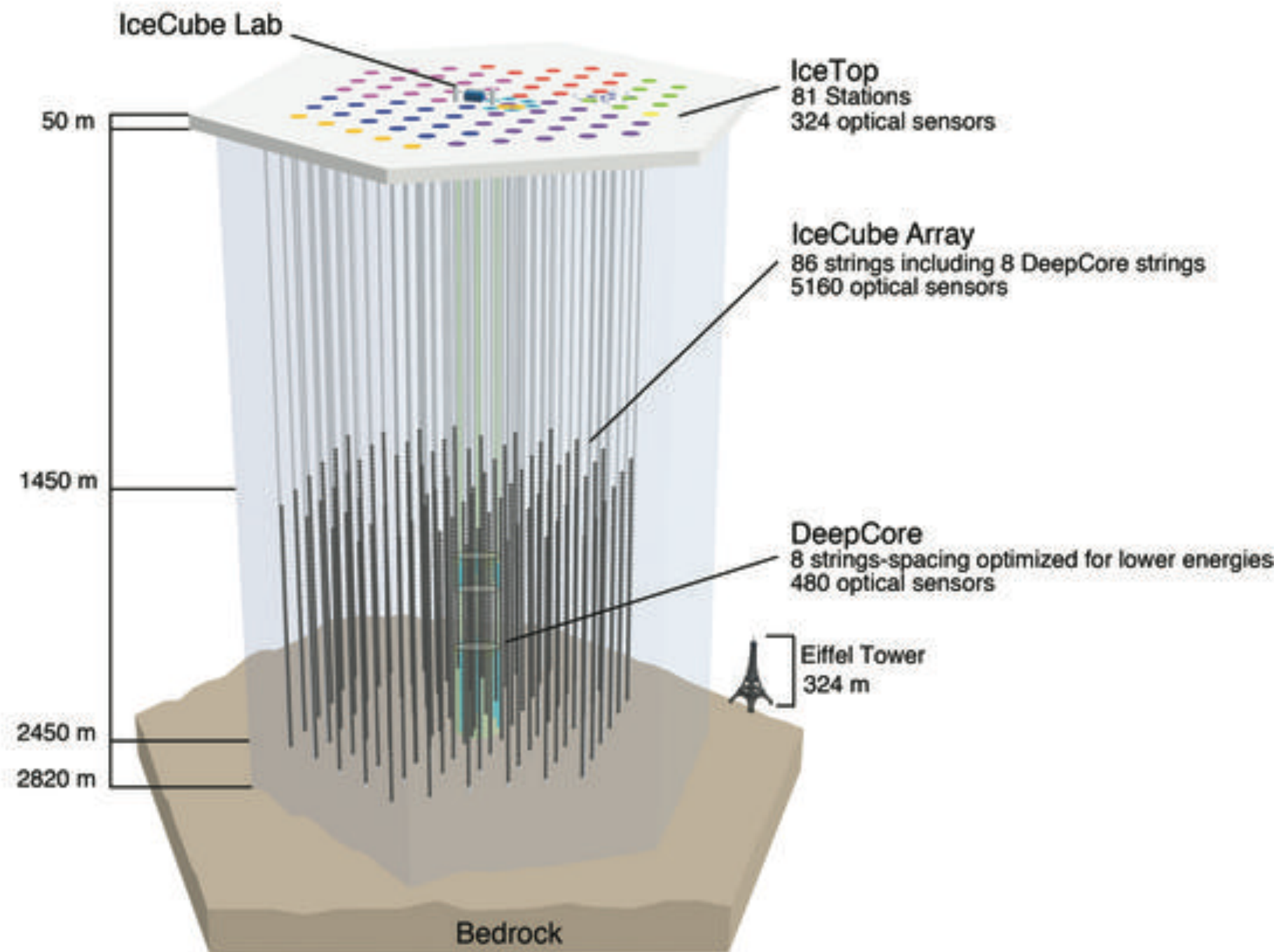
- Look for Neutrino-nucleon interaction
- Detect decay products via Cherenkov Radiation
- Reconstruct decay to estimate energy and direction of incoming neutrino

But...

- The cross-section is small
- Need spatial evolution of shower
- Atmospheric muons “look like” astrophysical neutrinos, and there are many more of them!
- Atmospheric neutrinos appear identical to astrophysical neutrinos, and dominate the neutrino sample.



Introducing the IceCube Neutrino Observatory



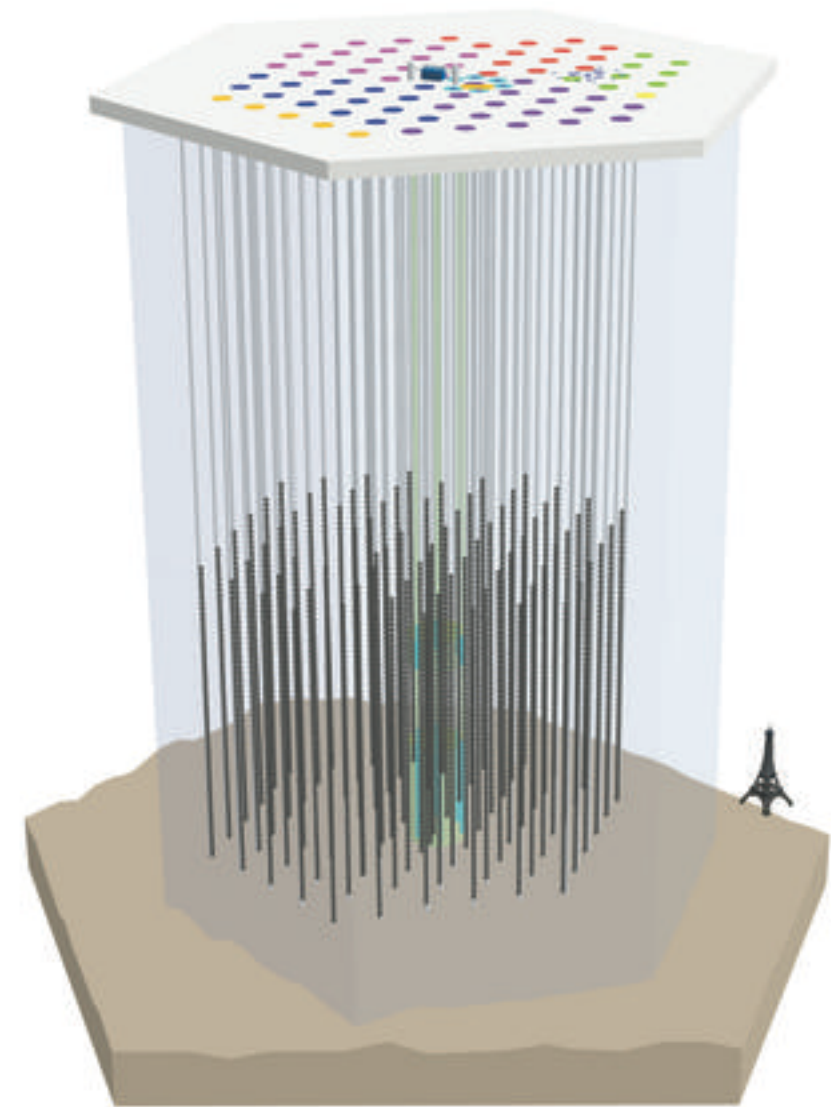
Does this solve the problem?

But...

- The cross-section is small
- Need spatial evolution of shower
- Atmospheric muons “look like” astrophysical neutrinos, and there are many more of them!
- Atmospheric neutrinos also “look like” astrophysical neutrinos

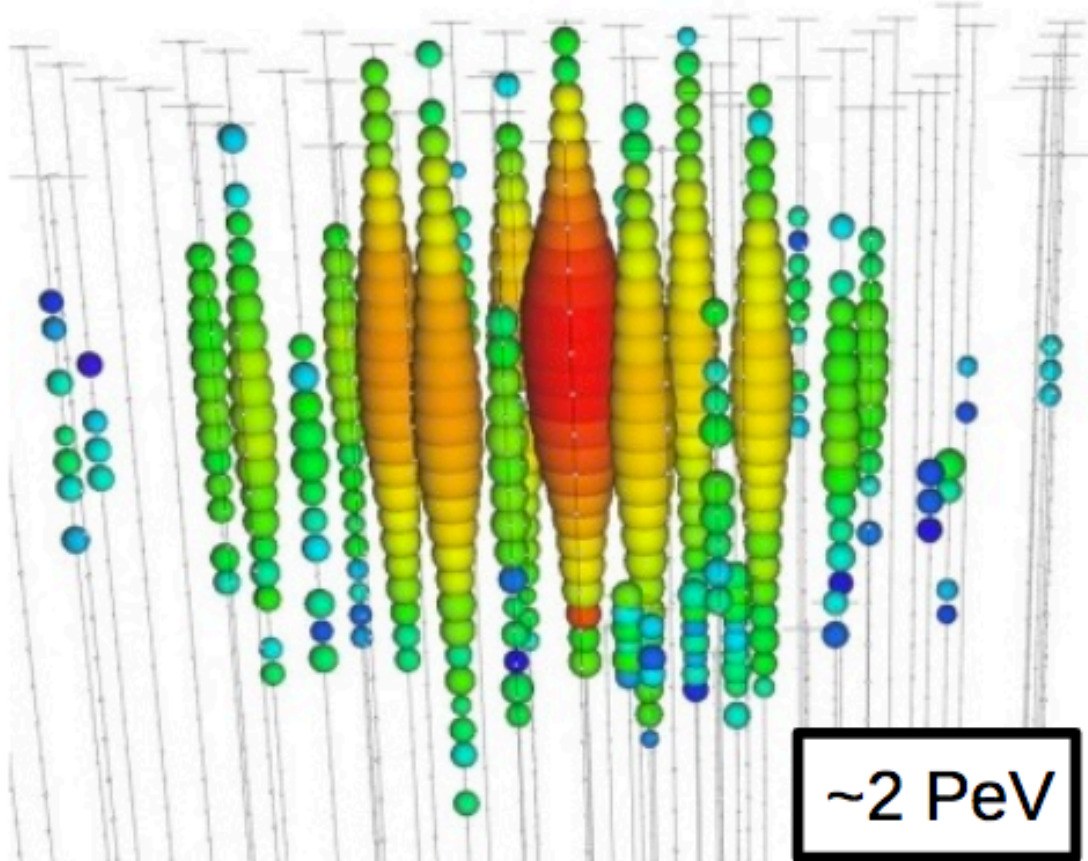
With IceCube...

- Huge detector volume
- Many DOMs throughout ice record shower
- For upgoing events, Earth absorbs muons
- Still have significant atmospheric neutrinos. This is the challenge for IceCube - “needle in a haystack”!



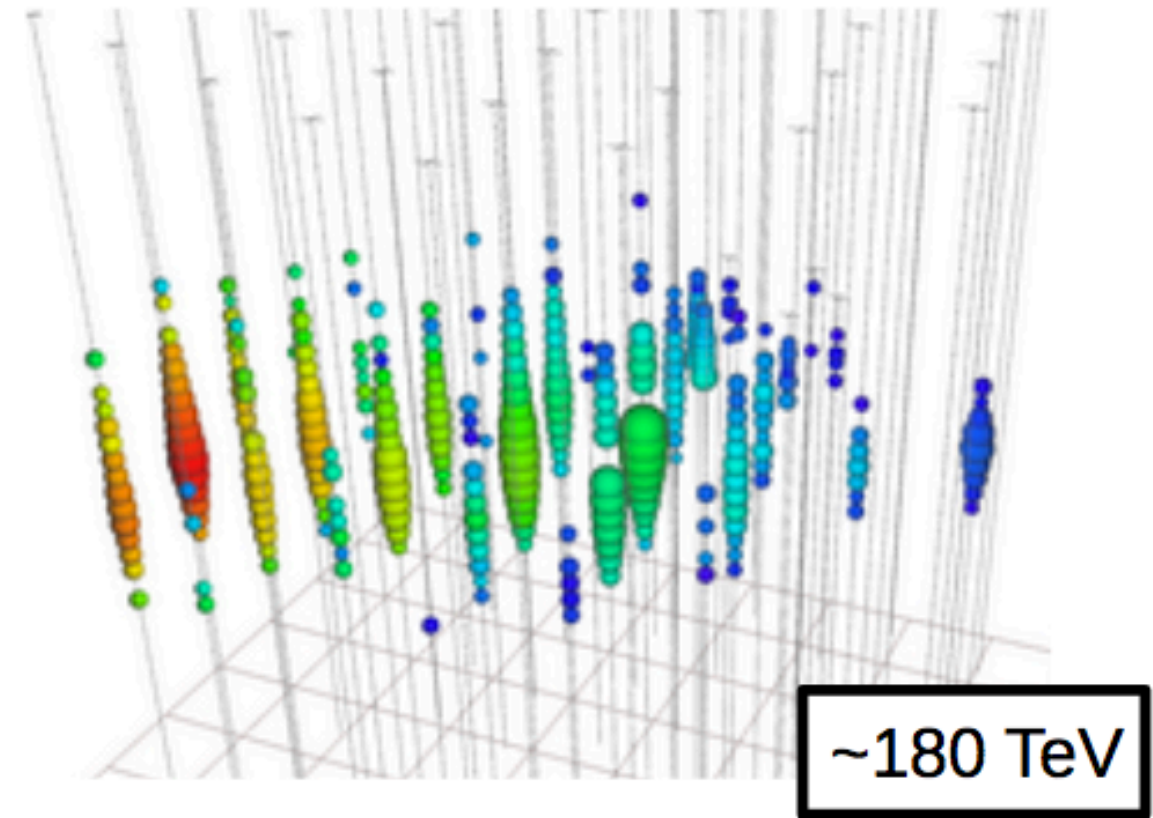
What does IceCube actually see?

Cascade-like events



- > charged current interactions of ν_e, ν_τ
- > neutral current interactions
- > good energy measurement

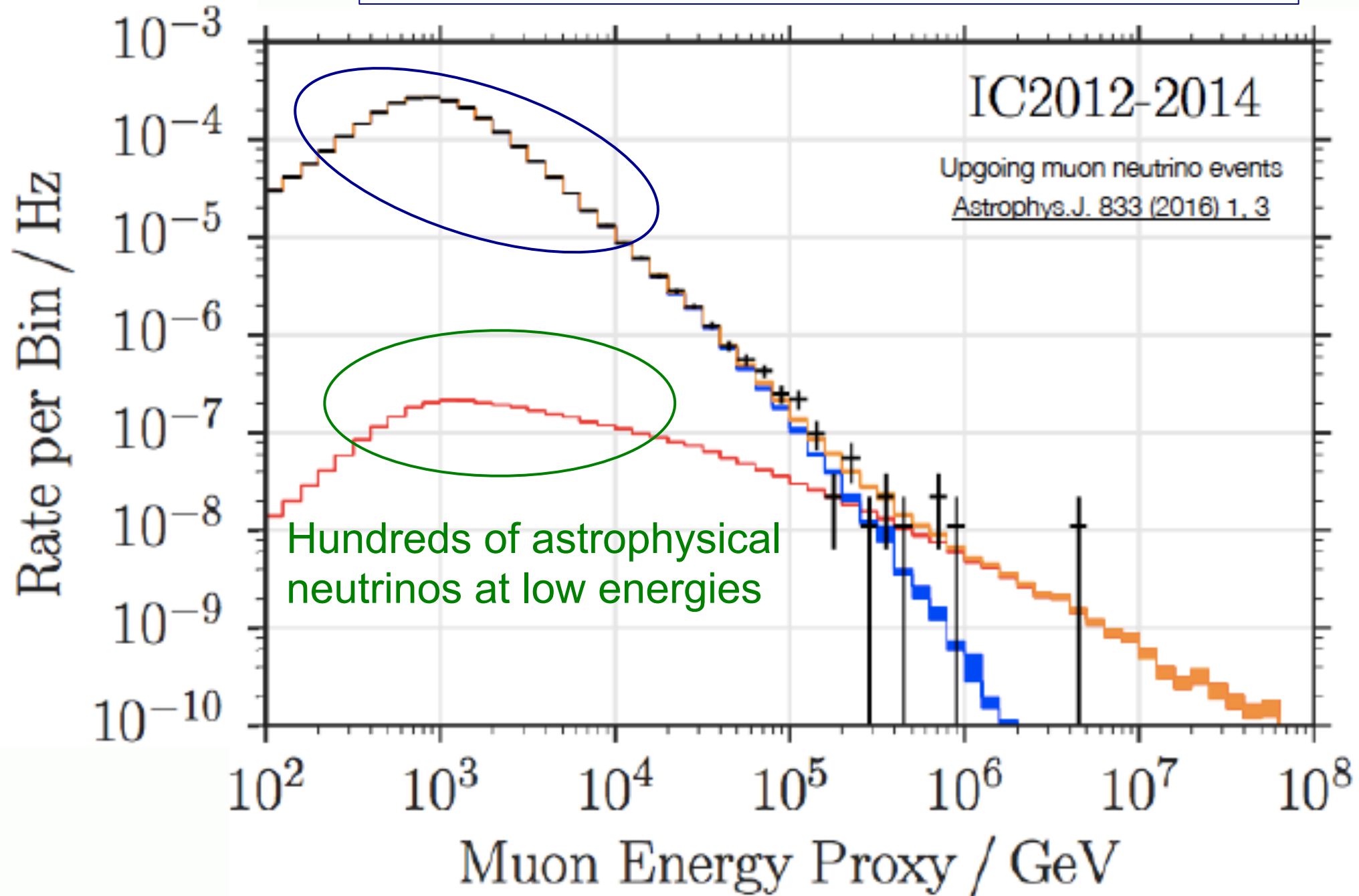
Track-like events



- > charged current interactions of ν_μ
- > good angular resolution of 1°
→ used in most point source searches

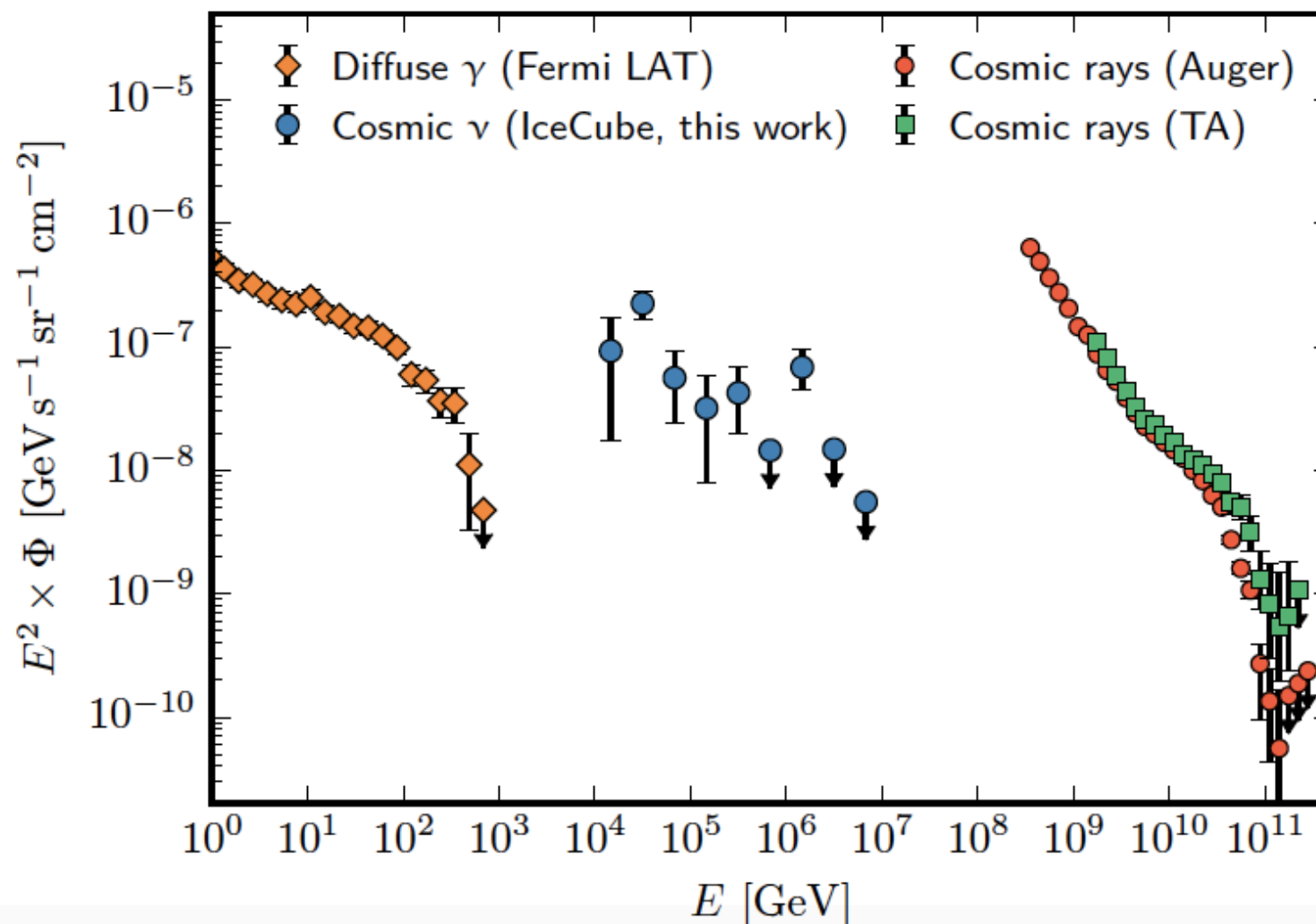
Putting it all together...

Atmospheric background: $O(1)$ events/deg²/year



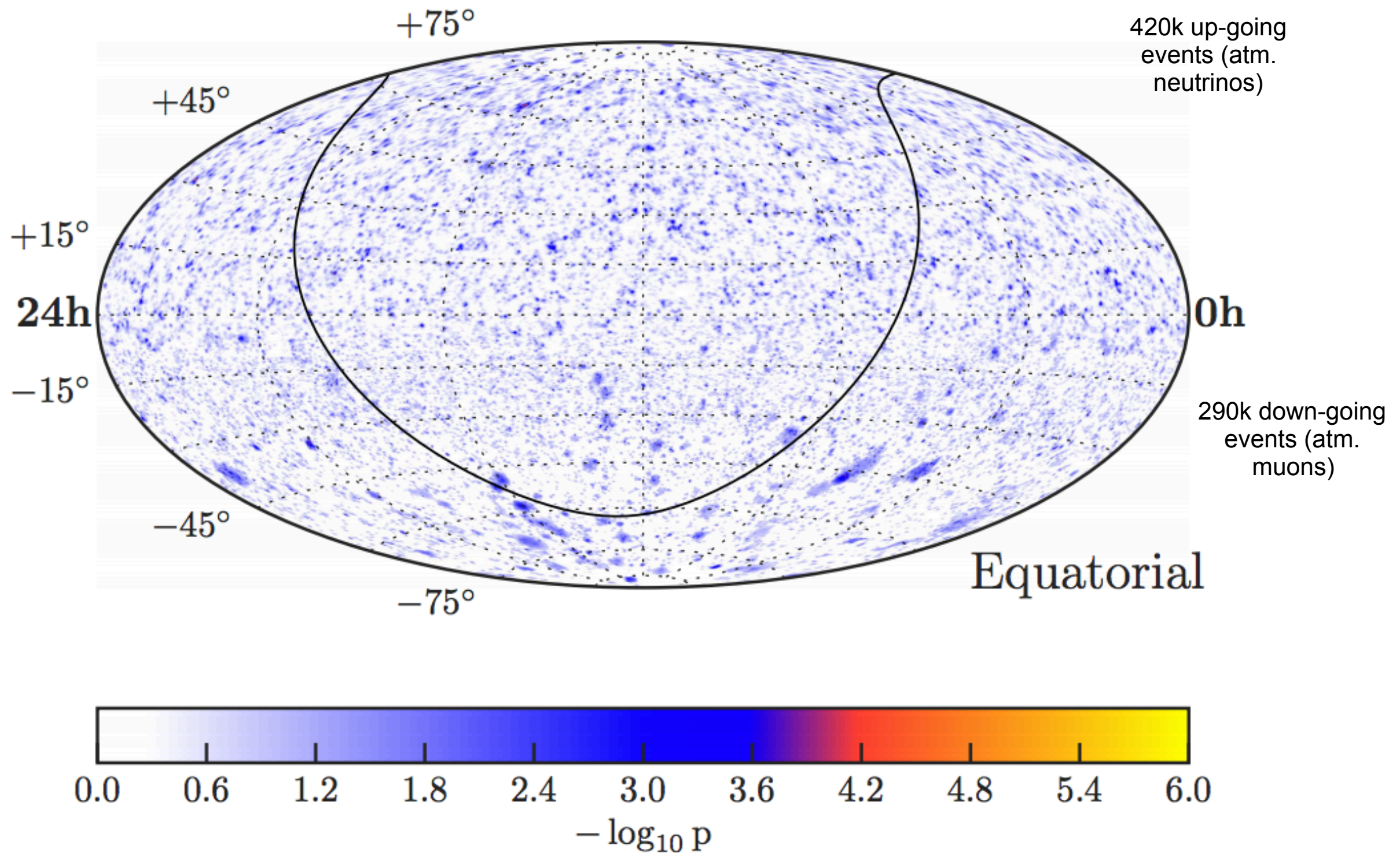
The Diffuse Astrophysical Neutrino Flux

- IceCube discovered a Diffuse Astrophysical High-Energy Neutrino Flux in 2013 (arxiv?)
- **But where do the neutrinos come from???**



Searching for Point Sources

All-Sky Search for Hotspots (IceCube Coll. ApJ, 835 (2017))



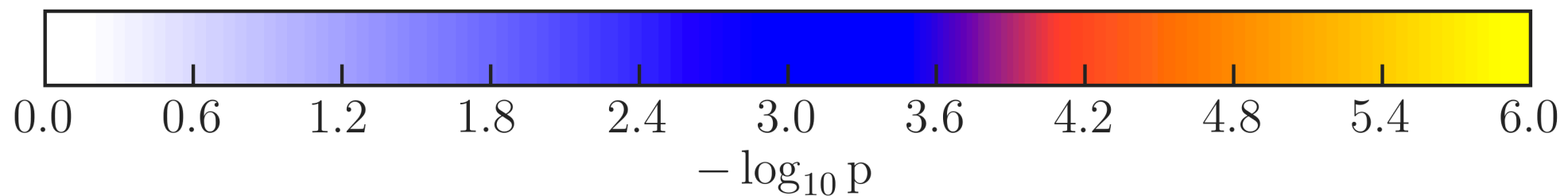
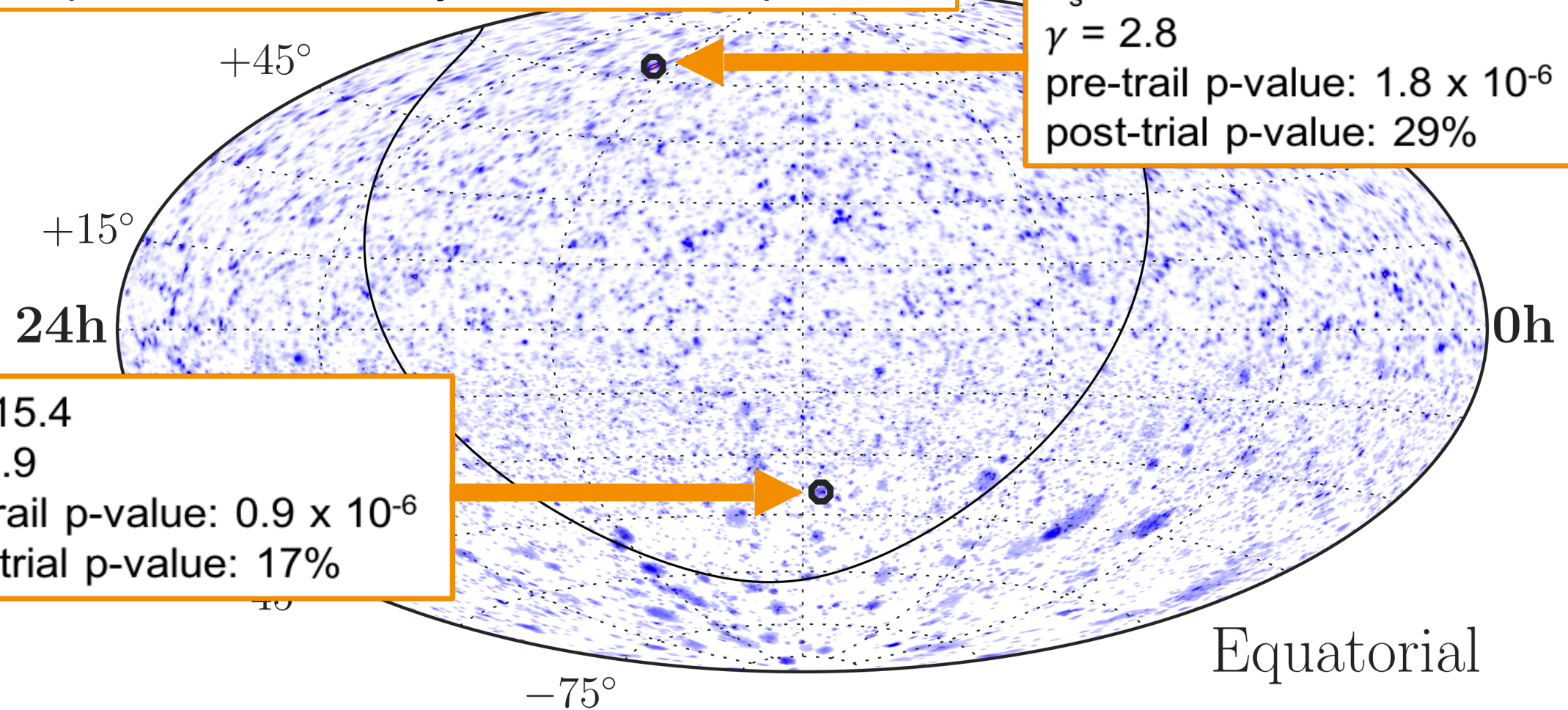
Searching for Point Sources

All-Sky Search for Hotspots (IceCube Coll. ApJ, 835 (2017))

Large **trails factor** due to "look elsewhere" effect
-> 5.67σ pre-trial is needed just to reach 3σ post-trial

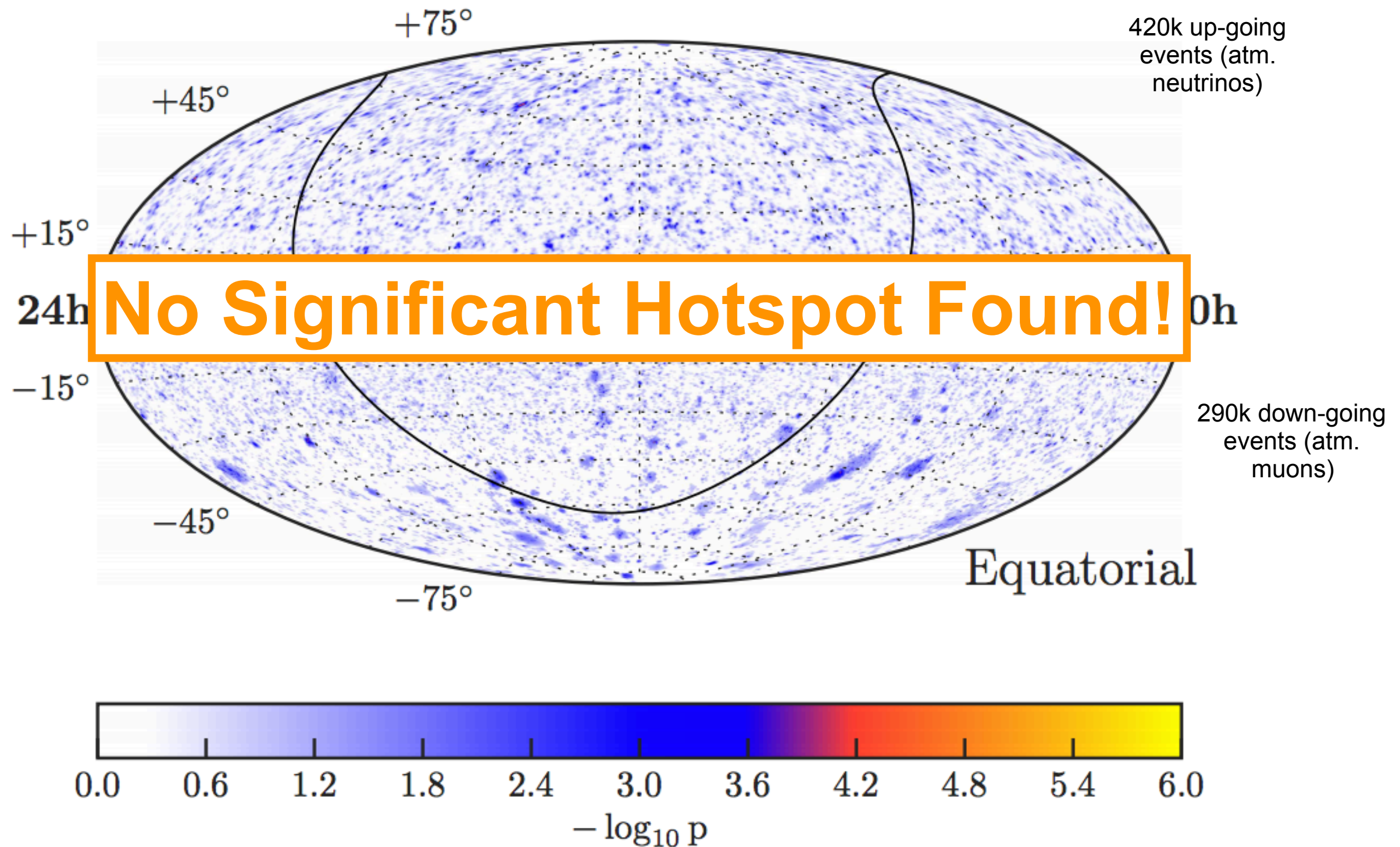
$n_s = 32.6$
 $\gamma = 2.8$
pre-trial p-value: 1.8×10^{-6}
post-trial p-value: 29%

$n_s = 15.4$
 $\gamma = 2.9$
pre-trial p-value: 0.9×10^{-6}
post-trial p-value: 17%



Searching for Point Sources

All-Sky Search for Hotspots (IceCube Coll. ApJ, 835 (2017))



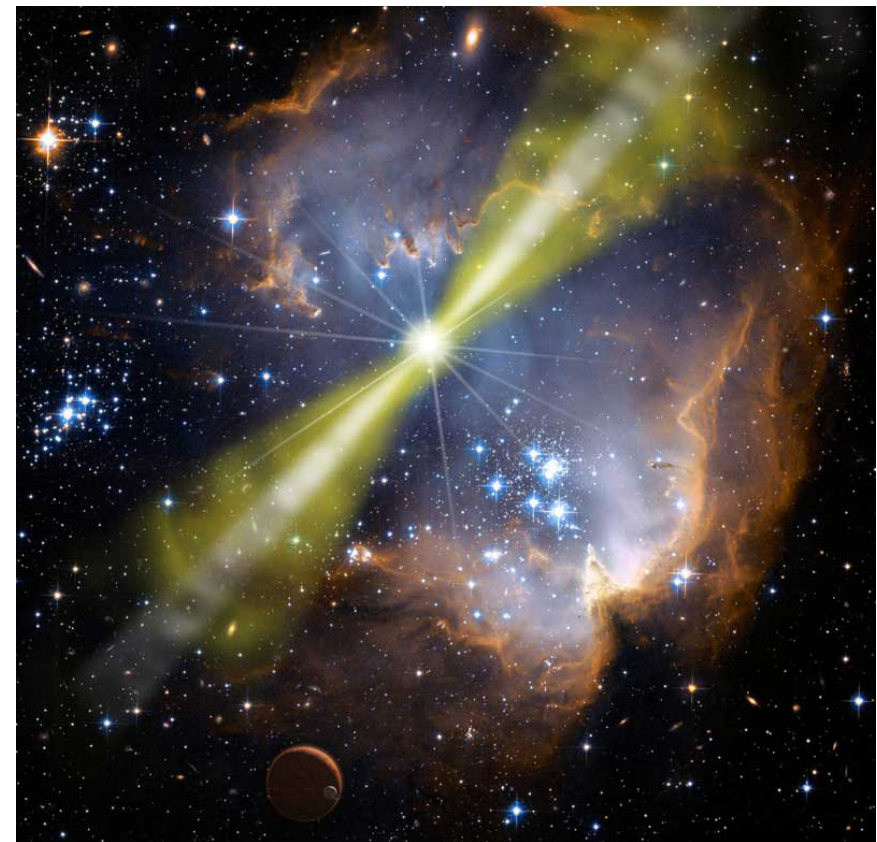
Searching for Point Sources

Cosmic Ray Accelerator Candidates

Blazars?



Gamma-Bright GRBs?

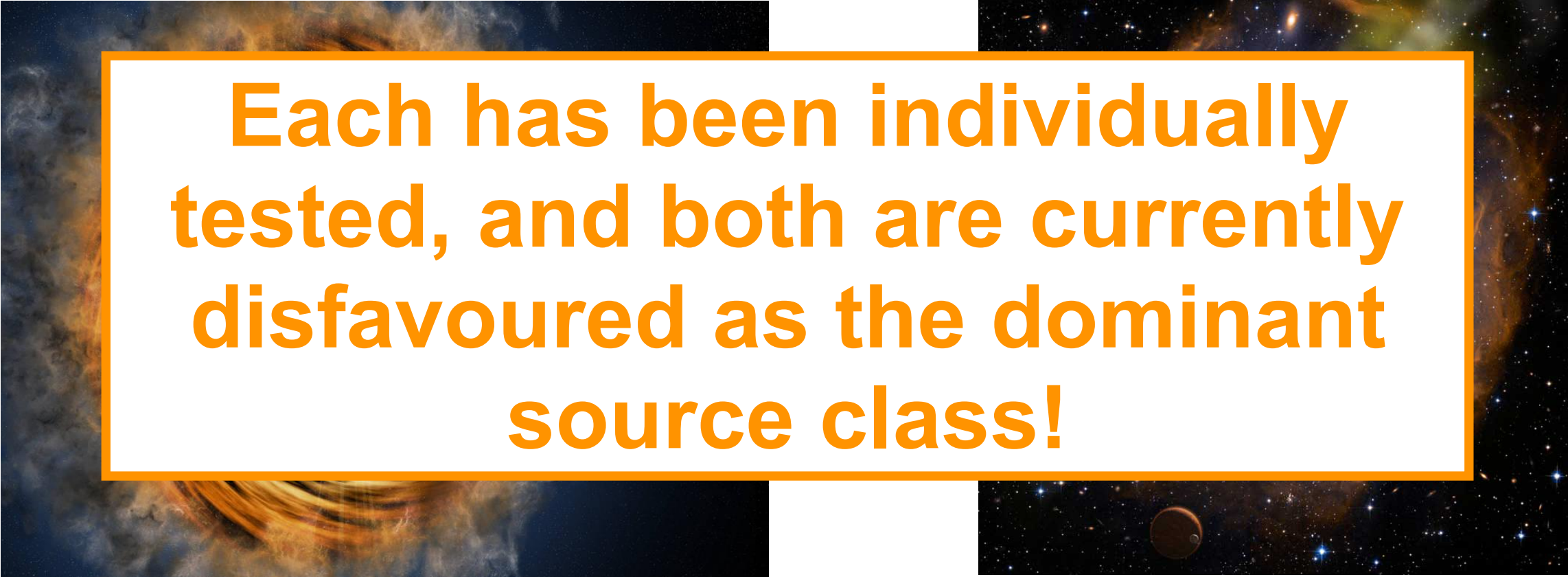


Searching for Point Sources

Cosmic Ray Accelerator Candidates

Blazars?

Gamma-Bright GRBs?



Each has been individually tested, and both are currently disfavoured as the dominant source class!

Could TDEs be the answer?

- TDEs are an interesting, untested source class
- Theoretical basis for expecting emission
- We expect the source class to have highly-energetic particle acceleration, e.g in jetted TDEs!



Do we expect neutrino emission?

Some recent theory papers

- Dai and Fang (2016) (<https://arxiv.org/pdf/1612.00011.pdf>)
 - *Jetted TDEs alone cannot dominate the IceCube flux. If all TDEs were neutrino-bright, we might detect them in IceCube data. Proposed time window of ~1 year before peak.*
- Biehl, Boncioli, Lunardini and Winter (2017) (<https://arxiv.org/pdf/1711.03555.pdf>)
 - *Jetted TDEs, with heavy disrupted stars, could explain both the neutrino and UHECR spectra.*
- Lunardini and Winter (2017) (<https://arxiv.org/pdf/1612.03160.pdf>)
 - *Jetted TDEs could reasonably explain 10% of the IceCube flux if jet parameters cover the full population, or most of the flux if jet parameters are assumed to scale with mass.*
- Guépin, Kotera et. al (2017) (<https://arxiv.org/pdf/1711.11274.pdf>)
 - *Contribution of jetted TDEs would be sub-dominant, but nearby TDEs can be detected by IceCube*

Do we expect neutrino emission?

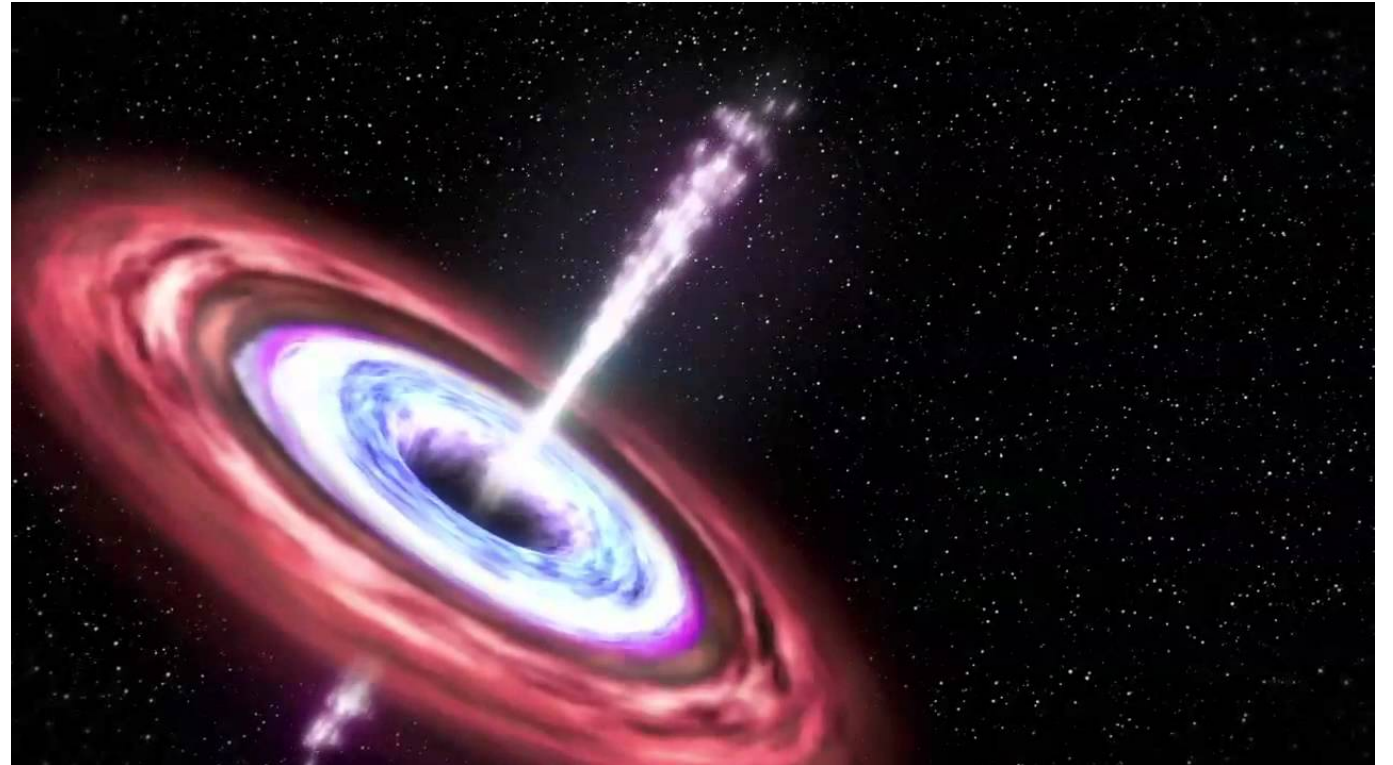
Some recent theory papers

- Dai and Fang (2016) (<https://arxiv.org/pdf/1612.00011.pdf>)
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- Luna et al. (2017) (<https://arxiv.org/pdf/1705.08001.pdf>)
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- Guépin, Kotera et. al (2017) (<https://arxiv.org/pdf/1711.11274.pdf>)
 - *Contribution of jetted TDEs would be sub-dominant, but nearby TDEs can be detected by IceCube*

Size of expected contribution varies, but all suggest this would be worth checking! The non-detection of neutrinos would constrain some TDE models.

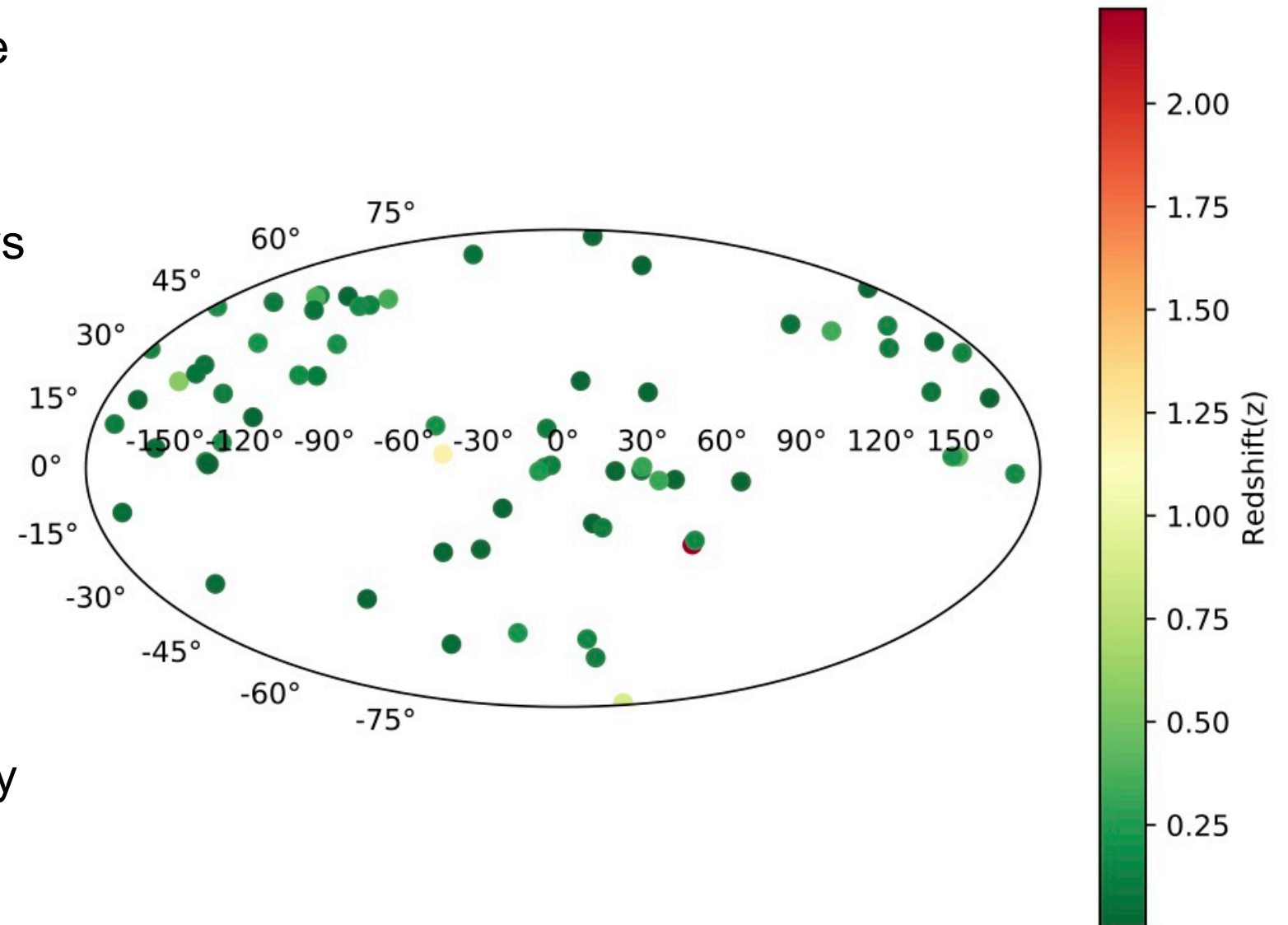
Where to begin?

- IceCube data stretches back to 2008, full detector in operation since 2011
- This period overlaps with the three jetted TDEs discovered by Swift, and many other TDEs
- Will define one catalogue of jetted TDEs
- Will define a second catalogue for all non-jetted TDEs in this period



What is a “stacking analysis”?

- Combine information from multiple TDEs, to provide a combined measurement
- Improved sensitivity to neutrinos vs individual analysis
- Neutrinos have an angular uncertainty of ~ 1 degree
- We are looking at a very small fraction of the sky: ~ 20 square degrees for each year of IceCube data
- Much less background than All-sky search!

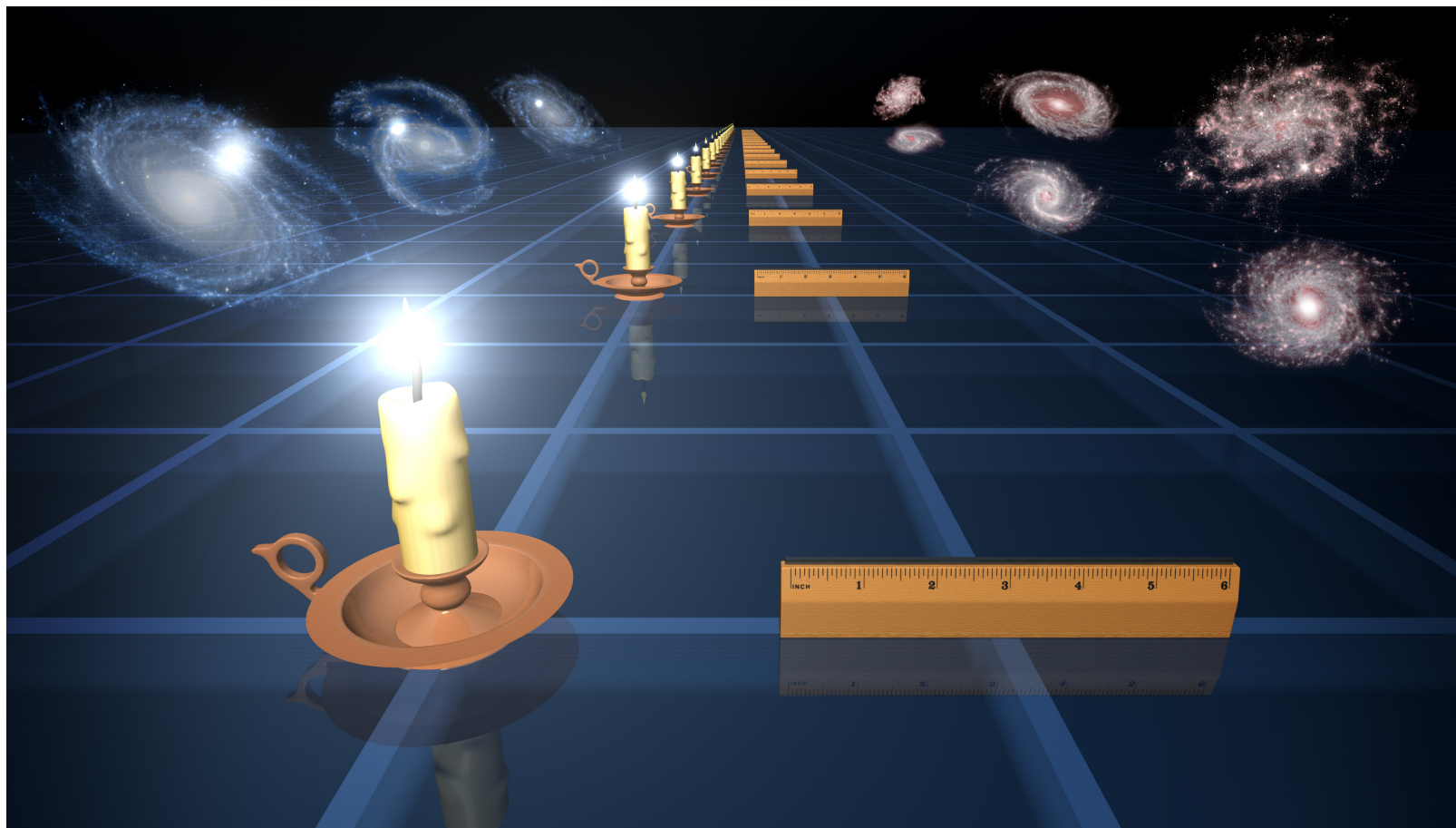


What information do we need?

- At a minimum, we will require:
 - Right Ascension
 - Declination
 - Redshift
 - Estimated Date of Peak
- Begin with The Open TDE Catalog (<https://tde.space/>)
- Add information from literature where needed
- Catalogue not yet fixed, but likely to contain ~35-40 TDEs

What weighting to use for TDEs?

- Simplest case is the Standard Candle approach, scaled by distance
- Could weight by relative brightness, if we assume this is correlated. But how to compare if peak was not observed?
- Recent SN analysis pioneered fitting the relative weight of sources, scaled by distance.

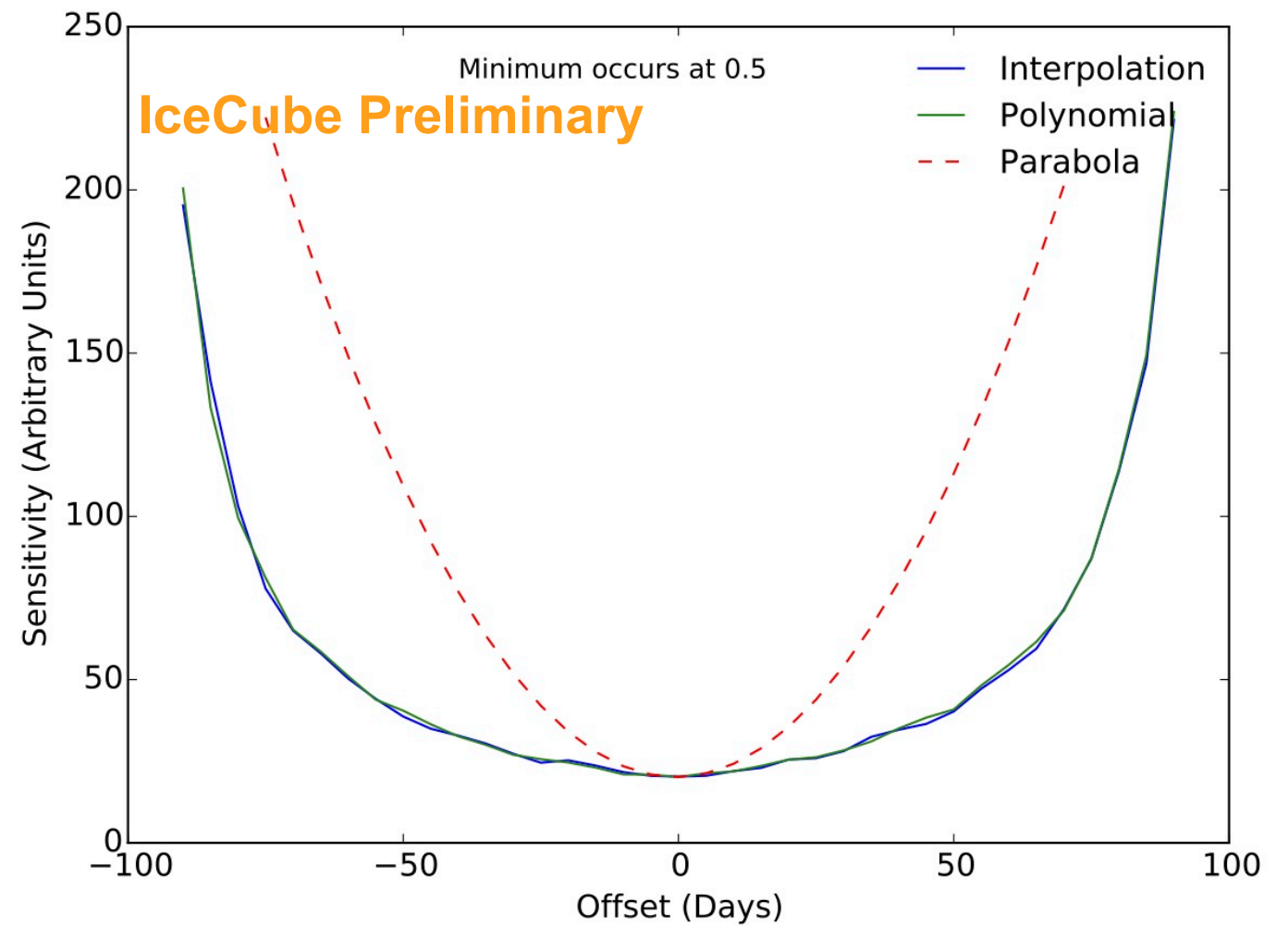
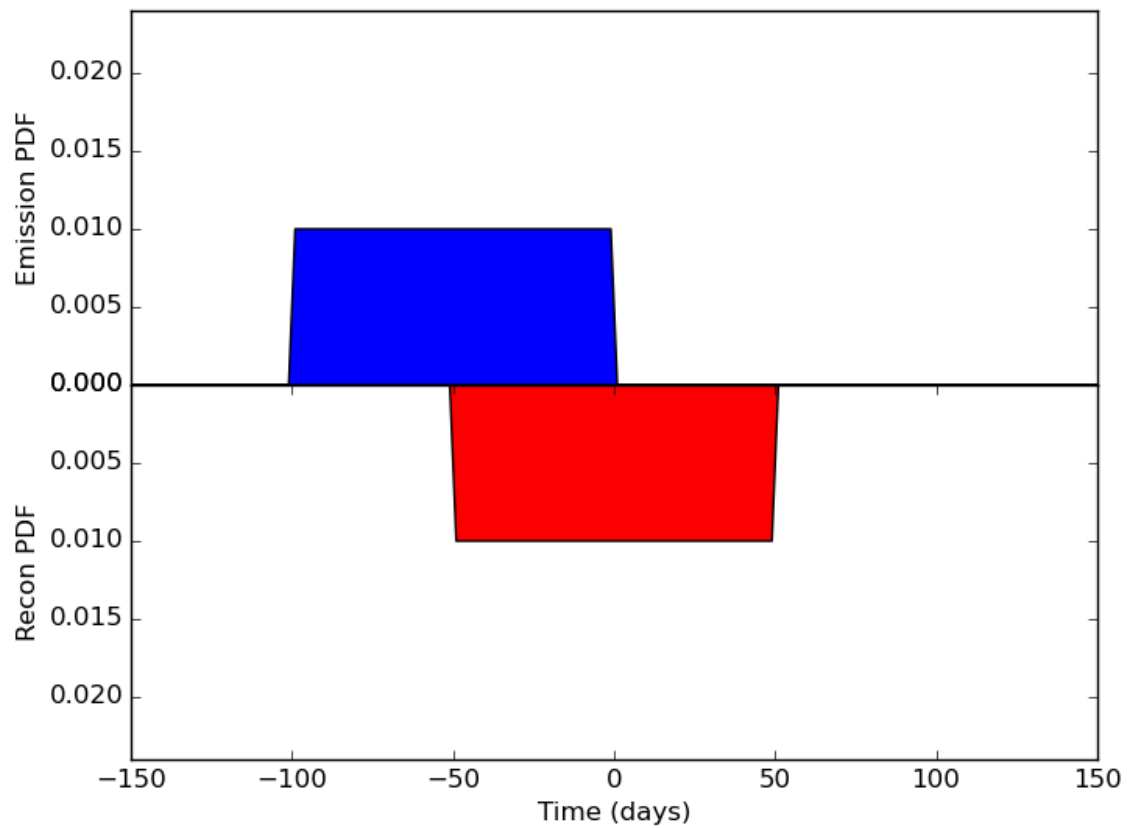


What are the problems?

- Several different neutrino emission models - which to use?
- The date of the lightcurve peak for known TDEs can be poorly constrained
- Relationship between Optical/X-ray and neutrino emission is unknown
- **What is the best approach, when we lack complete knowledge of neutrino emission?**

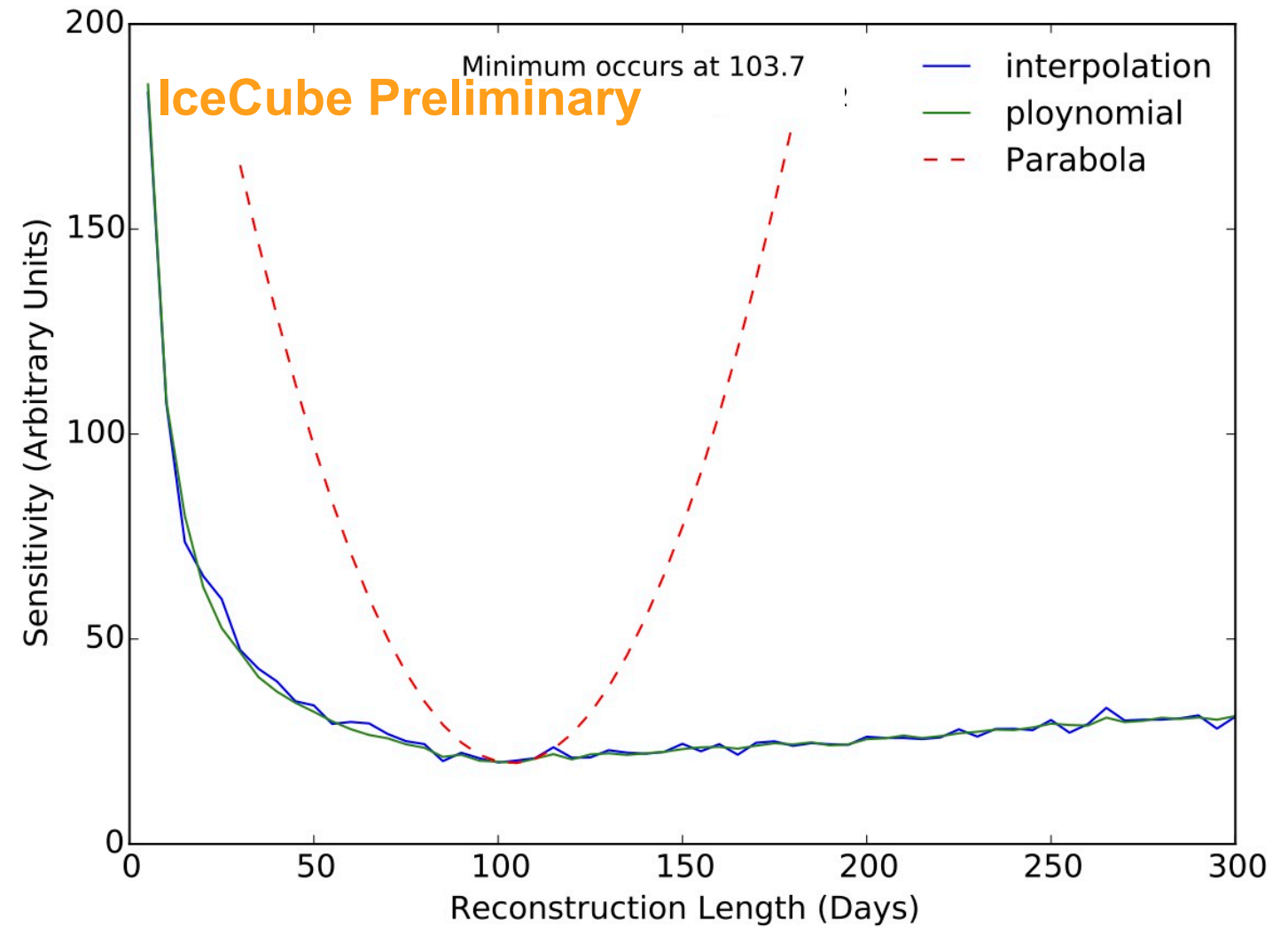
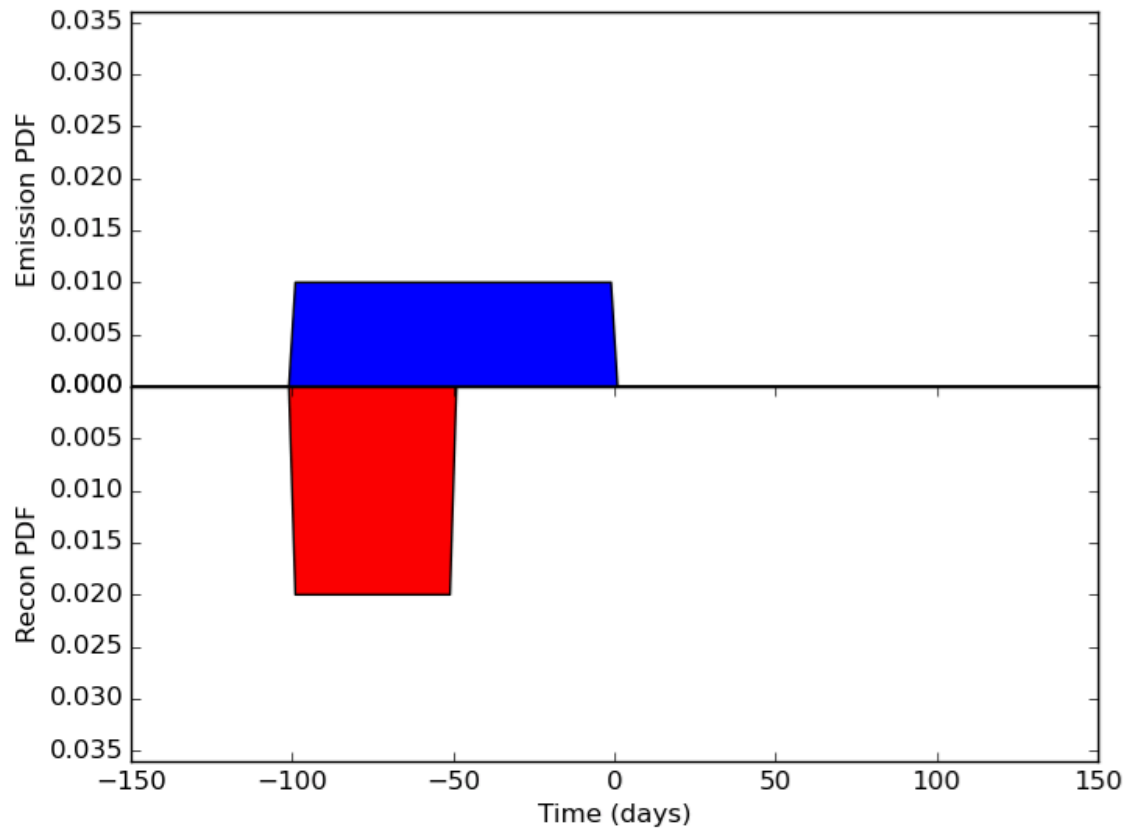
Looking too early, or too late?

An MC study into the impact of ignorance



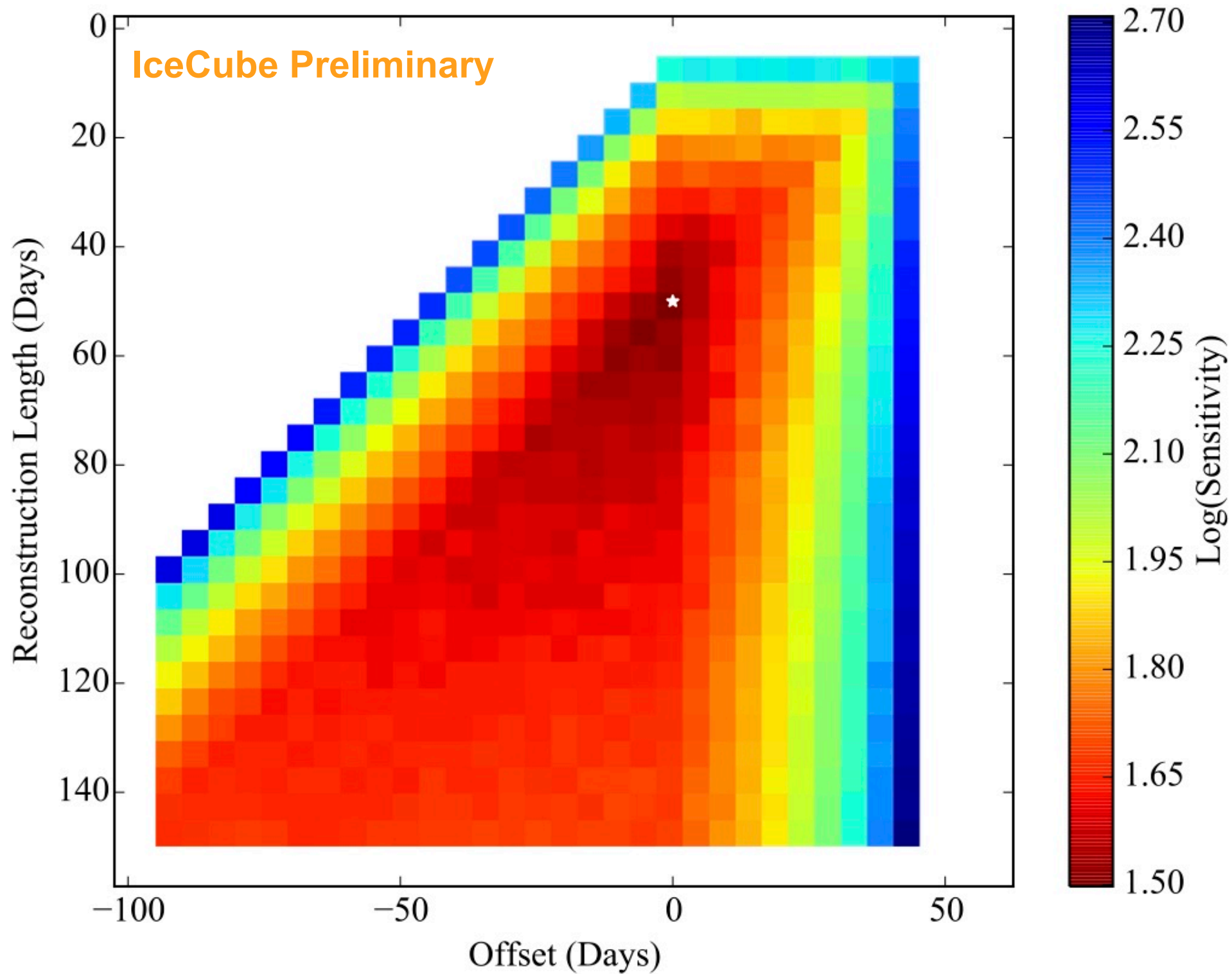
Looking for too long, or not long enough?

An MC study into the impact of ignorance



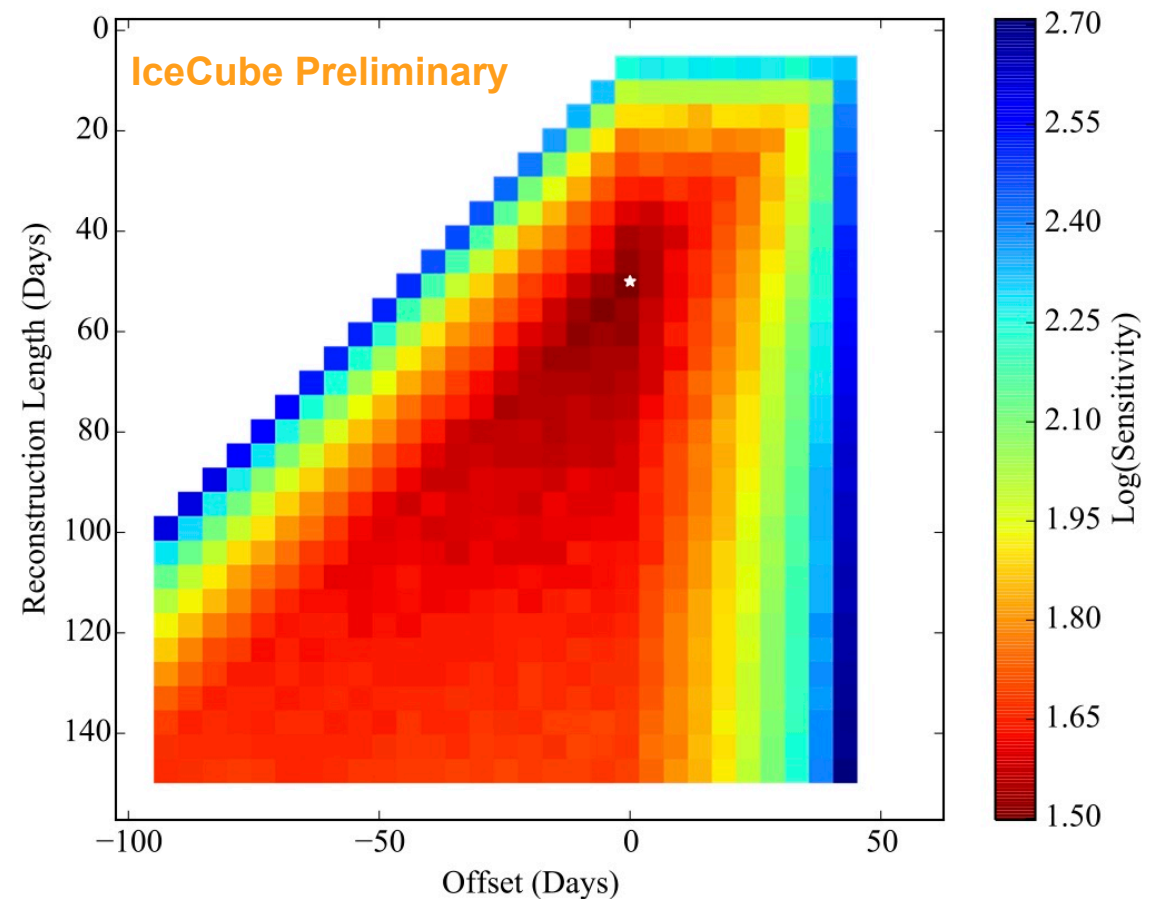
No idea when to look?

An MC study into the impact of ignorance



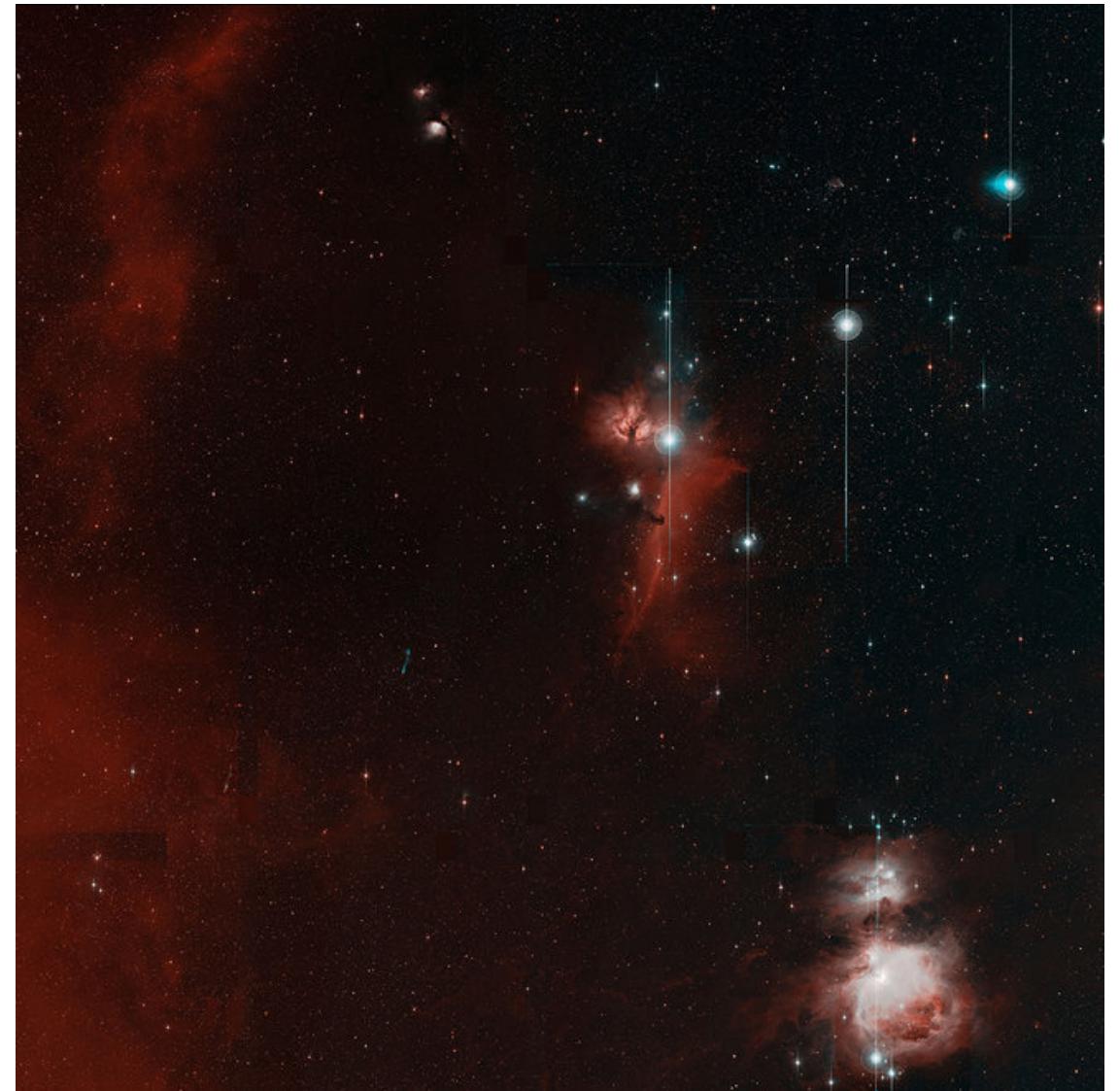
When should we look for neutrino emission?

- The impact of varying time windows for decay-like emission profiles has also been studied for this analysis
- In general:
 - Optimal window covers emission exactly
 - But missing some emission severely reduces sensitivity
 - Having a broad window marginally impacts sensitivity
 - **Have the shortest window which you confidently feel should cover all neutrino emission!**
- For this, we would consider perhaps one year preceding peak, up to 50-100 days after peak



What's the plan?

- Perform a stacking analysis on jetted TDEs, and non-jetted TDEs, separately
- Provide upper limits (or rates) for individual TDEs
- Establish a framework for TDE/Neutrino correlation studies, so we can repeat the analysis with more data
- We are optimistic for the future discovery prospects, particularly with ZTF
- In a later analysis, we could aim to incorporate more data-per-TDE, as well as more TDEs generally



Summary

- The IceCube Neutrino observatory has discovered a diffuse astrophysical neutrino flux, but not the sources!
- TDEs represent a promising, untested source class
- Will perform a Stacking Analysis of TDEs and IceCube Neutrino data, separating jetted and non-jetted TDEs
- Future prospects with ZTF are promising, so we envisage repeating this analysis with more data

