Neutrino Astronomy with IceCube

ULB

J. A. Aguilar for the IceCube collaboration

SOGAR 2015 Geneva

OUTLINE

- Cosmic Ray/Gamma-ray/Neutrino Connection
- The IceCube Observatory
- Search for Diffuse Neutrino Emission
- Search for Neutrino Point Sources
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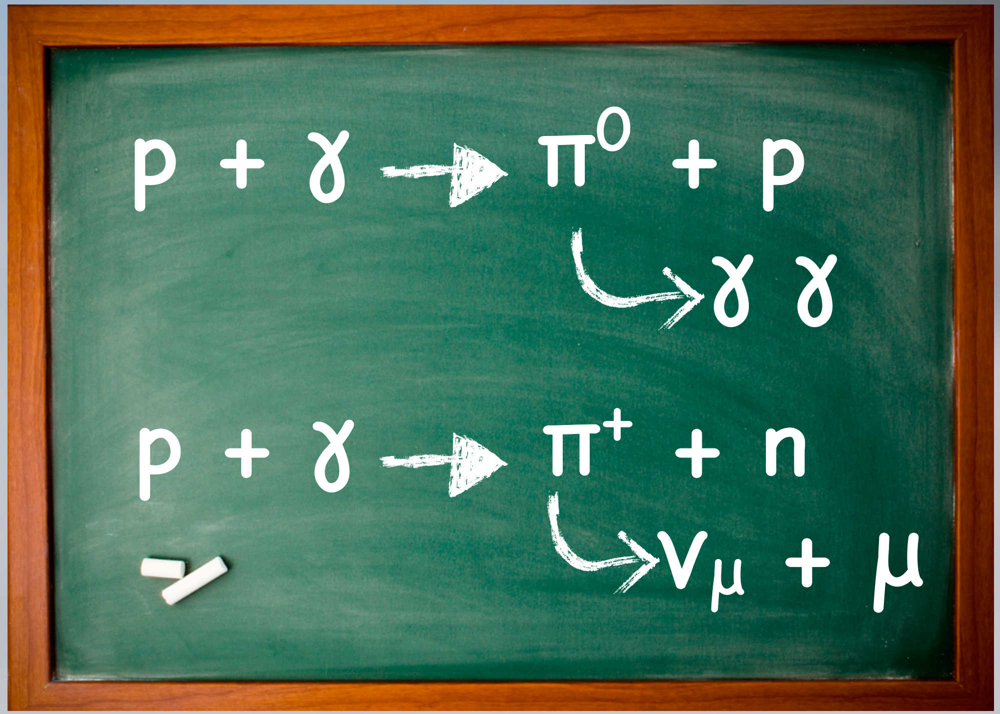
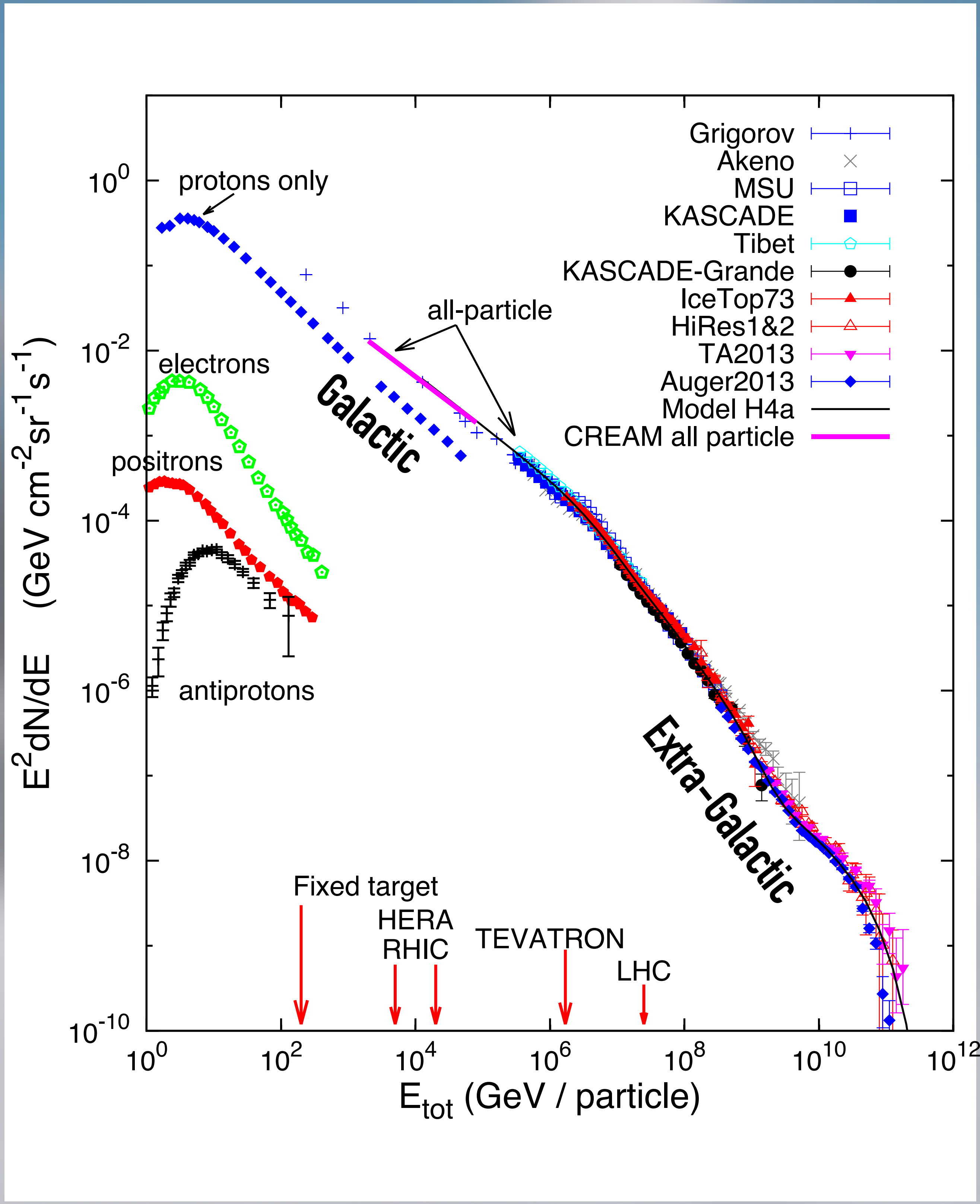
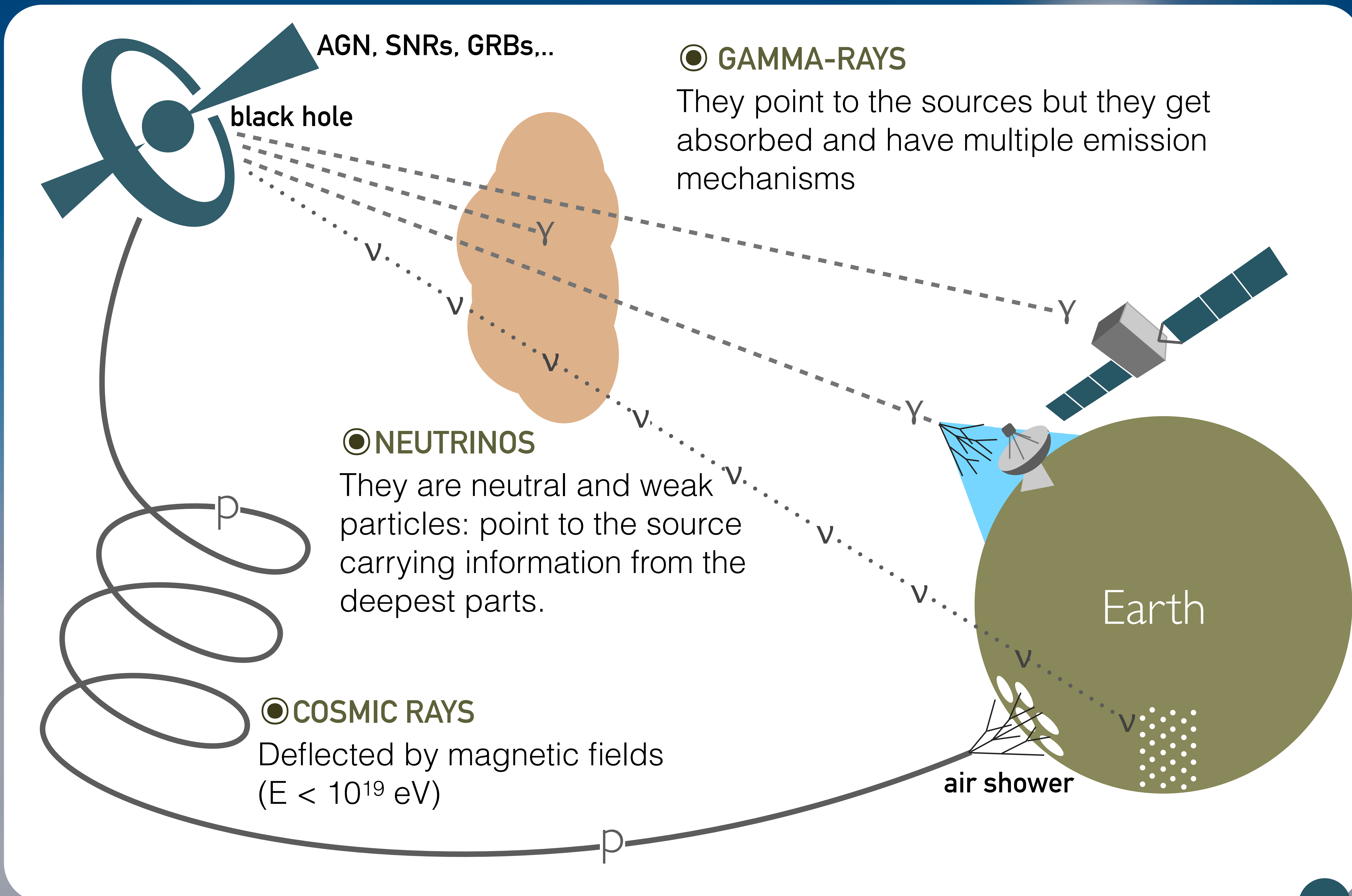
THE CR-ν-γ CONNECTION

- Cosmic Rays discovered by Victor Hess **(and others!)** in 1912
- Cosmic Rays spectrum spans 10 decades of energy. Origin still unknown.
  - Galactic CRs: Supernova remnants?
  - Extra-Galactic CRs: AGNs, GRBs, magnetars?

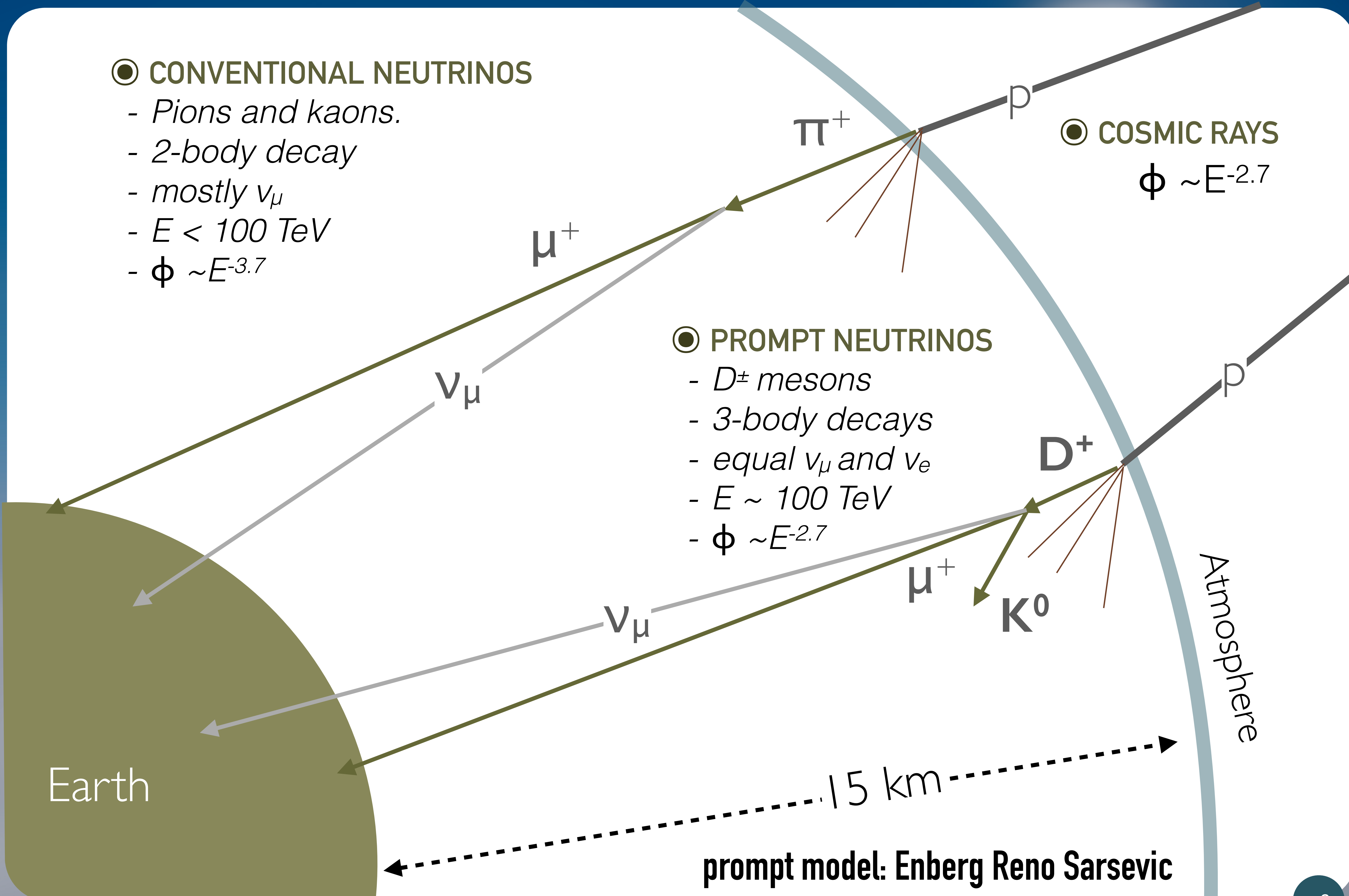




Cosmic Messengers



Atmospheric neutrinos at Earth

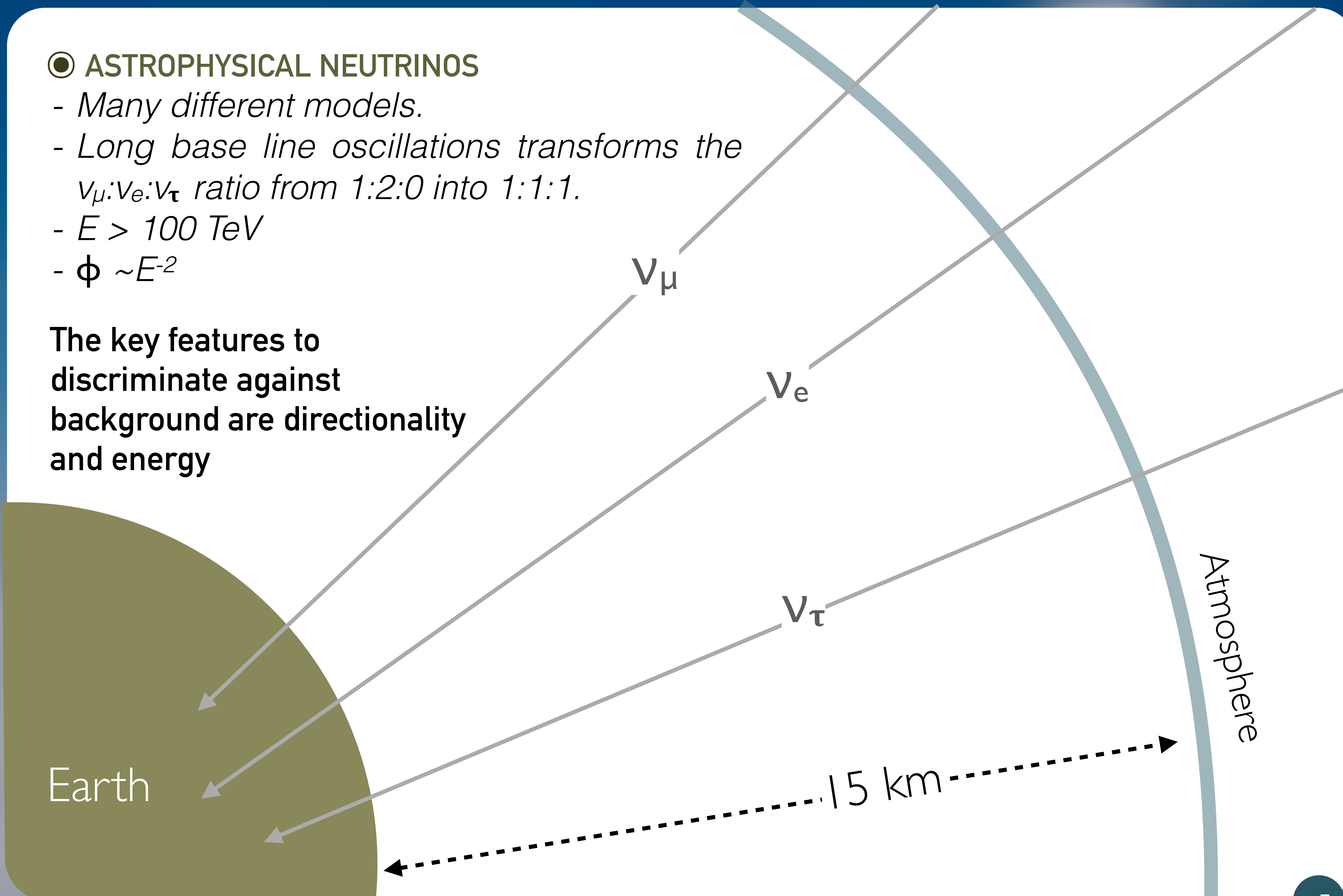


Astrophysical Neutrinos at Earth

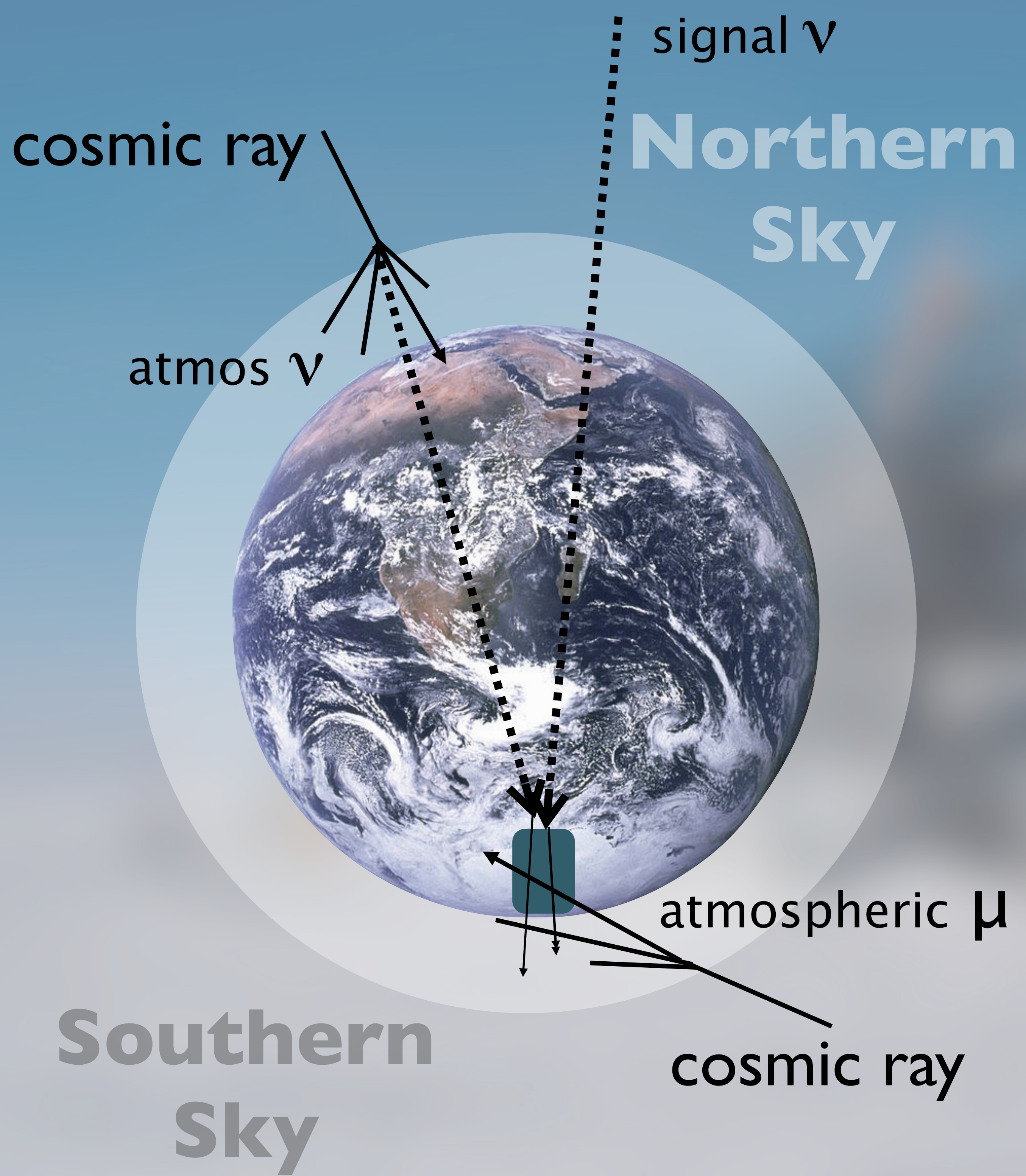
ASTROPHYSICAL NEUTRINOS

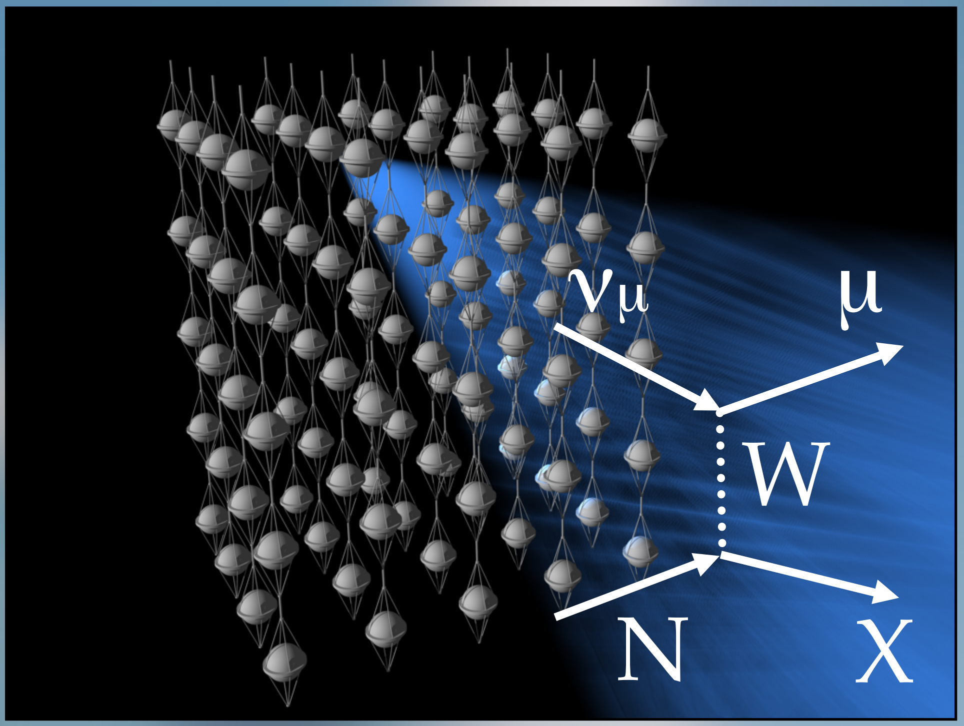
- *Many different models.*
- *Long base line oscillations transforms the $\nu_\mu:\nu_e:\nu_\tau$ ratio from 1:2:0 into 1:1:1.*
- *E > 100 TeV*
- $\phi \sim E^{-2}$

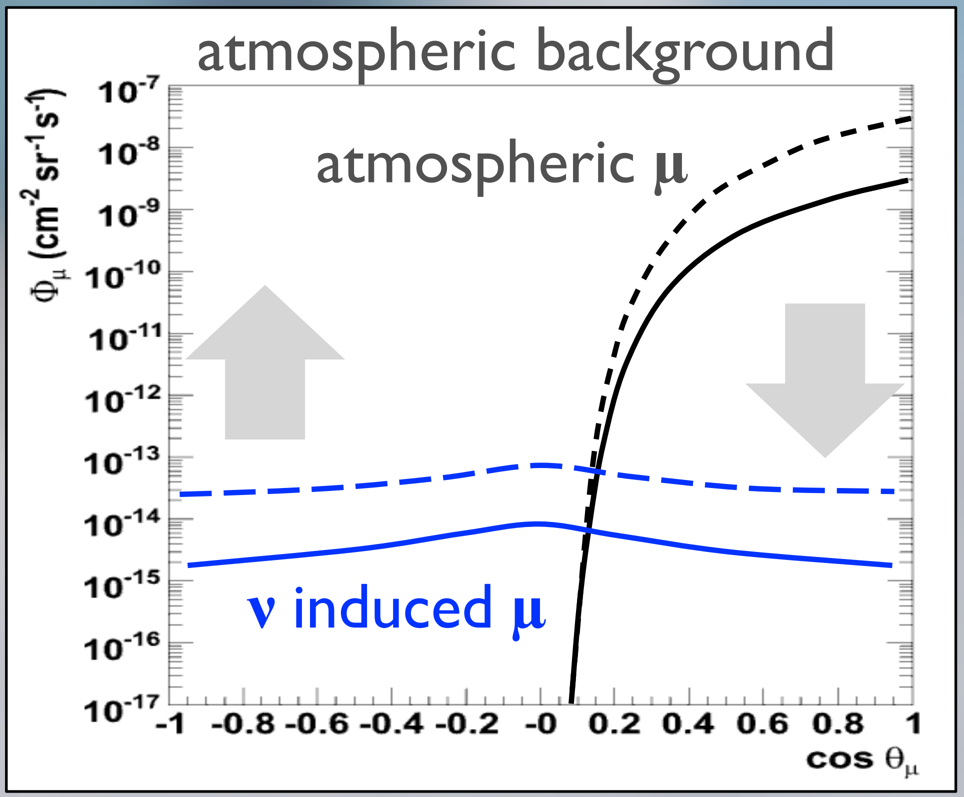
The key features to discriminate against background are directionality and energy



Detection Principle







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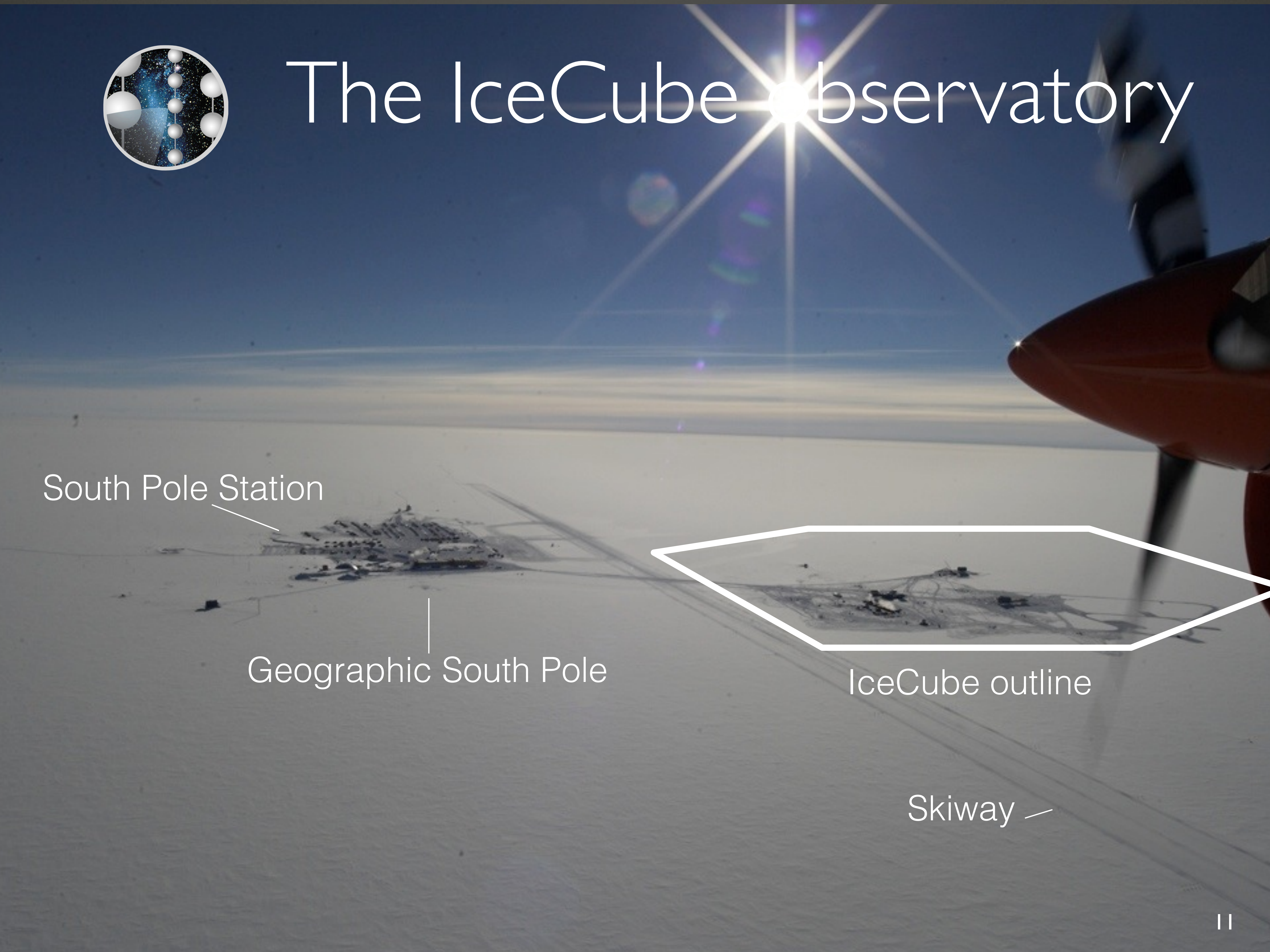
The IceCube Collaboration

10 countries, 40 institutions, ~260 collaborators

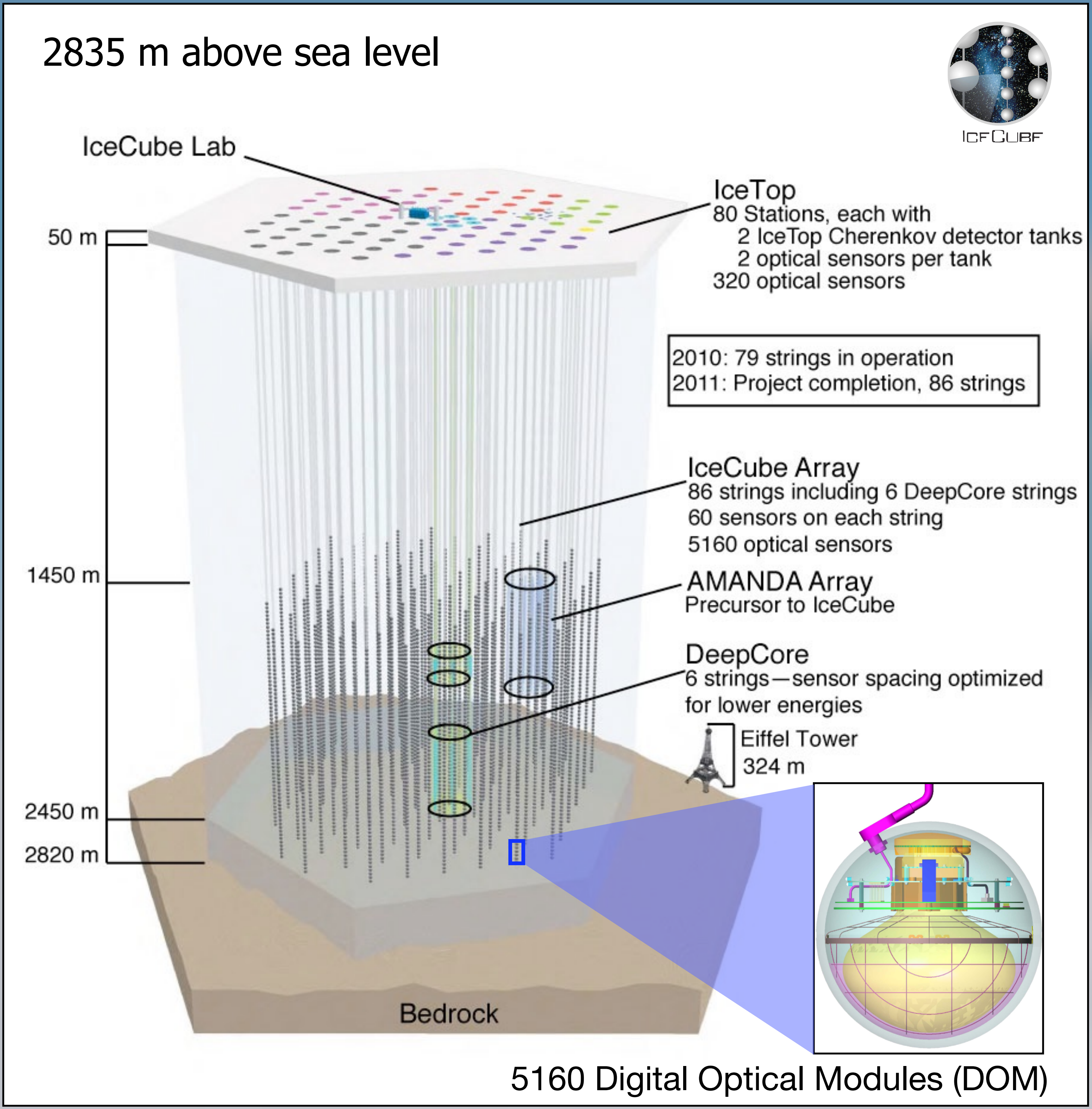
Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube Observatory



IceCube Observatory



20 years of construction from AMANDA to IceCube

IceCube phases:

IceCube 1 (2004-5)

⋮

IceCube 40 (2008-9)

IceCube 59 (2009-10)

IceCube 79 (2010-11)

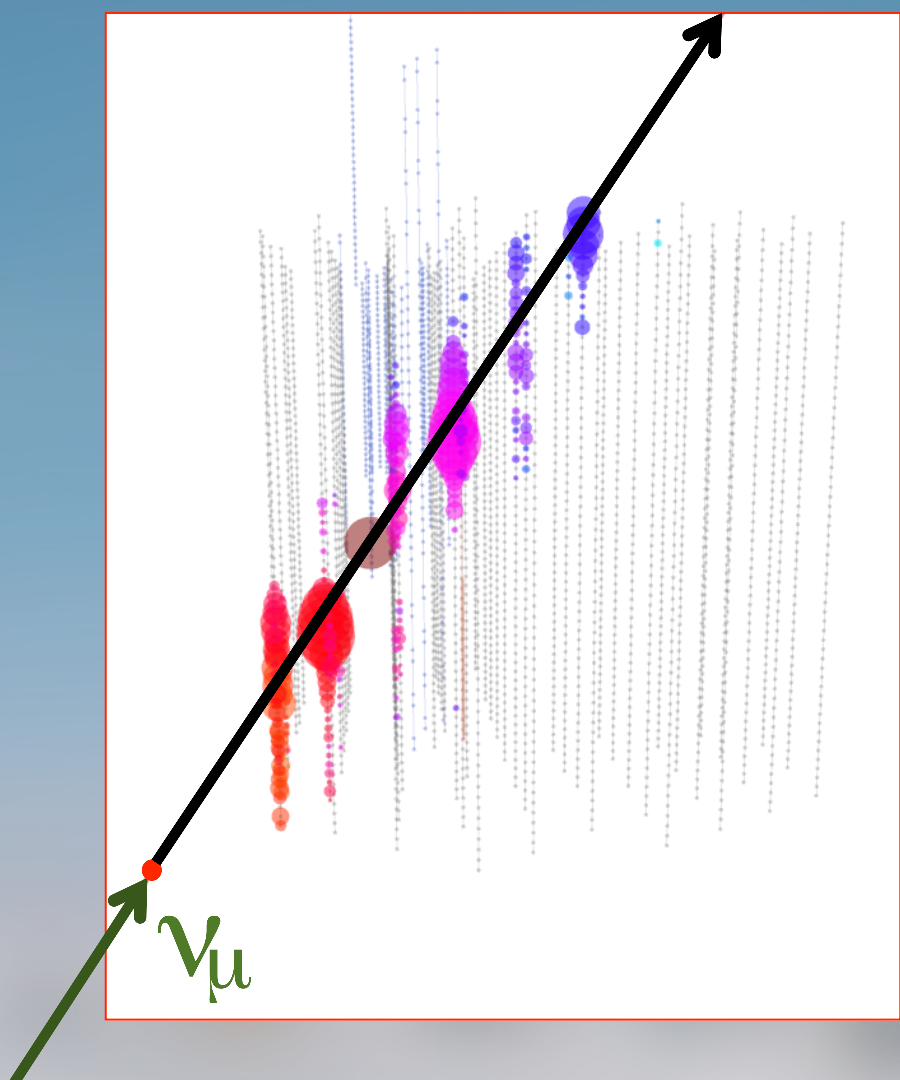
Completion with 86 strings in December 2010

IceCube 86-I (2011-12)

⋮

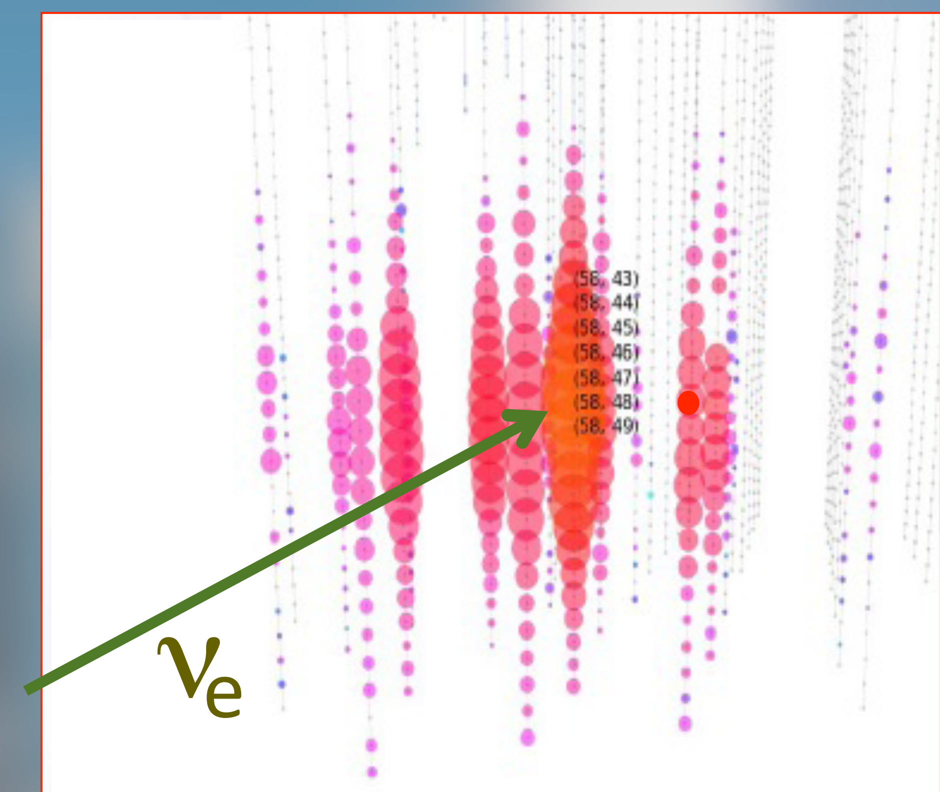
In-Ice Signatures

through-going muons → ν_μ



- Good angular resolution: **Neutrino Astronomy**
- Vertex can outside the detector: **Increased effective volume!**

cascade → all flavors



- **νe, $\nu\tau$** and all-flavor neutral current
- Fully active calorimeter: **High energy resolution**
- Angular reconstruction above ~50 TeV

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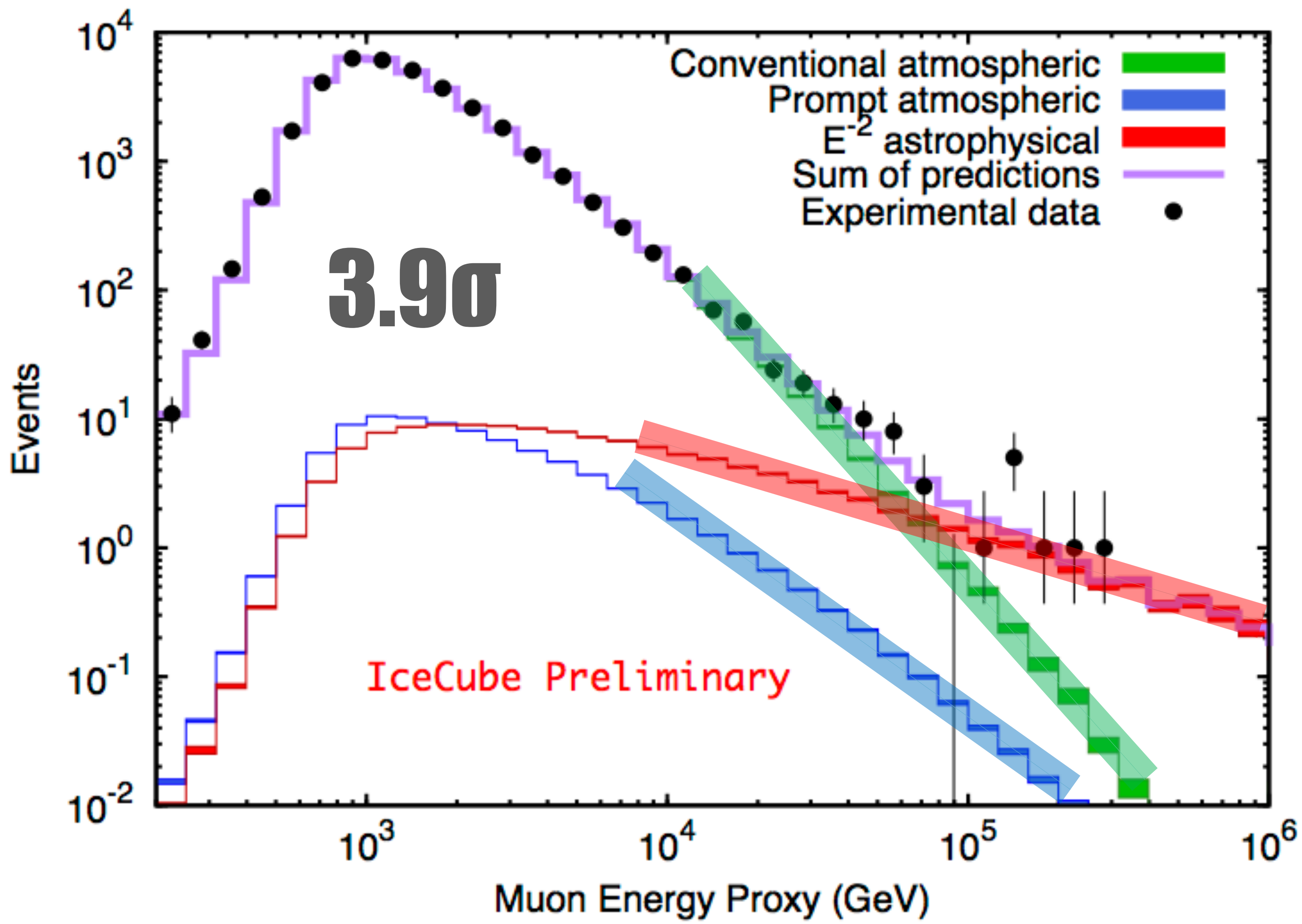
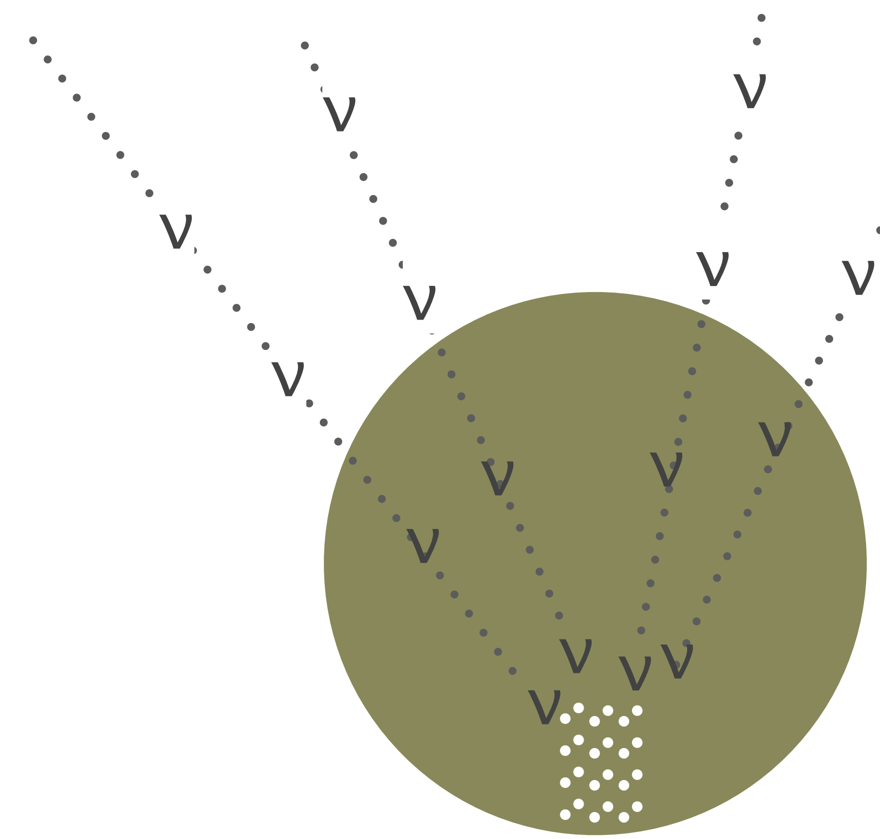
Search for Diffuse Neutrino Emission

Sources may be numerous and faint: hard to resolve individually

Up-going muon neutrino diffuse analysis. It rejects down-going atmospheric muons





- Atmospheric neutrinos as expected
- Astrophysical component $10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$
- Prompt emission: 0.45 × ERS

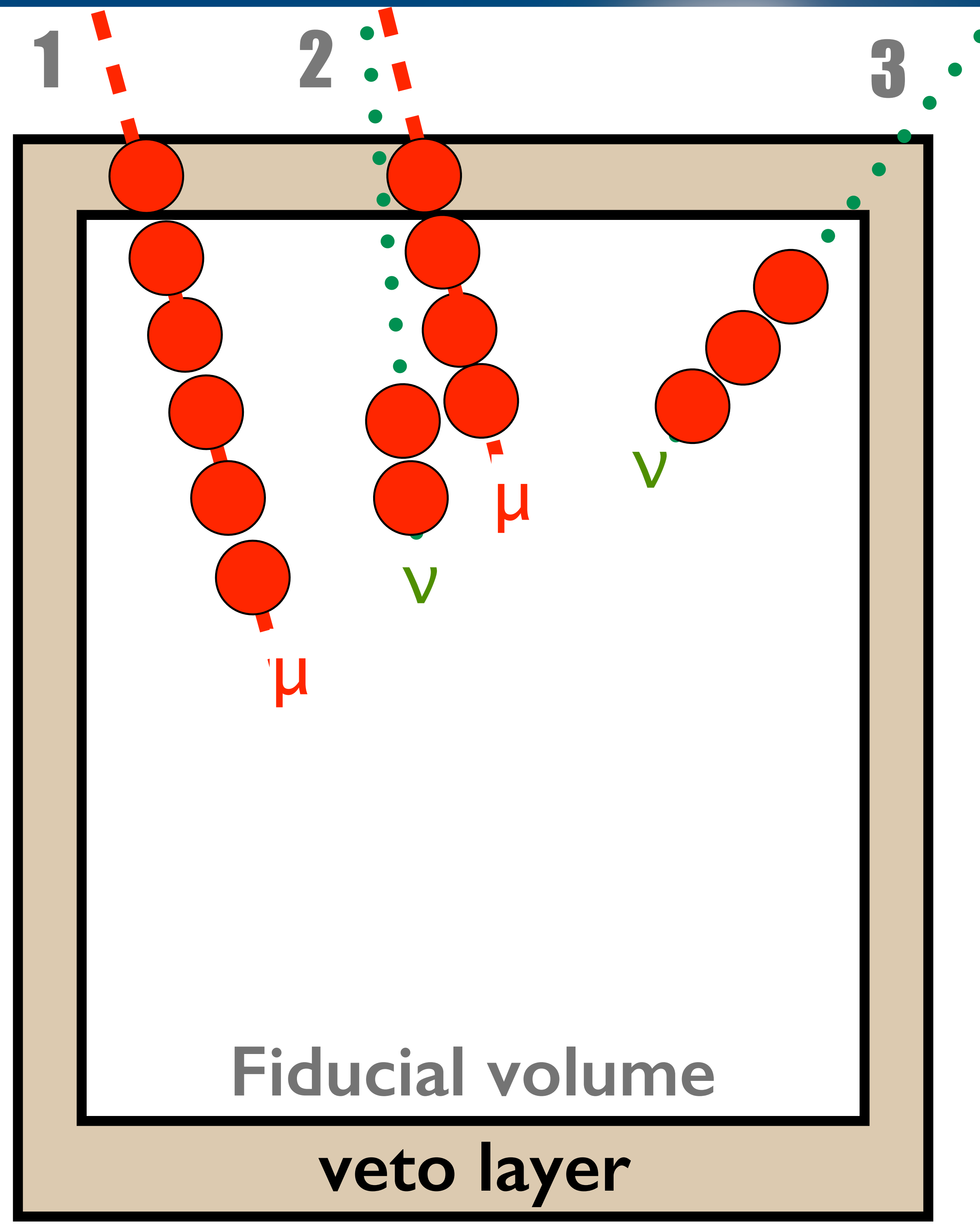
Active Veto Technique

Reject events with light deposition in veto layer and high charge in the fiducial volume.

1. Atmospheric muons rejected

2. Atmospheric neutrinos rejected
(due to accompanying muon)

3. High energy astrophysical neutrinos accepted



High Energy Starting Events: 3 YEARS

37 EVENTS

9 track-like events

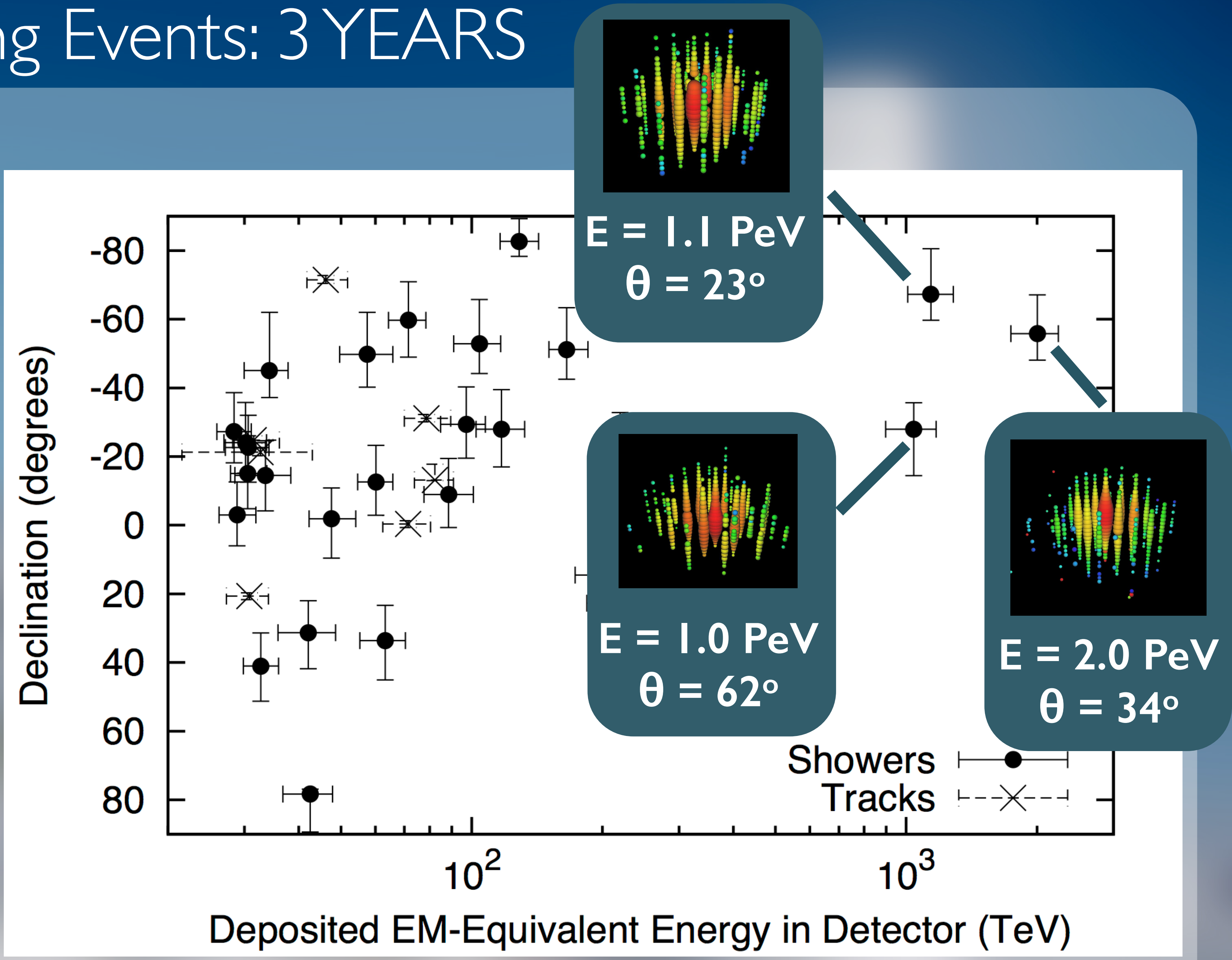
$\Psi = 1°$

Muon takes energy away

28 cascade-like events

$\Psi = 10° – 45°$

15% energy resolution



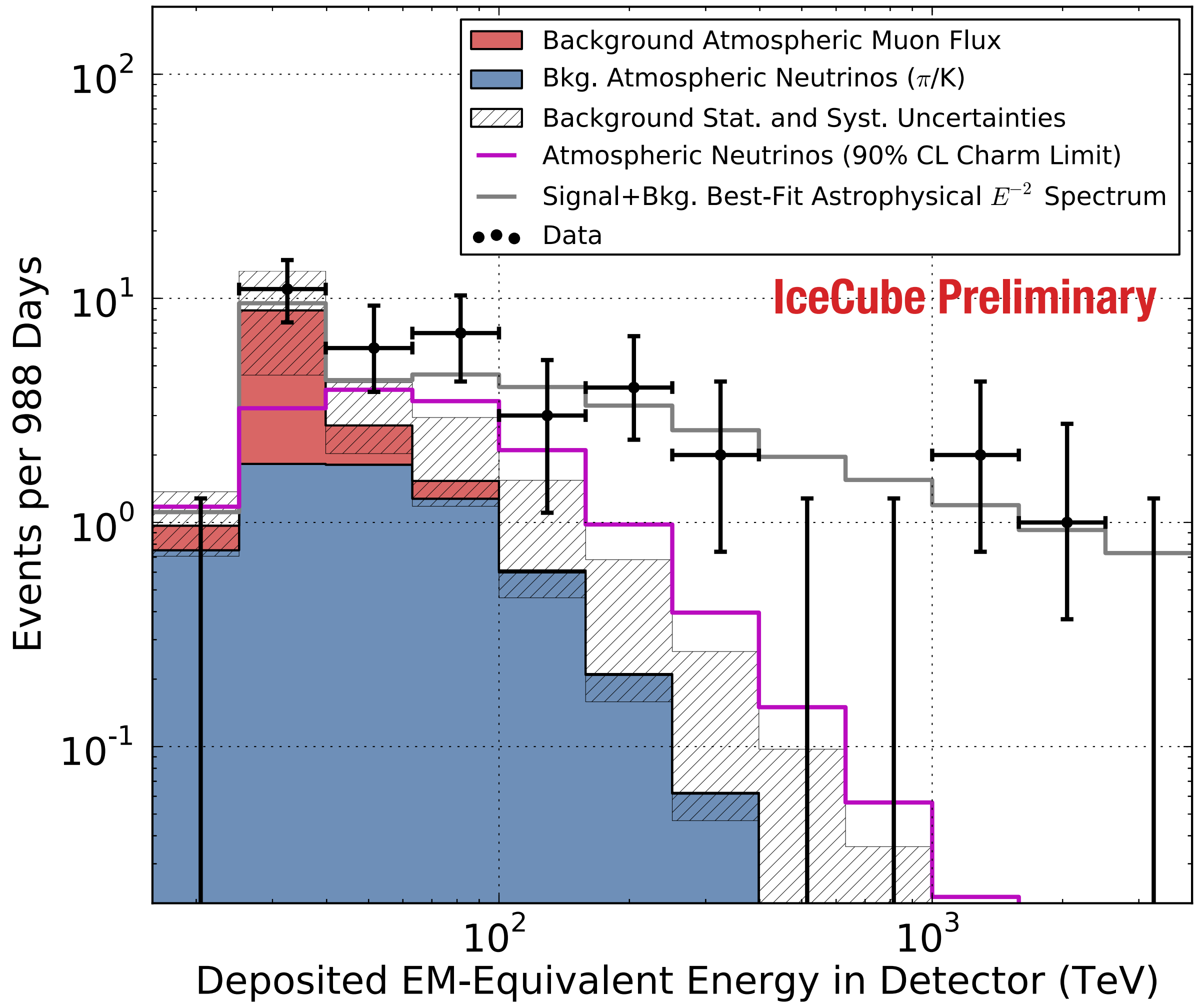
Estimated background:

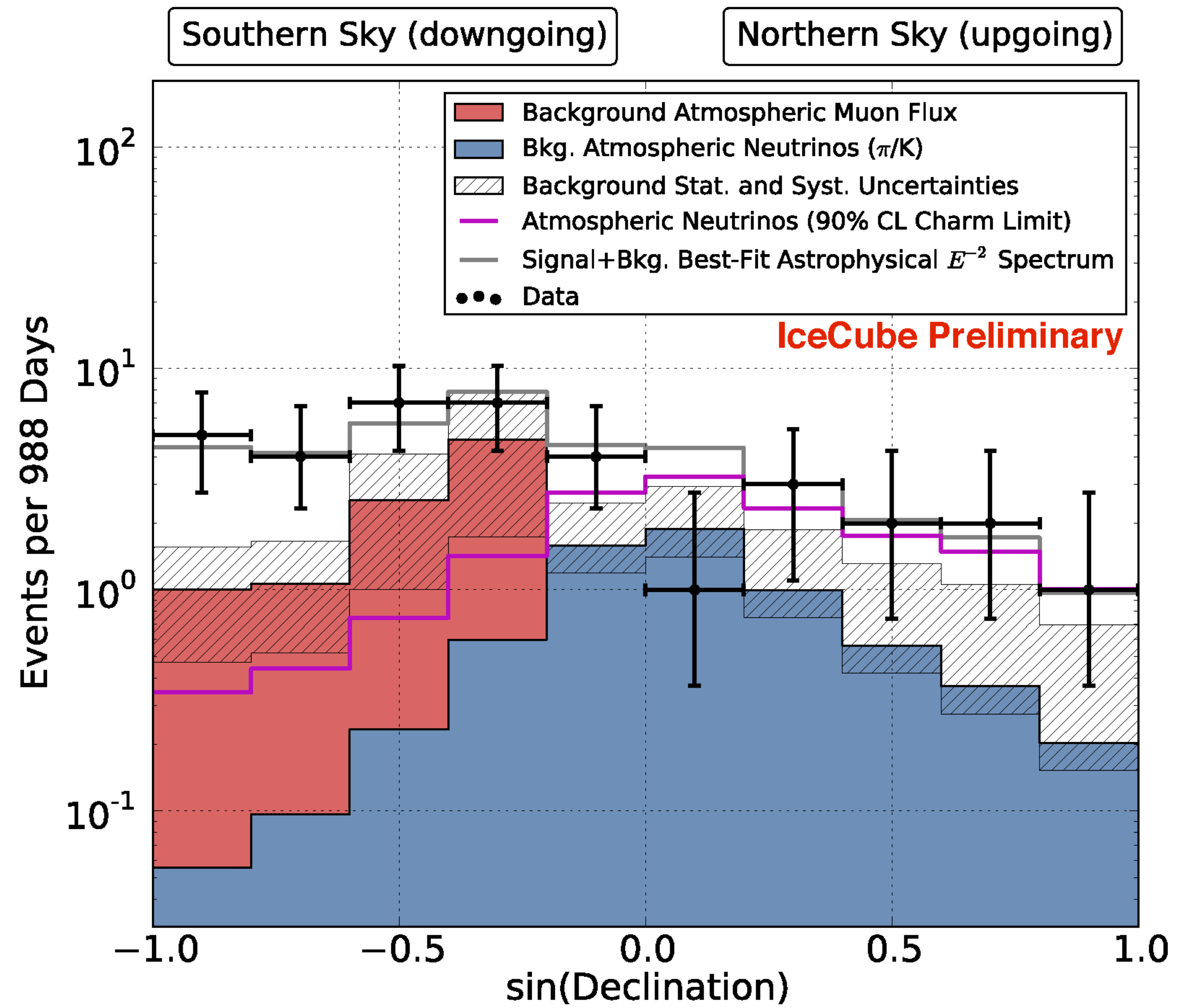
- $6.6^{+5.9}_{-1.6}$ atm. neutrinos
- 8.4 ± 4.2 atm. muons

4.8σ combining with 2.8σ from GZK results (35 + 2 events)

5.7σ full likelihood fit of all components (36 + 1 events)

Energy and Zenith Distribution

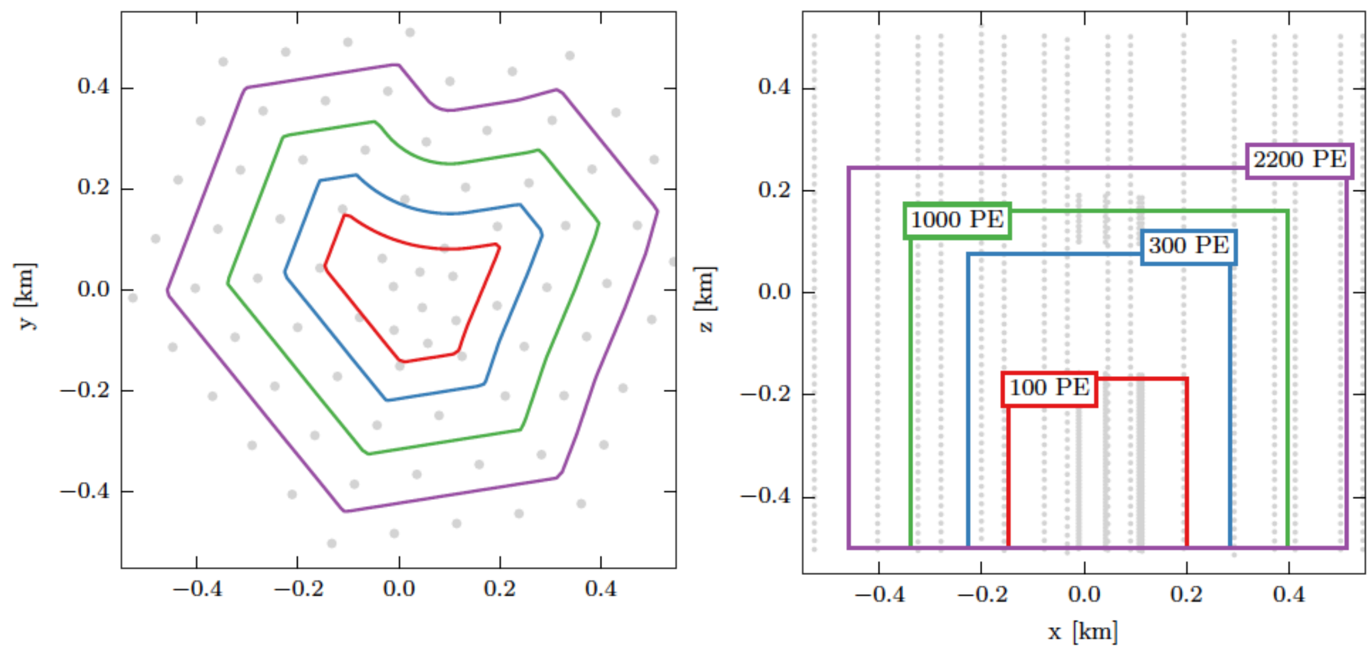




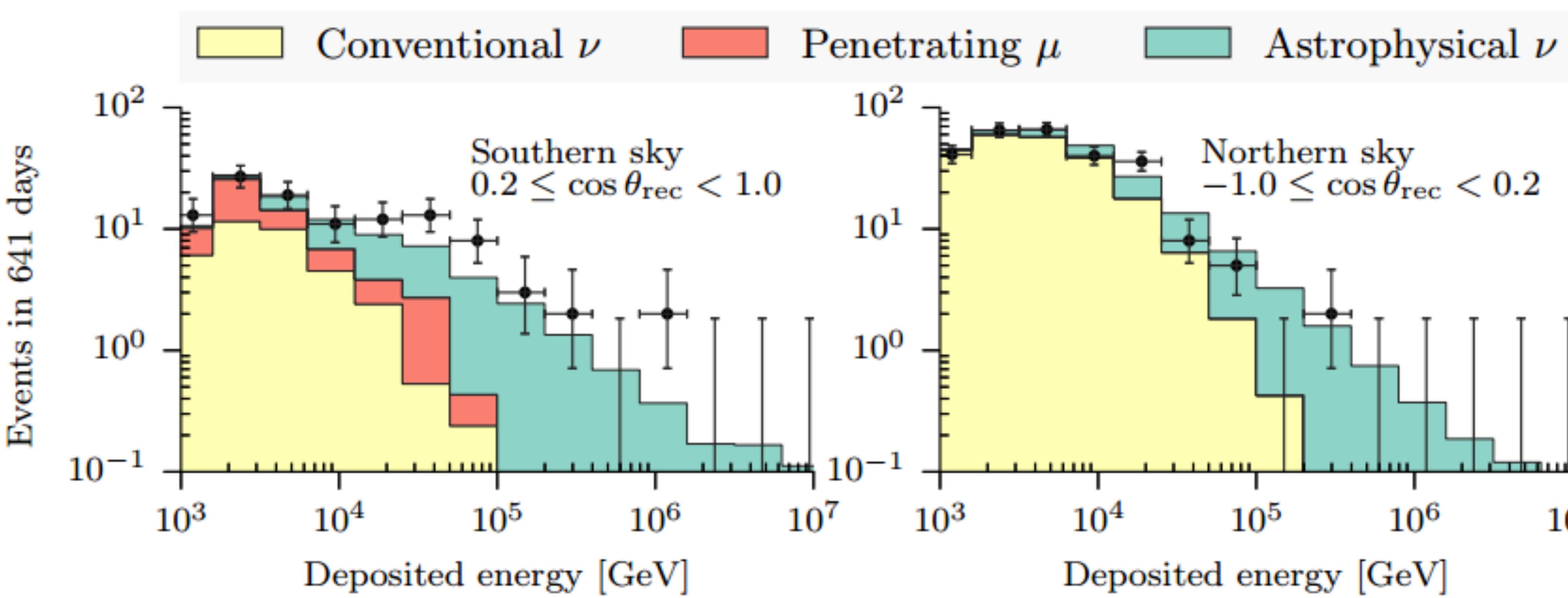
Harder than any expected atmospheric background. Best fit (per flavor):

$$E^2\Phi = 0.95 \pm 0.3 \times 10^{-8}\ (E/100\text{TeV})^{-0.3}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

Improving the veto technique to lower energies



- Thicker veto at lower energies.
- Threshold down to 1 TeV
- IC79/86-1 (641 days)
- 388 events (283 shower, 105 track, 92% neutrino)

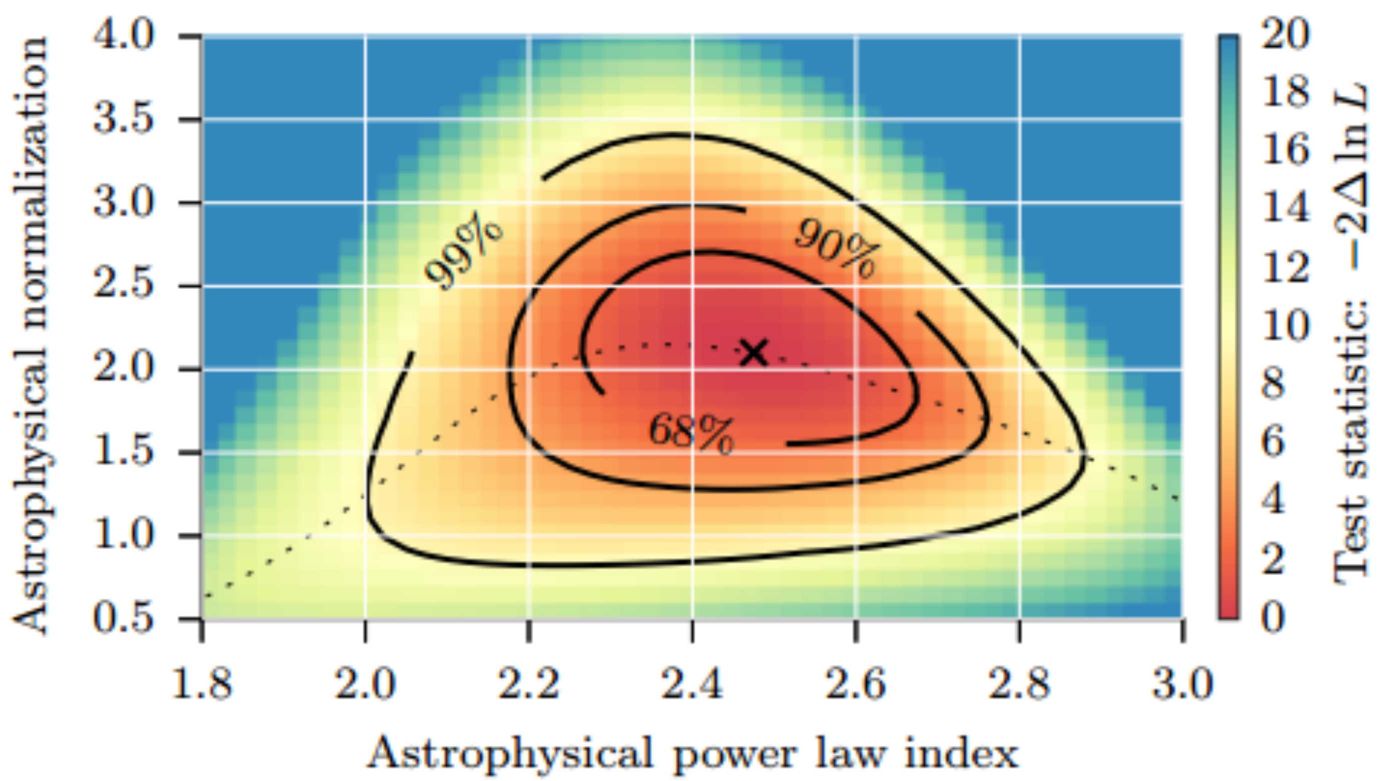


Best Fit parameters

- Best astrophysical fit:

$$2 \times 10^{-18} \, (E/10^5 \, \mathrm{GeV})^{-2.46} \, \mathrm{GeV}^{-1} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1} \, \mathrm{sr}^{-1}$$

- Limit on the prompt component 1.52 × ERS
- Fitted parameters are correlated and depend on the assumption of the astrophysical model.



IceCube Collaboration (2014) arXiv:1410.1749

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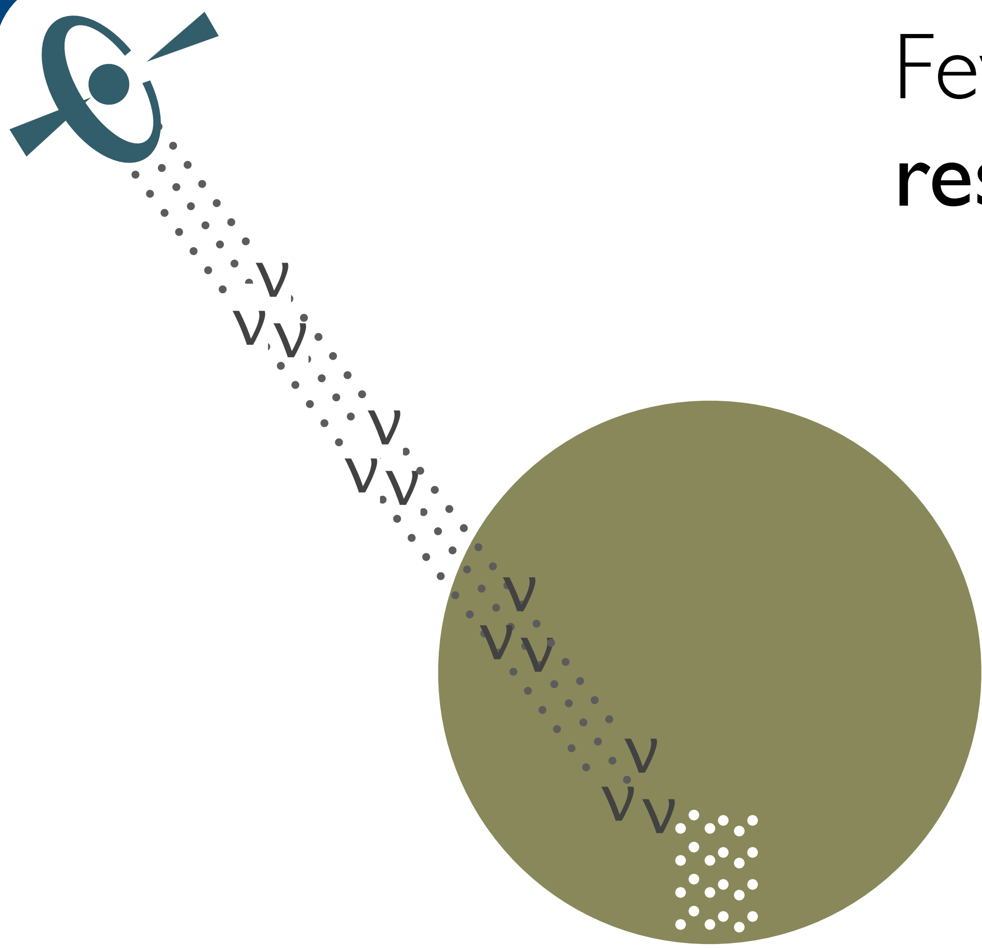
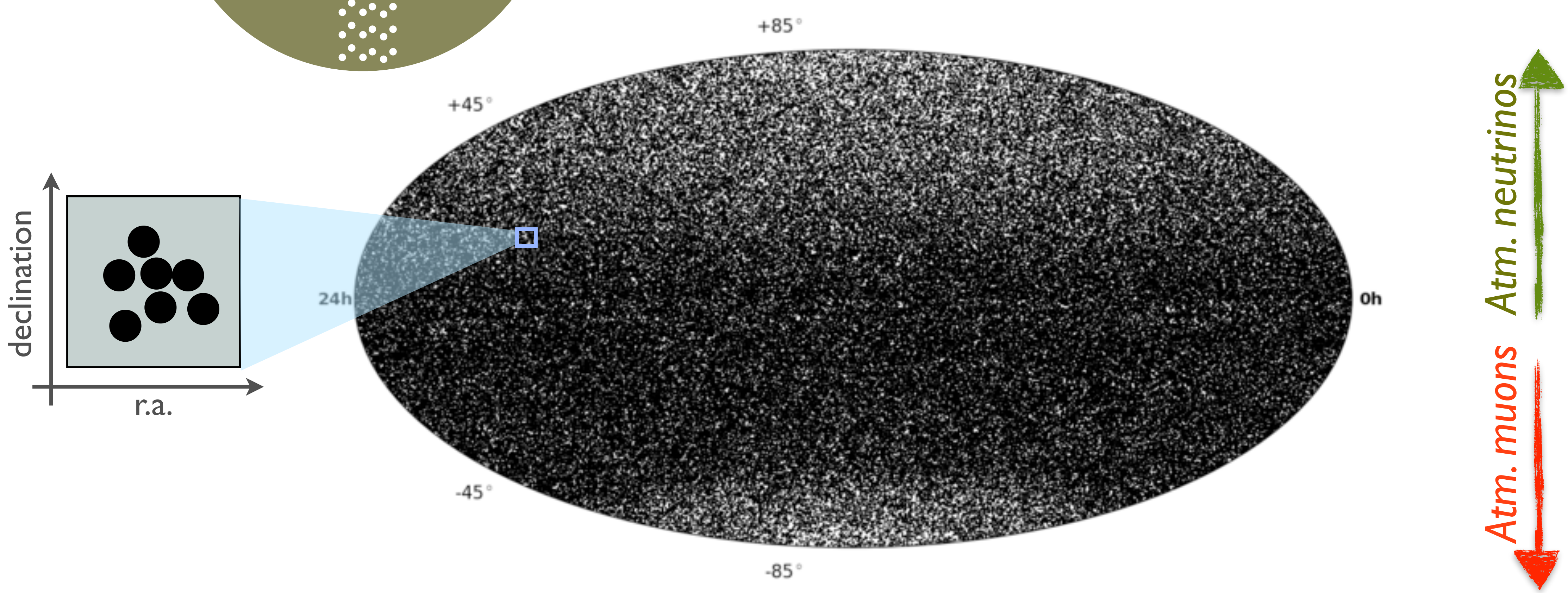
Through-going ν_μ point-source searches

Few but bright sources that could be **resolved individually**

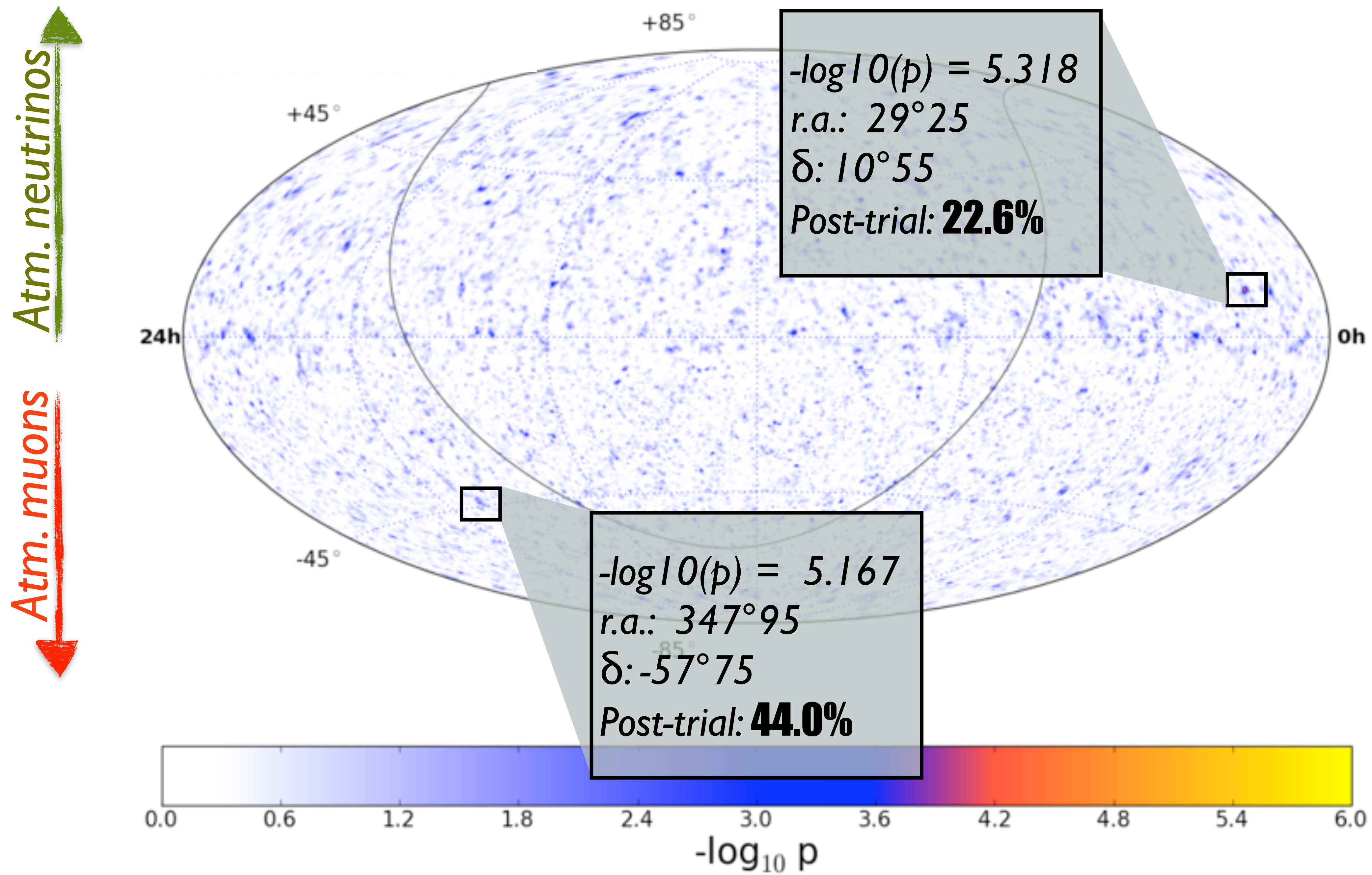
- *Background is atmospheric muons and neutrinos.*
- *Usually track-like events (muon neutrinos) are used for better pointing.*





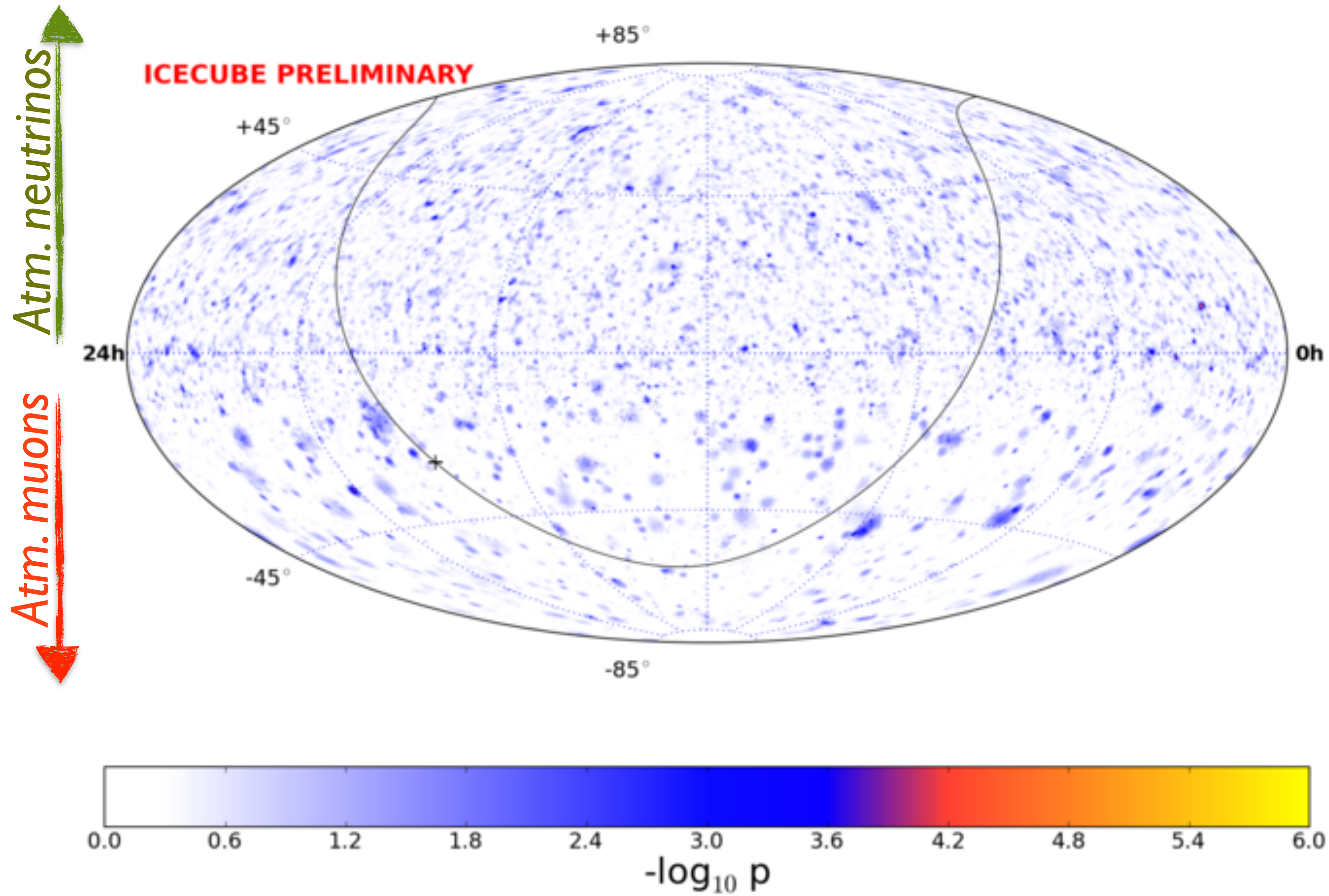
Point Source Search Skymap

- *4 YEARS standard through-event sample.*
- Total events: **394,000** (178k upgoing + 216k downgoing)
- Livetime: **1371 days**



MESE point-source analysis

- Combining through going-muons and starting tracks in the Southern Sky.
- 400,000 through going events + 549 downgoing starting tracks



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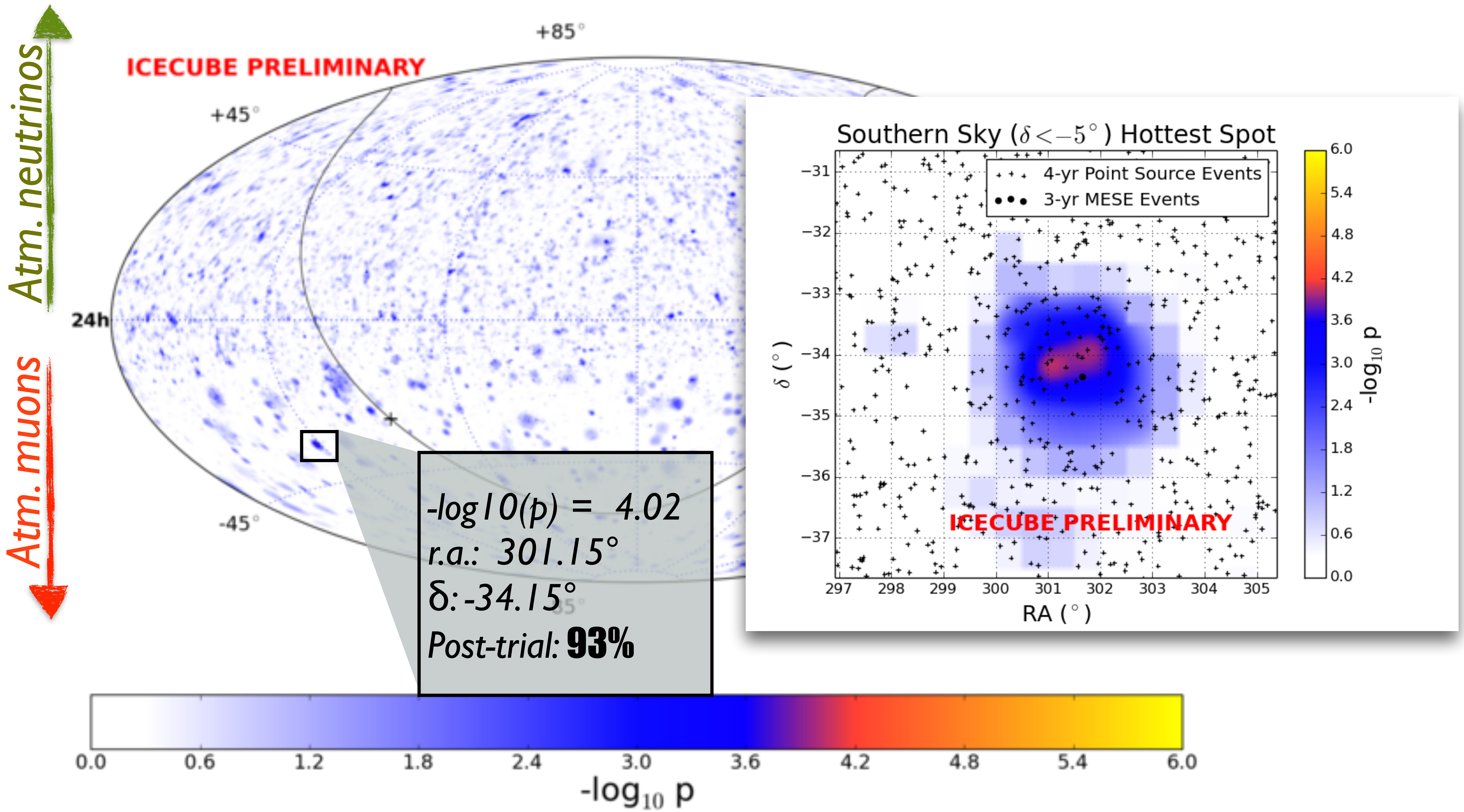
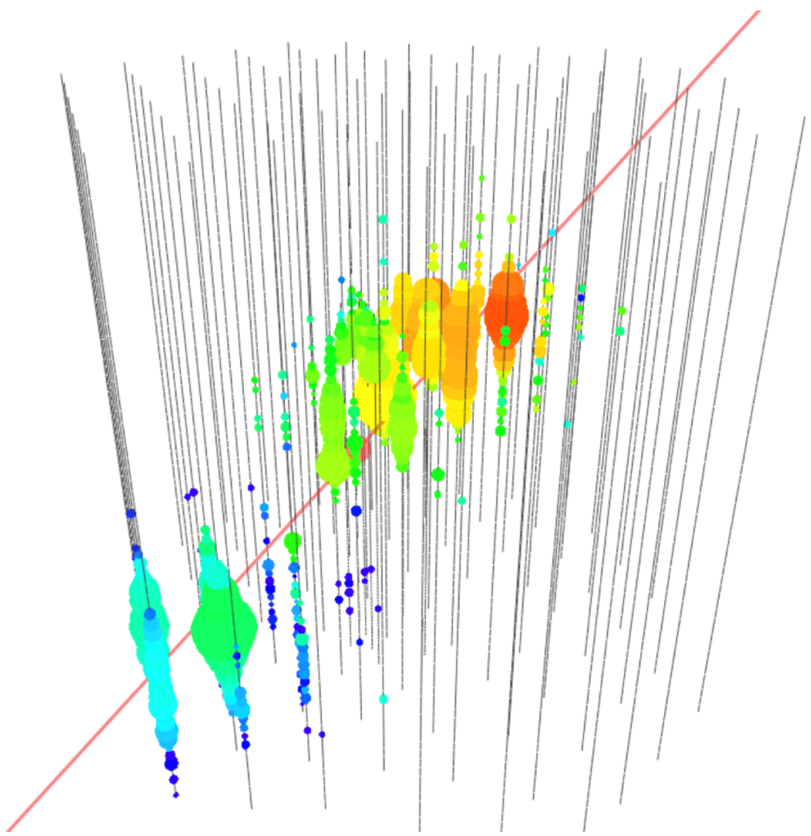
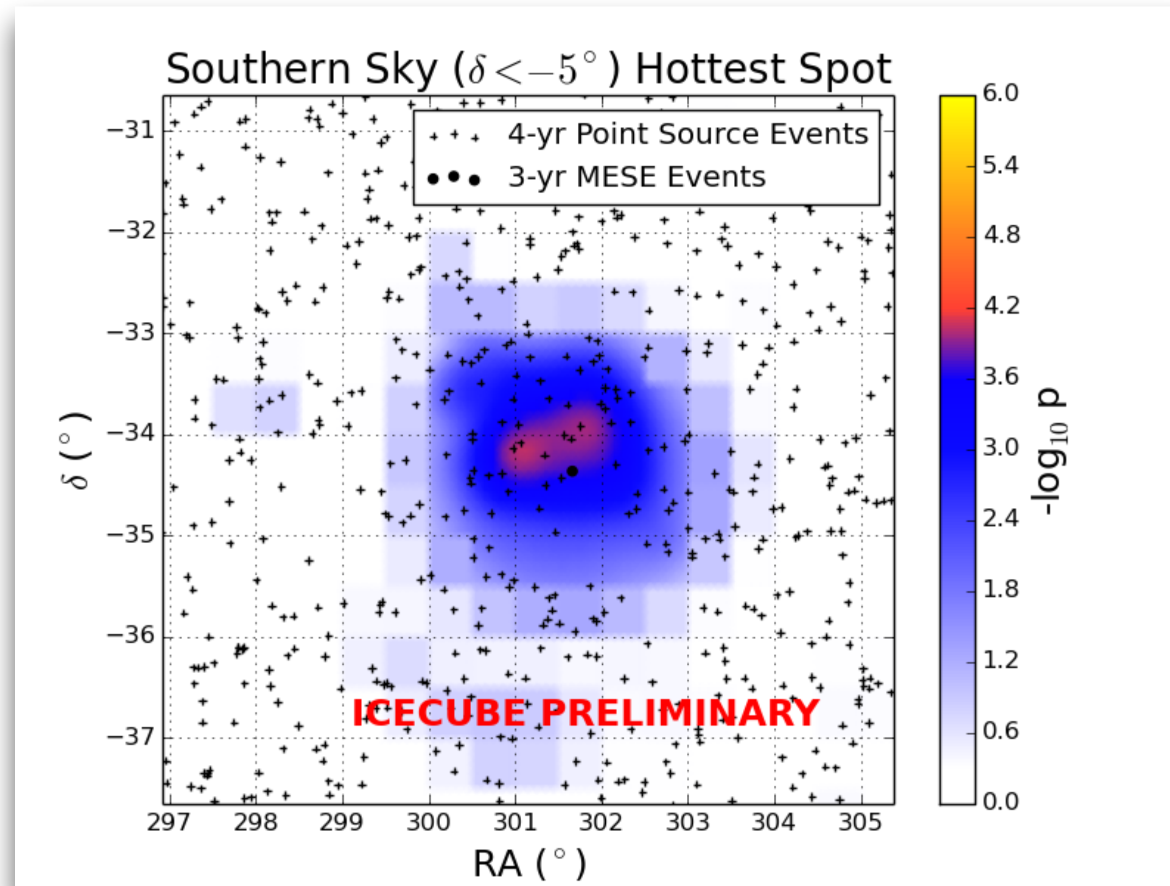


MESE results

- All consistent with background but one interesting event is part of the cluster.



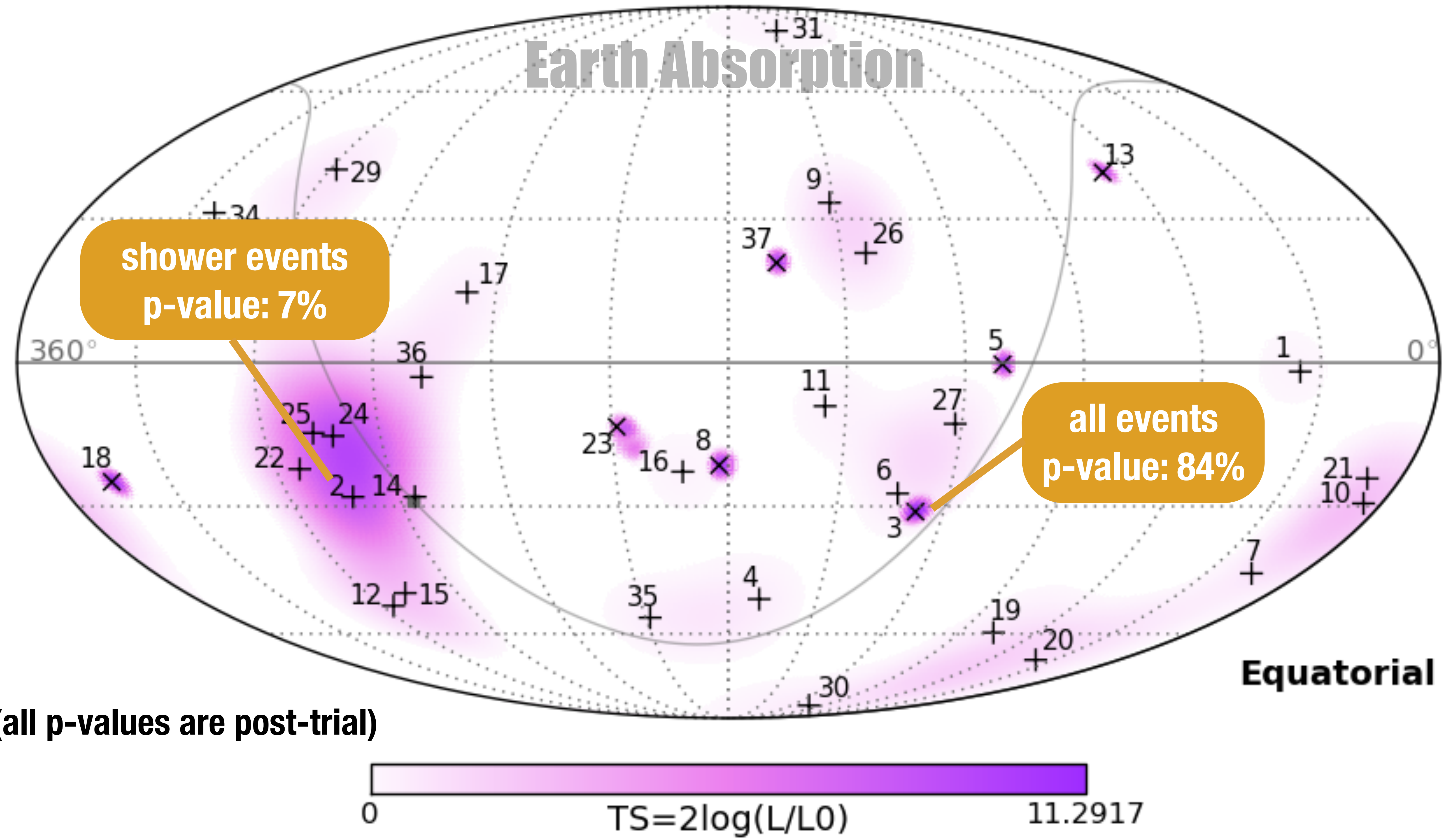


- Starting event, deep in detector.
  - Deposited energy: **84 TeV**
  - Angular resolution: **0.6°**
- Rate expected, if atmospheric ~0.0022 in 3 yrs: **2.8σ**

Down-going starting track ➜ best directionally reconstructed event with high probability of astrophysical origin.

What about the HESE sample?

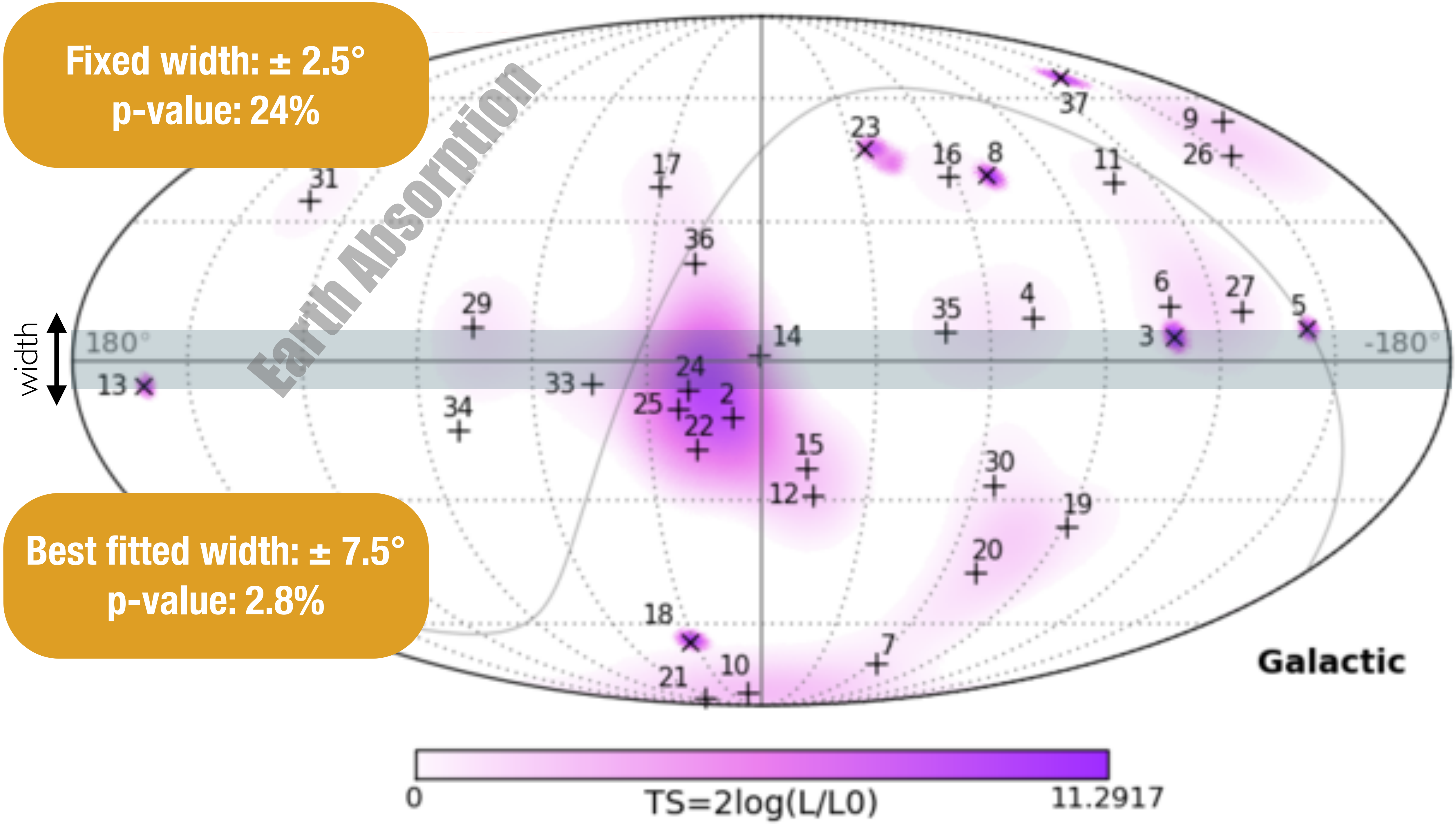
No significant clustering observed **3 years**



(all p-values are post-trial)

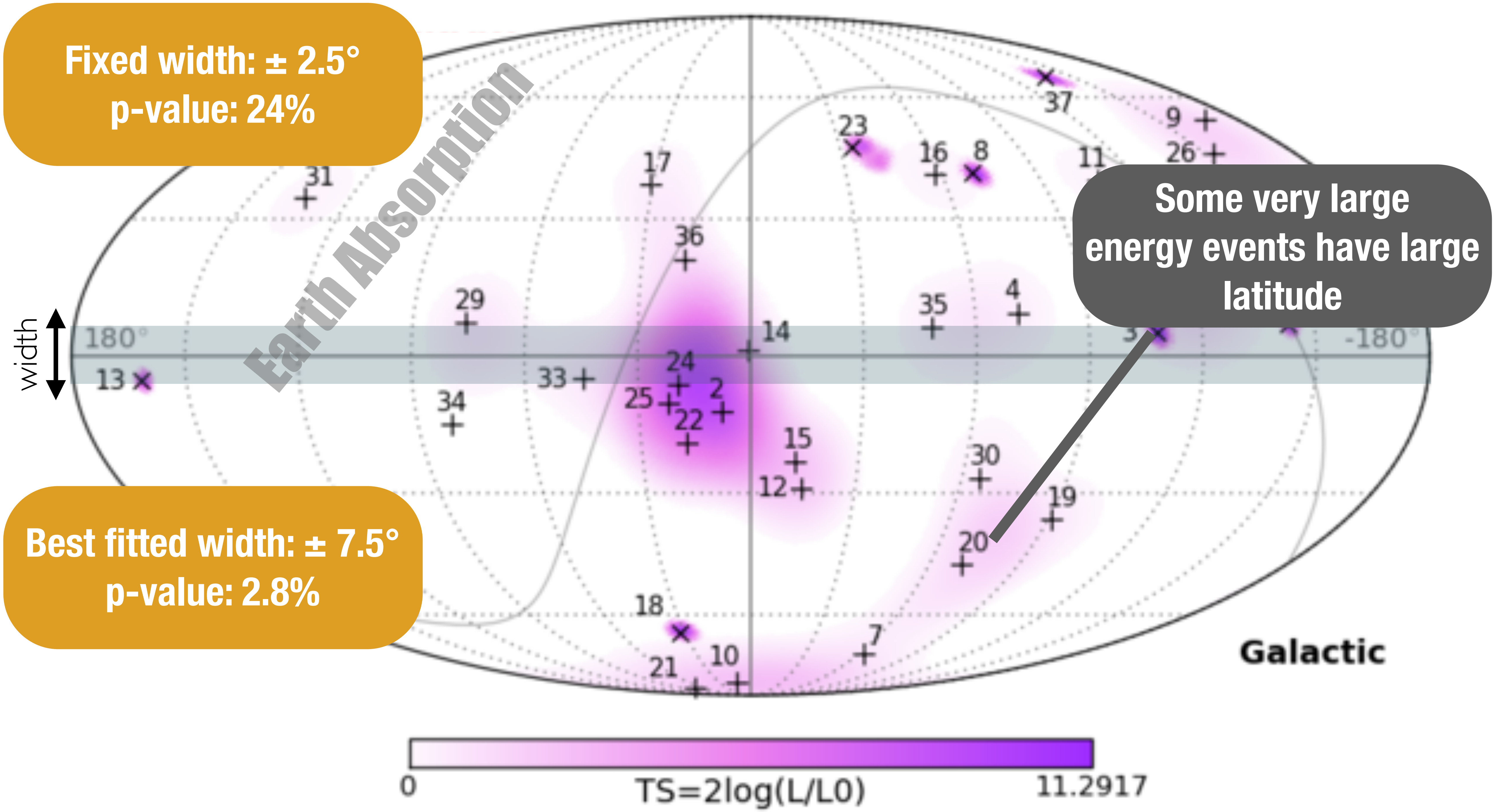
Does it correlate with the Galactic Plane?

Fixed width: ± 2.5°
p-value: 24%



Best fitted width: ± 7.5°
p-value: 2.8%

Does it correlate with the Galactic Plane?



What about its origin?

- Events at large galactic latitude and the absence of significant clusters suggests an extra-galactic origin.
- The soft spectral index and the disfavored E^{-2} suggests a galactic origin (see for instance Murase et al. arXiv:1306.3417).

What about its origin?

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We need more data! Let's build a bigger detector!

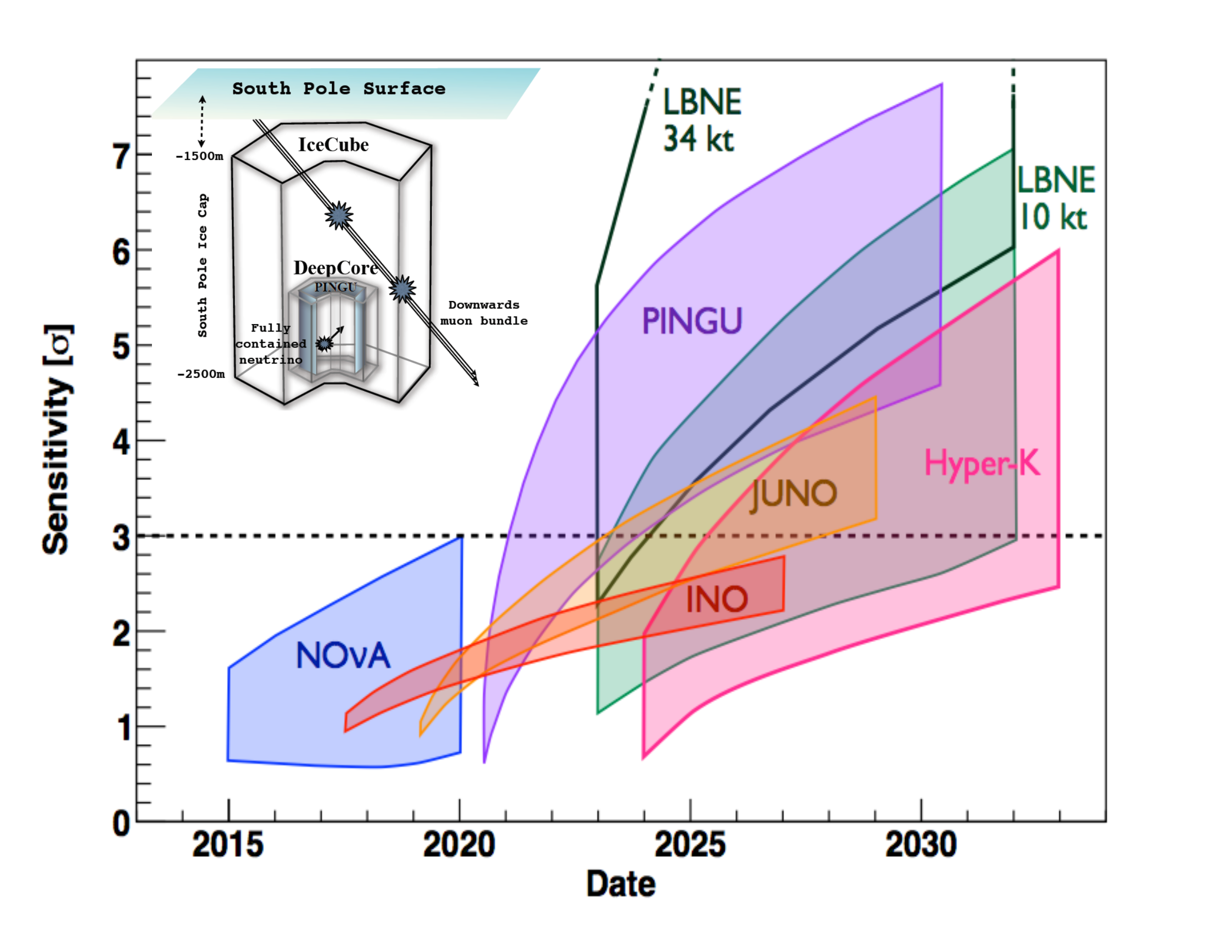
THE FUTURE: *ICECUBE-GEN2*

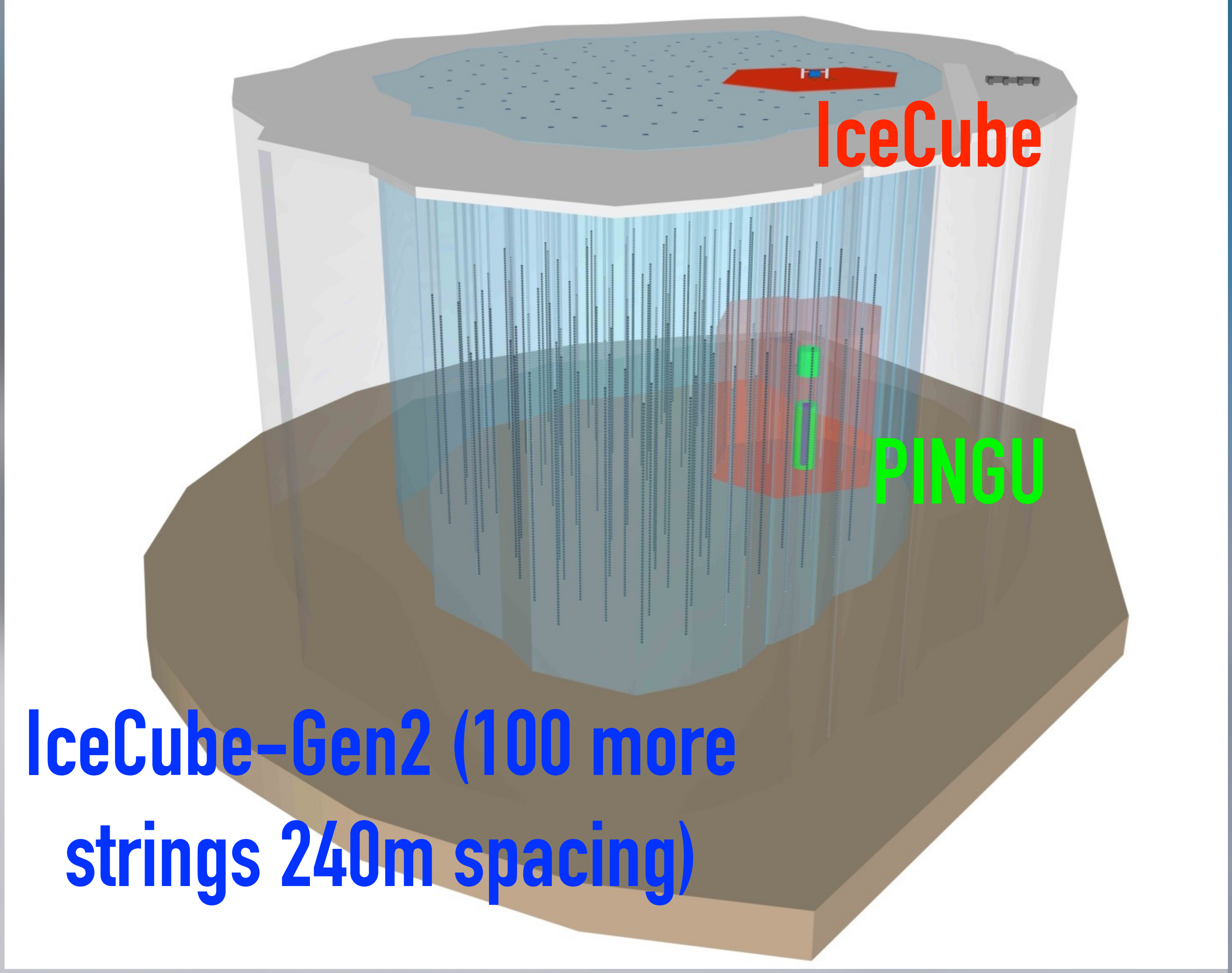
PINGU

Further in-fill of deep core.
Lower the energy threshold few GeV
Oscillations and Neutrino Mass Hierarchy

High Energy Extension

Extension of IceCube array
Look for high-energy events
GZK and **astrophysical neutrinos**





arXiv:1412.5106

Conclusions

No evidence yet of neutrino point and extended sources…

…but observation of a diffuse high-energy component beyond the atmospheric spectrum.

- IceCube has paved the road for neutrino astrophysics.
- More data will resolve the origin of these neutrinos.
- ***IceCube-Gen2*** will enlarge the energy range and widen the physics goals.

- Backup

OBSERVABLE UNIVERSE

Some reference values:

Galactic Centre	8 kpc
Local group (Andromeda M31)	0.725 Mpc
Markarian 421	~ 136 Mpc

Universe c/H_0 = 13.7 billion yrs
(e.g. z=1 ~ 6.6 Gpc)

Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \rightarrow \Delta^+ \rightarrow \pi^+ n$$

$$L_\gamma = \frac{1}{\sigma_{p-\gamma_{CMB}} n_\gamma} \sim \frac{1}{10^{-28}\mathrm{cm}^2 \times 400\mathrm{cm}^{-3}} \sim 10\ \mathrm{Mpc}$$

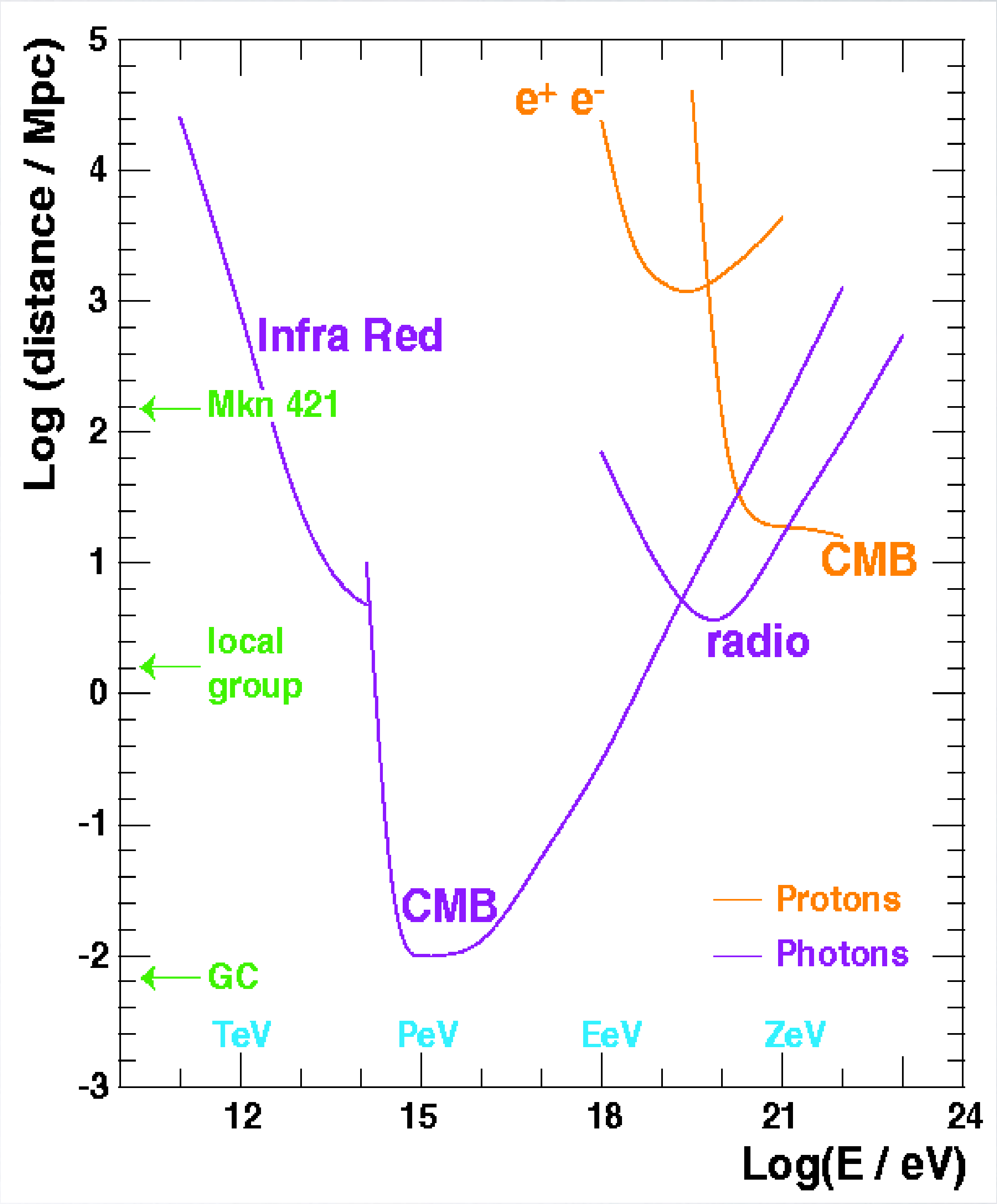
The neutrino horizon is comparable to the observable universe!

$$\bar{\nu}\nu_{1.95K} \rightarrow Z \rightarrow X$$

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4 \times 10^{21} \left(\frac{1\mathrm{eV}}{m_\nu}\right)\mathrm{eV}$$

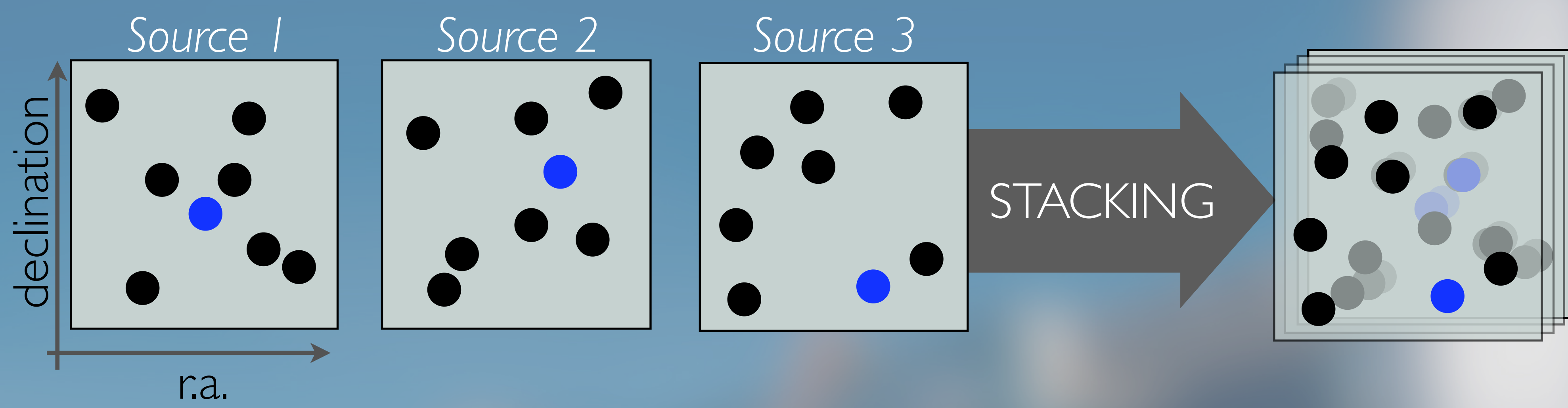
$$L_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6 Gpc$$

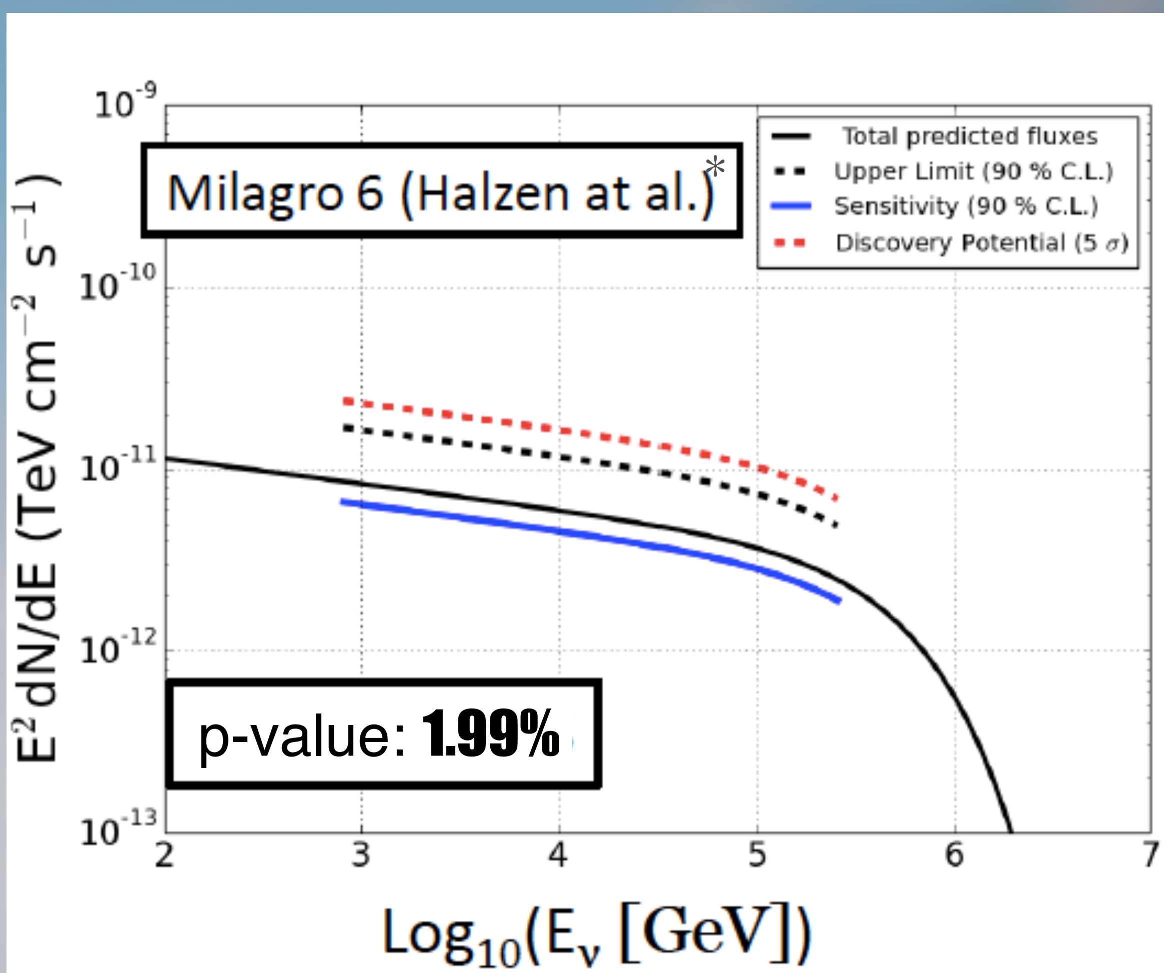
1Mpc = 3.26 Mly = 3.1 10^{24} cm



T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)

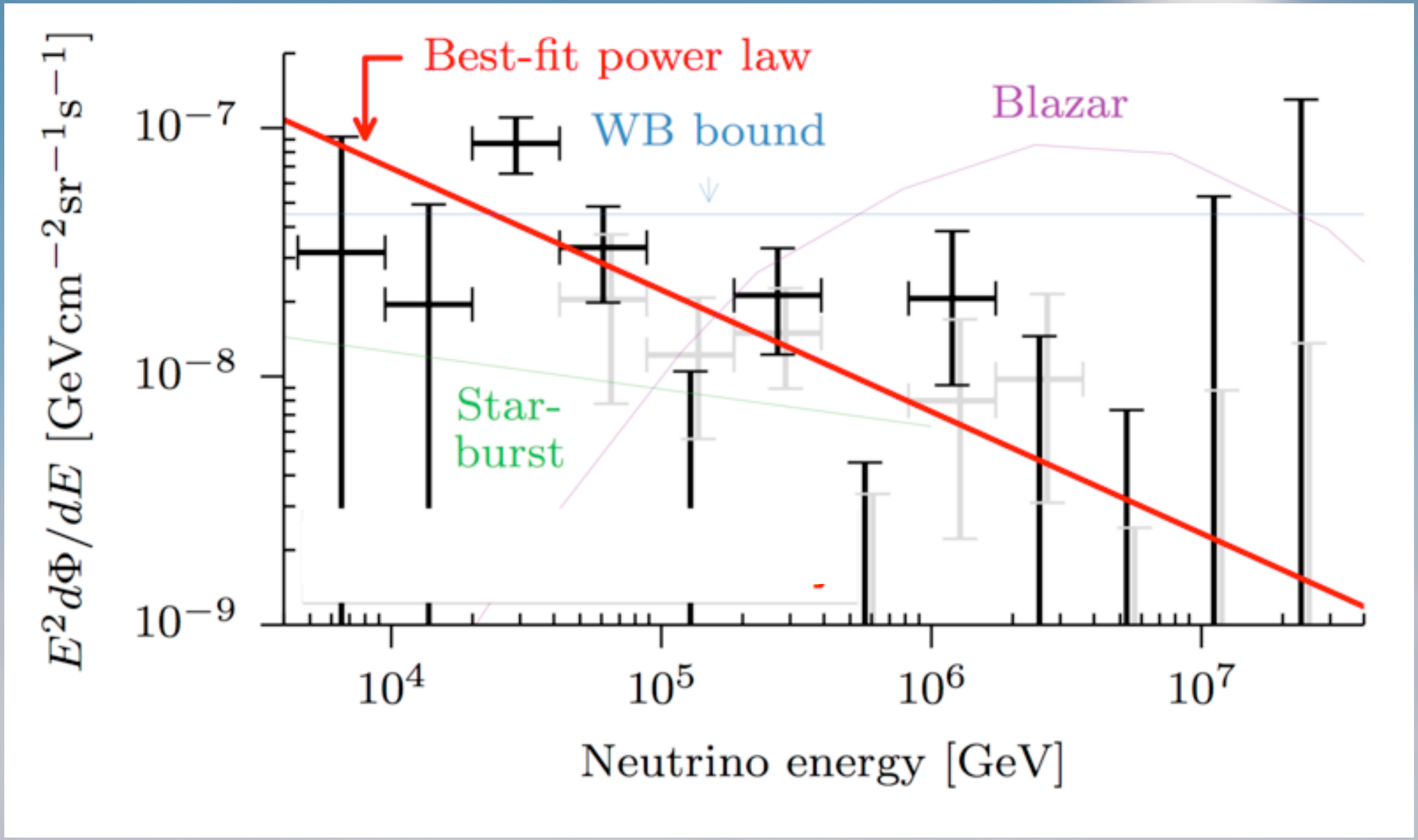
Stacking Searches





- 6 TeV associations with supernova remnants based on **Milagro observations**. Models from Halzen et al.
- p-value of 2% *a posteriori* in IC40.
- Evolved from under-fluctuation in IC59 and 20% in IC59+IC79.
- p-value in IC86+IC79+IC59: **1.99%**

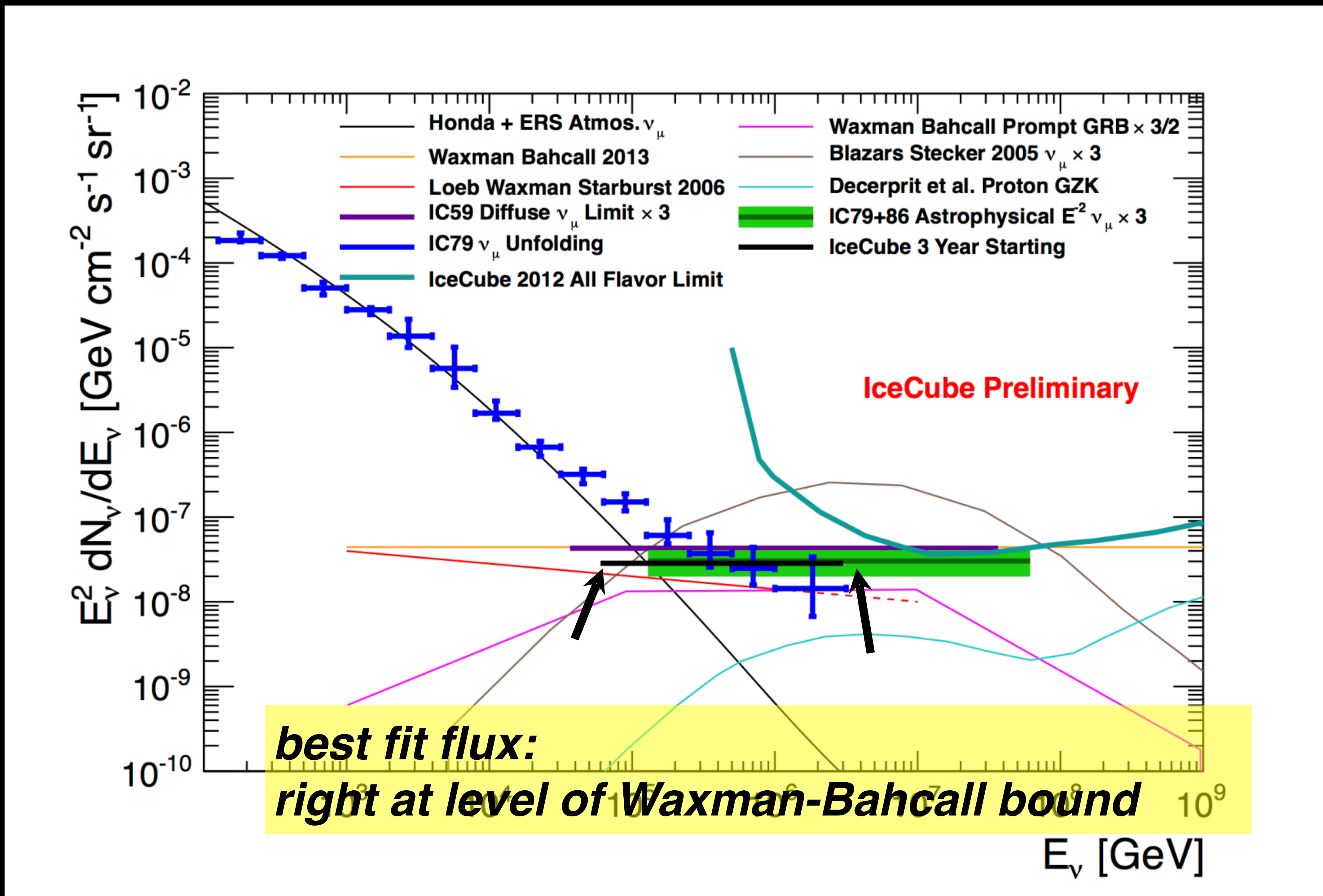
*F. Halzen, A. Kappes and A. O'Murchadha (Phys. Rev. D78:063004, 2008)



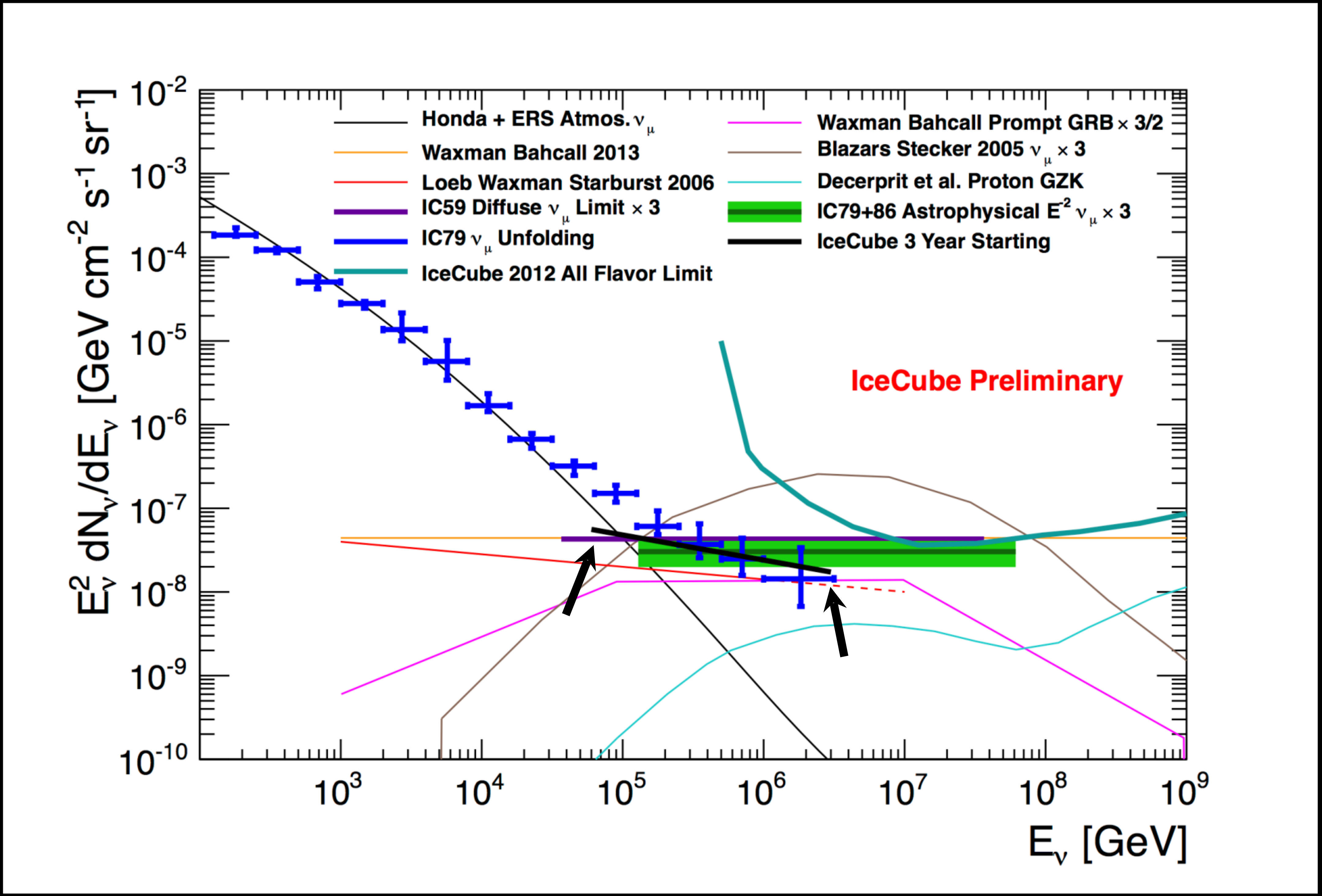
Best-fit power law
Blazar
WB bound
Star-
burst
10^{-7}
10^{-8}
10^{-9}
$E^2 d\Phi/dE$ [GeVcm^{-2}sr^{-1}s^{-1}]
10^4
10^5
10^6
10^7
Neutrino energy [GeV]

Global fit, energy (60 TeV – 3 PeV) vs angle,
best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (per flavour)

5.7 sigma rejection of atmospheric-only hypothesis



global fit, energy (60 TeV – 3 PeV) vs angle,
float astrophysical spectral index:
best fit spectral index = -2.3 +/- 0.3



Diffuse flux summary