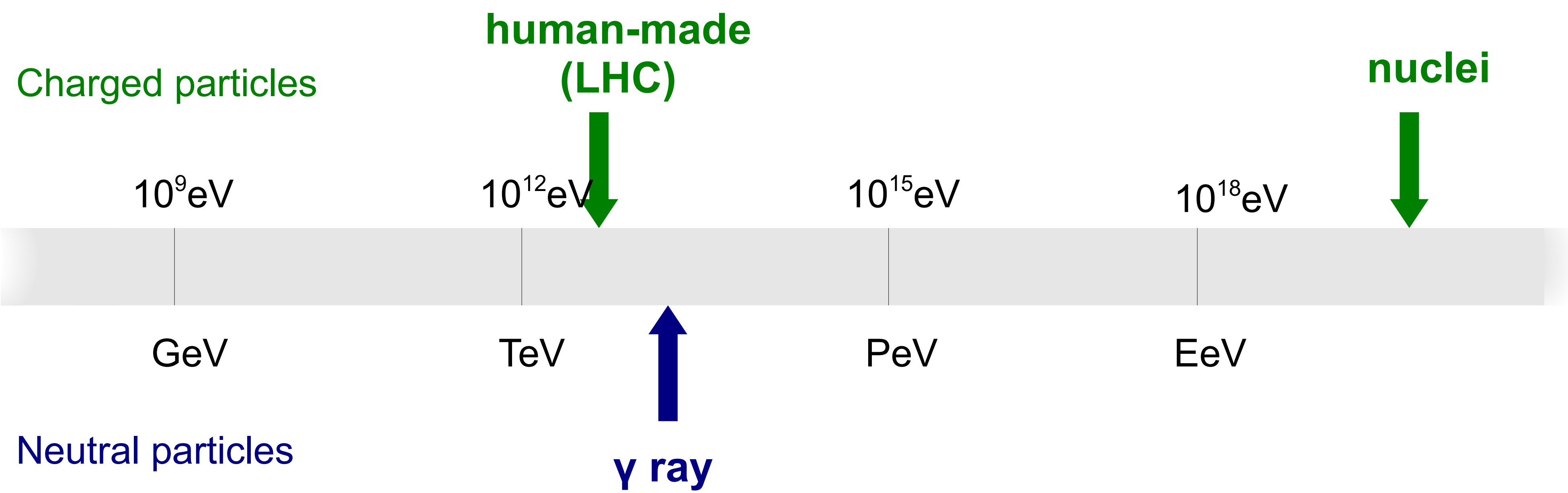
# Astrophysical Neutrinos at IceCube and a Hunt For Their Sources


**Naoko Kurahashi Neilson**
Drexel University


AMON Workshop
PSU Dec 3rd, 2015

# Highest energy particles observed



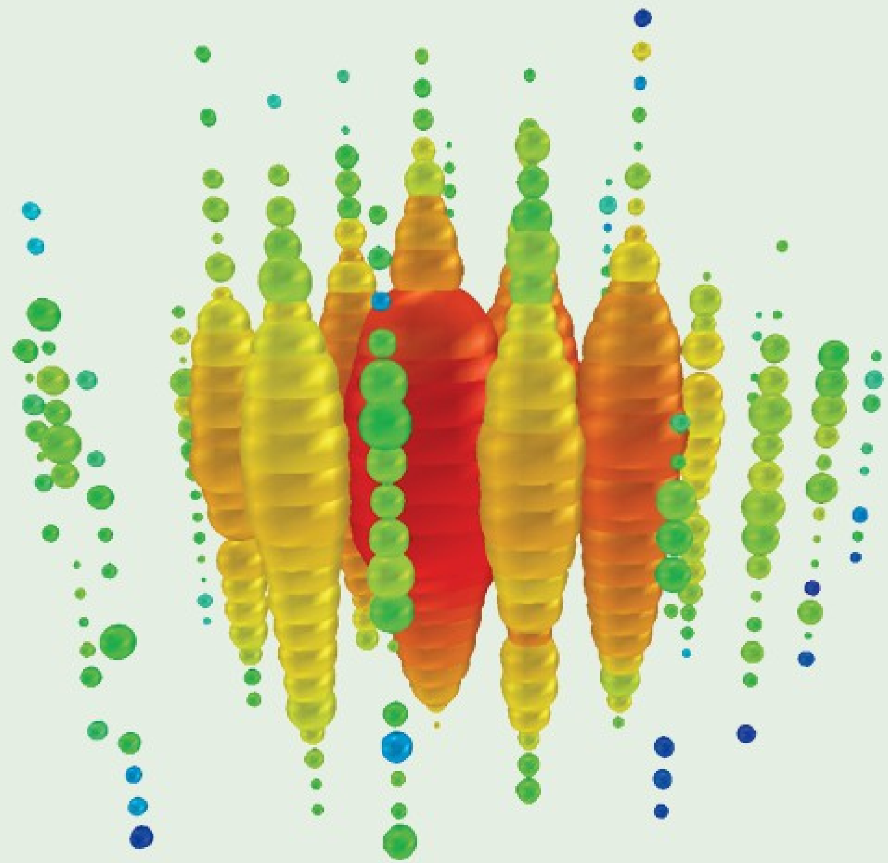
111

PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

2

# PHYSICAL REVIEW LETTERS™

Articles published week ending 12 JULY 2013



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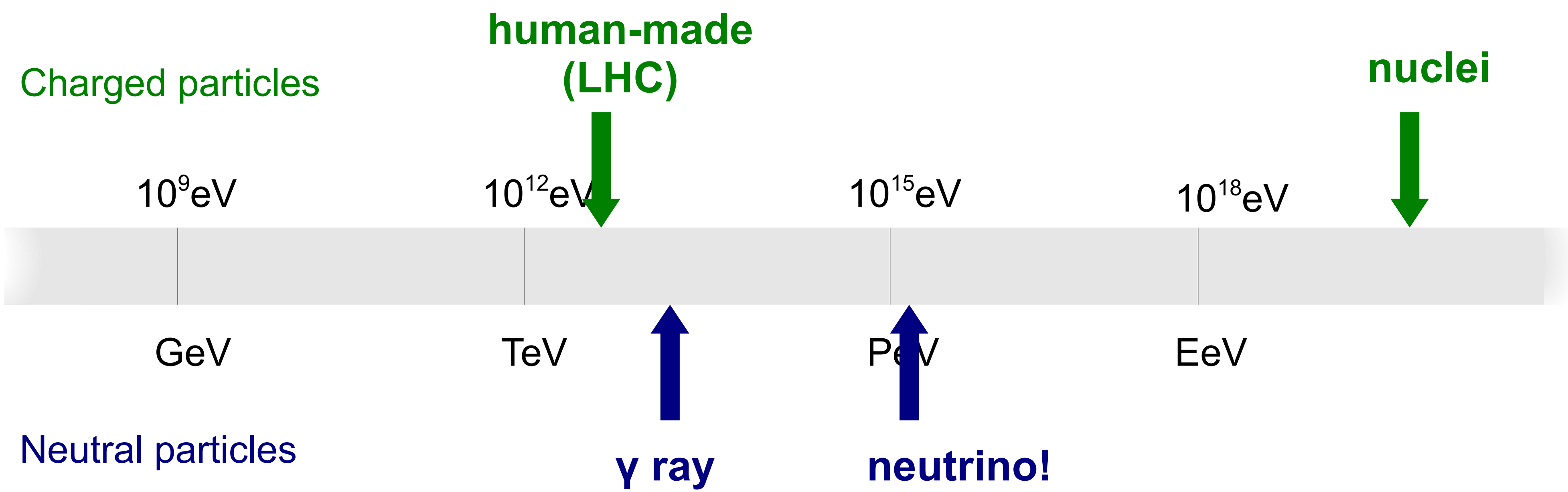
Volume 111, Number 2

# Highest energy particles observed



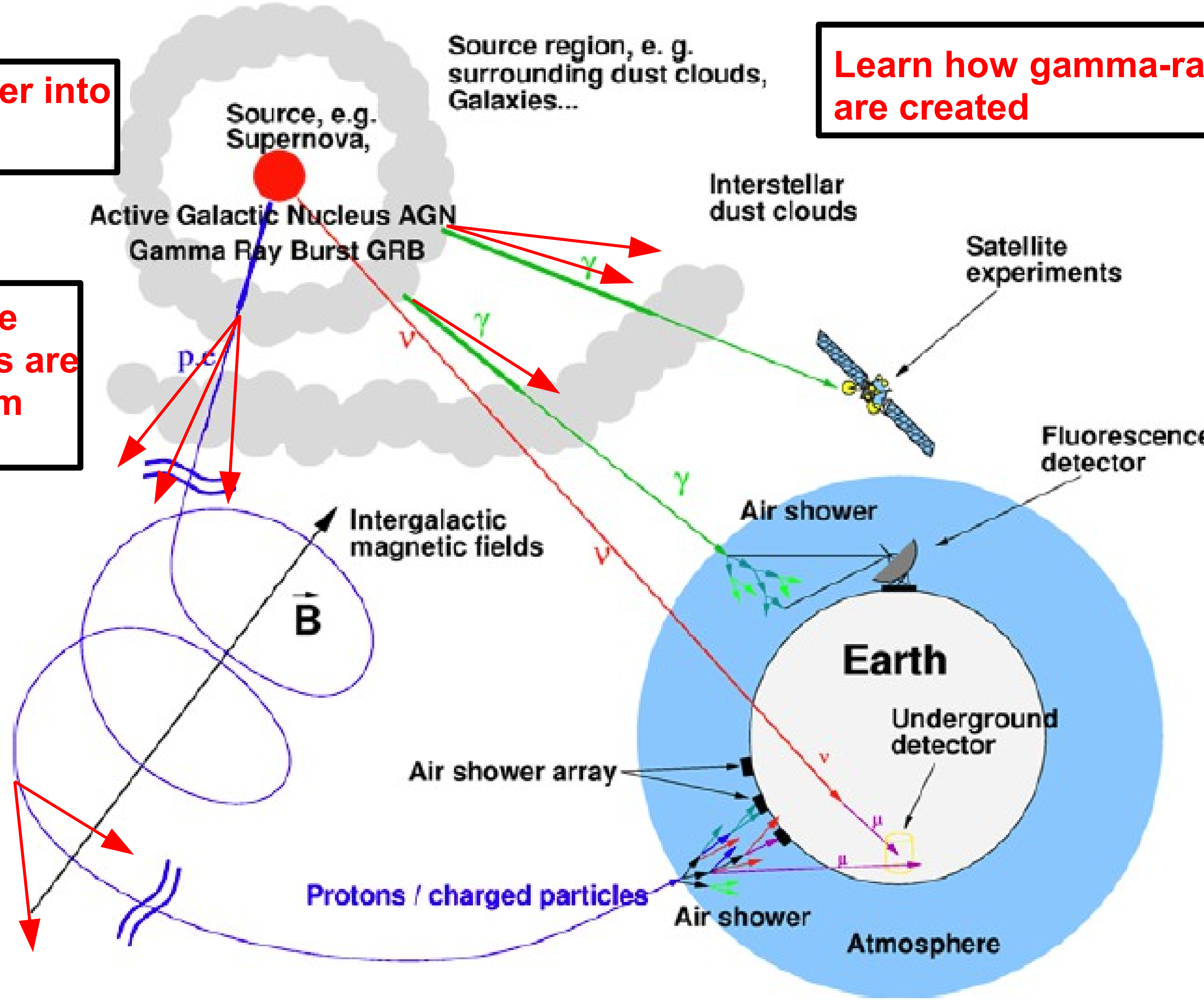

- How are neutral particles created at such high energies?
- Can neutrinos be created the same way γ-rays are?
- What are the most likely sources of these observed neutrinos? Background? Signal?
- Where do they come from? What does that tell us?

# Neutrino Astronomy

See deeper into sources

Learn how gamma-rays are created

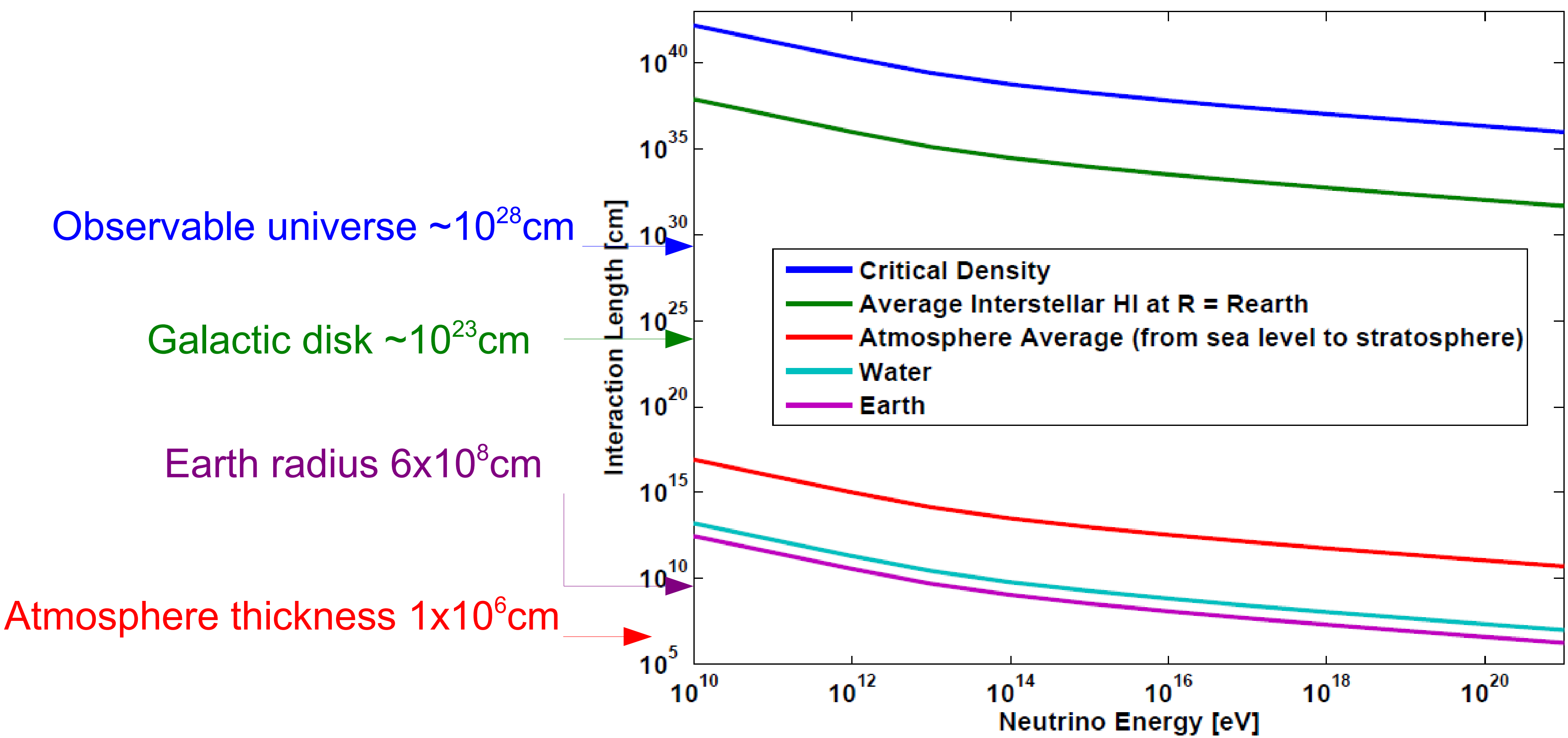
Learn where cosmic-rays are coming from



# Challenges of Neutrino Astronomy

Same characteristics that make neutrinos great messengers make them hard particles to detect

In some ways, this is front-loading the problem.
- Neutrinos: harder to detect but easier to interpret

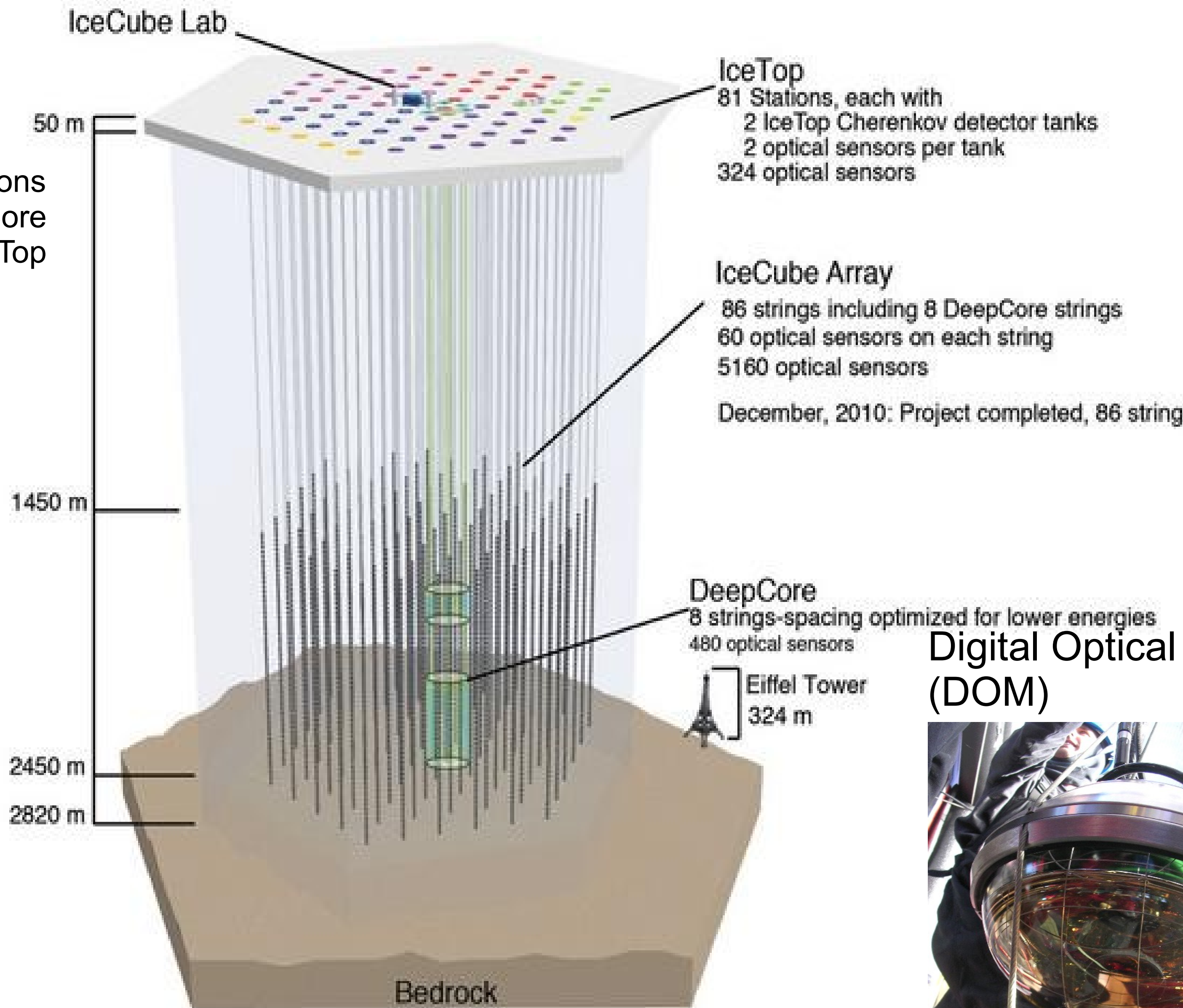



Cross section from **Gandhi et al., Phys. Rev. D 58 (1998) 093009**

# The IceCube Detector

IceCube and its two extensions
DeepCore
IceTop

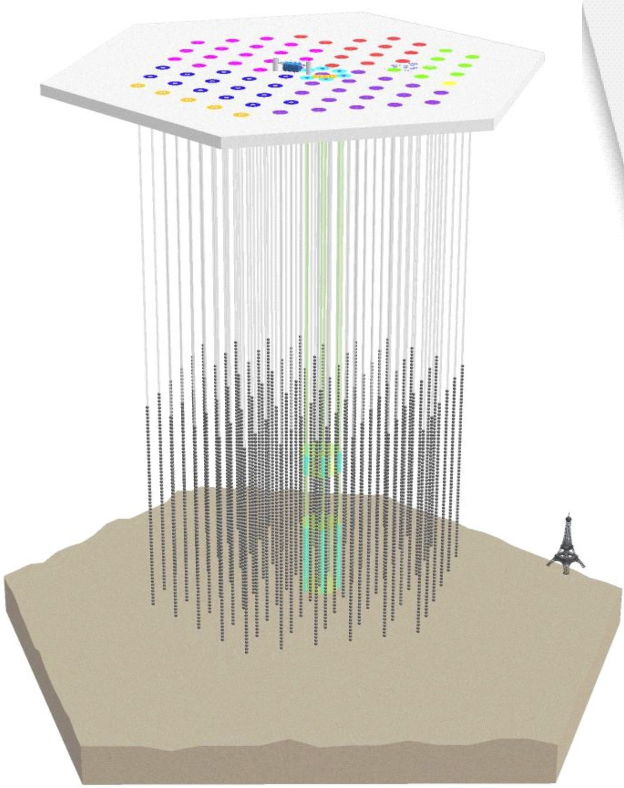
*17m vertical spacing*
*125 m String spacing*

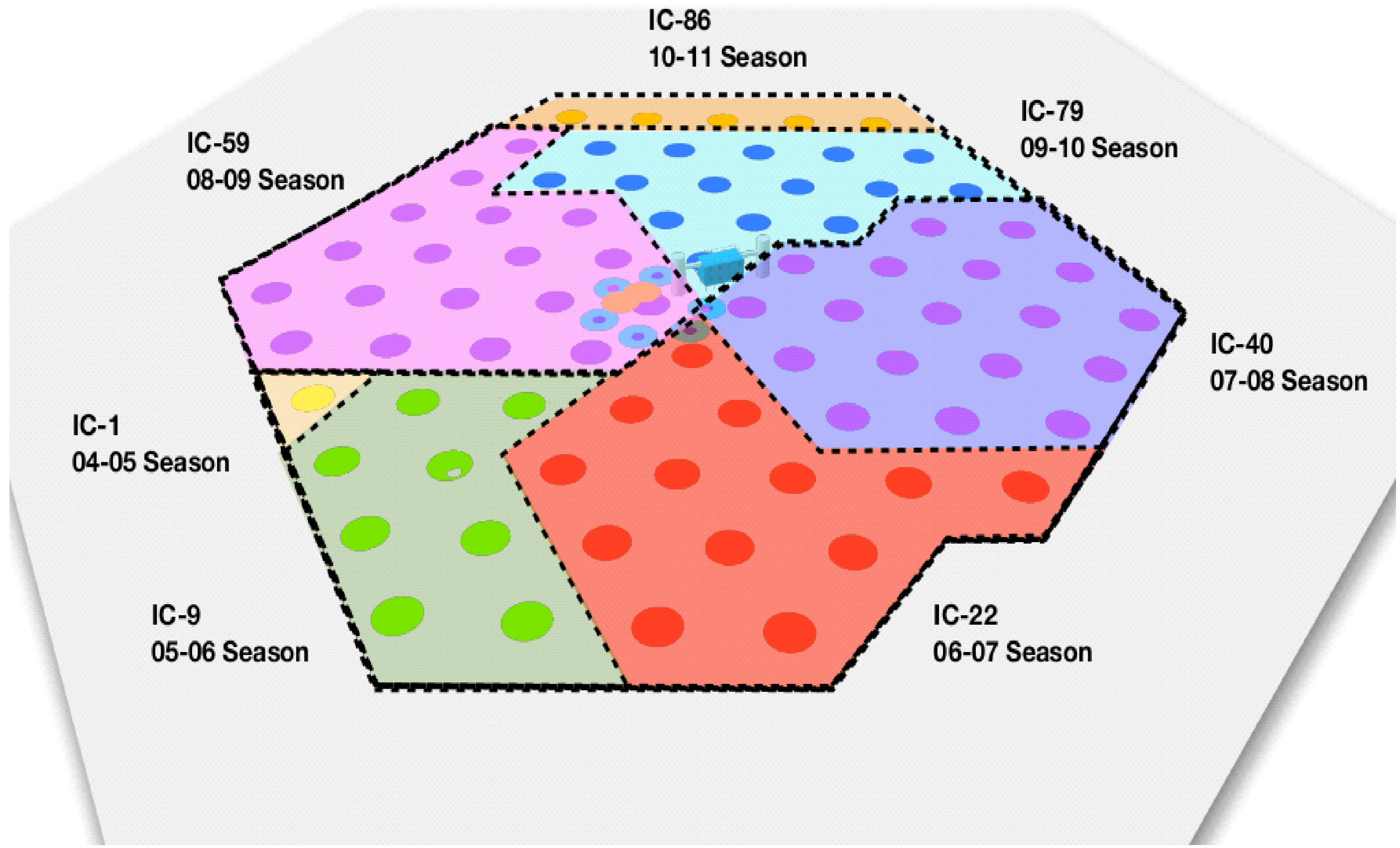



Digital Optical Module (DOM)

**Completed in Dec 2010!**

# More IceCube Jargon



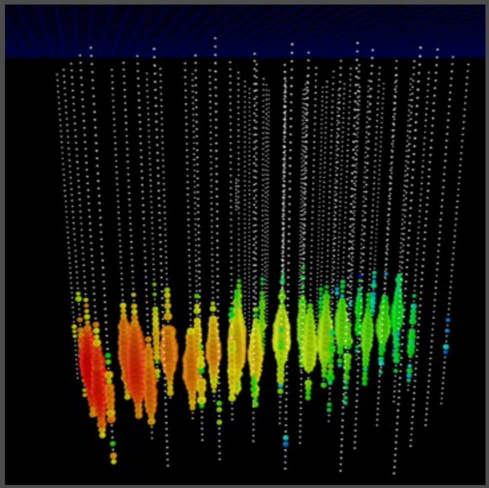


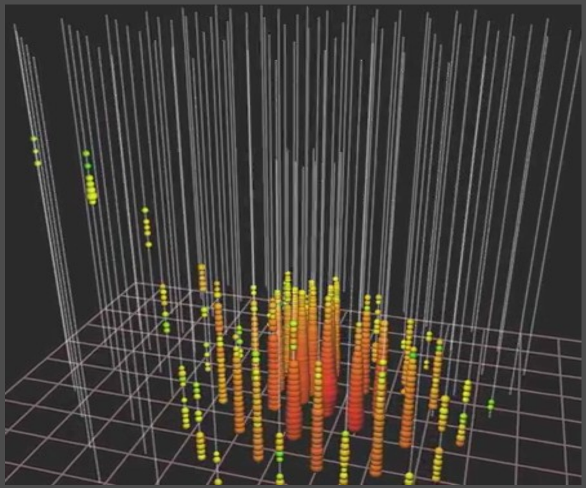

40-strings (IC-40), 376 days livetime, ~50% complete
59-strings (IC-59), 348 days livetime, ~50% complete
79-strings (IC-79), 333 days livetime, almost complete
86-strings (IC-86), 329 days livetime, complete

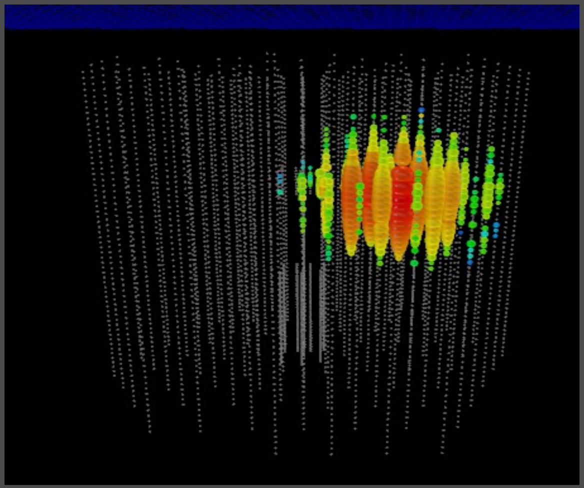
# Topologies of different event types

Charge Current Muon Neutrinos

Charge Current Electron/Tau Neutrinos
All Neutral Current Neutrinos







$$\nu_e + N \to e + X$$

$$\nu_x + N \to \nu_x + X$$

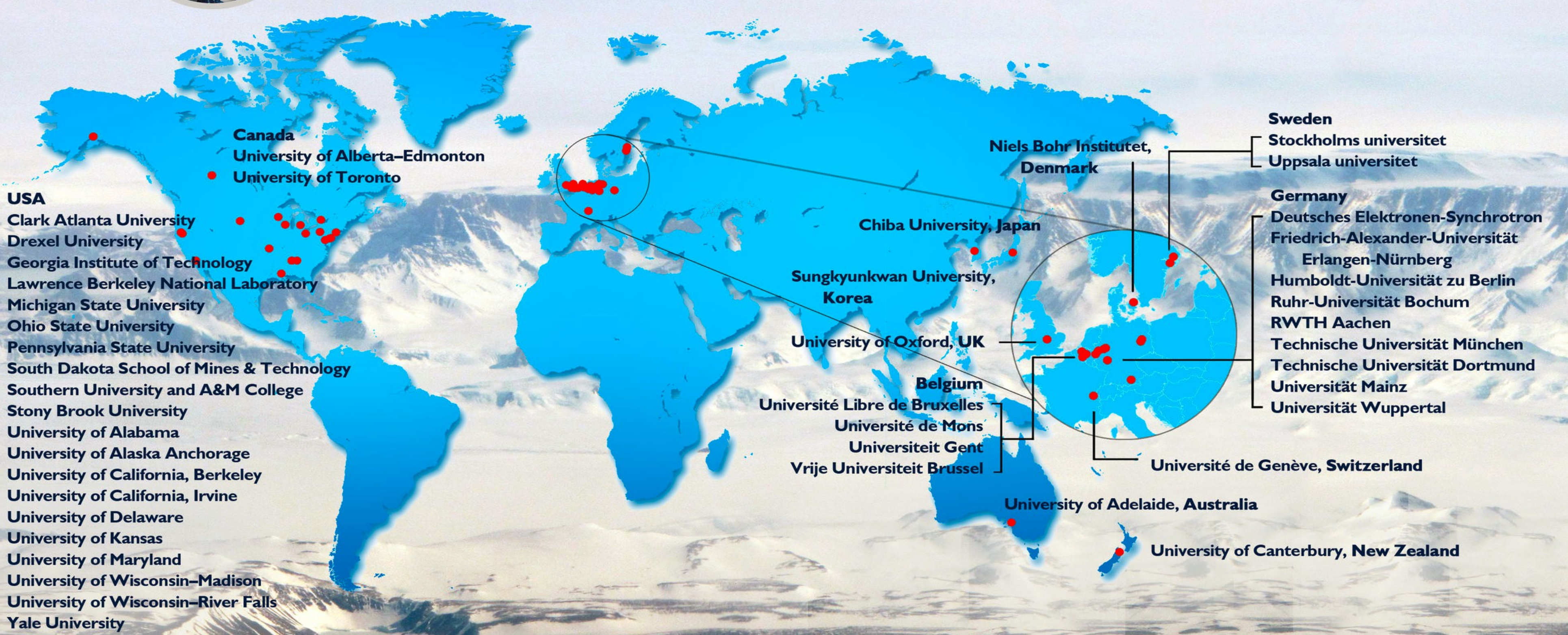
$$\nu_\tau + N \to \tau + X$$

$$\nu_\mu + N \to \mu + X$$

**Through-going Track** **Starting Track** **Shower**

**~250 people for ~40 institutions**

# The IceCube Collaboration



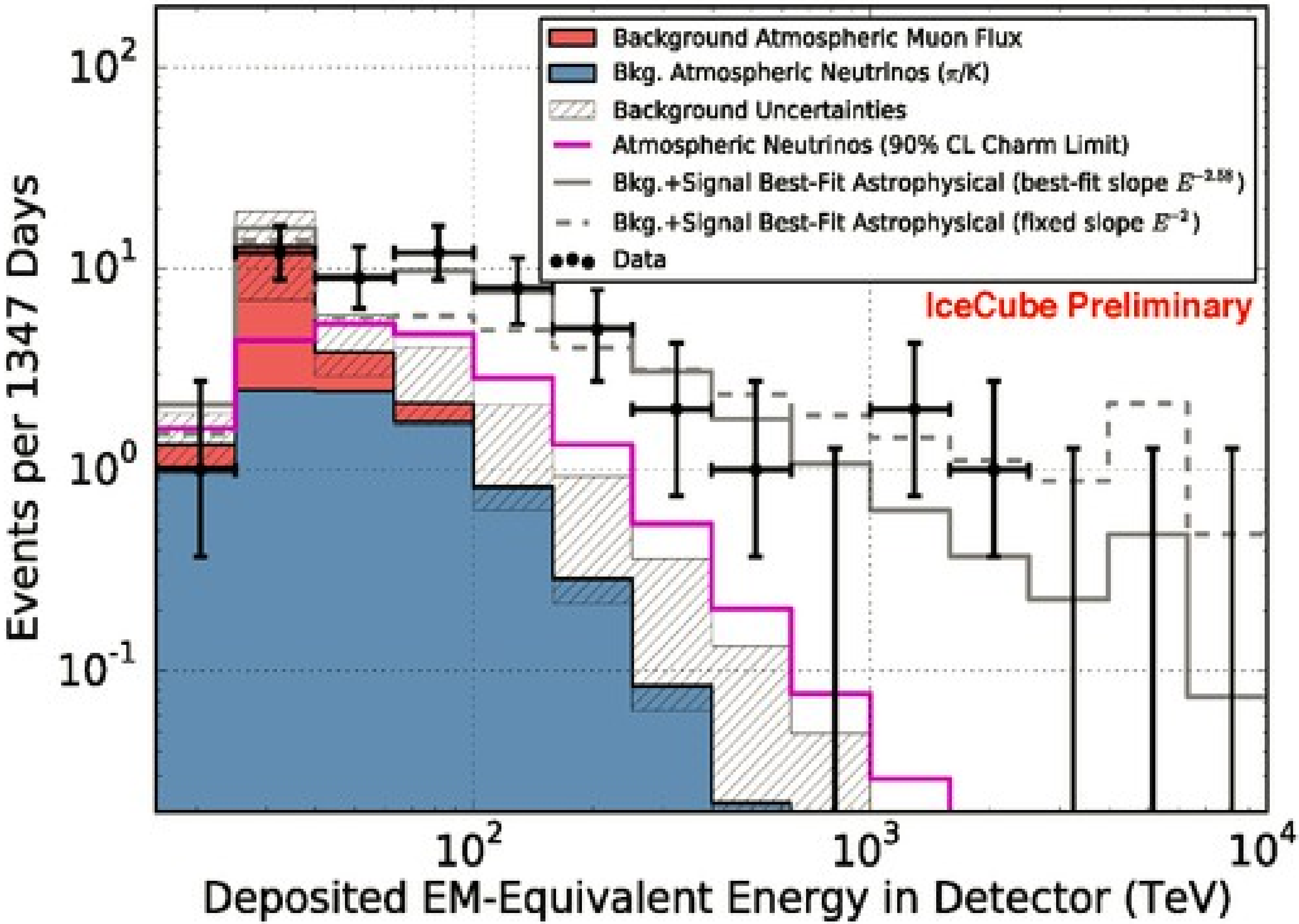

**Funding Agencies**

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)

Women Observing Stars, Ota Chou, 1936
Tokyo Modern Arts Museum

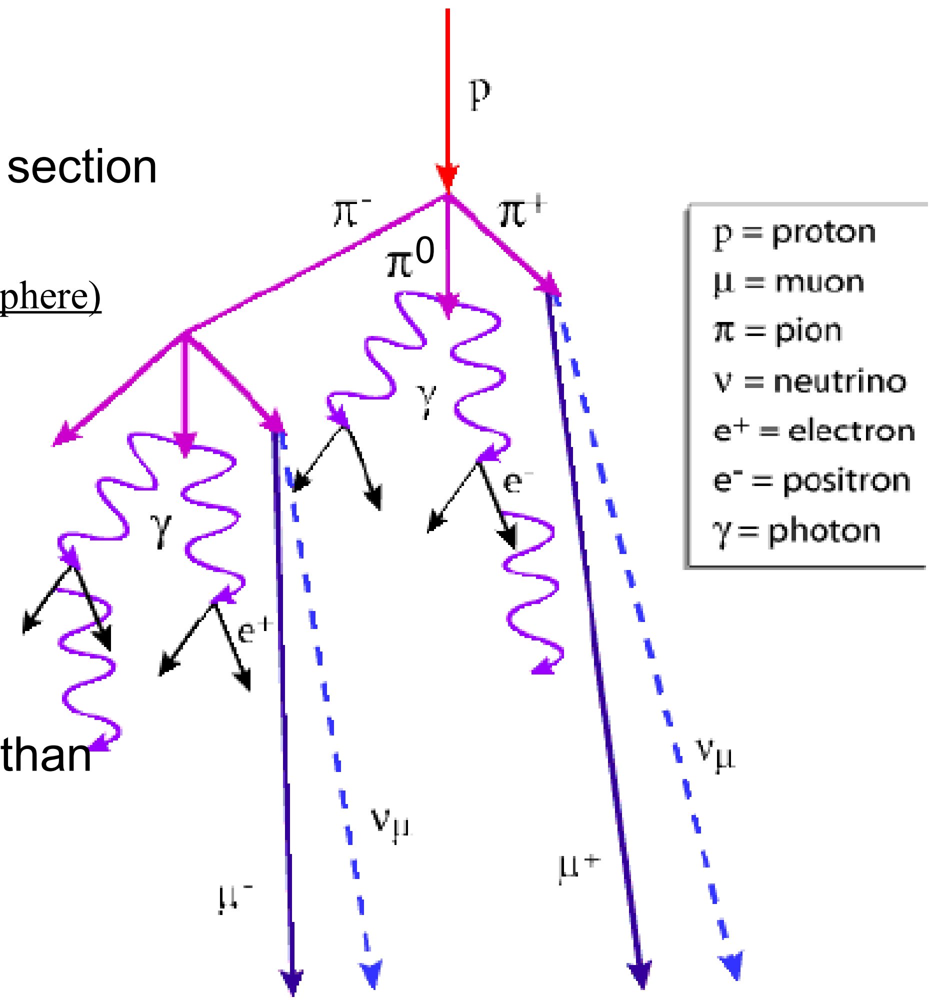
# The discovery of the celestial high-energy neutrino emission

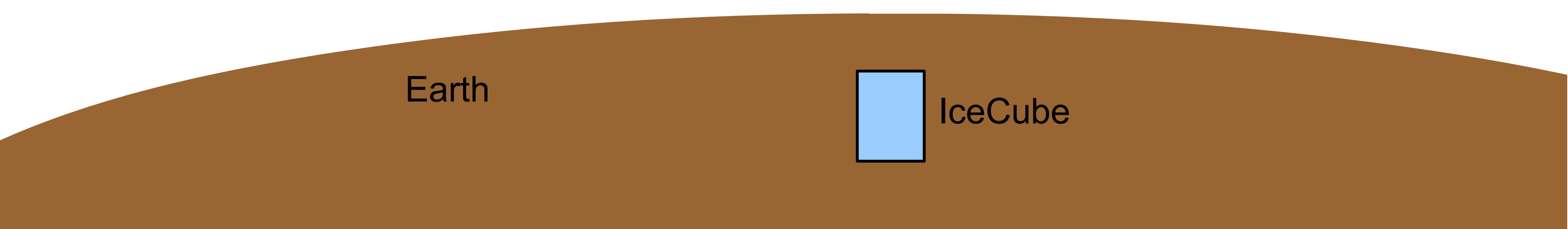
# IceCube Discovers Excess Events at High Energies Using a Veto Technique



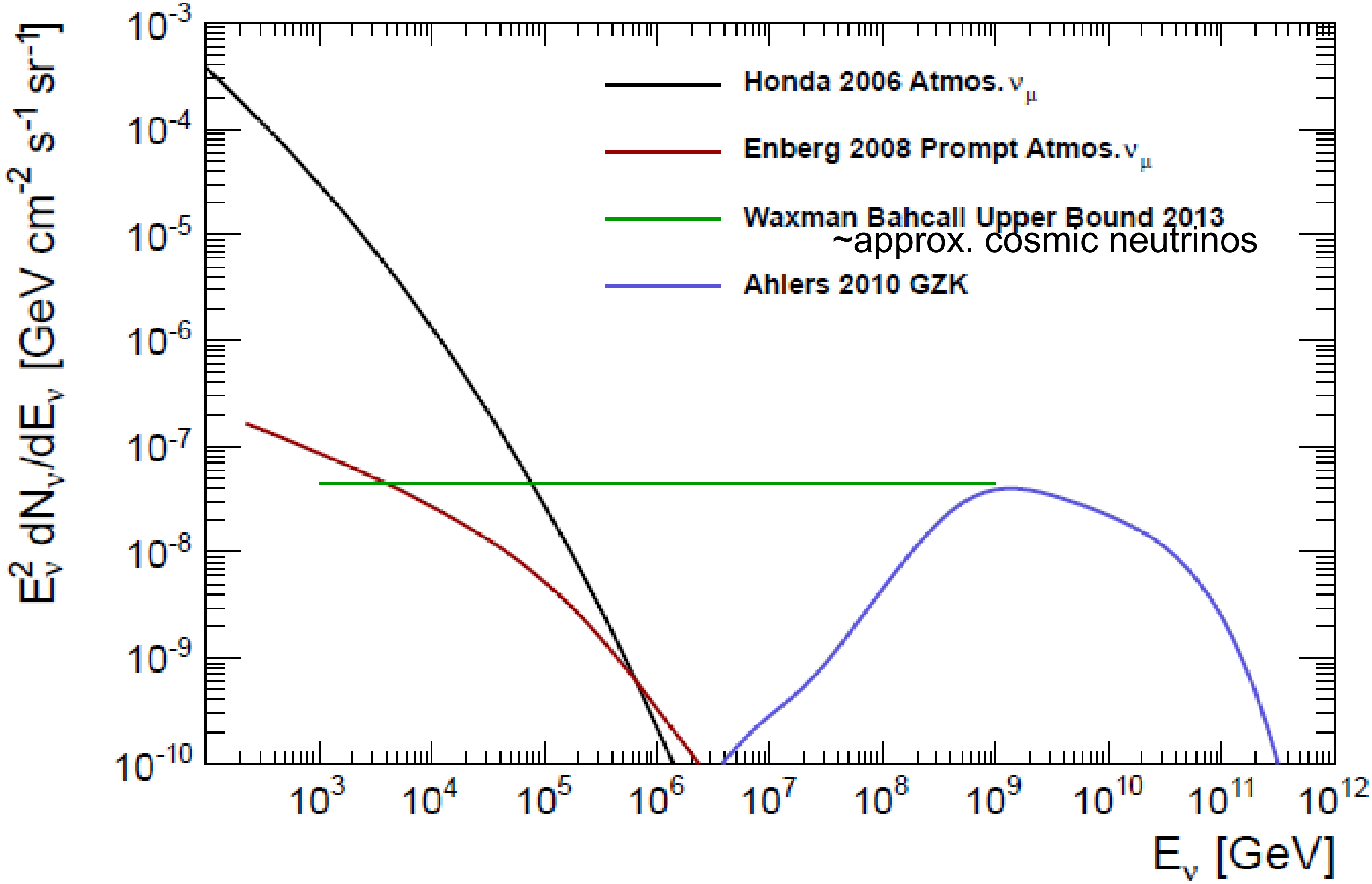
# IceCube backgrounds are atmospheric shower components

- Most charged π/K decay to μ rather than e
- ν produced in the same interaction, but lower cross section
  - Most common bkg: $\mu > \nu_\mu > \nu_e$ (Southern Hemisphere)
  - $\nu_\mu > \nu_e$ (Northern Hemisphere)
- At higher energy, meson lifetime is longer → more interact rather than decay
  - μ, ν Spectra softer than primary CR's
- At higher energies, charmed mesons produced
- Shorter lifetime, decay products are harder spectra than π/K decay → “prompt” flux



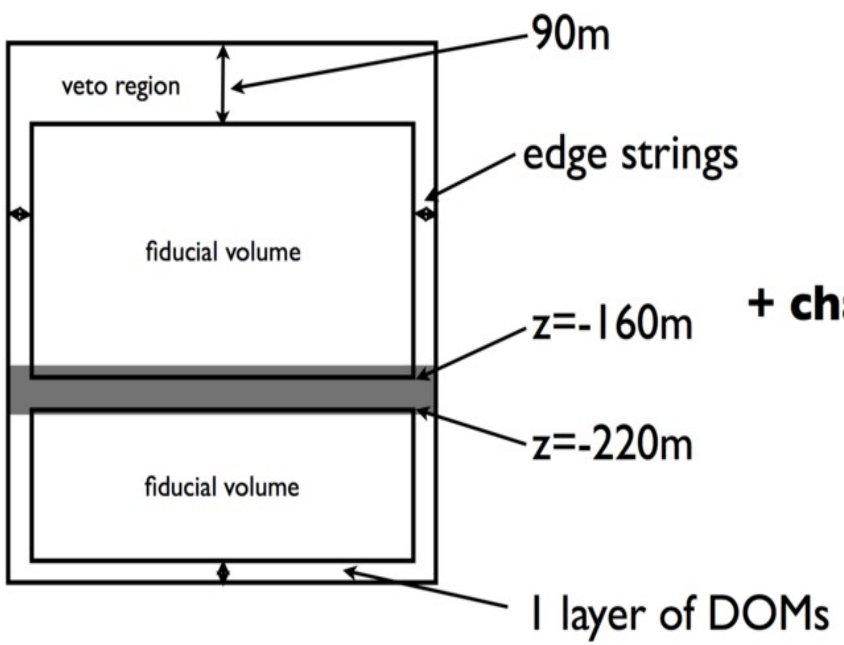



# Energy distribution

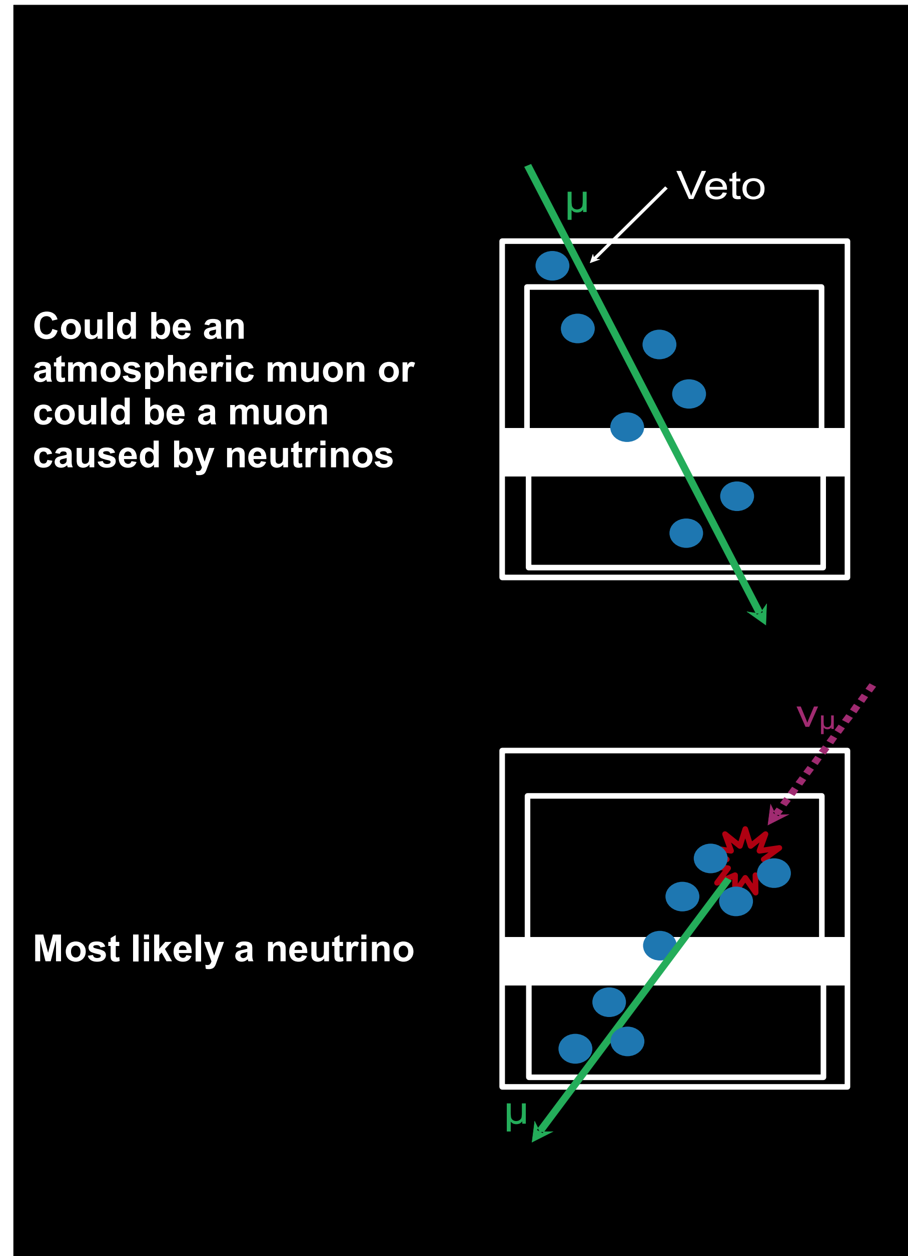



π/K Atmospheric Neutrinos (dominant < 100 TeV)
Prompt Atmospheric Neutrinos (expected > 300 TeV)
Astrophysical Neutrinos (maybe dominant > 100 TeV)
GZK Neutrinos ($10^6$ TeV)

Events with interaction vertices contained inside the IceCube detector → More likely to be neutrino events

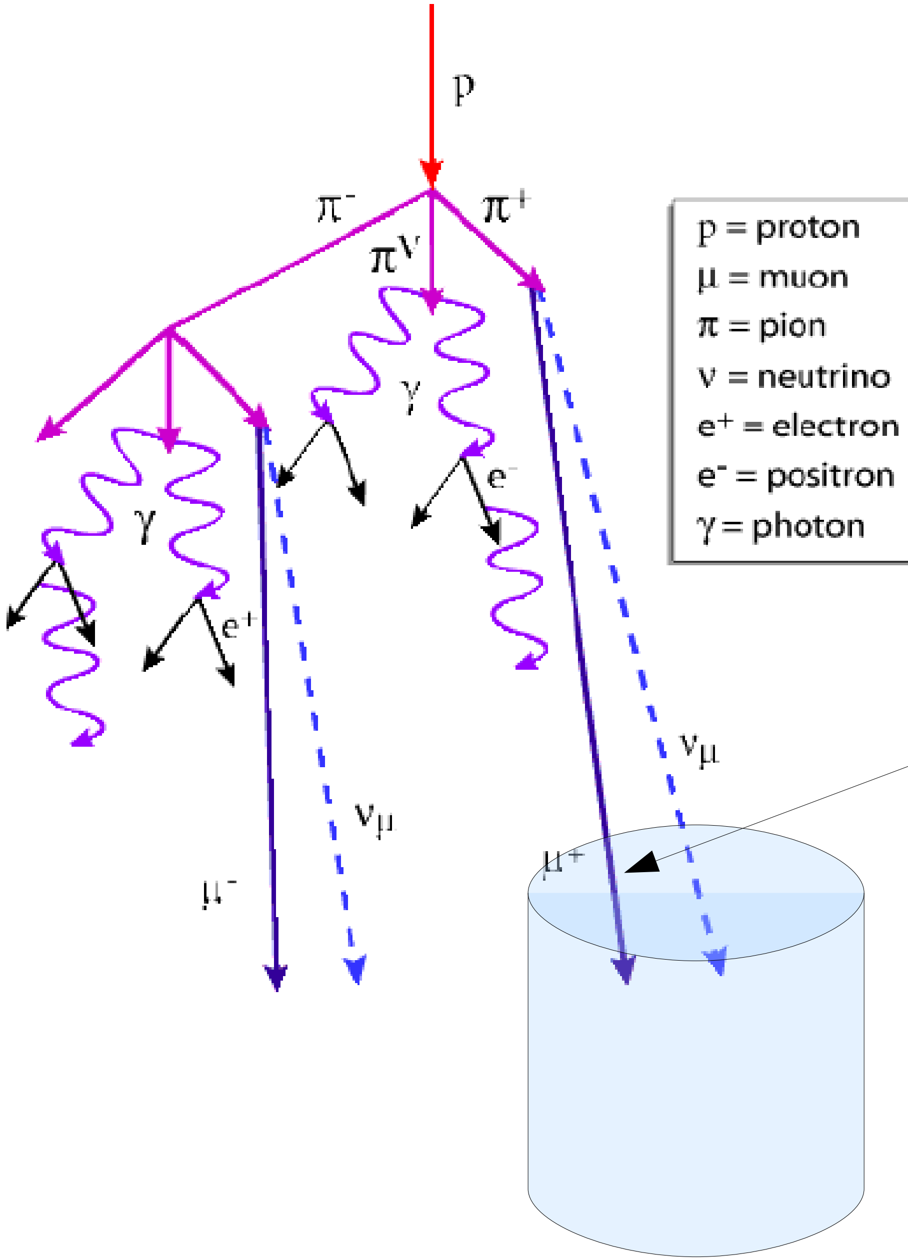



**+ charge cut**




The higher the energy, the better this works!

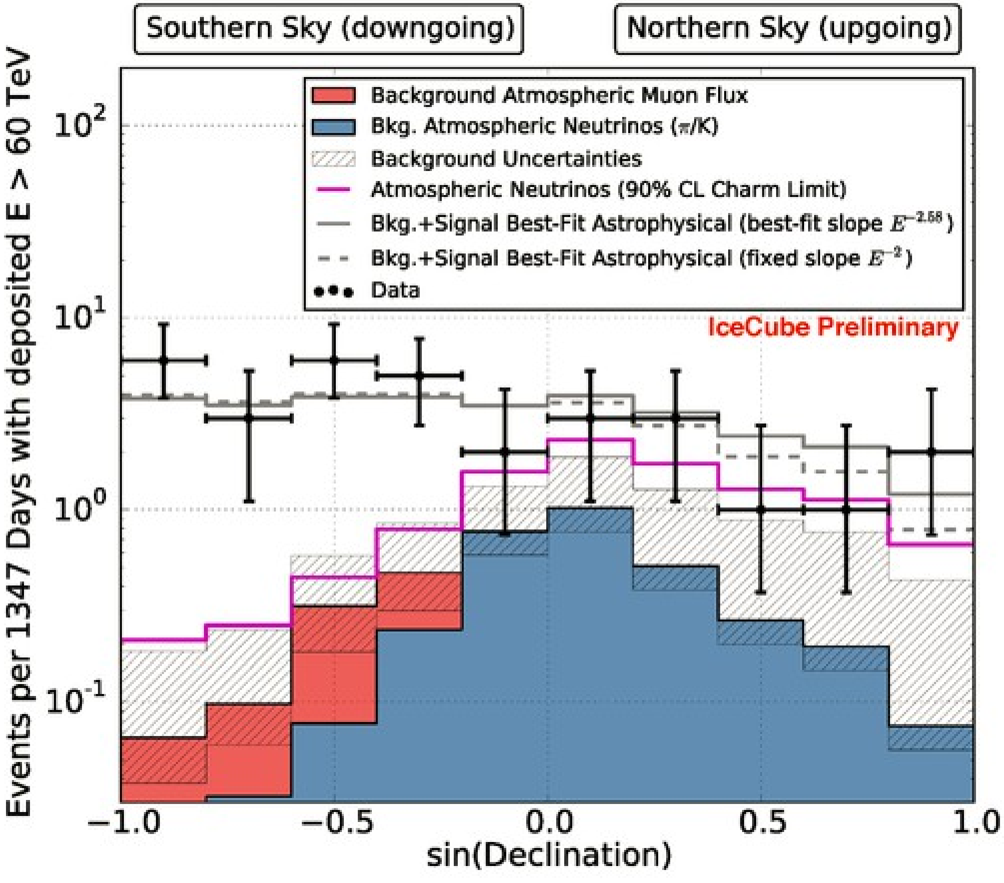
# Tagging atmospheric neutrinos




**The accompanying muon trips the veto! → "Self-veto"**

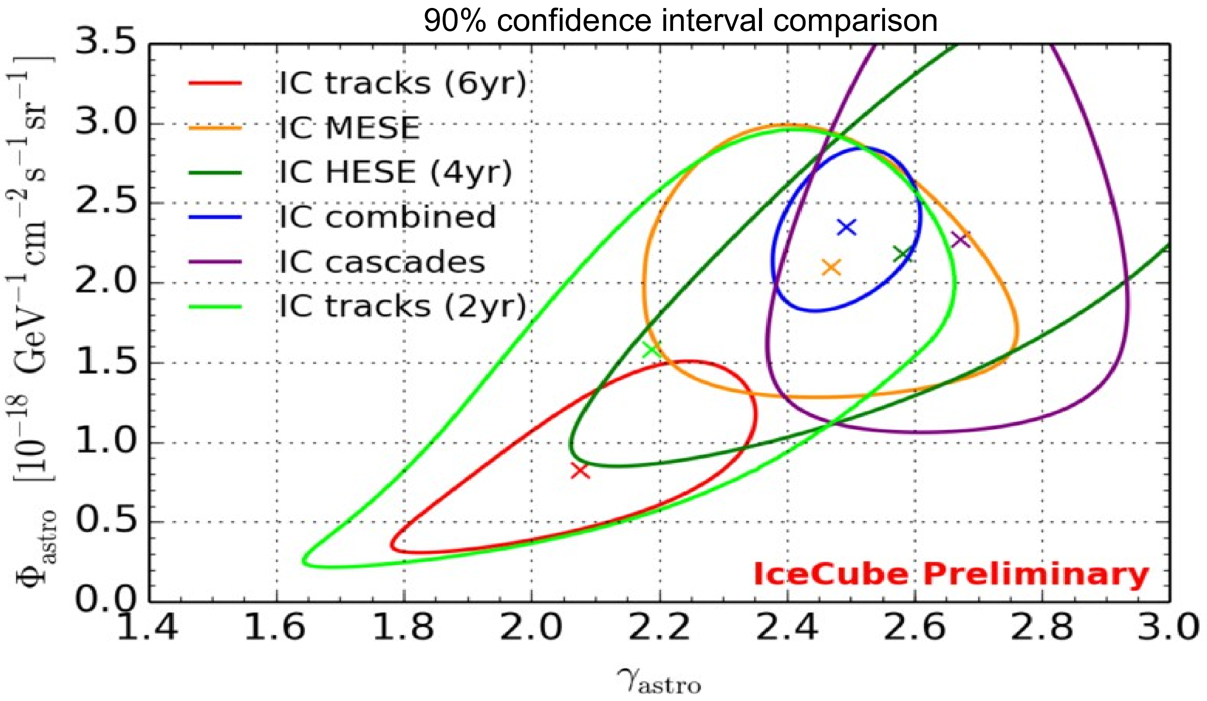
# What this analysis observed

- Flux Level:~1 x $10^{-8}$ $E^{-2}$ [/GeV/cm$^2$/s/sr] per flavor
- Spectral index: -2.6
- Isotropy: consistent with isotropic



# Diffuse Analysis Summary

- In addition two more analyses were performed:
  - Veto-passing events (previously shown)
  - Veto-passing events with lower energy threshold
  - Through-going tracks (North sky only)



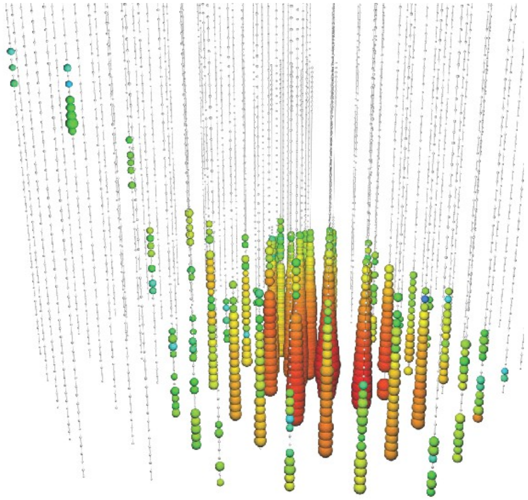

- Flux level at 100 TeV seem consistent in all three analysis
- Spectral index seems softer than -2, but how soft?
- Some indication of anisotropy? Only at lower energies?

Women Observing Stars, Ota Chou, 1936
Tokyo Modern Arts Museum

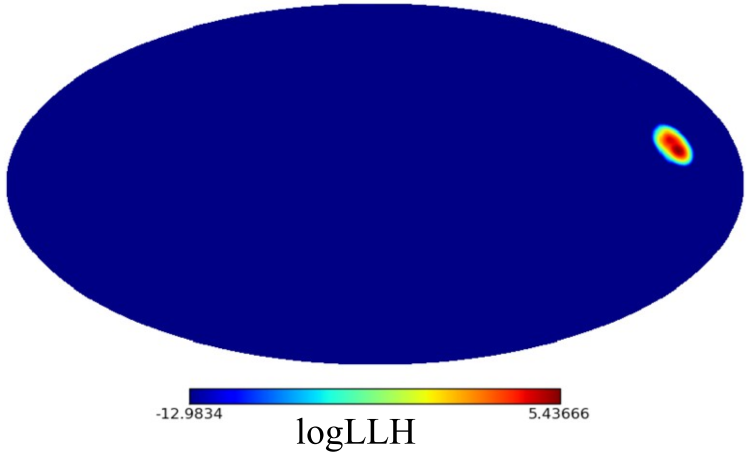
Can we spatially resolve their sources?

(I will leave transient cases for the next talk!)

# Reconstruction Capabilities

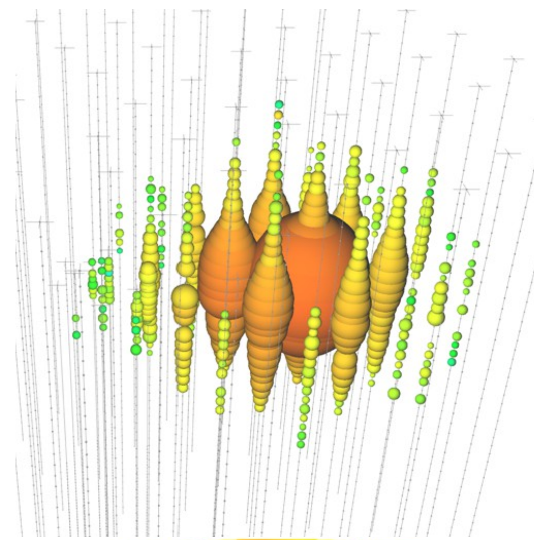


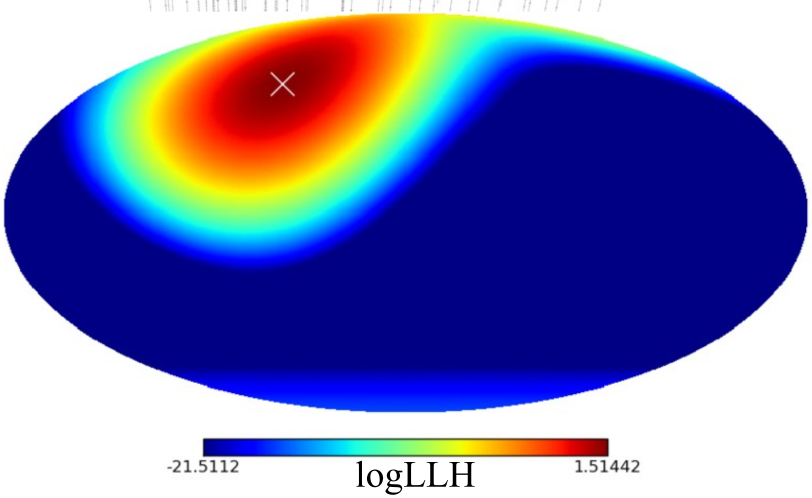
*These are highly event-sample dependent quantities!




| @ 100 TeV energies | Energy Reconstruction* | Directional Reconstruction* |
|---|---|---|
| Tracks | **~factor 2** | **~0.5 degrees** |
| Showers | **10%** | **~15 degrees** |

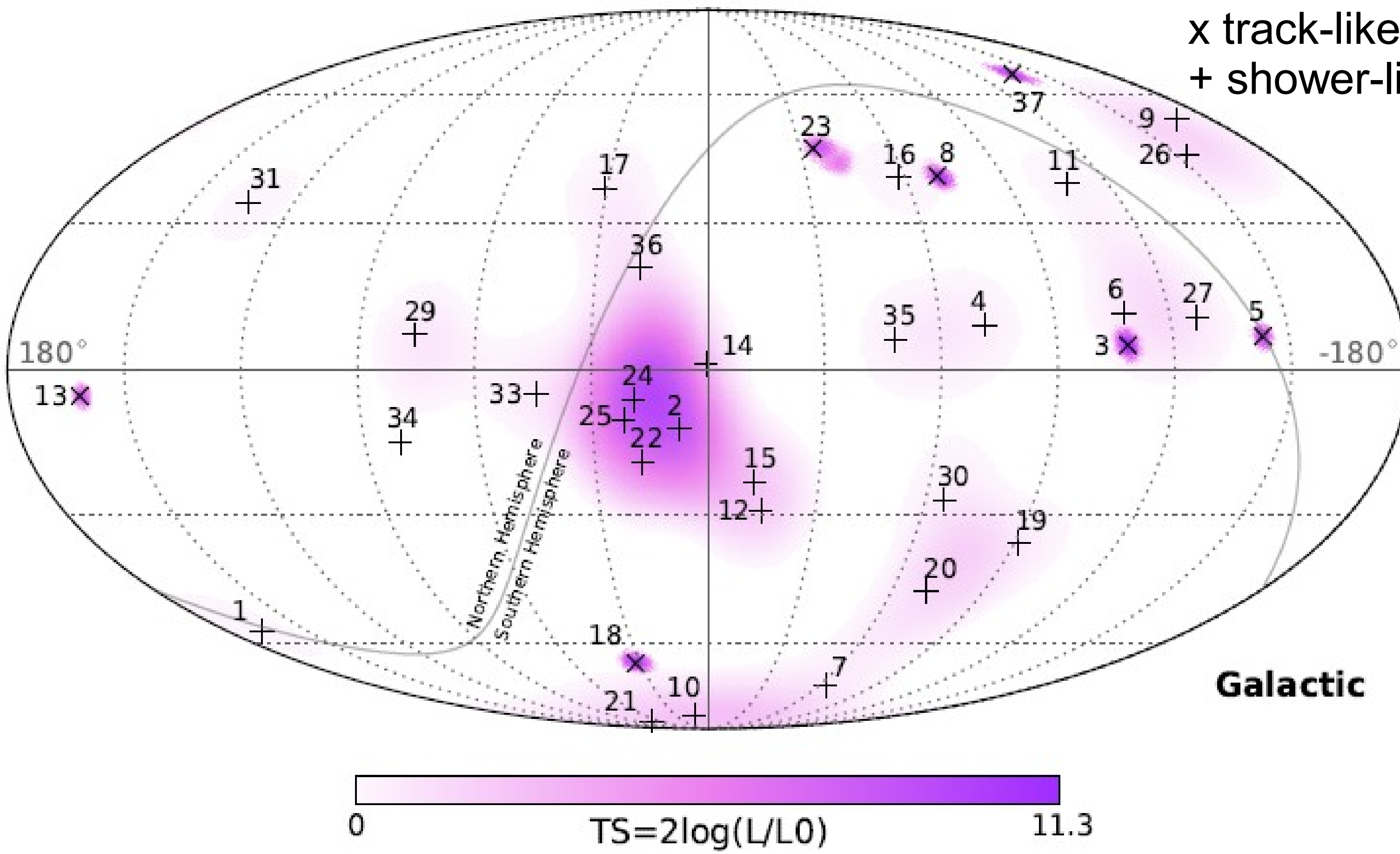
* against primary neutrino energy and direction





# Veto-passing HE Events (2013 *Science* paper)

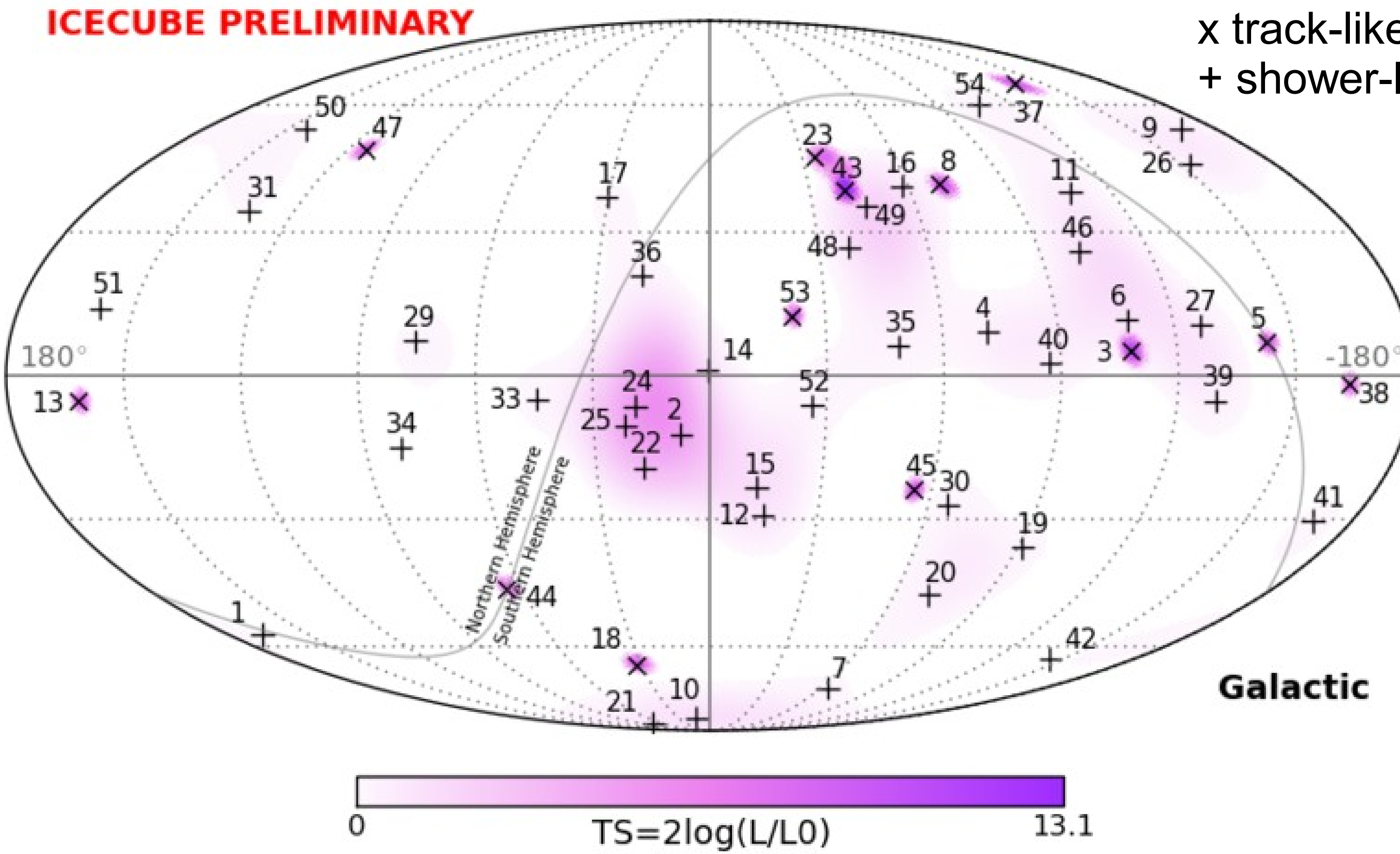
Most likely event direction
with event #
x track-like events
+ shower-like events




- No significant clustering
- Extragalactic component very likely

# Veto-passing HE Events (Updated)

Most likely event direction
with event #
x track-like events
+ shower-like events

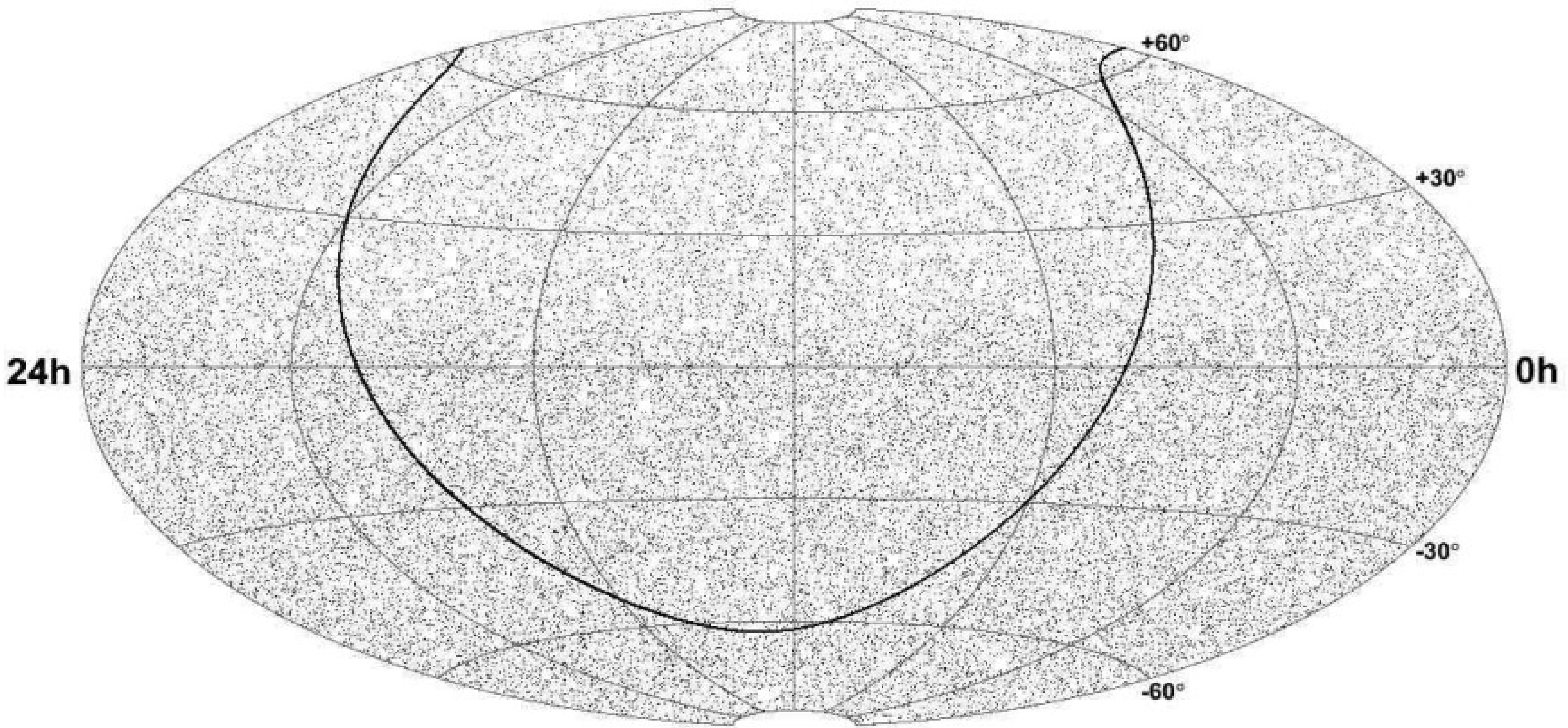



- No significant clustering
- Extragalactic component very likely

But that is actually not a good way to look for neutrino sources

# Through-going tracks: Collect all good quality tracks

Equatorial coordinates




“2008” year Old Data (40-strings detector)
~37,000 events
Can't make this plot for all the data we have anymore!

# Likelihood Search for a Source
# - Test Statistic (TS) Calculation -

Maximize the likelihood L assuming a source at point x with energy spectrum $E^{-\gamma}$

Total # of events

# of events from source
Varied to maximize L

$$L(x) = \prod_{i}^{n_{tot}} \left[ \frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Probability density that event i comes from a source at position x
×
Probability density that event i comes form a source with spectrum γ

Probability density that event i is from backgrounds expected at position x
×
Probability density that event i comes form a known background energy spectrum

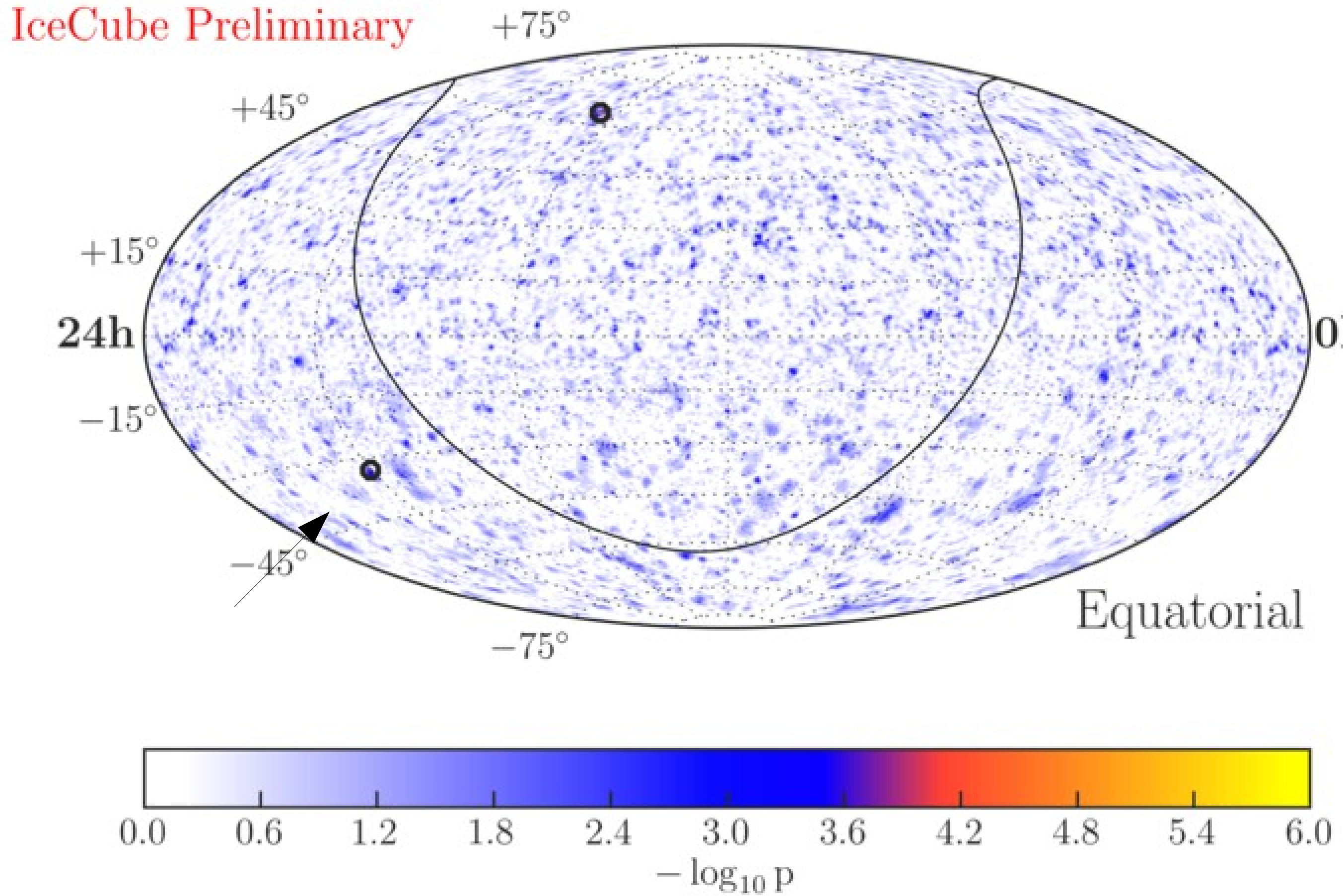
TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left( L(x) \big/ L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$

# Point Source Search

IC40 + IC59 + IC79 + IC86 2011-2013 data

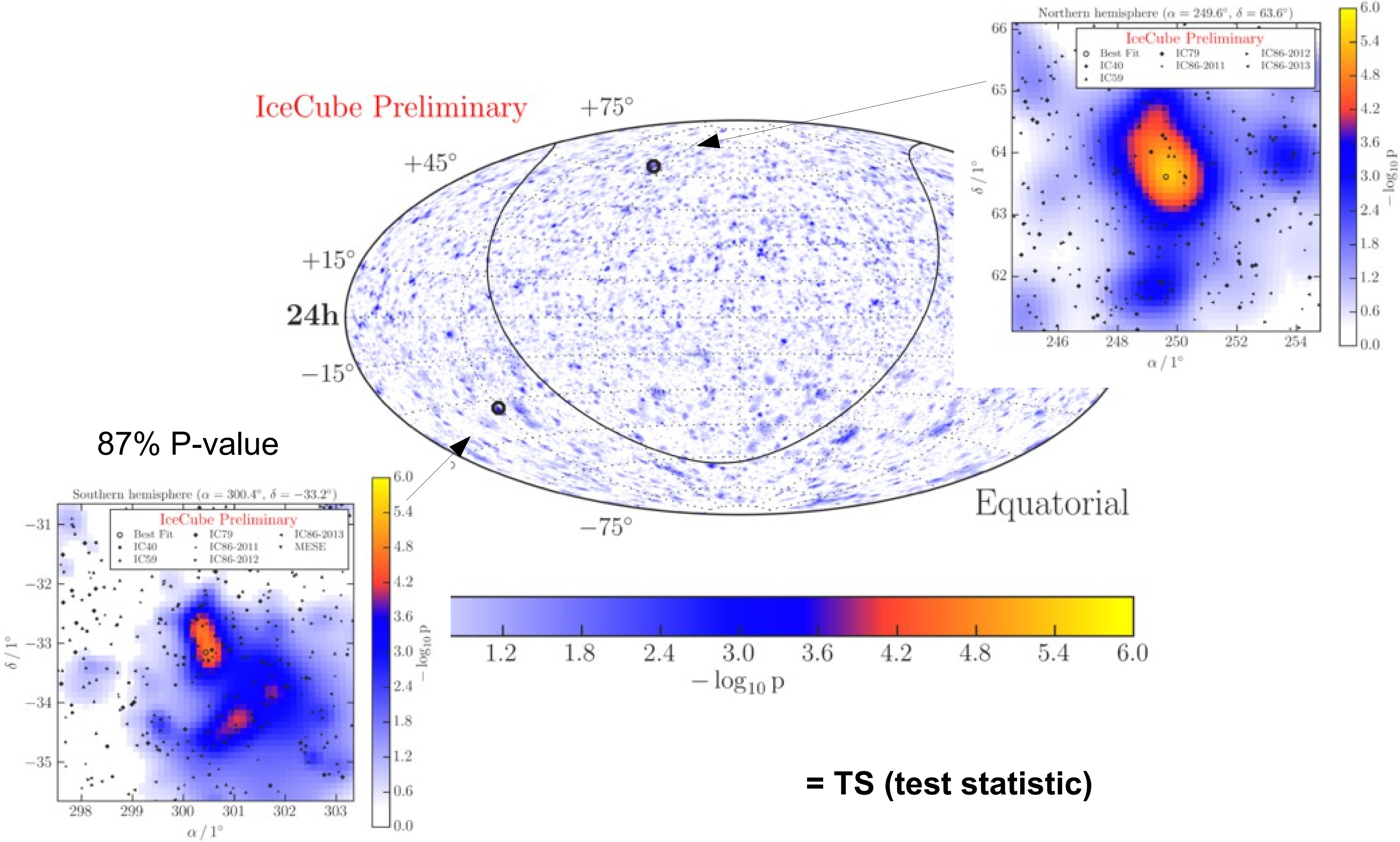



**= TS (test statistic)**

# Point Source Search

IC40 + IC59 + IC79 + IC86 2011-2013 data

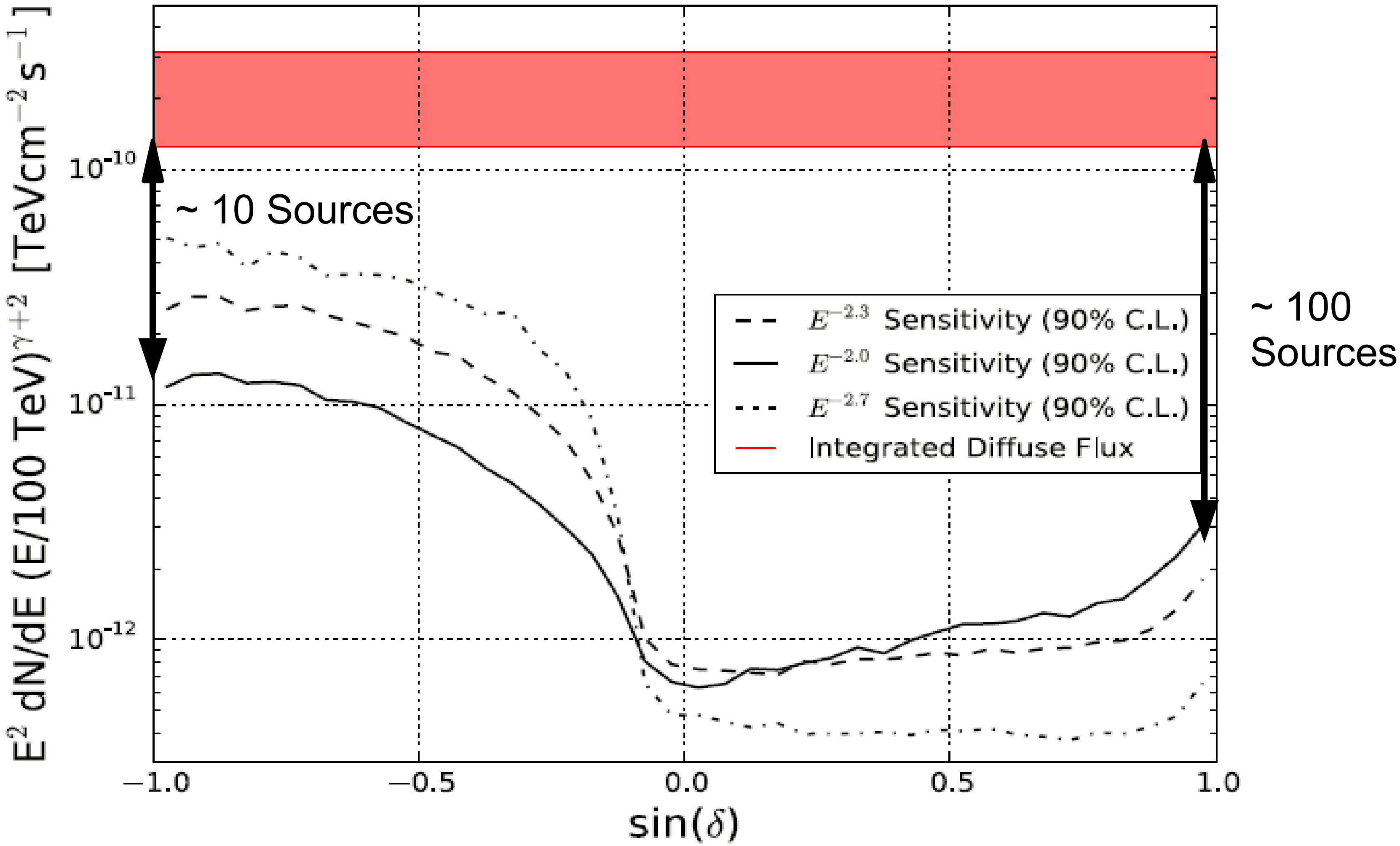
35% P-value




87% P-value

**= TS (test statistic)**

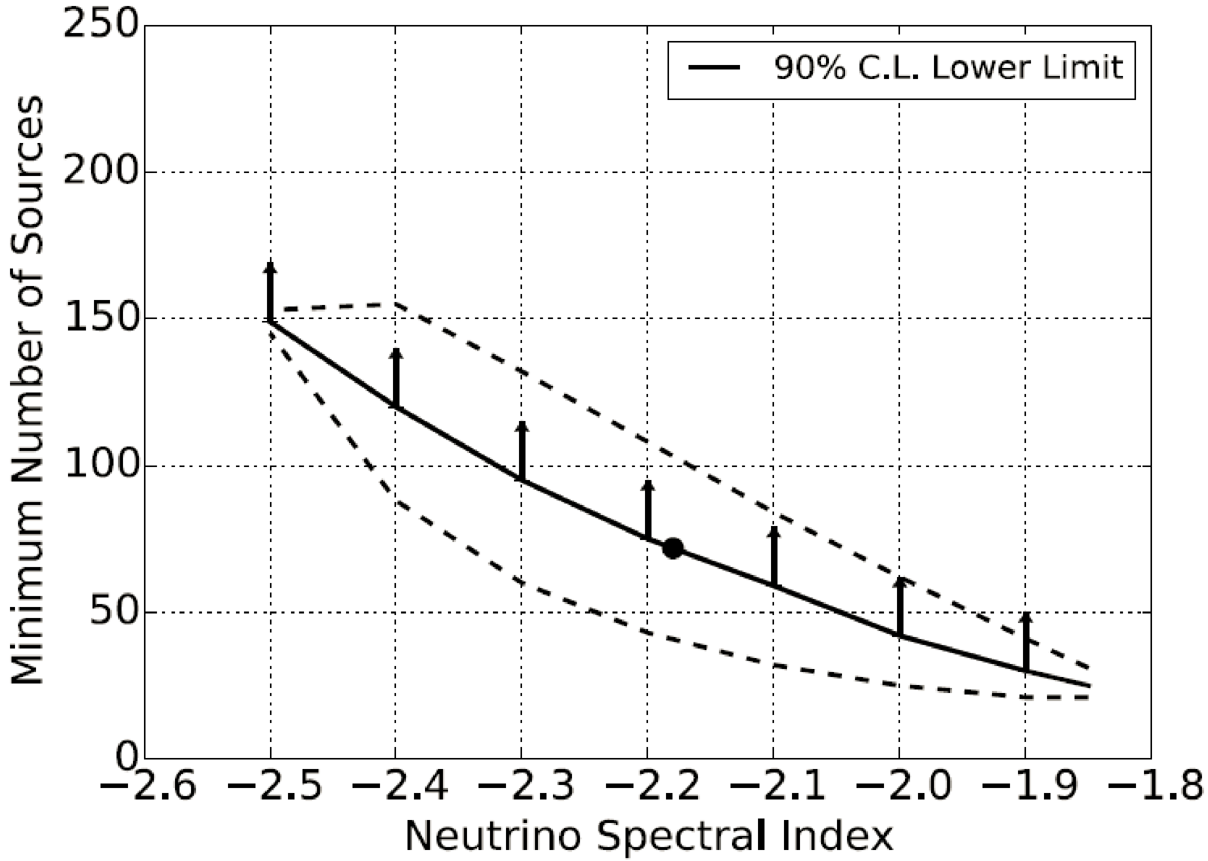
# No evidence of point source → Limit on point source flux




Ways around

- extended sources / large regions of emission
- cutoff in energy spectra

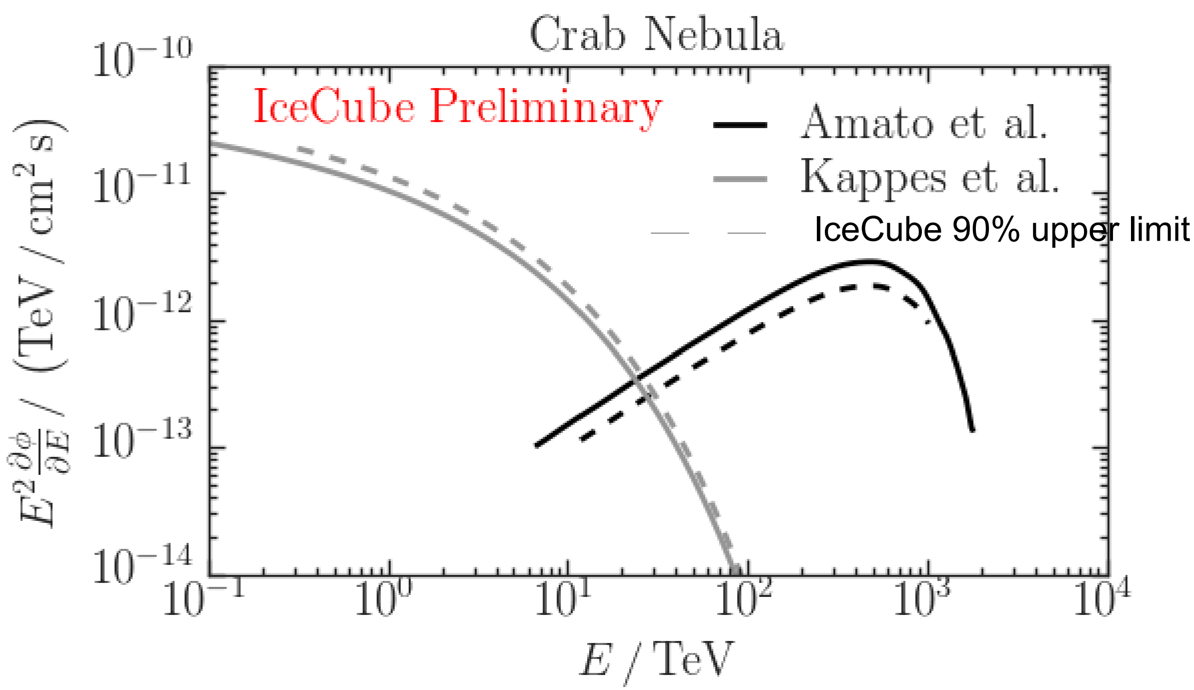
# With more statistical rigor...




Assume 1. all sources have the same spectral index
2. sources are isotropically distributed

Pick isotropically random points in the sky and subtract off the flux limit from that direction

# Limits on models of neutrino emission

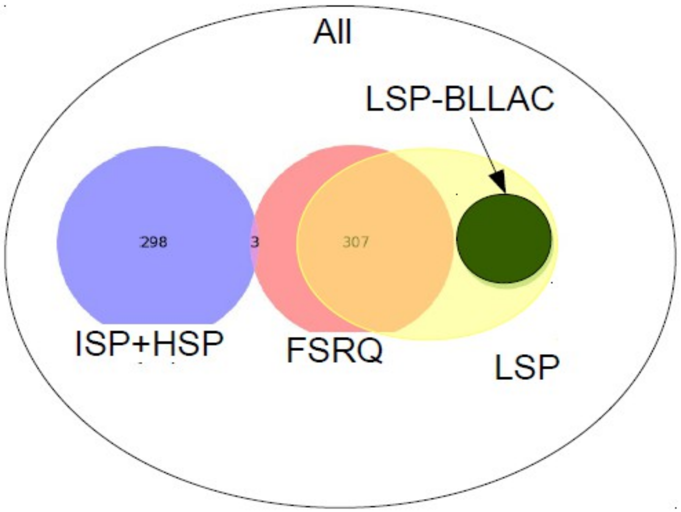


# Even if they don't self-cluster, do they come from known source locations?

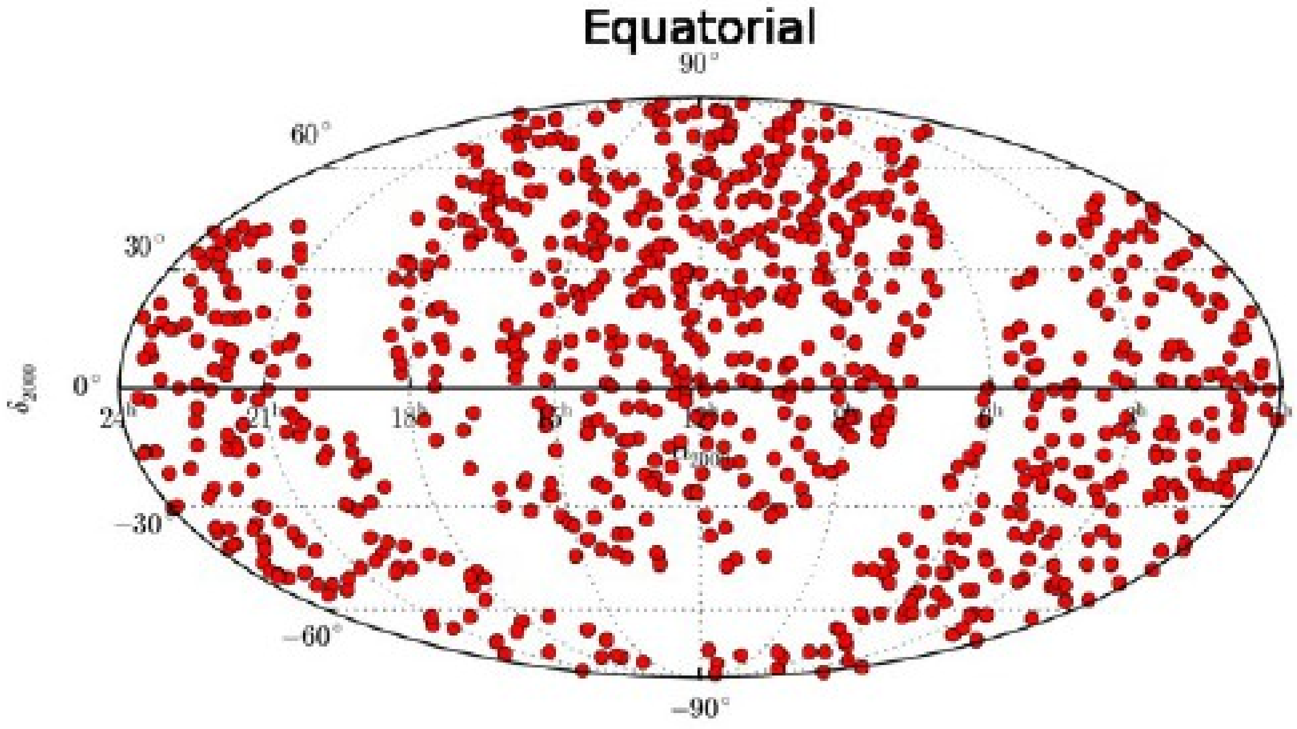
# Stacking Searches:
# Fermi Blazar Population Analysis

Quasi-diffuse search (~10% of the sky at our angular resolution)

(862 sources total)
Overlap between populations




Positions of All 862 2LAC Blazars



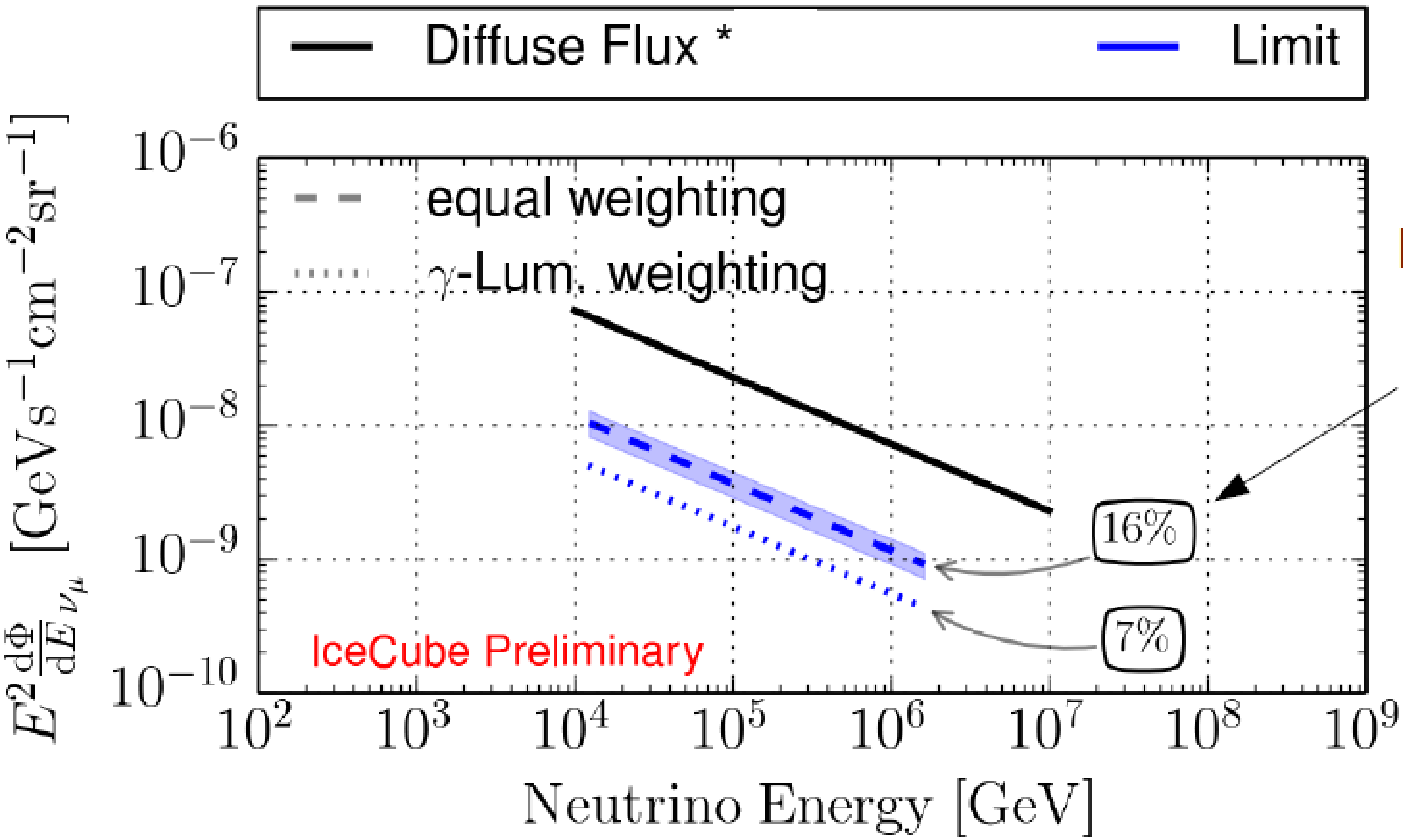
# Results – Blazar Population

***IceCube Preliminary**

| Gamma (E-flux) Weighting | | | | No of sources | Equal Weighting | | | |
|---|---|---|---|---|---|---|---|---|
| Name | $n_s$ | $\Gamma_{SI}$ | p-val | | Name | $n_s$ | $\Gamma_{SI}$ | p-val |
| All Blazars | 19 | -2.8 | 36% | 862 | All Blazars | 175 | -3.0 | 6% |
| FSRQ | 14 | -2.6 | 34% | 310 | FSRQ | 30 | -2.7 | 34% |
| LSP | 13 | -2.6 | 36% | 308 | LSP | 41 | -2.8 | 28% |
| ISP+HSP | 0 | | (>50%) | 301 | ISP+HSP | 103 | -3.3 | 11% |
| LSP-BLLAC | 38 | -3.2 | 13% | 68 | LSP-BLLAC | 56 | -3.0 | 7% |

- $n_s$ : best fit normalization parameter of signal pdf
- $\Gamma_{SI}$: best fit spectral index ( ~ +/- 0.4)

# Reconcile with observed diffuse astrophysical flux




**Max. contribution to best fit diffuse flux ($E^{-2.5}$)**

IceCube Collaboration (2014) arXiv:1410.1749

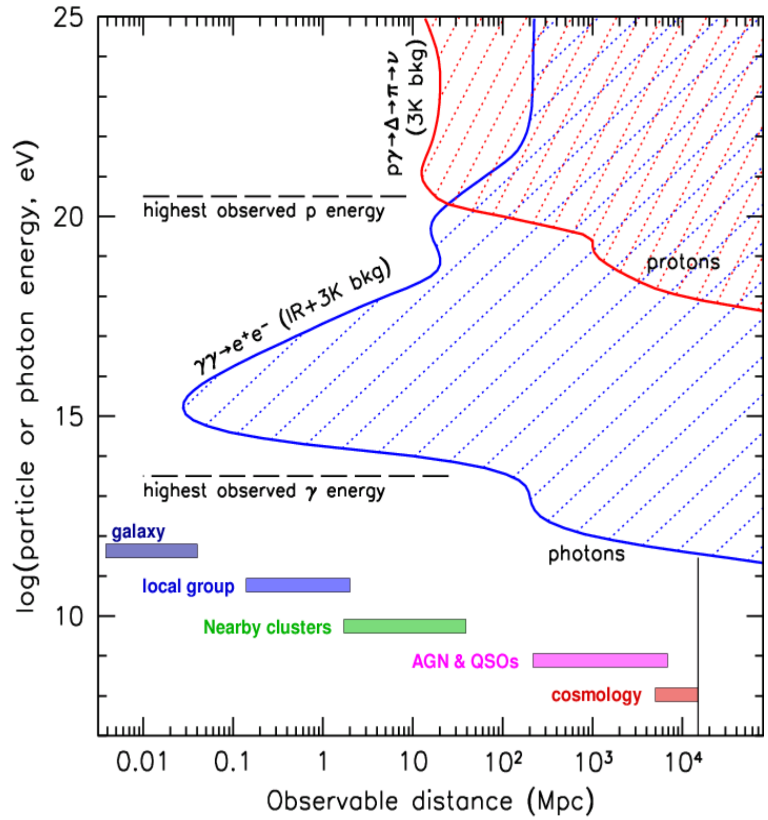
Assume 1:1:1 flavor ratio

# Limits to various source types

| | | Upper limit in diffuse flux | notes |
|---|---|---|---|
| Blazars | | ~ 17% | 862 from Fermi 2nd AGN cat.<br>Spectral index = -2.5 |
| Nearby Starburst Galaxies | | ~ 8% | 127 nearby<br>Spectral index = -2 |
| Galactic Sources | Young SNR | ~ 5% | 30 with no PWN or MC<br>Spectral index = -2 |
| | Young PWN | ~ 3% | 10 with no MC<br>Spectral index = -2 |
| Galactic Plane | | ~14% | Coming soon!<br>Spectral index = -2.5 to -2.7 |
| GRBs | | ~1% | 506 bursts observed<br>Spectral index = -2 to -2.7 |

# In the presence of diffuse astrophysical neutrino flux, how does one resolve sources?

- The unresolved astrophysical diffuse flux is a new background in resolving sources (a tricky background with a hard spectrum....)
- We expect the unresolved diffuse flux to be more significant than other messengers of astronomy (no horizon + no local "curtains")




"How do you see anything when you see everything?"

Women Observing Stars, Ota Chou, 1936
Tokyo Modern Arts Museum

# Summary and Outlook

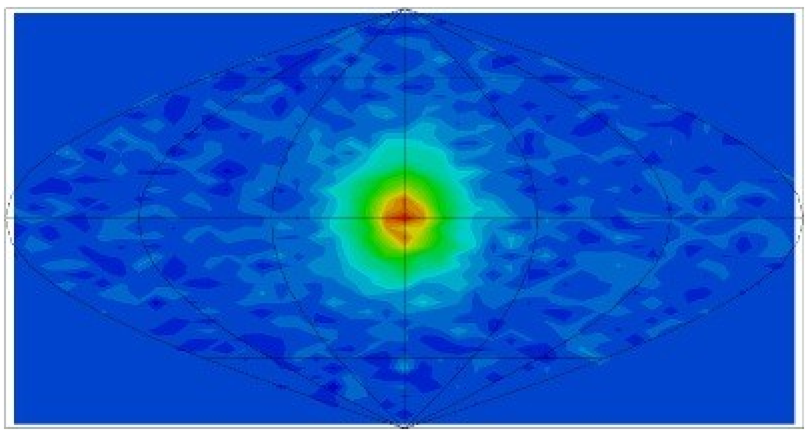
# State of Neutrino Astronomy

- **We see an astrophysical diffuse flux** at the
  $\sim 10^{-8}E^{-2}$[/GeV/cm$^2$/s/str] level, although the energy spectrum is most likely softer than $E^{-2}$
- No spatial clustering of events
- No clustering along the Galactic Plane
- All indication suggests many sources and source types contributing to the flux (at least some from extragalactic sources)
- No correlation to known HE astronomical objects yet, in fact, with the limits we set, we are running out of objects to correlate to (*model dependence caveat)

# Challenges of Neutrino Astronomy

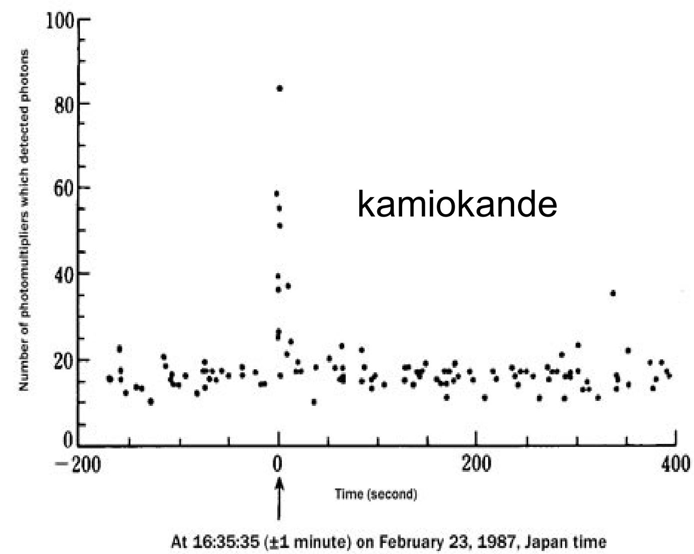
## The Neutrino Astronomy Catalog

The Sun



super-kamiokande

Supernova 1987A




VERY close by source

No direction, just timing

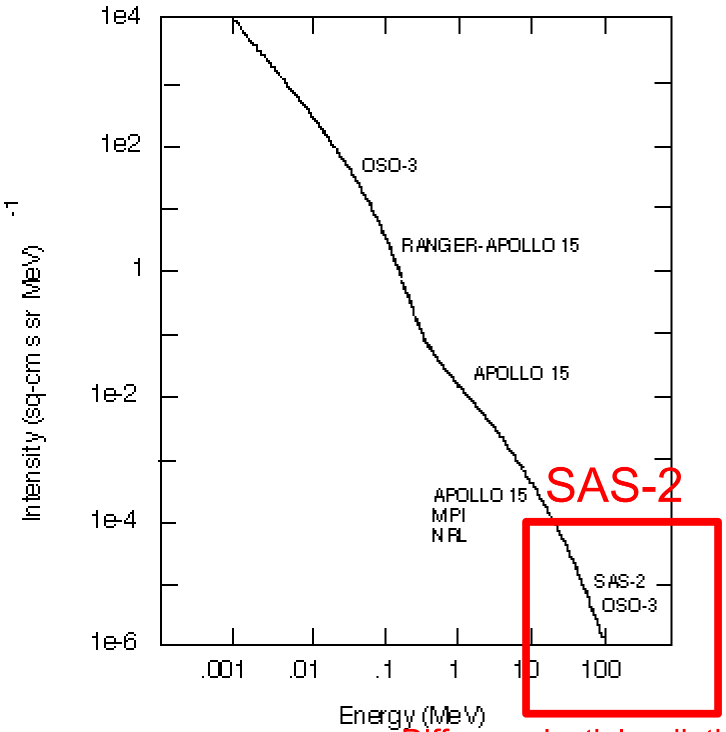
But maybe our first source is just around the corner....

History is on our side

# Gamma-ray Astronomy

Diffuse signal → first source → catalog!

1970's

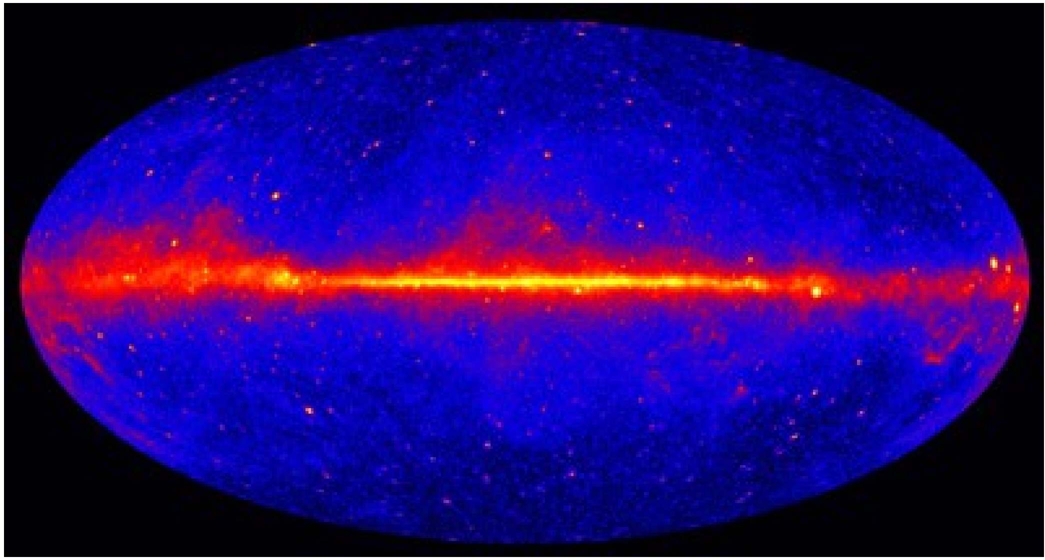



SAS-2

Diffuse celestial radiation

NOW

Fermi 5-year data

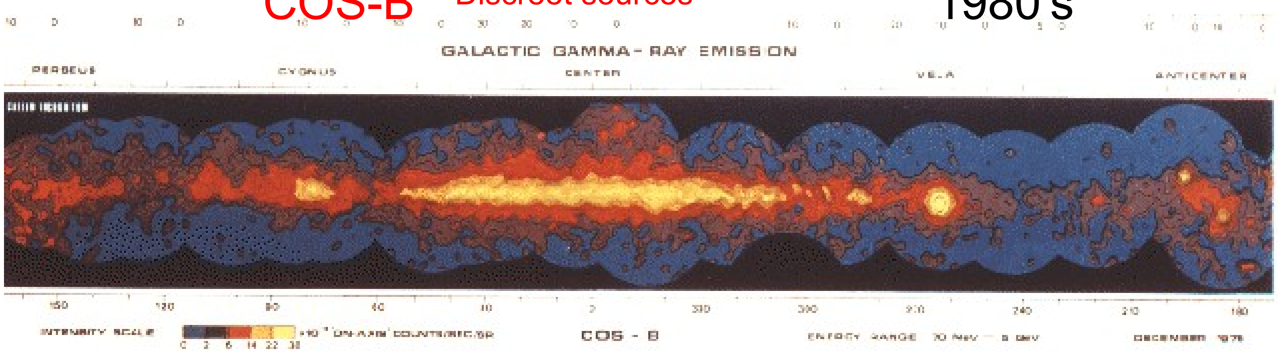


GSFC nasa.gov

COS-B

Discreet sources

1980's




GSFC nasa.gov

# X-ray Astronomy

Diffuse signal → first source → catalog

(Sun detected in x-rays 1940's)

Diffuse emission and Scorpius X-1 1960's

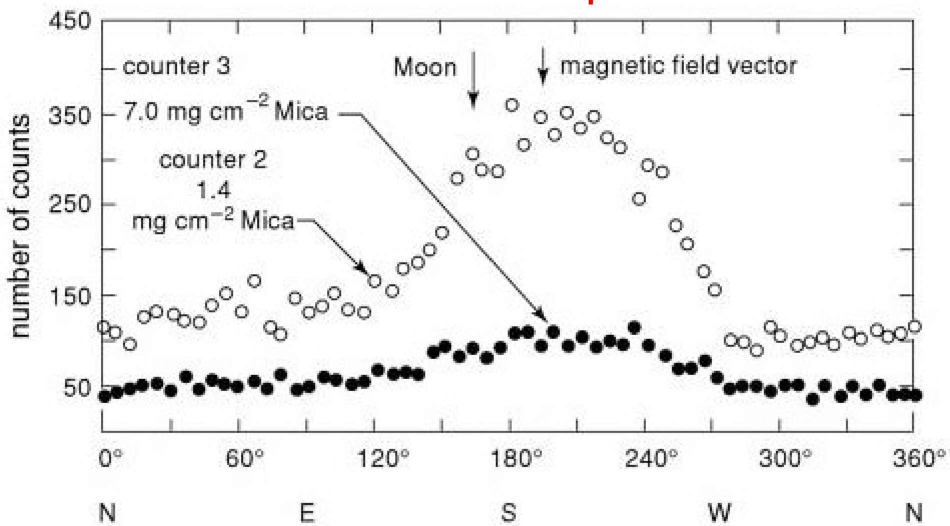
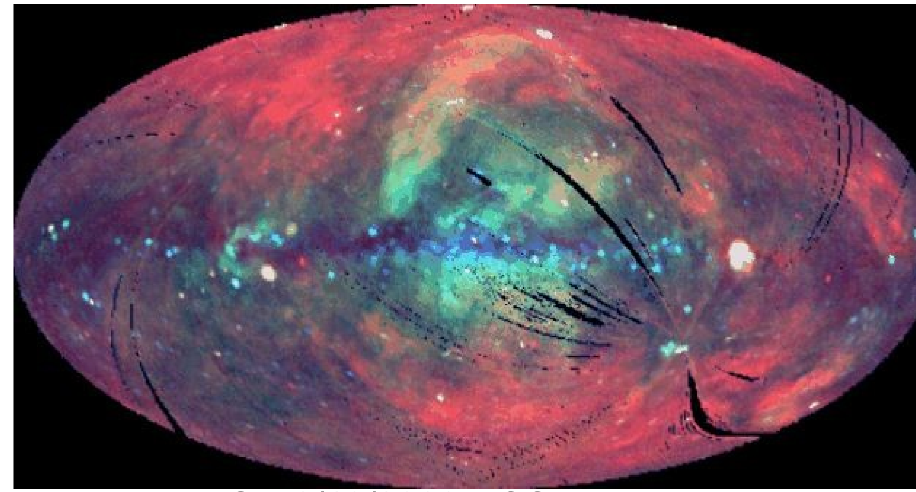
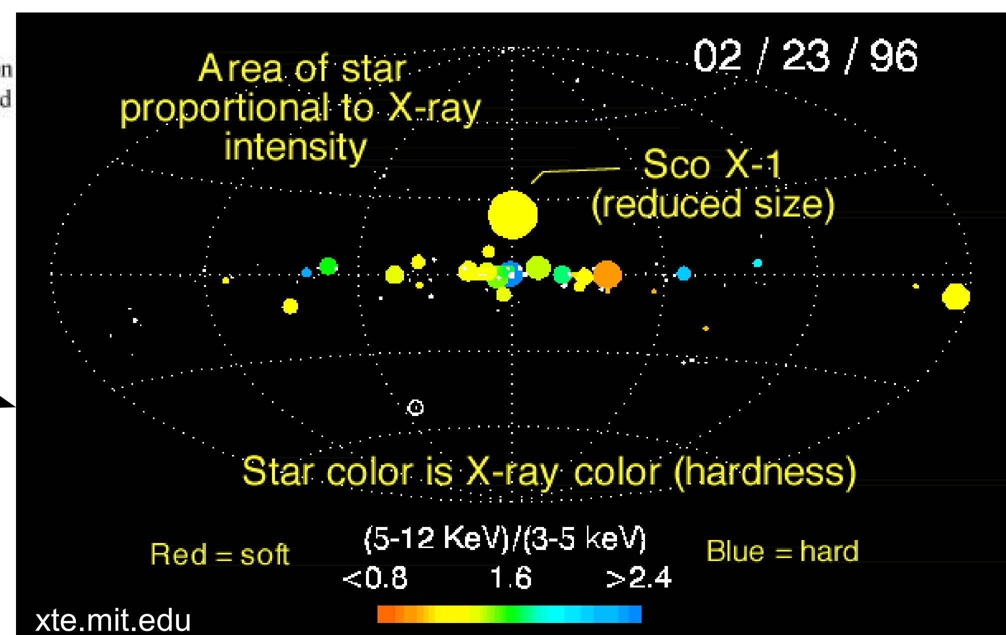



Figure 7.7: The discovery record of the X-ray source Sco X-1 and the X-ray background emission Giacconi and his colleagues in a rocket flight of June 1962. The prominent source was observed both detectors, as was the diffuse background emission (Giacconi *et al.*, 1962).

"The Cosmic Century" M. S. Longair



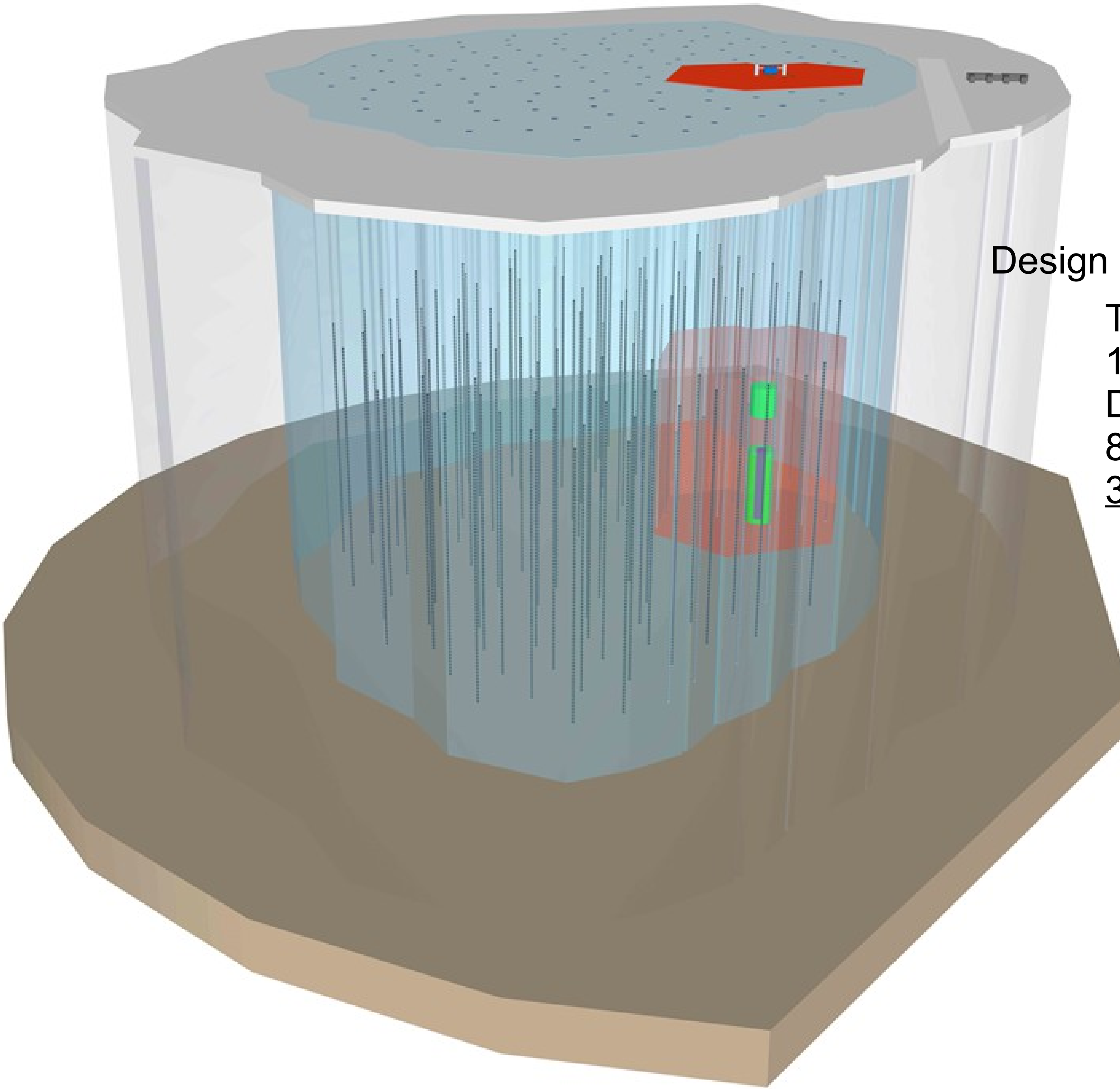
APOD 8/19/2000 ROSAT



# Discovery is always high-risk, high reward!

- I understand 1 degree error circle is not great for follow-ups that need to point
- It's a lot to ask instruments in more established astronomical fields to take a long time observing a large area, for most likely, nothing
- But lets not forget, the upshot is huge here!
- Your instrument can discover the first neutrino source in the sky!

# Stay Tuned: Next Generation IceCube



Design studies under way!

This figure:
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

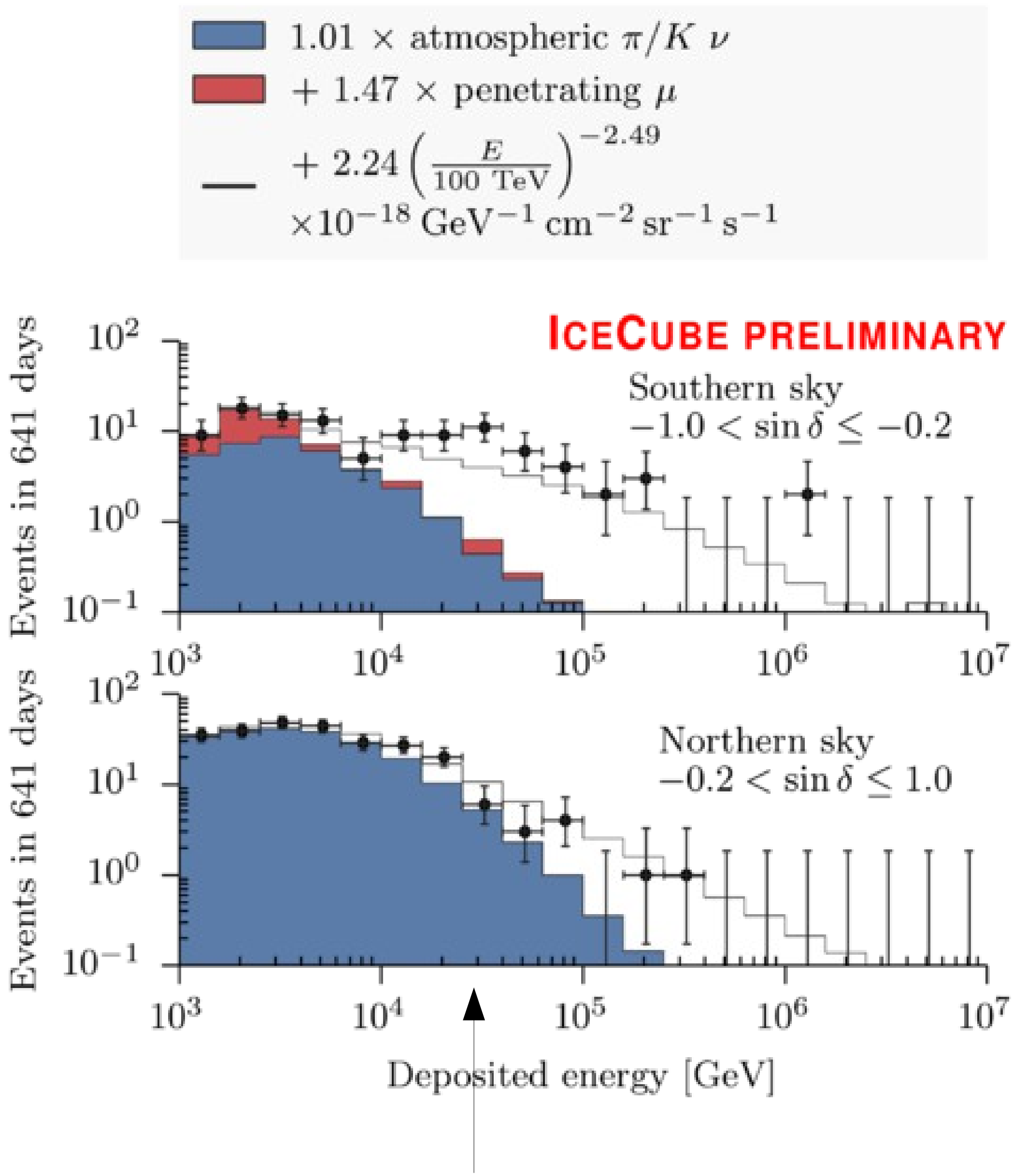
↓

Larger spacing probes higher energies

# Backup Slides

# Veto-passing Events: Lower Energy Threshold

IceCube Collaboration (2015) Phys. Rev. D. 91




Previous analysis' threshold

Flux Level:~2.2 $(E/100GeV)^{-2.5}$ $10^{-8}$ [/GeV/cm$^2$/s/sr] per flavor

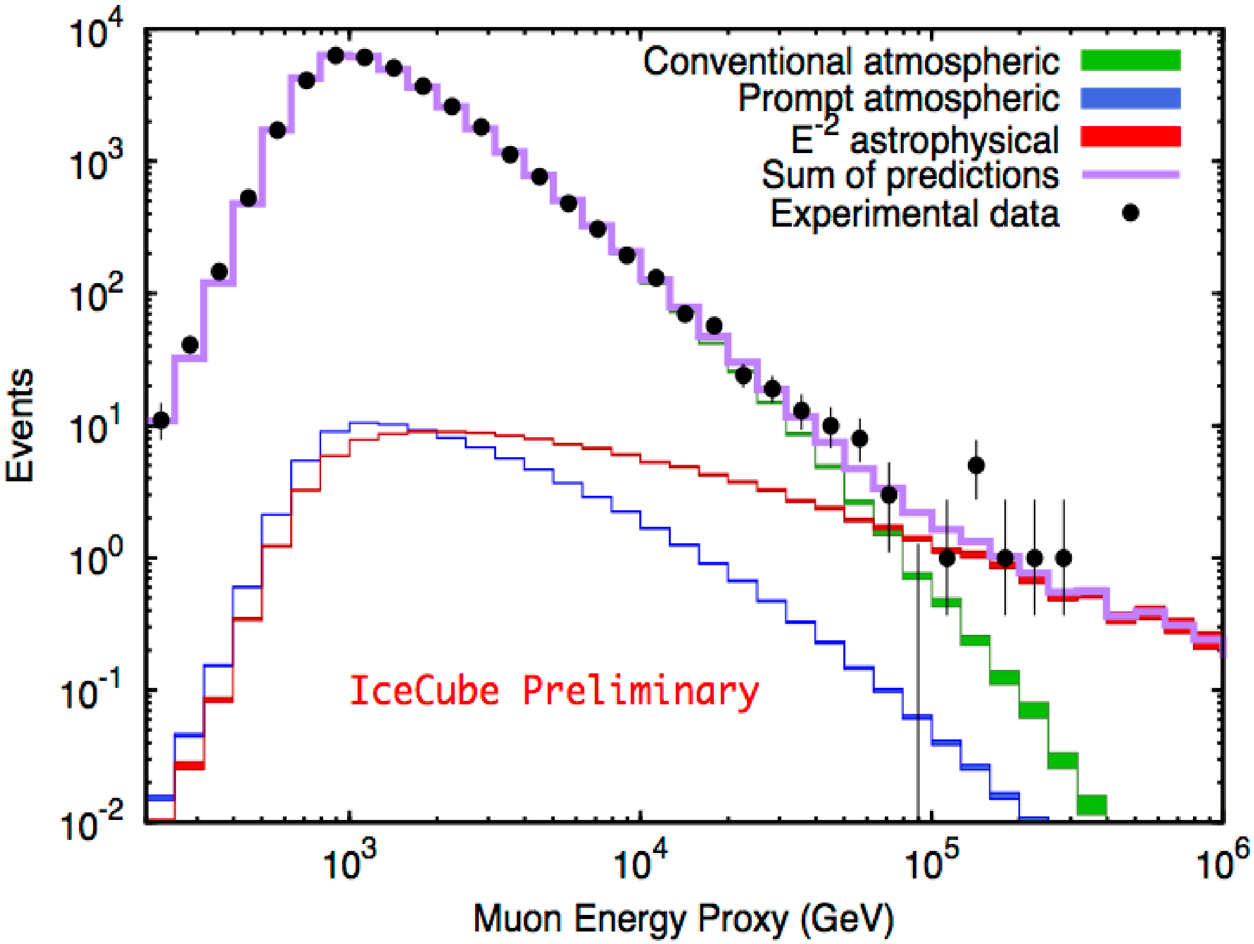
* $E^{-2}$ disfavored at 99% confidence level

Spectral index: -2.5 (+/- 0.1)

Isotropy: north/south discrepancy?

# Through-going, up-going Tracks

**35,300 events**
**< 25.5 events from atmospheric muons**



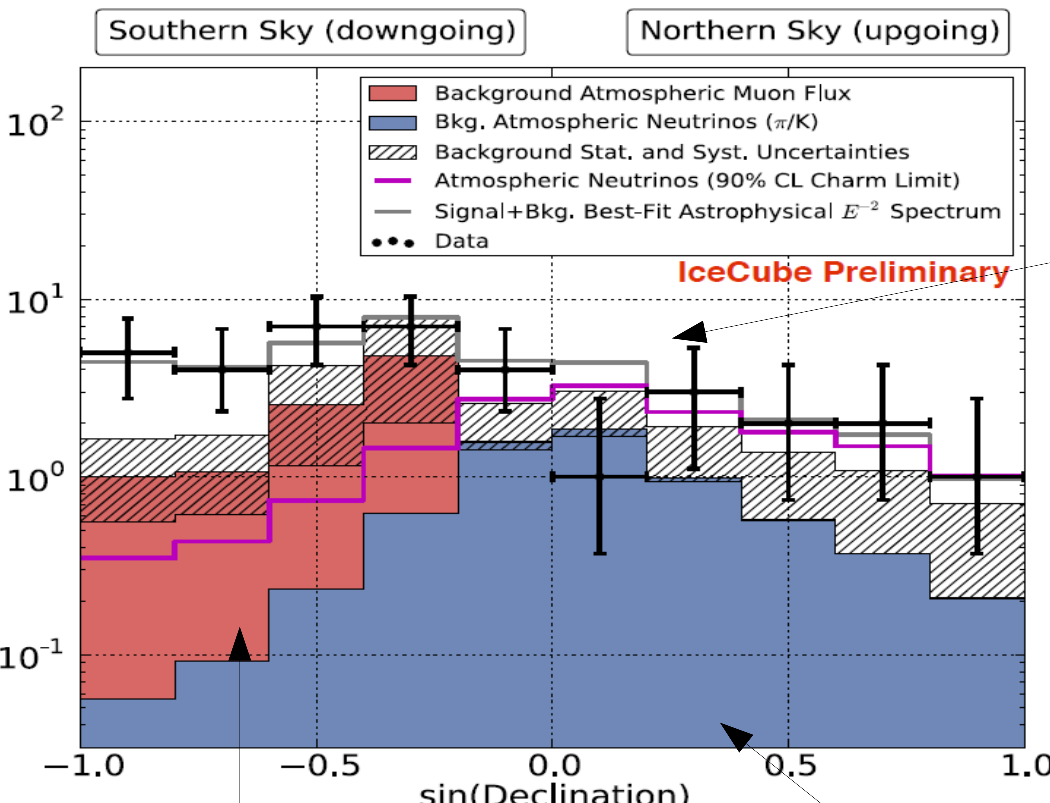

Flux Level: ~1 x $10^{-8}$ $E^{-2}$ [/GeV/cm$^2$/s/sr] for muon-neutrinos

Spectral index: -2.2(+/- ~0.4)

Isotropy: N/A

# Declination Distribution of Events

= zenith




Diffuse signal

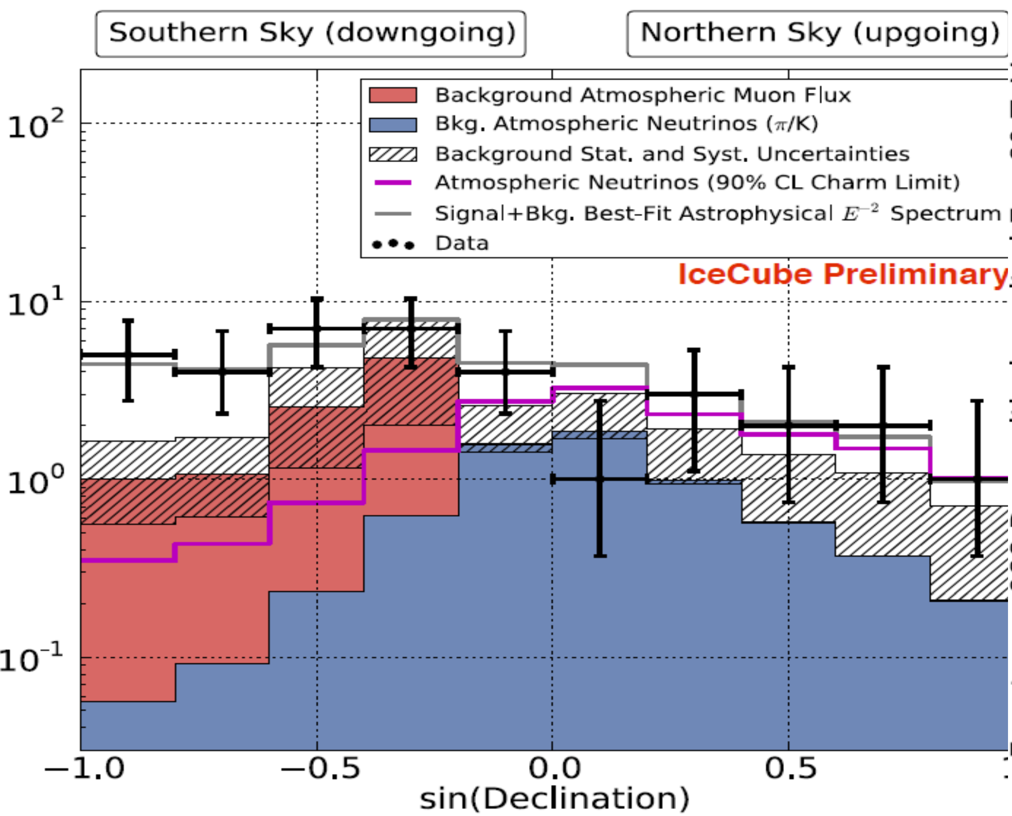
Muon background only in the southern sky

Atm. Neutrino background dominant
- in northern sky (tagging shower muons)
- but near the horizon (earth absorption)

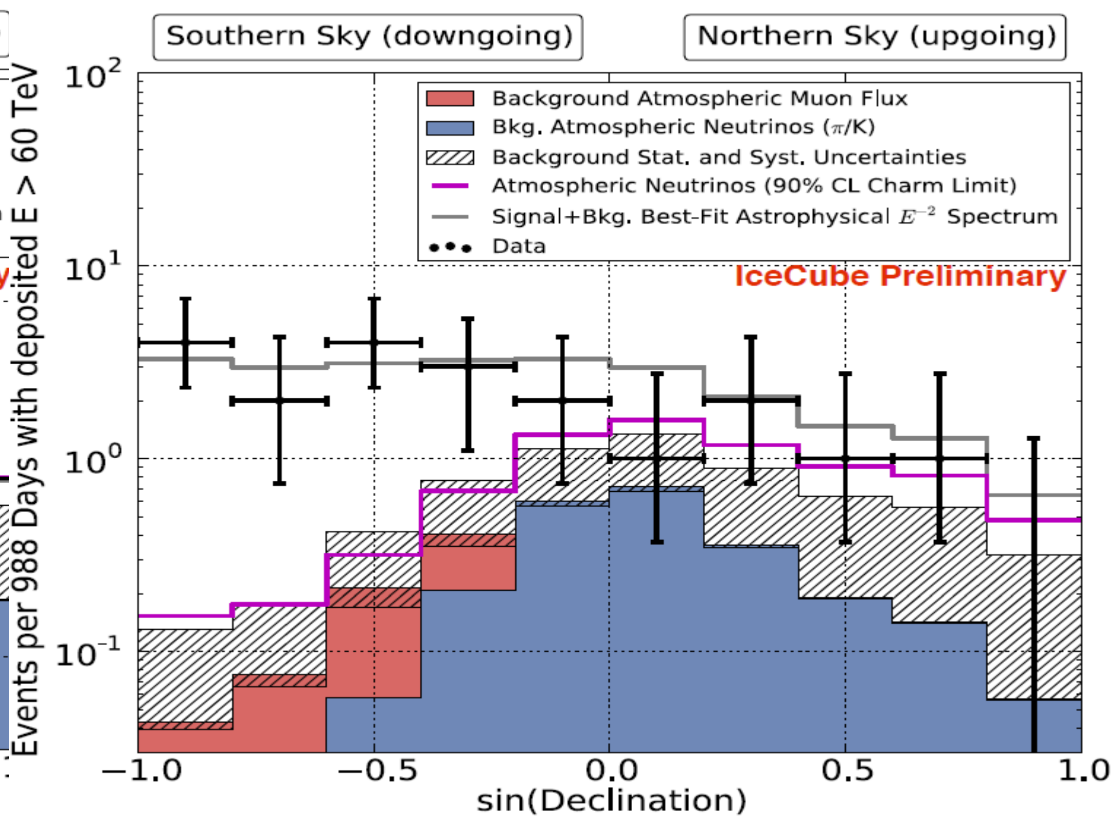
# Declination Distribution of Events

= zenith

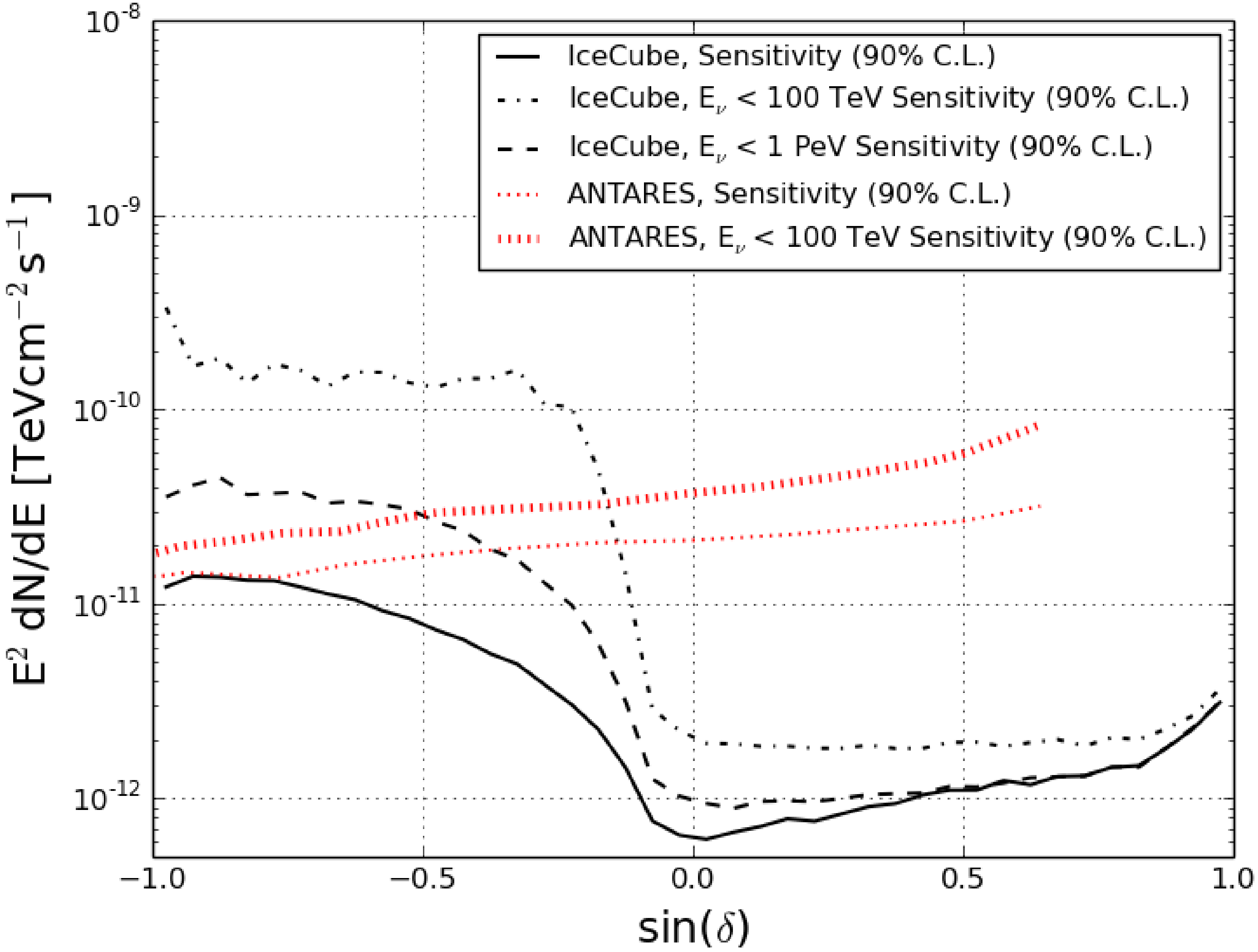
## ALL EVENTS




## EVENTS > 60 TeV

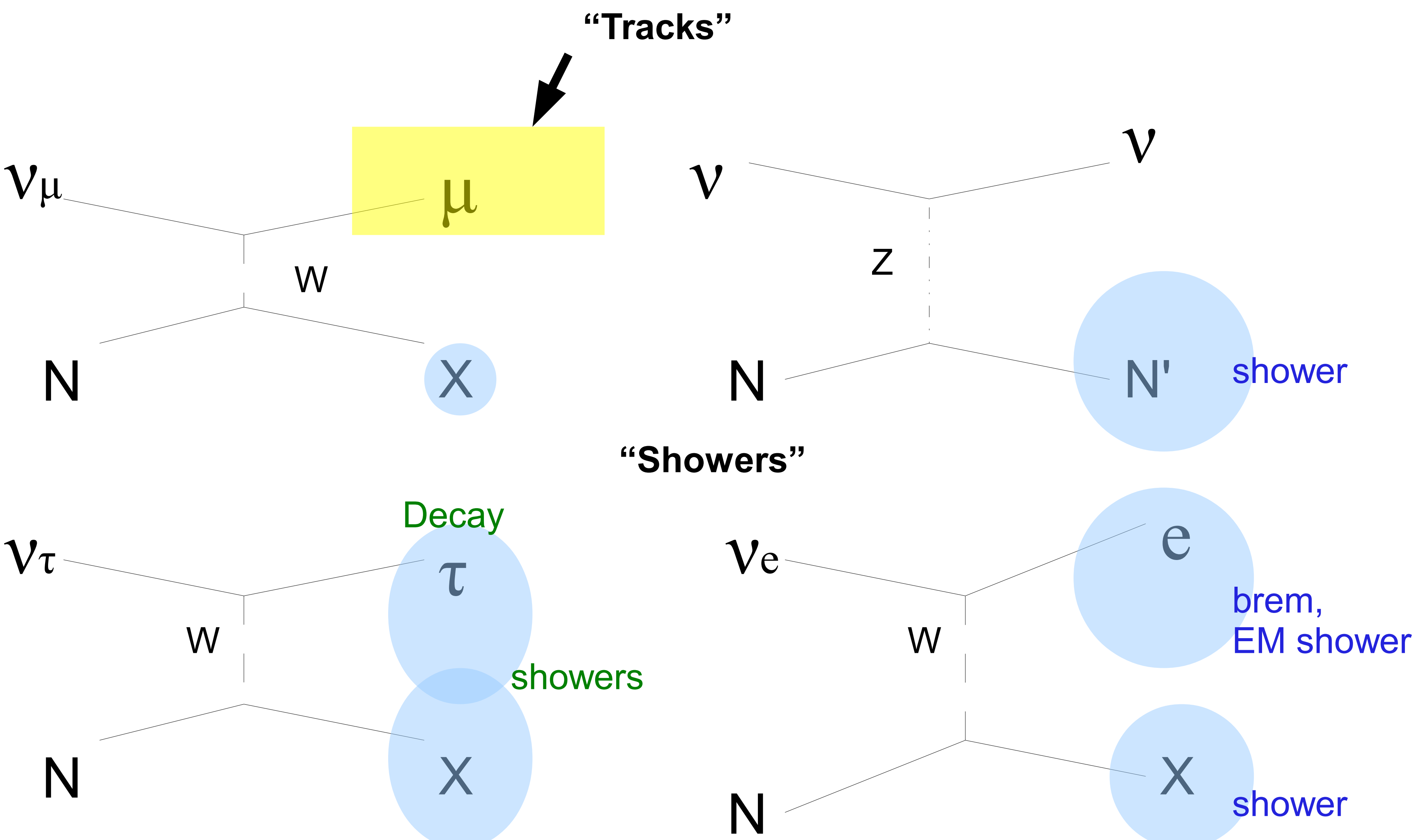


# Great improvement in the southern sky!



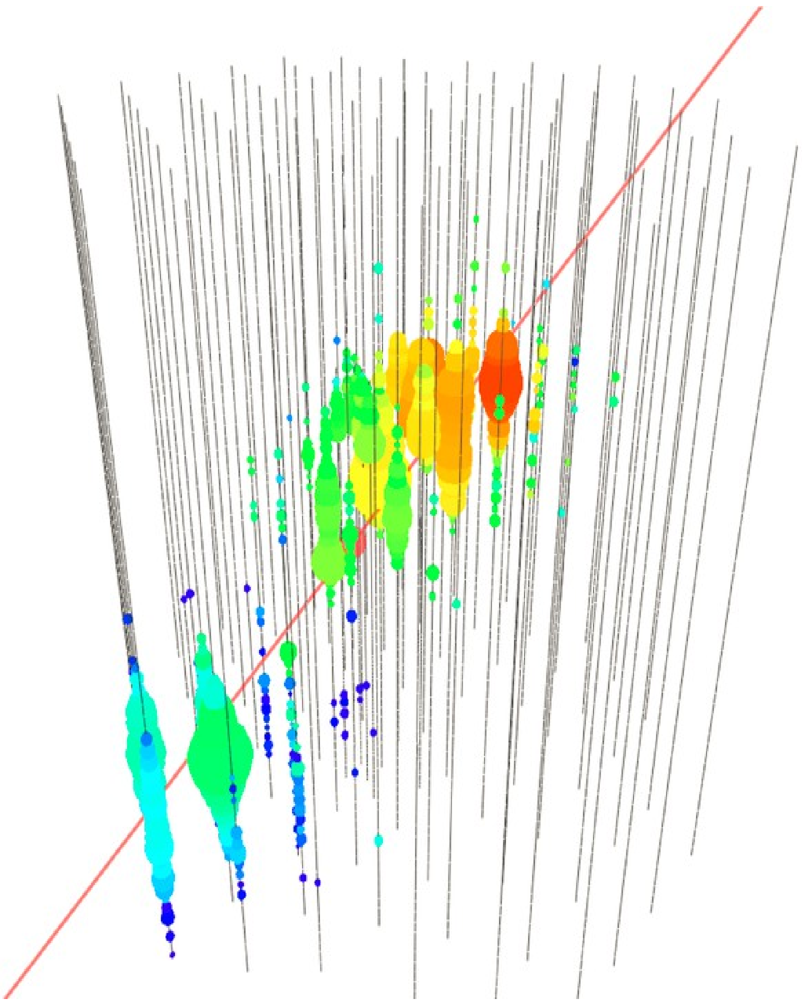
# Different Signals

> ~0.1Tev Deep Inelastic Scattering



# Interesting event found in a lower energy veto-passing sample of tracks

*Event is not in any of the diffuse astrophysical flux observation data set



- Starts inside the detector
- A track (points)
- Deposits ~80 TeV inside the detector
- Fairly downgoing (zenith angle ~56°)

Unlikely to be an atmospheric muon
because no detectable light in the top layers

→ < 0.0001 events expected in 3 yrs

Unlikely to be an atmospheric neutrino
because at this energy and angle, a muon from the same shower is expected to be seen in the detector

→ ~ 0.0022 events expected in 3 yrs

2.8σ fluctuation above background
* calculated a posteriori

# Since our *Science* Paper....

- We learned how to calculated the self-veto probability at lower energies
- We figured out a way to parametrize our muon background (original analysis used data to estimate the background)

Lower the energy threshold
(more statistics)

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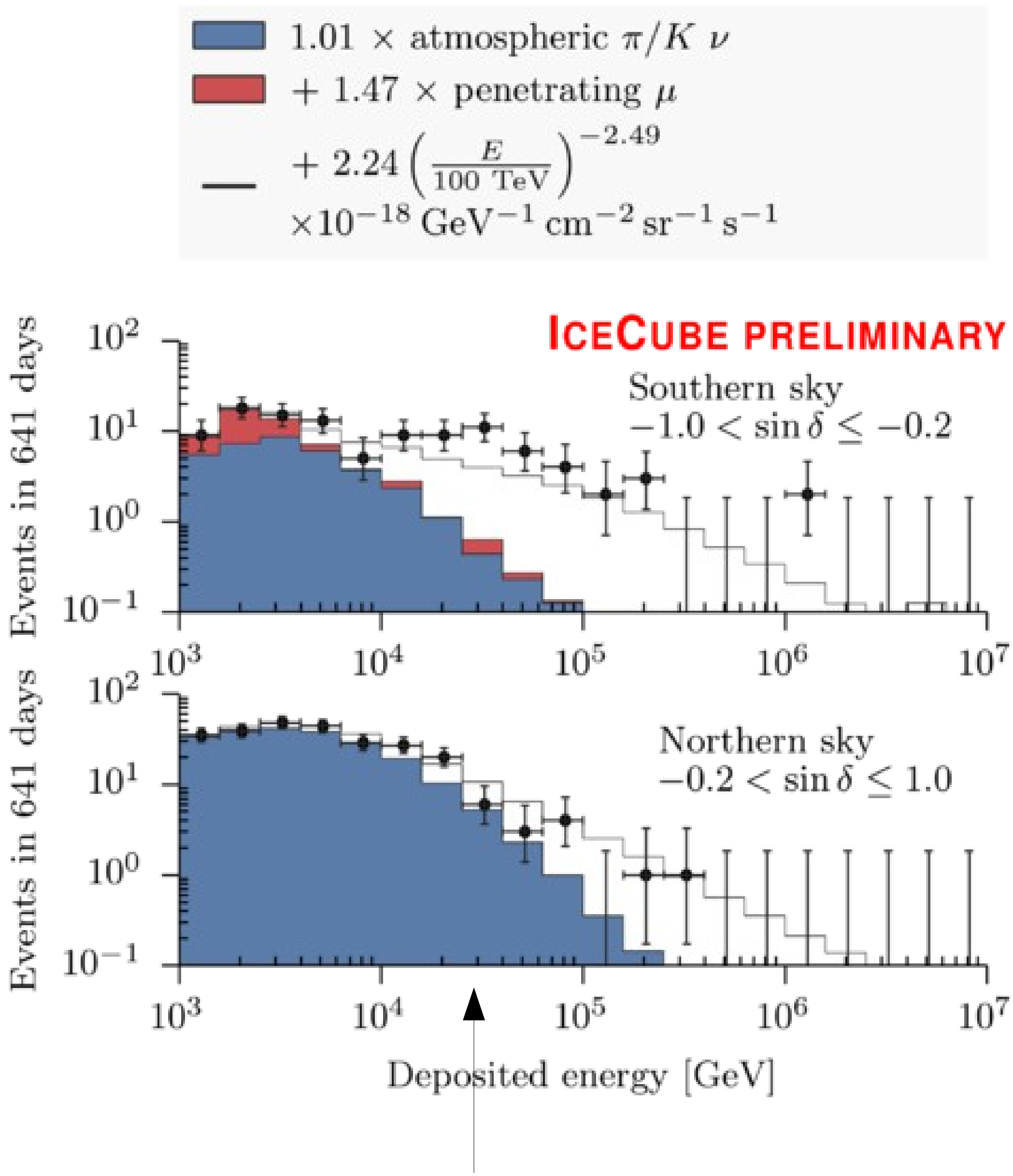


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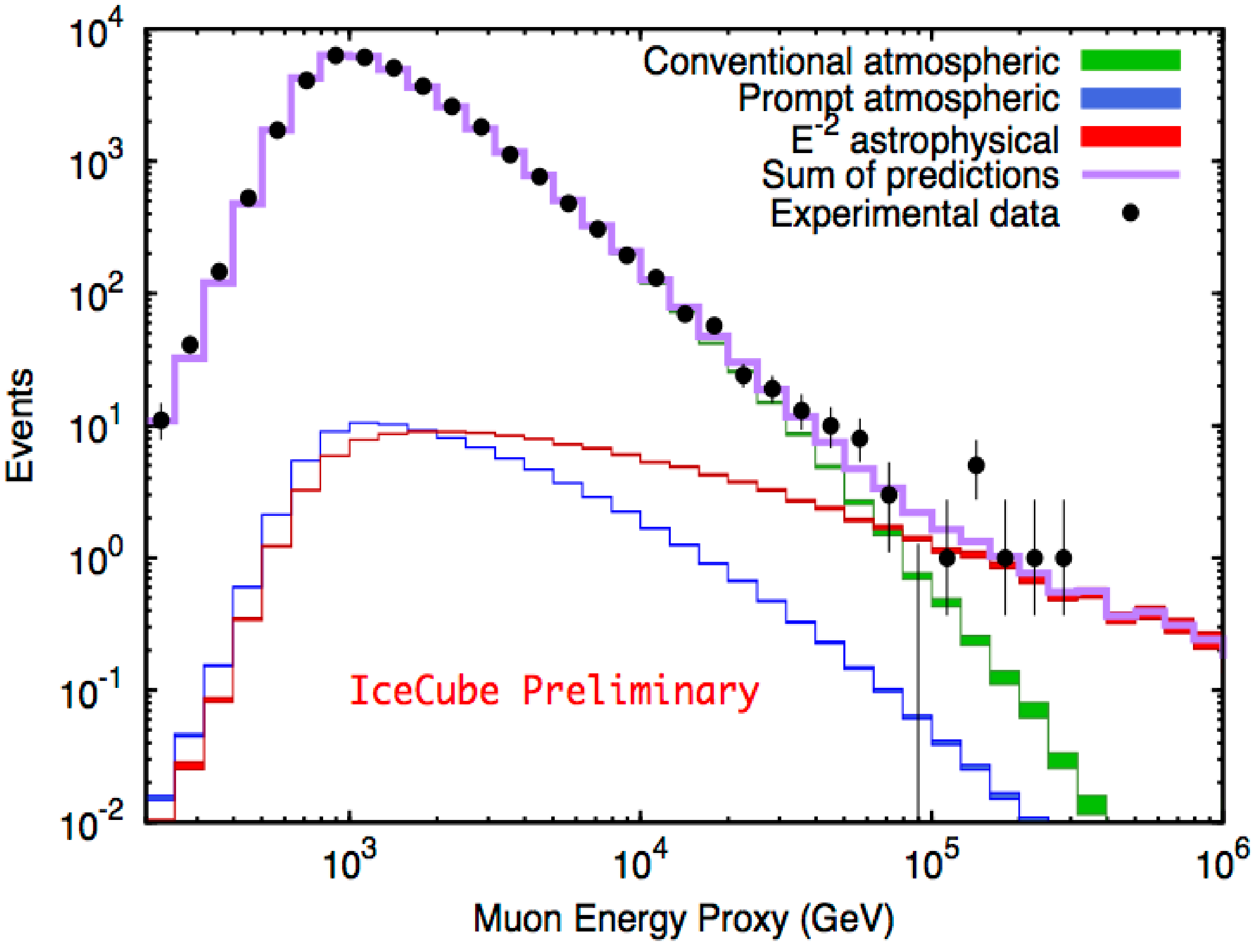


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