High-energy neutrinos

A new messenger from the non-thermal universe.

Markus Ackermann

Seminar talk
Fermilab

3/31/2016

HELMHOLTZ GEMEINSCHAFT

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Alexander von Humboldt
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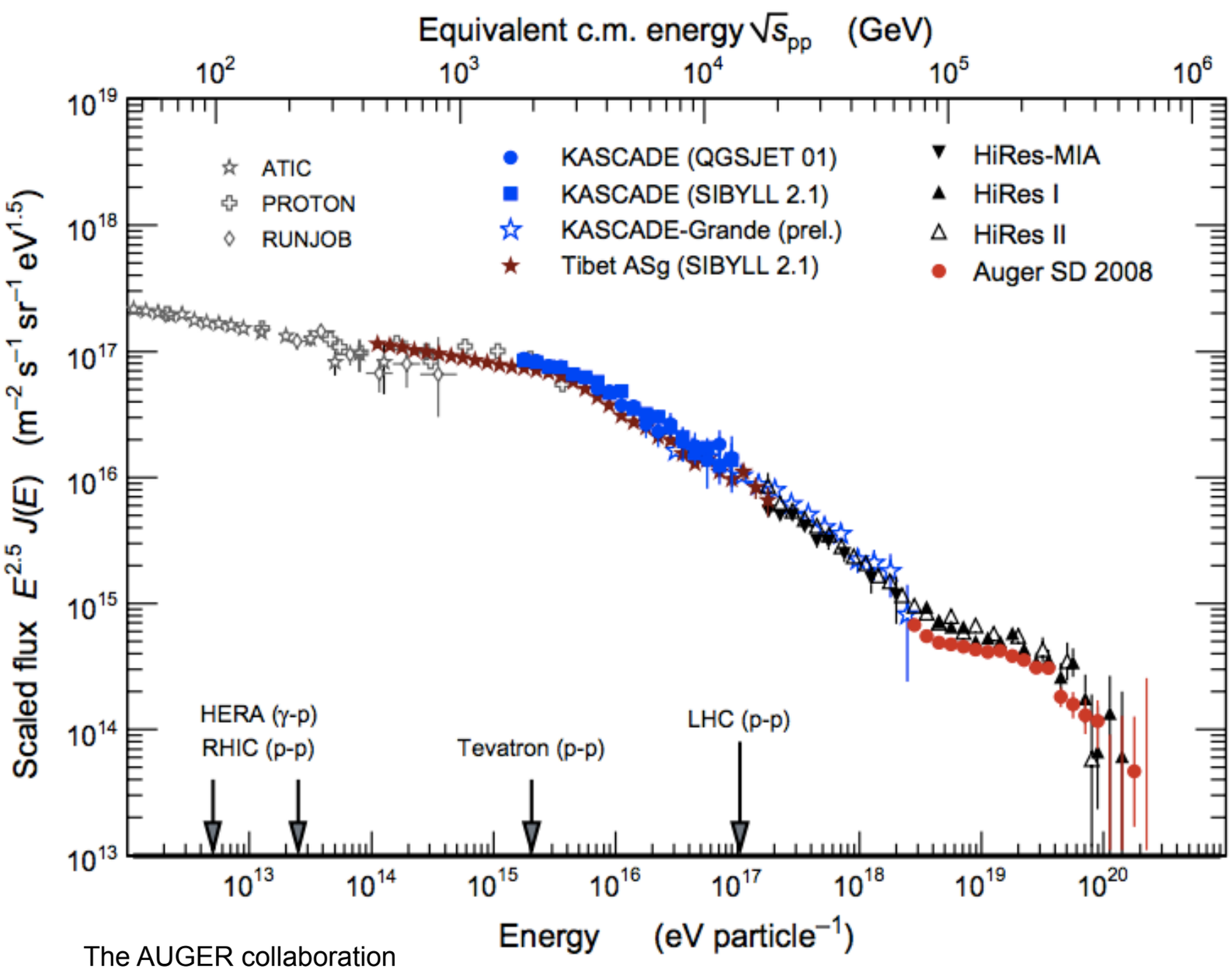
DESY

High-energy astrophysics: The cosmic-ray puzzle.

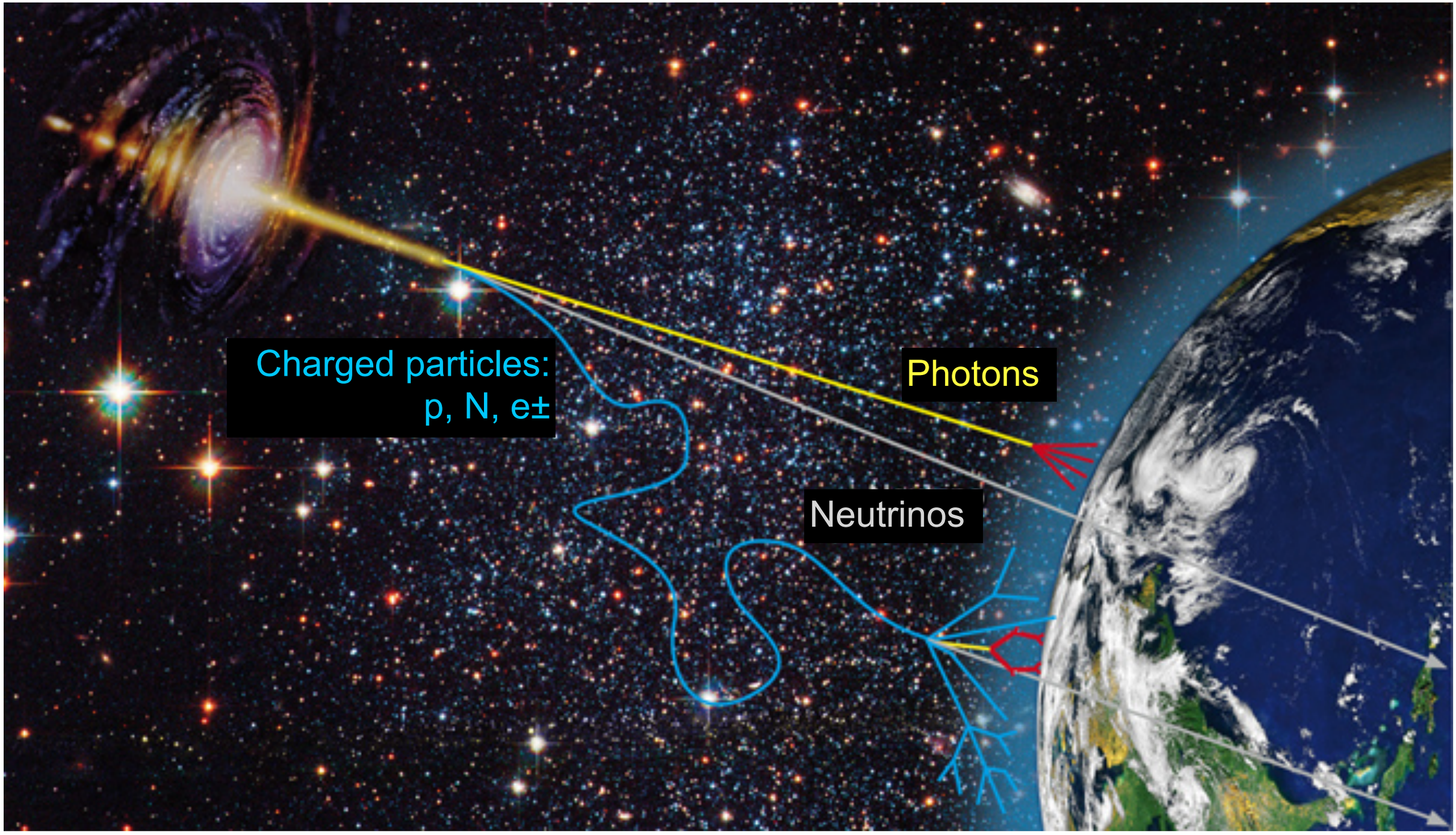


The AUGER collaboration
New Journal of Physics 12 (2010) 035001

- **Cosmic rays** can be observed to energies **> 10^{20} eV**
- Their **origin** is still **unknown,** even 104 years after their discovery.
- **Which sources** can accelerate particles to such high energies ?
- And what are the **physics processes** behind ?

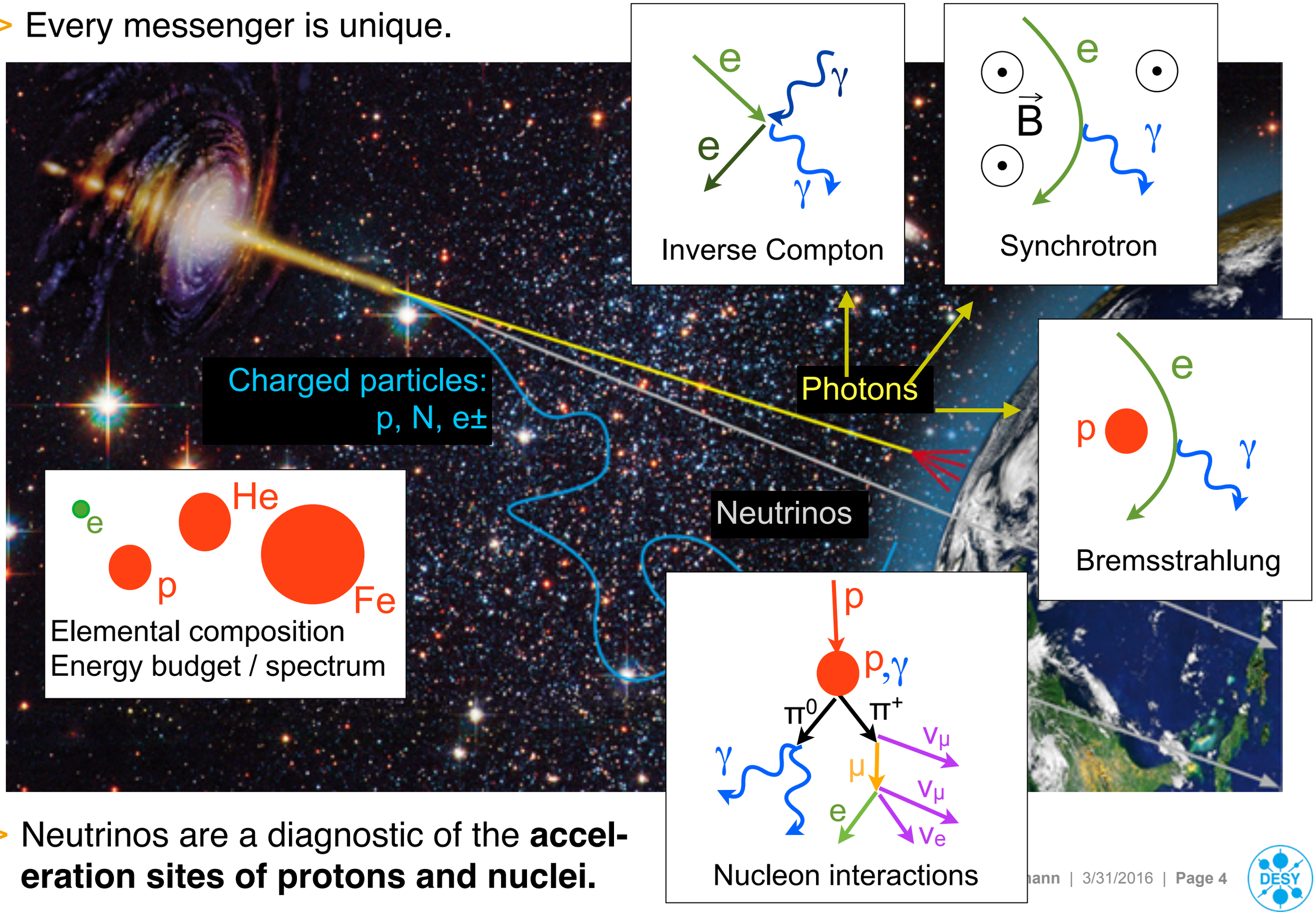
The cosmic-ray puzzle.

> Three messengers are available to study the non-thermal universe.



The multi-messenger approach.

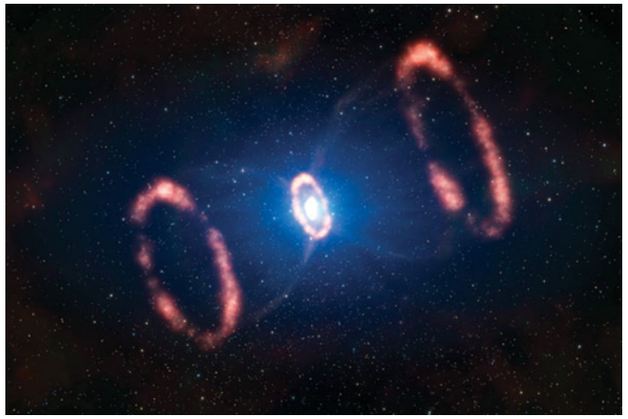
> Every messenger is unique.



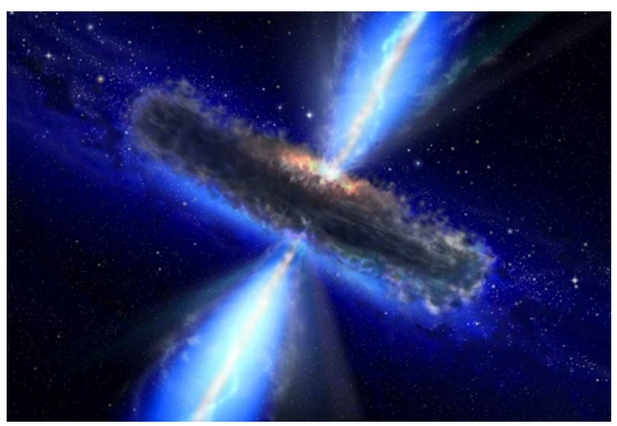
> Neutrinos are a diagnostic of the **acceleration sites of protons and nuclei.**

Neutrinos from dense environments.

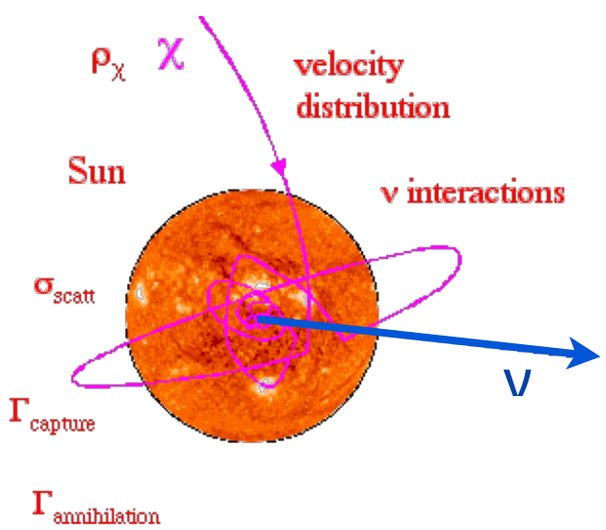
Neutrinos can **escape dense environments:**



> High-energy neutrinos from core-collapse SNe.
(e.g. Ando & Beacom, 2005)



> Neutrinos from the cores of active galactic nuclei
(e.g. Stecker et al., 1991)

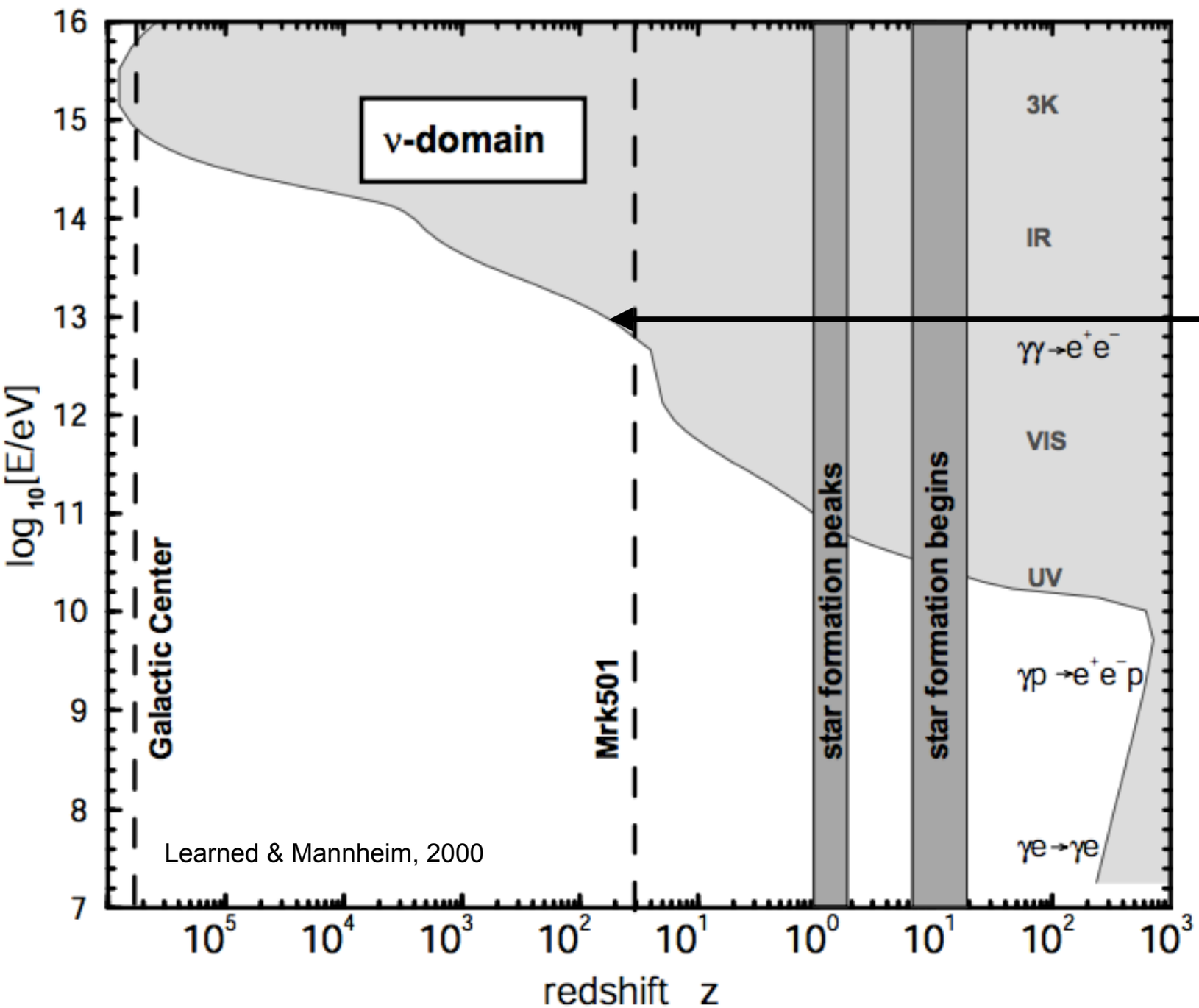


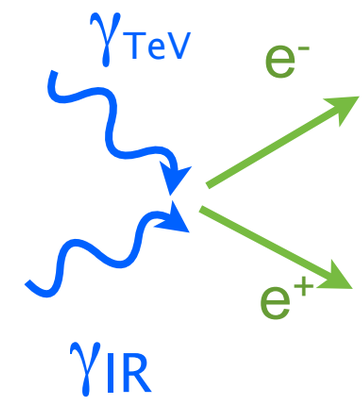
> High-energy neutrinos from dark matter annihilation in the sun.

The neutrino domain: PeV astronomy.

> Above 100 GeV the **universe** starts to turn **opaque for γ-rays**.

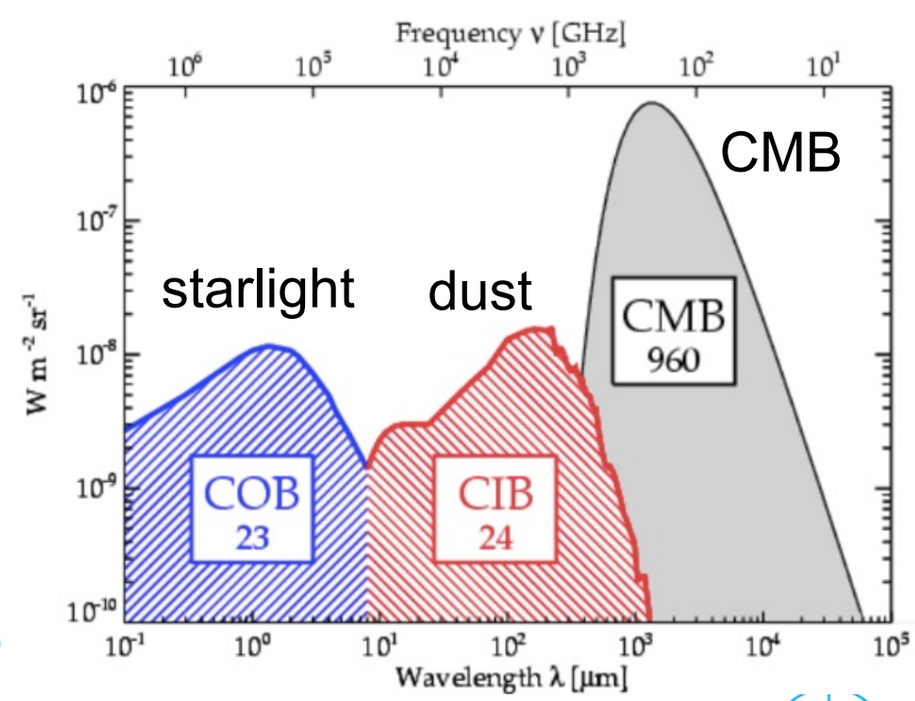
> Only neutrino telescopes can do **astronomy at PeV/EeV energies.**



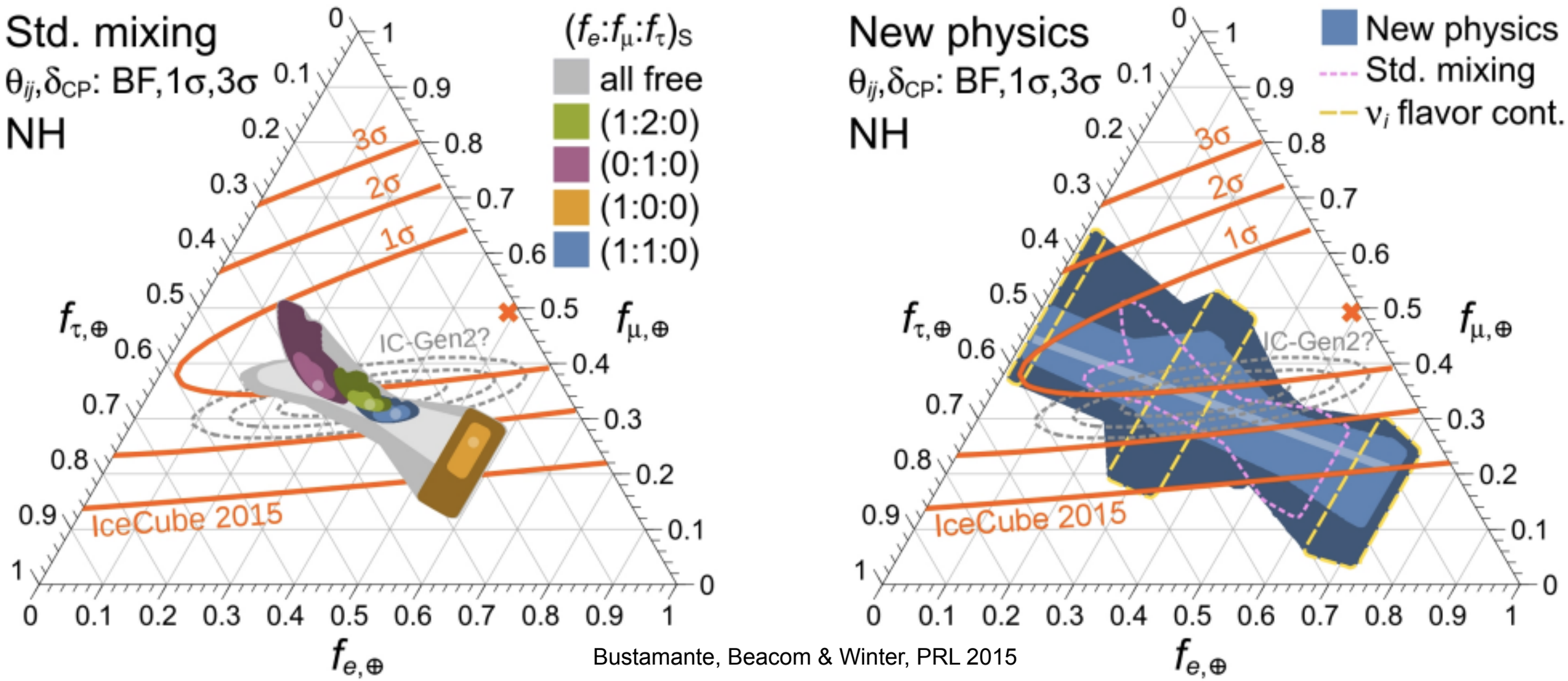


γ-ray horizon

Pair production in intergalactic photon fields



Neutrino flavors and astronomy.



Bustamante, Beacom & Winter, PRL 2015

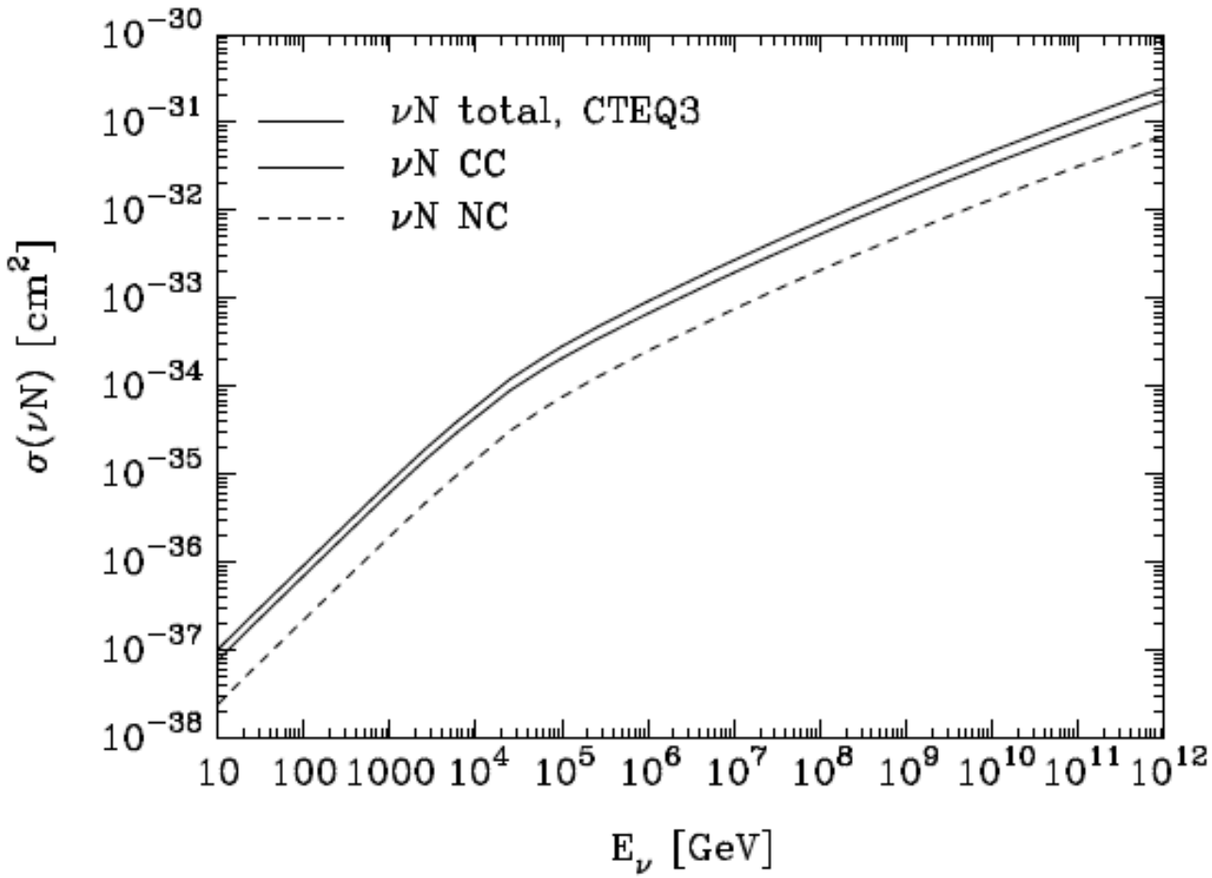
> Neutrinos carry flavor.

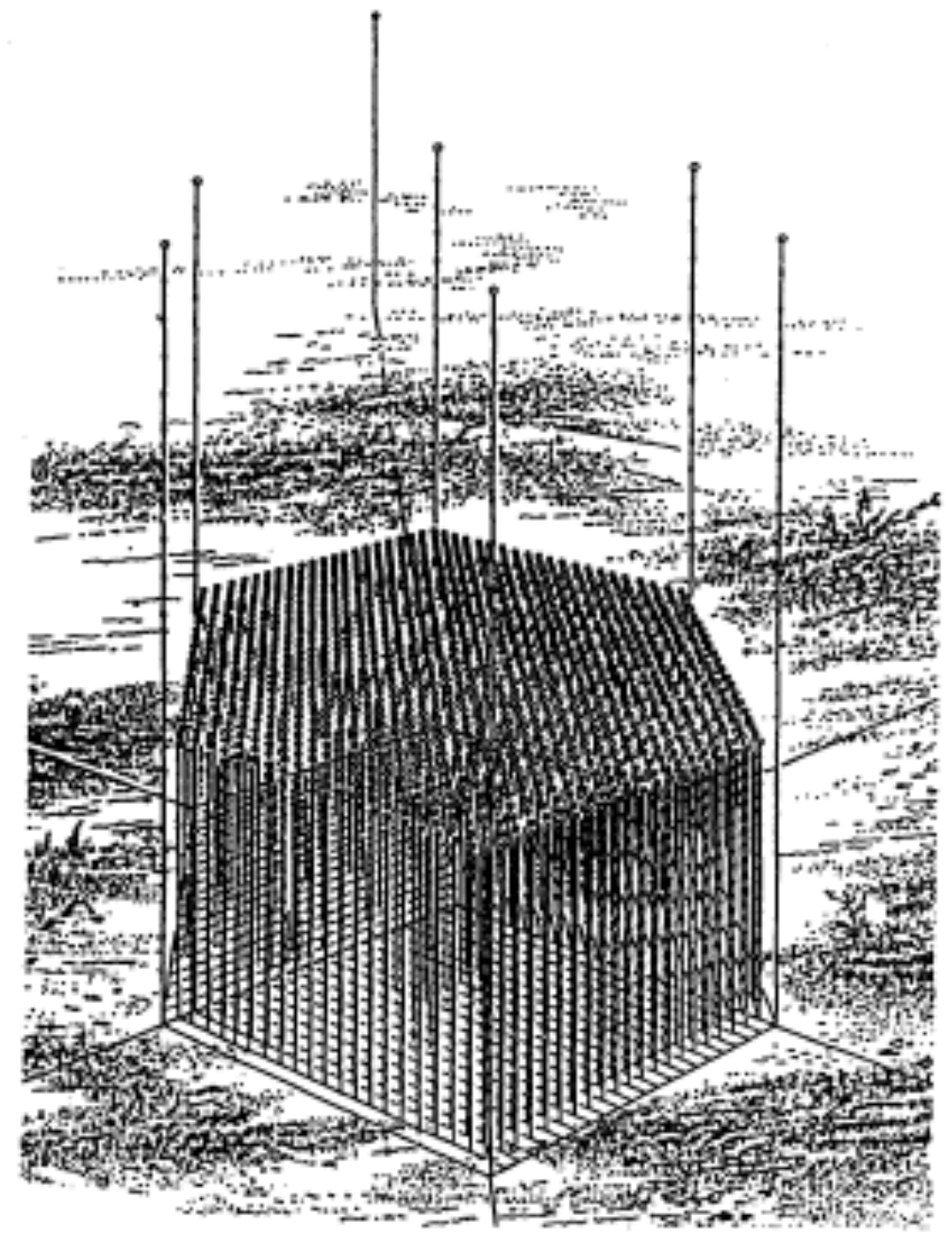
> **Flavor ratio** depends on **production mechanism / source environment**.

> Observations of an **unexpected flavor ratio** could identify **new physics.**

Neutrino astrophysics.

> **Small cross-section** of neutrinos requires **huge detectors.**



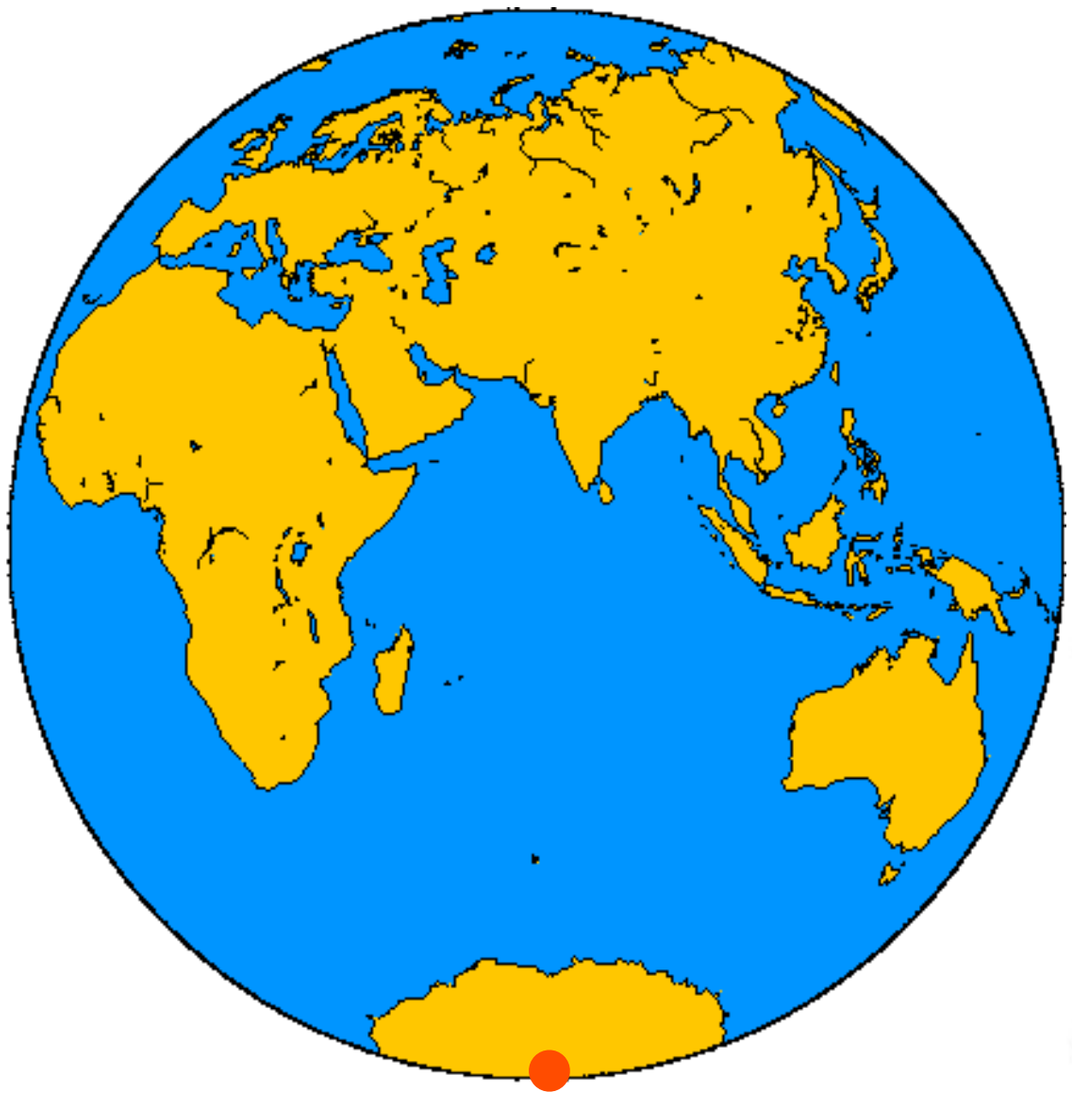


> **First design** of a **1 km³** underwater detector already in 1978

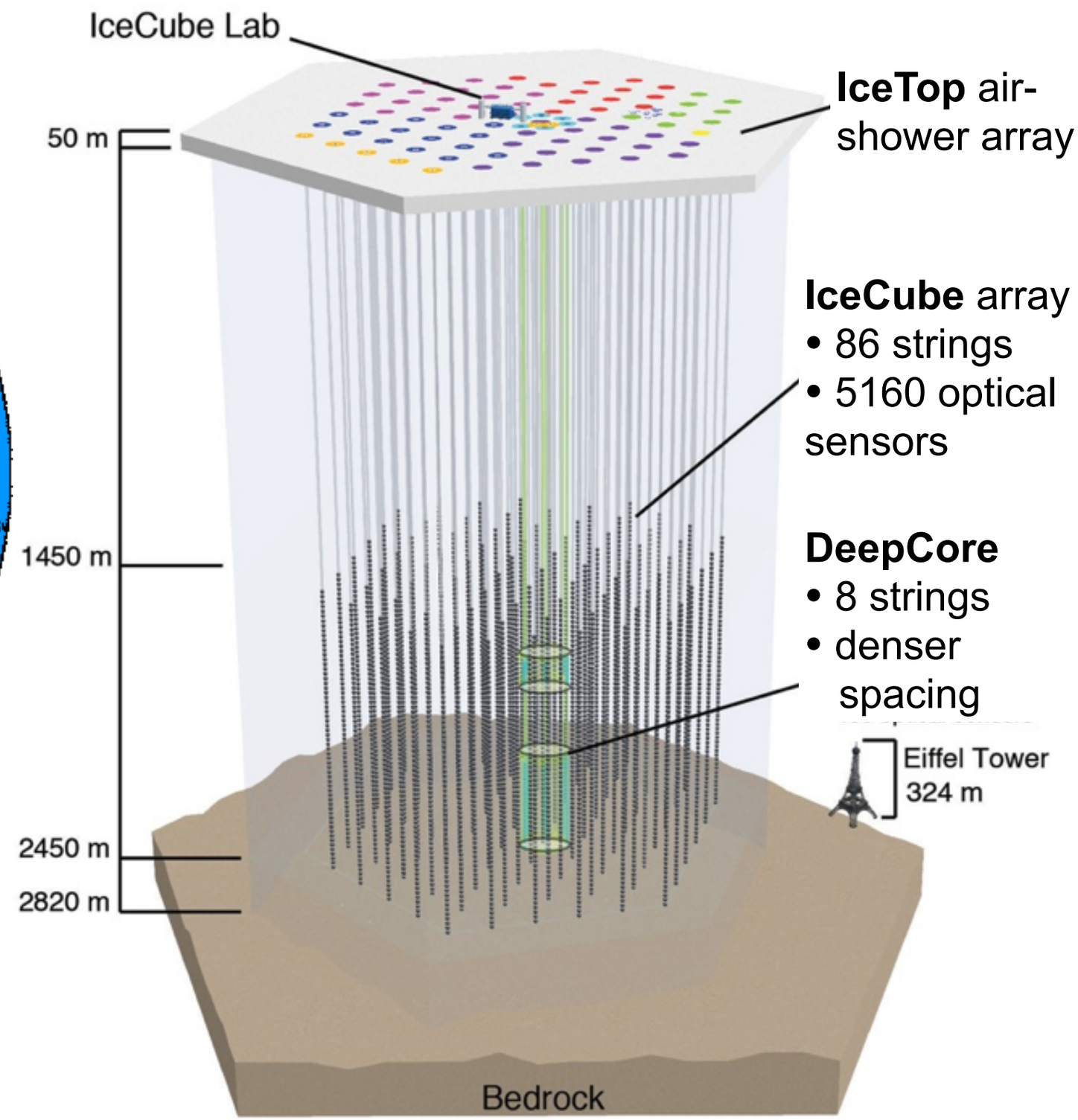
- DUMAND array off the coast of Hawaii
- Never built after first test strings failed

> **35 years later** we are finally there....

The IceCube neutrino telescope.



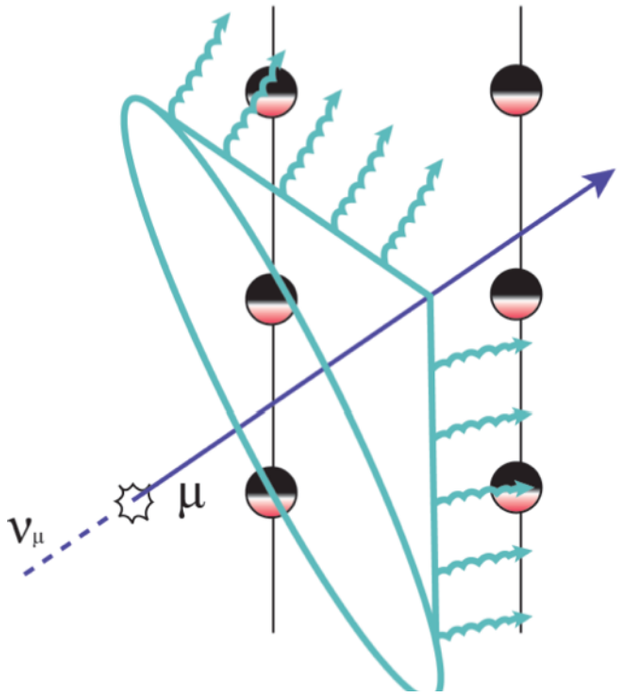
IceCube



> **Completed** in Dec **2010**.

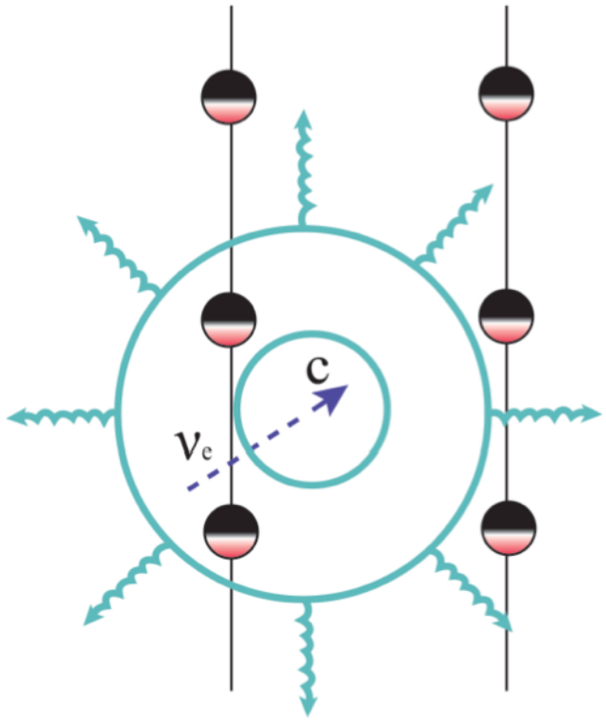
> Instrumented volume: **~ 1km³**

Neutrino detection by Cherenkov light.



> **Charged particles** produced in neutrino interactions emit **Cherenkov light**.

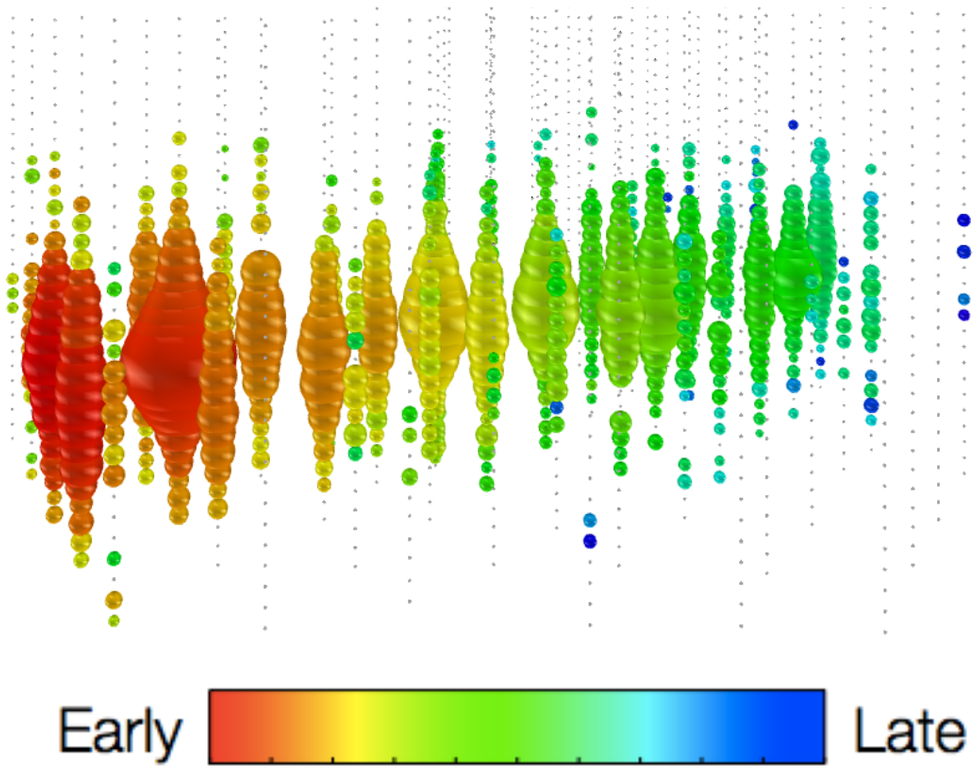
> **Optical sensors** deployed in **transparent medium** record arrival time and amplitude of light signal



> **Neutrino direction** from arrival time pattern

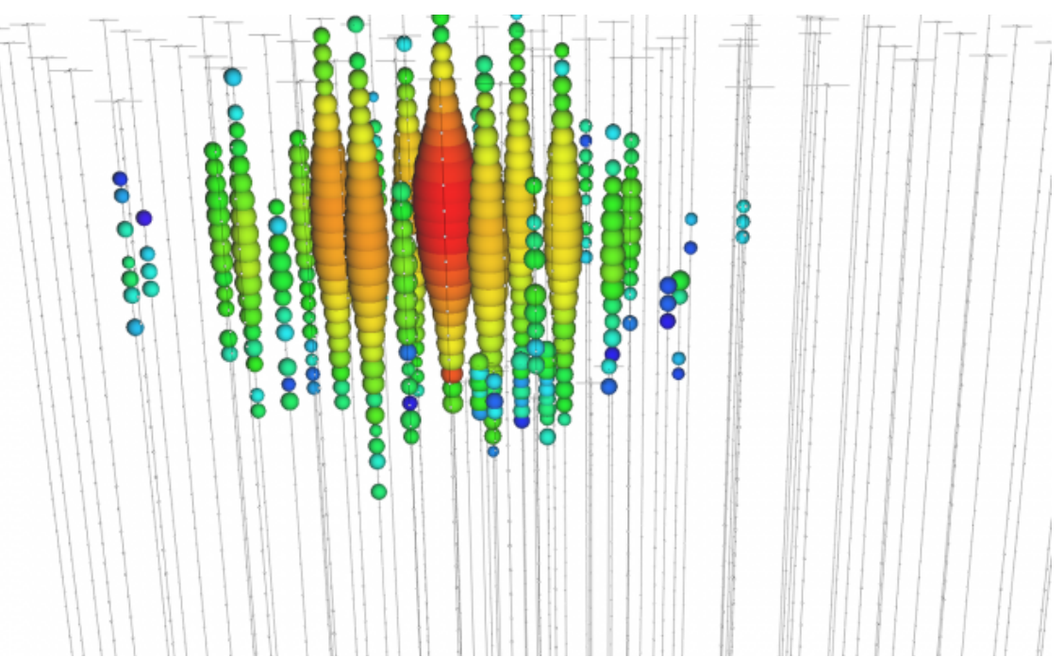
> **Neutrino energy** reconstruction from amplitude.

Detection of high-energy neutrinos.



> **Track-like event** signatures
(CC interactions of ν_μ)

- **Angular** resolution: < 1°
- Effective **volume:** up to tens of km³.
- **Energy** resolution: only indirect measure of μ energy.

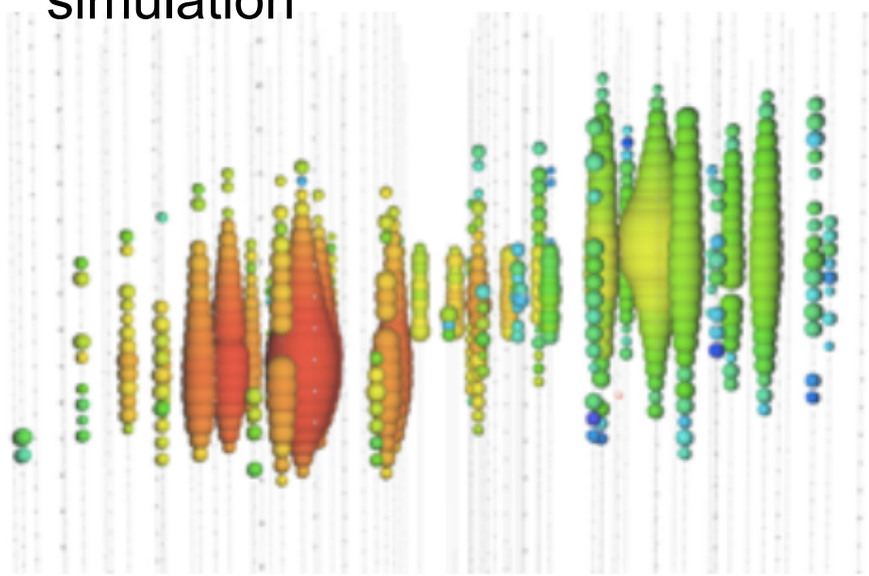


> **Shower-like event** signatures
(CC interactions of ν_e,ν_τ, NC interactions)

- **Angular** resolution: > 10°
- Effective **volume:** ~ 1 km³.
- **Energy** resolution: ~15% of deposited energy.

Detection of high-energy neutrinos.

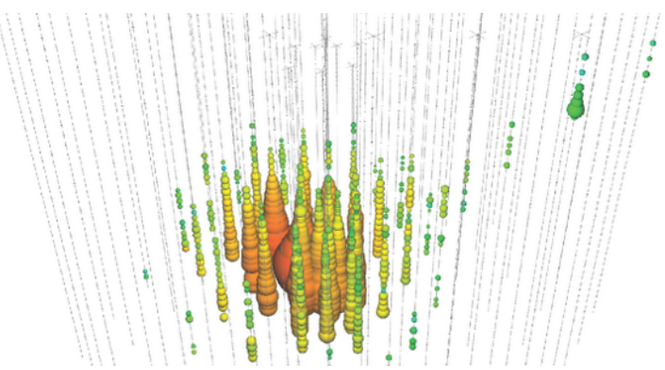
simulation

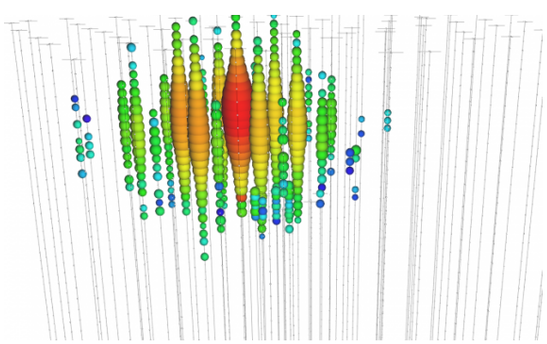


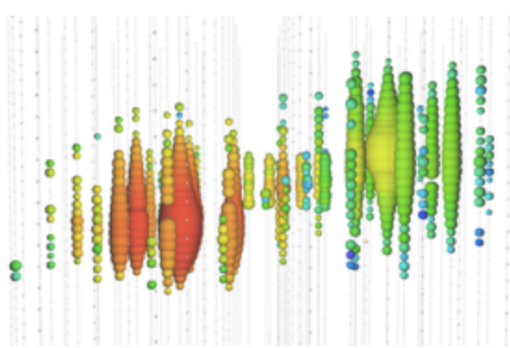
Early Late

> **High-energy ν_τ events**
(CC interactions ν_τ)

- ν_τ at PeV energies
- unique signatures that can identify a ν_τ interaction.





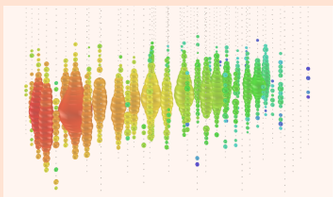


> **Starting events**
(all flavors)

- **Angular** resolution: < 1° - 15°
- Effective **volume:** <~ 0.5 km³
- **Energy** resolution: ~15% of deposited energy.

Neutrino flavors and event signatures.

ν_μ

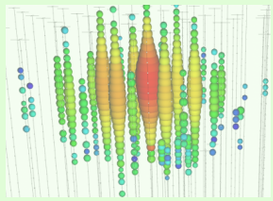


tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

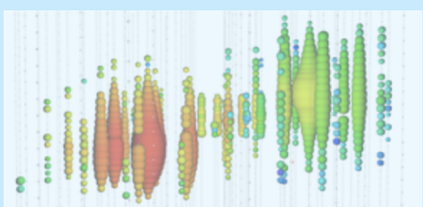
showers



- high statistics
- low background
- bad resolution

starting events

tau signatures



- very low statistics
- very low background

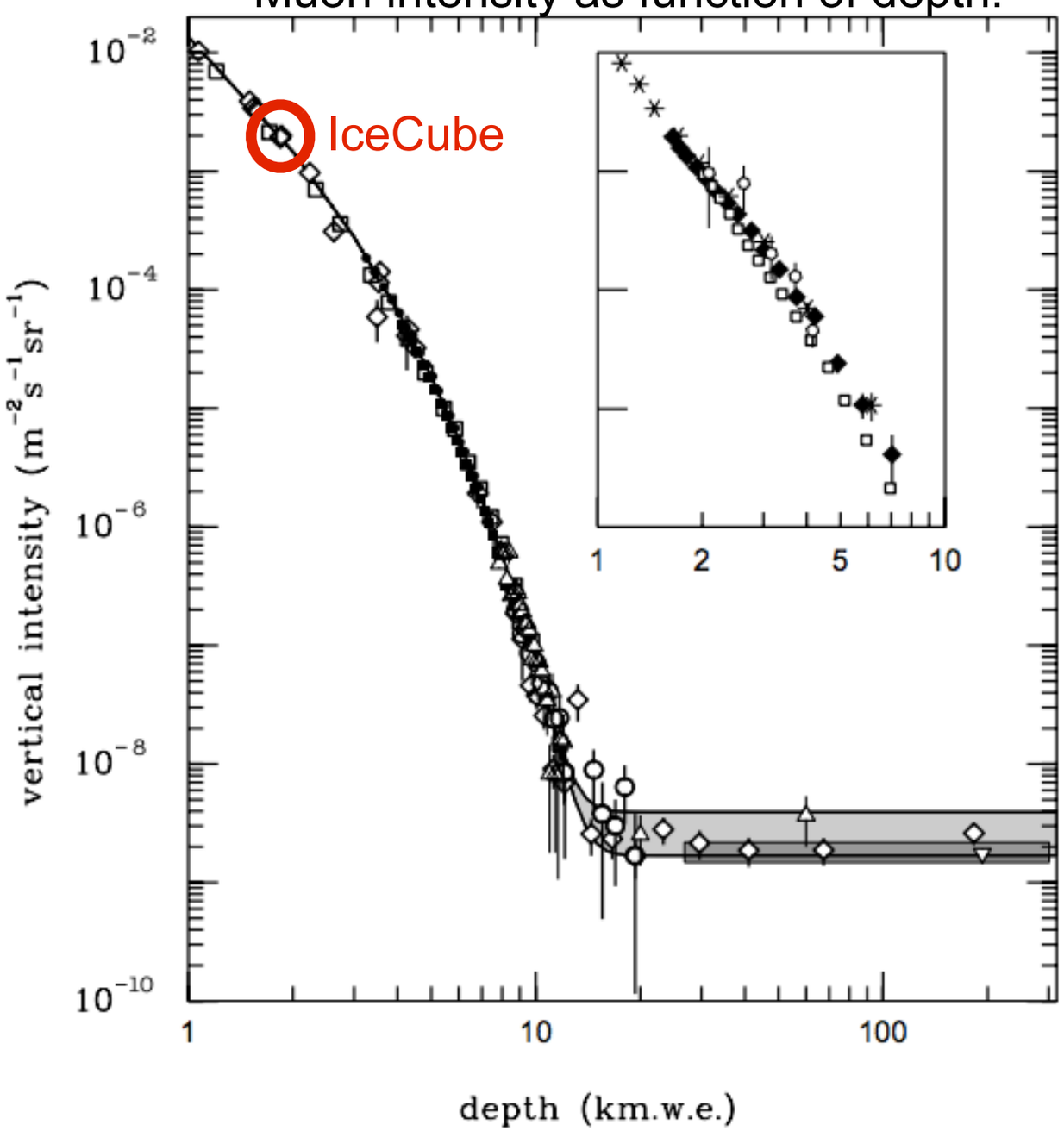
ν_τ

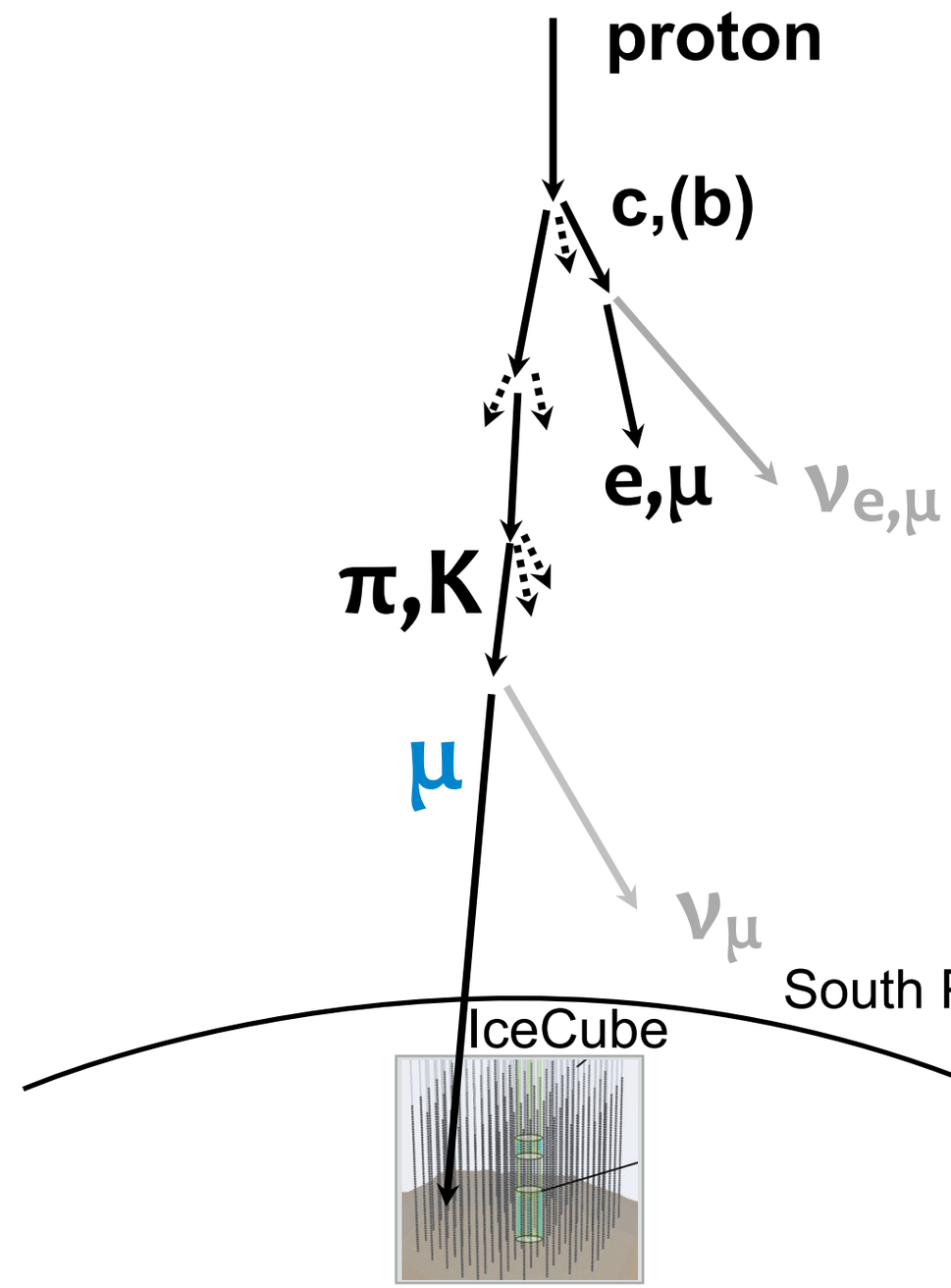
The challenge: Atmospheric backgrounds.

> **Muons from CR air showers** account for 99.9999% of all events seen by IceCube.

> Restricted to **Southern hemisphere.**

Muon intensity as function of depth.





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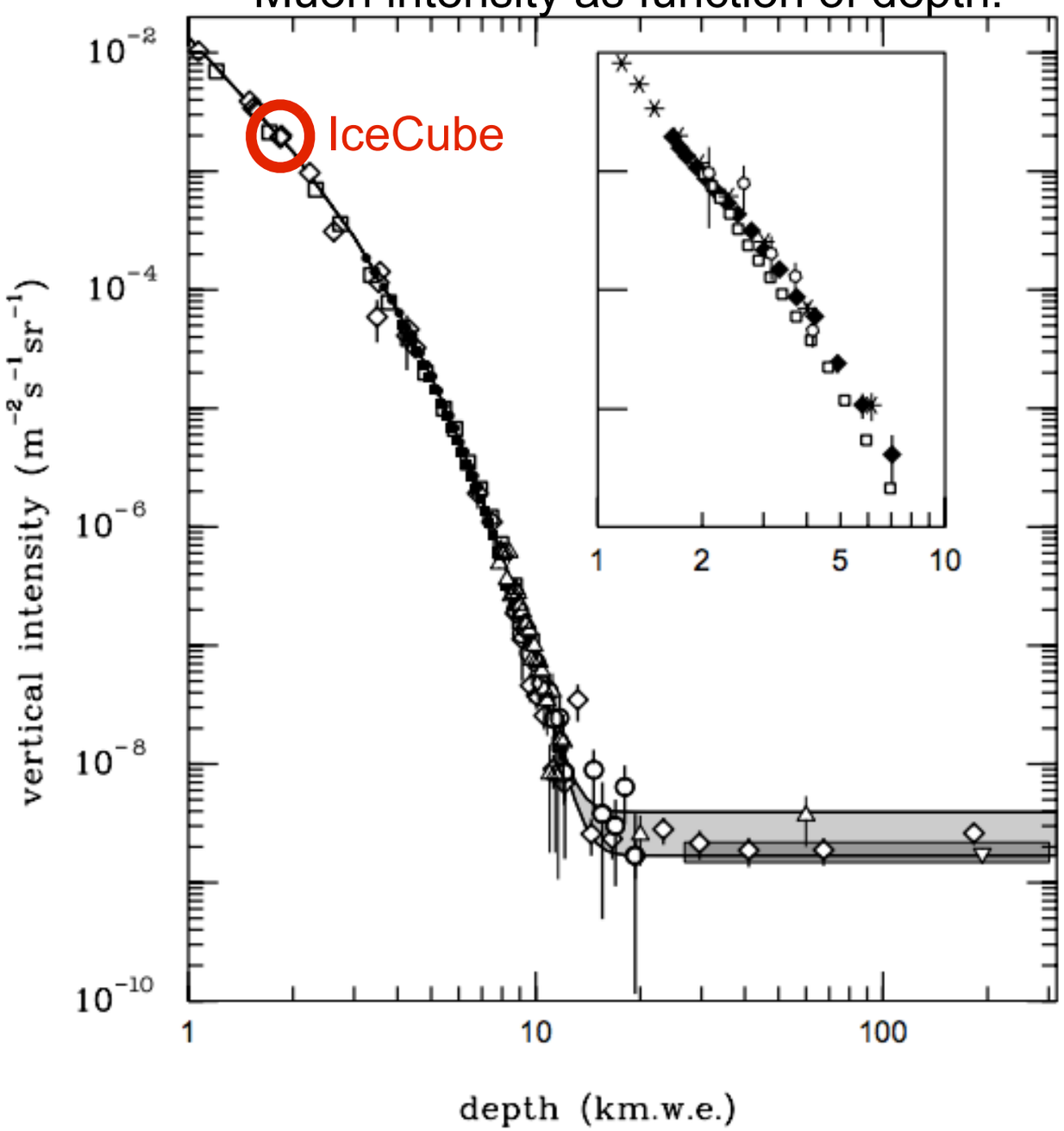

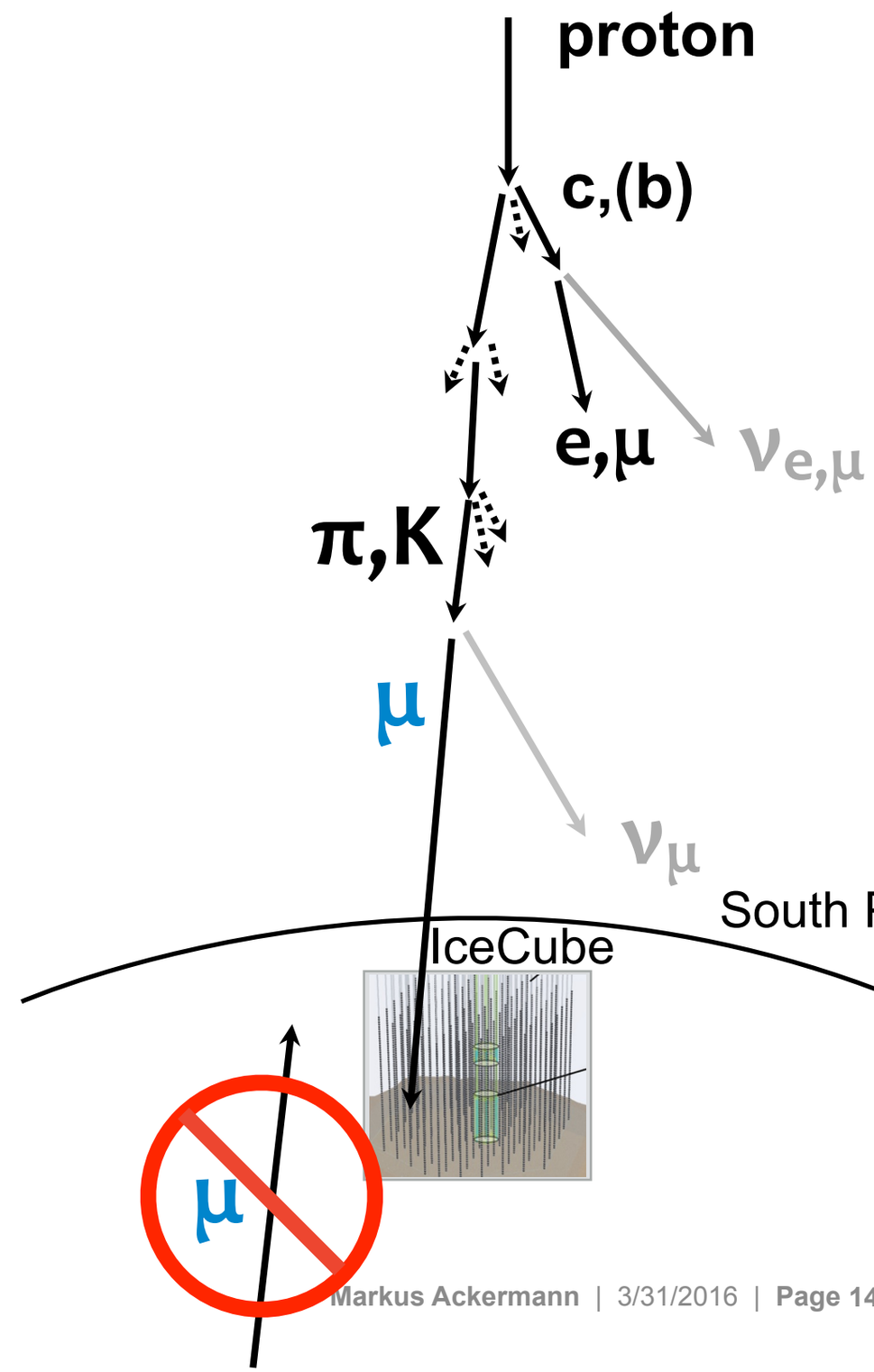

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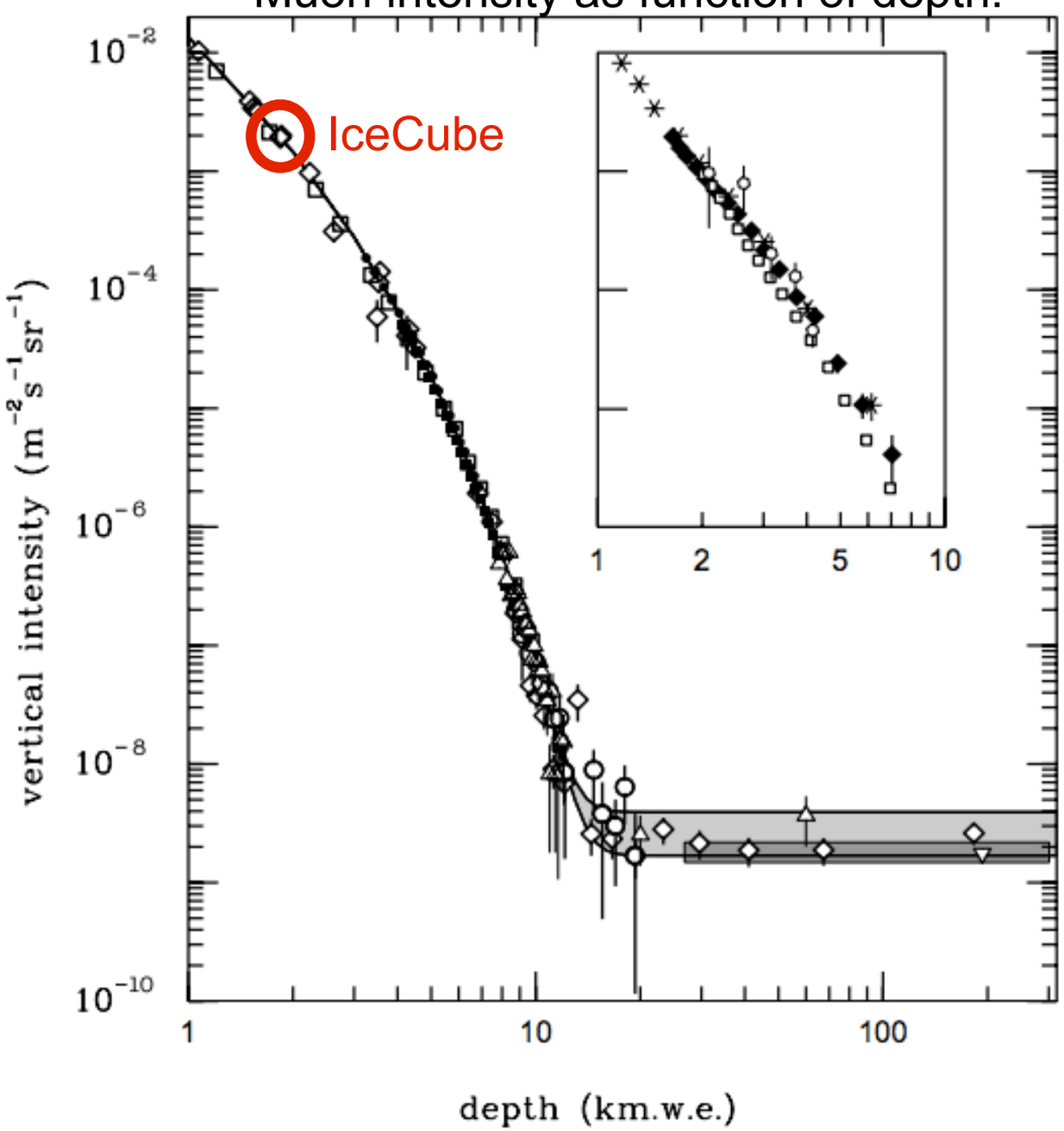
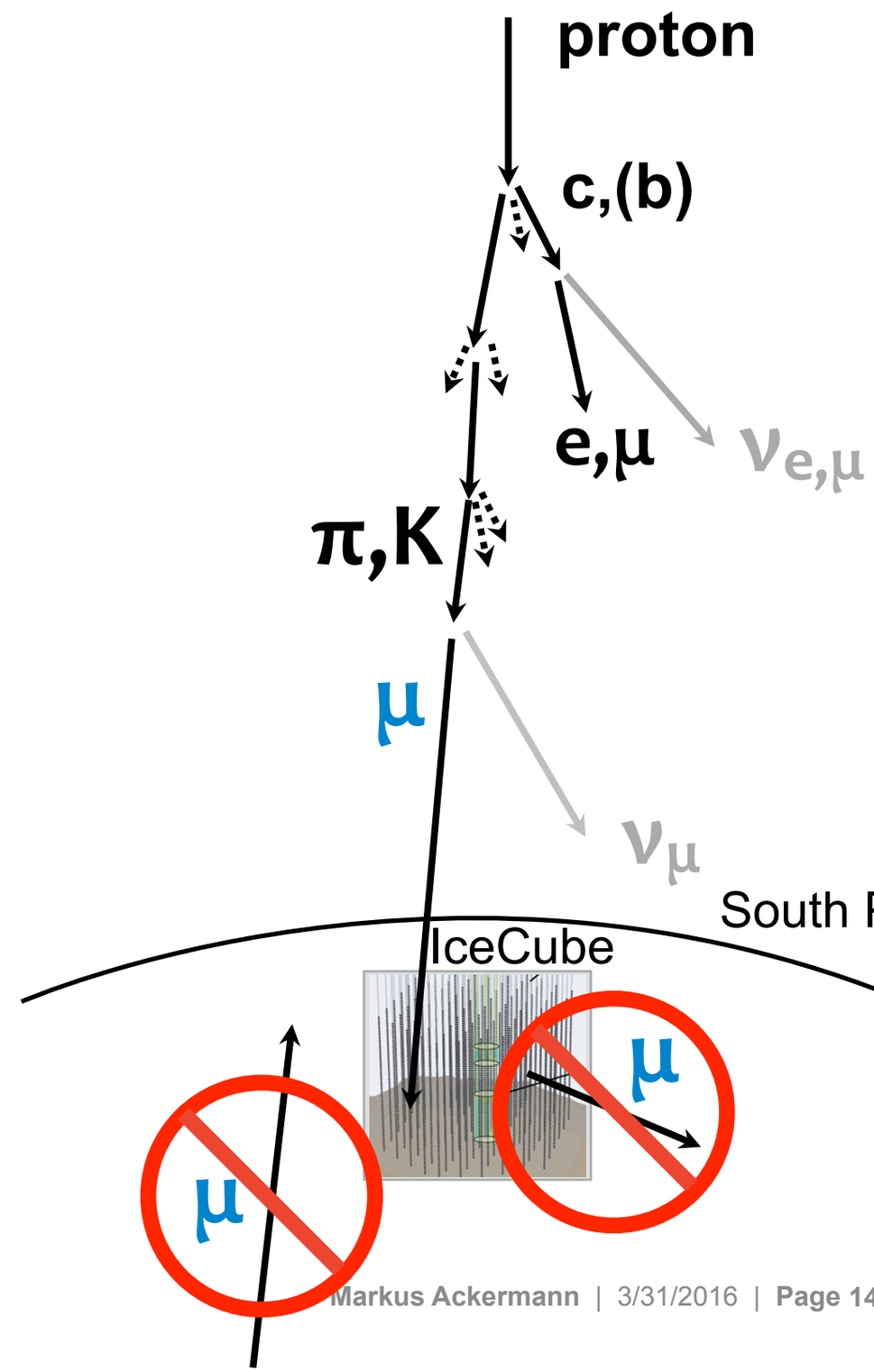
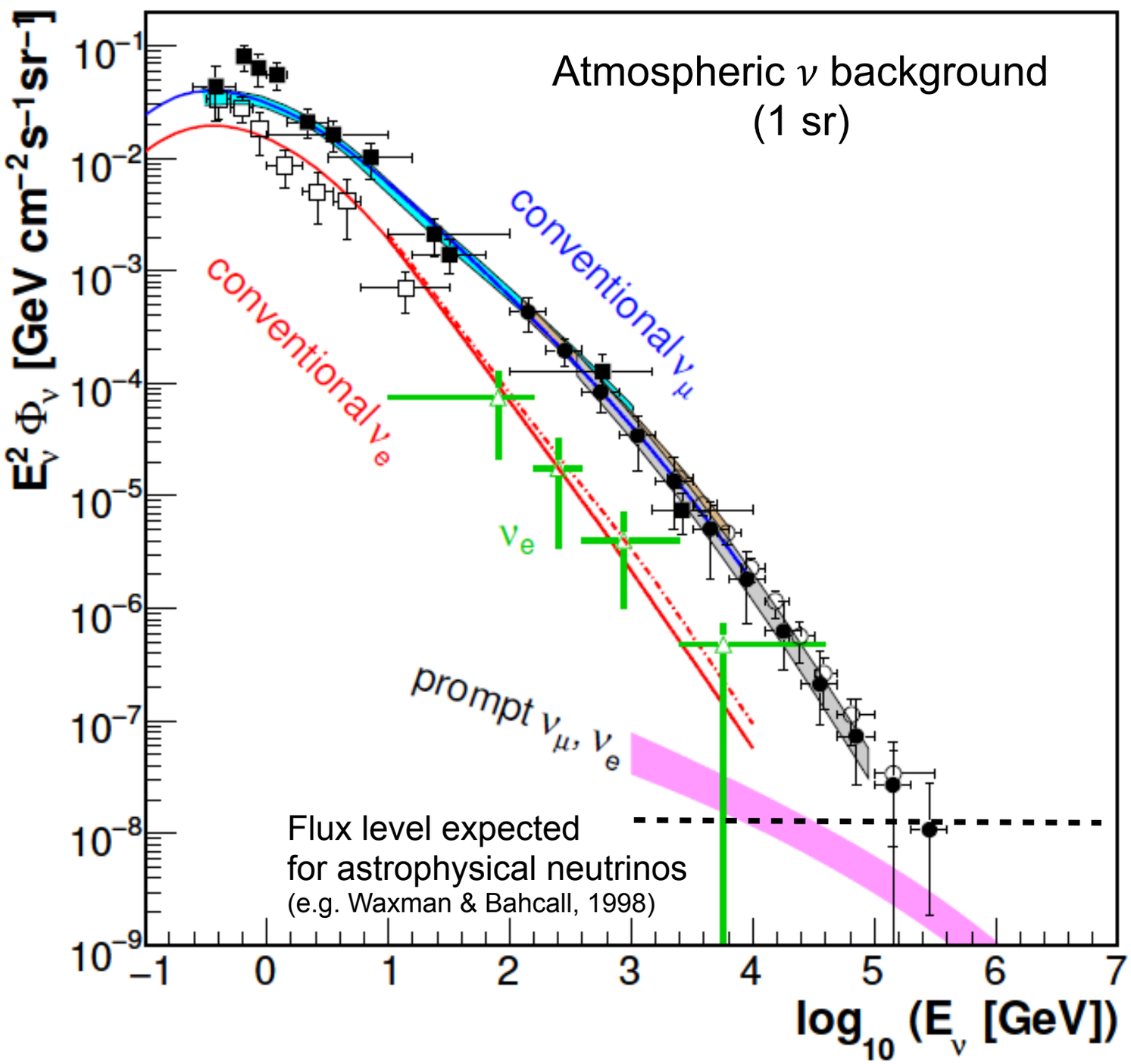


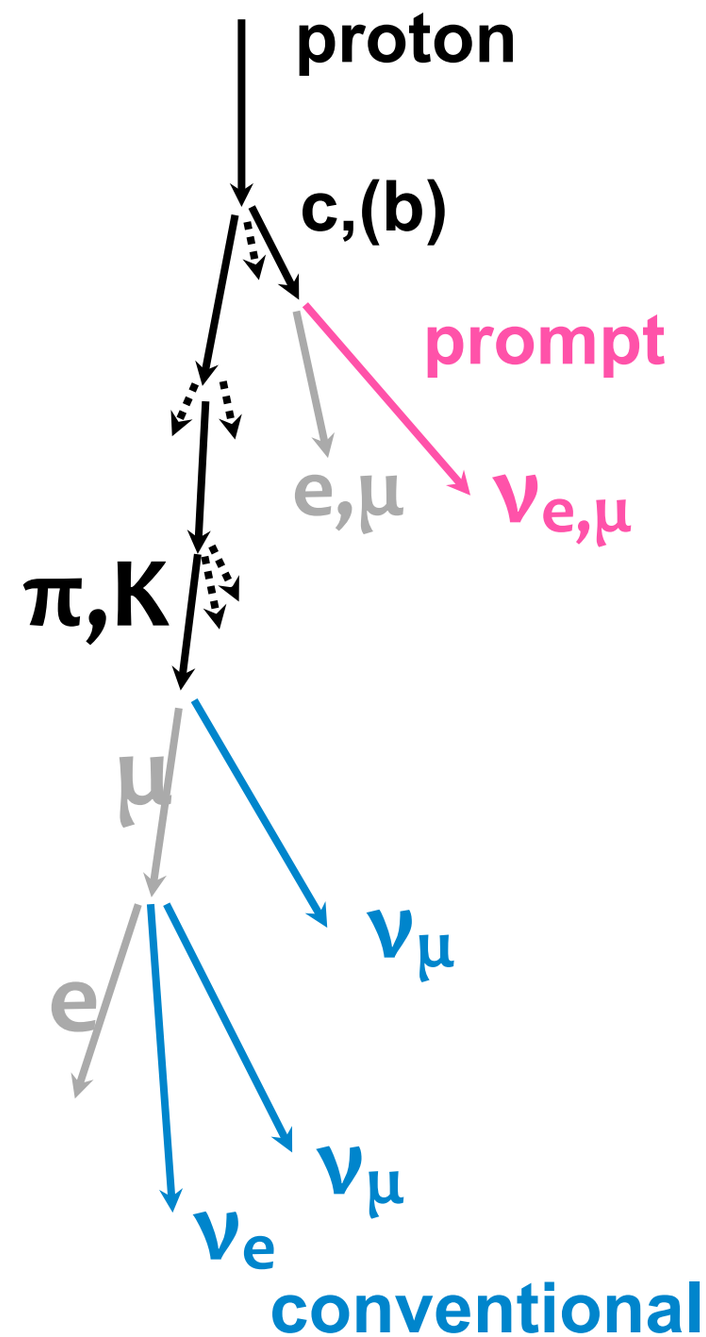


The challenge: Atmospheric backgrounds.

> **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.

> Atmospheric-ν are produced in **CR air shower interactions**.





The golden channel: Starting events

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

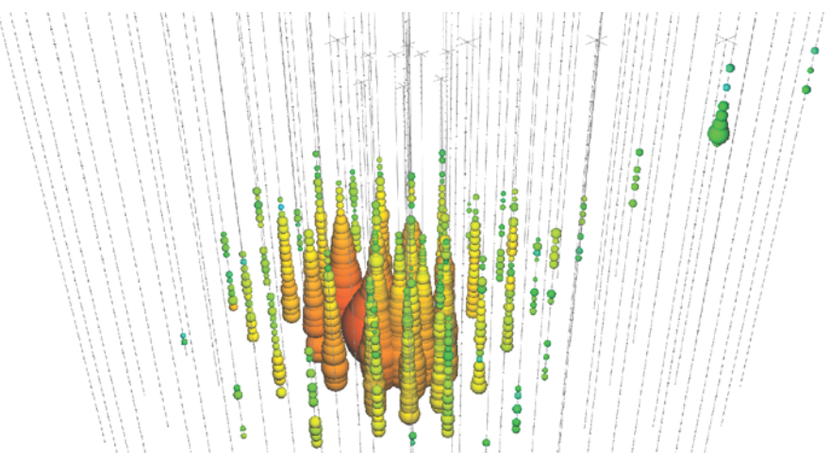
- high statistics
- low background
- bad resolution

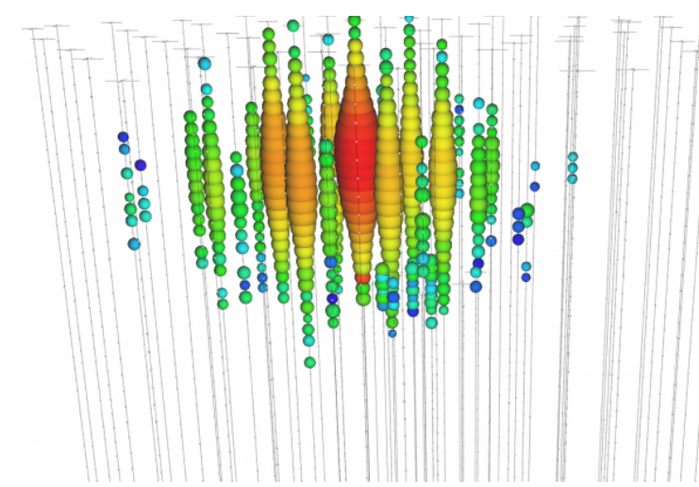
starting events

tau signatures

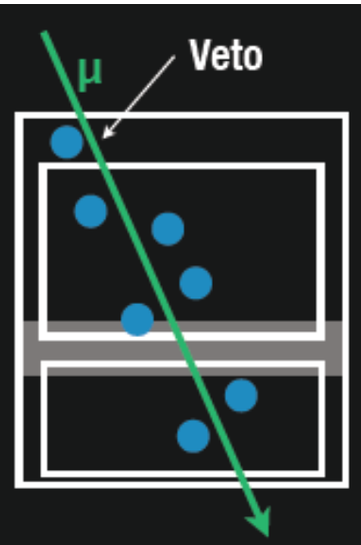
- very low statistics
- very low background

ν_τ



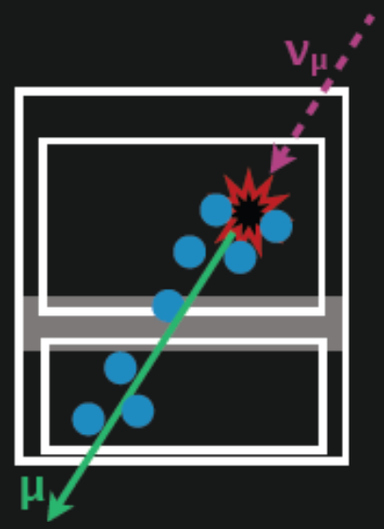


Neutrino induced showers and starting tracks…



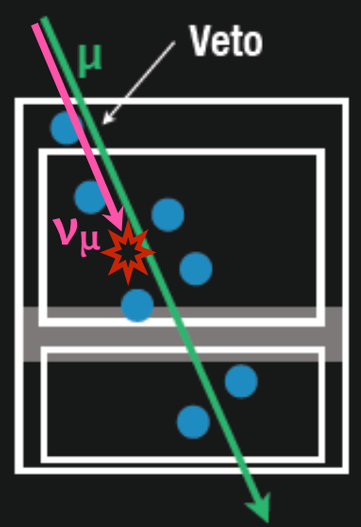
> **Atmospheric muons**

- Only from the surface (Southern hemisphere).
- Produce light in veto region.



> **Astrophysical neutrinos**

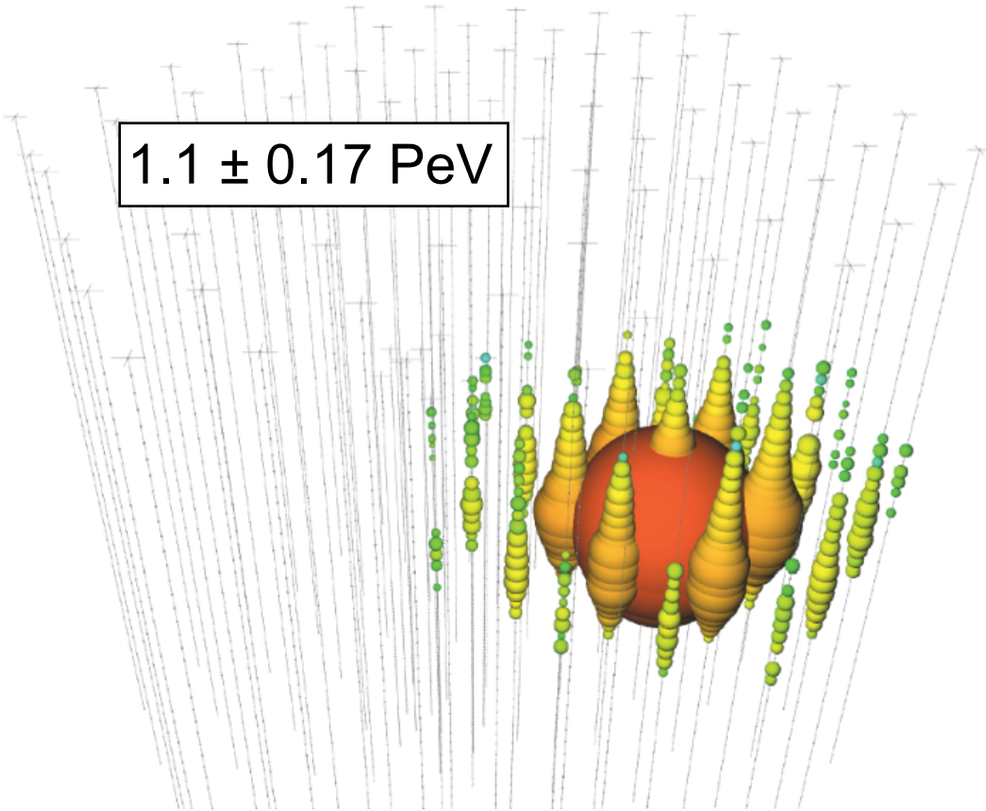
- No light in veto region.
- Compact shower or emerging track
- From both hemispheres.

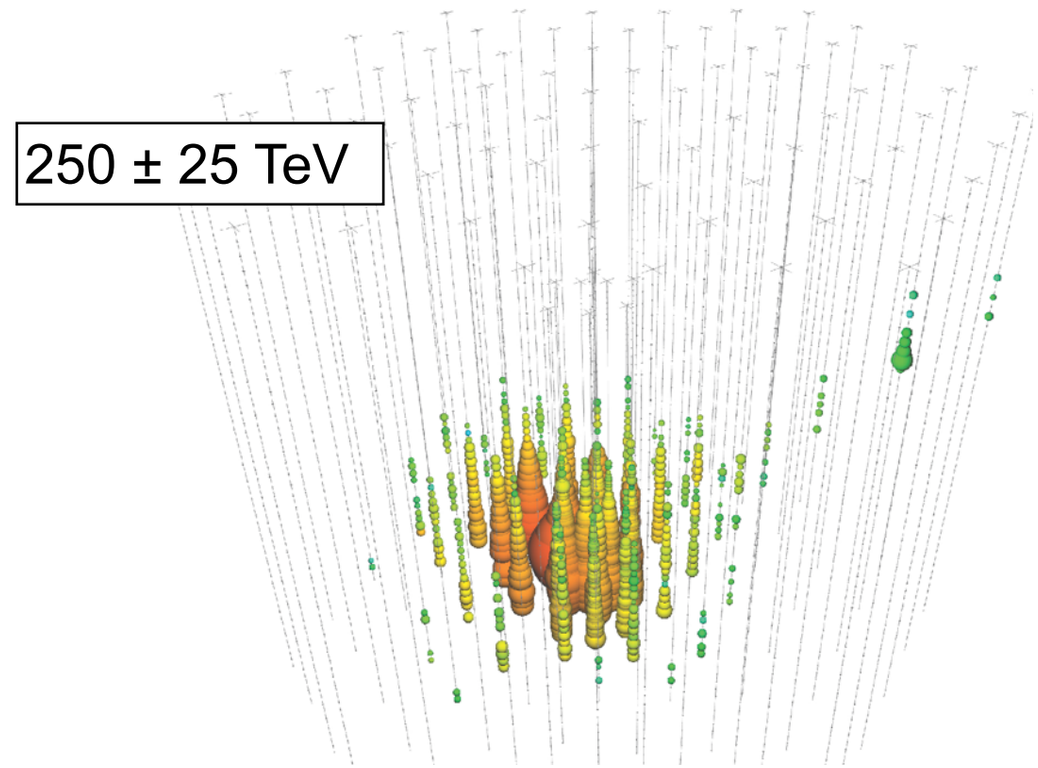


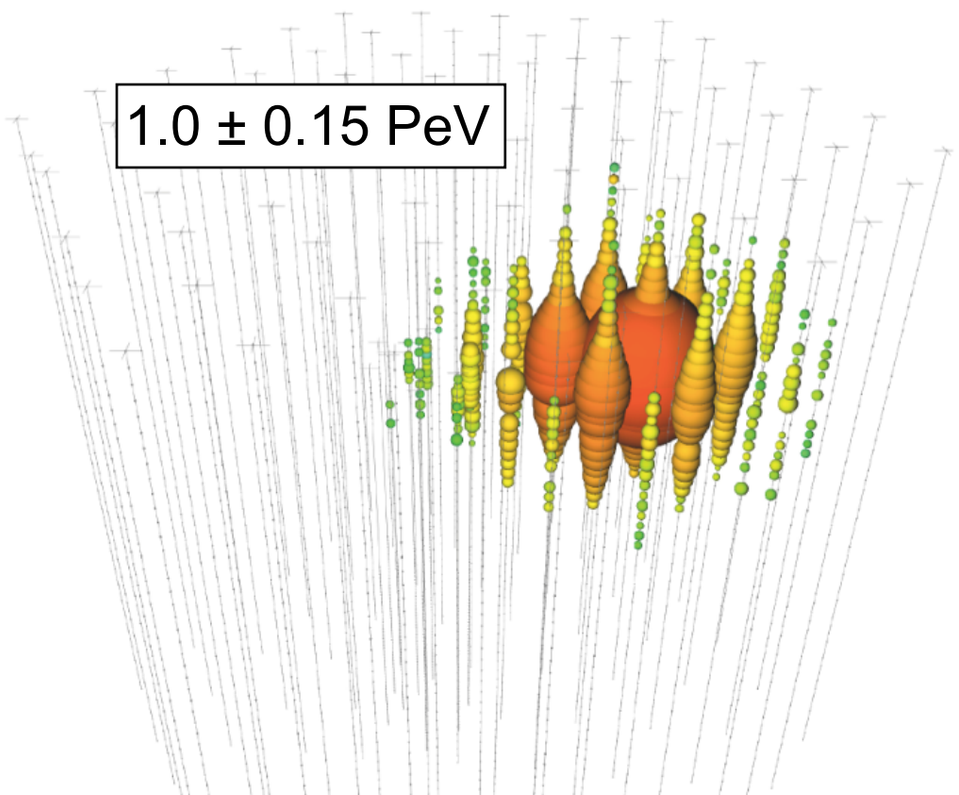
> **Atmospheric neutrinos**

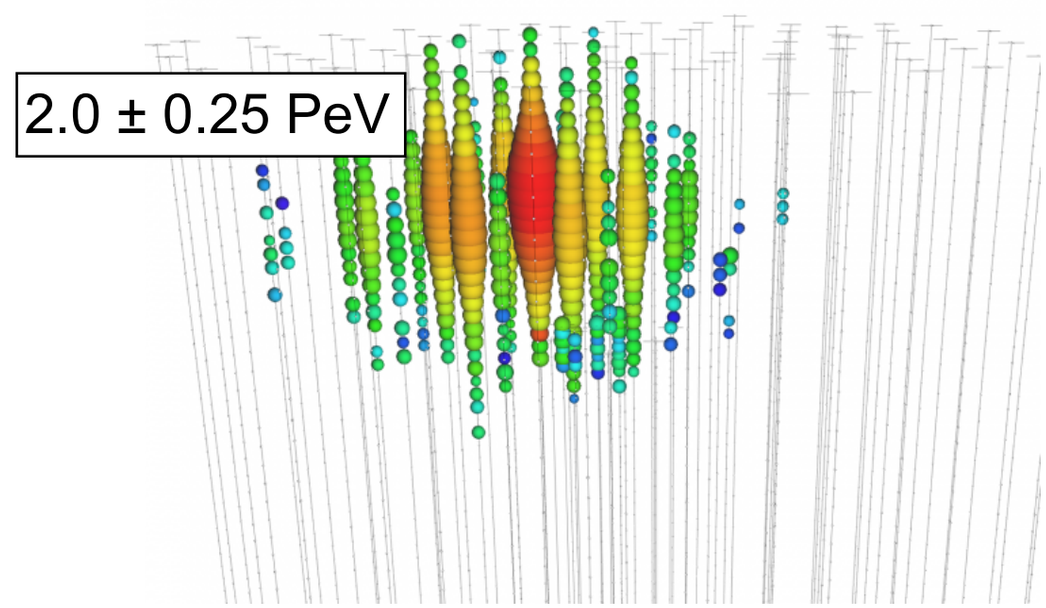
- likely accompanied by muon if produced by CR over the Southern hemisphere.
- Muon produces light in veto region

… lead to the discovery of cosmic neutrinos.

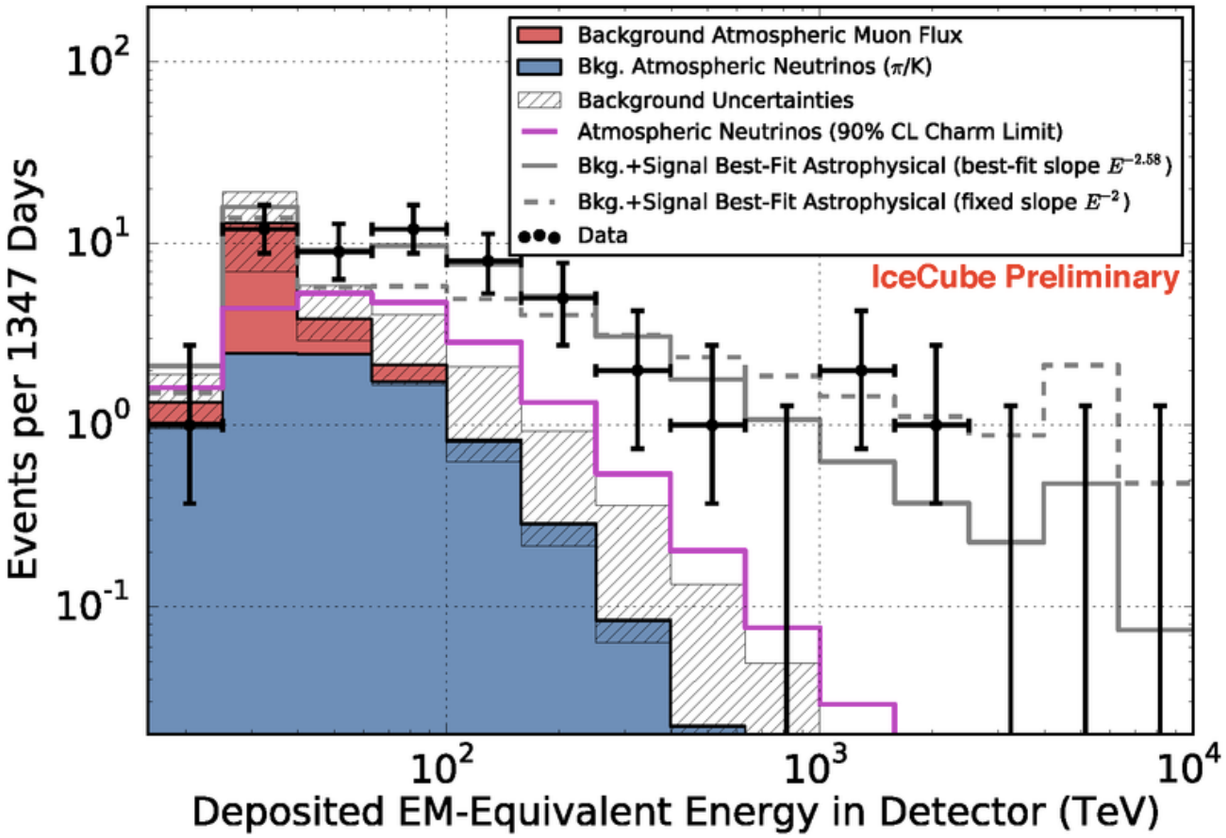


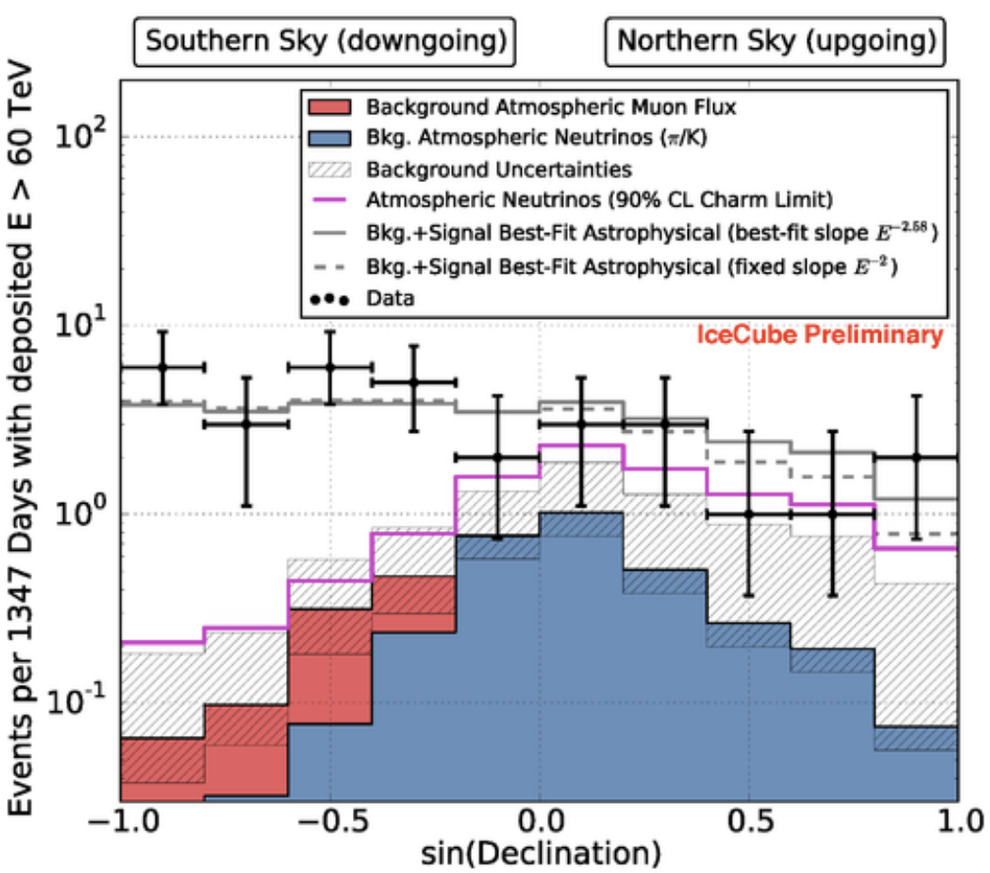






Observed events.

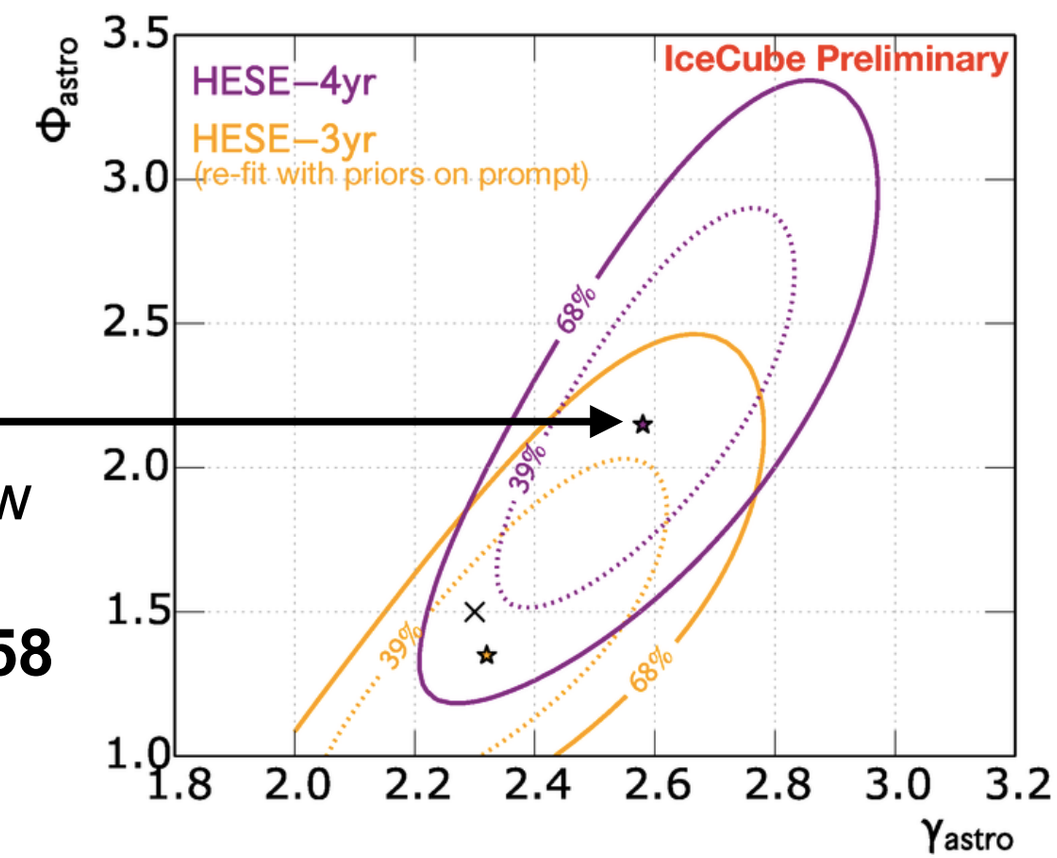




- **1347 days** observation time (May 2010 - Apr 2014)
- **54 events** above ~ 30 TeV energy detected.
- 3 events with energies **> 1 PeV**.
- >**5.7σ** statistical significance (we stopped counting…)

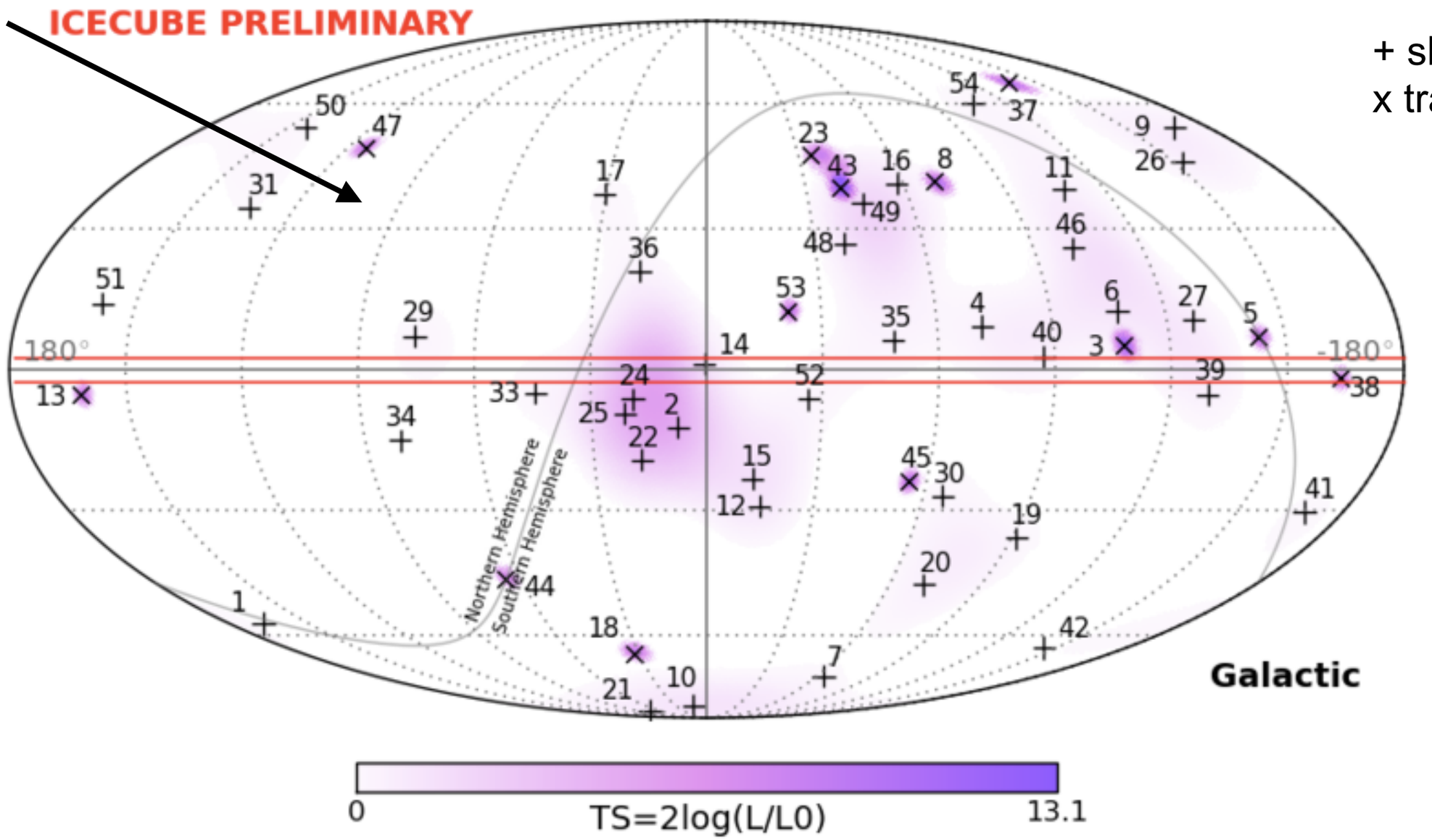
best-fit

power-law spectral index: **2.58**



Distribution on the sky.

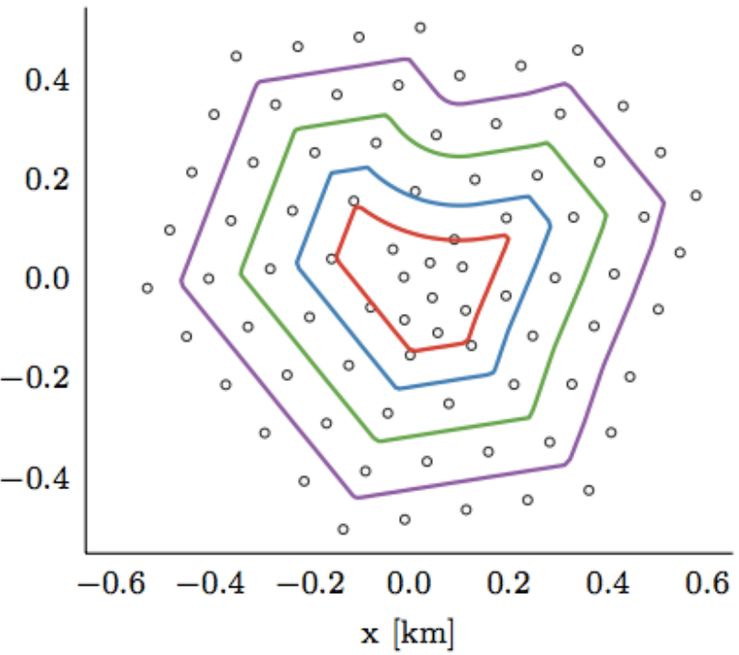
Earth absorbs ≳ 100 TeV neutrinos



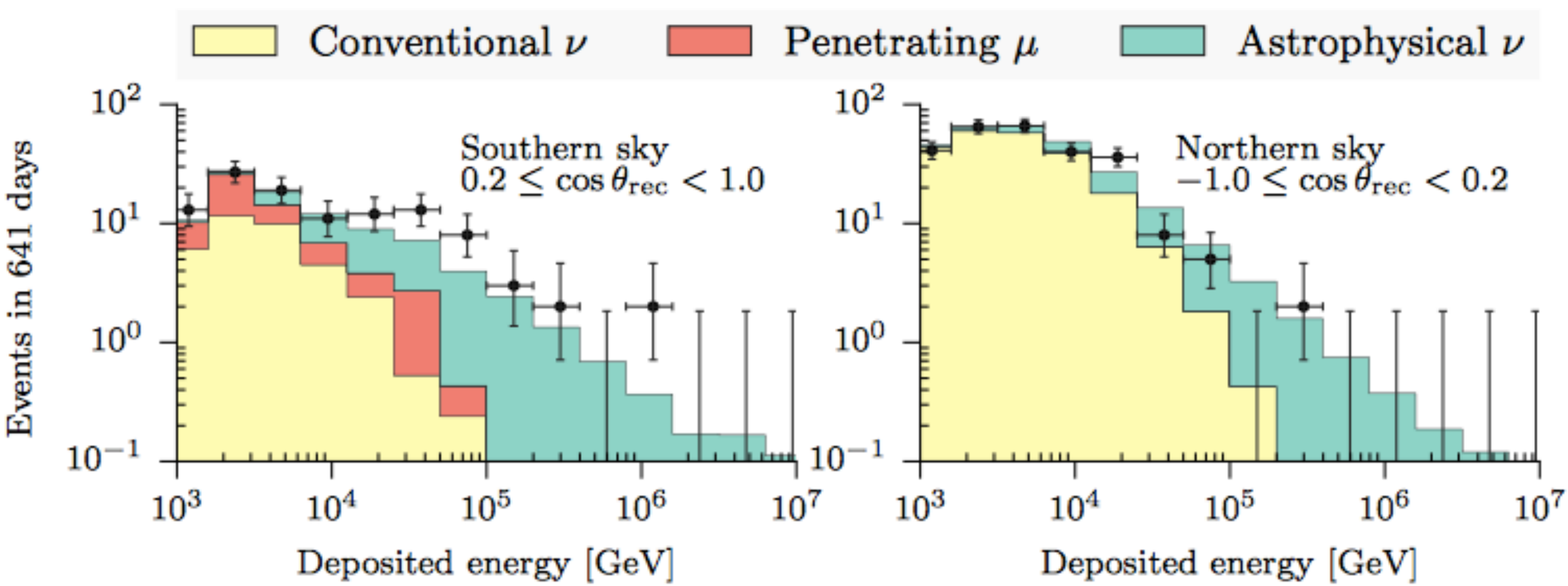
> Events from **high Galactic latitudes observed**.

> Event distribution is **compatible** with an **isotropic neutrino flux**.

Starting events at lower energies.

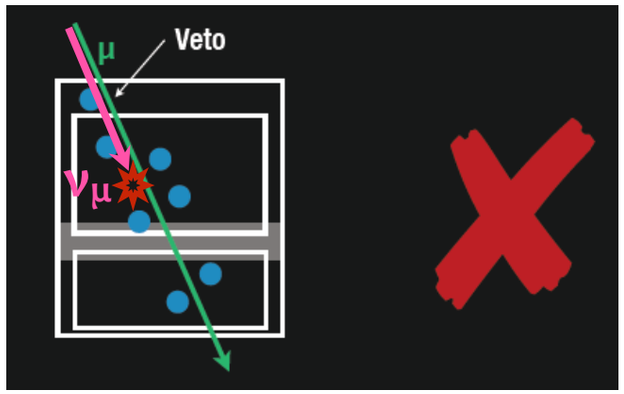


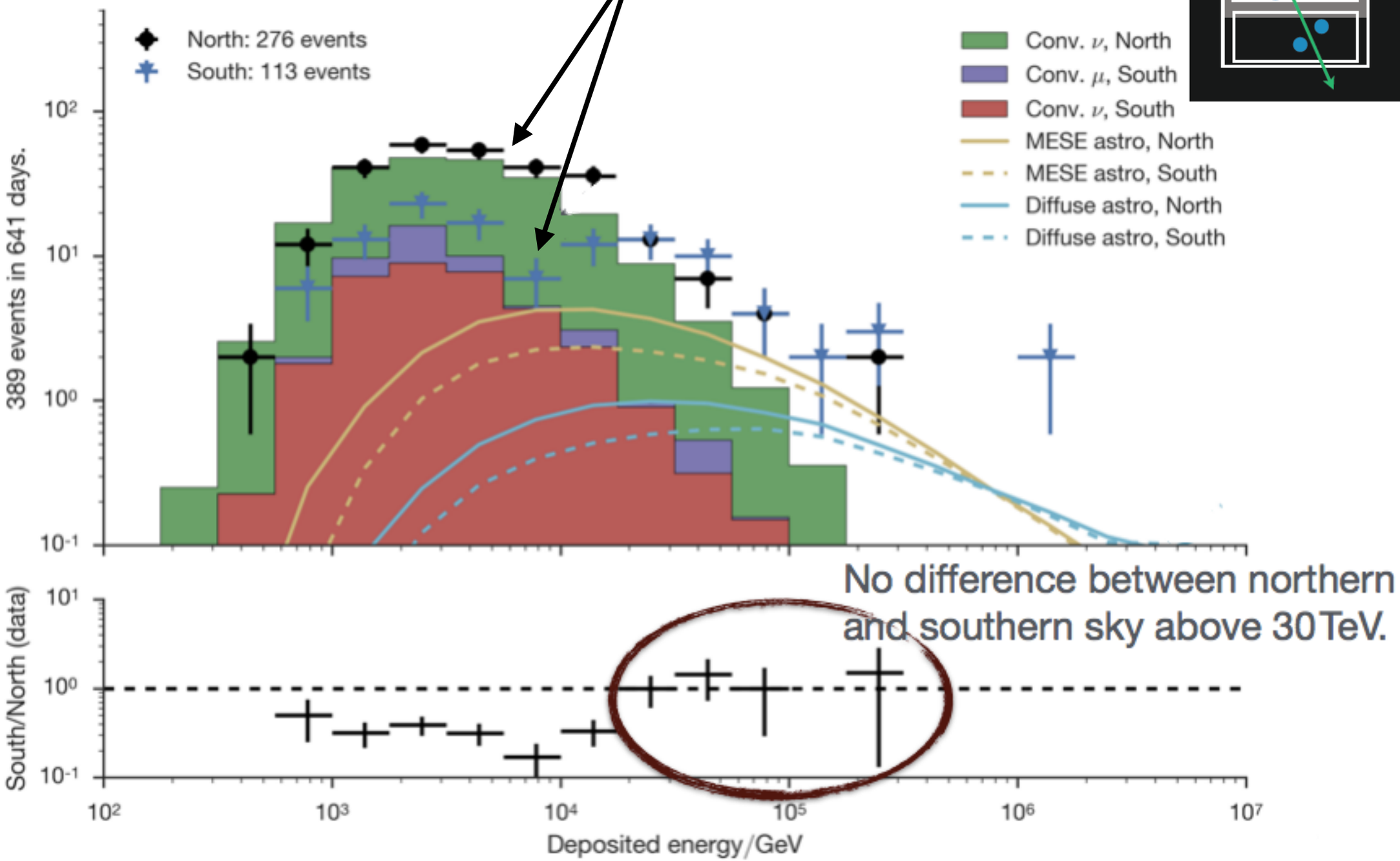
- Enlarge veto region to extend energy range below 30 TeV
- So far only applied to 2 years of IceCube data.
- Clear evidence for astrophysical neutrinos to energies ~ 10 TeV
- Best-fit spectral index: **2.5 ± 0.12**



Effects of the atmospheric neutrino veto.

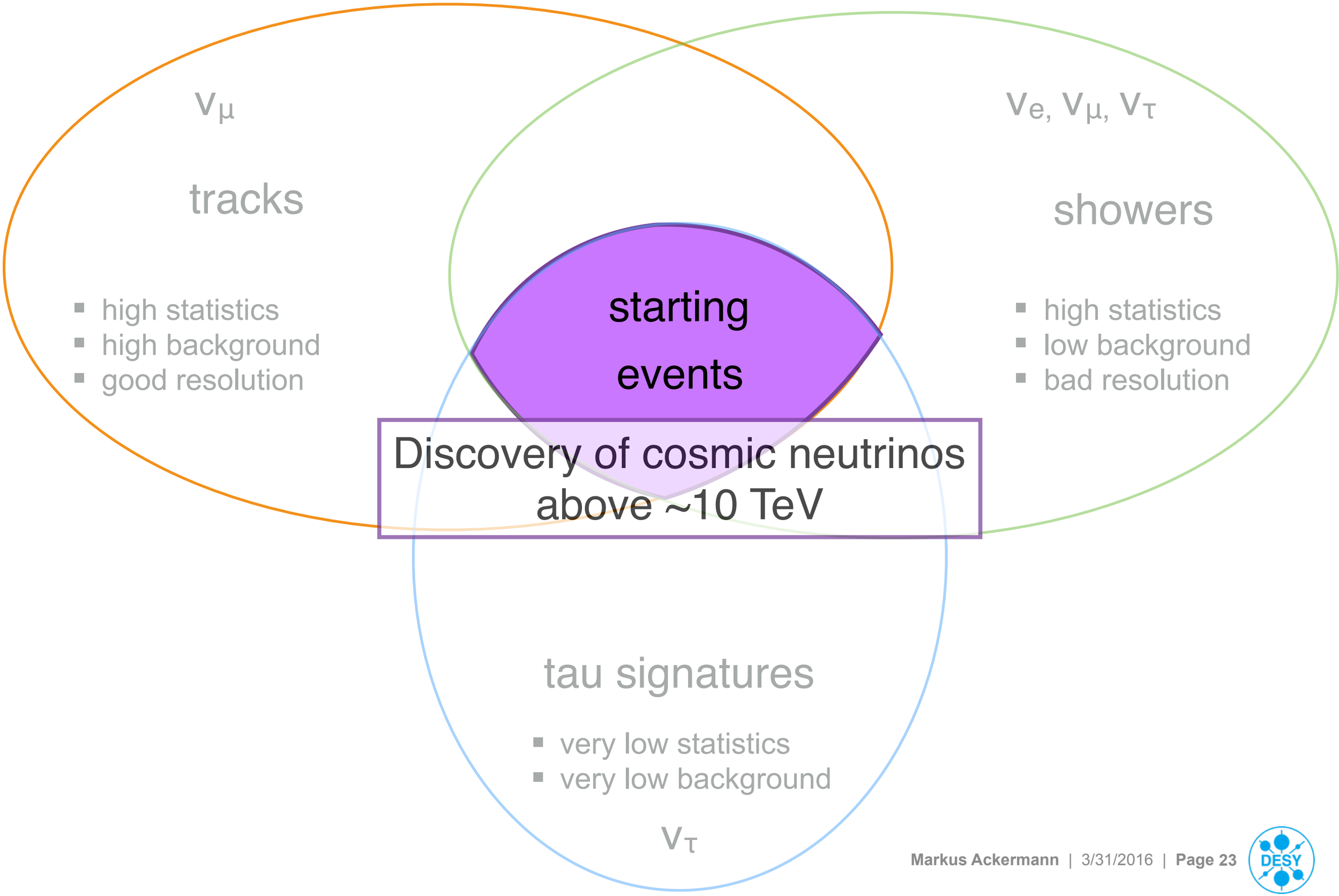
Background from Southern hemisphere suppressed
by self-veto of atmospheric neutrinos





No difference between northern
and southern sky above 30 TeV.

The golden channel: Starting events



More statistics: Contained / non-contained shower events

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

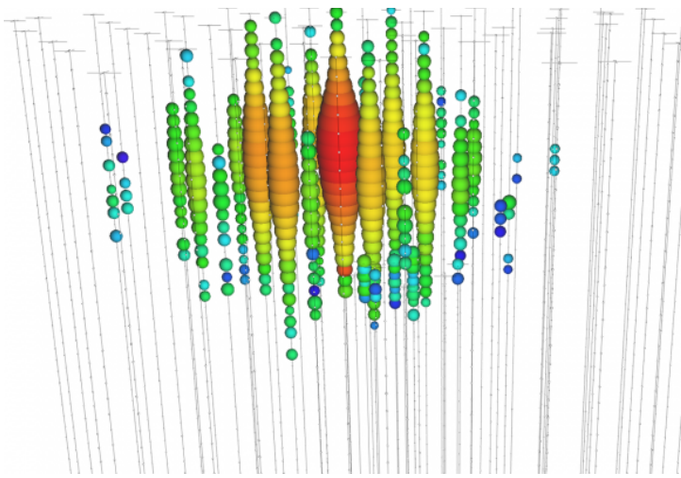
- high statistics
- low background
- bad resolution

starting events

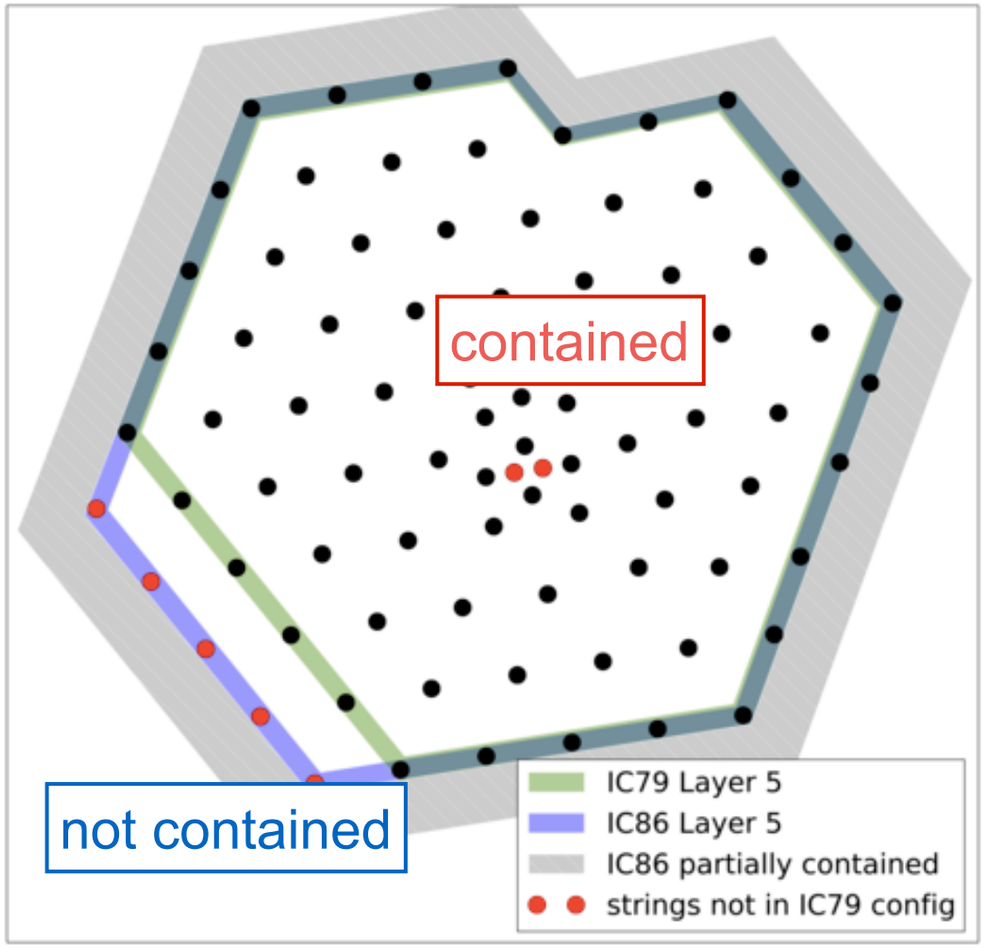
tau signatures

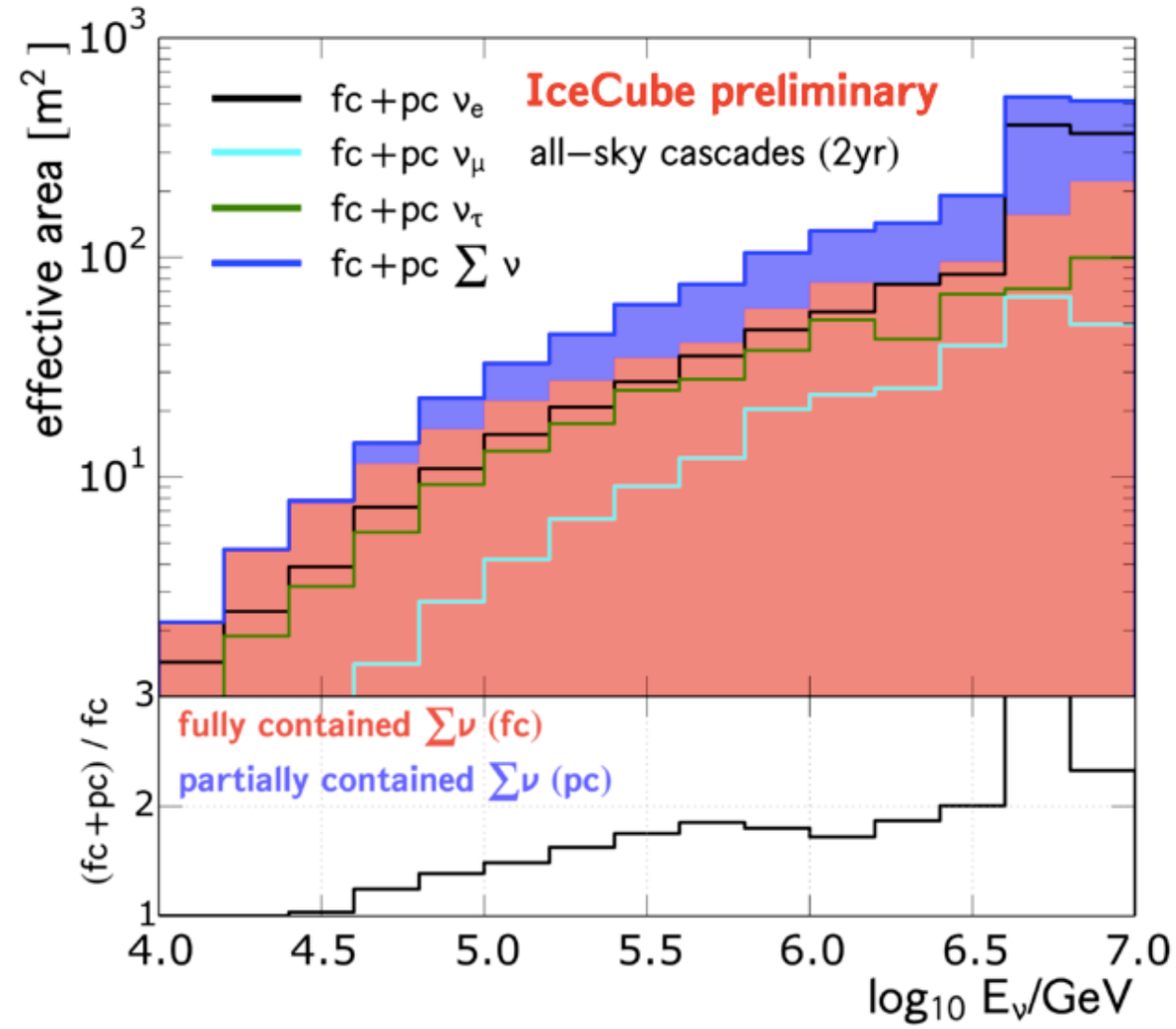
- very low statistics
- very low background

ν_τ

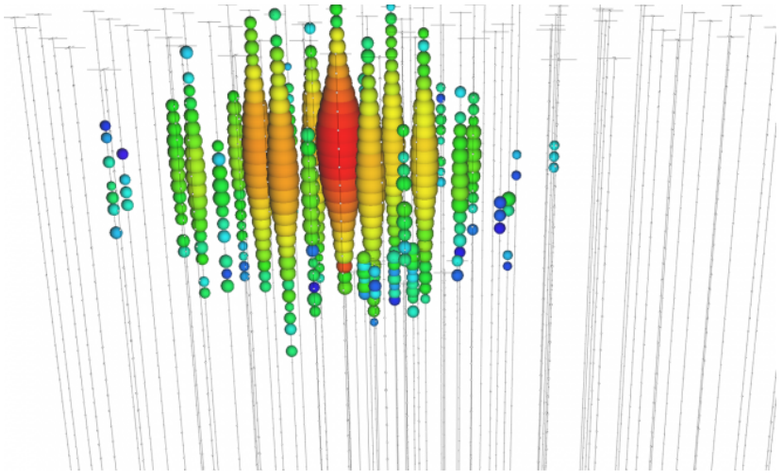


Shower events

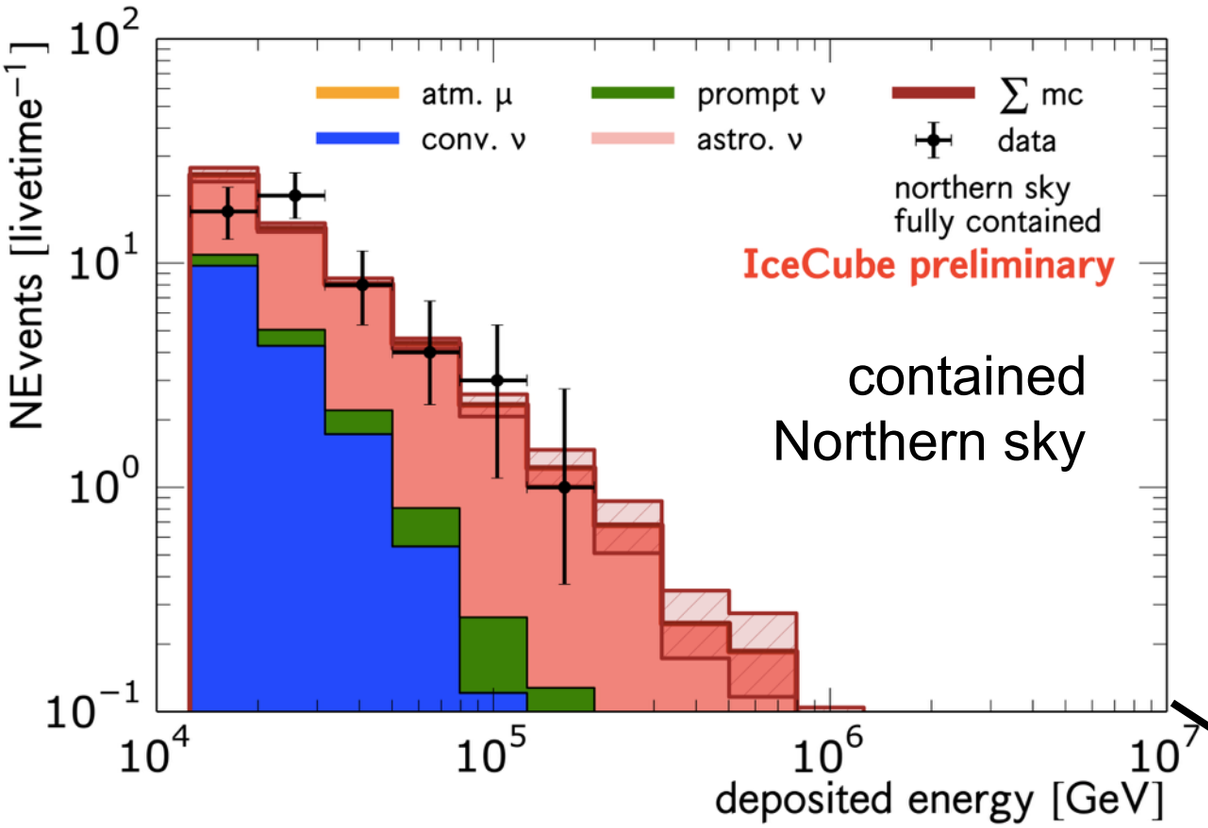


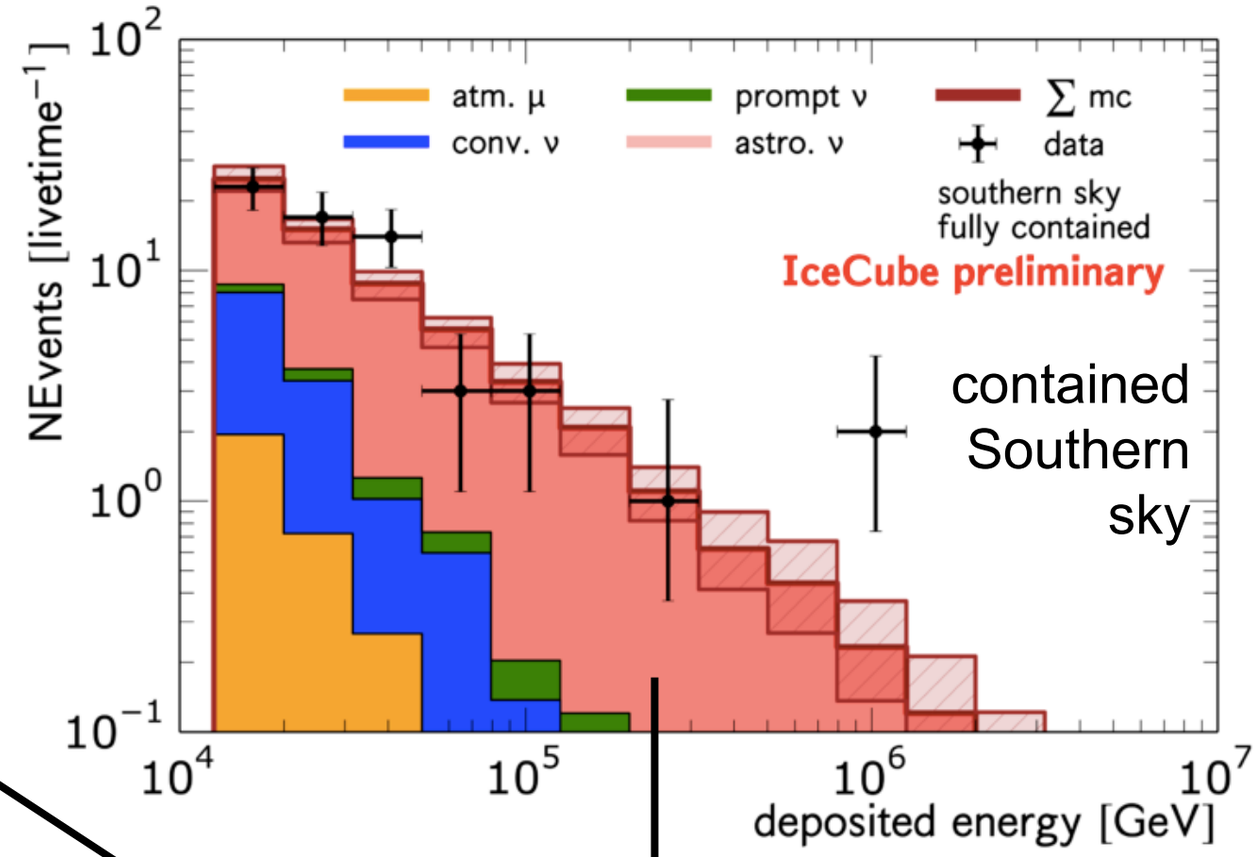


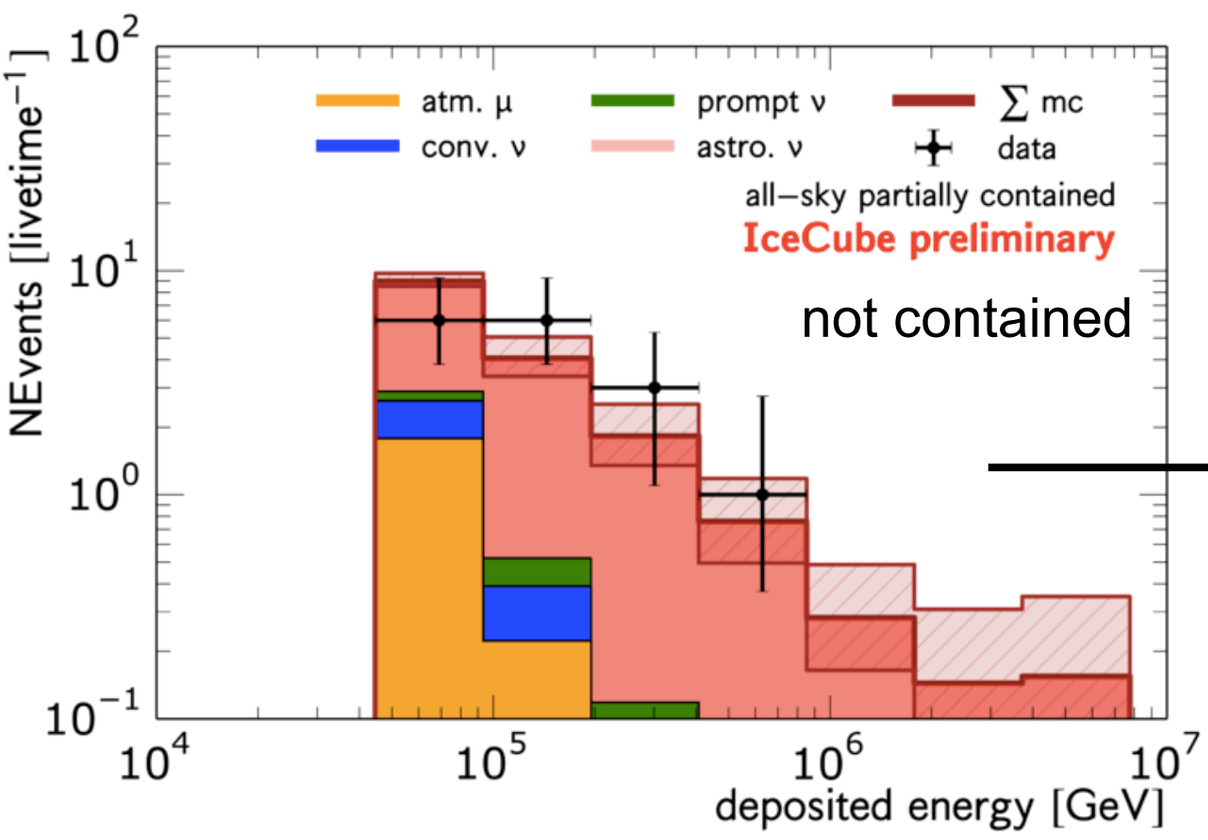
- Showers can be selected based on their **spherical light patterns**
- About **factor of 2 gain** in effective area above 300 TeV
- ~ 60% more events below ~ 100 TeV
- Accurate background simulation required.

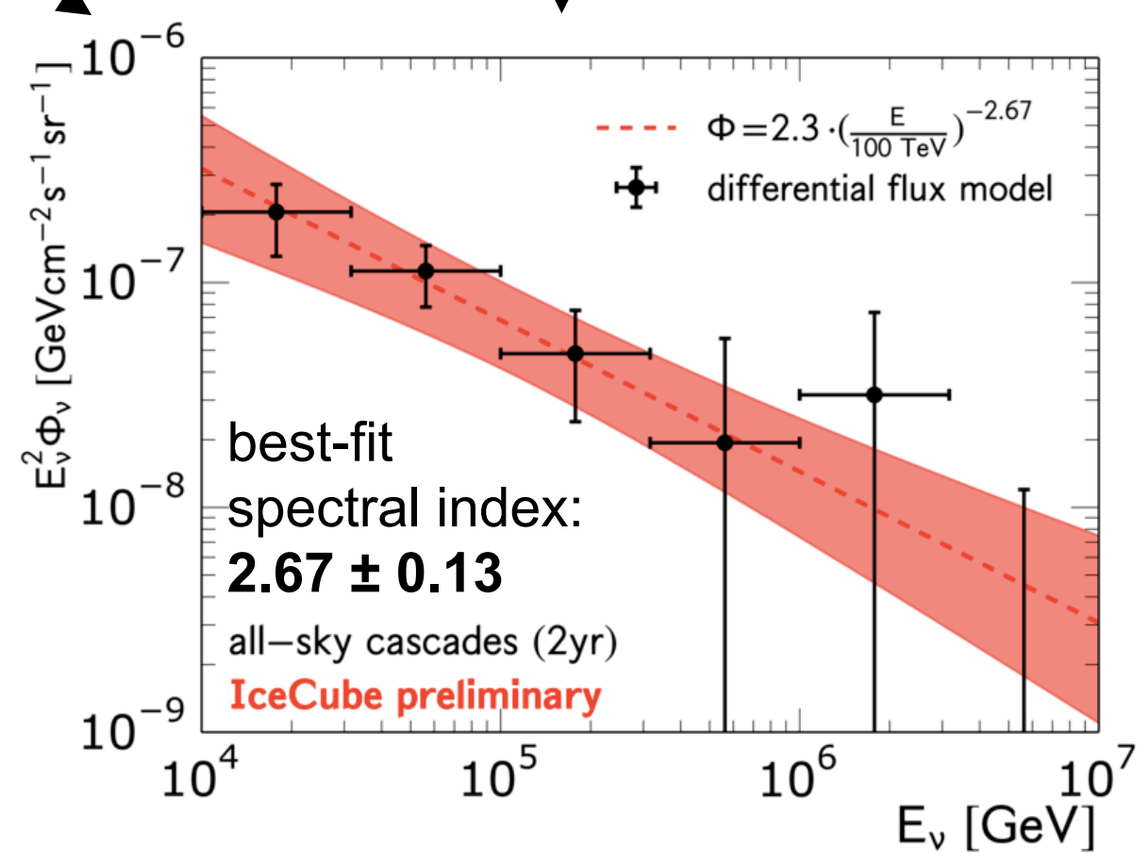


Shower events in two years of IceCube data.









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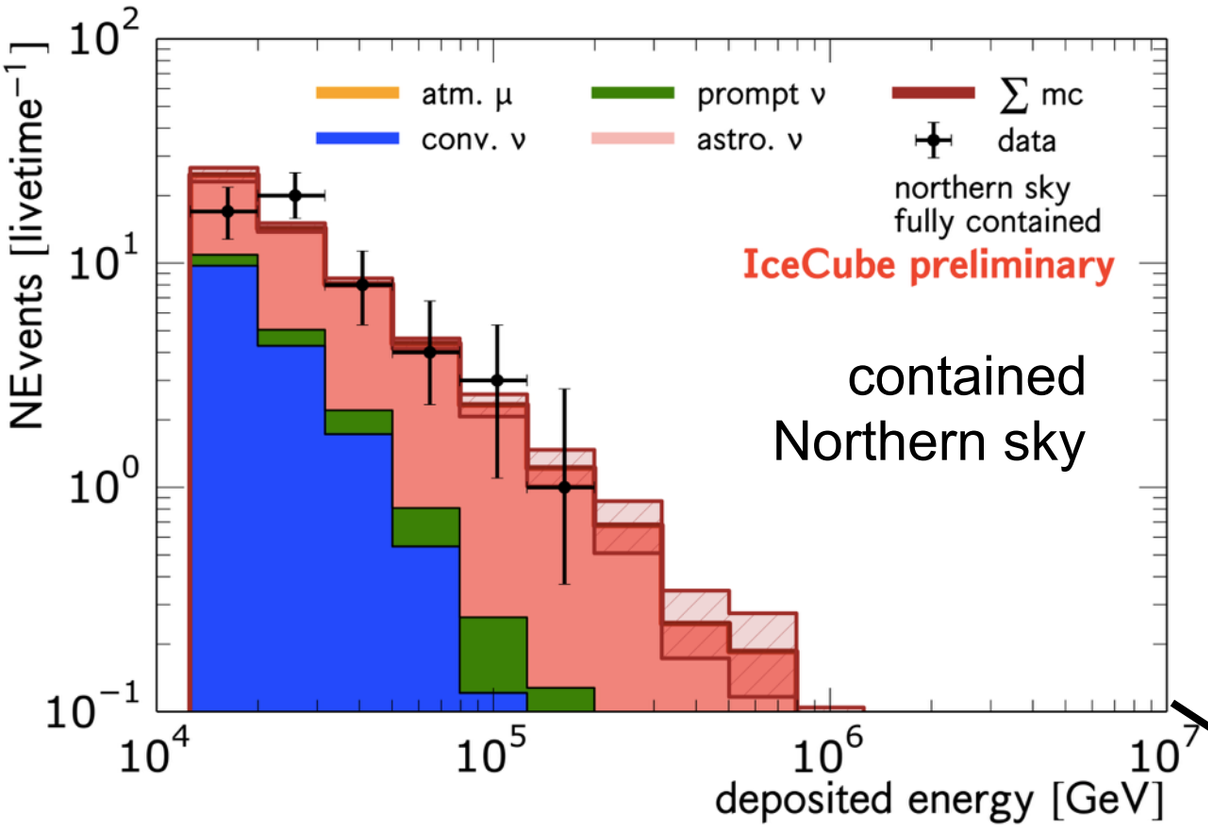

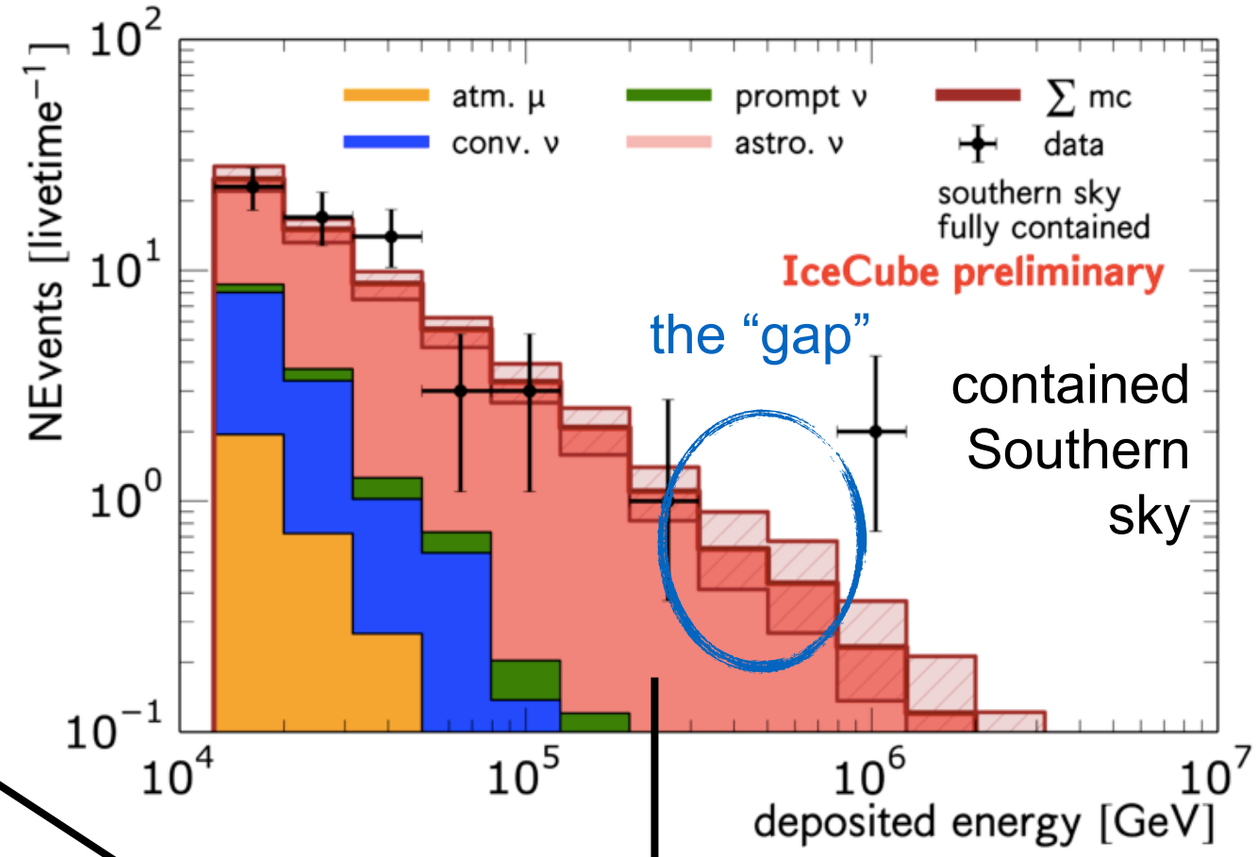

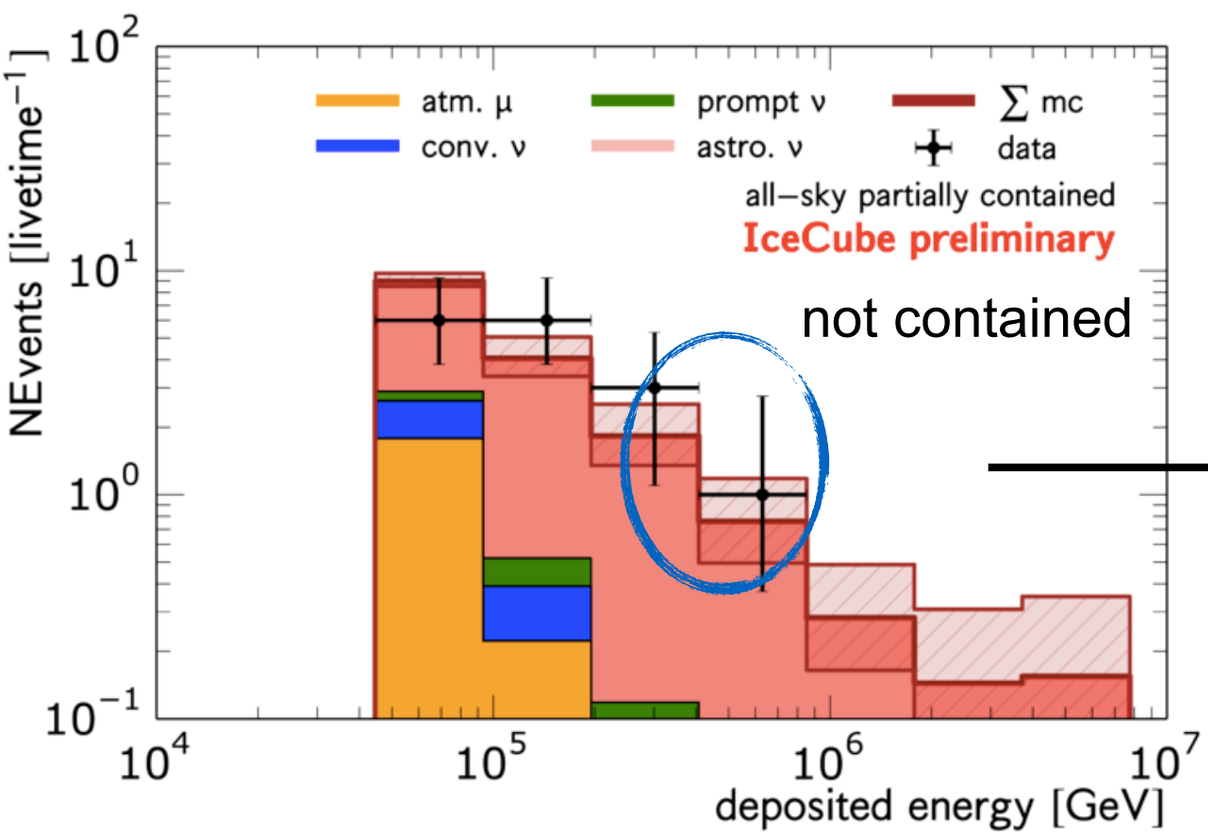

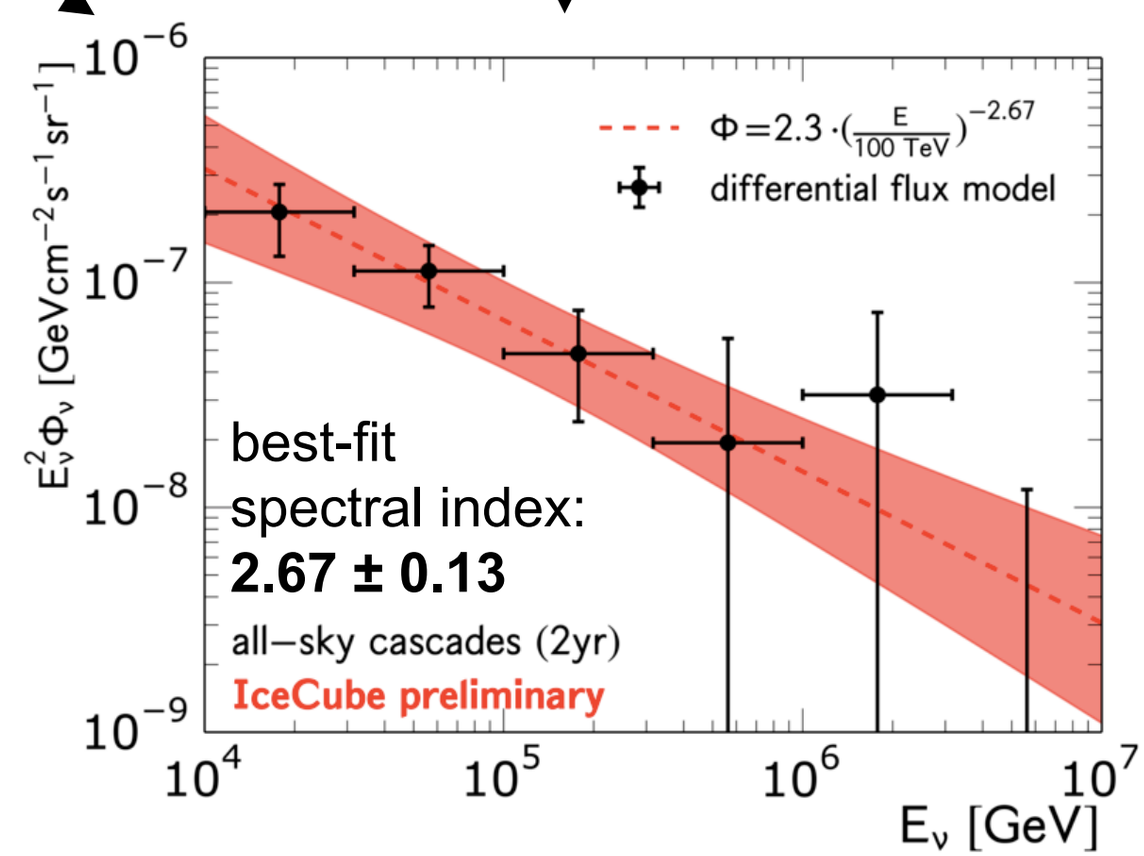

More statistics: Contained / non-contained shower events

ν_μ

tracks

- high statistics
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- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

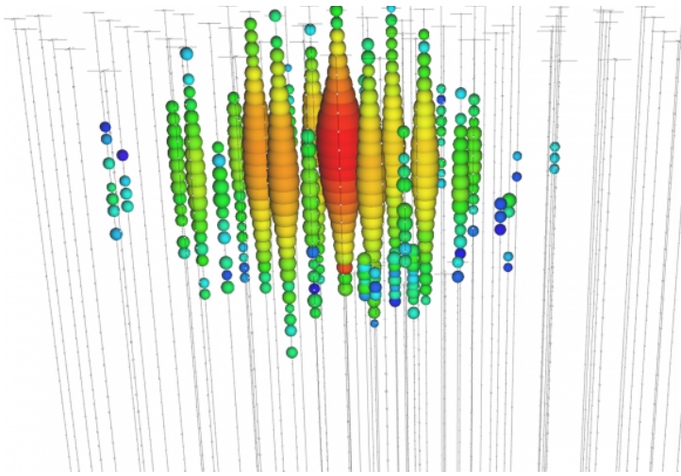
starting events

tau signatures

- very low statistics
- very low background

ν_τ

Confirmation of soft spectrum below 100 TeV
No spectral “gap” at few hundred TeV



The classic neutrino signature: tracks

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
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starting events

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- very low statistics
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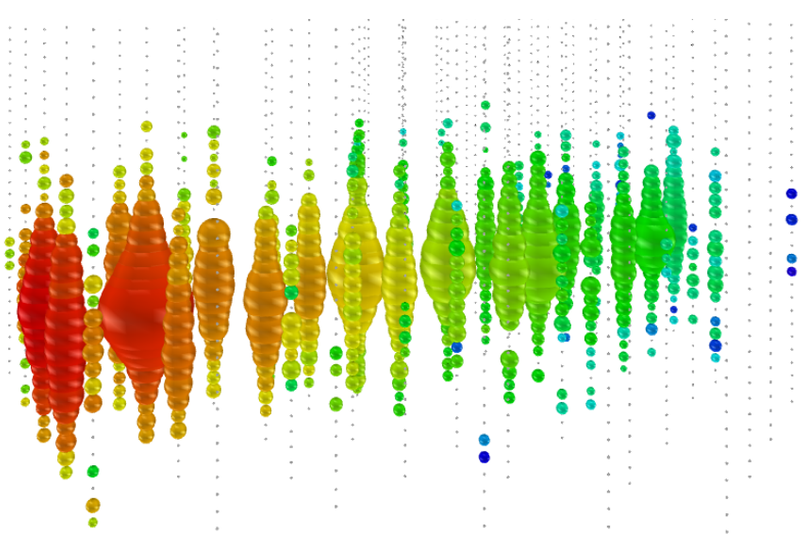
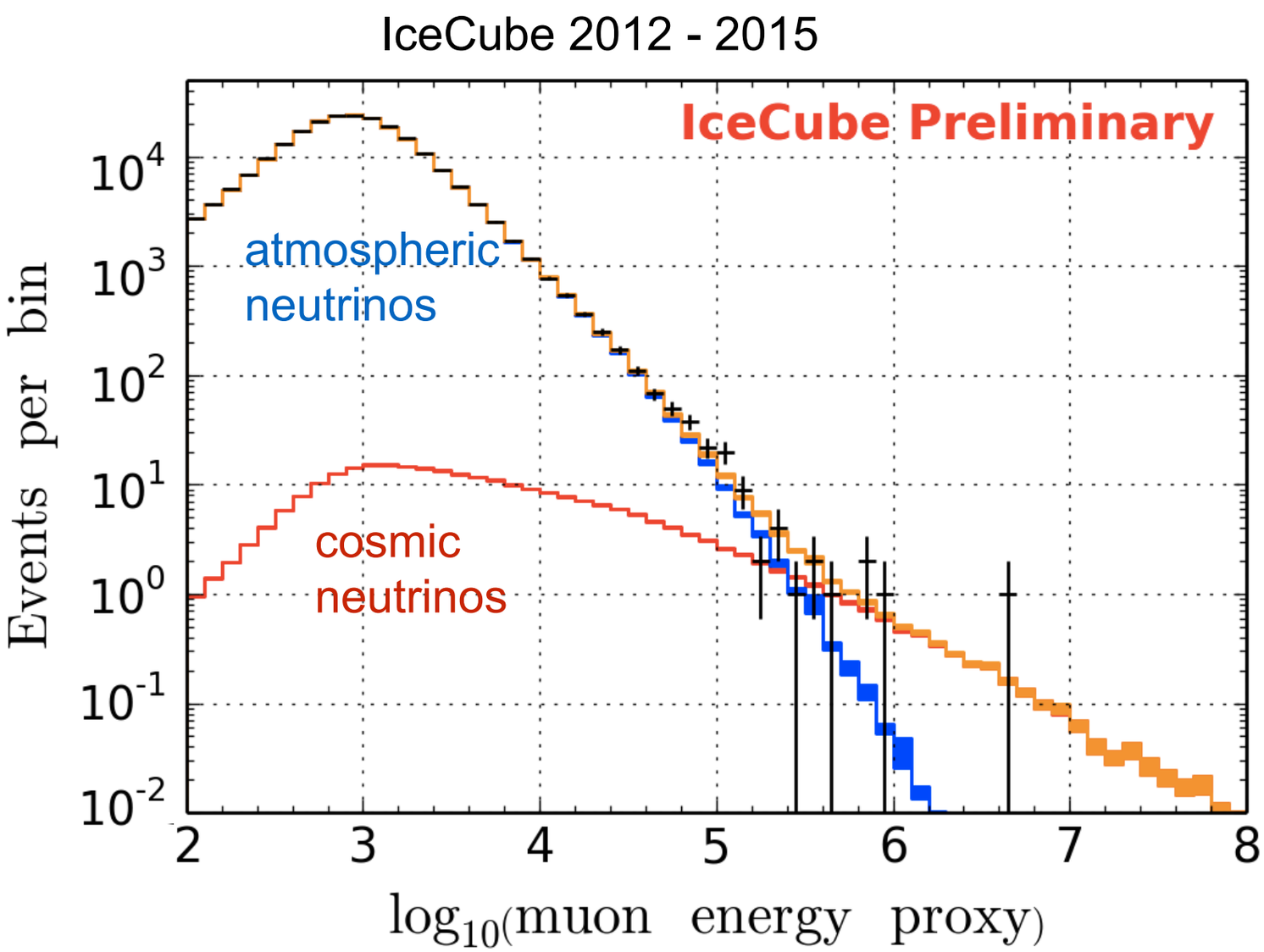
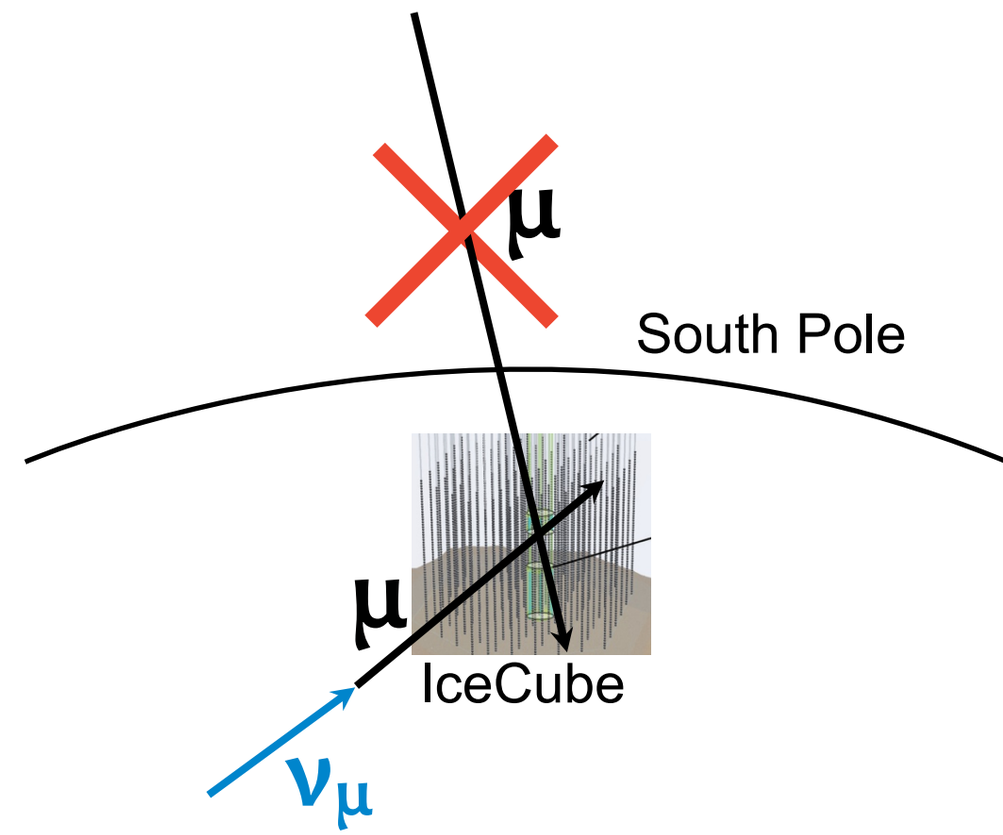
ν_τ



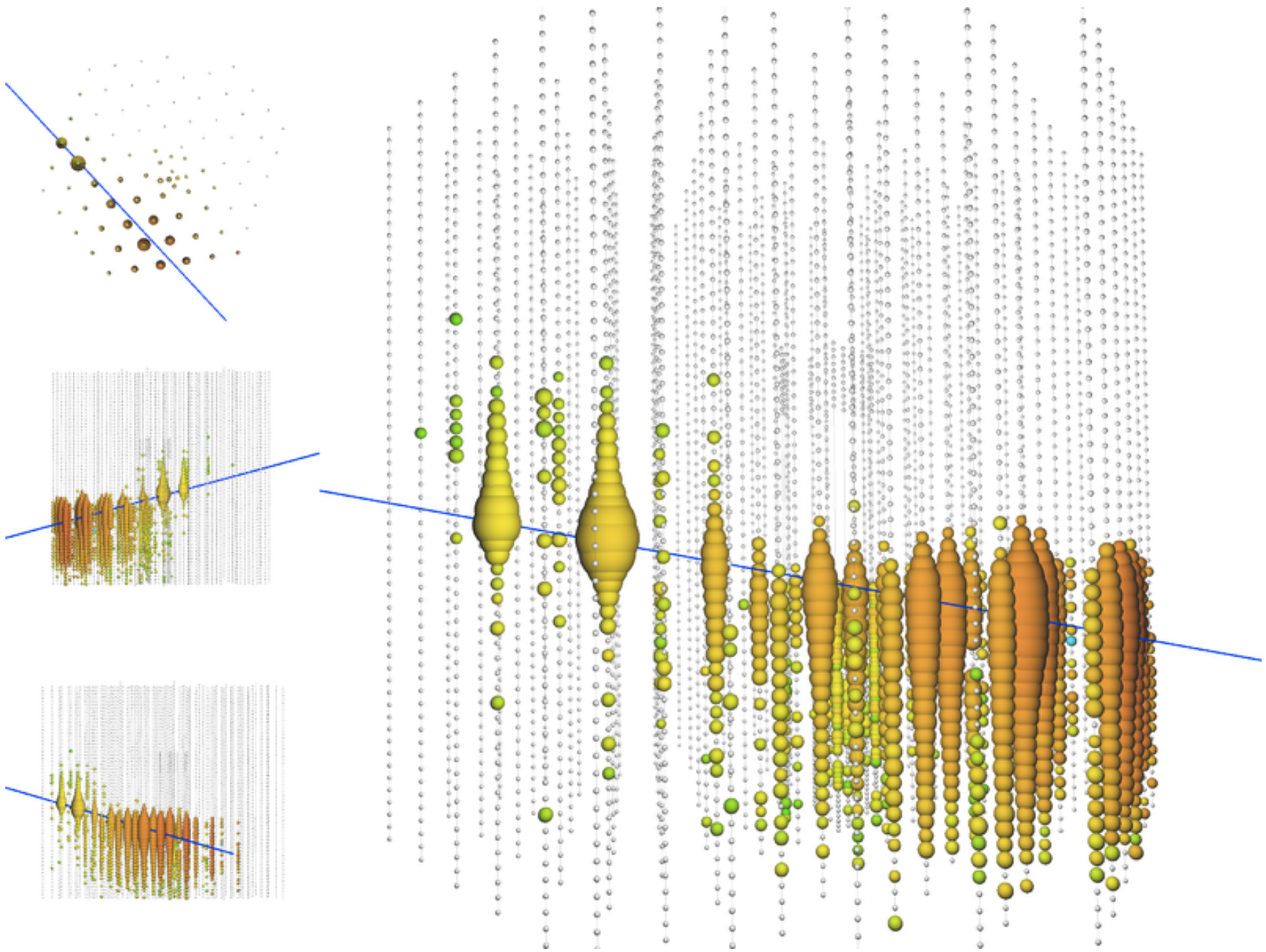
Search for high-energy through-going tracks





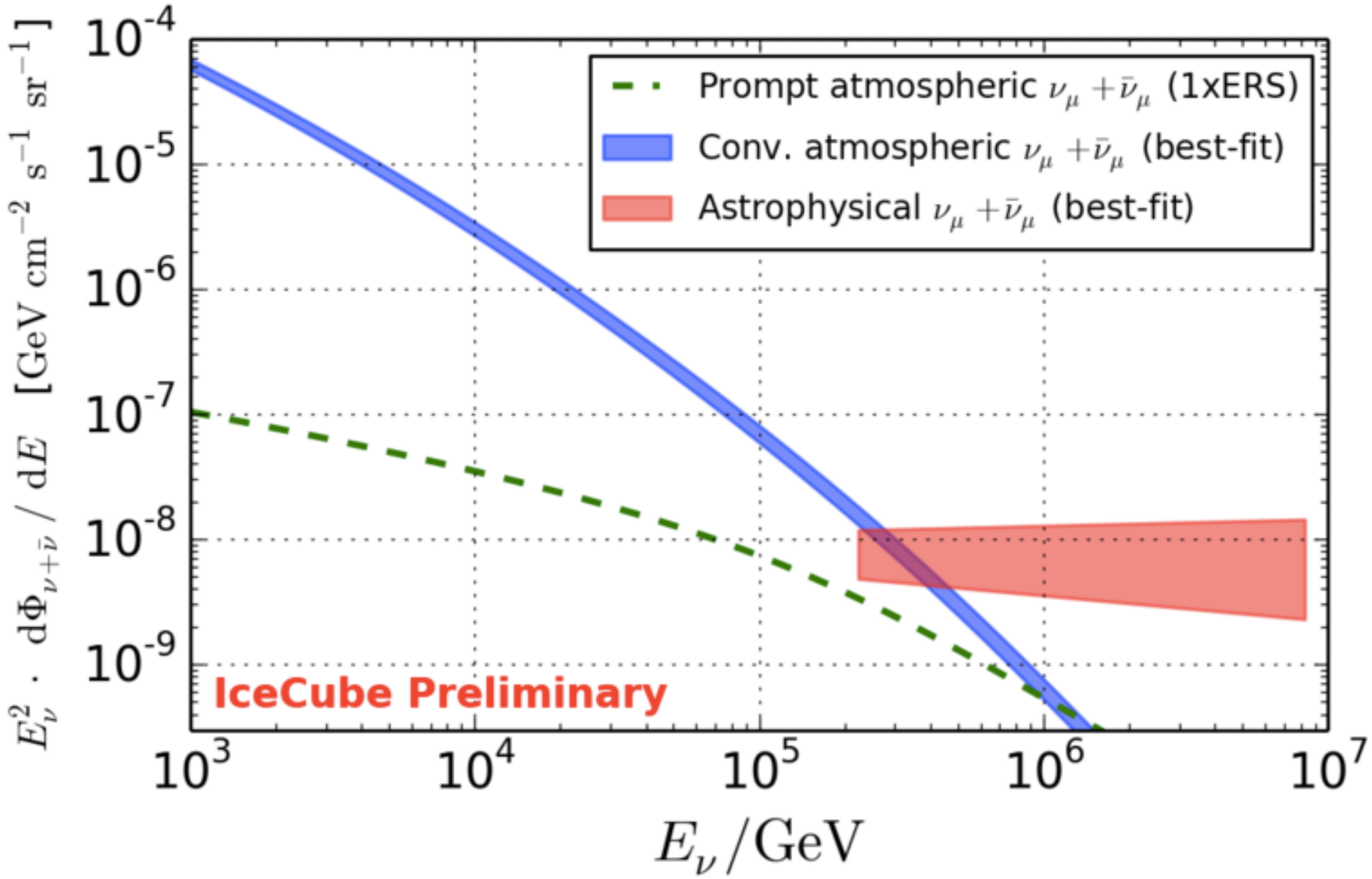
- Search for high-energy excess in 6 years of IceCube muon track data.
- Use low-energy atmospheric neutrino data to fit uncertainties in background.
- **Only Northern hemisphere**!

The highest energy neutrino observed so far….



- **2.6 ± 0.3 PeV** deposited in detector.
- Angular uncertainty: **0.27°**
- Probability for atmospheric origin: **<0.01%**

Spectral fit of through-going track sample.



- A **hard spectrum** is preferred by the muon-track data.
- Best fit spectral index: **2.08 ± 0.13**
- But **energy range is different** than for starting event / shower analyses.

The classic neutrino signature: tracks

ν_μ

tracks

- high statistics
- high background
- good resolution

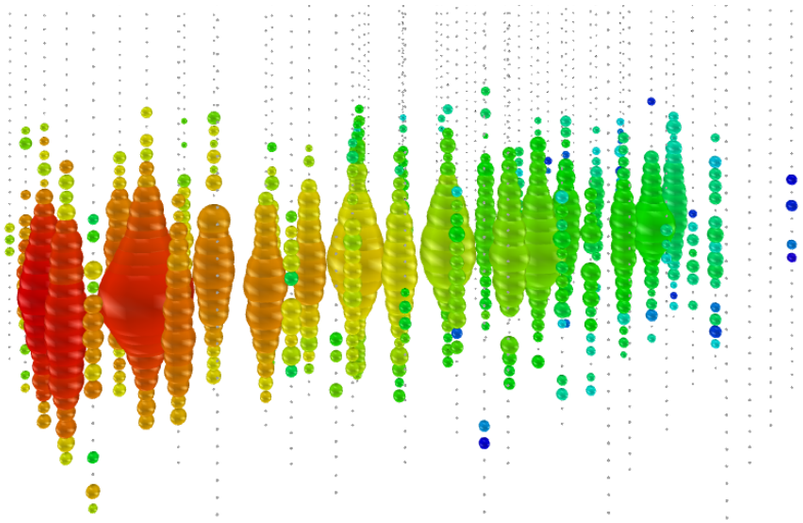
ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

starting events

Indications of a harder spectrum above few hundred TeV



tau signatures

- very low statistics
- very low background

ν_τ

High energy tau neutrinos

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

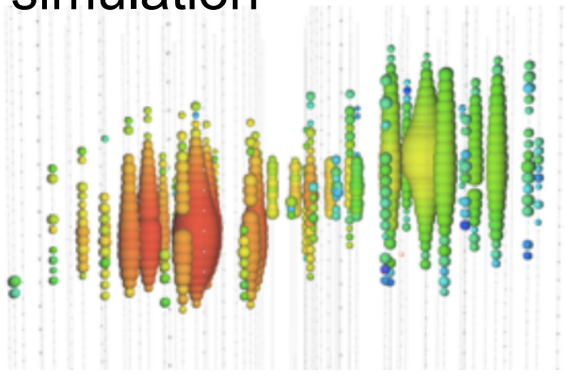
starting events

tau signatures

- very low statistics
- very low background

ν_τ

simulation



Search for tau neutrino signatures

Data samples	Events in 914.1 days (final cut)
Astrophysical ν_τ CC	$(5.4 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_μ CC	$(1.8 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_e	$(6.0 \pm 1.7) \cdot 10^{-2}$
Atmospheric ν	$(3.2 \pm 1.4) \cdot 10^{-2}$
Atmospheric muons	$(7.5 \pm 5.8) \cdot 10^{-2}$

Aartsen et al., submitted to PRD.

> 3 years of IceCube data analyzed

> **0.54** cosmic tau neutrinos **expected**, **none observed**

High energy tau neutrinos

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

starting events

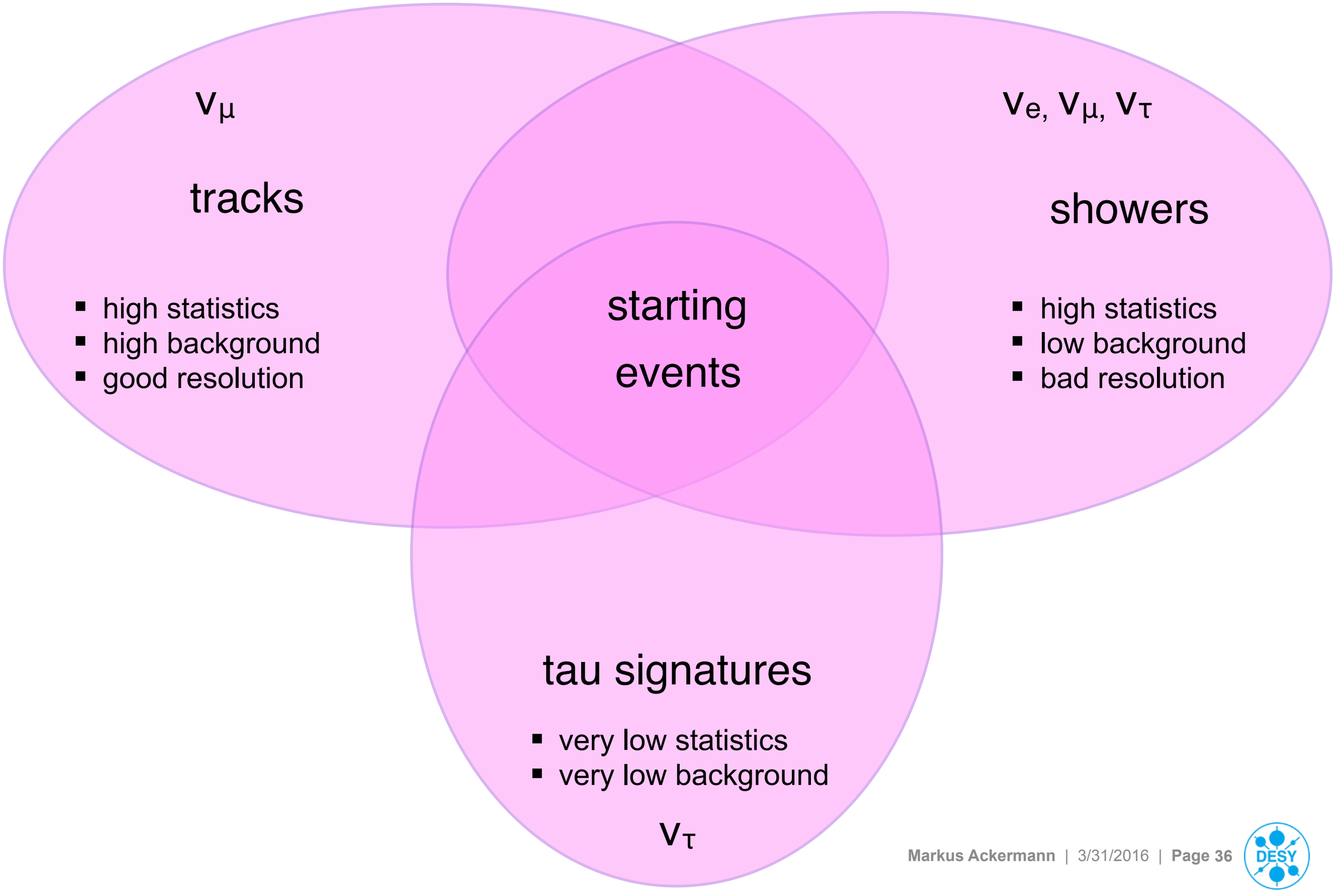
Non-observation compatible with expectations
Need more data !

tau signatures

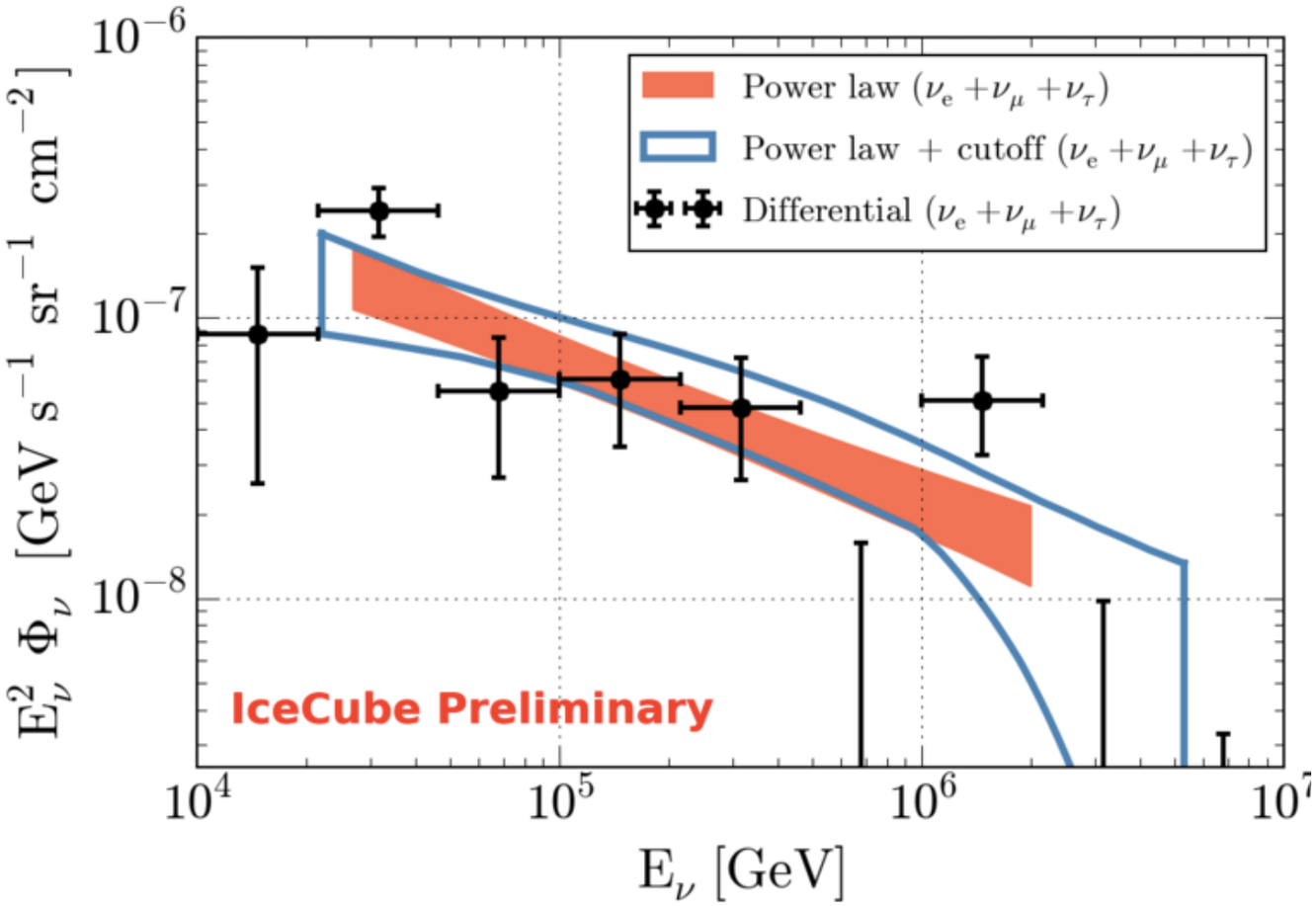
- very low statistics
- very low background

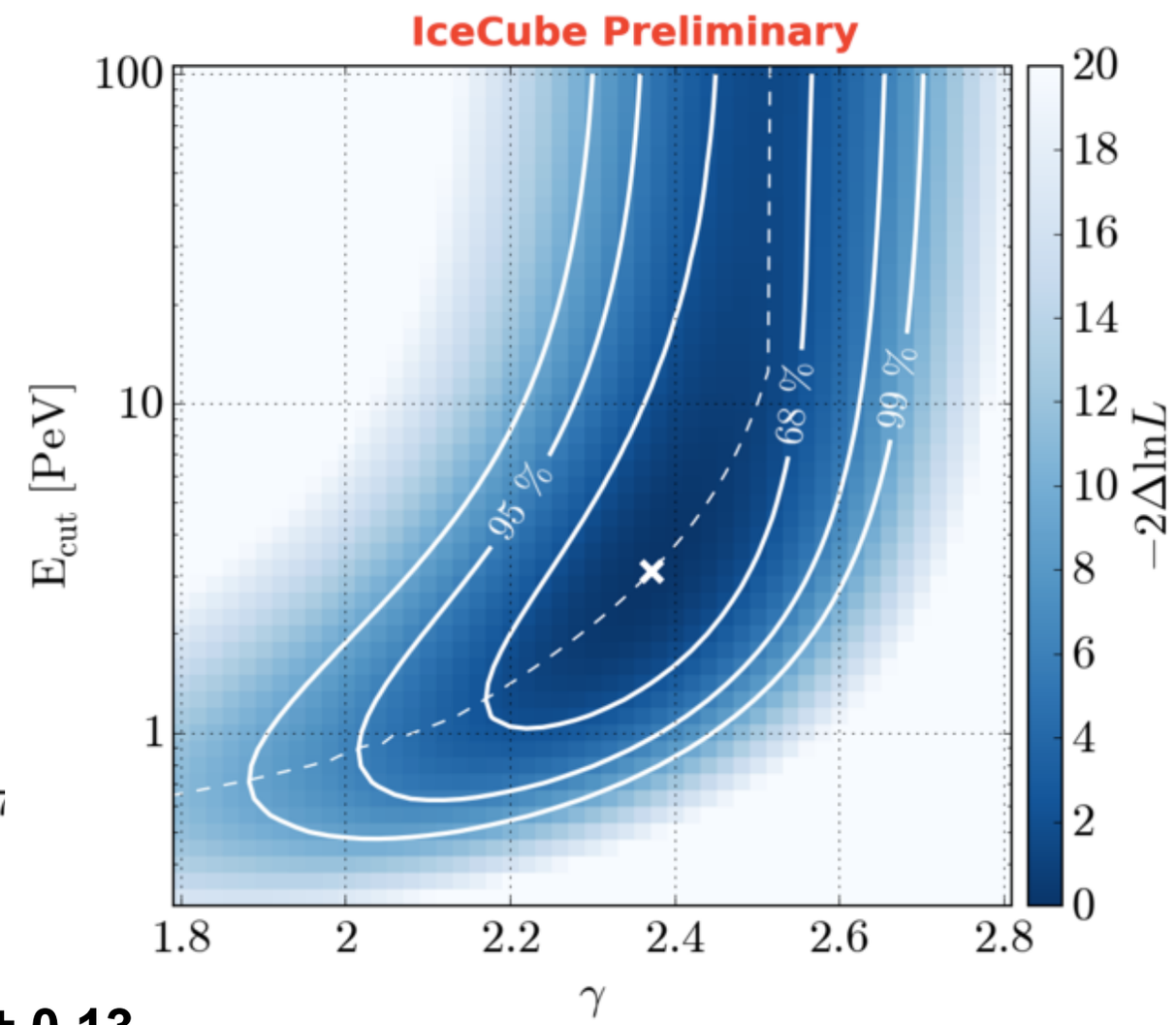
ν_τ

The global fit.



Best fit astrophysical neutrino spectrum using all channels

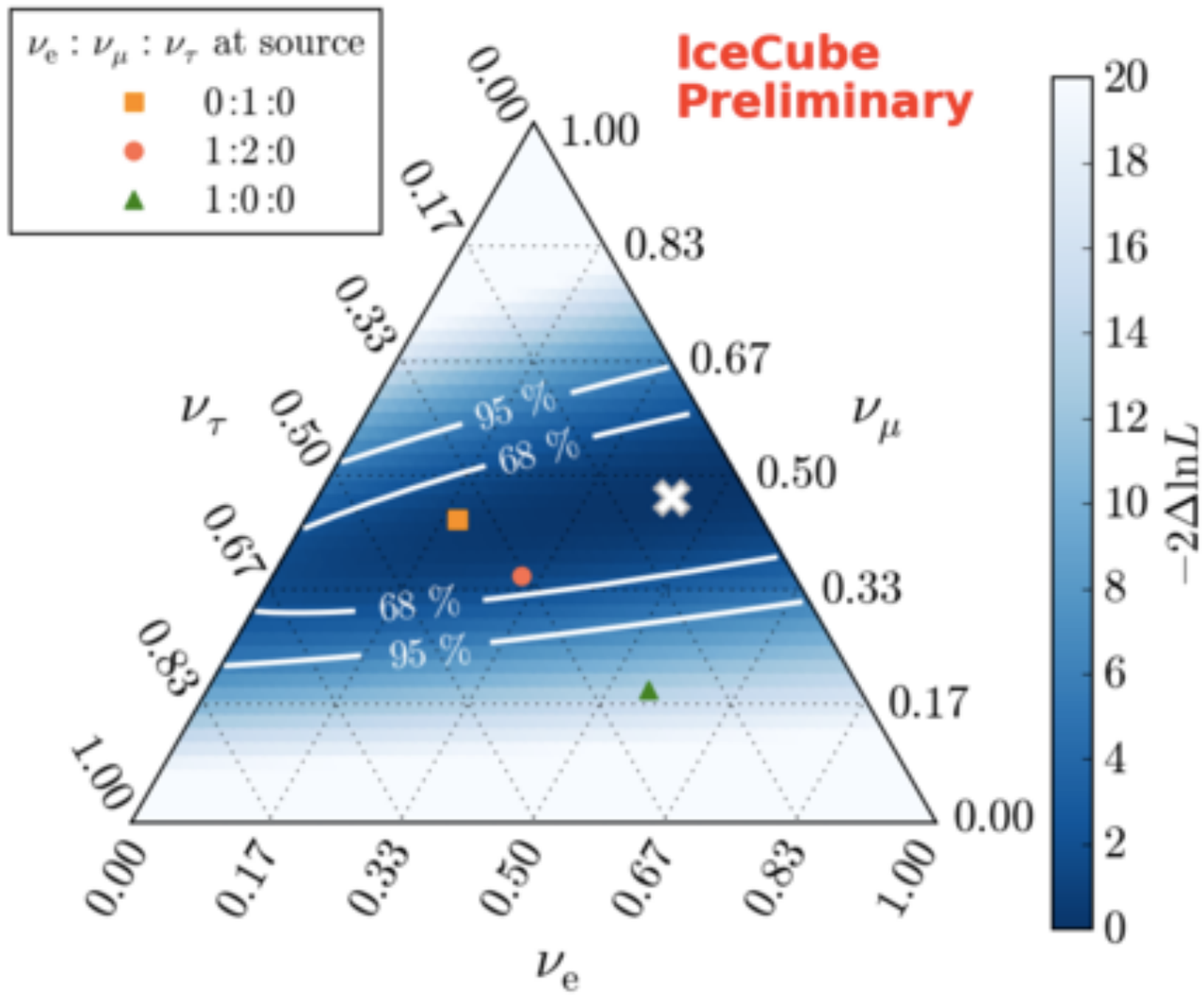




spectral index: **2.52 ± 0.07** or spectral index: **2.37 ± 0.13**
cutoff energy: **3.1 PeV**

- **Combines** starting event, shower, track and tau **channels**.
- Does only contain **3 years of through-going track** data !
- Simple power law spectrum and power law + cutoff both compatible with IceCube data.

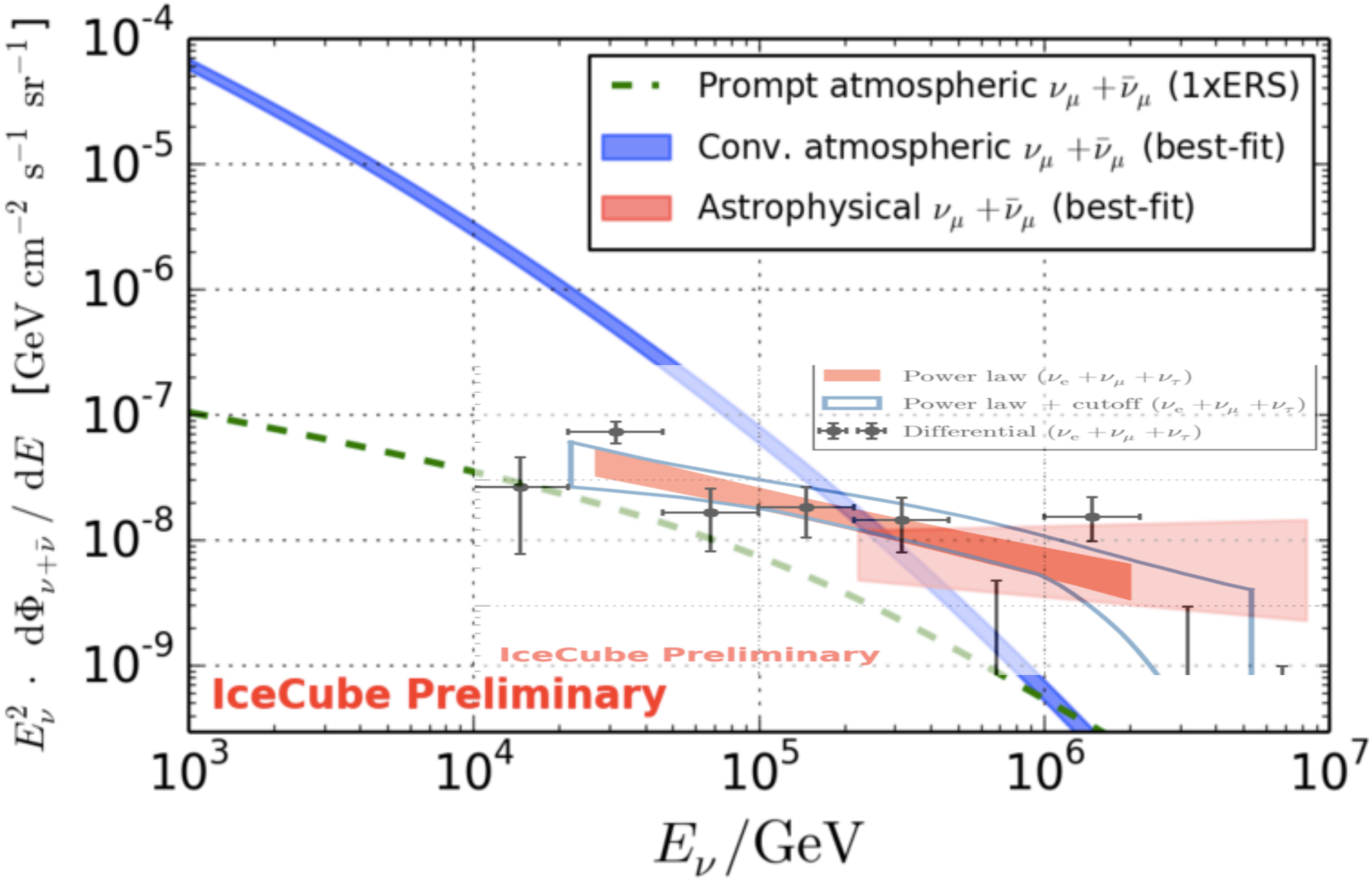
Neutrino flavor ratio constraints.



> Flavor ratios **compatible with standard pion decay production** (1:2:0) and **muon damped scenarios** (0:1:0)

> **Beta decay origin** (1:0:0) can be excluded at 3σ level.

Do we get a consistent picture ?



> **No real tension** due to different energy ranges.

> Some **indications for spectral hardening** at high energies.

> Significance still needs to be quantified.

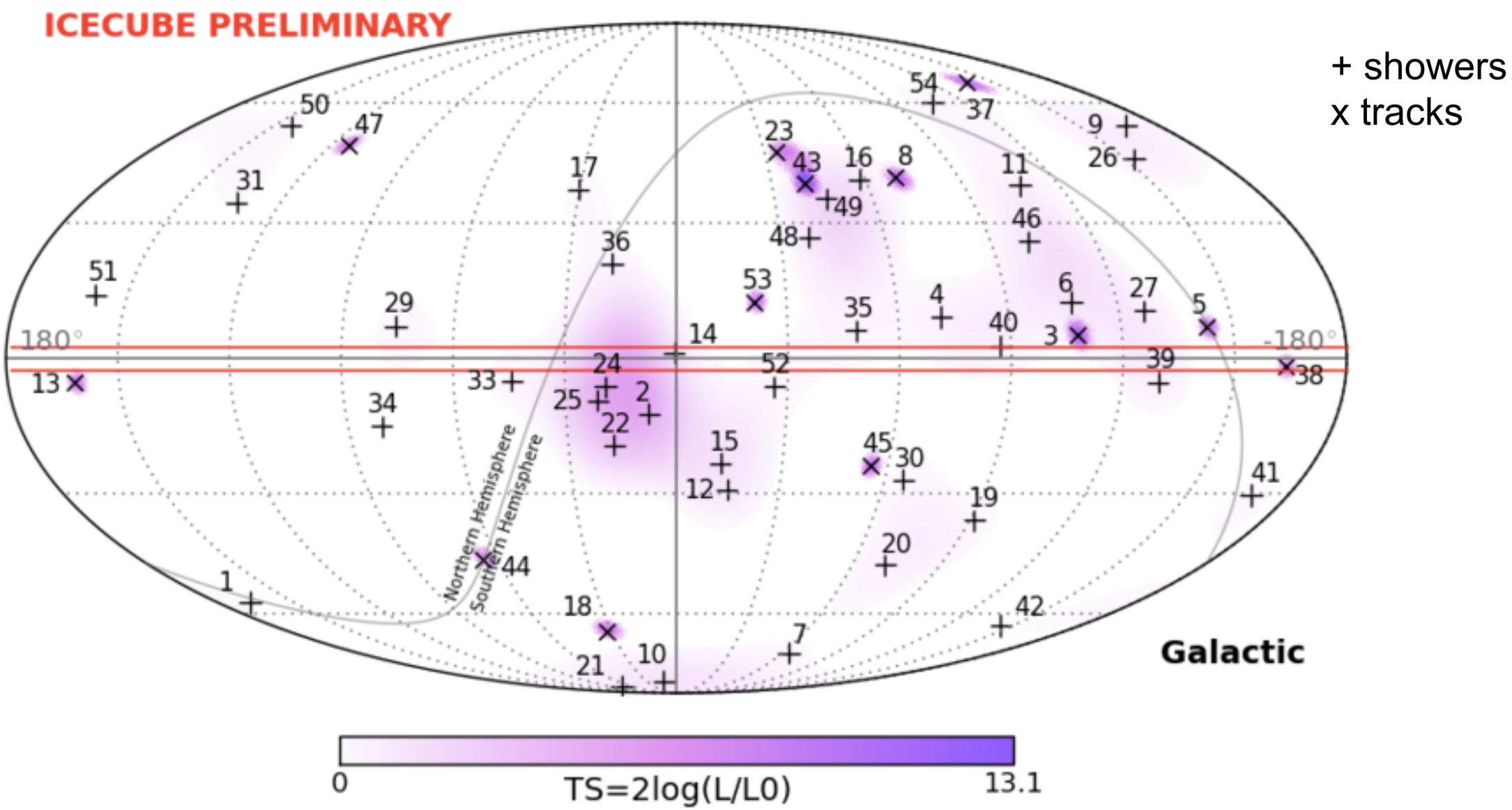
Where are the cosmic neutrinos from ?

Is it a single neutrino source / a few sources ?

Single source / few sources scenario.

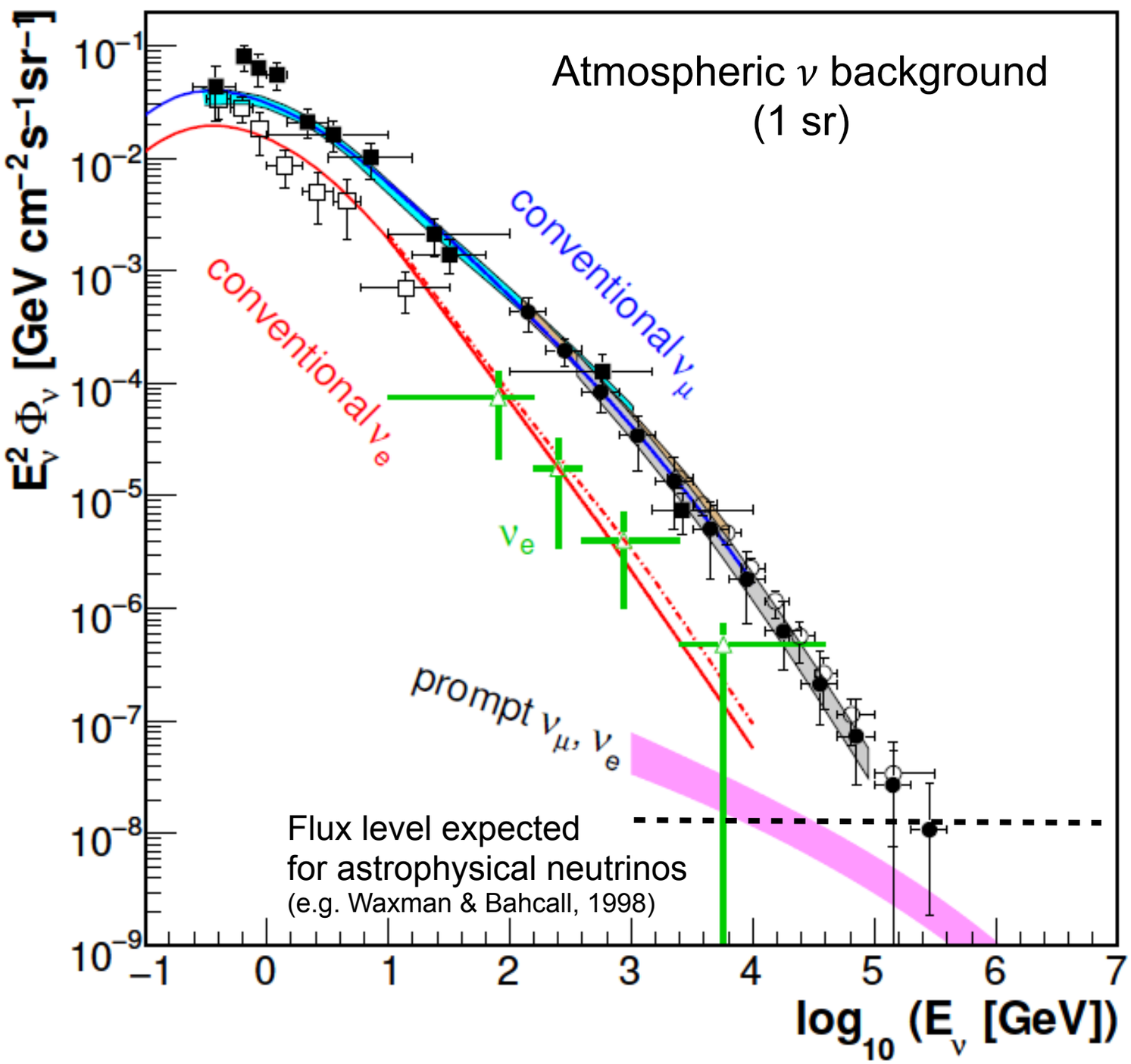
> This event distribution is not compatible with a single source !

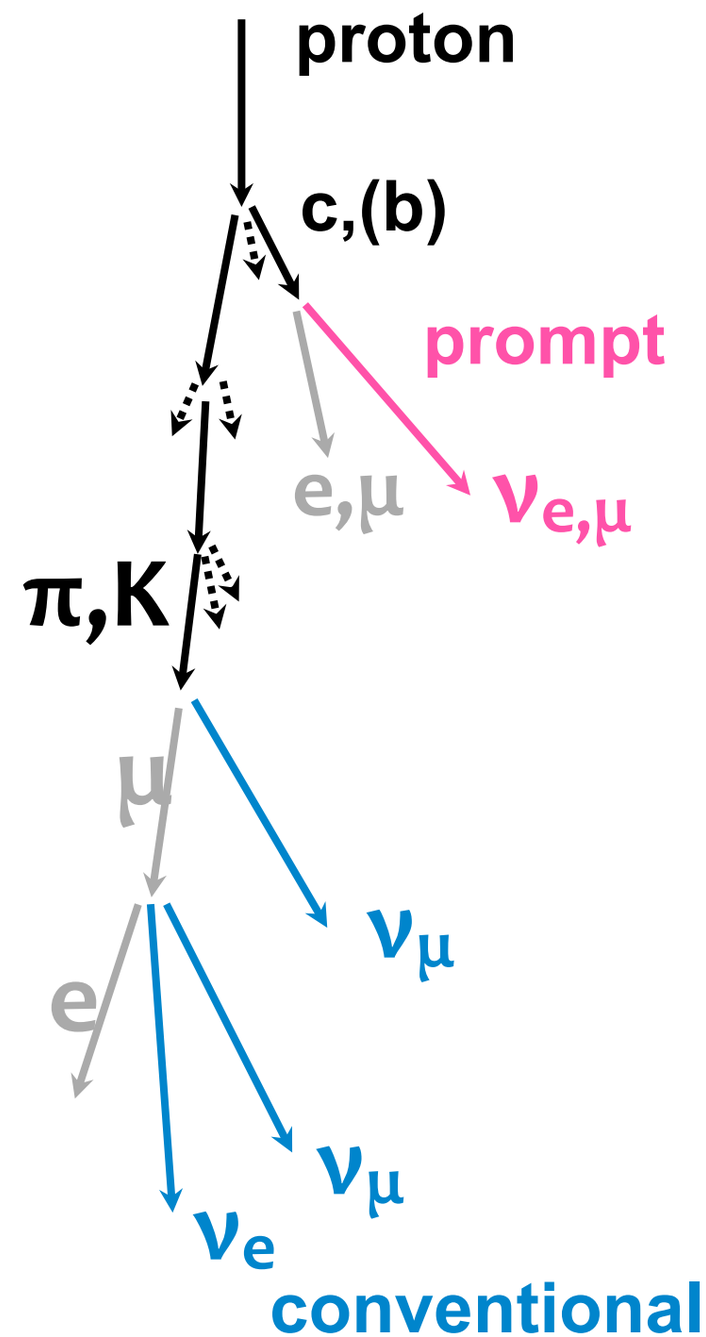
> But we can do better than this…..



Atmospheric backgrounds revisited…..

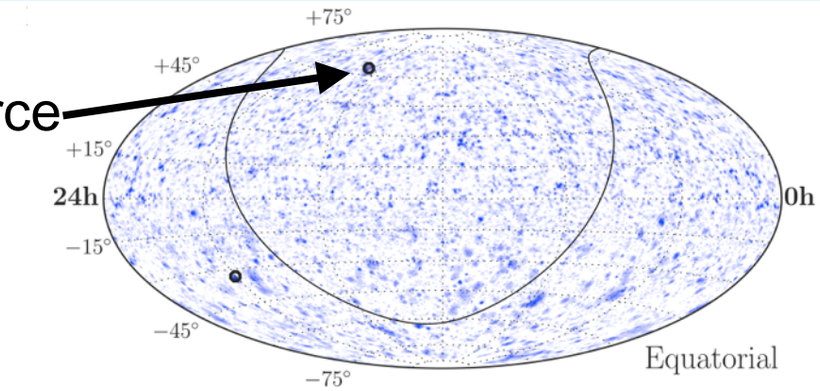
- **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.
- Angular resolution for ν_μ better than 1 deg.





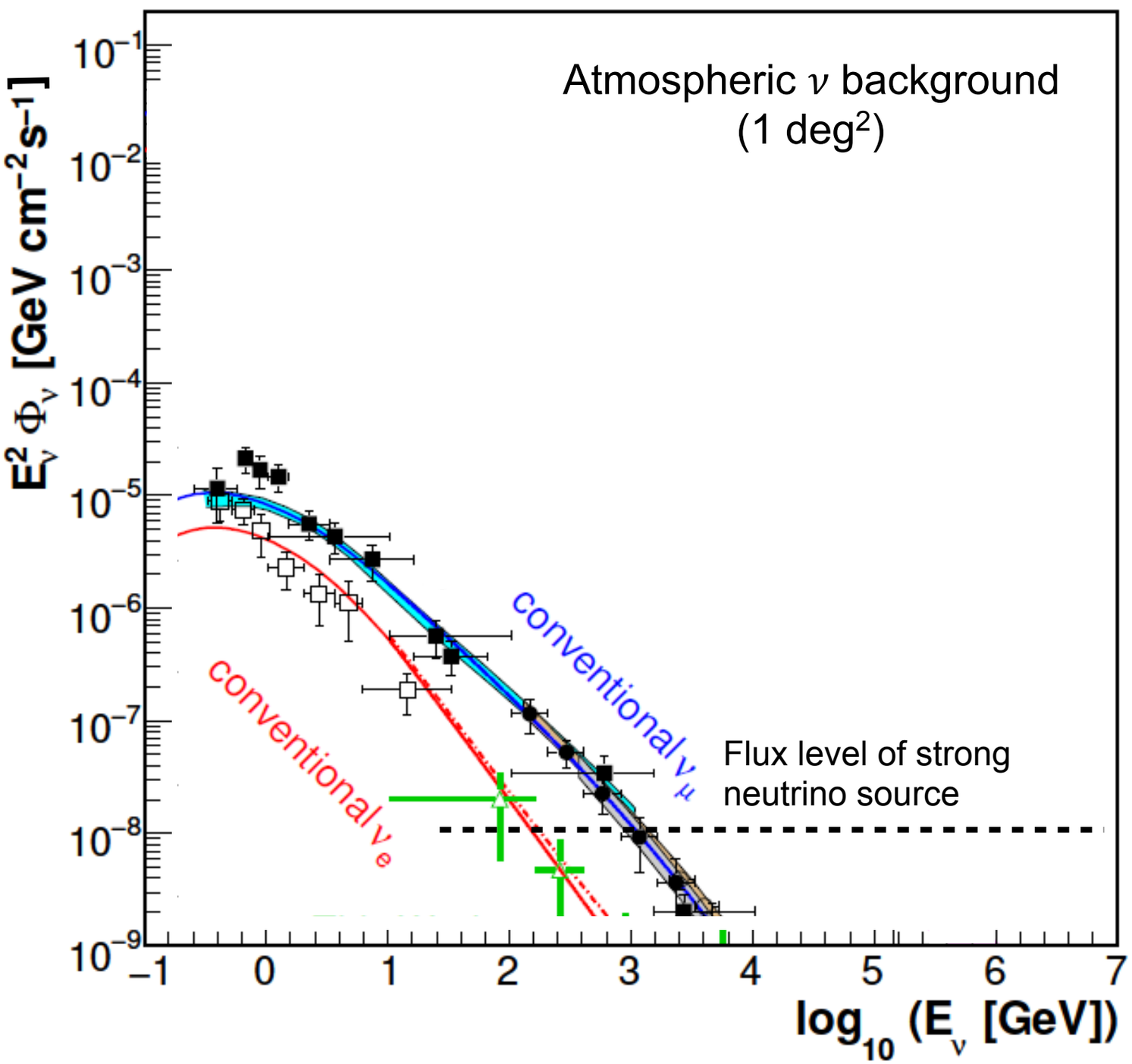
Atmospheric backgrounds for individual source searches

(Potential) neutrino source



Atmospheric neutrinos

> Angular resolution for ν_μ better than 1 deg.



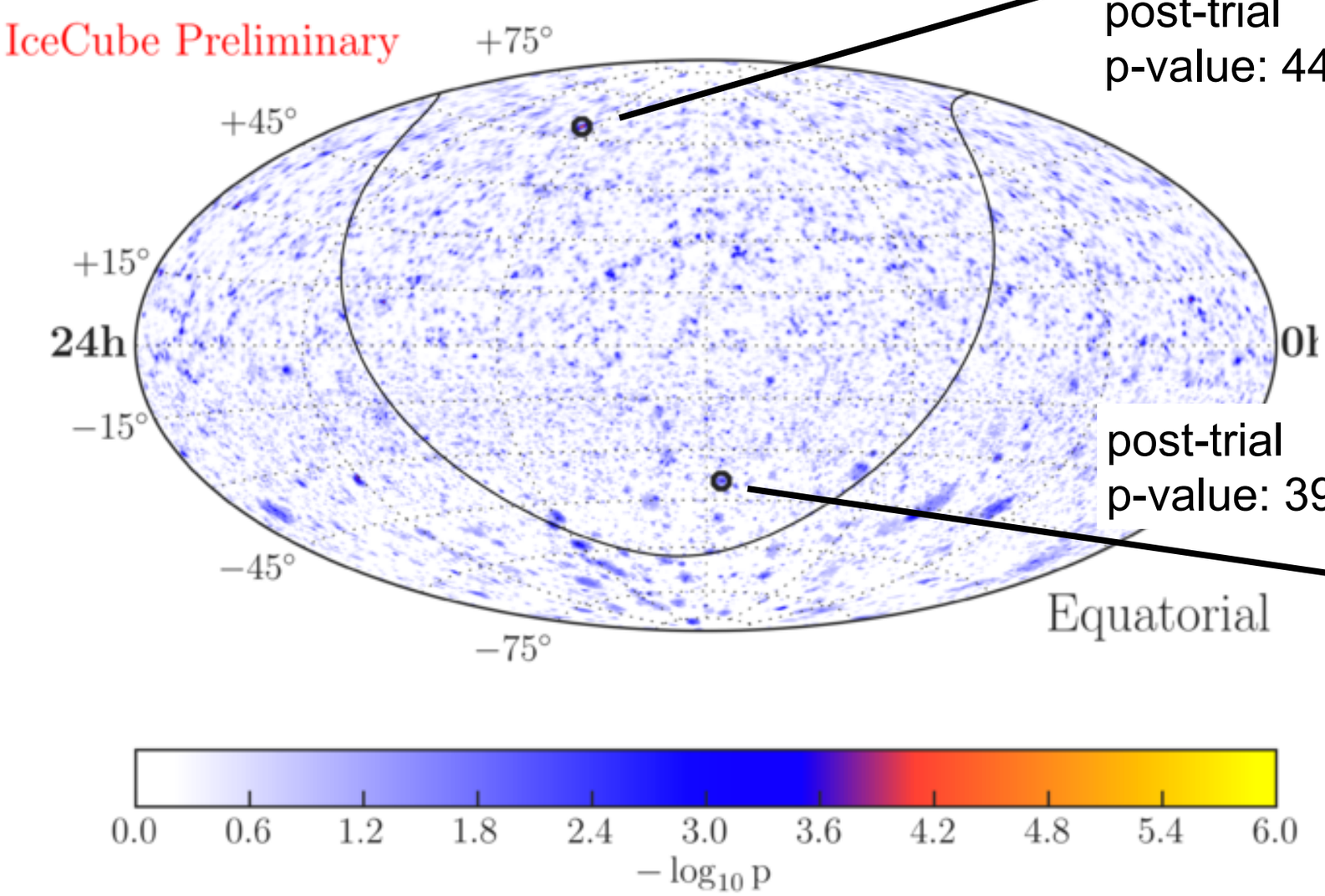
> Atmospheric background is reduced dramatically, if one looks for **individual neutrino sources**

> **Energy threshold** for individual source observation is lower than for a diffuse signal.

> **Sensitivity** is better.

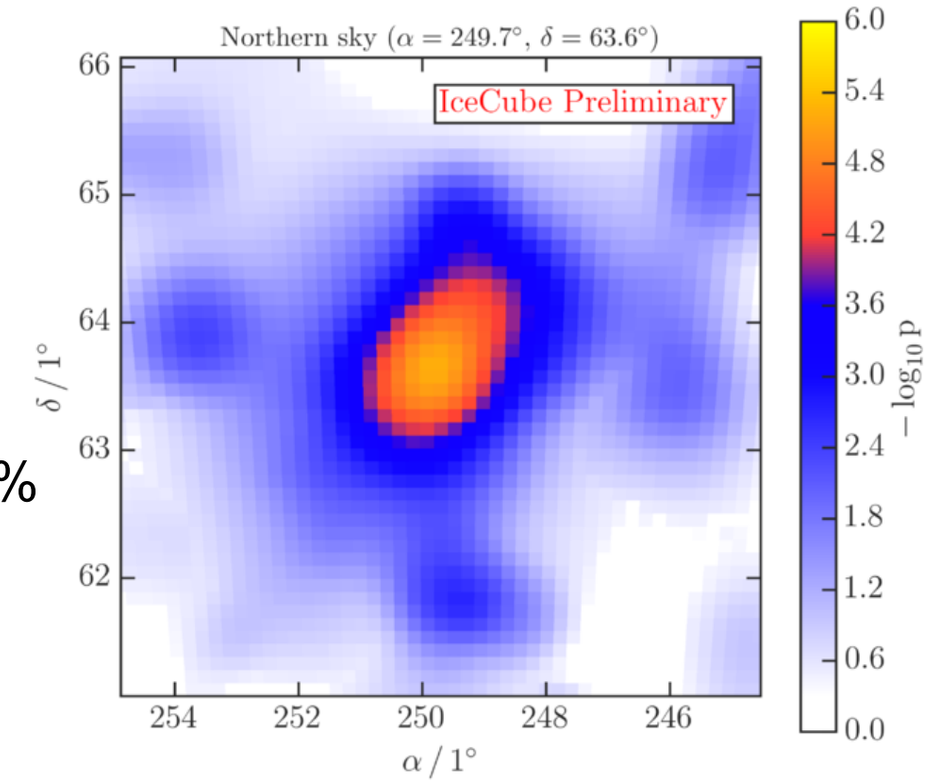
Search for individual neutrino sources: IceCube

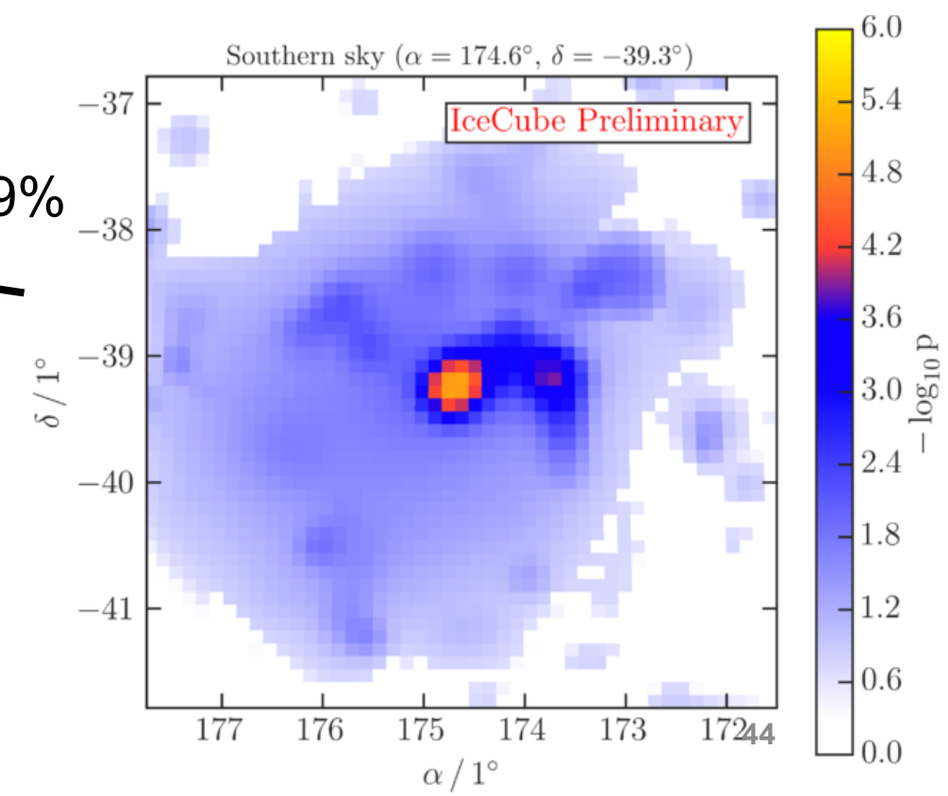
- 7 **years** of IceCube data (construction phase + full array)
- Sample of more than **700k muon track events**
- Median **angular resolution:** ~0.5 deg @ 10 TeV
- No statistically significant excess found.



post-trial
p-value: 44%

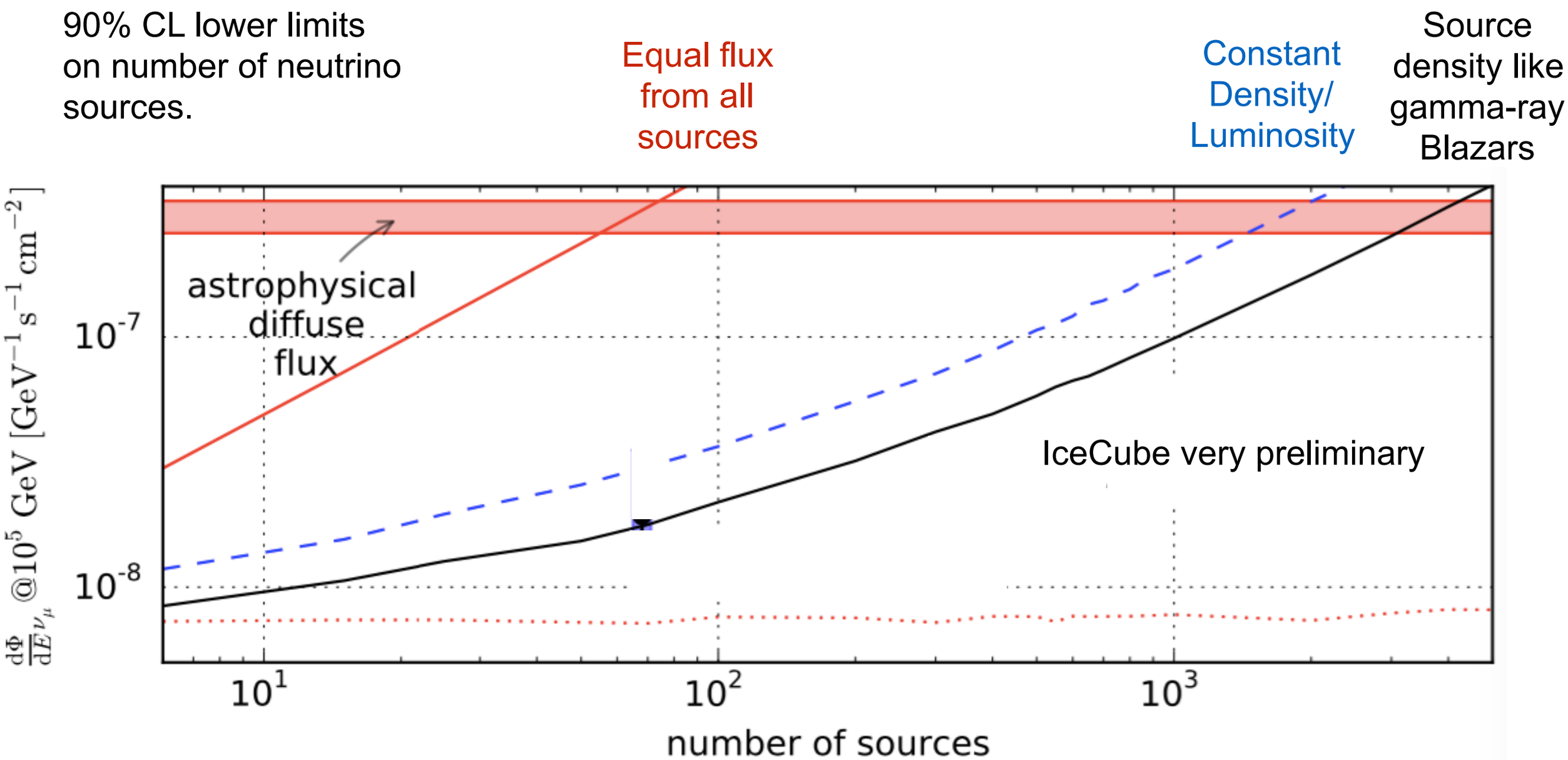
post-trial
p-value: 39%





How many sources do we need ?

90% CL lower limits on number of neutrino sources.

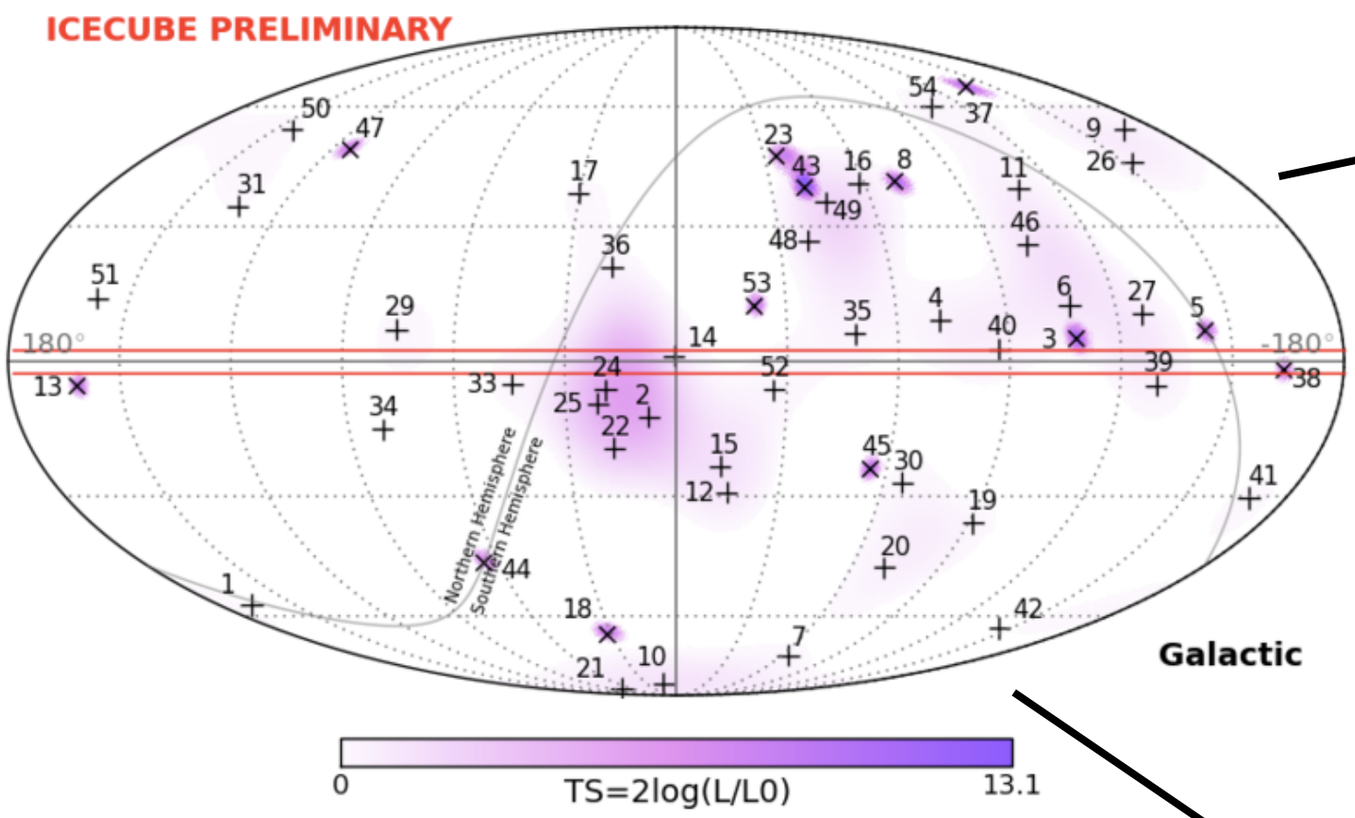


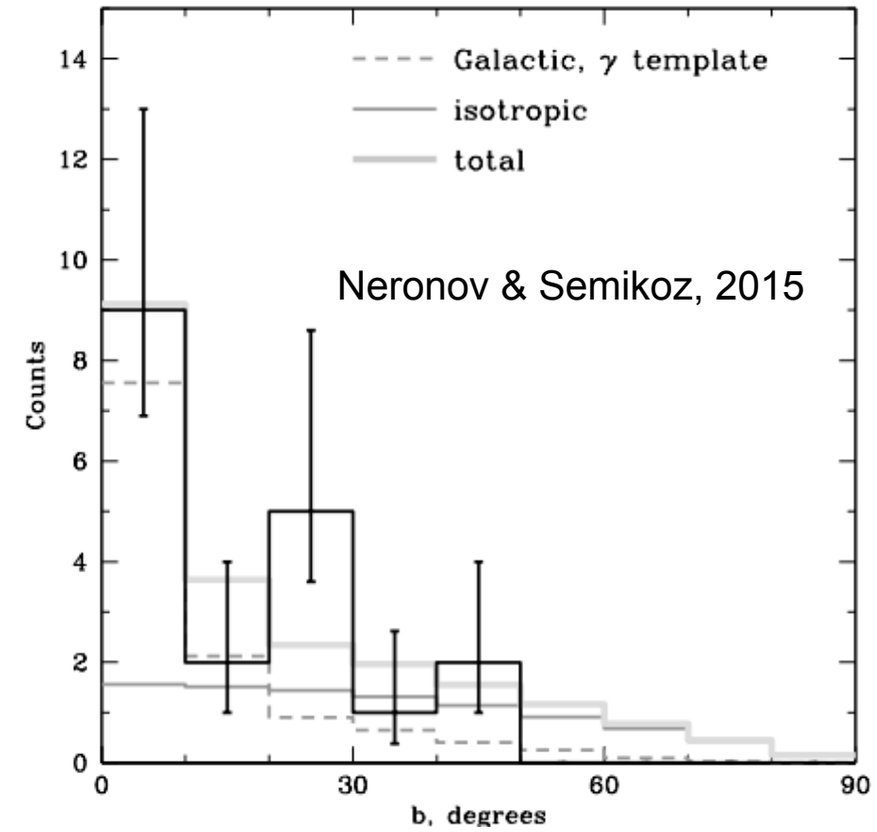
> More than O(10^3) sources need to be responsible for the bulk of the neutrino flux.

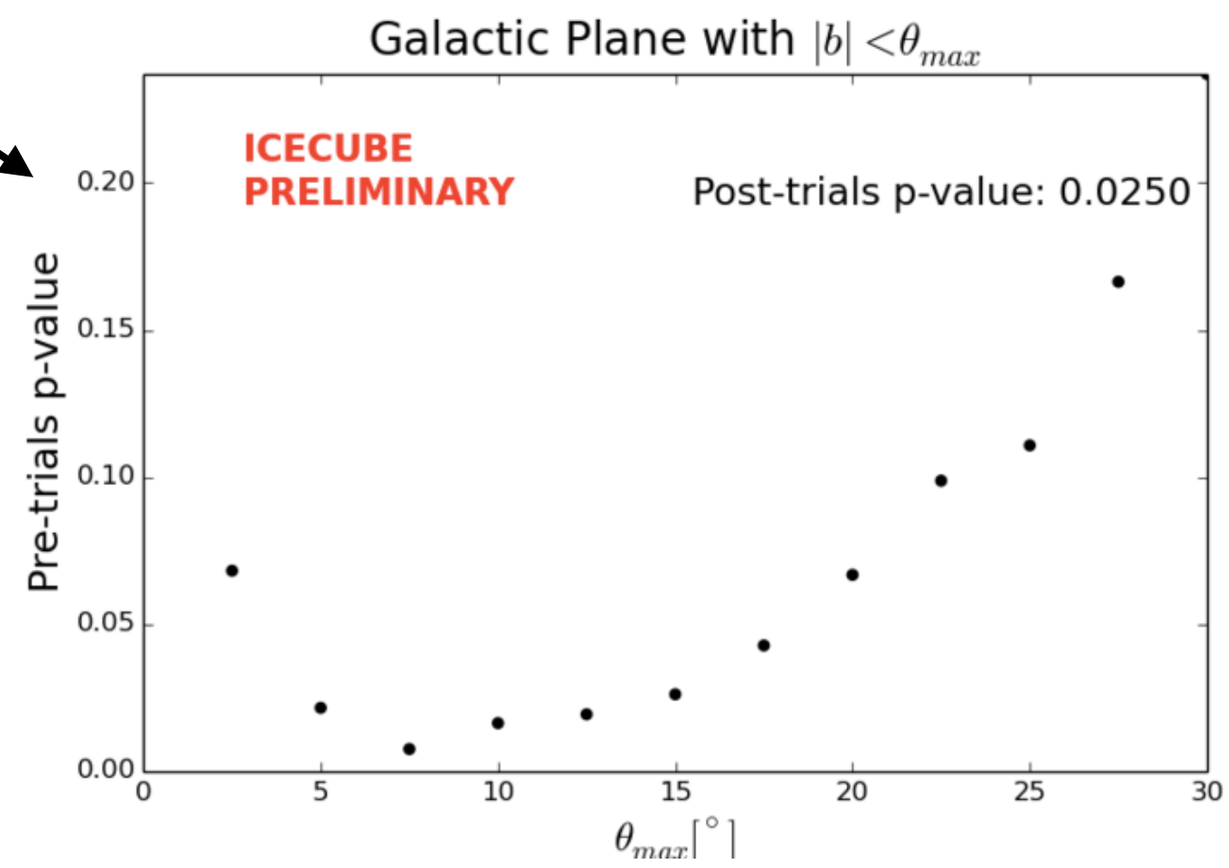
> Isotropic source distribution assumed.

Do we see neutrino emission
from the Galactic plane ?

Low significance Galactic plane excess.

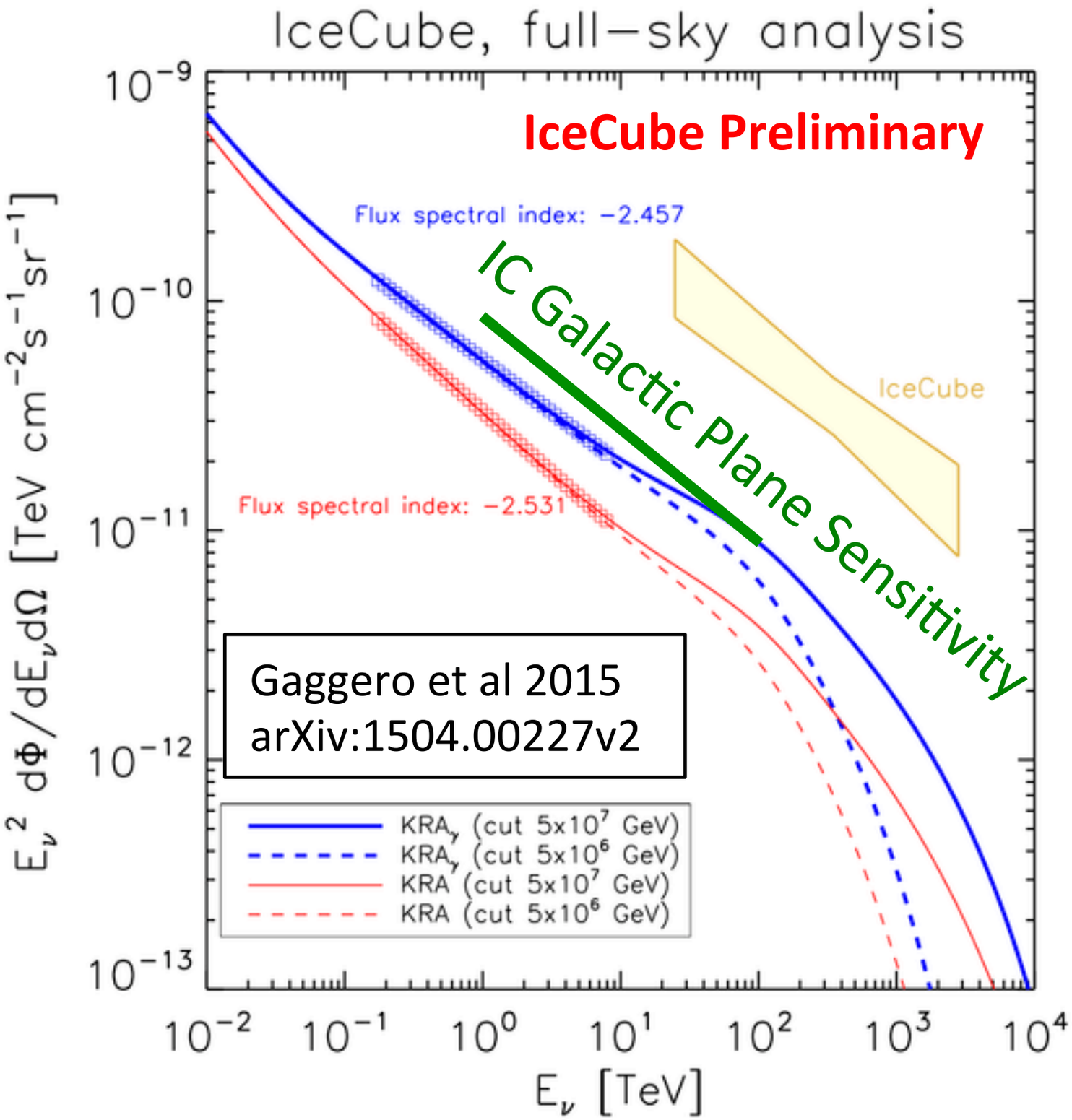






- Observed inside / outside the IceCube collaboration at 2σ / 3σ level.
- Analysis methods / energy thresholds are different between both analyses

More sensitive search with large sample of muon tracks….



- **7 years** of IceCube data
- Sensitive at lower energies.
- No correlation to Galactic plane found found.

What are the extragalactic candidates?

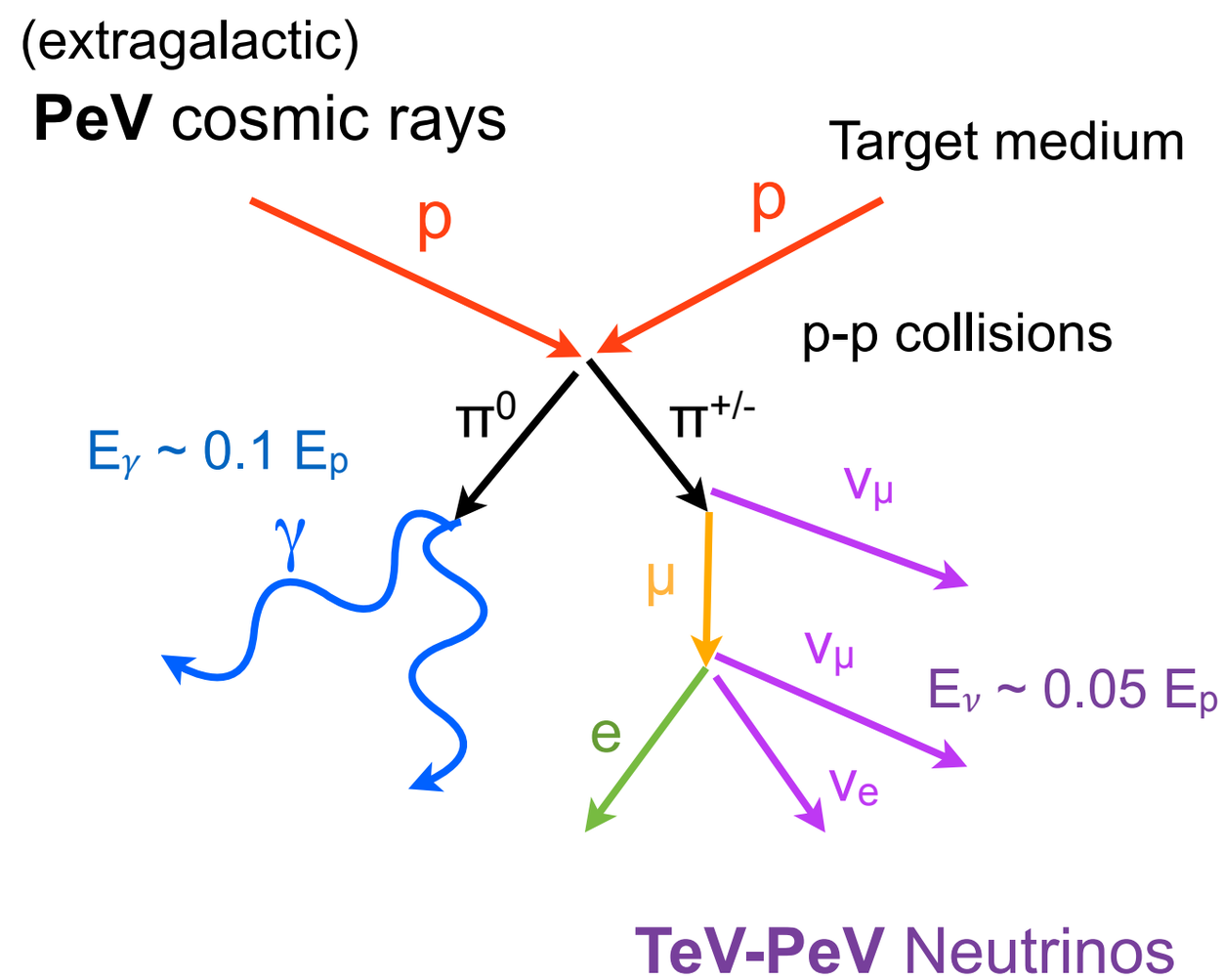
… let’s look at gamma rays

The cosmic-ray / gamma / neutrino connection

> Cosmic rays interact with a target medium close to the source.

> ν / γ - production via p-p or p-γ collisions

> Reprocessing of γ rays to GeV energies.



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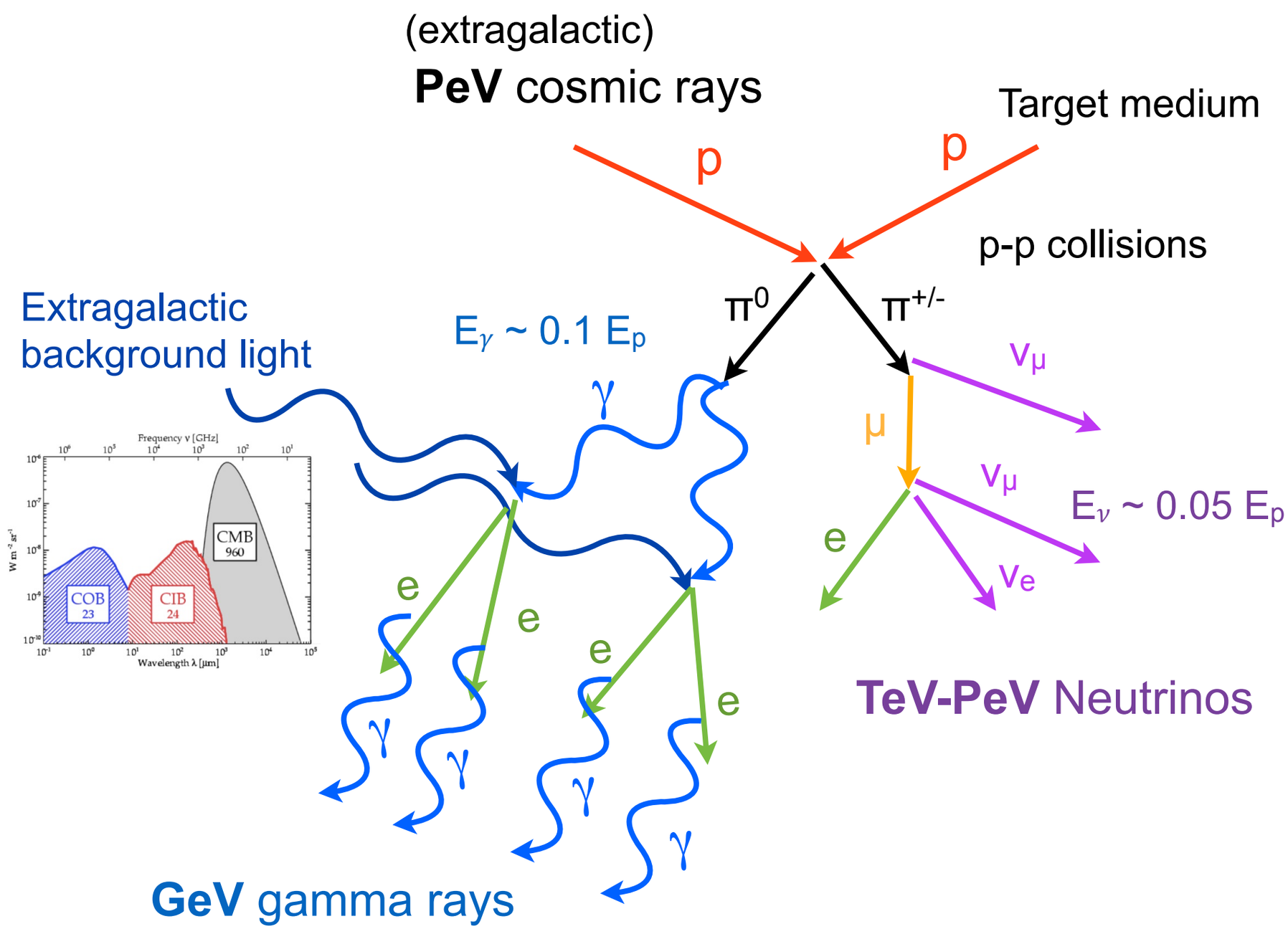
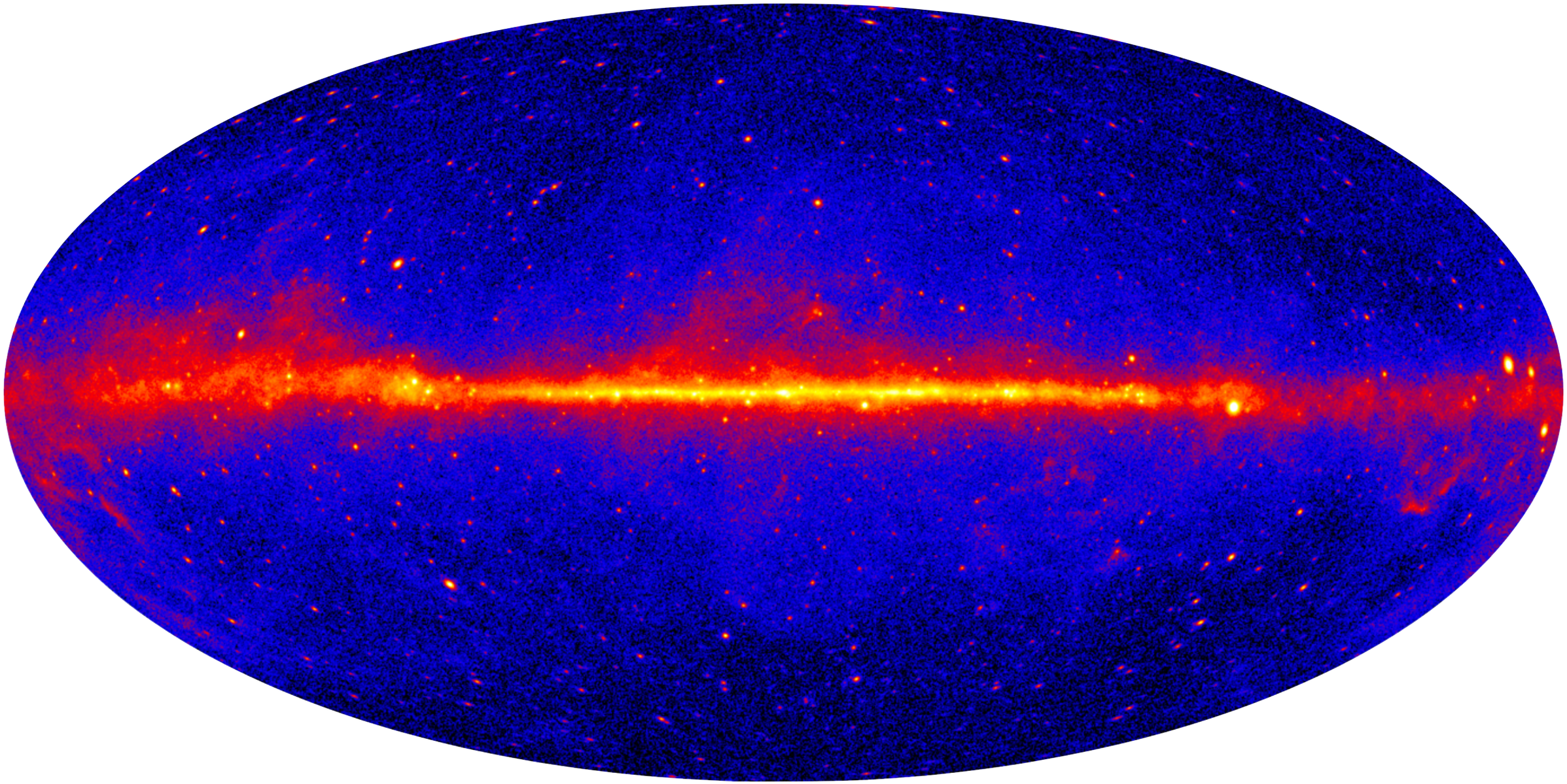


The GeV gamma-ray sky

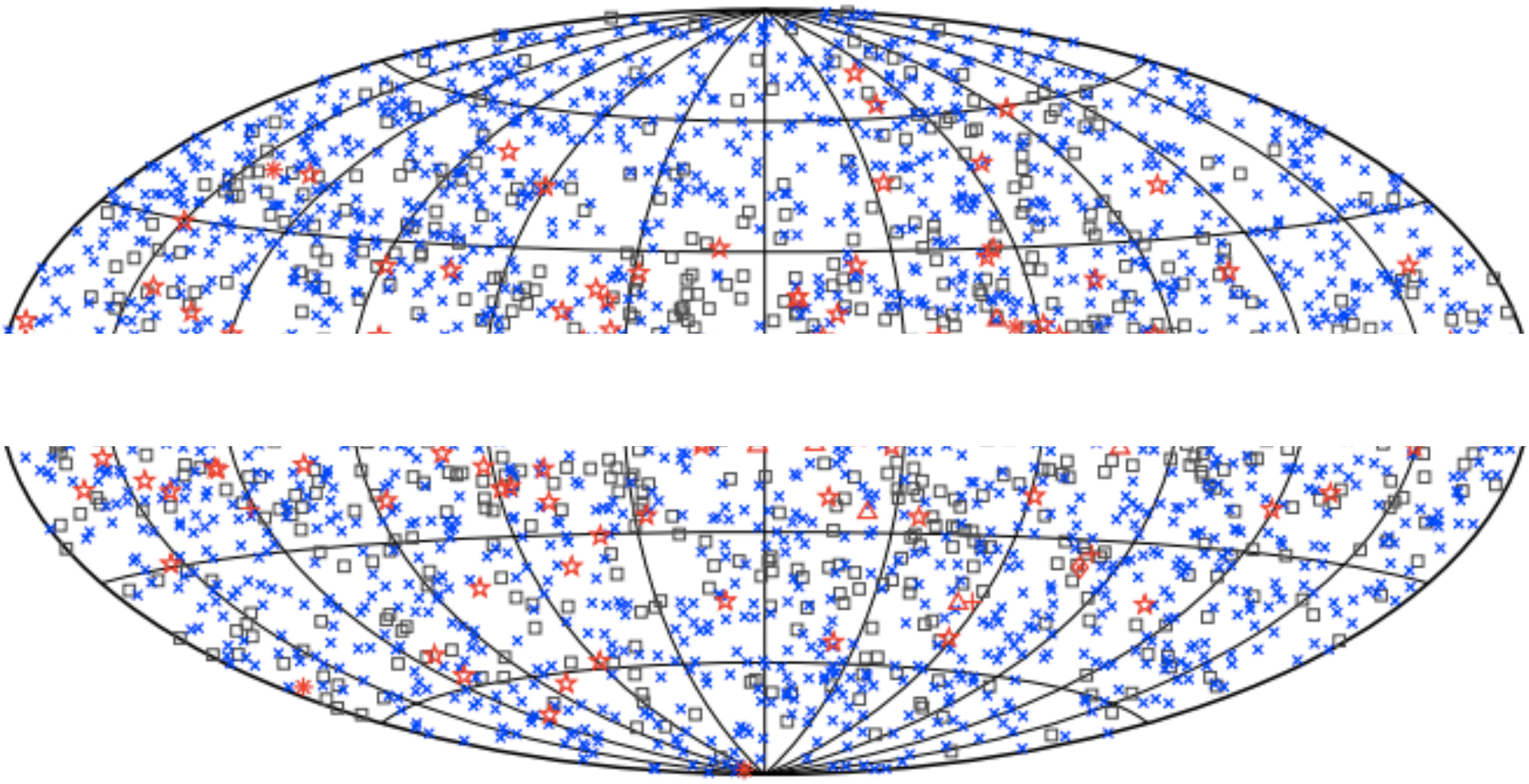
Fermi LAT, E > 1 GeV



> The most complete census of the non-thermal universe is the Fermi LAT sky survey at GeV energies.

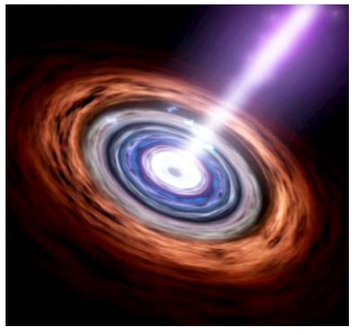
The GeV gamma-ray sky

Fermi LAT, E > 1 GeV



> The most complete census of the non-thermal universe is the Fermi LAT sky survey at GeV energies.

Extragalactic gamma-ray sources



Blazars

> Subtype of an active galaxy where jets are pointed at Earth.
> Quite rare, but very bright.

>2000 sources

(Misaligned) Active galaxies

> Galaxies with supermassive black holes at their centers.
> Observation of relativistic jets of high-energy particles.

~ 30 sources

Star-forming galaxies

> Normal galaxies (e.g. Milky Way).
> Very few neutrinos per Galaxy …but many Galaxies out there.

<10 sources

Gamma-ray bursts

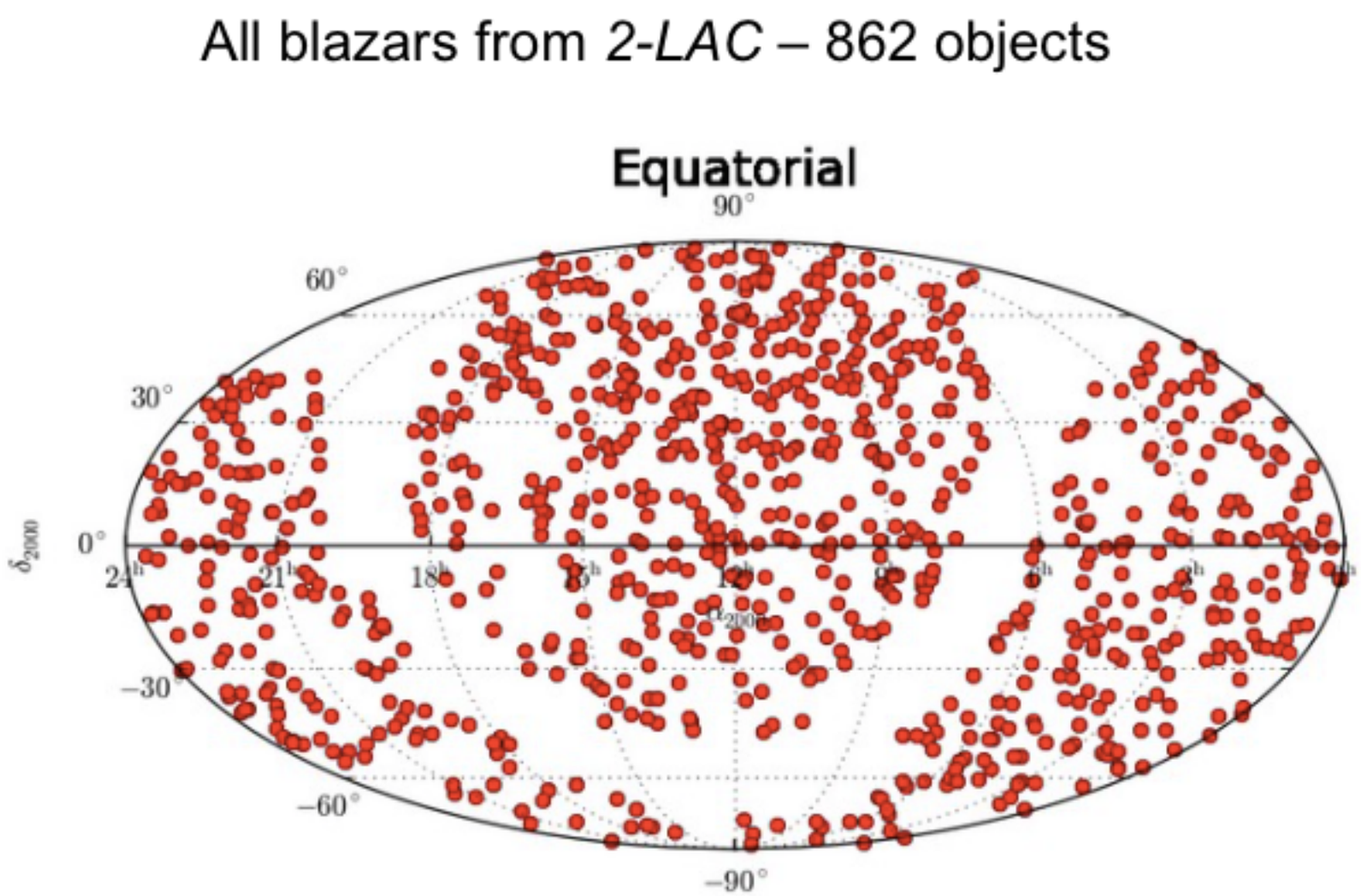
> Most violent explosions known.
> Likely related to explosions of massive stars or mergers of neutron stars/black holes.

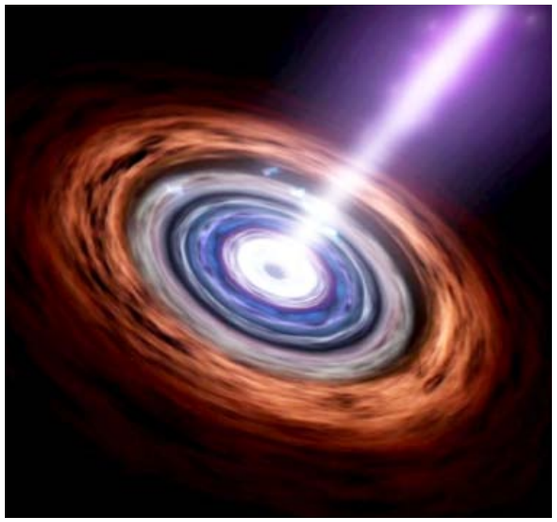
~250 / year

Search for correlation of ν to the sample of GeV Blazars.

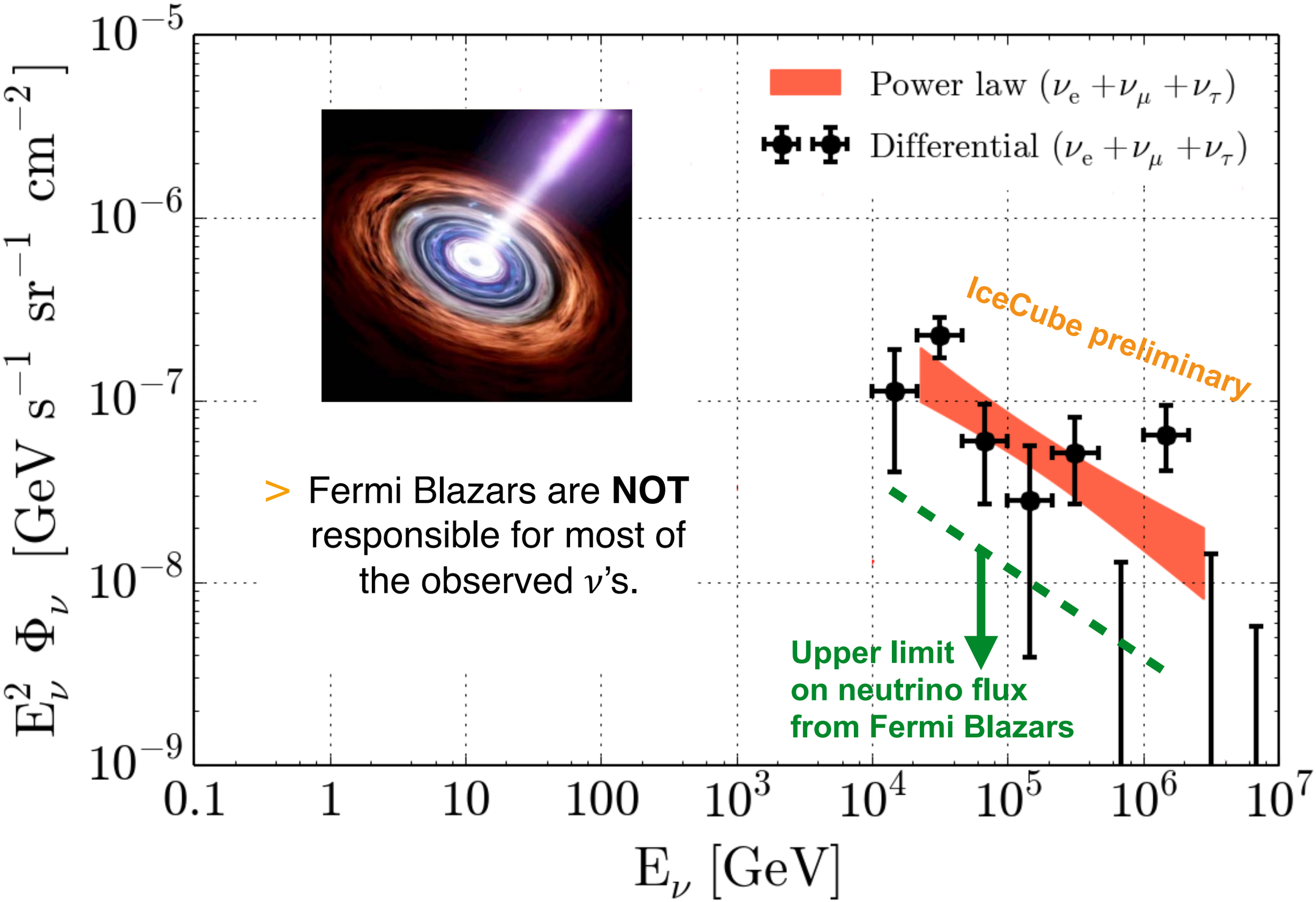
> Most of the extragalactic gamma-ray emission in the GeV band is from **Blazars.**

> Search for neutrino emission **spatially coincident with 2LAC Blazar** sample.



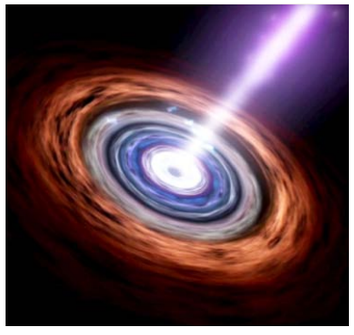


Extragalactic gamma rays and neutrinos.



> Fermi Blazars are **NOT** responsible for most of the observed ν's.

Extragalactic gamma-ray sources



Blazars

> Subtype of an active galaxy where jets are pointed at Earth.
> Quite rare, but very bright.

>2000 sources

…. as dominant v source population

(Misaligned) Active galaxies

> Galaxies with supermassive black holes at their centers.
> Observation of relativistic jets of high-energy particles.

~ 30 sources

Star-forming galaxies

> Normal galaxies (e.g. Milky Way).
> Very few neutrinos per Galaxy …but many Galaxies out there.

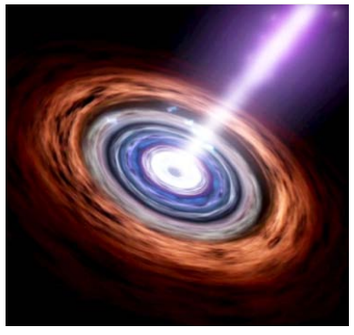
<10 sources

Gamma-ray bursts

> Most violent explosions known.
> Likely related to explosions of massive stars or mergers of neutron stars/black holes.

~250 / year

Extragalactic gamma-ray sources



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No significant detection

of any GRB or fast and bright ν transient.

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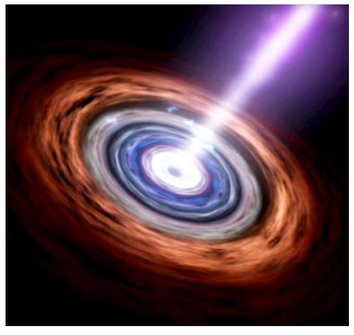
Extragalactic gamma-ray sources



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Hard to reconcile with observed gamma-ray emission

Gamma-ray bursts

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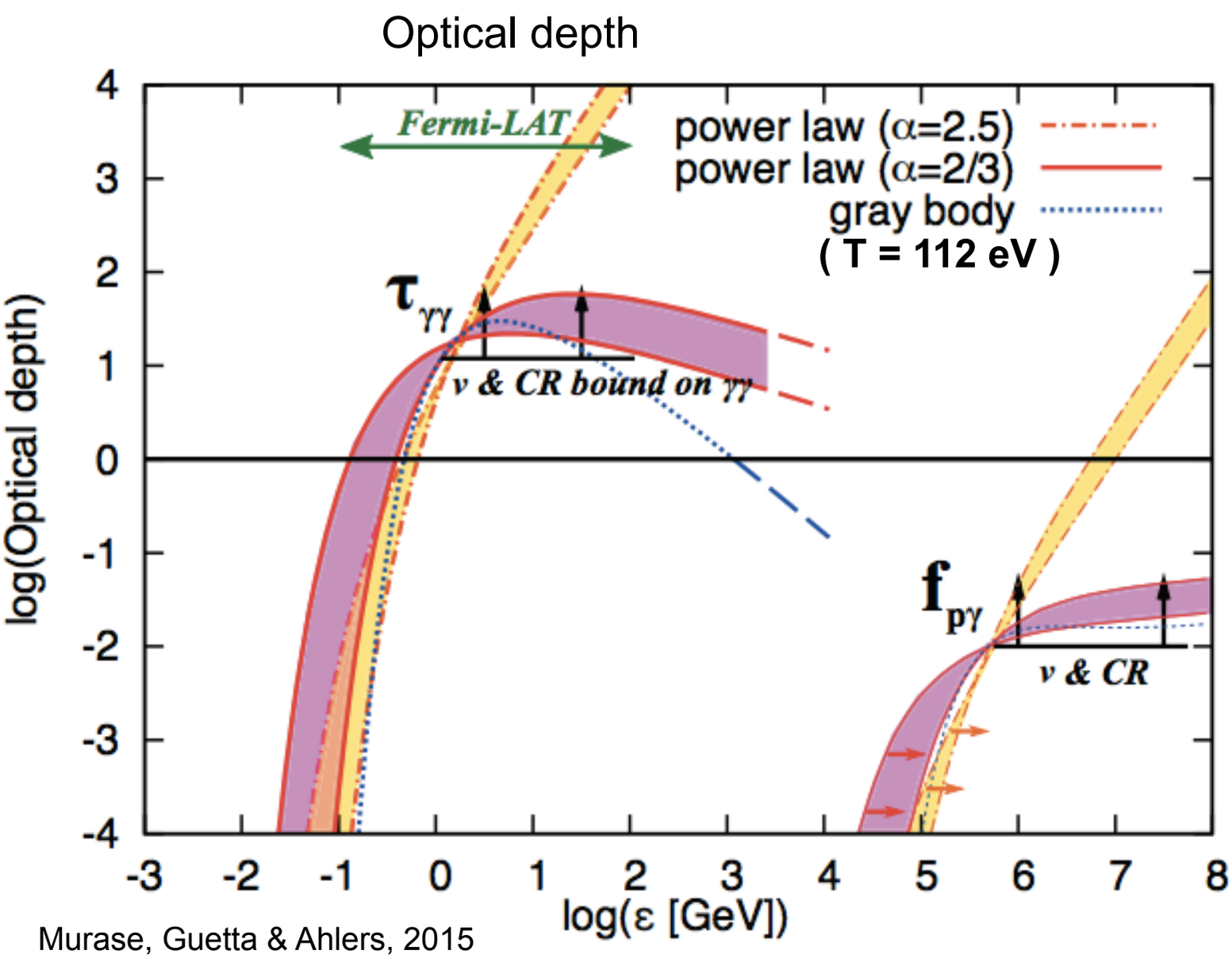
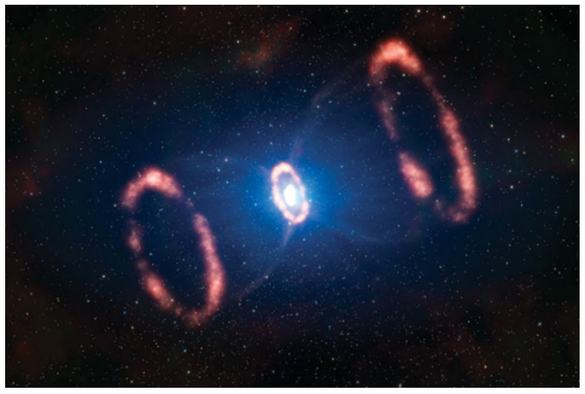
What remains ?

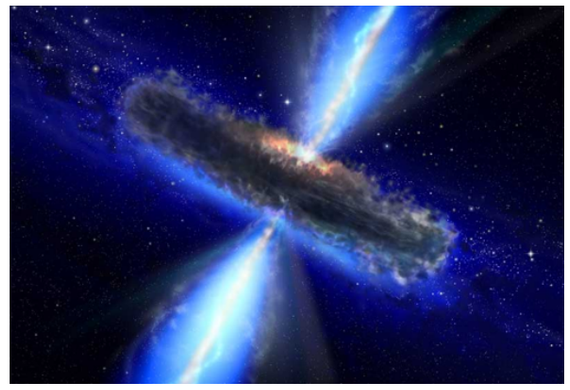
Gamma-ray opaque sources



Murase, Guetta & Ahlers, 2015

- Sources that efficiently absorb gamma rays in the GeV band:
- Accretion disks of AGNs
- Core-collapse supernovae
- etc.
- **The neutrino sky is very different to the gamma-ray sky!**



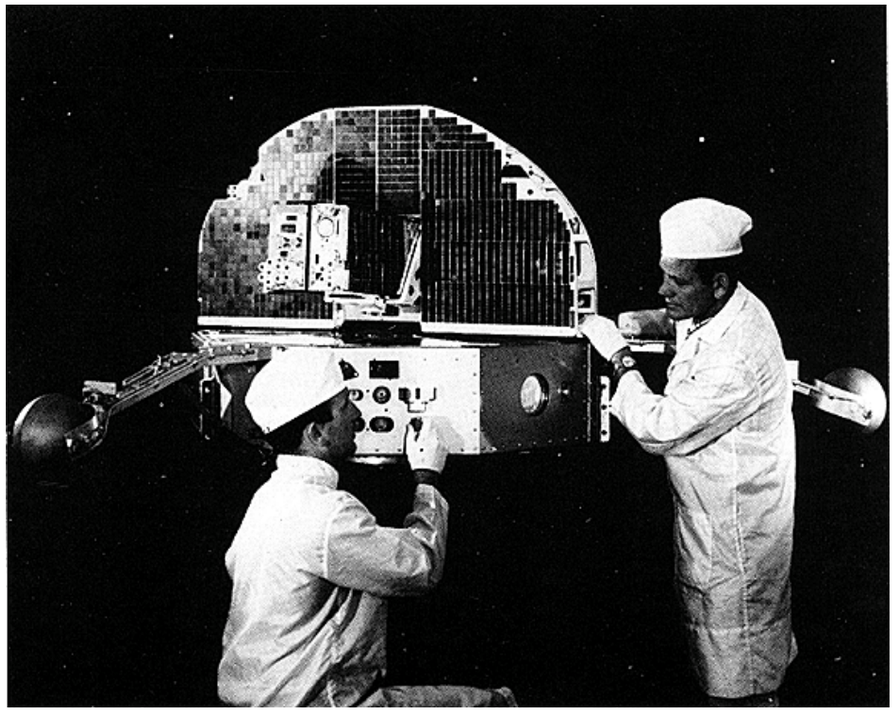


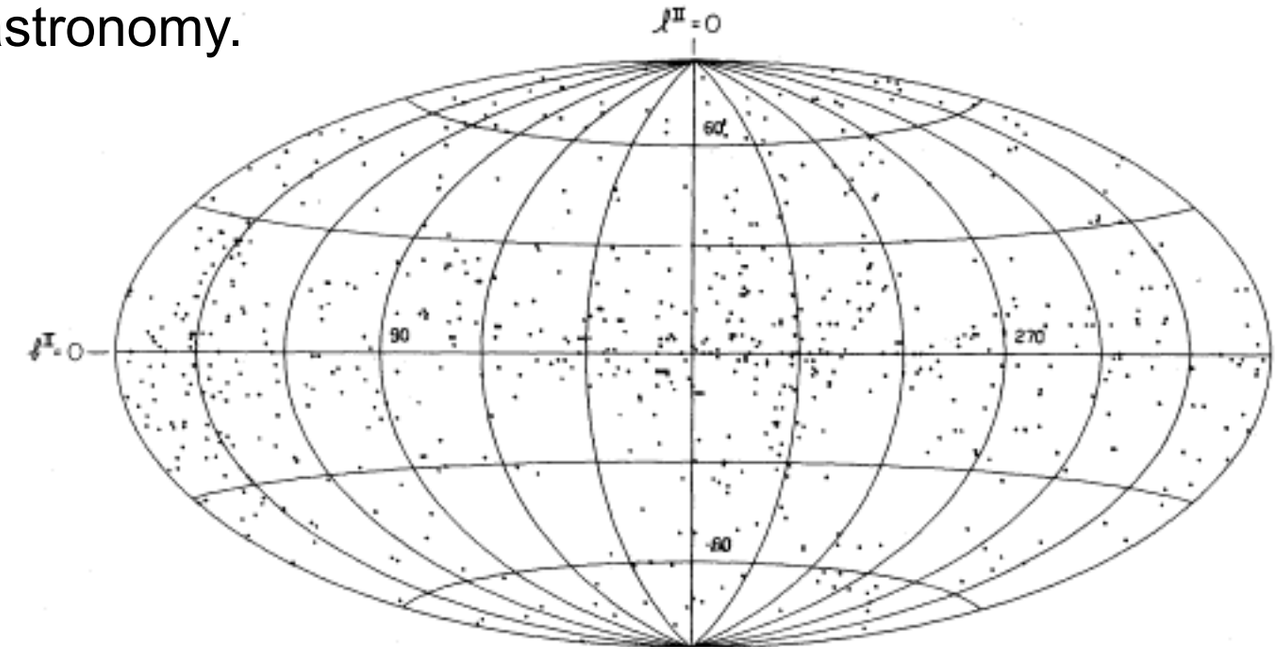
Where do we go from here ? *

* besides collecting 10 more years of great IceCube data.

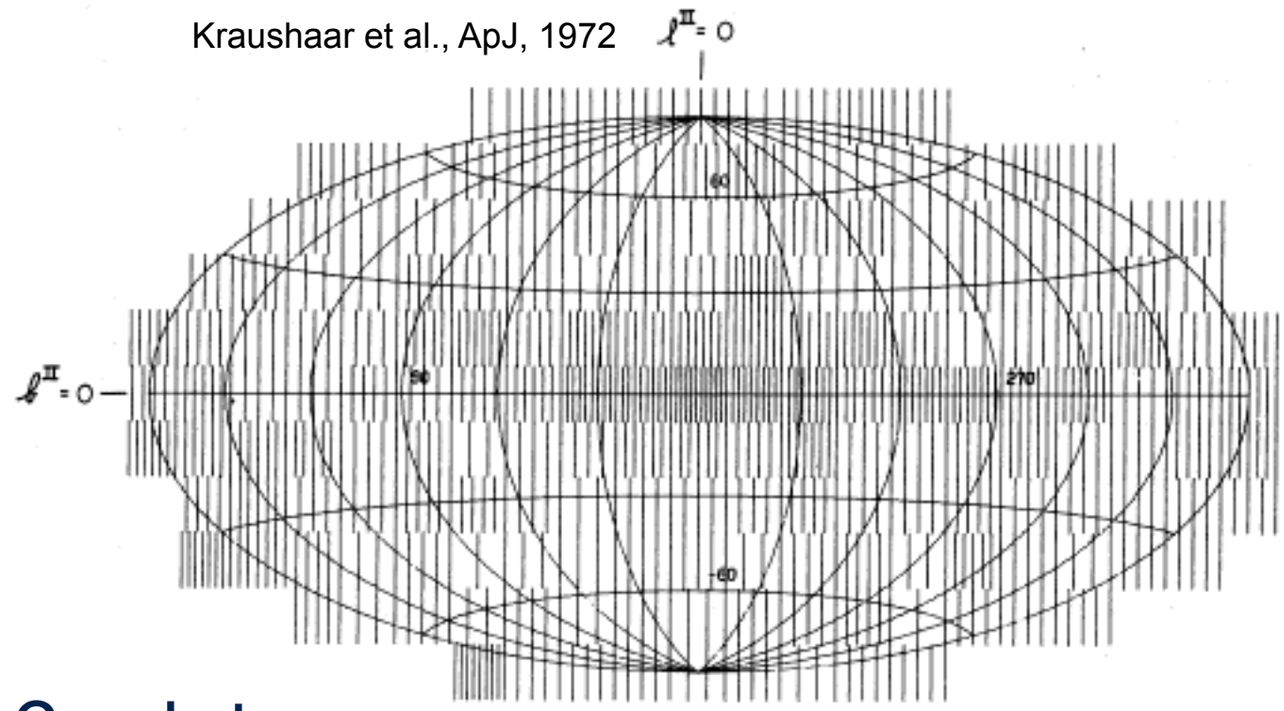
This is where we are now in neutrino astronomy….

… comparing to the history of gamma-ray astronomy.





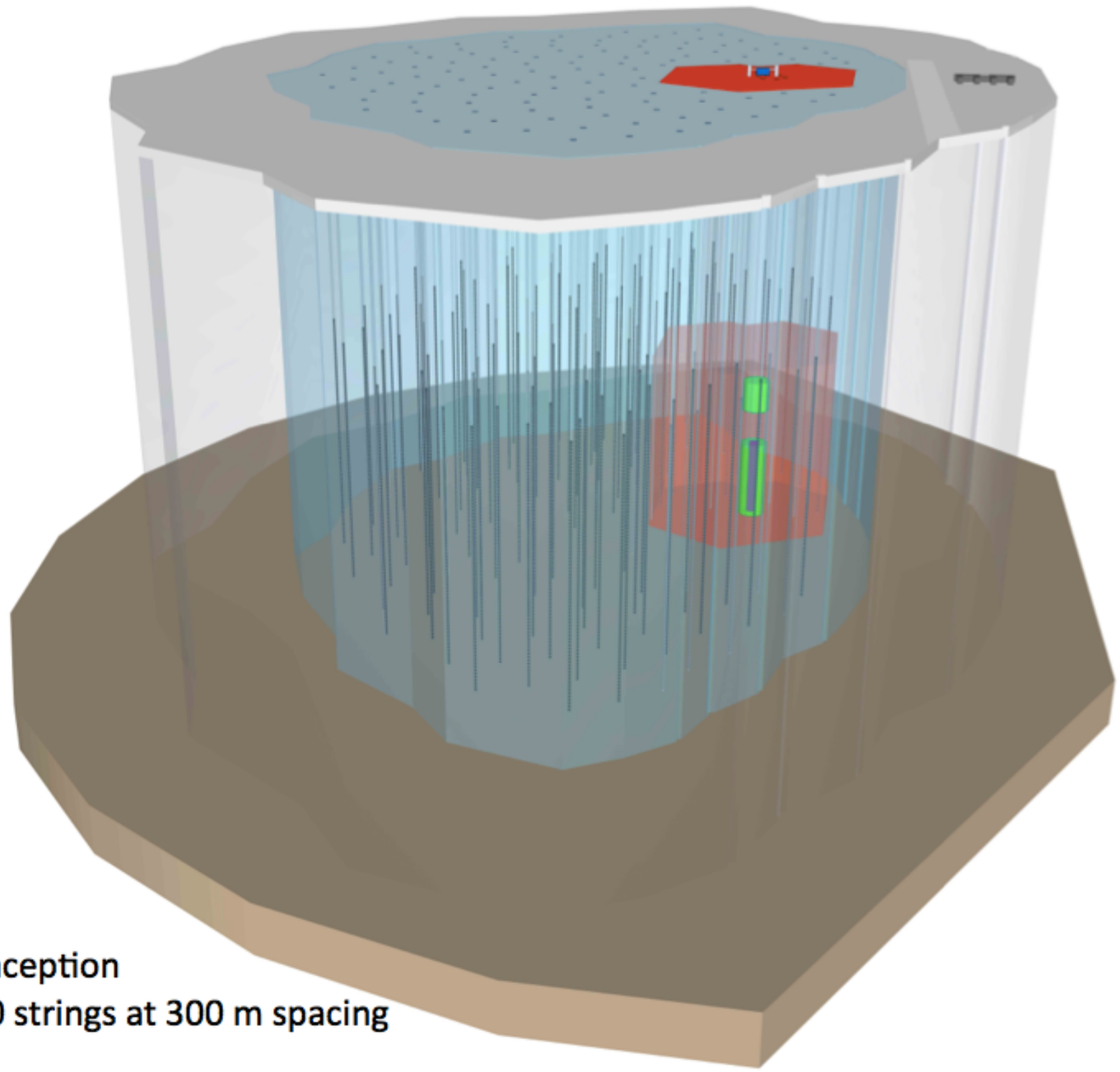
Kraushaar et al., ApJ, 1972



- OSO-3 launched 1967 on a Delta C rocket
- 621 photons above 50 MeV detected.
- No sources, but Galactic plane emission identified.

We need to make the next step: IceCube-Gen2.

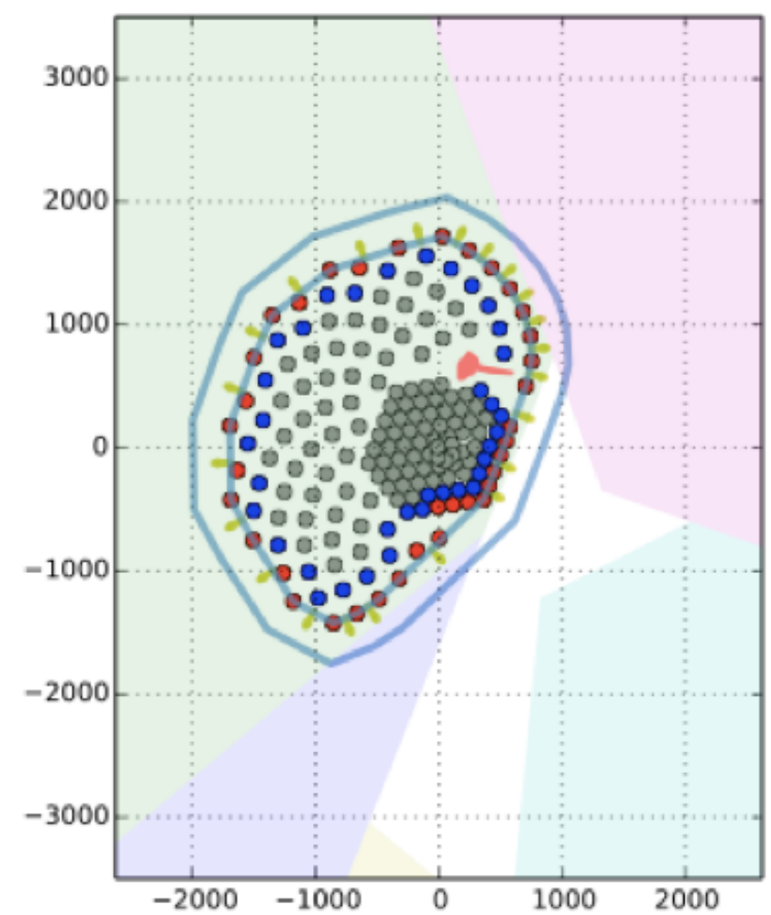
> Design options evaluated for a proposal to funding agencies.



Artist conception
Here: 120 strings at 300 m spacing

> Design option:

- About **100 new strings**.
- ~ **5 km²** surface area.
- ~ **7 km³** volume.
- > **5 x** IceCube sensitivity.



Summary.

> The first few years of neutrino astronomy are behind us.

> We are making quick progress in determining the properties of the cosmic neutrino signal.

> A substantial fraction of the neutrino flux seems to be extragalactic.

> Many (weaker) sources need to contribute to explain the absence of point sources.

> There are first indications that the neutrino sky is substantially different from the GeV gamma-ray sky.

… and there is a lot of great science with neutrino telescopes I didn't show today.