Uraniborg main building. Copper etching from Blaeu's Atlas Major, 1663.

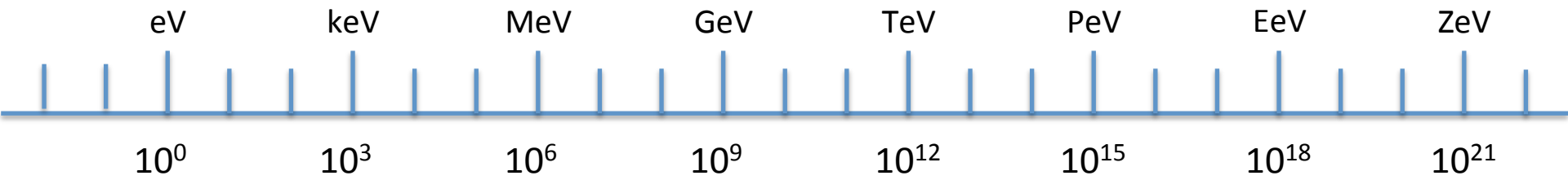
Arrays and Telescopes for the age of Neutrino Astronomy

GRAND Workshop
2015 Feb Paris

Chad Finley
Oskar Klein Centre
Stockholm University

Neutrino Astronomy

Neutrinos From Space



Neutrino Astronomy

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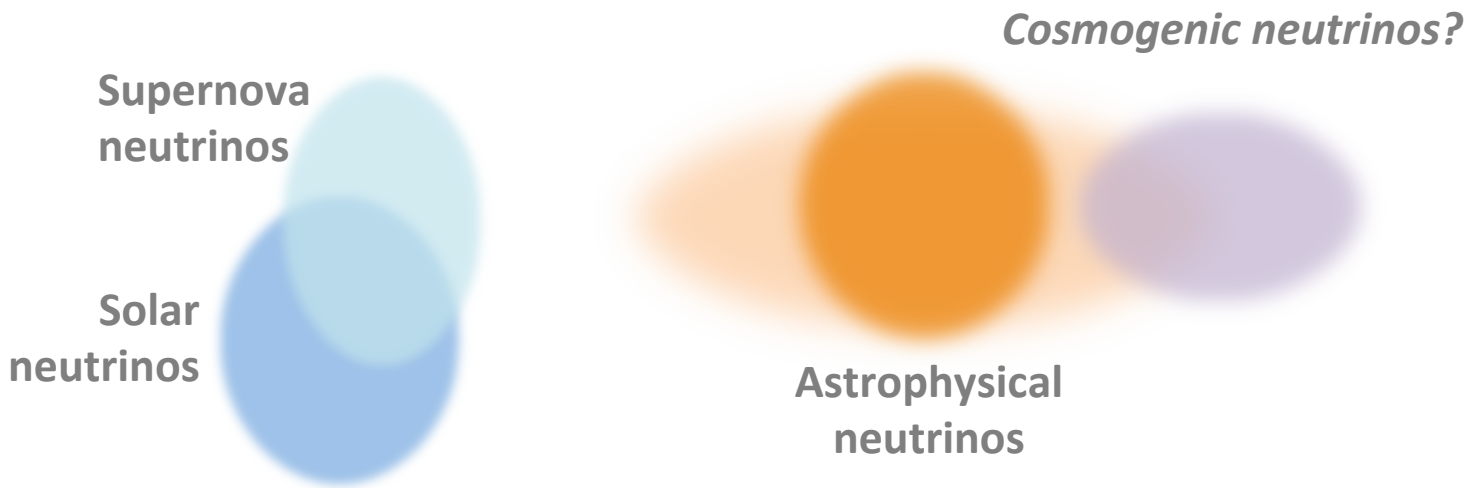

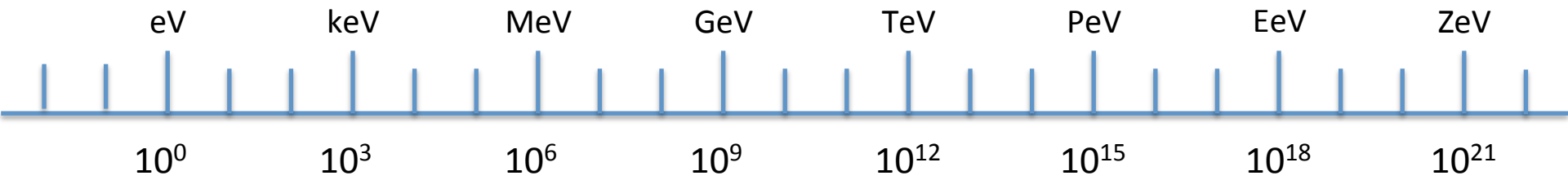

Neutrino Astronomy

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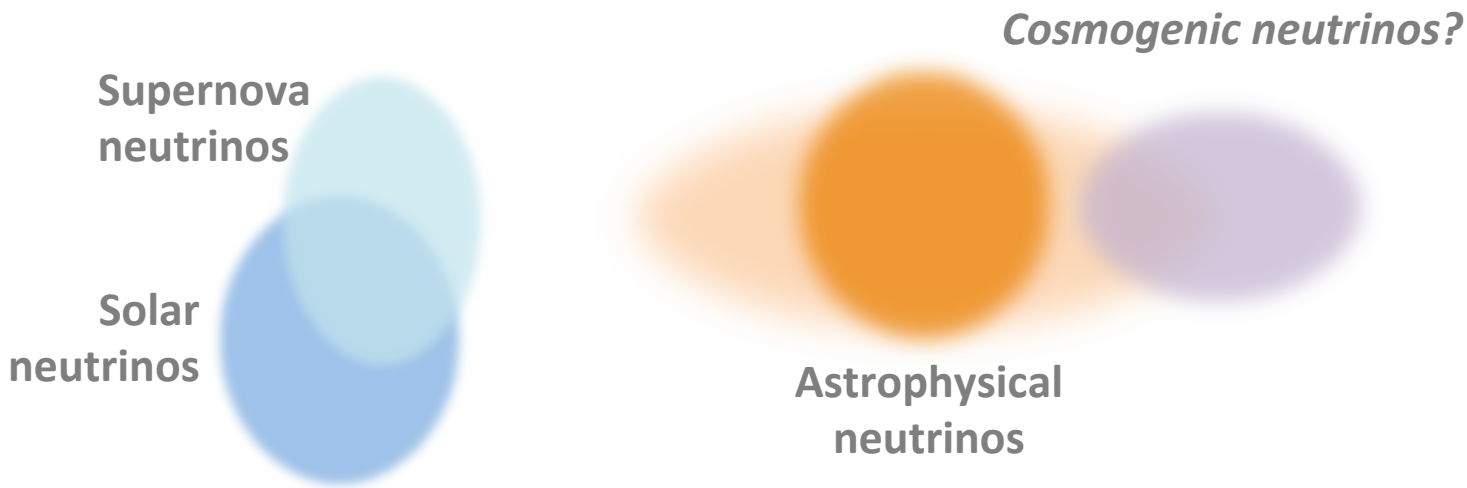
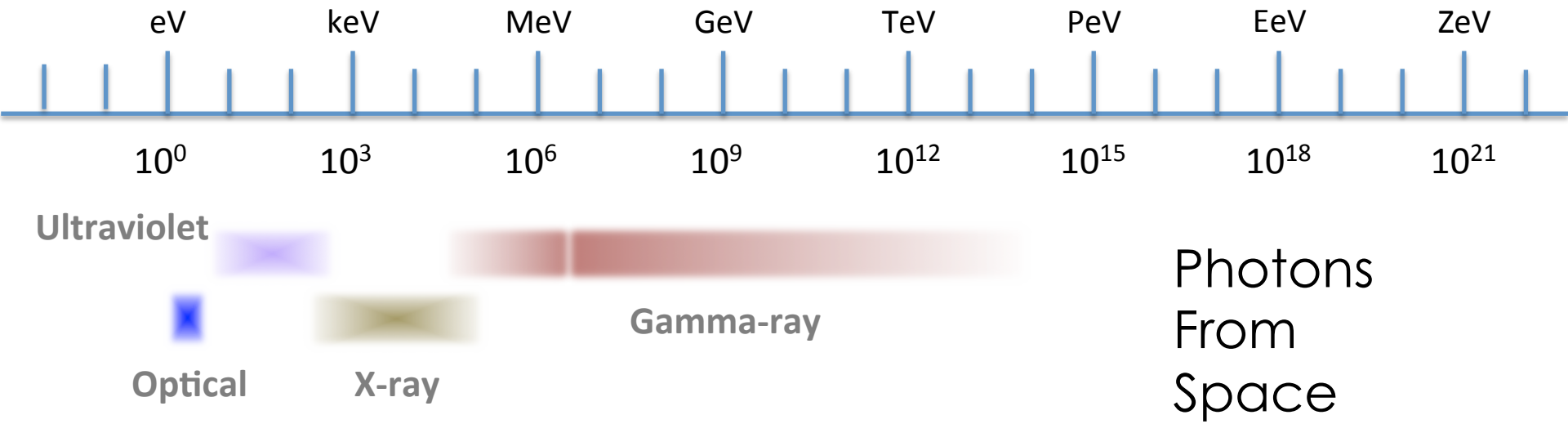
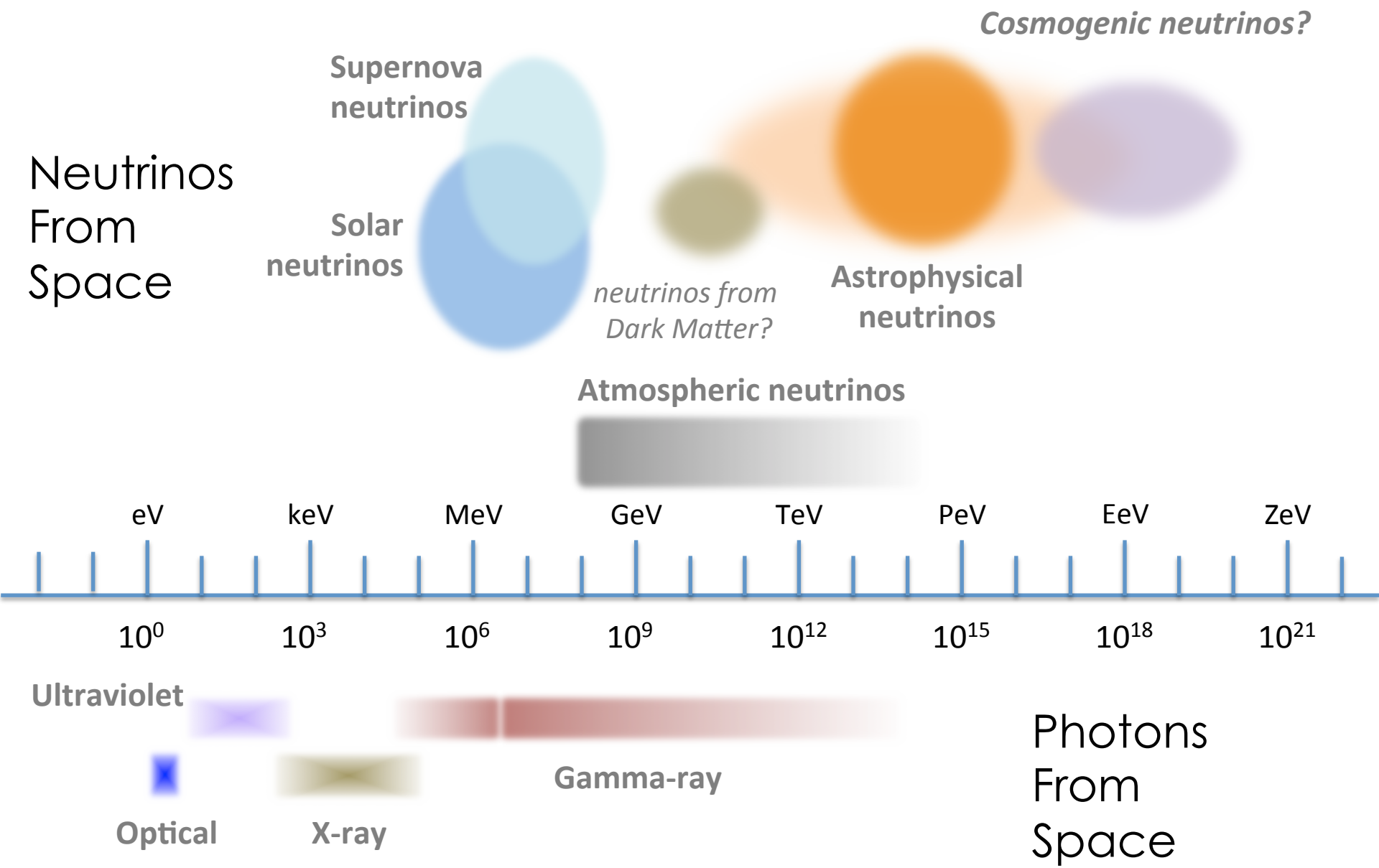




Photons From Space

Neutrino Astronomy



Complementarity…

- of energy scales
- of messenger particles
- of event classes or topologies
- field of view / sky coverage
- detection technique / resolutions / systematics

Even within a single detector such as IceCube, we benefit from many internal complementarities.

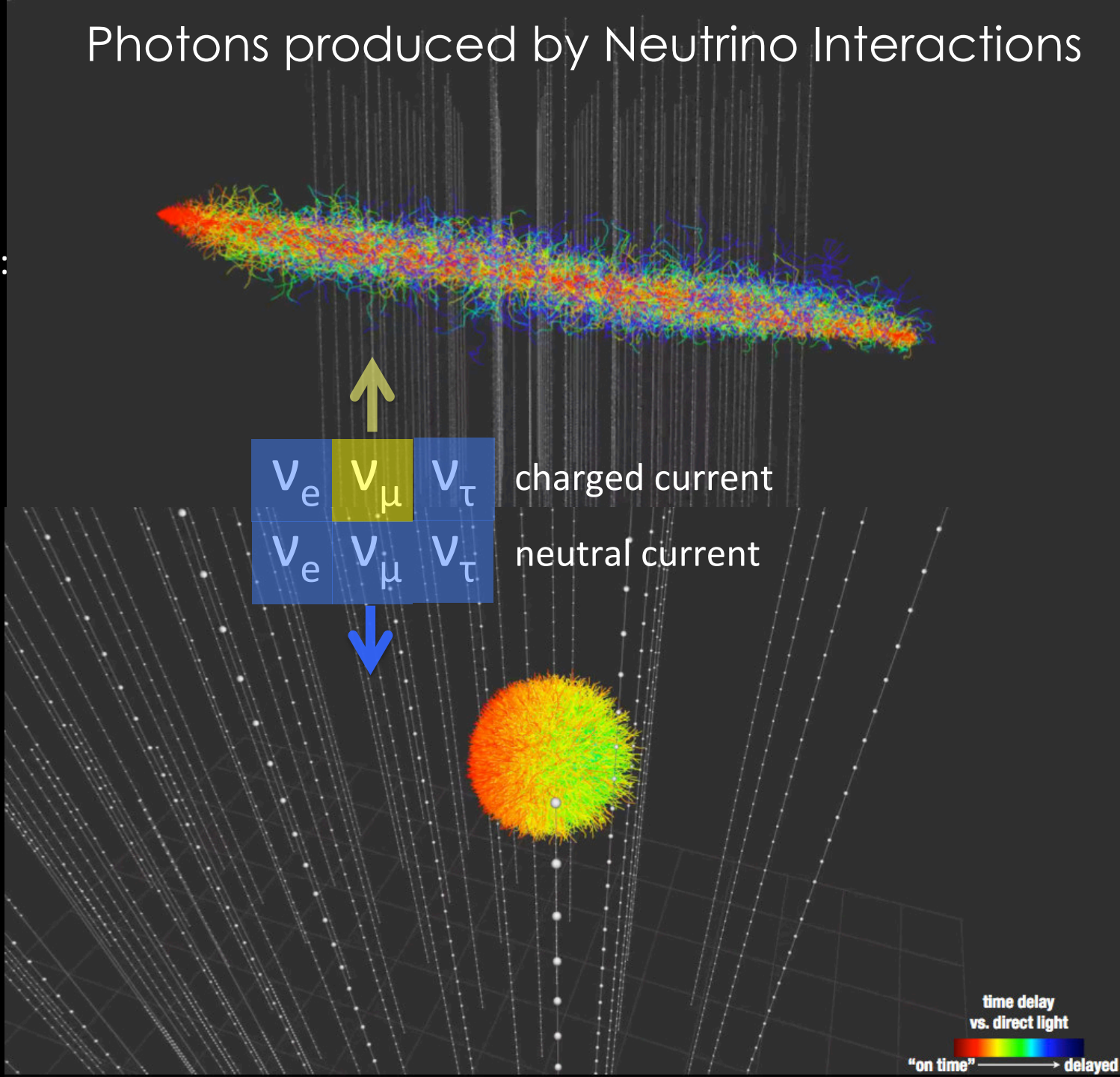
I will discuss the recent detection of a diffuse flux as an example relevant for UHEv radio arrays

Photons produced by Neutrino Interactions

Track topology

Energy measured: lower bound

Good pointing: 0.2° - 1°

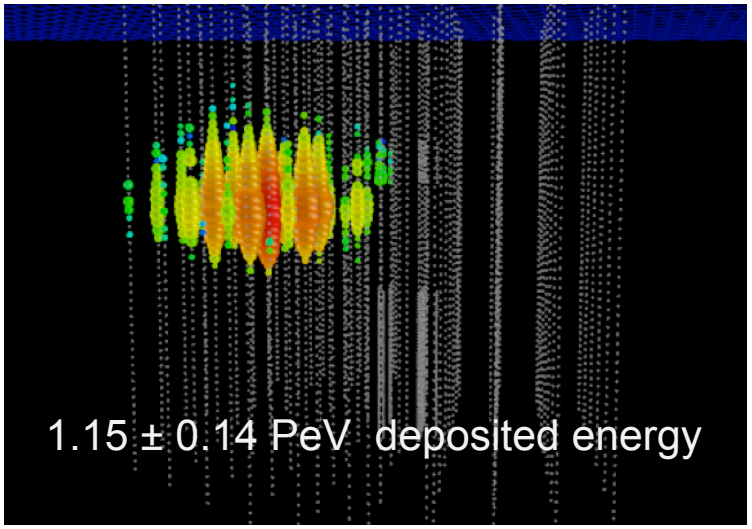


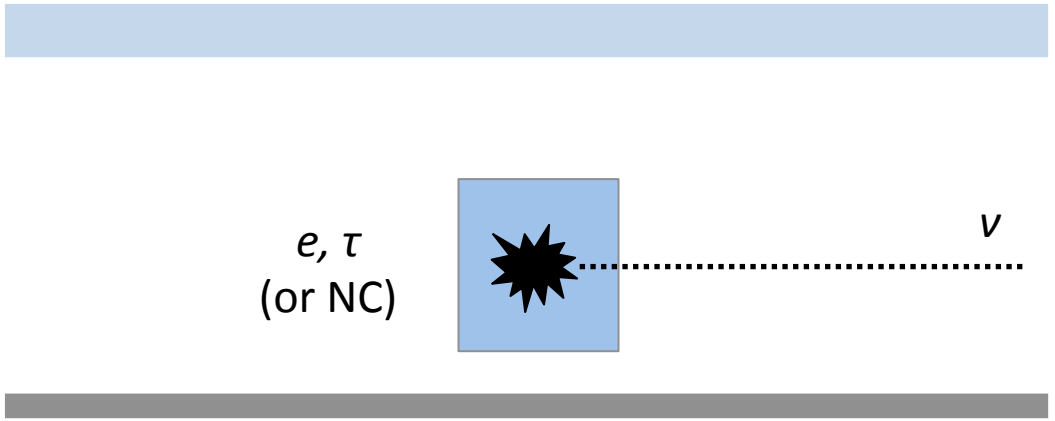
Cascade topology

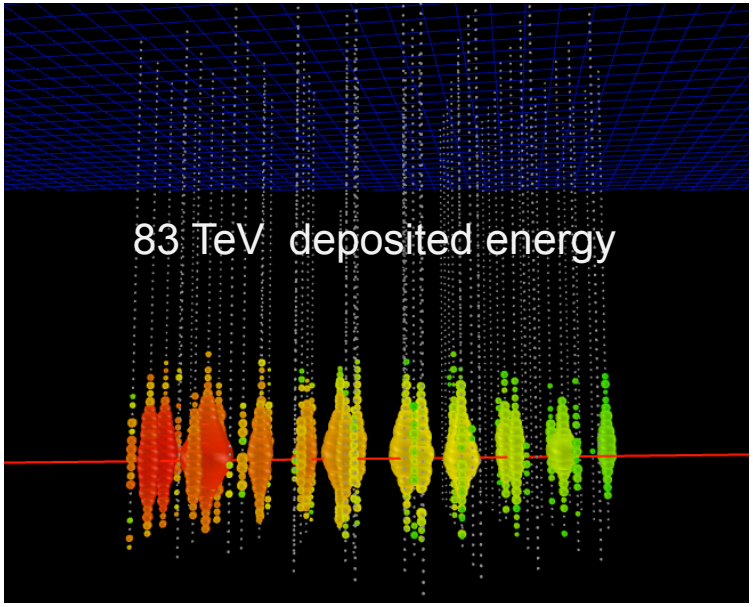
Good energy resolution, 15%

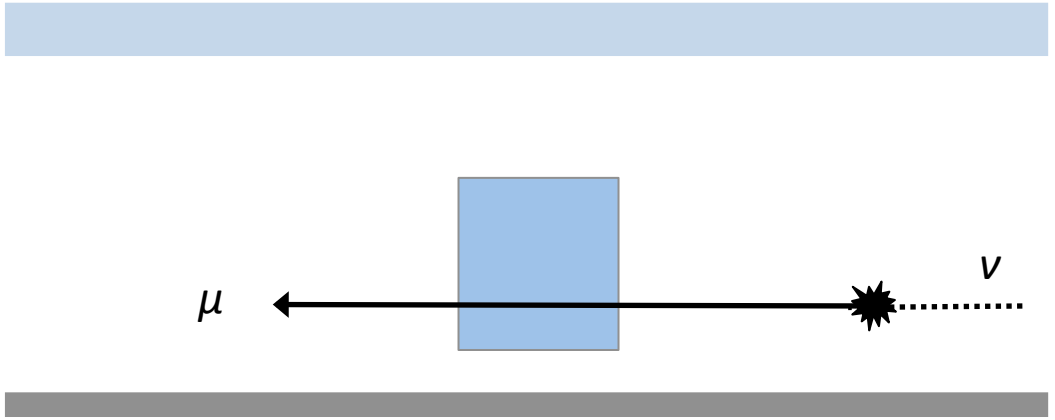
Some pointing, 10° - 15°

Shower and Track Topologies









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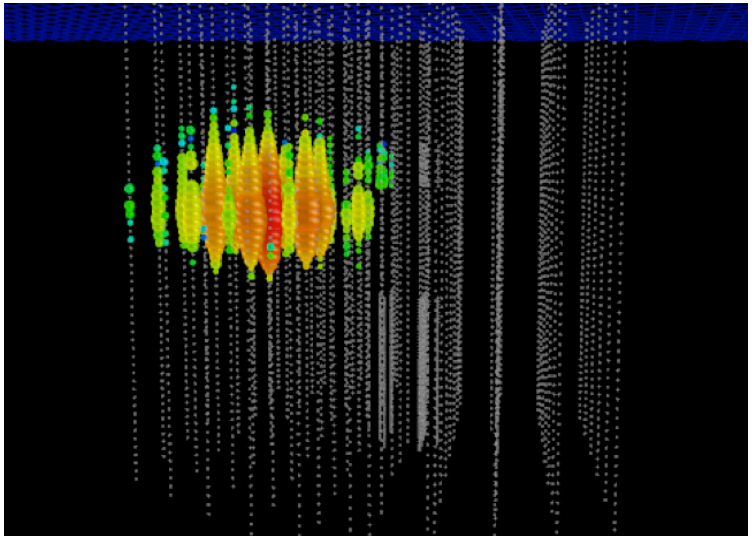
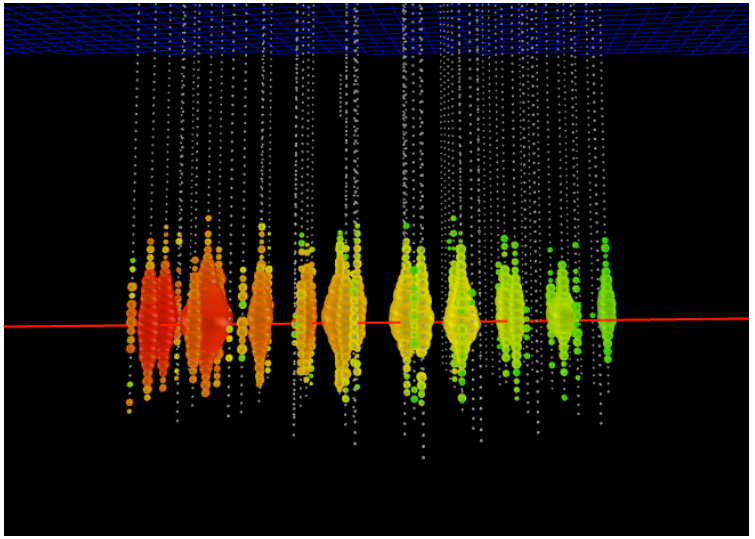


Contained Events / Shower Events:

- First detection of diffuse flux
- Measure energy spectrum



Track Events (ν_μ):

- Confirmation of diffuse flux
- Search for sources

Combined: measure neutrino flavor ratio

High Energy Starting Event Analysis

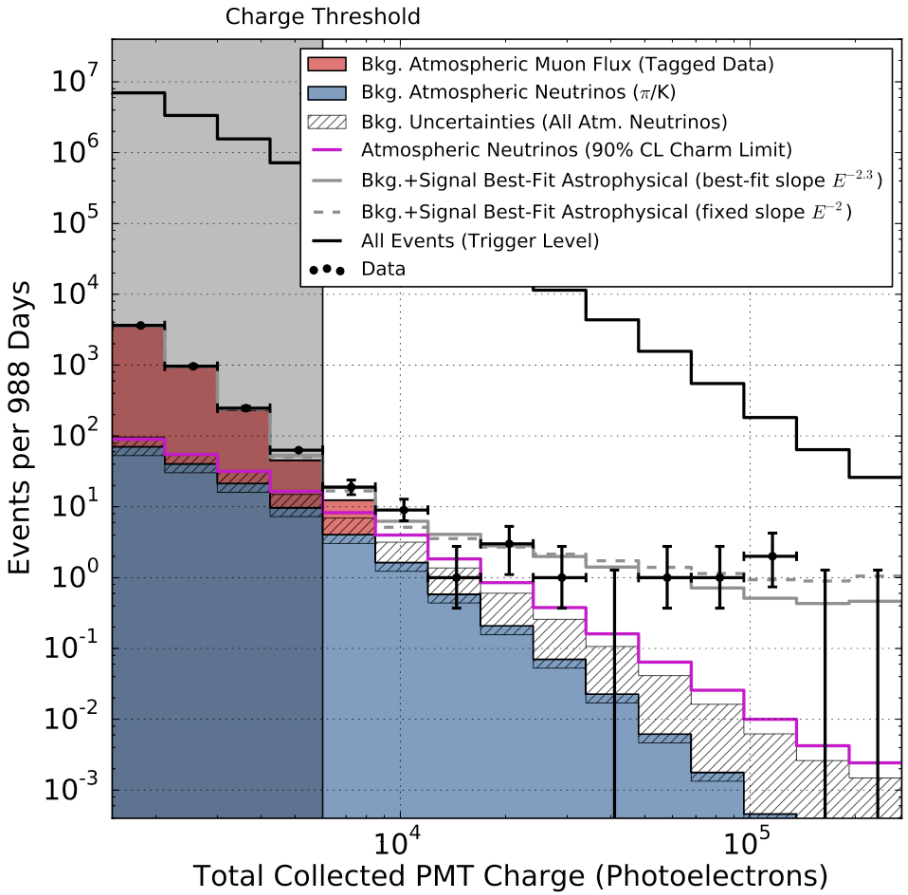
3-Year Analysis

36 events in 3 years

Note: ~ half of events are expected to be background: atm. muons and atm. neutrinos

Three events above PeV

Significance of astrophysical flux:
5.7 σ



PRL **113**, 101101 (2014)

High Energy Starting Event Analysis

3-Year Analysis

36 events in 3 years

Note: ~ half of events are expected to be background: atm. muons and atm. neutrinos

Three events above PeV

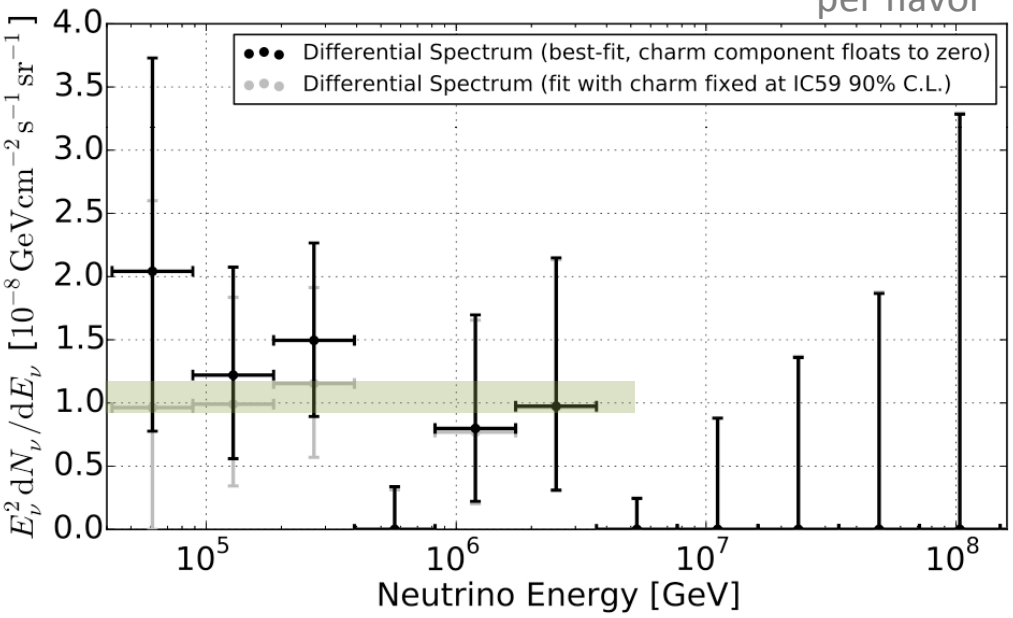
Significance of astrophysical flux:
5.7 σ

Can fit with E^{-2} up to ~ 2 PeV

Lack of events above 2 PeV
(3.1 expected in this analysis; more in the EHE analysis, PRL 111, 021103 (2013))

Suggests unbroken E^{-2} is disfavored

per flavor



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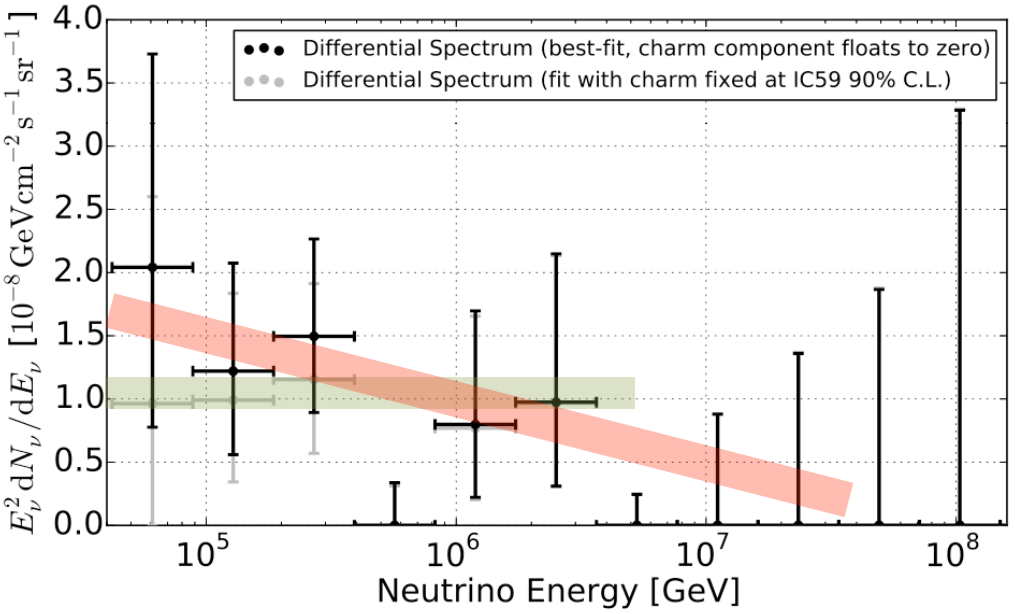
Three events above PeV

Significance of astrophysical flux:
5.7 σ

Best power-law fit gives spectral index: -2.3

In that case, no need for (or evidence of) a break or cut-off in spectrum



PRL **113**, 101101 (2014)

High Energy Starting Event Analysis

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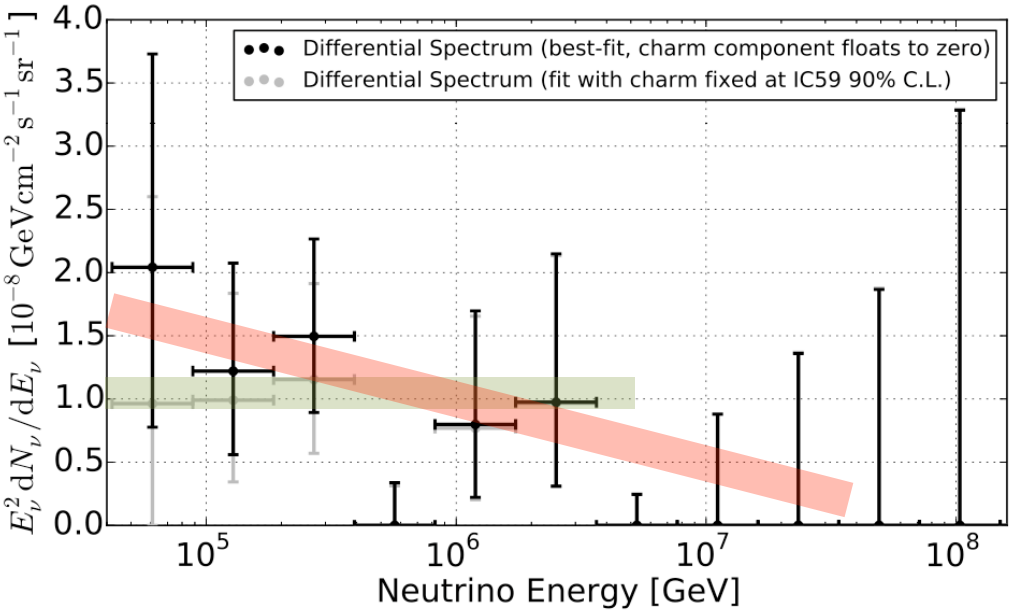
Note: ~ half of events are expected to be background: atm. muons and atm. neutrinos

Three events above PeV

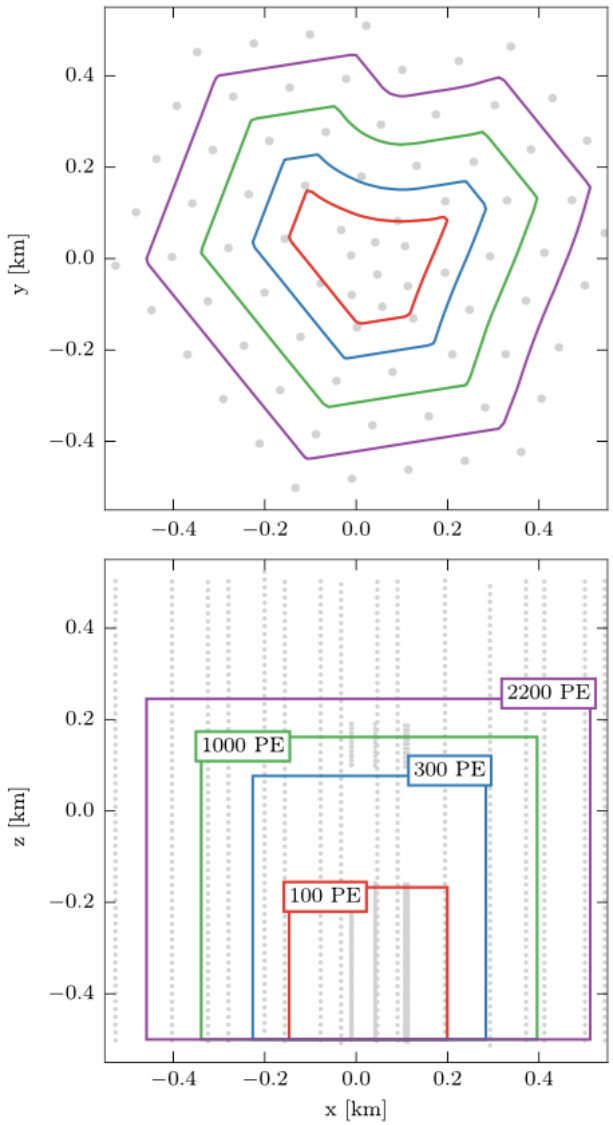
Significance of astrophysical flux:
5.7 σ

Results based on approx. 15 astrophysical signal events with good energy resolution (~ 15%)



PRL **113**, 101101 (2014)

Mid-Energy Starting Event Analysis



New analysis this fall (2 years of data):

Nested layers of vetoes

Series of lower energy thresholds deeper inside the veto

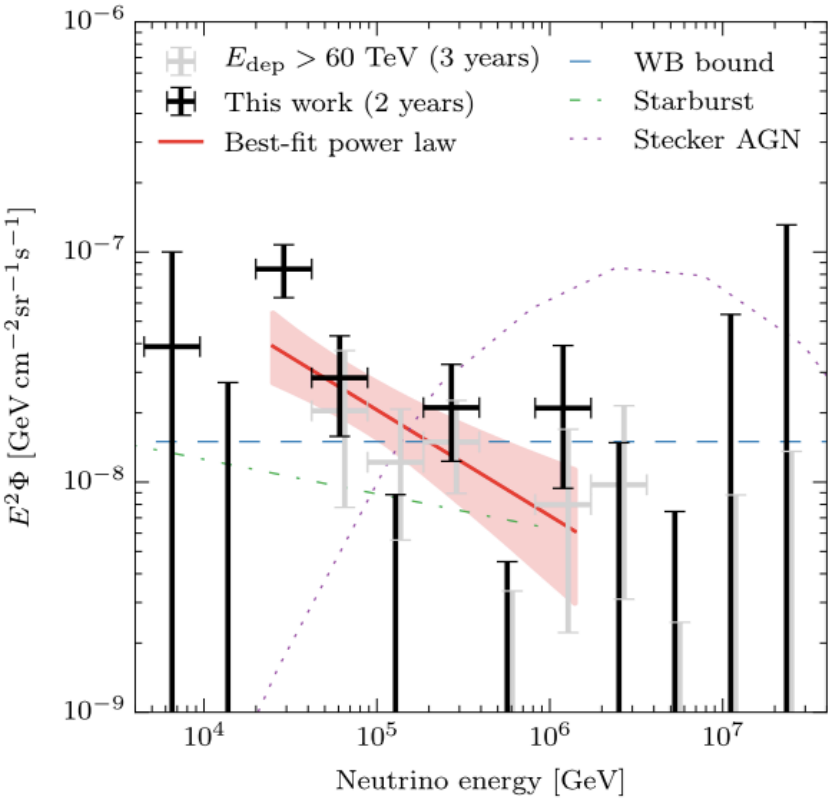
Events as low as ~ few TeV in sample

388 events selected in 2 years of data

87 ± 14 astrophysical neutrinos

PRD 91:022001 (2014)

Mid-Energy Starting Event Analysis



For the energy range:

20 TeV – 2 PeV

best-fit astrophysical spectral index $E^{-\gamma}$

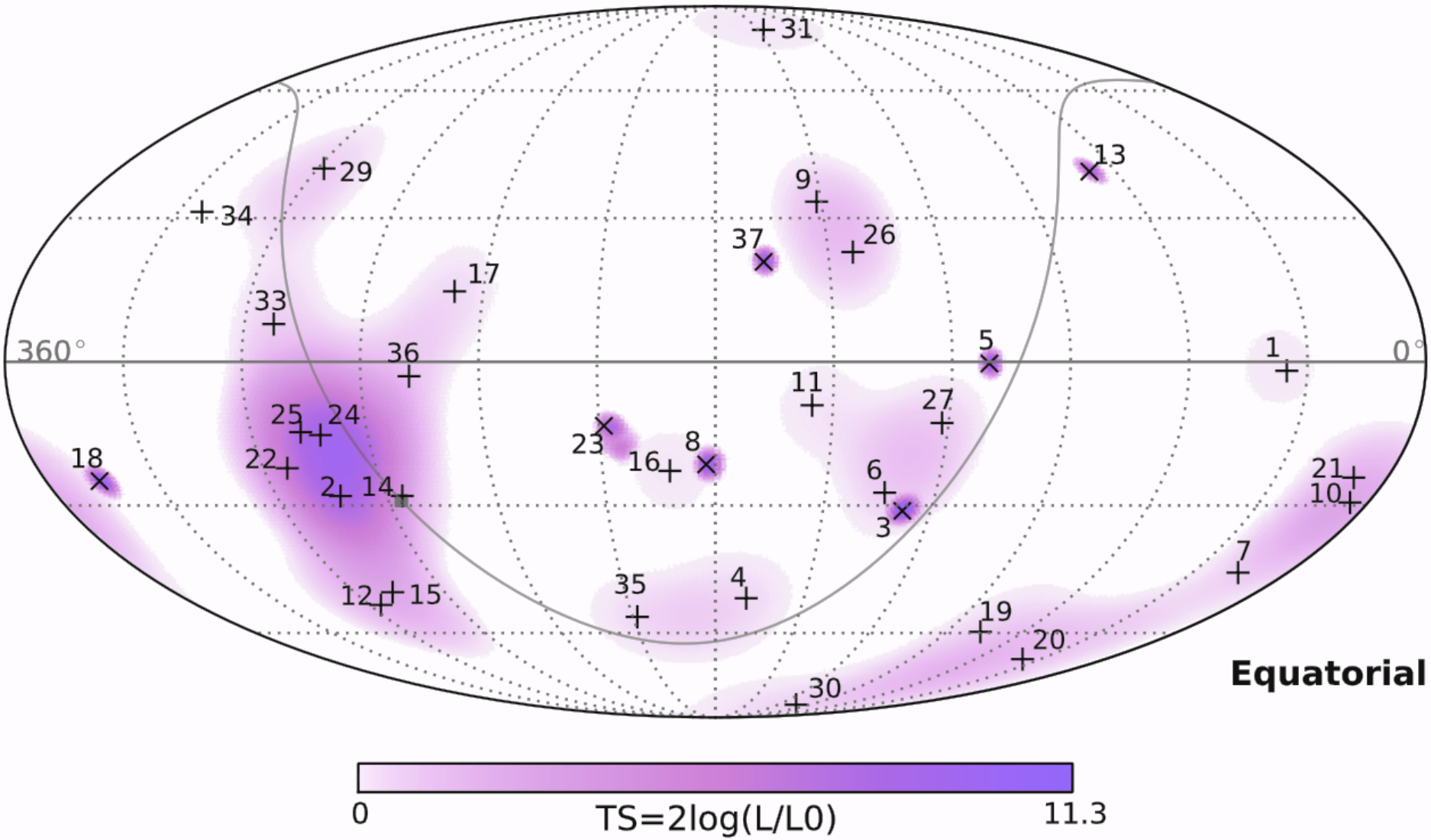
$\gamma = 2.46 \pm 0.12$

Softening of spectrum comes from additional events at lower energy, 20 – 60 TeV range

Same result as before if restricted to > 60 TeV

PRD 91:022001 (2014)

High Energy Starting Event Directions

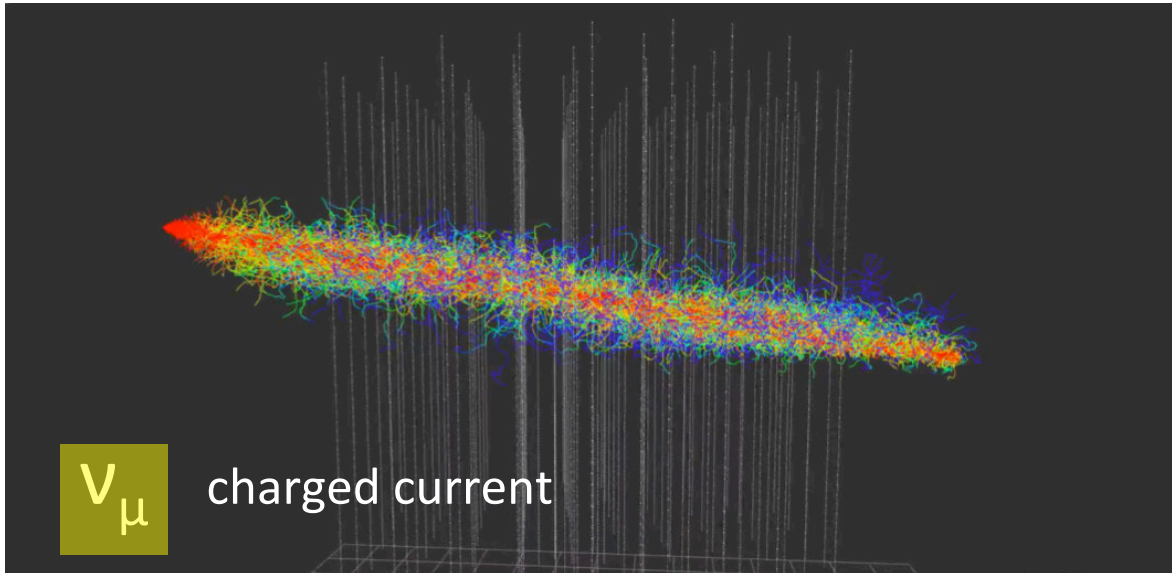


Muon Neutrino Diffuse Analysis

Complementary analysis to Starting Event analysis

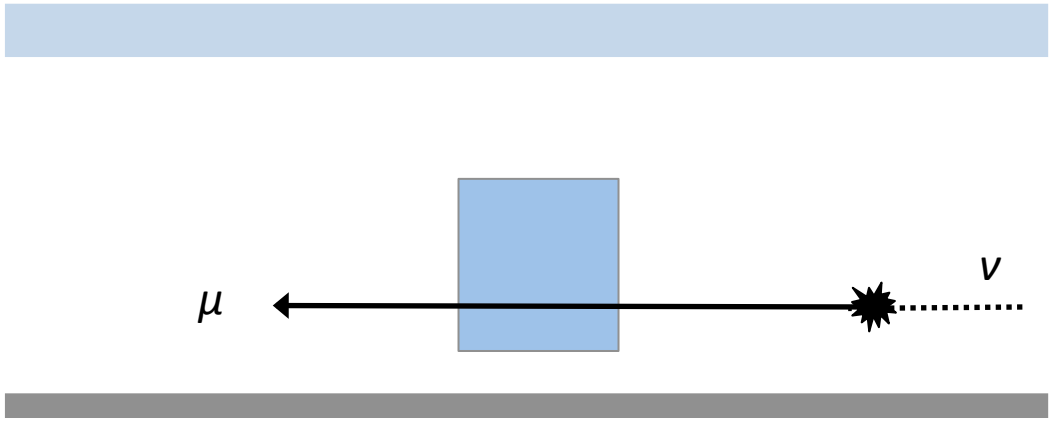
Allow tracks to enter from ***outside*** detector, use Earth as filter against muons from cosmic rays

→ muon neutrinos



$\log_{10}$ muon energy resolution ~ 0.3 (at energies ~ 100 TeV)

Good pointing: ~ 0.4°



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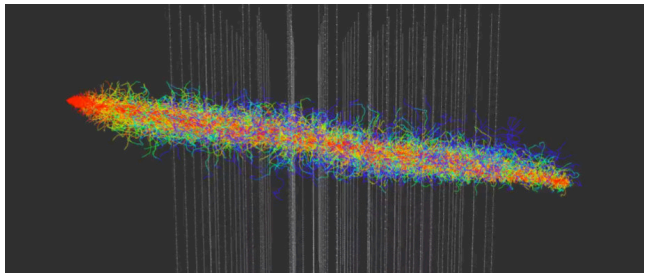


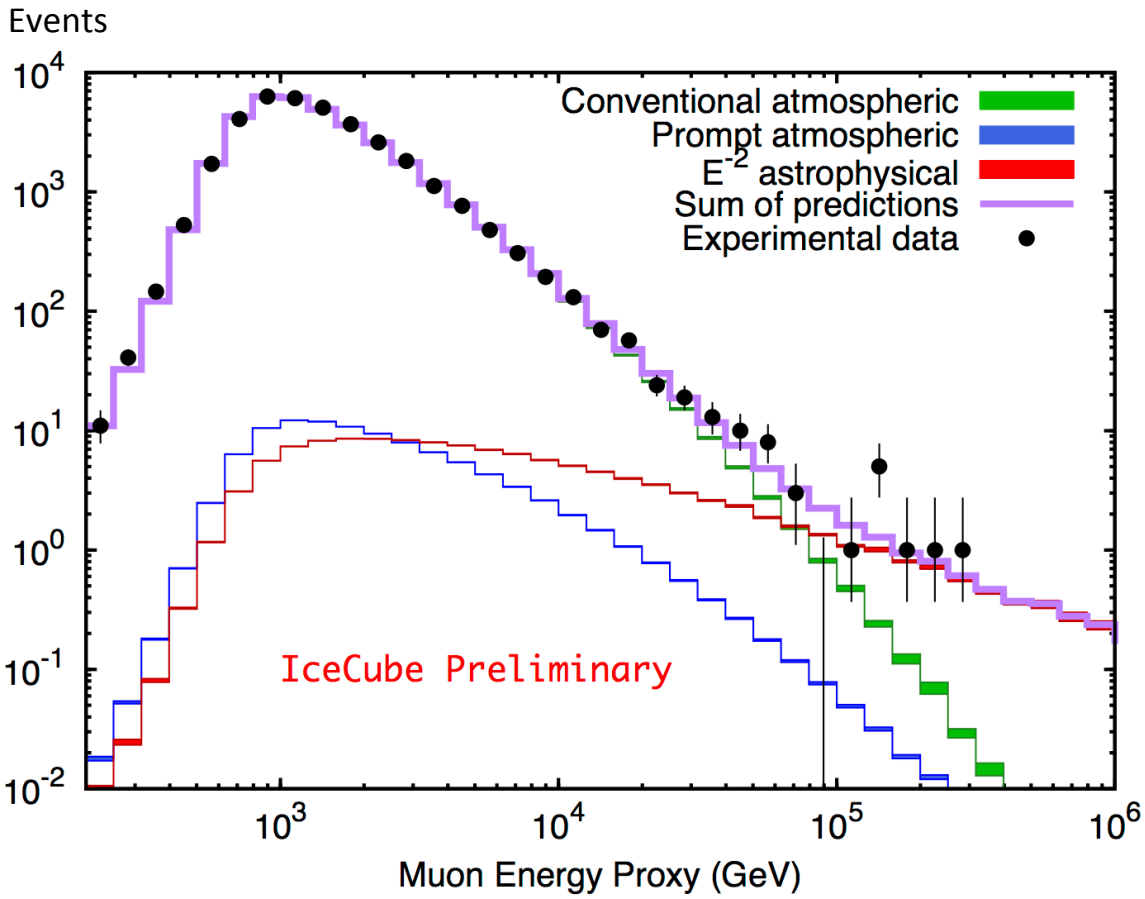
35 000 events in 2-year analysis

Estimated 99.9% pure muon neutrino sample

(use Earth as filter)

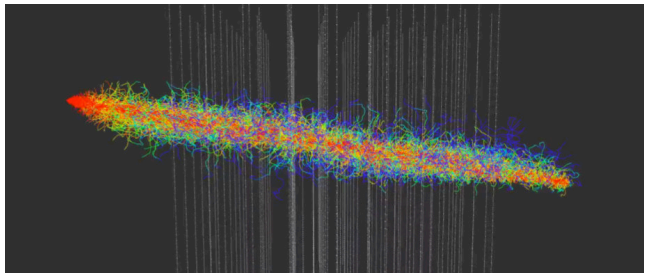
3.9σ evidence of astrophysical flux

(nearly) **independent** of starting event analyses



Energy estimate for the muon track.

Muon Neutrino Diffuse Analysis



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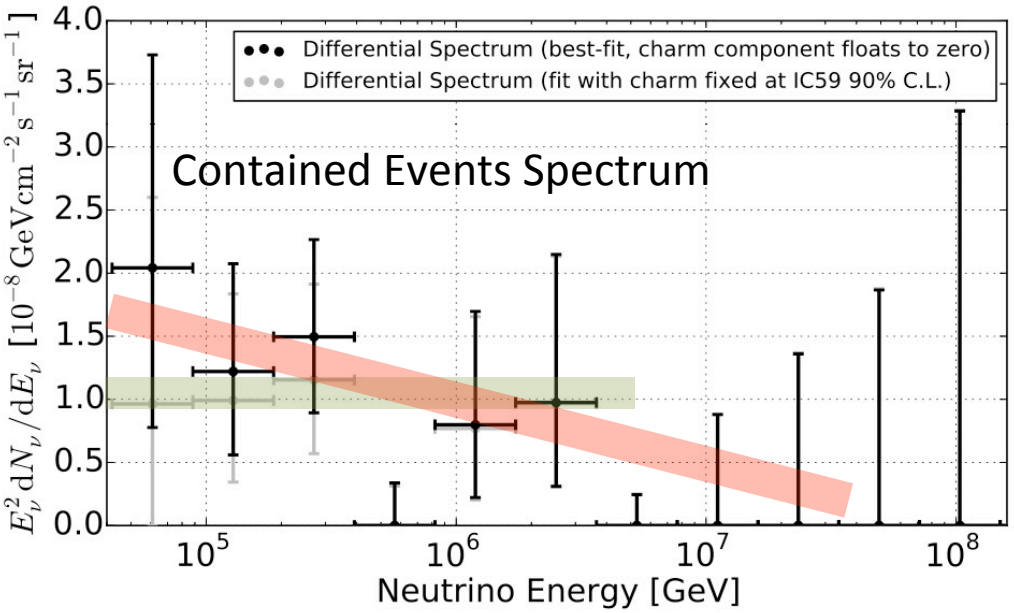
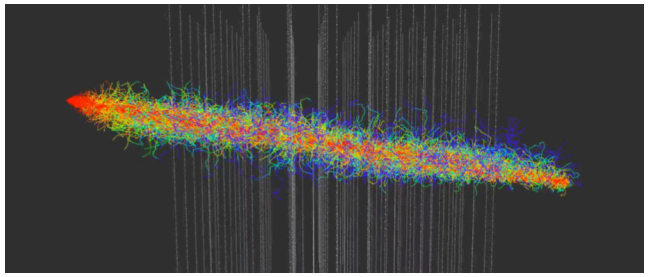


Compare spectrum measurement with before…

Muon Neutrino Diffuse Analysis



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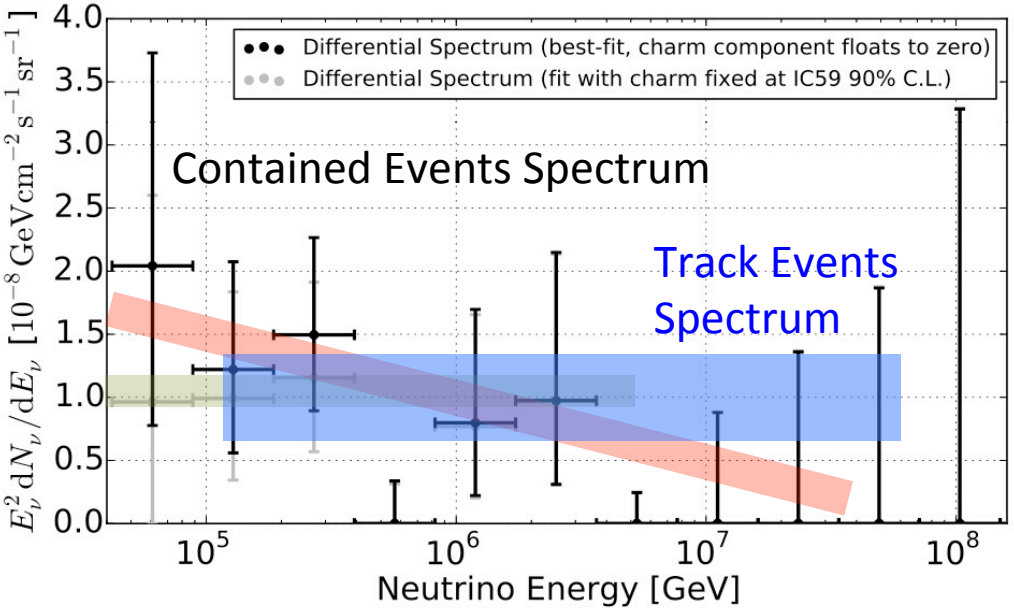
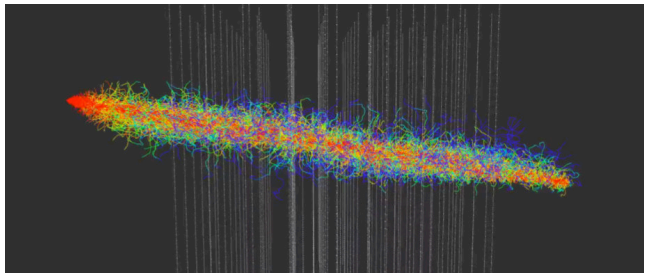


Compare spectrum measurement with before…

Larger uncertainty due to:

- factor 2 uncertainty of muon energy
- muon energy only lower bound on neutrino energy

Muon Neutrino Diffuse Analysis

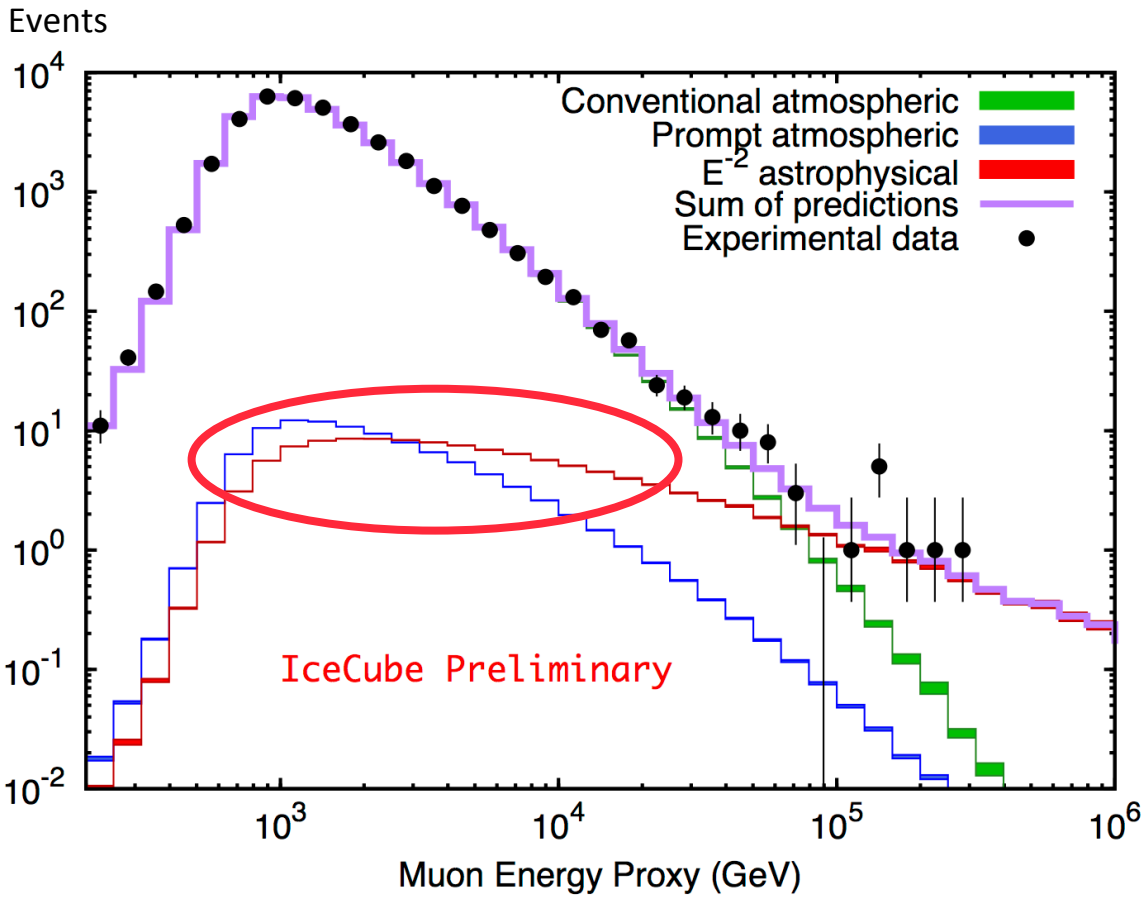


Diffuse Measurement only sensitive at energies above atmospheric neutrino backgrounds

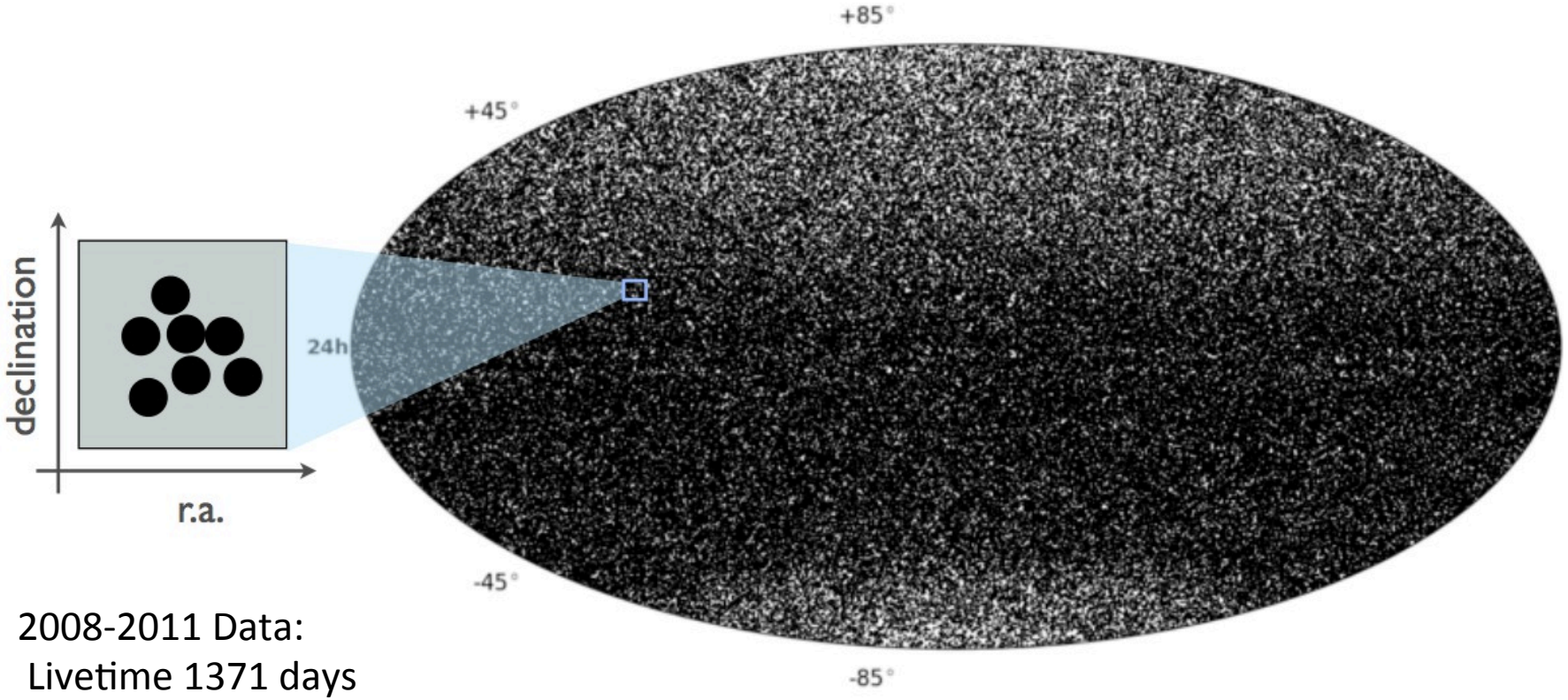
E^{-2} spectrum implies ~ **100** astrophysical events per year in track sample

$E^{-2.5}$ implies ~ **600** tracks / yr

Ang. Res. ~ 0.5° ➔ Point Source Search



Point Source Analysis



2008-2011 Data:
Livetime 1371 days

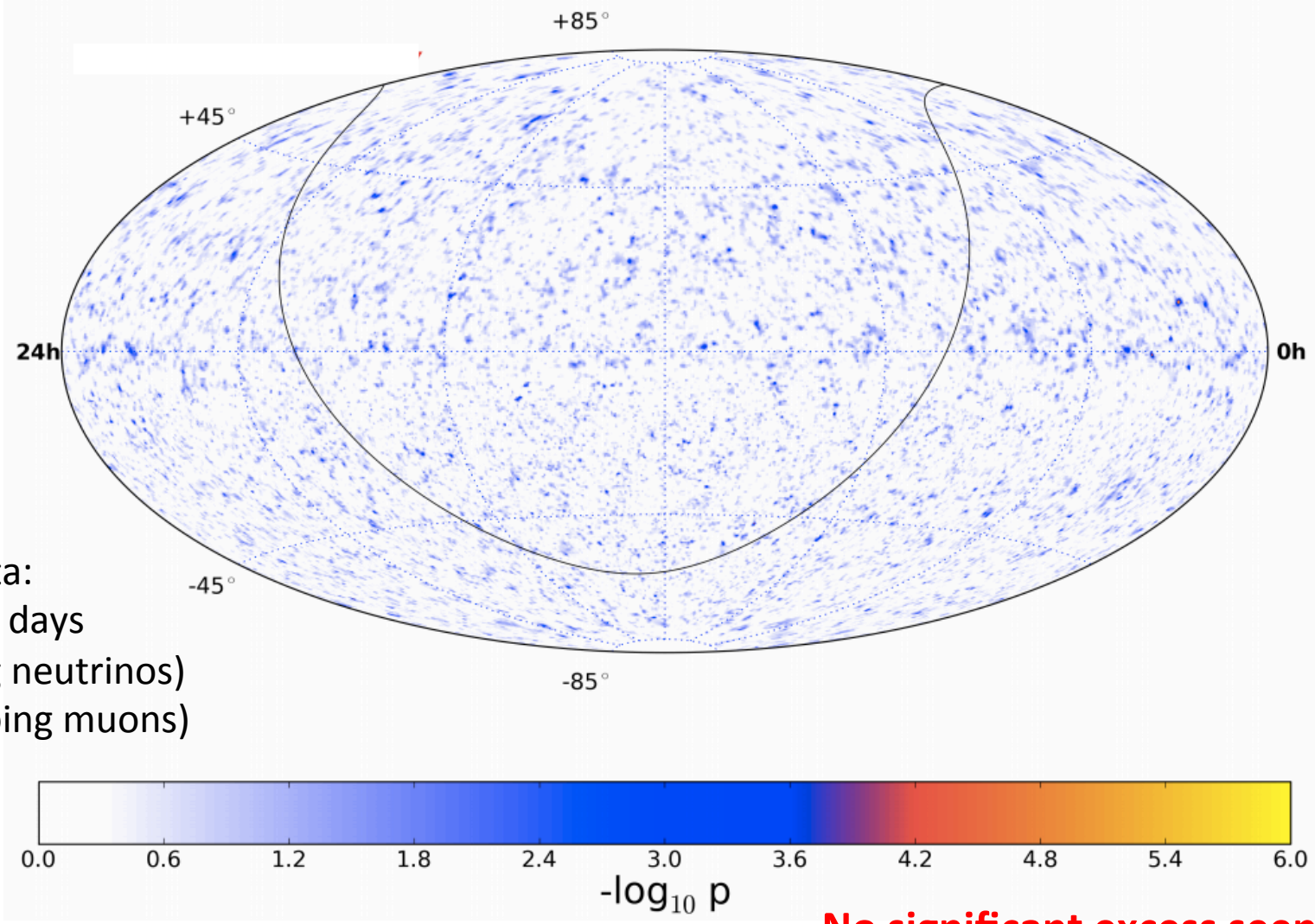
178 000 upgoing neutrinos

216 000 downgoing CR muons

Perform a search looking for significant clustering of events above random background expectation (unbinned maximum likelihood analysis)

Point Source Analysis

ApJ 796:109 (2014)

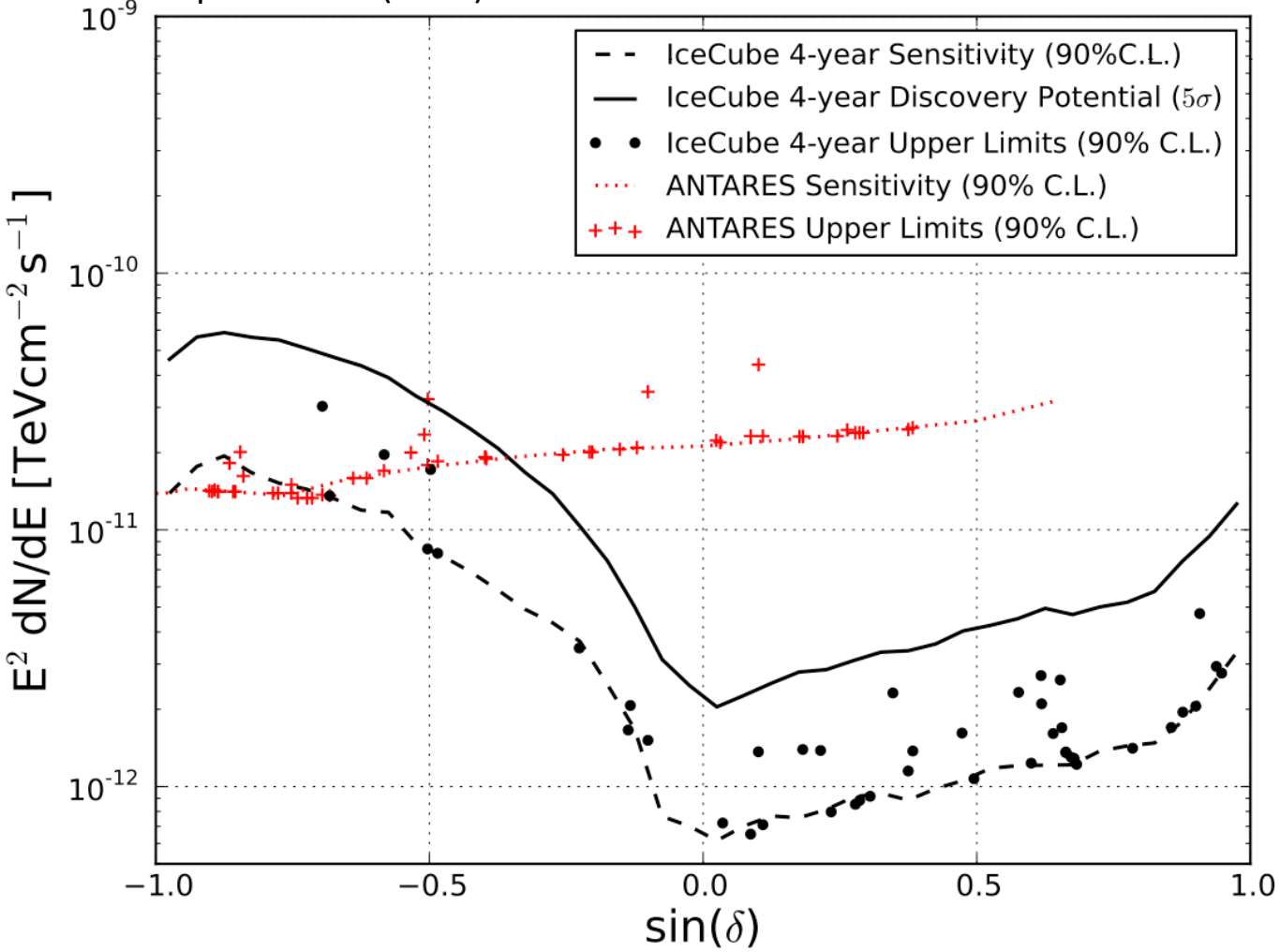


2008-2011 Data:
Livetime 1371 days
178k (upgoing neutrinos)
216k (downgoing muons)

No significant excess seen

Point Source Analysis

ApJ 796:109 (2014)



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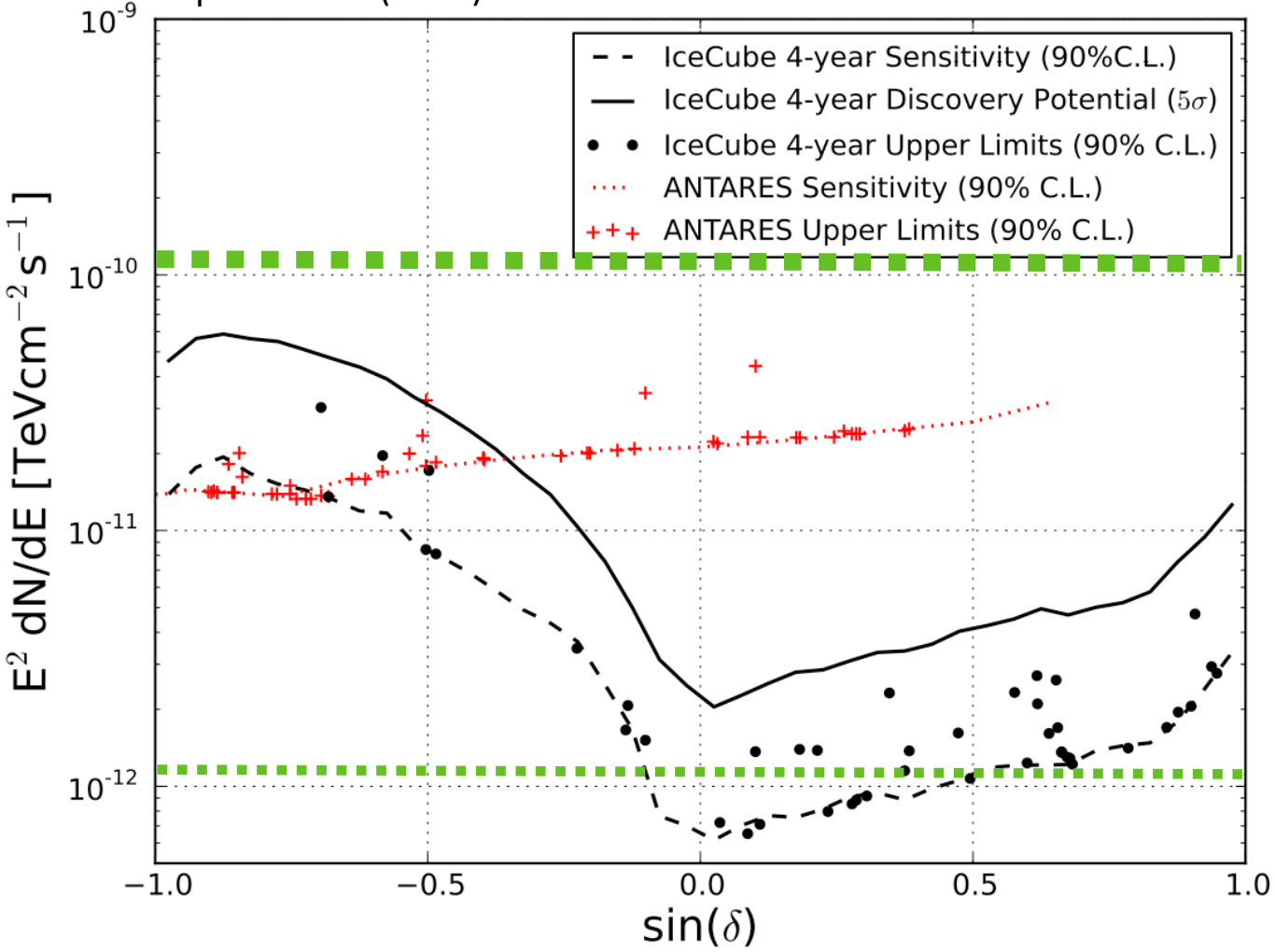


IF:

100% of diffuse flux from **one** point in the sky

10% of diffuse flux from **10** points in the sky

1% of diffuse flux from **10** points in the sky

Stacked Search for Neutrinos from Blazars

Stacked Neutrino Point Source Search

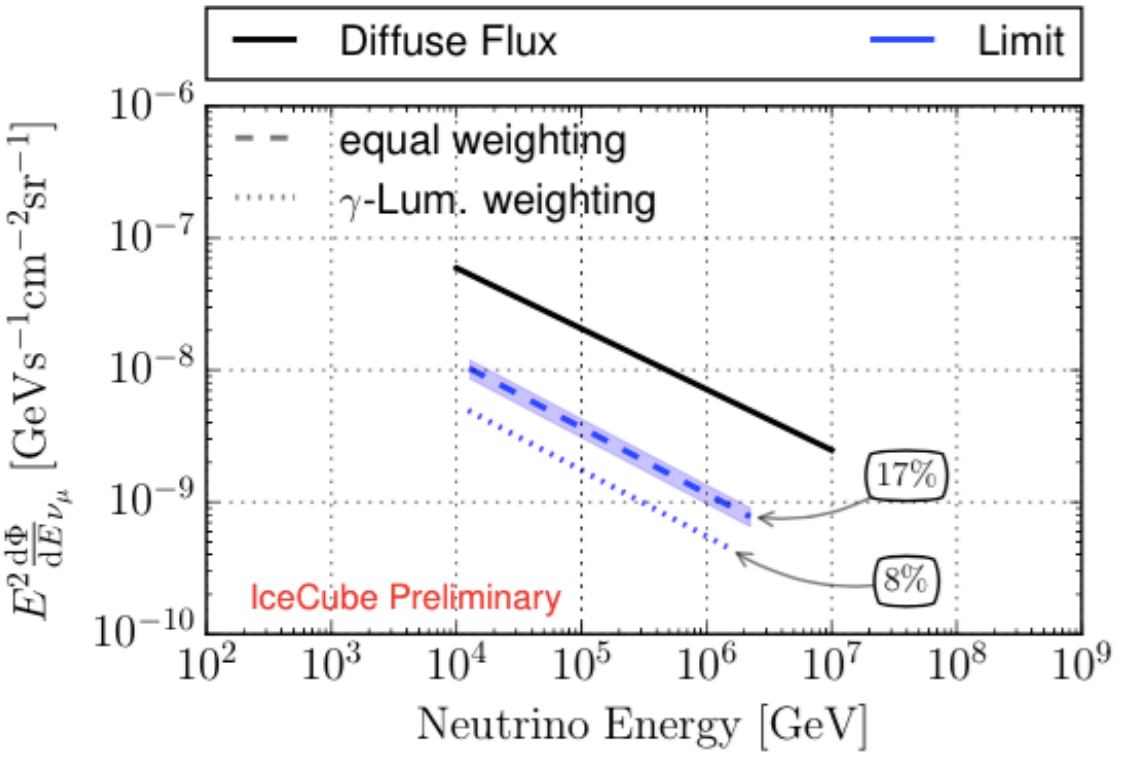
using Fermi LAT catalog of 862 Blazars

No significant excess seen

Total flux upper limit is well below measured diffuse neutrino flux

(Note: does not mean that blazars do not emit neutrinos…)

Glüsenkamp, RICAP 2014 Proceedings



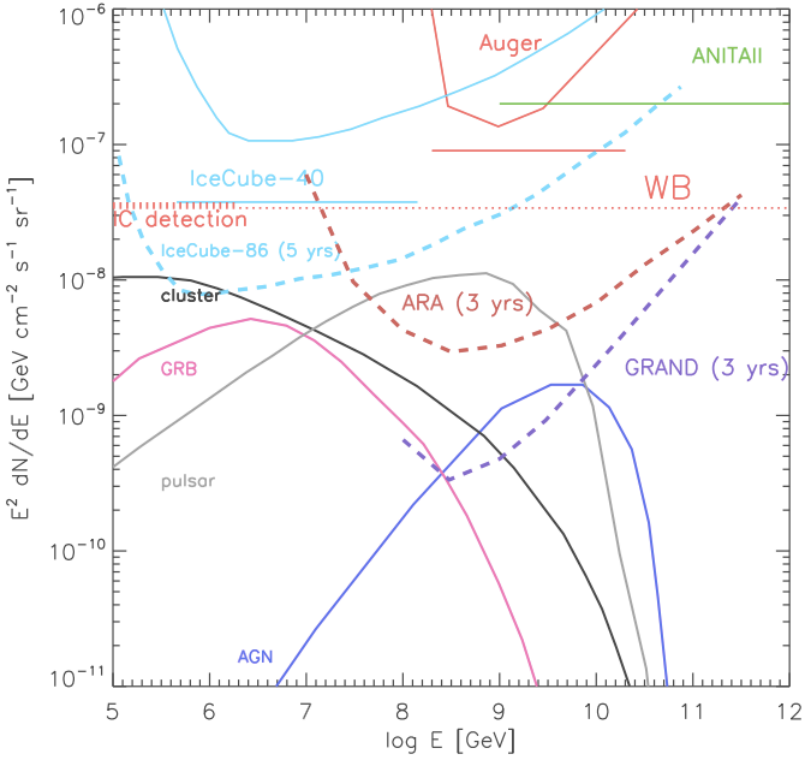
A Telescope's Reflections on Radio Array

Detecting Flux

- Be big enough! AMANDA → IceCube

Measuring Energy Spectrum

- Energy Resolution?
  - Missing energy ➔ lower bound only, but still useful over multiple decades in energy
  - For individual highest-energy events, want confidence not an overestimate



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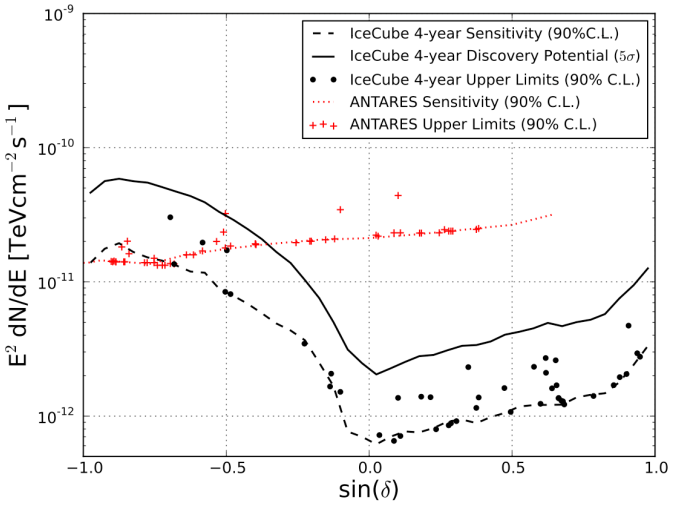
Identifying sources

- Probably need hundreds of signal events (unless sources are rare, e.g. GRBs)
- Cosmogenic neutrinos created at some distance from source, so nearby bright sources are not point-like (ang. res. less helpful)

- Skymap: What is sensitivity or exposure as function of declination? Good visibility only for select sources?



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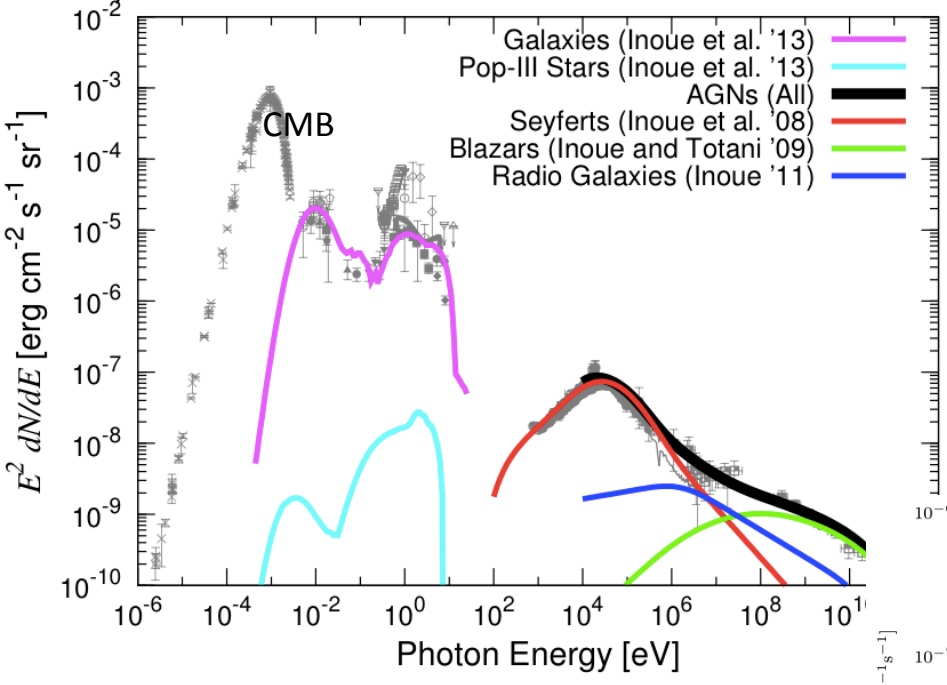
The time domain

- coincidence search with GRBs, AGN flares…
- will there be capability to send real-time alerts to optical, gamma telescopes?
  - there will be strong interest to perform rapid follow-up for outstanding HE events

Diffuse Cosmic Background

Y. Inoue, arXiv:1412.3886



Photons

Neutrinos