IceCube

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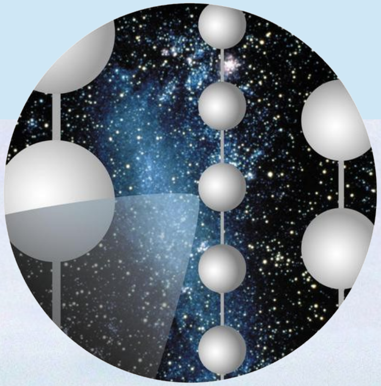
Stockholm University
Oskar Klein Centre

XVI International Workshop on Neutrino Telescopes, Venice, March 2015

The IceCube Collaboration



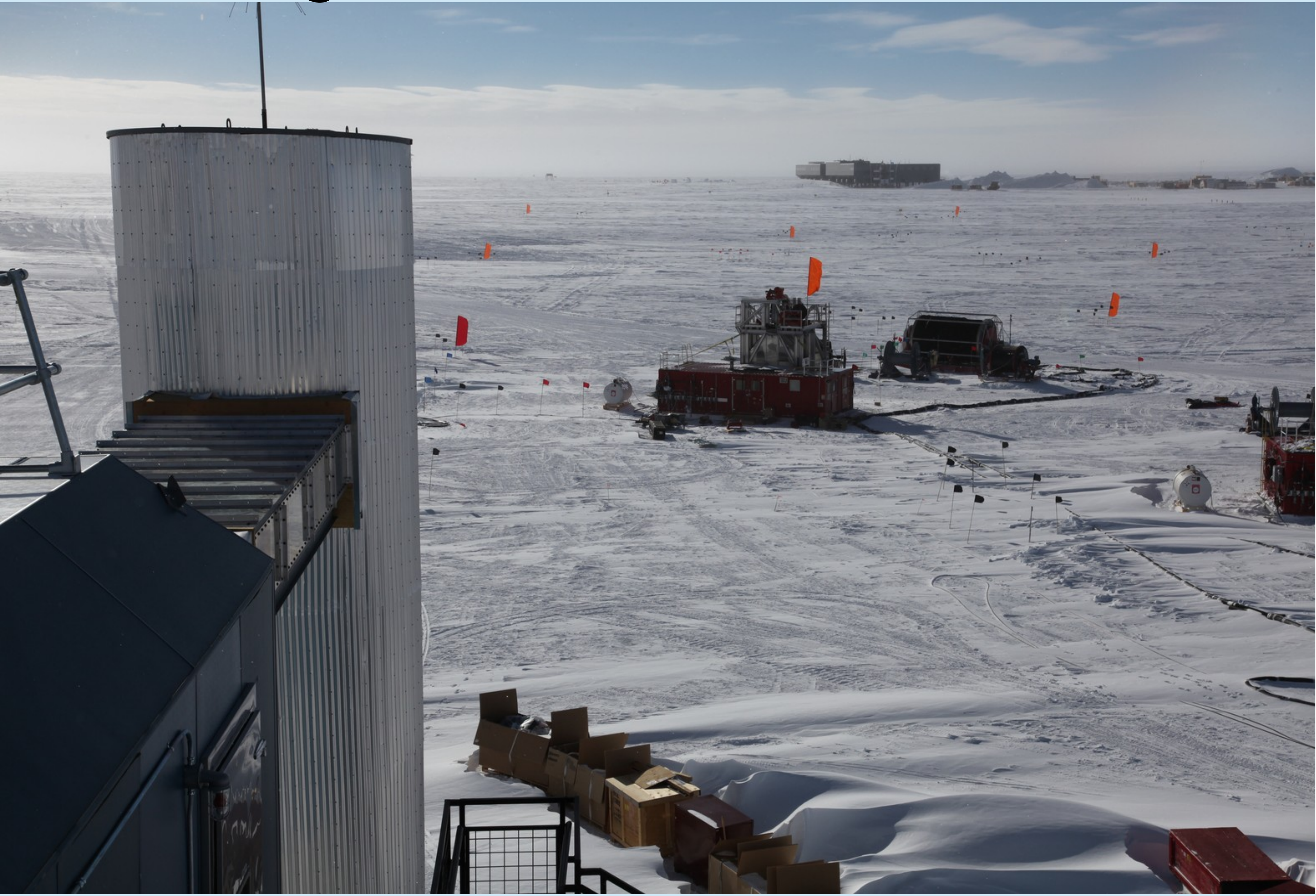
~300 physicists in 12 countries

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)

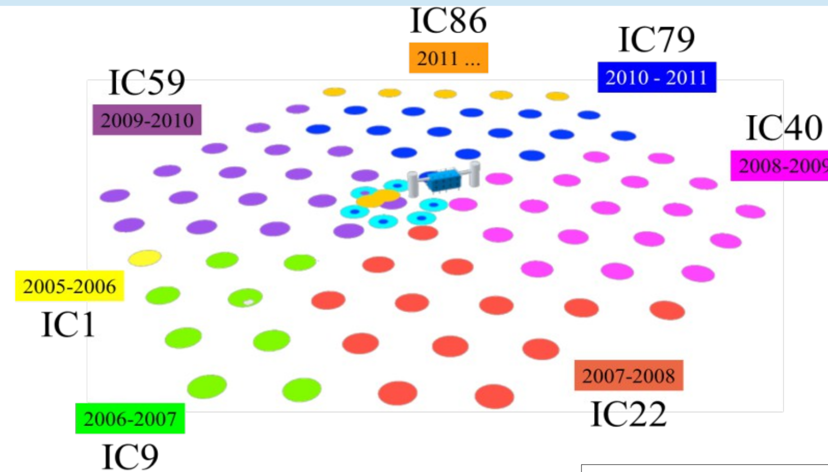
Per Olof Hulth 1943–2015

Last string down, December 2010

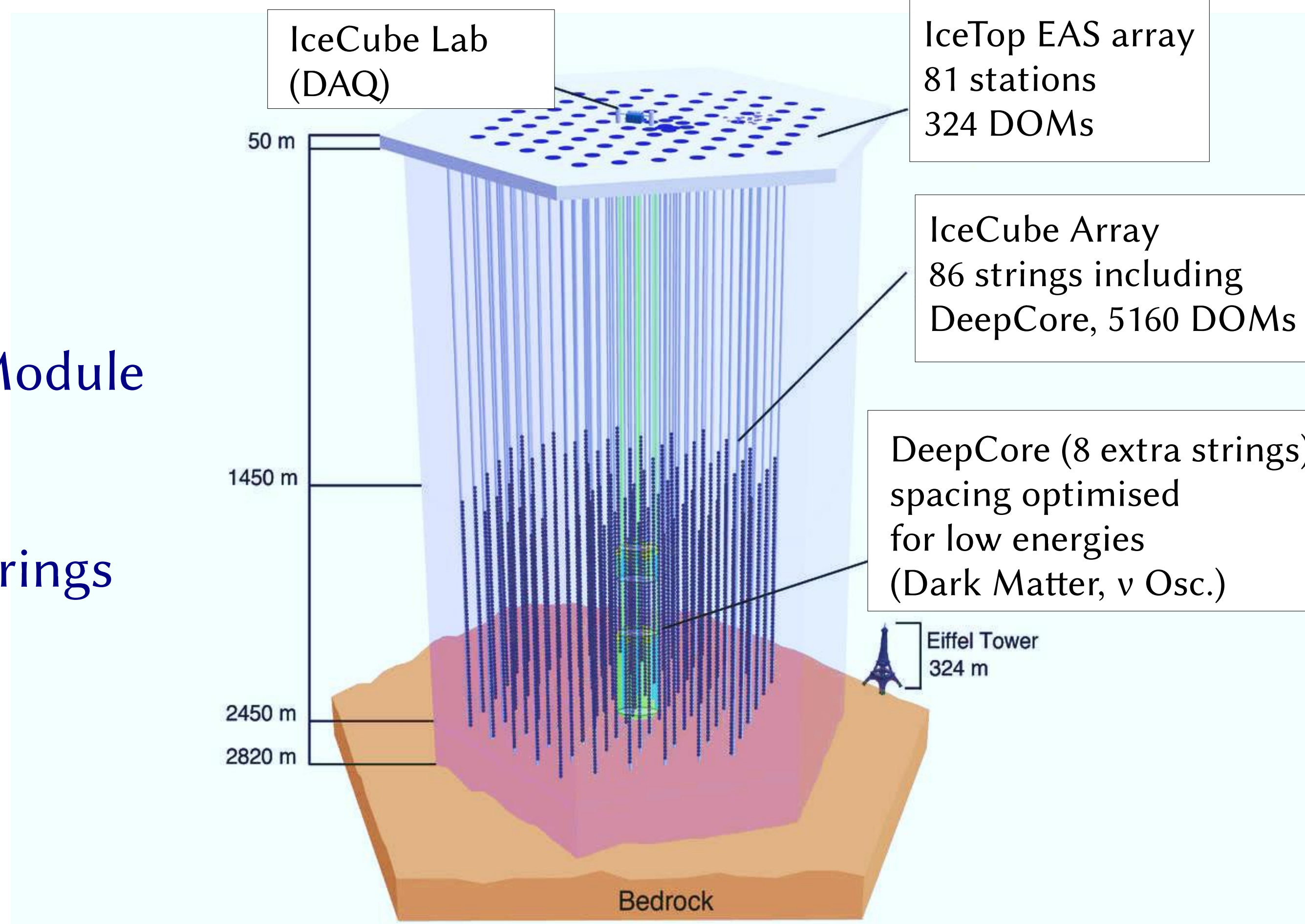


IceCube – Timeline

1993 : First AMANDA string
2000 : AMANDA completed; detection of atmospheric ν:s
2005 : IC1 deployed
2010 : IceCube completed
2013 : Detection of astrophysical ν flux
2015 : NOW
~2025: IceCube Gen2



Digital Optical Module (DOM)
17m spacing
125m between strings



IceCube physics

Opening a new window on the universe

- Supernova neutrinos
- Cosmic rays
- Atmospheric neutrinos
- Diffuse astrophysical neutrino fluxes
- Extended neutrino sources
- Point sources
- Transient sources

Closing in on fundamental physics

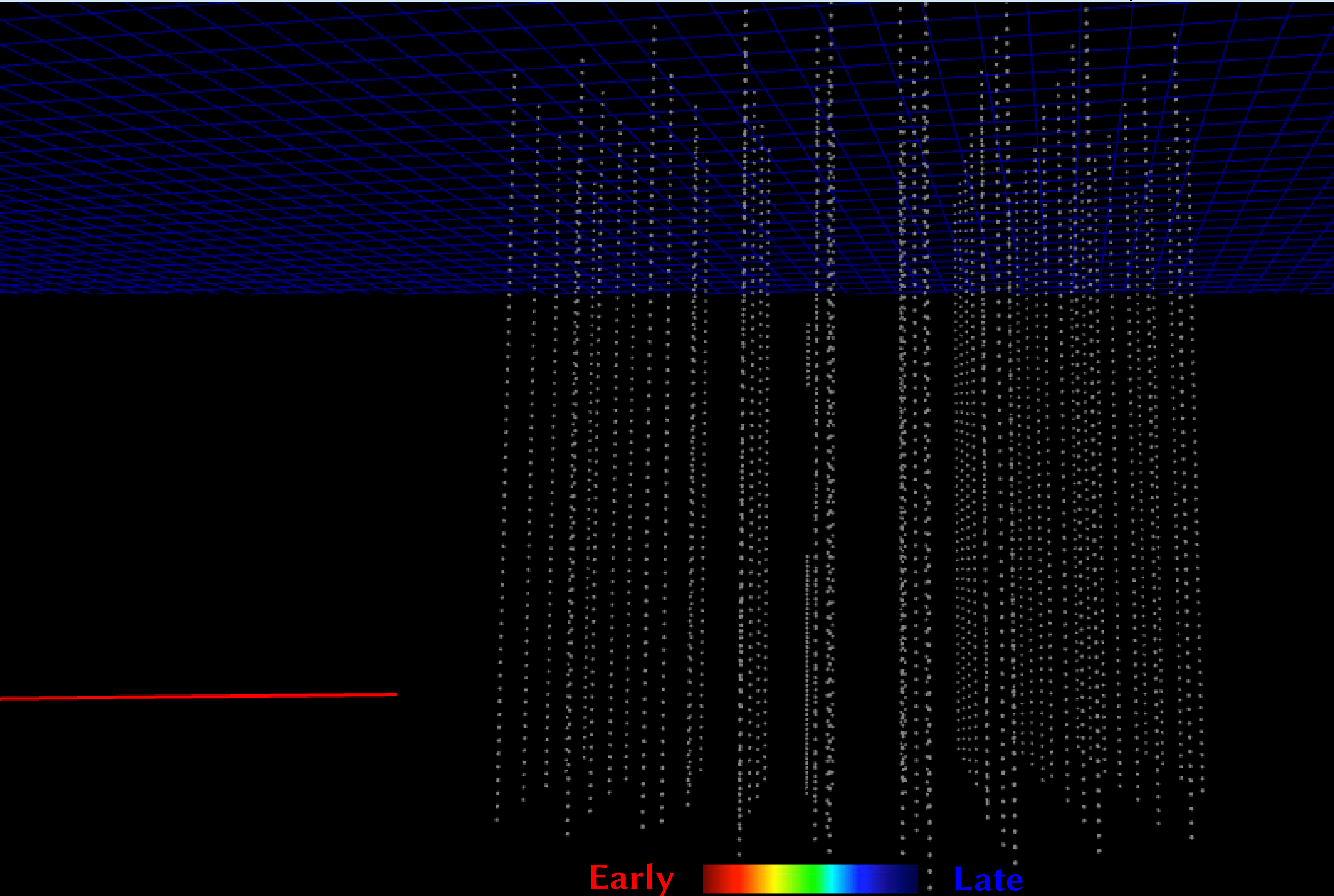
- Charm production
- Neutrino oscillations
- Dark Matter
- Exotic particles (magnetic monopoles, Q balls)
- Lorentz invariance violation
- Quantum decoherence

Outline:

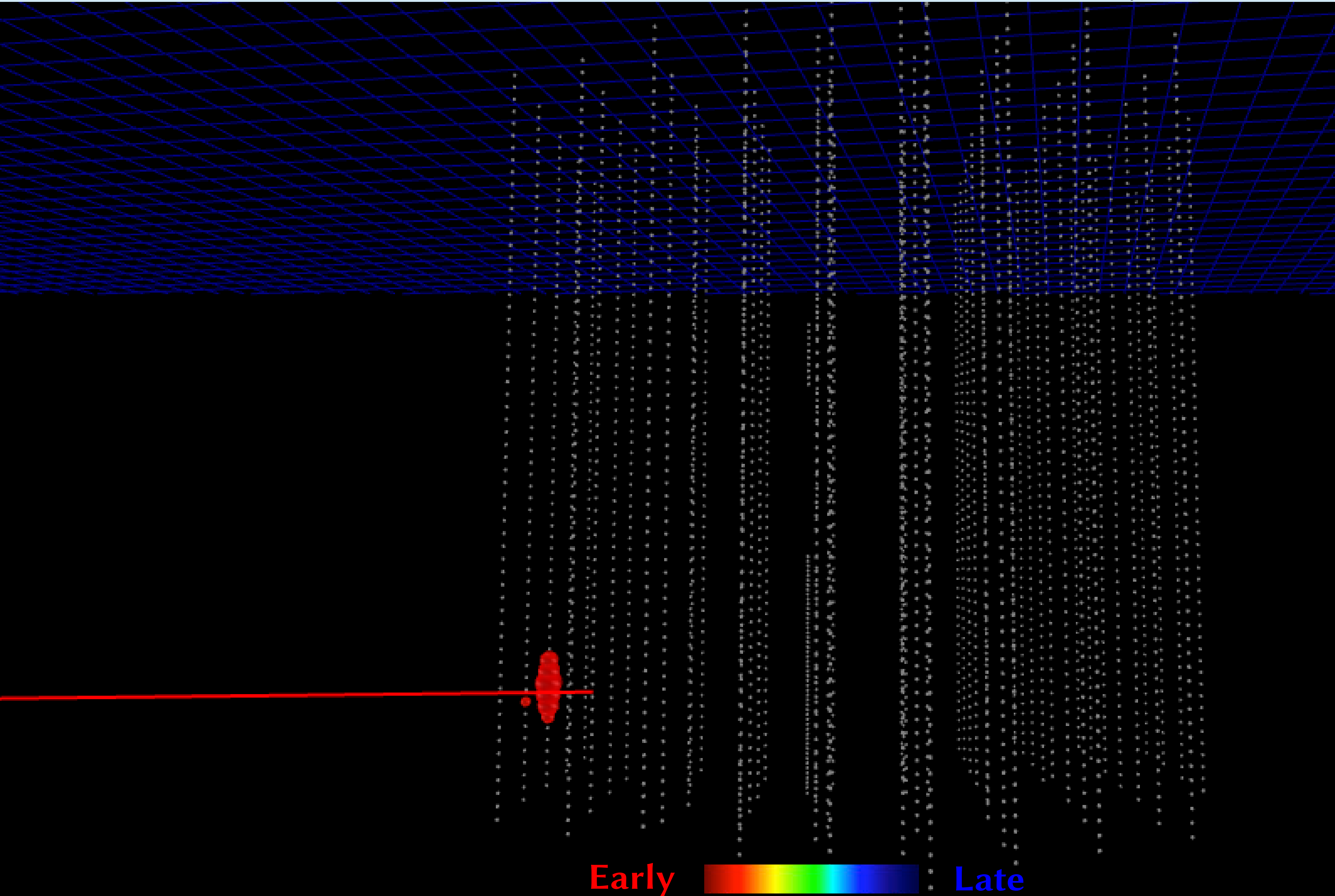
Events
Cosmic Rays
Starting Events
Flavours
Origins
What Next?

Events

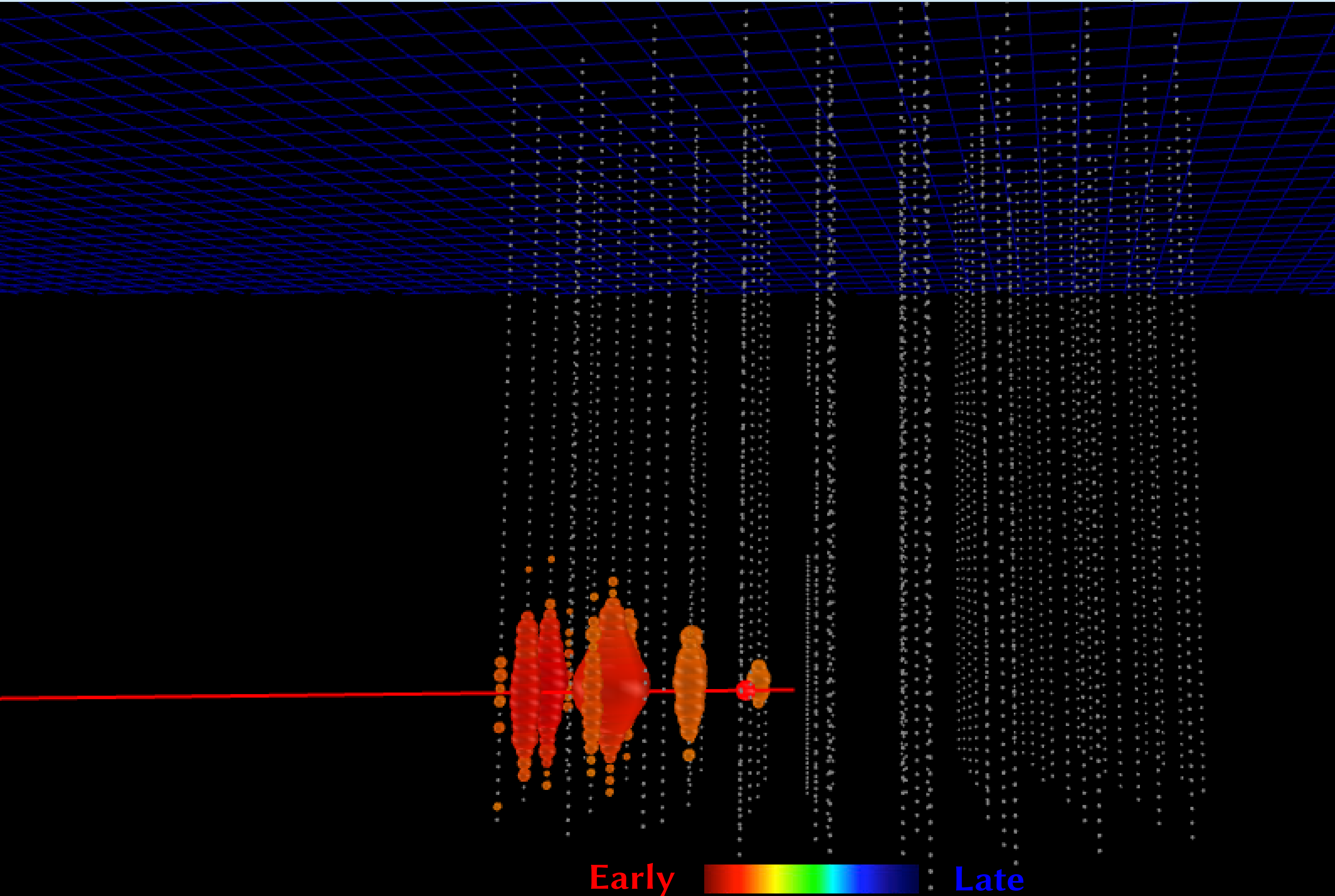
Muon track (IC59)



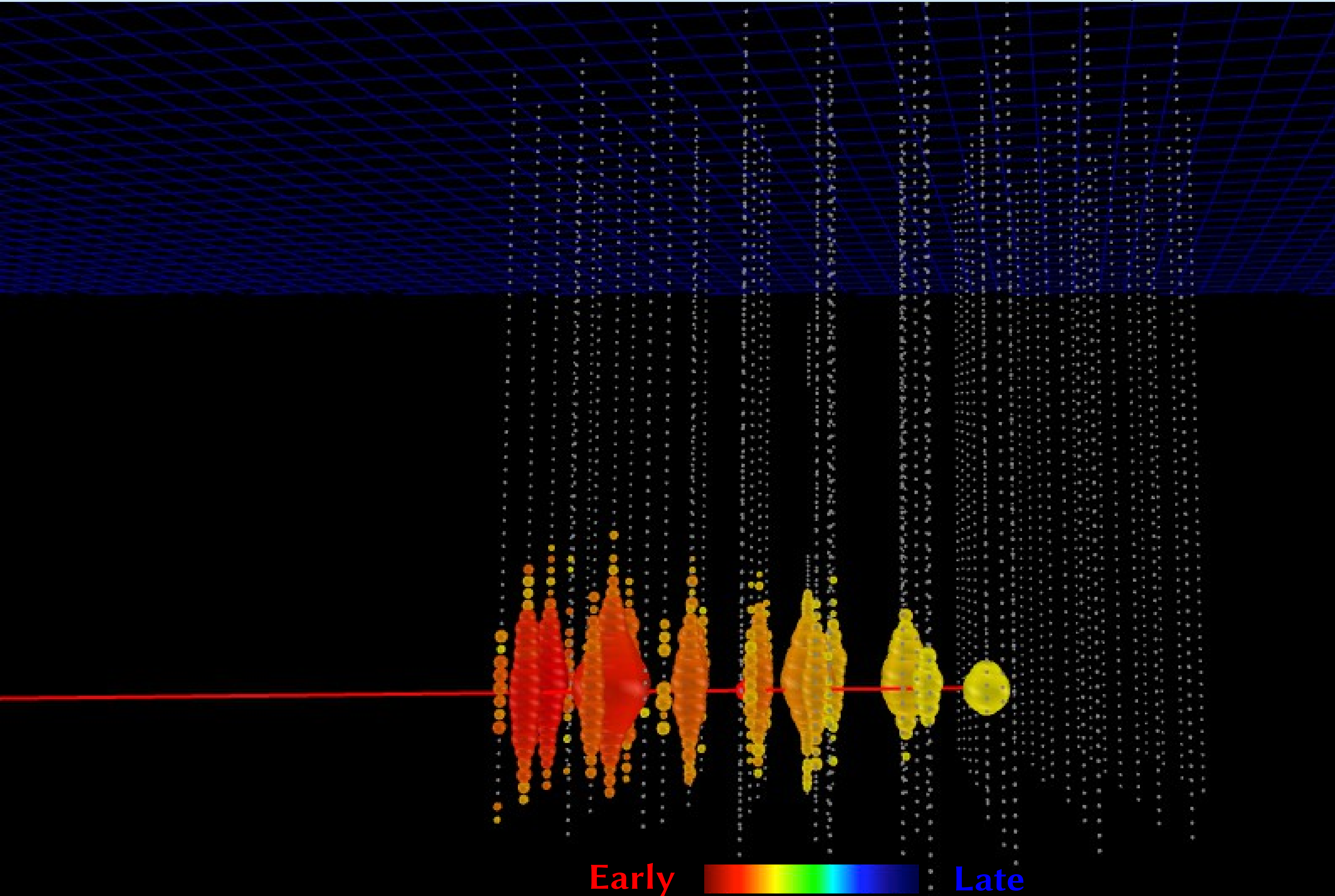
Muon track (IC59)



Muon track (IC59)



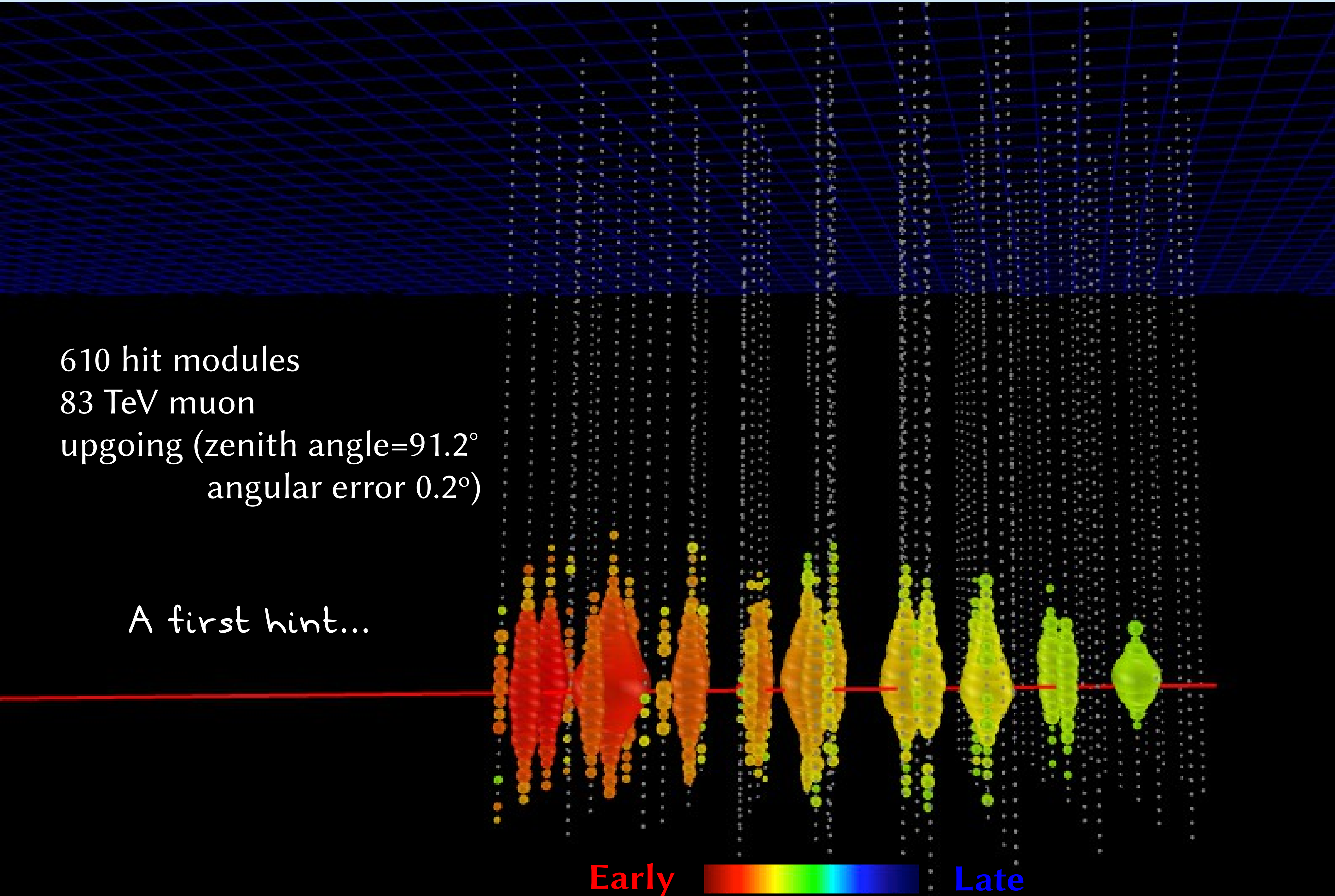
Muon track (IC59)



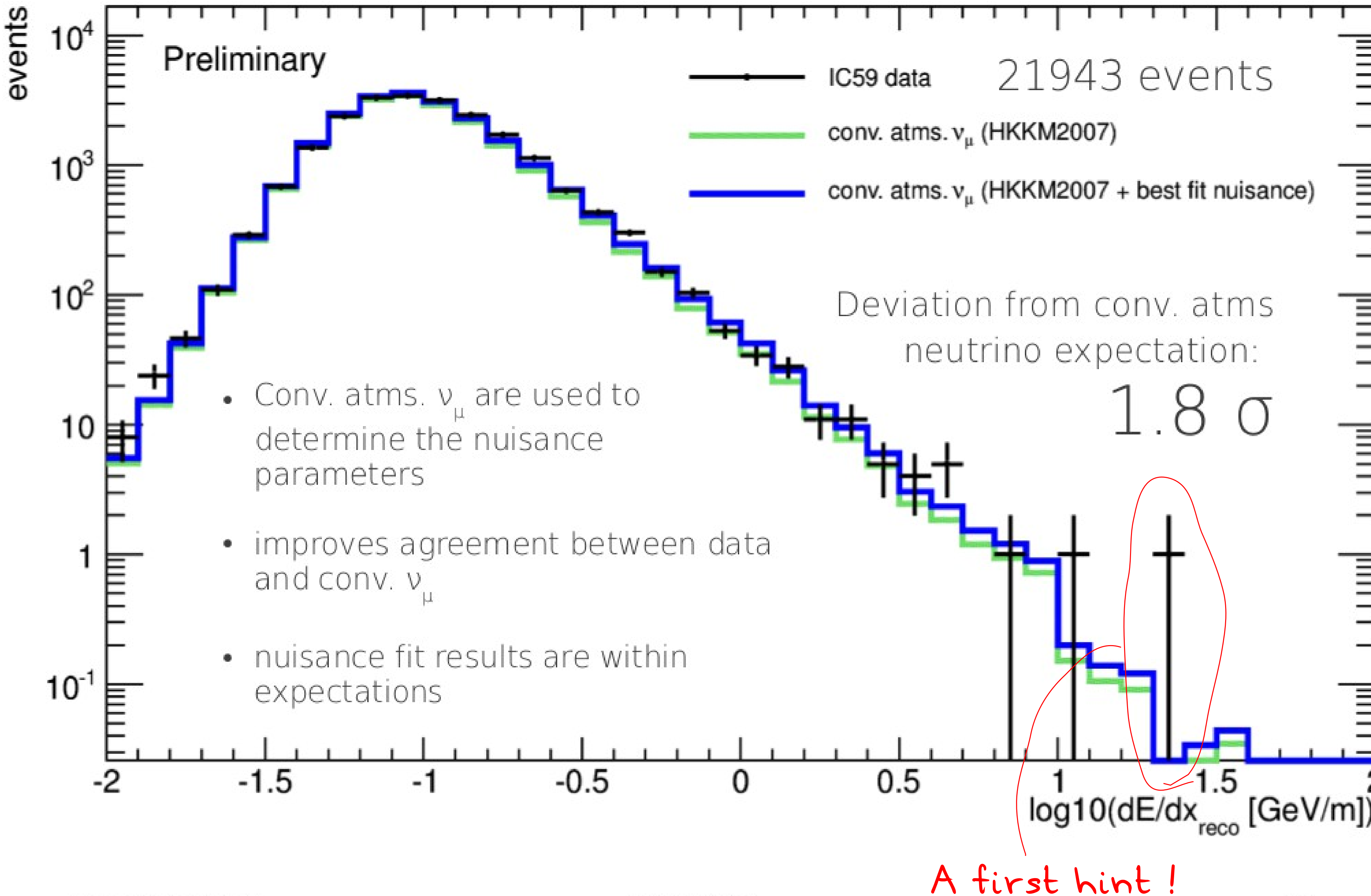
Muon track (IC59)

610 hit modules
83 TeV muon
upgoing (zenith angle=91.2°
angular error 0.2°)

A first hint...



IC59 diffuse flux analysis



- Conv. atms. ν_μ are used to determine the nuisance parameters
- improves agreement between data and conv. ν_μ
- nuisance fit results are within expectations

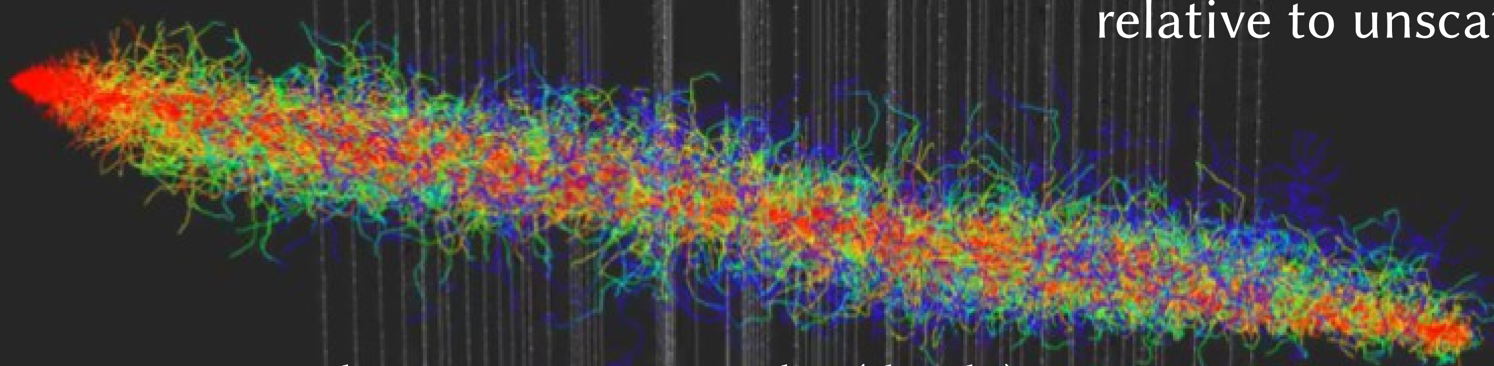
Anne Schukraft NOW2012 11

Track & Cascade events

MC photon tracking

On time — Delayed

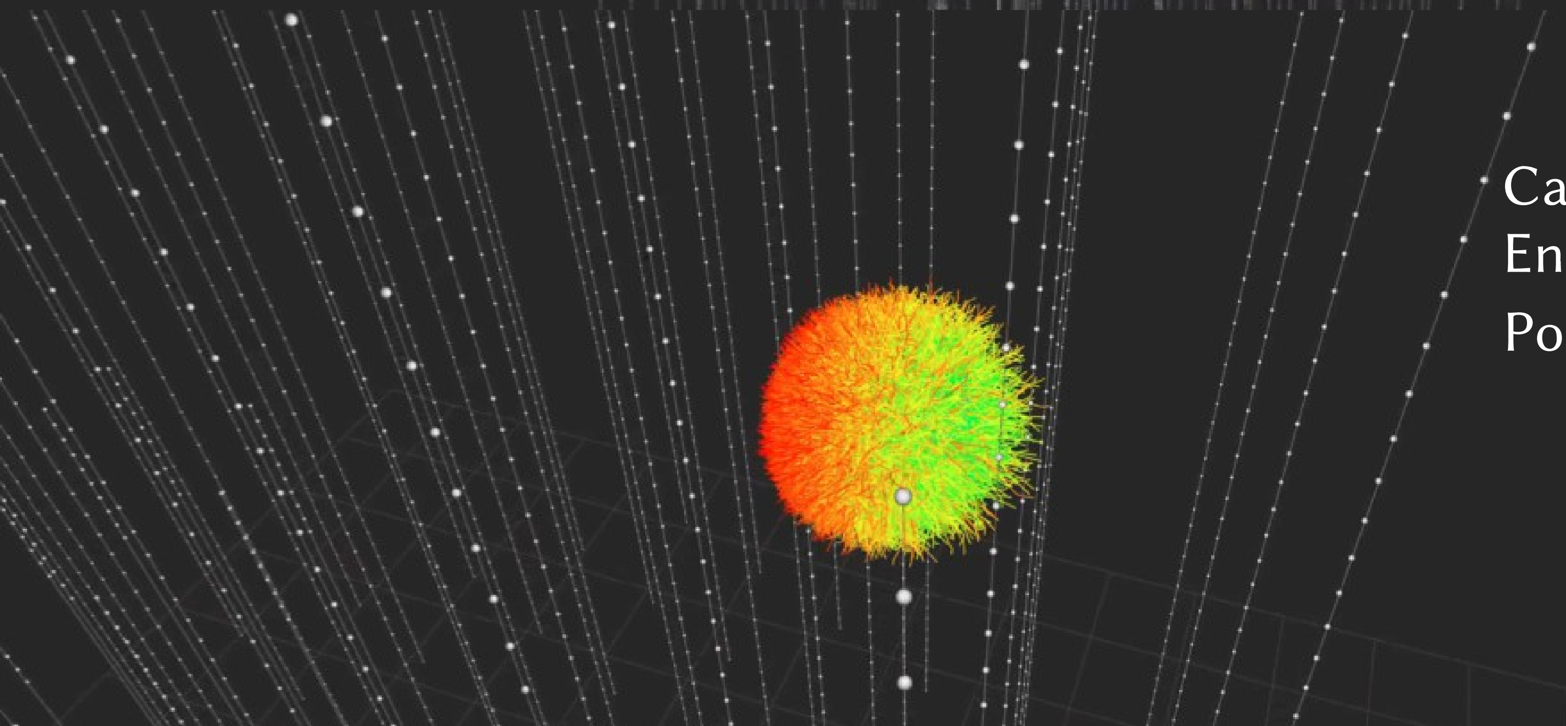
relative to unscattered photons



Tracks:

No E_ν measurement, only energy in IceCube (dE/dx)

Good pointing (0.2°– 1°)

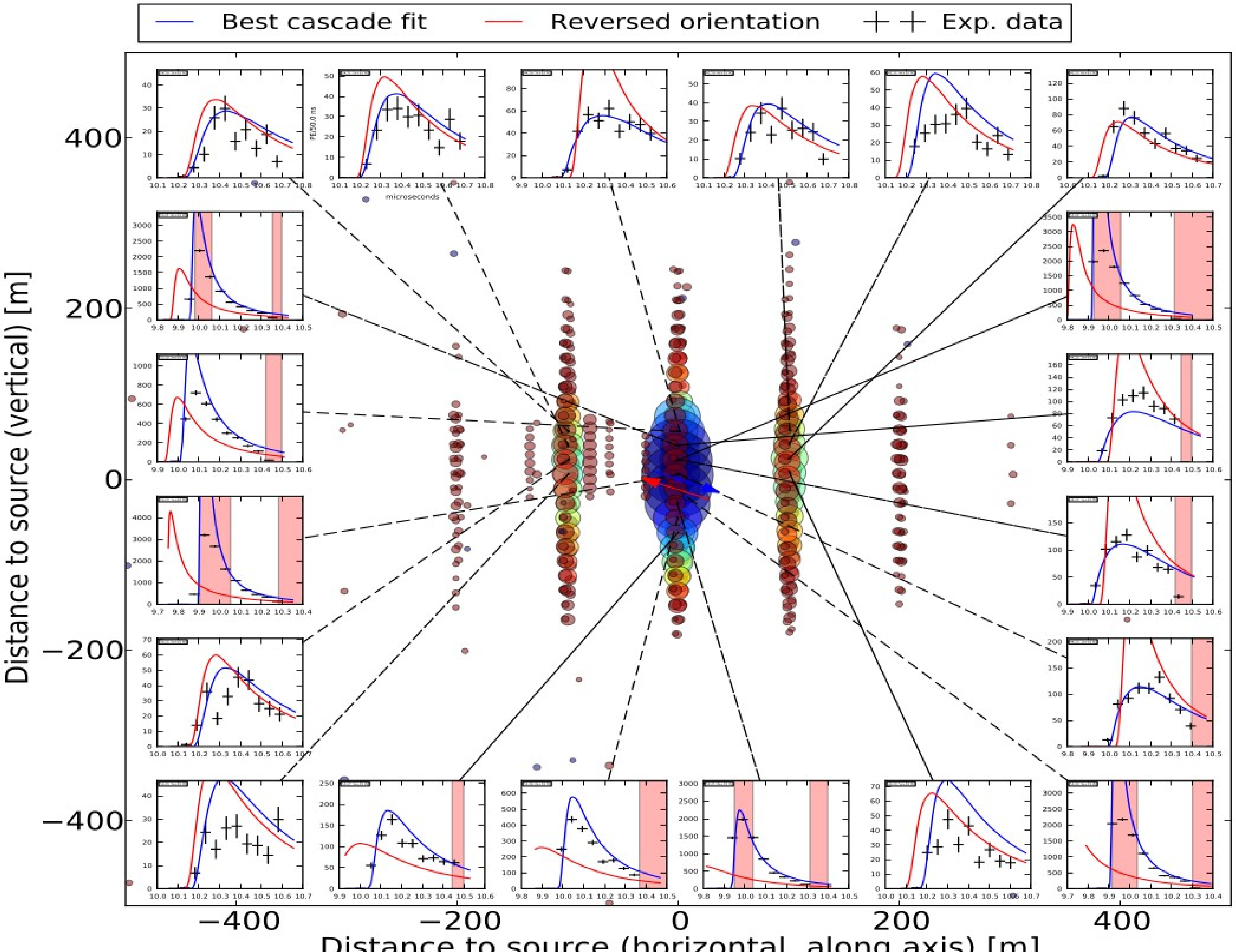


Cascades:

Energy resolution ~ 15%

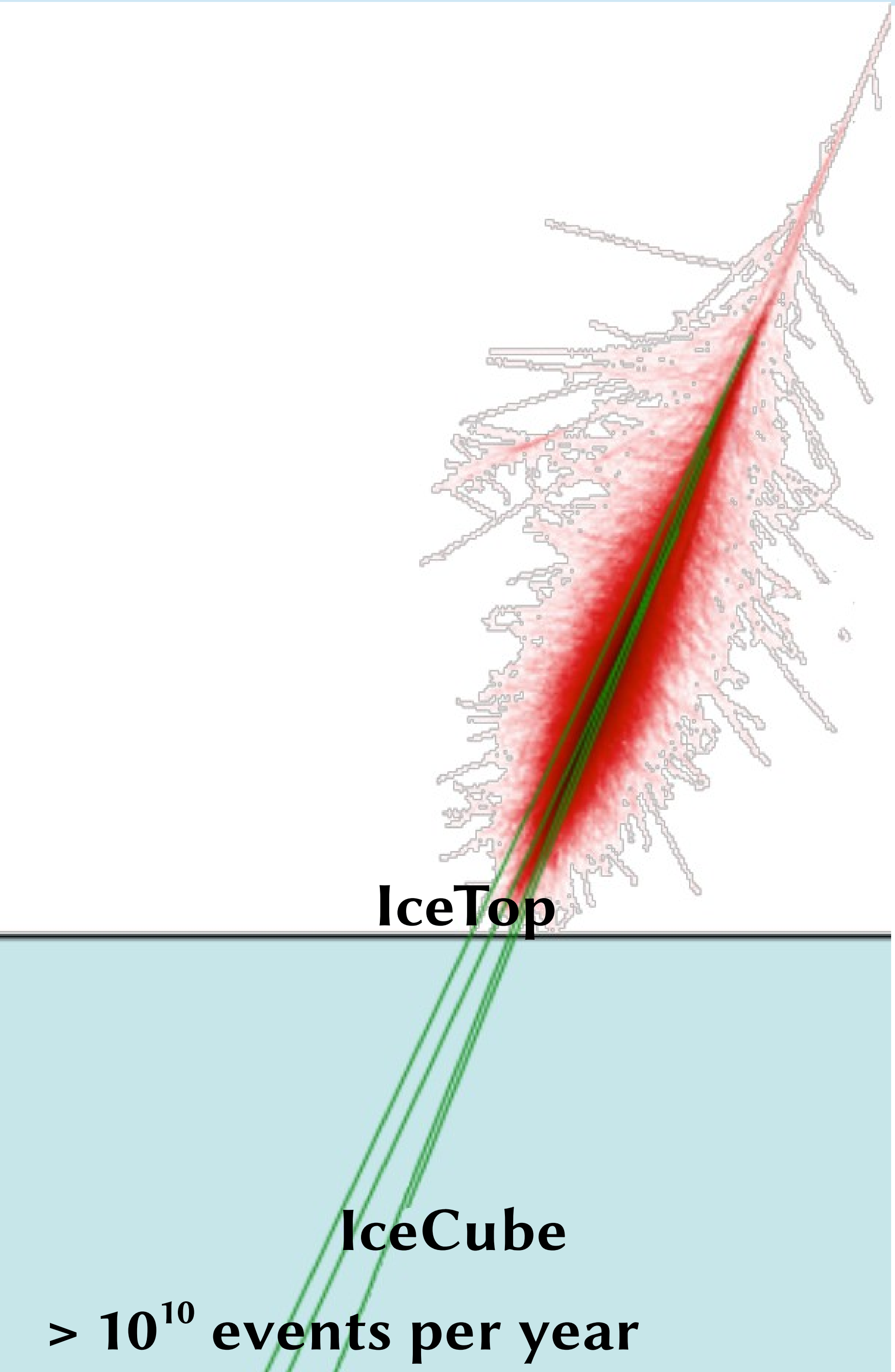
Pointing $\gtrapprox$ 10°

Cascade reconstruction



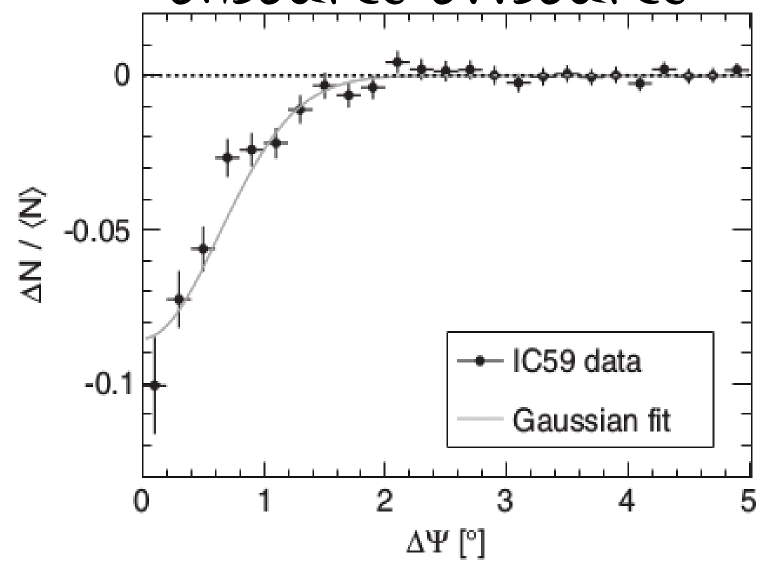
Cosmic Rays

Cosmic Rays in IceCube

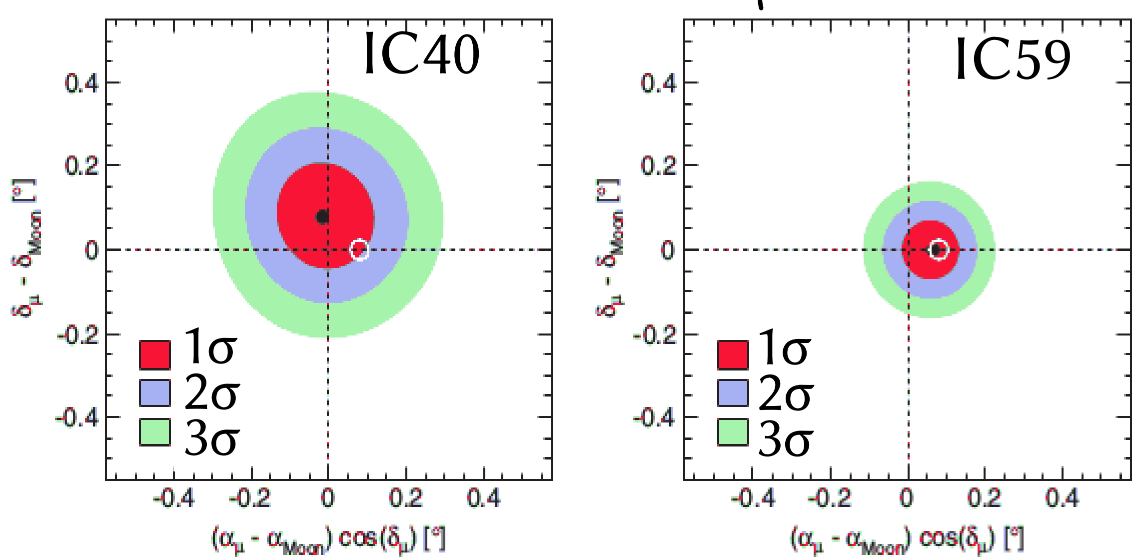


Shadow of the moon confirms understanding of angular reconstruction:
Phys.Rev. D89 (2014) 102004

onsource-offsource

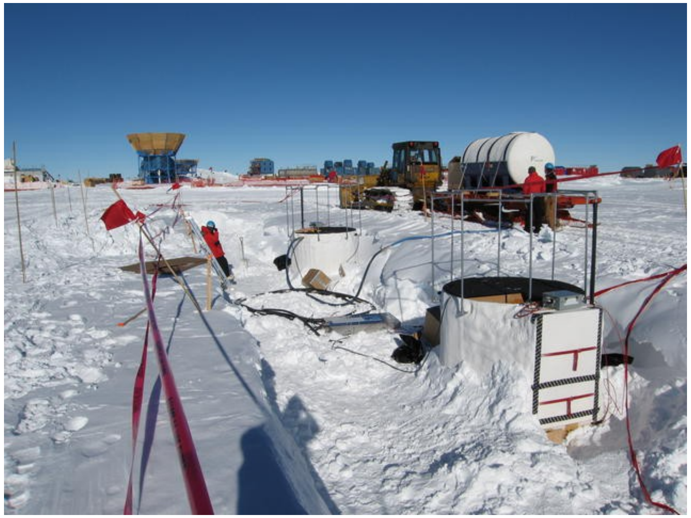


reconstructed moon position:



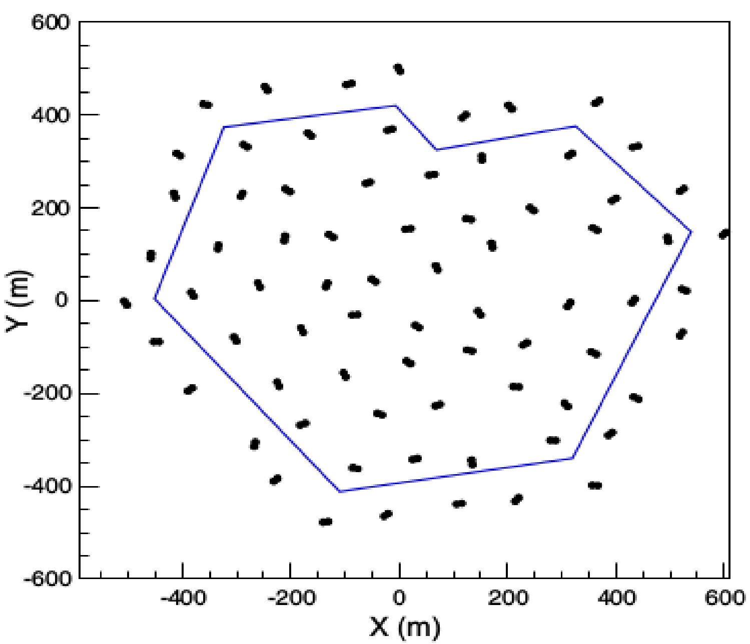
CR primary energy spectrum

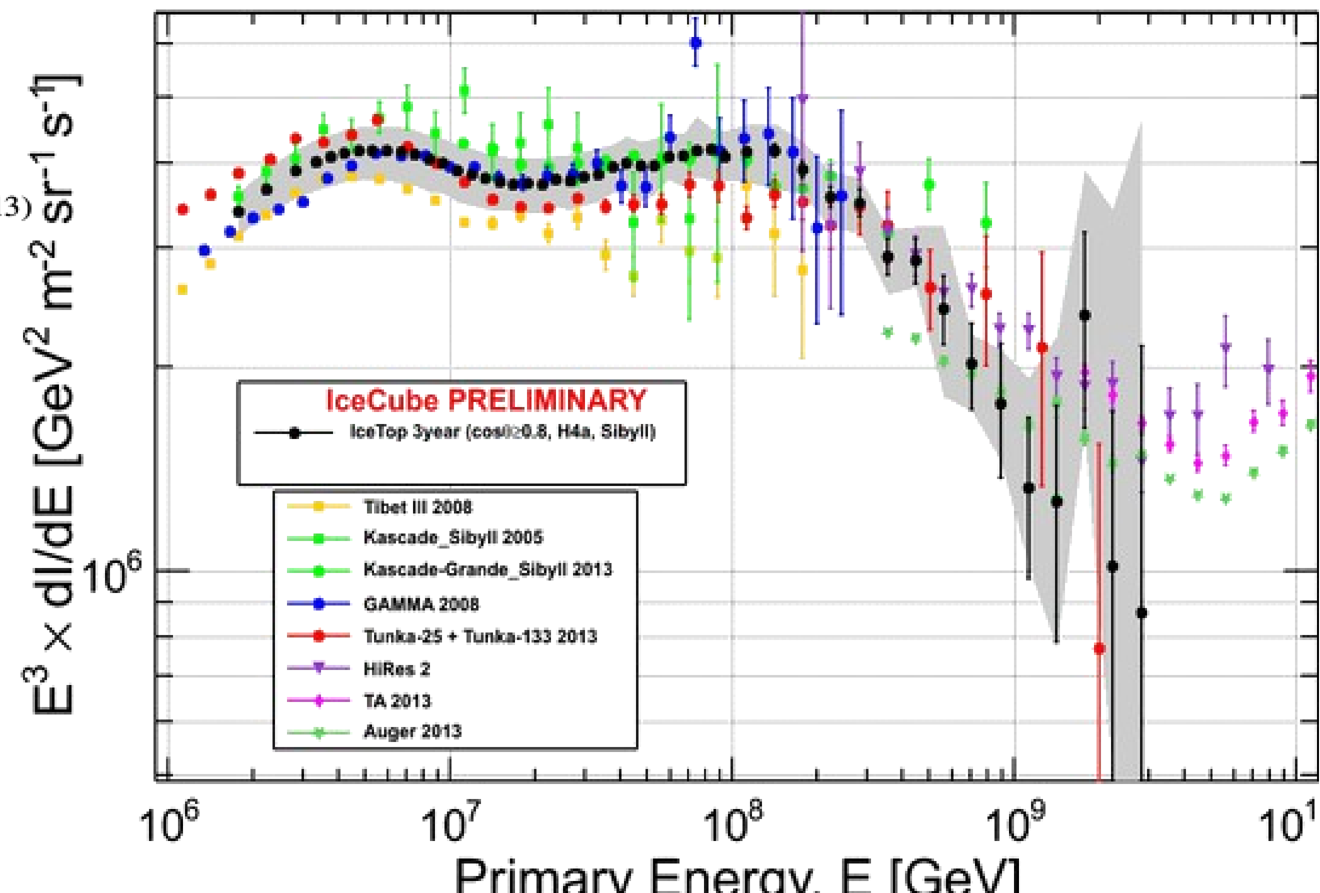
IceTop only, 3 years, 73 stations used



close to shower max (minimizes fluctuations)
Energy estimate based on particle density 125m from shower core (S_{125})

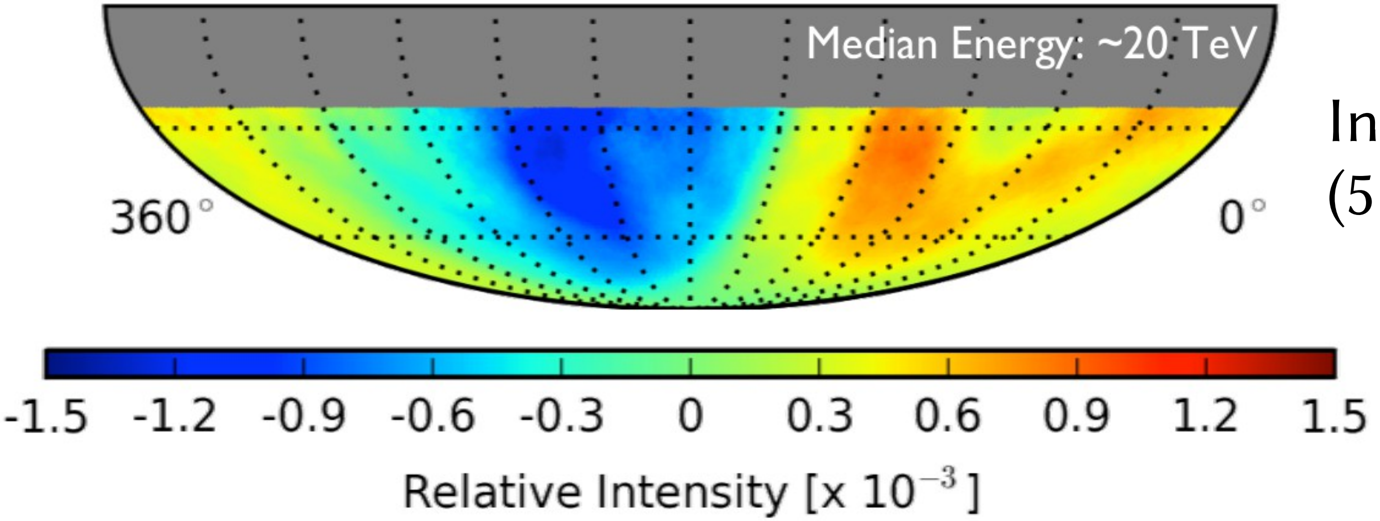
PHYSICAL REVIEW D **88**, 042004 (2013)



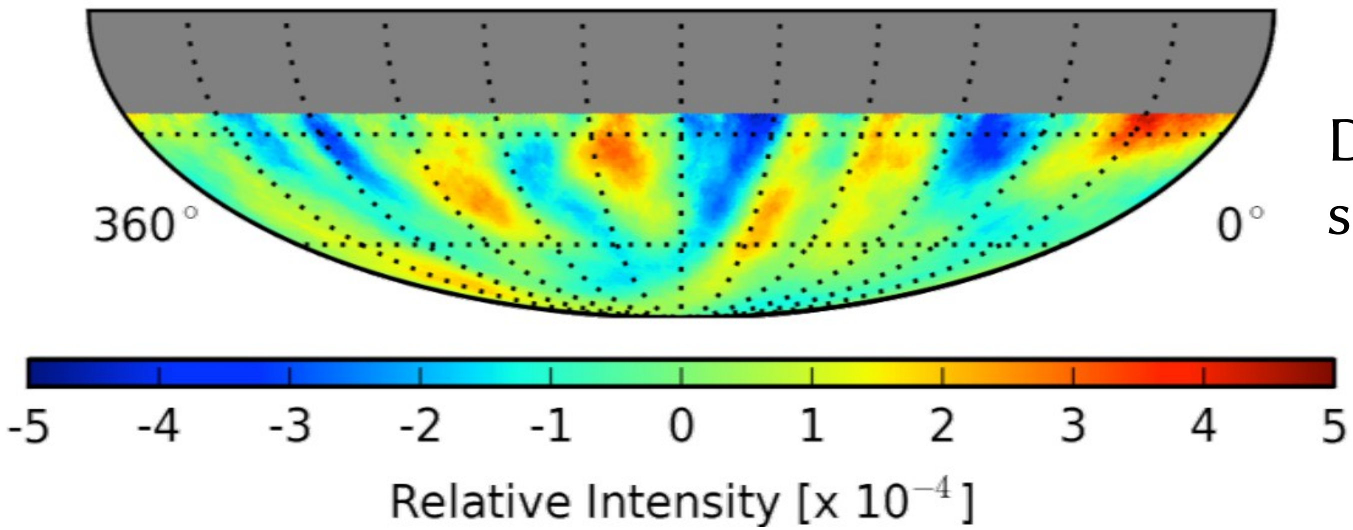


CR anisotropies – 5 years of data

McNally, Cosmic Ray Anisotropies WS, Bad Honnef, 2015



Intensity variations (5° smoothing applied)



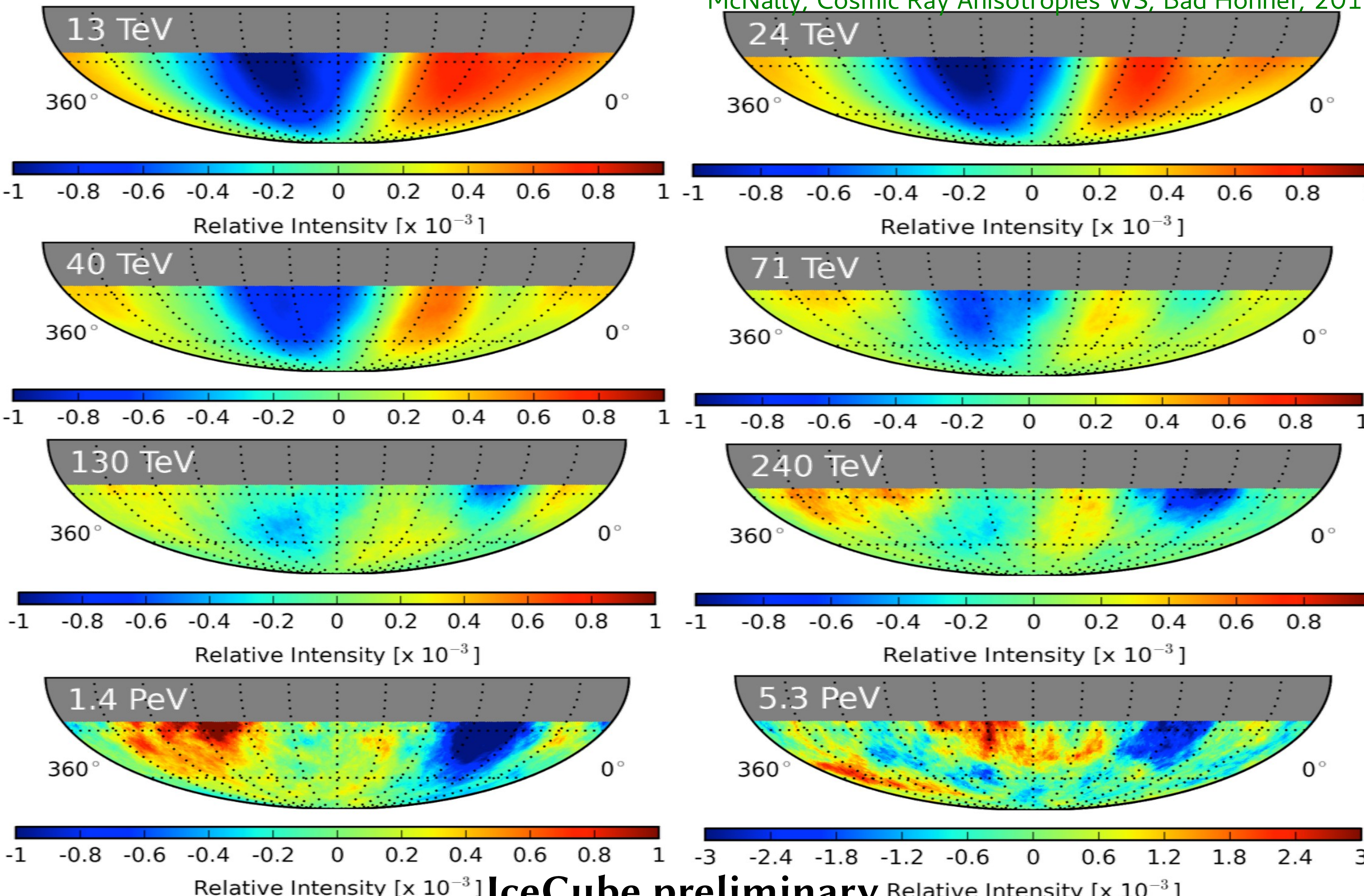
Dipole & Quadrupole subtracted

IceCube preliminary

2.5×10^{11} events

Energy dependence

McNally, Cosmic Ray Anisotropies WS, Bad Honnef, 2015

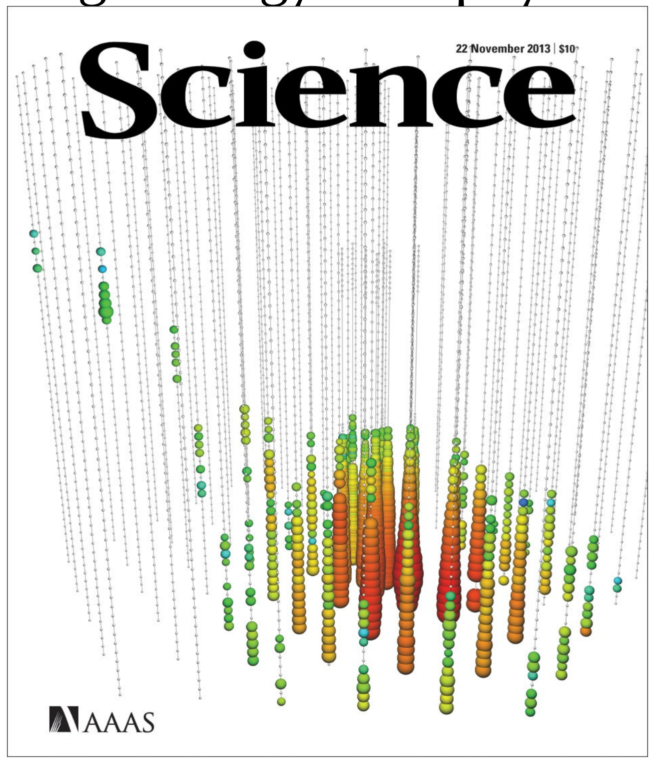


IceCube preliminary

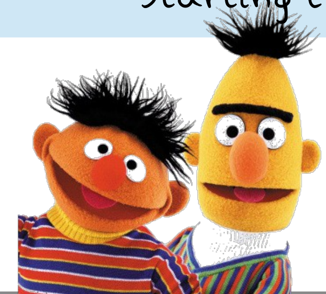
Starting events

The Muppet Show

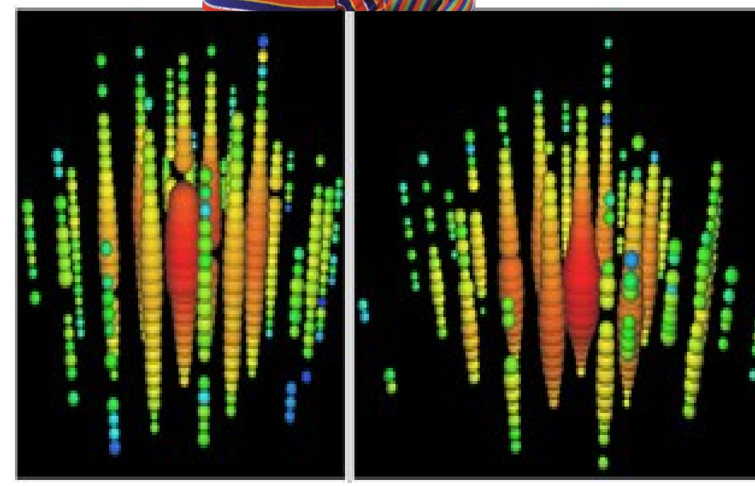
or the discovery of the high energy astrophysical neutrino flux:



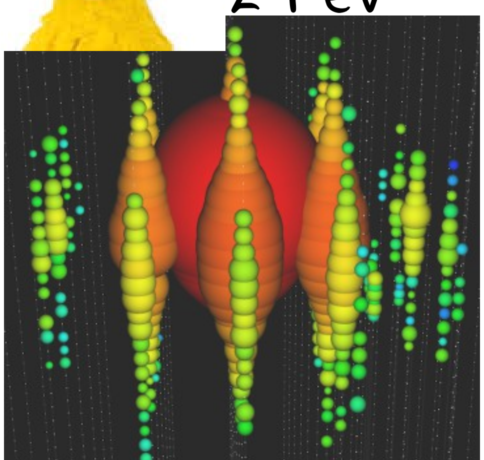
Bert
1.04 PeV



Ernie
1.14 PeV



Big Bird
2 PeV



Bert&Ernie found in 2 year EeV ν search (IC79+86)
PRL 111(2013)021103

Follow-up for events with less light detected found another 26 events at lower energy
Science 342 (2013) 1242856

Third year included Big Bird
PRL 113 (2014) 101101

Four-year analysis almost completed

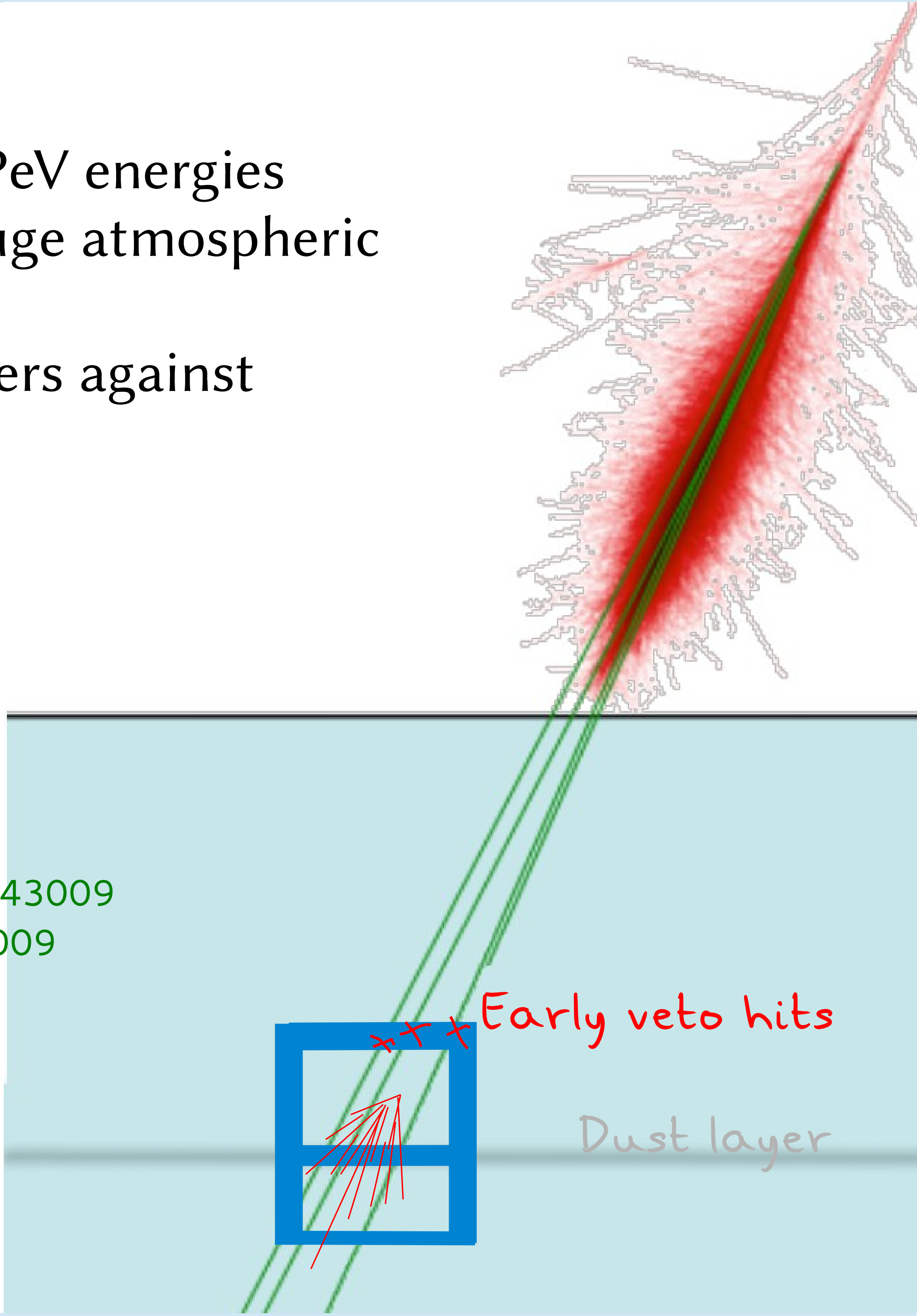
High Energy Starting Events (HESE)

- Follow-up to Bert & Ernie
- Earth is not transparent any more at ~PeV energies
- Need to look for downgoing events - huge atmospheric muon background!
- Use outer detector layers as veto counters against entering muons

⟶ Smaller effective detection volume

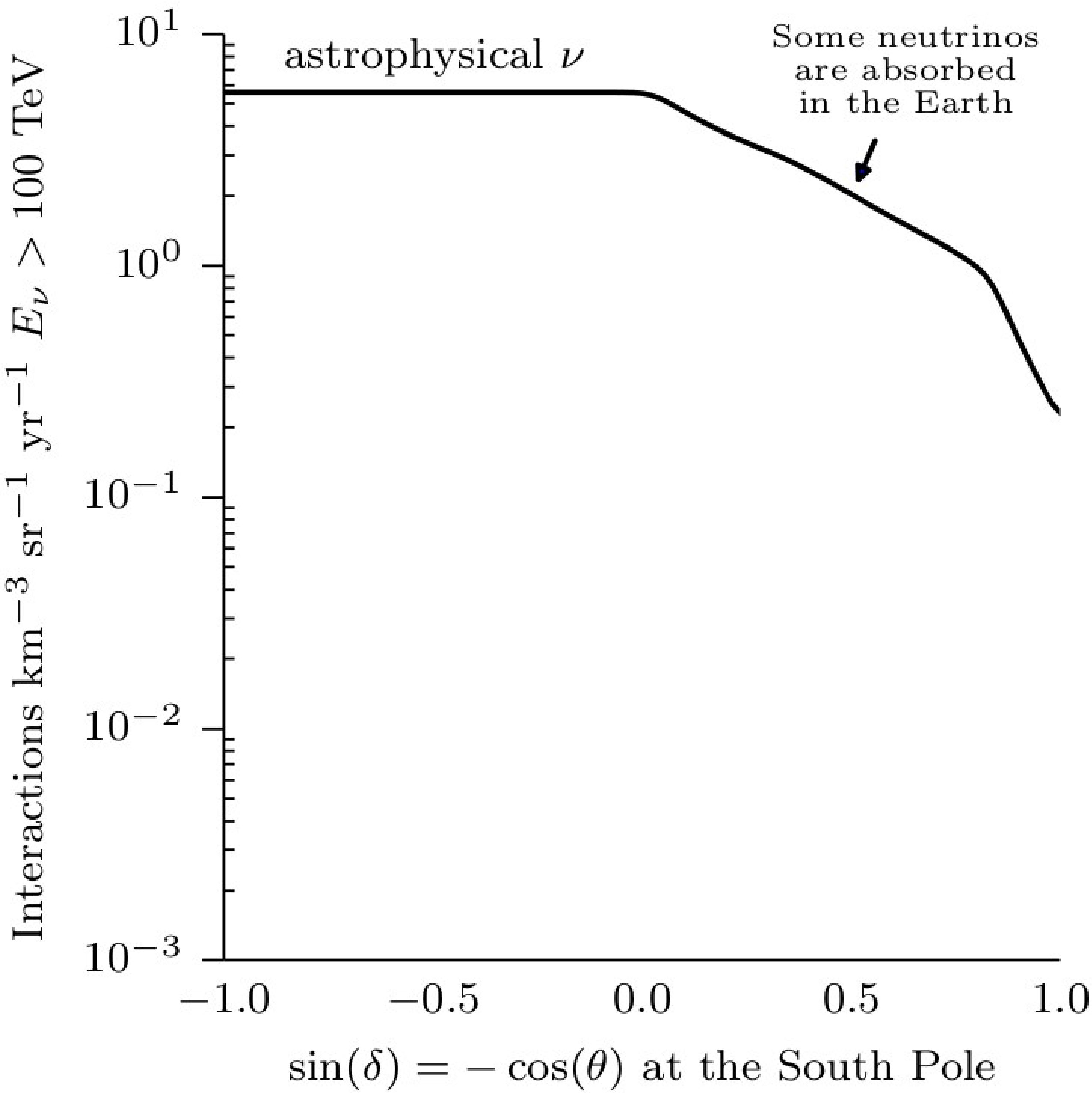
BUT: Veto works also against down-going neutrinos from CR showers!

Schönert, Gaisser, Resconi, Schultz, Phys Rev D79 (2009) 043009
Gaisser, Jero, Karle, van Santen, Phys Rev D90 (2014) 023009



Atmospheric neutrino self-veto

Jakob van Santen ISVHECRI 2014



Atmospheric neutrino self-veto

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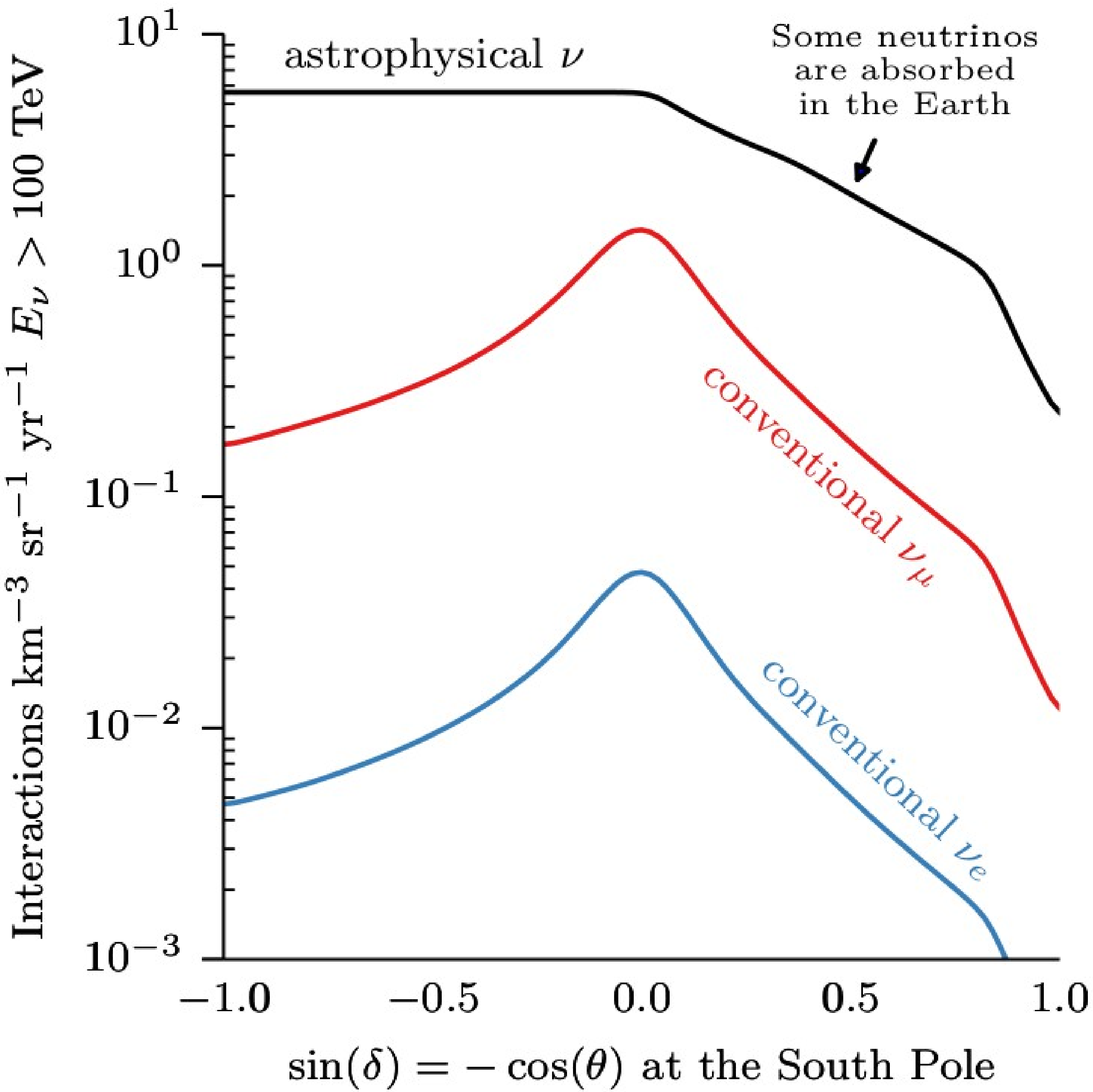

Atmospheric neutrino self-veto

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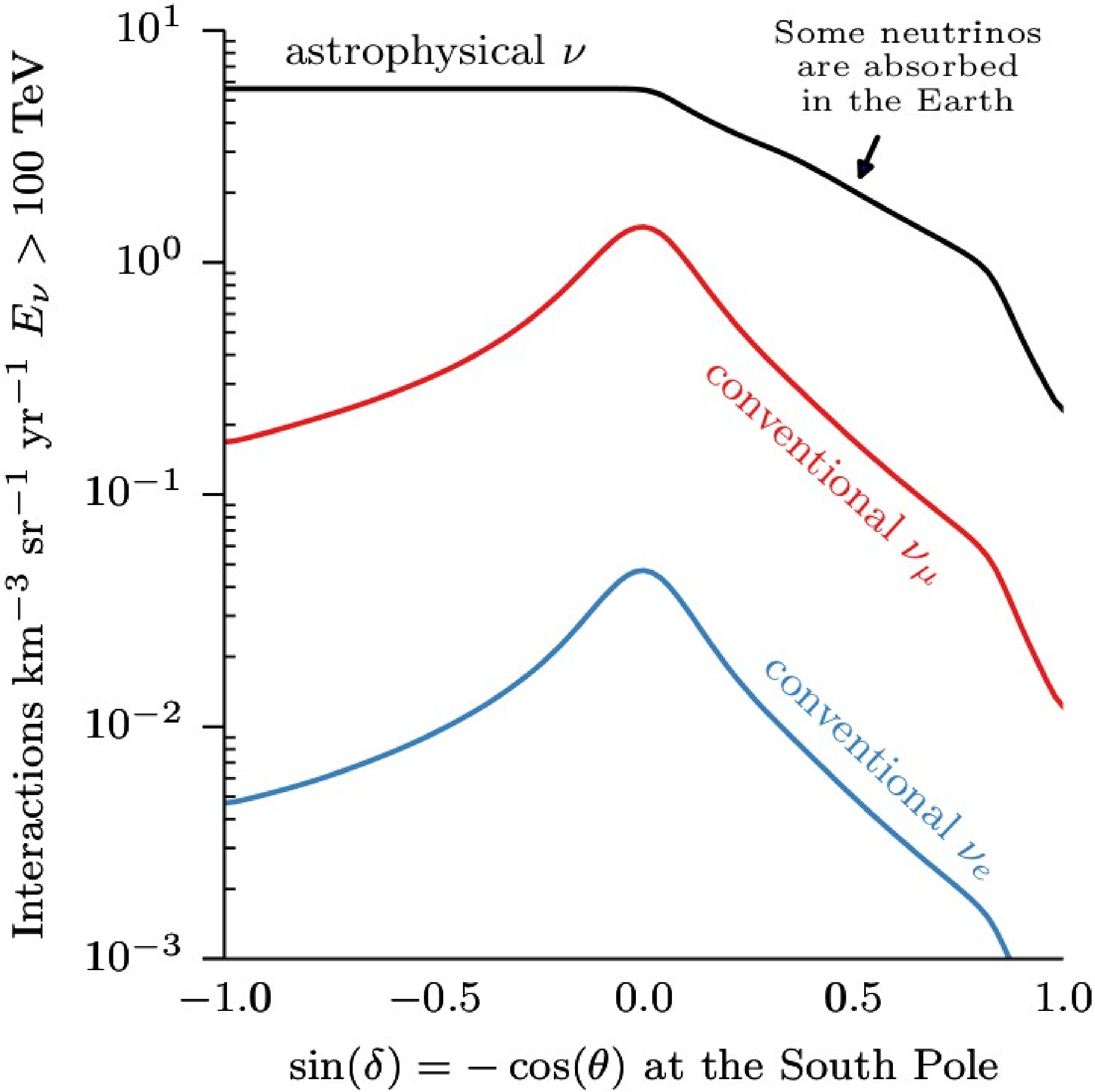
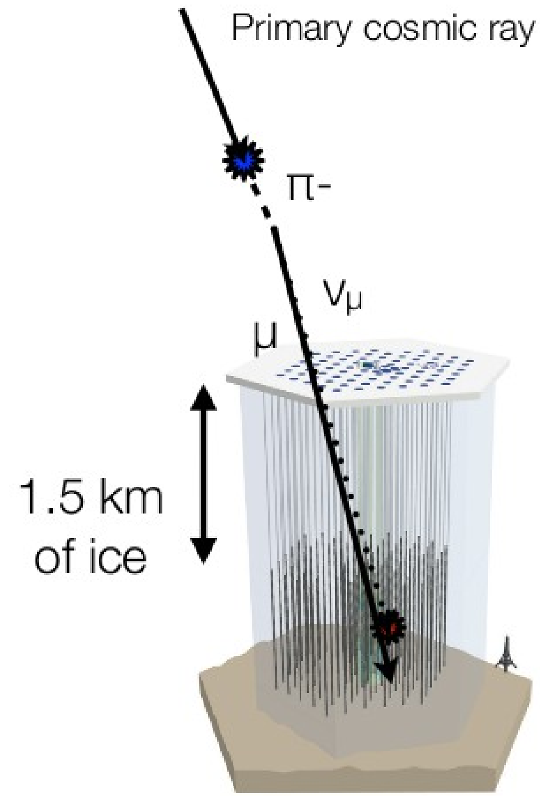


An active muon veto removes down-going atmospheric neutrinos.



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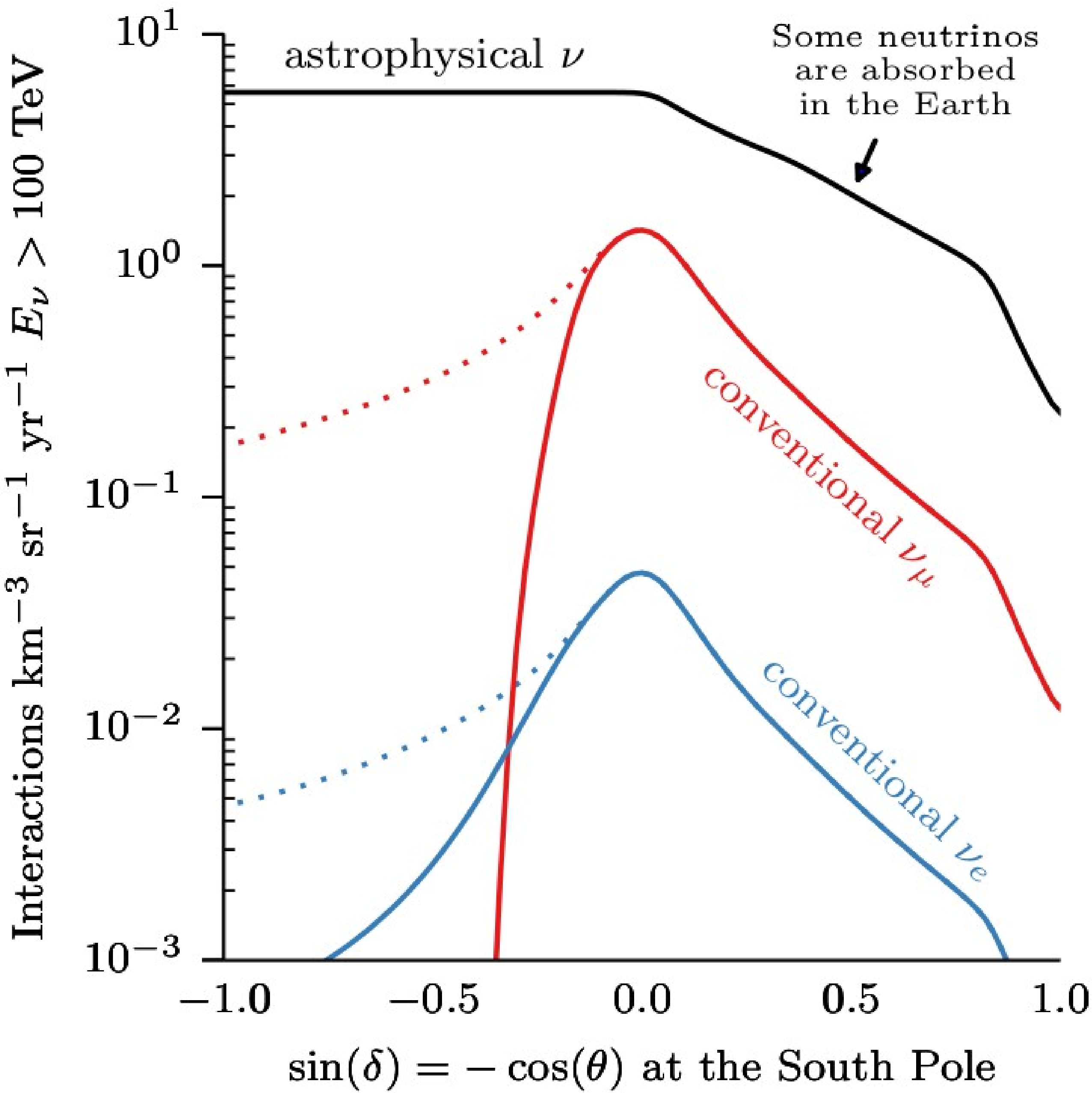

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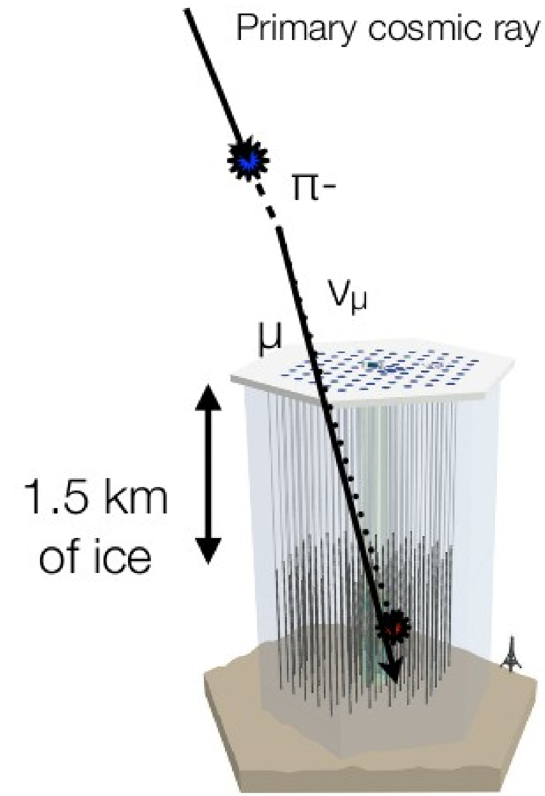
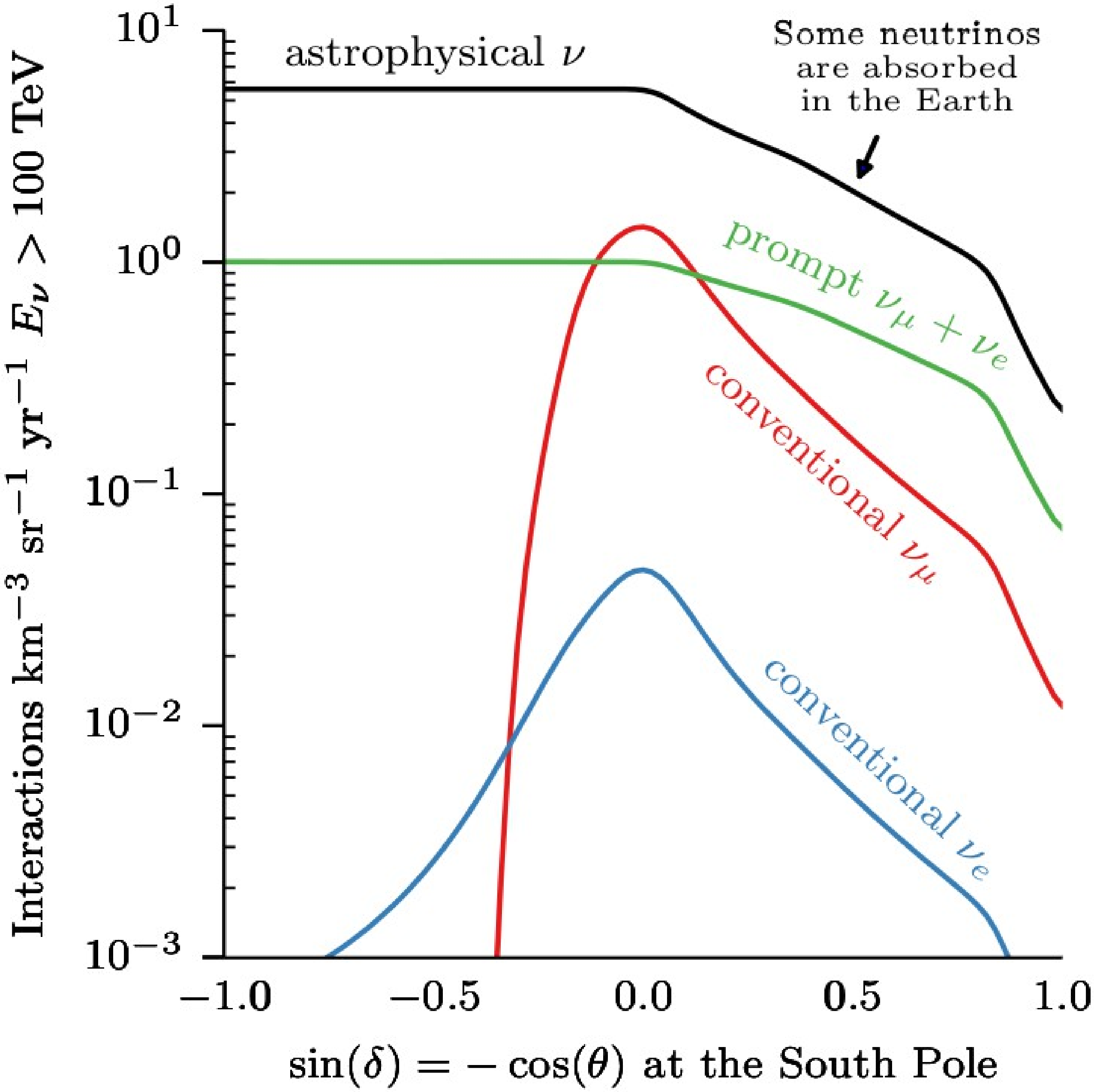


Atmospheric neutrino self-veto

Jakob van Santen ISVHECRI 2014



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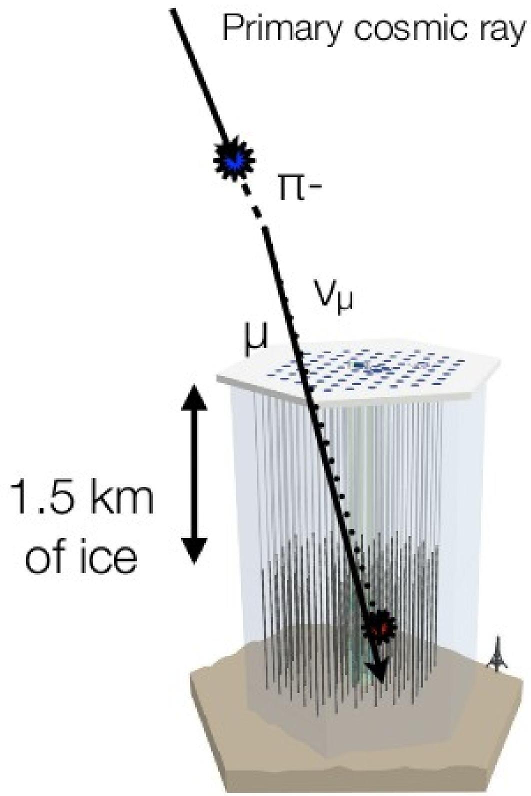
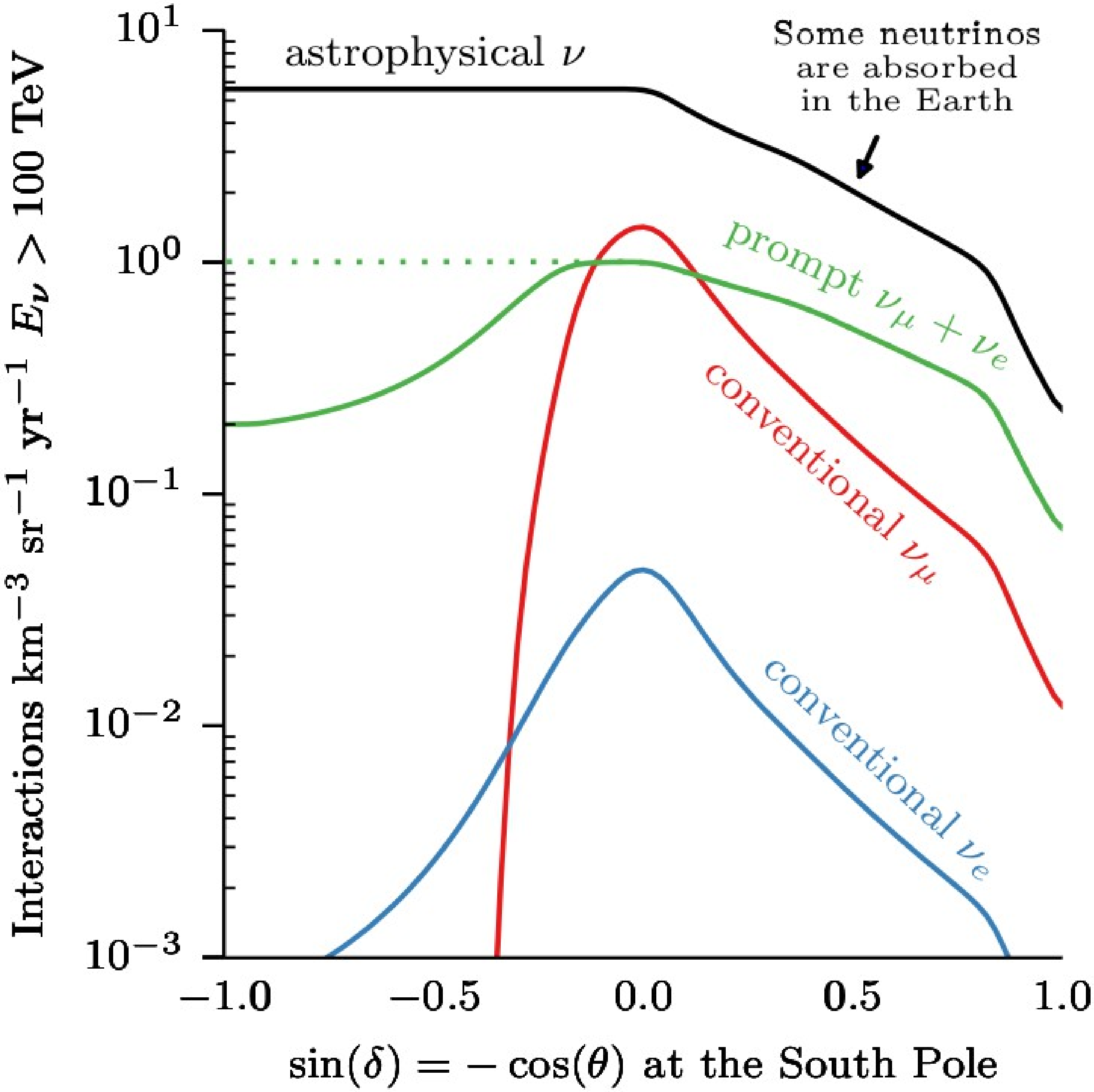
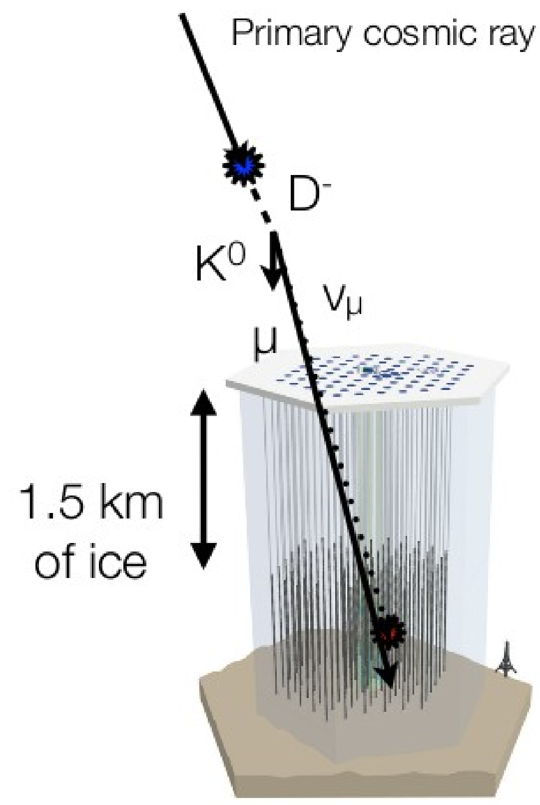


Atmospheric neutrino self-veto

Jakob van Santen ISVHECRI 2014

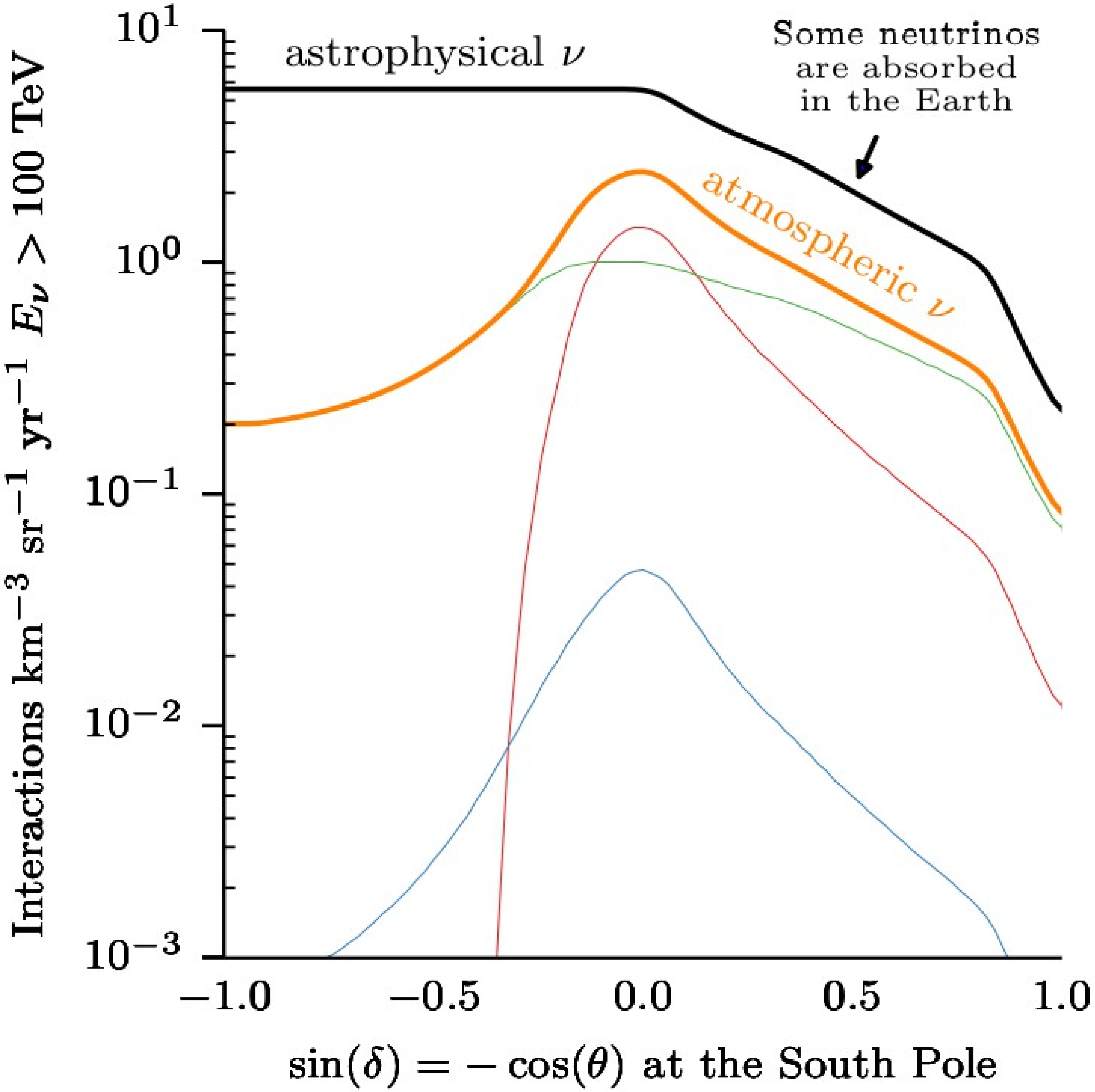


Prompt atmospheric neutrinos are vetoed, too.



Atmospheric neutrino self-veto

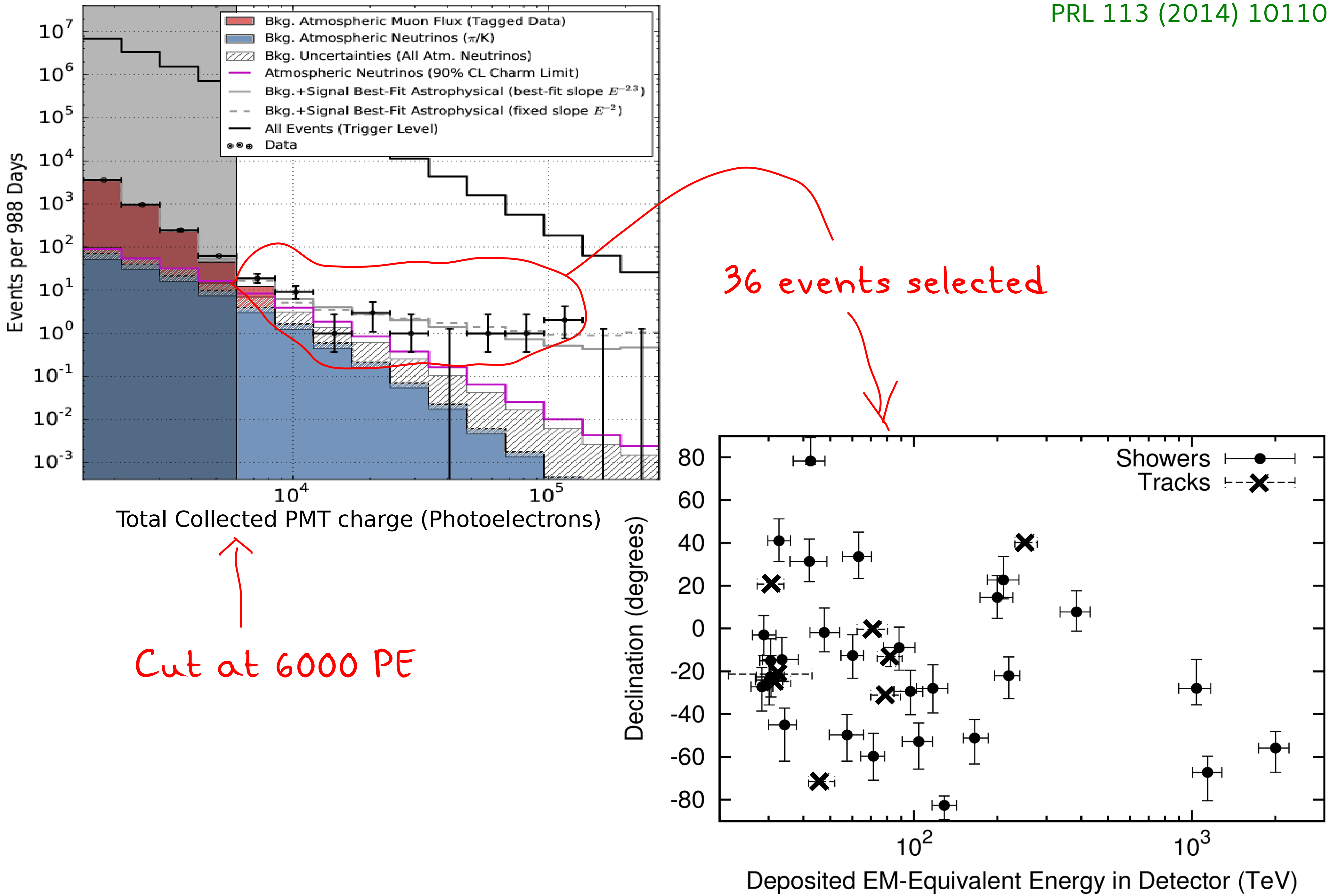
Jakob van Santen ISVHECRI 2014



The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

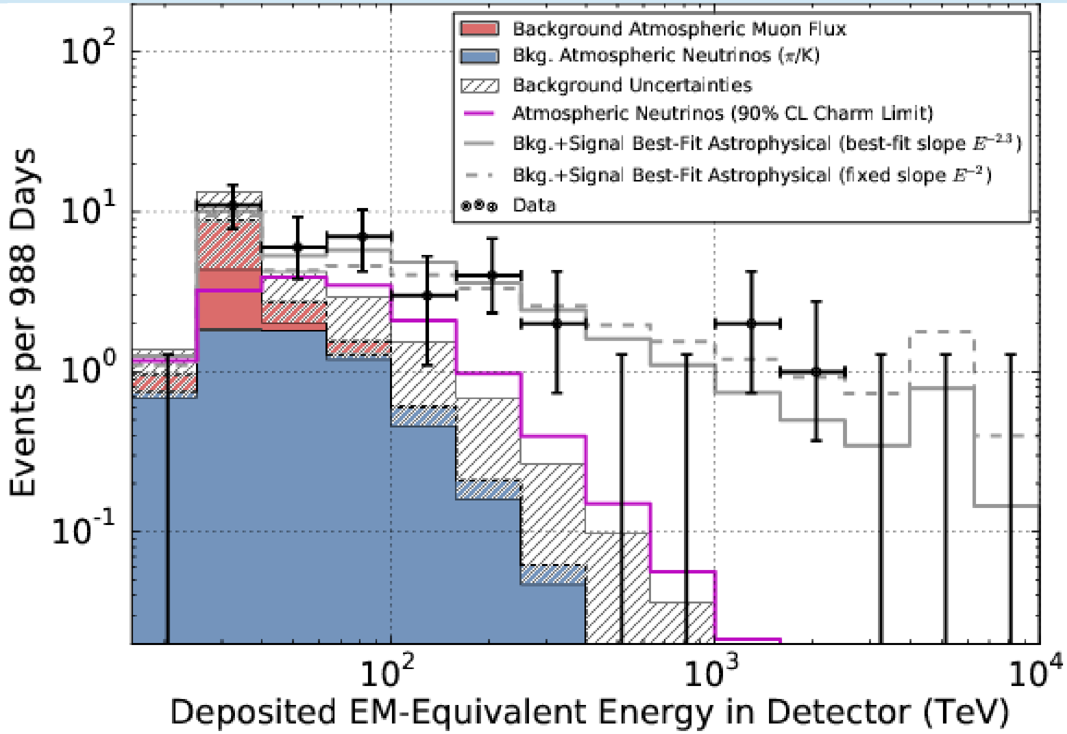
HESE 3 year results

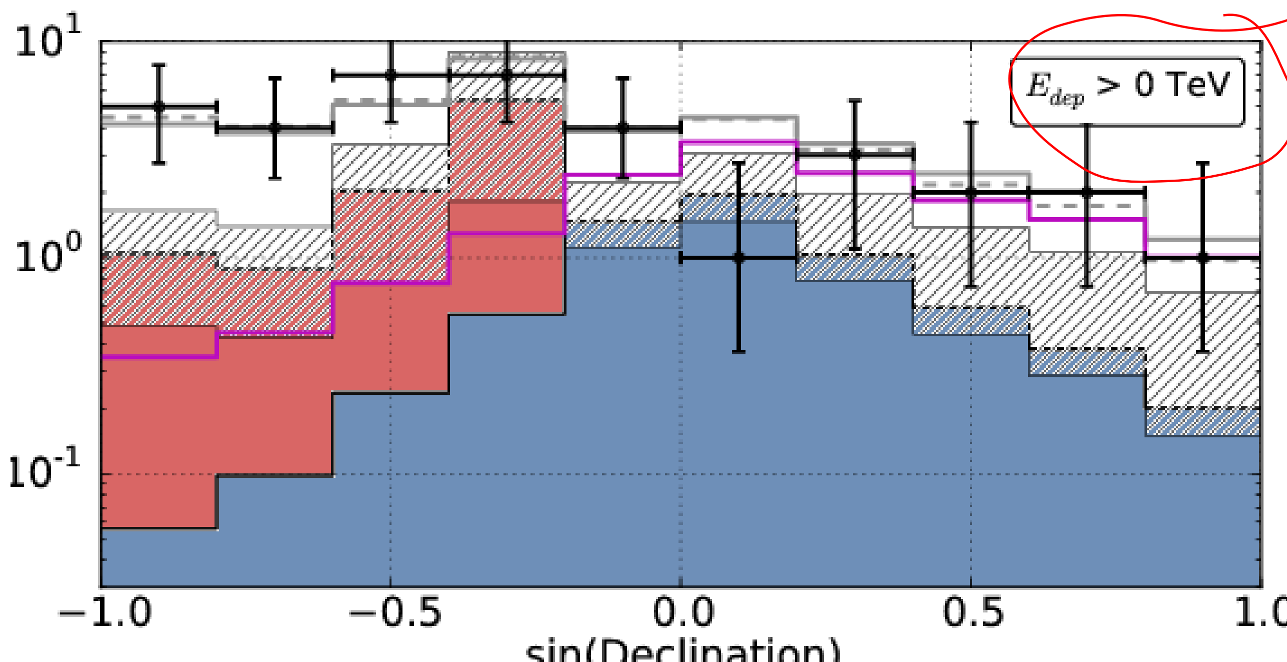
PRL 113 (2014) 101101



HESE 3 year self-veto turn-on

PRL 113 (2014) 101101

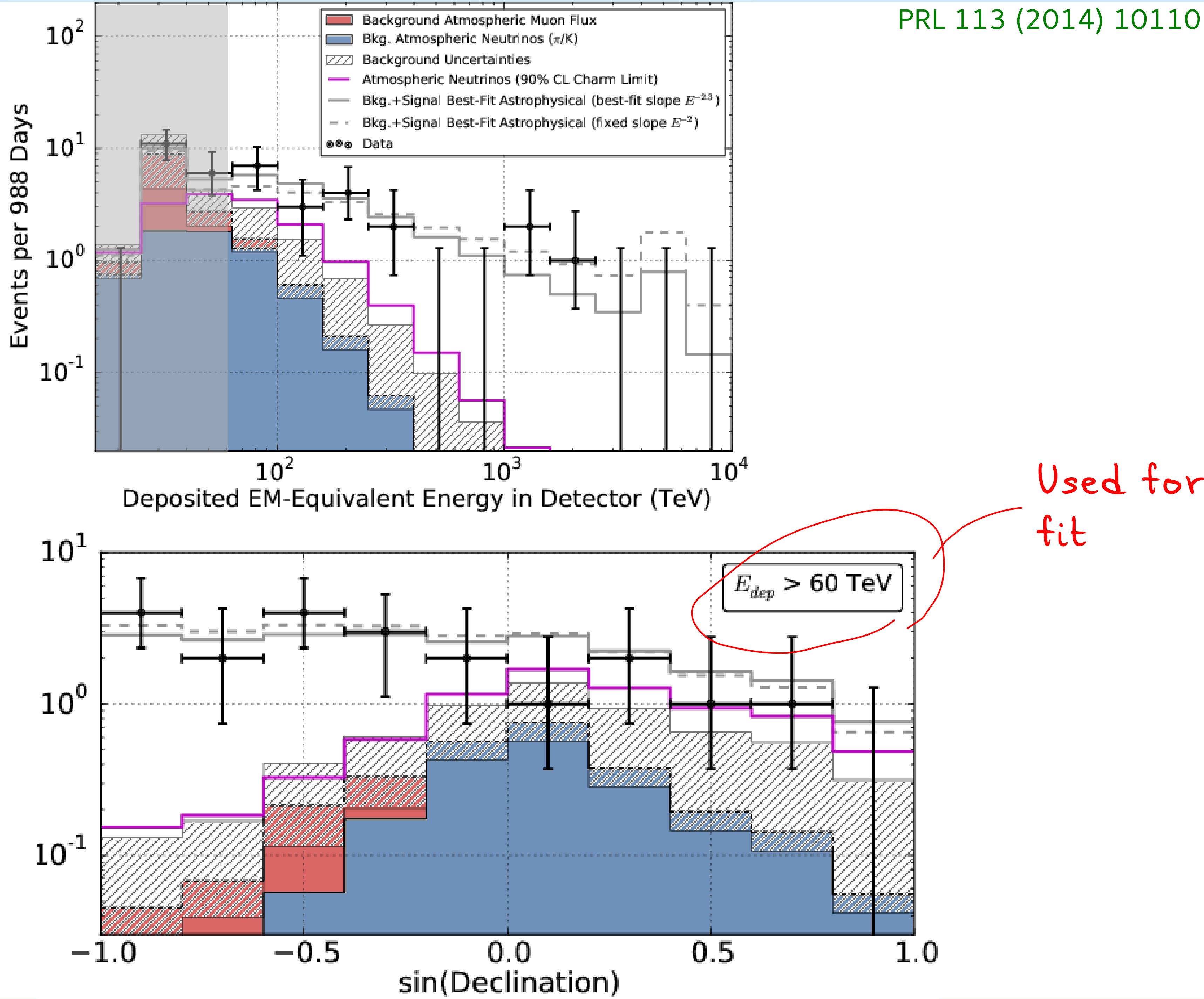




No energy cut

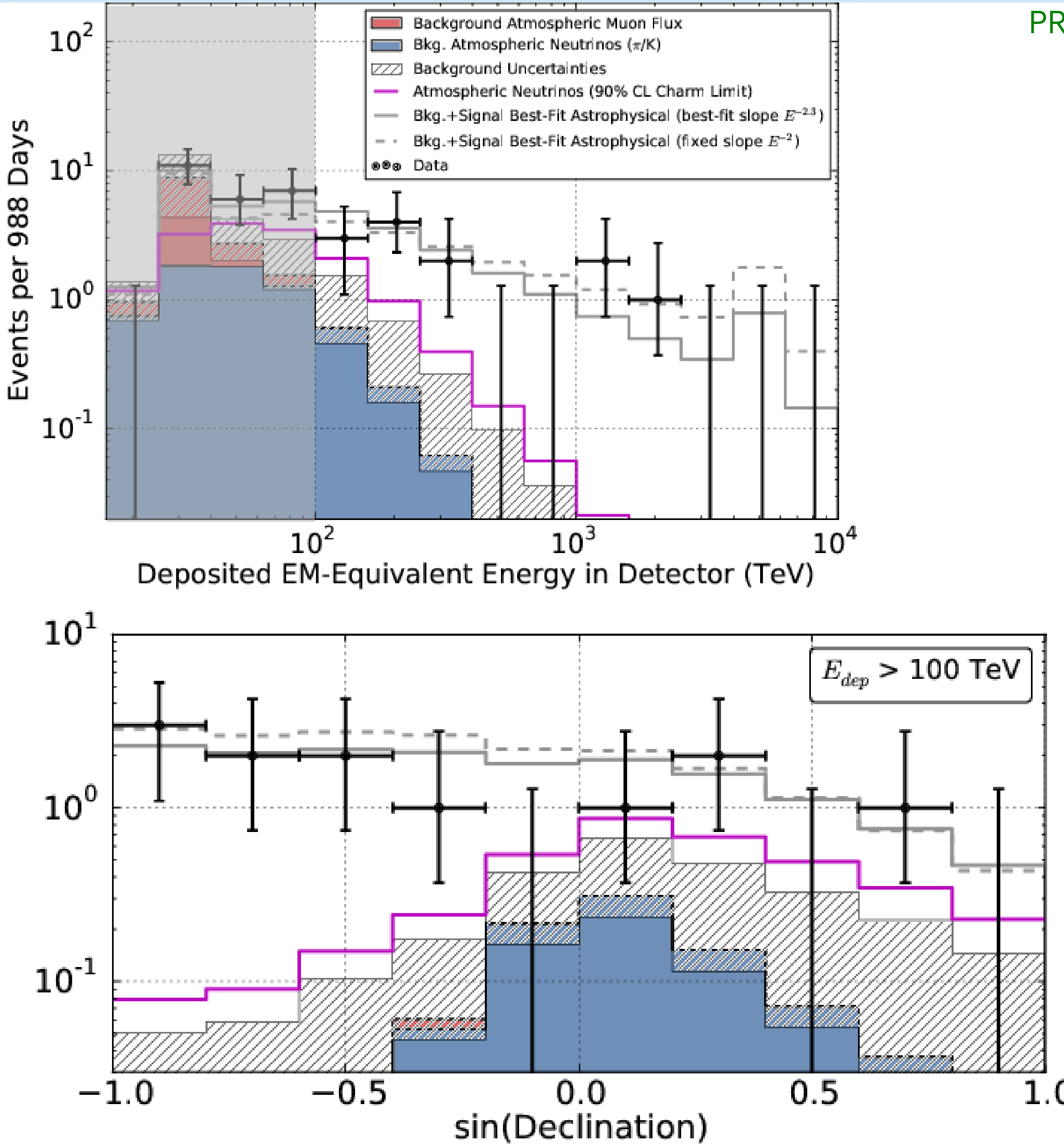
HESE 3 year self-veto turn-on

PRL 113 (2014) 101101



HESE 3 year self-veto turn-on

PRL 113 (2014) 101101



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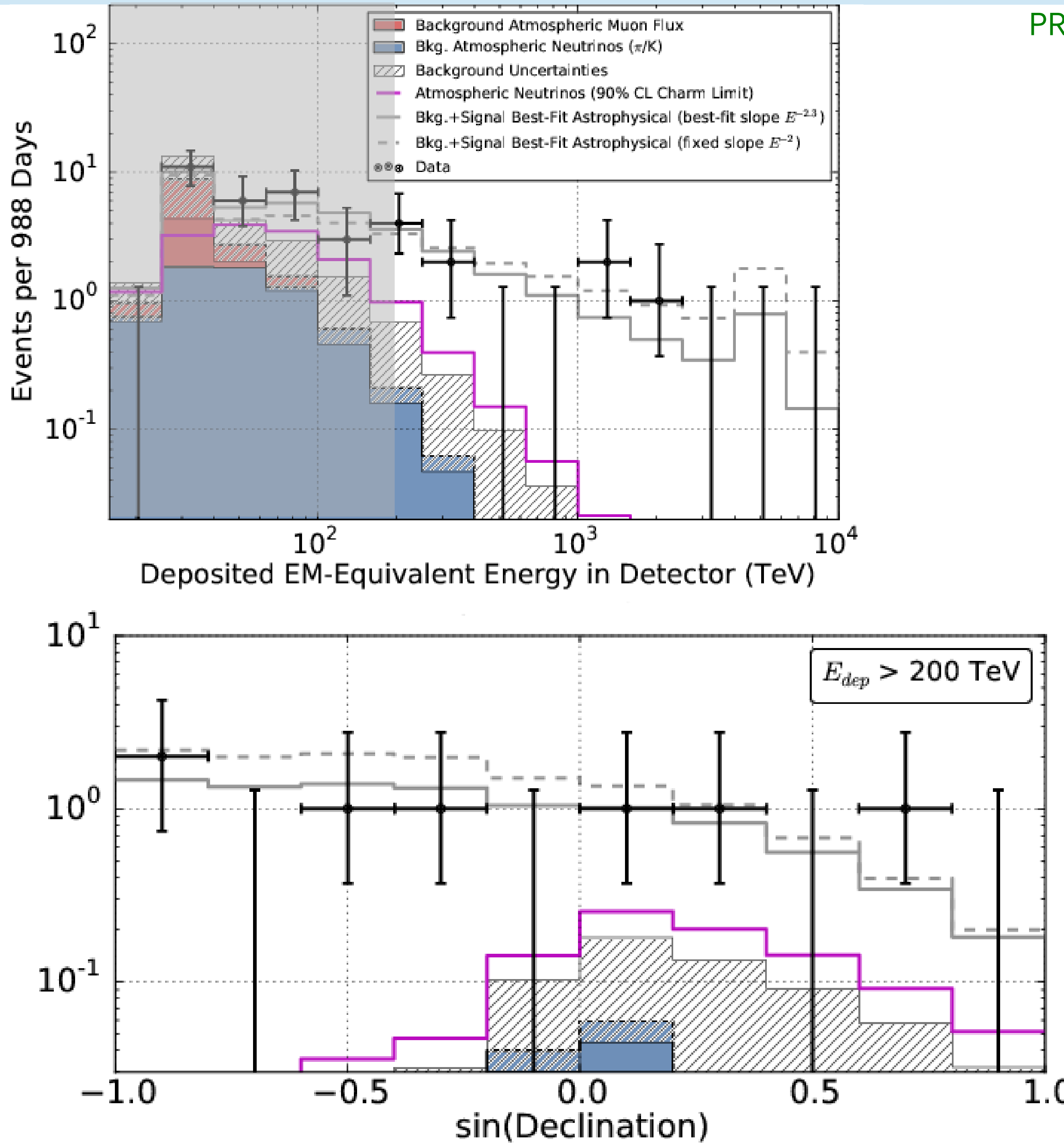
PRL 113 (2014) 101101



HESE 3 year results

PRL 113 (2014) 101101

Best fit unbroken E^{-2} spectrum to data above 60 TeV is

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

Favoured at 5.7 σ compared to purely atmospheric flux

Best fit power law is $E^{-2.3}$ (prompt flux fits to zero):

$$E^2\Phi = 1.5\times 10^{-8}\ (E/100\ \mathrm{TeV})^{-0.3}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

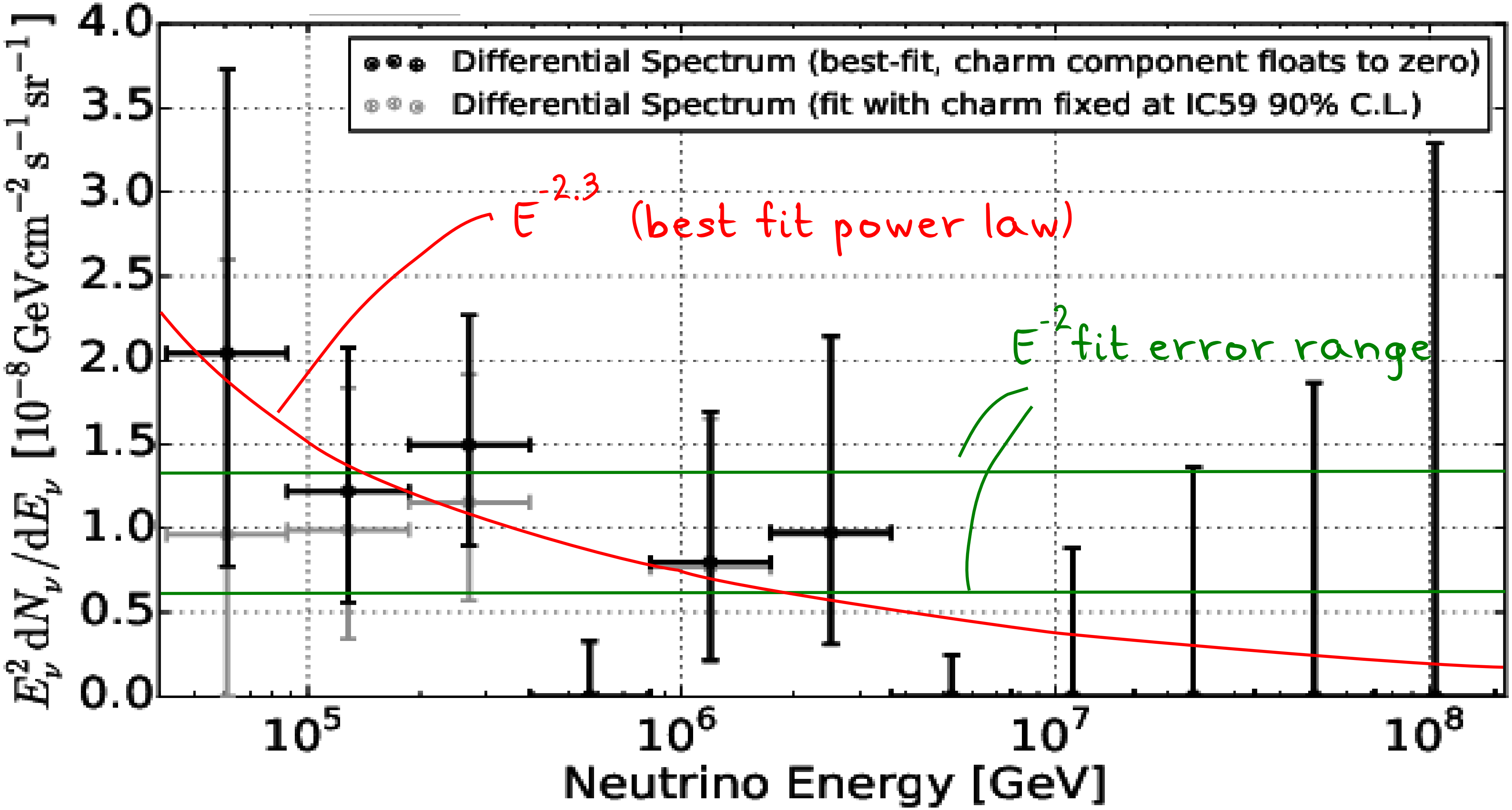
(or $\Phi = 1.5\times 10^{-18}\ (E/100\ \mathrm{TeV})^{-2.3}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)

Consistent with isotropic flux with $\nu_e:\nu_\mu:\nu_\tau=1:1:1$

Astrophysical HESE spectrum

PRL 113 (2014) 101101

Fit different E^{-2} normalisations in different energy intervals ("bins") → unfolded spectrum:

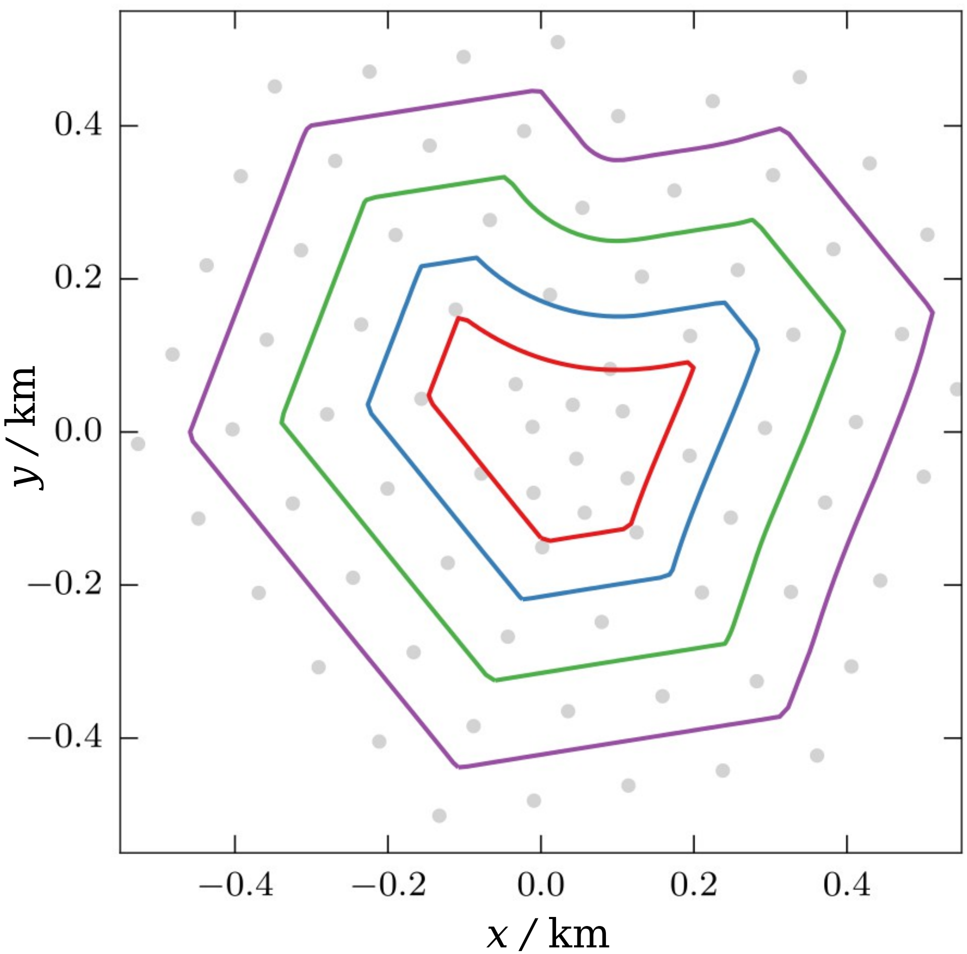


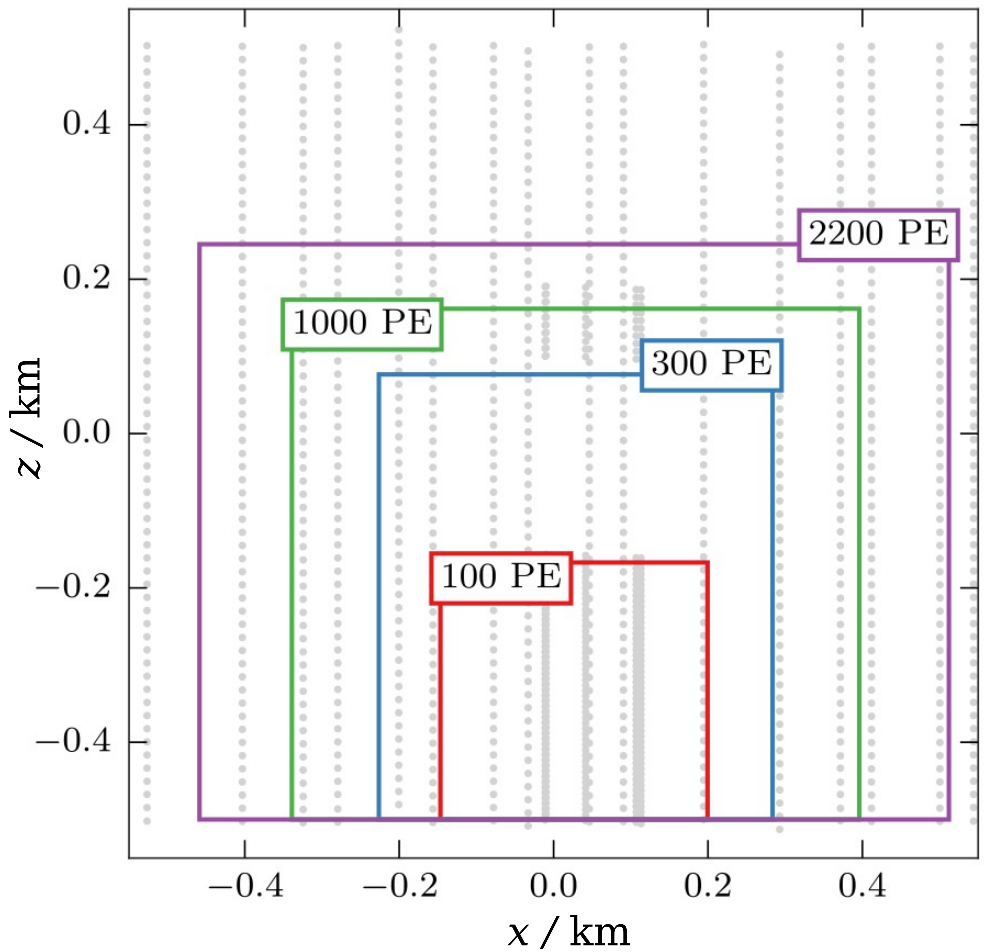
Steeper spectrum than E^{-2} or cutoff? Need more statistics!

Lower energy

The HESE veto layer (~5 DOMs deep at top and 1 string wide at the edge) is only efficient for high energies (hence the Q>6000PE requirement).

To go to lower energies, increase veto thickness with decreasing charge:

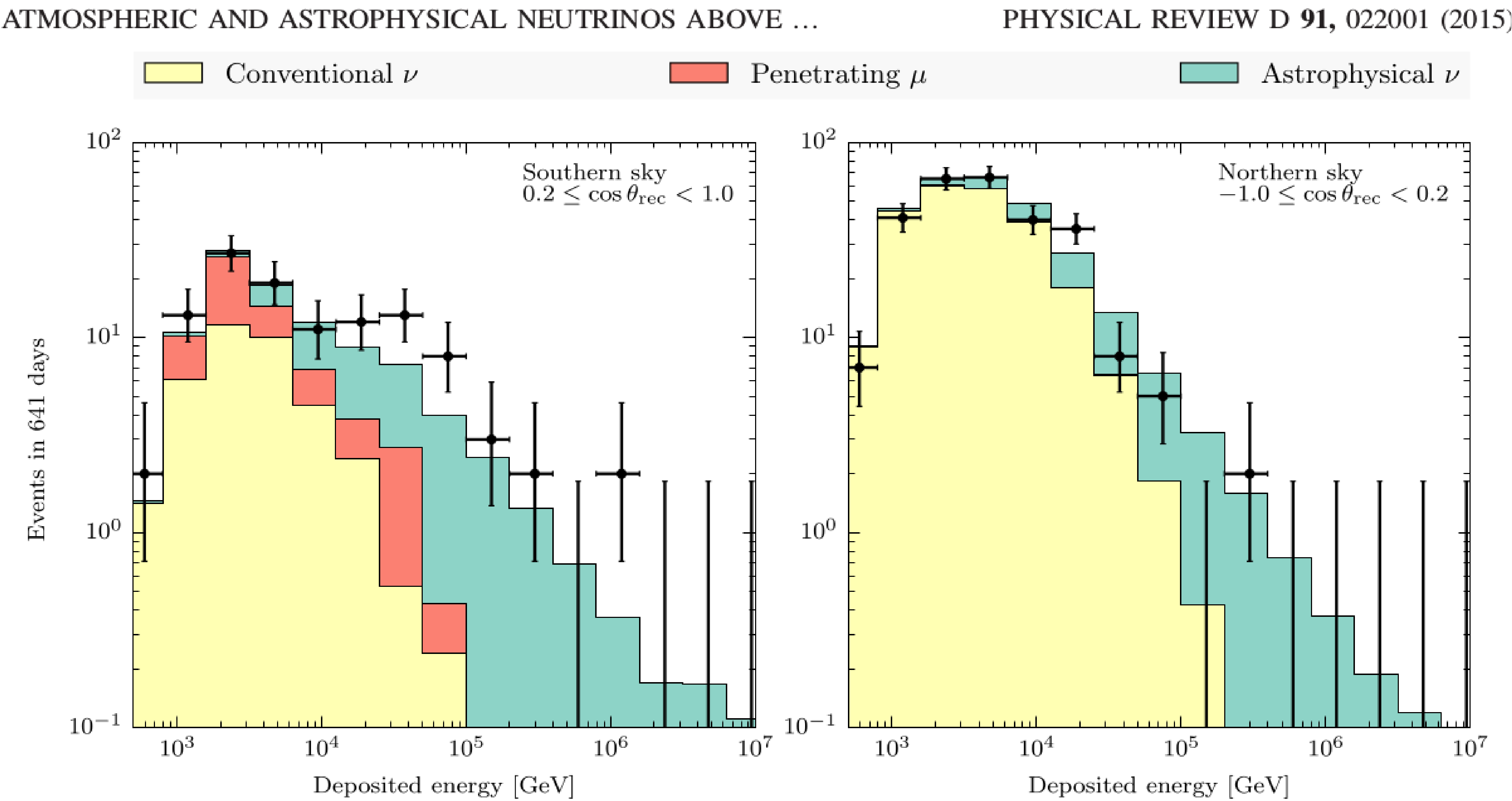




Also add stricter causality criteria to avoid noise vetoes.

Lower energy starting events

In two years of data (IC79+IC86): 283 cascades
105 tracks



Lower energy starting events

Phys Rev D91 (2015) 022001

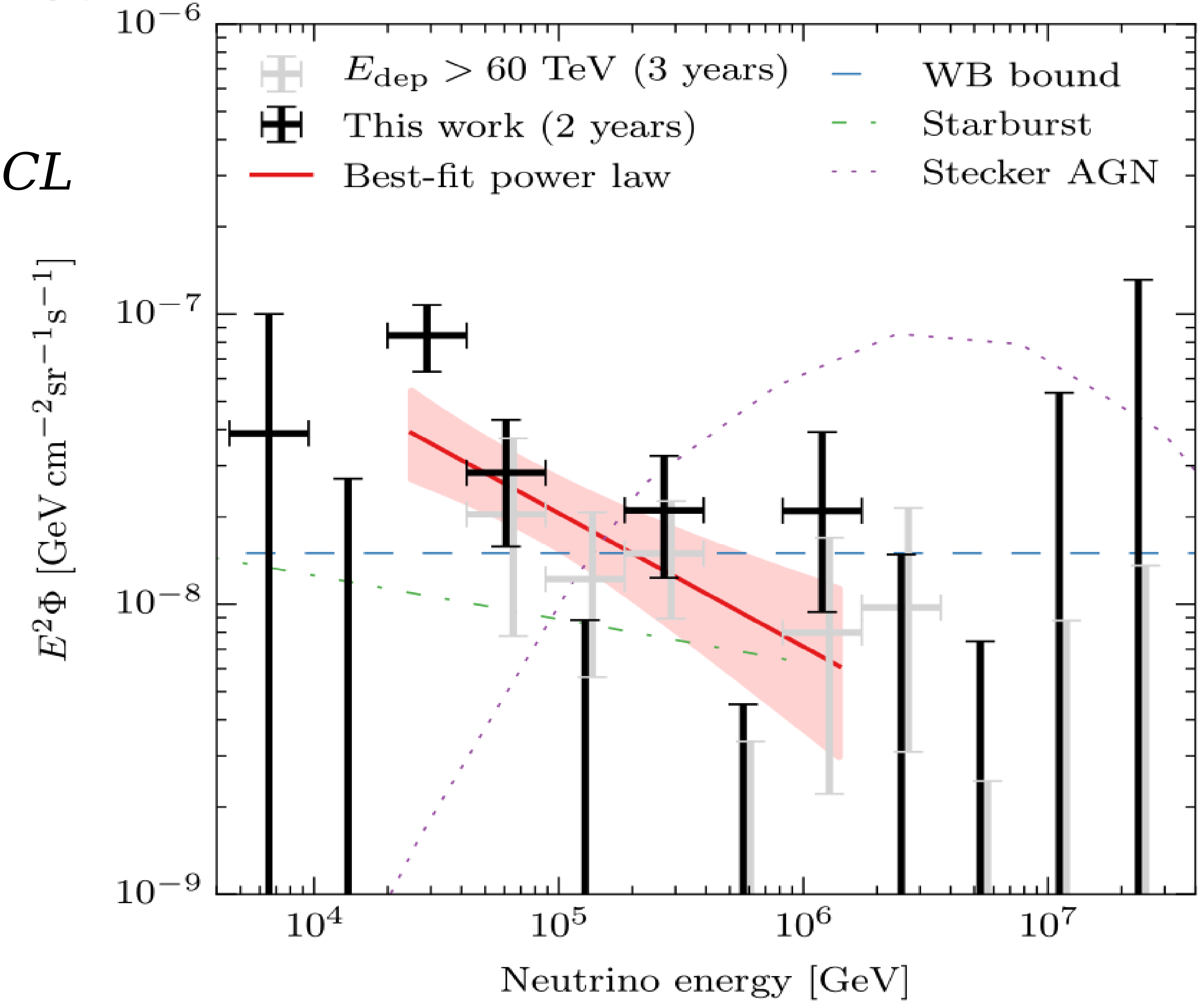
Best-fit power law:

$$\Phi_\nu = 2.06^{+0.4}_{-0.3} \times 10^{-18} (E_\nu / 10^5 \text{ GeV})^{-2.46 \pm 0.12} \text{GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$$

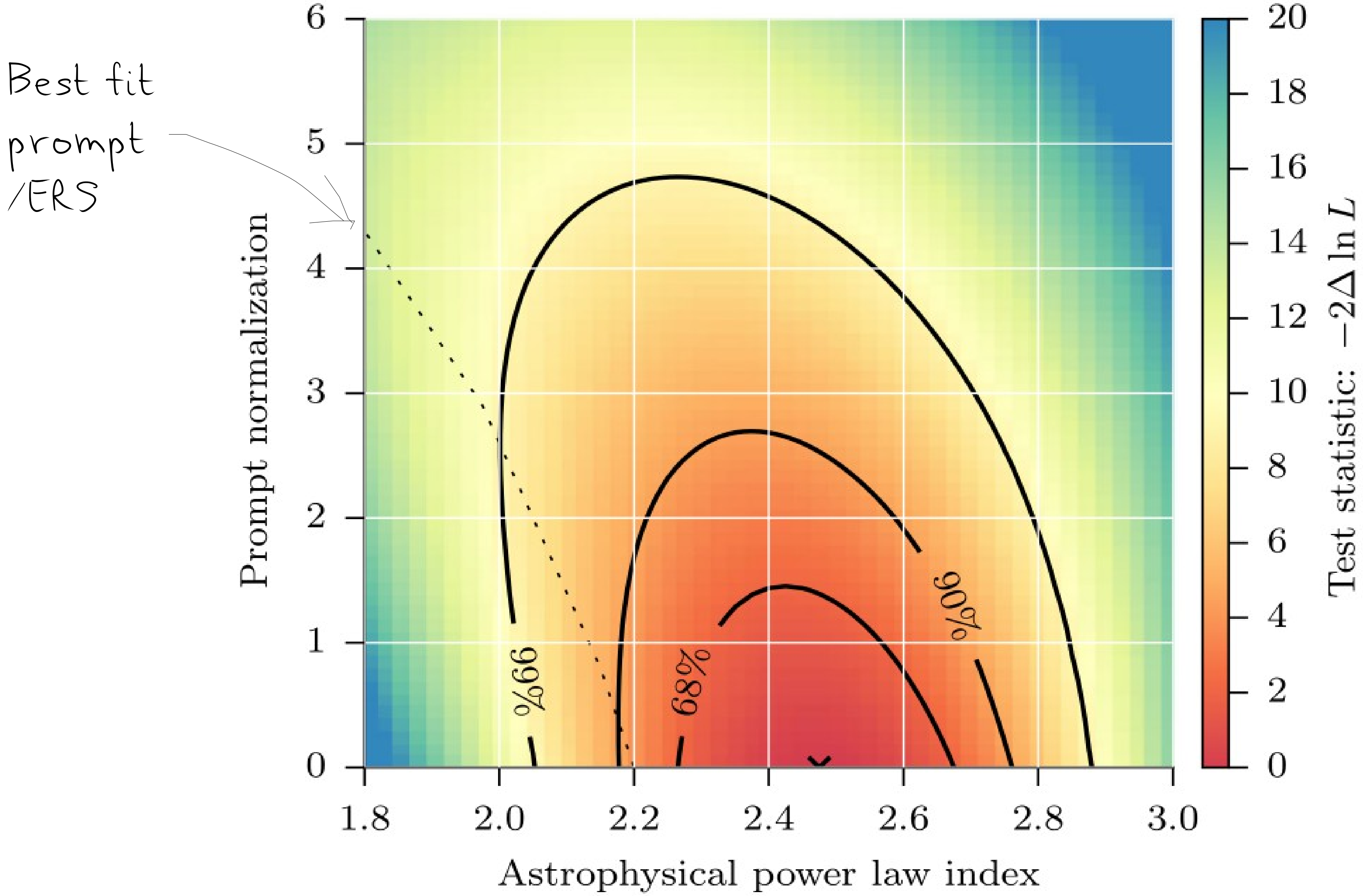
for $25 \text{ TeV} < E_\nu < 1.4 \text{ PeV}$

Prompt flux:

$$\Phi_\nu < 1.52 \ \Phi_{ERS} \ @ \ 90\% CL$$

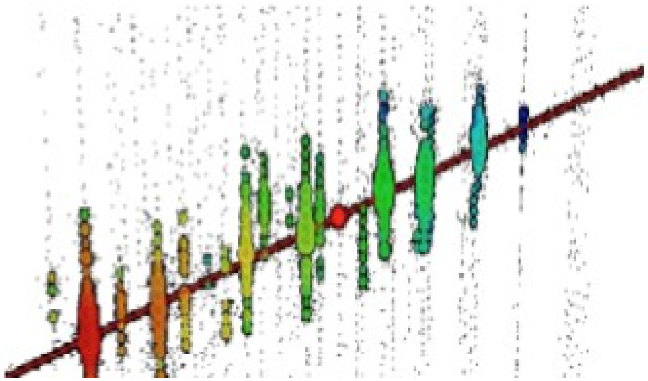


Lower energy starting events

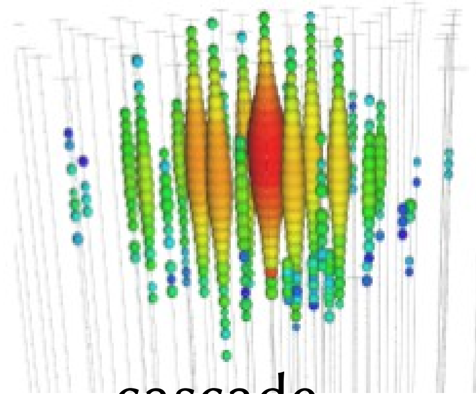


Flavours

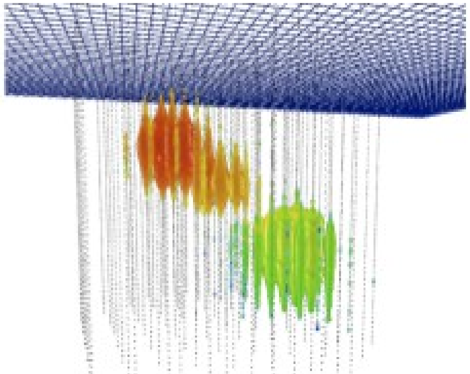
Topologies



track (ν_μ)



cascade
(not ν_μ CC)



simulated double bang (ν_τ)

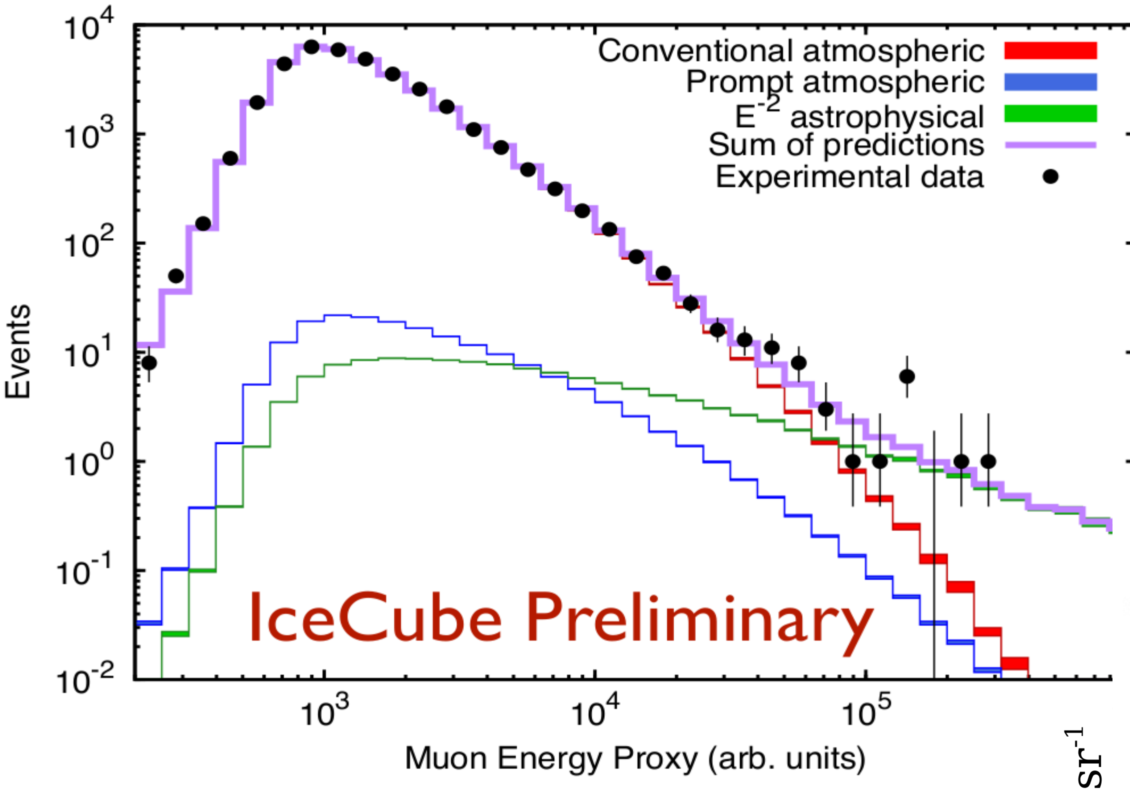
Starting event analyses, with veto layer, tend to select cascade-like topologies because

- ν_μ NC and (nearly) all ν_e , ν_τ interactions give cascades - only ν_μ CC gives tracks
- Energy is lost as the muon from ν_μ CC leaves the detector
- Low energy background muons which don't trigger the veto can suffer catastrophic energy loss and be seen as cascades.

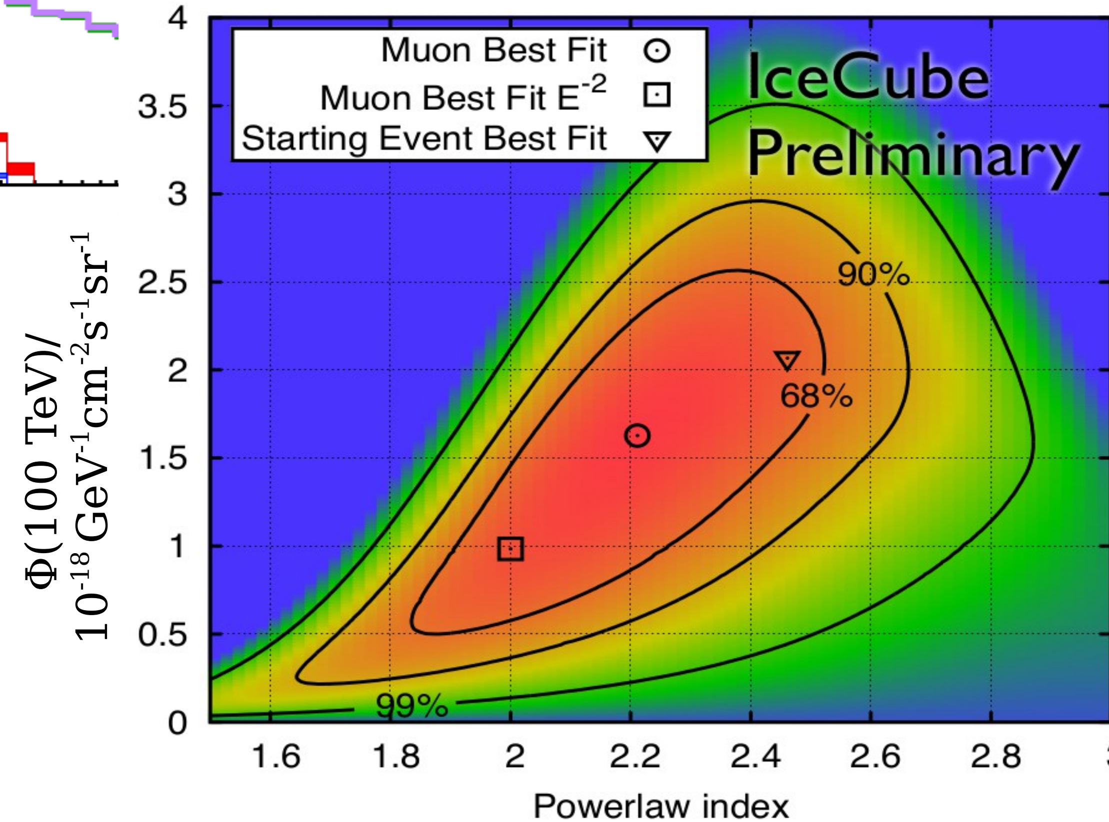
For ν_μ, exploit muon track length and look for upgoing **entering** events (classical approach). Important validation of astrophysical signal.

Upgoing ν_μ search

No veto - use energy to discriminate against atmospheric ν background.

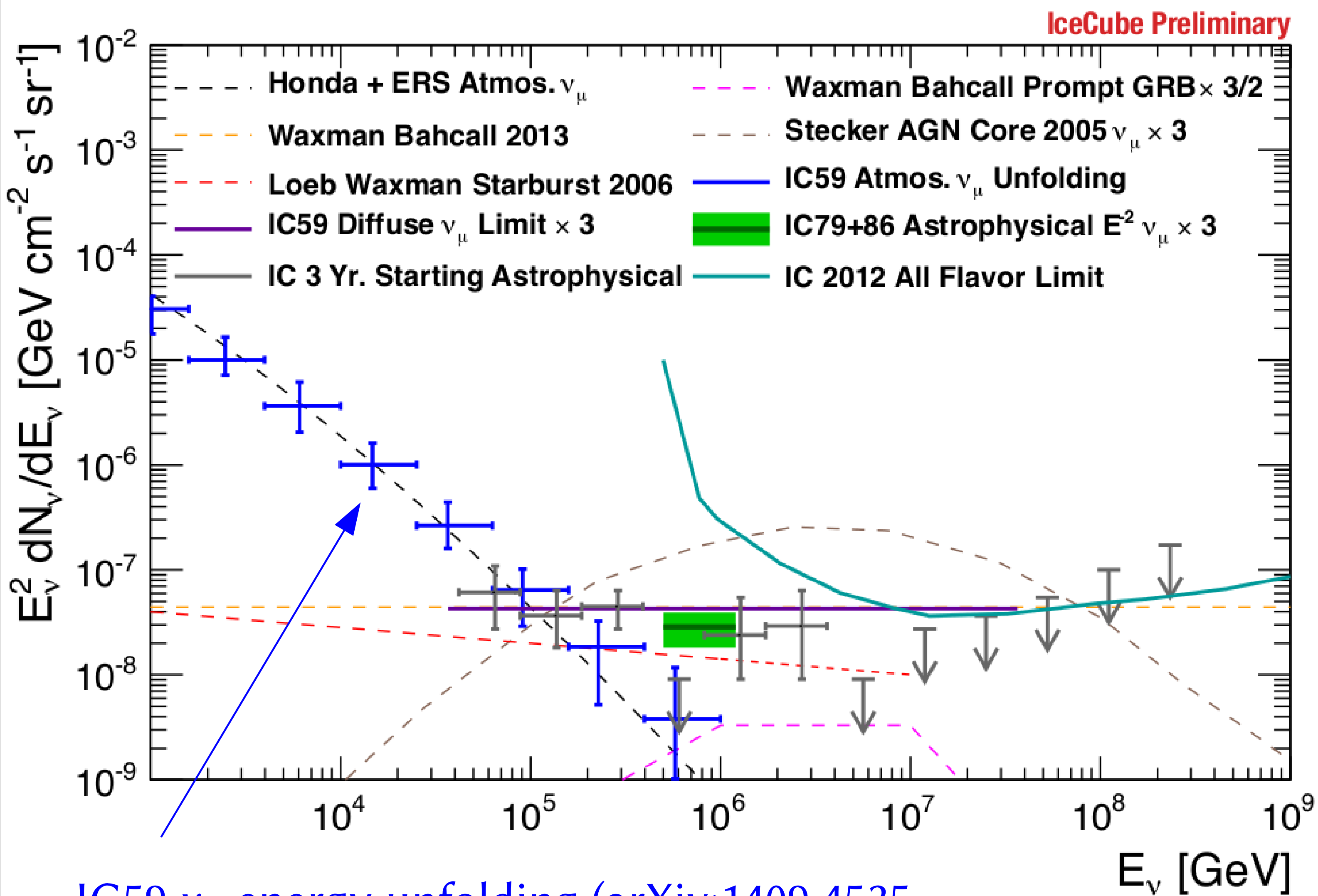


- 2 years of data
- 25000 events
- 3.7 σ excess over atmospheric ν_μ flux
- consistent with starting event analysis



Paper in collaboration review

Neutrino spectrum



IC59 ν_μ energy unfolding (arXiv:1409.4535, accepted by EPJ)

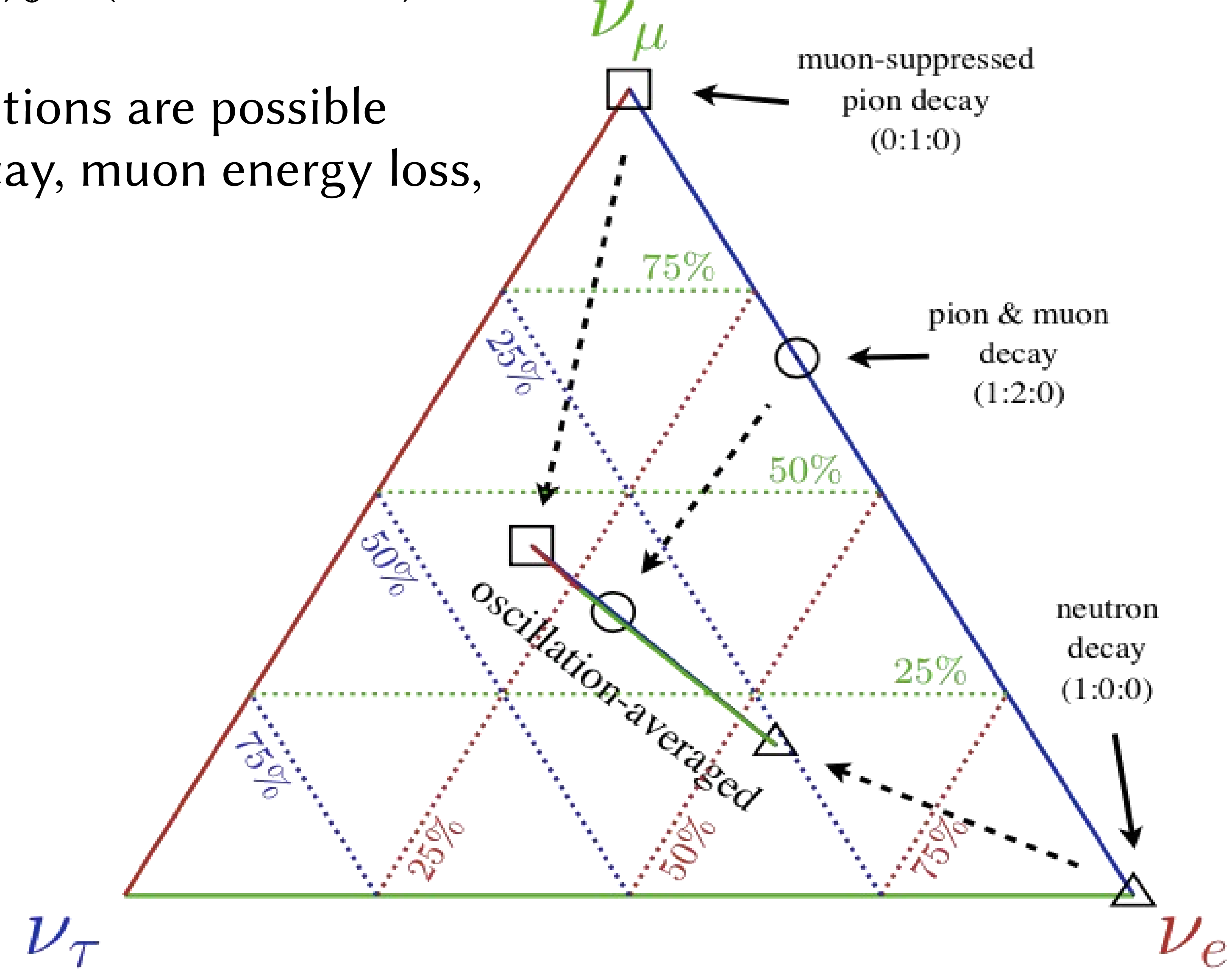
IC79 unfolding paper in preparation

Flavour ratio

$\pi \longrightarrow \mu\nu_\mu\,; \quad \mu \longrightarrow e\,\nu_e\,\nu_\mu$

Pion decay chain gives $(\nu_e{:}\nu_\mu{:}\nu_\tau)_S = (1{:}2{:}0)$ at source. Oscillations turn this into $(\nu_e{:}\nu_\mu{:}\nu_\tau)_\oplus = (0.95{:}1.02{:}1.05)$ at Earth.

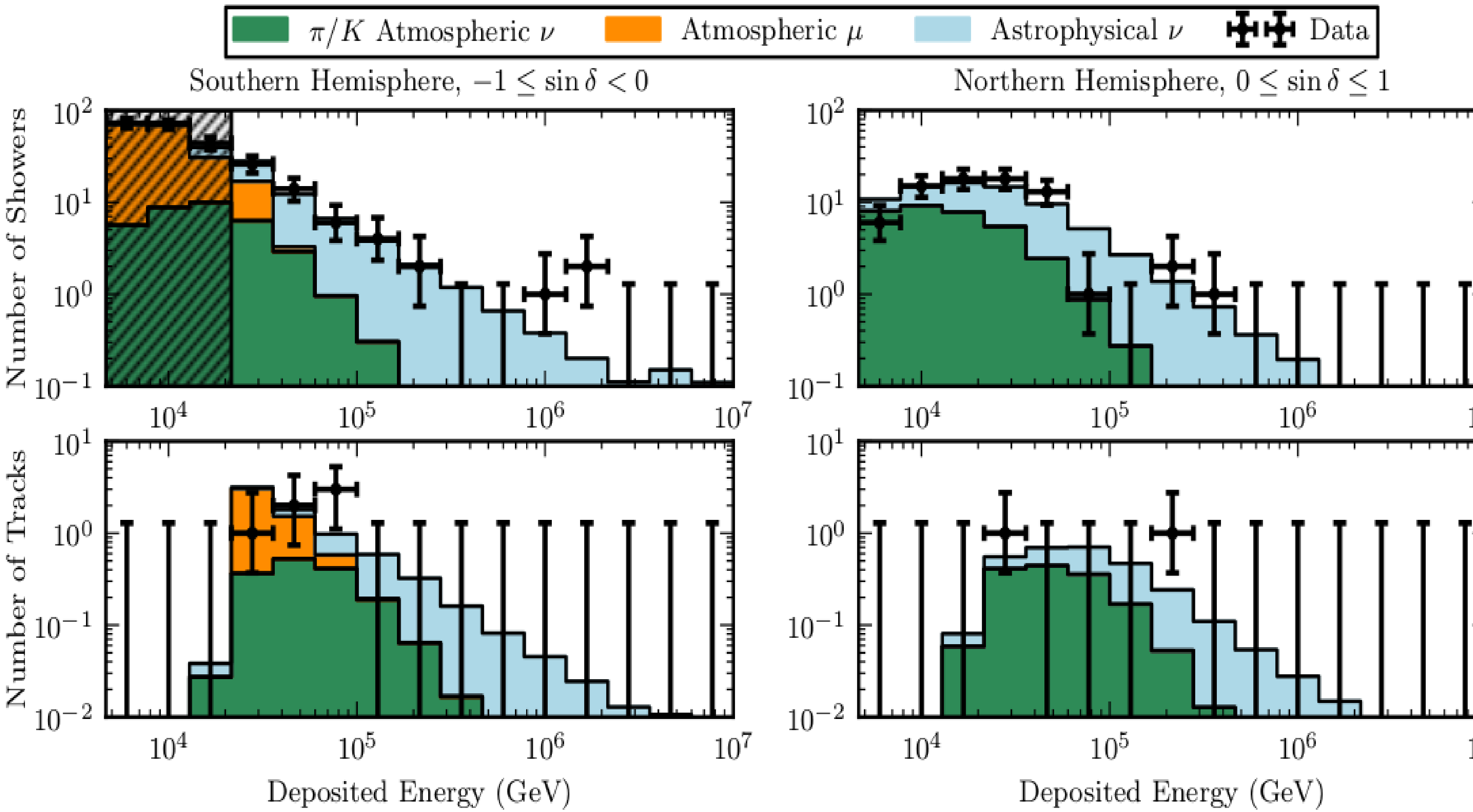
Other source compositions are possible (escaping neutron decay, muon energy loss, muon acceleration).



Flavour analysis

arXiv:1502:03376

- Use veto technique to select starting events
- Reduce threshold for showers from 6000 PE to 1500 PE
- Likelihood ratio to separate tracks and cascades



Results of flavour analysis

arXiv:1502:03376

129 showers + 8 tracks

Best fit to $E^{-\gamma}$, assuming $(\nu_e:\nu_\mu:\nu_\tau)_\oplus = (1:1:1)$

$\Phi(100\ \text{TeV}) = (2.3 \pm 0.4)\times10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$

$\gamma = 2.6 \pm 0.15$

best fit charm is zero

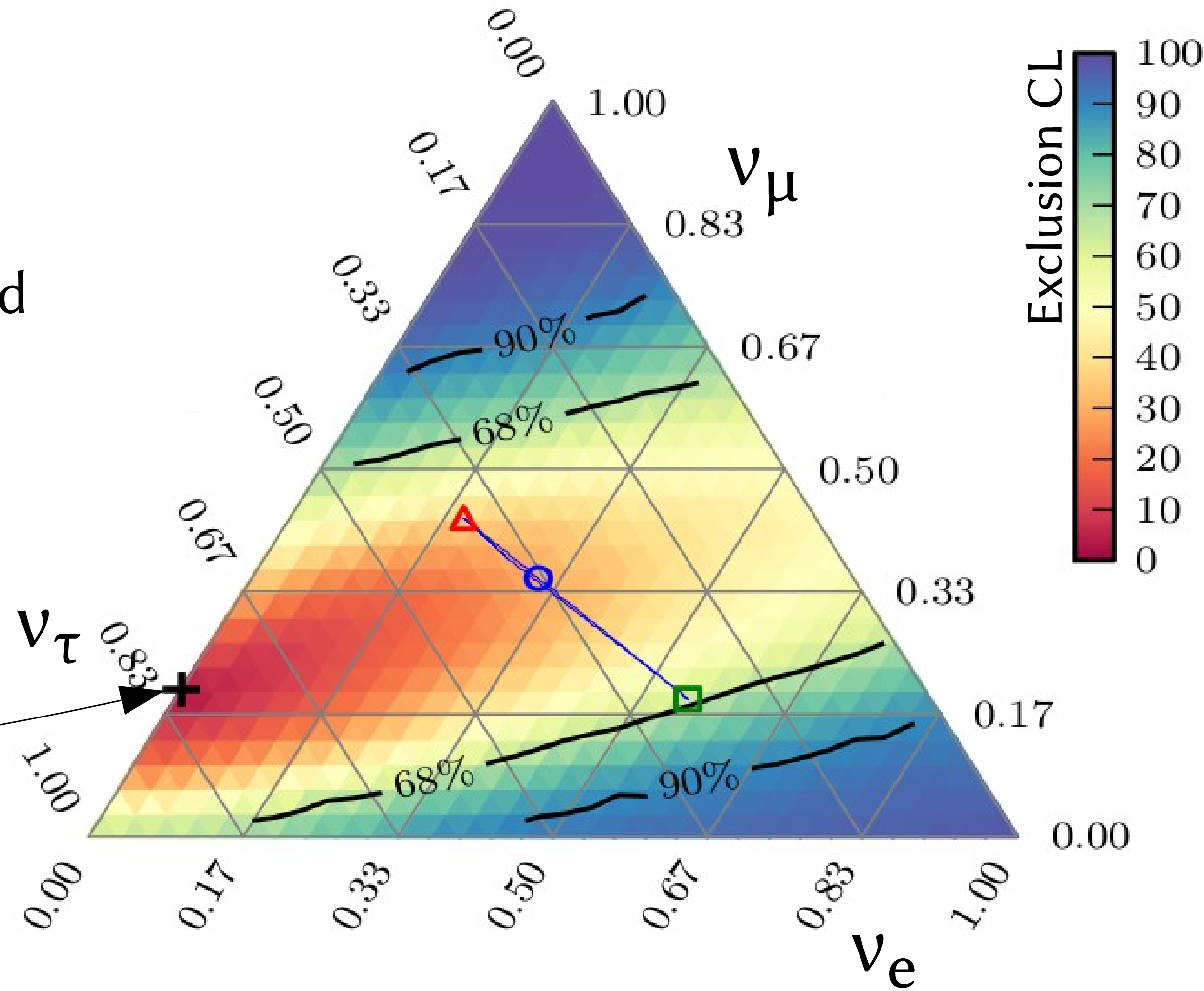
Fit for flavour ratio at Earth

No source composition excluded

$(0:1:0)_\oplus$ excluded at 3.3 σ

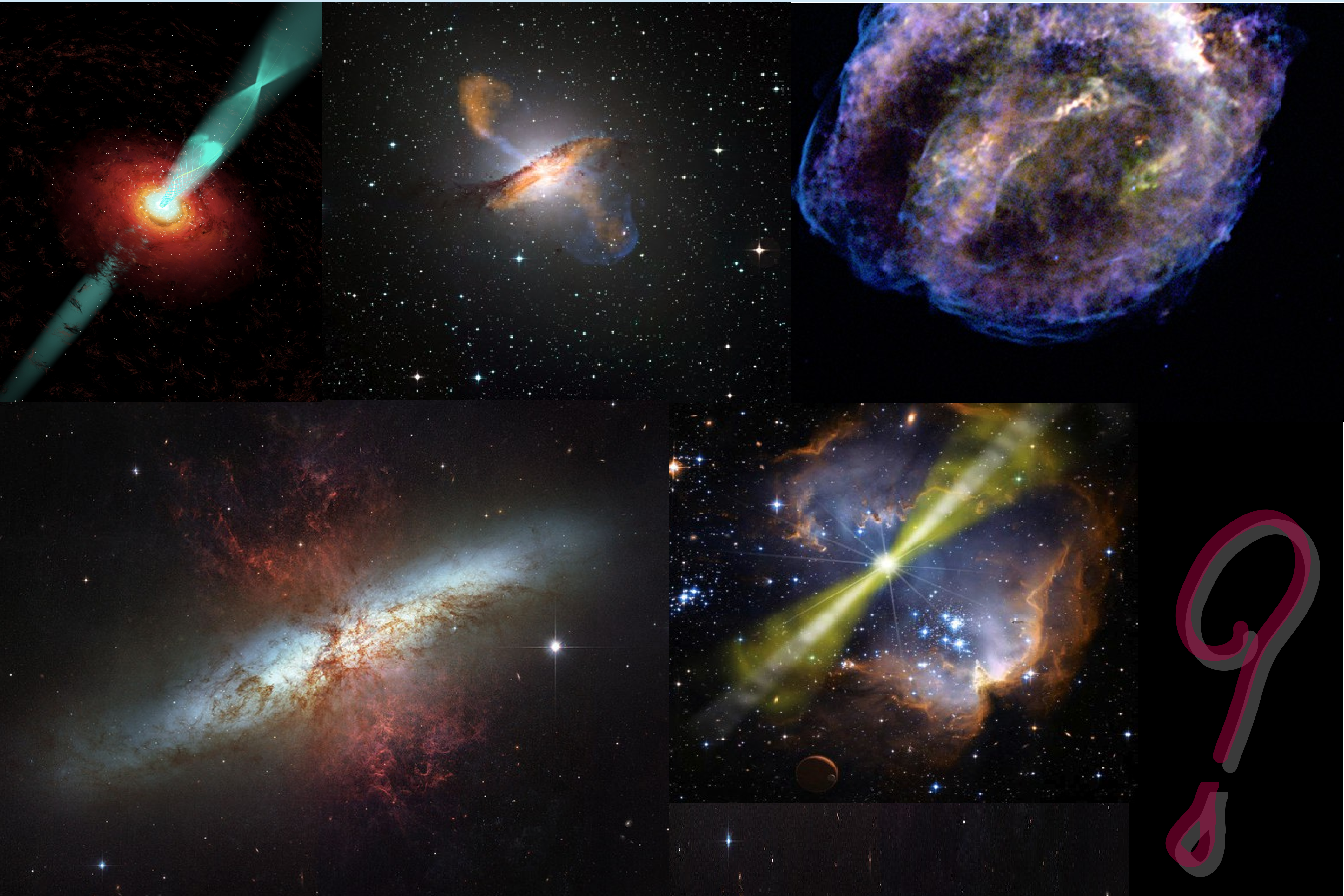
$(1:0:0)_\oplus$ excluded at 2.3 σ

Best fit: $(0:0.2:0.8)_\oplus$



Origins

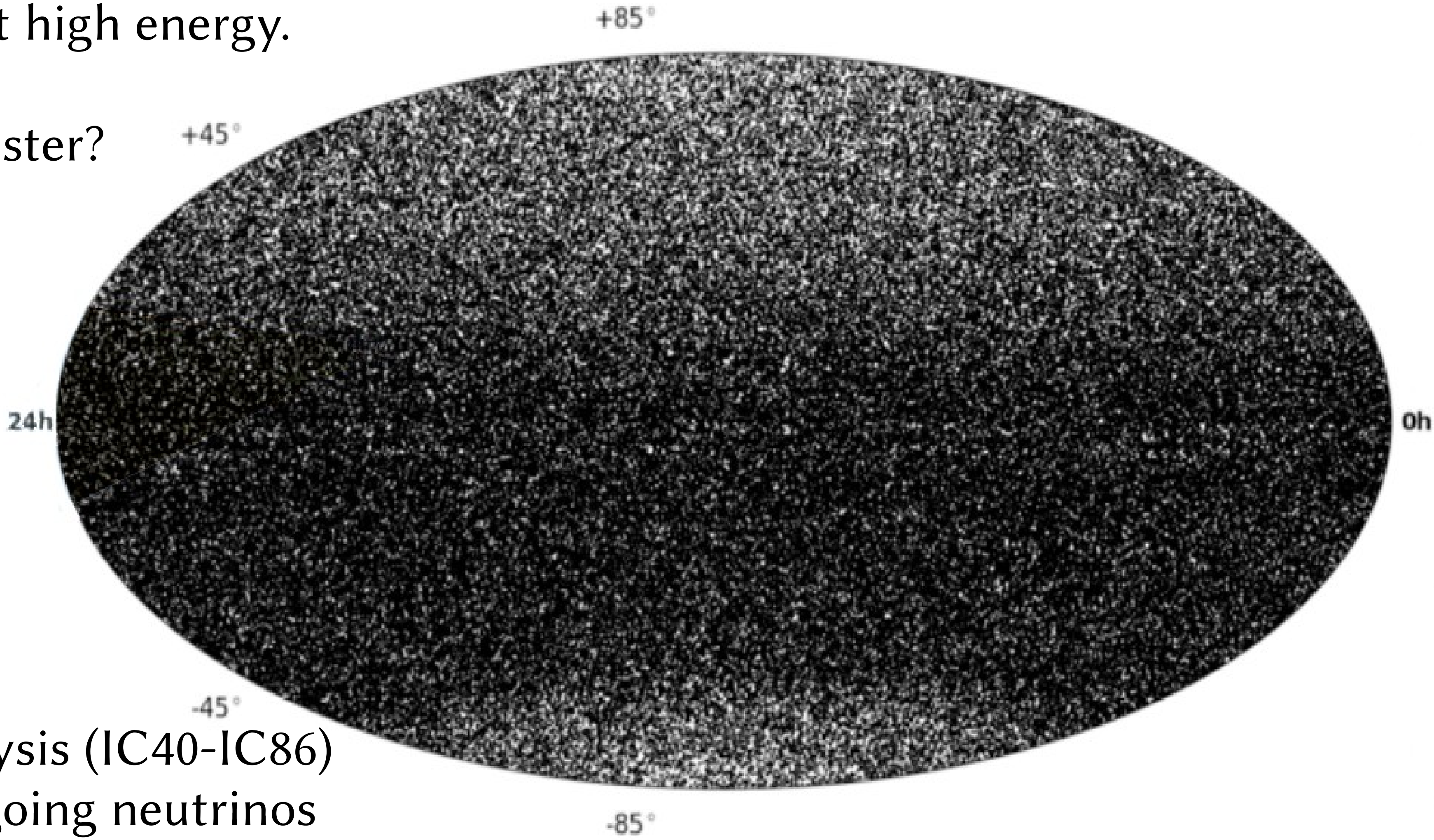
Where are they from?



All-sky steady point source search

Expect hundreds of astrophysical ν_μ events per year in data, based on detection at high energy.

Do they cluster?



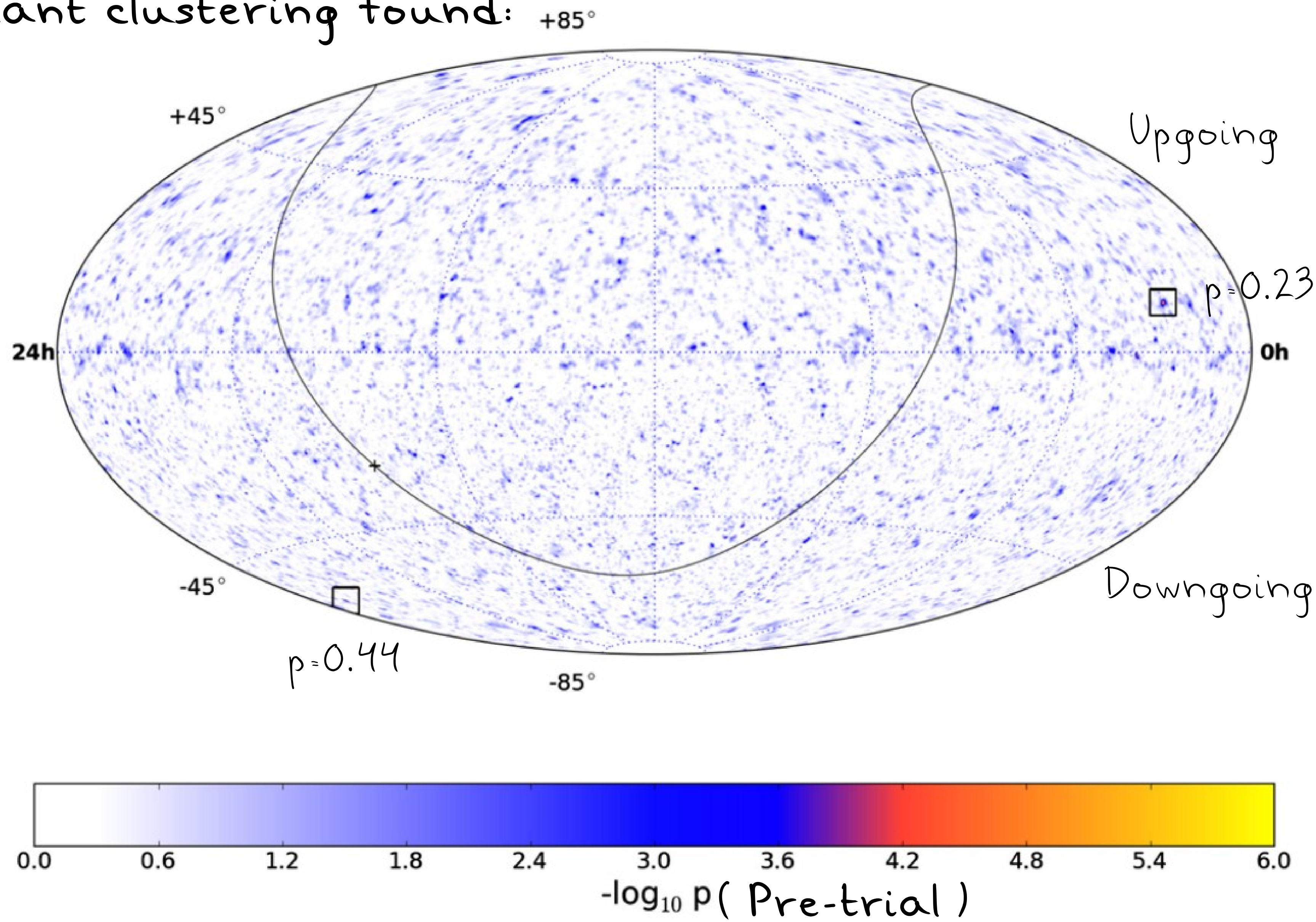
4-year analysis (IC40-IC86)
178 000 upgoing neutrinos
216 000 downgoing muons
(mostly background)

Unbinned maximum likelihood tests for fine grid of source hypotheses:

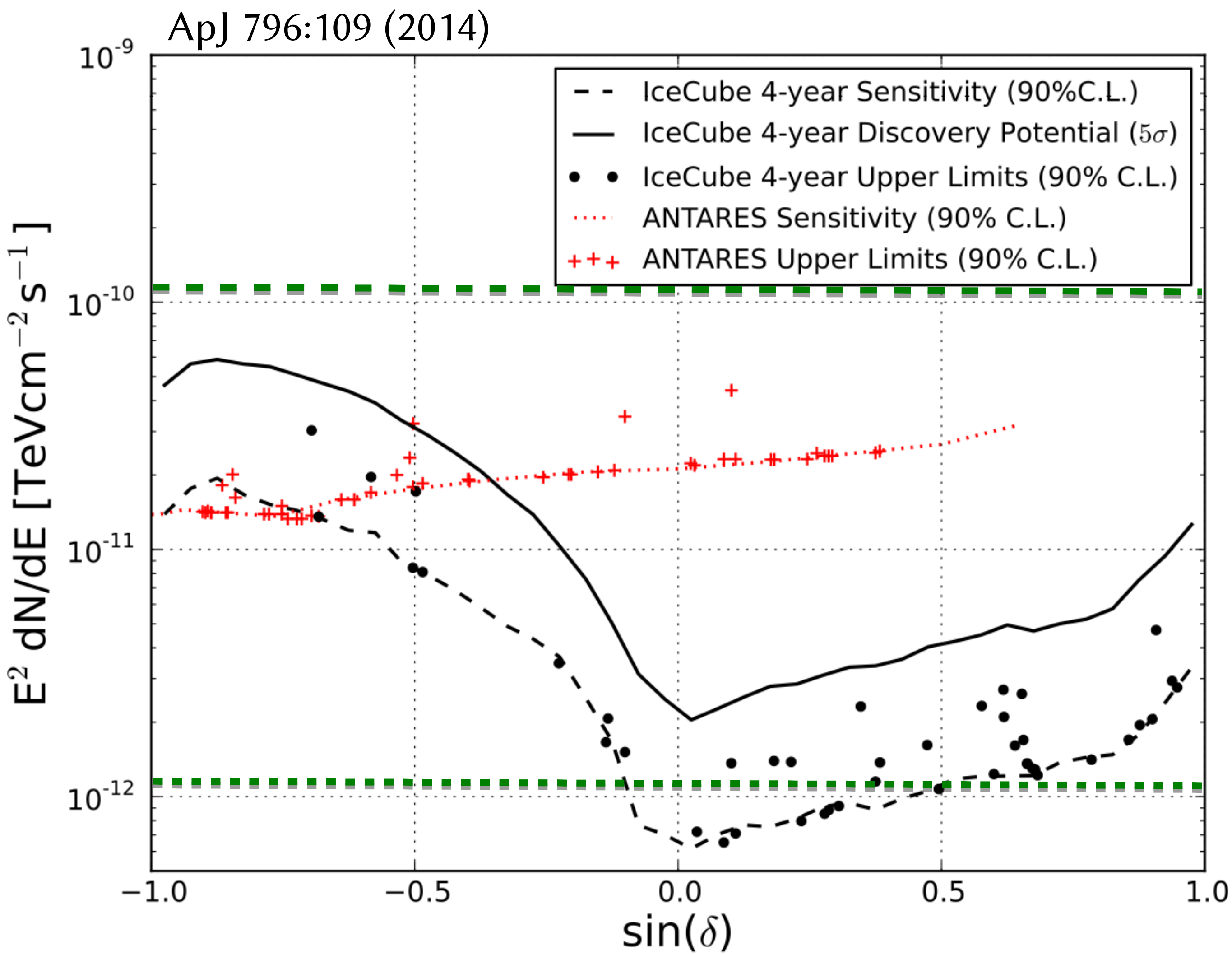
Significance skymap

THE ASTROPHYSICAL JOURNAL, 796:109 (14pp), 2014 December 1

No significant clustering found:



Point source sensitivity & limits



Point-source equivalent flux if the diffuse flux came from:

one point in the sky

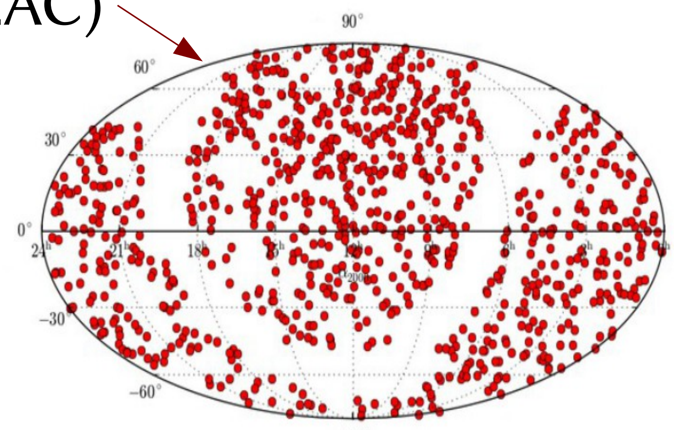
100 points in the sky

By testing many similar candidate sources together ("stacking"), sensitivity can be improved.

Blazars?

T. Glüsenkamp, RICAP 2014

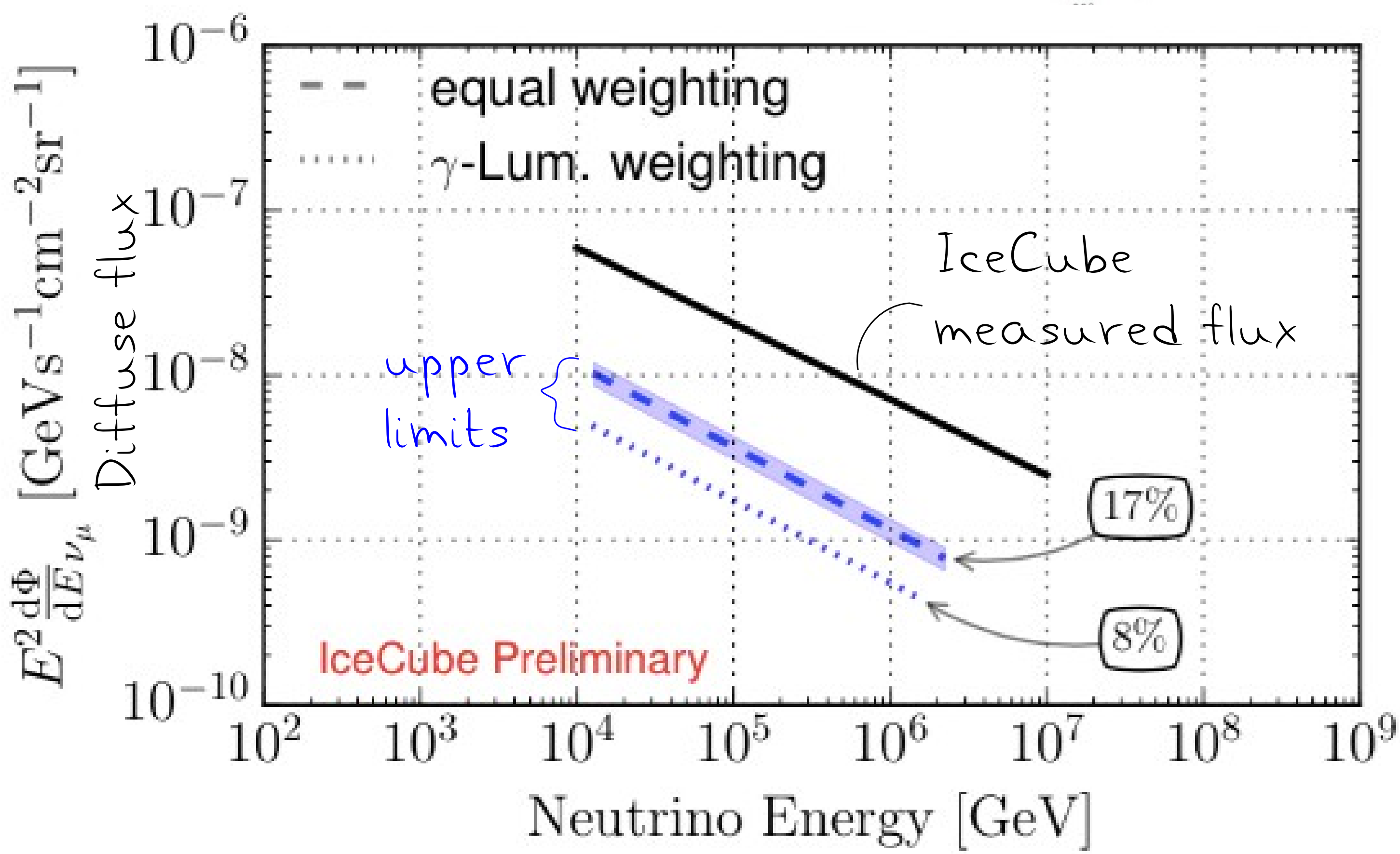
283 blazars in Fermi LAT catalogue (2LAC)



- Estimate signal from entire population
- Likelihood based on event directions and energies
- Single directional signal pdf from blazar positions and PSF

↓

- Slight excess (p=6%)
- At most ~20% of diffuse flux comes from blazars



GRBs?

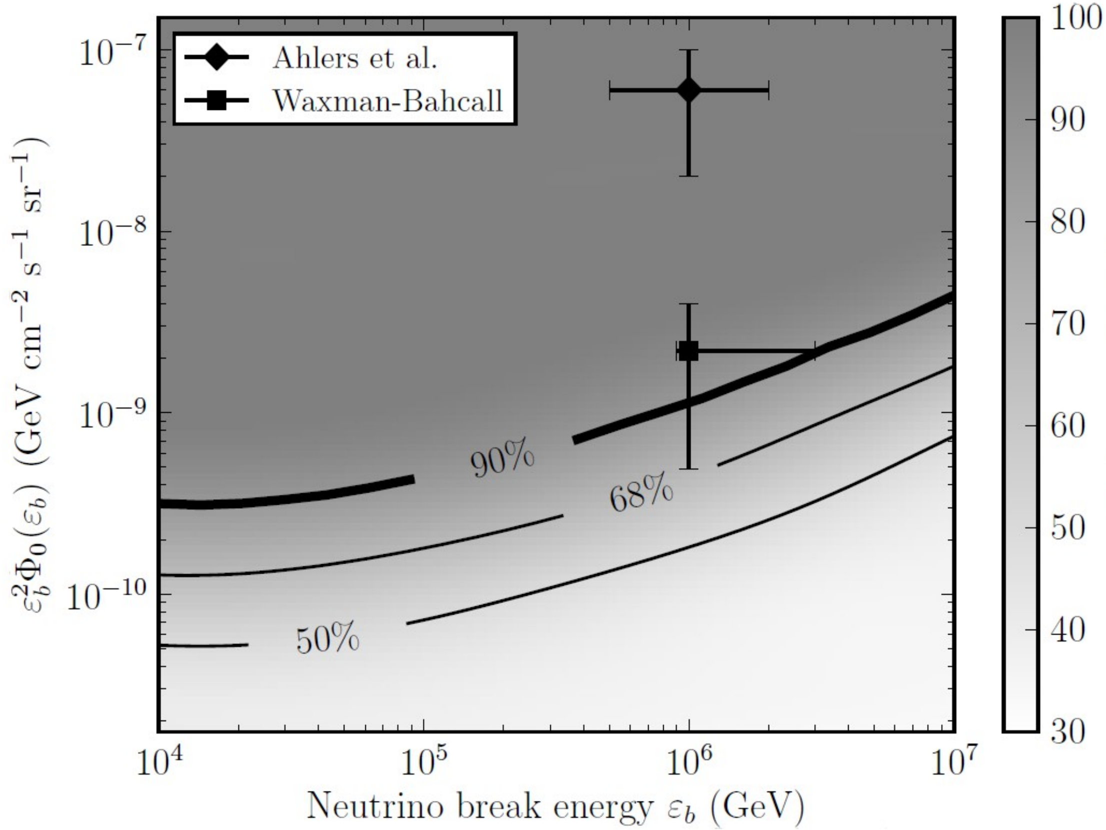
arXiv:1412.6510

Attempting to match ν_μ events to 506 bursts over four years.

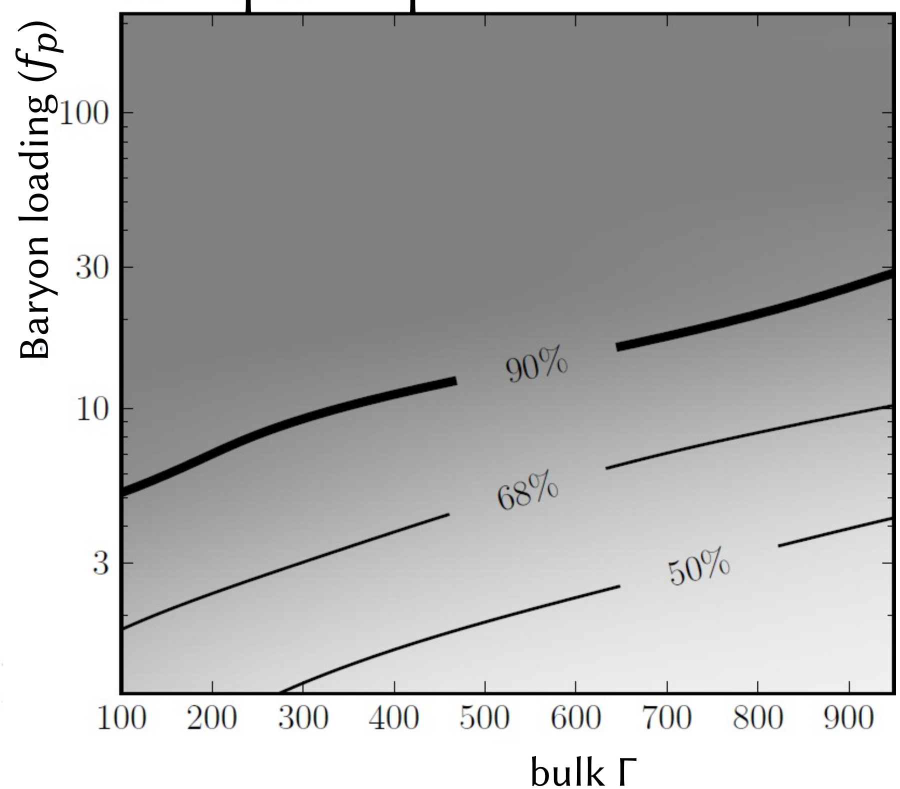
Timing information - very low background!

One matching track - not significant.

Simple double-break model limit:



More realistic models with individual fluxes also tested, e.g. photospheric emission:

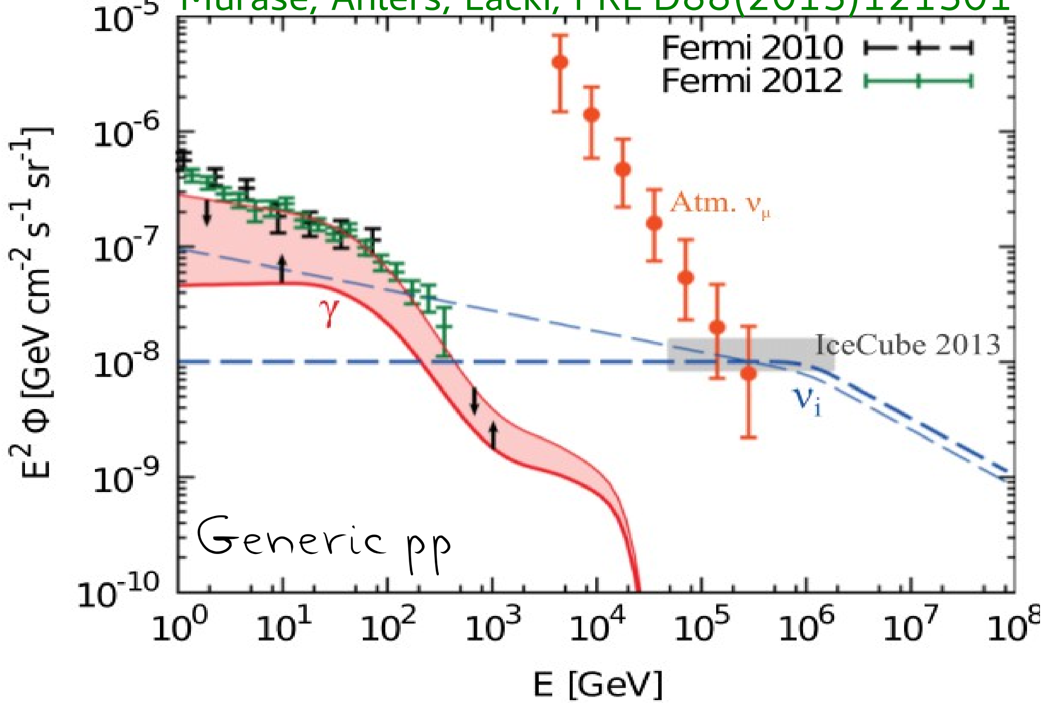


Only ~1% of diffuse neutrino flux can come from GRBs

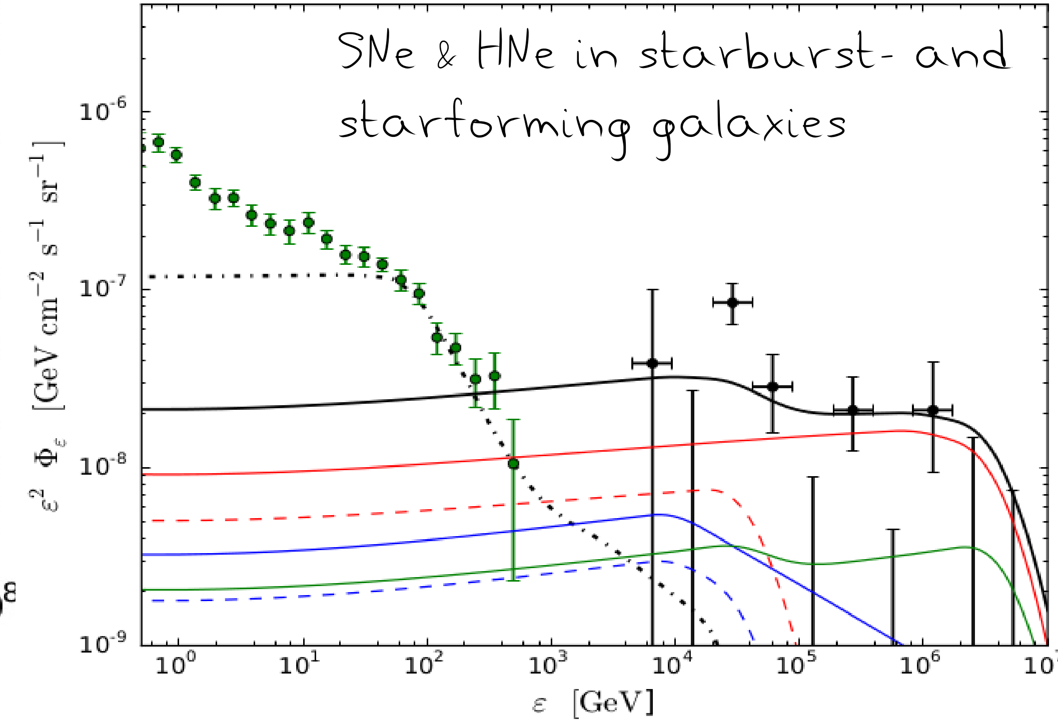
Online tool for testing favourite bursts vs. favourite model: icecube.wisc.edu/science/tools

Models

Murase, Ahlers, Lacki, PRL D88(2013)121301

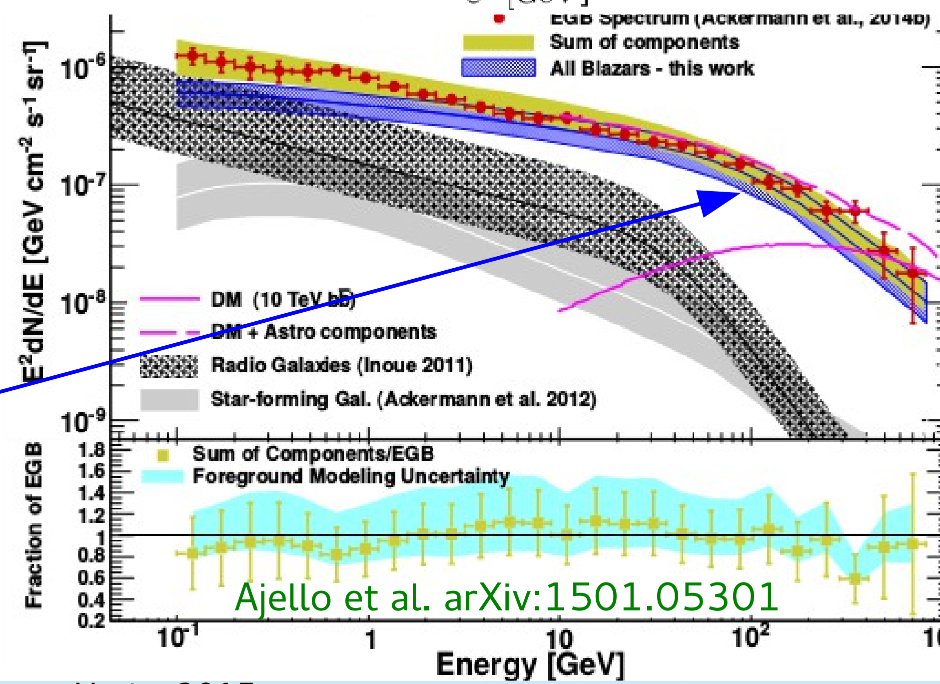


Senno et al. arXiv:1501.04934



pp→π+X; $\pi^\pm$→μν and π^0→γγ
gammas cascade and make large contribution to extragalactic γ background (EGB)

But Fermi EGB observation dominated by blazars above ~100 GeV



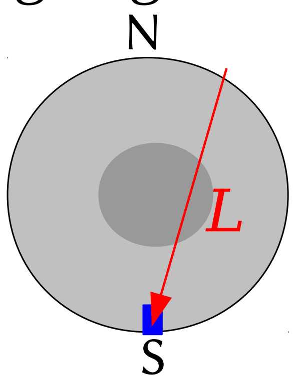
Where do the neutrinos come from?
pγ→π+X?

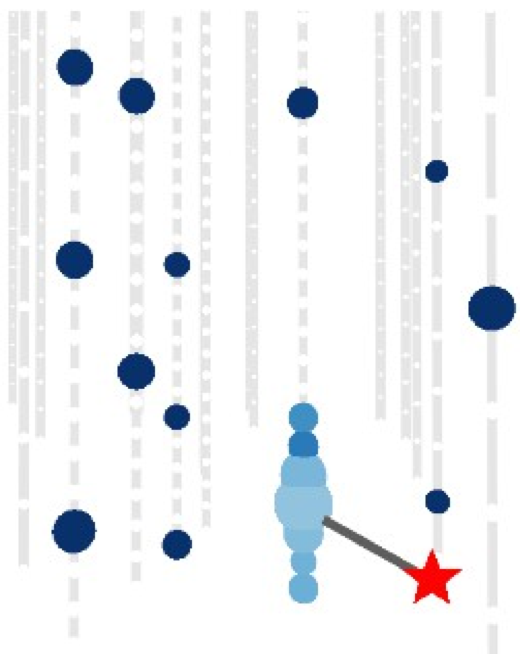
What Next?

Oscillations – a success story!

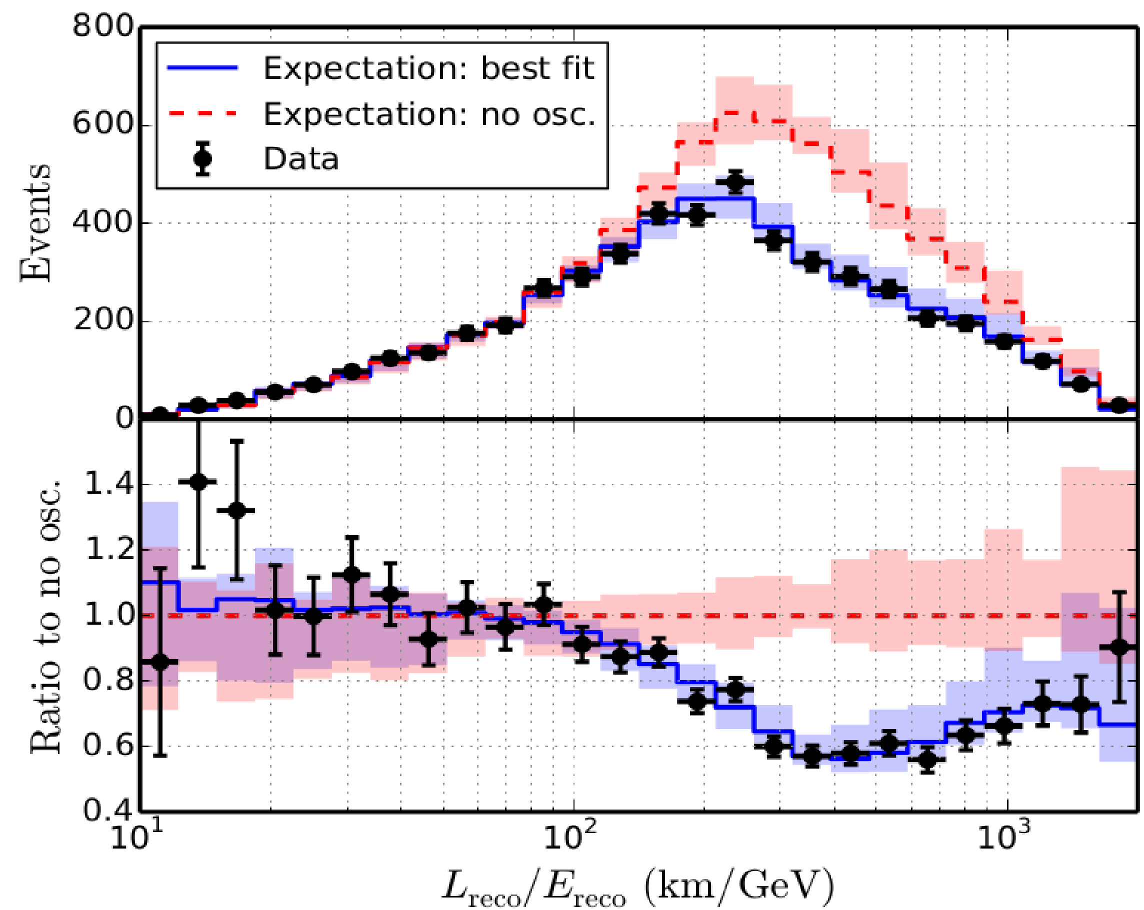
arXiv:1410:7227

- Three years of DeepCore data
- 5174 upgoing muon events selected



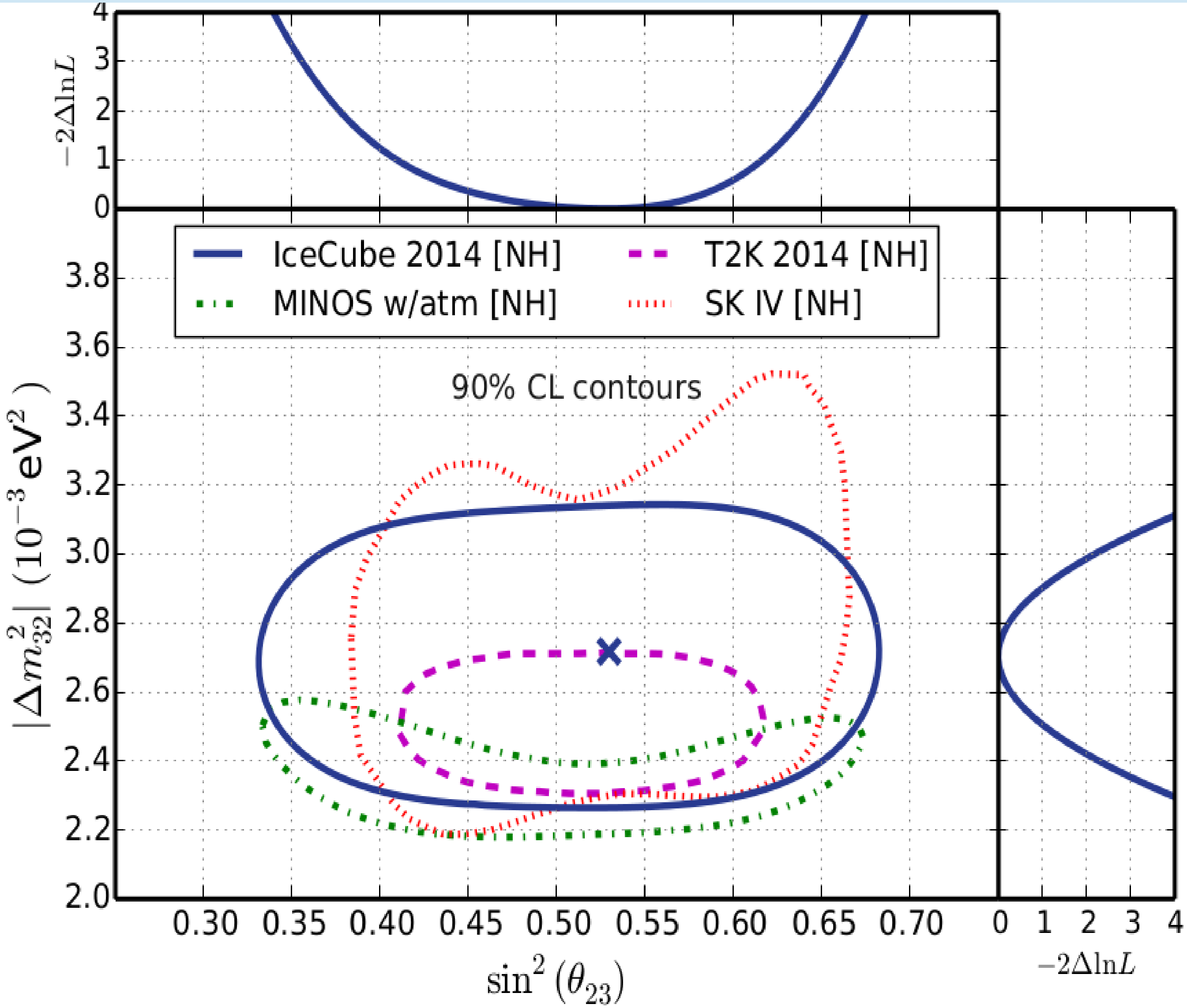


Simulated 12 GeV
ν_μ CC event



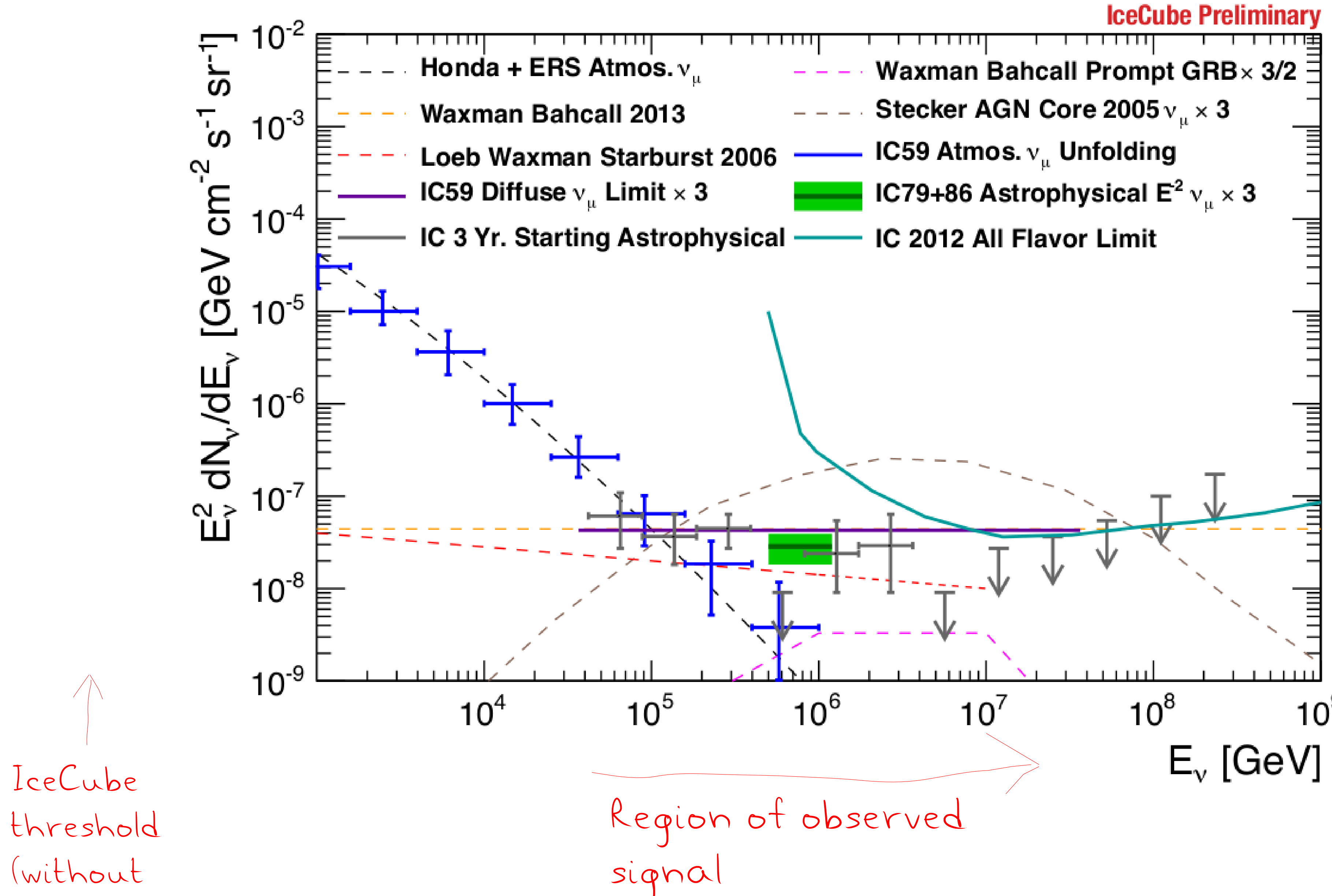
Oscillation result

arXiv:1410:7227



- DeepCore works fine for oscillation physics!
- Results will improve.
- But for mass ordering we need more sensitivity at low energy →

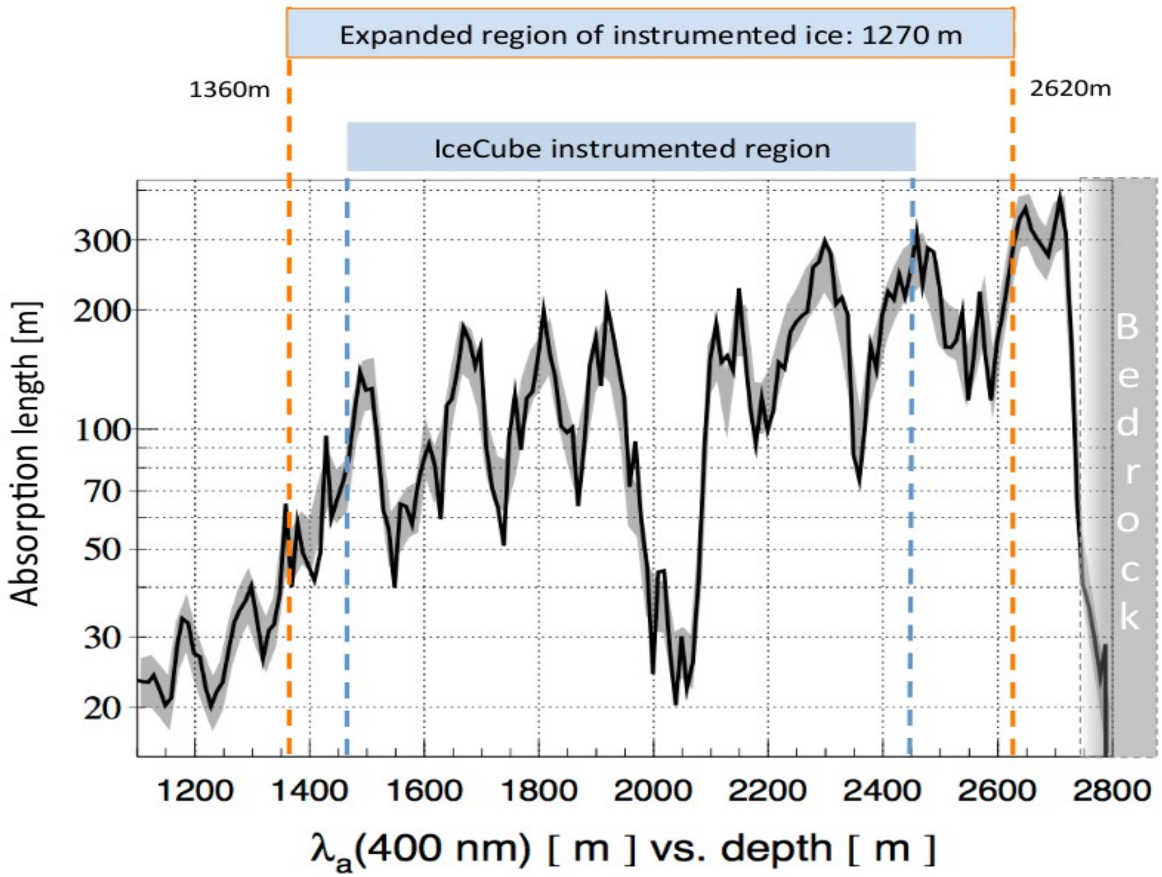
High Energy Extension

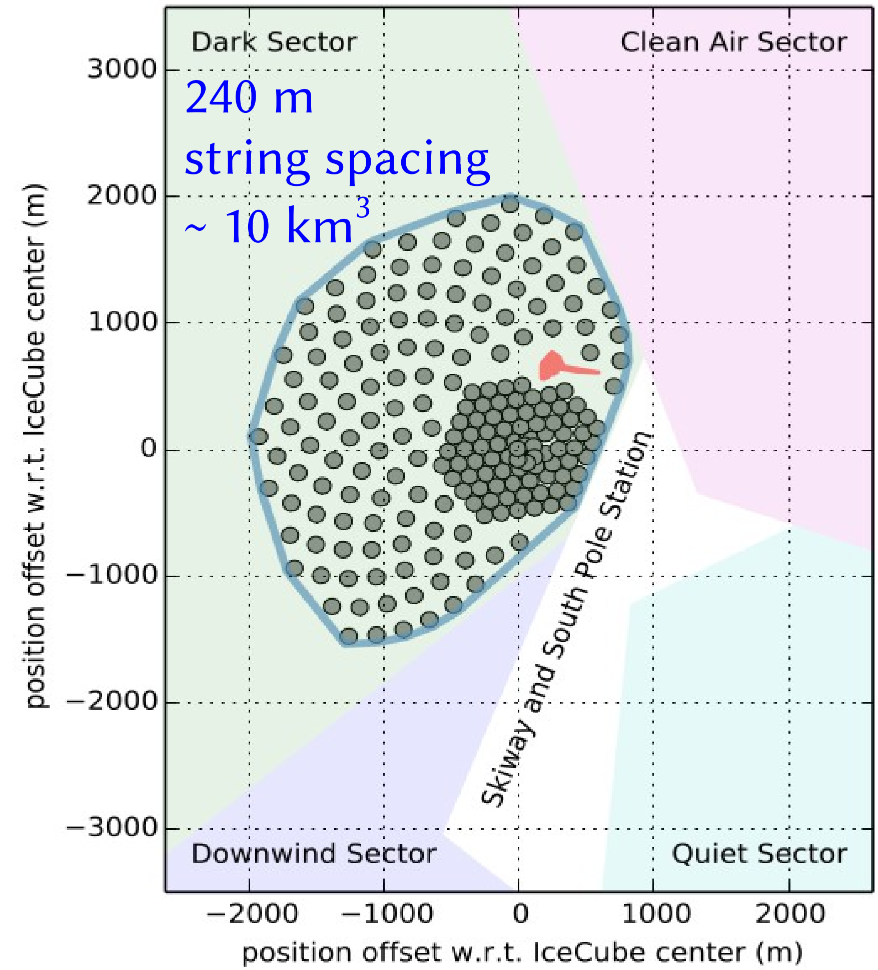


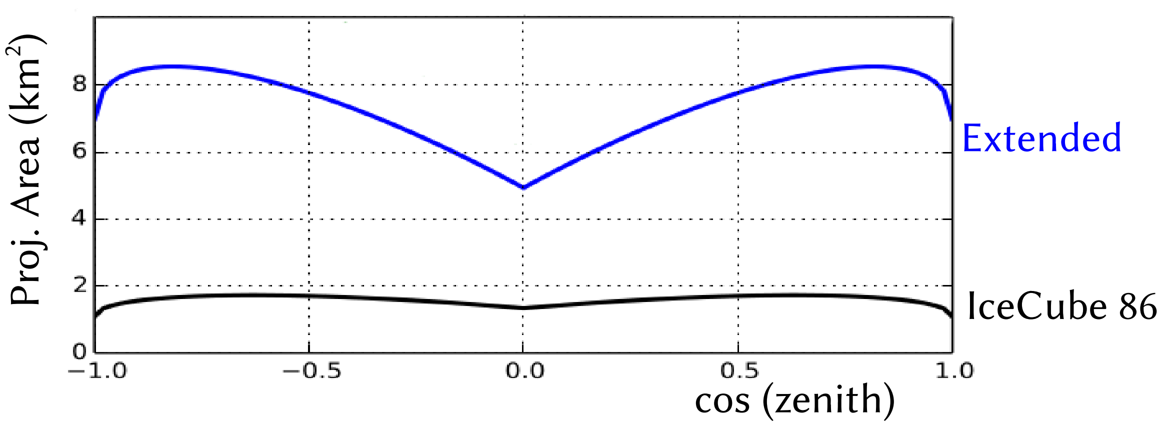
Re-optimize for higher energies!

High Energy Extension

Use larger string spacing and depth range. Geometries are under study







High energy extension white paper: arXiv:1412.5106

High energy extension could give...

- no problems (using established technology)

- 5x increase in effective area
- improved pointing for HE ν_μ
- 5x better point source sensitivity
- antineutrino detection via Glashow Resonance ($\bar{\nu}_e$+e $\longrightarrow$ W^-), if pp source
- GZK neutrino detection (~a few per year)
- ν_τ double bang events (~one per year)

IceCube-Gen2 Infrastructure

A "next generation IceCube" detector

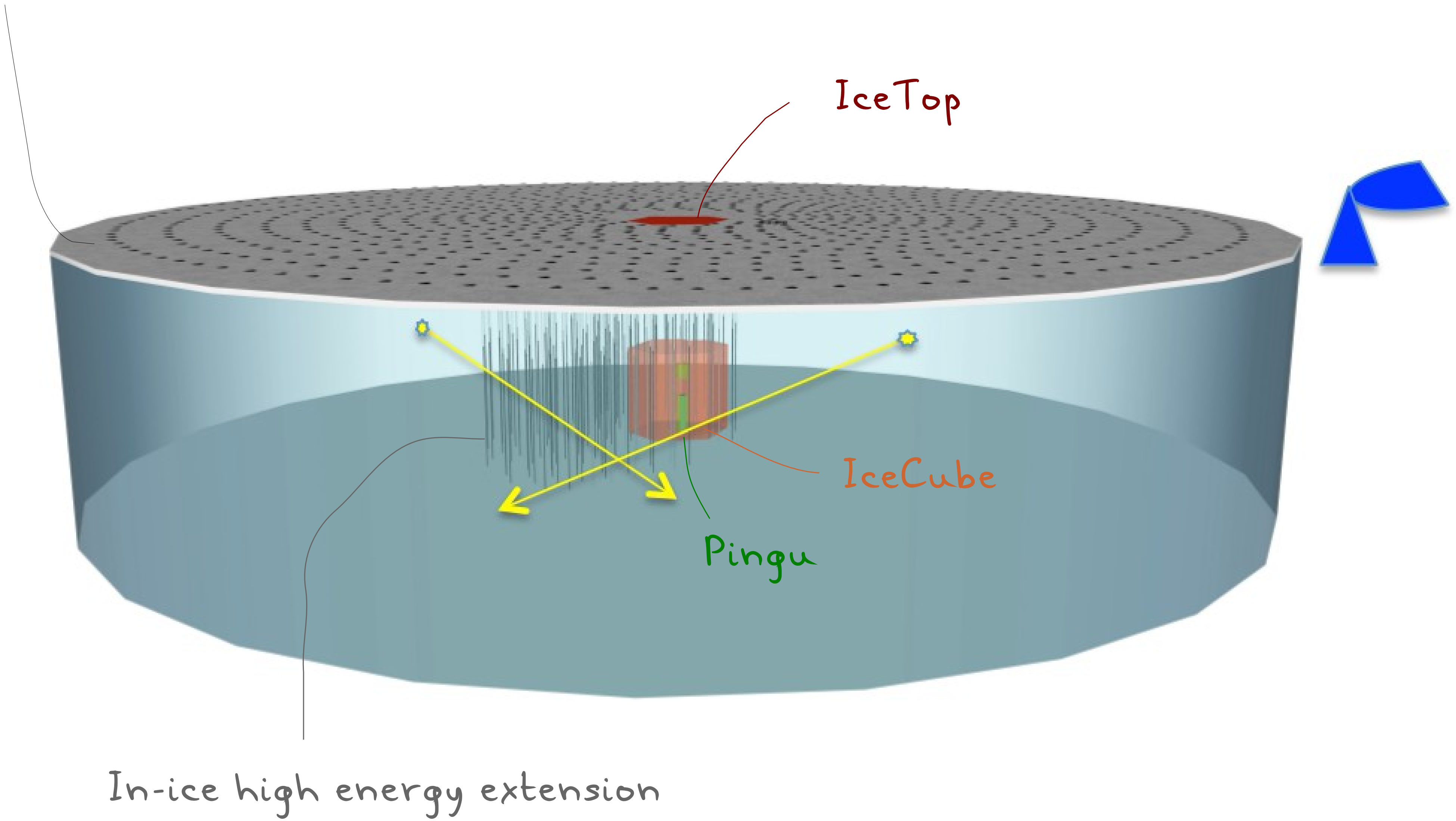
Claudio Kopper, Detector Design and Technology WS, Aachen, Dec 2014

Collaboration is forming

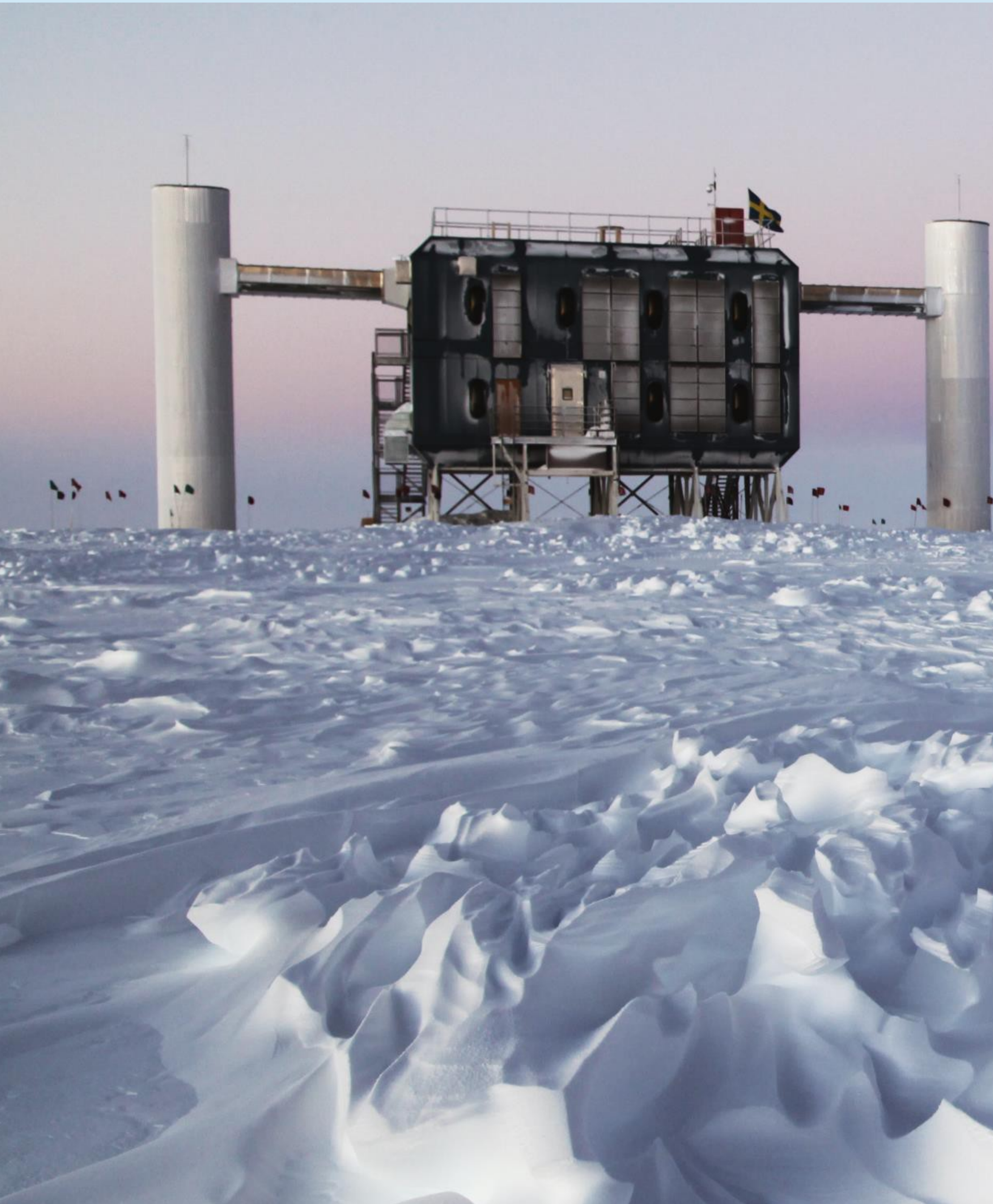
- **PINGU**
  - Scale: 40 strings, extending DeepCore
  - Physics goals: neutrino mass hierarchy, neutrino physics, dark matter
- **High-Energy In-Ice Component**
  - Scale: O(100) strings, O(10km^3)
  - Physics goals: identify astrophysical sources of neutrinos and cosmic rays, neutrino and particle physics, BSM
  - Surface component like IceTop
- **A large surface extension for vetoing downgoing bkg**
  - Several km larger than the detector
  - Optimal size and density under investigation [redacted]

IceCube Gen2

A large surface extension for vetoing downgoing background:



Summary



The window is open

We're seeing an astrophysical ν flux

What are the features of the neutrino spectrum?

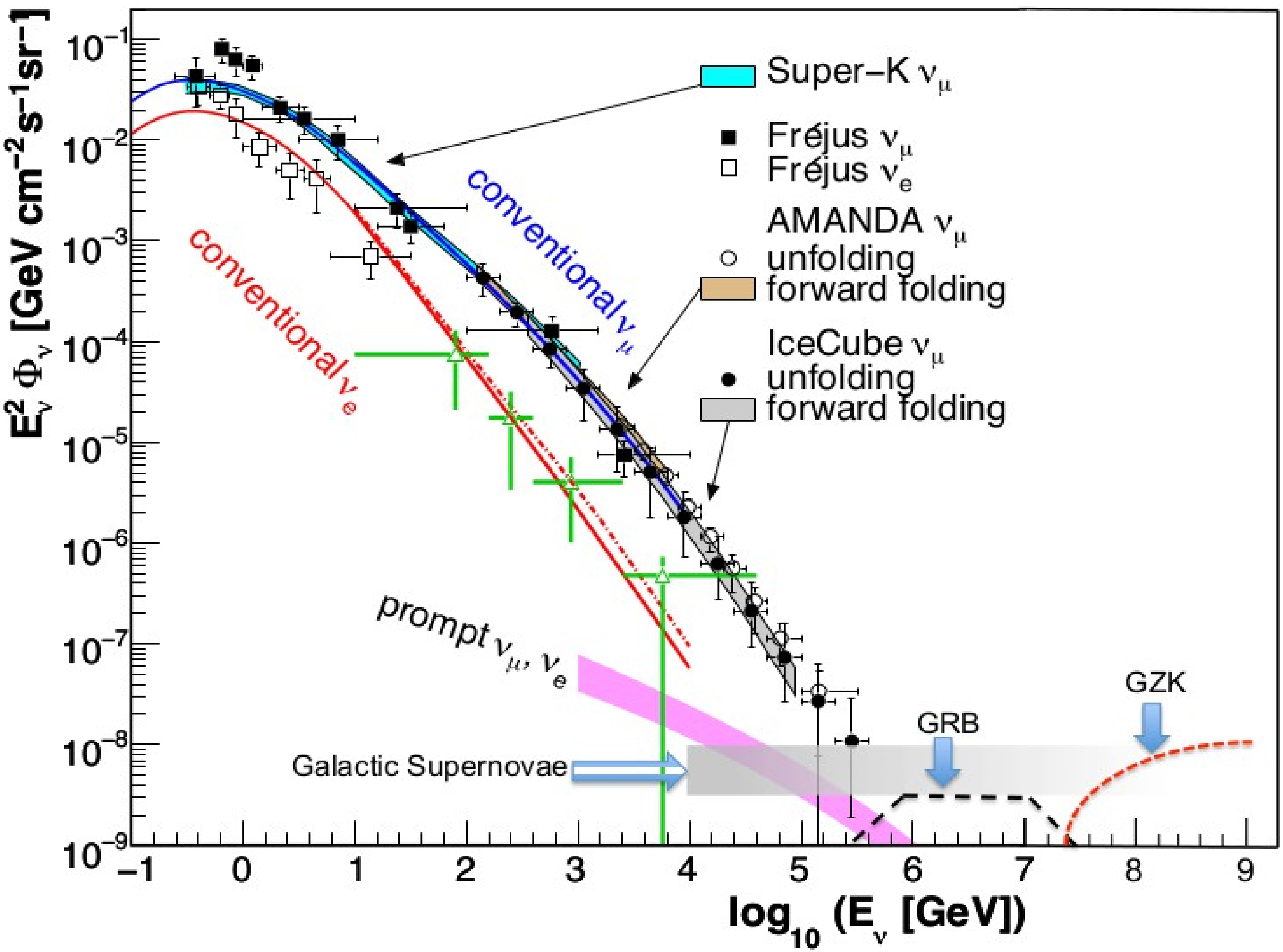
Where/what are the hadronic accelerators??

Need more statistics at low and high energy (IceCube Gen2)

Hoping for new physics!

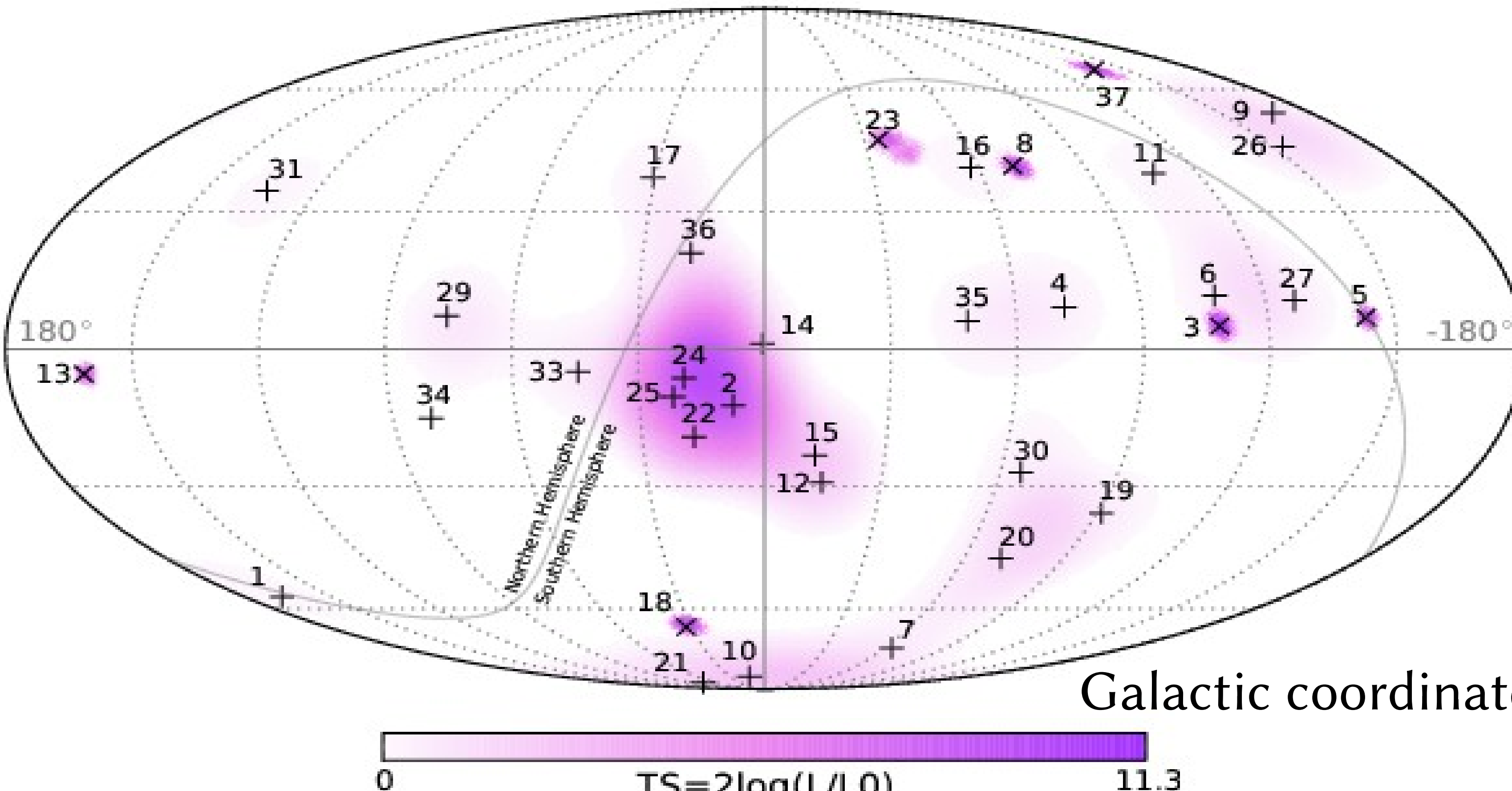
Backup

Neutrino fluxes



HESE skymap

Pre-trial significance - no significant clustering seen



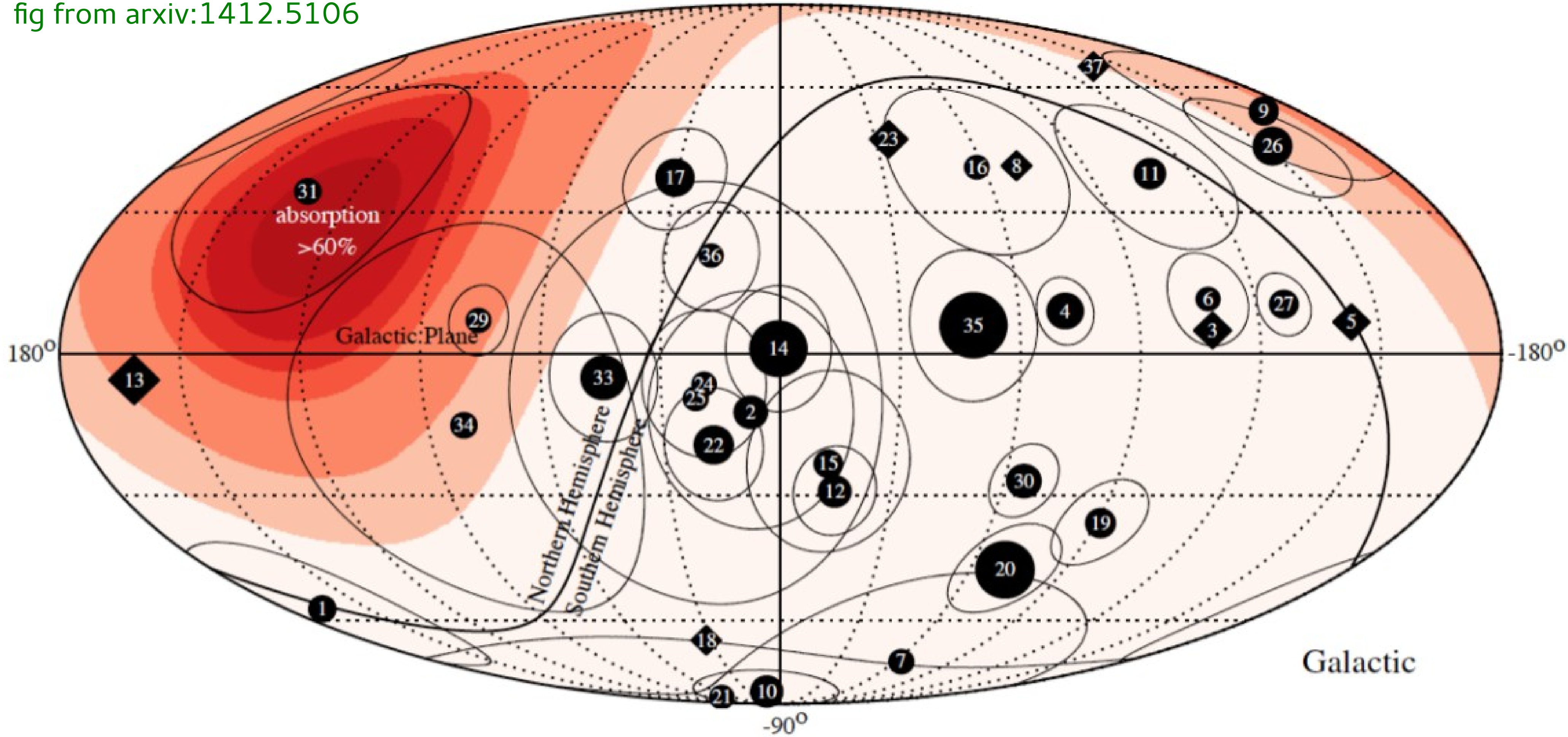
Galactic coordinates

p-values:

all events: 84%
showers: 7.2%
galactic plane: 2.8%

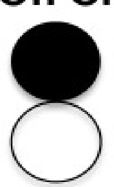
HESE directions & energies

fig from arxiv:1412.5106



diamonds: muon tracks (0.4 degree resolution)

circles : electromagnetic showers



: energy

: angular resolution

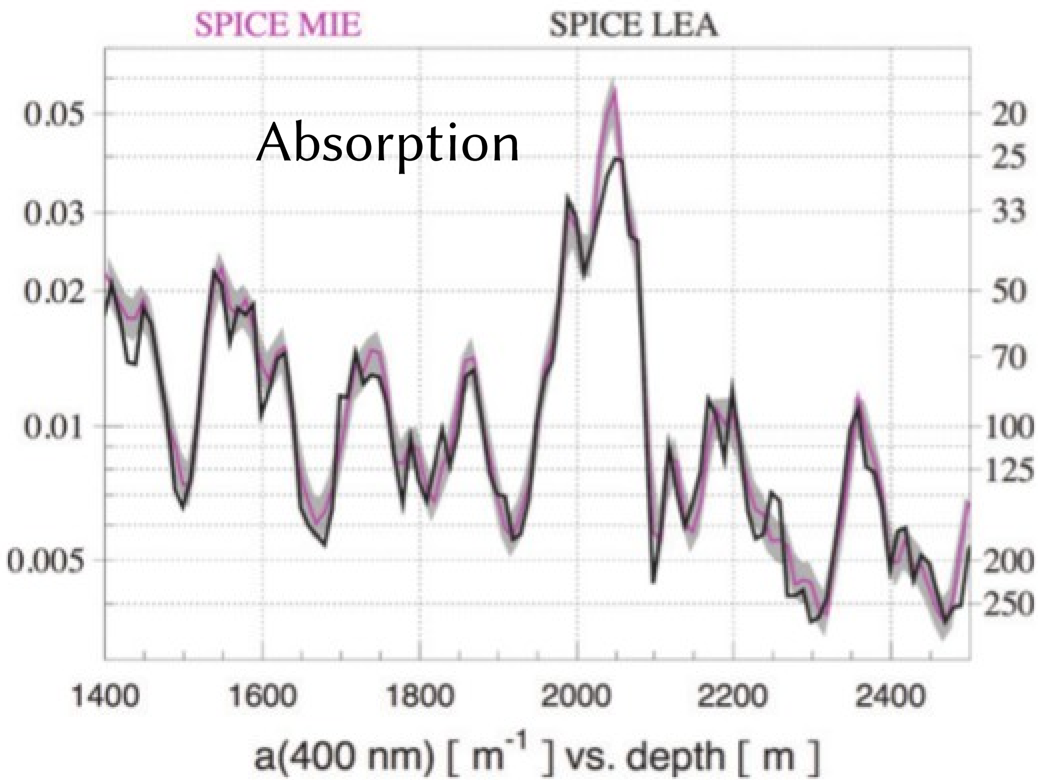
Event rates, 5–7 PeV

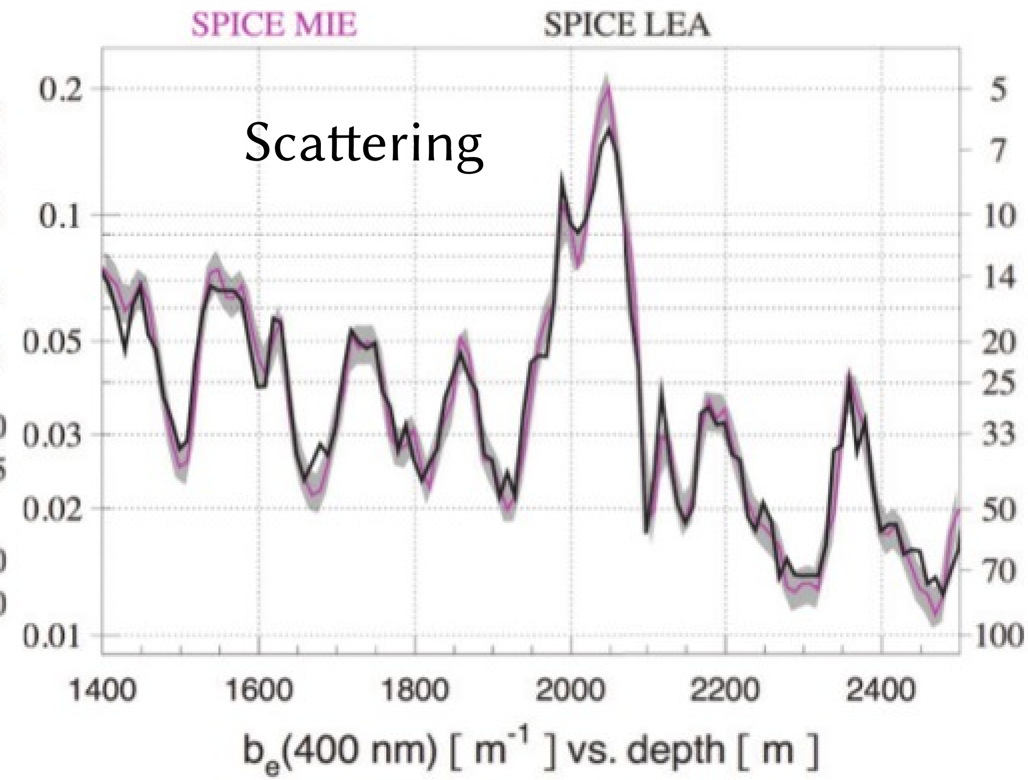
arxiv:1412.5106

Φ_{ν_e} $[\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}]$	interaction type	pp source IC-86	240m	360m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2	16
	DIS	0.09	0.8	1.6
$1.5 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.3}$	GR	0.38	3.1	6.8
	DIS	0.04	0.3	0.7
$2.4 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.7}$	GR	0.12	0.9	2.1
	DIS	0.01	0.1	0.2

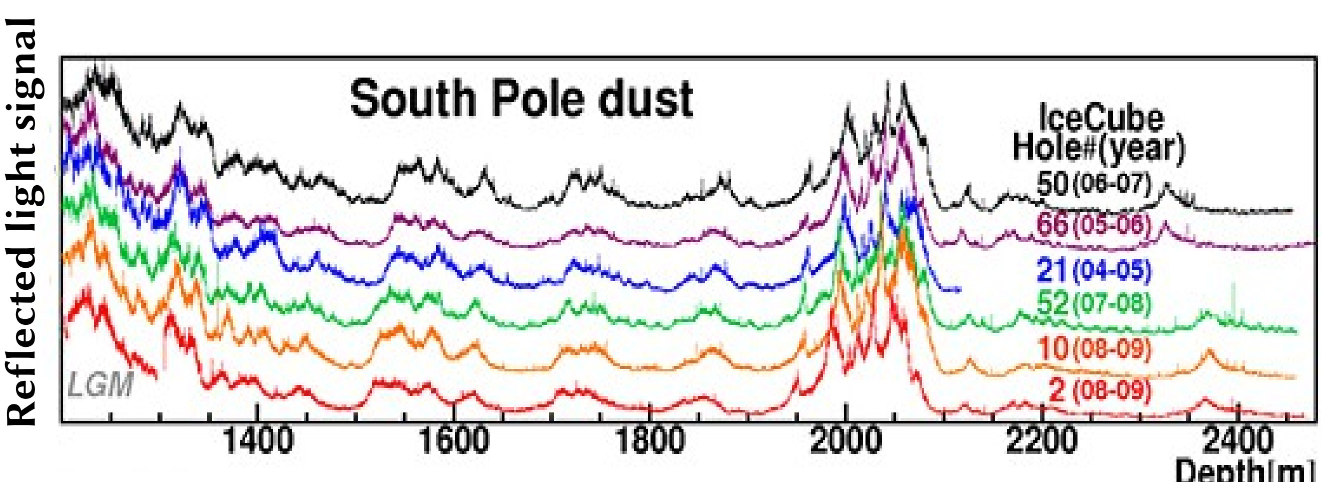
Ice Properties

From flashers:

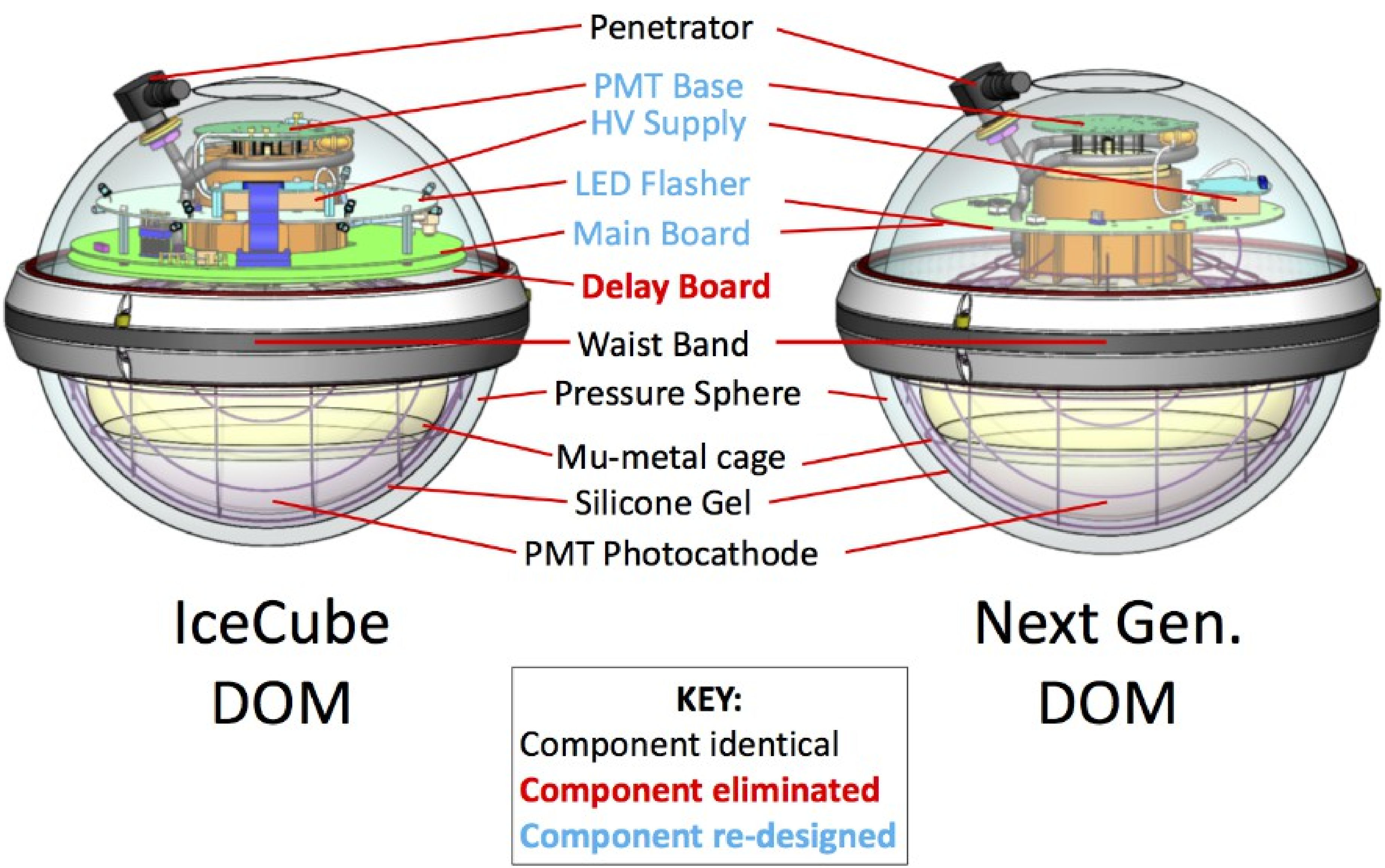




From dust logger:



DOM


Penetrator
PMT Base
HV Supply
LED Flasher
Main Board
Delay Board
Waist Band
Pressure Sphere
Mu-metal cage
Silicone Gel
PMT Photocathode
IceCube DOM
Next Gen. DOM
KEY:
Component identical
Component eliminated
Component re-designed

IC79 ν_μ energy unfolding result