Neutrinos from heaven and hell in IceCube

Latest results on astrophysical neutrinos and neutrino oscillations

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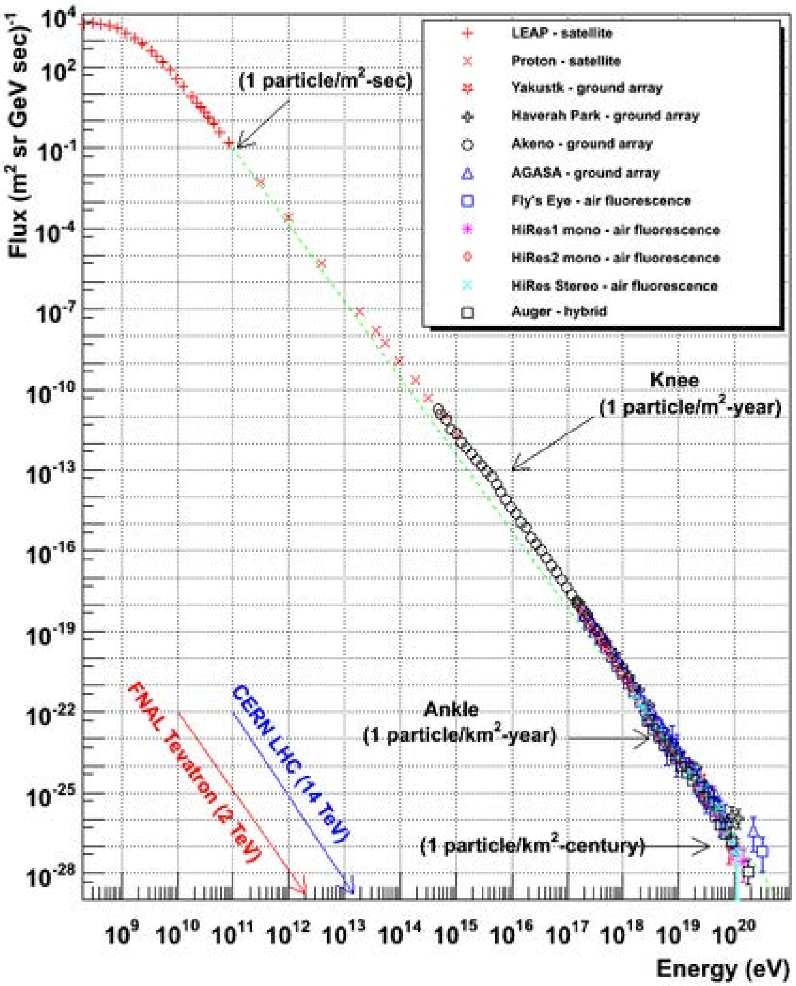
Neutrinos from Hell

TeV - PeV

Image credit: Aurore Simonnet, Sonoma State University

The promise of HE neutrinos

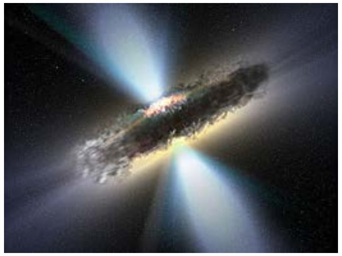
» A hundred year puzzle: the cosmic ray spectrum

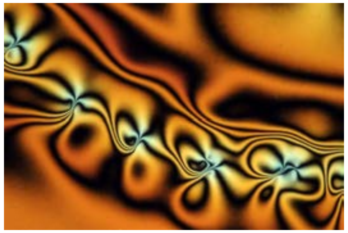


http://www.physics.utah.edu/~whanlon/spectrum.html

» Where do these particles come from?

» Cosmic accelerators? Exotic scenarios?

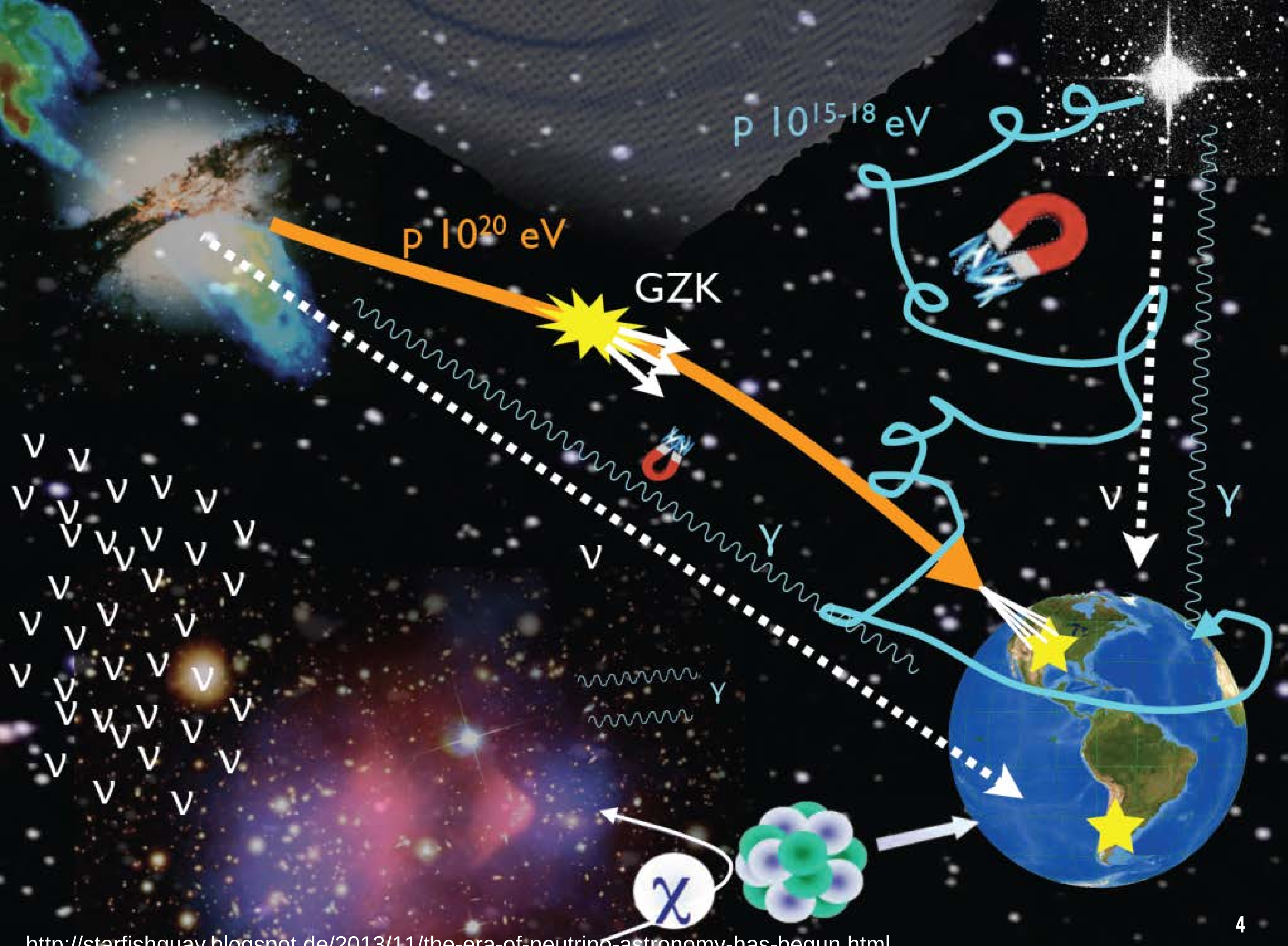




» ν's most likely involved → E ~ [TeV, PeV]

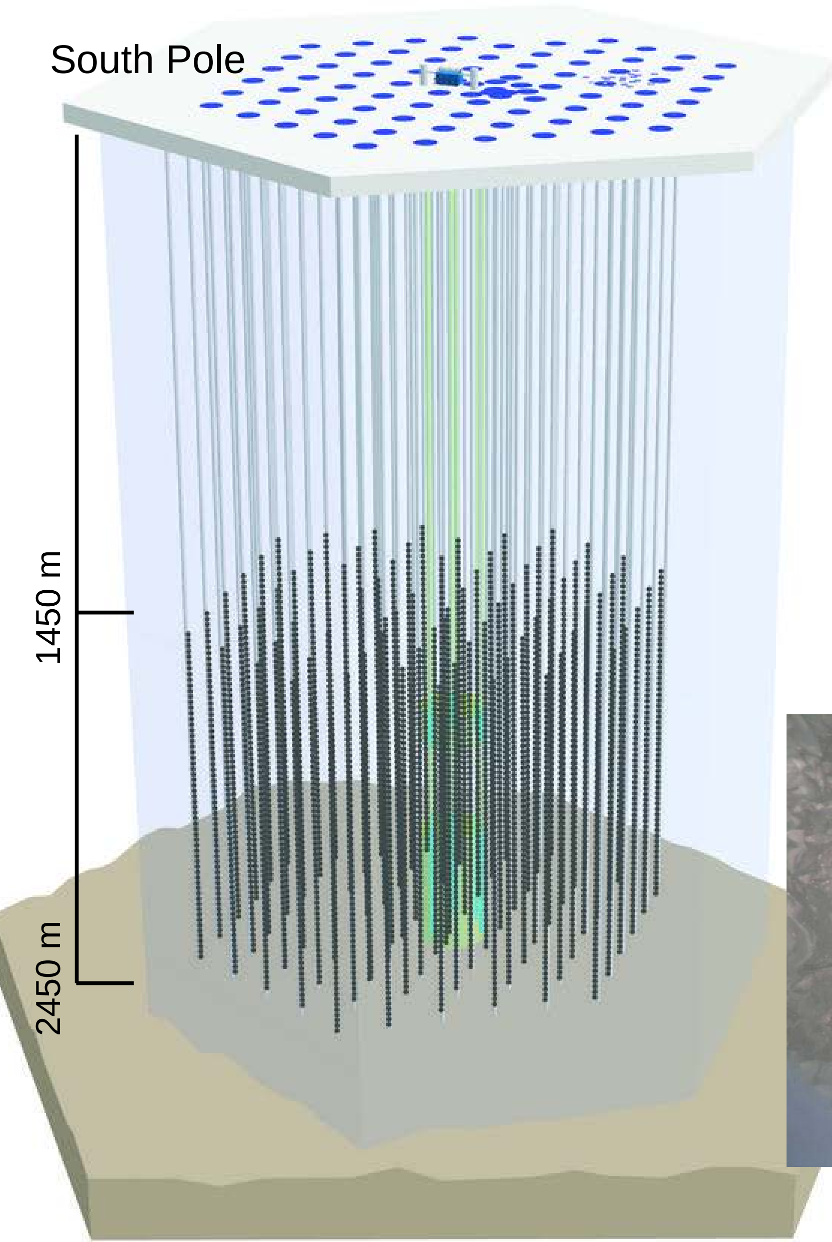
$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

when found ...

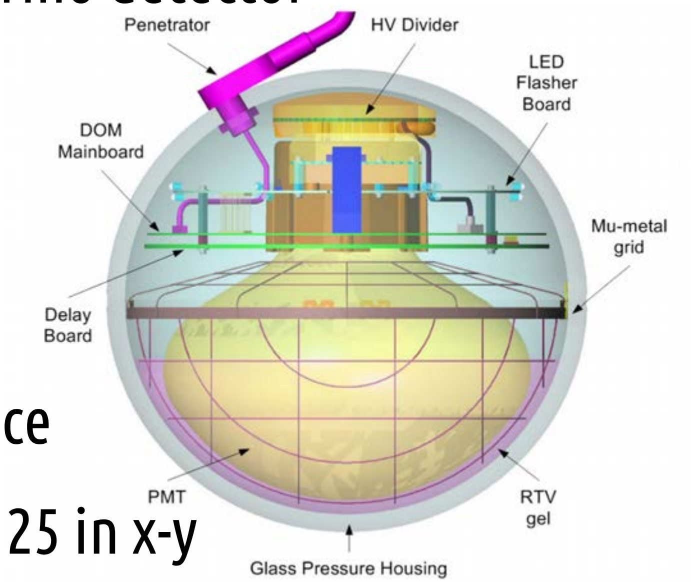


http://starfishquay.blogspot.de/2013/11/the-era-of-neutrino-astronomy-has-begun.html

IceCube
An instrument for neutrino astronomy



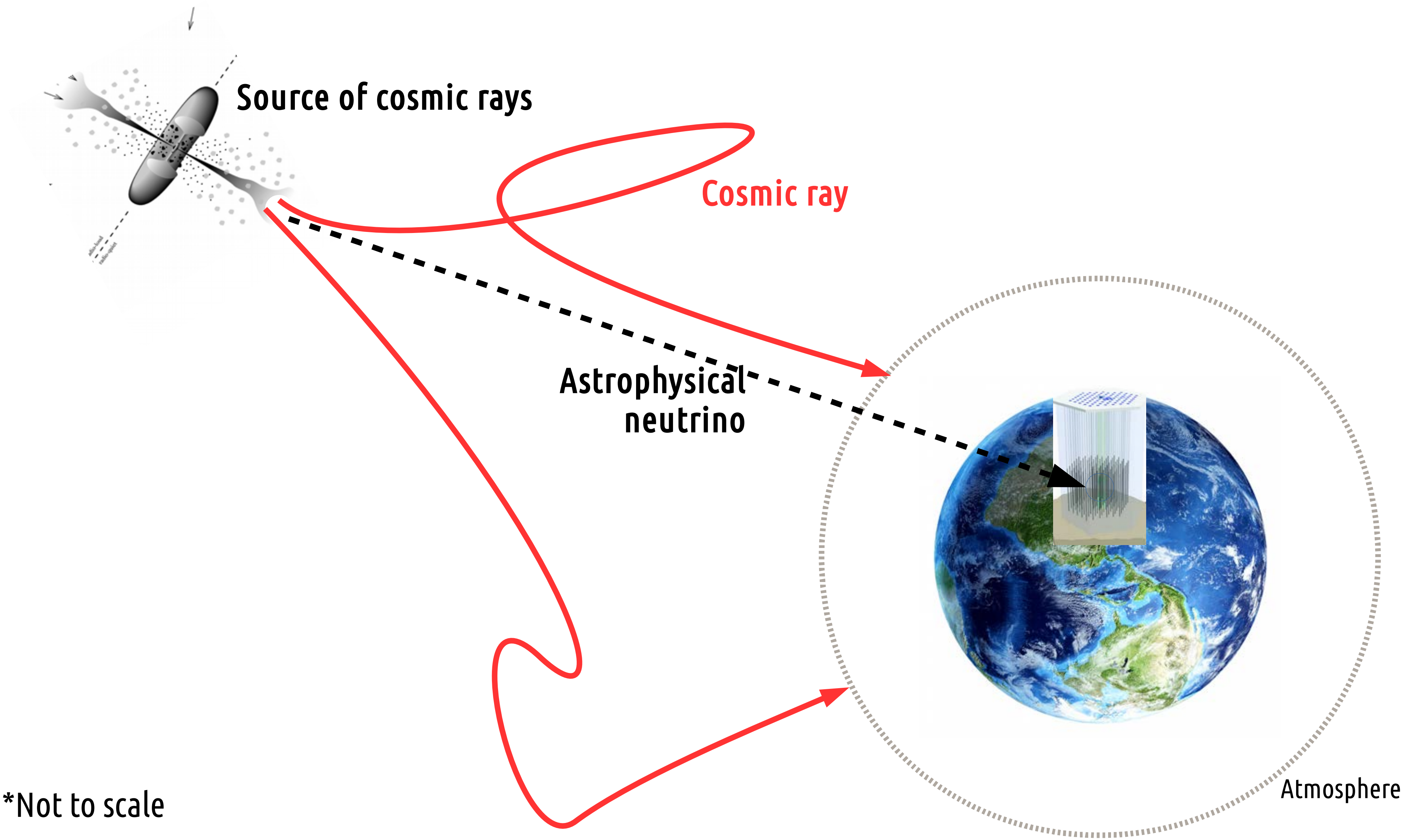
- Ice Cherenkov neutrino detector
- 5,160 DOMs
- 86 strings
- 1 km3 volume
- 1.5 – 2.5 km under ice
- Spacing: 17m in z, 125 in x-y



DOM being deployed

IceCube Lab

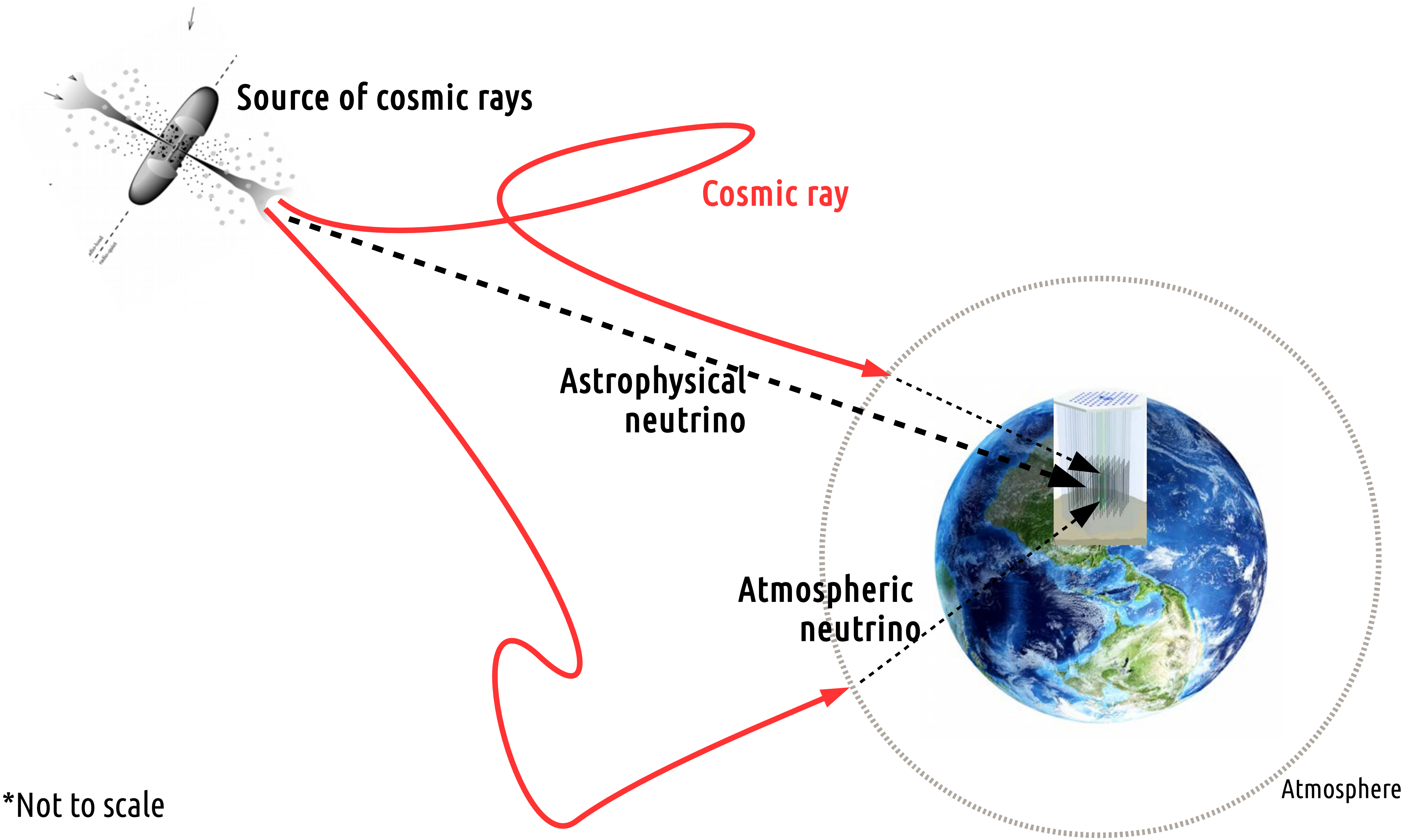
IceCube
An instrument for neutrino astronomy



*Not to scale

Image: http://globe-views.com/dreams/earth.html

IceCube
An instrument for neutrino astronomy

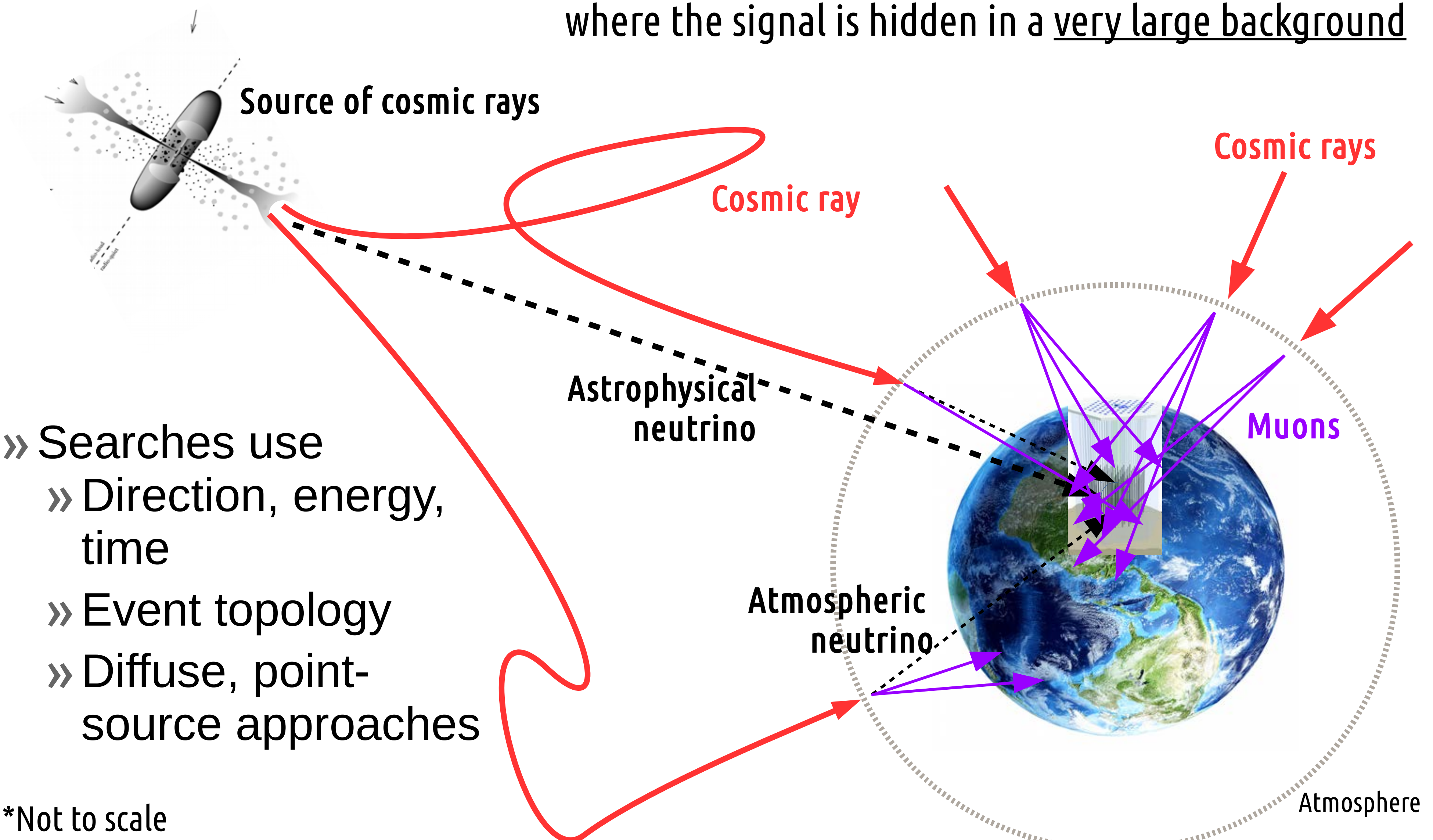


*Not to scale

Image: http://globe-views.com/dreams/earth.html

IceCube
An instrument for neutrino astronomy

where the signal is hidden in a <u>very large background</u>



- Searches use
  - Direction, energy, time
  - Event topology
  - Diffuse, point-source approaches

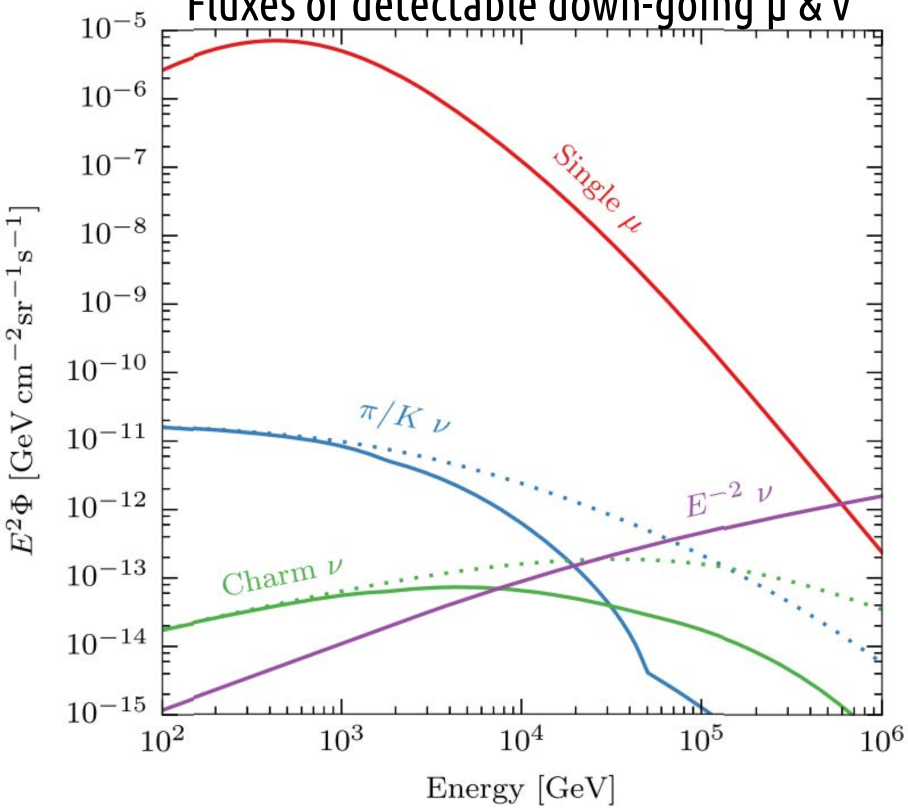
*Not to scale

Image: http://globe-views.com/dreams/earth.html

Diffuse, starting events

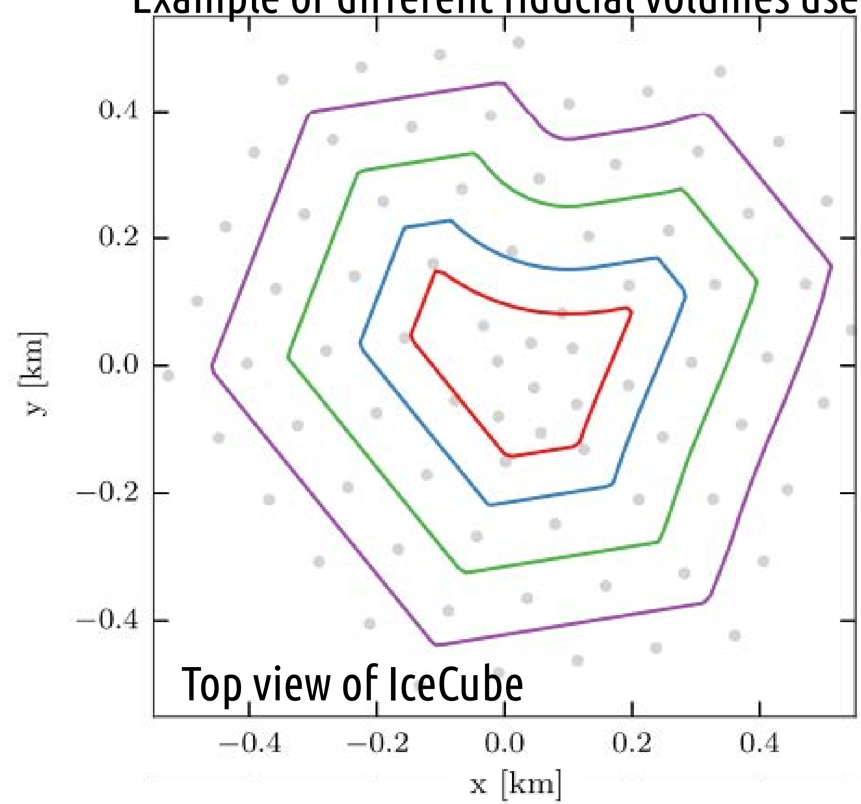
» Exploit different E spectra → focus on high energies

Fluxes of detectable down-going µ & ν

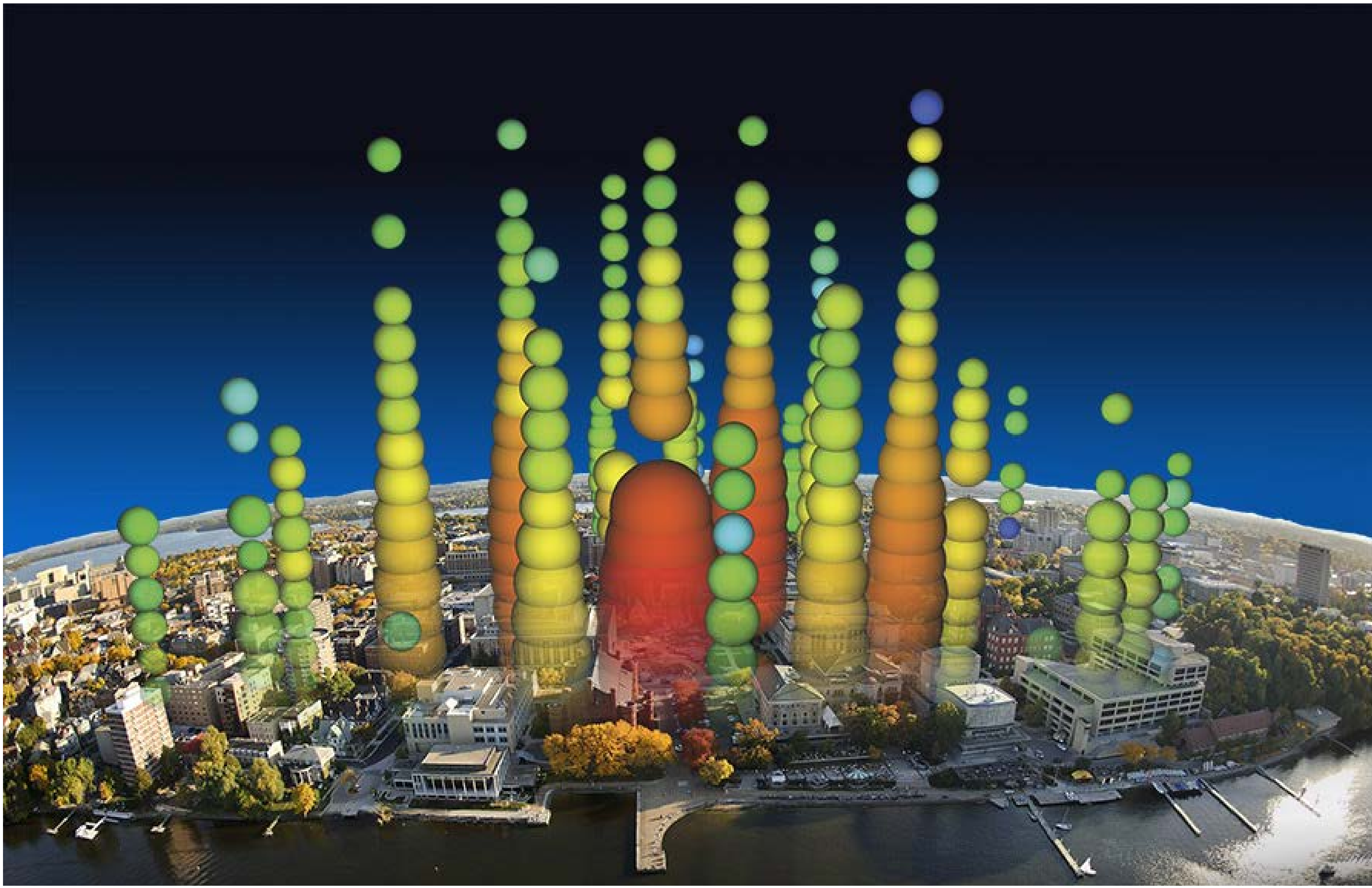


» Use the detector for vetoing → starting events

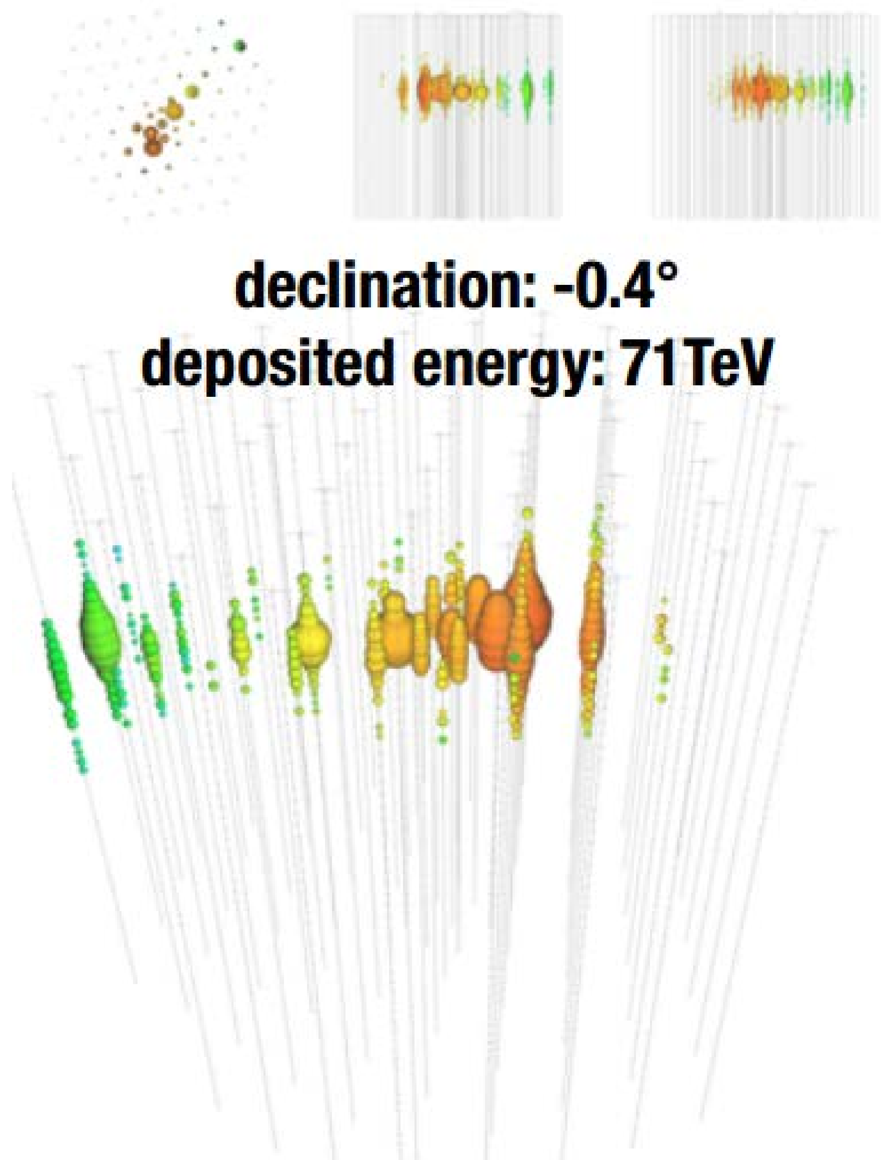
Example of different fiducial volumes used

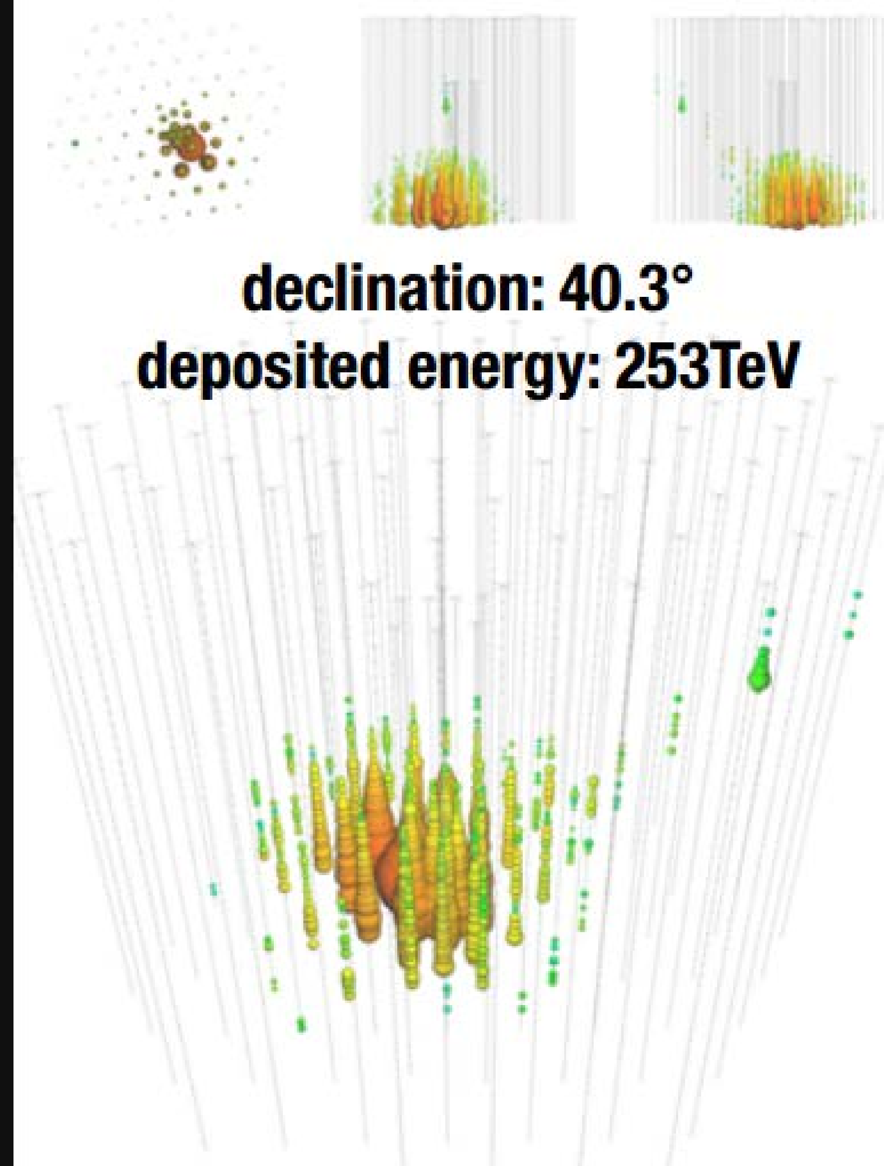


Diffuse, starting events



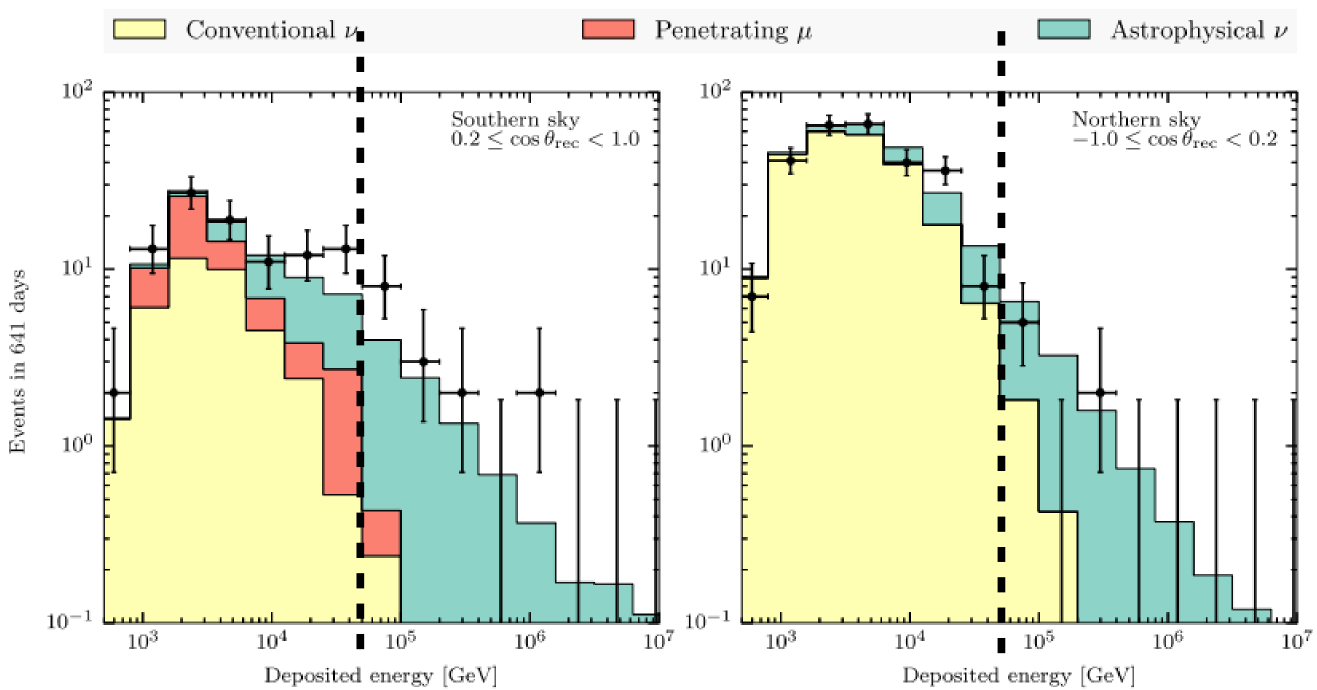
Diffuse, starting events





Diffuse, starting events

- HE search w/3 years of data Phys. Rev. Lett. 113, 101101 (2014)
  - 37 neutrino candidates, mostly cascades, 5.7σ over background
- Search extended to lower energies (2 years) Phys. Rev. D 91, 022001
  - 283 cascades + 105 tracks, large overlap with HE analysis

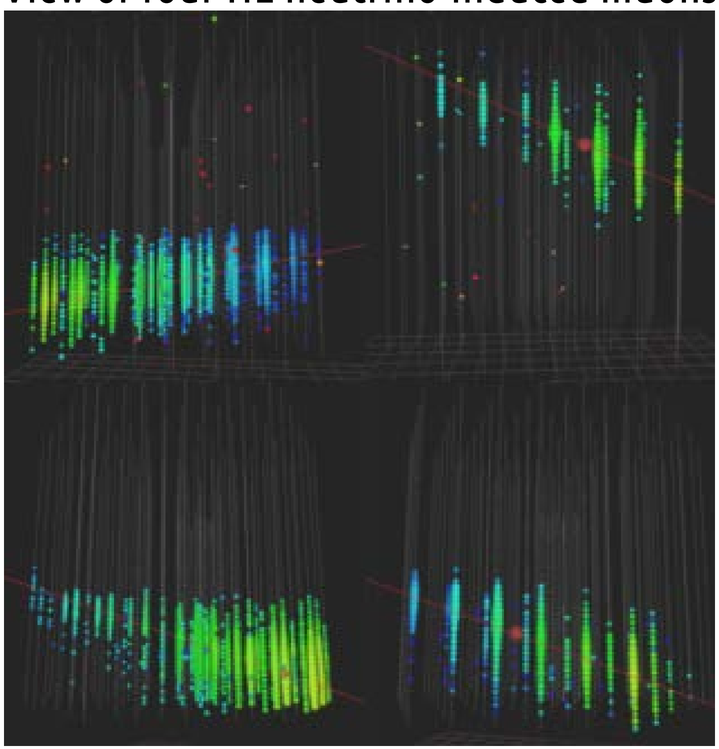


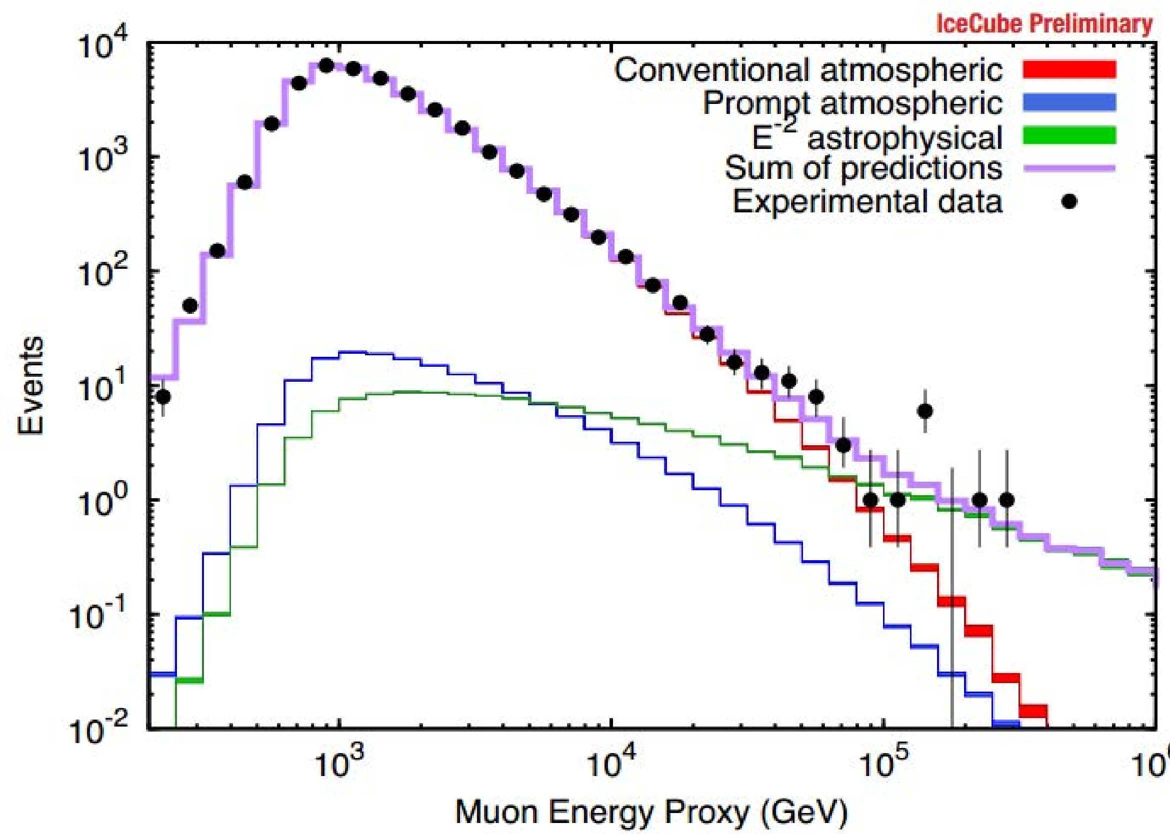
Diffuse, through-going muons

» Earth-crossing muons → must come from neutrinos

» Good angular resolution, lower limit in energy

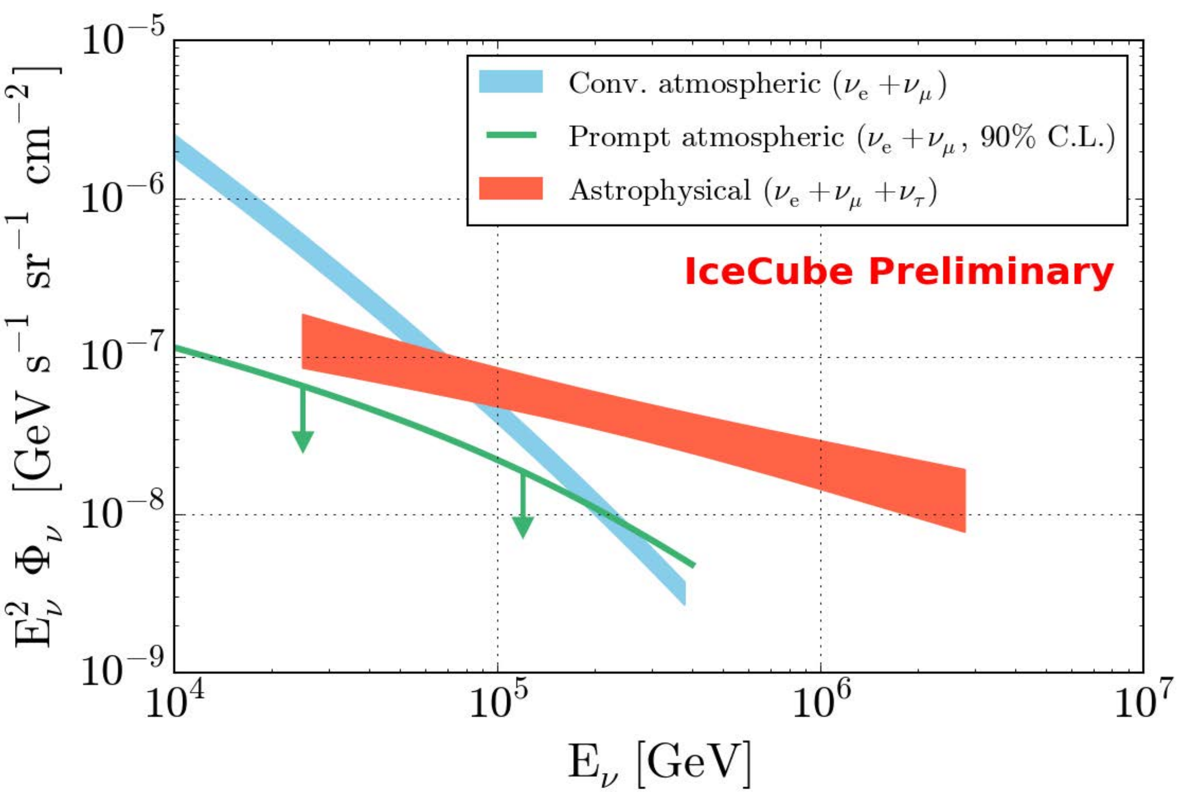
View of four HE neutrino-induced muons



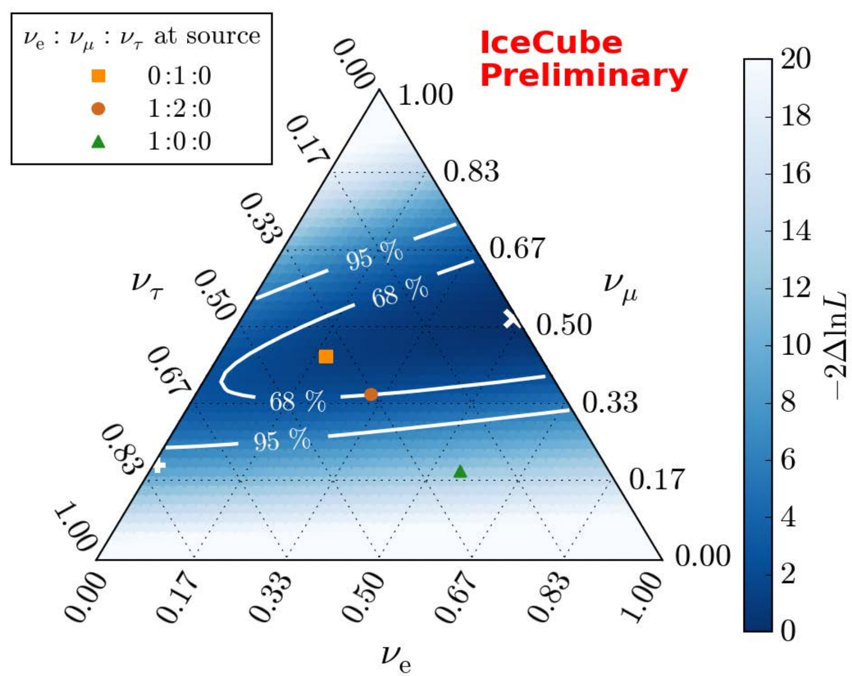


Joint analysis of diffuse searches

- Including all diffuse searches in IceCube (also from incomplete detector)
- Best fit by an unbroken power law spectrum
  - Flux Φ (at 100 TeV) = $(6.7\ ^{+1.1}/_{-1.2}) \cdot 10^{-18}$ (GeV s sr cm^2)$^{-1}$
  - Spectral index γ = -2.50 ± 0.09

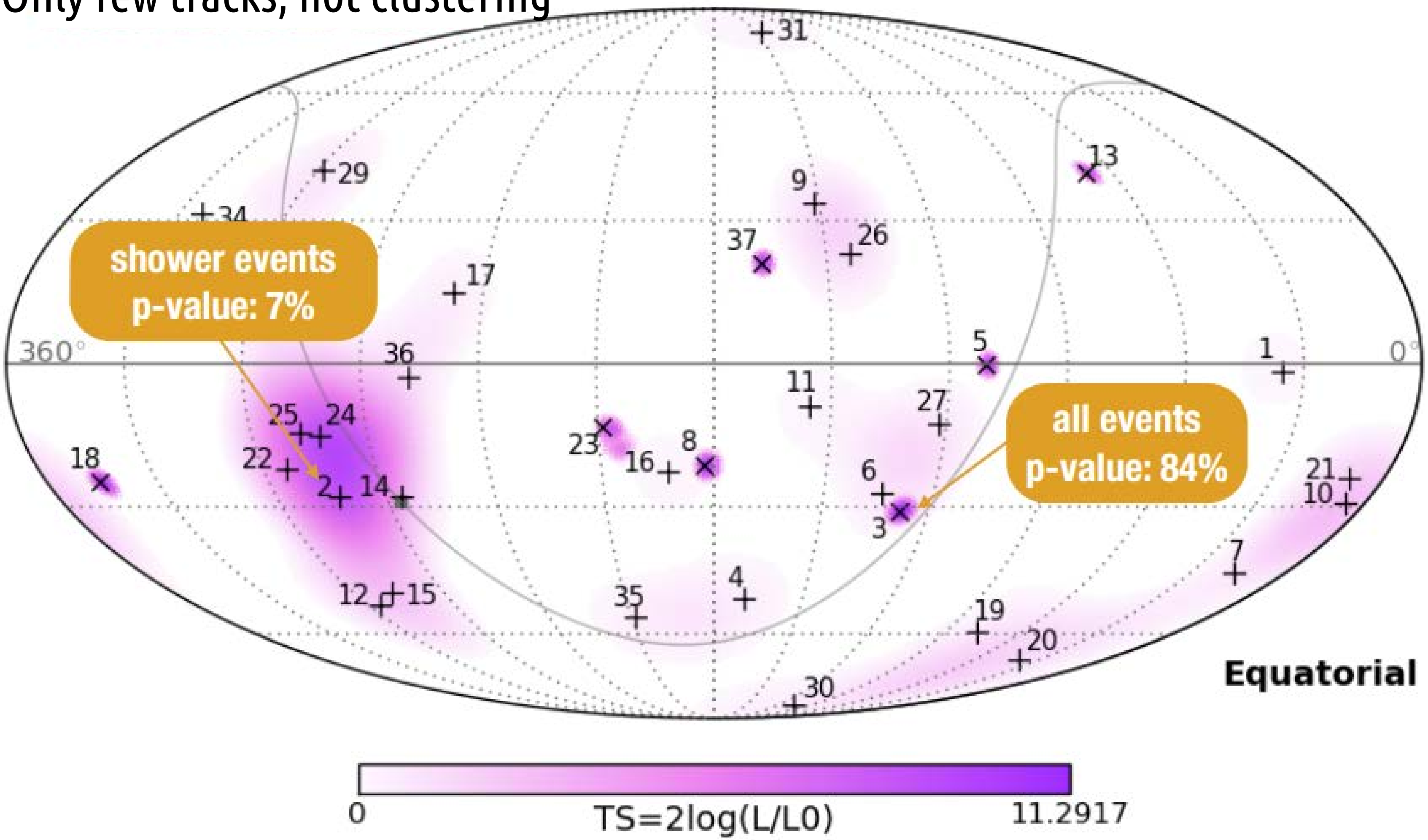


Fit flavor ratio at Earth is 1:1:0 (ν_e:ν_μ:ν_τ)
compatible with expected 1:1:1



What are the sources of HE ν's?

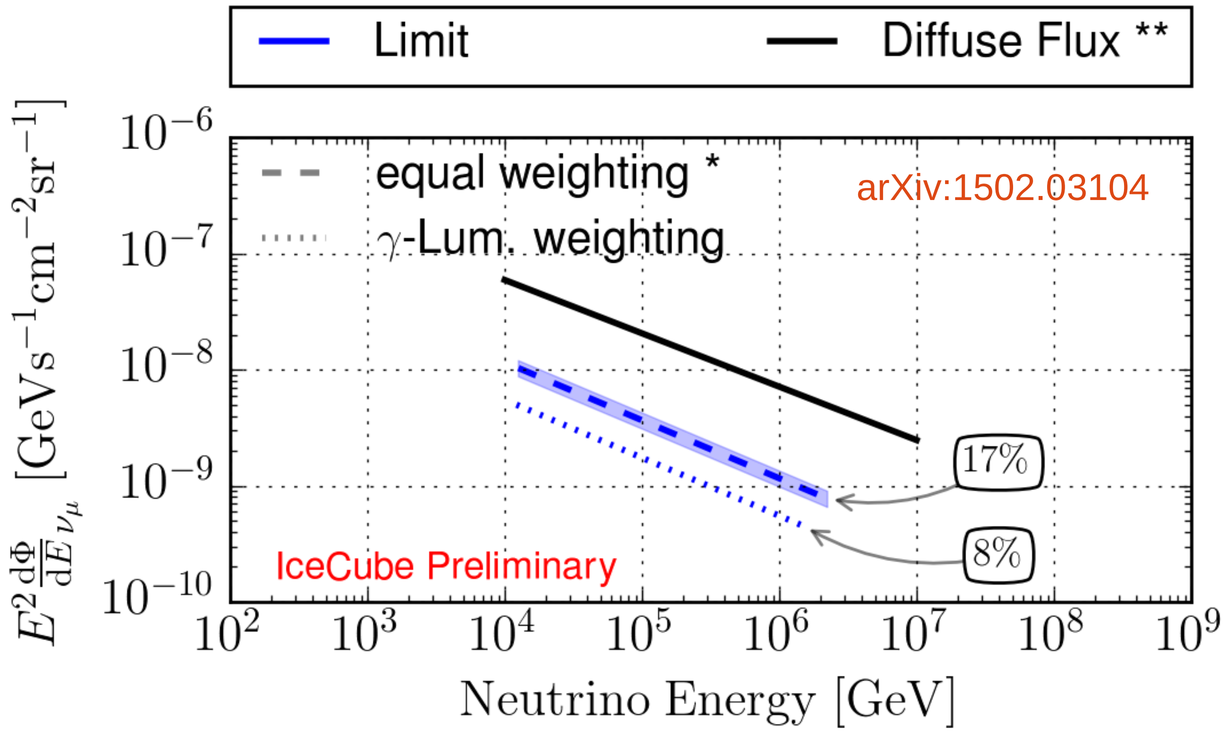
- No significant clustering of events in HE sample
  - Cascades seem to cluster → but they have poor resolution
  - Only few tracks, not clustering



Origin of diffuse HE neutrino flux

» Searches for point-like sources compatible with background
  » Full sky
  » Catalogue-based
  » Stacking of sources
  » Transients

» Limits on Fermi Blazars contribution to the diffuse flux
» GRBs largely excluded
Nature 484 (2012), 351-354



*) Band denotes central 90 % of outcomes of different realizations from the γ-Luminosity Function. This limit also holds for all (quasi-)isotropic subpopulations, independent of their gamma emission.

**) 1-flavor diffuse fit result [arxiv:1410.1749]

… we need more data

Neutrinos from Heaven

10 - 100 GeV

Wikipedia

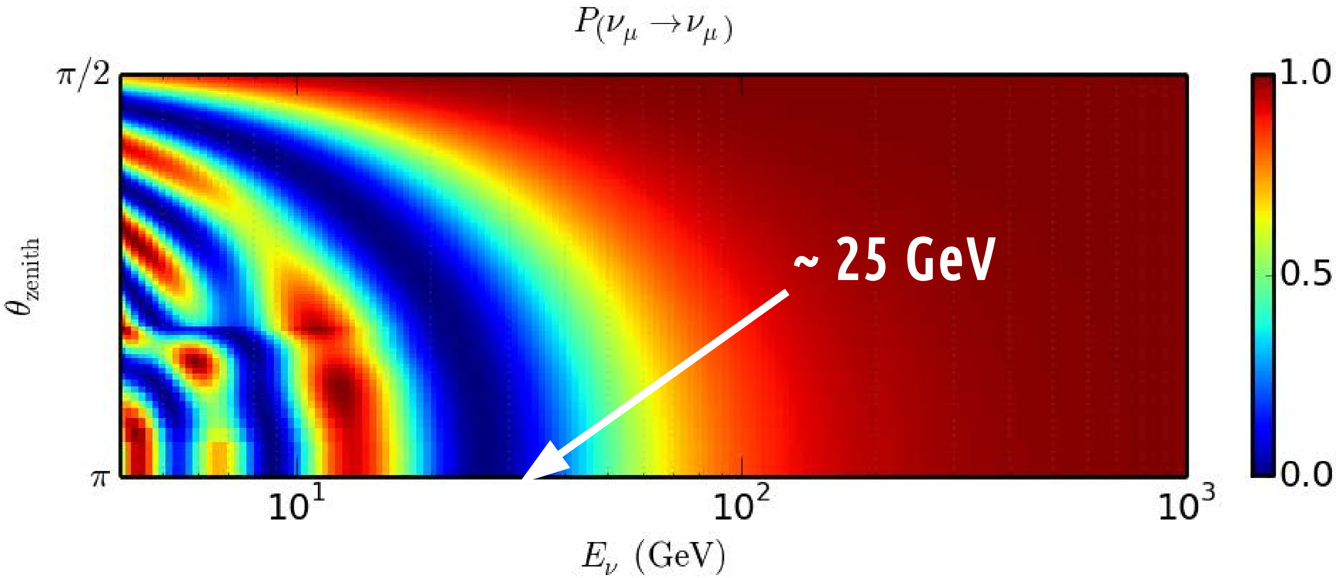
Atmospheric neutrino oscillations

» Neutrinos change flavor as they travel

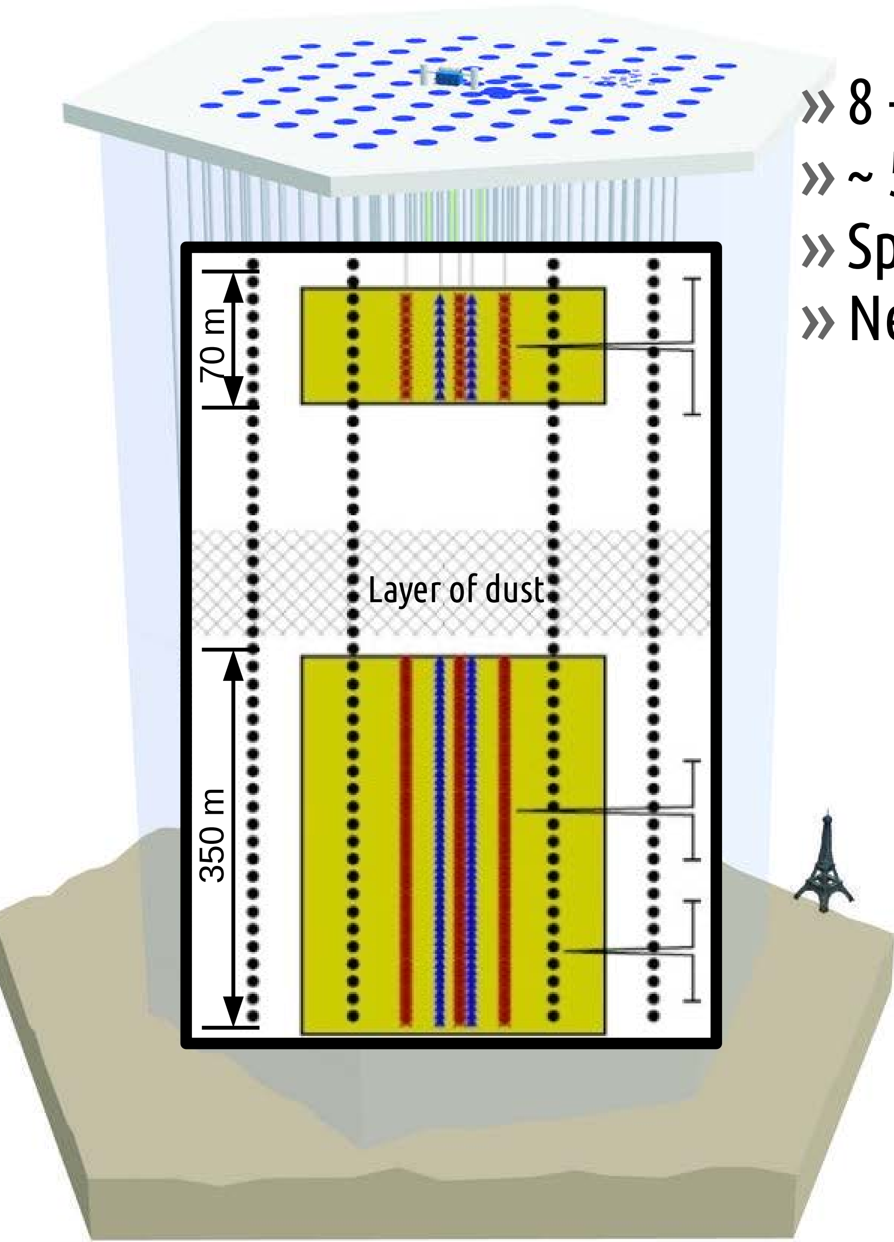
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

» Atmospheric neutrinos below 100 GeV

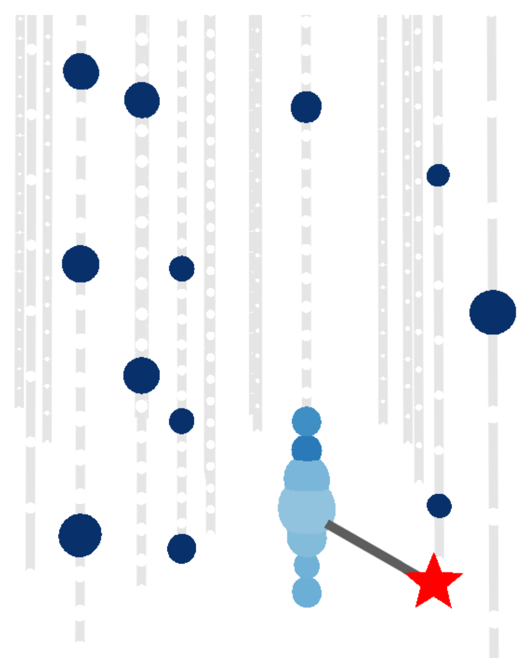
» Suitable probe for the "large" mass splitting $|\Delta m^2_{32}| \simeq |\Delta m^2_{31}|$



IceCube + DeepCore
An instrument for neutrino physics



- 8 + 7 strings (DC + IC)
- ~ 500 DOMs in fid. vol.
- Spacing: 7m in z, 40-70m in x-y
- Neutrino energy threshold ~ 10 GeV
- 0.02 km3 volume
- 2-2.5 km deep, clearest ice

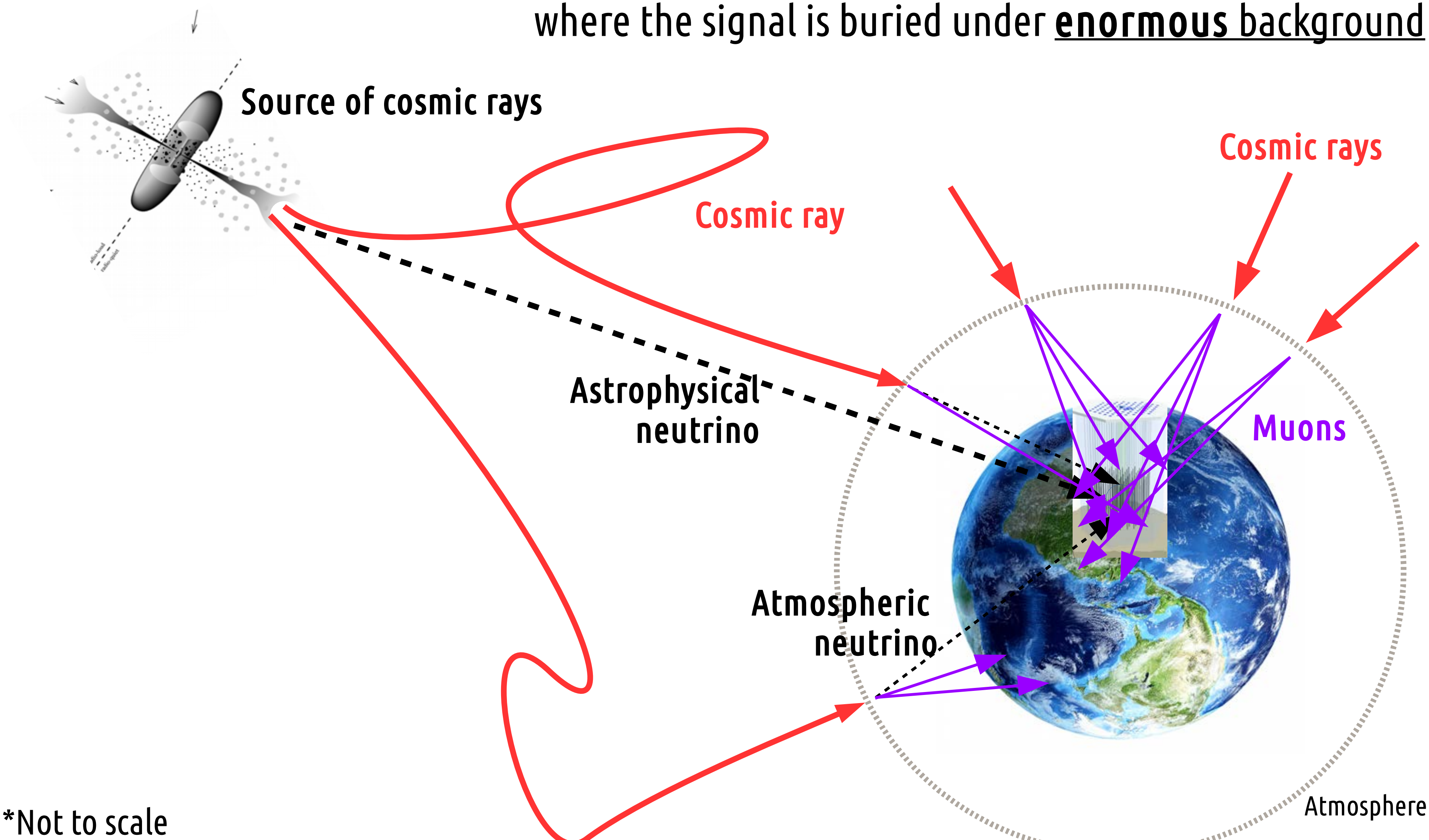


- Typical LE neutrino in DC
- 7 DOMs with signal hits
- Enu = 12 GeV
  - 8 GeV muon (42 m)
  - 4 GeV hadronic shower

IceCube + DeepCore

An instrument for neutrino physics

where the signal is buried under **enormous** background



*Not to scale

Image: http://globe-views.com/dreams/earth.html

IceCube + DeepCore
An instrument for neutrino physics

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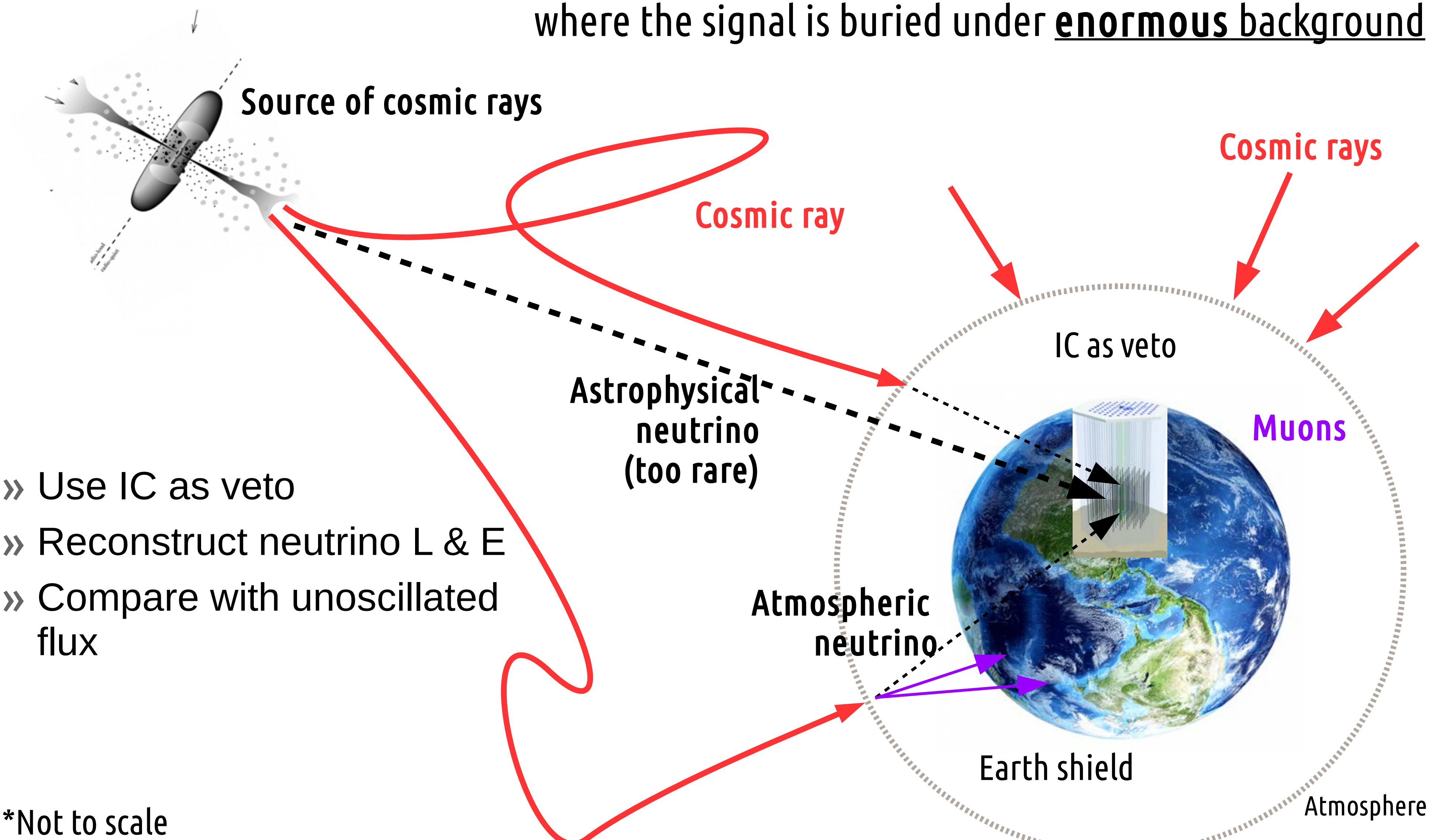


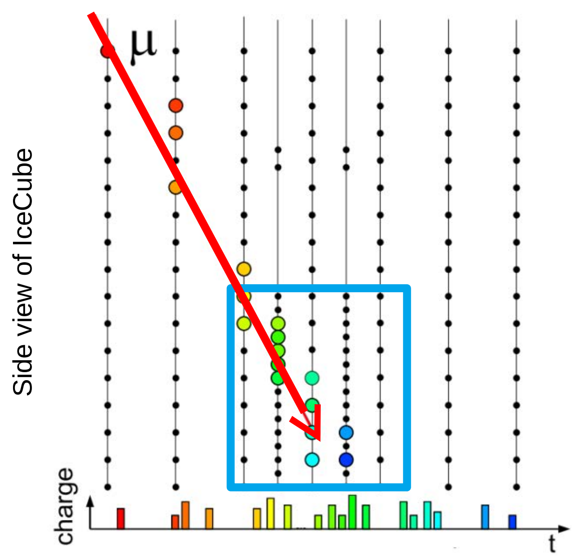
- Use IC as veto
- Reconstruct neutrino L & E
- Compare with unoscillated flux

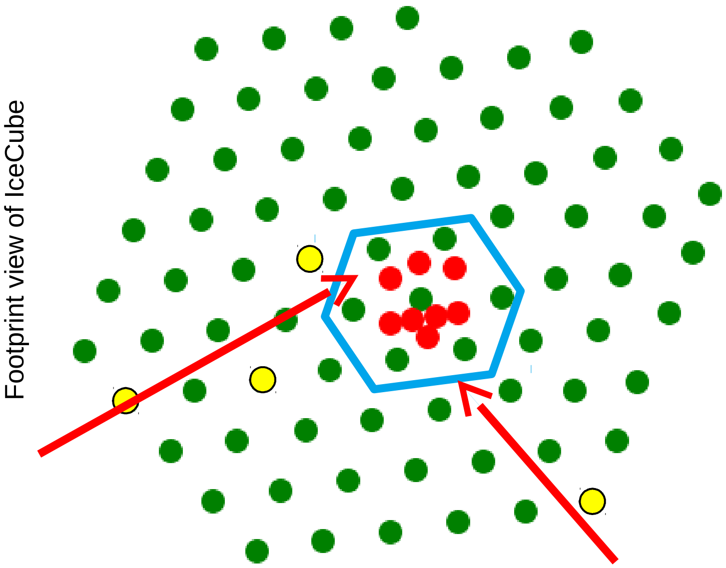
*Not to scale

Image: http://globe-views.com/dreams/earth.html

Measurement strategy

- Focus on ν_μ CC “golden” events
  - **Starting events → IceCube as veto for DeepCore**
  - Clear muon tracks
  - Core of *direct* photons





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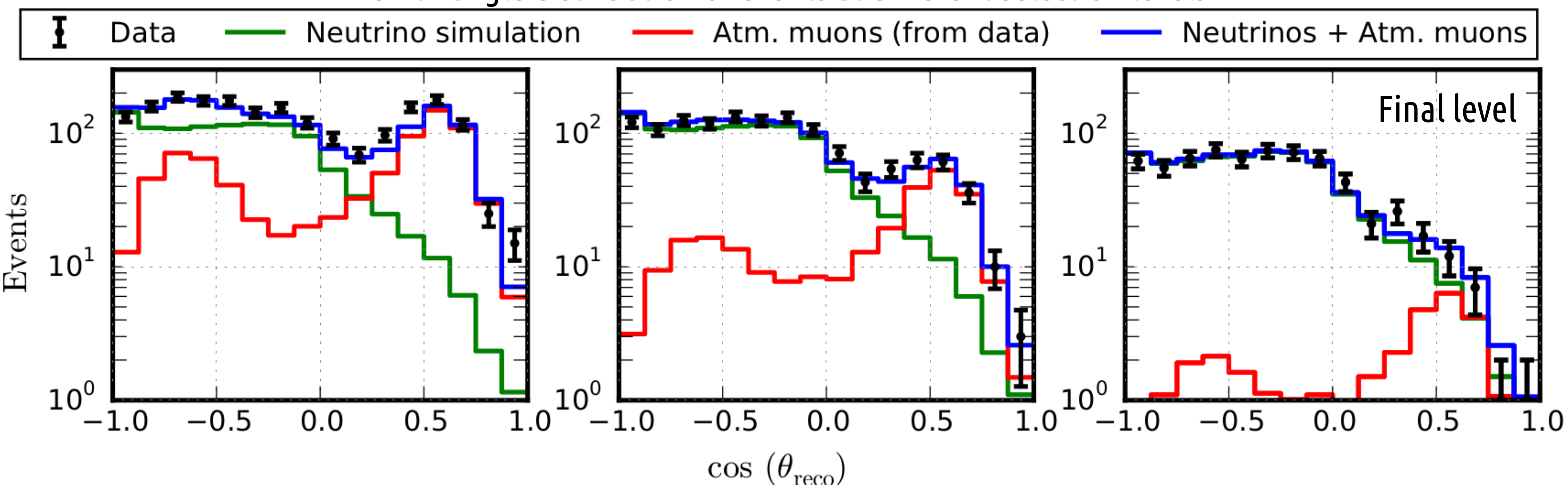
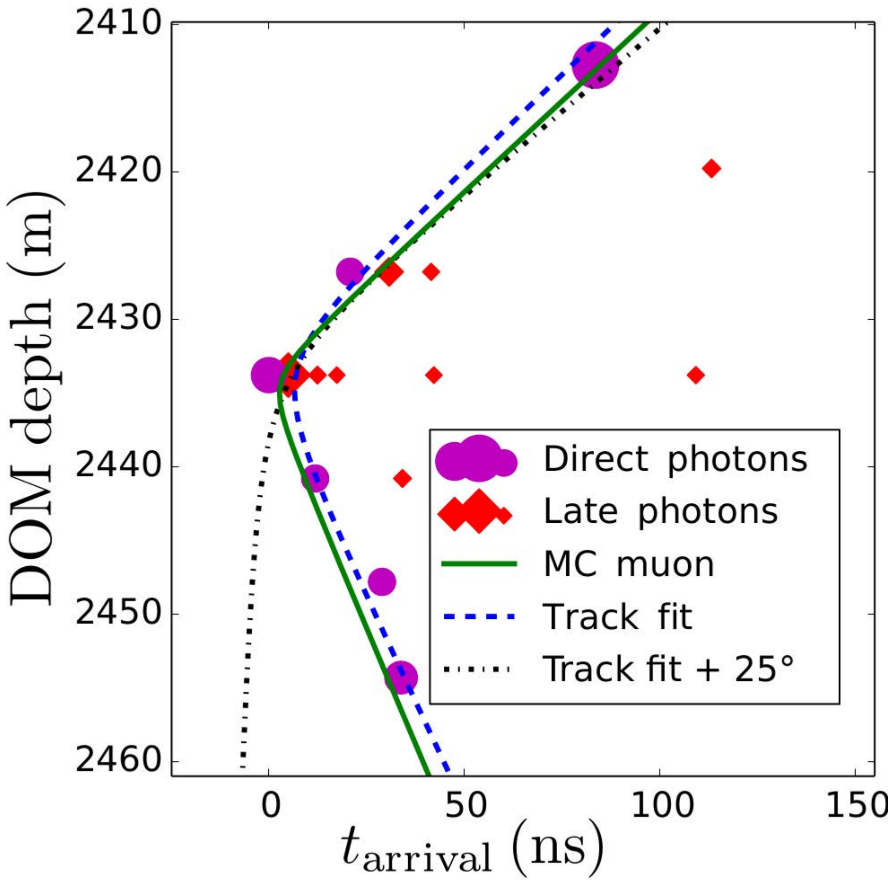
Zenith angle distribution of events at different selection levels



Measurement strategy

- Focus on ν_μ CC "golden" events
  - Starting events → IceCube as veto for DeepCore
  - **Clear muon tracks**
  - **Core of *direct* photons**
    - Minimize ice properties impact
    - ~ 30% signal efficiency
  - **"Easy" to reconstruct**
    - 10° res. in zenith angle
      - From time of arrival
    - 25% res. in neutrino energy
      - From observing charge/no charge



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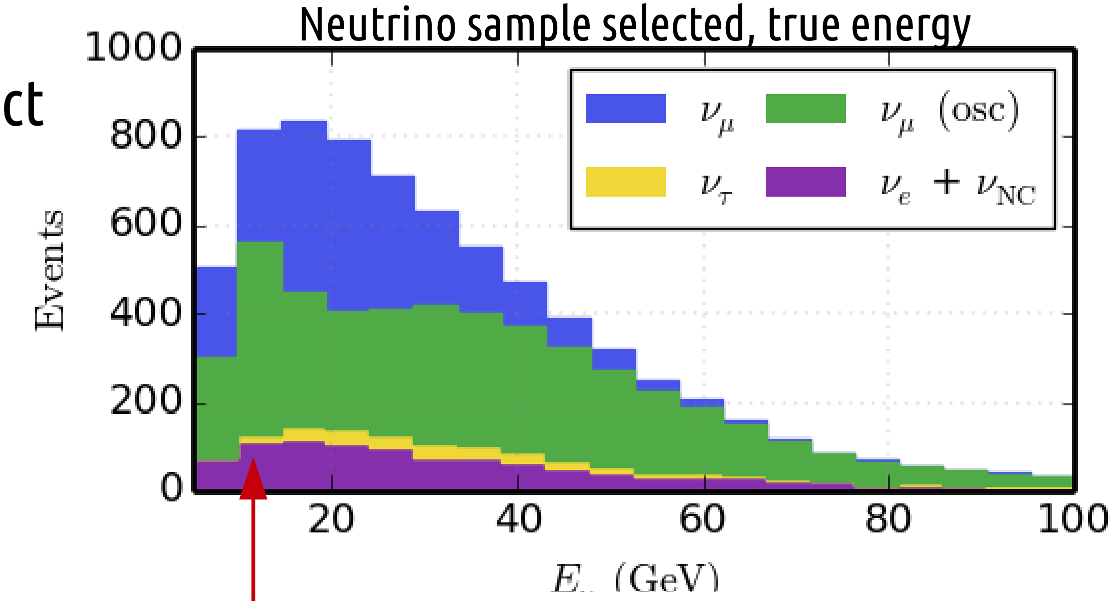
Neutrino sample selected, true energy

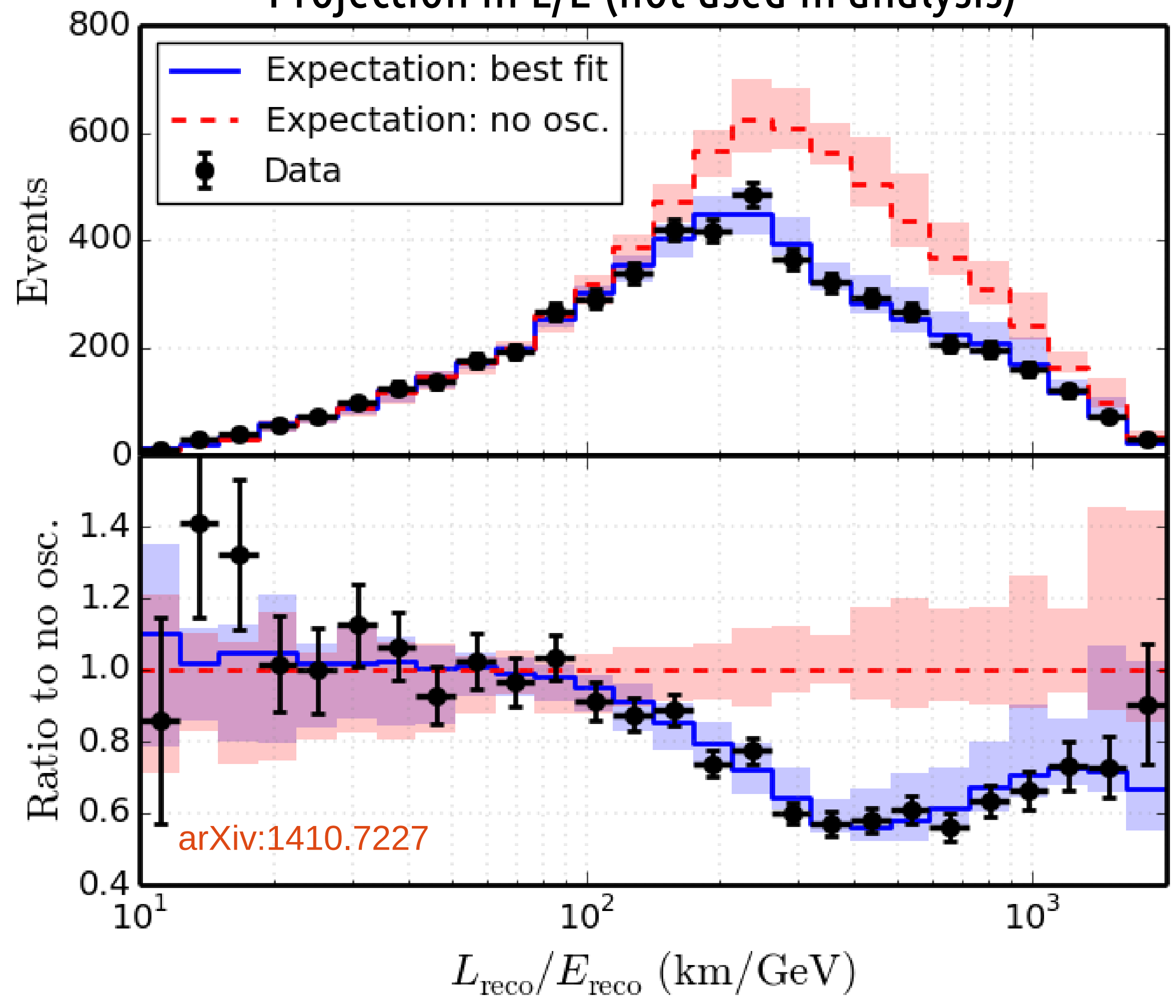


Background from other neutrino flavors

Agreement between data and MC

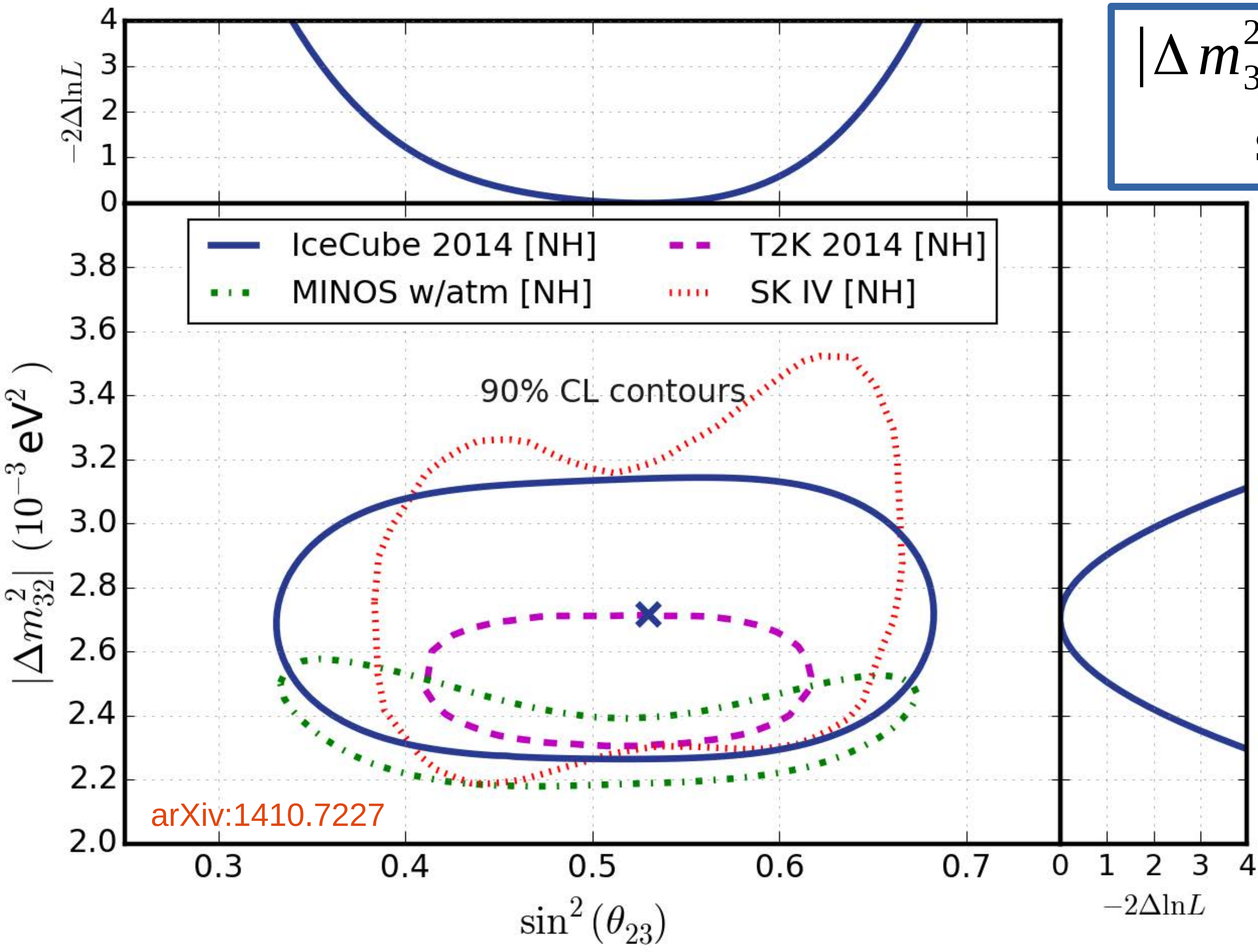
- »Best fit to the data from a 2D analysis (E, θ)
- »Up-going events
- »Using E < 56 GeV
- »5174 events in 3 years
- »In 2D fit histogram
  - »$\chi^2 = 54.9 / 56$ d.o.f.

Projection in L/E (not used in analysis)



Data of this analysis available at
http://icecube.wisc.edu/science/data/nu_osc

Best fit oscillation parameters



$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

- » First time a very large volume neutrino detector fits in this figure
- » Measuring large L/E range
- » Affected by different syst.
- » Stat. only errors

$$|\Delta m^2_{32}| = ^{+0.14}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = ^{+0.06}_{-0.08}$$

Data of this analysis available at
http://icecube.wisc.edu/science/data/nu_osc

… we need more, and better, data

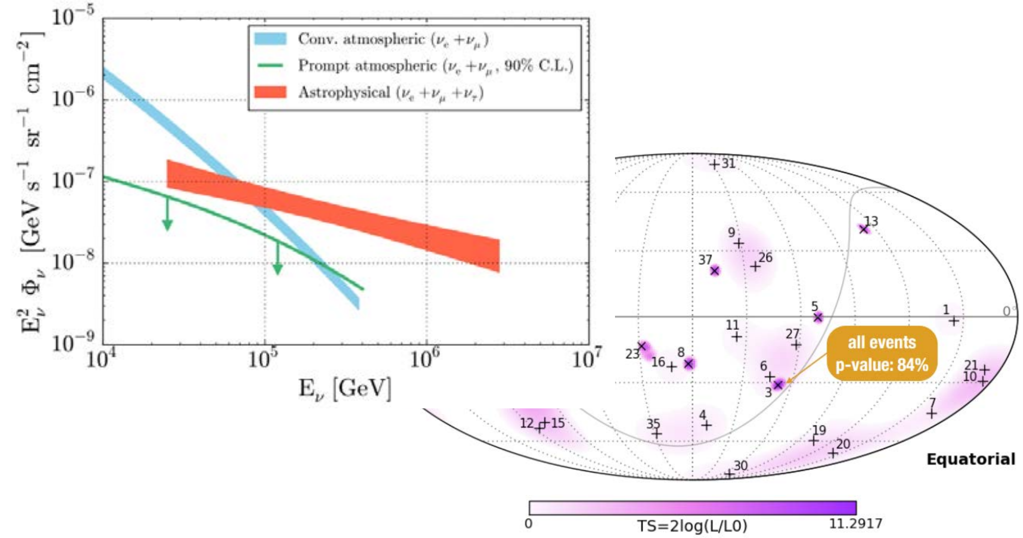
After visiting hell and heaven

Back to Earth

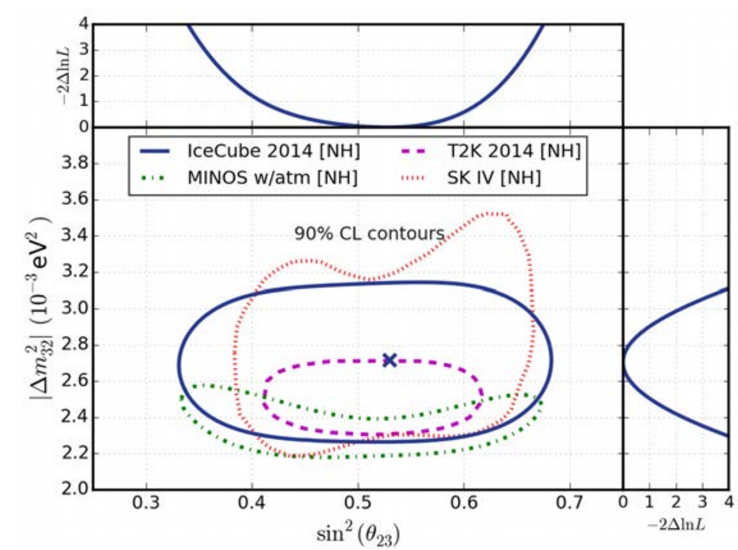
Wikipedia

IceCube is on its way to ...

- Neutrino astronomy
  - A diffuse flux has been observed
    - With high significance
    - In track and cascade channels
  - No point source identified until now
    - Too dim / frequent?



- Competitive particle physics results
  - Neutrino oscillations measured
    - Systematic uncertainties kept under control
    - Improving selection, reconstruction
    - Starting to look at other "channels"
  - Matter effects not significant until now



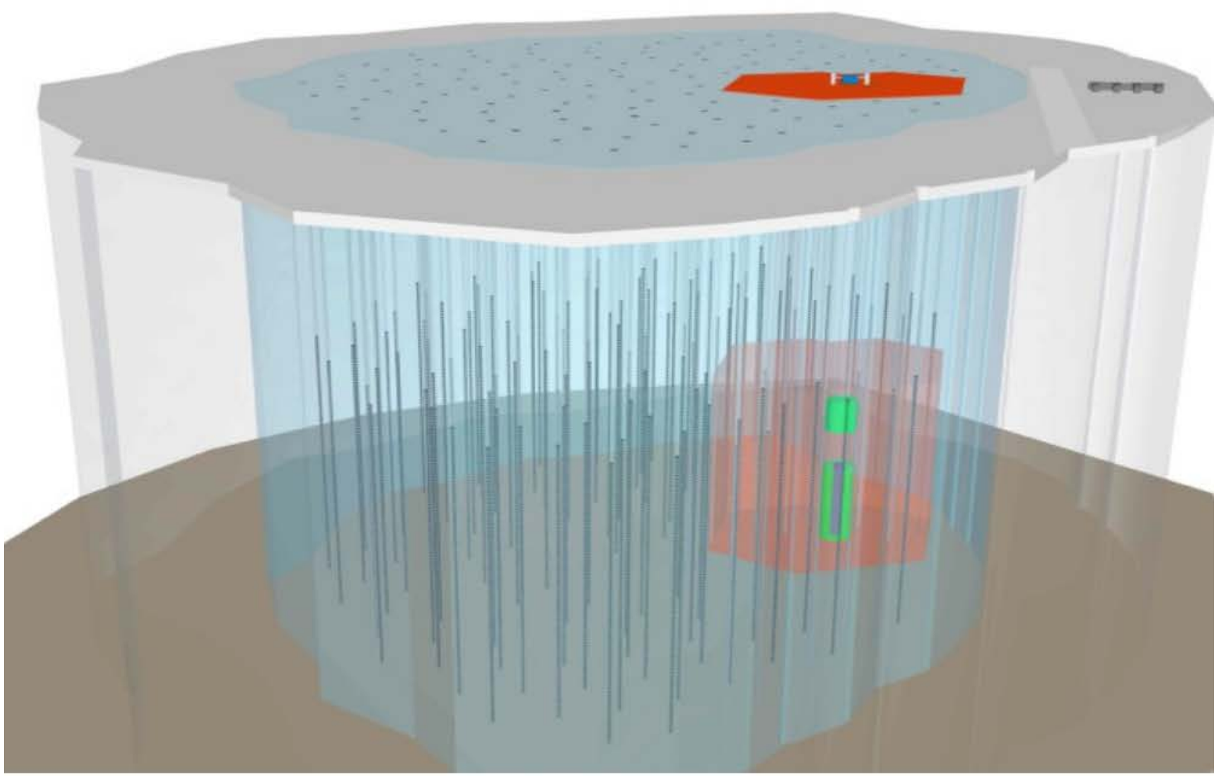
<u>On our way, not there yet</u>

A possible future

If it worked once, do it again

A possible future

- Next generation neutrino experiments at the South Pole
  - IceCube Gen2 – larger spacing, bigger volume, surface veto → point sources
  - PINGU – denser DeepCore, matter effects in oscillations → neutrino mass hierarchy



IceCube Gen2
→ +120 strings, 7,200 DOMs

IceCube
→ 86 strings, 5,160 DOMs

DeepCore
→ 8+7 strings, 500 DOMs

PINGU
→ +40 strings, 3,600 DOMs

Backup slides

FAQ from heaven

- Neutrino:antineutrino ratio = 2:1
- Tracks + cascades → next step
- Final muon contamination of the sample of 1%
- Fit of systematic uncertainties as nuisance parameters
  - Very small deviations from nominal value
- No sensitivity to mass ordering
- Study of electron-neutrino component underway

Measuring neutrino oscillations

- » Common to all oscillation experiments
  - » Compare neutrino flux at production/detection, explain discrepancies with oscillations
  - » Relevant differences between IceCube DeepCore and other oscillation experiments

<table>
<tr><th>IceCube DeepCore</th><th>Atmospheric
(Super-Kamiokande)</th><th>Accelerator
(MINOS, NovA, T2K)</th></tr>
<tr><td colspan="2">Initial flux obtained from models (tuned with measurements)
Large range in L (baseline) of 10-12,700 km</td><td rowspan="2">Near detectors → initial flux well understood
Tracking detectors
Dimensions: < 10m diameter x ~30 m length
Committed to single baseline
Narrow energy range</td></tr>
<tr><td rowspan="2">Complex natural medium
Open detector, order of Mton
Large range in energy, higher than any other experiment
Detection by Cherenkov light produced over ten's of meters
Limited particle ID: muon, non-muon
Interactions mainly deep inelastic scattering</td><td>Detection by Cherenkov rings
~ 22.5 - 40 kton detector</td></tr>
<tr><td colspan="2">Energy resolution ~ 10%
Densely instrumented detectors, good measurement of hadrons
Complicated neutrino interactions in “transition region” (< a few GeV)</td></tr>
</table>

Some of the main differences between experiments measuring the atmospheric parameters of oscillations.
T2K is complicated to place, as Super-Kamiokande acts as far detector.

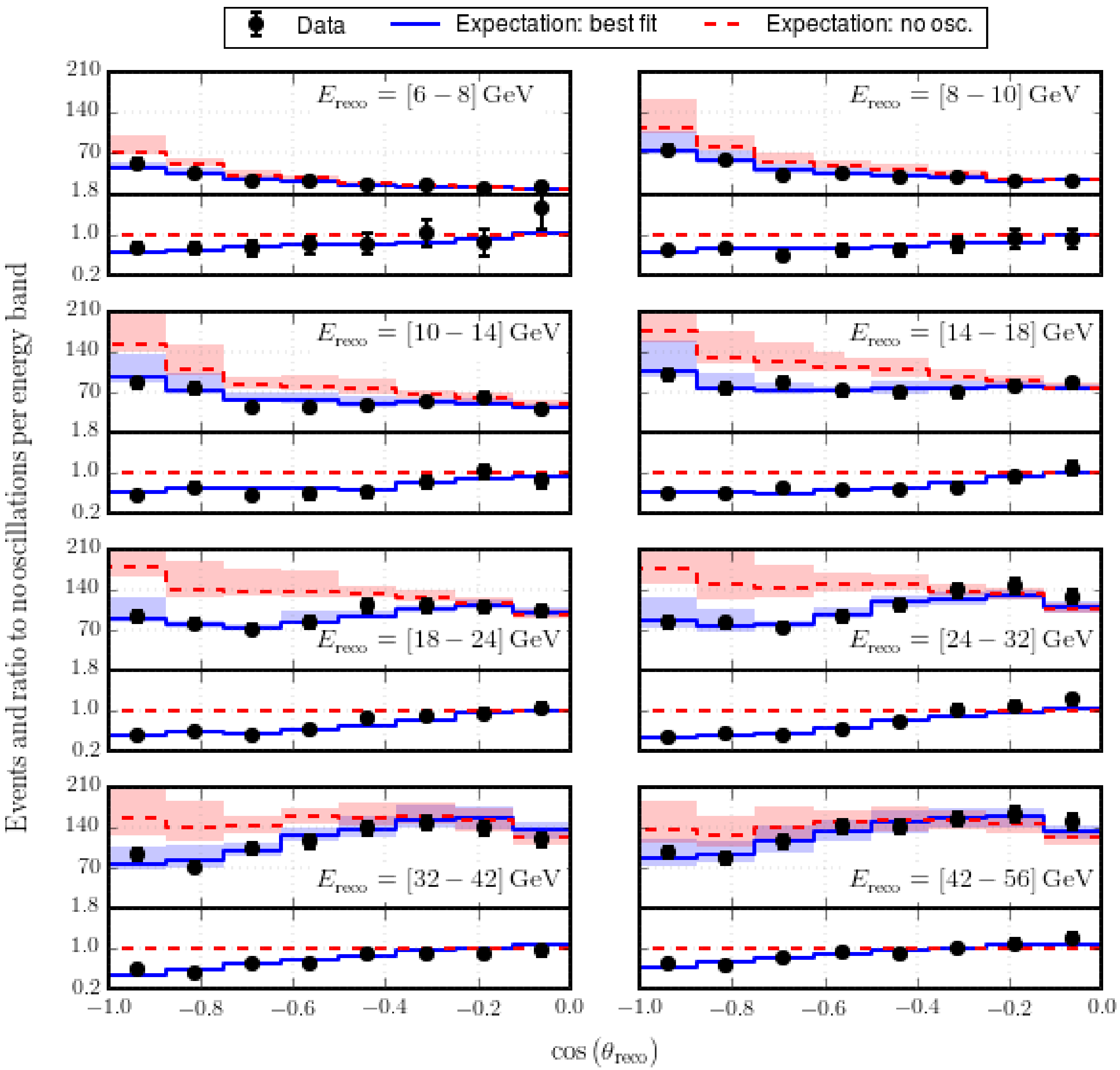
Systematic uncertainties used

Source of error		Nominal value from	Uncertainty
Neutrino interactions	Total cross-section scaling	GENIE model	Free
	Linear energy dependence		E^(+/-0.03)
	Axial mass of non-DIS events		~ +/-20%*
Atmospheric neutrino flux	Overall normalization	Honda 2012	Free
	Spectral index		E^(+/-0.04)
	NuE relative normalization		+/- 20%
Detection	Hadronic energy scaling	Geant4 (model)	+/- 5%
	DOM overall efficiency	Muons, flashers	+/- 10%
	DOM angular acceptance (scattering in hole-ice)	Fit to flasher data	As large as 50%‡
	Bulk-ice model		Two models

* Exact value depends on the individual process

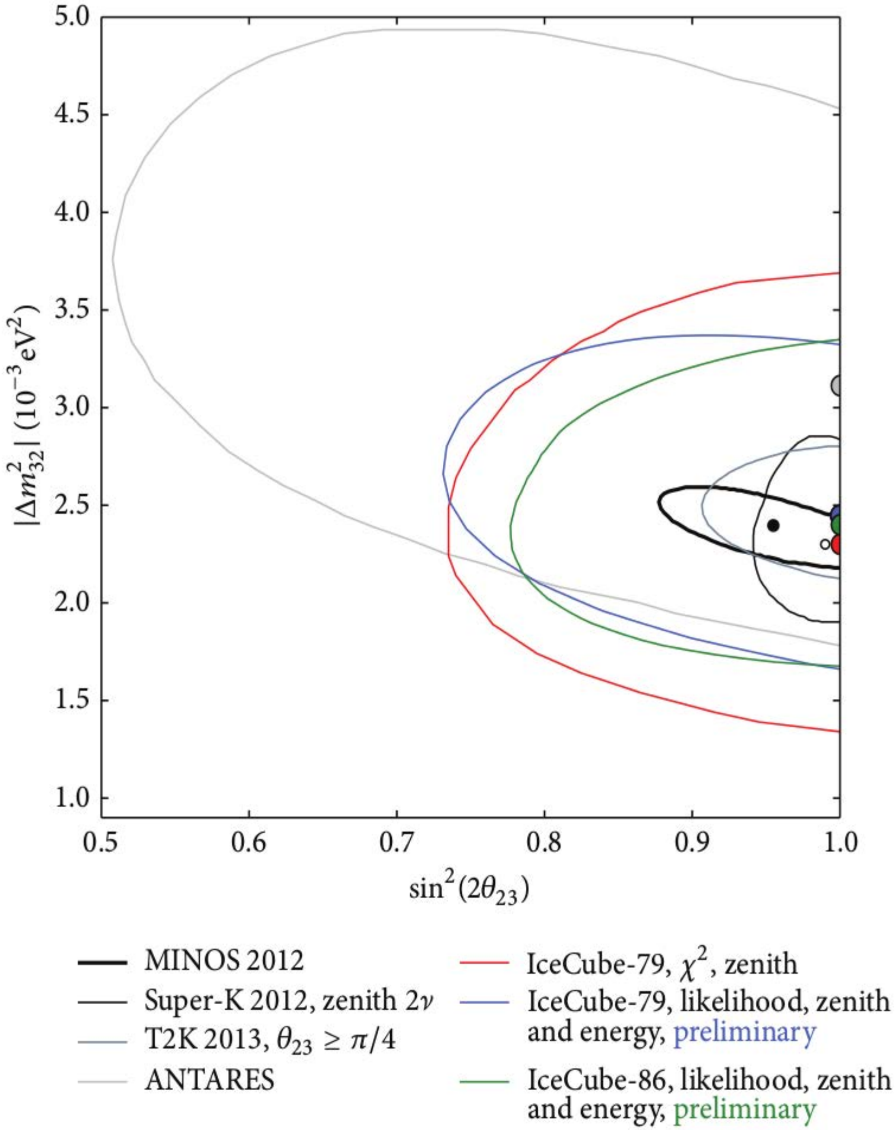
‡ Largest deviation for photons perpendicular to PMT direction

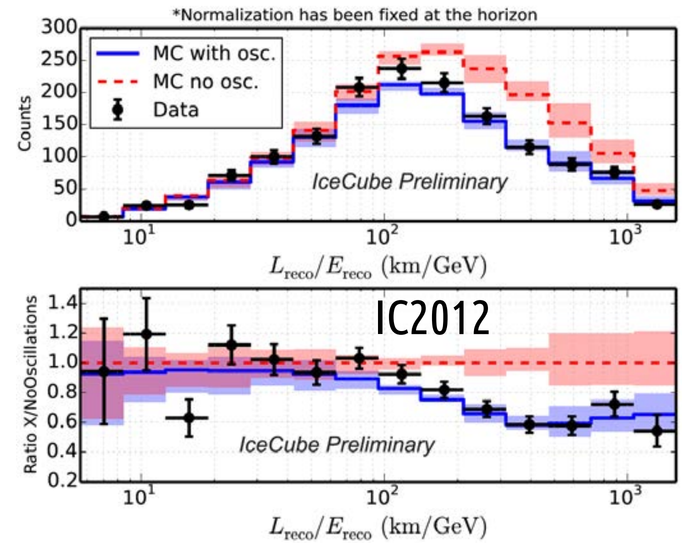
Agreement between data and MC

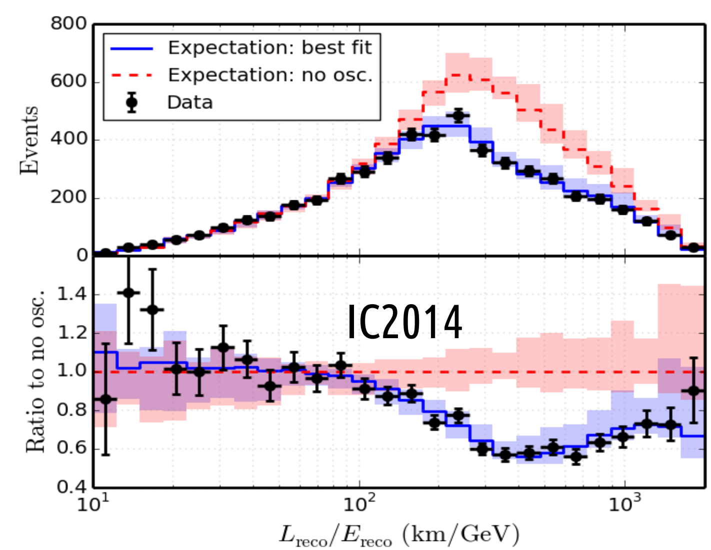


» Full 2D histogram neutrino oscillations

Evolution of oscillation analysis in IceCube DeepCore



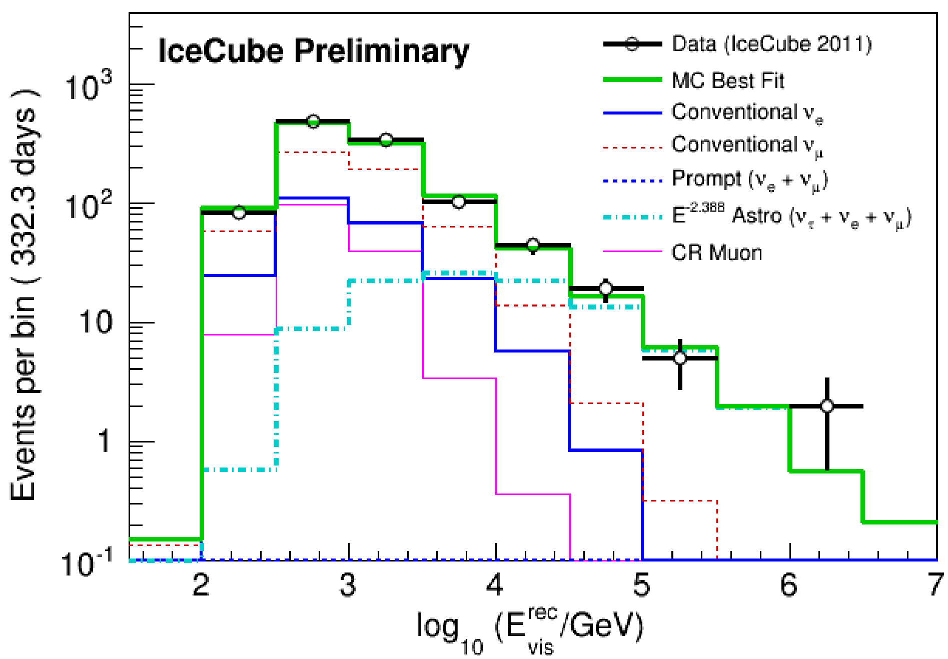


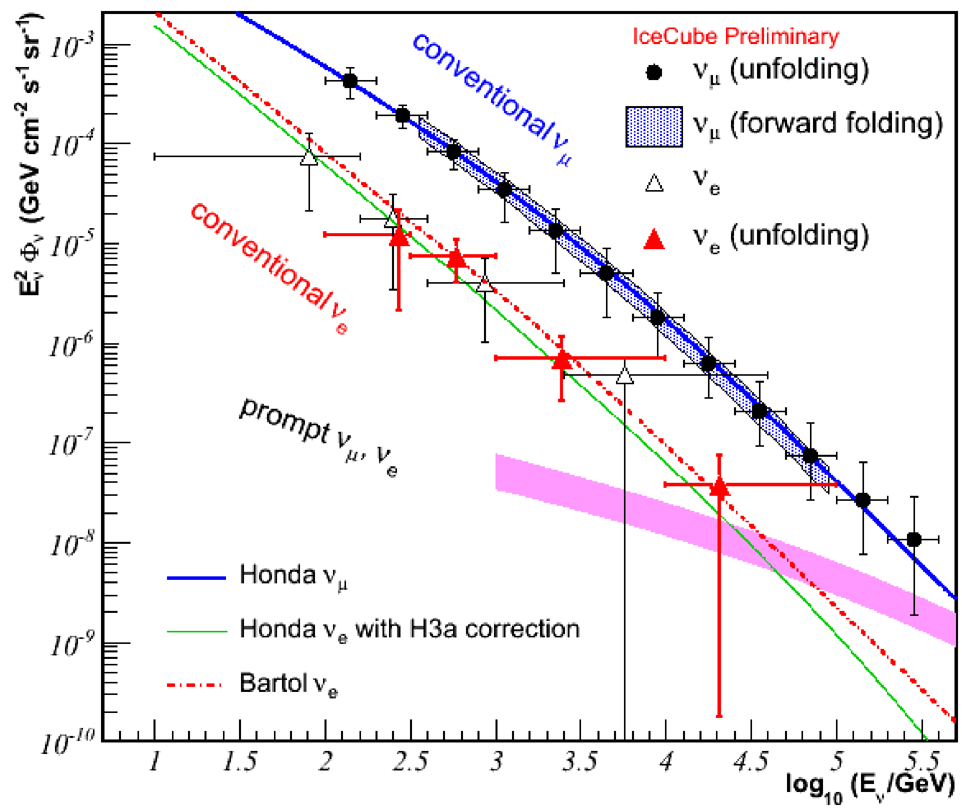


Electron neutrinos from the atm

- » Consistent with Honda flux
  - » Extrapolated to higher energies using H3a model

T. K. Gaisser, Astropart. Phys. 35, 801 (2012).
M. G. Aartsen et al. Phys. Rev. D 89, 062007





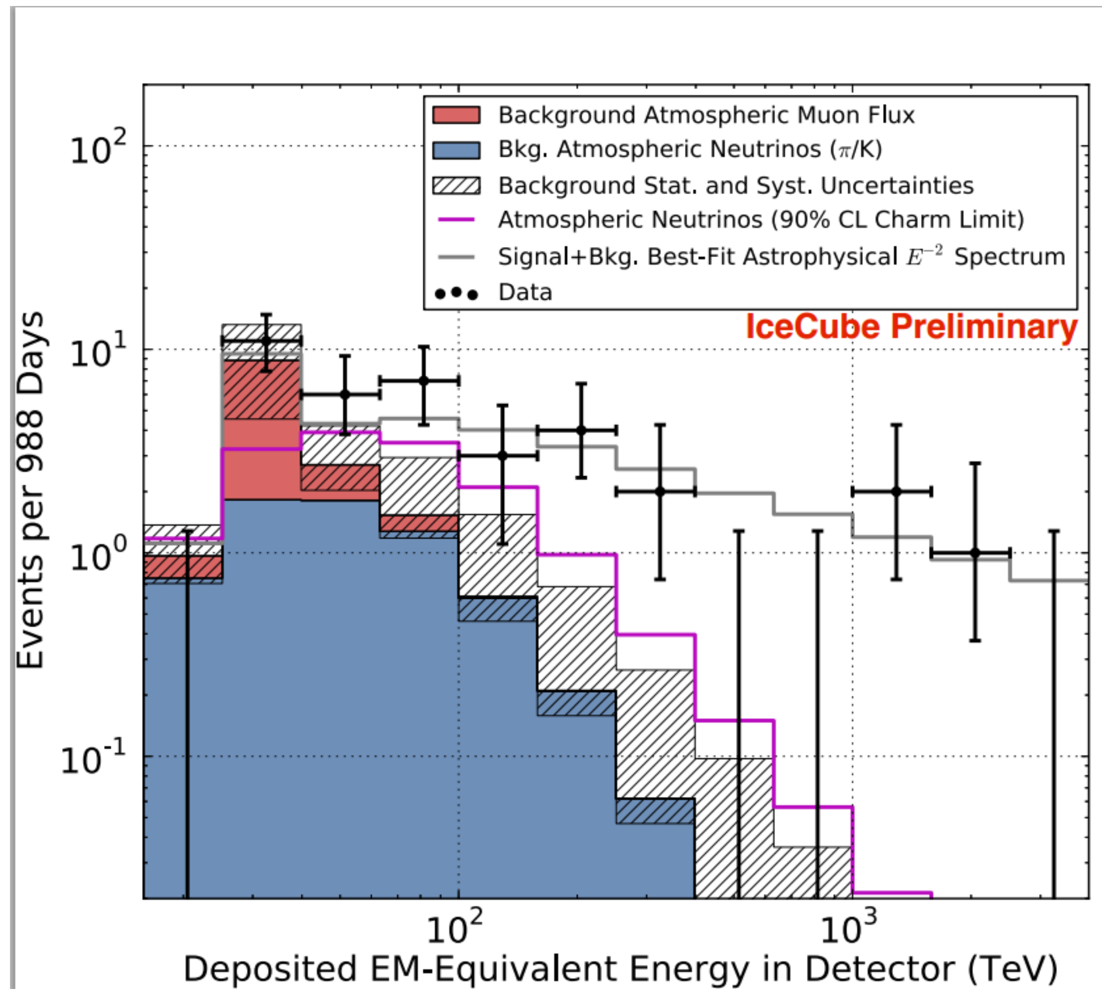
FAQ from Hell

- Galactic or extra-galactic?
  - No hints yet
- Northern vs southern sky?
  - Looks different, but not significant
- Going from tracks and cascades → flavor
  - Cascades ≈ NuE + NuTau + 0.4*NuMu
  - Tracks ≈ 0.6*NuMu
- “Prompt component” still uncertain
  - Not a major uncertainty in the astrophysical flux (veto)

Diffuse, HEstarting events

- »Using 3 years of data, HE starting events
- »37 neutrino candidates
  - »8 ± 4 atm. muons
  - »6 $^{+6}/_{-2}$ atm. neutrinos
- »5.7 σ over background
- »Cascade-dominated
  - »Poor angular resolution
- »Search extended to LE

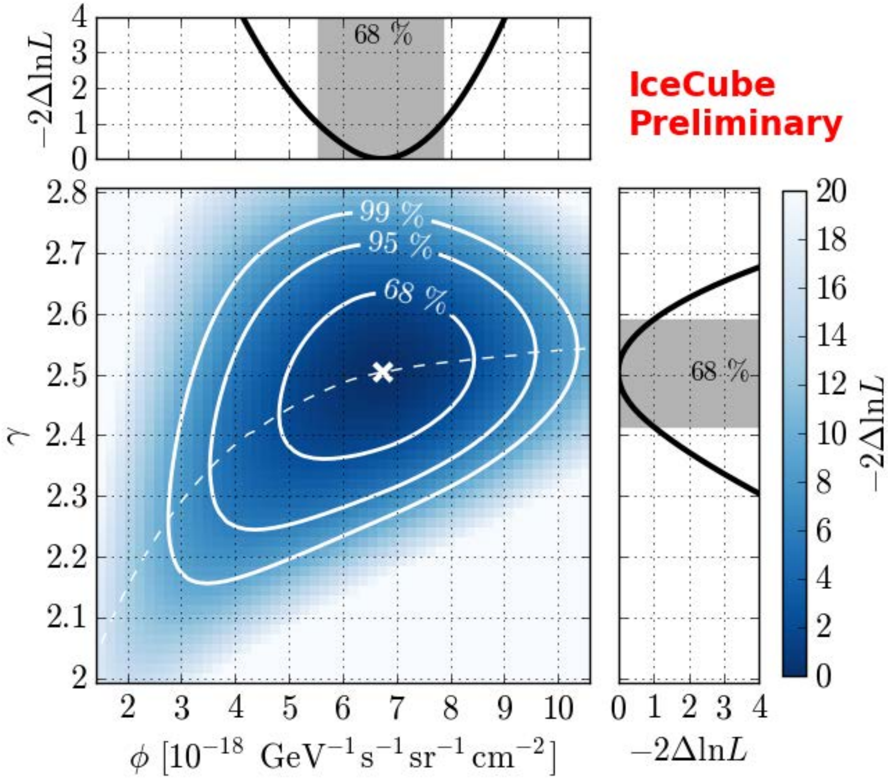
Phys. Rev. Lett. 113, 101101



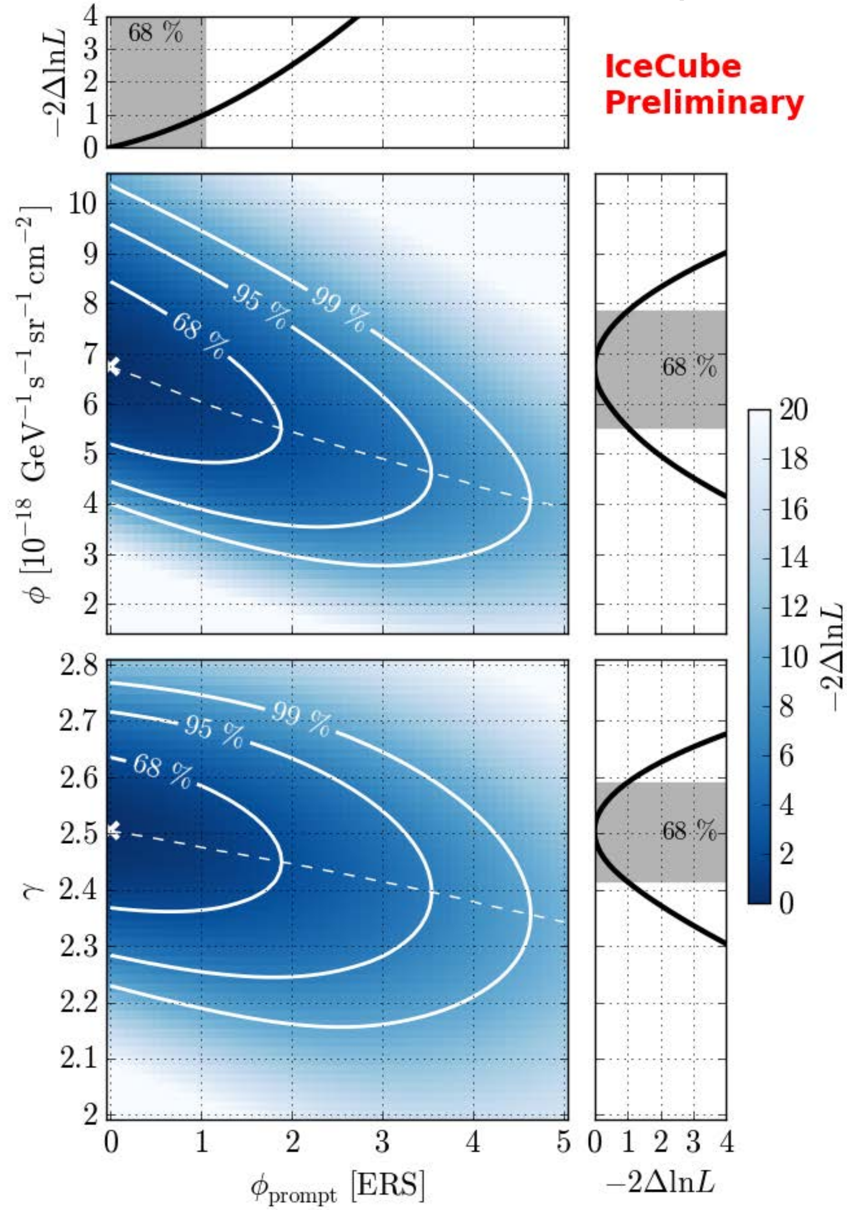
Joint analysis of diffuse searches

» Likelihood scans

Normalization vs spectral index

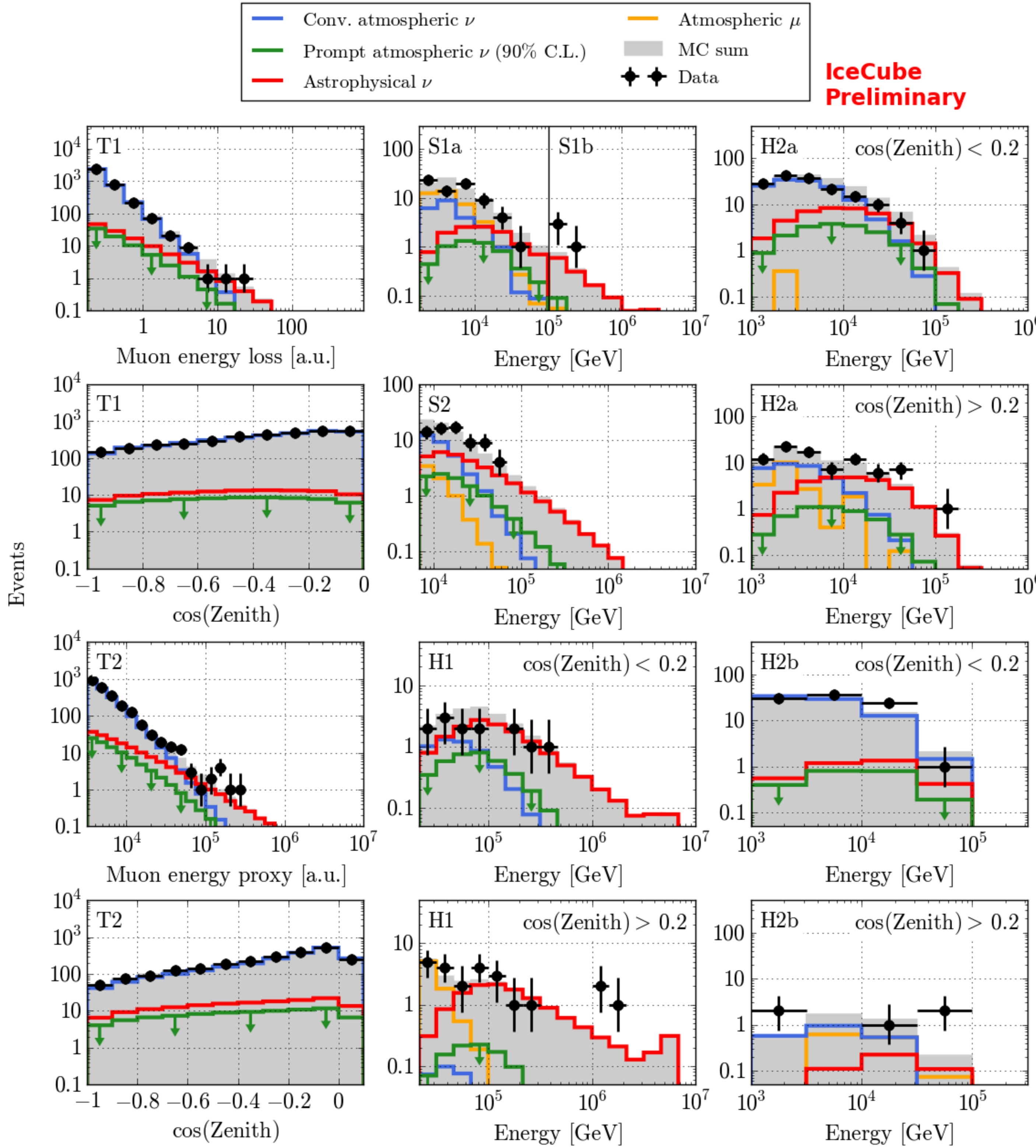


Normalization, index vs charm component



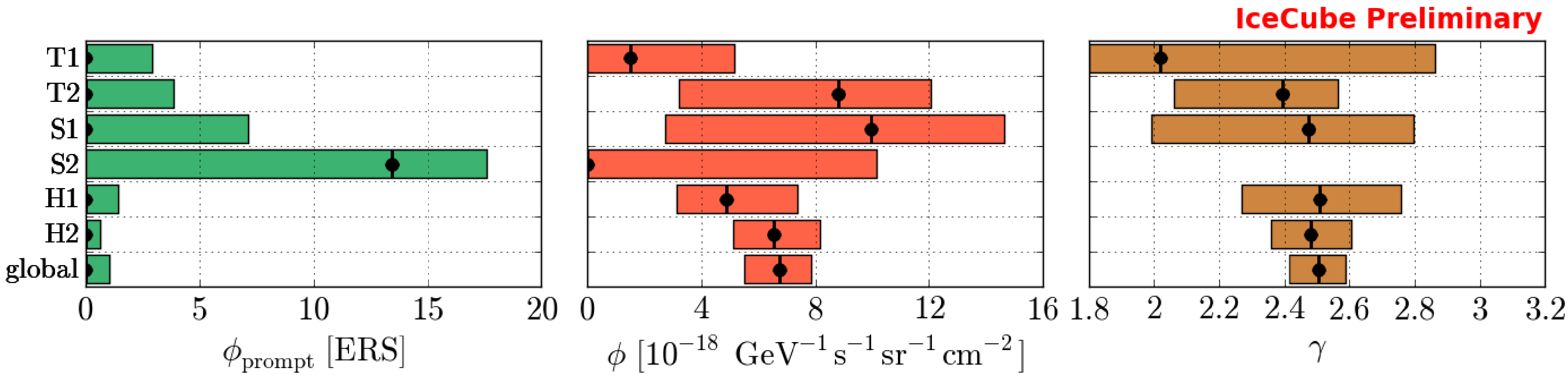
Joint analysis of diffuse searches

» Different samples used in the joint LLH analysis



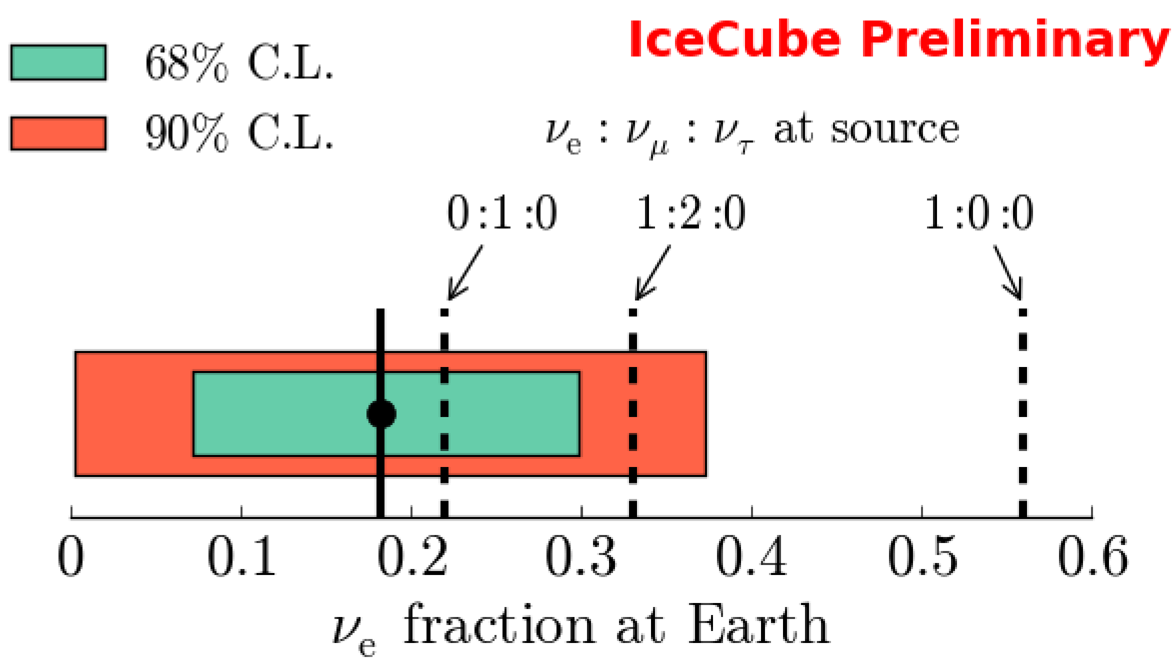
Joint analysis of diffuse searches

» Individual fits to different samples



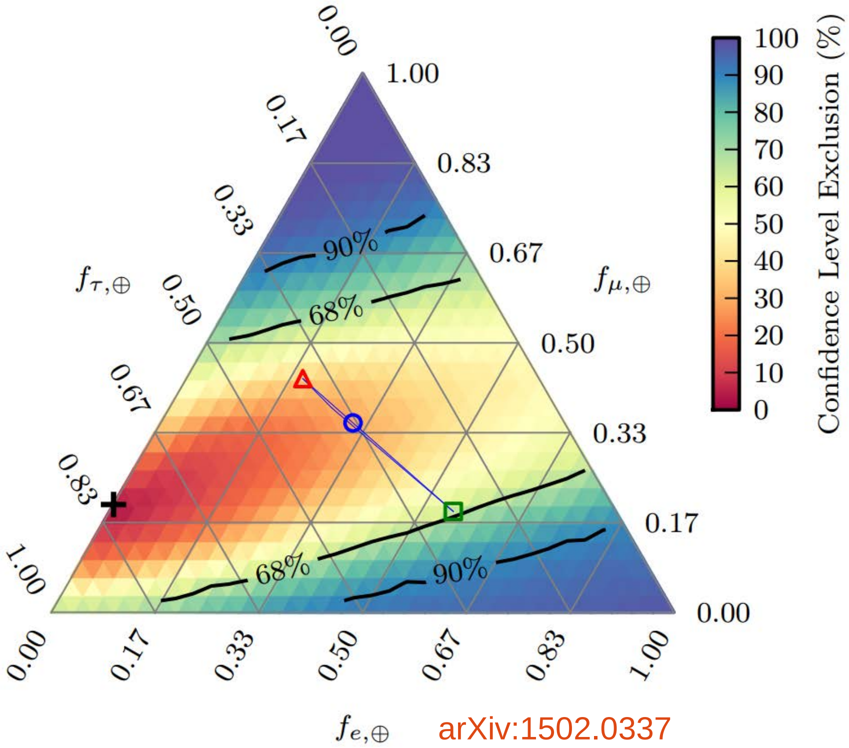
Joint analysis of diffuse searches

» Flavor ratio



Joint analysis of diffuse searches

» Flavor ratio (compared to previous result in arXiv)



arXiv:1502.0337