Results From IceCube & Prospects for PINGU

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August 2014
Interplay Between Particle and Astrophysics 2014
Queen Mary University of London

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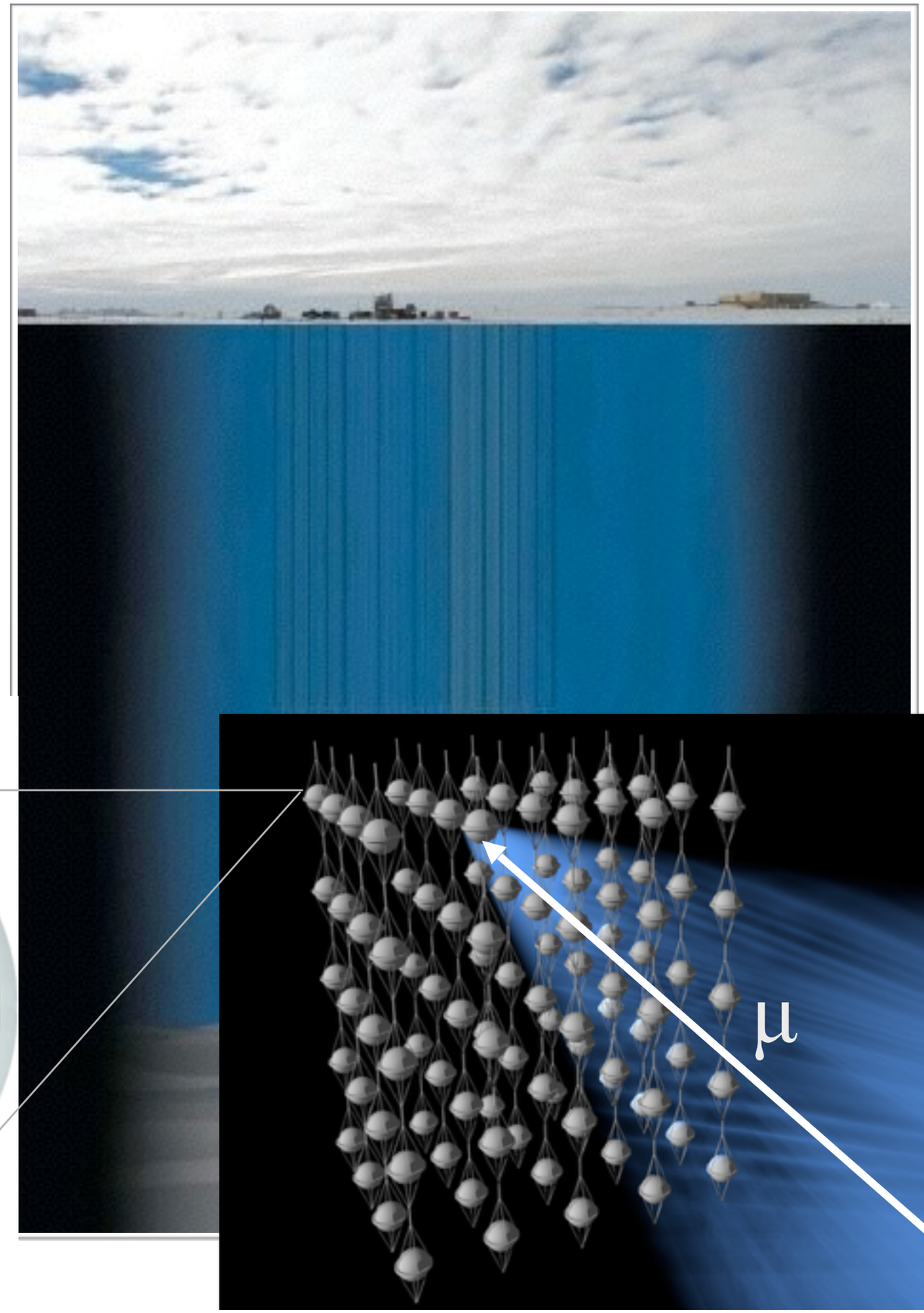
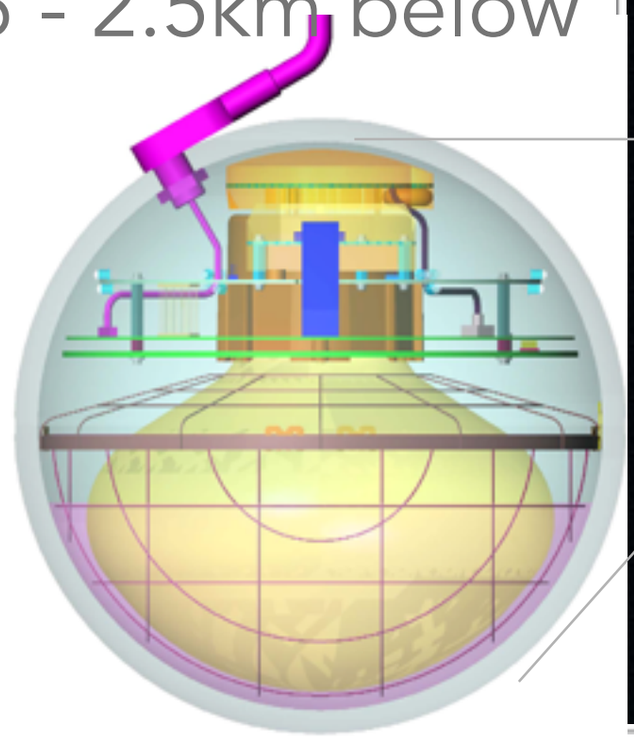
ICECUBE

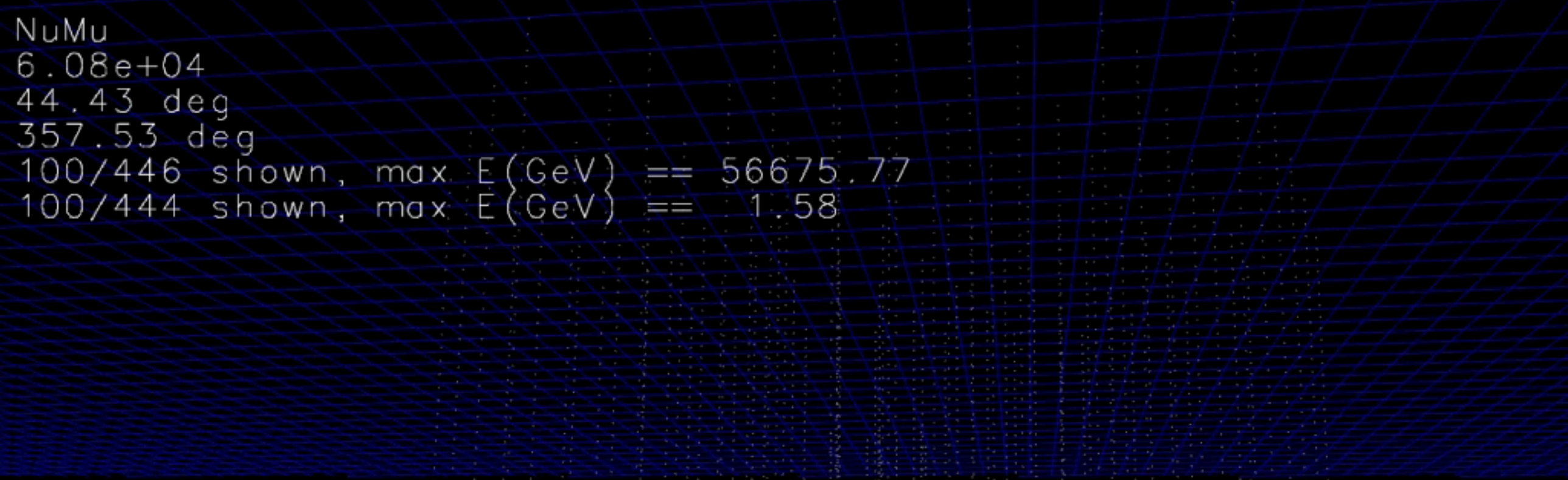
IceCube Detector

- ~1km^3 of instrumented ice
- Uses ~5k optical sensors across 86 vertical strings to detect Cherenkov radiation
- Deployed 1.5 - 2.5km below the surface





IceCube DOM

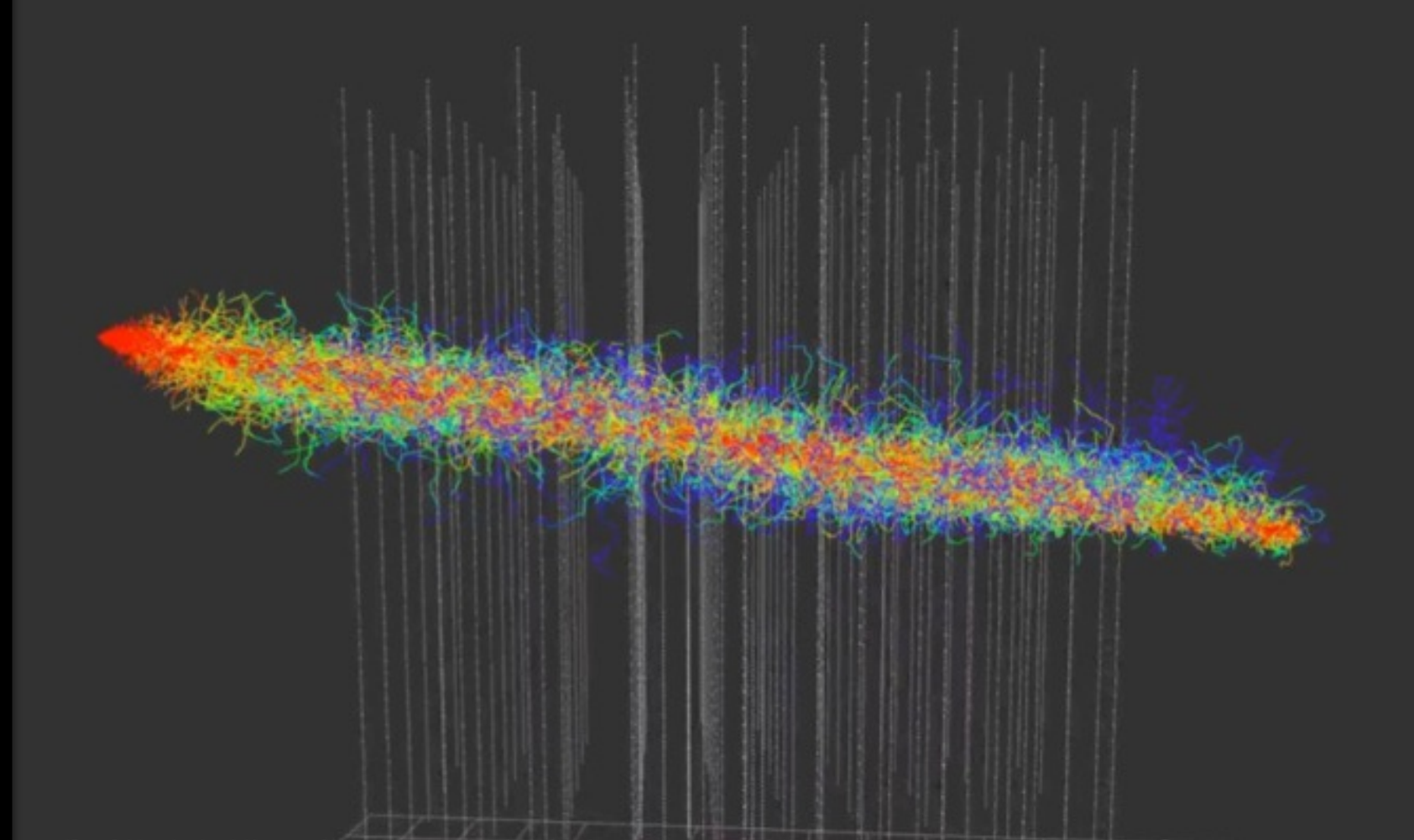

NuMu
6.08e+04
44.43 deg
357.53 deg
100/446 shown, max E(GeV) == 56675.77
100/444 shown, max E(GeV) == 1.58

Track topology

(e.g. induced by muon neutrino)

Good pointing,
0.2° - 1°

Lower bound on energy for through-going events

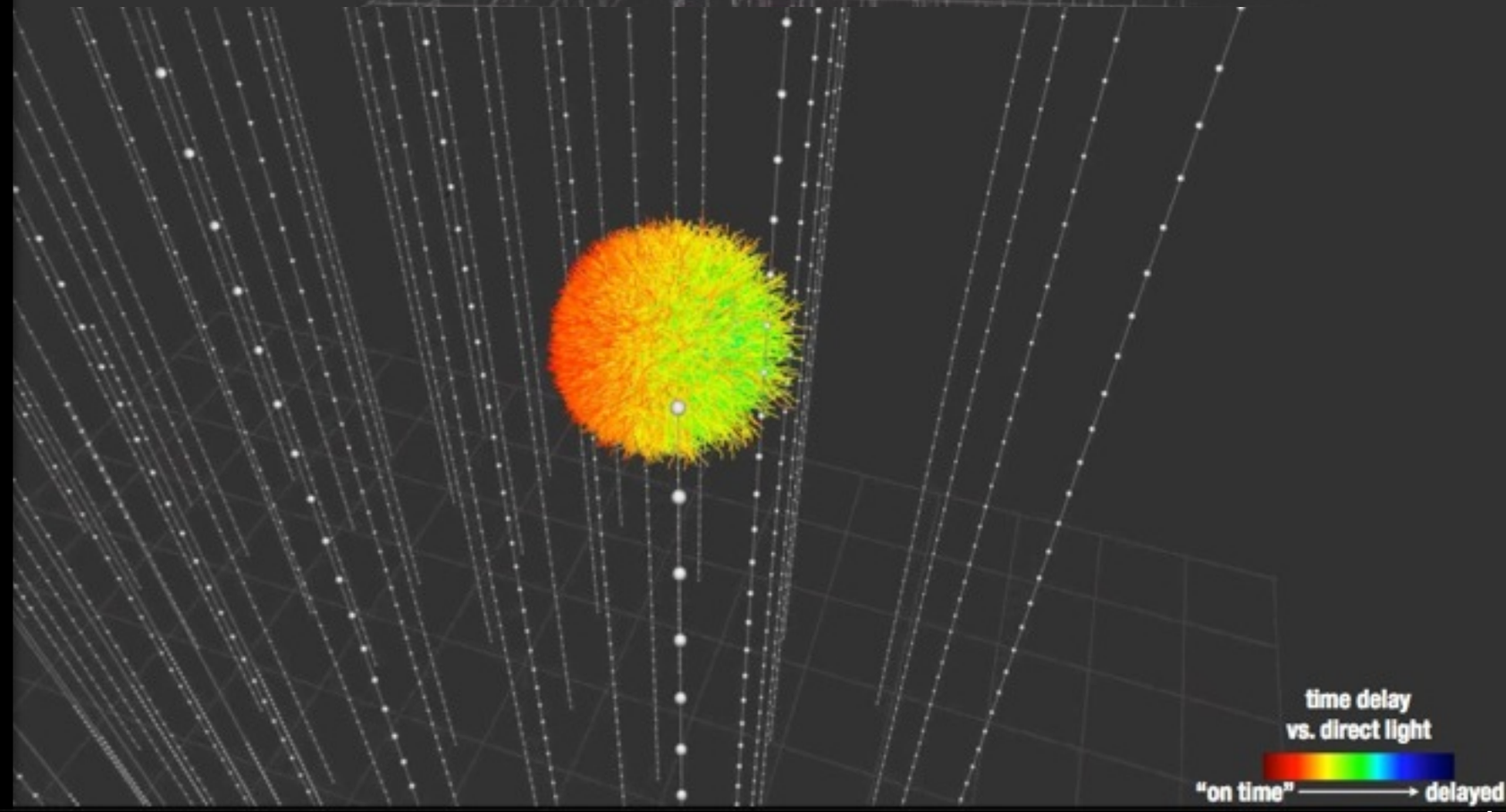


Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°



IceCube Classic

High Energy Starting Events (HESE)

- Follow-up to observation of two events > 1 PeV in IceCube search for Ultra-High Energy neutrinos

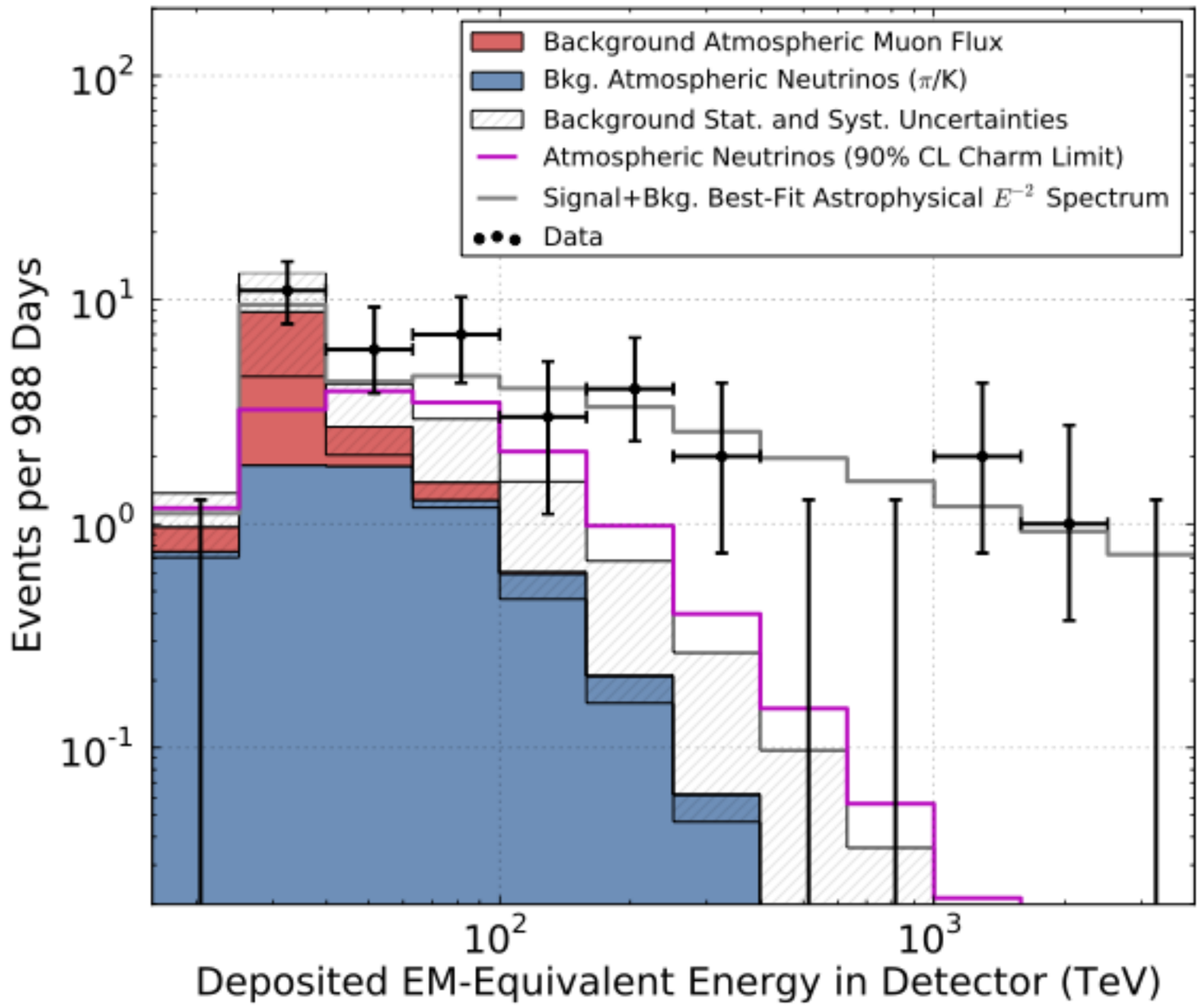
- Use outermost layer of IceCube as a veto region
  - Identifies possible muon background
  - Enforces neutrino interaction containment

- Focused on brightest events with > 6000 photoelectrons

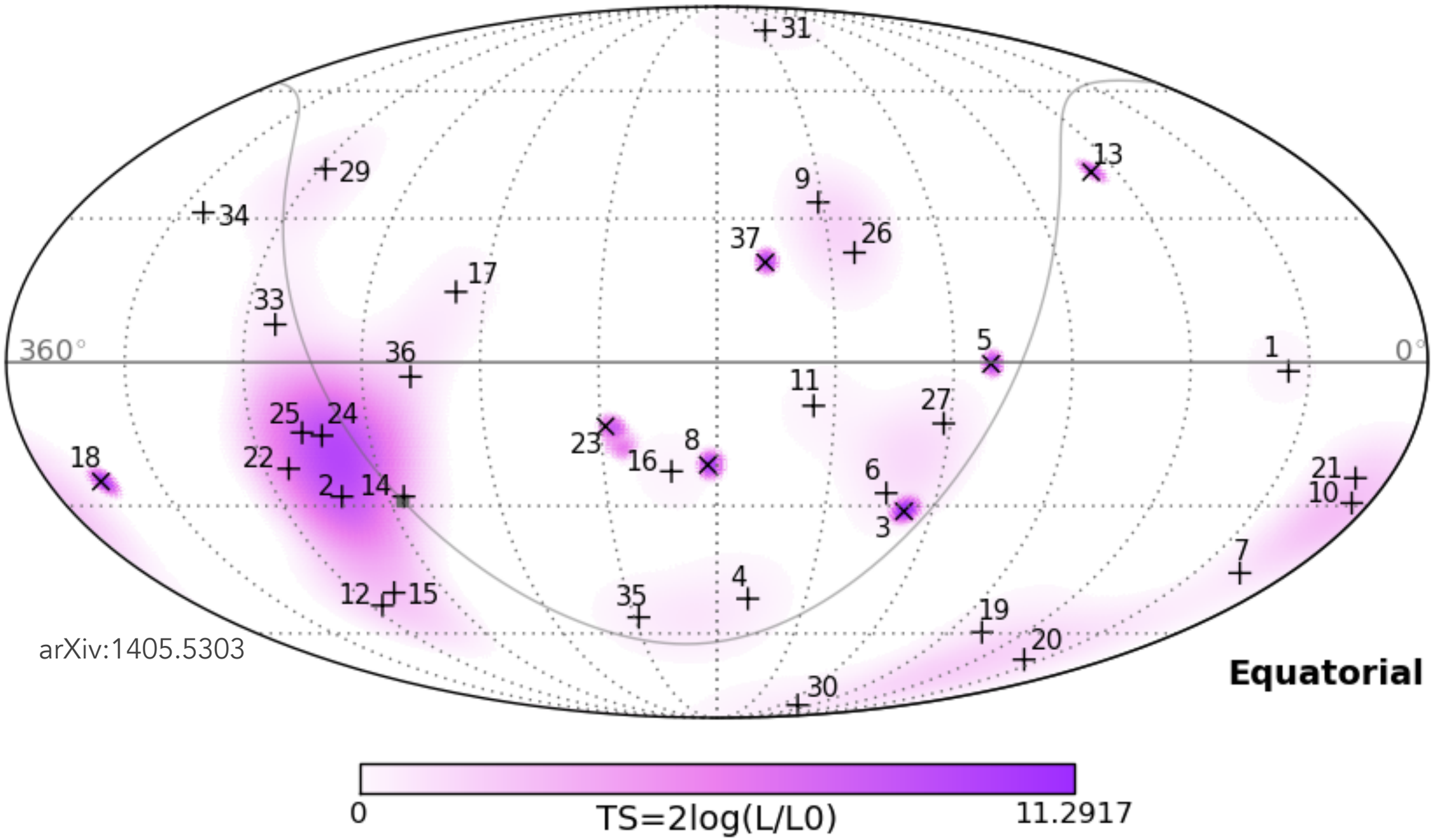
3-year HESE Result

- 36(+1) events total
  - 8.4 ± 4.2 atm. muons
  - $6.6^{+5.9}_{-1.6}$ atm. neutrinos

- 5.7σ rejection of only atmospheric neutrino flux

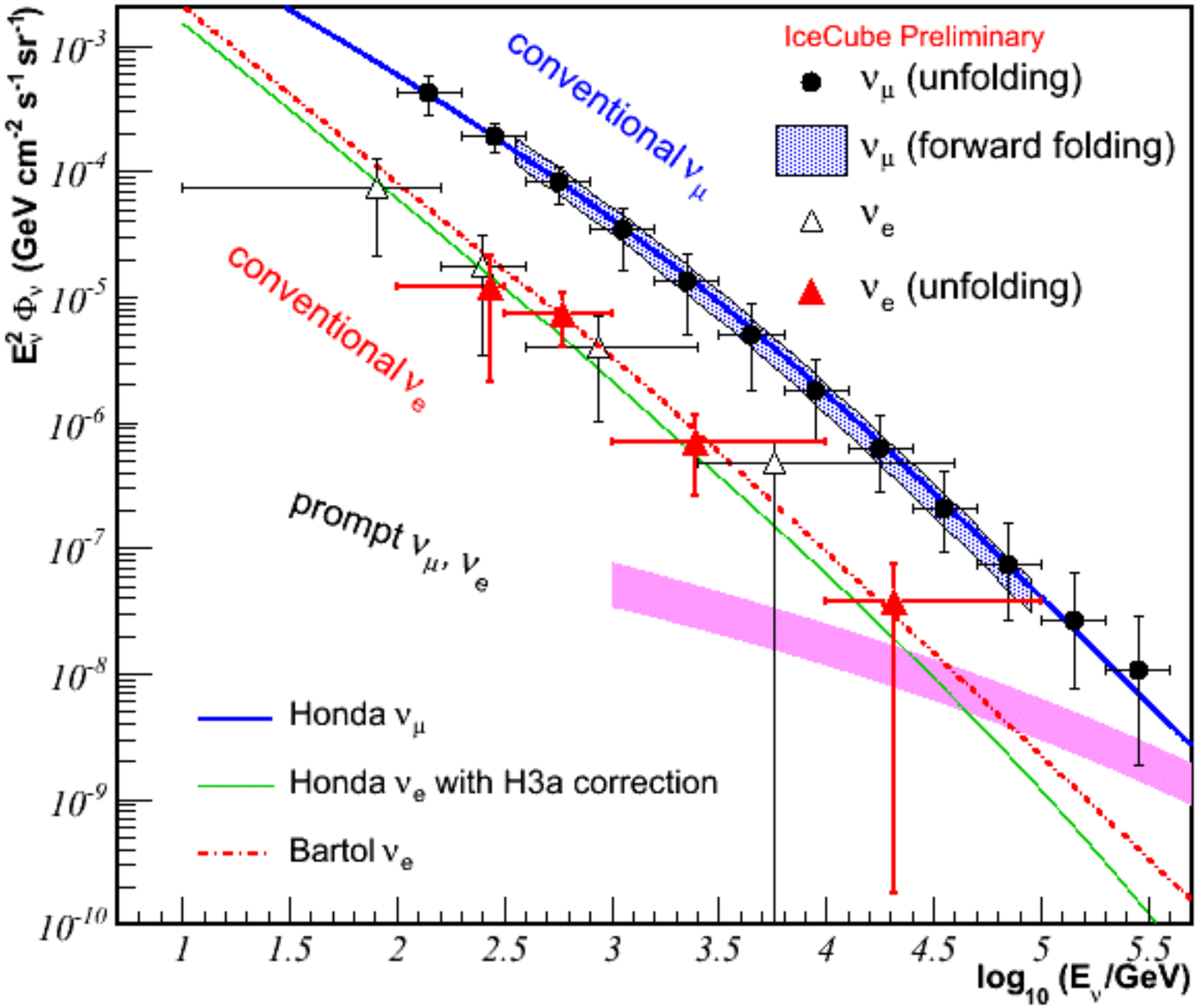


HESE-III Sky Map



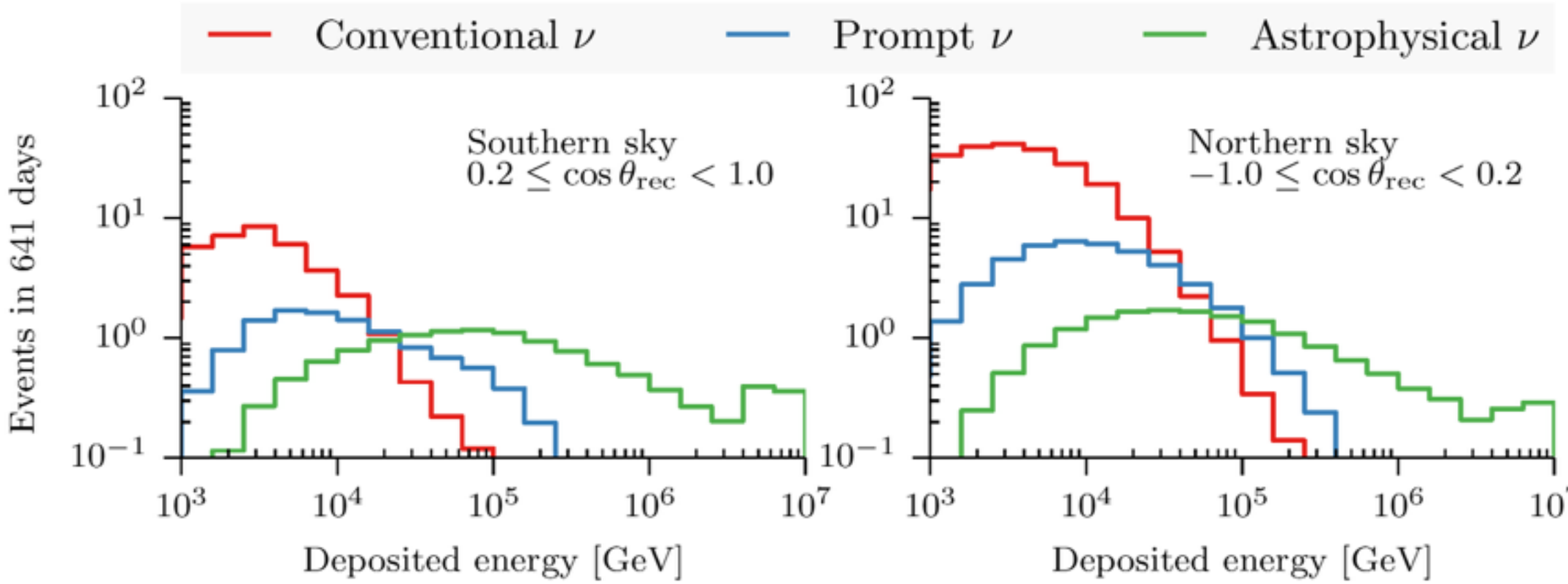
- No significant evidence for clustering

Natural Neutrino Flux



- Natural neutrino flux is a combination of conventional neutrino, high energy astrophysical, and possible prompt neutrinos from charm meson decay

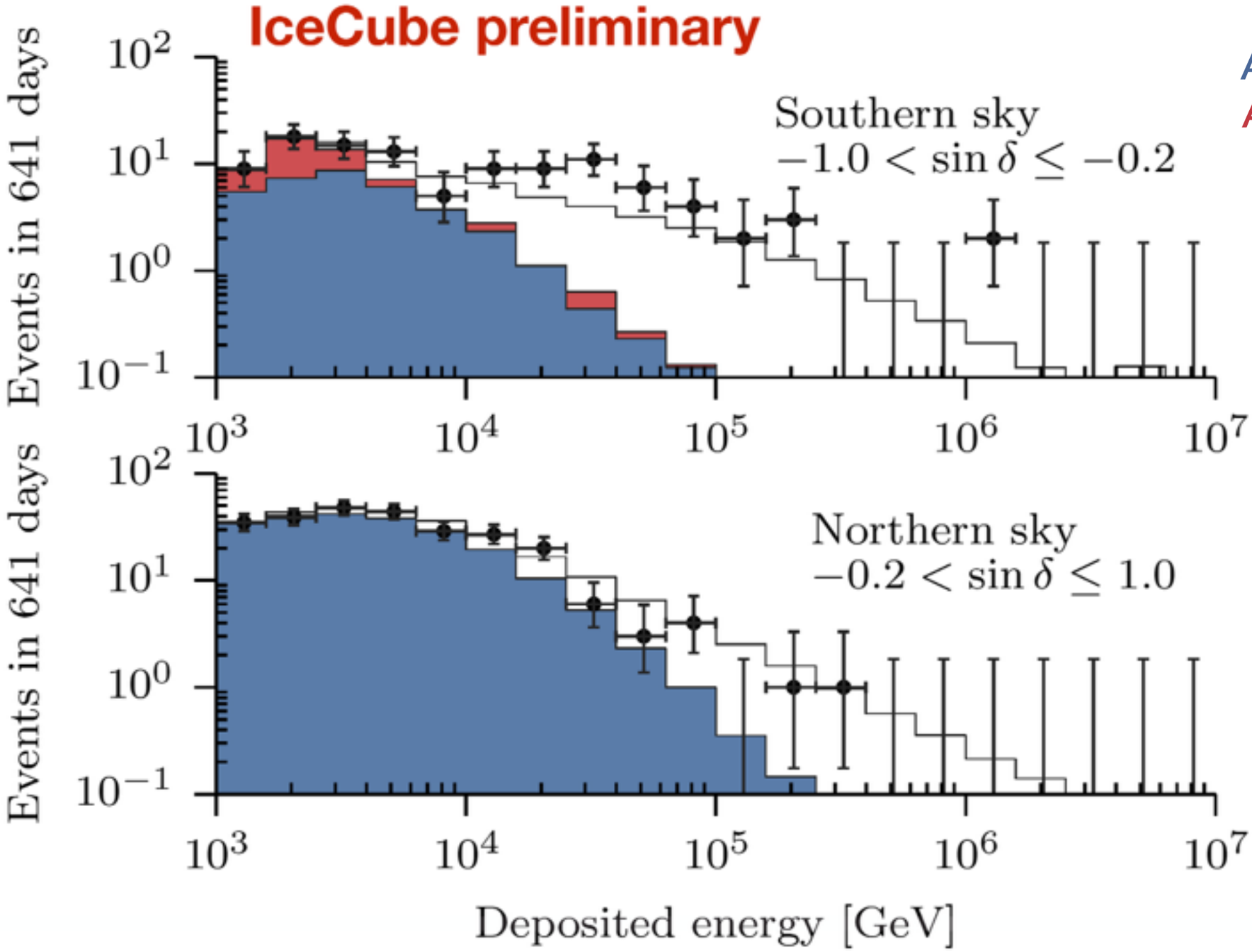
Prompt Component



- Prompt can be constrained by flux in the 10-50 TeV range
  - Higher energy is dominated by astrophysical flux
  - Lower energy is dominated by conventional flux (pion/kaon decay)

- Northern vs. Southern sky comparison weakly breaks the degeneracy between the astrophysical and prompt flux

A Prompt Result



Atm. Neutrinos
Atm. Muons

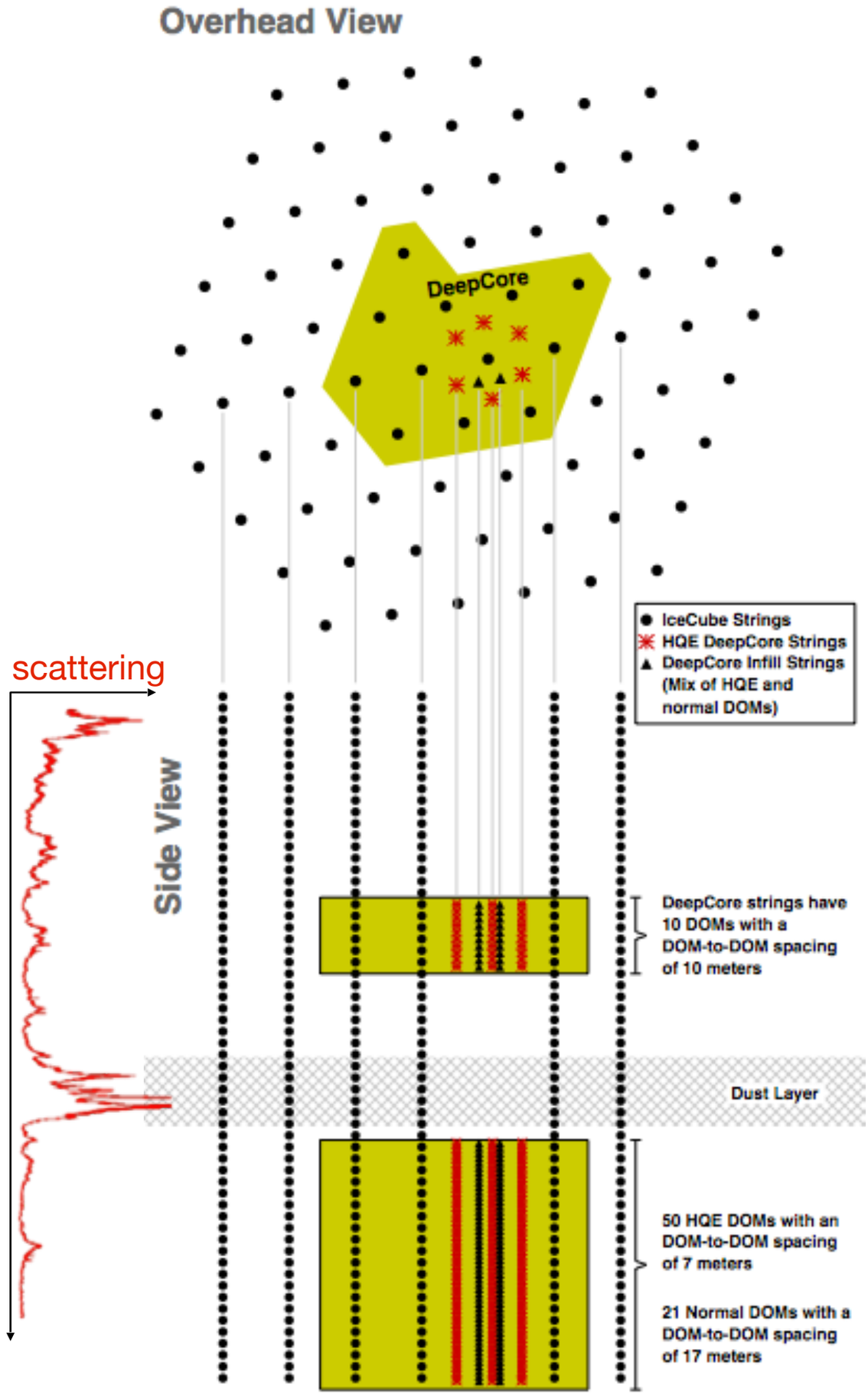
- Places upper limits on some prompt models (<1.4 ERS model)

Fundamental Physics with DeepCore

DeepCore

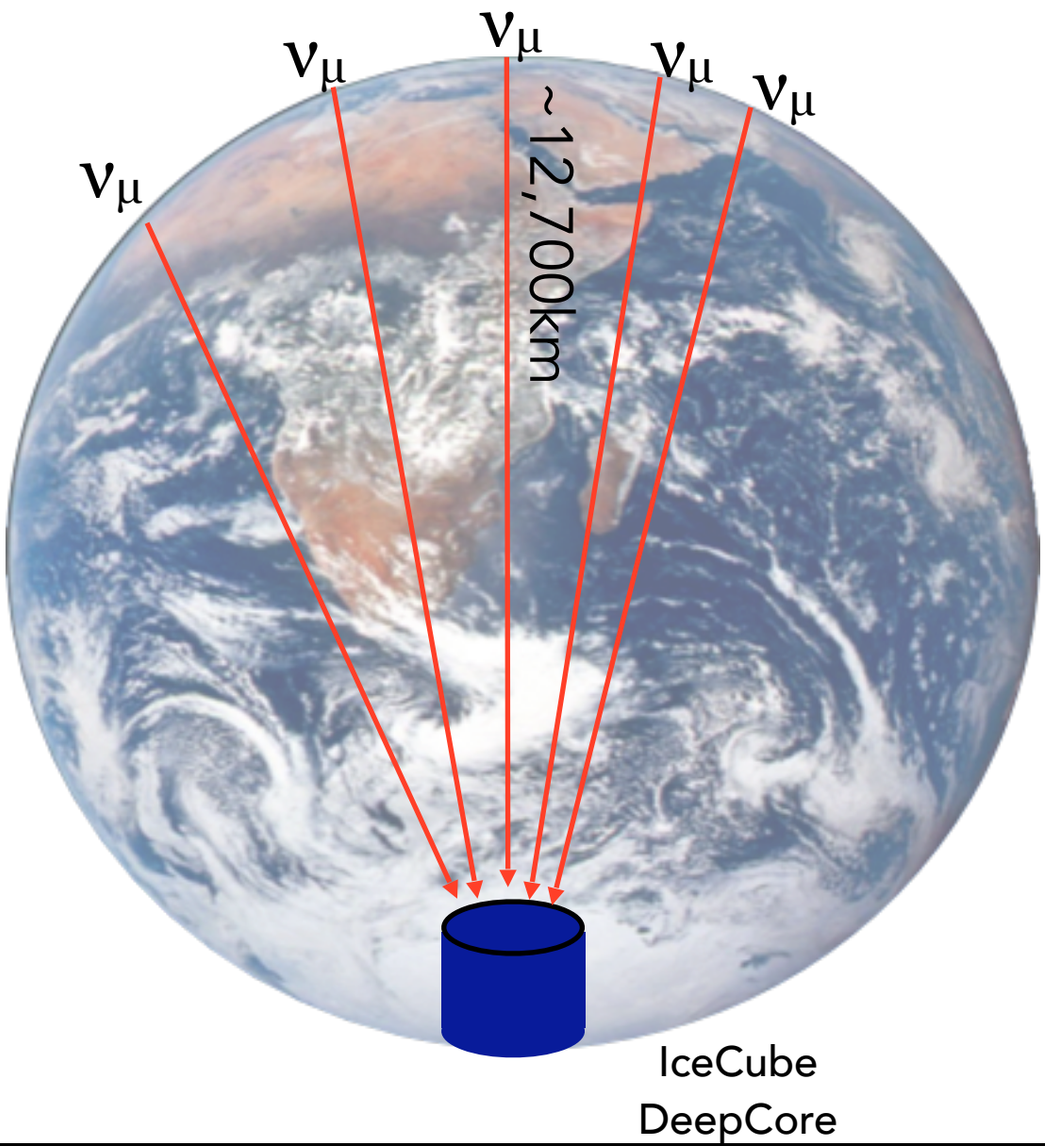
- Low-energy extension
  - Closer instrumentation
  - Clearer Ice
  - Higher efficiency PMTs

- Use surrounding IceCube as a veto volume

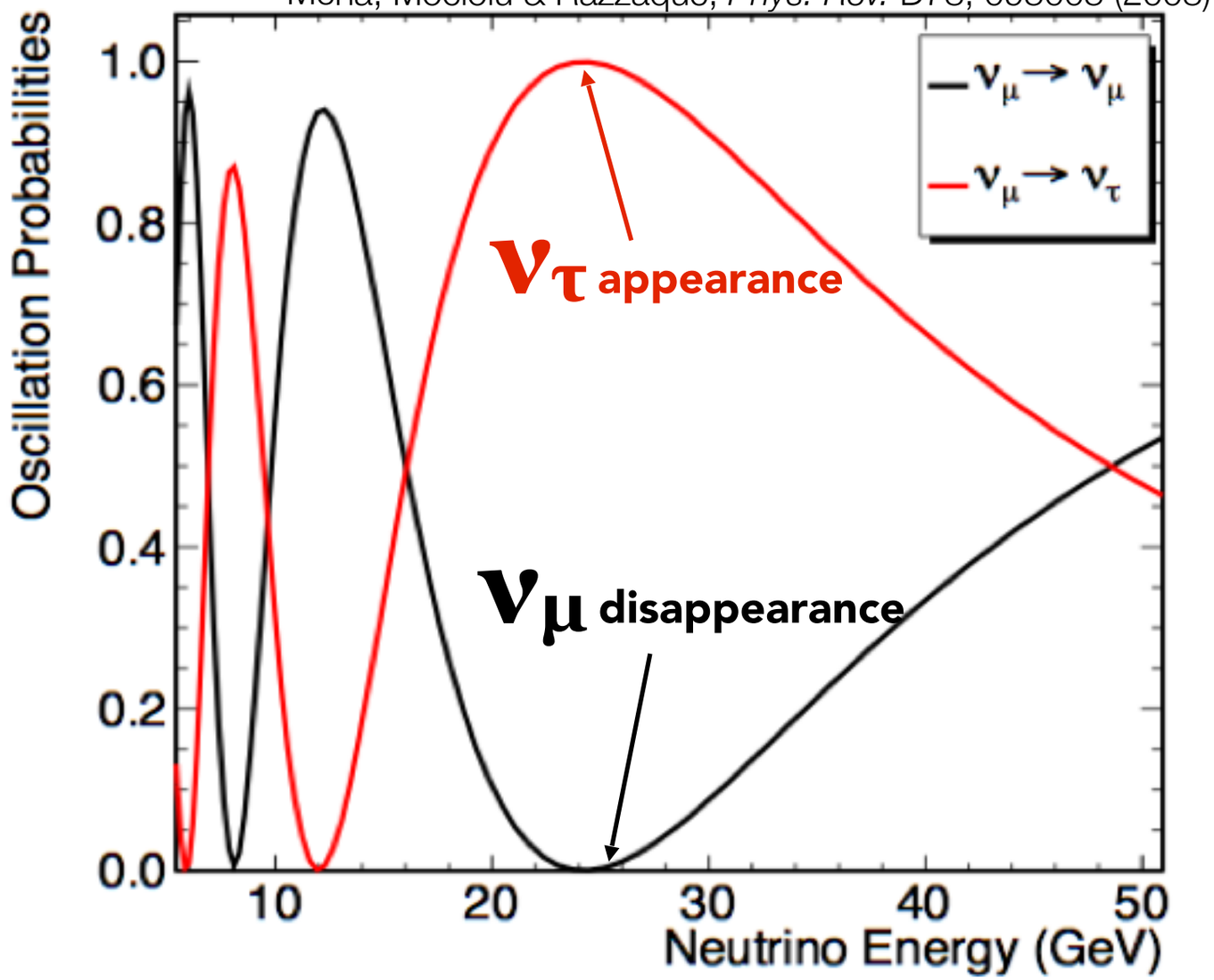


Neutrino Oscillation

- Northern Hemisphere ν_μ oscillating over one earth radii produces ν_μ (ν_τ) oscillation minimum (maximum) at ~25 GeV
  - Beam never turns off
  - Samples all terrestrial baselines



Mena, Mocioiu & Razzaque, *Phys. Rev.* D78, 093003 (2008)

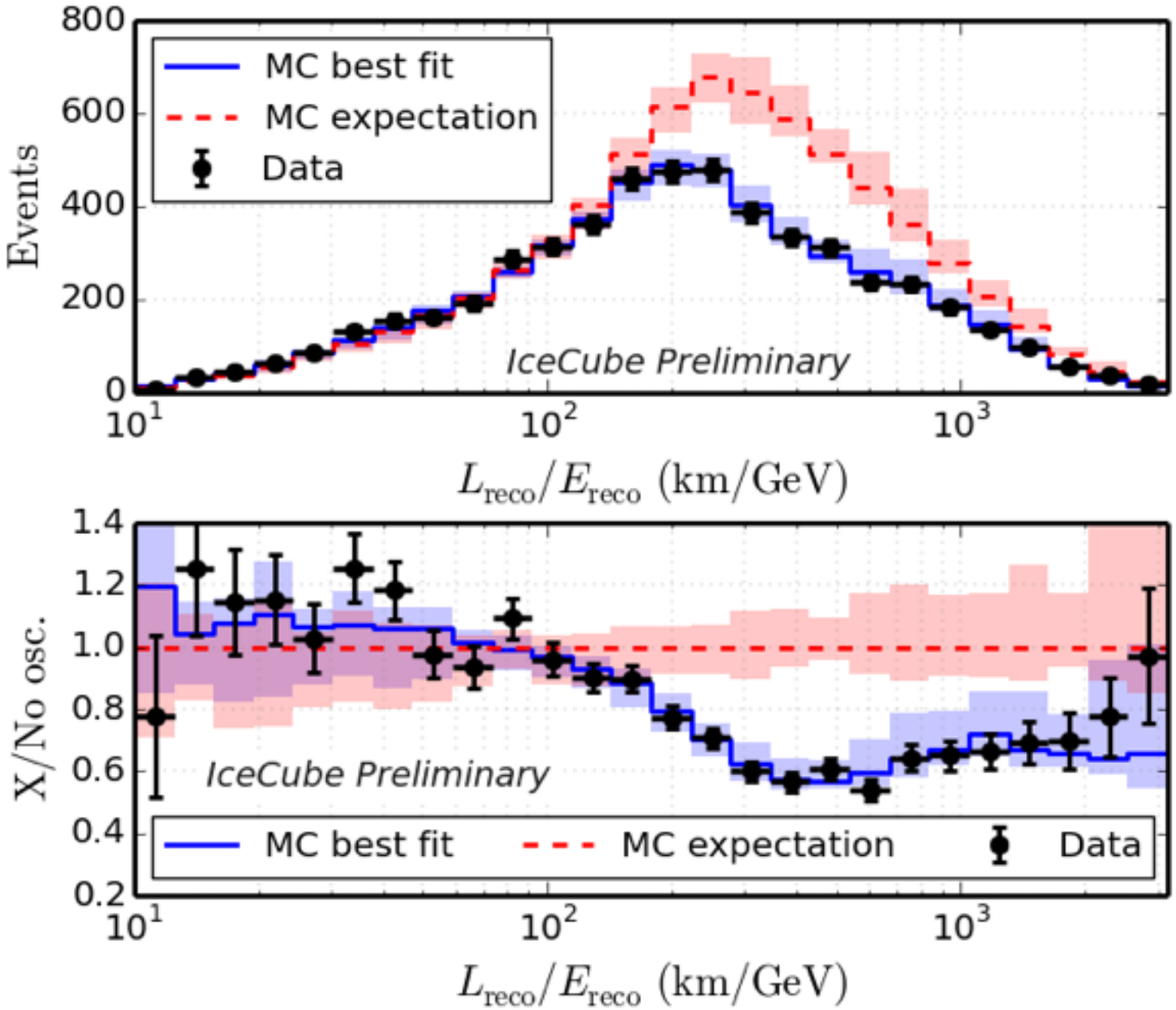


Neutrino Oscillation

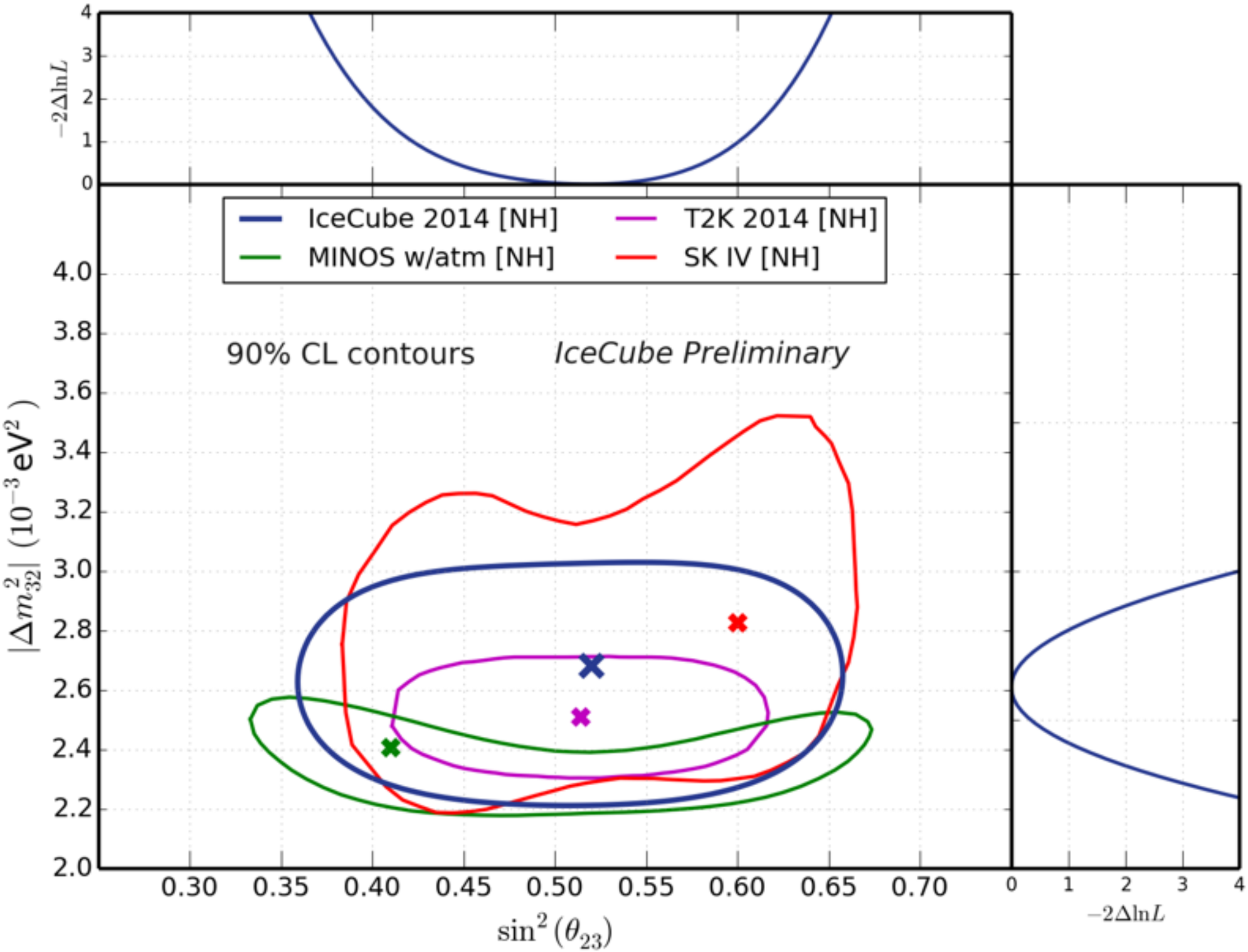
- High-purity analysis selected 5293 events over 2011-2014

MC Expectation (3-yr)

Type	Osc.	No Osc.
ν_μ	3755	5900
ν_τ	273	-
ν_e	678	650
ν_{NC}	418	
Atm. μ	54	
Total	**5178**	**7022**



Oscillation Contours



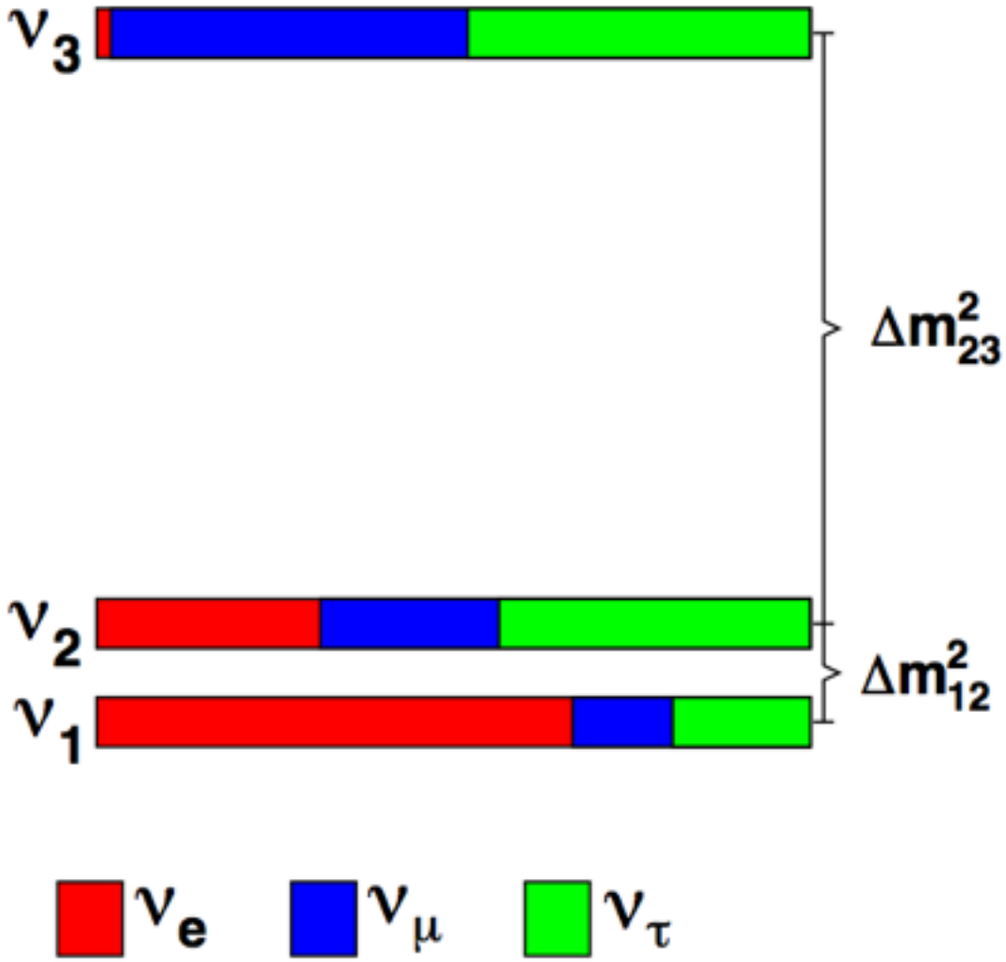
Next?

Two Directions

- Higher energy
  - Point sources
  - Neutrino flavor ratios
  - HEX - High Energy Extension

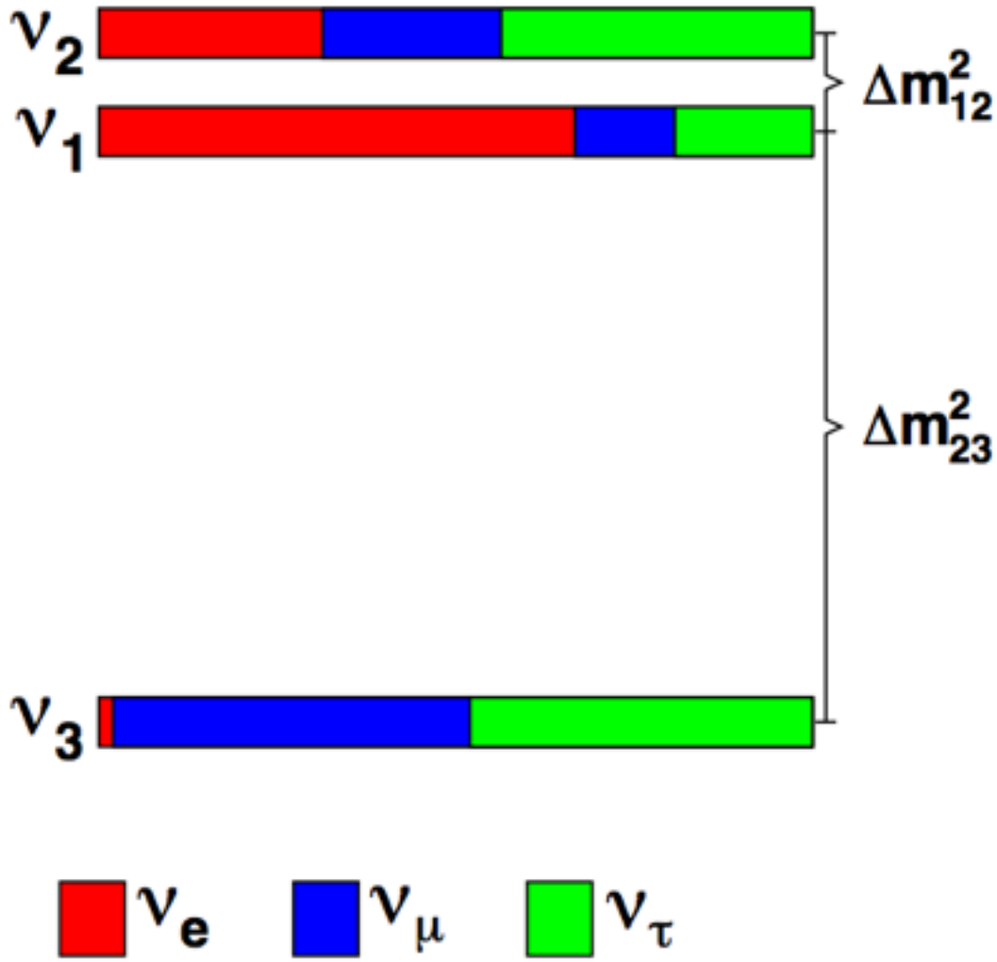
- Lower Energy - just past DeepCore at the O(1) GeV sensitivity:
  - Resolve the ordering of the Neutrino Mass Hierarchy
  - Improve neutrino oscillation
  - GeV scale Dark Matter
  - PINGU

Neutrino Mass Hierarchy



Normal

or



Inverted

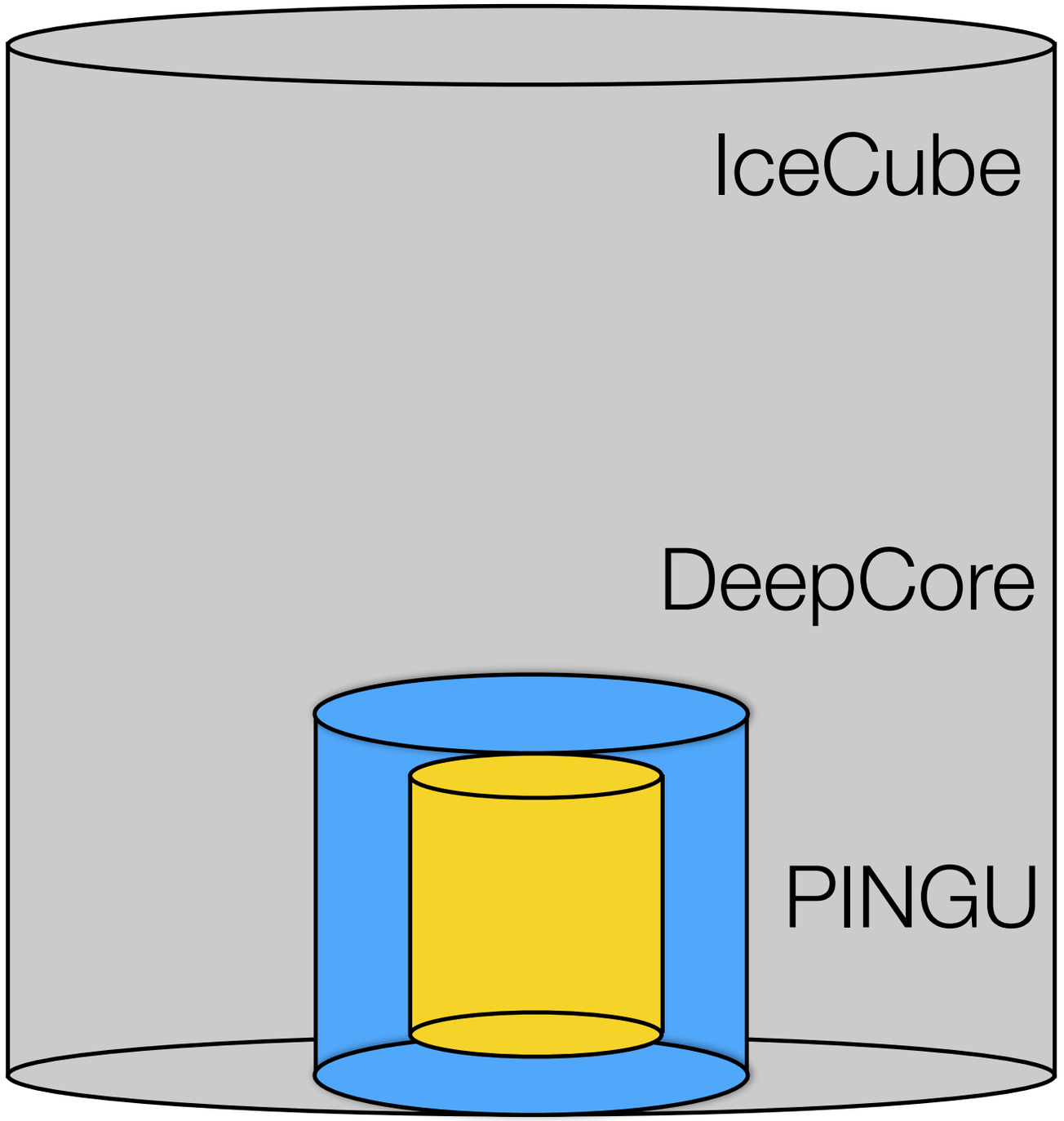
PINGU

Precision IceCube Next Generation Upgrade

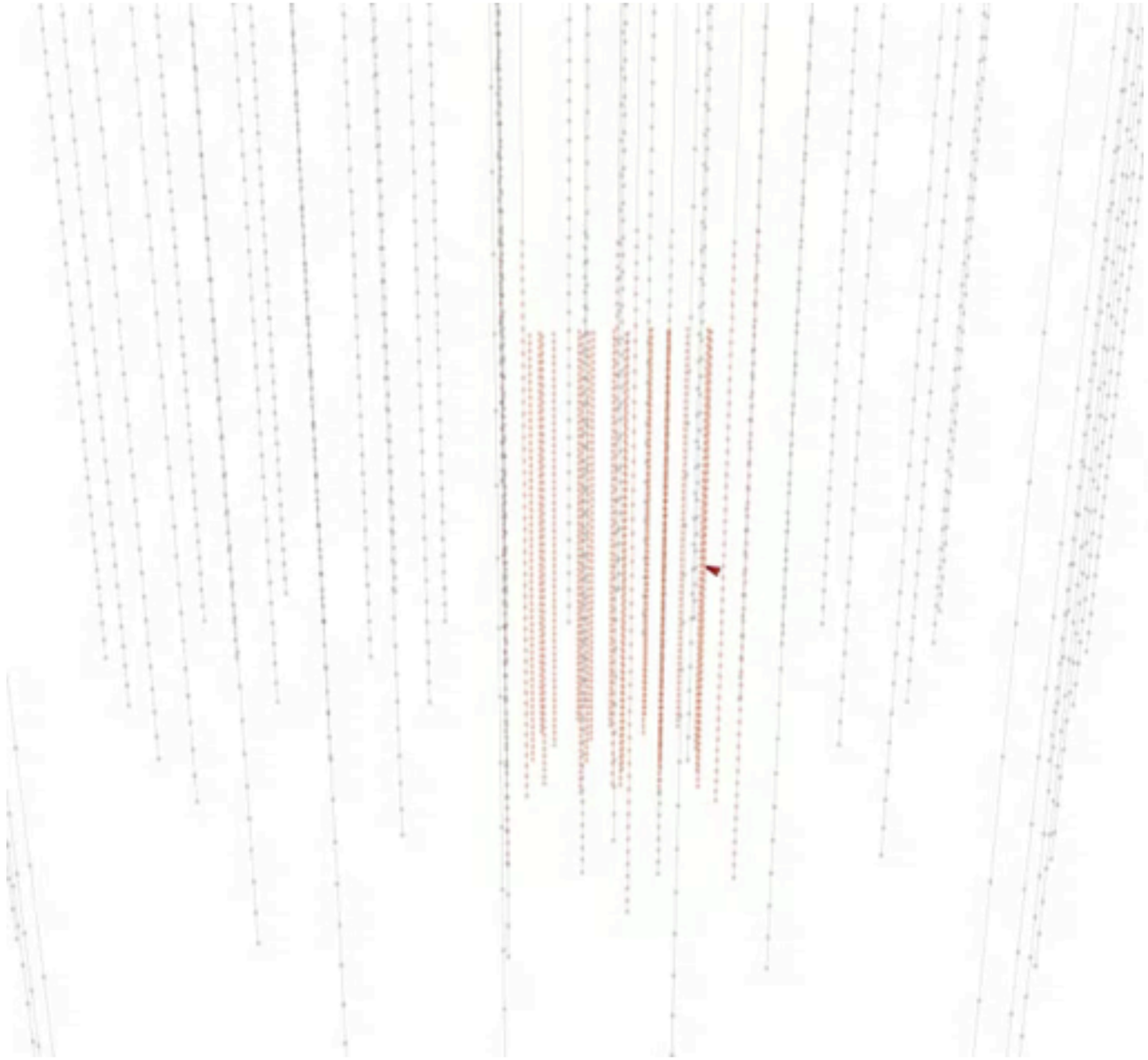
- Use existing and familiar technology to infill DeepCore

- Improve rejection of cosmic ray muon background

- Primary physics goal is resolving neutrino mass hierarchy

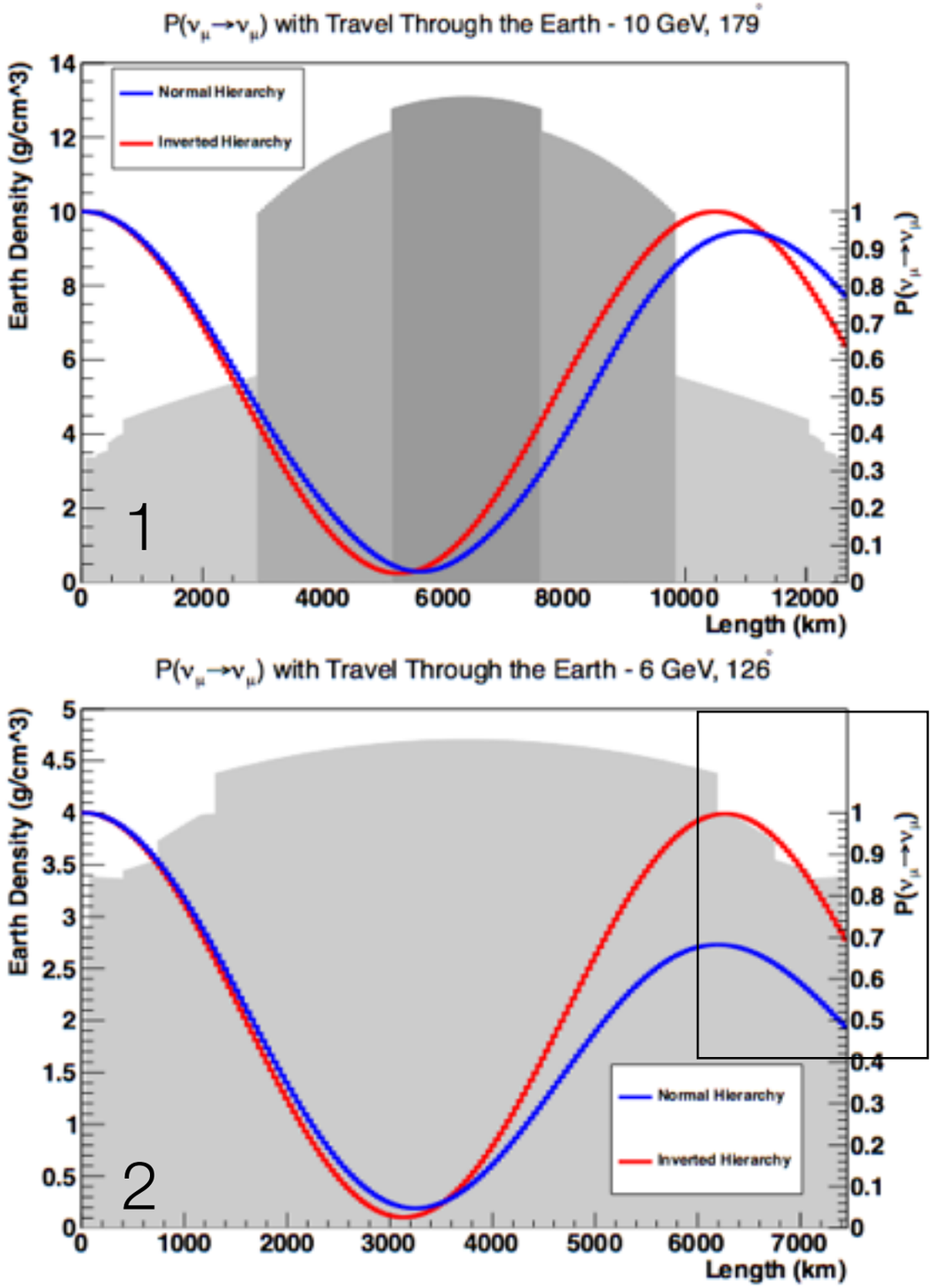


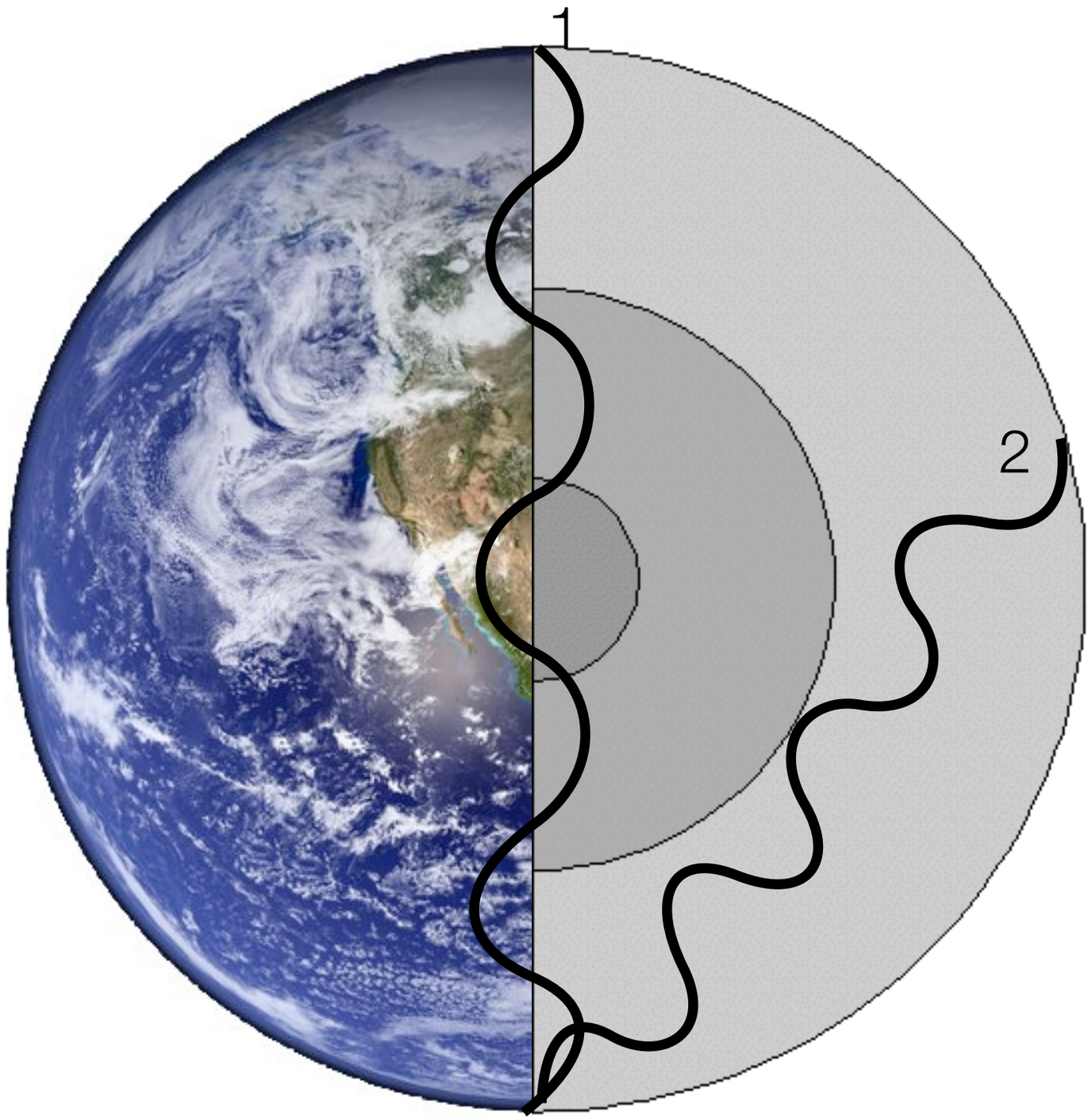
PINGU Simulation Event



- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- ~20 vs. ~50 Hit Modules

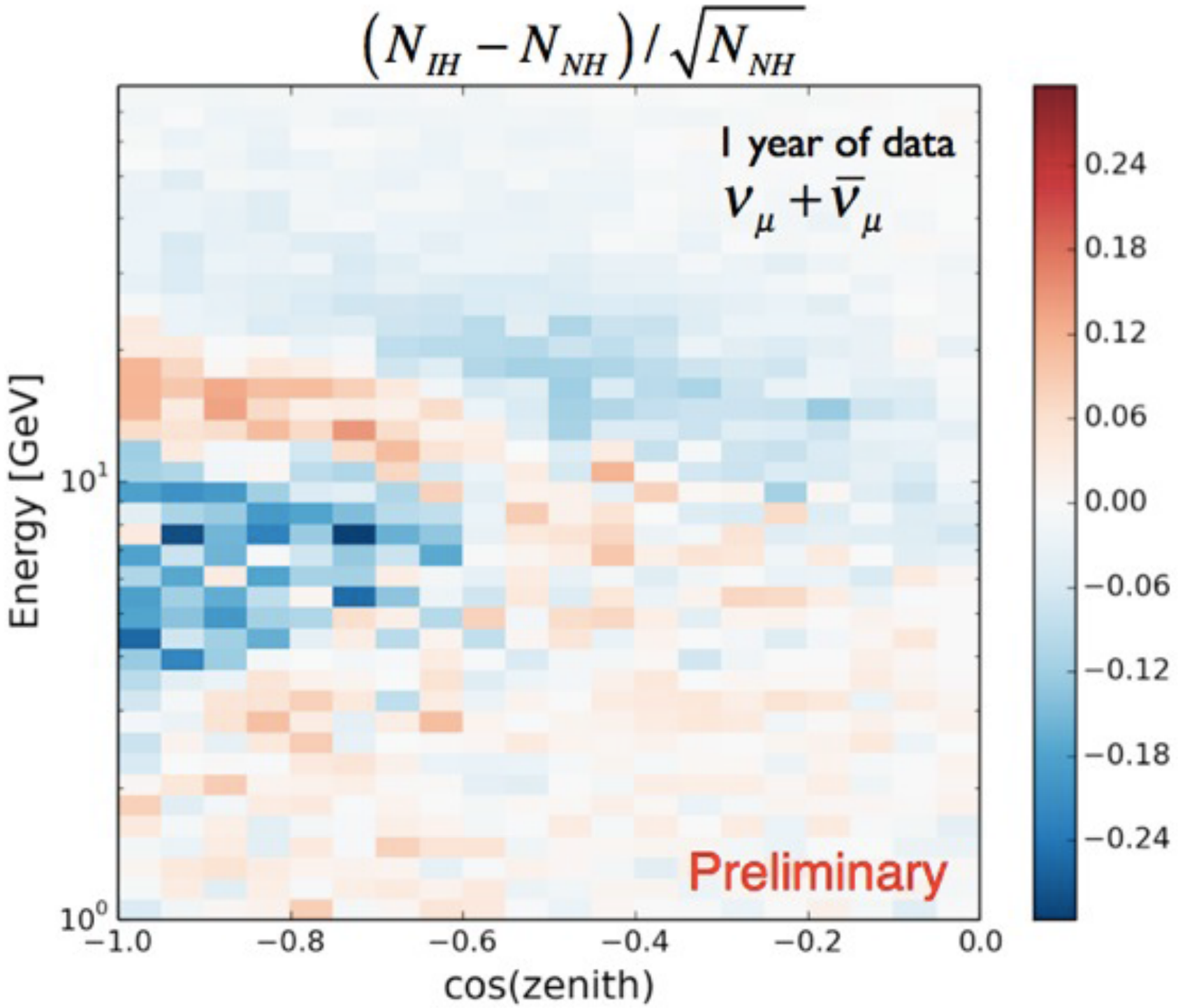
PINGU Neutrino Mass Hierarchy





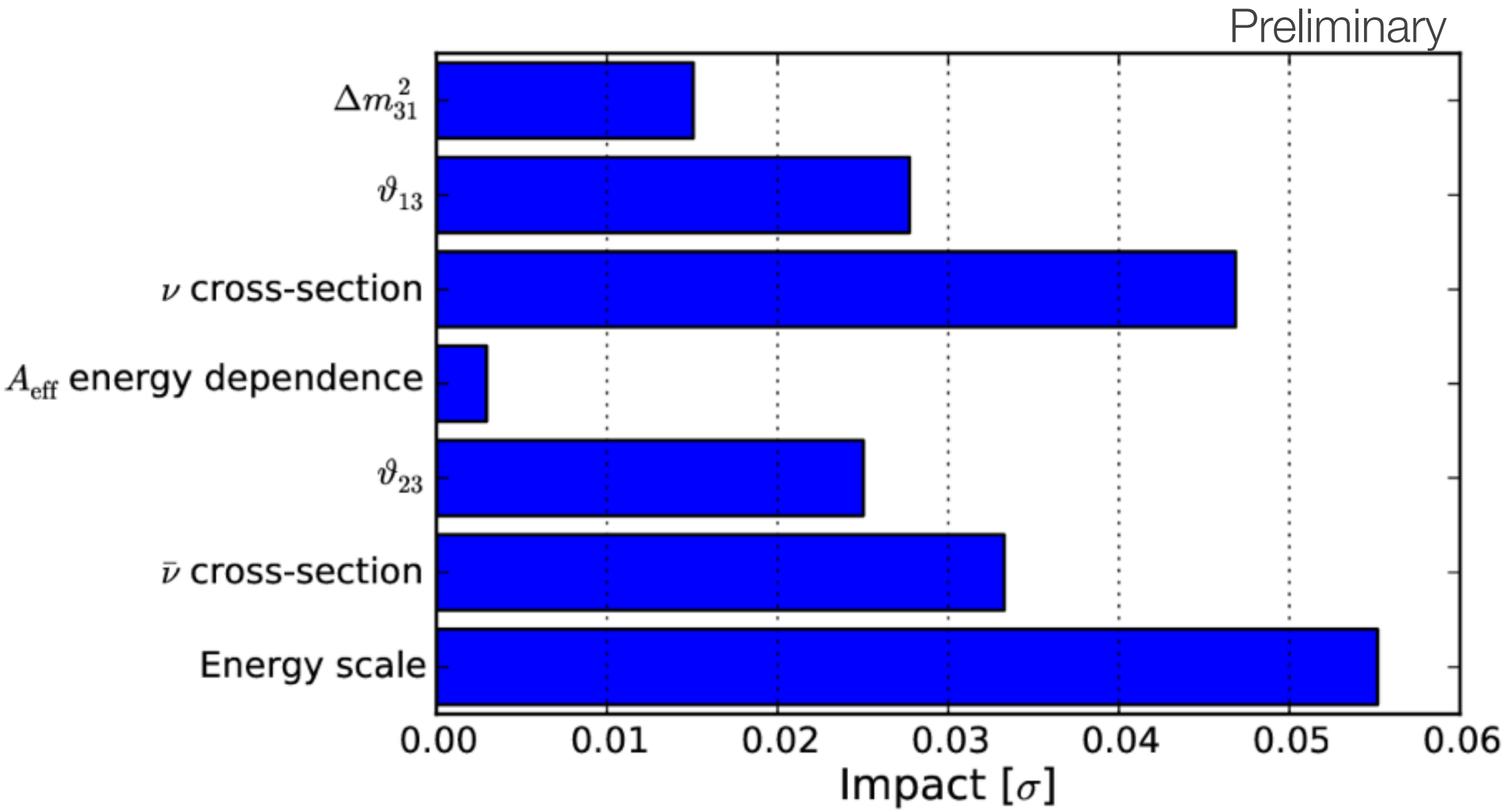
- Inverted/Normal hierarchy has up to a 20% difference in oscillation probability for specific energies and zenith angles (baselines)

Neutrino Mass Hierarchy by Eye

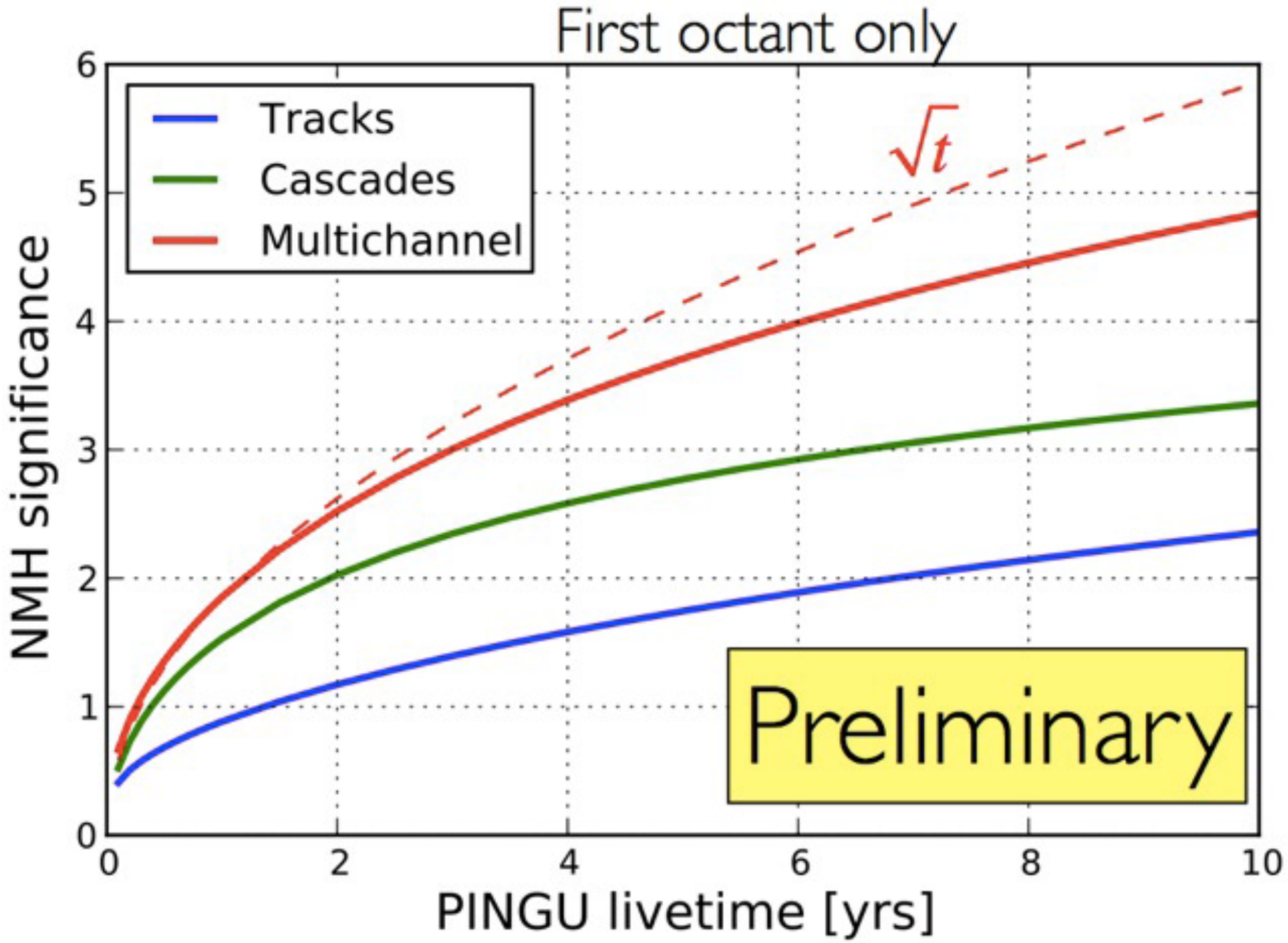


Systematics

- Several of the main systematics have been examined



Mass Hierarchy Bottom Line



Conclusions

- IceCube is opening a new window on neutrino astronomy with 5.7σ observation of astrophysical neutrinos and probing atmospheric charm meson production
- Potential with PINGU to quickly resolve the ordering of the neutrino mass hierarchy in addition to enhancing other physics (oscillation, O(1) GeV dark matter)

Backup

Science Portfolio

- Measurements
  - Cosmic Ray Anisotropy - arXiv:1105.2326
  - Diffuse Flux - arXiv:1104.5187
  - Atmospheric Neutrino Spectrum - arXiv:1010.3980
  - Neutrino Oscillation - arXiv:1305.3909
  - Atmospheric Electron Neutrino Flux - arXiv:1212.4760
- Searches
  - Supernova 2008D - arXiv:1101.3942
  - Neutrino Induced Cascades - arXiv:1101.1692
  - Neutrino Emission Constraints on 2010 Crab Flare - arXiv:1106.3484
  - Point Sources - arXiv:1307.6669
  - Gamma Ray Burst Neutrino Emission - arXiv:1204.4219

HESE-III Event Breakdown

all events

	Muons	π/K atm. ν	Prompt atm. ν	E^{-2} (best-fit)	Sum (central)	Data
Tot. Events	8.4 ± 4.2	$6.6^{+2.2}_{-1.6}$	< 9.0 (90% CL)	23.8	38.8	37 (36)
Up	0	4.0	< 5.8	8.2	12.2	9
Down	8.4	2.6	< 3.2	15.6	26.6	27
Track	~ 7.6	4.5	< 1.7	4.5	16.7	8
Shower	~ 0.8	2.1	< 7.3	19.3	22.2	28
Fraction Up	0%	61%	65%	34%	31%	25%
Fraction Down	100%	39%	35%	66%	69%	75%
Fraction Tracks	$> 90\%$	69%	19%	19%	43%	24%
Fraction Showers	$< 10\%$	31%	81%	81%	57%	76%

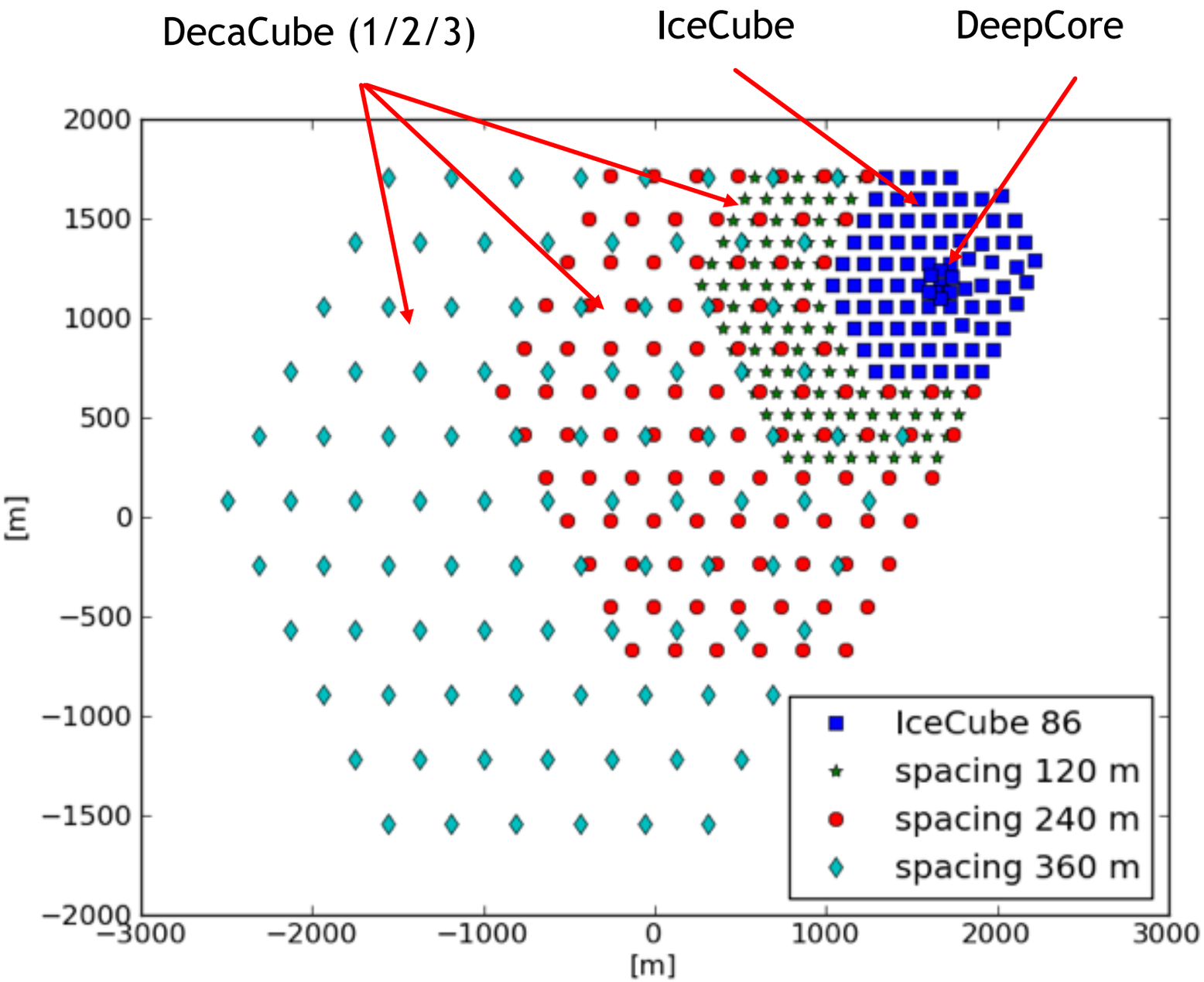
$E_{dep} < 60$ TeV

	Muons	π/K atm. ν	Prompt atm. ν	E^{-2} (best-fit)	Sum (central)	Data
Tot. Events	8.0	4.2	< 3.7	2.2	14.4	16
Up	0	2.5	< 2.3	1.2	3.7	4
Down	8.0	1.7	< 1.4	1.1	10.7	12
Track	~ 7.2	2.9	< 0.7	0.4	10.5	4
Shower	~ 0.8	1.4	< 3.0	1.8	4.0	12
Fraction Up	0%	60%	63%	51%	26%	25%
Fraction Down	100%	40%	37%	49%	74%	75%
Fraction Tracks	$> 90\%$	68%	19%	19%	72%	25%
Fraction Showers	$< 10\%$	32%	81%	81%	28%	75%

60 TeV $< E_{dep} <$ 3 PeV

	Muons	π/K atm. ν	Prompt atm. ν	E^{-2} (best-fit)	Sum (central)	Data
Tot. Events	0.4	2.4	< 5.3	18.2	21.0	20
Up	0	1.4	< 3.5	6.5	8.0	5
Down	0.4	0.9	< 1.8	11.7	13.0	15
Track	~ 0.4	1.7	< 1.0	3.8	5.9	4
Shower	~ 0.0	0.7	< 4.2	14.4	15.2	16
Fraction Up	0%	61%	67%	36%	38%	25%
Fraction Down	100%	39%	33%	64%	62%	75%
Fraction Tracks	$> 90\%$	71%	20%	21%	28%	20%
Fraction Showers	$< 10\%$	29%	80%	79%	72%	80%

Potential High Energy Extension (HEX)



Spacing 1 (120m): IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

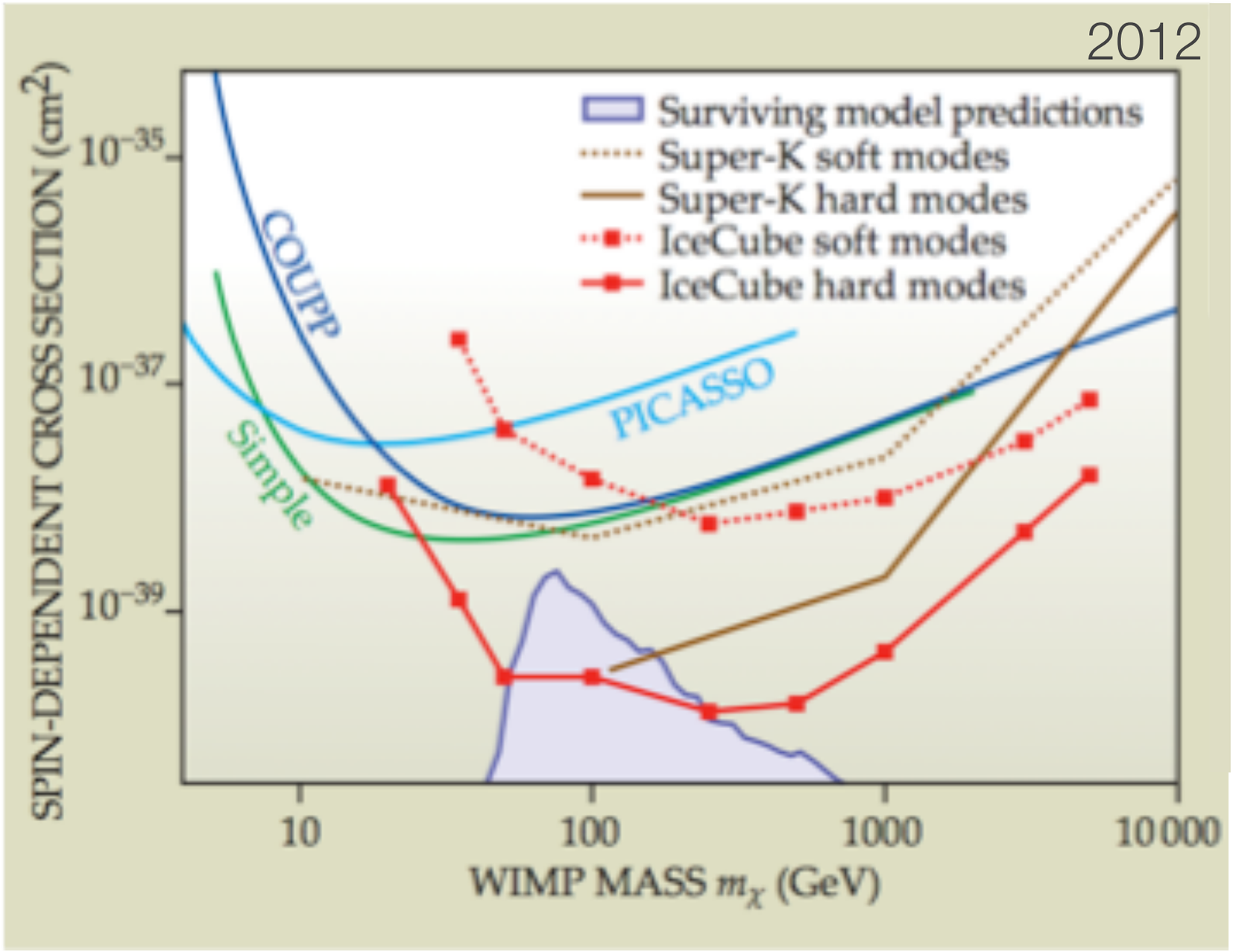
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

Chosen geometry not optimum (i.e. for HESE)
… historically chosen to demonstrate that we do respect boundary conditions

*courtesy of C. Wiebusch (RTWH Aachen)

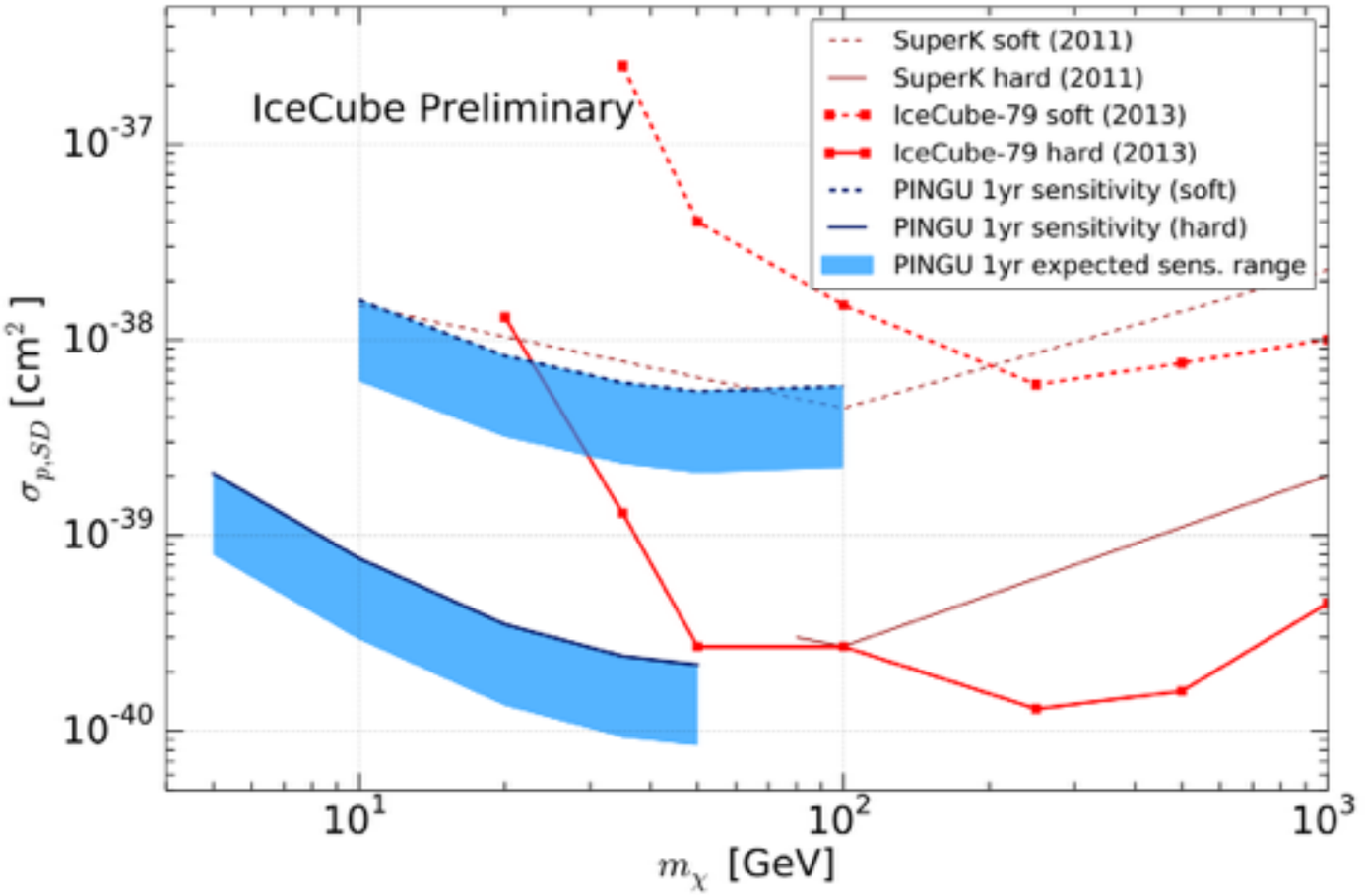
Solar WIMP Limits



- IceCube has competitive sensitivities for spin-dependent interactions

Dark Matter in PINGU

- Probes lower mass region



- Independent test of Spin-Independent results from direct detection experiments