CCAPP

THE OHIO STATE UNIVERSITY

Review of IceCube and PINGU

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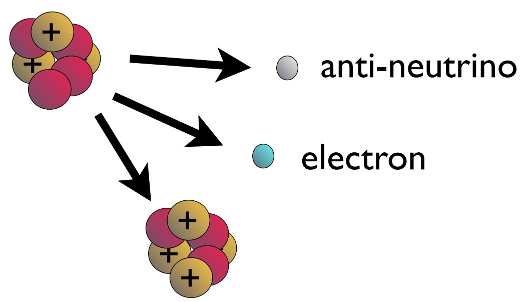
Outline

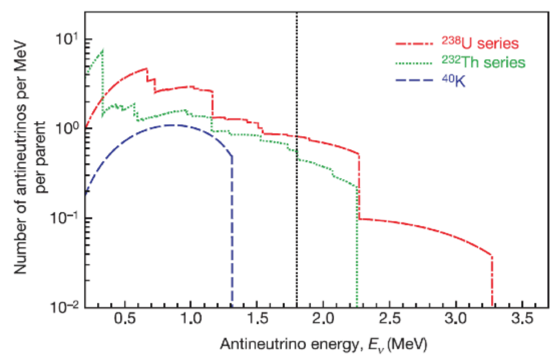
- Motivation
- Neutrino Telescopes and IceCube
- Overview of IceCube's Science Program
- Selected Results
- PINGU
- Conclusions

Sources of Neutrinos

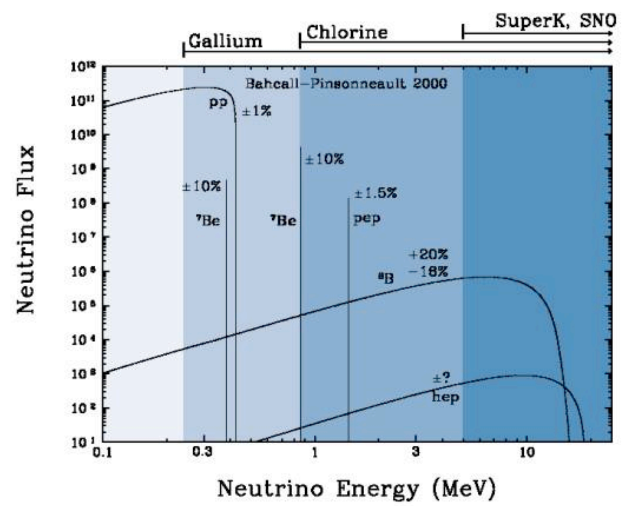
Earth
Nuclear Decay



Araki et al., 2005

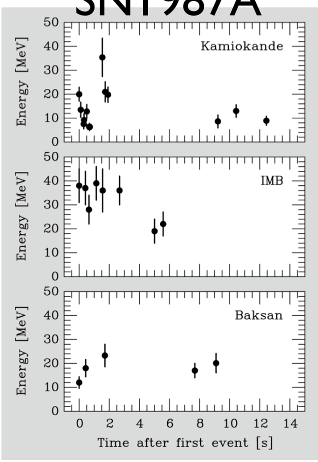


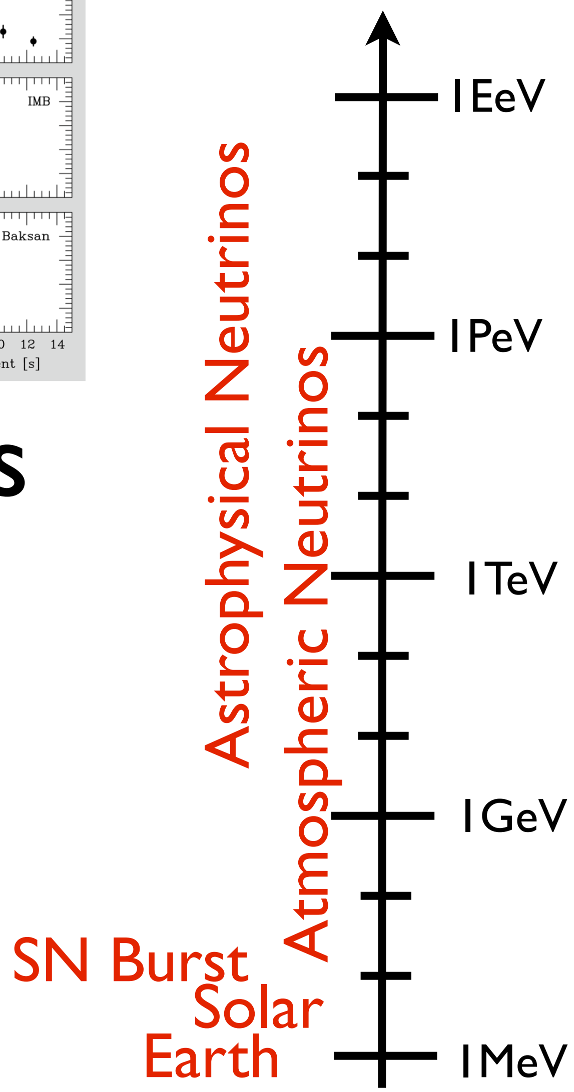
Sun
Nuclear Fusion



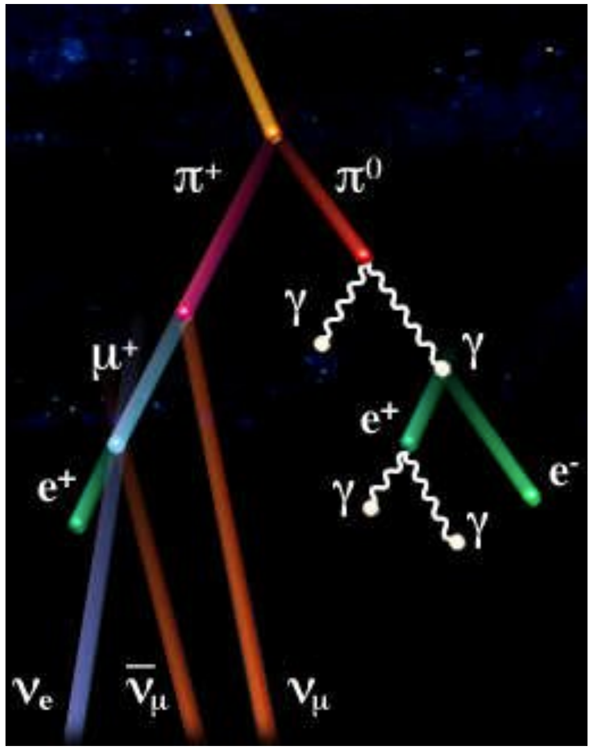
Supernova Burst

SN1987A

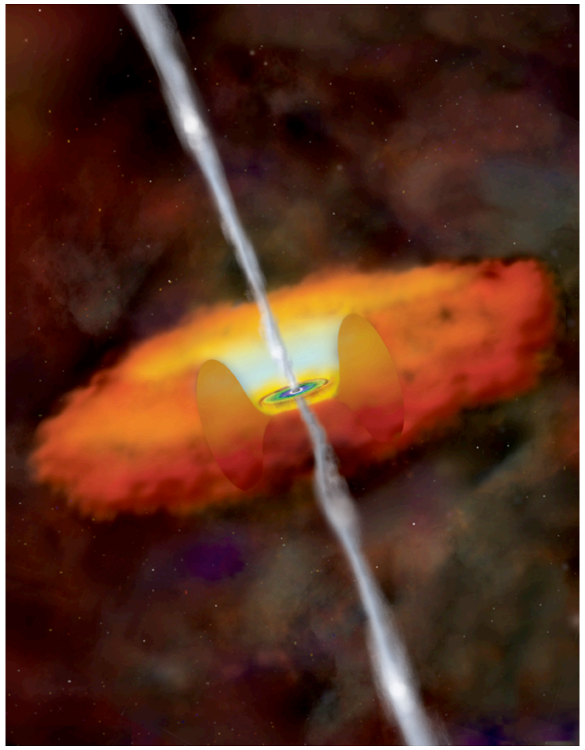




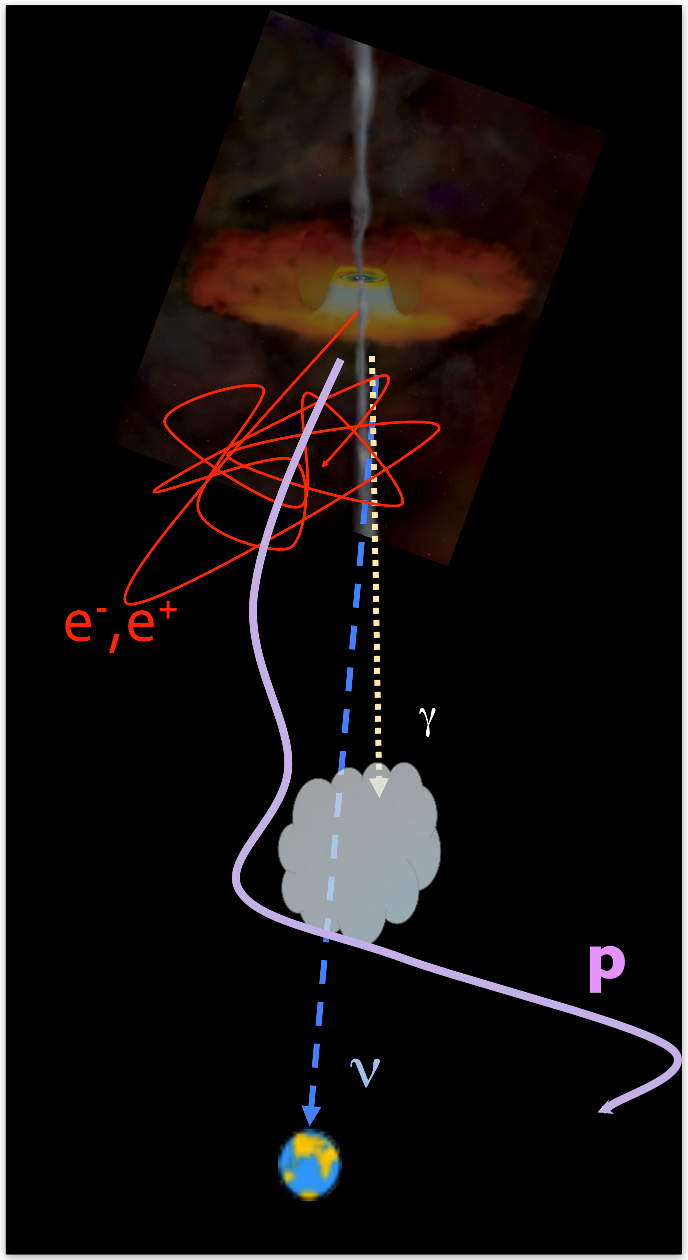
Earth Atmosphere
Particle Decay



Astrophysical Sources
Particle Decay

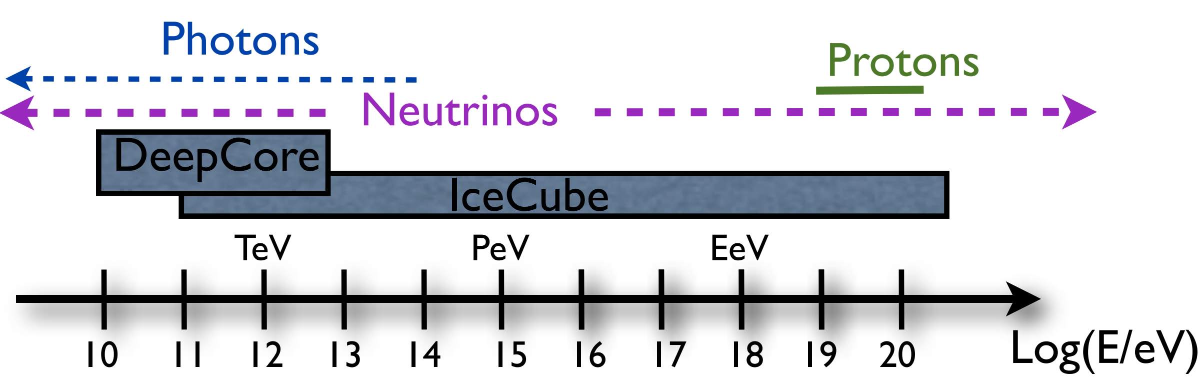


What makes Neutrinos so exciting as Messengers ?



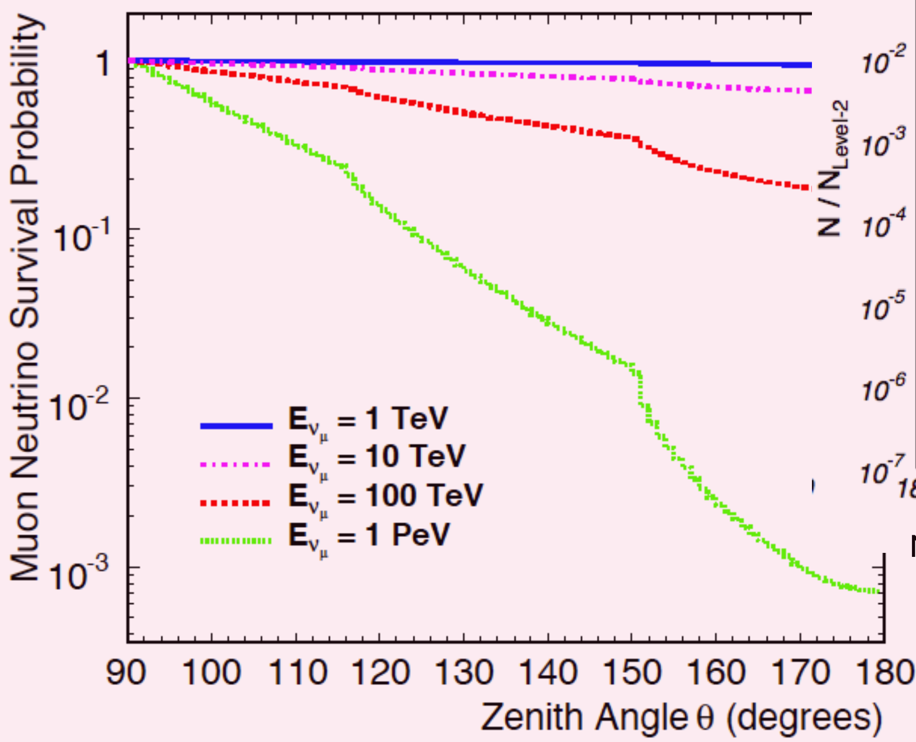
- New window to the cosmos
- What are the most energetic phenomena in the Universe and where do they take place ?
- Identify the sources of cosmic rays ?

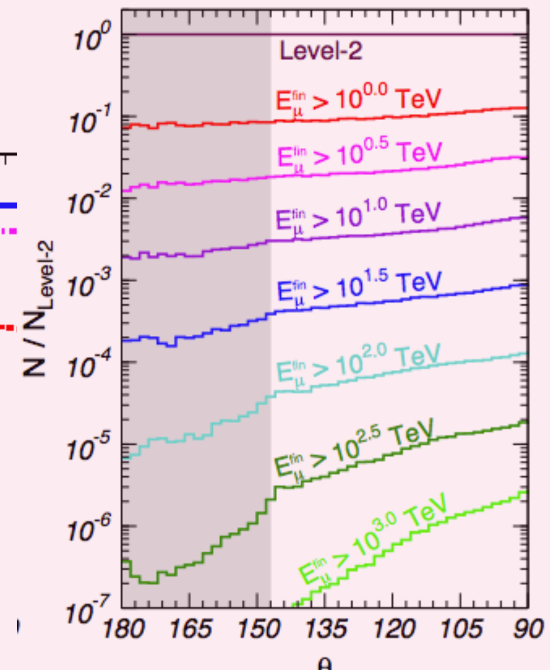
  - Why neutrinos ?
    - Unobscured view
    - Point back to their sources
    - Cover entire energy spectrum



Neutrino Facts

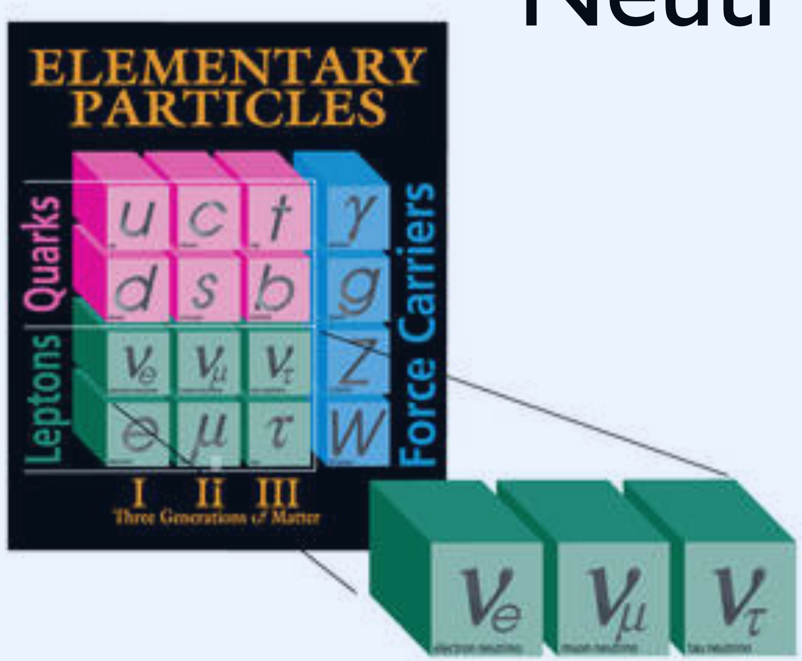
Neutrino absorption

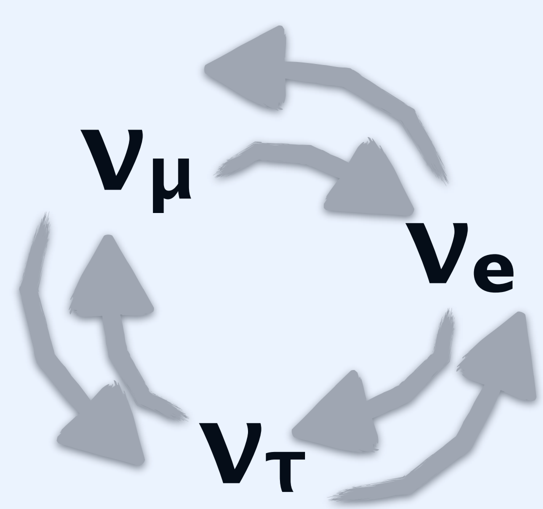


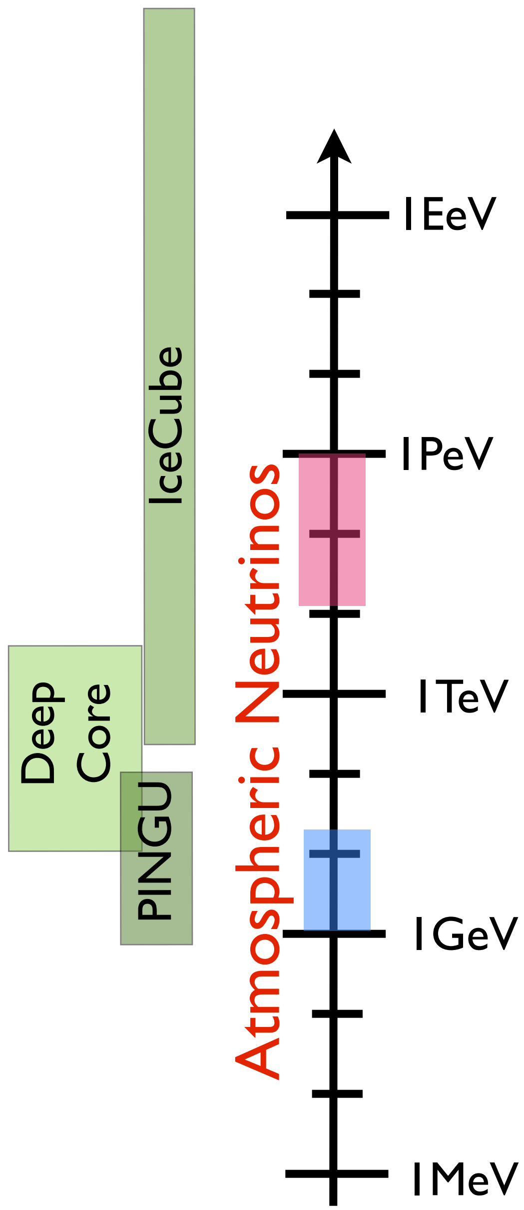


M.C. Gonzalez-Garcia, F. Halzen, M. Maltoni, H. Tanaka

Neutrino oscillations

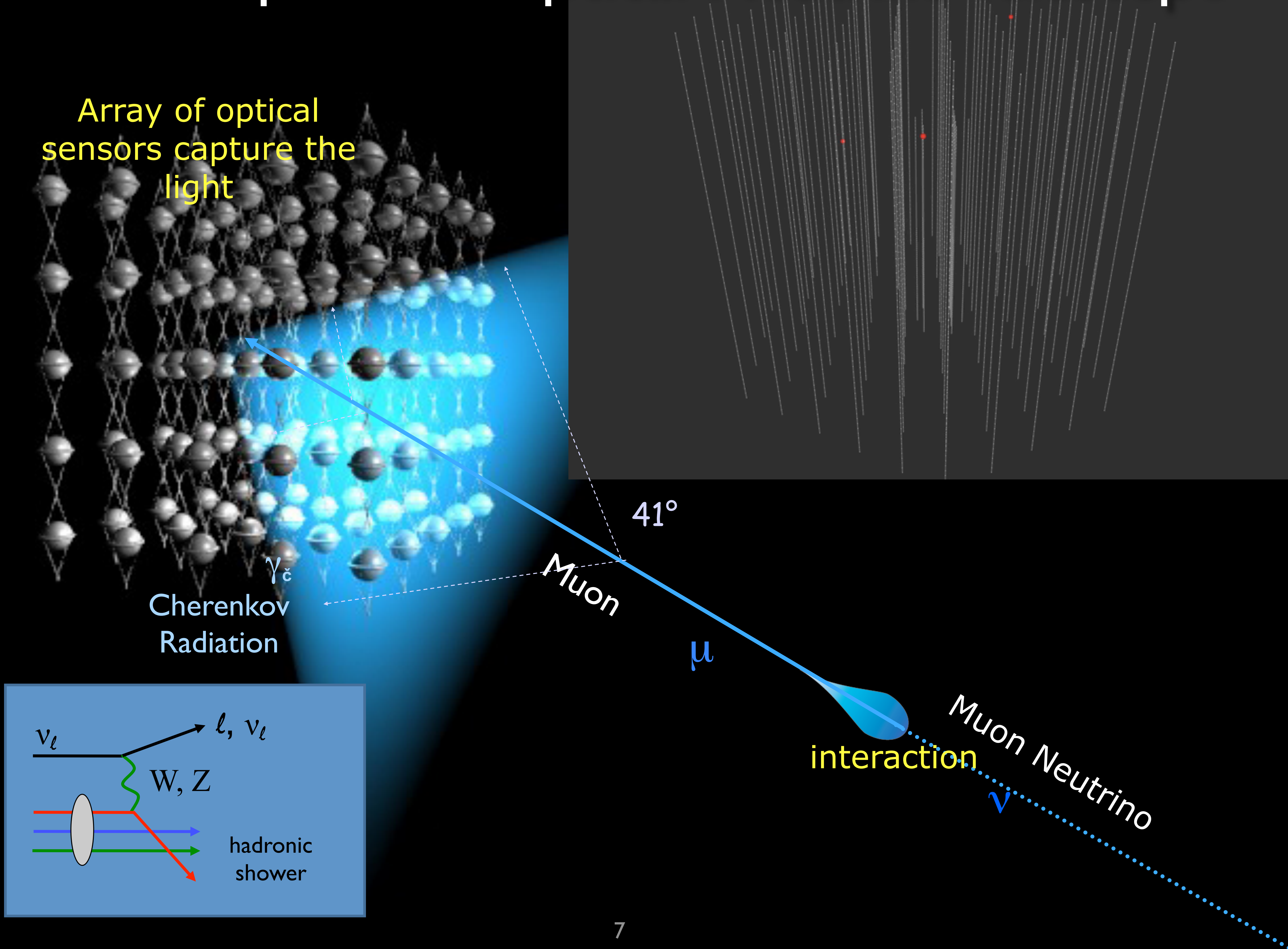




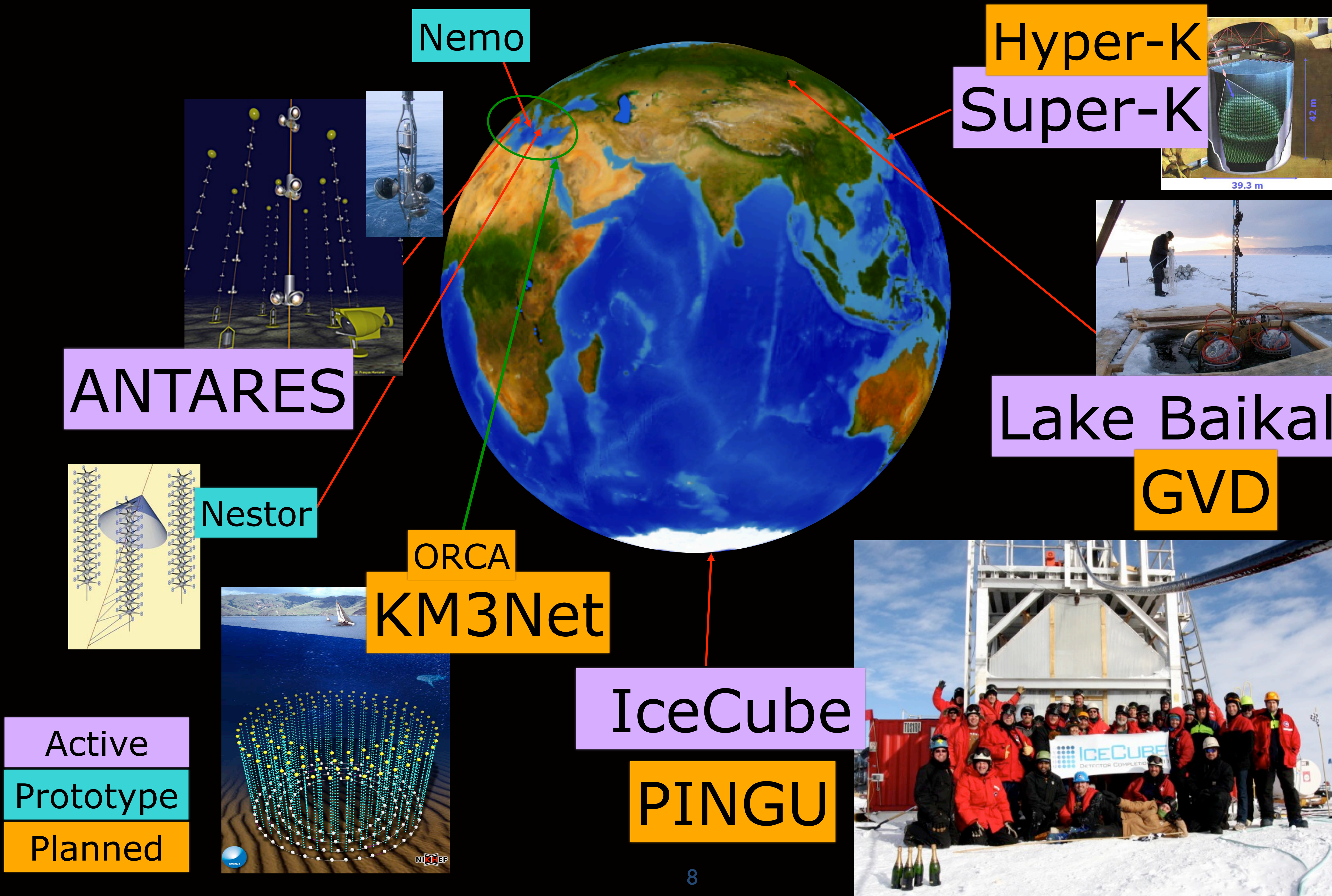


A new way to study the universe ... high-energy neutrinos

Principle of an optical Neutrino Telescope



Optical Neutrino Telescopes / Detectors

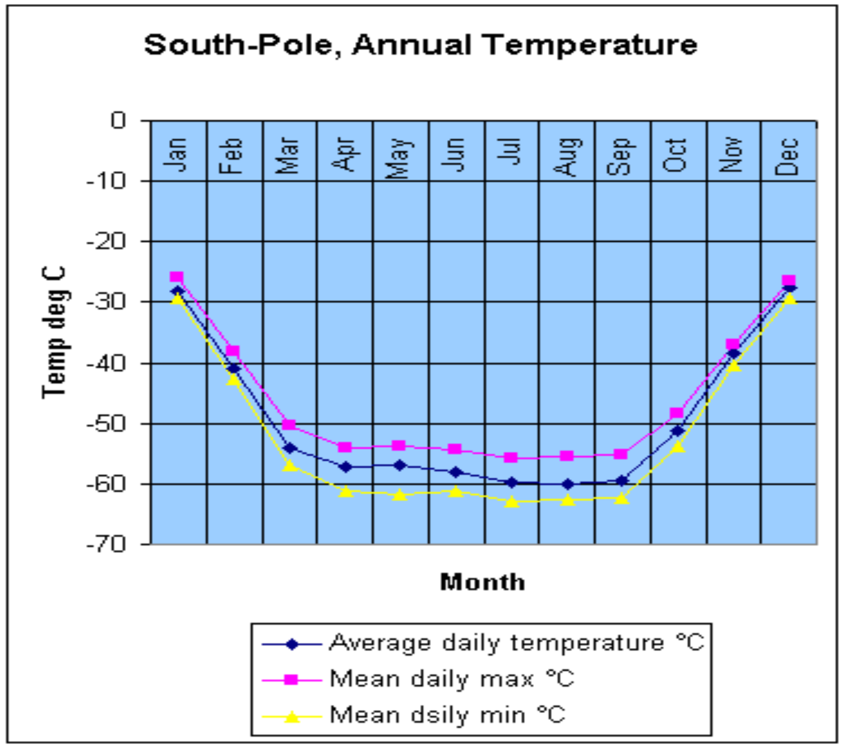


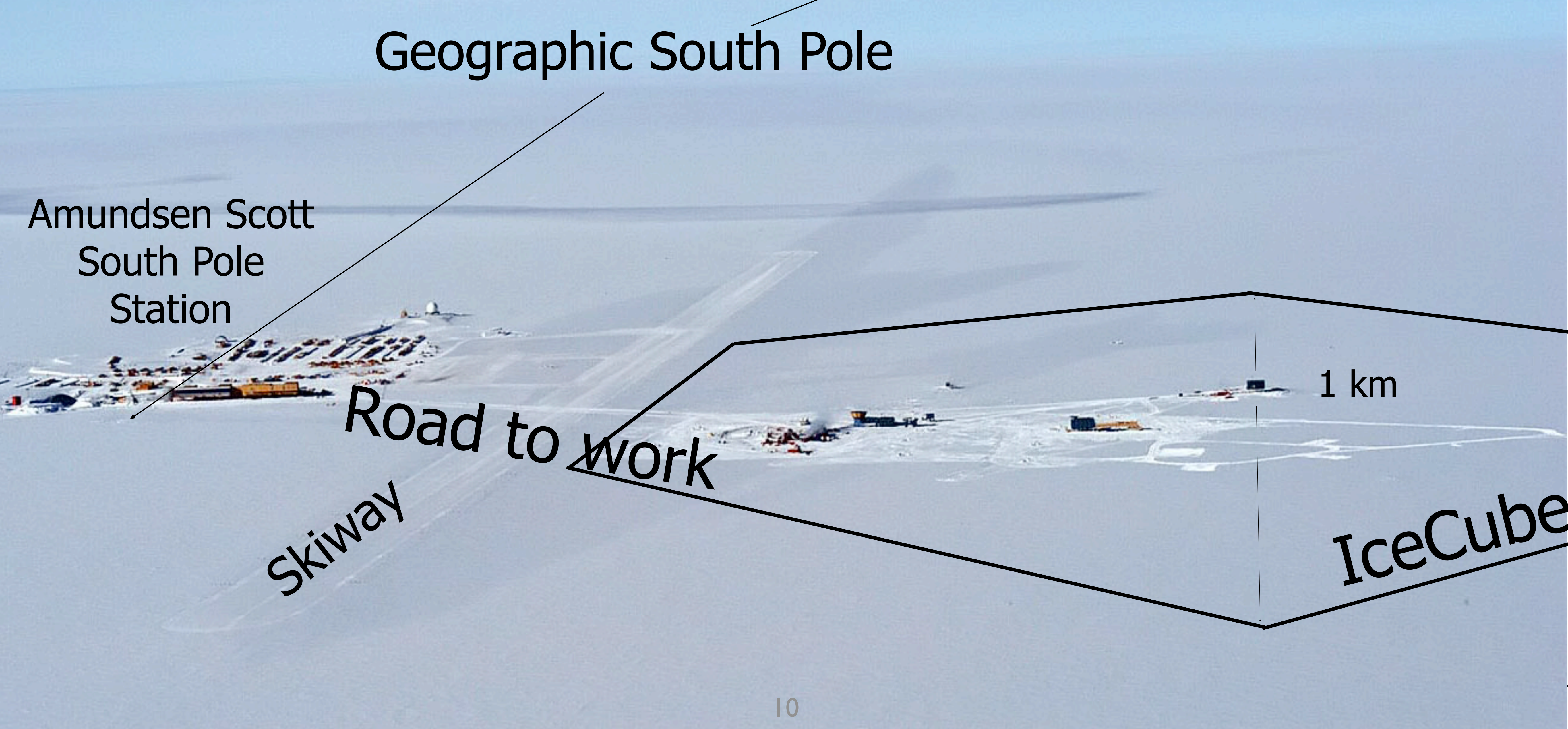
The IceCube Collaboration & PINGU

International 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)
Inoue Foundation for Science, Japan
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)

Laboratory at the South Pole

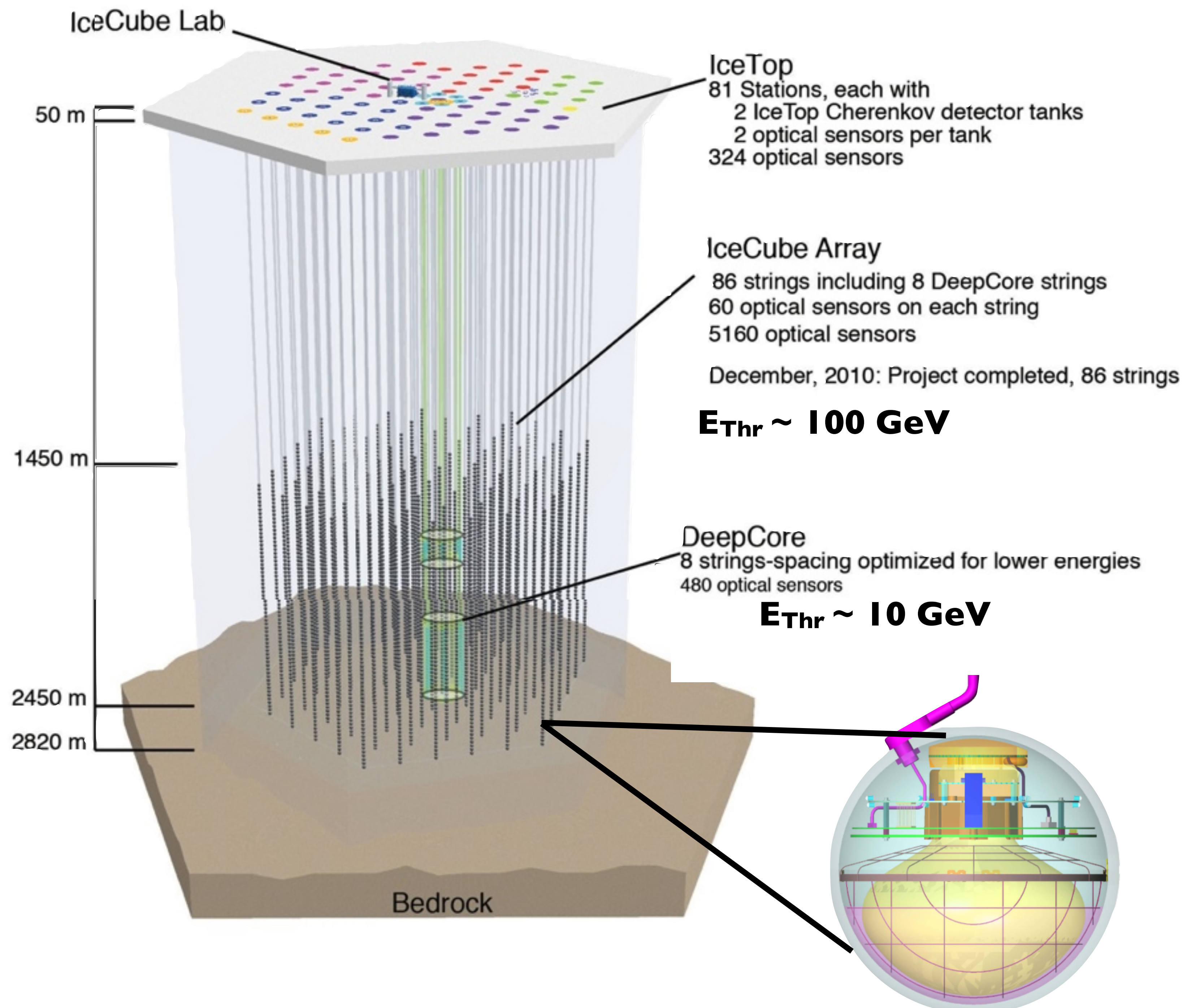




The IceCube Neutrino Telescope

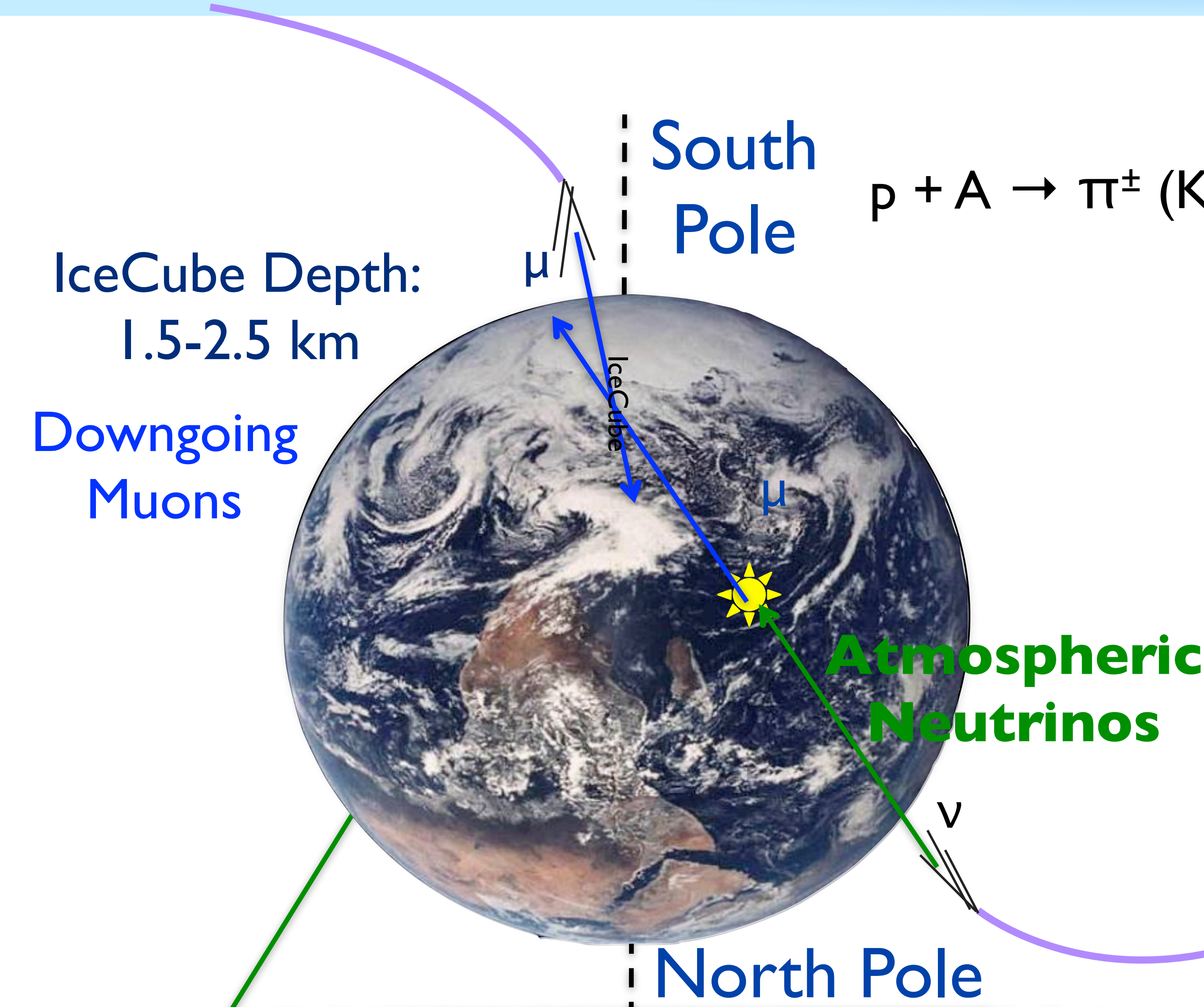
ICECUBE

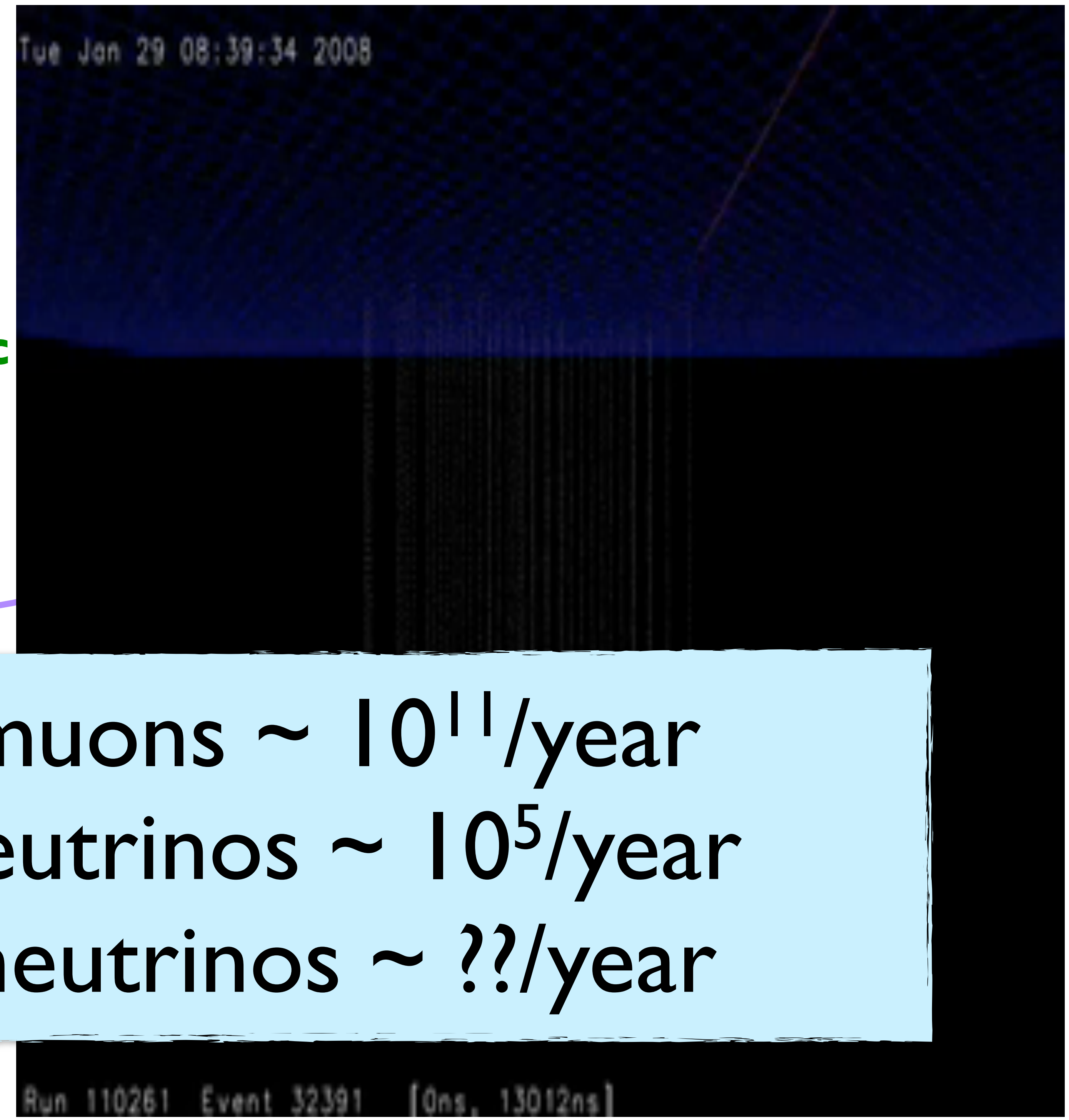
- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analyzed
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice



Signals in IceCube

$p + A \rightarrow \pi^{\pm}\ (K^{\pm}) + \text{other hadrons}\ \ldots\ \pi^{+} \rightarrow \mu^{+}\nu_{\mu} \rightarrow e^{+}\nu_{e}\nu_{\mu}\nu_{\mu}$





Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^{5}/year

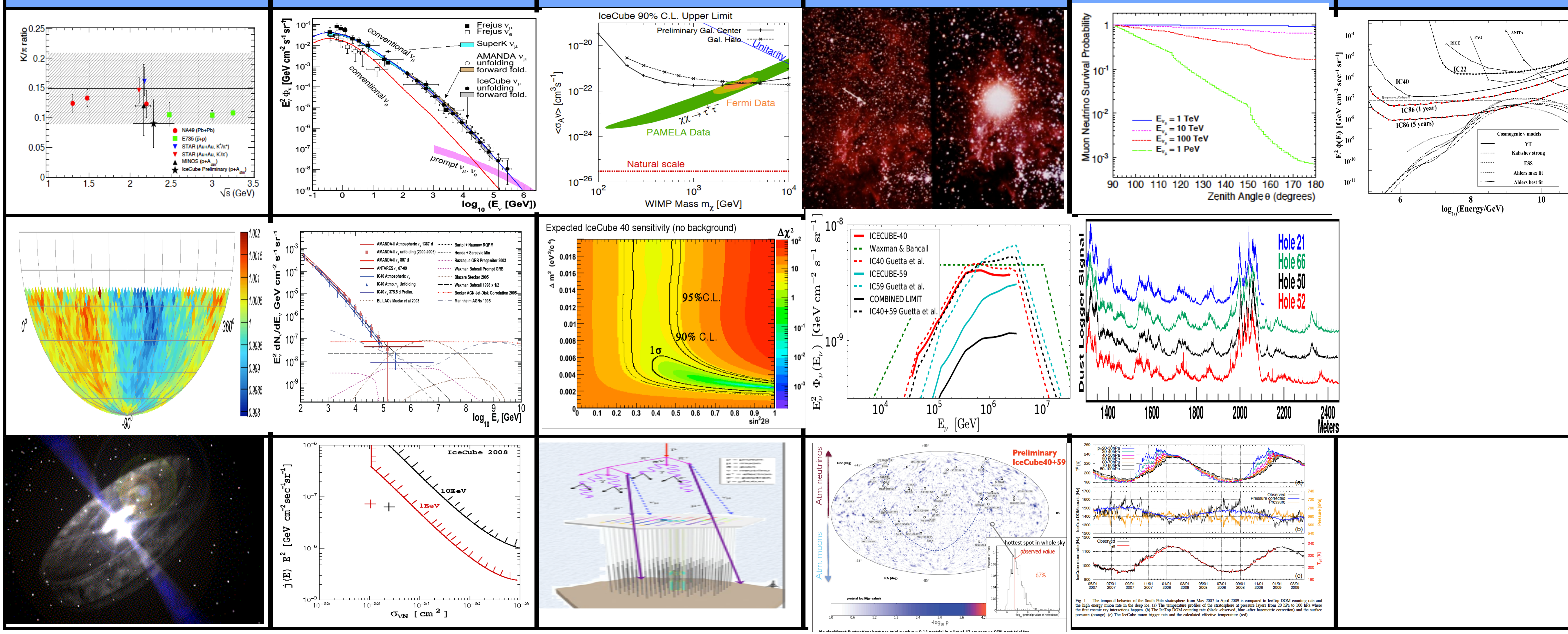
Astrophysical neutrinos ~ ??/year

irreducible neutrino background to extra terrestrial neutrino fluxes

IceCube Science

IceCube Science

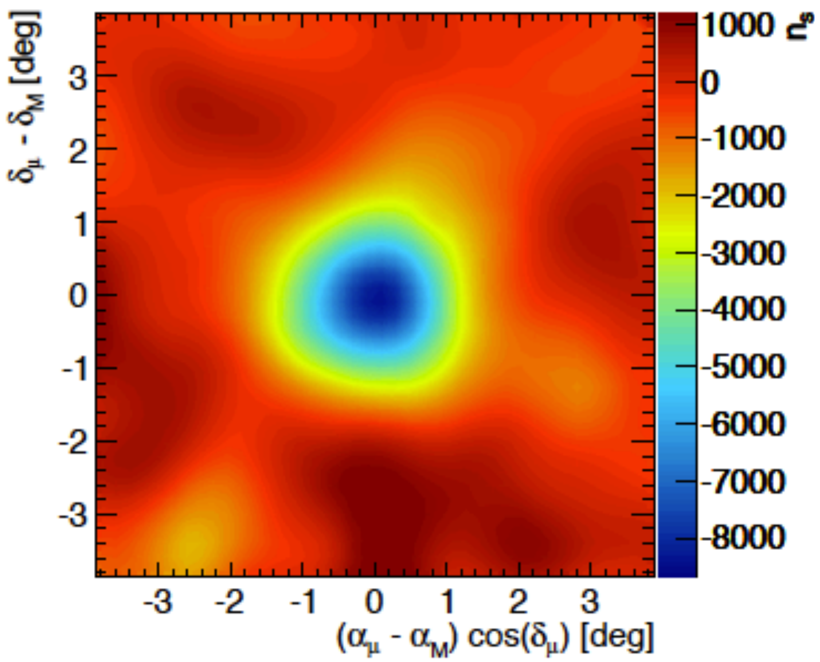
Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology

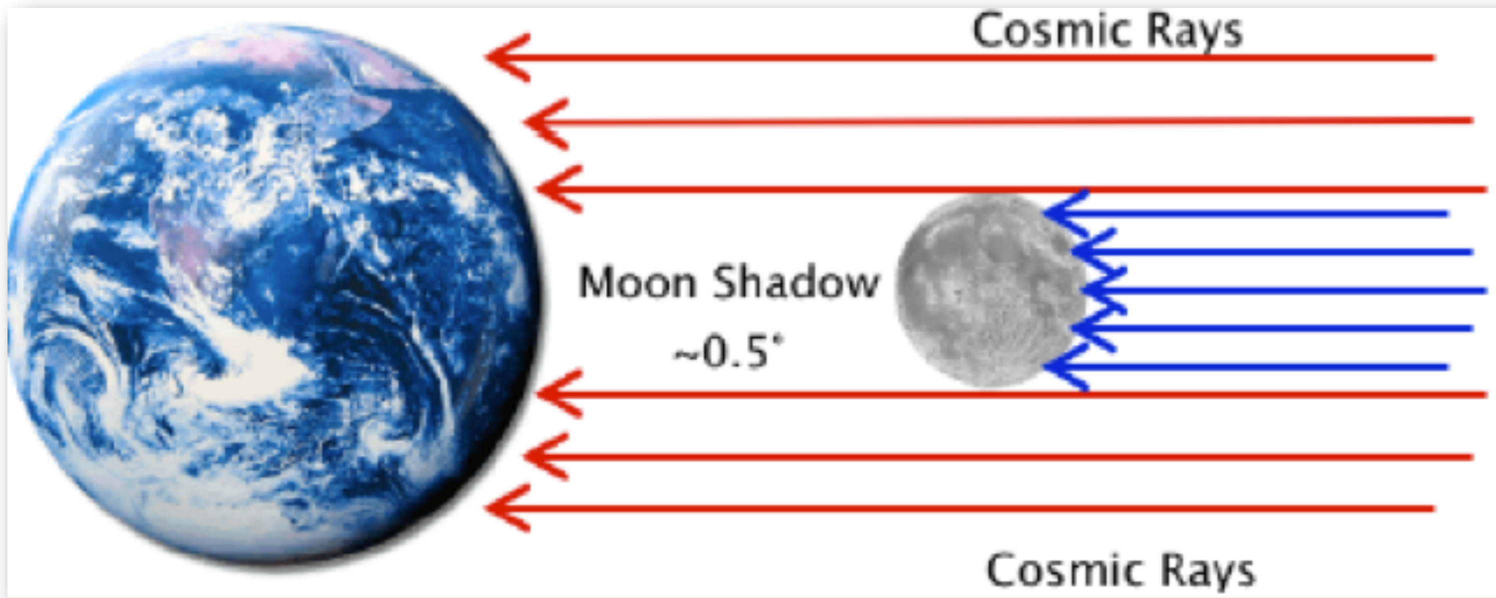


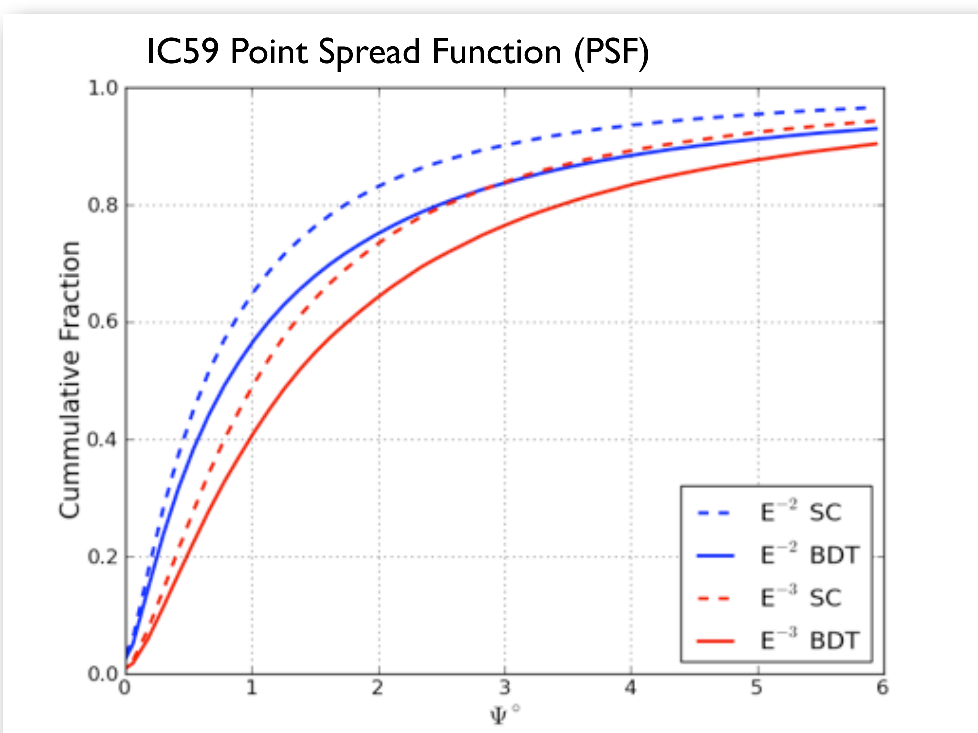
Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

IceCube Performance

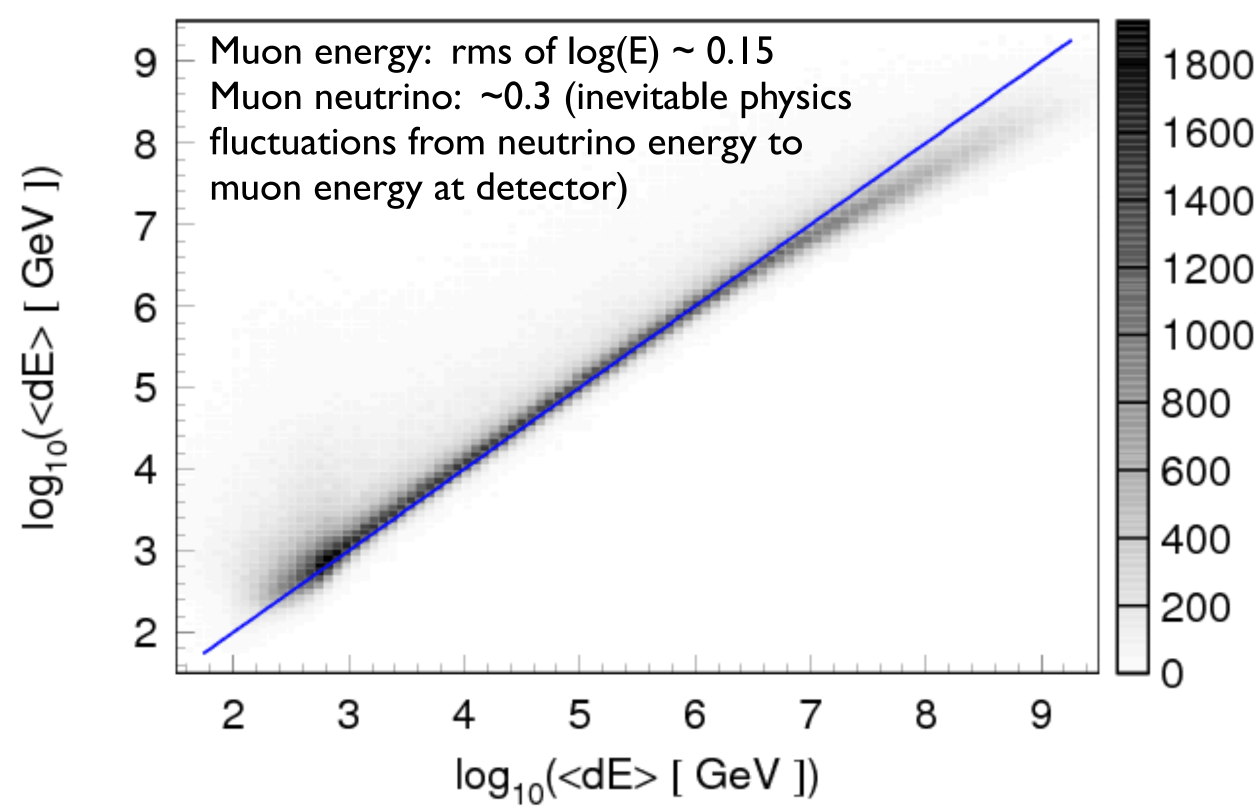
IceCube Collaboration arXiv:1305.6811





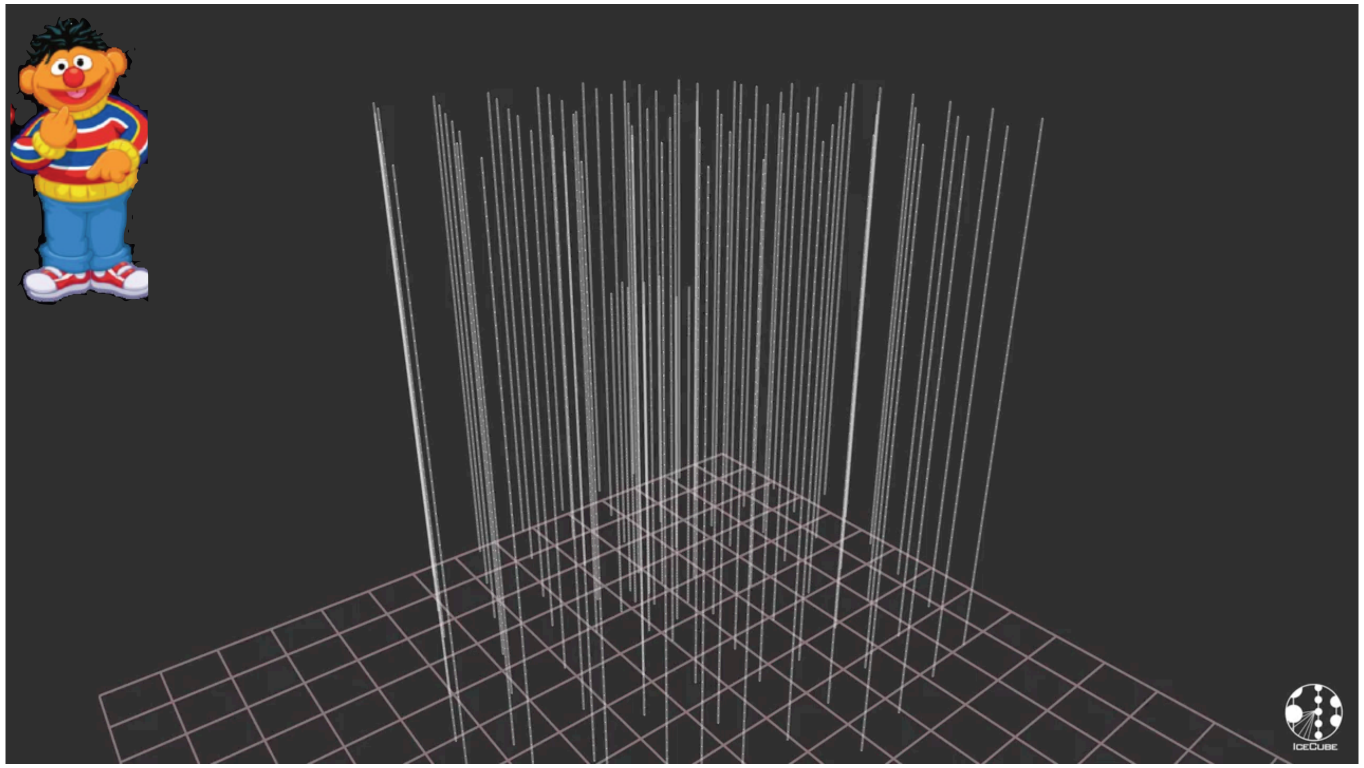


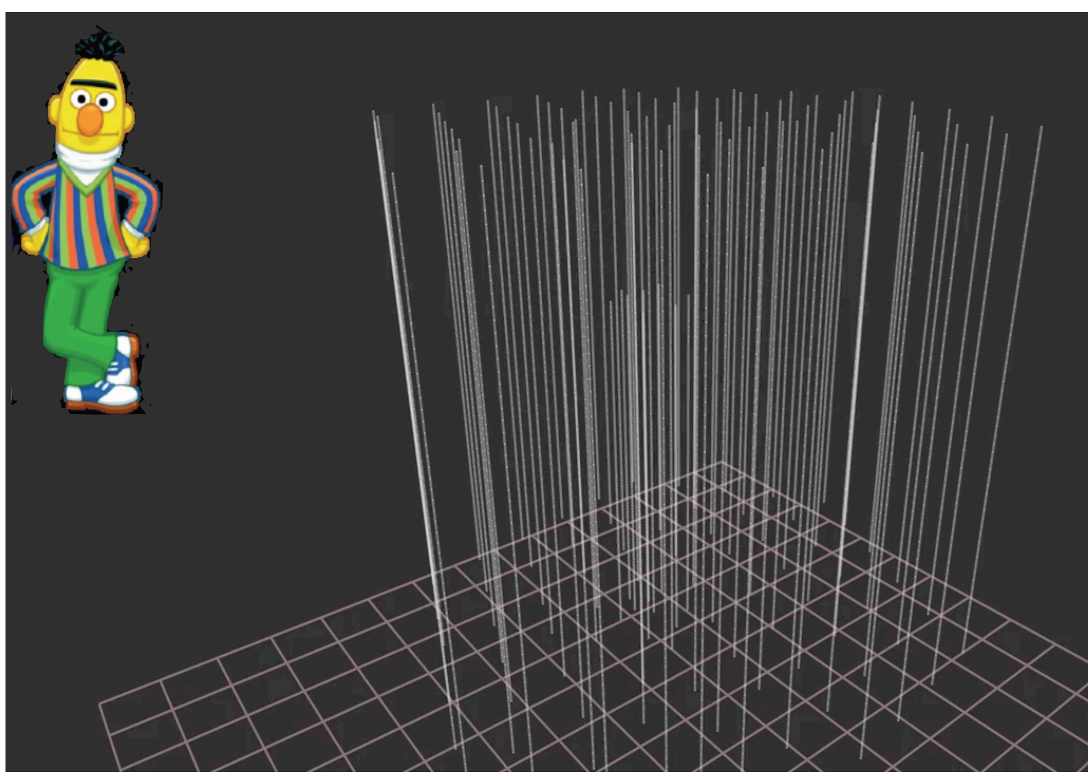
Angular resolution (median of PSF) vs. neutrino energy



Selected Results

Highest Energy Neutrino Search

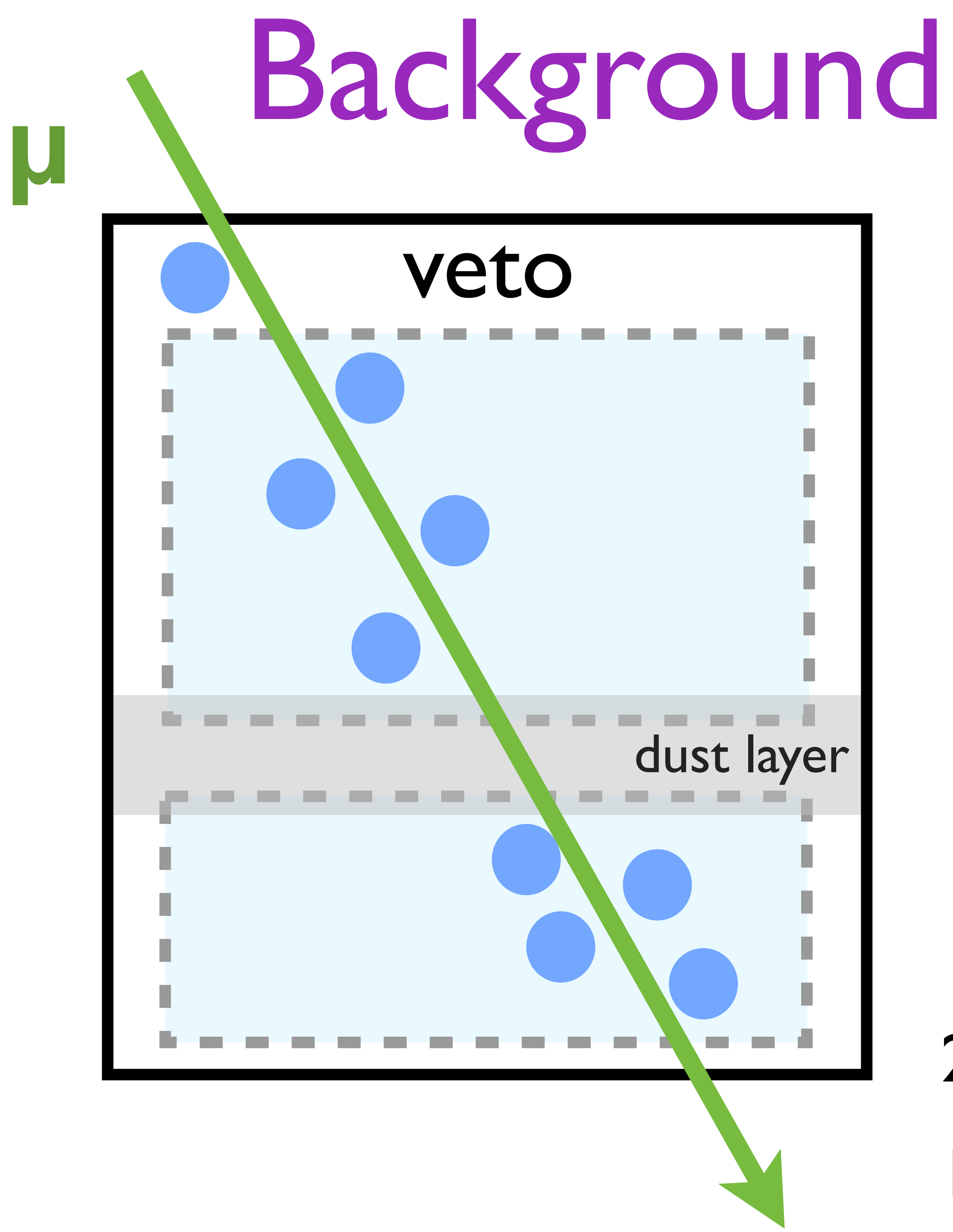


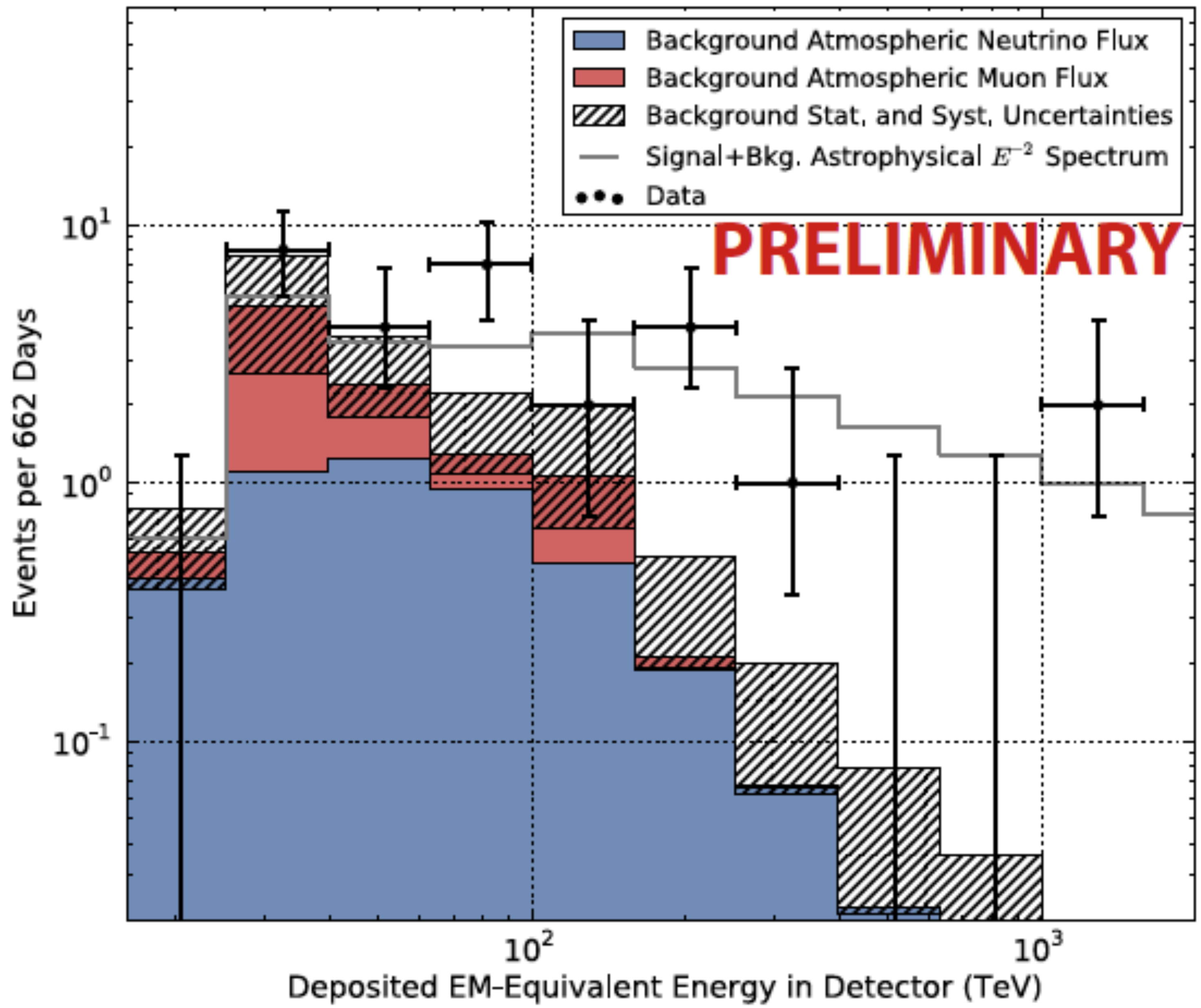


- Two events observed in the highest energy neutrino search
  - First reported at Neutrino 2012 in Kyoto
  - Difficult to explain with convenital backgrounds
- 1 PeV = $1.6 \cdot 10^{-4}$J
- Ernie ~1.15 PeV
- Bert ~ 1.05 PeV
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

see arXiv 1304.5356
Phys. Rev. Lett. 111, 021103 (2013)

High-energy neutrino search



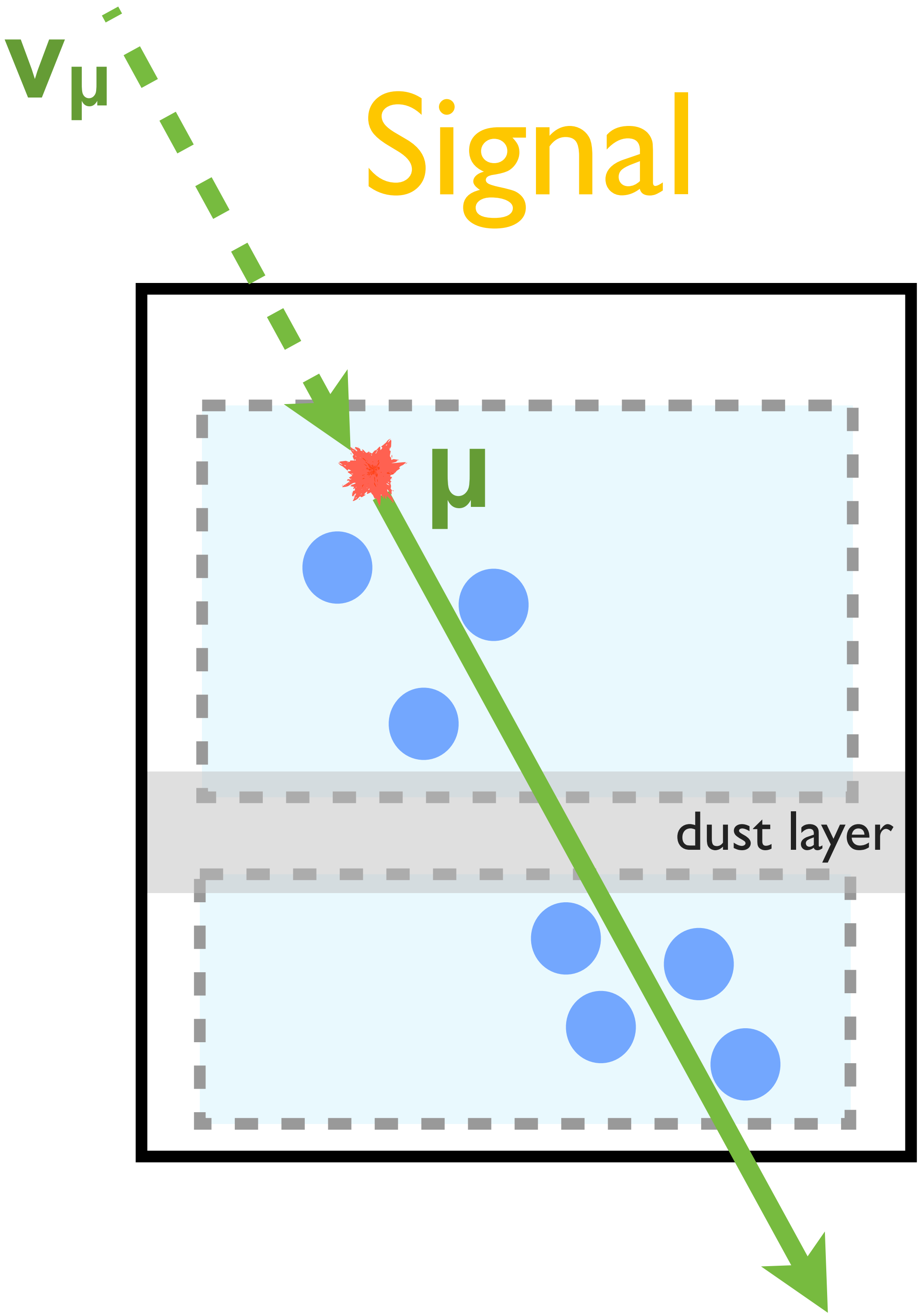


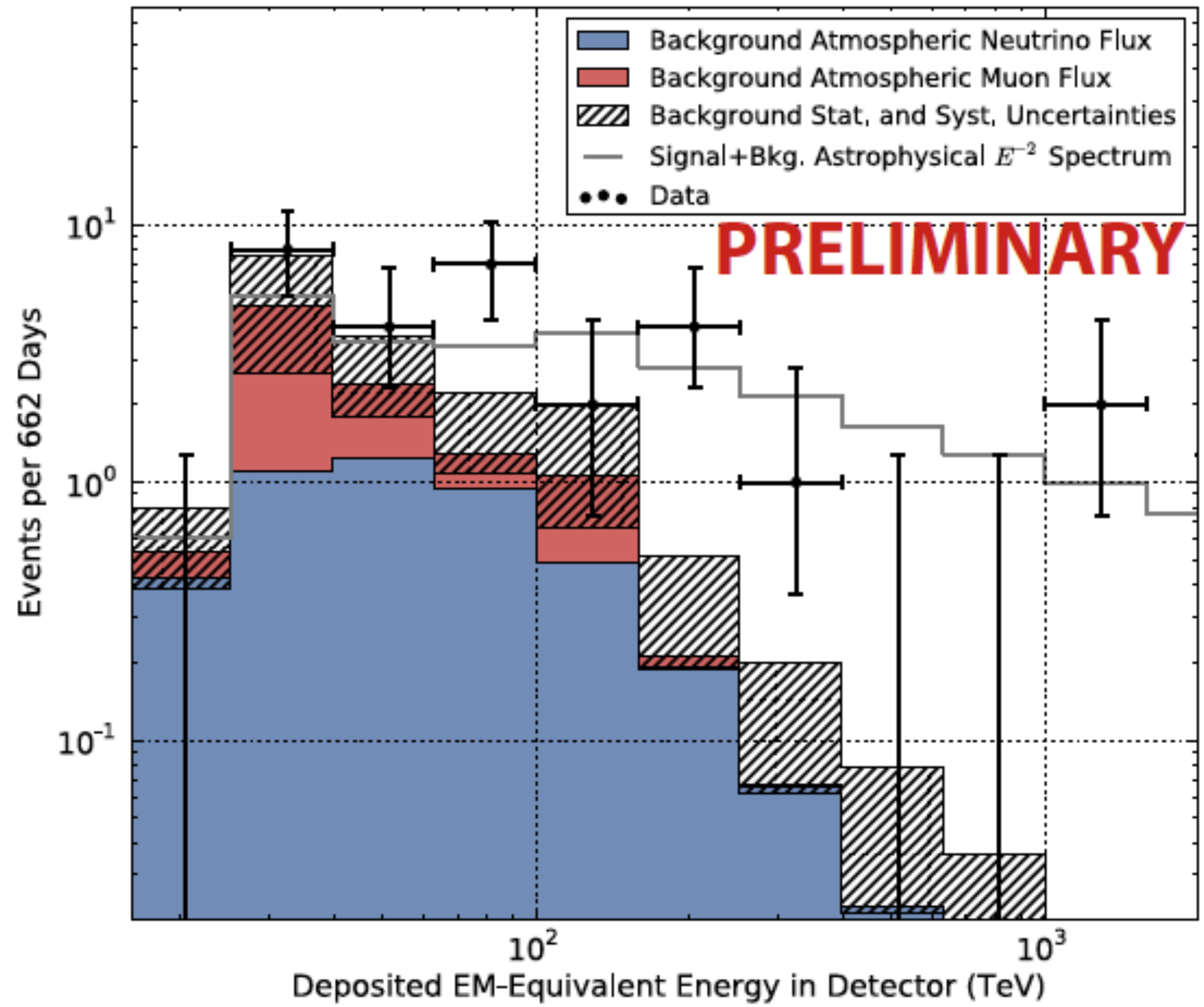
28 events (7 track-like, 21 showers) observed

Expectation:

$$10.6^{+2.9}_{-1.9} \text{ (12.1} \pm 3.4 \text{ with reference charm model)}$$

High-energy neutrino search





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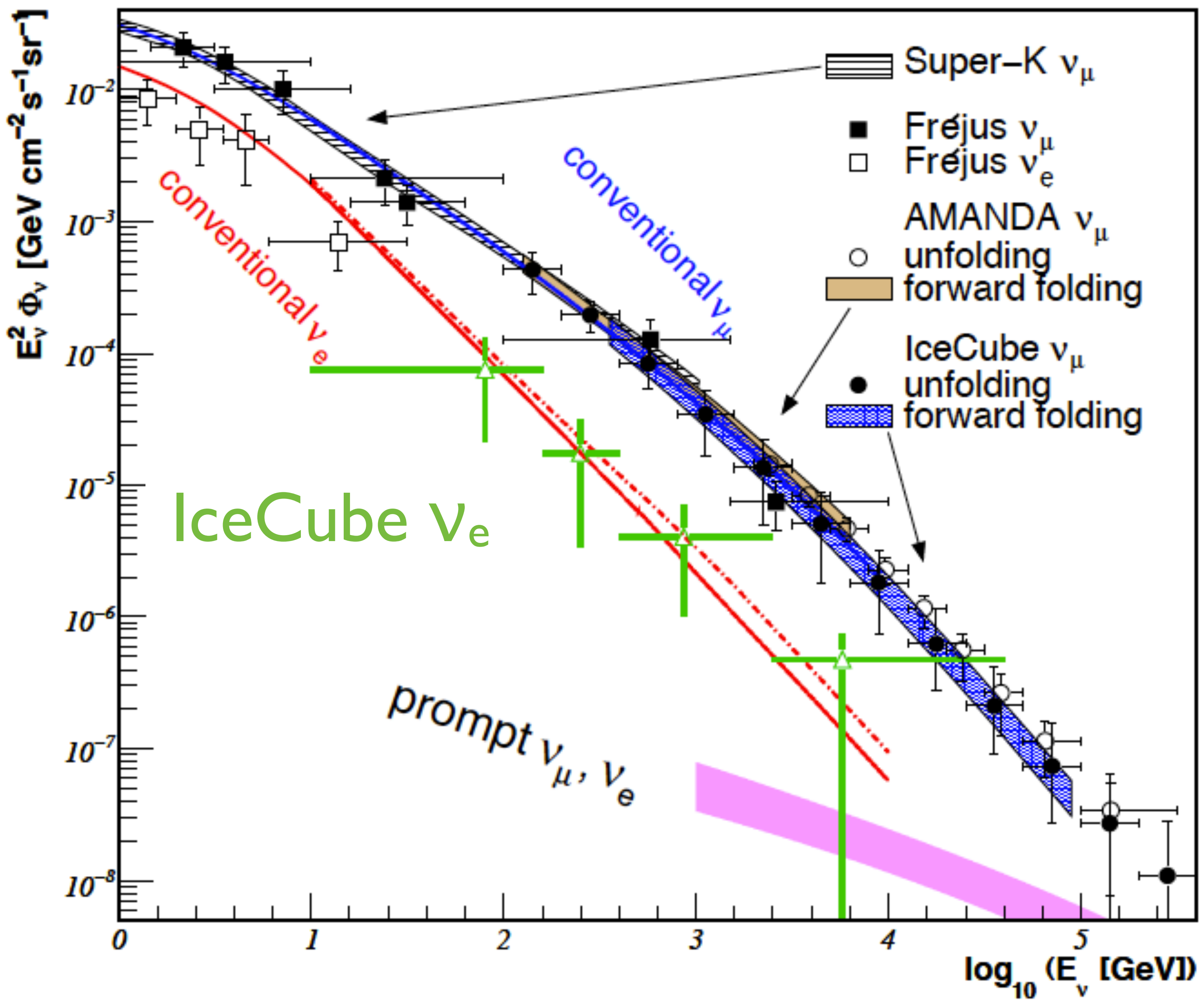
$10.6^{+2.9}_{-1.9}$ (12.1 $\pm$ 3.4 with reference charm model)

Atmospheric Neutrinos

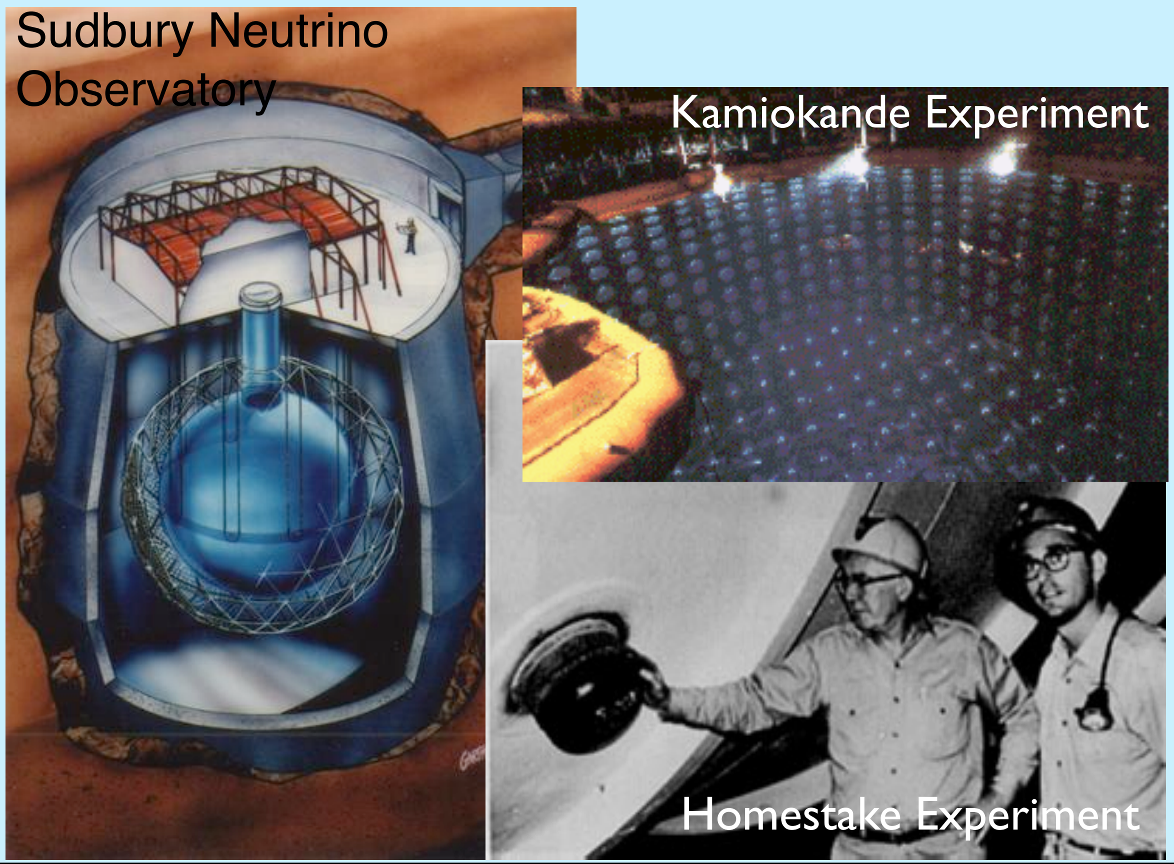
- Collisions of cosmic-rays with nuclei in the Earth's atmosphere produce neutrinos
  - pions, kaons→ν's
  - 4π
  - Neutrino energies extend up to ~100 TeV
- Higher energy contribution from "prompt" ν's from charm decays not yet observed
  - $(D_0,D_\pm,D_{s\pm},\Lambda_{c\pm})\to\nu$'s

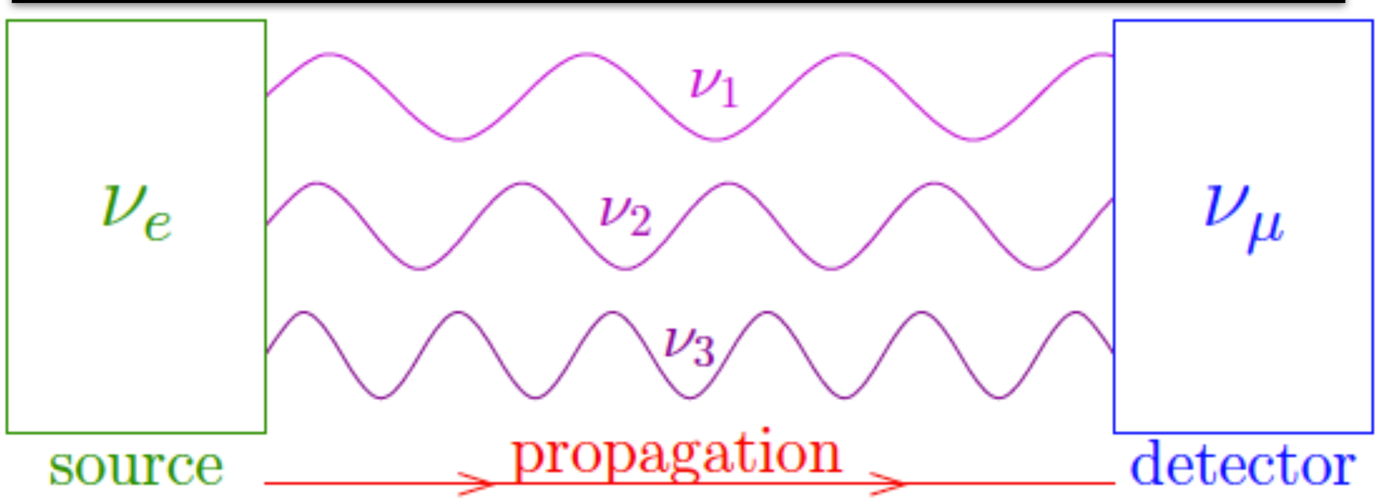
IceCube Collaboration arXiv:1212.4760v2



Neutrino Oscillations

Solar Neutrino Problem



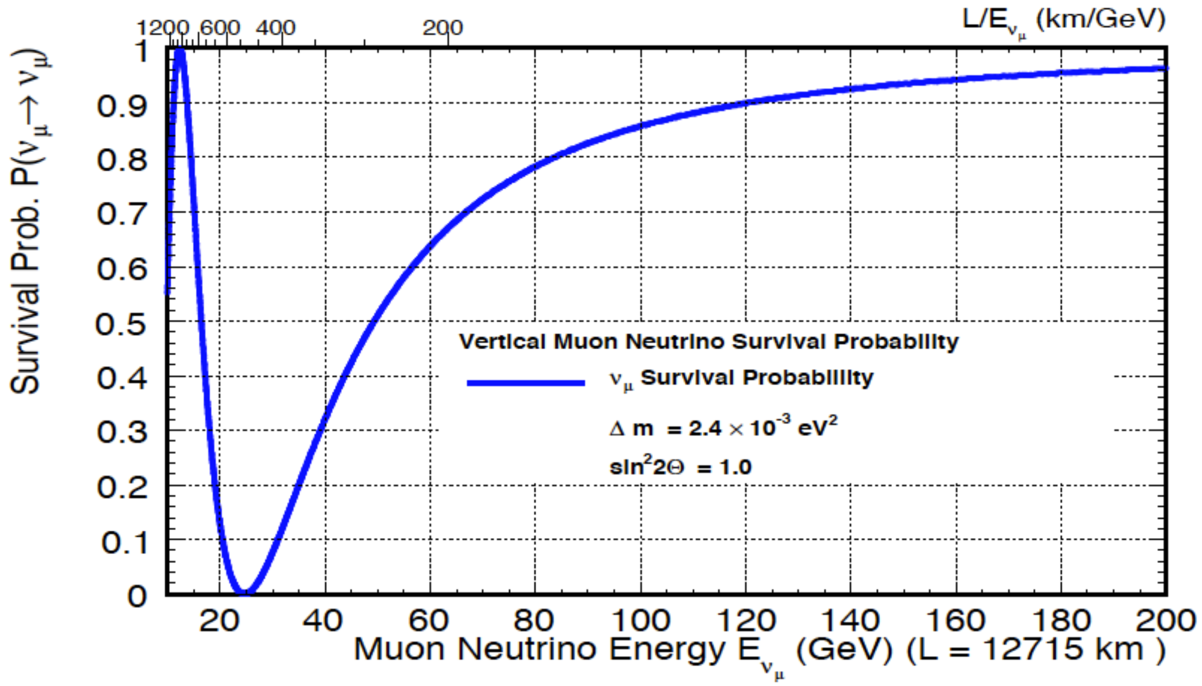


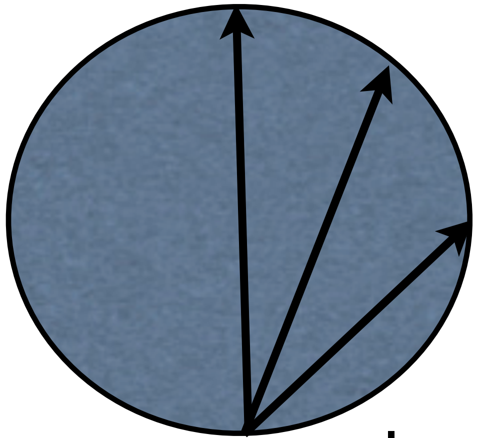
- Neutrinos come in 3 flavors produced in weak interactions:
  - ν_e - electron neutrino
  - ν_μ - muon neutrino
  - ν_τ - tau neutrino
- A Flavor Neutrino is a superposition of Massive Neutrinos (ν_1,ν_2,ν_3)
  - $|\nu_e\rangle = U_{e1}\ |\nu_1\rangle + U_{e2}\ |\nu_2\rangle + U_{e3}\ |\nu_3\rangle$
  - $|\nu_\mu\rangle = U_{\mu 1}\ |\nu_1\rangle + U_{\mu 2}\ |\nu_2\rangle + U_{\mu 3}\ |\nu_3\rangle$
  - $|\nu_\tau\rangle = U_{\tau 1}\ |\nu_1\rangle + U_{\tau 2}\ |\nu_2\rangle + U_{\tau 3}\ |\nu_3\rangle$
- U is a 3x3 the mixing matrix
- Mass states propagate from source to the detector
  - It is possible to observe a neutrino of different flavor at the detector than created at the source

Understanding fundamental parameters in the neutrino sector is of extreme importance and might lead the way to physics beyond the standard model of particle physics

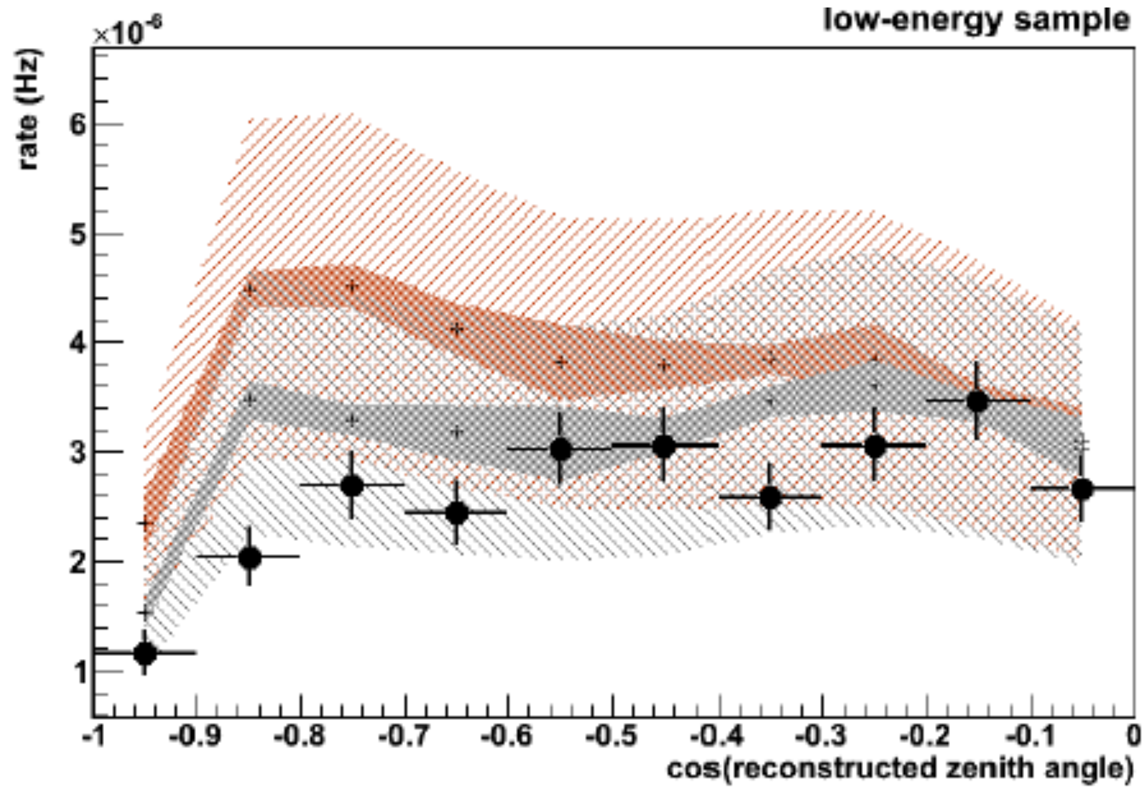
Recent Success

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23} L/E)$$

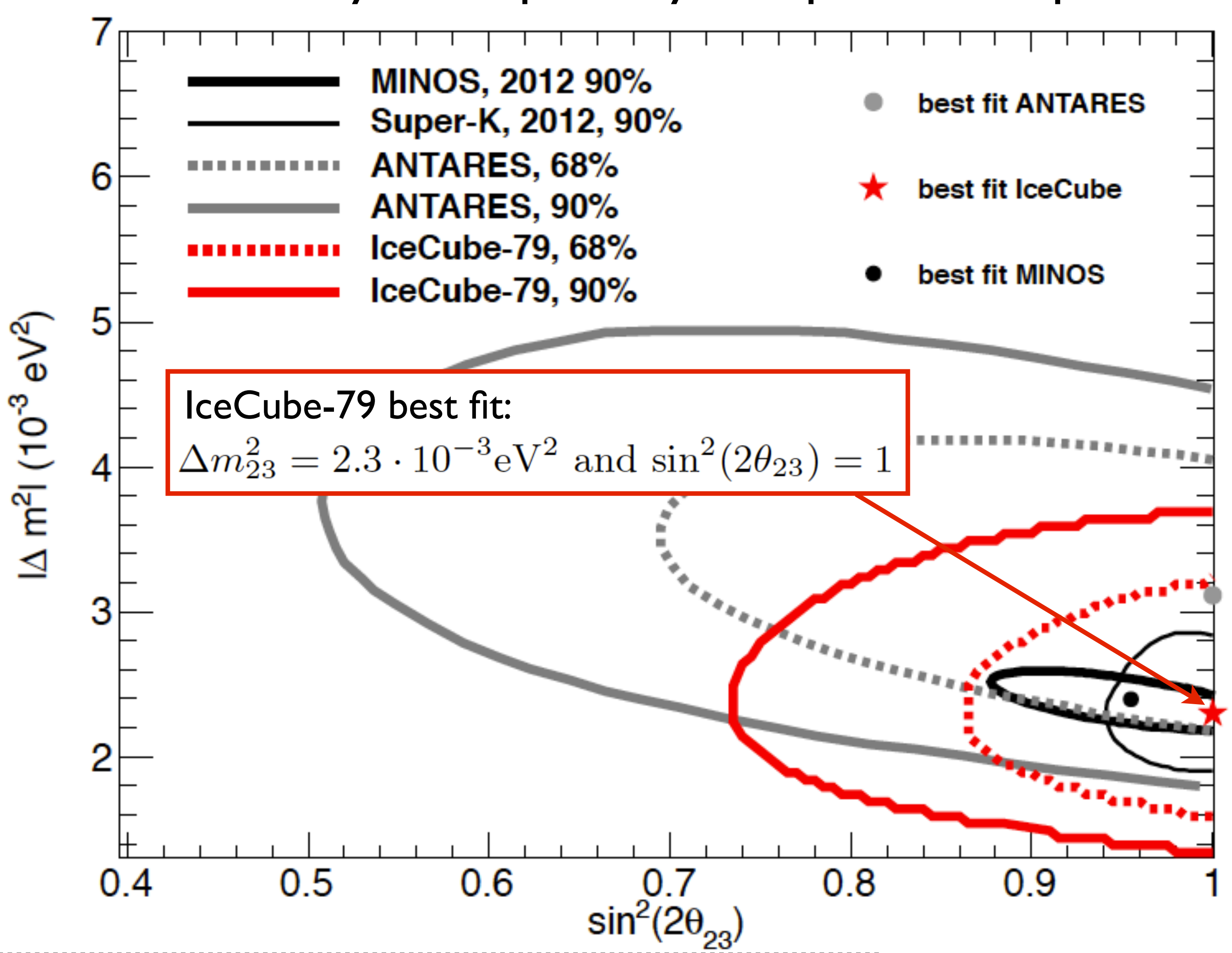




different **zenith angles θ** correspond to different **path length L**



1year of partially completed DeepCore



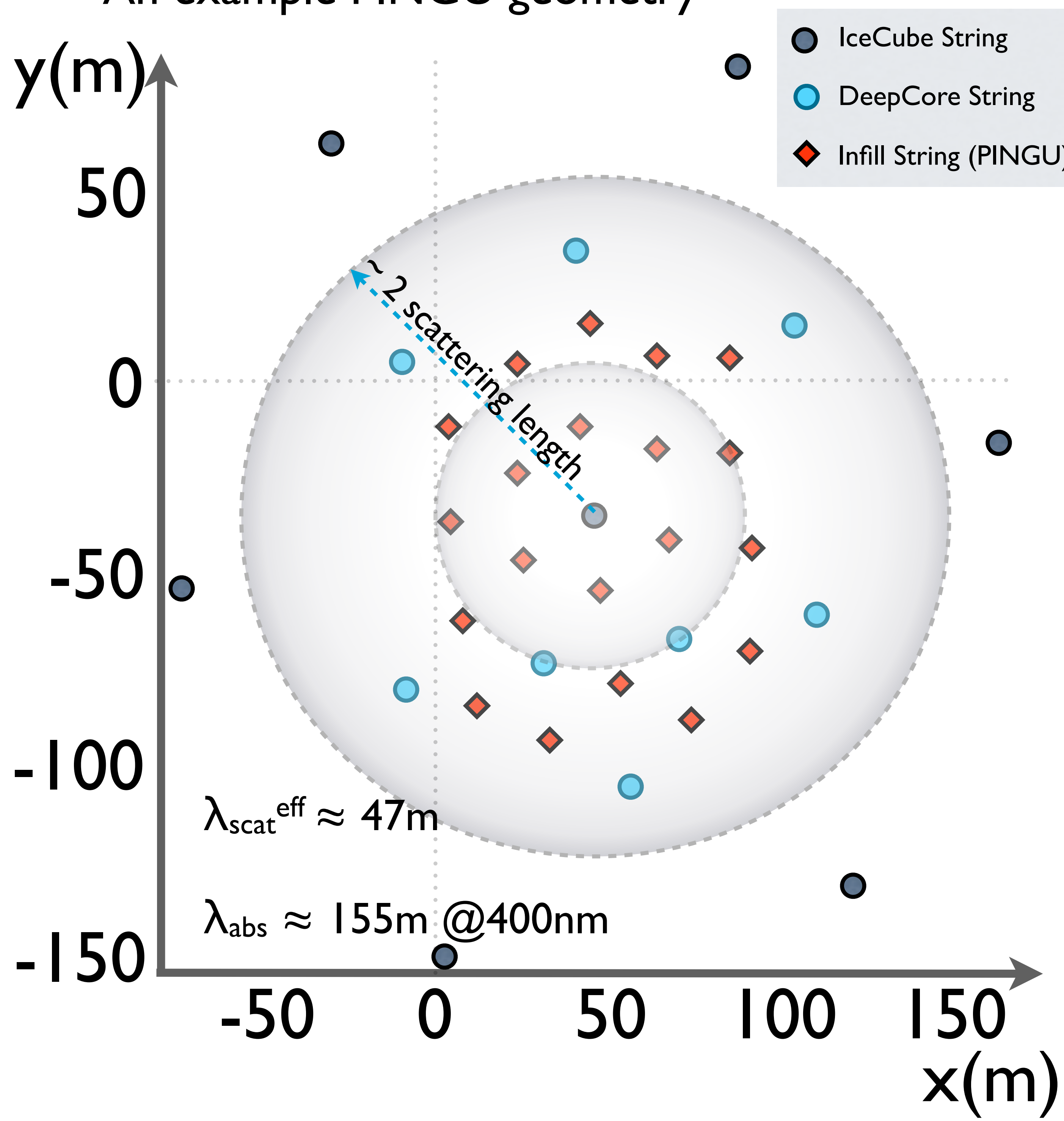
Demonstration that IceCube can observe neutrino oscillations

PINGU

PINGU - Precision IceCube Next Generation Upgrade

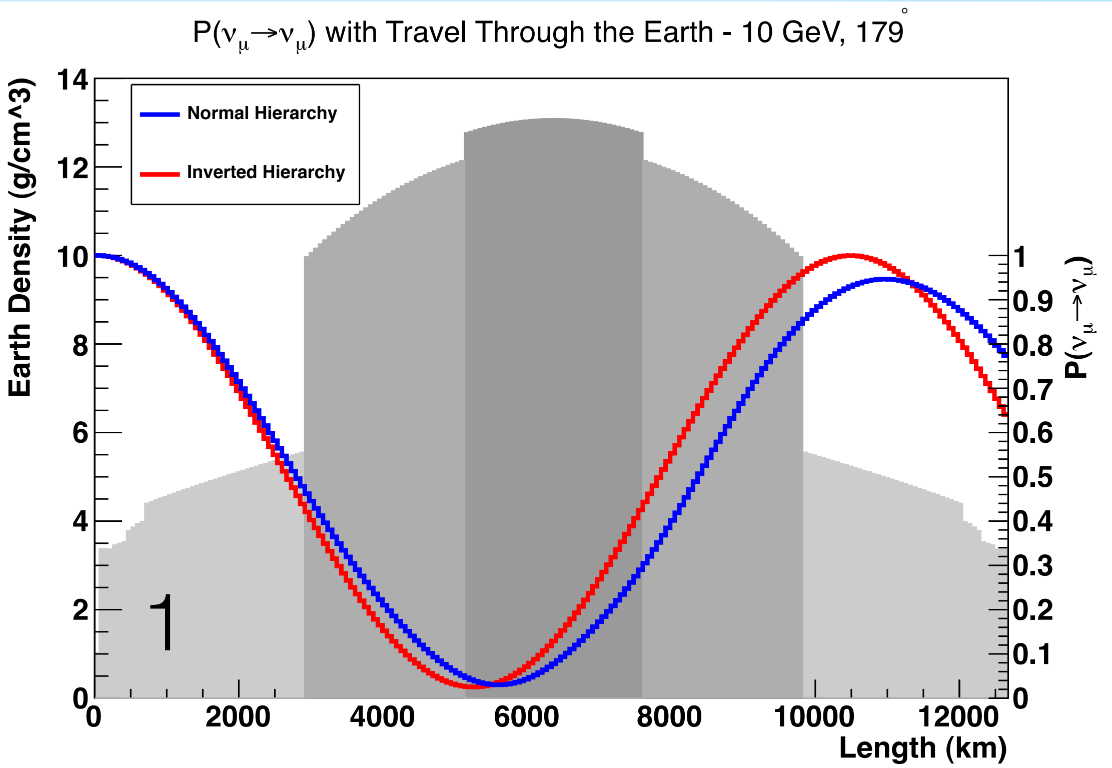
- PINGU is an in-fill extension to IceCube
  - It would lower the energy threshold to about 1GeV
  - PINGUs primary physics goal is a determination of the neutrino mass hierarchy; one of the last unmeasured fundamental parameters in the neutrino sector.
- PINGU design
  - Instrument a volume of about 10MT with ~20-40 strings each containing 60-100 optical modules
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors

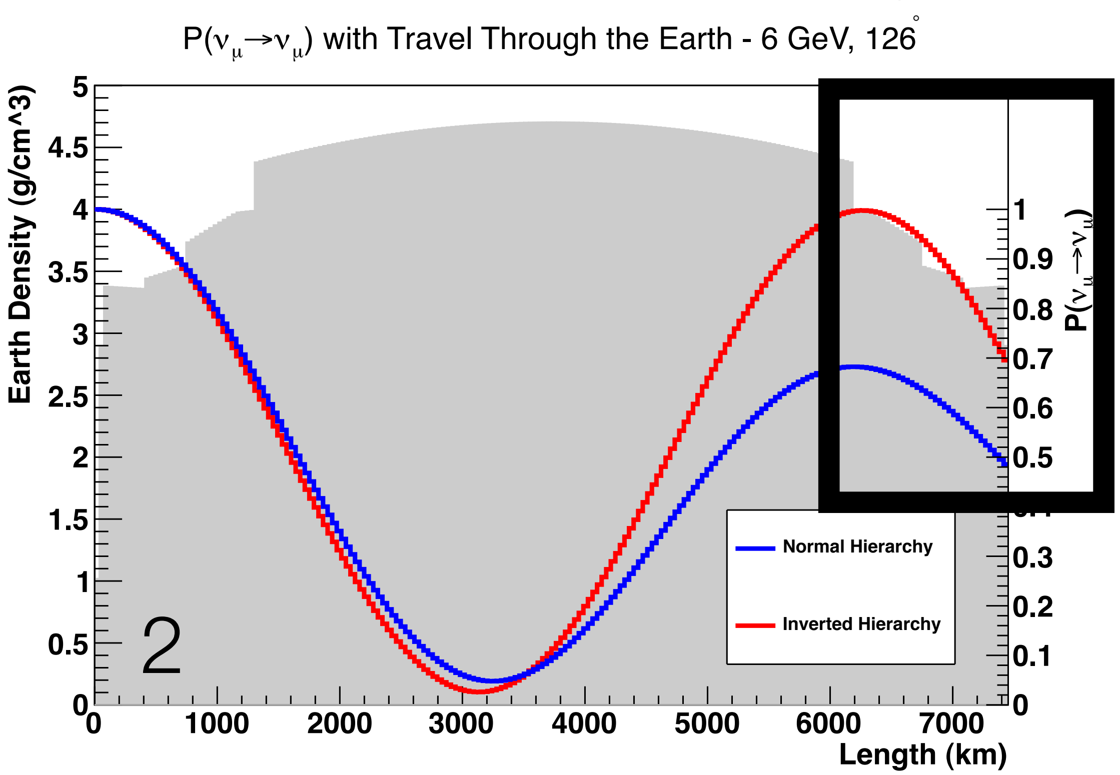
An example PINGU geometry

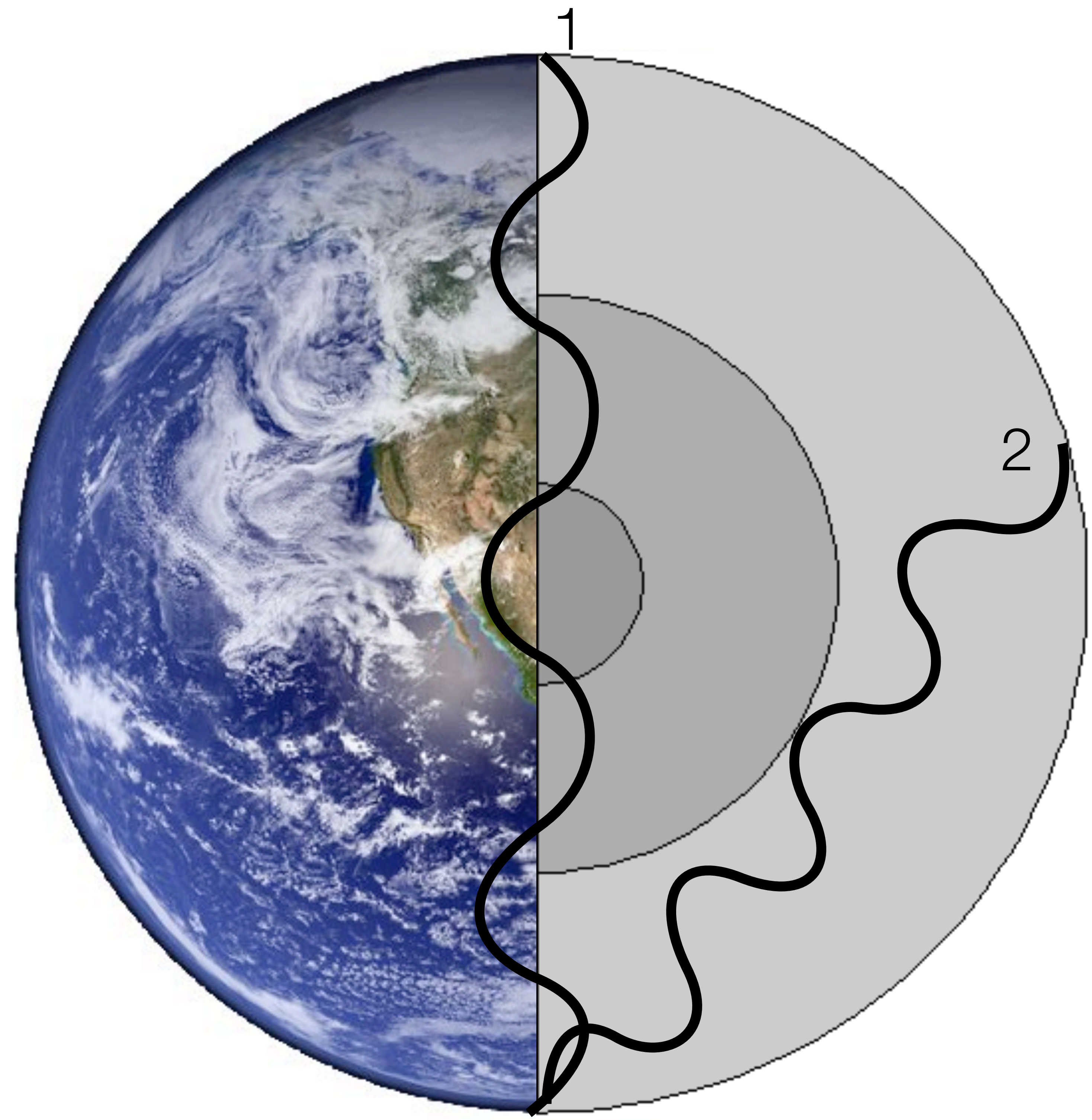


Neutrino Oscillations

Matter Effects and Mass Hierarchy







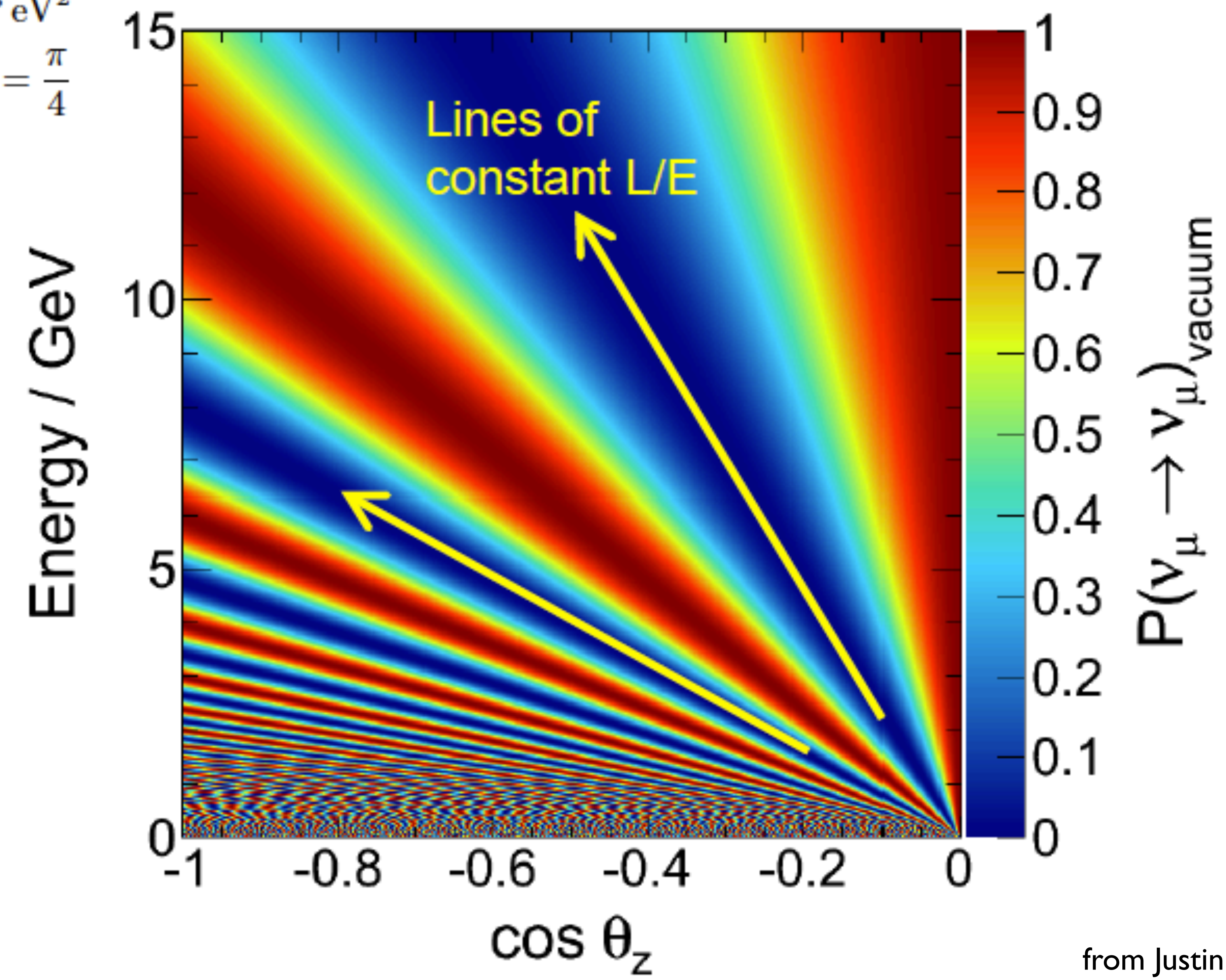
- Inverted/Normal hierarchy has up to a 20% difference in ν_μ oscillation probability for specific energies and zenith angles (baselines)

Neutrino oscillations in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Delta m^2_{32} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2(2\theta_{23}) = \frac{\pi}{4}$

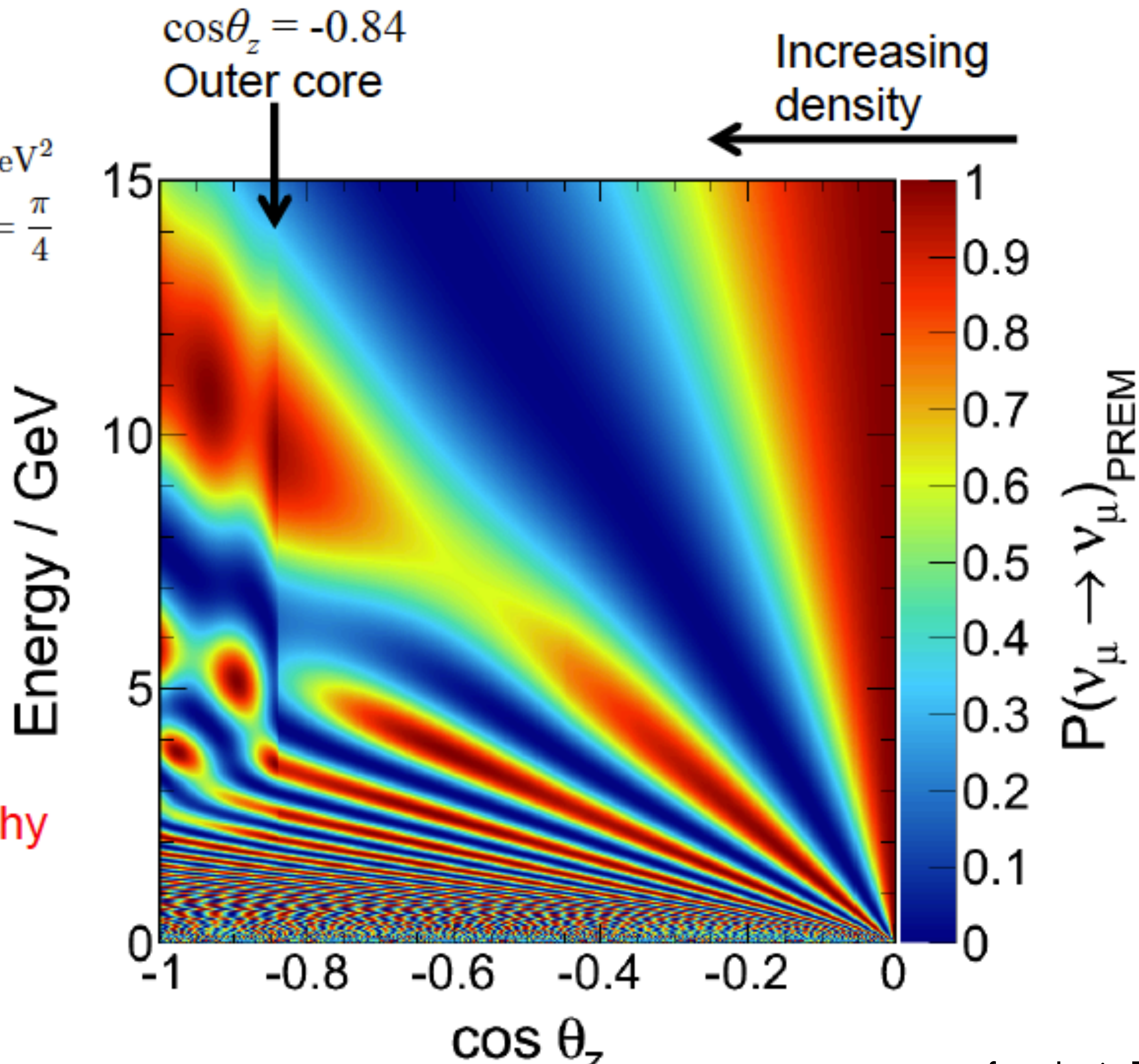


from Justin Evans (U. Manchester)

Neutrino oscillations in matter

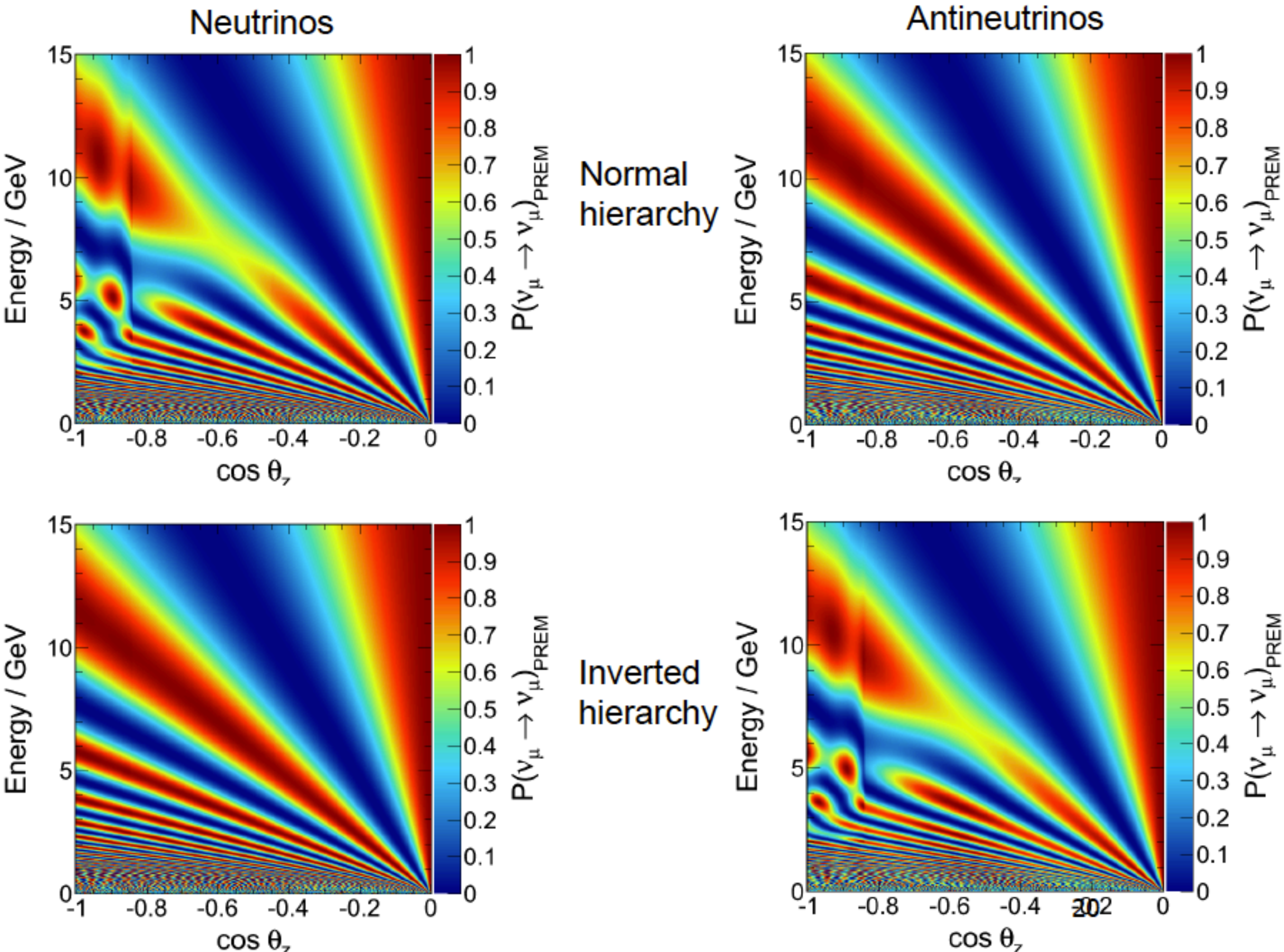
$\Delta m^2_{32} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2(2\theta_{23}) = \frac{\pi}{4}$



Normal hierarchy

from Justin Evans (U. Manchester)


Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θz
P(νμ → νμ)PREM
20

Distinguishing Hierarchy

- Use method outlined in Akhmedov, Razzaque, Smirnov - arXiv:1205.7071

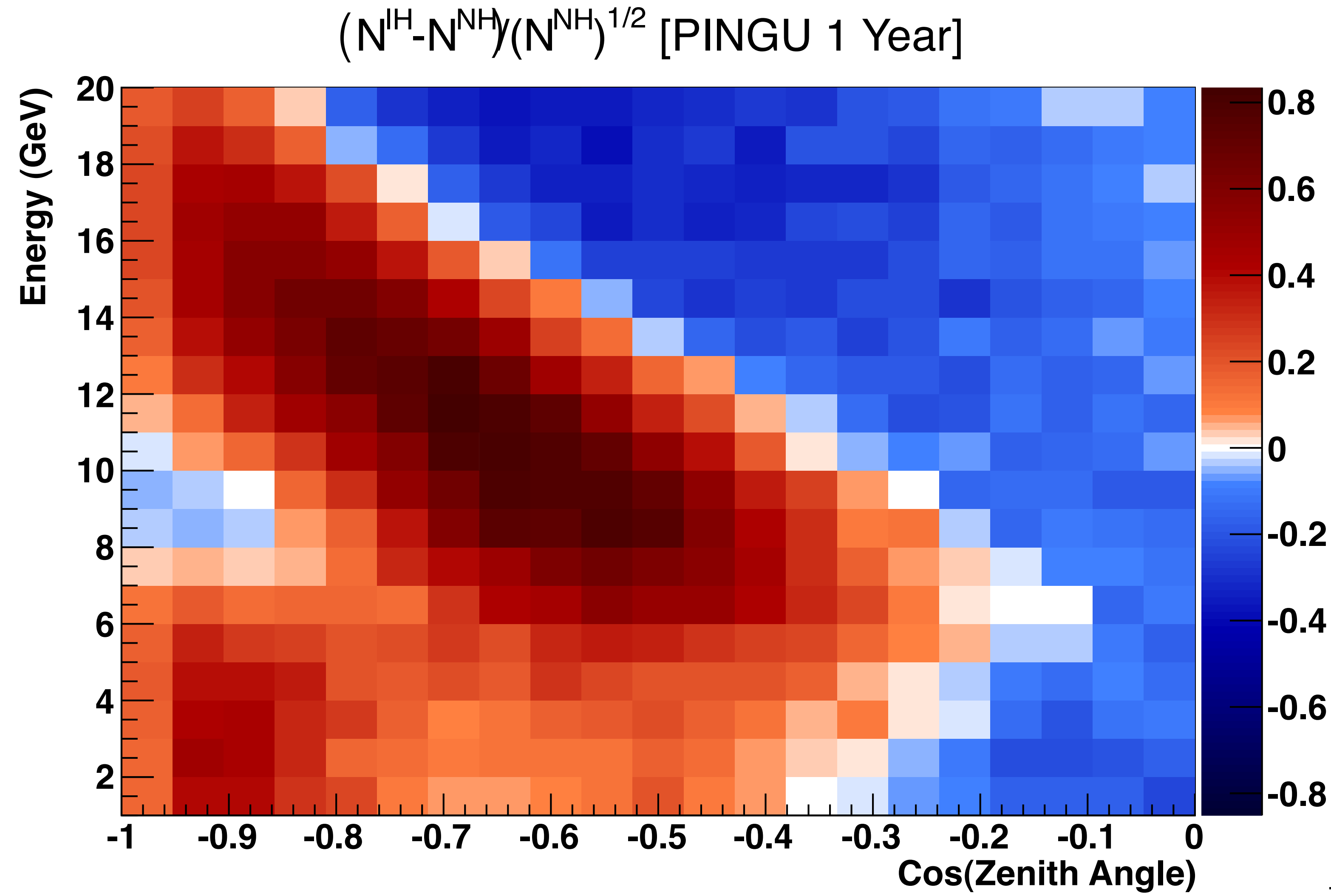
$$S_{tot} = \sqrt{\Sigma_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}} \qquad \begin{aligned} i &= \cos(zenith) \\ j &= energy \\ V^{eff} &= effective\ volume \end{aligned}$$

$$N_{i,j}^{NH} = P(\nu_\mu)_{i,j}^{NH} * \Phi(\nu_\mu)_{i,j} * \sigma(\nu_\mu)_j * V_{i,j}^{eff} + P^{NH}(\overline{\nu_\mu})_{ij} * \Phi(\overline{\nu_\mu})_{i,j} * \sigma(\overline{\nu_\mu})_j * V_{i,j}^{eff}$$

- How can we distinguish the mass hierarchy ?
  - For neutrinos oscillation effects are enhanced if the hierarchy is normal, in case of inverted hierarchy the oscillation effects for anti-neutrinos are enhanced

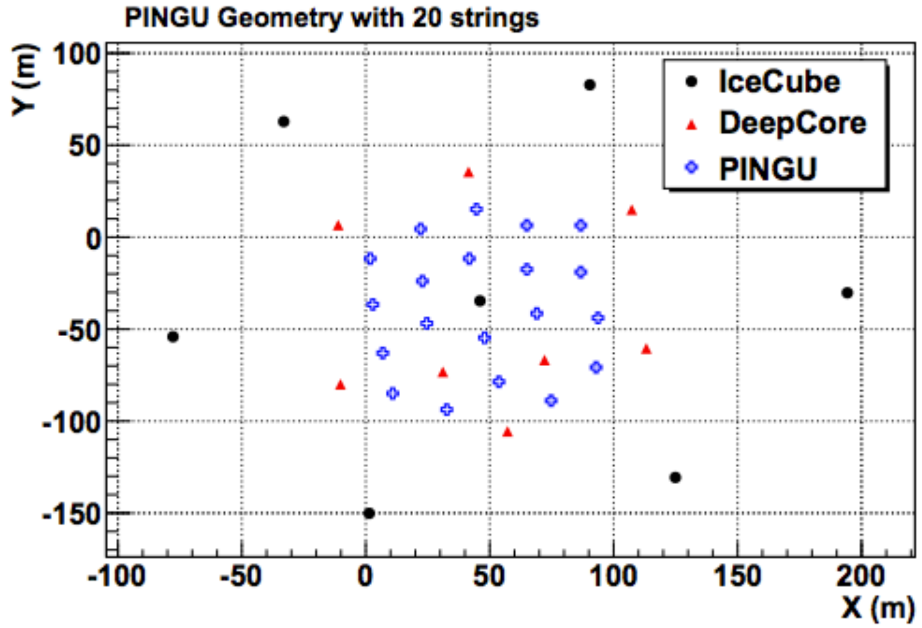
$$\begin{aligned} Probability &: P(\nu_\mu)^{IH} + P(\overline{\nu_\mu})^{IH} \neq P(\nu_\mu) \\ Flux &: \Phi(\nu_\mu) > \Phi(\overline{\nu_\mu}) \\ Cross-Section &: \sigma(\nu_\mu) > \sigma(\overline{\nu_\mu}) \end{aligned}$$

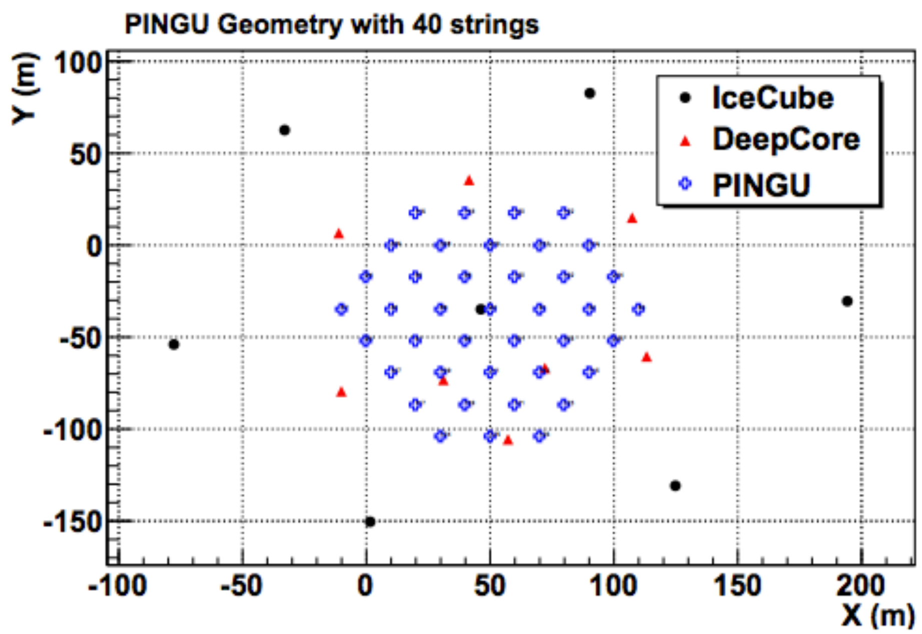
smeared: 3 GeV in ν_μ energy and 11.25° in μ zenith resolution

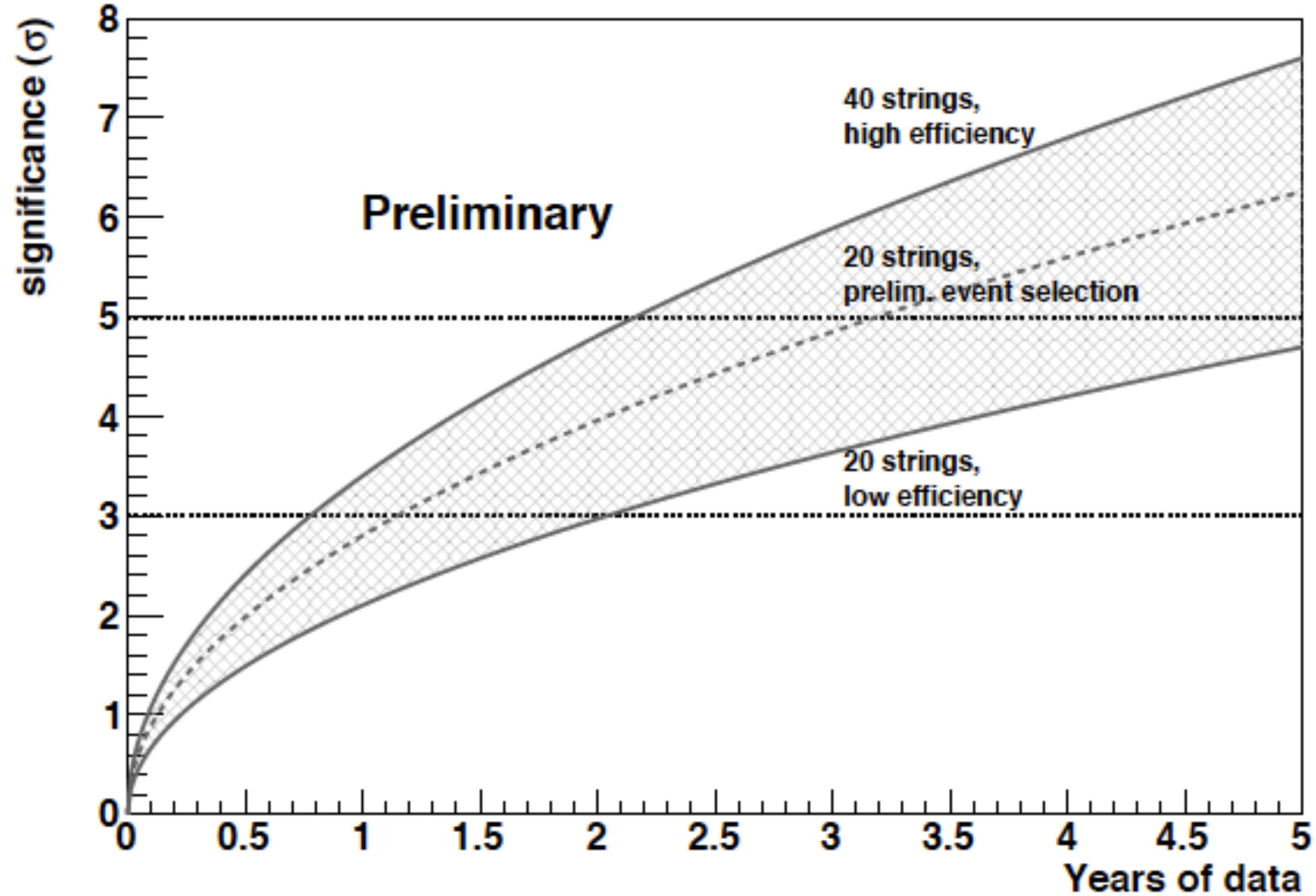


Mass Hierarchy Measurement

arXiv:1306.5846v1

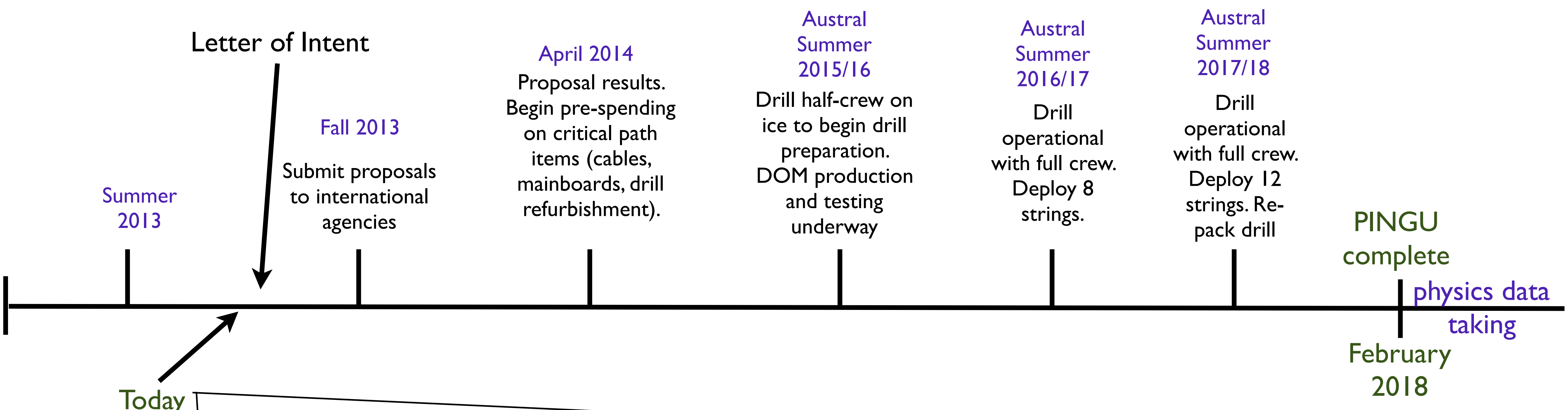






Estimated significance for determining the neutrino mass hierarchy with PINGU. The top of the range is based on a 40 string detector with a high assumed signal efficiency in the final analysis; the bottom uses a 20 string detector and assumed a lower signal efficiency.

A Possible Time line



Current Status

- Detailed Monte Carlo simulations nearing completion
- Low energy reconstruction algorithms from DeepCore being applied to PINGU events
- Estimation of sensitivity to neutrino mass hierarchy with full reconstruction underway
- Letter of Intent in preparation

Advantages of PINGU

- Well-established detector and construction technology
- Relatively low cost: ~$10M design/startup plus ~$1.25M per string
- Rapid schedule: deployment could be complete by 2017-18, depending on final scope
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Even with pessimistic assumptions the neutrino mass hierarchy can be determined at 3 sigma by 2020
- Multipurpose detector: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/water Cherenkov detectors

Conclusions

- IceCube and DeepCore are working extremely well
- DeepCore analyses have demonstrated that precision physics below 100GeV is possible at the South Pole, by using IceCube as a veto shield
- PINGU can significantly enhances IceCube capabilities ... sensitivity studies towards mass hierarchy measurement on-going
- PINGU Letter of Intent - entering final internal review
- PINGU Proposal to be submitted this fall
- Prospects for Geophysics: Neutrino Absorption (IceCube) Neutrino Oscillations (PINGU)