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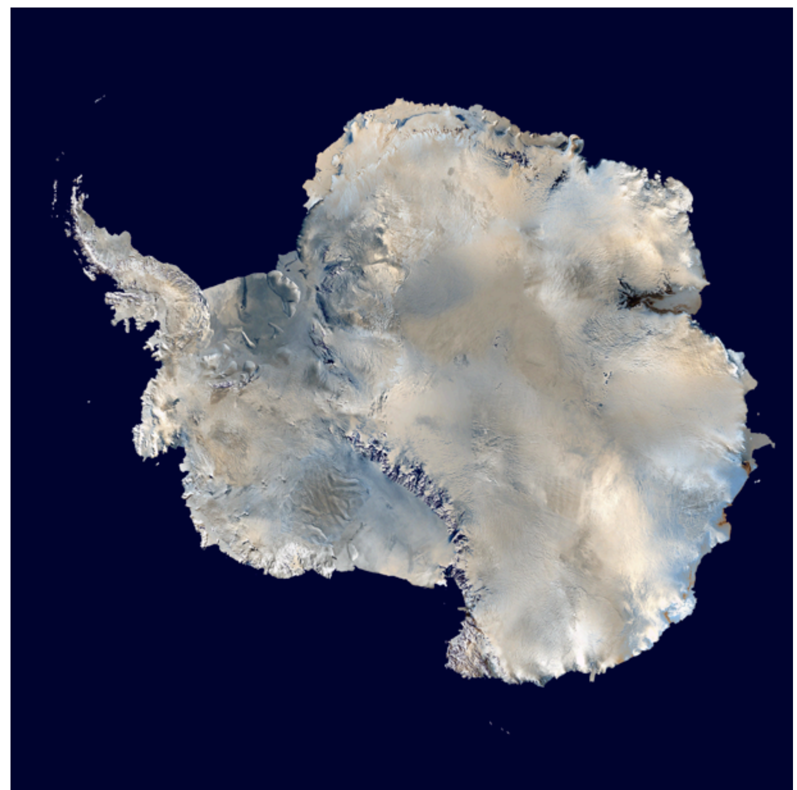
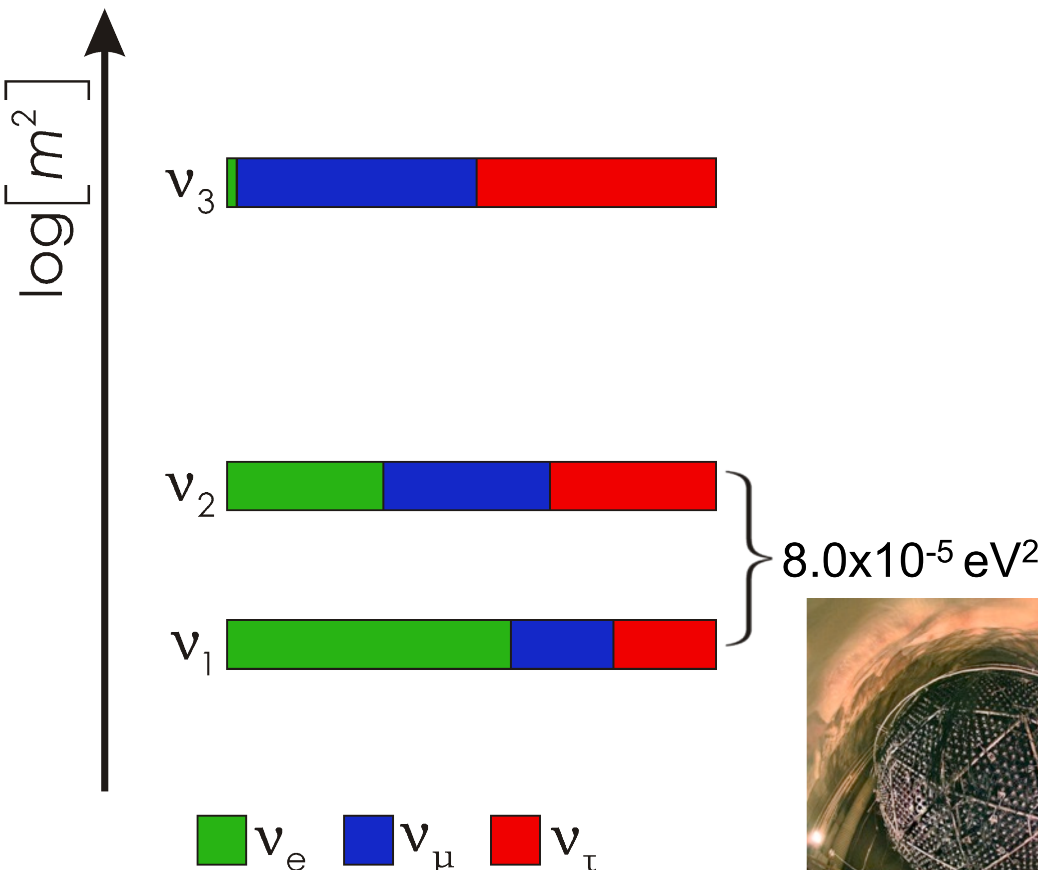
Measuring the neutrino mass hierarchy with PINGU

Justin Evans

PRECISION ICECUBE NEXT GENERATION UPGRADE



Oscillation parameters



Smallest mass splitting

- 'Solar' mass splitting

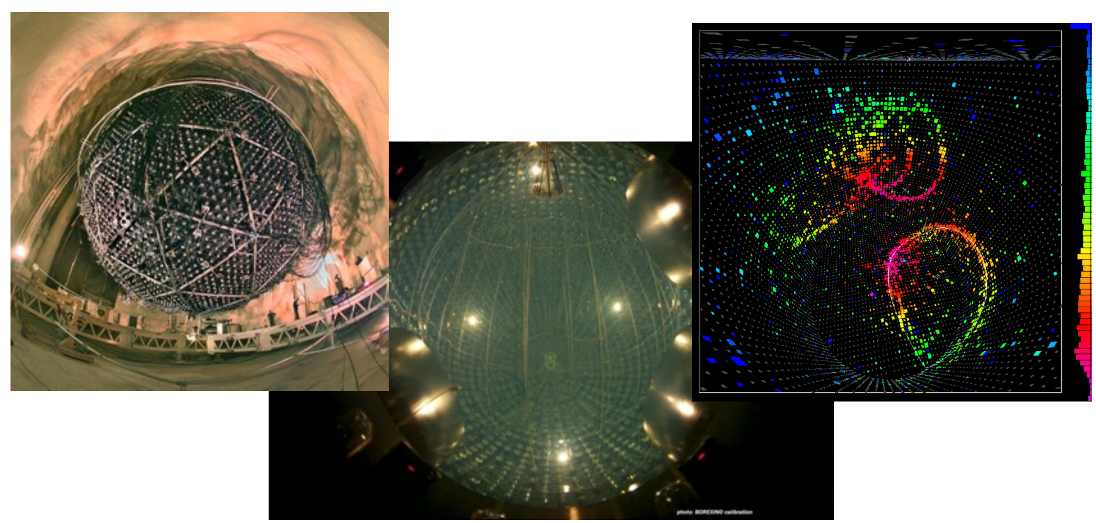
Require L/E ~ $\mathcal{O}(10^5$ km/GeV)

Solar neutrinos

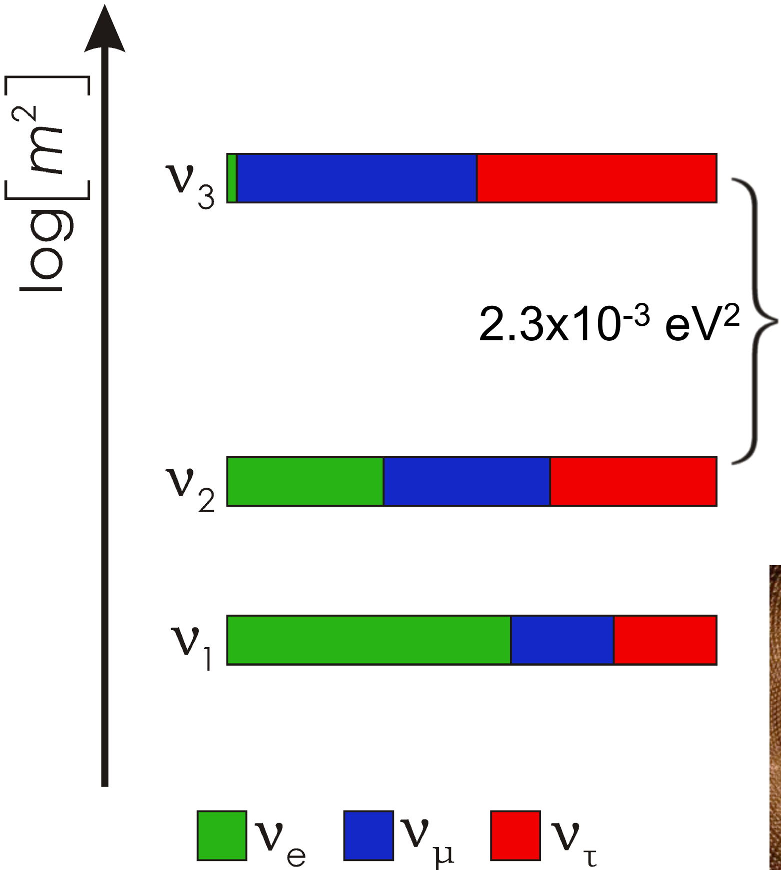
- SNO, Borexino, etc

Reactor neutrinos over $\mathcal{O}$(100 km)

- KamLAND



Oscillation parameters



Largest mass splitting

- ‘Atmospheric’ mass splitting

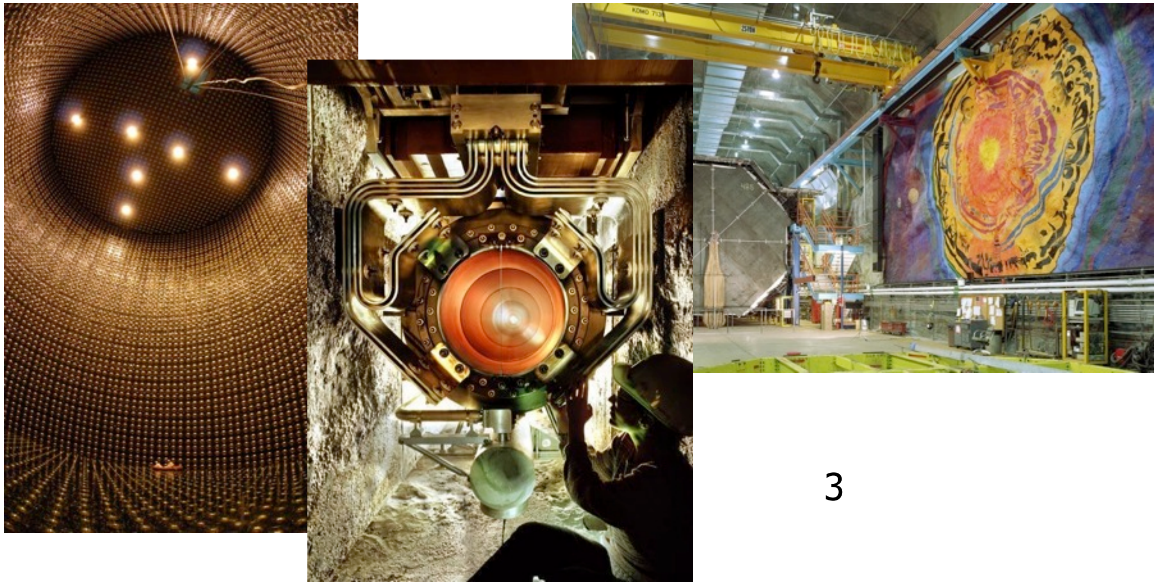
Require L/E ~ $\mathcal{O}(10^3$ km/GeV)

Atmospheric neutrinos

- Super-K, MACRO, Soudan2, etc

Accelerator neutrinos

- MINOS, T2K, NOνA, etc



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The PMNS matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric & accelerator
$\theta_{23} \sim 45^o$

Reactor & accelerator
$\theta_{13} \sim 9^o$

Solar & reactor
$\theta_{12} \sim 34^o$

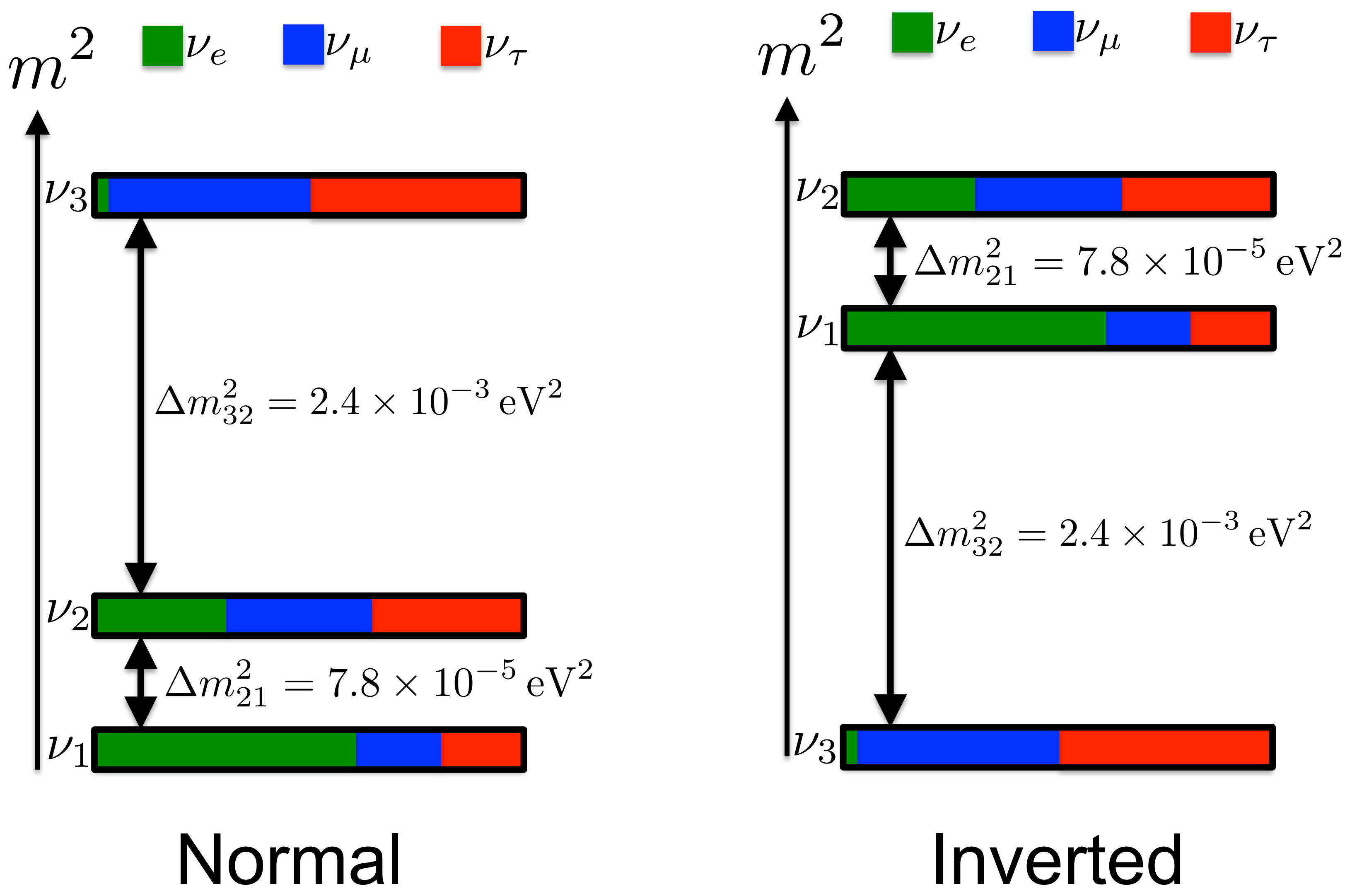
θ_{13} was measured in 2012

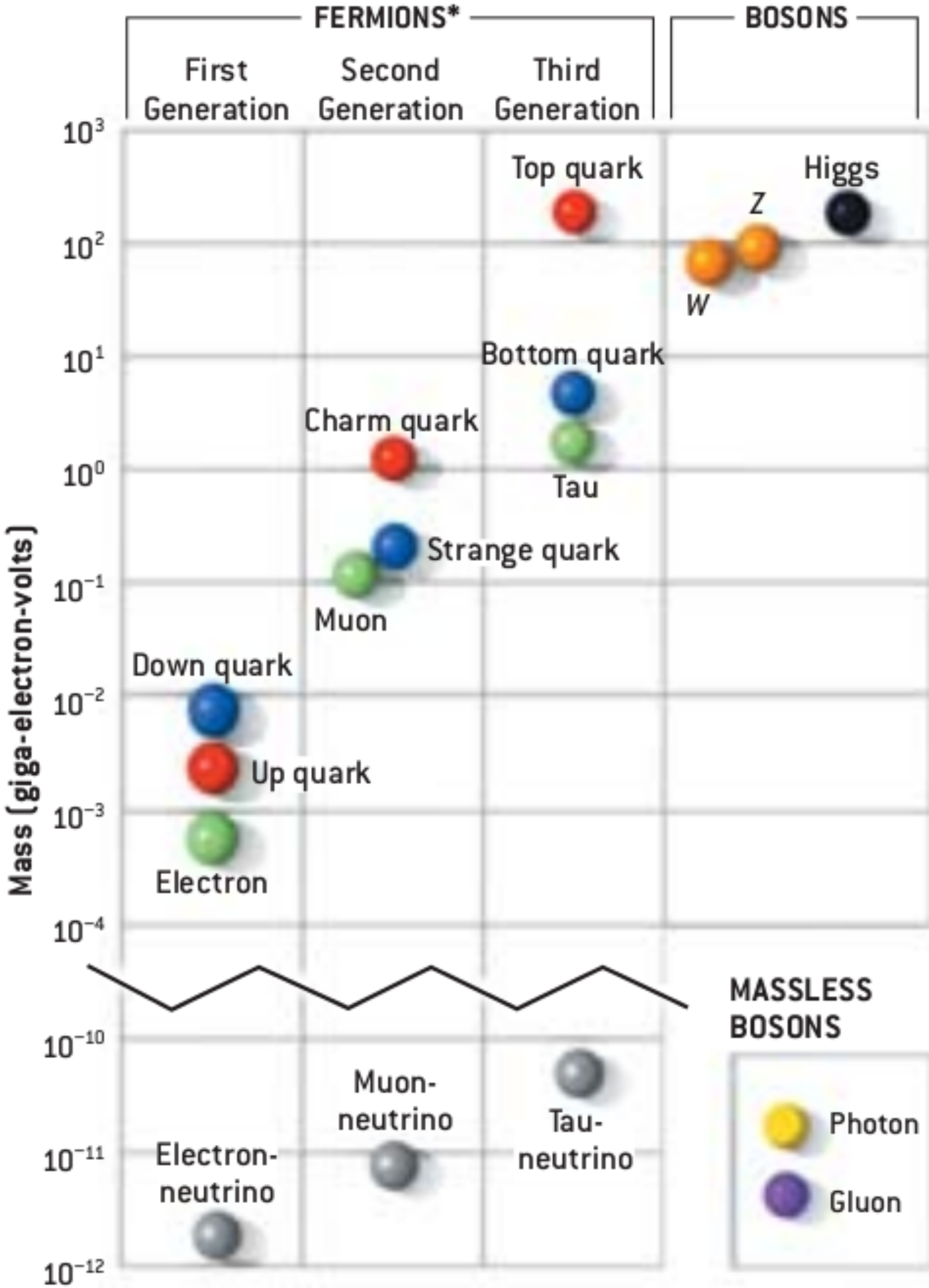
- Daya Bay, Reno, T2K, Double Chooz, MINOS

Three unknowns remain

- CP violating phase δ
- Octant of θ_{23}: only $\sin^2(2\theta_{23})$ has been measured; $\theta_{23} < 45^o$ or $\theta_{23} > 45^o$?
- **Mass hierarchy: the sign of Δm^2_{32}**

The mass hierarchy





Neutrino mass

Why are neutrinos so light?

- Orders of magnitude lighter than all other massive particles

What is the mass generation mechanism?

- See-saw model?

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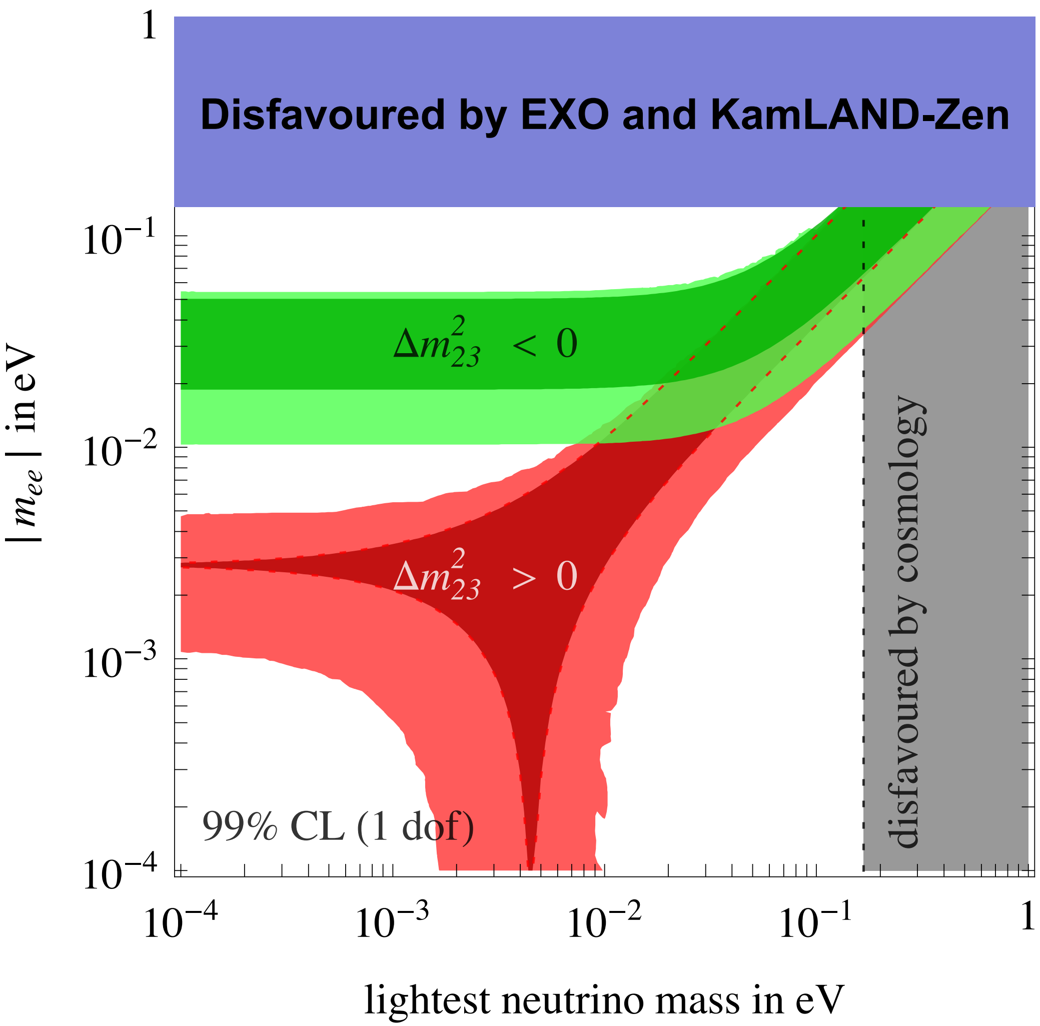
Neutrino mass



Neutrinoless double beta decay can tell us about neutrino mass

- What is the absolute mass?
- Are neutrinos Majorana

Majorana mass opens the way to see-saw models

Knowledge of the mass hierarchy is a key ingredient in this search

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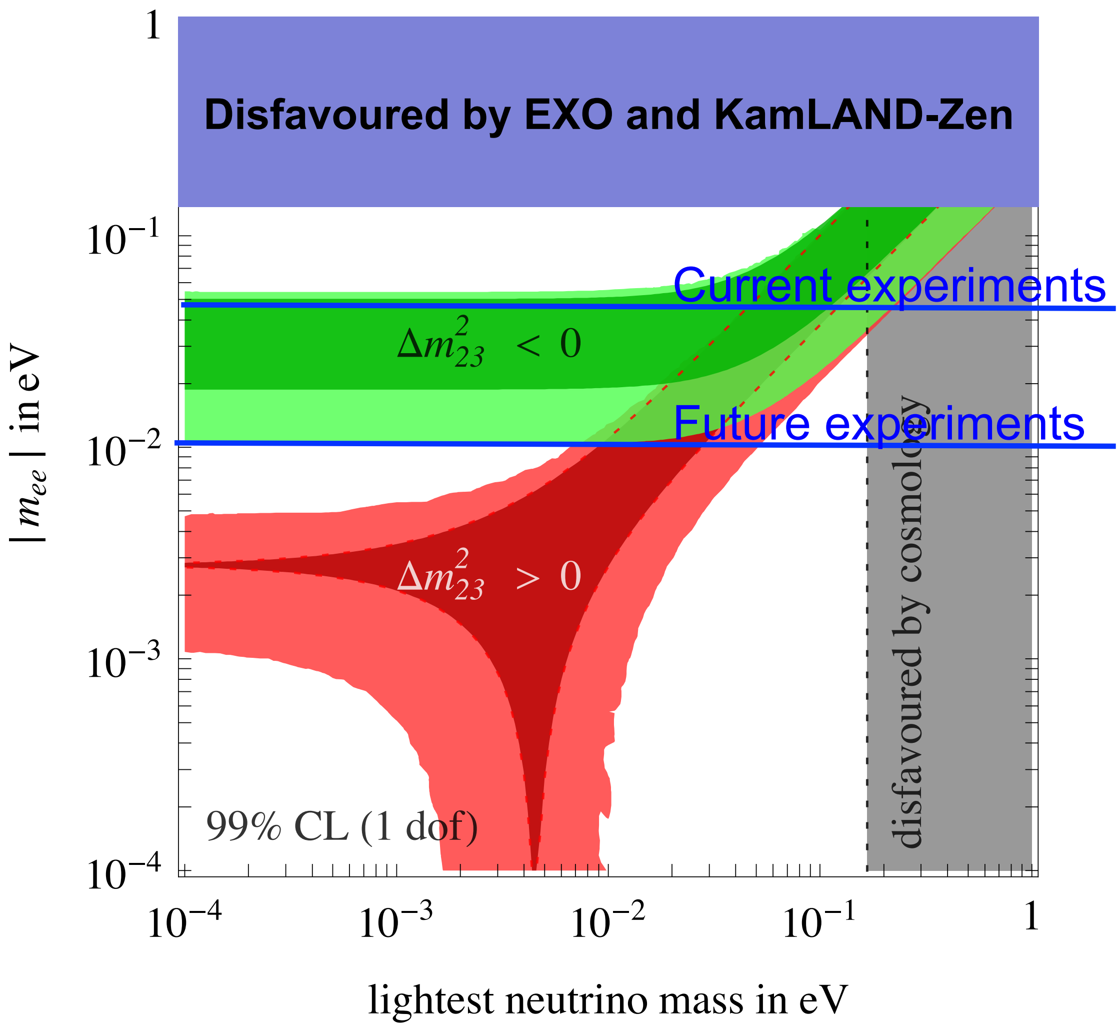
Neutrino mass



Neutrinoless double beta decay can tell us about neutrino mass

- What is the absolute mass?
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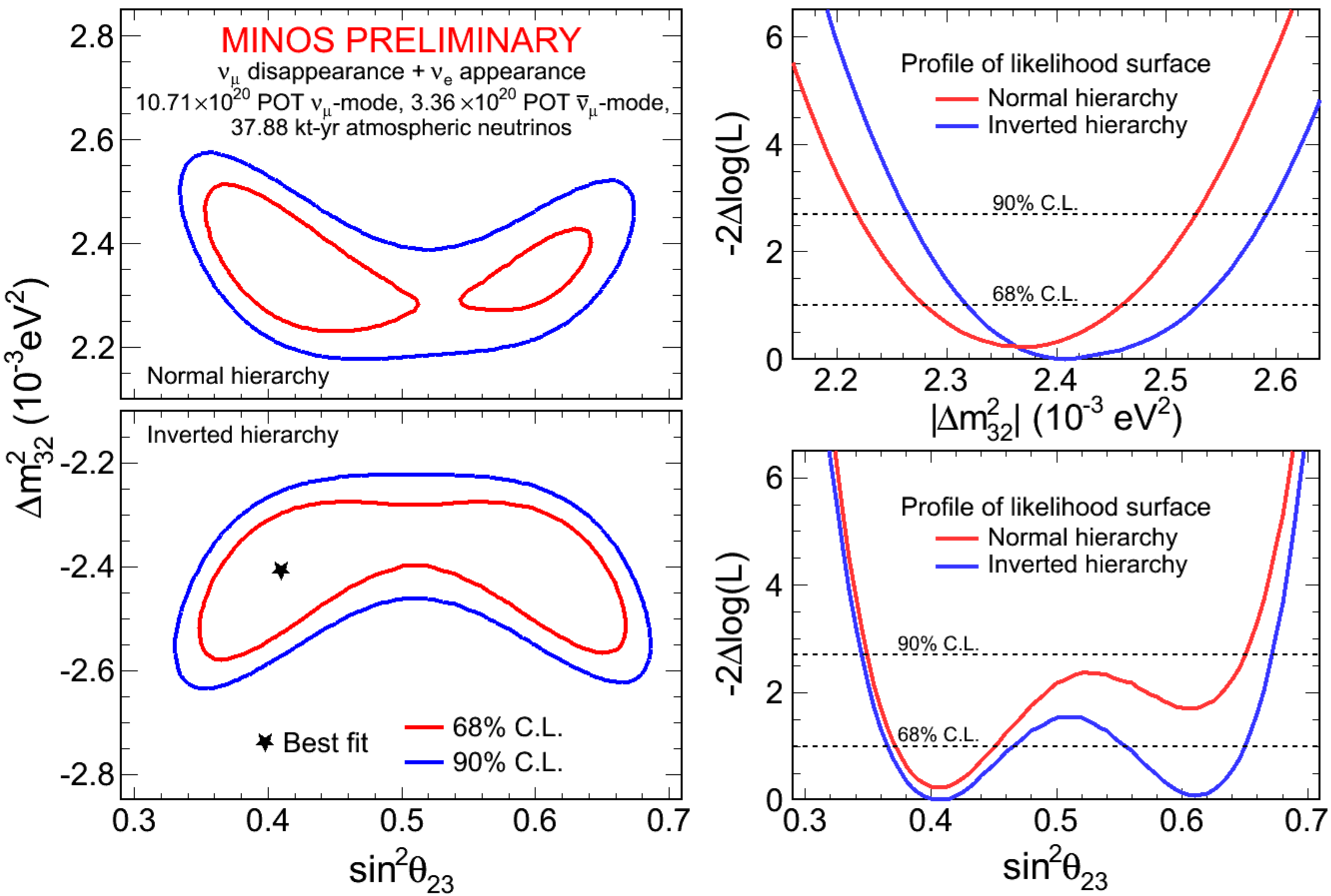
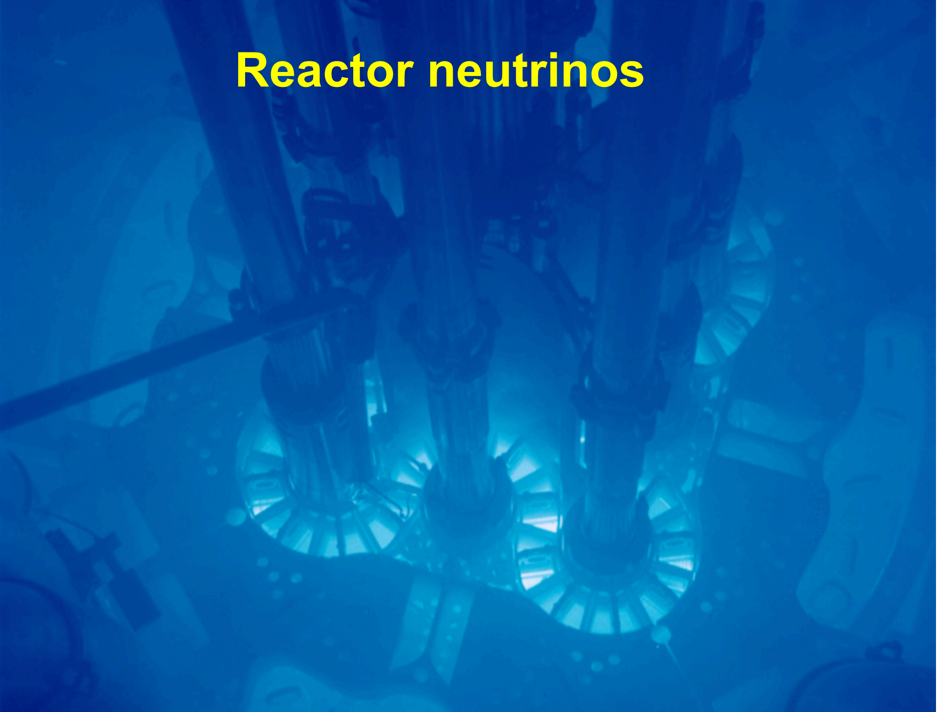
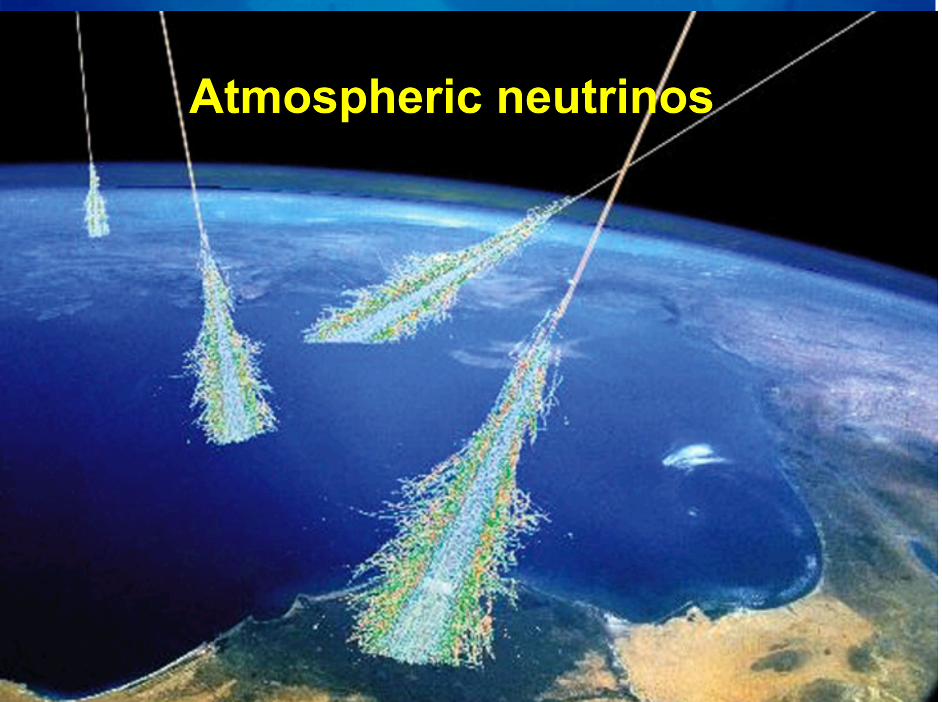
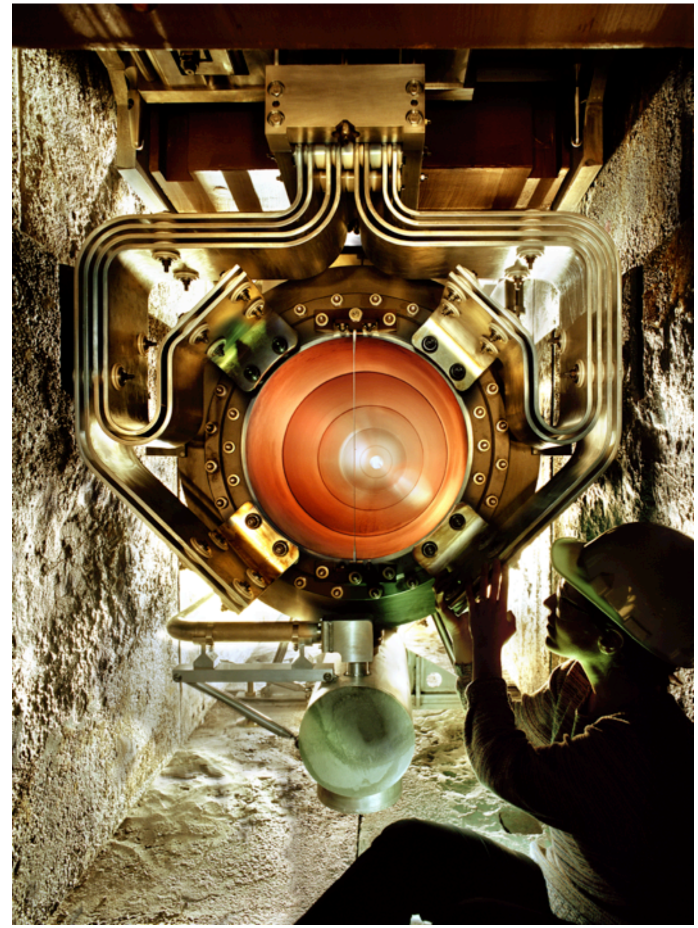
MINOS measurements



Neutrino sources







Beam neutrinos

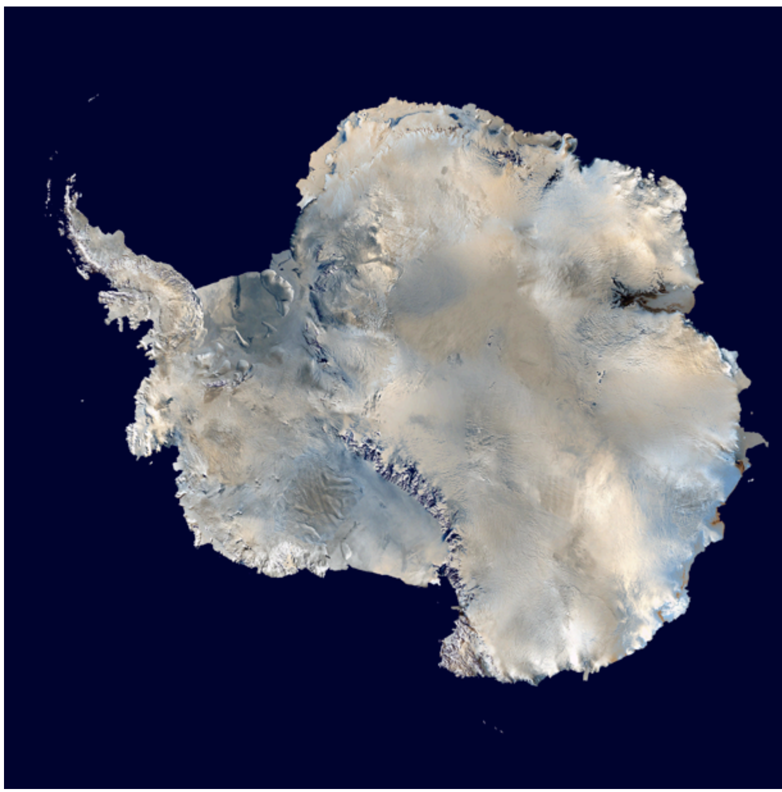
Massive detectors

The challenge in neutrino physics is statistics

- We need to instrument kiloton or even megaton detectors

H_2O is an excellent detection medium

- Huge natural bodies of water and ice exist if we can make use of them



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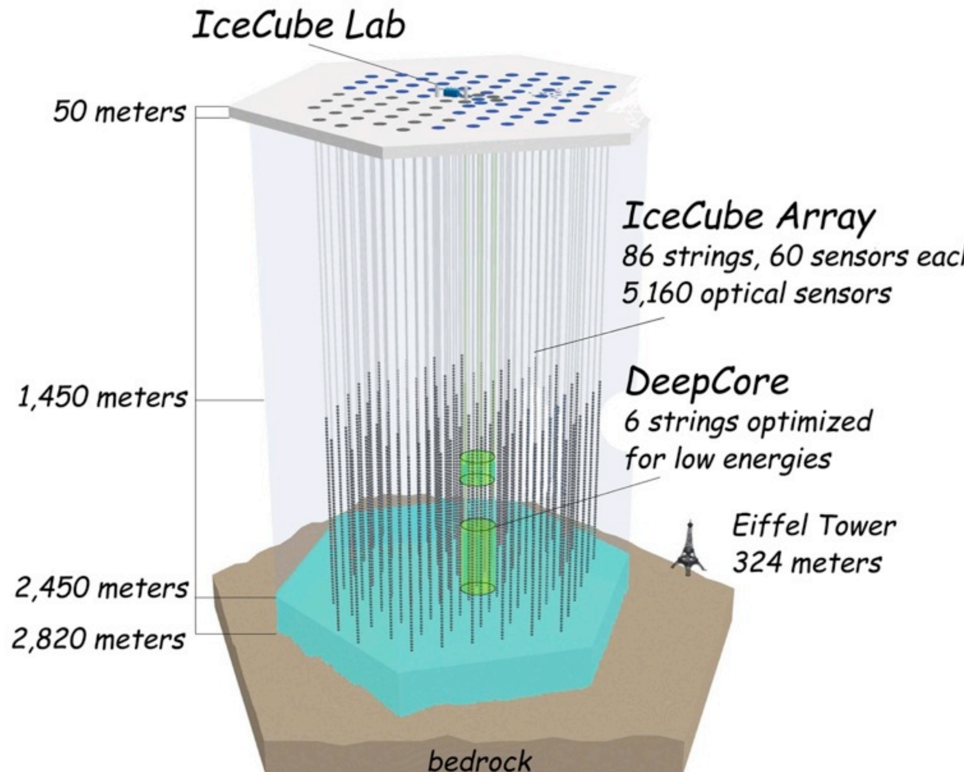
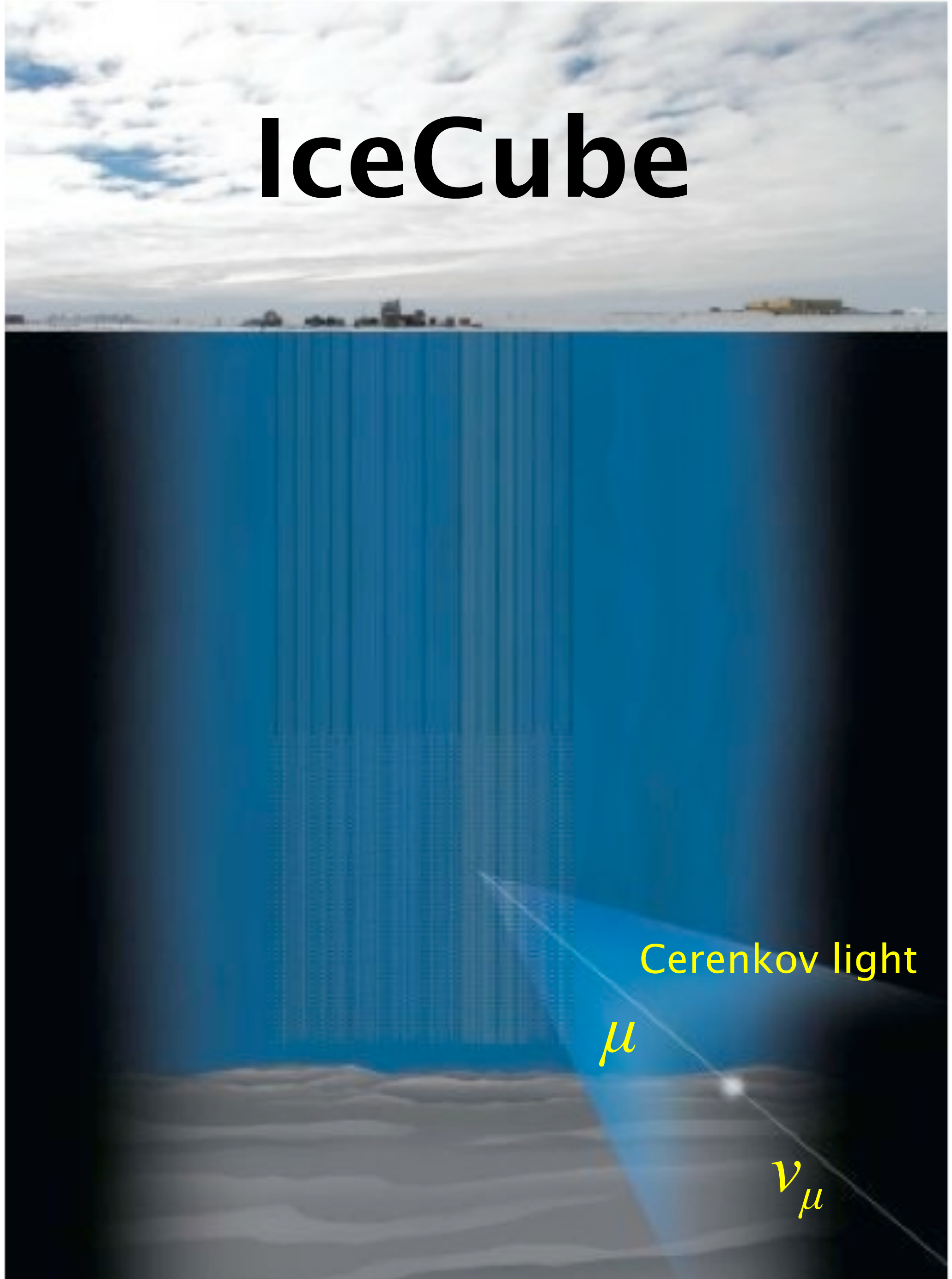
IceCube



- The world’s biggest neutrino detector
- 1 km^3 of ice

IceCube



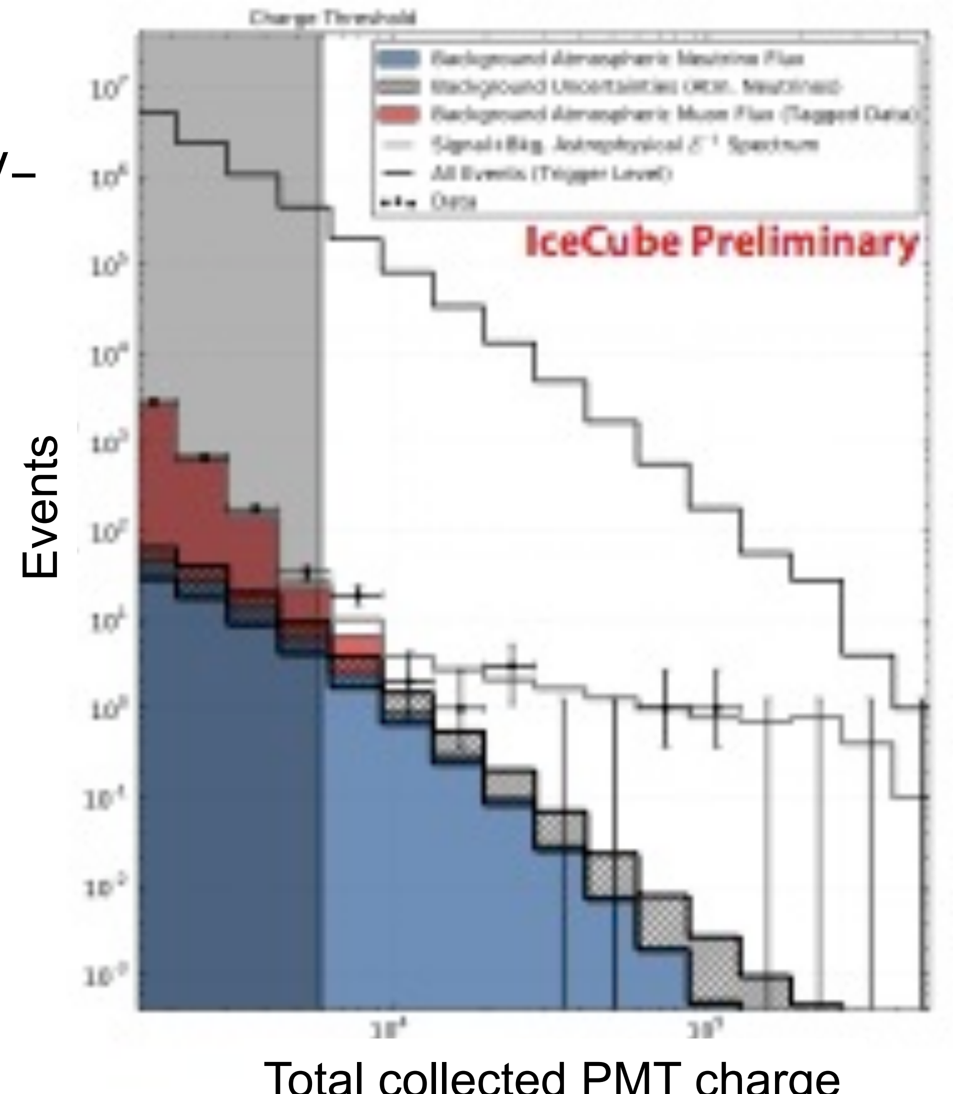
Highest energy neutrinos

IceCube has observed two PeV-energy neutrino candidates

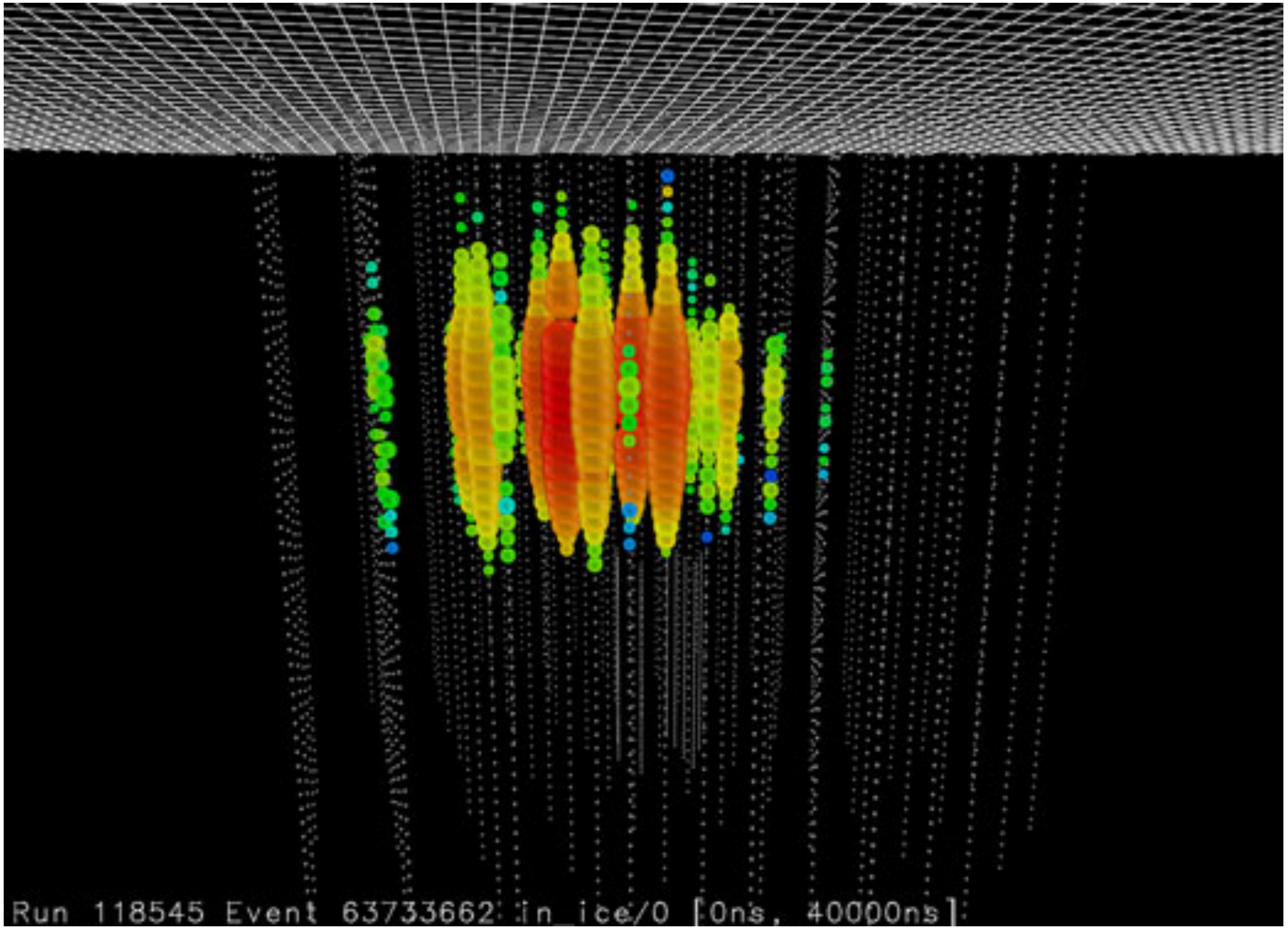
- Highest energy neutrinos ever observed

26 more high-energy candidates at lower energies

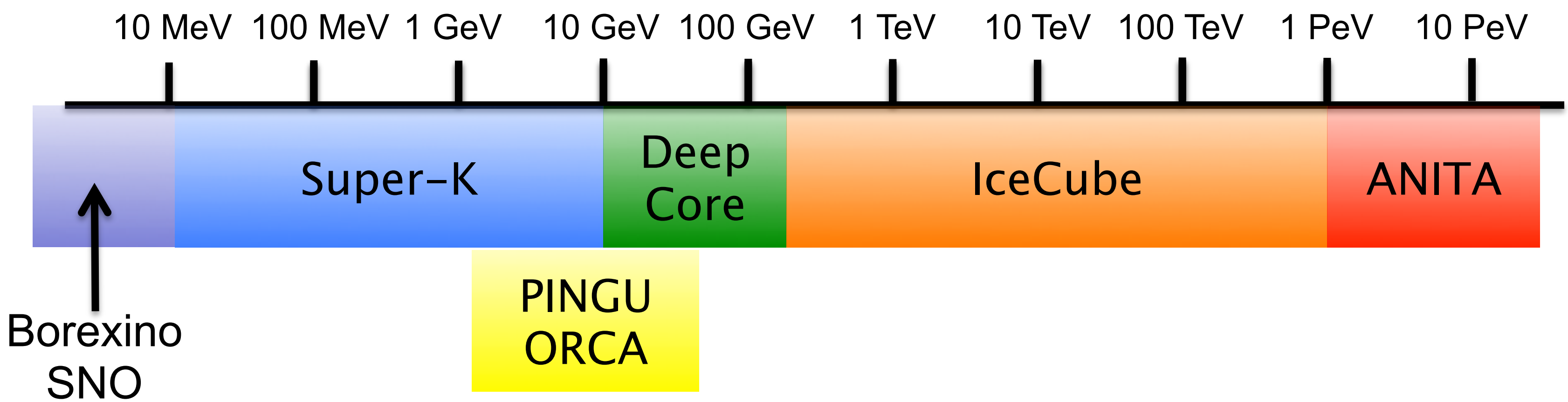
Inconsistent with standard atmospheric neutrino backgrounds at 4.1σ



A high energy IceCube event



Neutrinos from the sky



PINGU will study atmospheric neutrino oscillations in the 10–20 GeV region

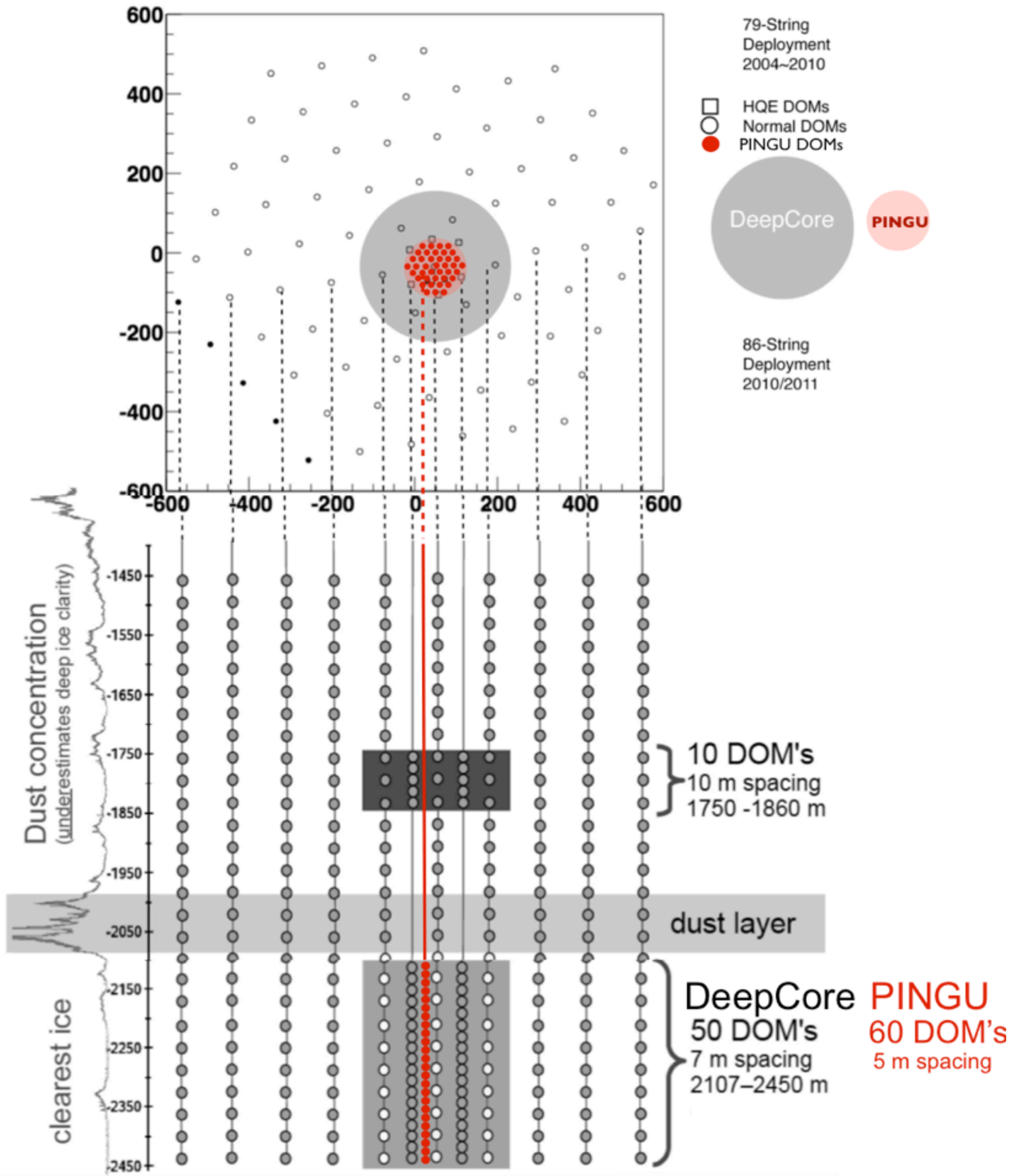
- Providing megaton-scale statistics
- ORCA is a similar proposed extension to ANTARES in the Mediterranean

PINGU

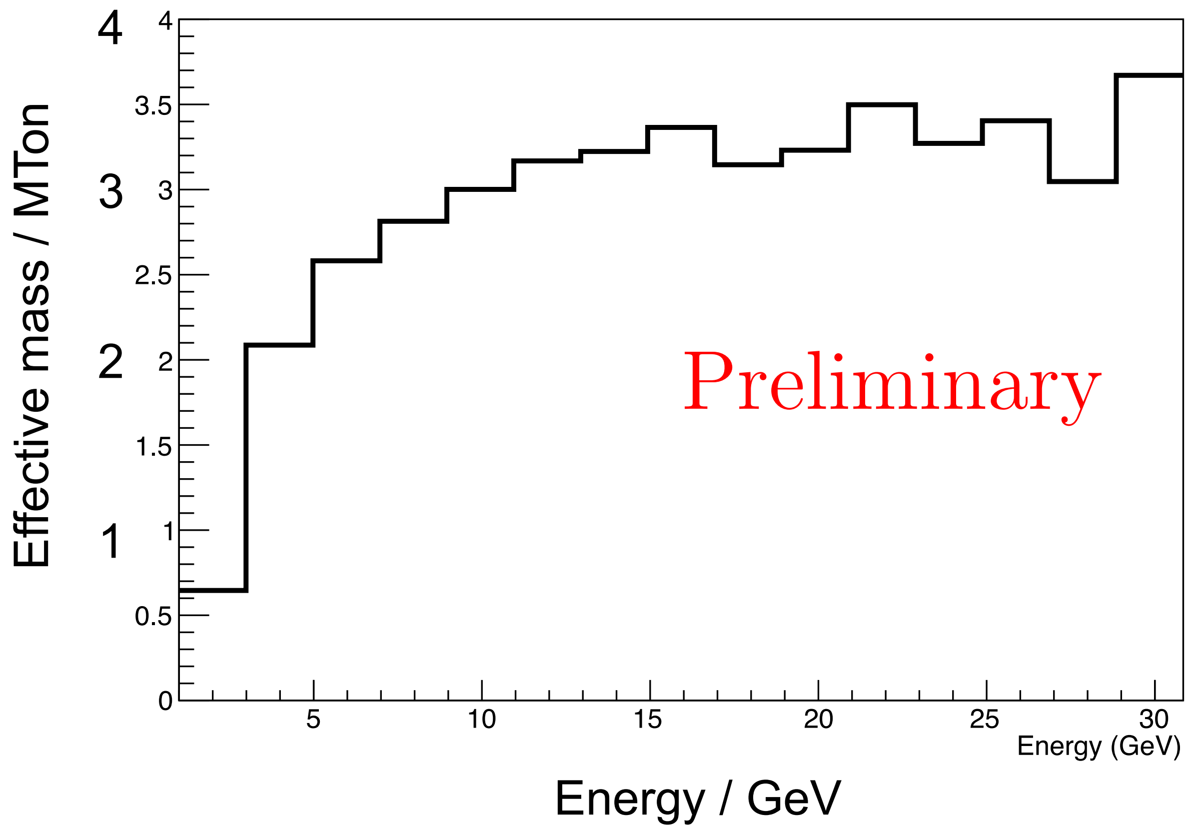
40 new strings in the central region of IceCube & DeepCore

- 20 m between strings
- 5 m vertically between DOMs

Energy threshold down to a few GeV



A megaton detector



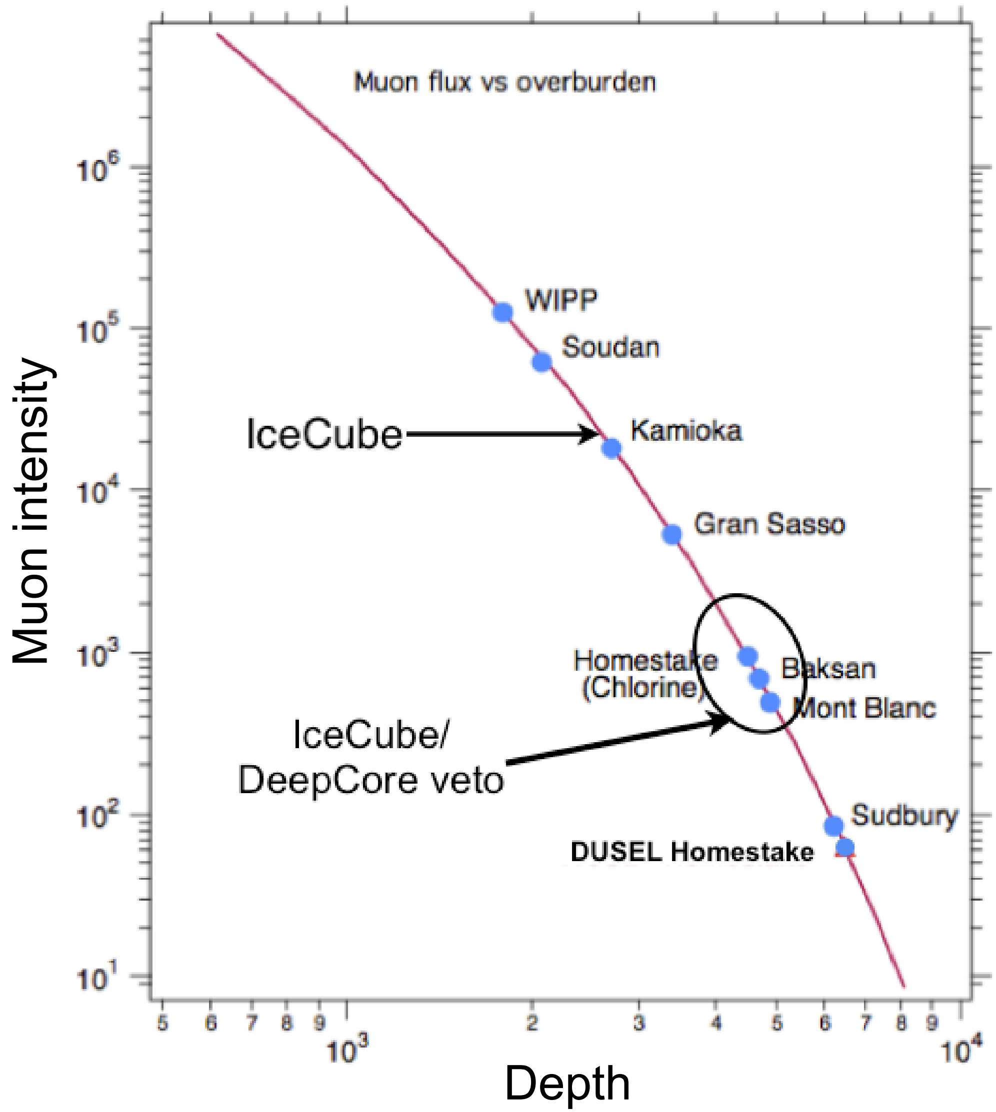
- Effective volume for muon neutrinos

Cosmic muon veto

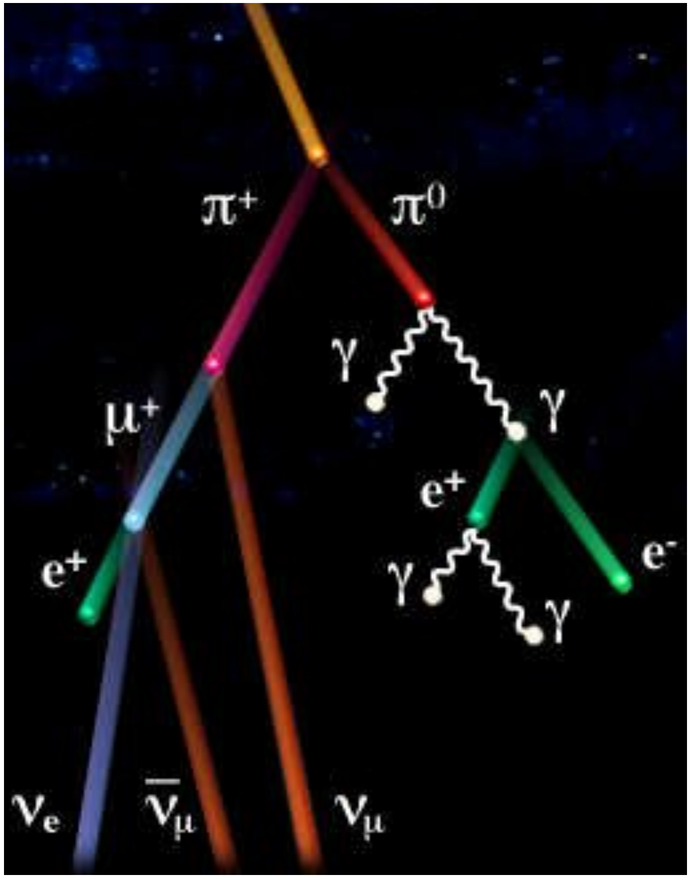
IceCube surrounds PINGU

- This can be used to veto cosmic muons

The resulting cosmic muon rate is comparable to that of deep mines



Atmospheric neutrinos



Cosmic rays strike the upper atmosphere

- Neutrinos produced from pion and muon decay

Produces a 2:1 ν_μ:ν_e ratio

- Fewer ν_e at higher energies when muons hit the ground before decaying

Antineutrino interaction cross section is a factor of ~2 lower than for neutrinos

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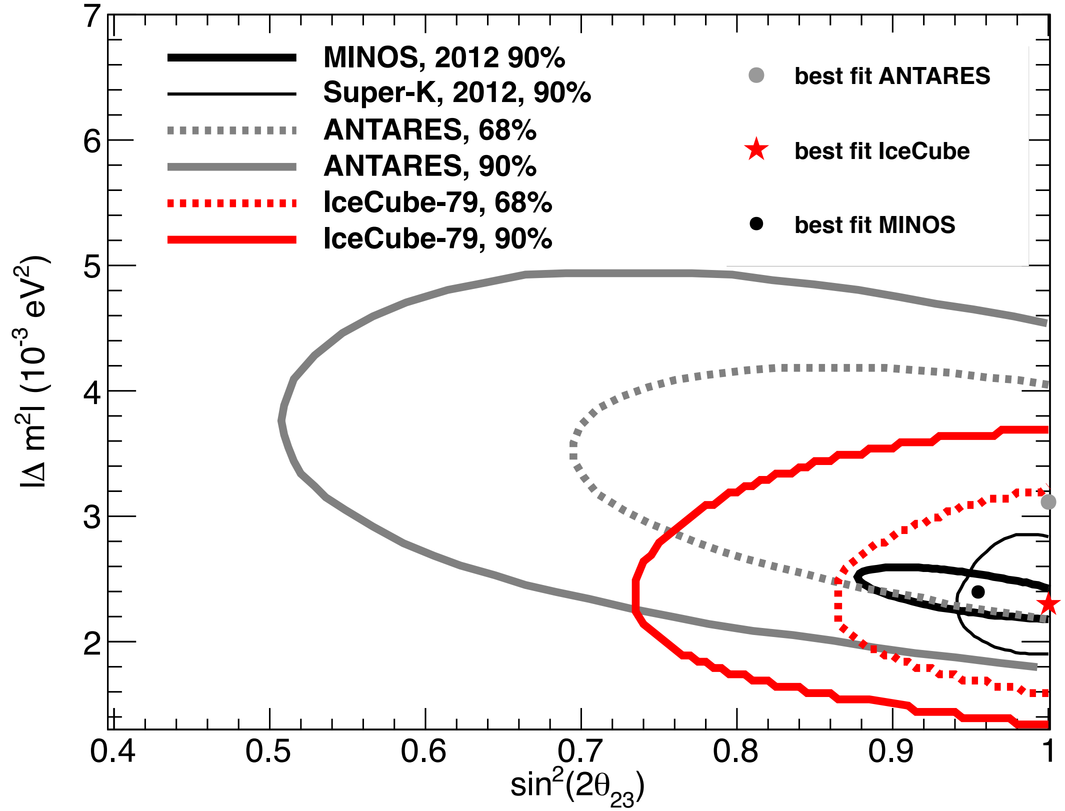
Neutrino oscillations



- DeepCore has already been used to measure the atmospheric neutrino oscillation parameters

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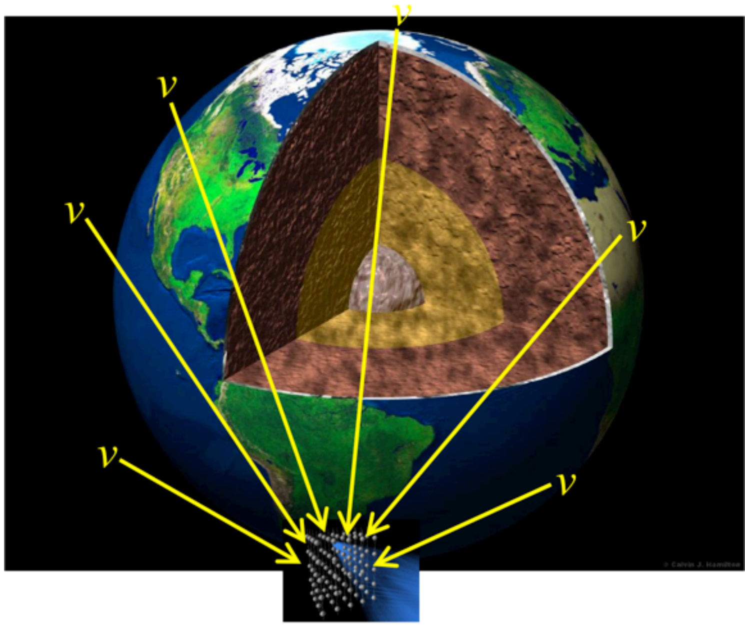
The MSW effect

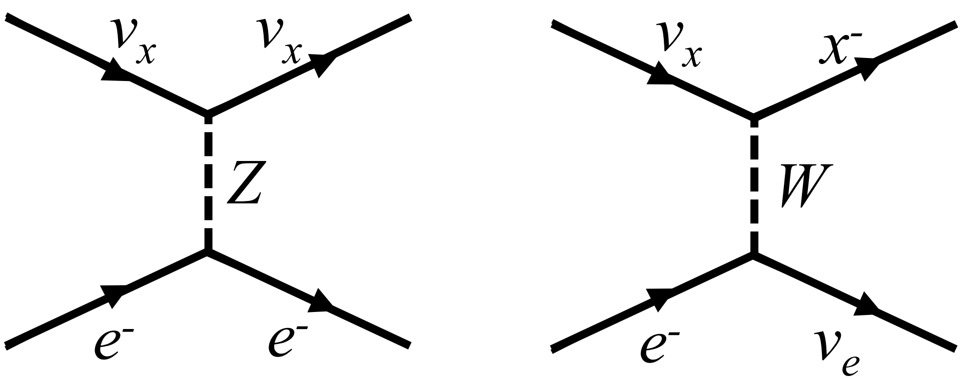
Atmospheric neutrinos pass through the Earth

- Feel an interaction with the Earth's matter

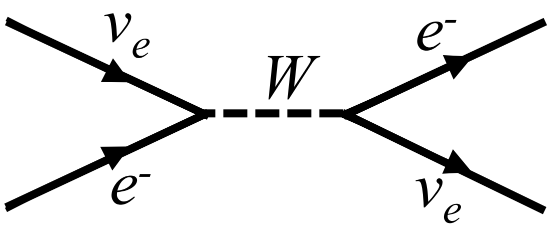
Electron neutrinos feel an additional interaction

- Acts like a refractive index
- This effectively changes the mixing angles





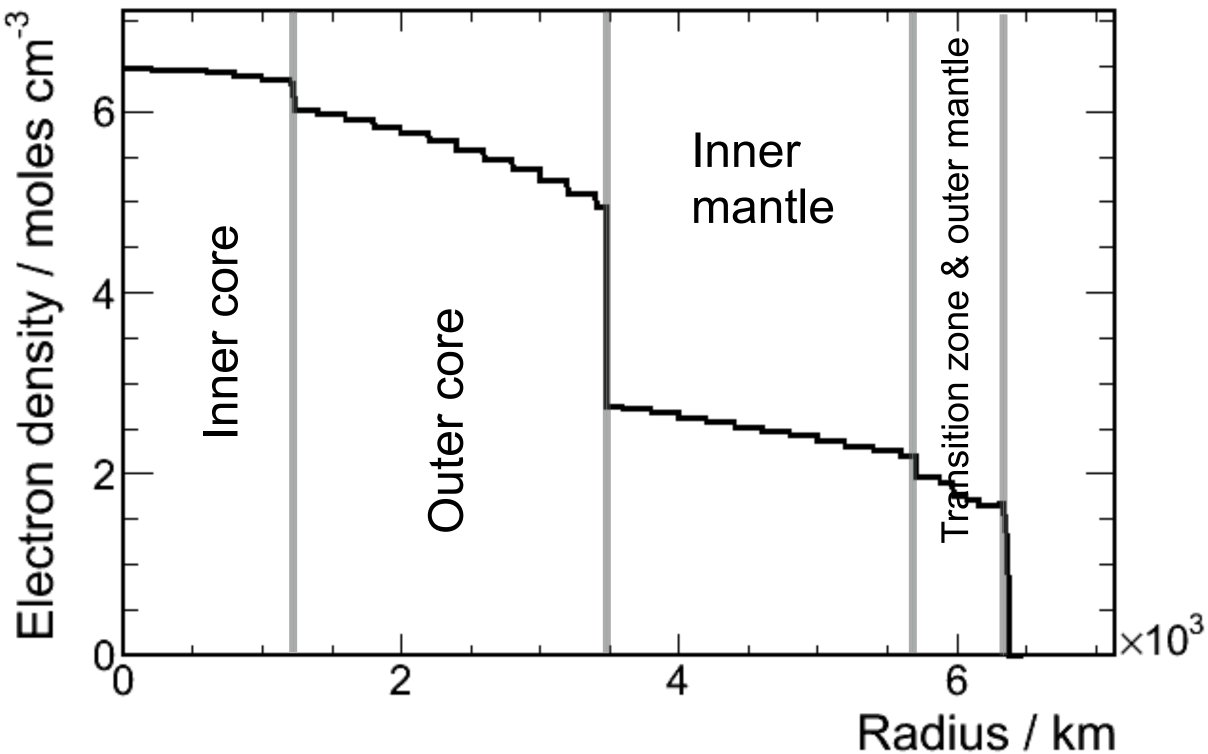
All flavours



Electron flavour

Preliminary Reference Earth Model (PREM)
Phys. Earth. Plan. Int. **25**, 297 (1981)

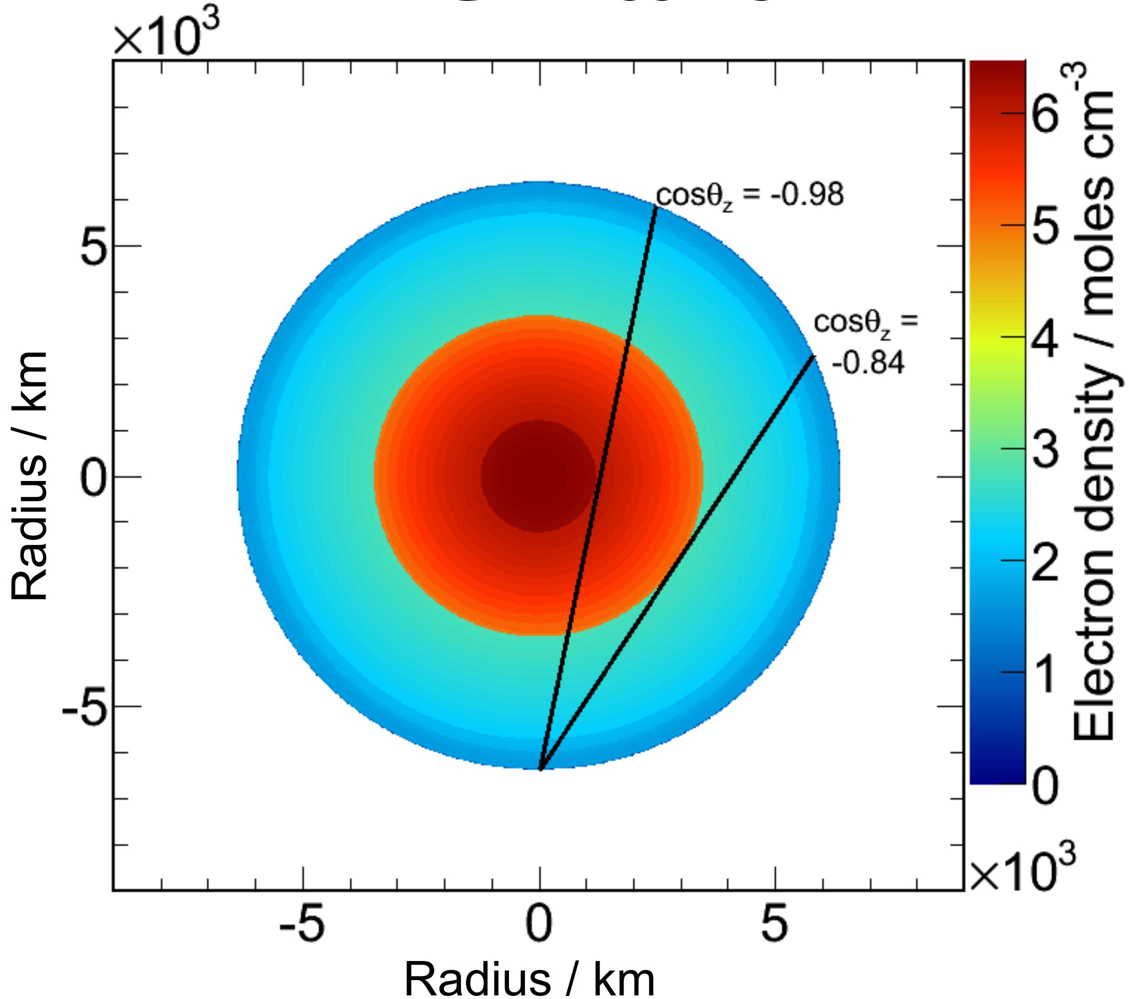
The Earth



Three distinct zones of density

- Sharp changes in density between the zones

The Earth

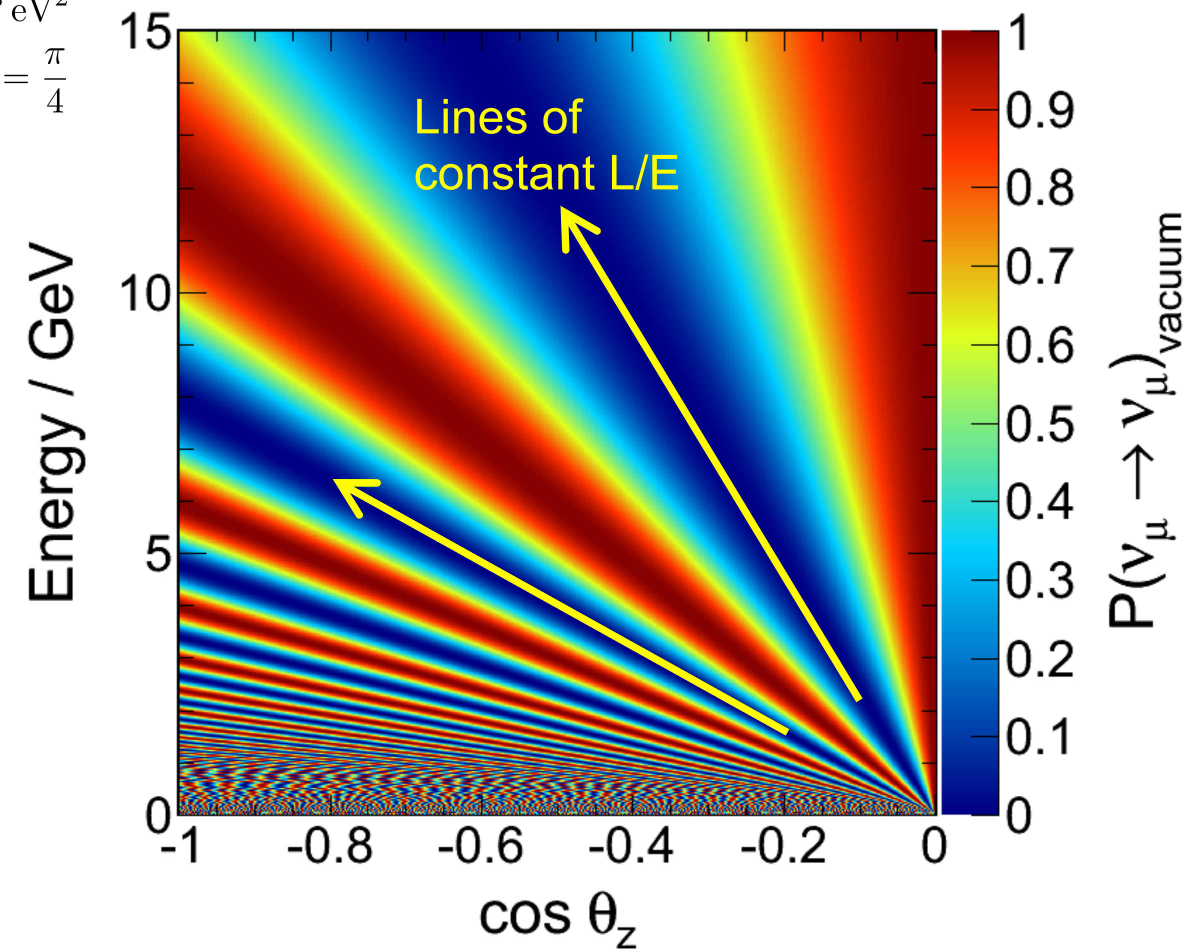


- The different regions can be probed by measuring the zenith angle of the neutrino

Neutrino oscillations in vacuum

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

$$\Delta m^2_{32} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) = \frac{\pi}{4}$$



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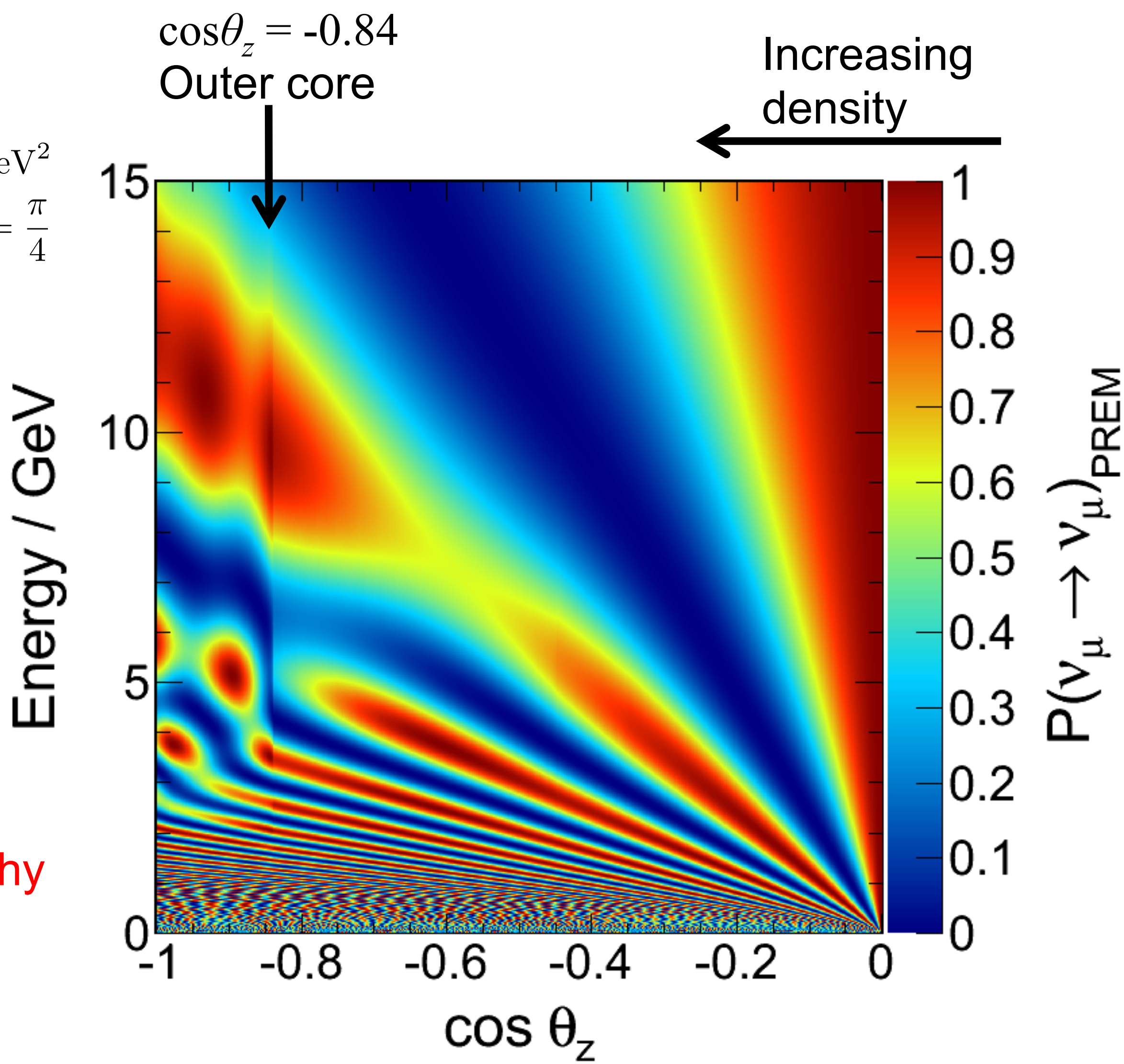
Neutrino oscillations in matter

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

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

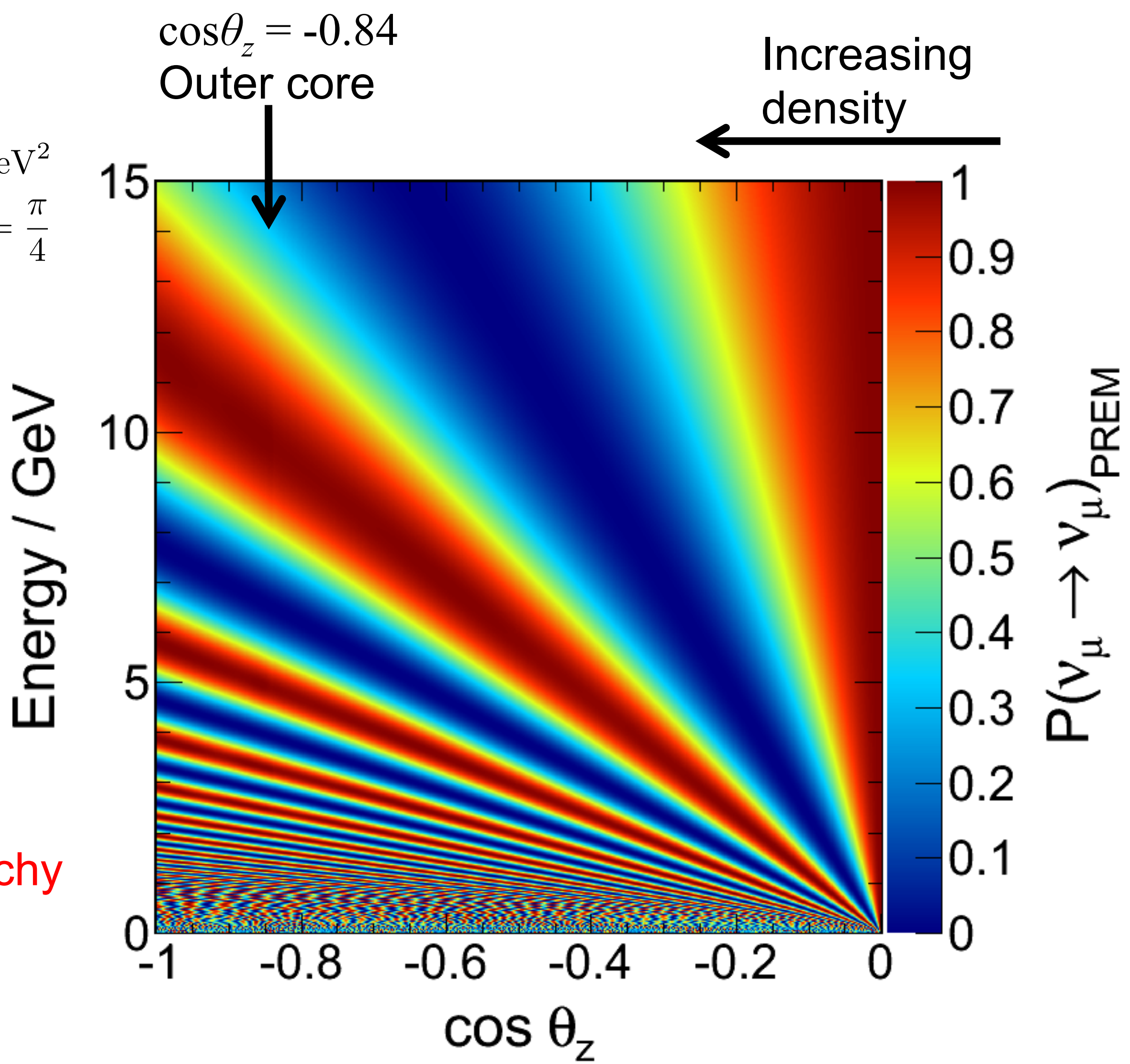


Neutrinos
Normal hierarchy

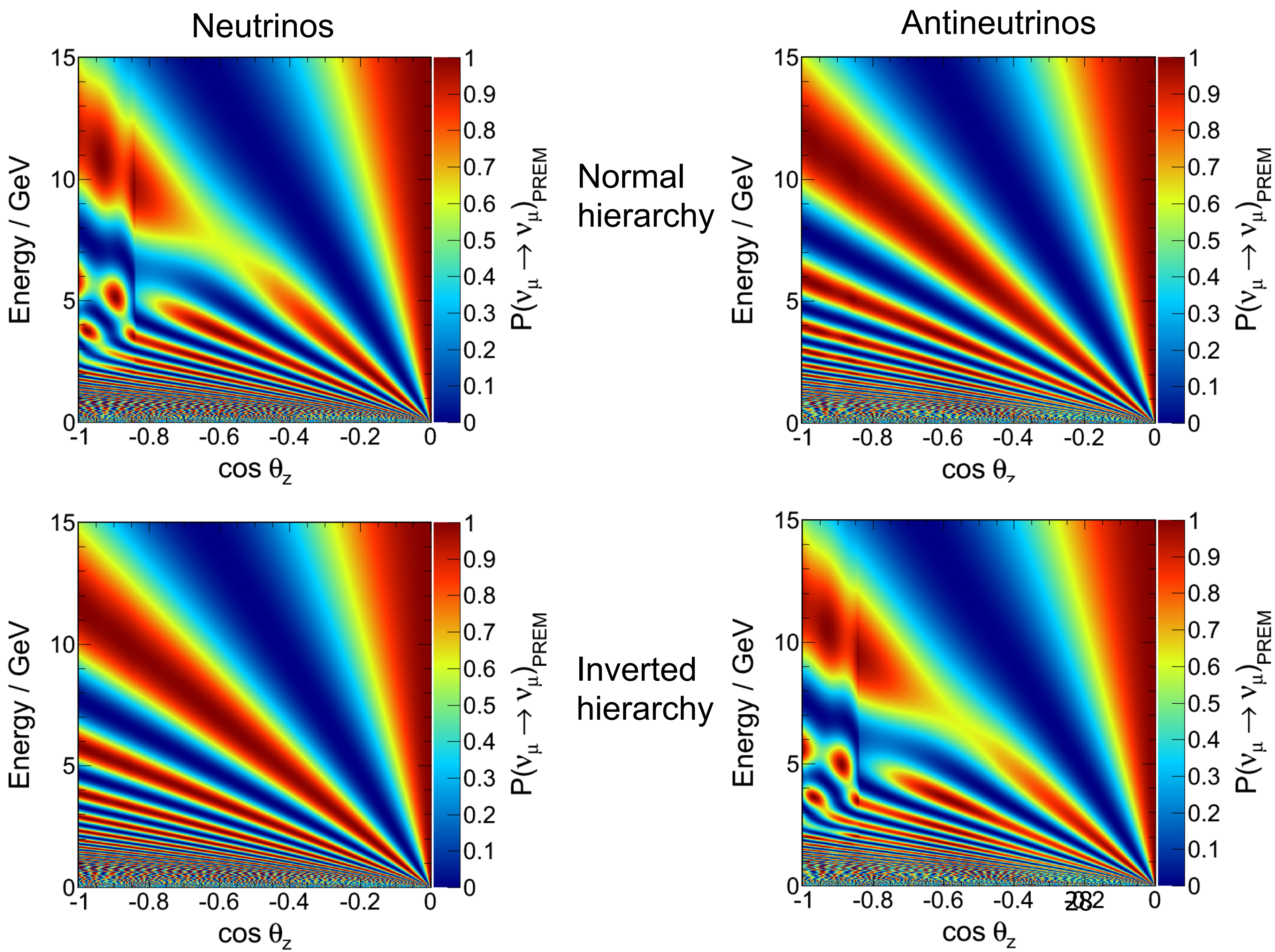
Neutrino oscillations in matter

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

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



Neutrinos
Inverted hierarchy


Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Energy / GeV
cos θ_z
$P(\nu_\mu \rightarrow \nu_\mu)_{PREM}$
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Why does this happen?

+ for neutrinos
- for antineutrinos

CC interactions of ν_e with matter

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos(2\theta) \pm \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

This modifies the neutrino mixing, producing effective mixing angles in matter:

$$\tan(2\theta_m) = \frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta) \mp \sqrt{2}G_F N_e}$$

- for neutrinos
+ for antineutrinos

This has a resonance condition for neutrinos in the normal hierarchy or antineutrinos in the inverted hierarchy

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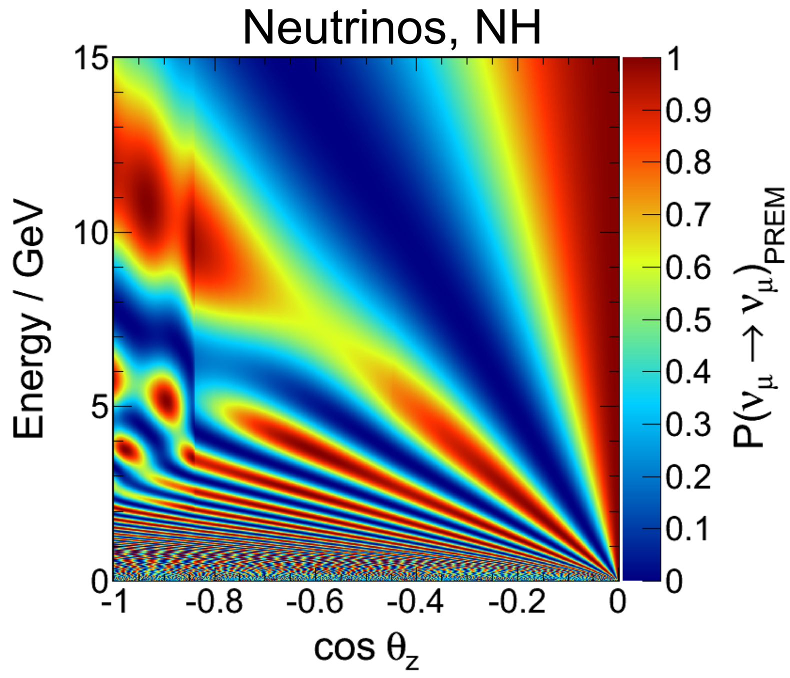
PINGU

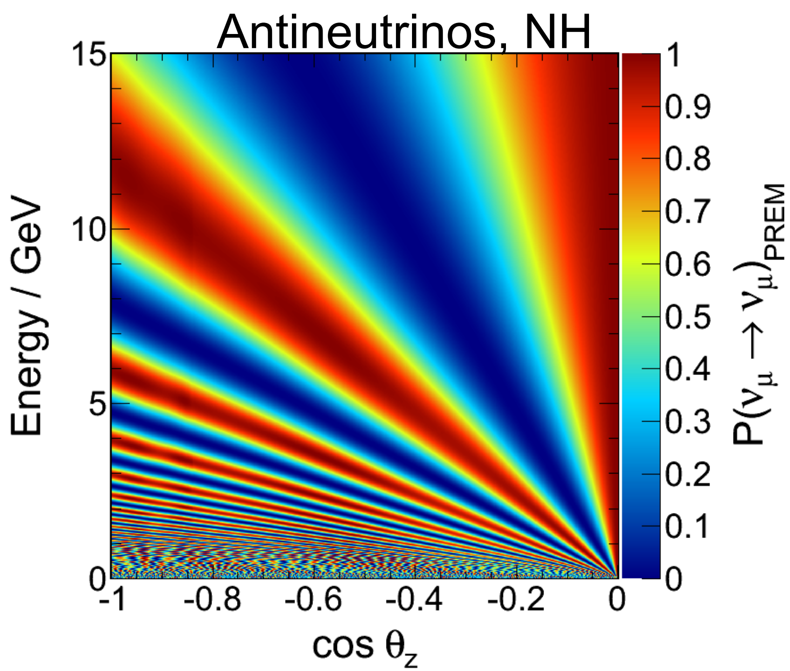
PINGU cannot distinguish neutrinos from antineutrinos

- No magnetic field

But the neutrino and antineutrino cross sections differ by a factor of two

- Statistically, there will be an observable difference between the hierarchies
- And at the megatonne scale, PINGU will have plenty of statistics





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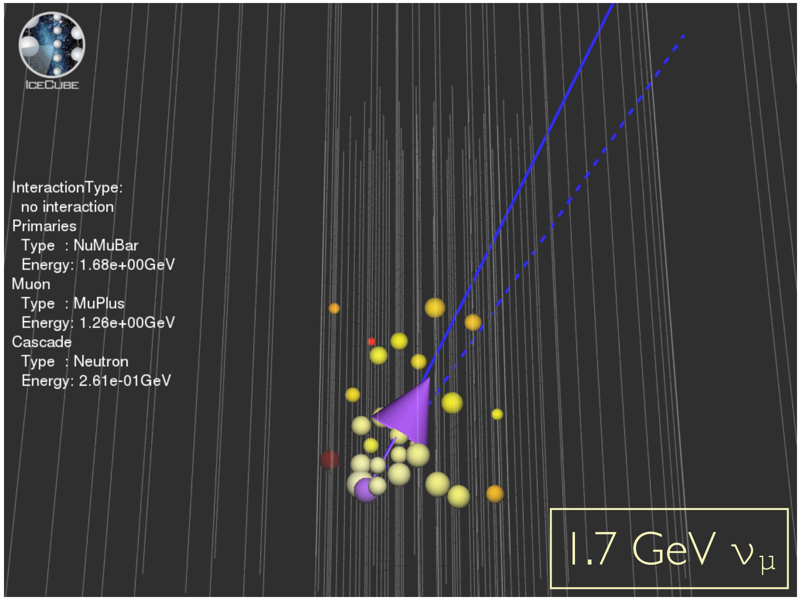
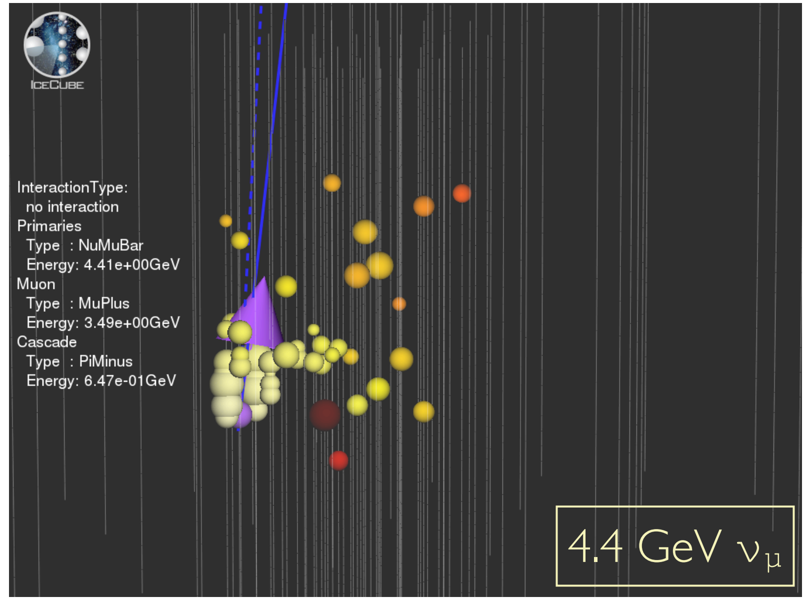
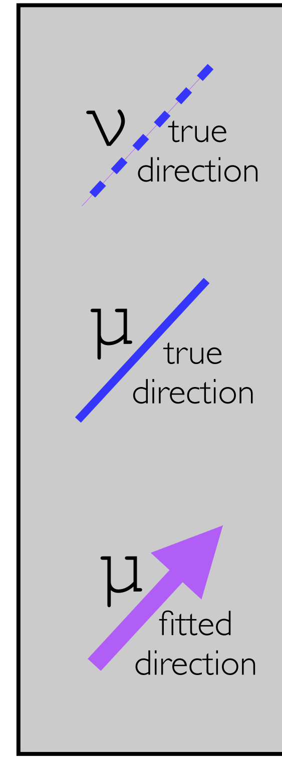
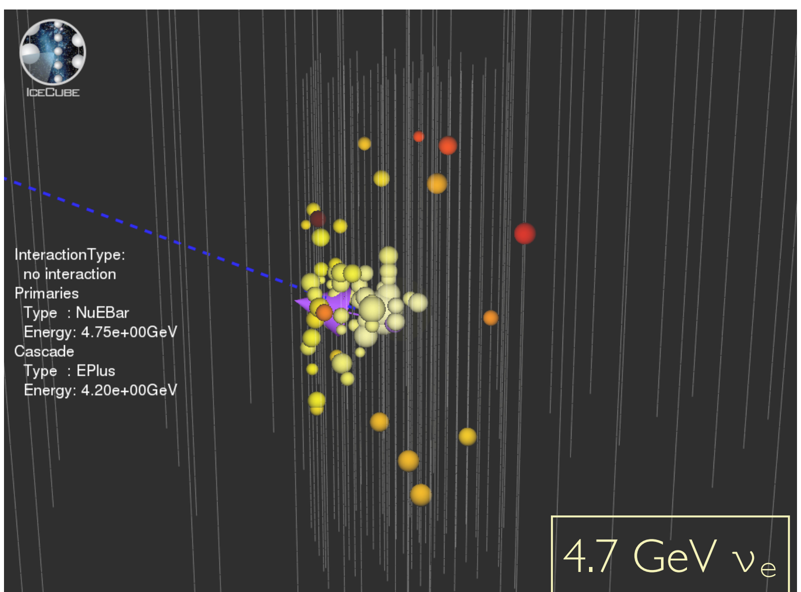
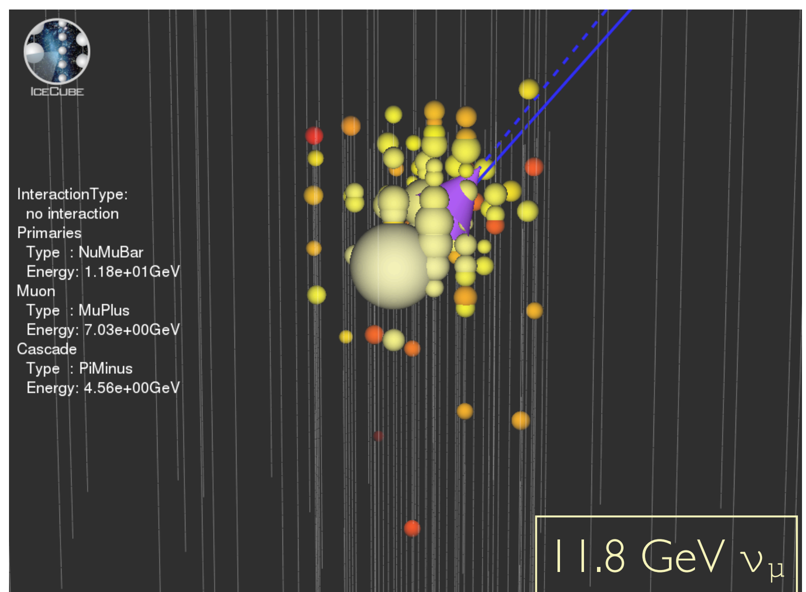
Sample reconstructed events





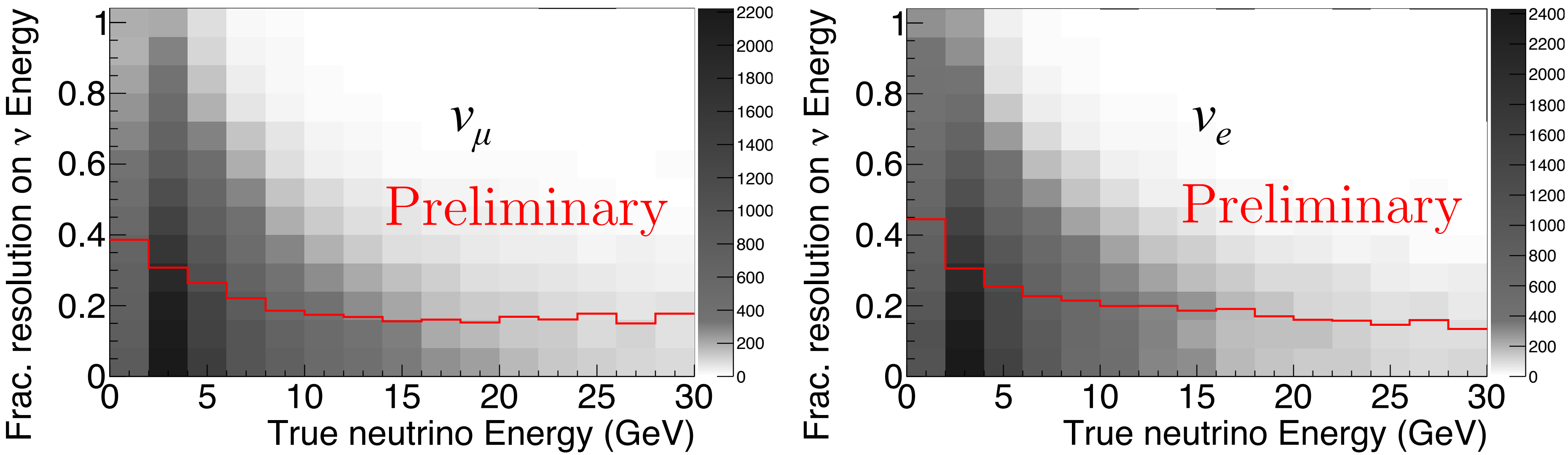






Size of circles: N_γ.
Color: t_γ.

Energy resolutions

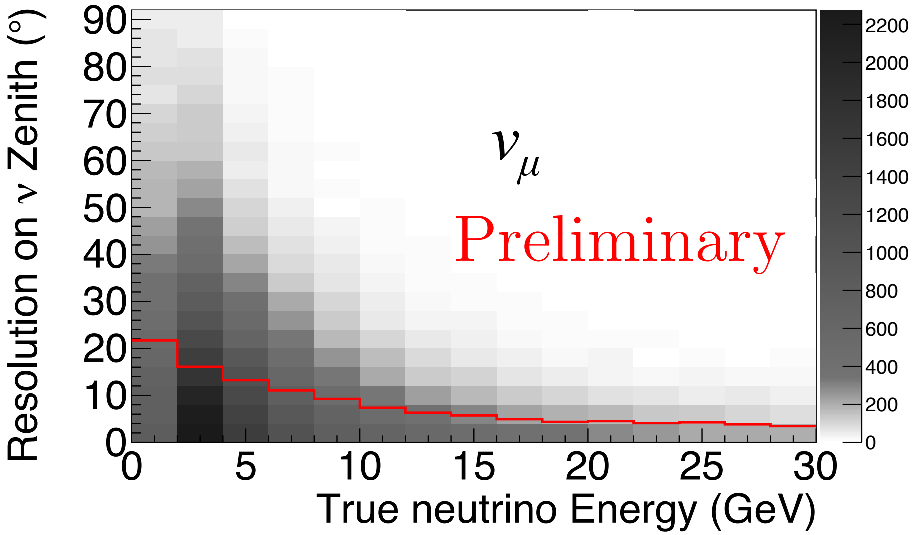


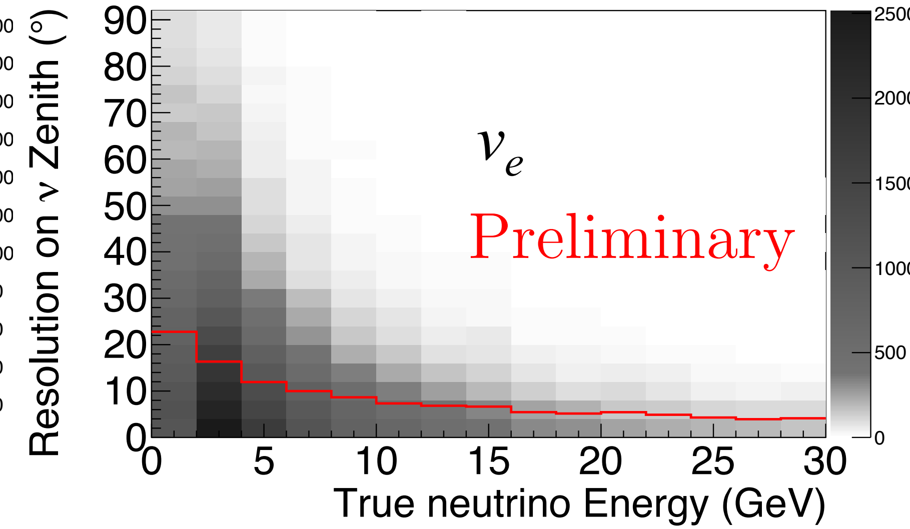
Red line shows median resolutions

Reconstruction subdivides the DOM readout pattern as a function of time

- Fits to a number of parameters: interaction position and time, μ track length and direction, hadronic cascade energy

Zenith angle resolutions





Red line shows median resolutions

Reconstruction subdivides the DOM readout pattern as a function of time

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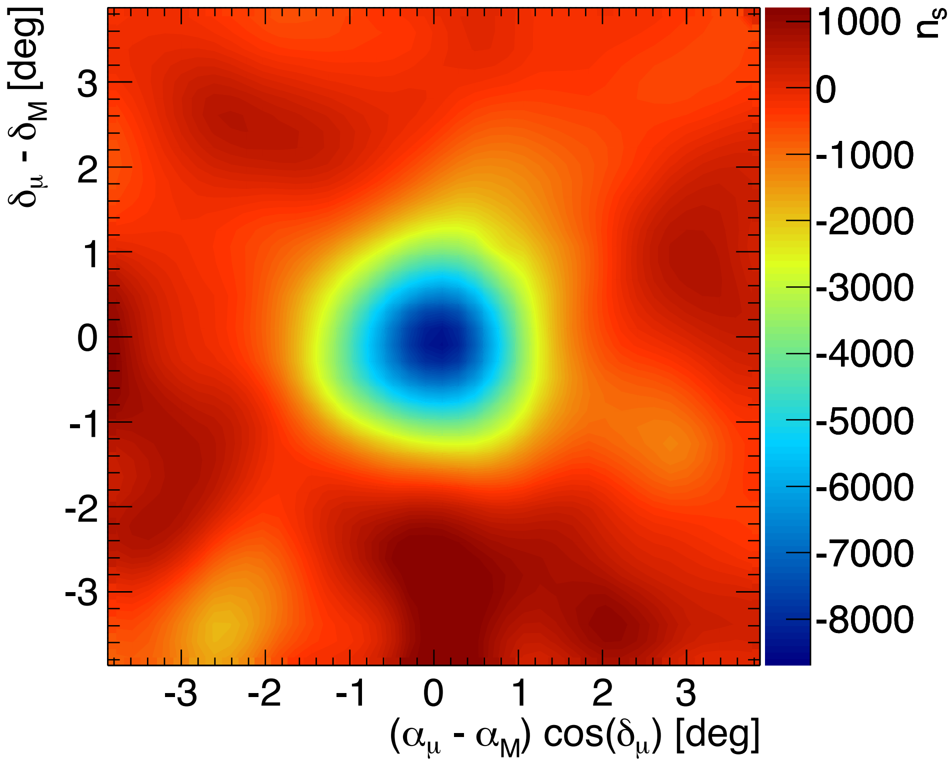
Muon pointing



IceCube observed the moon shadow to demonstrate an angular resolution of < 1° with TeV muons

PINGU's resolution will be lower

- But muons that trigger both IceCube and PINGU can be used to validate PINGU reconstruction

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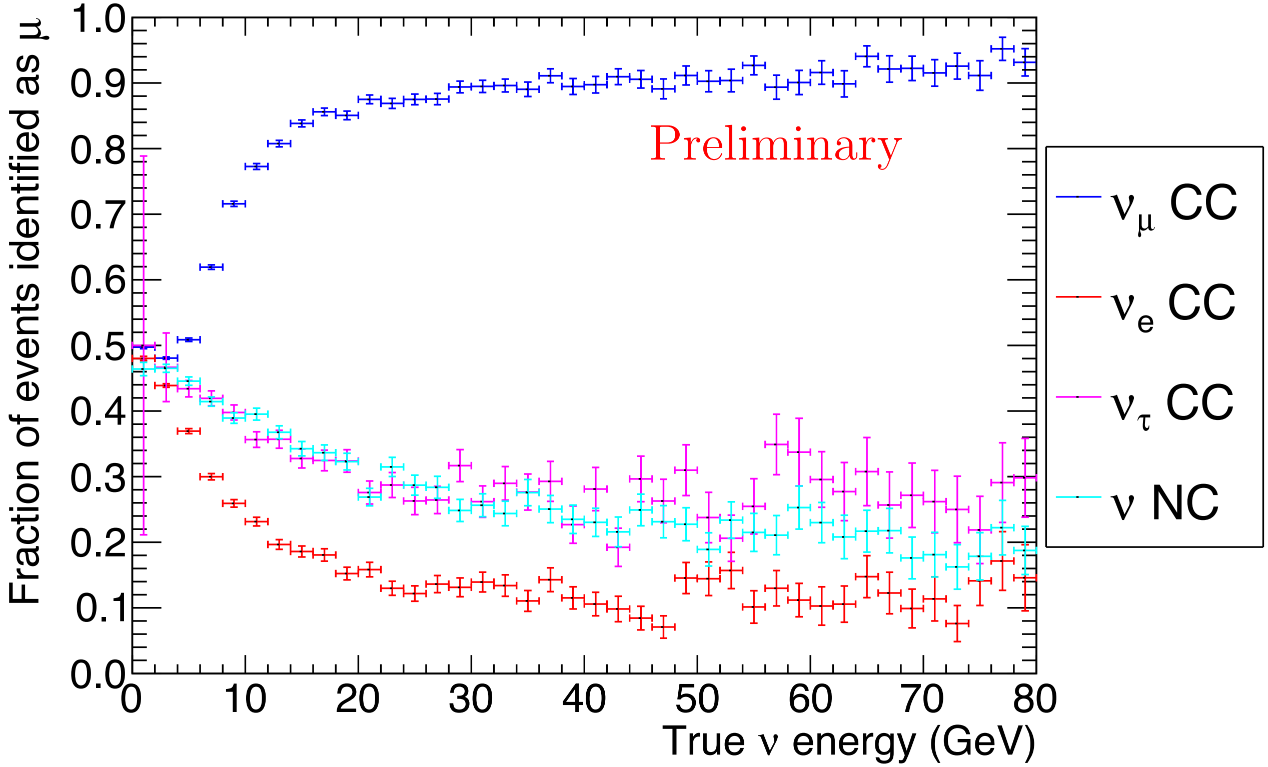
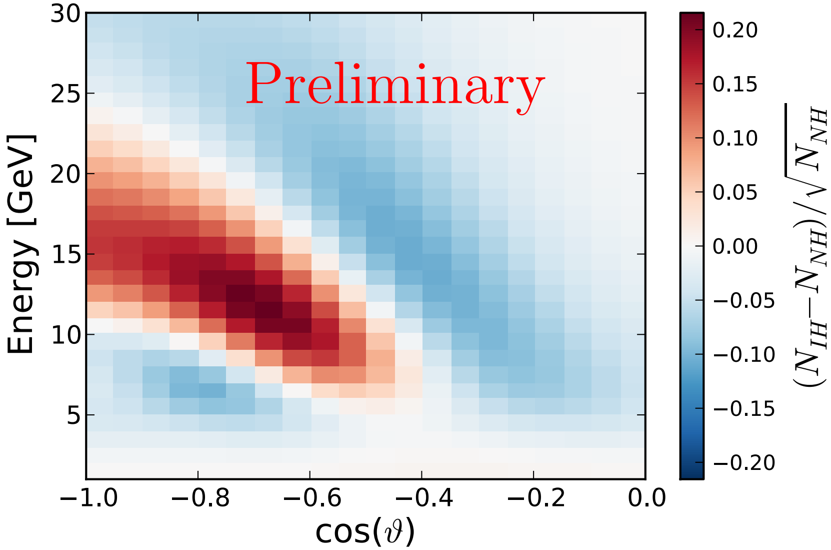
Event selection



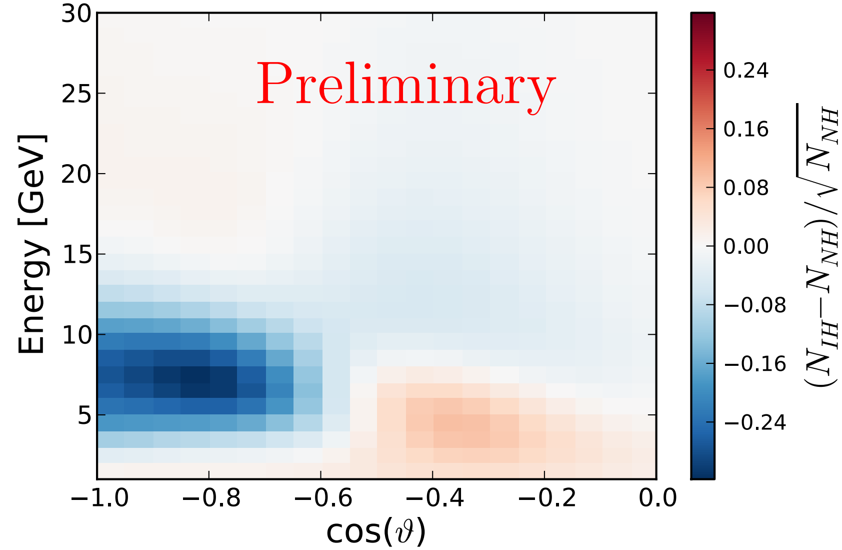
Separate events into track-like and cascade-like

- Based on reconstructed track length, quality of fit to track hypothesis

Hierarchy separation



ν_μ CC events



ν_e CC events

Distinguishability after one year of data

- With realistic resolutions and particle identification

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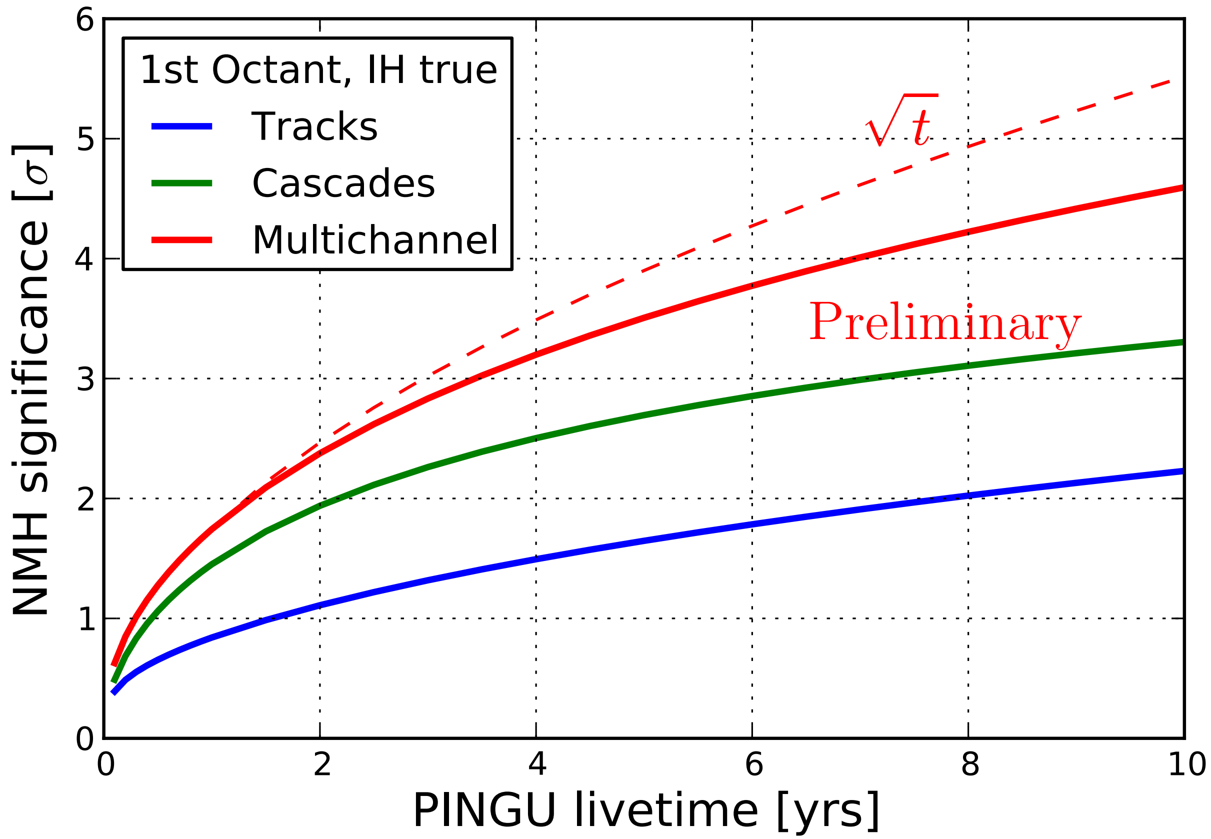
Hierarchy sensitivity



3σ sensitivity after three years of running

- Does not include livetime from partially-built detector
- Assumes $\theta_{23} = 40^{o}$

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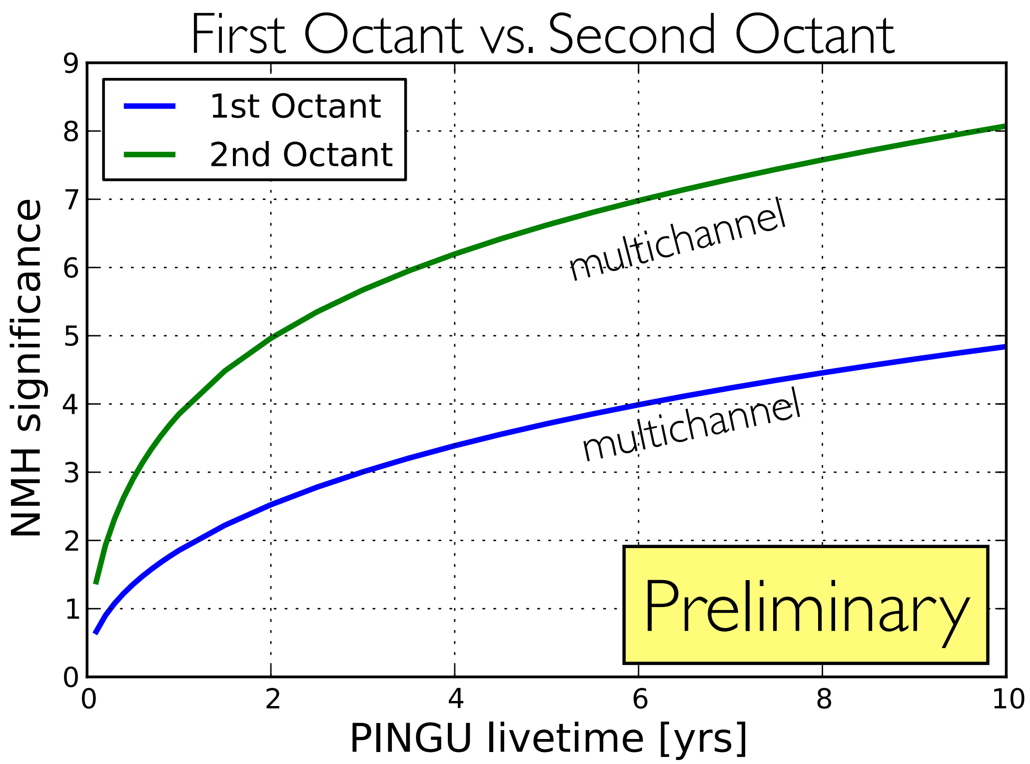
Dependence on octant



The hierarchy can be easier to determine, depending on the value of θ_{23}

- The baseline sensitivity assumes $\theta_{23} = 40^o$

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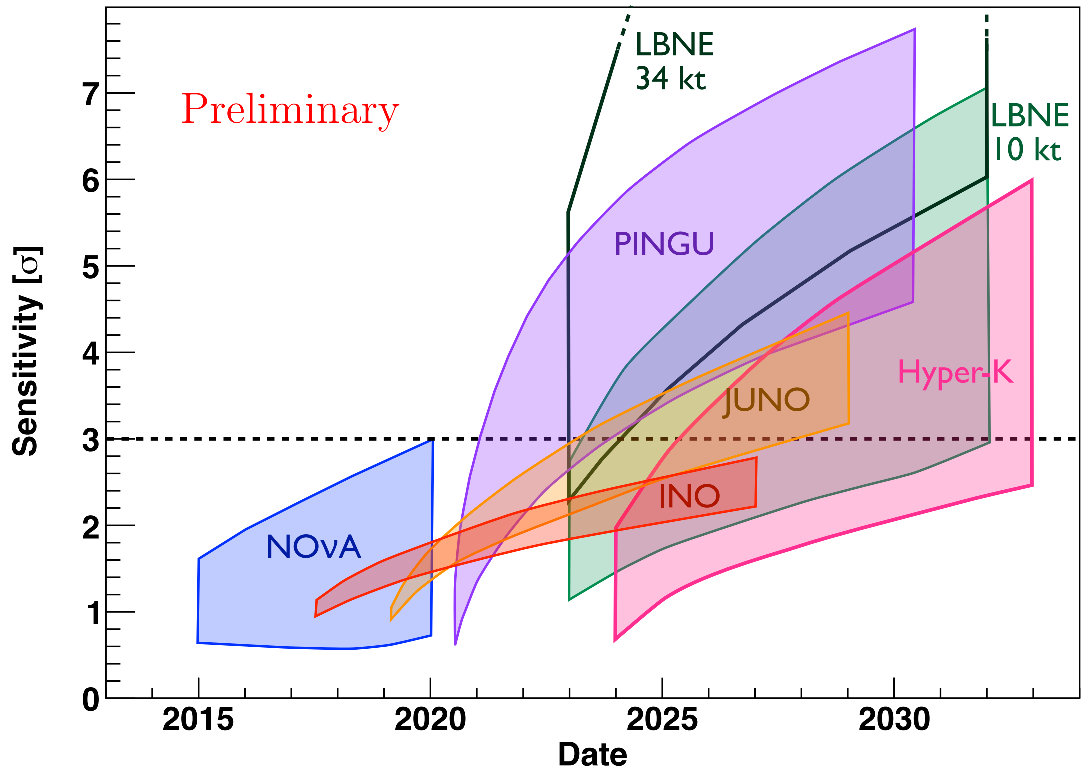
The global situation



Sensitivity to the mass hierarchy for various future experiments

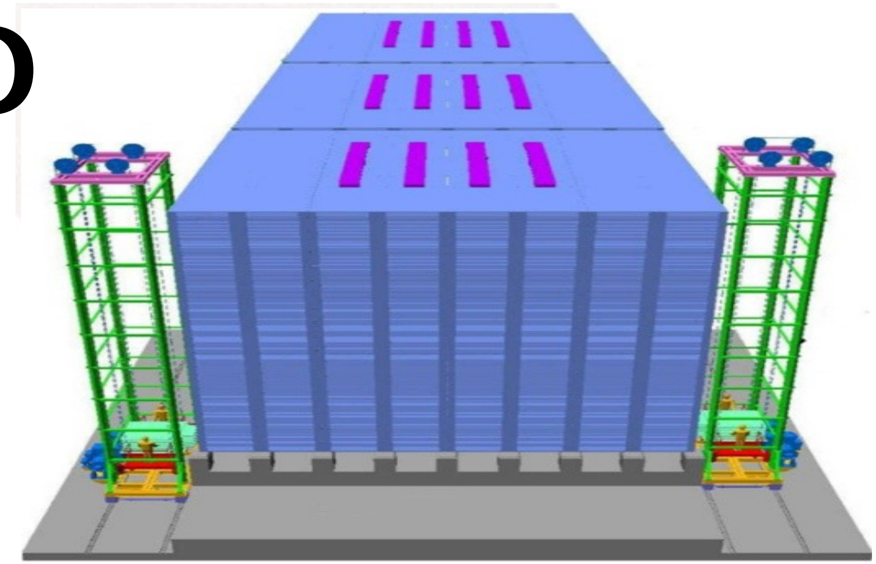
- The bands represent the dependence of the sensitivities on θ_{23}, δ_{CP} and the true hierarchy

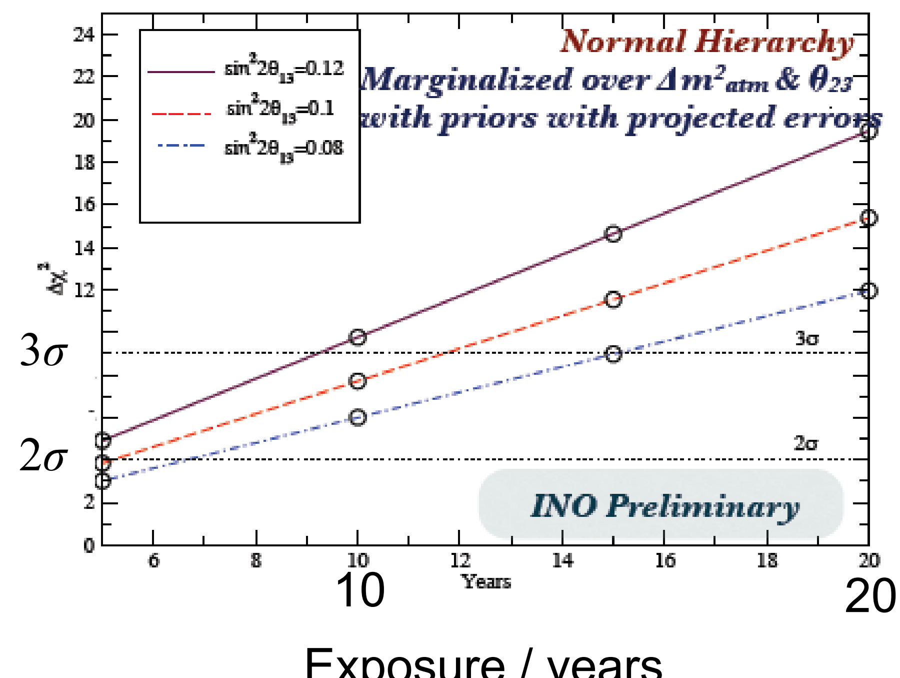
INO

A detector that can distinguish neutrinos from antineutrinos can use this information to disentangle the mass hierarchy

INO is a proposal that can do this

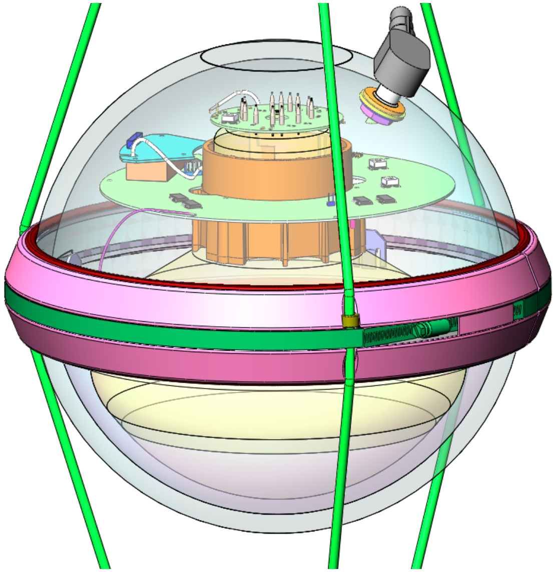
- Magnetised iron calorimeter
- The proposed mass is 50 kt, so the statistics are much smaller than PINGU





PINGU technology

IceCube



PINGU

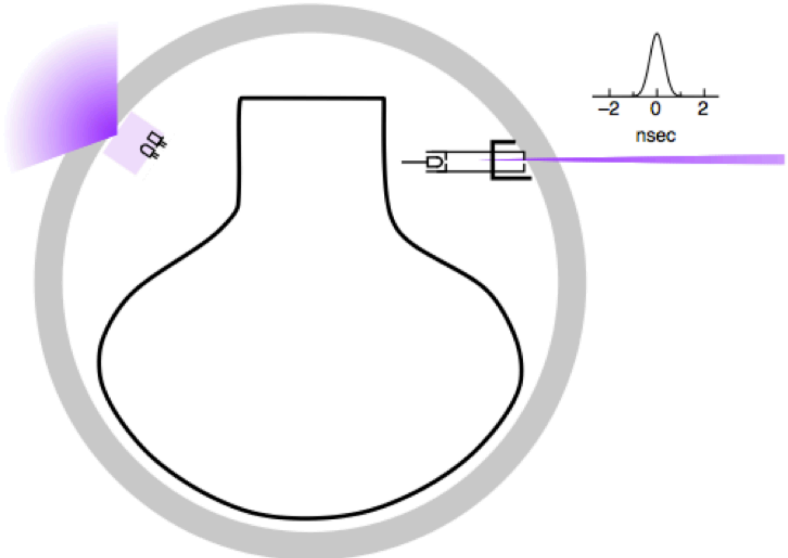
Minimal changes to the IceCube DOM design

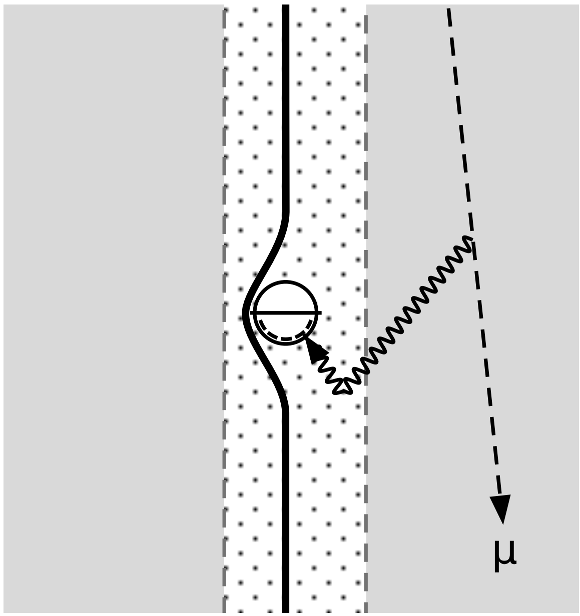
- Both use a 10” Hamamatsu PMT
- PINGU will have simplifications to the electronics boards

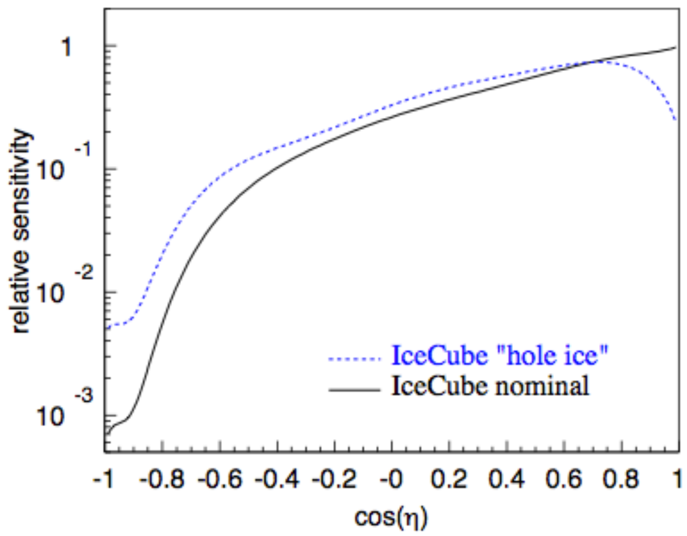
DOMs have proved very reliable

- 98.4% were operable after installation
- Only 0.4% have failed since

Calibration



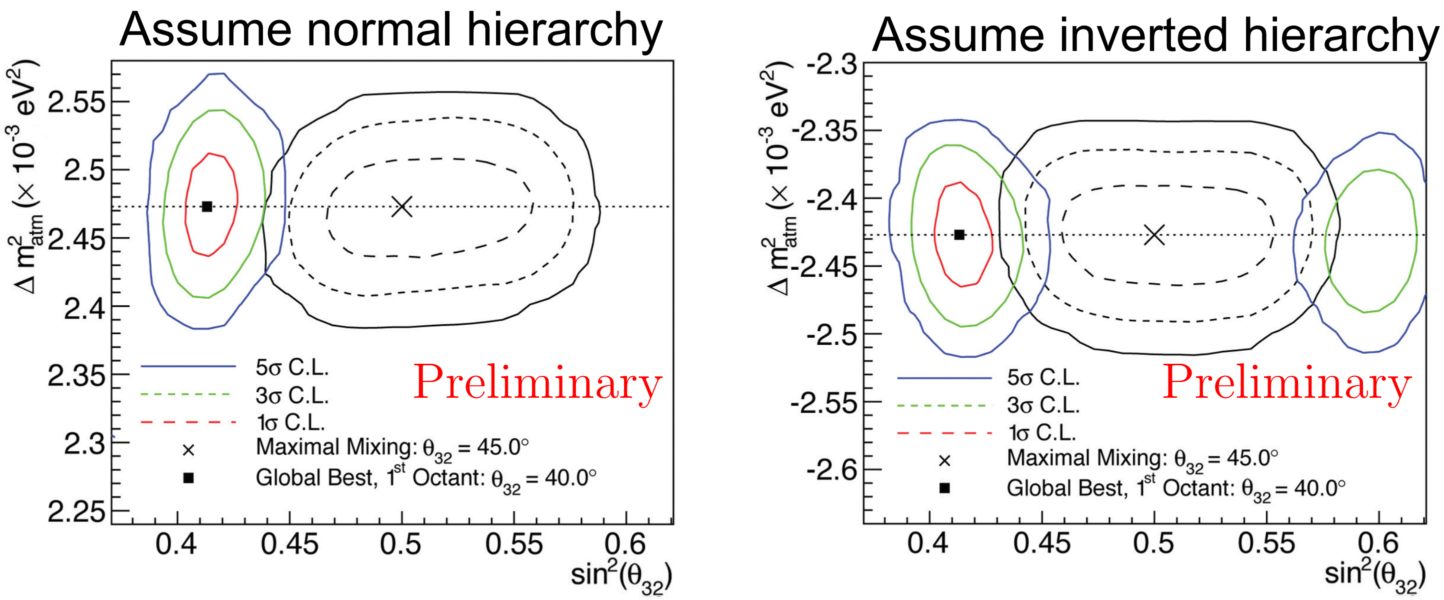




Cosmic muons and LED flashers monitor ice properties and DOM response

- LED light level calibrated to 3%
- Sensitivities use a 5% energy scale uncertainty

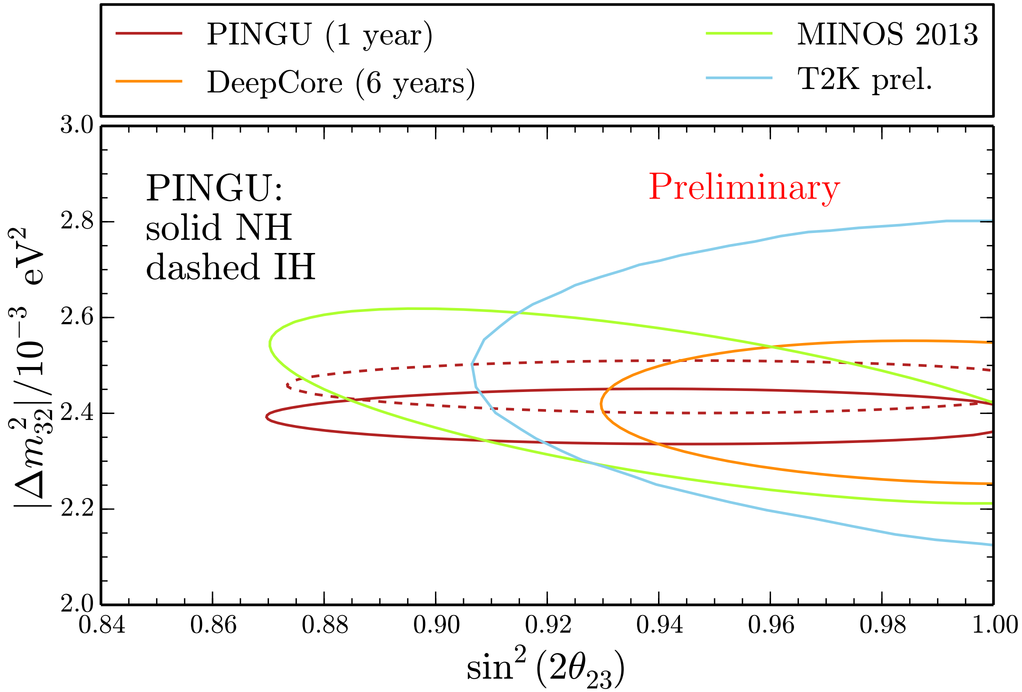
Octant determination



Sensitivity to θ_{23} shown for five years of data

- Depends on which hierarchy is true

Parameter measurements



- With one year of data, PINGU can make a precise measurement of the absolute values of the oscillation parameters

Schedule and budget

From start of funding

- 5 years to detector completion
- 3.5 years to first data

Budget (40 strings, with contingency)

- PINGU as a stand-alone project: $105M
- As part of IceCube facility: $80M
  - Resources shared between experiments

Summary

PINGU can measure the neutrino mass hierarchy

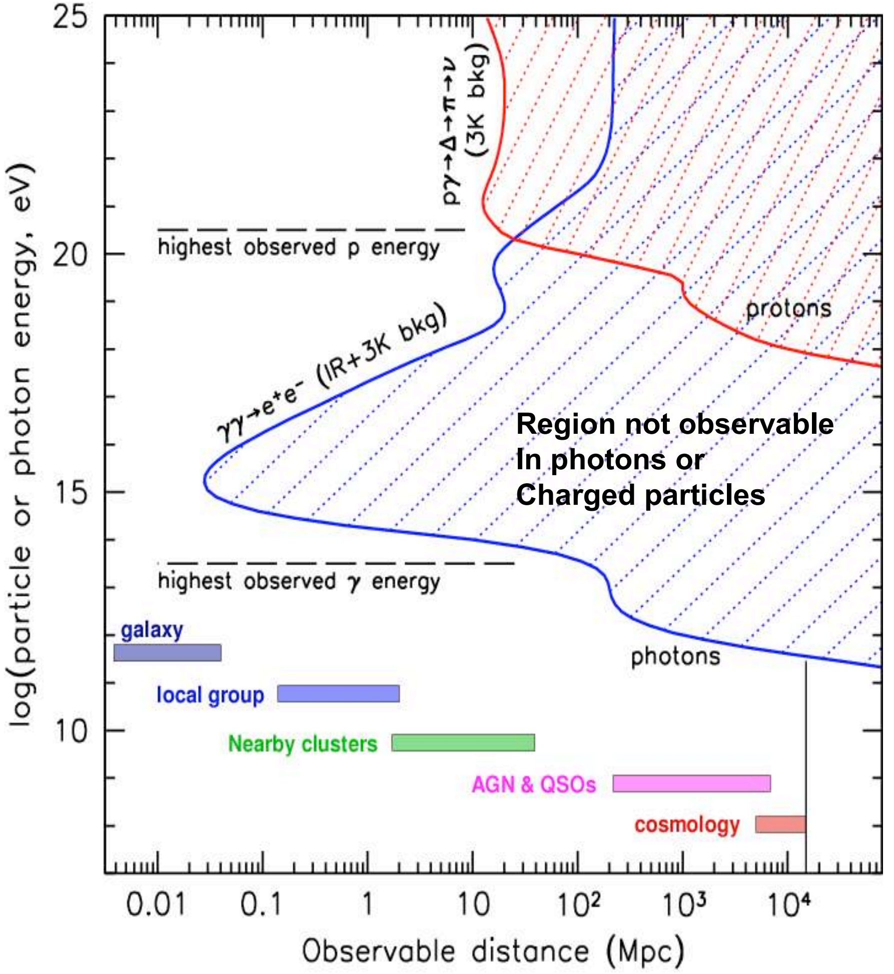
- 3σ in three years
- Complementary to NOνA, LBNE, reactor experiments
- Measurements in multiple experiments will be vital

PINGU will use well-understood technology

- Tried and tested with IceCube
- Can be built quickly

Cost is relatively low

Ultra high energy cosmic particles



Protons

- Relatively abundant
- No directional information due to galactic magnetic fields

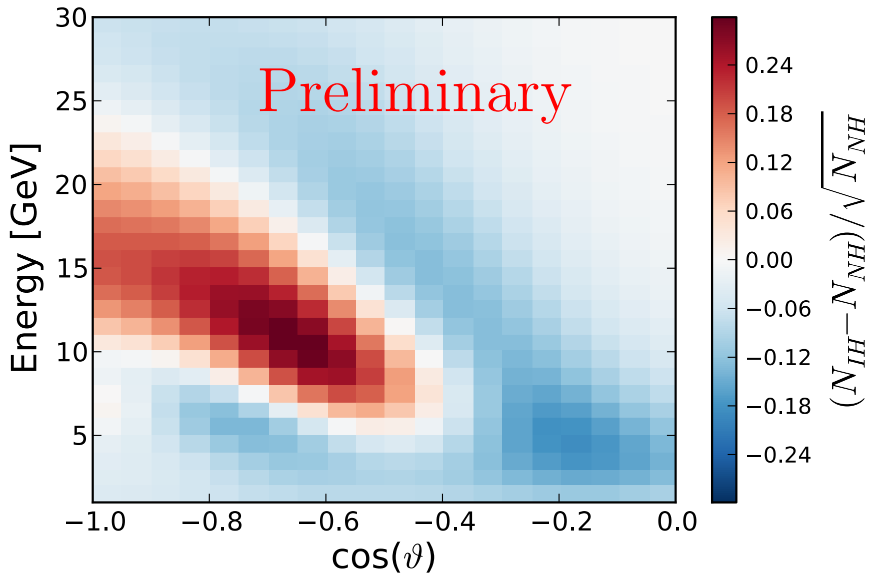
Photons

- Good directionality
- Above TeV energies, absorbed on cosmic background radiation

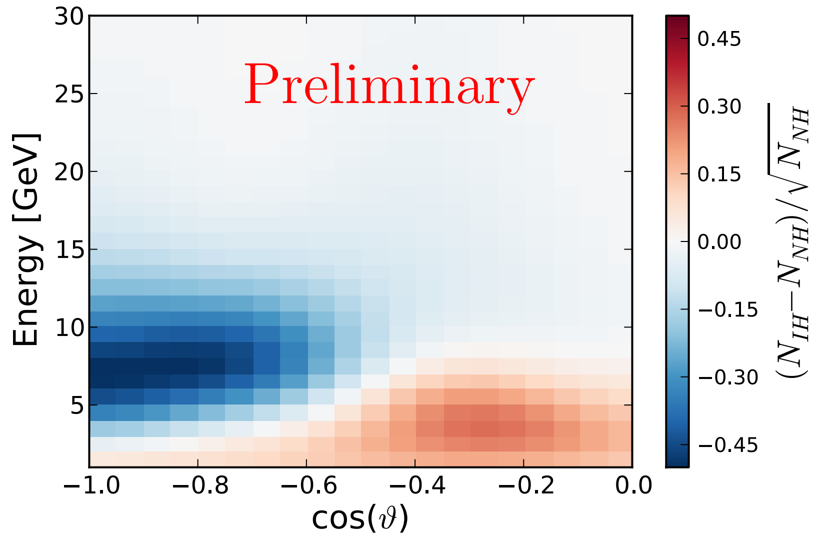
Neutrinos

- Good directionality
- Free to propagate at high energies
- Difficult to detect

Hierarchy separation after reconstruction



ν_μ CC events



ν_e CC events

These plots show the bin-by-bin significance for one year of data

- With realistic resolutions
- But perfect event selection

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