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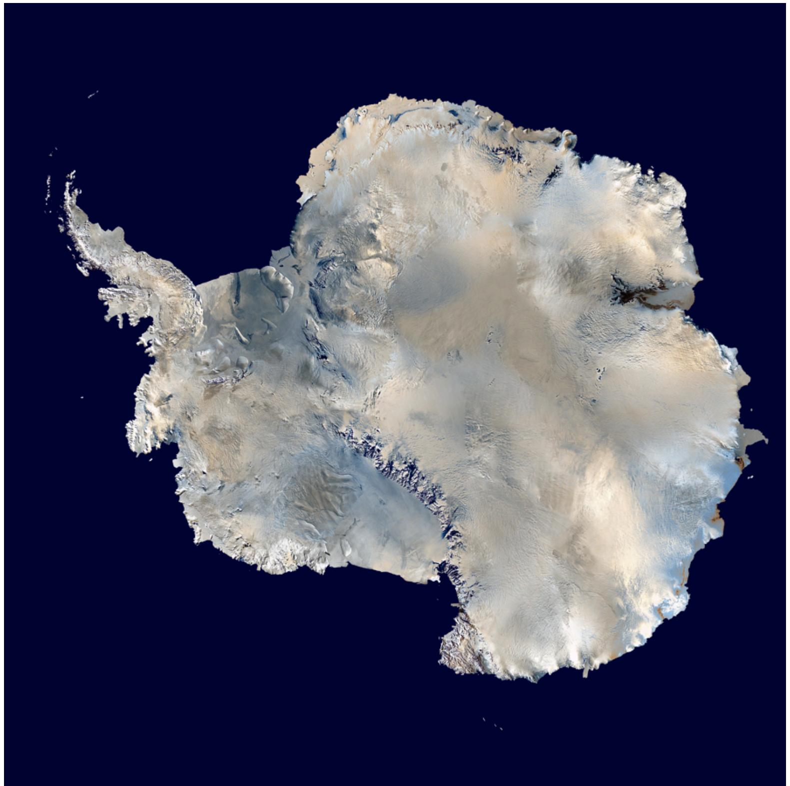
Measuring the neutrino mass hierarchy with PINGU

Justin Evans

PRECISION ICECUBE NEXT GENERATION UPGRADE



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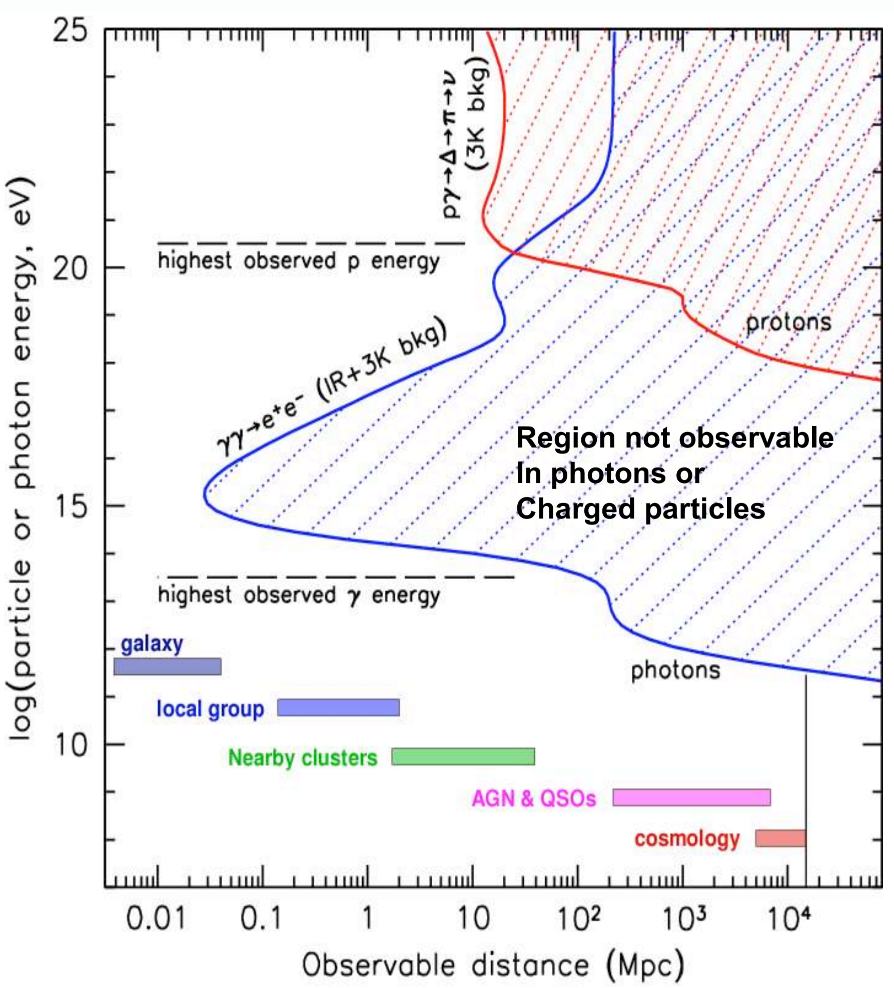
Ultra high energy cosmic particles



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

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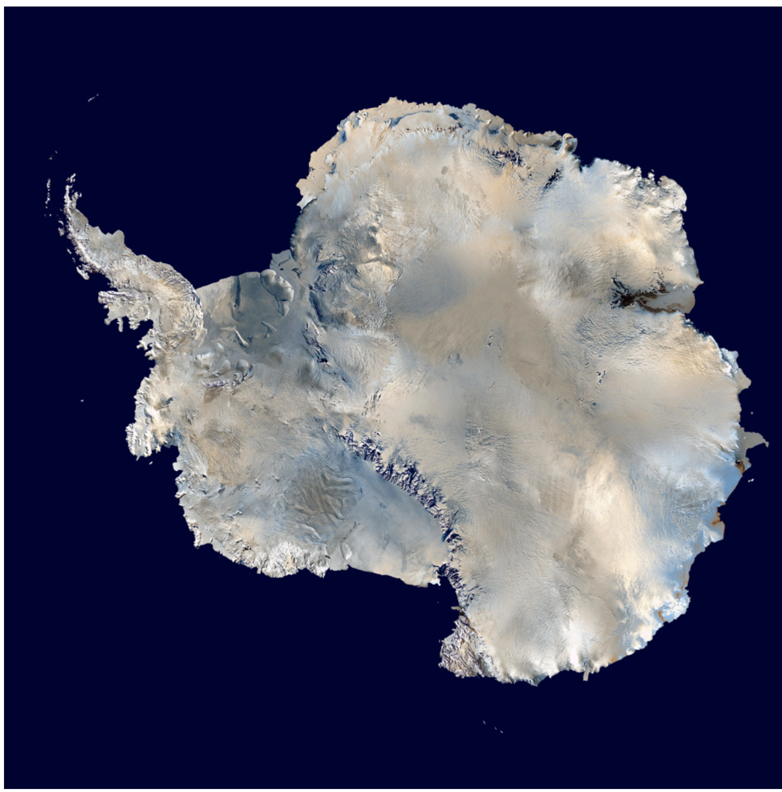
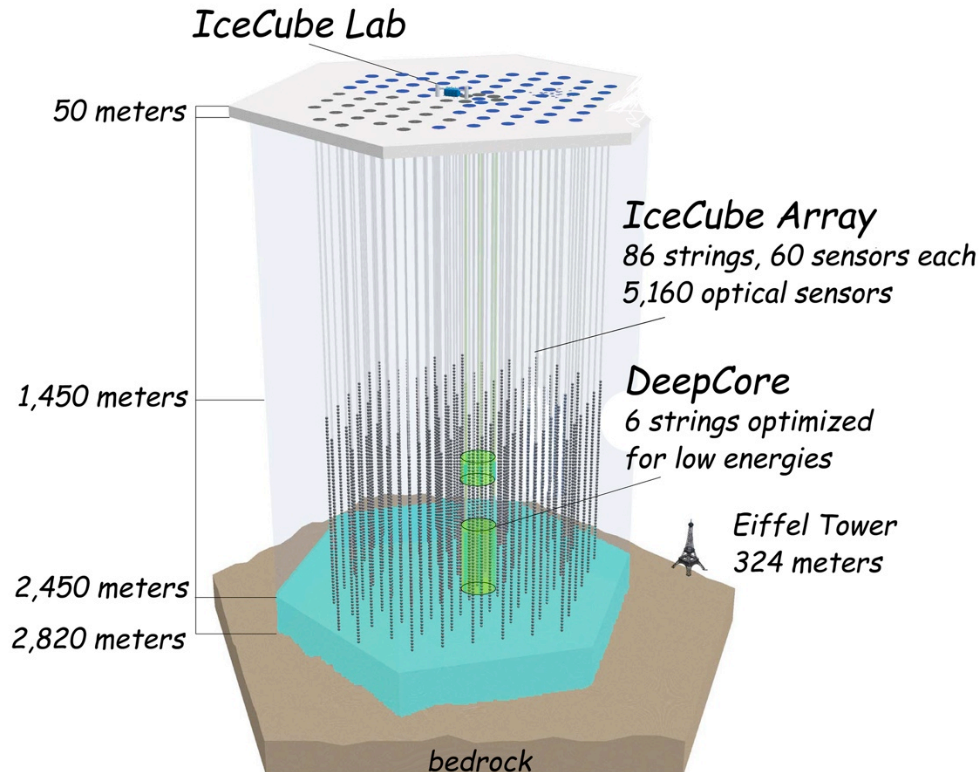
Ultra high energy neutrinos

Detecting UHE neutrinos requires massive detectors

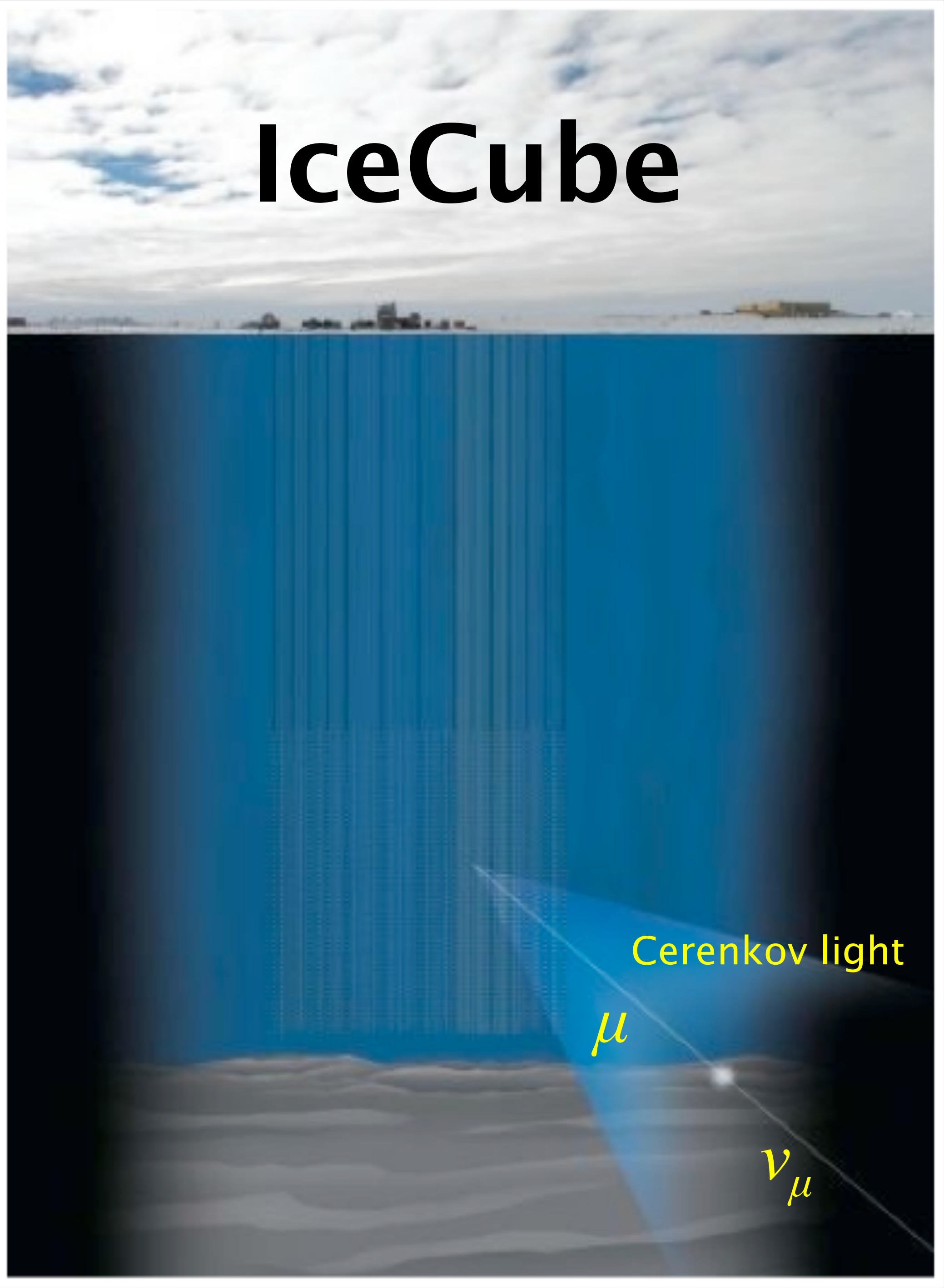
- Megatonnes
- At PeV energies, you can afford to instrument coarsely as the events are large



IceCube



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


IceCube
Cerenkov light
μ
ν μ

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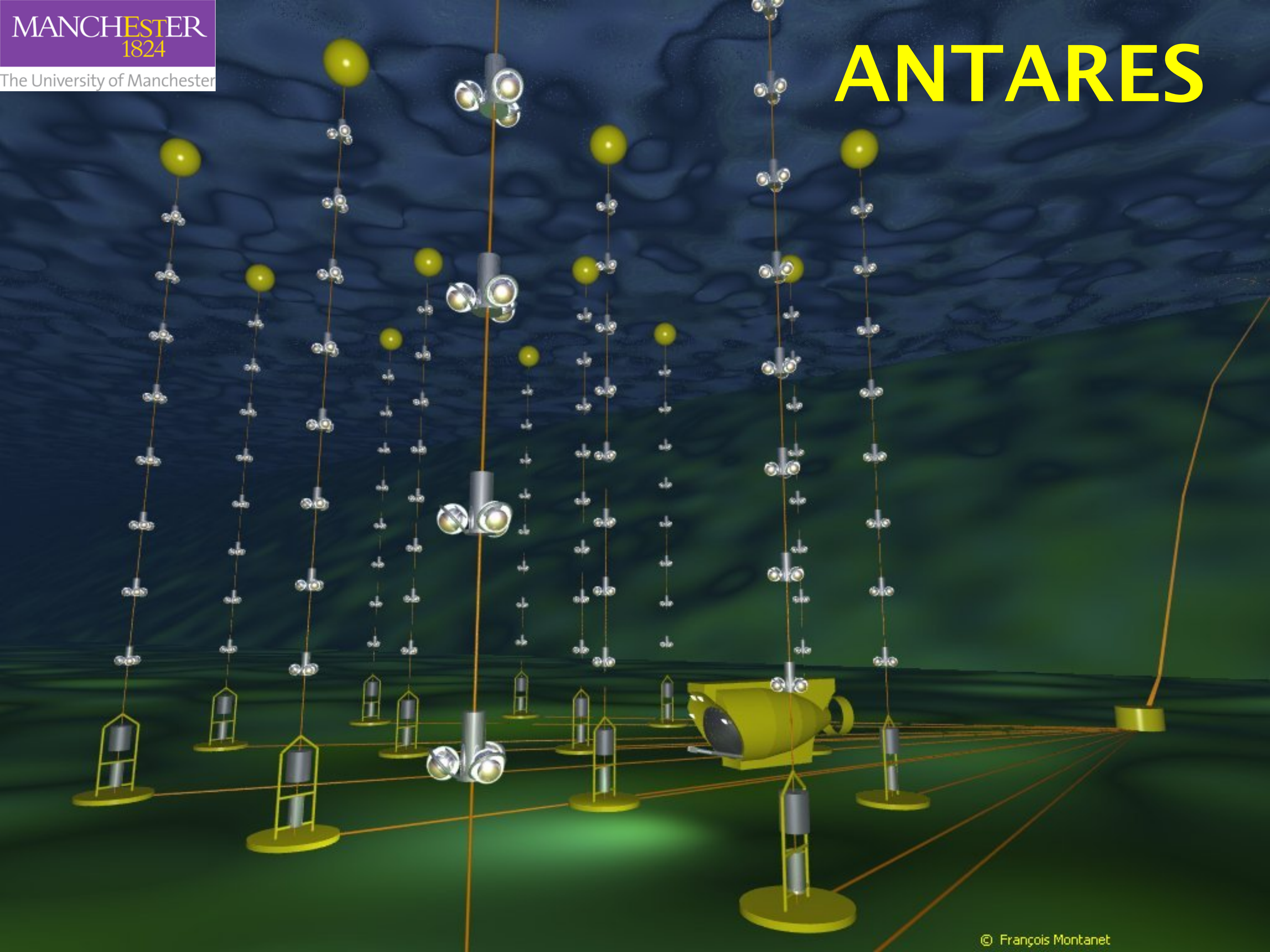
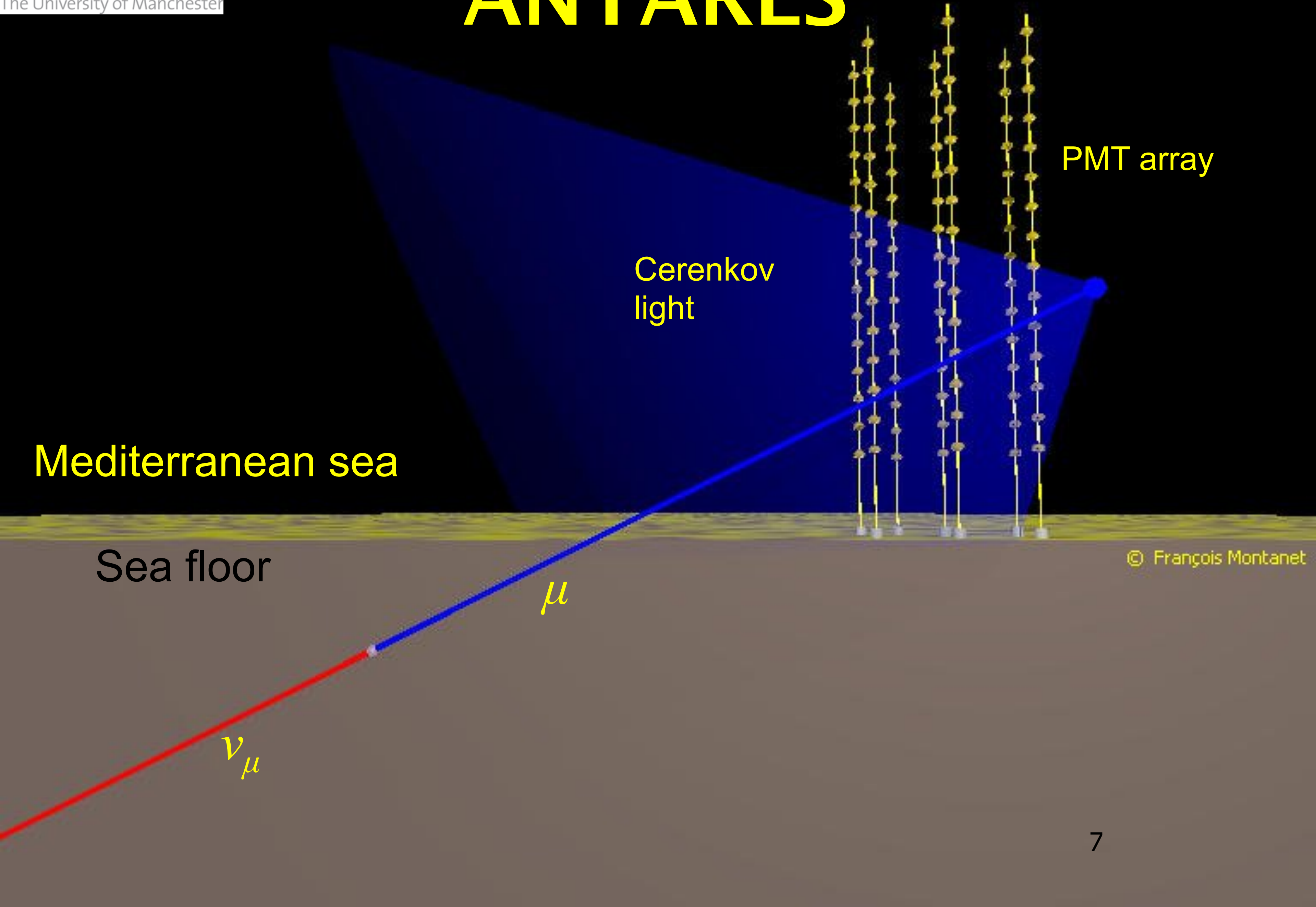
ANTARES



ANTARES


PMT array
Cerenkov
light
Mediterranean sea
Sea floor
© François Montanet
μ
ν_μ

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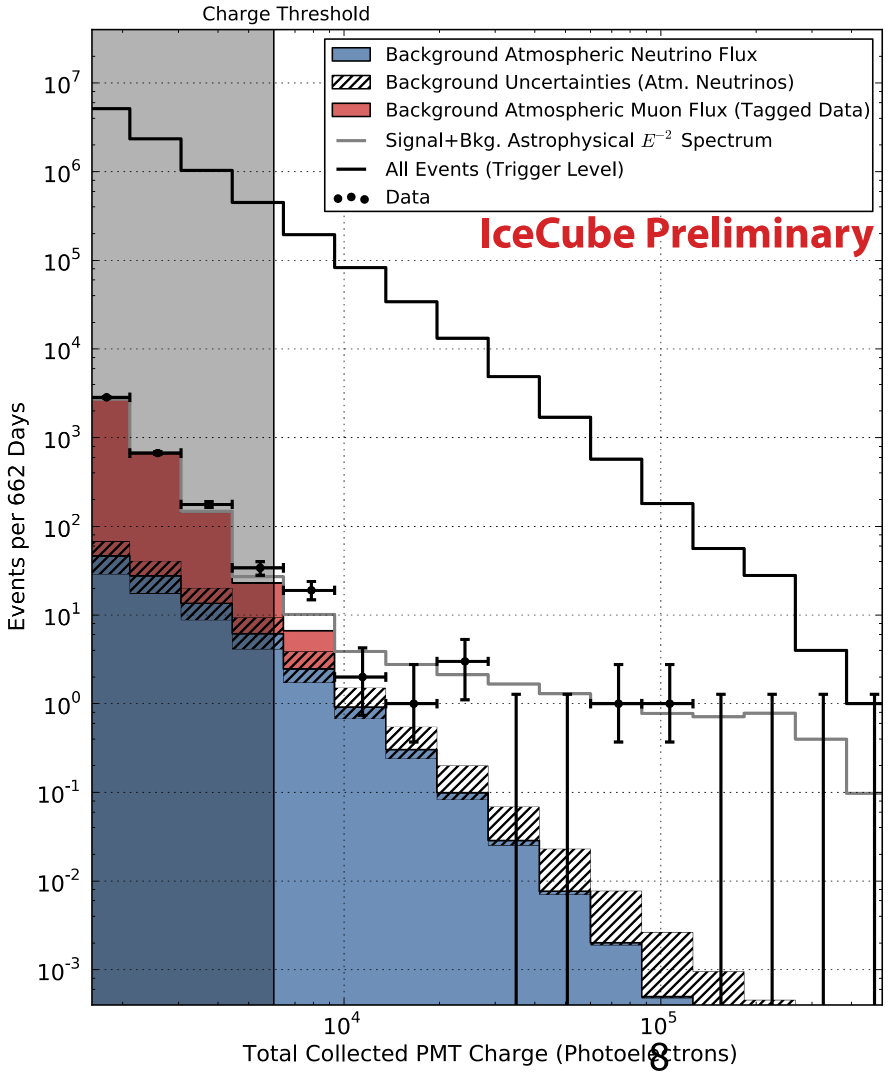
Highest energy neutrinos

IceCube has observed two PeV-energy neutrino candidates

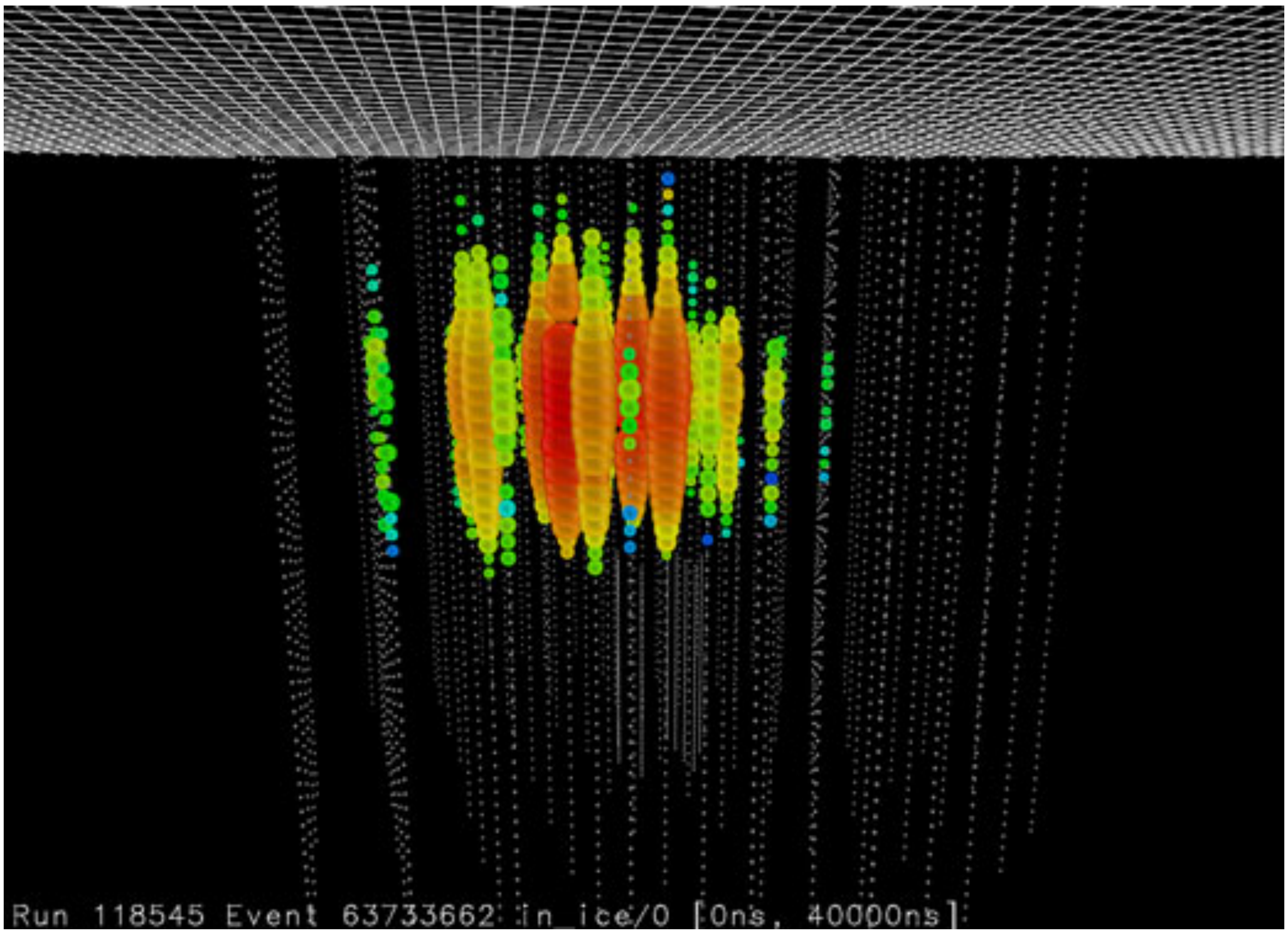
- Highest energy neutrinos ever observed

26 more high-energy candidates at lower energies

Inconsistent with standard atmospheric neutrino backgrounds at 4.1σ



A high energy IceCube event



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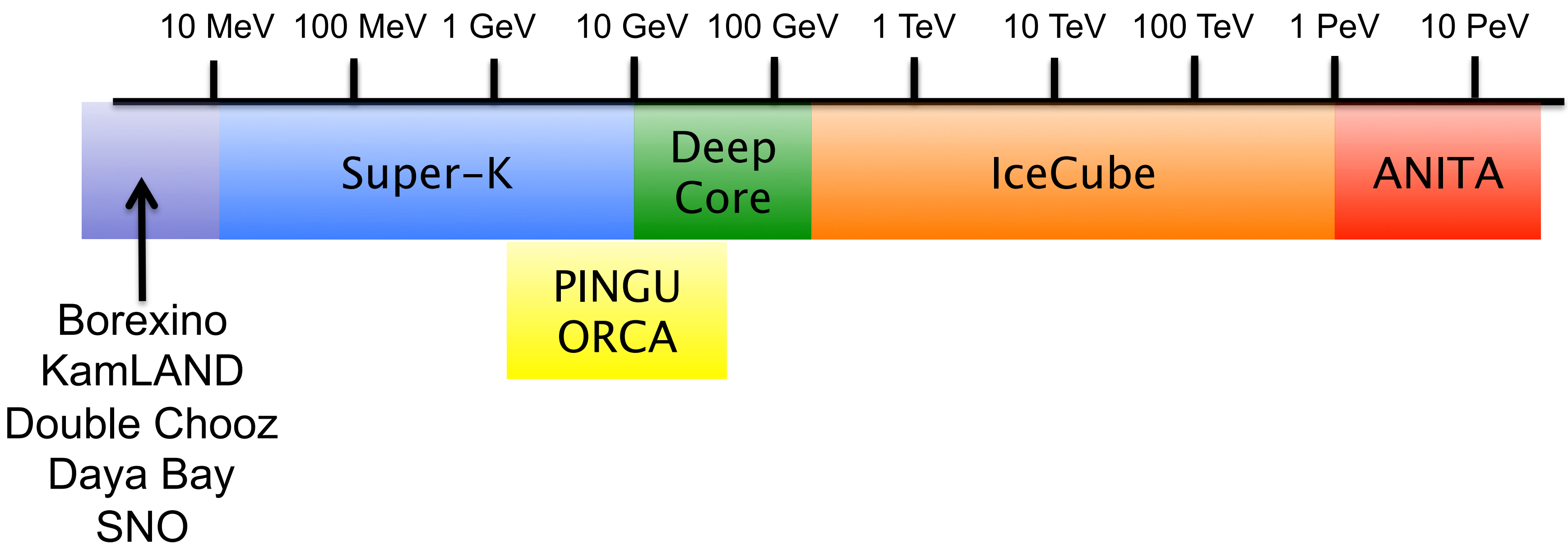
Lower energy neutrinos



Historically, the focus has been on increasing sensitivity to high energy neutrinos

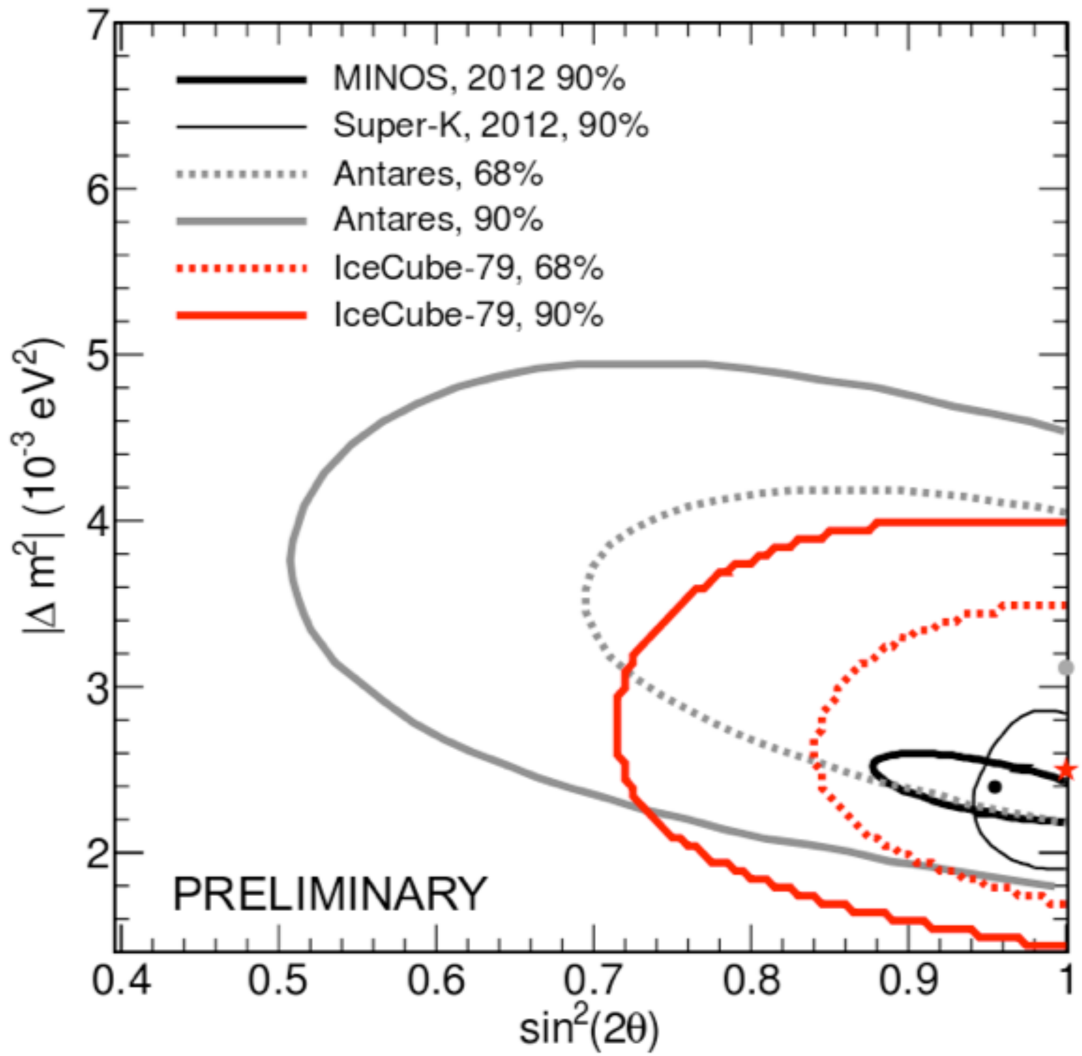
Now, these experiments are focusing on lowering the energy threshold

- Meeting the atmospheric neutrino oscillation experiments

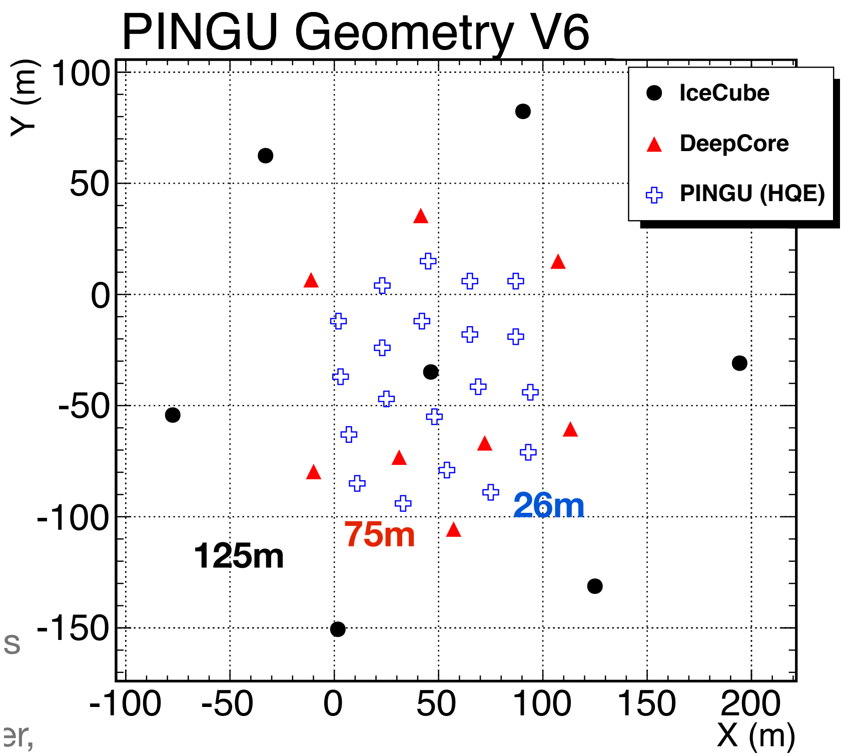
The 1—20 GeV region is where precision atmospheric neutrino oscillation physics can be done

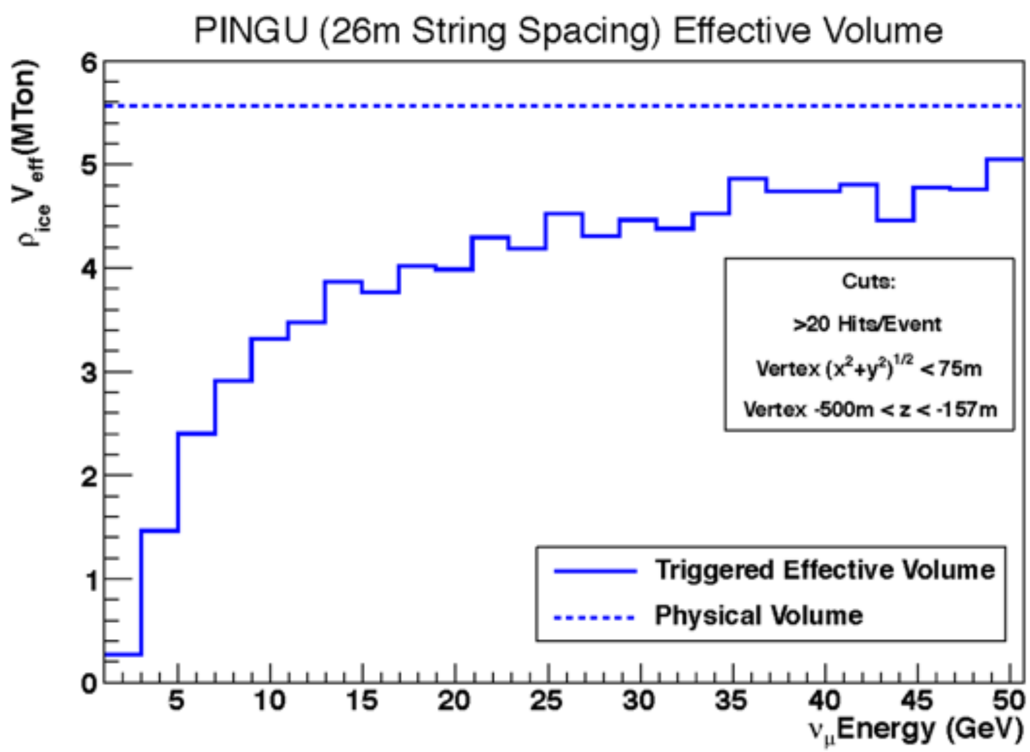
- PINGU and ORCA can provide megaton-scale statistics

Neutrino oscillations



PINGU





20—40 additional strings in the central region of IceCube

- ~25 m spacing (c.f. 125 m for IceCube)
- 60—100 PMT modules per string

Principle already demonstrated by DeepCore

ORCA is a similar extension planned for ANTARES

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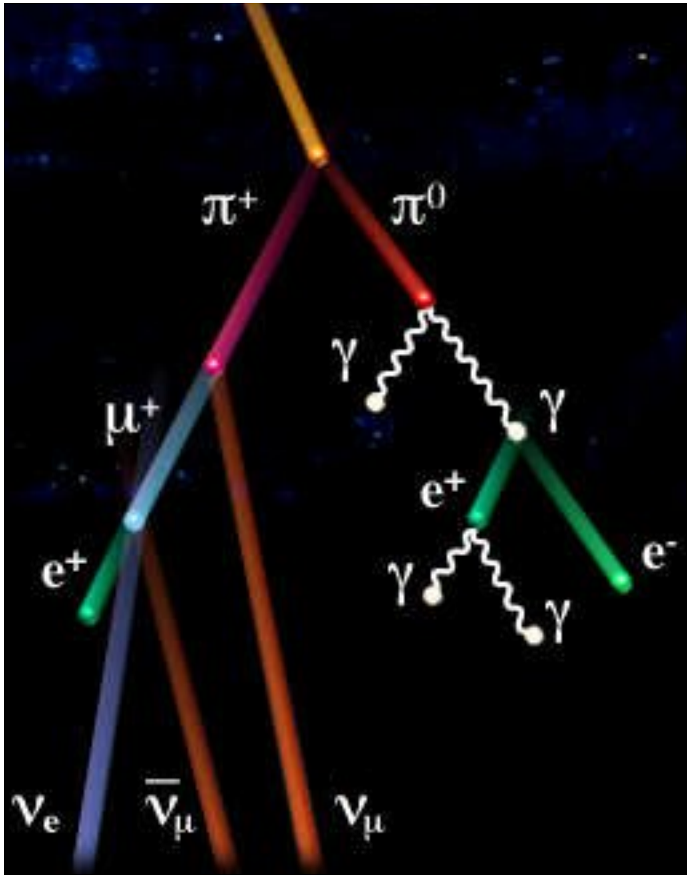
Atmospheric neutrinos



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

Approximately equal neutrino and antineutrino production

- Antineutrino interaction cross section is a factor of ~2 lower

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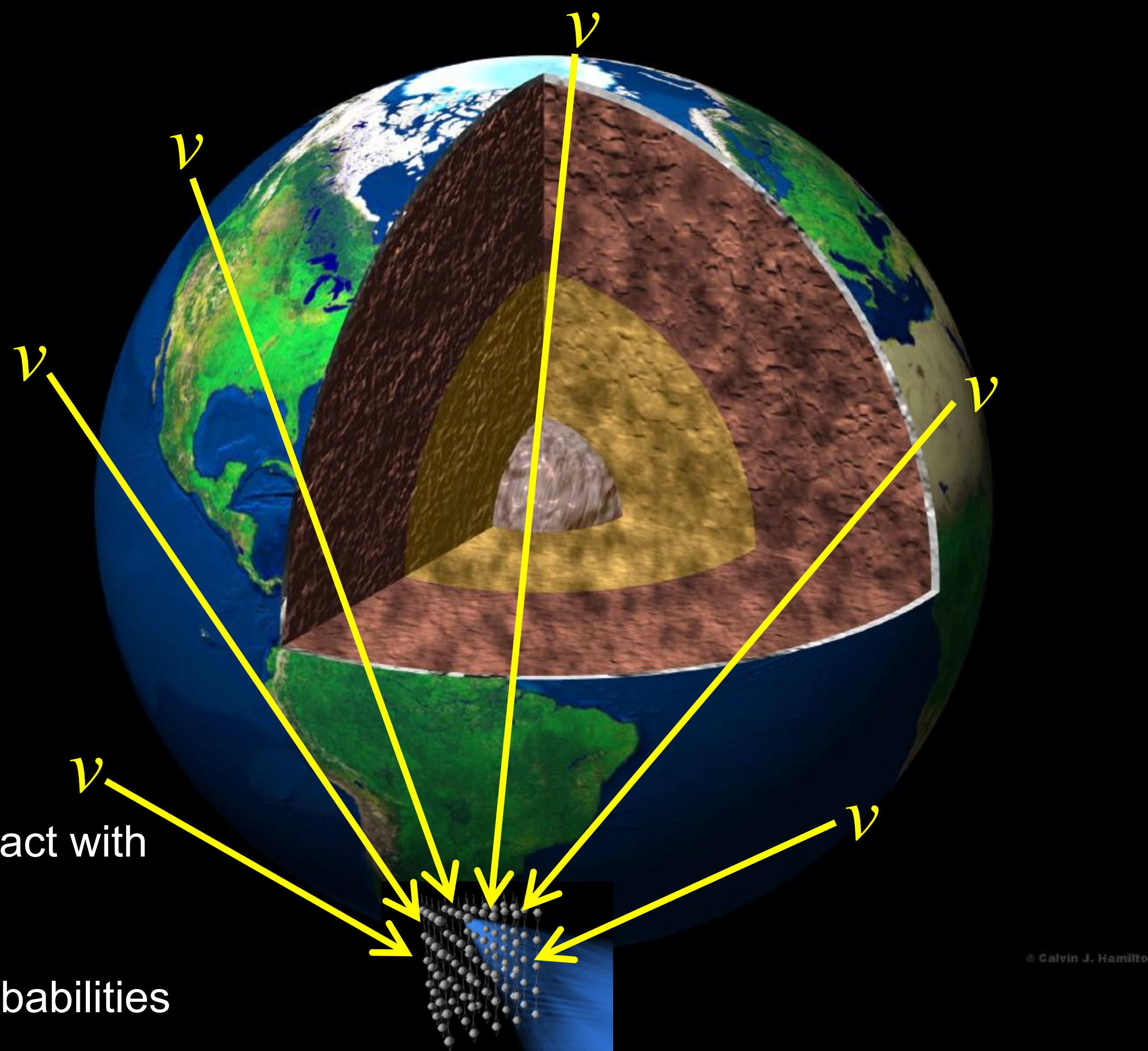
Matter effects



Atmospheric neutrinos interact with the Earth's matter

- MSW effect
- Alters oscillation probabilities

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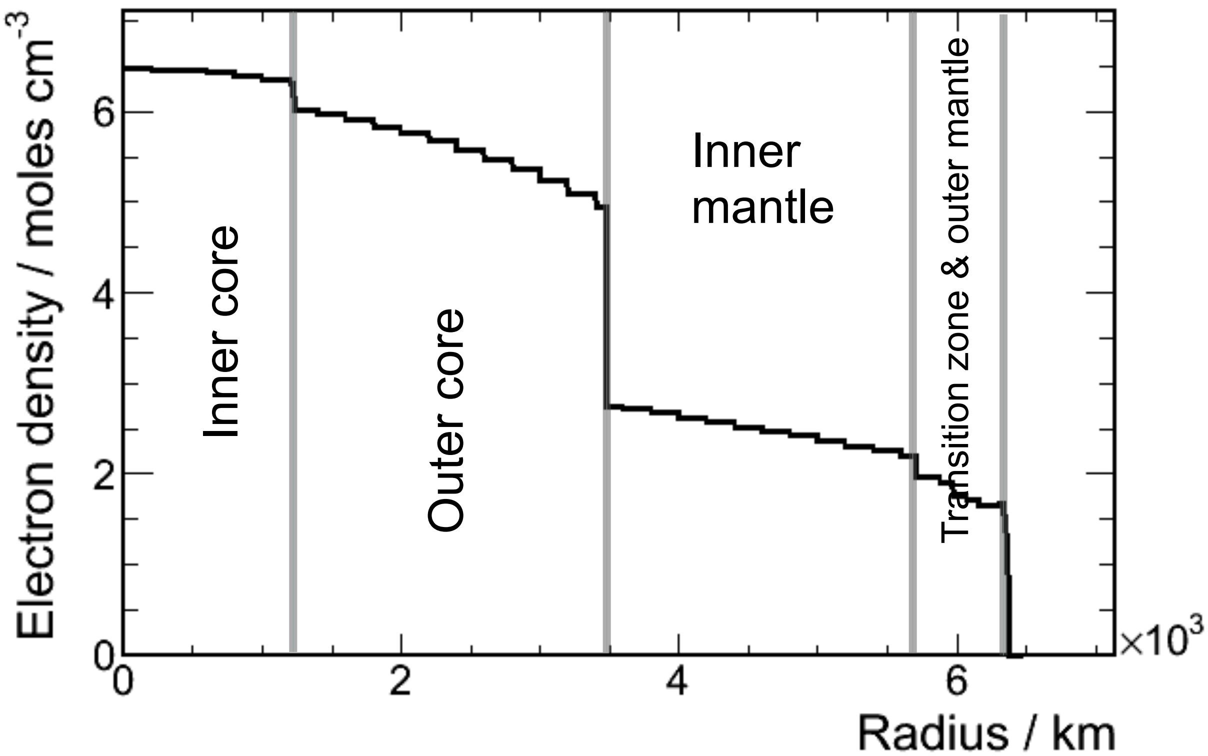
Preliminary Reference Earth Model (PREM)
Phys. Earth. Plan. Int. **25**, 297 (1981)

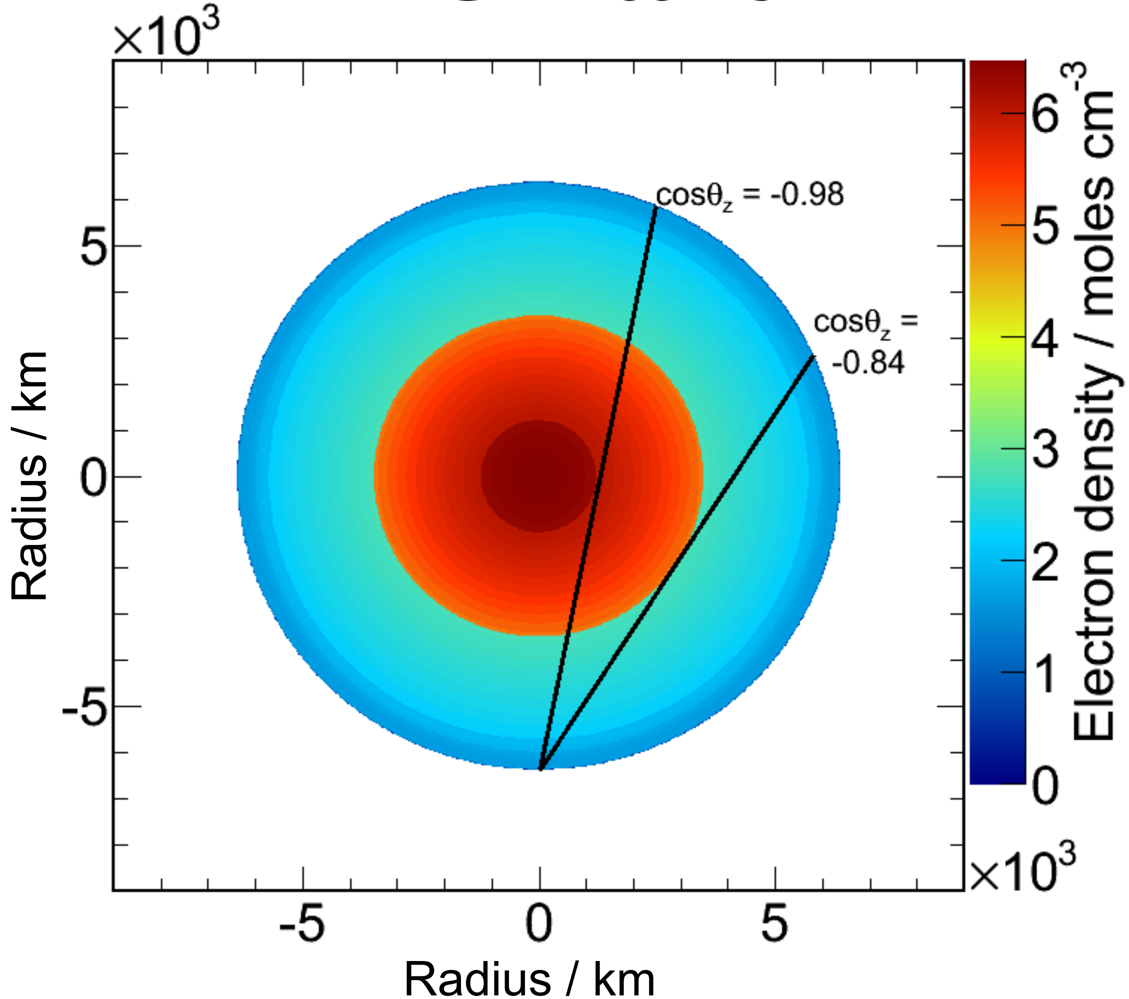
The Earth



Three distinct zones of density

- Sharp changes in density between the zones

The Earth

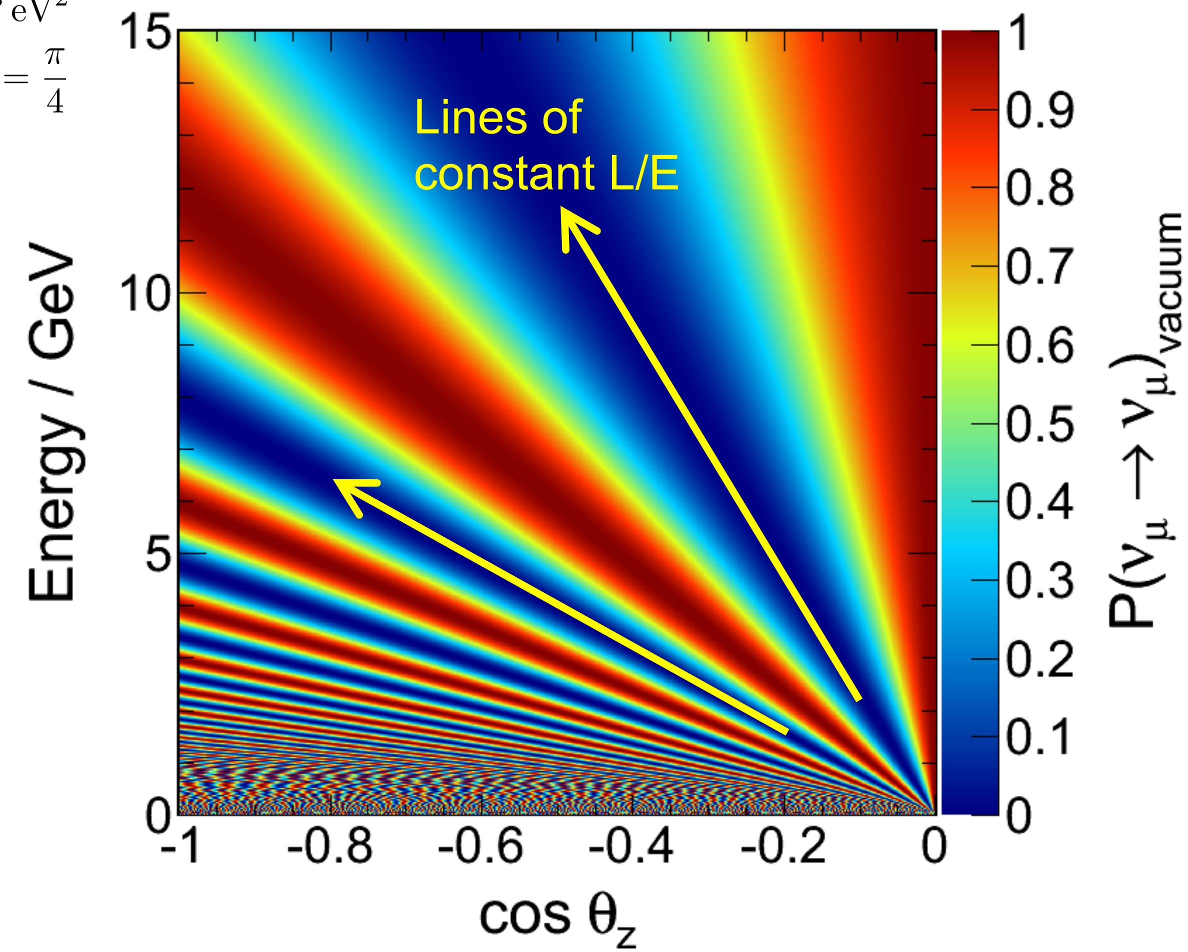


- The different regions can be probed by measuring the zenith angle of the neutrino

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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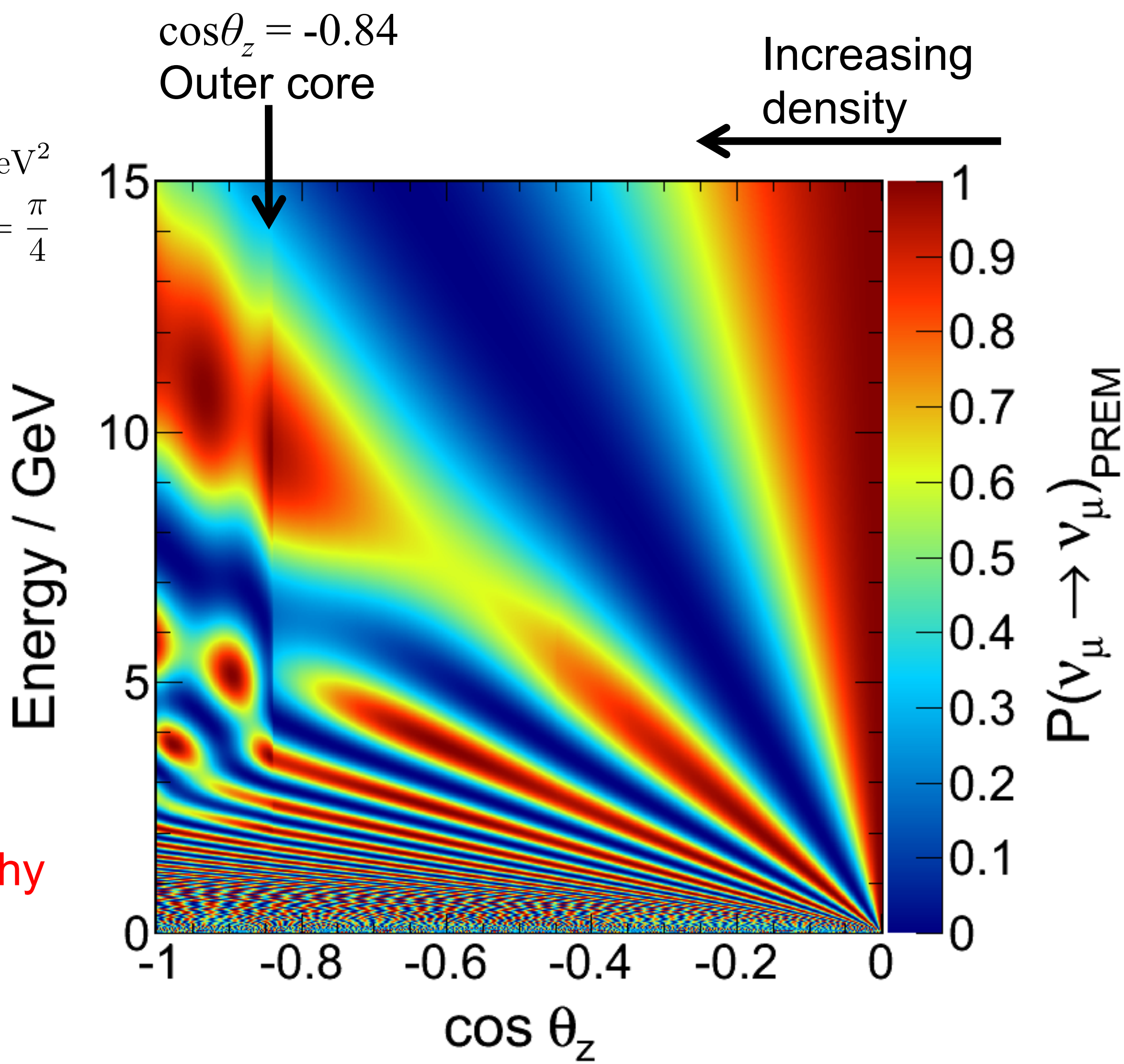
Neutrino oscillations in matter

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

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

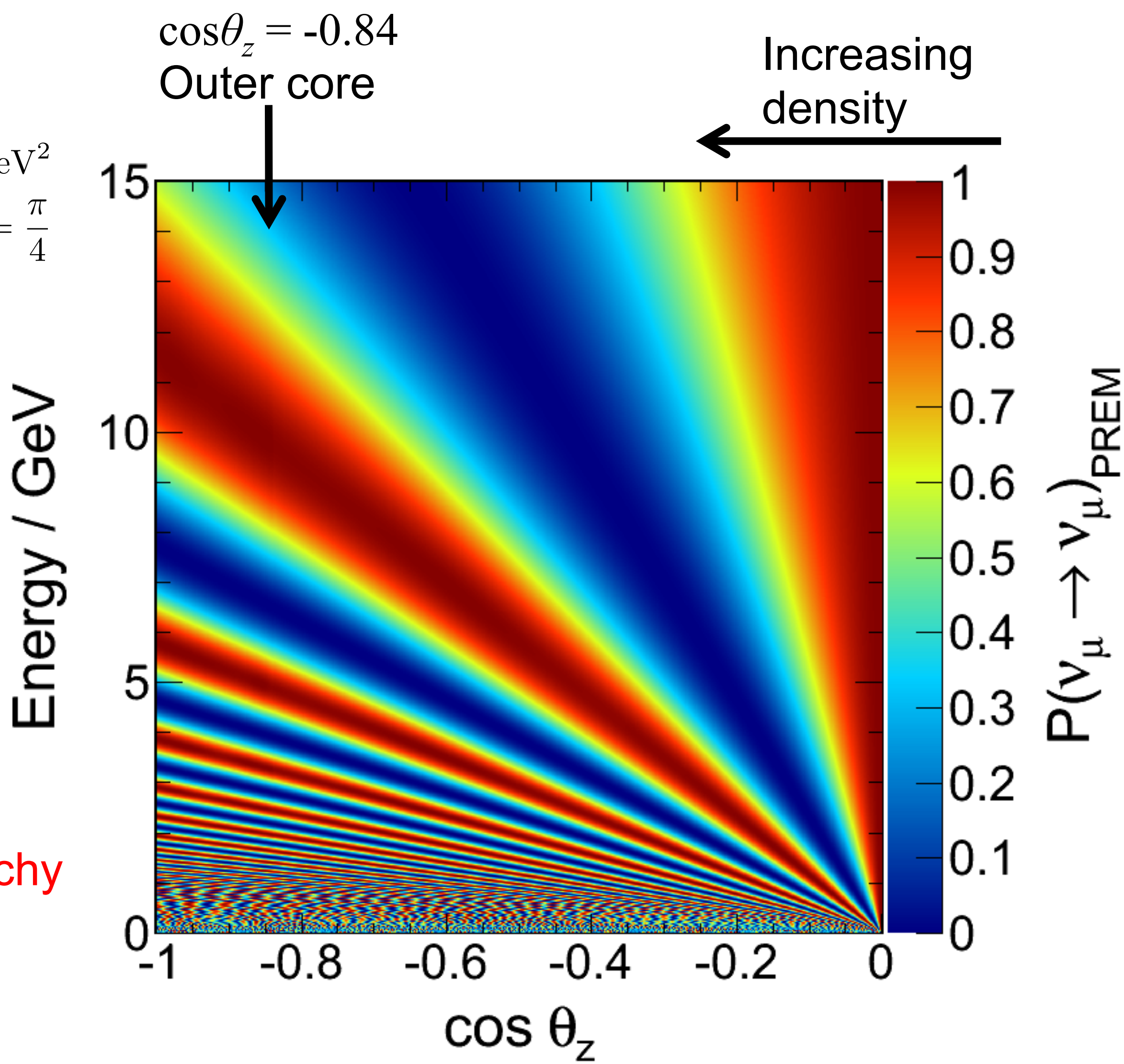
Neutrinos
Normal hierarchy



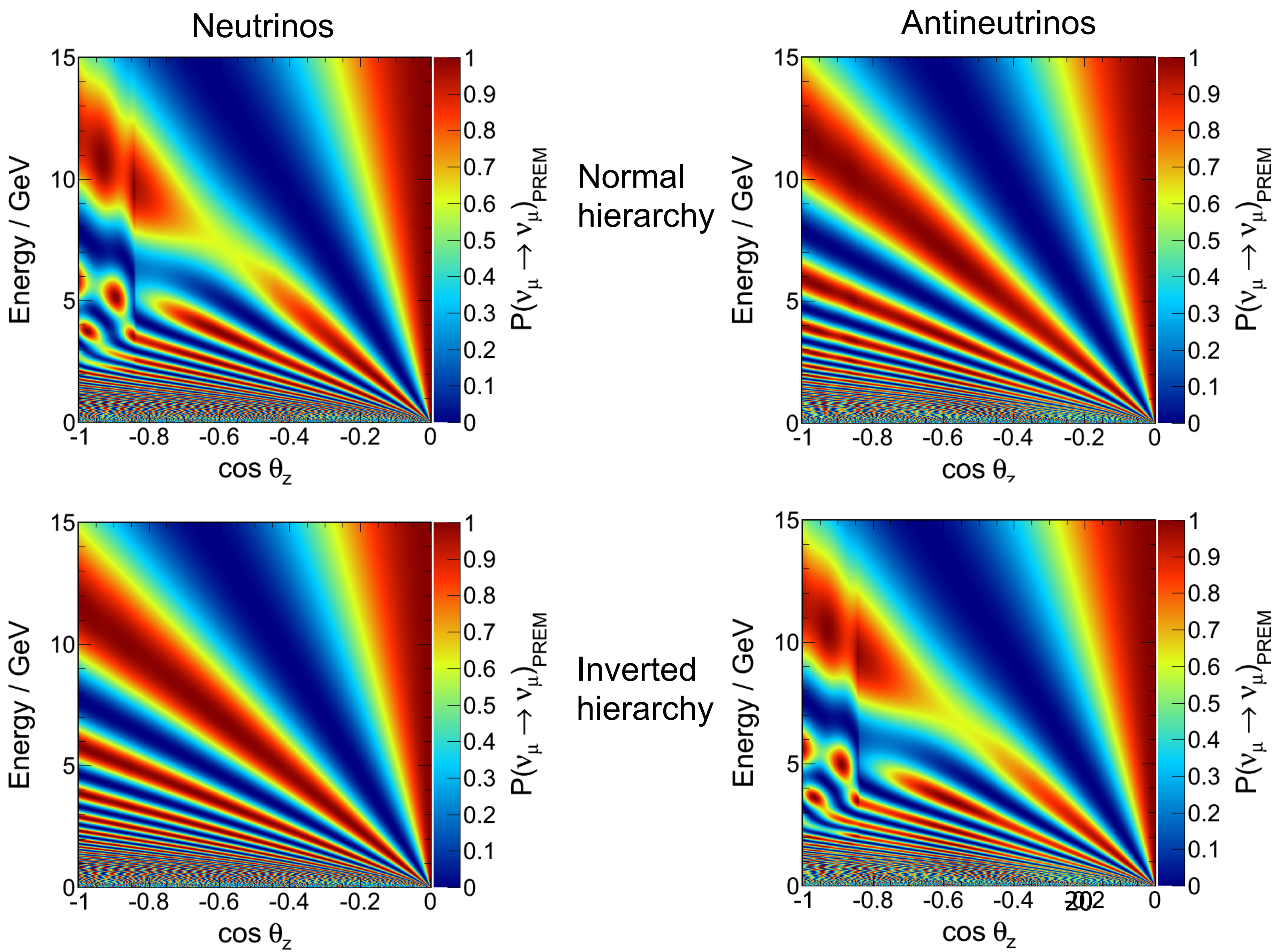
Neutrino oscillations in matter

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

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



Neutrinos
Inverted hierarchy


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

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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

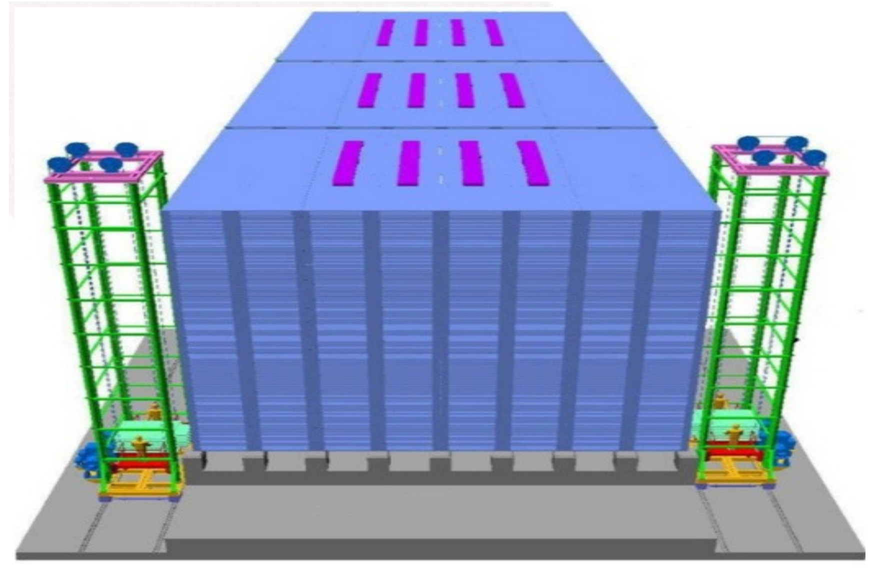
This has a resonance condition for neutrinos in the normal hierarchy or antineutrinos in the inverted hierarchy

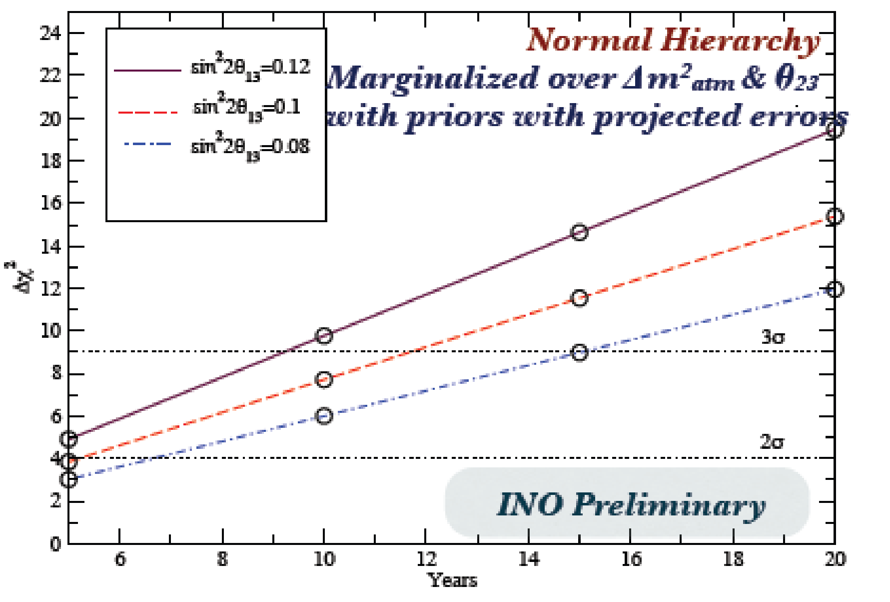
INO

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 or ORCA





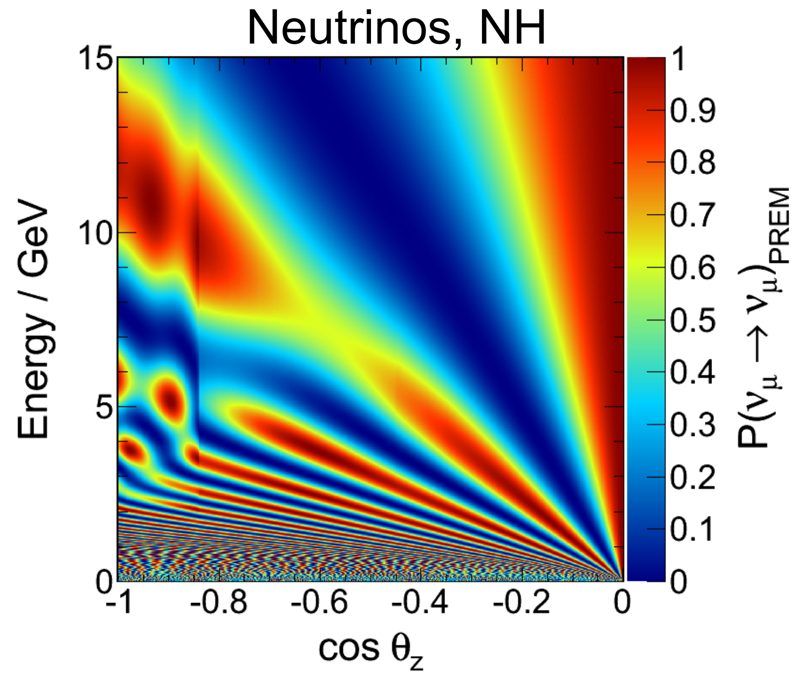
PINGU

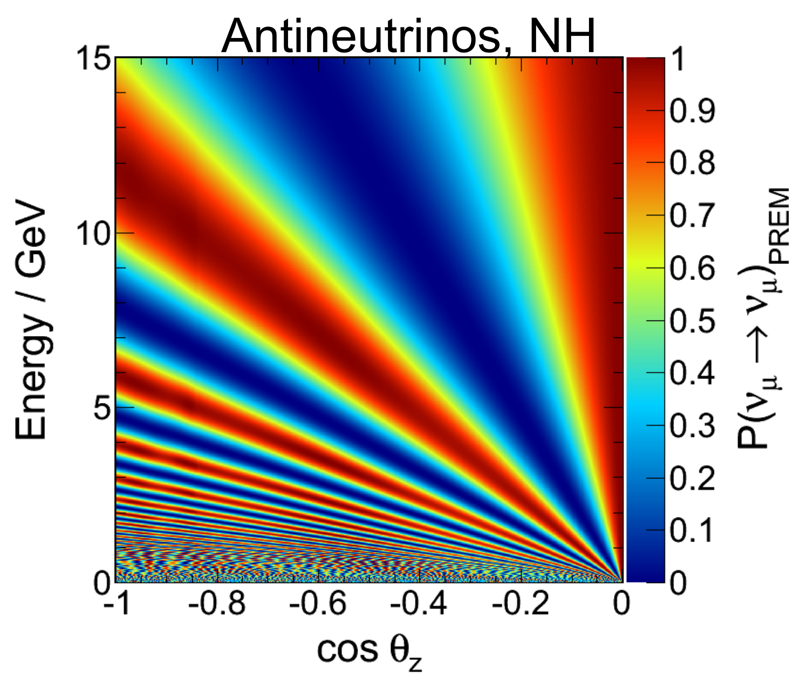
PINGU cannot distinguish neutrinos from antineutrinos

- 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



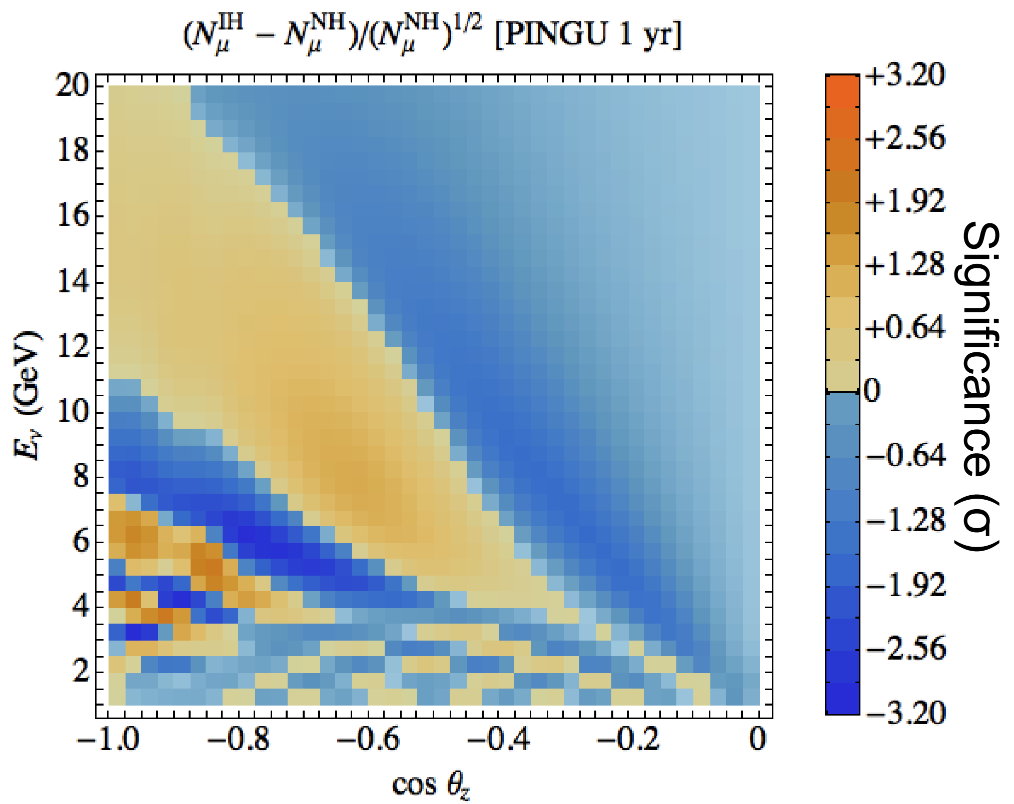


Hierarchy determination

This figure shows the situation for a perfect detector

- Perfect angle and energy resolution

With neutrinos and antineutrinos combined, the oscillogram differs significantly between the hierarchies



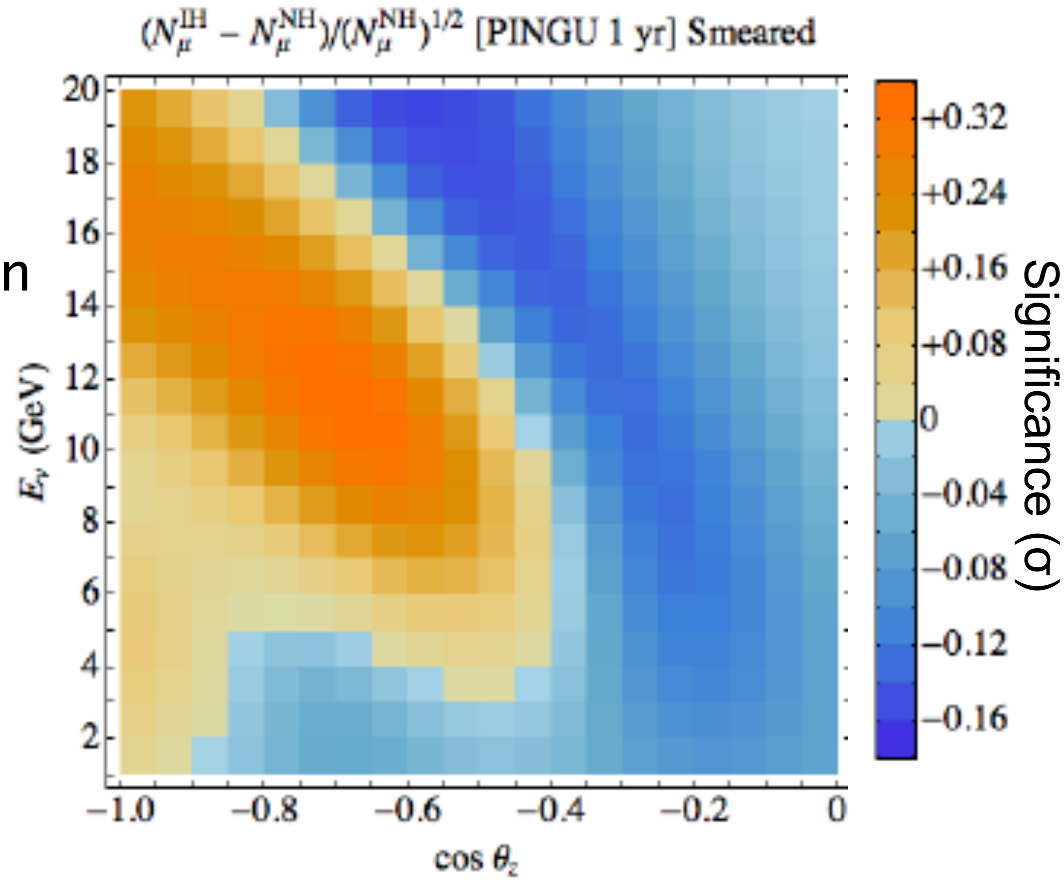
Akhmedov et al., JHEP **02**, 082 (2013)

Finite detector resolution

This figure includes a smearing to account for detector resolution

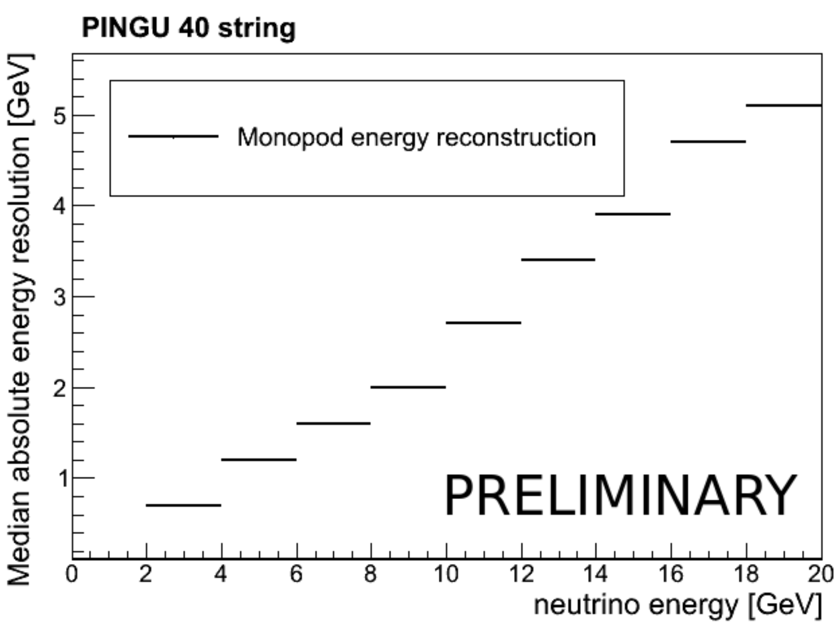
- 3 GeV energy resolution
- 15° angle resolution

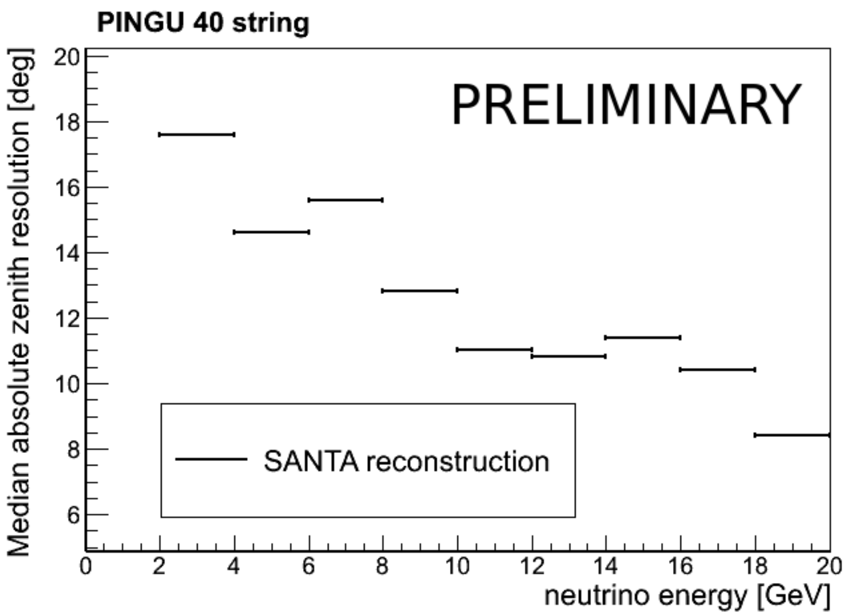
A difference between the two hierarchies is still visible



Akhmedov et al., JHEP **02**, 082 (2013)

Detector performance



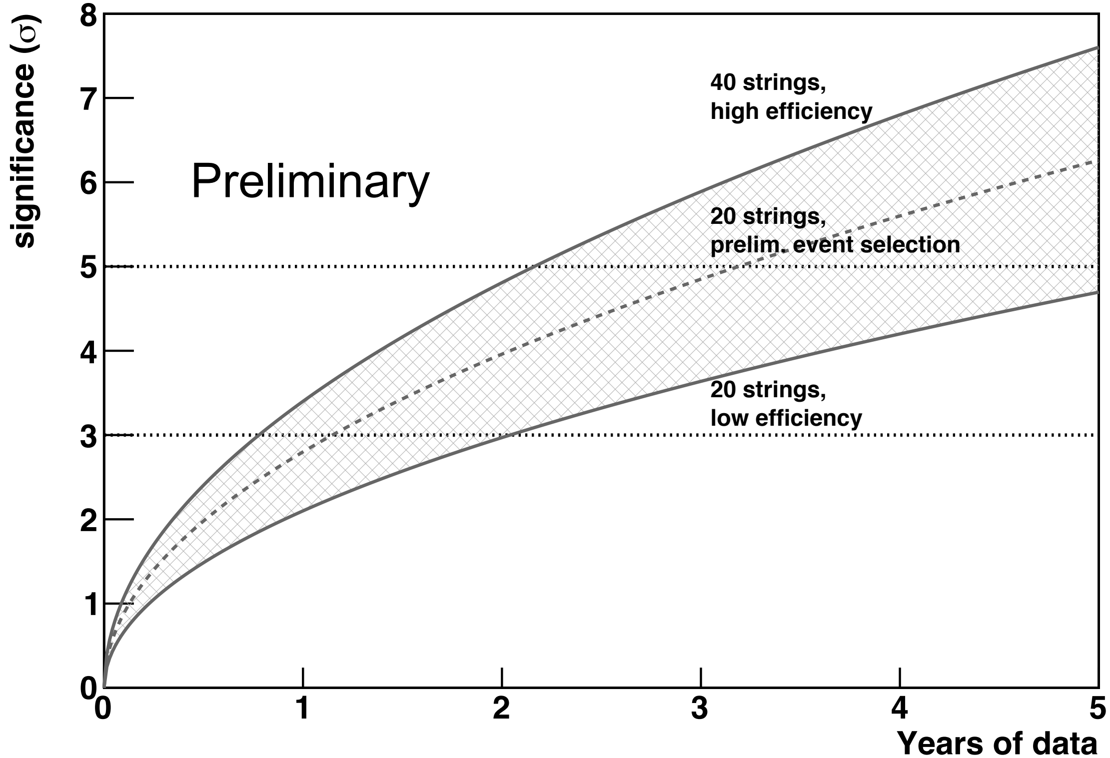


PINGU performance simulated using DeepCore algorithms

- Energy resolution: ~(0.7 GeV + 0.2E_ν)
- Angular resolution: 15° to 8° as energy increases from 5 GeV to 20 GeV

More computationally intensive algorithms can improve on this

PINGU sensitivity



Sensitivity depends on efficiency, resolution, background, etc

Even with pessimistic assumptions, the hierarchy can be determined at 3σ after two years

- 5σ within five years

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Advantages of PINGU

Relatively cheap

- Startup cost of \$8M–\$12M, then \$1.25M per string

Well understood technology

- IceCube and DeepCore have been very successful

Relatively fast

- Could start deployment in 2016, working over 2—3 years
- 3σ hierarchy determination by 2020?
- LBNE can then focus on CP violation

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Summary

Ultra high energy neutrino detectors are now looking at lower energies

- Precision atmospheric neutrino studies with megatonne fiducial masses

PINGU is an extension of IceCube

- Taking the energy threshold well below 10 GeV

Neutrinos passing through the Earth interact via the MSW effect

- ν_μ disappearance probability depends on the mass hierarchy

PINGU could determine the mass hierarchy at 3σ by 2020

- ORCA is a similar extension to ANTARES