Validating Layered Structure Inside Earth Using Neutrino Oscillations at IceCube DeepCore

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(For the IceCube collaboration)

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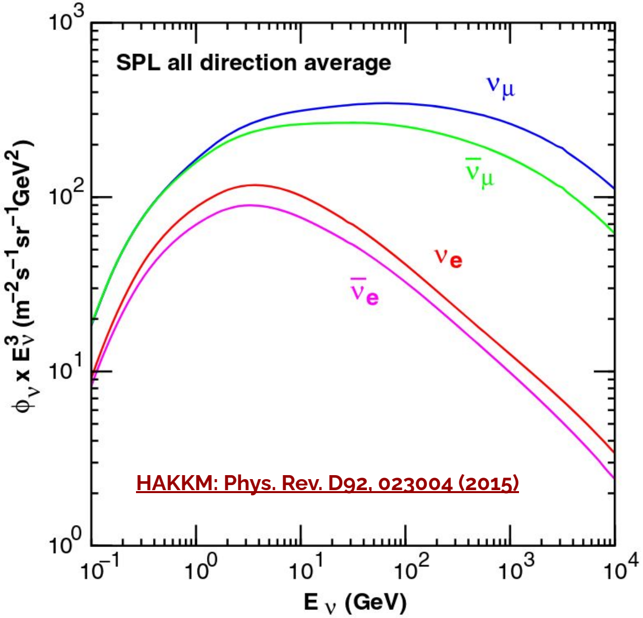
ICECUBE NEUTRINO OBSERVATORY

Department of Science & Technology, Government of India

SERB INDIA

Atmospheric Neutrinos

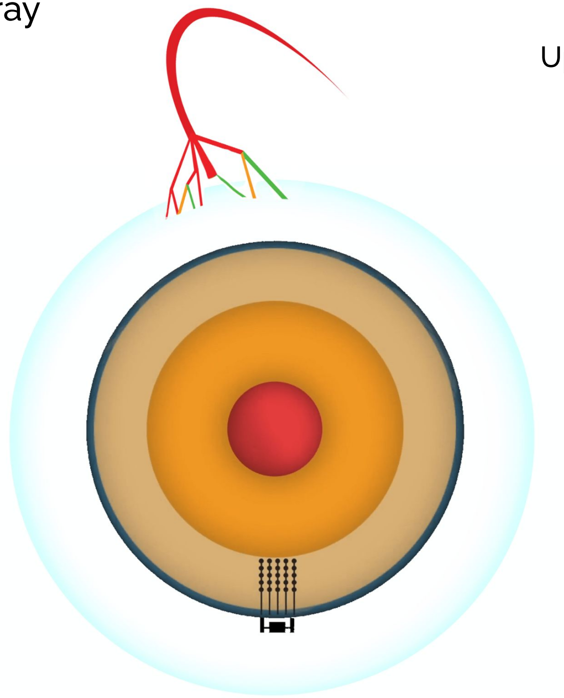
- Produced a few km above the Earth's surface by primary cosmic ray interactions



$$p + A_{air} \rightarrow p, n, \pi^{\pm}, k^{\pm} \ldots.$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$



- Steeply falling power-law spectra (~$E^{-2.7}$)
- Energy range: 0.1 GeV to ~10 TeV

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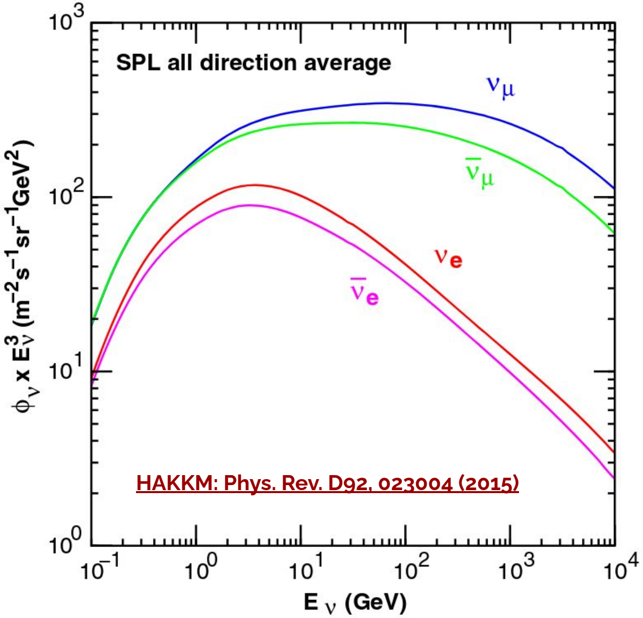

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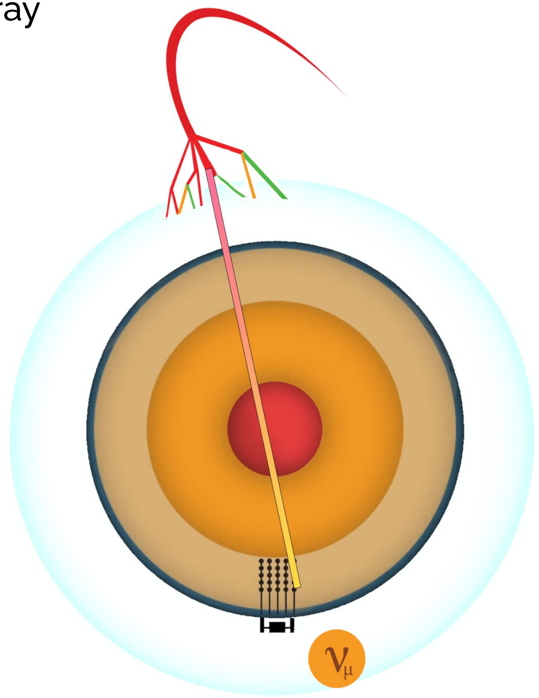
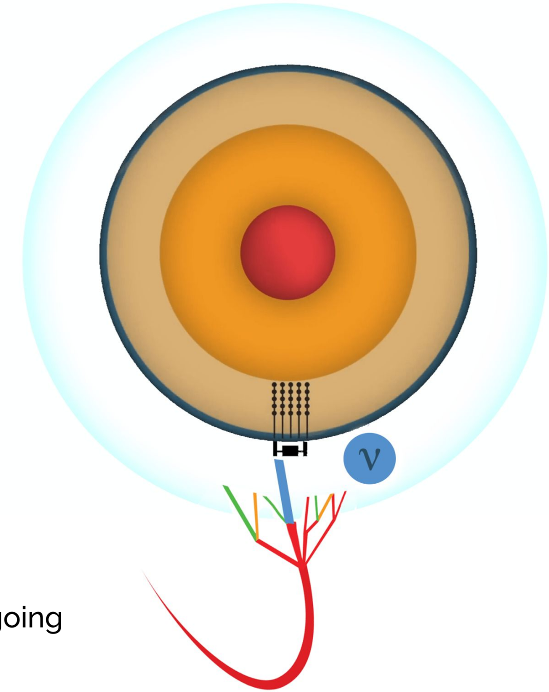
Up going



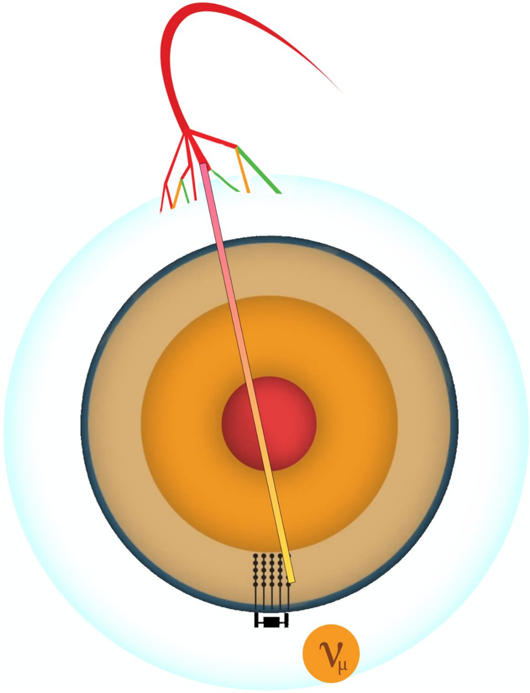
- Steeply falling power-law spectra (~$E^{-2.7}$)
- Energy range: 0.1 GeV to ~10 TeV

Atmospheric Neutrinos

- Flux should be up-down symmetric
- Baseline: 15 km to 12757 km

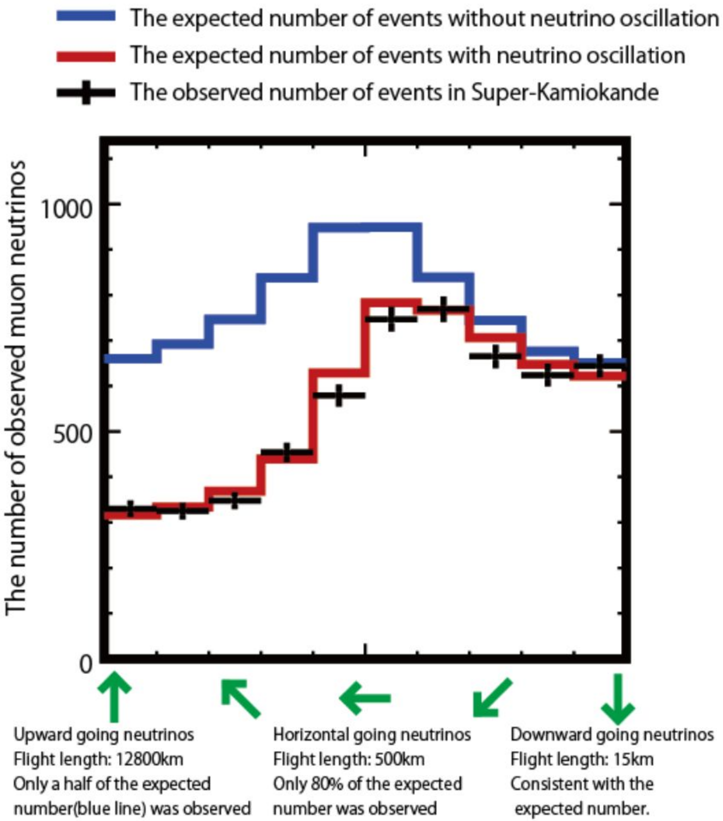


Down going



Up going

Atmospheric Neutrinos



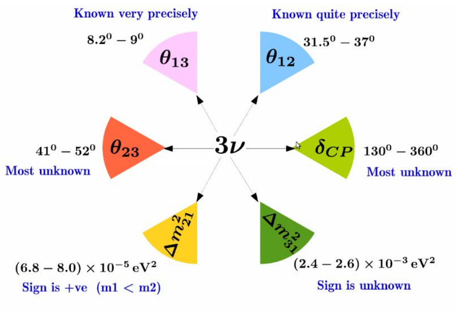
Ref: [The discovery of atmospheric neutrino oscillations in Super-Kamiokande]()

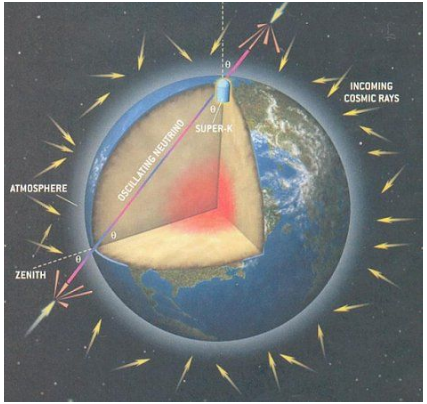
Neutrino Oscillations

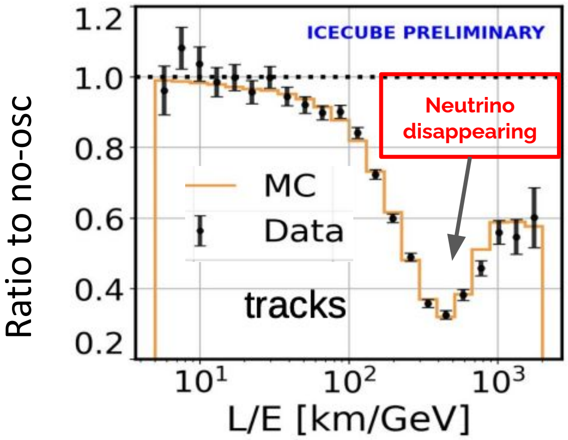
- Neutrino changes its flavor while propagating
- Quantum mechanical phenomenon
- Mixing described by PMNS matrix

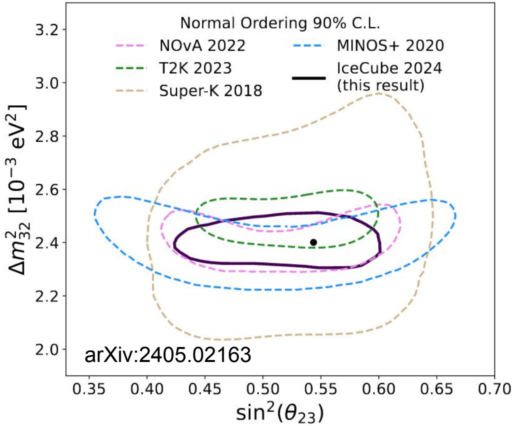
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

where, $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$









Neutrino Oscillation in Matter

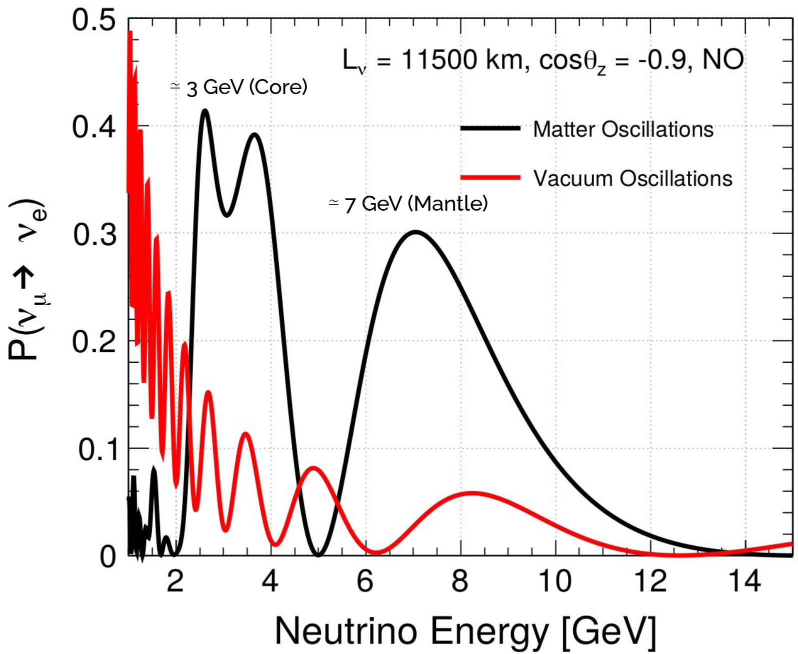
- Neutrino propagation through matter modify the oscillations significantly
- Coherent forward scattering of neutrinos with matter particles
- Charged current interaction of neutrino with electrons creates an extra potential for neutrino

$$V_{CC} = \pm\sqrt{2}G_F N_e \approx \pm 7.6 \times Y_e \times 10^{-14} \left[\frac{\rho}{g/cm^3}\right] \mathrm{eV}$$

$$Y_e = N_e/(N_p + N_n)$$

"ϱ" denotes the matter density

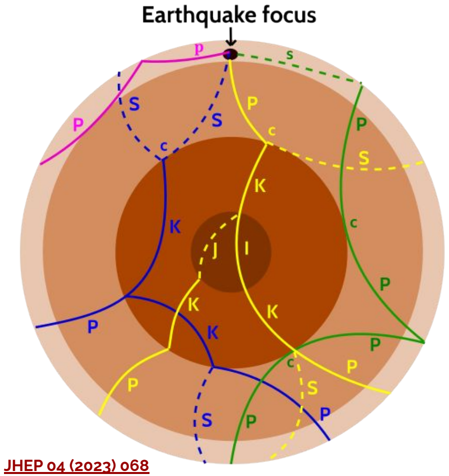
+1 (-1) for neutrino (antineutrino)



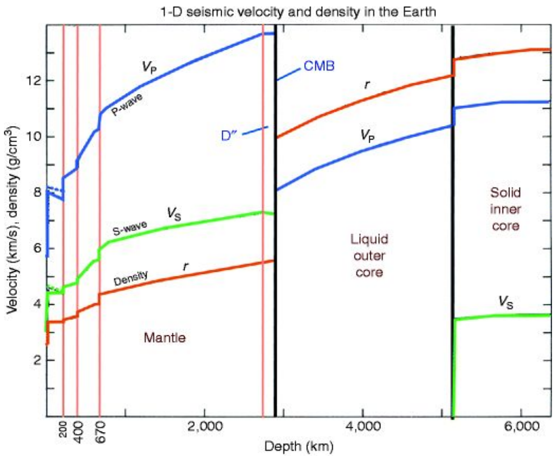
$$E_{\mathrm{res}} = \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7\ \mathrm{GeV}\left(\frac{4.5\ \mathrm{g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\ \mathrm{eV}^2}\right)\cos 2\theta_{13}$$

Current Knowledge About Earth

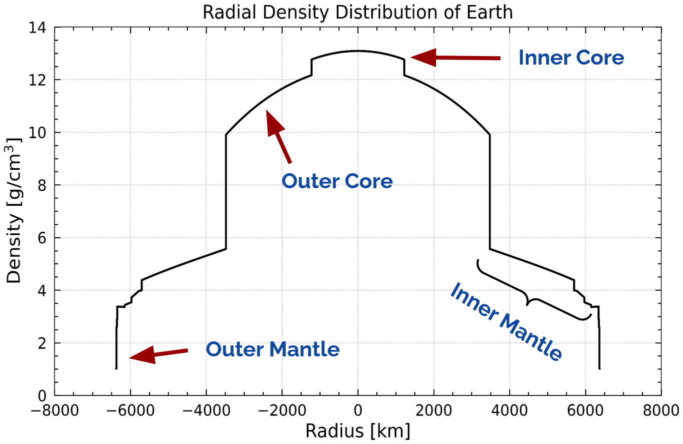
- Information about the interior of Earth is obtained from indirect probes using traditional **seismic** and **gravitational** studies → **Preliminary Reference Earth Model (PREM)**



JHEP 04 (2023) 068

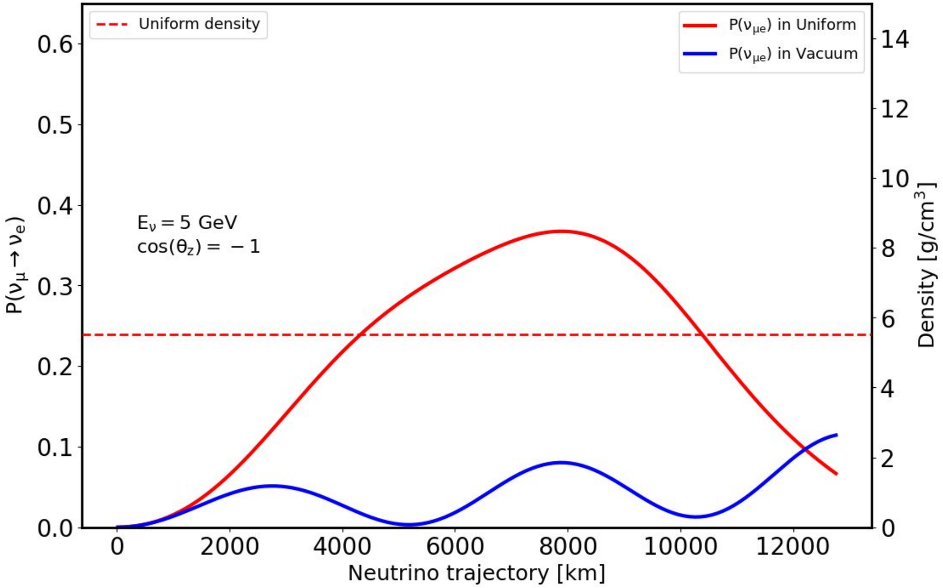


"PREM" Dziewonski and Anderson (1981)



- Broadly classified: two concentric shell - the outer one is mantle, and the inner one with a much higher density is core
- Mantle consists of hot rocks of silicate and core is composed of metals like iron and nickel
- Outer core is expected to be liquid (absence of S-waves and decrease in the velocity of P-waves)
- Core-Mantle Boundary (CMB): the largest chemical compositional and density discontinuity within the Earth

Layered Structure of Earth: In the Eyes of Neutrinos



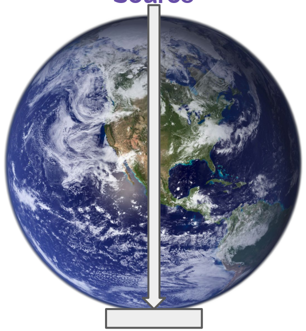
Source

Detector
(Observable probability)

- MSW resonance (L. Wolfenstein, PRD 17 (1978) 2369)

In Uniform

- **Interaction of neutrino with matter modifies the neutrino oscillation parameters**
- **Maximal mixing angle**
- **Maximum transition**



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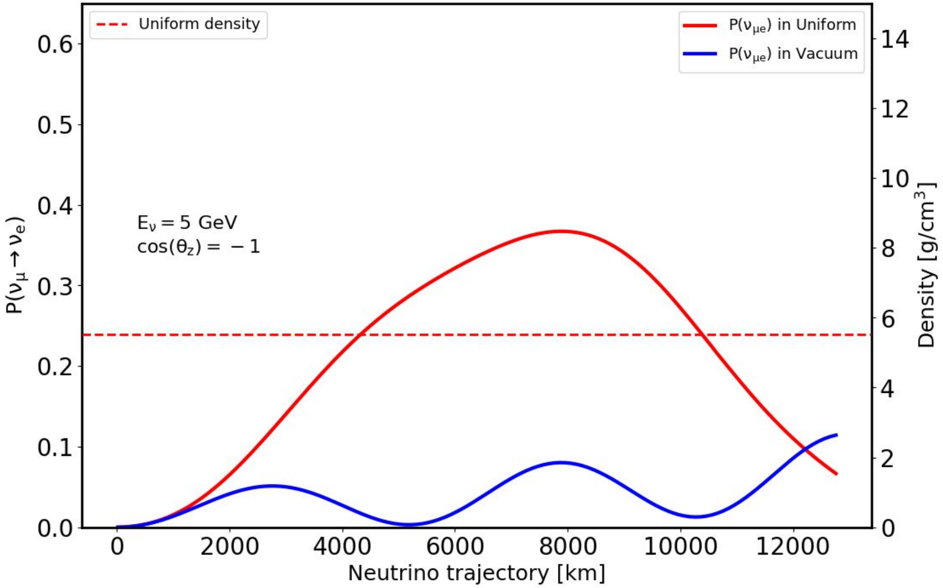

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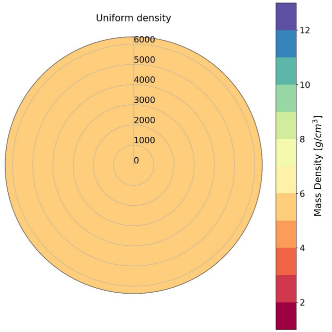
MSW Resonance



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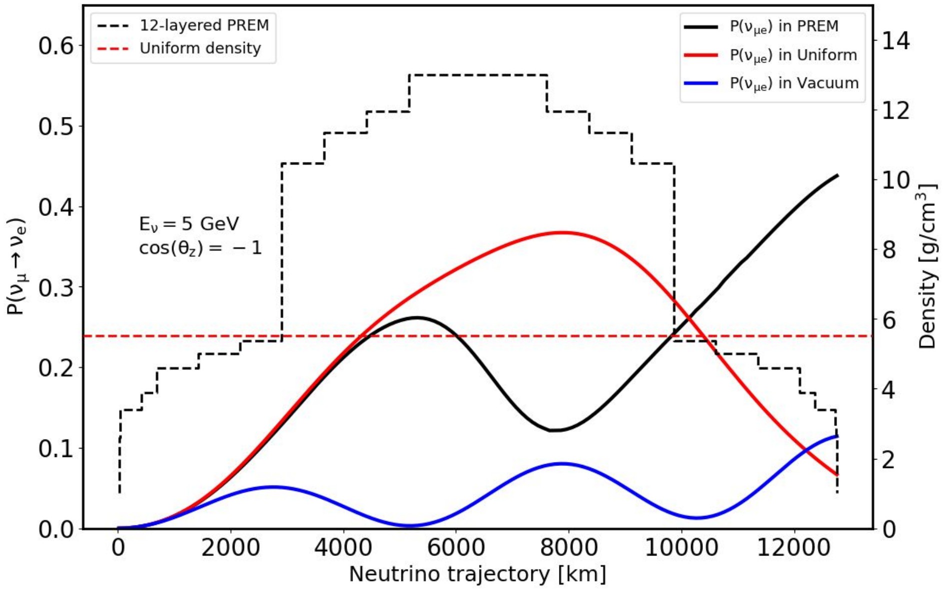
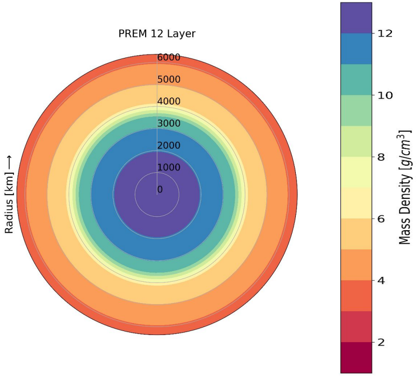


Source

Detector
(Observable probability)

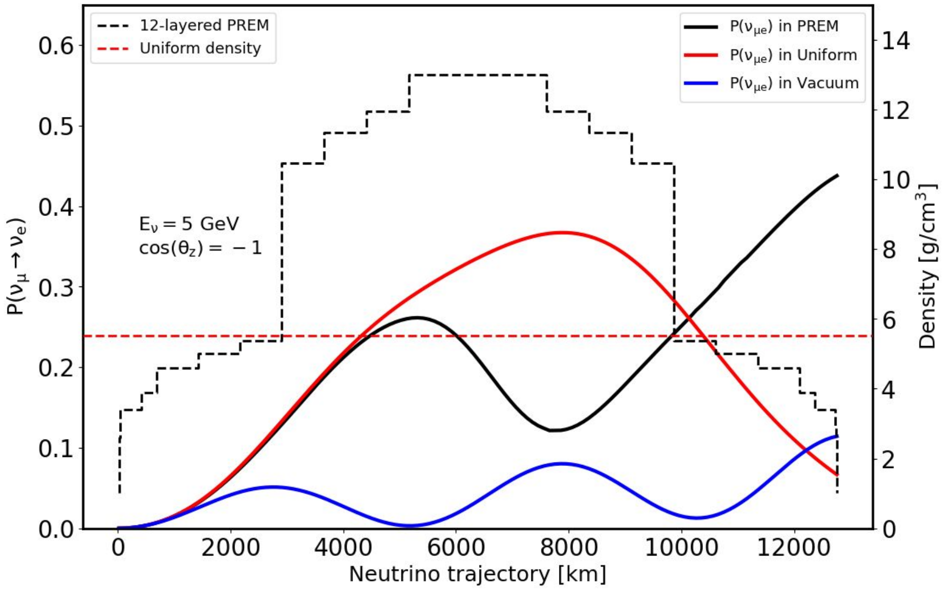
In PREM

- **If frequency of density modulation equals the frequency of oscillation, resonance occurs**



- Neutrino Oscillation Length Resonance (NOLR) ([Petcov, PLB 434 (1998) 321]) or Parametric Resonance (PR) ([Akhmedov, NPB 538 (1999) 25])
- Parametric effects in neutrino oscillations, [Physics Letters B, Volume 226, Issues 3–4, (1989)]

Layered Structure of Earth: In the Eyes of Neutrinos



Source

Detector (Observable probability)

Neutrino oscillation preserves the information that it encounters during the propagation

In PREM

- **If frequency of density modulation equals the frequency of oscillation, resonance occurs**

NOLR/PR Resonance

- Neutrino Oscillation Length Resonance (NOLR) (Petcov, PLB 434 (1998) 321) or Parametric Resonance (PR) (Akhmedov, NPB 538 (1999) 25)
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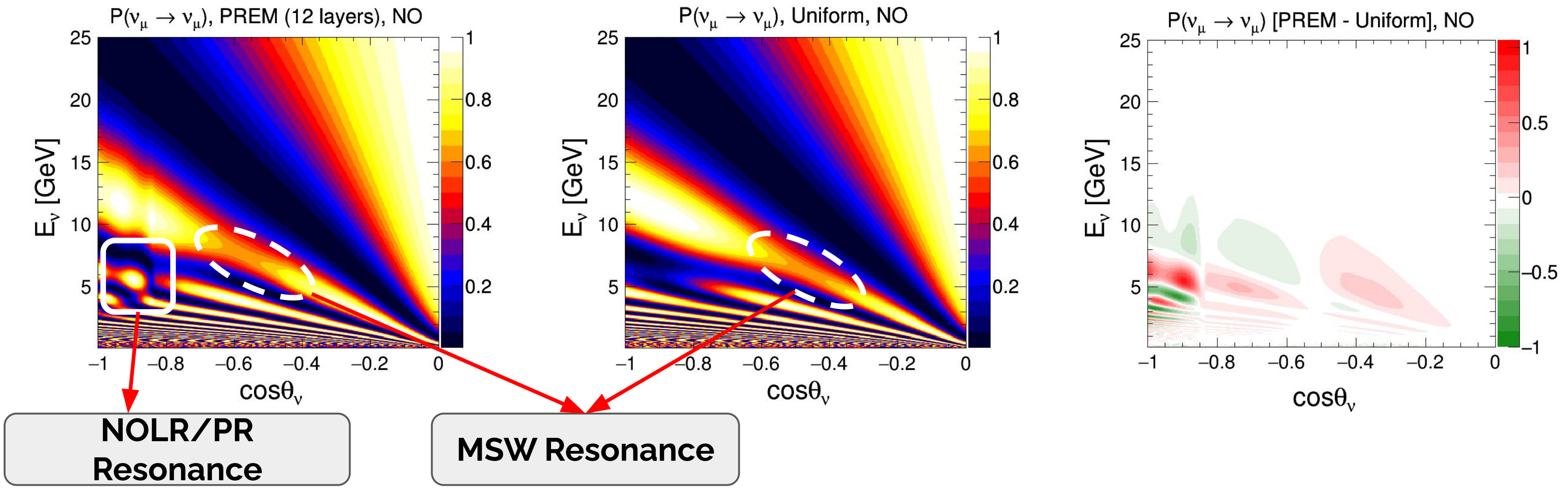
Neutrino Oscillogram: PREM and Uniform Density



- MSW resonance is visible in both the Earth profiles
- NOLR/PR resonance is only present in the PREM profile
- **Is it possible to infer information about the layered structure of Earth ?**

Motivation

PRL **100,** 061802 (2008) PHYSICAL REVIEW LETTERS week ending 15 FEBRUARY 2008

Radiography of Earth's Core and Mantle with Atmospheric Neutrinos

M. C. Gonzalez-Garcia,[1,2] Francis Halzen,[3] Michele Maltoni,[4] and Hiroyuki K. M. Tanaka[5,6]

[1]*Institució Catalana de Recerca i Estudis Avançats (ICREA), Departament d'Estructura i Constituents de la Matèria, 647 Diagonal, E-08028 Barcelona, Spain*
[2]*C.N. Yang Institute for Theoretical Physics, SUNY at Stony Brook, Stony Brook, New York 11794-3840, USA*
[3]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*
[4]*Departamento de Física Teórica & Instituto de Física Teórica UAM/CSIC, Facultad de Ciencias C-XI, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[5]*Earthquake Research Institute, University of Tokyo, 113-0032 Tokyo, Japan*
[6]*Atomic Physics Laboratory, RIKEN, 351-0198 Saitama, Japan*

(Received 20 November 2007; published 14 February 2008)

A measurement of the absorption of neutrinos with energies in excess of 10 TeV when traversing the Earth is capable of revealing its density distribution. Unfortunately, the existence of beams with sufficient luminosity for the task has been ruled out by the AMANDA South Pole neutrino telescope. In this Letter we point out that, with the advent of second-generation kilometer-scale neutrino detectors, the idea of studying the internal structure of Earth may be revived using atmospheric neutrinos instead.

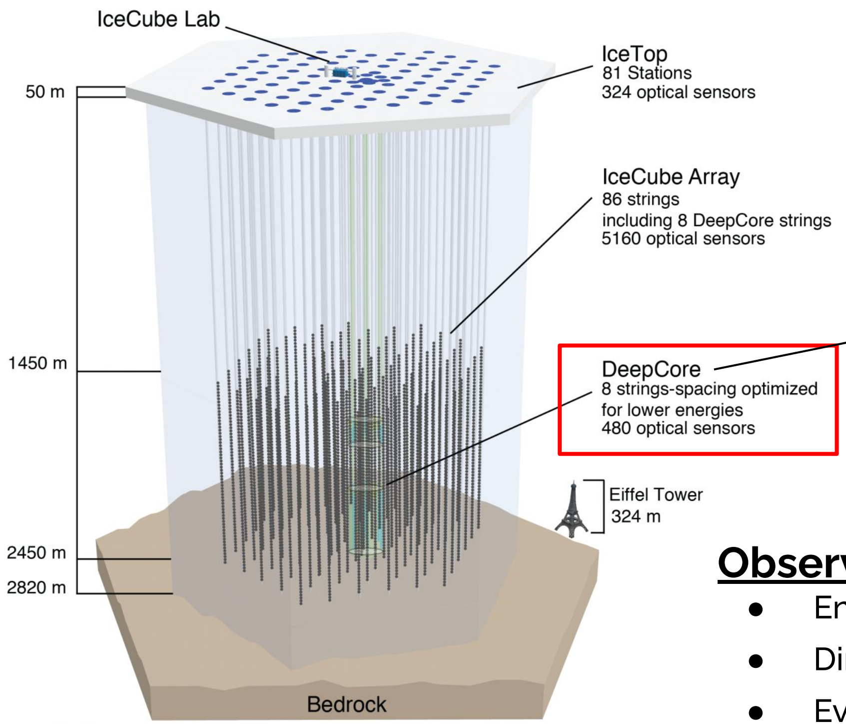
DOI: 10.1103/PhysRevLett.100.061802 PACS numbers: 13.15.+g, 14.60.Lm, 91.35.−x

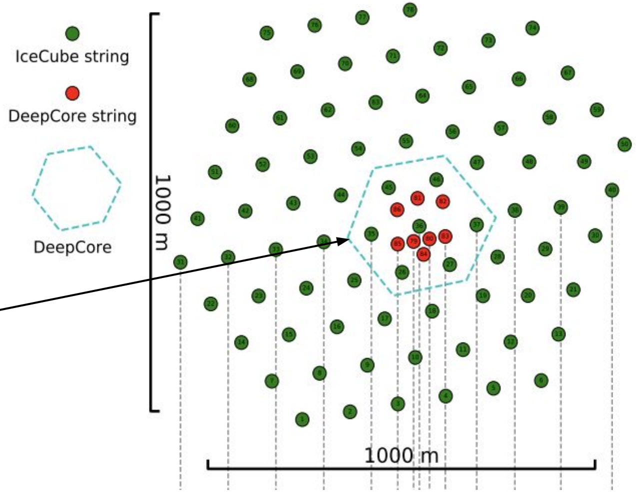
M.C. Gonzalez-Garcia et.al. *Radiography of Earth's Core and Mantle with Atmospheric Neutrinos*, PRL 100 (2008) 061802

- Can we exploit Earth's matter effect to validate the broad features of PREM?
- Is Earth homogenous or not?
- It was demonstrated in the paper using neutrino absorption at higher energy (TeV)
- IceCube can reject the homogeneity of Earth in 10 years with 3.4σ using absorption of TeV energy neutrinos

Can we show Earth is not homogenous using weakly interacting neutrinos?

IceCube DeepCore Neutrino Telescope





Observables

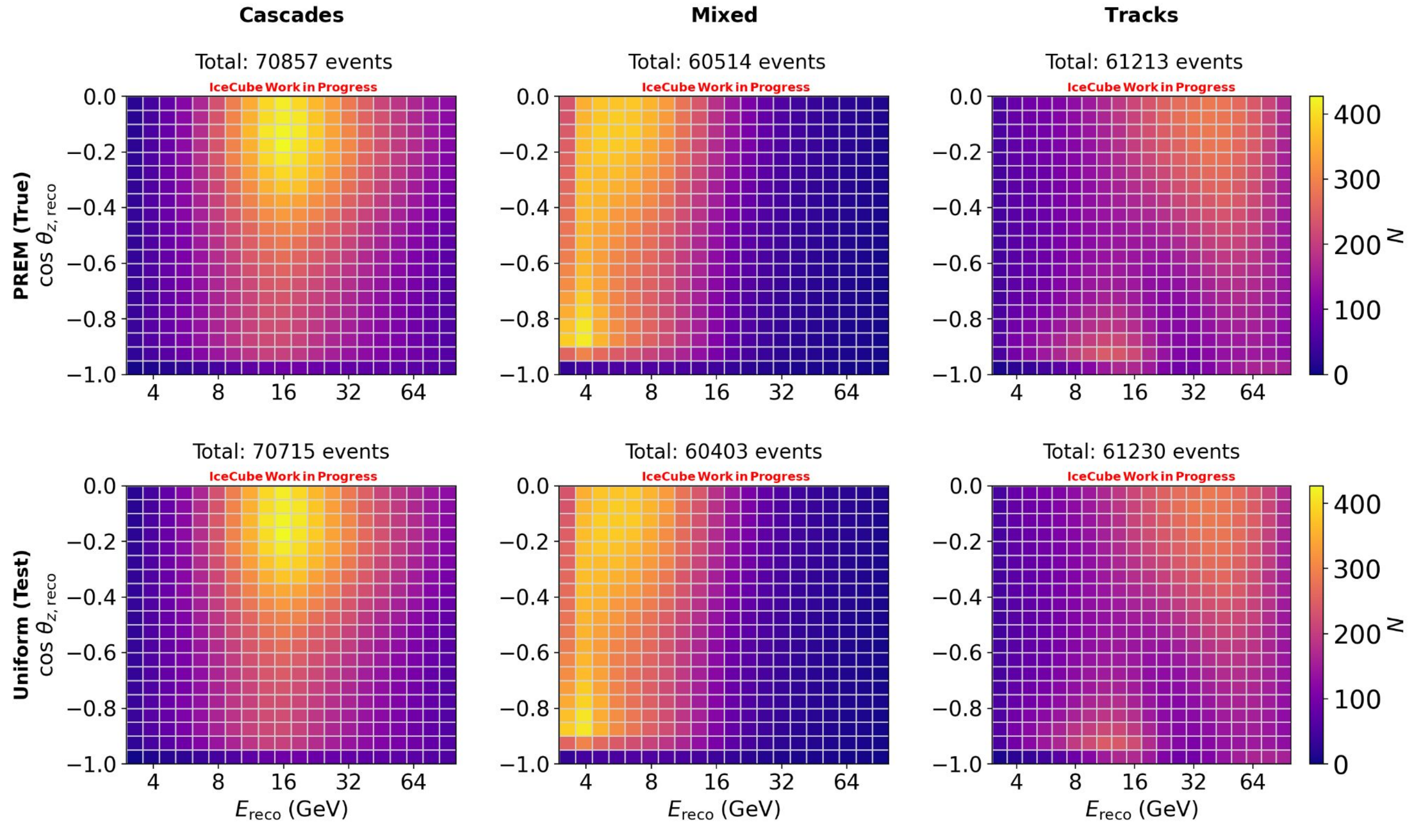
- Energy
- Direction
- Event type (PID)

DeepCore

- 8 dedicated strings with denser spacing
- Optimized for GeV scale neutrinos
- Uses IceCube as VETO

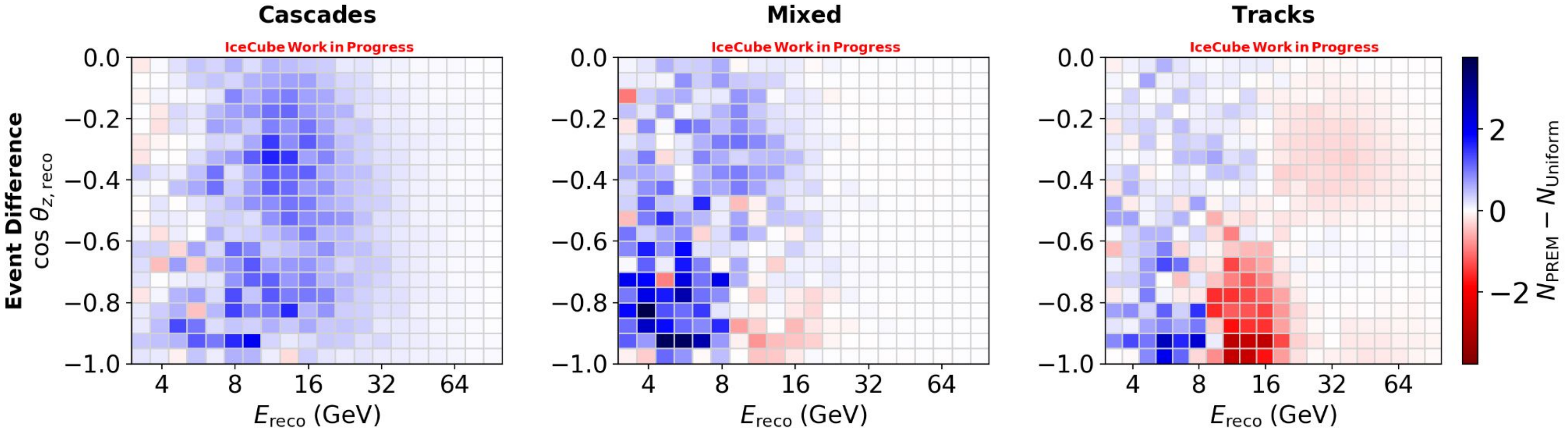
Ref. : The design and performance of IceCube DeepCore (2012) Astroparticle Physics, 35(10), 615-624 (2012)

Expected Event Distributions [PREM vs. Uniform], NO

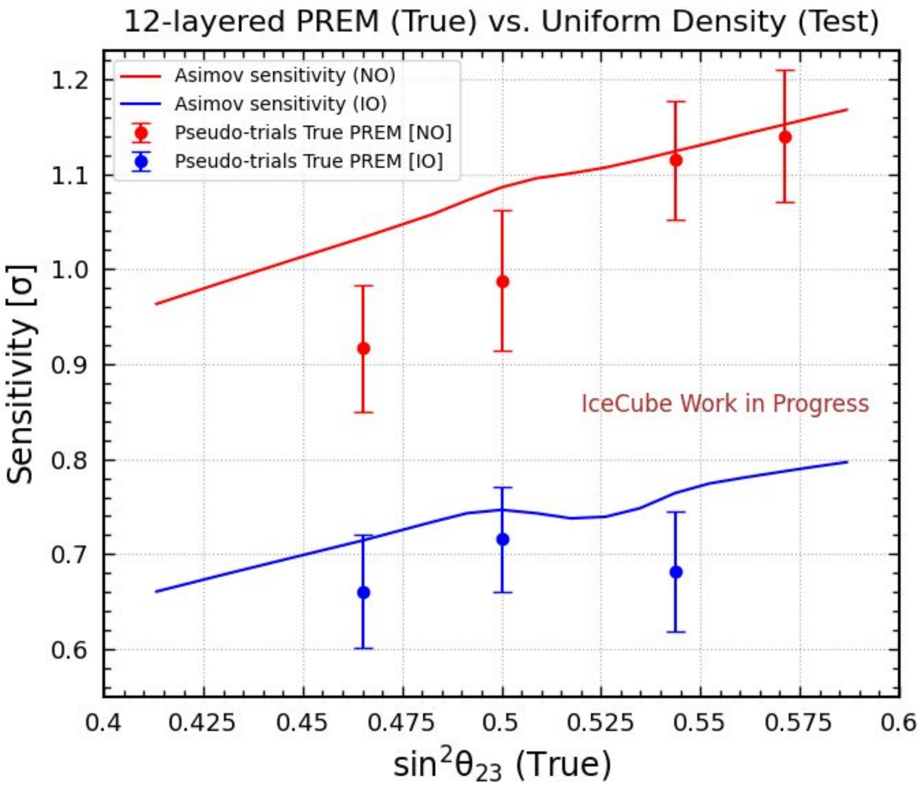


- **PREM & Uniform:** For true values of all oscillation and systematic parameters

Distribution of Simulated Event Differences NO



Sensitivity w/ Statistical Uncertainty

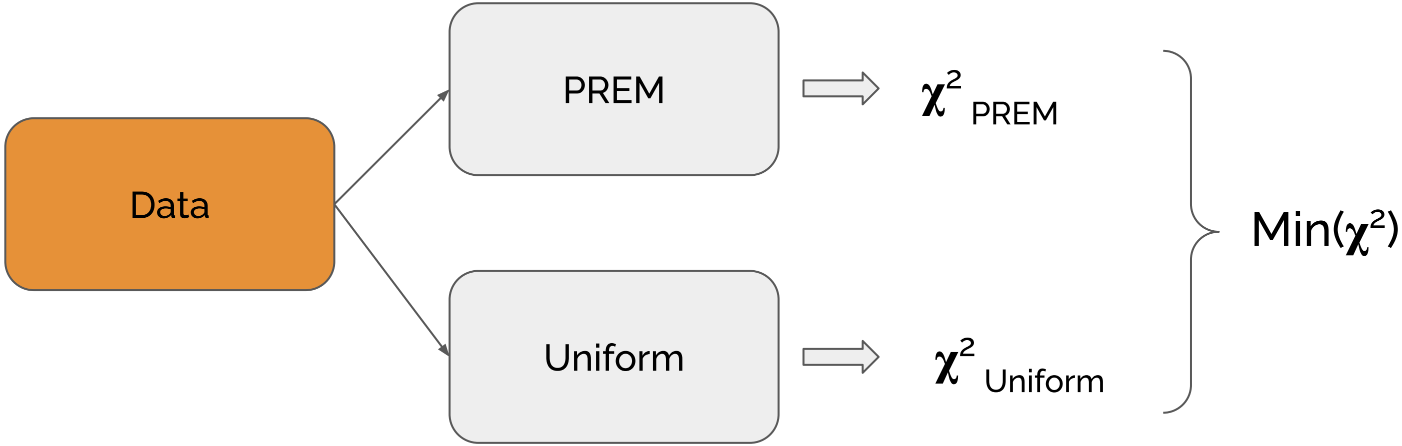


- **True hypo.:** 12-layered PREM
- **Test hypo.:** Uniform density
- Minimized over relevant oscillation and systematic parameters
- Sensitivity depends on neutrino mass ordering
- Sensitivity for NO is higher than IO due to the lower cross section and flux rate of antineutrino
- Sensitivity is increasing with θ_{23}

- For NO: $\boldsymbol{\theta_{23} = 47.5^\circ}$
  - Sensitivity = 1.1 σ
- For IO: $\boldsymbol{\theta_{23} = 47.5^\circ}$
  - Sensitivity = 0.76 σ

Experimental Result

Which hypothesis is preferred by the experimental data?



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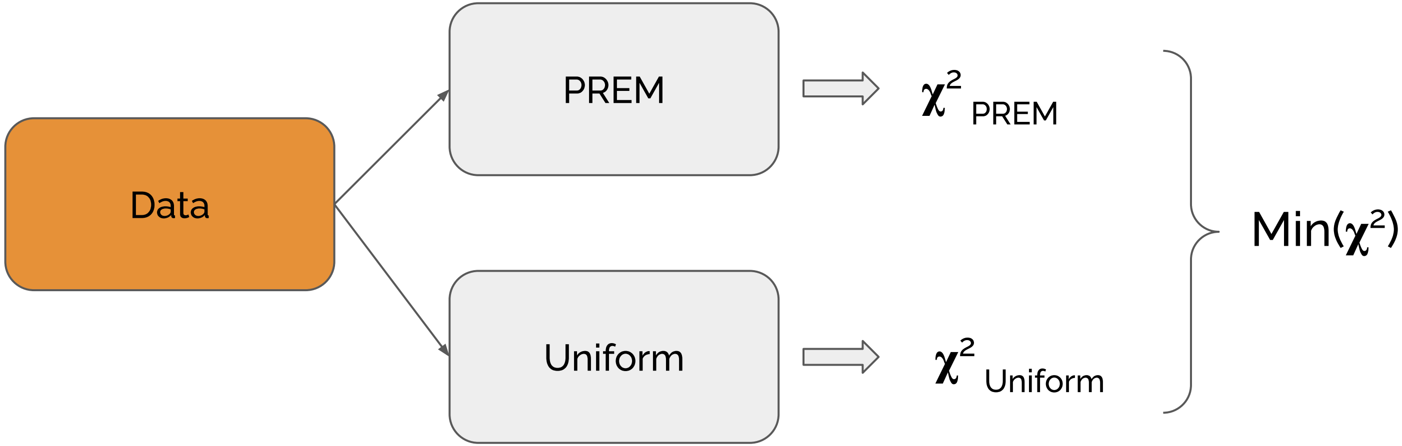
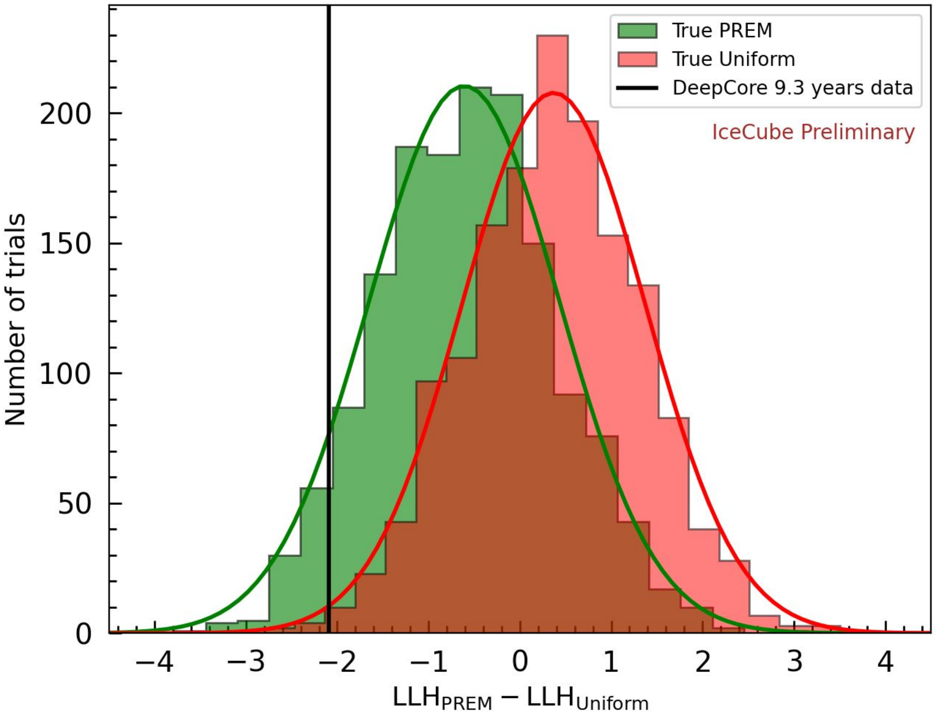


Data prefers PREM hypothesis

Experimental Result



P-value:

- **True PREM**: 94% (No. of trials right to the data line: 1406)
- **True Uniform**: 0.46% (No. of trials left to the data line: 7)
- **CLs** = (0.0046)/(1-0.94) = **7.6%**
- CL to reject uniform hypothesis 92.4%

$$\boxed{\text{significane}\,(\eta_\sigma) = \sqrt{2}\,\text{erfc}^{-1}(2 \times CL_s)}$$

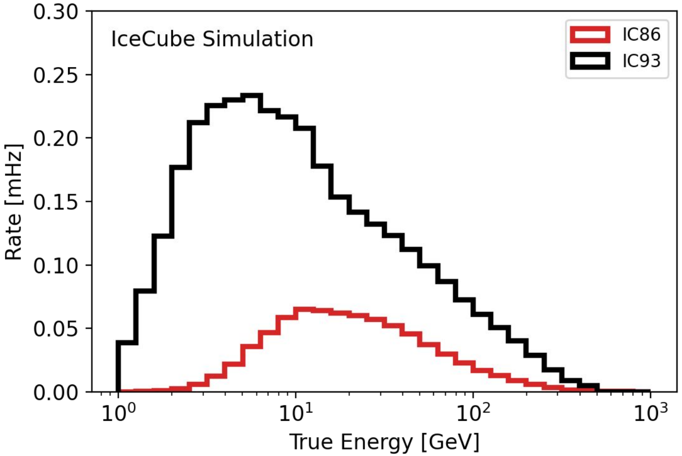
Ref: JHEP 03 (2014) 028

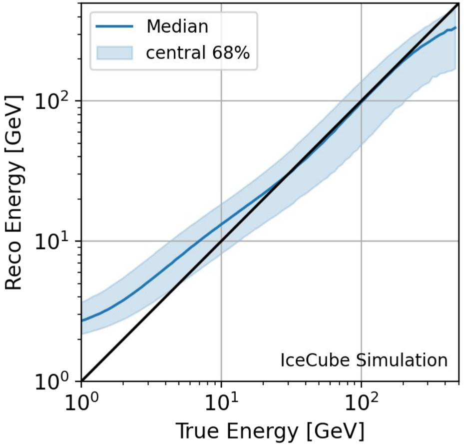
The significance of rejecting the homogeneous Earth matter density is ~1.4σ

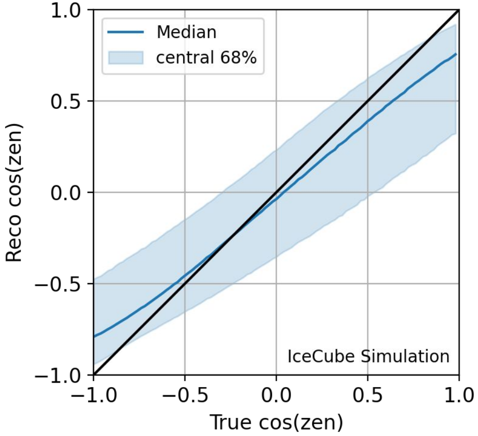
IceCube Upgrade

- New modules
  - D-Egg
  - mDOM
- Calibration devices
- R&D modules

- More strings in central region
- More photons/event
- Lower threshold
- Improved statistics
- Improved reconstruction

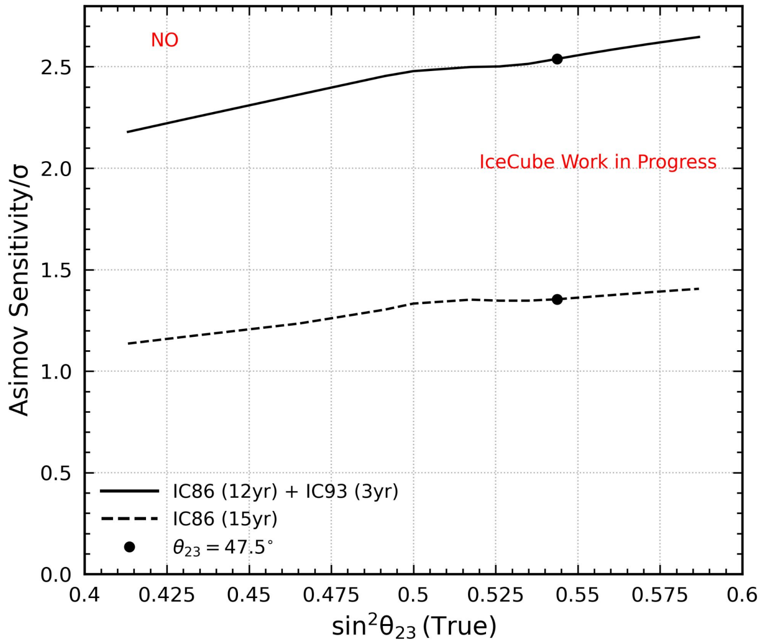






ICRC2019 arXiv:1908.09441 ICRC2023 arXiv:2307.15295

Asimov Sensitivity to Reject Uniform Hypo. with IceCube Upgrade



~ 2 times improvement in the sensitivity to reject homogeneous matter density

Summary

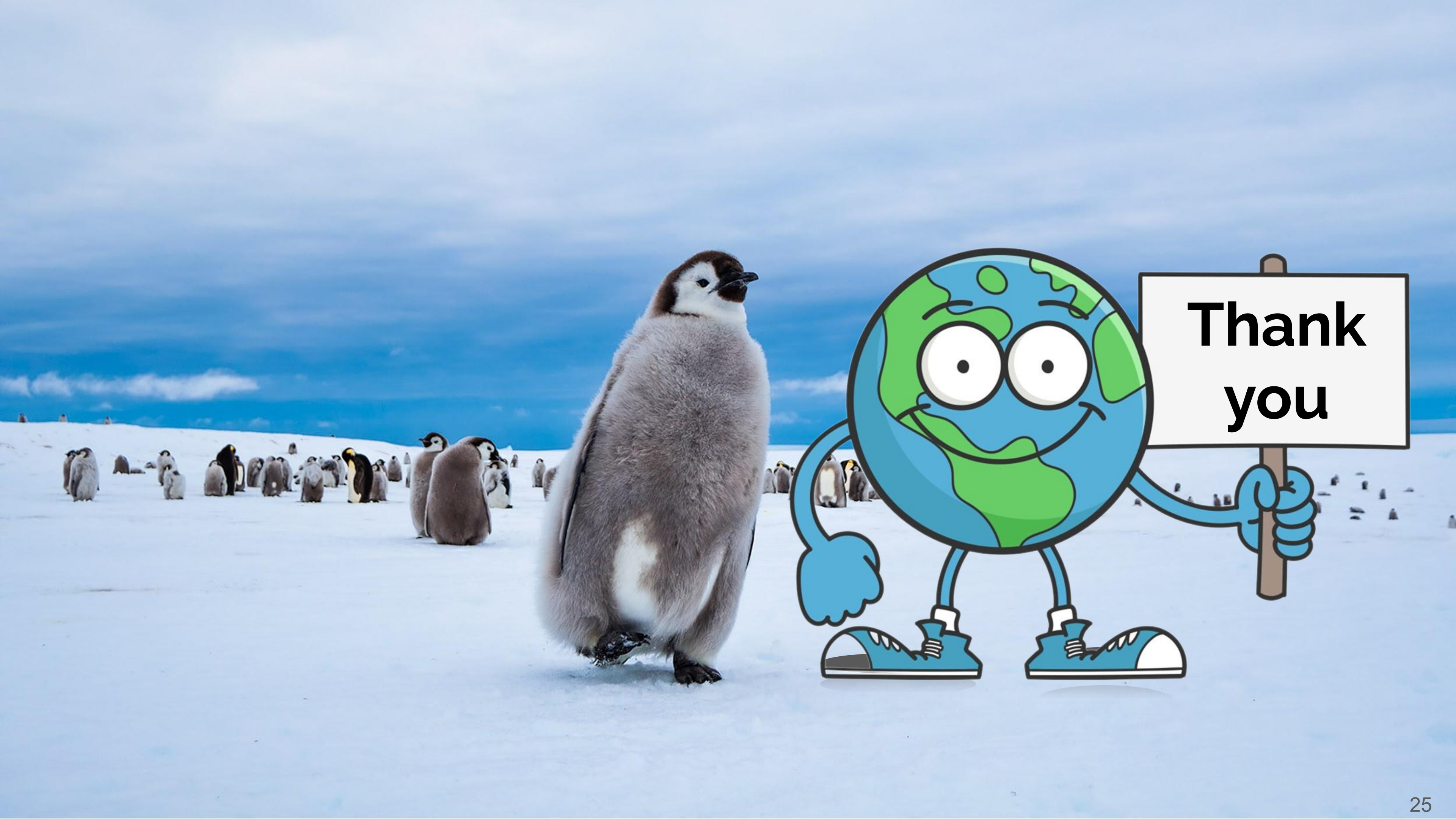
- Atmospheric neutrinos have energies in the multi-GeV range where Earth's matter effects are significant in neutrino oscillations - hence they would help to probe interior of Earth

- High statistics (~ 164 k events in 9.28 yr of data), low-energy threshold (~ 3 to 5 GeV), access to multiple baselines, better reconstructed energy and zenith help significantly

- **The significance of rejecting the homogeneous Earth matter density is ~1.4σ**

- Using IceCube DeepCore data, this study distinguishes Earth's layered structure from homogeneous matter density, motivating further exploration into refined properties of its interior.

- Expecting 2 times of improvement in the future with IceCube Upgrade

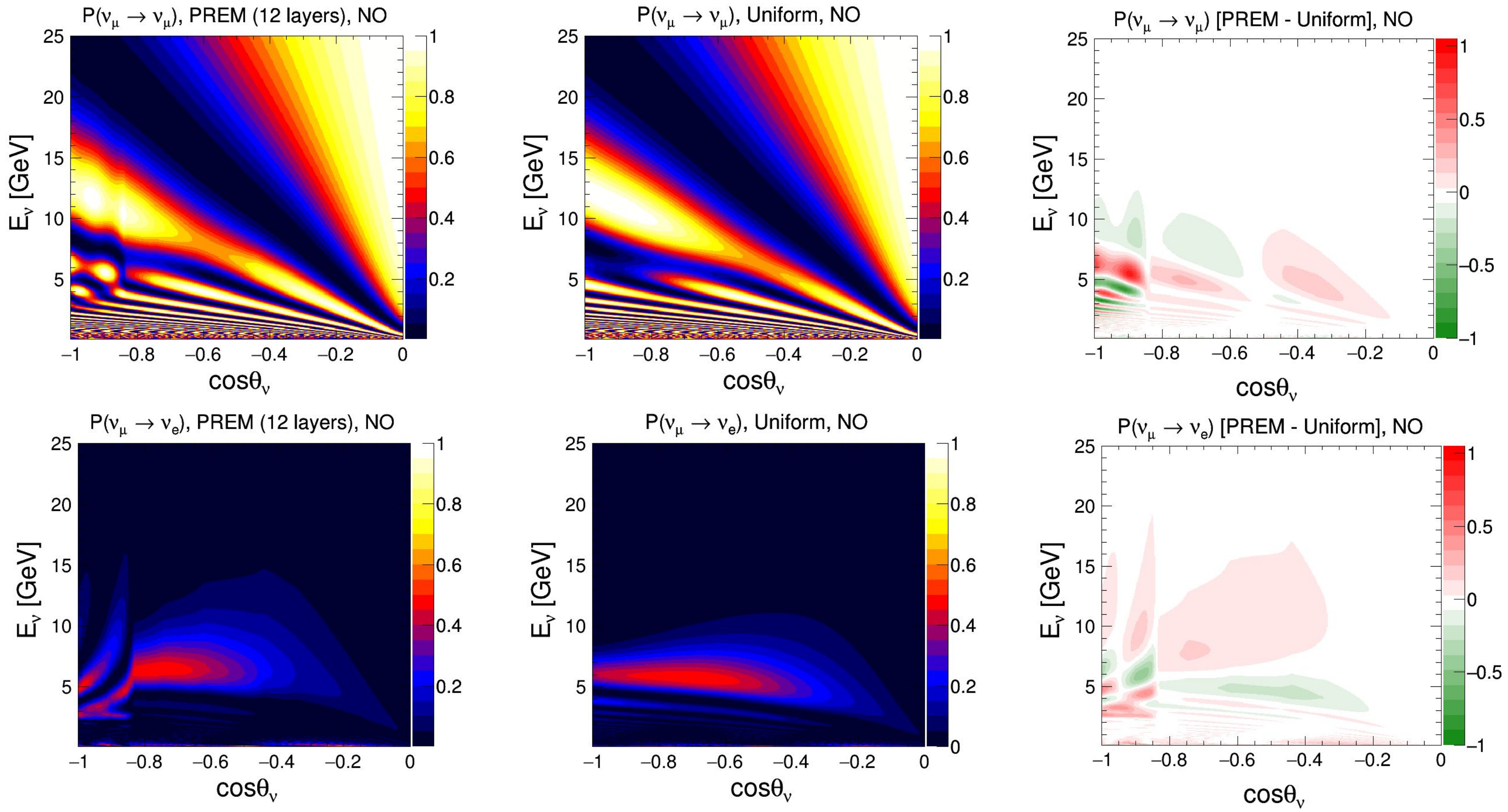

Thank
you

Backup

Probabilities & Their Differences [PREM vs. Uniform], NO

Track-like

Cascade-like



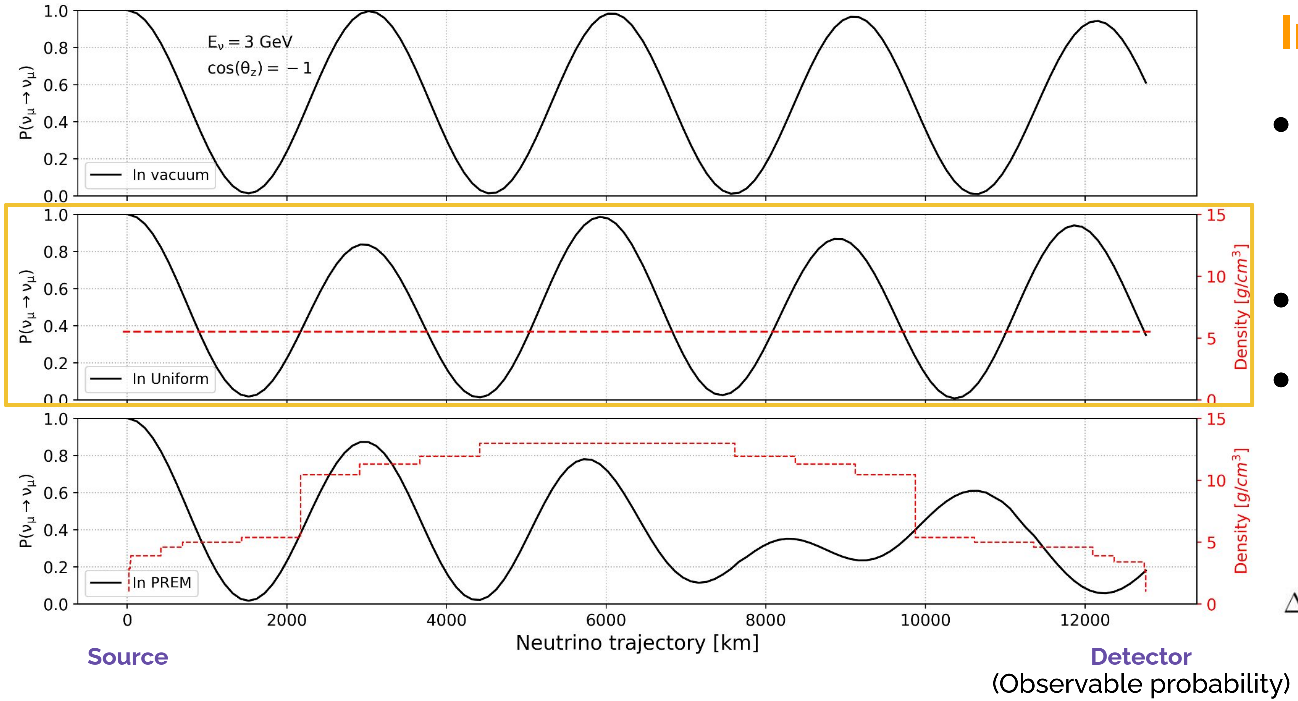
Benchmark Values of Oscillation Parameters

Mass ordering	θ_{12} (deg.)	θ_{13} (deg.)	θ_{23} (deg.)	Δm^2_{21} (eV^2)	Δm^2_{31} (eV^2)	δ_{CP} (deg.)
NO (IO)	33.41	8.54	47.5	7.41×10^{-5}	$2.47\ (-2.47) \times 10^{-3}$	0

NuFIT 5.2 (2022)

without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

Layered Structure of Earth: In the Eyes of Neutrinos



In Uniform

- Interaction of neutrino with matter modifies the neutrino oscillation parameters
- Maximal mixing angle
- Maximum transition

$$\sin 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m_M^2}$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$A_{CC} = 2\sqrt{2} G_F E \rho N_A Y_e$$

- MSW resonance (L. Wolfenstein, PRD 17 (1978) 2369)

MSW Resonance

$$E_{\text{res}} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

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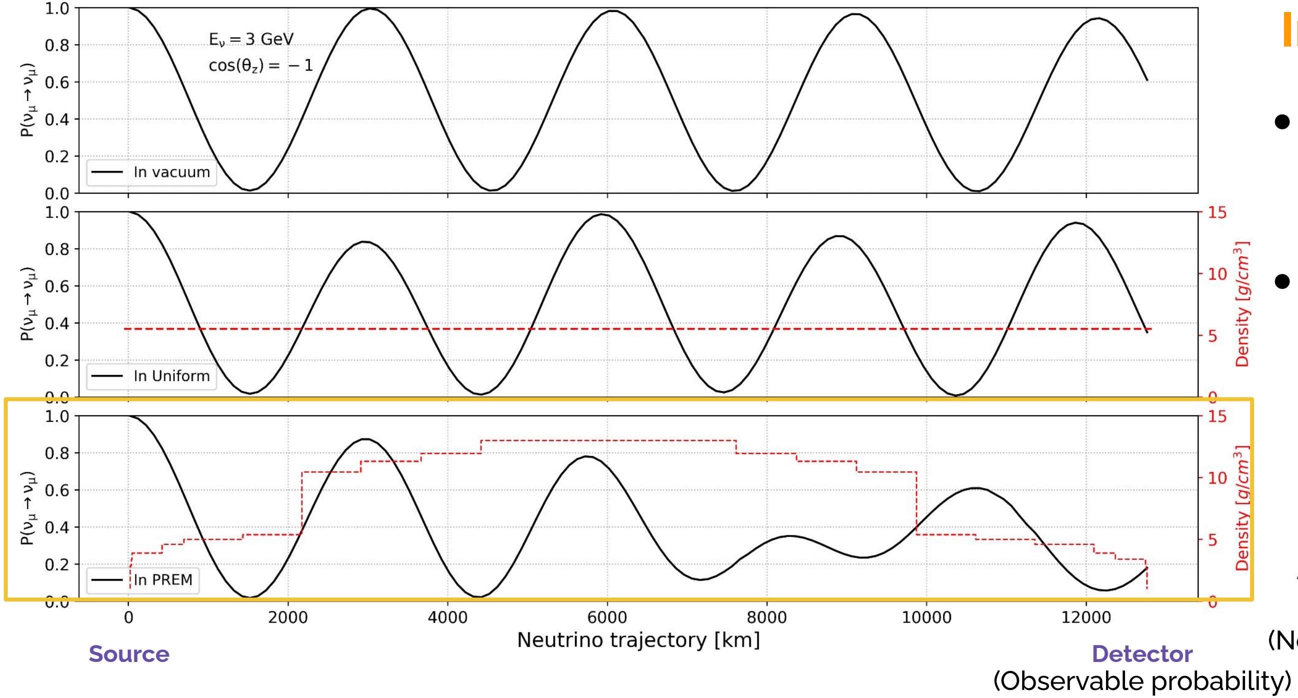


In PREM

- Periodic modulation of density (n)

$$n(x) = \bar{n} + n_1 \cos \omega_d x$$

- If frequency of density modulation equals to the frequency of oscillation, resonance occurs

$$k\omega_d = \Delta_m(\bar{n}), \ \ k = 1, 2..$$

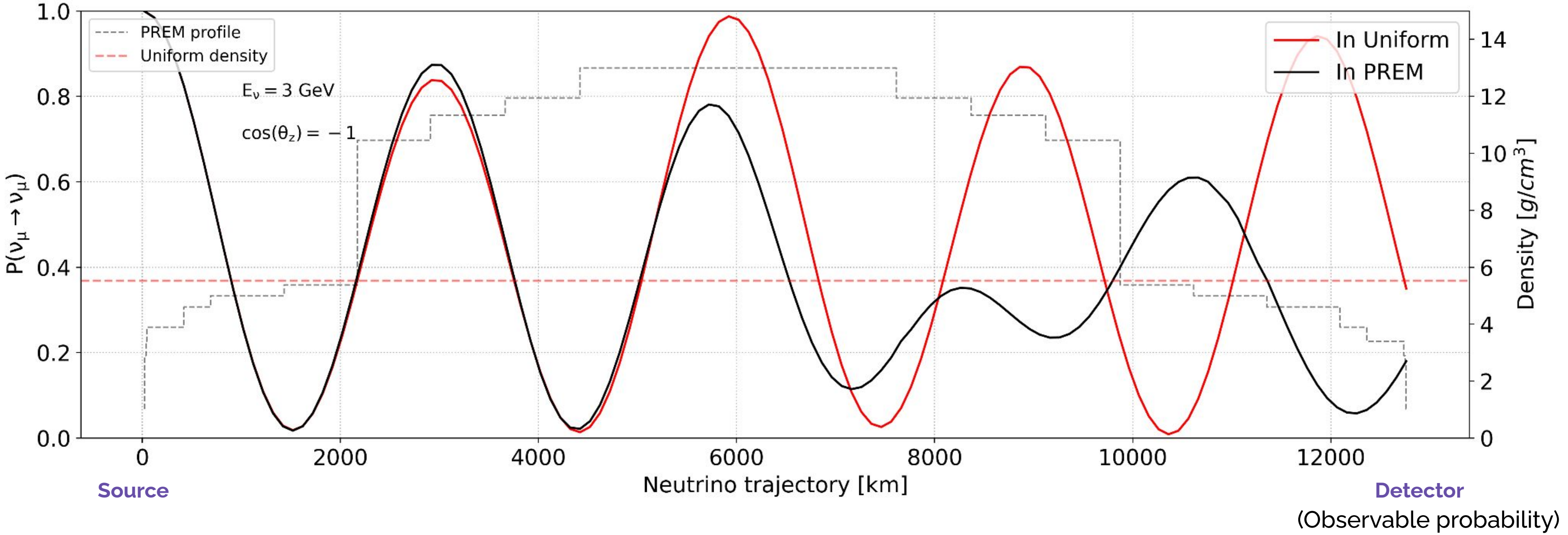
$$\Delta_m(\bar{n}) = \frac{\Delta m^2}{2E}[(\cos 2\theta - \frac{2VE}{\Delta m^2})^2 + \sin^2 2\theta]^{1/2}$$

(Neutrino oscillation frequency in average density)
(V - matter potential term)

- Neutrino Oscillation Length Resonance (NOLR) (Petcov, PLB 434 (1998) 321) or Parametric Resonance (PR) (Akhmedov, NPB 538 (1999) 25)
- Parametric effects in neutrino oscillations, Physics Letters B, Volume 226, Issues 3–4, (1989)

NOLR/PR Resonance

Layered Structure of Earth: In the Eyes of Neutrinos



- Probability in PREM profile start to differ from uniform density profile, once it sees the density jump in PREM (Outer core)
- Further deviation of probability in PREM is visible due to NOLR/PR resonance

Statistical Methods

- **Following Poissonian LLH**

$$\boxed{\text{Test Statistics (TS)} = \text{LLH} + \text{Prior pull} = \sum_{\mathrm{i}\in\mathrm{bins}}[-\lambda_\mathrm{i}+\mathrm{x_i}\ln(\lambda_\mathrm{i})-\ln(\mathrm{x_i}!)]+\frac{1}{2}\sum_{\mathrm{j}\in\mathrm{sys}}\frac{(\mathrm{p_j}-\hat{\mathrm{p}}_\mathrm{j})^2}{\sigma_\mathrm{j}^2}}$$

$\mathrm{x_i}$ - Observed value of i^{th} bin
λ_i - Expected value of i^{th} bin
$\mathrm{p_j}$, $\hat{\mathrm{p}}_\mathrm{j}$, and σ_j^2 are the nominal, best-fit, and Gaussian prior of j^{th} systematics, respectively

- **Sensitivity (to reject Uniform hypothesis)**

$$\eta_\sigma = \frac{(LLH_3 - LLH_4) - (LLH_1 - LLH_2)}{\sqrt{(2\times(LLH_3 - LLH_4)}}$$

(For the assumption of true PREM)

$$\Delta LLH = \quad N(\pm\overline{\Delta LLH}, 2\sqrt{\overline{\Delta LLH}})$$

LLH1: PREM (Data) → PREM (Theory)
LLH2: PREM (Data) → Uniform (Theory)

LLH3: Uniform (Data)* → PREM (Theory)
LLH4: Uniform (Data)* → Uniform (Theory)

* Uniform (Data) is generated with the best fit values from LLH2 fit

See: Mattias Blennow et al., (JHEP 03 (2014) 028) , X Qian et al., (PRD 86 113011 (2012)), and Emilio Ciuffoli et al., (JHEP 01 (2014) 095)

Systematic Treatment

IceCube

- **Flux uncertainties**
  - Cosmic ray spectrum
  - Pion & Kaon production uncertainties Barr et al., Phys. Rev. D 74, 094009
- **Cross section**
  - Axial mass uncertainty for resonance and quasielastic events
  - GENIE - CSMS transition for DIS
- **Detector and Ice properties**
  - Optical efficiency of the photo sensor
  - Ice scattering and absorption
  - Birefringence (double refraction of light due to anisotropy of ice) Cryosphere Discuss. 2022, 1 (2022)
  - Muon Light Yield (photon propagation in the ice from muons)
- **Atmospheric muon scale** Gaisser et al.+ Sibyll2.1
- **Normalization of neutrino event counts**

➔ In total, about 40 systematics are tested individually; around **20 high-impact** parameters are included as nuisance parameters and kept free in the analysis

For more details, see: Phys.Rev.D 108 (2023) 1, 012014

Binning Scheme

- Matter effect signal is significant at lower energies and higher baselines
- Binning optimization is necessary
- Reduced the energy threshold down to 3 GeV

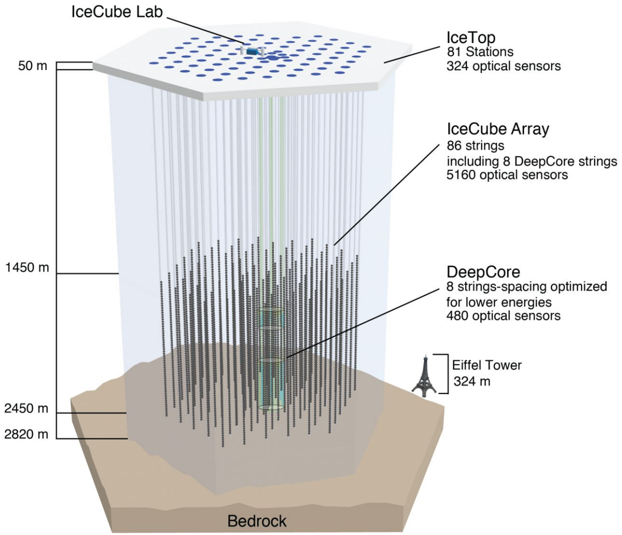
Observables	Number of Bins	Range	Step
Energy	20	[3, 100] GeV	log
cos(zenith)	20	[-1, 0]	linear
PID	3	[0, 0.33, 0.39, 1] [Cascade, Mixed, Track]	linear

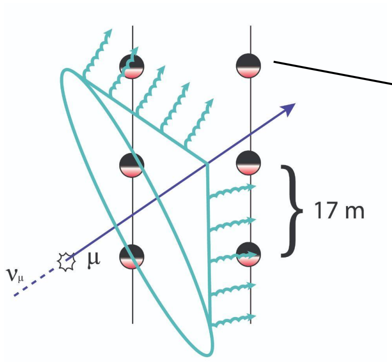
- **Following Poissonian LLH**

$$\text{Test Statistics (TS)} = \text{LLH} + \text{Prior pull} = \sum_{\mathrm{i}\in\mathrm{bins}} [-\lambda_\mathrm{i} + \mathrm{x_i}\ln(\lambda_\mathrm{i}) - \ln(\mathrm{x_i}!)] + \frac{1}{2}\sum_{\mathrm{j}\in\mathrm{sys}} \frac{(\mathrm{p_j} - \hat{\mathrm{p}}_\mathrm{j})^2}{\sigma_\mathrm{j}^2}$$

$\mathrm{x_i}$ - Observed value of i^{th} bin
λ_i - Expected value of i^{th} bin
$\mathrm{p_j}$, $\hat{\mathrm{p}}_\mathrm{j}$, and σ_j^2 are the nominal, best-fit, and Gaussian prior of j^{th} systematics, respectively

IceCube DeepCore Neutrino Telescope





DOM

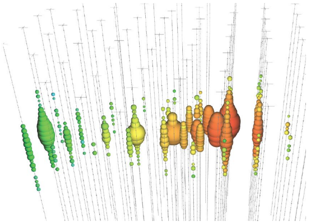
- $1\ km^3$ neutrino detector deep under ice at South Pole
- 5160 DOMs across 86 strings
- Optimized for TeV-PeV

- Neutrino interacts with ice and produces charged lepton
- Lepton direction closely aligned with neutrino
- Charged leptons emit Cherenkov radiation, when they travel faster than light in a medium
- Radiation detected by DOM (Digital Optical Modules)

Event Signatures in IceCube

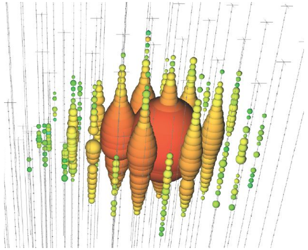
Track-like events:

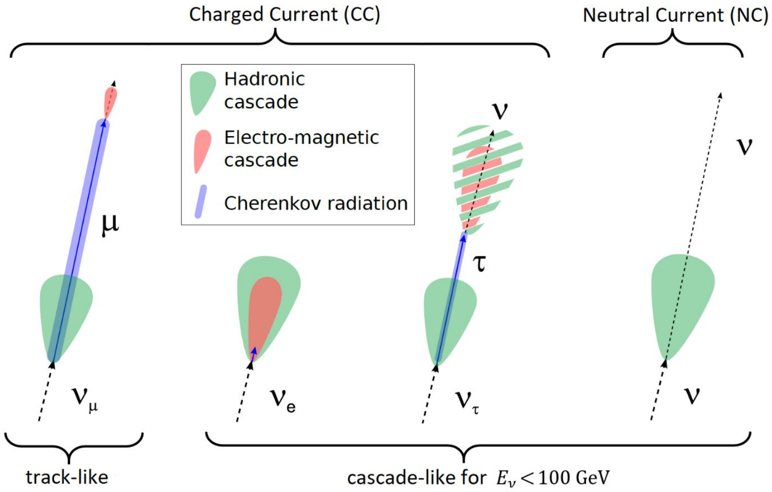
- Elongated
- Source: ν_μ CC



Cascade-like events:

- Spherical
- Source: ν_e CC, ν_τ CC, all NC

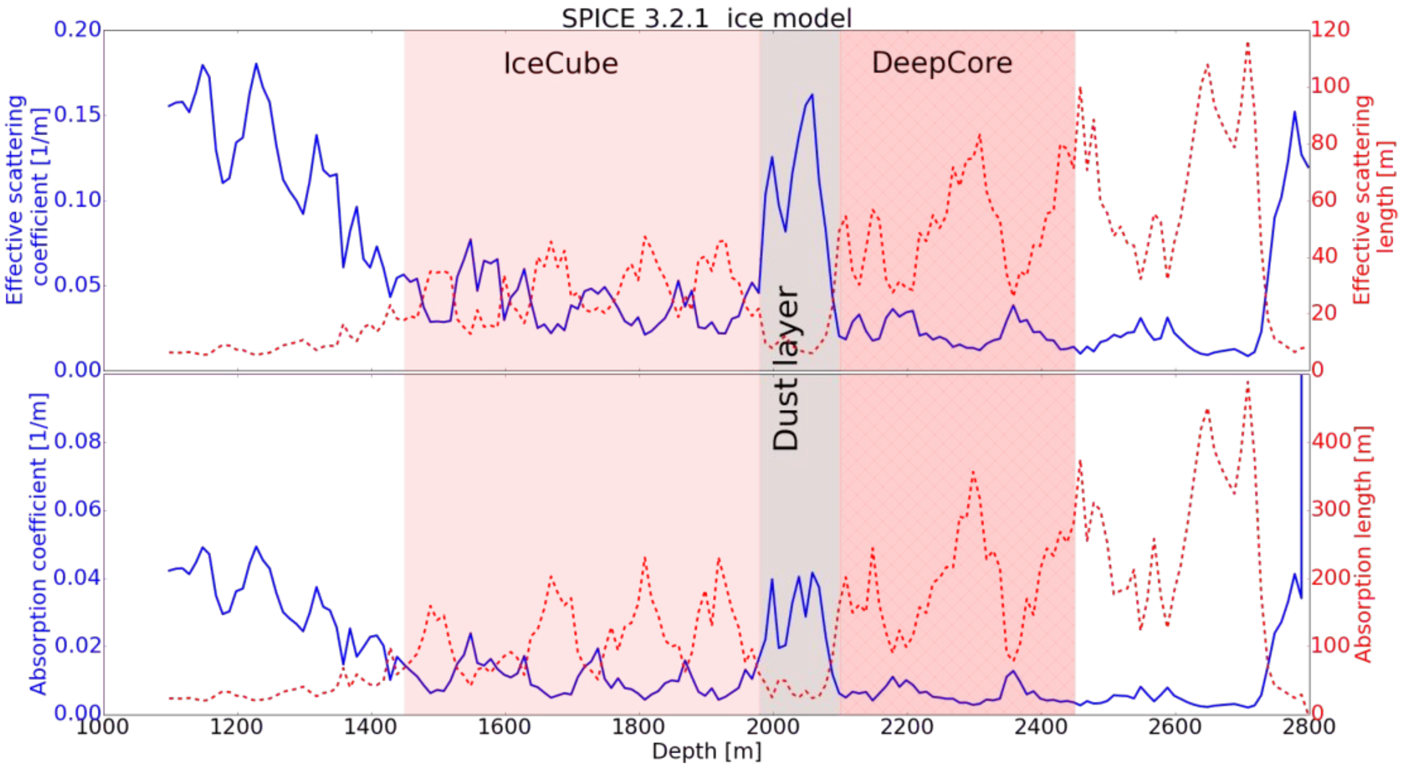




❑ **Observables:**
- ❑ Energy
- ❑ Direction
- ❑ Event type (PID)

Size of the colored sphere: Amount of photon/energy observed in a DOM

Ice


SPICE 3.2.1 ice model
IceCube
DeepCore
Dust layer
Effective scattering coefficient [1/m]
Effective scattering length [m]
Absorption coefficient [1/m]
Absorption length [m]
Depth [m]
0.20
0.15
0.10
0.05
0.00
0.08
0.06
0.04
0.02
0.00
120
100
80
60
40
20
0
400
300
200
100
0
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

Scattering