Earth for Neutrinos, Neutrinos for Earth

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TIFR MUMBAI

MULTI-MESSENGER TOMOGRAPHY OF EARTH (MMTE 2023)

APC, PARIS

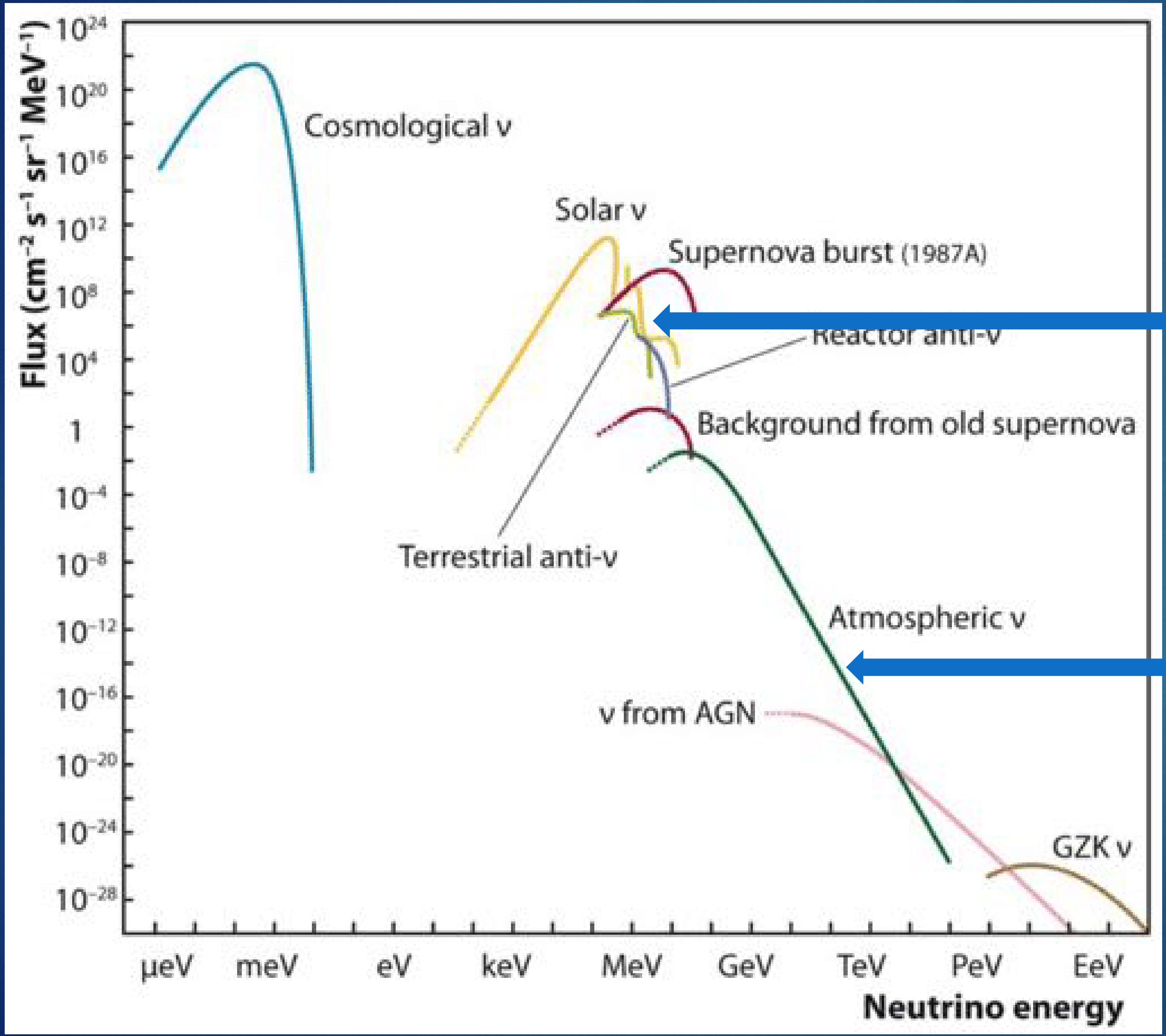
4 JULY 2023

Earth and Neutrinos

- **Earth for Neutrinos:**
  - Earth as a source: geoneutrinos, atmospheric neutrinos
  - Neutrino passage through Earth: discovery of neutrino oscillations
  - Earth as a medium: matter effects on neutrino propagation
  - Exploiting Earth for precision measurements of neutrino parameters
  - Mantle vs. core effects for identifying new physics scenarios
- **Neutrinos for Earth:**
  - Neutrino absorption tomography and oscillation tomography
  - Electron density distribution → Chemical composition
  - Core-mantle boundary, density jumps, density profile

Earth as a neutrino source

Earth as a Neutrino source



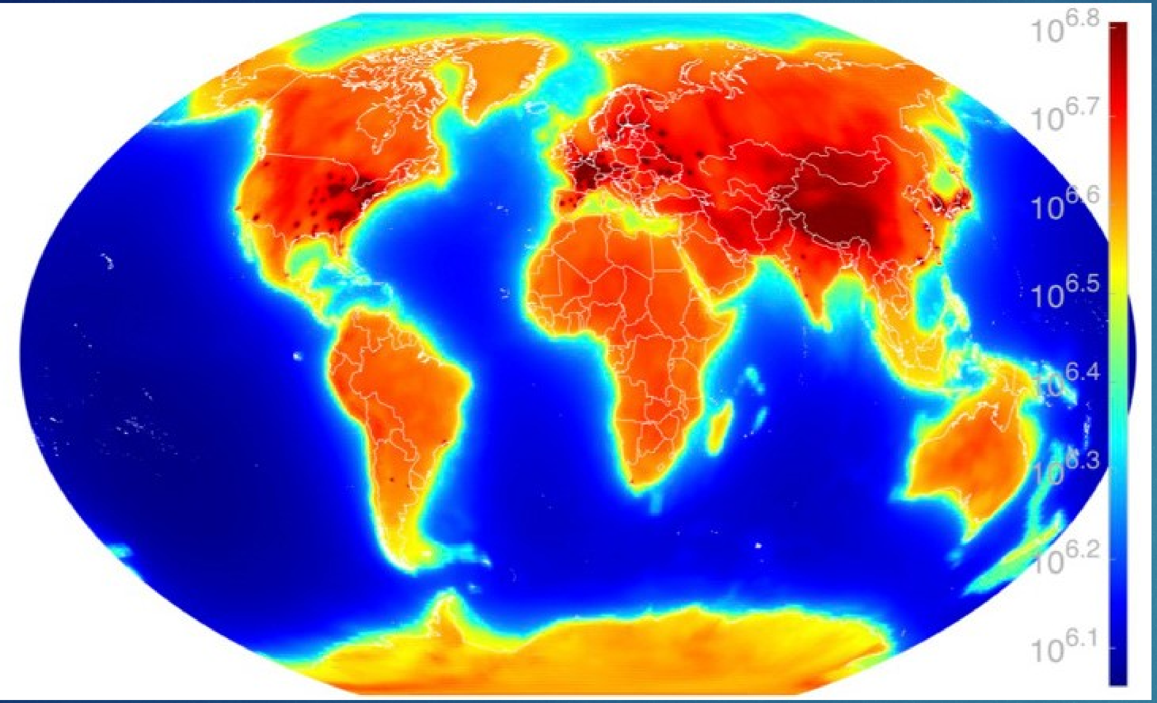
Neutrinos generated in/on Earth

Geoneutrinos

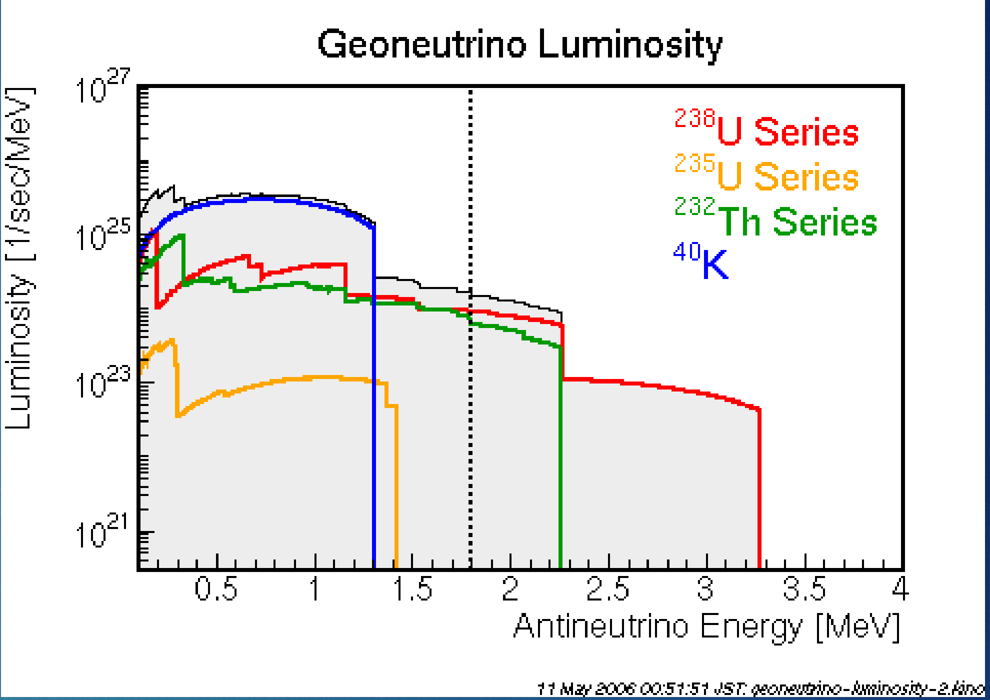
Atmospheric neutrinos

Katz and Spiering, 1111.0505

Geoneutrinos



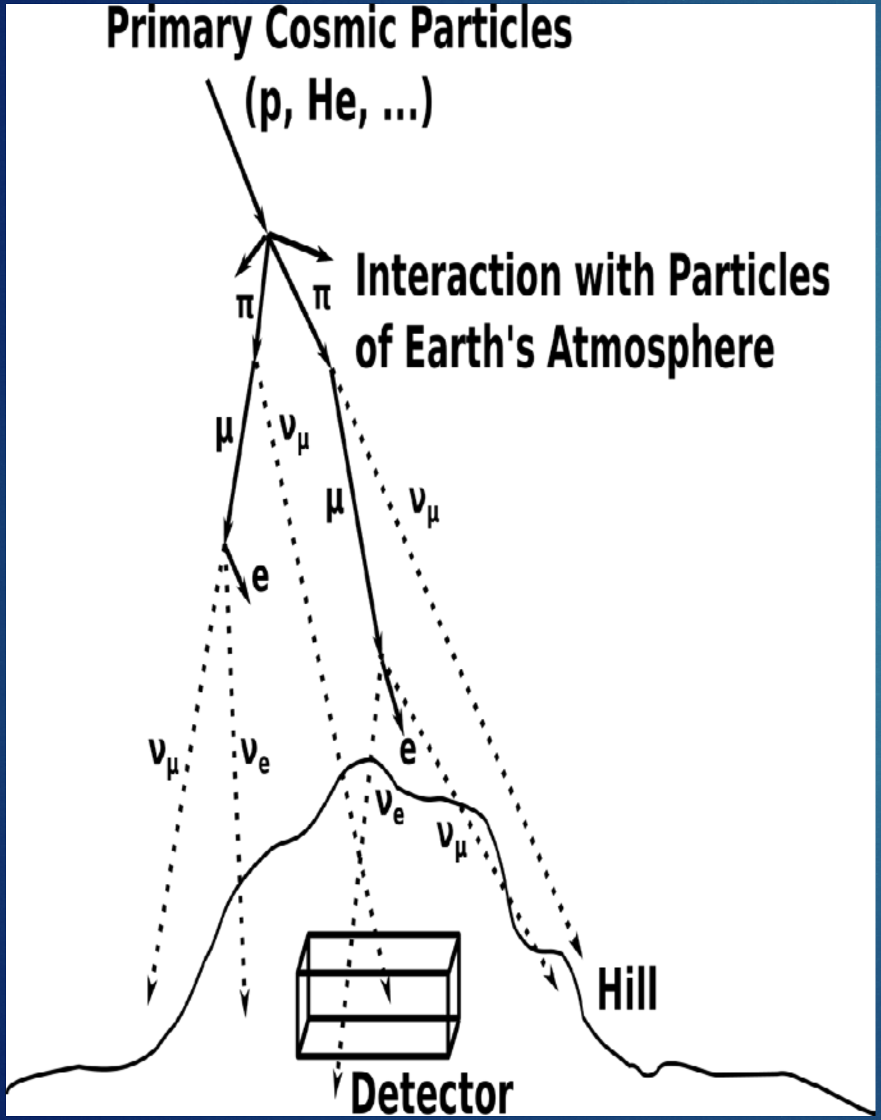
Antineutrino Global Map 2015
Usman, Jocher, Dye, McDonough, Learned
Sci Rep **5**, 13945 (2015)

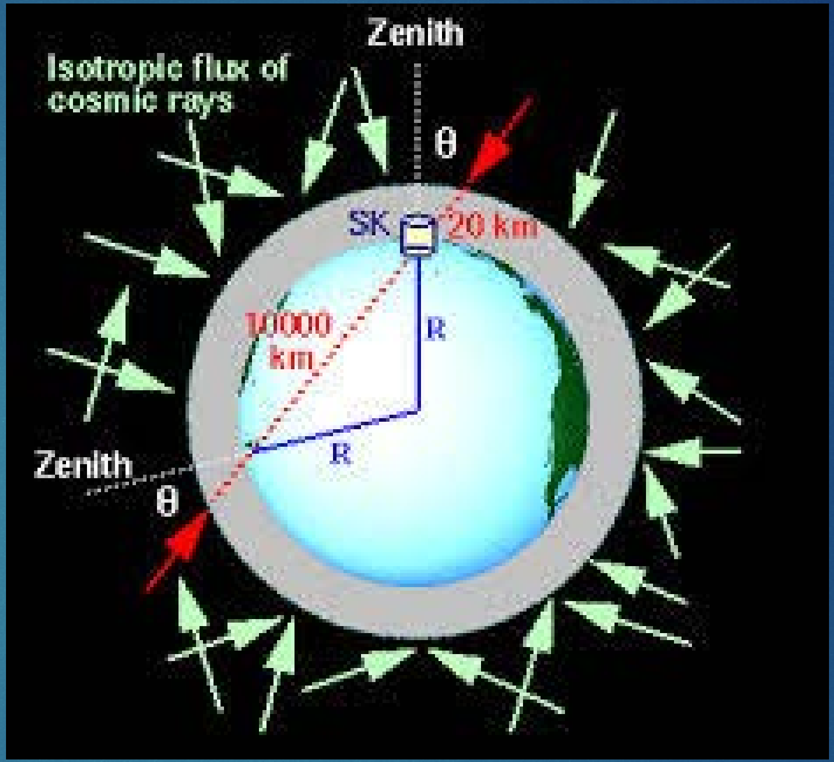


Enomoto Sanshiro
https://www.awa.tohoku.ac.jp/~sanshiro/research/geoneutrino/spectrum/

Talks by Livia Ludova and Virginia Strati

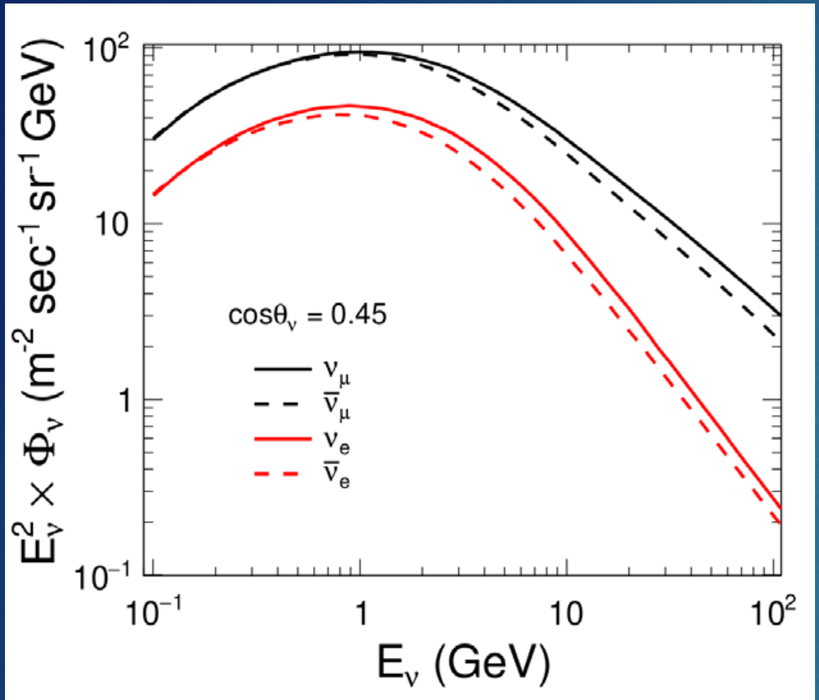
Atmospheric neutrinos



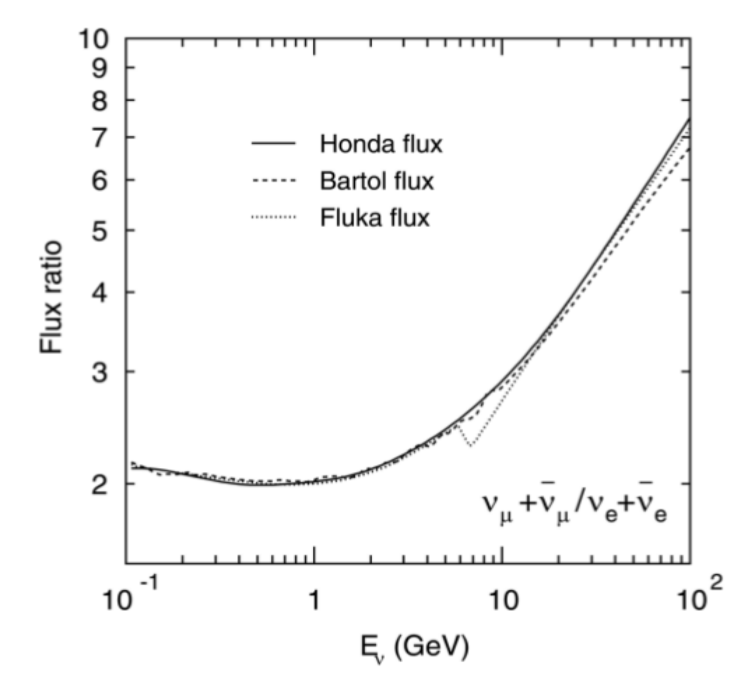


- Wide energy range: **E = 100 MeV – PeV**
- Wide range of distances to travel through:
  L = 15 km – 12800 km

Flavor dependence of fluxes



Simulated neutrino flux at Theni by Honda et al.
(https://www.icrr.u-tokyo.ac.jp/~mhonda/)



Fluxes at SK
T. Kajita, 10.1103/RevModPhys.88.030501

$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$

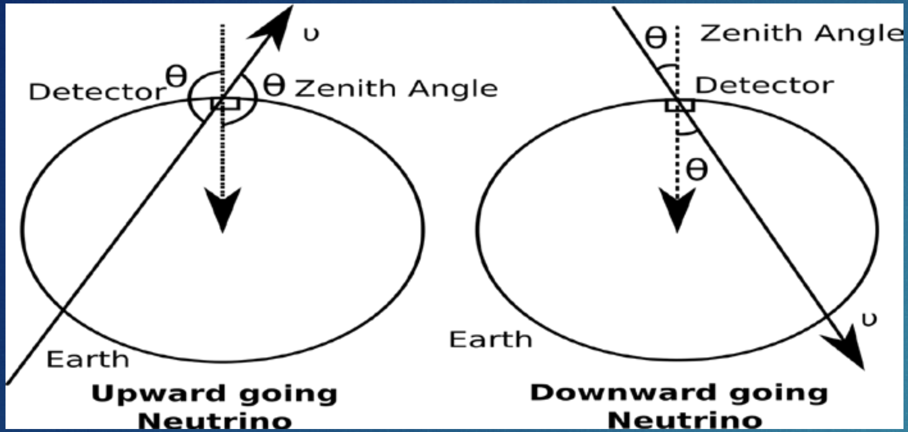
$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$
$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$

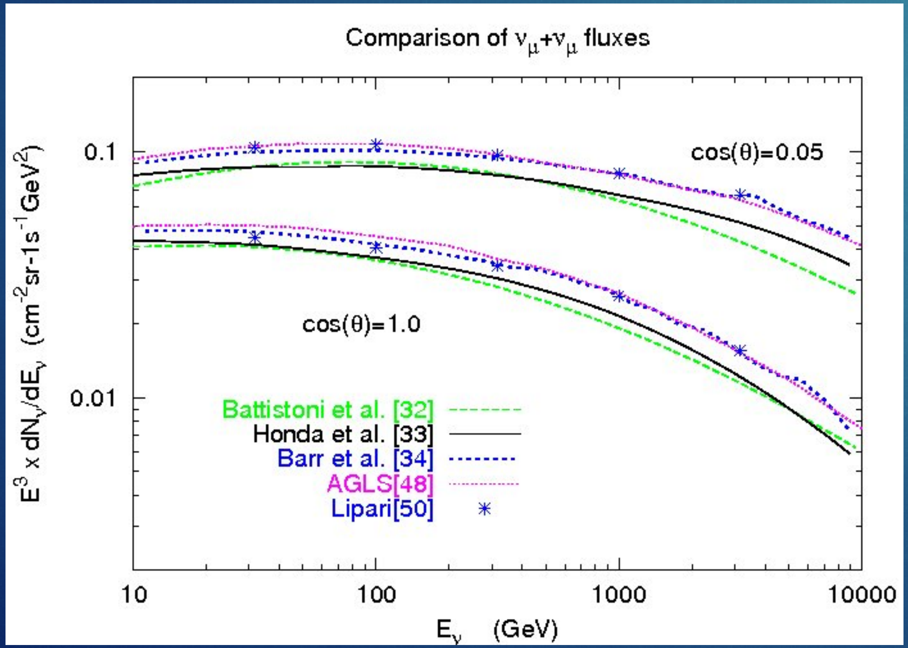
ν_μ / ν_e flux ratio

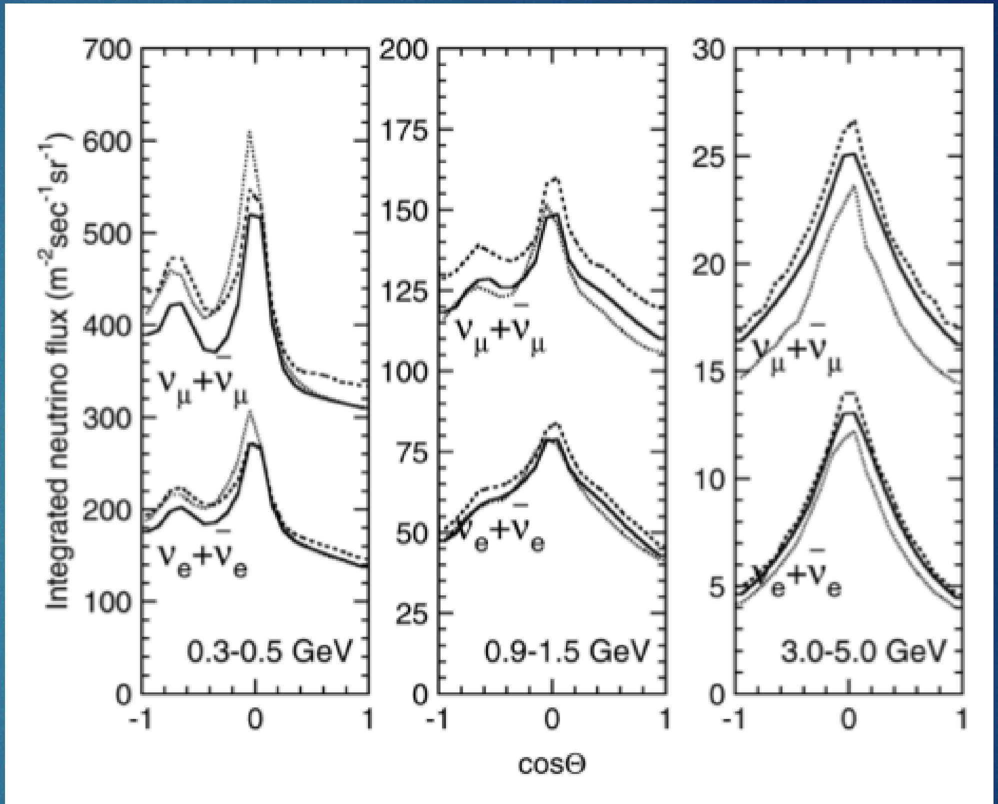
$$R = \frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}$$

- Low energies: $R \approx 2$
- High energies: $R > 2$ since some muons reach surface without decaying

Zenith angle dependence of fluxes





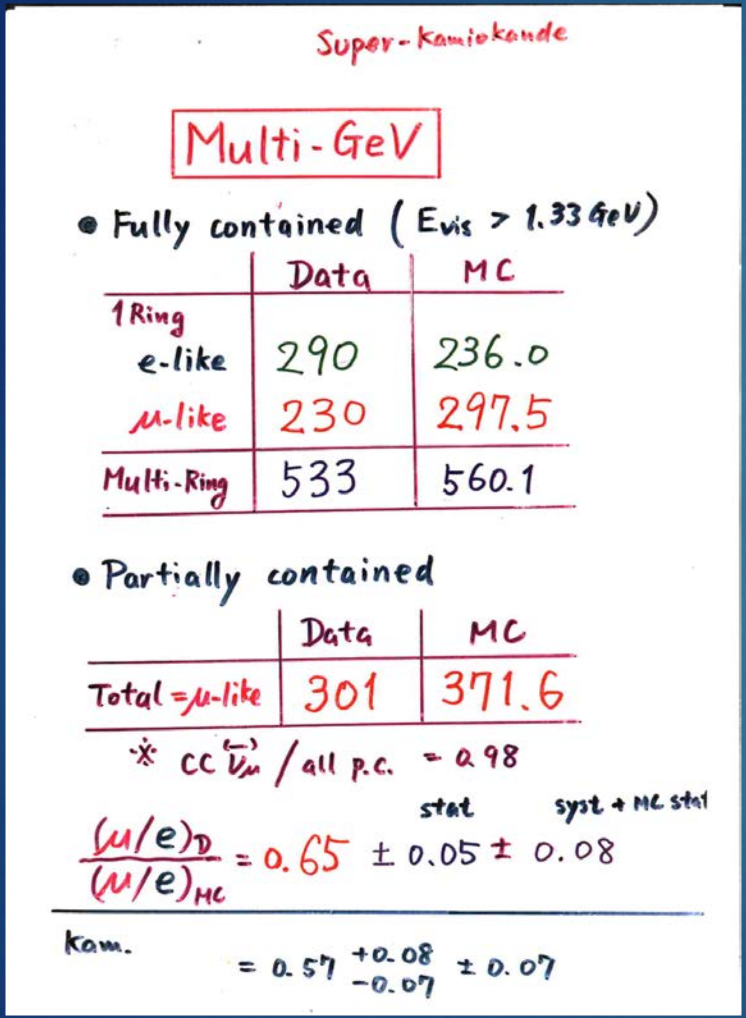


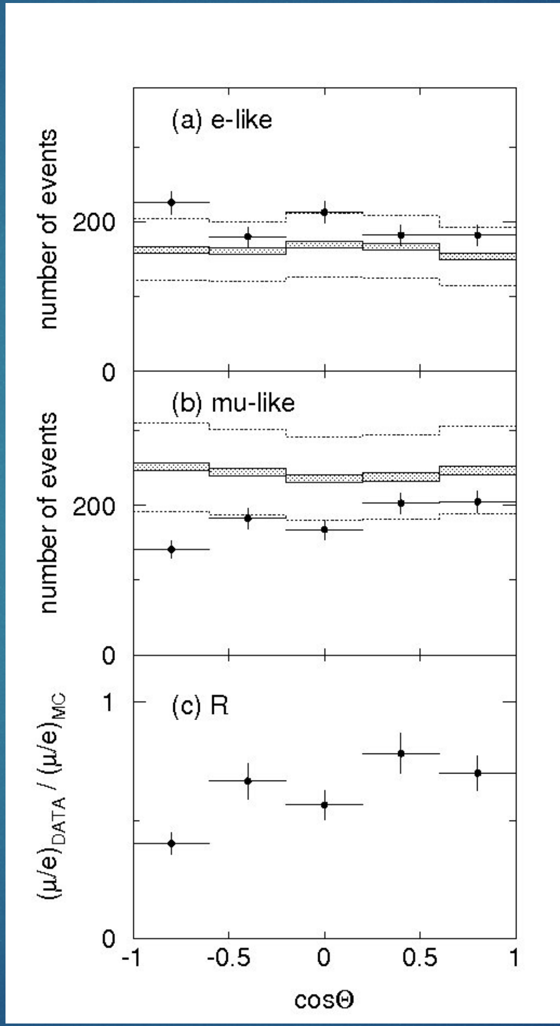
T. Kajita, 10.1103/RevModPhys.88.030501

- Horizontal muons get more time to decay
- Flux identical for θ and $\pi - \theta$

Discovery of neutrino oscillations

The atmospheric neutrino anomaly



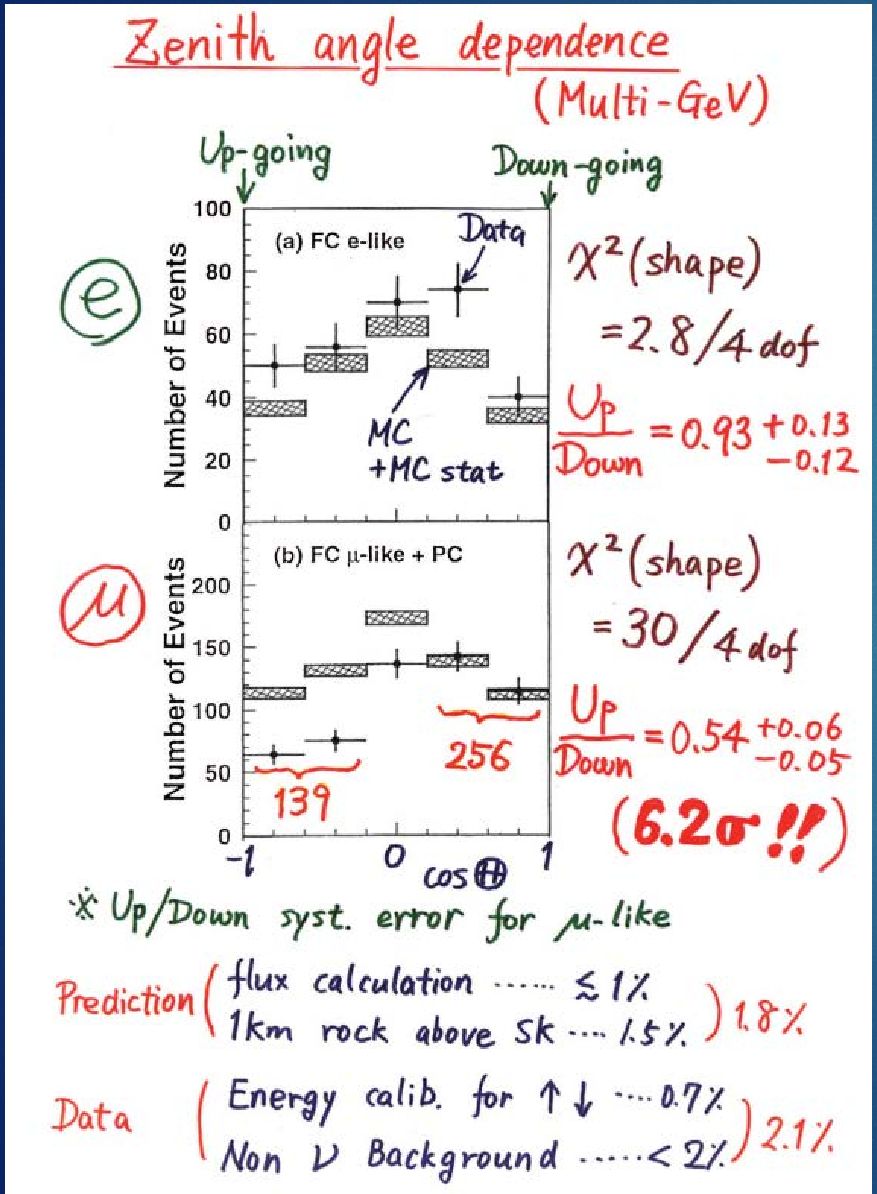


ν_μ / ν_e flux ratio R

- Smaller than expected
- Deficit had zenith-angle dependence

Slides of T. Kajita, SuperKamiokande
T. Kajita, 10.1103/RevModPhys.88.030501

The confirmation of neutrino oscillations



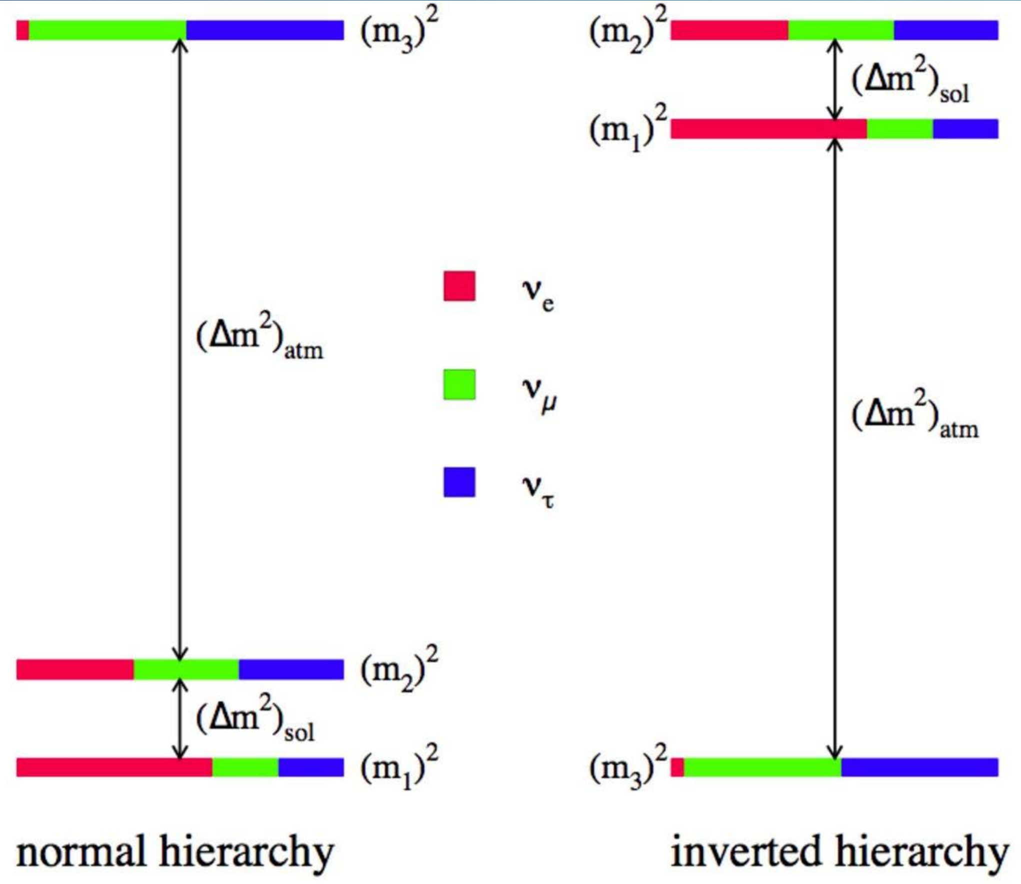
- Zenith angle dependence as the clinching evidence of neutrino oscillations

- For neutrinos to oscillate,
  - the flavor eigenstates must mix, and
  - the mass eigenstates must have distinct values !

T. Kajita, slide shown in Neutrino 1998
T. Kajita, 10.1103/RevModPhys.88.030501

Implications of neutrino oscillations

- Neutrinos have nonzero masses, and neutrino flavors mix !
- First confirmed signal beyond the Standard Model of particle physics



- Two mass-squared differences
  - $(\Delta m^2)_{sol} \approx m_2^2 - m_1^2$
  - $(\Delta m^2)_{atm} \approx m_3^2 - m_1^2$
- Three mixing angles
  - θ_{12} , θ_{23} , θ_{13}
- One CP-violating phase δ_{CP}

Role of atm- ν data in global fits

NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$
		Normal Ordering (best fit)		**Inverted Ordering ($\Delta\chi^2 = 6.4$)**	
		bfp $\pm 1\sigma$	**3σ range**	**bfp $\pm 1\sigma$**	**3σ range**
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

Inclusion of SK atmospheric data

- changes the measured value of θ_{23}
- Significantly increases the preference for normal ordering

NuFit collaboration

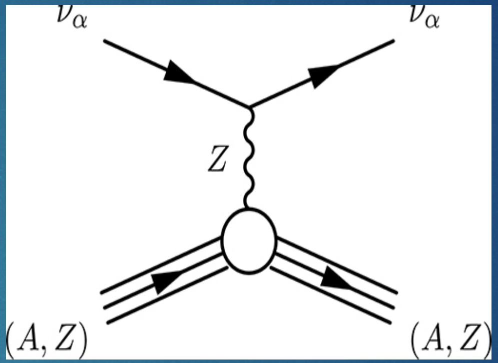
Earth as a medium:
Earth matter effects on neutrino propagation

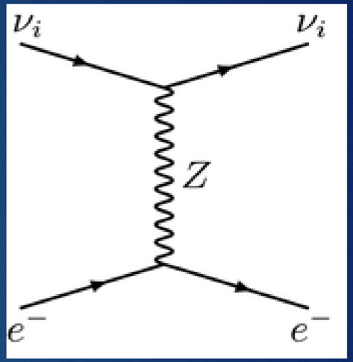
Neutrino Forward scattering on matter

- Neutrino-nucleon + neutrino-electron
  Neutral-current forward scattering

$V_{NC} = -G_F N_n/\sqrt{2}$ (for all neutrinos)

- No effect on neutrino mixing

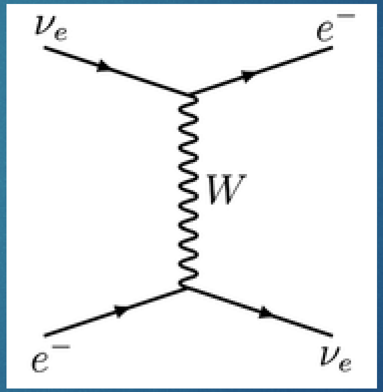




- Neutrino-electron charged-current scattering

$V_{CC} = \sqrt{2}\, G_F\, N_e$ (only for ν_e)

- Neutrino mixing affected



- Matter effects ⇒ Neutrino masses and mixings change !

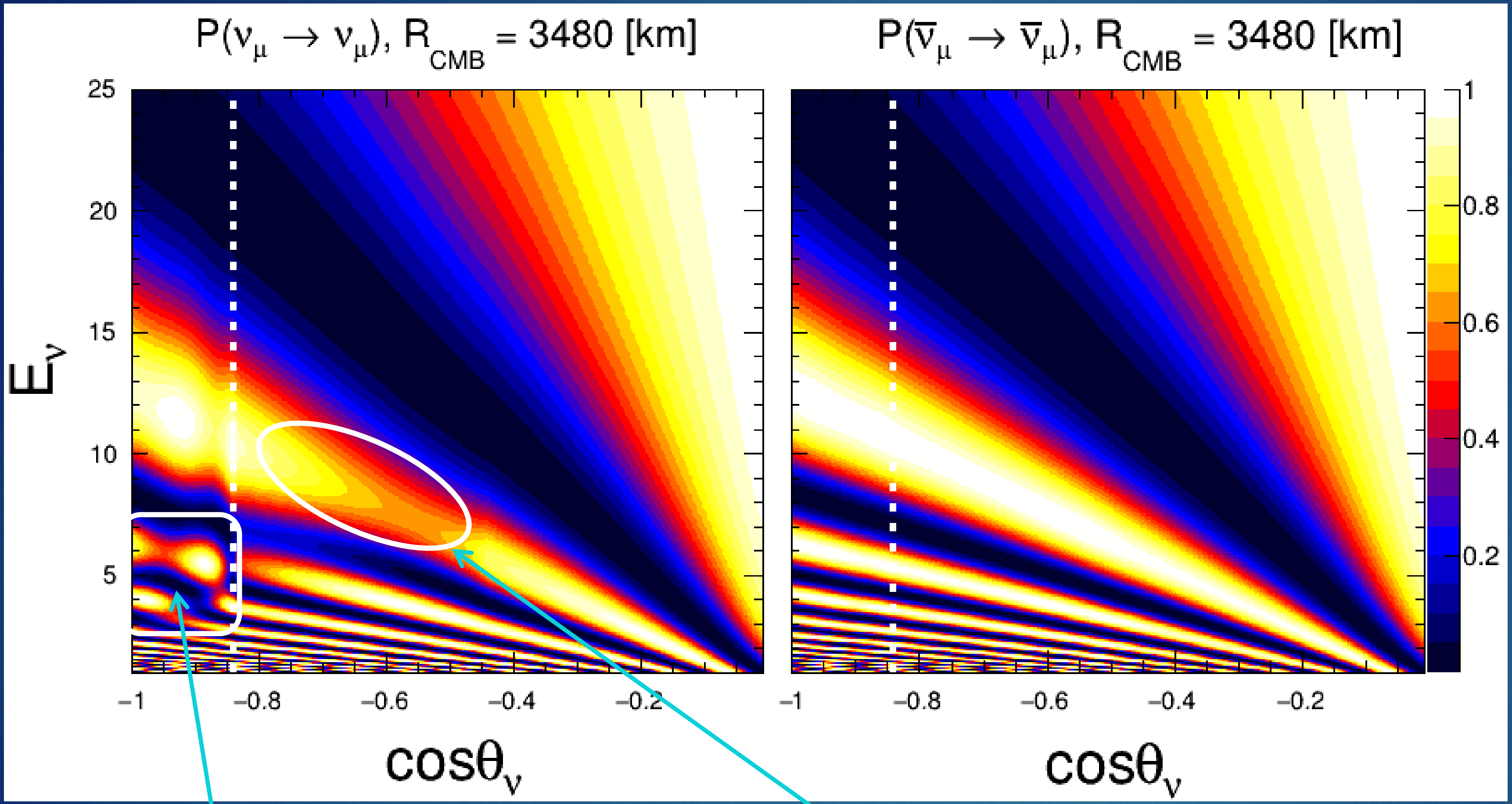
Salient features of Earth matter effects

- Depend only on the electron number densities neutrinos pass through
  - Independent of protons / neutrons / nuclei
  - Caveat: sterile neutrinos
- Affect neutrino masses, mixing angles
  - … and hence neutrino oscillation amplitudes and wavelengths
- Depending on the energy, the effects can be small or large (resonances !)
  - MSW (Mikheyev-Smirnov-Wolfenstein) resonance possible for atmospheric neutrinos at 6-10 GeV

    Wolfenstein 1978, Mikheyev, Smirnov 1985
  - Parametric / Neutrino Oscillation Length resonance possible for core-passing atmospheric neutrinos at 3-6 GeV

    Akhmedov 1998, Petcov 1998

Oscillograms for muon neutrino survival



- Neutrinos experience (more) matter effect for Normal ordering
- Antineutrinos experience (more) matter effect for Inverted ordering

(Parametric resonance / Neutrino Oscillation length resonance) + MSW in the core

$\cos\theta_\nu < -0.8$

$3\ \text{GeV} < E_\nu < 6\ \text{GeV}$

MSW Resonance Region

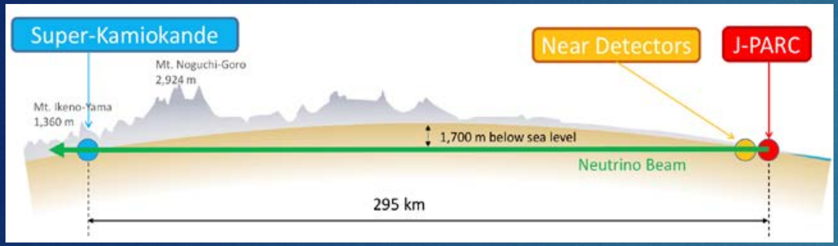
$-0.8 < \cos\theta_\nu < -0.5$

$6\ \text{GeV} < E_\nu < 10\ \text{GeV}$

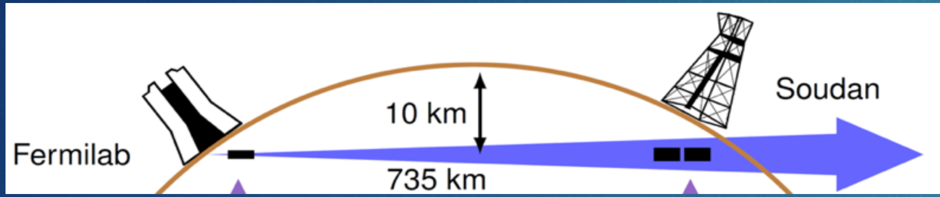
S. K. Agarwalla, Talk at MMTE 2022

Experiments to exploit matter effects

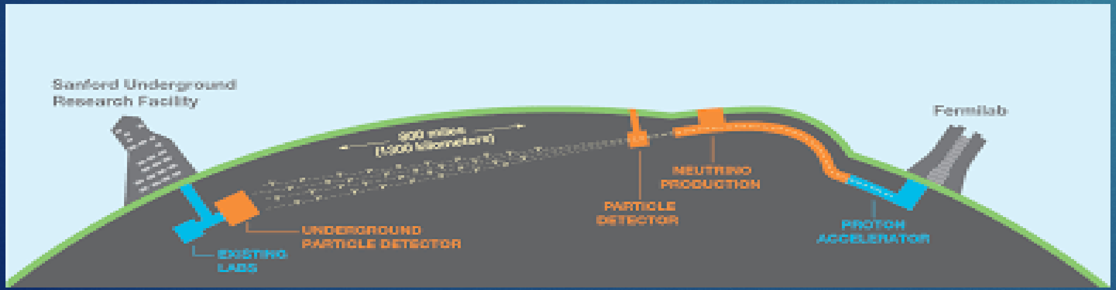
Fixed-baseline experiments



T2K/T2H

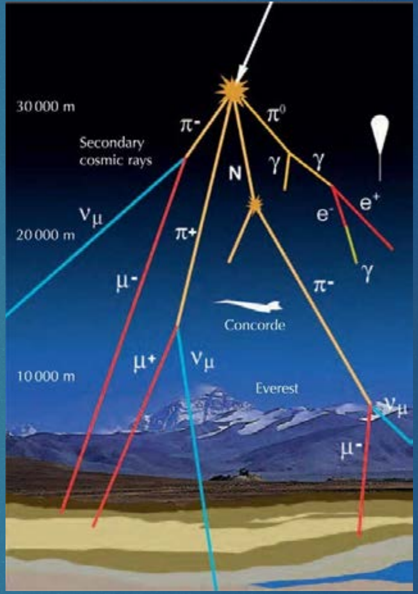


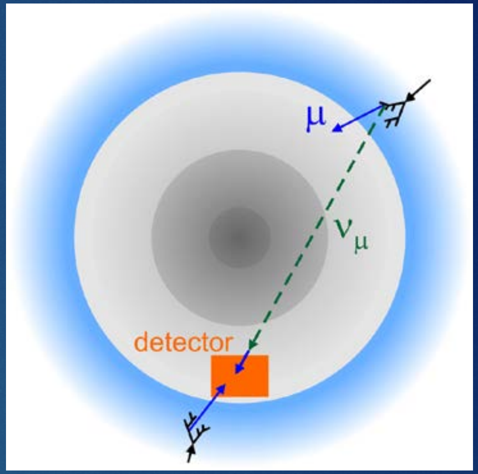
NOνA



DUNE

Atmospheric neutrino experiments

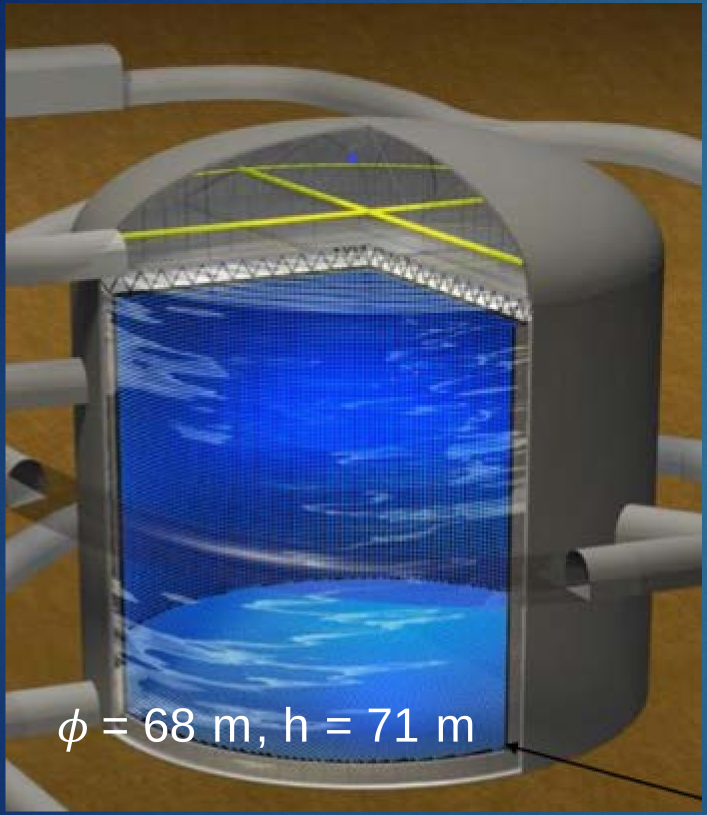




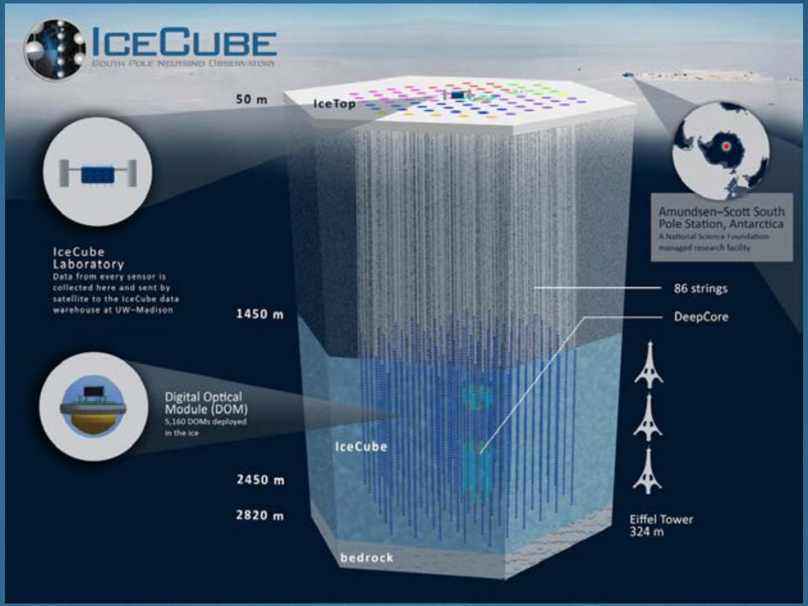
Controlled fluxes, Higher luminosity
vs.
Larger coverage of L and E

Water / ice Cherenkov

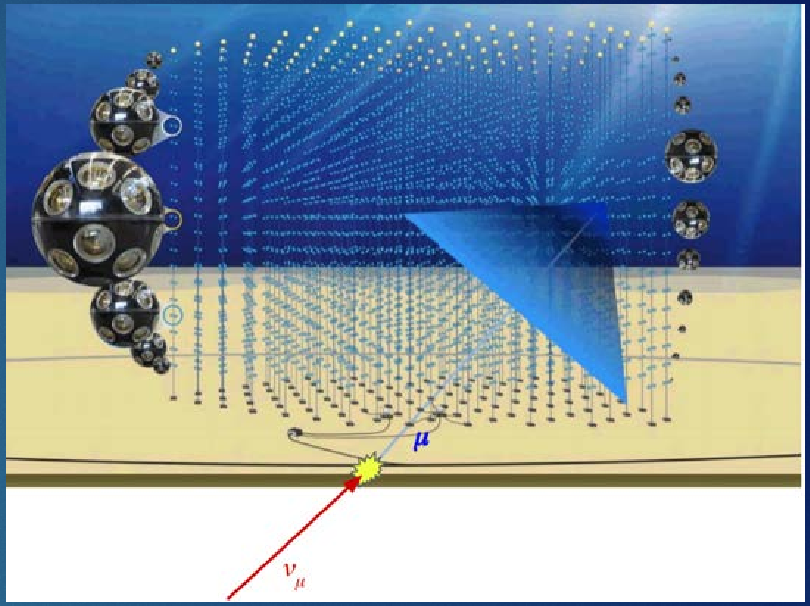
HyperKamiokande



IceCube



KM3NET



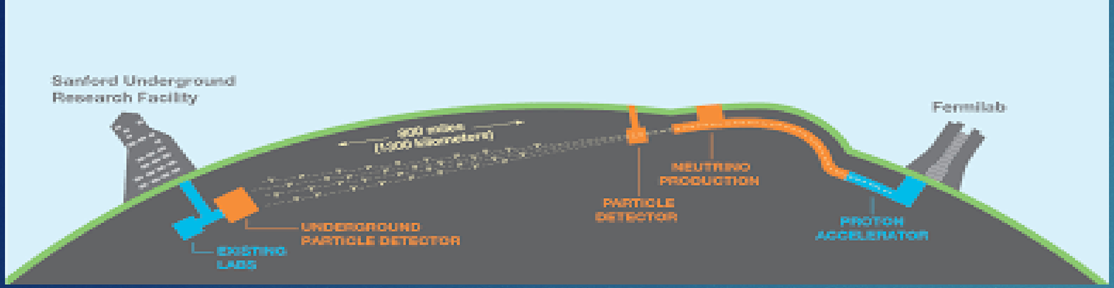
km^3 size

Energy : 100 GeV -- PeV

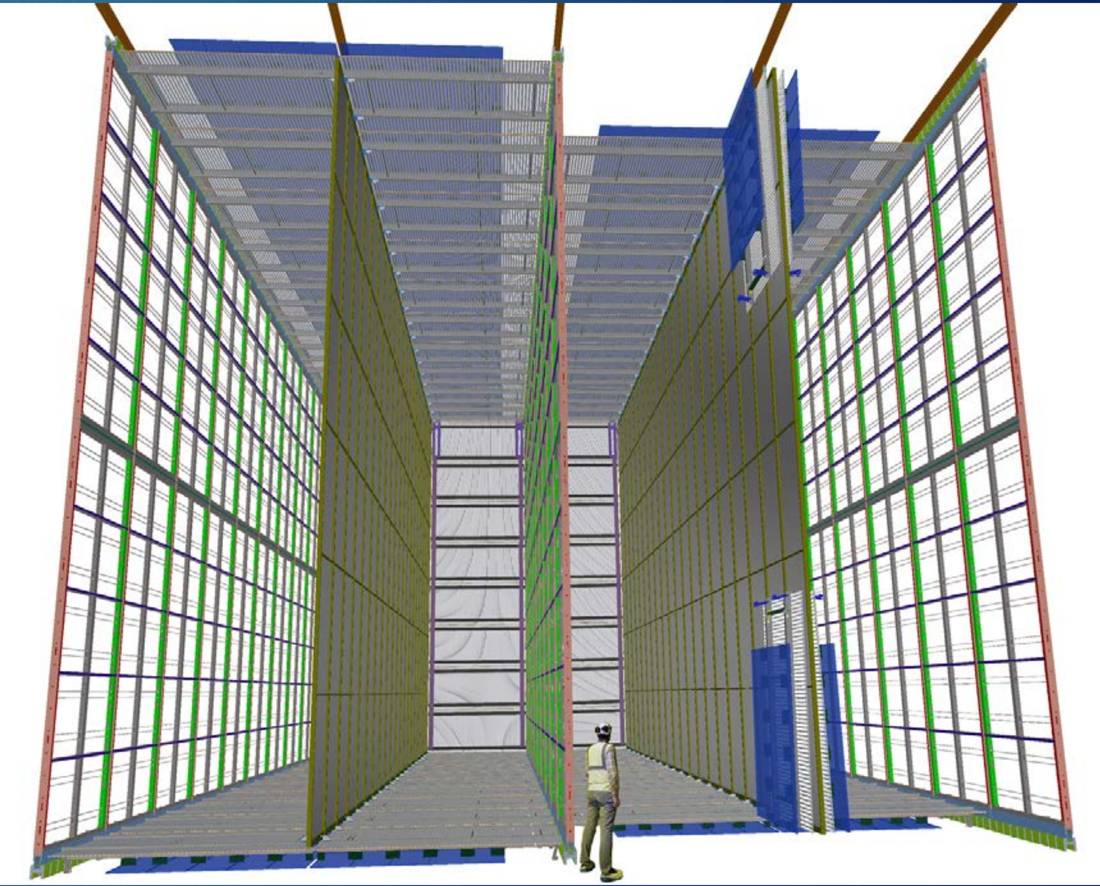
- IceCube Deep Core : Energy > 10 GeV

Energy: MeV – 5 GeV

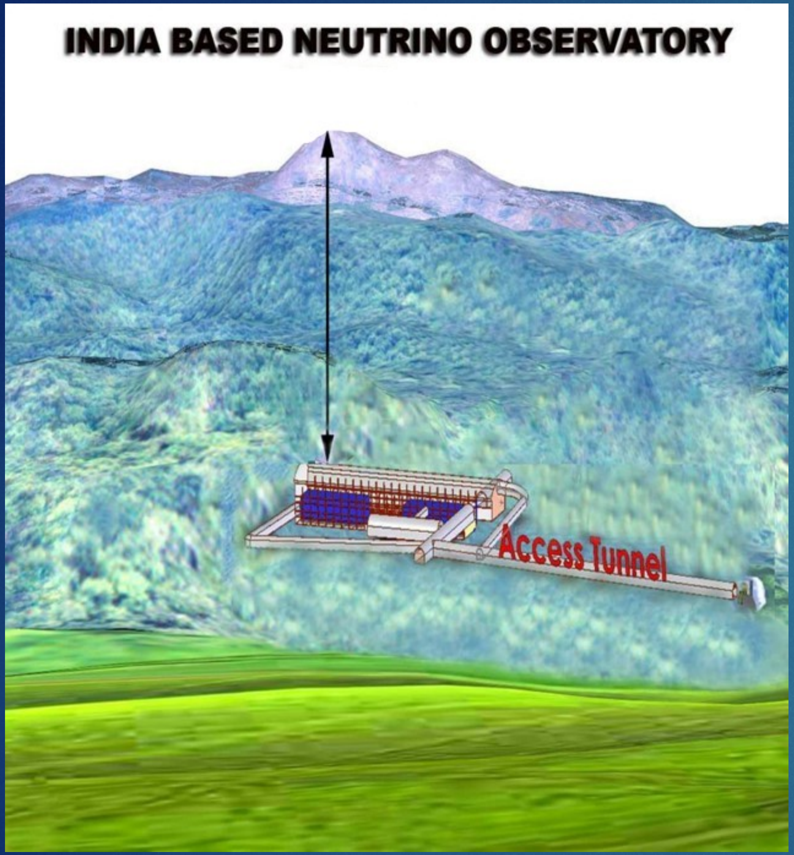
Liquid Argon TPC (@DUNE)

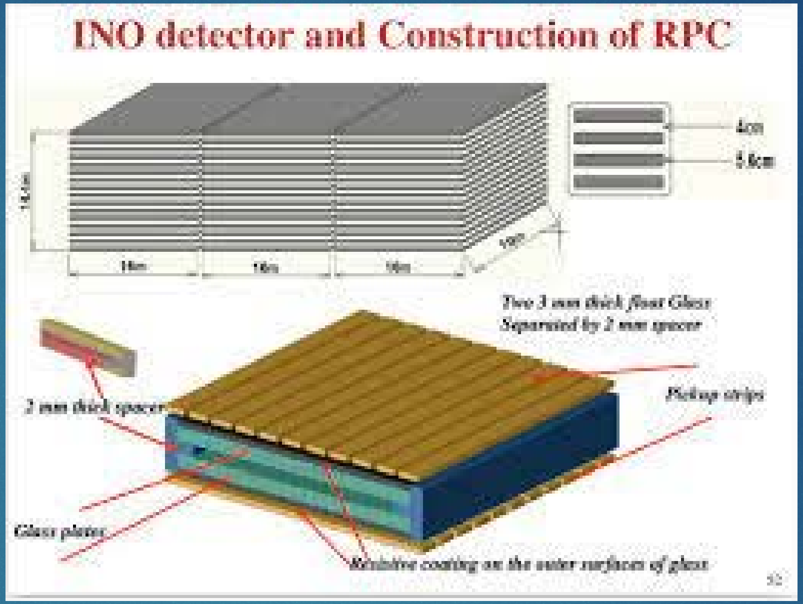


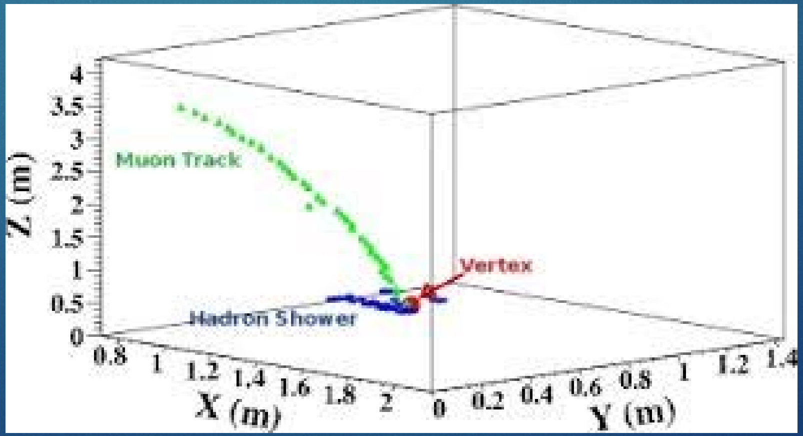
Energy : MeV – 10 GeV



Iron CALorimeter (ICAL) tracker



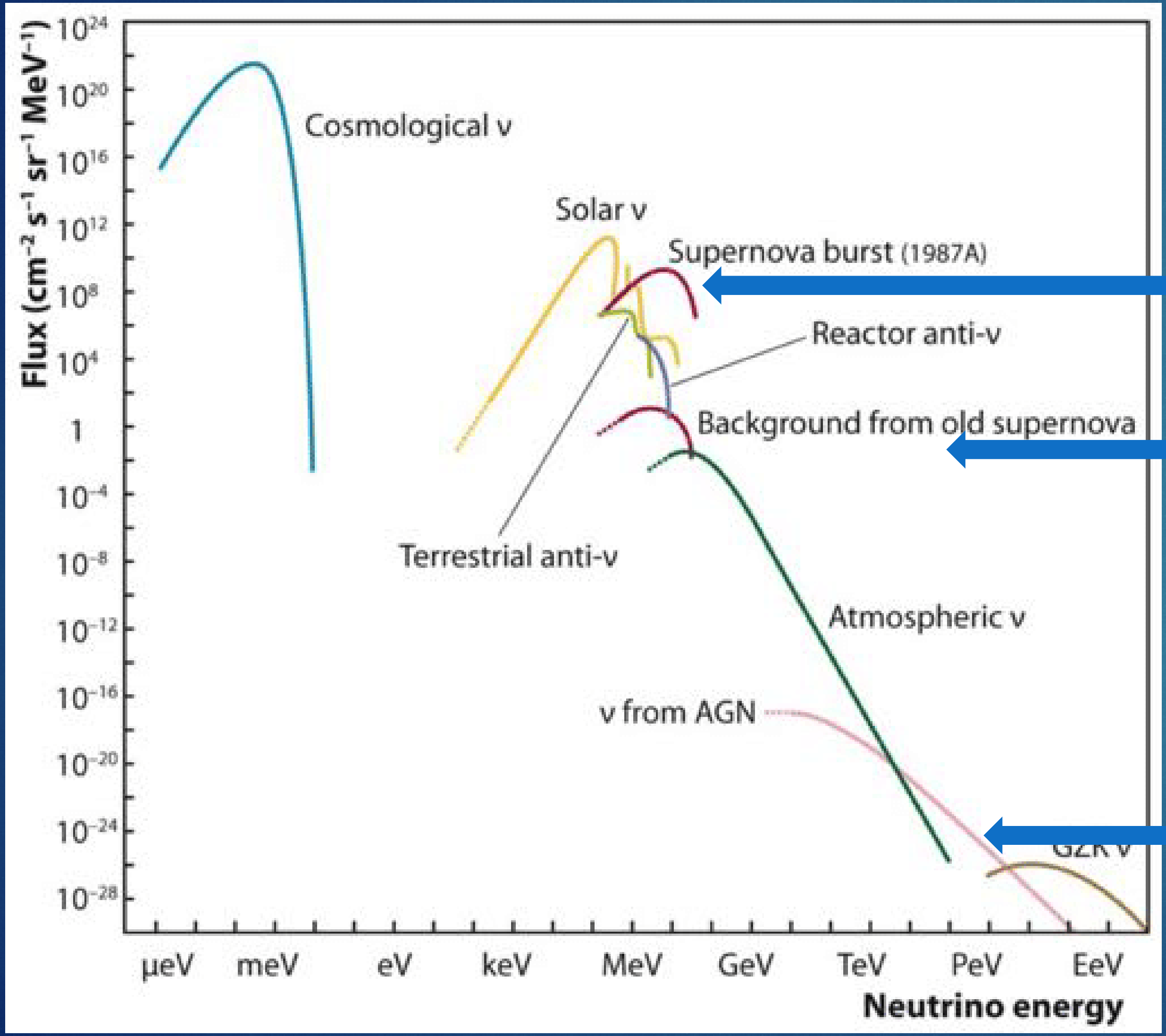




- Distinguishing neutrinos and antineutrinos using magnetic field
- Muon tracks and hadron showers
- Excellent energy and angular resolution for muons

Energy: 1 – 50 GeV

Earth effects for astrophysics



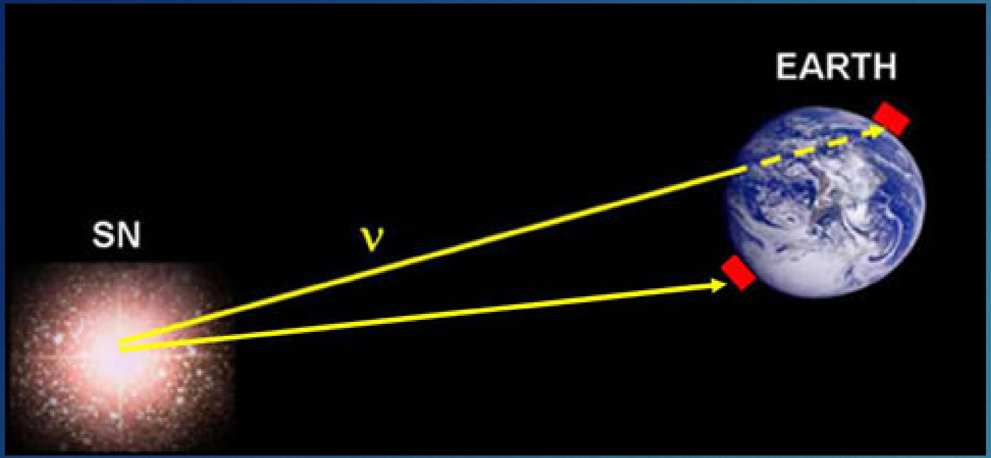
Astrophysical neutrinos

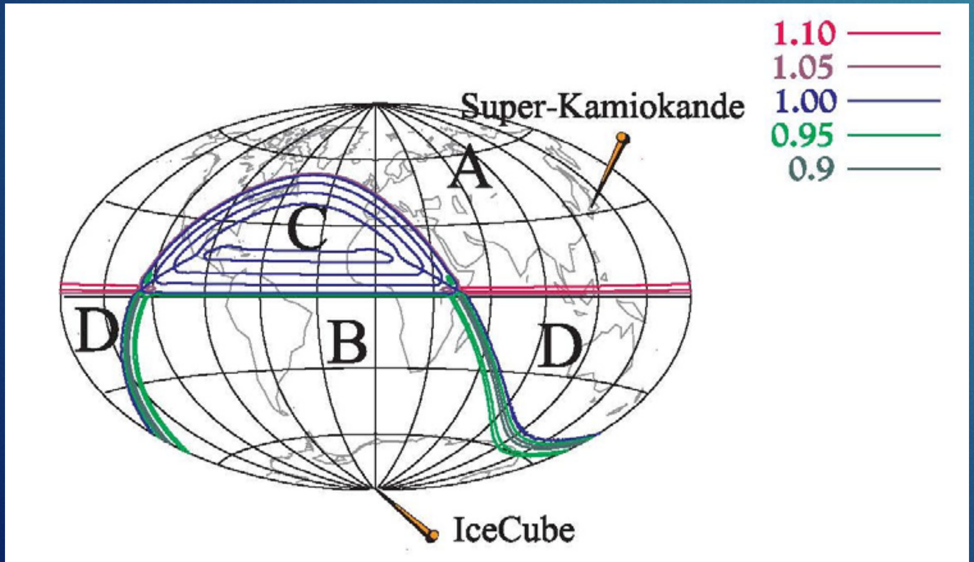
Supernova

High-energy astrophysical neutrinos

Katz and Spiering, 1111.0505

Comparing Supernova neutrino signals at two detectors

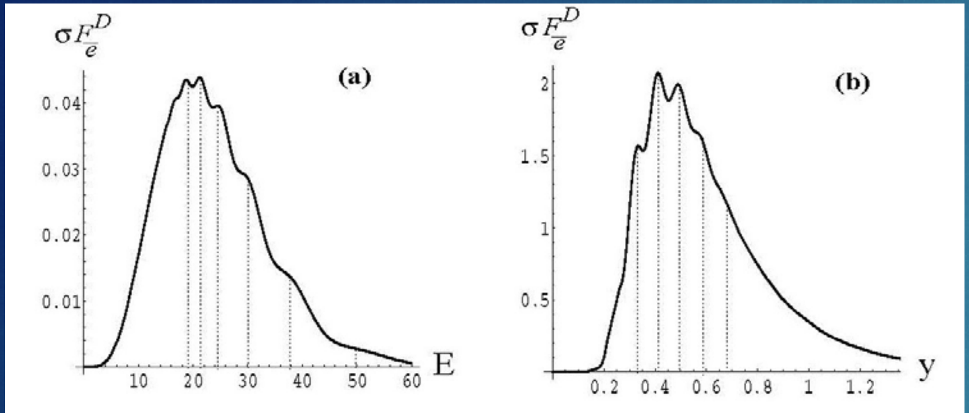


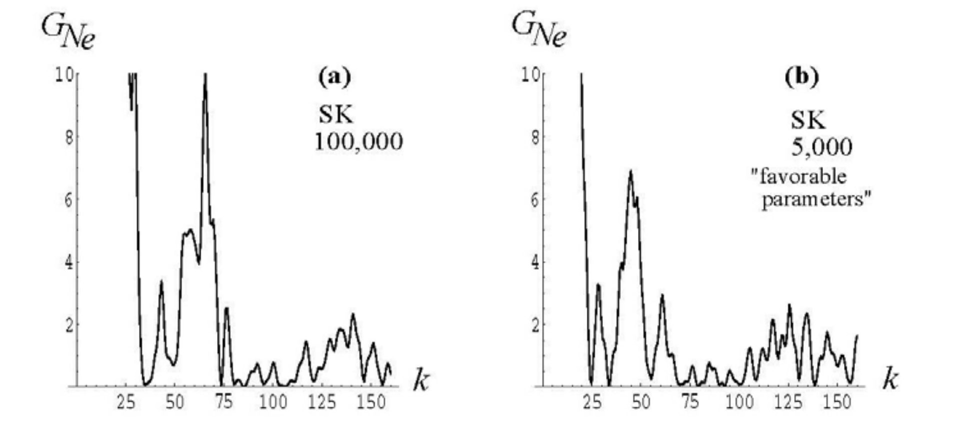


- Galactic SN can give ~10000 neutrino events at SuperKamiokande in 10 seconds !
- IceCube cannot detect individual MeV neutrinos, but can measure the total luminosity to more than a per cent precision.
- When compared to the time progression of neutrino signal at SK, Earth matter effects possible if the arriving fluxes are not depolarized.

AD, M. Keil, G. Raffelt, hep-ph/0303210

Earth effects on SN neutrinos at a single detector





AD, M. Keil, G. Raffelt, hep-ph/0304150

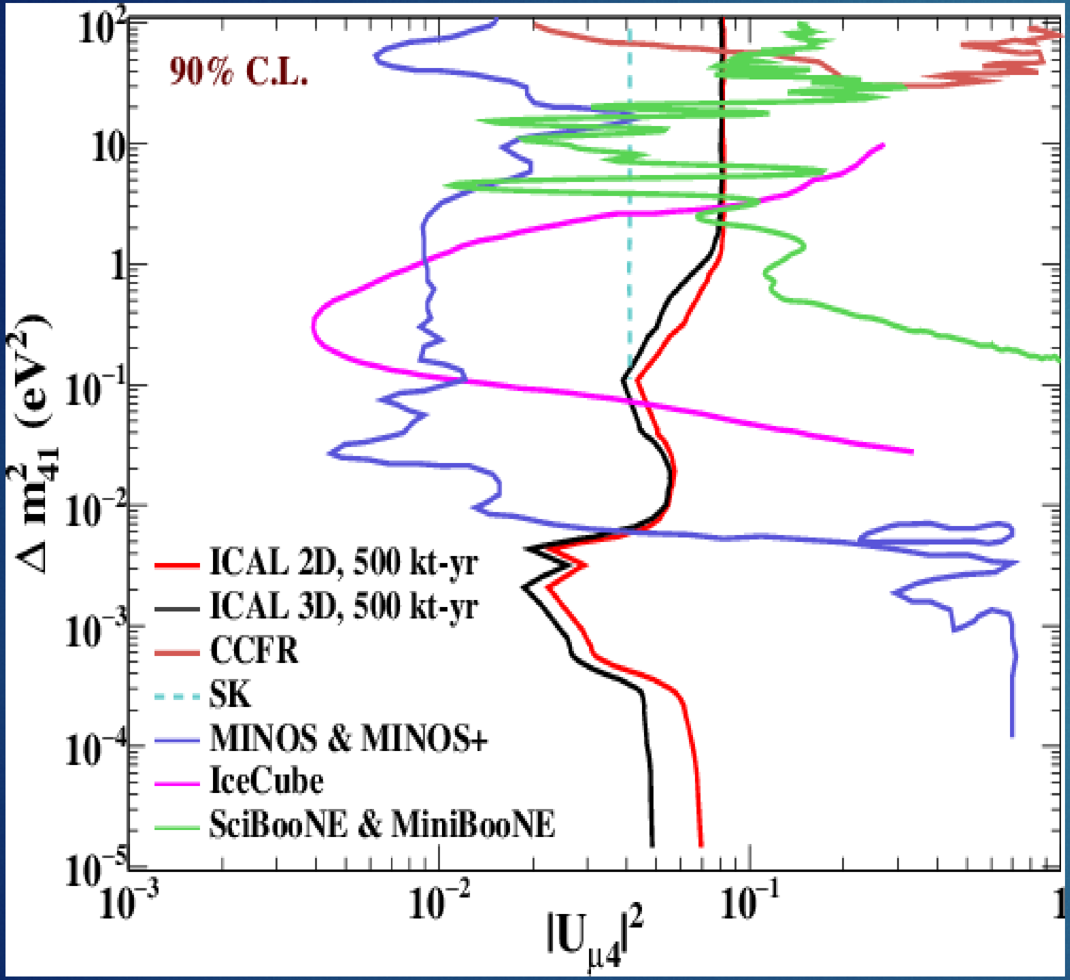
$$\bar{p}^D \approx \cos^2\theta_{12} - \sin 2\bar{\theta}^{\oplus}_{e2}\ \sin(2\bar{\theta}^{\oplus}_{e2} - 2\theta_{12})\ \sin^2\left(12.5\,\frac{\overline{\Delta m^2_{\oplus} L}}{E}\right),$$

- Earth effects introduce a fixed frequency in $y \equiv 1/E$ in the neutrino event spectrum (at constant density)
- Fourier transform in y can identify Earth effects at a single detector
- Detector resolution and number of events play a major role in feasibility, in addition to the difference in flavour fluxes

Talk by Sergio Palomares-Ruiz

Identifying new-physics scenarios in neutrino oscillations using Earth effects

Constraints on sterile neutrinos



M. M. Devi et al, 1804.09613

- Sensitivity to sterile neutrinos from the fact that sterile neutrinos *do not* undergo charged-current forward scattering (that ν_e , ν_μ , ν_τ can)
- Atmospheric neutrinos have sensitivity to sterile neutrinos for a large range of Δm^2_{41}
- Possible to determine sterile mass ordering as long as $\Delta m^2_{41} \in (10^{-4}, 10^{-2})$ eV^2

Constraining Non-standard ν interactions

Experiment	90% C.L. bounds	
	Convention in [21–23]	Our convention [10–12, 24, 25]
IceCube [21]	$-0.006 < \tilde{\varepsilon}_{\mu\tau} < 0.0054$	$-0.018 < \varepsilon_{\mu\tau} < 0.0162$
DeepCore [22]	$-0.0067 < \tilde{\varepsilon}_{\mu\tau} < 0.0081$	$-0.0201 < \varepsilon_{\mu\tau} < 0.0243$
Super-K [23]	$\lvert\tilde{\varepsilon}_{\mu\tau}\rvert < 0.011$	$\lvert\varepsilon_{\mu\tau}\rvert < 0.033$

Table 1: Existing bounds on $\varepsilon_{\mu\tau}$ at 90% confidence level. Note that the bounds presented in [21–23] are on $\tilde{\varepsilon}_{\mu\tau}$ that is defined according to the convention $V_{\rm NSI} = \sqrt{2}G_F N_d\, \tilde{\varepsilon}_{\mu\tau}$, while we use the convention $V_{\rm NSI} = \sqrt{2}G_F N_e\, \varepsilon_{\mu\tau}$ ($\varepsilon_{\mu\tau}$ is defined in Eq. 1.2). Since $N_d \approx 3N_e$ in Earth, the bounds in [21–23] on $\tilde{\varepsilon}_{\mu\tau}$ have been converted to the bounds on $\varepsilon_{\mu\tau}$, using $\varepsilon_{\mu\tau} = 3\,\tilde{\varepsilon}_{\mu\tau}$, as shown in the third column.

Anil Kumar et al, 2101.02607

- IceCube has an updated measurement:

$$-0.0041 < \tilde{\epsilon}_{\mu\tau} < 0.0031 \quad (2201.03566)$$

What can atmospheric ν experiments (using Earth effects) do that Long-baseline experiments cannot ?

Different physics, similar Hamiltonians

Non-standard interactions | Lorentz Violation

- Completely different origins and nature:

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\, G_F\, \varepsilon^{f\,C}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\eta P_L \nu_\beta\right)\left(\bar{f}\gamma_\eta P_C f\right)$$

$$\mathcal{L}_{\rm LV} = -a^{\lambda}_{\alpha\beta}\left(\overline{\nu}_\alpha \gamma_\lambda P_L \nu_\beta\right)$$

- Similar effective Hamiltonian (3-neutrino flavour basis):

$$\mathcal{H}_{\rm NSI} = \frac{1}{2E}\mathbb{U}\mathbb{M}^2\mathbb{U}^\dagger + \sqrt{2}G_F N_e \widetilde{\mathbb{I}} + \sqrt{2}G_F N_e \mathcal{E}$$

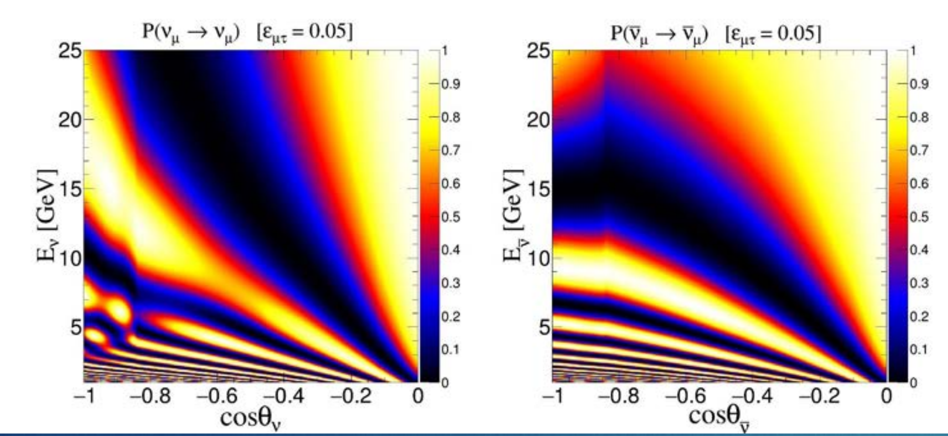
$$\mathcal{H}_{\rm LV} = \frac{1}{2E}\mathbb{U}\mathbb{M}^2\mathbb{U}^\dagger + \sqrt{2}G_F N_e \widetilde{\mathbb{I}} + \mathbb{A}$$

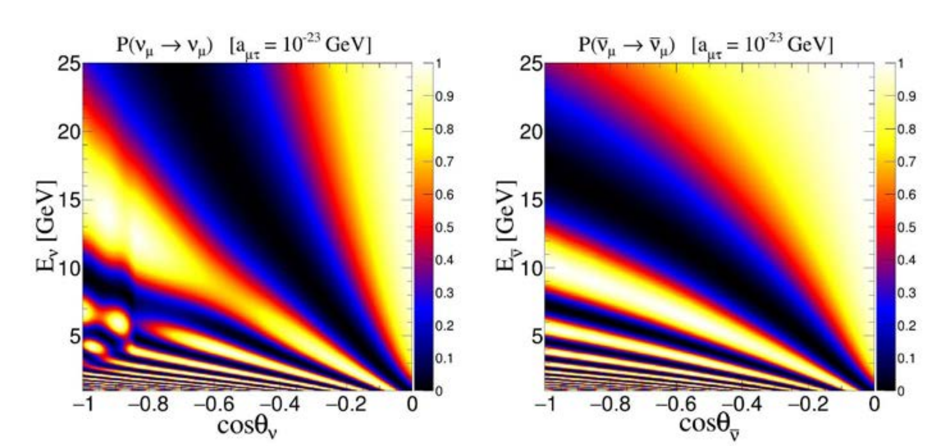
$$\mathcal{E} = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \qquad A = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{\mu e} & a_{\mu\mu} & a_{\mu\tau} \\ a_{\tau e} & a_{\tau\mu} & a_{\tau\tau} \end{pmatrix}$$

- When N_e is a constant, these models mimic one another !

Identical oscillations in LBL region

NSI, $\epsilon_{\mu\tau} = 0.05$





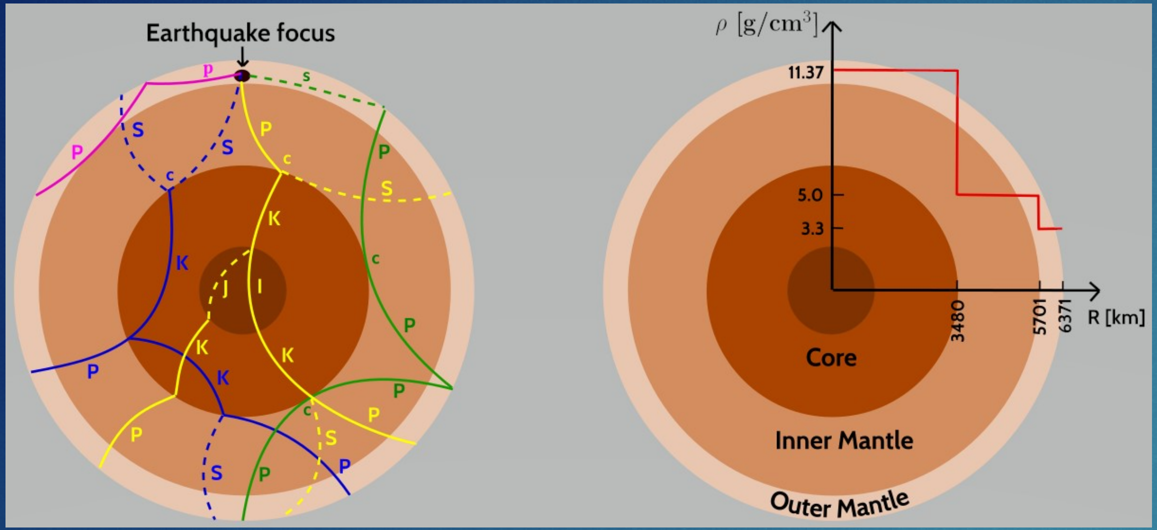
LIV, $a_{\mu\tau} = 10^{-23}$ GeV

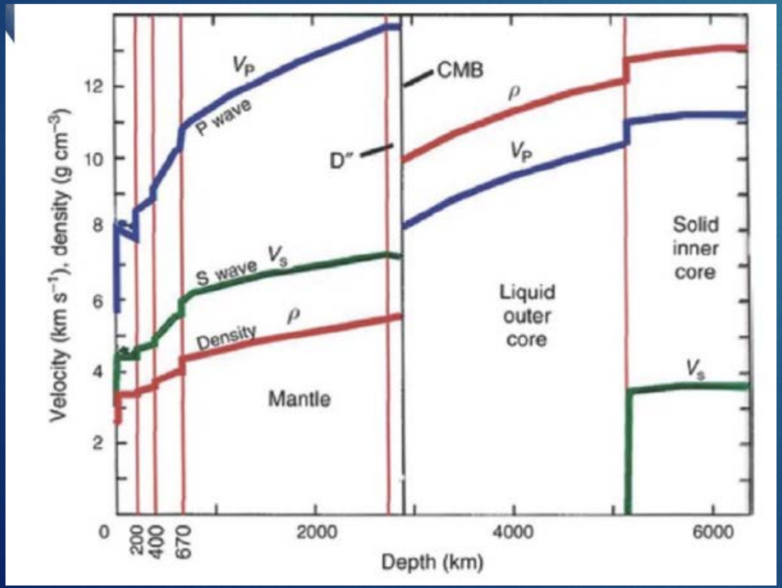
- As long as constant-N_e approximation works, any A can be mimicked by ϵ and vice versa
- $|\Delta P|$ (DUNE) < 0.0012 everywhere
- When neutrinos passing through the core are observed, this "mimicking'' vanishes
- Earth effects crucial for distinguishing between two new physics models

(Study for ICAL@INO)
Sadashiv Sahoo, Anil Kumar, S.K.Agarwalla, AD, 2205.05134

Earth tomography

Multi-messenger tomography of Earth





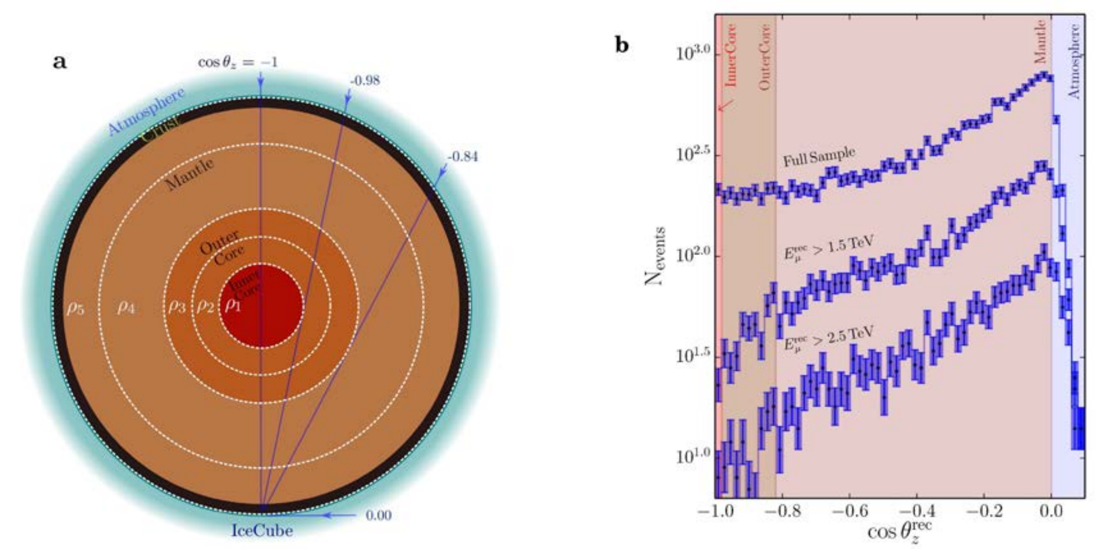
Propagation of earthquakes

- Big Unknowns:
  - Composition of the silicate Earth (Mg, Si, Fe, O)
    - Amount of recycled basalt in the mantle
      - In the Transition Zone?
      - In the deep mantle
  - Mineralogy of the Lower mantle
    - Mode % ferropericlase (sets the Mg/Si)
    - Mode % Ca-perovskite (sets amount of Th & U in Earth)
  - Amount of H_2O in the Mantle and H in the Core
  - geothermal (*viscosity*) gradient Mantle and Core
  - Composition of the Core (plus ?? H, C, O, Si, S, ..)
  - Radioactive power in the Mantle and Core

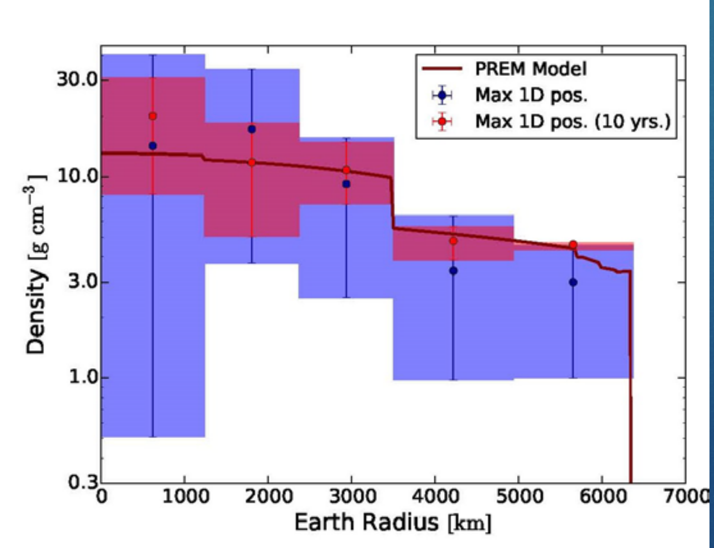
W. F. McDonough. Talk at MMTE 2022

What can neutrino propagation tell ?

Neutrino Absorption Tomography



- High-energy neutrinos ($E >$ TeV) start getting scattered in Earth
- The extent of scattering measures the matter content of earth using weak interactions [as opposed to gravitation/ EM (seismology)]



IceCube results indicate that the mass of Earth measured from weak interactions is consistent to the gravitational mass to within error bars (~ 30 %)

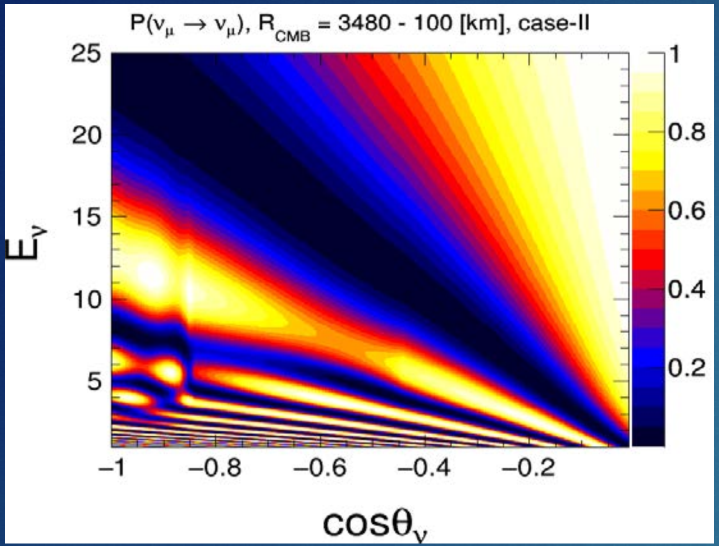
A. Donini, S. Palomares-Ruiz, J. Salvado, 1803.05901 (Nature Physics)

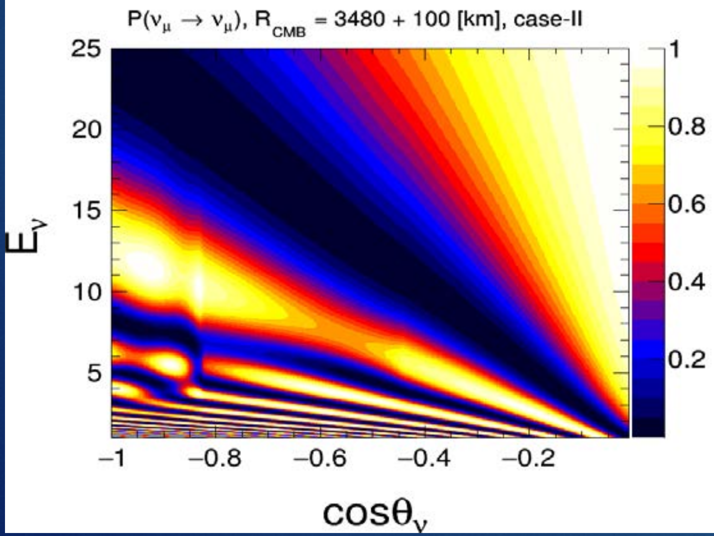
But absoption can only measure path-integrated density!
Cannot exploit oscillation phase information !

Neutrino oscillation tomography

- Oscillation probabilities sensitive to electron densities encountered
- Not just the total linear electron density, the distribution also matters
- In the energy range 3-10 GeV, resonances (MSW, parametric / NOLR) occur, increasing the effect on oscillation probabilities
- Sensitivity to sudden density jumps like at the core-mantle boundary

Effect of CMB Variation on Oscillations





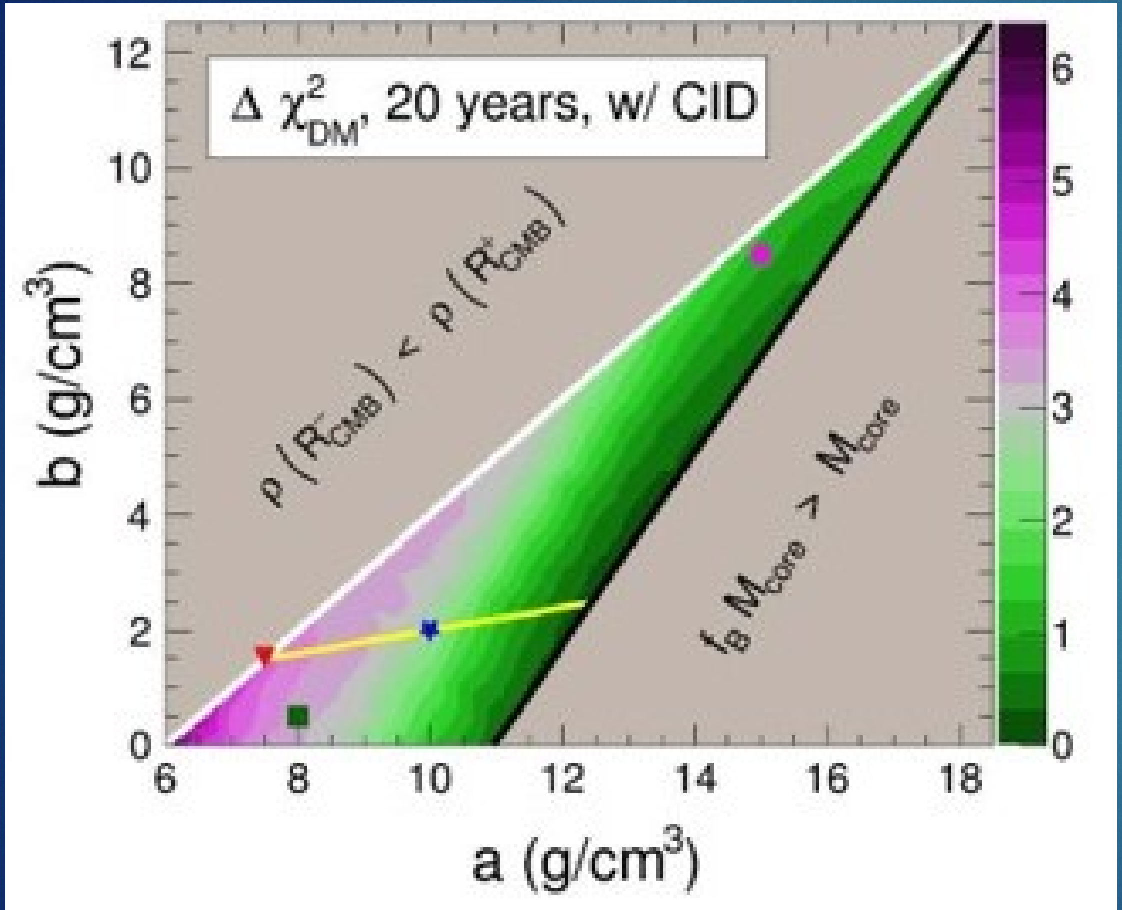
- Density of core modified (in simulations) such that the total mass of Earth remains constant.
- For decreasing core size, parametric resonance / NOLR region shrinks towards left
- For increasing core size, parametric resonance / NOLR the NOLR/PR expands towards right.

Study for ICAL@INO, Anuj K. Upadhyay et al, 2211.08688

Animation thanks to Anil Kumar, Talk at MMTE 2022

Talks by Anuj Upadhyay and Anil Kumar

Sensitivity to density profile in the core



- Baryonic density profile

$$\rho_B = a + b\left(\frac{r}{R_{CMB}}\right)^2$$

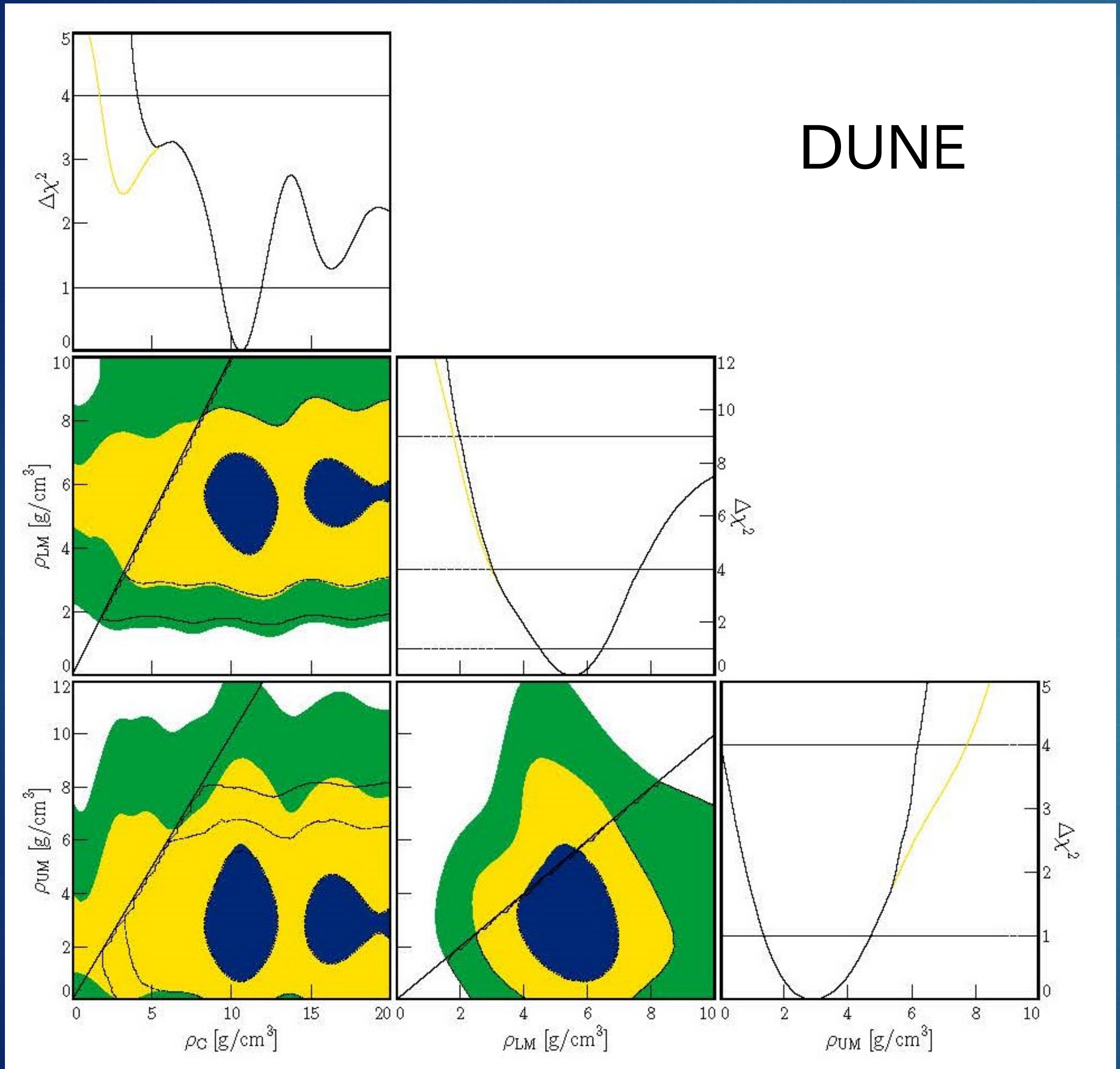
- Parameters a and b can be bounded

  ⇒ sensitivity to the profile shape of baryonic density

- Mass of Earth can be determined independently

Study for ICAL@INO:
Anuj K. Upadhyay, Anil Kumar, Sanjib K. Agarwalla, AD, 2112.14201

Oscillation tomography at detectors



- Average densities of core, lower mantle and upper mantle may be resolved using weak interactions

K. J. Kelly et al, 2110.00003

HyperK talk by Andrew Santos

JUNO talk by Mariam Rifai

KM3Net talk by Veronique Van Elewyck

IceCube / DeepCore by Sanjib K Agarwalla


Seismology
Geosciences
Gravity
Neutrinos

Earth and Neutrinos

- **Earth for Neutrinos:**
  - Earth as a source
  - ν passage through Earth: discovery of oscillations
  - Earth as a medium: matter effects on ν propagation
  - Earth for precision measurements of ν parameters
  - Mantle vs. core effects for identifying new physics scenarios
- **Neutrinos for Earth:**
  - Neutrino absorption and oscillation tomography
  - Electron density profile / Chemical composition
  - Core-mantle boundary, density jumps, density profile