Multi-Messenger Tomography of Earth

MMTE – 2022

Summary

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The Mini-Workshop on

"Multi-Messenger Tomography of Earth – MMTE 2022"

during 30th and 31st July was a success

A Fusion of Scientists from

Neutrino and Geoscience Communities

to discuss the knowns and unknowns of our planet Earth

Around 40 in-person and 50 virtual participants

Organizing Committee

Bill McDonough
Univ. of Maryland & Tohoku Univ.

Francis Halzen
Univ. of Wisconsin-Madison

Patrick Huber
Virginia Tech

Carsten Rott
Univ. of Utah & Sungkyunkwan Univ.

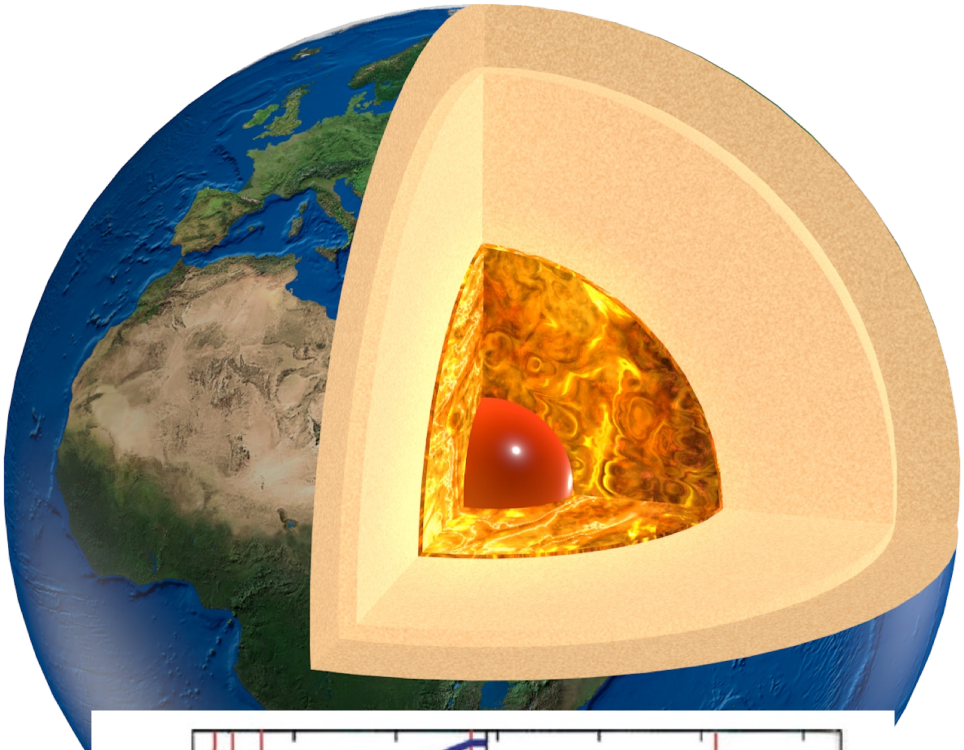
Hiroyuki Tanaka
ERI, Univ. of Tokyo

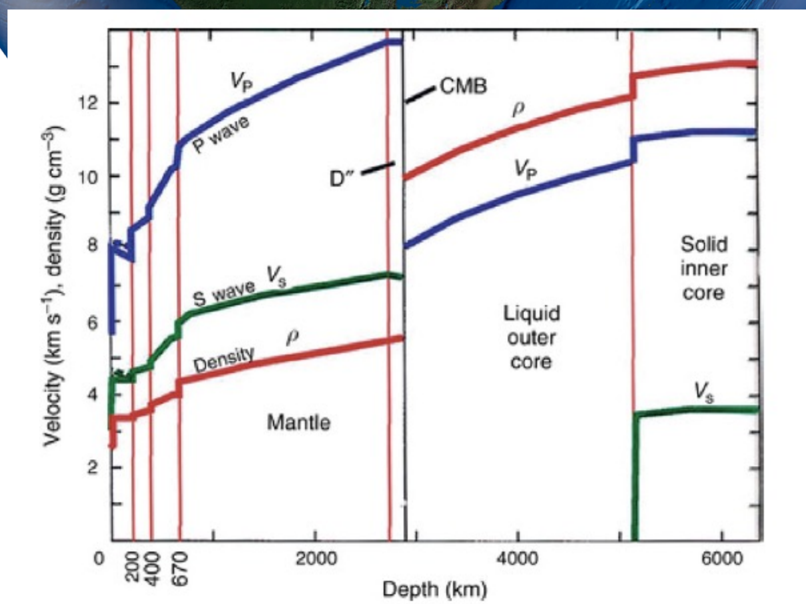
Hiroko Watanabe
Tohoku Univ.

Amol Dighe
TIFR

Sanjib Kumar Agarwalla
IOP, Bhubaneswar & UW Madison

The Interior of Earth





- What lies in the interior of Earth has been a long-standing puzzle and active research is being carried out in this direction

- The regions deep below the Earth's surface are inaccessible due to large temperatures, pressures, and extreme environments.

- The information about the interior of Earth is obtained indirectly using

  ➛ Gravitational measurements

  ➛ Seismic studies

- Neutrinos can penetrate deep inside the Earth and may shed light on internal structure and composition

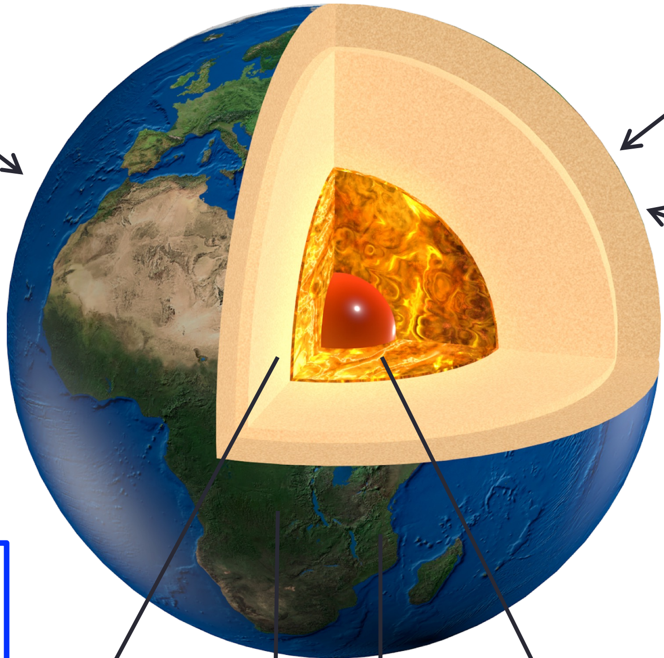
  ➛ ν oscillation tomography w/ low-energy neutrinos

  ➛ ν absorption tomography w/ high-energy neutrinos

Multi-Messenger Tomography of Earth

Gravitational measurements exploits the gravitational interactions of matter inside Earth and provide information on Earth's total mass and moment of inertia

Geophysicists use seismic waves from earthquakes exploiting the electromagnetic interactions of matter inside Earth.



Neutrinos get attenuated at energies greater than a few TeV using weak interactions

Neutrino Absorption Tomography

Sub-GeV and multi-GeV electron neutrinos undergo charged current coherent forward scattering with ambient electrons inside deep Earth via weak interactions and this results in the modification of oscillation patterns significantly

Neutrino Oscillation Tomography

Combine neutrino data with seismic and gravitational measurements

Start a new era of Multi-Messenger Tomography of Earth

This workshop was an important step along this direction!

S. K. Agarwalla, NuFact 2022, Salt Lake City, Utah, USA, 4th August 2022

Goal of MMTE – 2022

- The idea was to bring together leading experts from the neutrino and geoscience communities to discuss in depth the present status of the field and its future developments.

- The main aim of this workshop was to explore the role of oscillation and absorption neutrinos towards the tomography of Earth - complementary to the seismic studies and gravitational measurements - paving the way for multi-messenger tomography of Earth.

- The huge amount of high-precision atmospheric neutrino data that we expect to collect in the next 10 to 15 years using IceCube/IceCube-Gen2, DeepCore and its upgrade, ORCA and ARCA, Hyper-K, DUNE, and INO-ICAL with its unique muon charge identification (CID) capability, are going to play an important role towards neutrino tomography of Earth.

- These enormous amount of high-quality atmospheric neutrino data can measure the Earth's density profile.

- It may shed light on the composition [Z (atomic no.)/A (mass no.) ratio] and hydrogen content inside the Earth's core.

Scientific Program of MMTE 2022

local Utah time	Saturday July 30		Sunday July 31
0900-0915	Welcome (Carsten Rott)	0900-0945	Landscape of Neutrino Physics (Francis Halzen)
0915-0930	Workshop goals (Sanjib Kumar Agarwalla)	0945-1030	Earth's matter effect in neutrino oscillation (Sanjib Kumar Agarwalla)
0930-1015	Atmospheric Neutrinos for Non-Specialists (Edward Kearns)	1030-1100	Coffee break
1015-1100	The Internal Structure of the Earth (Bill McDonough)	1100-1125	Current understanding of the Earth's core (Francis Nimmo)
1100-1130	Coffee break	1125-1150	Neutrino tomography of the Earth: the potential of ORCA detector (Serguey Petcov)
1130-1215	Imaging the Earth's Interior using Seismic Waves (Vedran Lekic)	1150-1215	Current understanding of inner core structure and open questions (Keith D. Koper)
1215-1300	Present status and future prospects of geoneutrinos towards Earth tomography (Andrea Serafini)	1215-1240	Measuring the Earth's outer core composition using neutrino oscillations (Joao Coelho)
1300-1430	Lunch break	1240-1400	Lunch break
1430-1515	The first neutrino absorption Earth tomography (Andrea Donini)	1400-1425	An overview of the core-mantle boundary region from seismological studies (Mike Thorne)
1515-1540	Measuring density of Earth's core using high-energy neutrinos observed by IceCube (Kotoyo Hoshina)	1425-1450	Unstable structure and dynamics in Earth's deepest mantle (Mingming Li)
1540-1610	Coffee break	1450-1515	Neutrino oscillation tomography of the Earth and core composition with large water cherenkov detector (Akimichi Taketa)
1610-1655	Chemical composition and Hydrogen content inside Earth (Kei Hirose)	1515-1545	Coffee break
1655-1720	A coupled core-mantle evolution (Takashi Nakagawa)	1545-1610	Validating the Earth's Core using Atmospheric Neutrinos with ICAL at INO (Anil Kumar)
1720-1735	Oscillation tomography of Earth with Solar neutrinos and future experiments (Pouya Bakhti)	1610-1635	Superionic H-bearing iron alloys in the Earth's inner core (Wenzhong Wang)
1735-1800	Discussion (Patrick Huber and Vedran Lekic)	1635-1700	Observing the Earth's Core with Neutrino Oscillations (Rebekah Pestes)
		1700-1725	Neutrino Earth tomography in DUNE (Ivan Martinez-Soler)
		1725-1800	Discussion (Carsten Rott and Keith D. Koper)
Chairperson	Pre-Lunch Session: Patrick Huber		Pre-Lunch Session: Carsten Rott
	Post-Lunch Session: Vedran Lekic		Post-Lunch Session: Keith D. Koper

Total 22 Talks: 9 (in-person) and 13 (virtual)
2 Discussion Sessions

Gravitational Measurements

Gravitational measurements exploits the gravitational interactions of matter inside Earth.

Average density

- For given mass[1] ($\sim 5.97 \times 10^{24}$ kg) and radius of Earth (~ 6400 km), average density of Earth $\sim 5.5\ \mathrm{g/cm^3}$
- Density of ordinary rock $\sim 2.8\ \mathrm{g/cm^3}$, therefore, the density near the centre of Earth is higher than $5.5\mathrm{g/cm^3}$

Moment of inertia

- For uniform sphere, $I = \frac{2}{5}MR^2 \Rightarrow \frac{I}{MR^2} = 0.4$
- Measured[2], $\frac{I}{MR^2} \sim 0.33$, [3]$I_{\oplus} \sim 8.017 \times 10^{37}$ kg m^2.
- Since $I_{\text{measured}} < I_{\text{expected}}$, more matter is concentrated near the axis of rotation

[1] B. Luzum et al., Celest. Mech. Dyn. Astron. 110, 293 (2011).

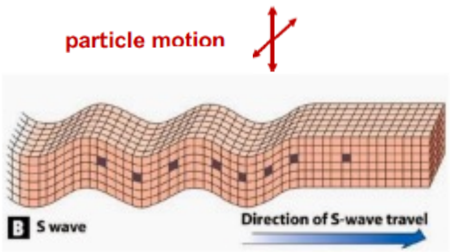
[2] Williams, James G. The Astronomical Journal. 108: 711 (1994)

[3] W. Chen, J. Ray, W. B. Shen, and C. L. Huang, J. Geod. 89, 179 (2015).

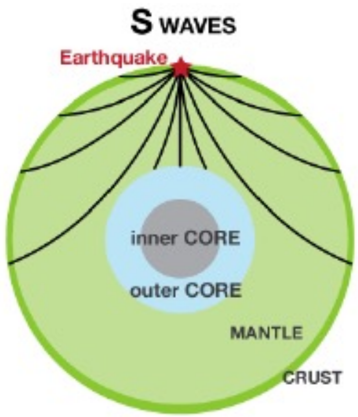
Seismic Measurements

Seismic measurements exploits the electromagnetic interactions of matter inside Earth.

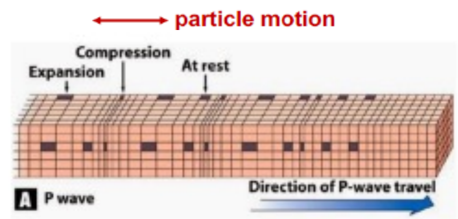
Body waves consisting of transverse vibrations are known as **S-waves**:



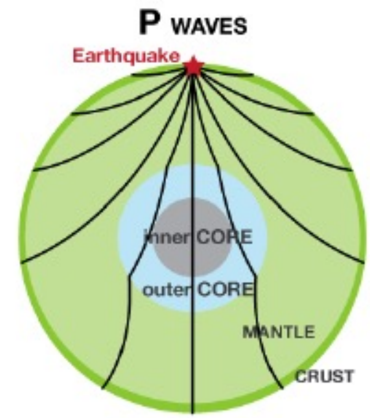
$$V_S = \sqrt{\frac{\mu}{\rho}}$$



Body waves consisting of longitudinal vibrations are known as **P-waves**:



$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$



Velocities of seismic waves depend upon the elastic constants of the material, such as density (ρ), bulk modulus (κ), shear modulus (μ)

P waves (fastest) : pressure waves

S waves (slower): shear waves

E. C. Robertson, The interior of the Earth, an elementary description, 1966.

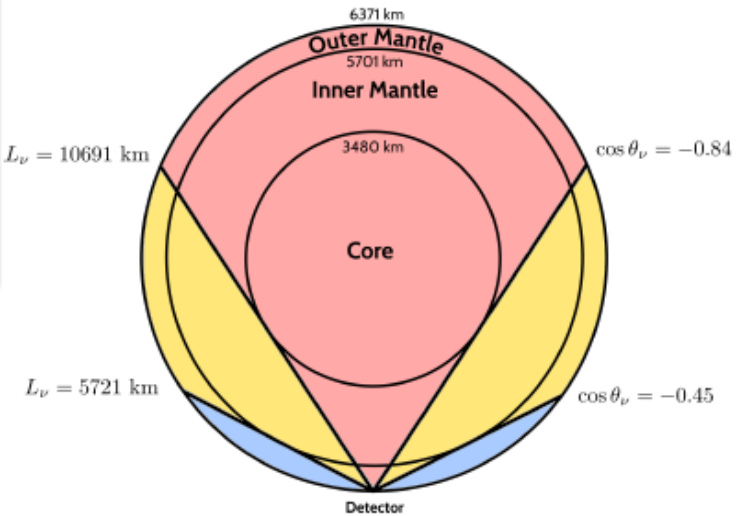
Image source: https://thinkgeogeek.blogspot.com/2014/01/seismic-waves.html

Internal Structure of Earth

The gravitational and seismic measurements are used to infer the density distribution inside Earth which is known as Preliminary Reference Earth Model (PREM).

Note that PREM is not a measured profile.

- **Crust**: solid, rocks, brittle, lowest density
- **Mantle**: hot, solid outer mantle, viscous plastic inner mantle
- **Core**: solid inner core, liquid outer core, iron and nickel



Three-layered model of Earth

References:

A.M. Dziewonski, and D.L. Anderson, Preliminary reference earth model, Phys.Earth Planet.Interiors 25 (1981) 297-356

E. C. Robertson, The interior of the Earth, an elementary description, 1966.

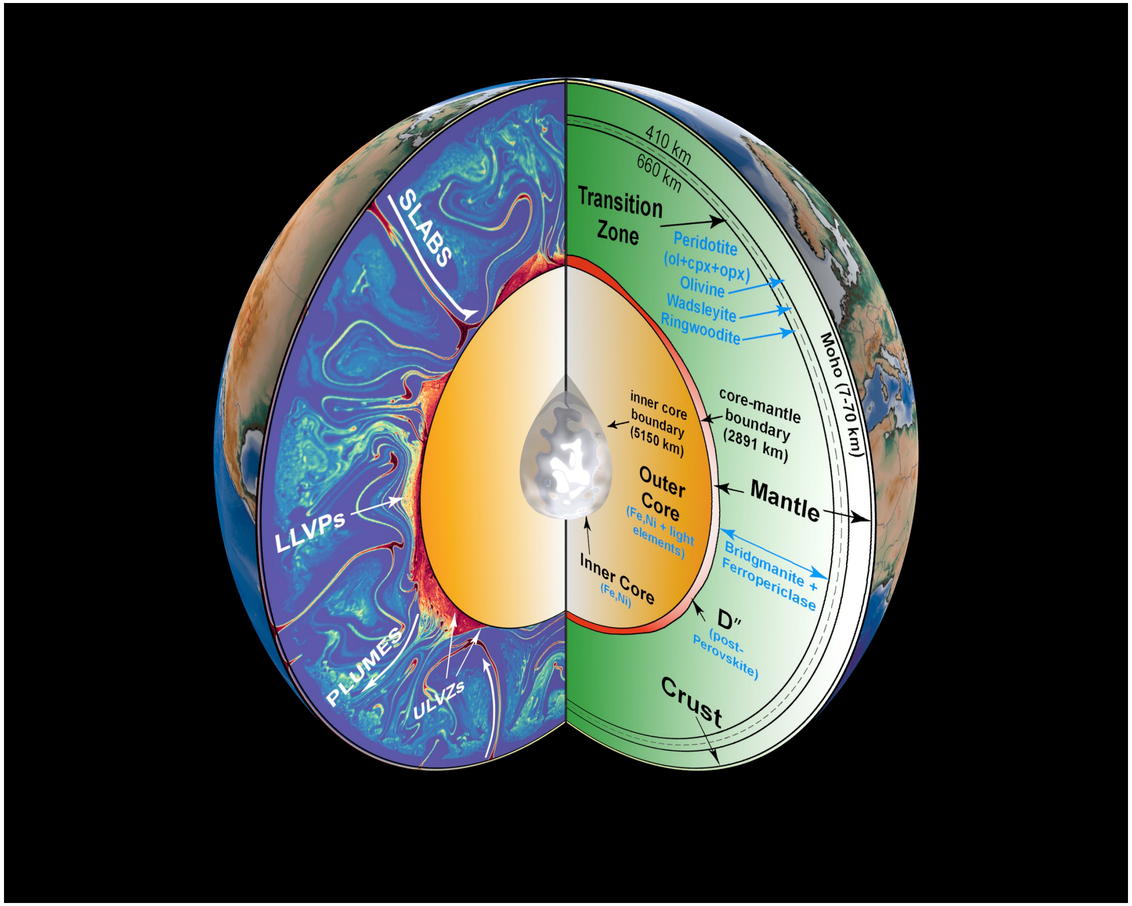
D. E. Loper and T. Lay, The core-mantle boundary region, Journal of Geophysical Research: Solid Earth 100 (1995), no. B4 6397–6420.

D. Alfè, M. J. Gillan, and G. D. Price, Temperature and composition of the earth's core, Contemporary Physics 48 (2007), no. 2 63–80.

- 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

Talk by William F McDonough

Internal Structure of Earth



Talk by Michael Thorne

Right: characterization by composition
(the 1-D background)

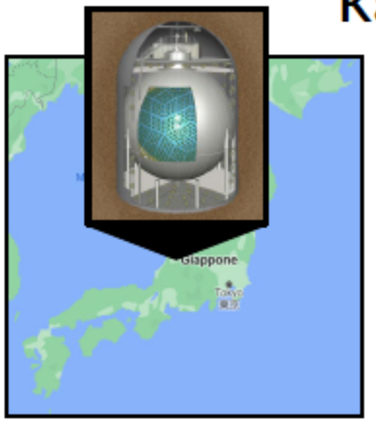
- Crust
- Mantle
  - Upper Mantle
  - Transition Zone
  - Lower Mantle
  - D"
- Outer Core
- Inner Core

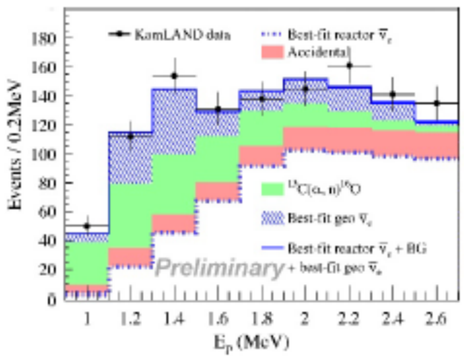
Left: overlain on this 1-D structure…
Dynamics (3-D, imaged in seismology as Variations from the 1-D background)

- Subducting slabs
- Plumes
- Large Low Velocity Provinces (LLVPs)
- Ultralow-velocity zones (ULVZs)

Borexino and KamLAND geoneutrino results

KamLAND

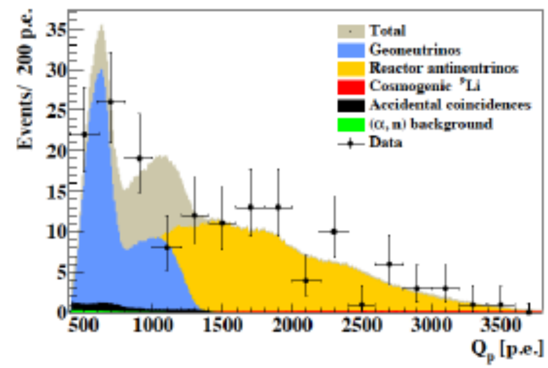




KamLAND is a **1 kton** liquid scintillator detector situated in **Japan**, in the Kamioka mine. It is surrounded by 1325 17" PMTs and 554 20" PMTs

Data-taking: 2002-2019			
	U	Th	U+Th
Events	$138.0^{+22.3}_{-20.5}$	$34.1^{+5.4}_{-5.1}$	$168.8^{+26.3}_{-26.5}$
Signal [TNU]	$26.1^{+4.2}_{-3.9}$	$6.6^{+1.1}_{-1.0}$	$\mathbf{32.1^{+5.0}_{-5.0}}$

Borexino



Borexino is **0.3 kton** liquid scintillator detector situated in **Italy**, at the Laboratori Nazionali del Gran Sasso. It is surrounded by ~2200 8" PMTs.

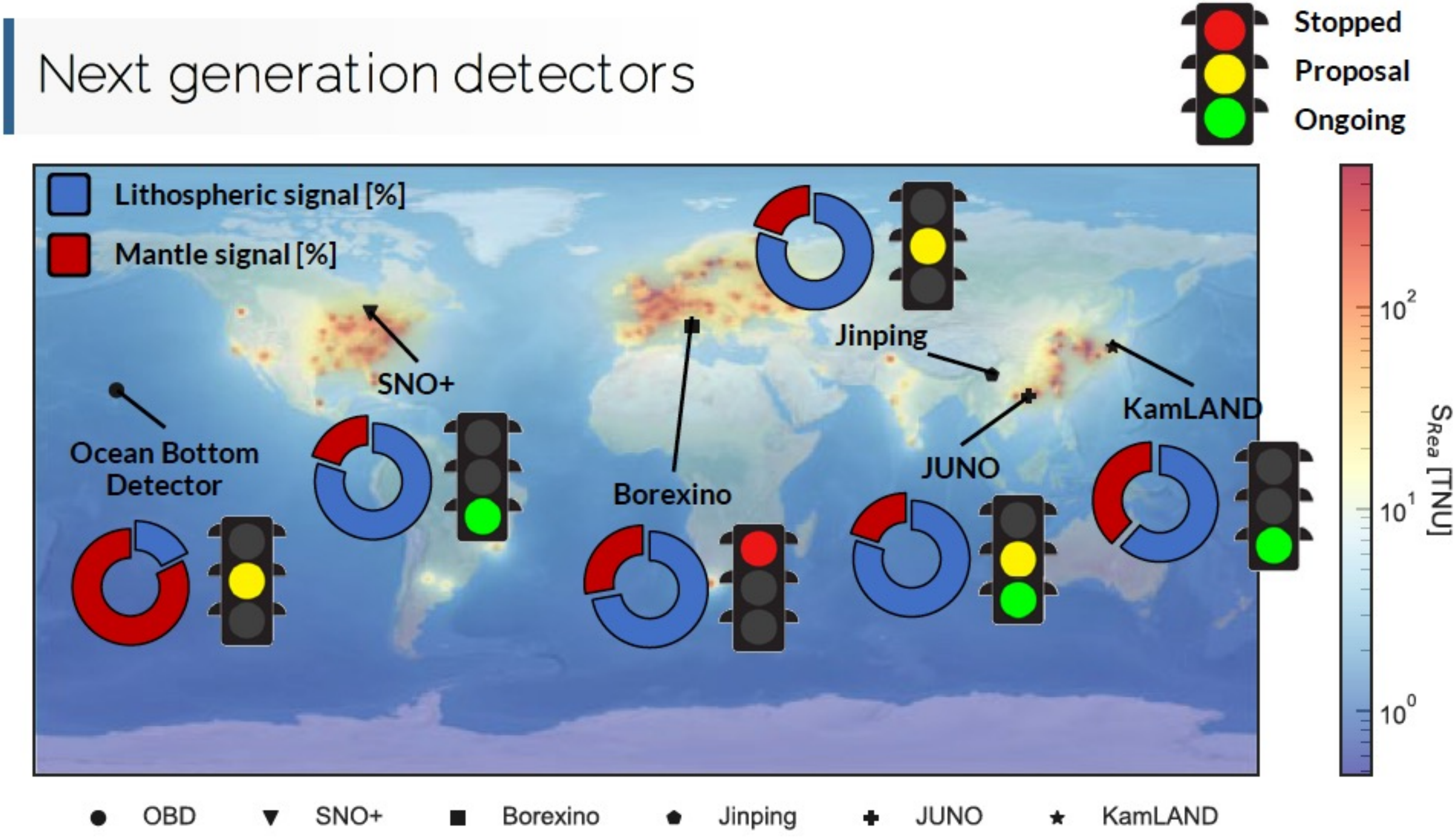
Data-taking: 2007-2019			
	U	Th	U+Th
Events	$41.1^{+7.5}_{-7.1}$	$11.5^{+2.2}_{-1.9}$	$52.6^{+9.6}_{-9.0}$
Signal [TNU]	$36.3^{+6.7}_{-6.2}$	$10.5^{+2.1}_{-1.7}$	$\mathbf{47.0^{+8.6}_{-8.1}}$

» Signal unit: 1 TNU = one event per 10^{32} free protons/year

Talk by Andrea Serafini

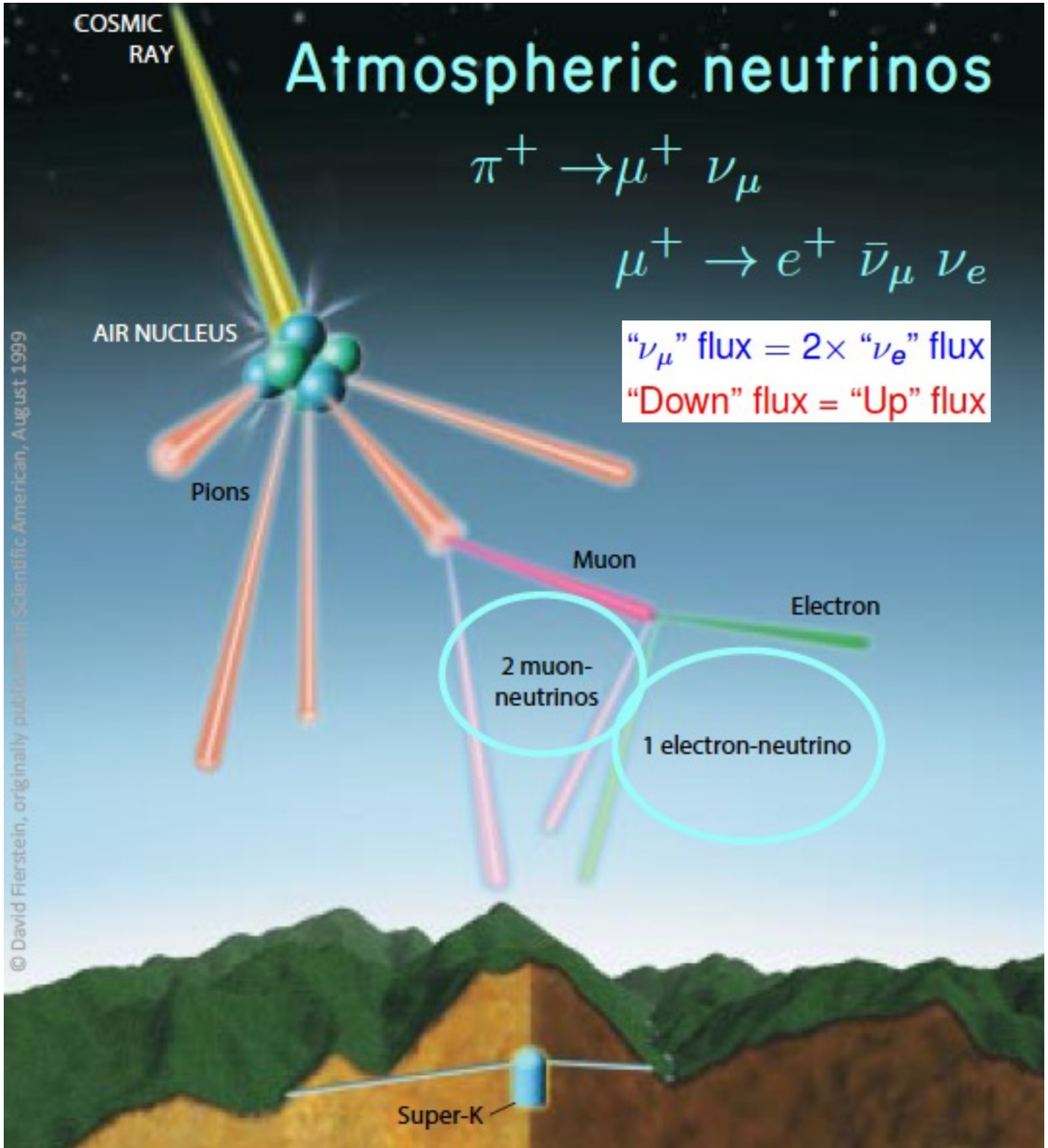
Brings crucial information about the mantle
Tells us the radiogenic contribution to Earth's heat budget

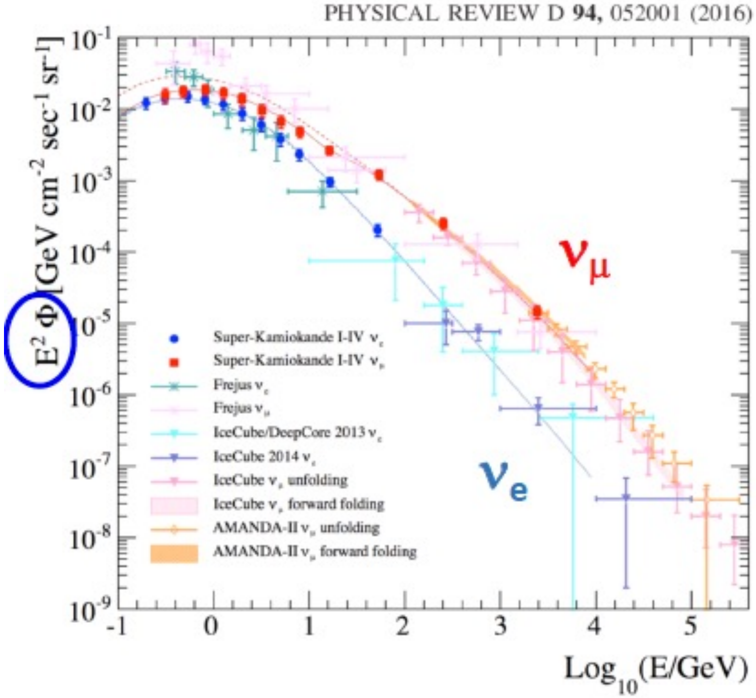
Next generation detectors



Talk by Andrea Serafini

Atmospheric Neutrinos





- Almost isotropic flux
  up-down symmetric
- Known flavor composition
  (ν_e, ν_μ, and their antiparticles)
- Wide range of energies
  (GeV to PeV)
- Steeply falling power-law spectrum

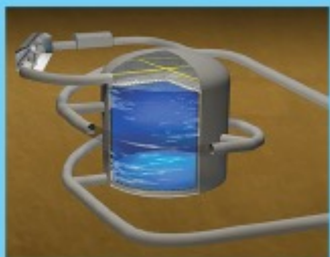
Inaugural Talk by Ed Kearns

Neutrino Detectors for Tomography of Earth

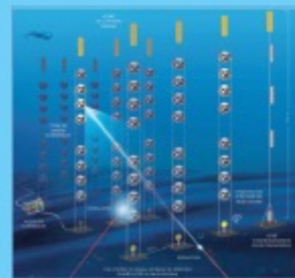
At low (GeV) energies: Neutrino oscillation tomography

(sub- or multi-)Megaton-scale detector

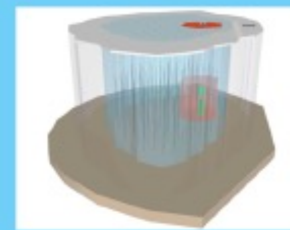
active
in construction
proposed/prototyping



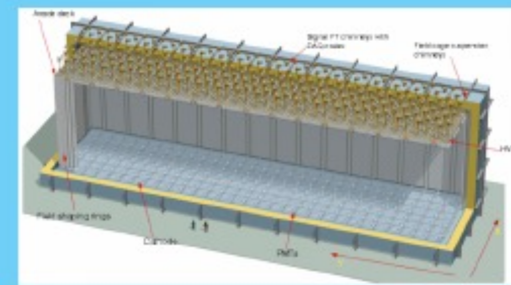
SuperK (50 kton)
HyperK (260 ktons)



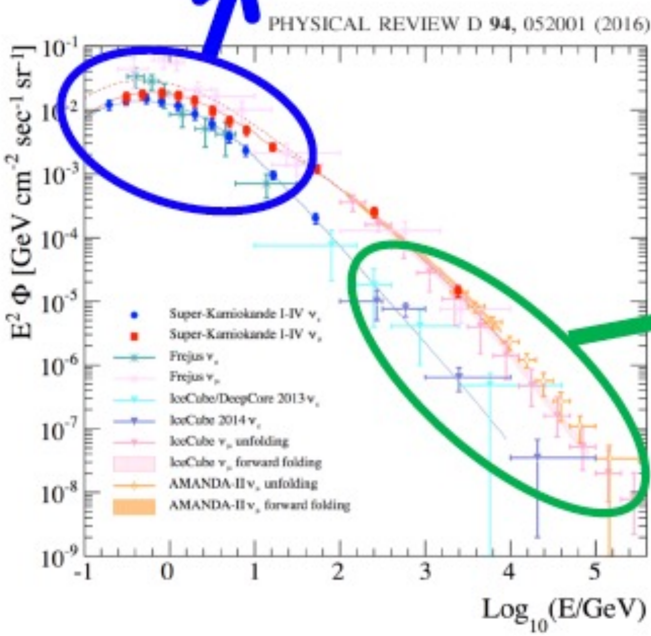
KM3NeT/ORCA (6 Mton)



PINGU (IceCube) (1-5 Mton)

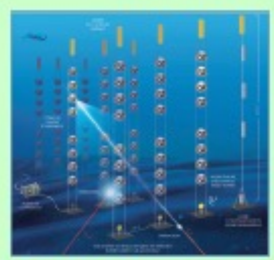


DUNE (40 kton)

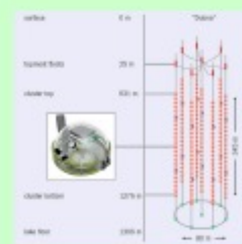


At high (TeV-PeV) energies:
Neutrino absorption tomography

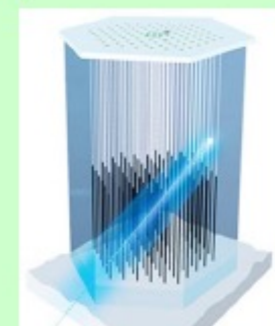
~ Gigaton-scale detectors



KM3NeT/ARCA (1 Gton)



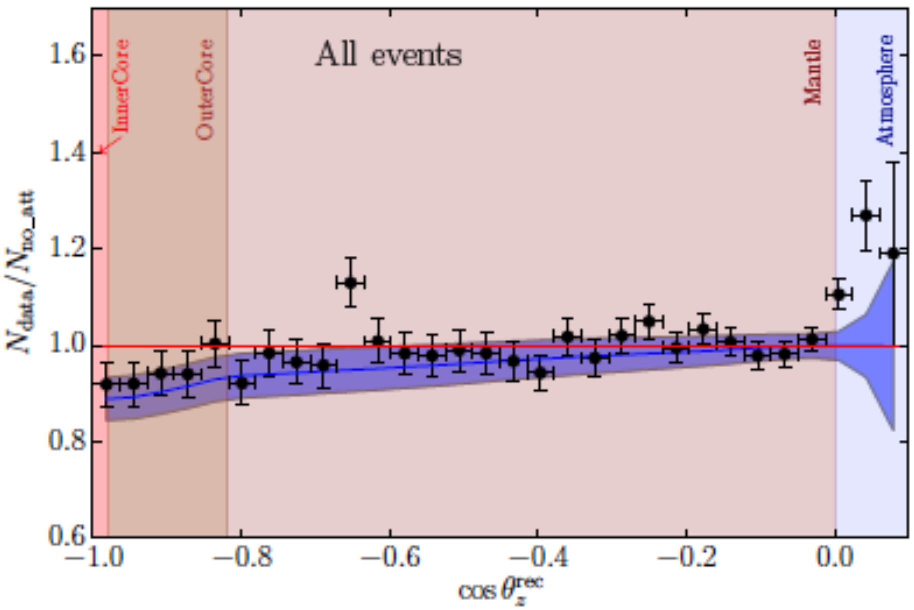
Baikal (1 Gton)

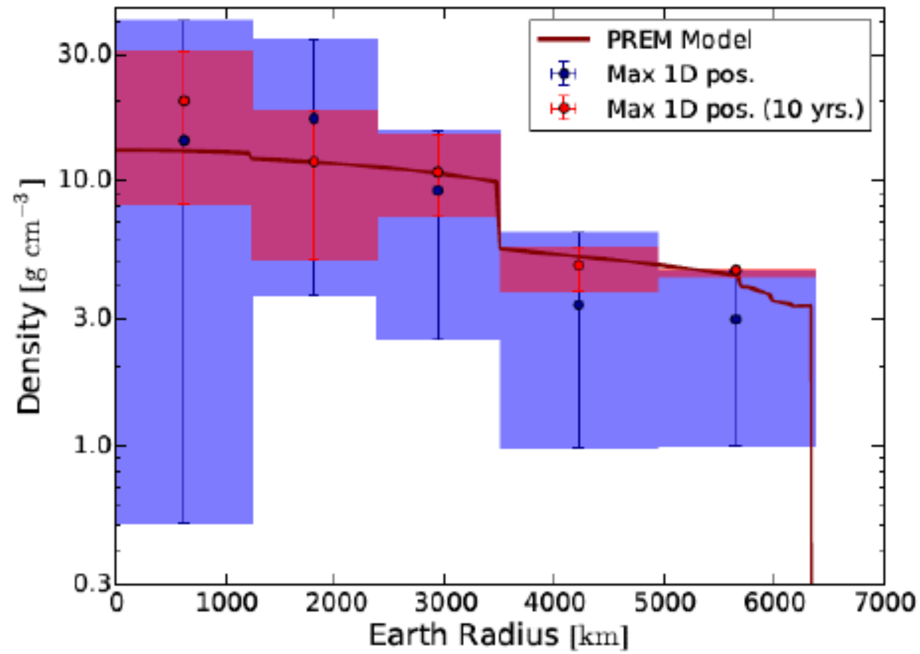


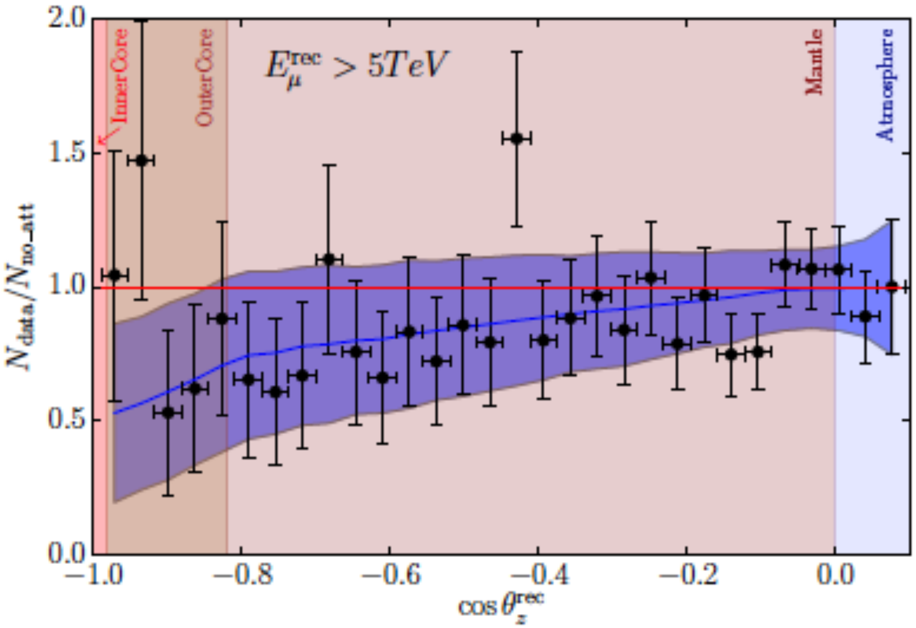
IceCube/Gen2 (1+ Gton)

Courtesy Veronique Van Elewyck

Neutrino Absorption Tomography: At High Energies



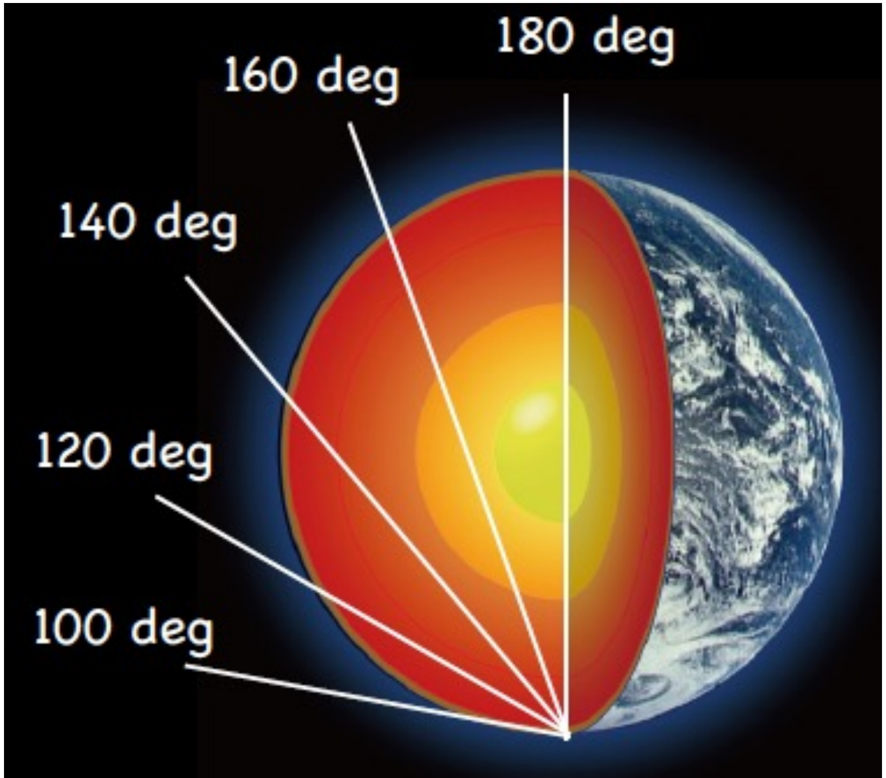




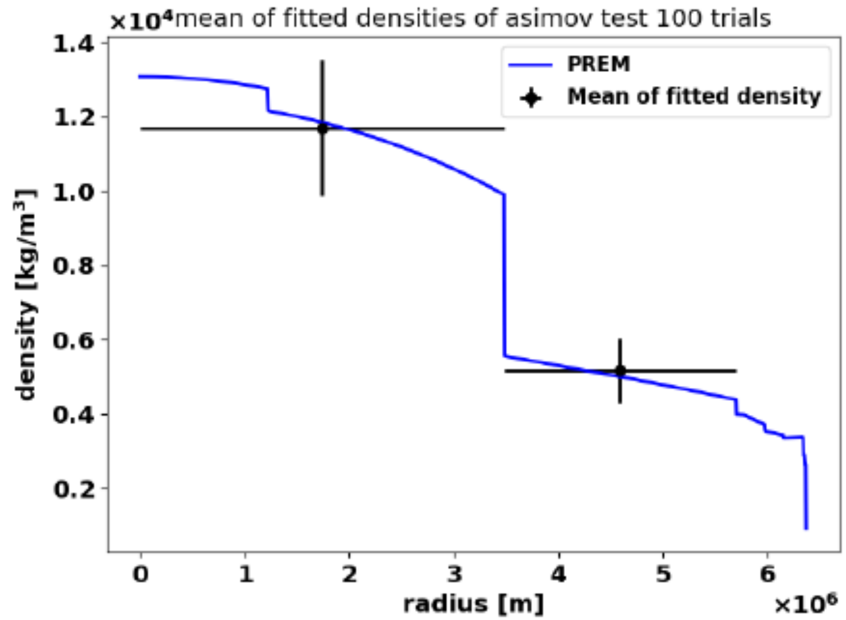
- 2018: first study with real IceCube data
- 1 year sample (2011 - 2012) – upgoing ν_μ
- Radial model with 5 layers of constant density
- Donini, Palomares-Ruiz, Salvado
  Nature Phys. 15 (2019) 1, 37-40

Talk by Andrea Donini

Neutrino Absorption Tomography: At High Energies



	Energy*
100 deg	7.1 PeV
120 deg	480 TeV
140 deg	150 TeV
160 deg	49 TeV
180 deg	35 TeV

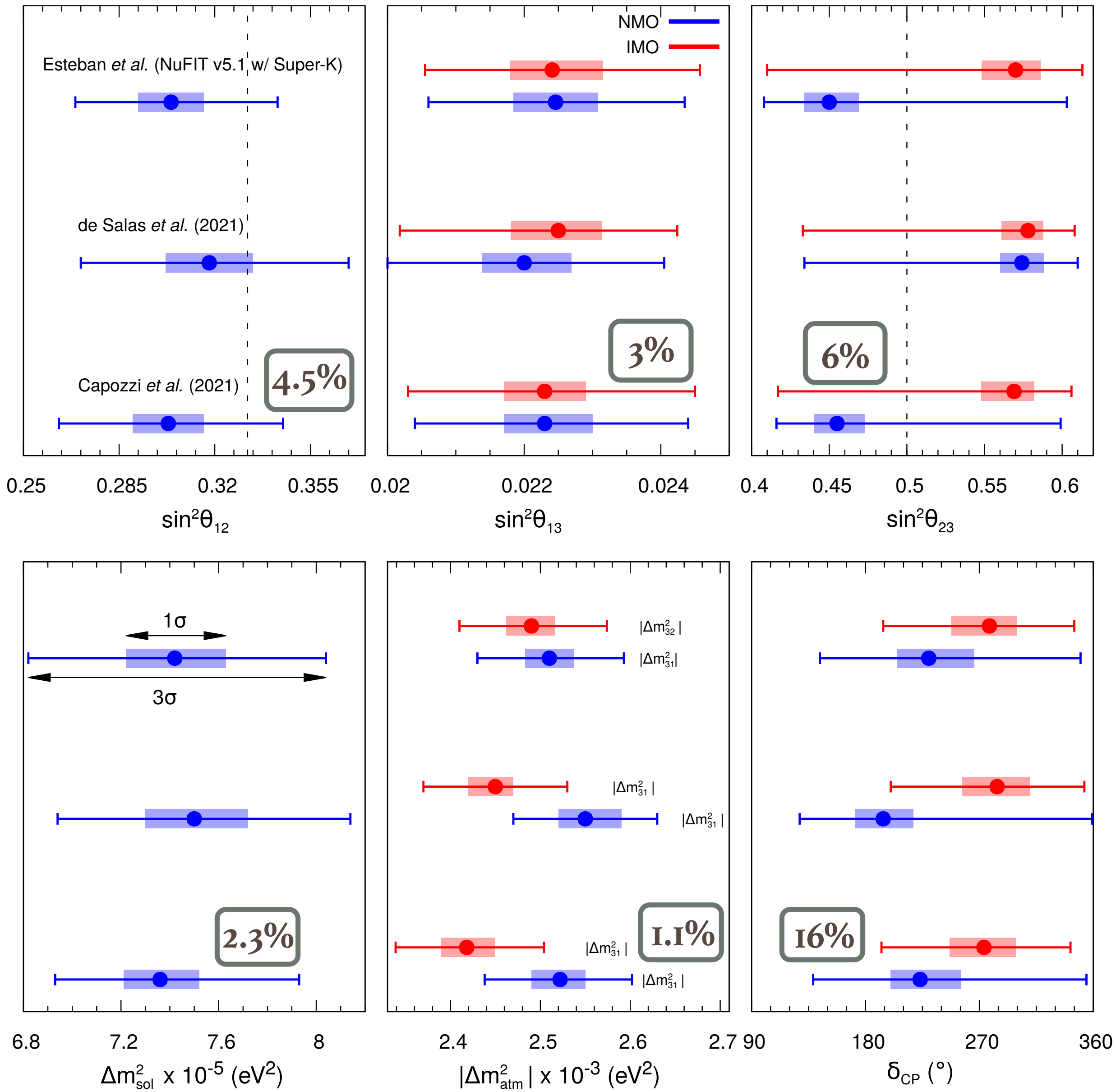


- Results from 100 Asimov Tests
- Scaled for 11 years of IceCube data
- Y-axis error bars represent standard deviations of fitted densities of 100 trials

Talk by Kotoyo Hoshina
IceCube Collaboration

Remarkable Precision on Neutrino Oscillation Parameters

Robust three-flavor neutrino oscillation paradigm

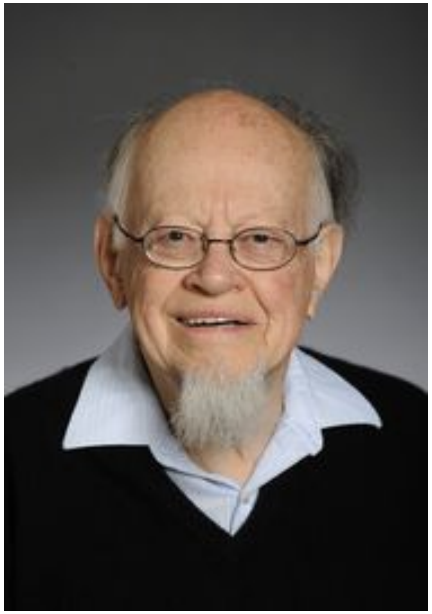


Huge boost for Neutrino Oscillation Tomography of Earth

Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206

Neutrino Oscillations in Matter: MSW Effect

- The MSW Effect (Wolfenstein, 1978; Mikheyev and Smirnov, 1985)
- Matter effect can change the pattern of **ν** oscillations significantly
- Resonant enhancement of oscillations and resonant flavor conversion possible
- Responsible for the flavor conversion of solar neutrinos (LMA MSW solution established)



Lincoln Wolfenstein

Stanislav Mikheyev

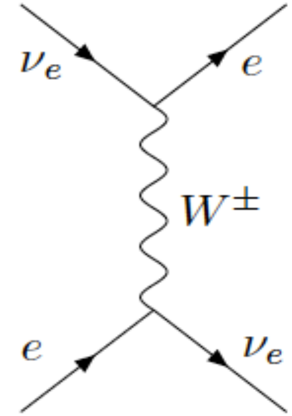
Alexei Smirnov

Neutrino Oscillations in Matter: MSW Effect

Neutrino propagation through matter modify the oscillations significantly

Coherent forward scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e



MSW matter term: $A = \pm 2\sqrt{2} G_F N_e E$ or $A(\text{eV}^2) = 0.76 \times 10^{-4} \rho \; (\text{g/cc}) E(\text{GeV})$

N_e = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to antineutrino mode

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$ → *even if $\delta_{CP} = 0$, causes fake CP asymmetry*

Matter term modifies oscillation probability differently depending on the sign of Δm^2

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\text{res}}^{\text{Earth}} = 6 - 8\,\text{GeV}$$ → *Resonant conversion – Matter effect*

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ *Resonance occurs for neutrinos (anti-neutrinos) if Δm^2 is positive (negative)*

Neutrino Oscillation Length Resonance / Parametric Resonance

- Oscillations of atmospheric neutrinos inside the Earth can feel this resonance when neutrino trajectories cross the core of the Earth

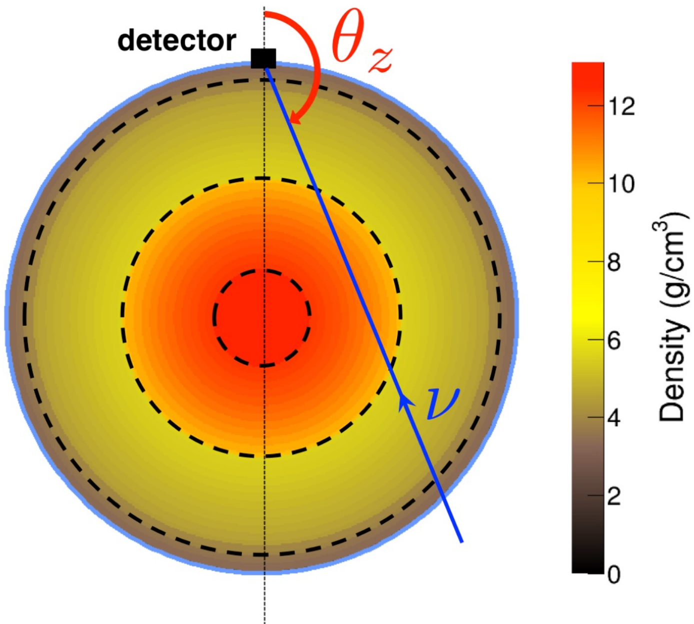
- The probabilities of ν flavor transitions can be strongly enhanced if the oscillation phase undergoes certain modification in matter

- This can happen if the variation of the matter density along the neutrino path is correlated in a certain way with the change of the oscillation phase

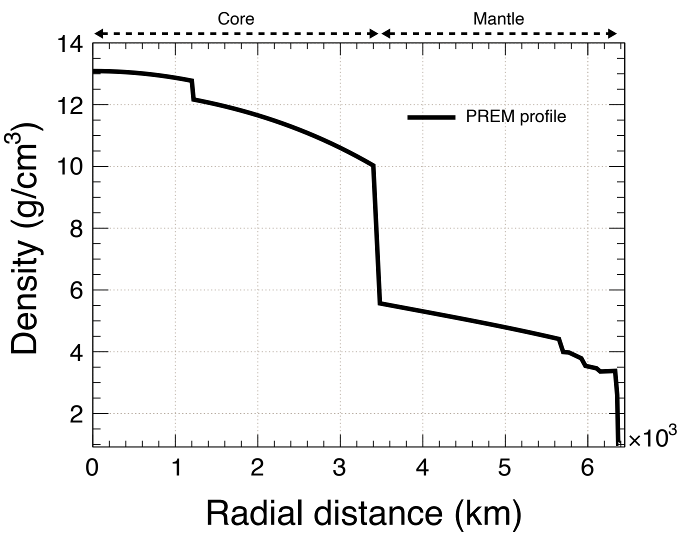
- This amplification of the neutrino oscillation probability in matter due to specific phase relationships has an interesting property that it can accumulate if the matter density profile along the neutrino path repeats itself (periodic)

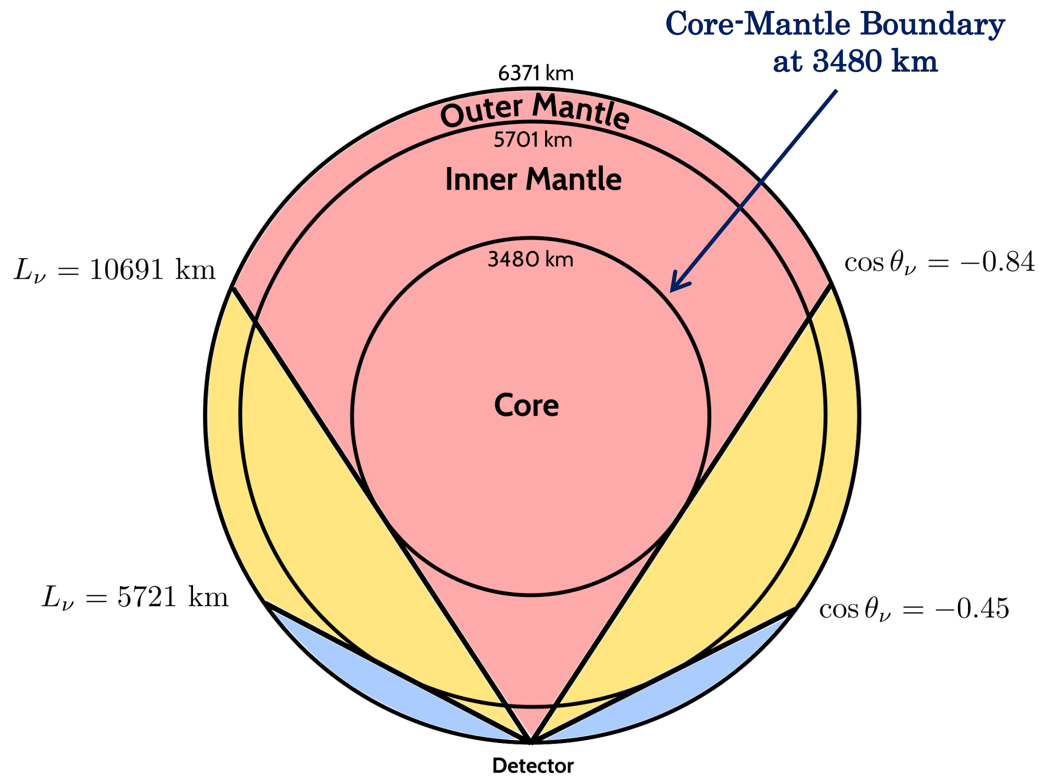
Petcov 1998, Liu and Smirnov 1998, Akhmedov 1998

PREM and Neutrino Trajectories Deep Inside the Earth



The gravitational and seismic measurements are used to infer the radial density distribution inside Earth – known as Preliminary Reference Earth Model (PREM)

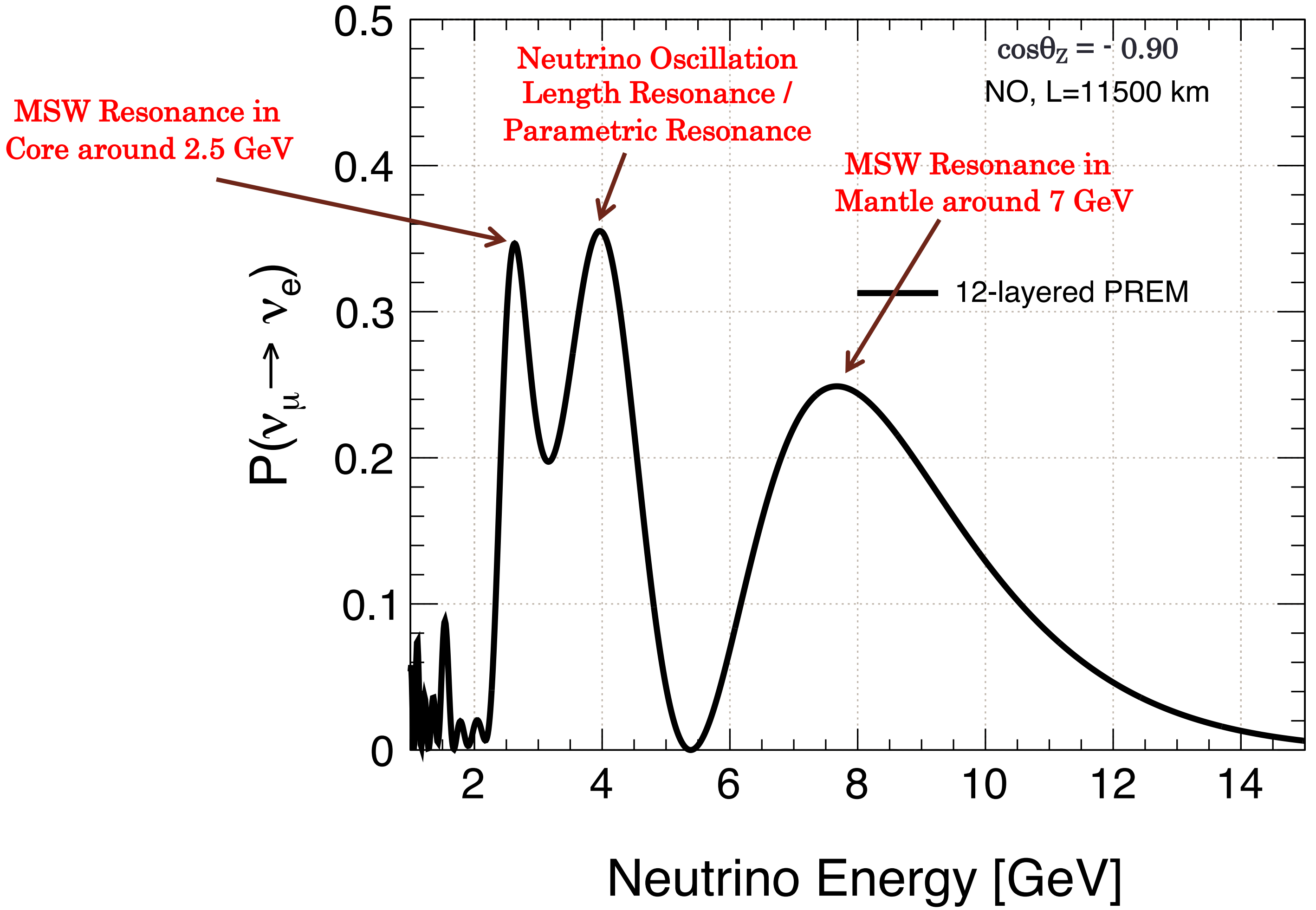




Three-Layered Model of Earth

PREM is not a measured profile!

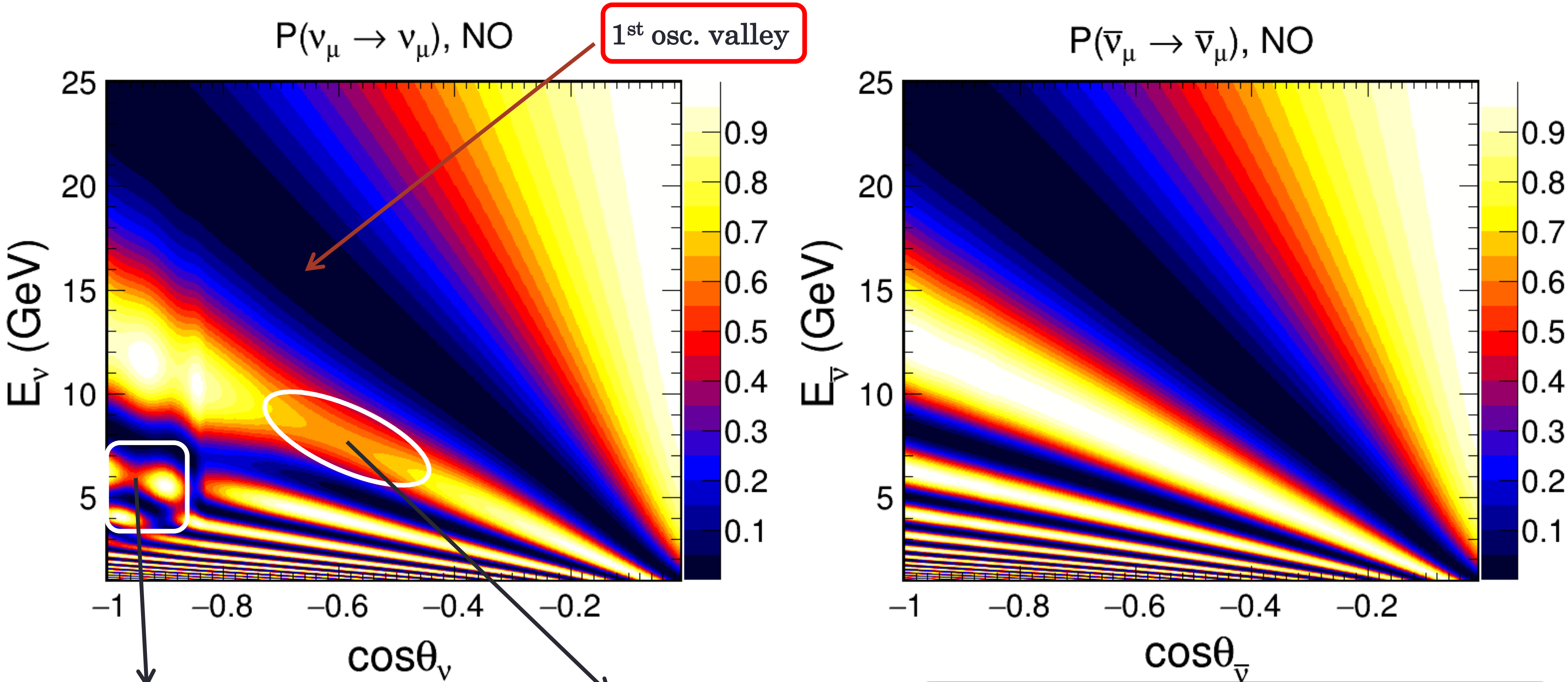
The Resonances inside the Earth



$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,{\rm eV^2}}\right)\cos 2\theta_{13}$$

Oscillation Valley

Neutrinos (antineutrinos) feel Earth's matter effect for normal (inverted) mass ordering



NOLR/PR region

$\cos\theta_\nu < -0.8$
$3\text{ GeV} < E_\nu < 6\text{ GeV}$
reducing threshold helps

MSW resonance region

$-0.8 < \cos\theta_\nu < -0.5$
$6\text{ GeV} < E_\nu < 10\text{ GeV}$

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

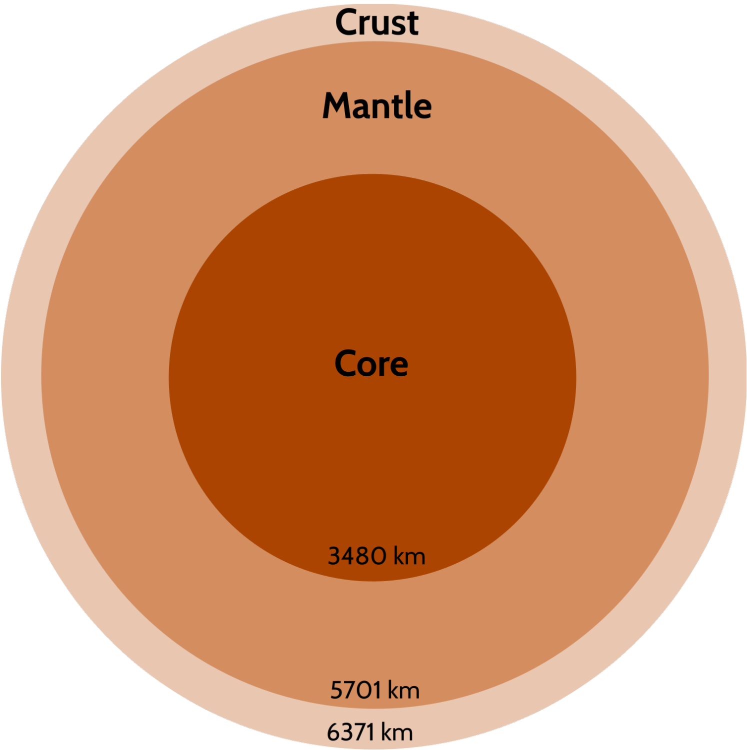
$$Y_e = N_e/(N_p + N_n)$$

ρ denotes the matter density
+1 (-1) for neutrino (antineutrino)

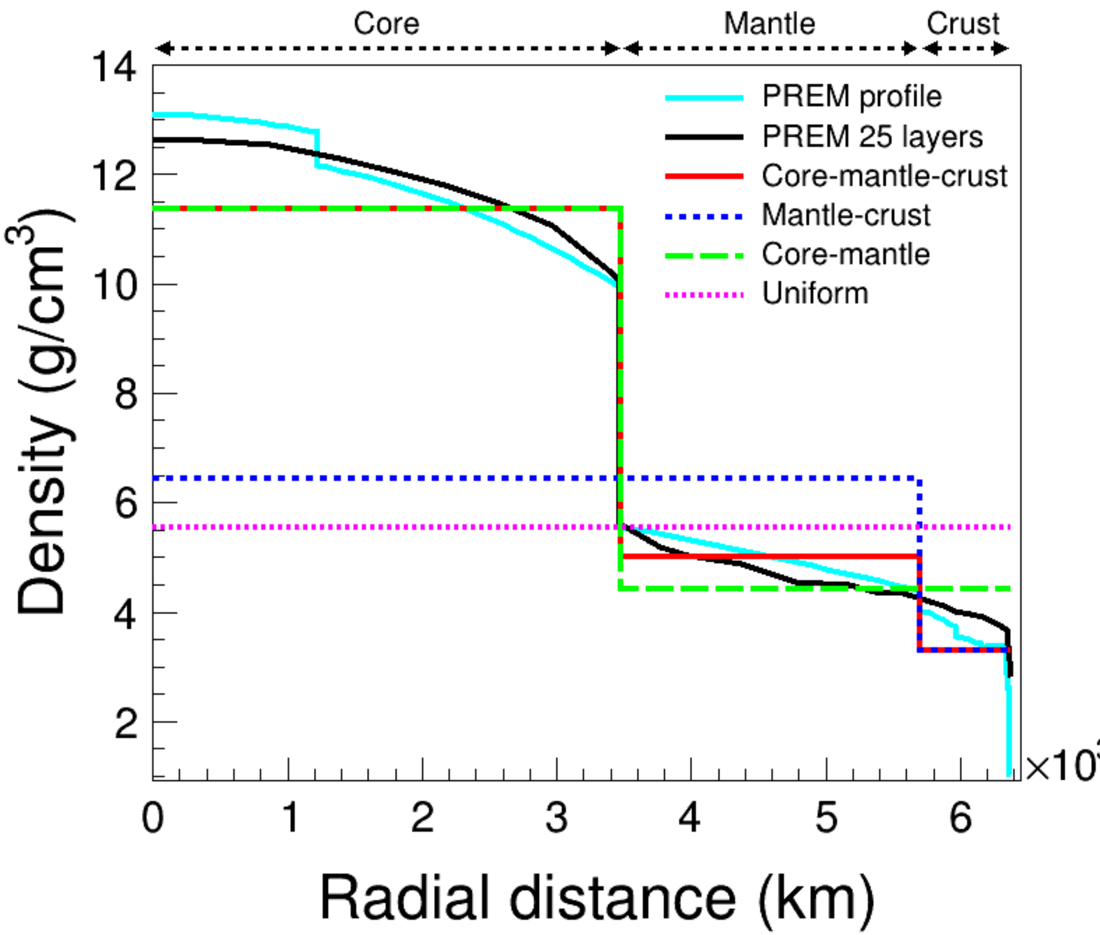
Kumar, Khatun, Agarwalla, Dighe, EPJC 81 (2021) 2, 190

Note: MSW or NOLR/PR resonances have not been observed yet!

Various Radial Density Profiles of Earth



Three-Layered Model of Earth



Anil Kumar and Sanjib Kumar Agarwalla, JHEP 08 (2021) 139

While constructing alternative profiles of Earth, the radius & mass of Earth remain invariant

Atmospheric neutrino experiments can distinguish between these alternative profiles of Earth utilizing neutrino oscillations in the presence of Earth's matter in multi-GeV energy range

Neutrino Oscillation Tomography with Atmospheric Neutrinos

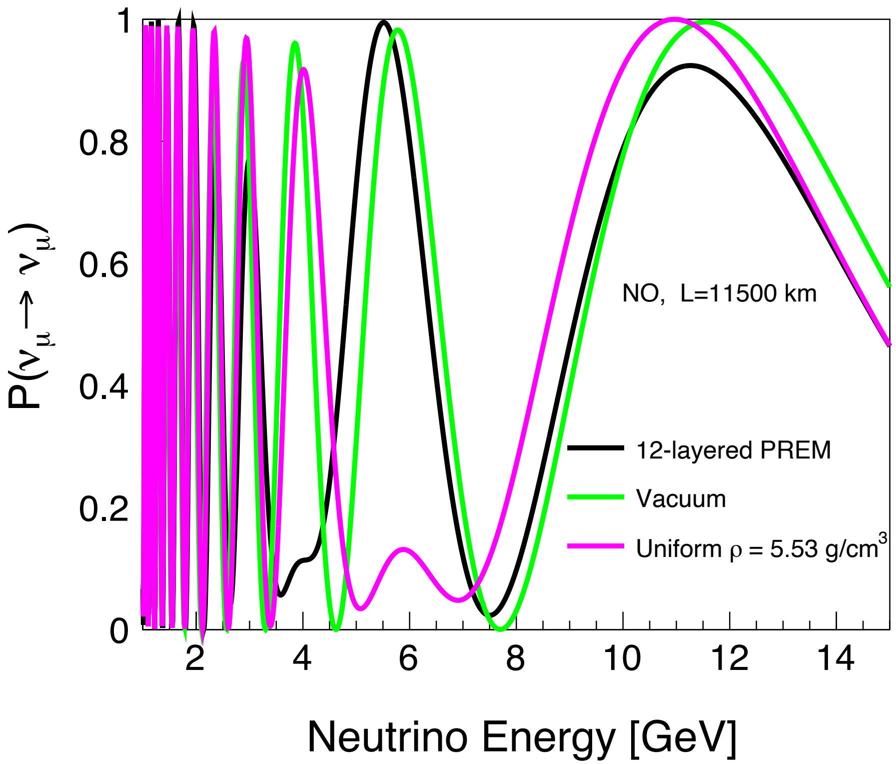
Atmospheric neutrinos have access to sub-GeV (resonance matter effect in core) and multi-GeV (resonance matter effect in mantle) energy ranges with a wide range of baselines passing through Earth's mantle and core

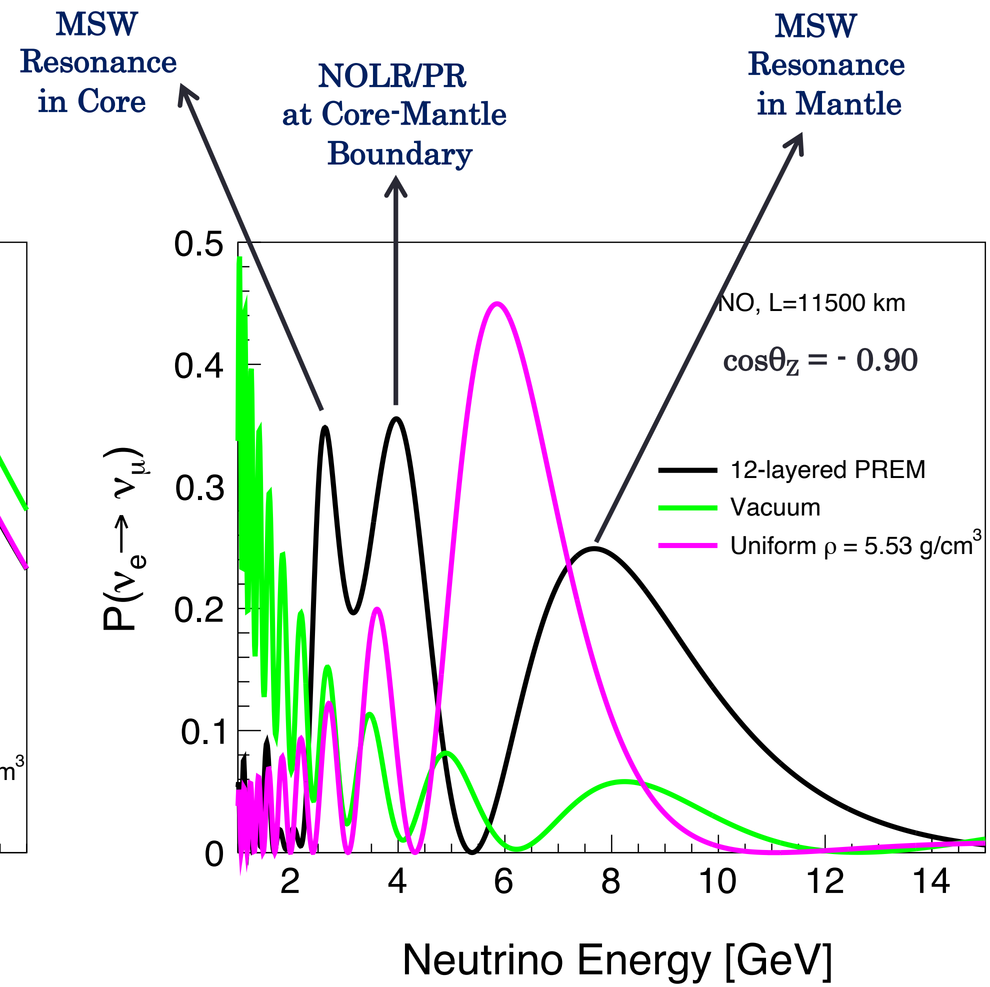
The recent advancement in the precision measurements of neutrino oscillation parameters opens the avenue to perform a rich neutrino oscillation tomography using currently running and upcoming atmospheric neutrino experiments.

One can address the following important issues related to Earth:

- Observing the presence of Earth matter
- Ruling out the homogeneous matter
- Measurement of mass of Earth
- Validating the presence of core
- Location of core-mantle boundary (CMB)
- Measurement of the density of core and mantle
- Chemical composition of core

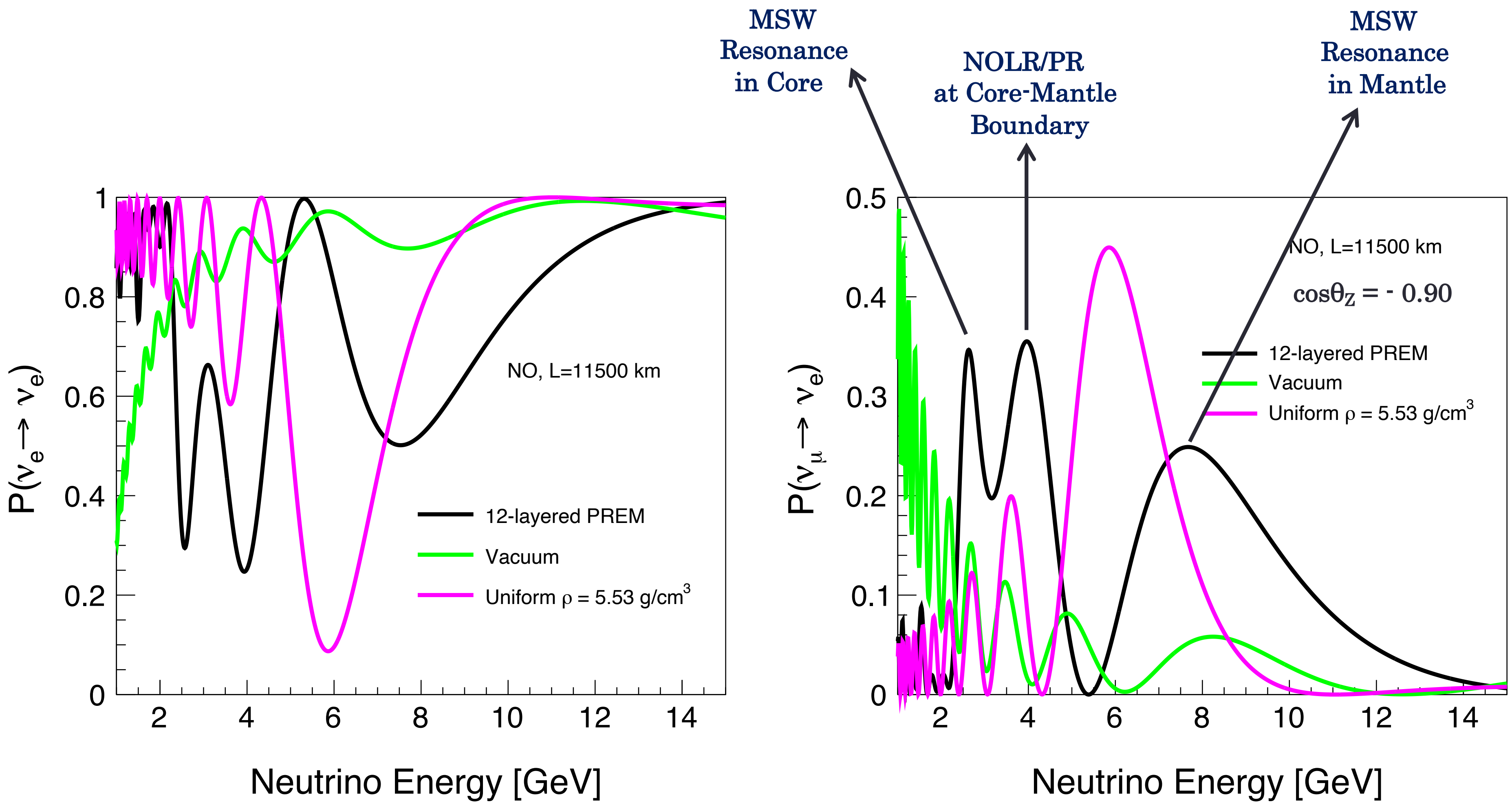
Neutrino Oscillation Probabilities for a Core-Passing Track-Like Events





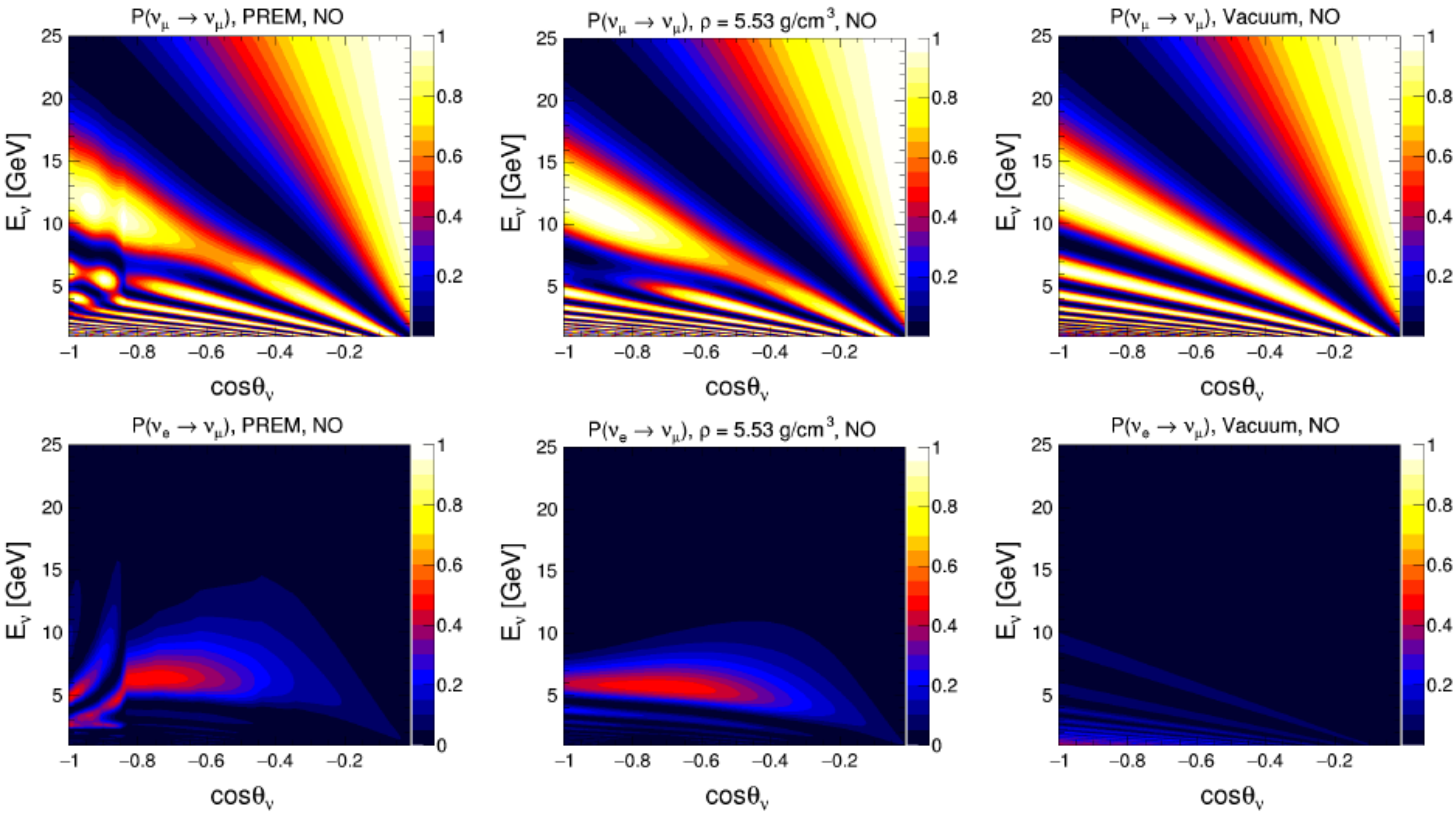
We get similar oscillation patterns for antineutrinos with inverted mass ordering

Neutrino Oscillation Probabilities for a Core-Passing Cascade-Like Events



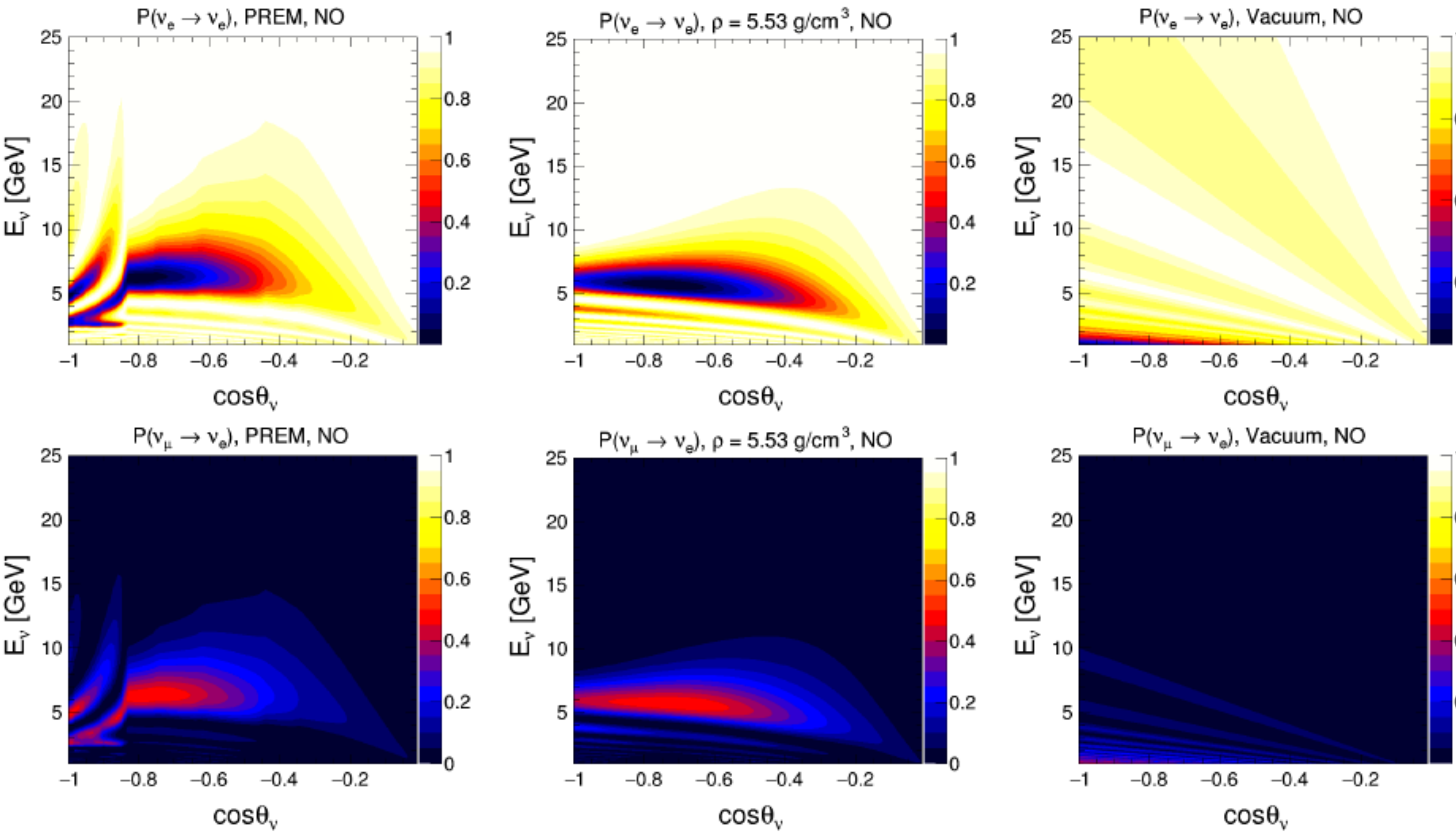
We get similar oscillation patterns for antineutrinos with inverted mass ordering

Neutrino Oscillograms for a Core-Passing Track-Like Events



We get similar oscillograms for antineutrinos with inverted mass ordering

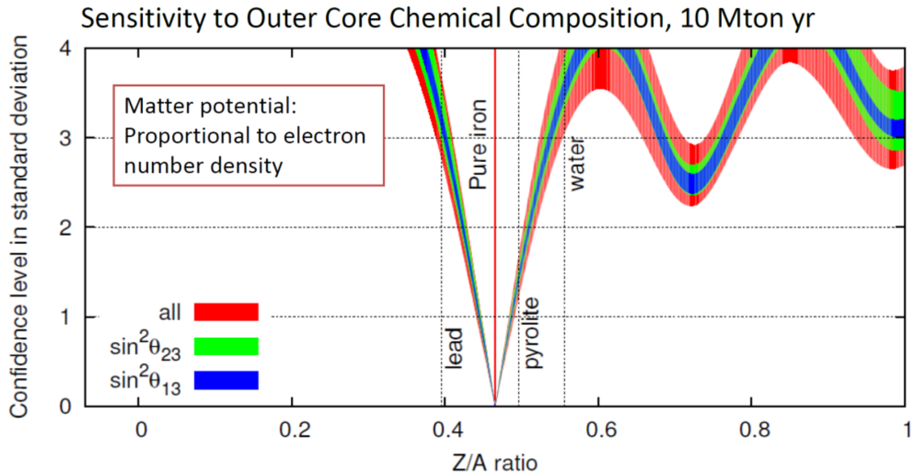
Neutrino Oscillograms for a Core-Passing Cascade-Like Events



We get similar oscillograms for antineutrinos with inverted mass ordering

Neutrino Oscillation Tomography w/ Hyper-Kamiokande

Application: Chemical composition of Earth's Outer Core



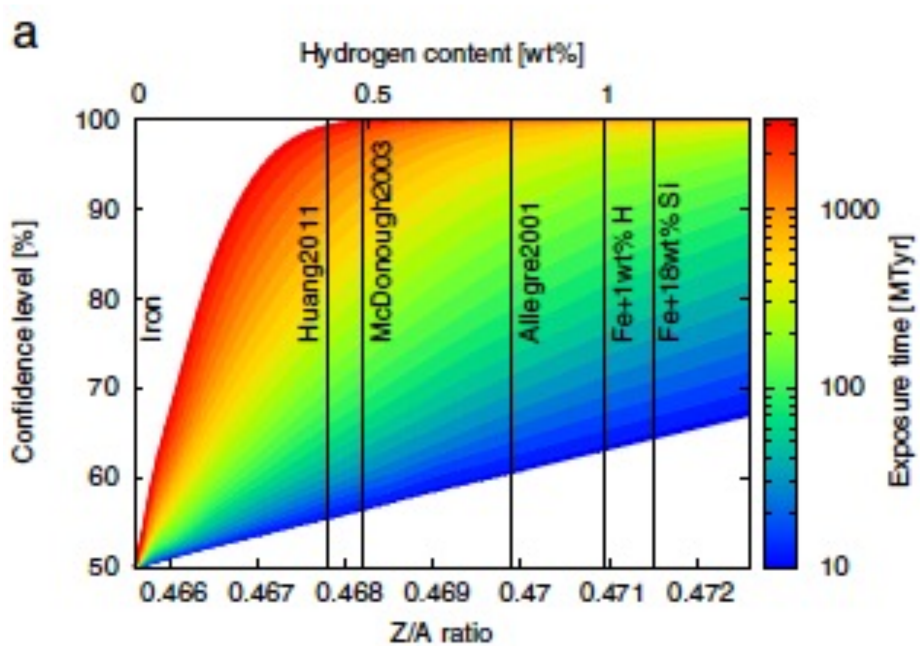
- With 10 Mtonyr exposure, some extreme cases (water or lead core) are excluded at 3 sigma level.

17

Hyper-Kamiokande Design Report
arXiv:1805.04163v2

Talk by Akimichi Taketa
Hyper-Kamiokande Collaboration

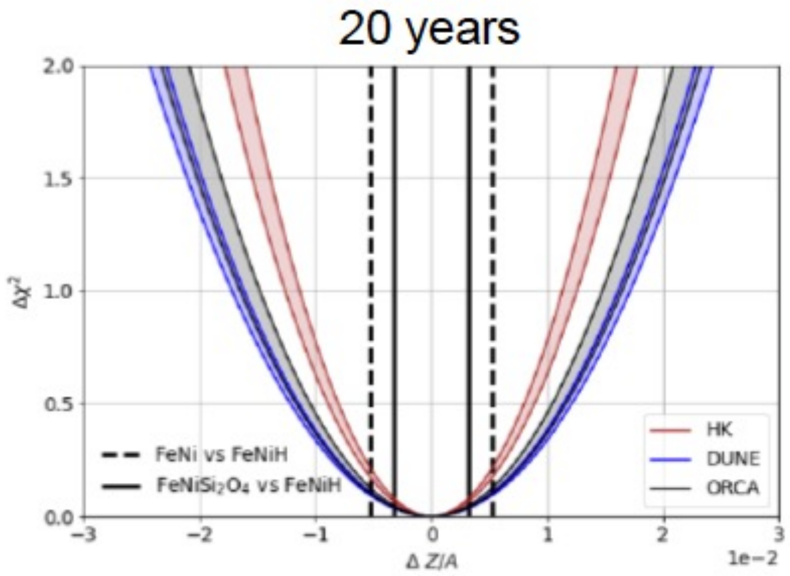
The major elements composition of pyrolite is about 44.71 weight percent (wt%) SiO_2, 3.98 wt% Al_2O_3, 8.18 wt% FeO, 3.17 wt% CaO, 38.73 wt% MgO, 0.13 wt% Na_2O

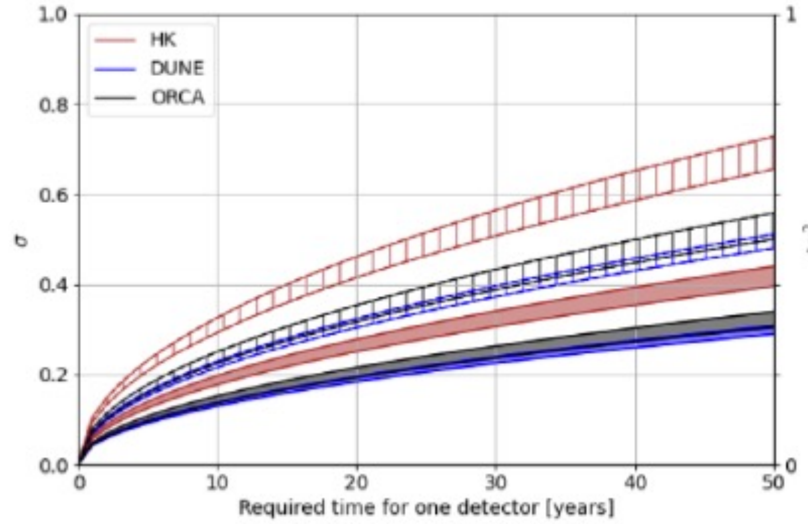


C. Rott, A. Taketa, D. Bose, 2015

Neutrino Oscillation Tomography w/ HK, DUNE, ORCA

- Upcoming generation of experiments will measure the outer core Z/A with precision between 0.01 and 0.02
- Hyper-K has the strongest power
- ORCA and DUNE achieve similar sensitivity
- This will be shy of resolving even most extreme models

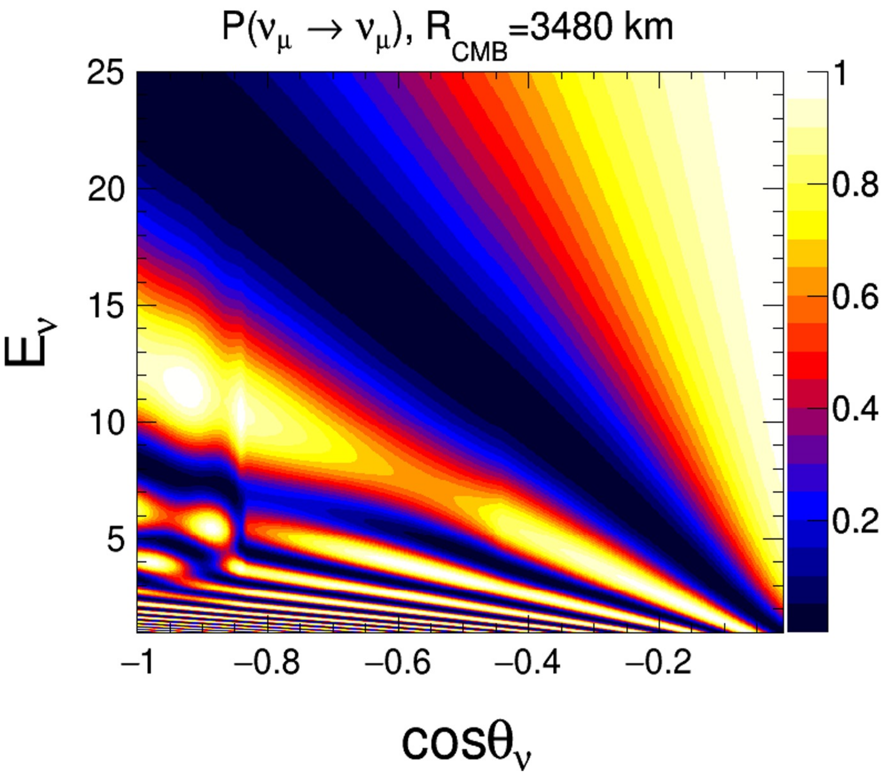


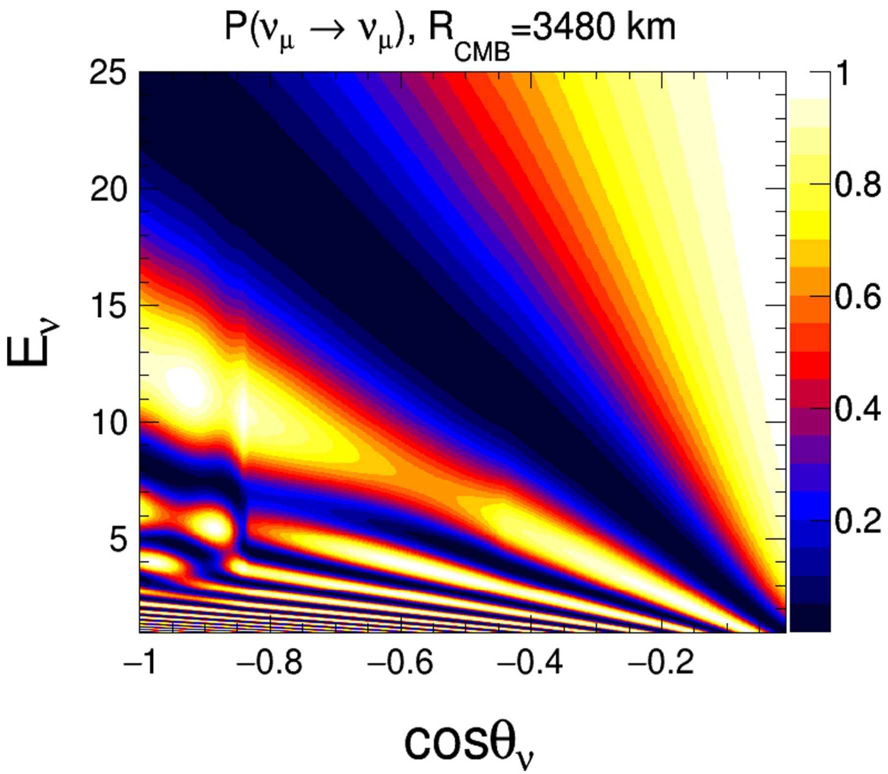


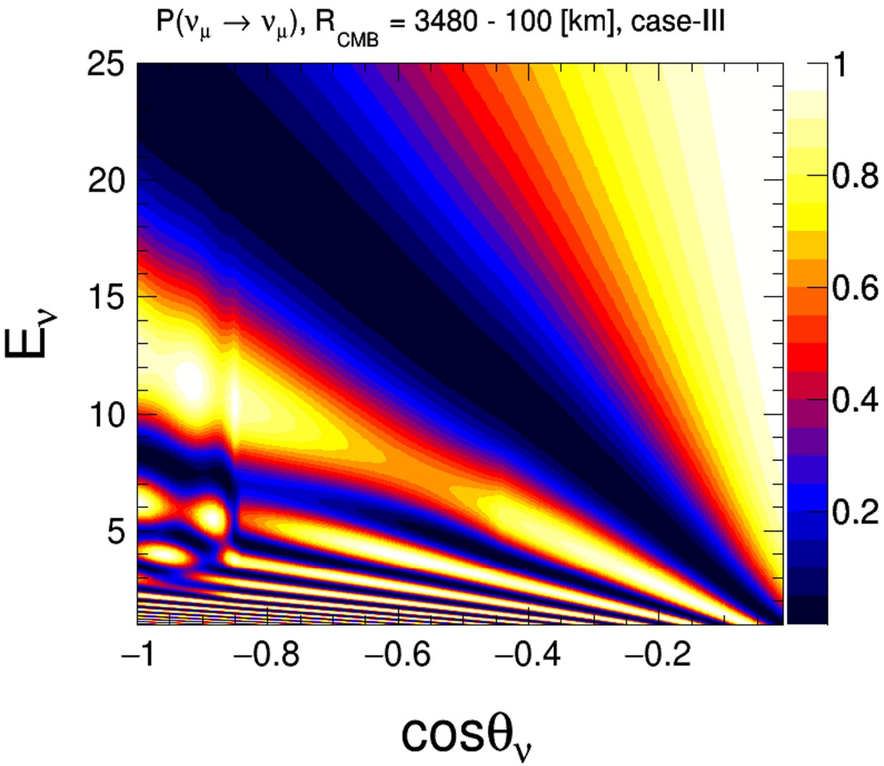
Detector	M (Mton)	E_{th} (GeV)	E_{pl} (GeV)	$\sigma(E)/E$	σ_θ (deg)	E_{th}^{class} (GeV)	E_{pl}^{class} (GeV)	P_{max}^{class}
ORCA-like	8	2	10	25%	$30/\sqrt{E}$	2	10	85%
HyperKamiokande-like	0.40	0.1	0.2	15%	$15/\sqrt{E}$	0.1	0.2	99%
DUNE-like	0.04	0.1	0.2	5%	5	0.1	0.2	99%
Next-Generation	10	0.5	1.0	$5\% + 10\%/\sqrt{E}$	$2 + 10/\sqrt{E}$	0.5	1	99%

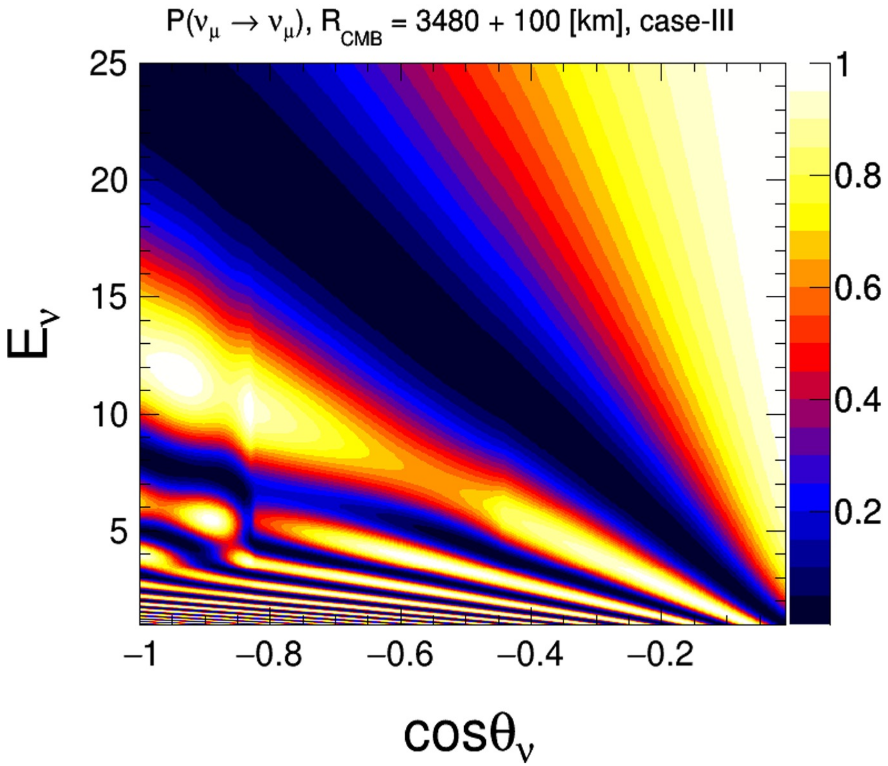
Talk by Joao Coelho

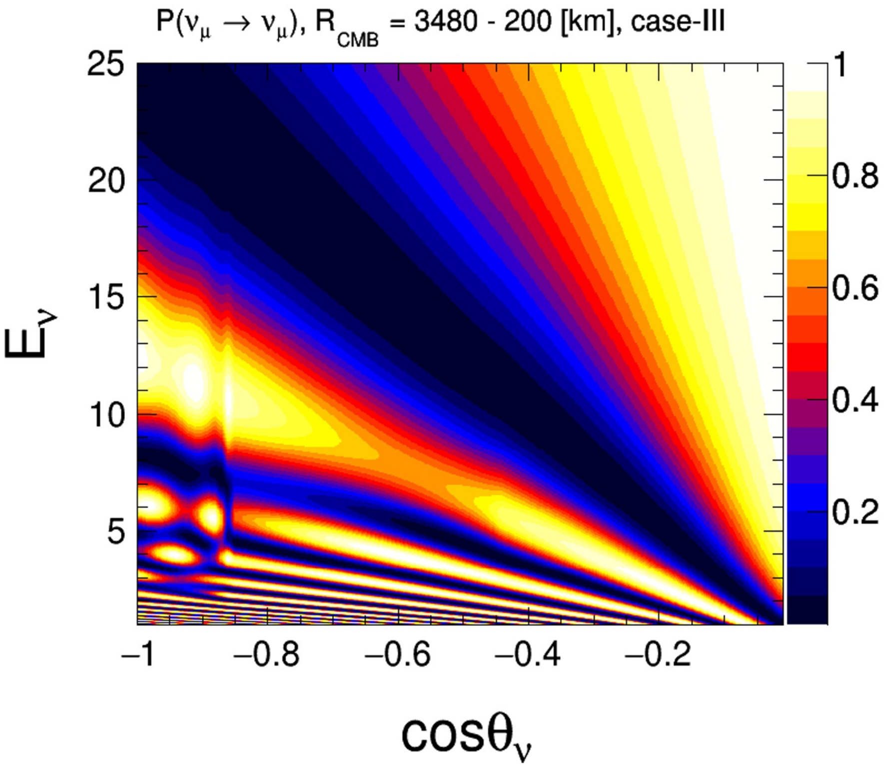
Locating Core-Mantle Boundary using Atmospheric Neutrinos



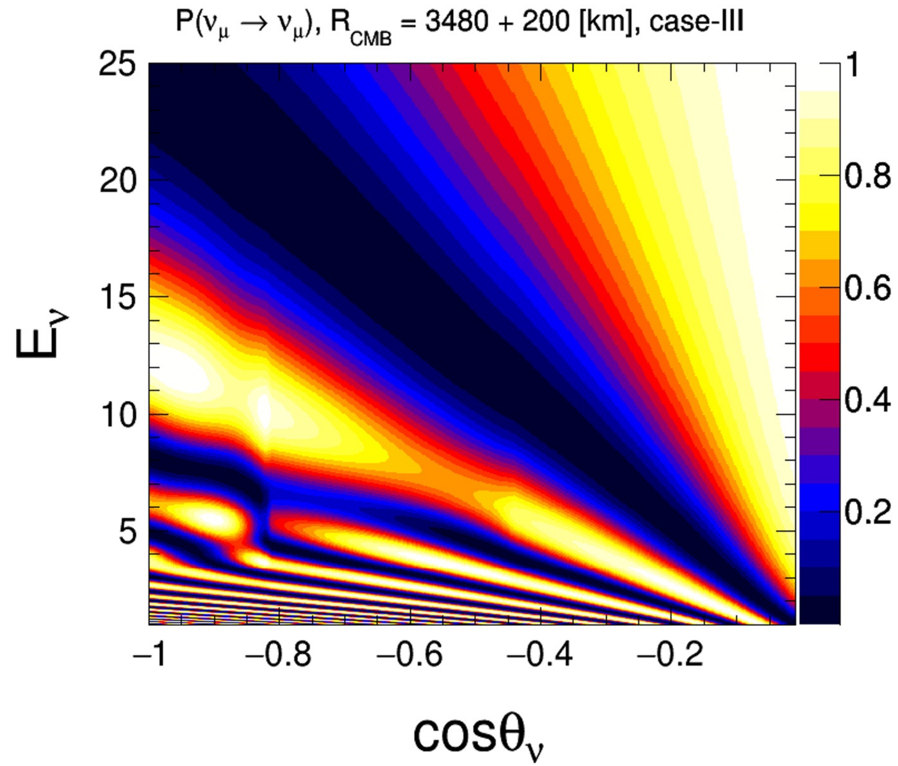



P(νμ → νμ), RCMB = 3480 - 100 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2

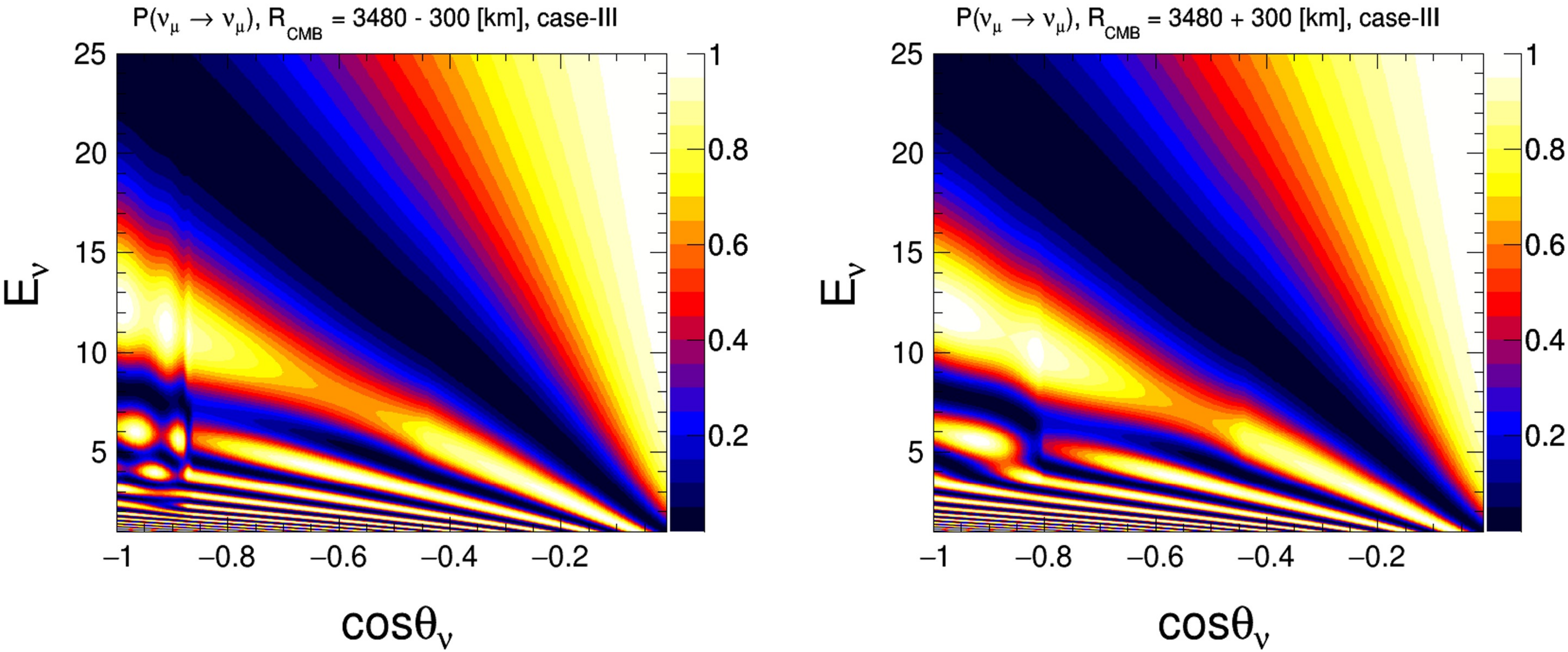

P(νμ → νμ), RCMB = 3480 + 100 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2



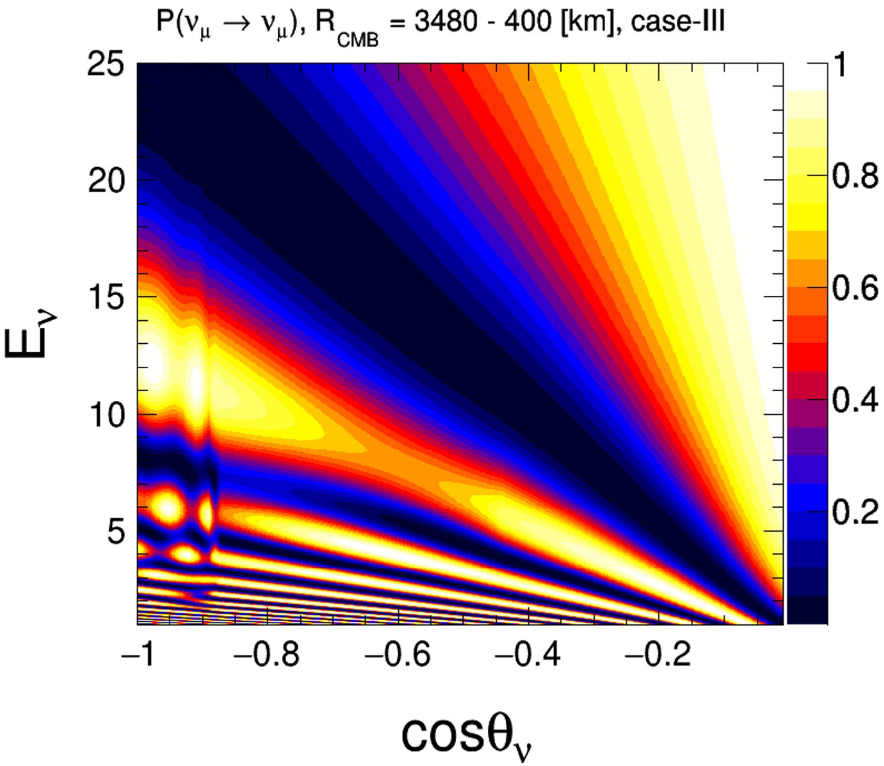
P(νμ → νμ), RCMB = 3480 - 200 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

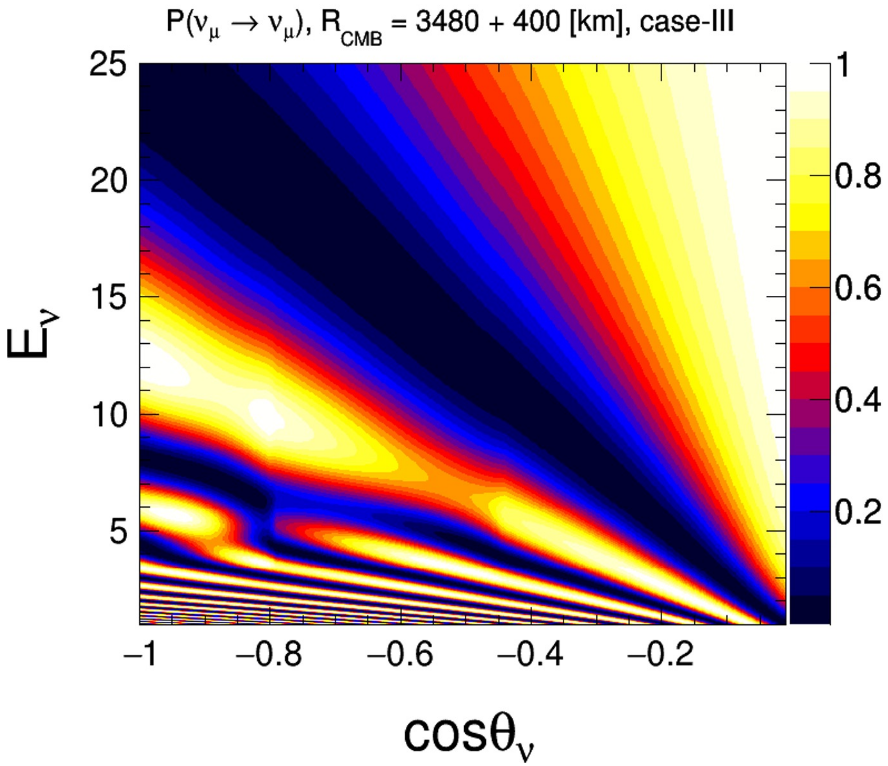


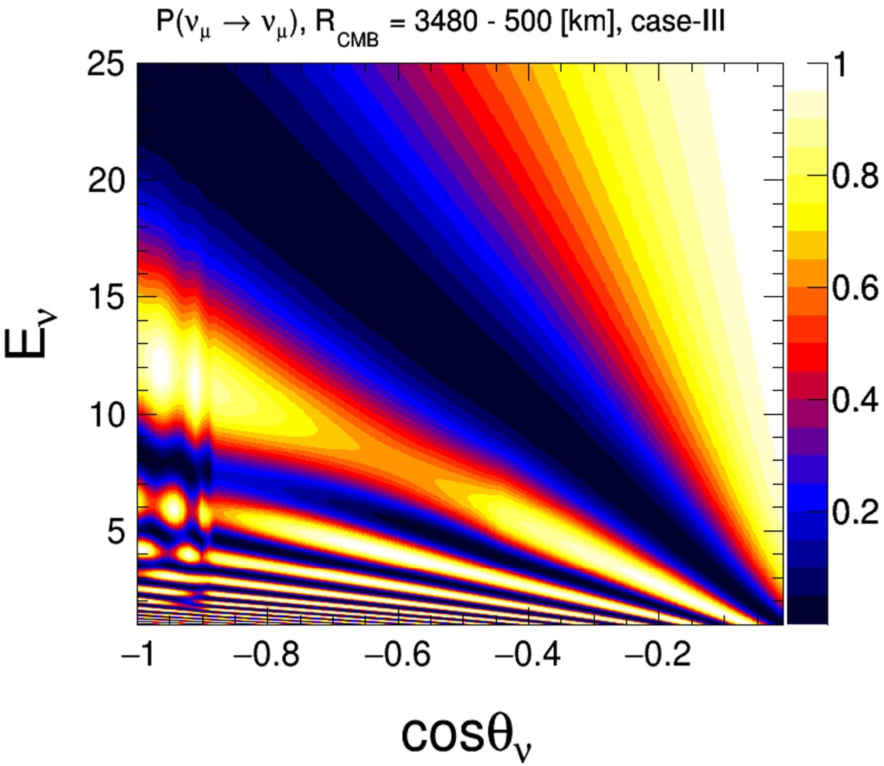
P(νμ → νμ), RCMB = 3480 + 200 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2



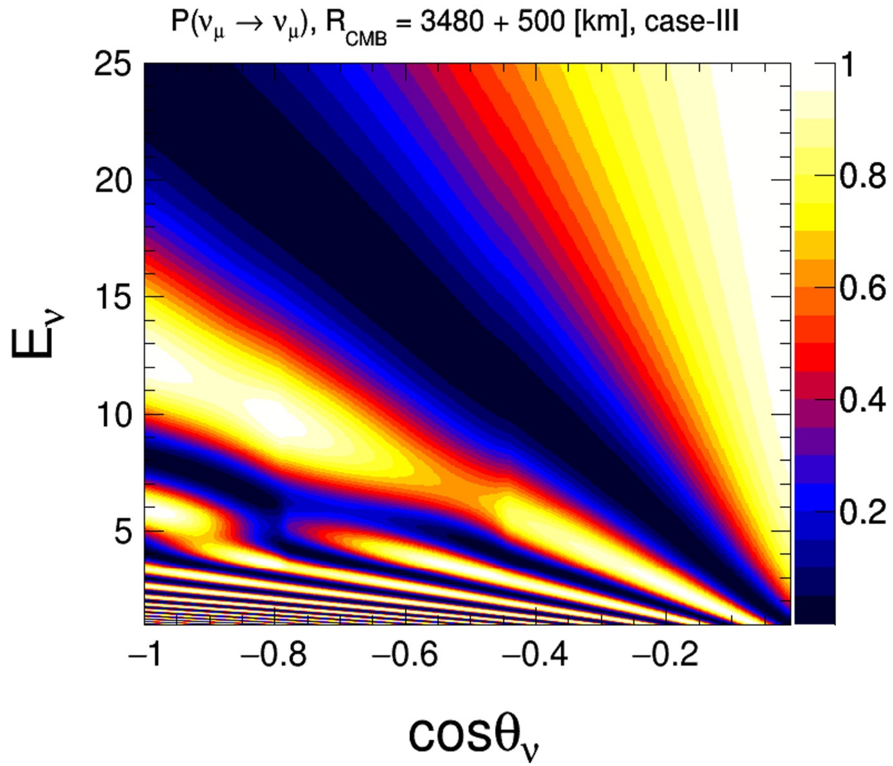
P(νμ → νμ), RCMB = 3480 - 300 [km], case-III
P(νμ → νμ), RCMB = 3480 + 300 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2


P(νμ → νμ), RCMB = 3480 - 400 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

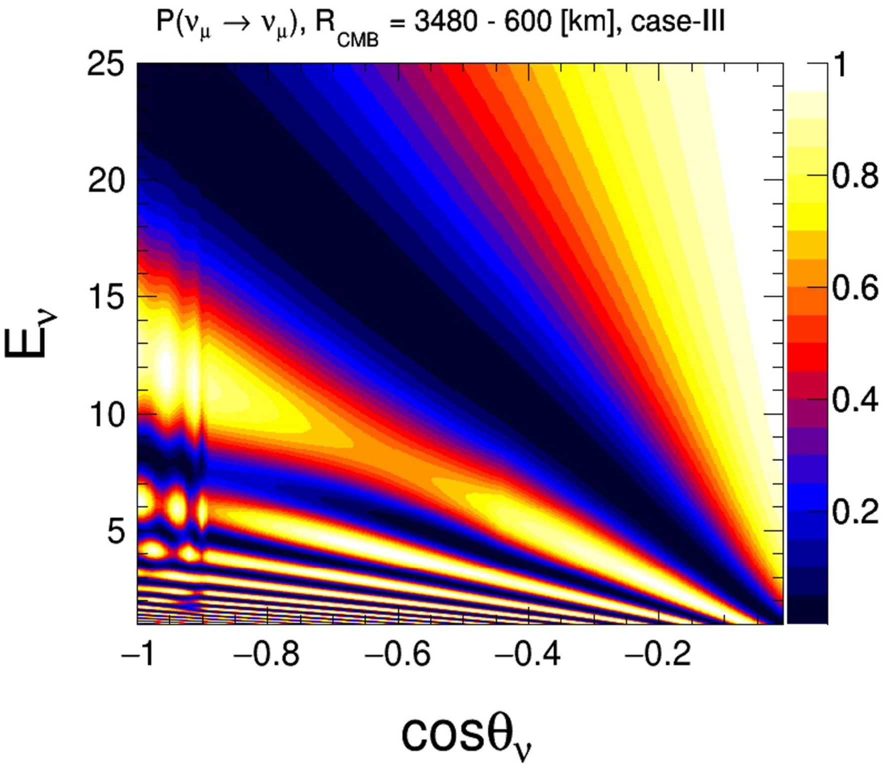

P(νμ → νμ), RCMB = 3480 + 400 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

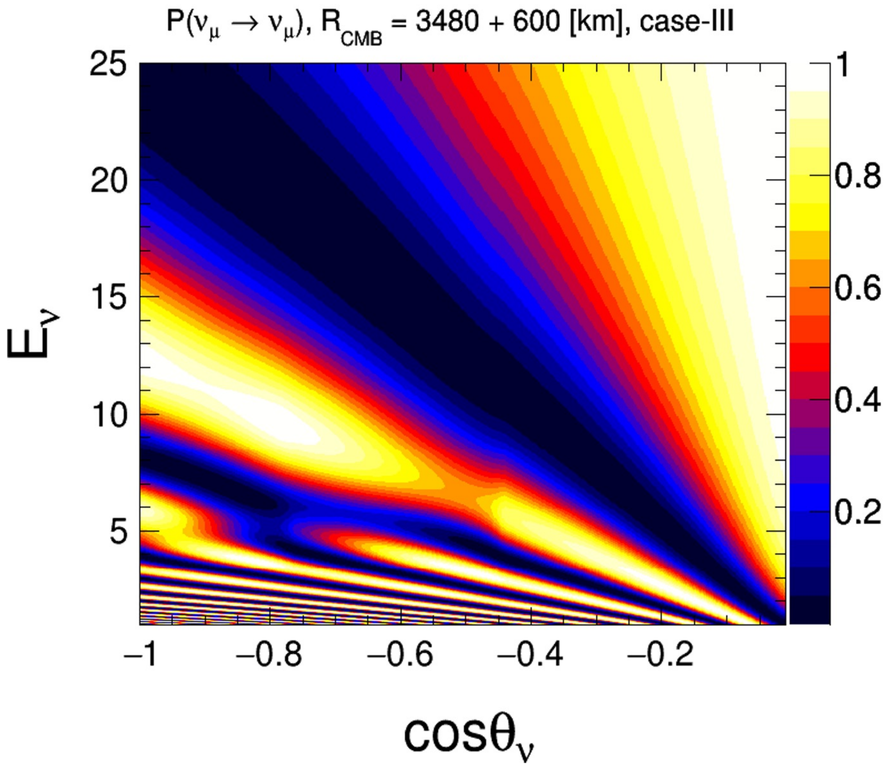


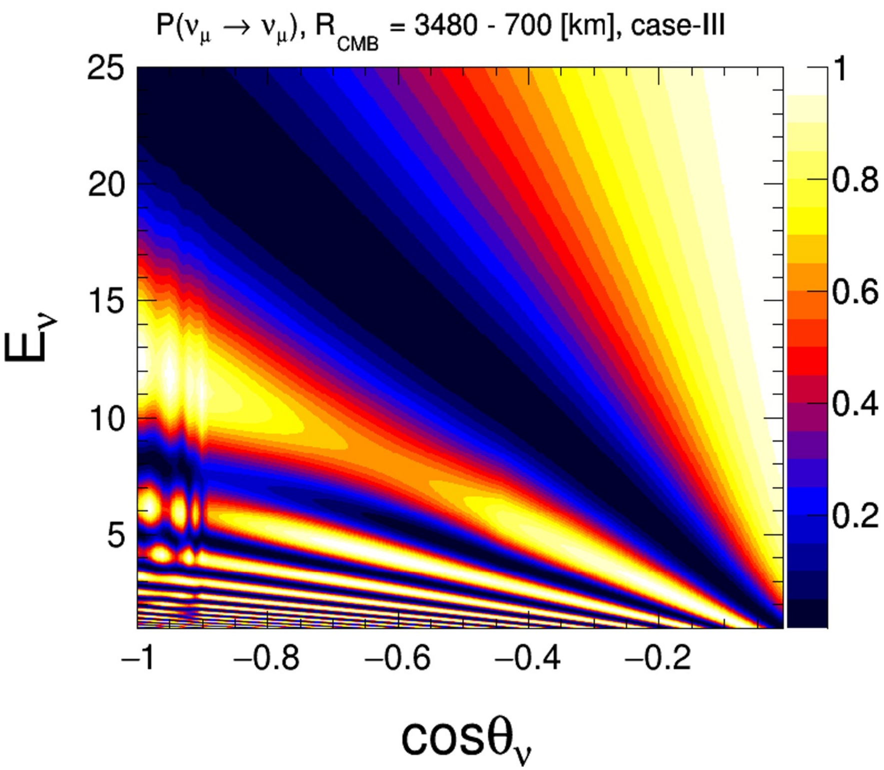
P(νμ → νμ), RCMB = 3480 - 500 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2



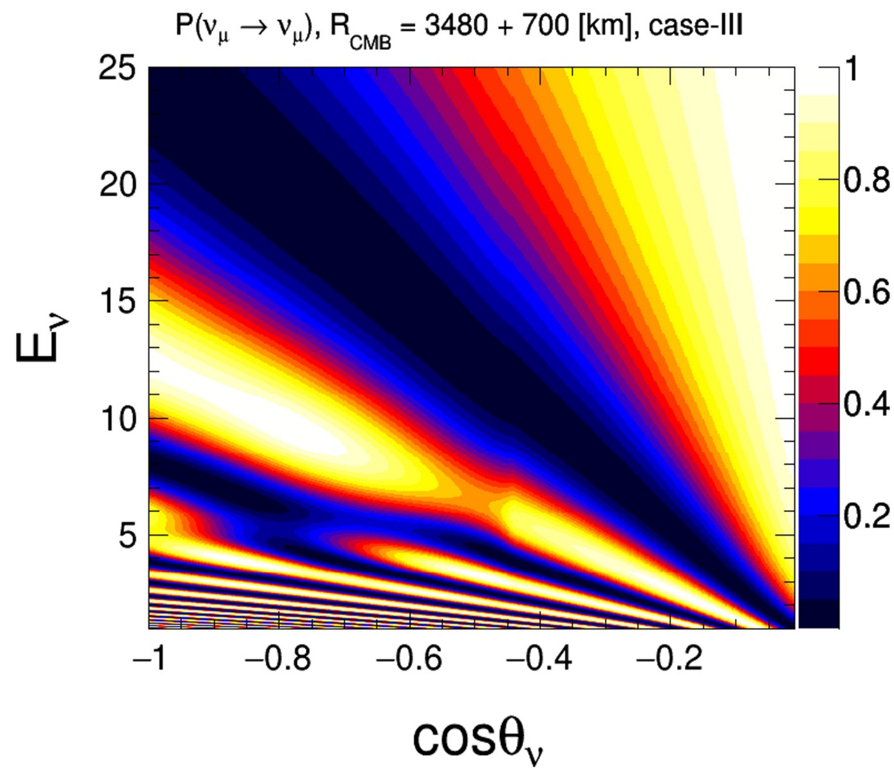
P(νμ → νμ), RCMB = 3480 + 500 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2


P(ν_μ → ν_μ), R_CMB = 3480 - 600 [km], case-III
25
20
15
10
5
E_ν
−1
−0.8
−0.6
−0.4
−0.2
cosθ_ν
1
0.8
0.6
0.4
0.2

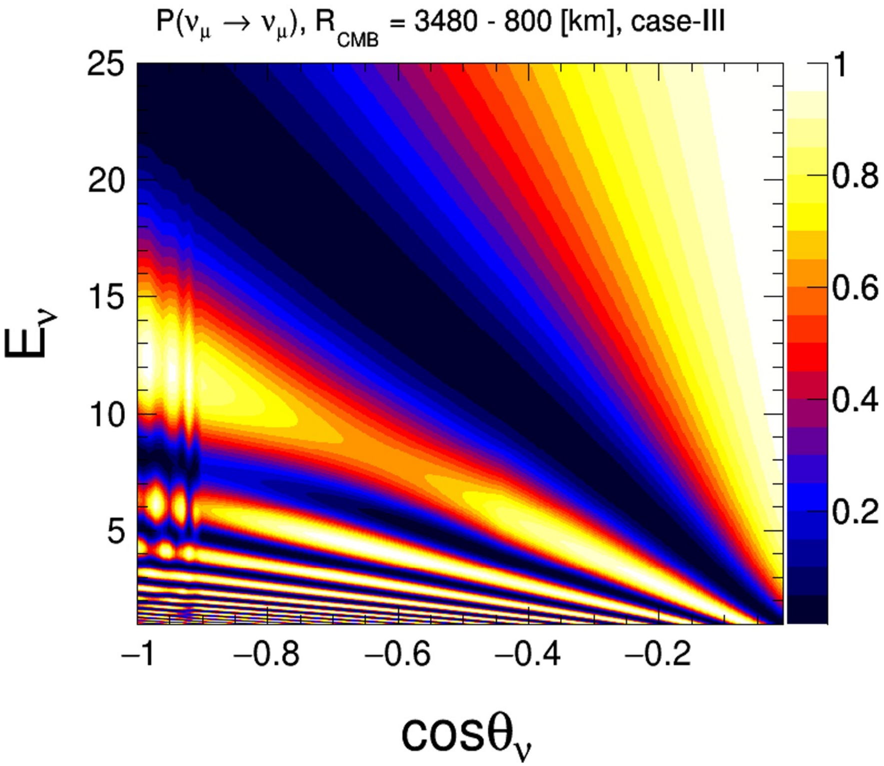

P(ν_μ → ν_μ), R_CMB = 3480 + 600 [km], case-III
25
20
15
10
5
E_ν
−1
−0.8
−0.6
−0.4
−0.2
cosθ_ν
1
0.8
0.6
0.4
0.2



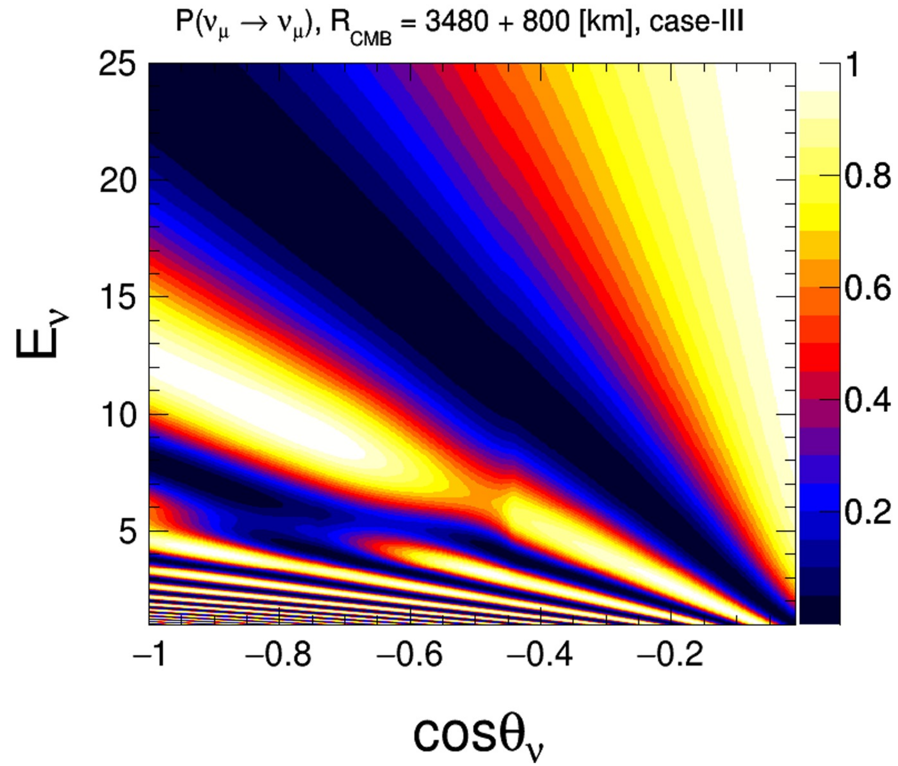
P(ν_μ → ν_μ), R_CMB = 3480 - 700 [km], case-III
25
20
15
10
5
E_ν
−1
−0.8
−0.6
−0.4
−0.2
cosθ_ν
1
0.8
0.6
0.4
0.2



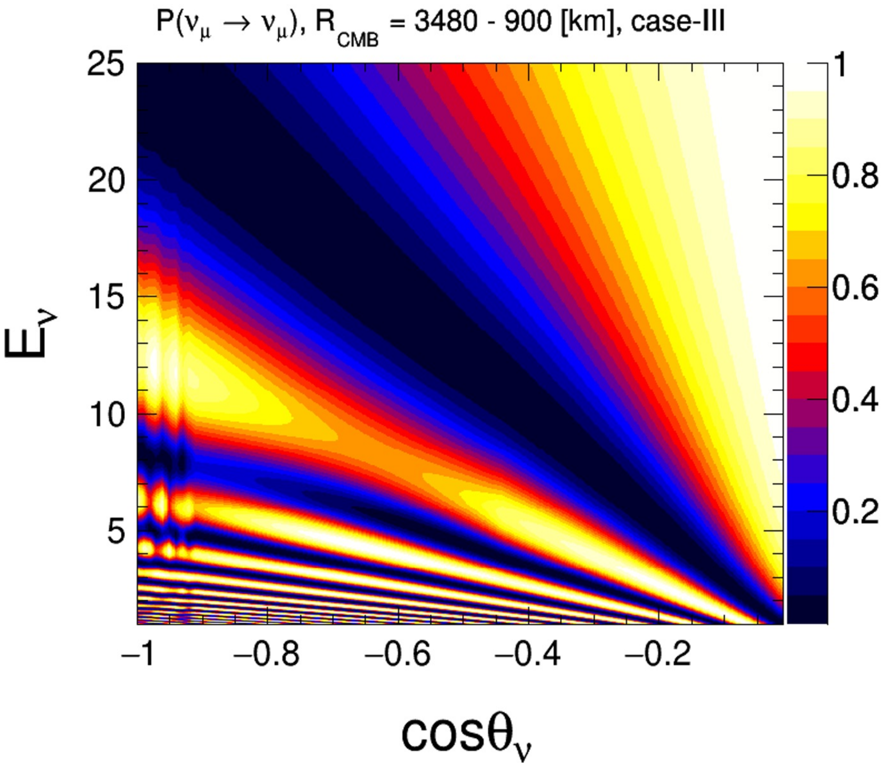
P(ν_μ → ν_μ), R_CMB = 3480 + 700 [km], case-III
25
20
15
10
5
E_ν
−1
−0.8
−0.6
−0.4
−0.2
cosθ_ν
1
0.8
0.6
0.4
0.2

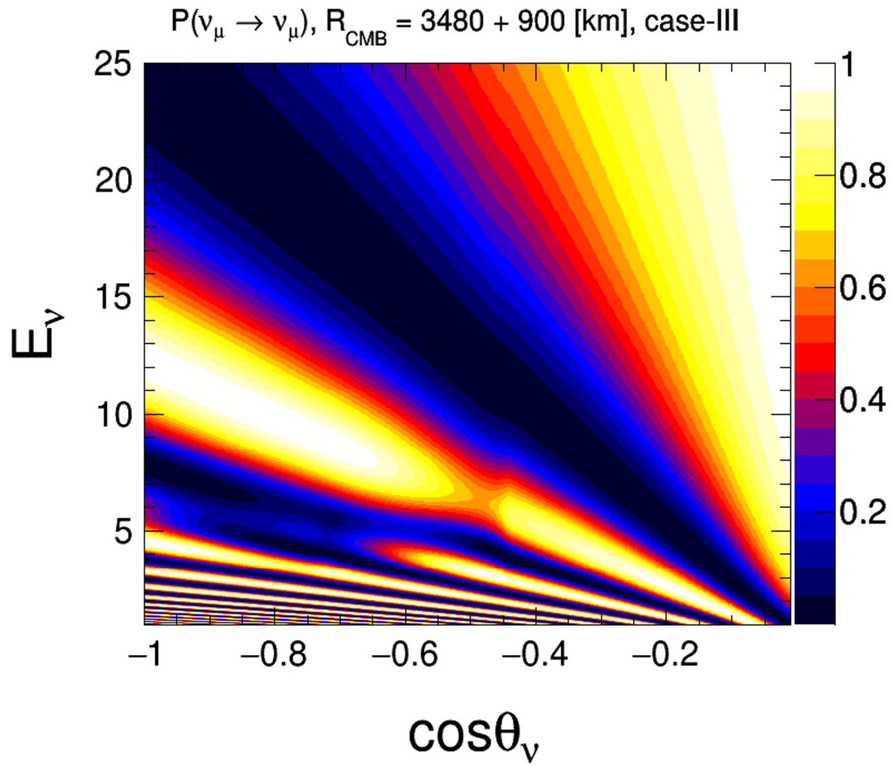


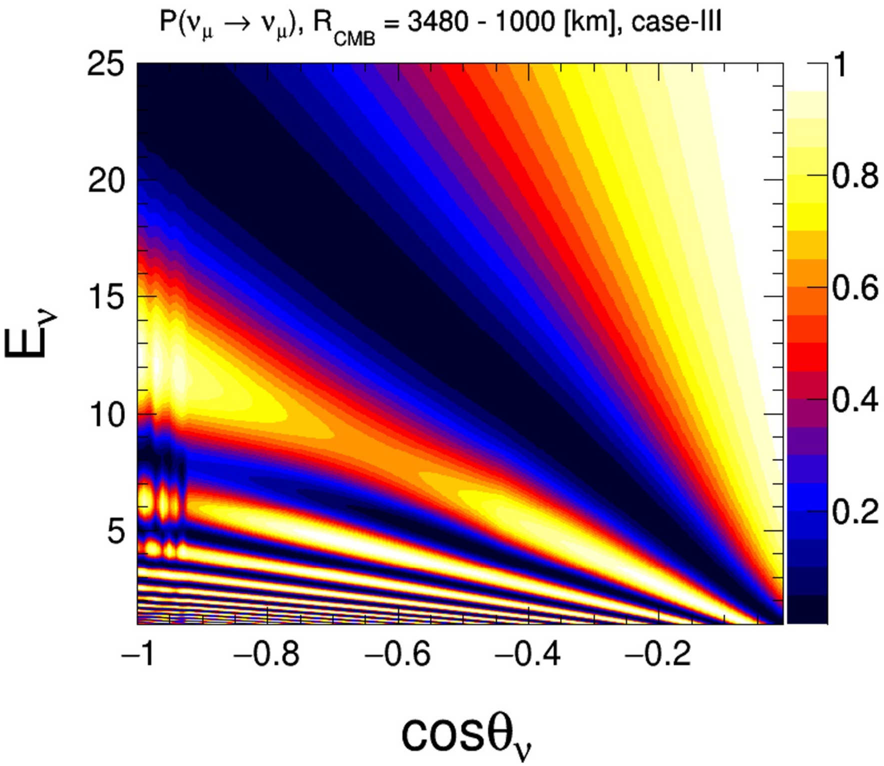
P(νμ → νμ), R_CMB = 3480 - 800 [km], case-III
25
20
15
10
5
Eν
1
0.8
0.6
0.4
0.2
−1
−0.8
−0.6
−0.4
−0.2
cosθν

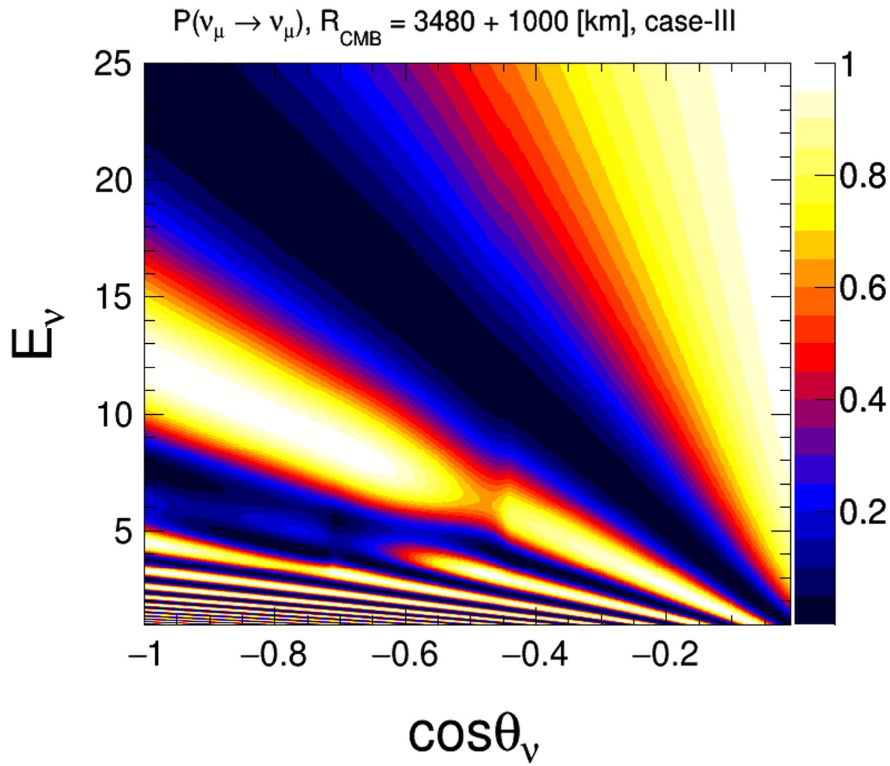


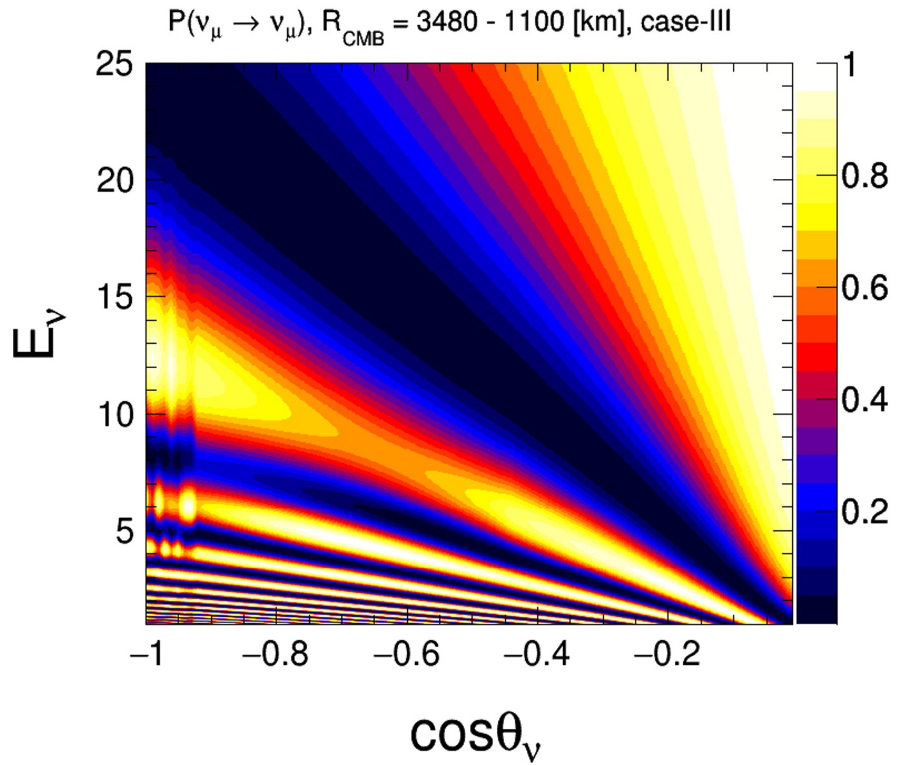
P(νμ → νμ), R_CMB = 3480 + 800 [km], case-III
25
20
15
10
5
Eν
1
0.8
0.6
0.4
0.2
−1
−0.8
−0.6
−0.4
−0.2
cosθν

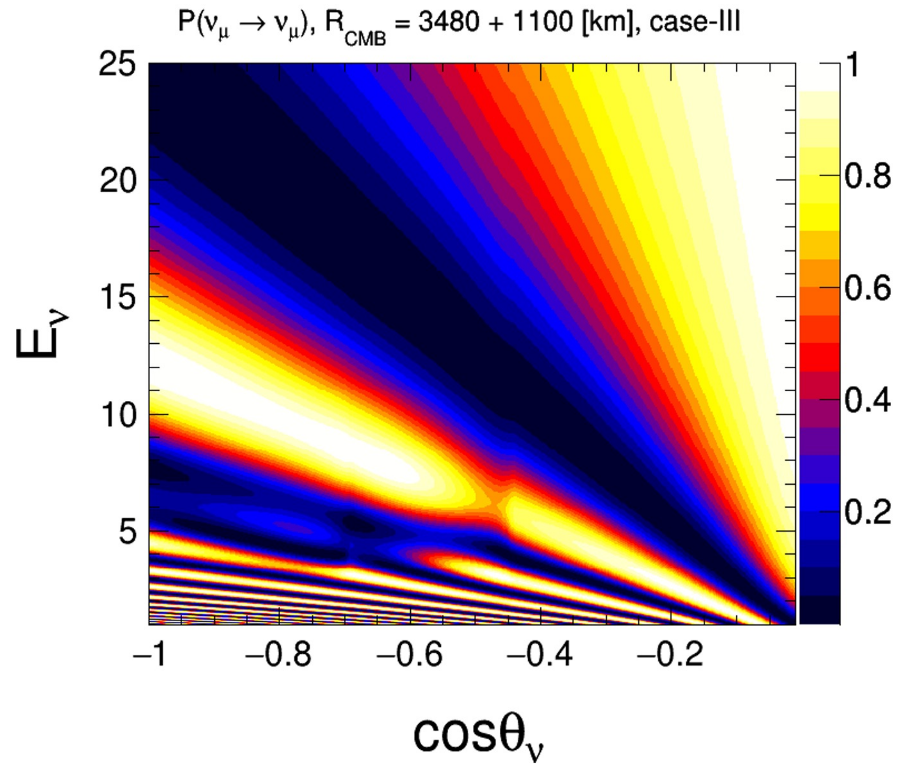

P(νμ → νμ), RCMB = 3480 - 900 [km], case-III
25
20
15
10
5
Eν
–1
–0.8
–0.6
–0.4
–0.2
cosθν
1
0.8
0.6
0.4
0.2

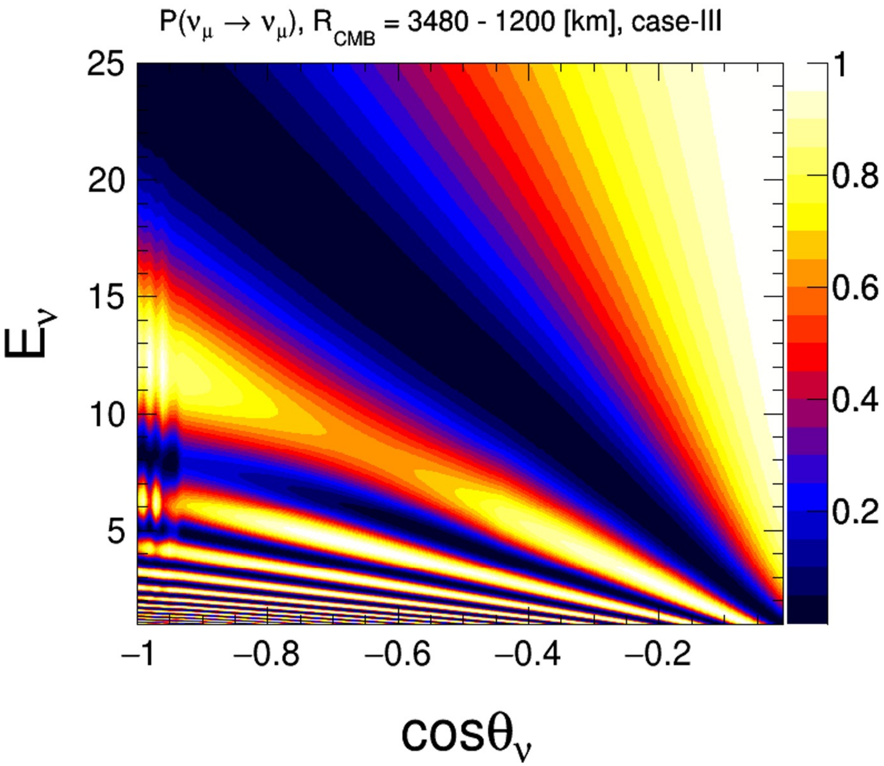

P(νμ → νμ), RCMB = 3480 + 900 [km], case-III
25
20
15
10
5
Eν
–1
–0.8
–0.6
–0.4
–0.2
cosθν
1
0.8
0.6
0.4
0.2

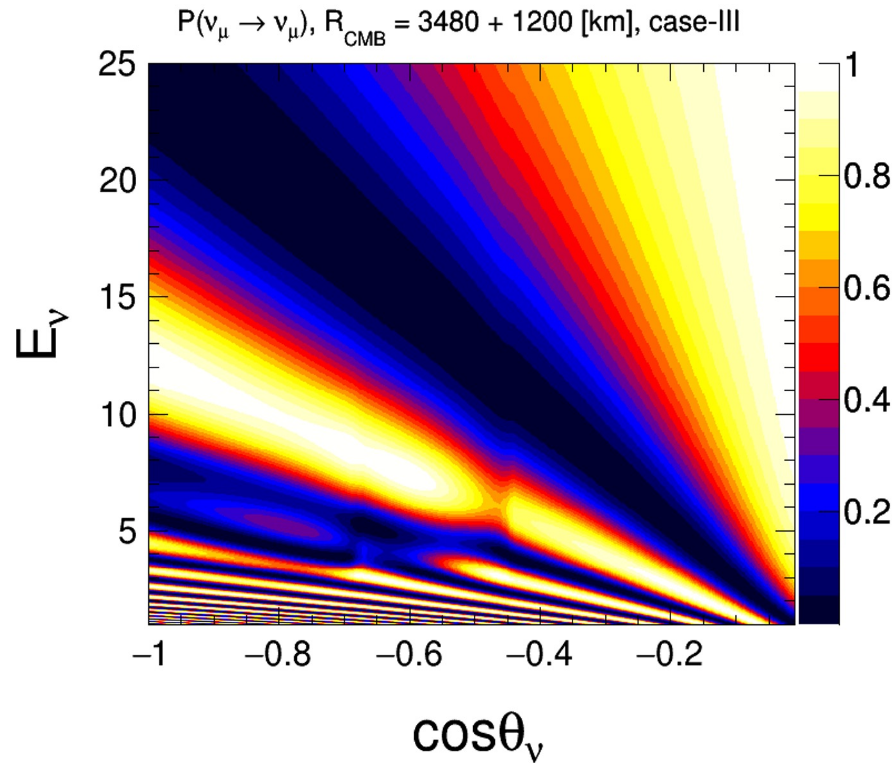

P(νμ → νμ), RCMB = 3480 - 1000 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

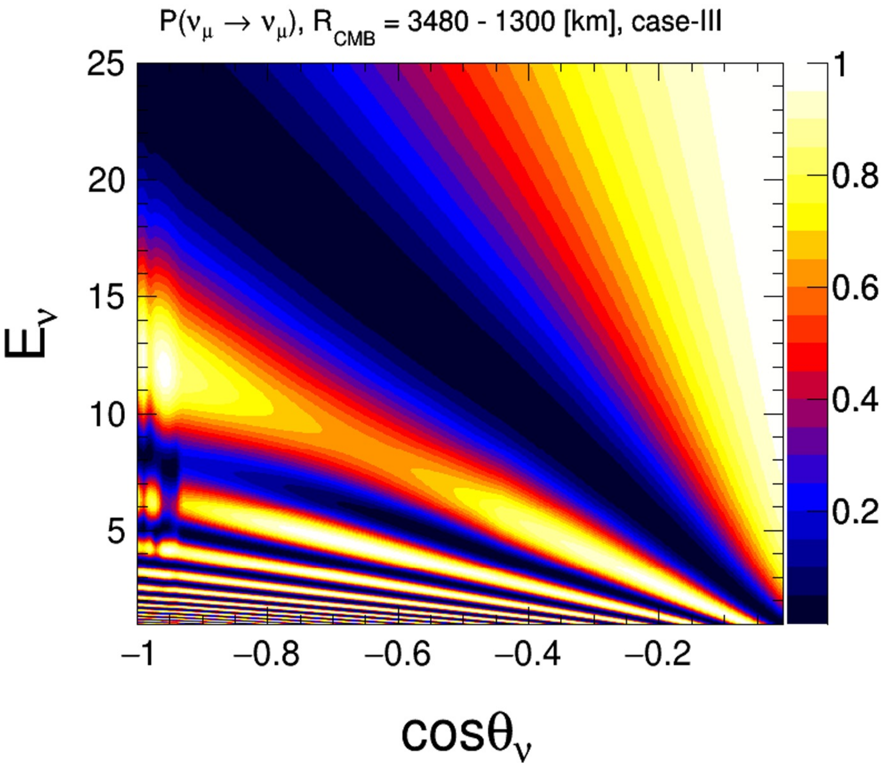

P(νμ → νμ), RCMB = 3480 + 1000 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

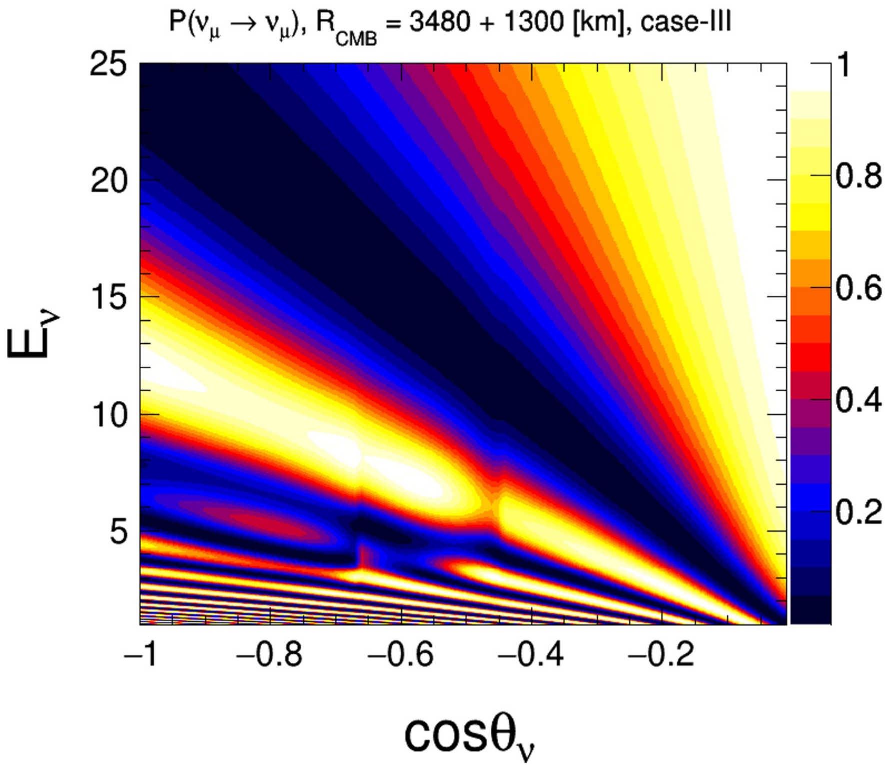

P(νμ → νμ), RCMB = 3480 - 1100 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

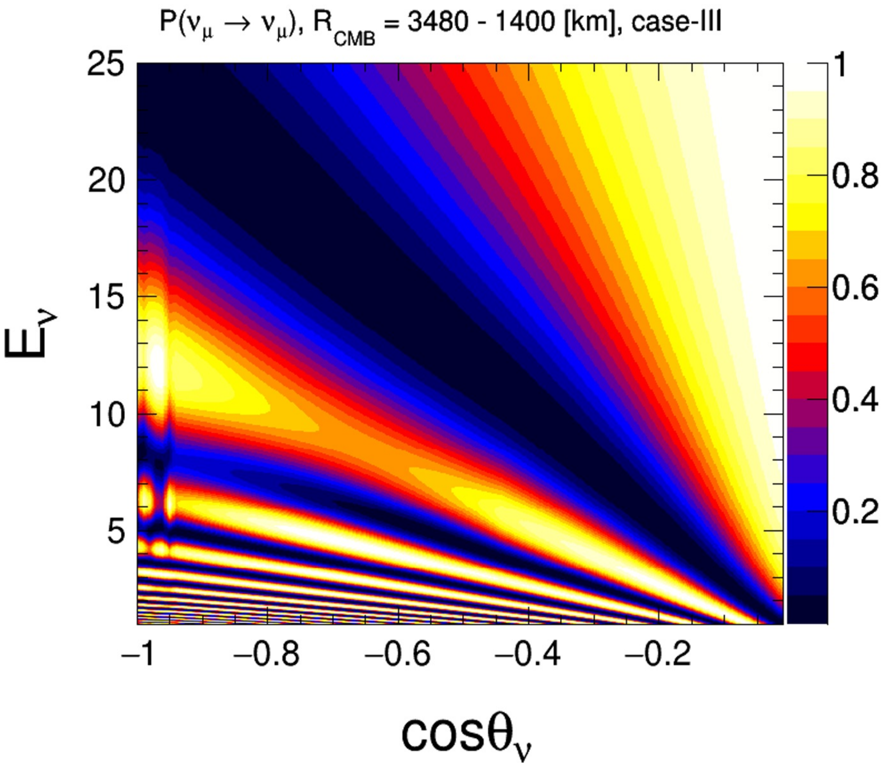

P(νμ → νμ), RCMB = 3480 + 1100 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

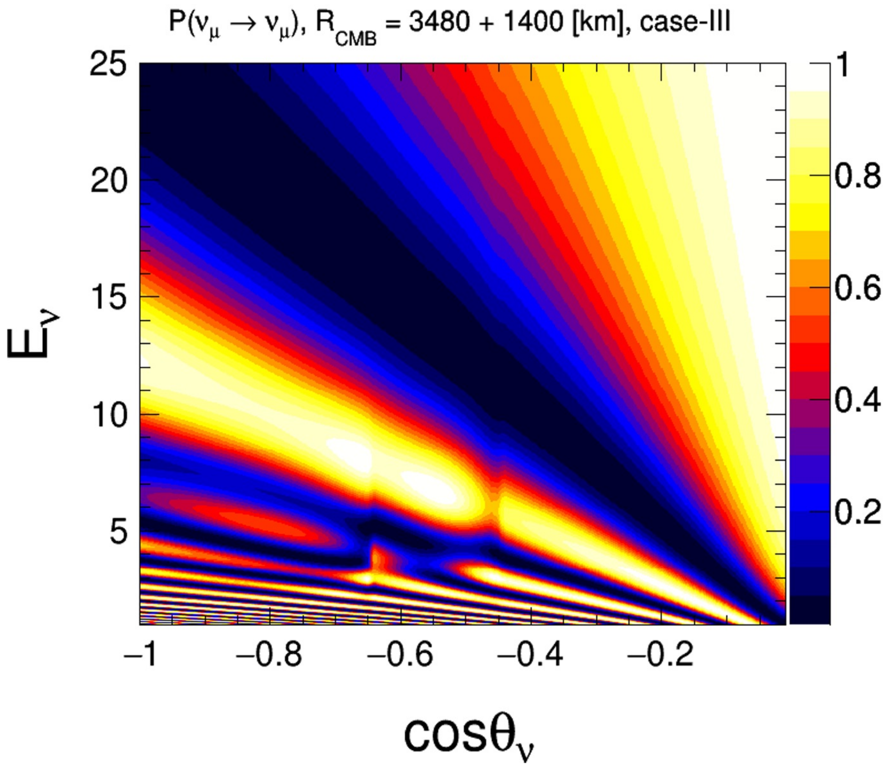

P(νμ → νμ), RCMB = 3480 - 1200 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

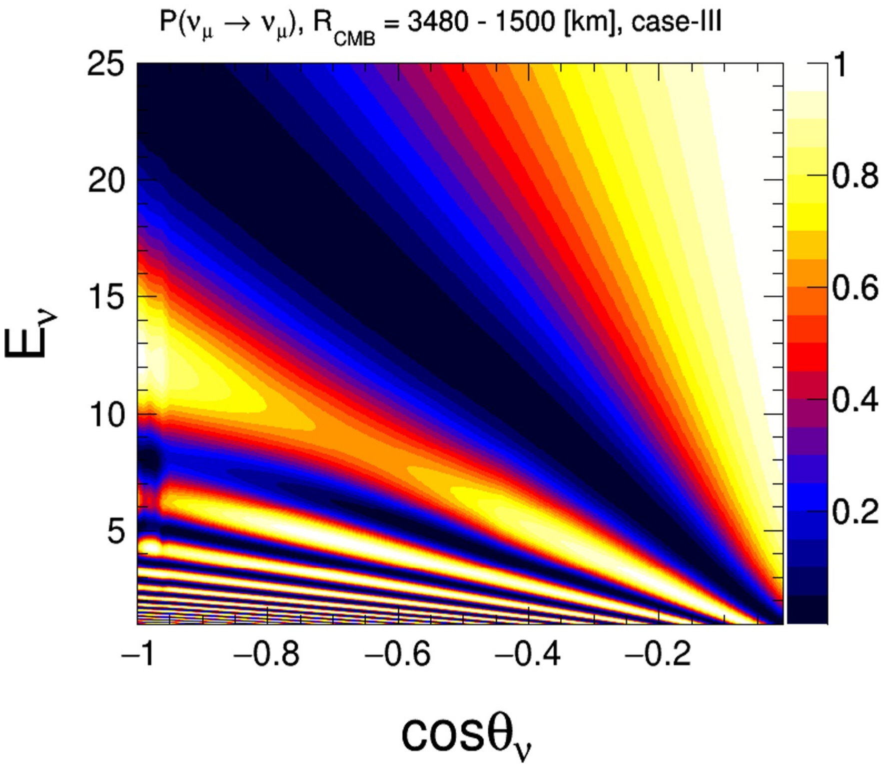

P(νμ → νμ), RCMB = 3480 + 1200 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

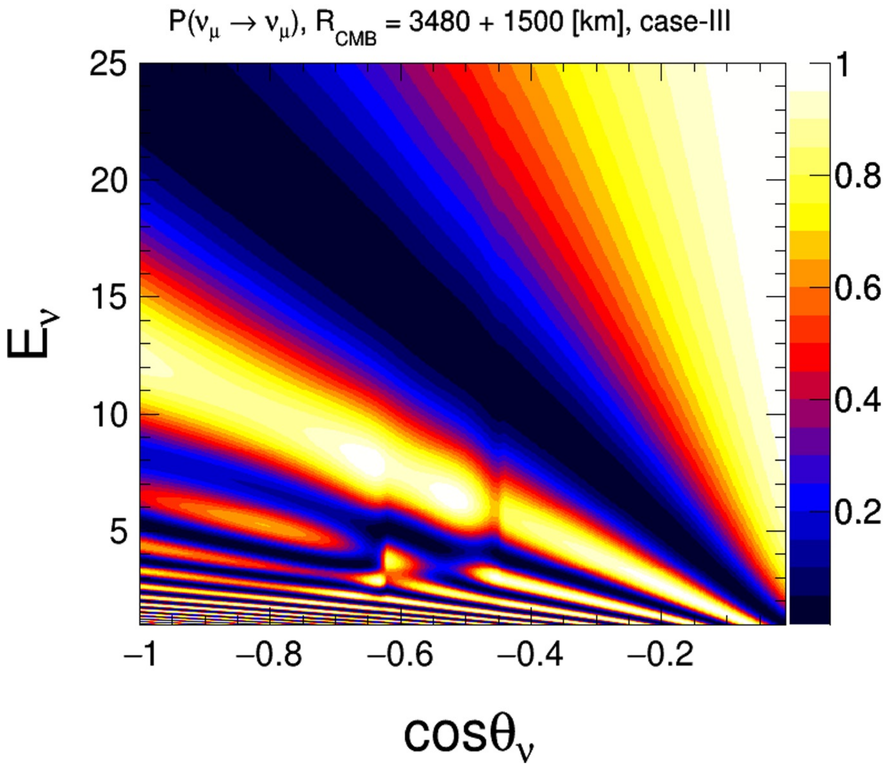

$P(\nu_\mu \to \nu_\mu)$, R_{CMB} = 3480 - 1300 [km], case-III
E_ν
$\cos\theta_\nu$
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

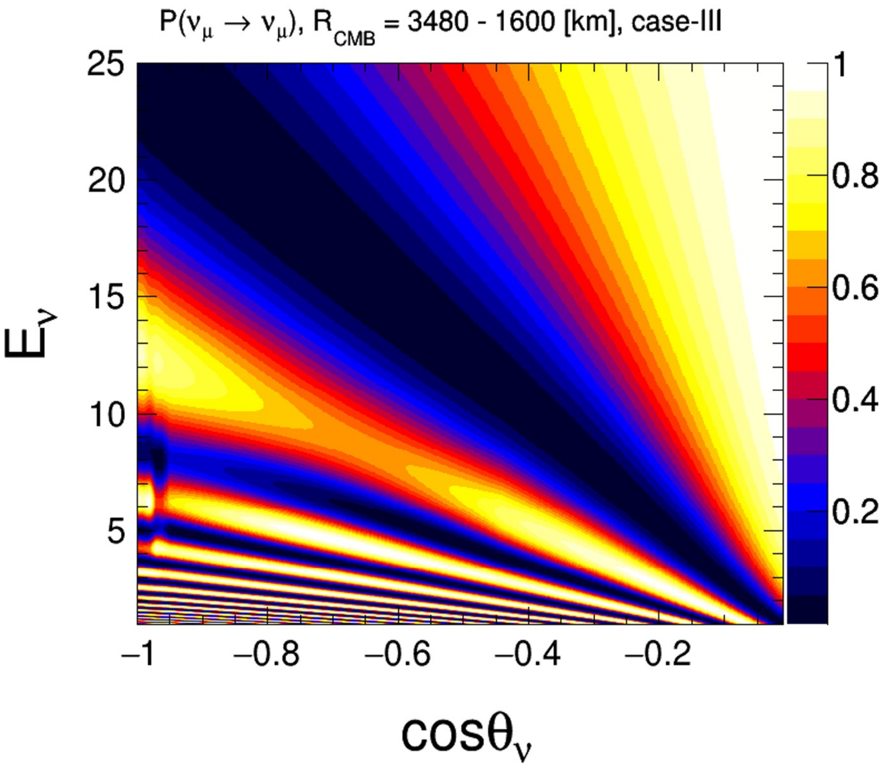

$P(\nu_\mu \to \nu_\mu)$, R_{CMB} = 3480 + 1300 [km], case-III
E_ν
$\cos\theta_\nu$
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2


P(νμ → νμ), R_CMB = 3480 - 1400 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

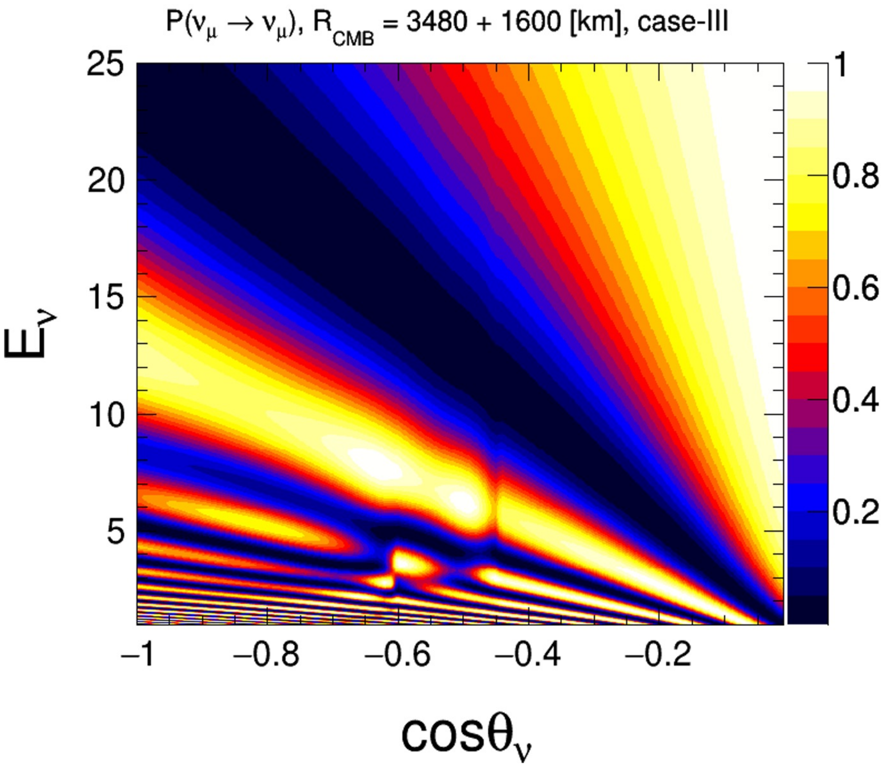

P(νμ → νμ), R_CMB = 3480 + 1400 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2


P(νμ → νμ), RCMB = 3480 - 1500 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

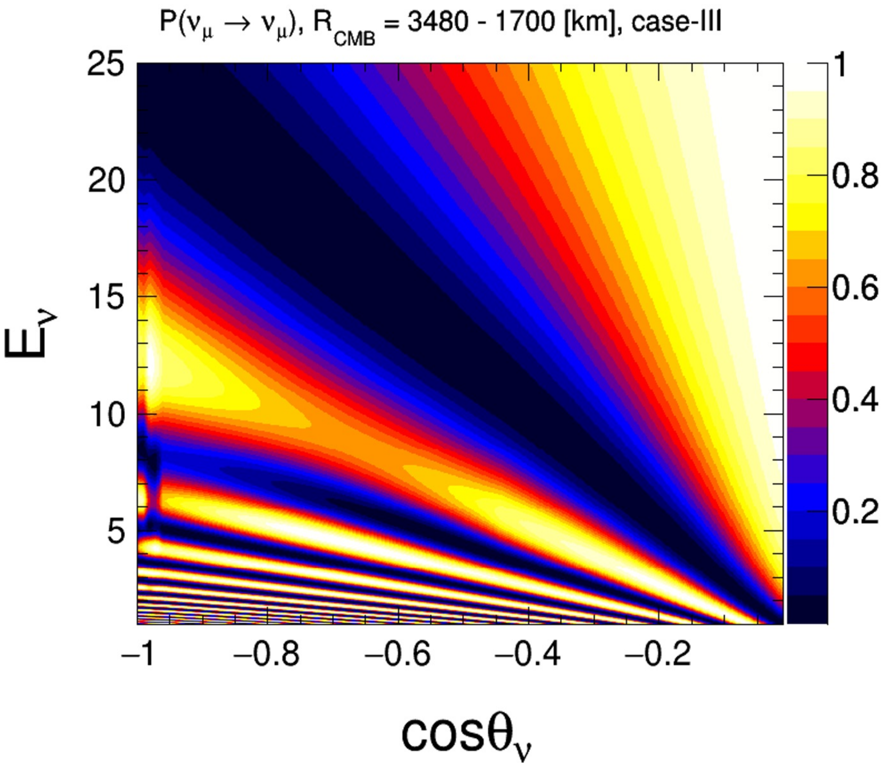

P(νμ → νμ), RCMB = 3480 + 1500 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

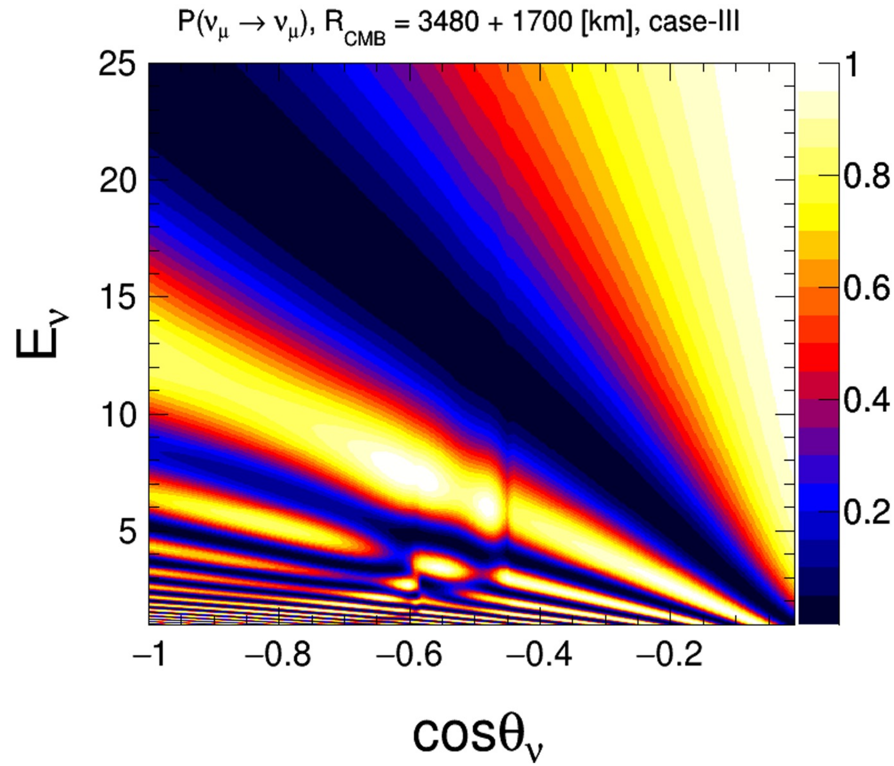


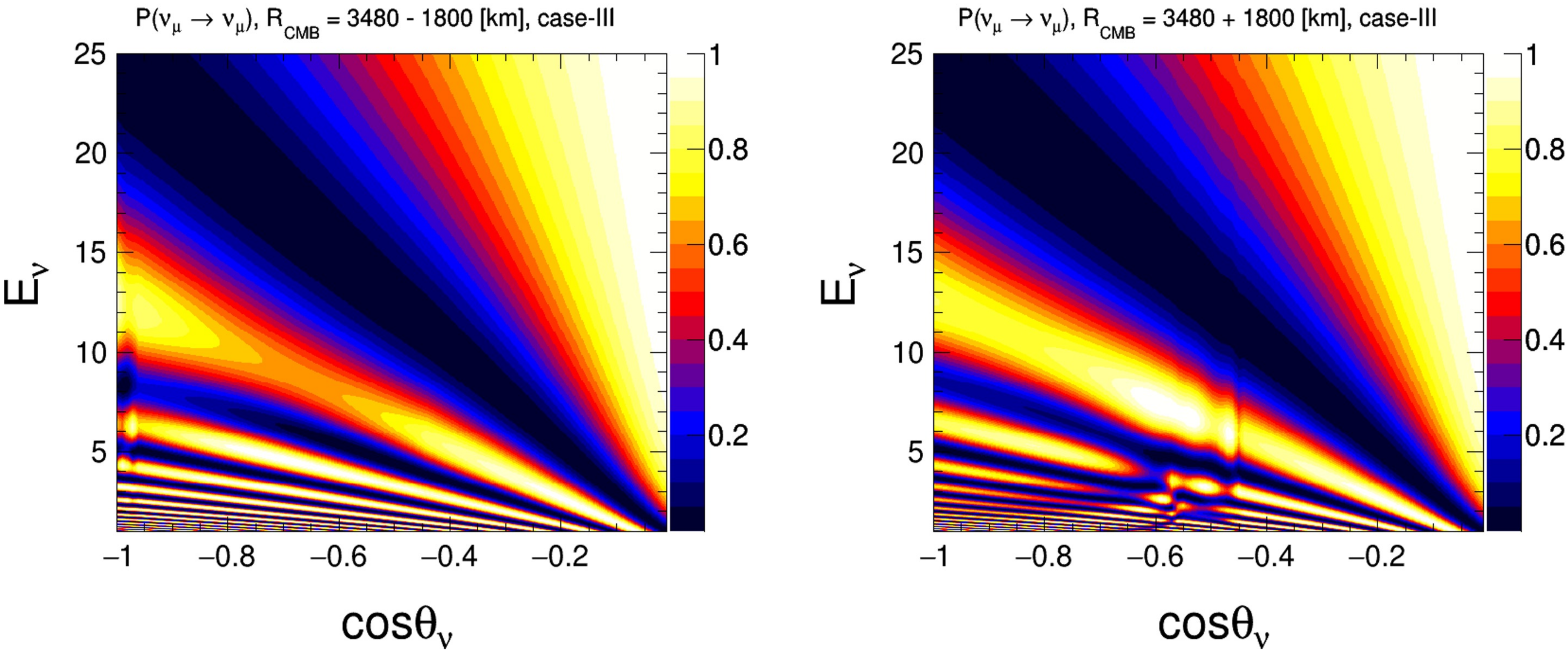
P(νμ → νμ), RCMB = 3480 - 1600 [km], case-III
25
20
15
10
5
Eν
1
0.8
0.6
0.4
0.2
−1
−0.8
−0.6
−0.4
−0.2
cosθν

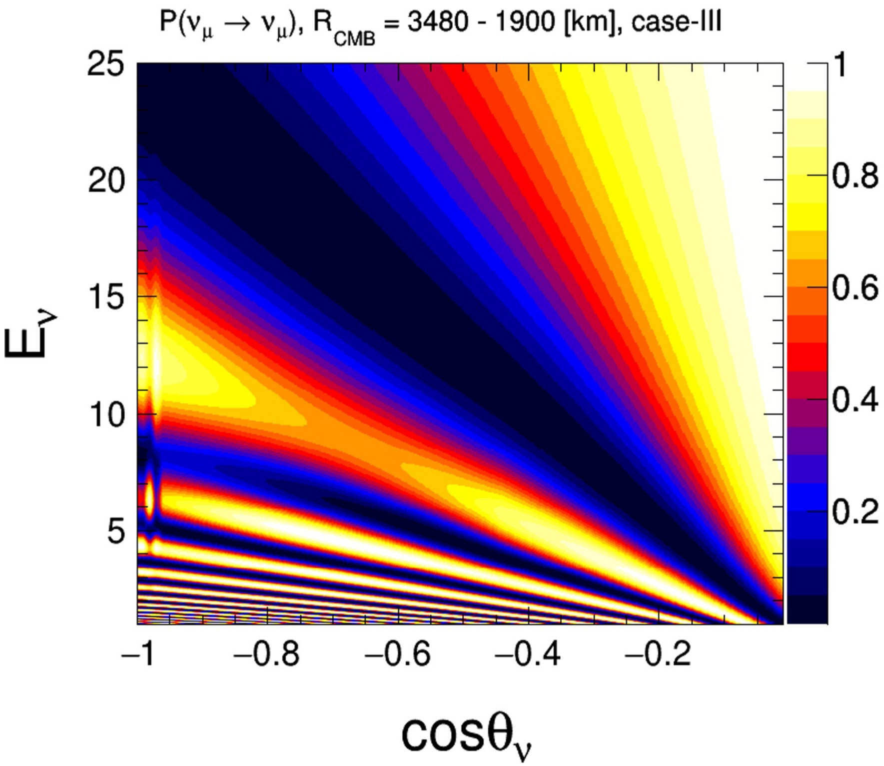


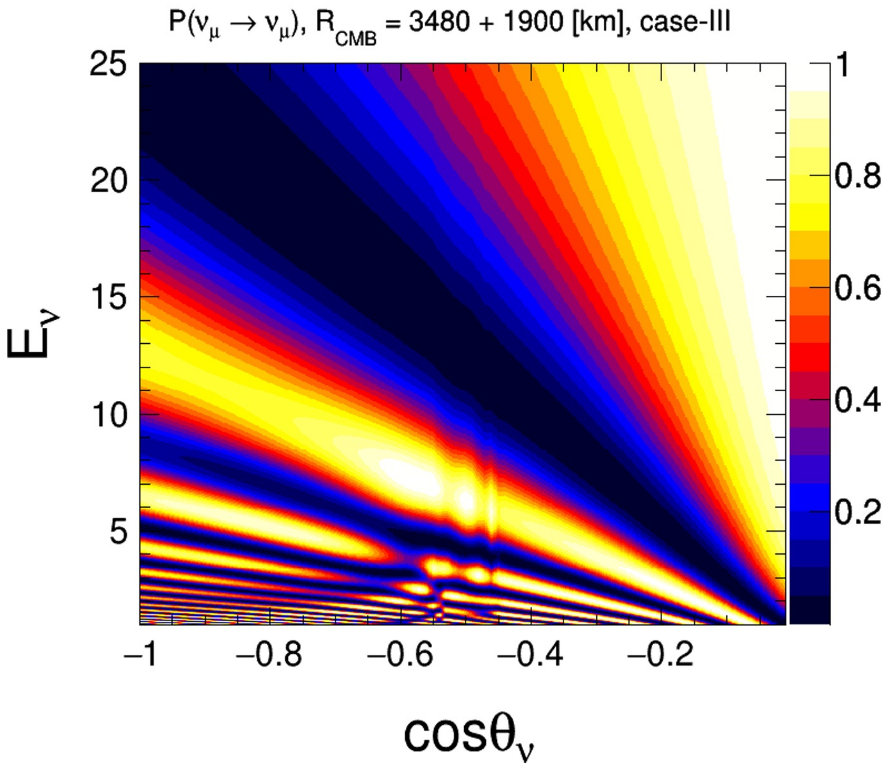
P(νμ → νμ), RCMB = 3480 + 1600 [km], case-III
25
20
15
10
5
Eν
1
0.8
0.6
0.4
0.2
−1
−0.8
−0.6
−0.4
−0.2
cosθν

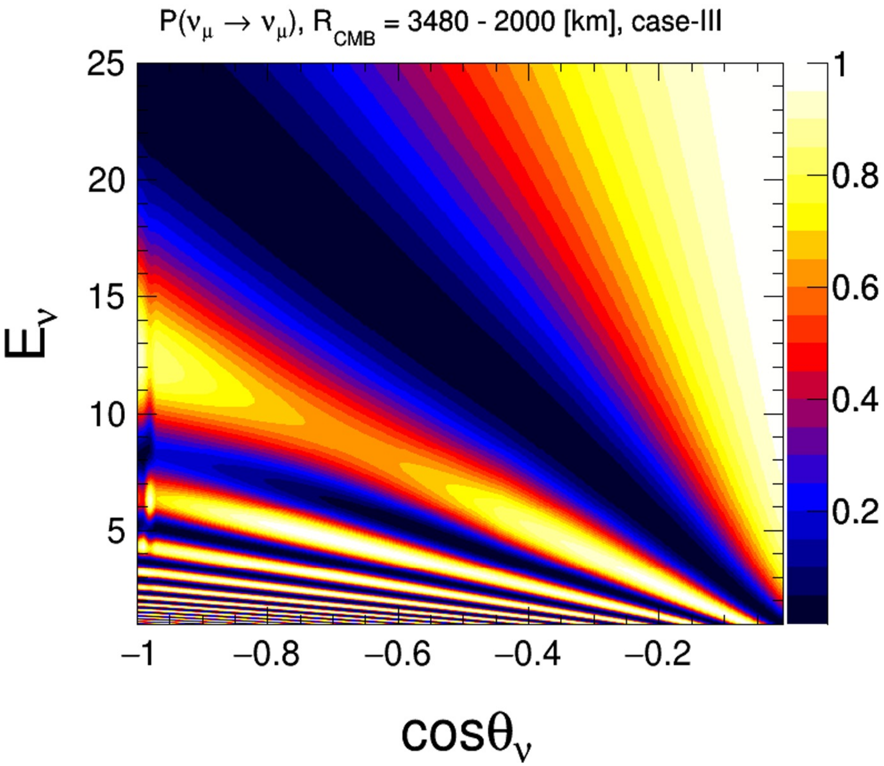

P(νμ → νμ), RCMB = 3480 - 1700 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2

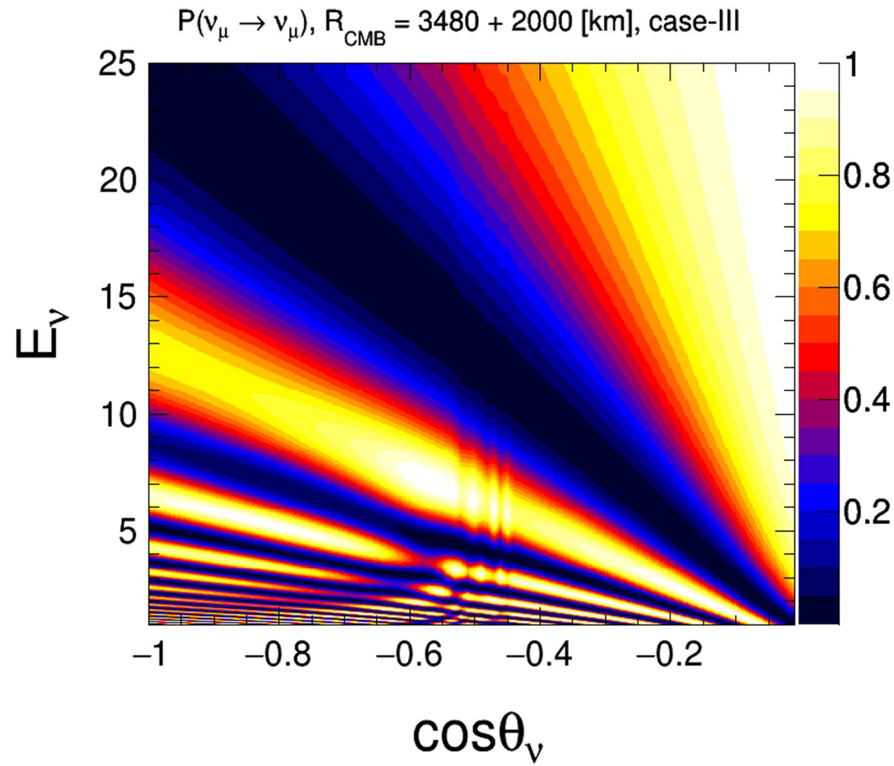

P(νμ → νμ), RCMB = 3480 + 1700 [km], case-III
Eν
cosθν
25
20
15
10
5
−1
−0.8
−0.6
−0.4
−0.2
1
0.8
0.6
0.4
0.2


P(νμ → νμ), R_CMB = 3480 - 1800 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2
P(νμ → νμ), R_CMB = 3480 + 1800 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2


$P(\nu_\mu \to \nu_\mu)$, R_{CMB} = 3480 - 1900 [km], case-III
E_ν
25
20
15
10
5
–1
–0.8
–0.6
–0.4
–0.2
$\cos\theta_\nu$
1
0.8
0.6
0.4
0.2


$P(\nu_\mu \to \nu_\mu)$, R_{CMB} = 3480 + 1900 [km], case-III
E_ν
25
20
15
10
5
–1
–0.8
–0.6
–0.4
–0.2
$\cos\theta_\nu$
1
0.8
0.6
0.4
0.2


P(νμ → νμ), RCMB = 3480 - 2000 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2


P(νμ → νμ), RCMB = 3480 + 2000 [km], case-III
25
20
15
10
5
Eν
−1
−0.8
−0.6
−0.4
−0.2
cosθν
1
0.8
0.6
0.4
0.2

Conference Proceedings and Whitepaper

There will be conference proceedings for MMTE 2022

Details are given on the webpage

We had an intense discussion on the possibility of writing a whitepaper based on the outcome of this workshop

We need your comments/feedbacks/opinions

Your participation and contribution are needed to make this happen!

Thank you