Atmospheric neutrinos in ESSnuSB

and muons too!

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1st ESSnuSB+ WP5 in-person workshop

Kalamata, Greece

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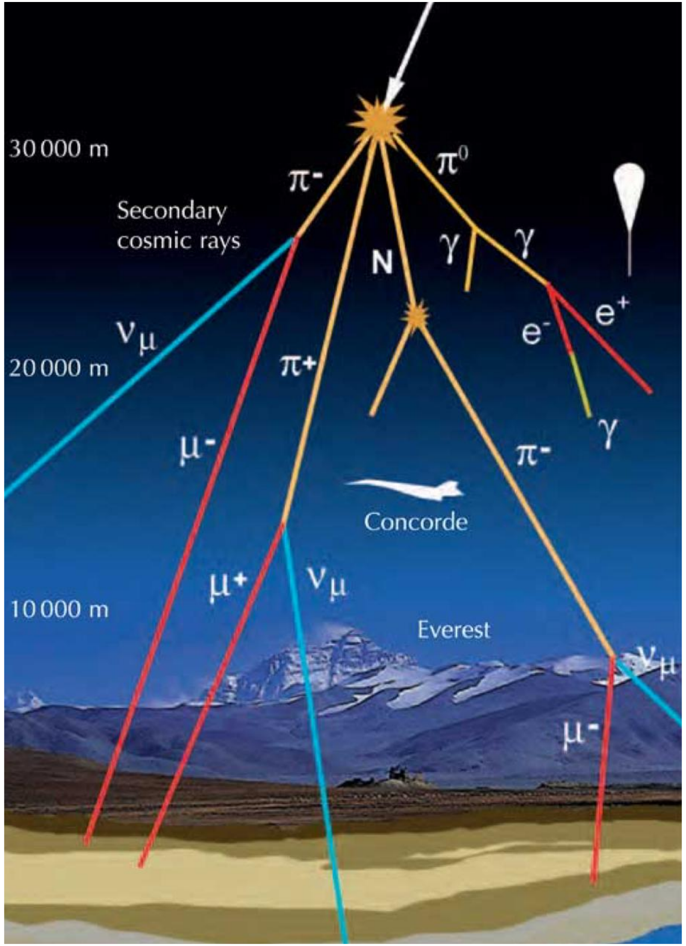
What are atmospheric neutrinos?

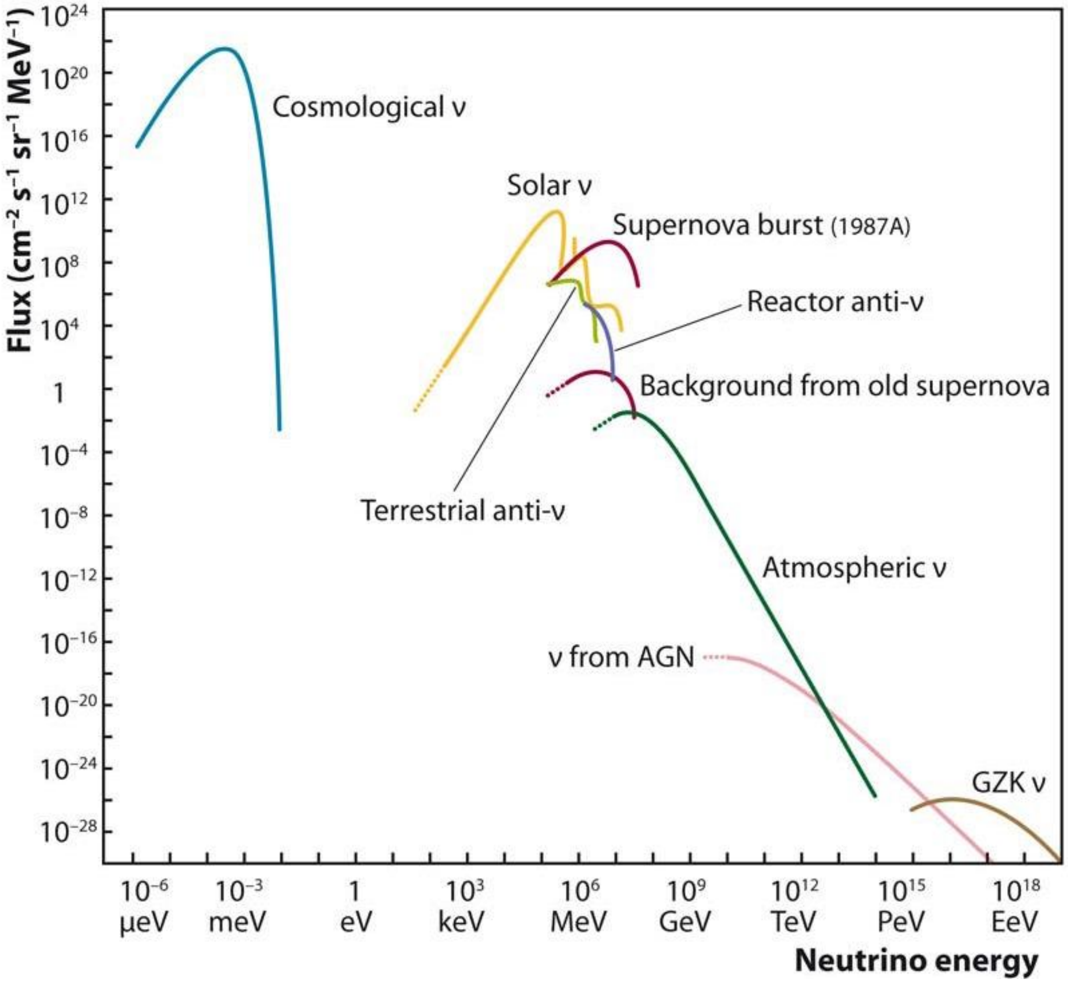
- Born when cosmic rays interact with atmosphere
- Wide range of energies: 0.1 – 10 TeV
- Produced around atmosphere



Production processes:

$$\boldsymbol{p},\ \boldsymbol{A} + \text{air}$$
$$\rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}$$
$$\rightarrow \mu^{\pm}, \nu_{\mu}, \bar{\nu}_{\mu}$$
$$\rightarrow e^{\pm},\ \nu_{e}, \bar{\nu}_{e},$$
$$\nu_{\mu}, \bar{\nu}_{\mu}$$

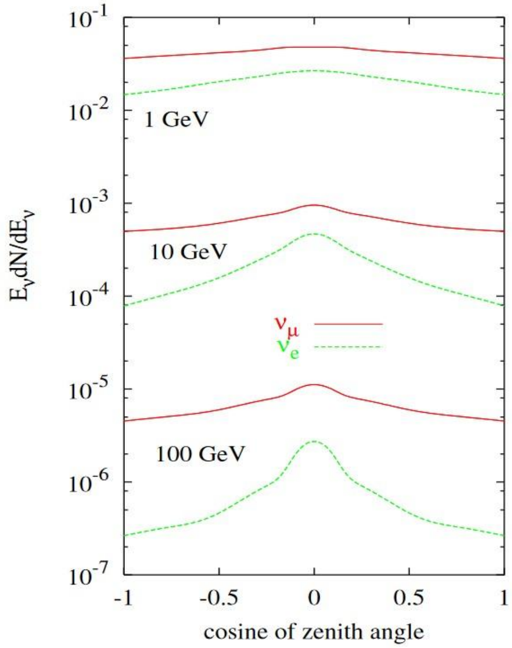
$$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+}\bar{\nu}_{\mu}\nu_{e}$$

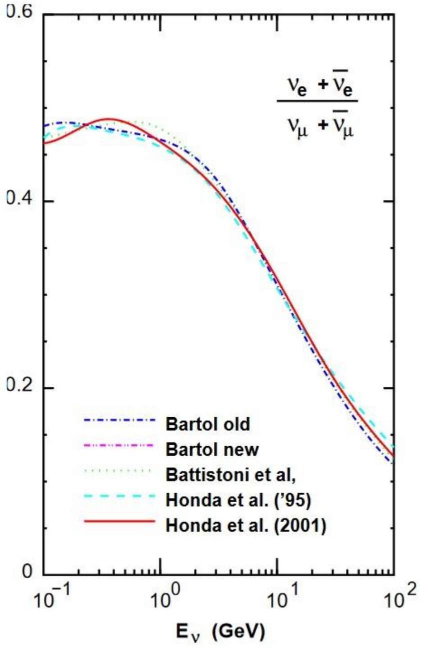


http://www.aspera-eu.org/

What is there to know about atmospheric fluxes?

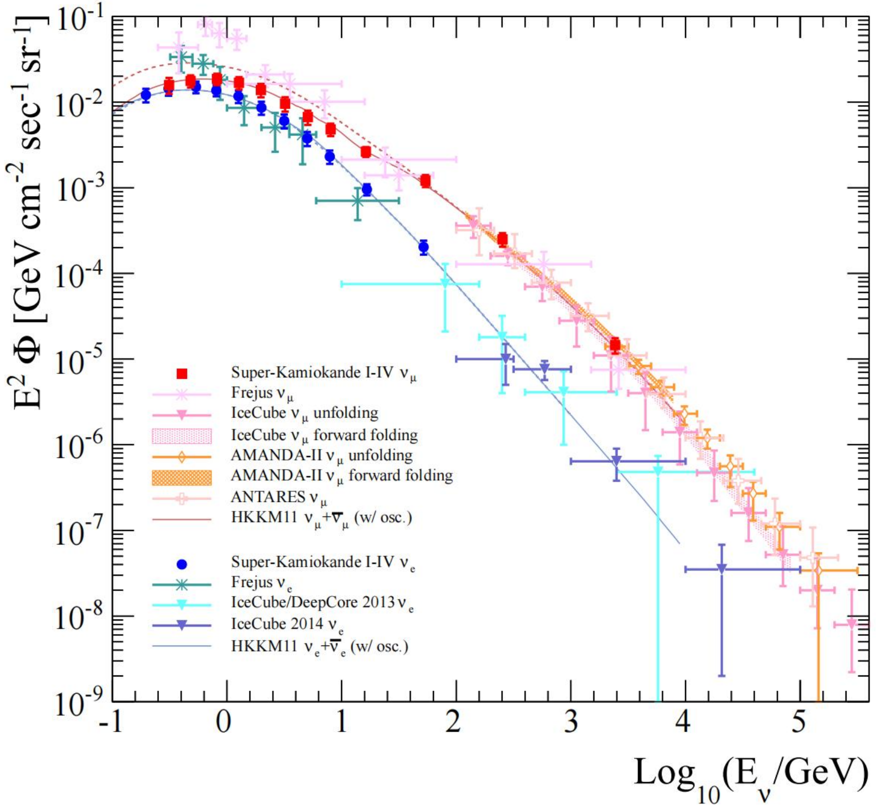
- Produced at about 15 km
- Up-down symmetric flux
- Average flux ~ 1 per min per cm^2
- Energies 100 MeV to 10 TeV
- Muon-to-electron neutrino ratio well known, ~2:1 at low energies



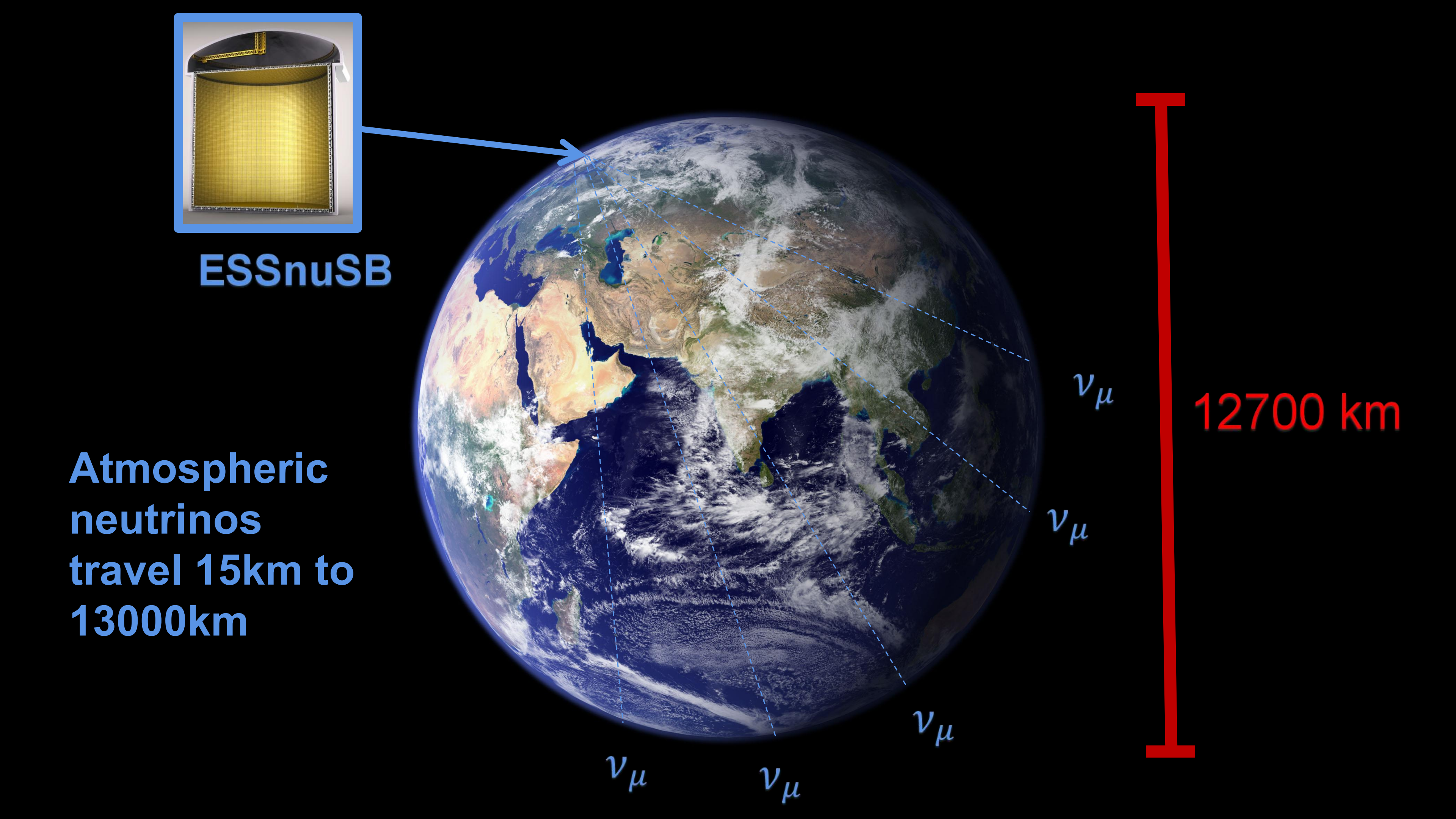


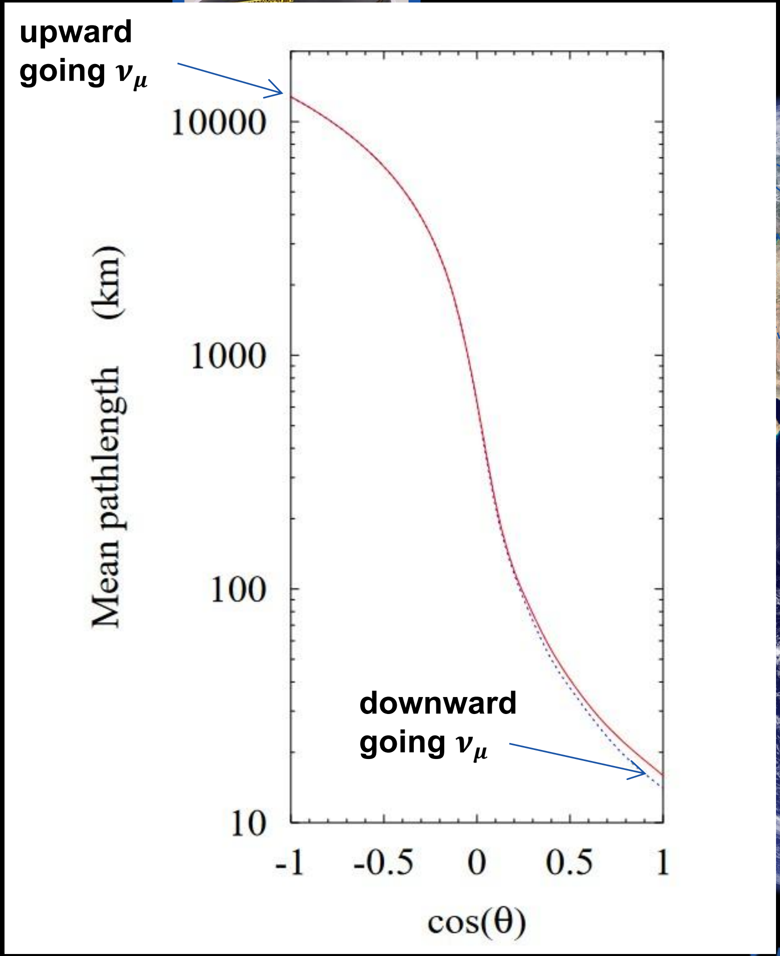
Phys.Rev.D 94 (2016) 5, 052001

What is there to know about atmospheric fluxes?

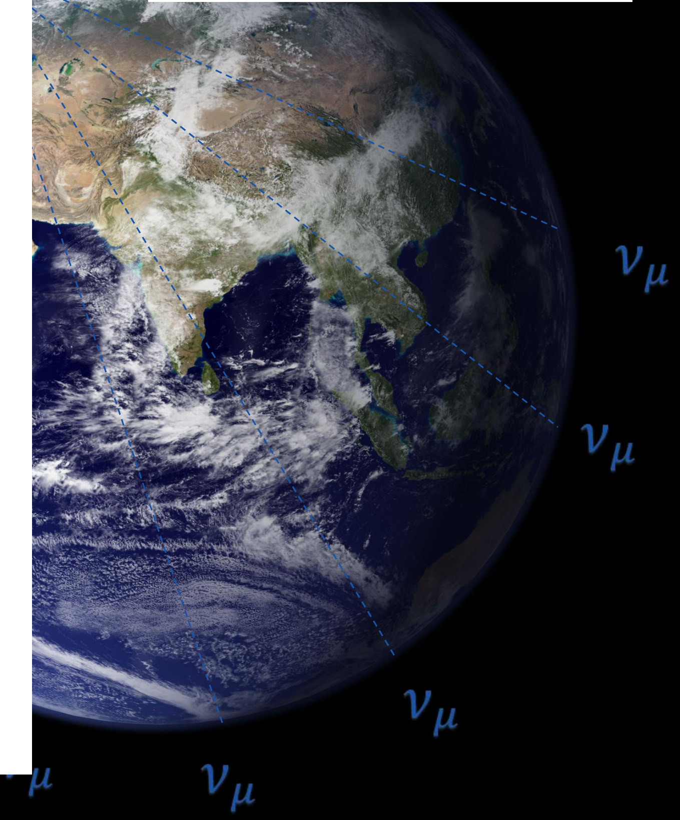


Phys.Rev.D 94 (2016) 5, 052001


ESSnuSB
Atmospheric neutrinos travel 15km to 13000km
12700 km
ν_μ
ν_μ
ν_μ
ν_μ
ν_μ



Traveled distance depends on the zenith angle



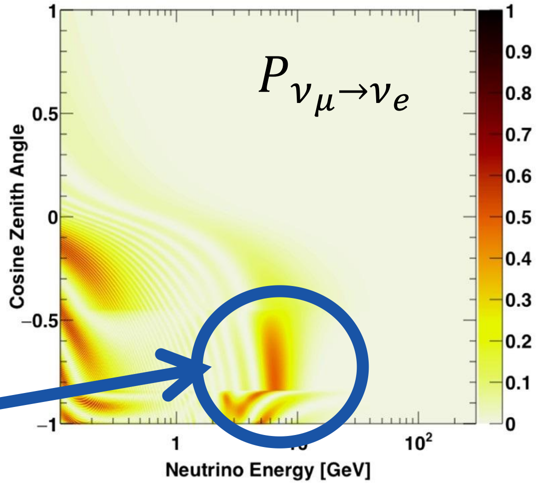
Oscillograms

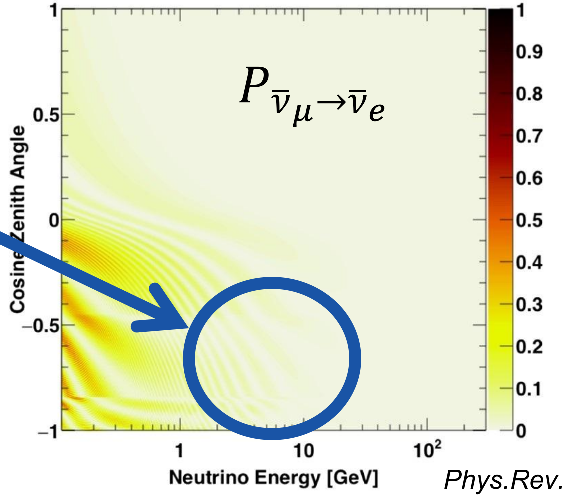
Sensitivities to mass hierarchy and CPV:

Enhanced ν_e appearance in normal hierarchy

No such effect for antineutrinos!

If hierarchy is IH, these patterns are inverted.



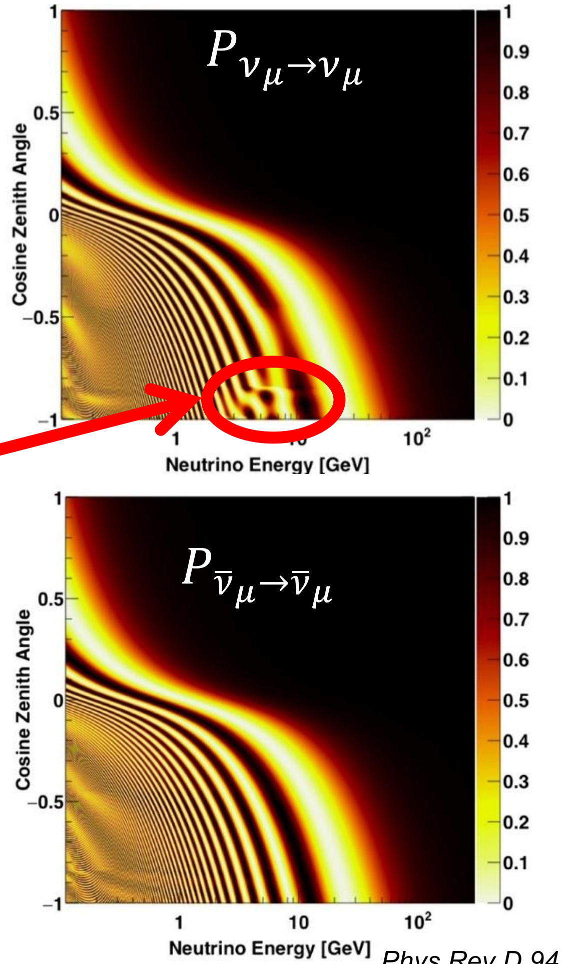


Phys.Rev.D 94 (2016) 5, 052001

Oscillograms

Sensitivities to mass hierarchy and CPV:

Distortions in ν_μ disappearance



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If hierarchy is IH, these patterns are inverted.

Oscillation probabilities

Two-neutrino oscillations:

Need to adjust this for maximal ν_e appearance

$$P_{\nu_\mu \to \nu_e}(E_\nu,\ L) \ \cong \sin^2\theta_{23}\sin^2\theta_{13}^m \sin^2\left(1.27\frac{L}{E_\nu}(\Delta m_{31}^2)^m\right)$$

Effective parameters

$$\sin^2\theta_{13}^m \ = \ \frac{\sin^2 2\theta_{13}\,(\Delta m_{31}^2)^2}{(\Delta m_{31}^2\cos 2\theta_{13} - A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$$

$$(\Delta m_{31}^2)^m = \sqrt{(\Delta m_{31}^2\cos 2\theta_{13} - A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$$

Oscillation probabilities

Two-neutrino oscillations:

Need to adjust this for maximal ν_e appearance

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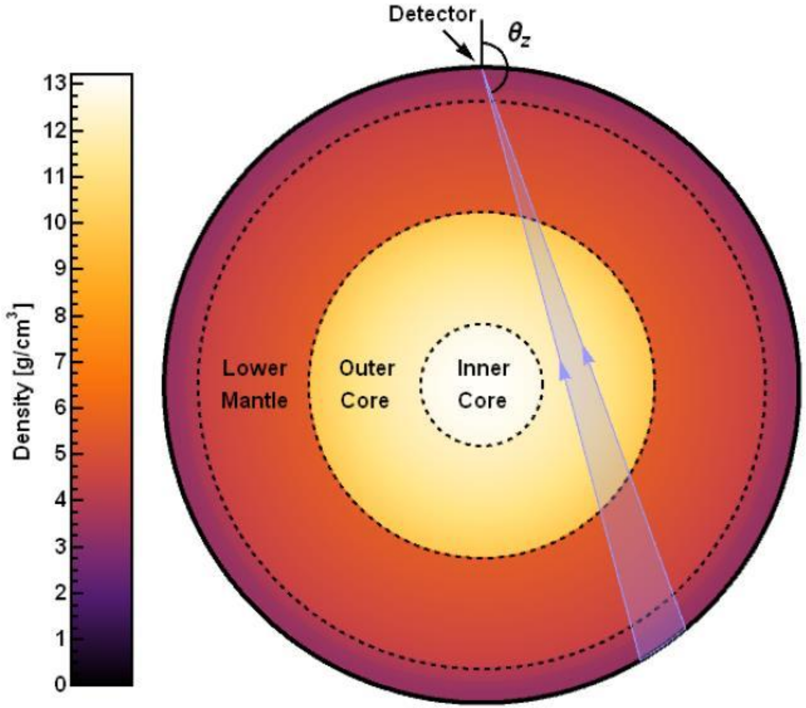
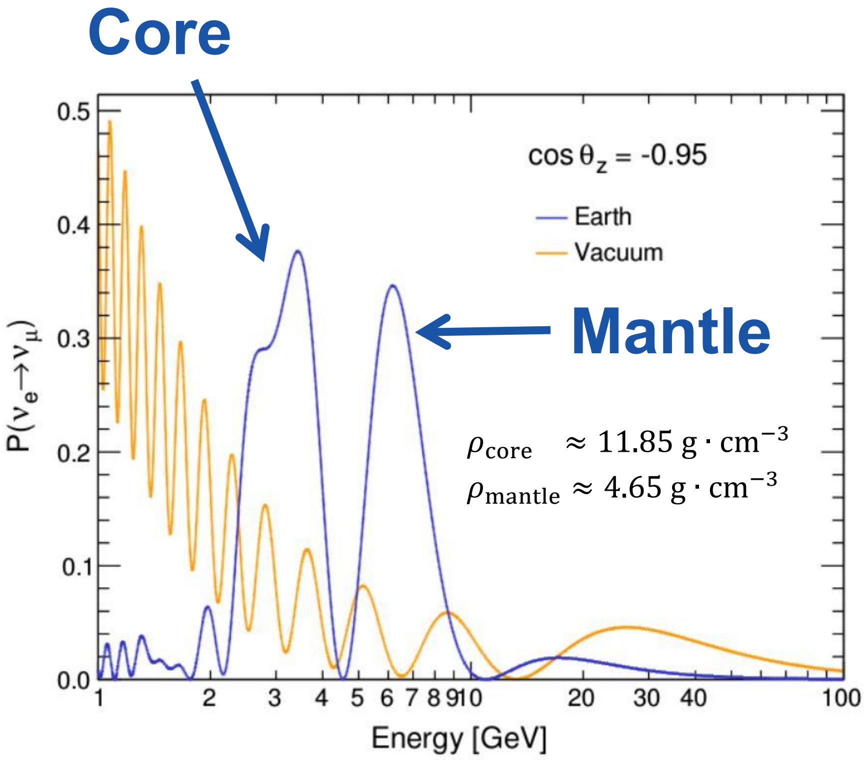
Resonance condition

$$E_\nu = \frac{\Delta m_{31}^2 \cos 2\theta_{23}}{2\sqrt{2}\, G_F\, N_e} \sim 7\ \mathrm{GeV} \left(\frac{4.5\ \mathrm{g} \cdot \mathrm{cm}^{-3}}{\rho}\right)$$

Earth tomography





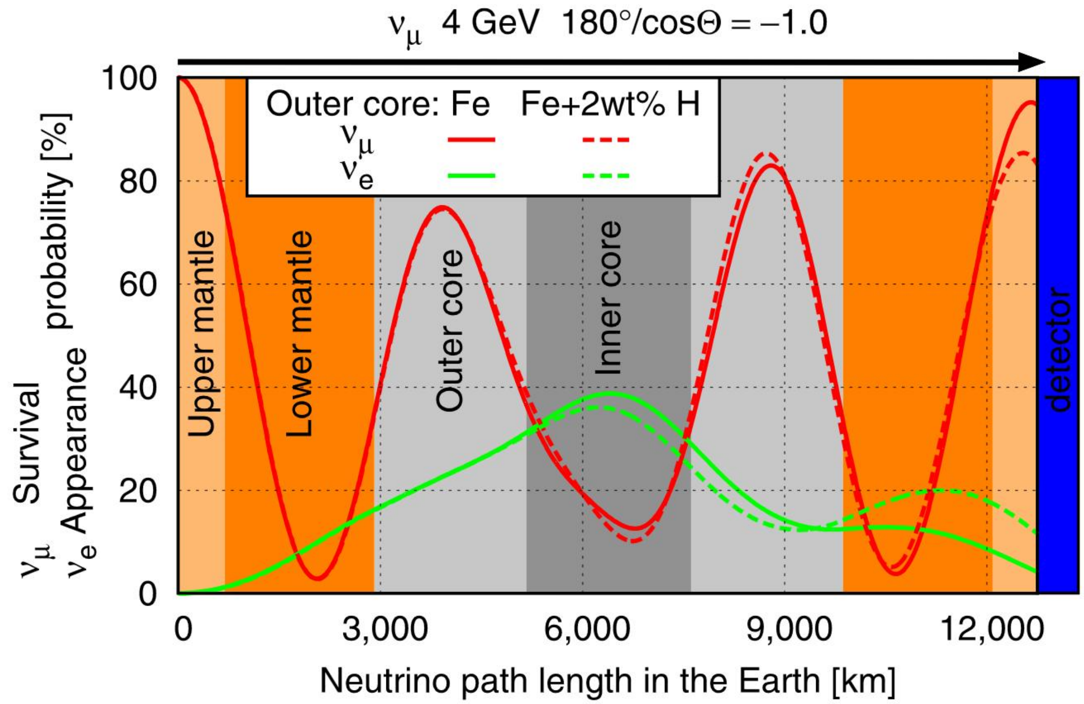
$\rho_{\text{core}} \approx 11.85\ \text{g} \cdot \text{cm}^{-3}$

$\rho_{\text{mantle}} \approx 4.65\ \text{g} \cdot \text{cm}^{-3}$

Earth tomography

Reality is more complicated

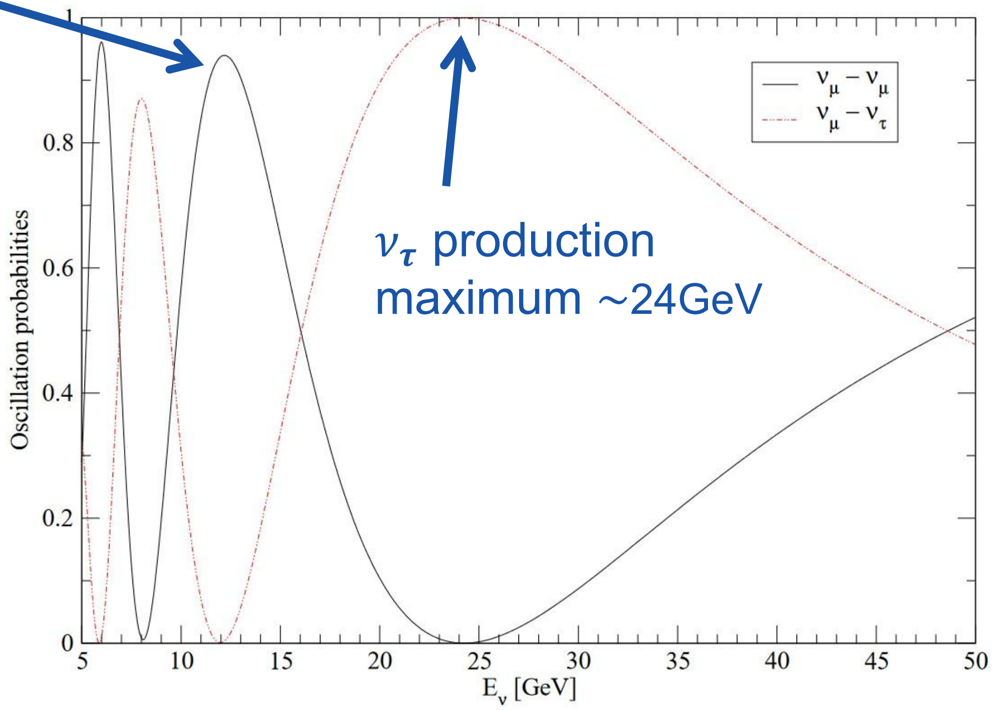
- Many more layers to consider
- Allows tests on chemical composition of the Earth



C. Rott, A. Taketa and D. Bose, *Sci. Rep. 5 (2015) 15225*

Tau neutrino physics in ESSnuSB

ν_μ maximum



Opportunities in ν_τ physics:

- Tests on PMNS unitarity
- Cross-sections
- New physics probes
  (non-unitarity, vector NSI...)

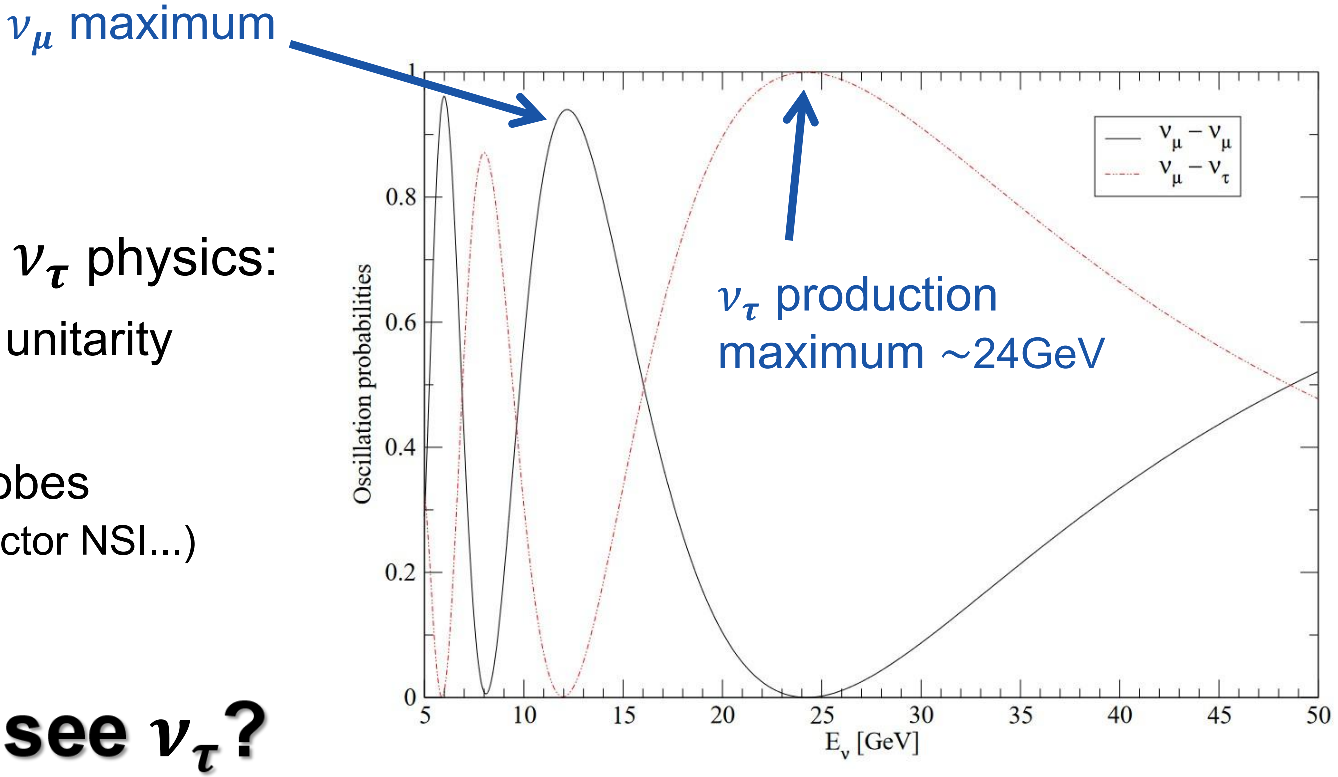
A. Donini *et al.*, *Phys. Rev D 78 (2008), 093003*

Tau neutrino physics in ESSnuSB

Opportunities in ν_τ physics:

- Tests on PMNS unitarity
- Cross-sections
- New physics probes
  (non-unitarity, vector NSI...)

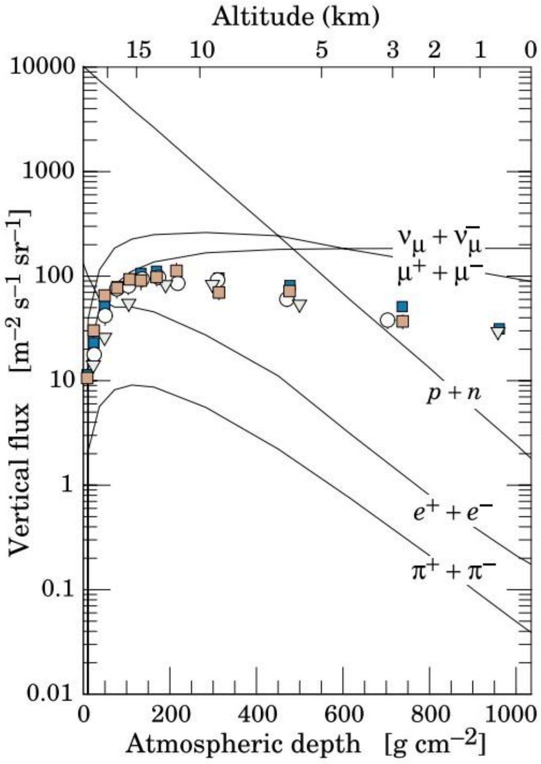
Can we see ν_τ?



A. Donini *et al.*, *Phys. Rev D 78 (2008), 093003*

Atmospheric muons

- Produced at similar numbers with atmospheric ν_μ and $\bar{\nu}_\mu$
- Very energetic
- Can be used for calibration
- Act as background to atmospheric neutrinos
- Crucial for cosmic neutrino searches



PDG, *Chin.Phys.C 40 (2016) 10, 100001*

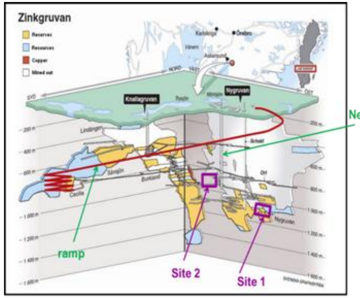
Atmospheric physics at ESSnuSB

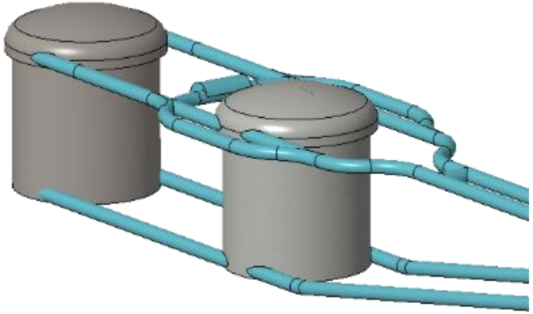
Excellent prospects at ESSnuSB far detector:

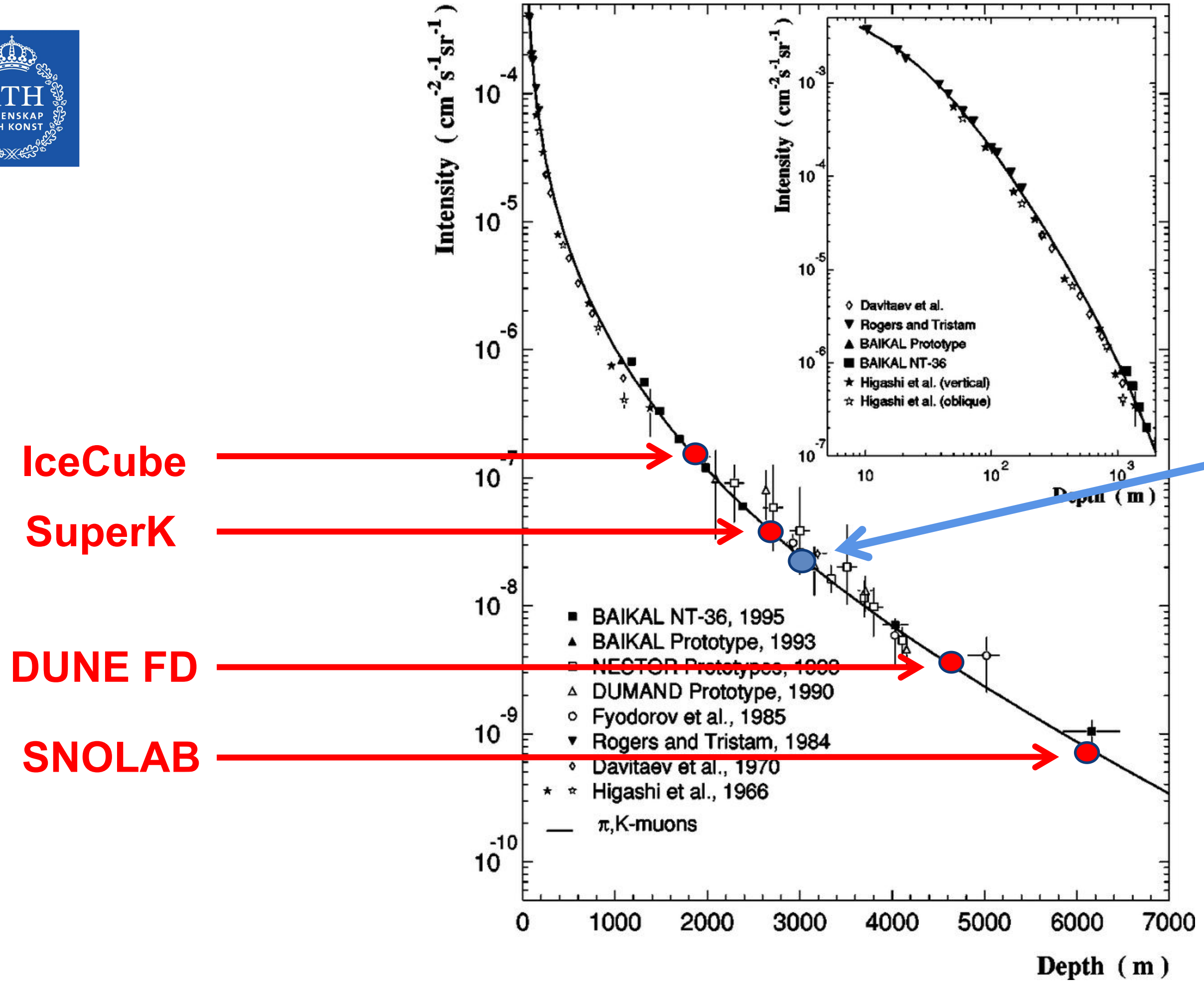
- 1Mt scale W.C. detectors

- 1km rock overburden

- Option for Gd doping






Intensity (cm^-2 s^-1 sr^-1)
Depth (m)
BAIKAL NT-36, 1995
BAIKAL Prototype, 1993
NESTOR Prototypes, 1993
DUMAND Prototype, 1990
Fyodorov et al., 1985
Rogers and Tristam, 1984
Davitaev et al., 1970
Higashi et al., 1966
π,K-muons
Davitaev et al.
Rogers and Tristam
BAIKAL Prototype
BAIKAL NT-36
Higashi et al. (vertical)
Higashi et al. (oblique)
IceCube
SuperK
DUNE FD
SNOLAB
Zinkgruvan

Scientific objectives

- What can atmospheric neutrinos tell us?
  - Mass hierarchy
  - Precision on standard parameters
  - Vector NSI
- Opportunities in Earth tomography
  - Core/mantle separation
  - Chemical composition
- Prospects in tau neutrino physics
  - Tests on PMNS unitarity
  - Advanced probes for new physics

Roadmap for atmospheric physics

- Learning GENIE → Step I: this is where we are currently at
- Find atmospheric fluxes for ESSnuSB → Preferably with Honda model; Currently using fluxes from LAGUNA-LBNO
- Integrate detector response → Needs GEANT4 simulation for more accurate results
- Simulation and analysis → MH, CPV, Earth tomography and tau physics...

Discussion and outlook

- ESSnuSB detector will have excellent prospects to study atmospheric neutrinos and muons
- Main scientific goals include MH and NSI sensitivities
- Further prospects in Earth tomography
- Simulations carried out with GENIE
- Applications nearly limitless, everyone is welcome to join!

Thank you for following!