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Sensitivity on earth core and mantle densities using atmospheric neutrinos

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Outlook

- Are earthquakes useful?
- Why neutrinos?
- Which neutrinos?
- How neutrinos?
- Results and conclusions

The Earth mass

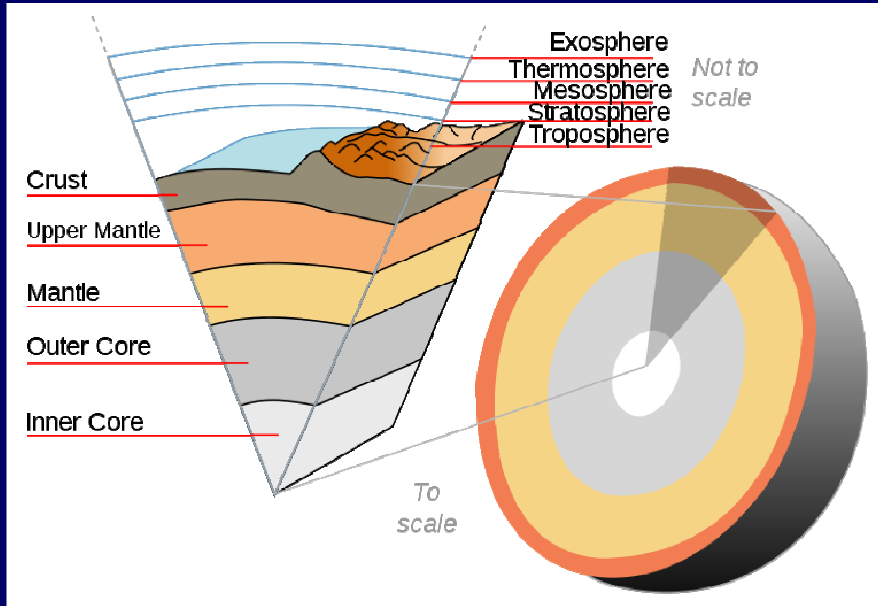
Eratostene (273-192 b.C.)	→	First measure of the Earth circumference (and then of the Earth radius)
Galilei (1564-1642)	→	Determination of the acceleration due to gravity
Newton (1642-1727)	→	Formulation of the laws of gravitation
Cavendish (1731-1810)	→	Determination of G_N

Calculation of the Earth mass and then of its average density:

$\rho_{av} \sim 5.5 \text{ g cm}^{-3}$

The Earth internal structure

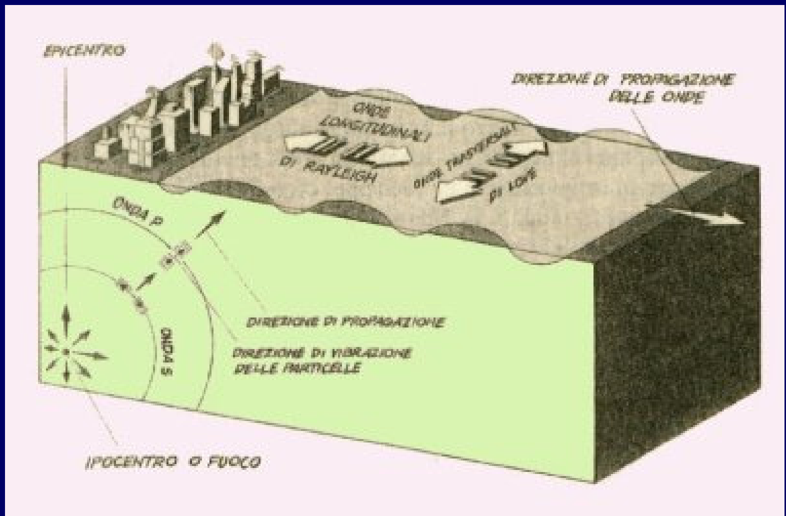
On the other side, the Earth crust density is about 2.7-2.8 g cm^{-3} (direct observations arrive to ~20 km). Information from samples brought to the surface by volcanic activity and by measuring the travel times of earthquake waves to sei-smograph stations. It is found that:



- the velocity generally increases gradually with depth in Earth, due to increasing pressure and rigidity of the rocks
- however, there are abrupt velocity changes at certain depths, indicating layering

The utility of earthquakes…

As the result of a earthquakes, explosions, or some other process (the incessant pounding of ocean waves, referred to as the microseisms, and the wind), **seismic waves** are continuously excited on Earth.
Earth quakes create two types of waves, body waves and surface waves:



- P waves (primary waves) are longitudinal body waves
- S waves (secondary waves) are transverse body waves
- L and R waves (Love and Raleigh waves) are horizontal and elliptical surface waves
- free oscillations are surface wave with wavelength comparable with the circumference of the Earth

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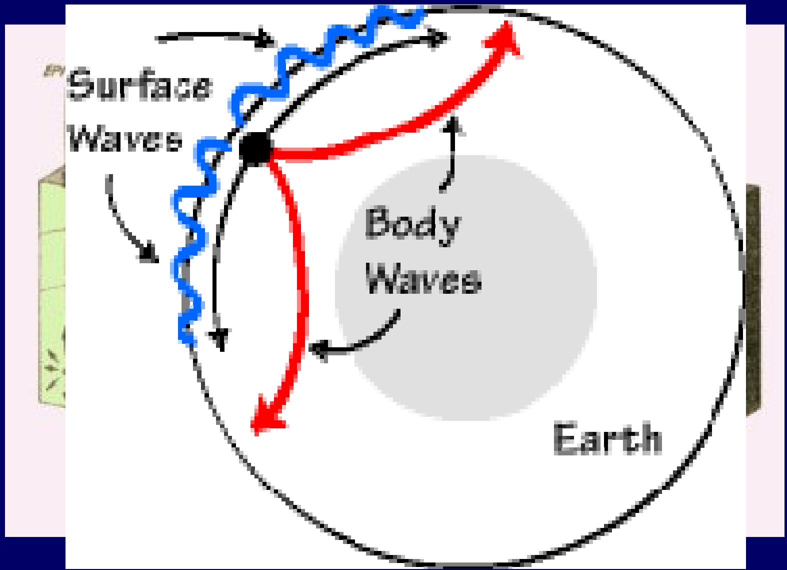

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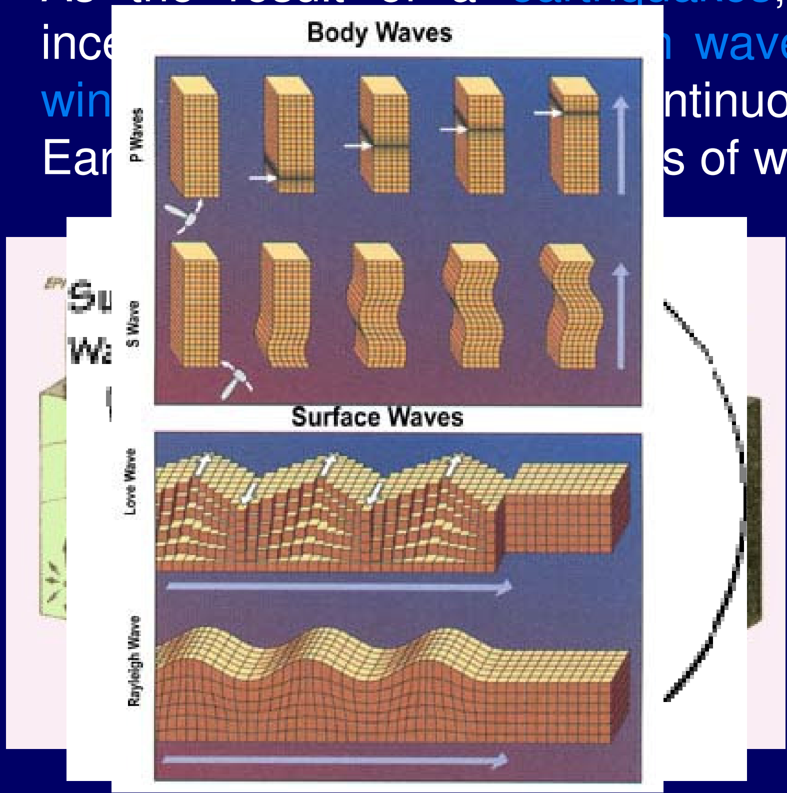

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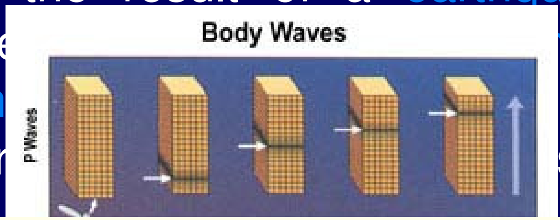

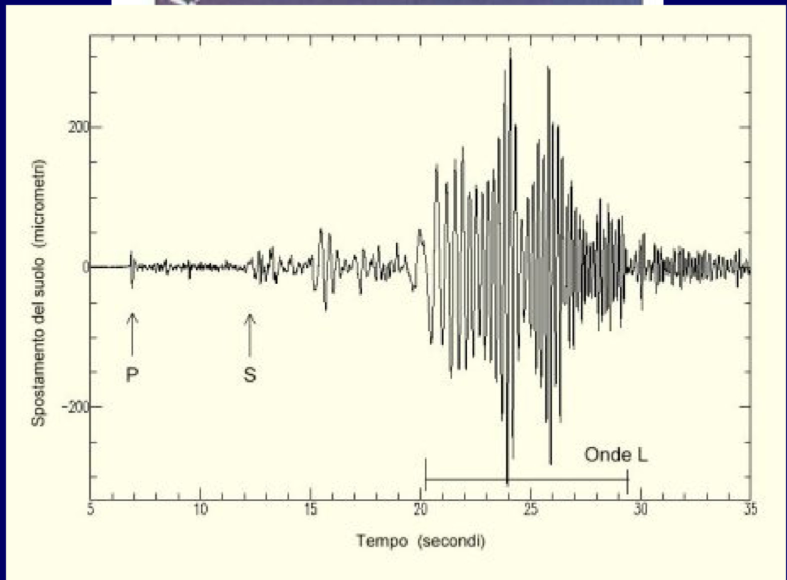

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The utility of earthquakes…

In solids, the P waves generally travel almost twice as fast as S waves and can travel through any type of material. S waves can travel only through solids, as fluids (liquids and gases) do not support shear stresses.

$$V_p = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}} \qquad V_s = \sqrt{\frac{\mu}{\rho}}$$

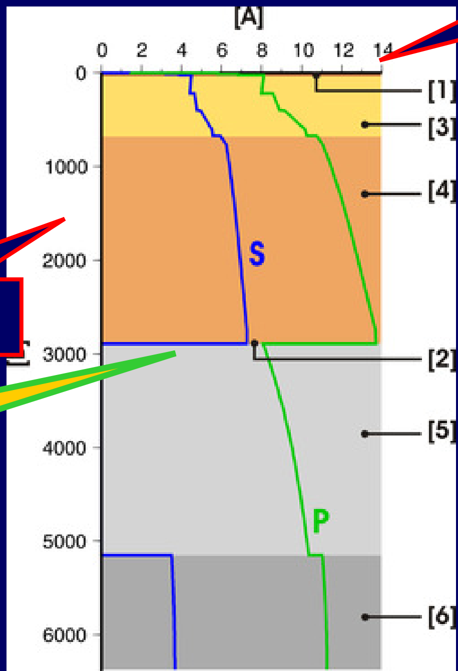
bulk modulus

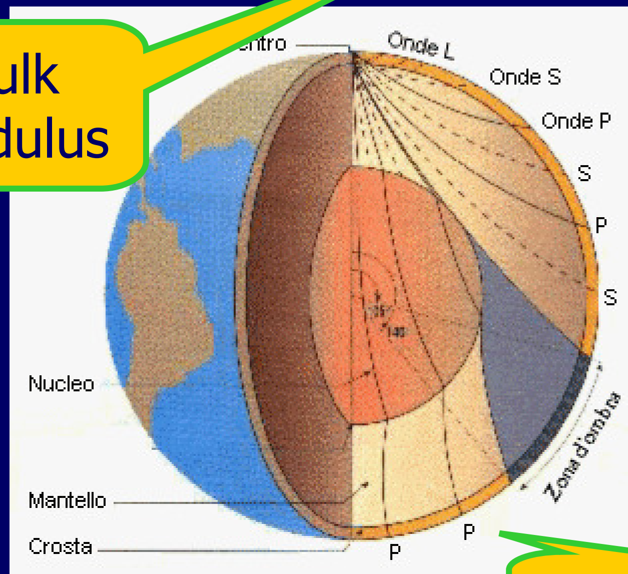
modulus of rigidity

v (km s^{-1})

depth (km)

CMB





PKP (P')

Limits of seismic tomography

- Global seismic tomography is limited by the irregularity in time and space of the source, and by the incomplete coverage of recording stations. The primary source is earthquakes, which are impossible to predict and only occur at certain locations around the world. In addition, the global coverage of recording stations is limited due to economic and political reasons. Because of these limitations, seismologists must work with data that contains crucial gaps.

- Free-oscillation data only reveal 1-dimensional structure.

Limits of seismic tomography

• Global seismic tomography is limited by the irregularity in time and … incomplete coverag… ource is earthqu… nly occur at certa… ne global coverag… omic and political… nologists must w…

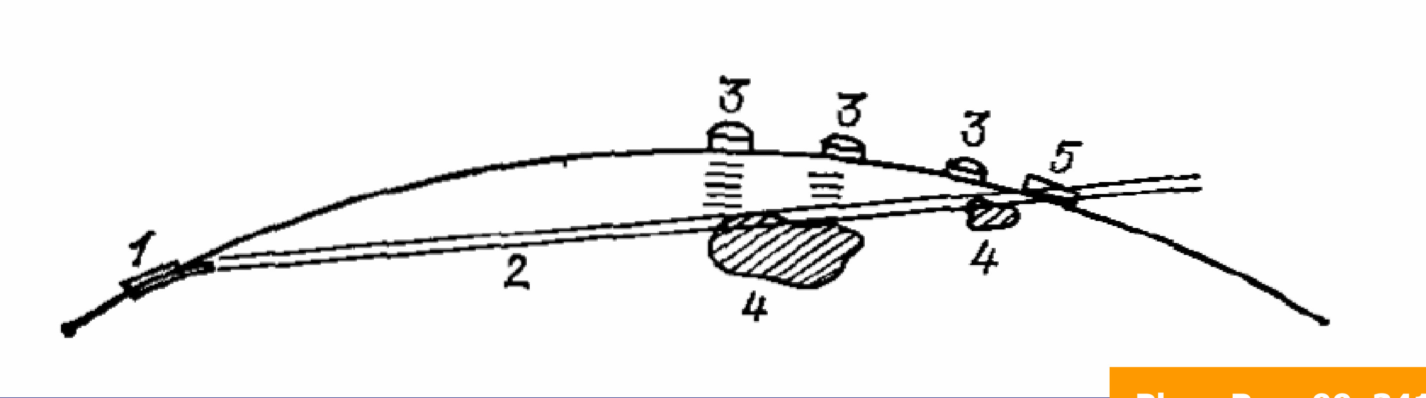
Although this information is more precise than what we can realistically expect from neutrino radiography in the near future, aspects of the global structure of the earth require confirmation.

• Free-oscillation data only reveal 1-dimensional structure.

Earth radiography by neutrinos

$$\lambda = \frac{1}{\sigma_{\nu N}\ \rho\ N_A}$$

$\lambda \sim 2\ R_{earth} \Leftrightarrow E \sim 10$ TeV



Askaryan, Usp. Fiz. Nauk 144, 523 (1984)

Phys. Rep. 99, 341 (1983)

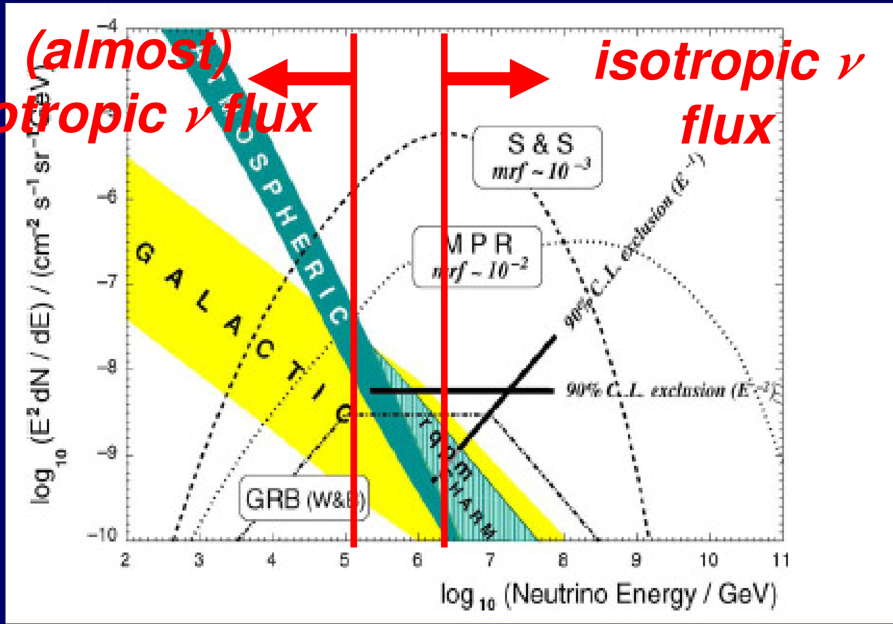
First proposal to use neutrino beams for Earth radiography by De Rujula, Glashow, Wilson, and Charpak in 1983: a neutrino moving in rock produces a shower which ionizes the medium and generates an acustic signal. Moreover, the muons accompanying the neutrino beam can be detected at the point of emergence from the Earth.

Which ν's for Earth radiography?

Neutrinos

Neutrinos are one of the components of cosmic radiation. The atmospheric and the extragalactic contributions, which are mainly isotropic, dominates on the galactic component in two energy regimes. In particular, for $E \lesssim 10^5$ GeV the statistics of atmospheric ν is larger than that expected from other cosmic sources.

Astrop. Phys. 20 (2004) 507

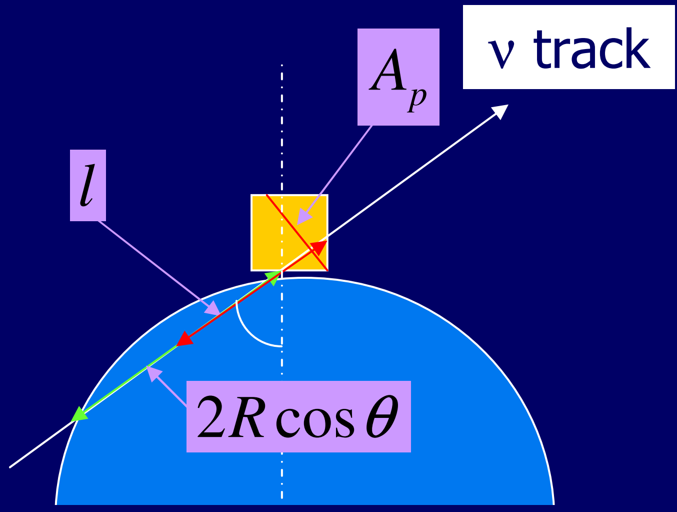


Probe of geophysical structures

s^{-1} m^{-2} sr^{-1} GeV^{-1}

Event rate can be written as

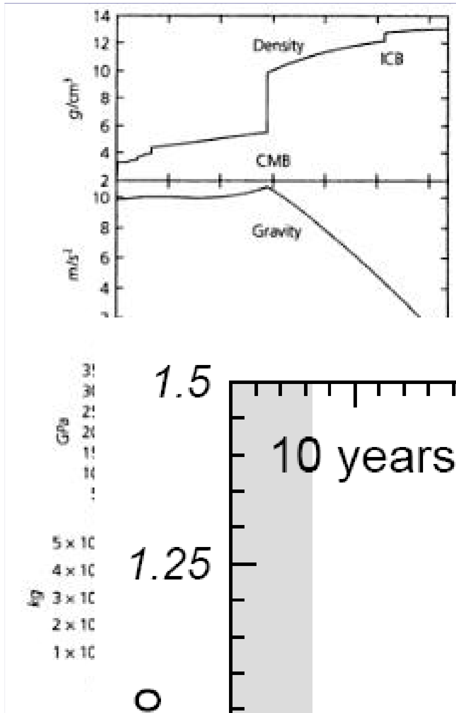
$$\Gamma(E_\nu) = \int d\Omega \, A_{eff} \frac{d\phi}{d\Omega}$$



where the ***effective area***, $A_{eff} \cong \rho\, \sigma\, N_A\, V_{eff}$, (the detector effective volume, $V_{eff}=A_p\, l$, divided by the neutrino interaction length) is ***sensible to the density of matter*** crossed by neutrinos.

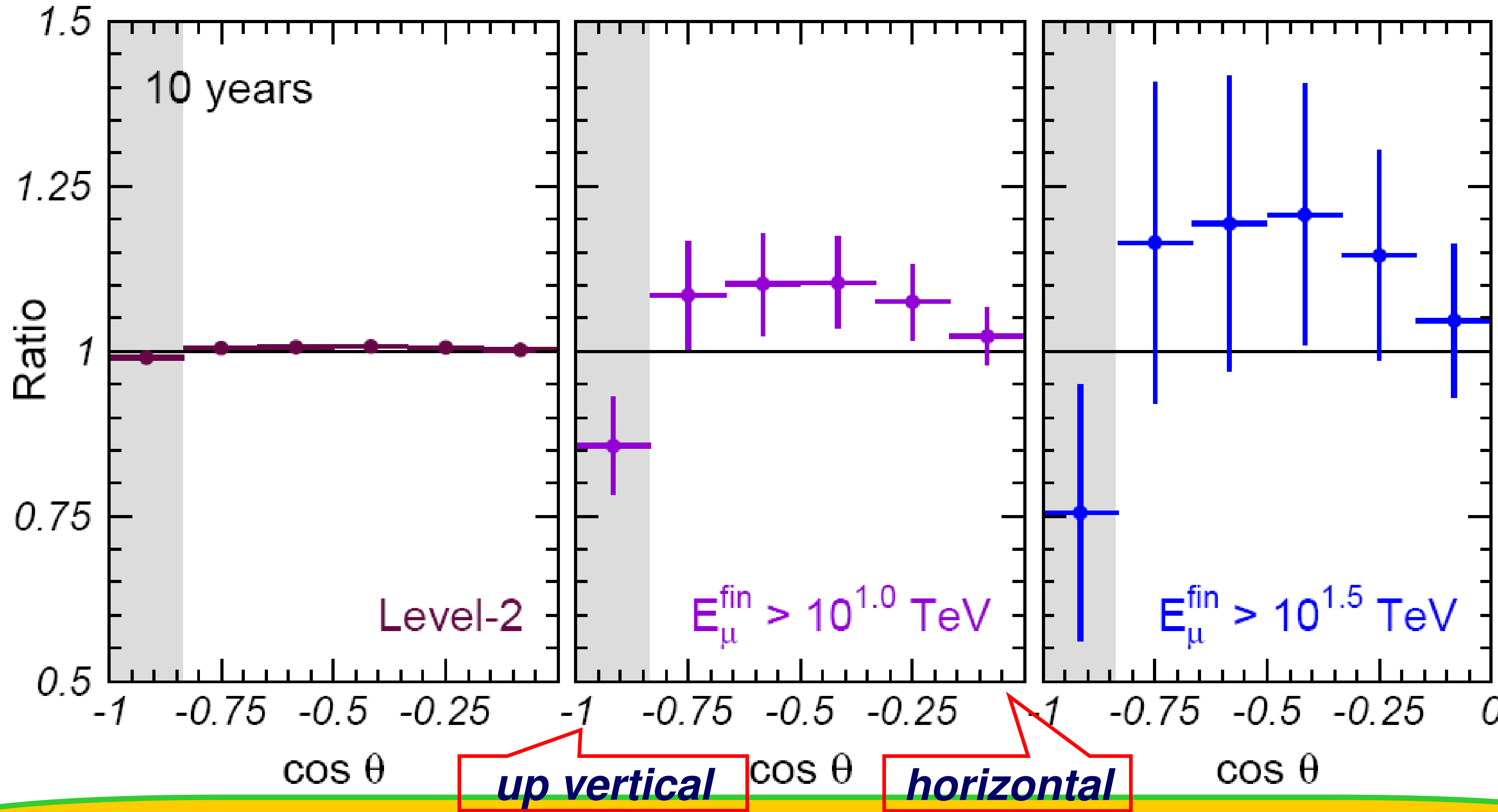
A_p = area of the detector projected against the neutrino direction

l = portion of the neutrino path to which the detector is sensible

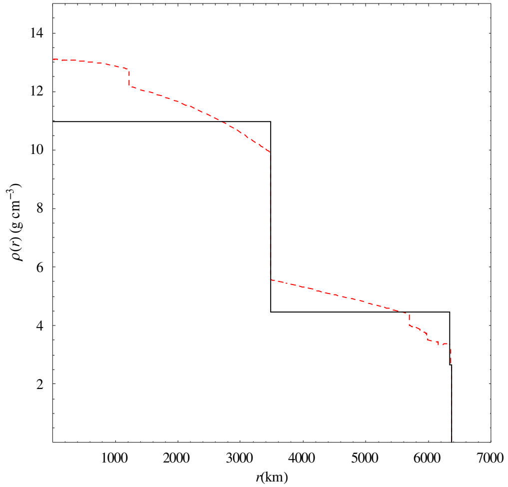


PREM versus homogeneous

Gonzales-Garcia, Halzen, Maltoni, Tanaka, PRL100 (2008) 061802



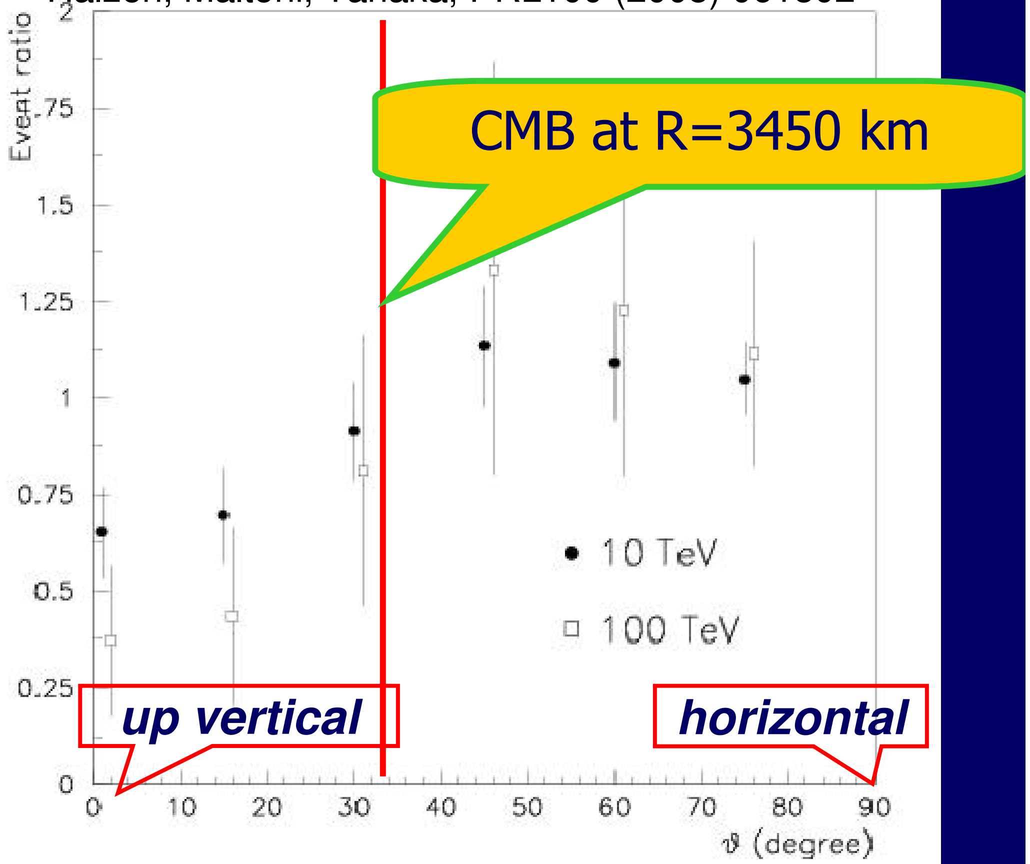
For high E_{th} the attenuation factor due to the earth density becomes relevant and the number of detected events gives information on the earth density.



PREM versus homogeneous

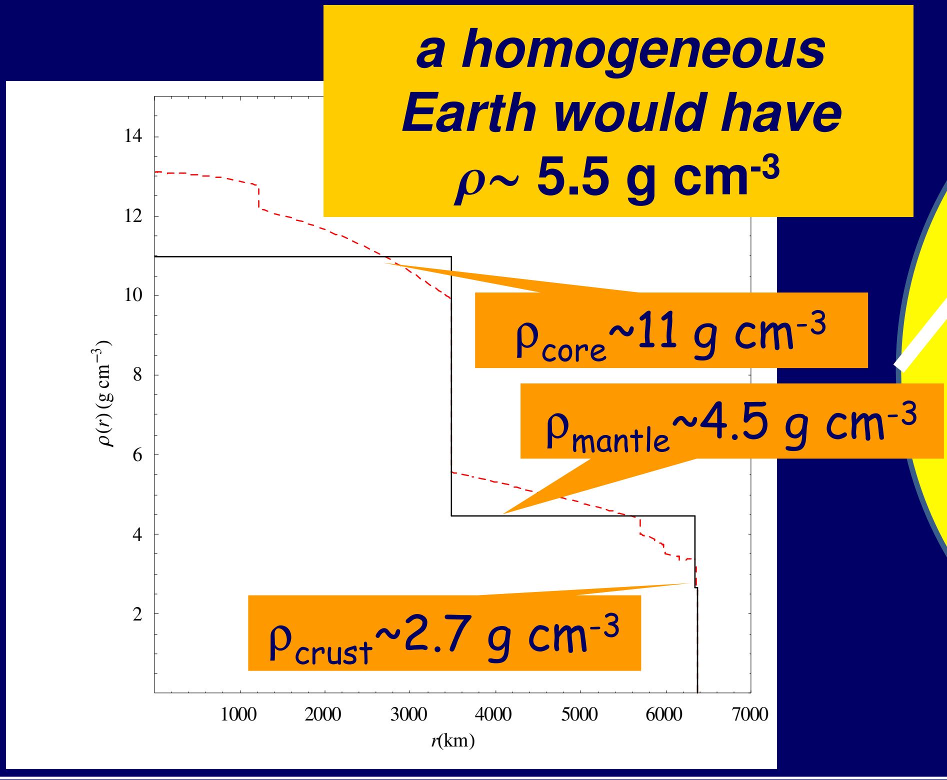
Ratio of zenith angle distribution of expected events for the sPREM over the expectations with an homogeneous Earth matter distribution for different values of the energy. The error bars in the figure show the expected statistical error in 10 years of data taking.

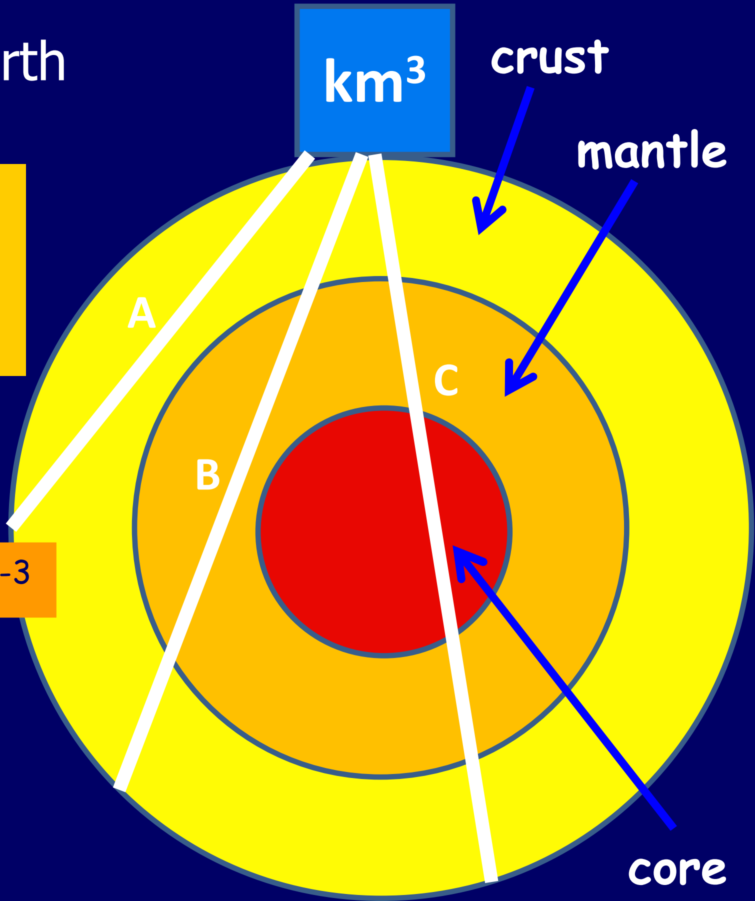
Analytic results agree with Gonzales-Garcia, Halzen, Maltoni, Tanaka, PRL100 (2008) 061802



Neutrinos through the Earth

- a simplified parametrization of Earth radial density profile (sPREM)

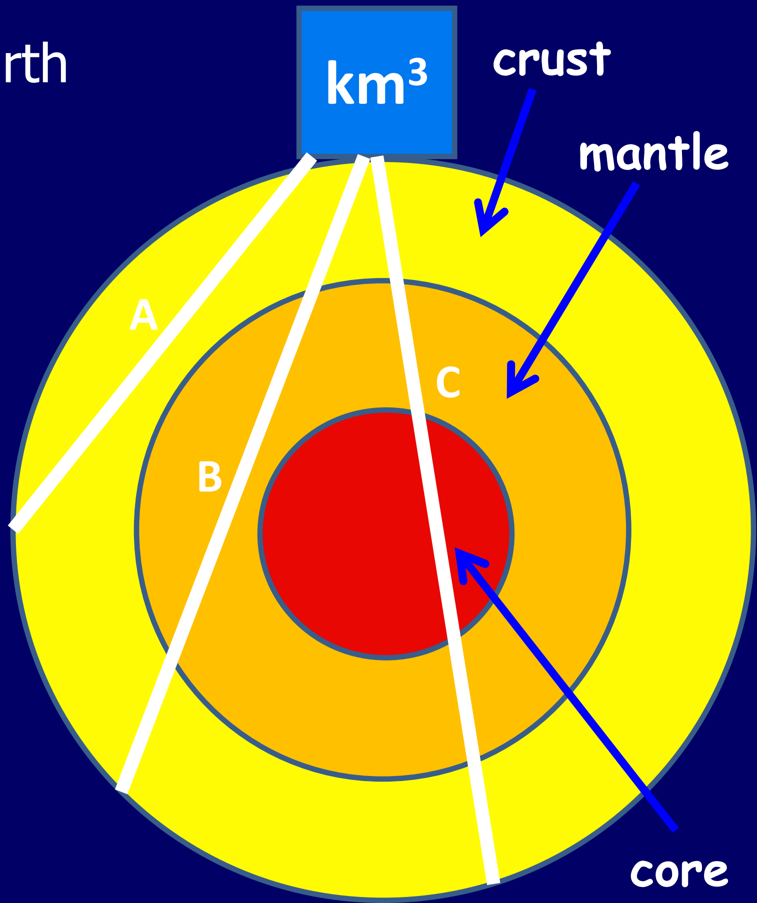




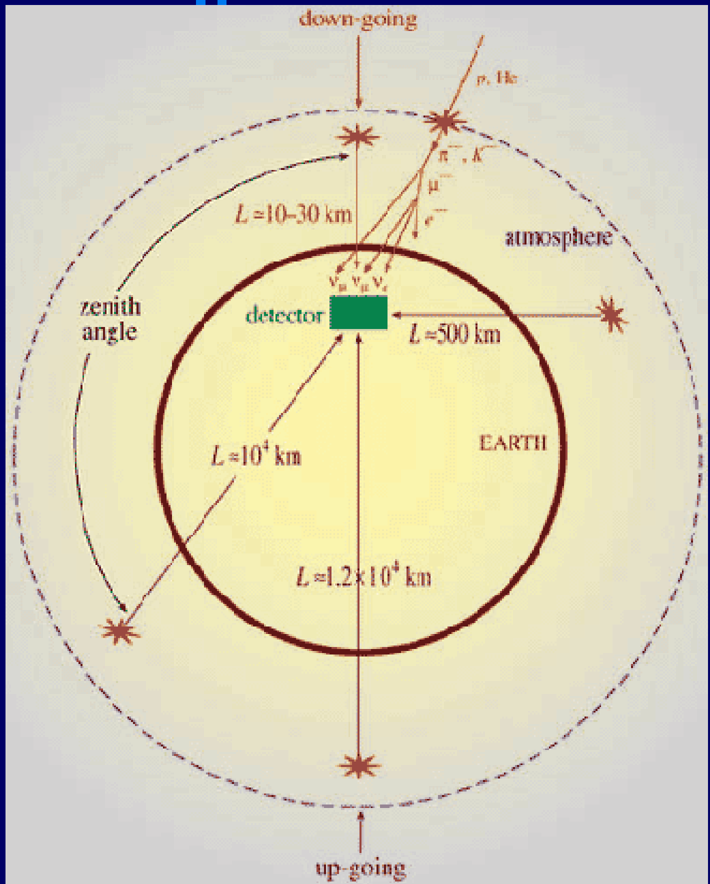
Neutrinos through the Earth

- a simplified parametrization of Earth radial density profile (sPREM)
- three different type of tracks crossing the fiducial volume (described by a Digital Elevation Map)
- neutrinos injected at one side of the tracks according to known spectrum

Honda et al., PR D75:043006 (2007)



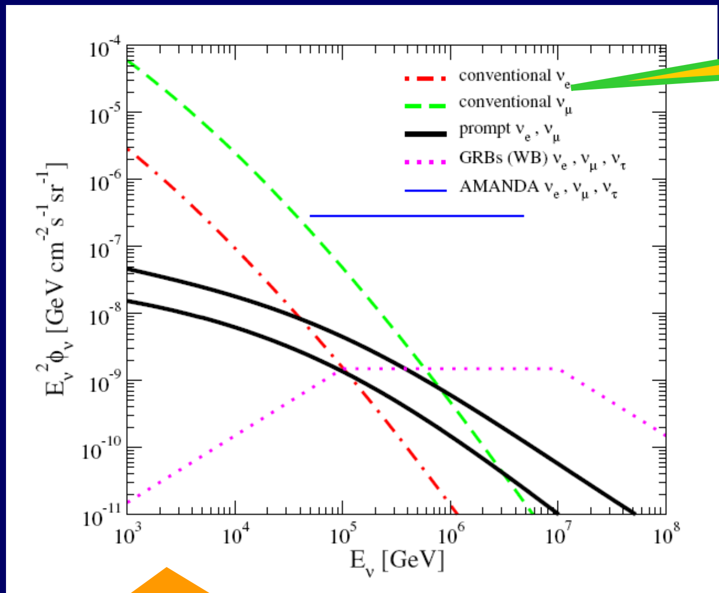
Atmospheric Neutrinos



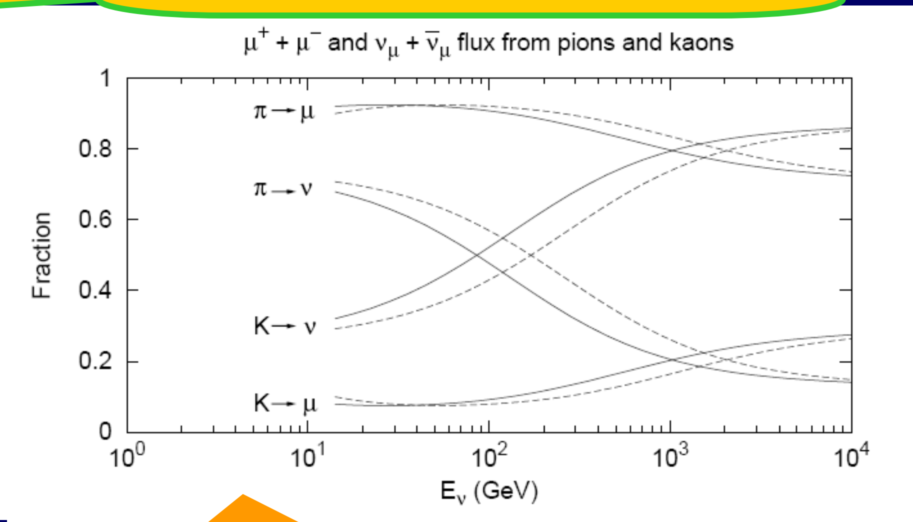
The atmospheric neutrino spectrum falls as $E^{-\gamma}$, with $\gamma \approx 3$-3.7. The spectral index is similar to the CR one at lower energies, while it becomes steeper at higher energies. This happens because the higher the energy of the mesons produced in the atmosphere, the larger the amount of energy lost during their propagation before they decay.

Atmospheric Neutrinos

The “conventional” part comes from pion and kaon decays (low energy), a “prompt” isotropic contribution from short lived charmed hadrons (high energy). In the energy range of interest, the contribution from kaons dominates (~80%) and decay of muons can be neglected. Tau neutrinos are negligible since oscillation are very suppressed.



Averaged over zenith angle

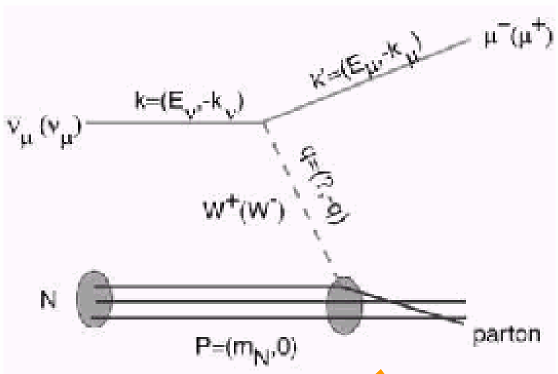


Beacom & Candia, JCAP 11, 009 (2004)

i Teoric

Gaisser, Earth Planets Space 58, 1 (2006)

Neutrino interaction



$Q^2 \equiv - q^2 = -(k-k')^2$

$x = Q^2/(2\ m_N\ \nu)$

$y = \nu/\ E_\nu = (E_\nu - E_l)/\ E_\nu$

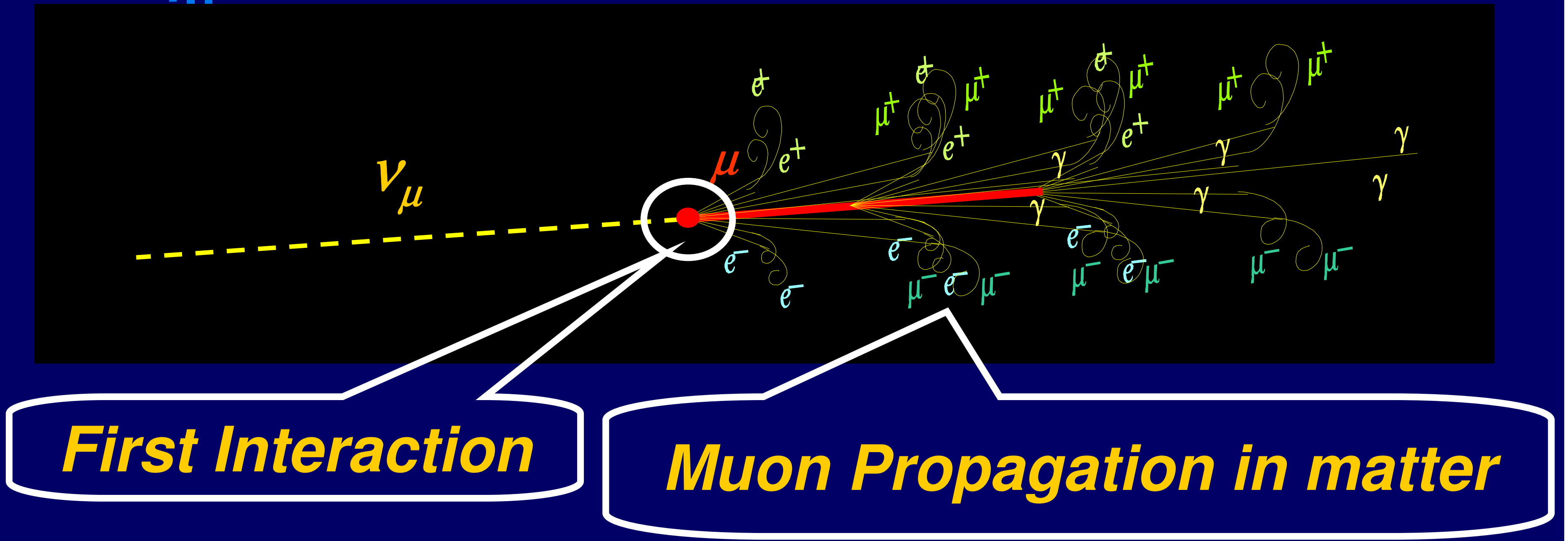
$Q^2 = 2\ m_N\ E_\nu\ x\ y$

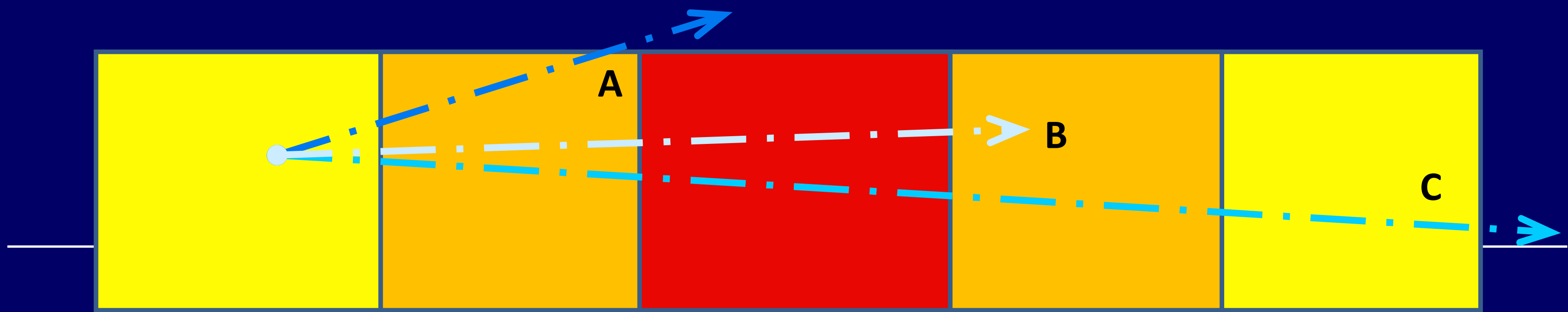
TABLE I. Charged-current and neutral-current cross sections and their sum for νN interactions according to the CTEQ4-DIS distributions.

E_ν [GeV]	σ_{CC} [cm^2]	σ_{NC} [cm^2]	σ_{tot} [cm^2]
1.0×10^1	0.7988×10^{-37}	0.2492×10^{-37}	0.1048×10^{-36}
2.5×10^1	0.1932×10^{-36}	0.6033×10^{-37}	0.2535×10^{-36}
6.0×10^1	0.4450×10^{-36}	0.1391×10^{-36}	0.5841×10^{-36}
1.0×10^2	0.7221×10^{-36}	0.2261×10^{-36}	0.9482×10^{-36}
2.5×10^2	0.1728×10^{-35}	0.5430×10^{-36}	0.2271×10^{-35}
6.0×10^2	0.3964×10^{-35}	0.1255×10^{-35}	0.5219×10^{-35}
1.0×10^3	0.6399×10^{-35}	0.2039×10^{-35}	0.8438×10^{-35}
2.5×10^3	0.1472×10^{-34}	0.4781×10^{-35}	0.1950×10^{-34}
6.0×10^3	0.3096×10^{-34}	0.1035×10^{-34}	0.4131×10^{-34}
1.0×10^4	0.4617×10^{-34}	0.1575×10^{-34}	0.6192×10^{-34}
2.5×10^4	0.8824×10^{-34}	0.3139×10^{-34}	0.1196×10^{-33}
6.0×10^4	0.1514×10^{-33}	0.5615×10^{-34}	0.2076×10^{-33}
1.0×10^5	0.2022×10^{-33}	0.7667×10^{-34}	0.2789×10^{-33}
2.5×10^5	0.3255×10^{-33}	0.1280×10^{-33}	0.4535×10^{-33}
6.0×10^5	0.4985×10^{-33}	0.2017×10^{-33}	0.7002×10^{-33}
1.0×10^6	0.6342×10^{-33}	0.2600×10^{-33}	0.8942×10^{-33}
2.5×10^6	0.9601×10^{-33}	0.4018×10^{-33}	0.1362×10^{-32}
6.0×10^6	0.1412×10^{-32}	0.6001×10^{-33}	0.2012×10^{-32}
1.0×10^7	0.1749×10^{-32}	0.7482×10^{-33}	0.2497×10^{-32}

R. Gandhi, C. Quigg, M.H. Reno, and I. Sarcevic, 1998

Event simulation

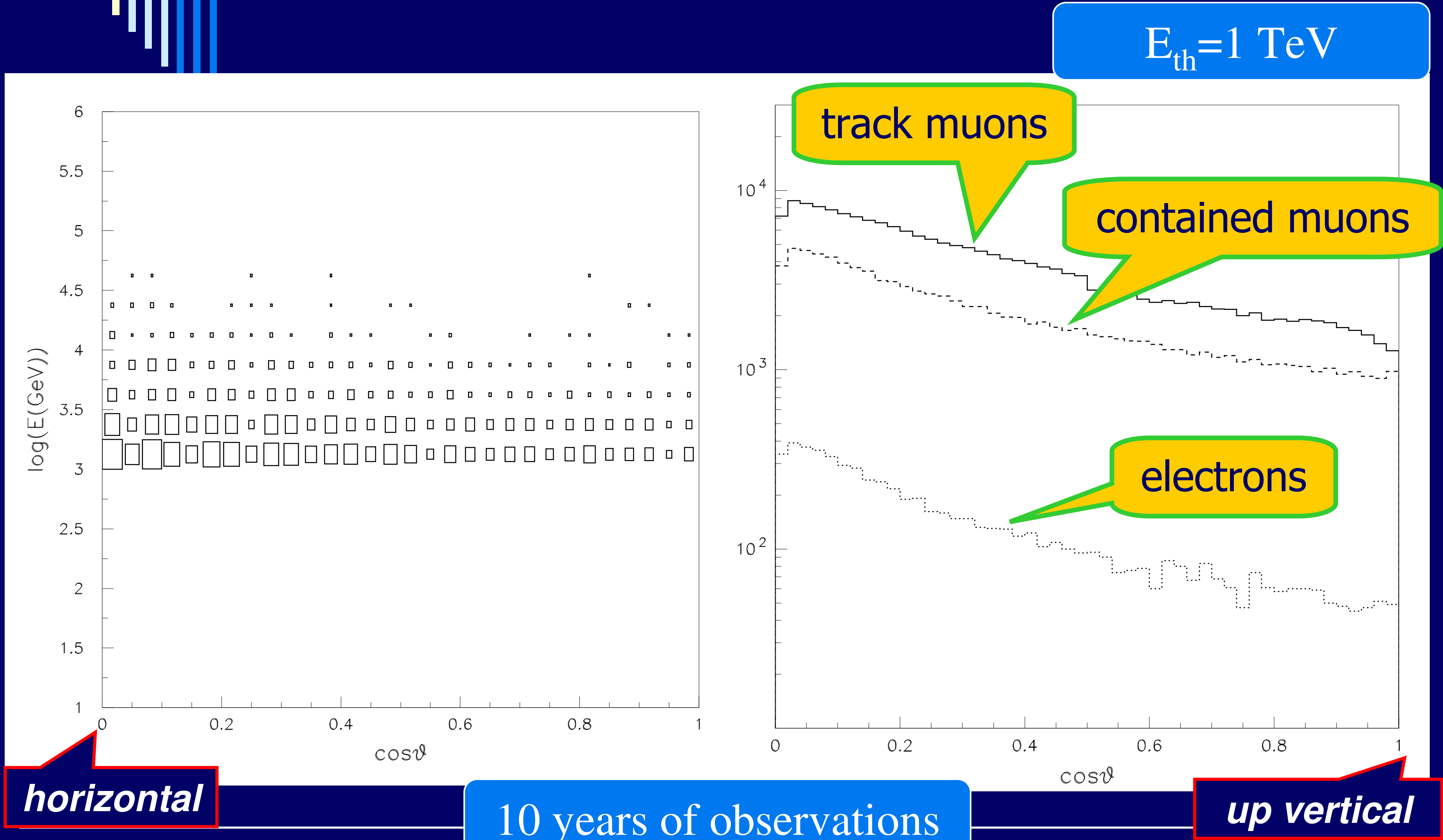




Summary of simulation details

- *e* and μ (anti)neutrinos injected according to the atmospheric ν flux in the range $1 \div 10^2$ TeV (Honda et al., 2007). Negligible oscillation -> no τ contribution
- neutrino regeneration by NC processes
- μ energy loss in matter (ionization, bremsstrahlung, pair production, nuclear interaction)
- energy thresholds of 1 TeV and 10 TeV
- no details of the experimental apparatus, except for the request of a minimal track length of 300 m in the NT
- detectable events: *track* and *contained* events

Particles at the detector



Likelihood analysis

$4 \leq \rho_m/(\mathrm{g\ cm^{-3}}) \leq 5$
$9 \leq \rho_c/(\mathrm{g\ cm^{-3}}) \leq 12$

We consider 5 angular bins for the interval cosθ = 1 (upgoing) to cosθ = 0 (horizontal) and make the analysis integrating the muons at different energies in the two case E_{th} = 1 TeV and E_{th}=10 TeV.

Observables N_i produced for a grid of 20 theoretical models of densities. Then, likelihood analysis with likelihood function $L \propto e^{-\chi^2/2}$ and

overall uncertainty on φ and σ

Δξ=0.25

$$\chi^2(\rho_m,\rho_c,\xi,\eta) = \sum_{i=1}^{5} \frac{\left[N_i(\rho_m,\rho_c)(1+\xi)(1-\eta\langle\cos\vartheta\rangle_i) - N_i^0\right]^2}{N_i^0} + \left(\frac{\xi}{\Delta\xi}\right)^2 + \left(\frac{\eta}{\Delta\eta}\right)^2$$

uncertainty between h. and v. φ

Δη =0.05

expected counts for the sPREM

Likelihood analysis

E_{th}=1 TeV

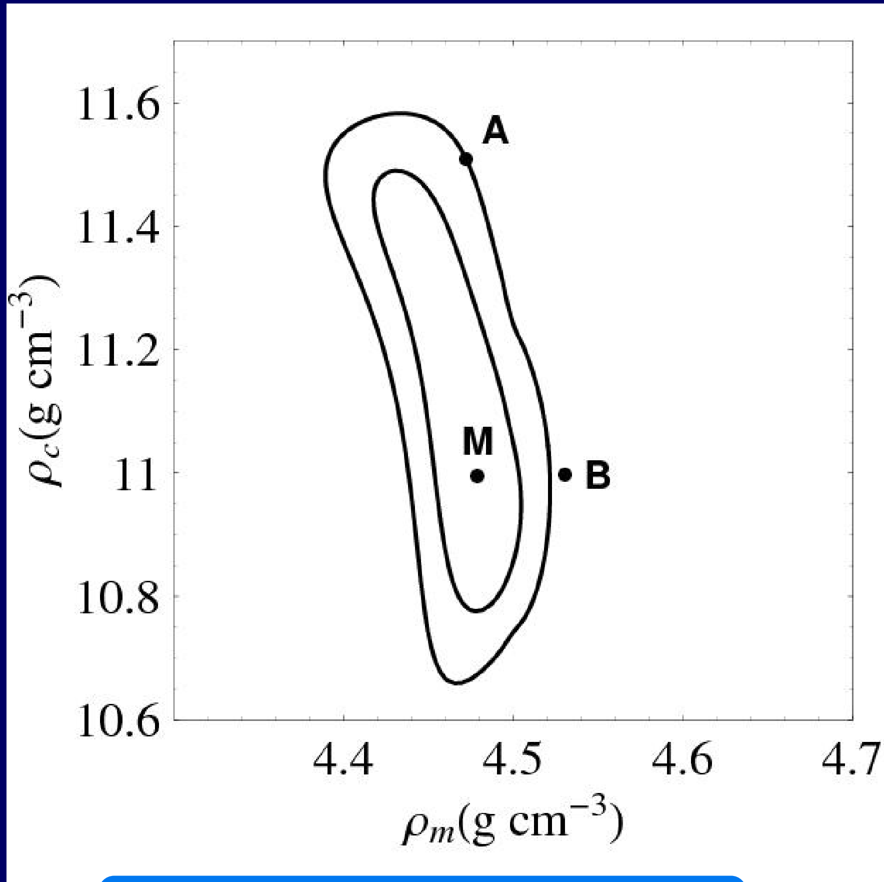
2% (5%) uncertainty on ρ_m (ρ_c) at 2σ

$$\rho_m = 4.47\,^{+0.02}_{-0.03}\,\left(^{+0.04}_{-0.06}\right)\ \mathrm{g\ cm^{-3}}$$

$$\rho_c = 11.0\,^{+0.3}_{-0.1}\,\left(^{+0.5}_{-0.2}\right)\ \mathrm{g\ cm^{-3}}$$

$$R_c = 3440 \pm 30\,\left(^{+70}_{-50}\right)\ \mathrm{km}$$

$\cos\vartheta$	sPREM (M)	A	B
[0, 0.2]	113436	113860	112876
[0.2, 0.4]	72393	75456	73981
[0.4, 0.6]	47334	48142	47790
[0.6, 0.8]	34105	34144	33503
[0.8, 1.0]	26781	27392	26780



10 years of observations

Likelihood analysis

E_{th}=10 TeV

2% (5%) uncertainty on ρ_m (ρ_c) at 2σ

$$\rho_m = 4.47\,^{+0.02}_{-0.03}\,\left(^{+0.04}_{-0.06}\right)\ \mathrm{g\ cm^{-3}}$$
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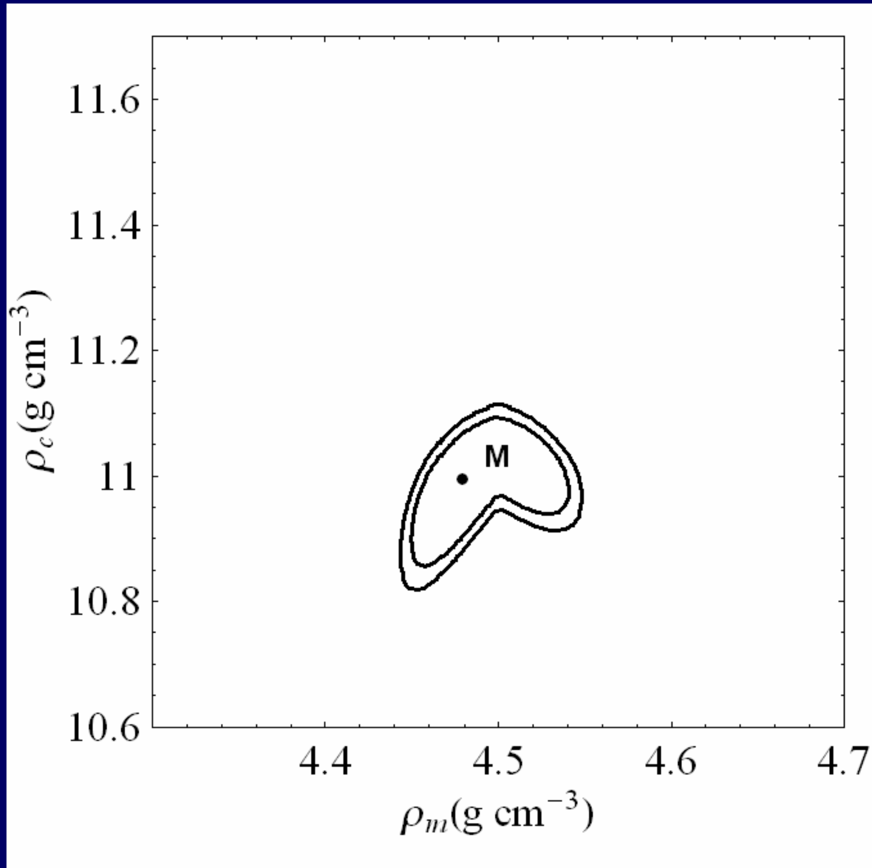

10 years of observations

Conclusions

- study of the sensitivity of a NT to Earth interior for a simplified Earth model (sPREM)
- 2% (5%) uncertainties (at 2σ level) on ρ_m (ρ_c) for 10 years of observations and E_{th}=1 TeV
- low number of model parameters $\Rightarrow$ good level of sensitivity in their determination
- no details of the experimental apparatus