The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

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2047-6

Workshop Towards the Neutrino Technologies

13 - 17 July 2009

Sensitivity on Earth Core and Mantle densities using Atmospheric Neutrinos

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Sensitivity on Earth Core and Mantle densities using Atmospheric Neutrinos

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Based on **JCAP 0906:030,2009,** by E. Borriello, G. Mangano, A. Marotta, G. M., P. Migliozzi, C.A. Moura, S. Pastor, O. Pisanti, P. Strolin

Outlook

- How to use earthquakes?
- Why neutrinos?
- Which neutrinos?
- How neutrinos?
- A toy model to test sensitivity

The Earth mass

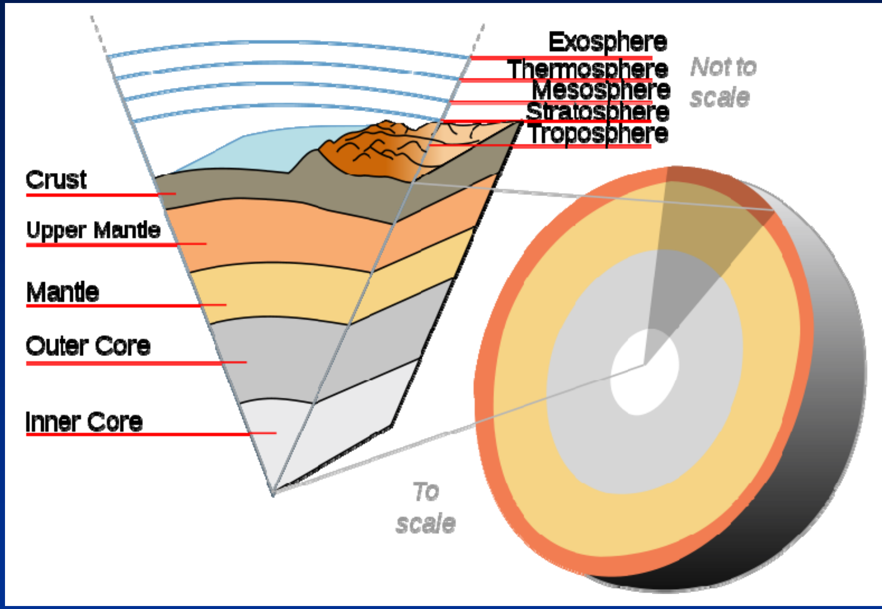
Eratostene (273-192 b.C.)	→	First measure of the Earth circumference (and then of the Earth radius)
Galilei (1564-1642)	→	Determination of the acceleration due to gravity
Newton (1642-1727)	→	Formulation of the laws of gravitation
Cavendish (1731-1810)	→	Determination of G_N

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

$$\rho_{av} \simeq 5.5\ \mathrm{g\ cm^{-3}}$$

The Earth internal structure

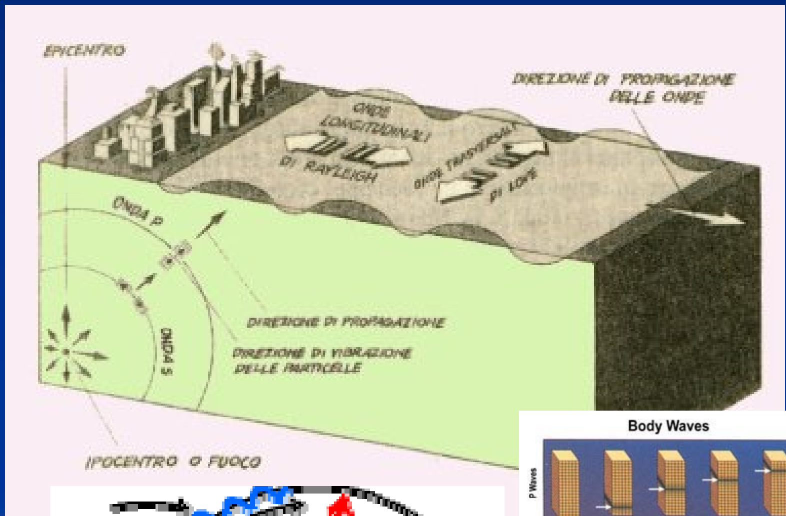
The Earth crust density is about 2.7 - 2.8 g cm^{-3} (direct observations till ~ 20 km depth). Information from samples brought to the surface by volcanic activity and by measuring the propagation speed of earthquake waves.
It is found that:

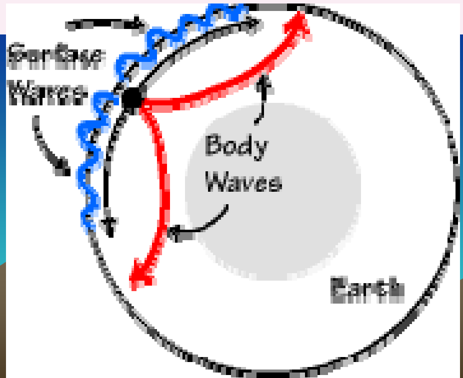


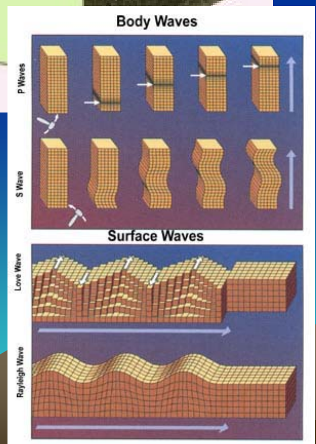
- the velocity generally increases gradually with depth in Earth, due to increasing pressure and rigidity of the rocks
- however, there are abrupt velocity changes at certain depths, indicating layering

What we learn from earthquakes

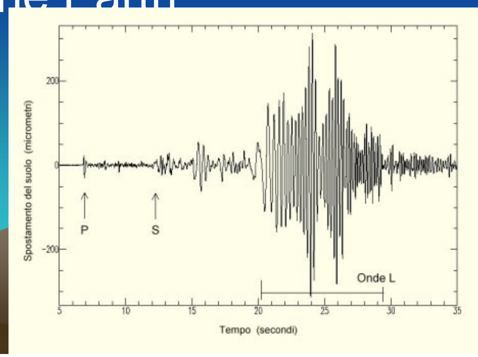
As the result of earthquakes, explosions, or some other process (the incessant pounding of ocean waves, referred to as the microseisms, and the wind), **seismic waves** are continuously excited on Earth.
Earthquakes create two types of waves, body waves and surface waves:





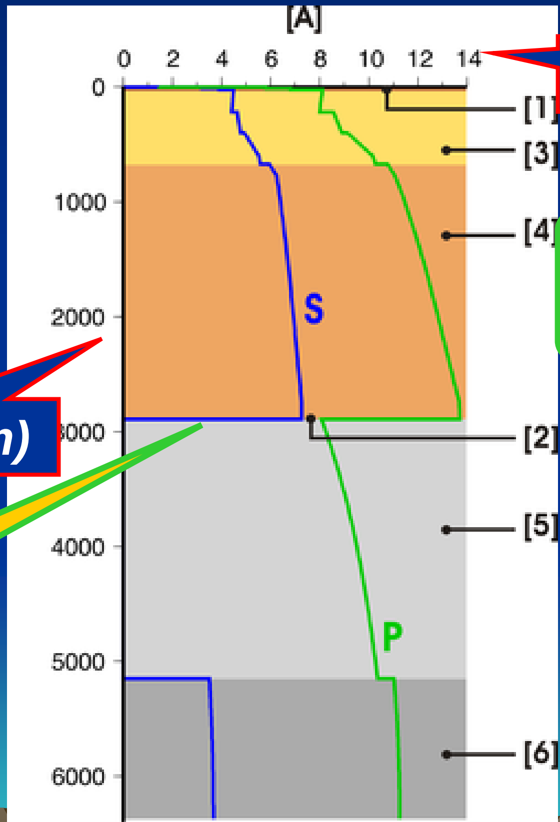


- P waves (primary waves) are longitudinal body waves
- S waves (secondary waves) are transverse body waves
- L and R waves (Love and Raleigh waves) are horizontal and elliptical surface waves
- free oscillations are surface wave with wavelength comparable with the circumference of the Earth



Wave propagation in the Earth

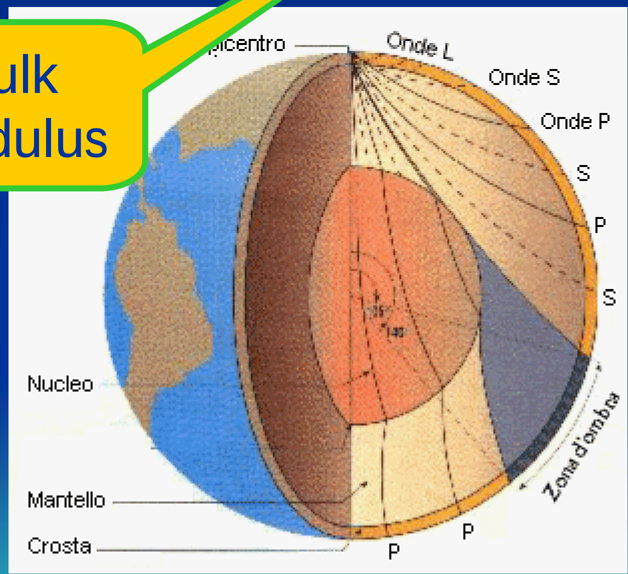
In solids, the P waves generally travel almost twice as fast as S waves and can travel through any type of material. S waves can travel only through solids, as fluids (liquids and gases) do not support shear stresses.



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

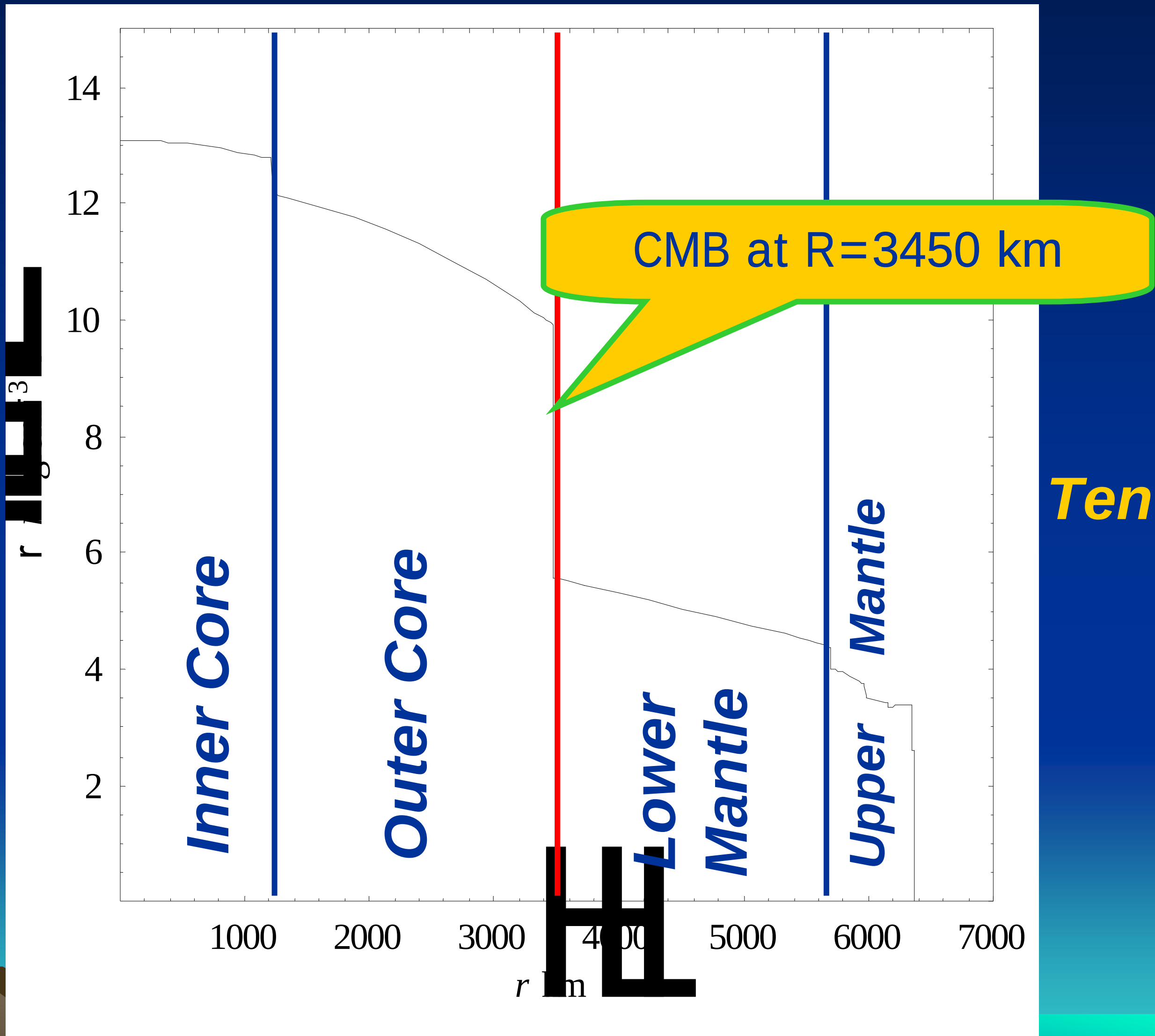
bulk modulus

modulus of rigidity



Preliminary Reference Earth Model (PREM)

A.M. Dziewonski and D.L. Anderson, Phys. Earth Planet. Inter. 25, 297 (1981)



Ten layers

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 can require an independent confirmation.

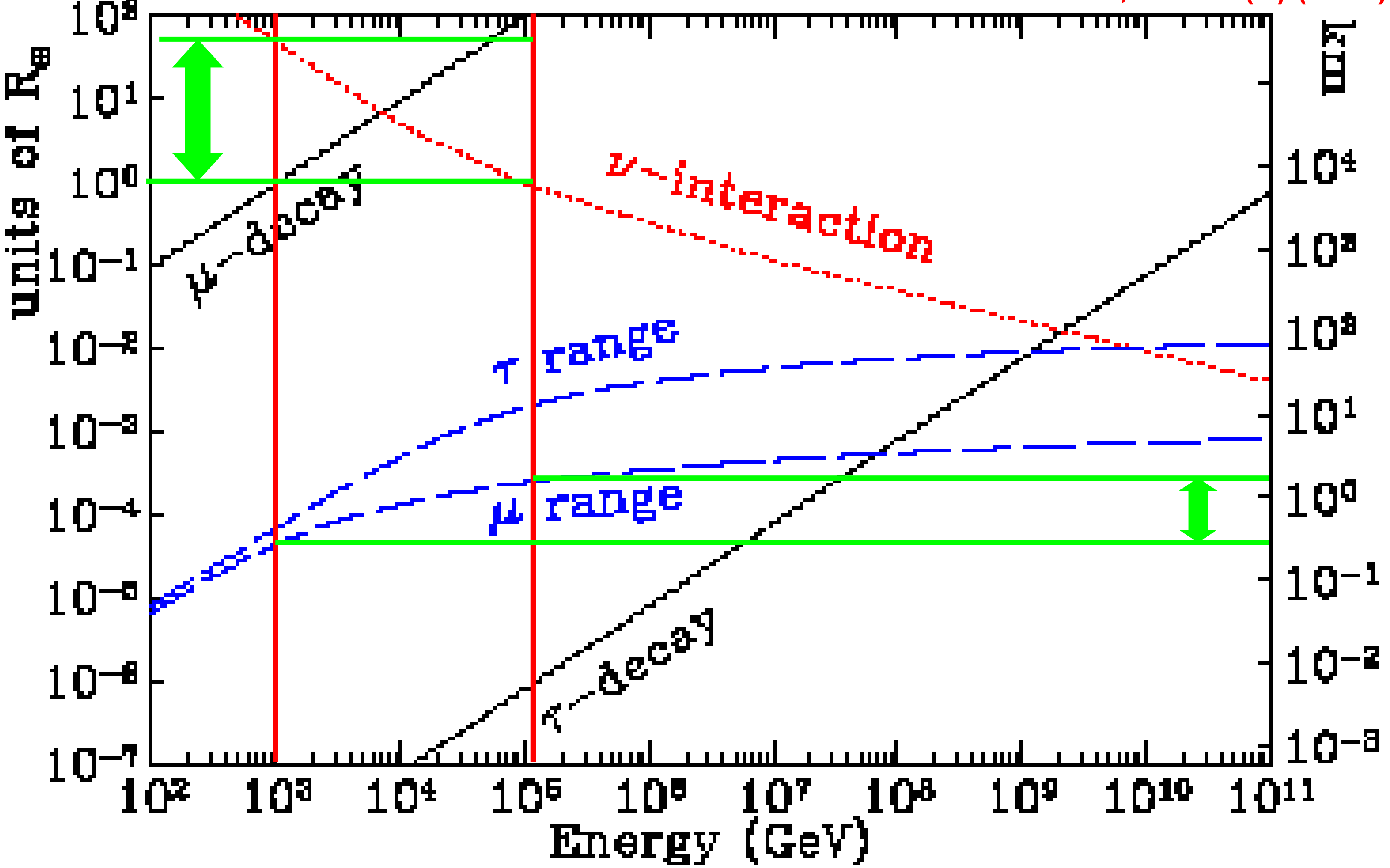
Limits of seismic tomography

• Global seismic tomograp… limited by the irregularity in time and space of the source… and by the incomplete coverage of recording stations. Th… 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.

Neutrinos are elusive particles!

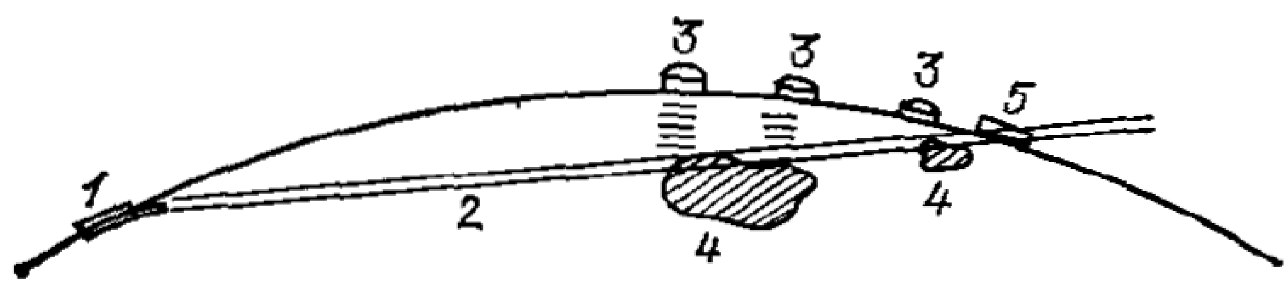
PRD 66, 021302(R) (2002)



Earth radiography by neutrinos

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

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



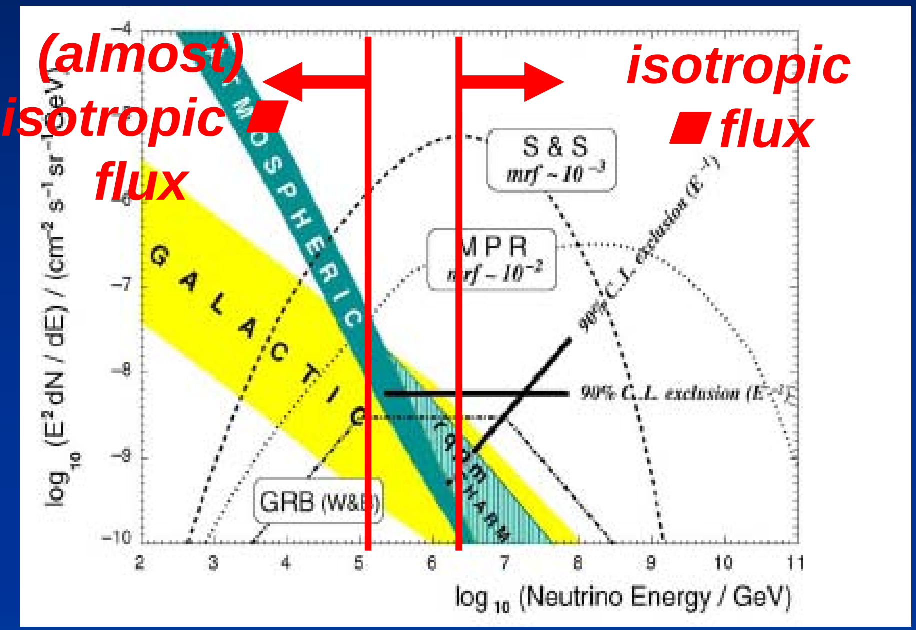
Askaryan, Usp. Fiz. Nauk 144, 523 (1984)

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?

Astrop. Phys. 20 (2004) 507



Neutrinos

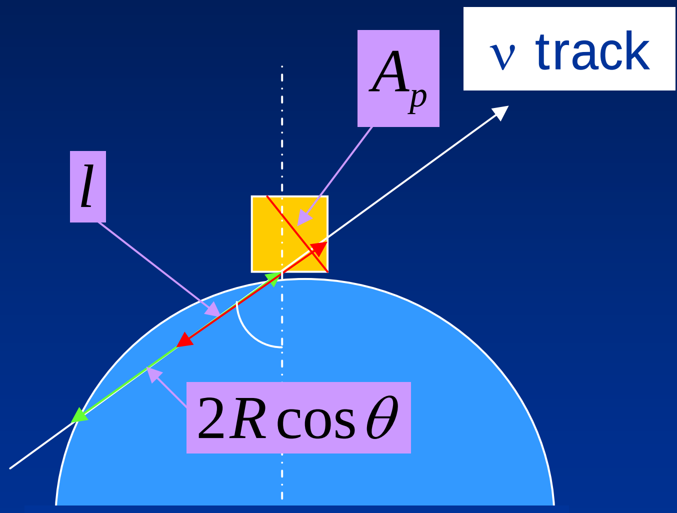
Neutrinos are one of the components of cosmic radiation. The atmospheric and the extragalactic contributions, which are mainly isotropic, dominates on the galactic component in two energy regimes. In particular, for $E \lesssim 10^5$ GeV the statistics of atmospheric ν is larger than that expected from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

Probe of geophysical structures

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

Event rate can be written as

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

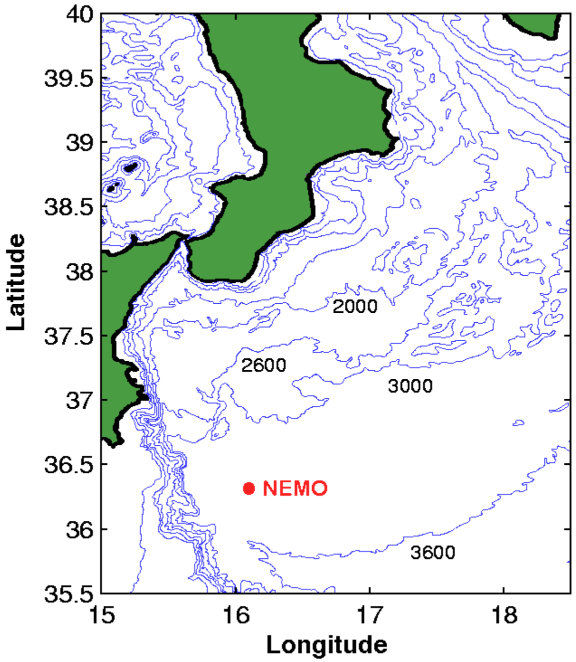


where the ***effective area***, $A_{eff} \cong \rho \, \sigma \, N_A \, V_{eff}$, (the detector effective volume, $V_{eff}=A_p \, l$, divided by the neutrino interaction length) is ***sensible to the density of matter*** crossed by neutrinos.

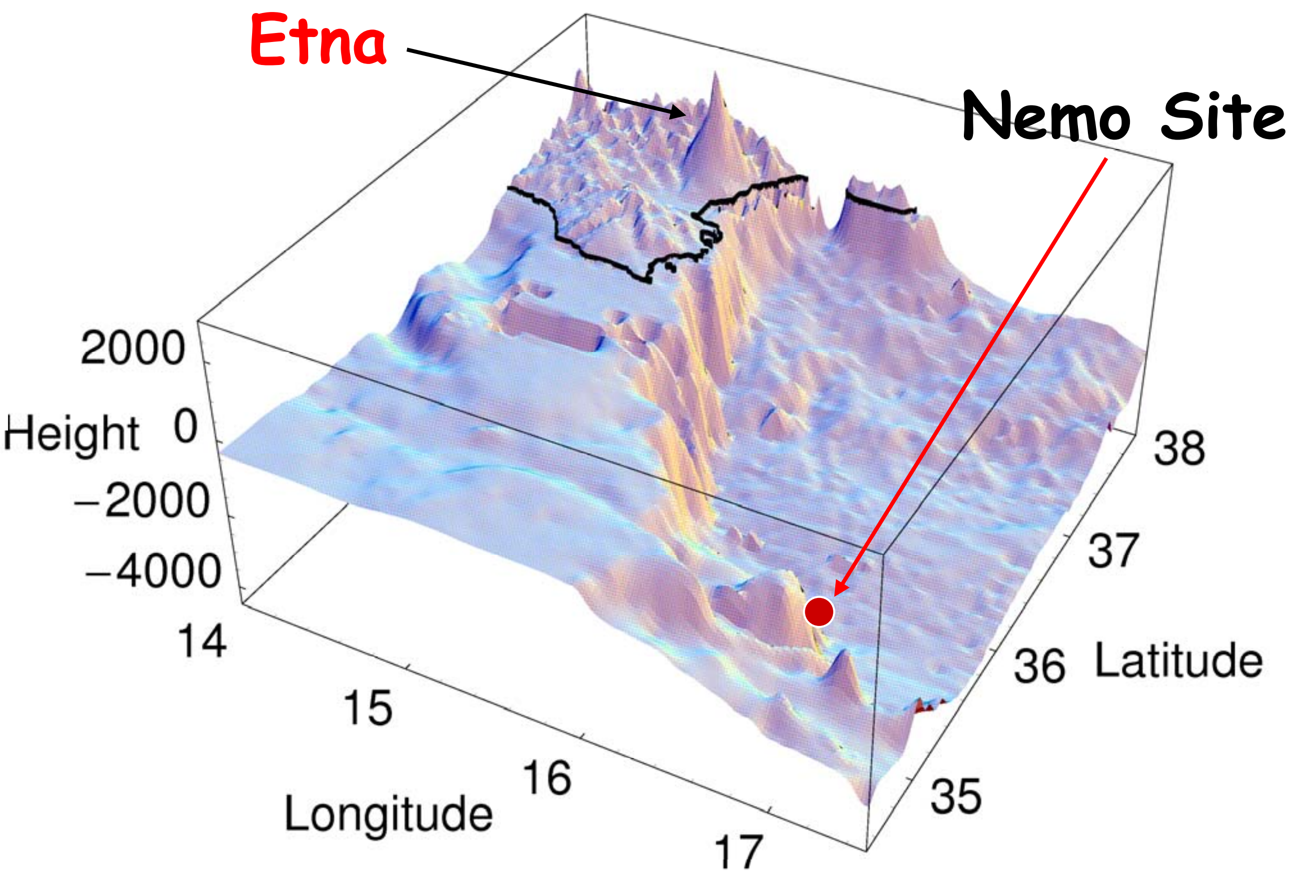
A_p = area of the detector projected against the neutrino direction

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

NEMO Site



We consider an under sea km^3 NT

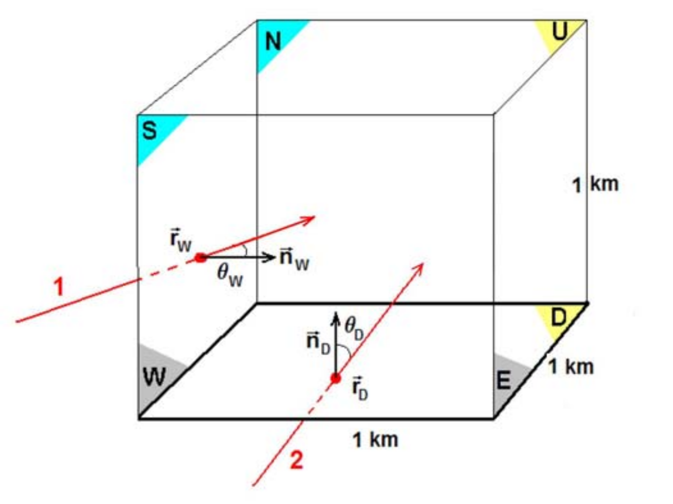


- Site Location
  36°21′ N, 16°10′ E
- Average Deep
  ”3500 m
  (3424 in our simulation)

The rate of lepton events in 1 km^3

$$\frac{dN_l}{dt} = D \sum_a \int d\Omega_a \int dS_a \int dE_\nu \frac{d^2\Phi_\nu(E_\nu,\theta_a)}{dE_\nu d\Omega_a} \int dE_l\, \varepsilon(E_l) \cos(\theta_a)\, k_a^l(E_\nu, E_l; \vec{r}_a, \Omega_a)$$

Same calculation for Auger in PLB634:137-142 (2006)

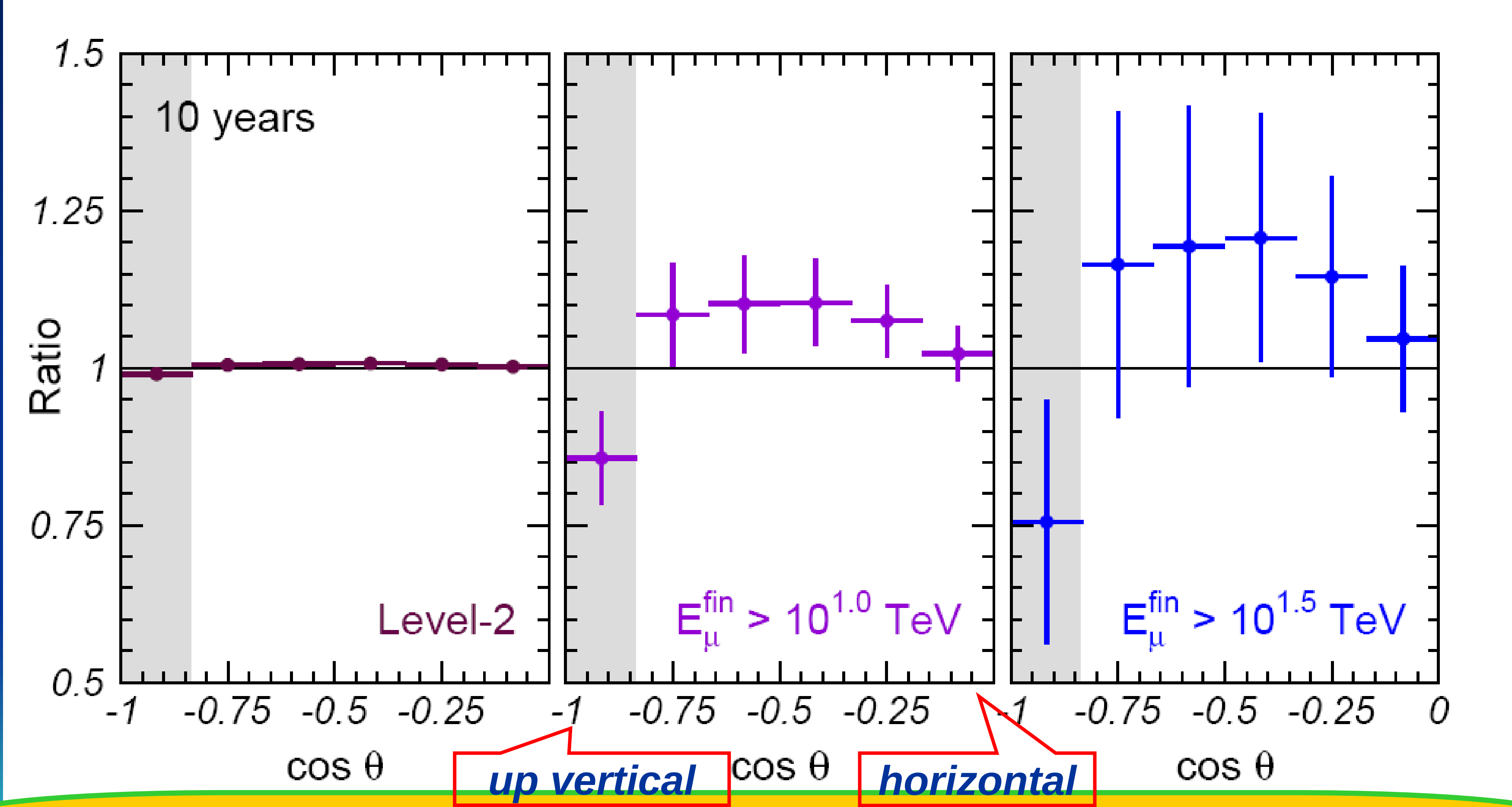


PRD 77:045019 (2008)

Probability that an incoming ν, with energy E_ν and direction Ω_a, crossing the Earth, produces a lepton l which enters the fiducial volume with energy E_l through the lateral surface dS_a at the position r_a.

PREM versus homogeneous

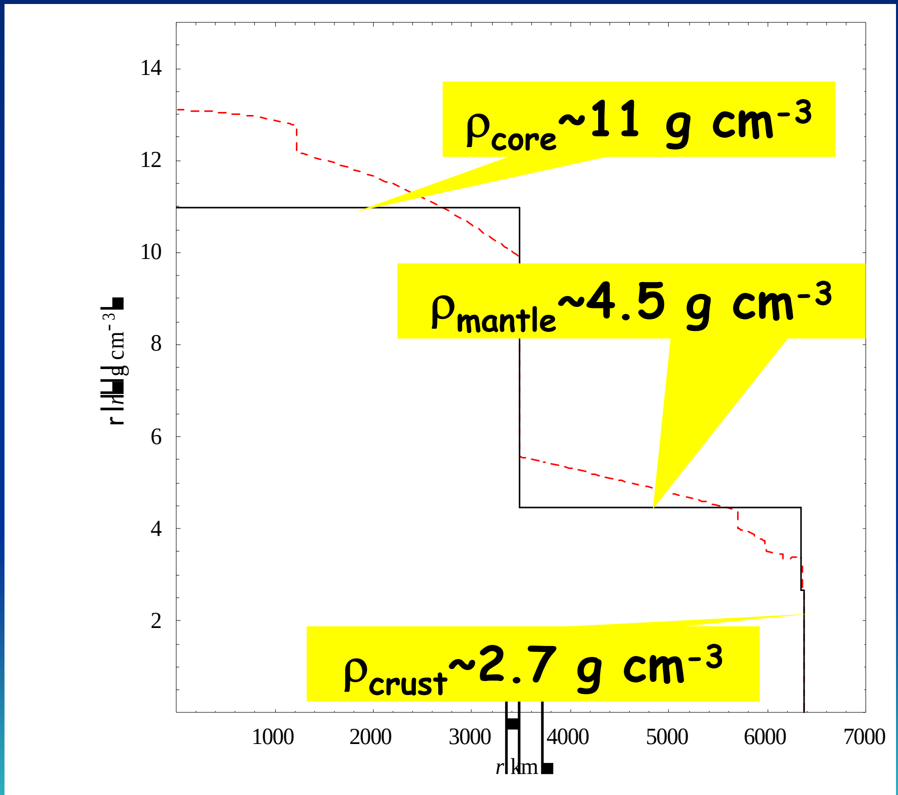
Gonzales-Garcia, Halzen, Maltoni, Tanaka, PRL100 (2008) 061802

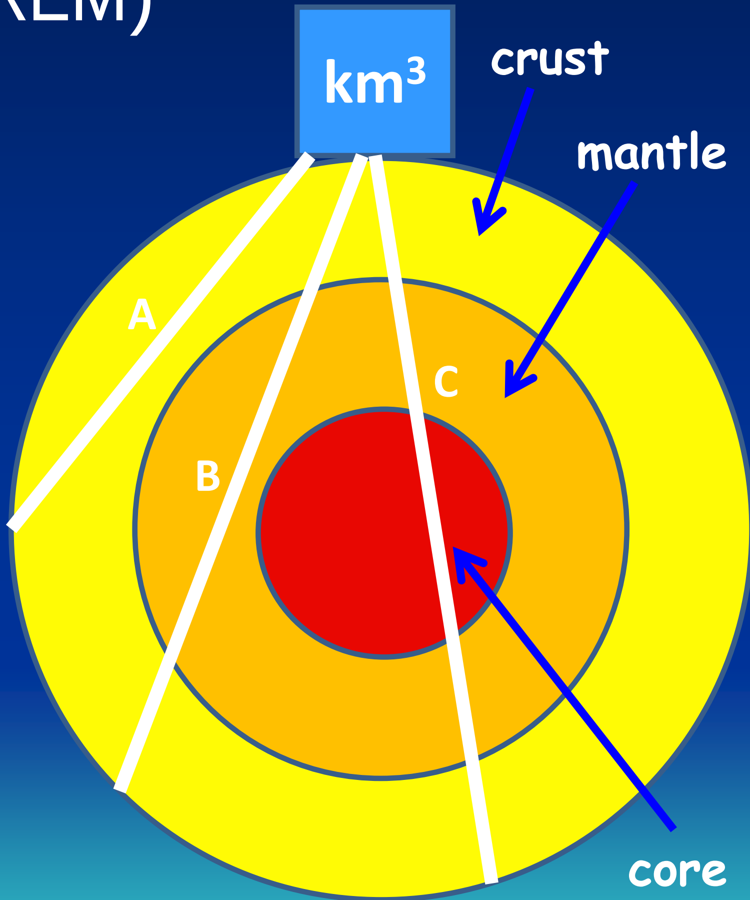


For high E_{th} the attenuation factor due to the earth density becomes relevant and the number of detected events gives information on the earth density.

Neutrinos through the Earth

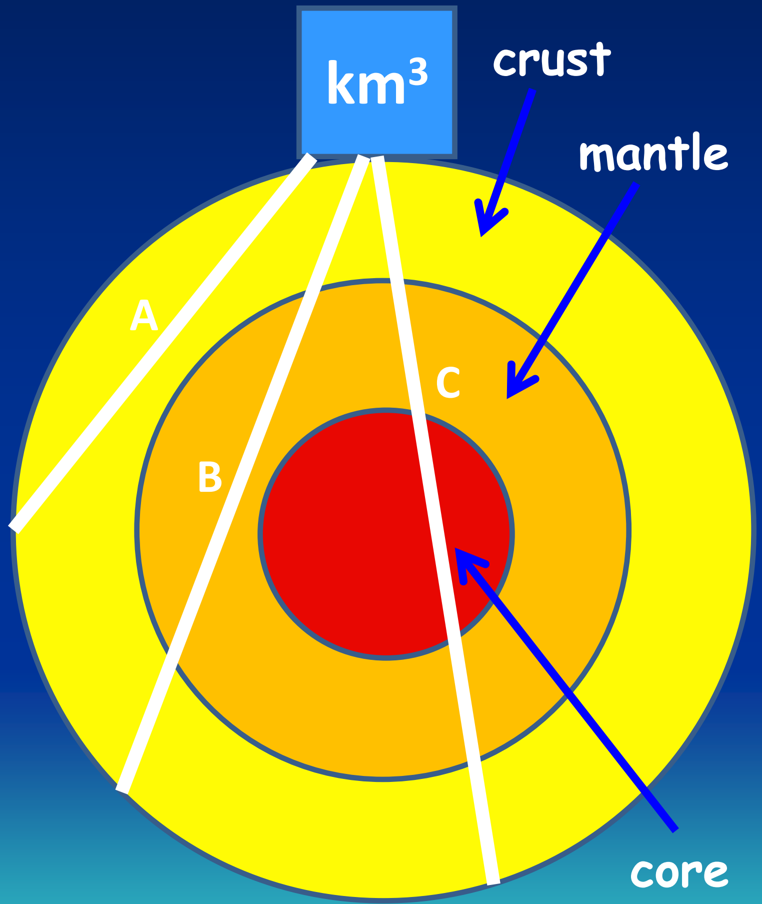
A simplified parametrization of Earth radial density profile (sPREM)





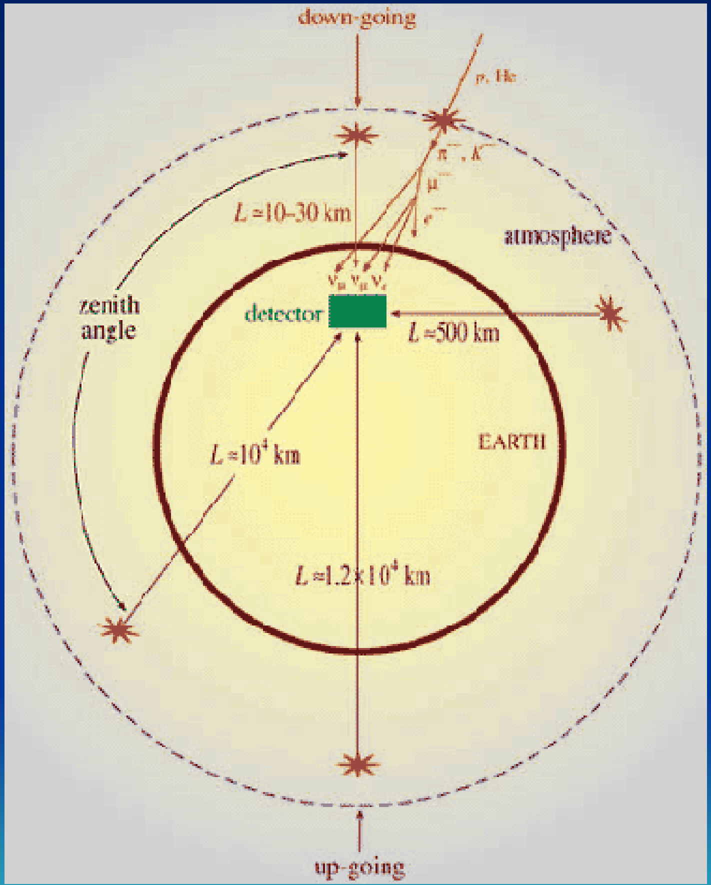
Neutrinos through the Earth

- 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)

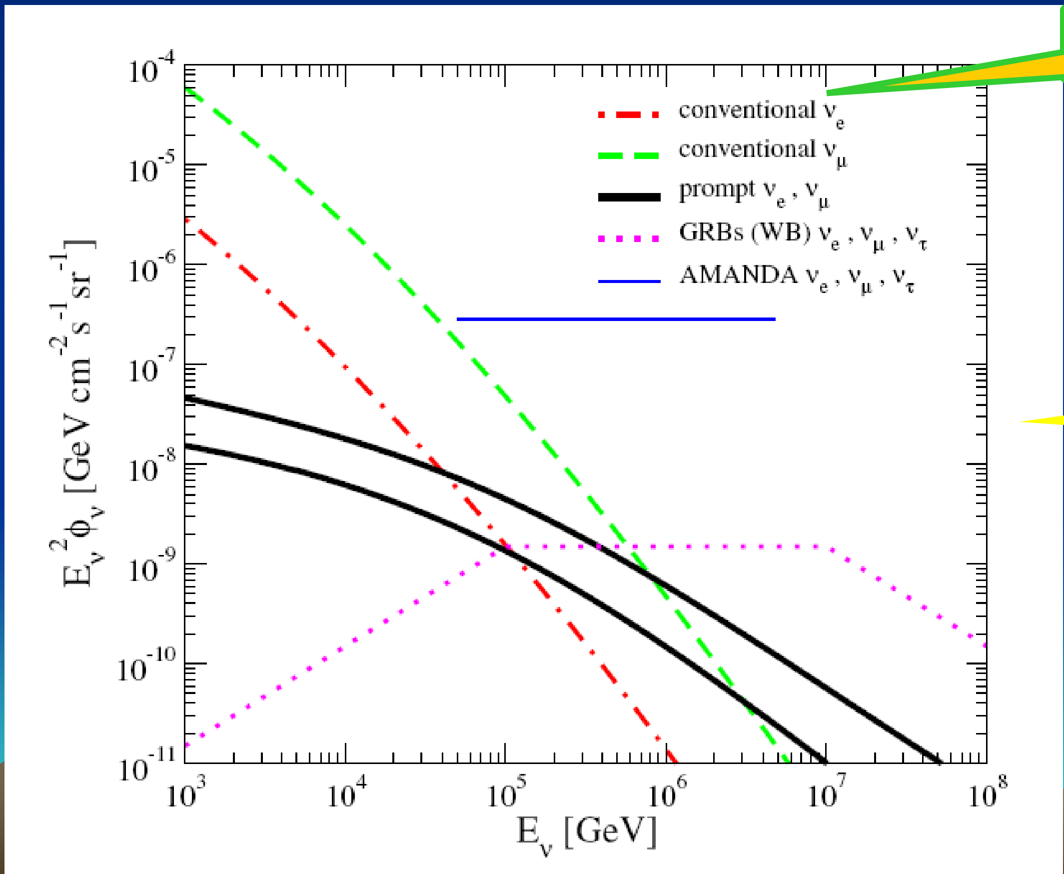
Atmospheric Neutrinos



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

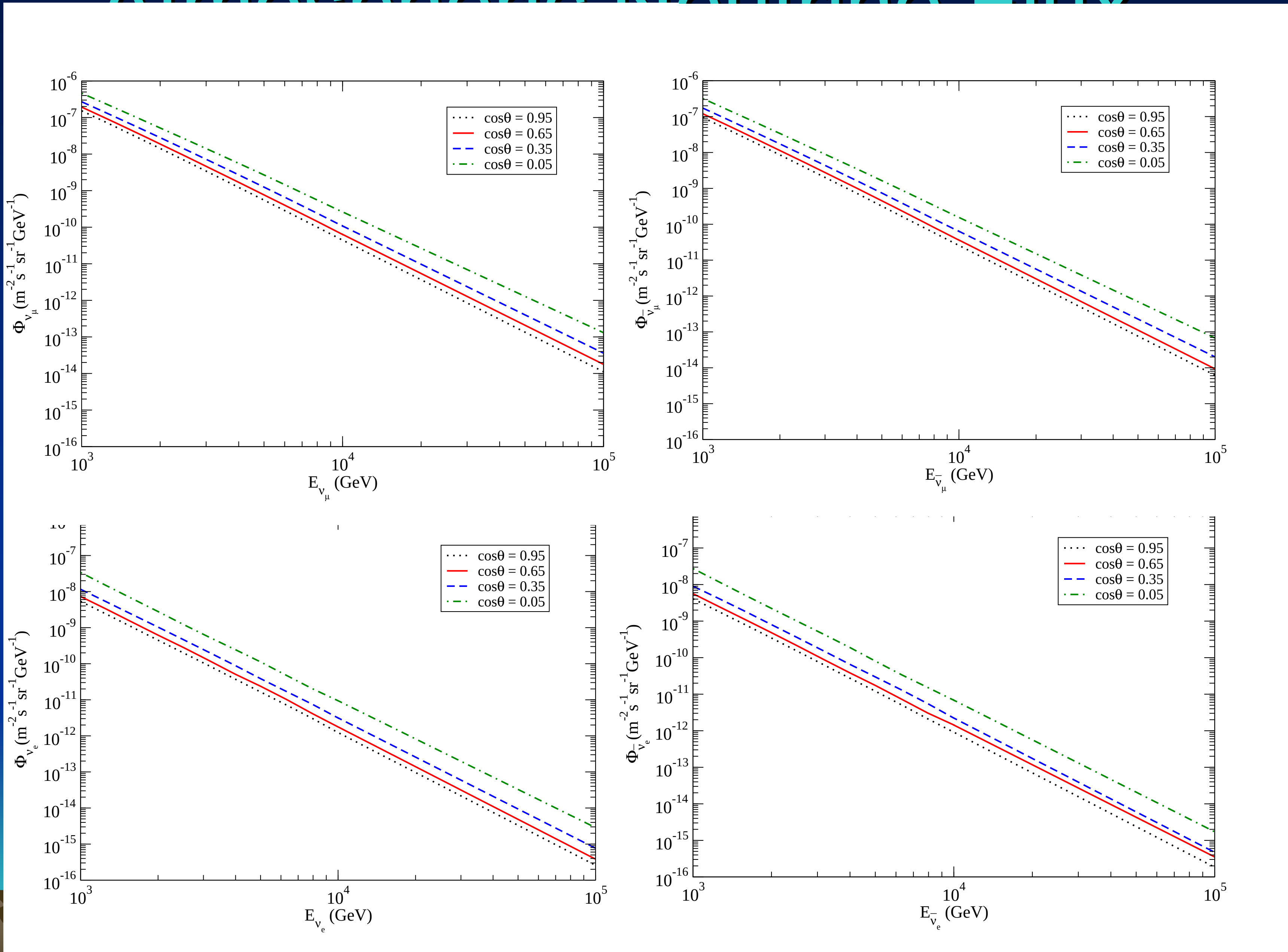
The "conventional" part comes from pion and kaon decays (low energy), a "prompt" isotropic contribution from short lived charmed hadrons (high energy). In the energy range of interest, the contribution from kaons dominates (~80%) and decay of muons can be neglected. Tau neutrinos are negligible since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



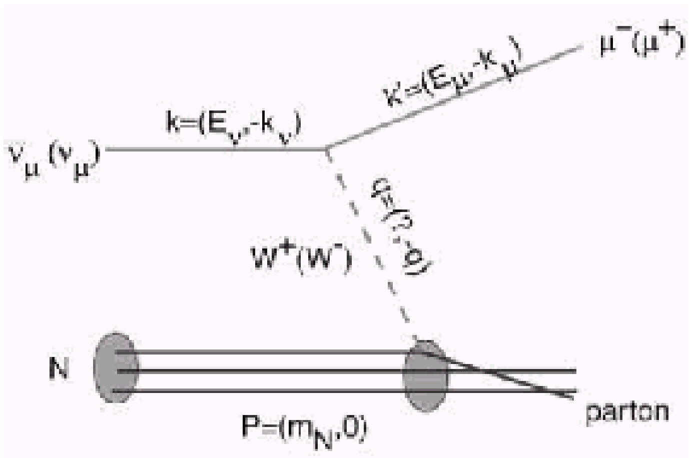
Averaged over zenith angle

Beacom & Candia, JCAP 11, 009 (2004)

Atmospheric Neutrino Flux



Neutrino interaction



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

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

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

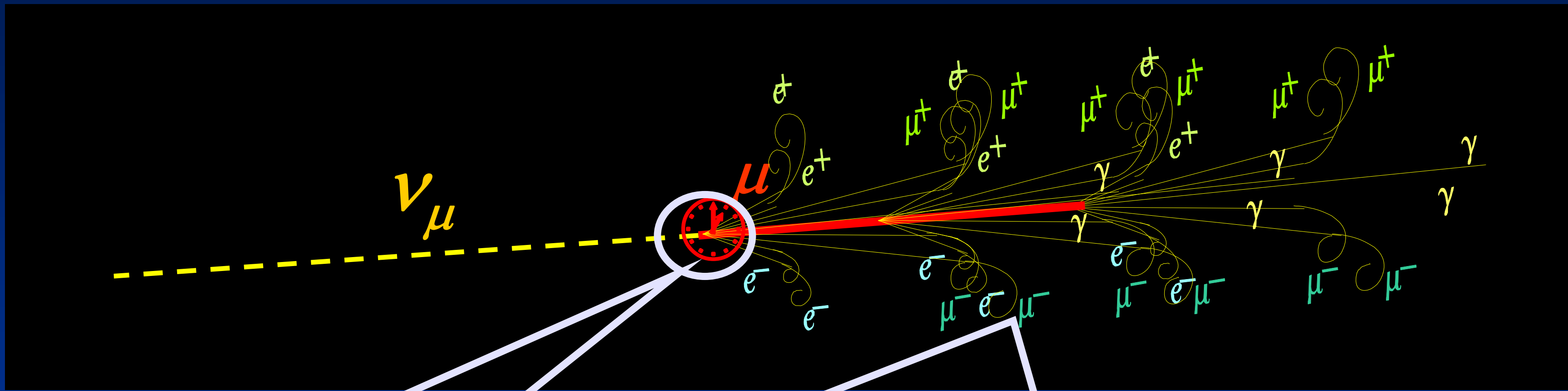
$Q^2 = 2\, m_N\, E_\nu\, x\, y$

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}

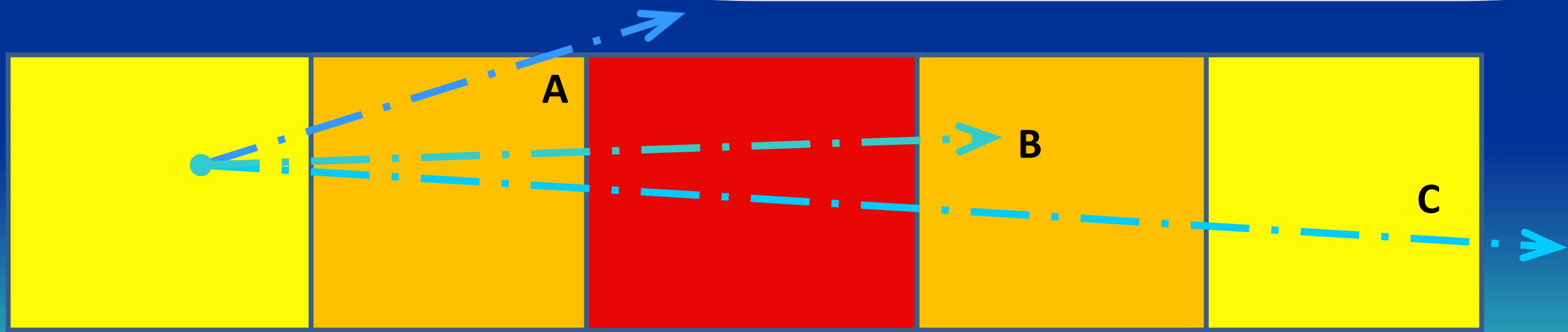
R. Gandhi, C. Quigg, M.H. Reno, and I. Sarcevic, 1998

Event simulation



First Interaction

Muon Propagation in matter

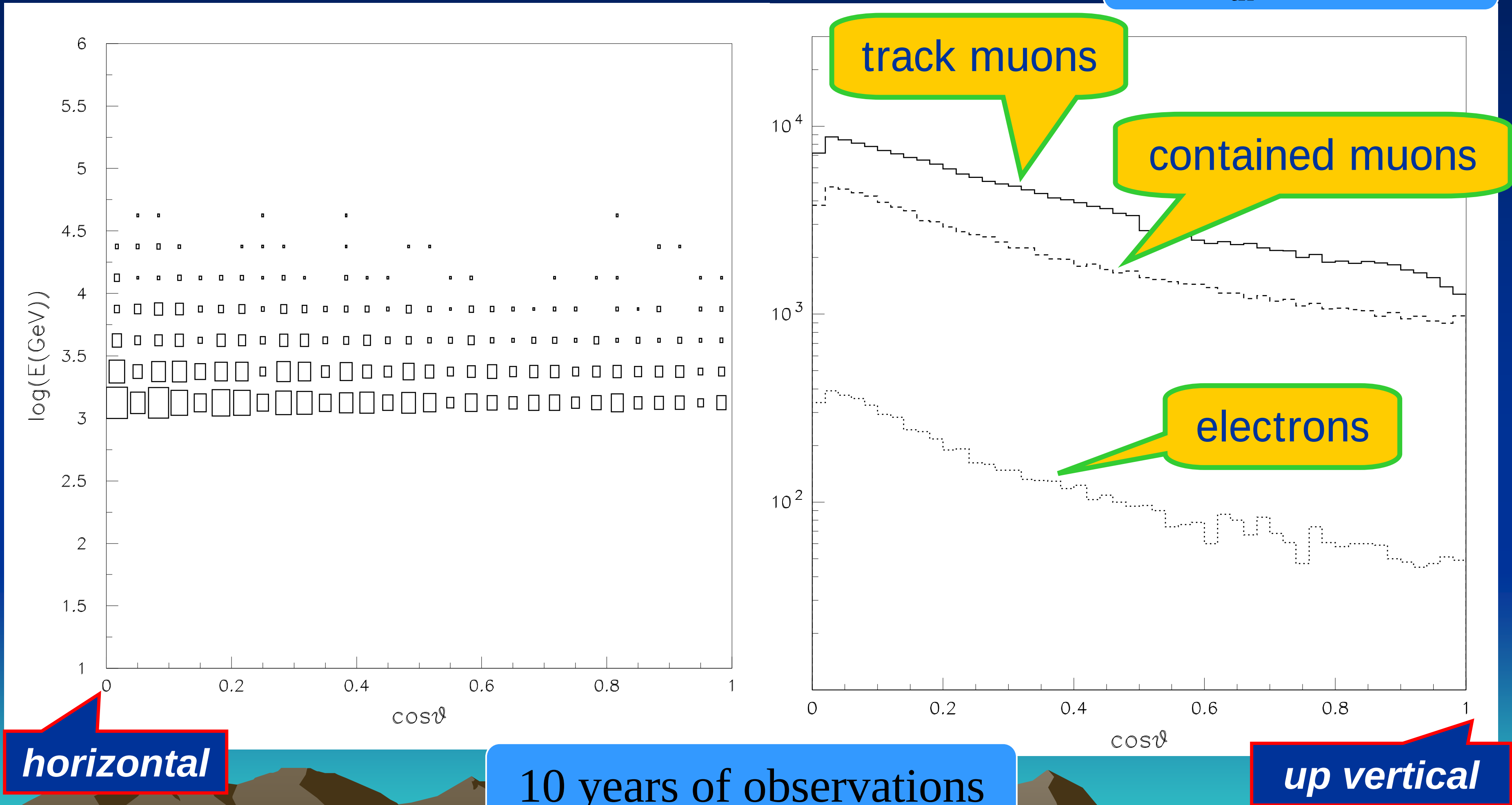


Summary of simulation details

- *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 (optimized value!)
- 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

E_{th}=1 TeV



10 years of observations

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 for E_{th} = 1 TeV (optimized value).

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

Δξ=0.25

overall uncertainty on ϕ and σ

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

uncertainty on ϕ due to ang. distr.

Δη =0.05

expected counts for the sPREM

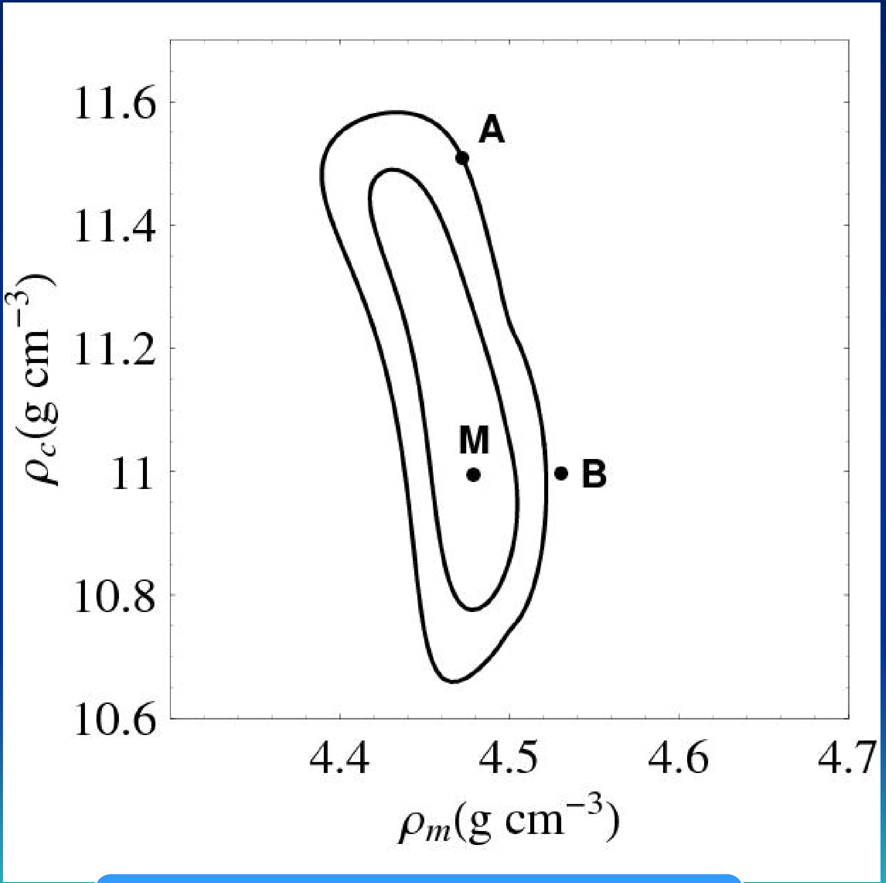
Likelihood analysis

E_{th}=1 TeV

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

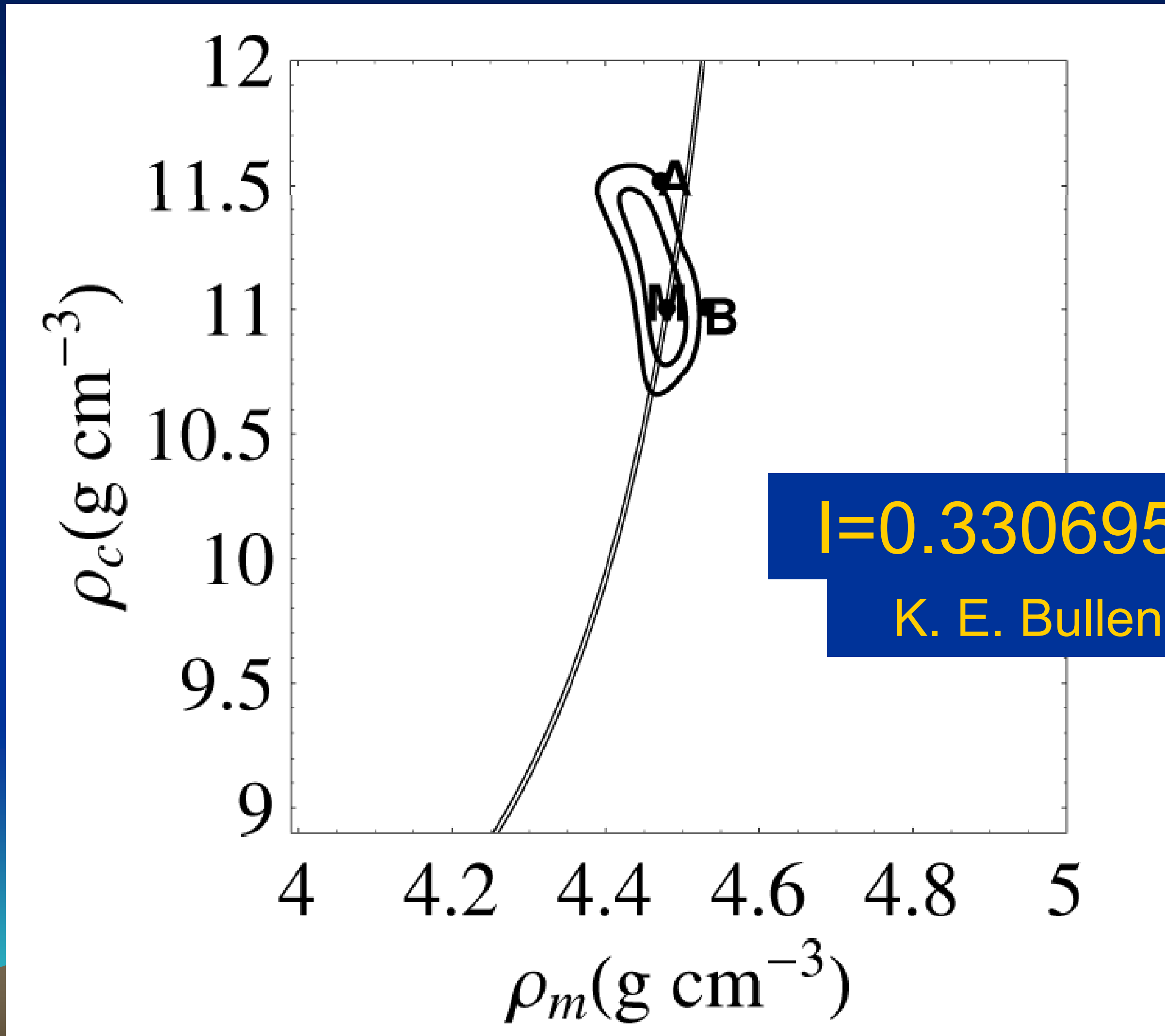
$$\rho_m = 4.47\,^{+0.02}_{-0.03}\,\left(^{+0.04}_{-0.06}\right)\ \mathrm{g\ cm^{-3}}$$
$$\rho_c = 11.0\,^{+0.3}_{-0.1}\,\left(^{+0.5}_{-0.2}\right)\ \mathrm{g\ cm^{-3}}$$
$$R_c = 3440 \pm 30\,\left(^{+70}_{-50}\right)\ \mathrm{km}$$

$\cos\vartheta$	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

Taking into account the Moment of Inertia of the Earth



$I=0.330695\ M_E\ R_E^2$

K. E. Bullen *1930'*

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 with no details of the experimental apparatus
- Low number of model parameters $\Rightarrow$ good level of sensitivity in their determination $\Rightarrow$ By using all geological inputs one can perform a more realistic study expecting a good resolution on the free parameters