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Spectrometry of the Earth using neutrino oscillations

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Abstract

We demonstrate that large neutrino detectors could be used in the near future to significantly improve our understanding of the Earth's inner chemical composition. Each composition model predicts a characteristic ratio of protons to neutrons or equivalently electrons to nucleons. Neutrinos, which are naturally produced in the atmosphere, traverse the Earth and undergo oscillations that depend on the Earth's electron density. Contrarily seismic measurements are sensitive to the matter density. Hence, by combining observations from large neutrino detectors with seismic measurements the Earth's chemical composition can be constrained. We present a method that will allow us to distinguish between composition models of the outer core. We demonstrate that the understanding of the chemical composition of the deep Earth could be significantly improved using large neutrino detectors.

Introduction

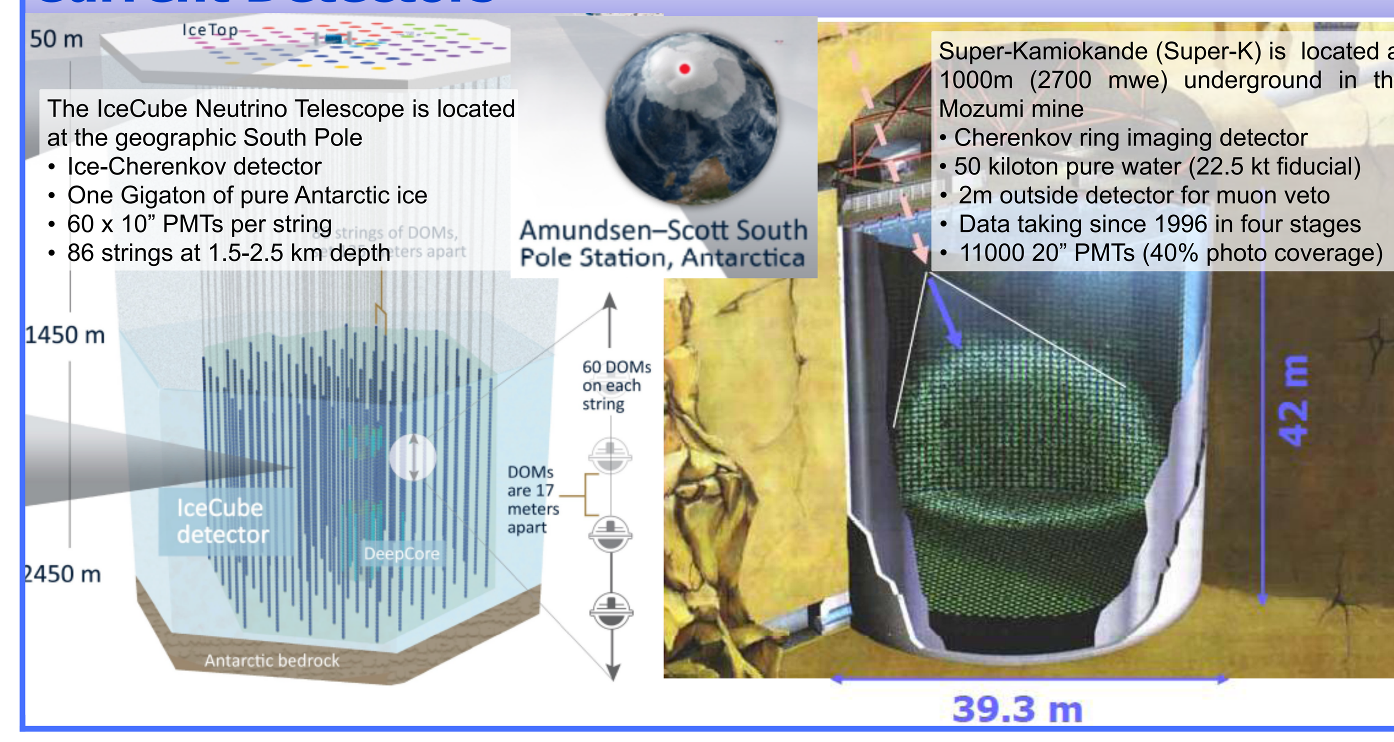
Mass density structure of the Earth well know from seismic data

Inner Earth elemental composition cannot be directly measured

Light elements besides Iron and Nickel are required to match observed densities at outer core pressures

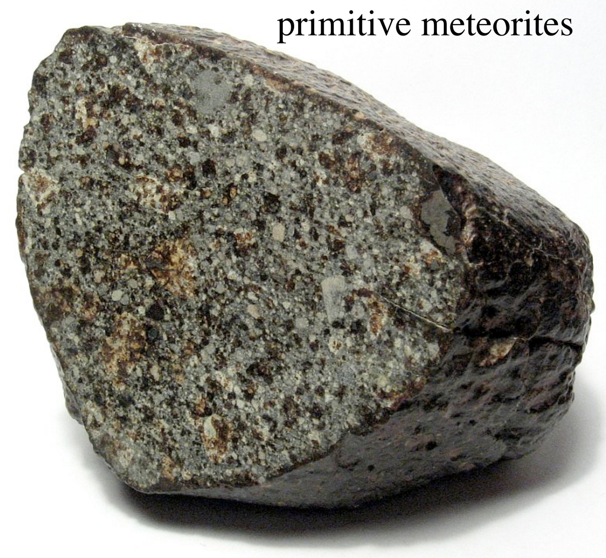
The electron density is related to the mass density,ρ , via the factor Y = Z/A (the proton to nucleon ratio), weighted by the relative elemental abundances.

Current Detectors

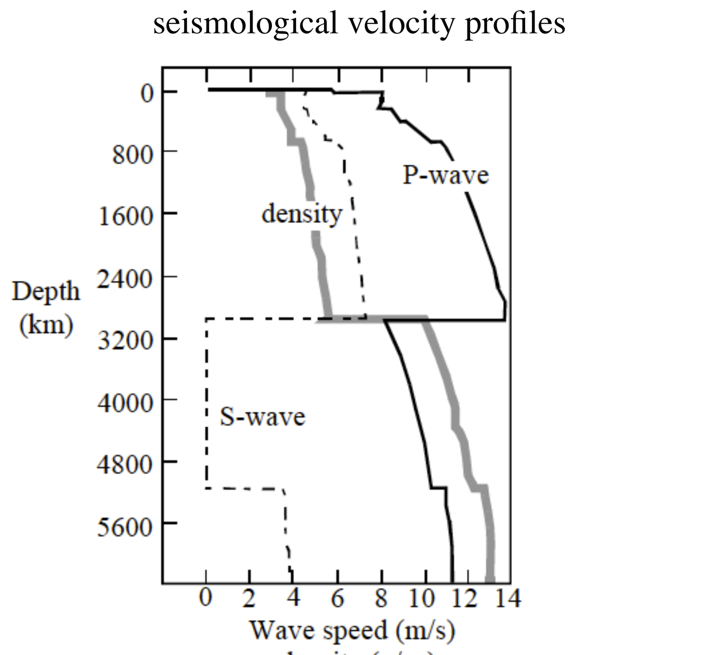


How to determine the Inner Earth Composition ?

primitive meteorites



seismological velocity profiles



William F. McDonough "The Composition of the Earth"

high pressure experiments

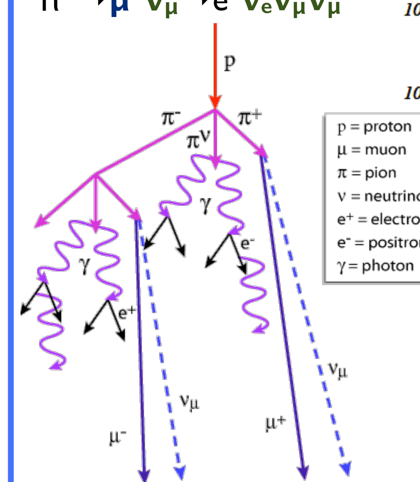
Model name	Z/A ratio	O(wt%)	C(wt%)	S(wt%)	H(wt%)	Si(wt%)
Single-light-element model (maximum abundance)						
Fe + 11 wt%O[32,56]	0.4693	11	—	—	—	—
Fe + 12 wt%C[5]	0.4697	—	12	—	—	—
Fe + 13 wt%S[5]	0.4699	—	—	13	—	—
Fe + 1 wt%H[5]	0.4709	—	—	—	1	—
Fe + 18 wt%Si[32]	0.4715	—	—	—	—	18
Multiple-light-element model						
Huang2011[31]	0.4678	0.1	—	5.7	—	—
McDonough2003[30]	0.4682	0	0.2	1.9	0.06	6
Allegre2001[29]	0.4699	5	—	1.21	—	7

Atmospheric Neutrinos

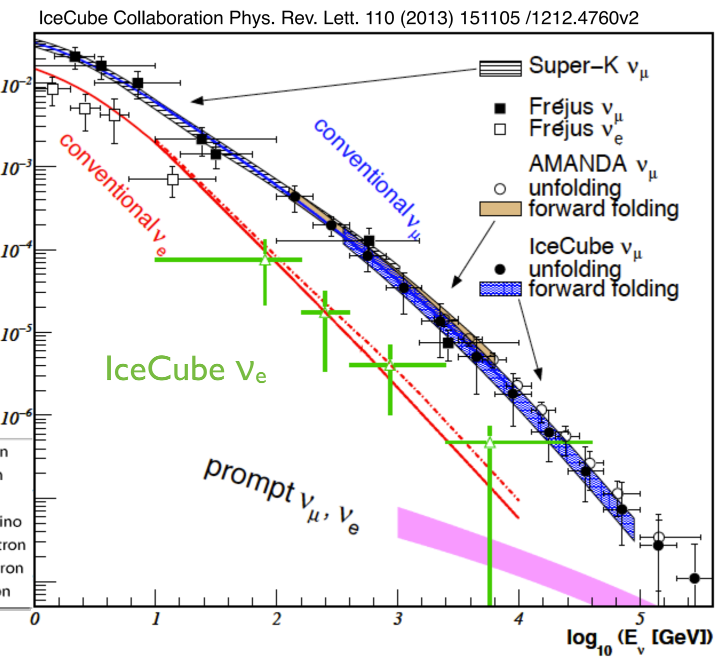
Cosmic rays interact in the upper atmosphere and produce neutrino in particle showers

p + A → π± (K±) + other hadrons …

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$



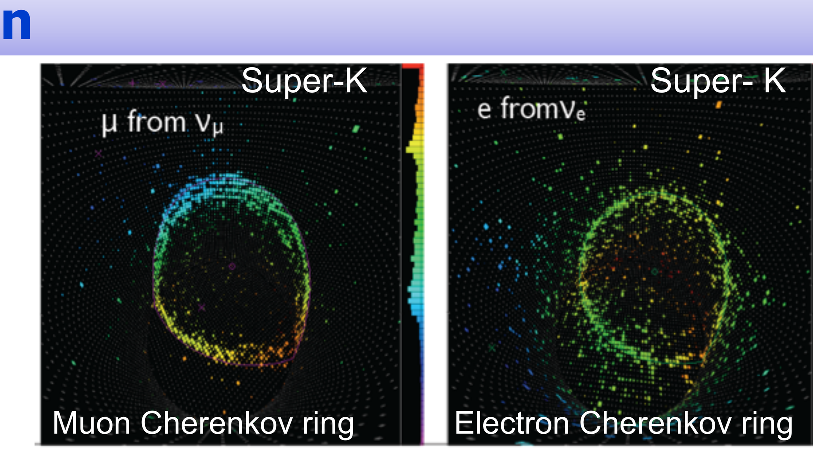
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2

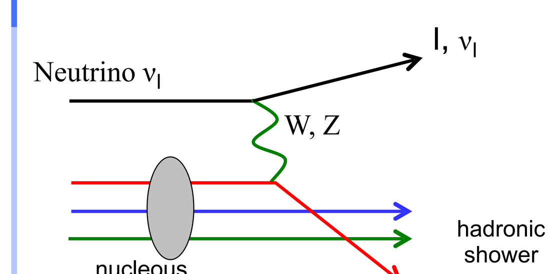


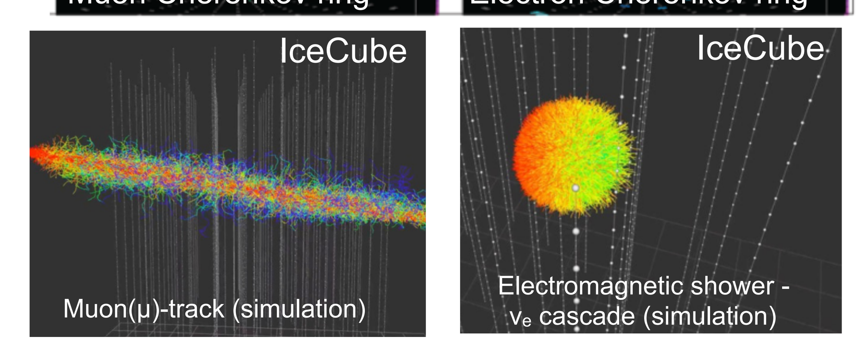
Atmospheric neutrinos give a natural well understood source of high energy neutrinos

Neutrino (ν) Detection

Cherenkov radiation from secondary particles produced in a neutrino interaction in an optical transparent medium can be observed by sensor arrays. Examples for Super-Kamiokande and IceCube are shown on the right.







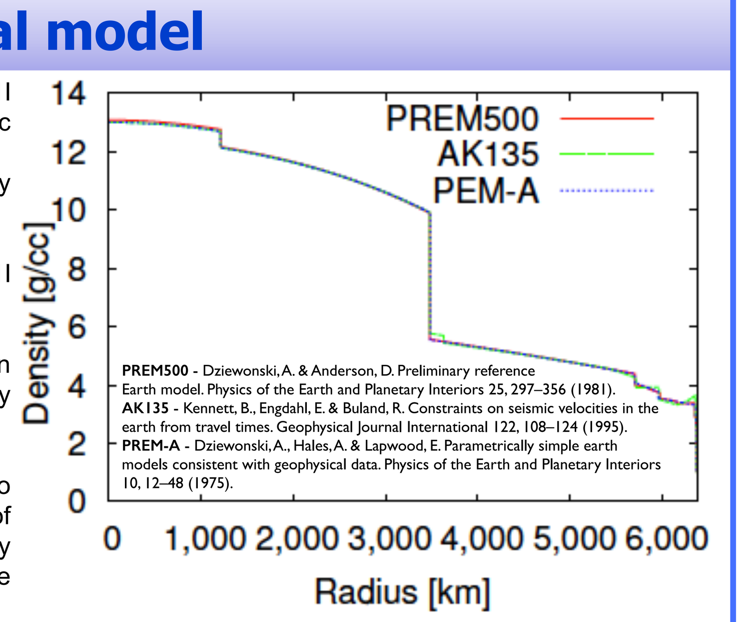
Earth structural model

Earth structure very well understood based on seismic measurements.
Standard model is the Preliminary Reference Earth Model (PREM)

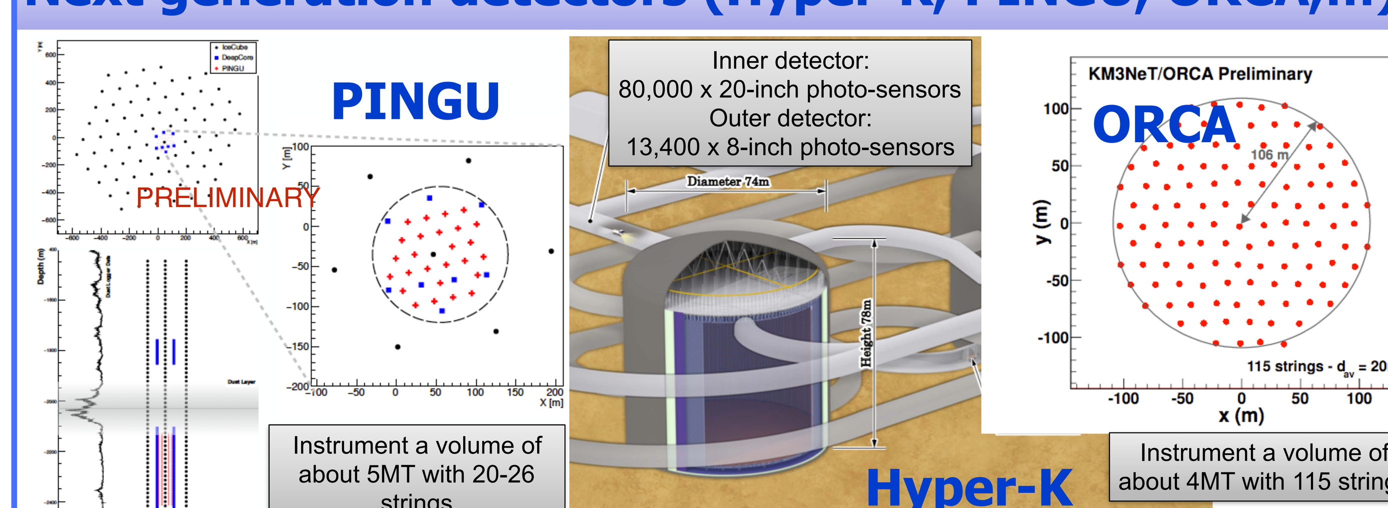
Composition far less well understood

The average composition determines the electron density based on the mass density

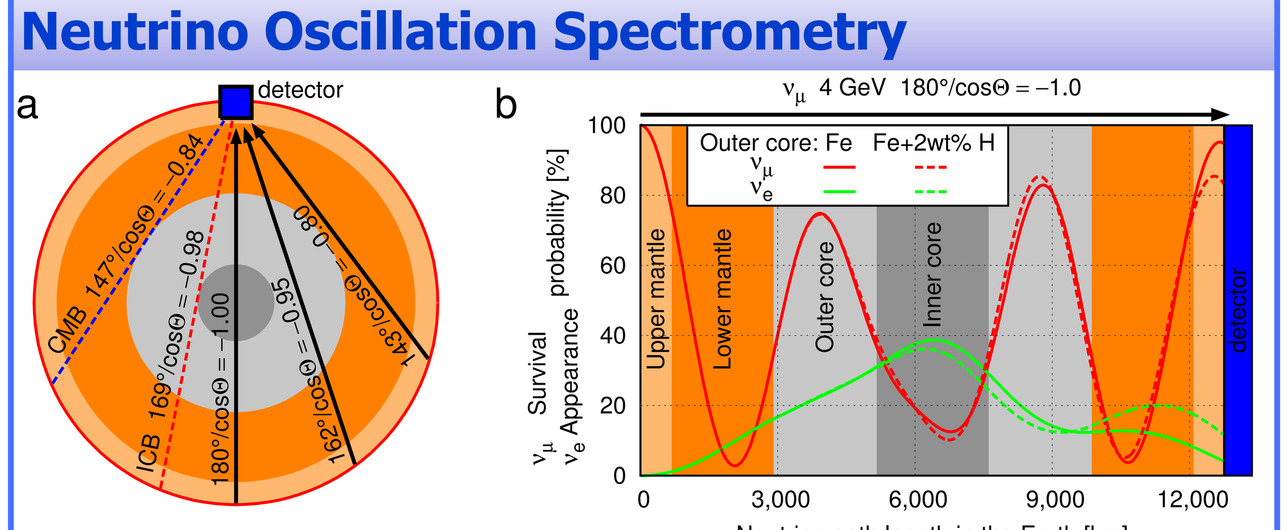
Mantle composition is assumed to be pyrolite (hypothetical mixture of distinct minerals, which accurately represent the constituents of the Earth's mantle)

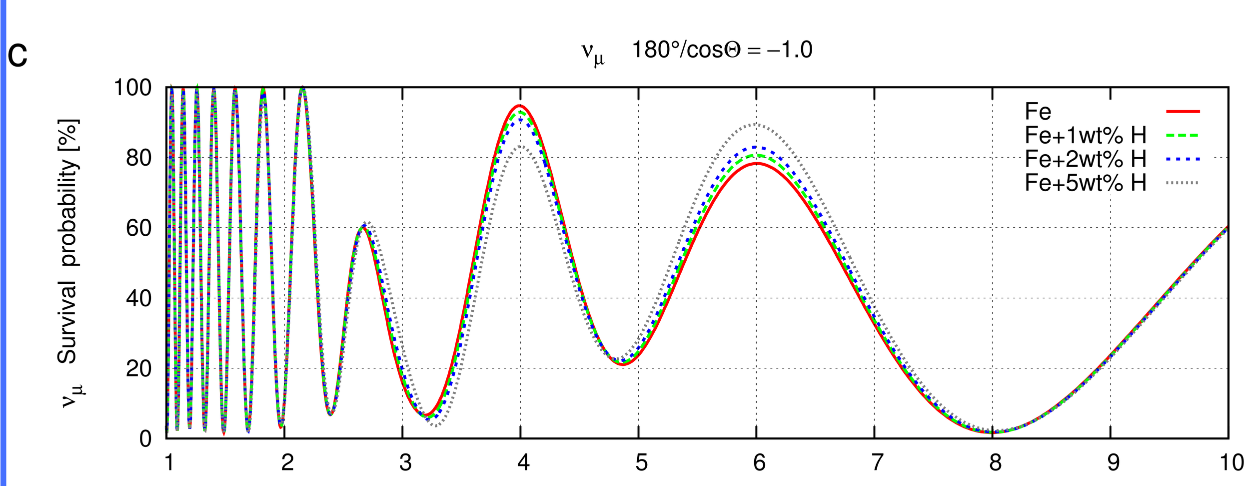


Next generation detectors (Hyper-K, PINGU, ORCA,…)



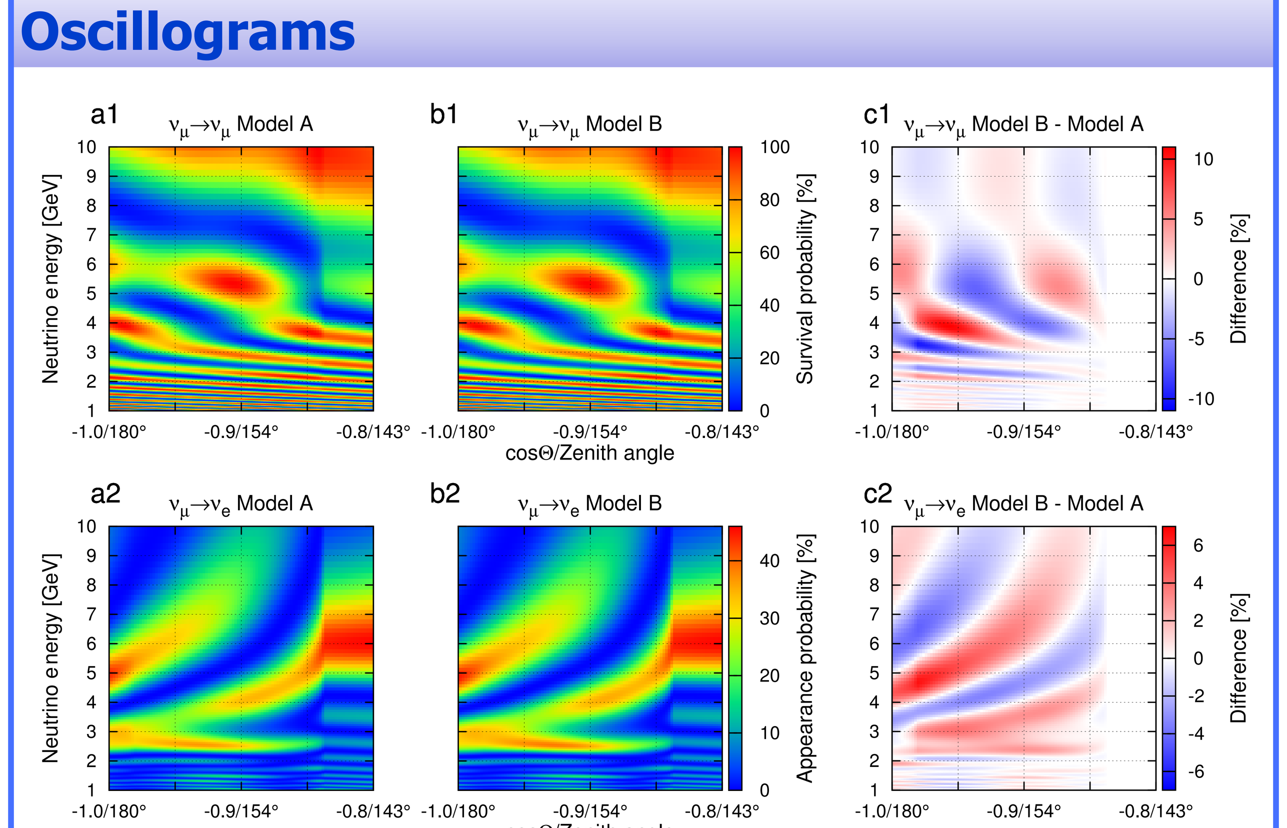
Neutrino Oscillation Spectrometry





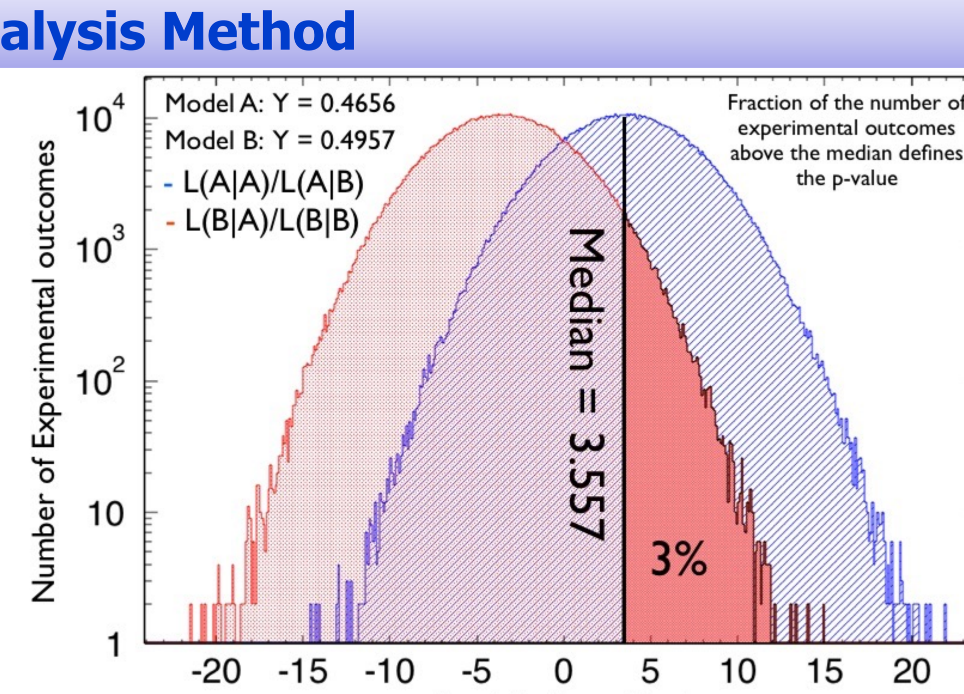
Schematic diagram of a neutrino's path through the Earth and the corresponding zenith angles. Inner core boundary (ICB) at 169º and the core mantle boundary (CMB) at 147º are shown.

Oscillograms



Comparison of oscillation probabilities for different core compositions: Model A – iron; Model B – an mixture of iron and 2 wt% hydrogen.

Analysis Method



Log-likelihood method. Ensembles of pseudo datasets are drawn from each template m_{ij}^A and m_{ij}^B that are repeatedly varied following Poisson statistics. The log of the Poisson likelihood of the pseudo data for a specific bin is calculated with respect to the corresponding bin in m_{ij}^B and m_{ij}^A. Given an experimental outcome O, with bins o_{ij}, we take the sum of $(-2)\log\left(\mathrm{P}\left(o_{ij}, m_{ij}^A\right)\right)$ to obtain the total likelihood. In this way, for each pseudo dataset, two likelihoods are calculated and are labelled $\mathcal{L}$ (pseudo data, template). The likelihoods are used to calculate LLR. We calculate two distributions for pseudo data o_{ij} drawn from m_{ij}^A given by $\mathcal{L}(o(M^A)|M^A)/\mathcal{L}(o(M^A)|M^B)$ and $\mathcal{L}(o(M^B)|M^A)/\mathcal{L}(o(M^B)|M^B)$. A total of 10,000 pseudo datasets are used to achieve adequate coverage of the probability space. We obtain expected significances from our ensemble of pseudo experiments. The probability of distinguishing model A from B is obtained by calculating the fraction of cases in which events drawn from M^A have a likelihood ratio that is more consistent with M^A than M^B. An illustration of this method is given in Fig. 3.

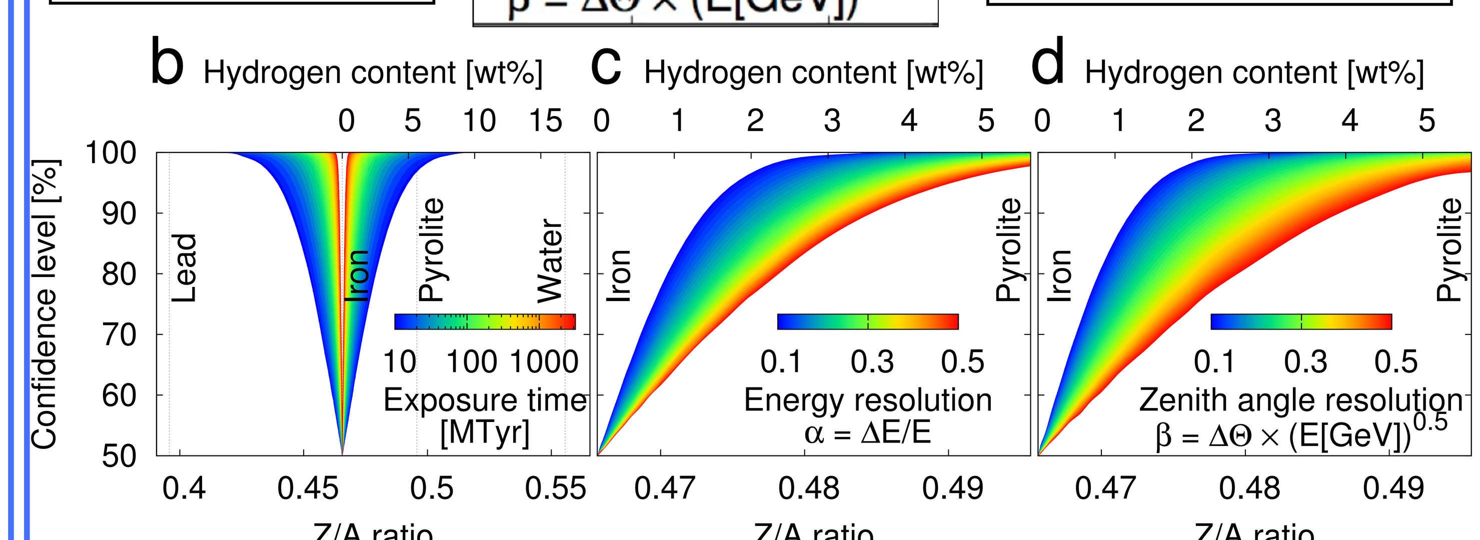
Neutrino Oscillation Spectrometry Sensitivity

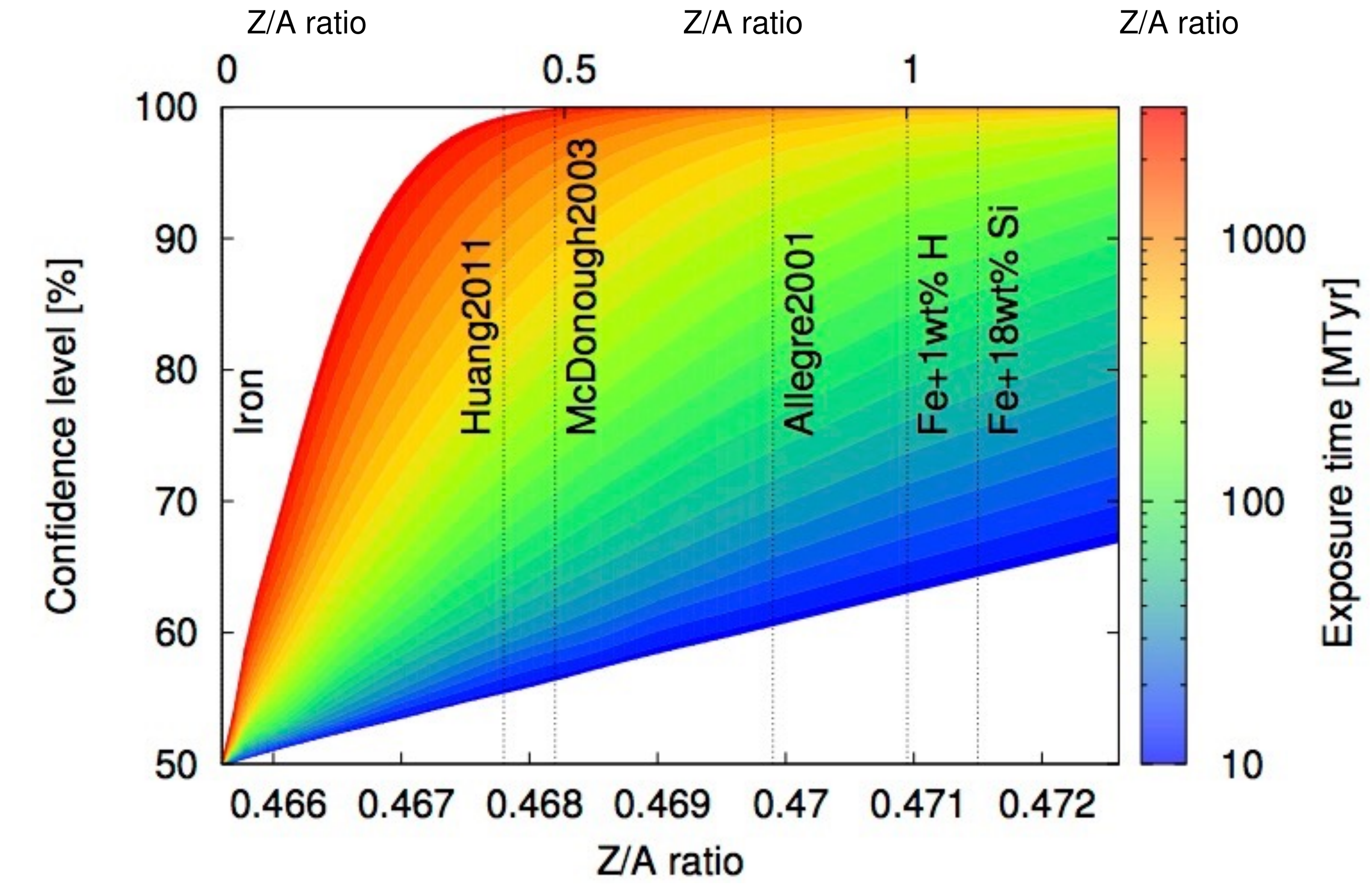
Sensitivities are evaluated for a generic detector

Energy resolution $\alpha = \Delta E/E$

Zenith angle resolution $\beta = \Delta\Theta \times (E[\text{GeV}])^{0.5}$

We adopt a value of α=0.2 and ΔΘ=0.25 as benchmarks





Conclusions

- Neutrino oscillation tomography offers the potential to measure the Earth interior composition
  - Good sensitivity to hydrogen
- PINGU/ORCA/Hyper-K could test extreme Earth Core composition models within first few years of operations (given normal mass hierarchy)
- Next-generation, large volume detectors are needed to distinguish specific core models
  - Very large - high statistics sample
  - Good energy resolution and angular resolutions
- More detailed studies are needed
  - Systematic uncertainties
  - Complementarity: Oscillation Tomography with high-pressure experiments, …
- Prospects of neutrino beams to be evaluated

References

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