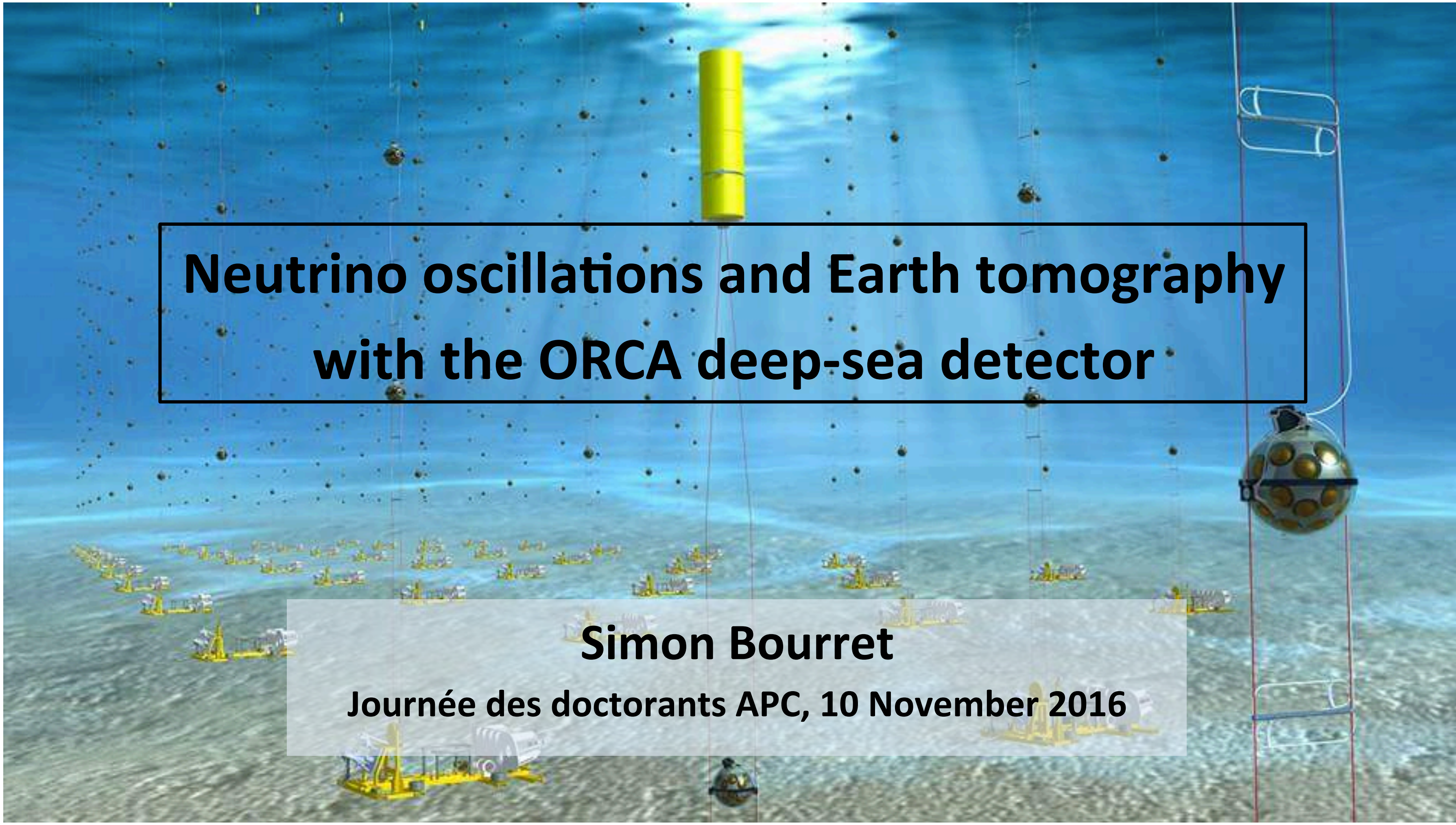
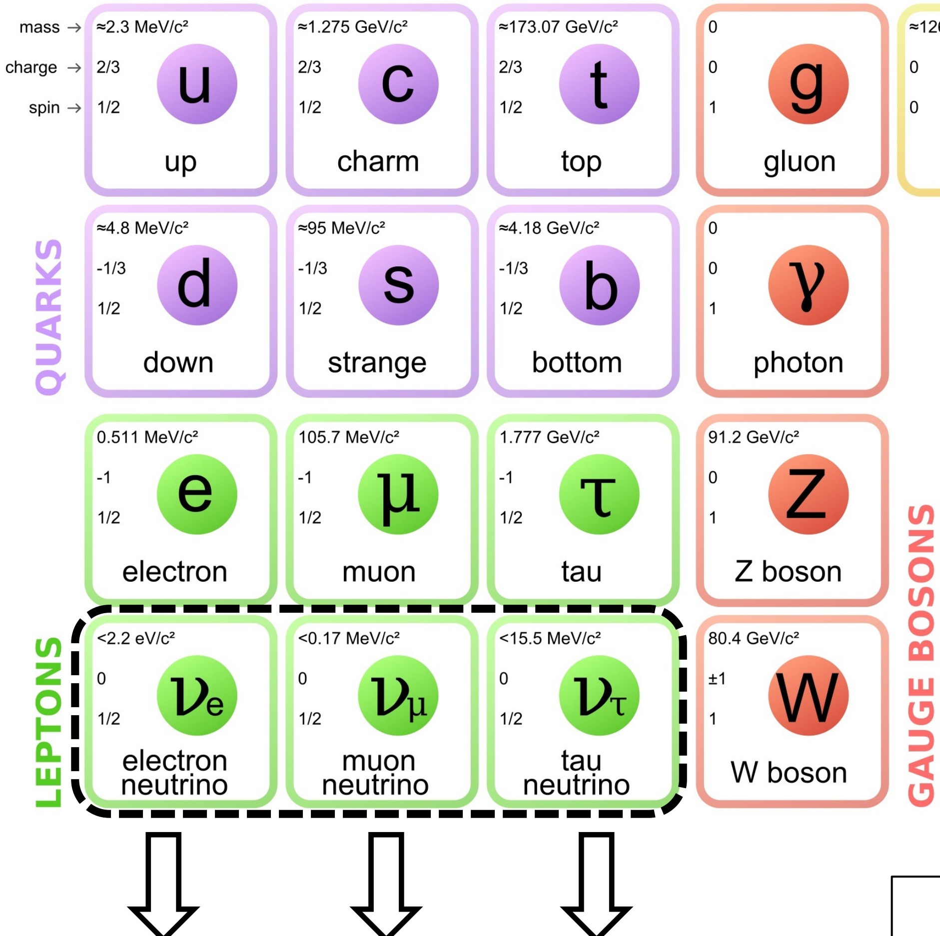


Neutrino oscillations and Earth tomography with the ORCA deep-sea detector

Simon Bourret

Journée des doctorants APC, 10 November 2016

Neutrino oscillations



- ✓ 3 generations or flavours
- ✓ flavour mixing

NEUTRINO

→ interacts very weakly with matter
→ massless in Standard Model
→ actually not massless… but almost !

(Flavour mixing) & (Distinct masses)

$\Downarrow$

Flavour oscillations

ORCA ?

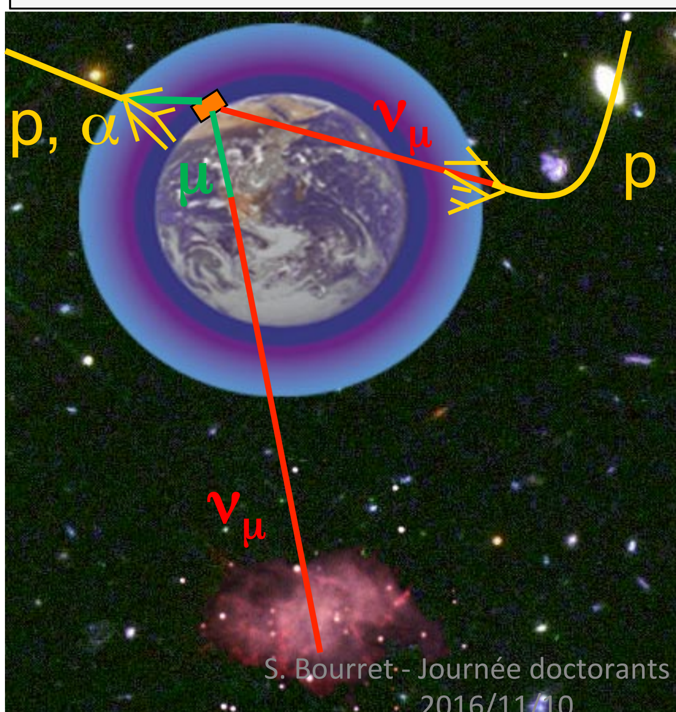
« Oscillation Research with Cosmics in the Abyss »

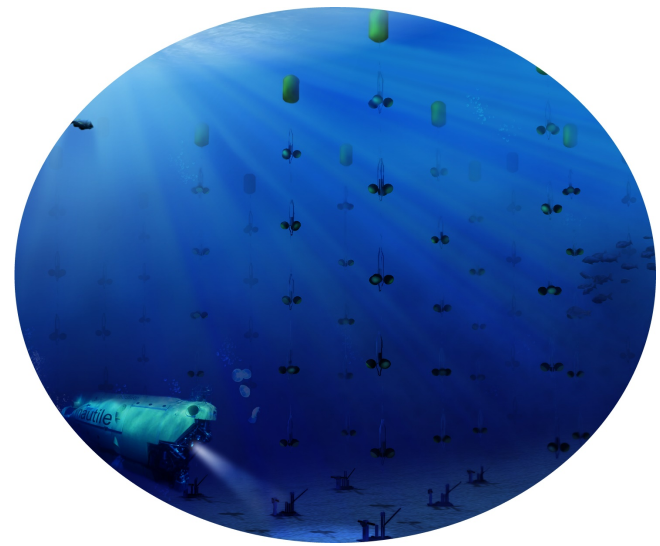
- ✓ *Very large detection volume*
- ✓ *Background reduction*

ORCA ?

« <u>O</u>scillation <u>R</u>esearch with <u>C</u>osmics in the <u>A</u>byss »

Cosmic rays induce atmospheric neutrinos





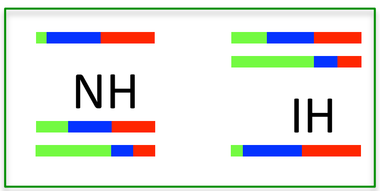
- ✓ *Very large detection volume*
- ✓ *Background reduction*

ORCA ?

« Oscillation Research with Cosmics in the Abyss »

Neutrino flavour oscillations

→ Neutrino mass hierarchy



→ Earth tomography

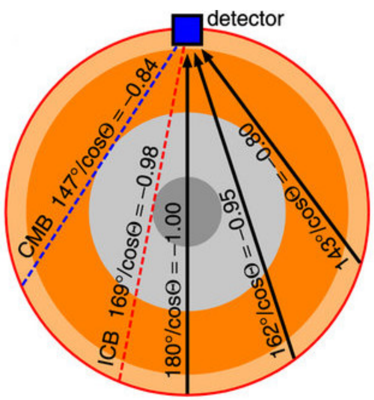
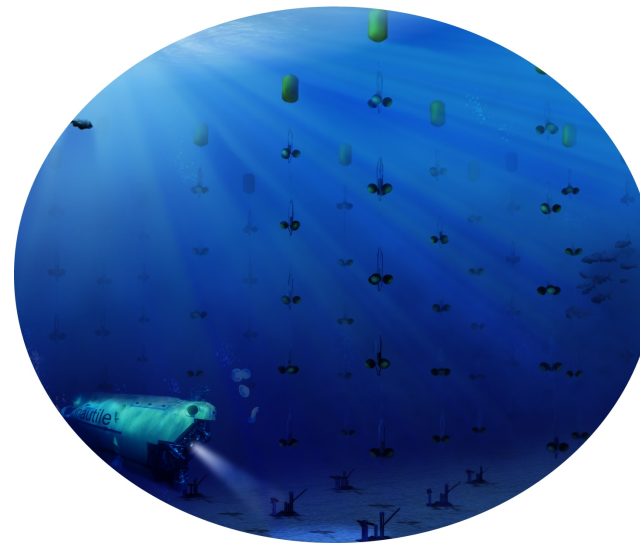


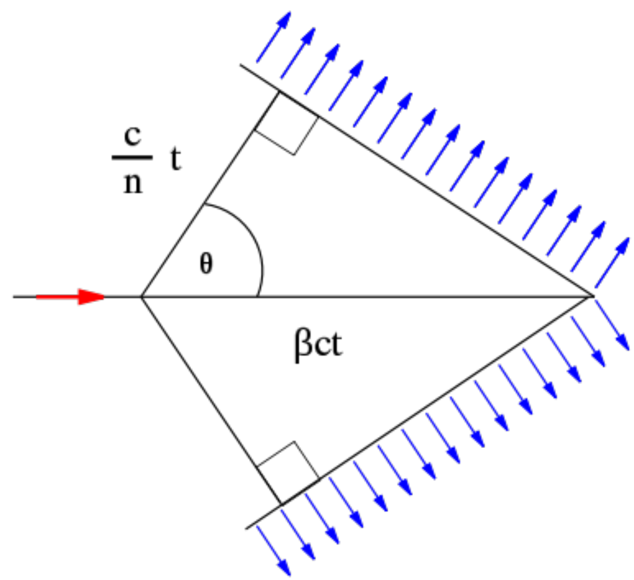
figure C. Rott

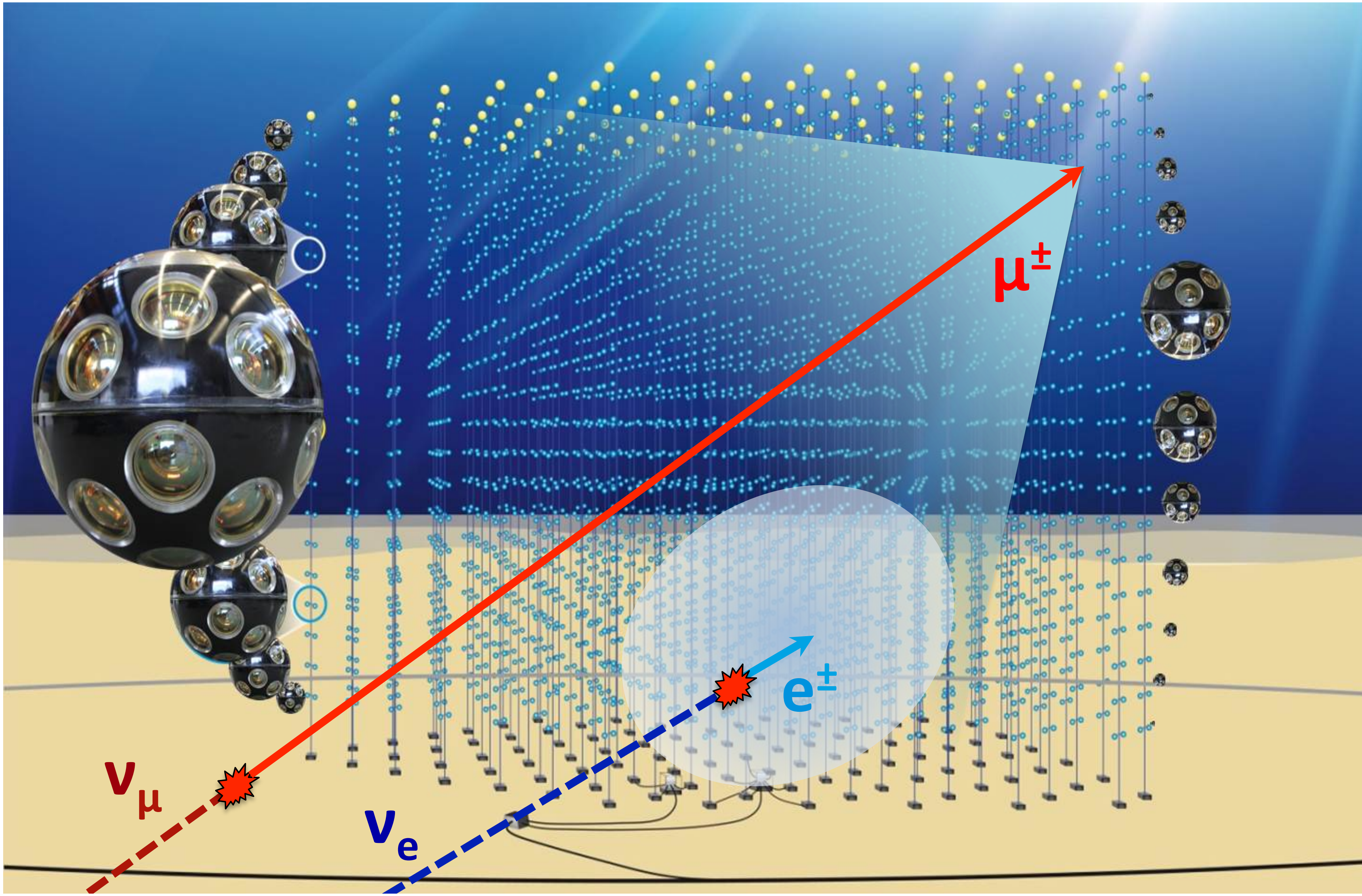


- ✓ *Very large detection volume*
- ✓ *Background reduction*

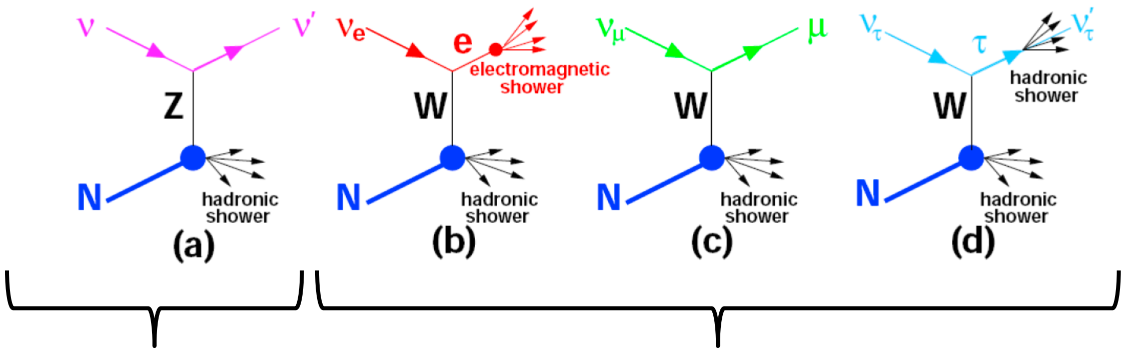
Detection principle : Cherenkov radiation

- Particles moving faster than the phase velocity of light in a dielectric medium produce coherent radiation → « Cherenkov cone »
- Neutrino-nucleus scattering → Charged secondary particles → Cherenkov emission
- Cherenkov angle **$\theta \sim$ 43°**, energy-independent for highly relativistic particles in water




$\mu^{\pm}$
$e^{\pm}$
ν_μ
ν_e

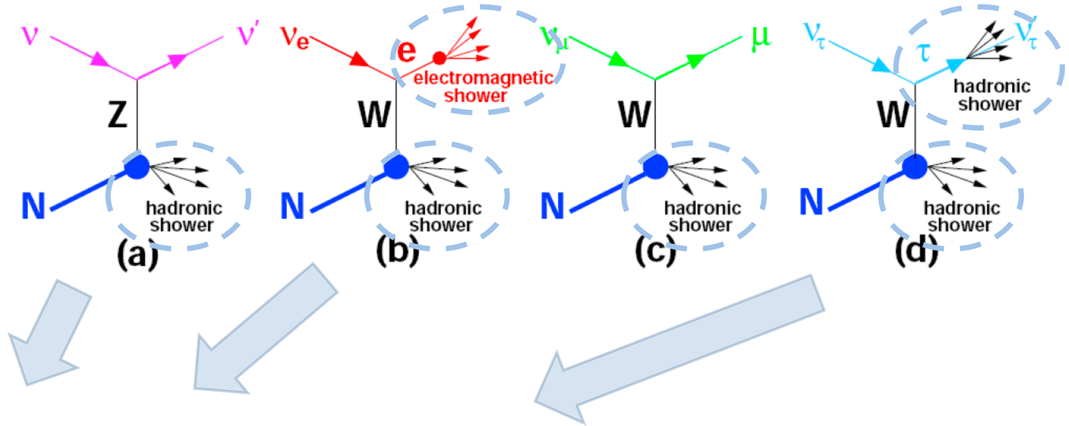
Neutrino interactions and signatures

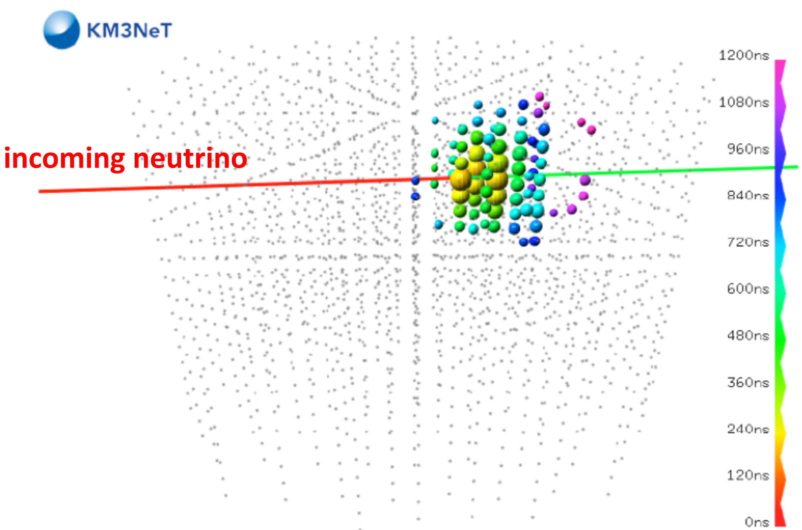


Neutral Current (NC)
Flavour-insensitive

Charged Current (CC)
→ Flavour identification

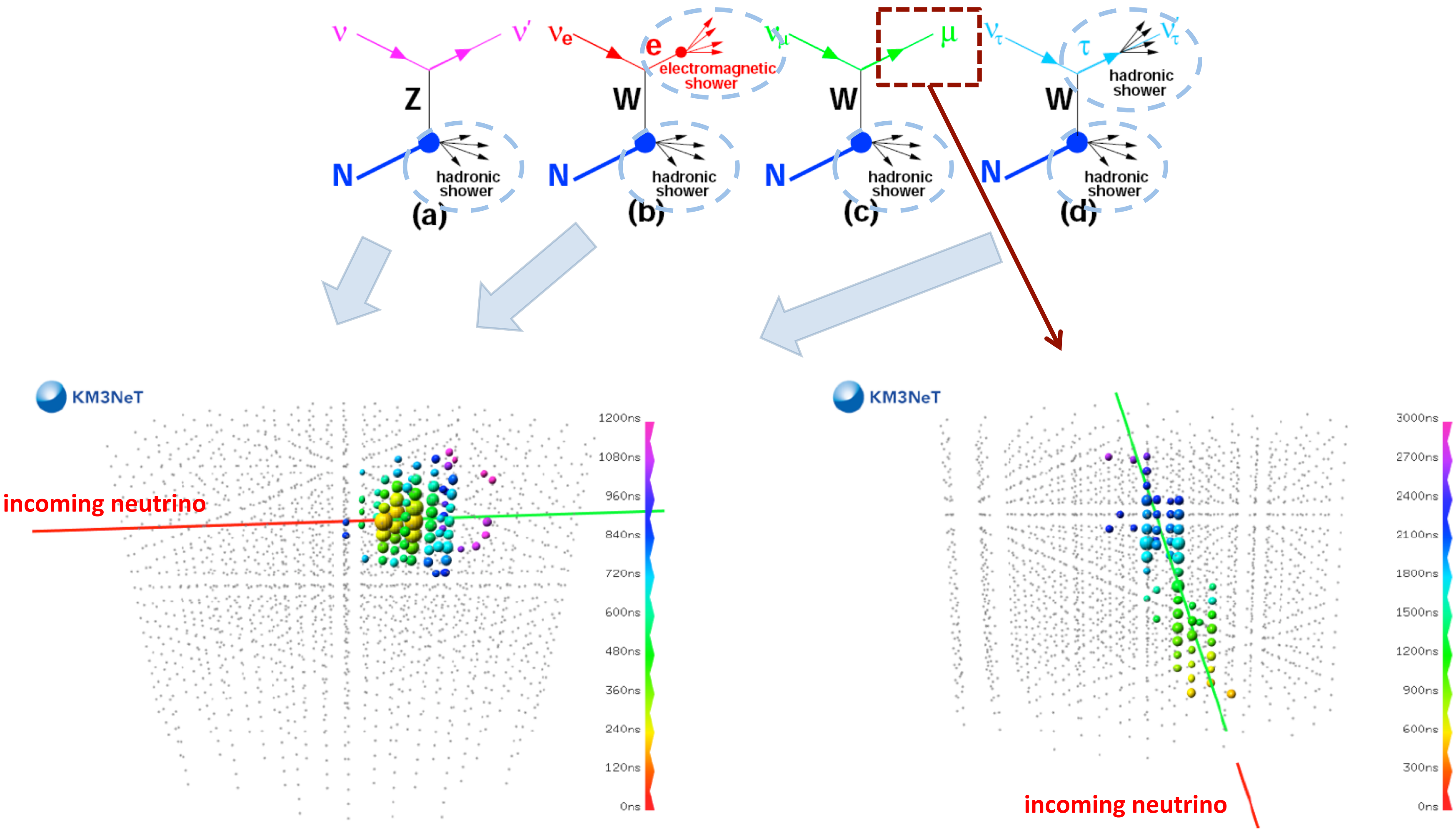
Neutrino interactions and signatures





Cascade-like event

Neutrino interactions and signatures

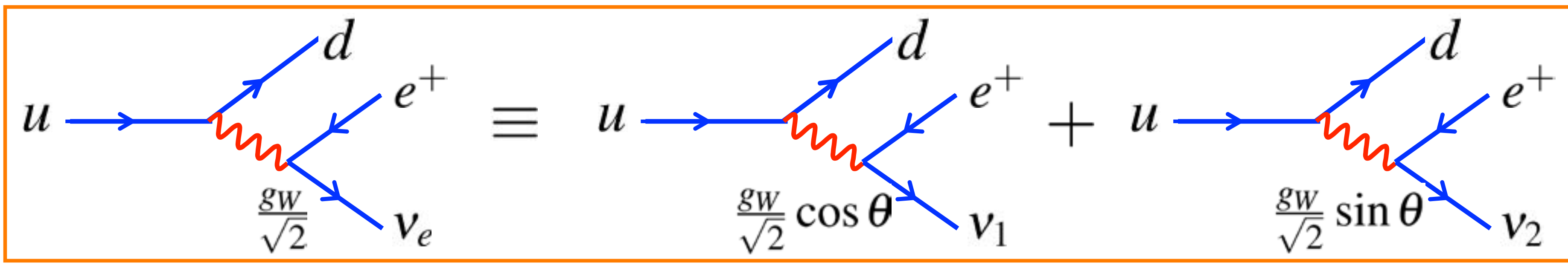


Cascade-like event

Track-like event

Weak and mass eigenstates

- Let's assume two massive neutrinos.
- Neutrinos are produced and interact as weak eigenstates ν_e, ν_μ
- The weak eigenstates are coherent superposition of the fundamental mass eigenstates ν_1, ν_2
- The mass eigenstates are the solutions of the free Hamiltonian and represent the propagation of the neutrinos in space.



$$\theta = \text{mixing angle}$$

Mass eigenstates

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Weak eigenstates

Two neutrino flavor oscillations

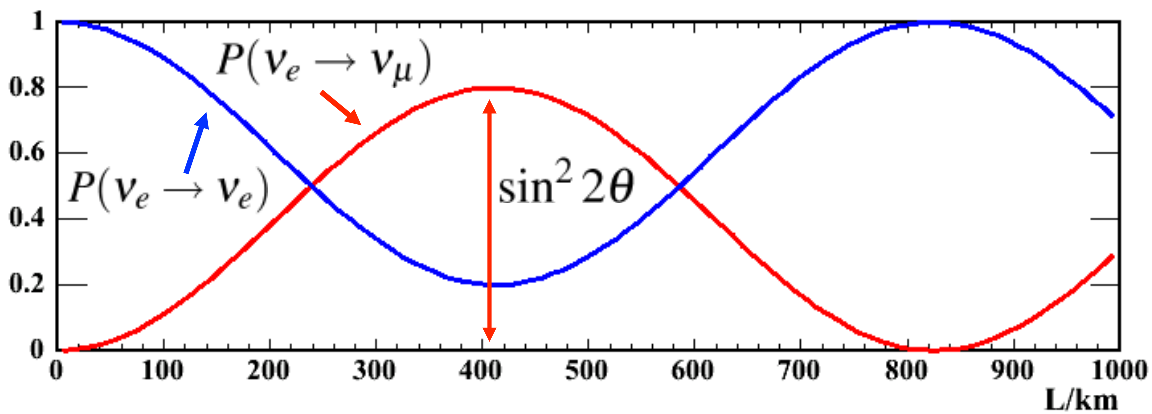
- If the masses are different, the two mass eigenstates propagate with different phases. The resulting state is the quantum mechanical superposition.
- At a distance L from the source, neutrinos will be detected in a given flavor (=weak eigenstate) with a probability depending the neutrino energy:

$$\boxed{P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)}$$

Distance source-detector: L
Neutrino energy: E

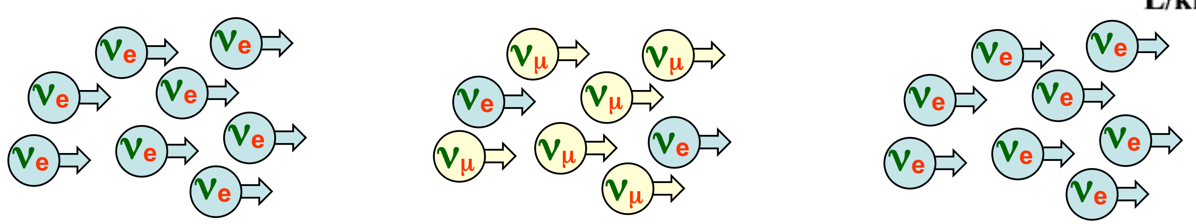
$$\Delta m^2 \equiv m_2^2 - m_1^2$$

- **e.g.** $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$



- **wavelength**

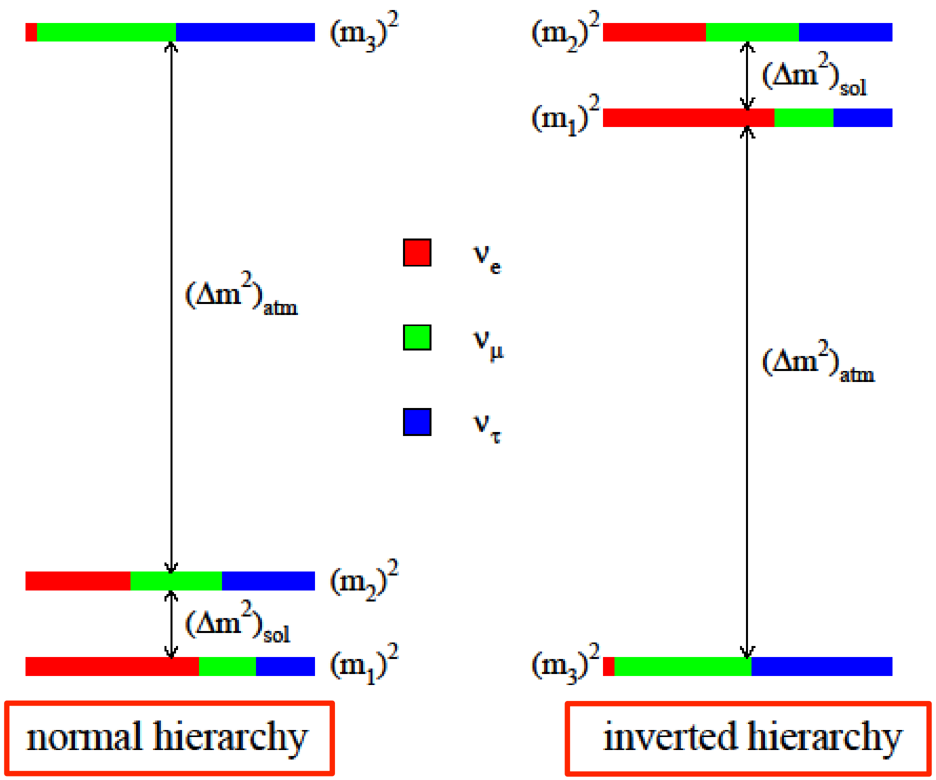
$$\boxed{\lambda_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2}}$$



(Two neutrinos flavor)

Neutrino Mass Hierarchy (NMH)

- Standard oscillation experiments are not sensitive to the sign of Δm^2_{ij}
- The sign of $\Delta m^2_{21} = (\Delta m^2)_{sol}$ has been determined from solar oscillations
- Two situations : normal hierarchy (NH) vs. inverted hierarchy (IH)

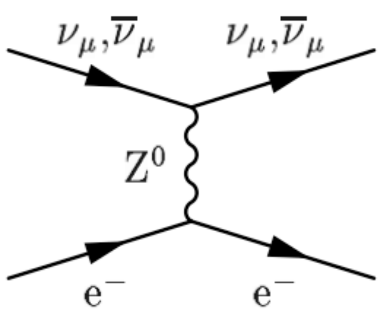


Matter effects in the Earth (MSW effect)

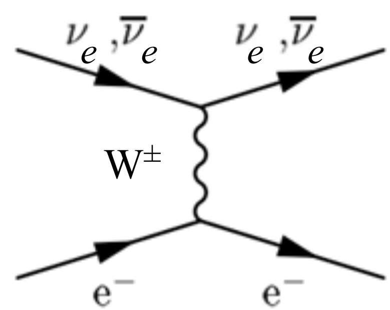
Propagation of atmospheric neutrinos through the Earth

→ Scattering off nucleons and electrons (« coherent forward scattering »)

- neutrino-nucleon : all neutrino flavours involved
- neutrino-electron :



Neutral current : all flavours



Charged current : ν_e only

→ Electronic and muonic components of the atmospheric neutrino flux do not see the same matter potential

Matter effects: simple picture

- Vacuuum oscillations in 2-flavour approximation

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2(1.27 \times \Delta m^2 \times \frac{L}{E})$$

- 2-flavour oscillation in constant matter density with electron density N_e

$$\theta \to \theta_m$$

Matter potential
⇒ mass eigenstates shifted
⇒ effective mixing angle

$$\tan(2\theta_m) = \frac{\Delta m^2 \sin^2 2\theta}{\boxed{-A + \Delta m^2 \cos 2\theta}}$$

Resonance when A = A_{res}

$$A(\nu) = +2\sqrt{2}G_F \times E \times N_e$$

$$A(\overline{\nu}) = -2\sqrt{2}G_F \times E \times N_e$$

Matter effects: less simple picture

$$P^m_{3\nu}(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos^2 \boxed{\theta^m_{13}} \sin^2 \left(\frac{(\Delta m^2_{31} + \boxed{\Delta^m m^2})L}{8E_\nu} + \boxed{\frac{AL}{4}} \right)$$

$$- \sin^2 2\theta_{23} \sin^2 \boxed{\theta^m_{13}} \sin^2 \left(\frac{(\Delta m^2_{31} - \boxed{\Delta^m m^2})L}{8E_\nu} + \boxed{\frac{AL}{4}} \right)$$

$$- \sin^4 \theta_{23} \sin^2 \boxed{2\theta^m_{13}} \sin^2 \left(\frac{\boxed{\Delta^m m^2} L}{4E_\nu} \right)$$

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2 \theta_{23} \sin^2 \boxed{2\theta^m_{13}} \sin^2 \left(\frac{\boxed{\Delta^m m^2} L}{4E_\nu} \right)$$

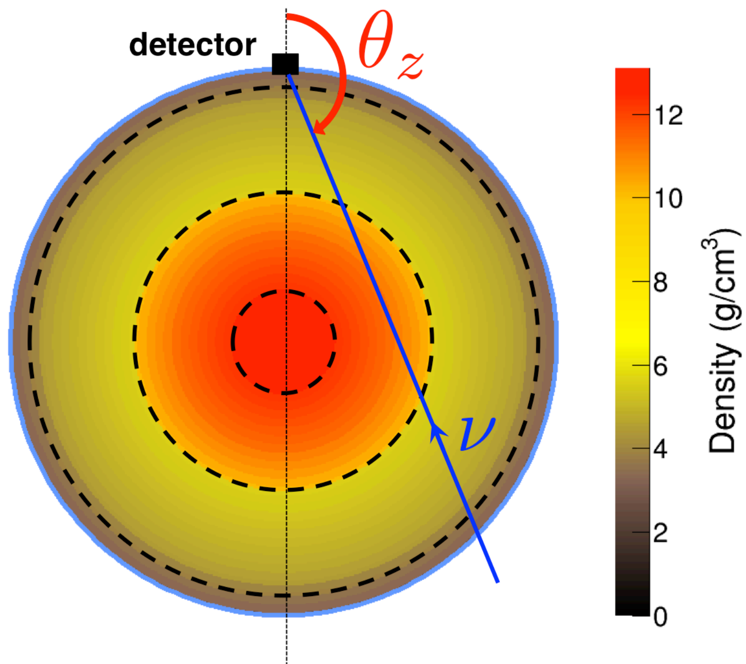
$$\boxed{\sin^2 2\theta^m_{13}} \equiv \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{31}}{\boxed{\Delta^m m^2}} \right)^2$$

$$\boxed{\Delta^m m^2} \equiv \sqrt{(\Delta m^2_{31} \cos 2\theta_{13} - 2 E_\nu \boxed{A})^2 + (\Delta m^2_{31} \sin 2\theta_{13})^2}$$

$$\boxed{A = \pm\sqrt{2} G_F N_e}$$

Matter effects: less simple picture

Varying matter density in the Earth
→ Use discretized model with constant density steps based on geophysics standard model
→ Step-by-step numerical resolution of evolution equation



$$L = 2R_{\mathrm{Earth}}\cos\theta_z$$

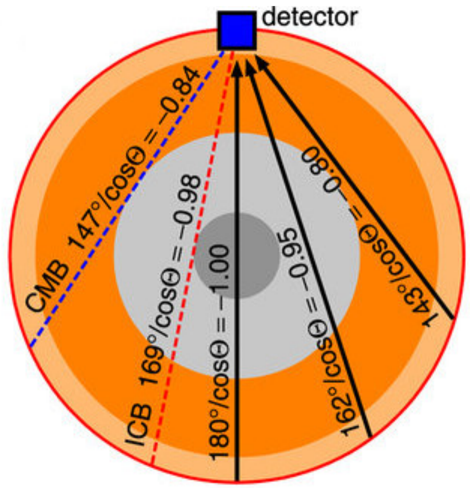
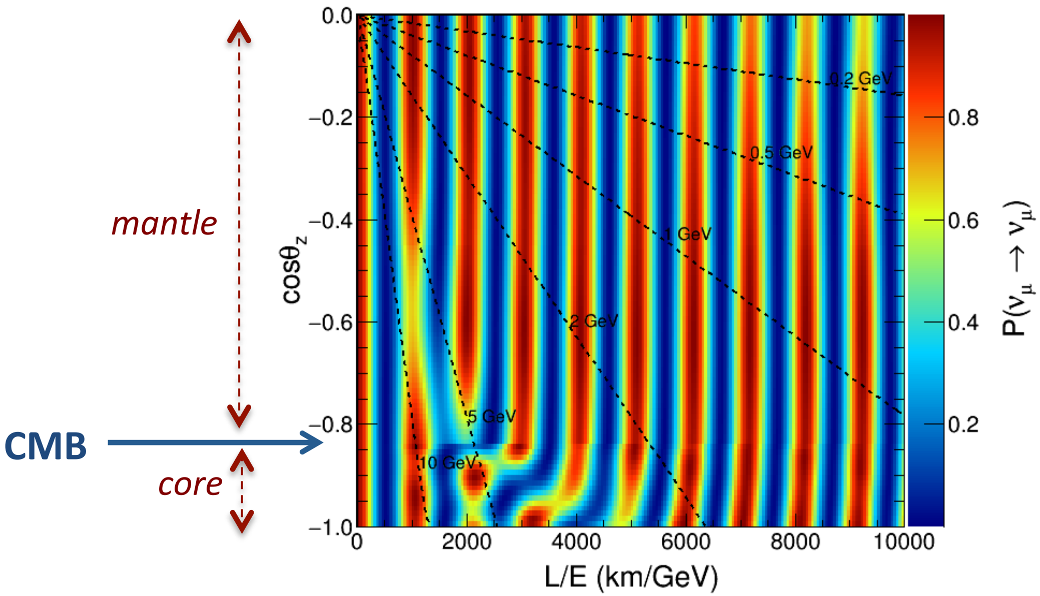


figure C. Rott



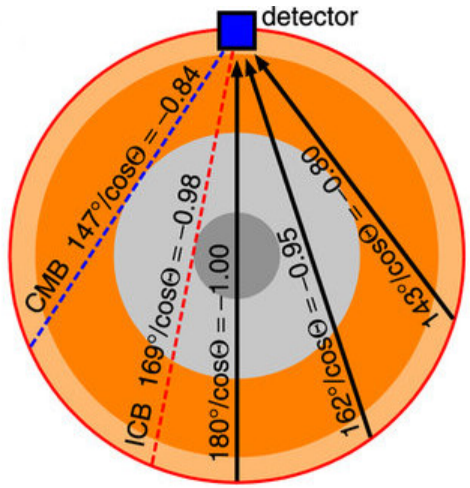
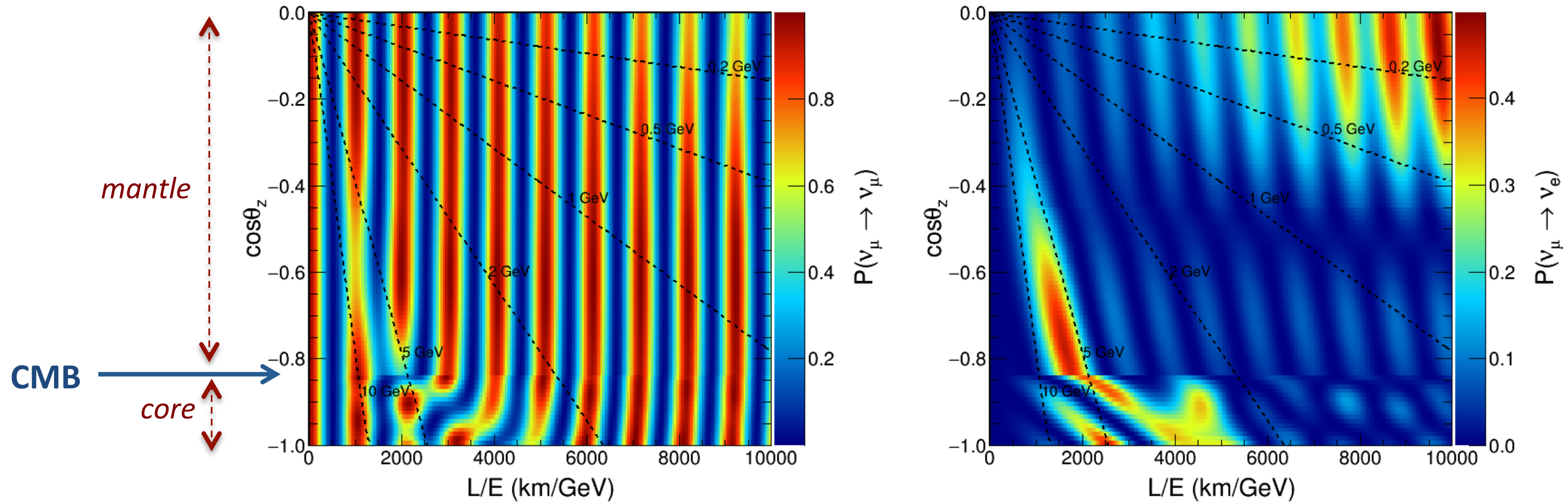


figure C. Rott



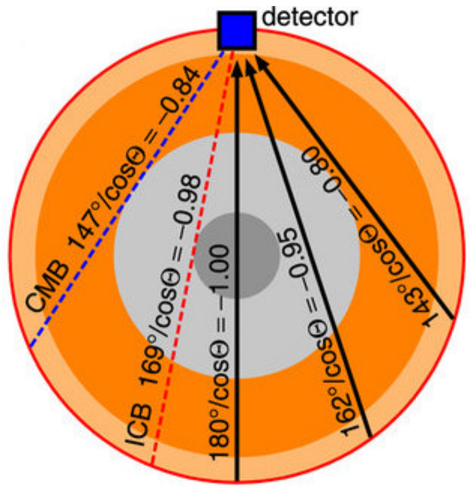
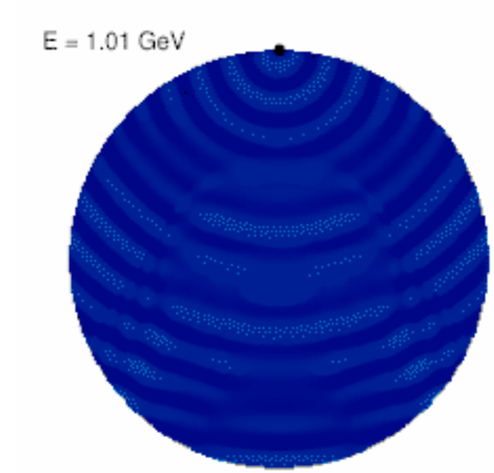
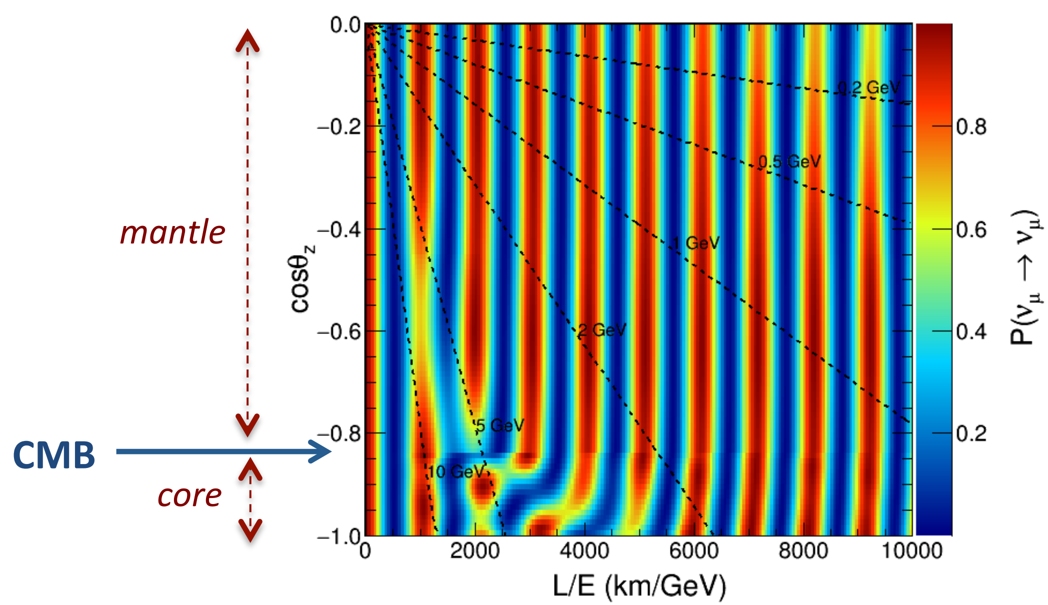
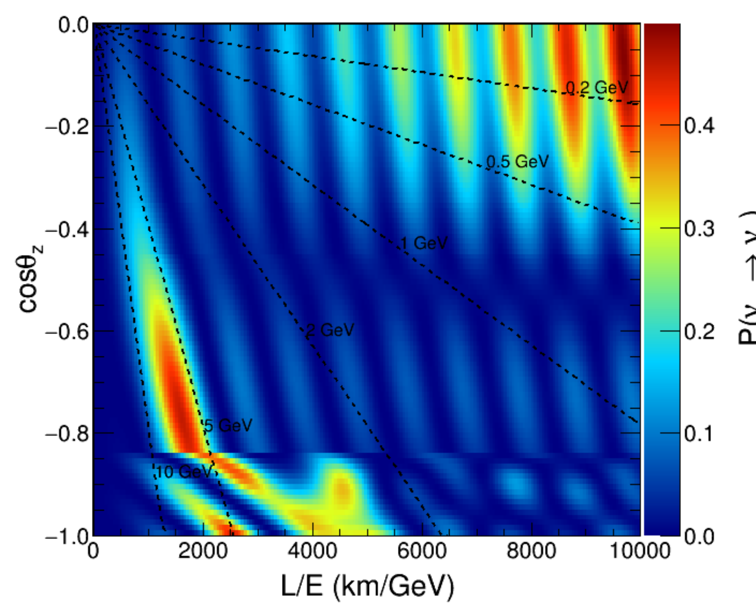


figure C. Rott



animation J. Coelho





Electron density vs. matter density

Electron to mass density ratio → depends on the **chemical composition** of the medium

w_i = weight fraction of chemical element i

Proton-to-nucleon ratio ≈ 0.5

$$\frac{Z}{A} \equiv \sum w_i \frac{Z_i}{A_i} \Rightarrow n_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{\mathrm{matter}}$$

Electron density
=> measured with neutrino oscillations

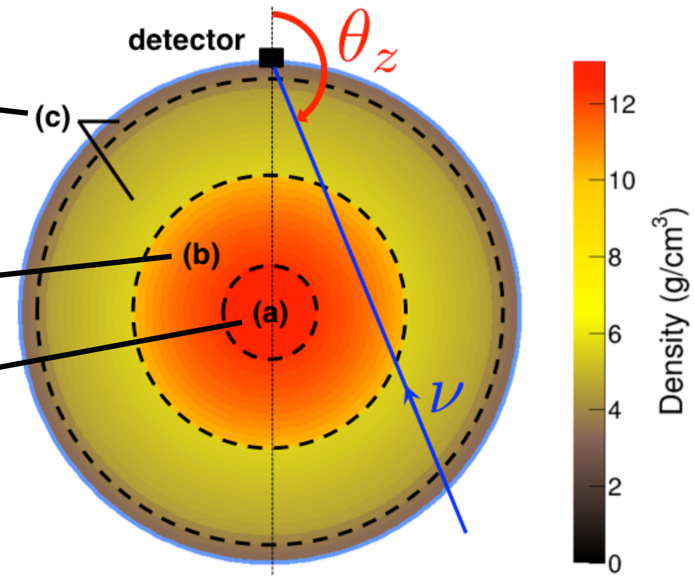
Matter density (→ nucleons)
=> measured with geophys. techniques

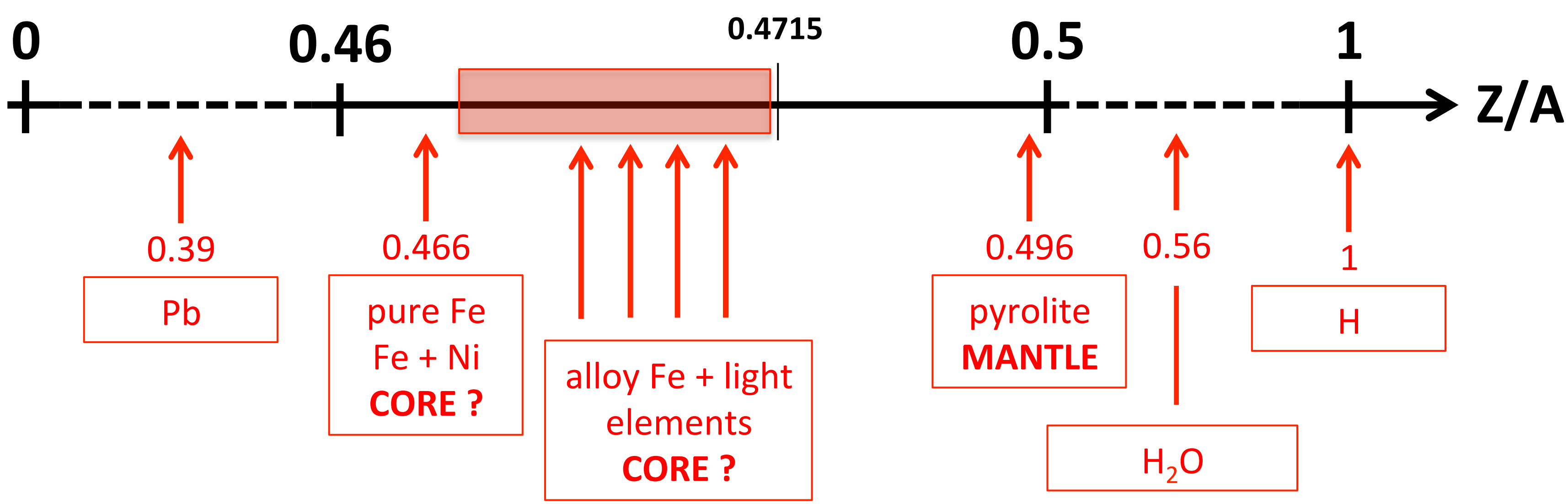
Earth composition: knowns and unknowns

Mantle and crust: $R_{ext} \approx 6400$ km
silicate rocks: Si, O, Mg, Fe, Na, K, …

Outer core: $R_{ext} \approx 3480$ km
liquid Fe + few % Ni + <1% light elements ?

Inner core: $R_{ext} \approx 1220$ km
solid Fe





22

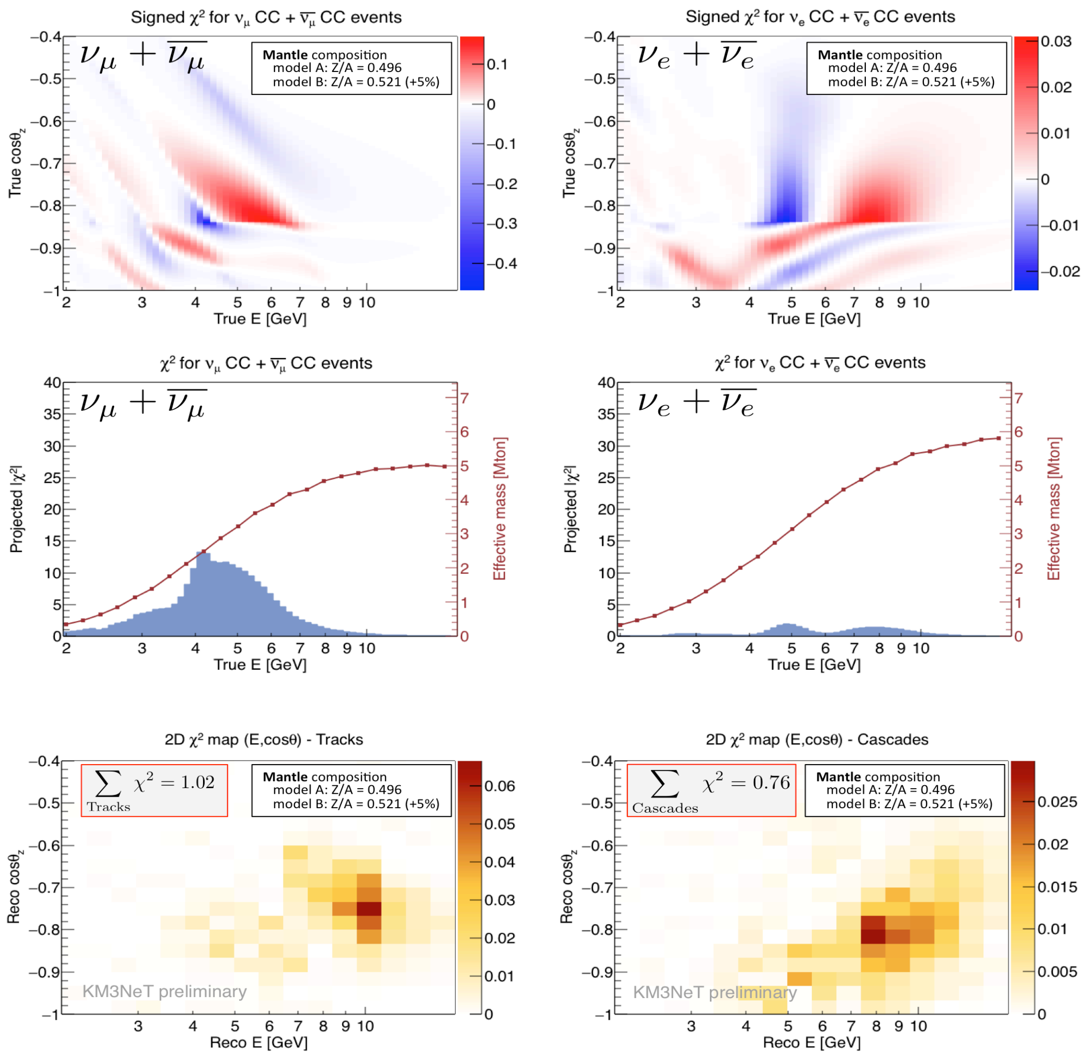
From the principle to the measurement

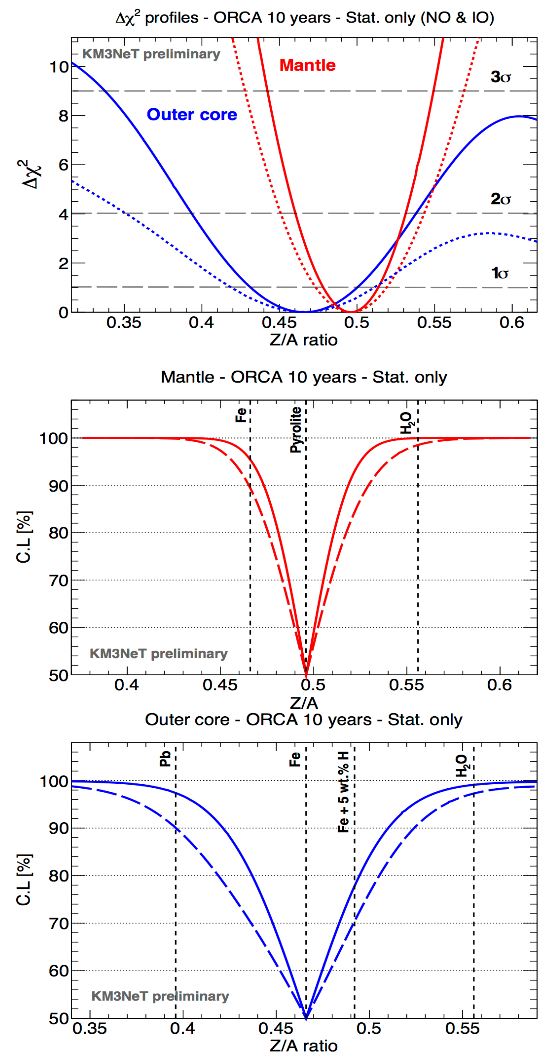
- Limitations:
  - poor detection efficiency below 2 GeV (≈ max at 10 GeV)
  - limited angular and energy resolution at low energy
  - no neutrino / antineutrino distinction on event-by-event basis
  - flavour ID limited to 2 broad classes: track and showers

- Detector response based on extensive Monte Carlo simulations

- Sensitivity evaluation: statistical model taking into account
  - statistical fluctuation
  - systematic uncertainties due to unknown parameters in the model: oscillation physics, detector response parameters, etc.

Results → come to the PHD seminar





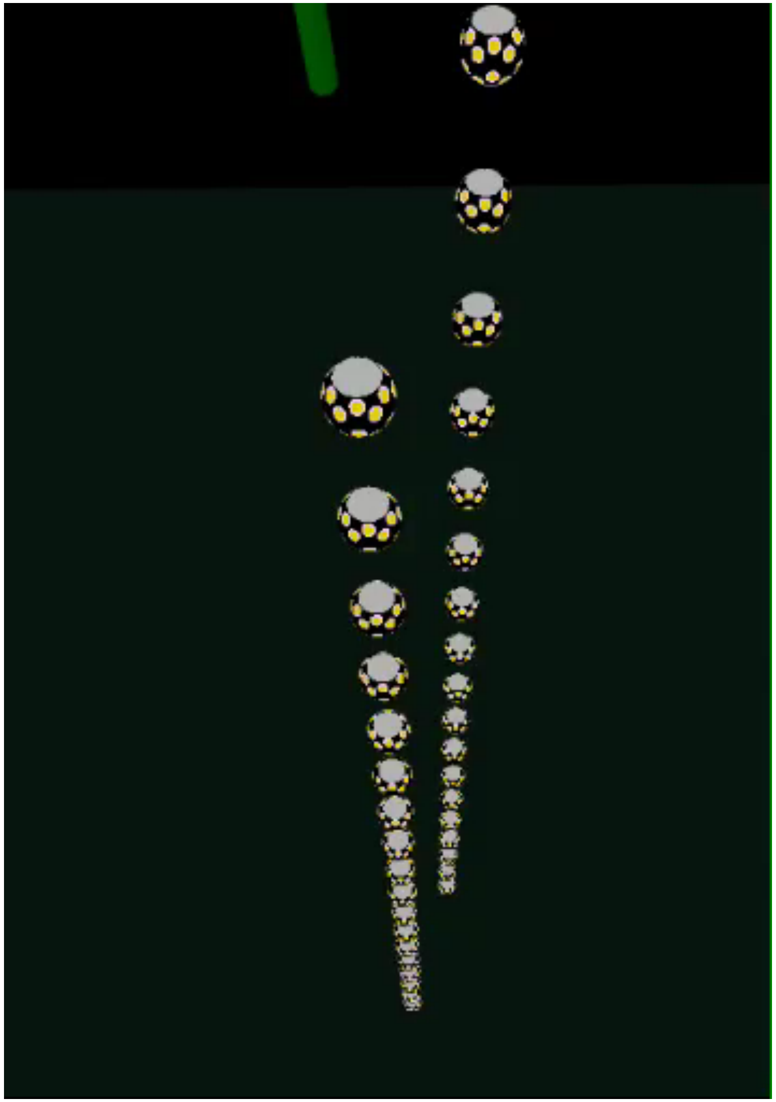
Thank you for your attention !

& come to the PHD seminar **next Thursday**

Thursday 17 Nov. 14h30

(once every 2 weeks, tell us if you are not on the mailing list)

Bonus: first KM3NeT 2-strings data



Additional slides

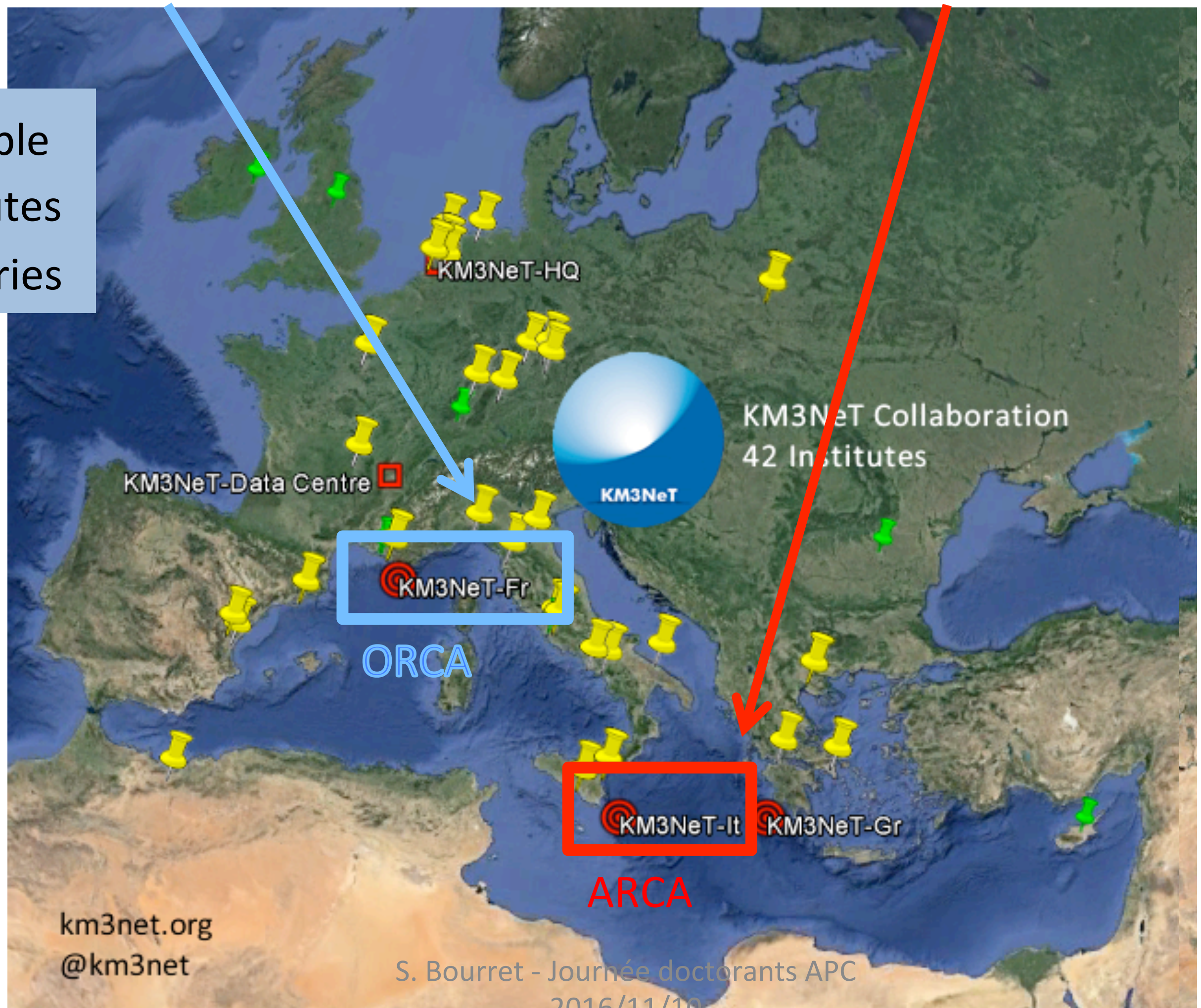
Where & who

KM3NeT is a distributed research infrastructure with 2 main physics topics:

Oscillations and **A**stroparticle **R**esearch with **C**osmics in the **A**byss

Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos

240 people
42 institutes
12 countries



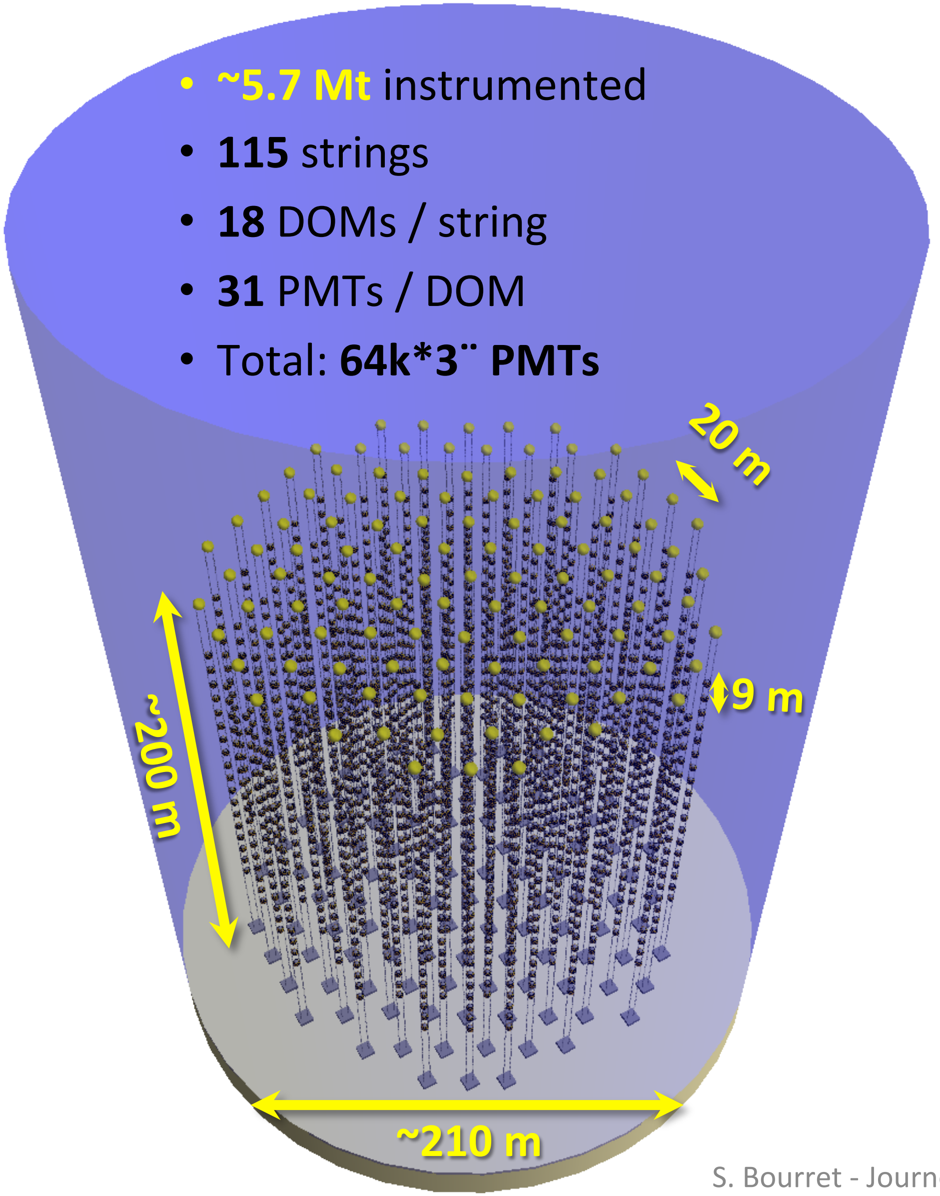
2 sites currently under construction in France and Italy:

KM3NeT-Fr (Toulon, close to ANTARES)

KM3NeT-It (Capo Passero, Sicily)

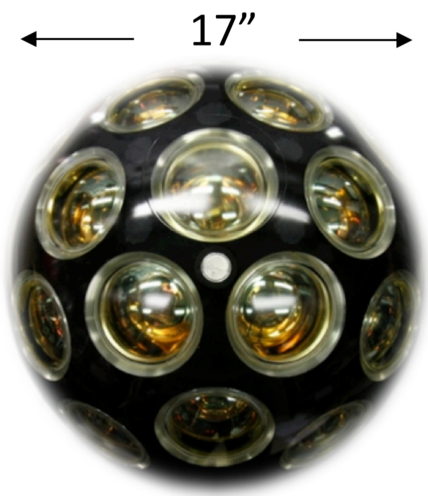
The ORCA detector

- **~5.7 Mt** instrumented
- **115** strings
- **18** DOMs / string
- **31** PMTs / DOM
- Total: **64k*3¨ PMTs**



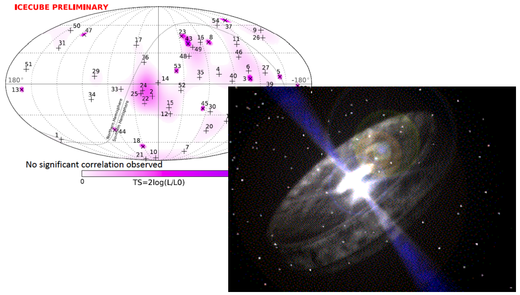
Depth=2475m

Digital Optical Module



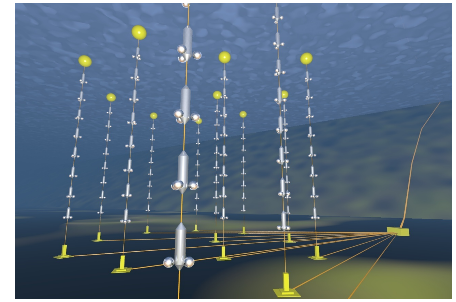
- 31 x 3” PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Background rejection
- All data to shore

slide P. Choyle / J. Coelho



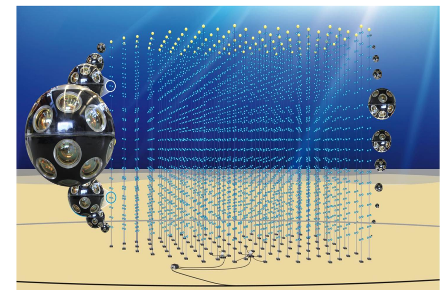
Antares 2008-2016

Neutrino astronomy



KM3NeT 2015-...

Neutrino astronomy + neutrino oscillations

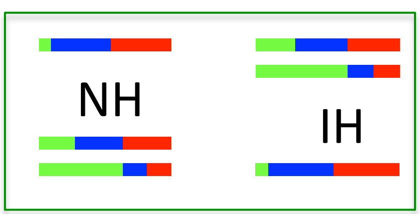


ARCA

Neutrino astronomy

ORCA

Atmospheric neutrinos
Oscillations



Neutrino Mass Hierarchy
+ other neutrino parameters

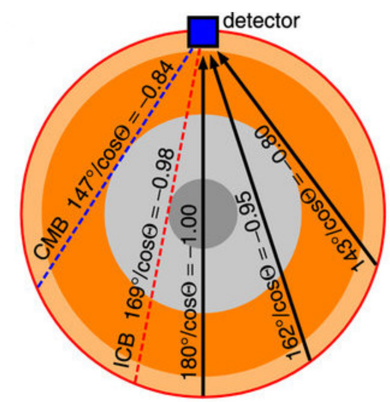
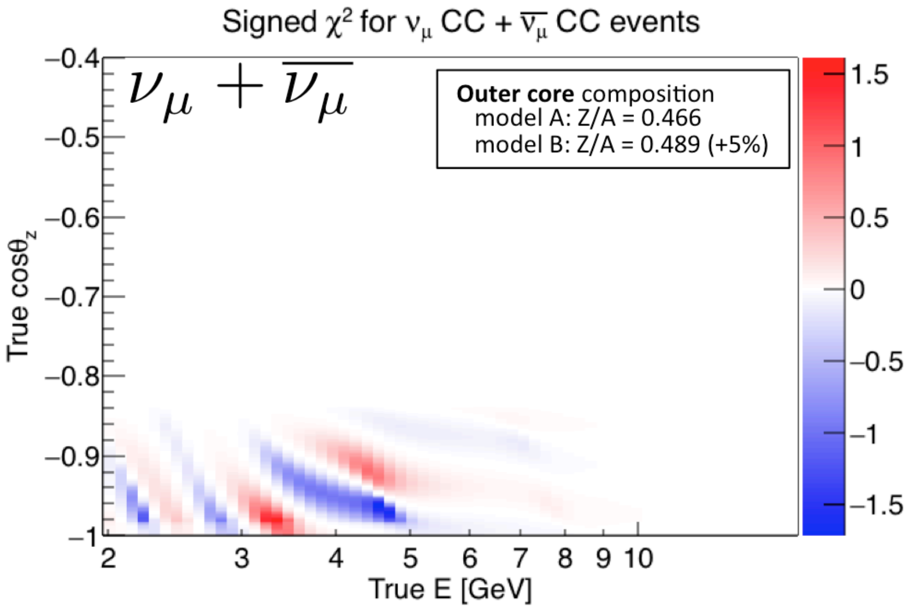
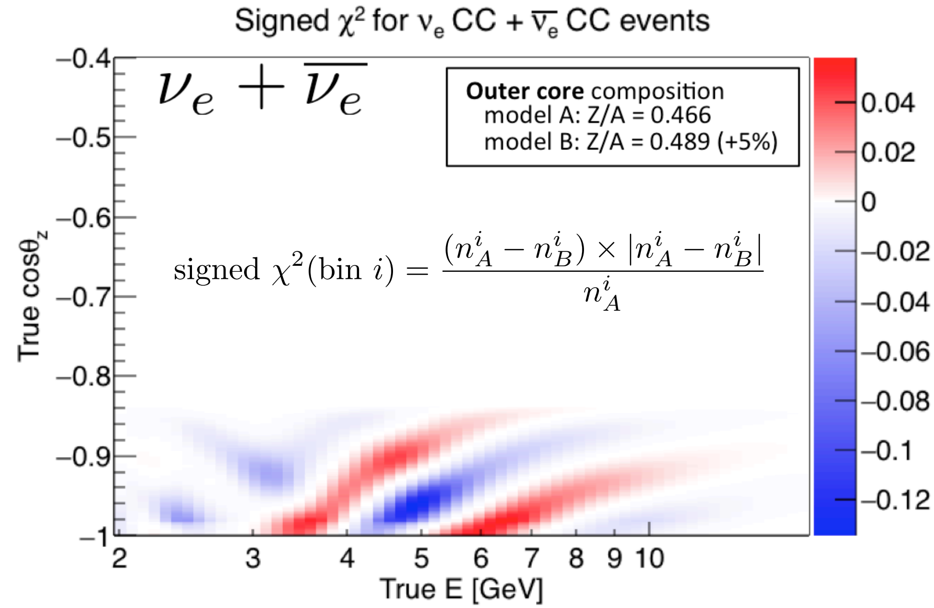


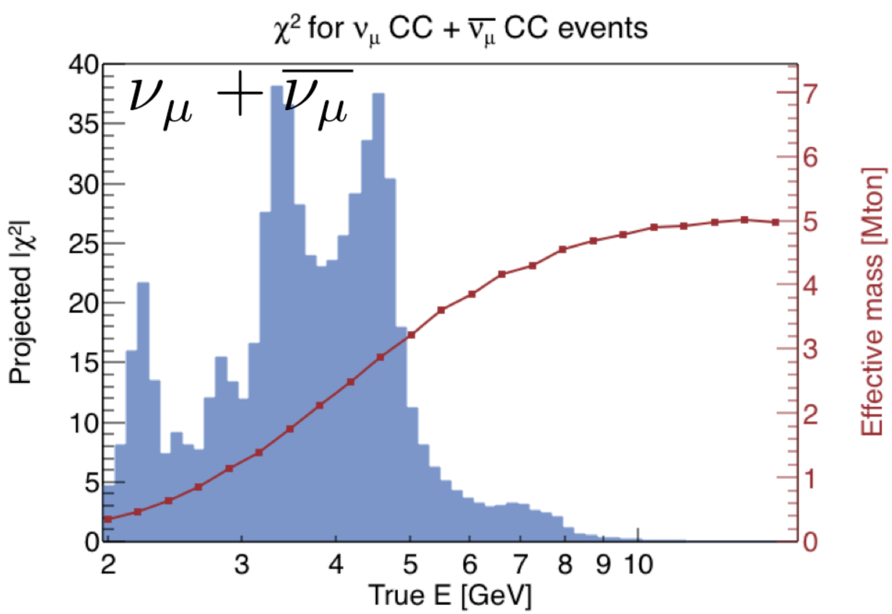
figure C. Rott

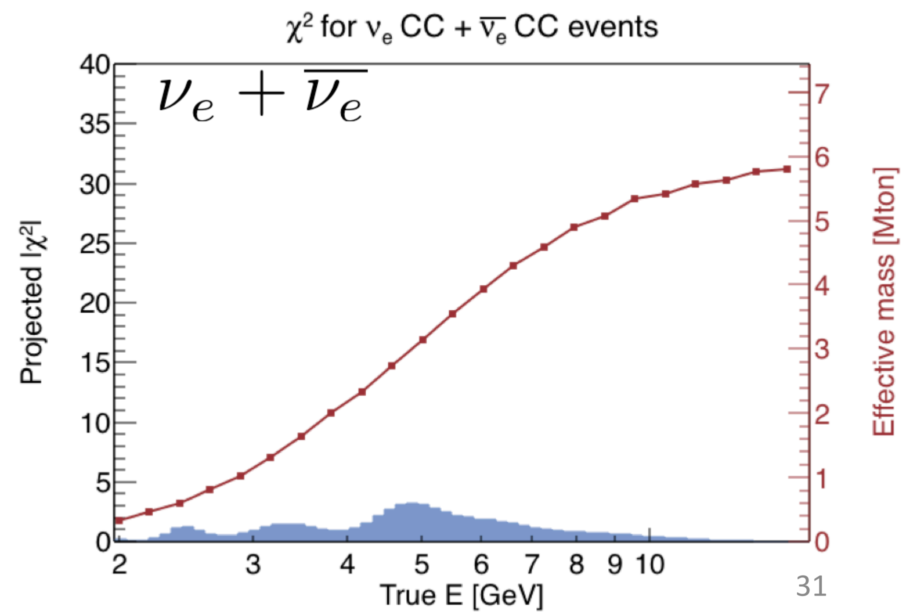
Tomography of the Earth
with neutrino oscillations

Perfect detector signal – Outer core tomography

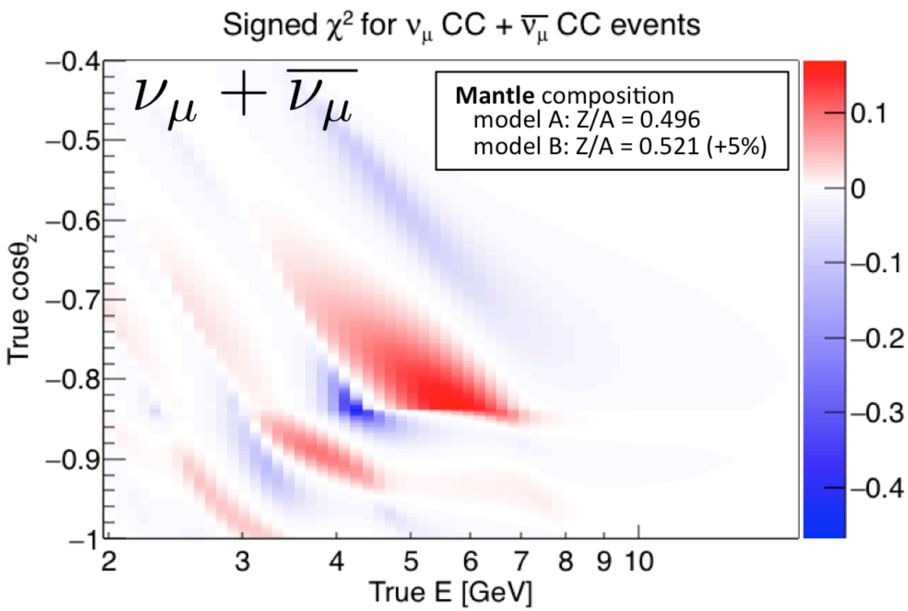


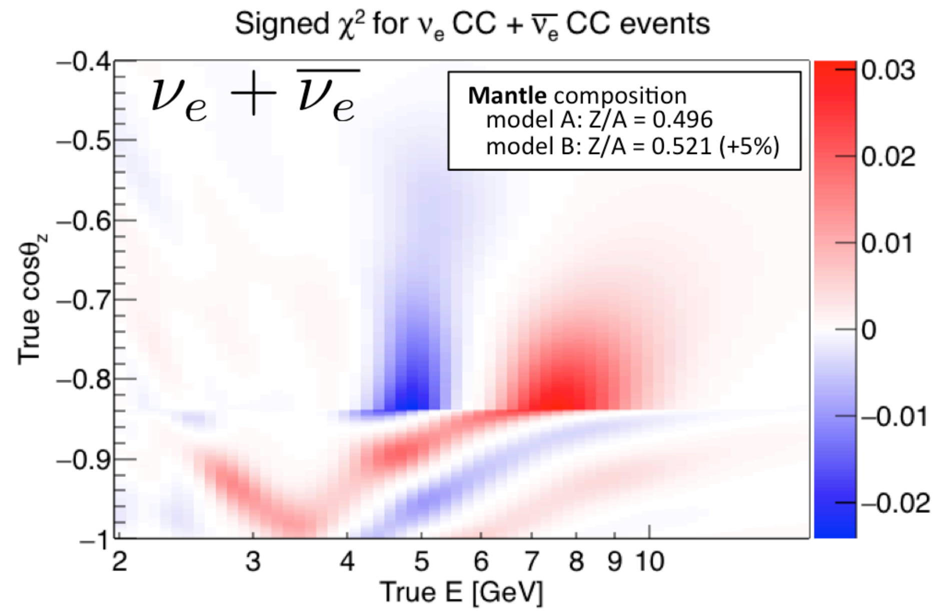


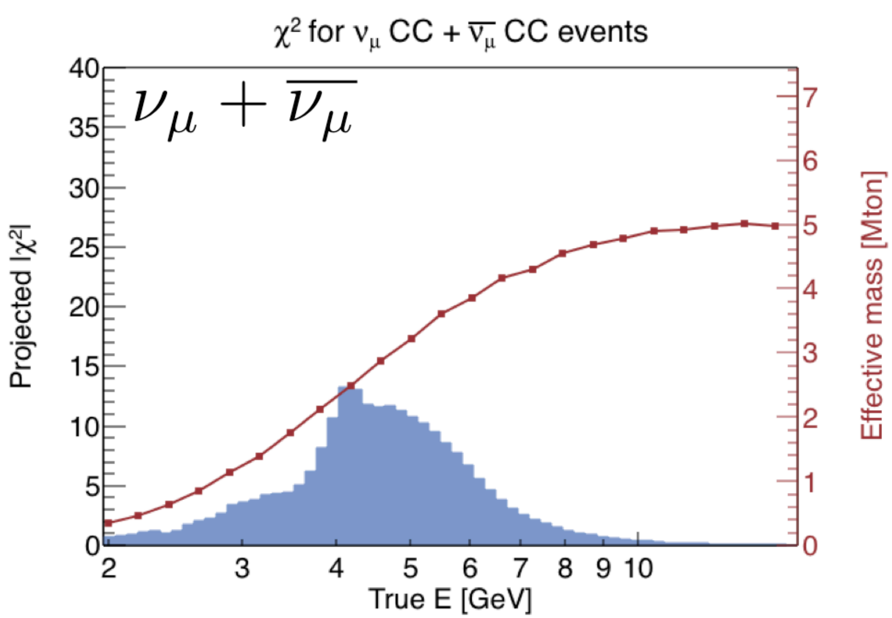


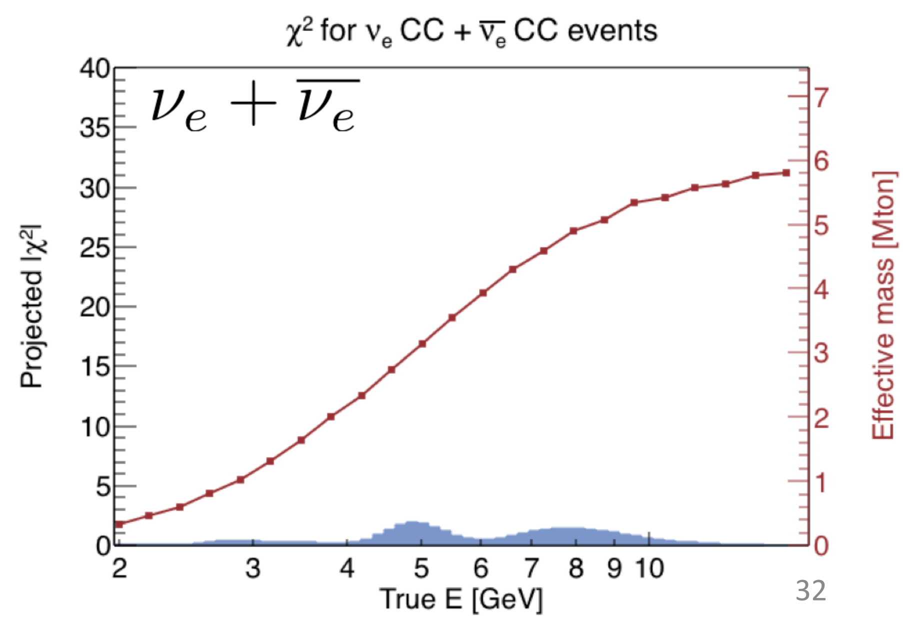


Perfect detector signal – Mantle tomography









Detector response

→ « event-by-event » response stored into 6D sparse histograms
→ Discrete channels: 12 for CC events, 4 for NC events
→ Atmospheric muon contamination not included yet

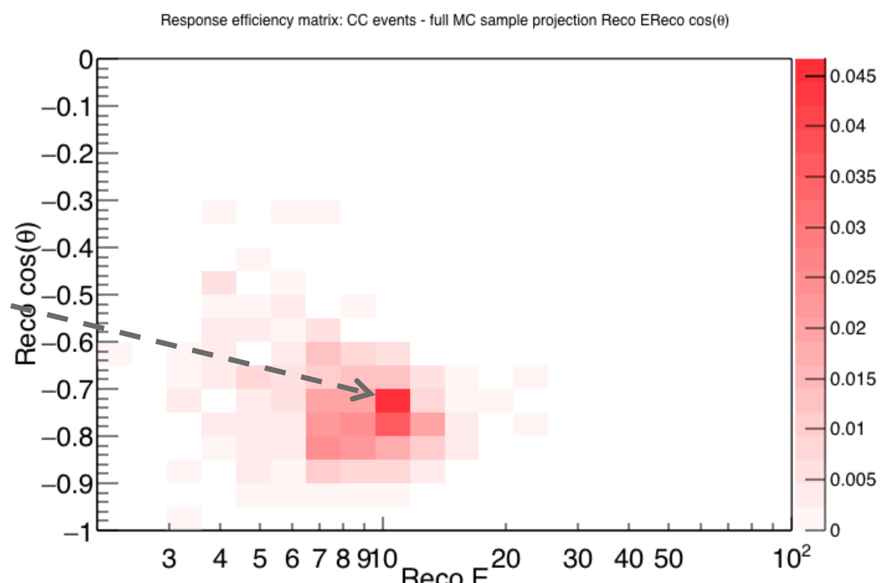
- True $(E, \cos\theta_z, Y_{\mathrm{Bj}})$
- True channel:
  $\rightarrow$ CC $\nu_e/\overline{\nu_e}$, $\nu_\mu/\overline{\nu_\mu}$, $\nu_\tau/\overline{\nu_\tau}$
  $\rightarrow$ NC $\nu/\overline{\nu}$

Reconstruction & Classification

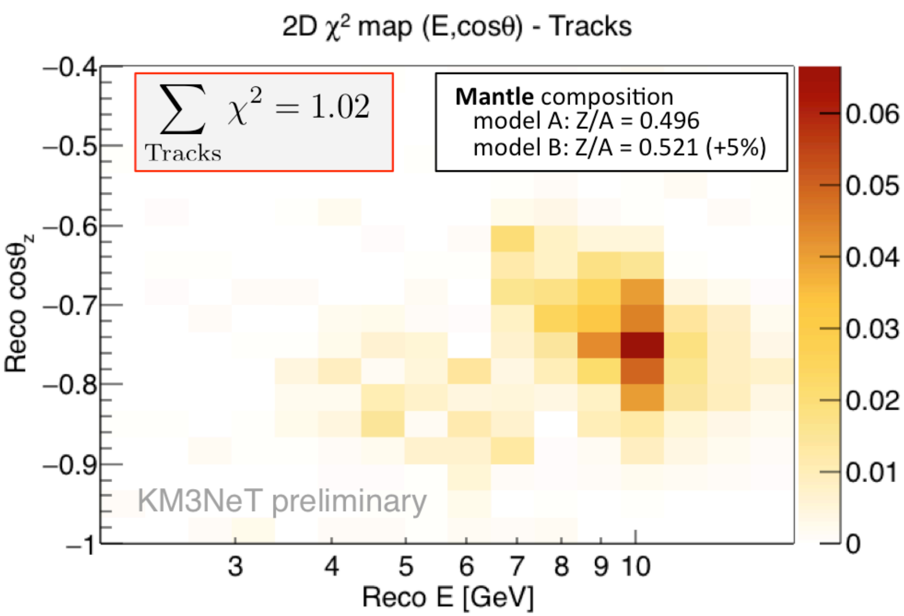
- Reco $(E, \cos\theta_z, Y_{\mathrm{Bj}})$
- Event classification ("flavour ID"):
  $\rightarrow$ Track / Cascade / μ_{atm}

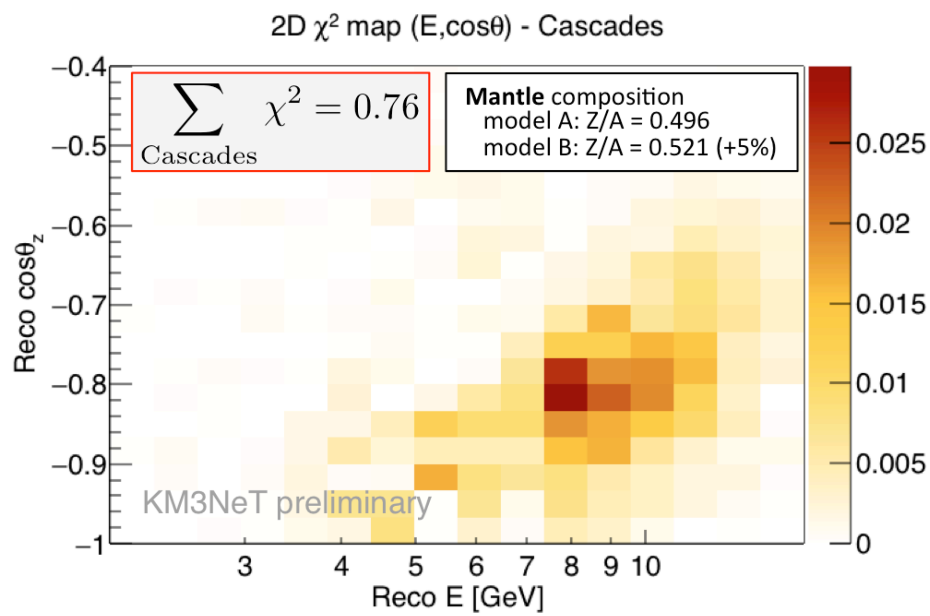
Example of 2D projection of response:

- **Truth** = only one bin
  - E ≈ 10 GeV
  - cosθ ≈ -0.75
- **Reconstructed** = 2D distribution



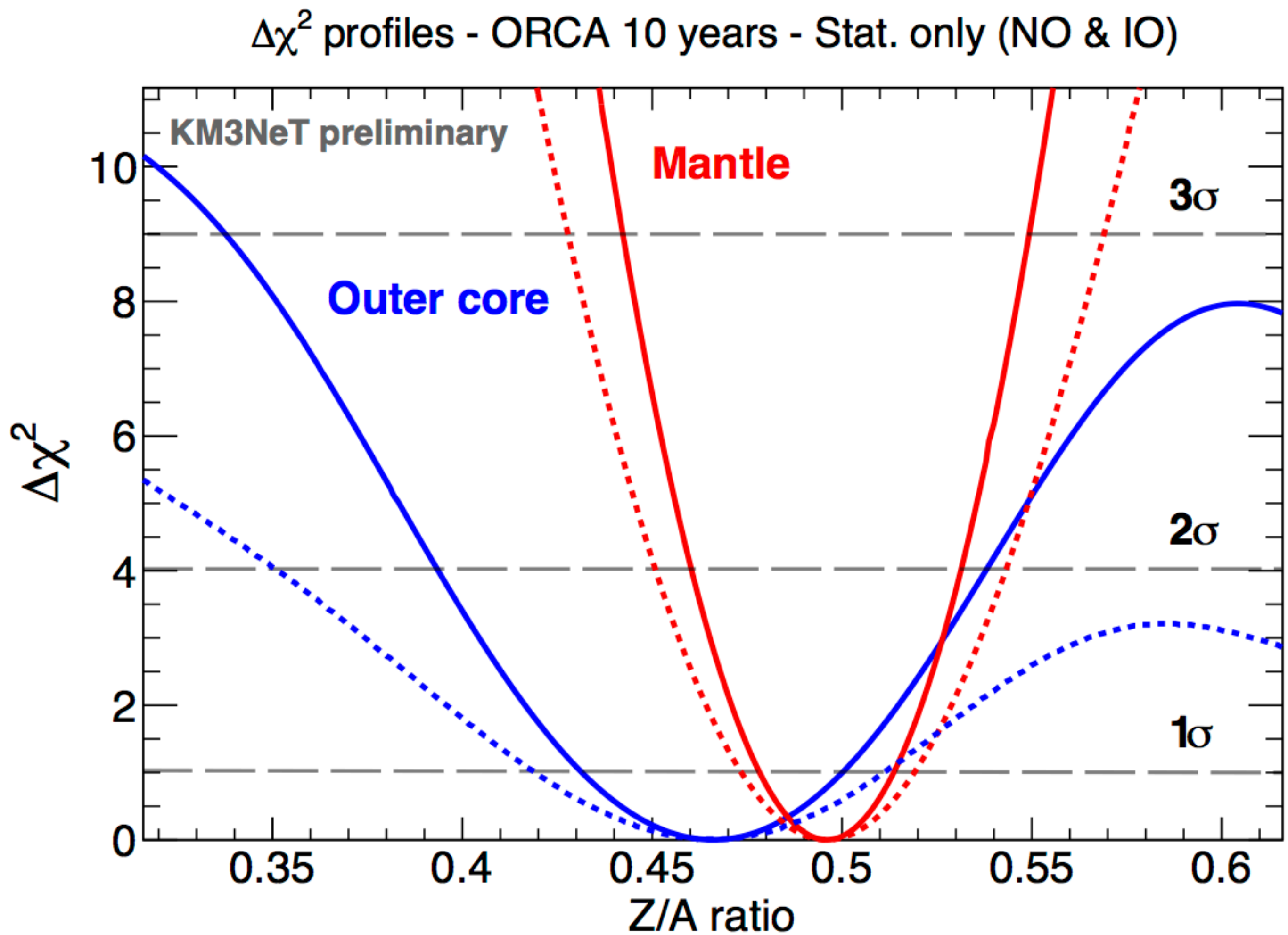
Measured signal: Mantle – ORCA 10 years



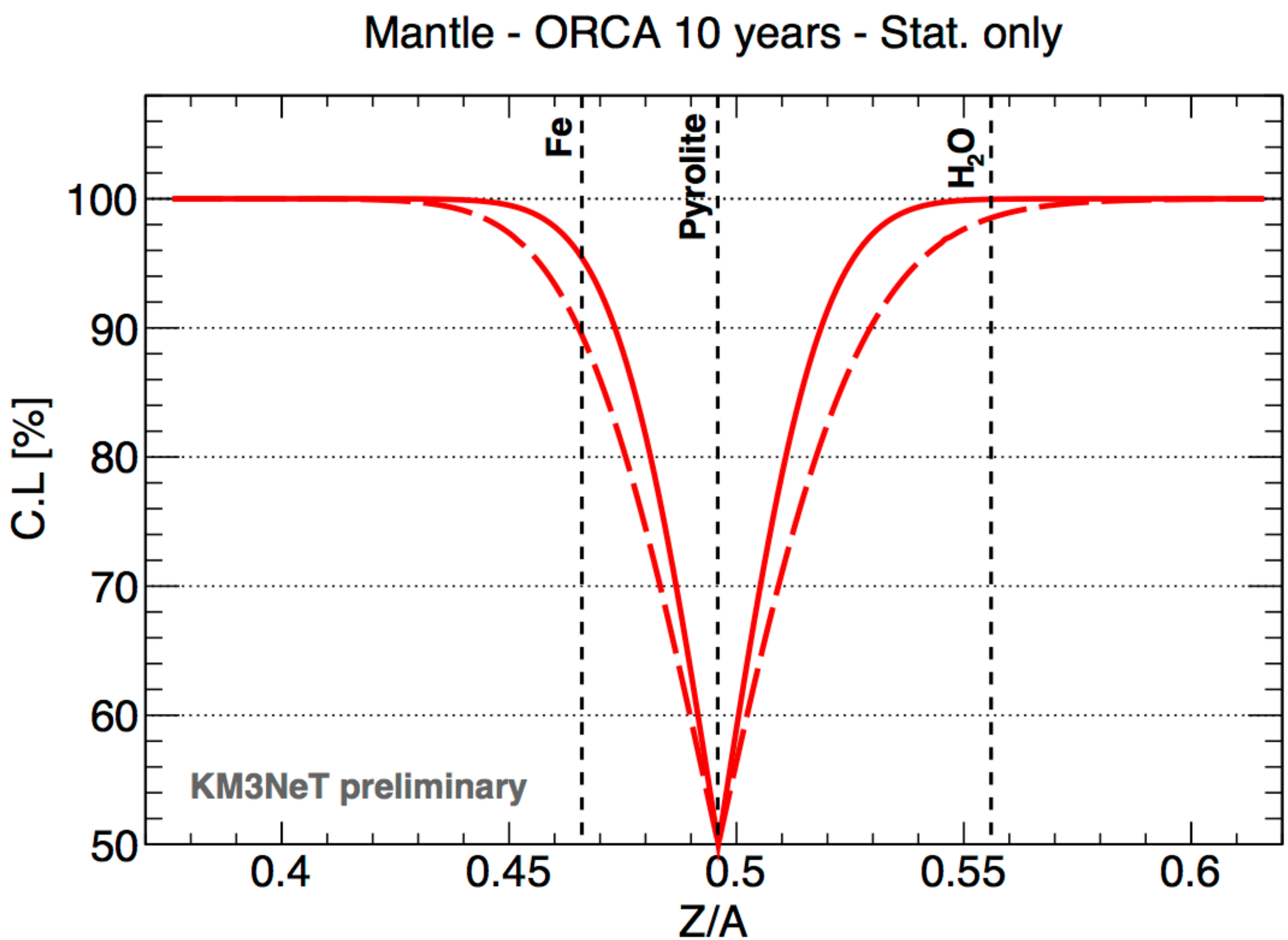


$$\Delta\chi^2 = \sum_{\substack{\text{Tracks,}\\ \text{Cascades}}} \sum_{\substack{\text{bins } E\\ \text{bins } \cos\theta_z}} 2\left[n_A - n_B + \log\left(\frac{n_B}{n_A}\right)\right]$$

Statistical significance – ORCA 10 years



Confidence level for rejecting basic composition of **mantle** (pyrolite) vs alternative True Z/A



Confidence level for rejecting basic composition of **outer core** (pure Fe) vs alternative True Z/A