UNIVERSITY OF LIVERPOOL

Physics in Collision
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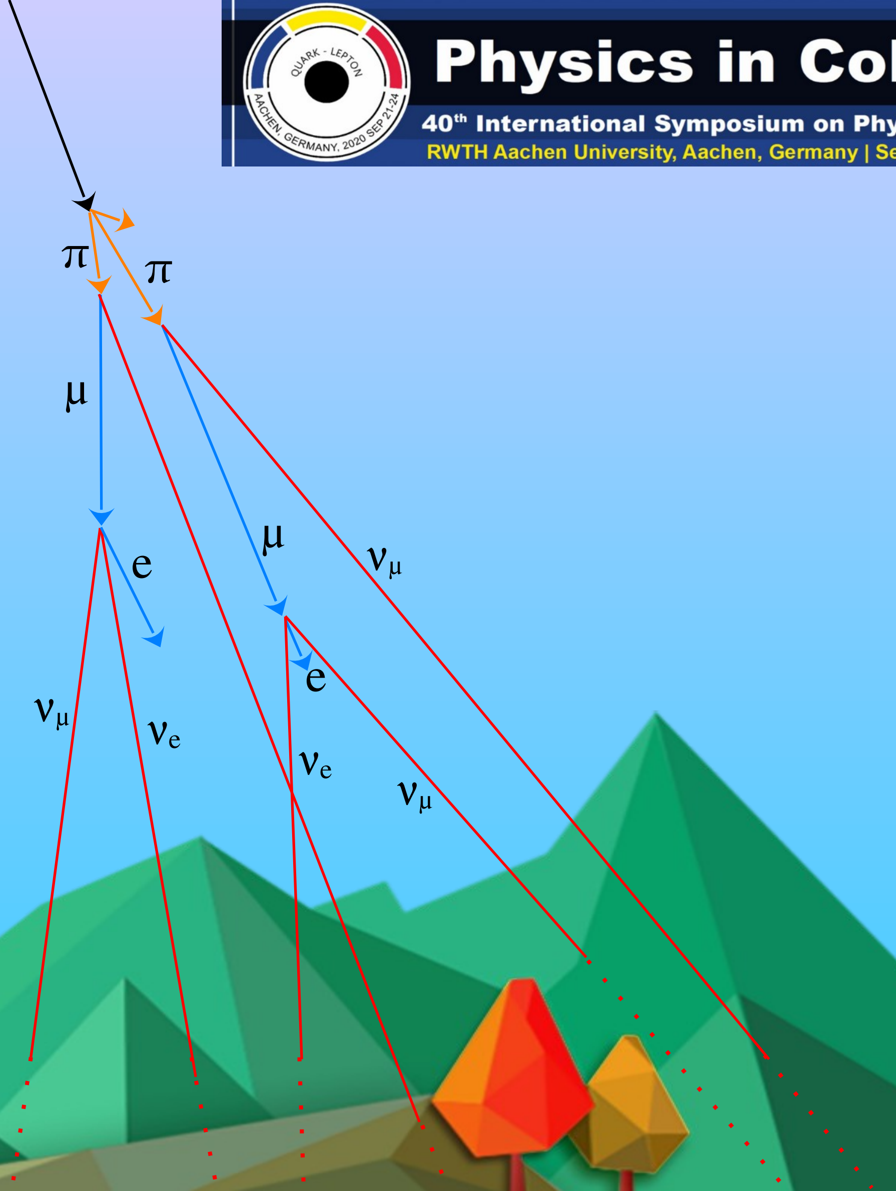
Atmospheric neutrinos

Pablo F. – University of Liverpool



Atmospheric Neutrinos – Outline

- **Origin and Introduction of Atmospheric Neutrinos**

- **Flux of Atmospheric Neutrinos**
  - Models and calculations
  - Other features: solar activity, geomagnetic effects, seasonal variations…

- **Neutrino Oscillations**
  - Standard three-flavour and matter effects
  - Non-standard interactions
  - Sterile neutrinos

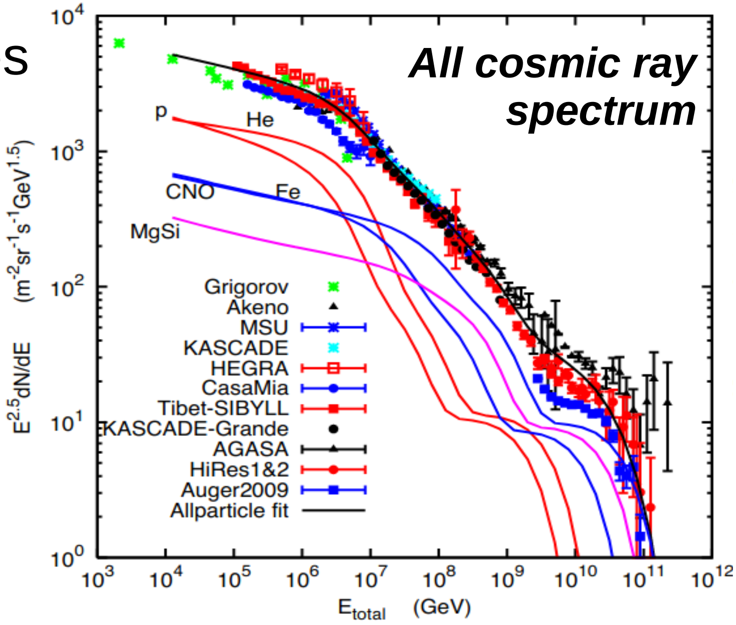
- **Atmospheric Neutrino Experiments**

- **Atmospheric Neutrinos, the Latest Results**

- **Summary and Prospects**

Origin and Introduction of Atmospheric Neutrinos

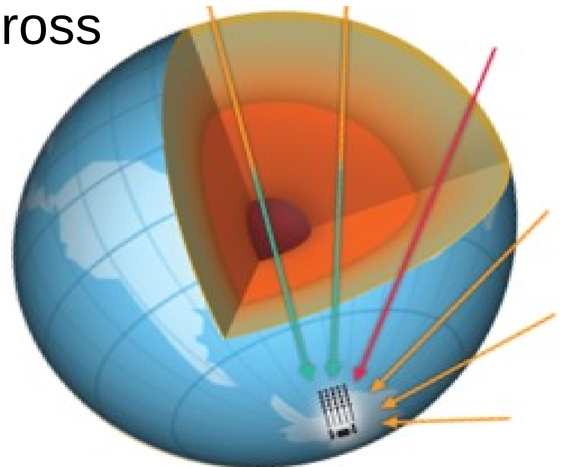
- Cosmic rays (mainly *p* and *α*) interact with the molecules present in the upper layers of Earth's atmosphere
  - ➢ Atmospheric neutrinos are mainly produced from the decay of primary and secondary heavier particles



- At low energies (< *GeV*), approximately, two $\nu_\mu+\overline{\nu}_\mu$ are produced for each $\nu_e+\overline{\nu}_e$, dominated by decays of charged pions and kaons

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu) \rightarrow e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

- Atmospheric neutrinos allow for the exploration of physics across
  - ✓ wide range of energies
  - ✓ Low and/or reducible background
  - ✓ Variety of baselines from production (*10 – 10,000 km*), approximately determined by their direction
  - ✓ Two types of neutrinos at origin and a mixture of all three (*existing?*) types at surface



Flux of atmospheric neutrinos

The basic **atmospheric** flux for each **neutrino type** convolves the **primary cosmic ray** flux by the **Earth’s magnetic field** and the **neutrino yield** per primary particle

$$\phi_{\nu_i} = \phi_p * R_p * Y_{p\rightarrow\nu_i} + \sum_A \left(\phi_A * R_A * Y_{A\rightarrow\nu_i} \right)$$

protons (indices p) *nucleons in ion* (indices A)

Ann.rev.nucl.part.sci.52:153-199,2002

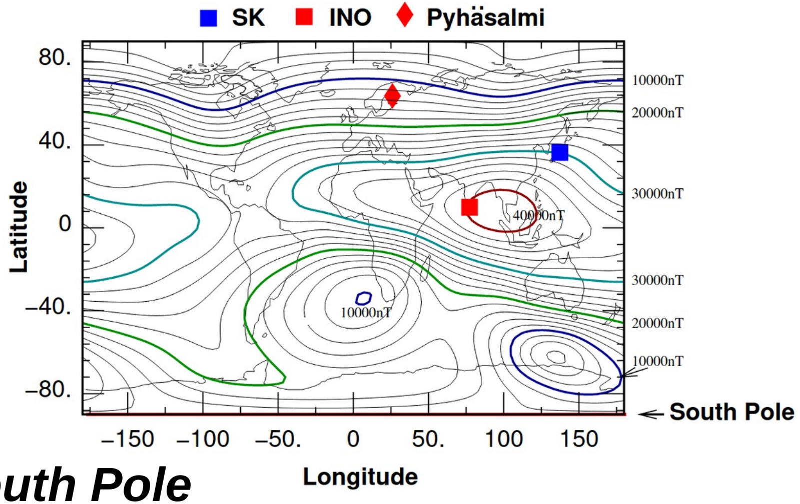
There exist a variety of models covering the current uncertainties in the above depending on:

- energy range of interest
- hadronic models
- additional cosmic ray sources
- coordinates of detection point

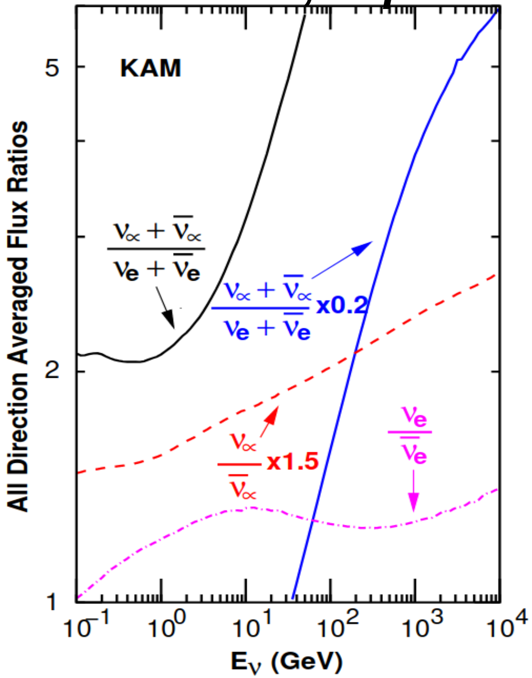
- energy range of interest
- hadronic models
- solar activity
- seasonal effects

Flux of atmospheric neutrinos

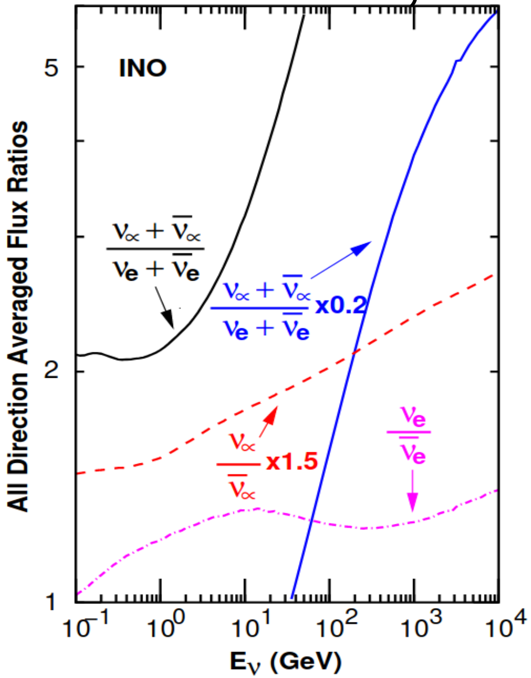
Neutrino type ratios depending on surface location



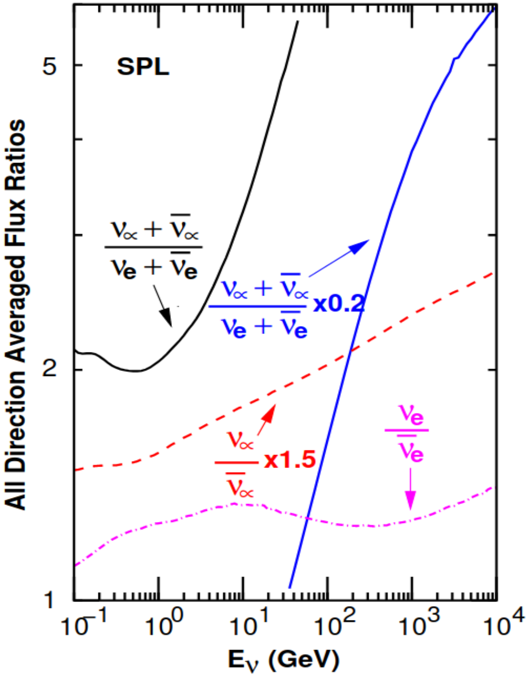
Kamioka, Japan



Bodi West Hills, India

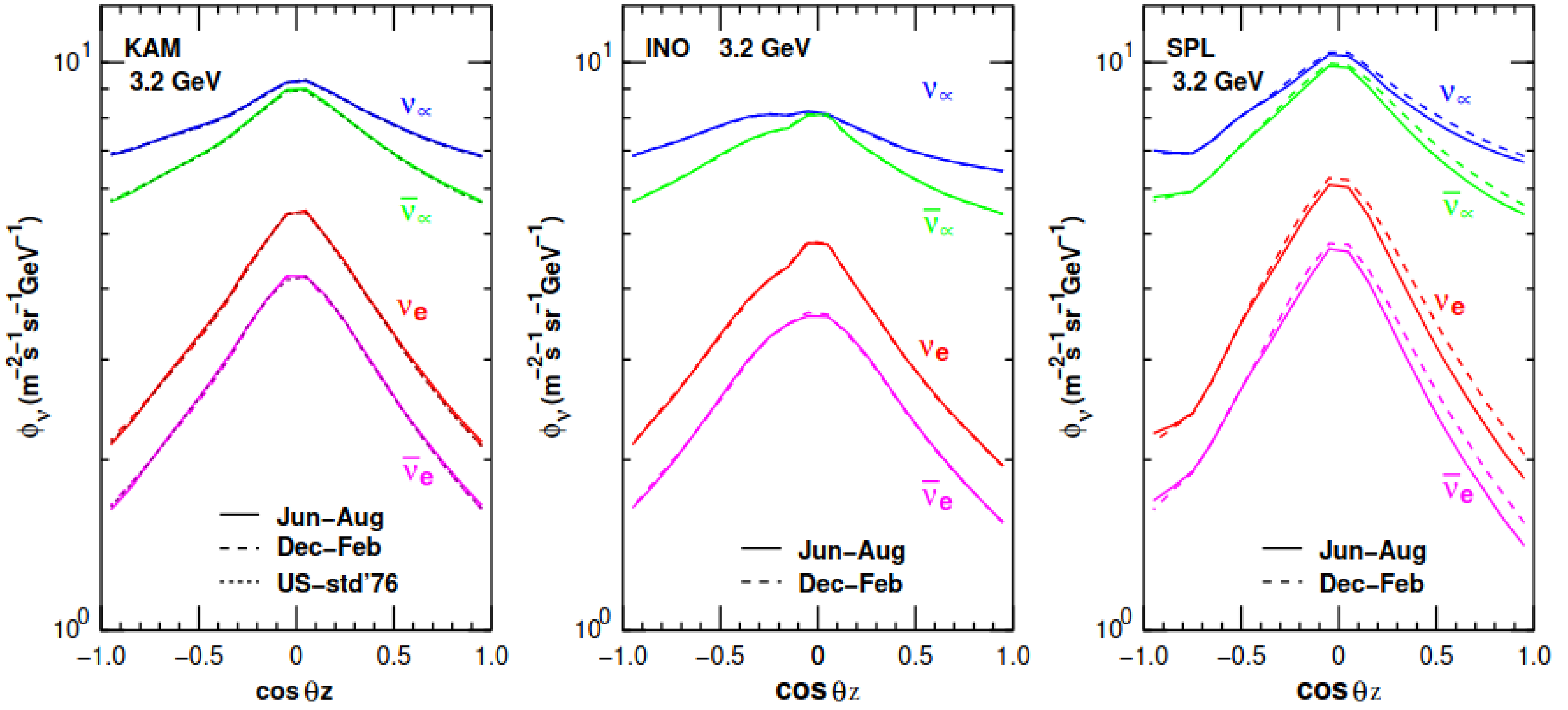


South Pole



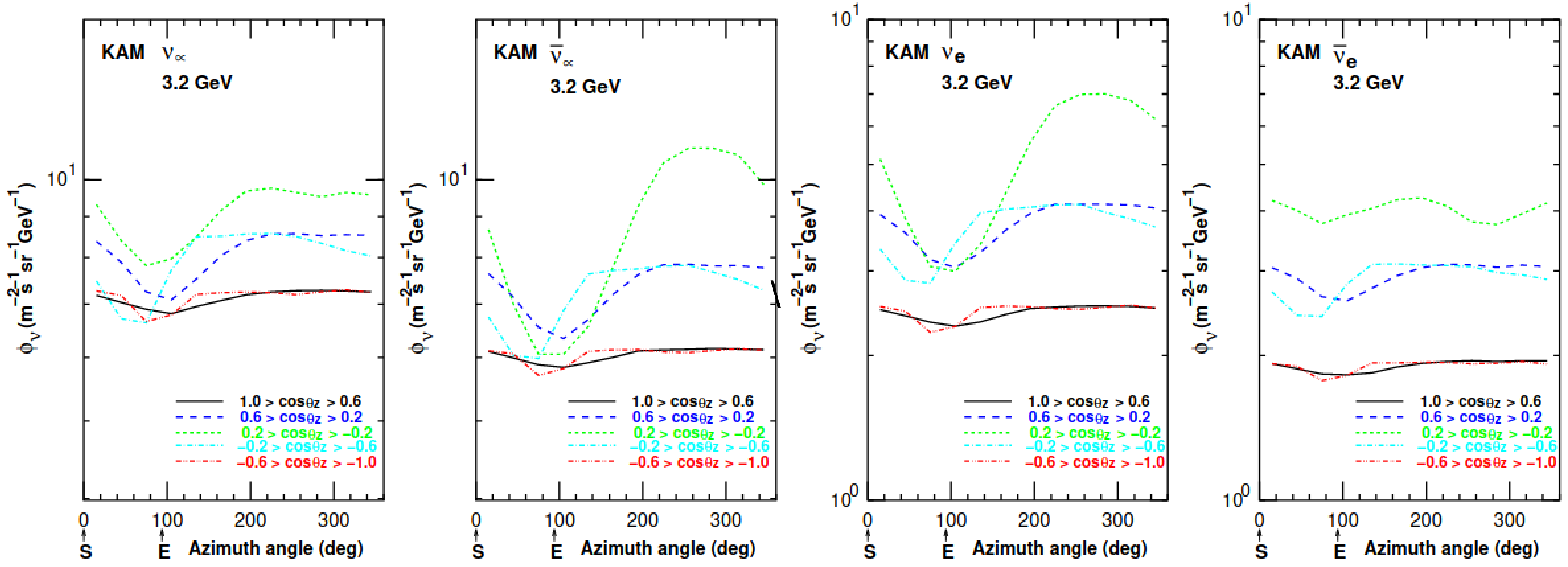
Flux of atmospheric neutrinos

Atmospheric neutrino flux also varies depending on the zenith angles

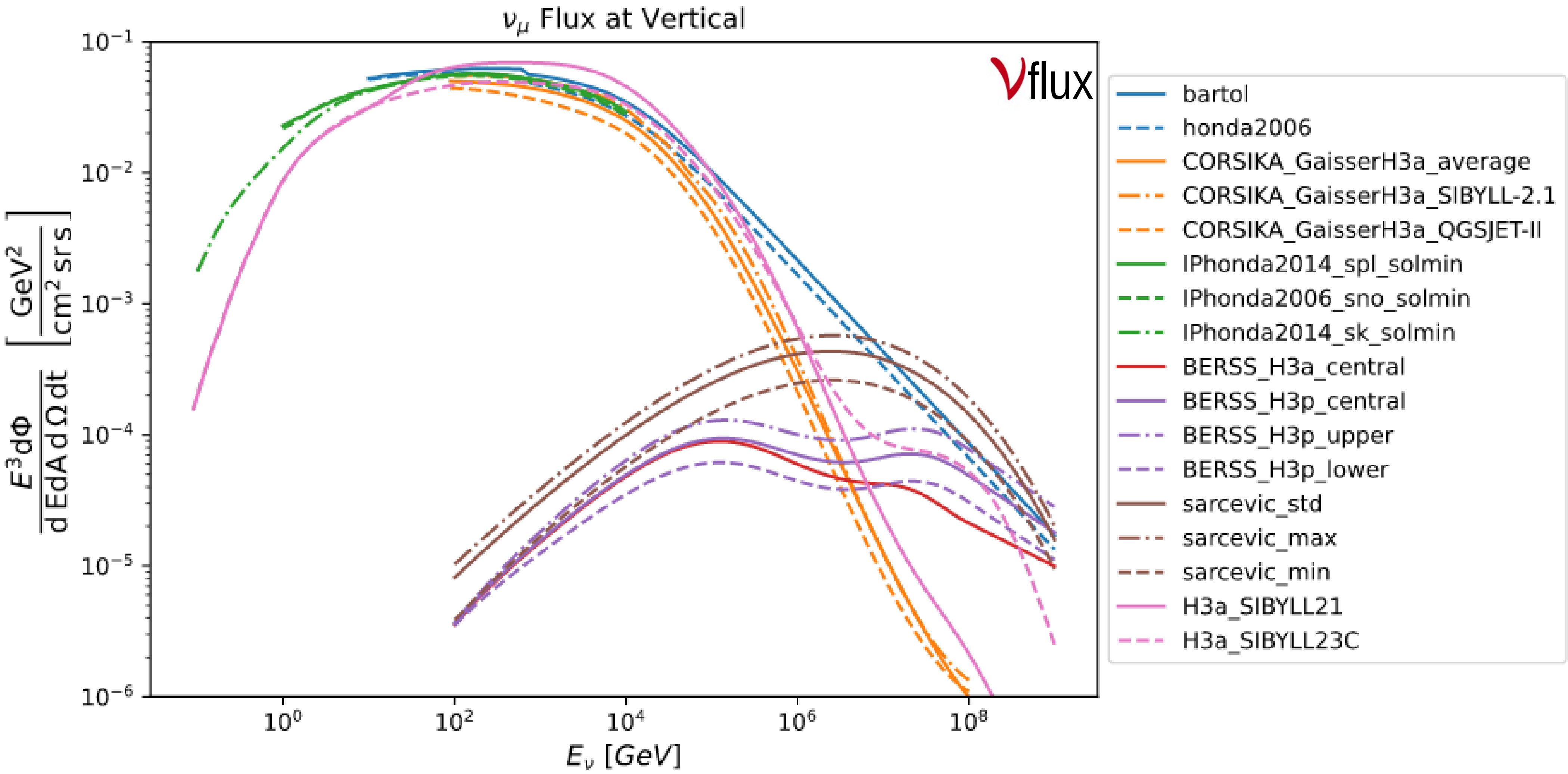


Flux of atmospheric neutrinos

Atmospheric neutrino flux also varies depending on the azimuth angles

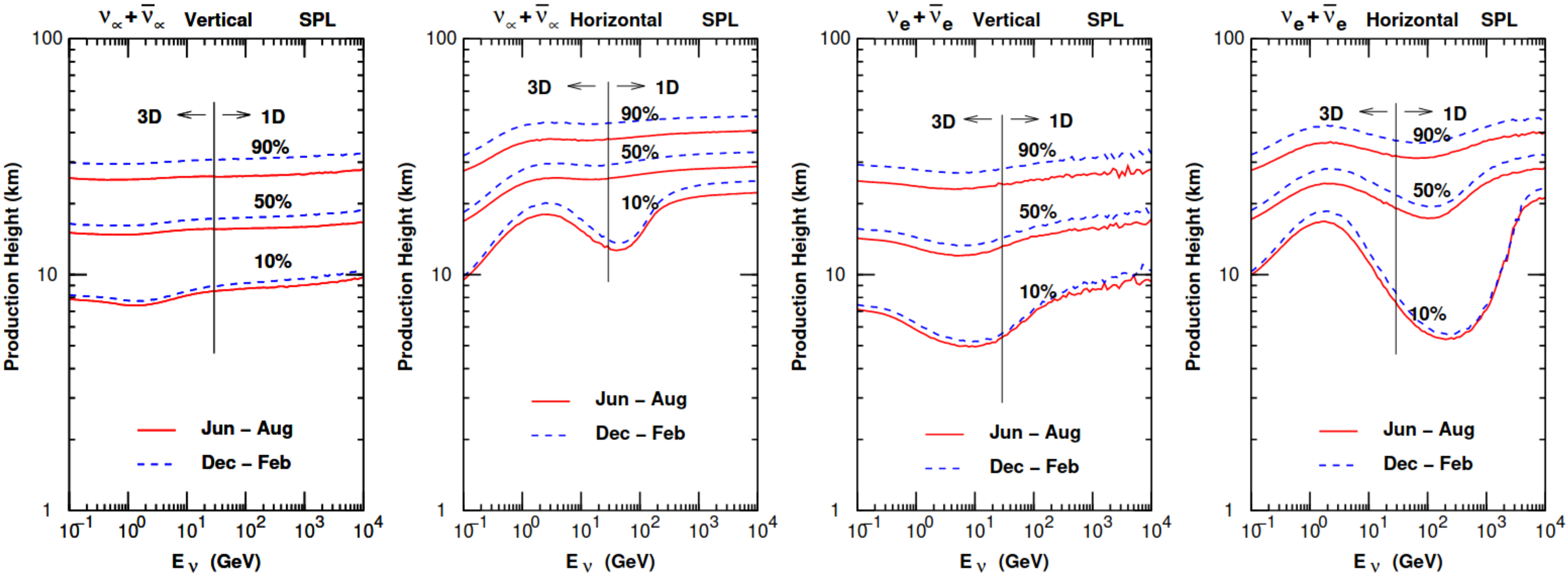


Flux of atmospheric neutrinos



Flux of atmospheric neutrinos

In addition to the complicated flux modelling, the production height is relevant and a sizeable source of uncertainty for the analysis of atmospheric neutrinos



Neutrino oscillations

Standard 3-flavour neutrino oscillations are governed by the PMNS matrix, which mixes the neutrino flavour (interaction) and mass (propagation) eigenstates.

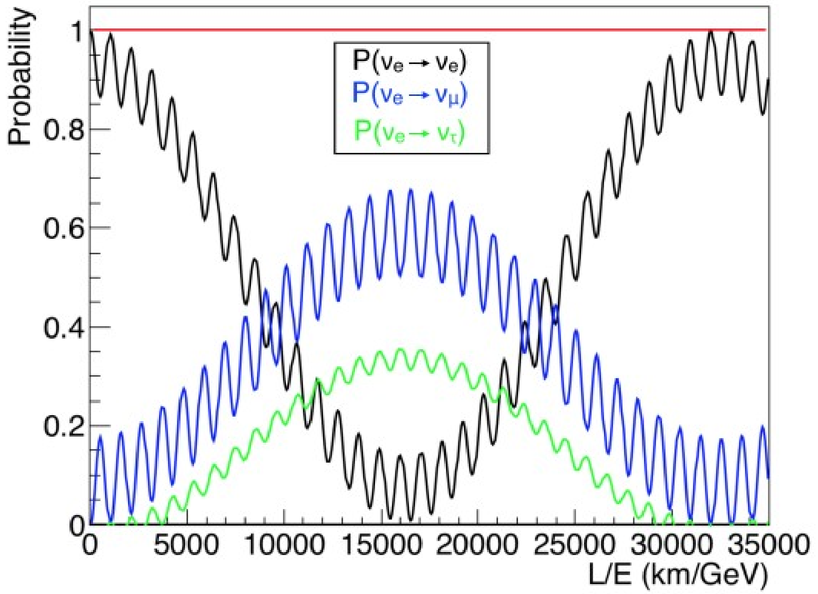
$$|\overline{\nu}_l\rangle = \sum_l U^{li}_{PMNS} |\overline{\nu}_i\rangle \qquad U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

These are vacuum oscillations and affect atmospheric neutrinos coming from above

baseline

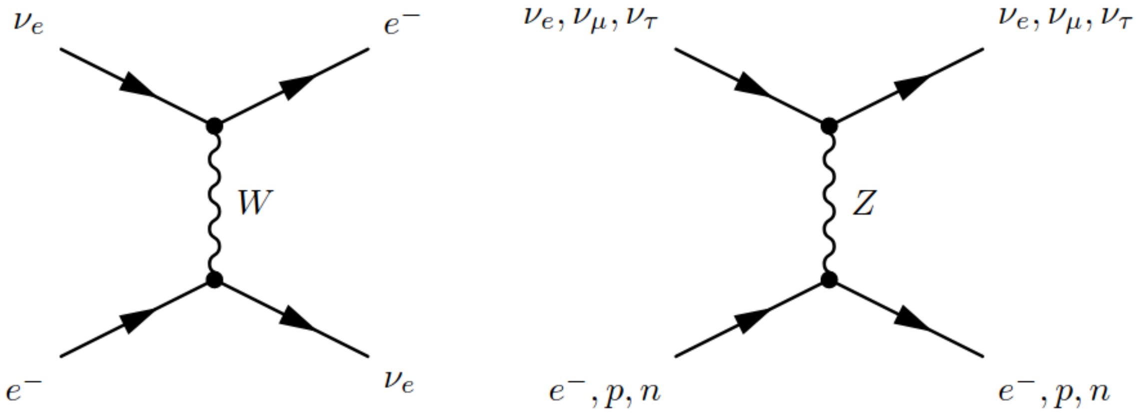
$$P_{\nu_l \to \nu_{l'}}\left(L/E\right) \approx \sum_{i,j} U^{l'i}_{PMNS} \left(U^{li}_{PMNS}\right) \left(U^{l'j}_{PMNS}\right) U^{lj}_{PMNS} \, e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

neutrino energy



Neutrino oscillations

Oscillation probabilities of neutrinos coming from below are modified by virtue of coherent forward elastic scattering with the electrons they encounter across the Earth.



This introduces an additional factor in the electron part of the hamiltonian, which in turn, alters the neutrino propagation.

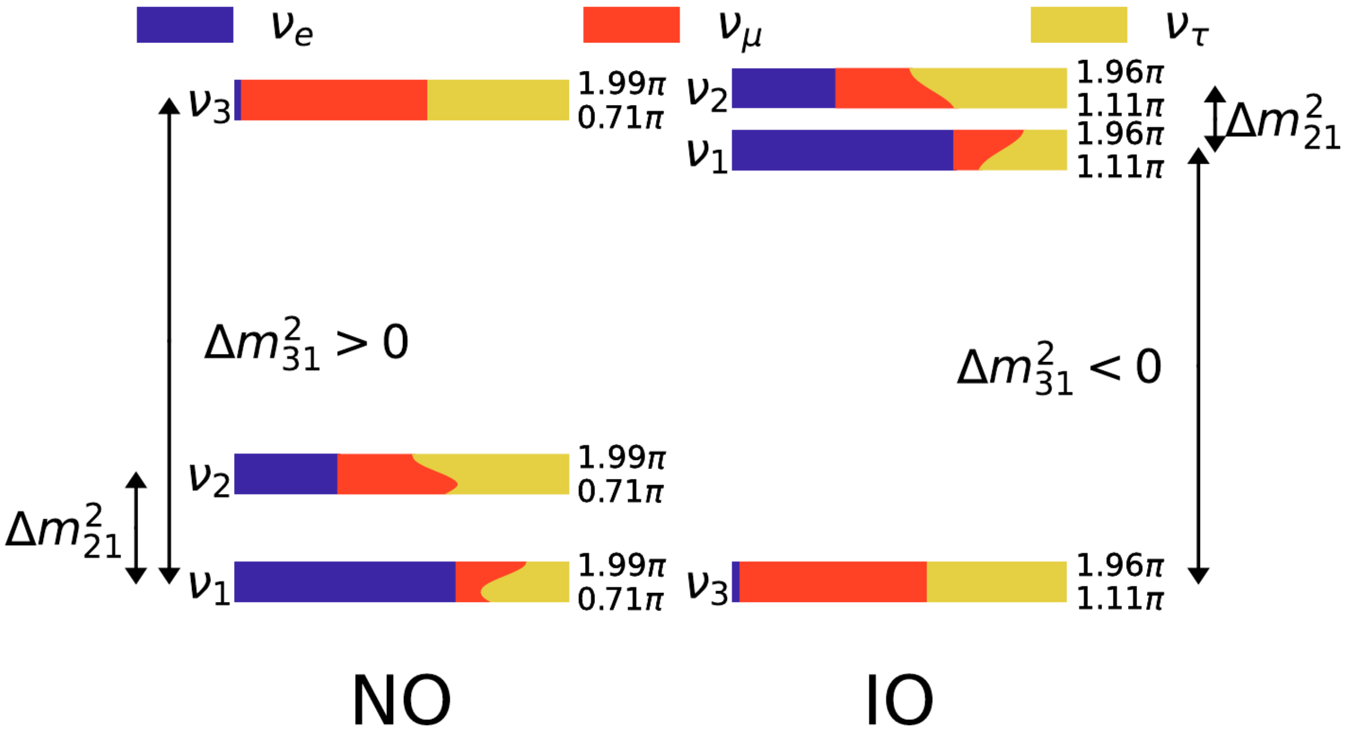
neutrinos (+) / *antineutrinos* (−)

Earth's electron density (N_e)

$$H = H_{vac} \pm V_{matter} = H_{vac} \pm \sqrt{2} G_F N_e \, diag(1,0,0)$$

Neutrino oscillations

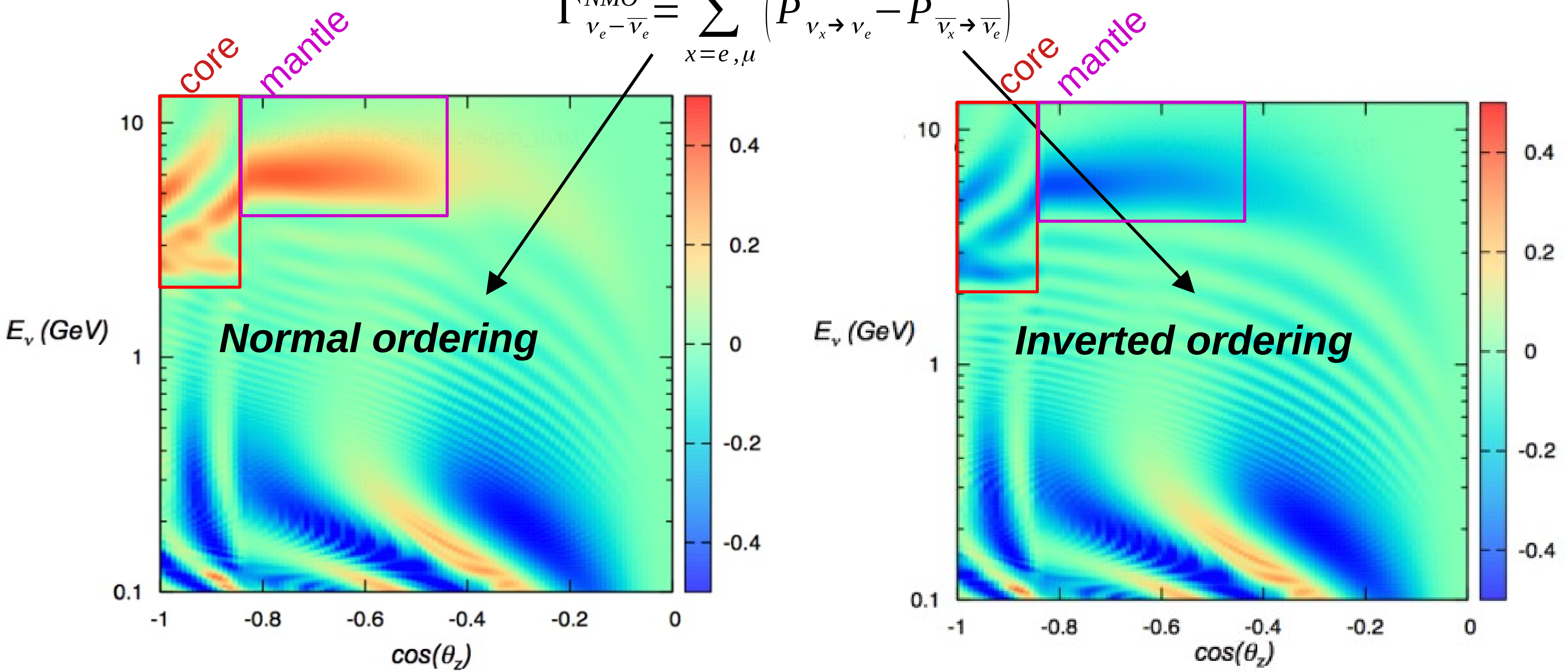
Matter effects show opposite behaviour between normal and inverted neutrino mass ordering (NMO) and thus, are crucial to measure the neutrino parameters



Neutrino oscillations

Matter effects show opposite behaviour between normal and inverted neutrino mass ordering (NMO) and thus, are crucial to measure the neutrino parameters

$$\Gamma^{NMO}_{\nu_e - \overline{\nu}_e} = \sum_{x=e,\mu} \left(P_{\nu_x \to \nu_e} - P_{\overline{\nu}_x \to \overline{\nu}_e} \right)$$



Neutrino oscillations

Other phenomena of physics Beyond the Standard Model are also very suited to be explored with atmospheric neutrinos:

- **Non-standard interactions**: motivated by some GUT models where the existence of heavy (~TeV) bosons allow flavour-changing neutrino interactions

  This introduces an additional term in the matter part of the hamiltonian

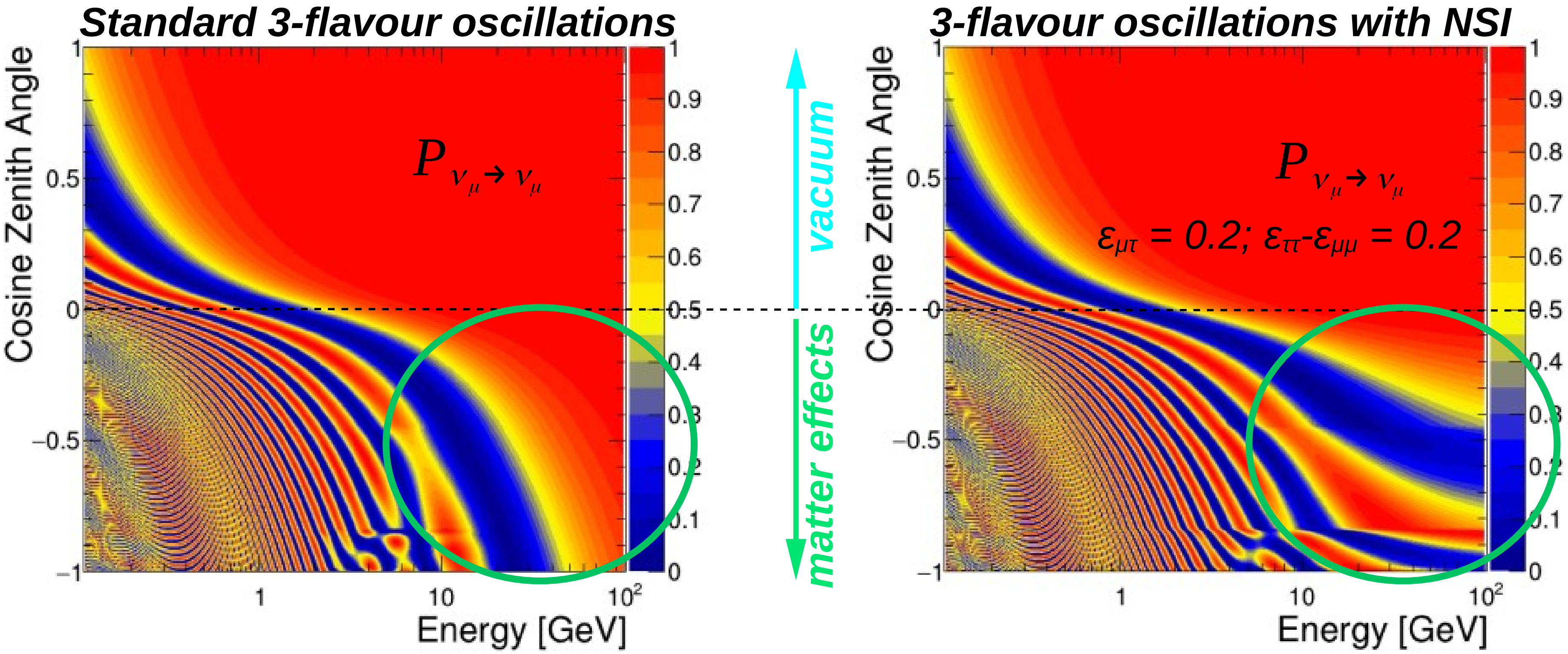
$$H = H_{vac} \pm V_{matter} \pm V_{NSI} = H_{vac} \pm V_{matter} \pm \sqrt{2}\, G_F N_f \begin{pmatrix} \varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Earth's fermion density

Neutrino oscillations

Other phenomena of physics Beyond the Standard Model are also very suited to be explored with atmospheric neutrinos:

- **Non-standard interactions**: motivated by some GUT models where the existence of heavy (~TeV) bosons allow flavour-changing neutrino interactions



Neutrino oscillations

Other phenomena of physics Beyond the Standard Model are also very suited to be explored with atmospheric neutrinos:

- **Sterile neutrinos**: additional types of neutrinos which do not interact via weak bosons (sterile) and could potentially explain some experimental anomalies/tensions (LSND, GALLEX, SAGE)
  There exist numerous models introducing one or more (*N*) sterile neutrinos, which generalize the **PMNS** mixing matrix to *3+N*

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$H = H_{vac} \pm V_{matter} \pm V_s =$$

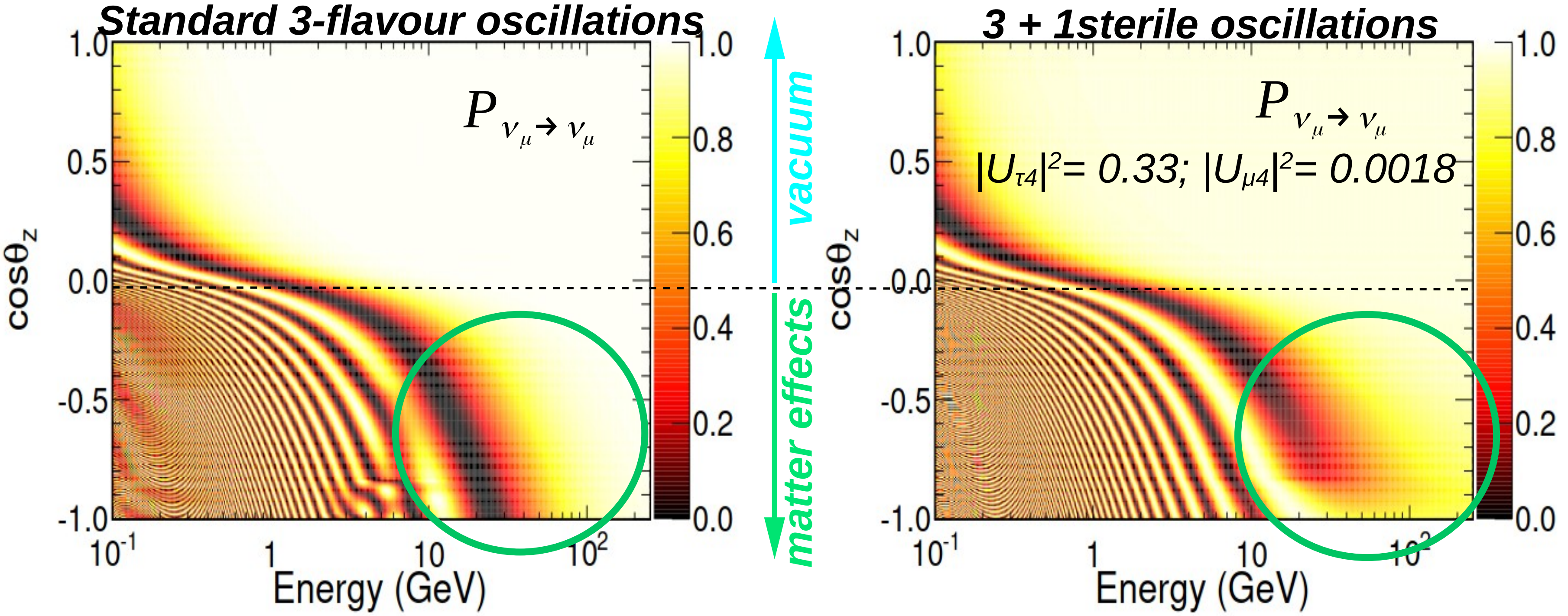
$$H_{vac} \pm \sqrt{2} G_F N_e \, diag(1,0,0,\ldots) \pm \sqrt{2} G_F N_n \, diag(0,0,0,N_n,\ldots)$$

Earth's neutron density

Neutrino oscillations

Other phenomena of physics Beyond the Standard Model are also very suited to be explored with atmospheric neutrinos:

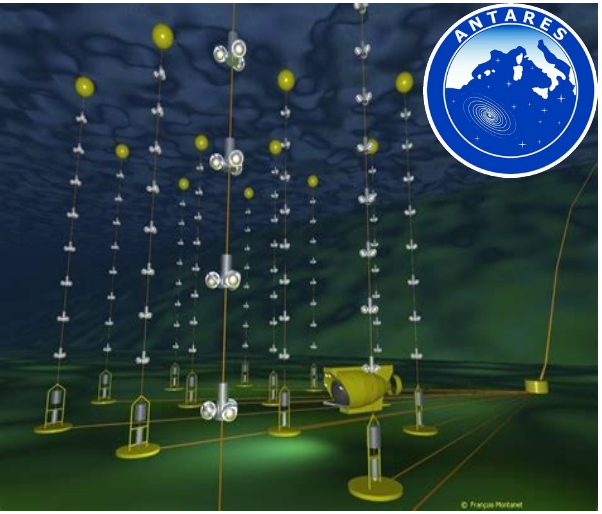
- **Sterile neutrinos**: additional types of neutrinos which do not interact via weak bosons (sterile) and could potentially explain some experimental anomalies (LSND, GALLEX, SAGE)

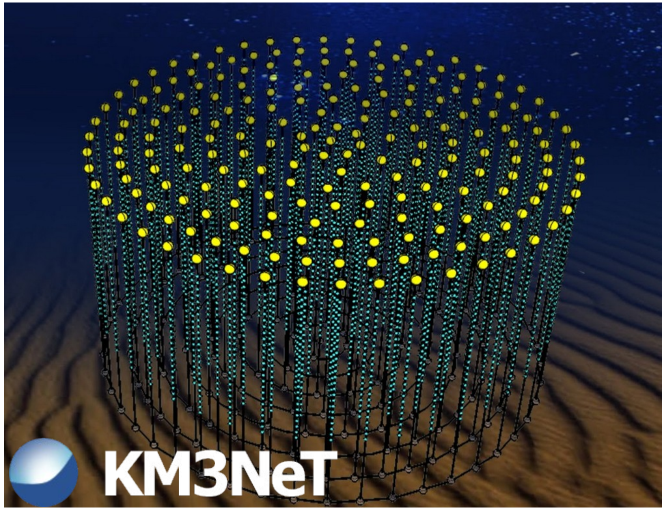


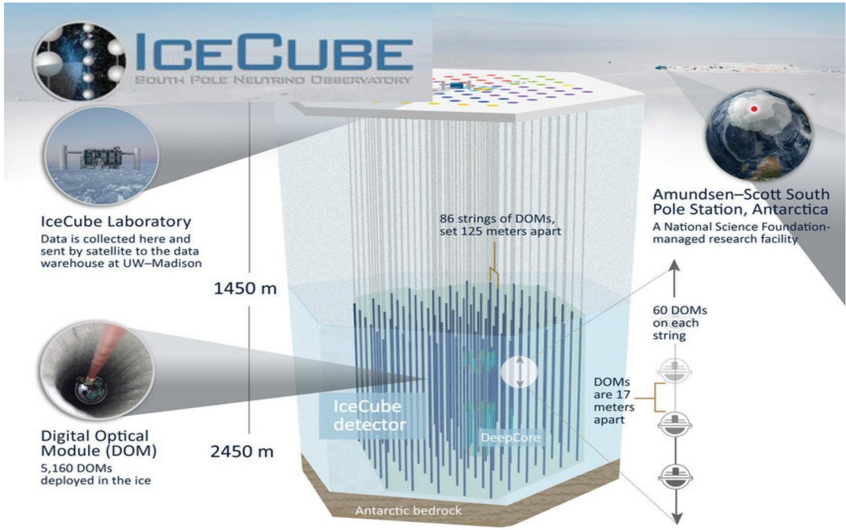
Atmospheric neutrino experiments

Currently active atmospheric neutrino experiments

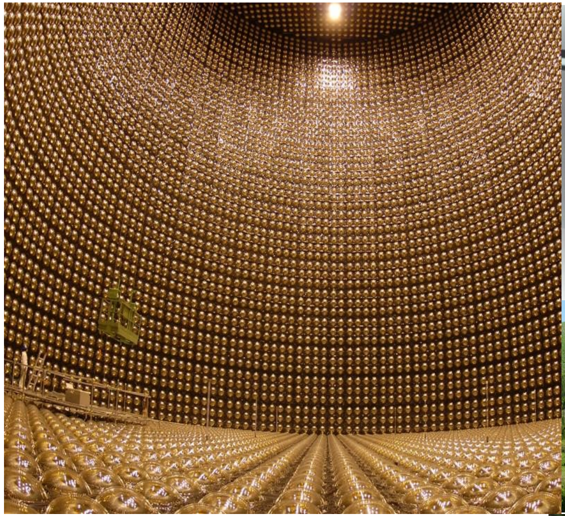
- **Super-Kamiokande** and **IceCube** provide the best results with large statistics
- **ANTARES** and the starting **KM3NeT** provide promissing results for next generation experiments

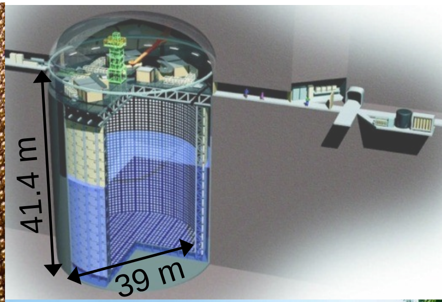






→ Super-Kamiokande and SuperK-Gd

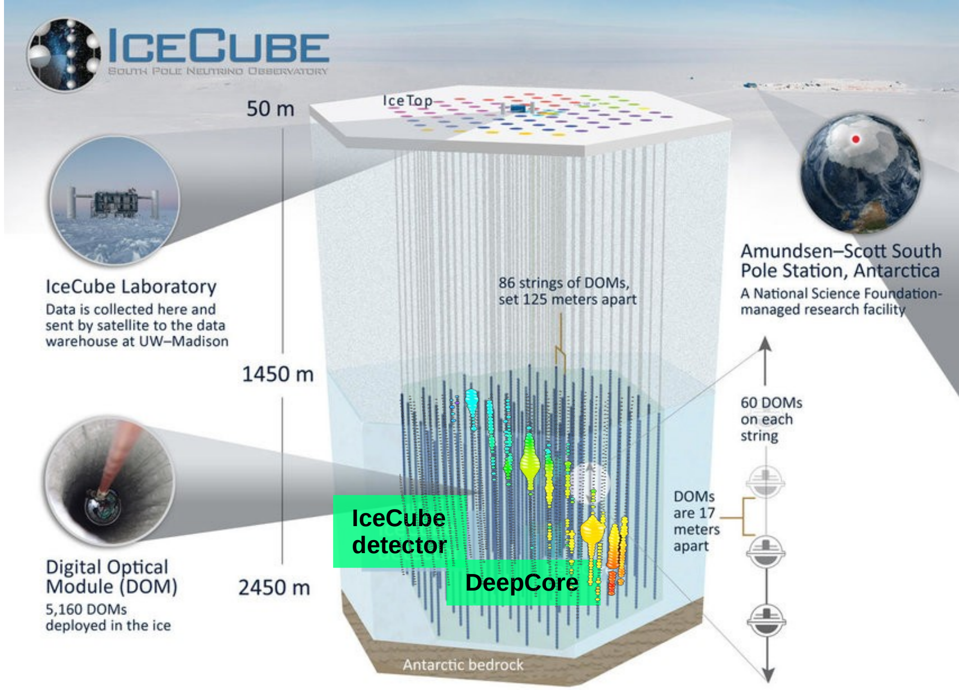


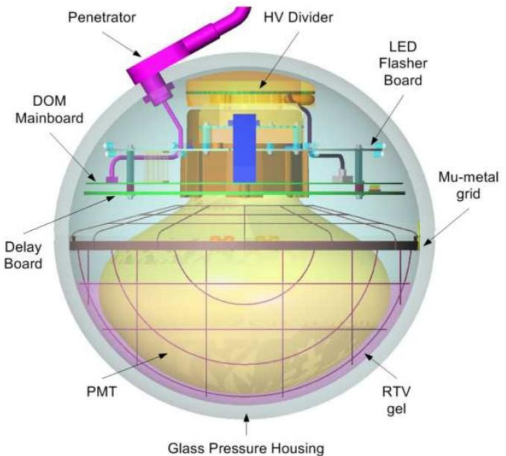


- 25-year-old water-Cherenkov detector
- Located in Kamioka, Japan
- Overburden 1km of rock
- Total of **50 kton** of ultra-pure water
  - Currently doped with **Gd sulfate**
- Optically divided into inner (ID) and outer (OD) detectors, instrumented with
  - **ID:** ~11000 20”-PMTs → 40% coverage
  - **OD**: ~1900 8”-PMTs primarily used as veto
- Covers a wide variety of fundamental physics: Solar, **atmospheric**, LBL, SN and astrophysicsal νs, proton decays…
- Discovery of non-zero neutrino masses in 1998 (Nobel 2015)
- Still at the forefront of ν physics with the *ongoing* upgrade, **SuperK-Gd**
  - Eventually with 0.1% of Gd dissolved, will detect 90% of neutrons

→ IceCube and DeepCore

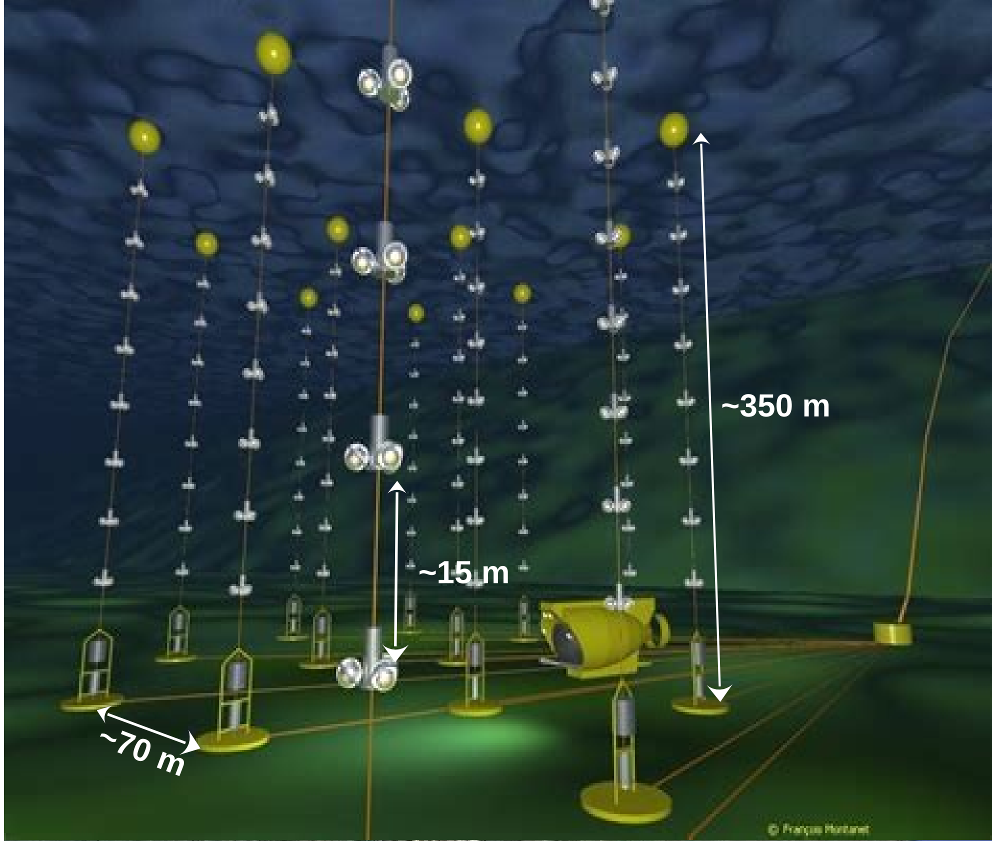
- Ice-Cherenkov detector;
  taking data since 2011
- World's largest-volume neutrino detector
  - ➔ Deep South Pole ice is most optically-transparent material on Earth
- Located nearby the Amundsen-Scott South Pole Station
- Consists of 86 strings of 60 optical modules
- With an active volume of $1km^3$ and placed 1450 to 2450 m below surface
- DeepCore: 8 strings with 480 optical sensors and smaller spacing for lower energies (few GeV)
- Digital Optical Modules (DOMs) contain a PMT to receive light and mainboard to digitize signal
- Dedicated to high energy astrophysical and **atmospheric** neutrinos, and indirect dark matter searches





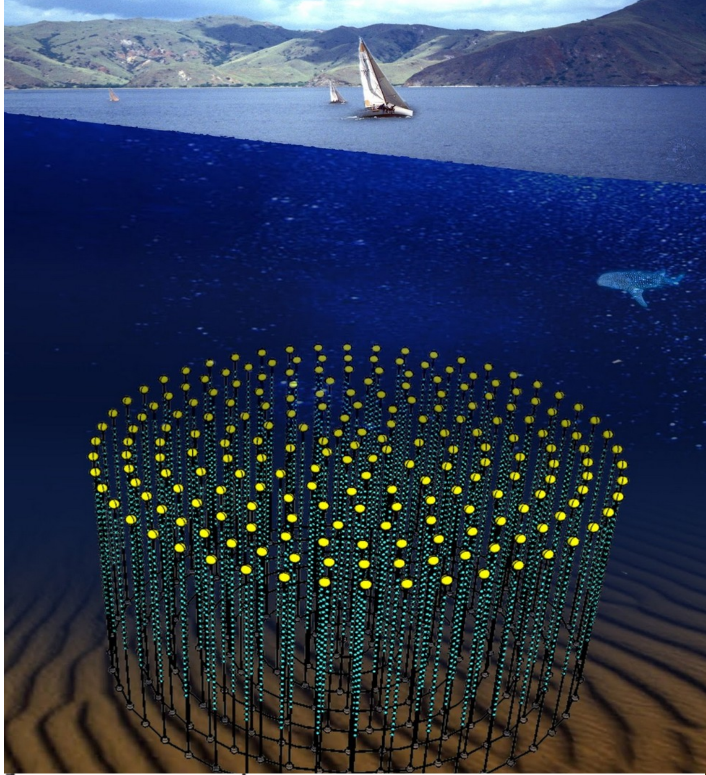
→ ANTARES

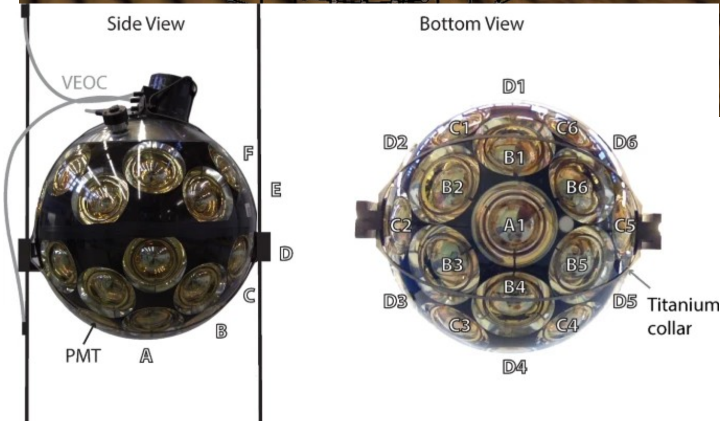
- Deep-sea water-Cherenkov detector completed in 2008
- Located 40 km offshore Toulon (France), in the Mediterranean Sea
- 12 vertical strings anchored to the sea floor and of 25 storeys each
- 3 10" PMTs per storey (885 in total) pointing 45º downwards
- Active volume of ~0.01 km^3 and placed at 2500 m deep
- A first step toward the network of kilometric scale detectors **KM3NeT**
- Dedicated to high energy astrophysical and **atmospheric** neutrinos, and indirect dark matter searches



→ KM3NeT/ORCA

- KM3NeT consists of two deep-sea water-Cherenkov detectors in the Mediterranean Sea
  - ARCA (Astropart. Research with Cosmics in the Abyss)
    - 80 km offshore the Sicilian coast (Italy)
    - TeV-PeV neutrino astronomy
  - **ORCA** (Osc. Research with Cosmics in the Abyss)
    - 40 km offshore Toulon (France) at a sea bottom depth of about 2450 m
    - 8 Mton volume
    - More-densely instrumented, goal of 64170 PMTs
    - Optimised for neutrino oscillations
    - Deployed 6 detection units (5%)
- Despite being **currently under construction**, the KM3NeT collaboration has been able to analyse data from the first detection units deployed

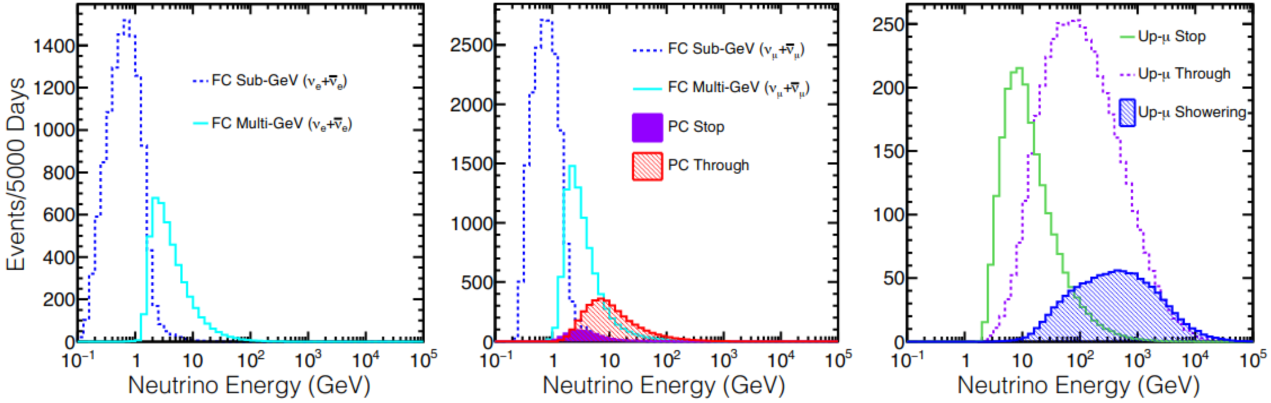


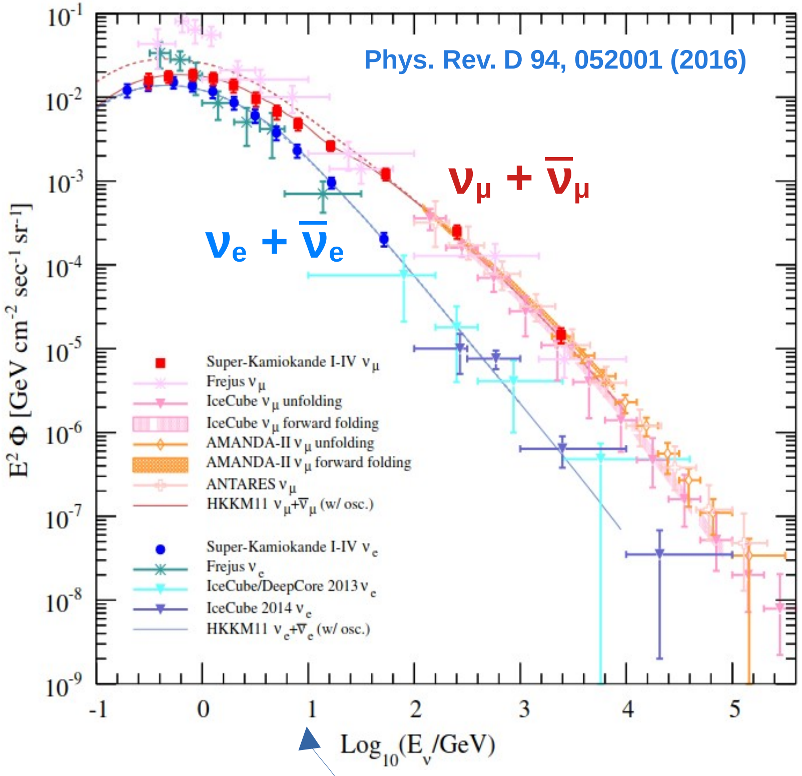


Atmospheric Neutrinos, the Latest Results

Atmospheric ν flux from Super-K

Events are classified depending on the Cherenkov-ring pattern (*e-like* or *μ-like*) and their topology, achieving a comprehensive event clasification, key for their analyses





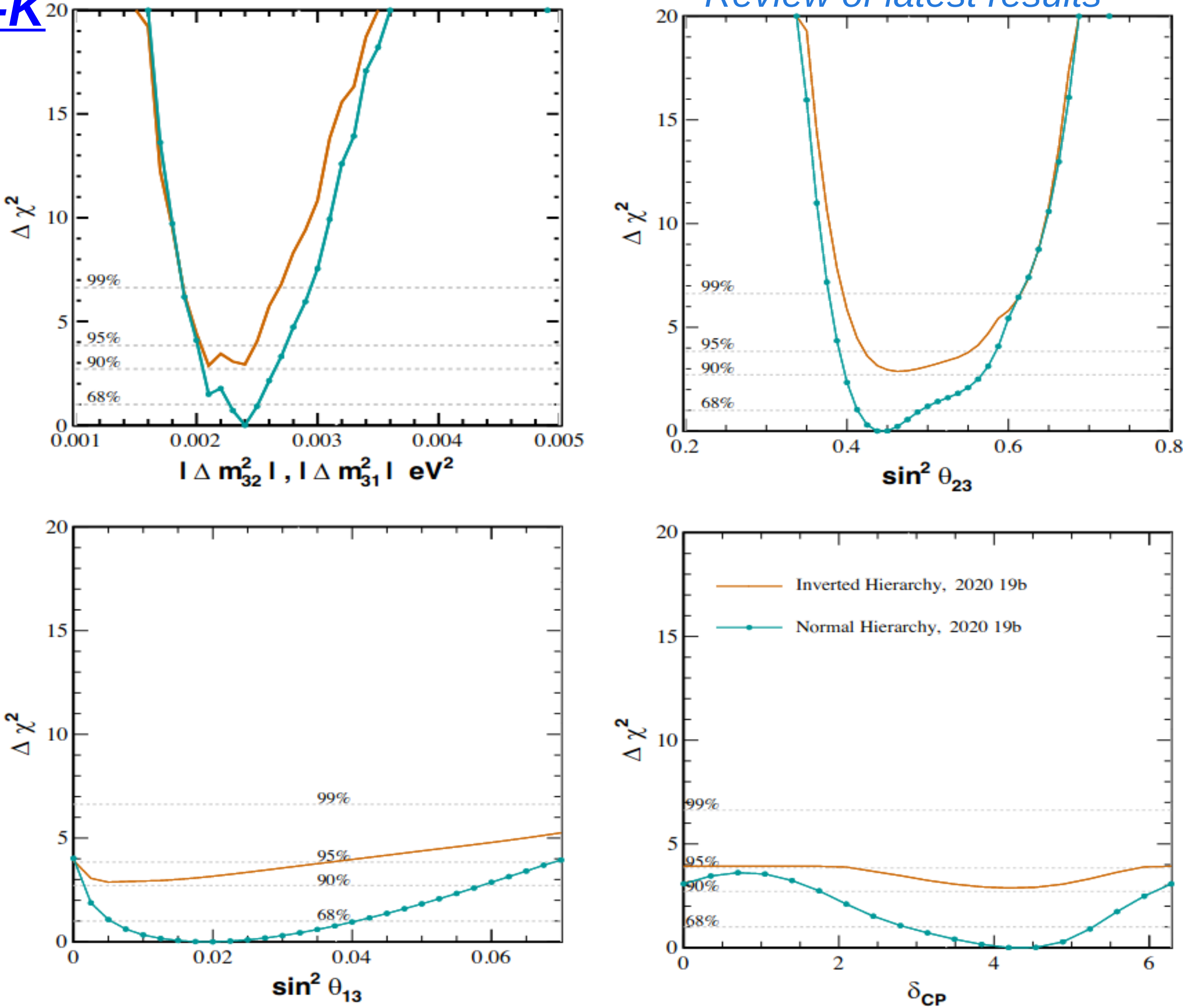
The measured atmospheric flux agrees with the Honda model from 100 MeV to 100 GeV and for both muon and electron neutrinos

Atmospheric Neutrinos, the Latest Results

Standard oscillations from Super-K

Review of latest results

- Results prefer θ_{23} to be in the first octant
- Normal mass ordering is still prefered at <u>*$\Delta\chi^2(IH) - \Delta\chi^2(NH) = 2.8$*</u>
- δ_{CP} best fit value agrees with that of T2K
- Some constraining power over θ_{13} and consistent with reactor and LBL experiments

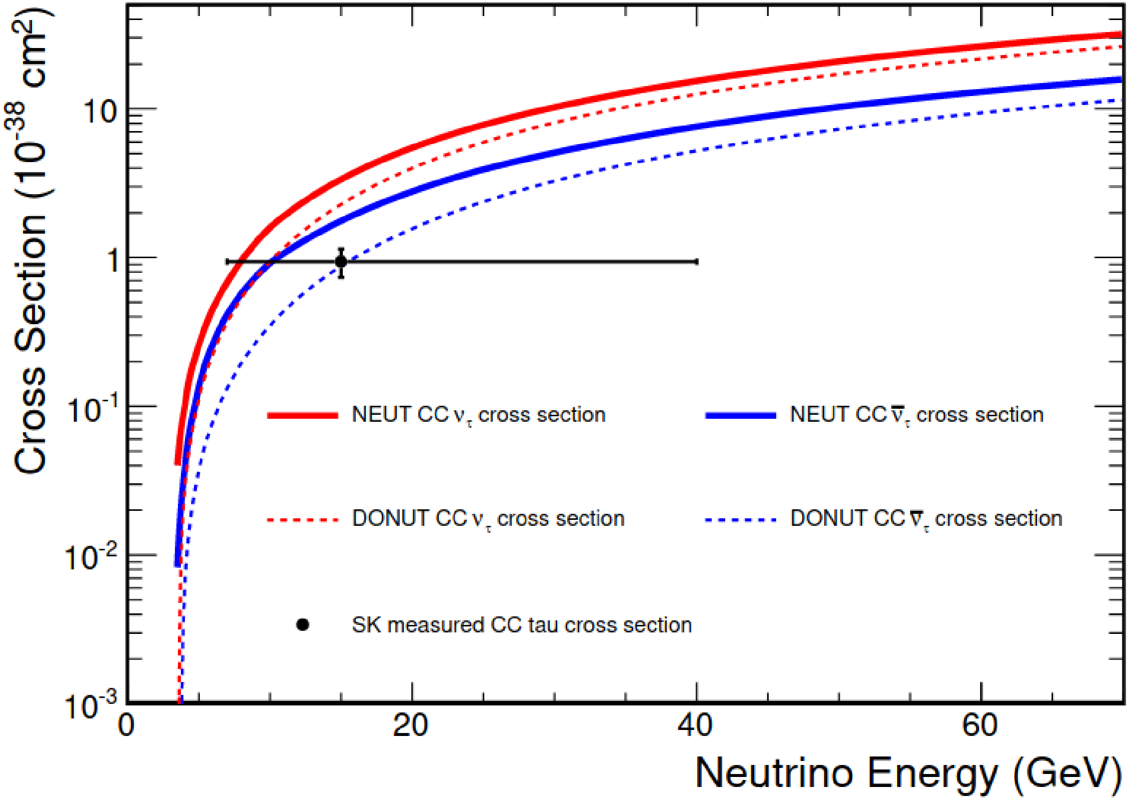


Atmospheric Neutrinos, the Latest Results

Standard oscillations from Super-K

- Thanks to oscillations, a significant amount of ν_τ arrive at SuperK
- Additionally, SK reports a measurement of the ν_τ cross-section
- Combined cross-section of ν_τ and $\overline{\nu}_\tau$ averaged over 5 GeV to 40 GeV

Phys. Rev. D 98, 052006 (2018)

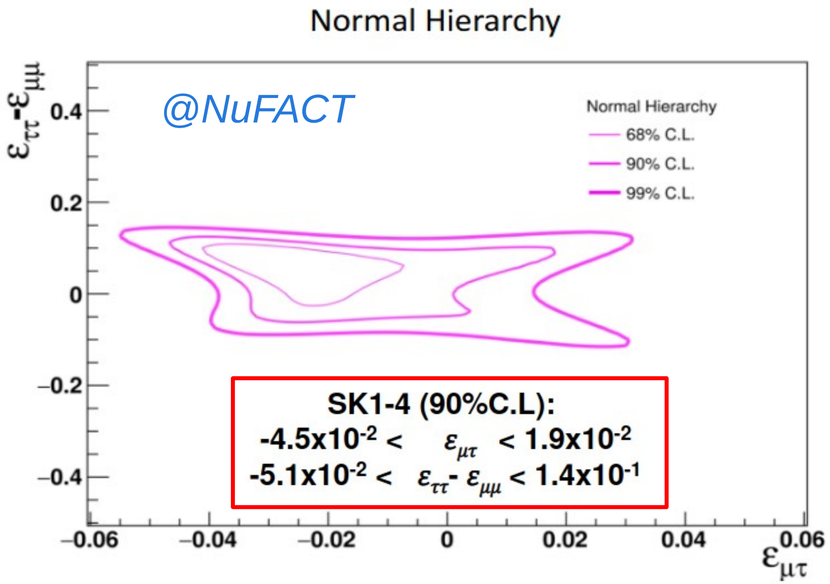


Atmospheric Neutrinos, the Latest Results

NSI searches from Super-K

Several analyses are performed to explore and set limits to NSI in the μ-τ and e-τ sectors

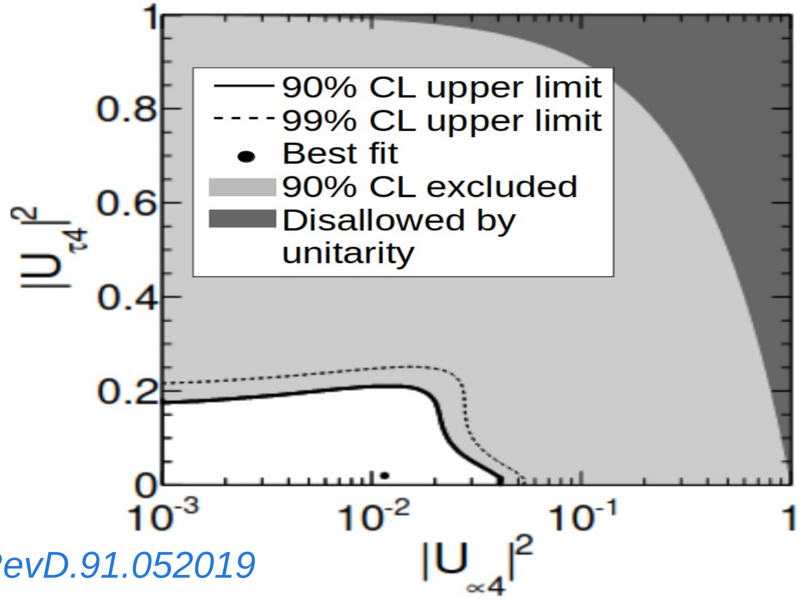
Results are consistent with other experiments and with the absence of NSI



Sterile ν searches from Super-K

As in the NSI search, the analysis is limited by low high energy (above 10 GeV) statistics

Still, results prefer the 3-flavour scenario with no additional sterile neutrino



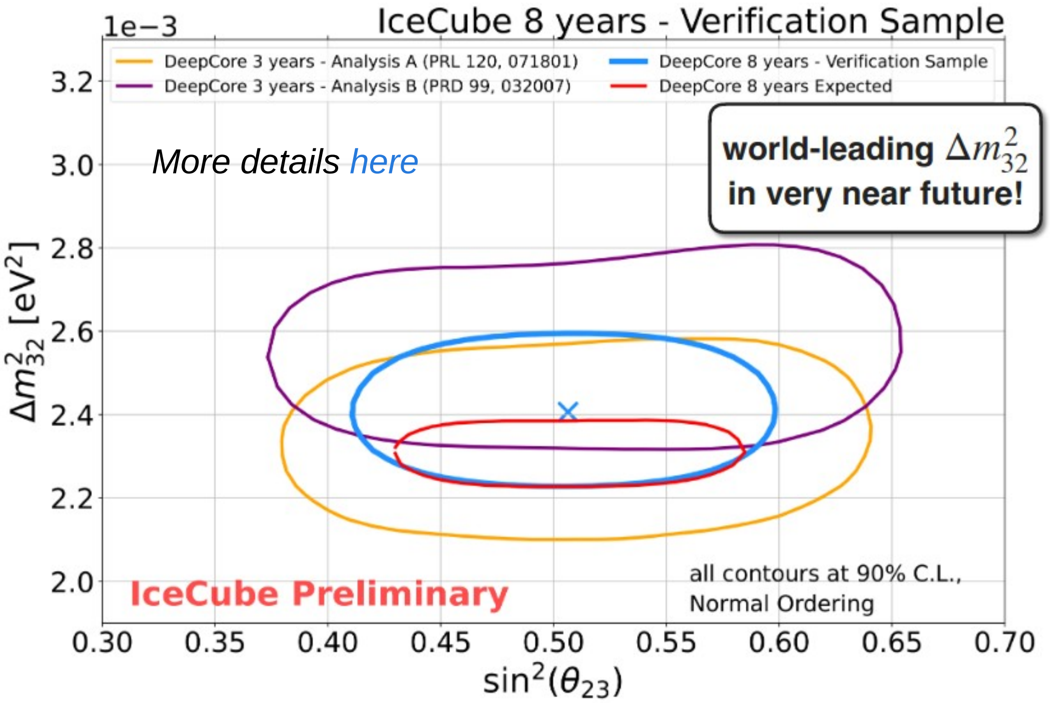
PhysRevD.91.052019

Atmospheric Neutrinos, the Latest Results

Standard oscillations from IceCube and DeepCore

DeepCore has an energy threshold of 5 GeV and can distinguish CCν_μ from the rest of interactions (NC, ν_e and ν_τ)

- New analysis will be available soon with 8 years of atmospheric neutrinos and improved calibration
- Analysis of the so-called "Verification Sample" (~23000 well-reconstructed ν_μ events)
  - ➔ Very constraining results for the atm. Mixing parameters, especially for the squared mass difference
- Analysis of the whole data set expect to lead the measurement of Δm^2_{32}

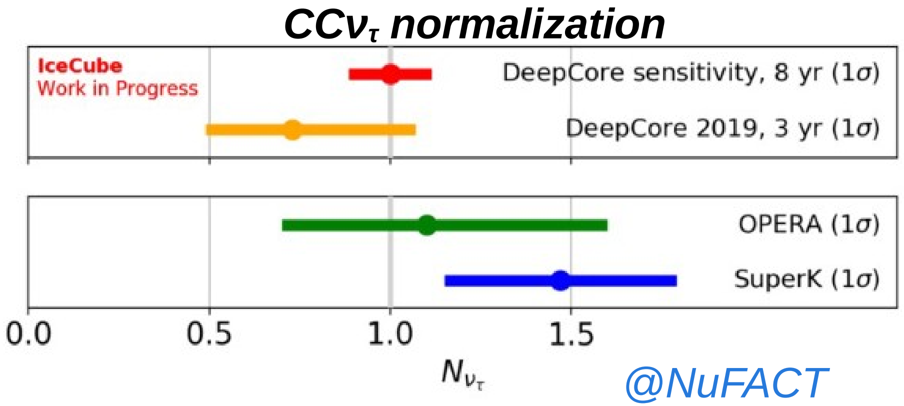


Atmospheric Neutrinos, the Latest Results

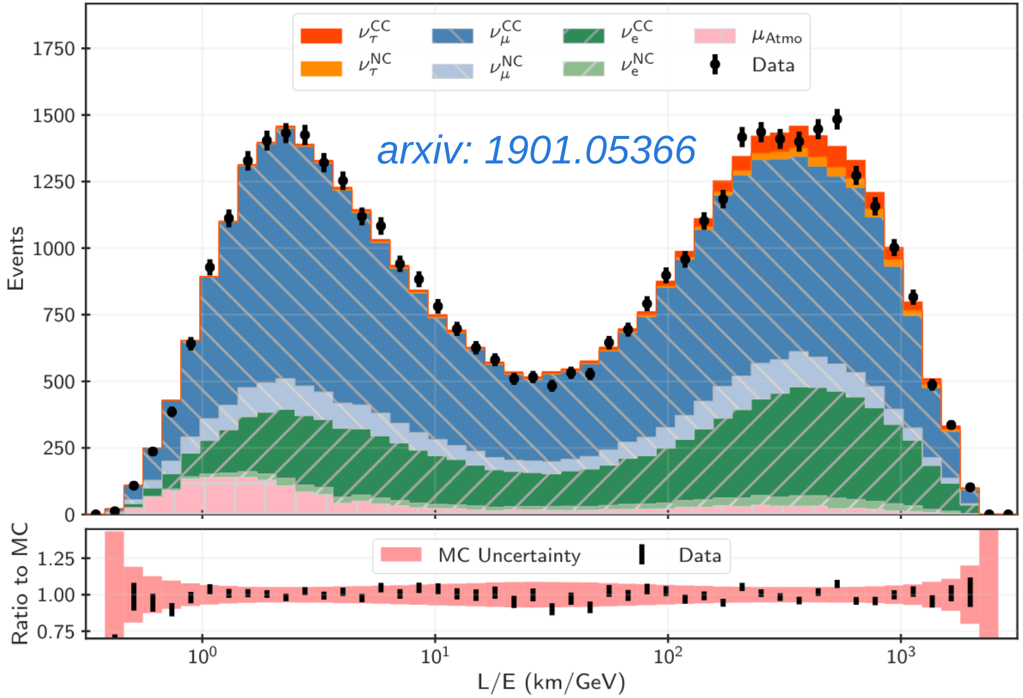
Standard oscillations from IceCube and DeepCore

DeepCore is very competitive in the analysis of tau neutrino appearance

- Large statistics above the $CC\nu_\tau$ threshold



@NuFACT



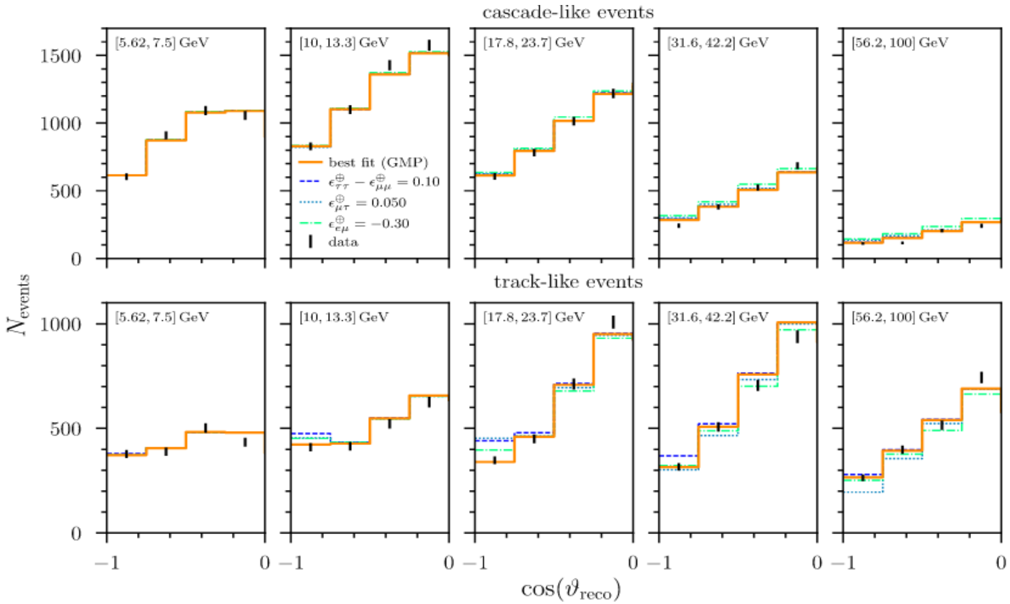
Atmospheric Neutrinos, the Latest Results

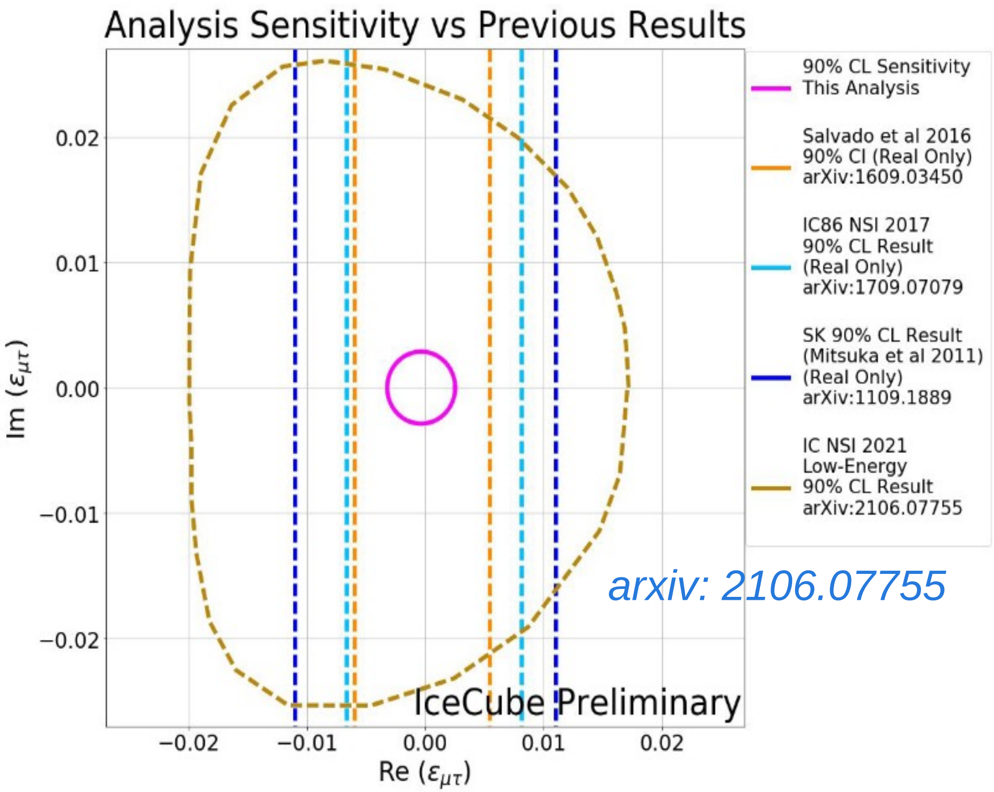
Non-standard interactions from IceCube and DeepCore

The collaboration is producing two independent analyses, low and high energy:

- Low energy (O(10 GeV)) analysis is under way, sensitive to $\varepsilon_{\tau\tau}$-$\varepsilon_{\mu\mu}$ and $\varepsilon_{e\mu}$
- High energy analysis recently published, most sensitive to $\varepsilon_{\mu\tau}$

➔ Promising projections for upcoming NSI measurements





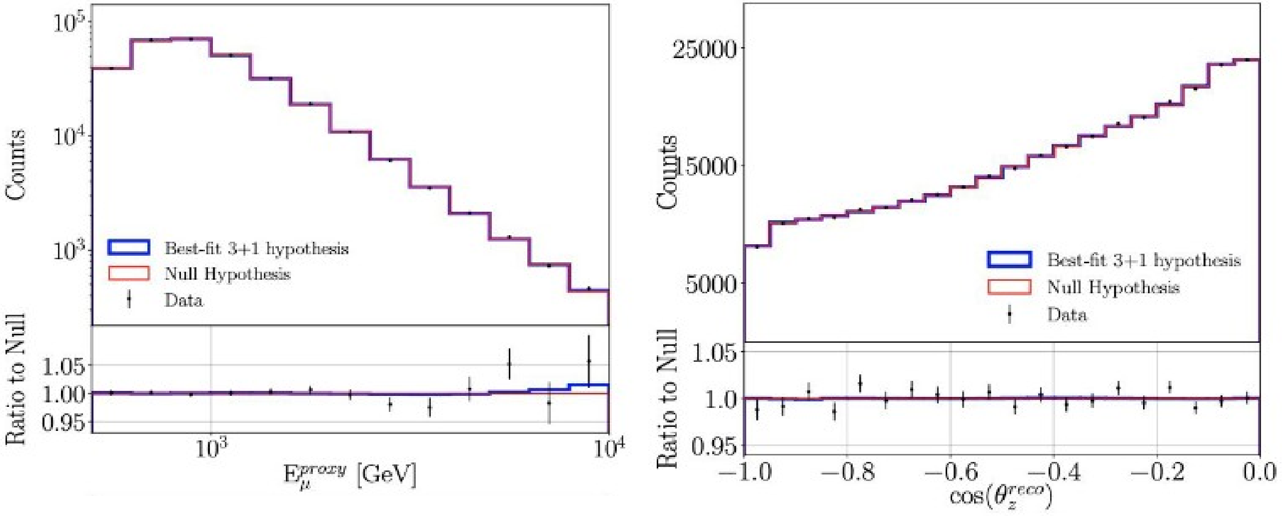
arxiv: 2106.07755

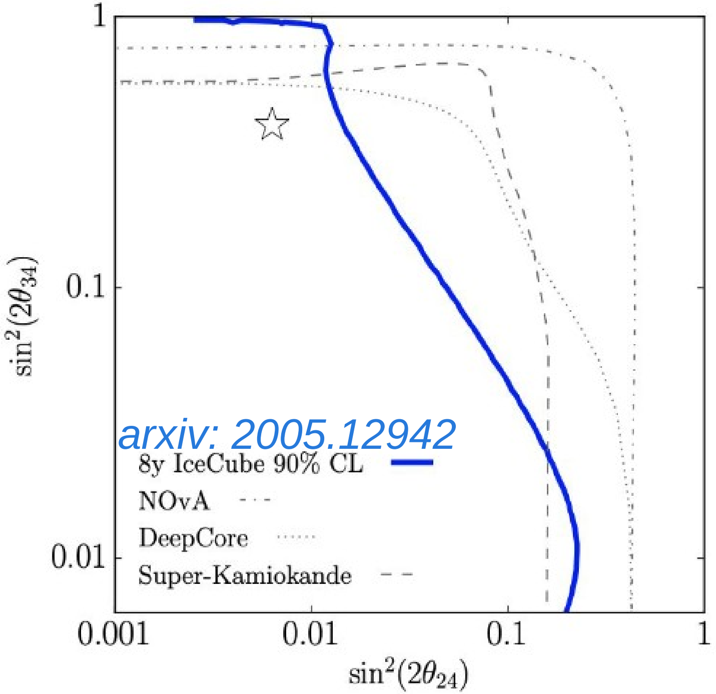
Atmospheric Neutrinos, the Latest Results

Sterile ν searches from IceCube and DeepCore

Competitive and complementary contraints to the existence of additional sterile neutrinos

➔ Results prefer the 3-flavour scenario





Additional BSM ν searches from IceCube and DeepCore

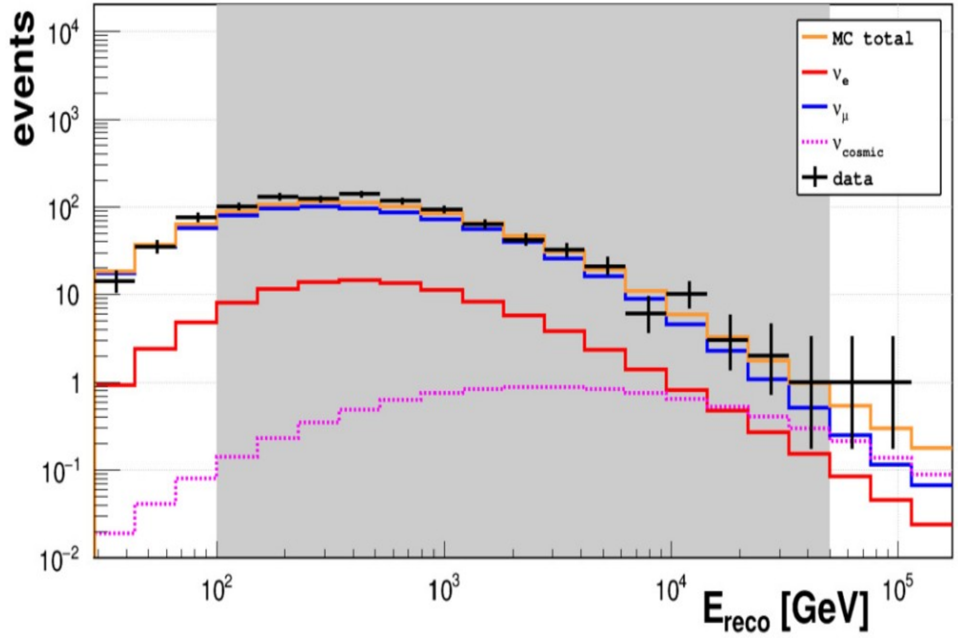
Other studies like “Neutrino Decoherence from Quantum Gravitational Space-Time Fluctuations are carried out, more details here and here

Atmospheric Neutrinos, the Latest Results

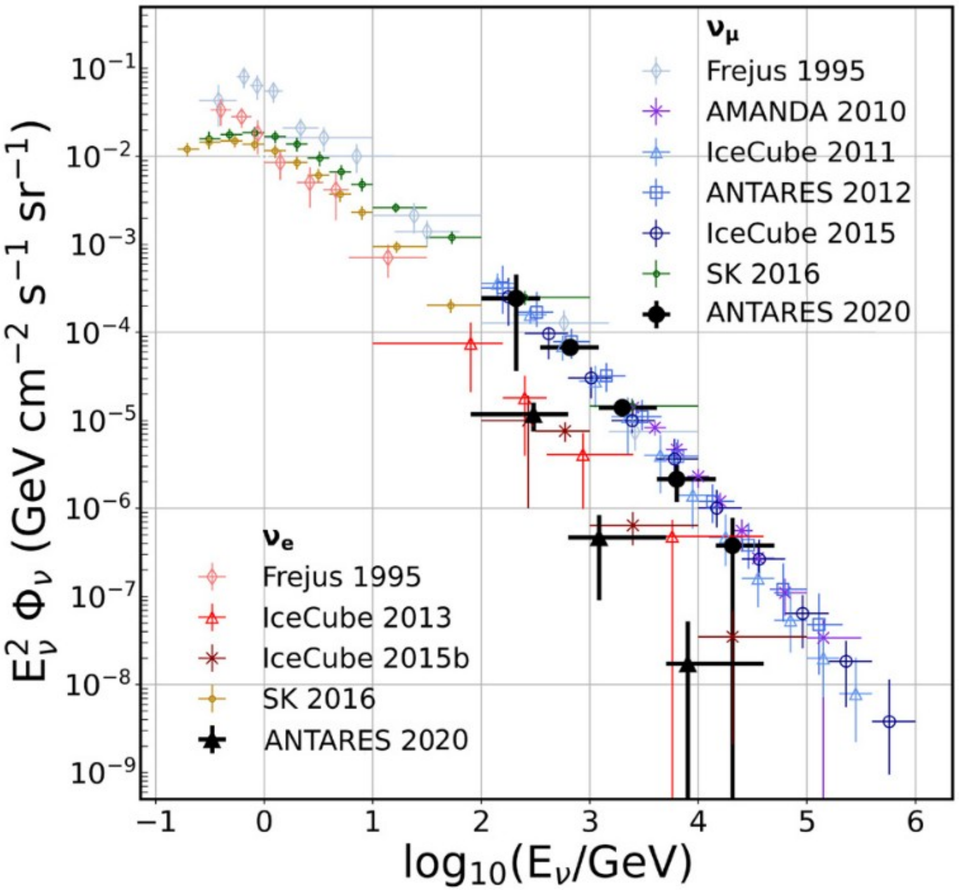
Atmospheric ν flux from ANTARES

Events are classified as shower (mainly ν_e) and starting track-like (mainly ν_μ)

The flux measurement reaches very large energies from 100 GeV and up to 10 TeV



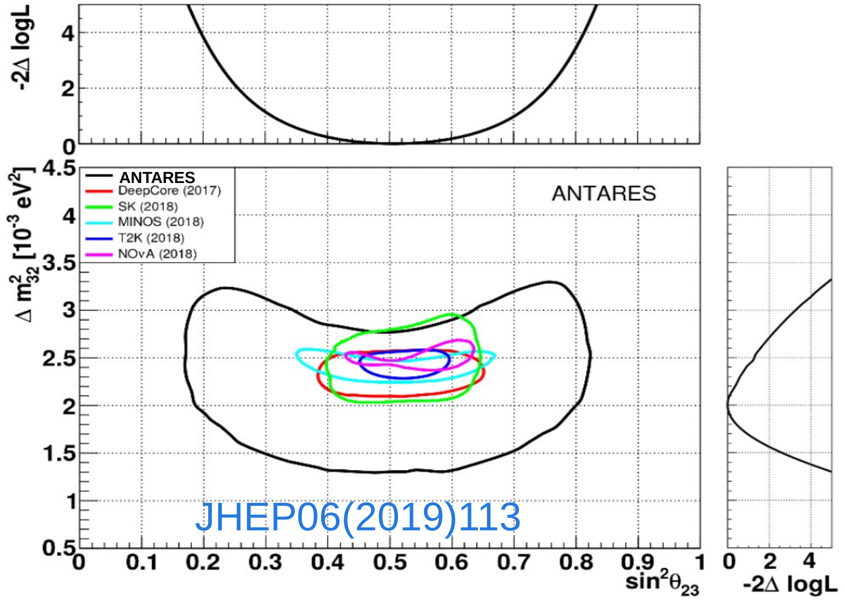
Physics Letters B 816 (2021) 136228



Atmospheric Neutrinos, the Latest Results

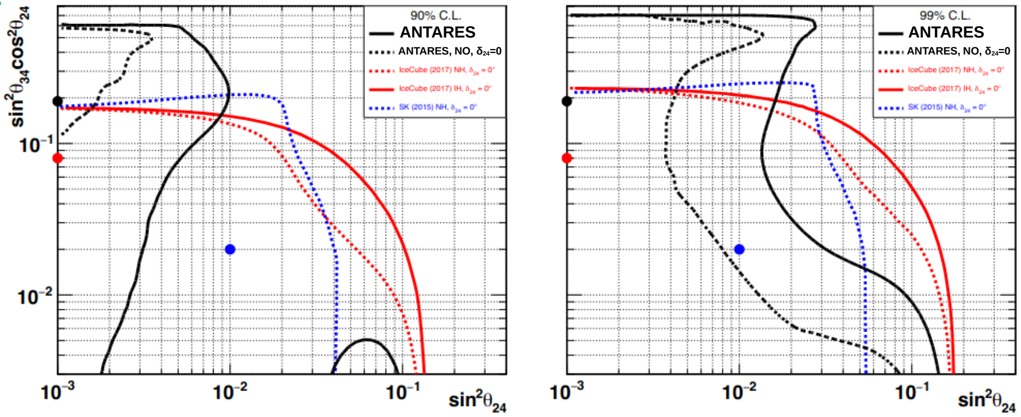
Standard oscillations from ANTARES

- Analysis limited by low statistics in the relevant regions for neutrino oscillations (<10 GeV)
- Analysis has no sensitivity to the NMO
- Results are consistent with the rest of neutrino experiments



Sterile neutrino searches from ANTARES

- Very senstive analysis to the higher energy part of oscillations where the sterile ν presence would be more sizeable
- Results are consistent with no sterile neutrinos



Atmospheric Neutrinos, the Latest Results

Standard oscillations from KM3NeT/ORCA

No flavour distiction capabilities yet, but has already outperform ANTARES oscillation results (10 years)

Very good agreement of data with simulation and expectation

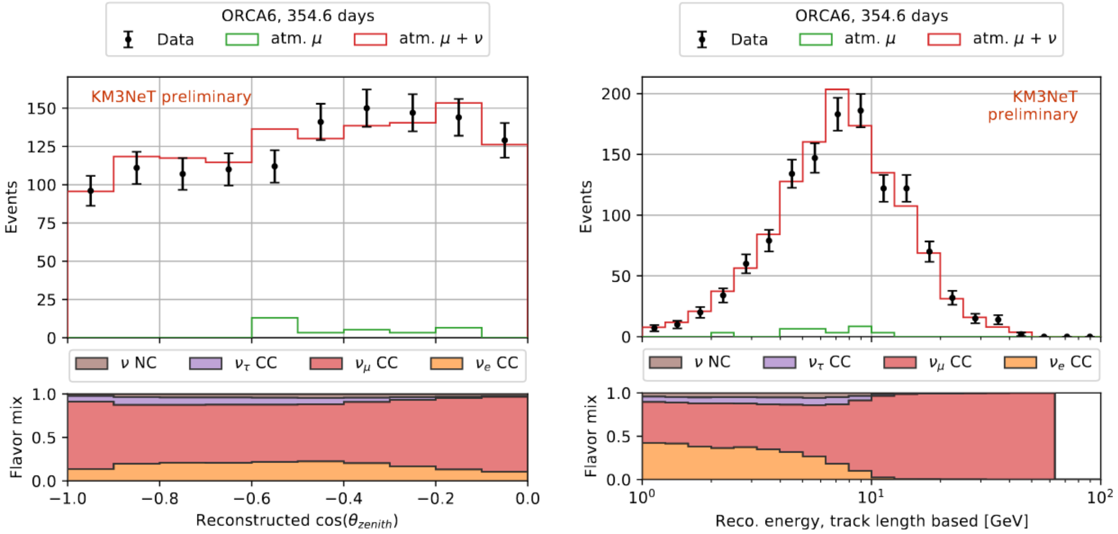
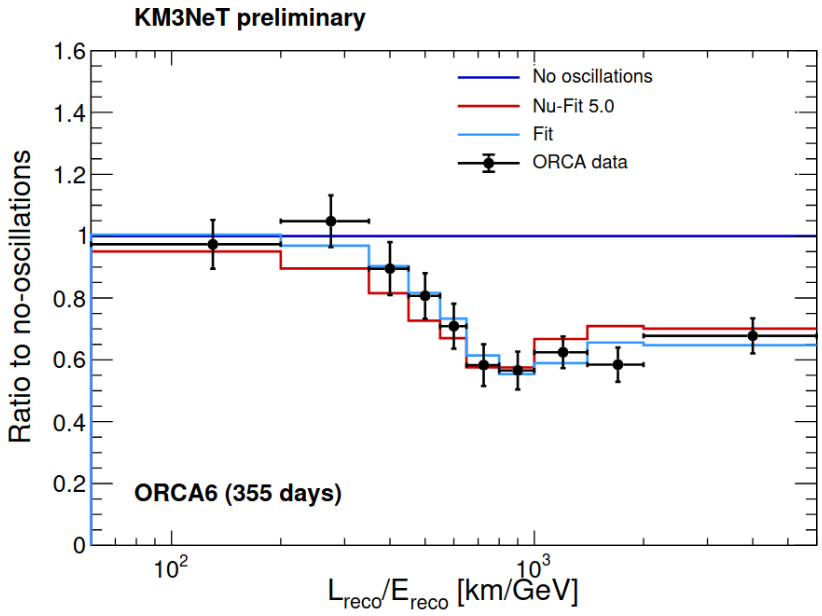


Figure 2: Left: Reconstructed incoming angle distribution after applying the cuts for both data and MC. Right: Reconstructed energy distribution after applying the cuts for both data and MC. Both figures show ORCA6 data and MC.



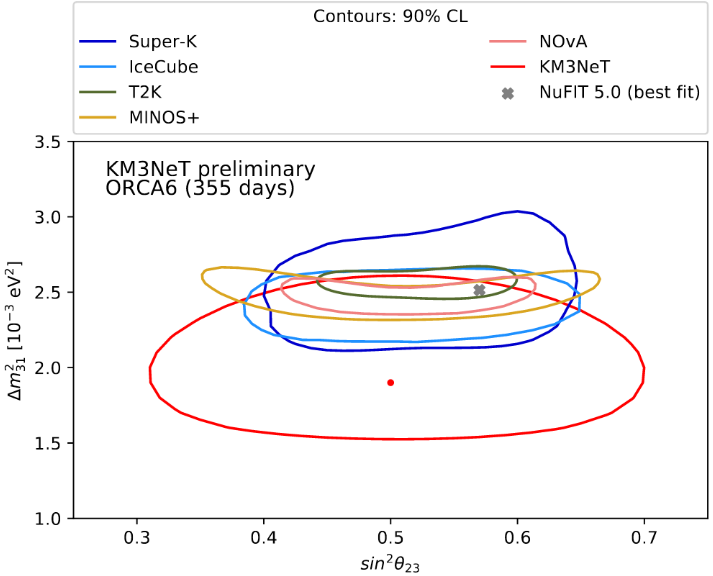
Atmospheric Neutrinos, the Latest Results

Standard oscillations from KM3NeT/ORCA

Very competitive data results and for the sensitivity to the atmospheric oscillation parameters

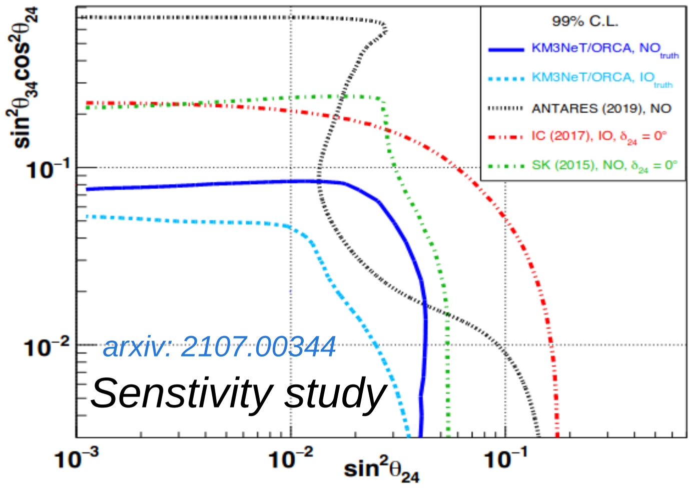
Looking forward to the full instrumentation of ORCA, for which the sensitivity studies show great promise

arxiv: 2103.09885



Sterile neutrino searches from KM3NeT/ORCA

As is the standard oscillations scenario, senstivity studies for the fully instrumented ORCA detector show very constraining power on the mixing parameters for the sterile neutrino case



Summary

The four main atmospheric neutrino experiments currently in operation and their main results have been reviewed

- Helping constraining the atmospheric neutrino models over seven orders of magnitude in neutrino energy
- Complementary, consistent and very competitive measurements of the standard 3-flavour oscillation parameters θ_{23}, Δm_{32} and the neutrino mass ordering
- All experiments agree on the absence of sterile neutrinos and NSI, narrowing the limits for these BSM searches

Prospects

The four main atmospheric neutrino experiments currently in operation and their main results have been reviewed

It is a great period for them and getting better. New reconstruction and analysis techniques (machine lerning) and experiments being upgraded:

- SK has moved to the Gd-doped phase → More discriminating power between neutrinos and antineutrinos through neutron tagging, which will lead to extra sensitivity to the mass ordering and the CP-phase
- IceCube will soon release results using more data and be upgraded in 2022-2023
- ANTARES has lead the way for KM3NeT. Construction of ORCA (and ARCA) will continue and, given its performace with only 5% of the detector, the results will have a significant impact.

As we are getting closer to the next generation of neutrino experiments with larger volumes (statistics) and improved performance (event reconstruction), more experiments will measure atmospheric neutrinos:

- Hyper-Kamiokande
- DUNE
- IceCube Gen2, PINGU
- Indian Neutrino Observatory (INO)