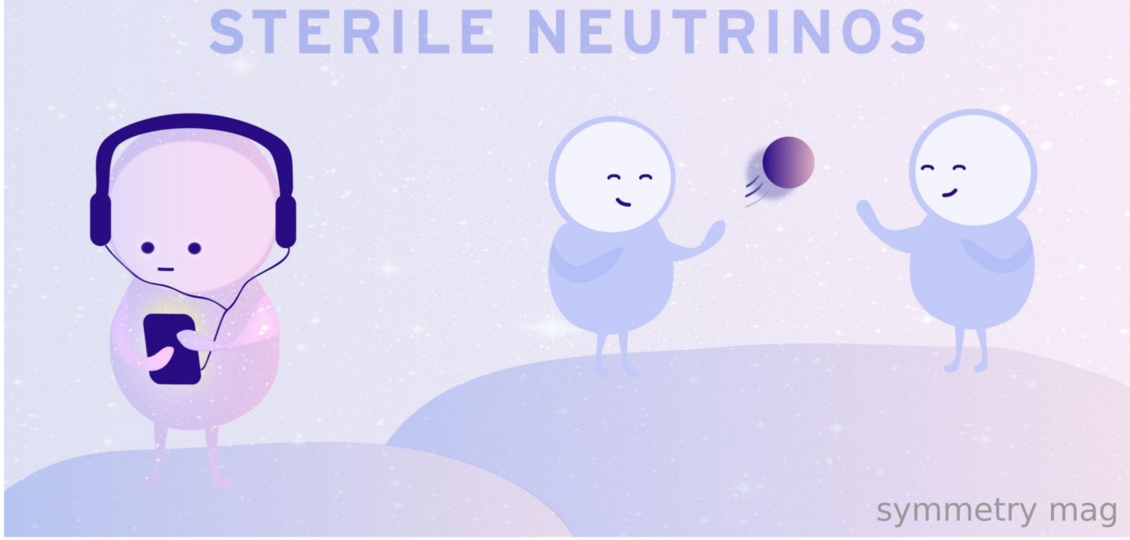
Sterile neutrinos with IceCube

> Searching for a shy particle



Andrii TERLIUK
for the IceCube collaboration

NeuTel 2017
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HELMHOLTZ
ASSOCIATION

Neutrino oscillations: standard case

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

> Standard model:

- 2 neutrino mass differences
- 3 mixing angles
- 1 CP phase

weak states ≠ mass eigenstates	X	differences between mass states	=	changes of flavor (neutrino oscillations)

Two flavor approximation: $P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2\,[eV^2]\,\frac{L\,[km]}{E\,[GeV]}\right)$

> Anomalies:

- Short baseline accelerator experiments (LSND/MiniBooNE)
- Reactor anti-neutrino flux
- Early radio-chemical experiments

- Resolved by heavier (~eV) neutrinos
- LEP measurements : $N_\nu^{active} = 3$

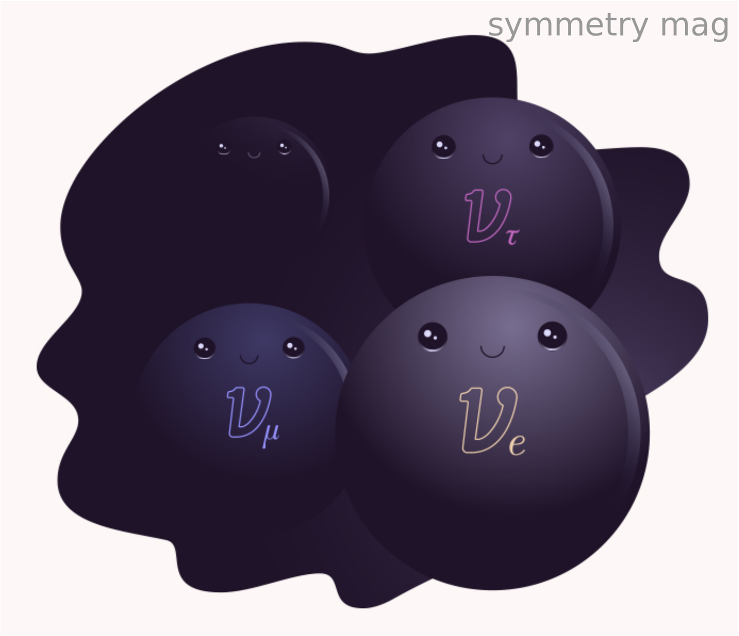
> Sterile neutrinos:

- No standard weak interaction
- Mixed with active neutrinos

Sterile neutrino mixing: 3+1 model

> Simplest extension:

- +1 sterile neutrino
- New parameters:
  - ▻ 1 mass
  - ▻ 2 CP violating phases
  - ▻ 3 mixing angles



Standard PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

$$|U_{\mu 4}|^2 = \sin^2\theta_{24} \cdot \cos^2\theta_{14}$$

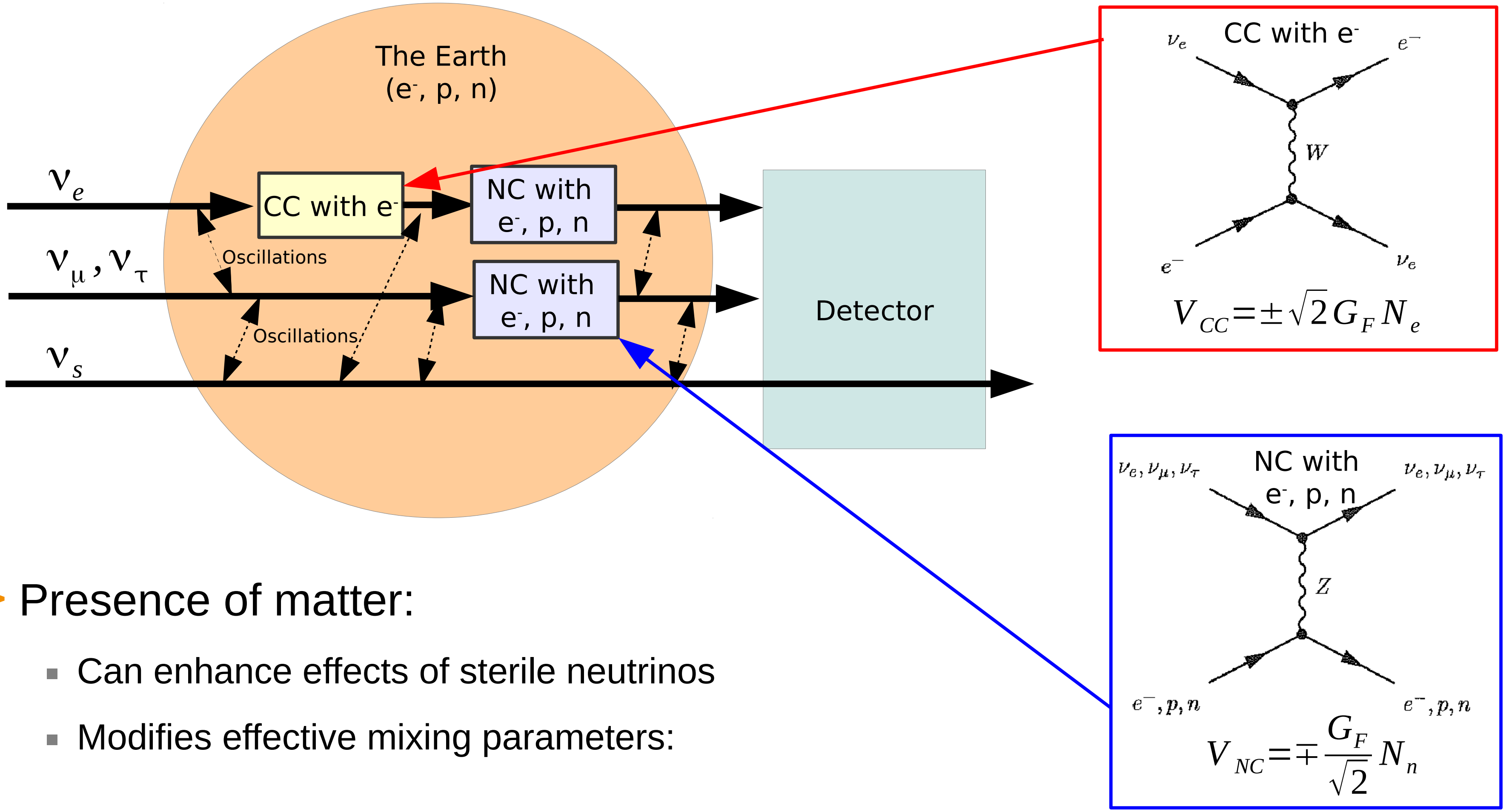
$$|U_{\tau 4}|^2 = \sin^2\theta_{34} \cdot \cos^2\theta_{24} \cdot \cos^2\theta_{14}$$

> Modifies detected atmospheric neutrino flux

> Assumptions:

- $\delta_{CP} = 0$

And the matter matters



> Presence of matter:

- Can enhance effects of sterile neutrinos
- Modifies effective mixing parameters:

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 \pm \frac{2 E V_{\mathrm{int}}}{\Delta m^2 \cos 2\theta}} \qquad \Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta \pm 2 E V_{\mathrm{int}})^2 + (\Delta m^2 \sin 2\theta)^2}$$

High energy (~TeV) effects of sterile neutrinos

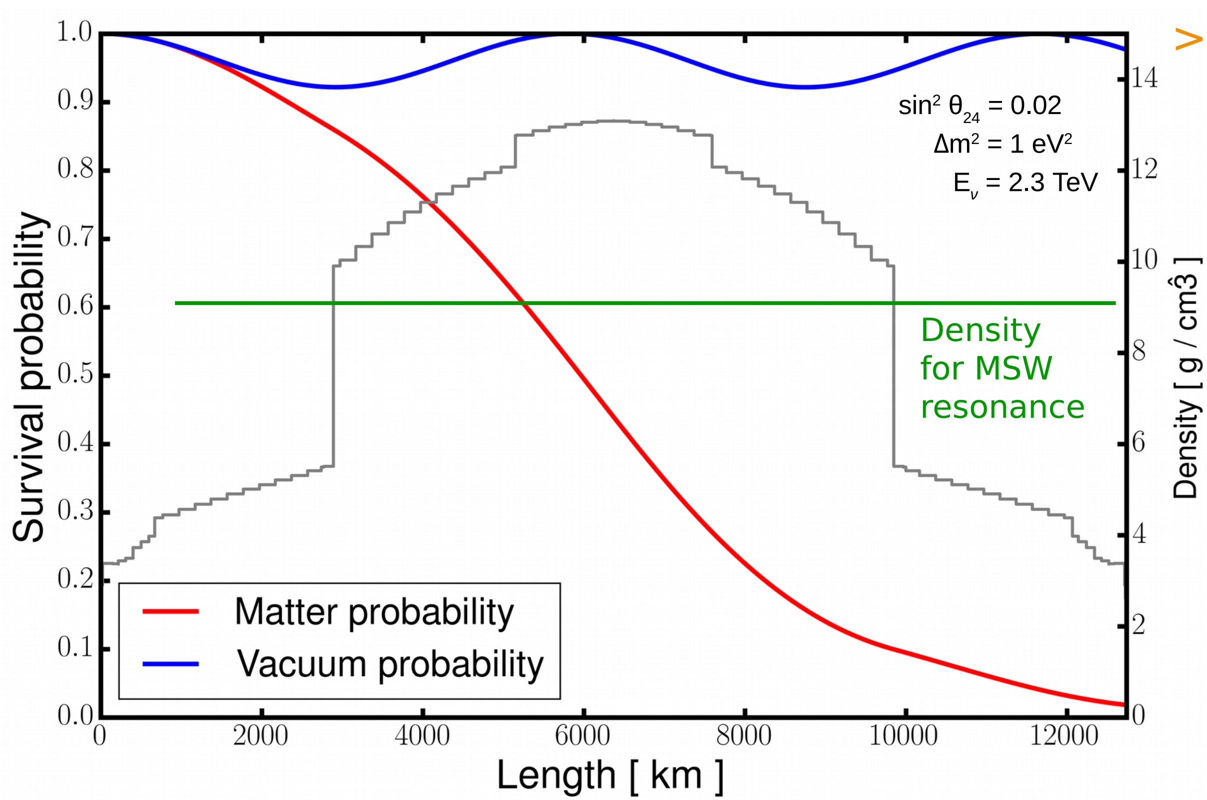
Sterile neutrinos: resonance

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{2EV_{int}}{\Delta m^2 \cos 2\theta}}$$

Changes amplitude of oscillations

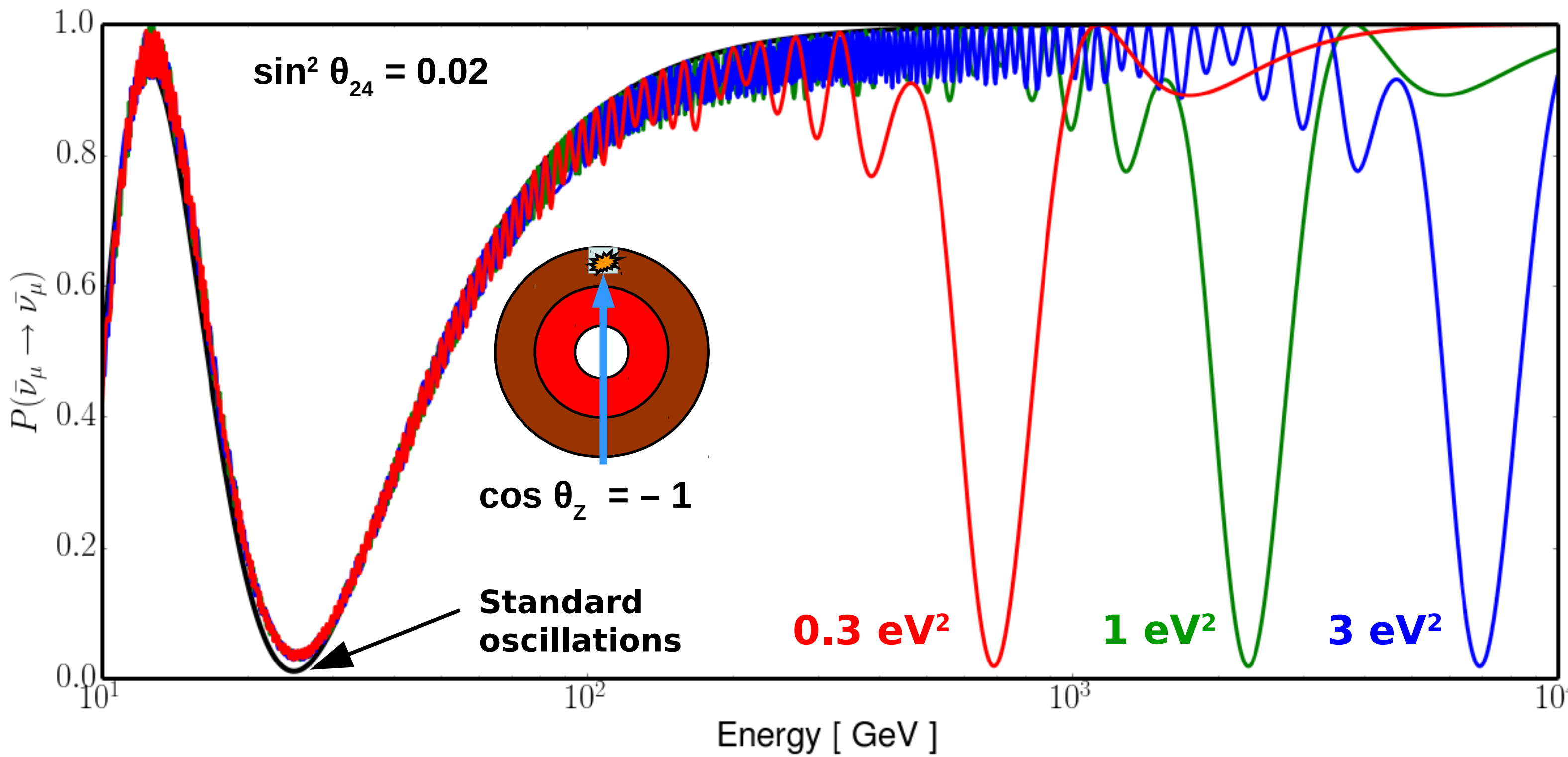
$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2EV_{int})^2 + (\Delta m^2 \sin 2\theta)^2}$$

Changes period of oscillations



- Neutrino oscillation length resonance (NOLR):
  - Not MSW resonance!
  - Matter enhancement of sterile mixture in mantle and core
  - Constructive interference of oscillations in matter and core
  - Oscillation length in core ~2 core sizes
  - Resonant disappearance of muon anti-neutrinos
  - Resonance energy ~ TeV

The resonant enhancement



- Energy of the resonance proportional to the mass splitting
- Sensitivity to $|U_{\mu4}|^2$ (or θ_{24}) and sterile mass
- Sensitivity with IceCube using high energy atmospheric neutrinos

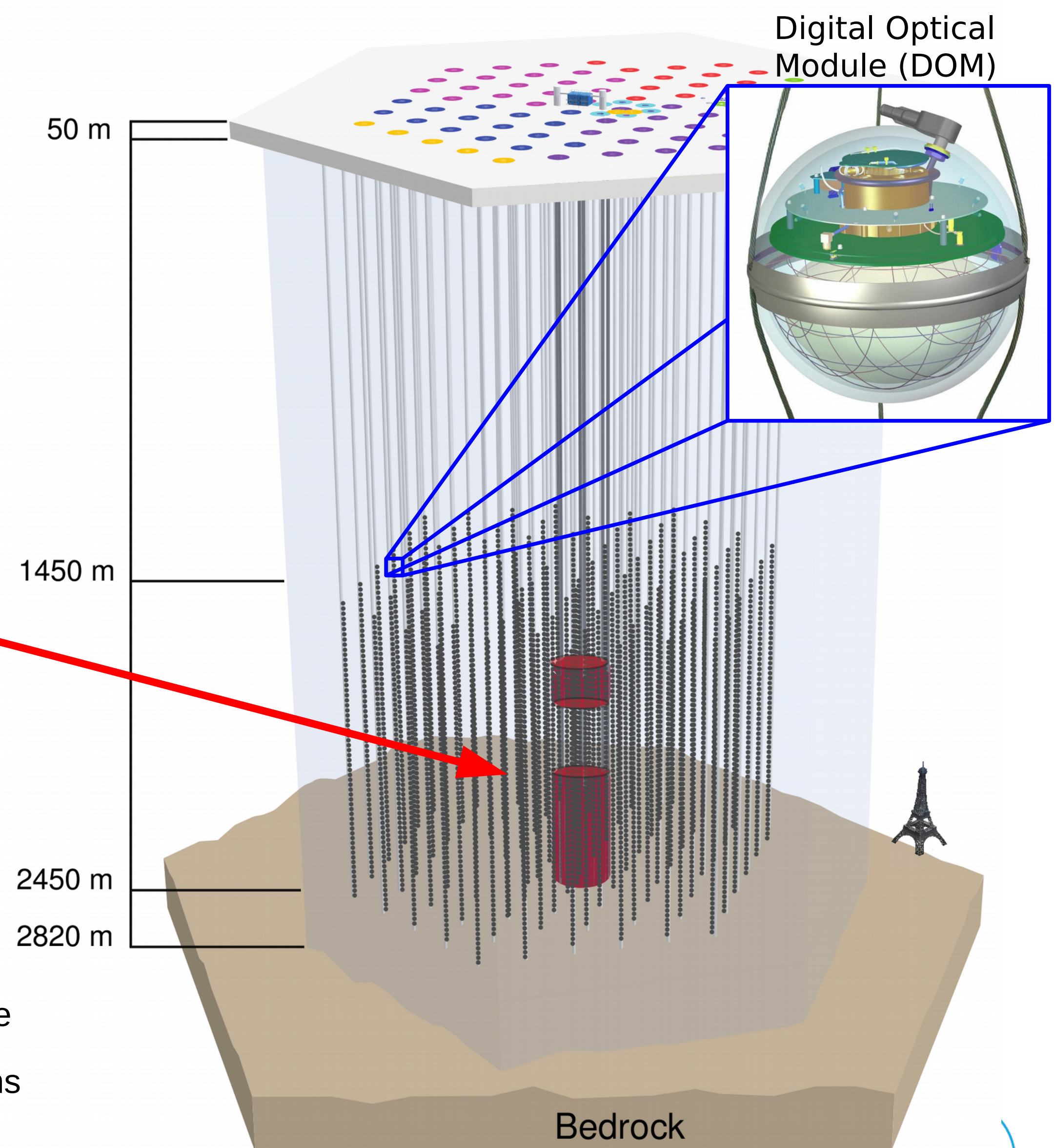
IceCube Neutrino Observatory

> IceCube detector:

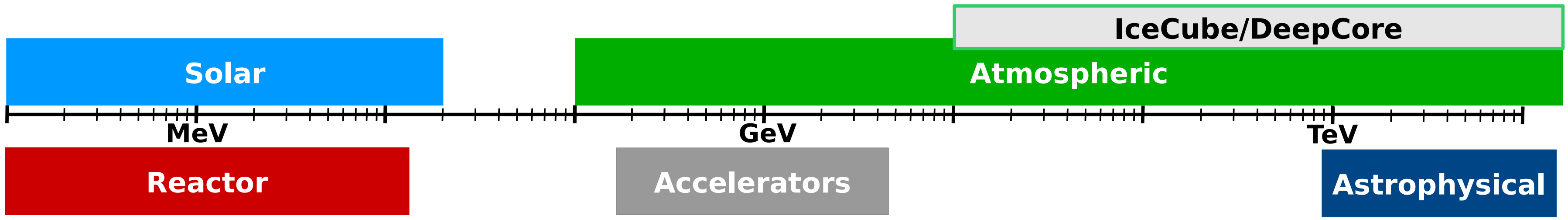
- 1 km^3 ice Cherenkov detector
- Depth: 1450-2450 m
- 17 m vertical and 125 m horizontal spacing
- Energy threshold ~100 GeV

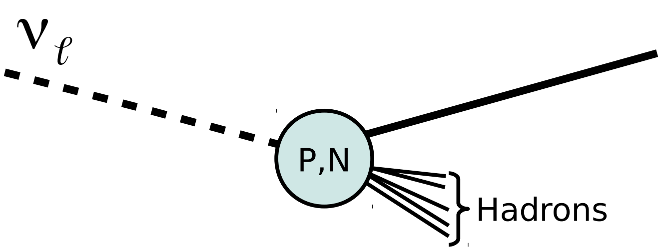
> DeepCore:

- Denser instrumentation:
  - 7 m vertical and 40-60 m horizontal spacing
- Energy threshold ~10 GeV
- Deep inside IceCube:
  - Depth: 2100-2450 m
  - Best optical properties of the ice
  - Veto against atmospheric muons



IceCube energy scales





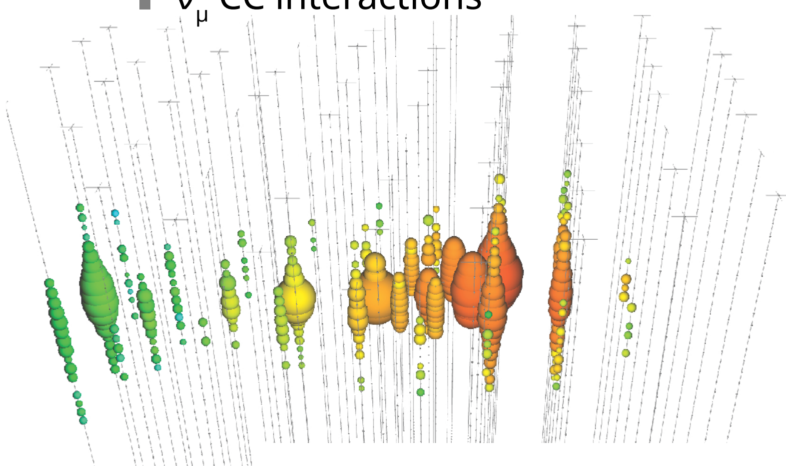
ℓ – charged current (CC) interaction

ν_ℓ – neutral current (NC) interaction

> Secondary particles emit Cherenkov light

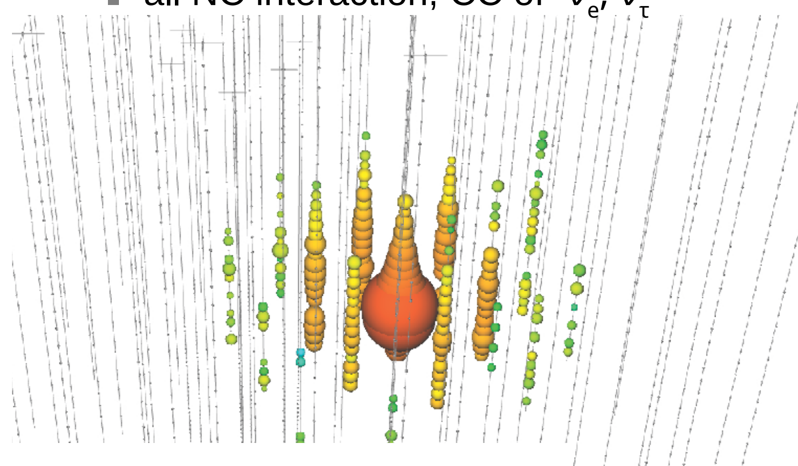
> Track like events:

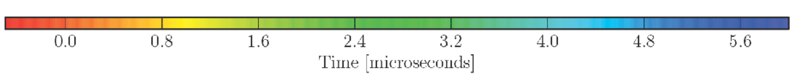
- ν_μ CC interactions



> Cascade like events:

- all NC interaction, CC of ν_e, ν_τ





High energy sterile neutrino search: sample

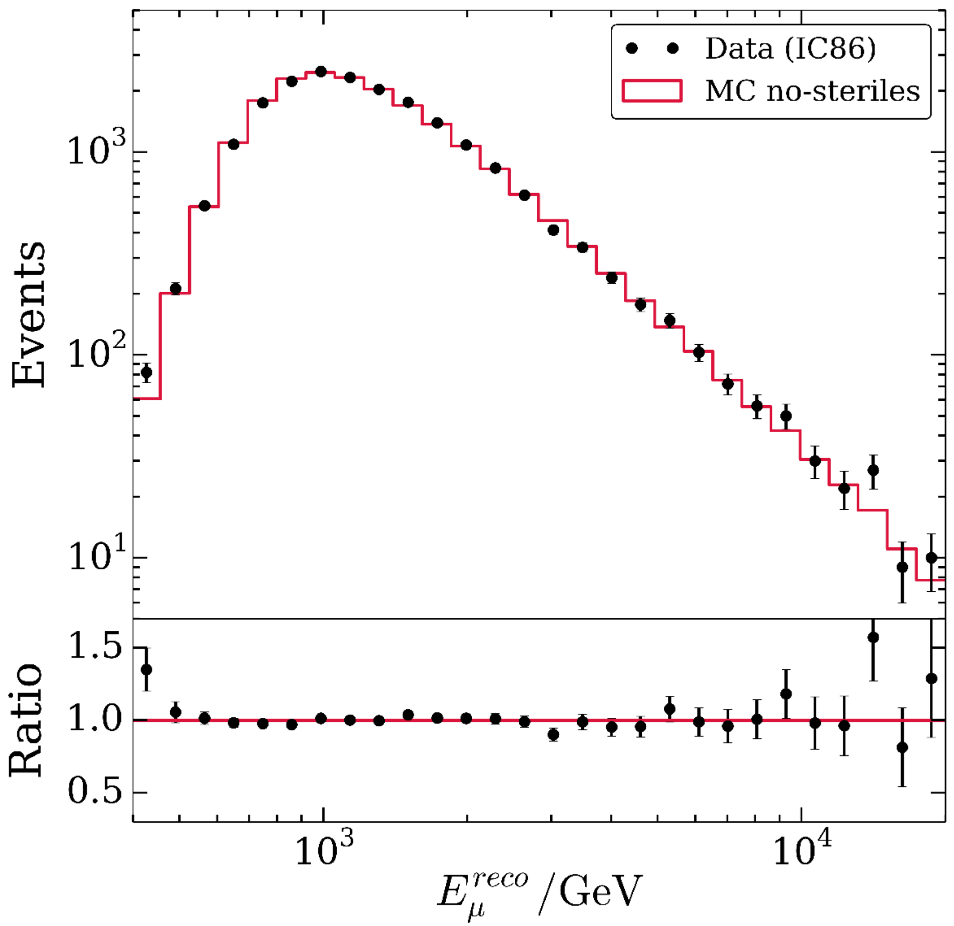
- Up-going muon neutrinos (muon tracks)
- Energies: [400 GeV , 20 TeV]
- Energy estimate:
  - From stochastic losses of muons
  - Energy resolution

$$\sigma_{\log_{10} E_\mu} \sim 0.5$$

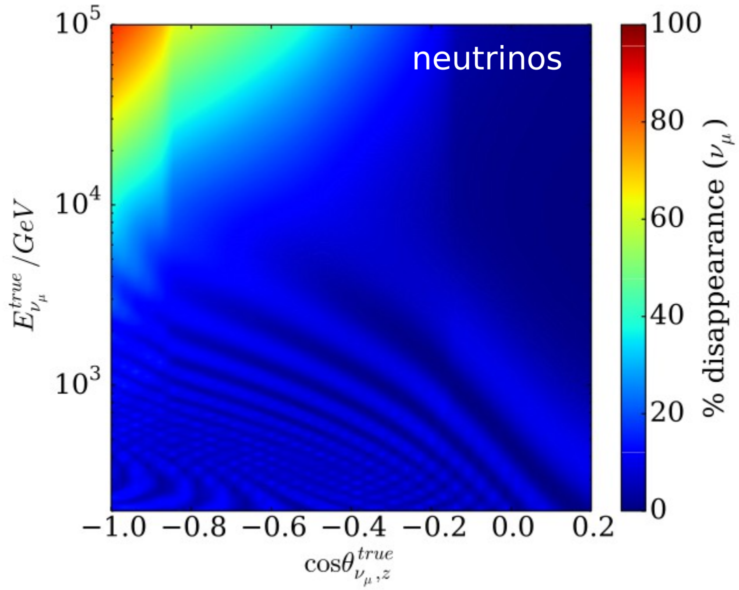
- Direction resolution:

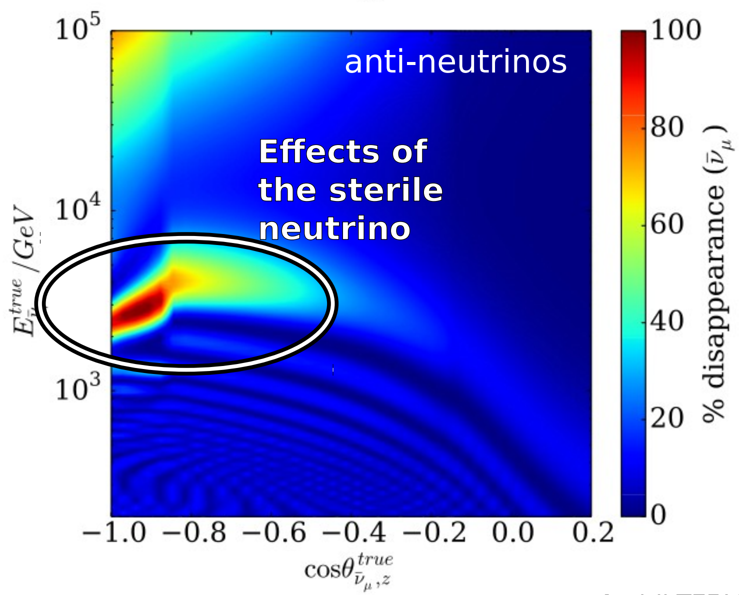
$$\sigma_{\cos\theta_z} \sim 0.005 - 0.015$$

- 99.9% neutrino purity



Sterile neutrinos at high energies

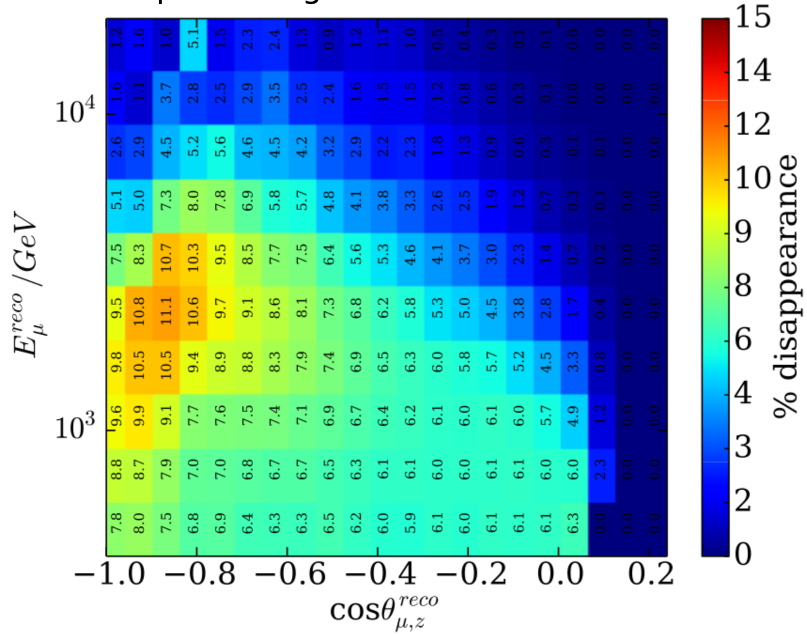




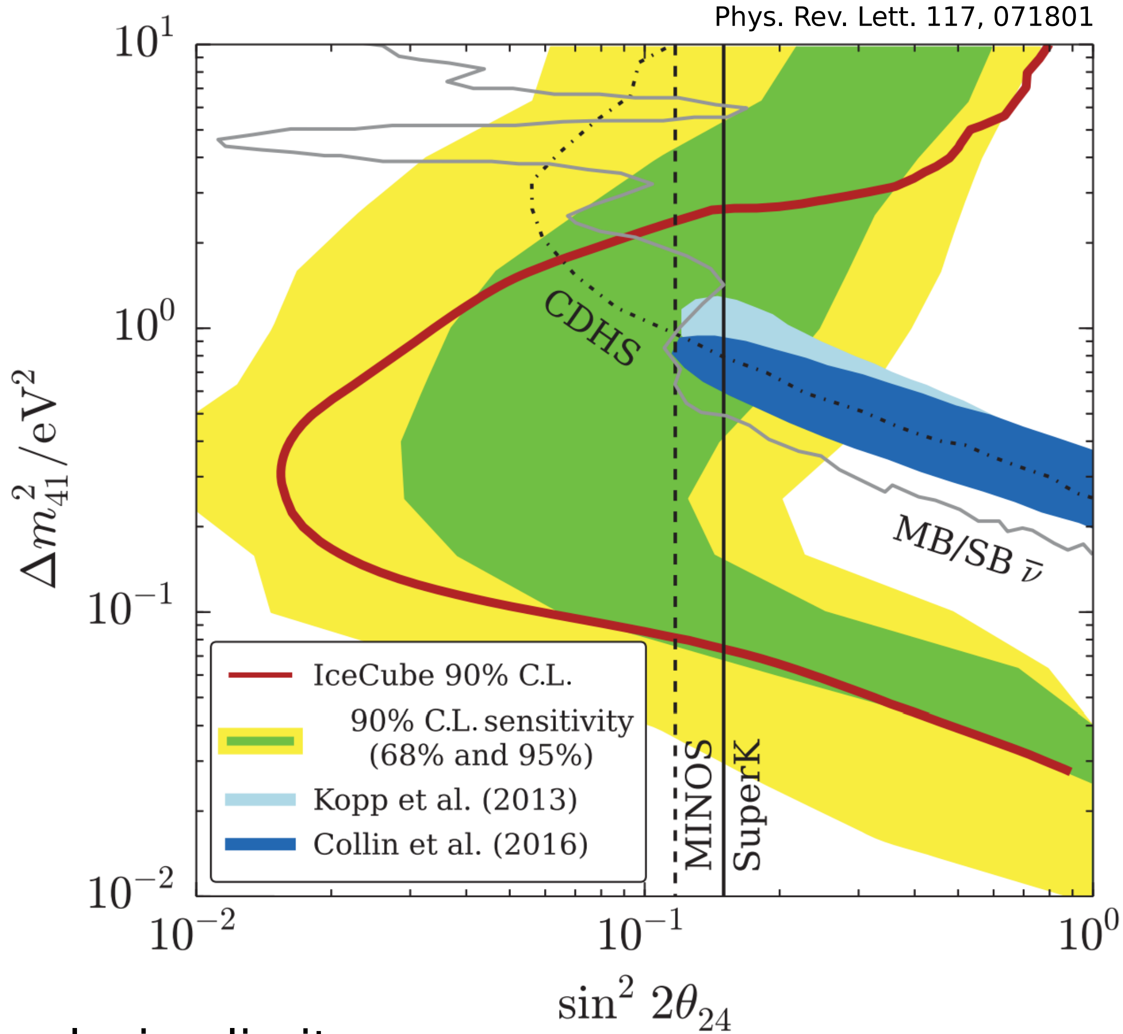
> Effects above 100 GeV:

- MSW resonance-like transition to sterile state
- Muon-anti neutrinos
- Energy of resonance $\sim \Delta m^2_{41}$
- Sensitive to angle θ_{24}

Expected signature:



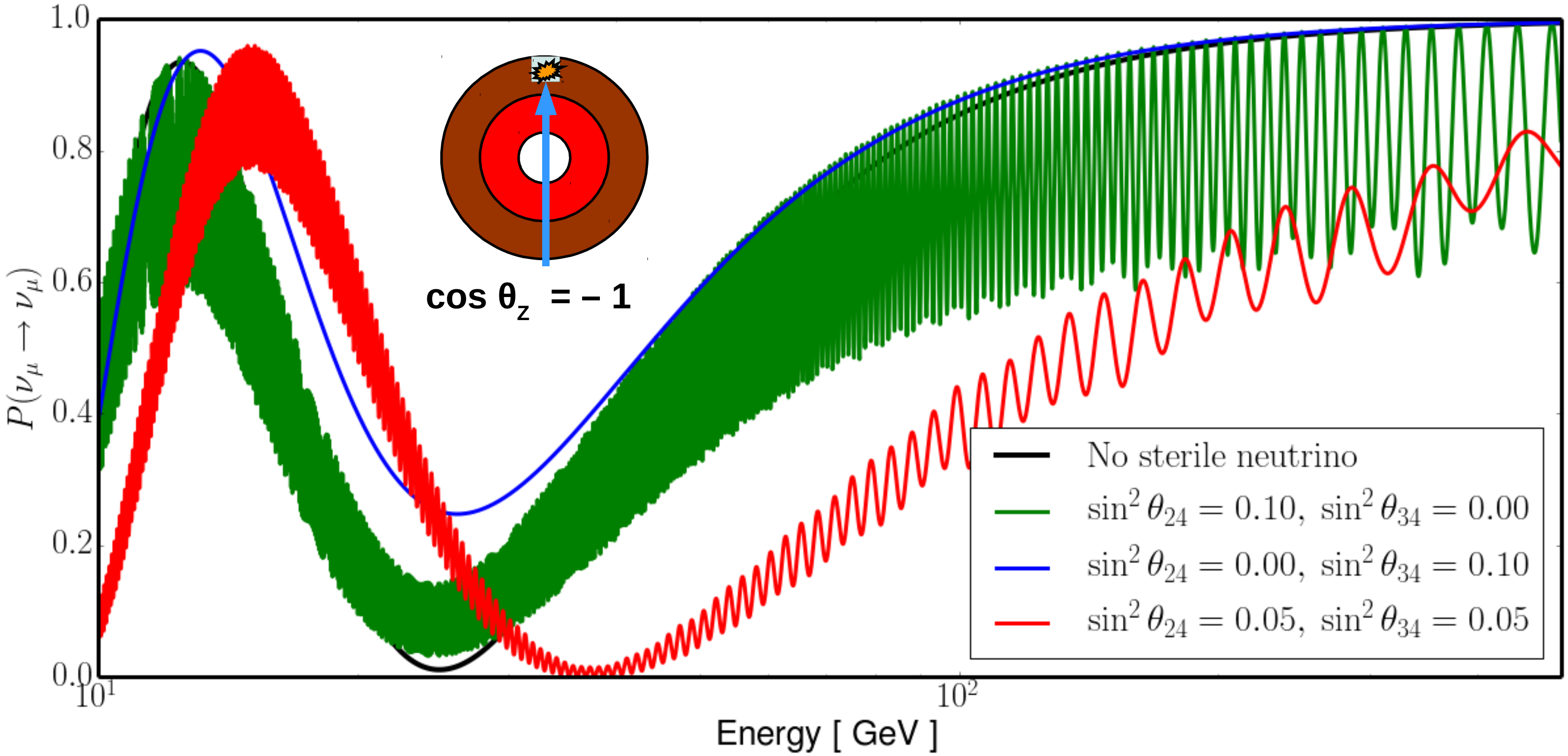
Sterile neutrinos at high energies: results



- Strong exclusion limits
- Only 1 year of data used

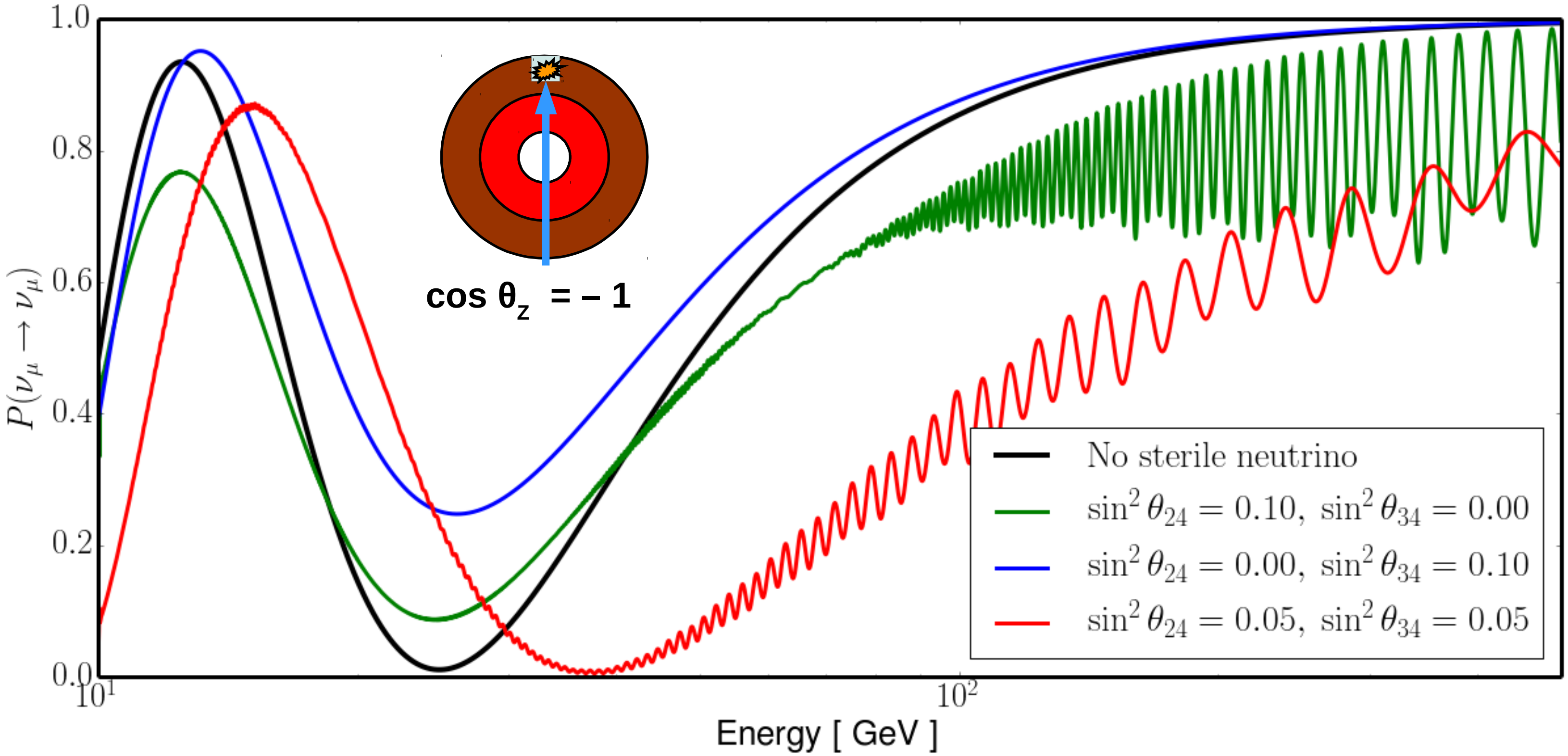
Low energy (<100 GeV) effects of sterile neutrino

Sterile neutrinos at low energies



- Modification of the standard numu disappearance
- “Fast” oscillating component is averaged → independent from sterile neutrino mass
- Sensitive to angles θ_{24} and θ_{34}

Sterile neutrinos at low energies



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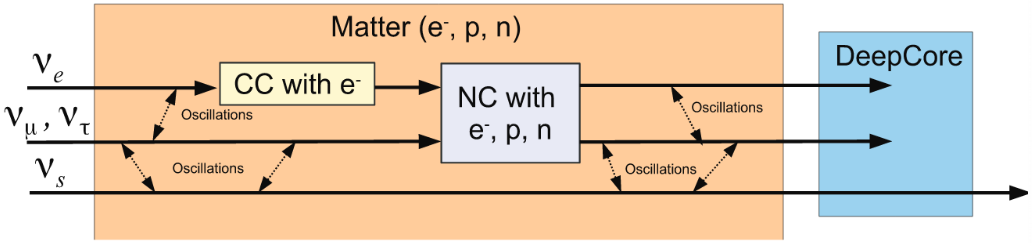
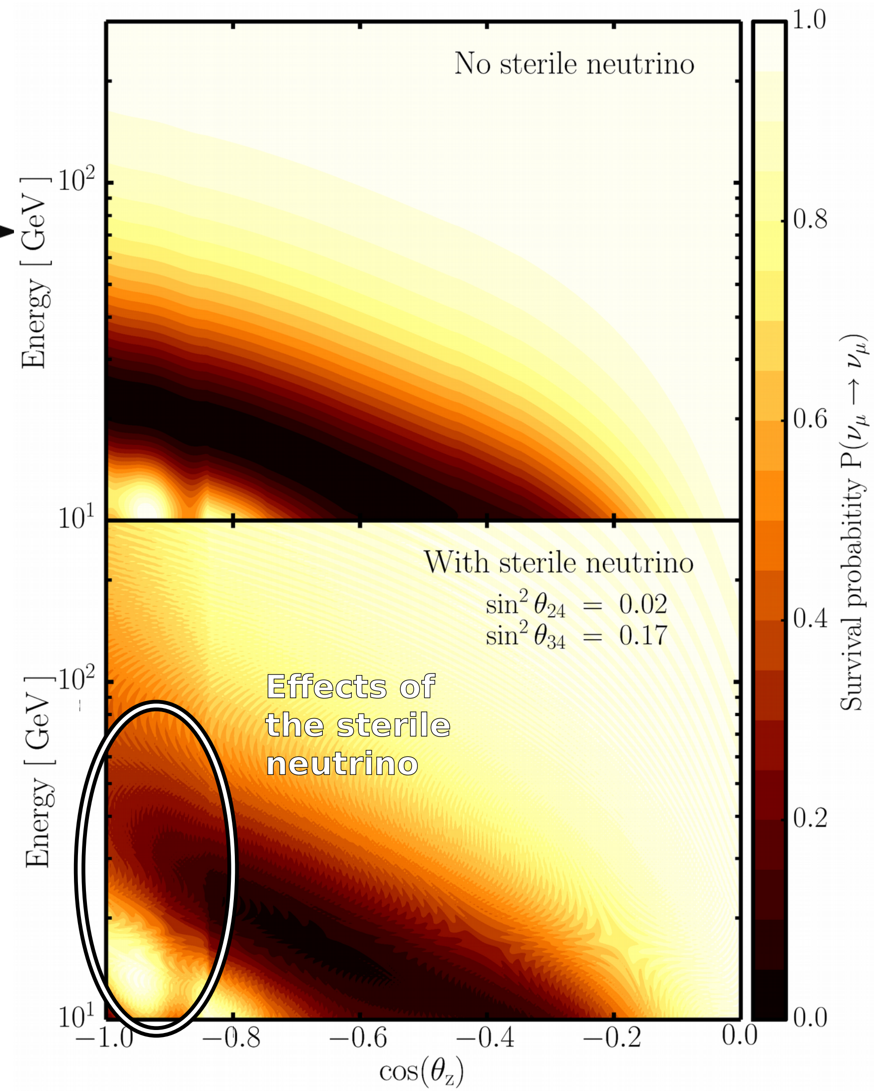
Sterile neutrinos at low energies



> Effects below 100 GeV:

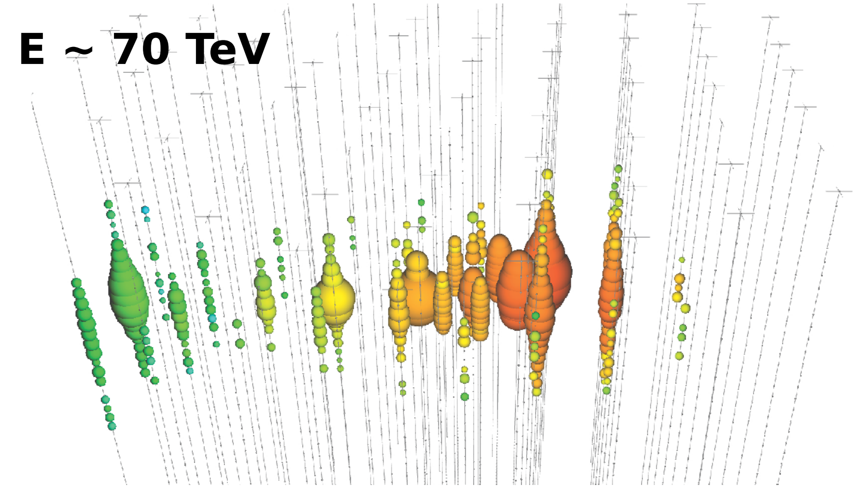
- Modifications of standard oscillations
  - shifts of oscillations minimum
  - changes of amplitude
- Independent of sterile neutrino mass (for $\Delta m_{41}^2 > 0.3\, eV^2$)
- Sensitive to the angles θ_{24} and θ_{34}
- Effect proportional to matter density

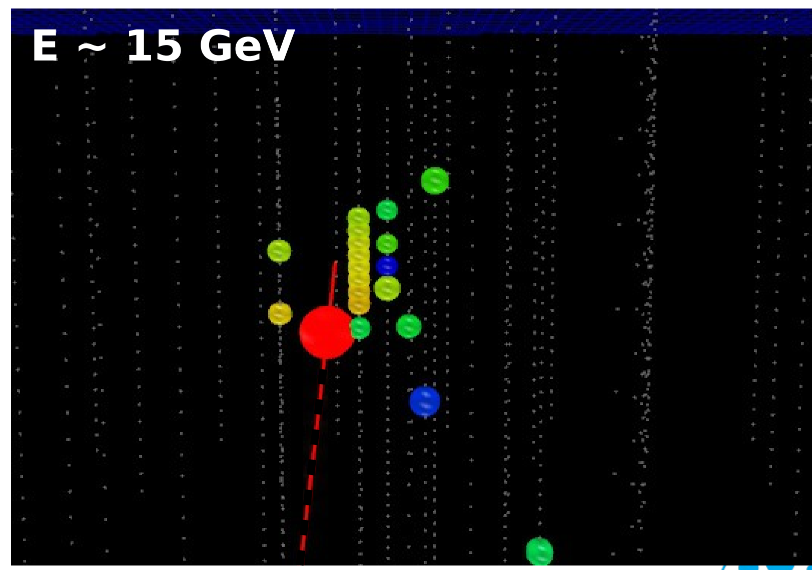


Low energy events

> High energy events:
  - Long and bright muon tracks

> Low energy events:
  - Relatively short MIP muon track
  - Overlayed with hadronic shower from neutrino interaction
  - Dim with few signals in the detector
  - Challenging selection and reconstruction





DeepCore: reconstruction challenge

> Low energy events:

- few signals in the detector
- affected by systematic uncertainties (ice optical properties etc.)
- most of the light in a few strings

> Using "direct photons":

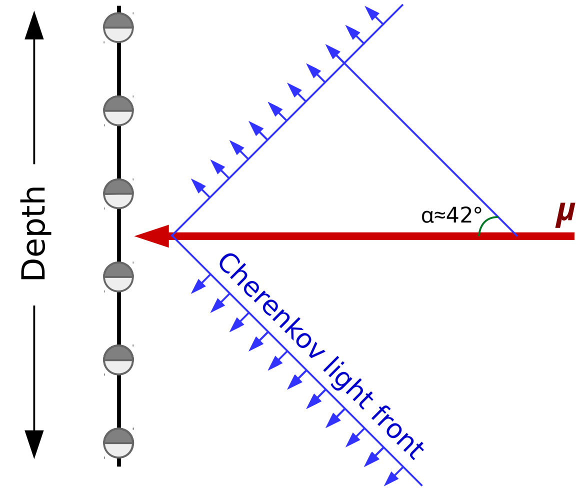
- no scattering in ice
- narrow time window
- specific hyperbolic pattern for muons
- selects "golden events"

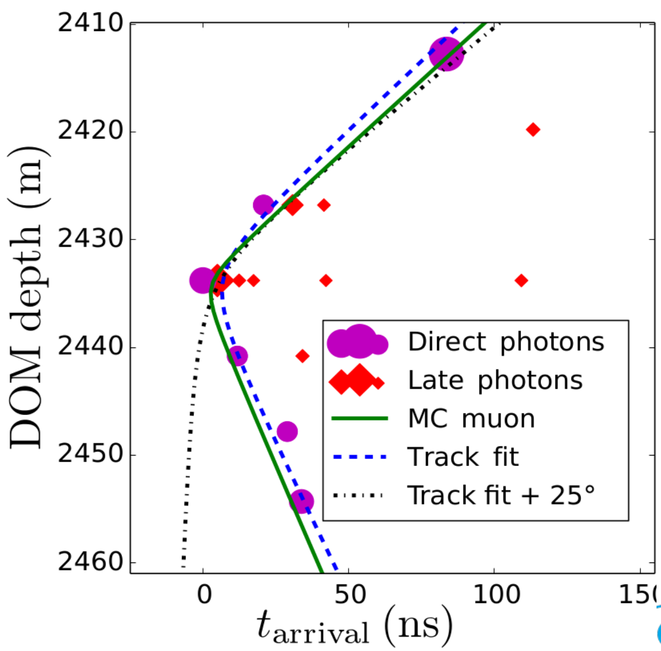
> Energy reconstruction:

$$E_{\nu} \approx E_{had} + a \cdot L_{\mu}$$

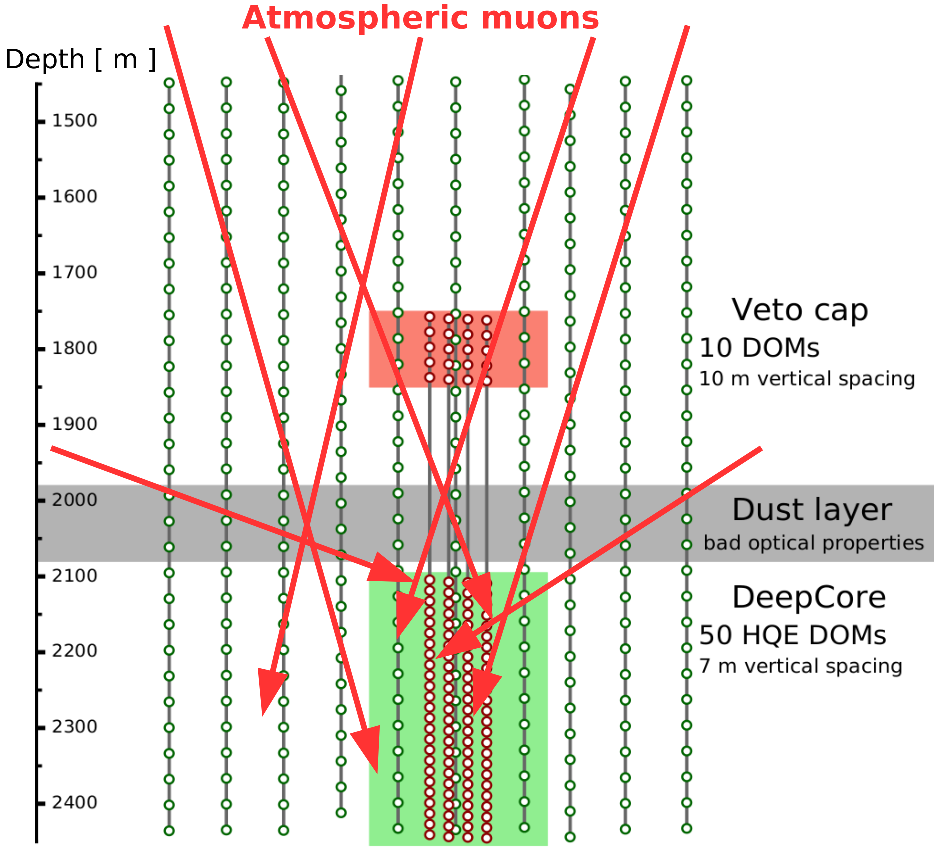
> Typical resolutions:

- Zenith angle: 5-10° median resolution
- Energy: ~ 20-25 % median resolution





DeepCore: background challenges

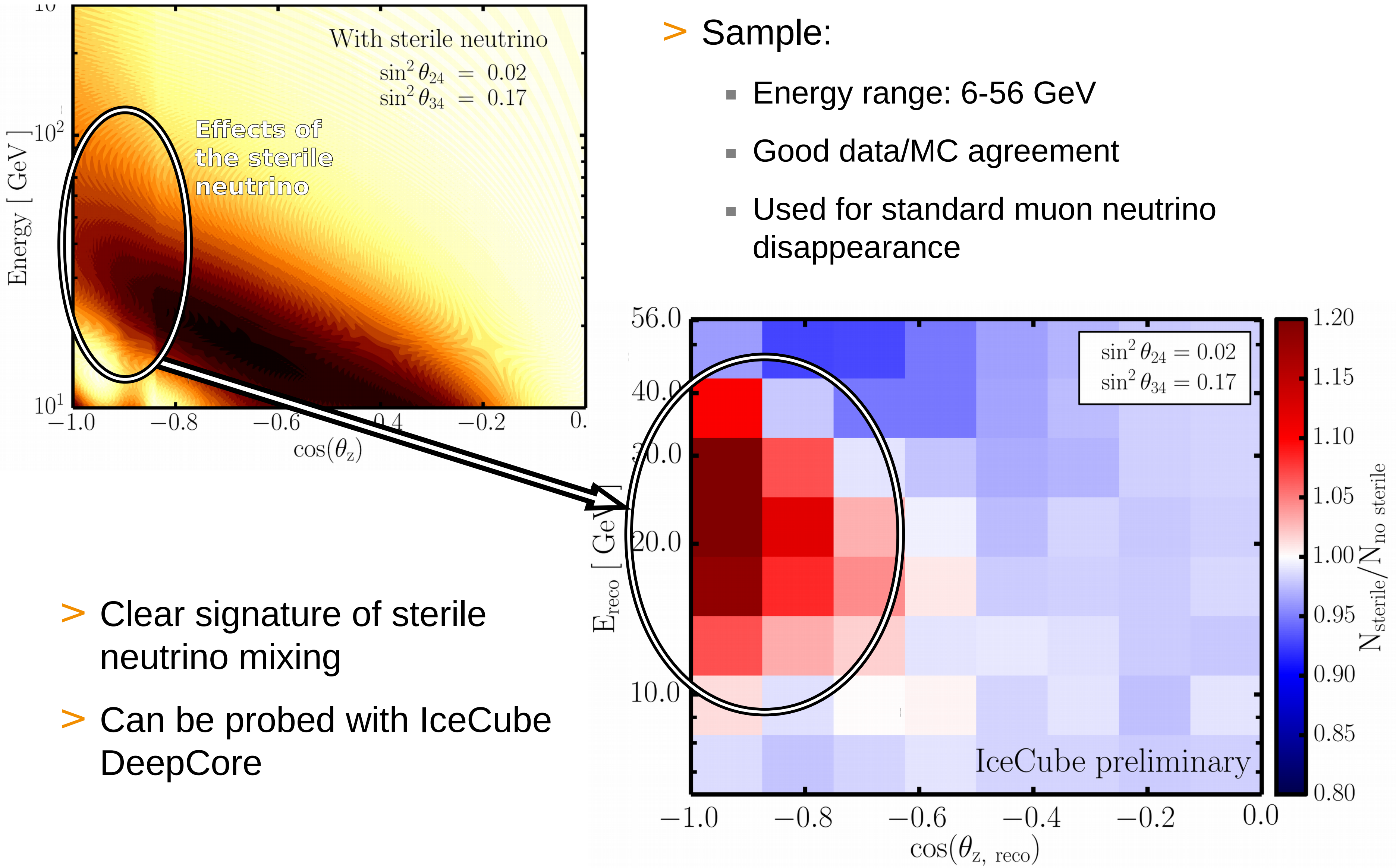


> Prevailing rate of atmospheric muons:
  - Trigger level: 1 neutrino : ~10^7 muons
  - Final level: 1 neutrino : <0.01 muons

> Vetoing techniques:
  - Up-going events – the Earth as the veto
  - Outer layers of IceCube as veto

> Most complicated muons:
  - Corridors formed by detector geometry
  - “Dust layer” above DeepCore

Sterile neutrino effect on the sample

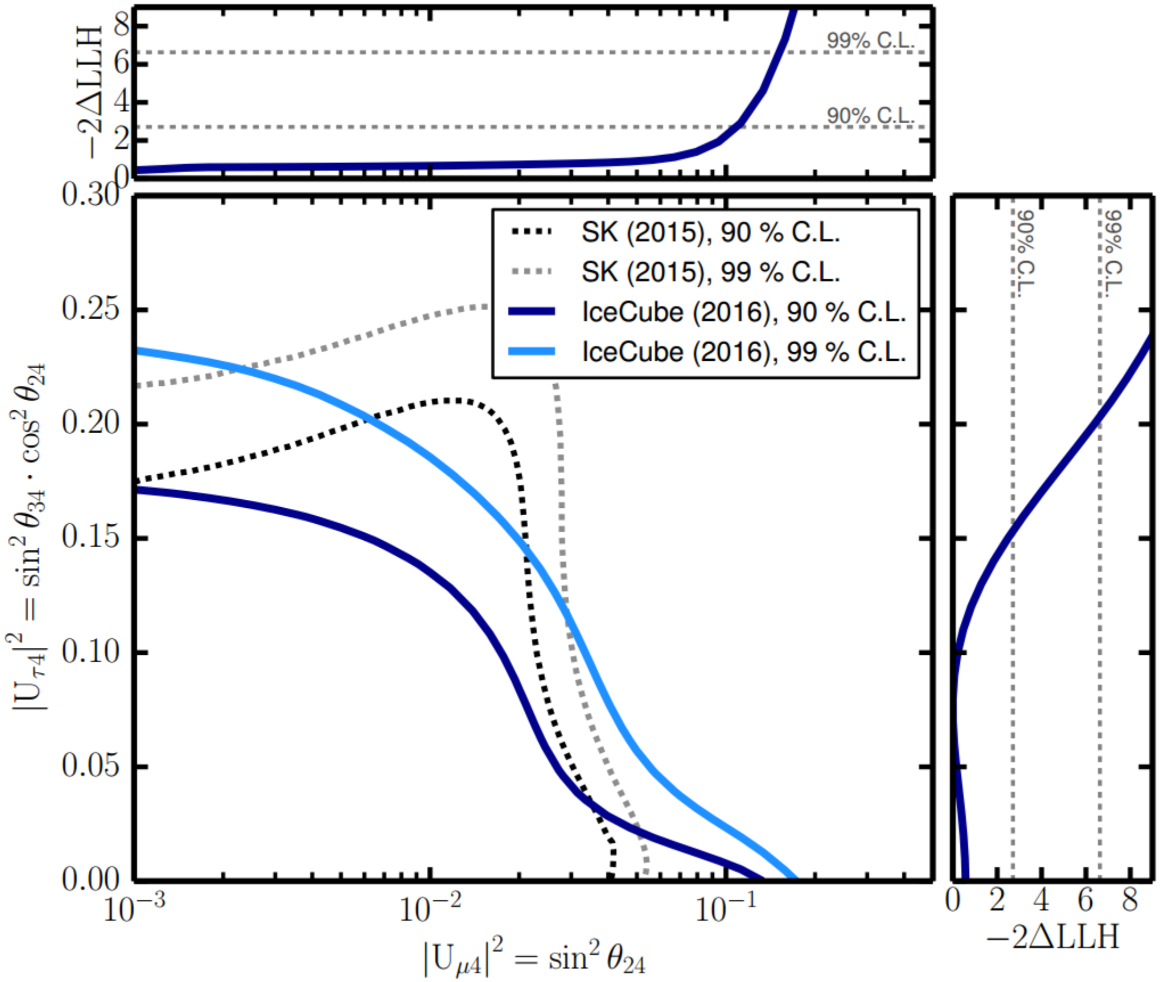


> Sample:
  - Energy range: 6-56 GeV
  - Good data/MC agreement
  - Used for standard muon neutrino disappearance

> Clear signature of sterile neutrino mixing

> Can be probed with IceCube DeepCore

Sterile neutrinos at low energies: results

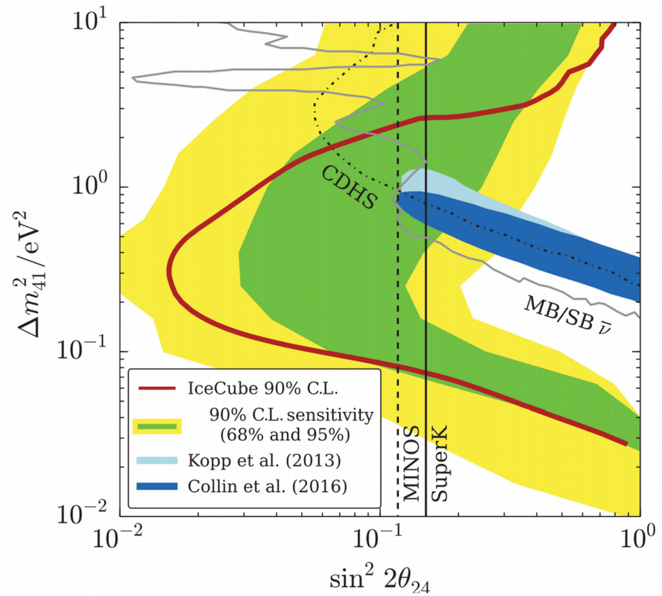


- Strong exclusions of $|U_{\tau 4}|^2$
- Submitted to journal, arXiv preprint: [arXiv:1702.05160](https://arxiv.org/abs/1702.05160) **[hep-ex]**

Summary

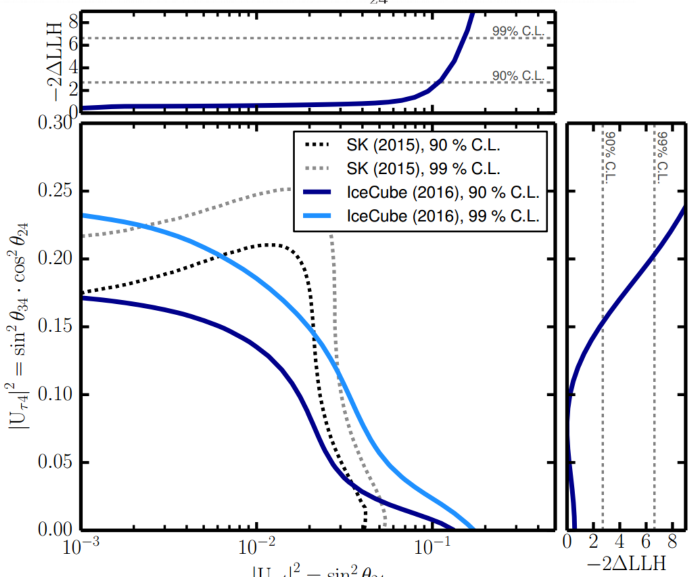
> Sterile neutrinos in IceCube:

- Great tool to detect sterile neutrinos
- Results are consistent with standard 3 neutrino hypothesis
- Great limits for muon and tau neutrino mixing to the sterile state.



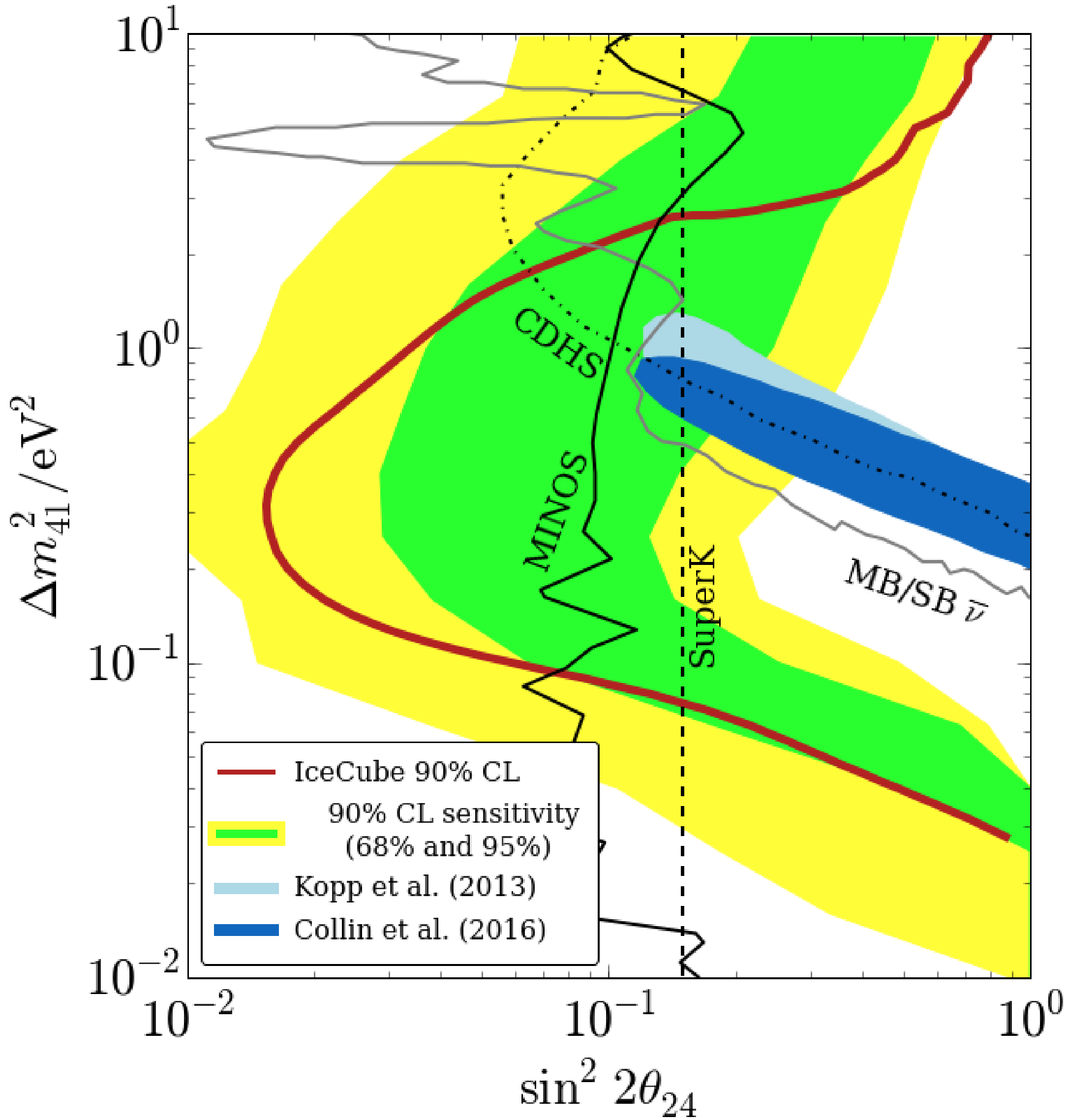
> Next in IceCube:

- More data
- More event signatures
- Even better sensitivity to sterile neutrinos



Backup

HE exclusions with newest MINOS



Sterile neutrinos: resonance

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{2 E V_{\text{int}}}{\Delta m^2 \cos 2\theta}}$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2 E V_{\text{int}})^2 + (\Delta m^2 \sin 2\theta)^2}$$

At MSW resonance

$$E_R = \frac{\Delta m^2 \cos 2\theta}{2 V_{\text{int}}}$$

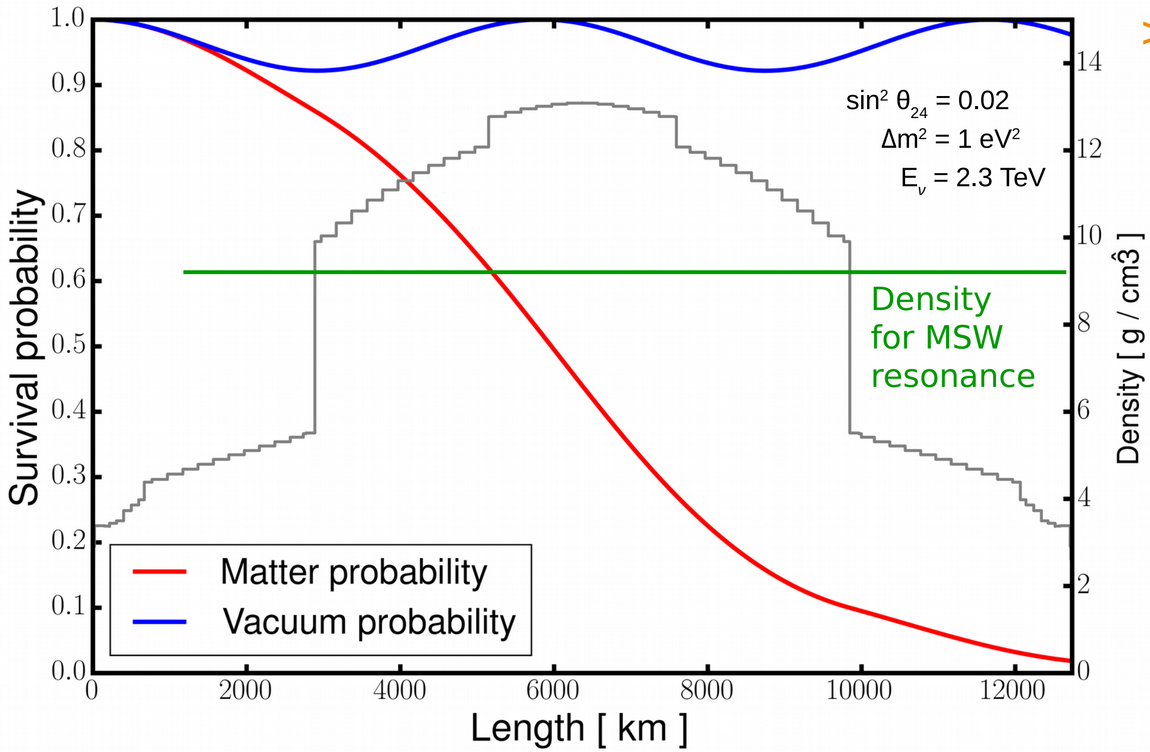
Maximal mixing:

$$\theta_M = \frac{\pi}{4}$$

$$\Delta m_M^2 = \Delta m^2 \sin 2\theta$$

Maximal oscillations length

> Matter can enhance sterile neutrino signal



> Parametric resonance (NOLR):

- Not MSW resonance!
- Matter enhancement of sterile mixture in mantle and core
- Constructive interference of oscillations in matter and core
- Oscillation length in core ~2 core sizes
- Resonant disappearance of muon anti-neutrinos
- Resonance energy ~ TeV