Neutrino oscillations with IceCube

State of the art measurements

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NOW 2018, Ostuni, Italy

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

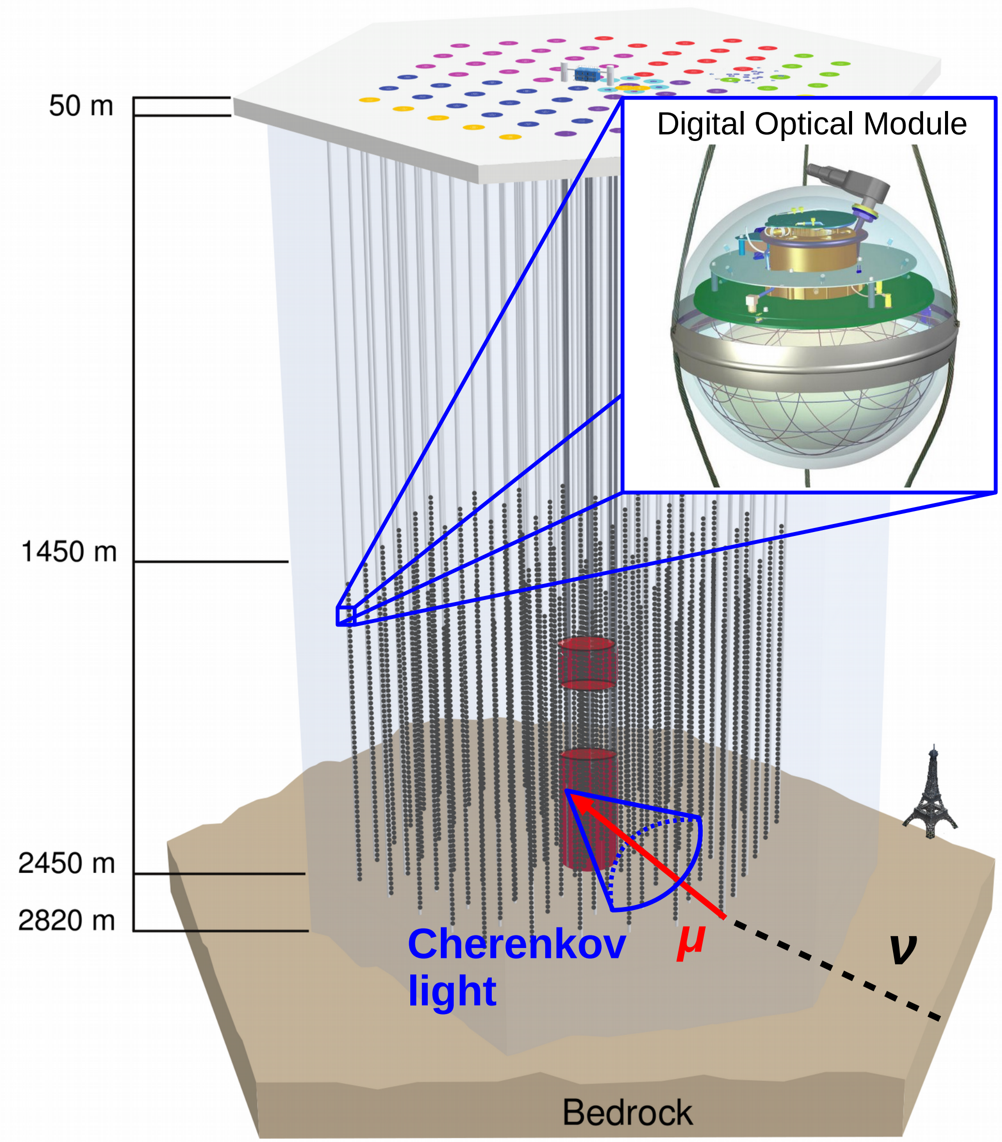
DESY.

IceCube Neutrino Observatory

A cubic kilometer detector

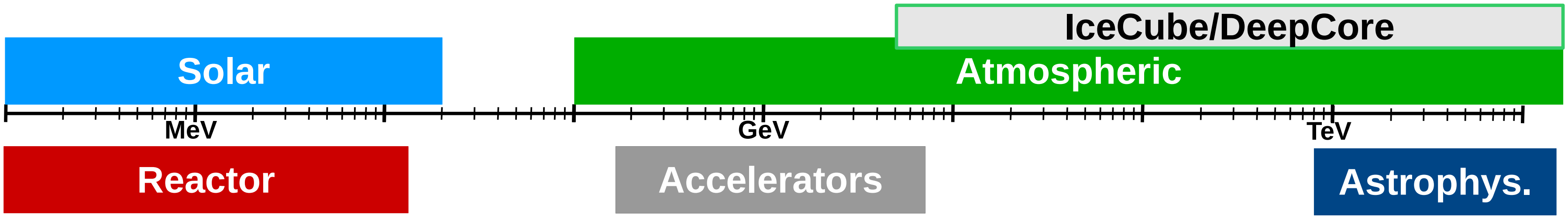
- IceCube detector:
  - 5160 DOMs with 10” PMTs
  - Ice as optical medium
  - Cherenkov light detection
- DeepCore sub-detector:
  - The clearest ice
  - Denser instrumentation
  - +35% higher quantum efficiency
  - IceCube as active veto against atmospheric muons

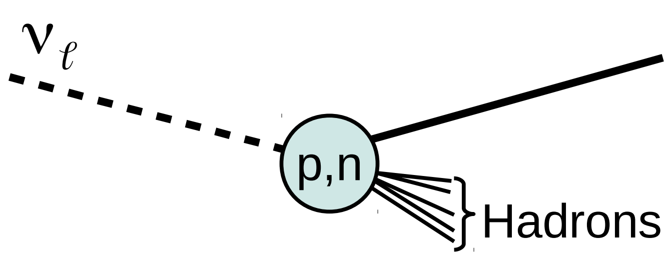
	Hor. [m]	Vert. [m]	Threshold [GeV]
IceCube	125	17	~100 GeV
DeepCore	40-60	7	~5 GeV



IceCube Neutrino Observatory

What events do we measure





ℓ – charged current (CC) interaction

ν_ℓ – neutral current (NC) interaction

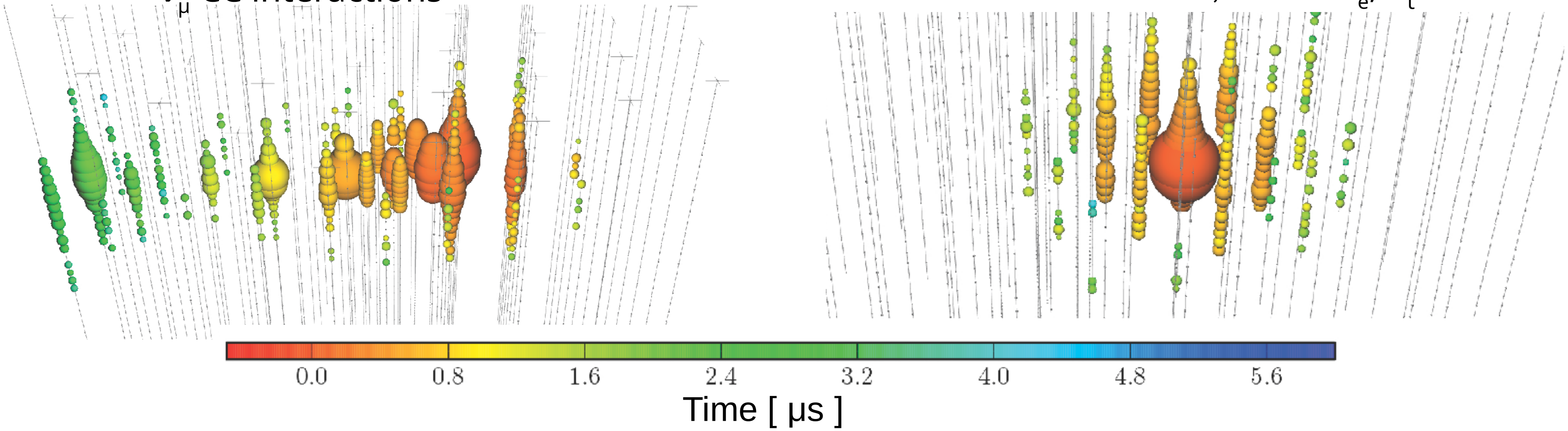
> Secondary particles emit Cherenkov light

> Track like events:

- ν_μ CC interactions

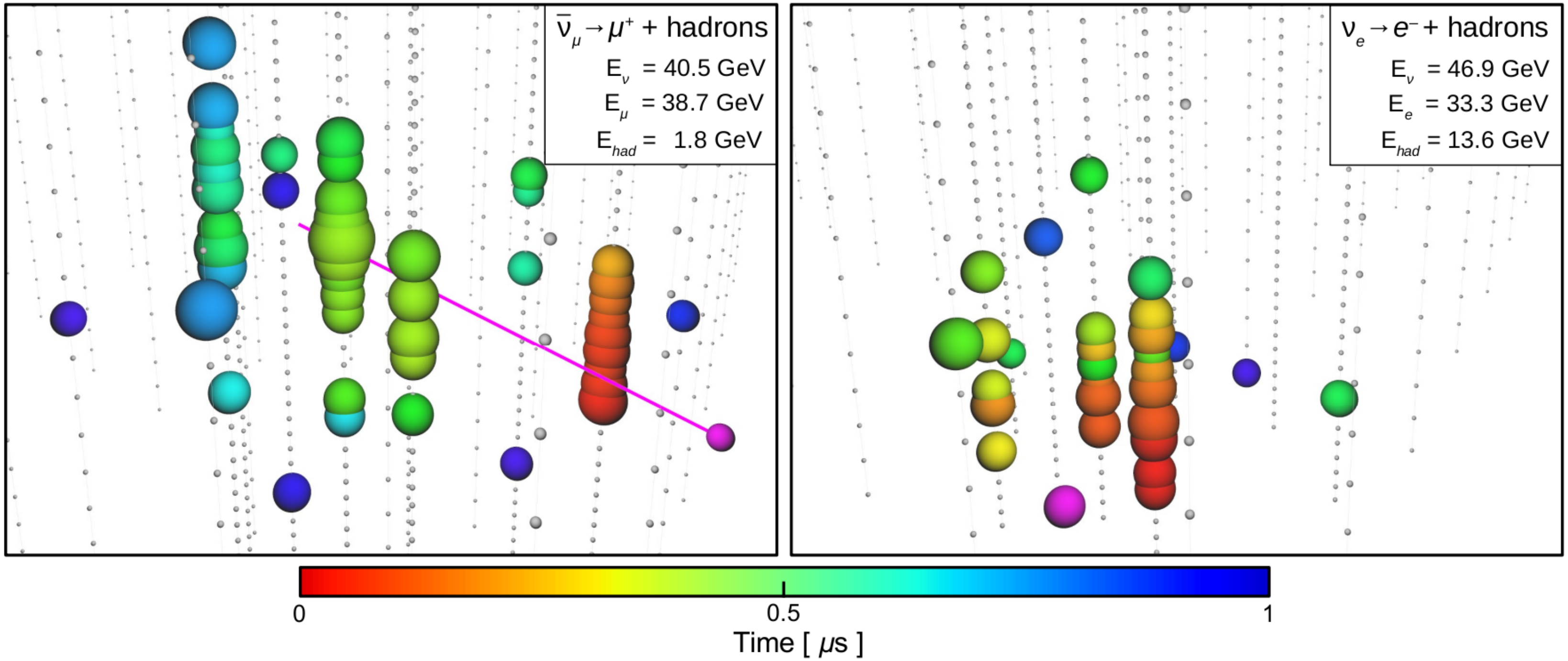
> Cascade like events:

- all NC interaction, CC of ν_e, ν_τ



IceCube Neutrino Observatory

Events in DeepCore



- Events below 50 GeV:
  - Dim and produce little light
  - More affected by detector uncertainties
  - Challenging to select
  - Challenging to reconstruct

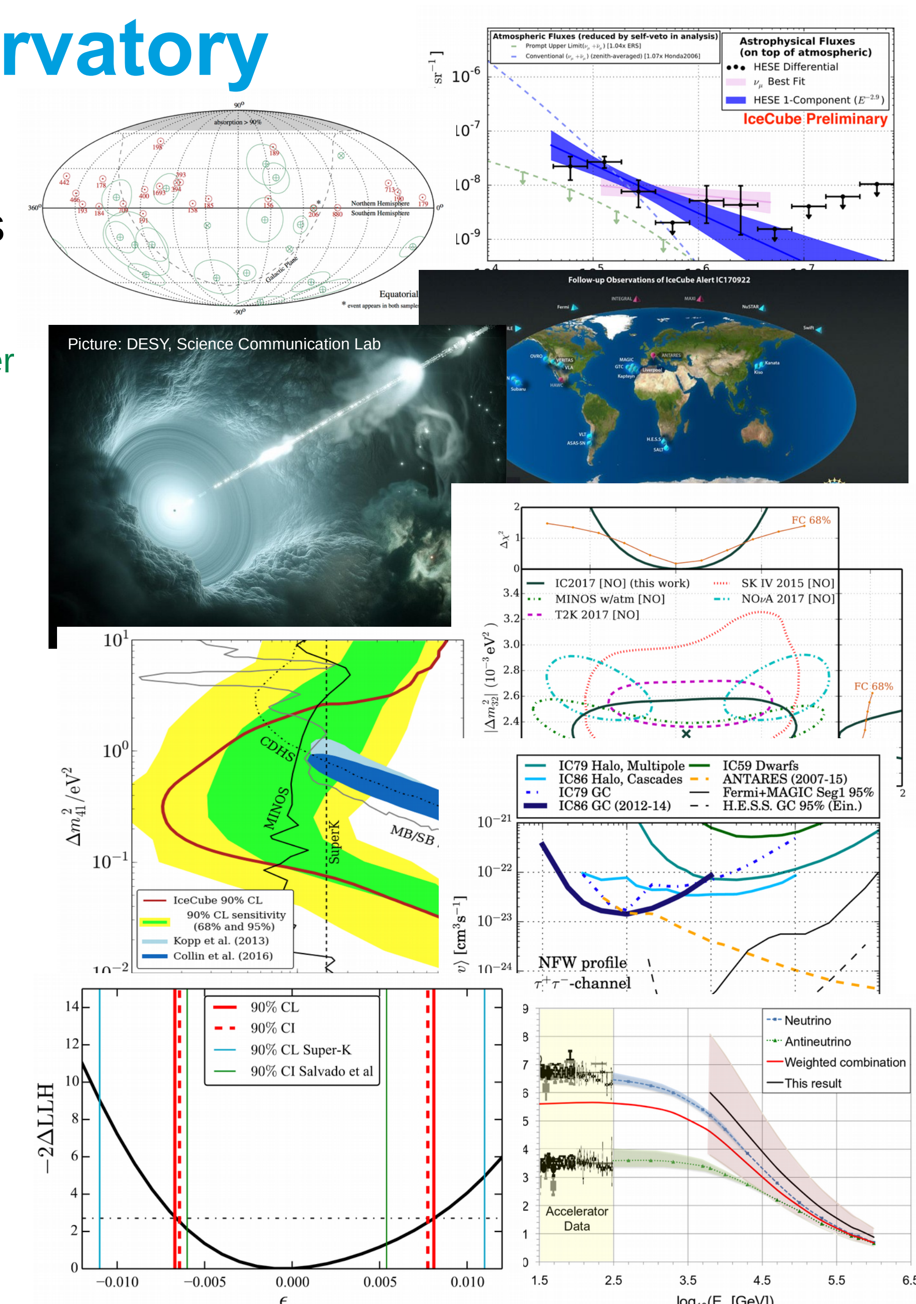
Careful treatment of systematic uncertainties is a key

IceCube Neutrino Observatory

We are doing great physics!

- A broad range of breakthrough physics studies:
  - Astrophysics: See talk by Claudio Kopper
    - Neutrino sources, diffuse fluxes, transients, cosmic rays...
    - Multi-messenger astronomy
  - Neutrino properties:
    - Atmospheric neutrino oscillations
    - Sterile neutrinos, non-standard interactions
    - Cross sections, neutrino fluxes
  - Beyond standard physics:
    - Dark Matter, monopoles, Lorentz violation...
  - Glaciology, Earth tomography
- A lot of studies in progress!

this talk



Atmospheric neutrino oscillations

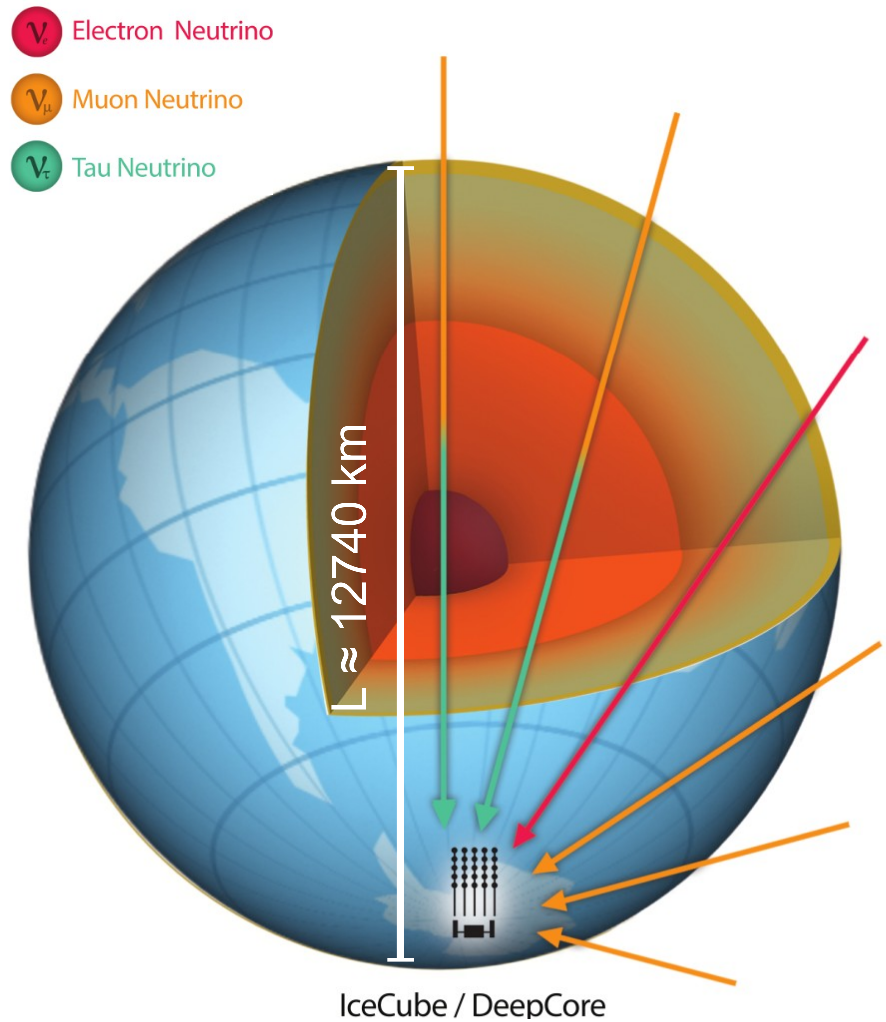
Multi-baseline measurement

- Main effect: transition between muon and tau neutrinos

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

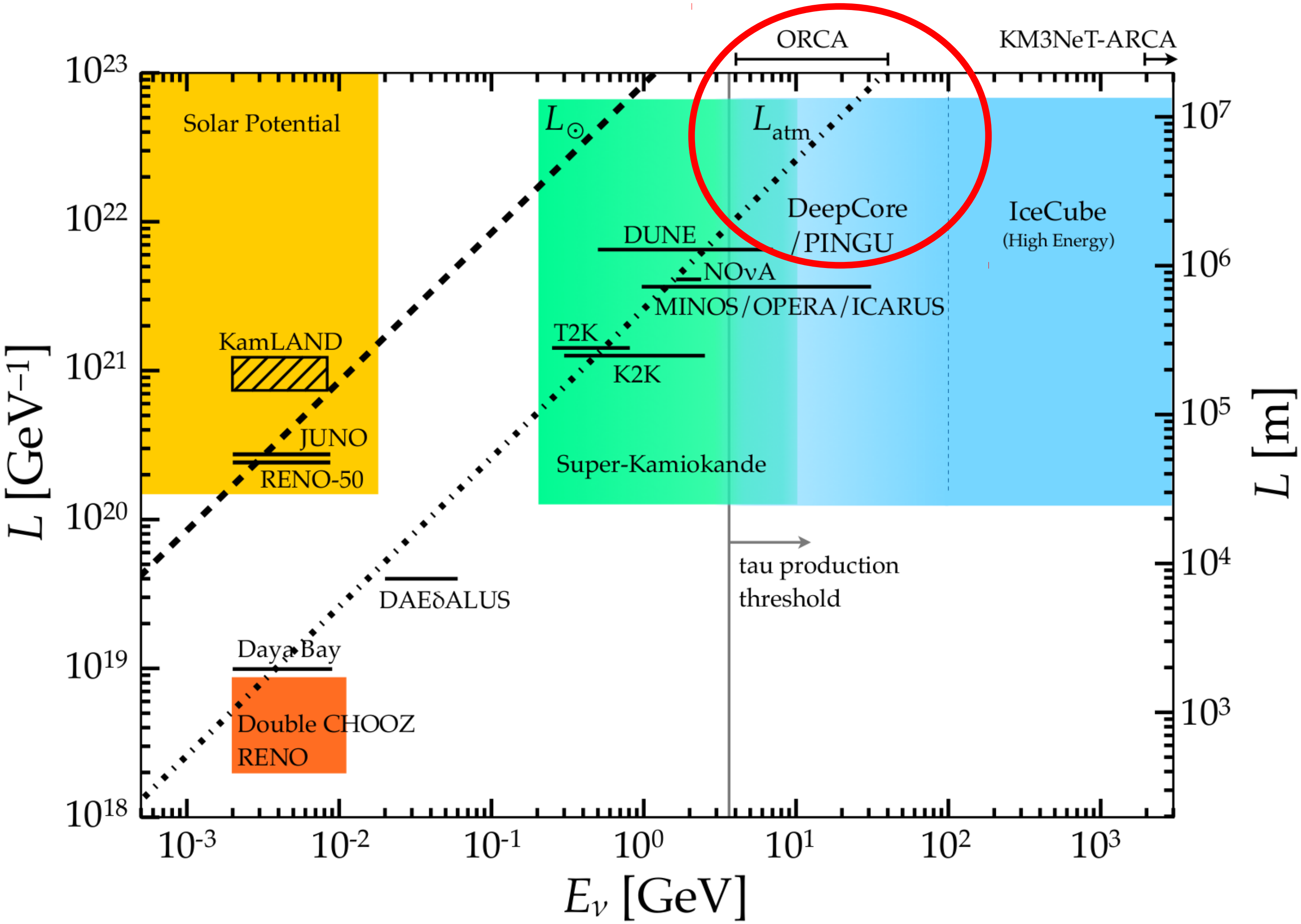
- Different arrival directions $\cos(\theta_{zen})$ → different baselines:
  - Range between 25 and 12760 km

- Disappearance and appearance channels accessible with neutrino telescopes



Atmospheric neutrino oscillations

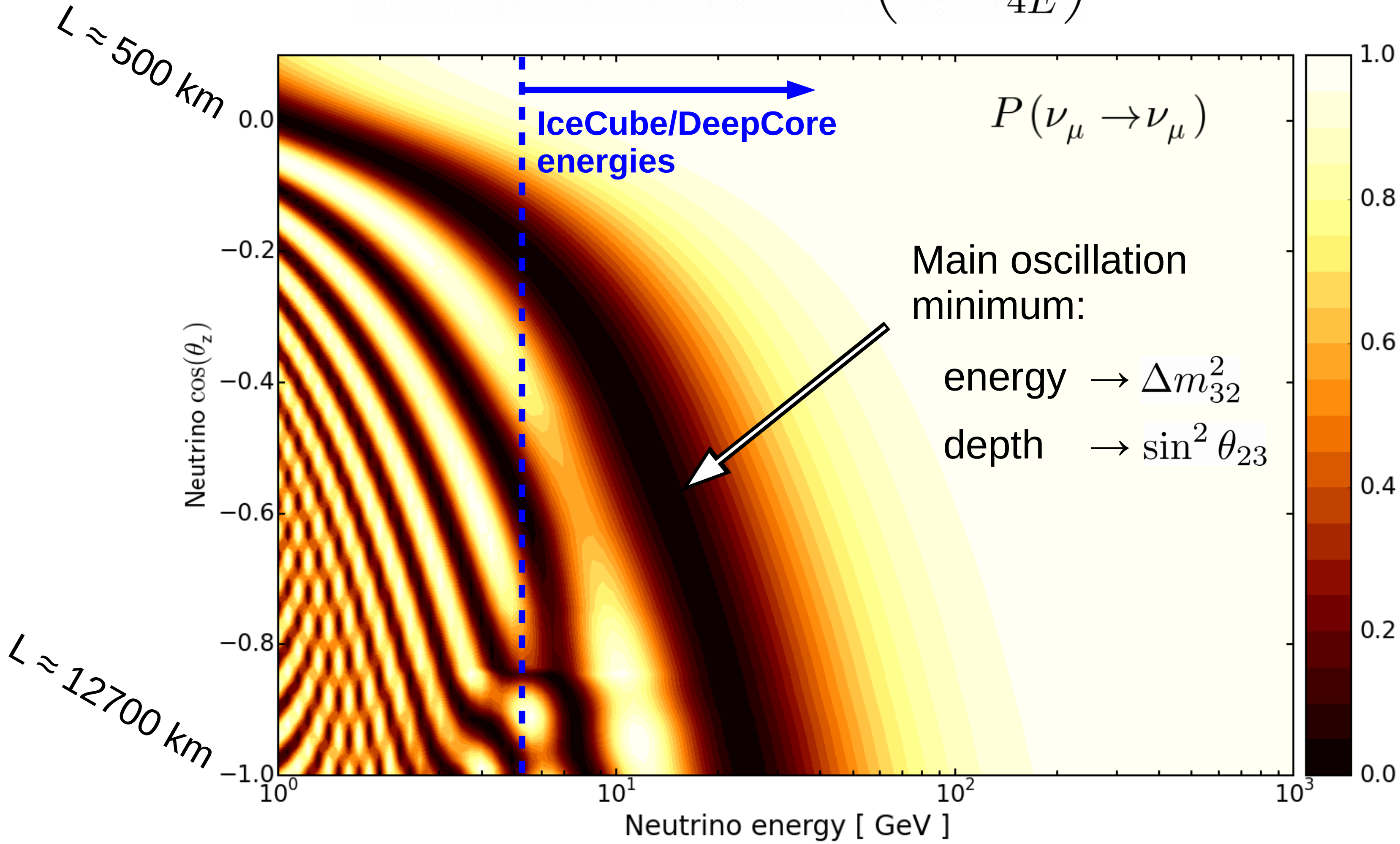
A unique way to probe oscillations at the highest energies



Atmospheric neutrino oscillations

Muon neutrino → tau neutrino transition

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

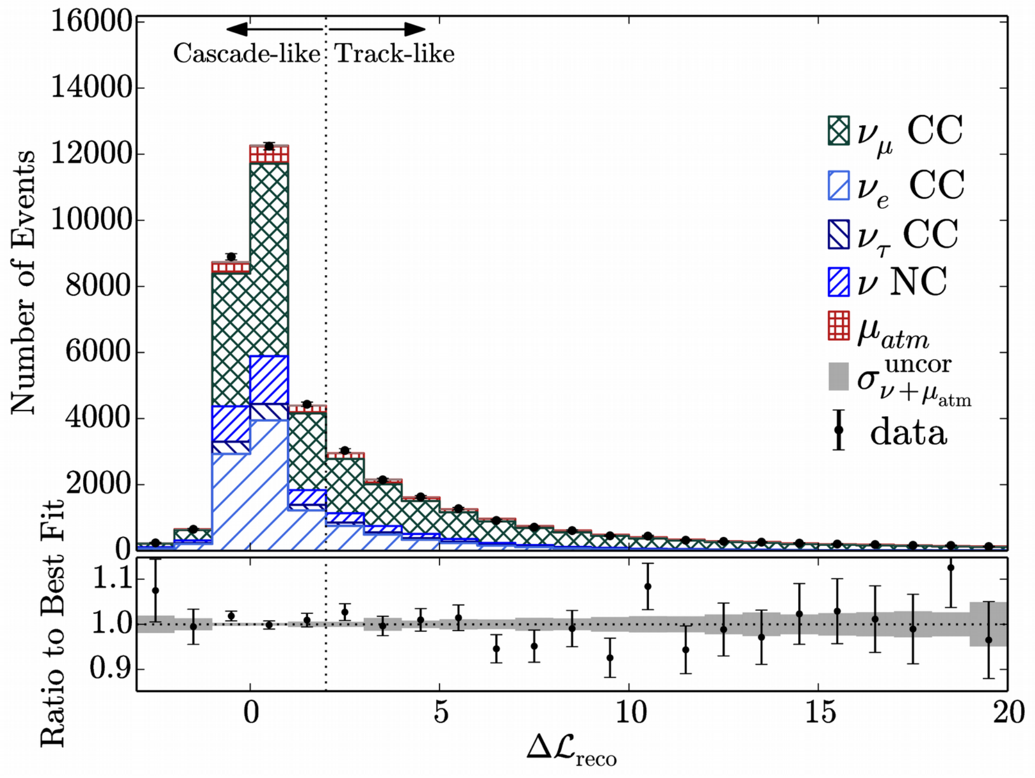


* studies are done using full three-neutrino model in IceCube

Measuring oscillations in IceCube

Few words about analysis

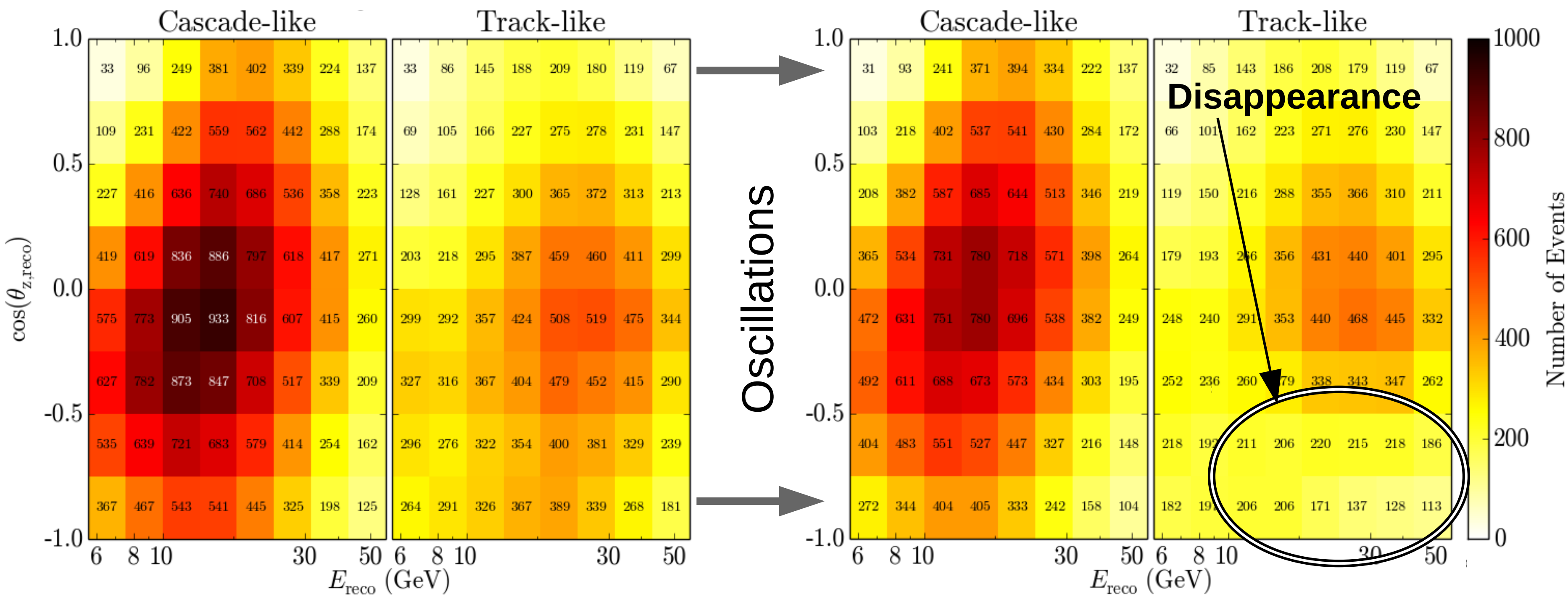
- Event selection:
  - Fighting 10^7 background from atmospheric muons
  - Mix of direct cuts and multivariate analysis techniques
- Reconstruction:
  - 8 parameters corresponding to ν_μ CC interaction:
    - (x,y,z,t) for vertex
    - θ, φ for direction
    - E_{had}, L_μ for energy
  - Ratio of likelihoods to identify events with tracks (PID)



Measuring oscillations in IceCube

What does the signal look like

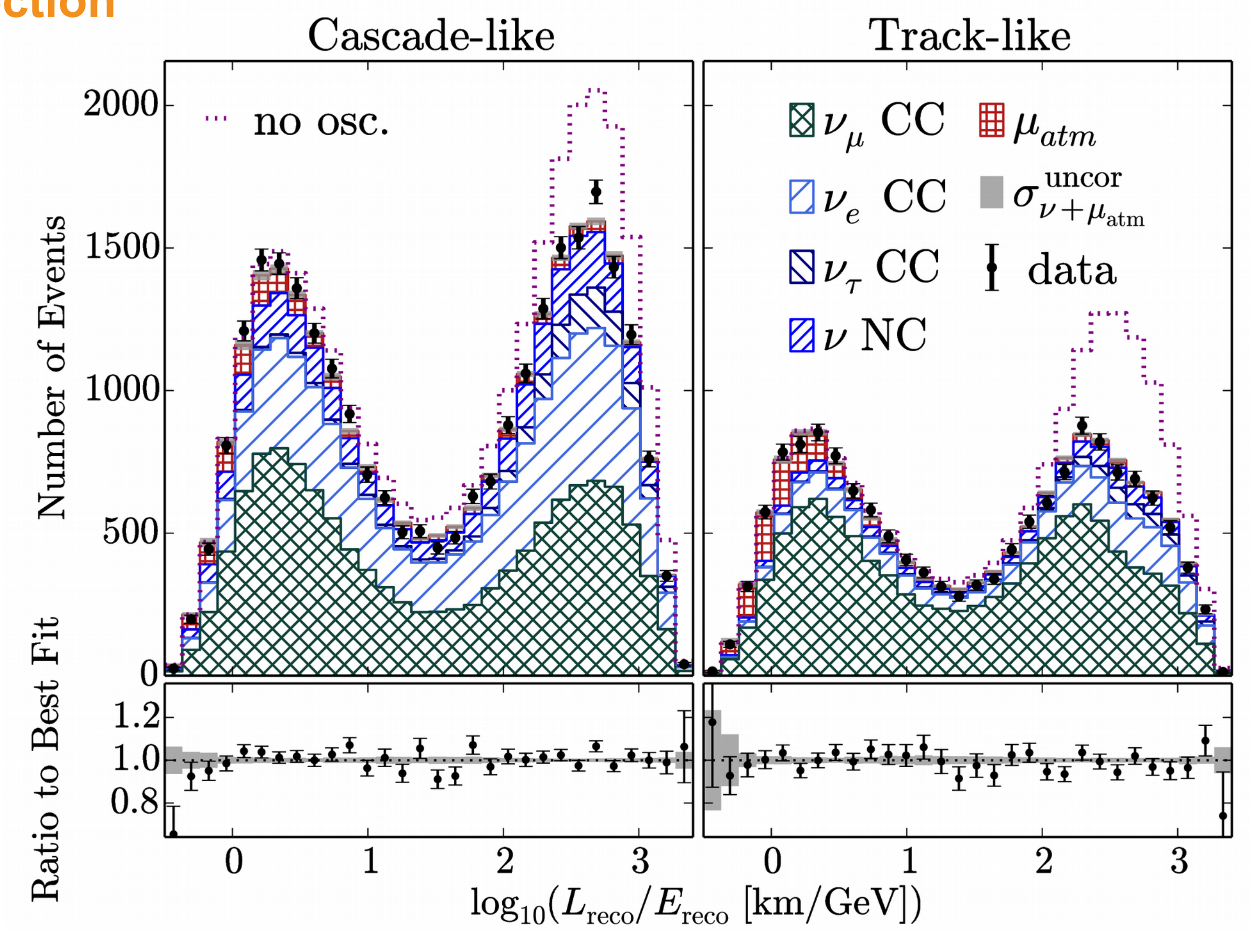
- No oscillations
- With oscillations



- Typically considered systematic parameters:
  - Neutrino fluxes: CR properties, hadronic physics in showers, overall rate
  - Cross-section: axial masses, NC normalization
  - Detector uncertainties: DOM efficiency and angular acceptance, ice optical properties
  - Atmospheric muon contamination

Measuring oscillations in IceCube

L/E projection



> Data clearly prefers oscillations

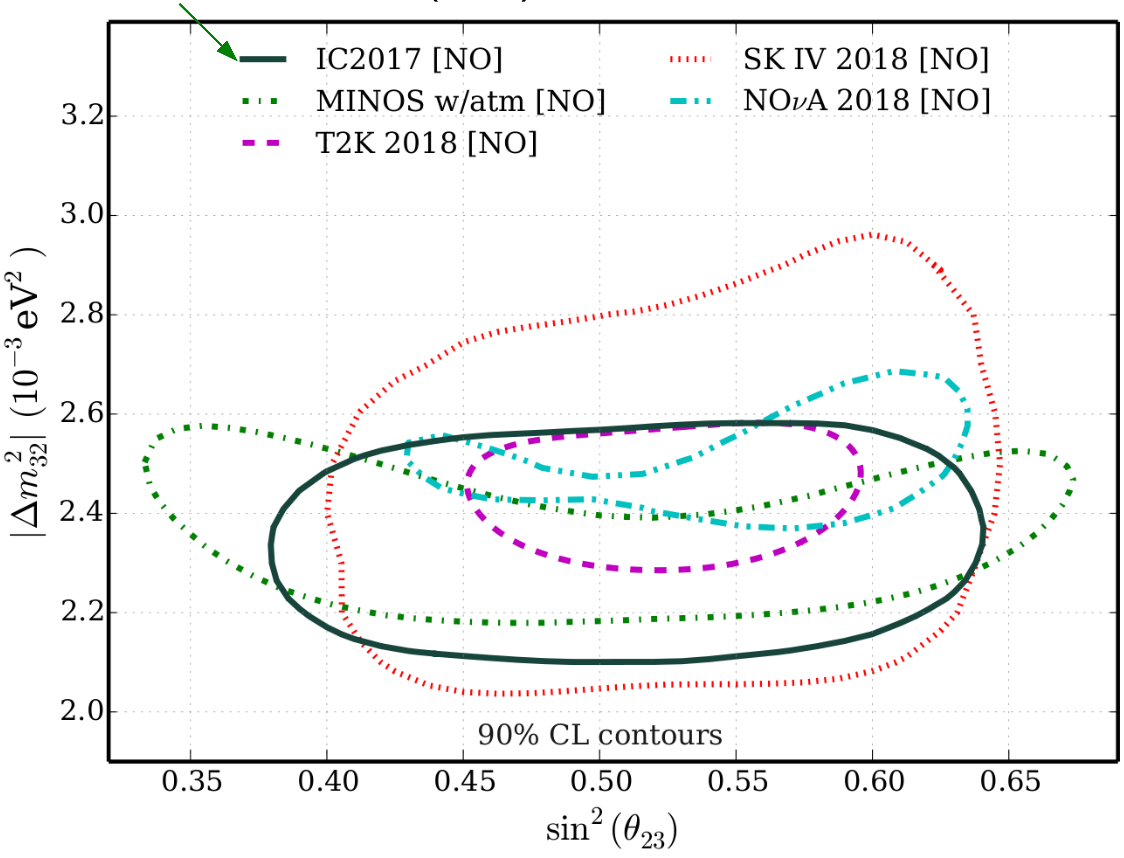
> Down-going neutrinos for normalization

Muon neutrino disappearance

The results with 3 years of data

- Three years of data:
  - 2012-2014 data seasons
- Performed on 3D histograms
  - E_ν: [6, 56] GeV
  - $\cos\theta_z$: [–1, +1]
  - PID: track- or cascade-like
- All studies are performed in blind way:
  - Strict internal review process
  - Good data/MC is ensured
  - Minimal bias of physics-related parameters

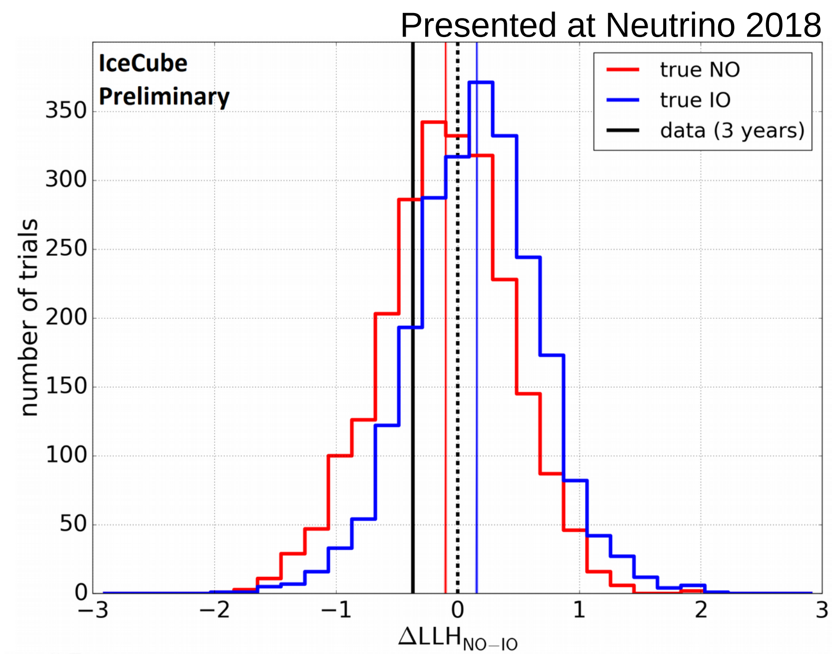
PRL. 120, 071801 (2018)

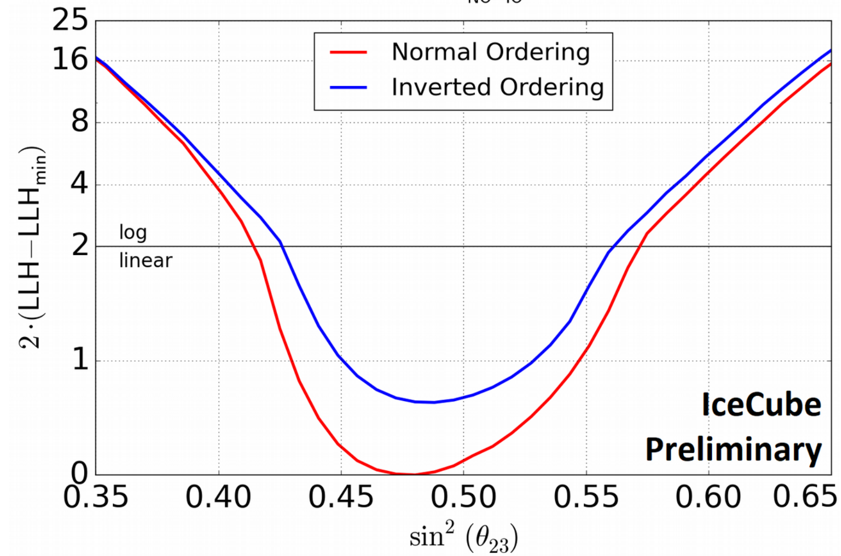


- Approaching precision of dedicated accelerator experiments!

Neutrino mass ordering

Heavy or light?





- First measurements of ordering by IceCube
- Testing statistical tools and analysis techniques
- Normal ordering is marginally preferred

Physics beyond the three-neutrino model

Is three a magic number?

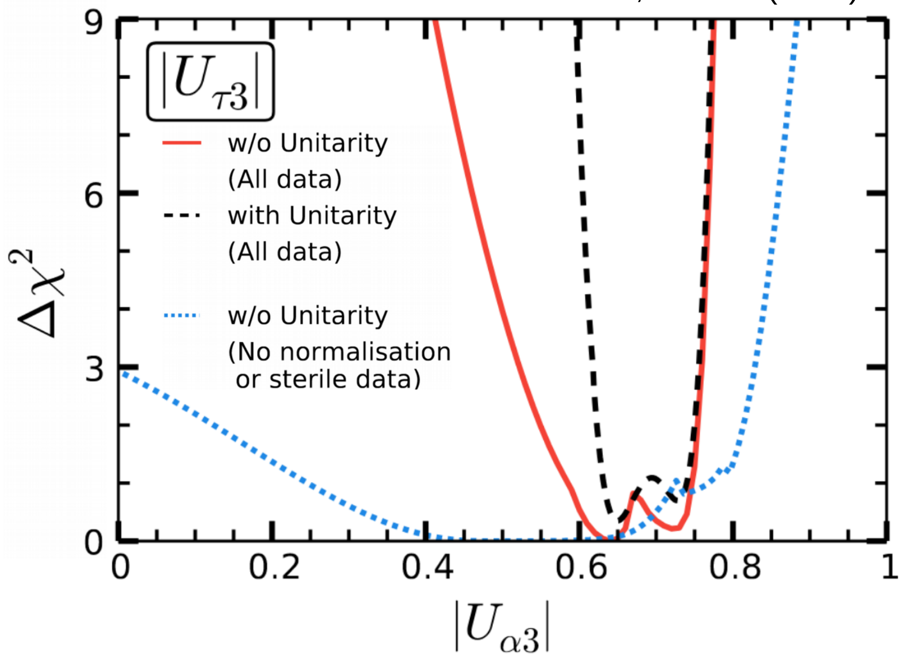
- Standard PMNS matrix:
  - 3 mass states
  - 3 flavour states
  - Matrix is unitary
- Non-unitarity of three-neutrino PMNS matrix → new physics
- Ways to probe:
  - Normalization of appeared tau neutrinos
  - Effects induced by sterile neutrino mixing

Standard mixing

$$U^{\text{Extended}}_{\text{PMNS}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U^{3\text{x}3}_{\text{PMNS}}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

New physics

PRD 93, 113009 (2016)

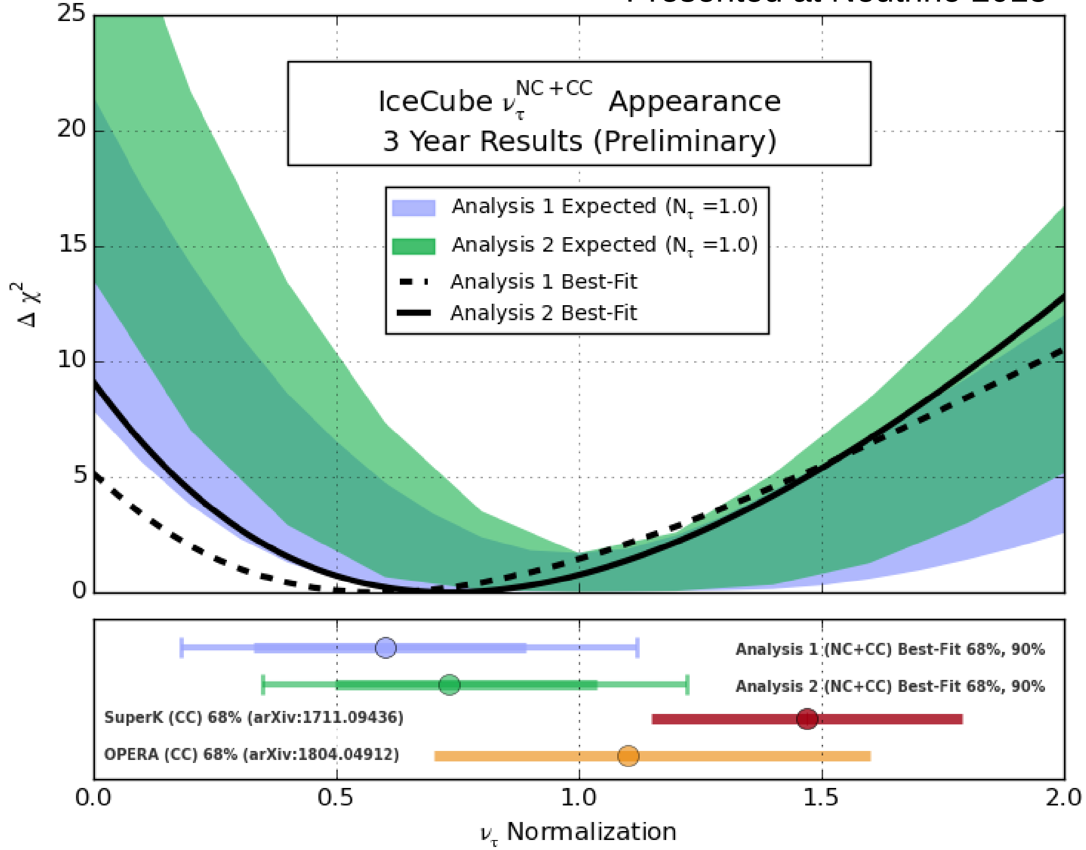


Tau neutrino normalization

The results

- First results for tau neutrino appearance with IceCube
- 3 years of data (2012-2014)
- Two independent analysis chains:
  - PRL 2018 sample (Analysis 1)
  - Parallel analysis (Analysis 2)
- Paper in preparation:
  - Details about systematics, statistical approach, event selection, reconstruction etc.
  - Both ν_μ disappearance and ν_τ appearance

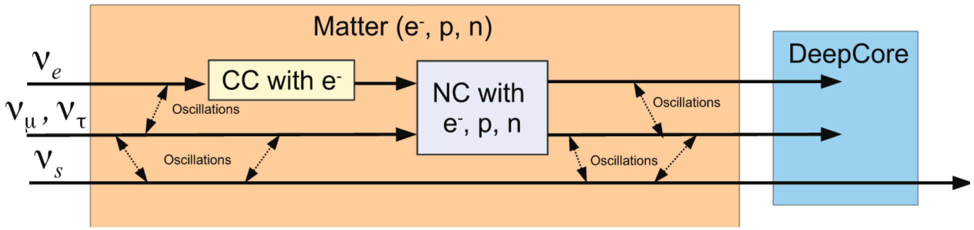
Presented at Neutrino 2018



- Results in agreement with standard three-neutrino oscillations

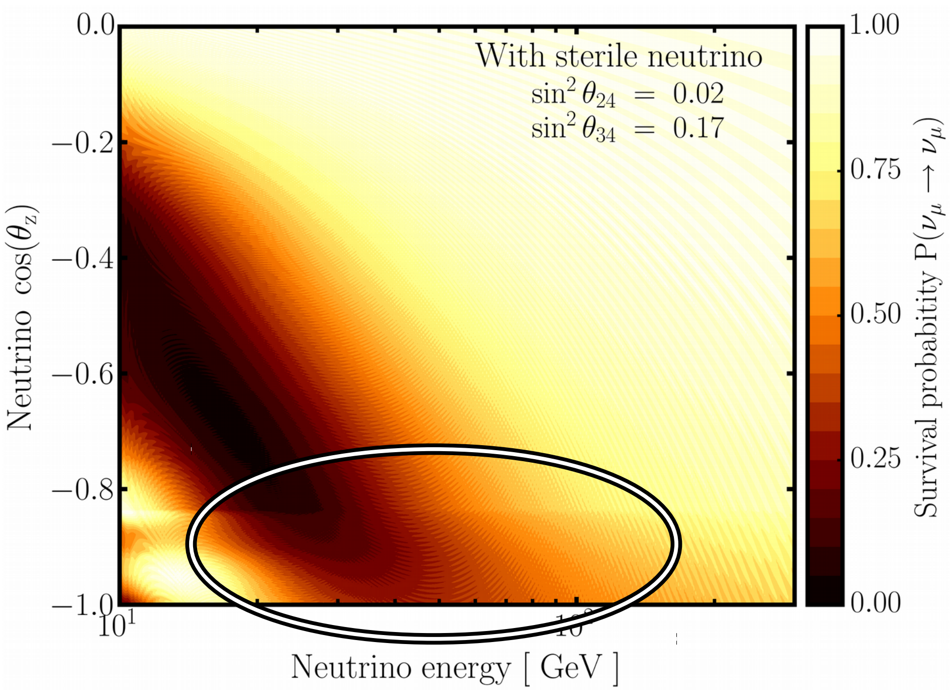
Sterile neutrinos with IceCube

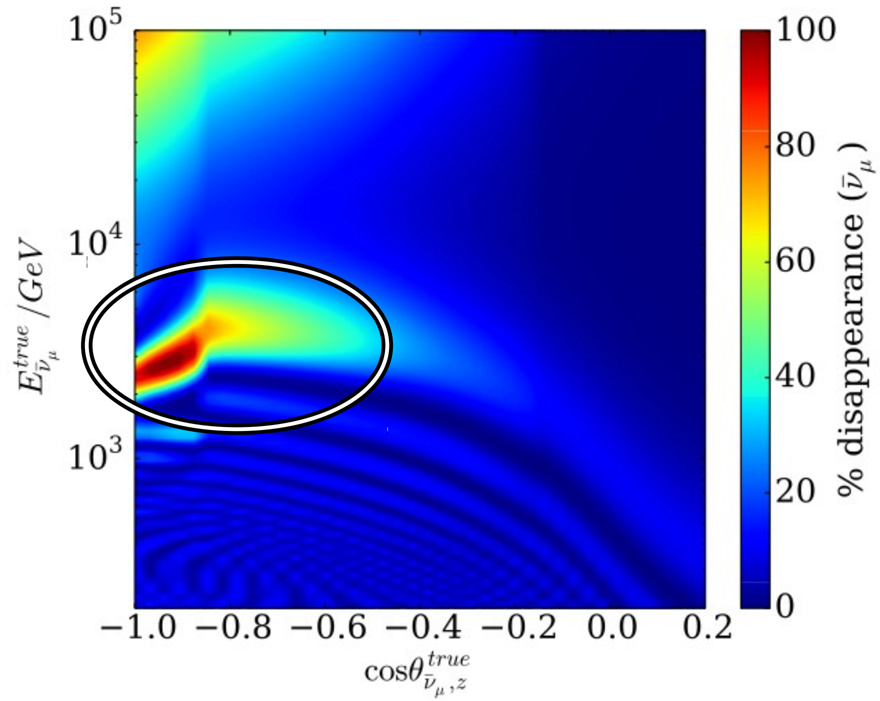
Searching for matter-induced effects



$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4} \\ U_{\tau 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Probing ν_μ, ν_τ sectors with IceCube





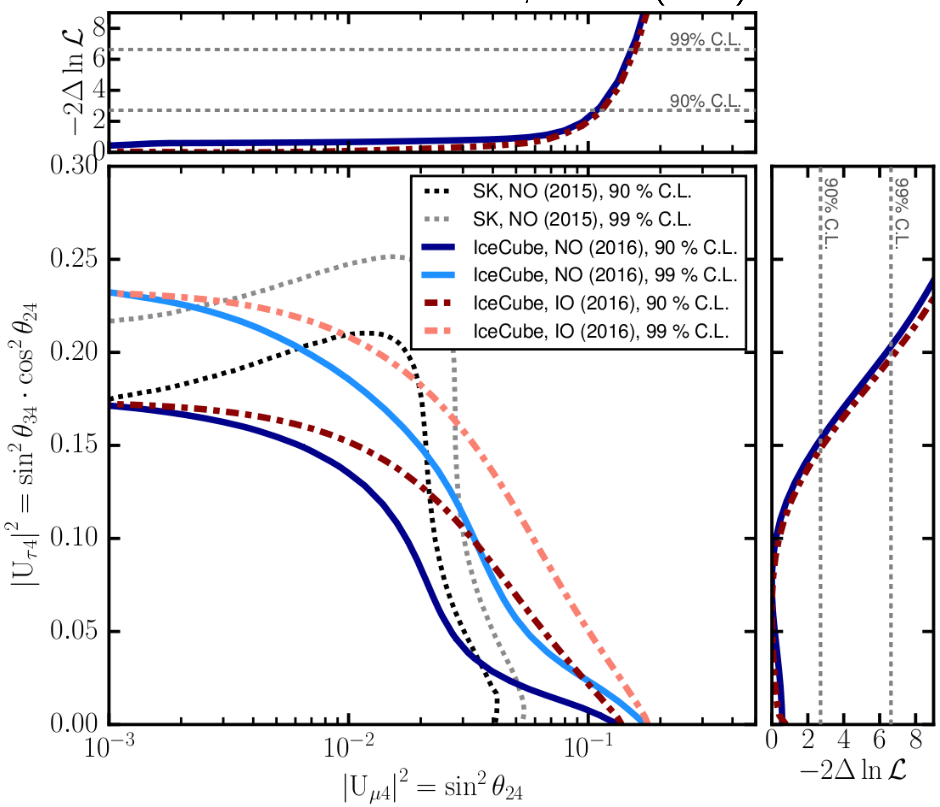
- Modification of standard three-neutrino oscillations at low energies (<100 GeV)
- Resonance disappearance of muon antineutrinos at a few TeV

Sterile neutrinos with IceCube

Our limits

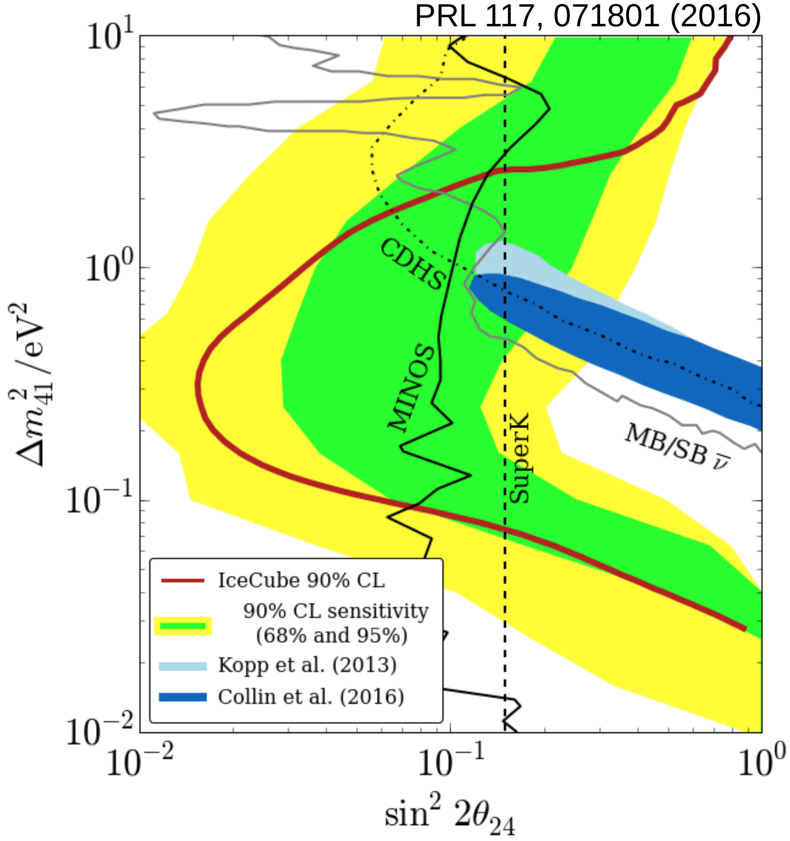
> Sterile neutrinos with DeepCore

PRD 95, 112002 (2017)



> TeV search for sterile neutrinos

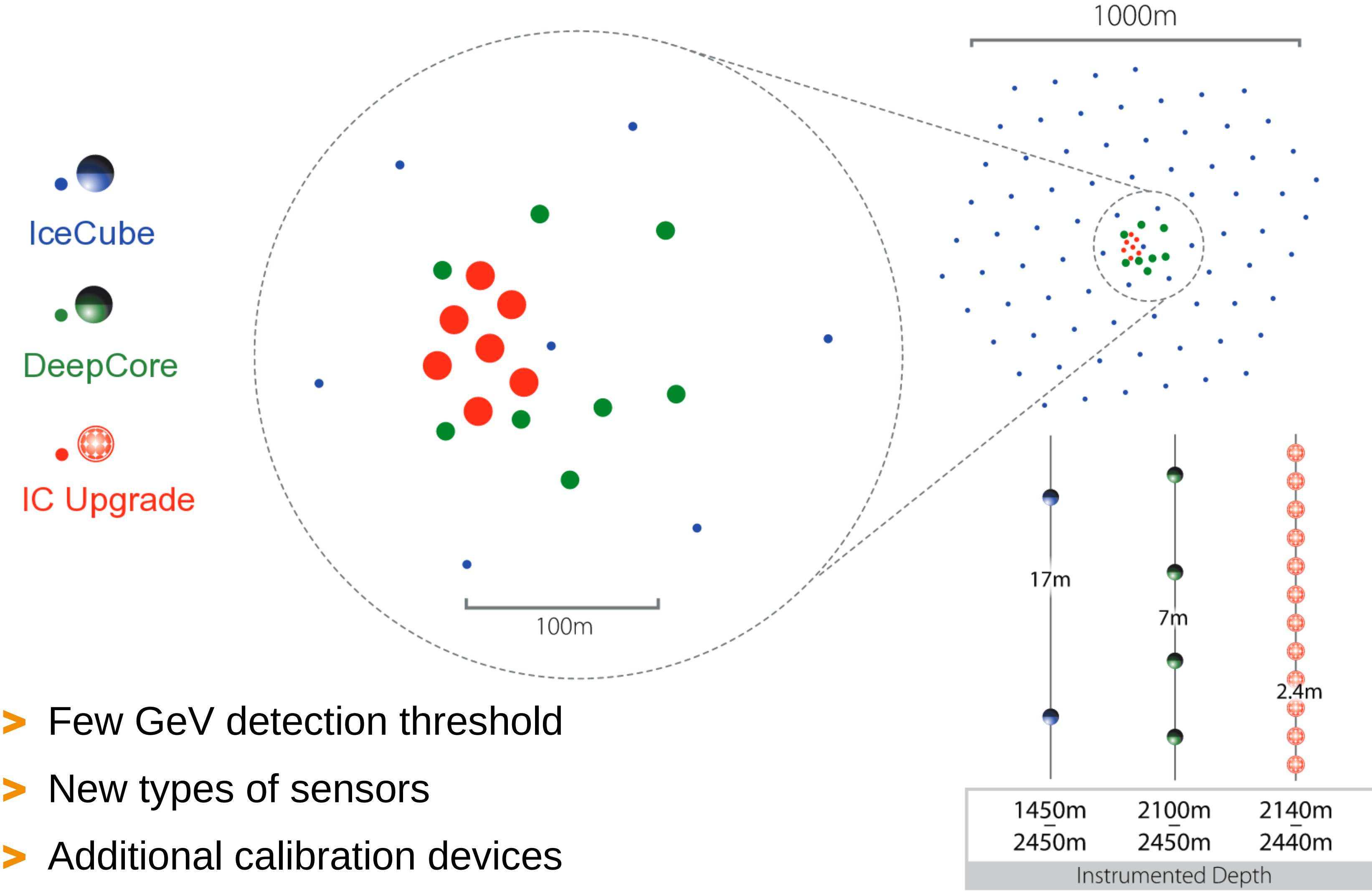
PRL 117, 071801 (2016)



> Constraining limits on sterile neutrino mixing in muon and tau sectors

IceCube Upgrade

New tool for studies of atmospheric neutrinos

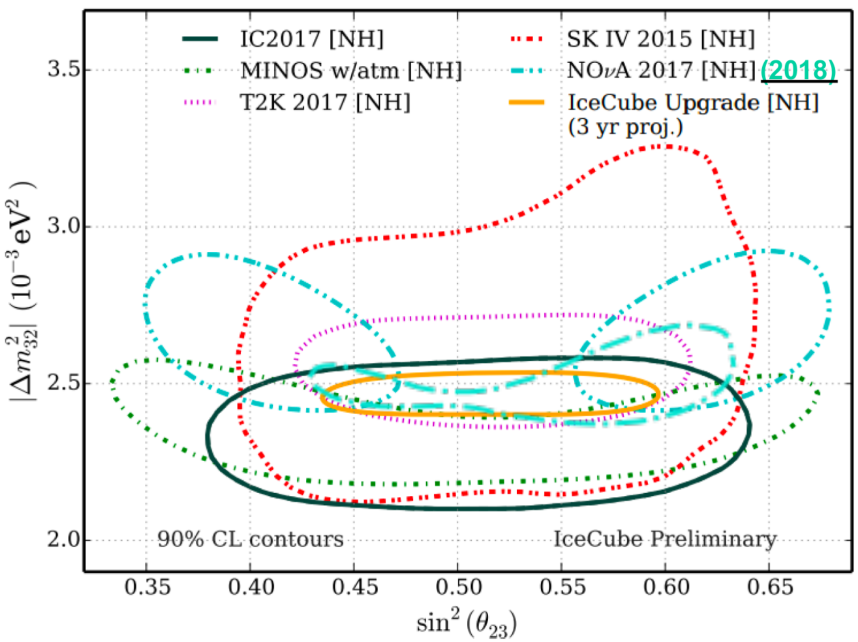


- Few GeV detection threshold
- New types of sensors
- Additional calibration devices
- See talk by Marek Kowalski

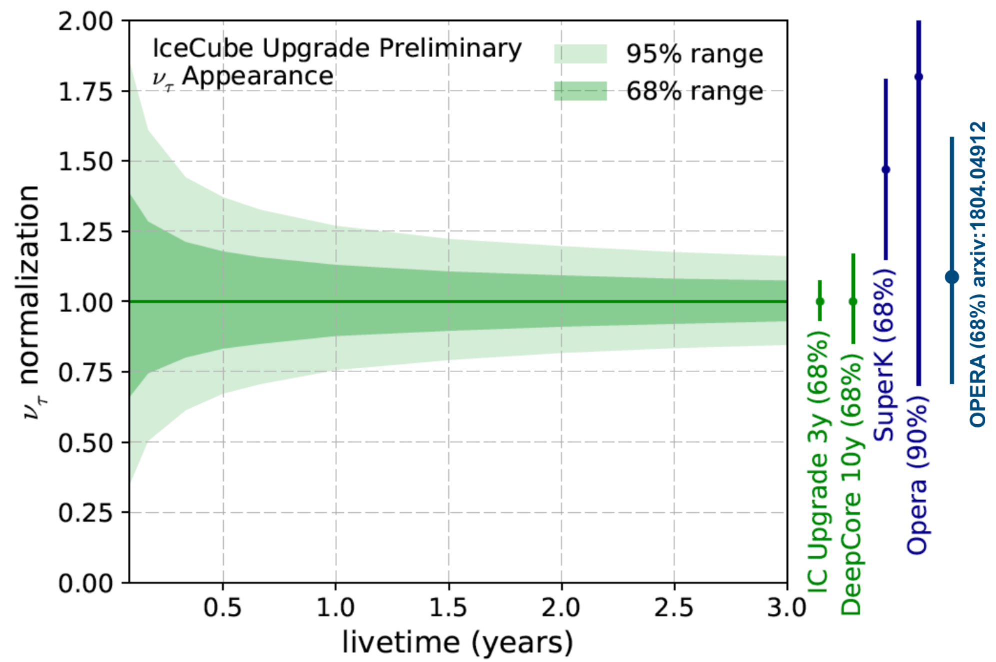
IceCube Upgrade

What we can achieve

> Muon neutrino disappearance



> Tau neutrino appearance



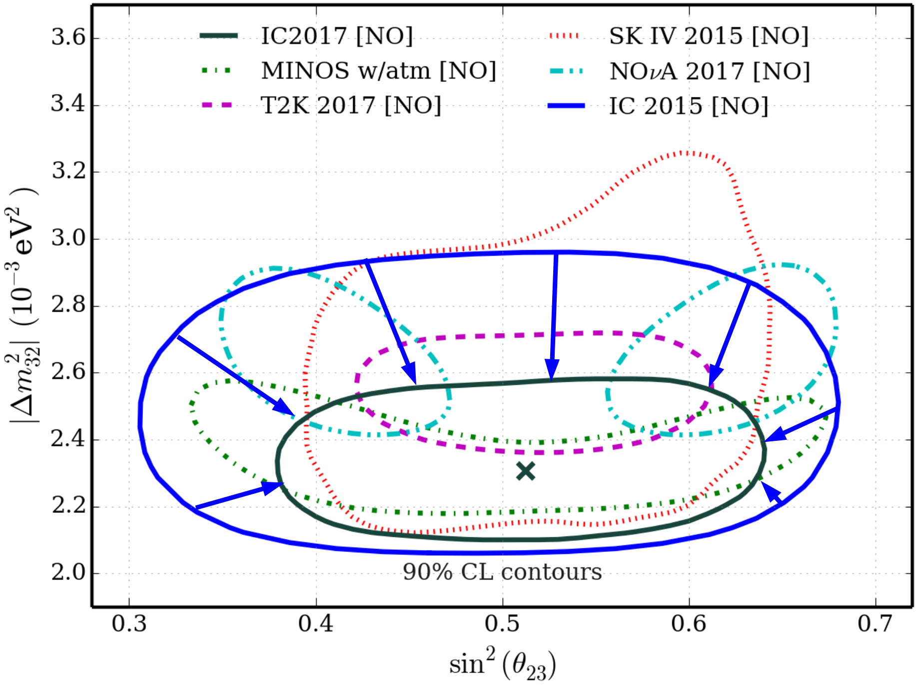
> Precision frontier for neutrino oscillations using atmospheric neutrinos

Summary

Highlights from IceCube DeepCore measurements

- IceCube – major neutrino oscillation experiment
- Key results using atmospheric neutrinos
  - Muon neutrino disappearance
  - Tau neutrino appearance
  - Sterile neutrino mixing
- Mainly using only 3 years of data
  - Not systematically limited
  - Ongoing work to use full detector live time
  - 6-7 year studies are expected very soon
  - Stay tuned and keep an eye on conferences and arXiv
- IceCube Upgrade is expected in mid-near future

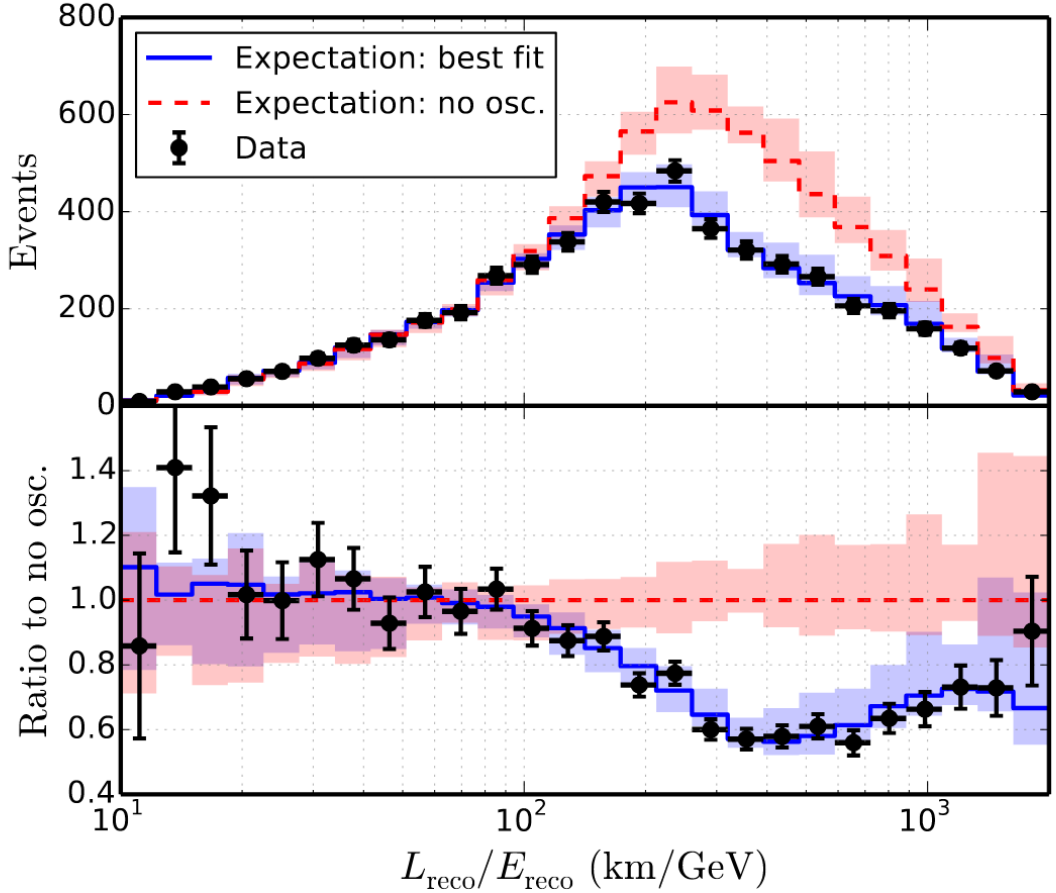
Our improvement in less than 3 years!



Backup

Backup

2015 IceCube Measurement



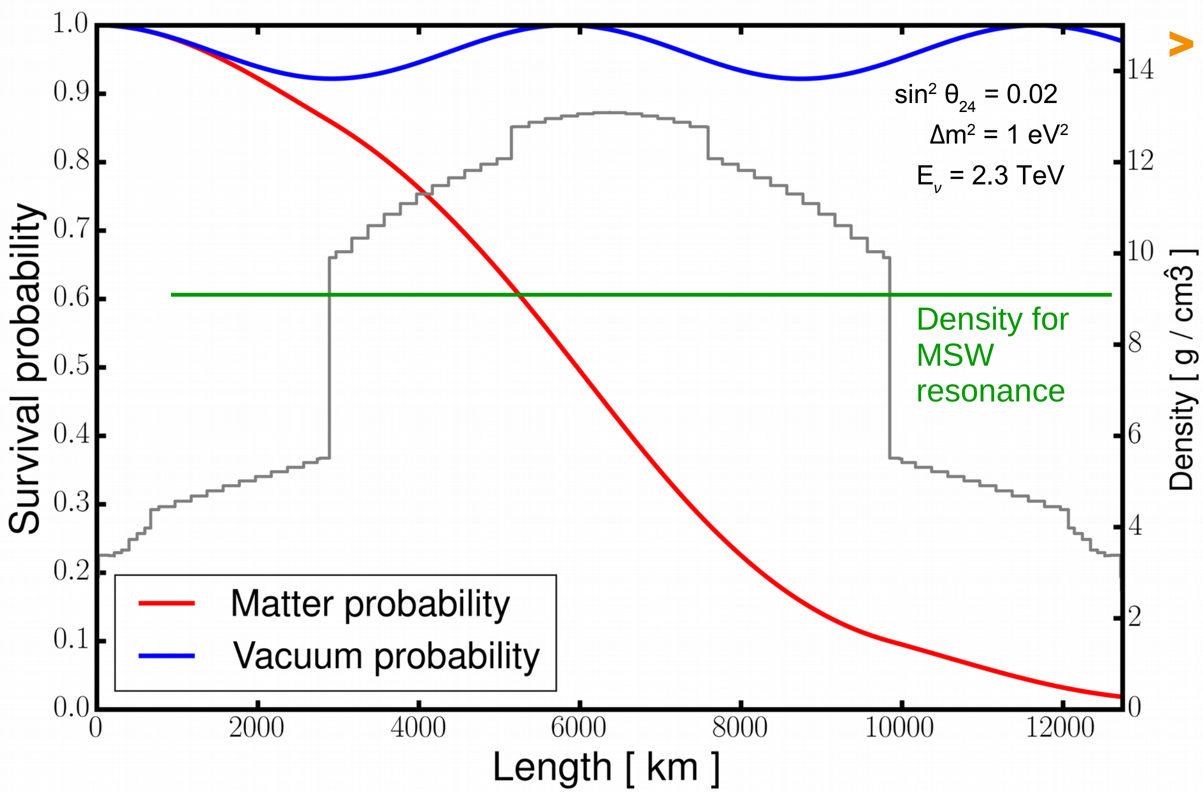
- Up-going events only, 6-56 GeV
- Track-only events

Backup

HE sterile effect

$$\underbrace{\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{2 E V_{\text{int}}}{\Delta m^2 \cos 2\theta}}}_{\text{Changes amplitude of oscillations}}$$

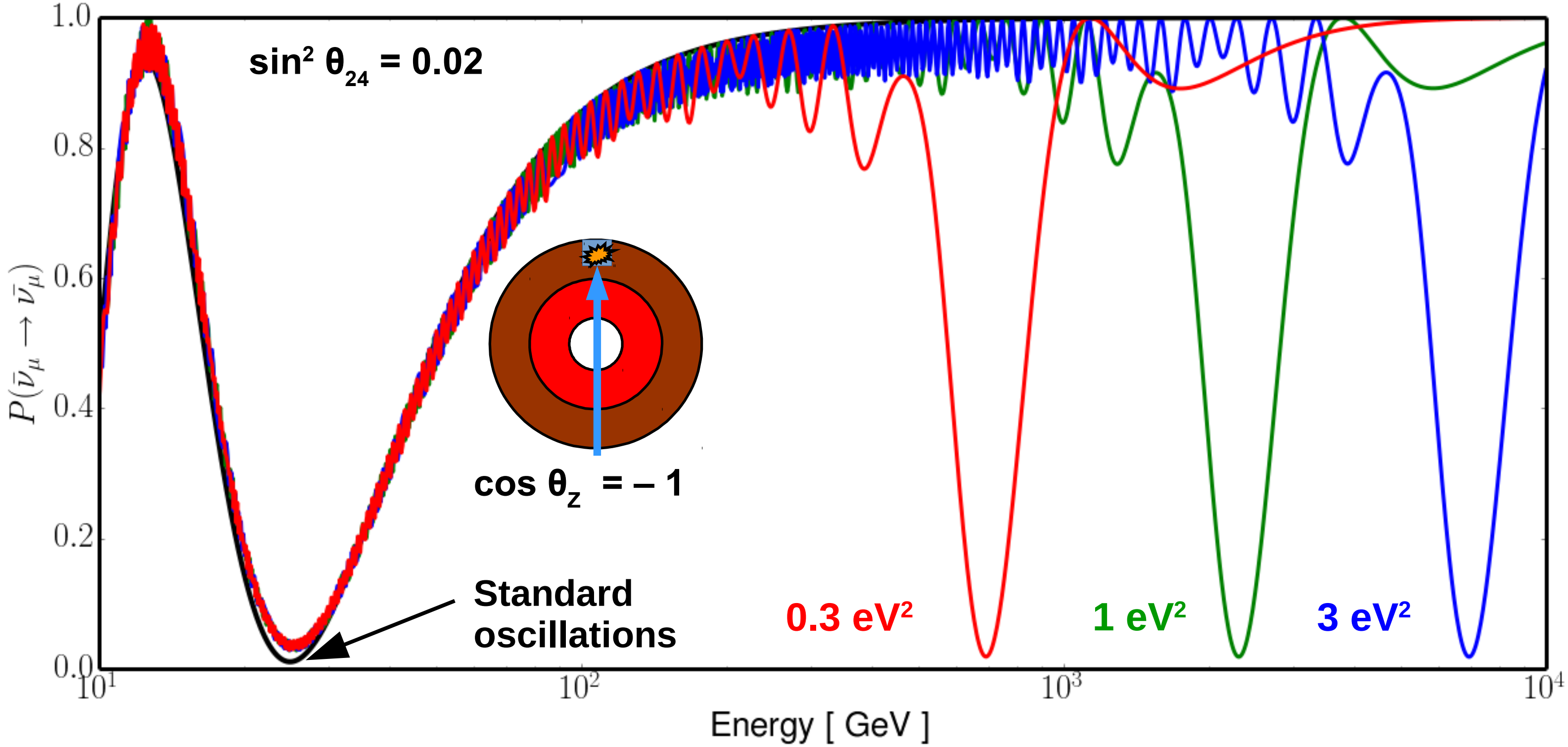
$$\underbrace{\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2 E V_{\text{int}})^2 + (\Delta m^2 \sin 2\theta)^2}}_{\text{Changes period of oscillations}}$$



- 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

Backup

HE sterile effects



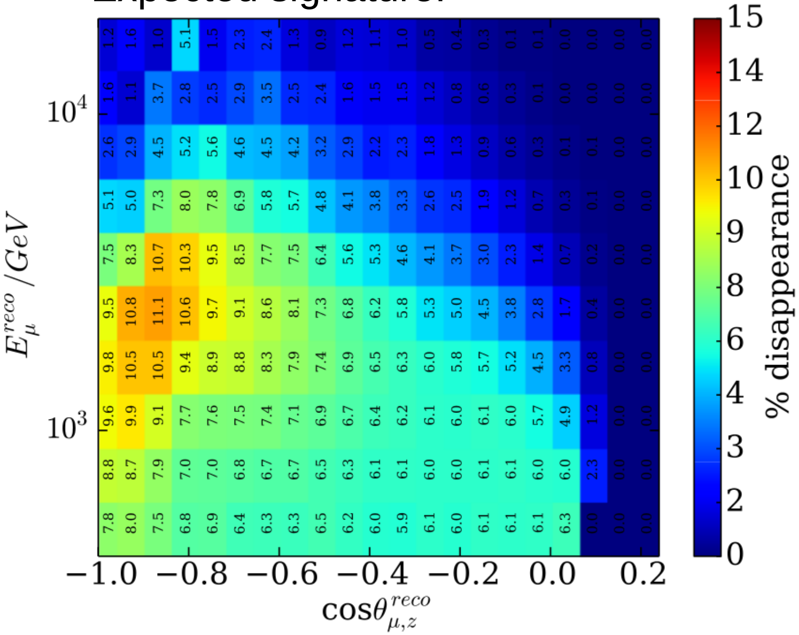
- Energy of the resonance proportional to the mass splitting
- Sensitivity to $|U_{\mu 4}|^2$ (or θ_{24}) and sterile mass
- Sensitivity with IceCube using high energy atmospheric neutrinos

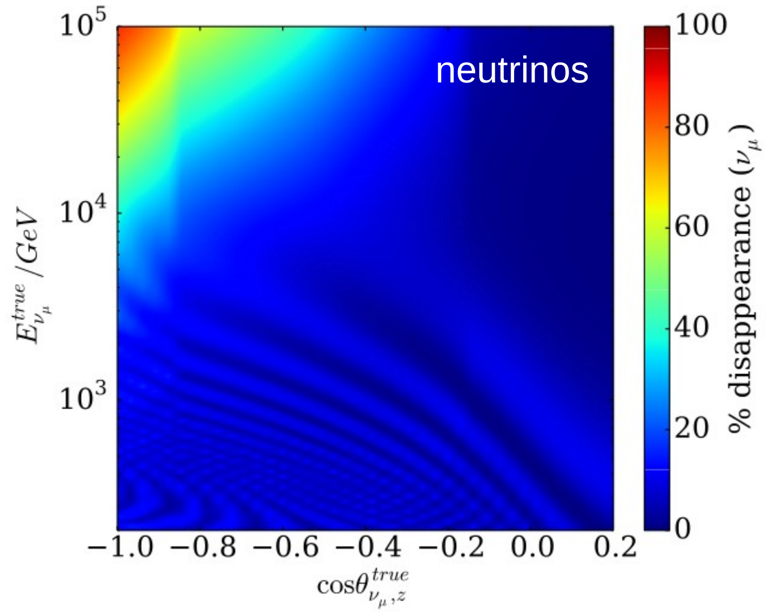
Backup

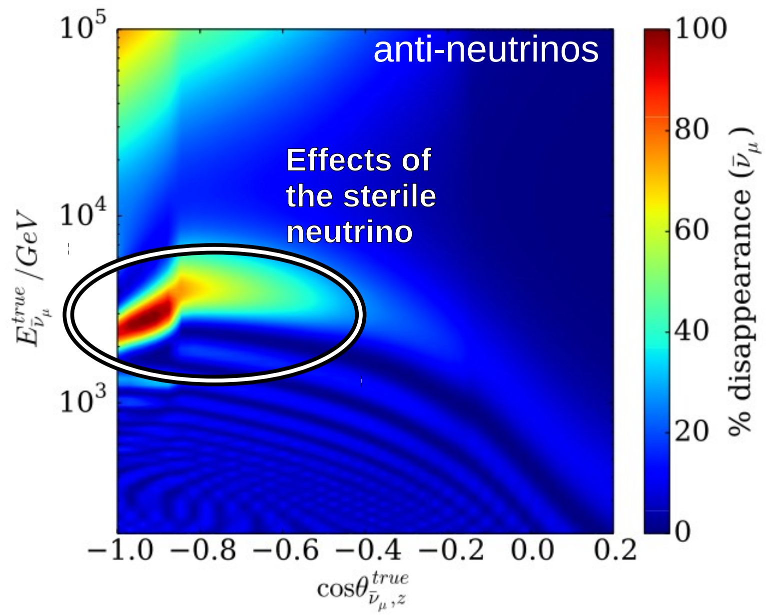
HE sterile effects

> Effects above 100 GeV:
  - MSW resonance-like transition to sterile state
  - Muon-anti neutrinos
  - Energy of resonance
  - Sensitive to angle θ_{24}

Expected signature:

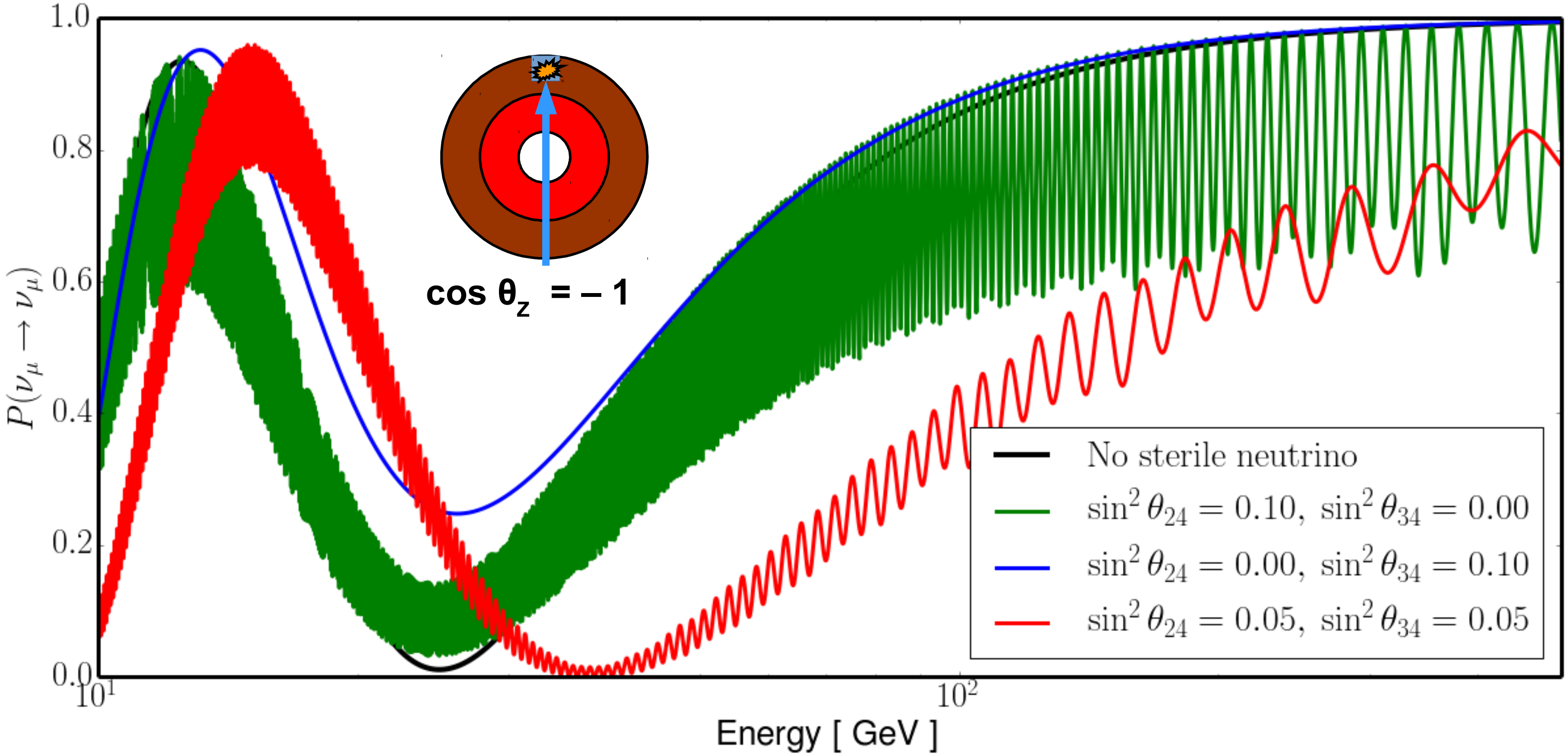






Backup

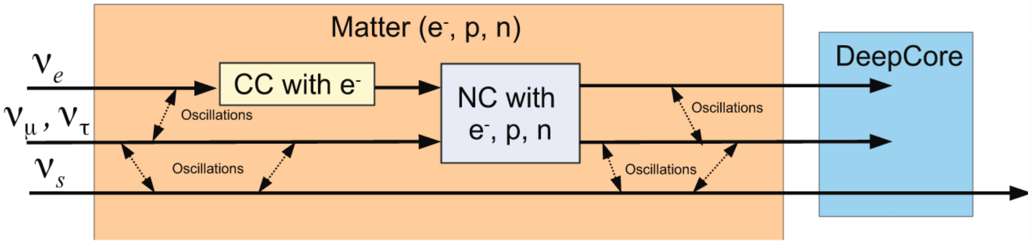
LE oscillations effects



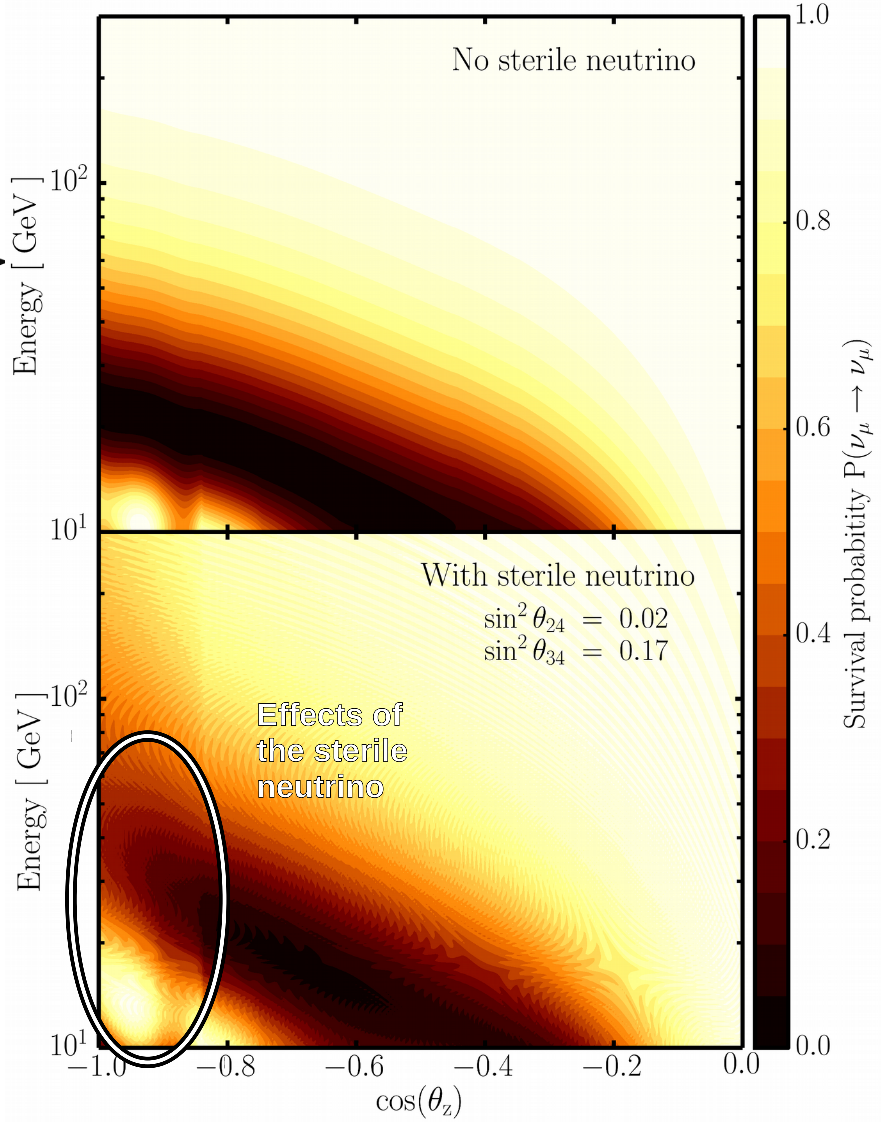
- Modification of the standard numu disappearance
- “Fast” oscillating component is averaged → independent from sterile neutrino mass
- Sensitive to angles θ_{24} and θ_{34}

Backup

LE sterile effects

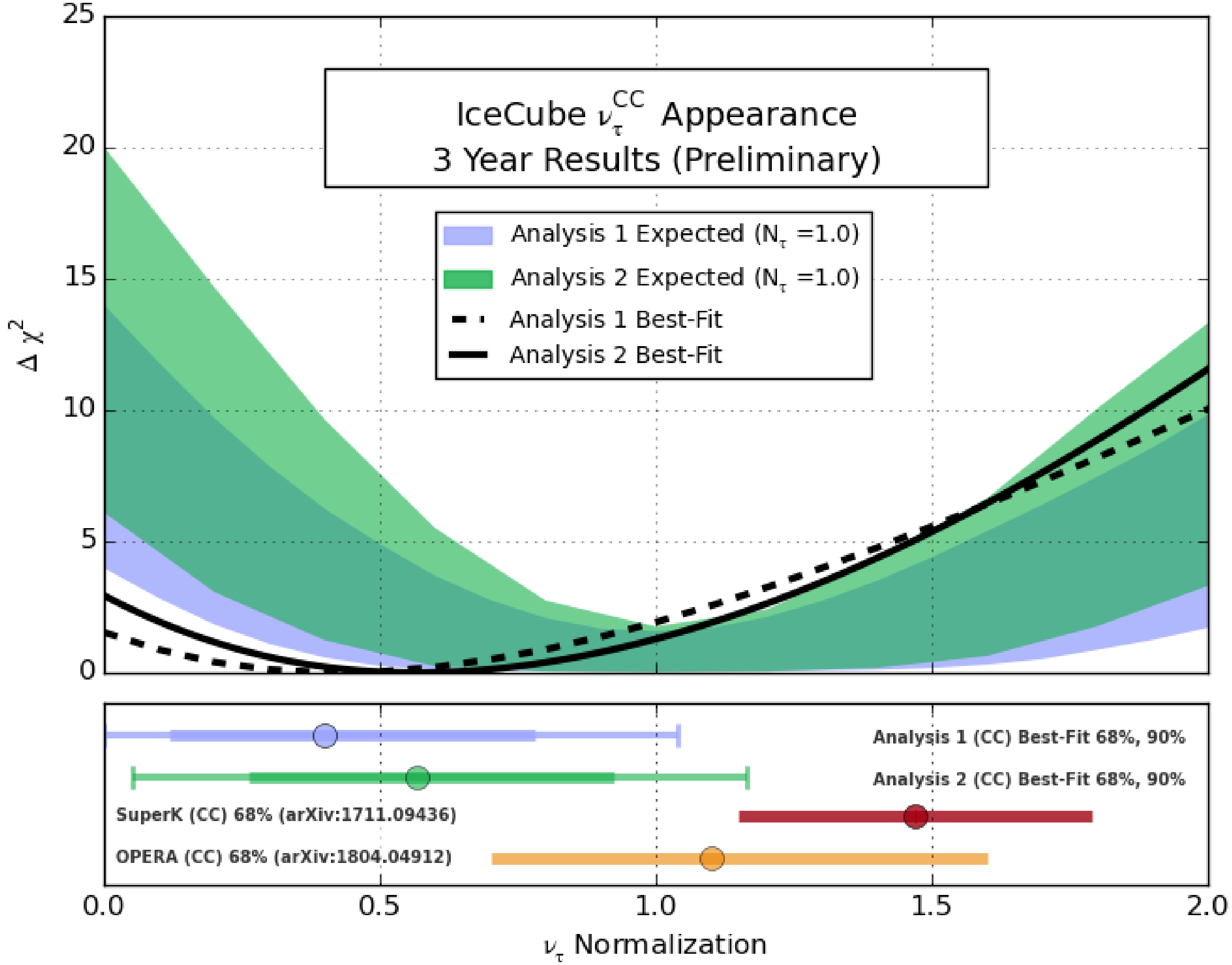


- Effects below 100 GeV:
  - Modifications of standard oscillations
    - shifts of oscillations minimum
    - changes of amplitude
  - Independent of sterile neutrino mass (for $\Delta m^2_{41} > 0.3\,eV^2$)
  - Sensitive to the angles θ_{24} and θ_{34}
  - Effect proportional to matter density



Backup

NuTau appearance CC only



Backup

Cross-check analysis for disappearance