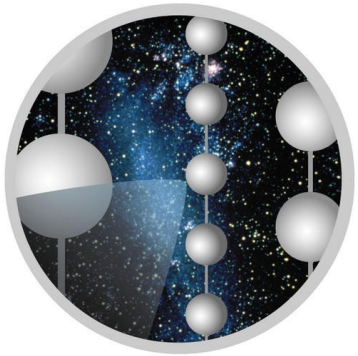
IceCube Neutrino Observatory

> Fundamental physics of neutrinos



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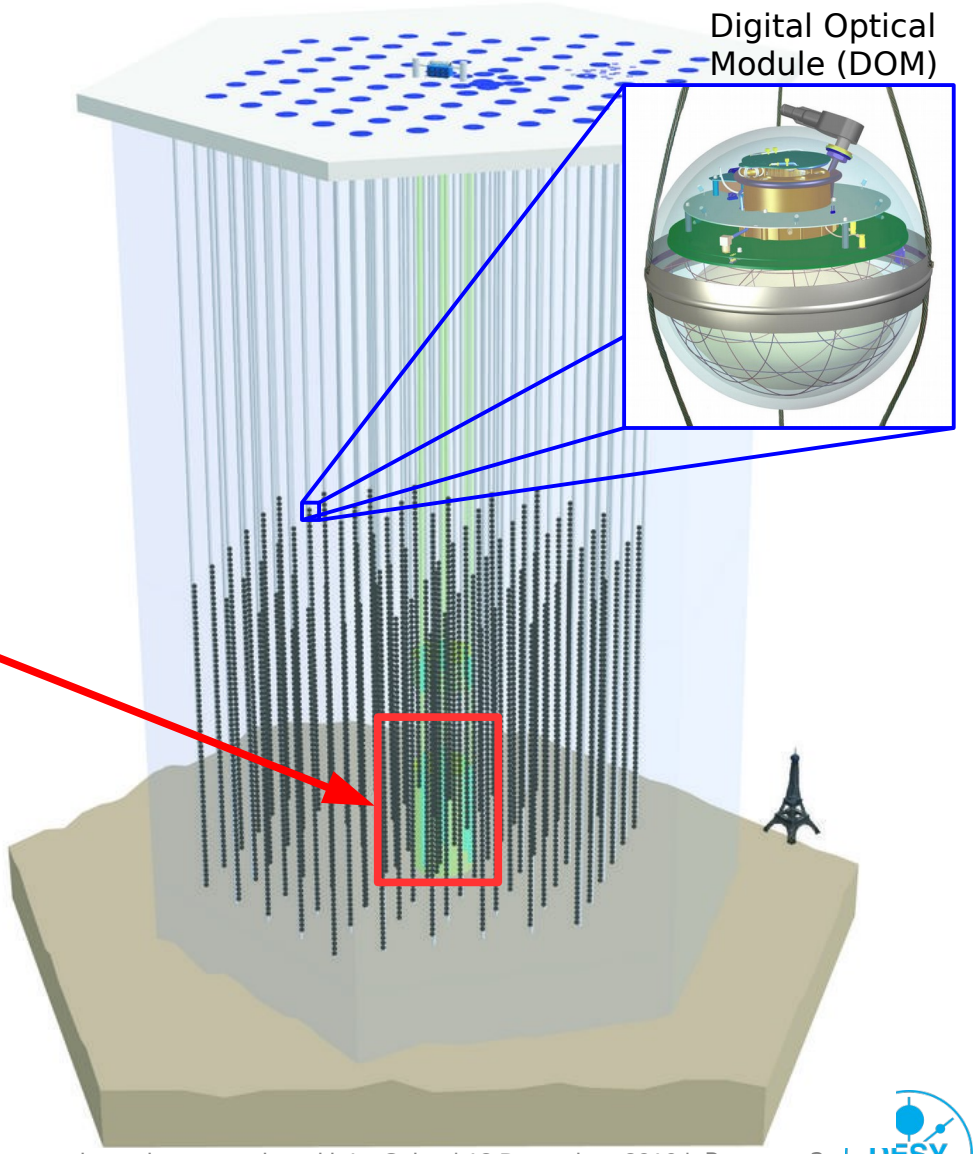
MU Programmtag
Mainz, Germany
December 12, 2016

HELMHOLTZ ASSOCIATION

DESY

IceCube Neutrino Observatory

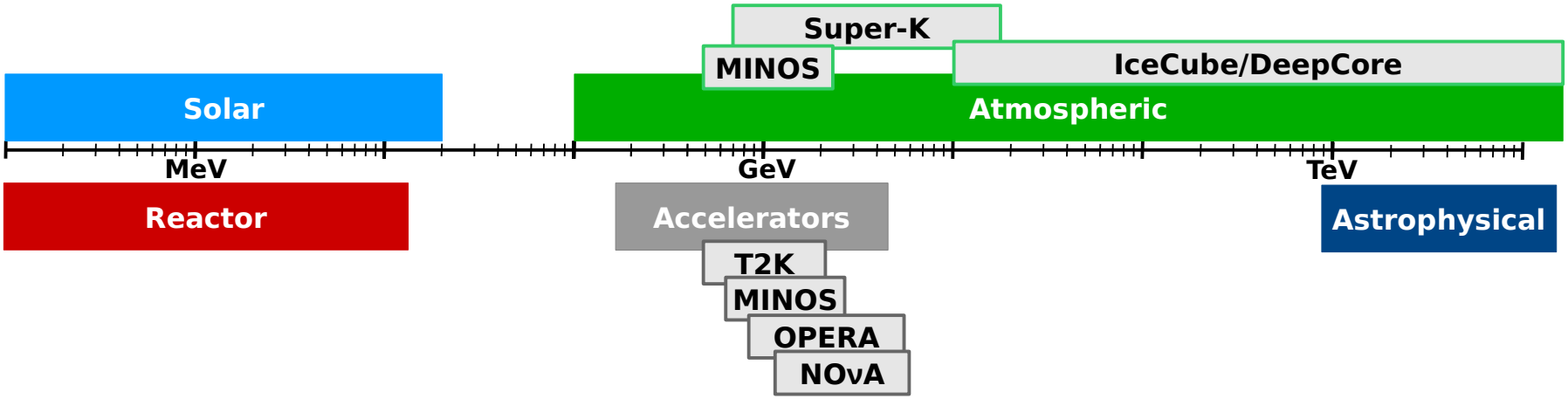
- IceCube detector:
  - 1 km^3 ice Cherenkov detector
  - Depth: 1450-2450 m
  - 17 m vertical and 125 m horizontal spacing
  - Energy threshold ~100 GeV
- DeepCore:
  - Denser instrumentation:
    - 7 m vertical and 40-60 m horizontal spacing
  - Energy threshold ~10 GeV
  - Deep inside IceCube:
    - Depth: 2100-2450 m
    - Best ice optical properties
    - Veto against atmospheric muons



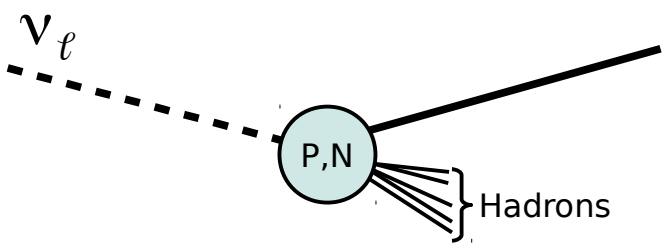
IceCube and the World

- IceCube physics:
  - neutrino astrophysics
  - cosmic ray physics
  - **neutrino oscillations**
  - new physics
  - and more

- This talk:
  - Measurement of neutrino mixing parameters
  - Search for sterile neutrinos



IceCube: how it works



ℓ – charged current (CC) interaction

ν_ℓ – neutral current (NC) interaction

> Secondary particles:

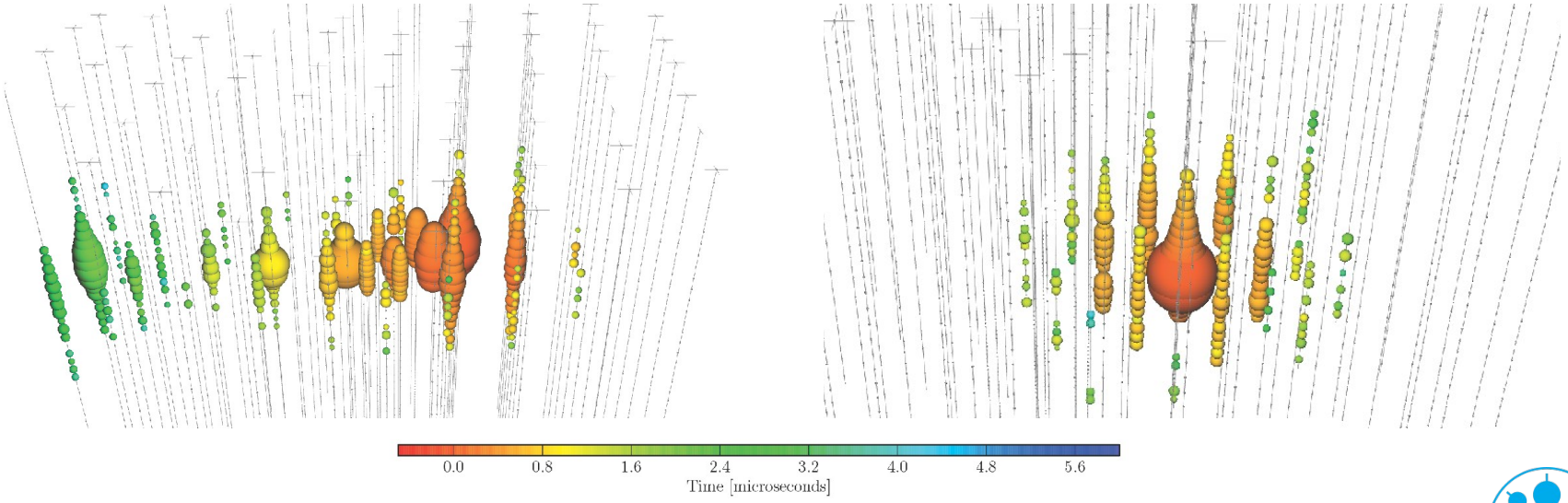
- relativistic
- Cherenkov light emission

> Track like events:

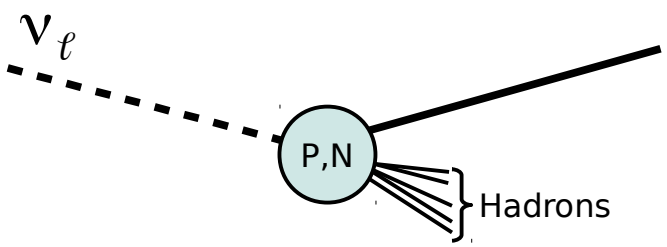
- ν_μ CC interactions

> Cascade like events:

- all NC interaction, CC of ν_e, ν_τ



IceCube: how it works



ℓ – charged current (CC) interaction

ν_ℓ – neutral current (NC) interaction

> Secondary particles:

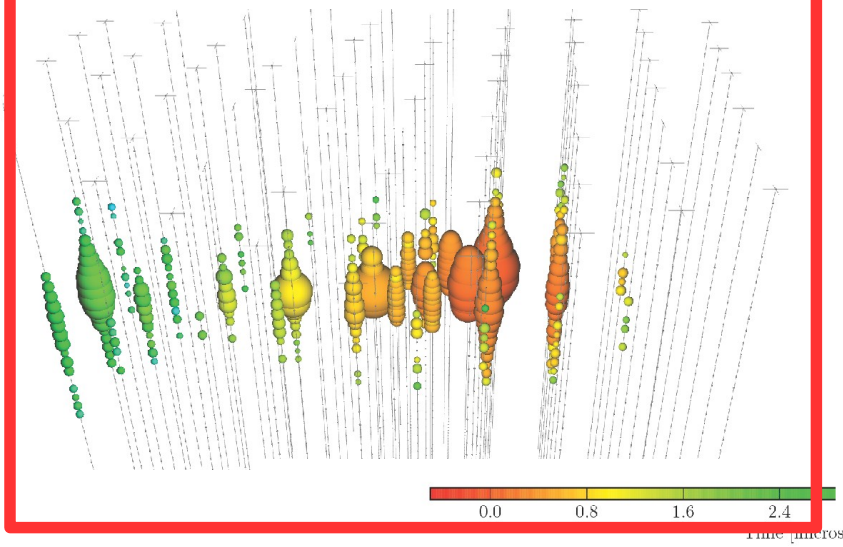
- relativistic
- Cherenkov light emission

Focus of this talk

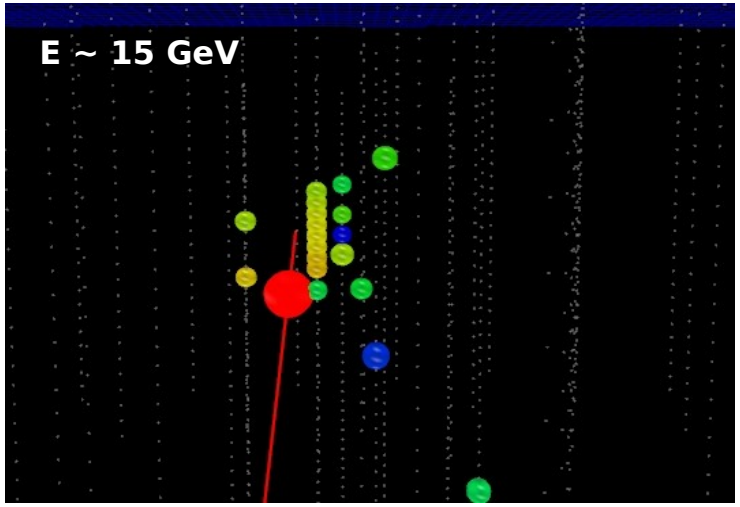
> Track like events:

- ν_μ CC interactions

E ~ 70 TeV

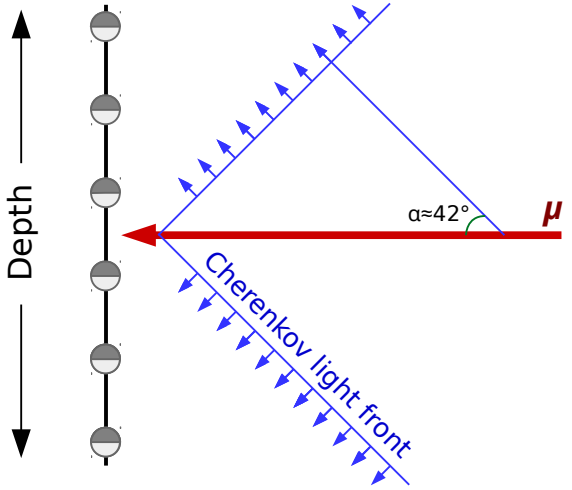


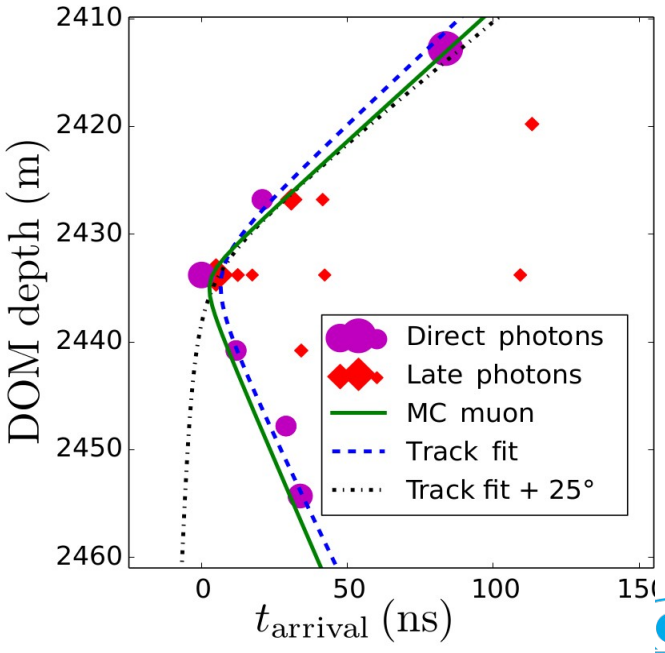
Actual low energy event



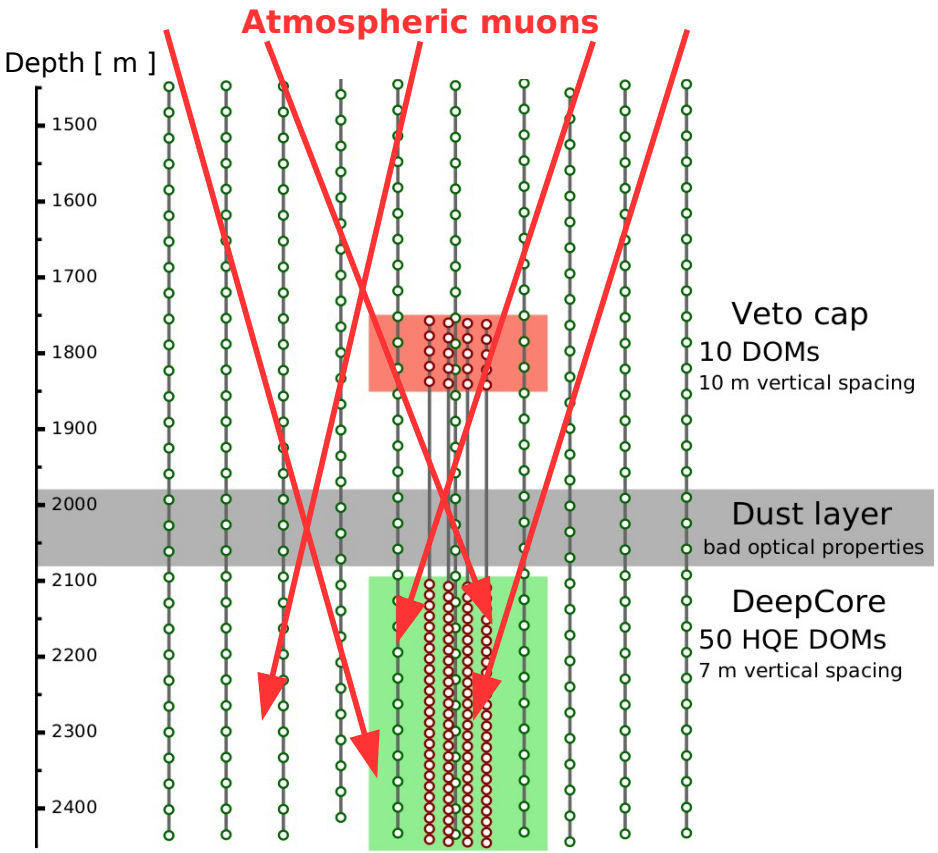
DeepCore: reconstruction challenge

- 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 of muons
  - selects “golden events”
- Typical resolutions:
  - Zenith angle: 5-10° median resolution
  - Energy: ~ 20-25 % median resolution



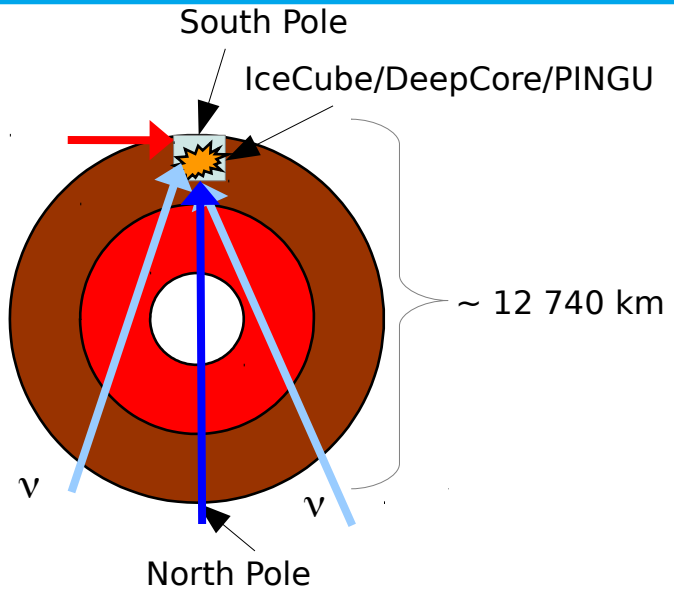


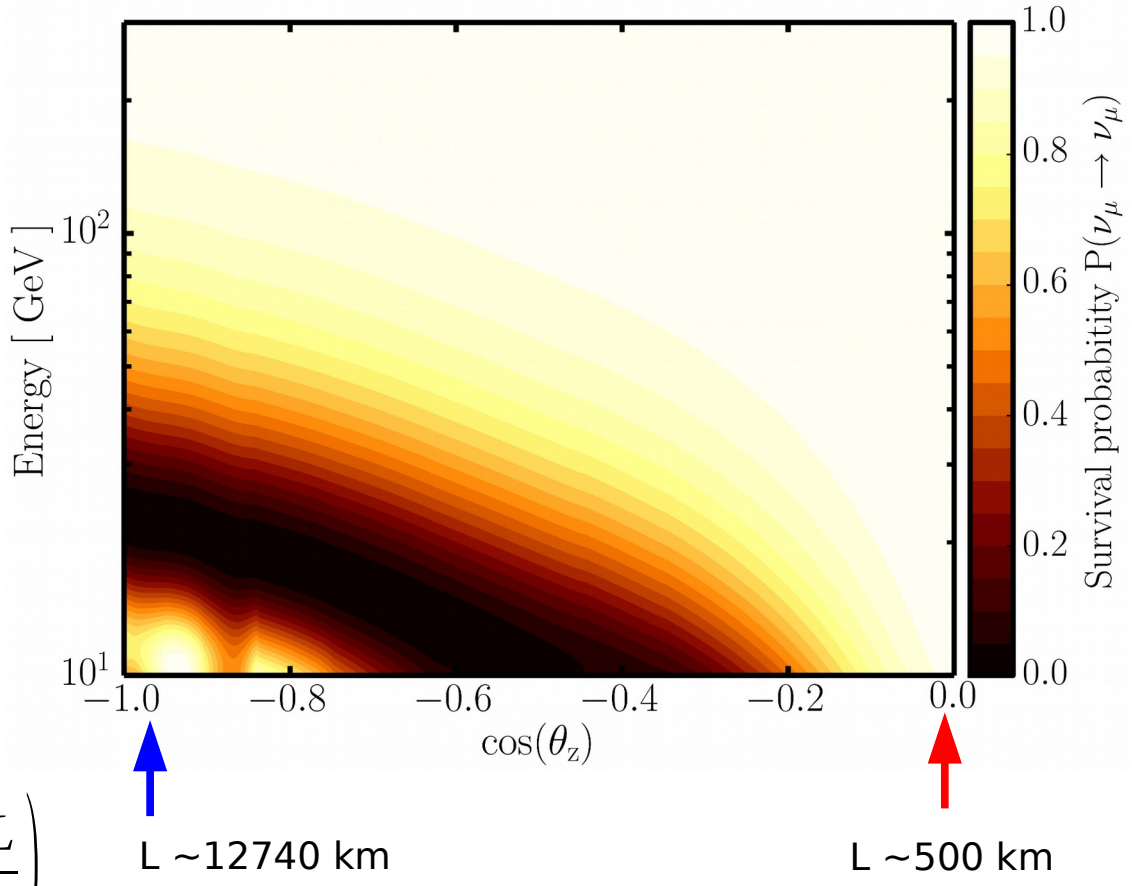
DeepCore: background challenges



- 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

Neutrino oscillations: introduction





> Leading term for IceCube:

Position of the minimum

$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

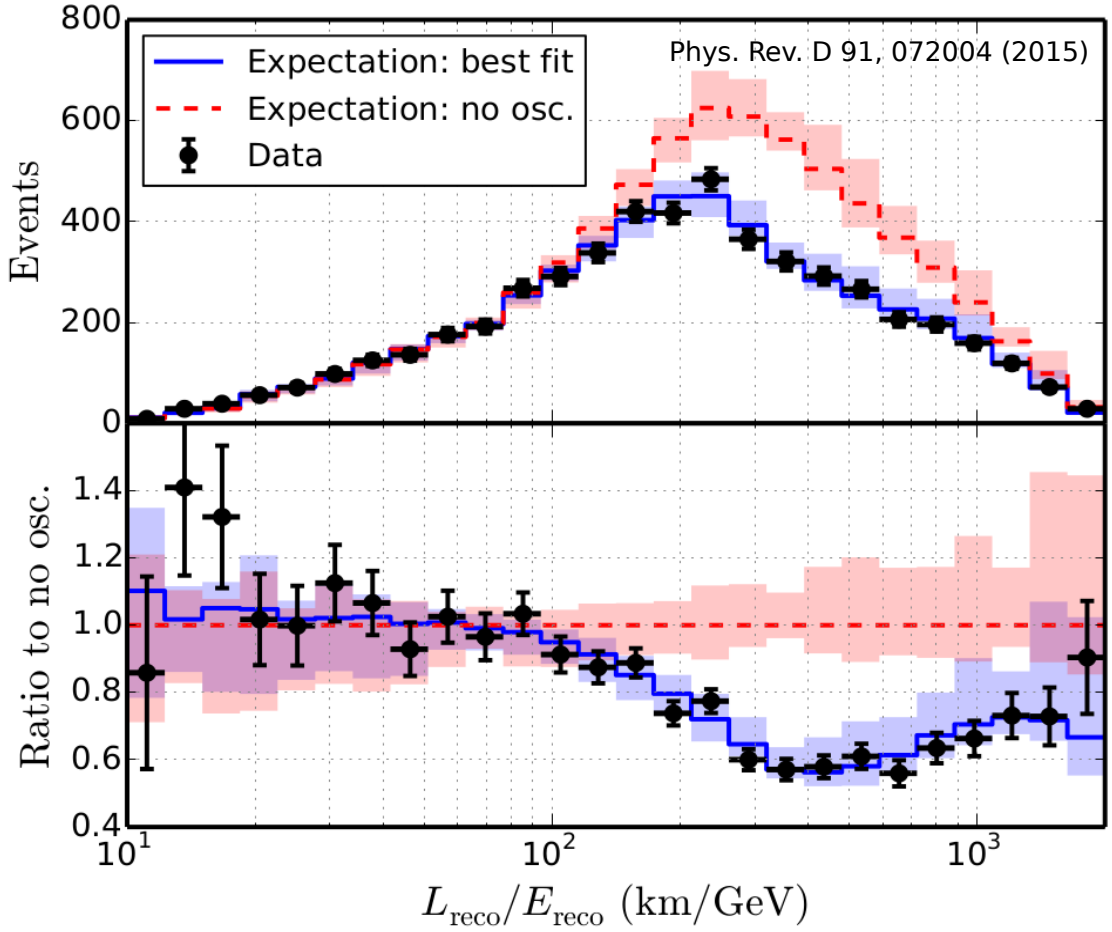
Depth of the minimum

> Length to production point:

- Defined by arrival direction

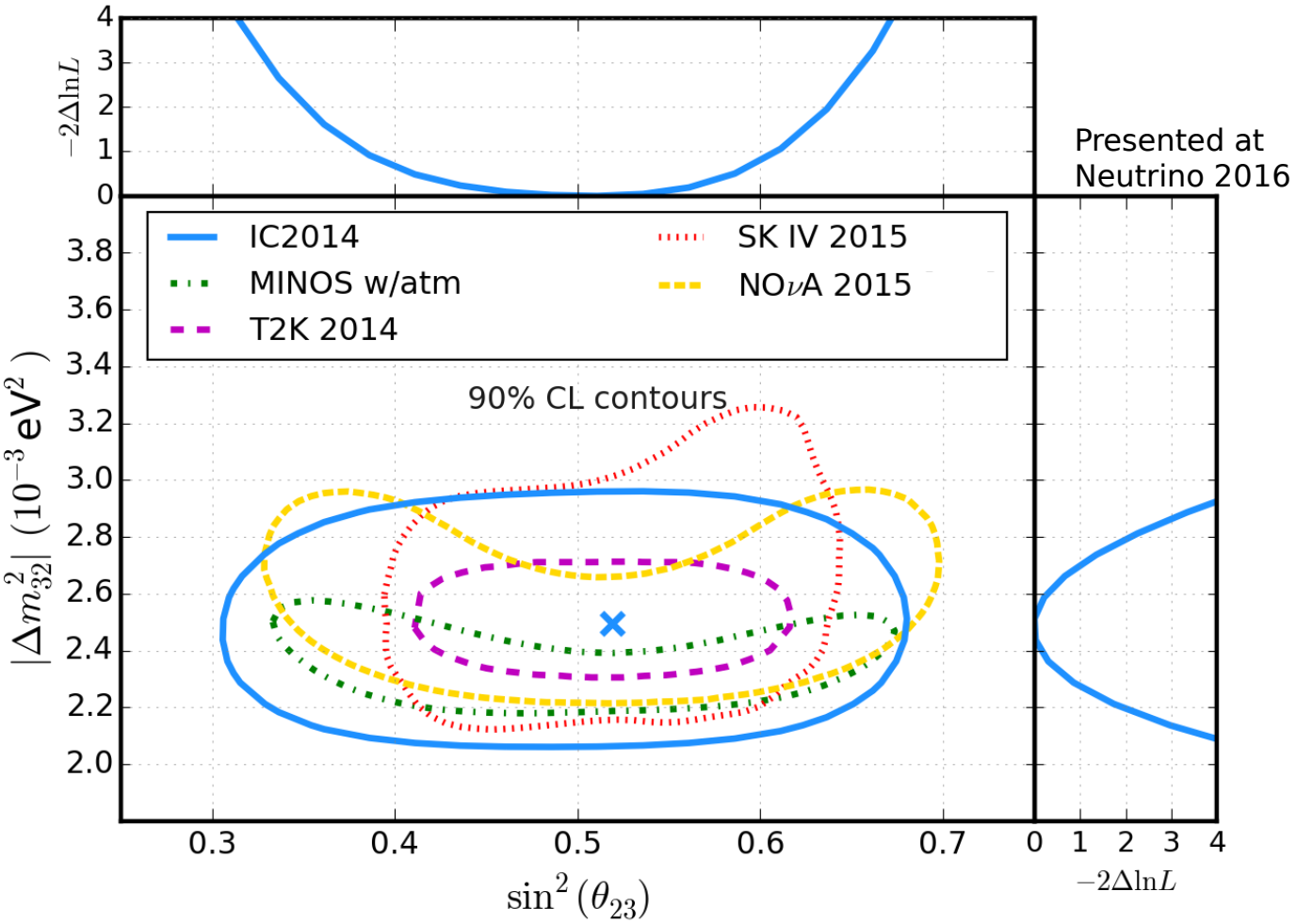
> Transition to tau neutrinos

Neutrino oscillations: L/E distribution



- Energy range: 6-56 GeV
- Good data/MC agreement
- Clear signature of muon neutrino disappearance

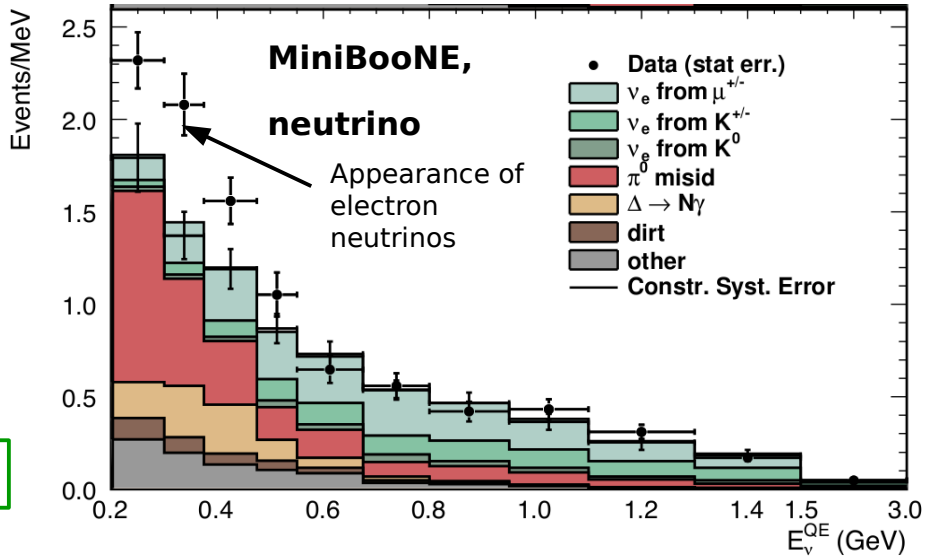
Neutrino oscillations: results



- IceCube DeepCore among leading neutrino oscillation experiments
- 3 years of data used

Neutrino oscillations: sterile neutrino intro

- Sterile neutrinos:
  - An additional neutrino family
  - Explain the tension between some oscillations experiments
  - No standard weak interaction (n_ν =3 from Z decay width)



- Sterile mixing:

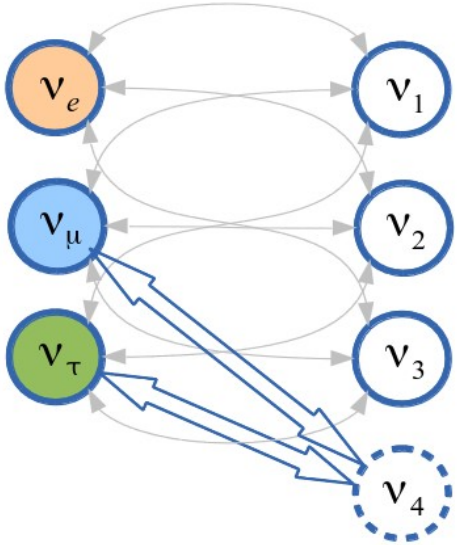
Standard PMNS matrix

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

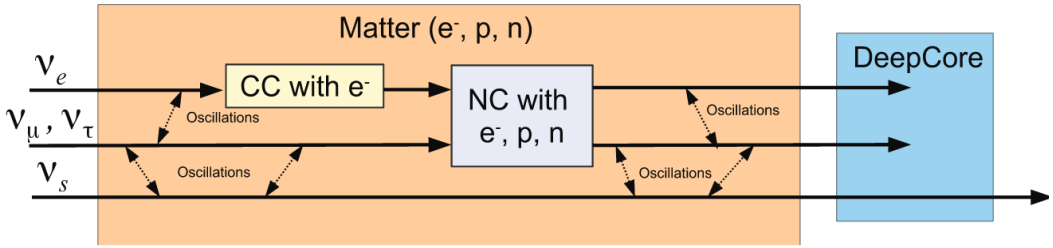
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$

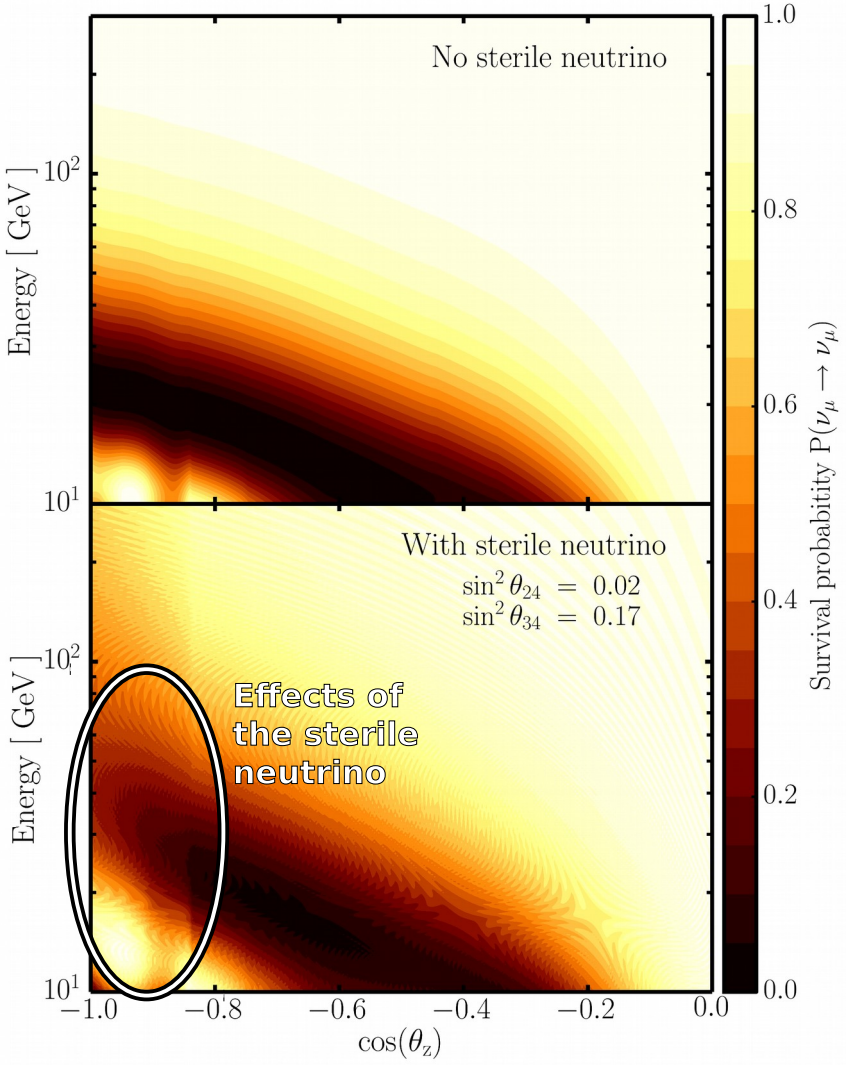
$$|U_{\tau 4}|^2 = \sin^2\theta_{34}\cdot\cos^2\theta_{24}$$

- Changes muon neutrino oscillations



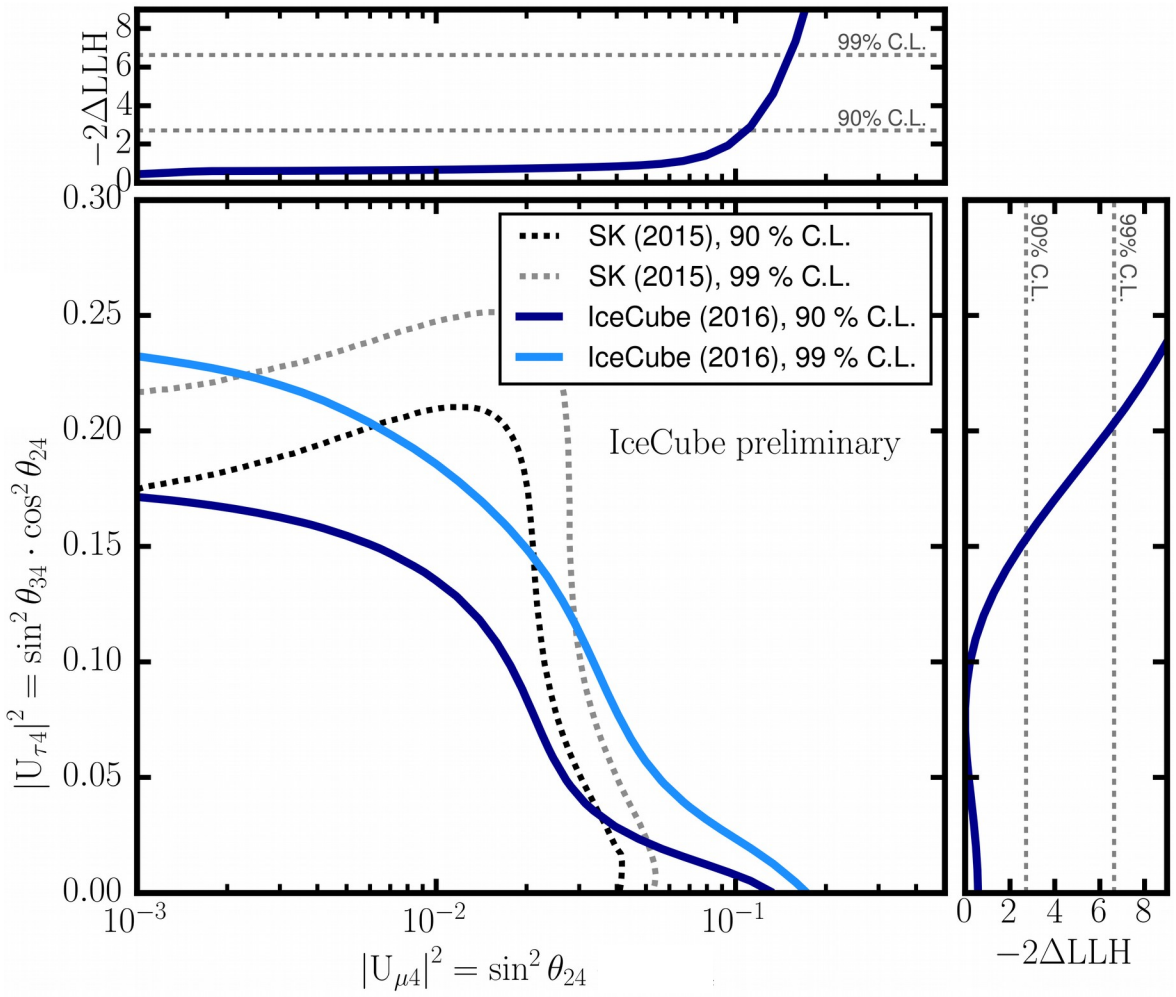
Sterile neutrinos at low energies





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

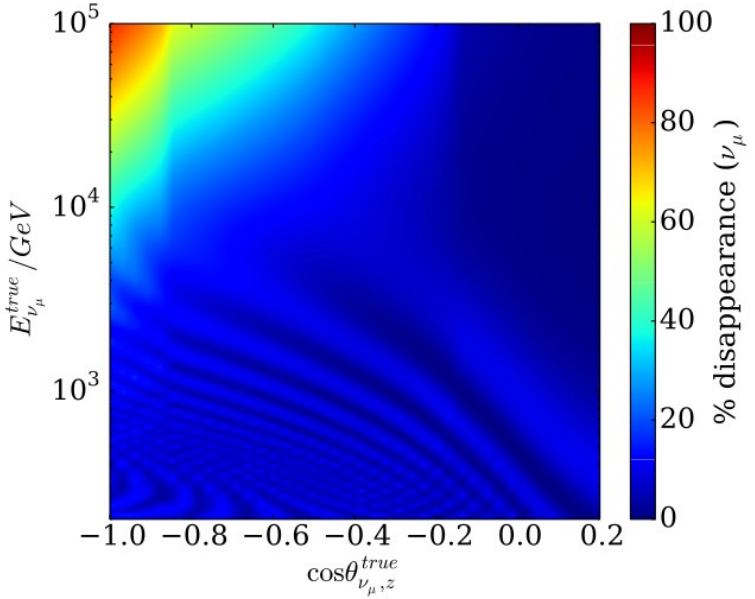
Sterile neutrinos at low energies: results

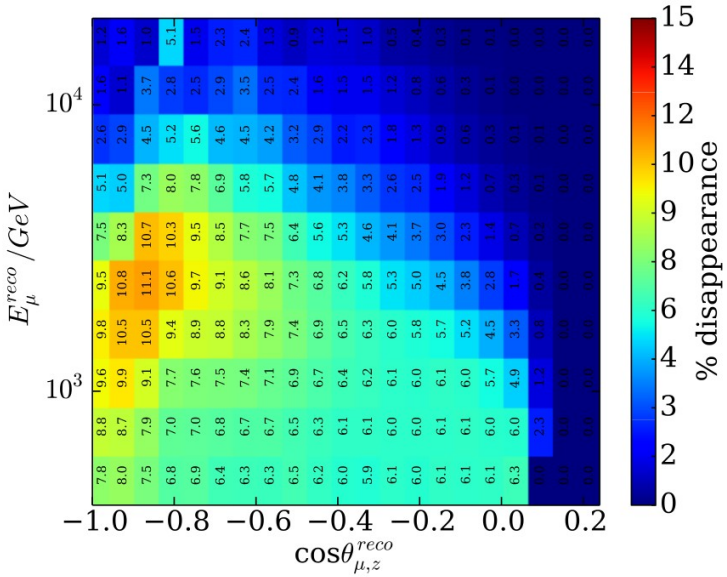


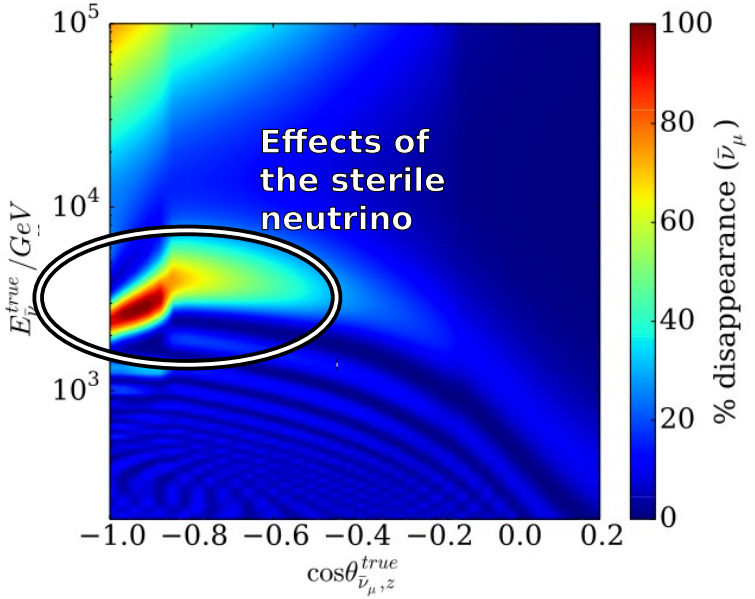
- Strong exclusions of $|U_{\tau 4}|^2$
- Publication in preparation

Sterile neutrinos at high energies

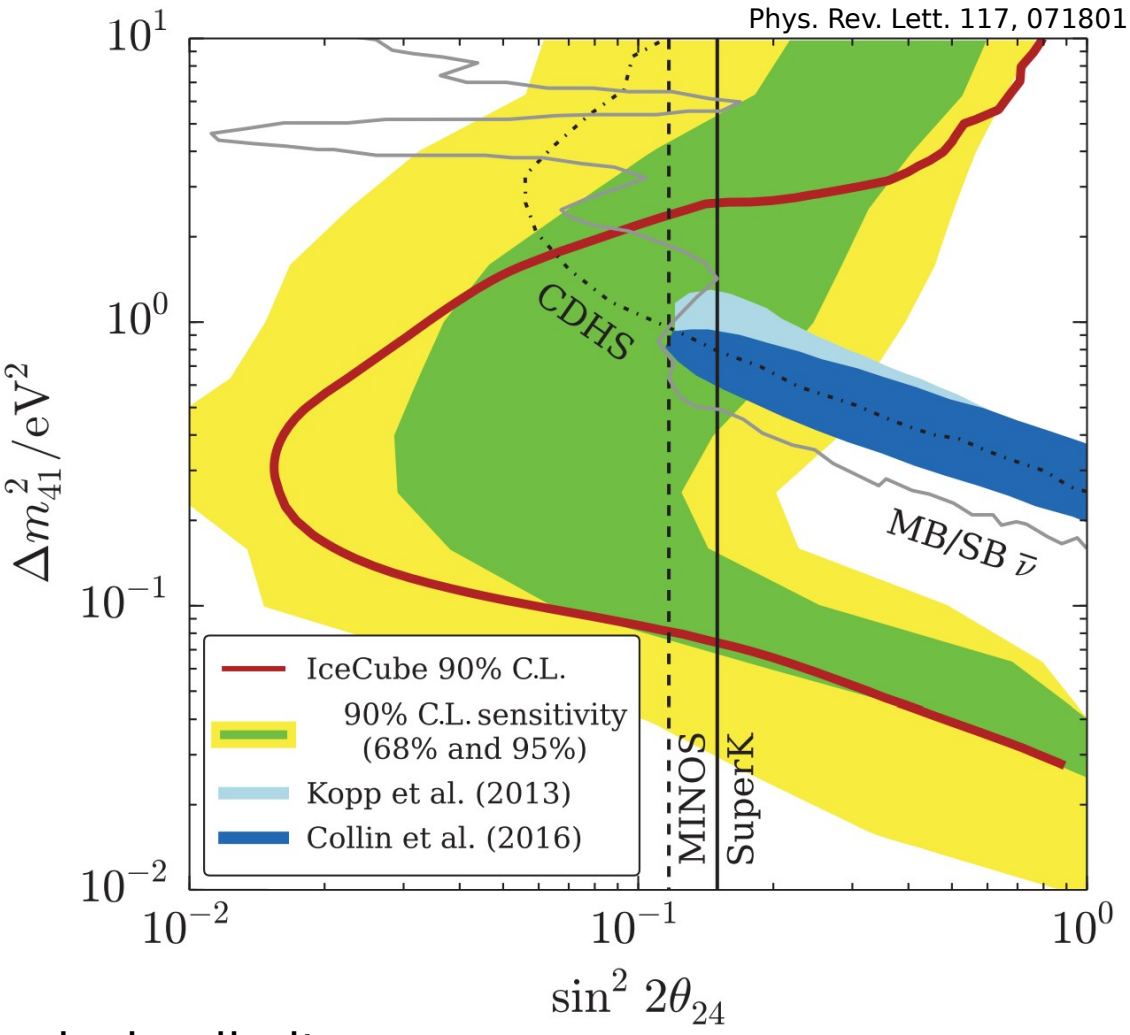
- Effects above 100 GeV:
  - MSW resonance-like transition to sterile state
  - Muon-anti neutrinos
  - Energy of resonance $\sim \Delta m^2_{41}$
  - Sensitive to angle θ_{24}







Sterile neutrinos at high energies: results

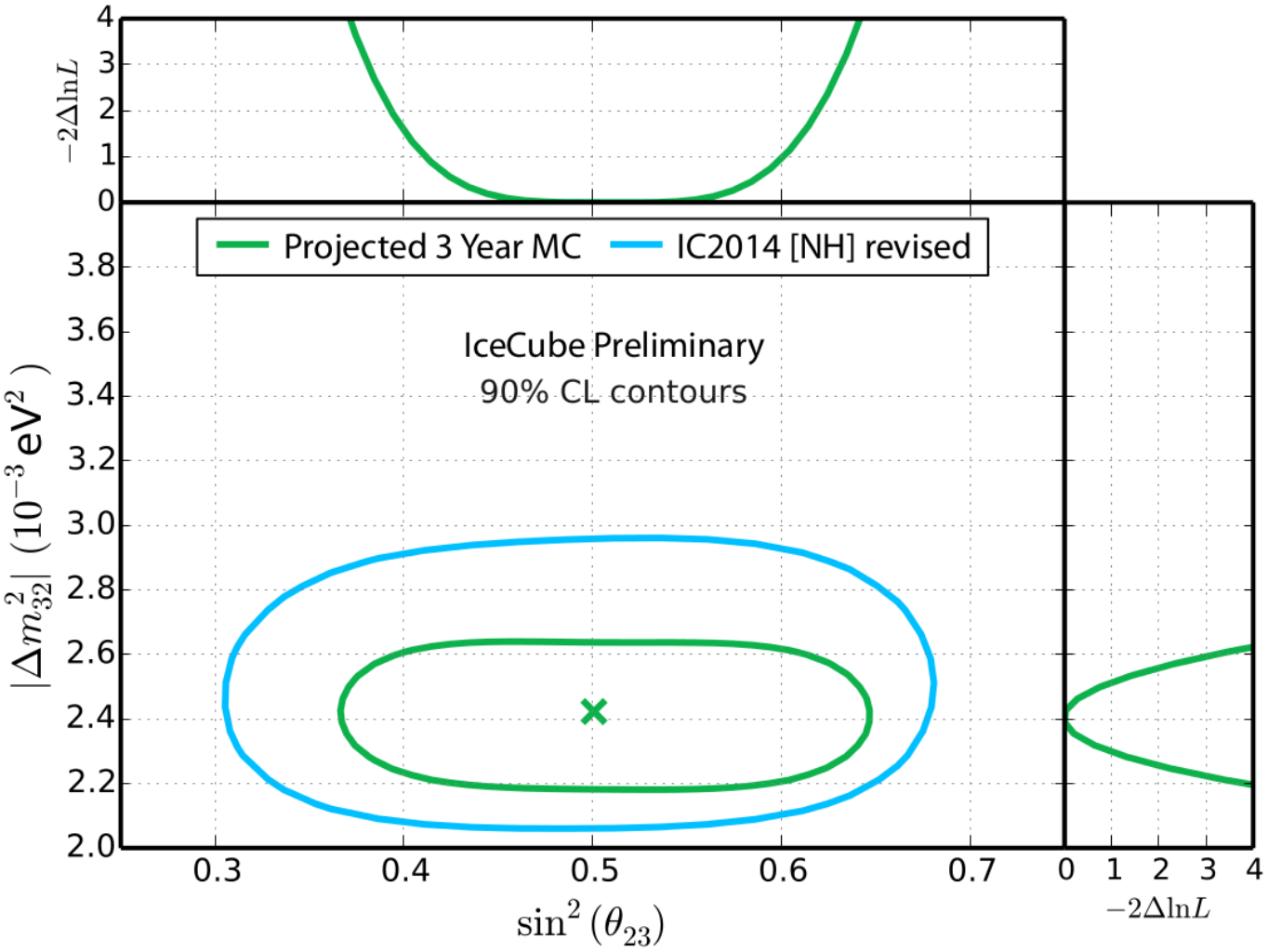


- Strong exclusion limits
- Only 1 year of data used

Neutrino oscillations: future development

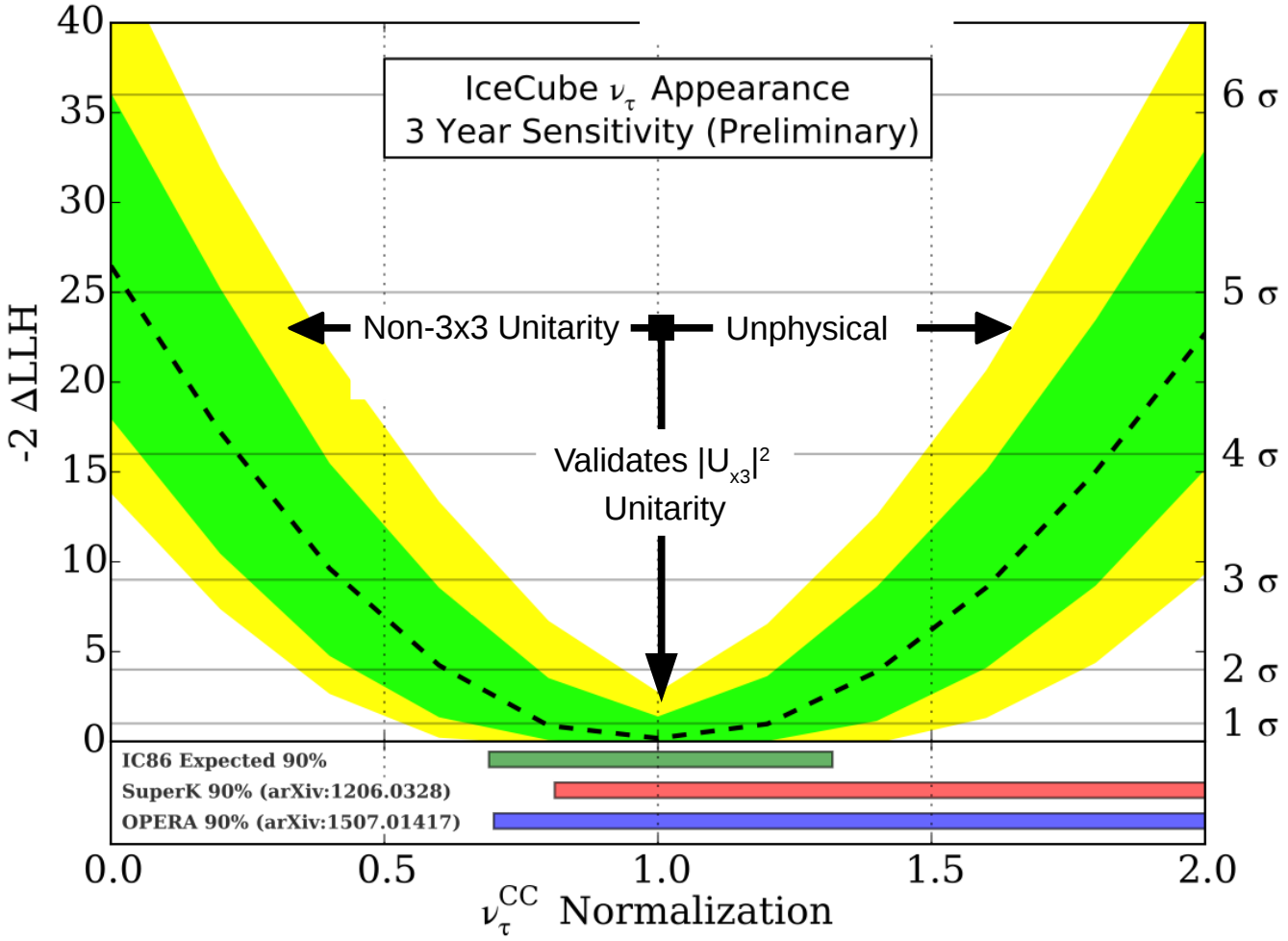
- Only “golden events” used in current studies
- Next: use non-”golden” events:
  - Increase of statistics
  - Addition of “cascade” channel
- Complications:
  - time-consuming reconstruction
  - worse directional resolution for cascades
  - using scattered photons → systematic uncertainties
  - larger background (atmospheric muons, detector noise)
- Increased sensitivity to
  - Appearance of tau neutrinos
  - Mixing parameters $\sin^2 \theta_{23}$, Δm^2_{32}
  - Sterile neutrinos

Neutrino oscillations: projection numu disappearance



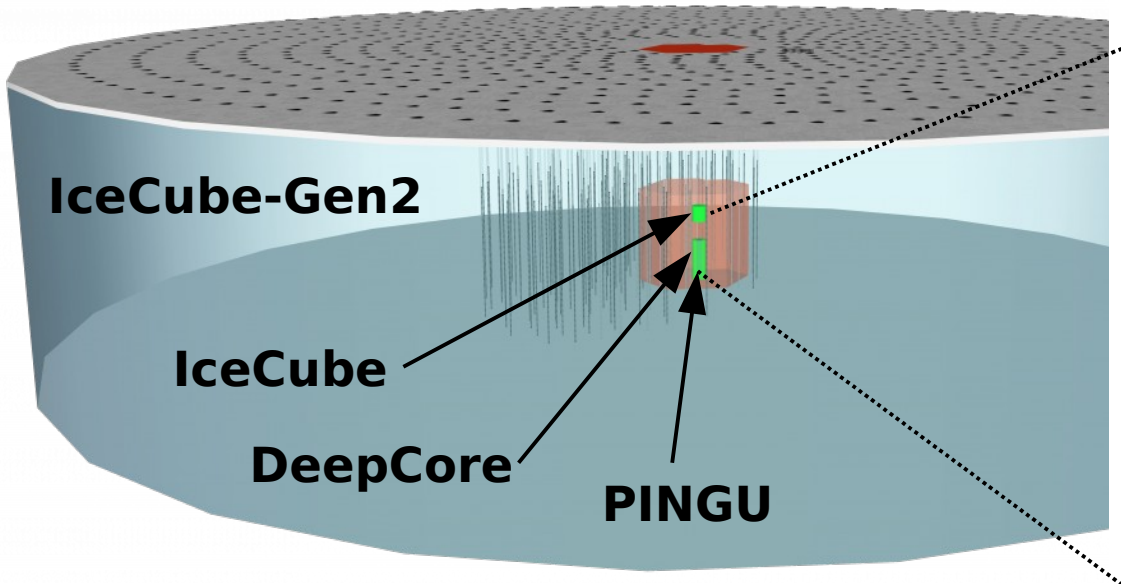
> Significant improvement in sensitivity

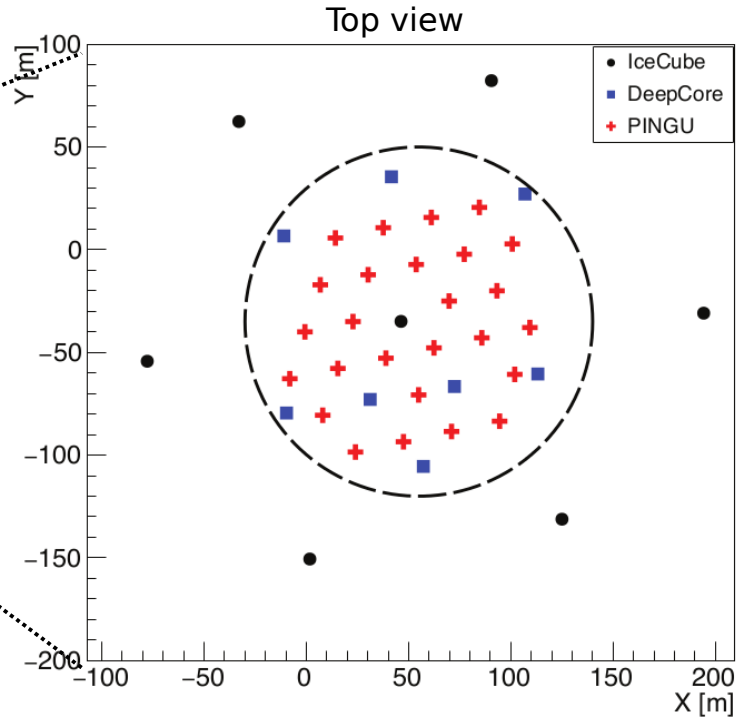
Neutrino oscillations: appearance of tau neutrinos



> A powerful probe of new physics

The **P**recision **I**ceCube **N**ext **G**eneration **U**pgrade (PINGU)





IceCube-Gen2: arXiv:1412.5106 **[astro-ph.HE]**
PINGU: arXiv:1607.02671 **[hep-ex]**

> PINGU physics program

- Neutrino mass ordering
- Precise measurement of neutrino oscillations
- Precise ν_τ physics
- New physics

> Even denser instrumentation:

- 26 strings
- 20 m lateral distance
- ~2 m DOM-DOM distance

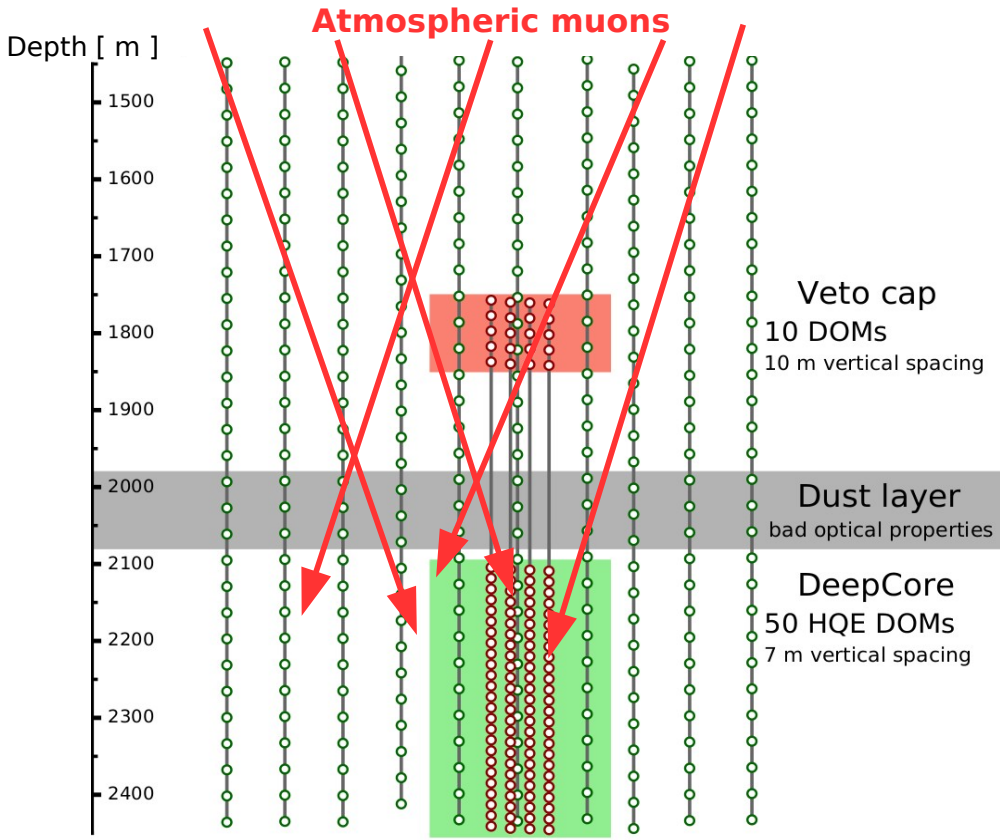
> Energy threshold: few GeV

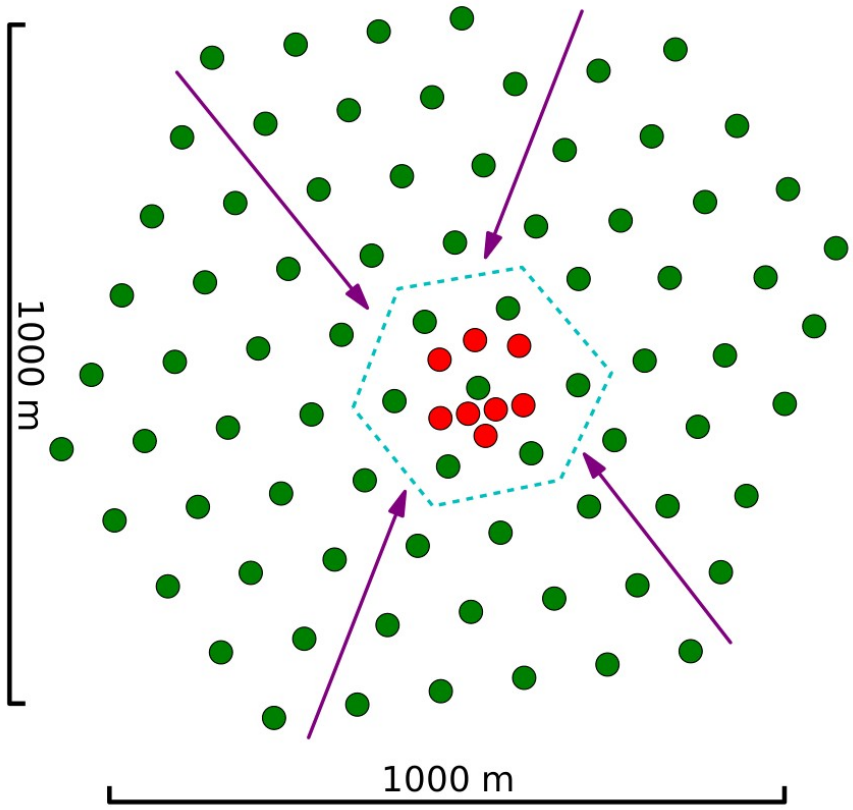
Conclusions

- Fundamental properties with IceCube Neutrino Observatory:
  - Atmospheric neutrino oscillations
  - Sterile neutrinos:
    - Strong limits on mixing to muon state
    - One of the leading experiments in the field
  - And more (not presented in this talk):
    - Cross section studies
    - Non standard interaction
    - Dark Matter/WIMPs
- Next in IceCube:
  - New analysis techniques
  - More years of data
  - Precise measurement of mixing parameters
  - Sensitivity to tau neutrino sector
- Future:
  - IceCube-Gen2/PINGU:
    - Neutrino mass ordering
    - Precise nutau appearance
    - Sterile neutrinos
    - Dark Matter
    - ...

Backup slides

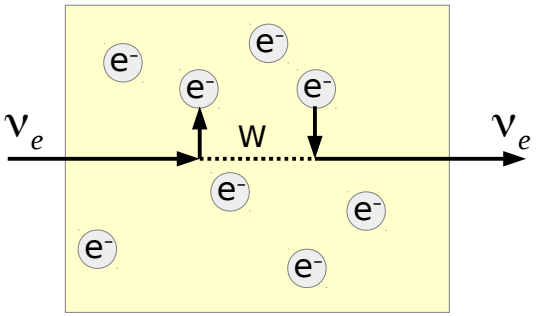
DeepCore: background challenges



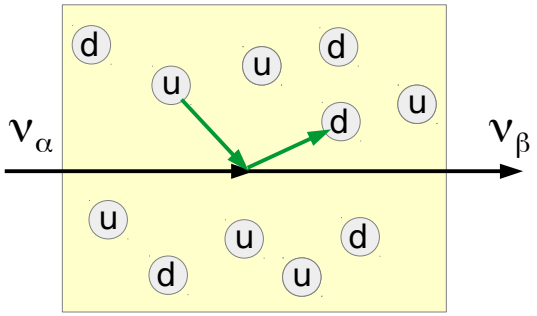


Neutrino oscillations: non standard interactions

Standard interactions



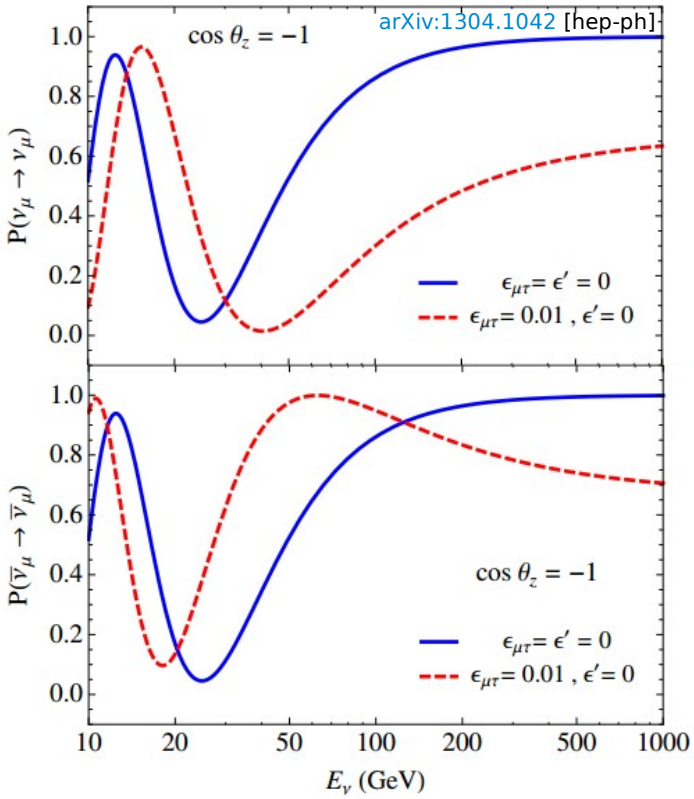
Non-standard interactions



> Evolution of flavors

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

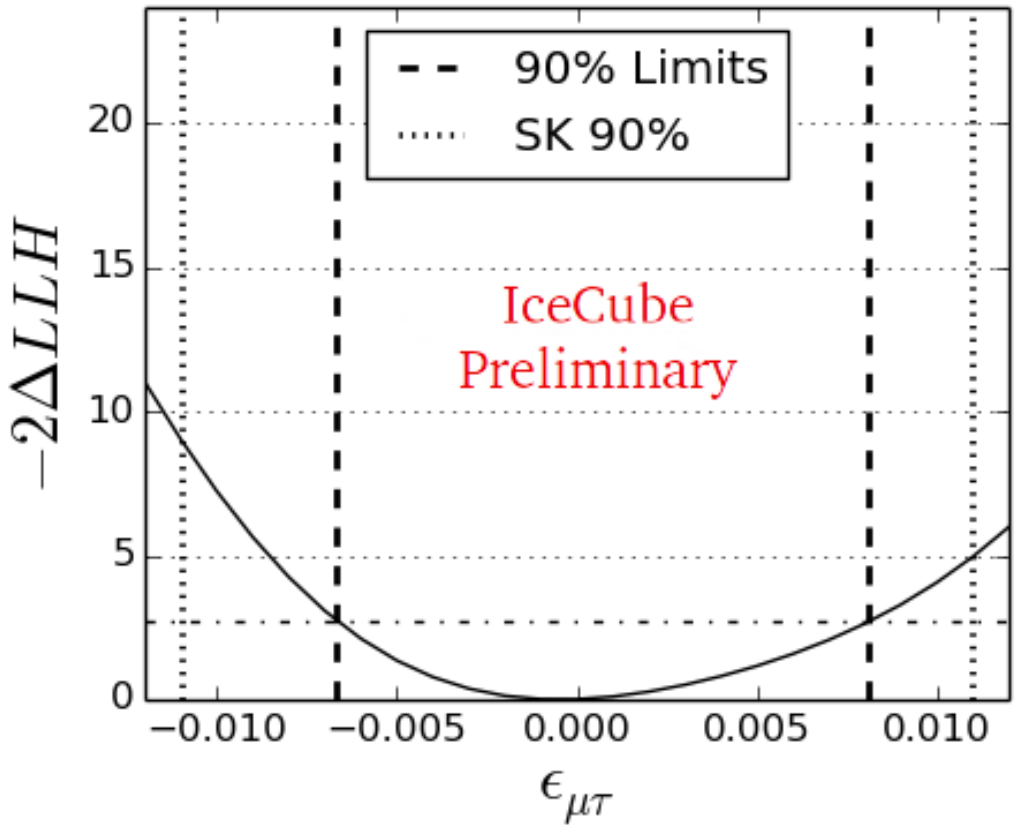
NSI coefficients



> Modifications of the oscillations pattern

> Possible to measure/constrain with IceCube

Neutrino oscillations: non standard interactions



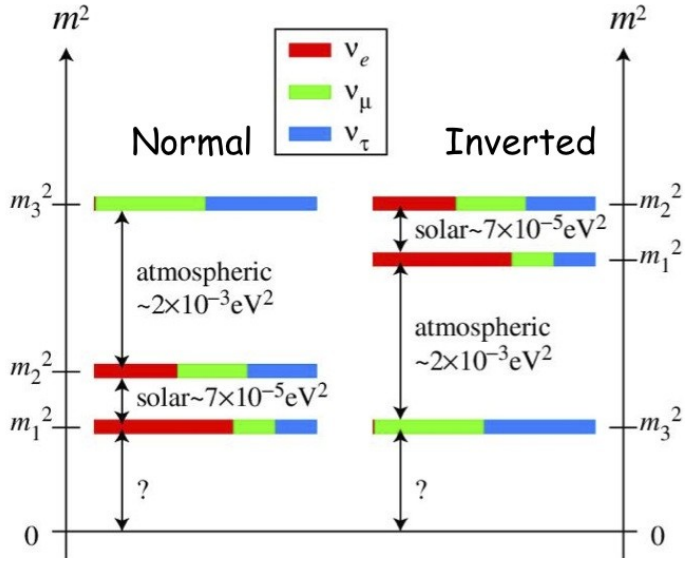
- Expectation compatible with standard physics
- Strong exclusion limits
- Publication in preparation

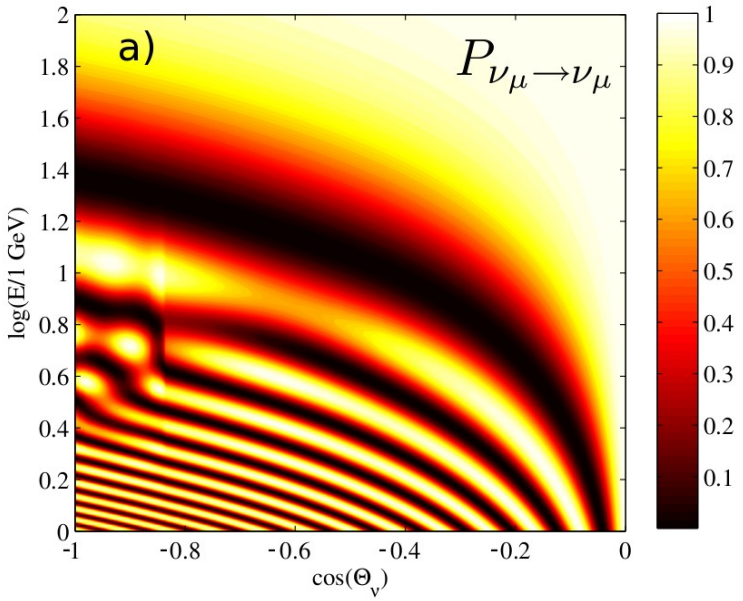
Future:

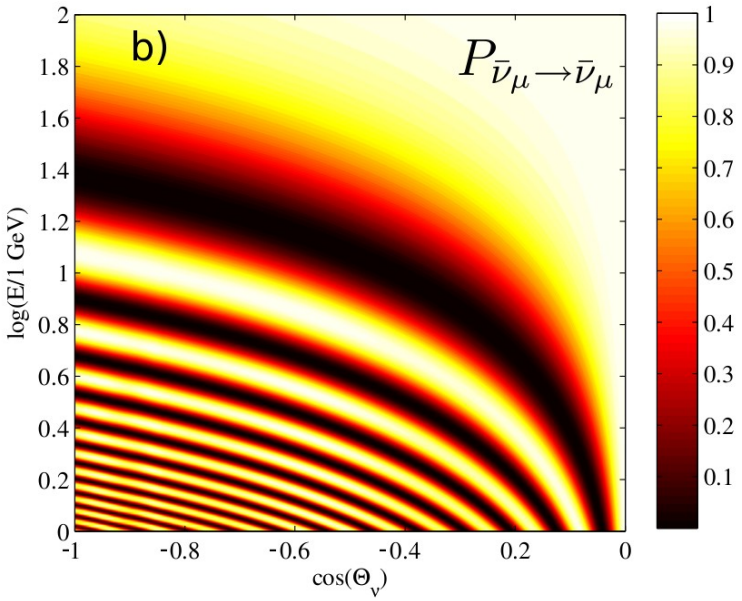
developing DeepCore
PINGU/IceCube-Gen2

PINGU: measuring NMO

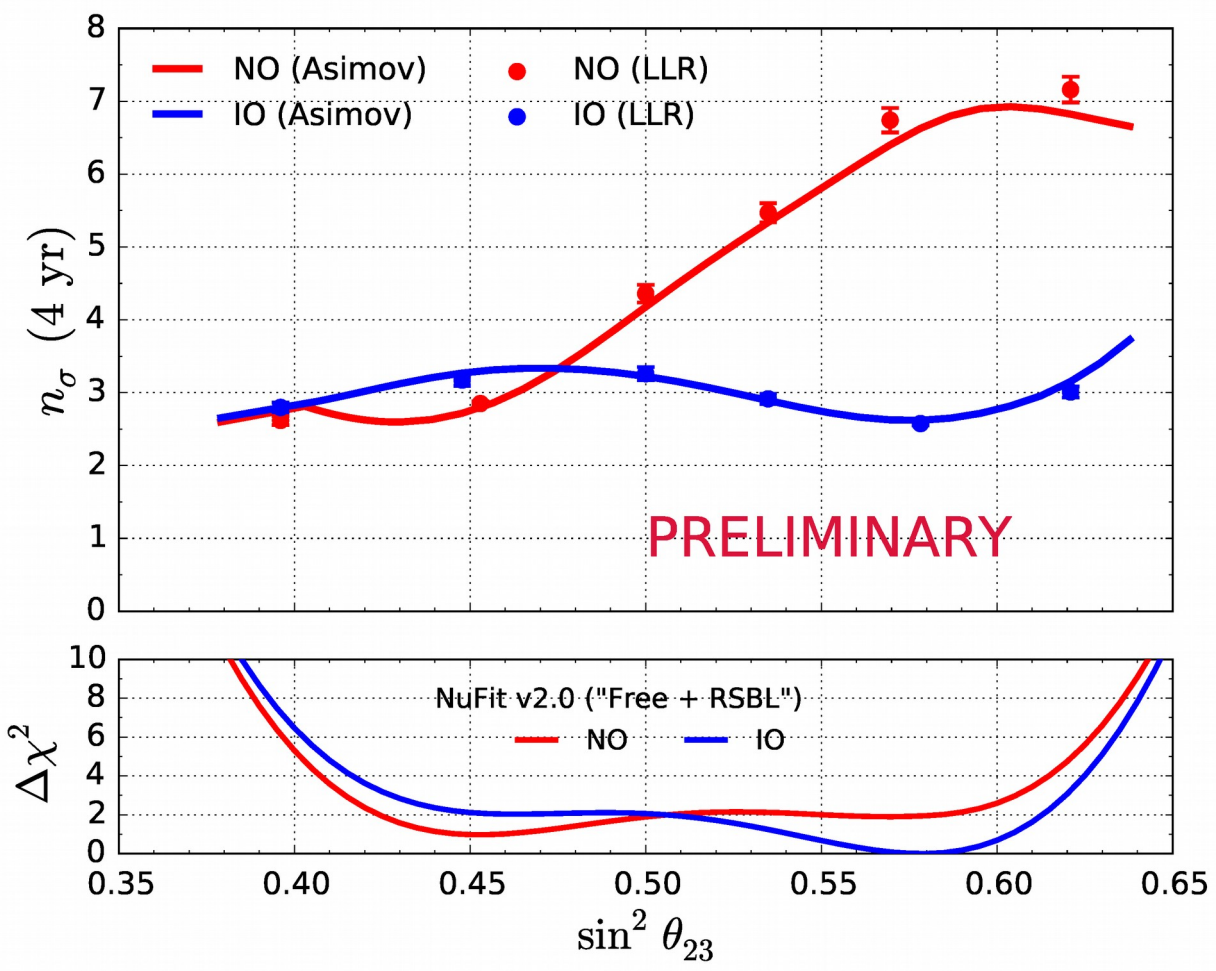
- Ordering of states 3 and 1(2) unknown
- Resonance:
  - For neutrinos for NO
  - For anti-neutrinos for IO
- Difference in fluxed/cross sections





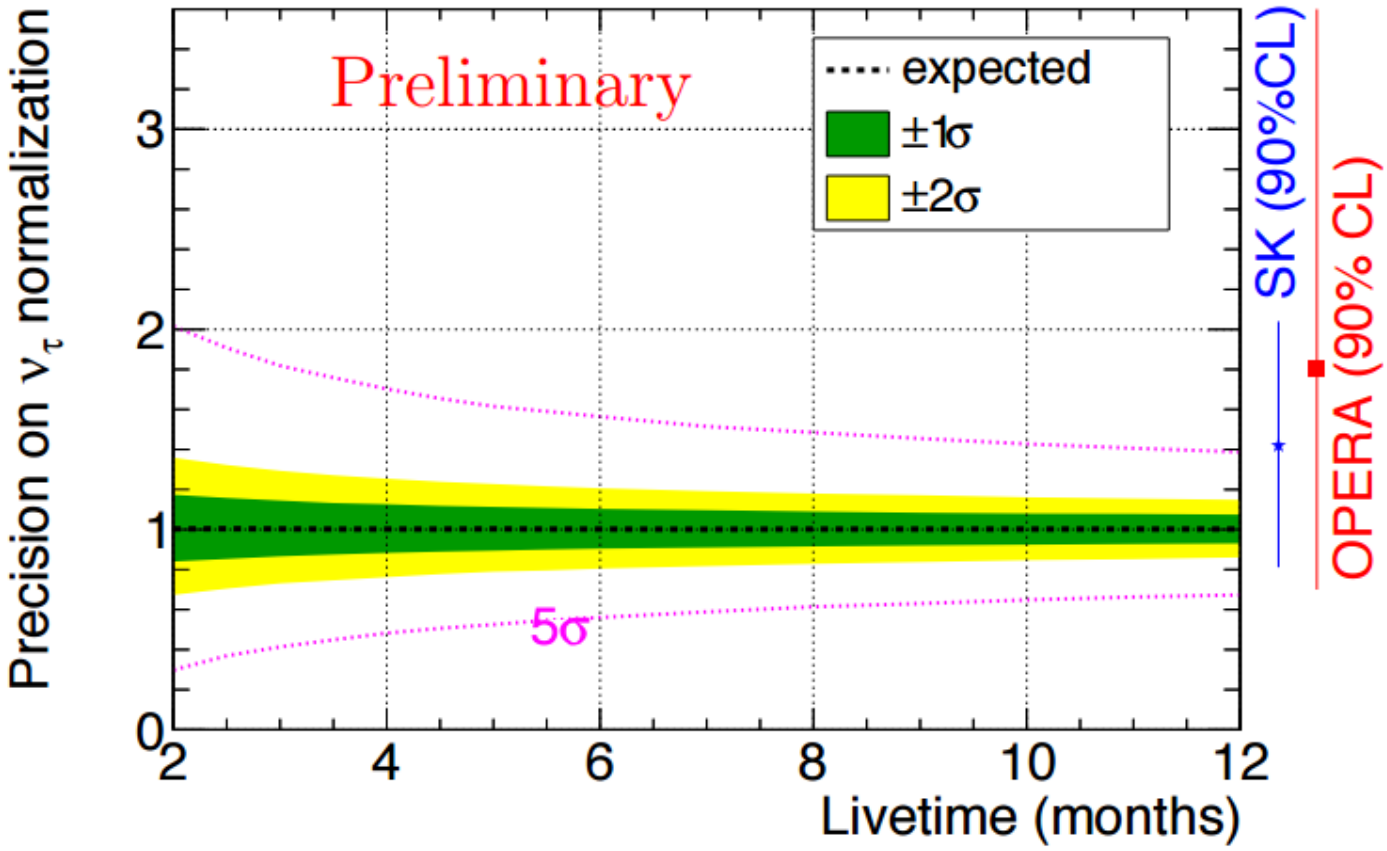


PINGU sensitivity to NMO



> NMO with ~3σ in 4 years of data taking

PINGU sensitivity to NMO



> Precise measurement of ν_τ normalization