Sterile neutrino searches with IceCube

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CrossTalk Workshop | Brussels | Jan 18th 2017

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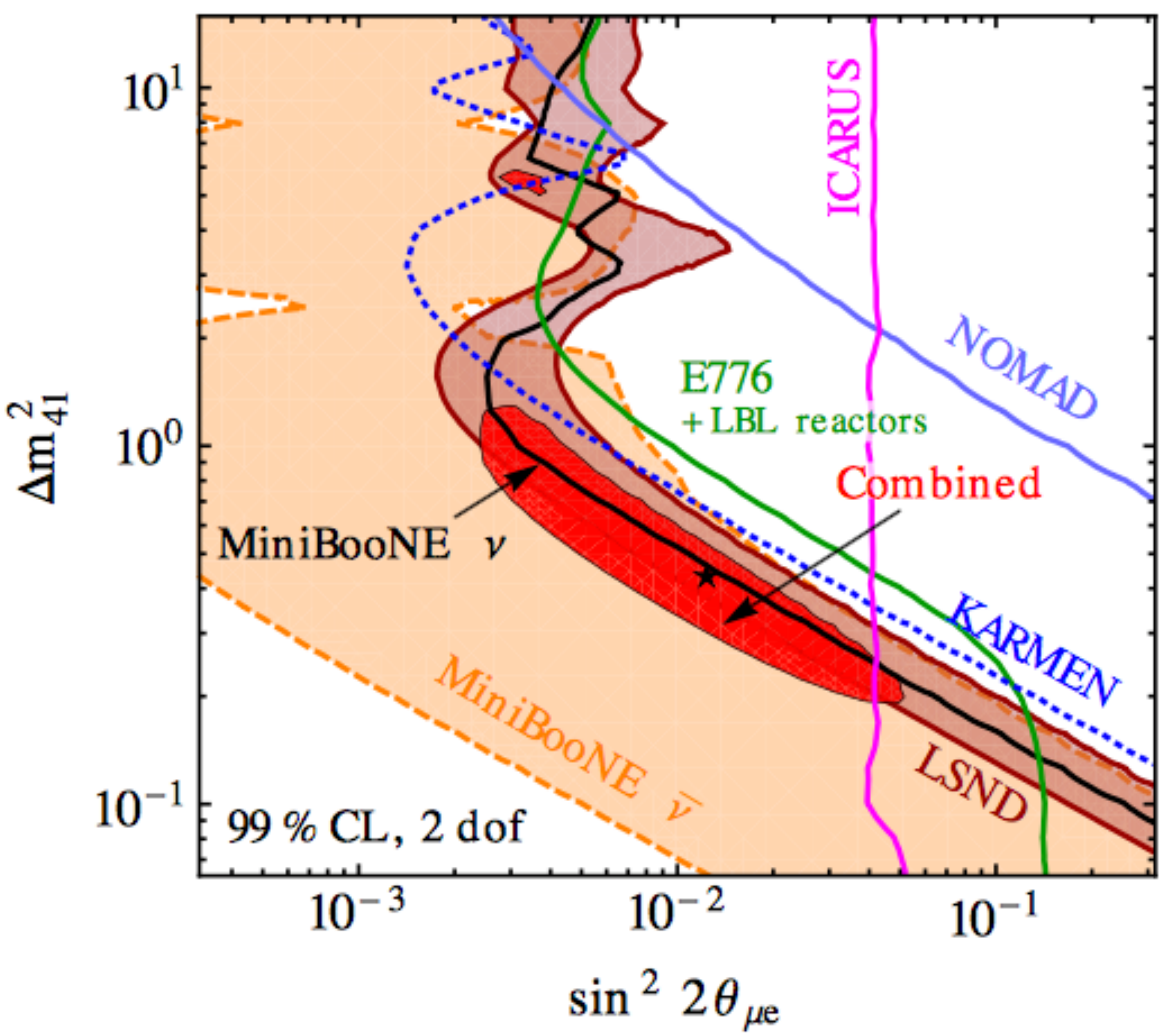
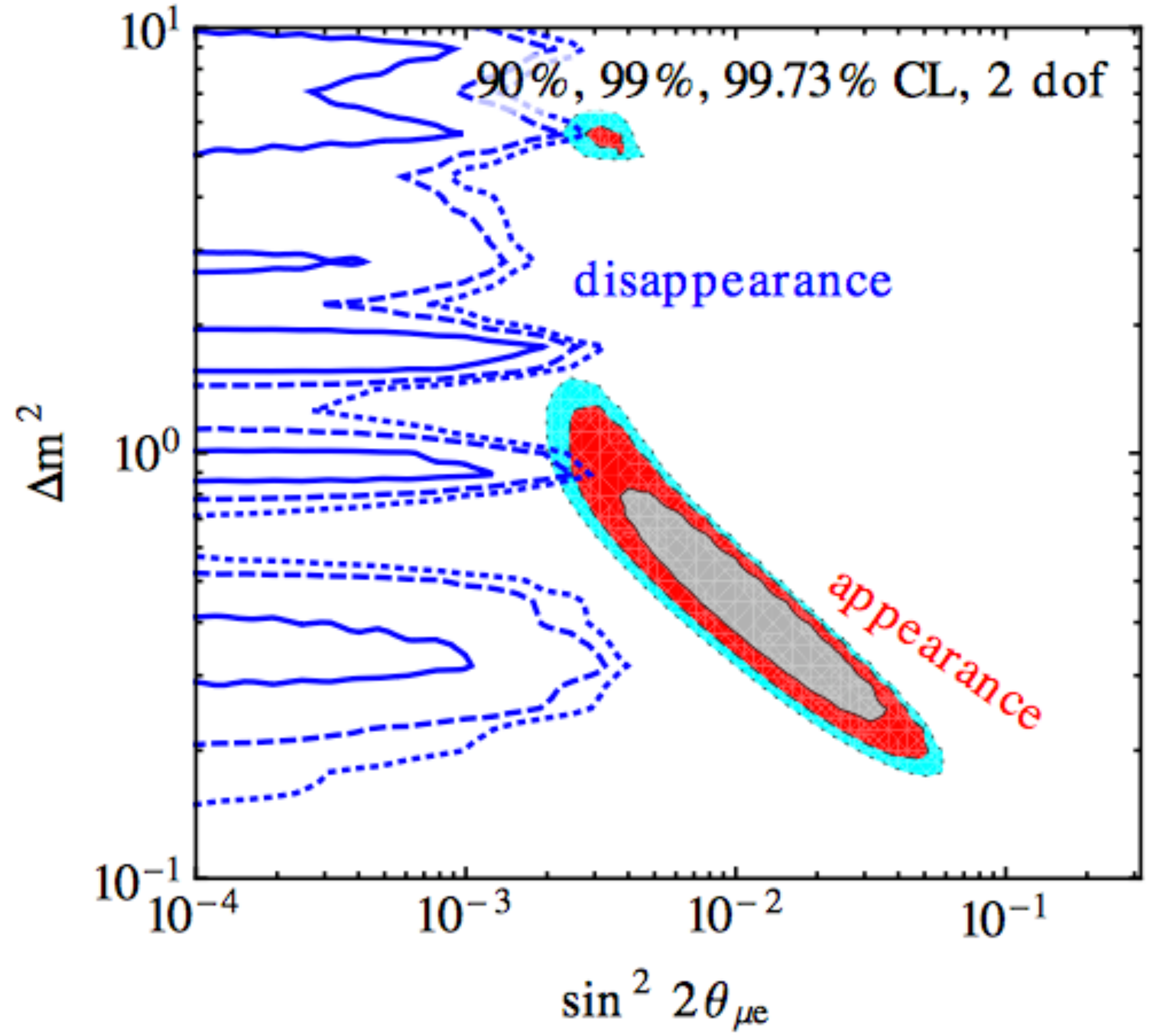
World Data, pre-IceCube

[Kopp et al. JHEP 1305 (2013) 050]

Appearance only



Appearance and disappearance



Potential sterile neutrino candidate

- $\Delta m^2_{41} \sim 1 eV^2$
- $\sin^2(2\theta_{\mu e})$ ~ $3 \cdot 10^{-3}$ ← small effect → needs large neutrino sample !??

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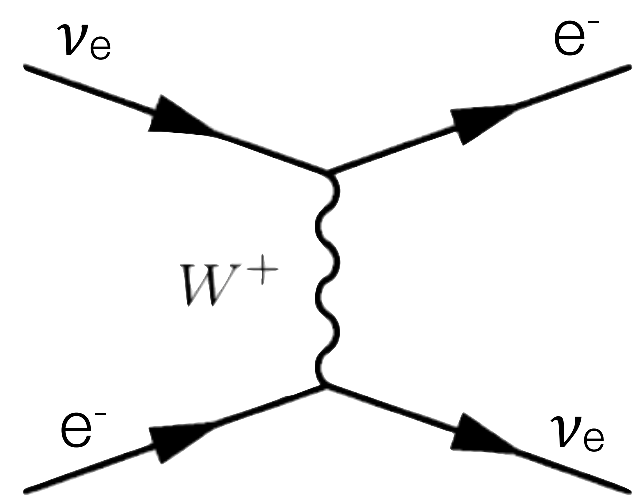
The MSW resonance

Electron neutrinos

- additional interaction with electrons
- effective mass and mixing (2-flavour approximation)
  - depend on electron density N_e



$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

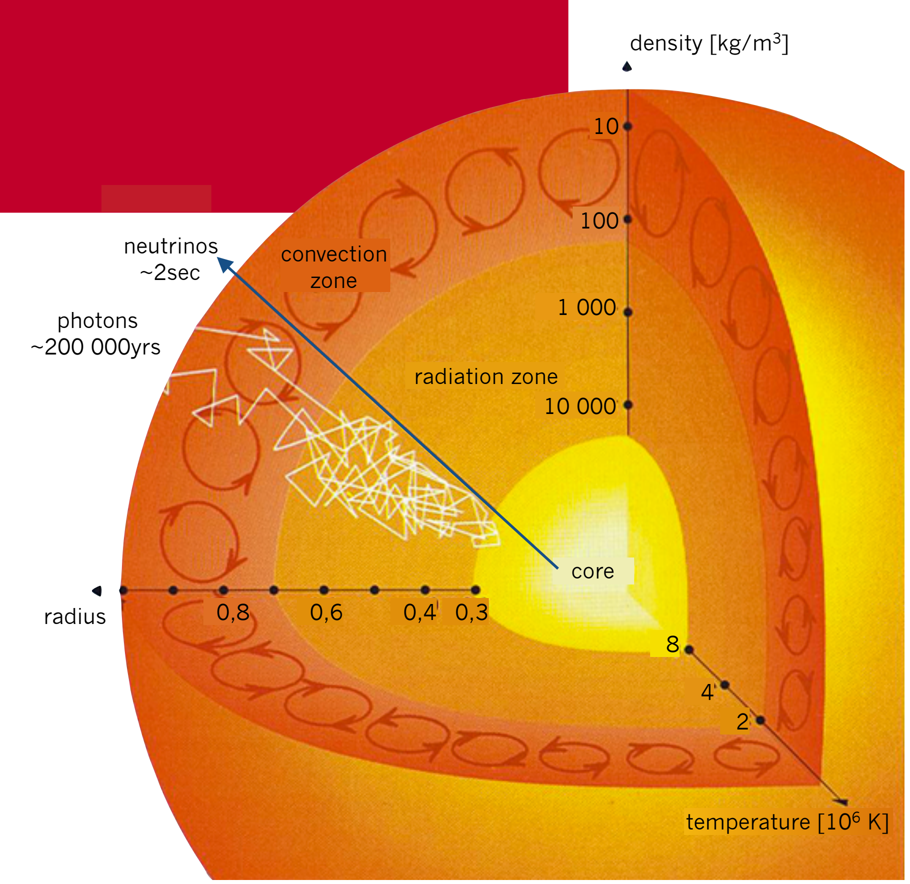
Neutrino energy

Electron density

Resonance behaviour

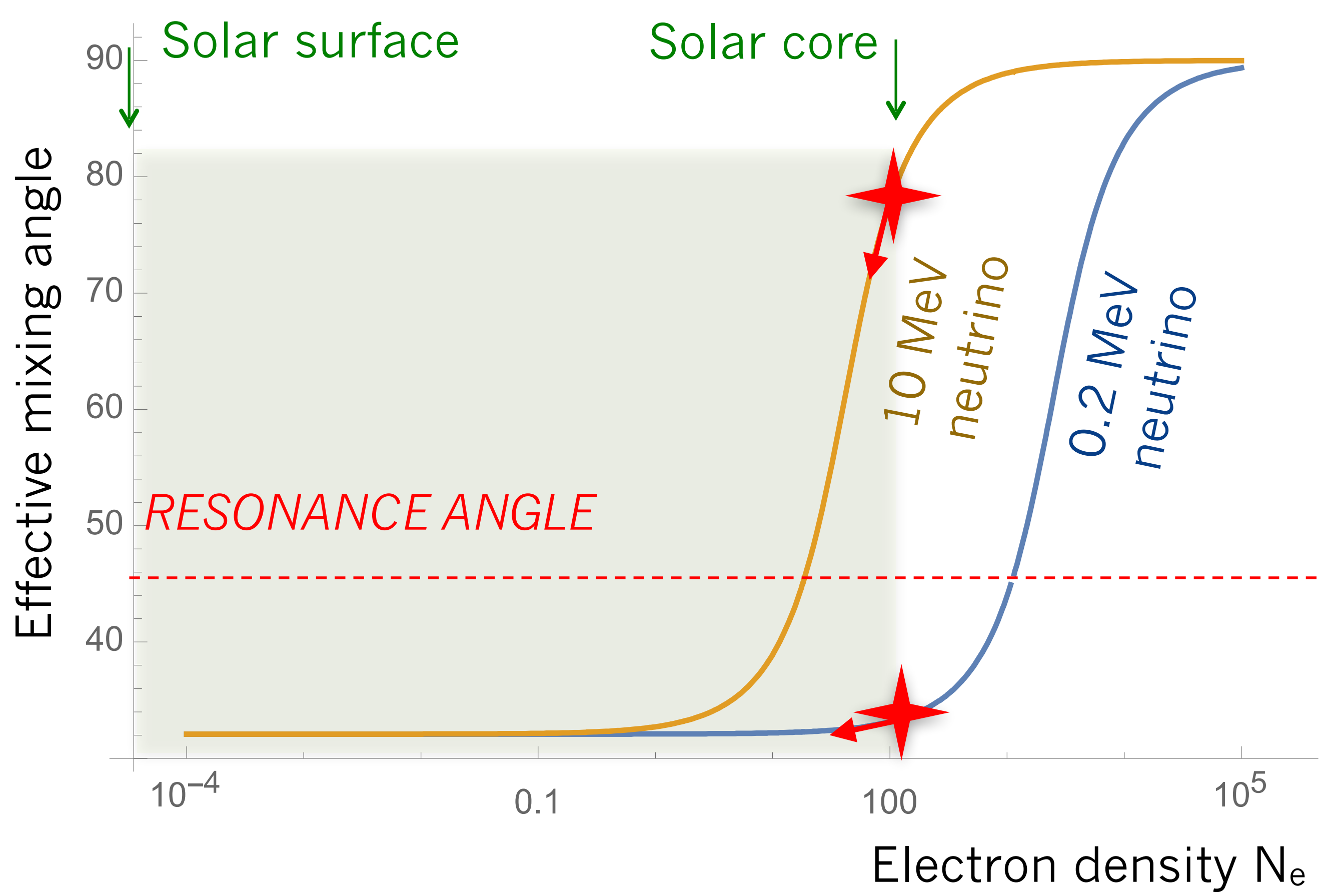
- for x = cos(2θ) there is $\sin^2(2\theta_M) \rightarrow 1$
  - largest possible oscillation amplitude:
  - independent of original mixing angle θ

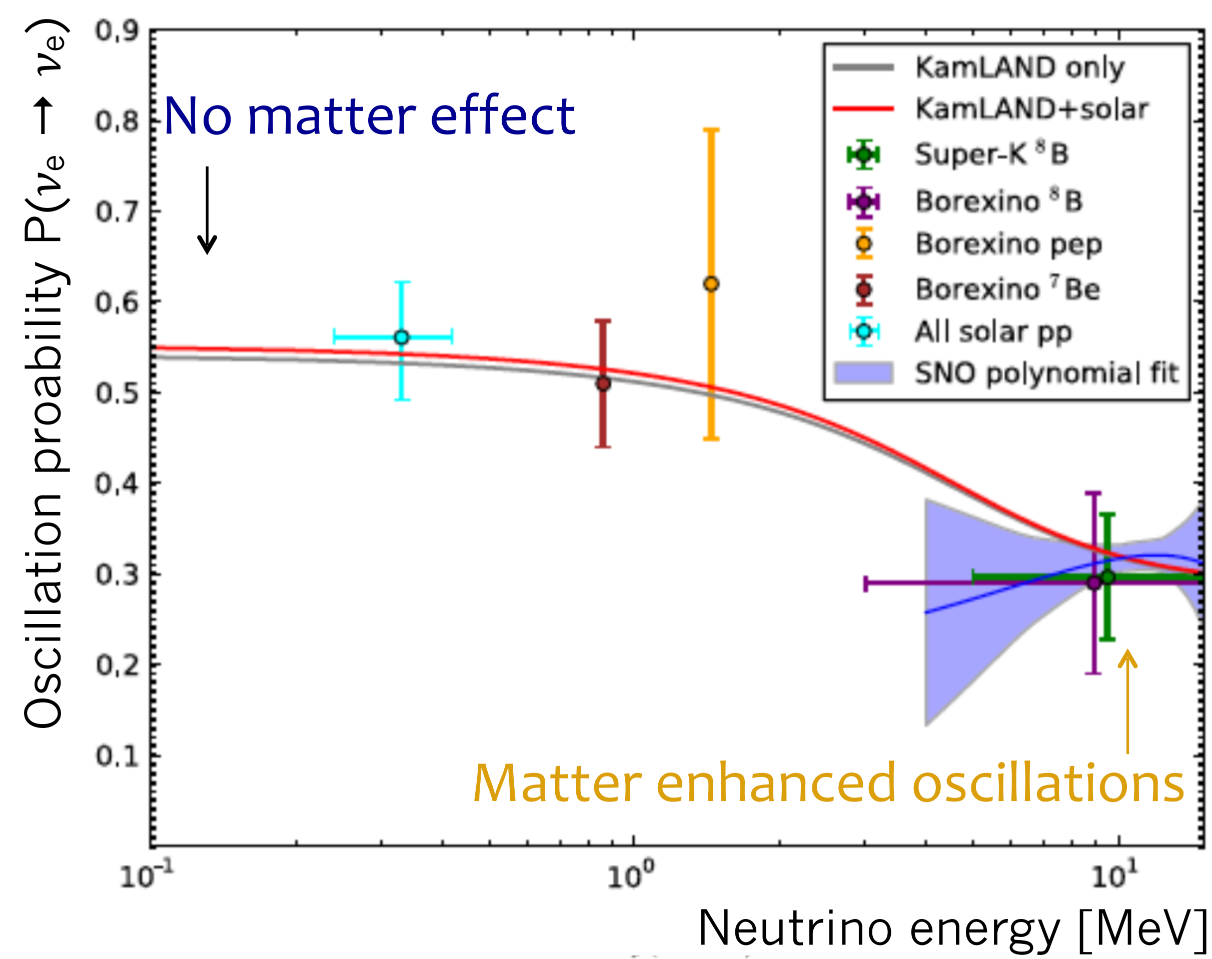
MSW effect in the sun



Solar neutrinos generated in core

- pp-cycle: $E_\nu \sim 0.2$MeV
- ^{8}B-cycle: $E_\nu \sim 10$ MeV
  - adiabatic transition through maximum resonance region





Sterile Neutrinos & matter effects

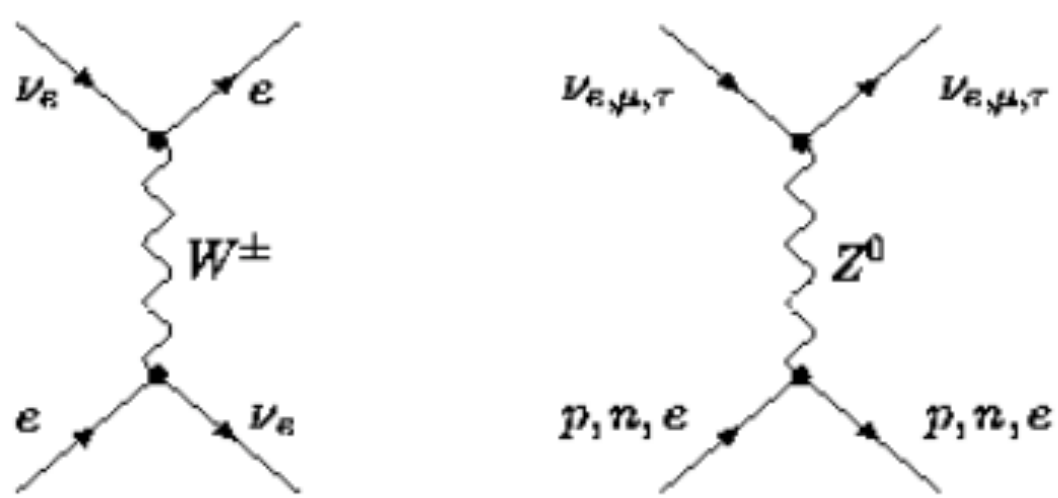
Sterile neutrinos

- no interactions with matter at all
- participate in oscillations
  - 3x3 mixing matrix → 4x4 mixing matrix

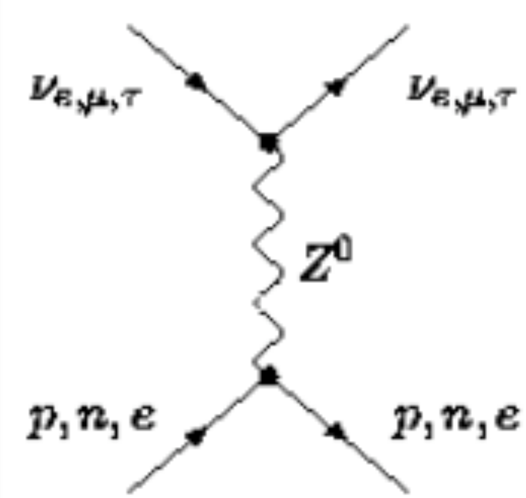
➔ New oscillation effects are to be expected.

Full phenomenology:

- Esmali and Smirnov [JHEP 1312 (2013) 014]
- Chizov and Petcov [Phys.Rev. D63 (2001) 073003]



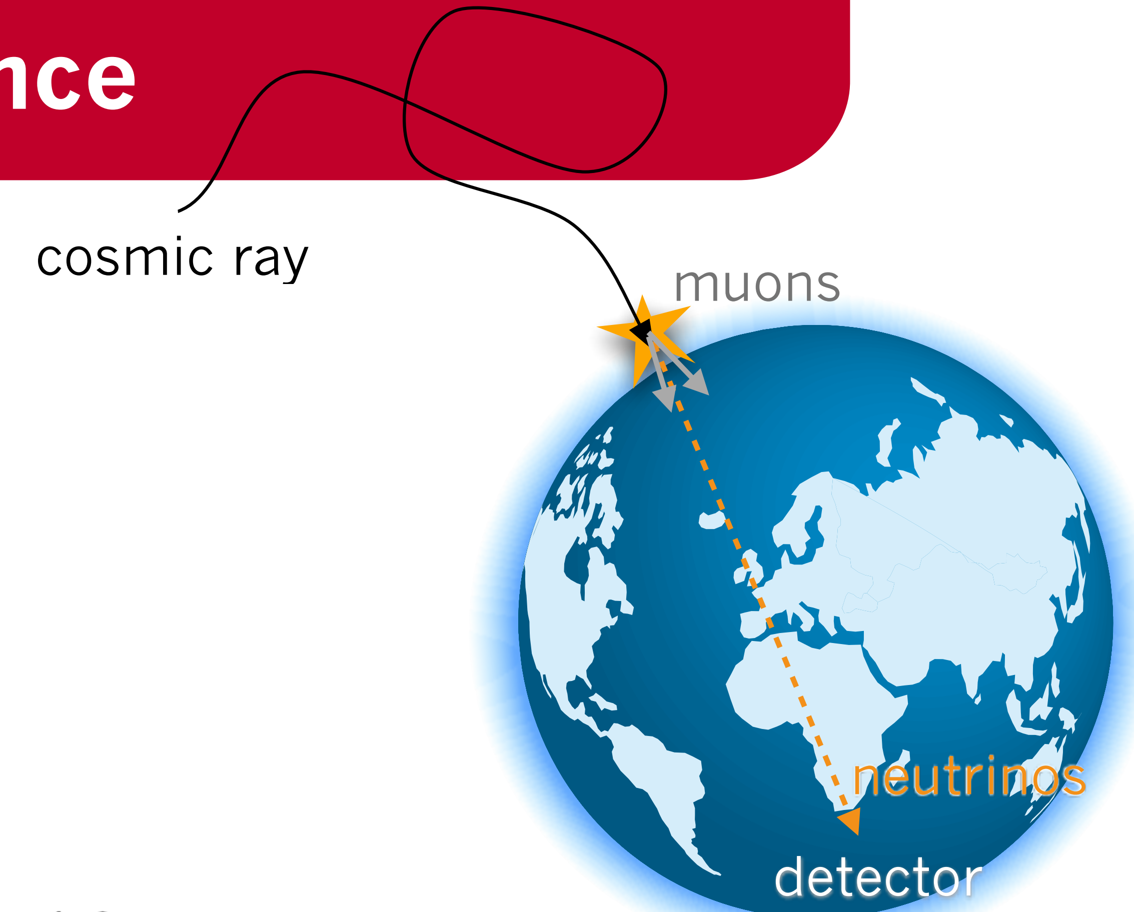
electron flavor



muon / tau flavor

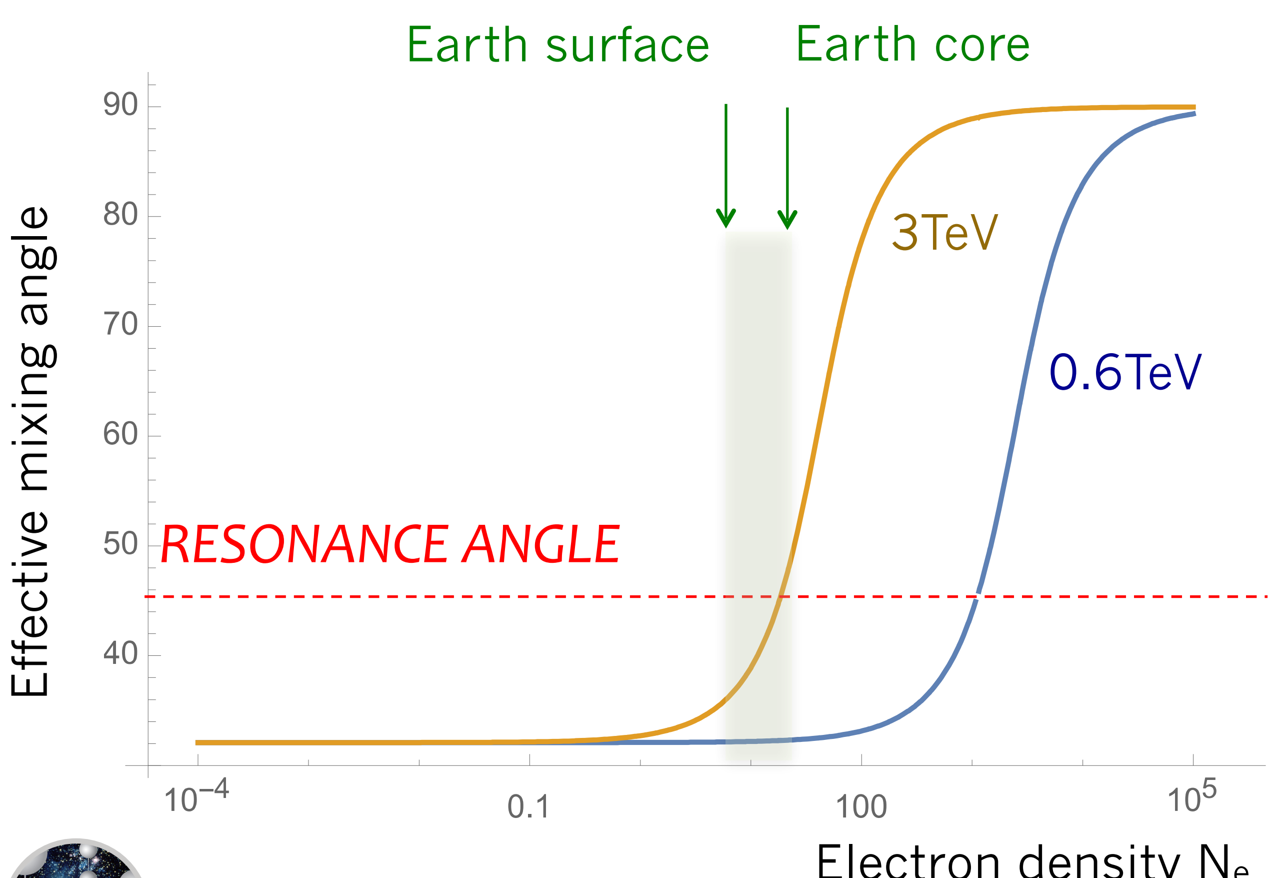
sterile flavor

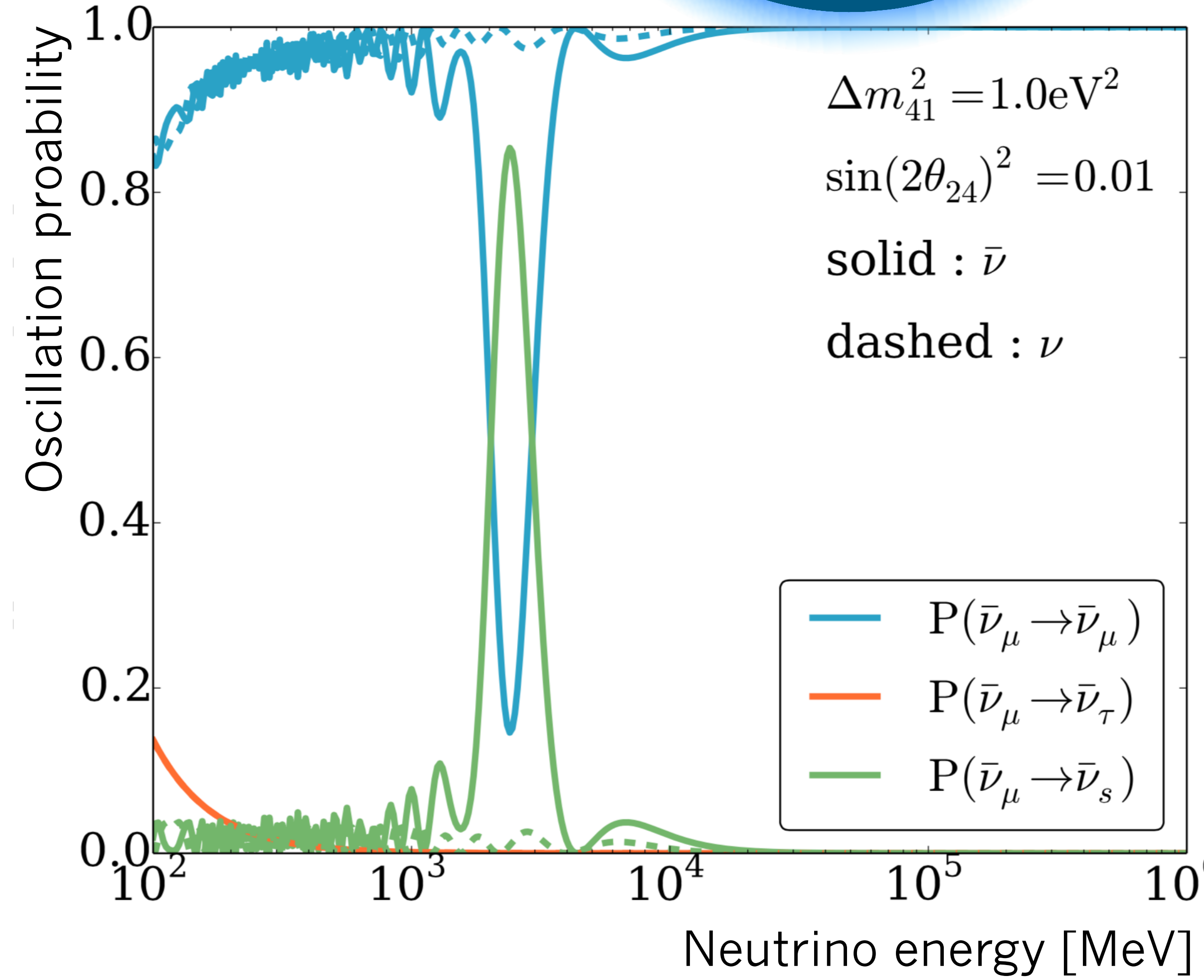
Sterile neutrino MSW Resonance

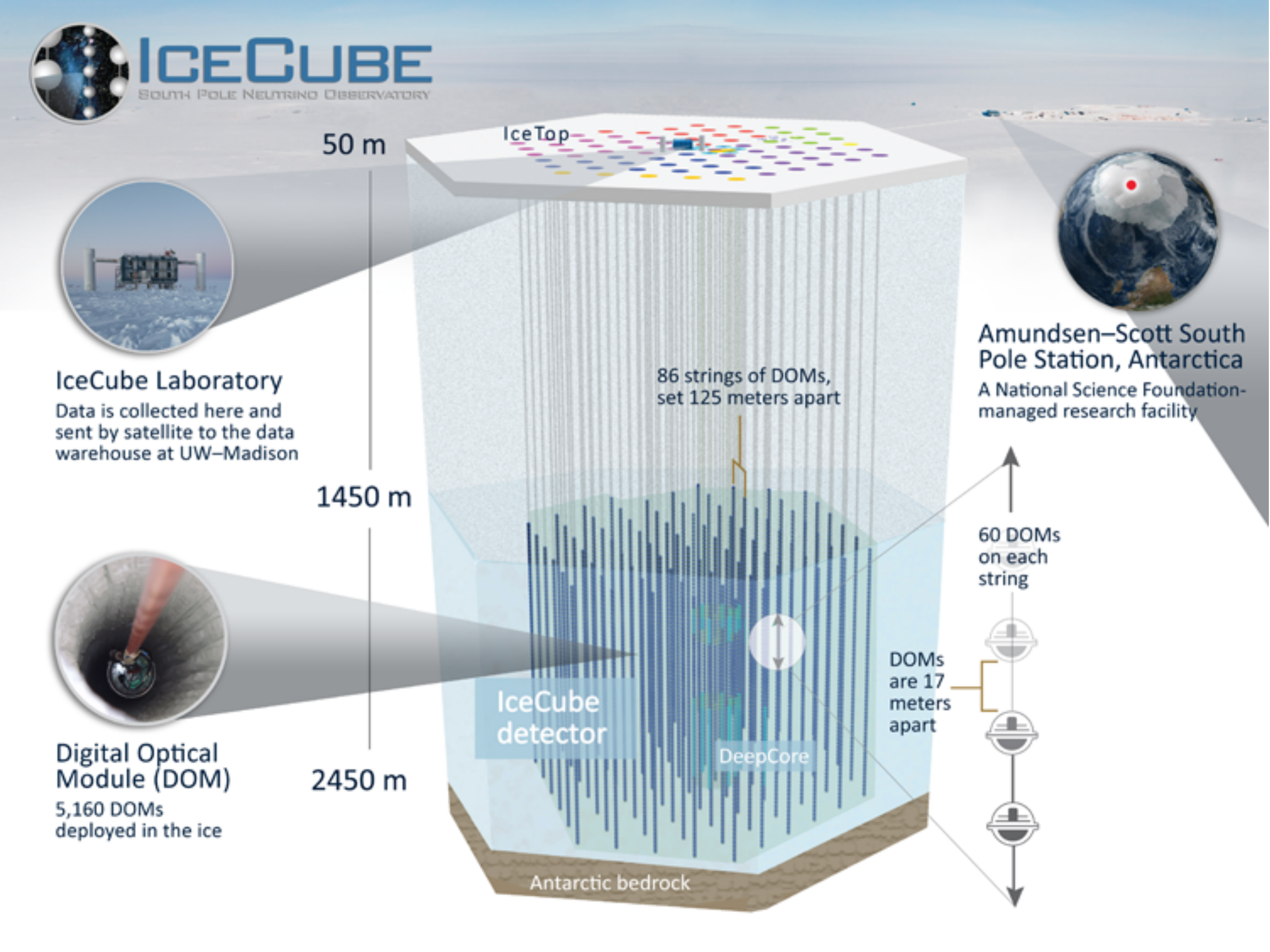


Atmospheric neutrinos

- generated in earth atmosphere
- oscillation in earth matter
  - resonance-like transitions in earth core-mantle region

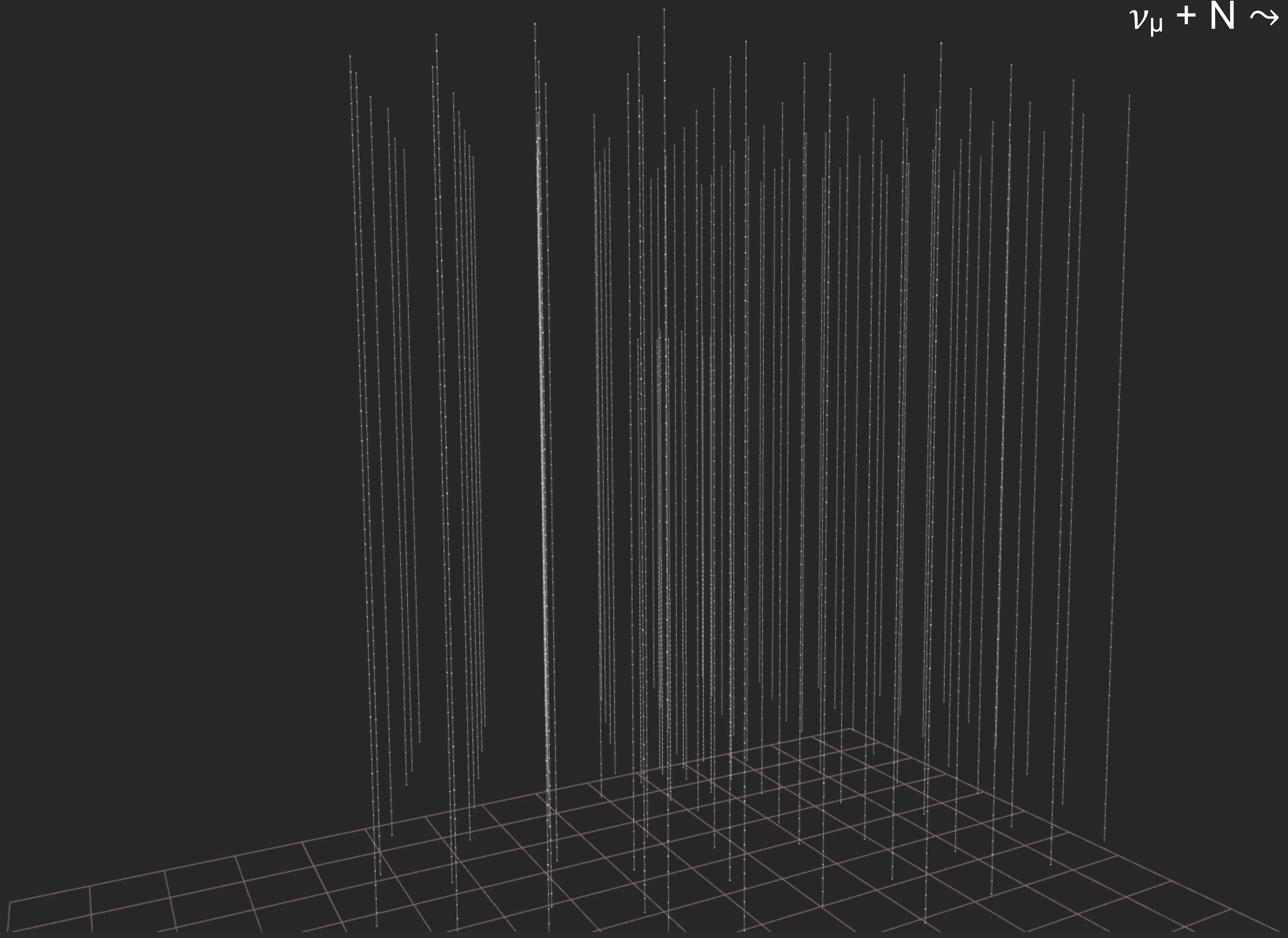




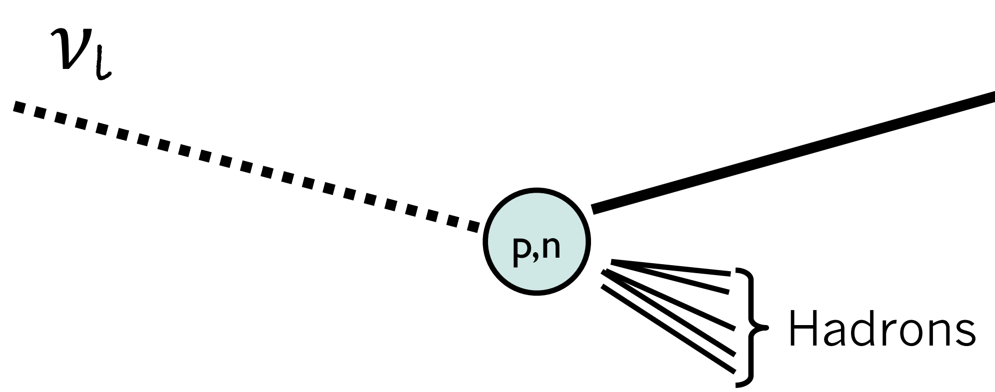

IceCube
South Pole Neutrino Observatory
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

Cherenkov light from ν_μ

$\nu_\mu + N \rightsquigarrow \mu$ (100 TeV)



IceCube event signatures



l – charged current (CC) interaction

ν_l – neutral current (NC) interaction

Relativistic secondary particles:

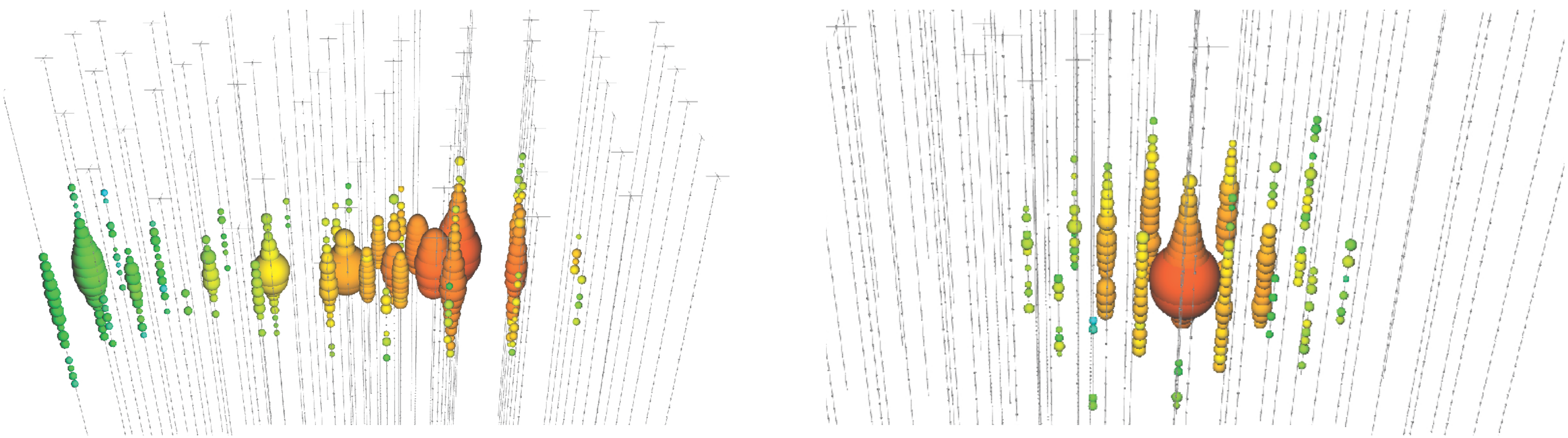
- Cherenkov light emission

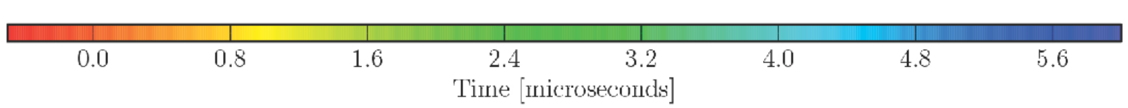
Track like events:

- ν_μ CC interactions

Cascade like events:

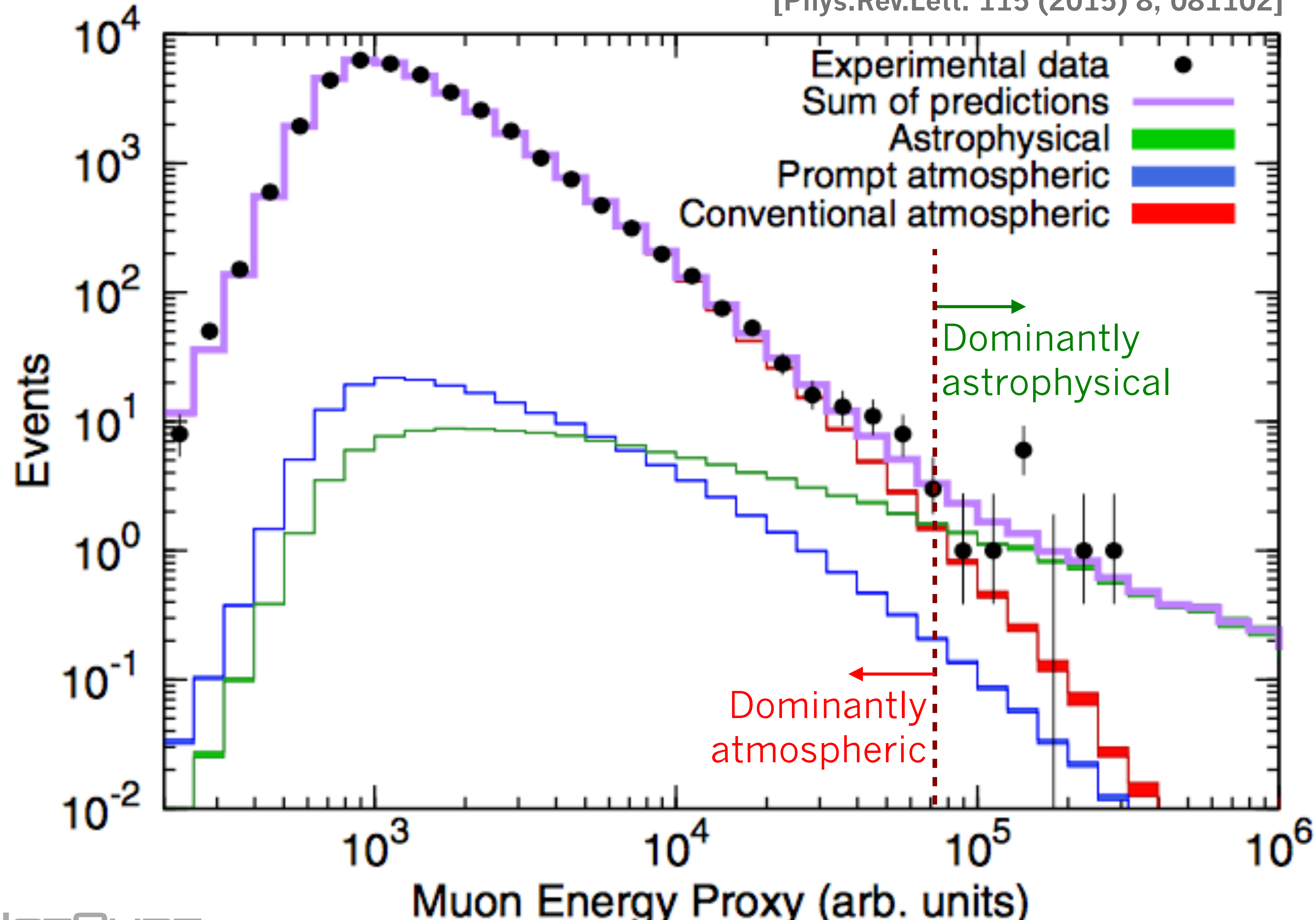
- all NC interaction, CC of ν_e, ν_τ





Muon neutrino spectrum in IceCube

[Phys.Rev.Lett. 115 (2015) 8, 081102]



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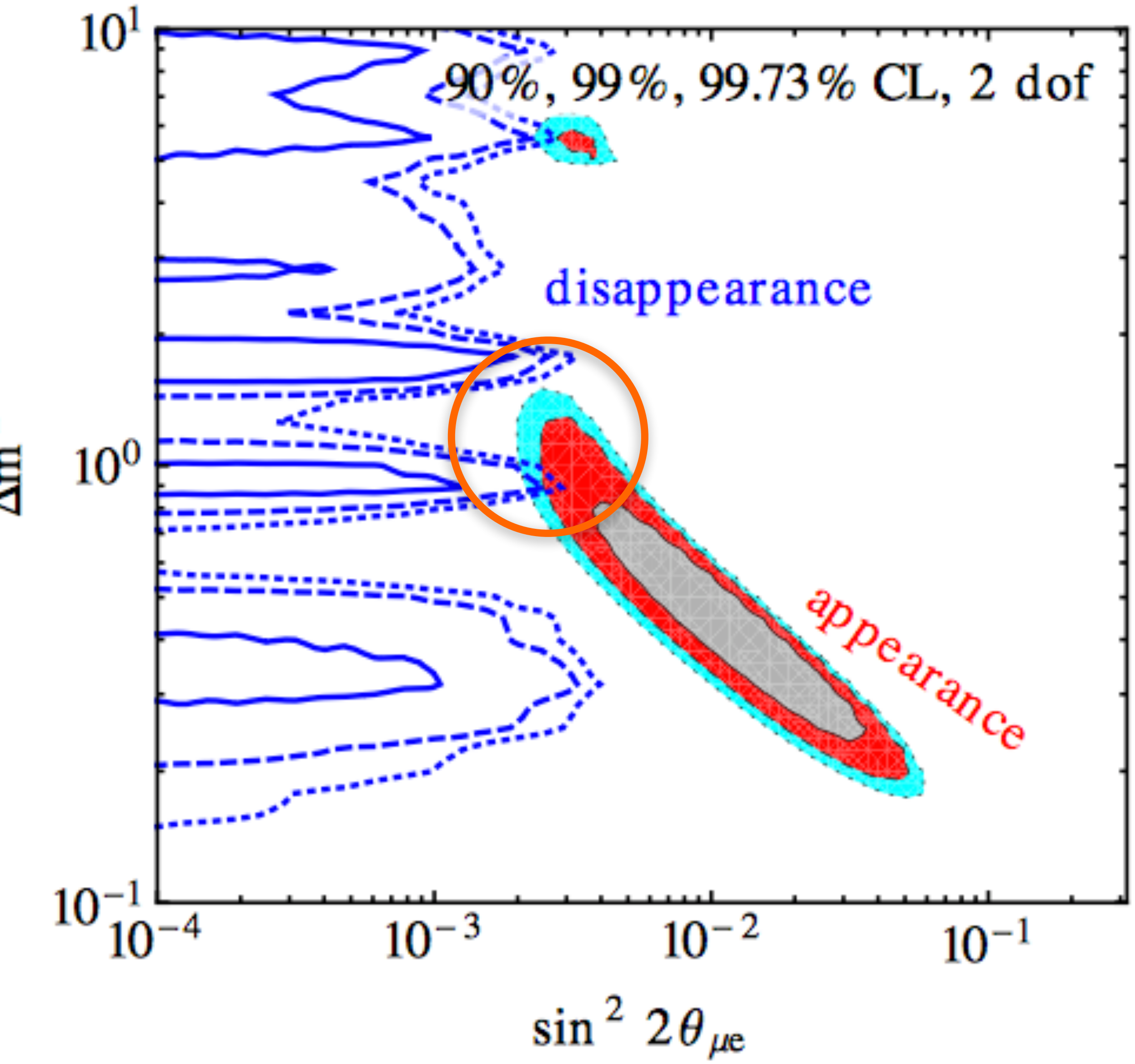
Where is the MSW resonance?



[Kopp et al. JHEP 1305 (2013) 050]

Experiments

- appearance and disappearance

Island allowed by both

- $\Delta m^2 \sim 1 eV^2$

MSW resonance occurs at:

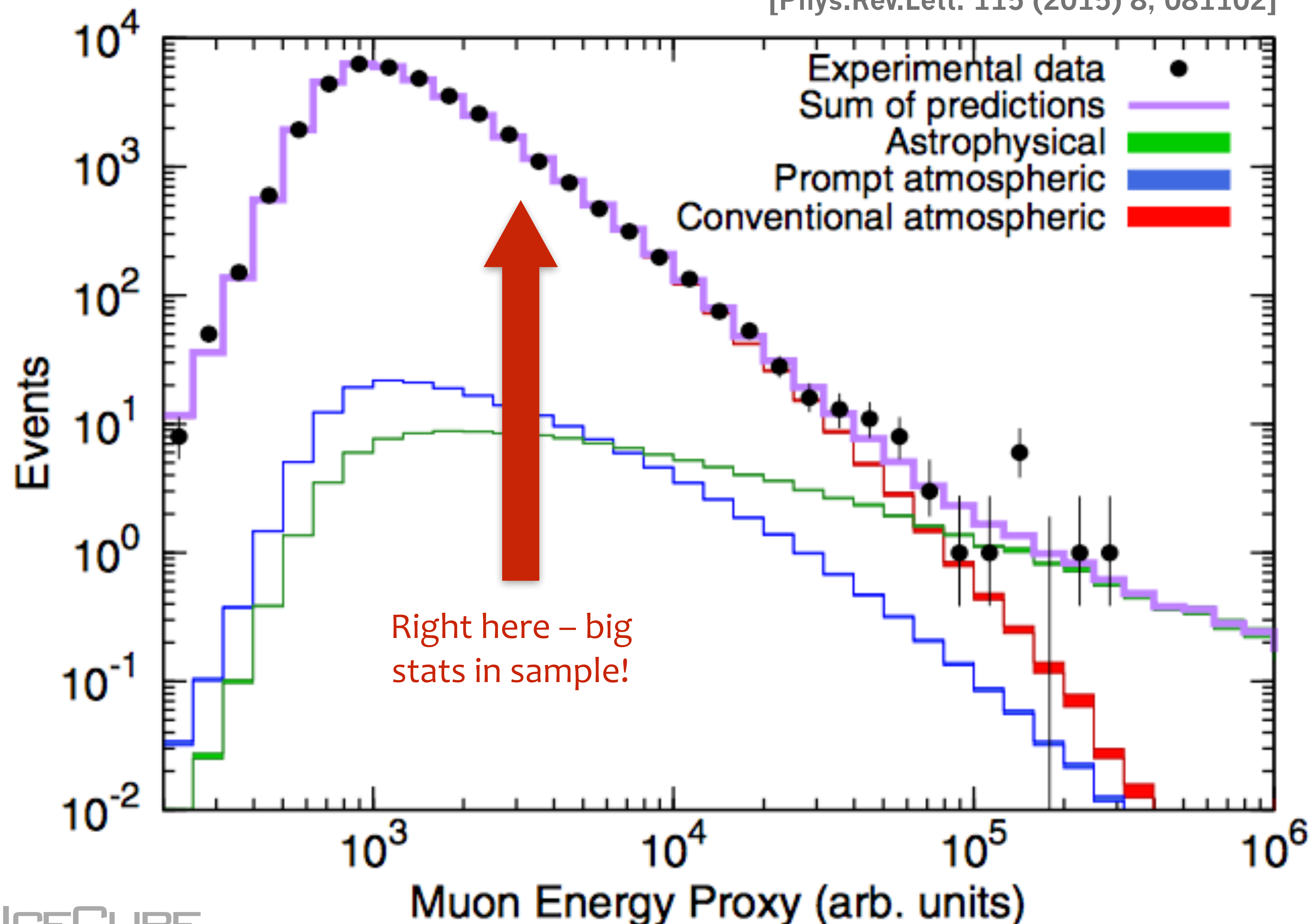
$$E_{res} = \frac{\Delta m^2 cos2\theta}{\sqrt{2} G_F N_e}$$

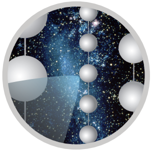
For Earth matter density:

$$E_{crit} = 3\ TeV$$

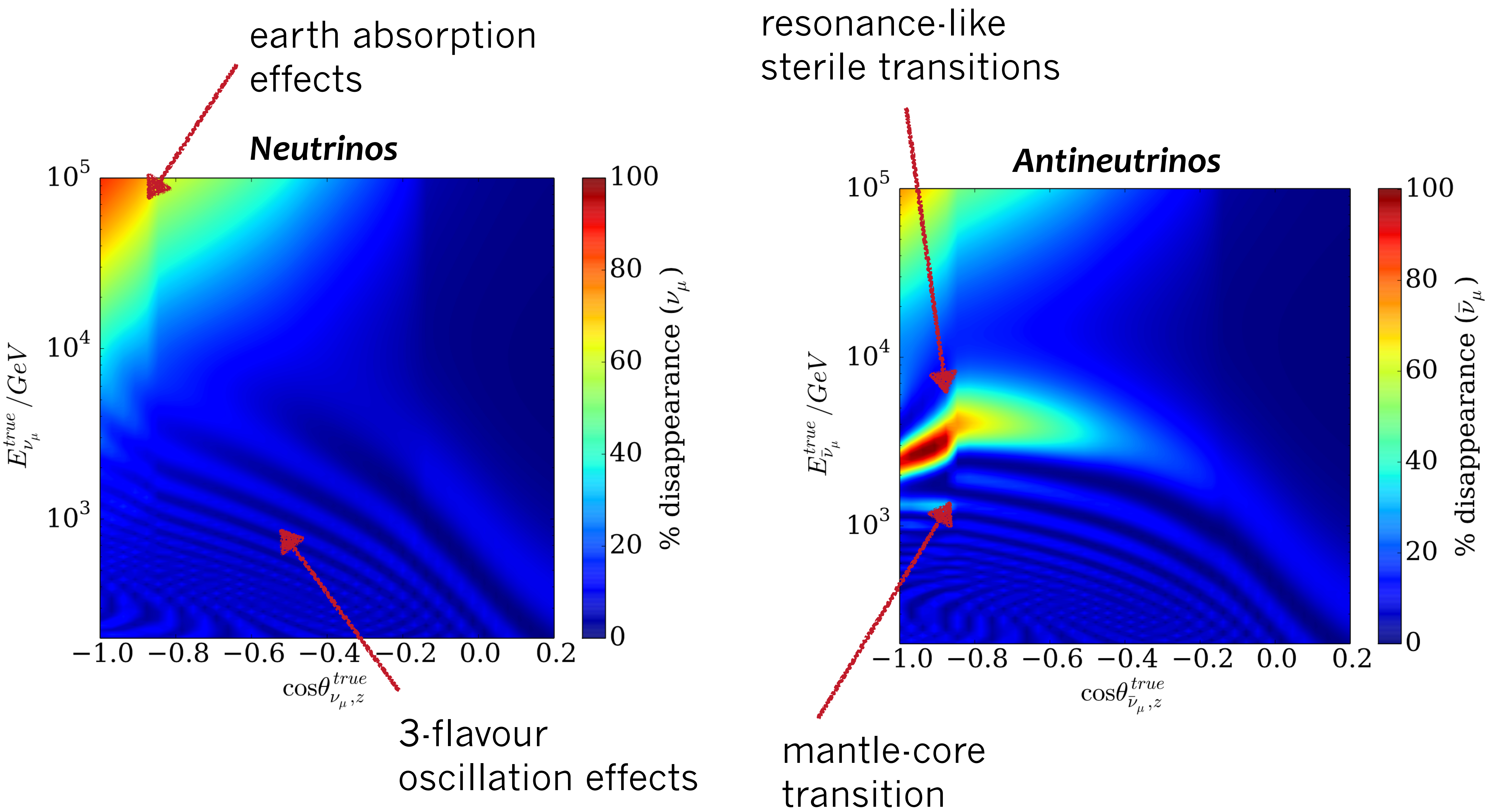
Resonance energy

[Phys.Rev.Lett. 115 (2015) 8, 081102]





Oscillation signature



Sterile signature in IceCube

Sample

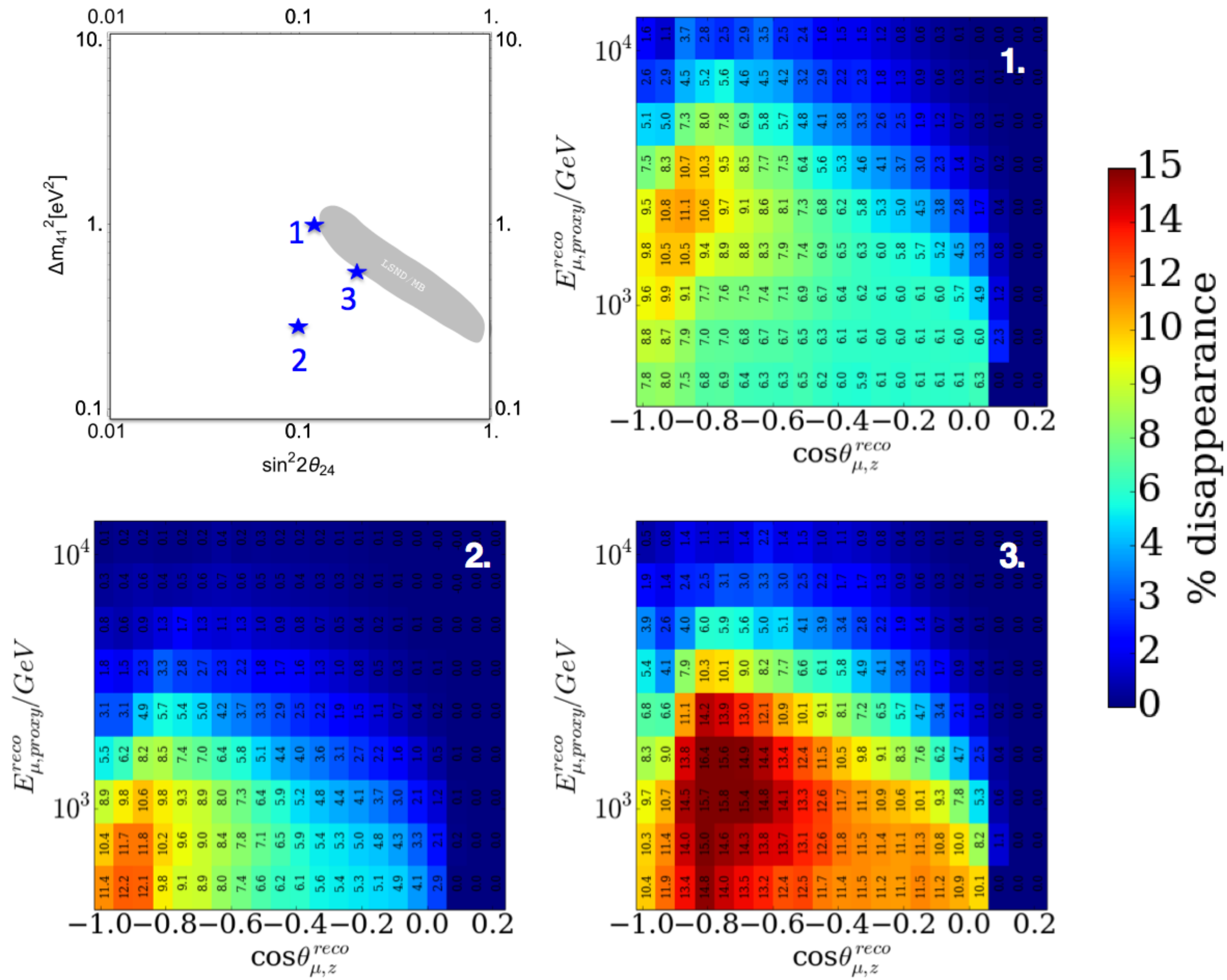
- livetime ~ 1yrs
- purity ~ 100%

Energy resolution

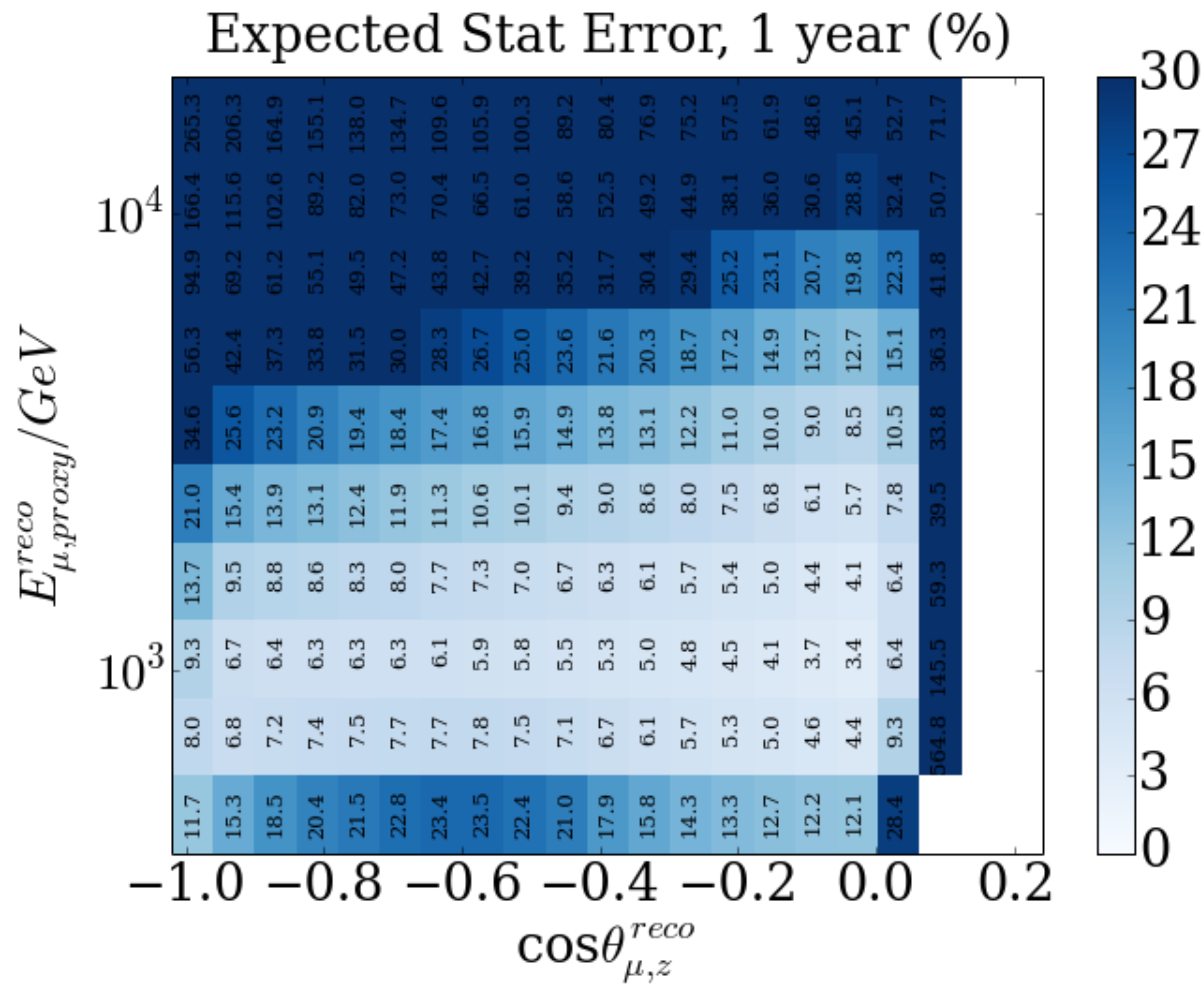
- σ_E ~ 0.3 log10(E)
  - mostly not contained

Angular resolution

- σ_Ψ ~ 1°



Statistical uncertainty per bin



Systematic effects

see later

Continuous parameter	Central value	Gaussian prior width
normalization	1	no prior[1]
DOM Efficiency	0.99	no prior
cosmic ray spectral shift	0	0.05
π/K ratio	1	0.1
$\nu/\overline{\nu}$ ratio	1	0.025
atmospheric density shift	0	tuned per-model

Continuous parameters

- adjusted in fit

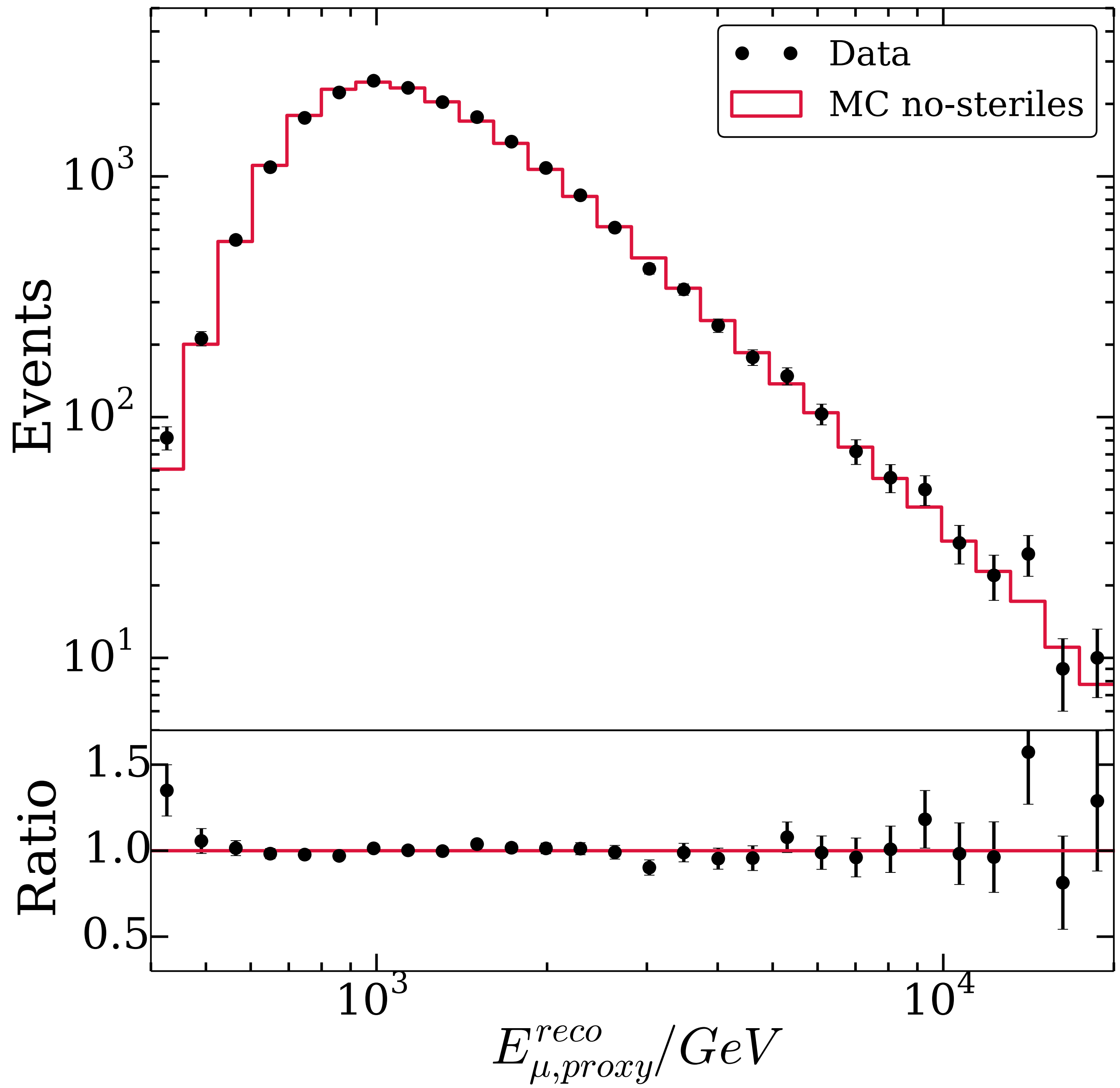
Discrete parameters

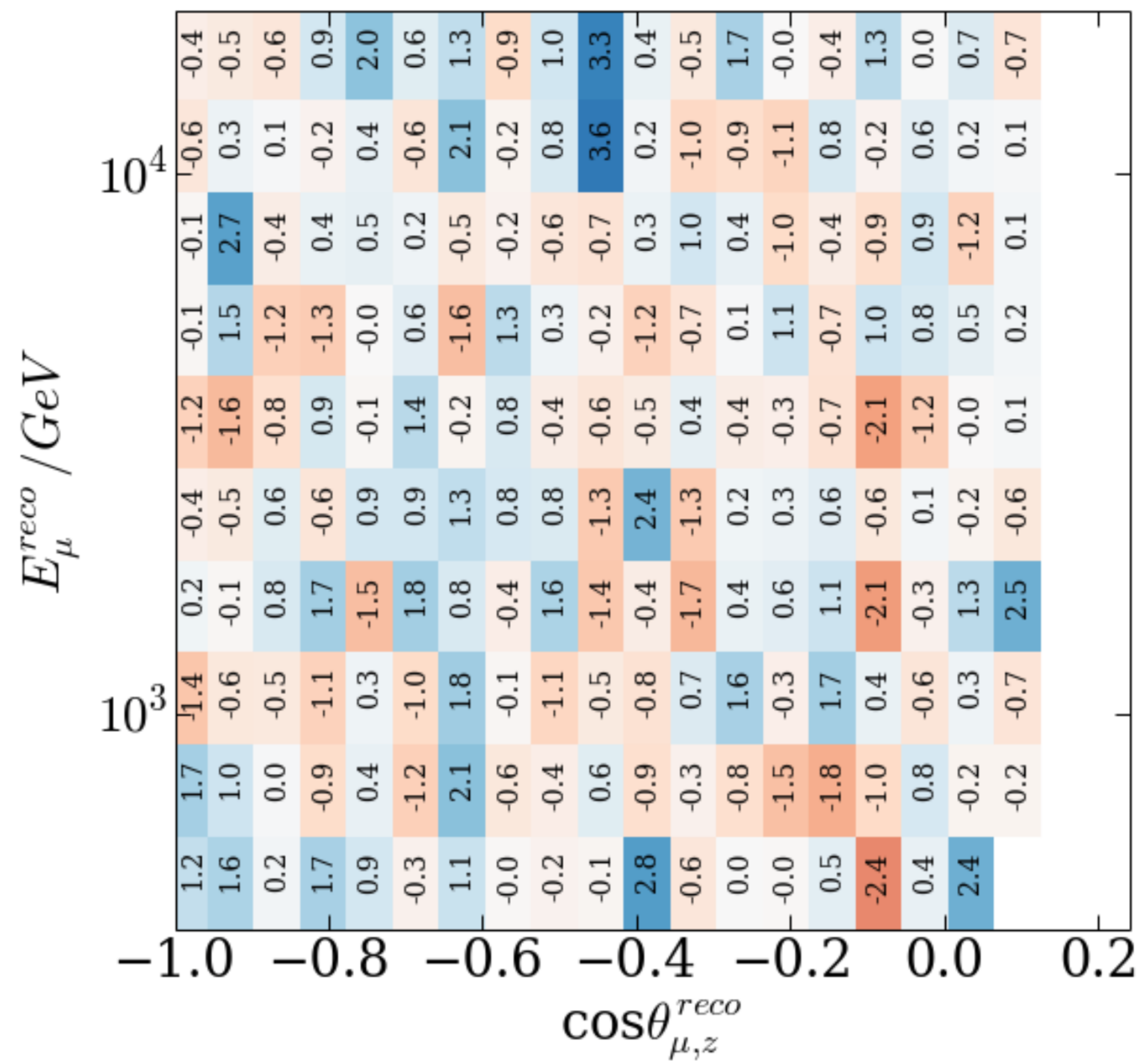
- no continuous adjustment
  - select best-fit model

Discrete variant	Variant numbers
Central model *SPICEMie, PREM, HERAPDF*	0
Ice absorption +10%	1
Ice scattering +10%	2
SPICELea (anisotropy)	3
No hole ice effect	4
Flux variants	5-10
Cross section variants	11-15
Earth model variants	16-24

The Data (IC86 1 year)

Comparison of data to no-steriles hypothesis, after accounting for systematics





Shape and Rate+Shape analysis

IceCube *blind* result

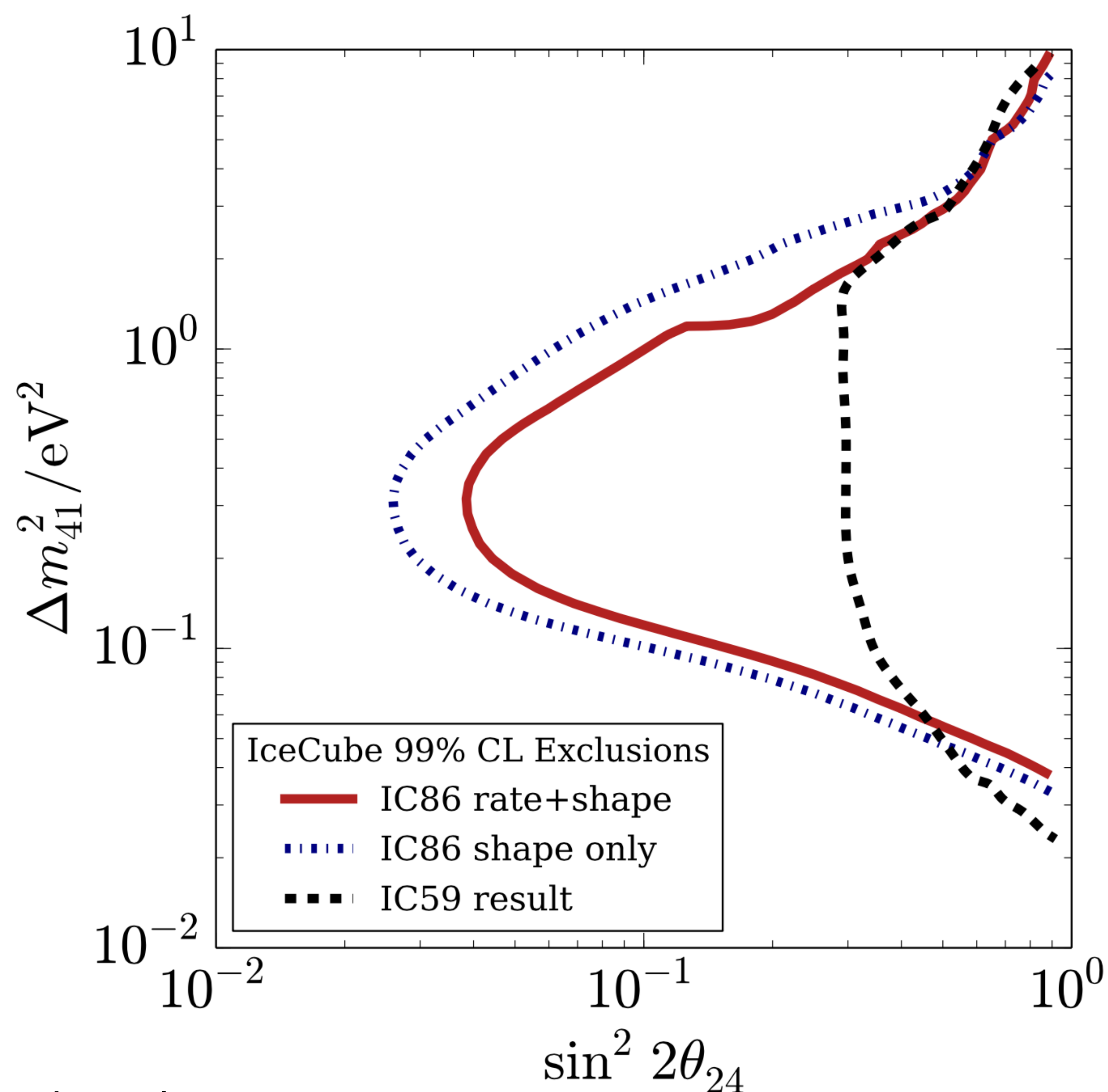
- **IC86 shape** only
  - flux normalization
    ~ factor 2 too high
  - best-fit value for $\Delta m^2_{41} \sim 10 eV^2$
- unresolved fast oscillations
  - acts like flux suppression

A-posteriori **IC86 rate+shape** result

- added normalization constraints
  - mildly weaker due to normalization tension at best-fit.

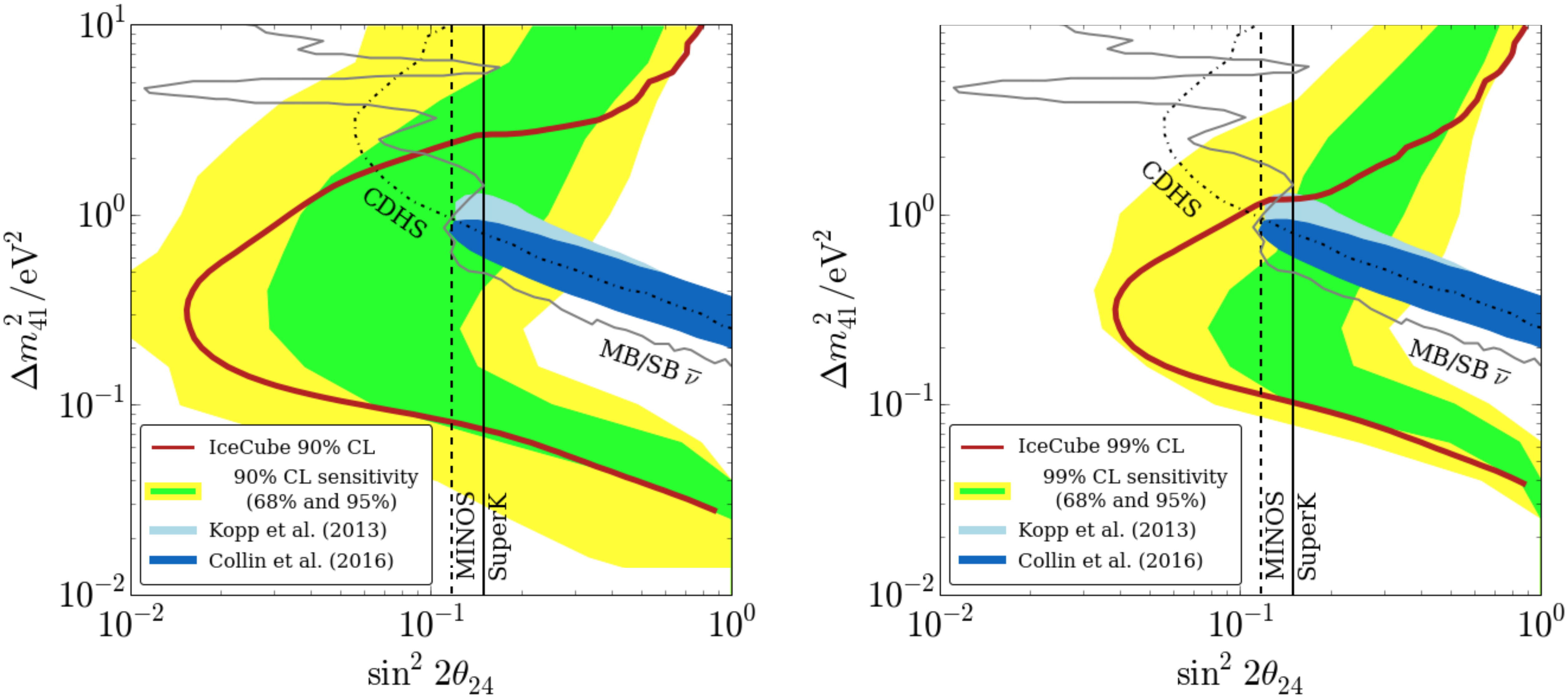
Independent analysis

- 1 year of data from partly-built 59-string detector



Final result

[IceCube Collaboration PRL 117, 071801 (2016).2]



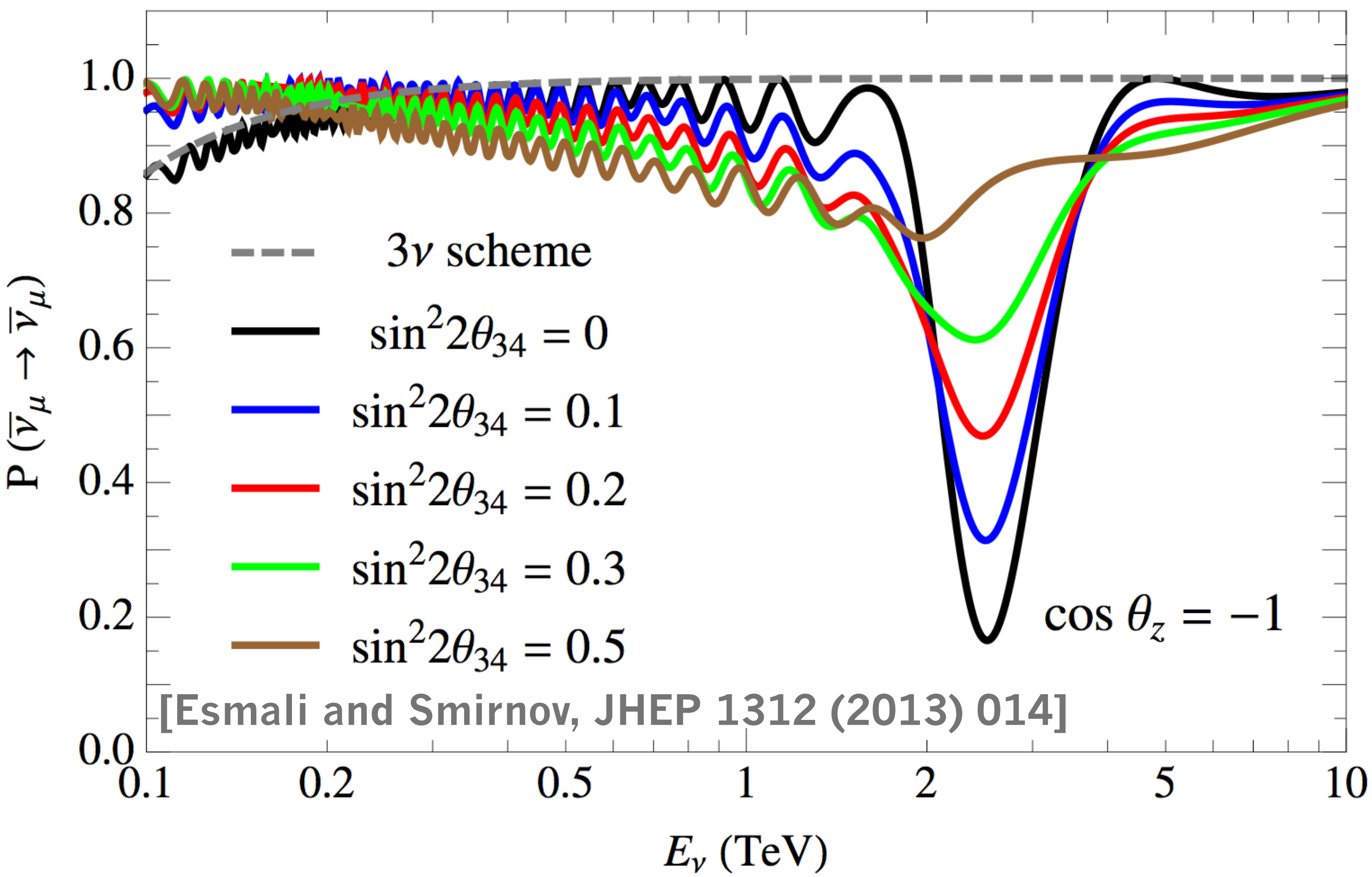
Sensitivity comparison

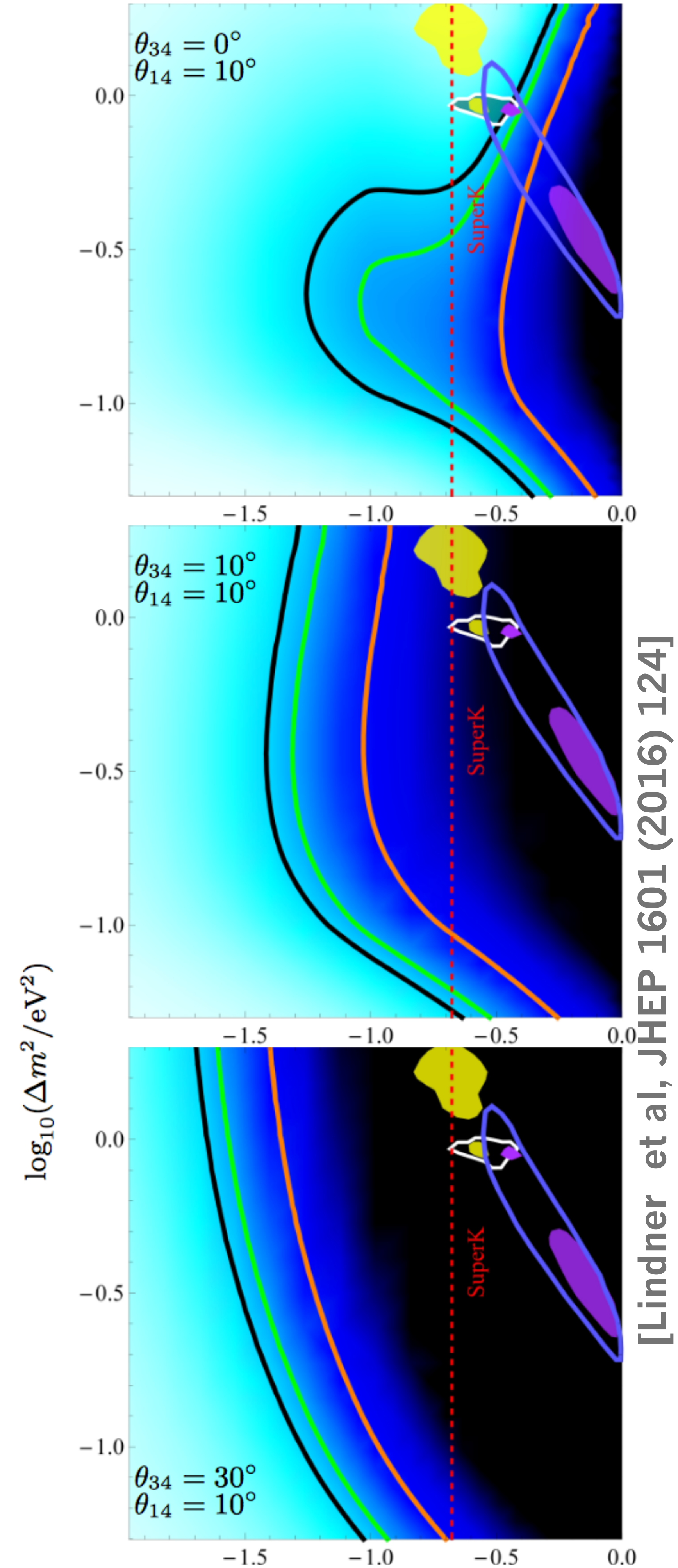
- stronger than median sensitivity
  - within 95% band from pseudo-data trials

Global-fit comparison

- appearance allowed region rejected at 99%CL

Addressing assumptions: θ_{34}=0?





Constraint from Minos data

- $\theta_{34} < 25°$ at 90%CL
  [Phys.Rev.Lett. 107 (2011) 011802]

Sensitivity exploration

- θ_{34}=0 gives most conservative limit on θ_{24}

IceCube

Addressing assumptions: θ_{14} = ?

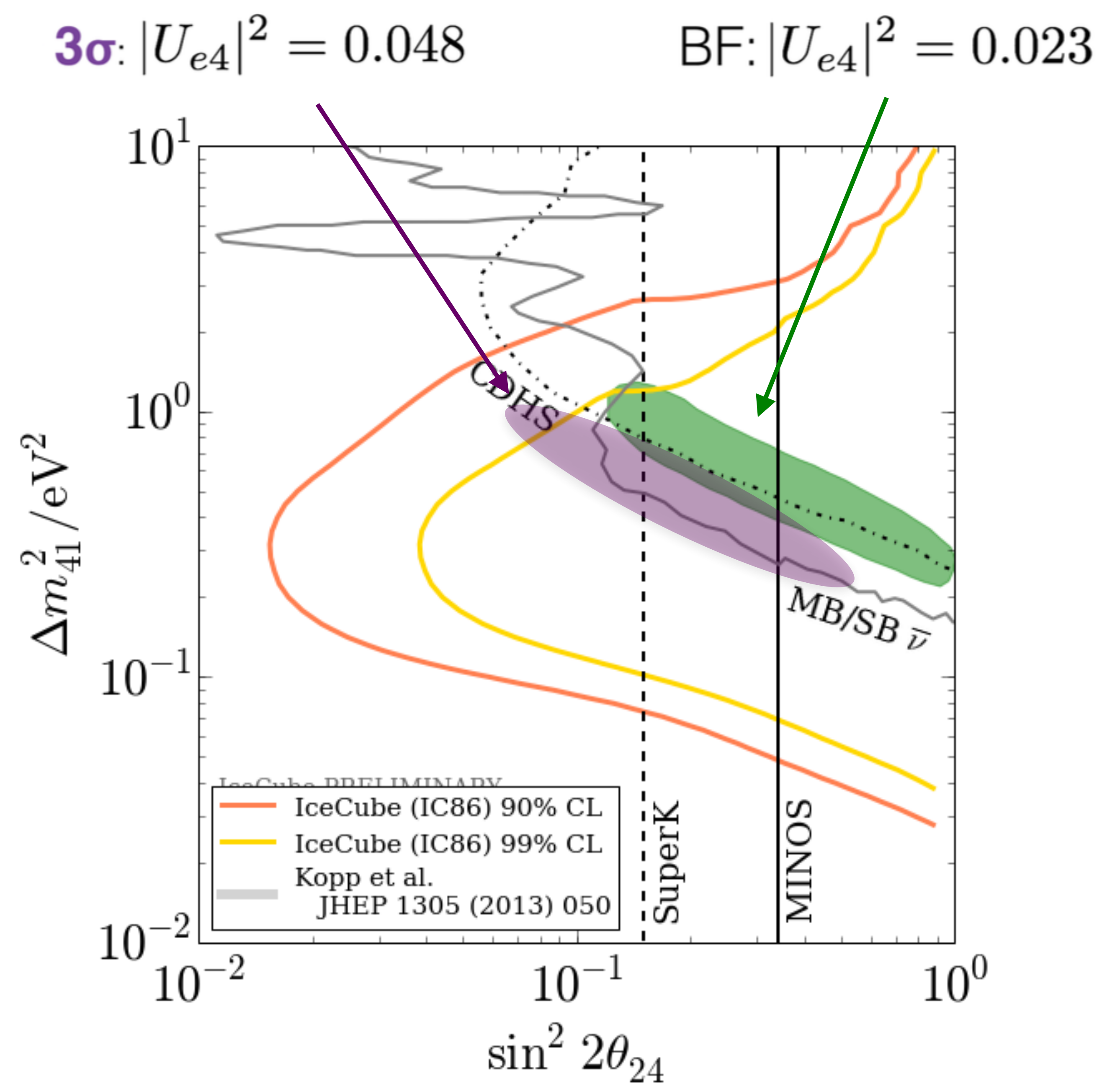
This analysis

- $|U_{e4}|$ fixed at world best fit from $\nu_e \rightarrow \nu_e$ experiments
  - constraint on θ_{14}

Constraints

- $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$
  - reactor experiments
- $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$
  - MINOS, SK, (this analysis)
- $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$
  - LSND, MB, KARMEN, NOMAND

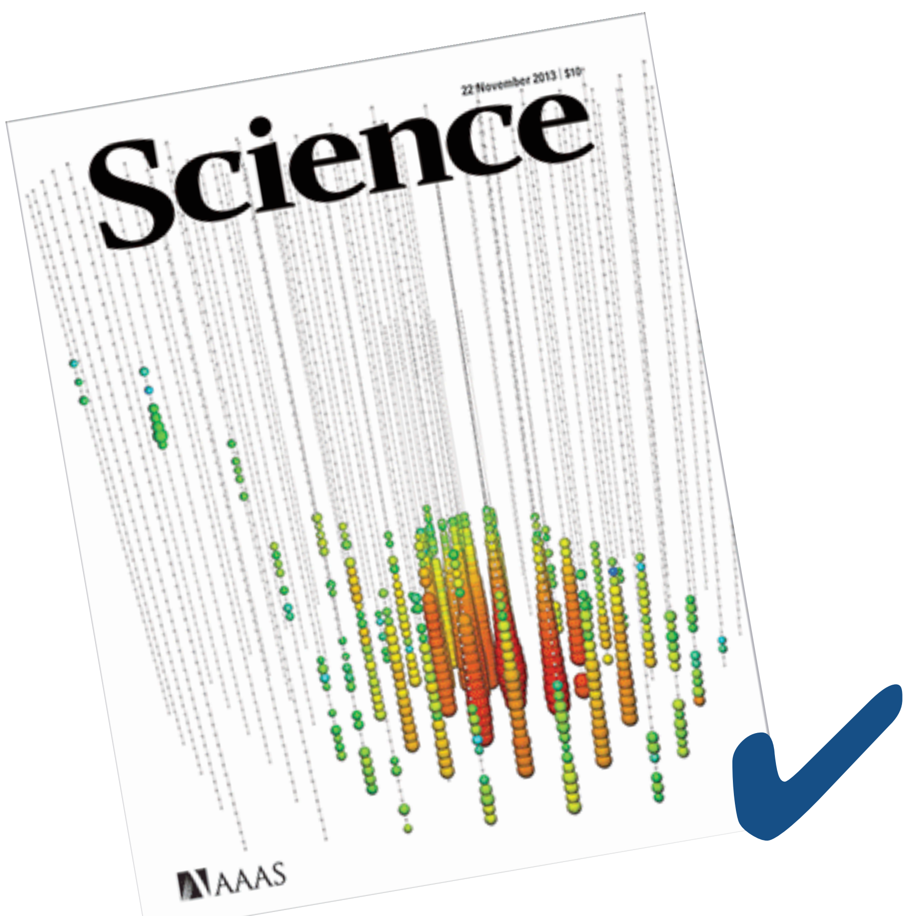
➔ how far can MB /LSND slide?

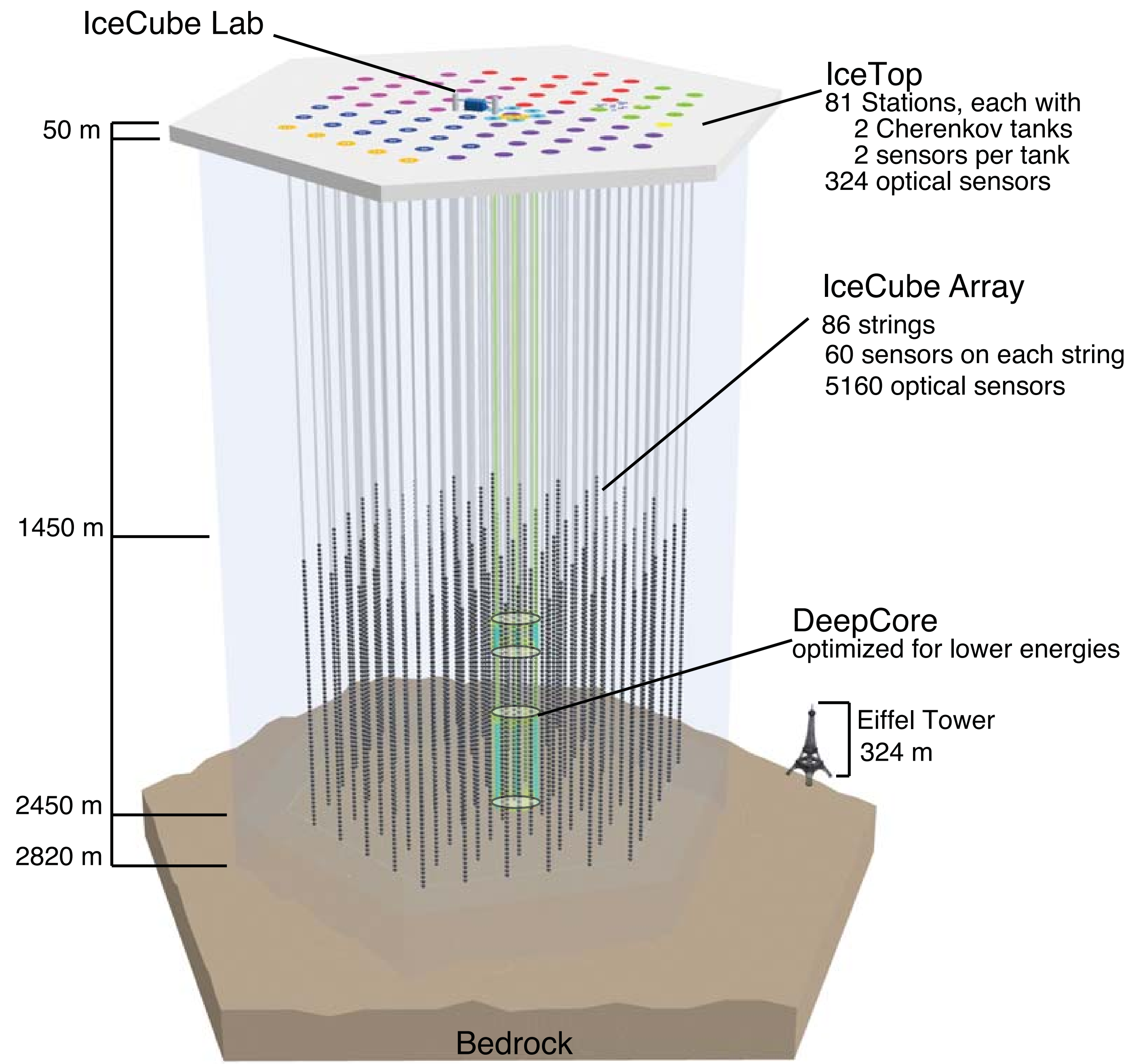


IceCube

IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV
  - optimized for astrophysical CR-sources
  - discovered!





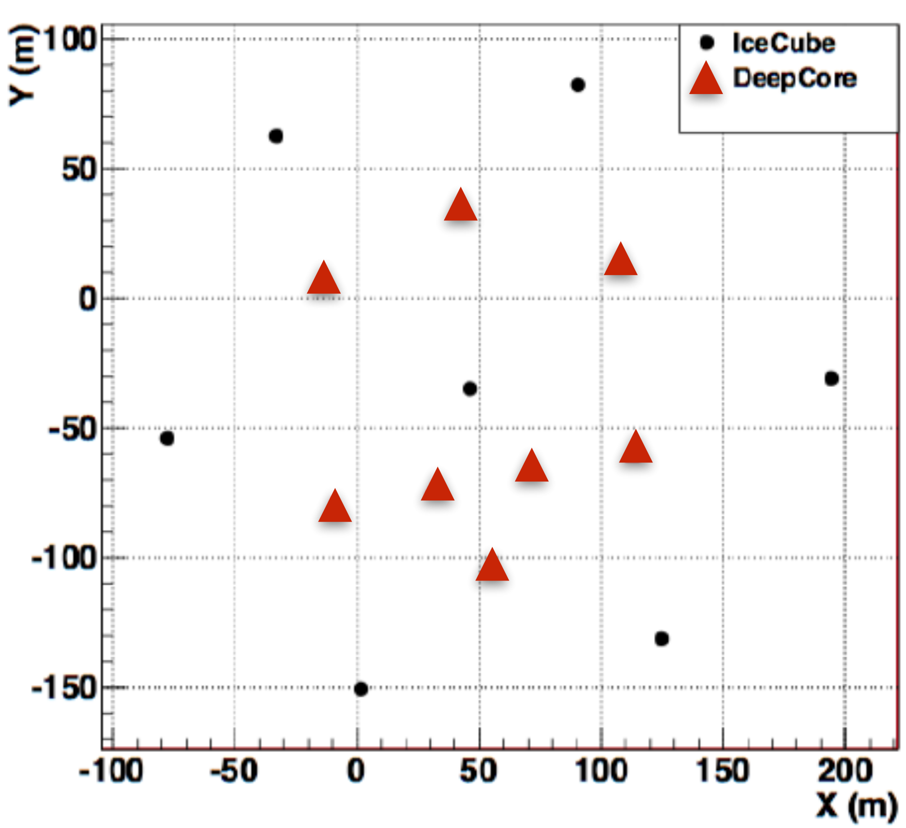
IceCube's low-energy ν detector

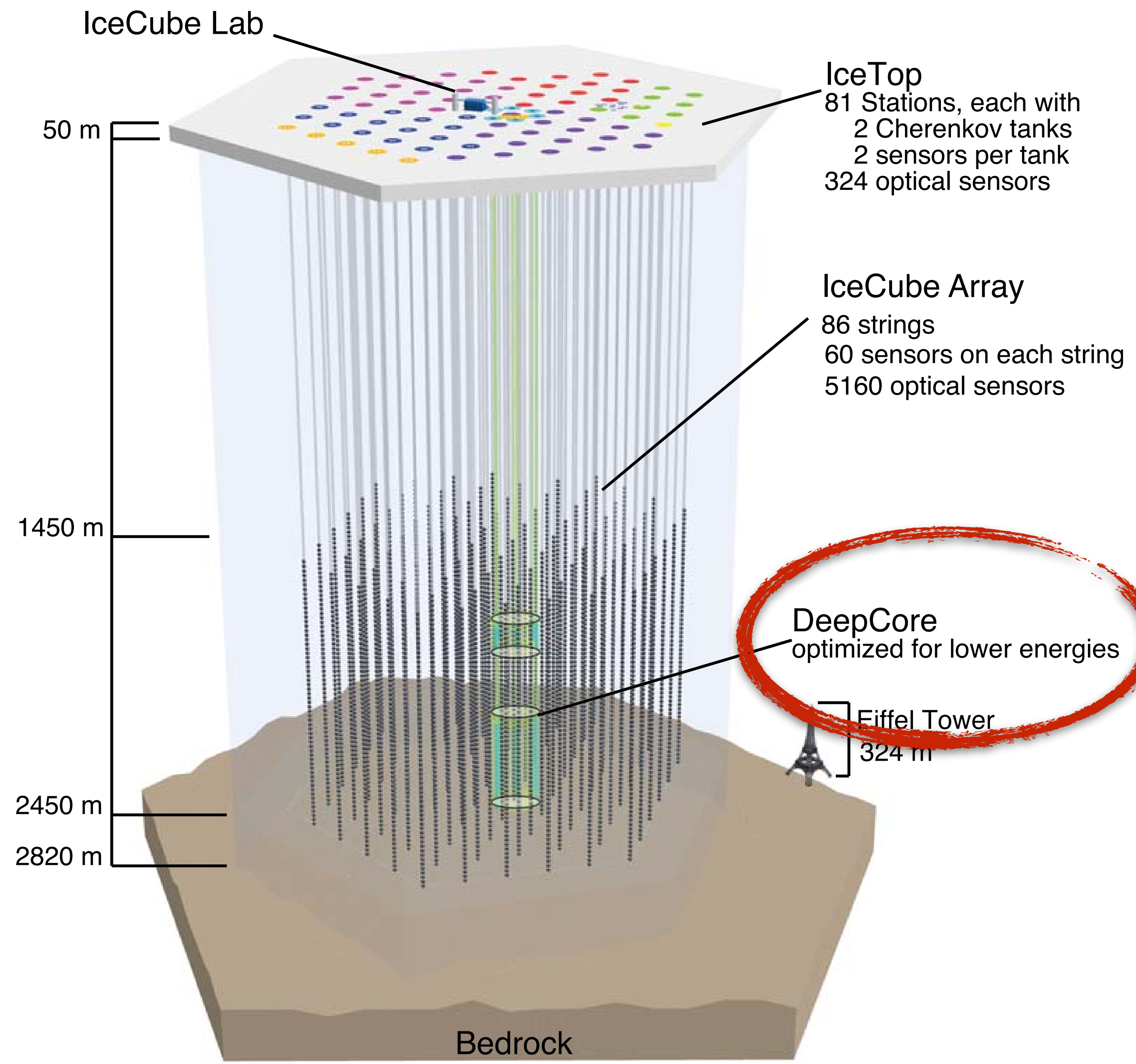
IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV

DeepCore (in operation)

- +8 strings, 72m / 7m spacing
- E_{thresh} ~ 10 GeV



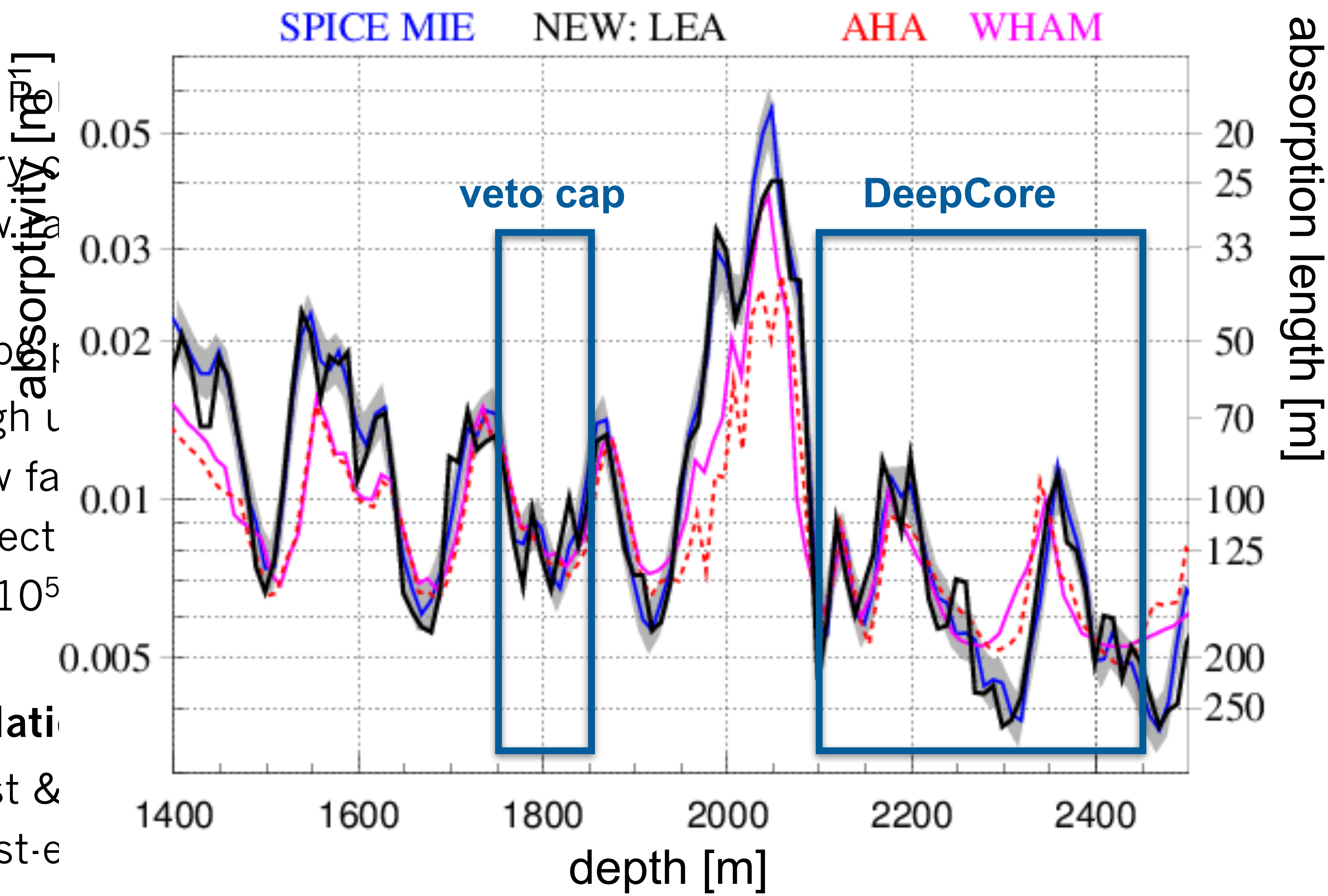


Why at this depth?

South Pol
- very c
- low a

IceCube p
- high u
- low fa
- effect
  - 10^5

Installati
- fast &
- cost-e

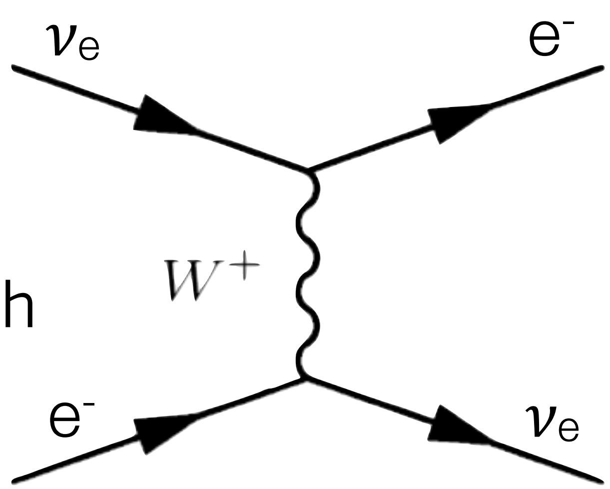


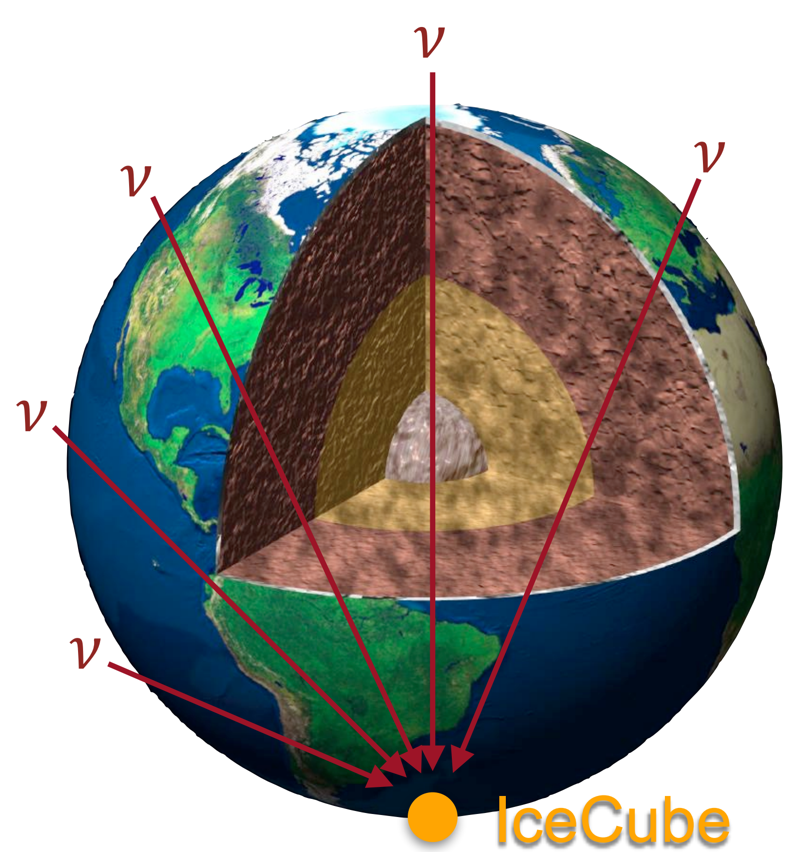
+ stronger atmospheric muon suppression!

Low-energy matter effects in the earth

Atmospheric neutrinos

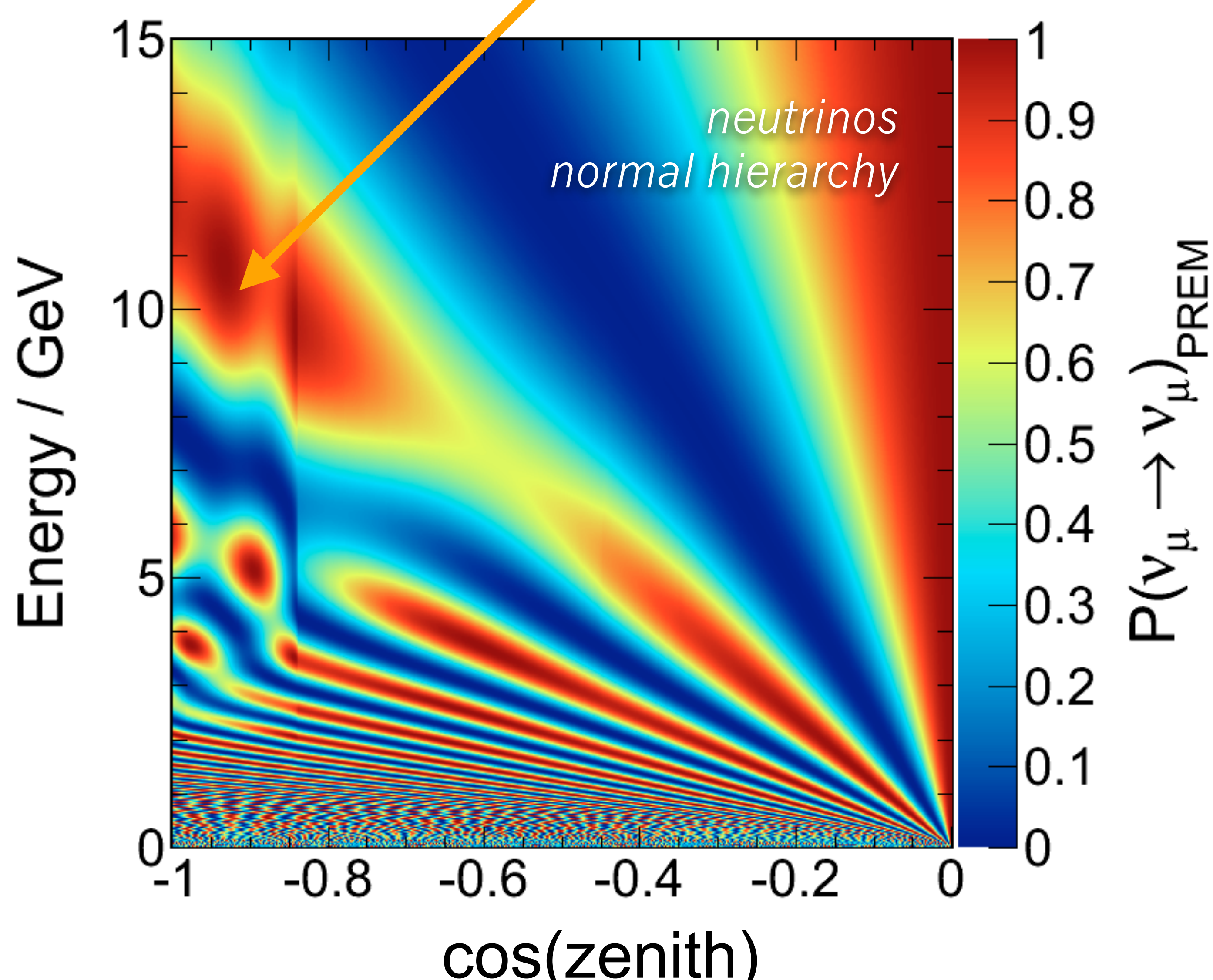
- 3-flavour ν-oscillations in earth
  - wide range of L/E
- matter effects
  - affect neutrinos





matter effects

- strongest in core
- E_ν ~ 3-15 GeV



Event Reconstruction

Challenge

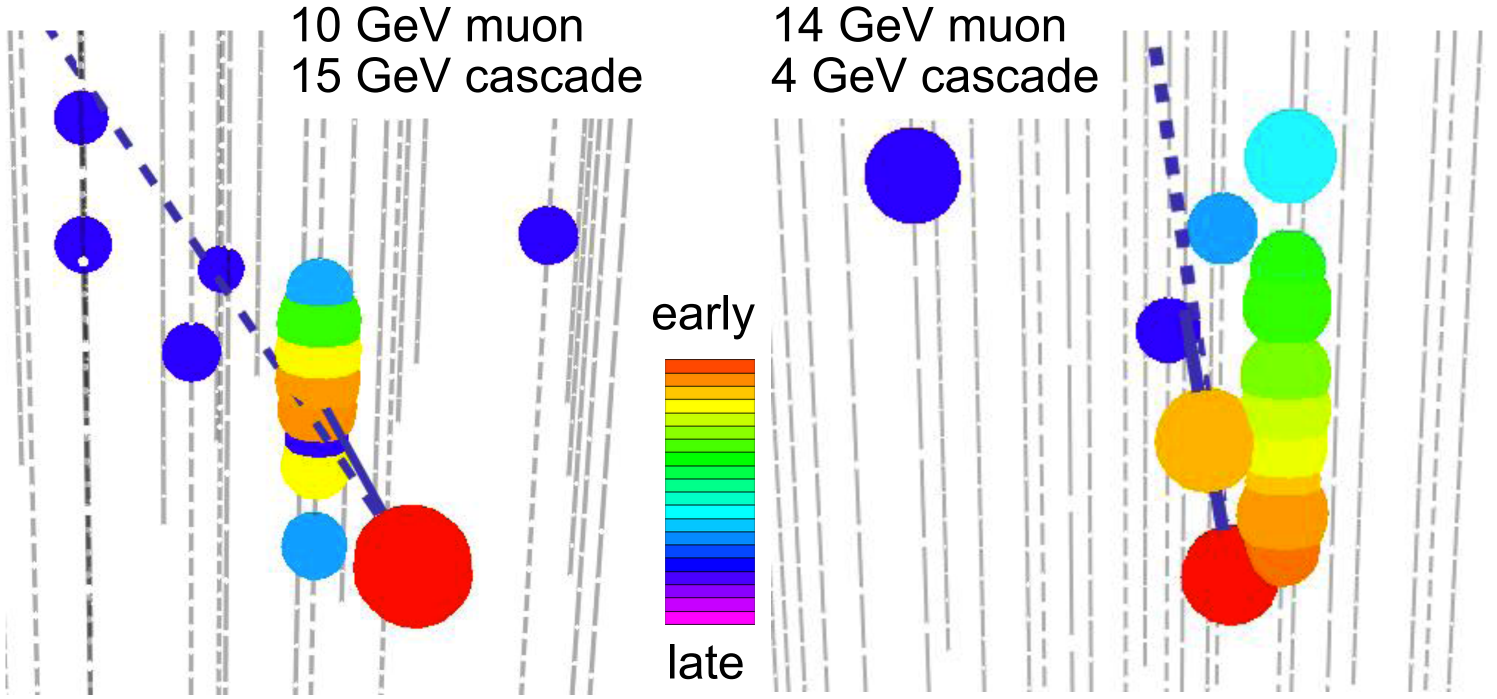
- **few hits** per event
- light is scattered and absorbed
- module self-noise

Method

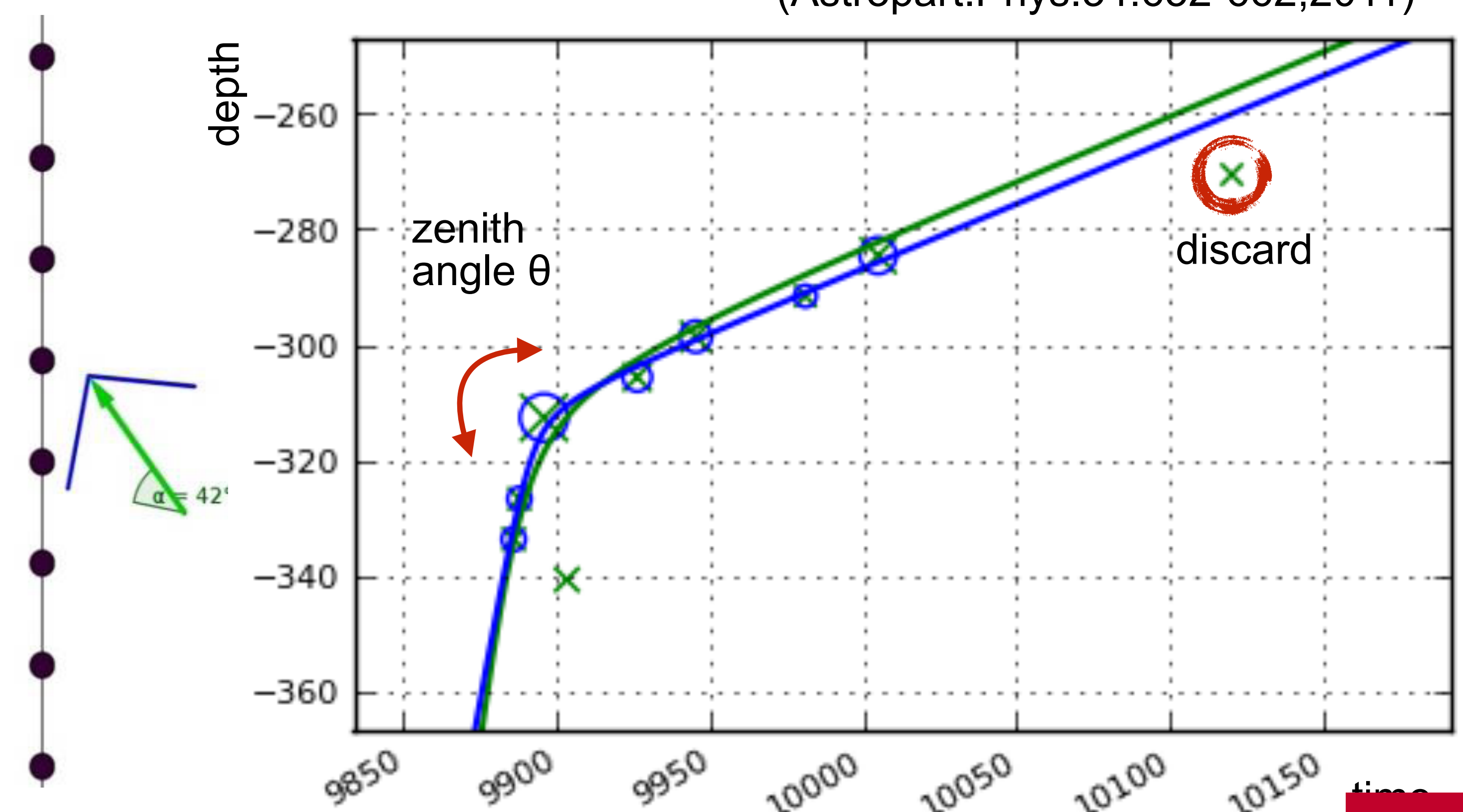
- only use direct (unscattered) light

Energy resolution

- $\sigma_E \sim 25\%$ ($E_\nu > 10$ GeV)
- $\sigma_\theta \sim 15^\circ$-$5^\circ$ ($E_\nu >$ 5 GeV)



(Astropart.Phys.34:652-662,2011)

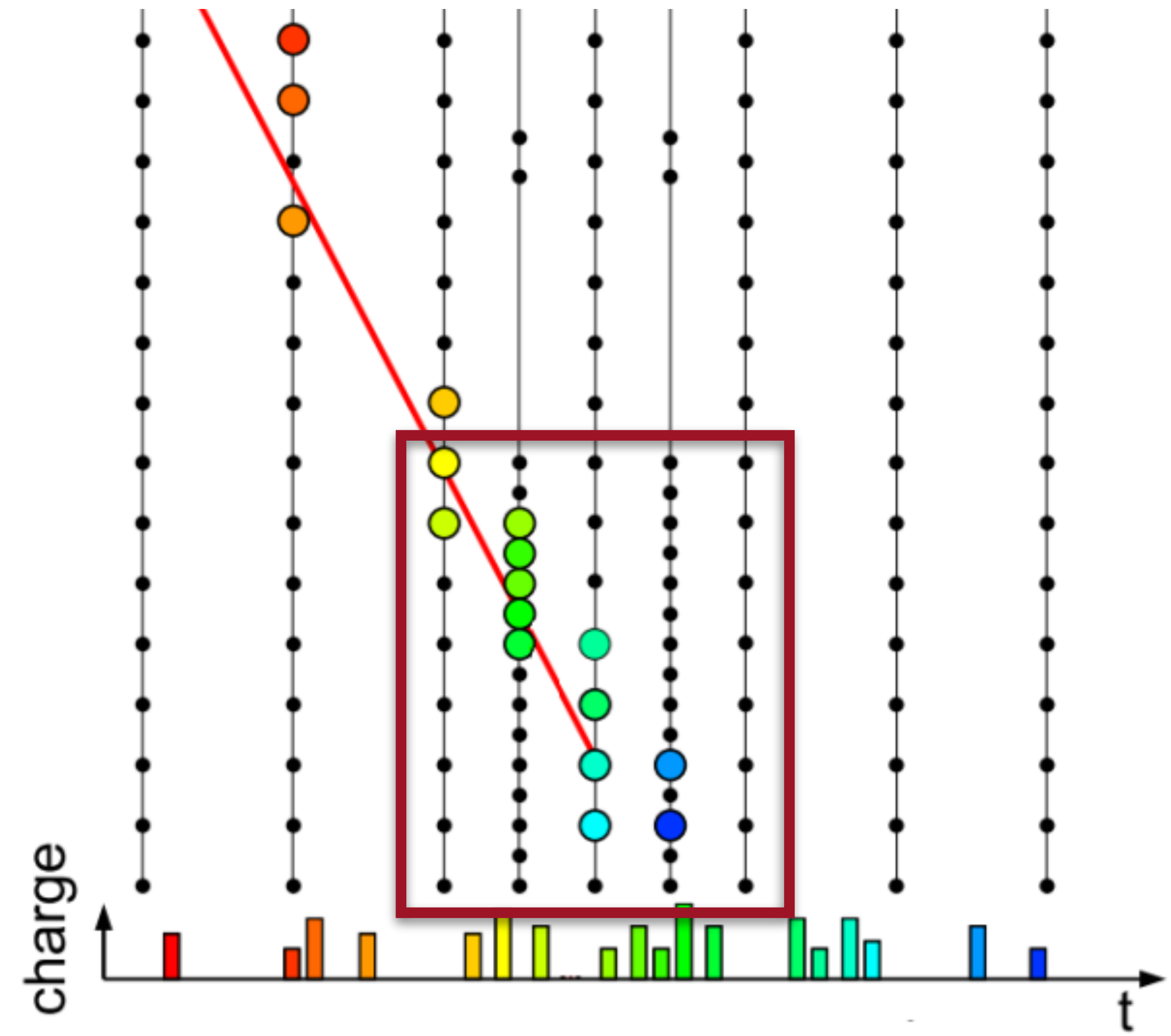


Standard oscillation analysis

The challenge: muon background

- Trigger level
  - 10^6 atm. μ per ν_μ
- Analysis level
  - 10^{-2} atm. μ per ν_μ (DeepCore only)

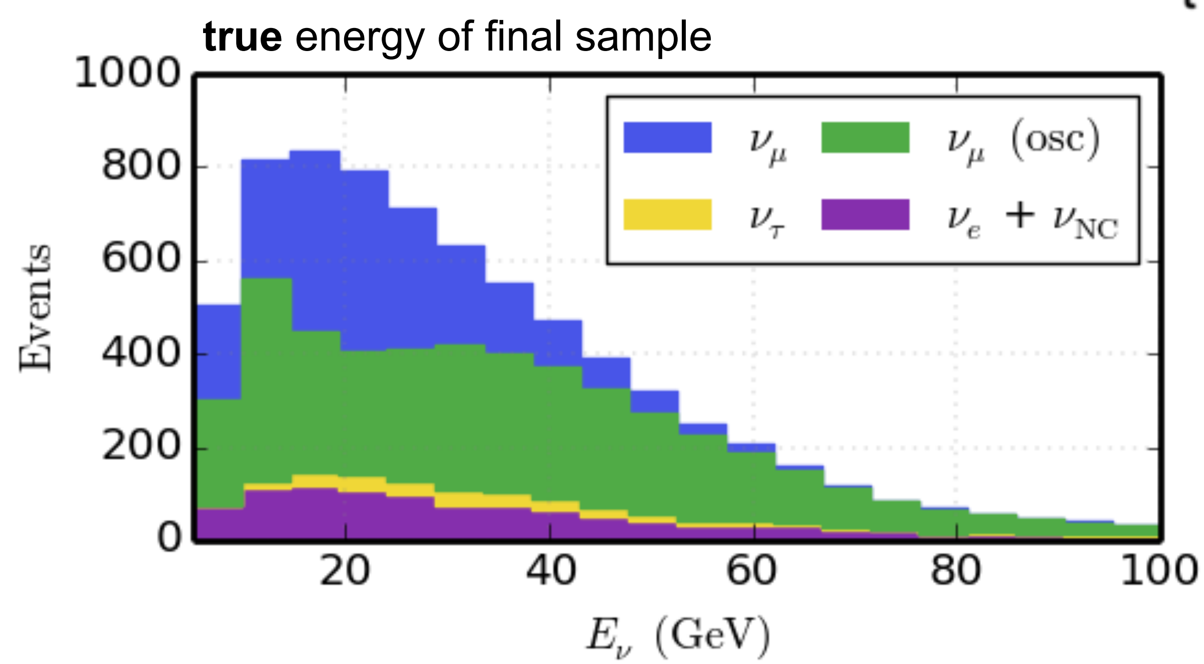
➔ Only use highest-quality events



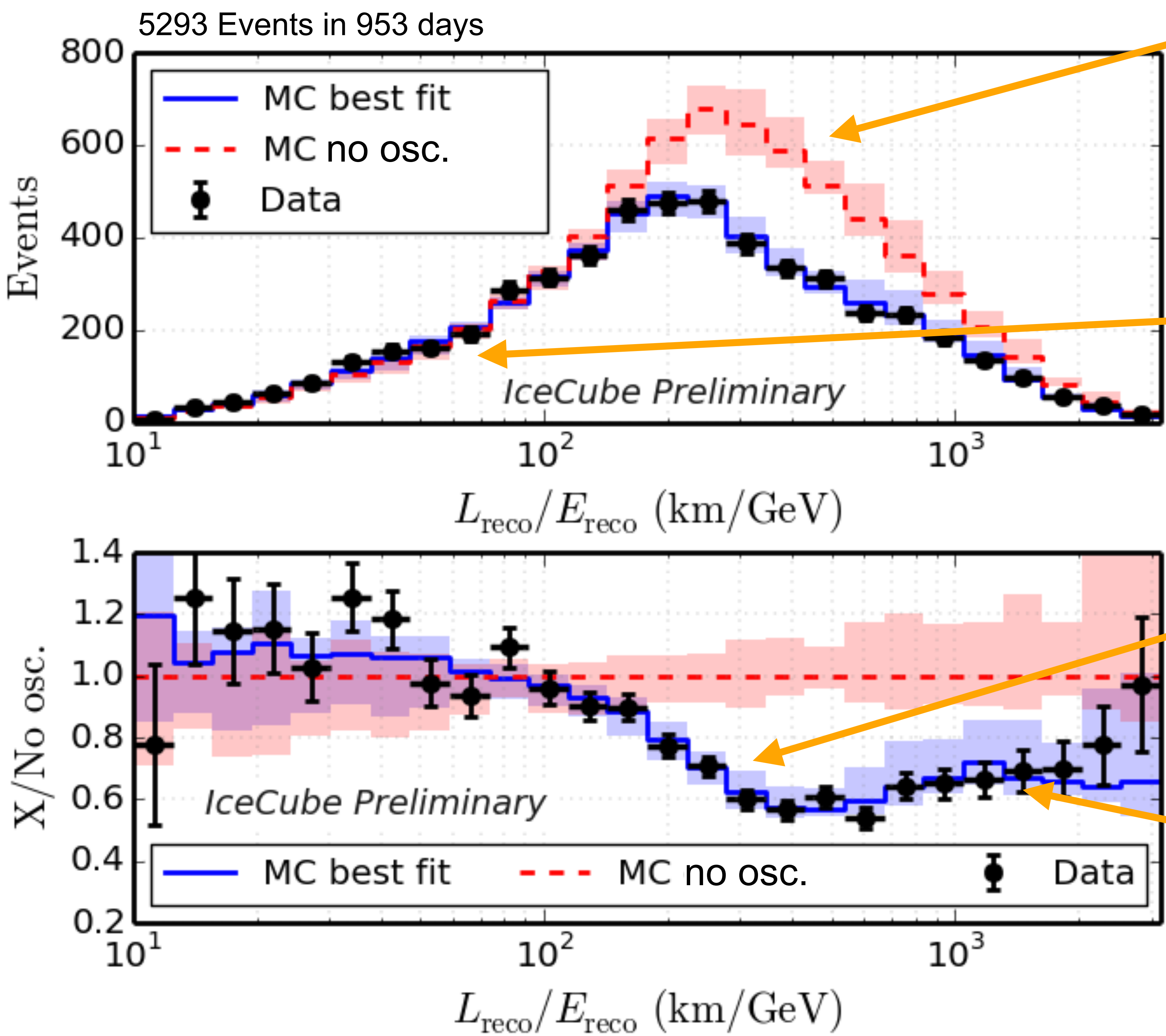
Events at final level

- 3yrs ➔ 953 days livetime

Component	oscillated	no osc.
ν_μ	3755	5900
ν_τ	273	-
ν_e	678	650
ν_{NC}	418	
atm. μ	54	



Oscillation analysis



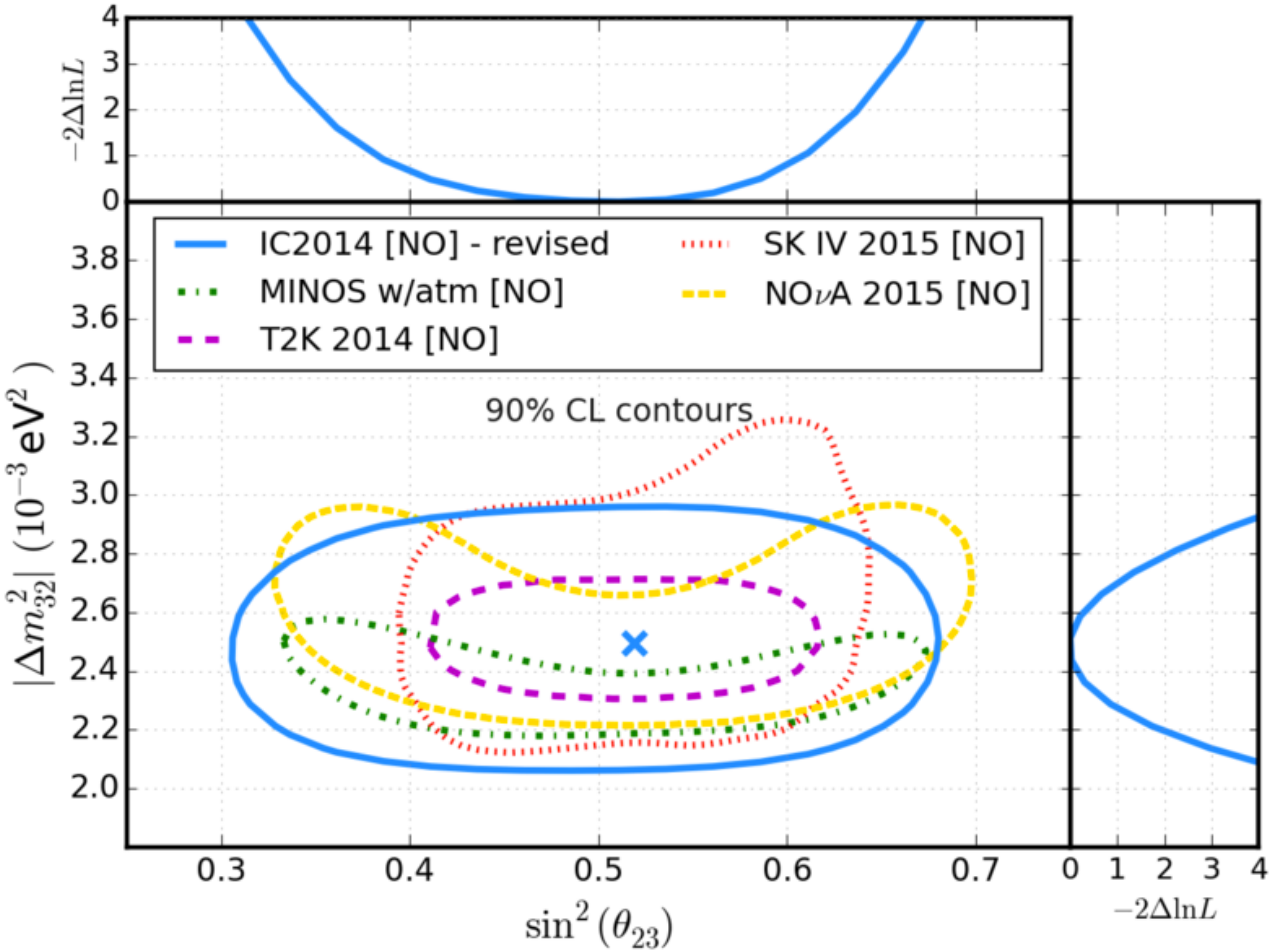
sample peaks at oscillation minimum

good agreement (limited statistics) in control region

good description of oscillation region

observing oscillation maximum and rise

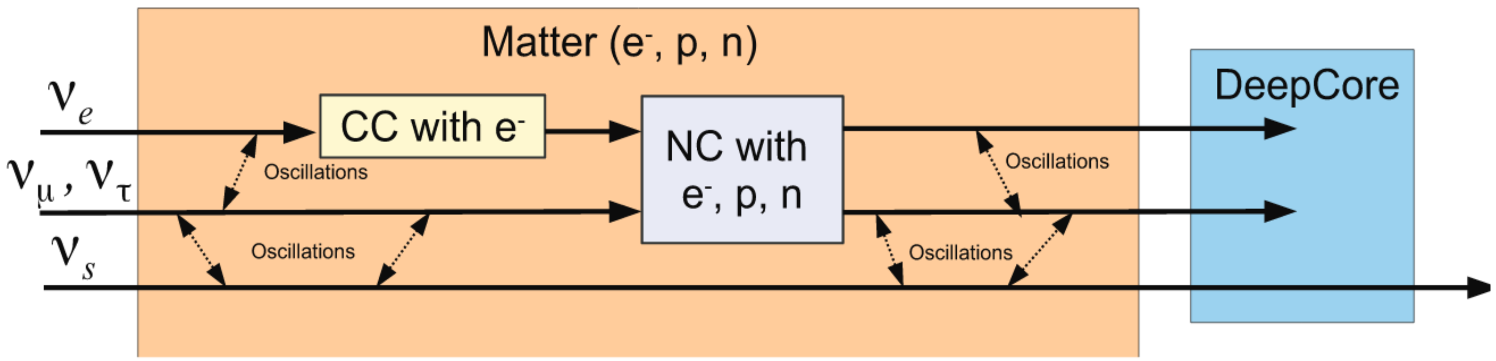
Oscillation result



DeepCore

- precision oscillation physics comparable to long-baseline experiments
  - still statistics limited

Sterile neutrinos at low energies

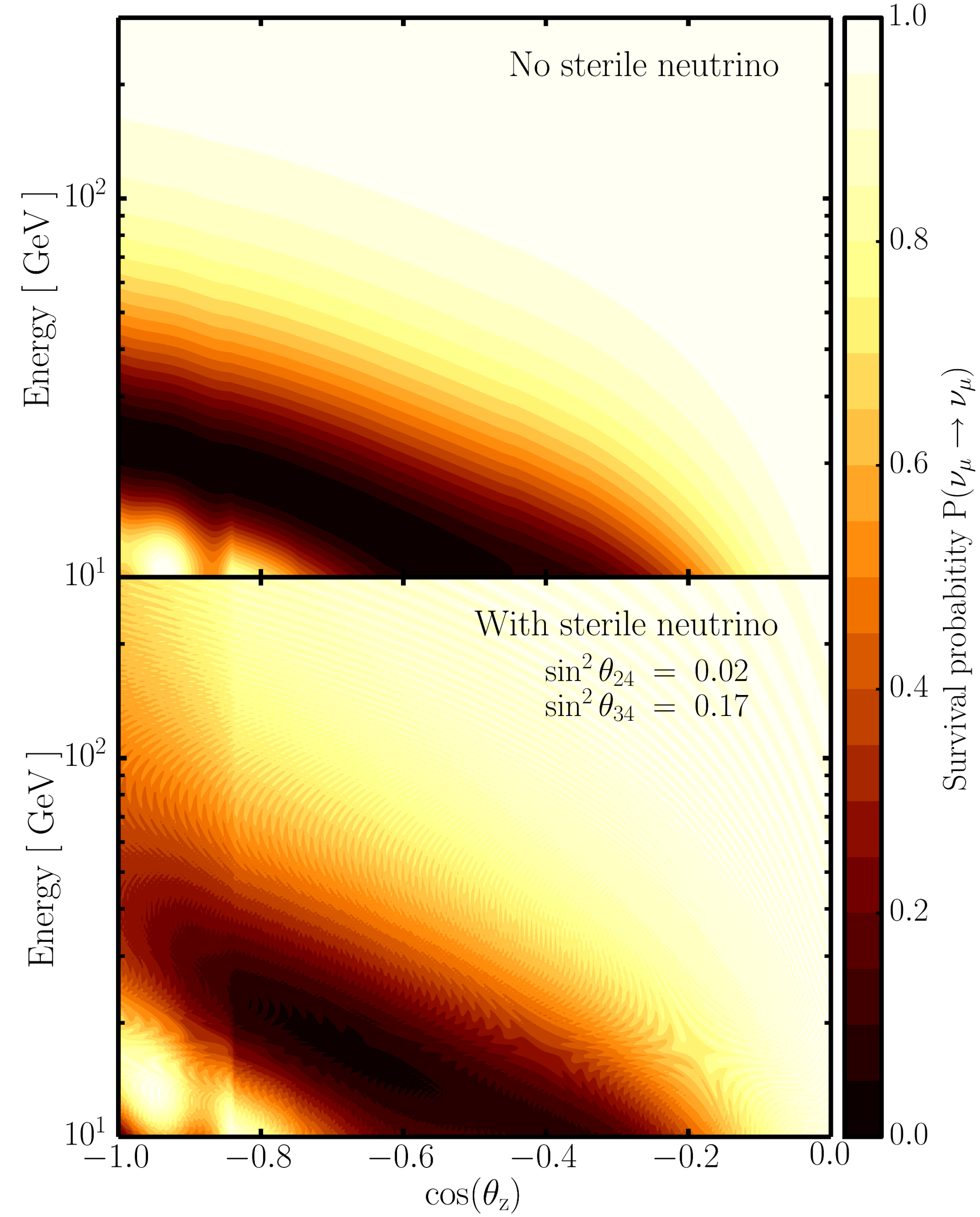


Effects below 100 GeV:

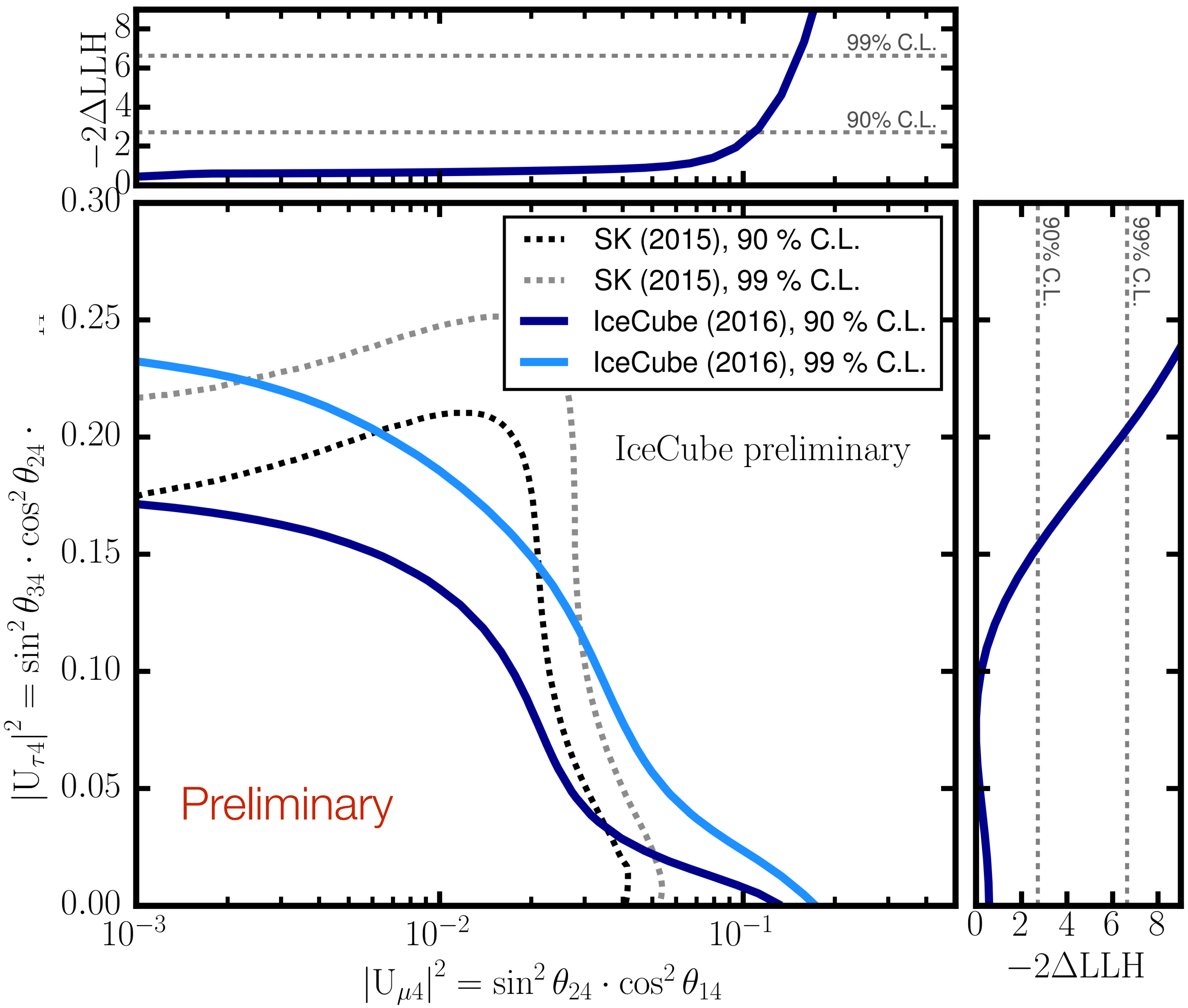
- sensitive to the angles θ24 and θ34
  - shifts of oscillations minimum
  - changes of amplitude

Characteristics

- effects proportional to matter density
  - highest sensitivity in core
- for Δm41² > 0.3eV² (resolution limit)
  - independent of sterile neutrino mass



Sterile neutrinos at low energies: results



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

Outlook

High-energy muon neutrinos

- high sensitivity to sterile neutrinos via resonance-like mixing in earth core
  - previous ~1eV^2 sterile neutrino best-fit mostly excluded

Low-energy neutrinos (both ν_e and ν_μ)

- sensitivity to $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$

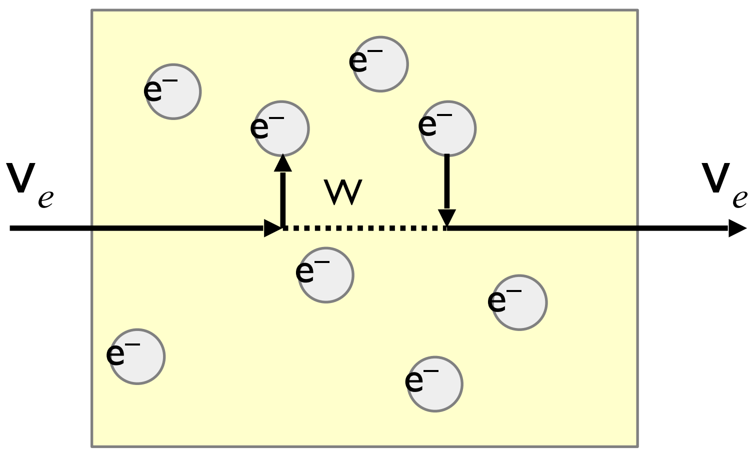
Outlook

- more then 6 yrs of data recorded by now
- improved methods
  - starting tracks with better energy resolution for high energy
  - improved reconstruction criteria for low energy

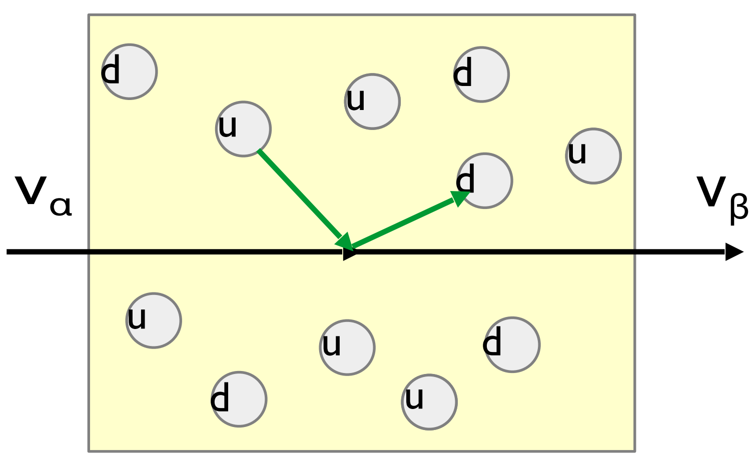
We will keep exploring!

Non-standard interactions

Standard interactions



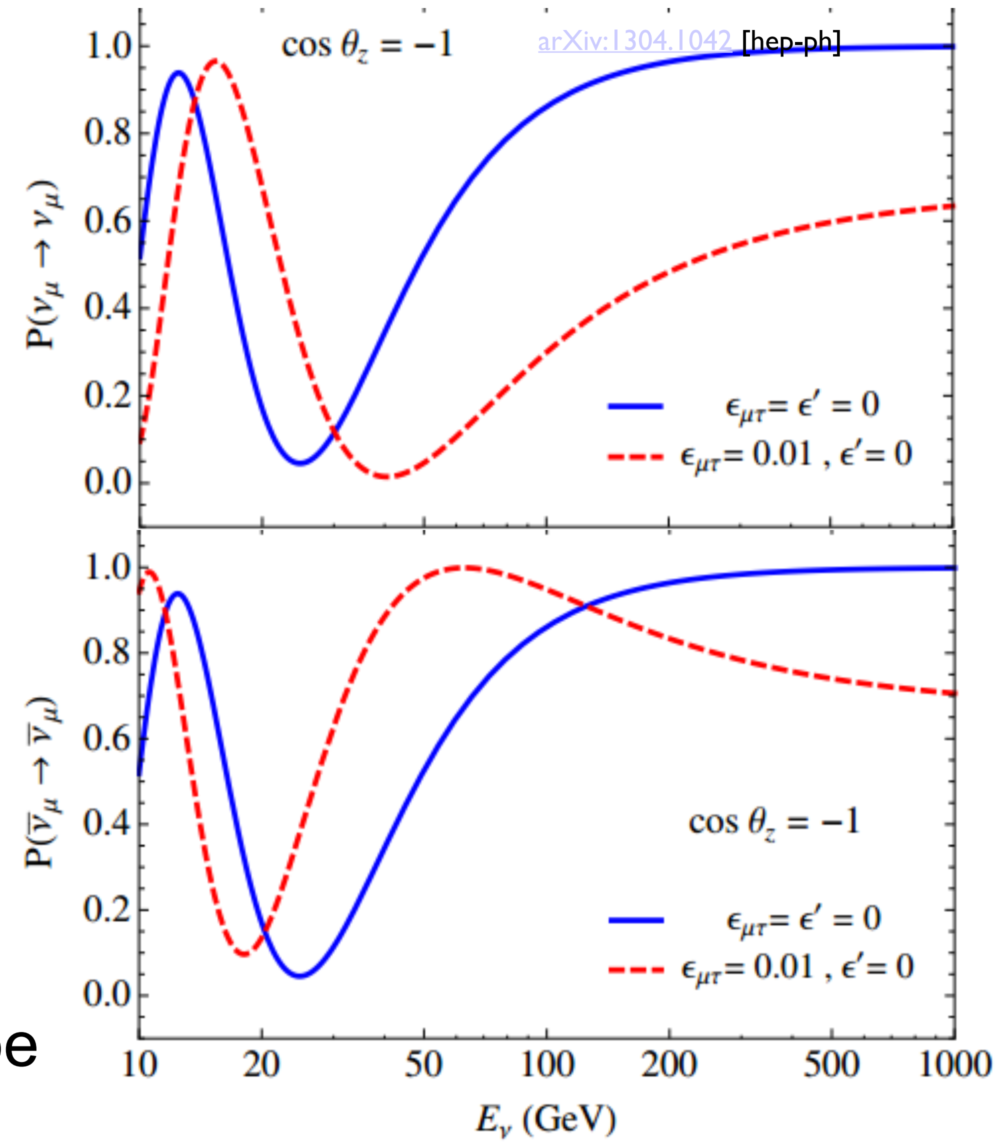
Non-standard interactions



- Evolution of flavors

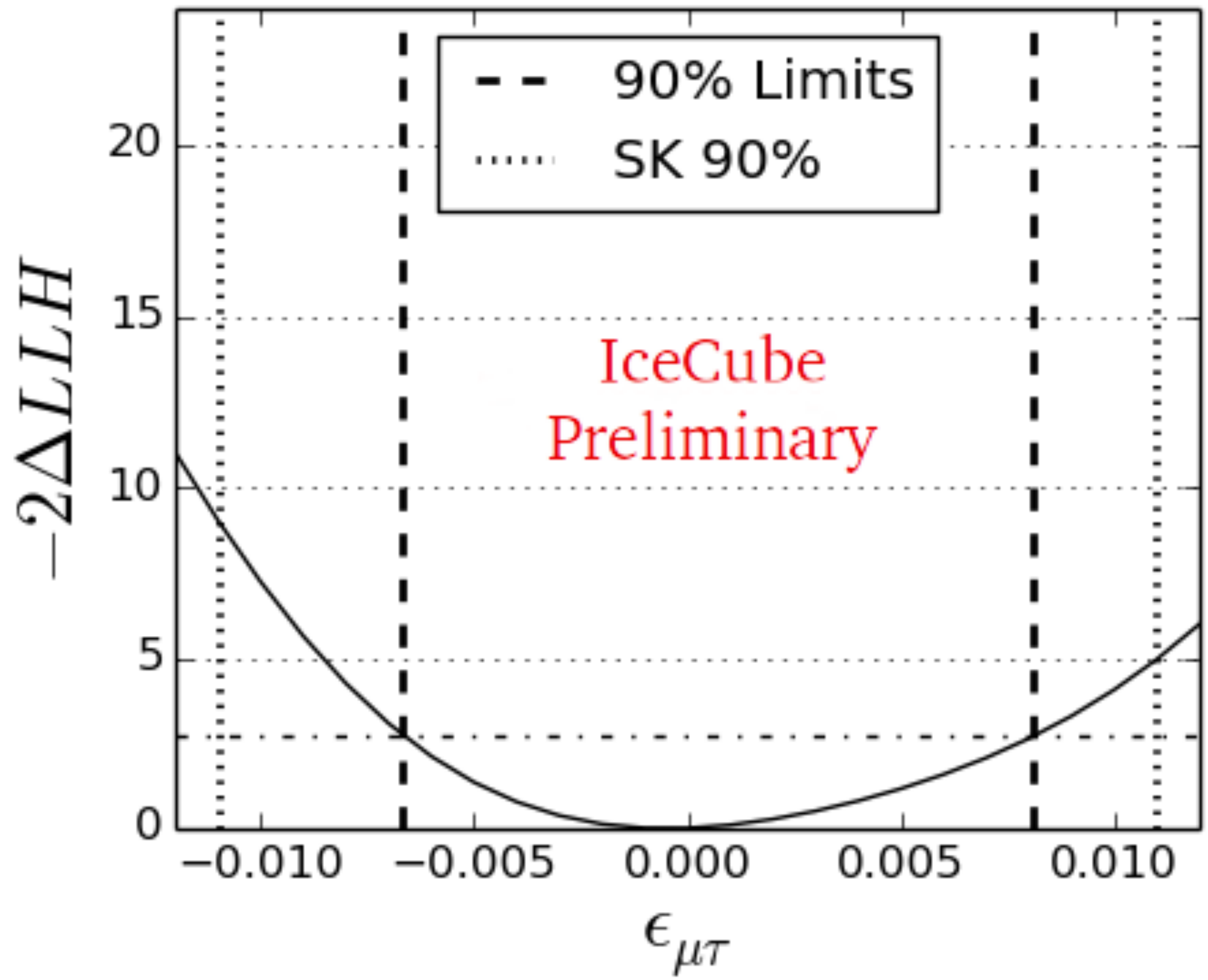
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu}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

NSI coefficients



- Modifications of the oscillations pattern
- Possible to measure/constrain with IceCube

Non-standard interactions: results



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