Neutrino oscillations with IceCube

State of the art measurements

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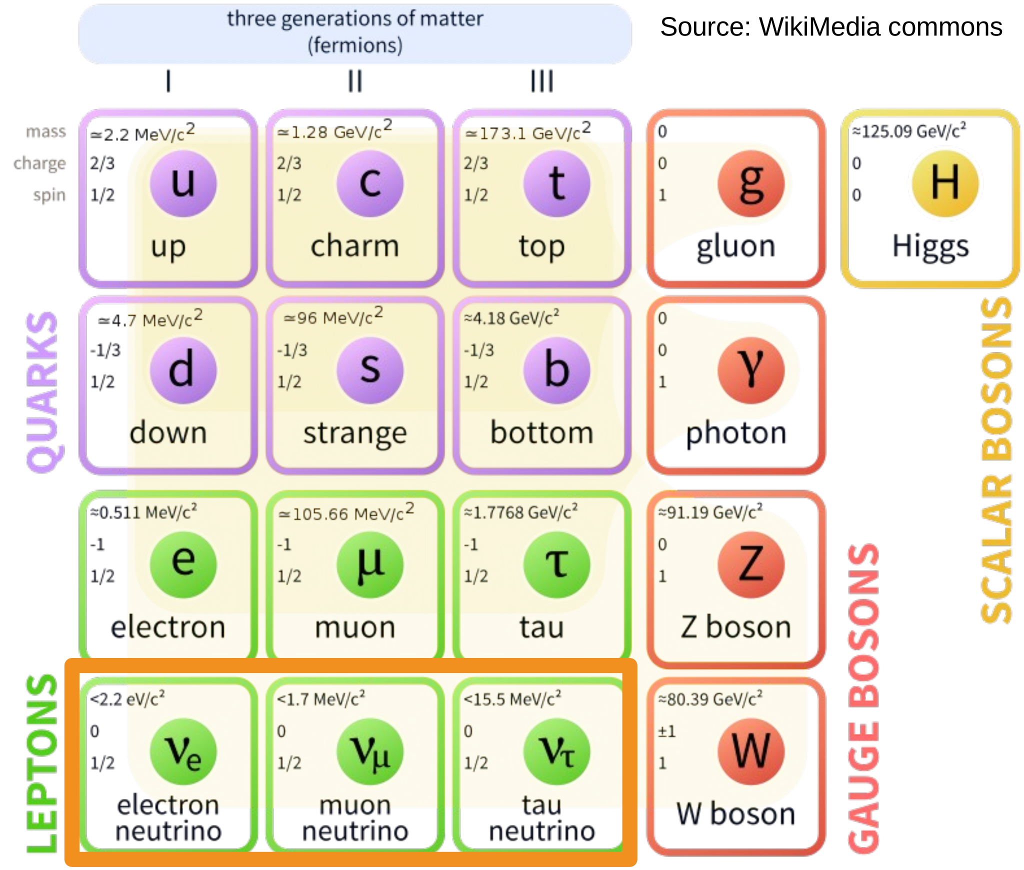
DESY, Zeuthen

CPPM seminar, 19.11.2018

The Standard Model and neutrinos

A theory of everything?

Source: WikiMedia commons



> Standard Model:
- gauge theory
- behavior of elementary particles

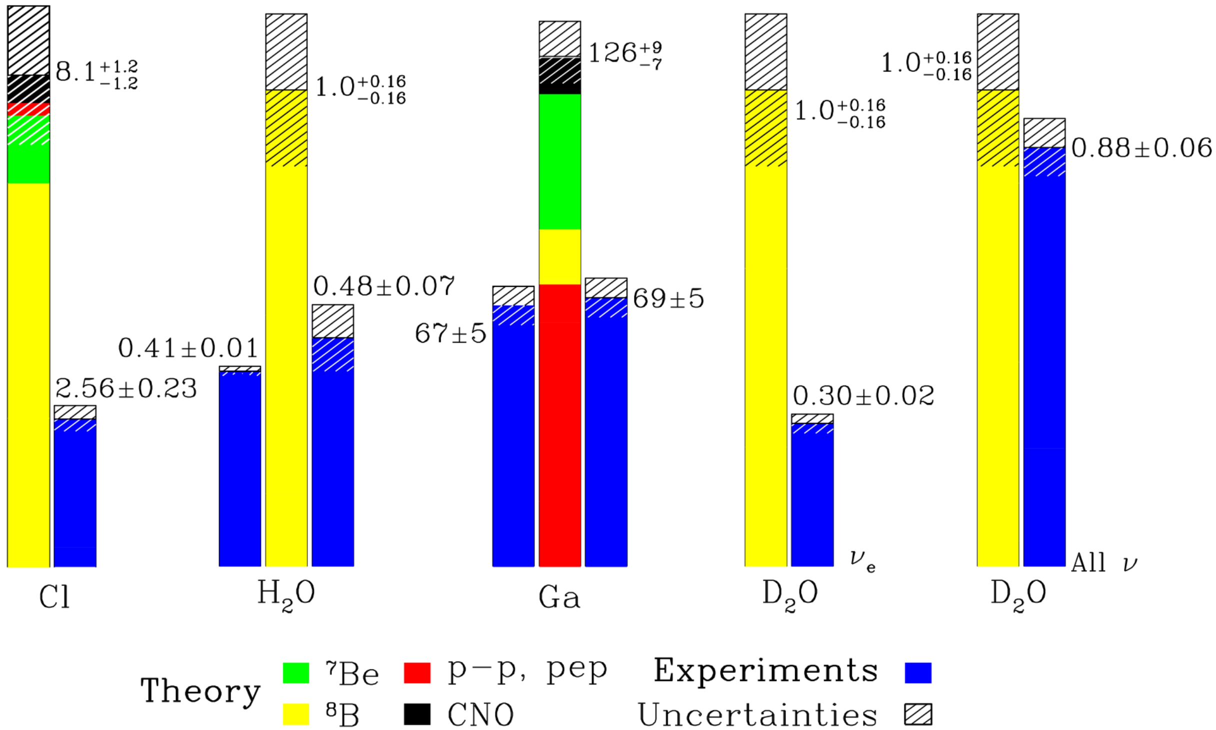
> Neutrinos in SM:
- 3 families
- Only weak interaction
- Left-handed
- Mass-less

> Existence of neutrino oscillations:
- Weak != propagation states
- Neutrinos have mass

> Requires modification of the Standard Model
- Right handed neutrinos
- Potential new symmetry or new physical processes

Neutrino oscillations

Solar neutrino problem



- Way less ν_e
- Transition of neutrinos between types!

Expectation

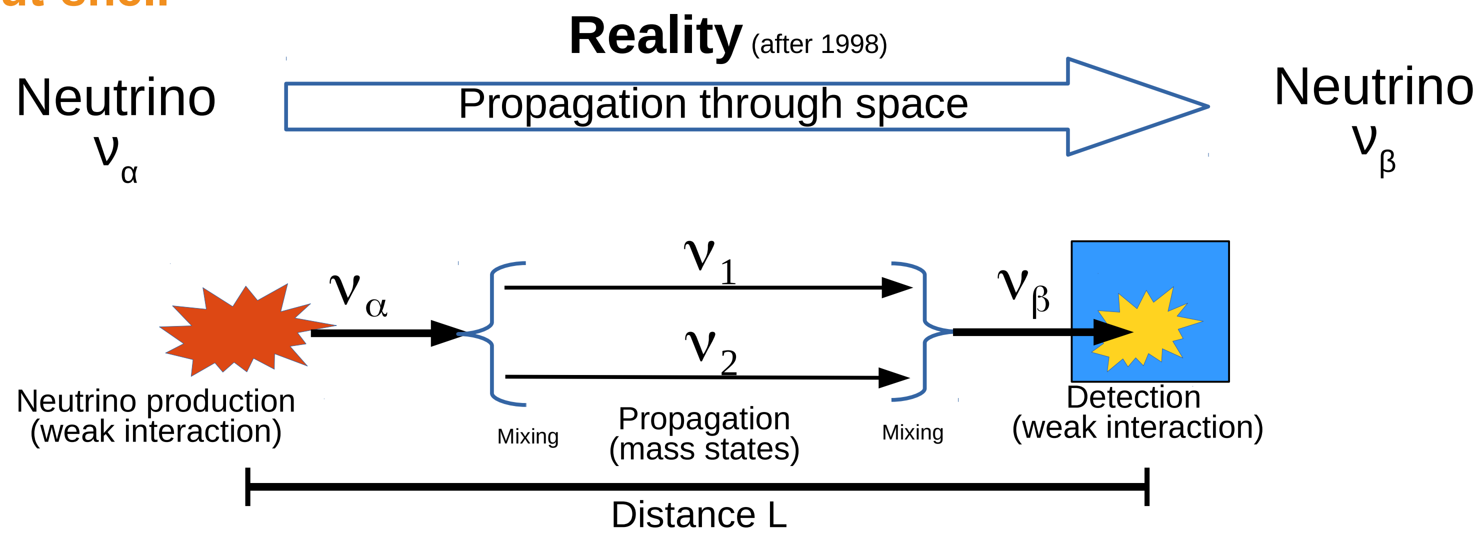
Neutrino ν_α → Propagation through space → Neutrino ν_α

Reality (pre 1998)

Neutrino ν_α → Propagation through space → Way less of neutrino ν_α

Neutrino oscillations

In a nut-shell



> Neutrino propagation and interaction states are different!

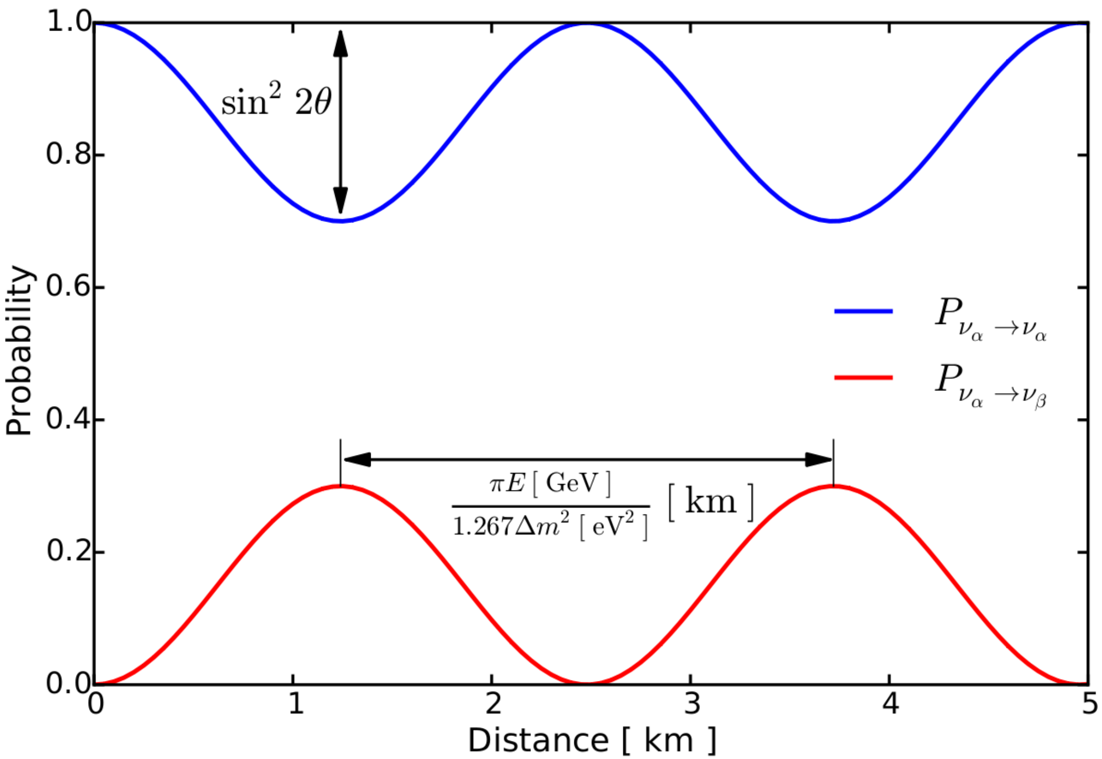
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavor (“weak”) states — Neutrino mixing — Mass (“propagation”) states

> Mass states have slightly different speeds → quantum interference

Neutrino oscillations

In a nut-shell



$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

> Only possible if neutrinos:
- Have non-zero mixing
- Have non-zero masses non-degenerate masses

> Type change probability:

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2(2\theta) \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

Amplitude

Period $\Delta m^2 = m_2^2 - m_1^2$

Three flavour mixing

Full (almost) PMNS matrix

Flavour (interaction) basis → $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$; PMNS matrix → U ; Mass (propagation) basis → $\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

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

$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric mixing}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor mixing}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar mixing}}$$

Atmospheric mixing: $\nu_\mu \leftrightarrow \nu_\tau$ — Reactor mixing: $\nu_e \leftrightarrow \nu_\tau$ — Solar mixing: $\nu_e \leftrightarrow \nu_\mu$

- Naming by the corresponding source
- Similar to CKM matrix:
  - Mixing angles are way larger in comparison

*(Majorana phases are ignored here)

Three-neutrino mixing

Current knowledge

$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

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- 2 mass differences

$$\Delta m^2_{sol} = \Delta m^2_{21} \approx 7.5 \cdot 10^{-5}\ \text{eV}^2$$

$$|\Delta m^2_{atm}| \approx |\Delta m^2_{32}| \approx 2.5 \cdot 10^{-3}\ \text{eV}^2$$

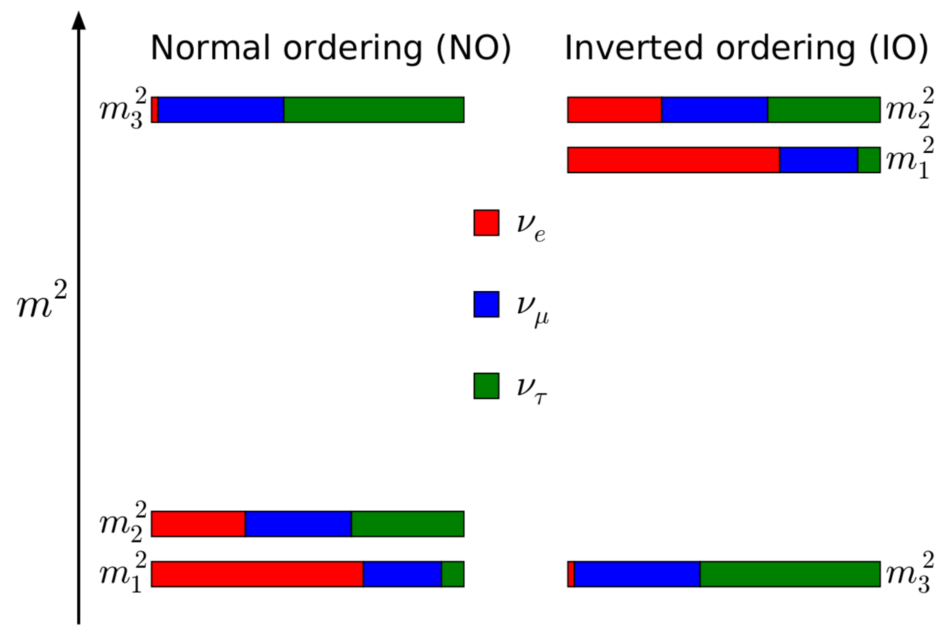
- 3 mixing angles

$$\sin^2\theta_{12} \approx 0.31 \qquad \sin^2\theta_{13} \approx 0.022$$

$$\sin^2\theta_{23} \approx 0.4 \ldots 0.6$$

- Unknown properties:
  - Neutrino mass ordering ($m_2>m_1>m_3$ or $m_3>m_2>m_1$)
  - (Non-)Maximal θ_{23}
  - CP-violating phase δ

- Precise measurement for possible underlying symmetry identifications are needed!



Three-neutrino mixing

Current knowledge

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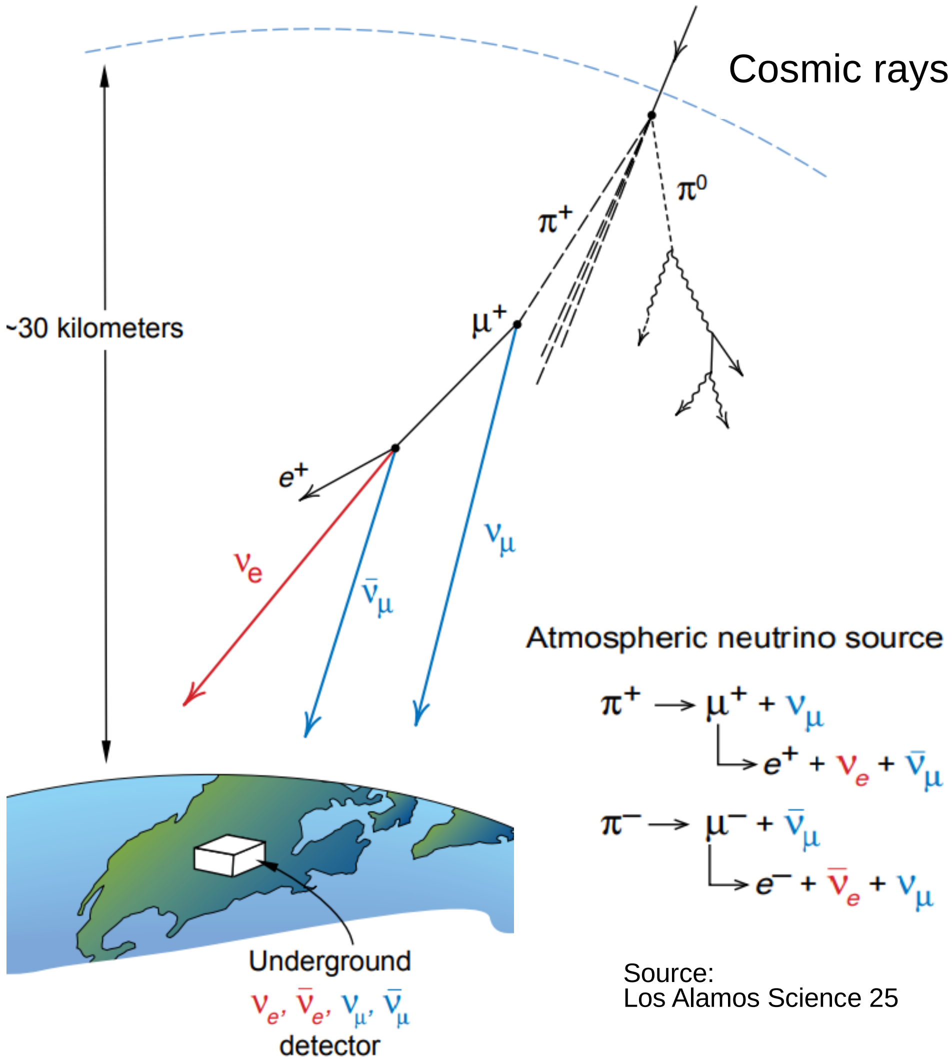
- THIS TALK: measuring atmospheric oscillations with IceCube

Atmospheric neutrinos and oscillations

Atmospheric neutrinos

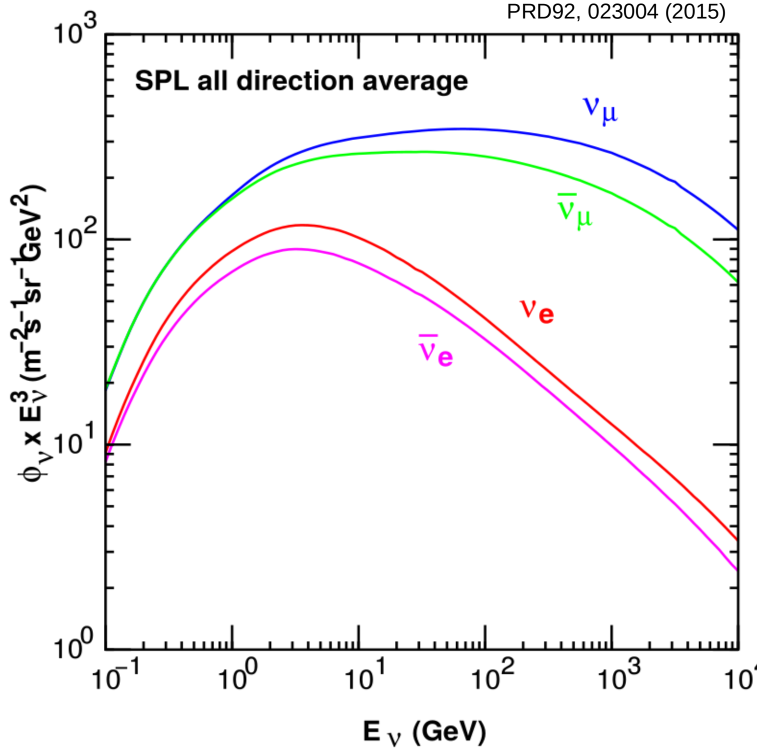
An organic neutrino beam for free!



Source:
Los Alamos Science 25

- Neutrino production from hadron decays (π, K...)
- Energies: 100 MeV – 10+ TeV
- Enormous flux of neutrinos!
- But also muons – main background

PRD92, 023004 (2015)



Atmospheric neutrino oscillations

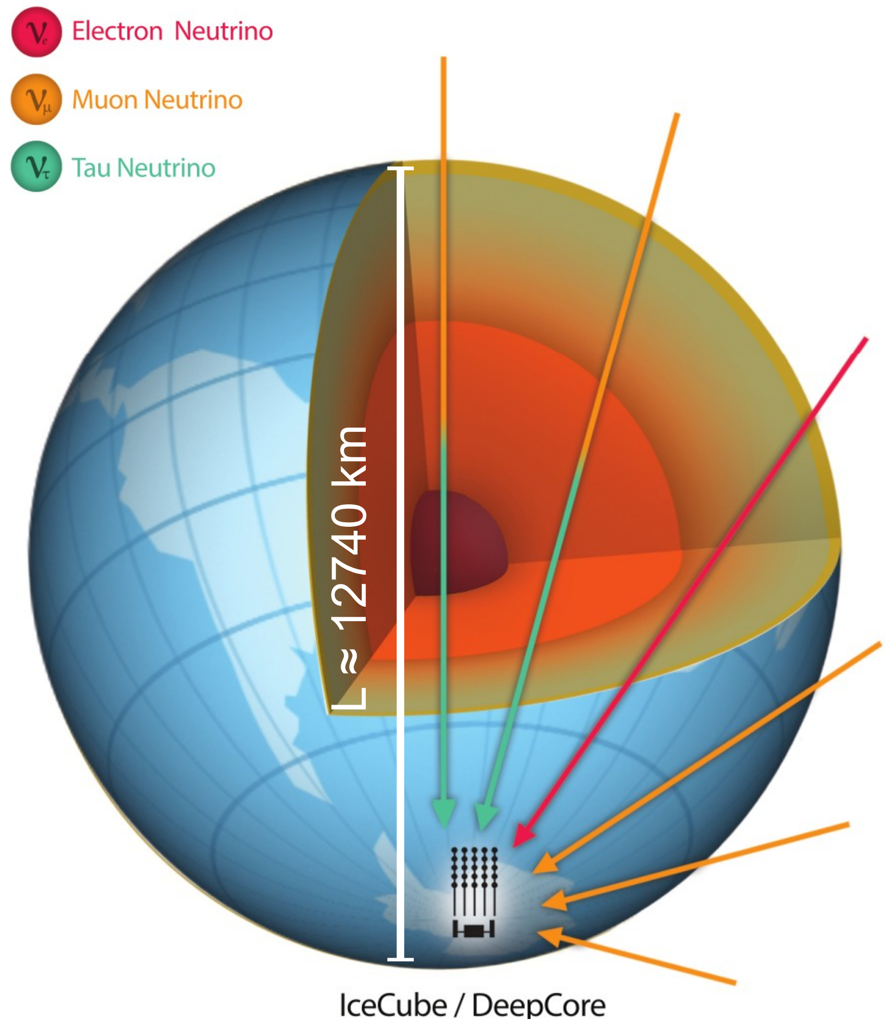
Multi-baseline measurement

- 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

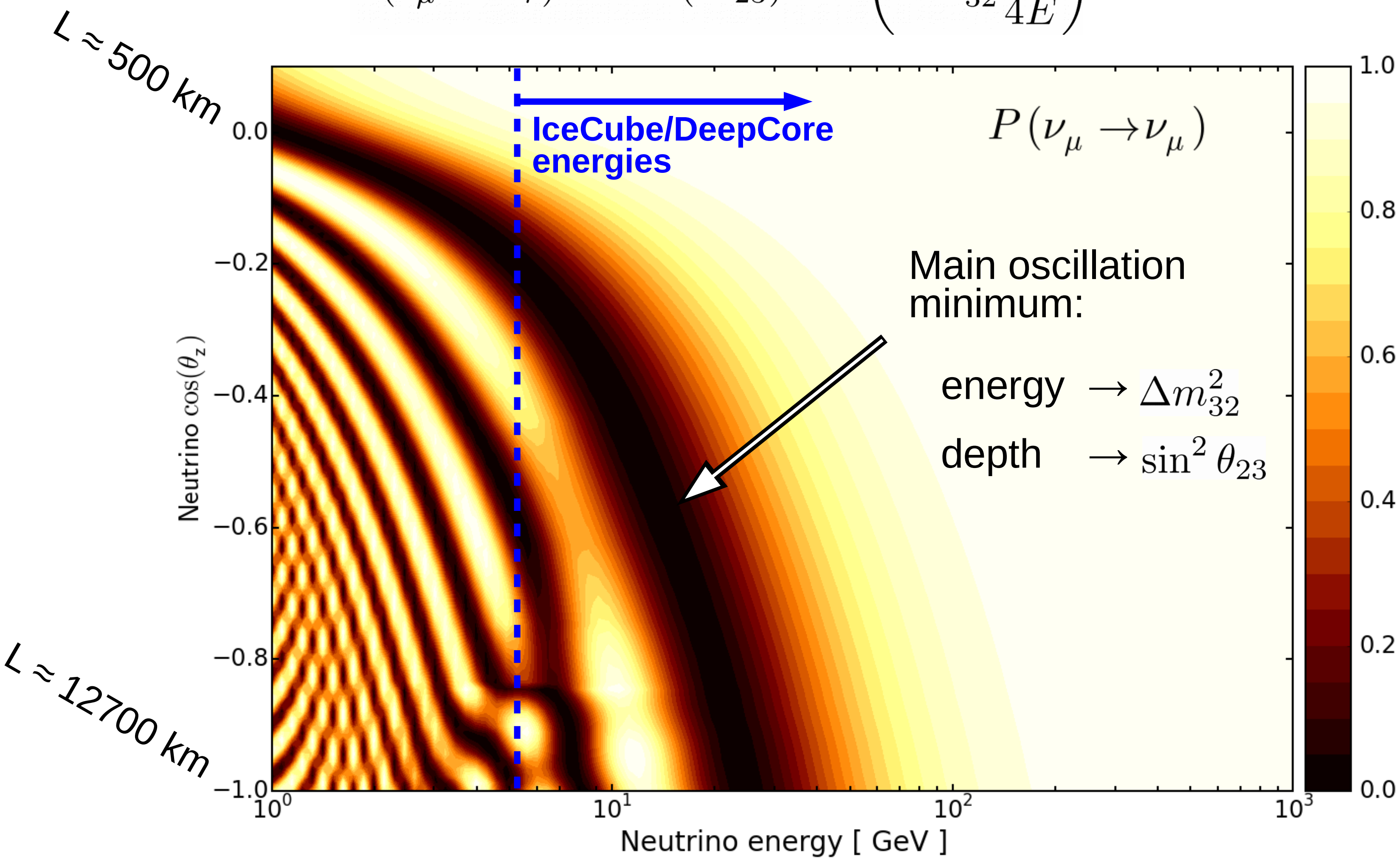
- Disappearance and appearance channels accessible with neutrino telescopes



Atmospheric neutrino oscillations

Muon neutrino → tau neutrino transition

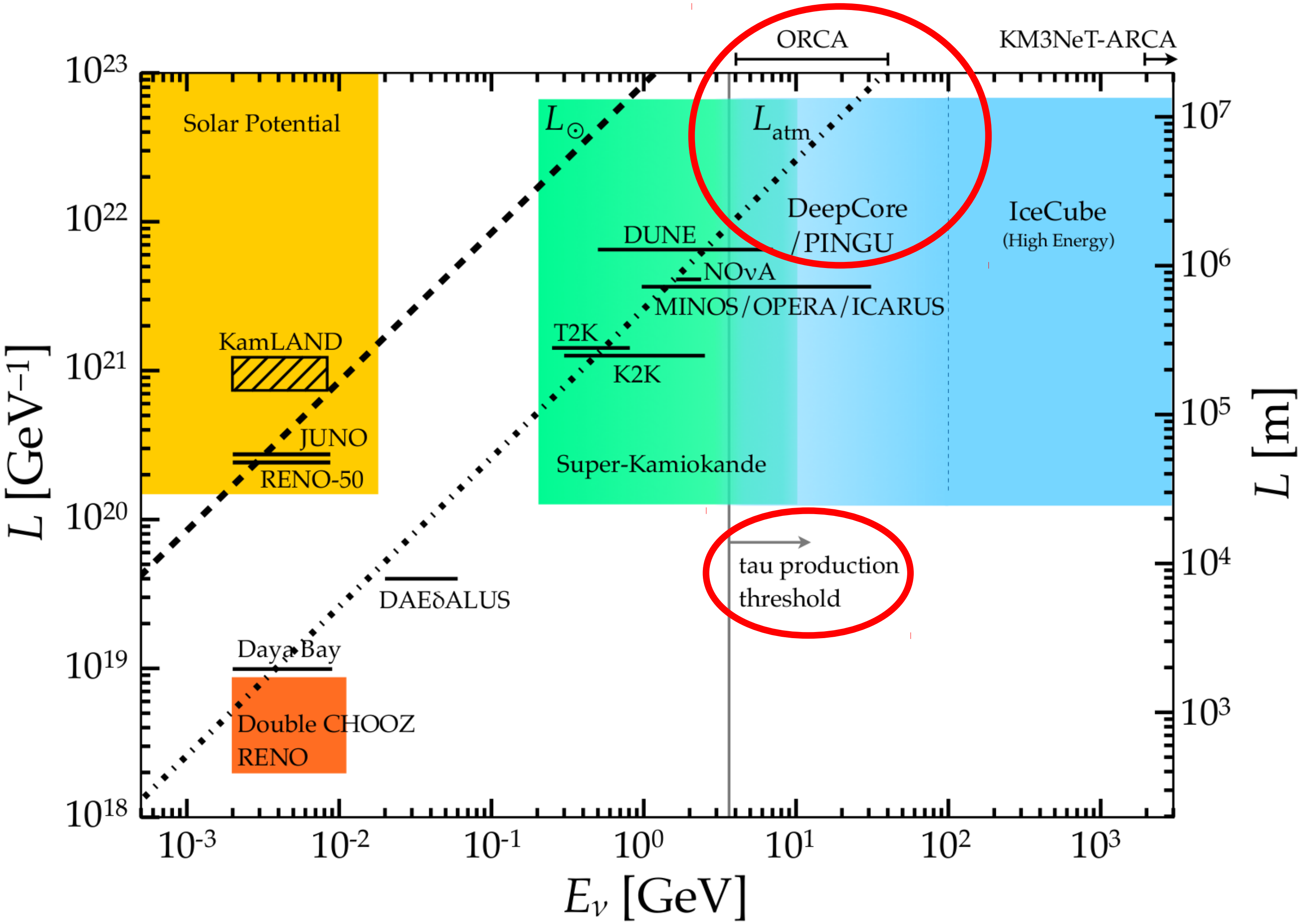
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2 \left(\Delta m^2_{32} \frac{L}{4E} \right)$$



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

Atmospheric neutrino oscillations

A unique way to probe oscillations at the highest energies



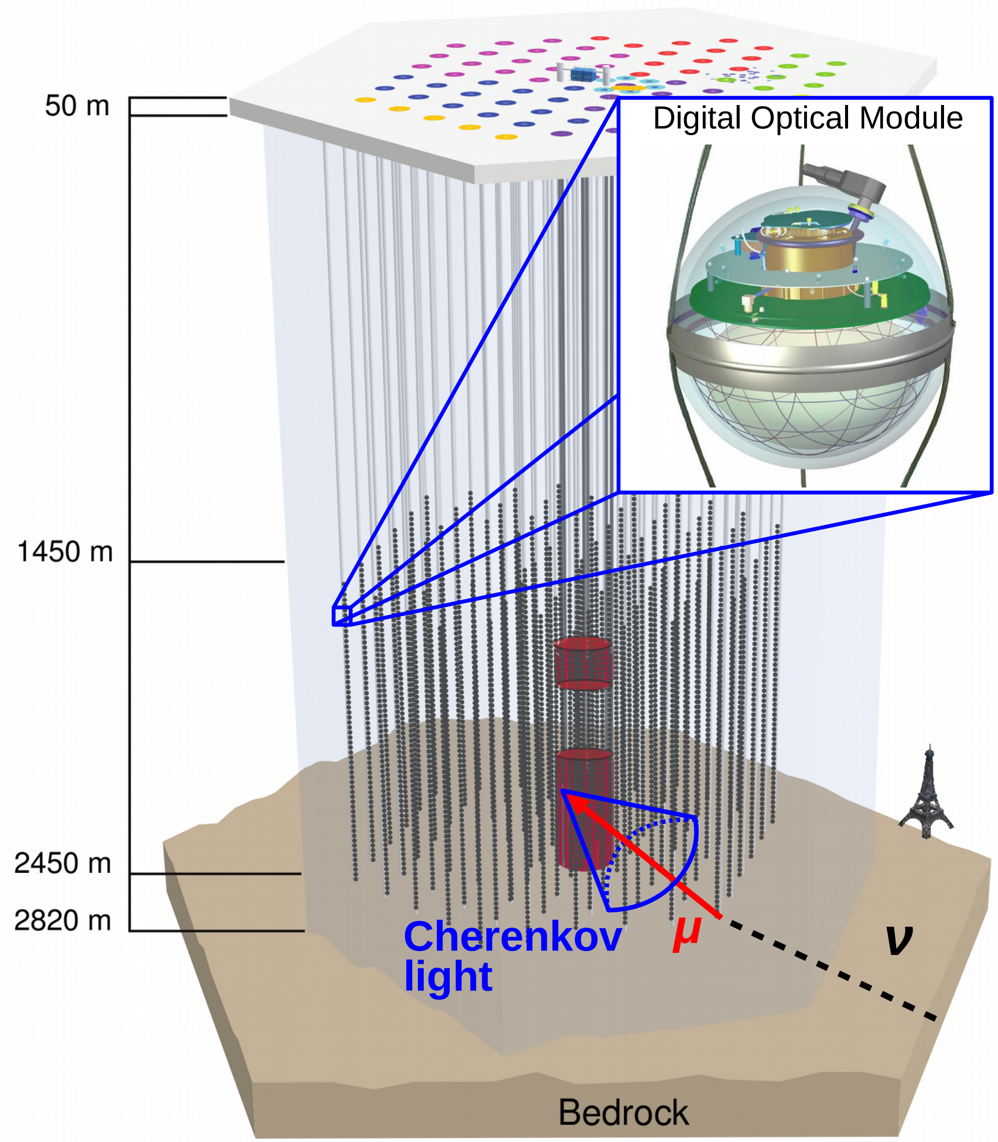
What is IceCube?

IceCube Neutrino Observatory

A cubic kilometer detector

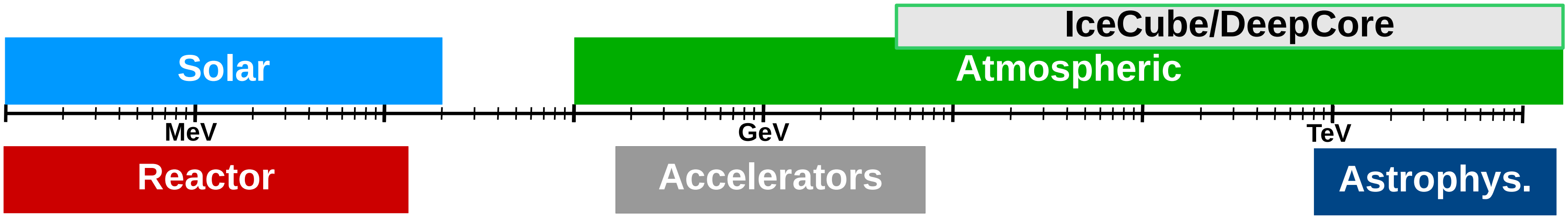
- **IceCube detector:**
  - 5160 DOMs with 10" PMTs
  - Ice as optical medium
  - Cherenkov light detection
- **DeepCore sub-detector:**
  - The clearest ice
  - Denser instrumentation
  - +35% higher quantum efficiency
  - IceCube as active veto against atmospheric muons

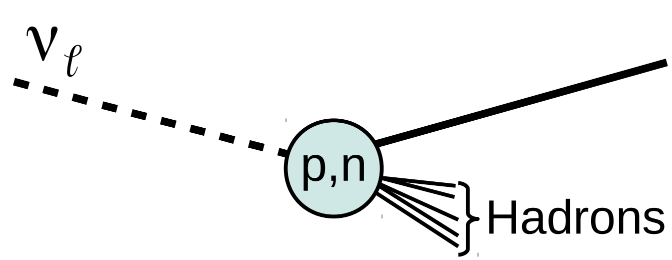
	Hor. [m]	Vert. [m]	Threshold [GeV]
IceCube	125	17	~100 GeV
DeepCore	40-60	7	~5 GeV



IceCube Neutrino Observatory

What events do we measure





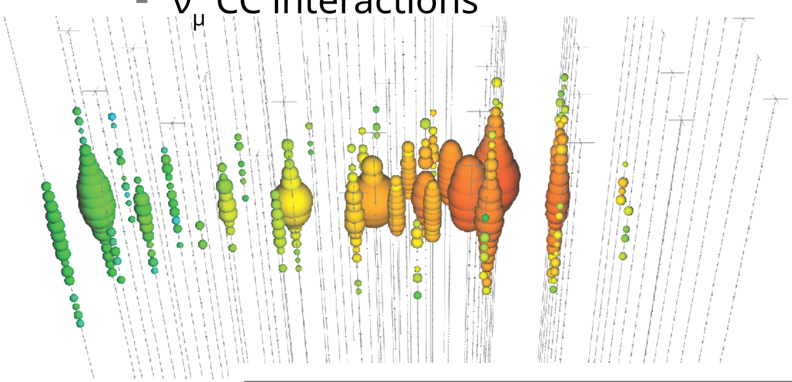
ℓ – charged current (CC) interaction

ν_ℓ – neutral current (NC) interaction

> Secondary particles emit Cherenkov light

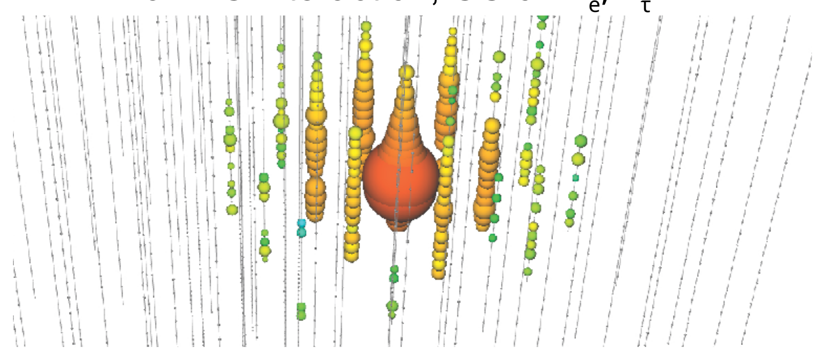
> Track like events:

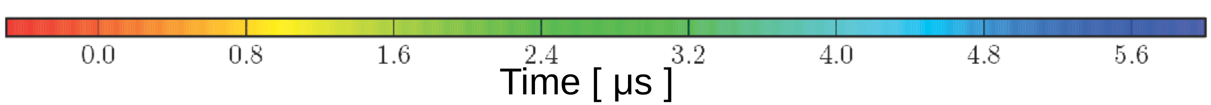
- ν_μ CC interactions



> Cascade like events:

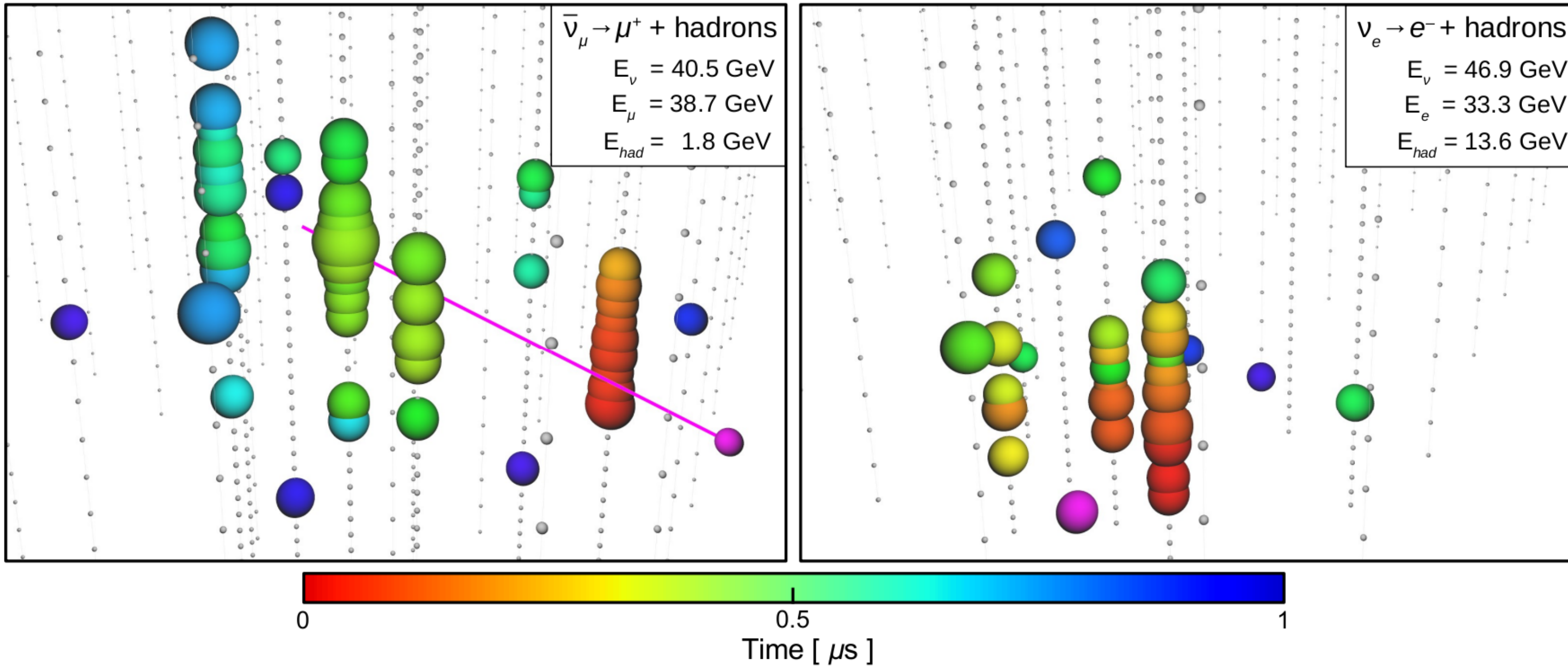
- all NC interaction, CC of ν_e, ν_τ





IceCube Neutrino Observatory

Events in DeepCore



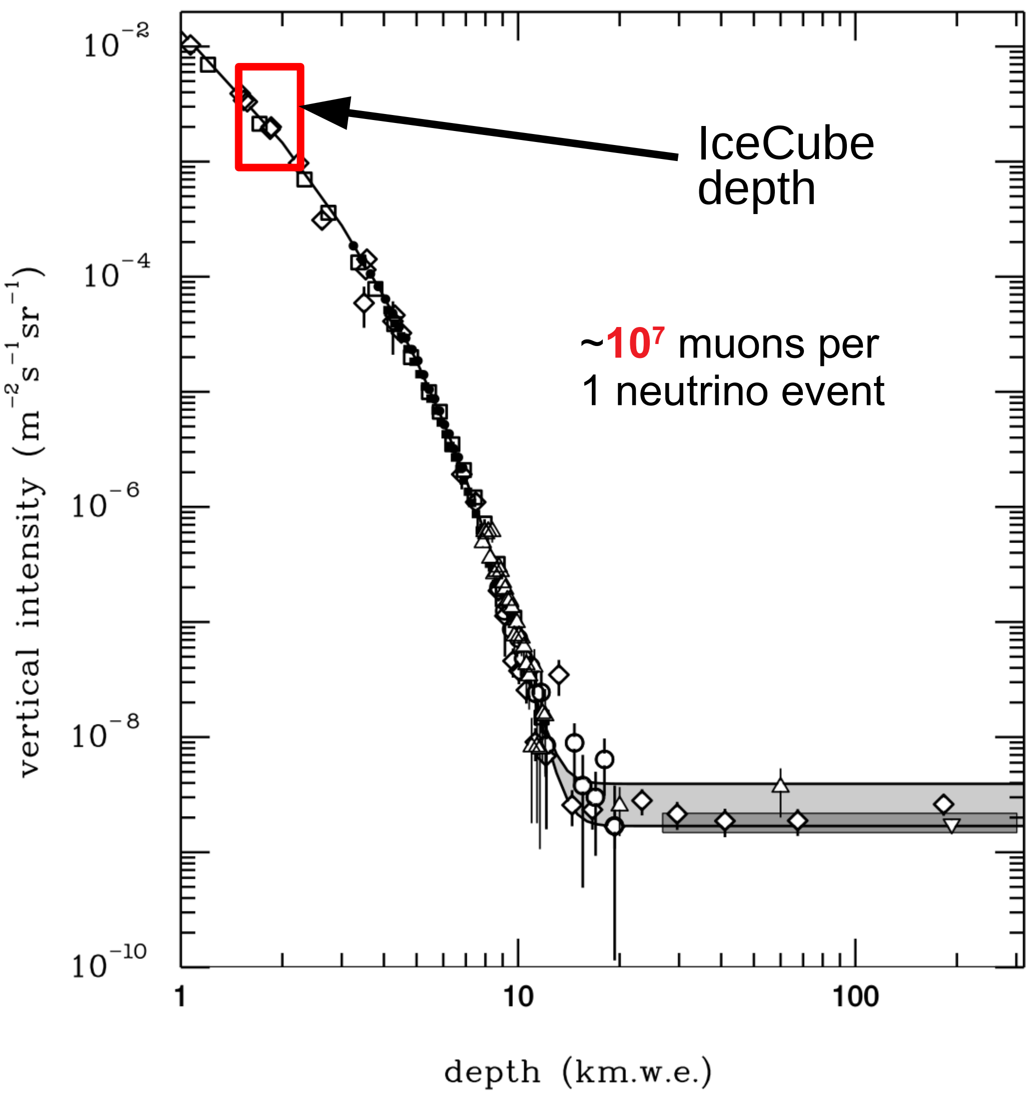
> Events below 50 GeV:
- Dim and produce little light
- More affected by detector uncertainties
- Challenging to select
- Challenging to reconstruct

Careful treatment of systematic uncertainties is a key

Measurement of the standard neutrino oscillations

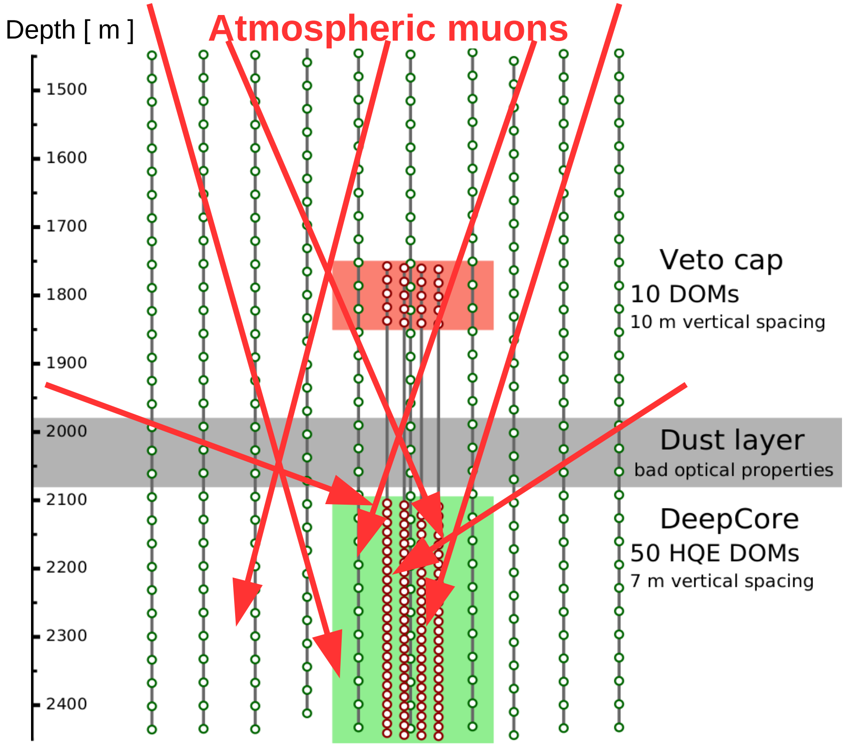
Measuring oscillations in IceCube

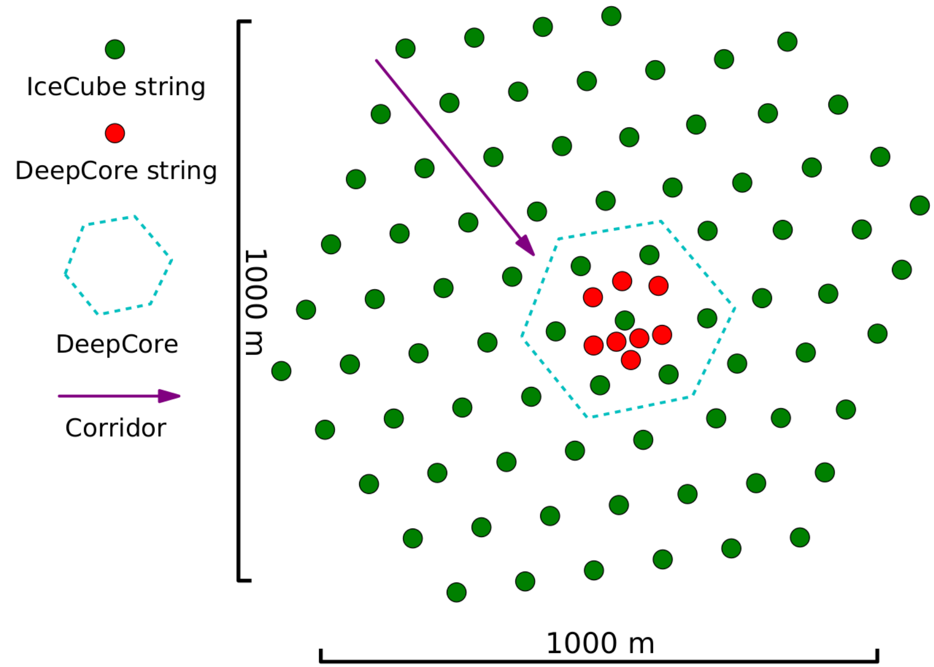
Rejecting the background



Measuring oscillations in IceCube

Rejecting the background

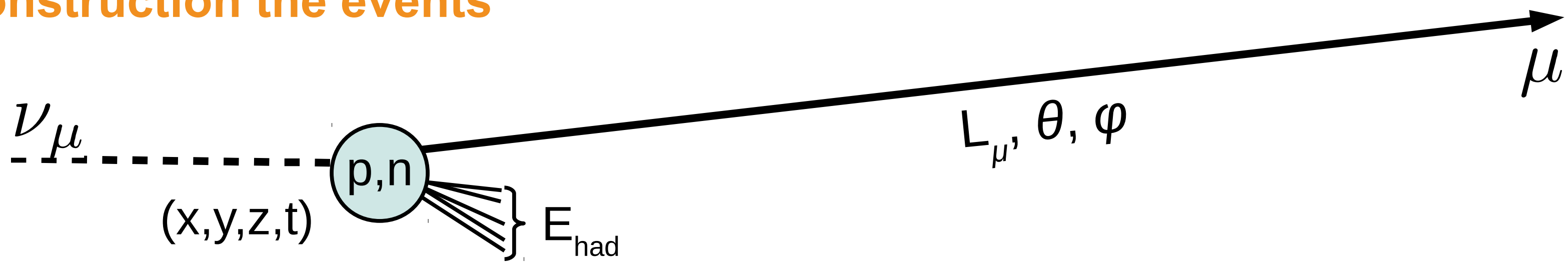




- Vetoing techniques:
  - Checking signals in outer regions of IceCube
  - Containment in DeepCore
- Most complicated muon events:
  - corridors formed by detector geometry
  - “dust layer” above DeepCore
- Dedicated time/space algorithms to reject

Measuring oscillations in IceCube

Reconstruction the events

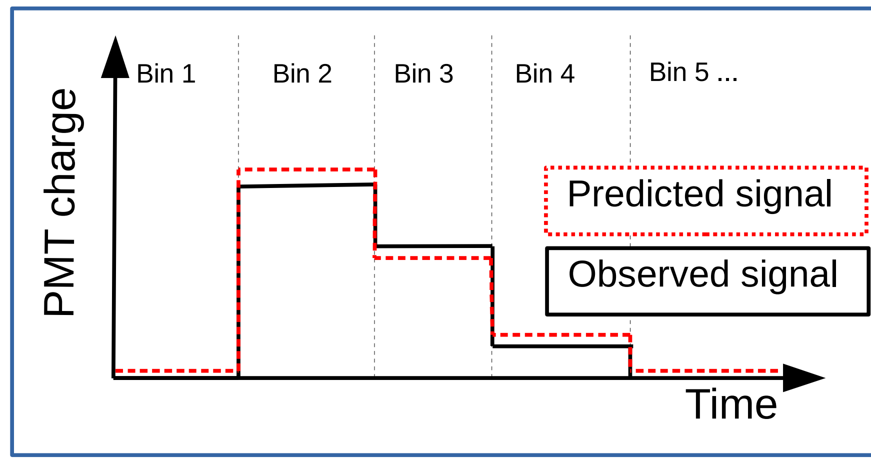


- Reconstruction:
  - 8 parameters as for ν_μ CC interaction
  - Total neutrino energy

$$E_\nu \approx E_{had} + \alpha L_\mu$$

  - Neutrino direction = muon direction
  - Matching PMT signals in time bins

For every DOM:

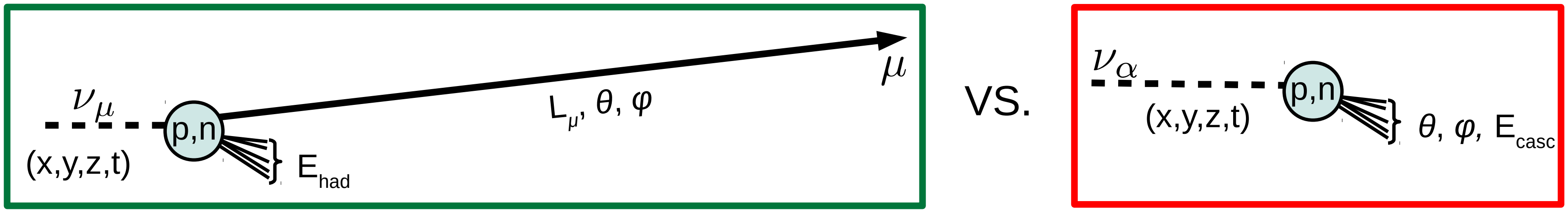


- Caveats:
  - Lookup tables for every position/direction in the detector – **HUGE and SLOW**
  - Very bumpy likelihood space

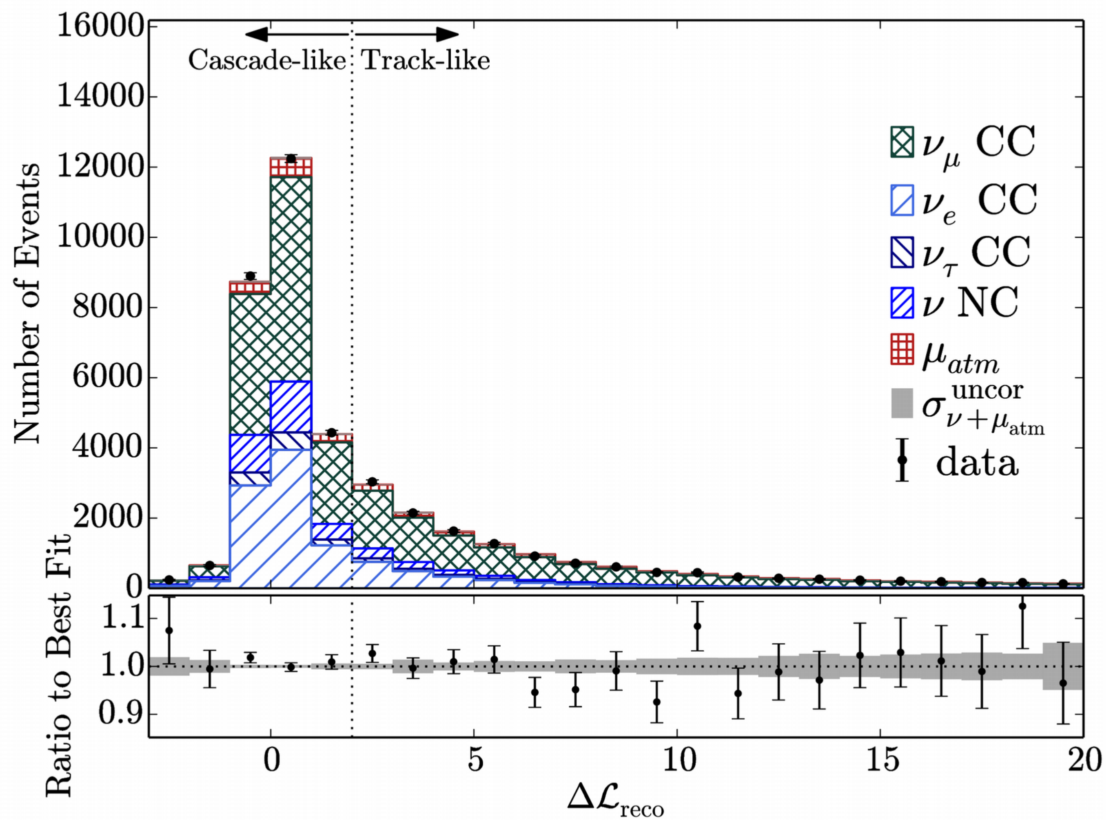
- Time consuming reconstruction
- Complicated minimization algorithms
- Answer can be not deterministic

Measuring oscillations in IceCube

Identifying muon neutrinos



> Particle identification = difference between full and cascade-only fits

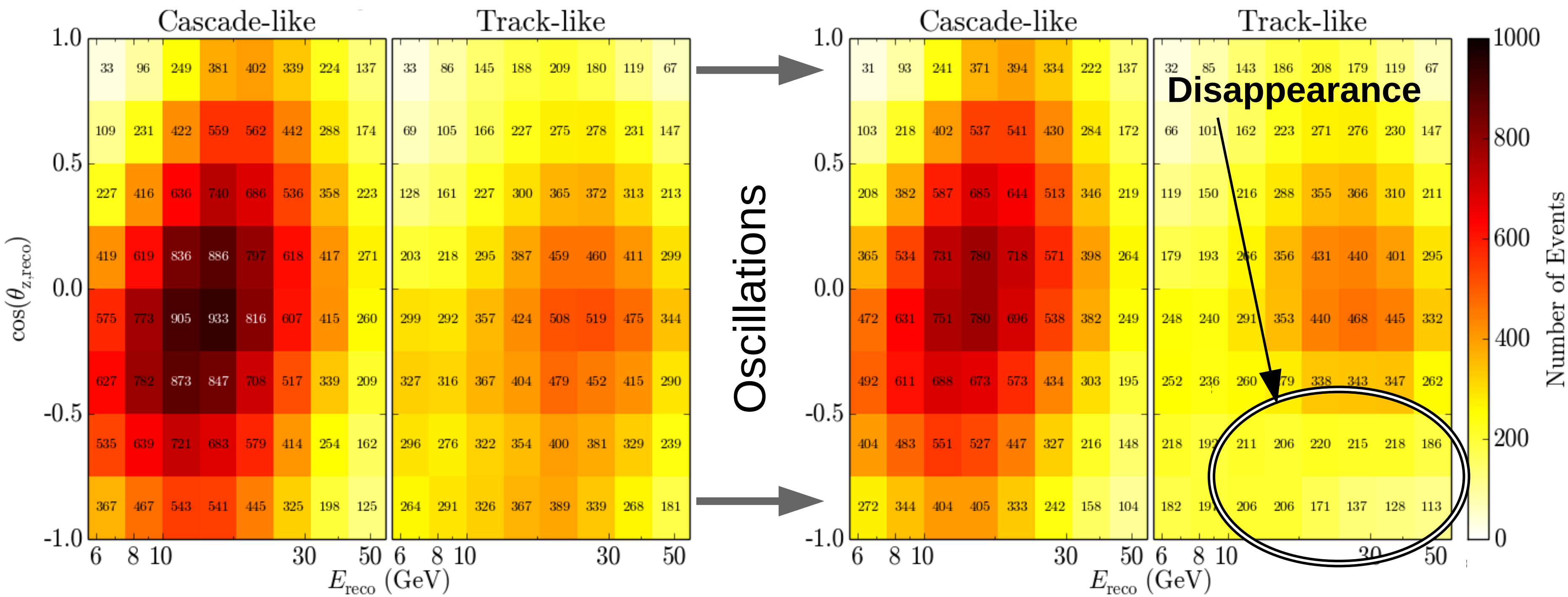


Measuring oscillations in IceCube

What does the signal look like

> No oscillations

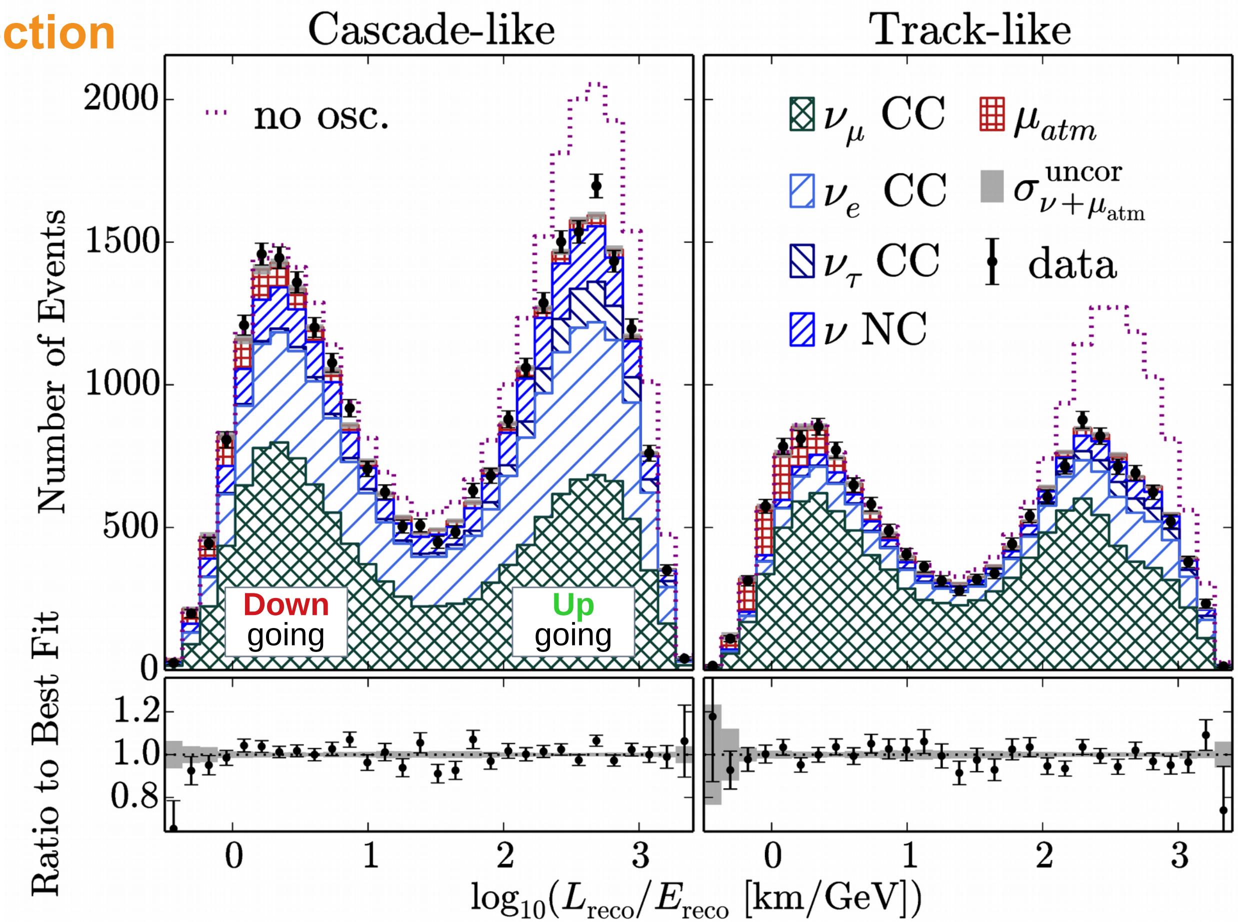
> With oscillations



> Expected clear disappearance signature!

Measuring oscillations in IceCube

L/E projection

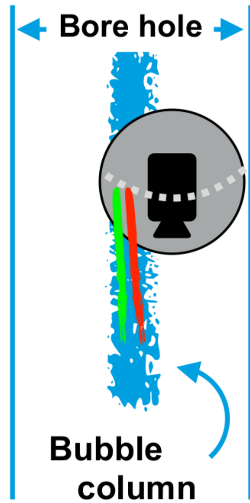


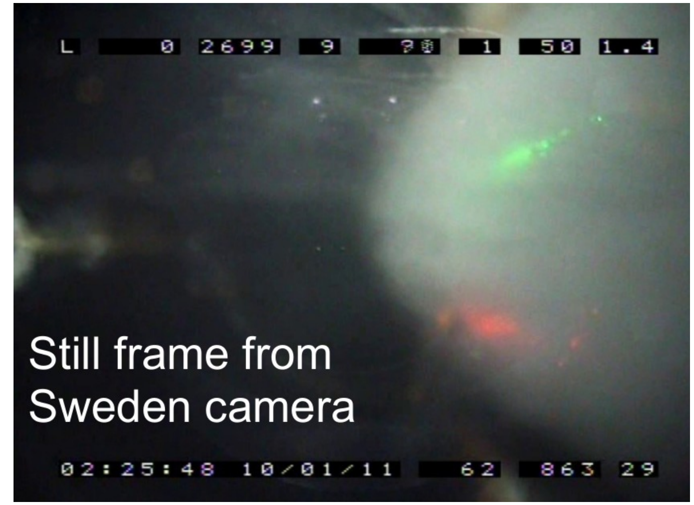
- **Down**-going neutrinos for normalization and **up**-going for signal
- Data clearly prefers oscillations

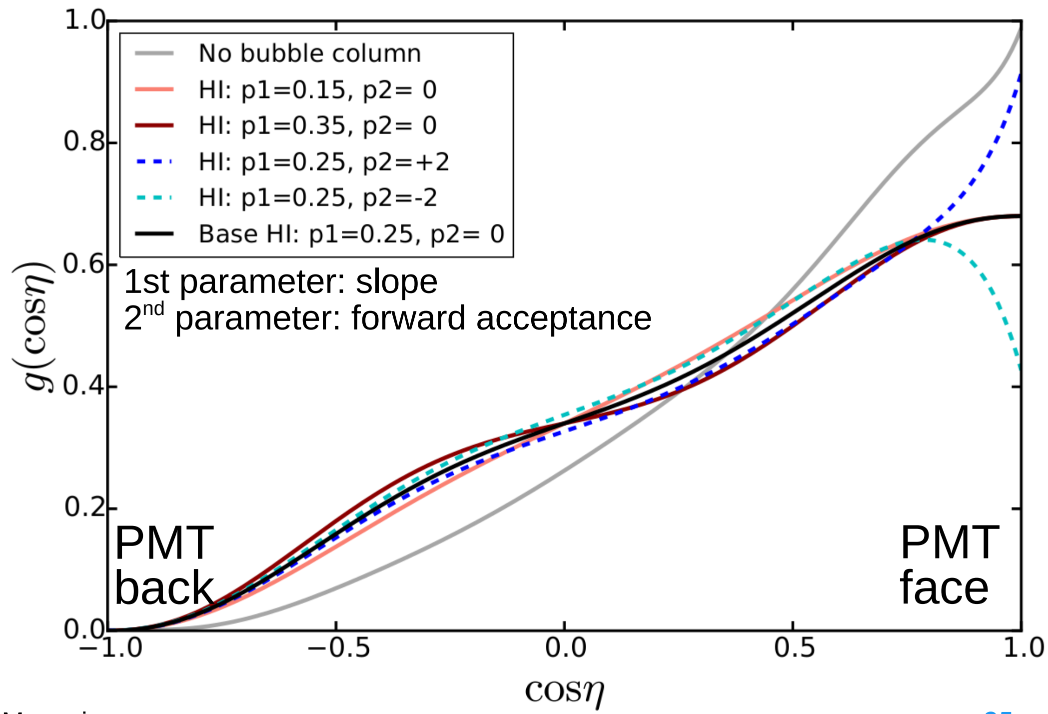
Systematic parameters

Parameters of the bore hole

- Plenty of systematic uncertainties considered:
  - Flux, cross-section, background, **detector**…
- Bore hole ice properties
  - Impurities/gas are released during melting and deployment
  - Pushed towards the centers of the holes along the strings
  - “hole ice” has much more scattering than original ice
- Effect of the bubble column:
  - Modifies angular acceptance of photons by DOMs
  - Modelled by effective angular acceptance curve





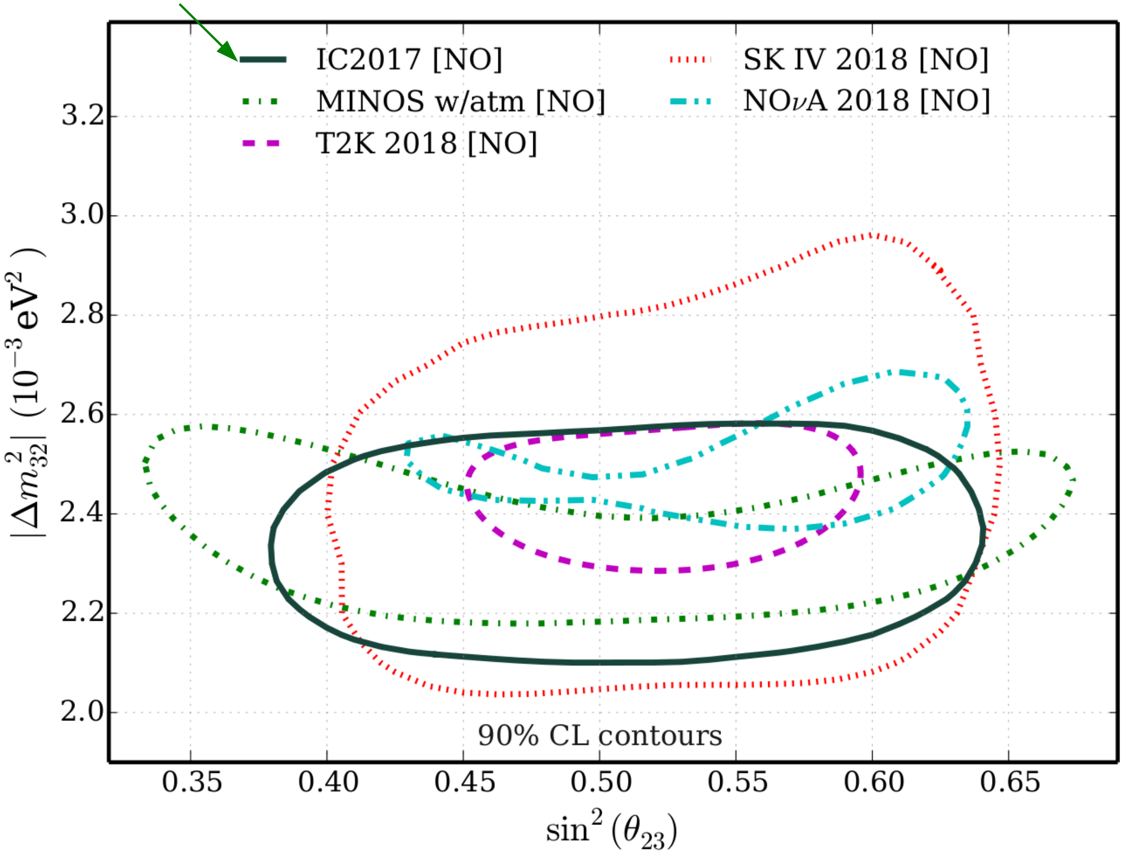


Muon neutrino disappearance

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)

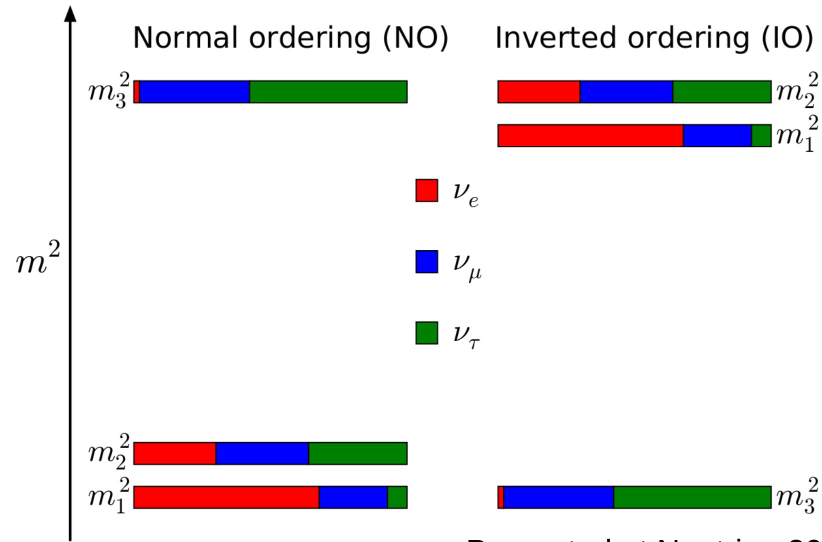


- Approaching precision of dedicated accelerator experiments!

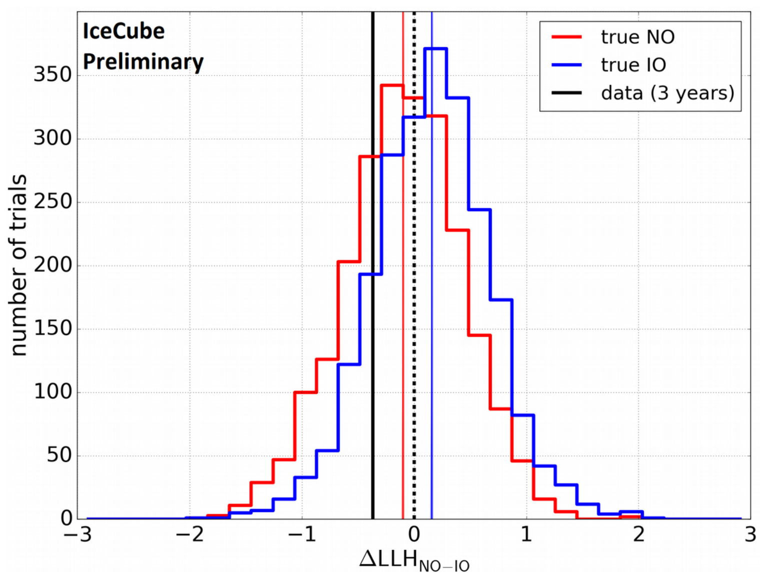
Neutrino mass ordering

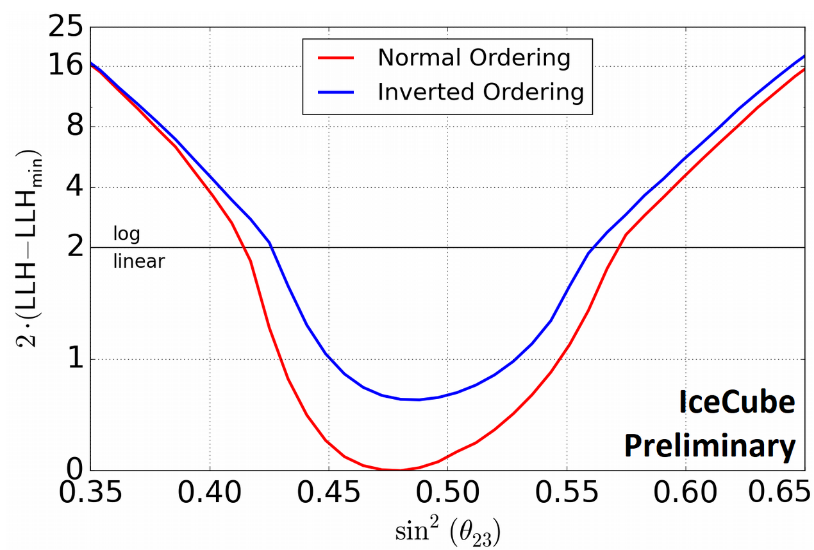
Heavy or light?

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



Presented at Neutrino 2018

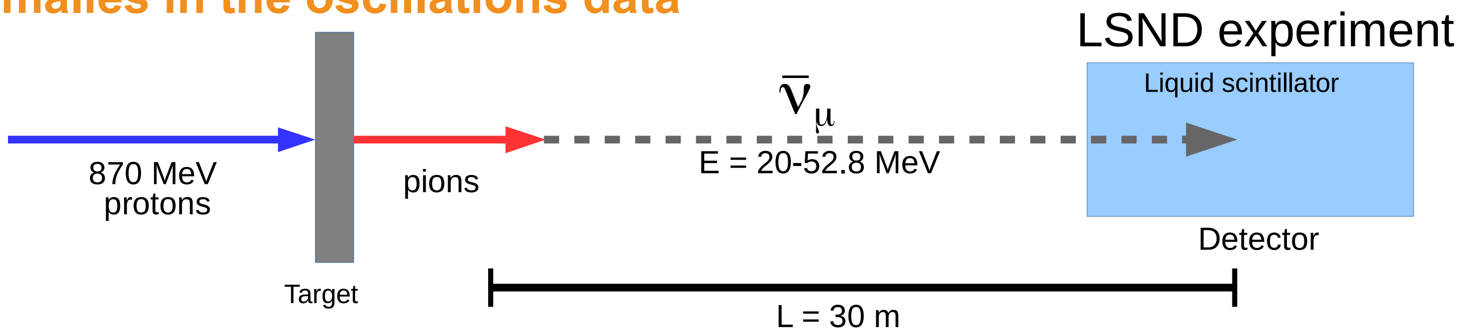




Looking beyond the three neutrinos

Non expected oscillations

Anomalies in the oscillations data

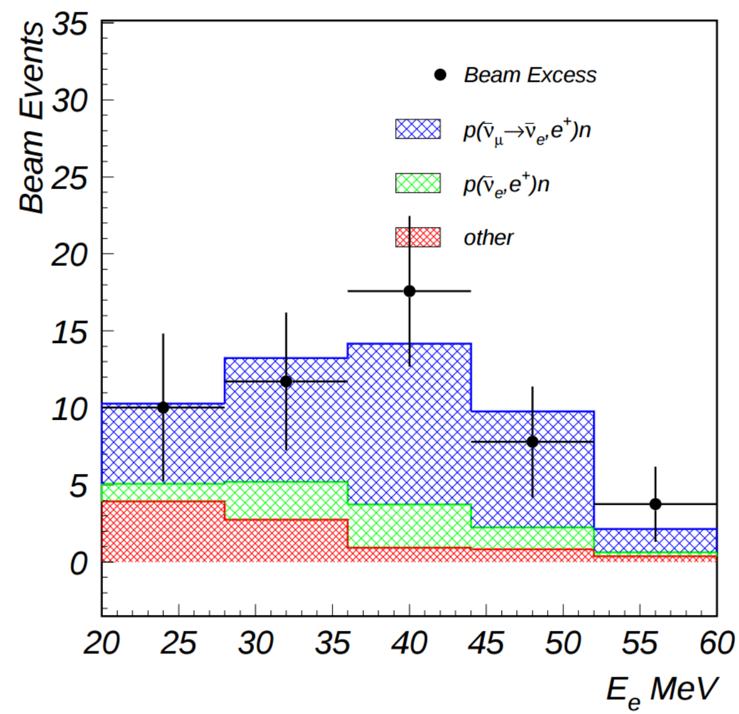


- Placing detector near neutrino source:

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

  - Very tiny probability to get electron neutrinos
  - Significant excess observed by LSND
  - Confirmed by MiniBooNE at higher energies

- Reason?
  - Systematic uncertainties?
  - New neutrino types?



Sterile neutrinos

Anomalies in the oscillations data

- Anomalies:
  - Short baseline neutrino experiments
  - Reactor anomaly
  - Gallium anomaly

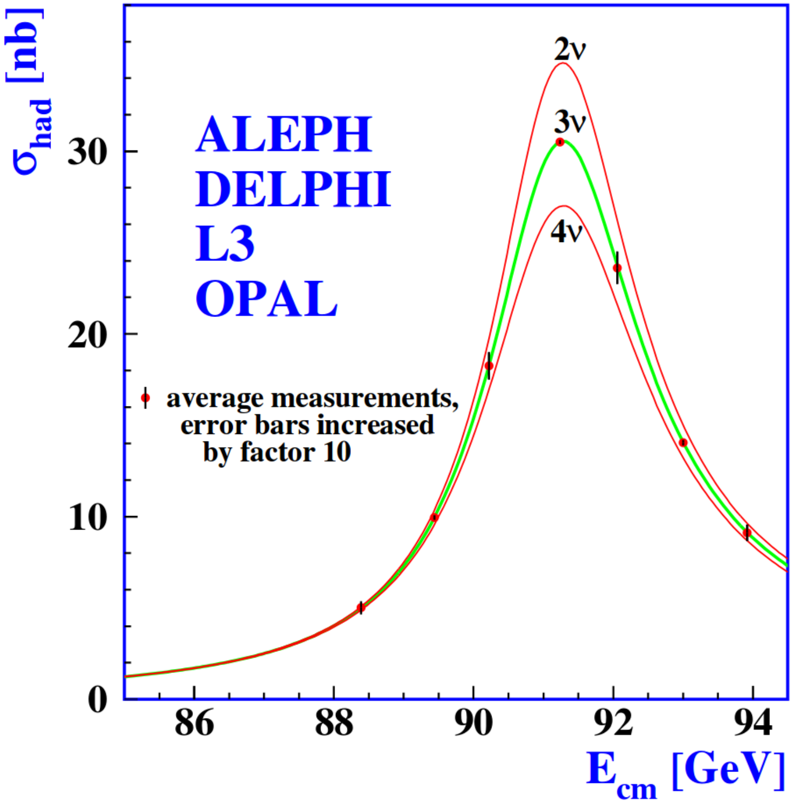
Can be resolved by adding heavier ~eV neutrinos

- LEP results
  - Measuring Z decay width

$$n_\nu = 2.9840 \pm 0.0082$$

  - New light neutrinos cannot interact via the weak interaction

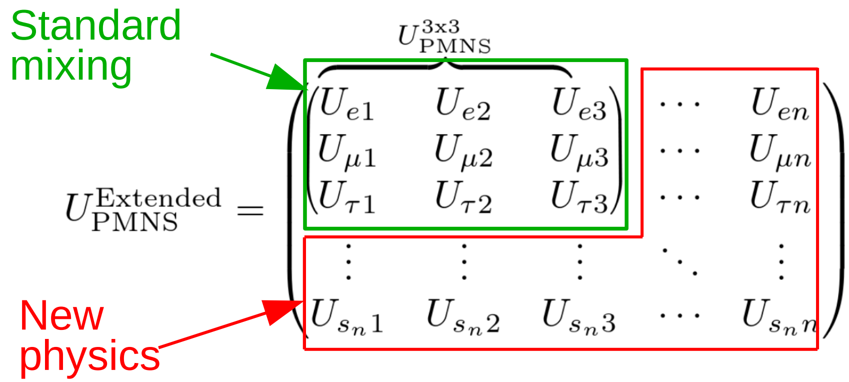
- Sterile neutrinos!



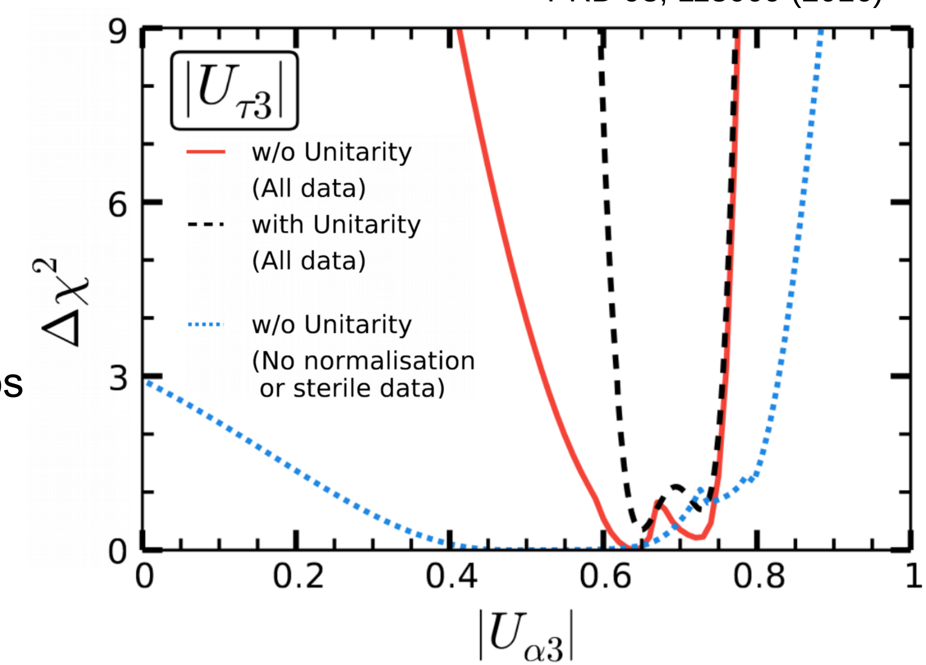
Physics beyond the three-neutrino model

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

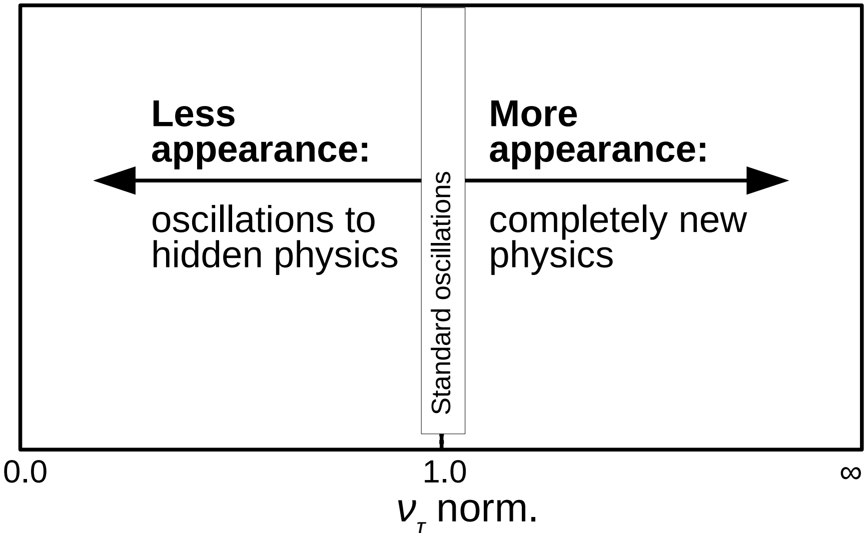


PRD 93, 113009 (2016)



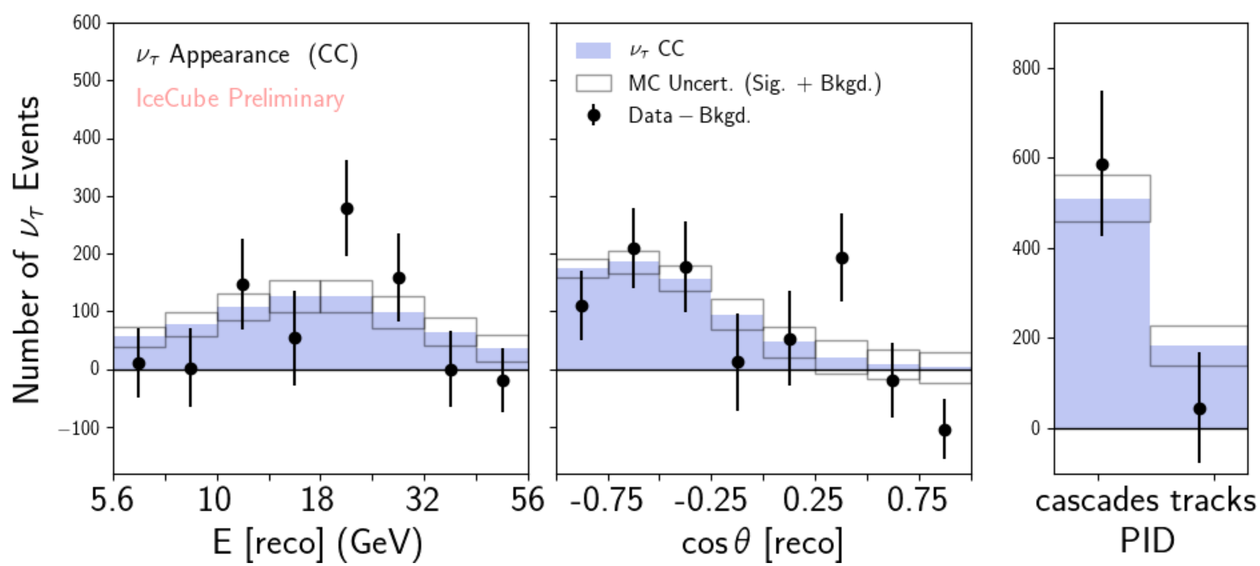
Tau neutrino normalization

Is the same amount appeared as disappeared?



- Very few tau neutrinos observed/ identified ever:
  - 4 in DONUT
  - 5 in OPERA
  - 1-2 in IceCube (PeV energies)
- It can hide unexpected physics

- Search in DeepCore:
  - Excess/deficit of events
  - Statistical way
  - Cannot identify tau neutrinos on event basis

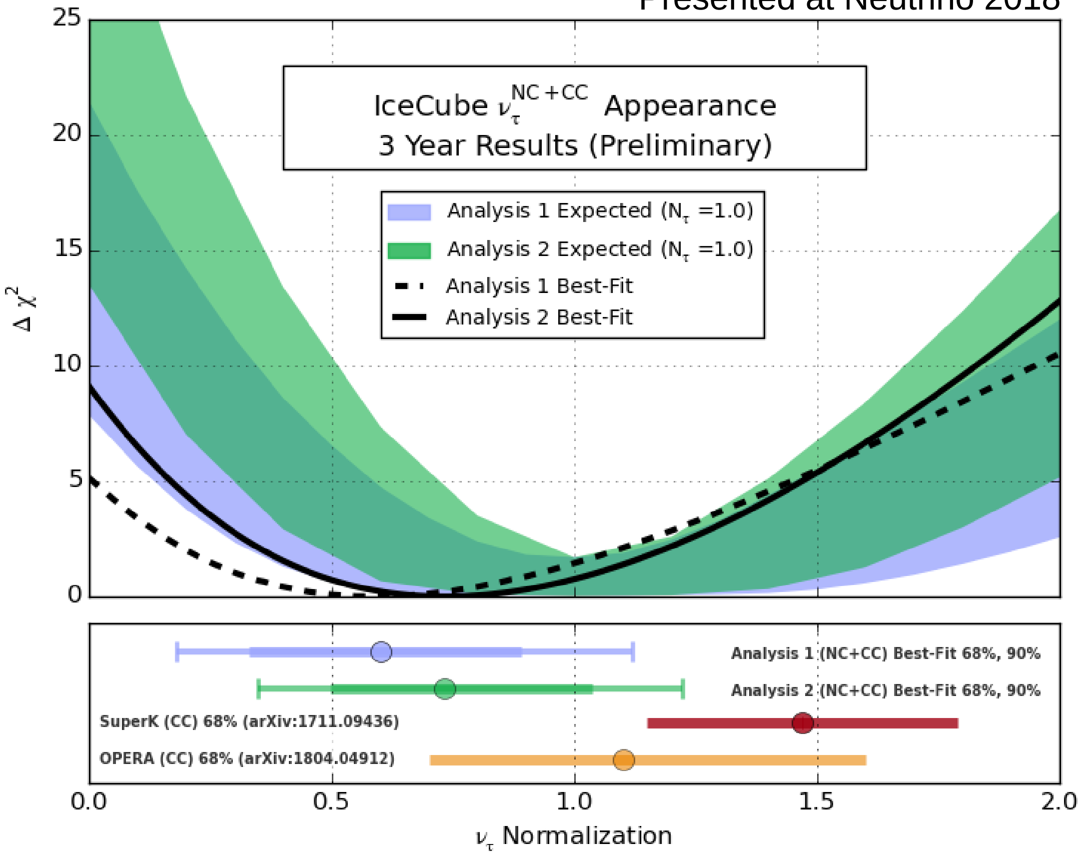


Tau neutrino normalization

Is the same amount appeared as disappeared?

- 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

Testing the standard 3 neutrino paradigm

- Simplest extension:
  - "3+1" model (3 standard + 1 sterile)
  - Sterile neutrino is the heaviest

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

source: symmetry mag

- New parameters:
  - 1 mass difference
  - 3 mixing angles
  - 2 CP-violating phases

- Assumptions:
  - no CP phases
  - θ_{14} =0

- Modifies atmospheric neutrino oscillations

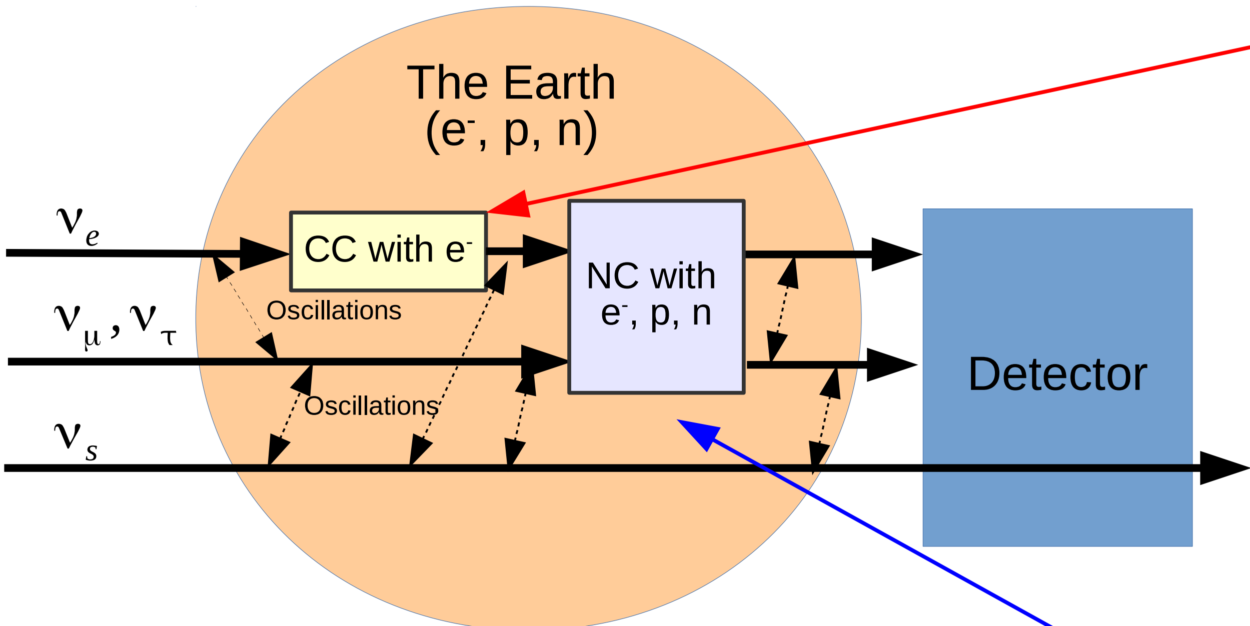
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$

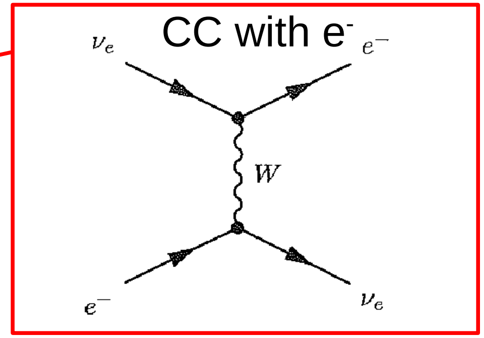
$$|U_{\tau 4}|^2 = \sin^2\theta_{34}\cos^2\theta_{24}$$

- Effects of sterile neutrinos are small
- But Earth matter can enhance the effect

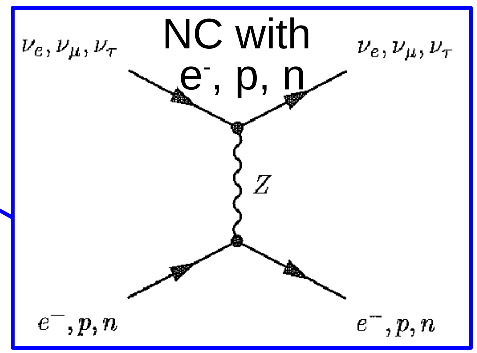
Sterile neutrino effect

Matter effects





$$V_{CC} = \pm\sqrt{2}\, G_F N_e$$



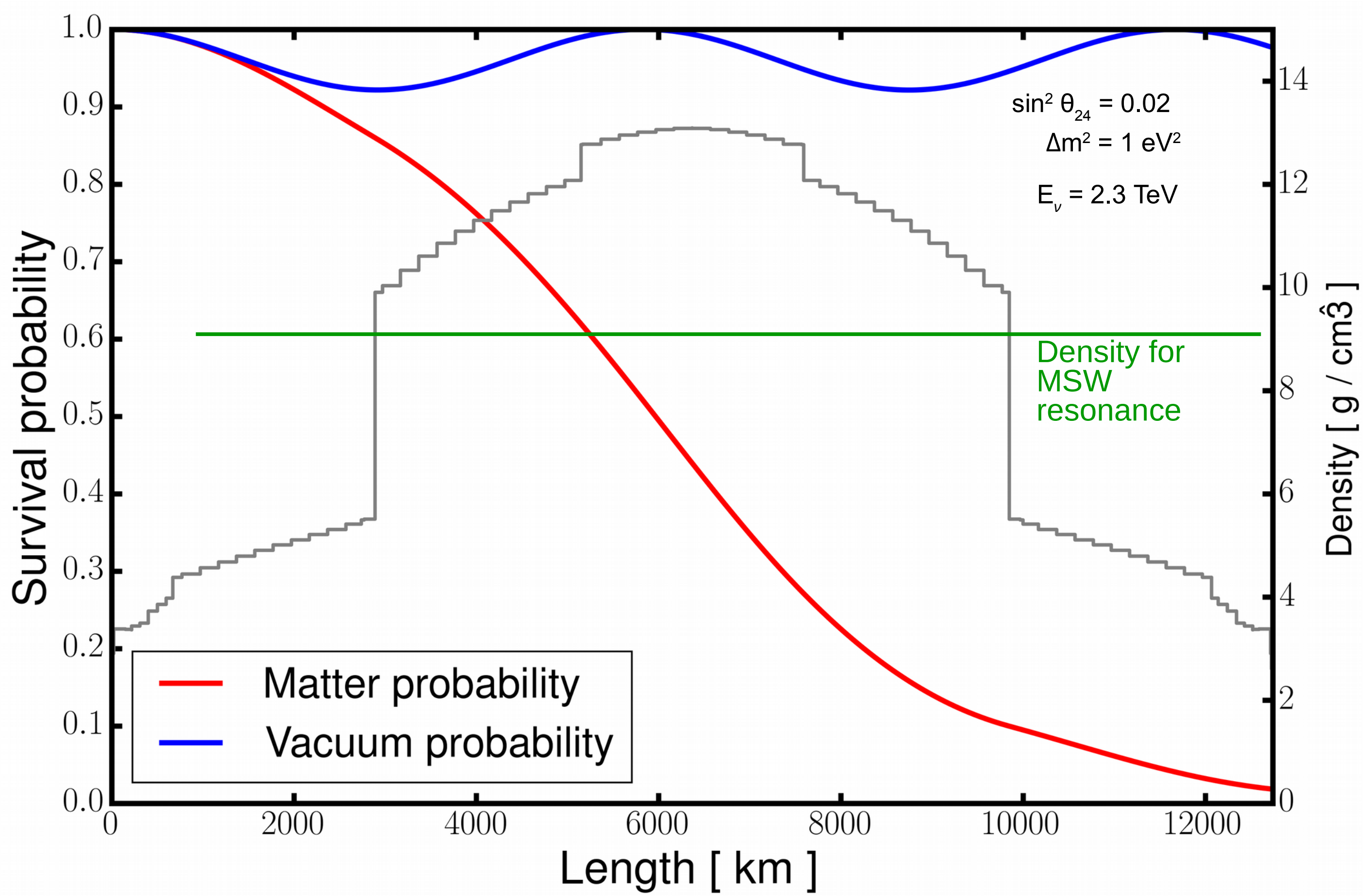
$$V_{NC} = \mp \frac{G_F}{\sqrt{2}} N_n$$

- Different neutrinos feel different matter potential
  - Results in modification of oscillation probabilities
- Presence of matter:
  - Modifies effective mixing/neutrino mass
  - Can enhance efects of sterile neutrinos

Sterile neutrino effect

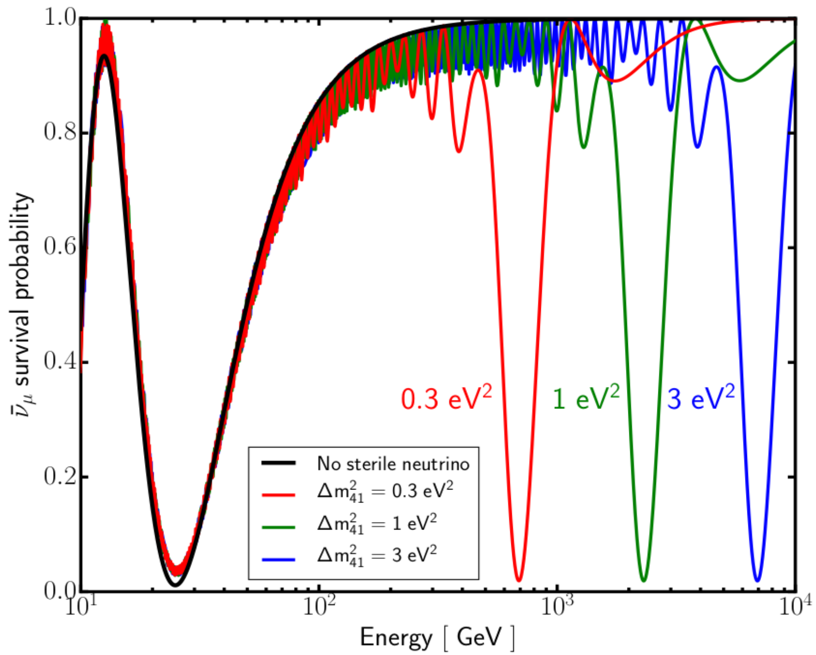
Effects of matter

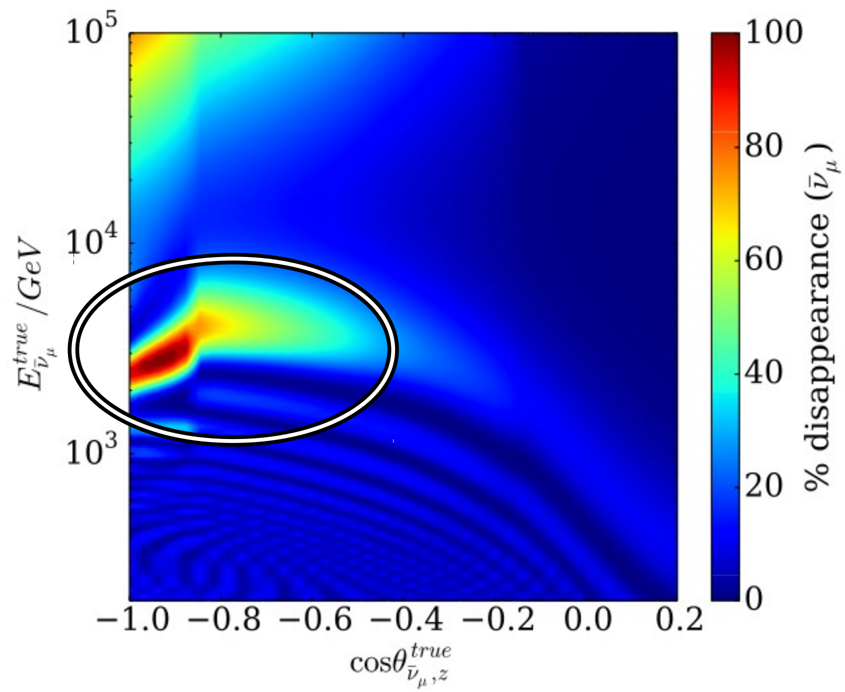
- Neutrino oscillation length resonance (NOLR): mantle-core-mantle enhancement



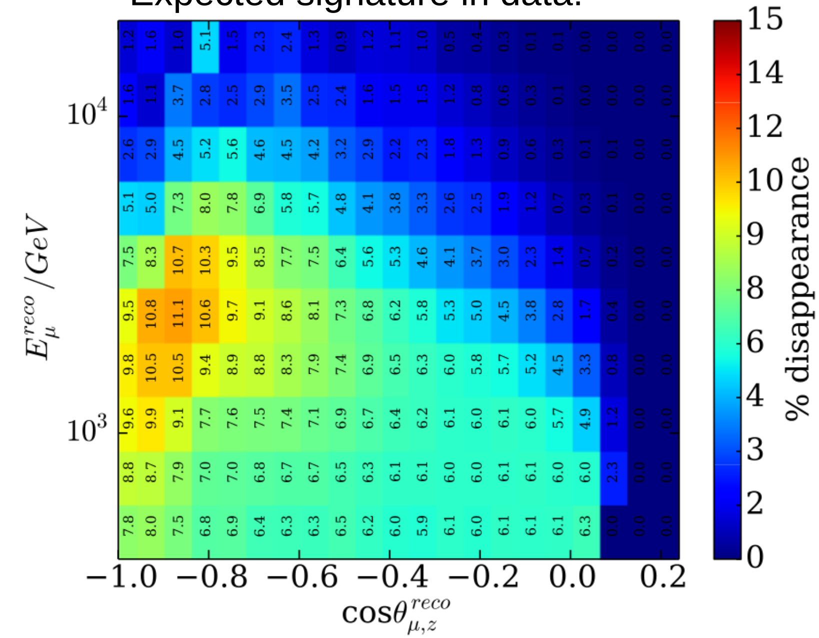
Sterile neutrino effect

Resonant transition at a few TeV





Expected signature in data:

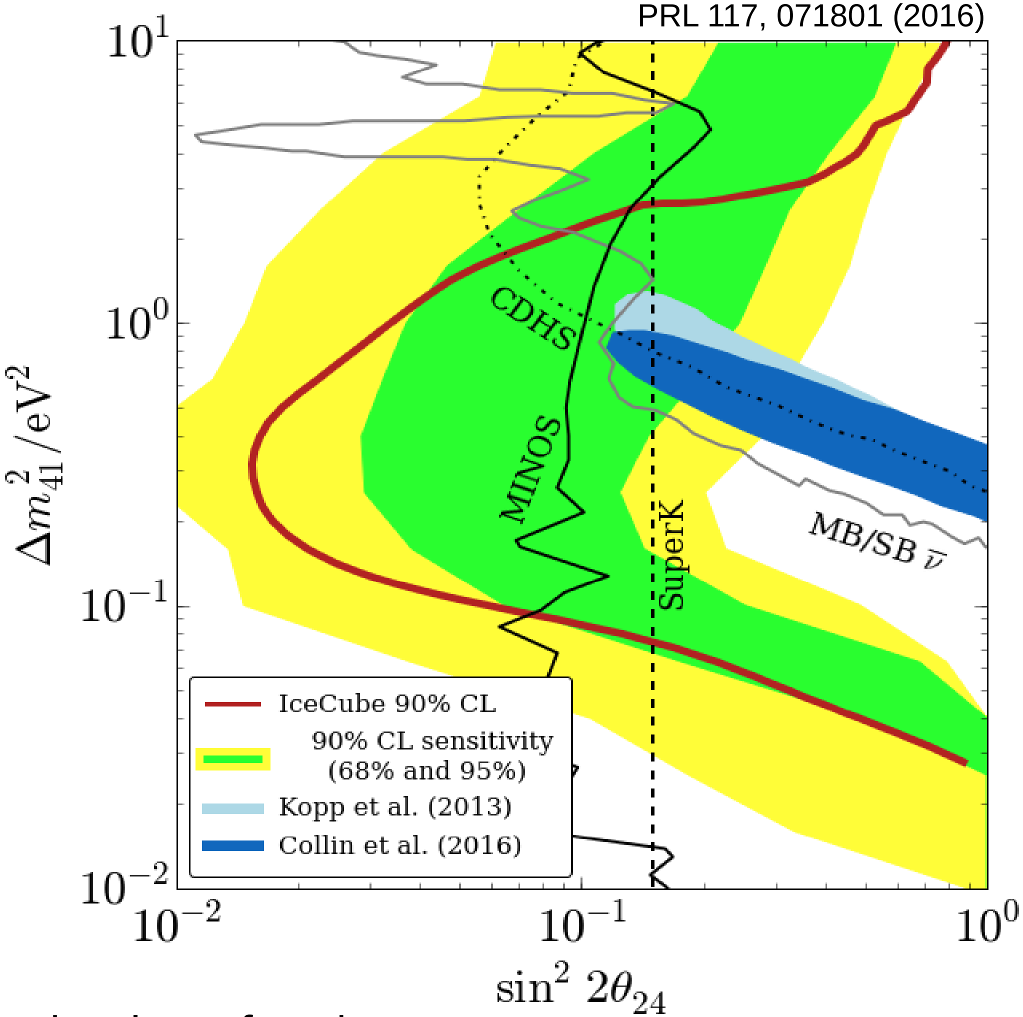


- > Resonant transition at few TeV for neutrinos crossing the core
- > Disappearance for muon antineutrinos
- > Side note: this is not MSW effect (you can be eaten alive by theorist if you call it so)

Limits on sterile neutrino mixing

Results of the TeV search

PRL 117, 071801 (2016)

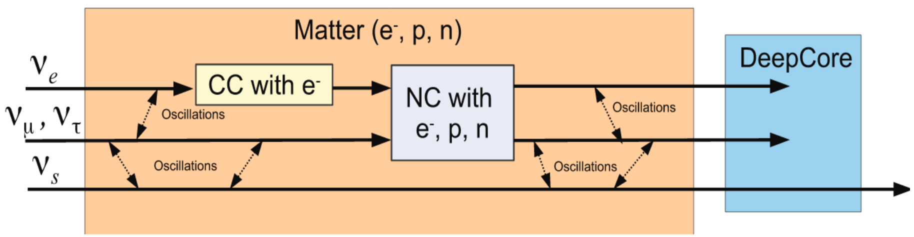


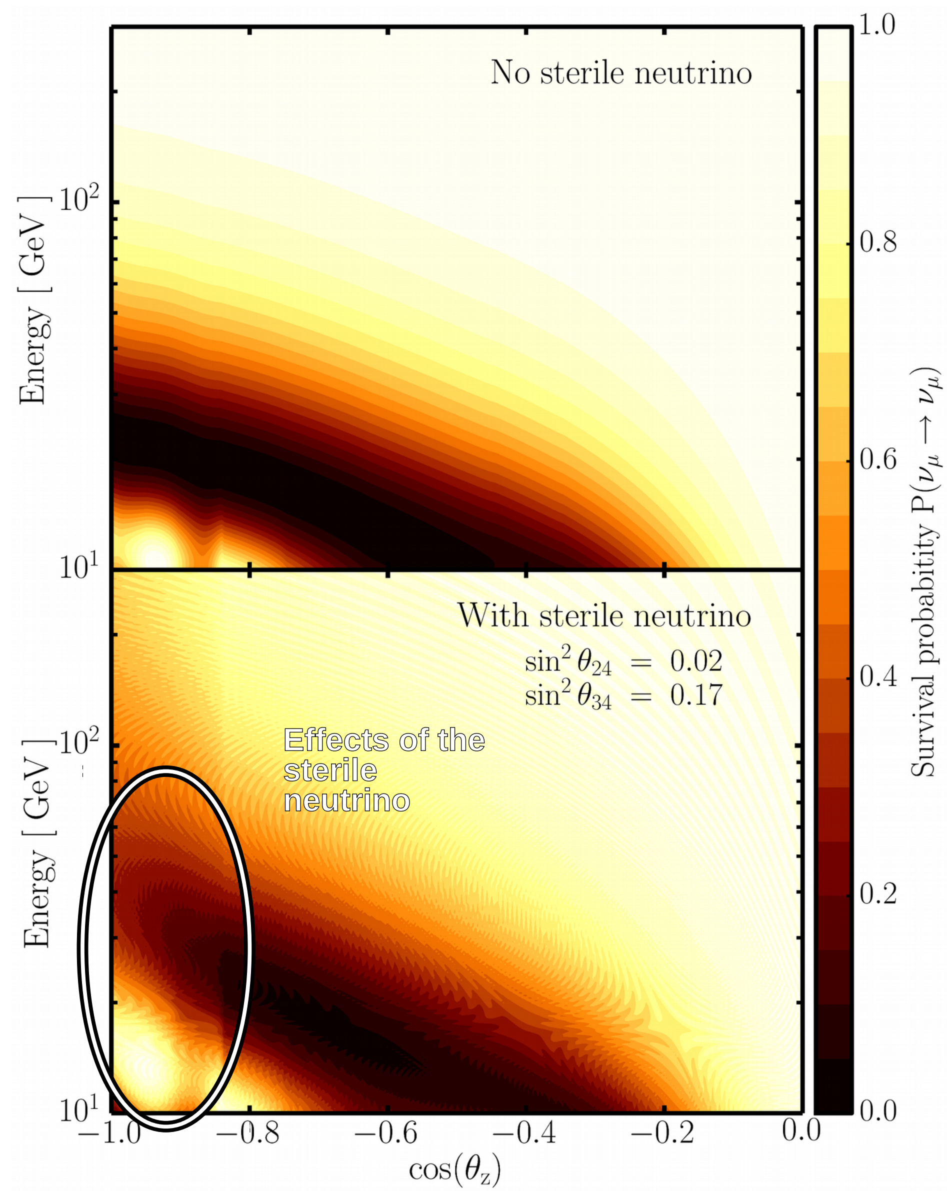
> No sterile neutrino signal was found

> Placing stringent limits for allowed sterile neutrino mixing

Sterile neutrinos with DeepCore

Searching for matter-induced effects



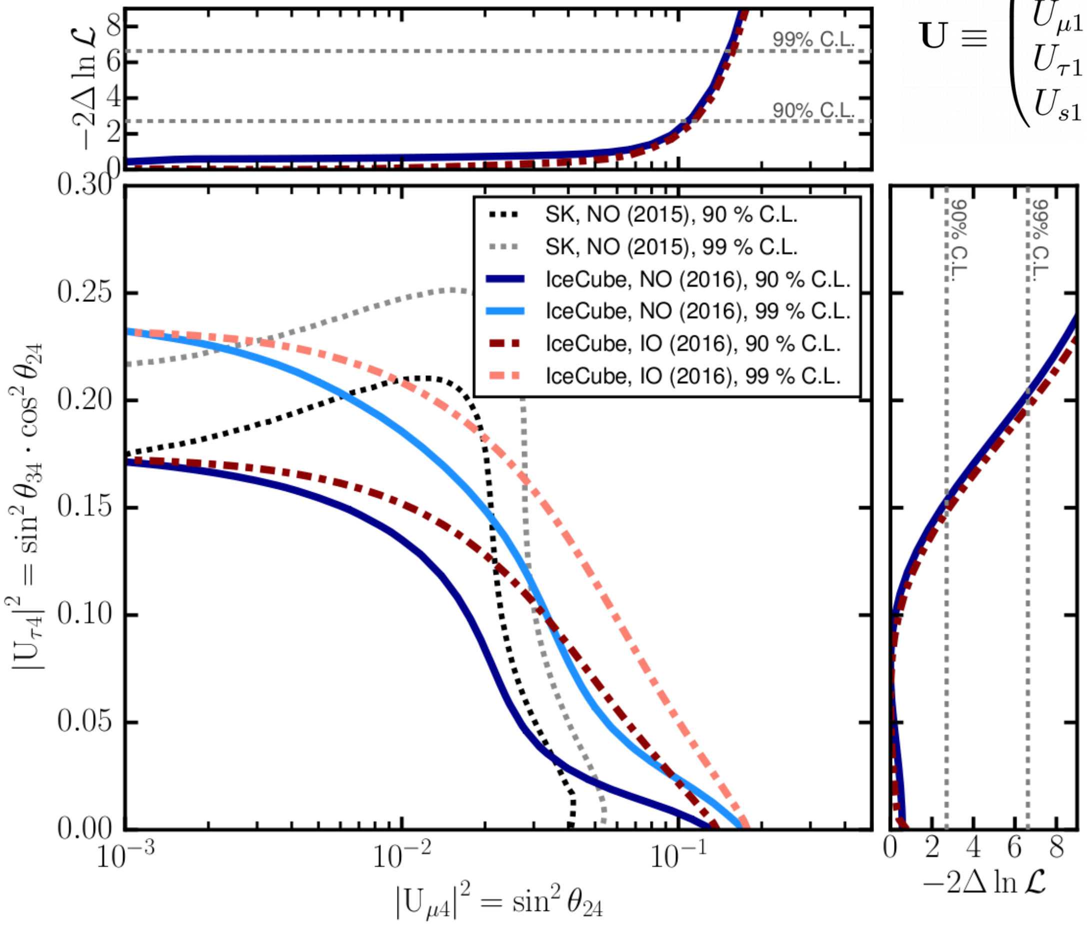


- Effects below 100 GeV:
  - Modifications of standard oscillations
    - shifts of oscillations minimum
    - changes of amplitude
  - Independent of sterile neutrino mass (for $\Delta m^2_{41} > 0.3\, eV^2$)
  - Sensitive to the angles θ_{24} and θ_{34}
  - Effect proportional to matter density

Limits on sterile neutrino mixing

Search under 100 GeV

PRD 95, 112002 (2017)



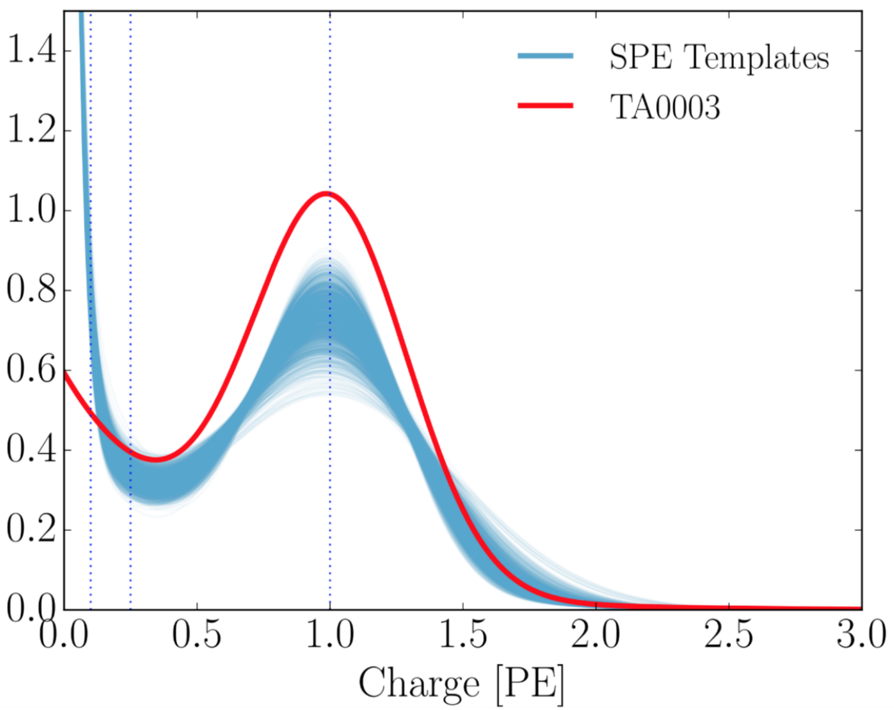
$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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

Current studies

On the way to a new measurements

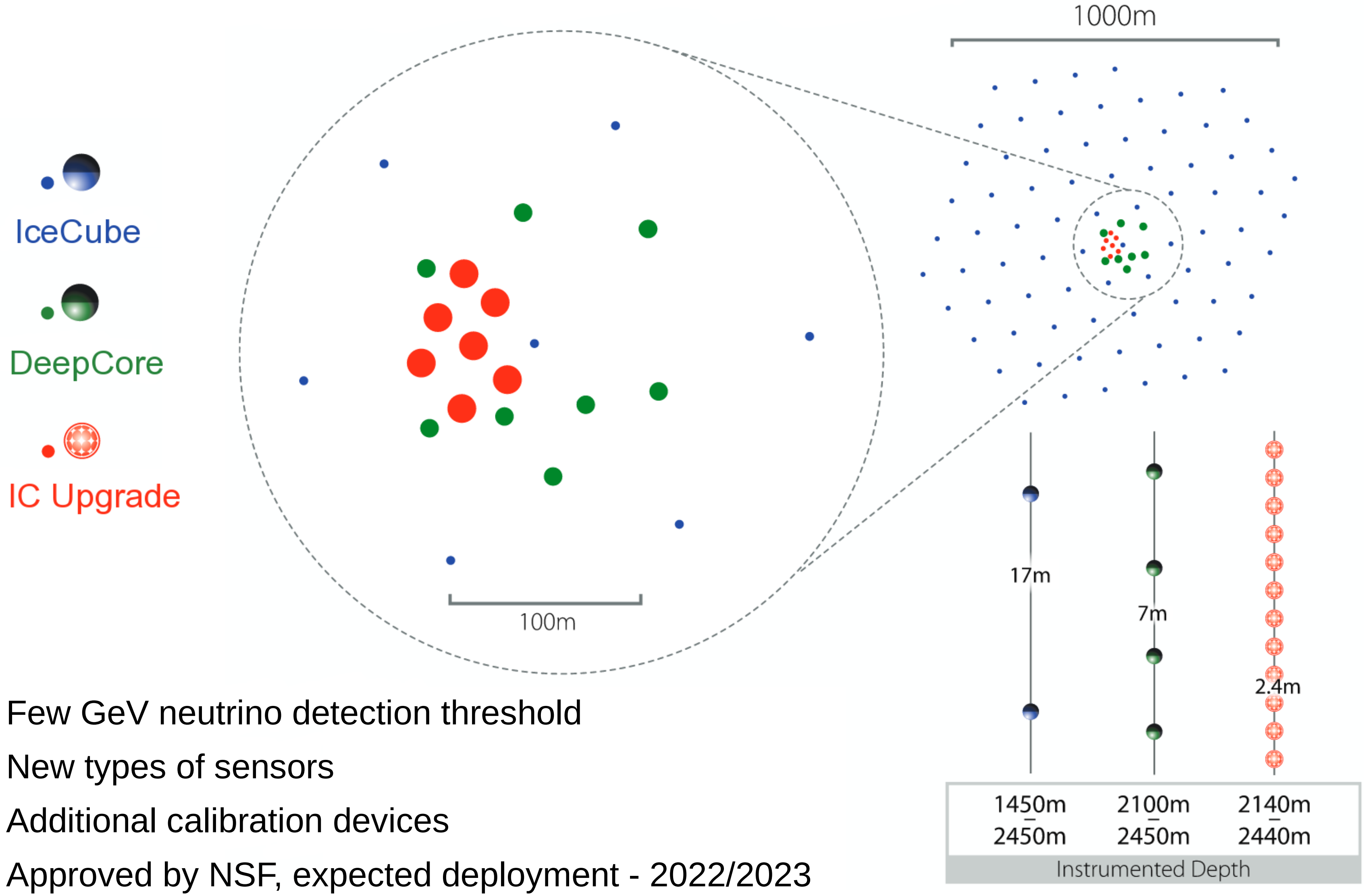
- Current studies: 1-3 years of data
- For new studies in IceCube:
  - New PMT charge responses
  - Re-calibration of glacial ice using all detector LED flashers
- We have 7 years of data
  - Currently going through major revision of selection, simulations, reconstruction
  - Main limitation: manpower
  - Main reason: see next slides



Upgrading the IceCube

IceCube Upgrade

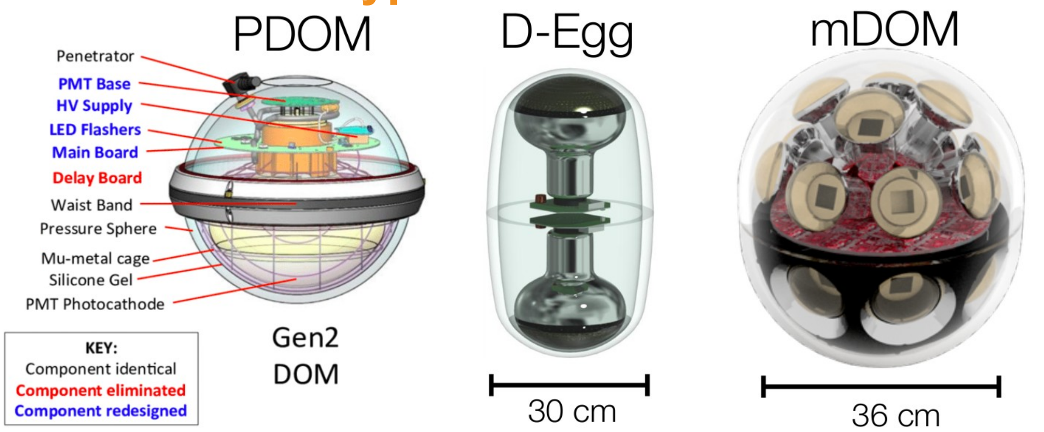
New tool for studies of atmospheric neutrinos

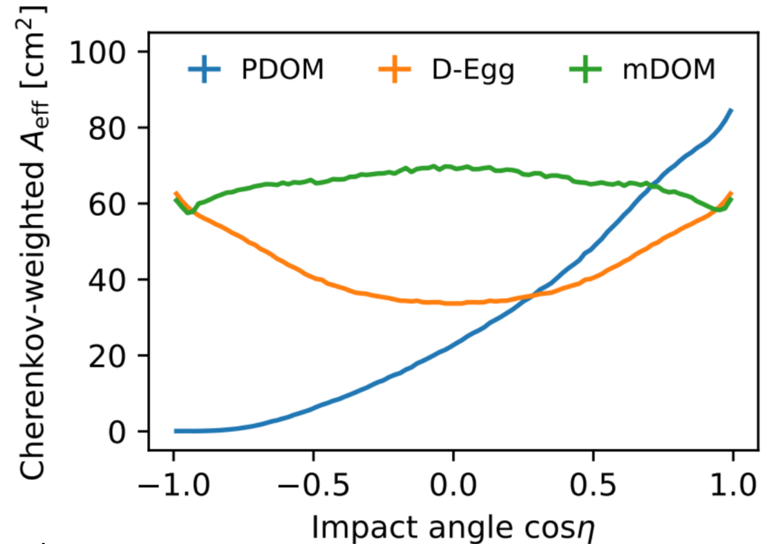


- Few GeV neutrino detection threshold
- New types of sensors
- Additional calibration devices
- Approved by NSF, expected deployment - 2022/2023

IceCube Upgrade

New sensor types





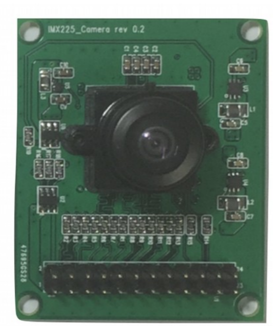
- Larger photo-cathode area and better angular acceptance

New calibration devices

- New on-module and stand-alone calibration devices
- Better calibration of modules and glacial ice properties

Piezo-module

CCD



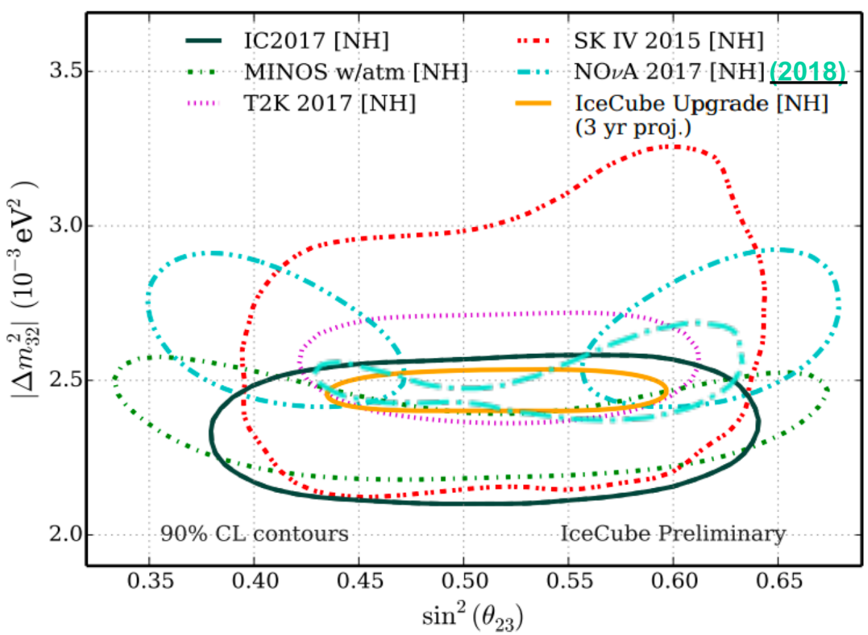
CMOS

POCAM

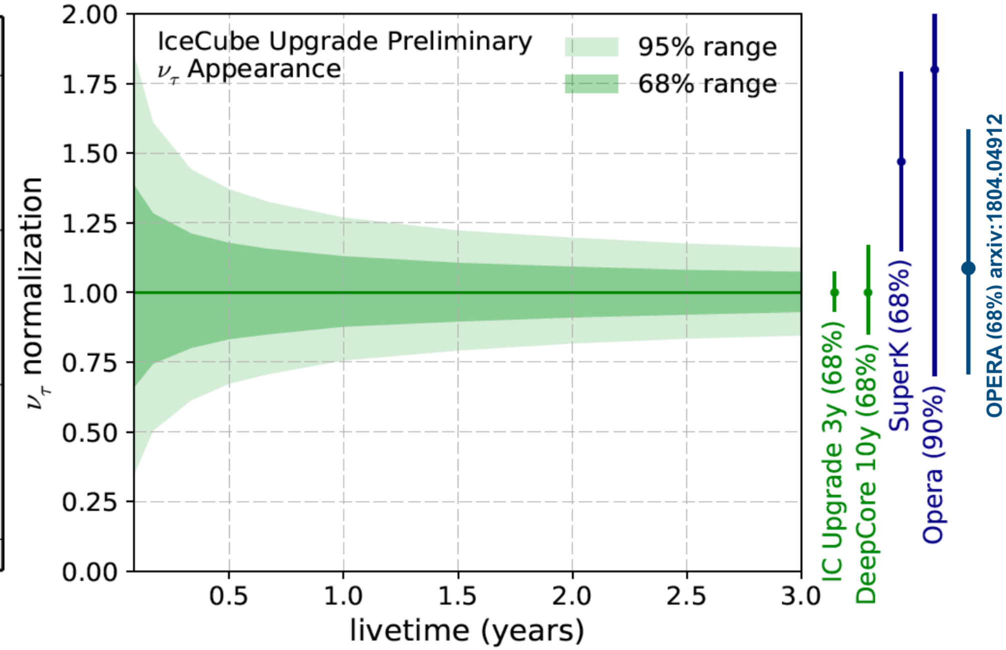
IceCube Upgrade

What we can achieve

> Muon neutrino disappearance



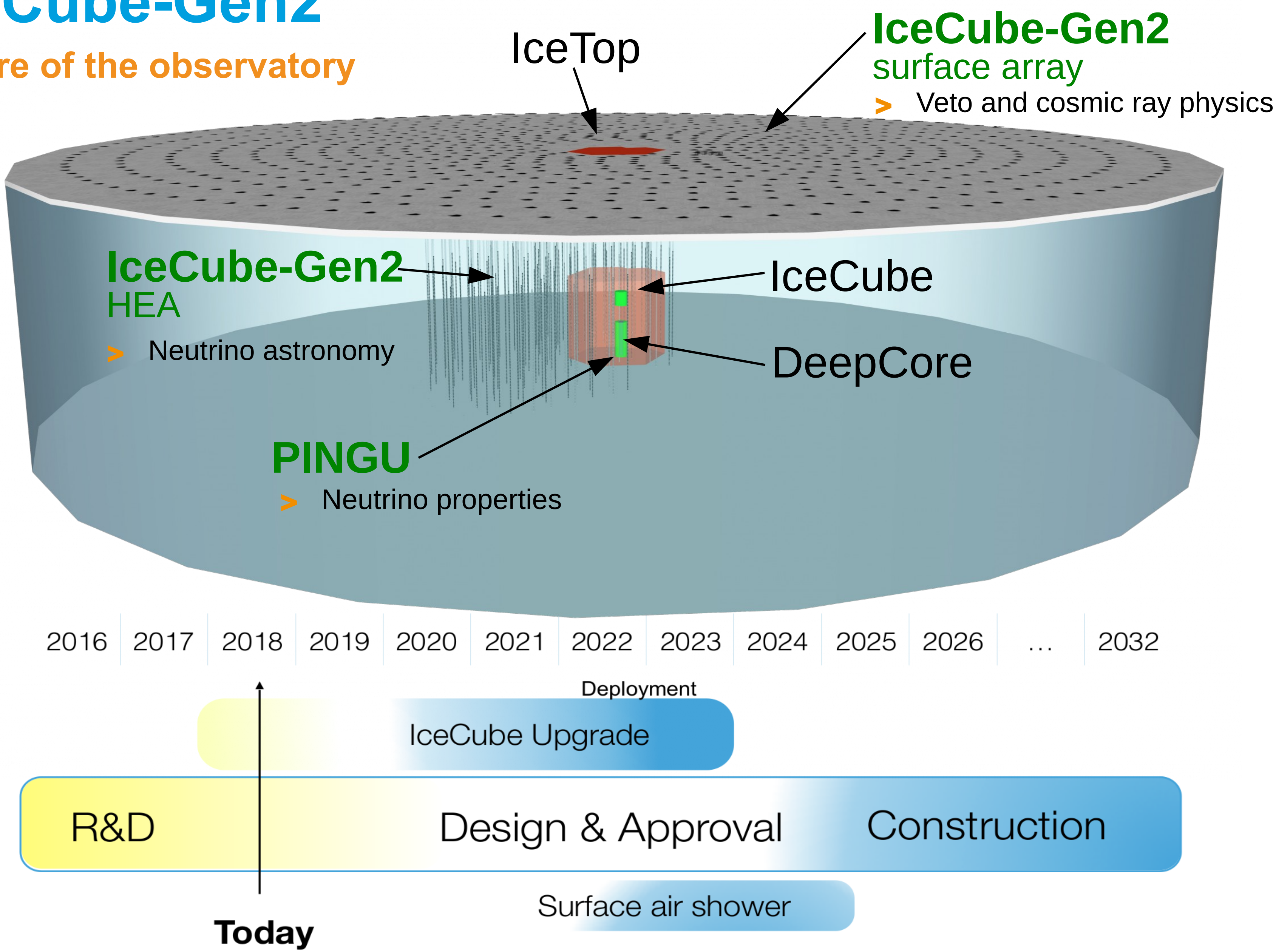
> Tau neutrino appearance



- Precision measurement of atmospheric neutrino properties
- Program similar to DeepCore:
  - Standard oscillations, tau neutrino appearance, sterile neutrinos, non-standard interactions, Dark Matter searches
  - Current sensitivity predictions do not include future calibration improvements

IceCube-Gen2

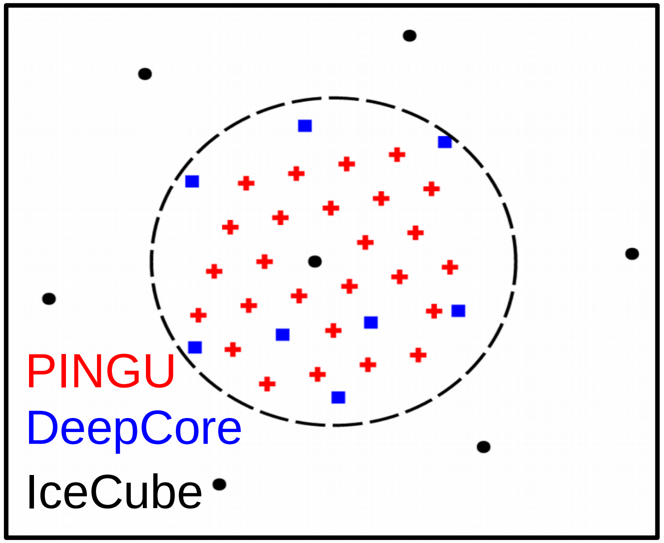
Future of the observatory

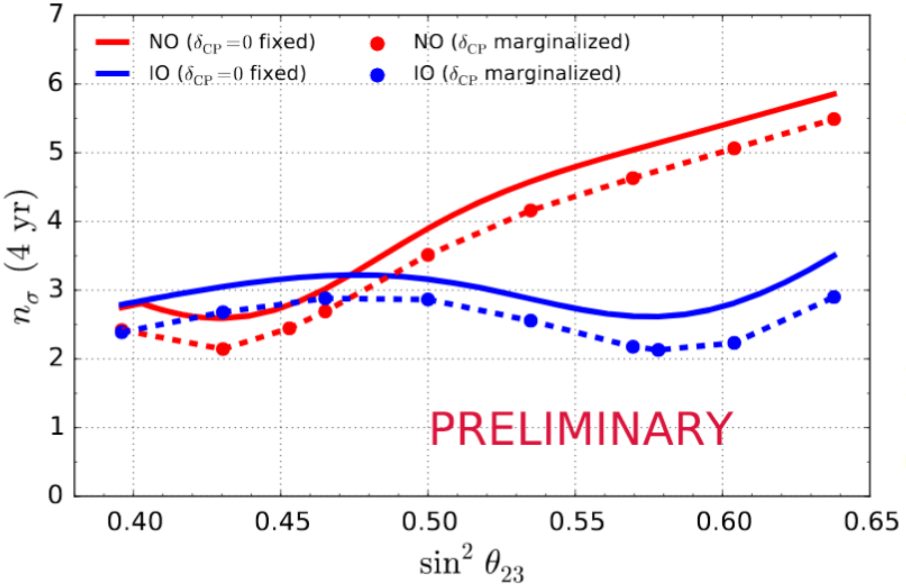


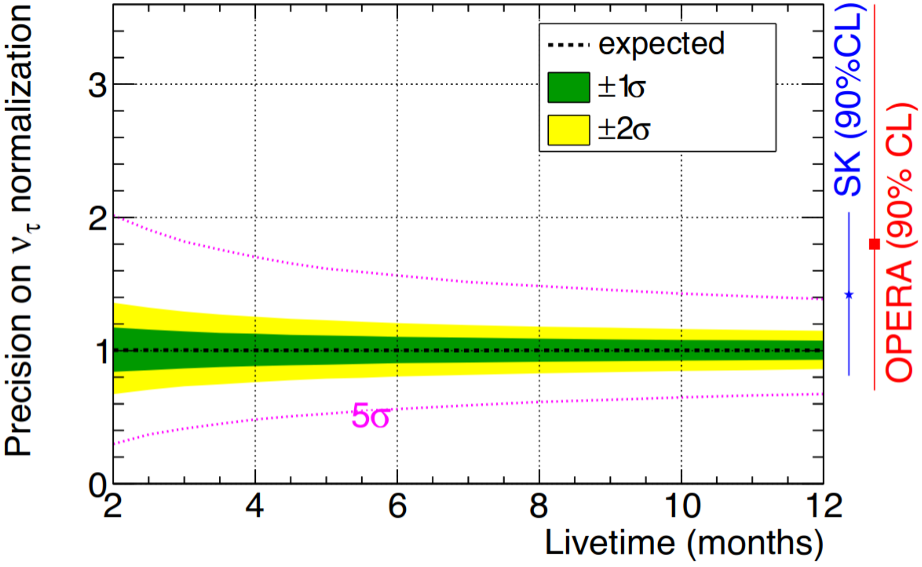
PINGU

The Precision IceCube Next Generation Upgrade

> Main goals of PINGU:
  - Precision in atmospheric oscillations
  - Neutrino mass ordering
  - Sterile neutrinos
  - tau neutrinos
  - DarkMatter, supernovas...





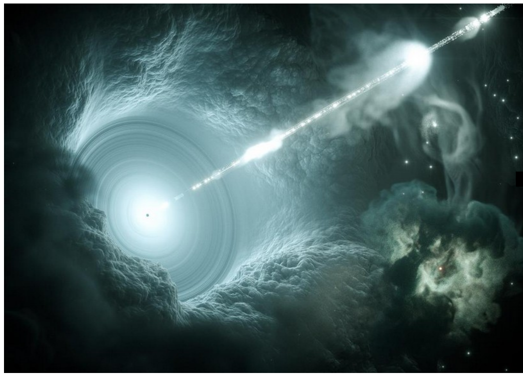


Flavor physics with astrophysical sources

Flavor physics with astrophysical neutrinos

Probing extremes

Astrophysical sources



Neutrino production

$$p + X \to \text{hadrons}$$

$$\pi^{\pm} \to \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

$$\mu^{\pm} \to e^{\pm} + \overset{(-)}{\nu}_{\mu} + \overset{(-)}{\nu}_{e}$$

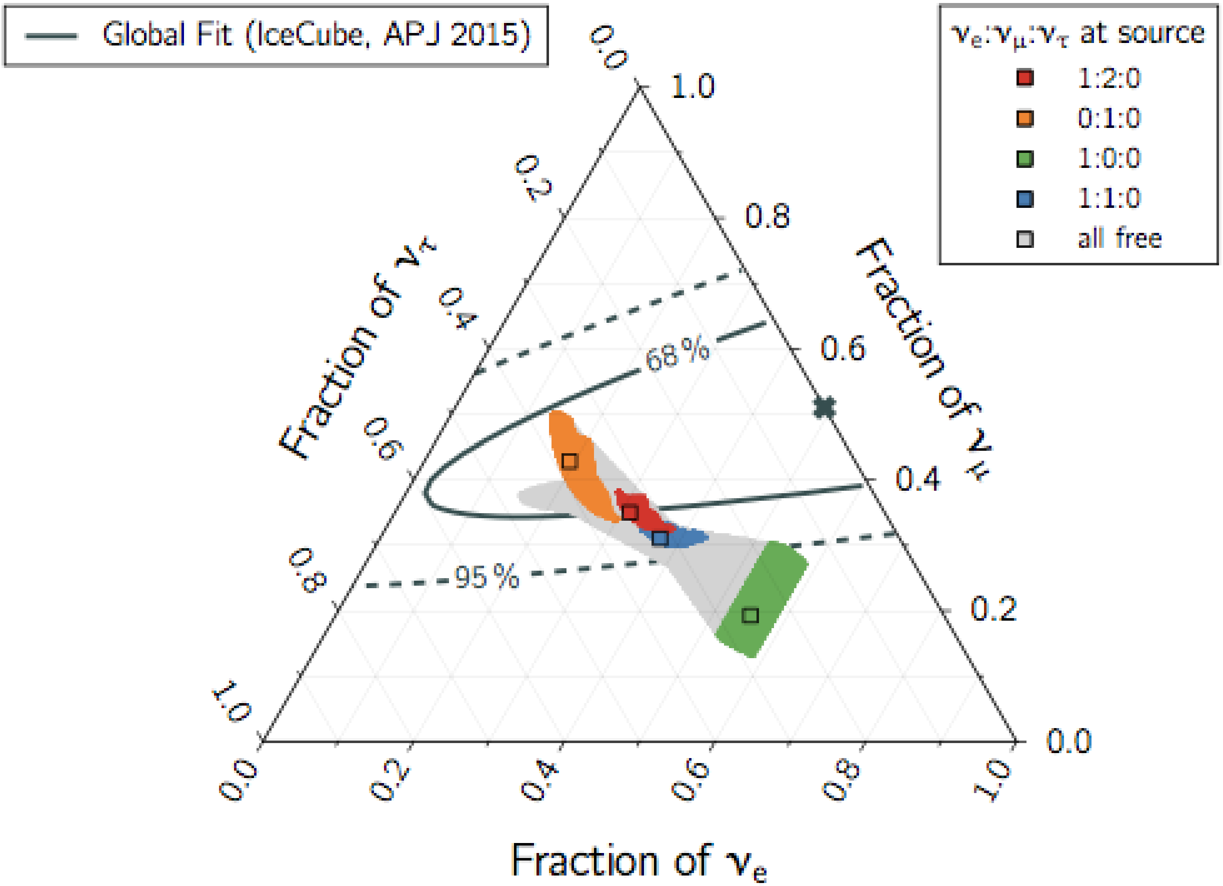
Expected flux:
$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

- Other scenarios are also possible:
  - (0 : 1 : 0) or (1 : 0 : 0), (1 : 1 : 0)
  - And realizations in between

- After production neutrinos propagate through astrophysical distances:
  - Neutrinos oscillate
  - Distances >> decoherence distance
  - Final flavour ratio → averaged mixing

Flavor physics with astrophysical neutrinos

Flavor triangle

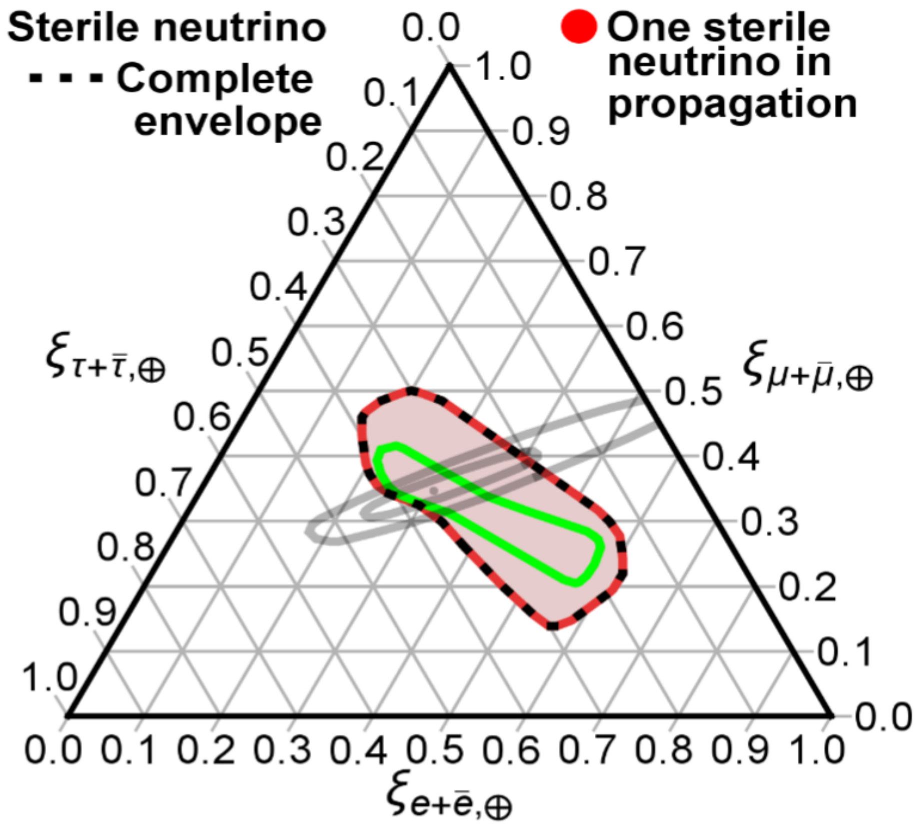


- All realizations are pushed towards the center
  - **Bad news:** harder to identify real flavour composition at source
  - **Good news:** We can use this to find new neutrino oscillation/interaction effects

Flavor physics with astrophysical neutrinos

Expanding the limits

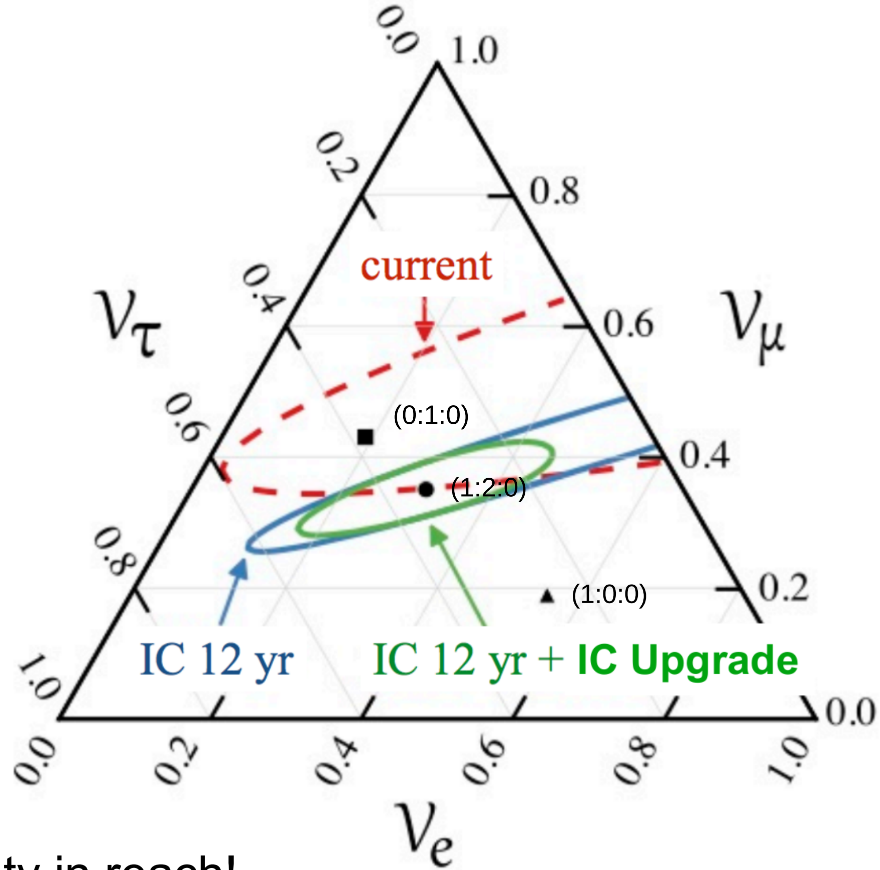
Phys. Rev. D 96, 083018 (2017)



- New physics during neutrino creation/propagation/detection can significantly broaden allowed phase space
- Measuring flavor ratio = sensitivity to potentially new physics
- For full details see: Phys. Rev. D 96, 083018 (2017)

Flavour physics with astrophysical neutrinos

Current measurements and near time sensitivivt



- Expected sensitivity in reach!
- Upgrade will provide better calibration → better sensitivity to tau neutrinos
- But probably a bit early to draw conclusions

Summary

Highlights from IceCube

- Neutrino oscillations:
  - echo of physics beyond the Standard Model
  - Precise measurements are needed to identify underlying symmetry
- IceCube – tool to study neutrinos:
  - Standard atmospheric oscillations
  - PMNS unitarity
  - Sterile neutrinos
  - More was left out: non-standard interactions, cross-sections, DarkMatter and much more
- Potential probe of new physics at astrophysical scales
- IceCube Upgrade:
  - Approved and in preparation
  - Deployment in 2022/2023

Backup