Neutrino Oscillations in Ice

D. Jason Koskinen

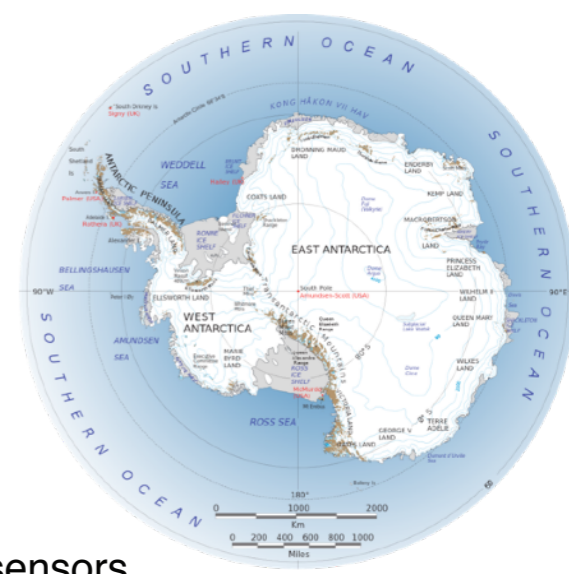University of Copenhagen - Niels Bohr Institute

Here, There, & Everywhere
NBI Ph.D. School
July, 2021

CARLSBERGFONDET

*Felipe Pedreros, IceCube/NSF

IceCube/DeepCore

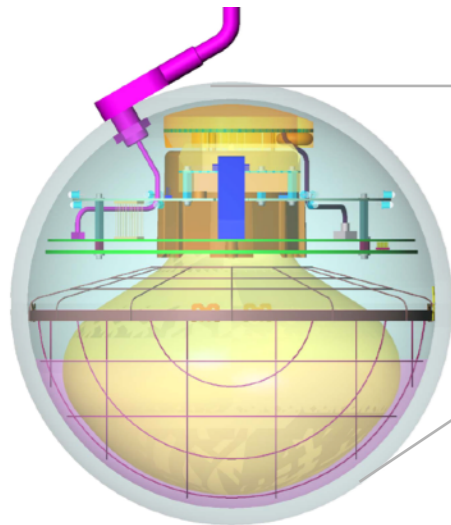IceCube Lab

IceTop
81 Stations
324 optical sensors

50 m

IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors

1450 m

DeepCore
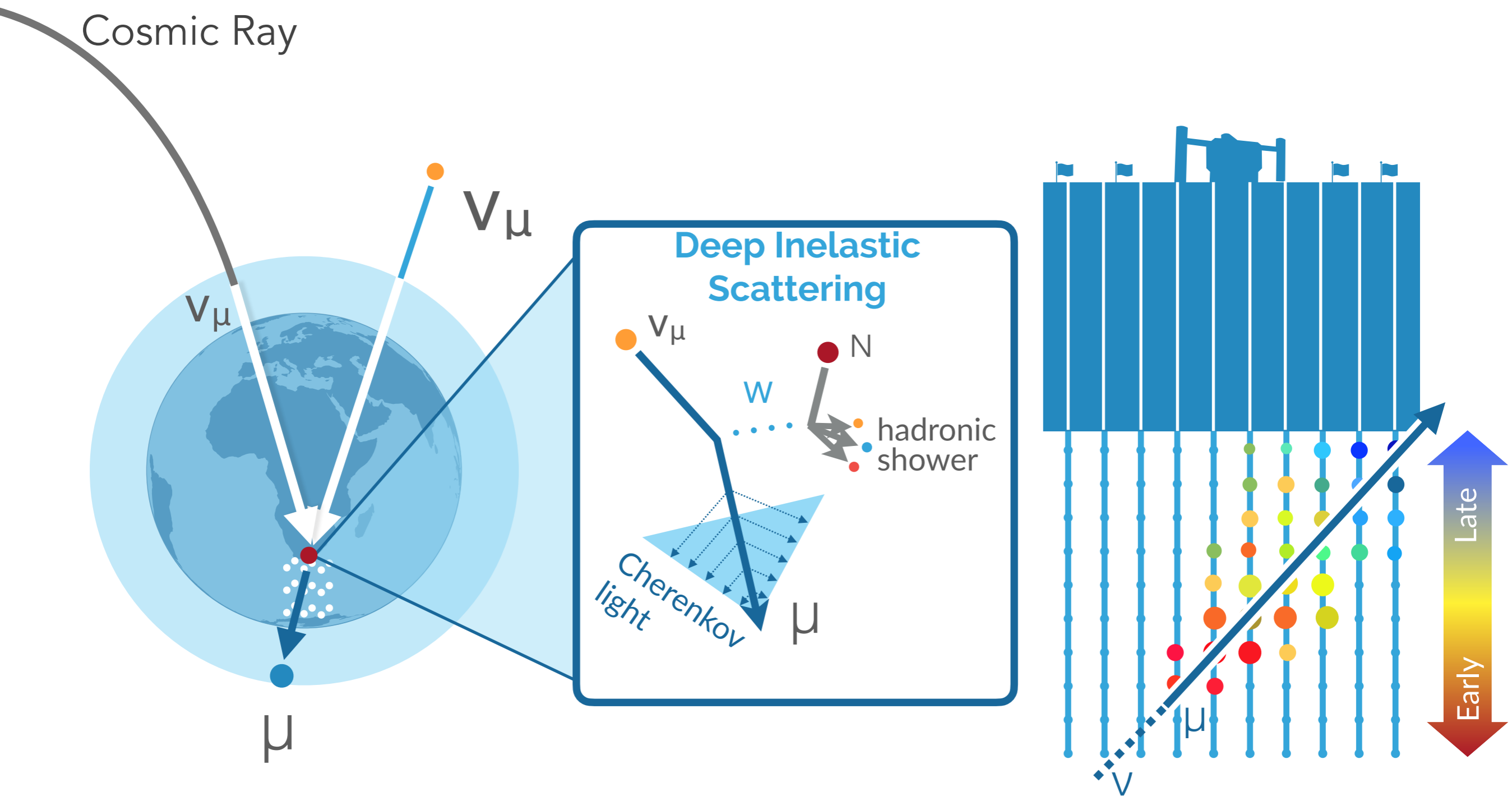8 strings-spacing optimized
for lower energies
480 optical sensors

Eiffel Tower
324 m

2450 m

2820 m
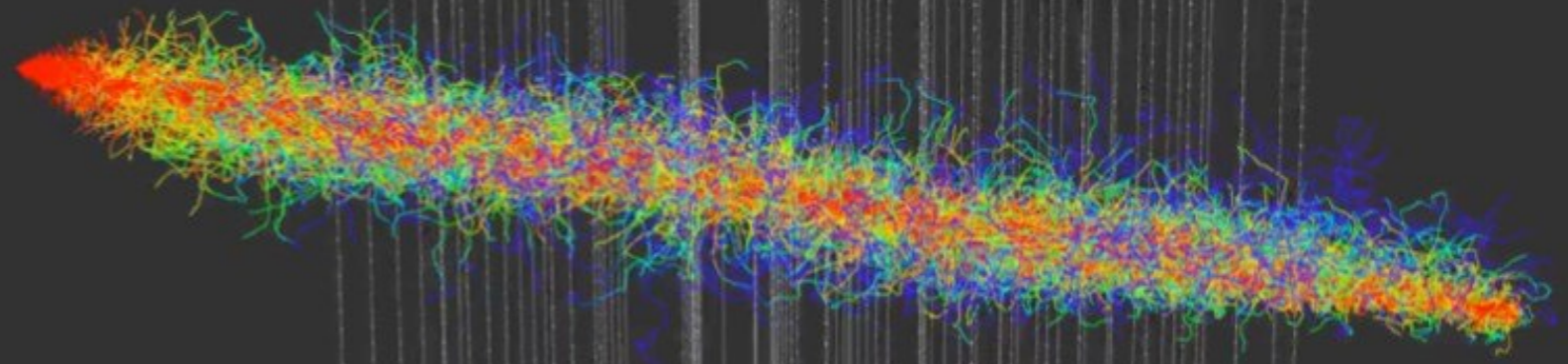
IceCube Digital Optical
Module (DOM)

Bedrock

Detection in IceCube

Cosmic Ray

ν_μ

ν_μ

μ

Deep Inelastic Scattering

ν_μ N

w

hadronic shower

Cherenkov light

μ

Late

Early

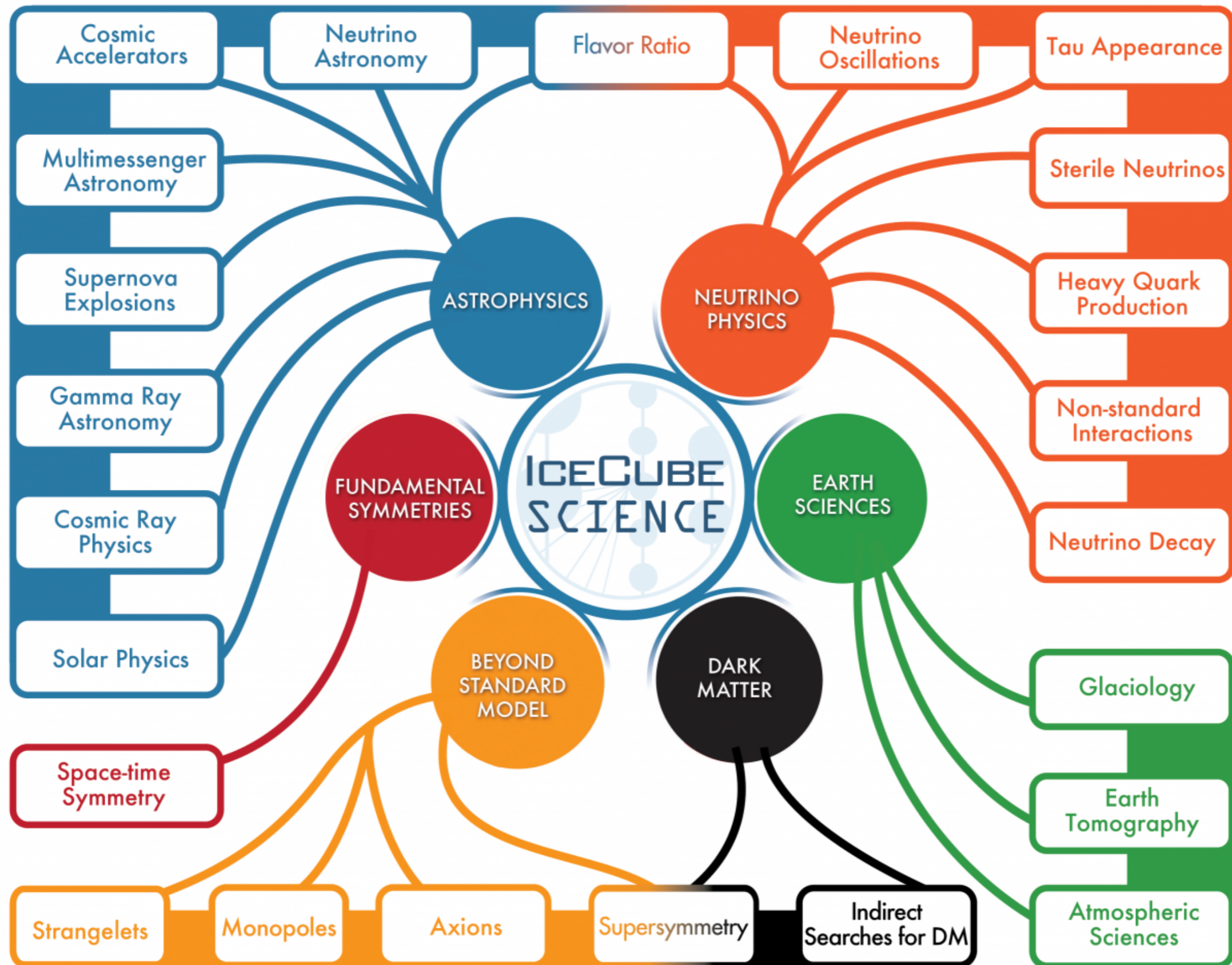μ

ν

Track topology
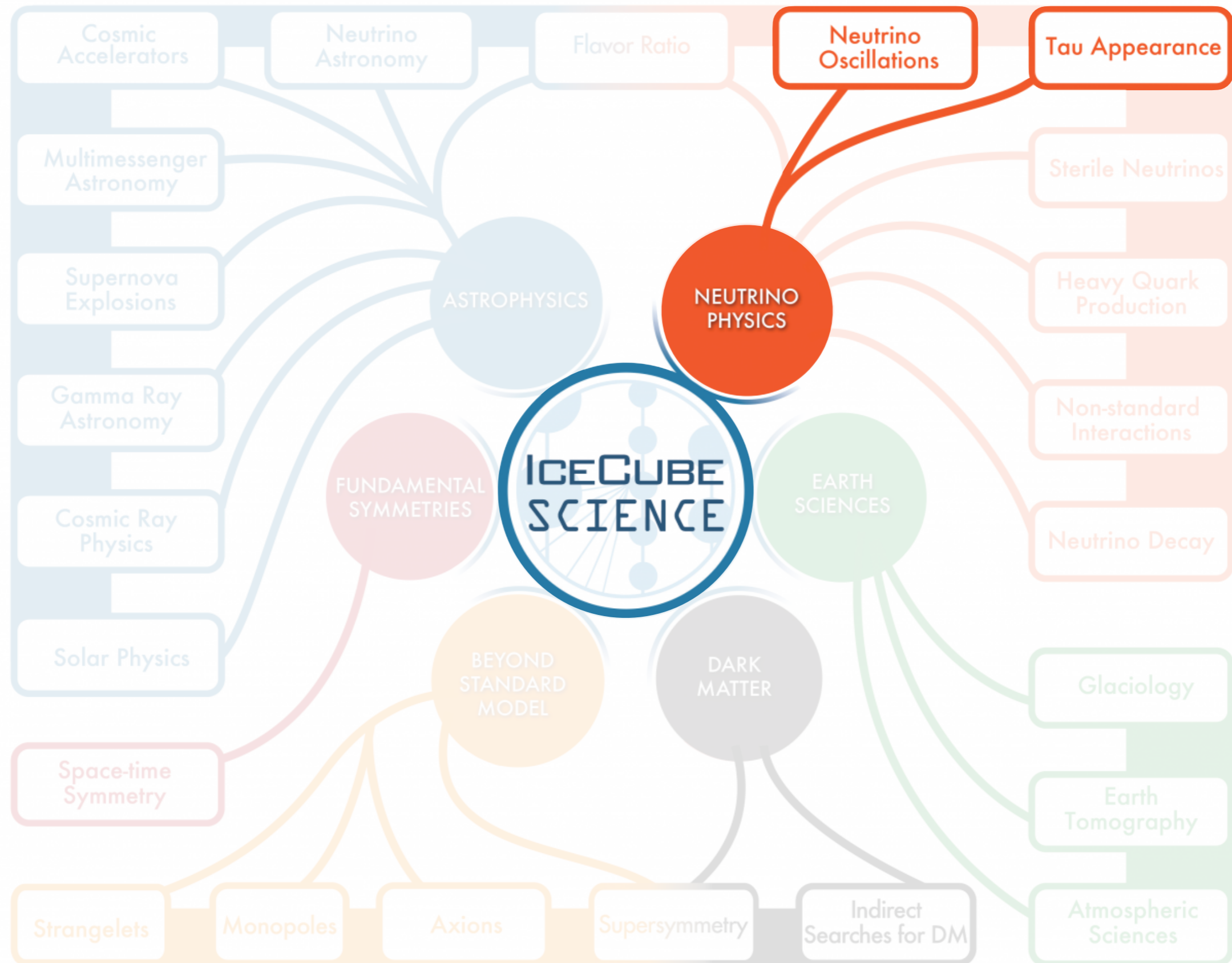(e.g. induced by muon neutrino)

Good pointing

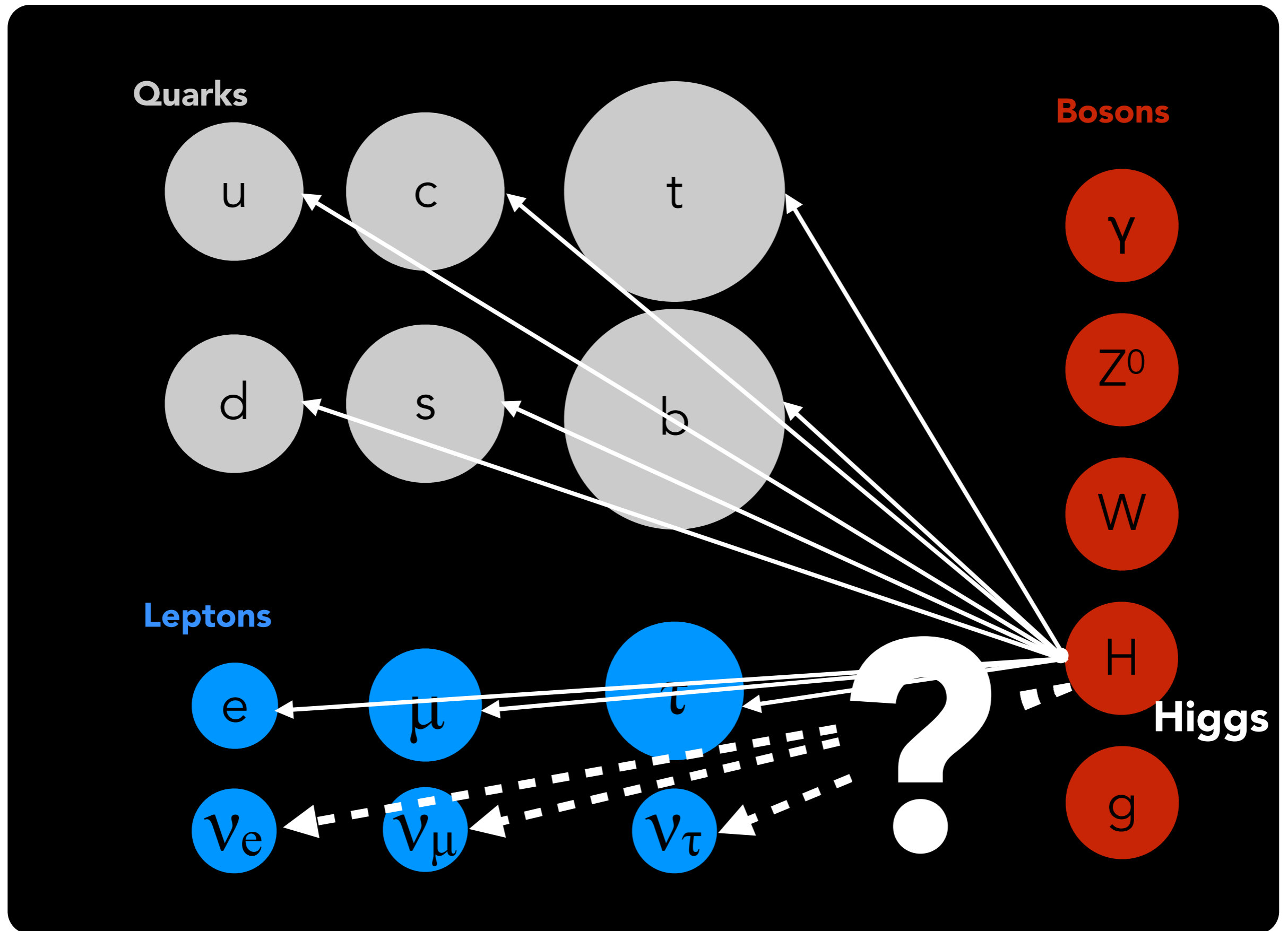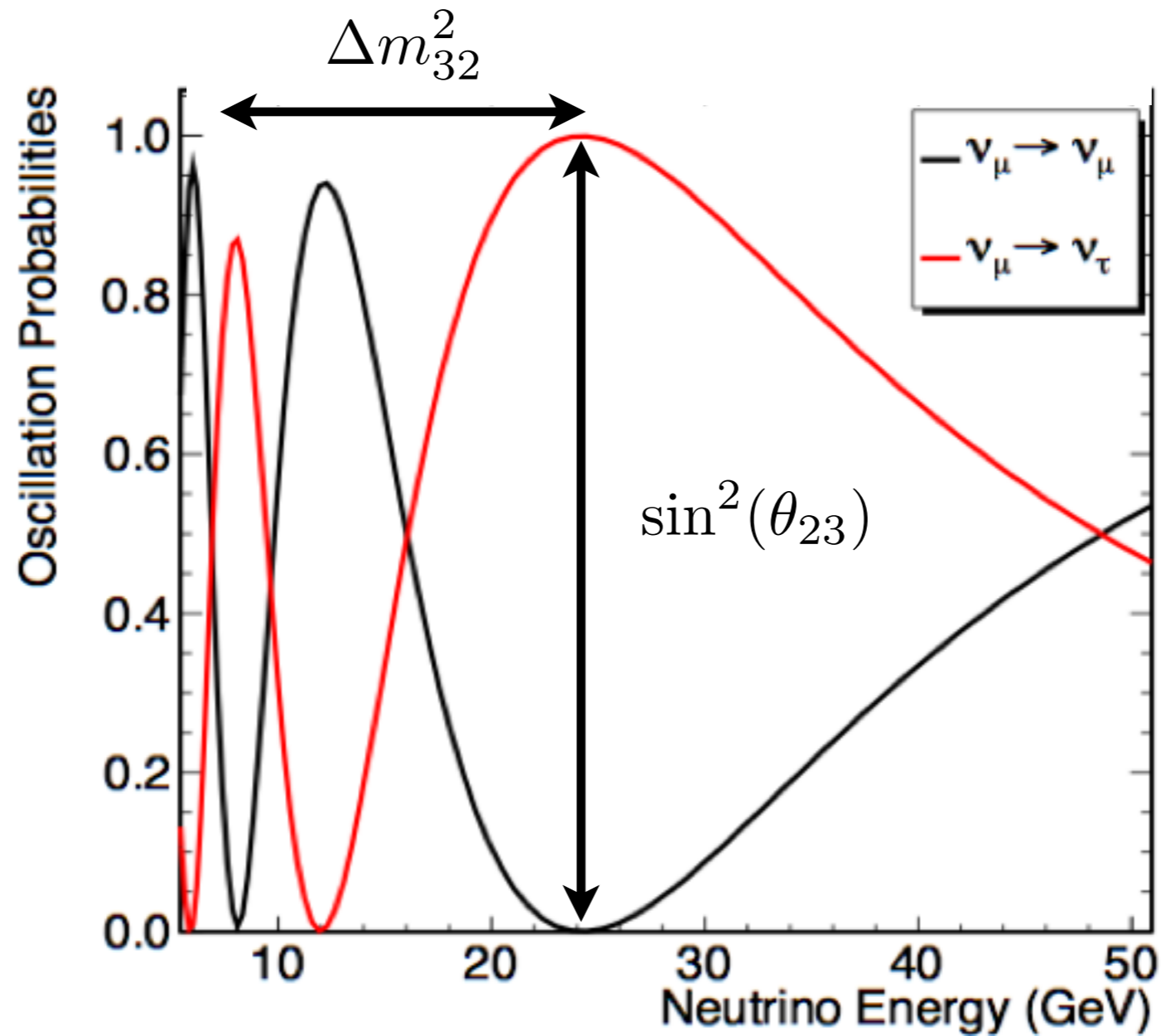ν and $\bar{\nu}$ are, essentially, indistinguishable

IceCube Science

IceCube Science

Standard Model & Neutrinos
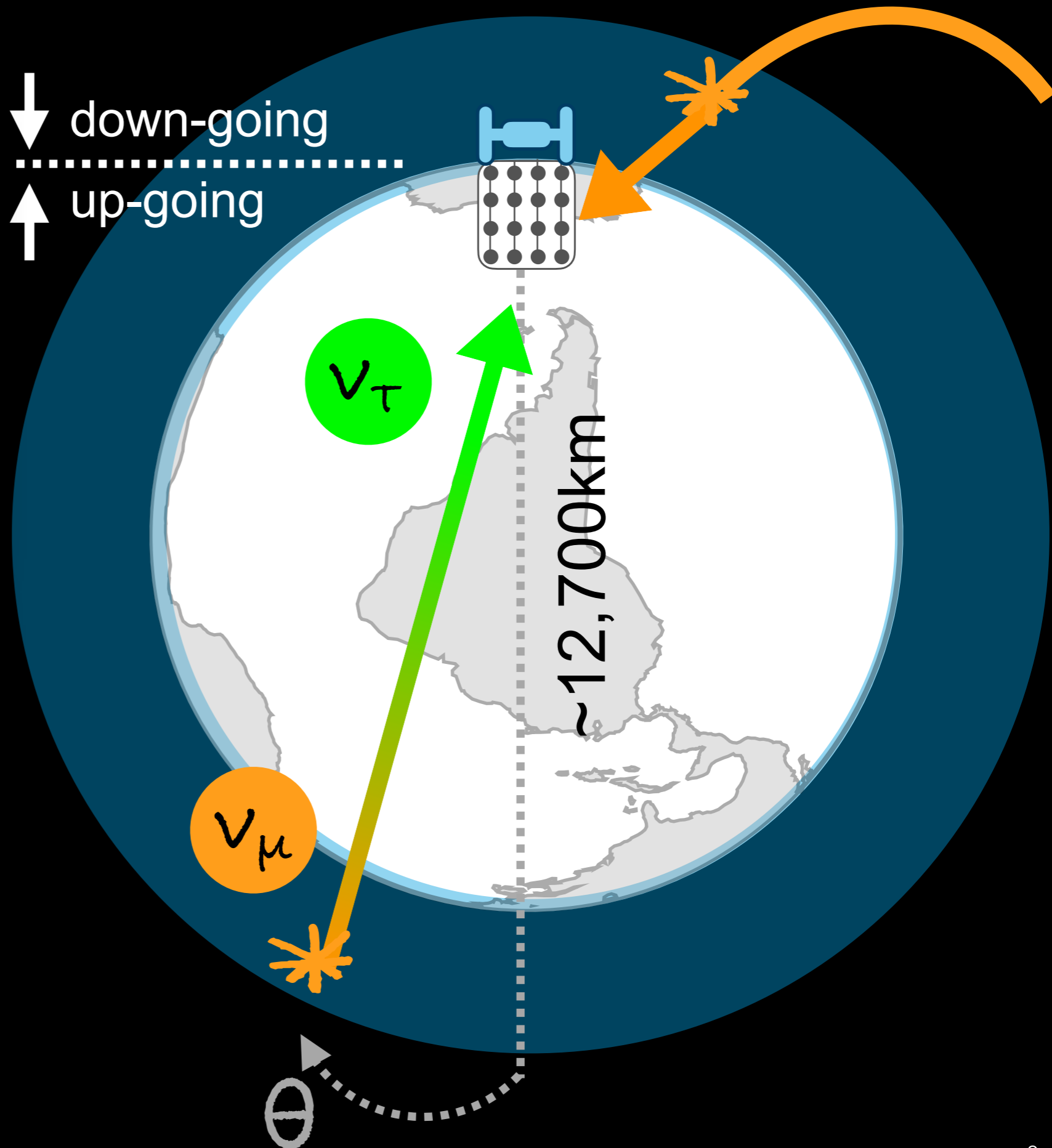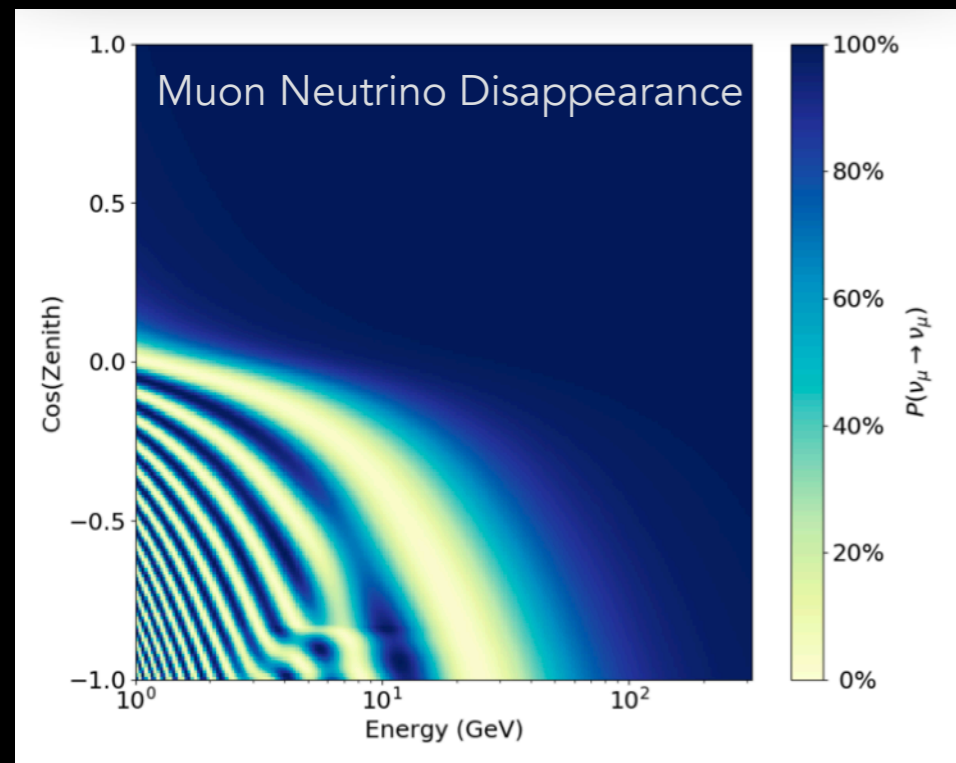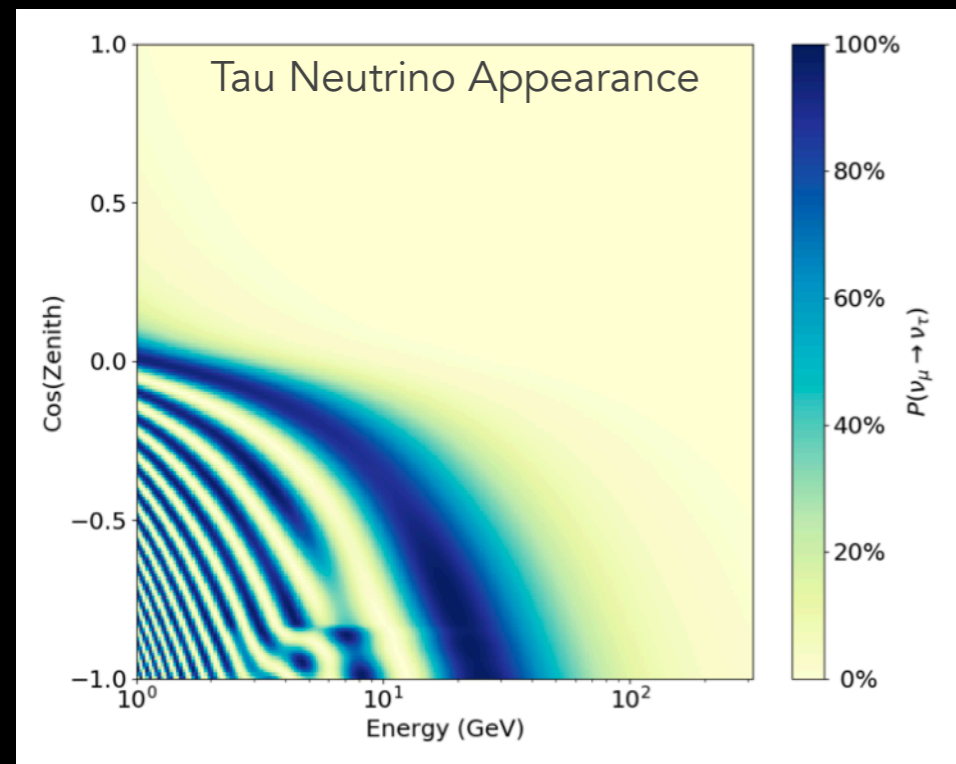
Generic Oscillation (Atm. Disappearance)

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

L = travel length
E = energy

Measurement

down-going

up-going

Tau Neutrino Appearance

Muon Neutrino Disappearance

ν_τ

ν_μ

~12,700km

θ

IceCube/**DeepCore**
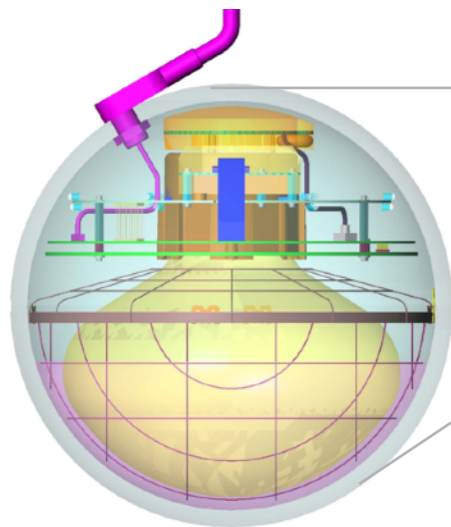

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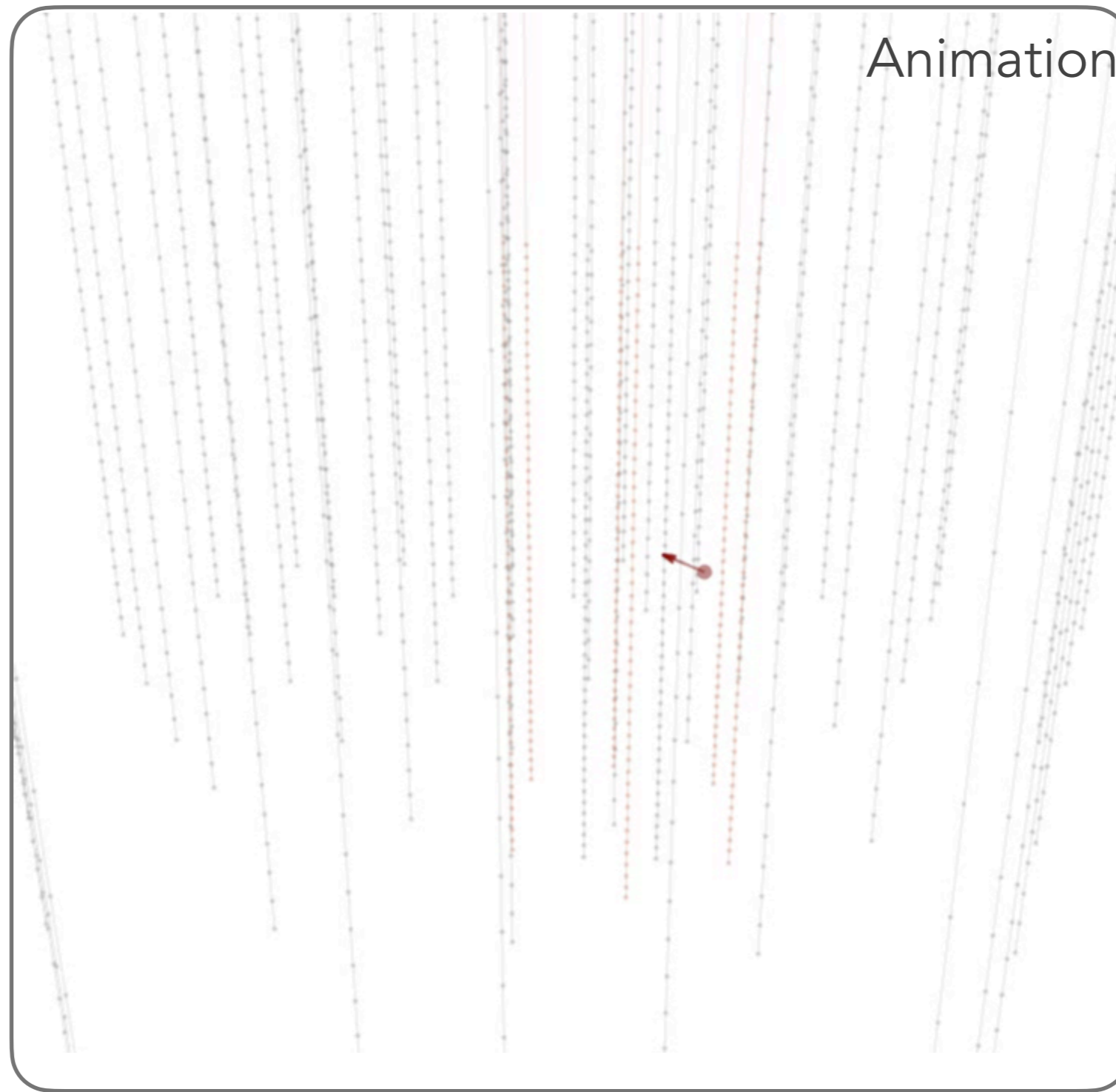for lower energies
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IceCube Digital Optical
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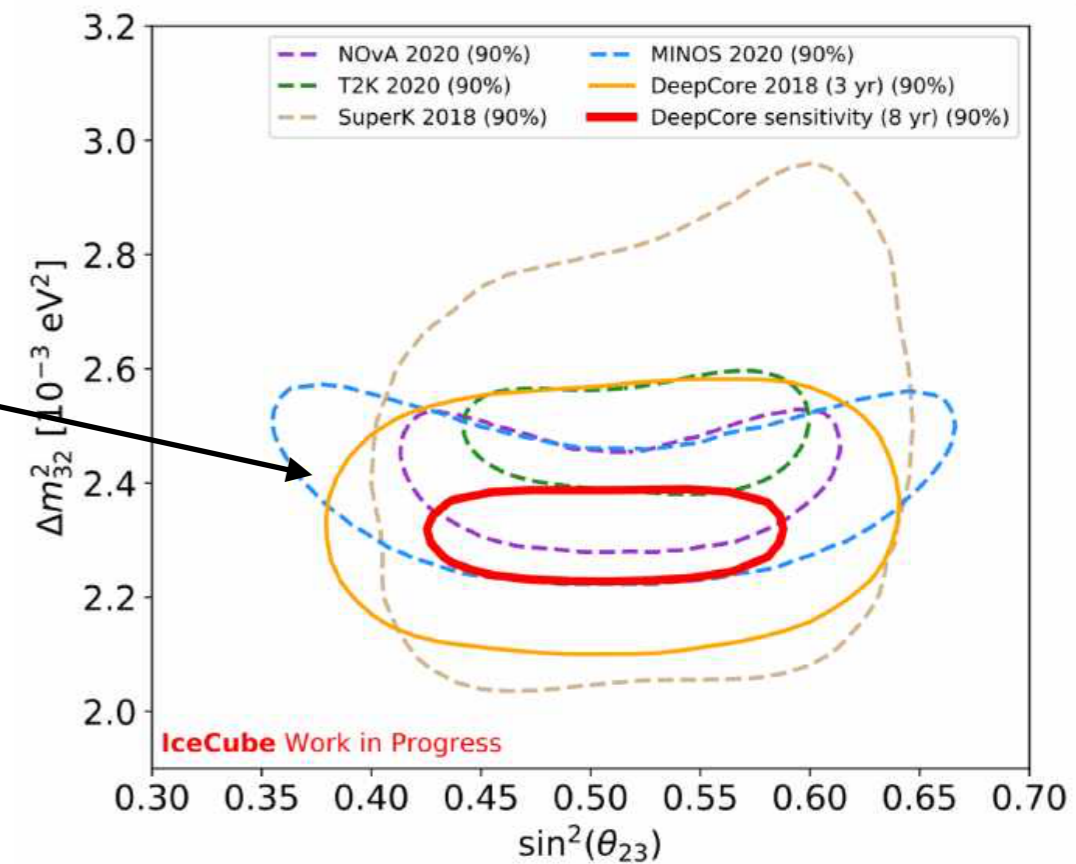
Bedrock

DeepCore Reality

Animation

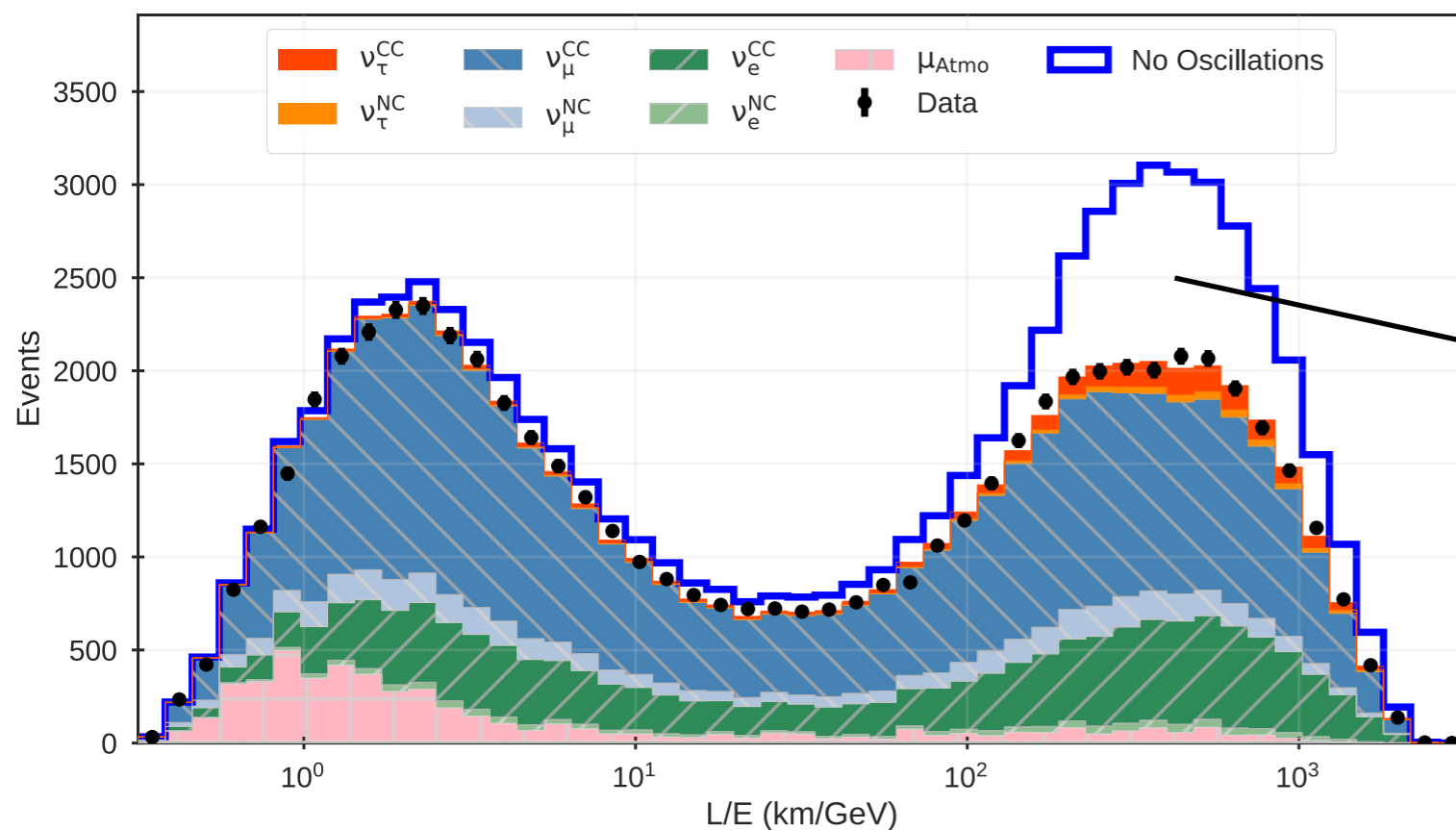9.28 GeV ν_μ: 4.9 GeV muon, 4.5 GeV cascade

IceCube-DeepCore Oscillation

- ~60k neutrino candidates in 3 years of DeepCore data

- Upcoming 8-year analysis is expected >250k neutrino candidates

Neutrino Oscillation

Flavor Eigenstate

Mass Eigenstate

$$
\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \mathcal{U}_{\mathrm{PMNS}} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}
$$

$$
= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}
$$

- Neutrino flavor eigenstates are related to mass eigenstates via the PMNS unitary mixing matrix

- The 3 conventional angles (θ_{12}, θ_{13}, θ_{23}) fully describe the 3x3 mixing matrix **only if** the mixing matrix is unitary
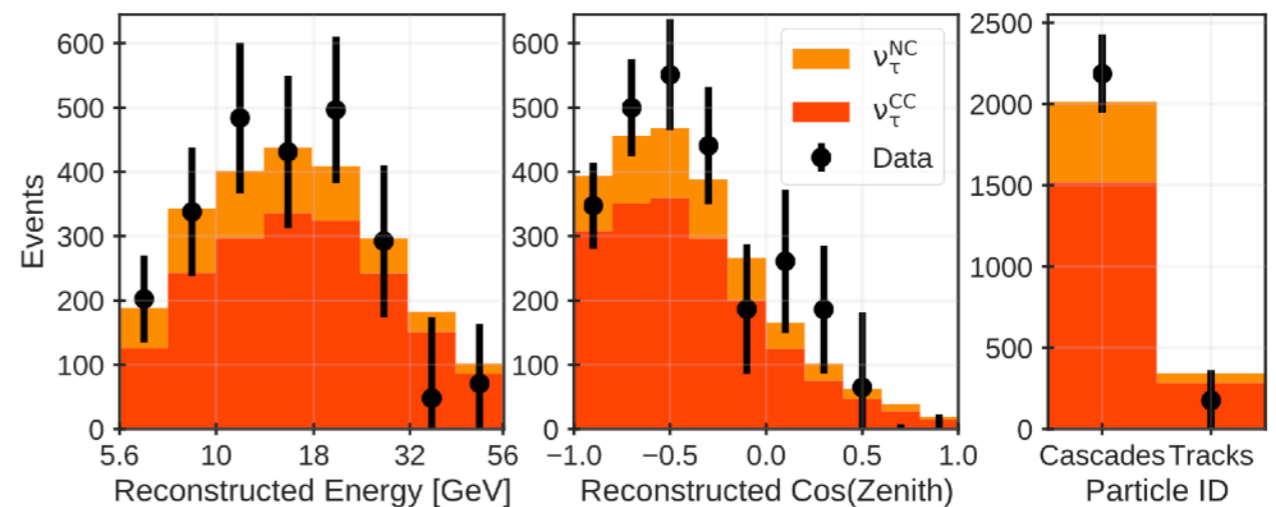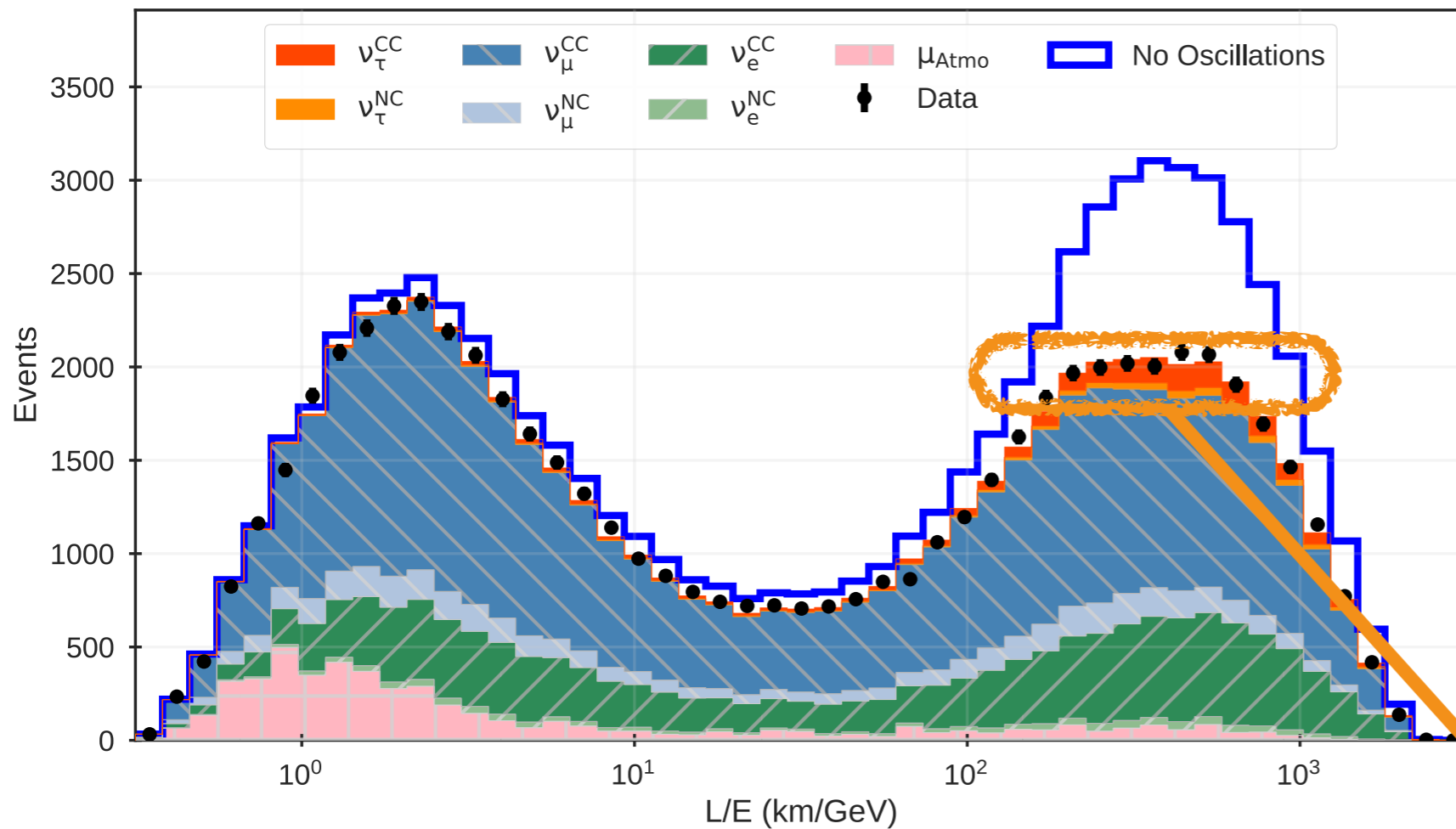
Unitarity

- Minimal assumption direct experimental constraints for PMNS unitarity **<u>need</u>** to be improved upon
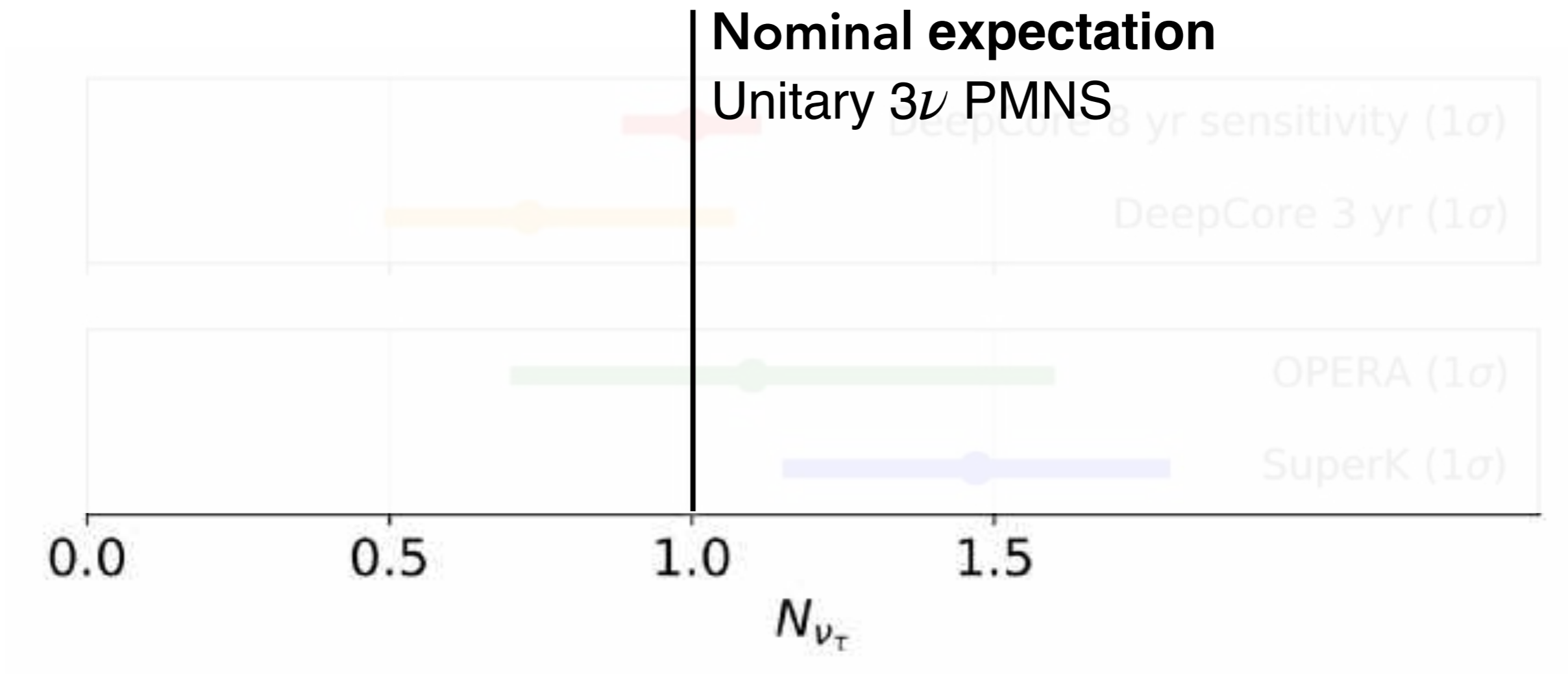
*arXiv:1508.05095
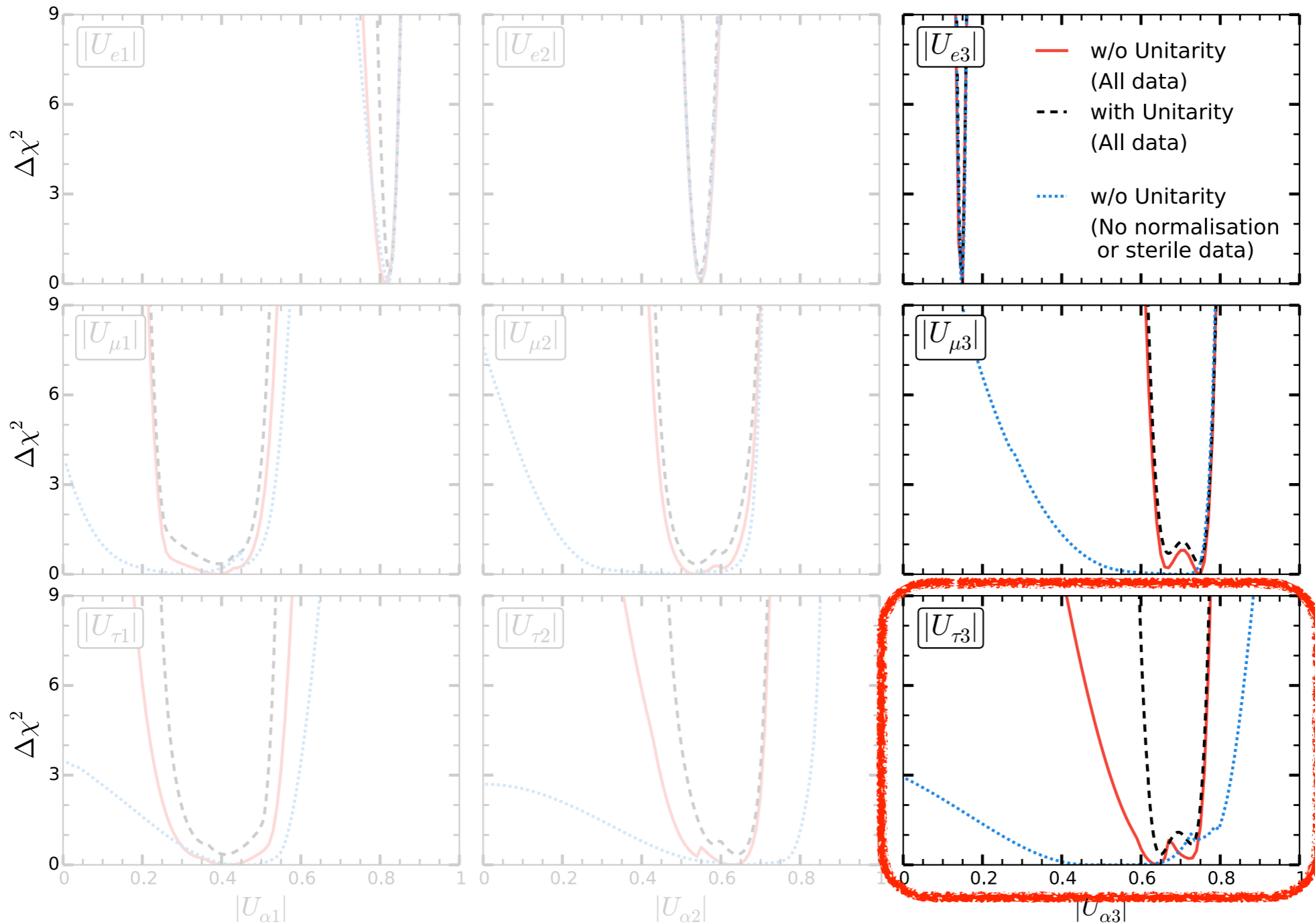
Updated global analysis can be found in arXiv:2008.01088

IceCube-DeepCore ν_τ appearance
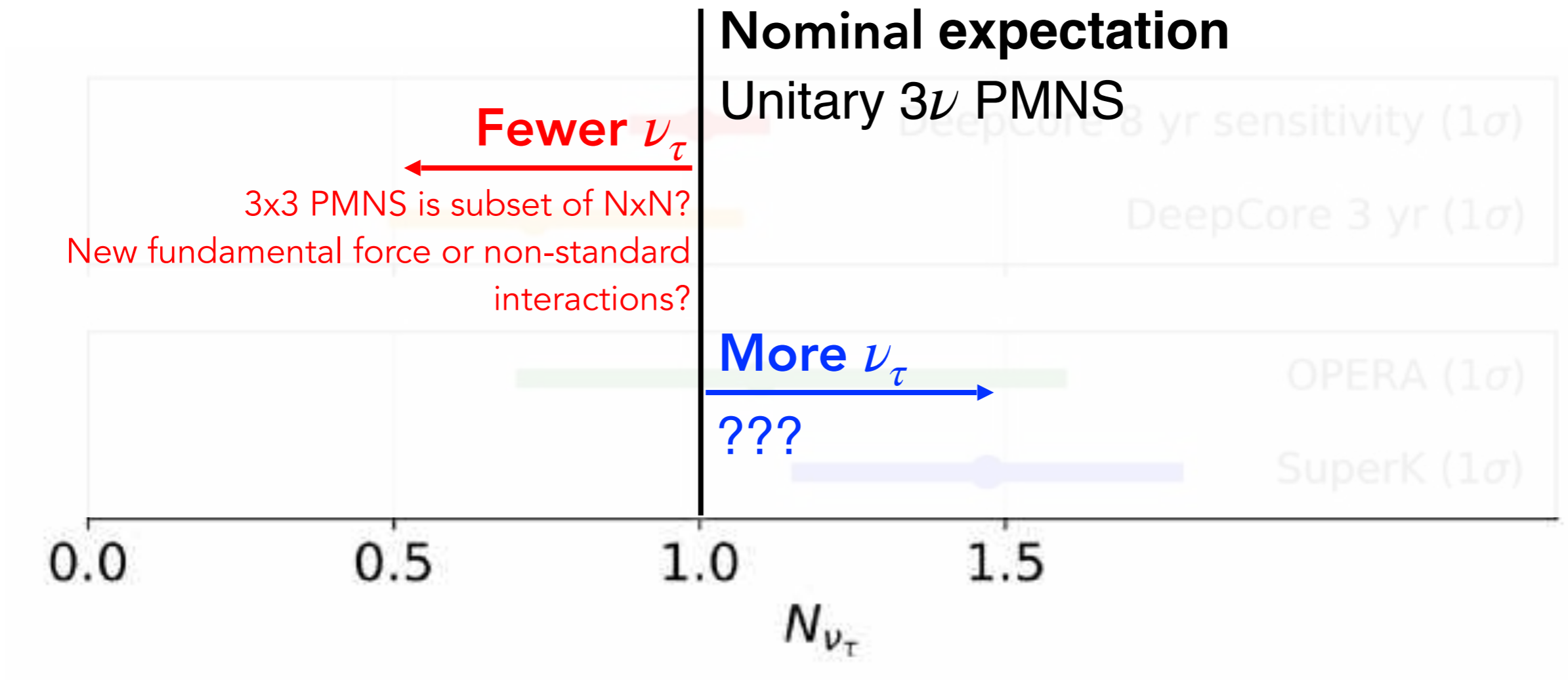

Data fit in [energy, cos(zenith), PID] space
Searching for 3D distortions (shape-only)

*arXiv:1901.05366

DeepCore ν_τ appearance results

Nominal **expectation**
Unitary 3ν PMNS

DeepCore 8 yr sensitivity (1σ)

DeepCore 3 yr (1σ)

OPERA (1σ)

SuperK (1σ)

N_{ν_τ}

ν_τ template scaled relative to unitary expectation

DeepCore ν_τ appearance results

Nominal expectation
Unitary 3ν PMNS

DeepCore 8 yr sensitivity (1σ)

Fewer ν_τ

3x3 PMNS is subset of NxN?
New fundamental force or non-standard
interactions?

DeepCore 3 yr (1σ)

More ν_τ

???

OPERA (1σ)

SuperK (1σ)

0.0   0.5   1.0   1.5

N_{ν_τ}

ν_τ template scaled relative to
unitary expectation

DeepCore ν_τ appearance results

Take away message

- World-leading ν_τ appearance measurement precision @ DeepCore
- Results consistent with standard oscillation picture

Coming soon
New measurement with ~5x statistics

y (1σ)

yr (1σ)

A (1σ)

SuperK (1σ)

0.0   0.5   1.0   1.5

N_{ν_τ}
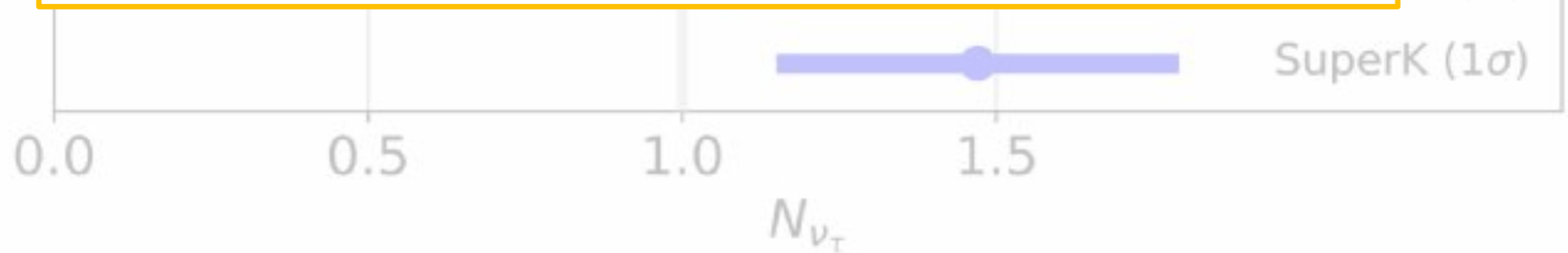
ν_τ template scaled relative to unitary expectation

What's Next?

IceCube Future

- Expand

  - Leading results from 2019

  - Neutrino Oscillations

  - Dark Matter
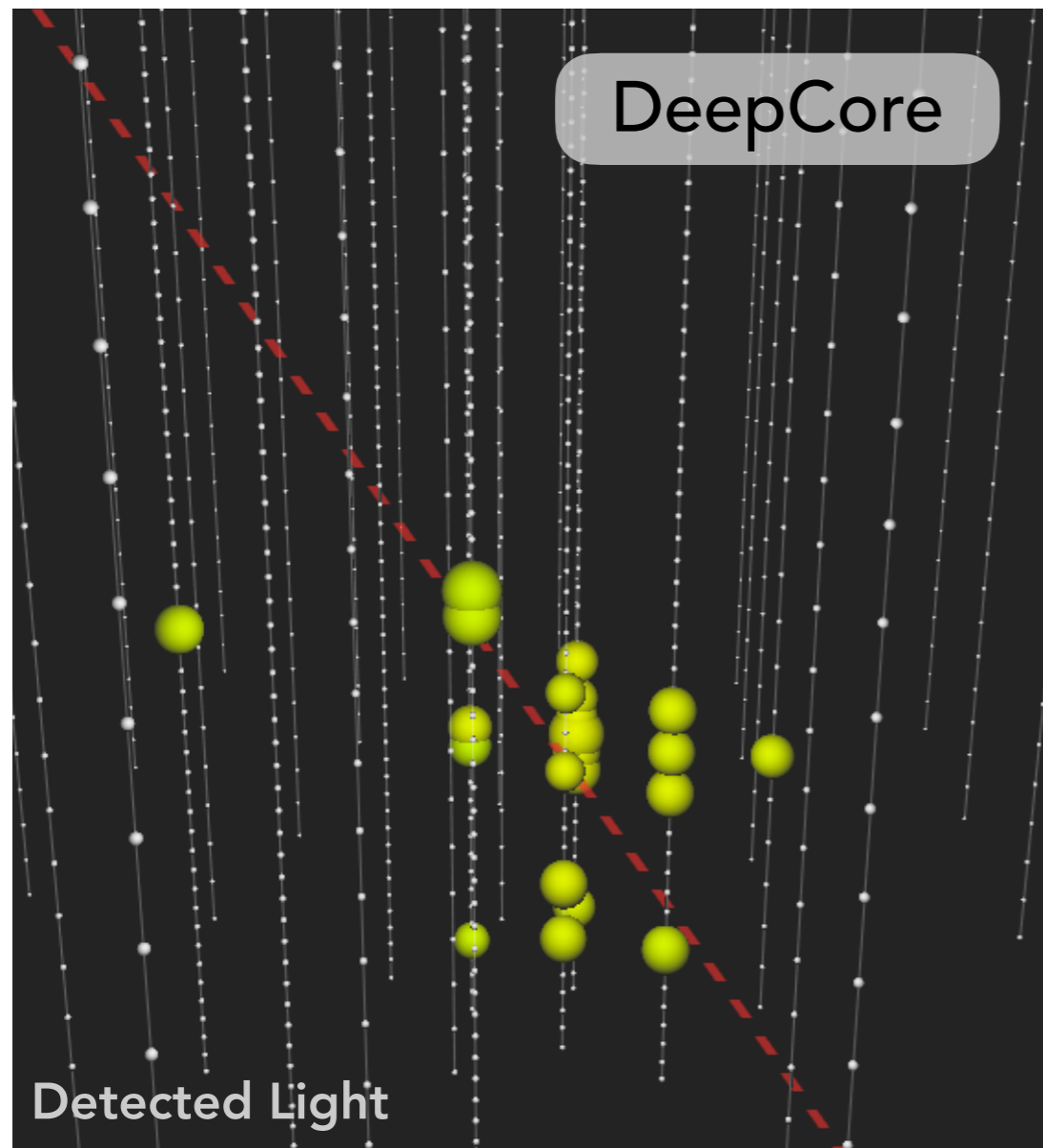
  - Low-energy neutrino transients

- IceCube Upgrade

  - Deployment goal of 2022/23… before COVID

  - 10x improvement for new energy region
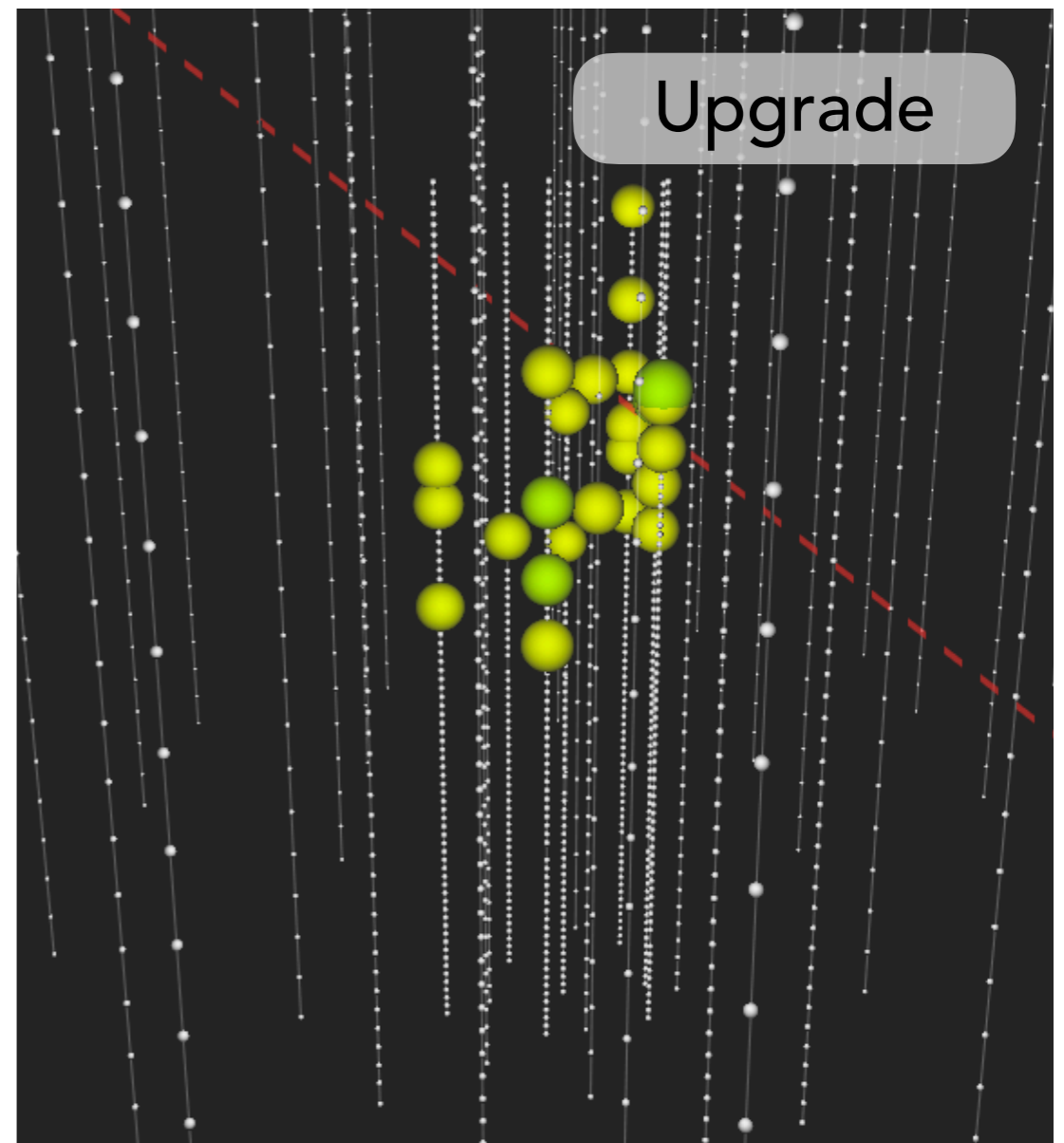

High Energy Array

IceCube Upgrade

DeepCore

IceCube

New Optical Sensors
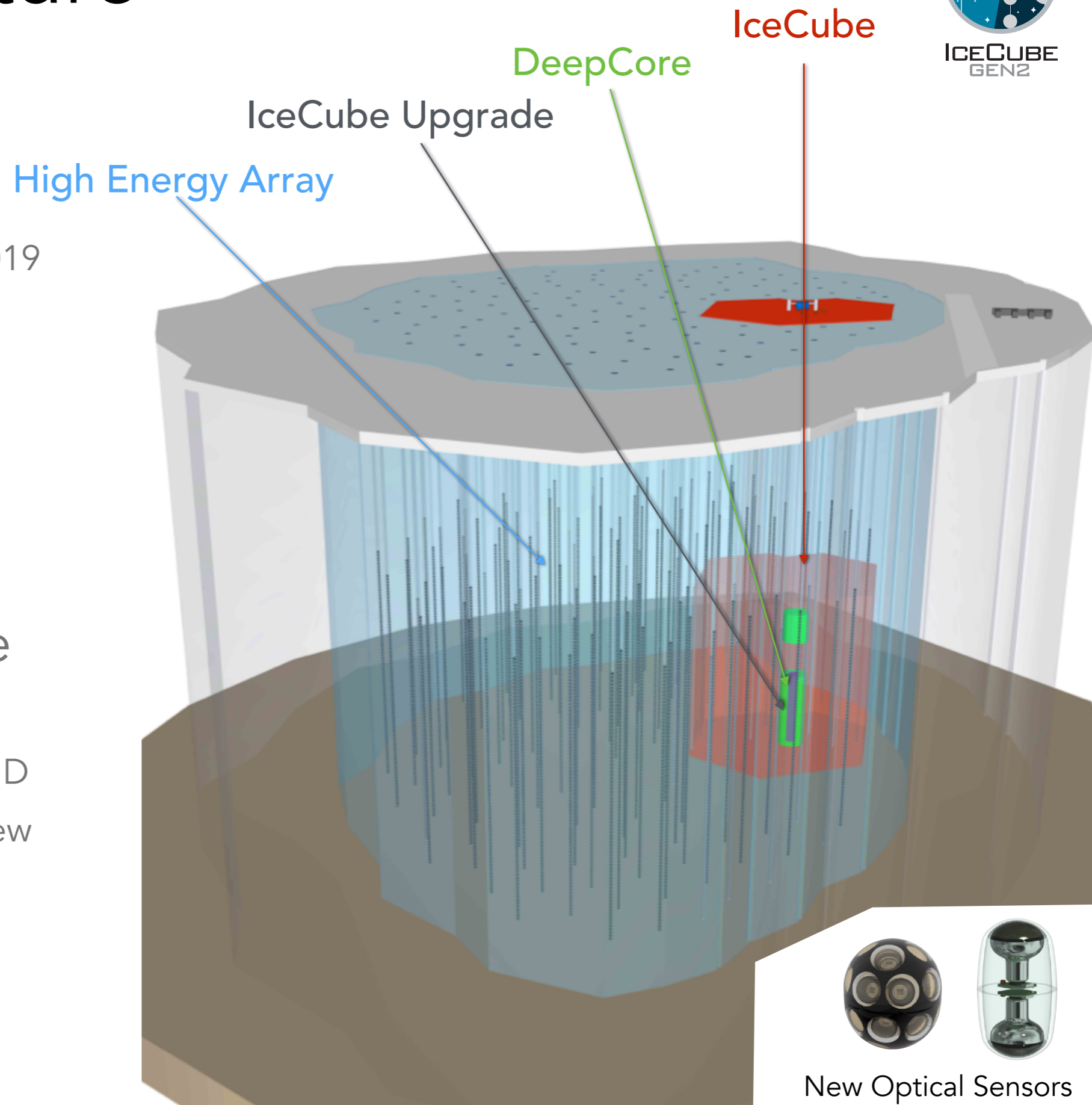
IceCube-Upgrade

- Dense instrumentation within inner core
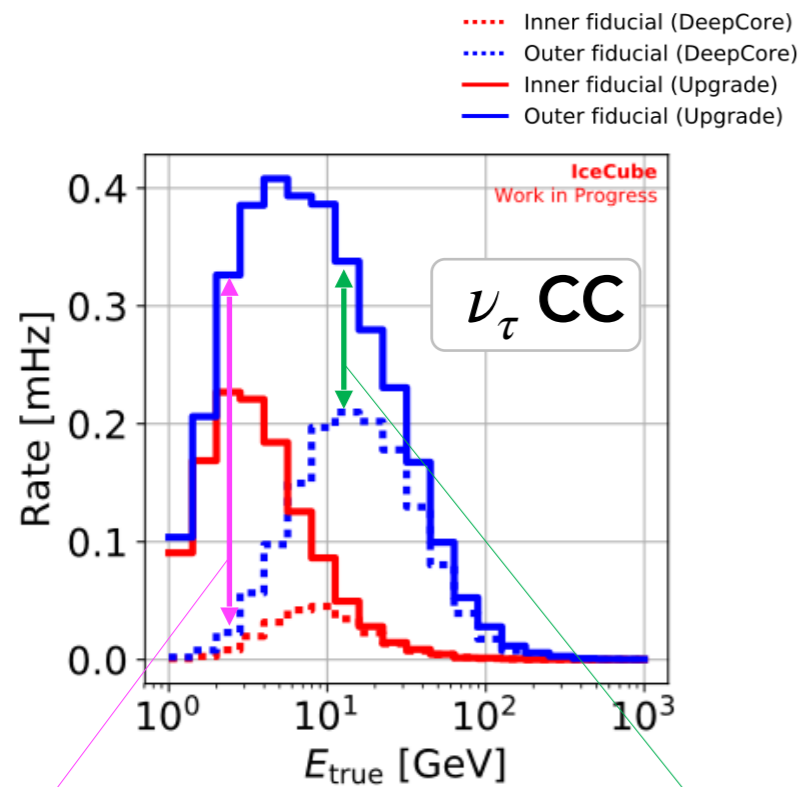
$$30 \text{ GeV } \nu_\mu$$
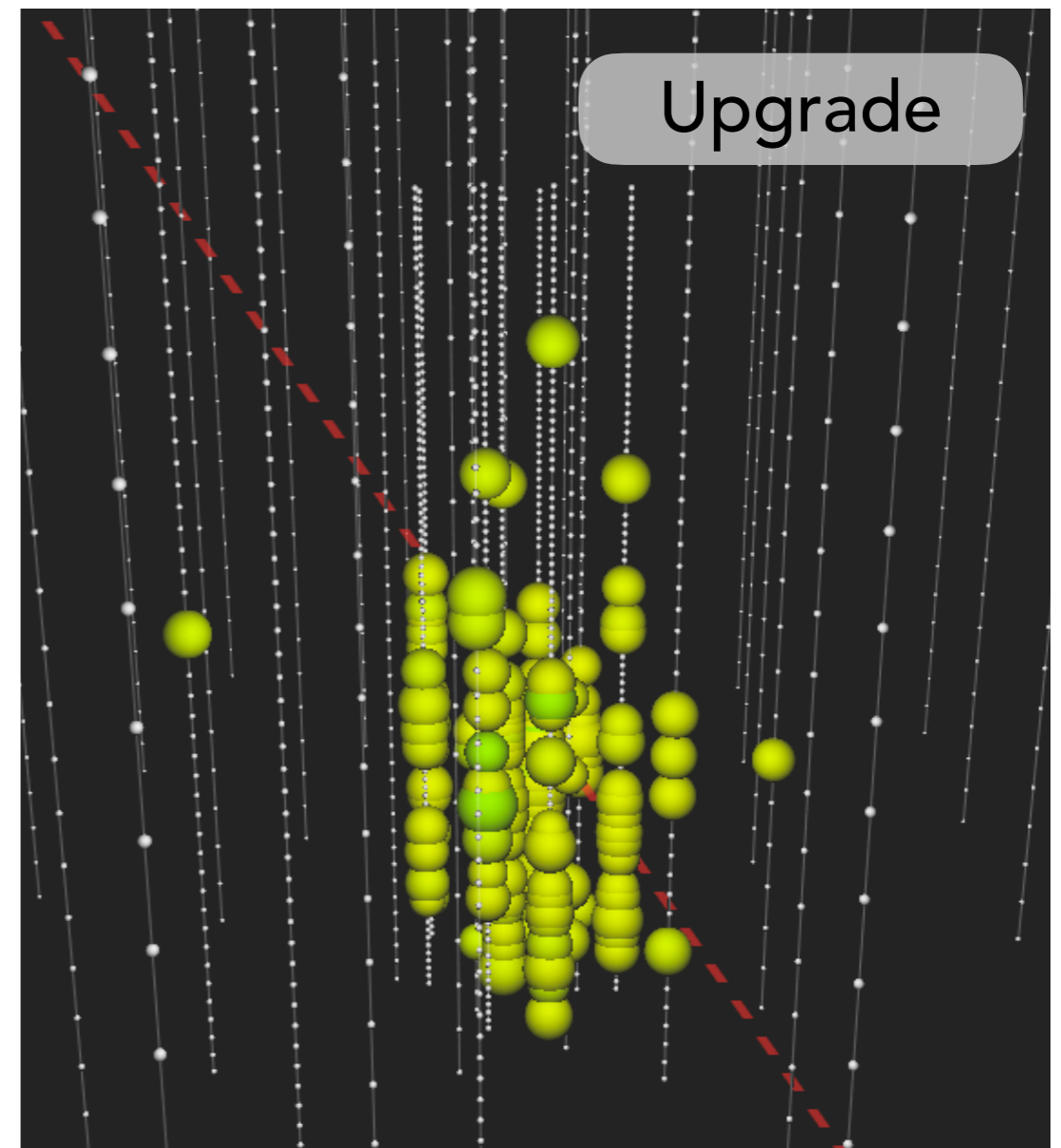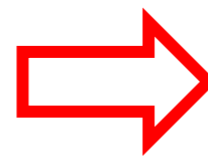
IceCube-Upgrade

- Dense instrumentation within inner core

$$4 \text{ GeV } \nu_\mu$$
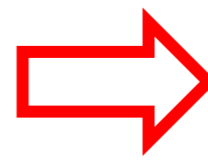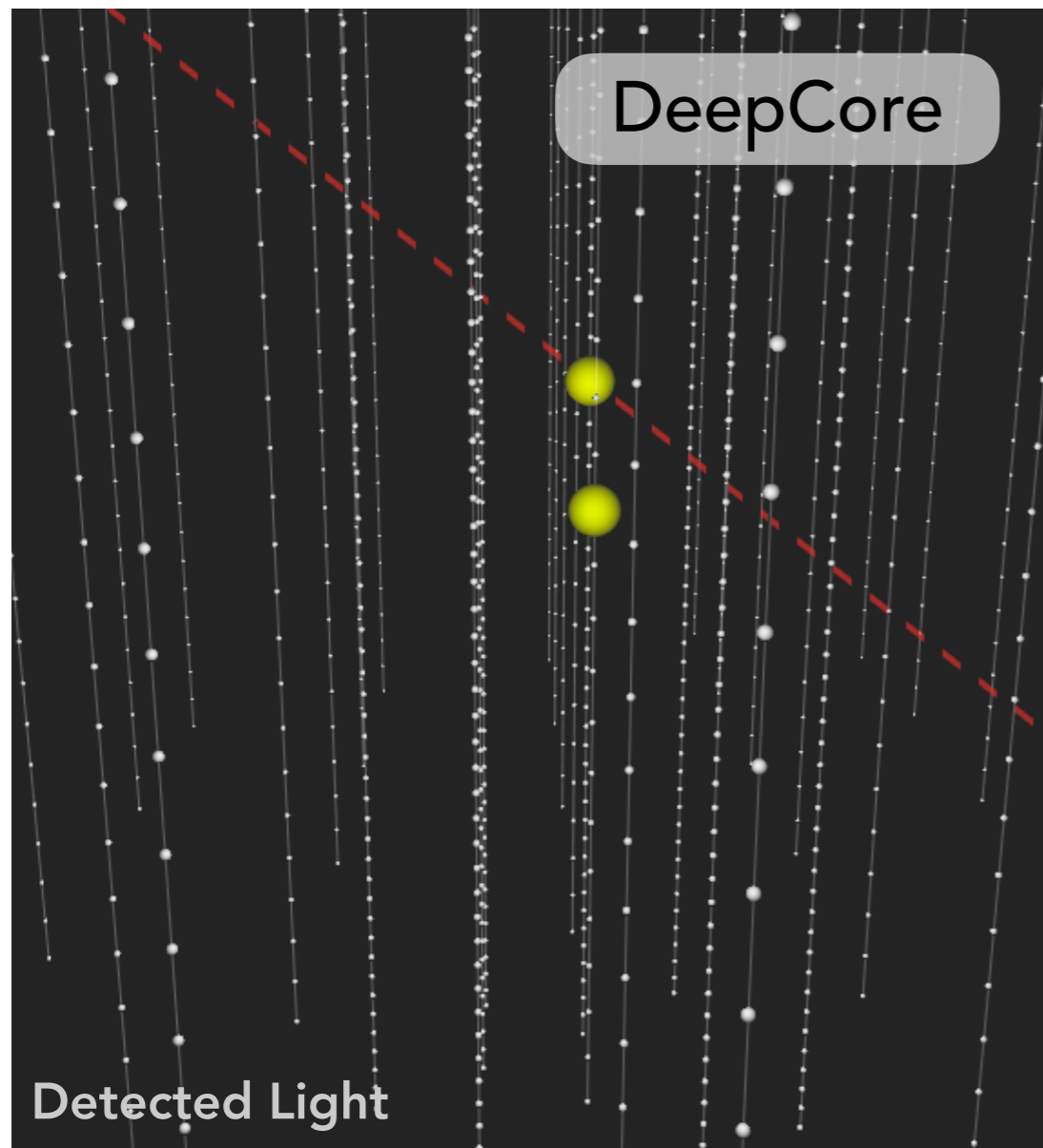
Upgrade Performance

- Major improvement in detection rate and energy/direction resolution

Huge increase in <10 GeV ν rate

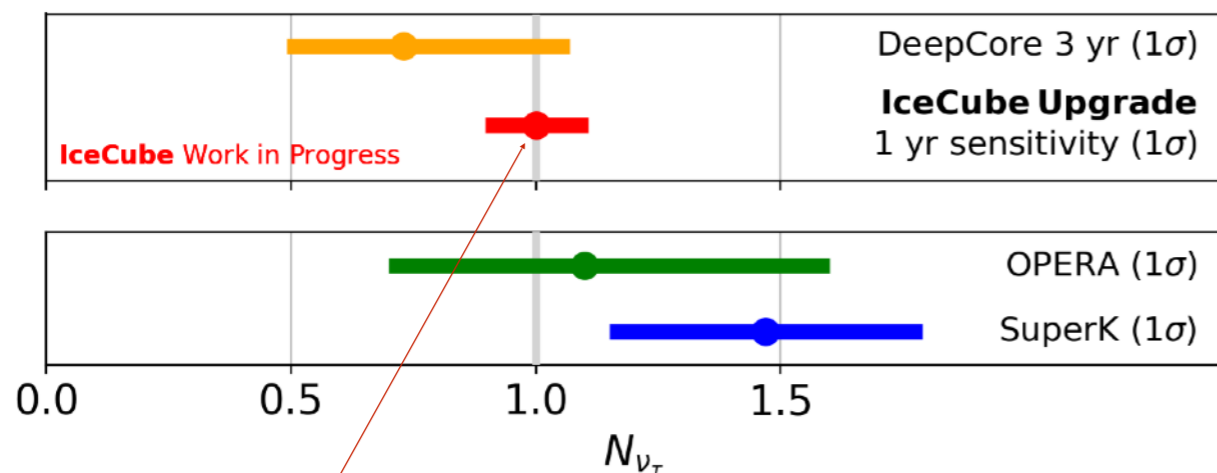**Enhanced rate for all oscillation energies**
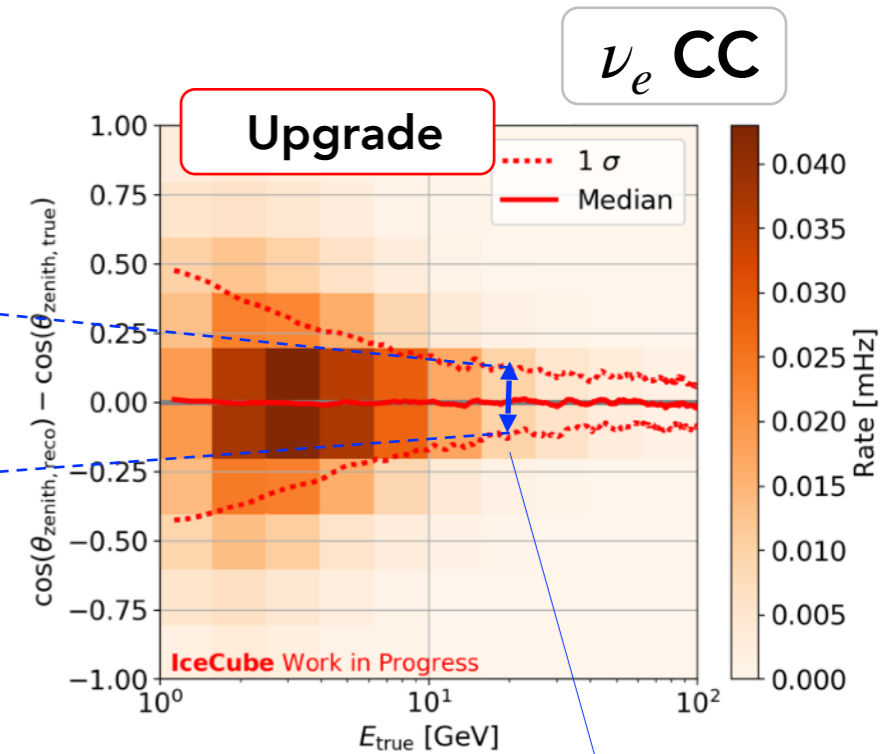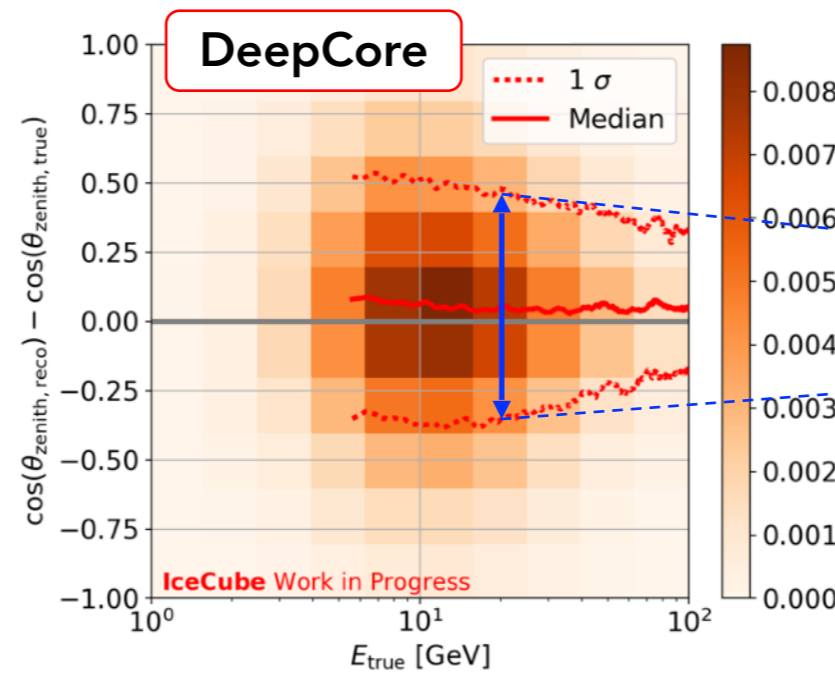
3x improvement @ ν_τ appearance energies

Upgrade & Oscillations

- ν_τ appearance is Upgrade primary physics goal

- Broad oscillation program

- Conservative treatment of systematic uncertainties, event selection, and reconstruction resolutions
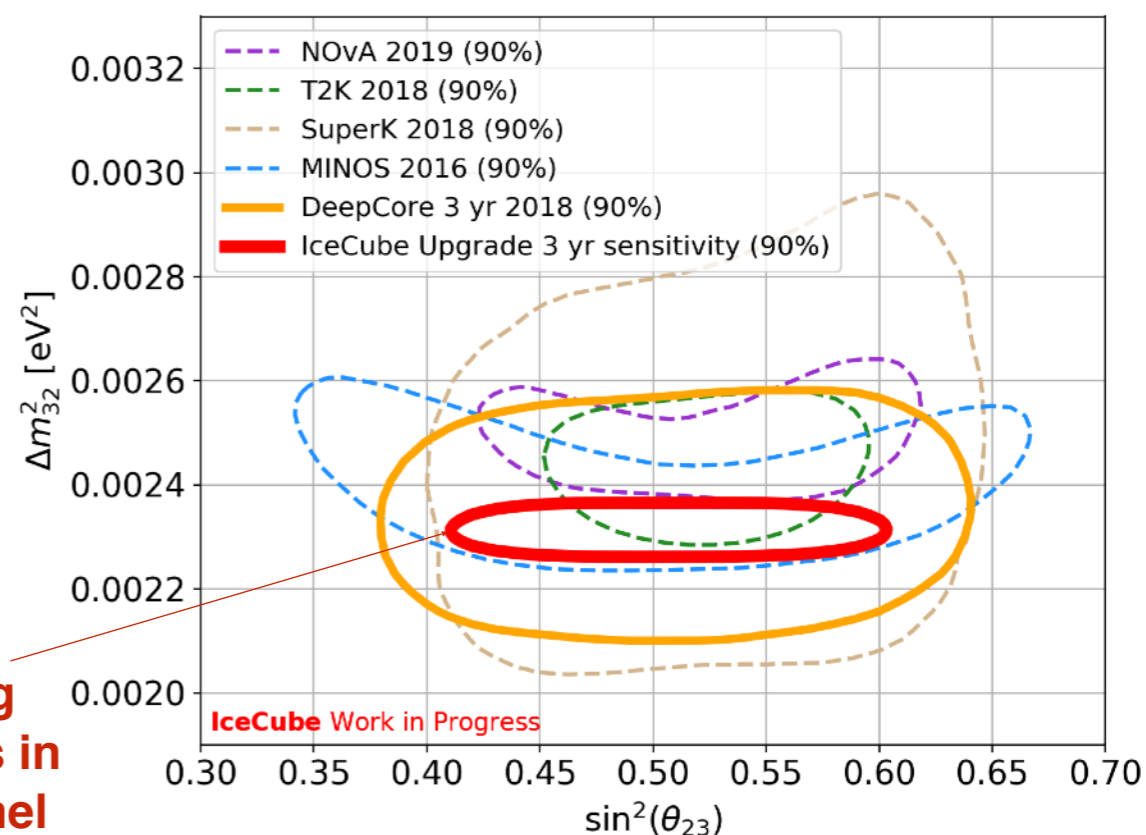
Conclusion

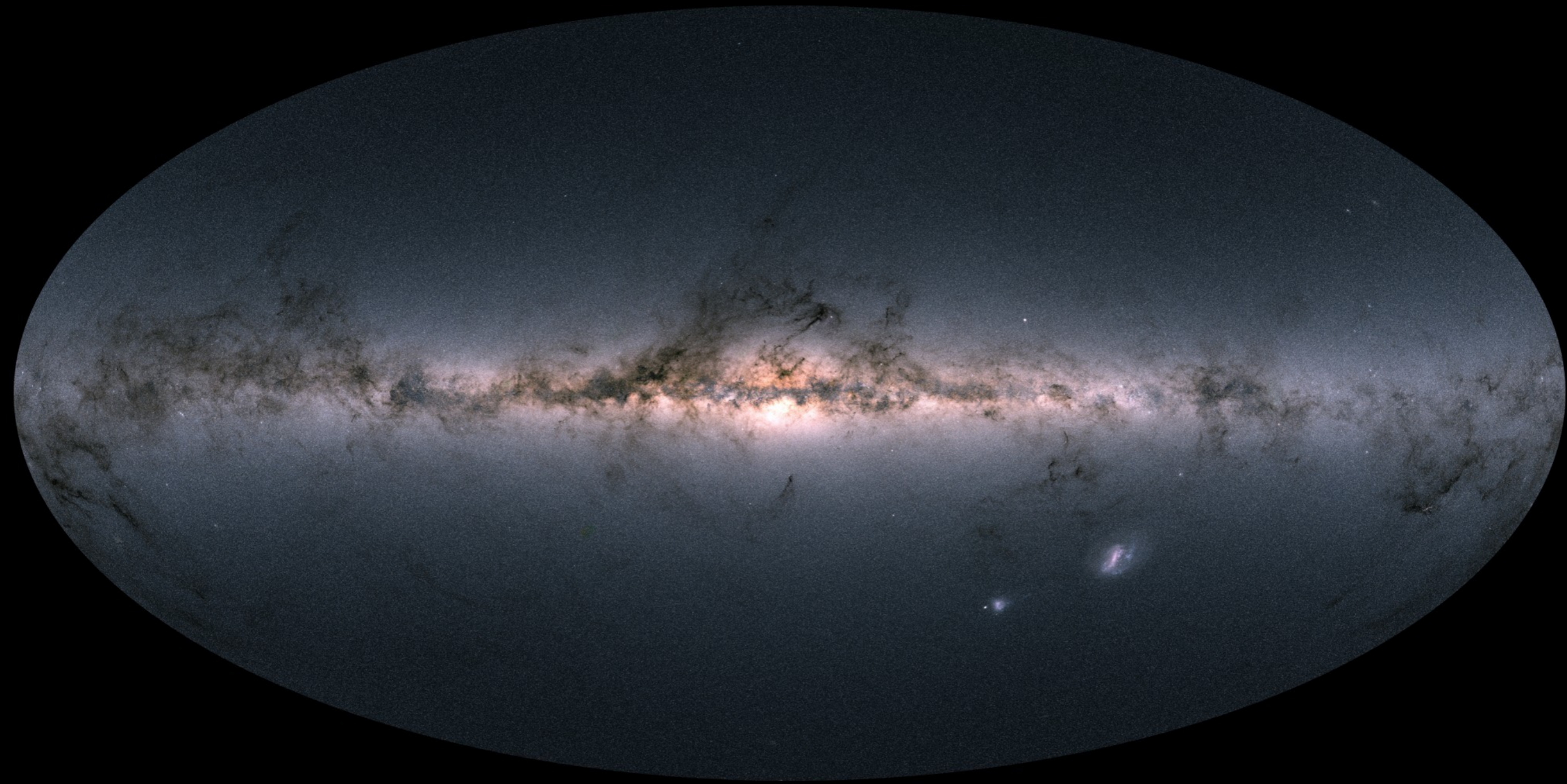IceCube is unlocking the fundamental particle physics secrets of the neutrino

Neutrinos and multi-messenger astronomy are an incredible new window into our Universe

Backup

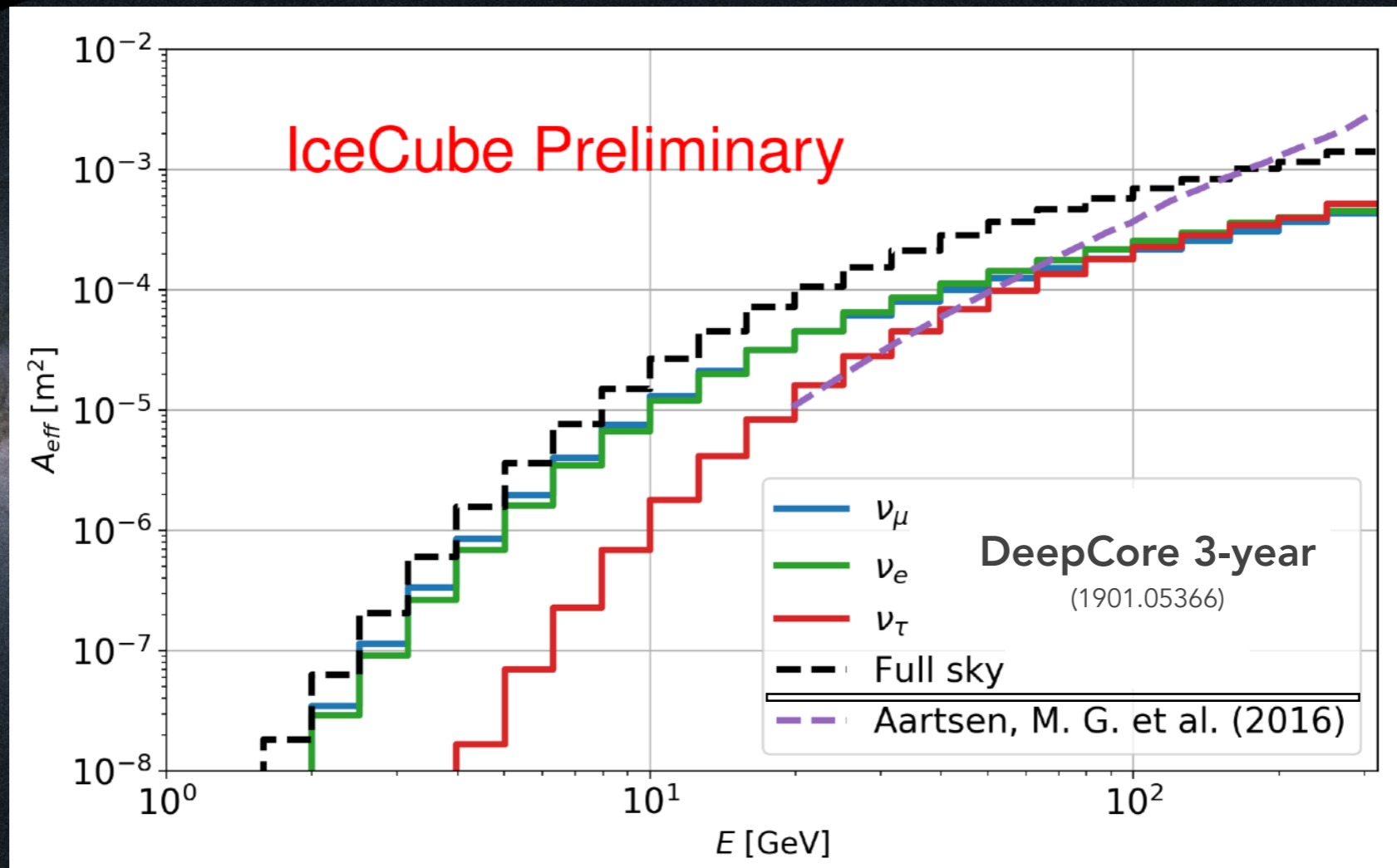# Low-Energy Astrophysical Neutrinos & IceCube

Skymap

*ESA/Gaia/DPAC

D. Jason Koskinen - Here, There, & Everywhere 2021

28

Neutrinos + Astronomy
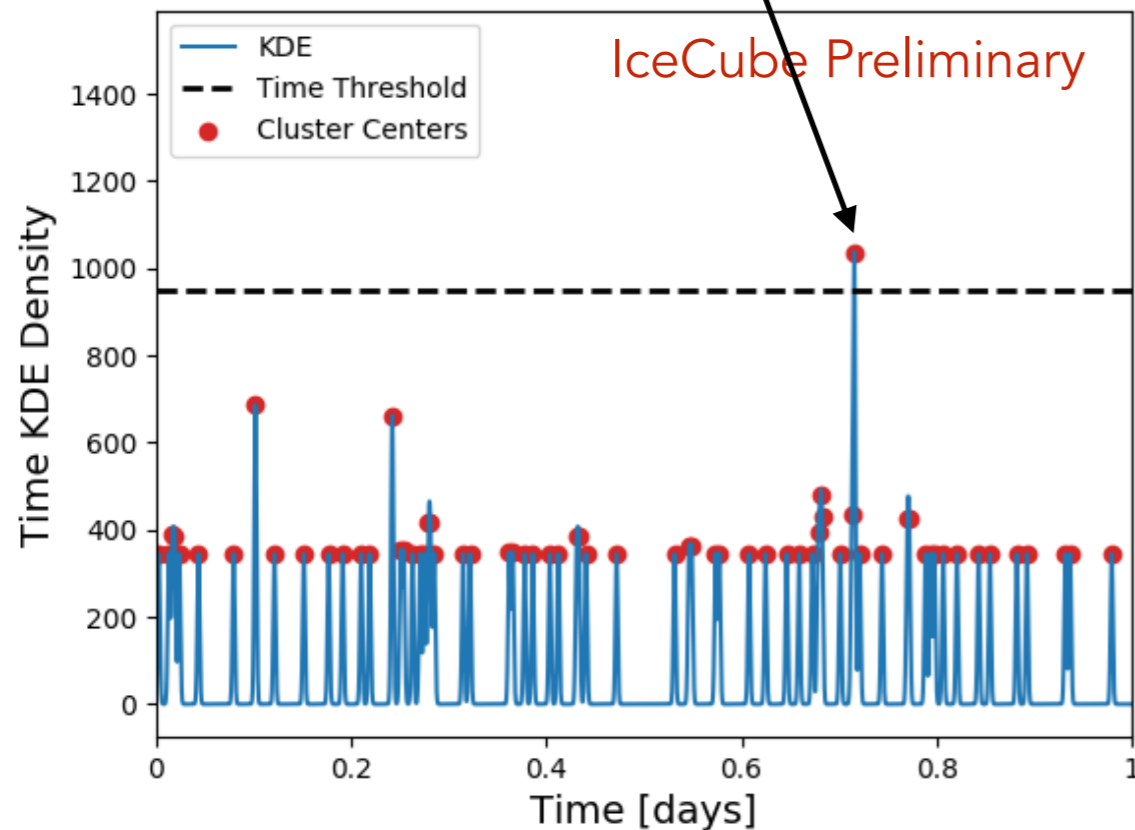
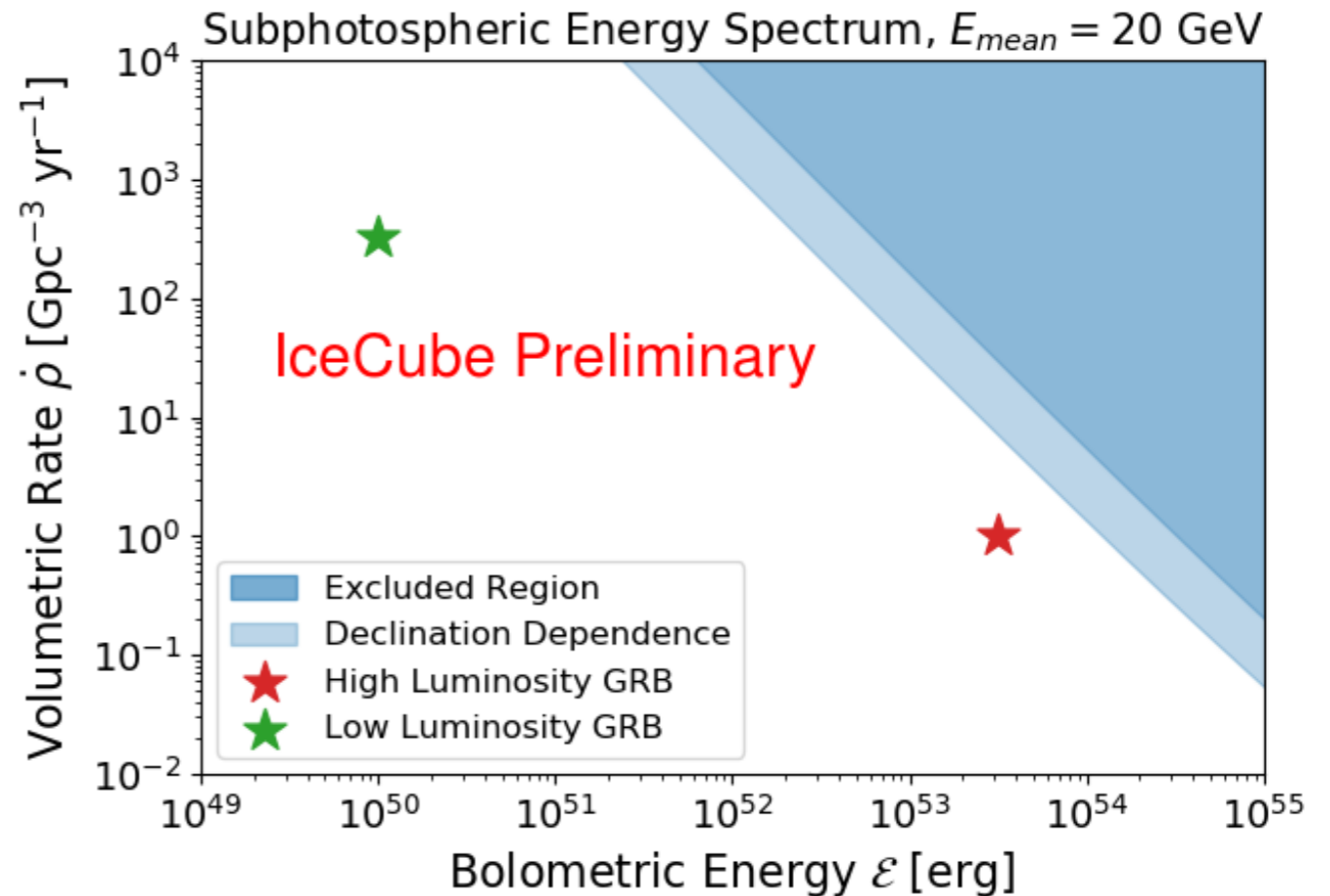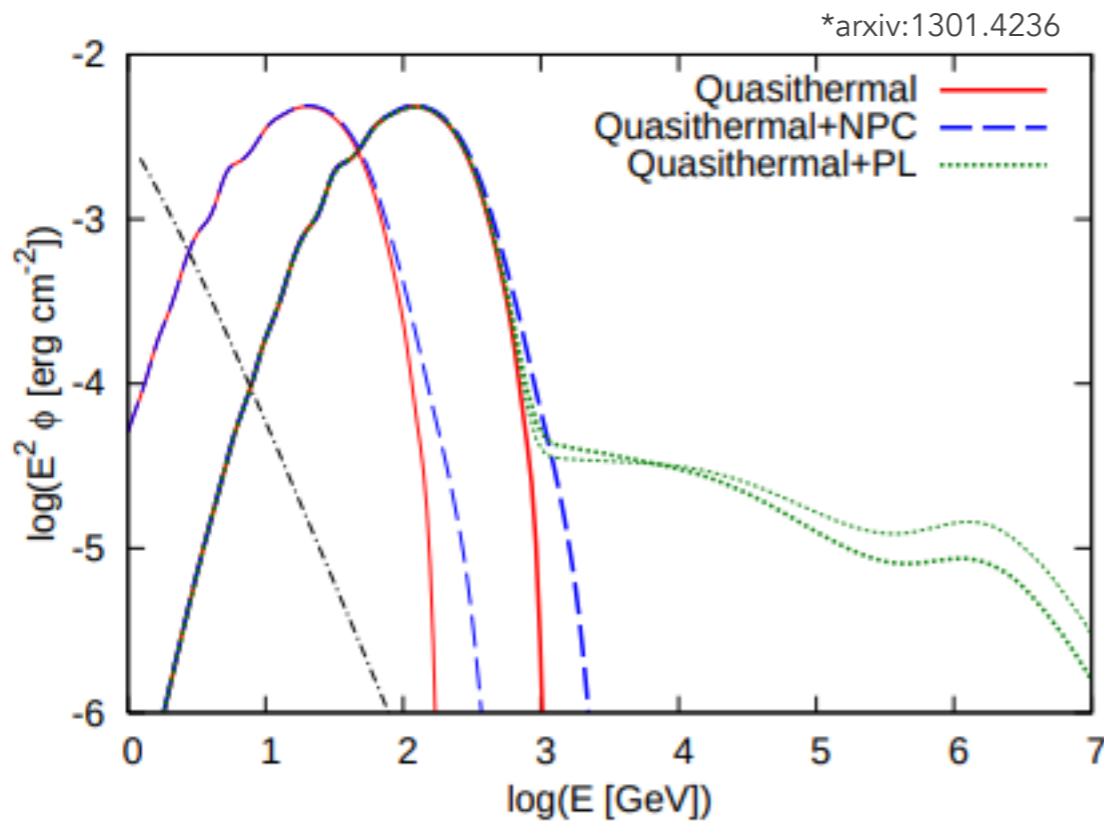Other higher-energy IceCube
analyses begin ~100 GeV

*ESA/Gaia/DPAC

DeepCore Neutrino Astronomy

- Use event selection developed for neutrino oscillations to search for transient astrophysical sources
  - Find neutrino multiplets from generic point sources
 - Localized in time and space

Result

*arxiv:1301.4236
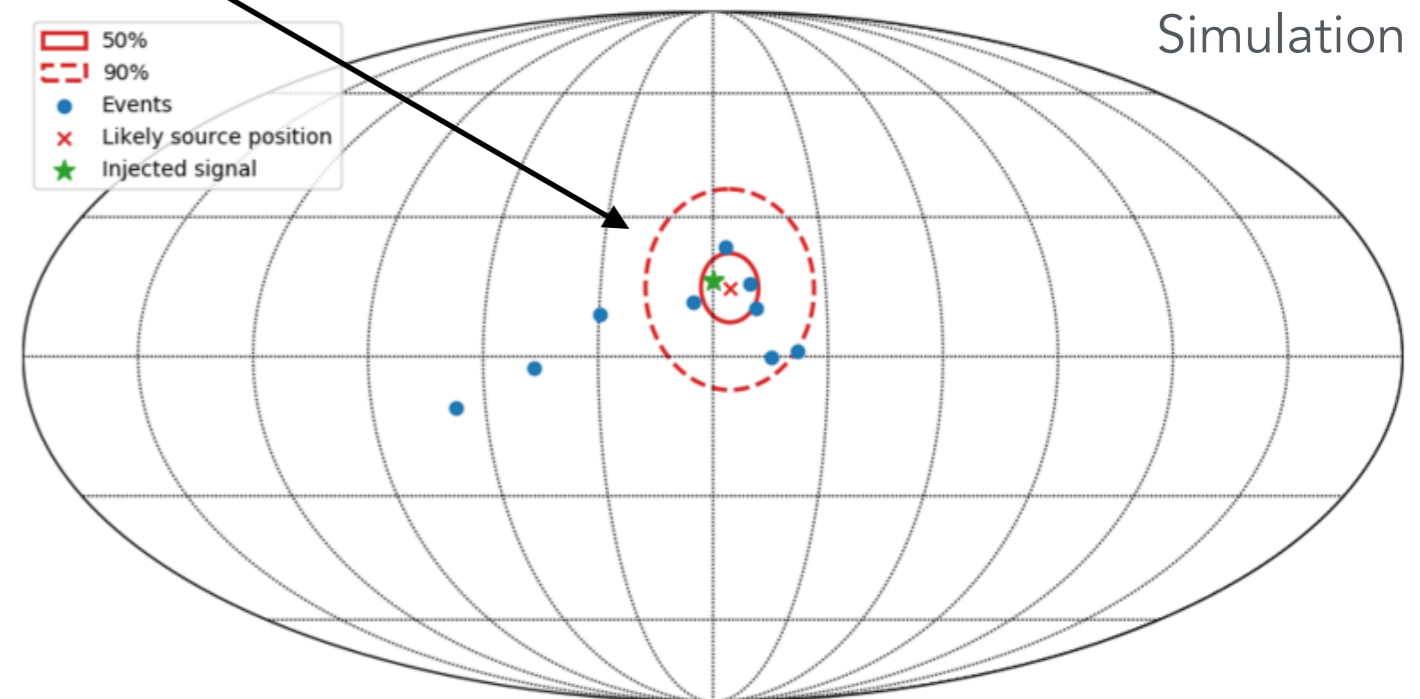
- Generic spectra is based on a sub-photospheric gamma ray burst. Tested using spectra peaked at 20 GeV and 100 GeV.

- 3-years of data is consistent with of background of atmospheric neutrinos

- Work in progress to include DeepCore and lower energy neutrinos within the global multi-messenger family

Oscillation w/ DeepCore

- IceCube + DeepCore collects > 100k isotropic neutrinos *at trigger level*, tens of thousands have undergone oscillation. Even single percent final analysis efficiency contains 1,000s of atm. ν events/year
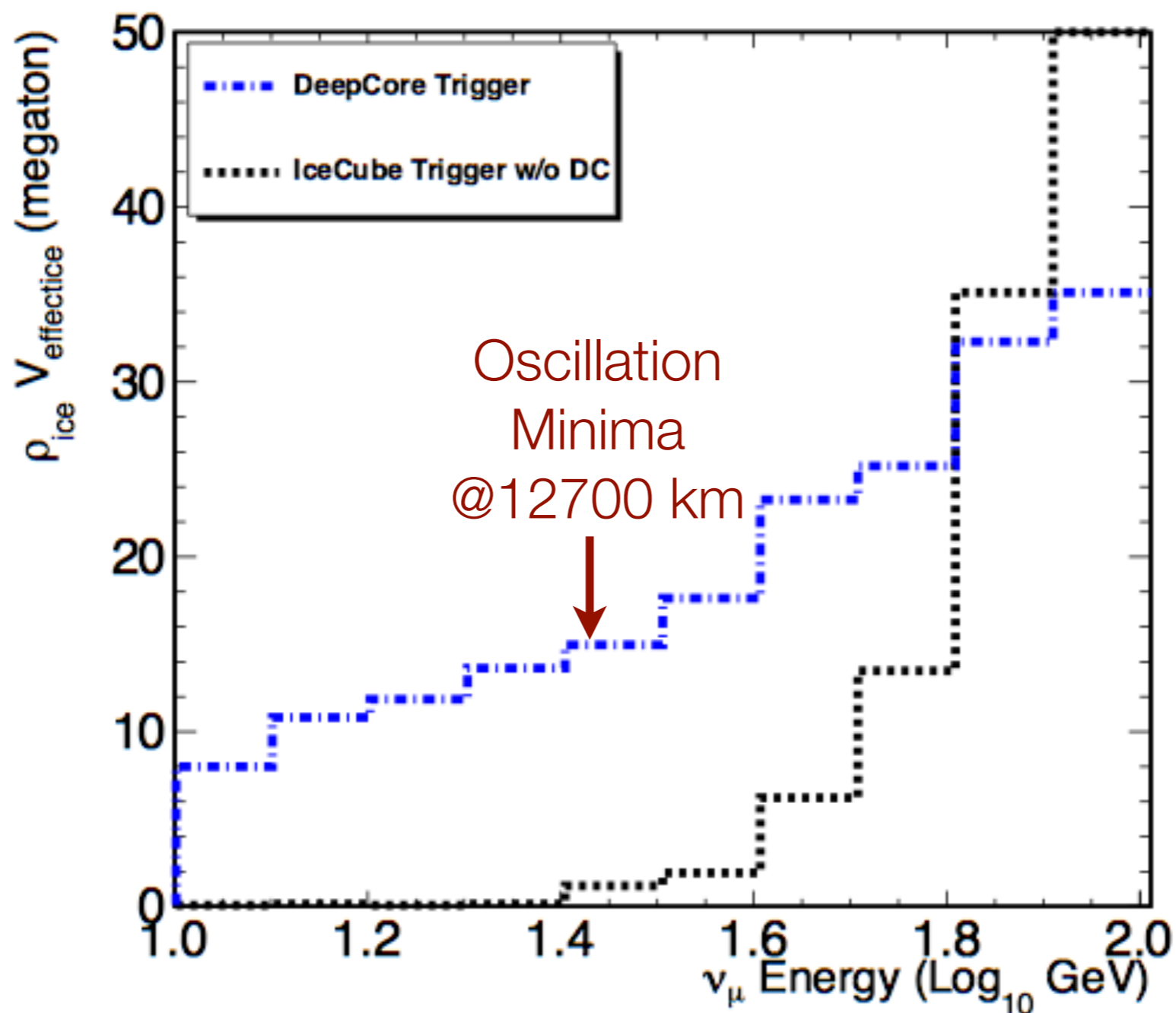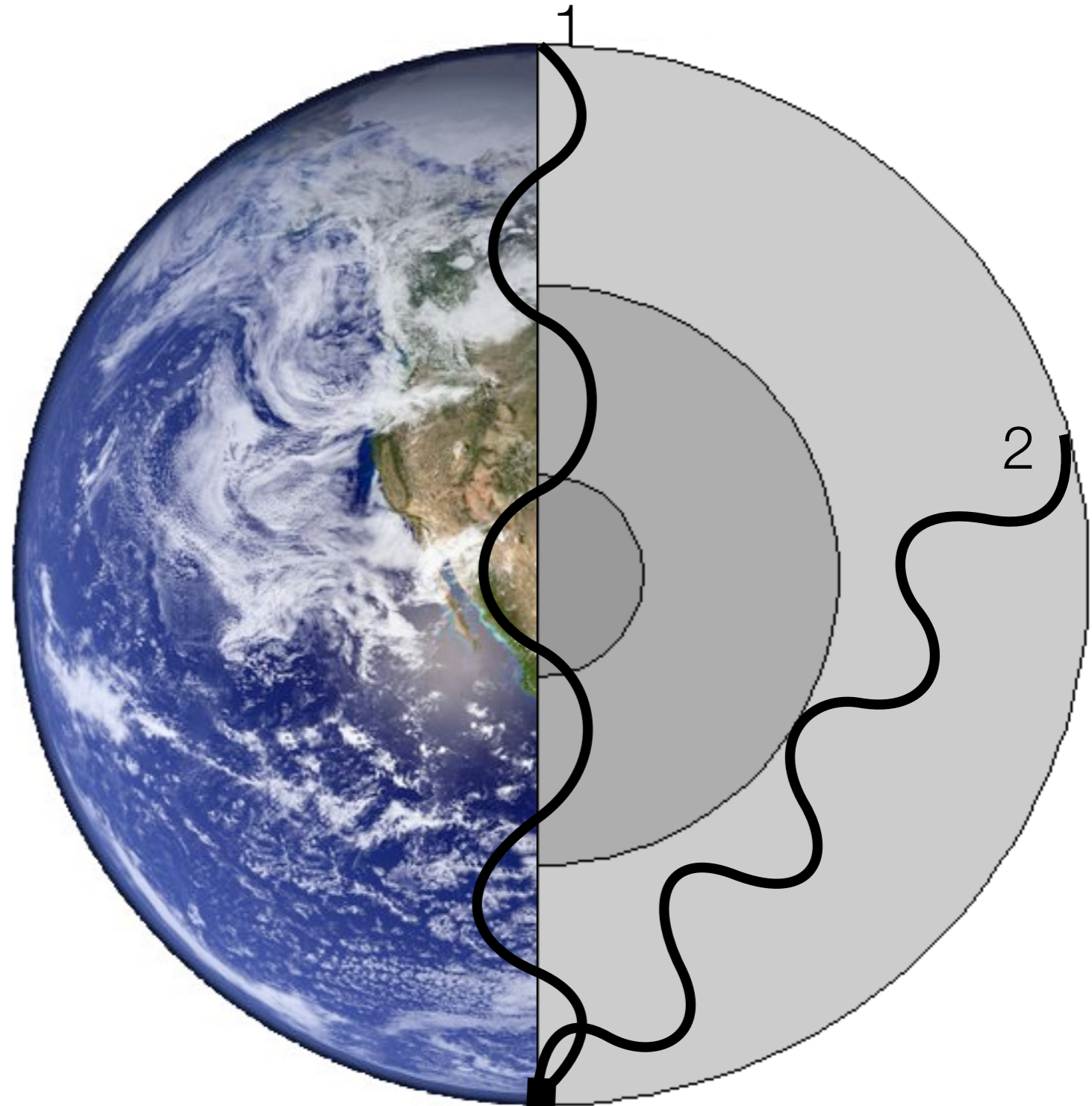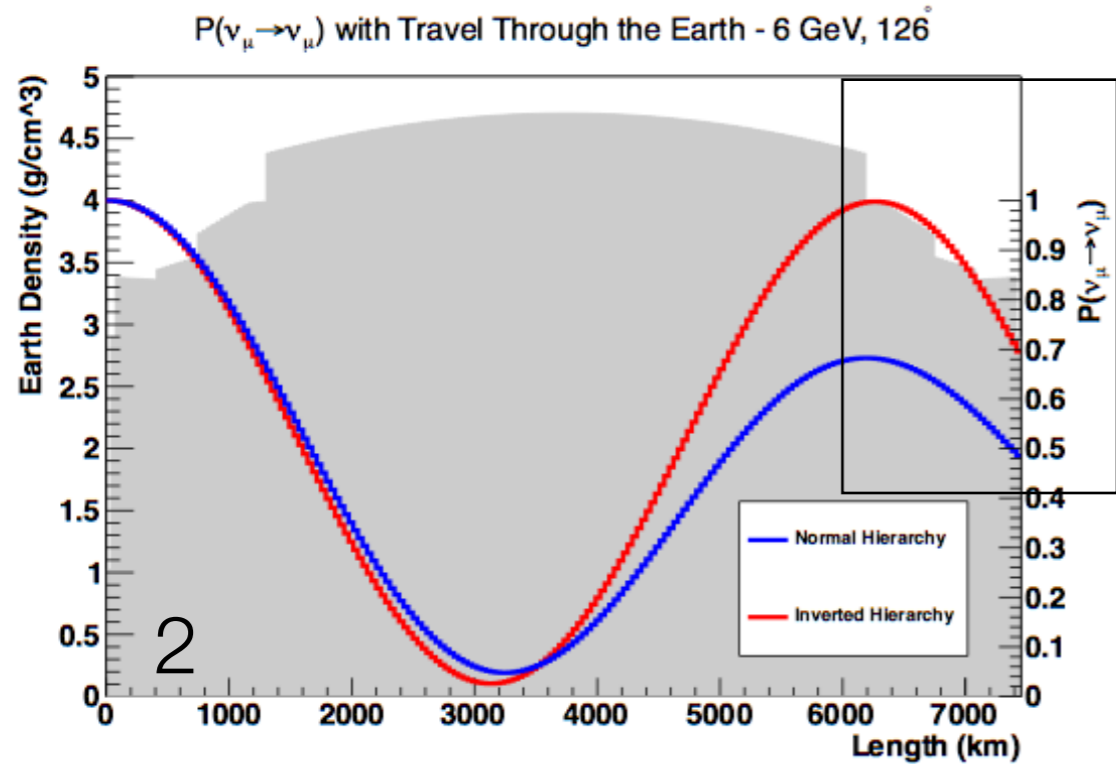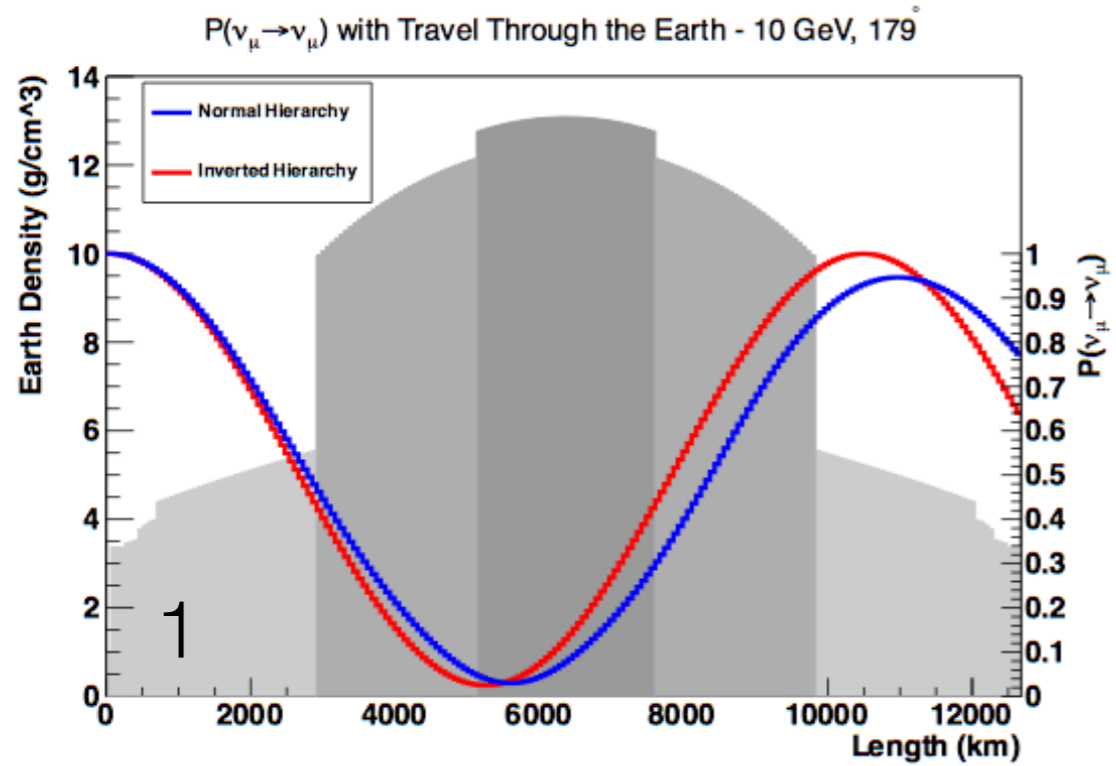
Neutrino Mass Ordering

Δm_{23}^2 is $\approx 2.4 \times 10^{-3}\,\mathrm{eV}^2$, but the sign is not known

Δm_{21}^2 is $\approx 7.5 \times 10^{-5}\,\mathrm{eV}^2$ and $m_1 < m_2$

or
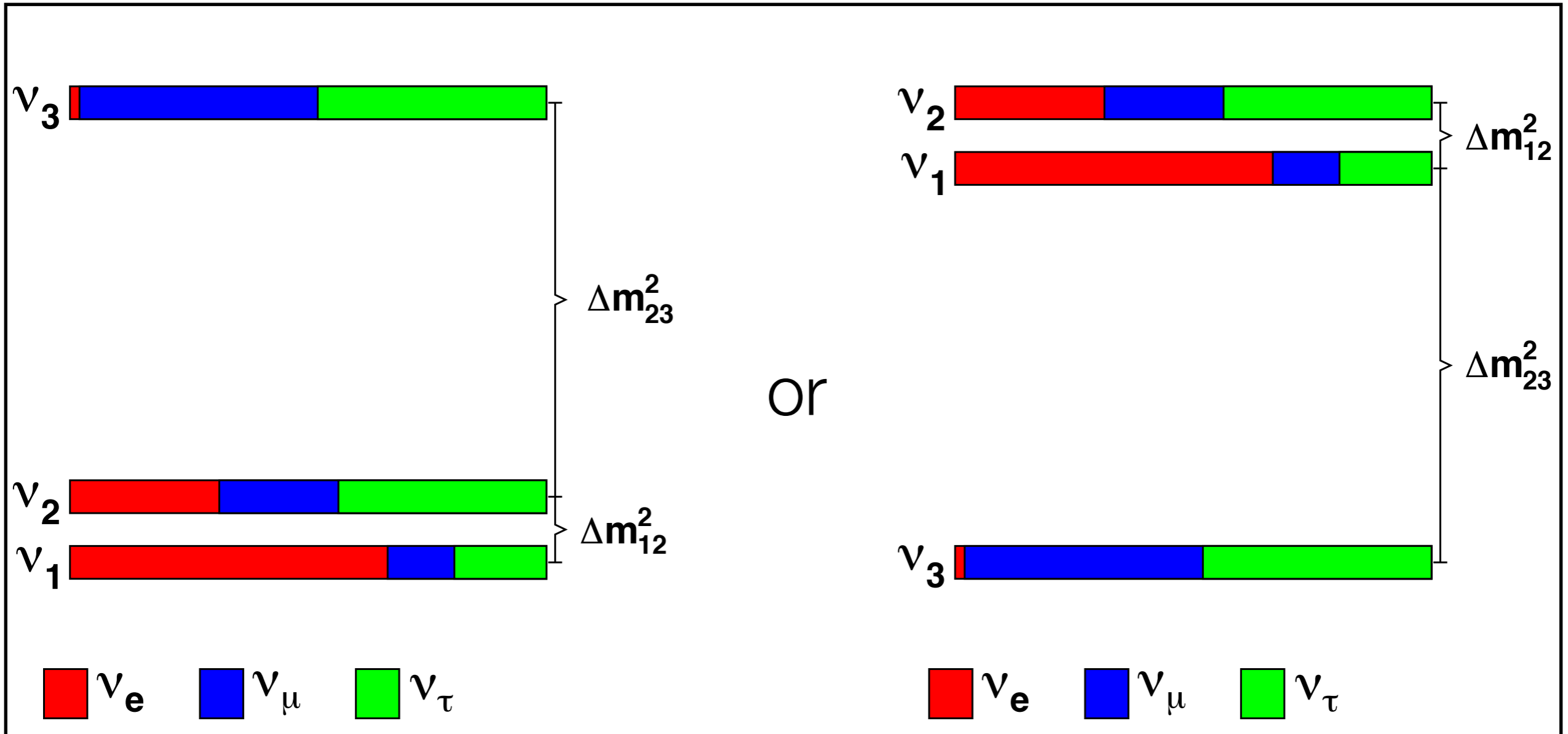
Neutrino Mass Ordering

- Inverted/Normal ordering has up to 20% different in oscillation probability for specific energies and zenith angles (baselines)