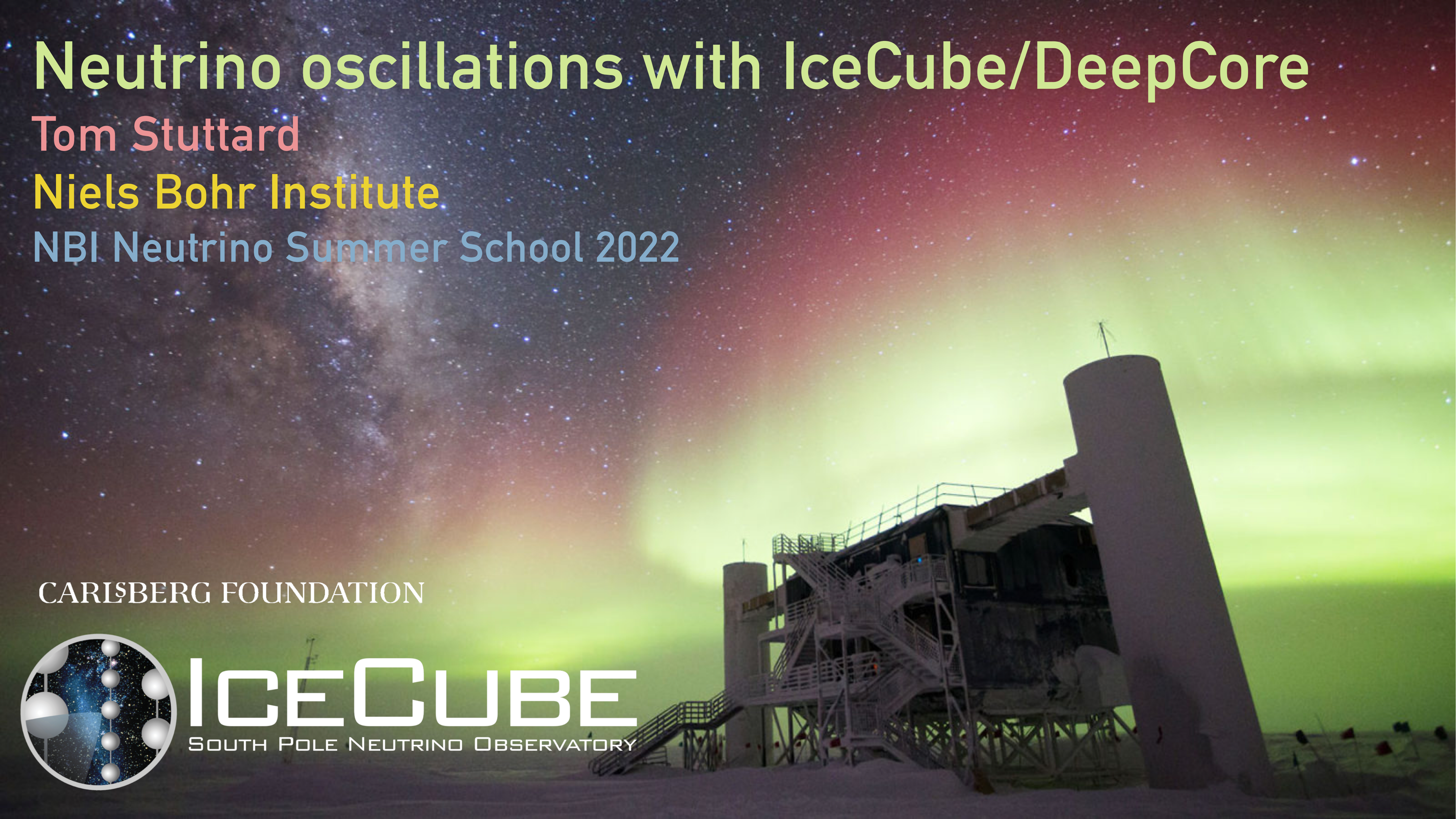


Neutrino oscillations with IceCube/DeepCore

Tom Stuttard

Niels Bohr Institute

NBI Neutrino Summer School 2022

CARLSBERG FOUNDATION

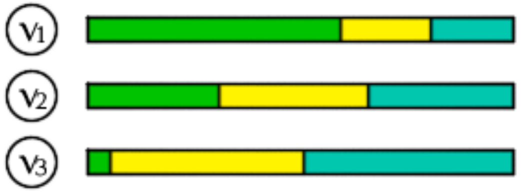
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Neutrino oscillations

- There are **3 neutrino flavor states** → one per lepton flavour (e, μ, τ)

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

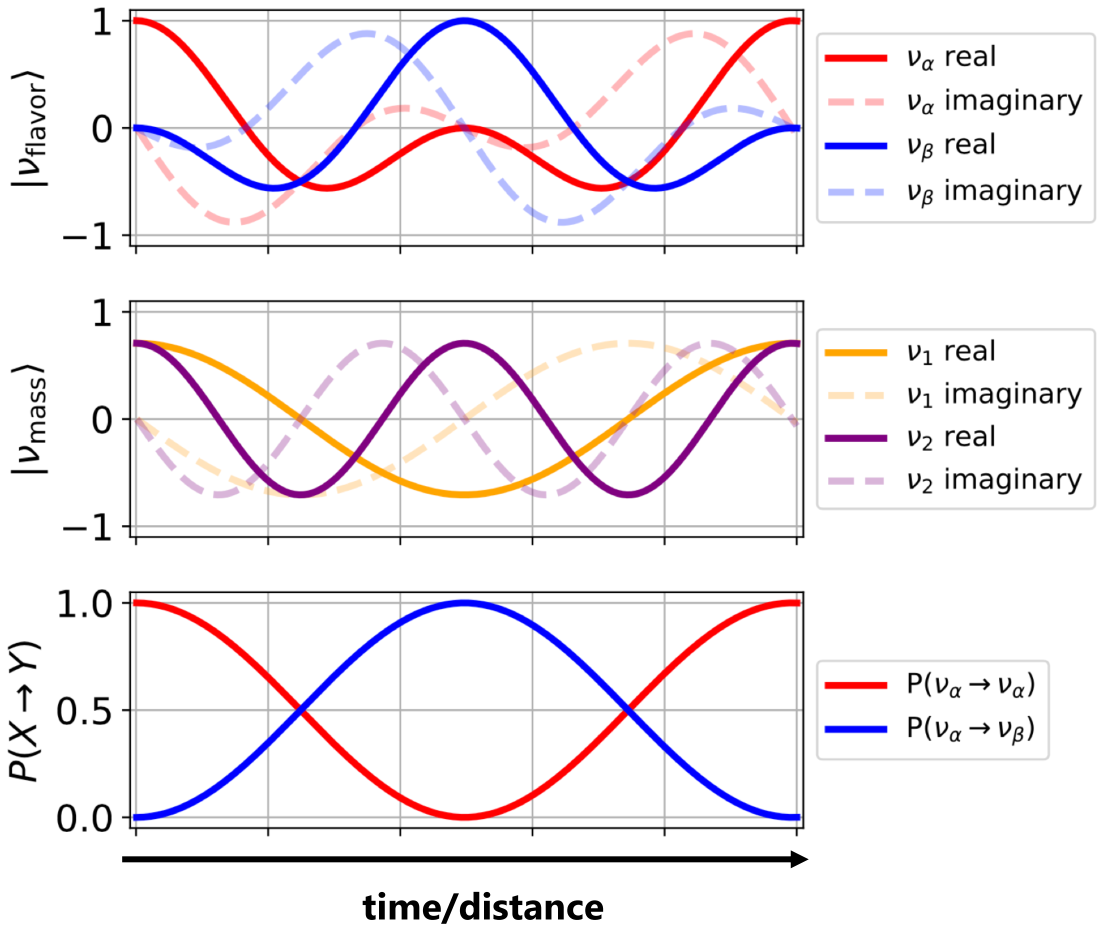
- However, there is **mixing between these flavor states and the neutrino mass states**
  - Characterised by the PMNS matrix



- A neutrino produced as a given flavor is thus a **superposition of all three mass states**
- The wavefunction of each mass state evolves with a different frequency (defined by its mass) as they propagate
- The **superposition of the flavor states therefore changes over time** → time-dependent flavour composition
- A neutrino **produced as one flavor can therefore be detected later as another** → this is **neutrino oscillations**

A simple example

- Visualise the superposition effects and resulting oscillations using simplified model…
  - 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
  - $m_2 = \sqrt{2}\, m_1$



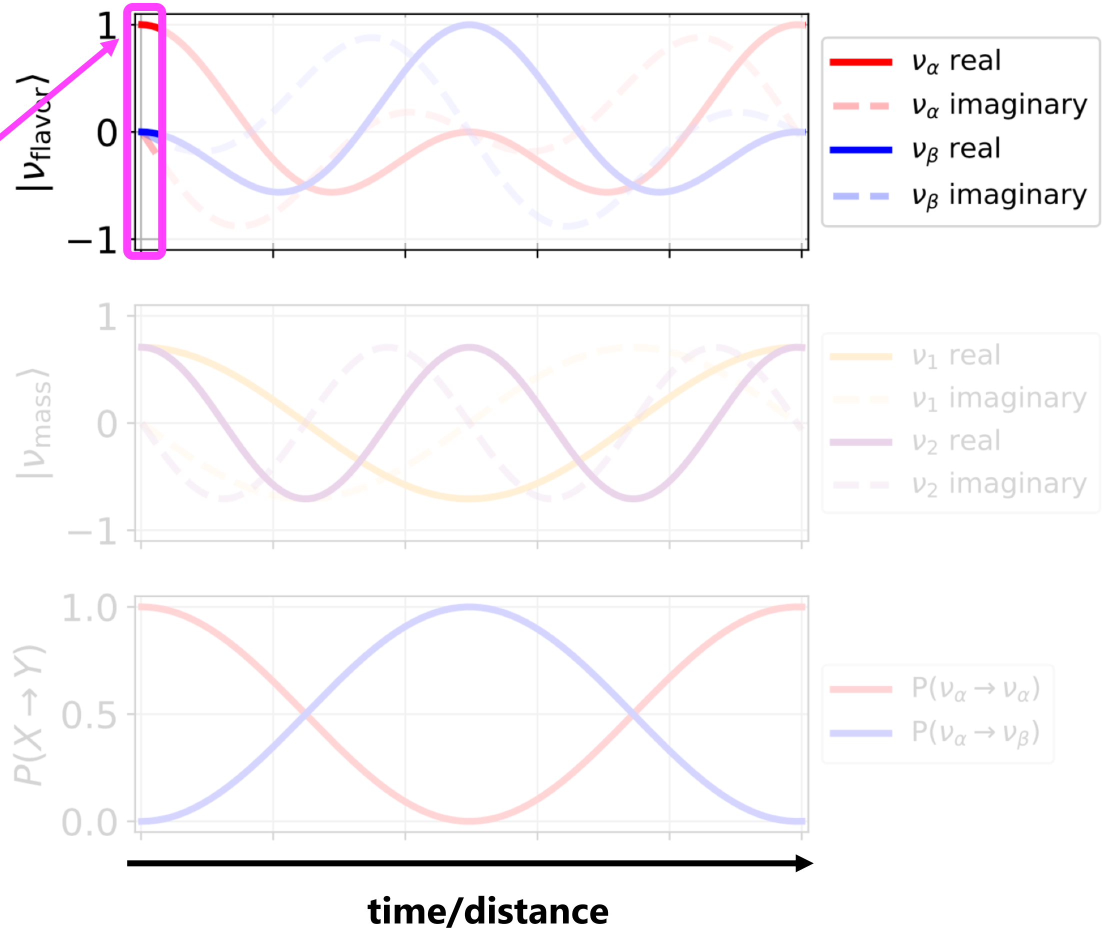
$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

A simple example

- Visualise the superposition effects and resulting oscillations using simplified model…
  - 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
  - $m_2 = \sqrt{2}\, m_1$

1) Neutrino produced in pure (single) flavor state

In this case ν_α

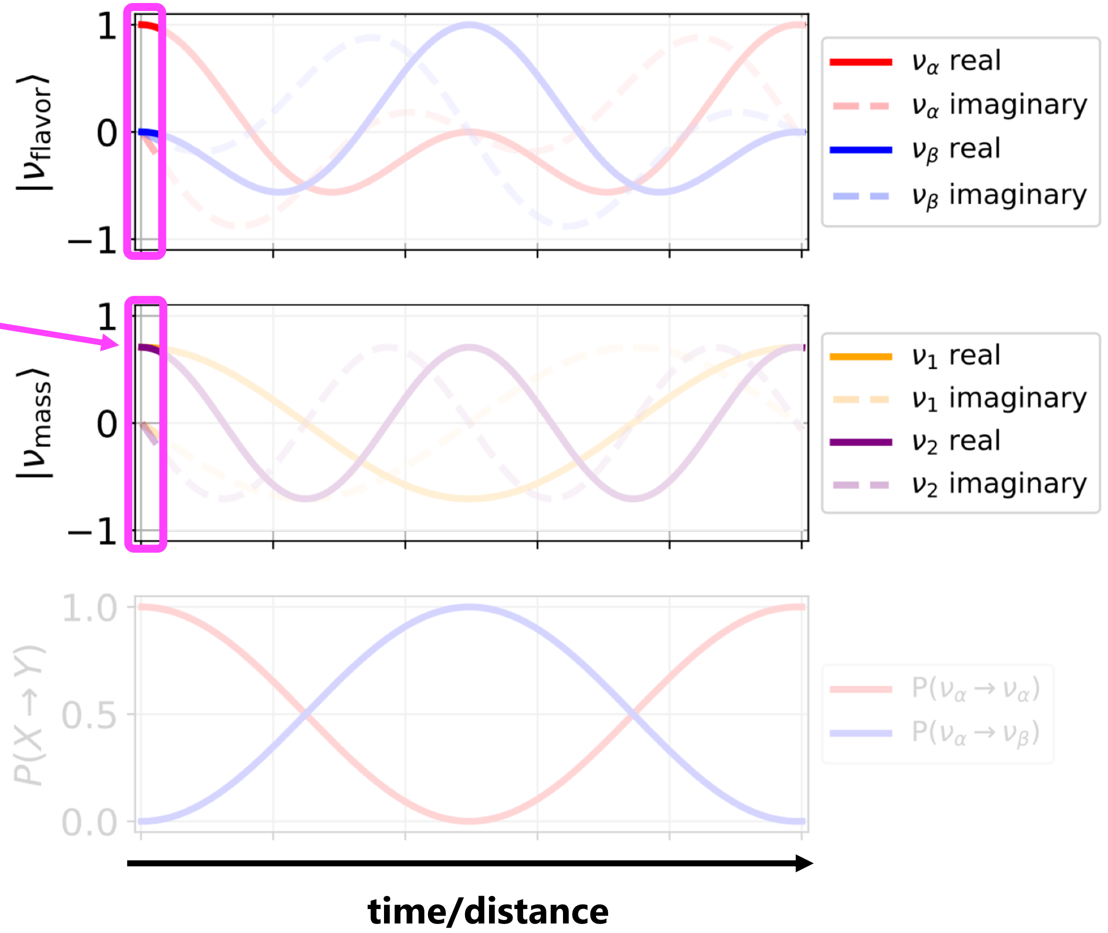


A simple example

- Visualise the superposition effects and resulting oscillations using simplified model…
  - 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
  - $m_2 = \sqrt{2}\, m_1$

2) This means the neutrino is initially an equal mix of the two mass states

Because of 50:50 mixing in this example



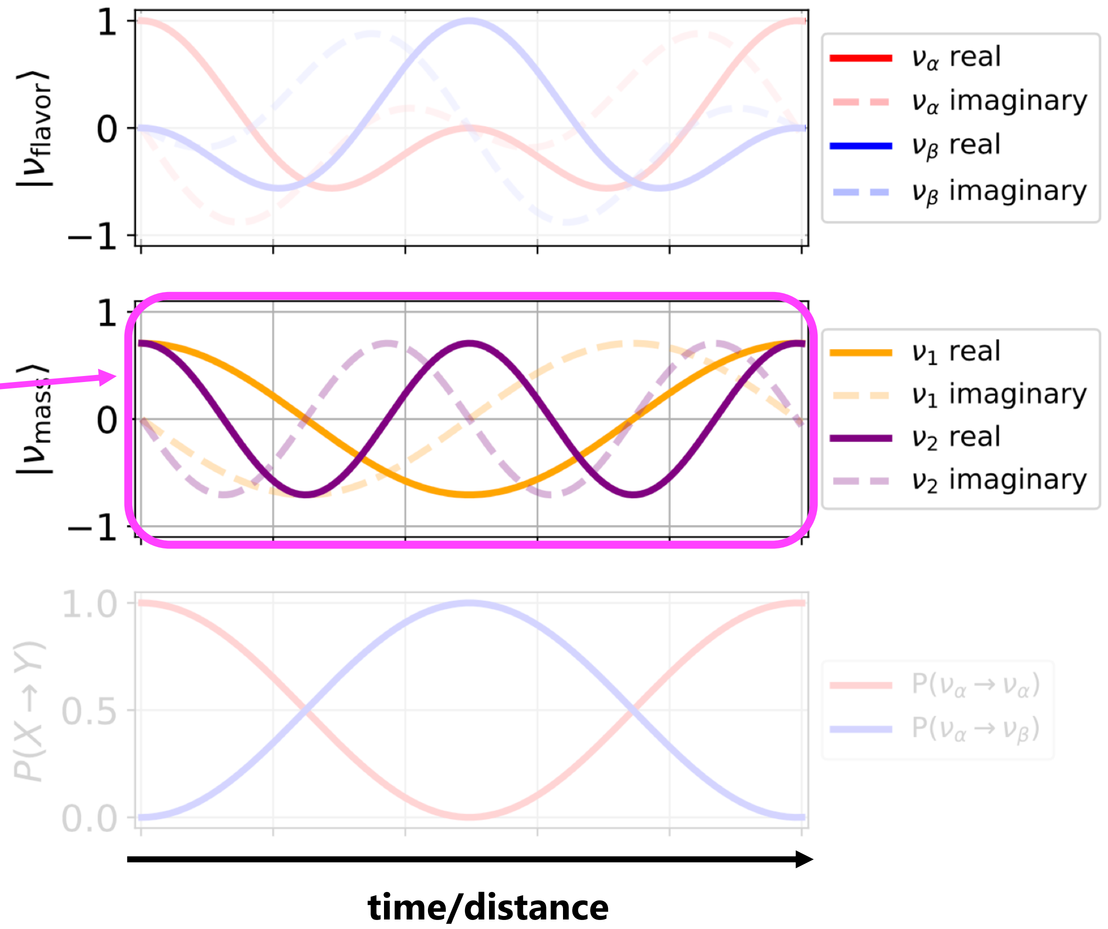
A simple example

- Visualise the superposition effects and resulting oscillations using simplified model…
  - 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
  - $m_2 = \sqrt{2}\, m_1$

3) The wavefunctions of the mass states evolve over time

The frequency of this evolution depends on the mass state mass

The frequency of ν_2 is 2x ν_1 in this example



$$|\nu_j(L)\rangle = \exp\left\{-i\frac{\boxed{m_j^2}L}{2E}\right\}|\nu_j(0)\rangle$$

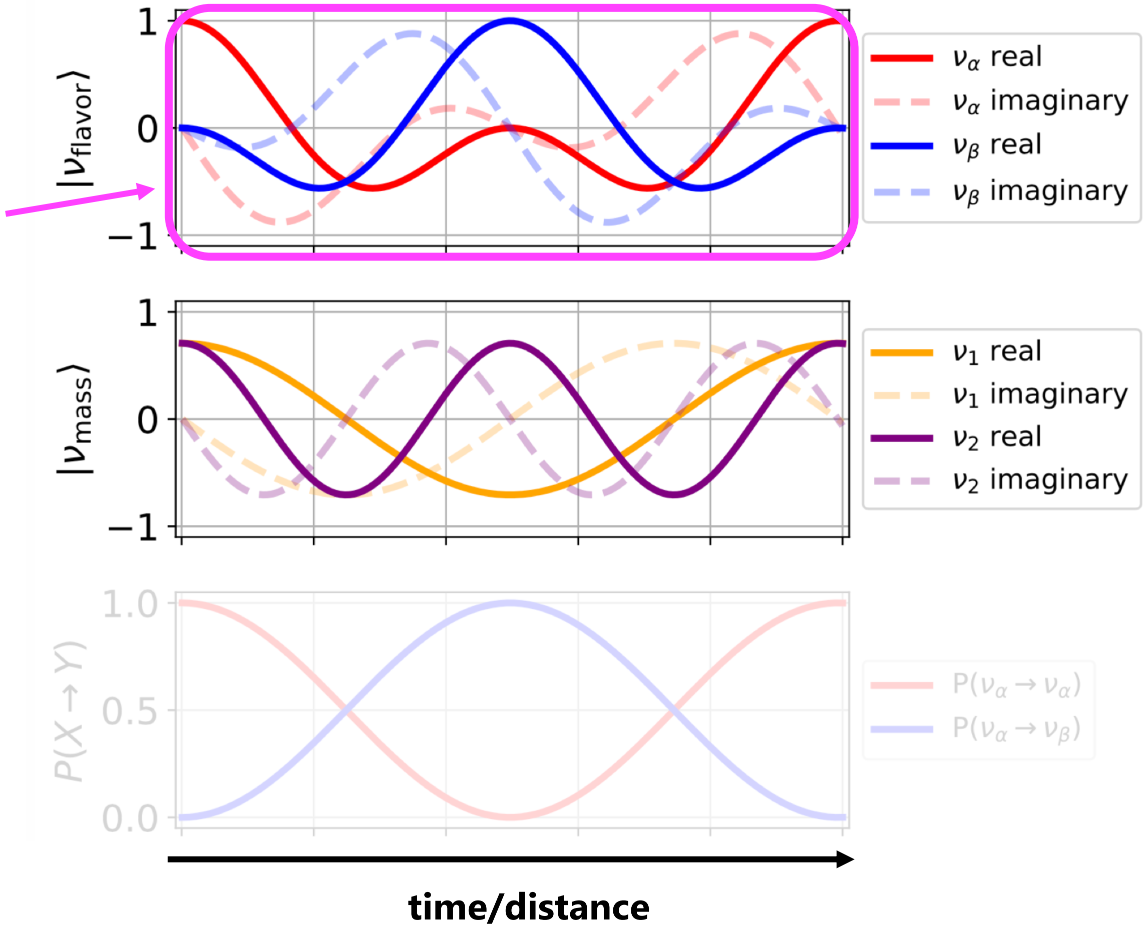
Mass state evolution

(Plane wave)

A simple example

- Visualise the superposition effects and resulting oscillations using simplified model…
  - 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
  - $m_2 = \sqrt{2}\, m_1$

4) The evolution of the mass states modified the flavor state superposition over time



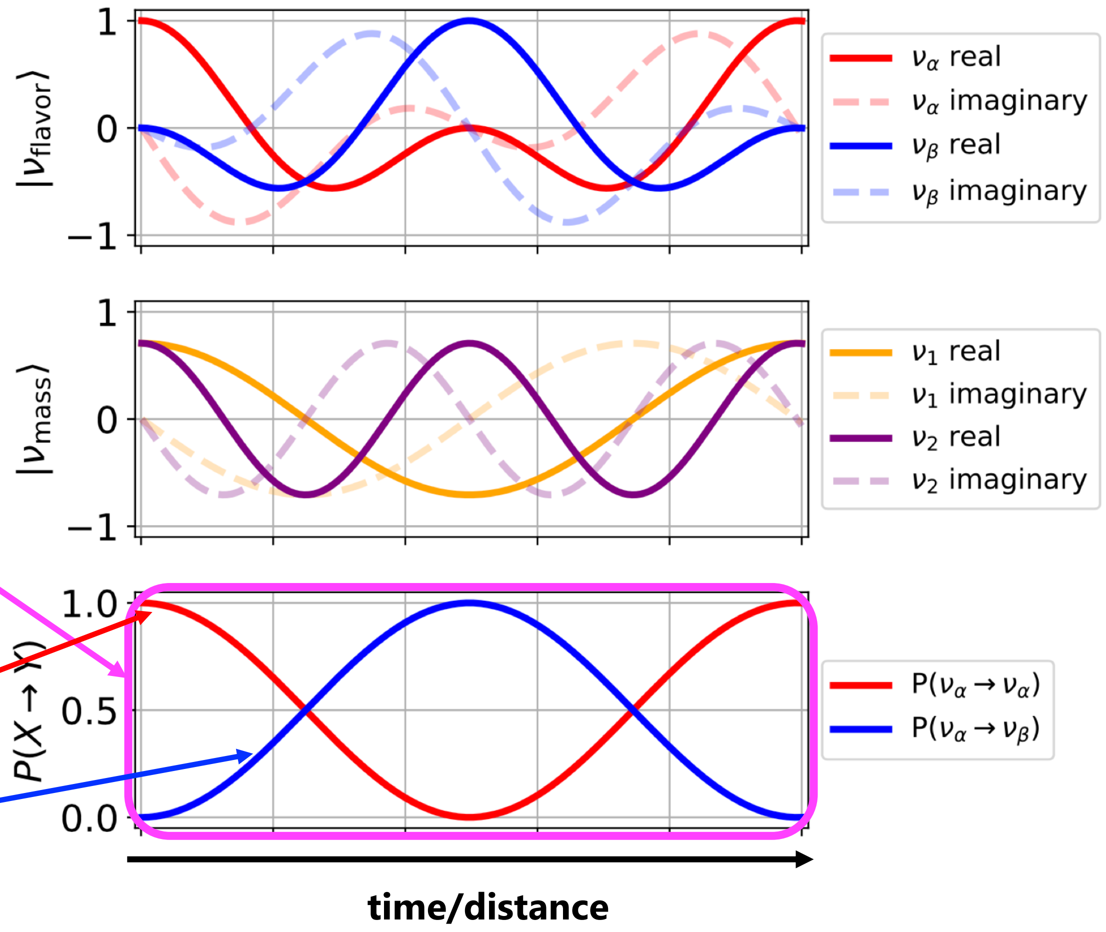
$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

Mass state evolution

(Plane wave)

A simple example

- Visualise the superposition effects and resulting oscillations using simplified model…
  - 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
  - $m_2 = \sqrt{2}\, m_1$



$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

Mass state evolution
(Plane wave)

5) The probability to be detected as a given flavor thus changes over time

Initially the probability to detect as the production flavor is 100%

Probability to detect as another flavor (*oscillate*) rises and falls over time

Basic neutrino oscillation phenomenology (1 of 2)

- Neutrino mixing characterised by the (complex) PMNS matrix:

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

- If unitary, can be parameterised as 3 mixing angles and a CP-violating phase:

$$\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{CP}$$

- Oscillation frequency depends on the mass-difference between mass states:

$$\Delta m^2_{21},\ \Delta m^2_{31}$$

→ 6 oscillation parameters to measure in experiments

Basic neutrino oscillation phenomenology (2 of 2)

- Probability of oscillating between flavors (for simplified 2-flavour case):
  - Full 3-flavor expression far more complex

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

Frequency also depends on L/E ratio for a given neutrino

Mixing defines oscillation amplitude

Mass-difference defines frequency

Basic neutrino oscillation phenomenology (2 of 2)

- Probability of oscillating between flavors (for simplified 2-flavour case):
  - Full 3-flavor expression far more complex

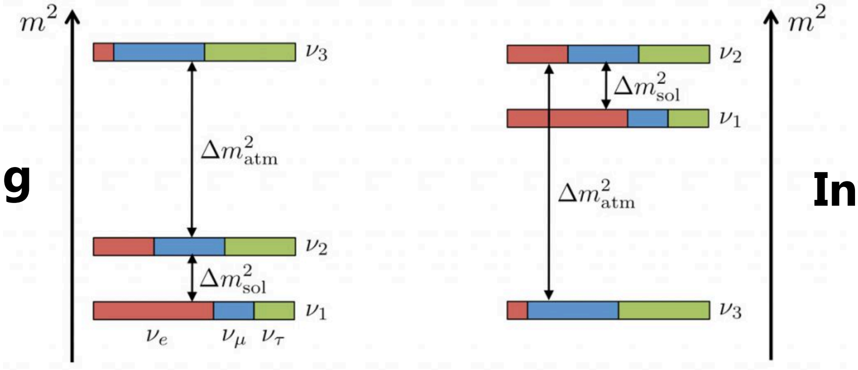
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Frequency also depends on L/E ratio for a given neutrino

Mixing defines oscillation amplitude

Mass-difference defines frequency

- Insensitive to the sign of Δm^2 → neutrino mass ordering problem
  - Unknown if ν_3 is heaviest or lightest mass state



Normal ordering

Inverted ordering

Basic neutrino oscillation phenomenology (2 of 2)

- Probability of oscillating between flavors (for simplified 2-flavour case):
  - Full 3-flavor expression far more complex

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

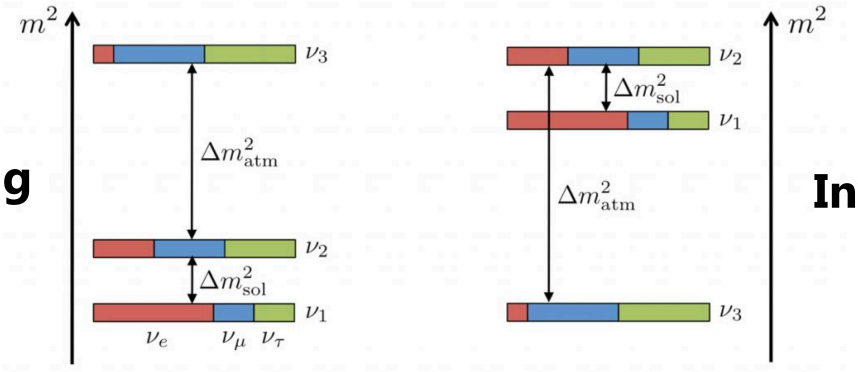
Frequency also depends on L/E ratio for a given neutrino

Mixing defines oscillation amplitude

Mass-difference defines frequency

- Insensitive to the sign of Δm^2 → neutrino mass ordering problem
  - Unknown if ν_3 is heaviest or lightest mass state

Normal ordering



Inverted ordering

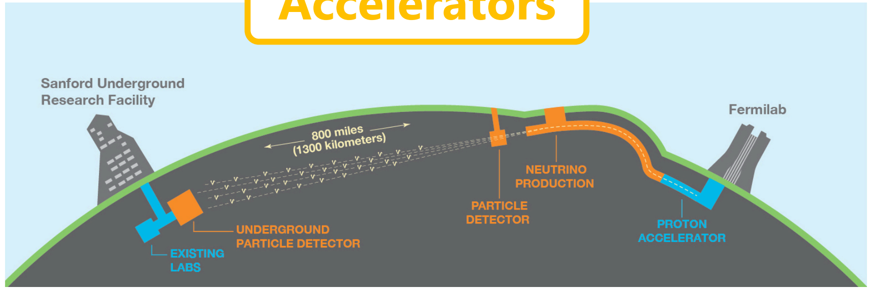
- Modified oscillation effects for neutrinos passing through matter
  - MSW, parametric resonance, absorption, τ/NC re-generation, …

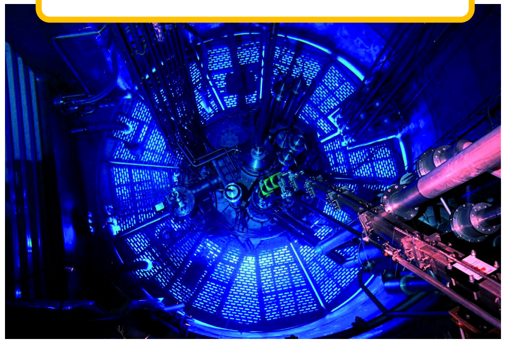
Why study neutrino oscillations?

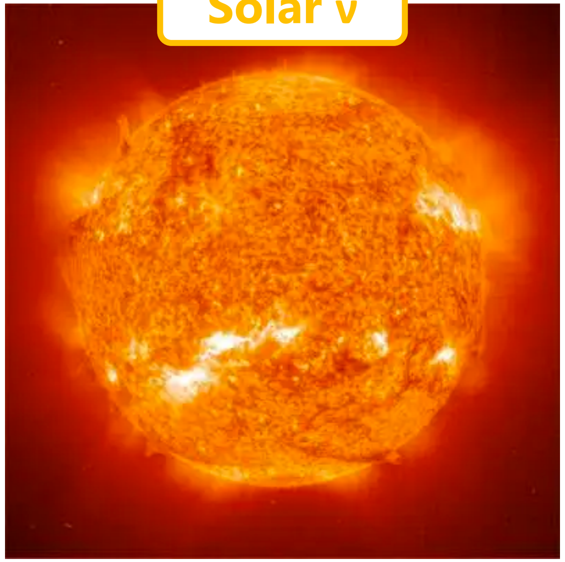
- Neutrino oscillations imply **neutrinos have mass**, contrary to SM
    - Only proven example of BSM physics
- **Neutrino masses are tiny** compared to other particle however
    - How is this mass generated? Sterile neutrinos? See-saw mechanism? New field?
- Why are the mixing angles what we measure? Some underlying symmetry?
    - Why so different to CKM matrix describing quark mixing?
- **Is CP symmetry violated** in neutrino oscillations (e.g. is $\delta_{CP} \neq 0$)?
    - How is this related to the **matter-antimatter asymmetry** of the Universe?
- Rare opportunity to study a quantum system over macroscopic scales
- **Oscillations are modified by many BSM theories**
    - Sterile neutrinos, non-standard interactions (NSI), Lorentz Invariance violation, decoherence, …

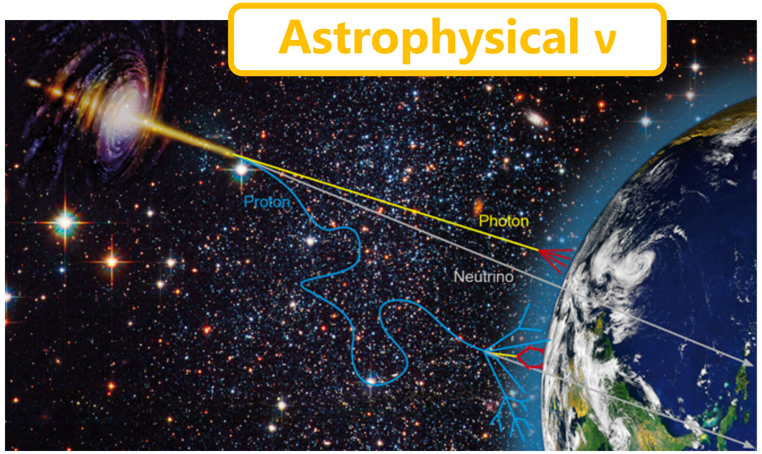
Neutrino oscillation experiments

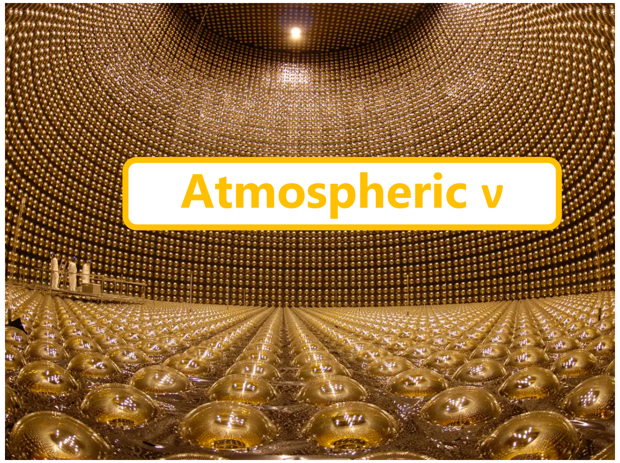
- Need to measure a range of neutrino flavors, energies and baselines to measure all oscillation parameters
  - Requires a broad range of oscillation experiments with differing neutrino sources


Accelerators


Nuclear reactors

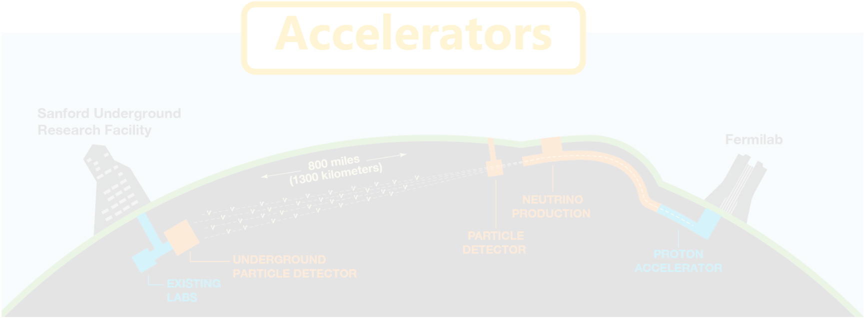

Solar ν

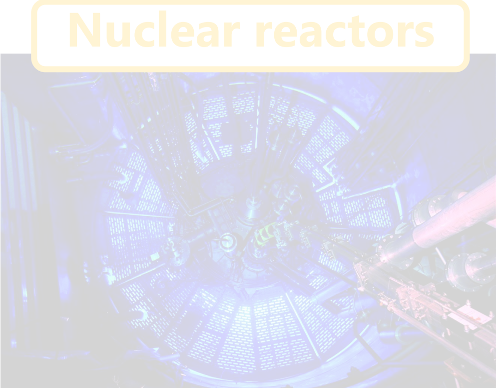

Astrophysical ν

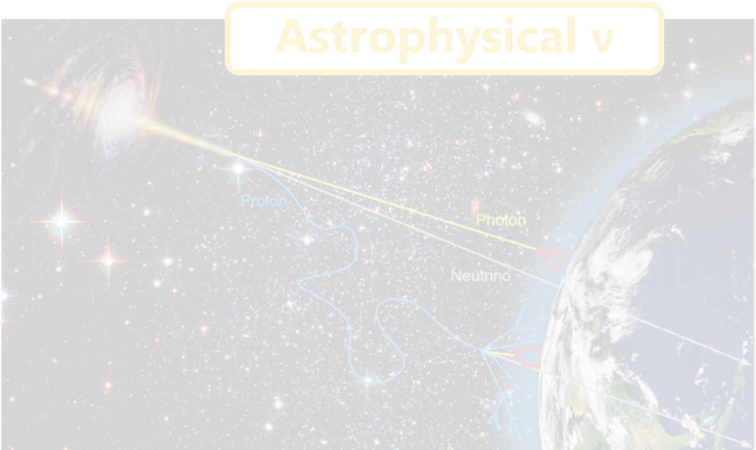

Atmospheric ν

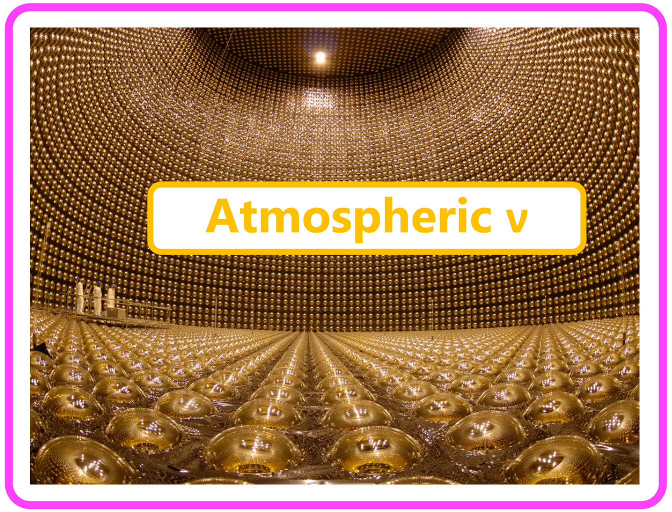
Neutrino oscillation experiments

- Need to measure a range of neutrino flavors, energies and baselines to measure all oscillation parameters
  - Requires a broad range of oscillation experiments with differing neutrino sources



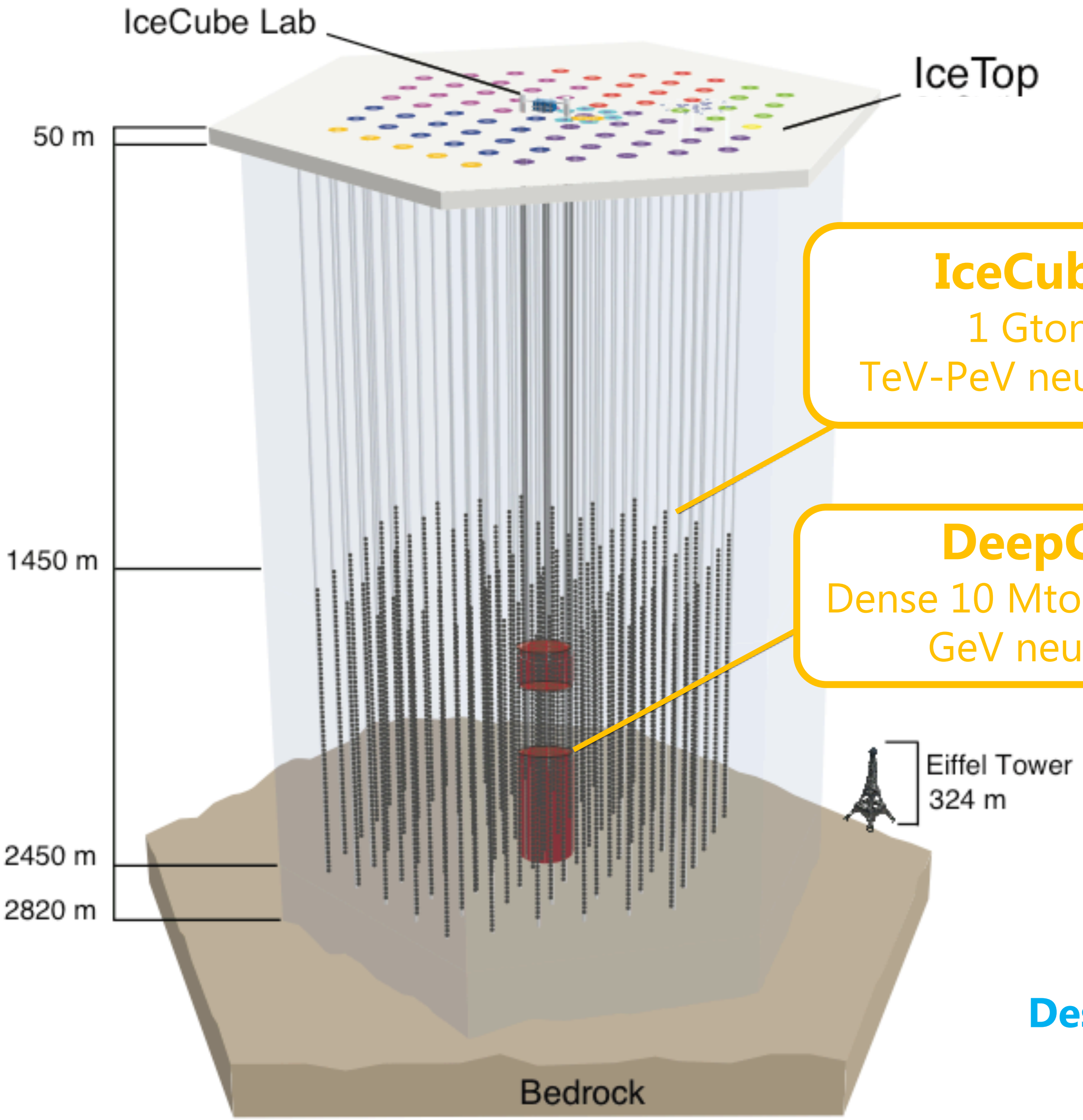






Subject of this talk!

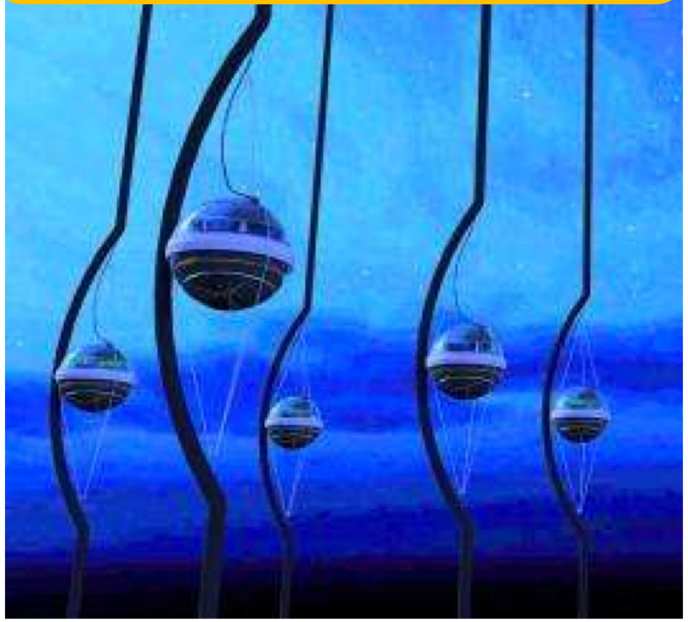
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



IceCube
1 Gton
TeV-PeV neutrinos

DeepCore
Dense 10 Mton sub-array
GeV neutrinos

5160 PMTs in glacial ice
(natural detection medium)

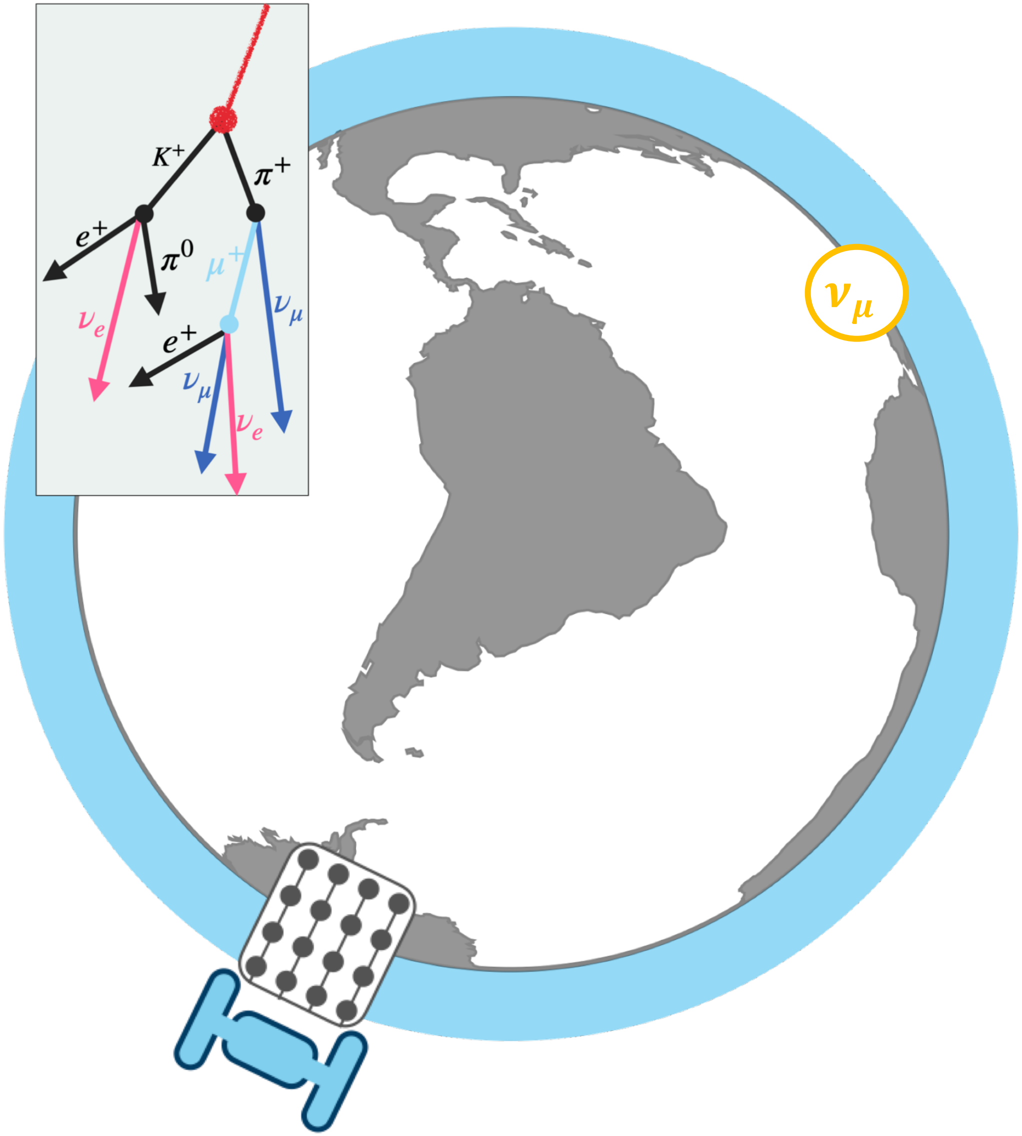


Designed to discover high energy astrophysical ν

Also detects large flux of atmospheric ν

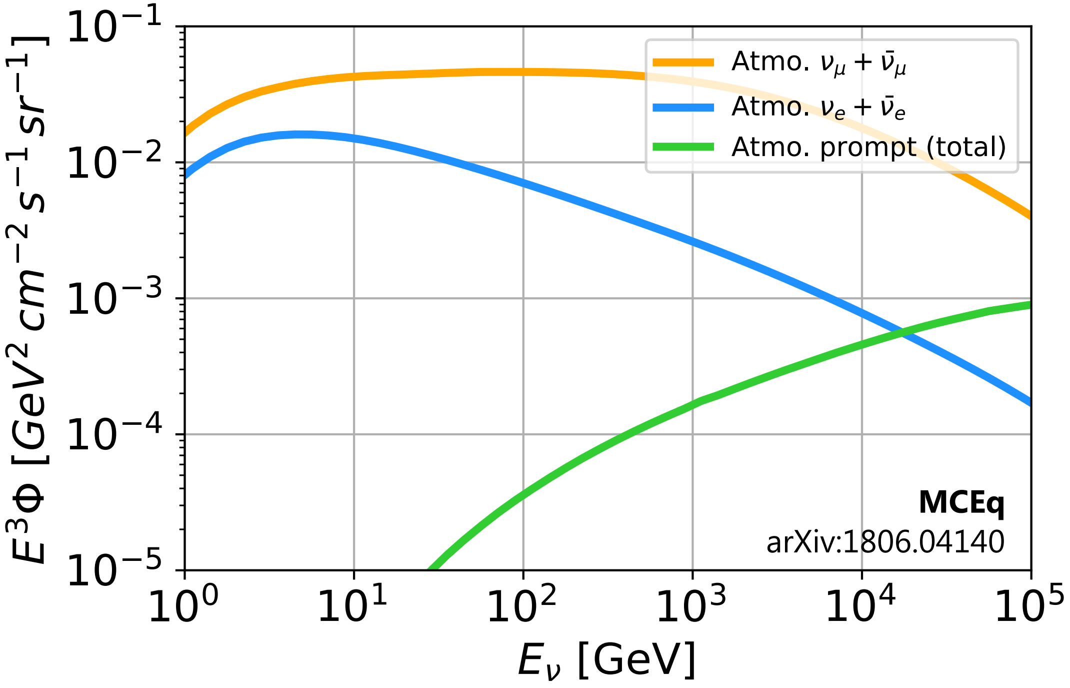
Atmospheric neutrinos in IceCube

Atmospheric neutrinos in IceCube

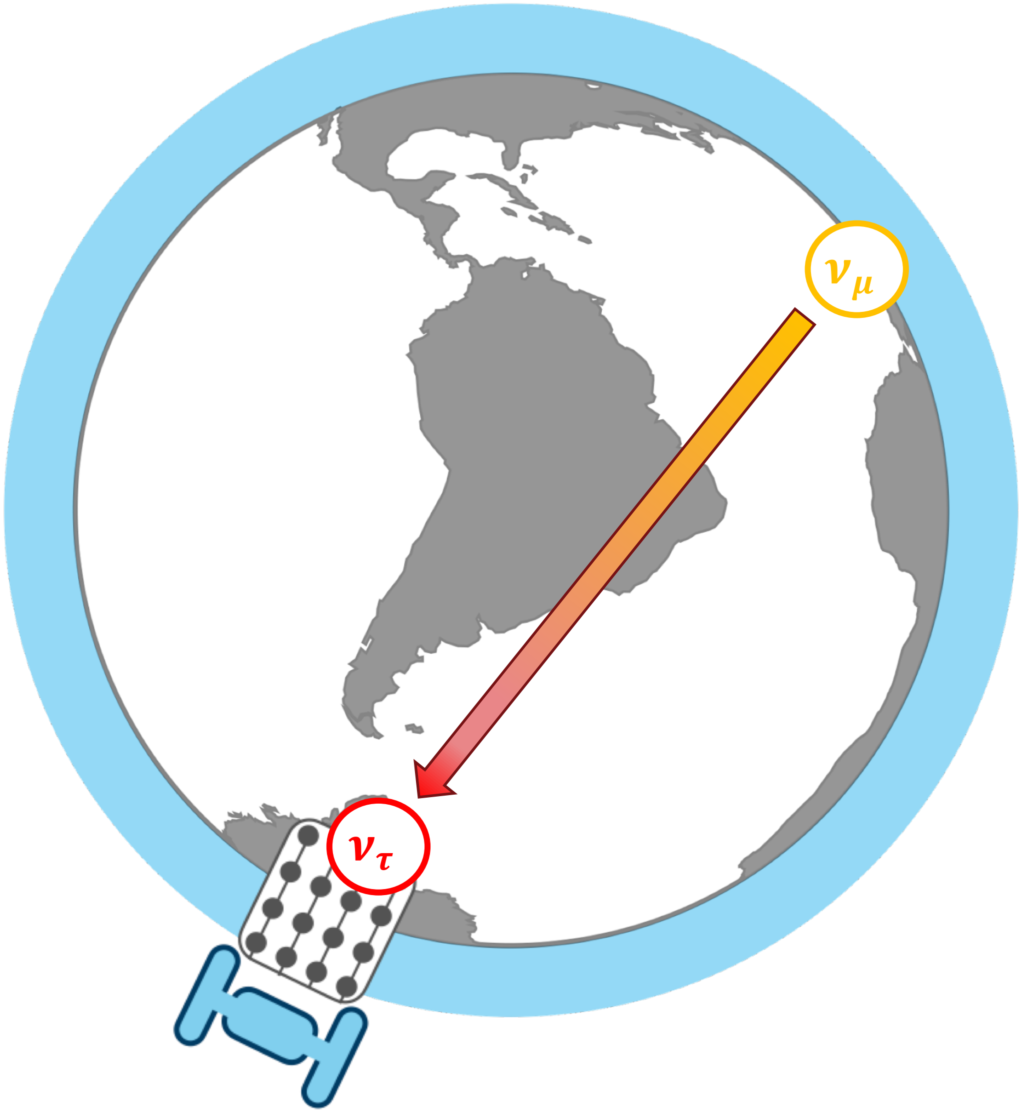


(1) Cosmic rays interact in the atmosphere and produce air showers

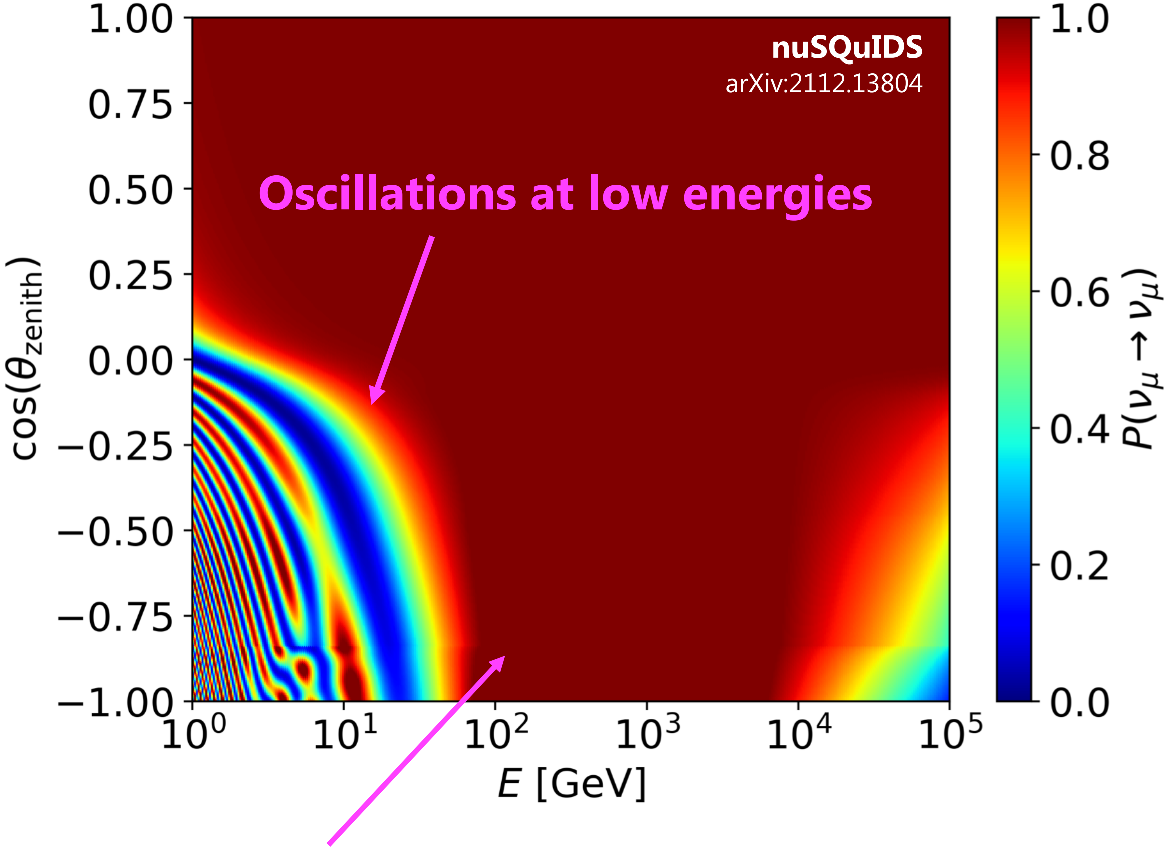
→ **Large flux of high energy neutrinos**



Atmospheric neutrinos in IceCube



(2) Neutrinos propagate across the Earth

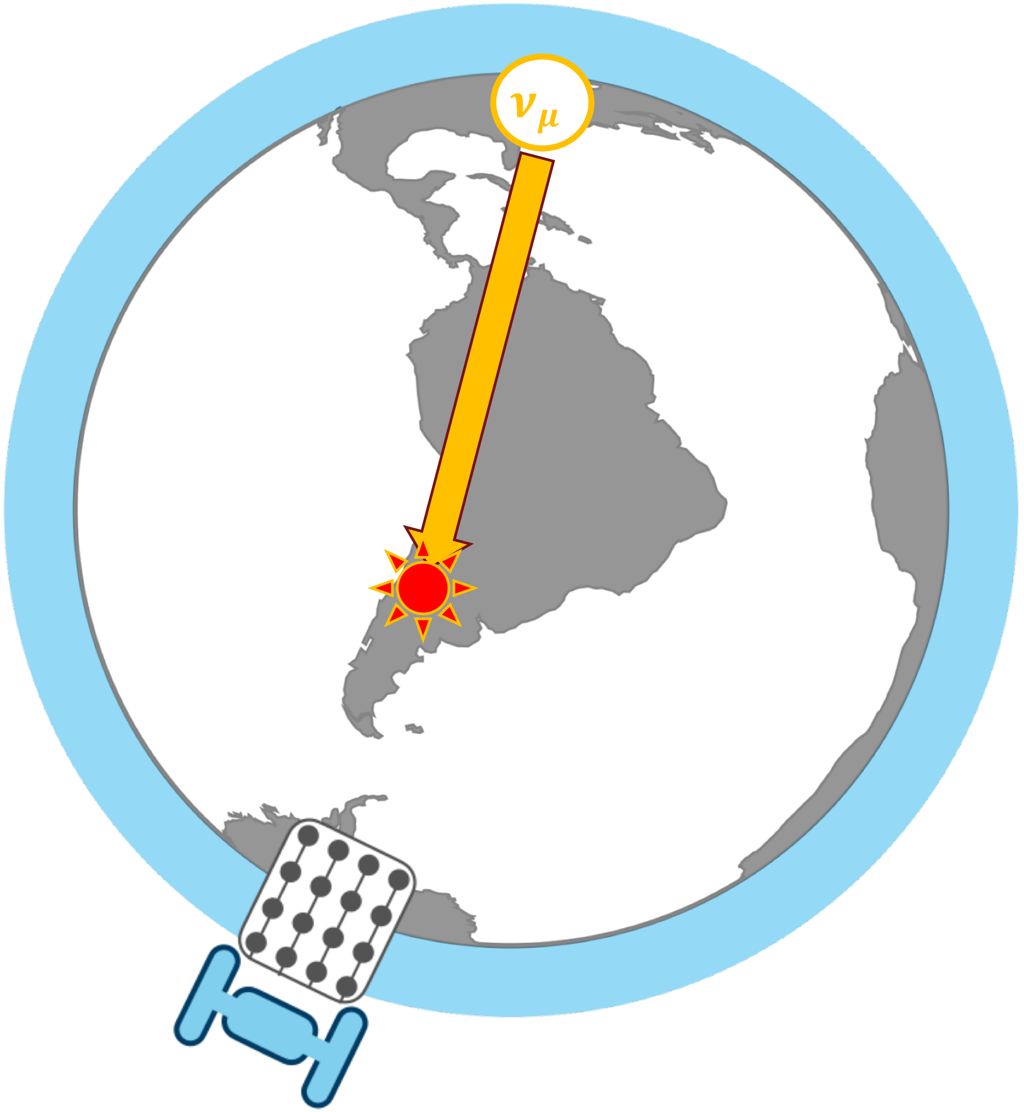


nuSQuIDS
arXiv:2112.13804

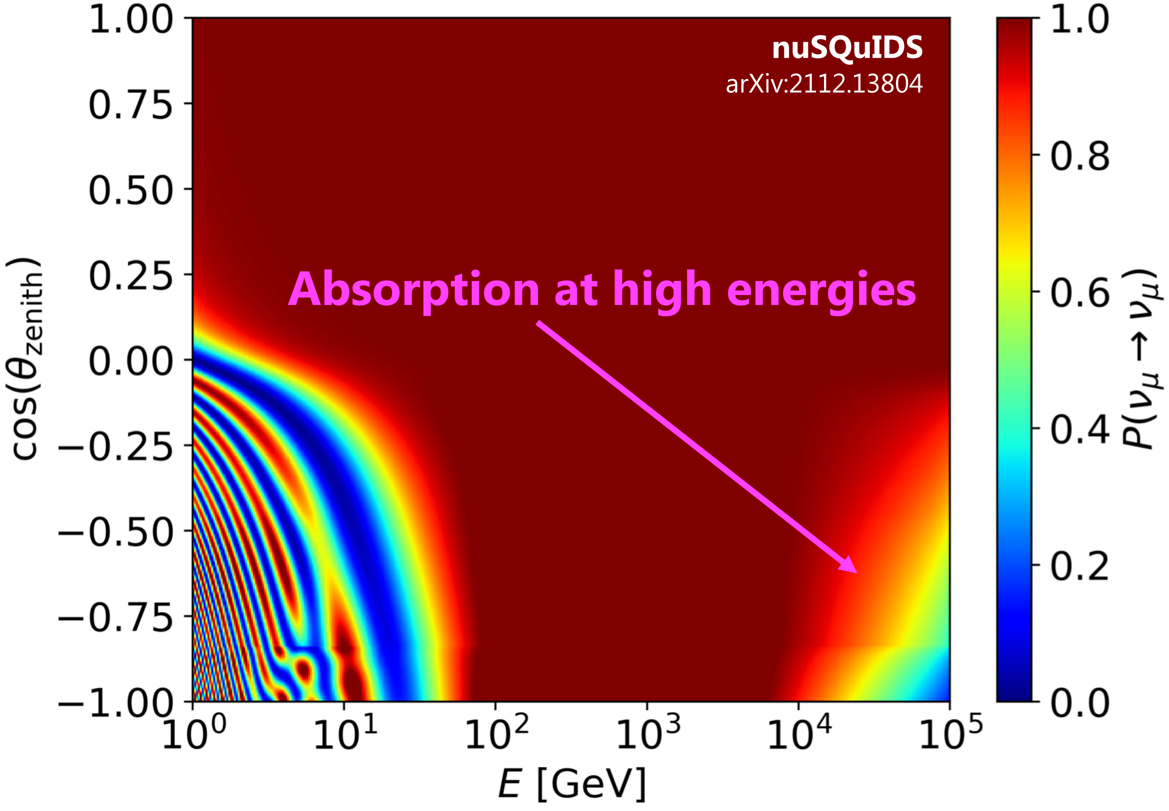
Oscillations at low energies

When E is ≳100 GeV, oscillation baseline is larger than the Earth's diameter

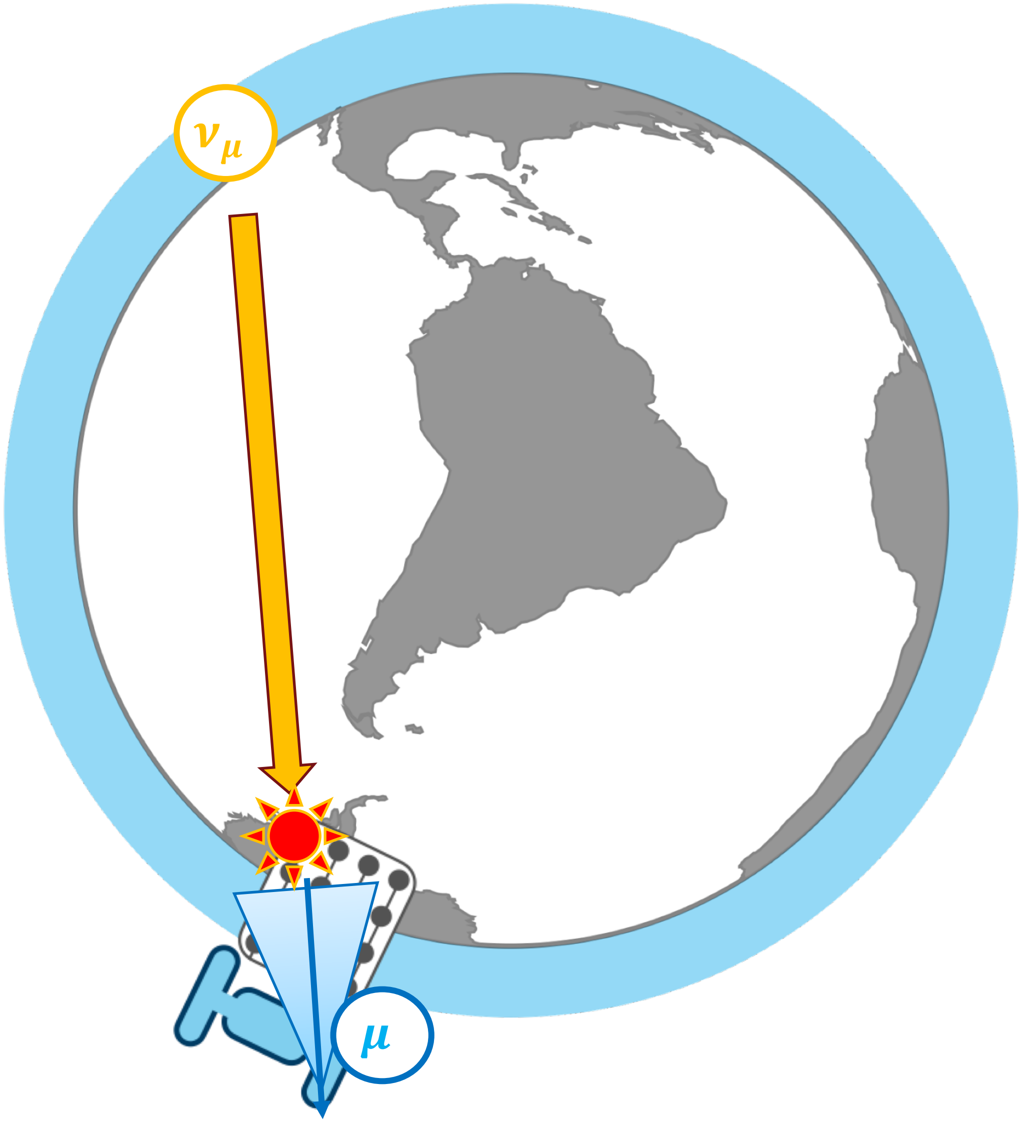
Atmospheric neutrinos in IceCube



(2) Neutrinos propagate across the Earth



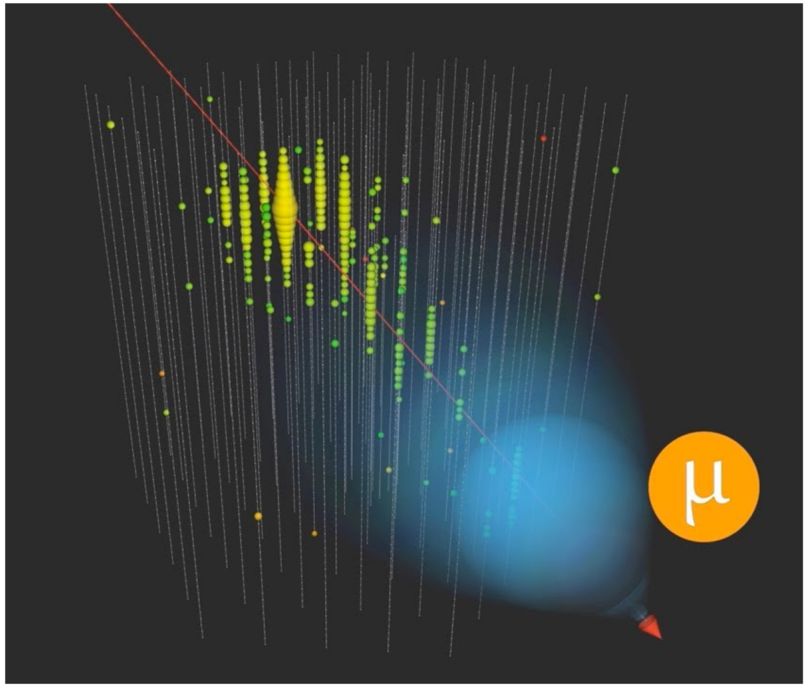
Atmospheric neutrinos in IceCube



(3) Detection via Cherenkov emission from products of $\nu - N$ interactions

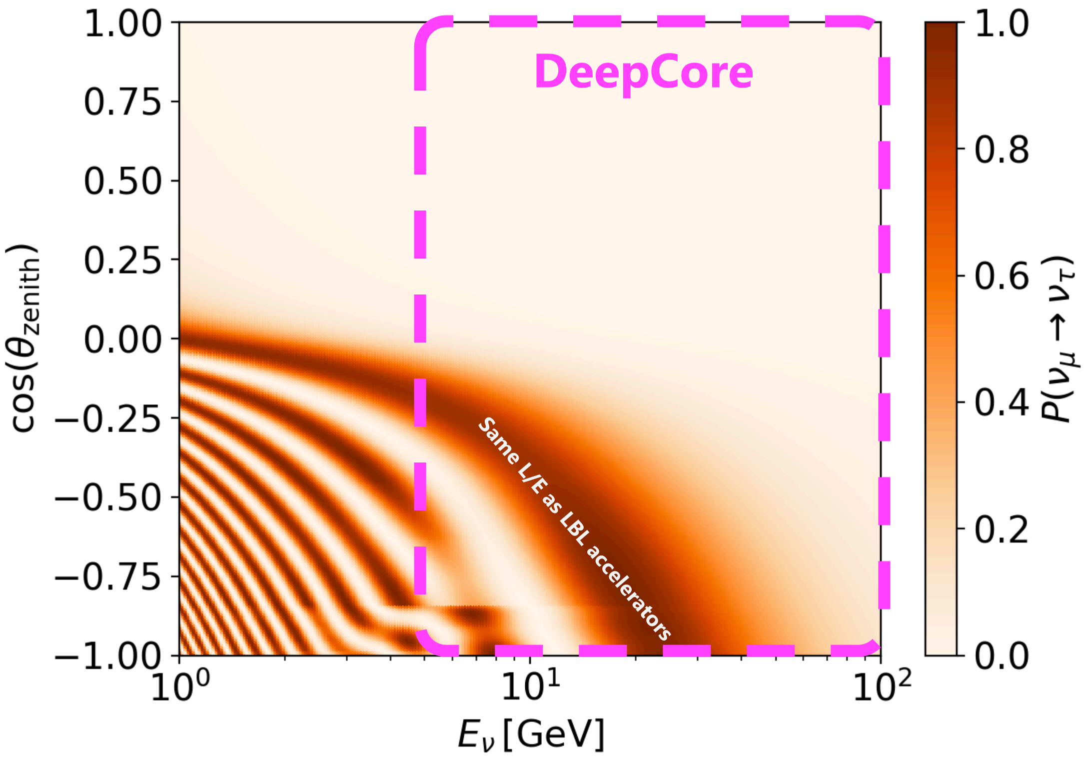
Predominantly Deep Inelastic Scattering (DIS)

"Tracks" from secondary μ
"Cascades" from secondary e, τ and hadrons



Atmospheric neutrino oscillations in IceCube-DeepCore

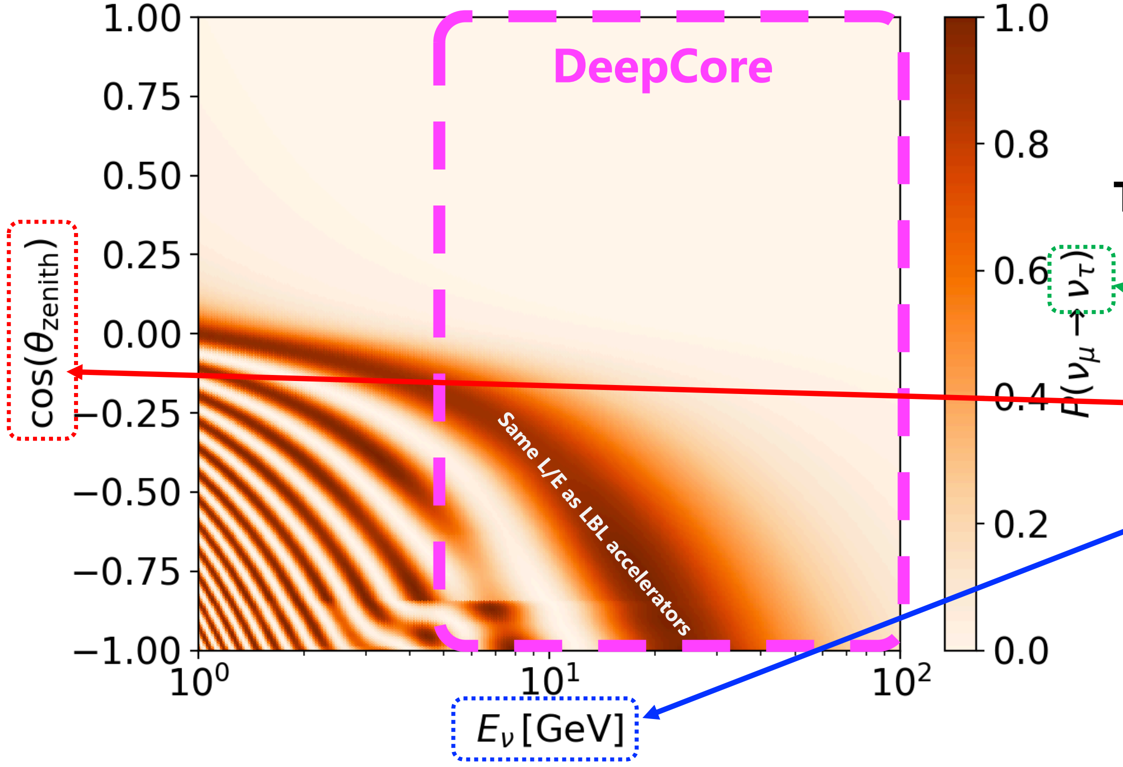
- The DeepCore sub-array of IceCube can measure atmospheric neutrino oscillations in the 5 – 100 GeV energy range
  - Earth-crossing ν_μ **near maximally oscillate to** ν_τ → measures $\boxed{\theta_{23}}$ and $\boxed{\Delta m^2_{32}}$



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

Atmospheric neutrino oscillations in IceCube-DeepCore

- The DeepCore sub-array of IceCube can measure atmospheric neutrino oscillations in the 5 – 100 GeV energy range
  - Earth-crossing $\boldsymbol{\nu_\mu}$ **near maximally oscillate to** $\boldsymbol{\nu_\tau}$ → measures θ_{23} and Δm^2_{32}



To measure these effects, for each neutrino must reconstruct:

Flavor – also known as Particle ID (PID)

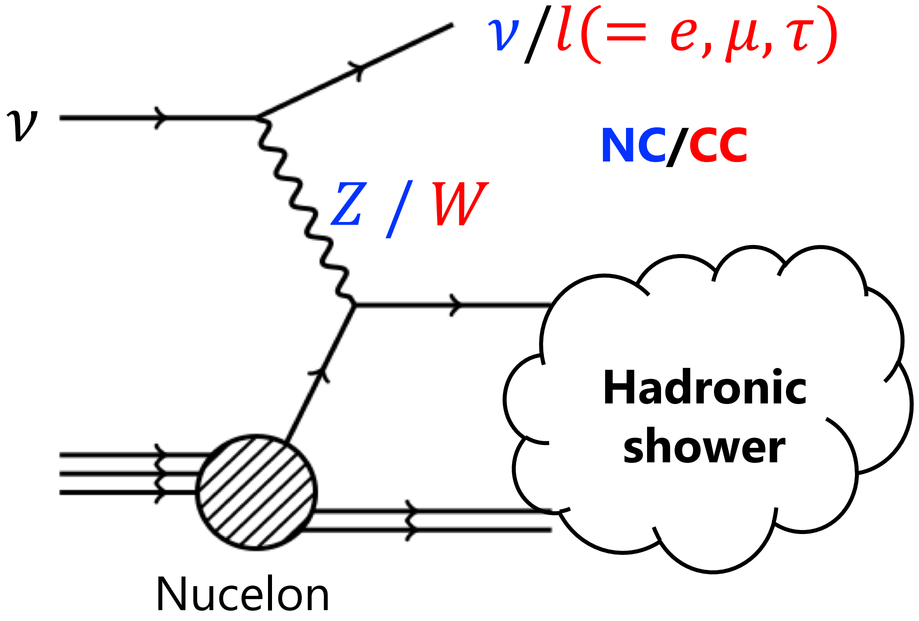
Baseline - determined from arrival (zenith) angle

Energy

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

Detecting neutrinos in DeepCore

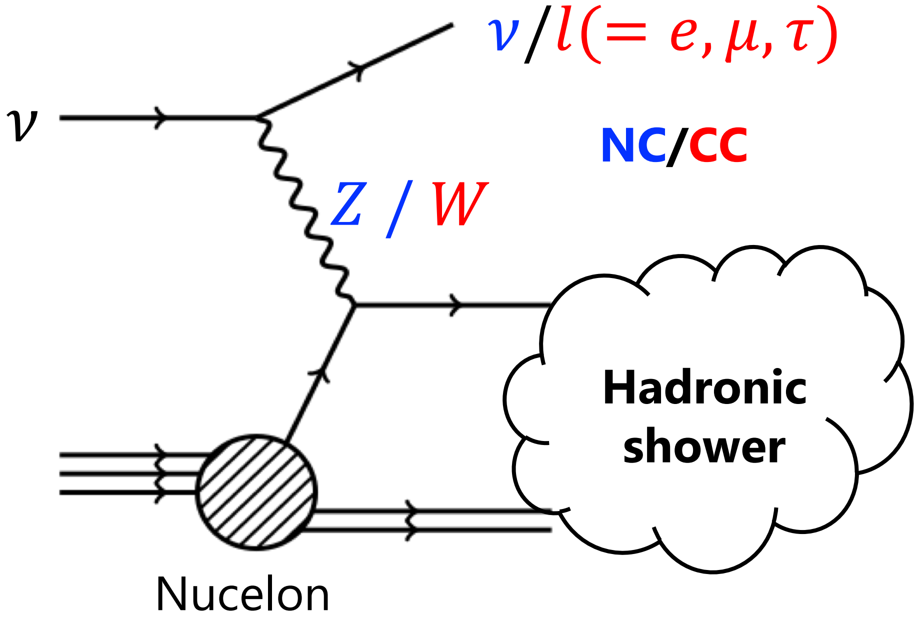
- Primarily detect ν-ice **Deep Inelastic Scattering** (DIS) interactions
- **Charged-** and **Neutral-Current** (CC/NC)

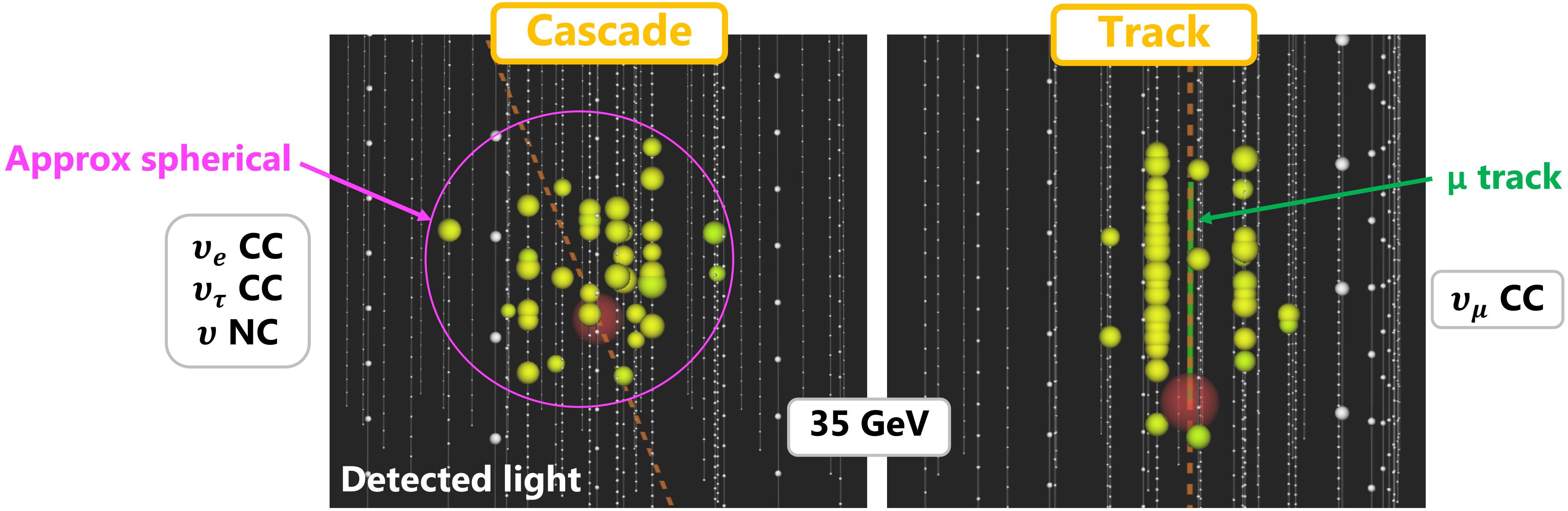


Detecting neutrinos in DeepCore

- Primarily detect ν-ice **Deep Inelastic Scattering** (DIS) interactions
- **Charged-** and **Neutral-Current** (CC/NC)

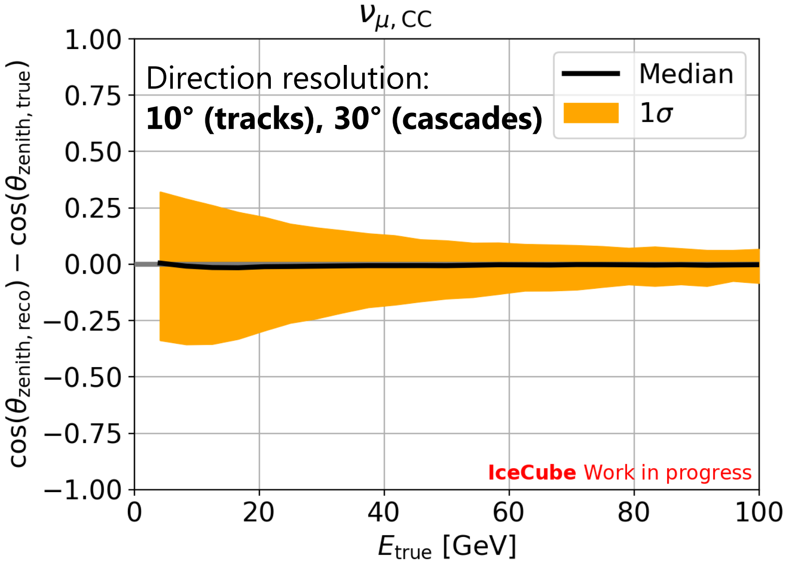
- Two event topologies @ oscillation energies:





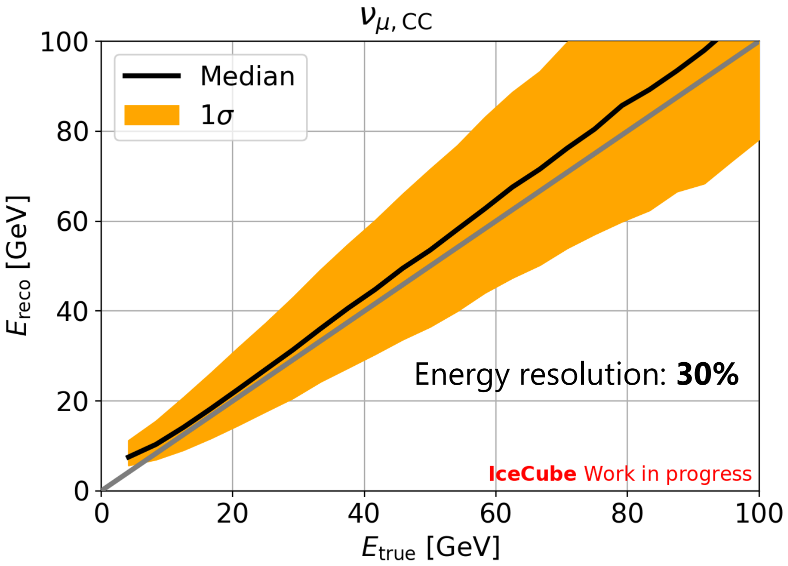
arXiv:2203.02303

DeepCore reconstruction and PID



Direction resolution:
10° (tracks), 30° (cascades)

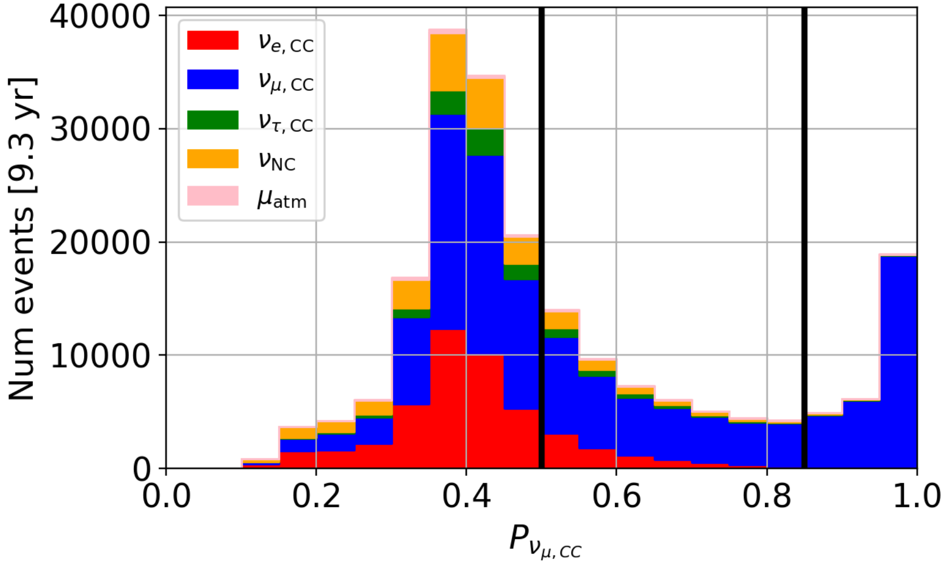
IceCube Work in progress



Energy resolution: **30%**

IceCube Work in progress

PID (XGBoost classifier)



PID is prediction of whether event is charged current ν_μ event (vs any other flavor/interaction)

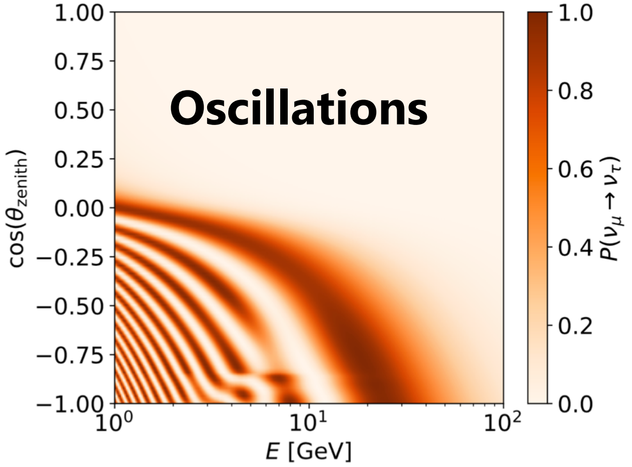
Mainly based on whether muon track is observed

Measuring oscillations

- Measure **3D distortions in reconstructed [energy, zenith, PID]**
  - Robust against systematic uncertainties

Flux

+



+

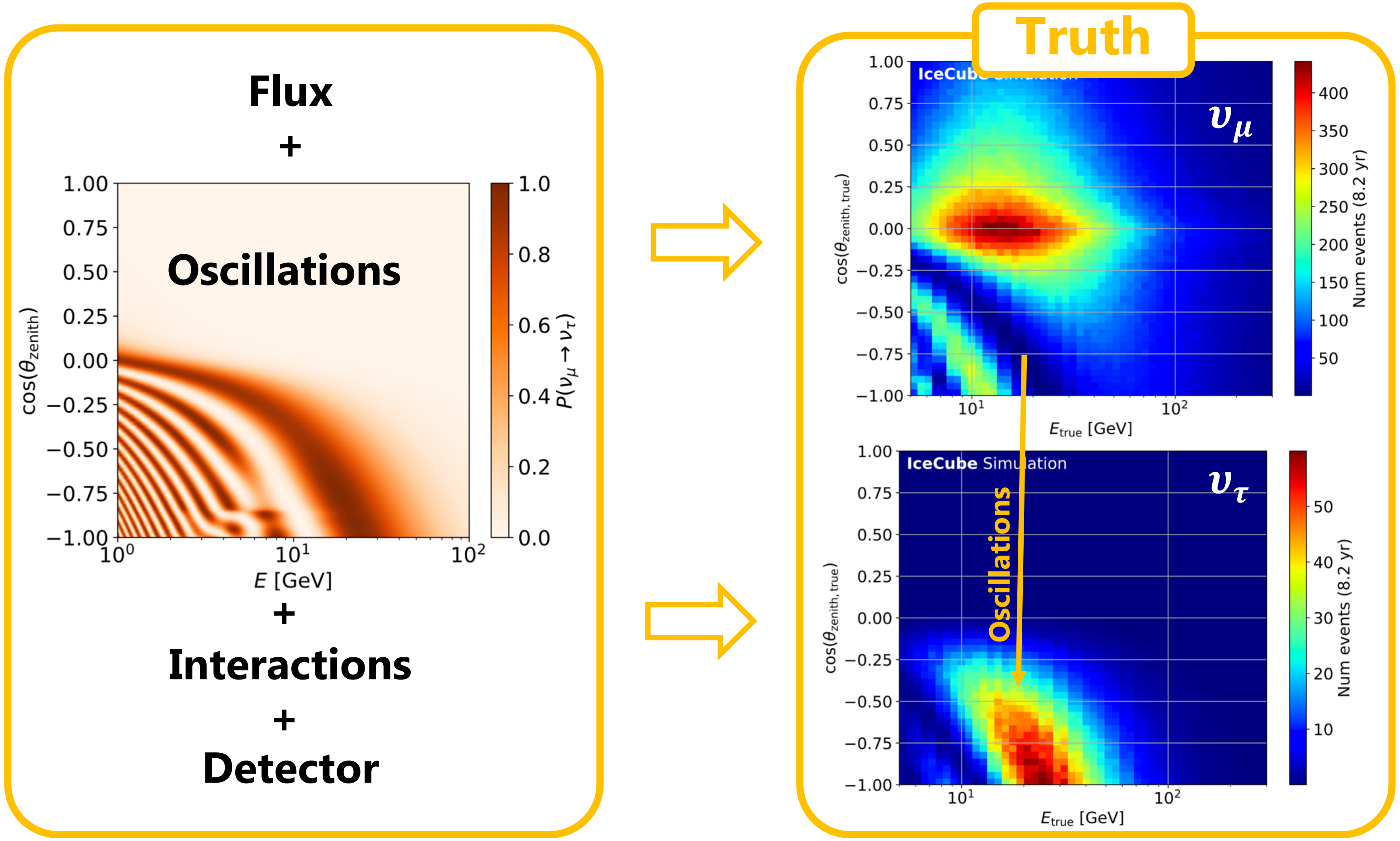
Interactions

+

Detector

Measuring oscillations

- Measure **3D distortions in reconstructed [energy, zenith, PID]**
  - Robust against systematic uncertainties



Flux

+

Oscillations

+

Interactions

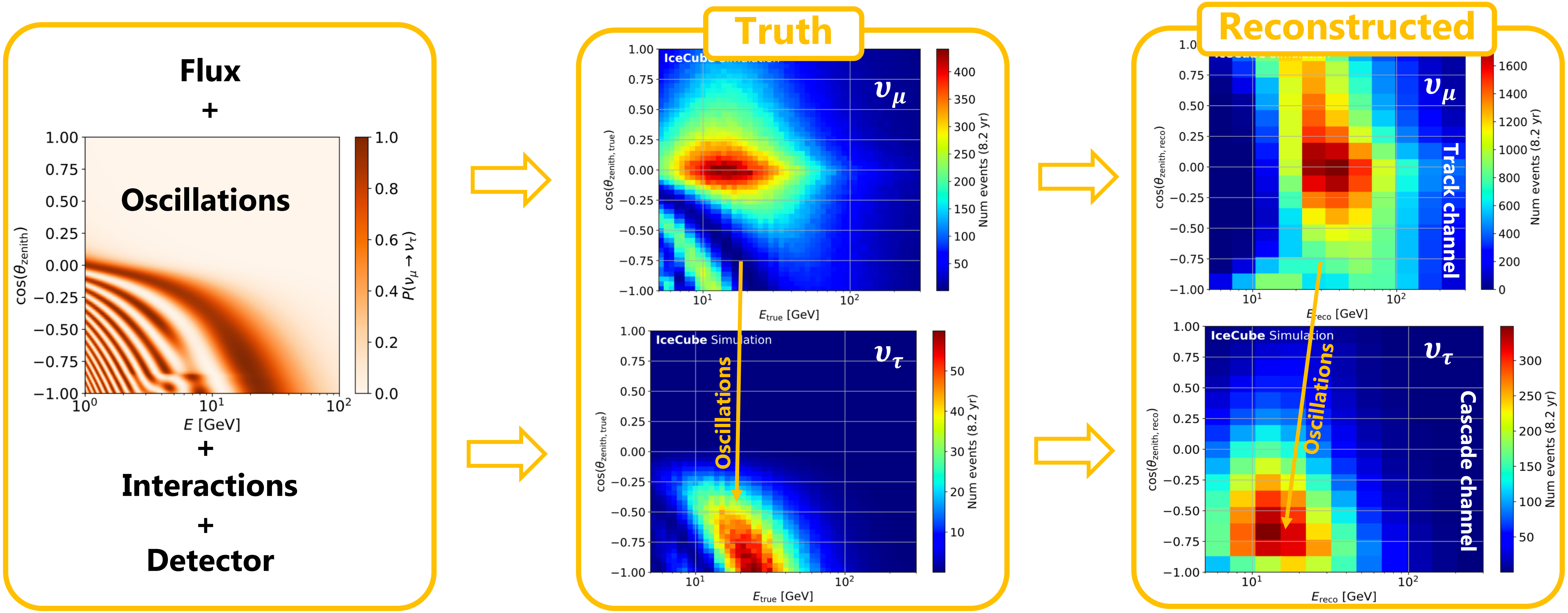
+

Detector

Truth

Measuring oscillations

- Measure **3D distortions in reconstructed [energy, zenith, PID]**
  - Robust against systematic uncertainties



Flux

+

Oscillations

+

Interactions

+

Detector

Truth

Reconstructed

DeepCore's oscillation program

Strengths:

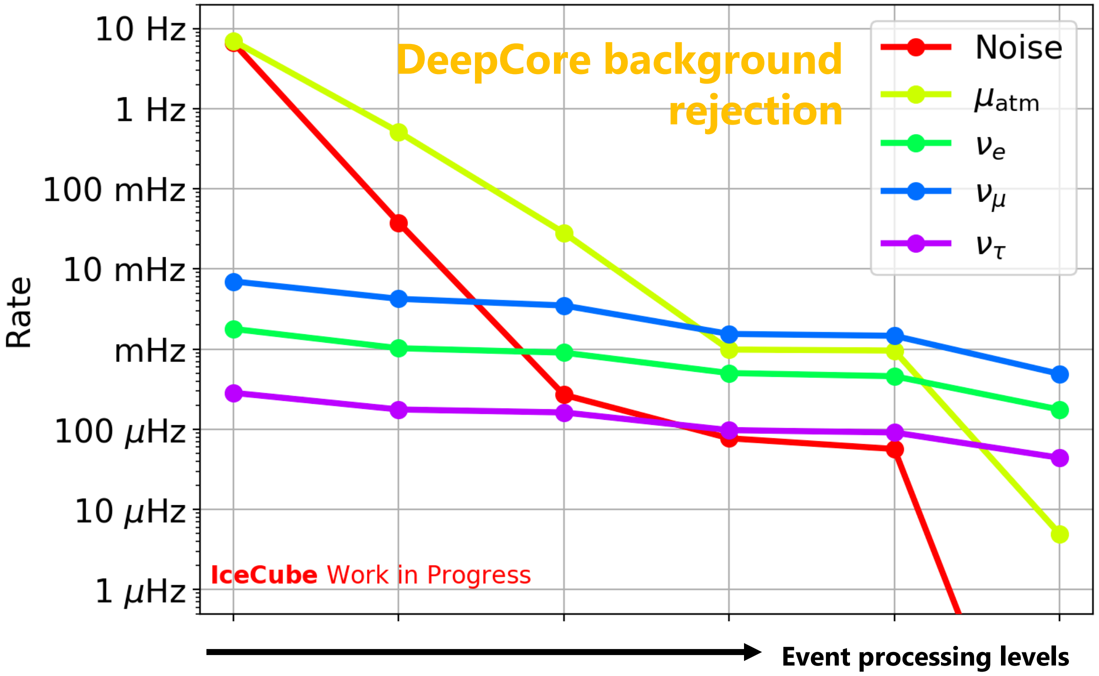
- **Very high statistics** (large flux, huge detector)
- High energy, large baselines and dense matter yield **sensitivity to BSM physics**
- Mostly observe **DIS** interactions → theoretically simple
- **Complimentary to accelerators:** Same oscillation parameters but at 10x the energy, with differing uncertainties (detector, flux, cross section)

Weaknesses:

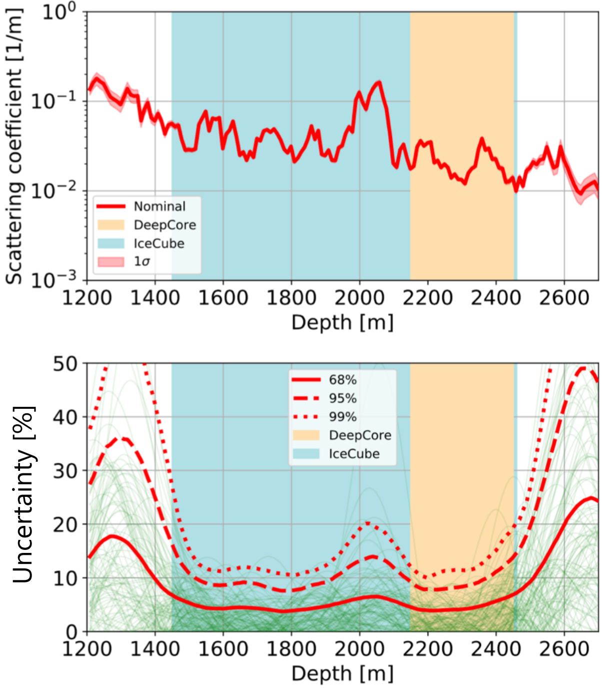
- **Natural detection medium** → hard to calibrate ice properties
- **Sparse** → PMTs are 7.5 m apart → only observe tiny fraction of light in event
  - Results in **poor resolution** compared to e.g. accelerators
- Uncertainties in atmospheric neutrino flux
- **Large backgrounds** of atmospheric muons and detector noise

Current generation of oscillation analyses

- Over 9 years of detector livetime → 210,000 neutrinos
- Backgrounds suppressed by many orders of magnitude to 0.7% of sample
    - High purity and high statistics!
- Sophisticated models of systematic uncertainties
    - Ice properties, flux, cross sections, backgrounds

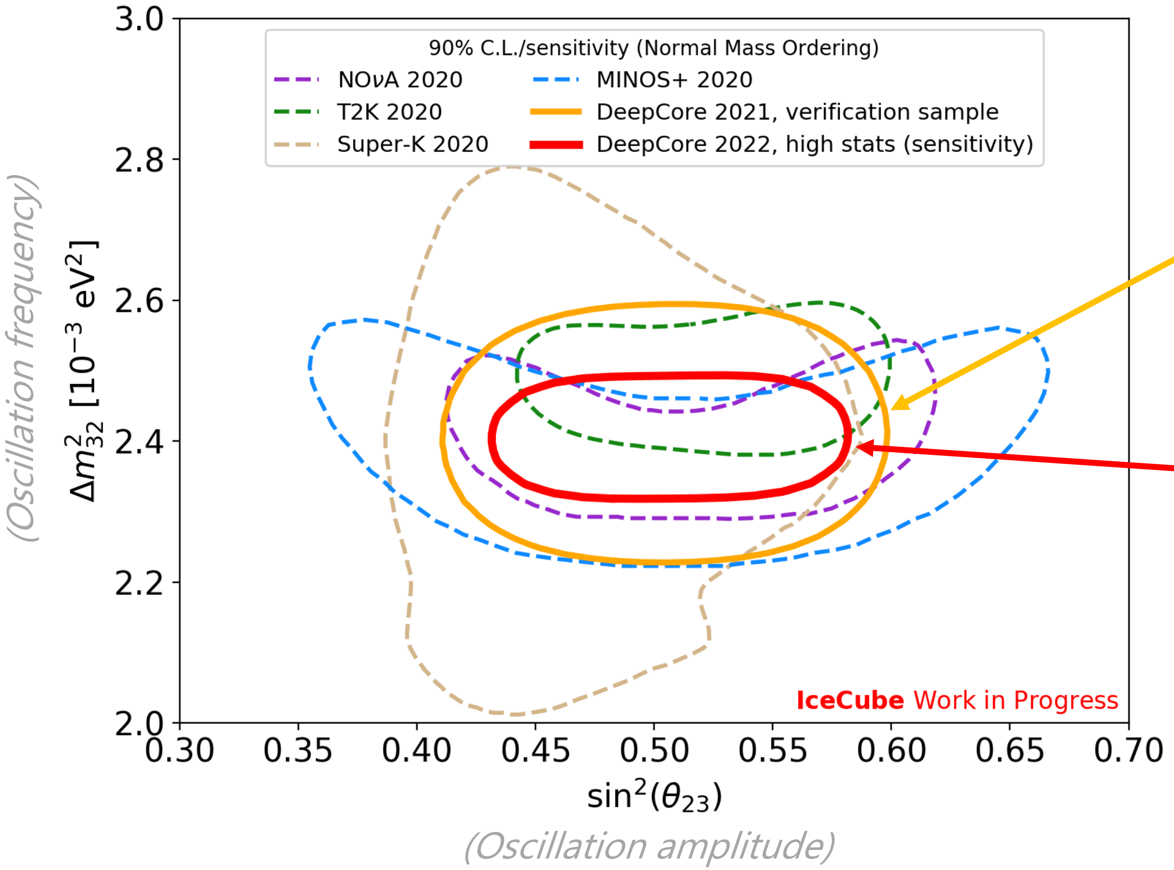


Ice properties vs depth



Current generation of oscillation analyses

Oscillation parameter precision/sensitivity



Recent result!

"Golden" sub-sample of 23,000 ideal neutrinos

Upcoming result!

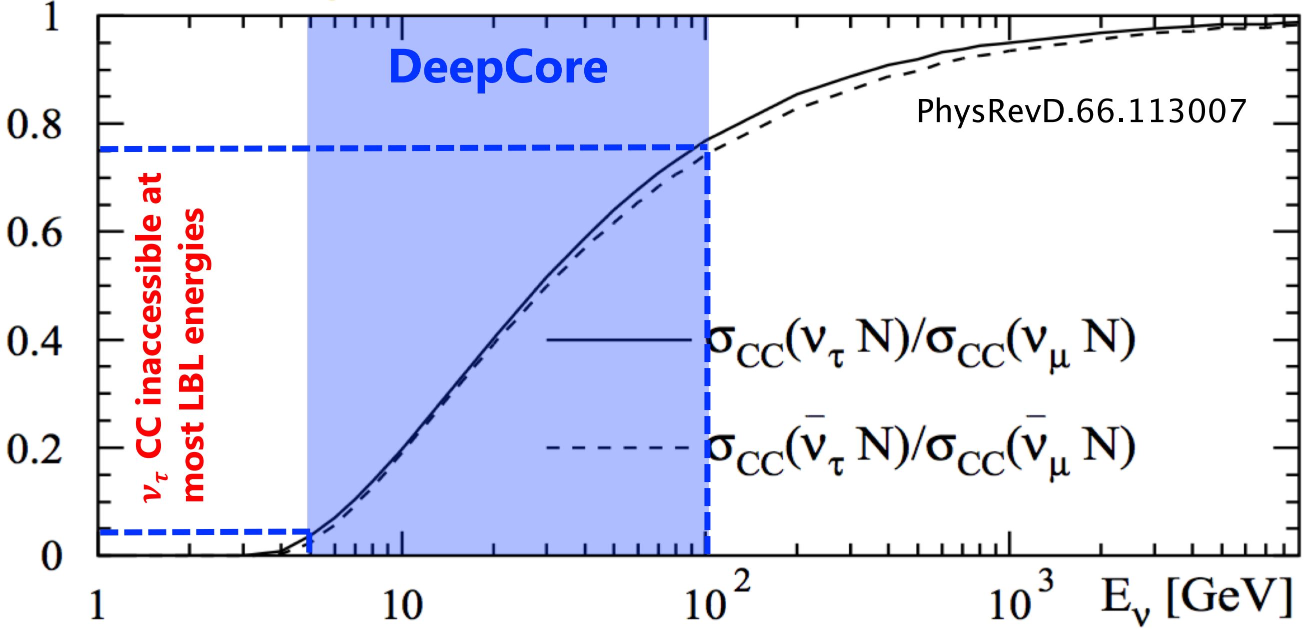
All 210,000 neutrinos

Sensitivity competitive with accelerators

ν_τ appearance

- Dominant oscillation channel in both atmospheric neutrino and long baseline accelerator experiments is $\nu_\mu \rightarrow \nu_\tau$
- However, ν_τ charged current interactions are only possible ≳3.5 GeV
  - And suppressed ≲1 TeV
  - Results from the large mass of the τ lepton that must be produced

ν_τ charged current cross section suppression



ν_τ appearance at DeepCore

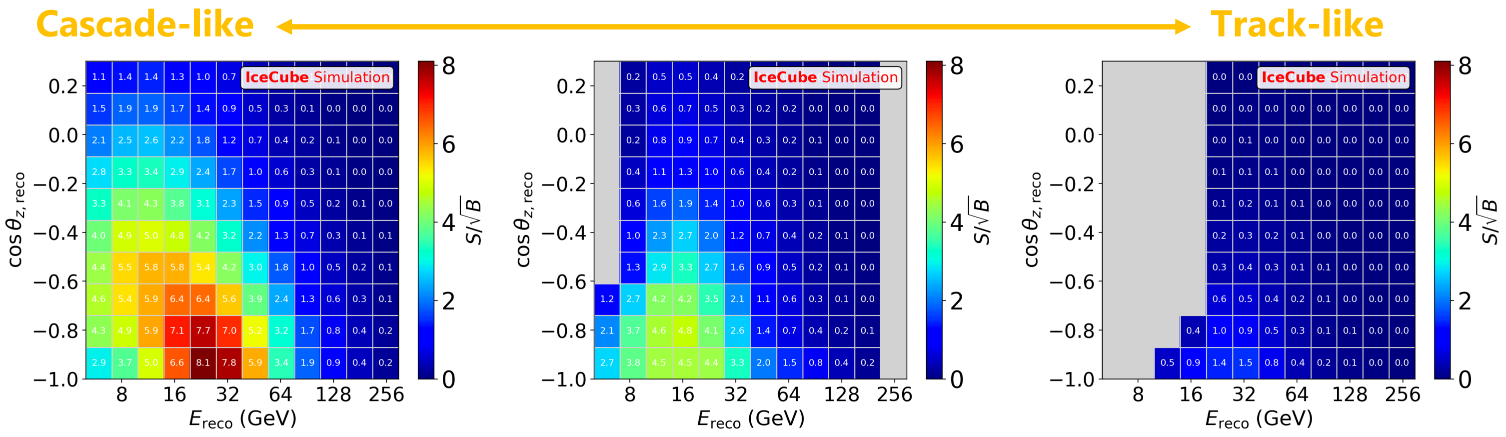
- Most neutrino oscillation measurements are below 3.5 GeV → they only see the **ν_μ disappearing**
- DeepCore is measuring in the 5-100 GeV range → can also see the corresponding **appearance of ν_τ**
- Tests **PMNS unitarity** → observing too few ν_τ could indicate some ν_μ are oscillating to **sterile neutrinos** (that are not observed)

$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \left(\begin{array}{ccc} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}^{U_{\mathrm{PMNS}}^{3\mathrm{x}3}} & \begin{matrix}\cdots \\ \cdots \\ \cdots\end{matrix} & \begin{matrix}U_{en} \\ U_{\mu n} \\ U_{\tau n}\end{matrix} \\ \begin{matrix}\vdots & \qquad\vdots & \qquad\vdots\end{matrix} & \ddots & \vdots \\ \begin{matrix}U_{s_n1} & U_{s_n2} & U_{s_n3}\end{matrix} & \cdots & U_{s_nn} \end{array}\right)$$

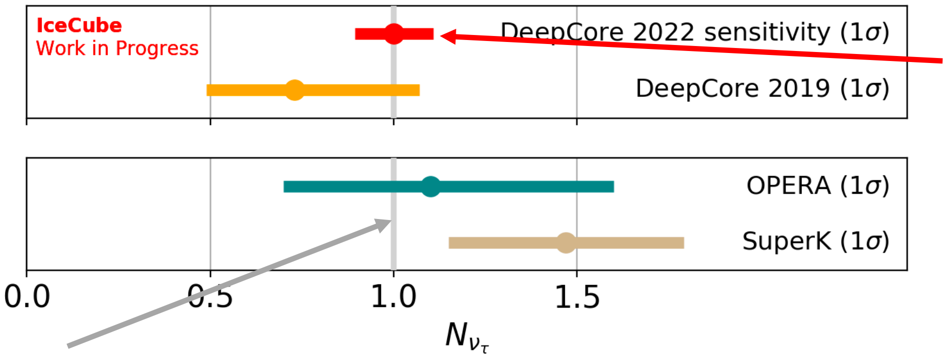
arXiv:1508.05095

DeepCore ν_τ appearance performance

- Signal at IceCube is appearance on cascade events in the [E, coszen] region where track events are disappearing



- DeepCore has world-leading sensitivity to this effect:



11% precision

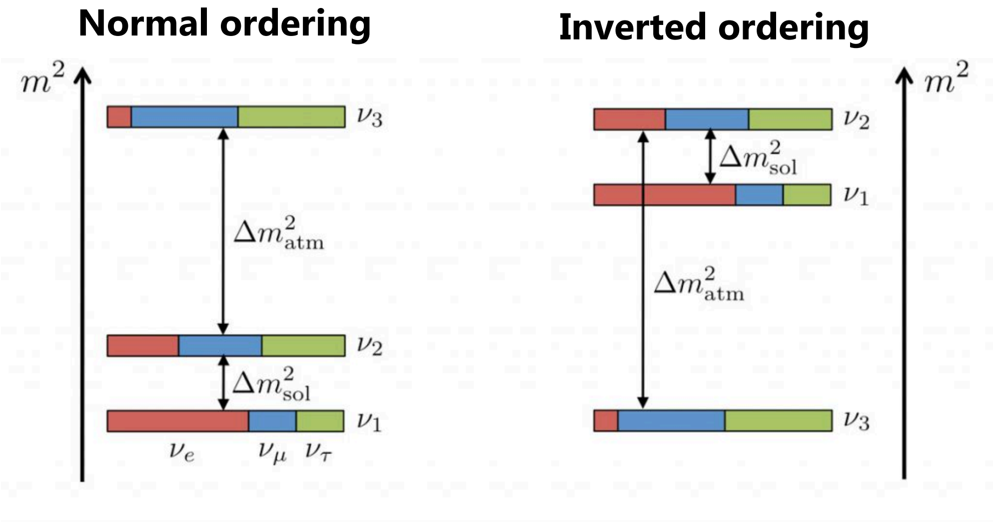
Results from high stats (>9,000 ν_τ)

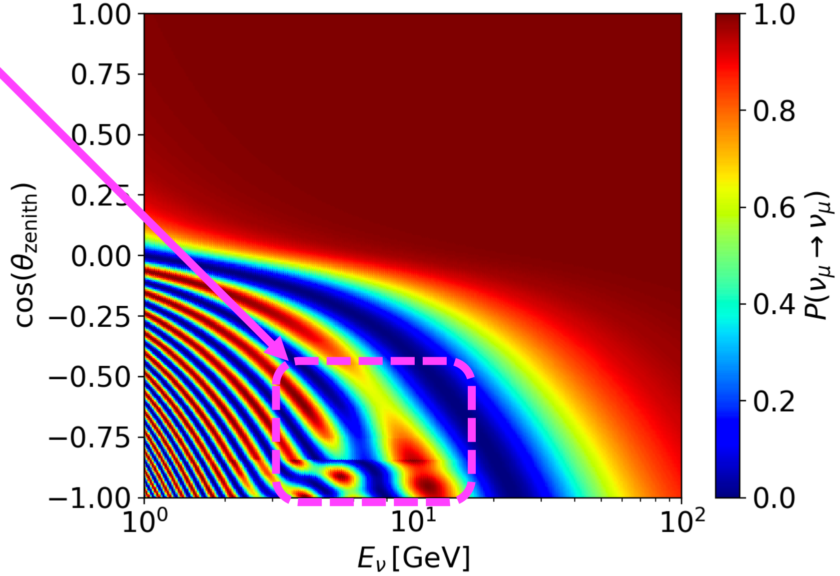
c.f. ~200 ν_τ in total from all other experiments

Measure ν_τ rate relative to PMNS matrix expectation

Neutrino Mass Ordering (NMO)

- In vacuum: Atmospheric oscillations depend on only $|\Delta m^2_{32}|$
  - e.g. not sensitive whether ν_3 is the heaviest or lightest mass state
- In matter: **Small distortion effects** when crossing the **Earth's dense core**
  - Manifests in ν **for the normal ordering,** $\bar{\nu}$ **for the inverted ordering**
  - DeepCore cannot distinguish $\nu/\bar{\nu}$, but larger ν flux and cross sections leads to net signal





- Will be able to probe this with the upcoming IceCube Upgrade detector!

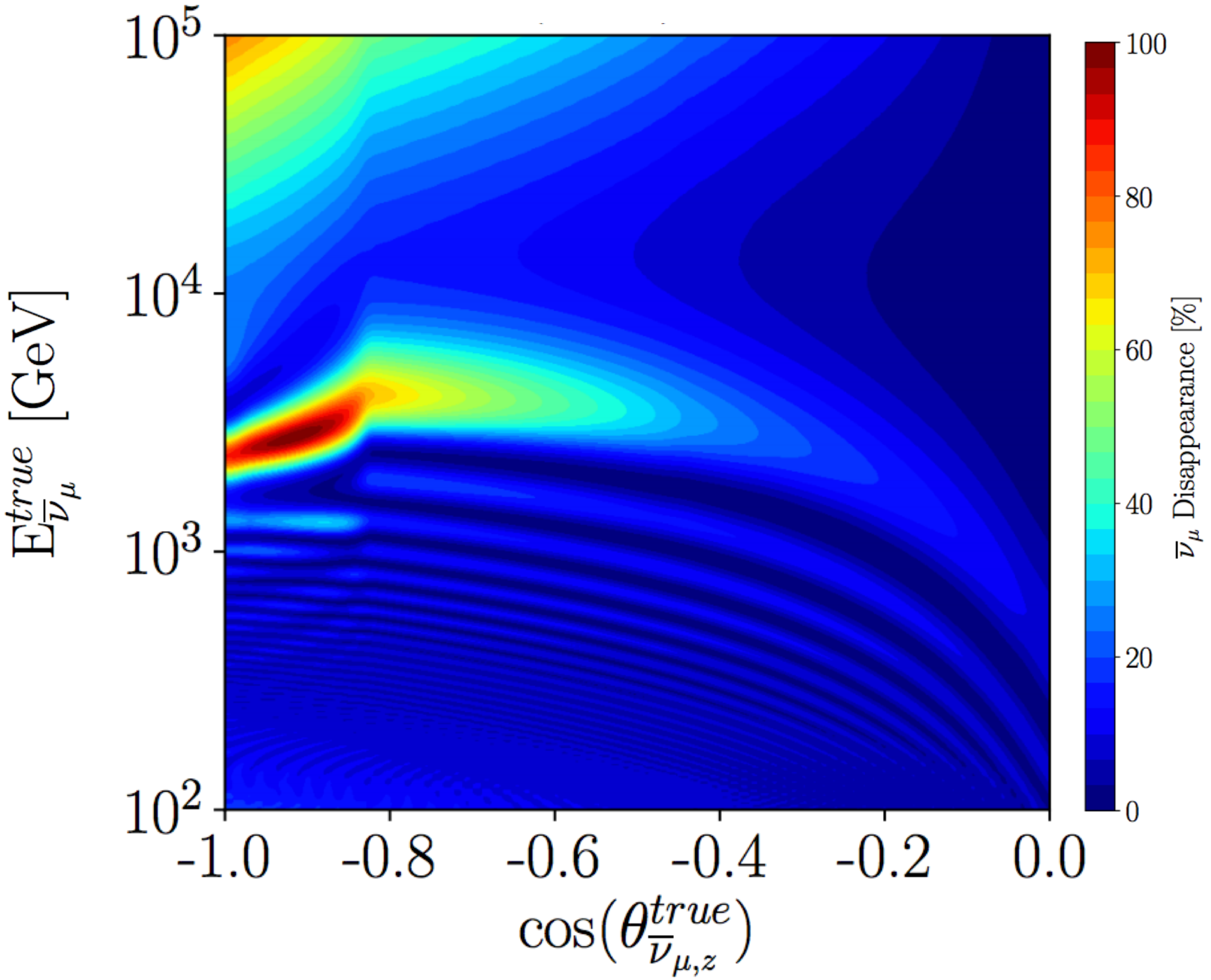
Summary

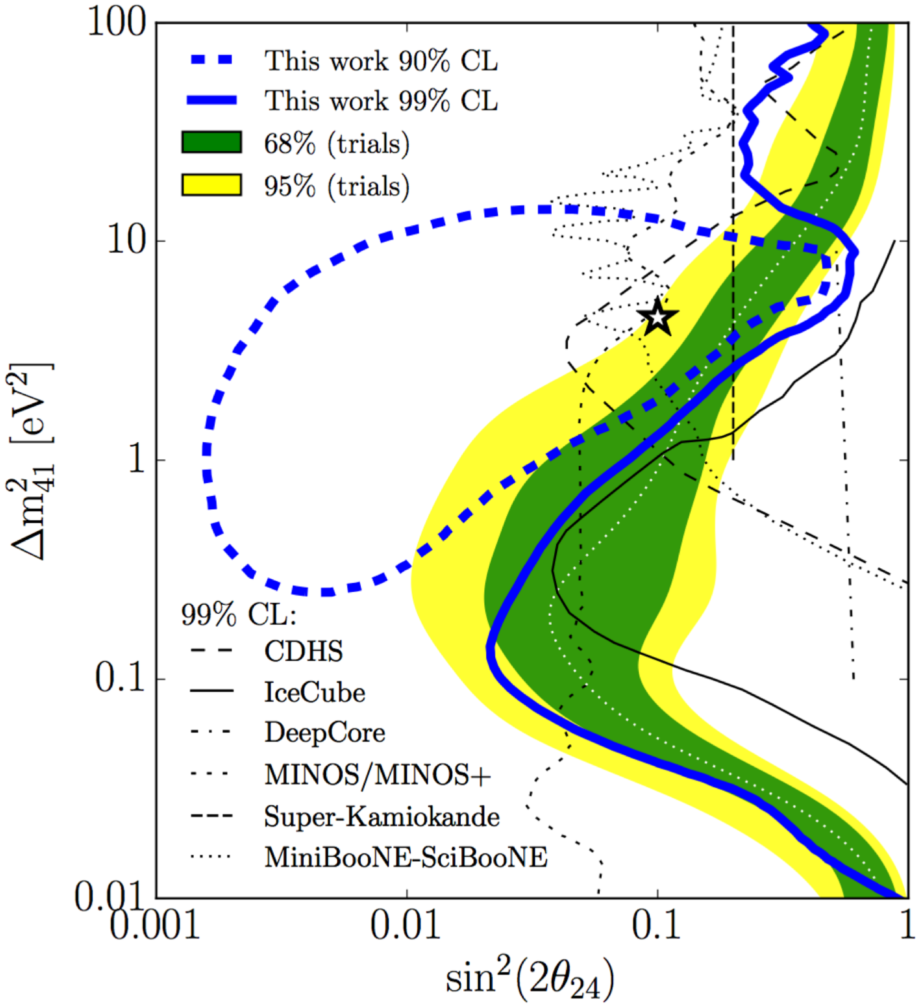
- Neutrino oscillations provide a direct window to new physics and are a leading topic in modern particle physics research
- We still do not know the origin of neutrino mass, or how neutrinos contribute to the matter-antimatter asymmetry of the Universe
- IceCube-DeepCore provide high statistics, high energy measurements of atmospheric neutrino oscillations
  - Mixing parameter measurements competitive with accelerators
  - World-leading ν_τ and BSM oscillation sensitivity
- Next-generation experiments including the IceCube Upgrade usher in the precision era in neutrino oscillation measurements
  - Will our current models hold, or will deviations start to appear?

Thank you

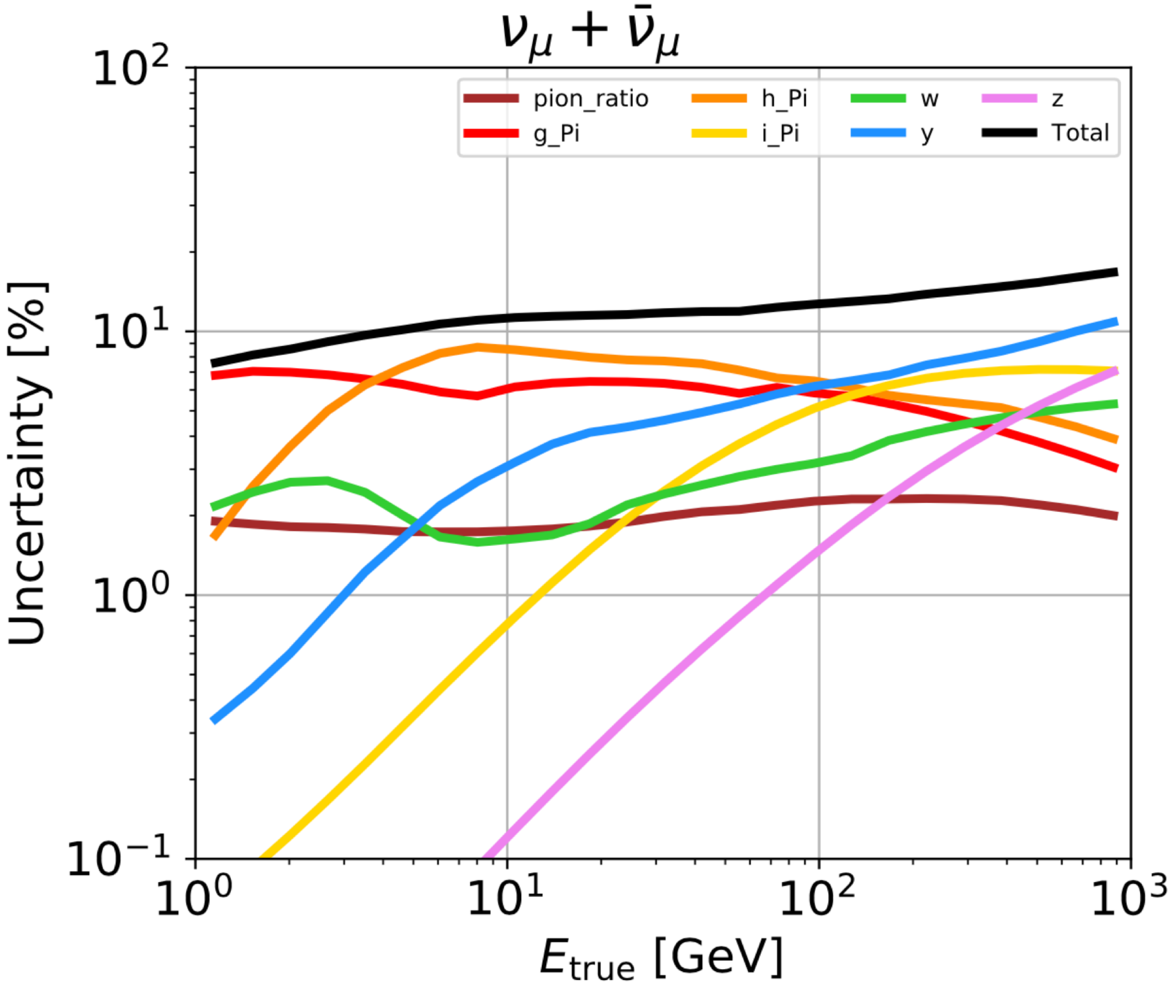
arXiv:2005.12942, 2005.12943

Sterile neutrinos

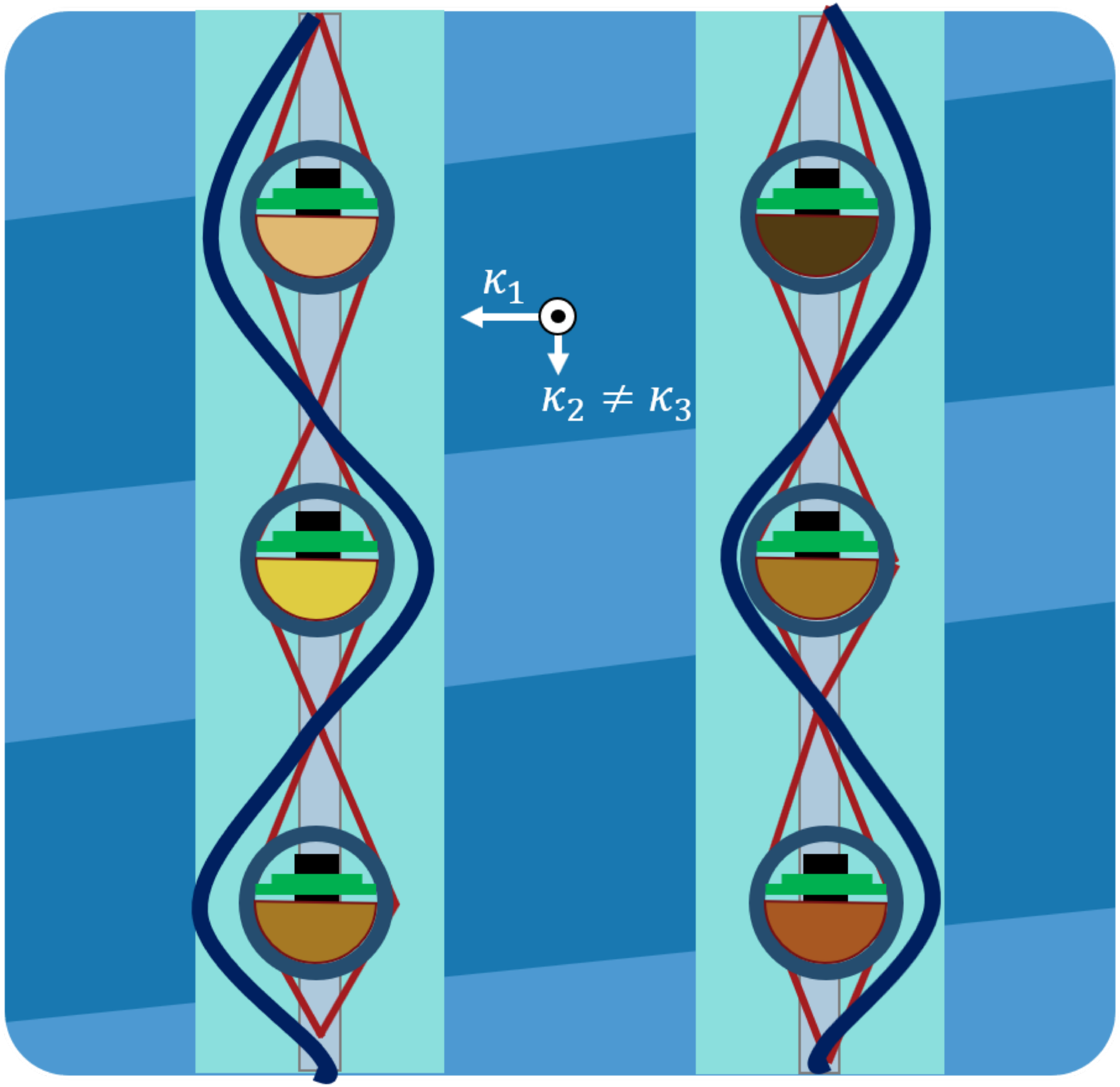




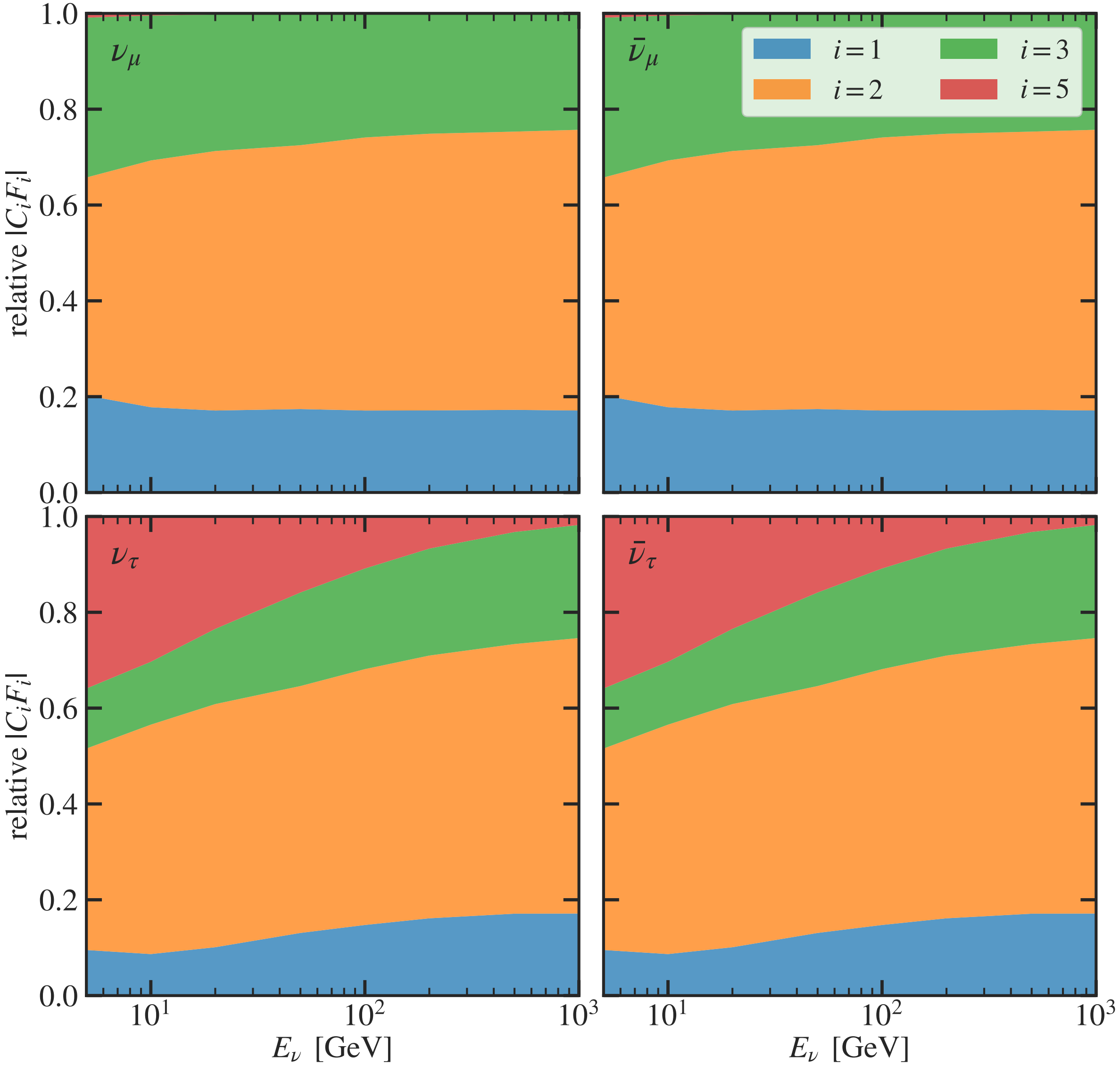
Flux uncertainties



Ice uncertainties



Comparing ν_μ and ν_τ DIS cross sections (LO)

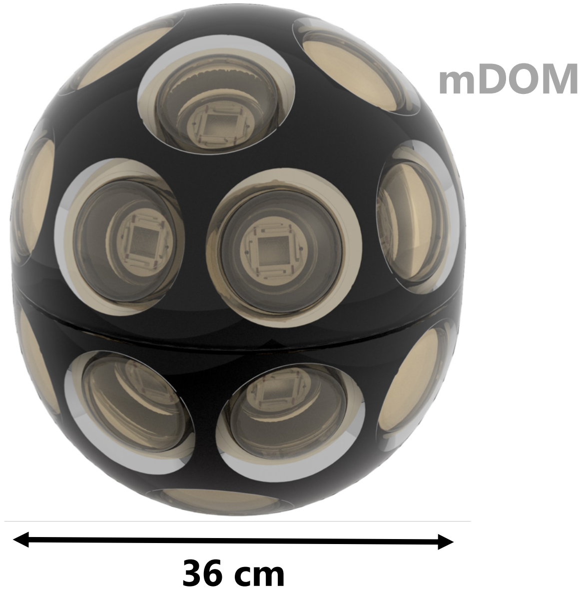


CTEQ66 PDFs

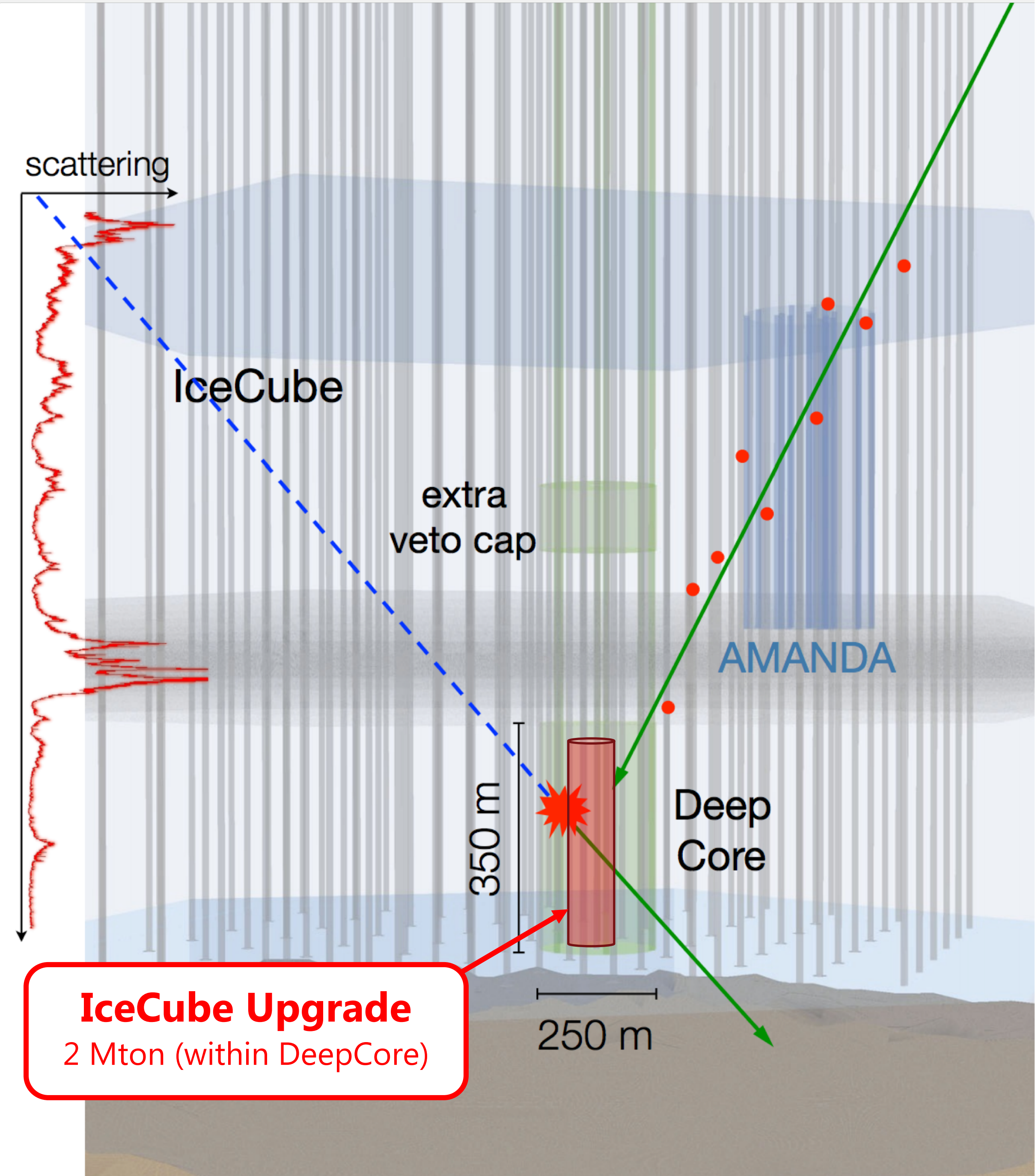
$$\frac{d^2\sigma^{\nu/\bar{\nu}}}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left\{ \left(y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\right) F_1(x,Q^2) + \left[\left(1-\frac{m_l^2}{4E_\nu^2}\right) - \left(1+\frac{M_N x}{2E_\nu}\right)y\right] F_2(x,Q^2) \right.$$
$$\left. \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_l^2 y}{4E_\nu M_N}\right] F_3(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x} F_4(x,Q^2) - \frac{m_l^2}{E_\nu M_N} F_5(x,Q^2) \right\}$$

The IceCube Upgrade

- **Low-energy extension to IceCube**
  - Deployment in **2025/6**
  - **Drop threshold to 1 GeV**
- 700 multi-PMT sensors
- Improved detector/ice calibration



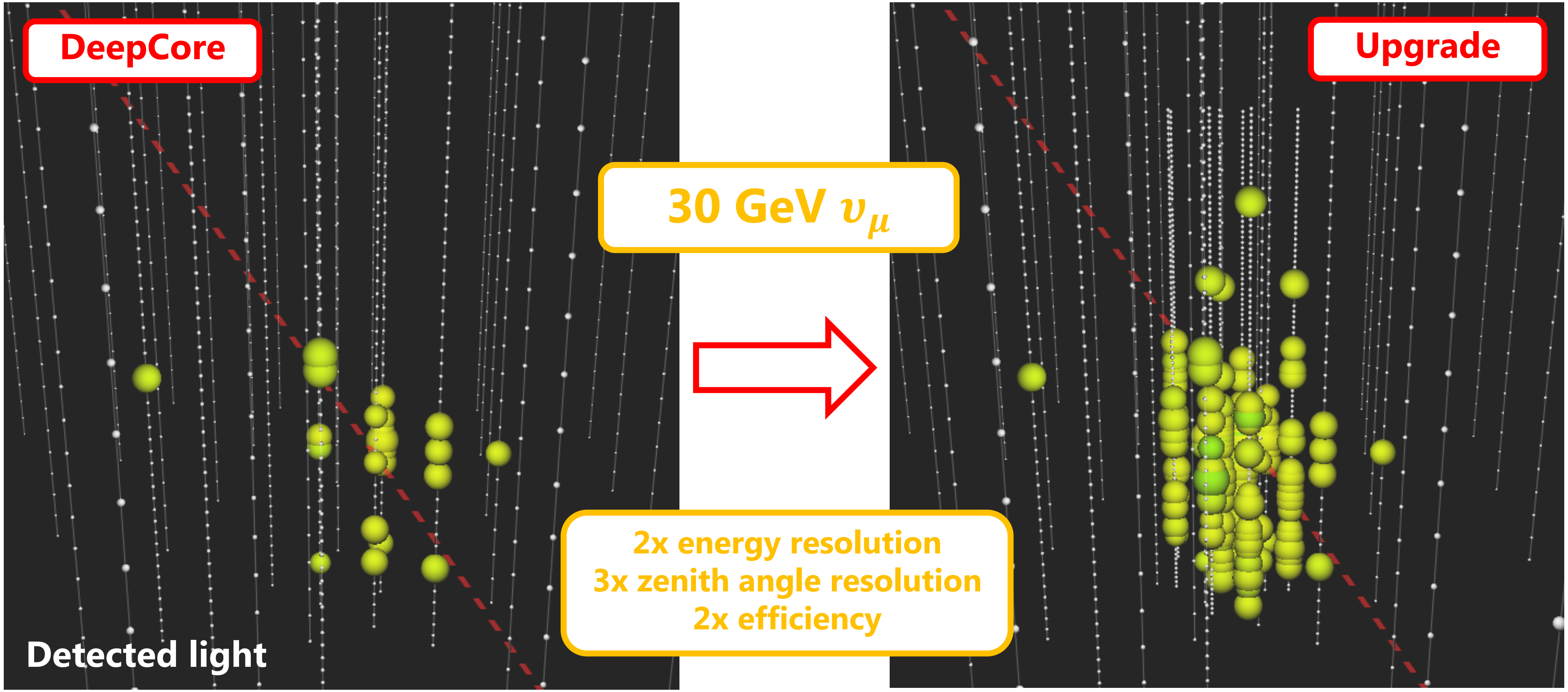
arXiv:1908.09441



IceCube Upgrade
2 Mton (within DeepCore)

IceCube Upgrade: Increased photocathode density

- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive down to ~**1 GeV neutrinos**

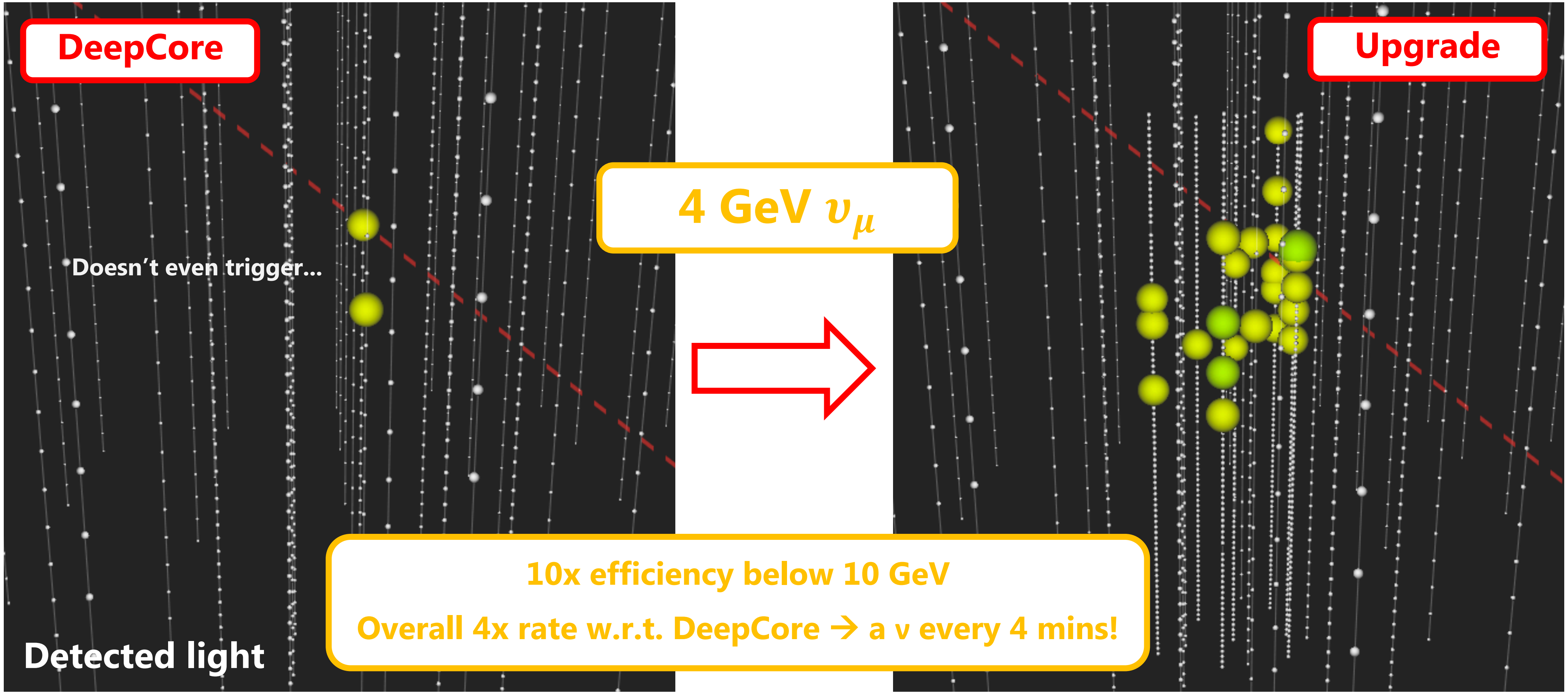


30 GeV υ_μ

2x energy resolution
3x zenith angle resolution
2x efficiency

IceCube Upgrade: Increased photocathode density

- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive down to ~**1 GeV neutrinos**



4 GeV ν_μ

10x efficiency below 10 GeV

Overall 4x rate w.r.t. DeepCore → a ν every 4 mins!