

# IceCube - Particle Physics and Astrophysics on Ice

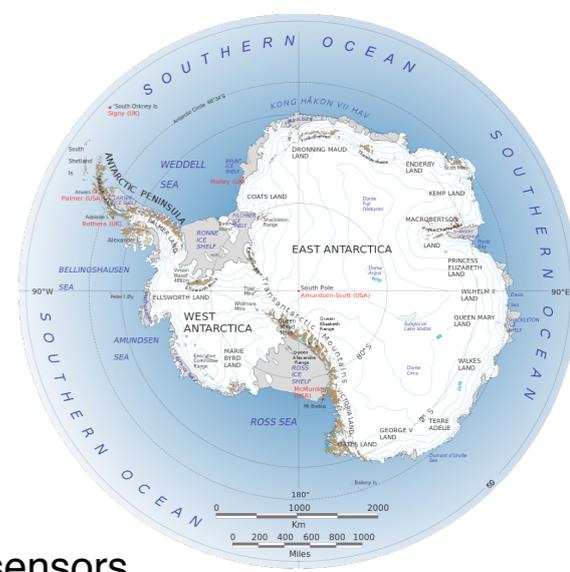
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University of Copenhagen - Niels Bohr  
Institute

Nordic Conference on Particle Physics  
Norway  
2020



# IceCube/DeepCore



IceCube Lab

**IceTop**  
81 Stations  
324 optical sensors

50 m

**IceCube Array**  
86 strings including  
8 DeepCore strings  
5160 optical sensors

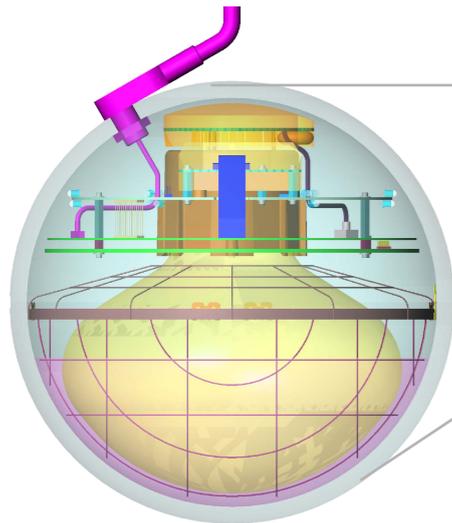
1450 m

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

2450 m

2820 m

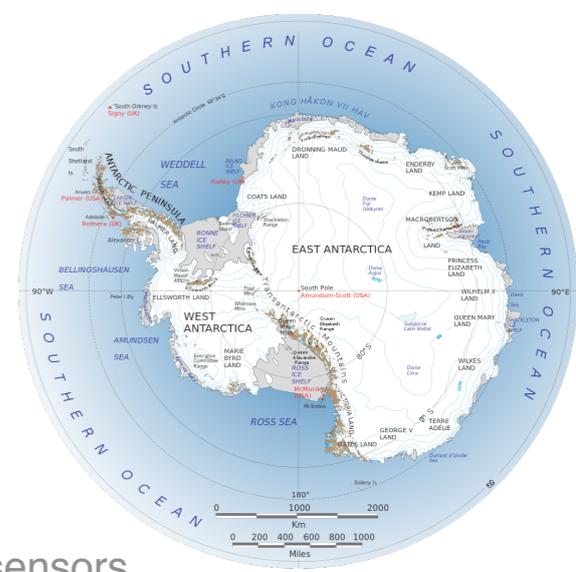
Eiffel Tower  
324 m



IceCube Digital Optical  
Module (DOM)

Bedrock

# IceCube/DeepCore



IceCube Lab

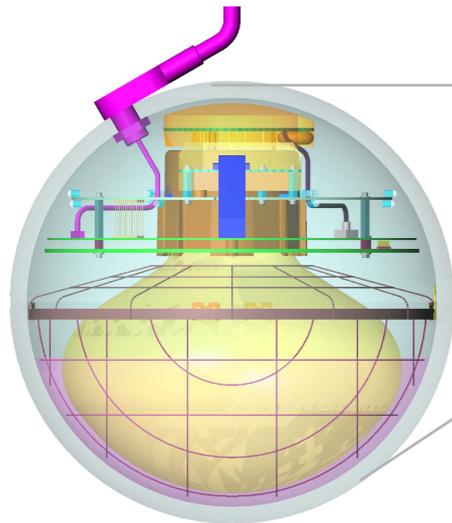
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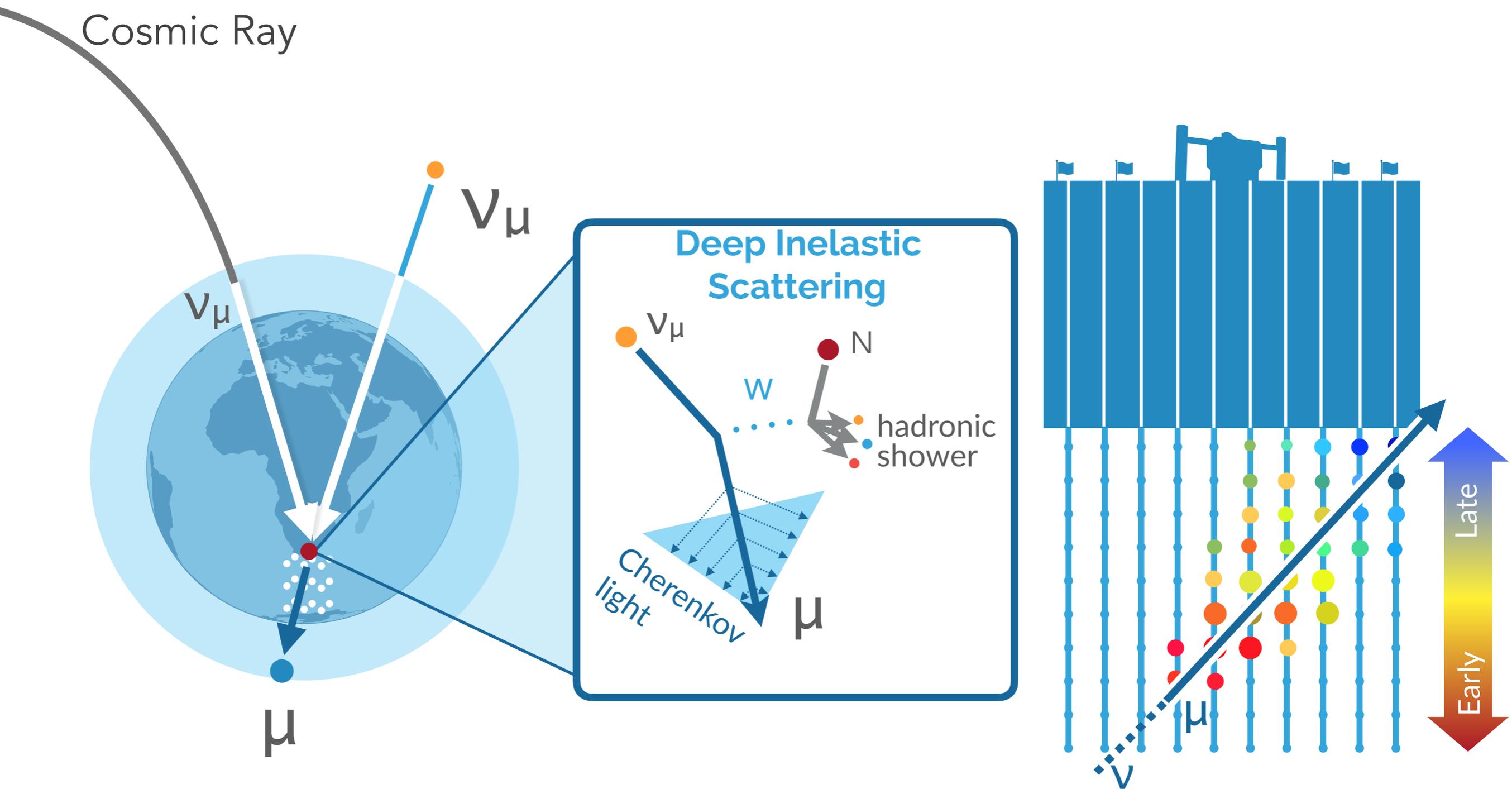
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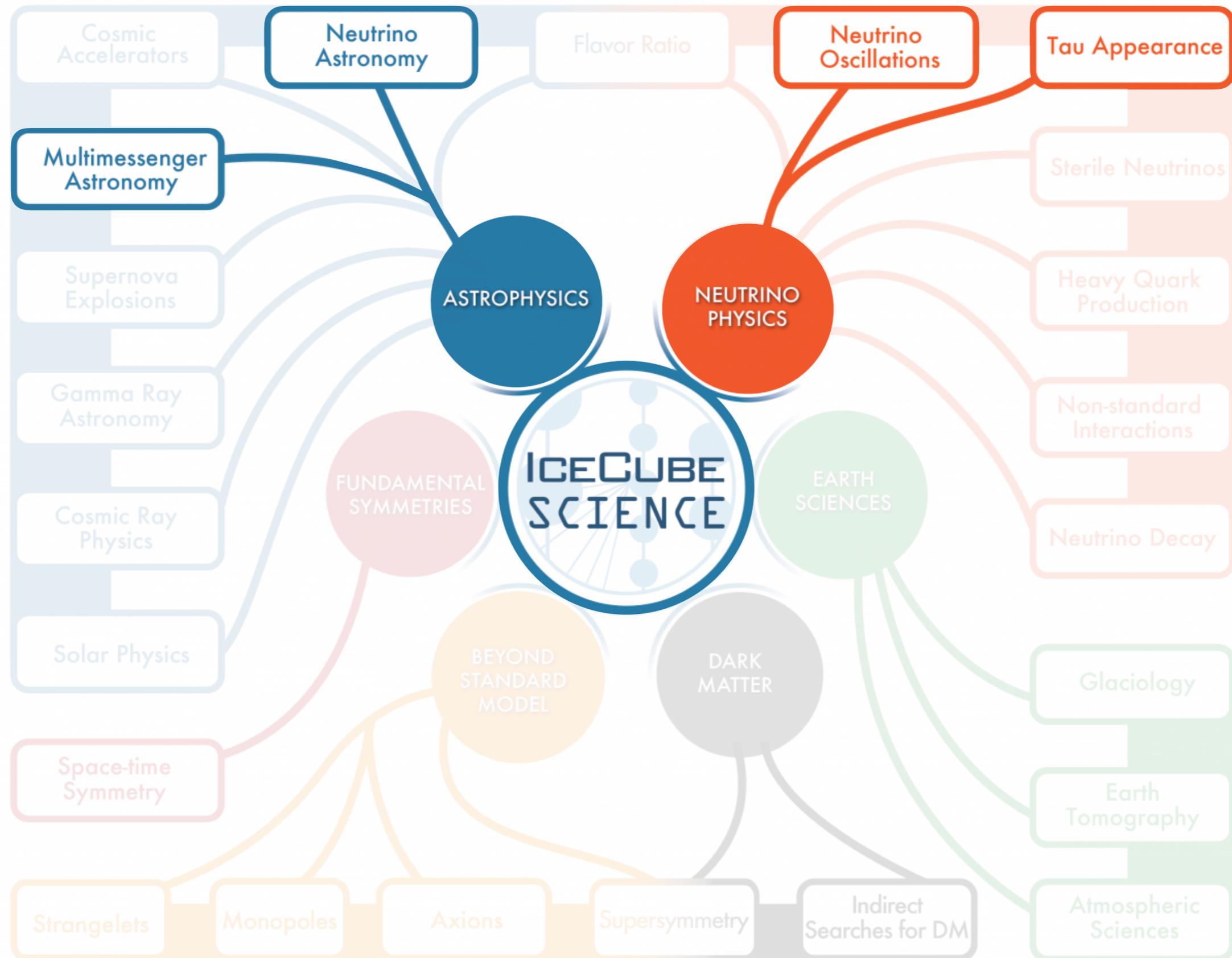
Bedrock

IceCube Digital Optical  
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# Detection in IceCube

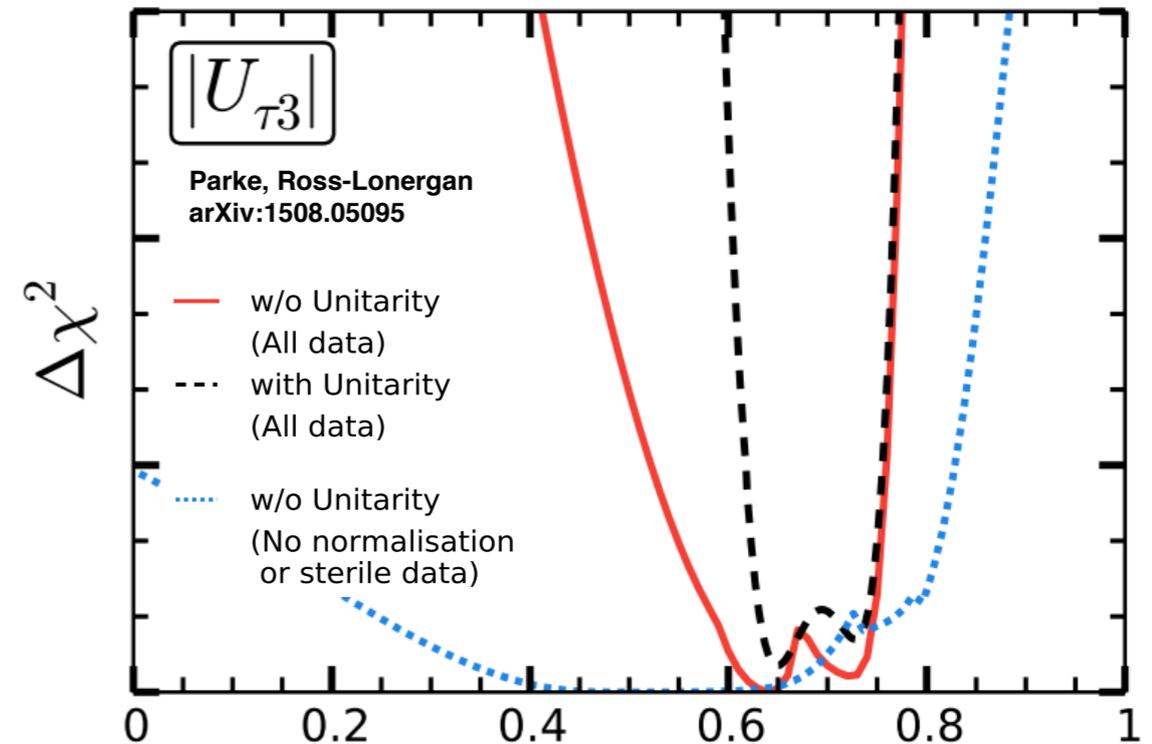


# IceCube Science



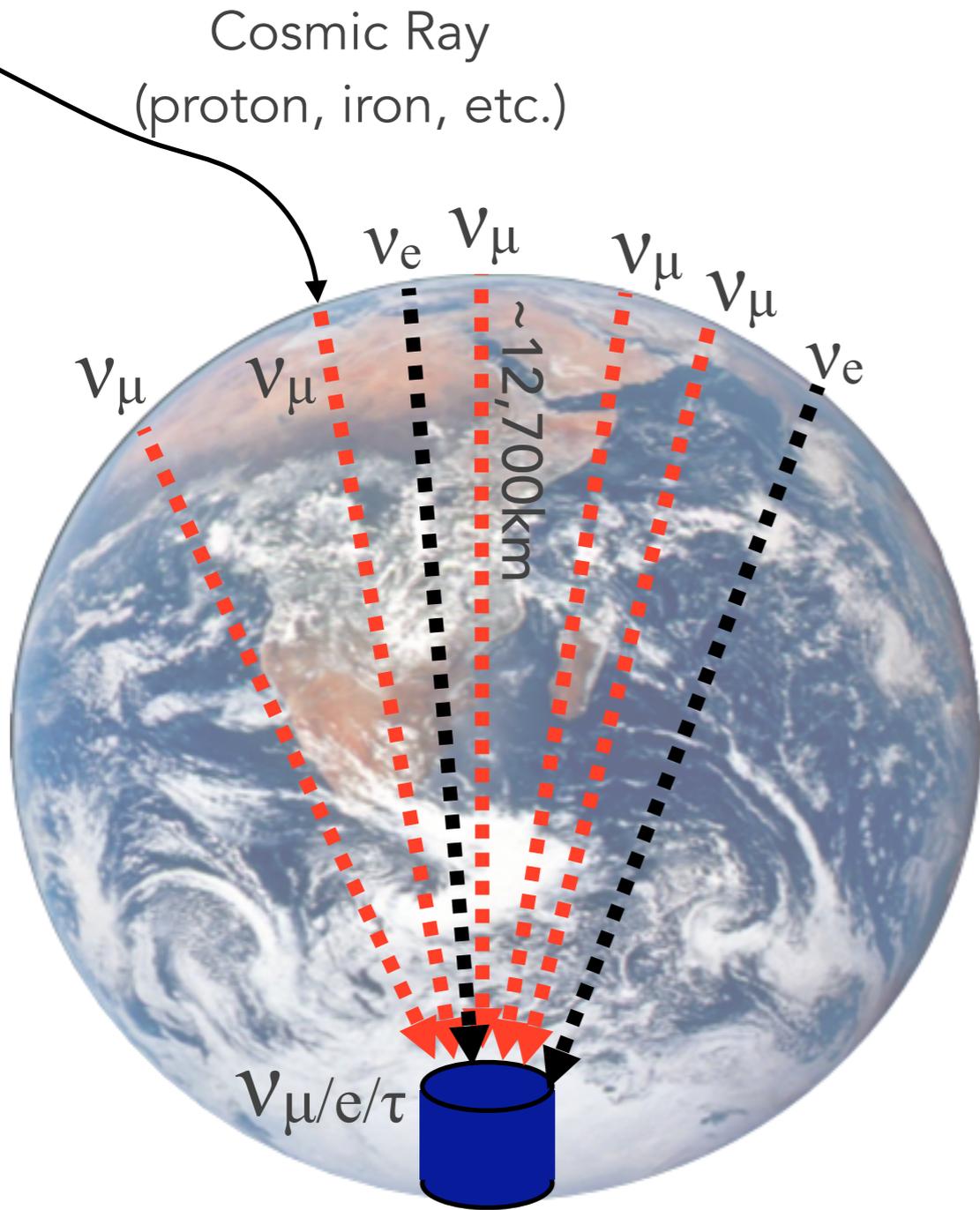
# Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \begin{pmatrix} \overbrace{U_{e1} \quad U_{e2} \quad U_{e3}}^{U_{\text{PMNS}}} & & \\ U_{\mu 1} \quad U_{\mu 2} \quad U_{\mu 3} & \cdots & \\ \boxed{U_{\tau 1} \quad U_{\tau 2} \quad U_{\tau 3}} & & \\ \vdots & & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$

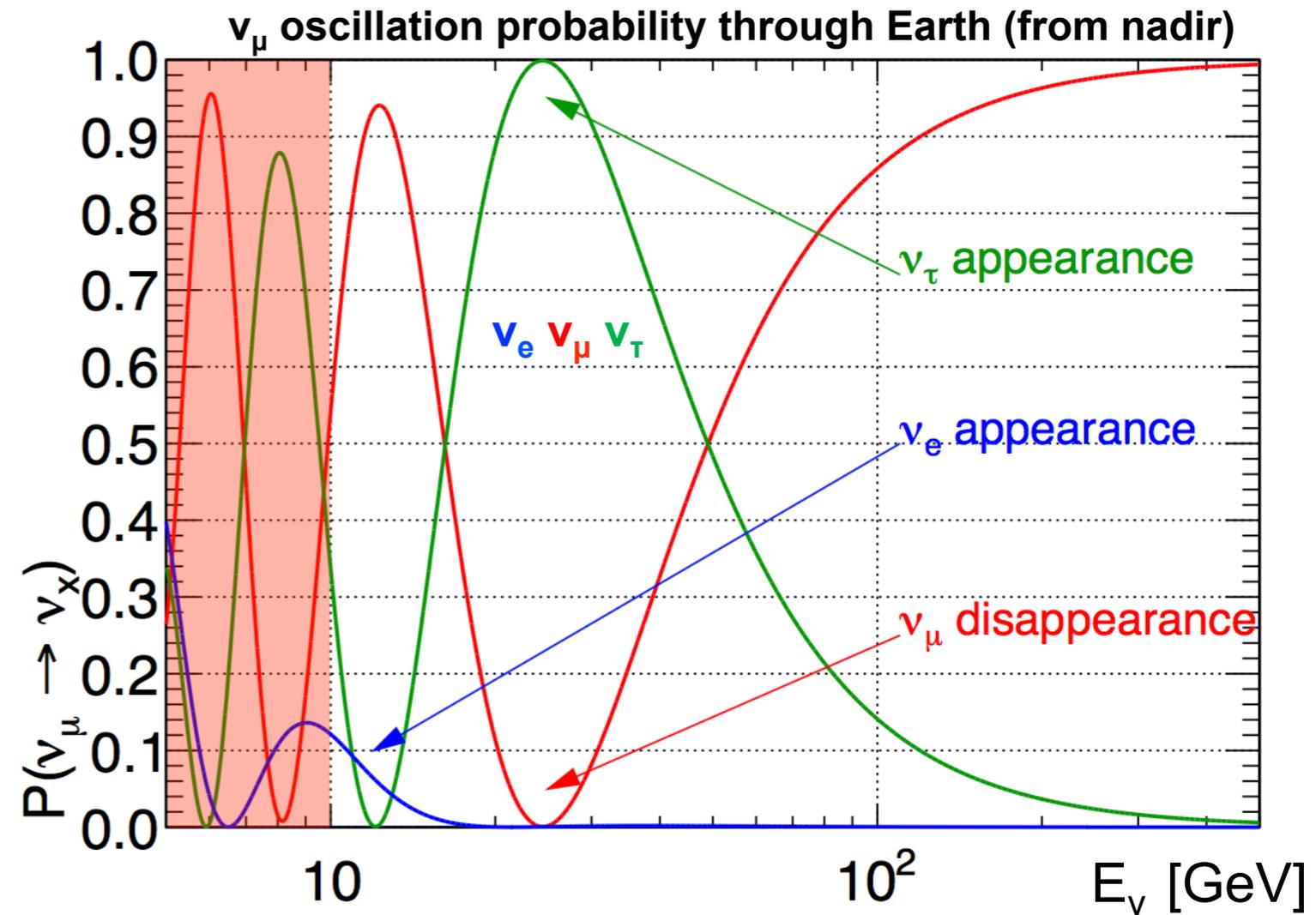


- Neutrino mixing matrix (PMNS) is unitary in standard oscillation picture
- New physics
  - Additional (sterile?) states implies 3x3 matrix is subset of full unitary matrix
  - New BSM interactions or couplings can manifest as non-unitarity
- Test unitarity by measuring 3x3 matrix elements
  - Tau-elements least well measured

# Atmospheric Neutrino Oscillation



IceCube-DeepCore energy  
sensitivity starts 5-10 GeV

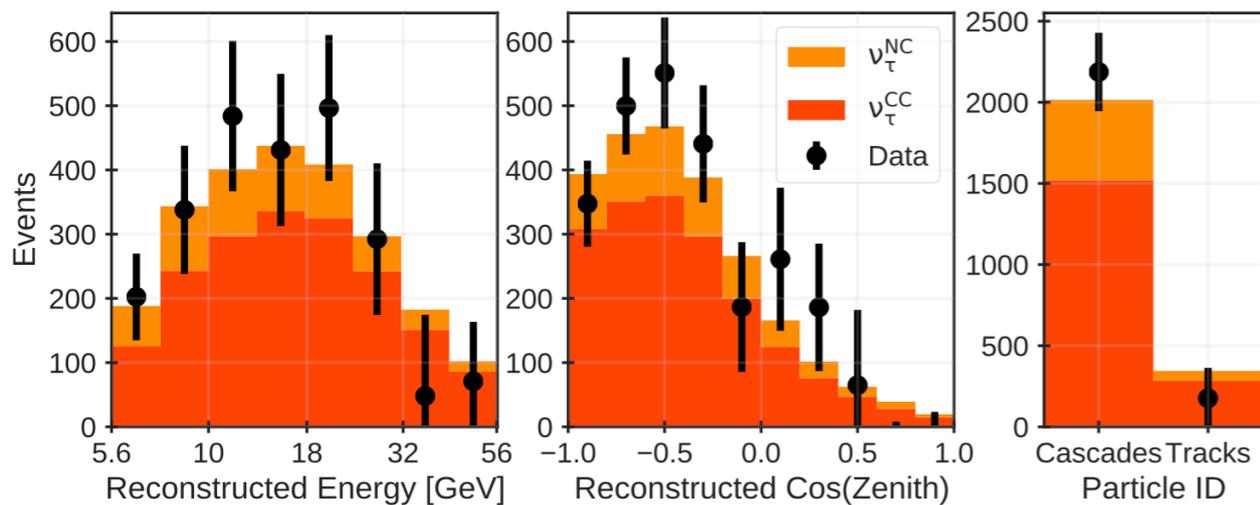


$$P(\nu_\mu \rightarrow \nu_\mu) \propto \sin^2(\theta_{23}) \sin^2\left(\frac{\Delta m_{32}^2 L}{E}\right)$$

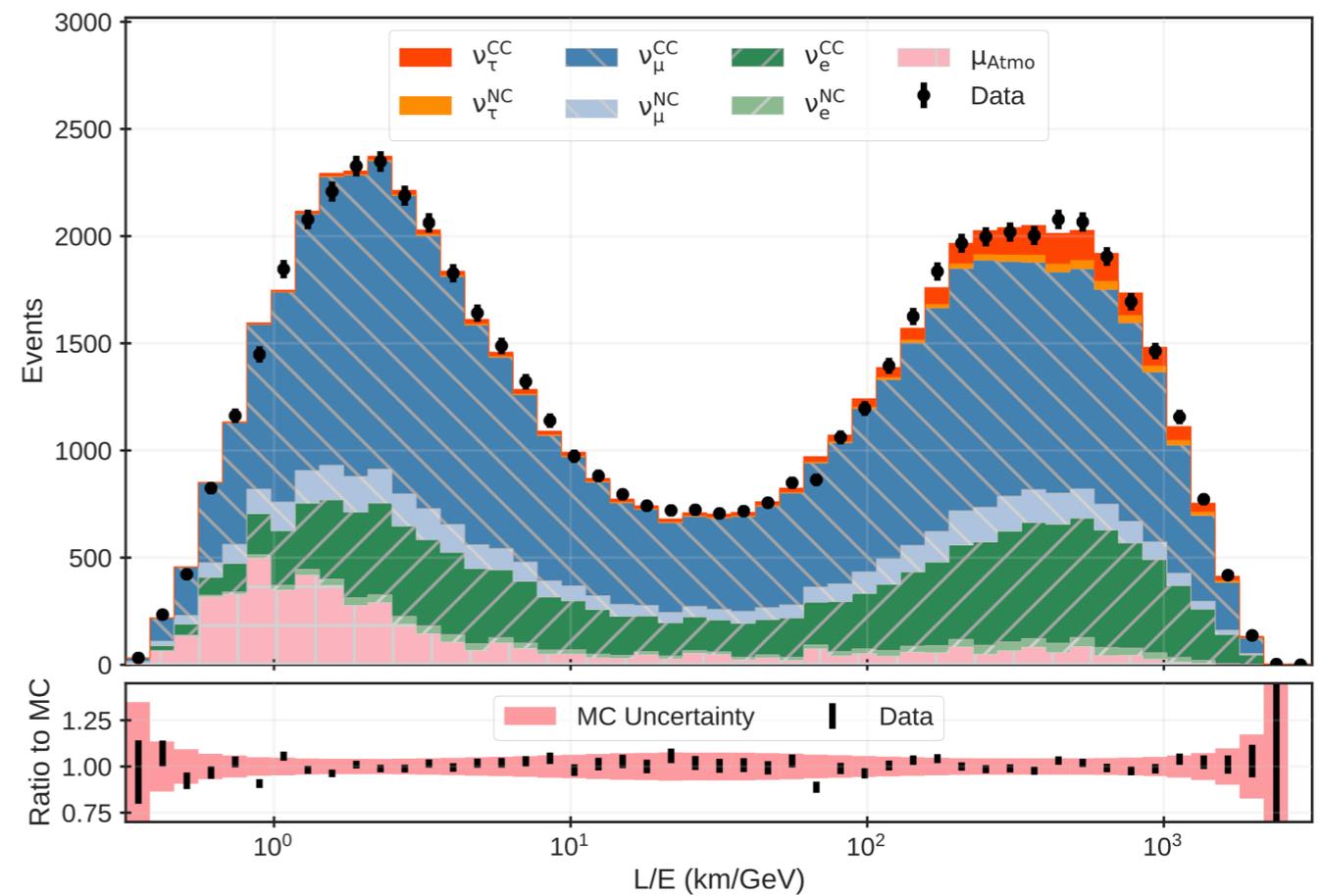
$L$  = travel length  
 $E$  = energy

# DeepCore $\nu_\tau$ appearance results

- 2 measurements performed with 3 years of DeepCore data

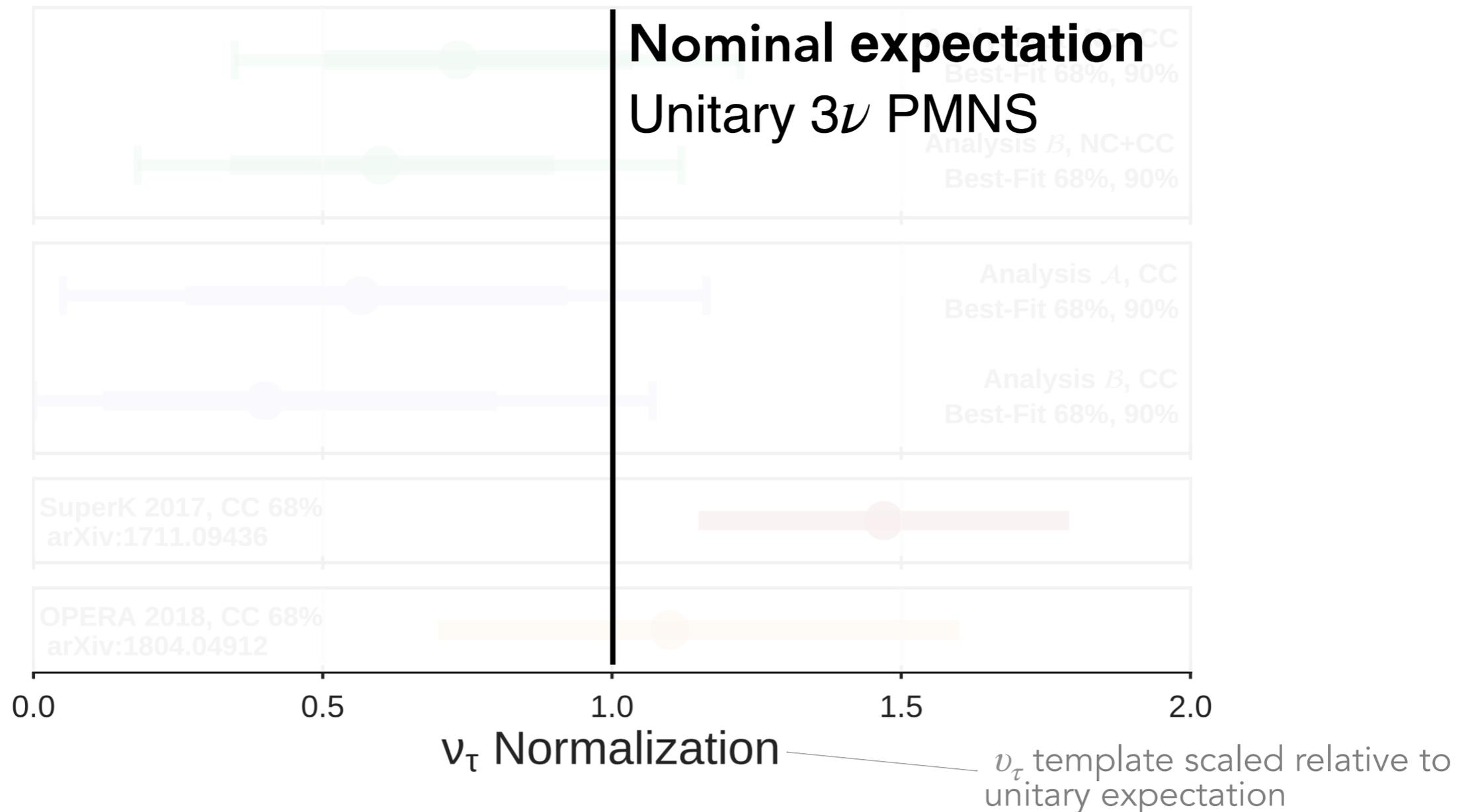


**Data fit in [energy, cos(zenith), PID] space**  
Searching for 3D distortions (shape-only)



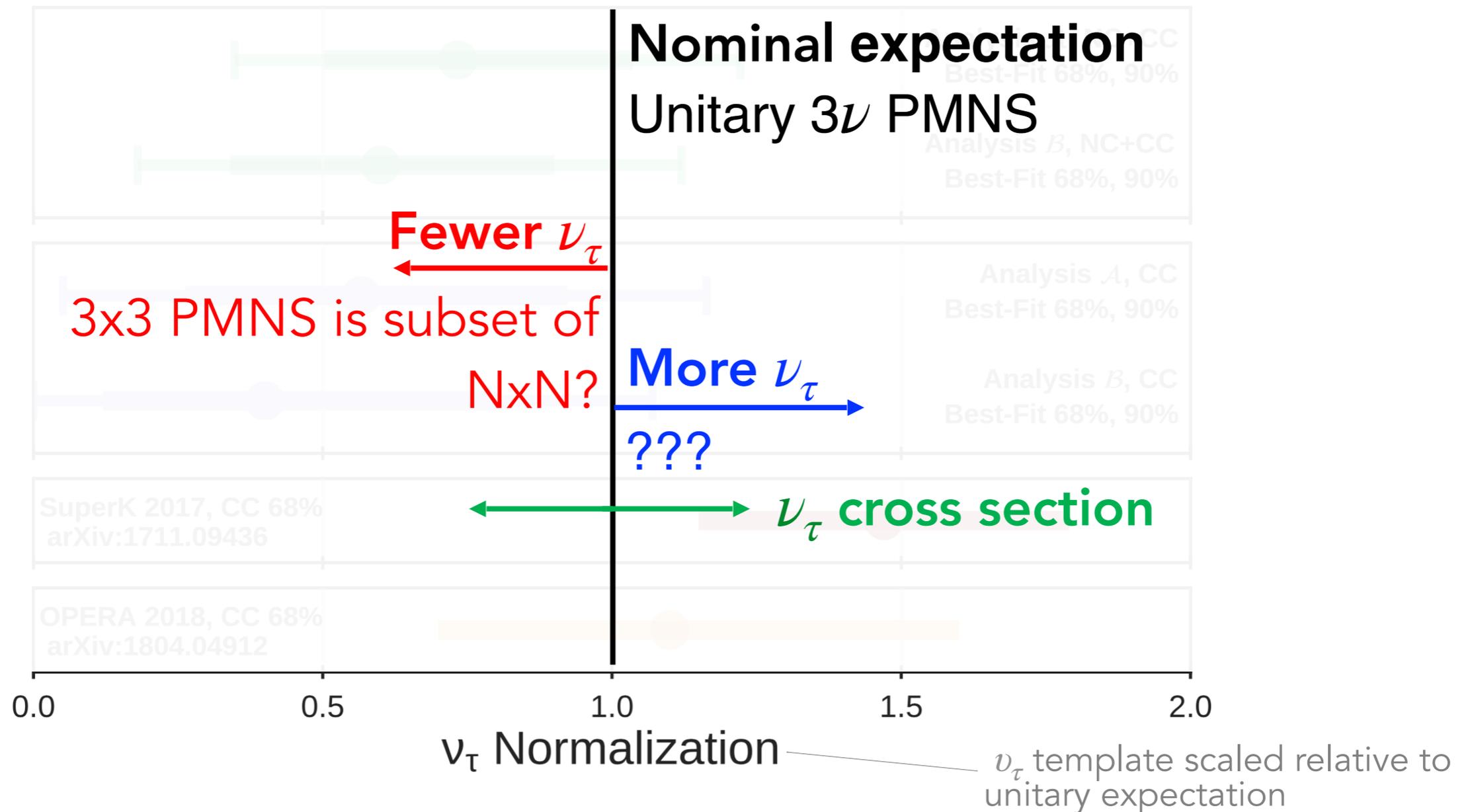
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# DeepCore $\nu_\tau$ appearance results

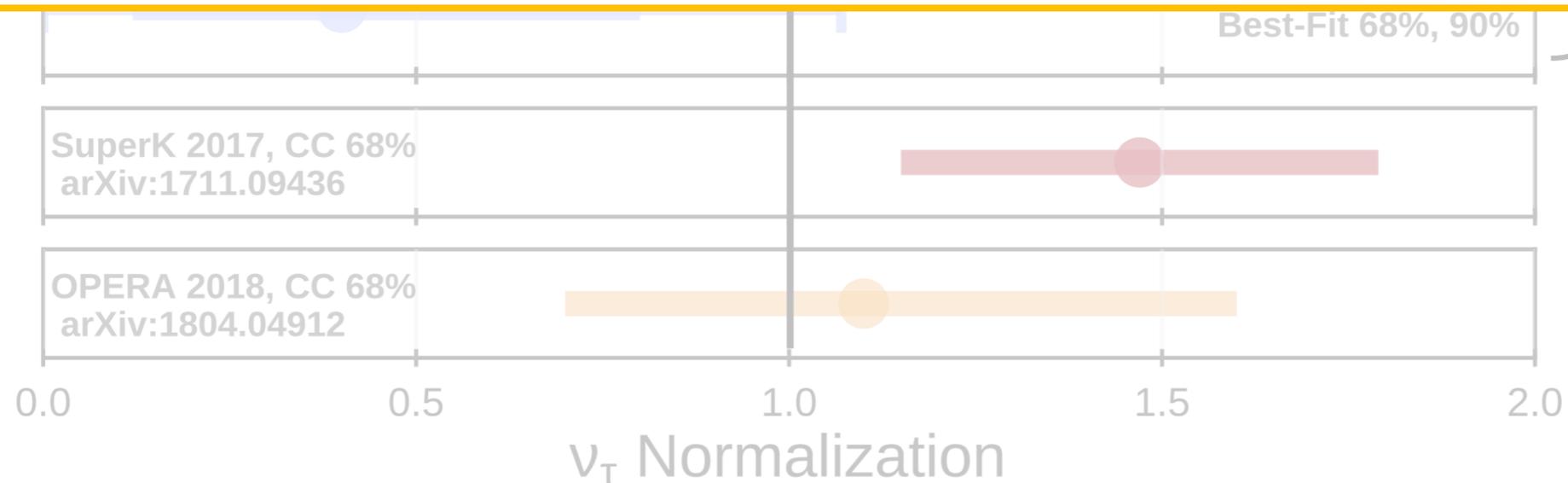
- 2 measurements performed with 3 years of DeepCore data

## Take away message

- World-leading  $\nu_\tau$  appearance measurement precision @ DeepCore
- Results consistent with standard oscillation picture

## Coming soon

New measurement with >5x statistics



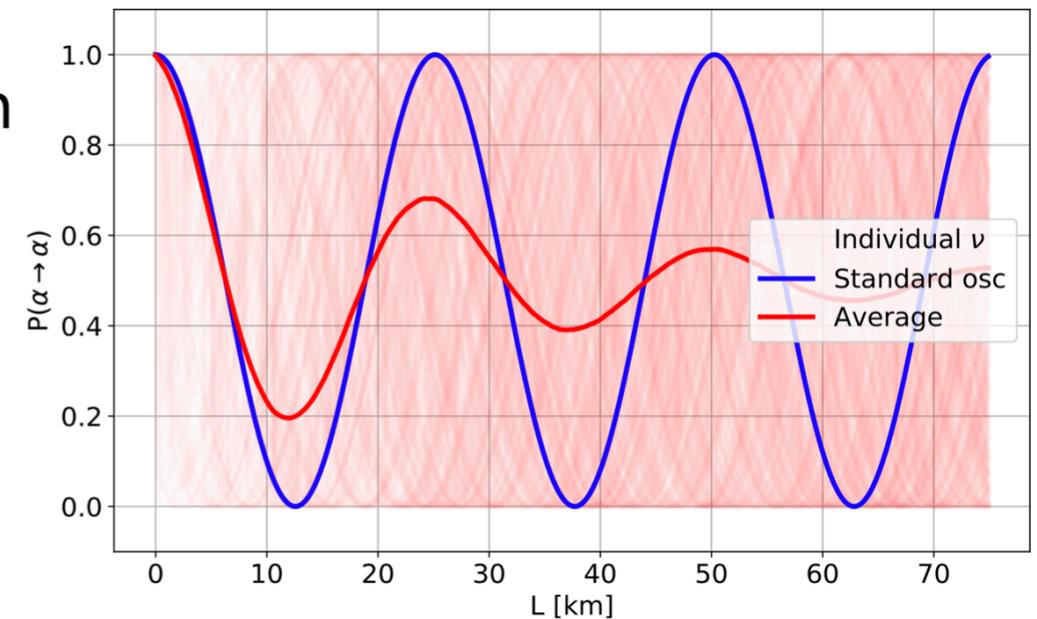
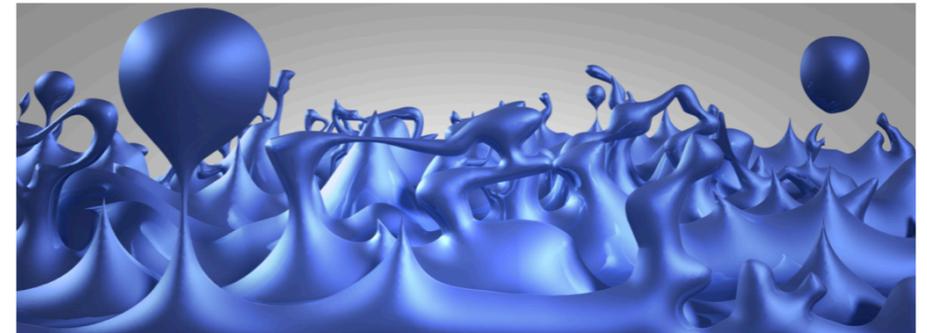
DeepCore results  
(Consistent)

# Inspired by Gravity

## Environmentally-induced neutrino decoherence

- What if a neutrino experiences perturbations from the environment as it propagates?
  - e.g. fluctuating space-time (quantum gravity)
- If perturbations are stochastic:
  - wavefunction phase shift
  - neutrino population loses coherence
  - damping of oscillation probability

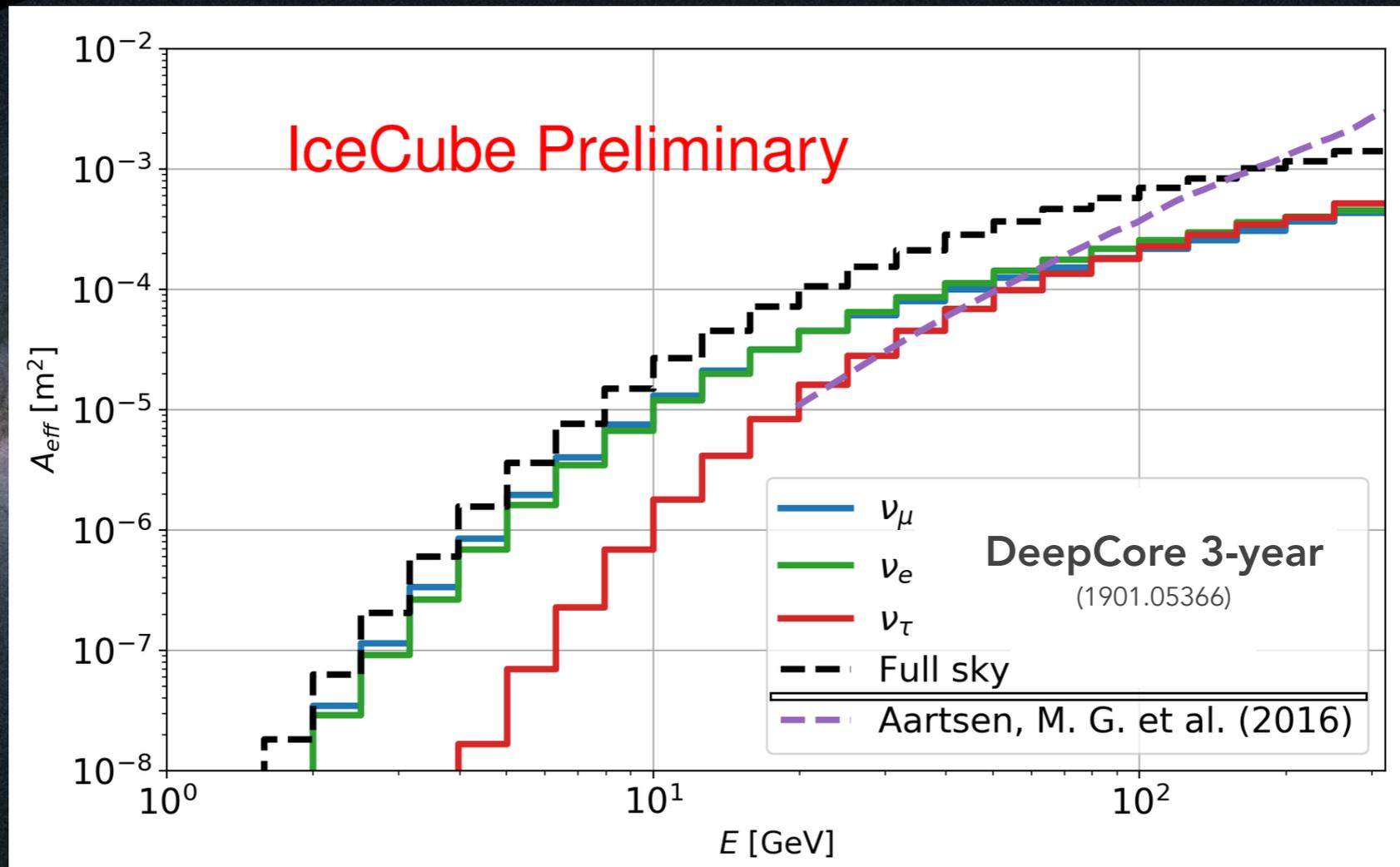
Credit: [Chandra](#)



\*T. Stuttard, Particle Physics with Neutrino Telescope 2019

# Neutrinos + Astronomy

Other higher-energy IceCube analyses begin ~100 GeV



10 MeV

100 MeV

1 GeV

10 GeV

100 GeV

1 TeV

10 TeV

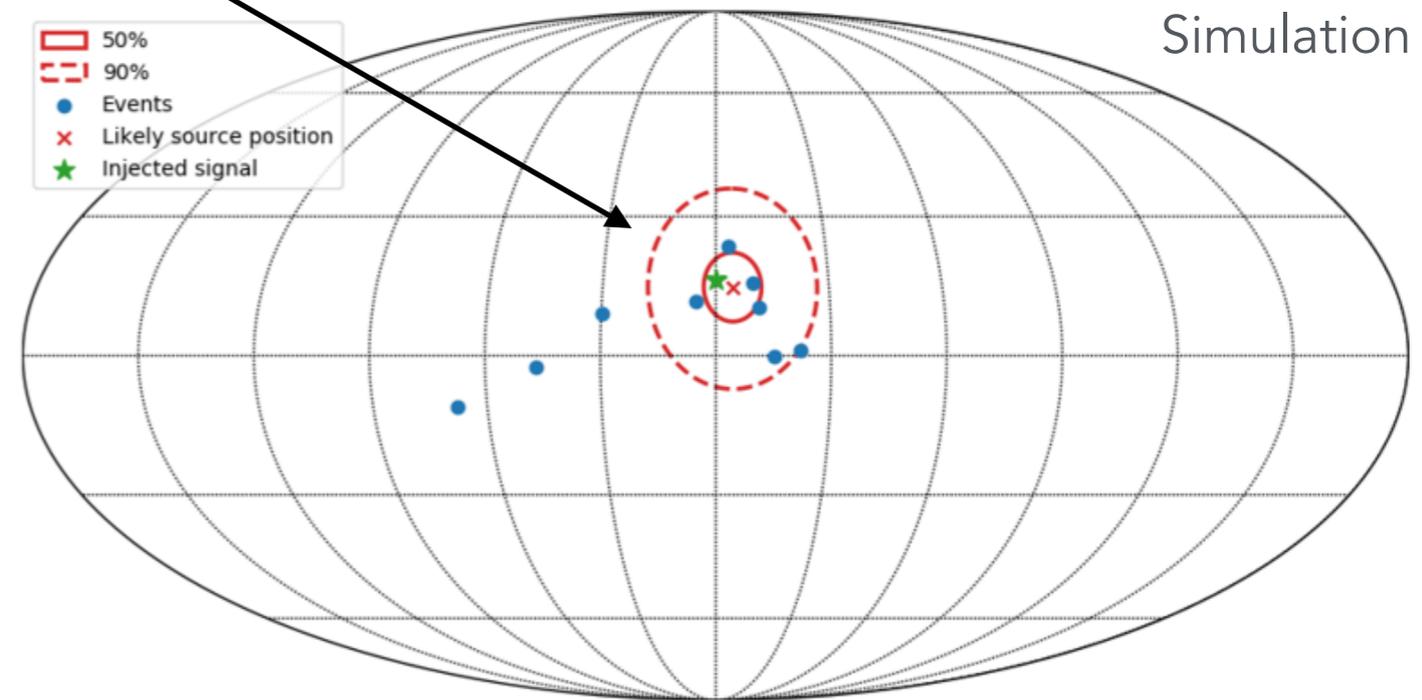
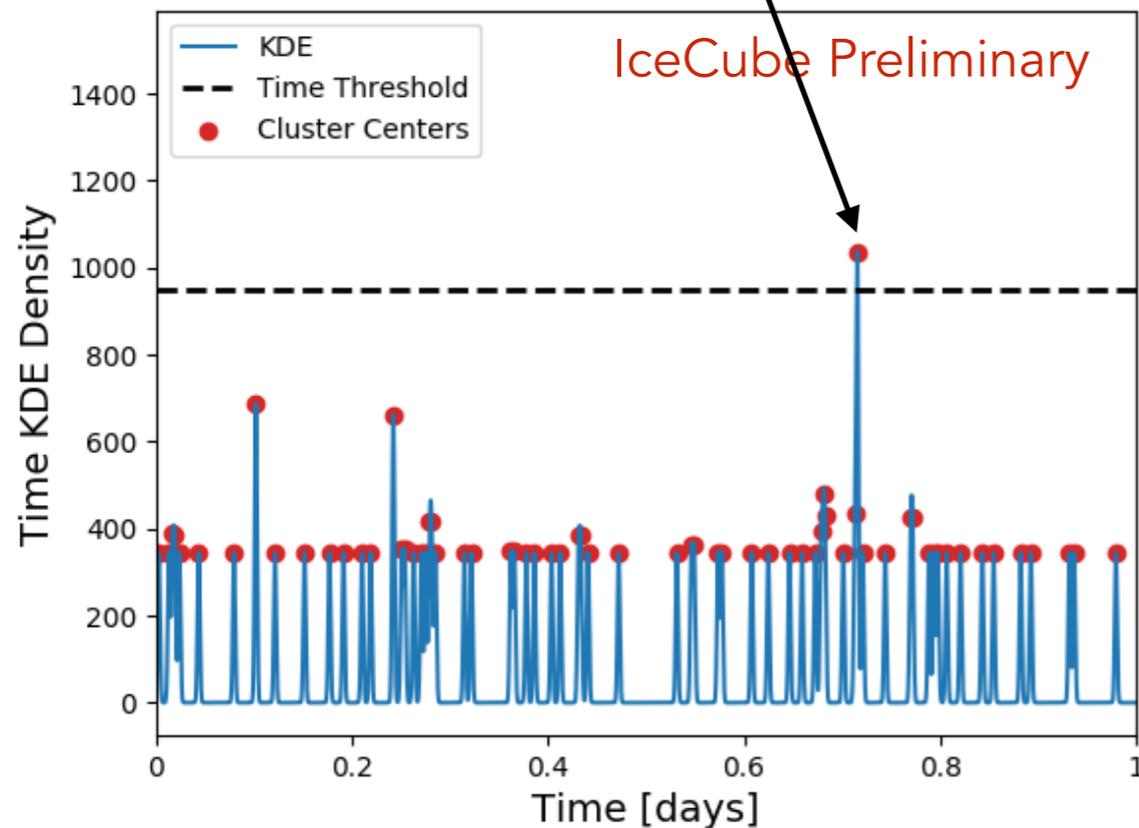
10 PeV

DeepCore

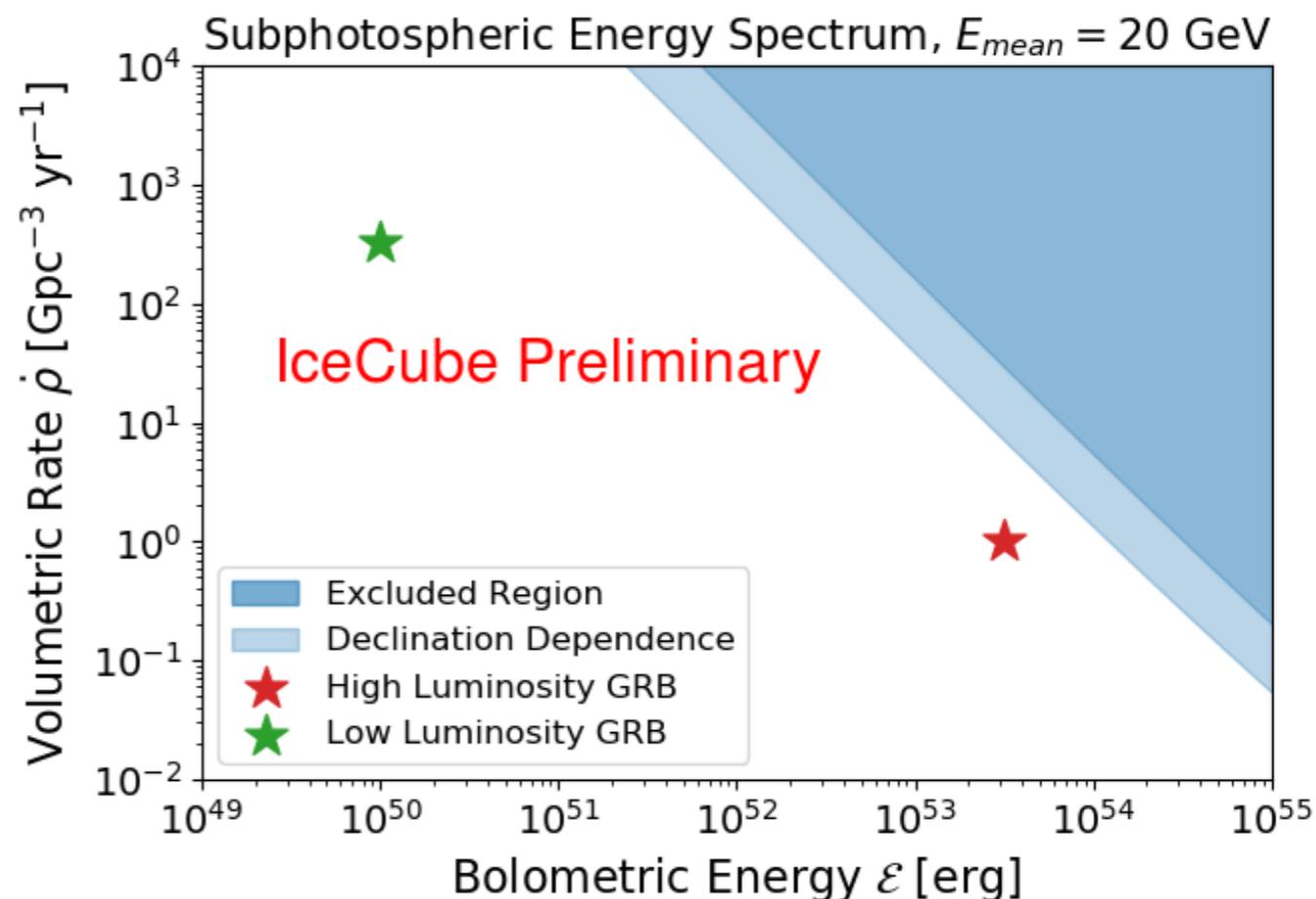
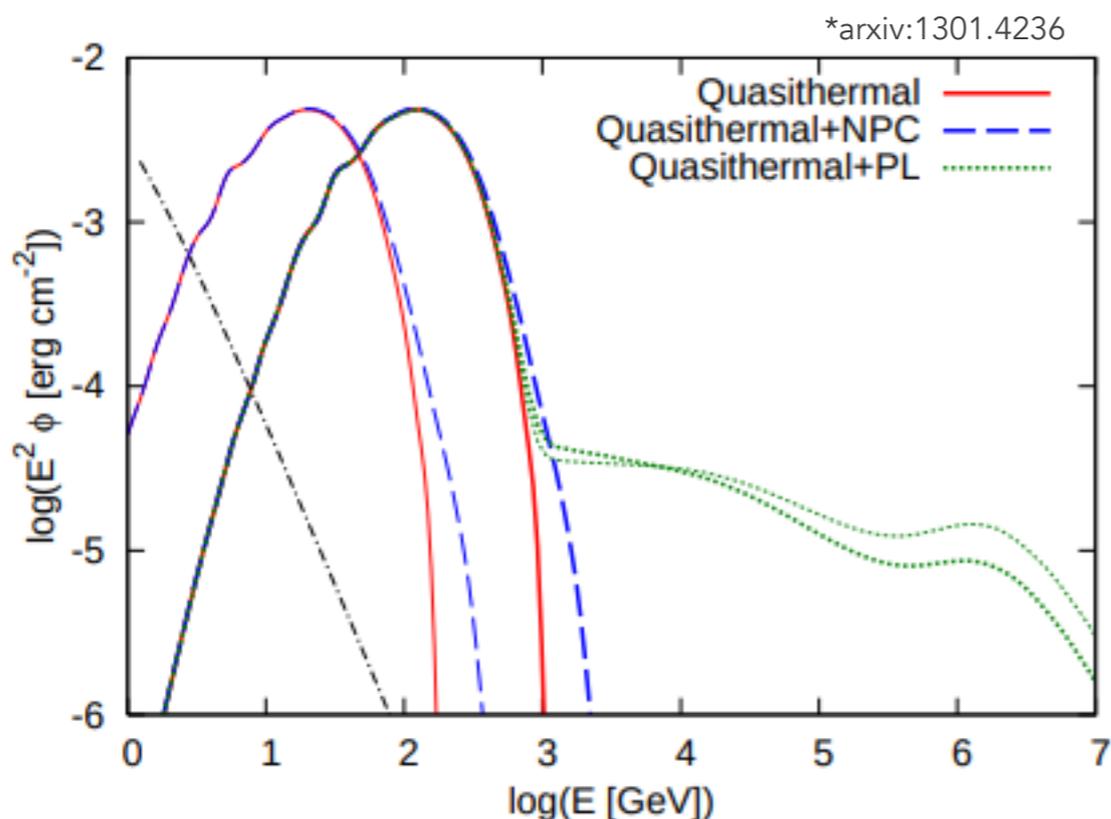
IceCube

# 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



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

# IceCube Future

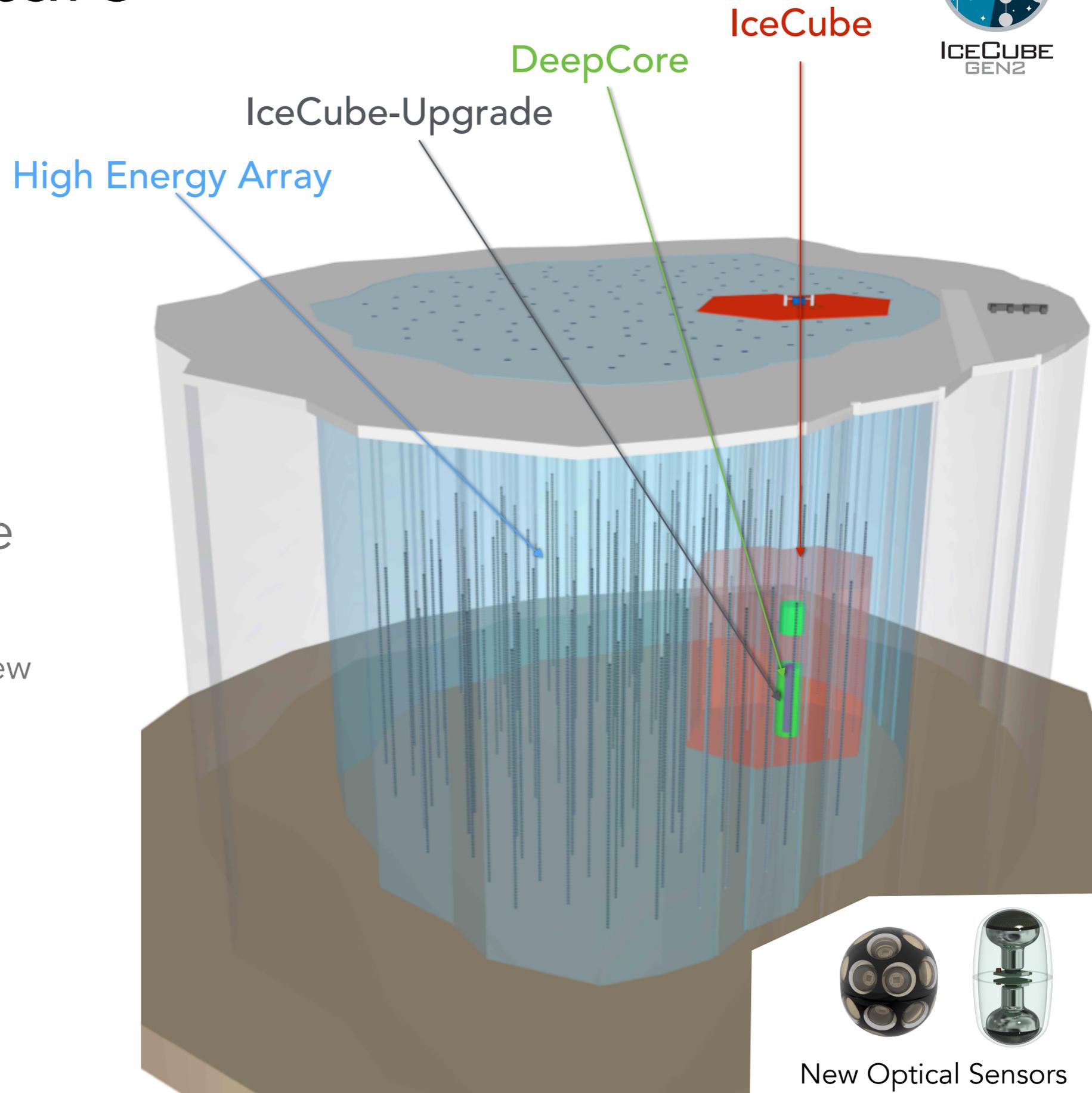


- Expand

- Leading results in 2019
- Neutrino Oscillations
- Dark Matter

- IceCube-Upgrade

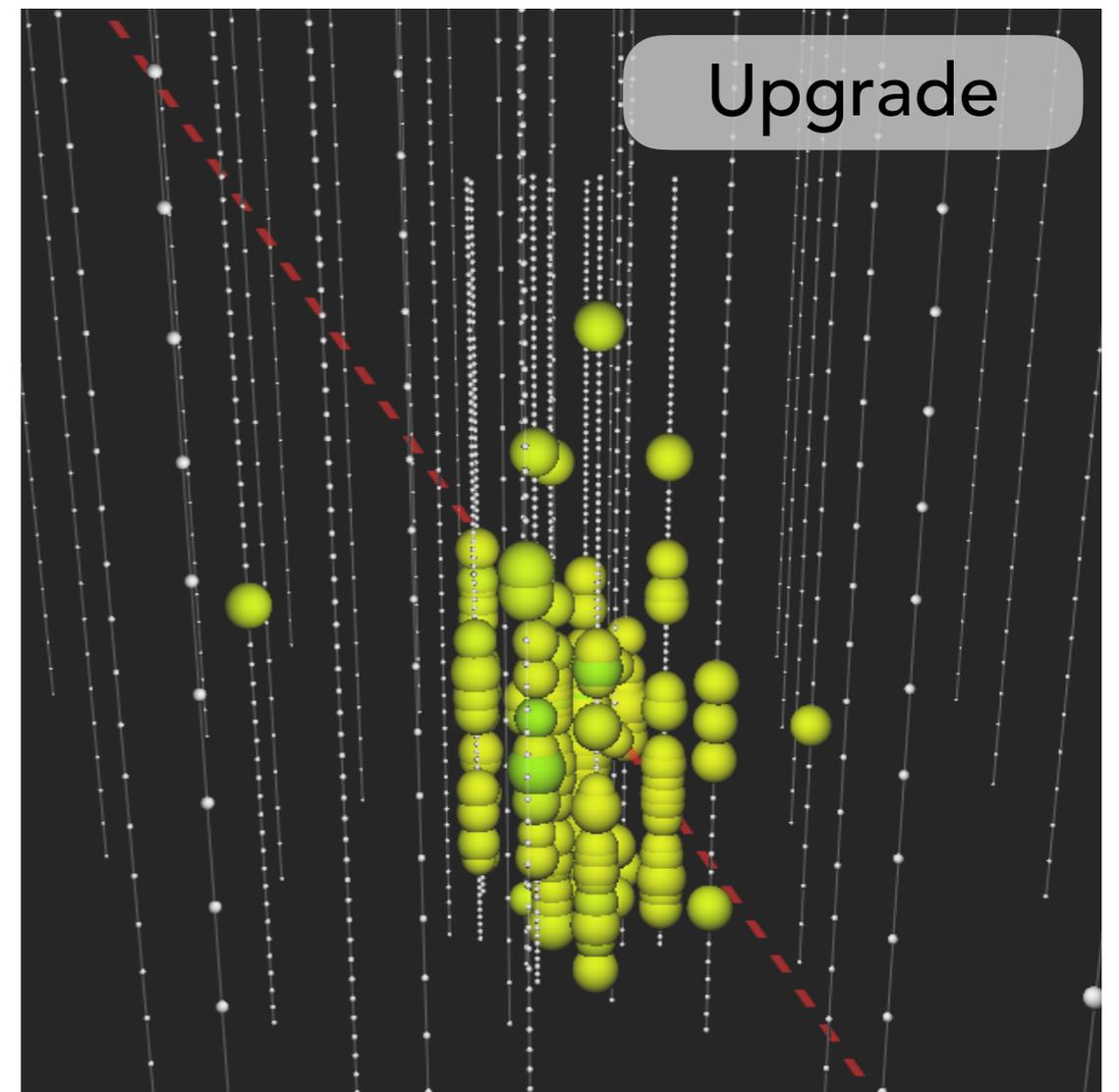
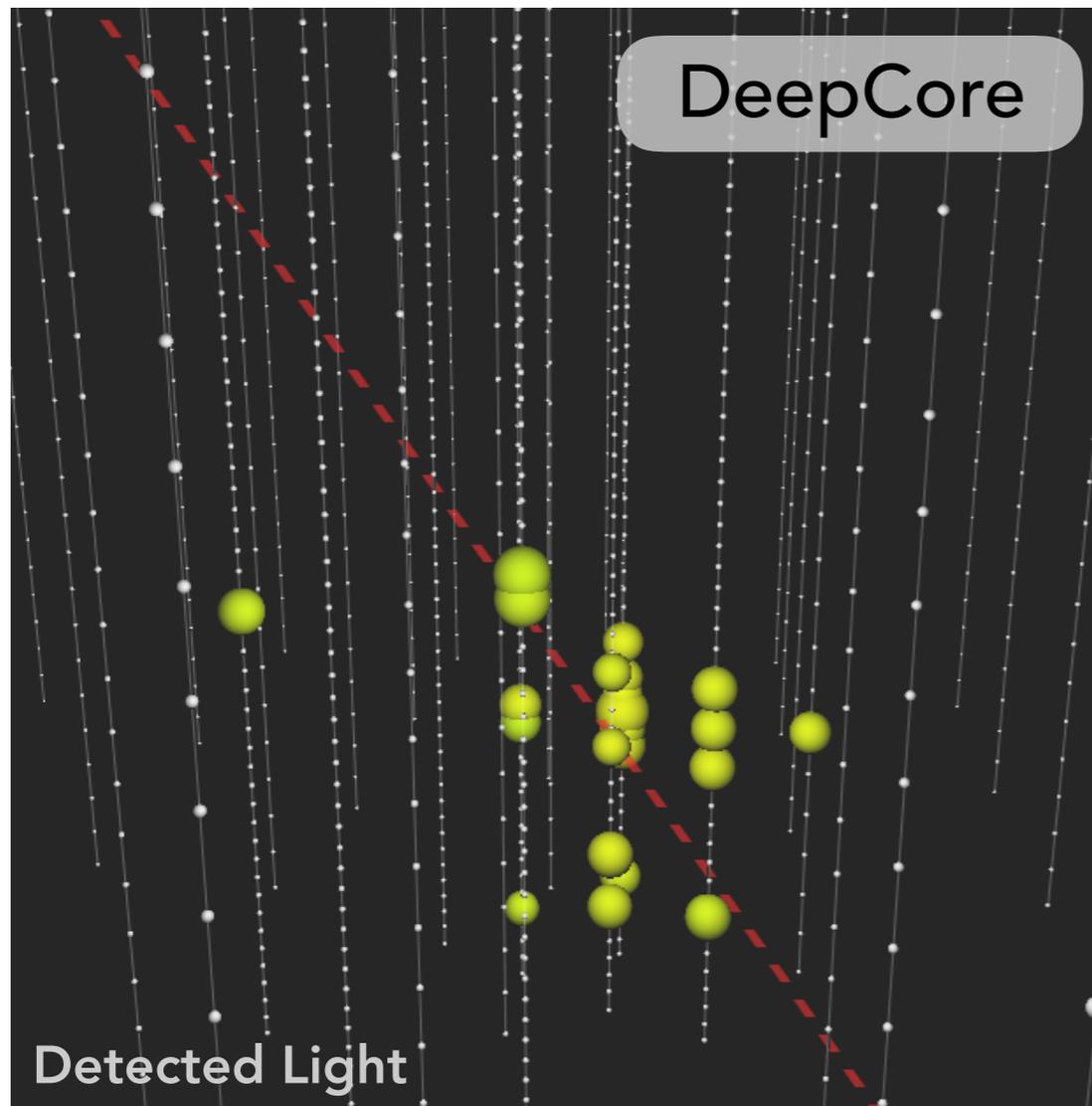
- Deploying in 2022/23
- 10x improvement for new energy region



New Optical Sensors

# IceCube-Upgrade

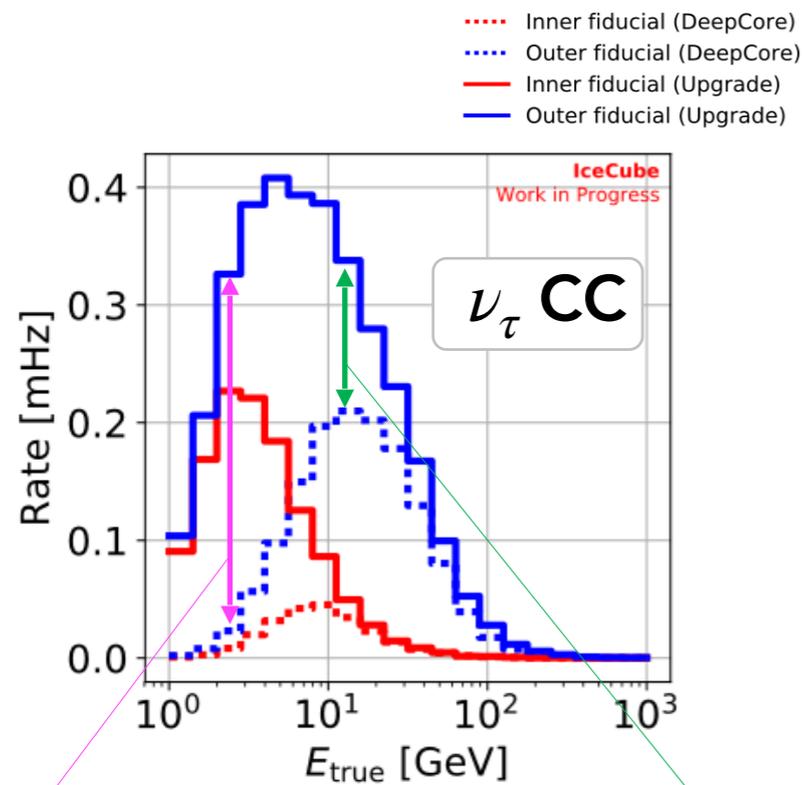
- Dense instrumentation within inner core



30 GeV  $\nu_{\mu}$

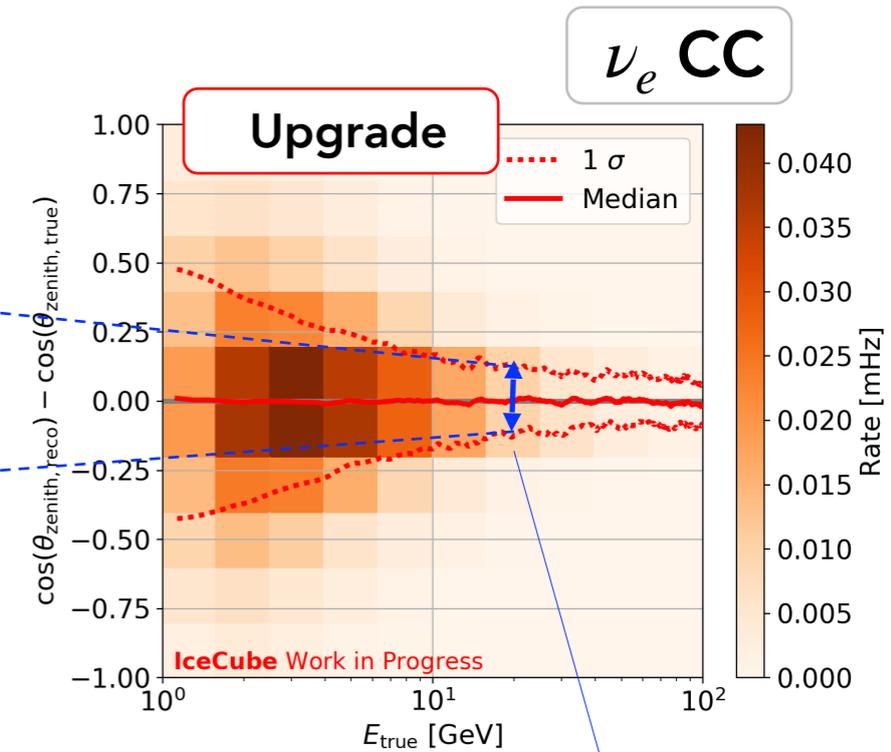
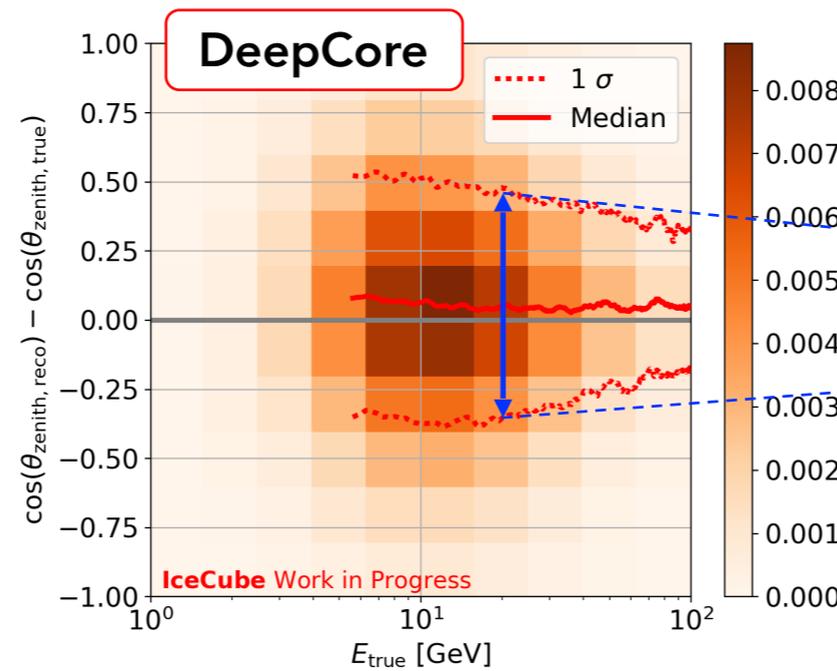
# Upgrade Performance

- Major improvement in detection rate and energy/direction resolution



Huge increase in  $<10$  GeV  $\nu$  rate

Enhanced rate for all oscillation energies

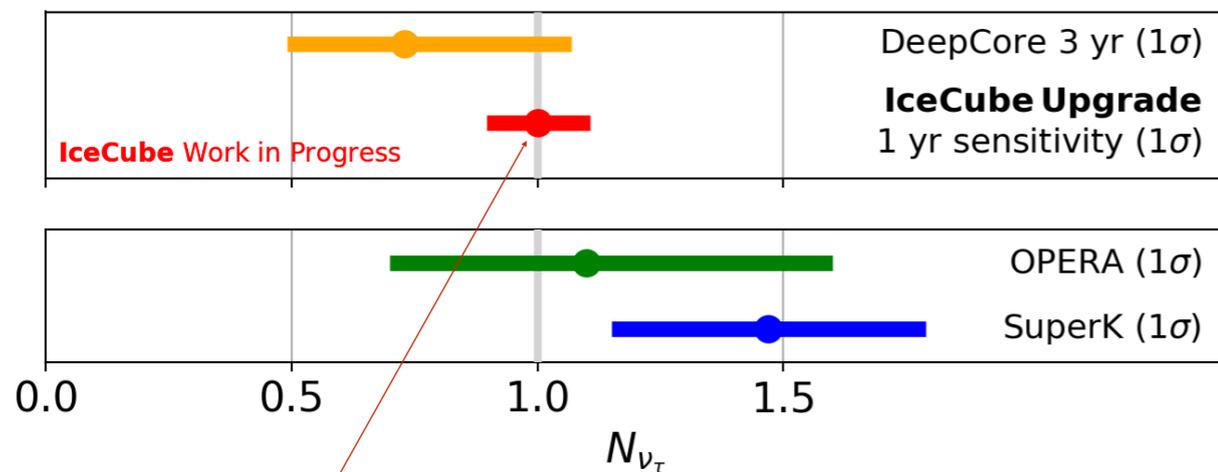


3x improvement @  $\nu_\tau$  appearance energies

# Upgrade & Oscillations

- $\nu_\tau$  appearance is Upgrade primary physics goal
- Broad oscillation program

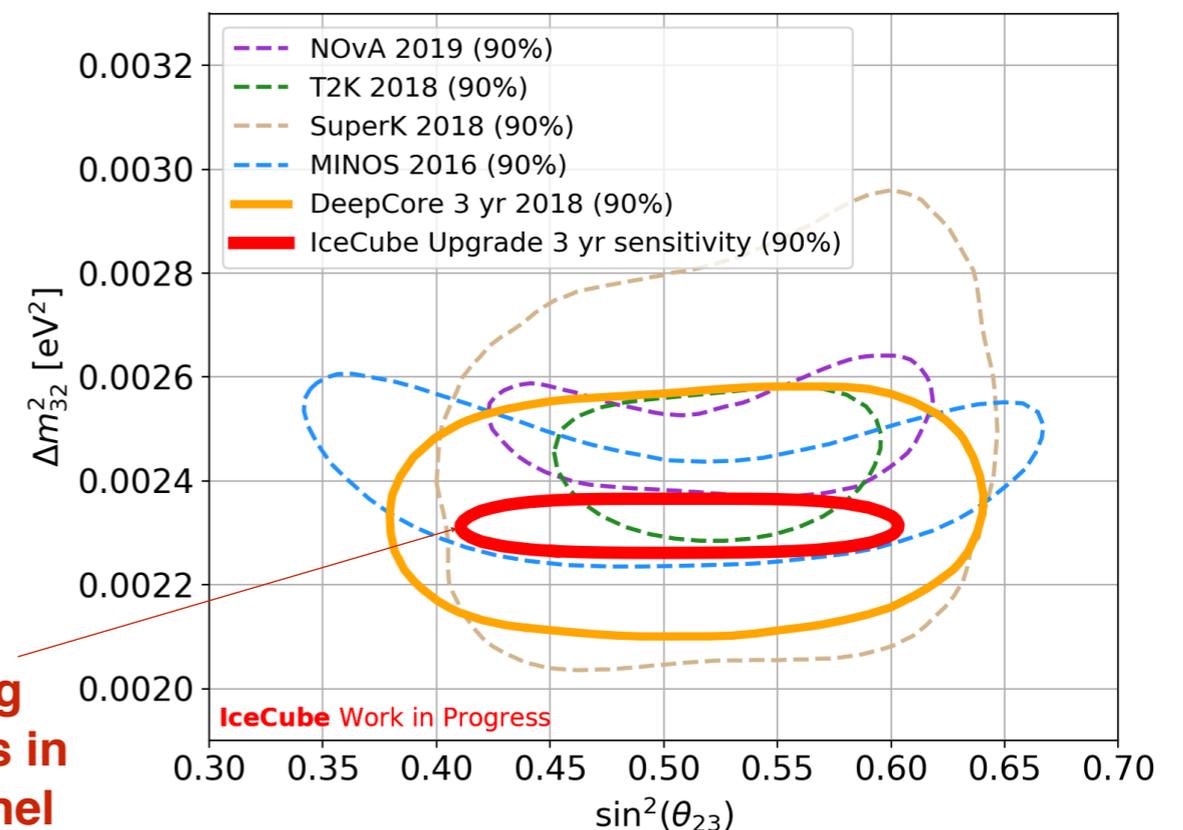
$\nu_\tau$  appearance sensitivity (1 yr)



10% precision after 1 year  
(6% after 3 years)

Competitive with long  
baseline experiments in  
disappearance channel

$\nu_\mu$  disappearance sensitivity (3 yr)



# Conclusion

- Testing PMNS unitarity offers a powerful, model-independent search for BSM physics
- DeepCore offers exciting opportunity to probe astrophysics at new energy regimes
- Deploying in 2022/23, the IceCube Upgrade can achieve 10% precision in tau-neutrino sector ( $|U_{\tau 3}|$ ) after 1 year of operation

# Backup

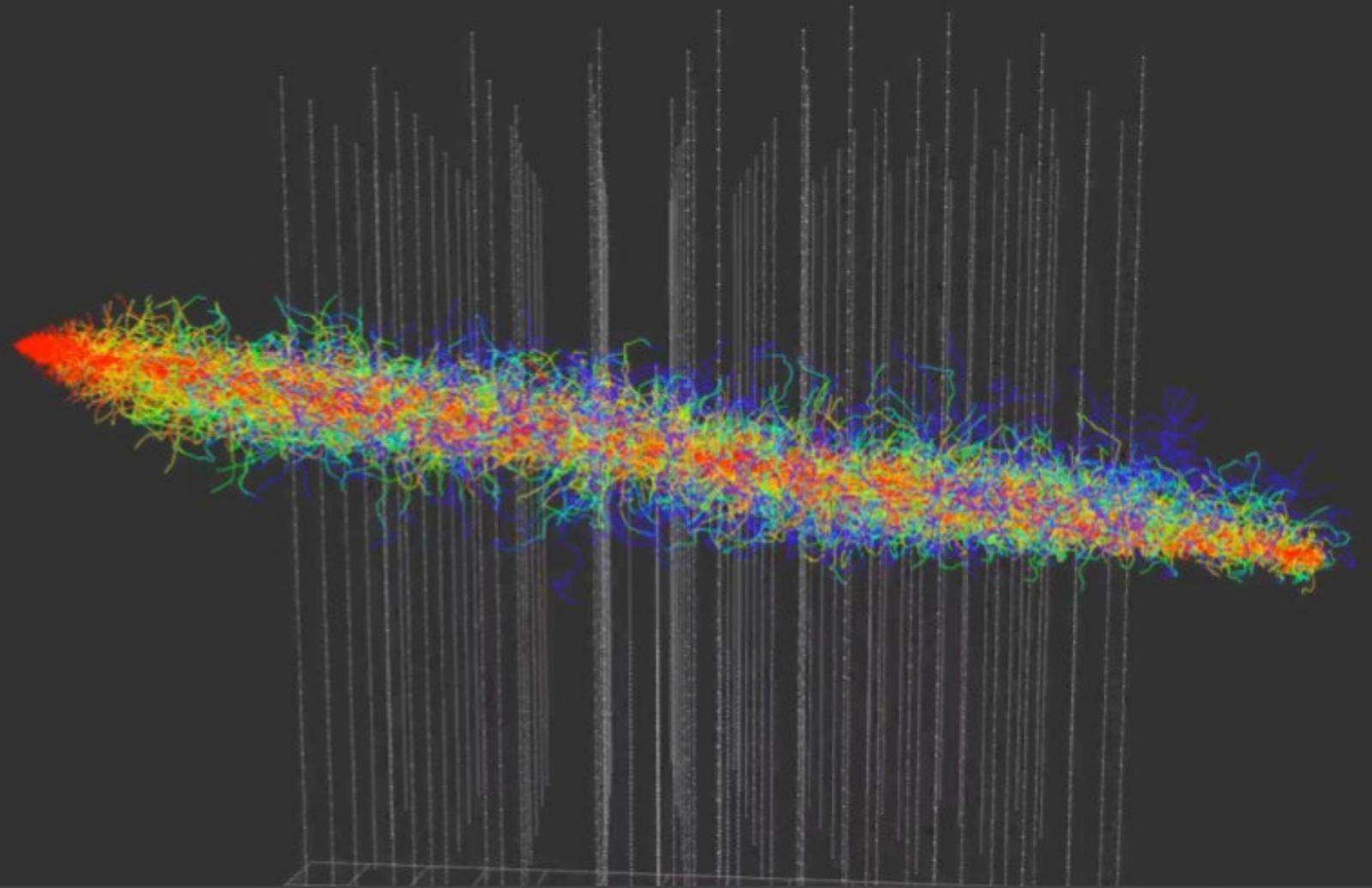
# Track topology

(e.g. induced by  
muon neutrino)

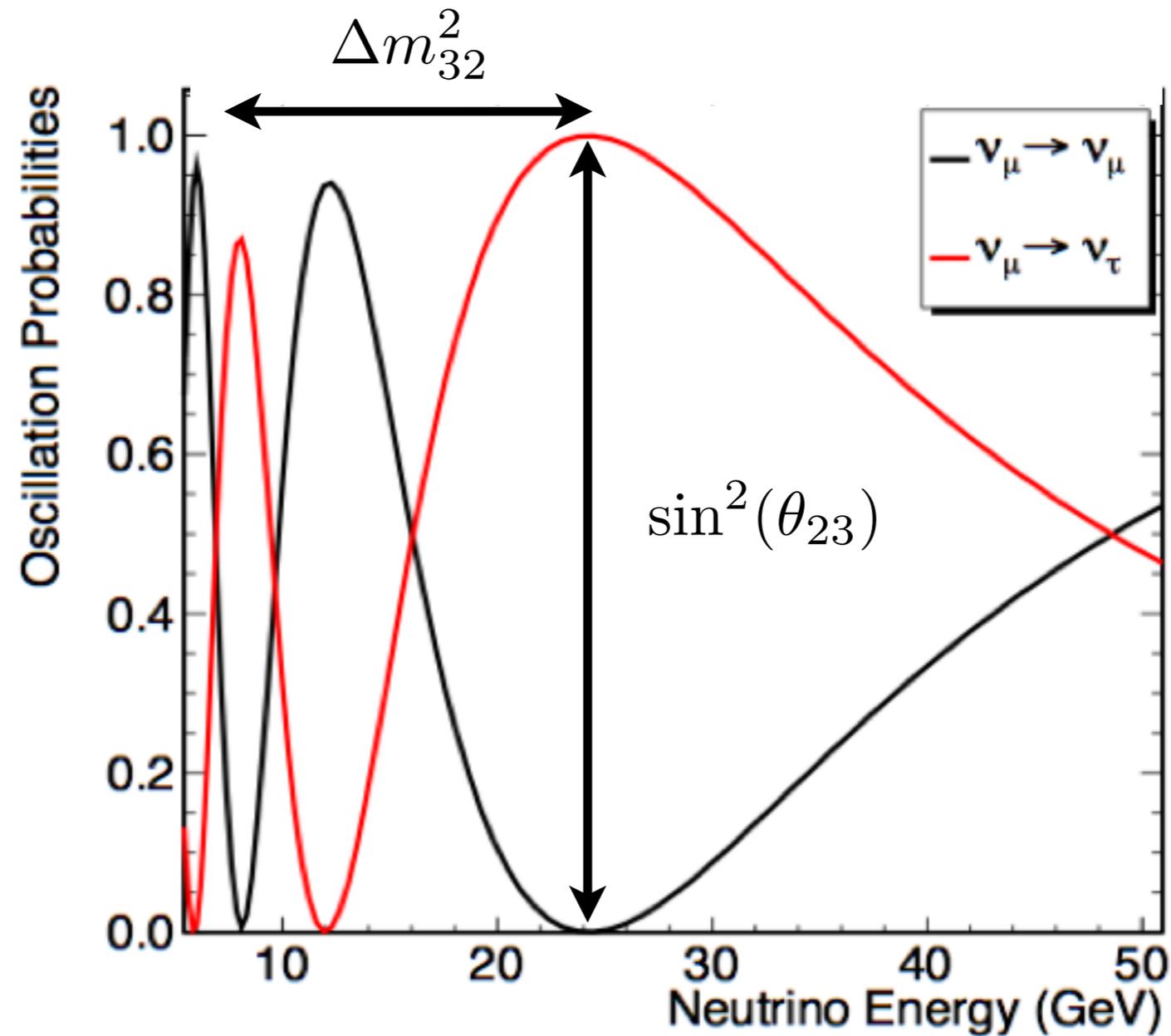
## Good pointing

*IceCube*: lower bound on  
energy for through-going  
events

*DeepCore*: well  
contained and provide  
good energy via muon  
track length



# Generic Oscillation (Atm. Disappearance)



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

$L$  = travel length

$E$  = energy

# 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.  $\nu$  events/year

