IceCube Neutrino Observatory

- A very biased overview

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on behalf of the IceCube Collaboration
LHC Days 2024, Hvar, Croatia

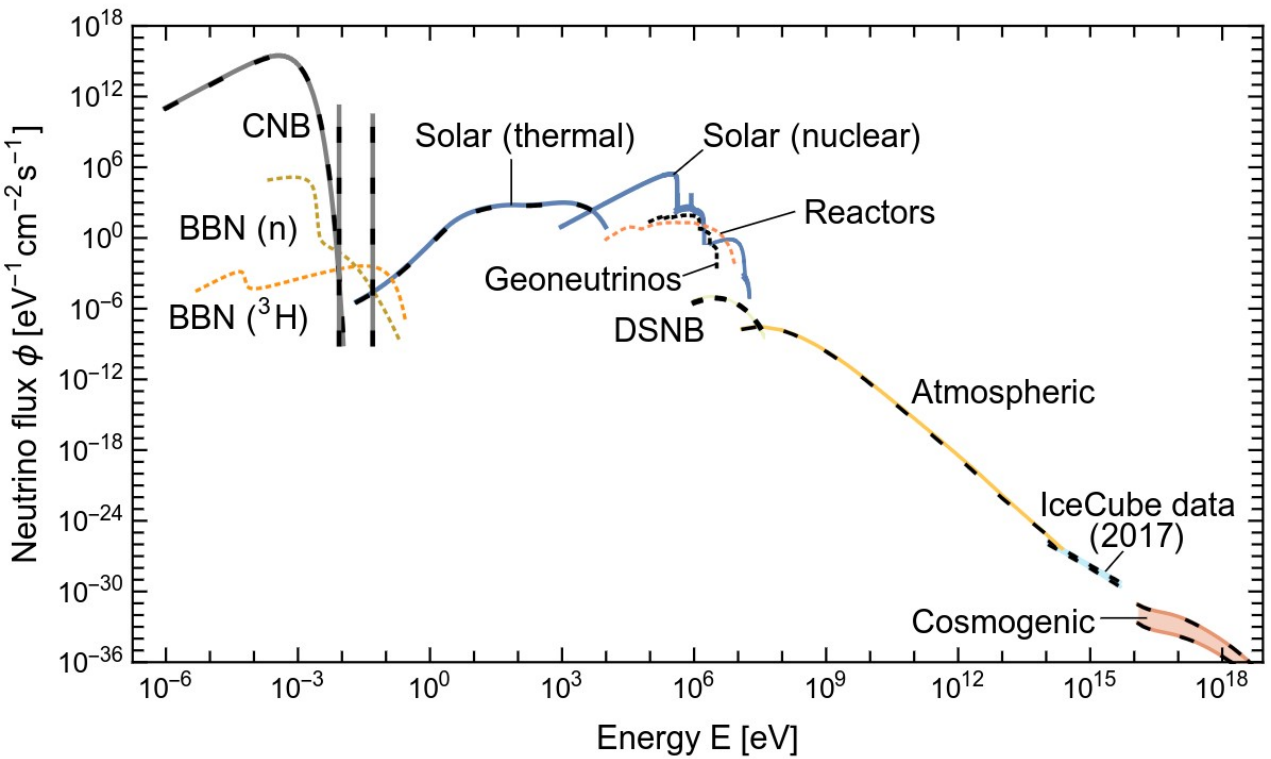
Technical University of Munich

IceCube Neutrino Observatory

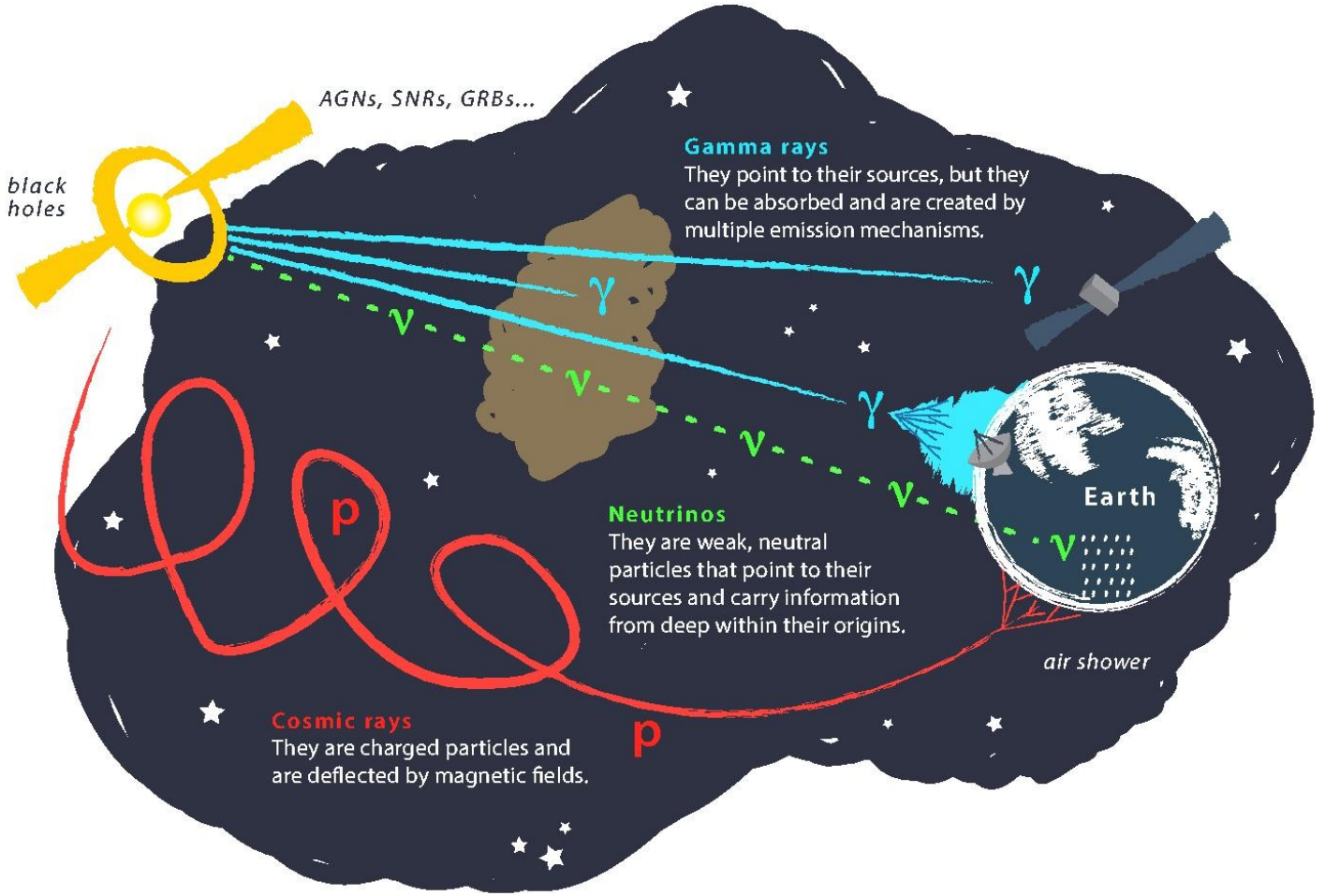
Neutrinos in the Universe

- Neutrinos are one of the most abundant particles in the Universe
- Spectrum covering an extremely wide range of energies
- Require enormous detectors to detect due to low cross-section and/or small fluxes

arXiv:2211.08641 [hep-ex]



Why neutrinos?

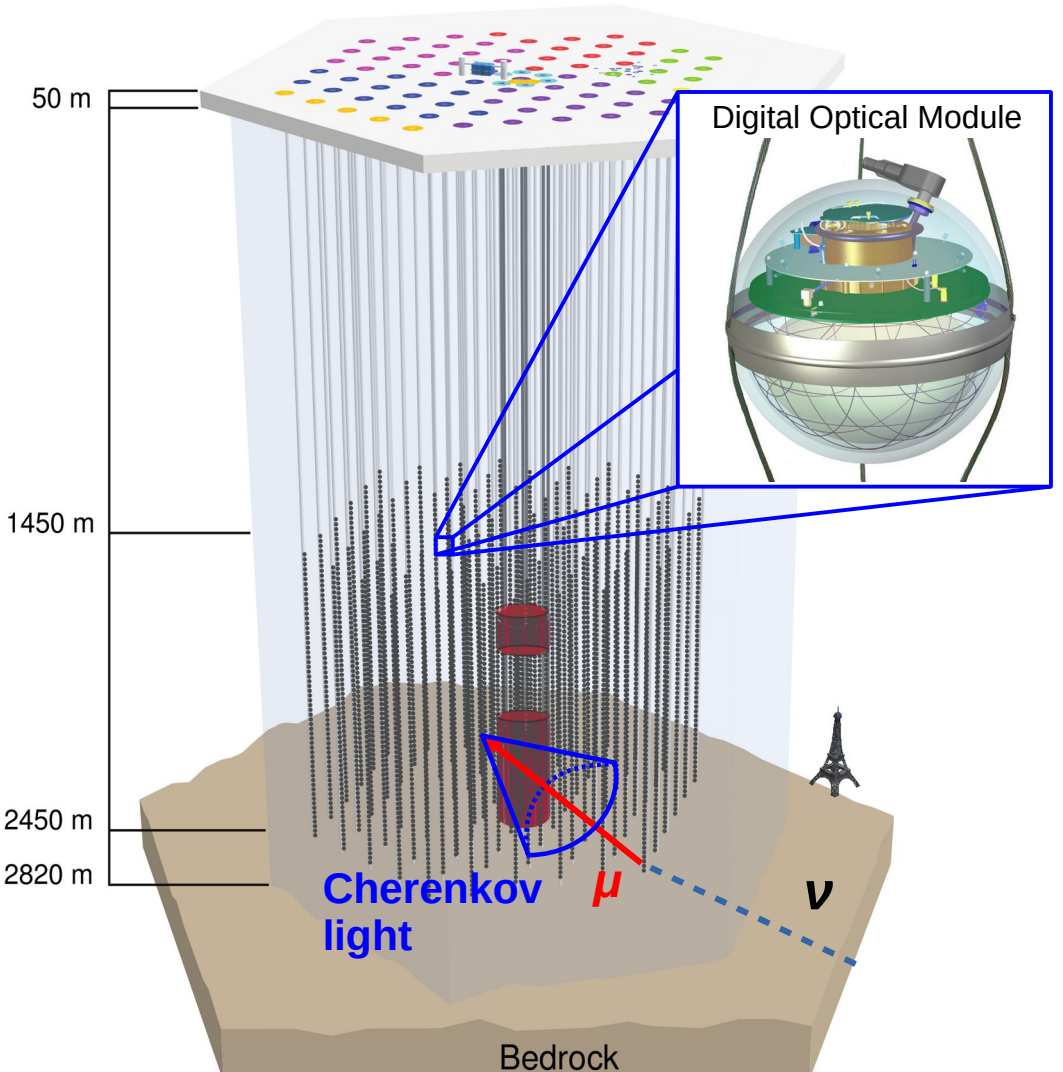


- Offers a unique way to probe the most extreme environments in the Universe!

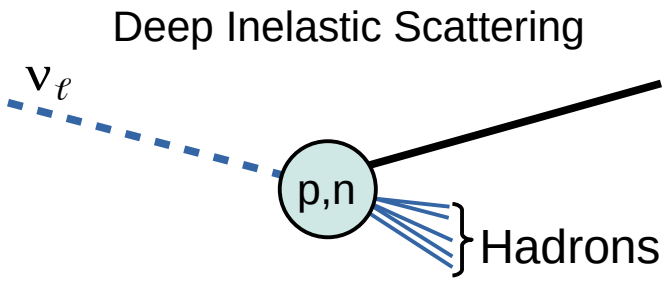
IceCube Neutrino Observatory

- IceCube detector:
  - Cherenkov neutrino detector at the South Pole
  - Ice as an optical detection medium
  - 5160 DOMs with 10” PMTs
- DeepCore sub-detector
  - central-bottom part of IceCube
  - the clearest ice
  - denser instrumentation

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



IceCube neutrinos



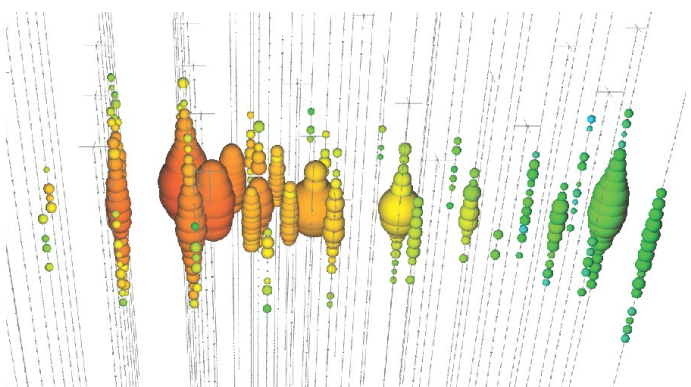
ℓ – charged current (CC) interaction

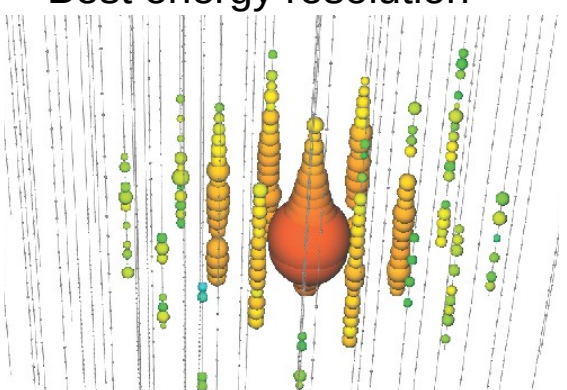
ν_ℓ – neutral current (NC) interaction

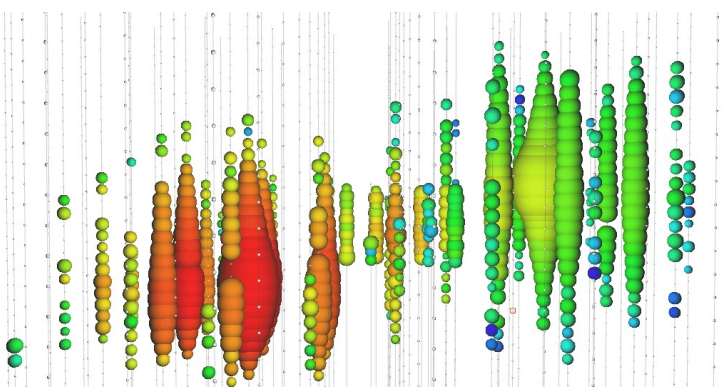
- Track-like: ν_μ CC
- Best pointing

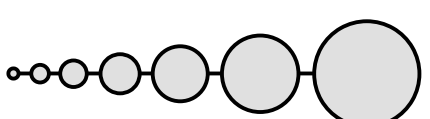
- Cascade-like: NC, CC of ν_e and ν_τ
- Best energy resolution

- Double-bang: ν_τ CC
- Unique to ν_τ



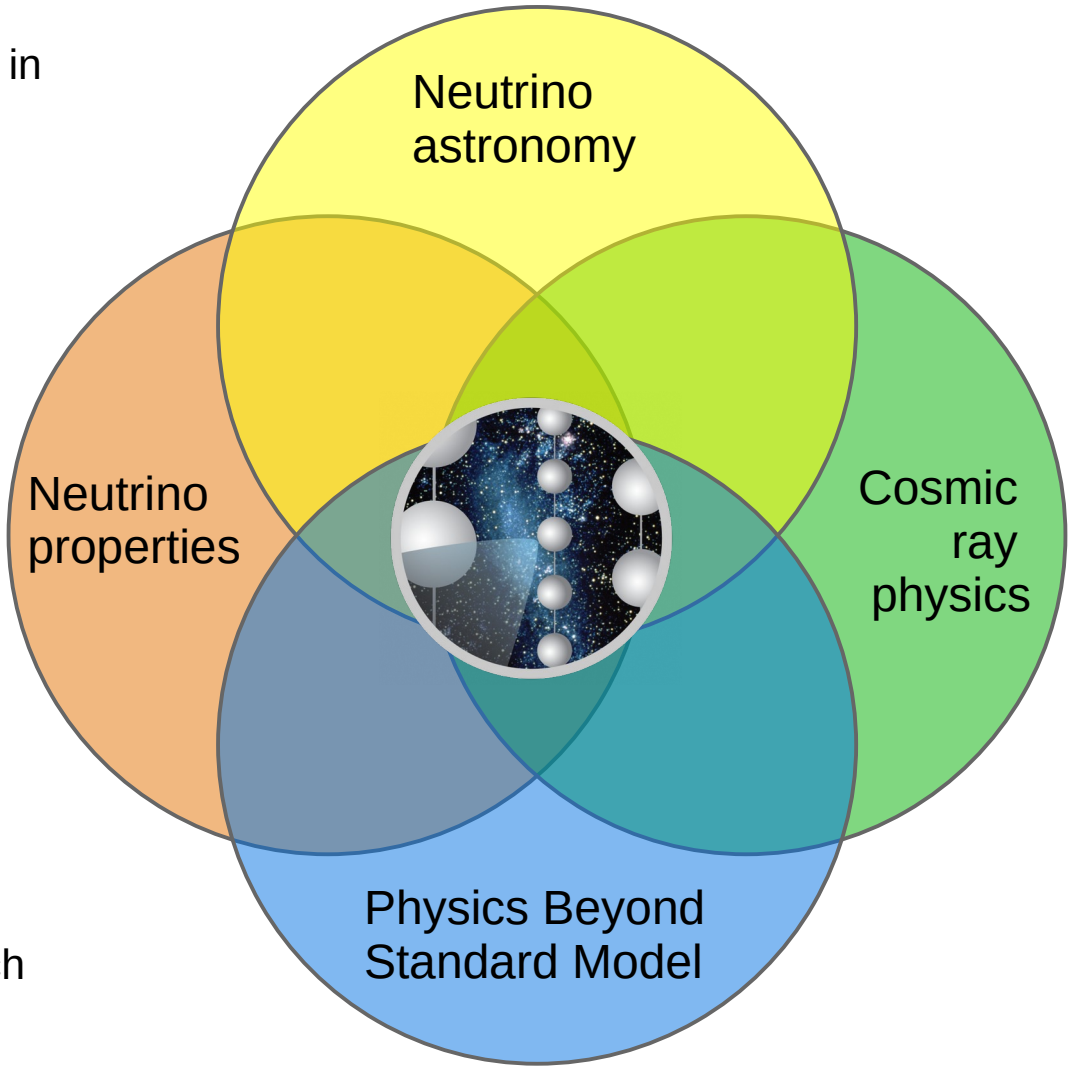




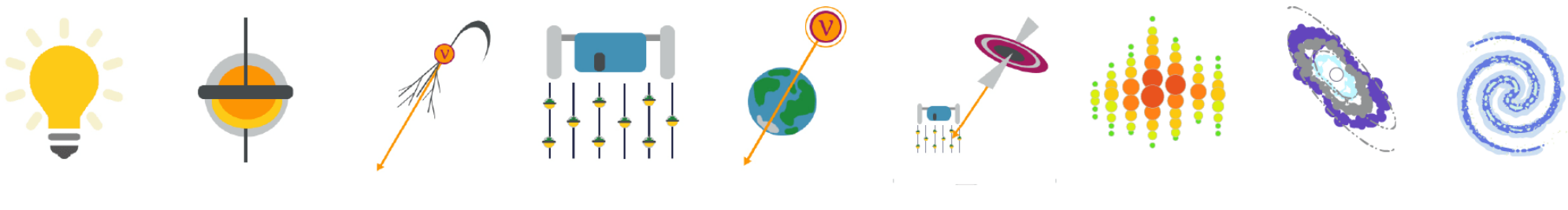


Wide range of physics reach

- Identifying and understanding neutrino sources in the Universe
- Looking for an origin of the Cosmic Rays
- Probing neutrino properties as the extreme energies
- Understanding neutrino mass and mixing
- Searching for Dark Matter and other beyond Standard Model phenomena
- Glaciology and further inter-disciplinary research



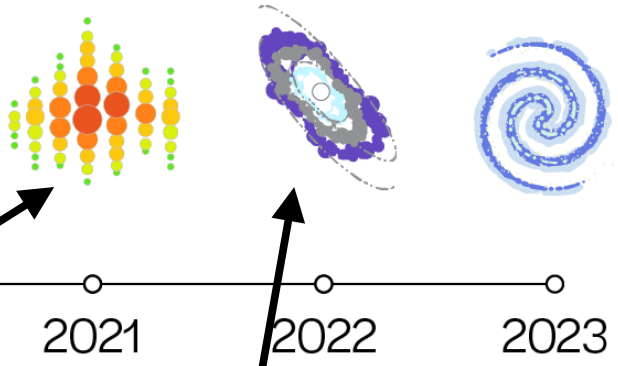
Paving the path towards neutrino astronomy



Idea and detector construction

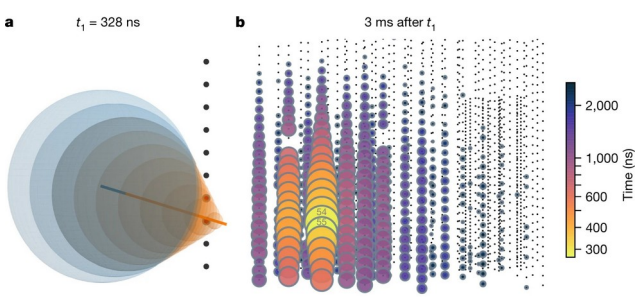
Era of discoveries

Recent highlights



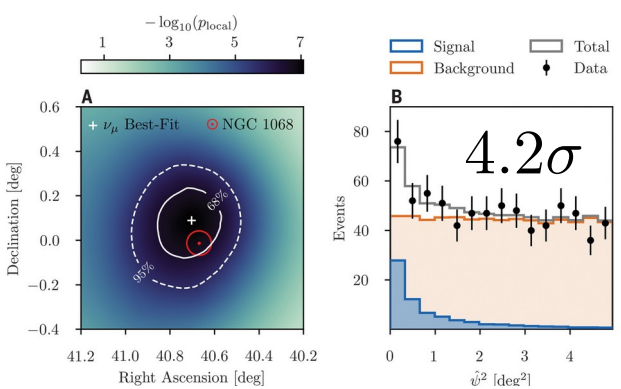
Nature 591, 220–224 (2021)

Glashow resonance candidate



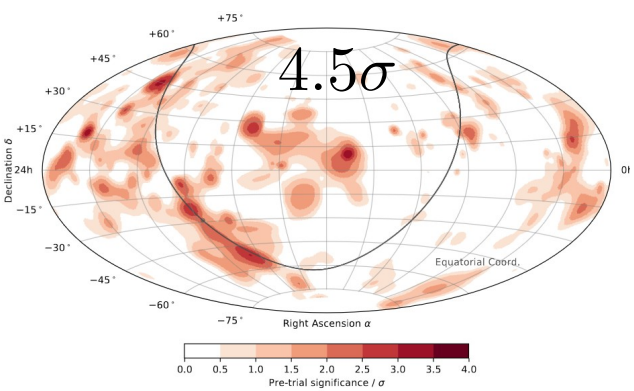
Science 378 (2022) 538-543

NGC 1068 as neutrino source



Science 380, 6652 (2023)

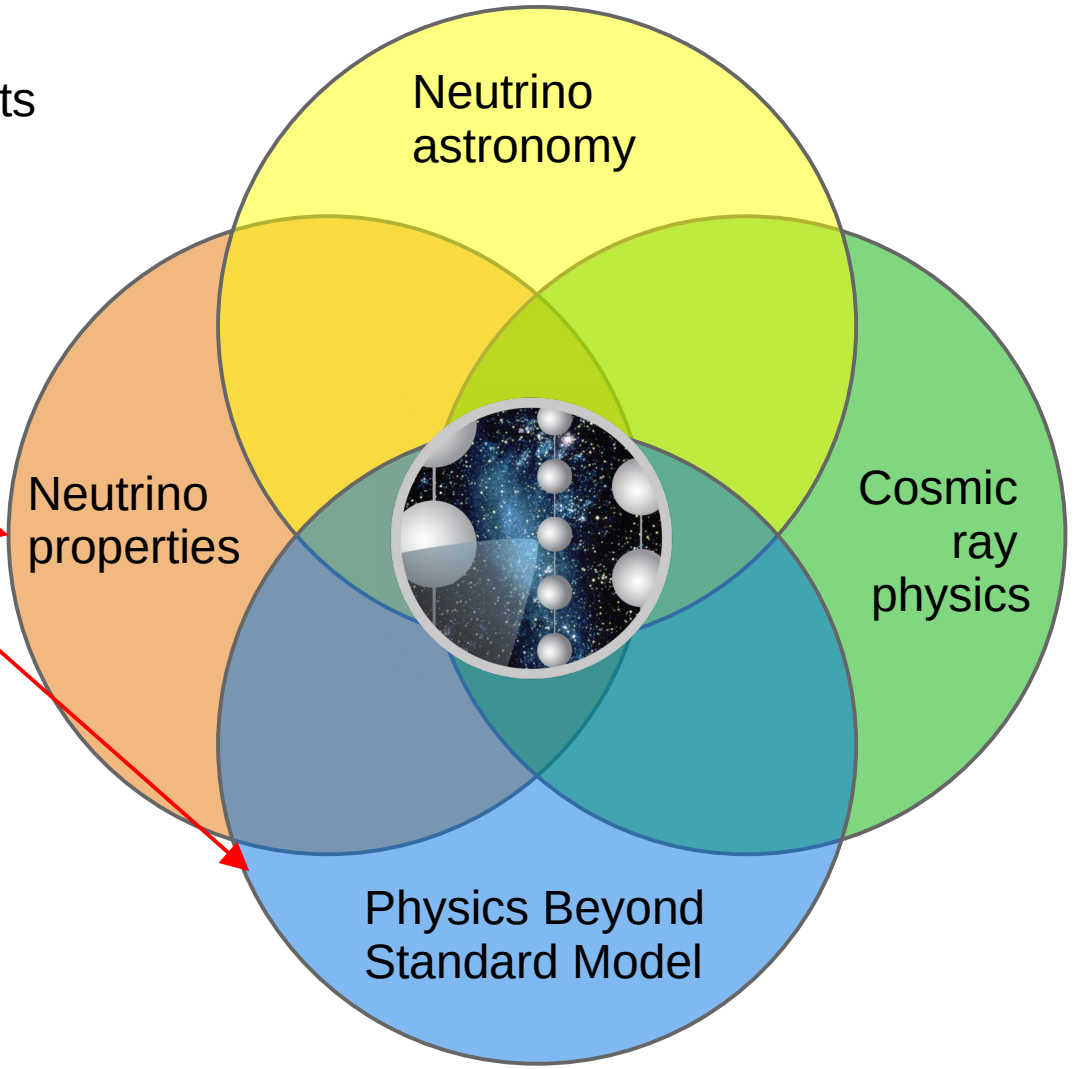
Galactic plane ν emission



The Disclaimer

- Impossible to squeeze even main highlights into ~20 minutes

A biased selection from here

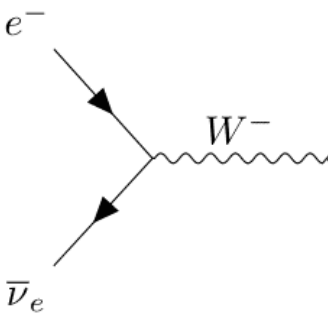


- Ask me at the coffee breaks if you want to hear more!

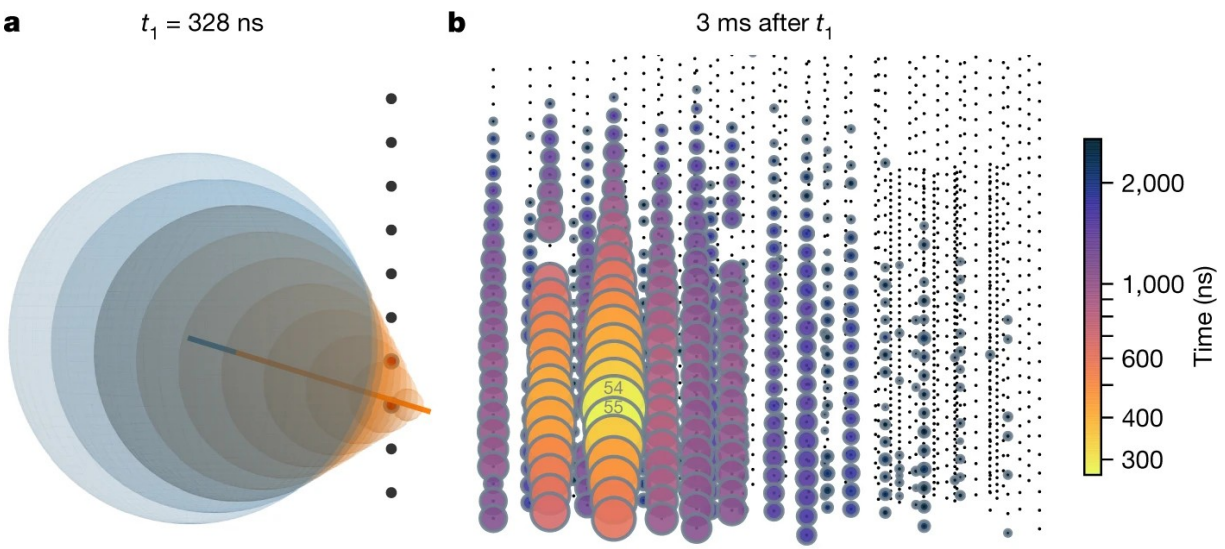
The “Glashow event”

Nature 591, 220–224 (2021)

- Observed event compatible with Glashow resonance (~6.3 PeV)



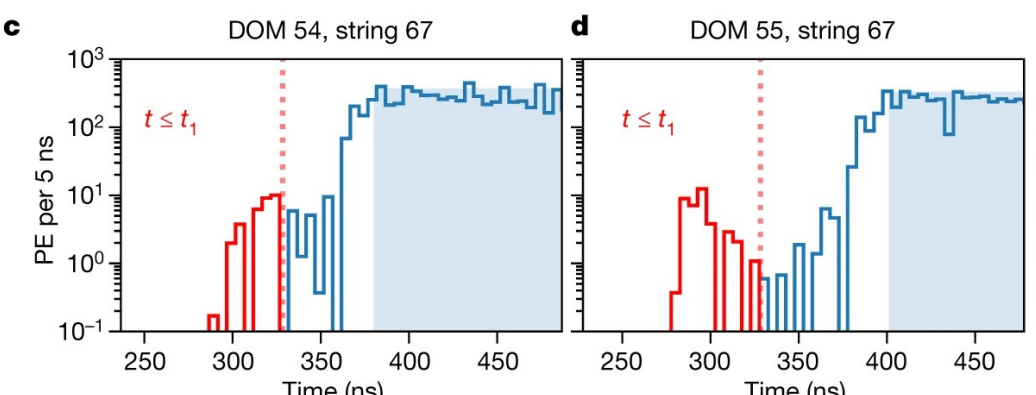
$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{hadrons}$$



- Reconstructed energy from Cherenkov light

$$6.05 \pm 0.72 \text{ PeV}$$

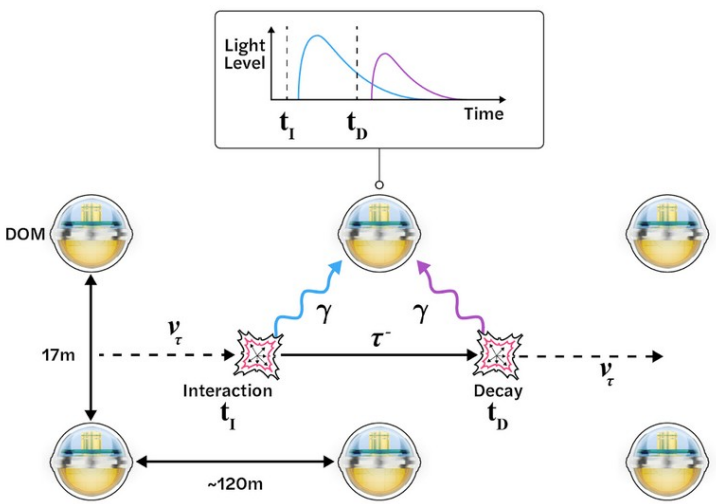
- Early light consistent with muons expected in hadronic decay of W boson

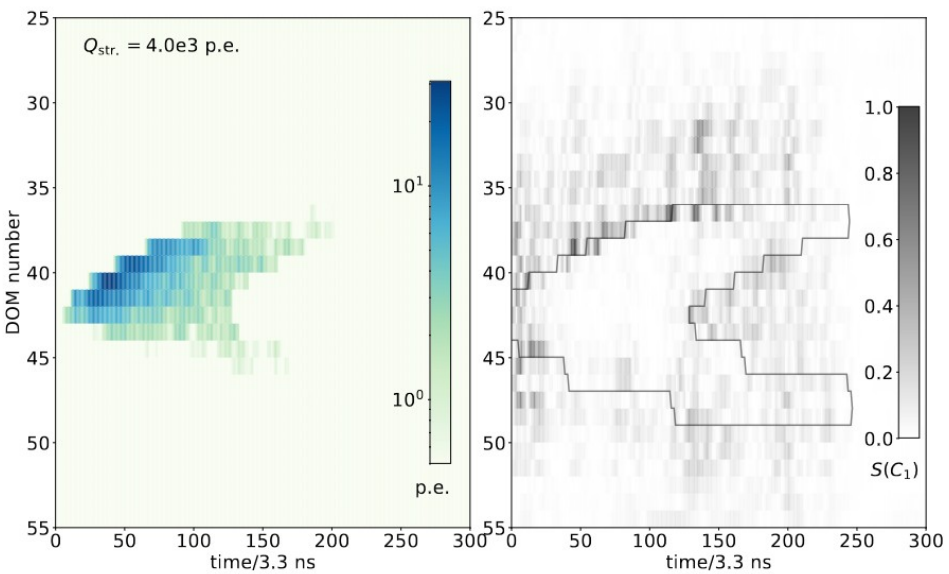


Looking for tau neutrino interactions

PRL 132 (2024) 15, 151001

- Detection of $\nu_\tau \rightarrow$ definitive proof of astrophysical neutrino flux
- Using CNN to identify events with double cascade from ν_τ interaction
- 7 events in 9.7 years of data $\rightarrow$ over 5σ significance of astrophysical ν_τ flux



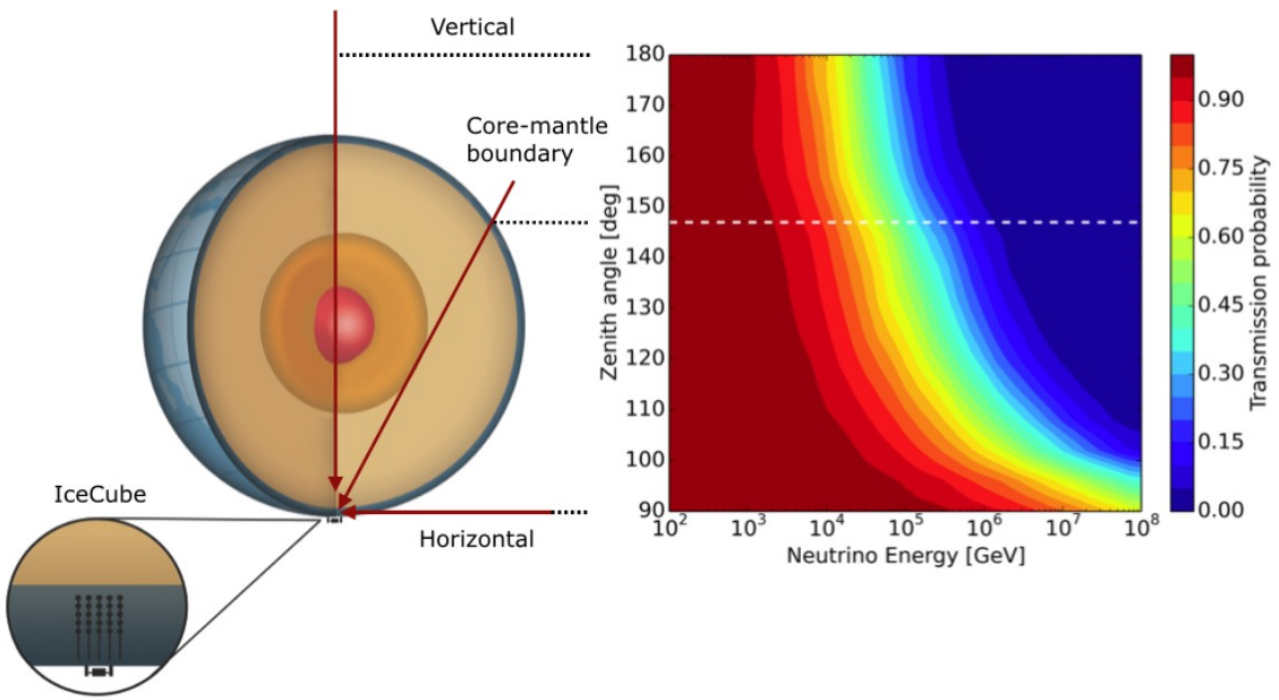


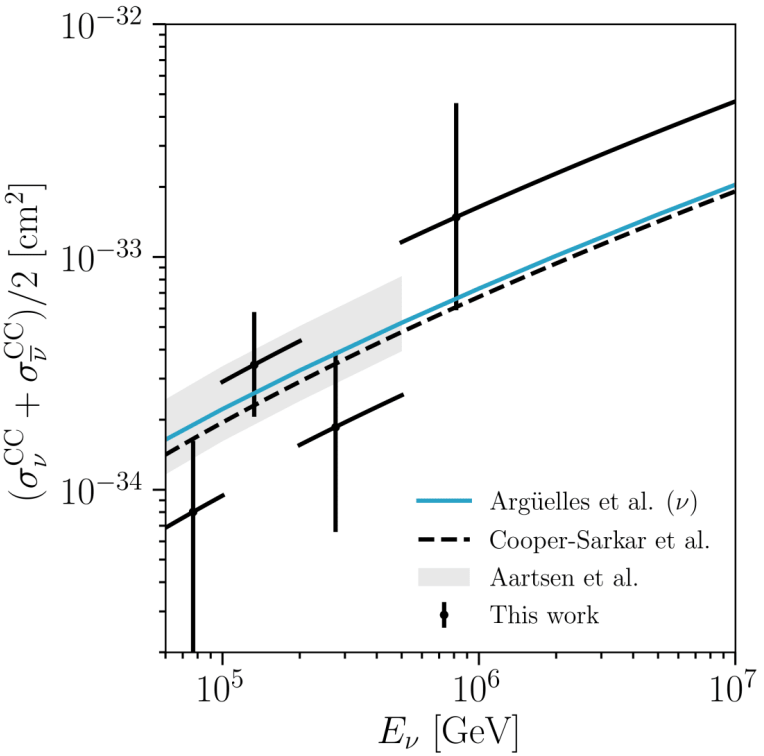
- **"No Tau? No Astronomy!"** $\rightarrow$ we have **taus**, and we have **astronomy**

Neutrino cross sections at highest energies

PRD104 (2021) 022002

- The Earth is not transparent for neutrinos at highest energies

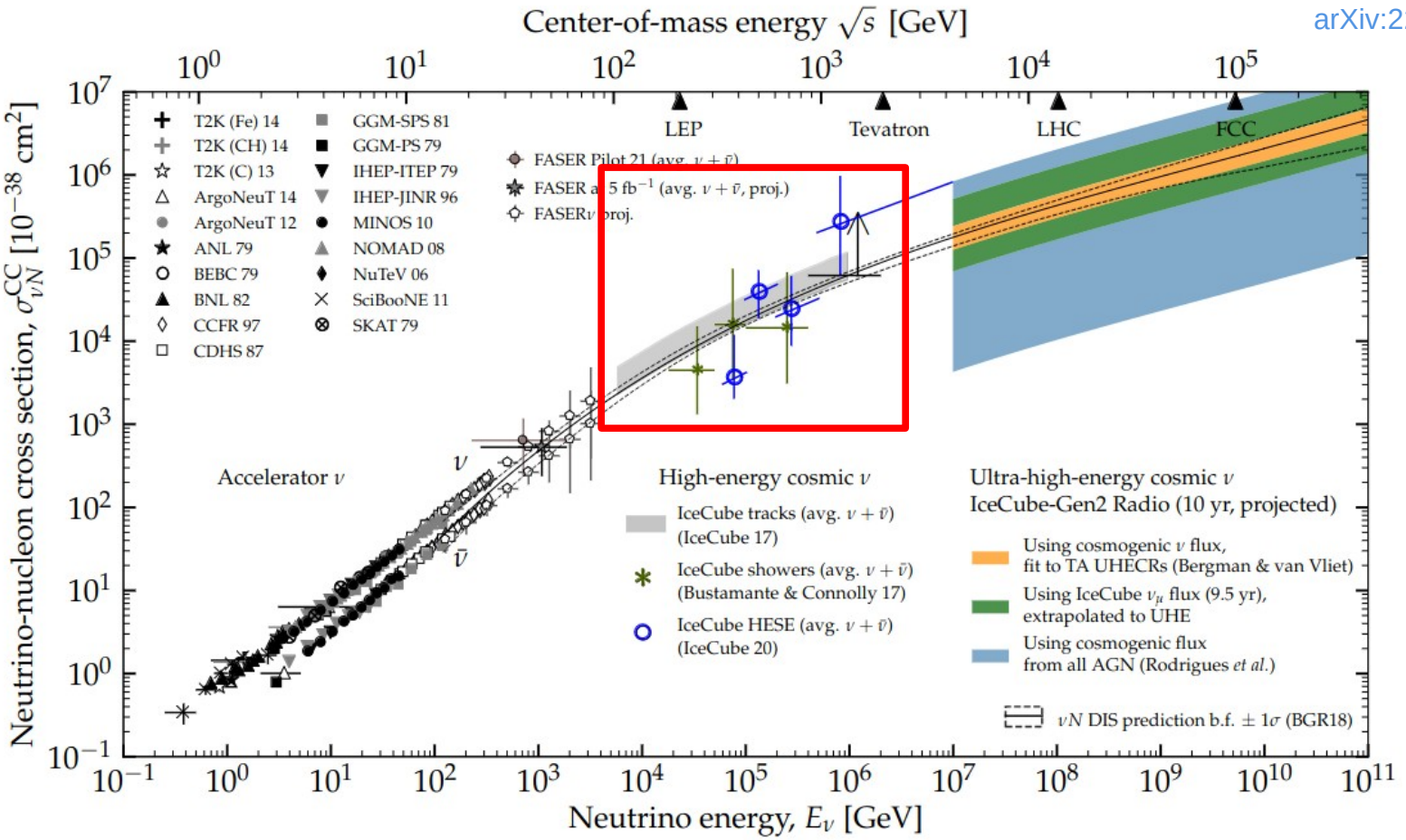




- Studying neutrino absorption → measuring the cross-sections

IceCube in global cross section landscape

arXiv:2203.08096 [hep-ph]

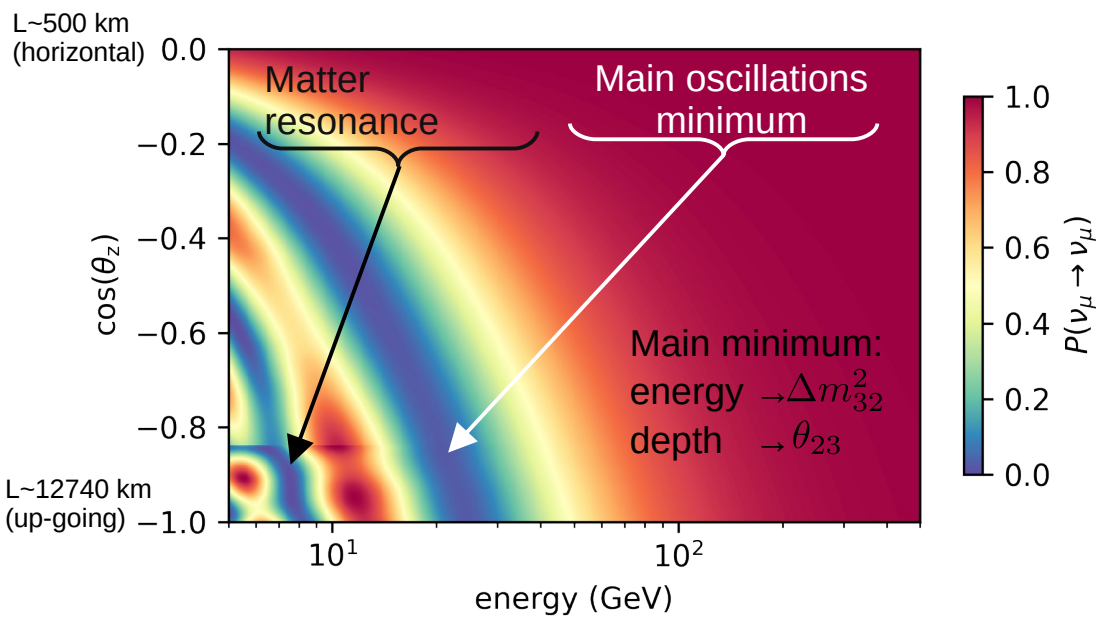


- Unique access to cross sections at unprecedented energies

Atmospheric neutrino oscillations

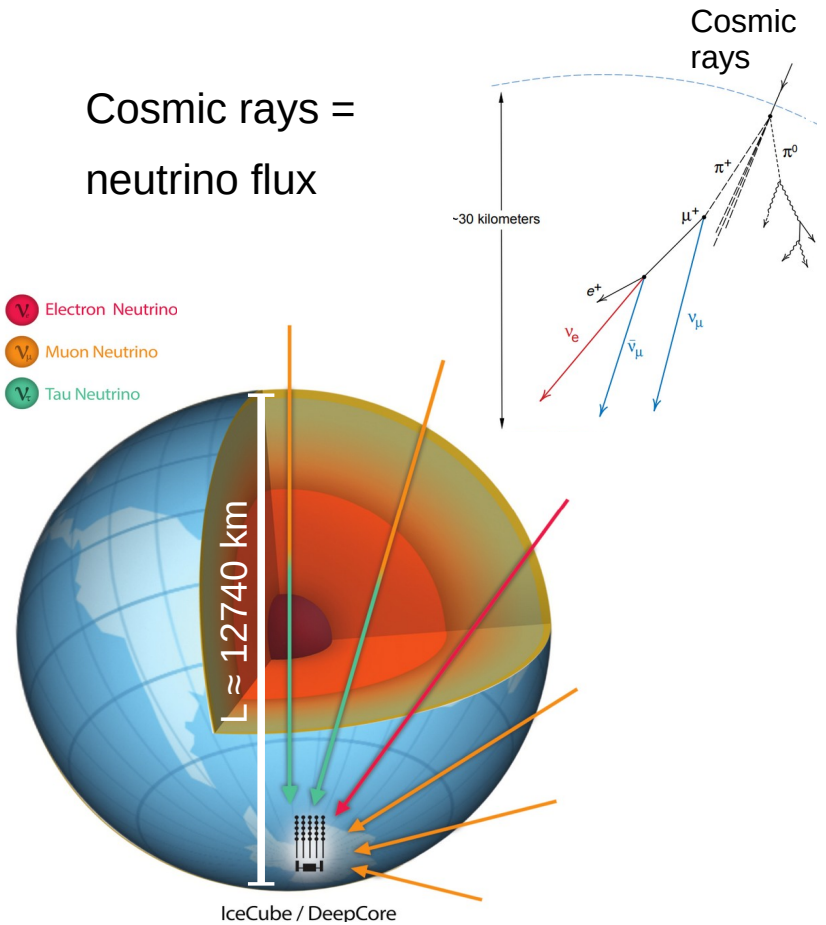
- Leading term = muon neutrino “disappearance”

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



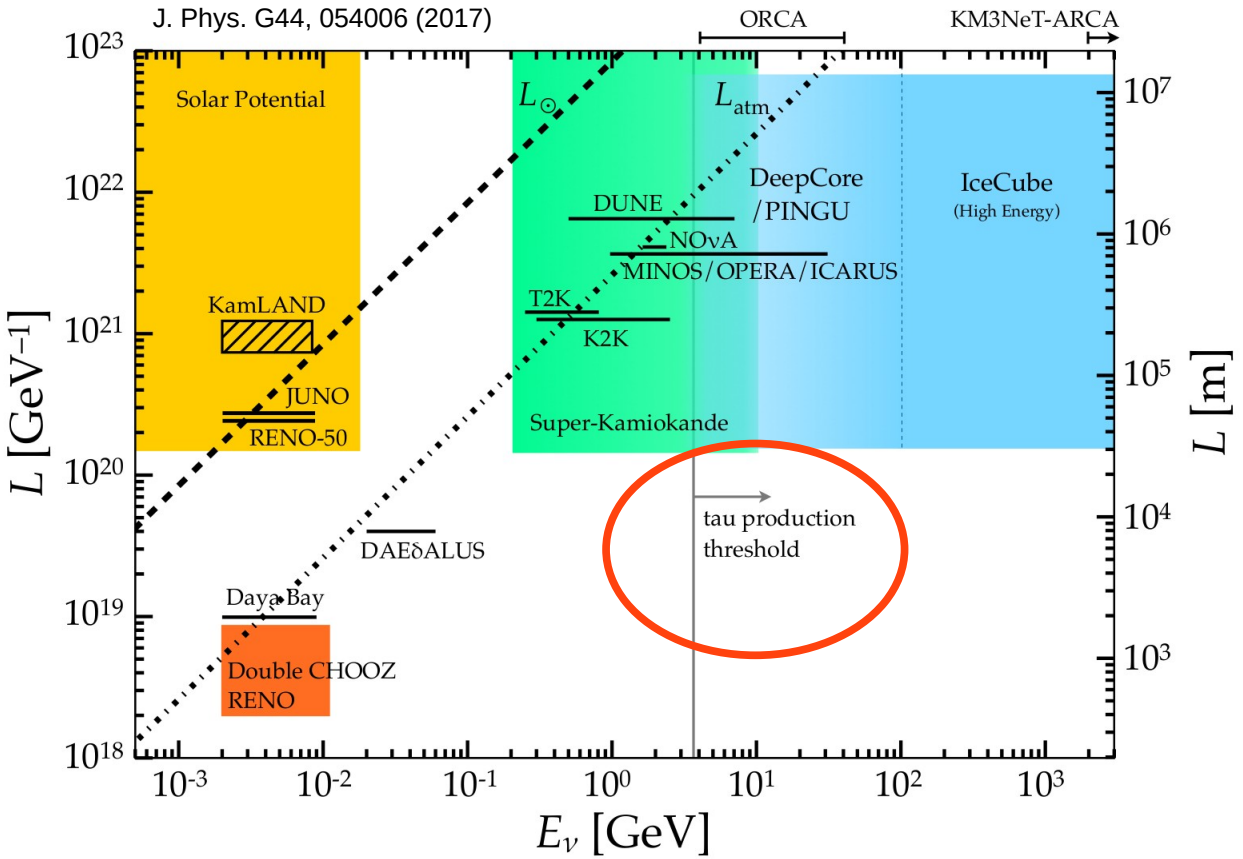
Cosmic rays =

neutrino flux



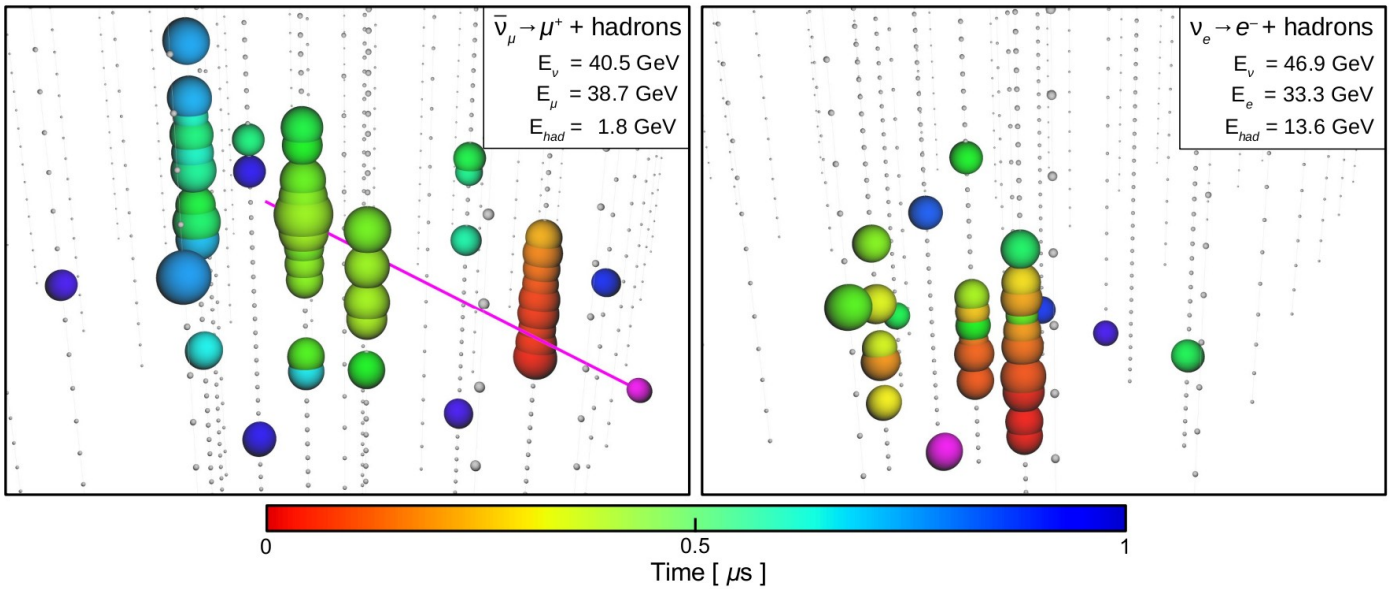
- Arrival direction → baselines between 20 and 1500

Neutrino telescopes and oscillations



- Measurement of oscillations at the highest possible energies on Earth
- Above tau production threshold → disappearance and appearance studies possible

DeepCore events



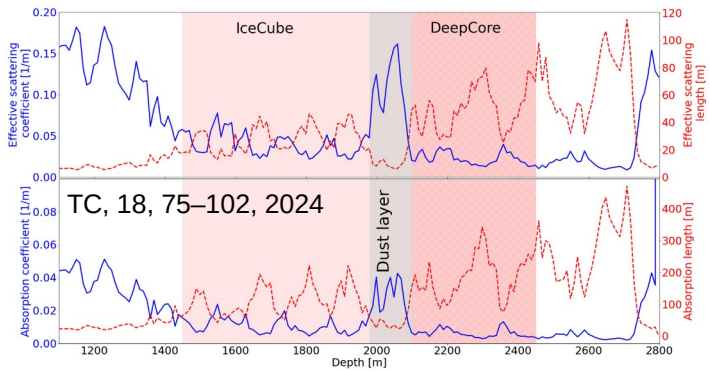
- Low energies (<100 GeV) neutrinos in IceCube
  - Primarily detected in DeepCore
  - Produce less light
  - Challenging to select and reconstruct
  - More affected by systematic uncertainties

makes oscillations studies challenging

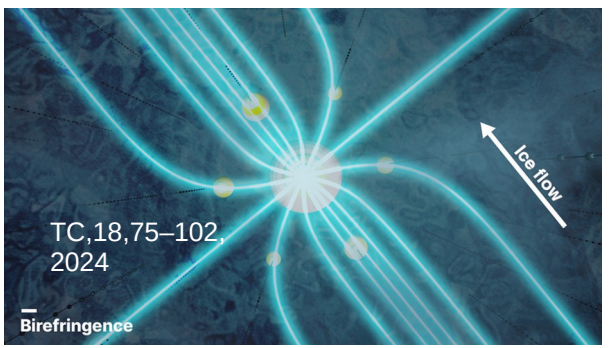
Understanding the detector

- More data → more precise measurement → more sensitivity to systematics
- Constant refinement of the detector knowledge

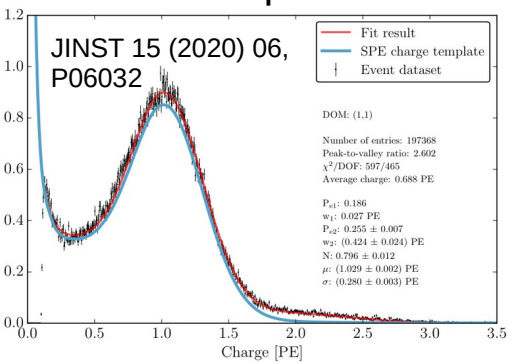
Bulk ice properties



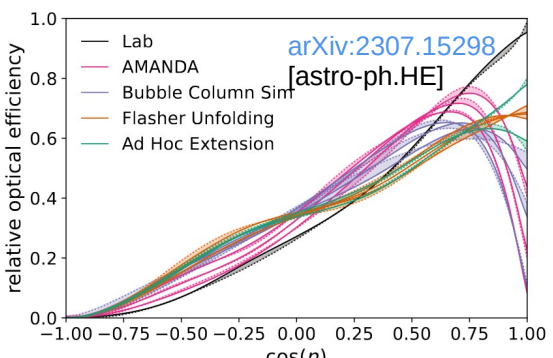
Light propagation

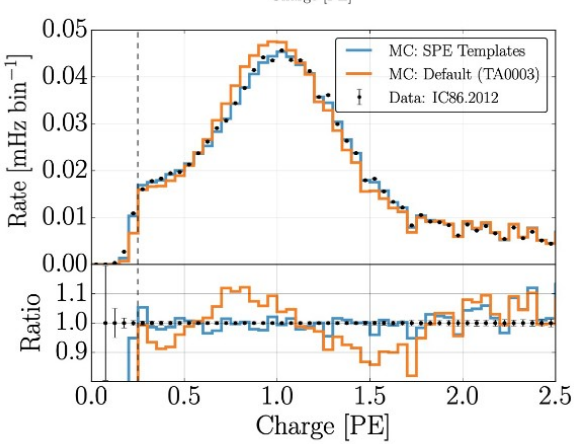


DOM response



Refrozen “hole” ice properties



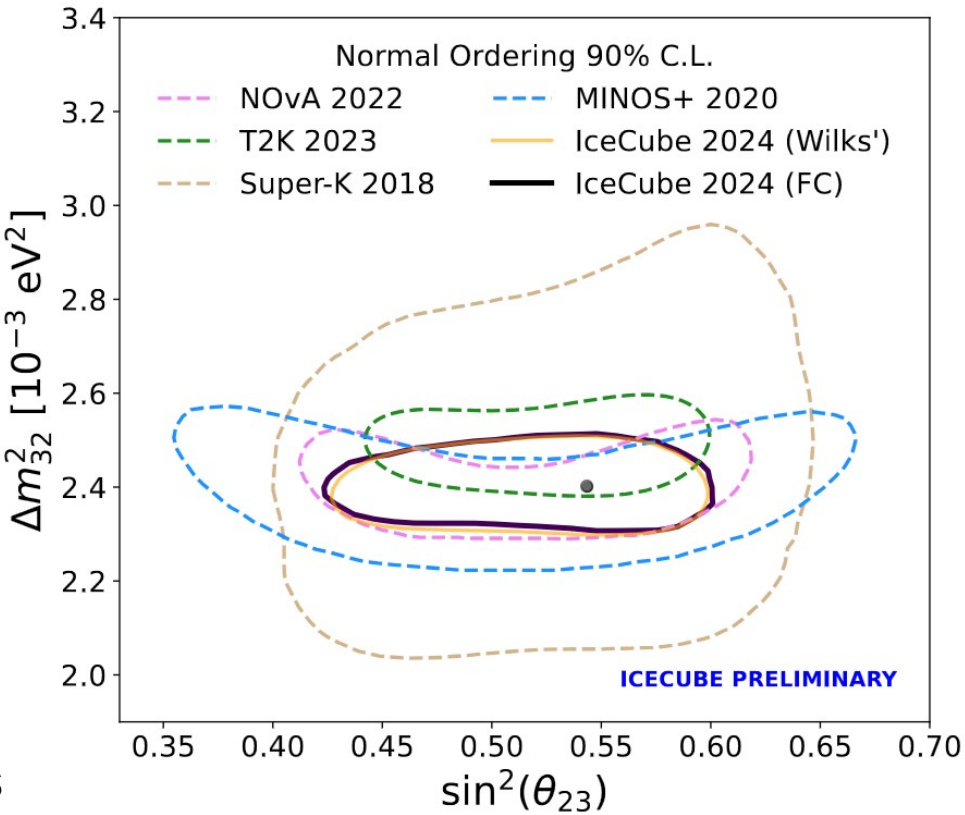


Muon neutrino disappearance

arXiv:2405.02163 [hep-ex]

- 150k events in 9.3 years of IceCube data
- Measured oscillations parameters (68% C.L.)

$$\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \cdot 10^{-3} eV^2$$
$$\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$$

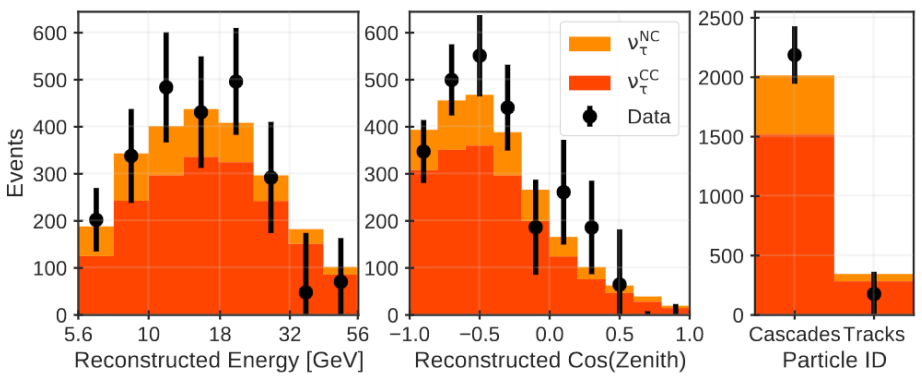


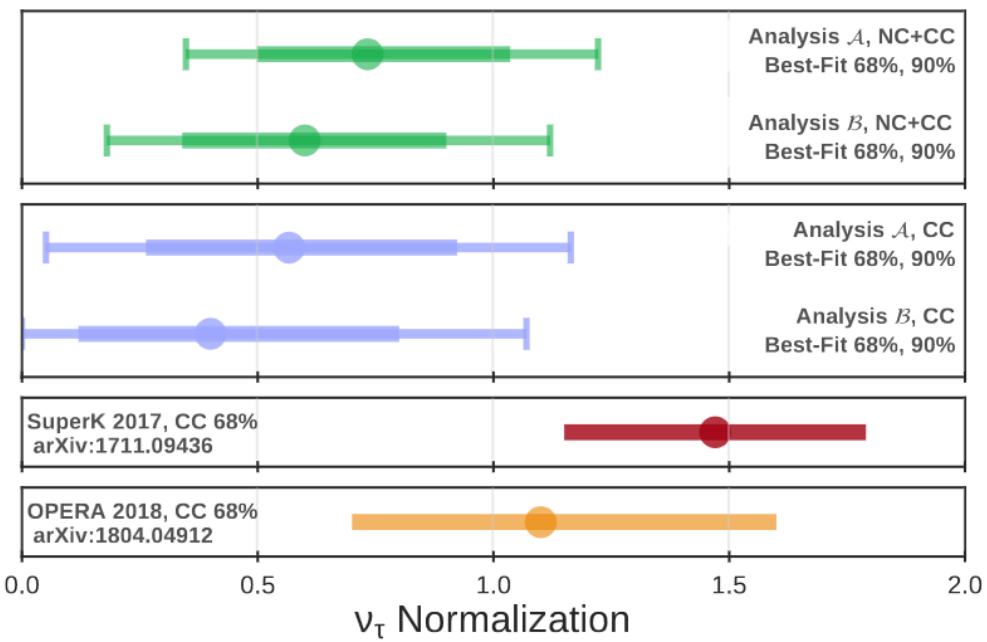
- The most precise measurement of mixing parameters using atmospheric neutrinos
- On part with dedicated accelerator experiments

Tau neutrino appearance

- Disappeared muon neutrinos appear as tau neutrinos
- Deviation from nominal → beyond standard mixing physics
- Identifying tau neutrinos at statistical level

PRD 99, 032007 (2019)





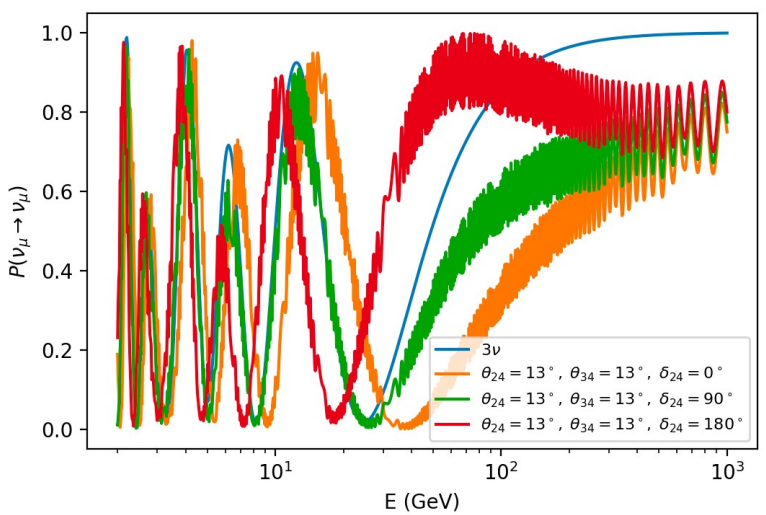
- No surprises found with 3 years of data
- Analysis of new high statistics samples in progress

Looking for sterile neutrinos at low energies

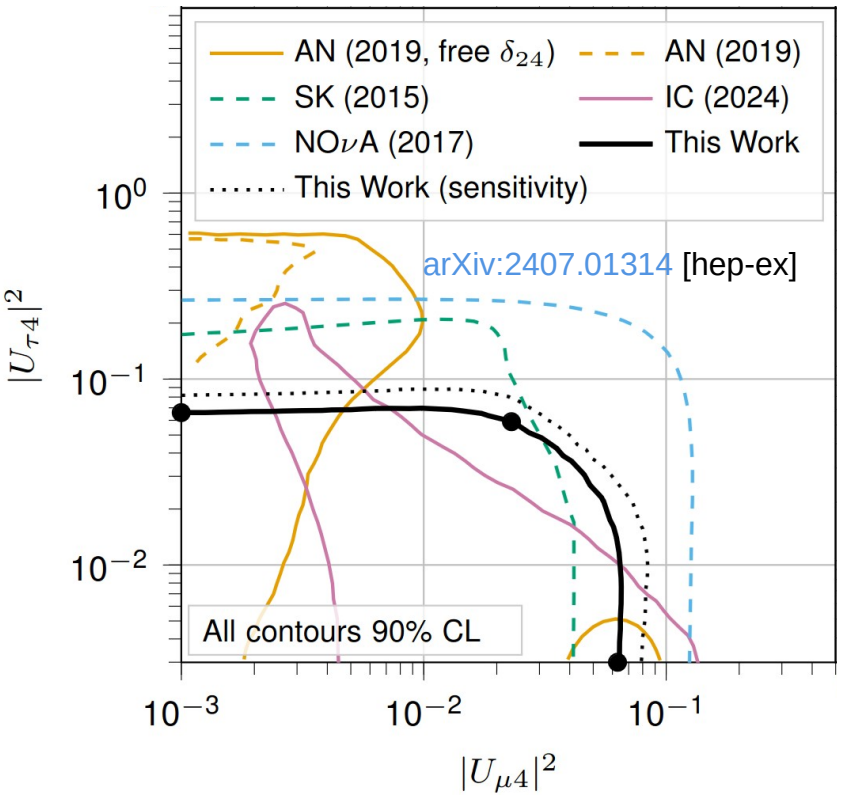
- Mixing in 3+1 model

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

- Affects standard oscillations via matter effects



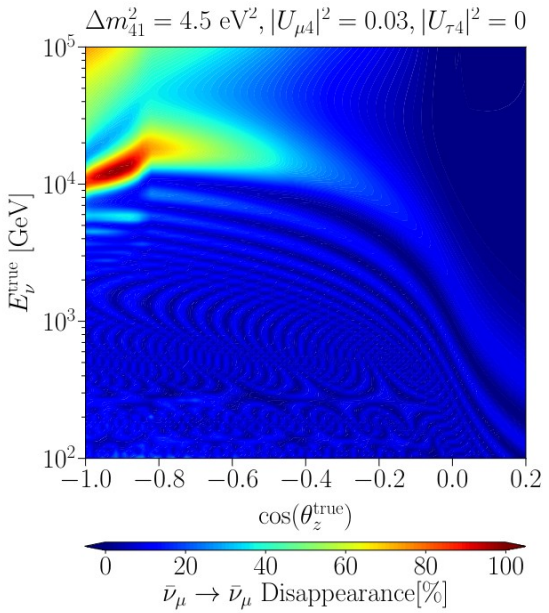
- Limits with 7.5 years of “golden event” sample



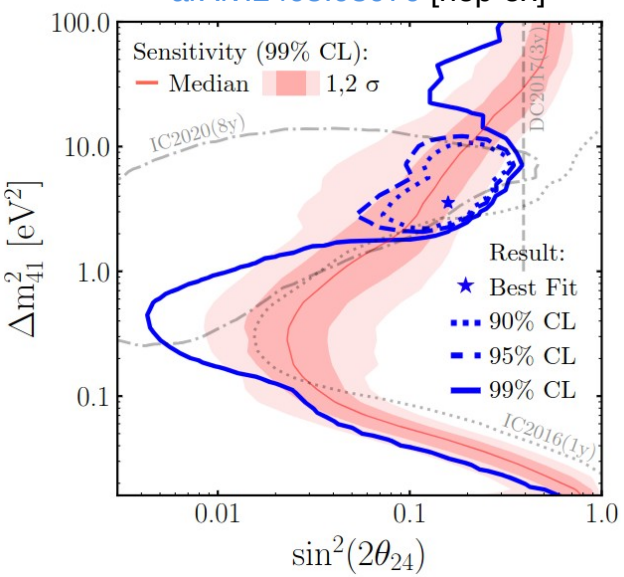
$$|U_{\mu 4}|^2 < 0.0534$$
$$|U_{\tau 4}|^2 < 0.0574$$
(90% C.L.)

Sterile neutrino search at TeV range

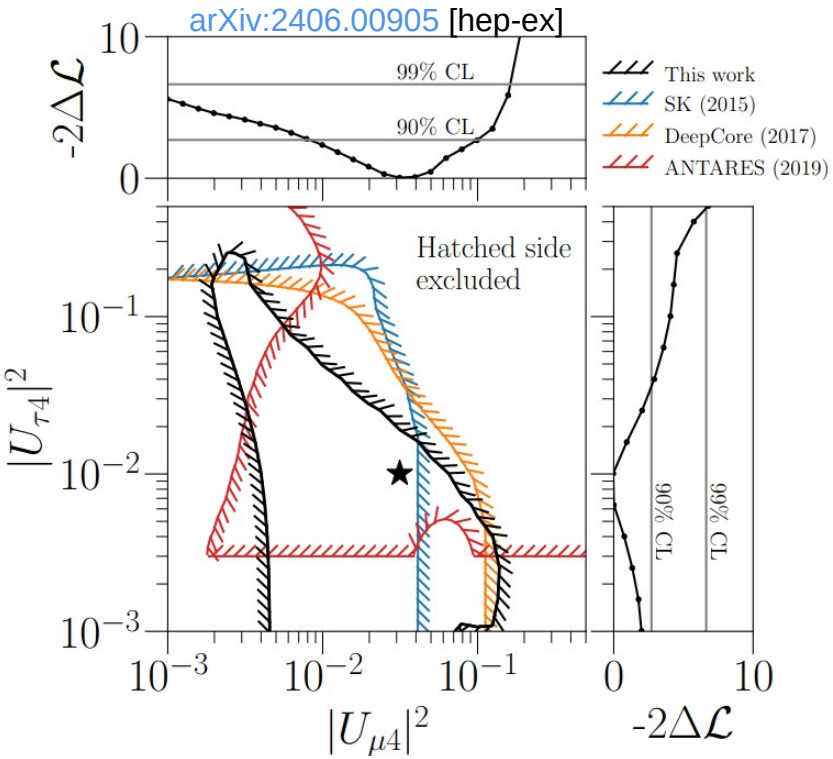
- Resonant transition into sterile state due to matter effects
- Sensitive to both muon and tau mixing elements



arXiv:2405.08070 [hep-ex]

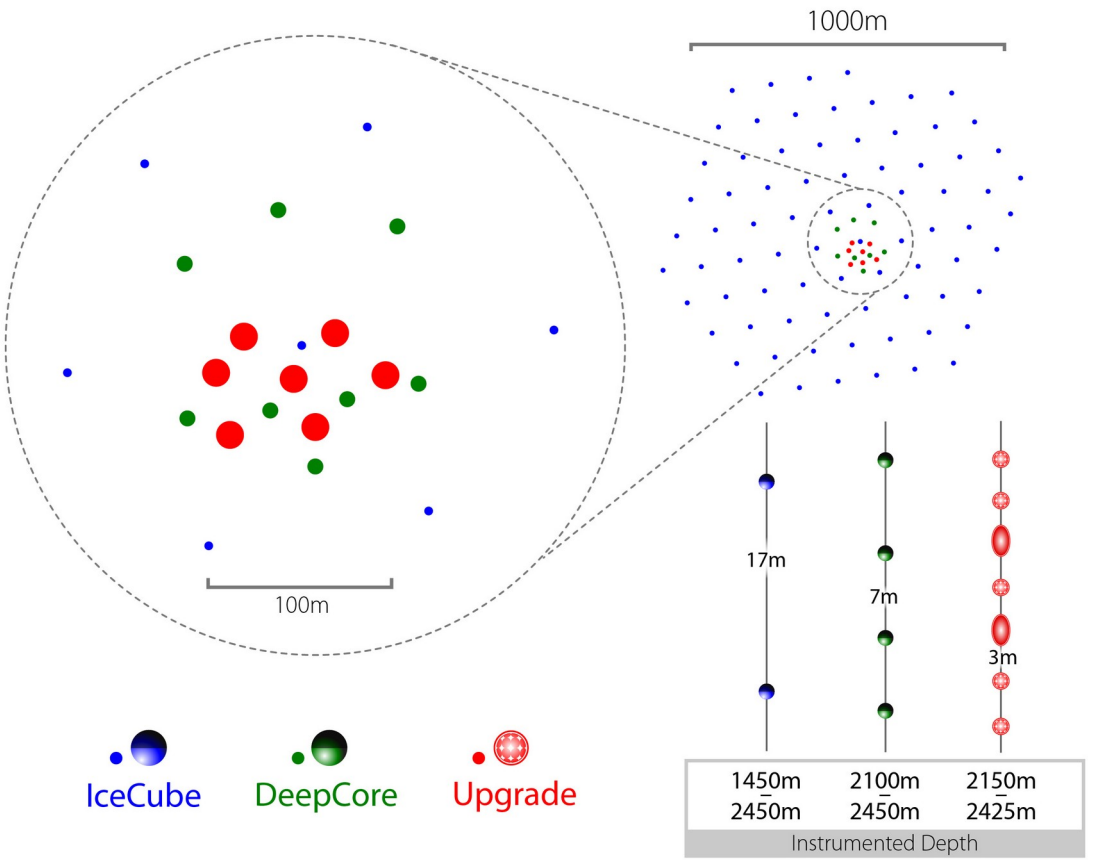


arXiv:2406.00905 [hep-ex]

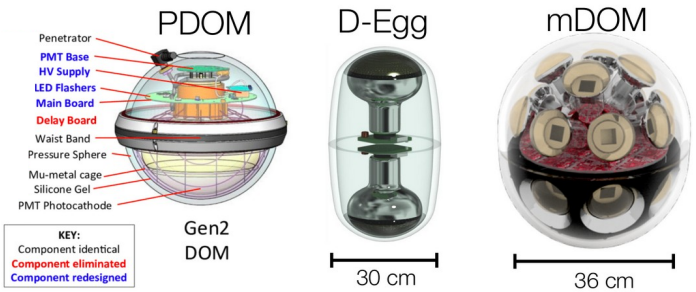


- Compatible with no-sterile mixing hypothesis (p-value ~ 3-4%)

IceCube Upgrade



- Over 800 new modules
  - New multi-PMT detection modules

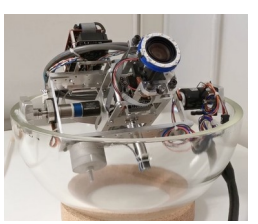


  - New dedicated calibration modules

POCAM (isotropic light)

Pencil Beam (collimated light)

Swedish Camera (camera system)

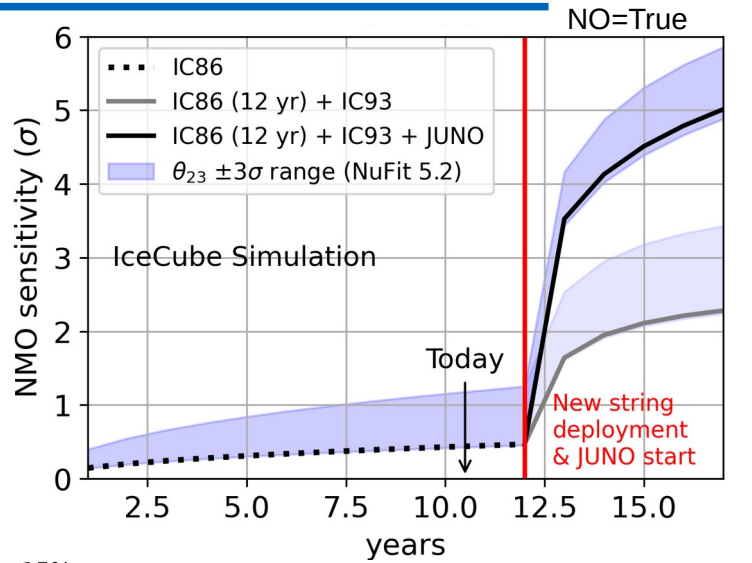


  - flashers and cameras in detection modules
  - and more special devices
- R&D platform for future IceCube-Gen2

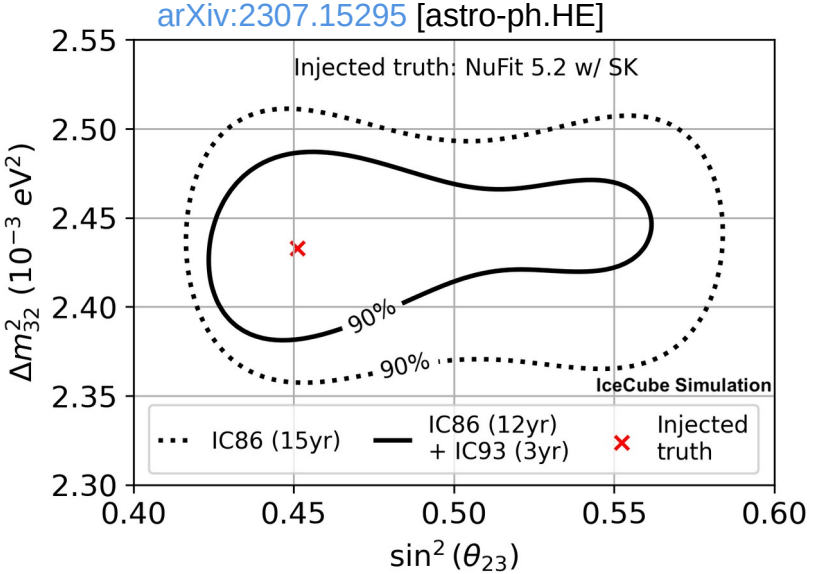
- Fully funded and to be deployed in 2025/26 season

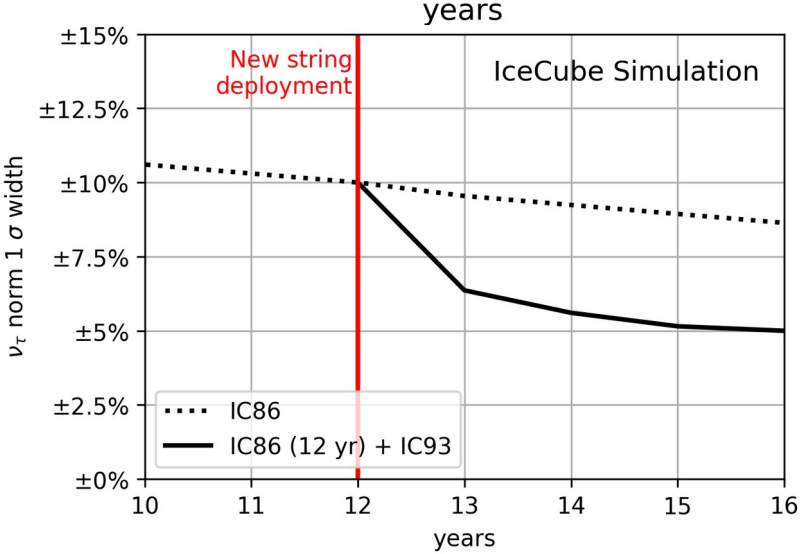
Reach of IC Upgrade

- Precision measurements of θ_{23} and Δm^2_{32}
- ~3σ sensitivity to ν mass ordering (5σ with JUNO)
- 5% precision of tau neutrino appearance
- And more:
  - BSM physics, Dark Matter, calibration, improved reconstruction for high energy neutrinos …



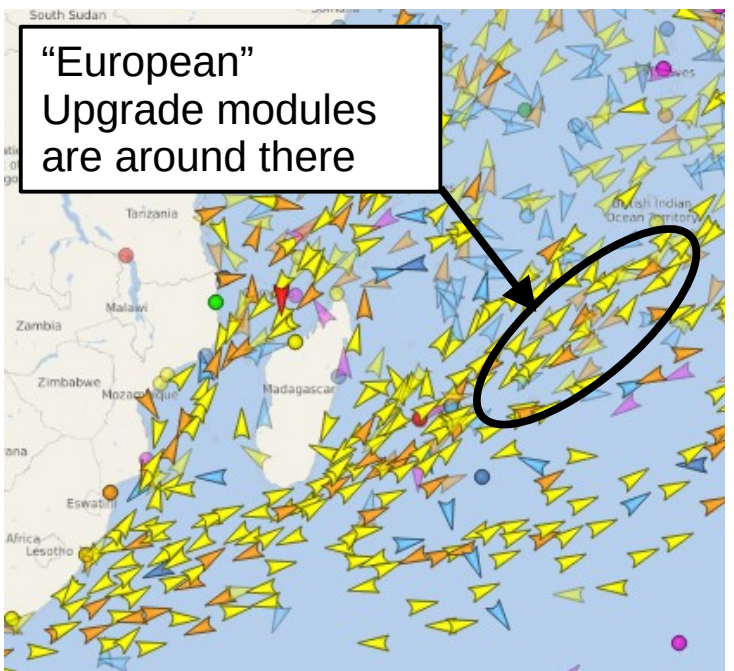
arXiv:2307.15295 [astro-ph.HE]





Summary

- IceCube enters an era of discoveries:
  - Discovering astrophysical neutrinos
  - Identifying sources of neutrinos in the Universe
  - Unique probe of neutrino properties at the highest energies
  - State of the art measurement of neutrino oscillations
  - and much more
- IceCube Upgrade is under way:
  - Wide physics reach in neutrino oscillations, Dark Matter, BSM physics and more
  - New calibration devices to improve knowledge of the current detector
- Stay tuned for more updates!



Backups