

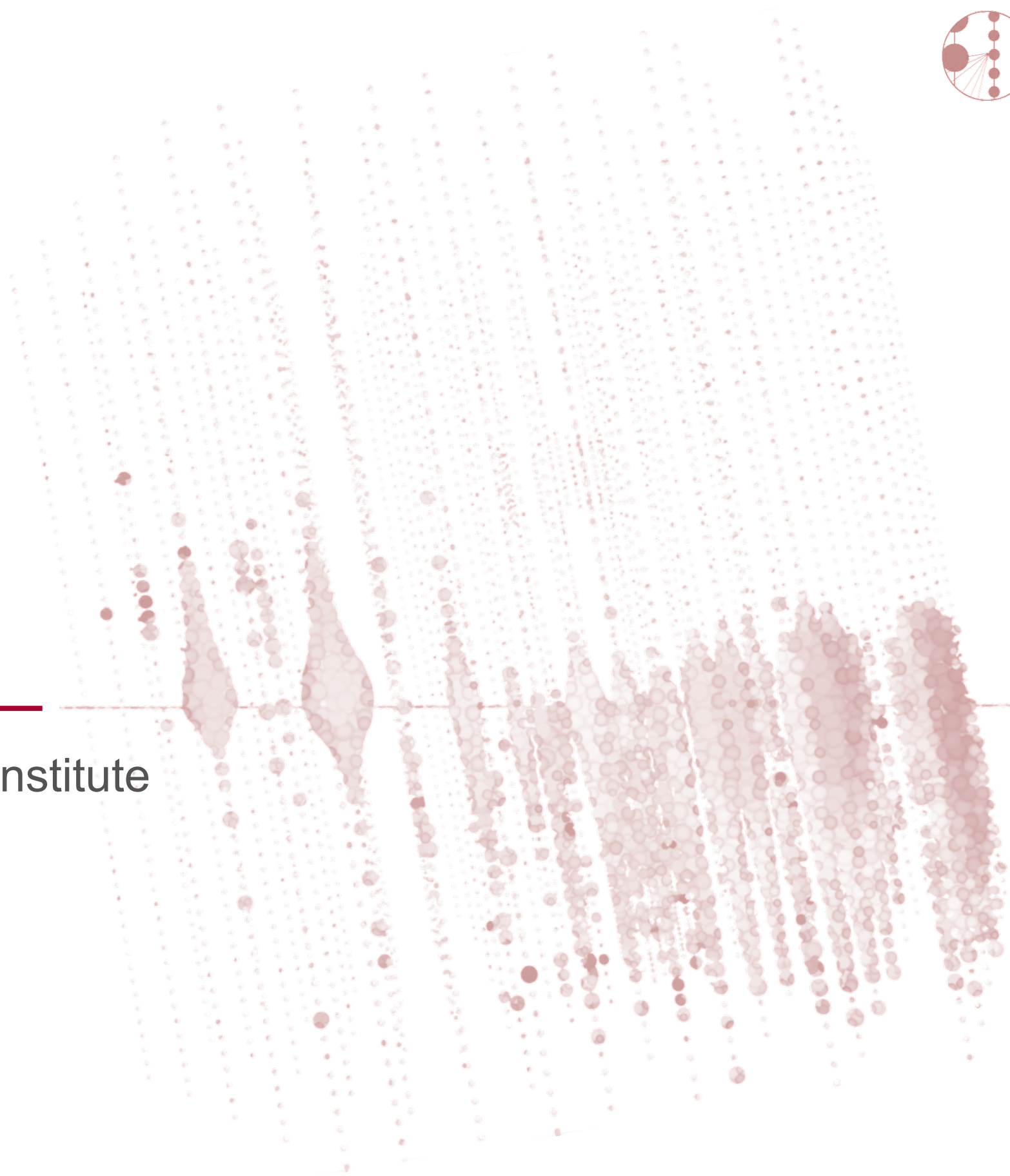


IceCube

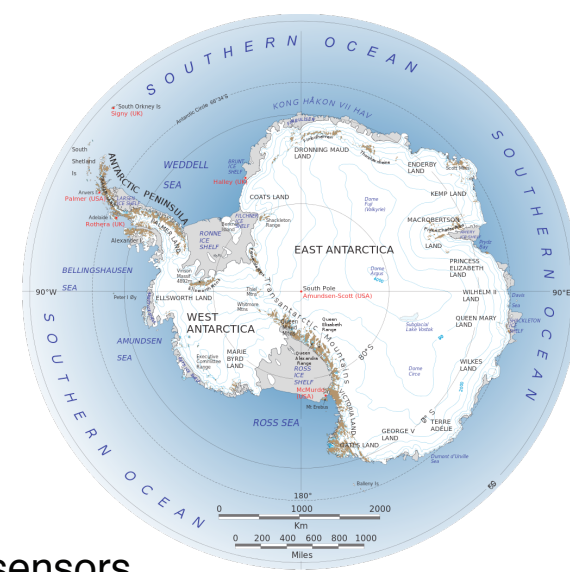
D. Jason Koskinen - Niels Bohr Institute

rECFA meeting in Denmark

May 2022



IceCube/DeepCore



IceCube Lab

IceTop
81 Stations
324 optical sensors

50 m

IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors

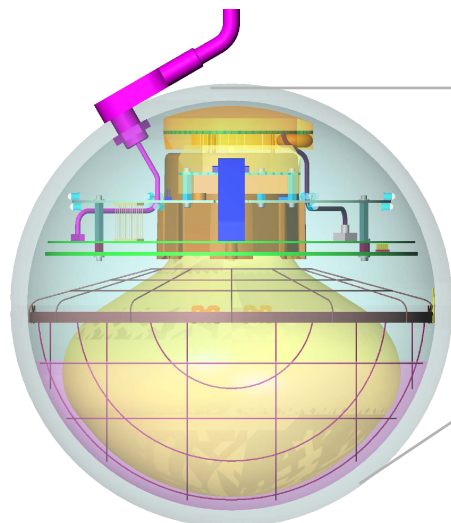
1450 m

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

2450 m

2820 m

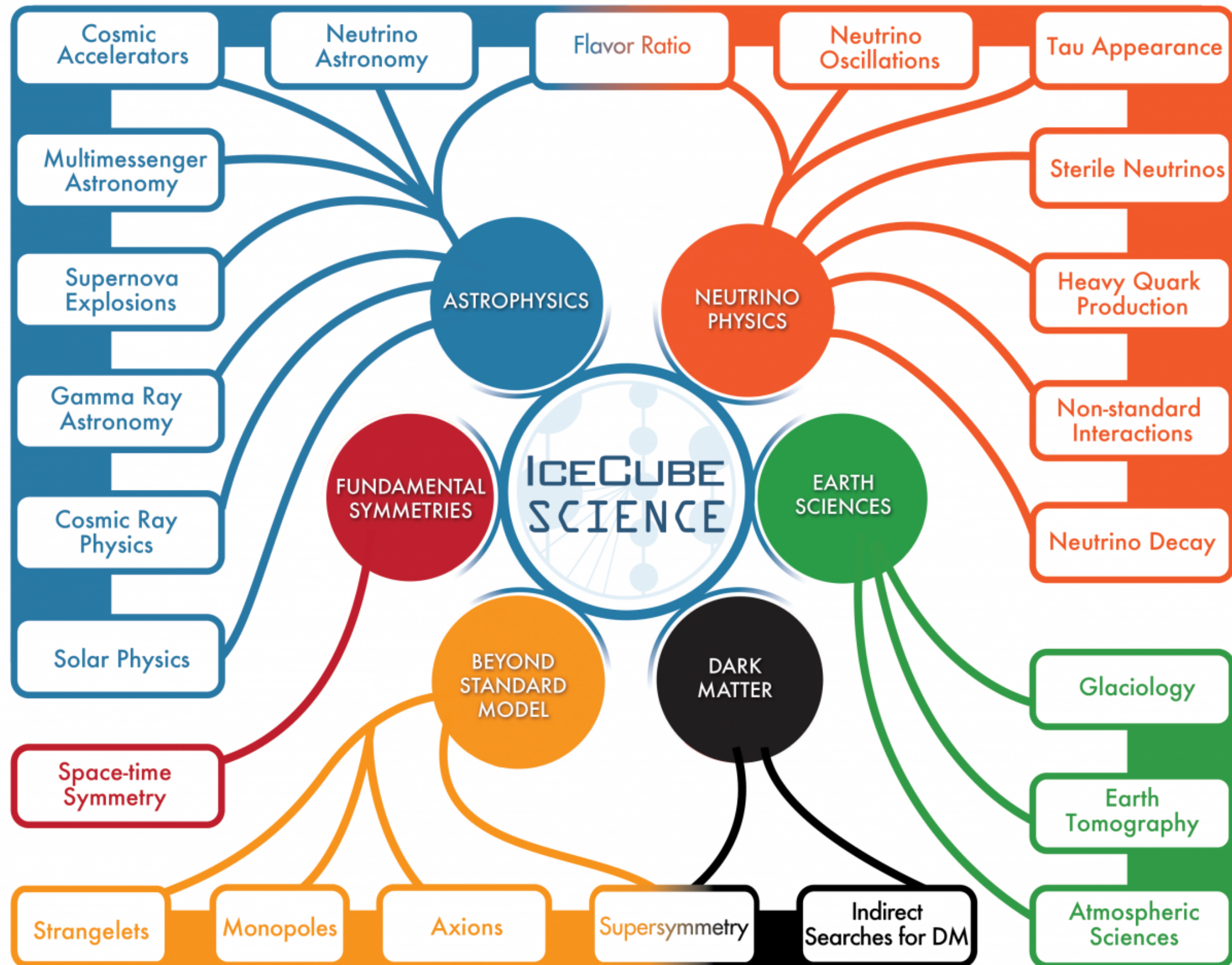
Eiffel Tower
324 m



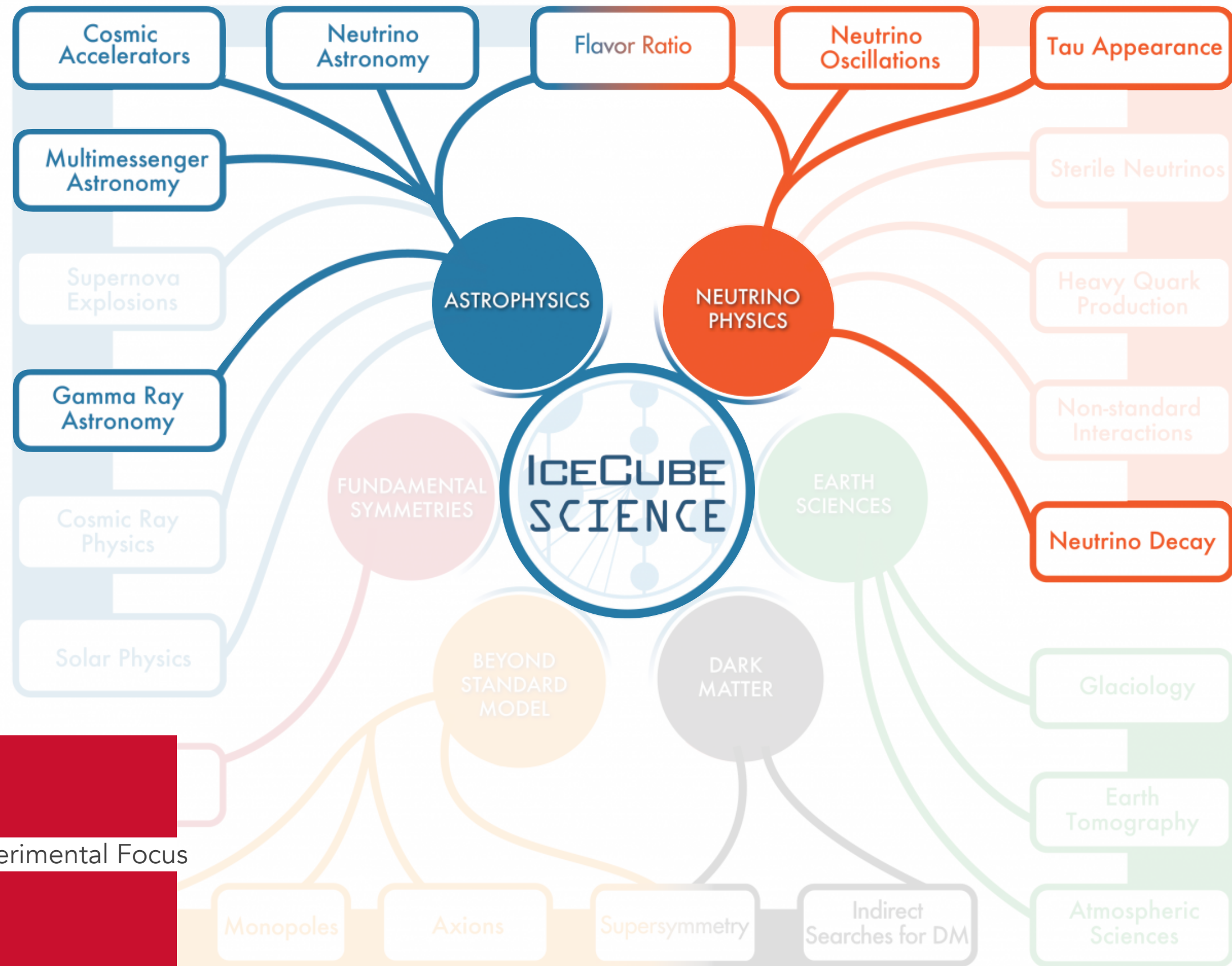
IceCube Digital Optical
Module (DOM)

Bedrock

IceCube Science



IceCube Science



Danish Experimental Focus

IceCube Collaboration



IceCube Collaboration - Denmark

- ~2-2.5 senior personnel (1-1.5 permanent, 1 tenure-track)
- In 2022, 100% supported by private foundation grants to individual PIs
 - ~2 Ph.D. students (1 experimental, 1 theory/pheno)
 - 2 postdocs and 1 Marie-Curie Fellow
- Lead oscillation(s) & astrophysical sources analyses, event selection, simulation development, and analysis tools

 **GERMANY**
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
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and Technology
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and A&M College
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University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas

University of Maryland
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin-Madison
University of Wisconsin-River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)

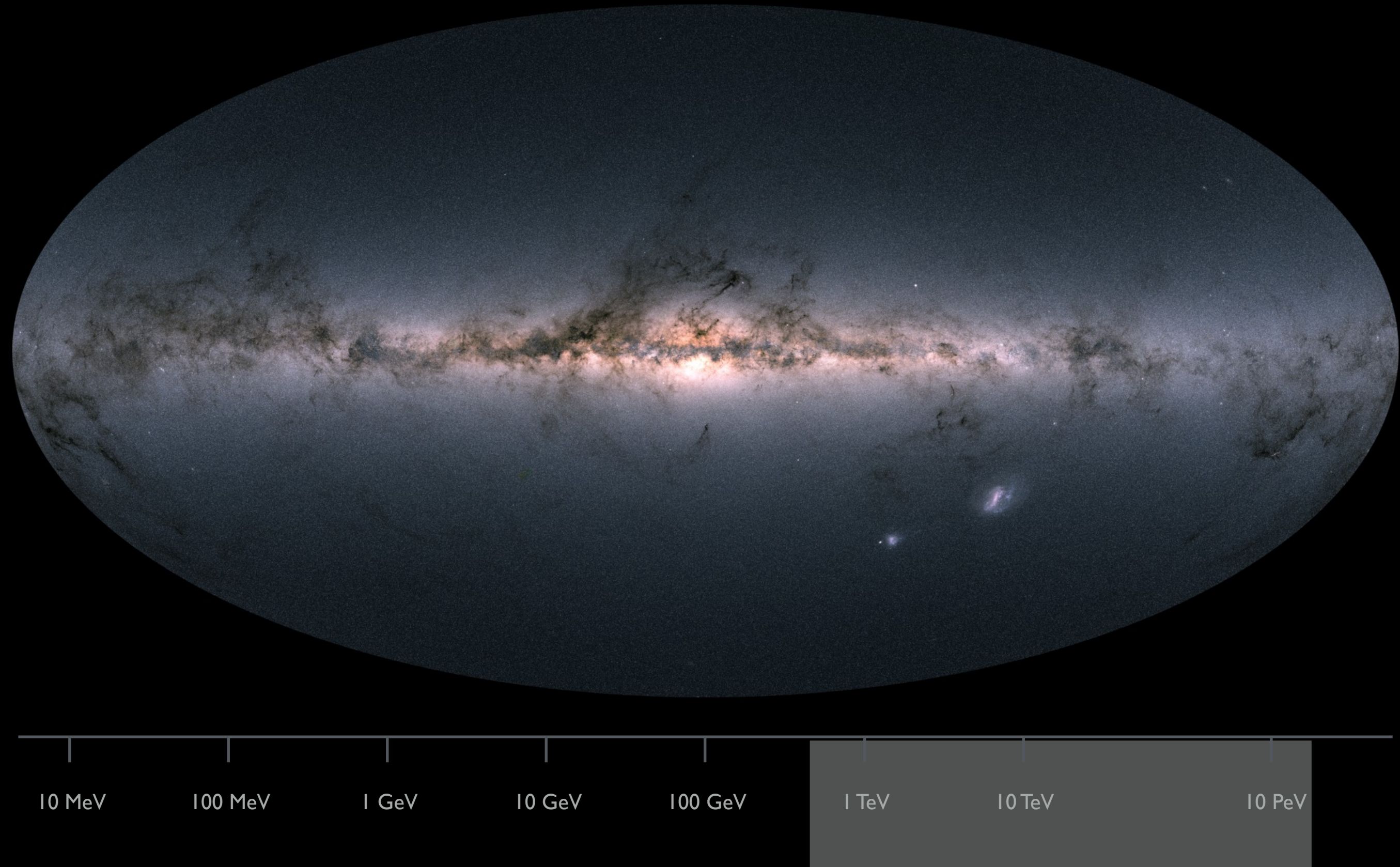
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Astrophysical Neutrinos & IceCube

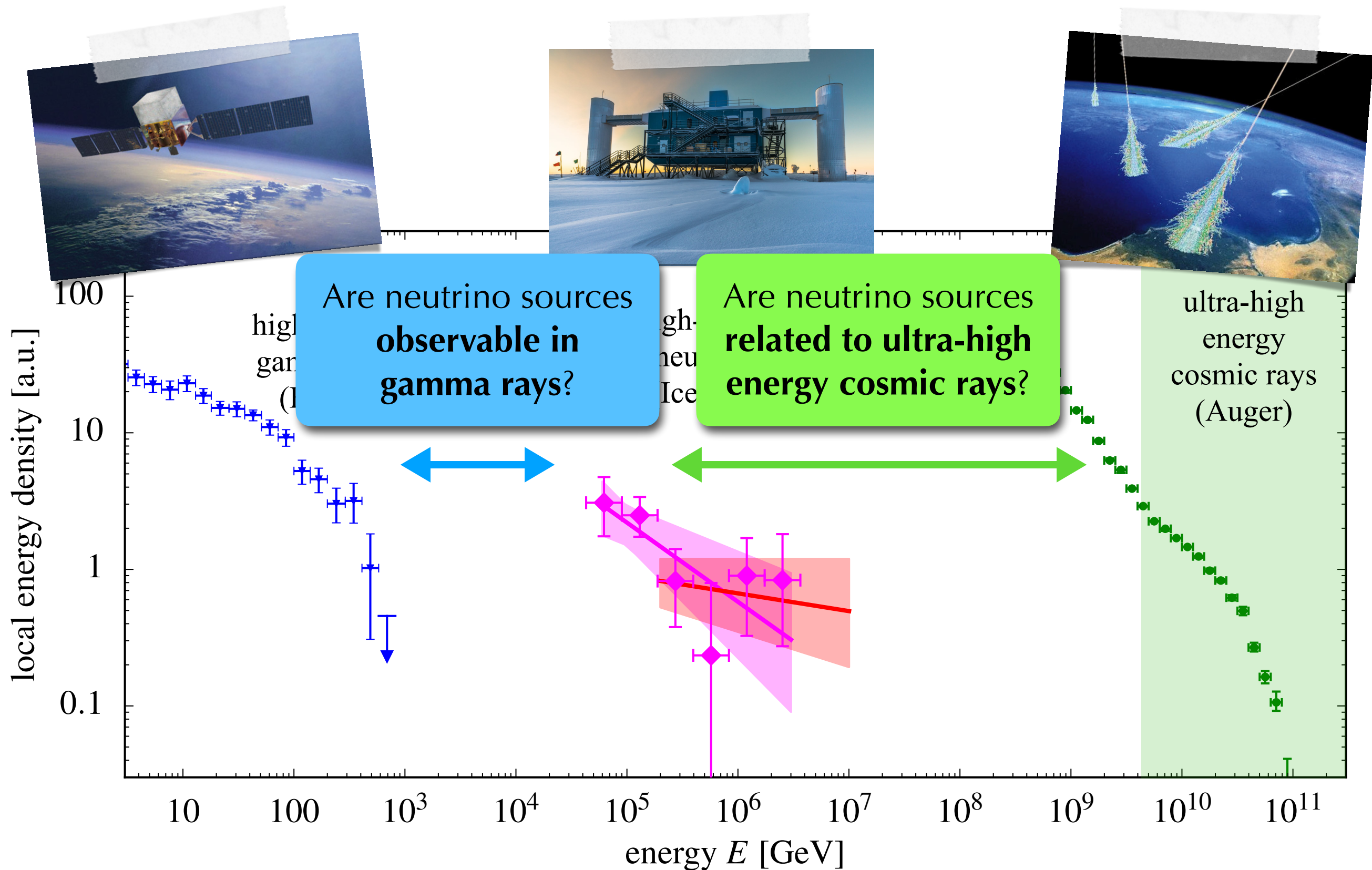
Neutrino+ Astronomy



*ESA/Gaia/DPAC

IceCube

Multi-Messenger Panorama

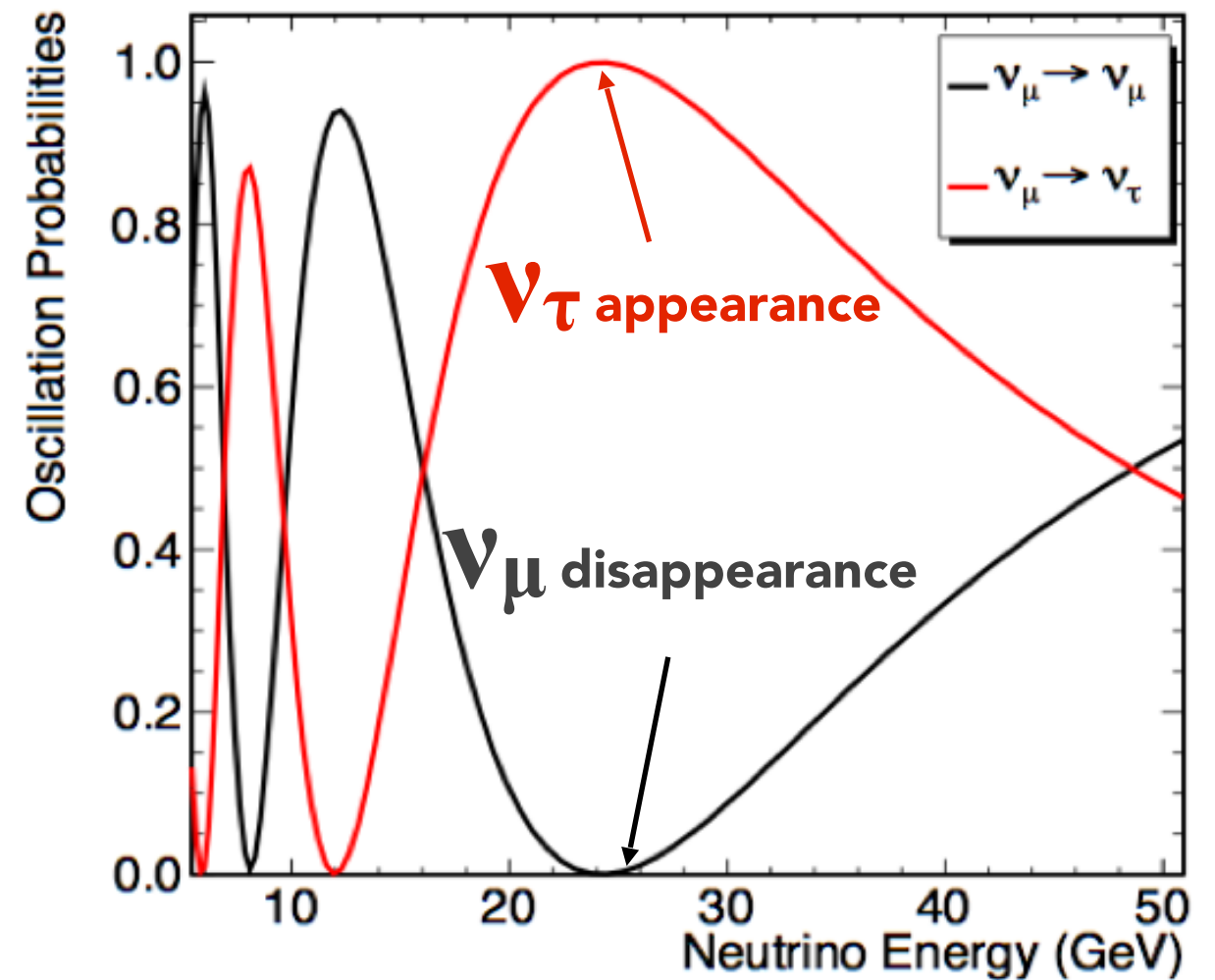
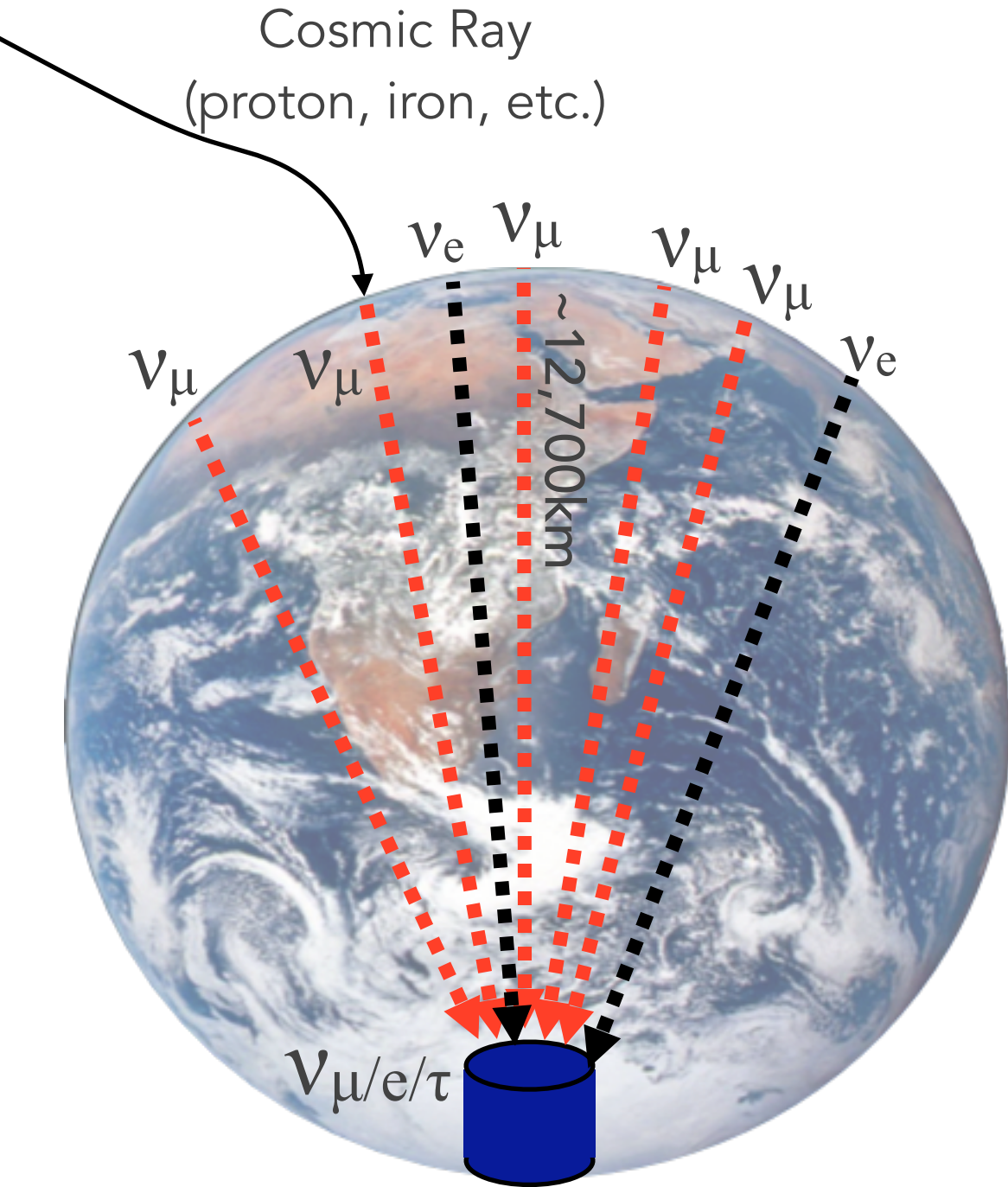


Particle Physics with Neutrinos

-

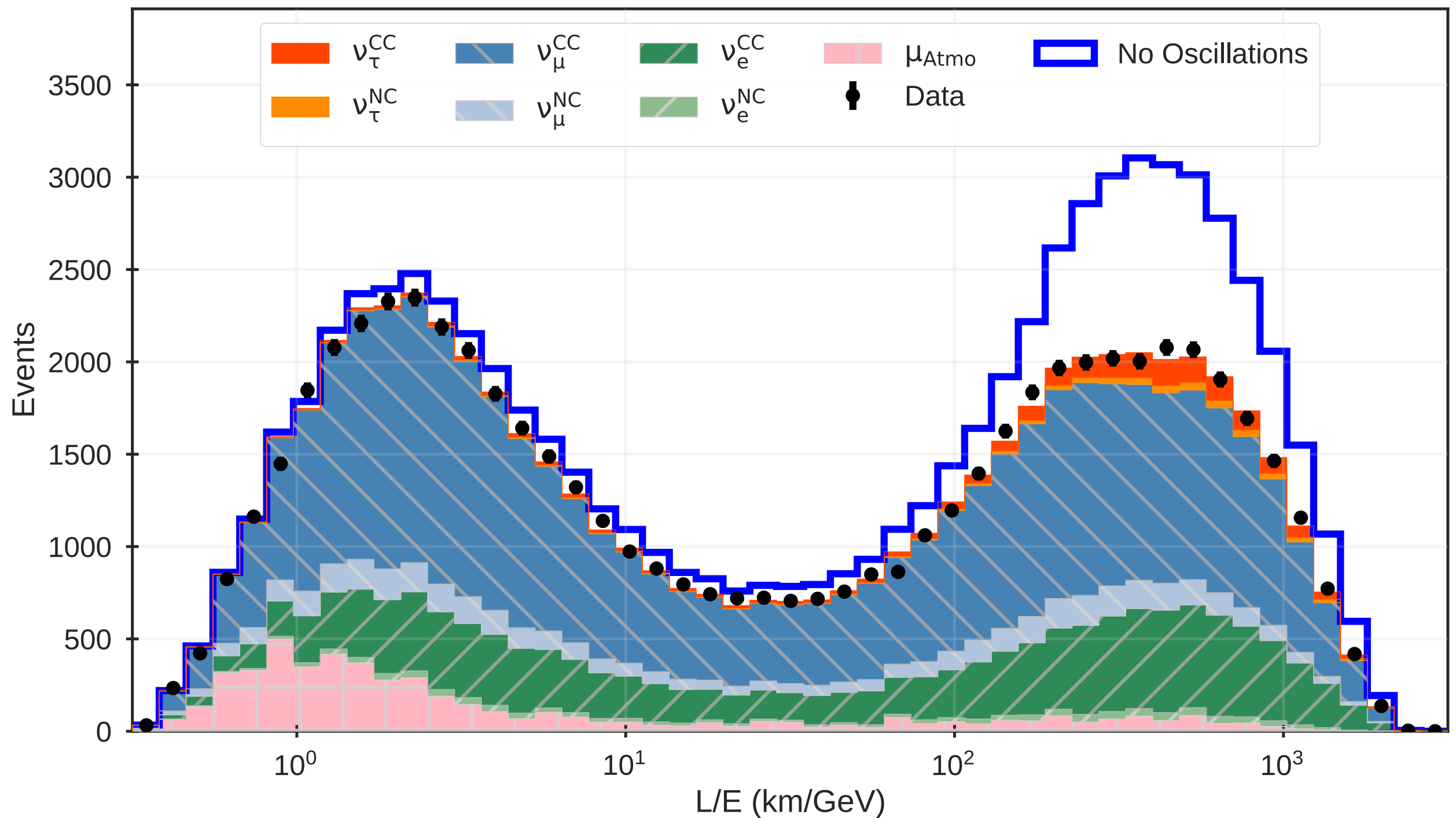
Neutrino Oscillation

Atmospheric Neutrino Oscillation



- Neutrinos interact in flavor states (ν_μ , ν_e , ν_τ), but they quantum mechanically oscillate between flavors as fundamental mass states (ν_1 , ν_2 , ν_3)

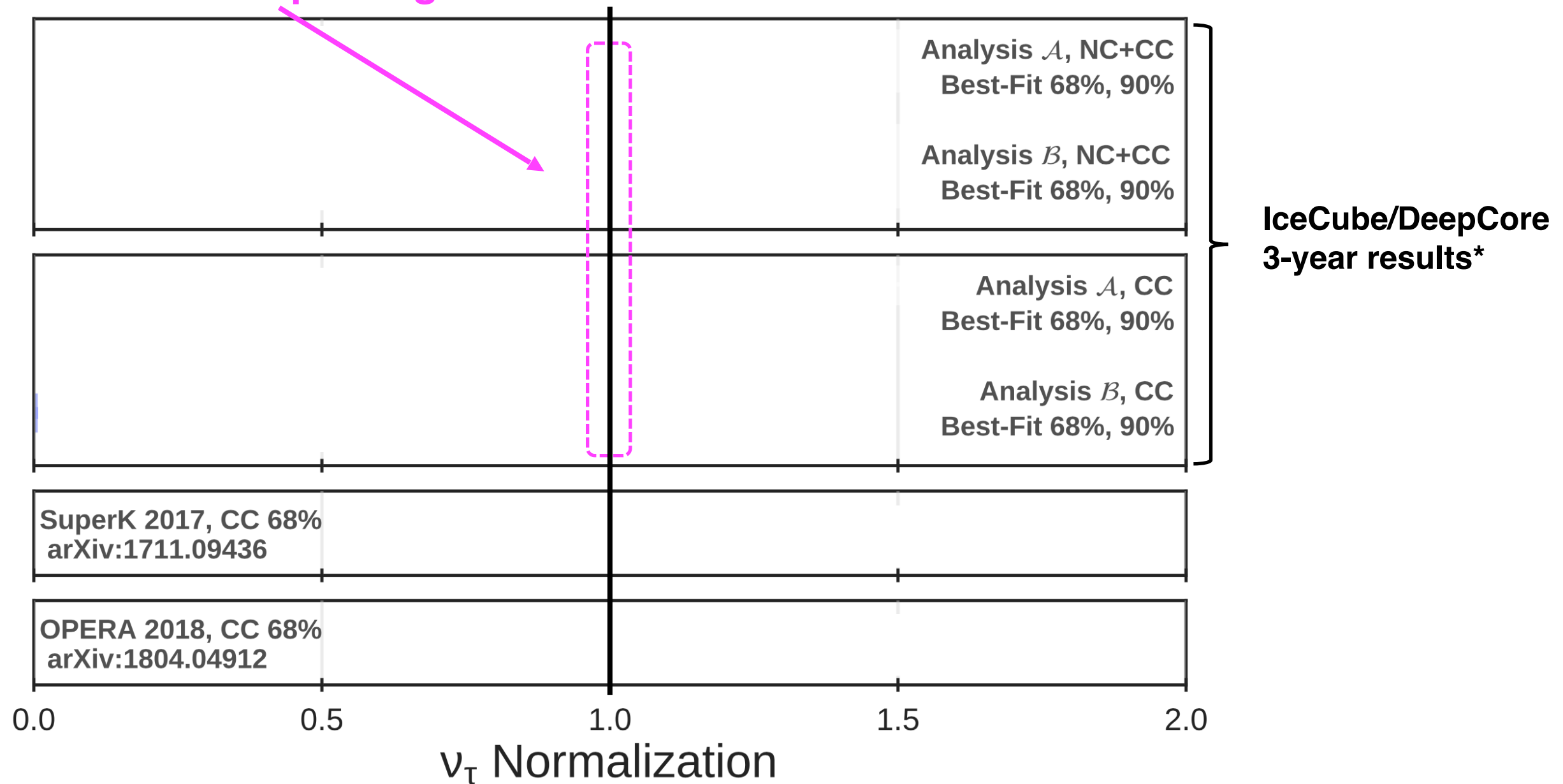
Neutrino Oscillation Data



2.35k tau neutrinos
(1.8k charged current & 550 neutral current)

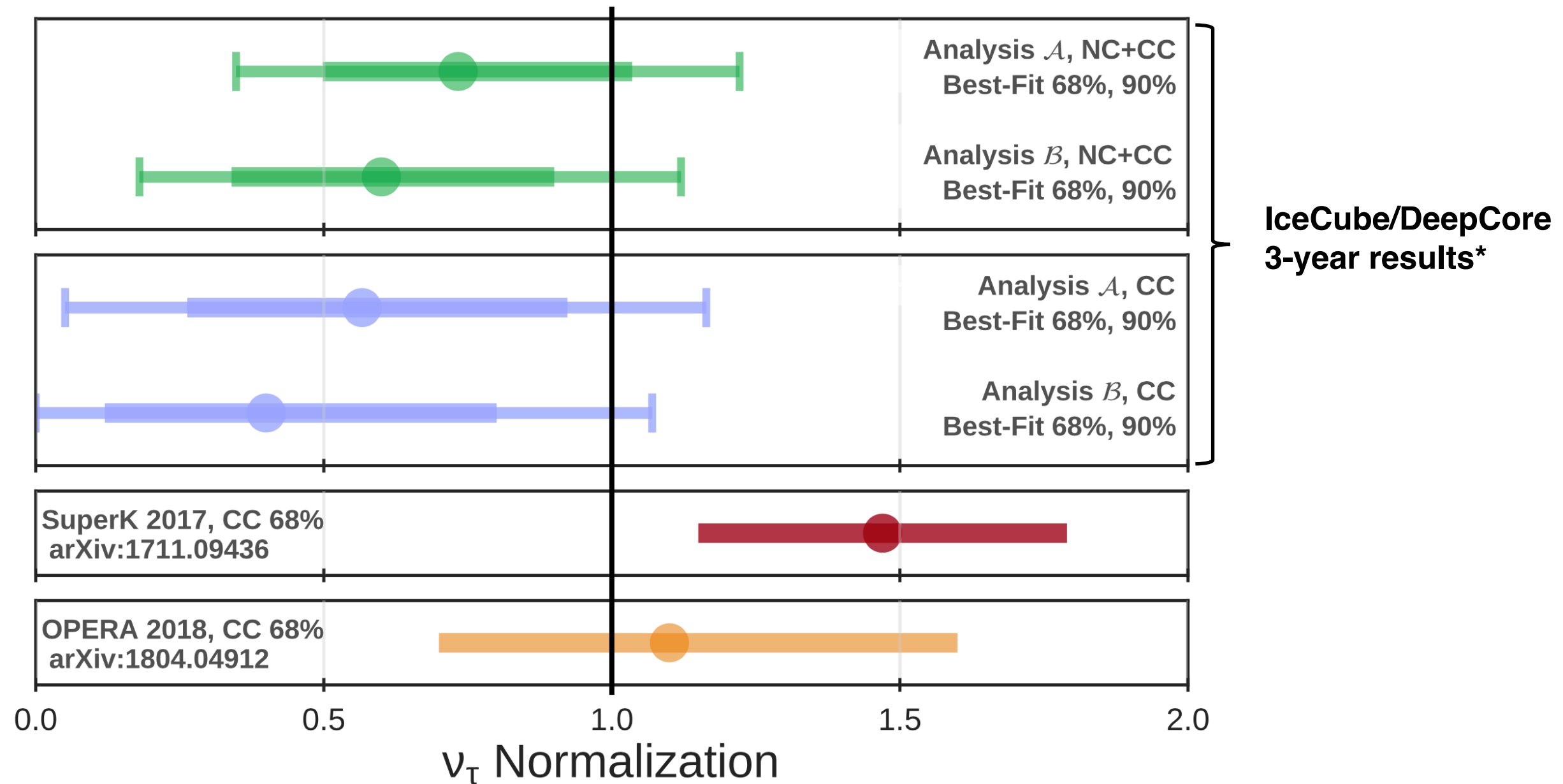
Results

Consistent with standard
neutrino oscillation paradigm



*arXiv:1901.05366

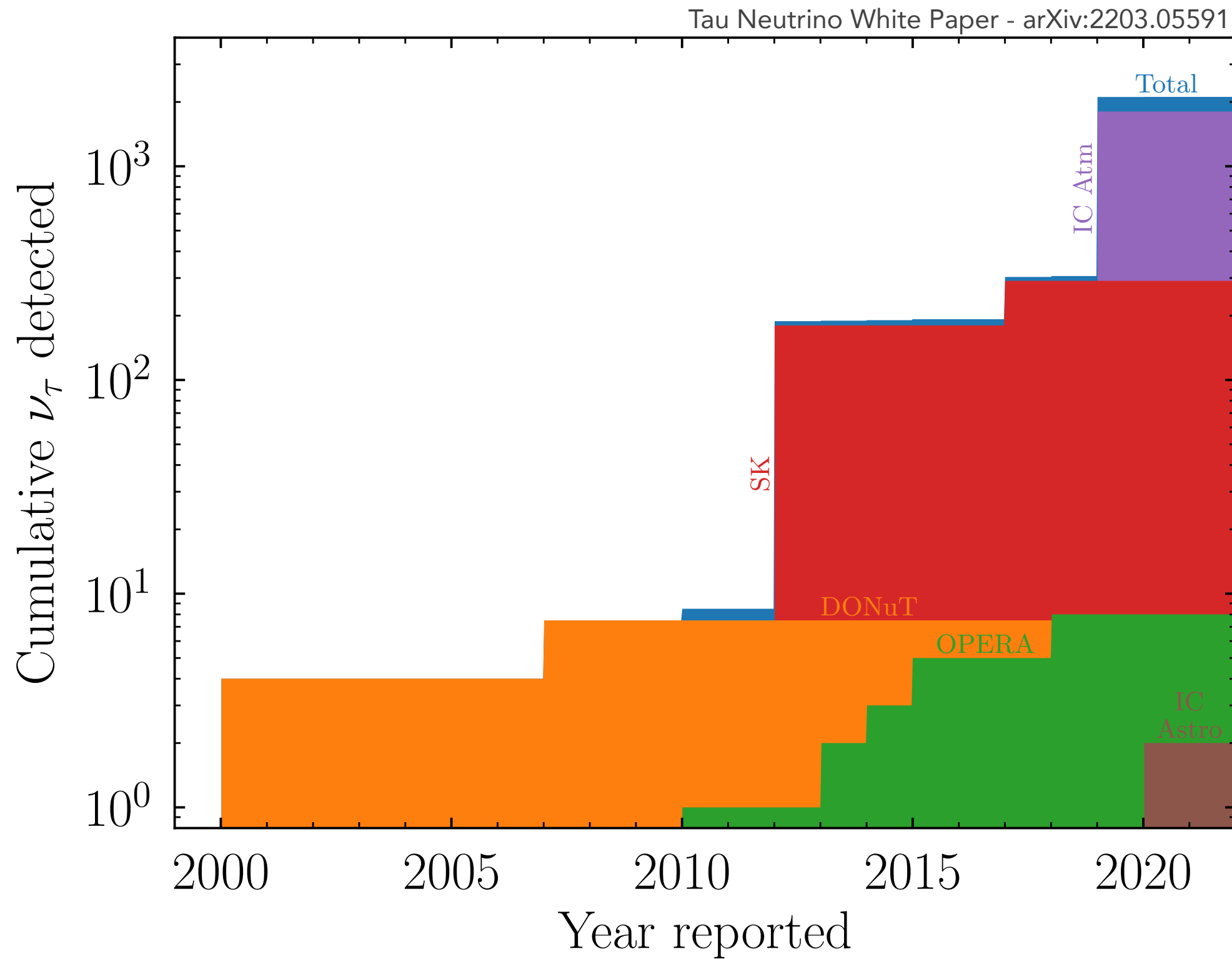
Recent Results



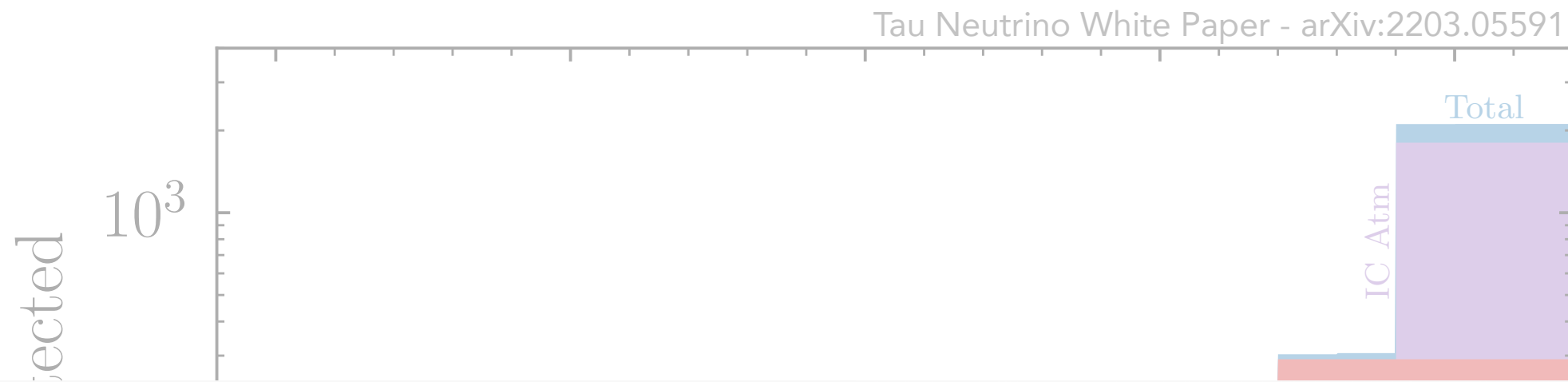
- Any value away from 1.0 is direct evidence of non-unitarity for neutral leptons i.e. neutrinos
- Tau neutrinos are the least well measured particle in the Standard Model
- 8+ year result should be ready for summer 2022 conferences

*arXiv:1901.05366

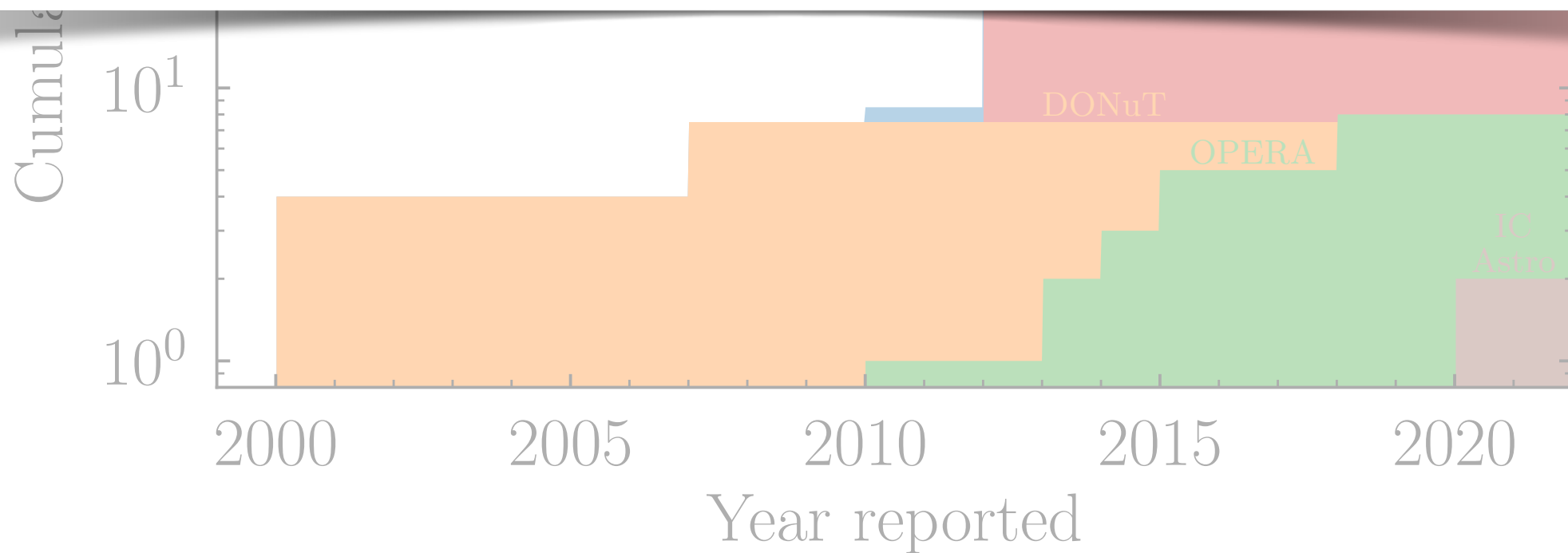
Tau Neutrinos



Tau Neutrinos



86% of all collected tau neutrinos are in IceCube data



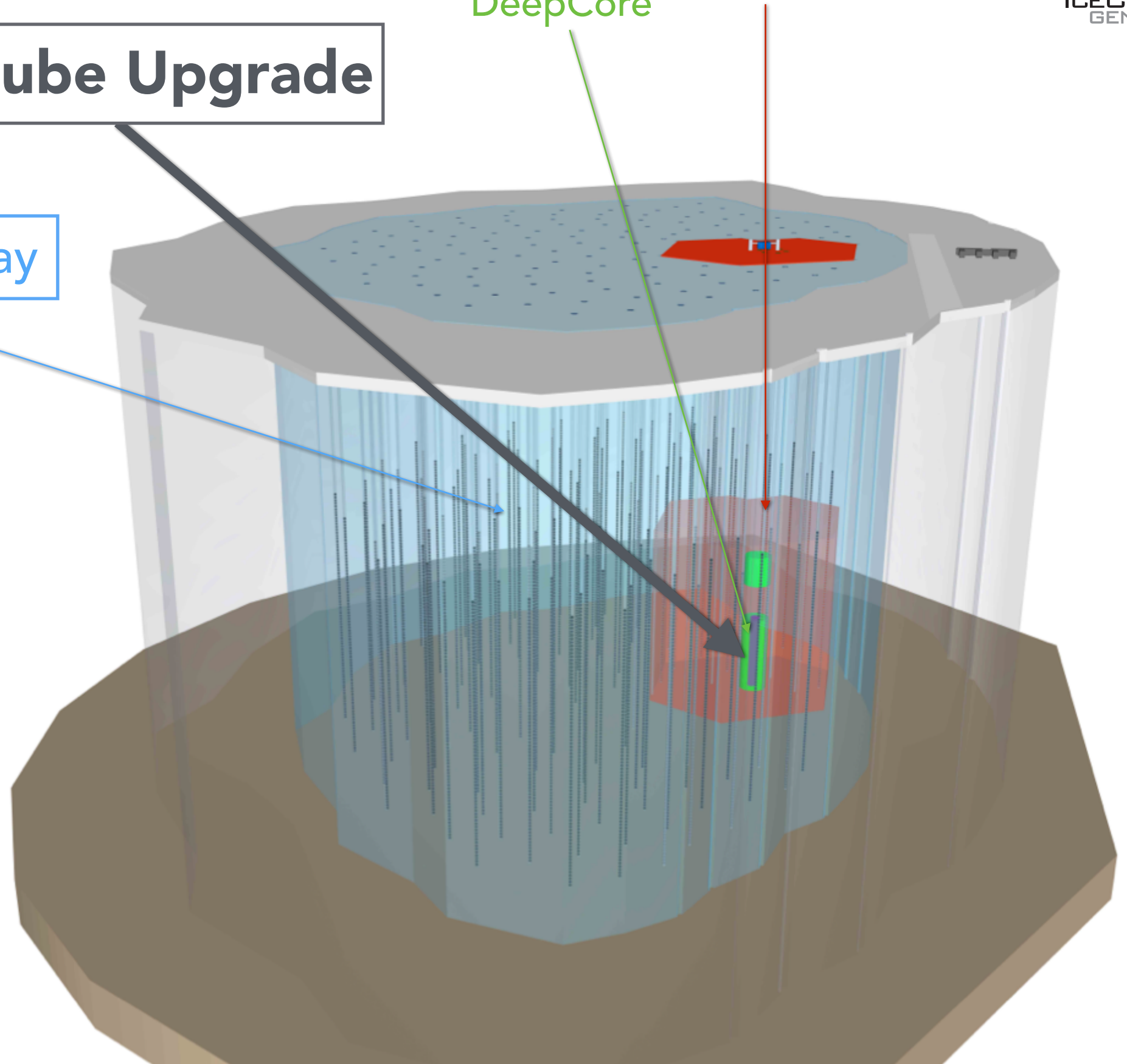
IceCube Future

IceCube Upgrade

High Energy Array

DeepCore

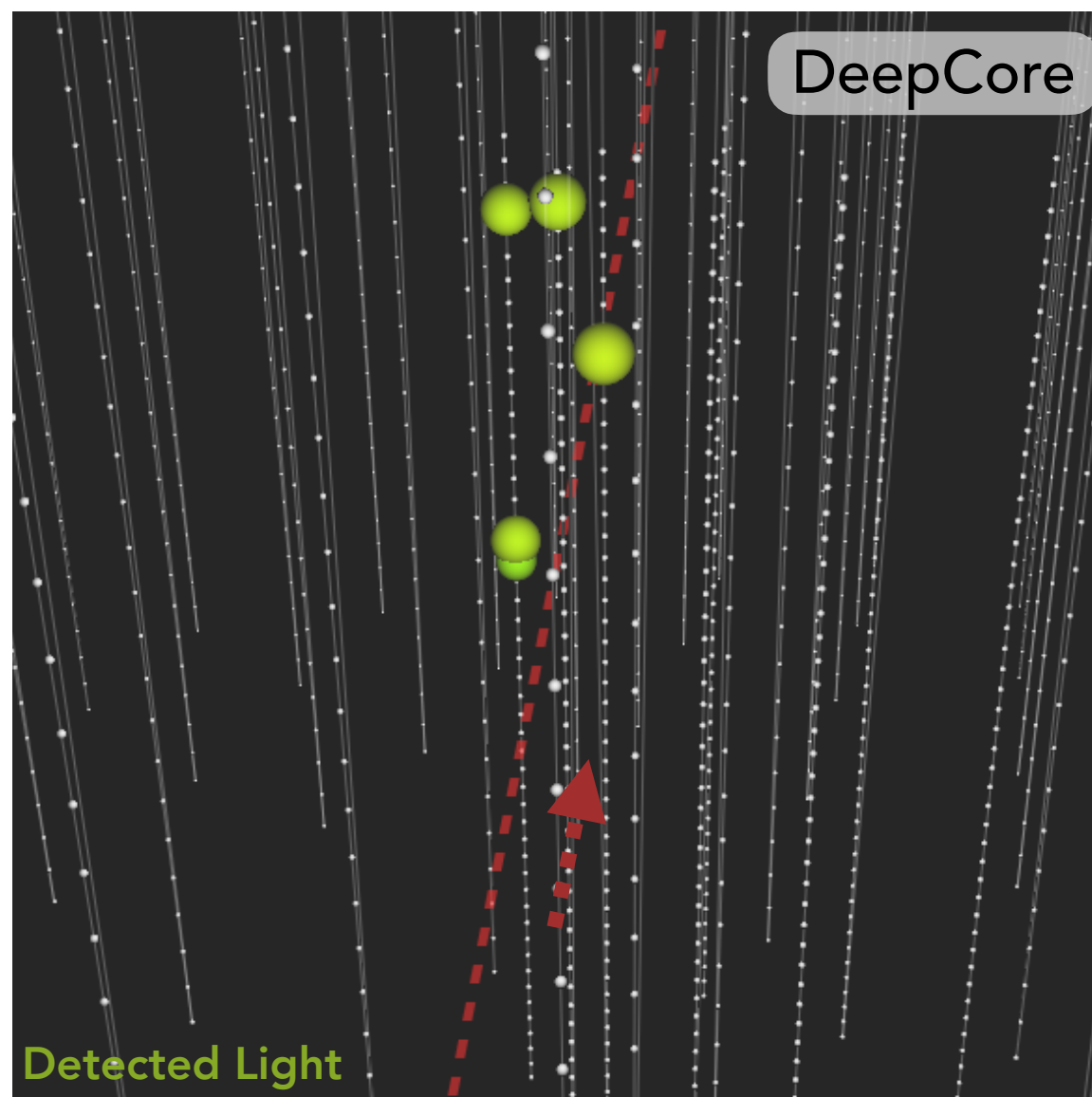
IceCube



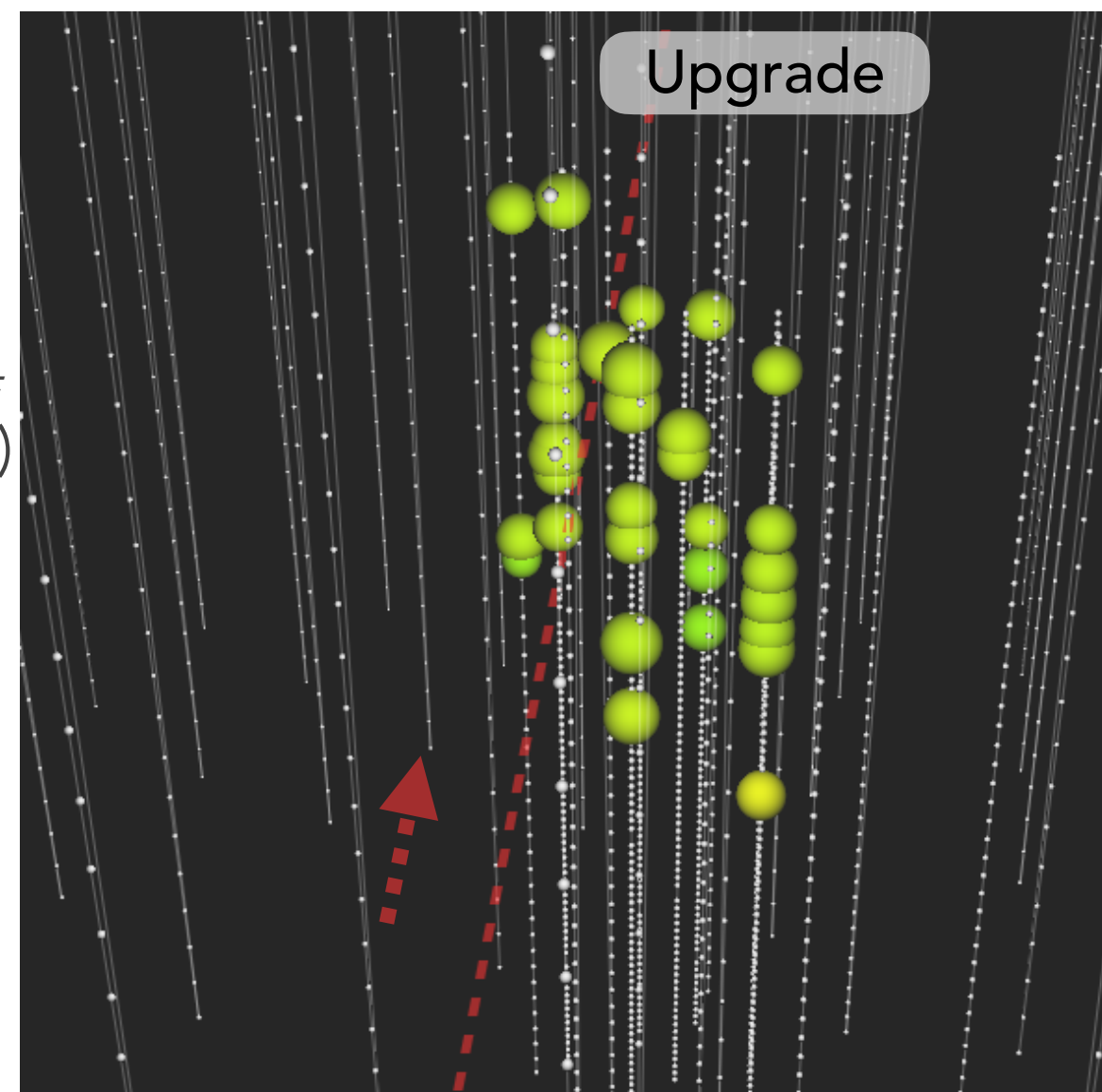
New Optical Sensors

IceCube Upgrade

- Dense instrumentation within inner core
- Dramatic enhancement in precision oscillation analyses and all neutrino analyses $< \mathcal{O}(100)$ GeV
 - 3x improvement in reconstruction resolution
 - 2x improvement in oscillated tau neutrino statistics
- Deployment in 2025/26
- Currently, simulation and all analyses for the IceCube Upgrade are led by the NBI



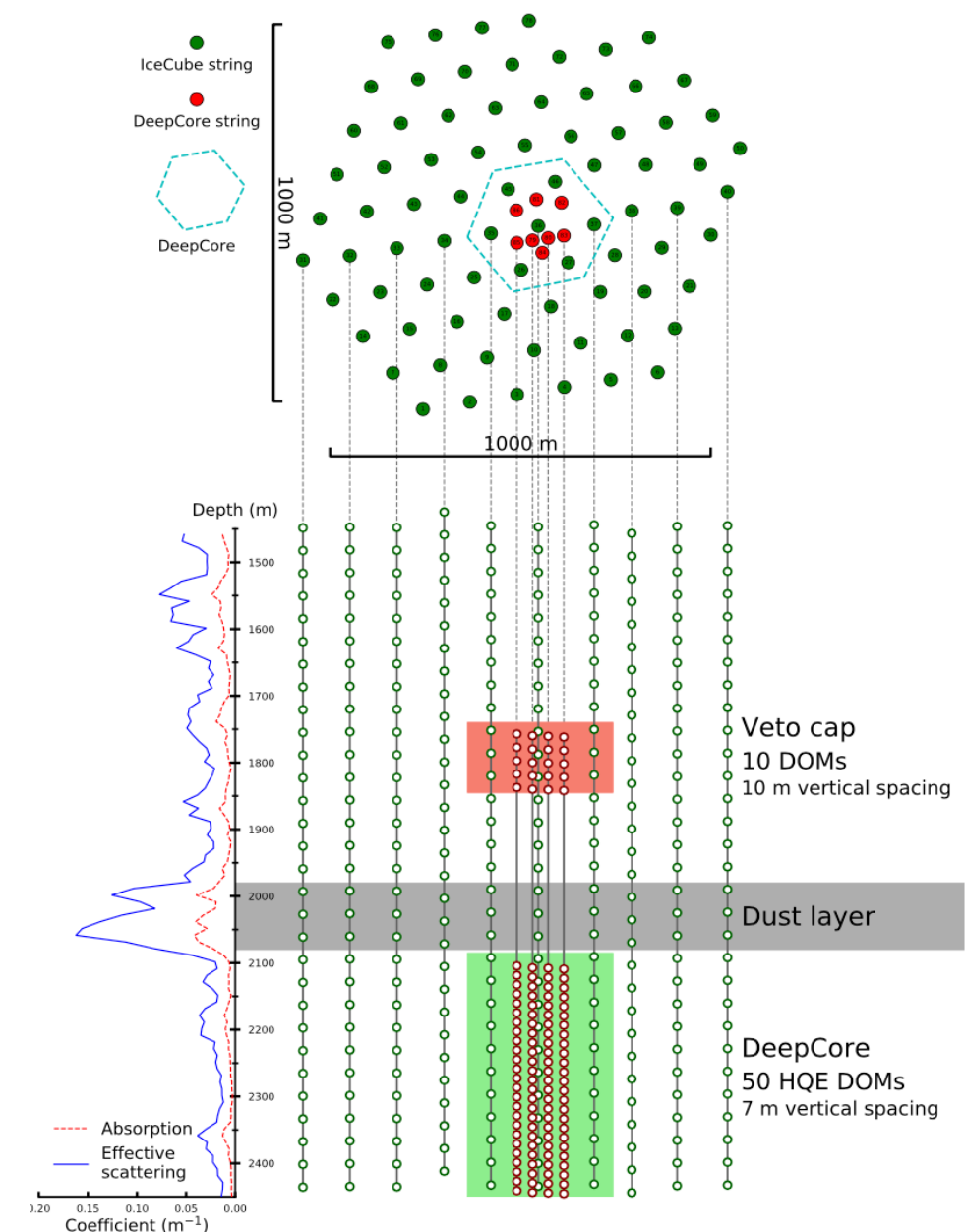
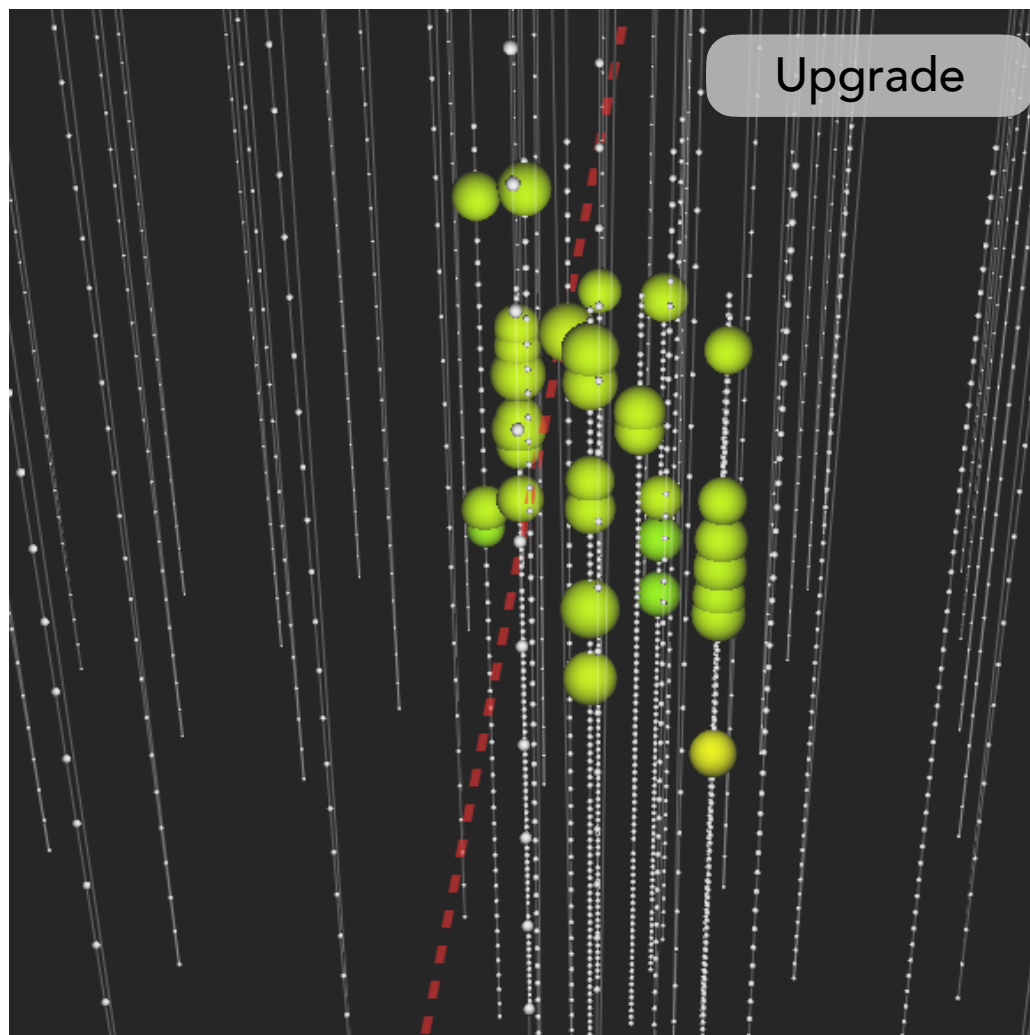
29 GeV ν_τ
(up-going)
→

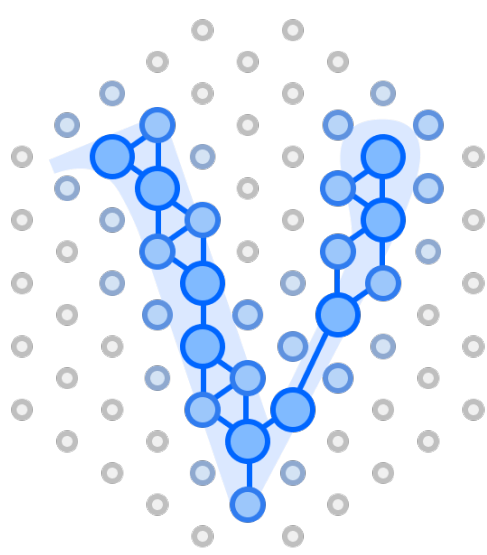


Tools

Analysis Tools & Machine Learning

- IceCube is a sparsely instrumented and asymmetric detector
 - Will get more complicated and asymmetric with the IceCube Upgrade
 - Data is structured, but irregular





GraphNeT

Graph Neural Networks for
Neutrino Telescope Event Reconstruction

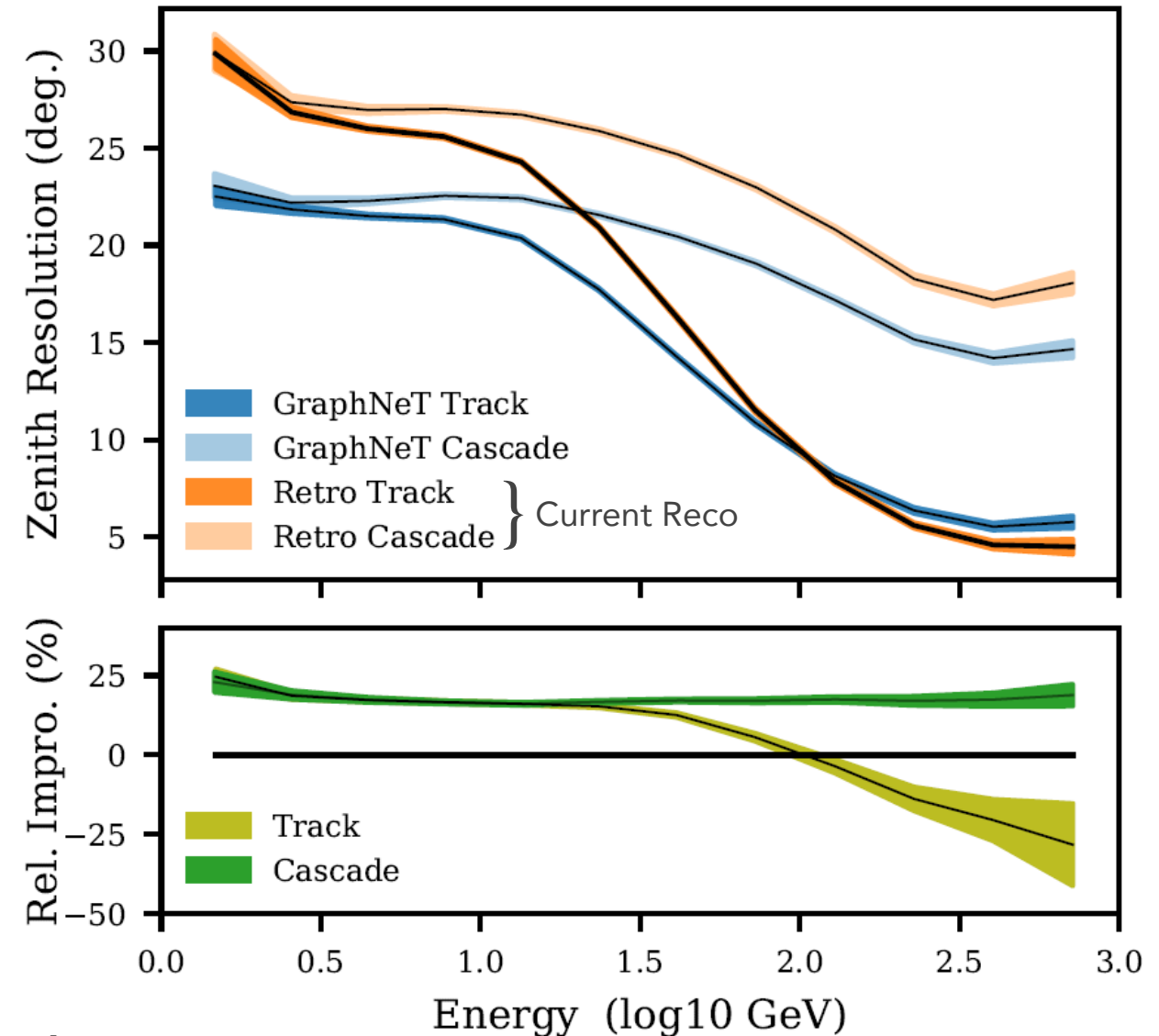
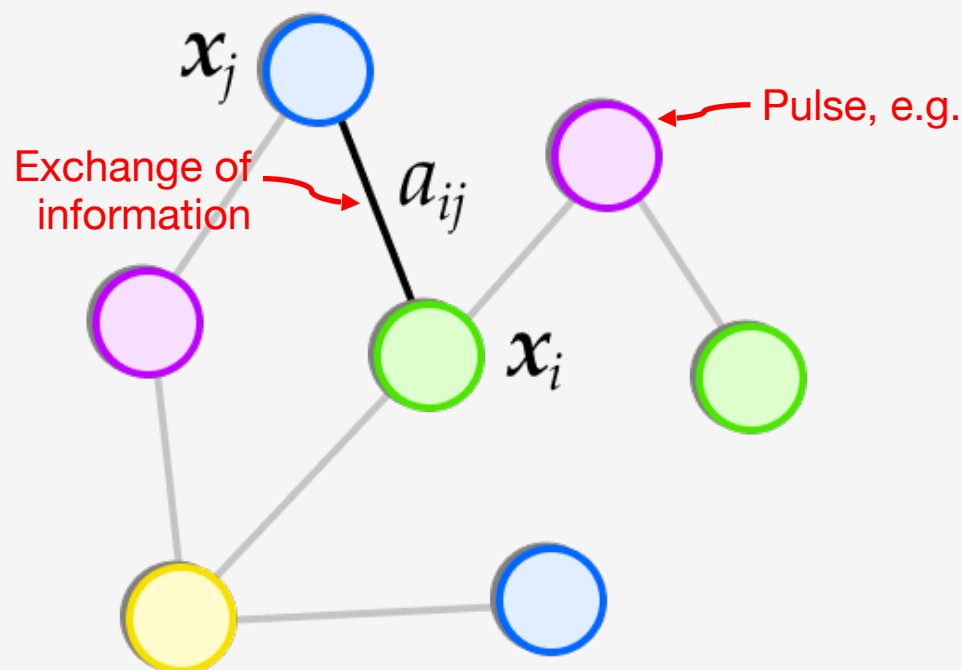
Graph Neural network — GNN

Representation

Data \mathbf{x}_i on nodes a graph; nodes connected by edges \mathbf{a}_{ij}

Structure

Any that can be encoded through *adjacency* of nodes



Development

- Inter-collaboration working group with the largest N. Hemisphere neutrino telescope (KM3NeT)
- Shared development, locally, between IceCube & ATLAS groups

Conclusion & Priorities

- Significant contributions to multi-messenger astronomy and neutrino oscillations
- Prepare for first data from IceCube Upgrade
- Develop analysis tools for existing, near future, and farther future IceCube detector(s)



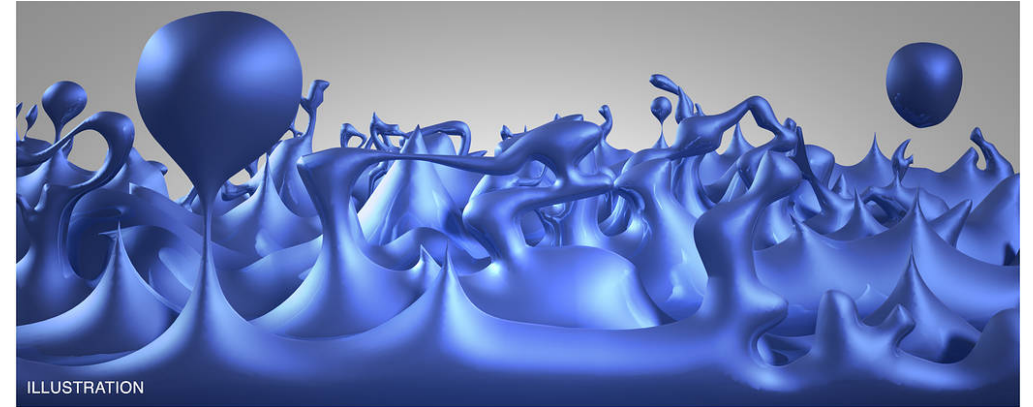
Thanks

Backup

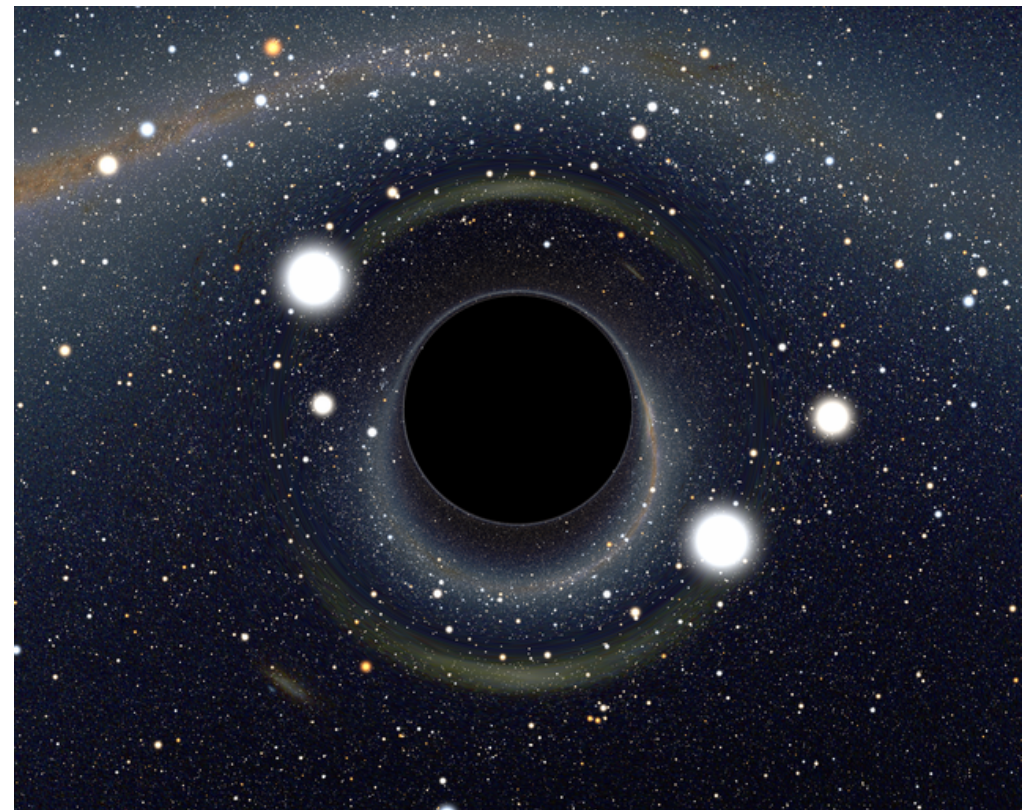
Quantum gravity

Although no accepted theory of quantum gravity exists, some general features can be predicted:

- **Space-time fluctuates** at tiny distances
- Often called **space-time foam**
- Can result in short-lived, microscopic "**virtual black holes**"



[www.nasa.gov/chandra]



[arxiv.org/abs/1511.06025]

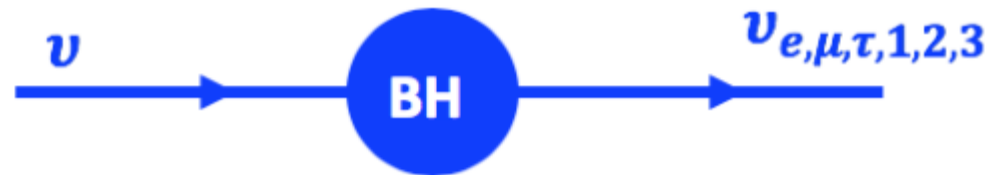
Quantum gravity and neutrinos

Virtual black hole interactions:

Extreme phase perturbation



Neutrino flavor/mass state democratically selected

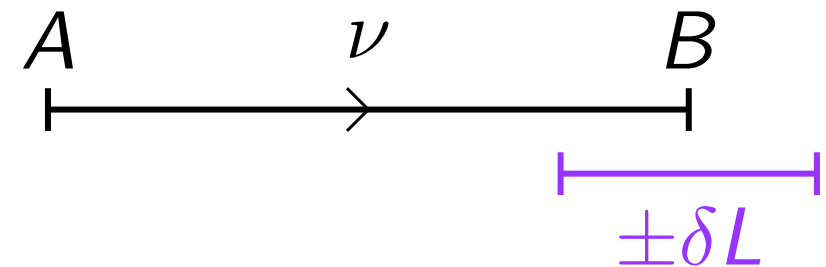


Neutrino lost

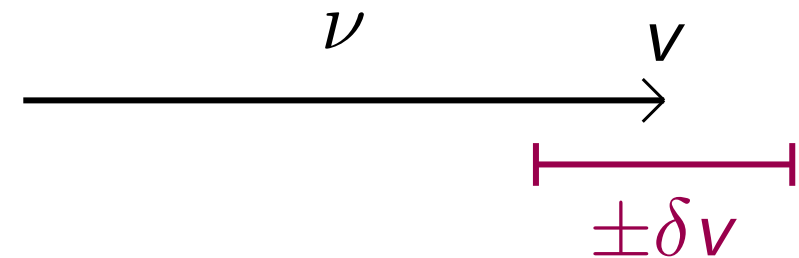


Lightcone fluctuations:

Distance fluctuations



Velocity fluctuations



[arxiv.org/abs/2007.00068]

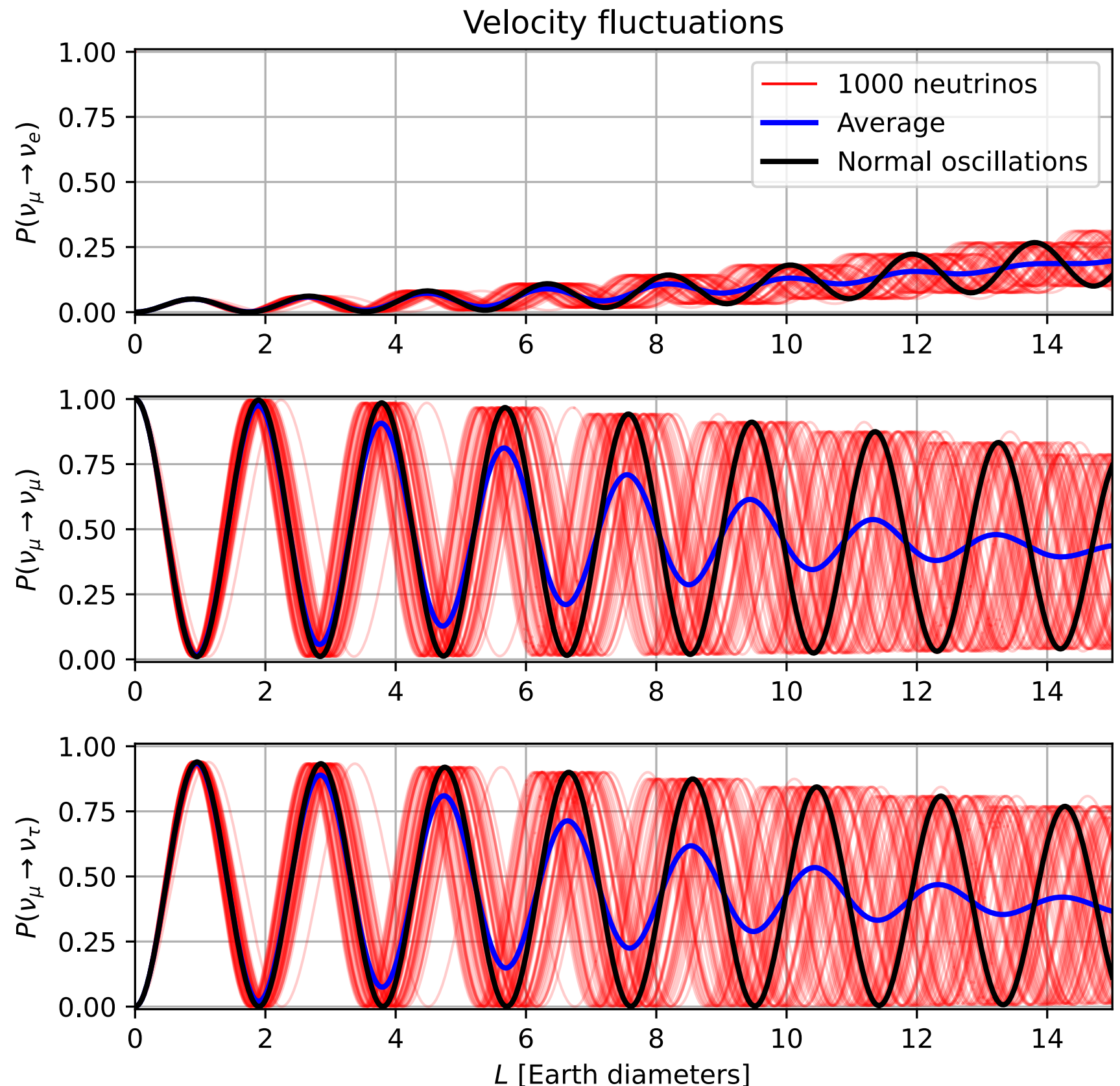
[arxiv.org/abs/2103.15313]

Toy model simulations

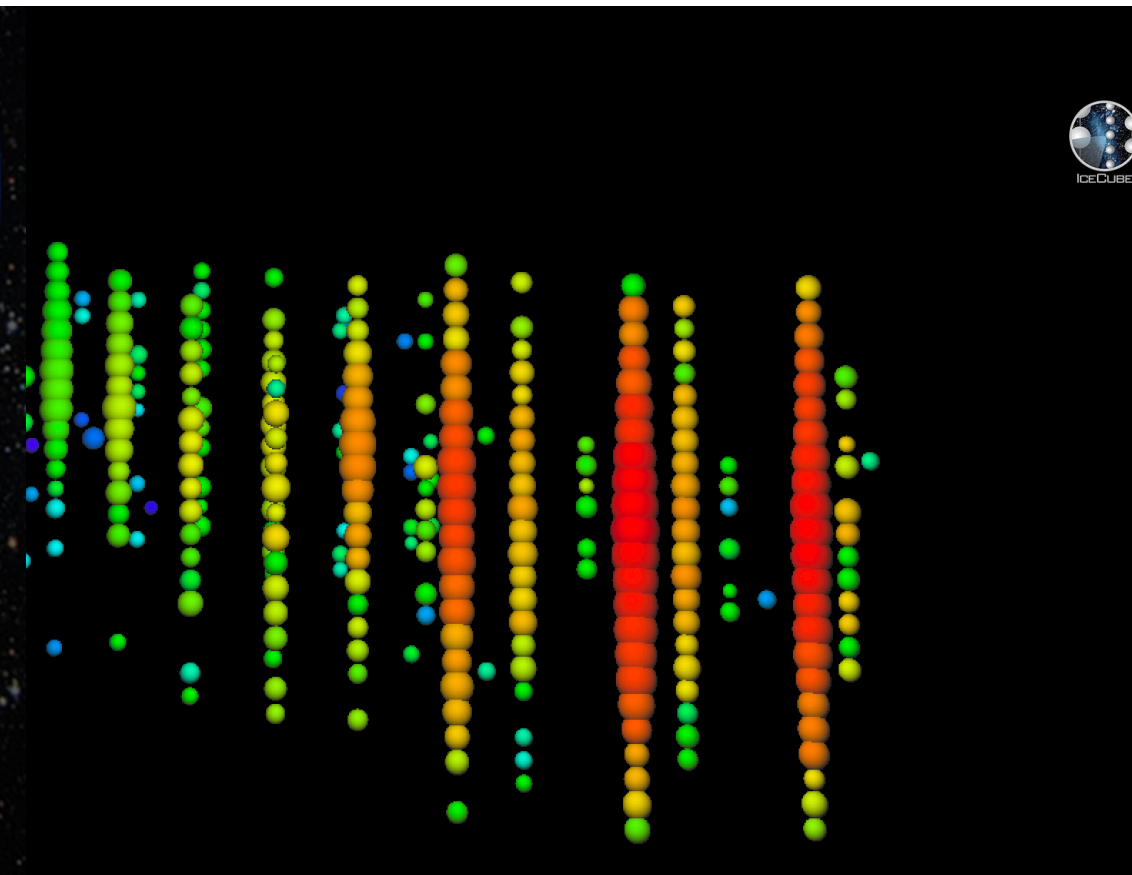
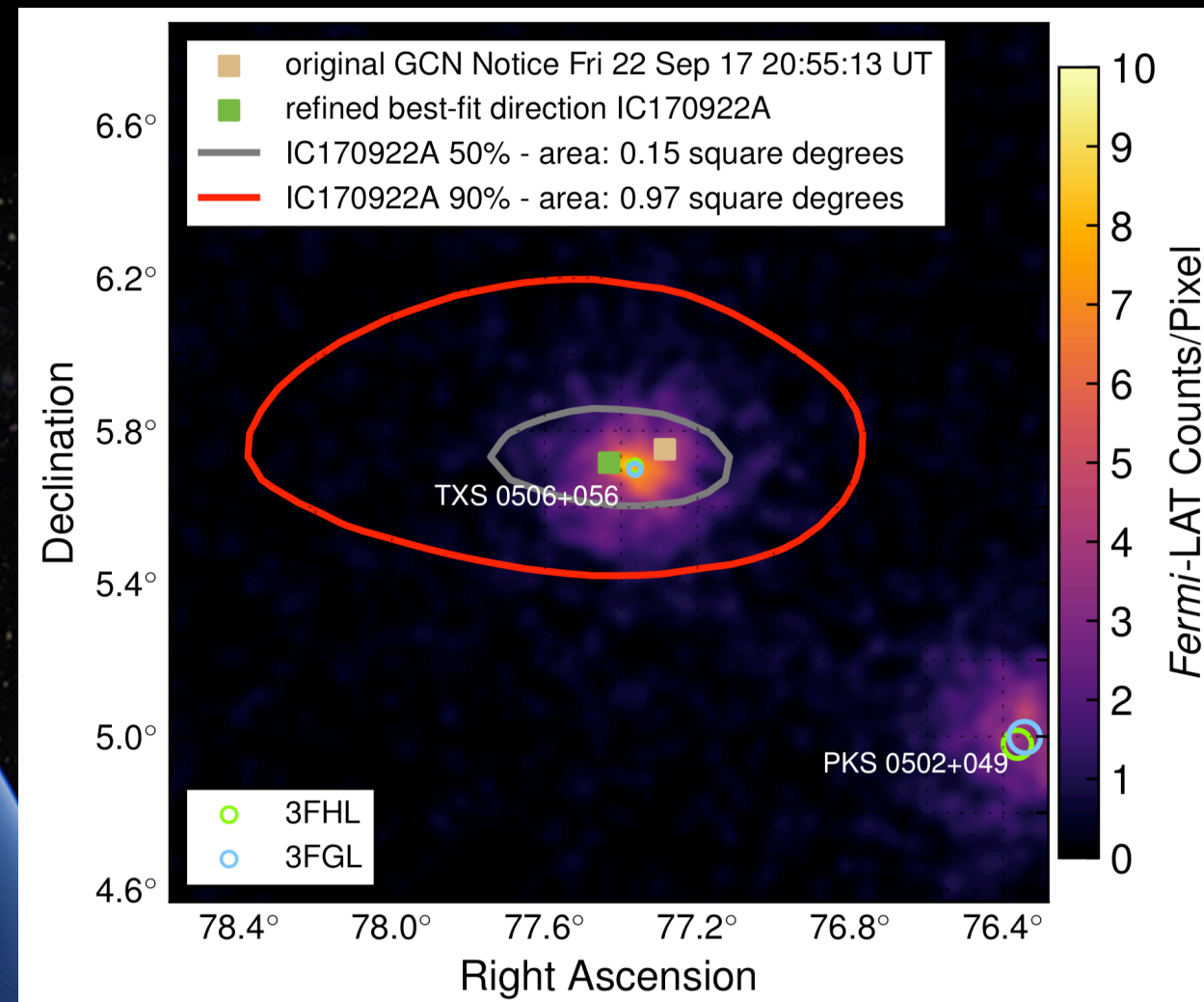
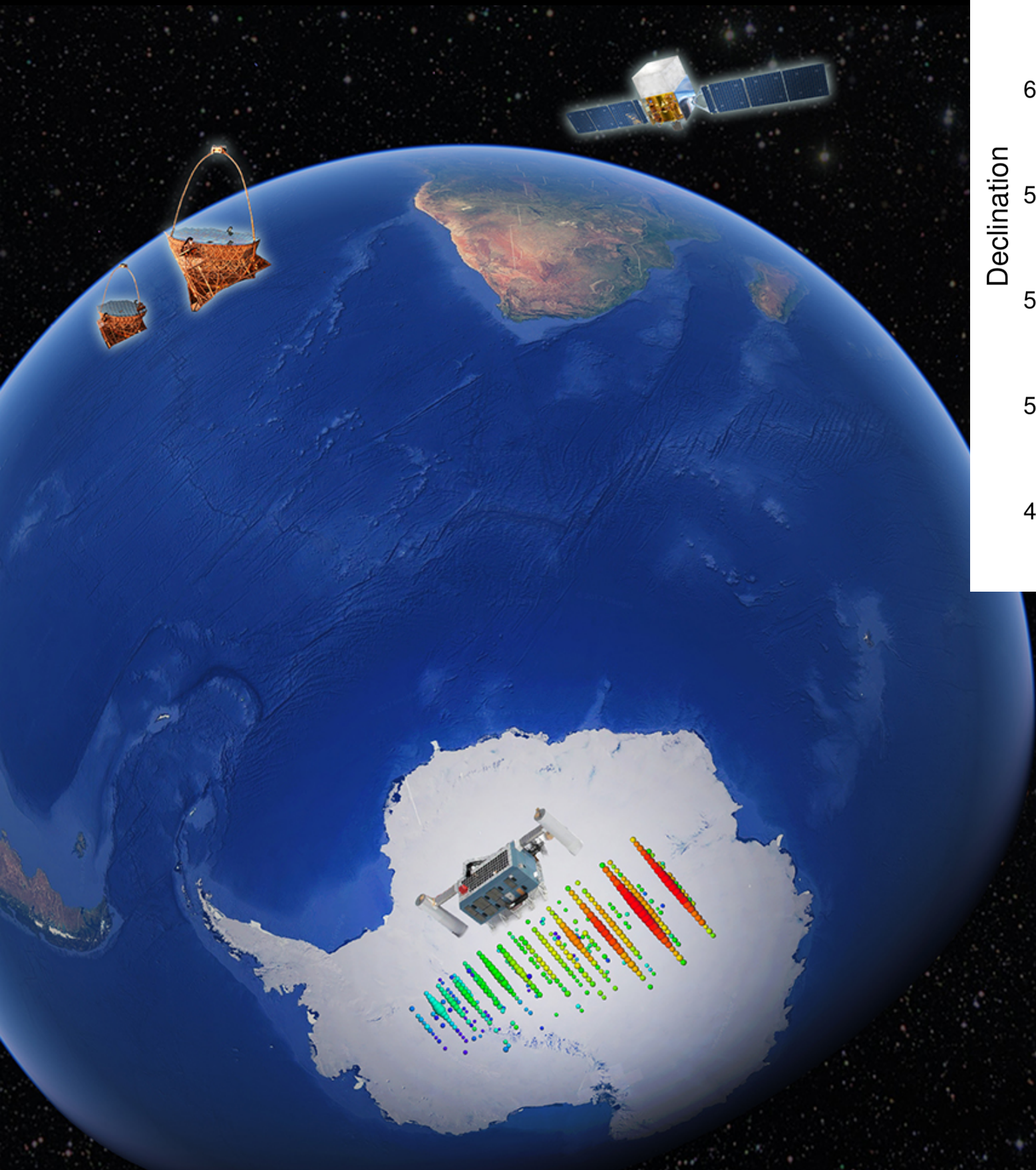
Propagate 1000
neutrinos

Inject random phase
perturbations,
distance
fluctuations etc.

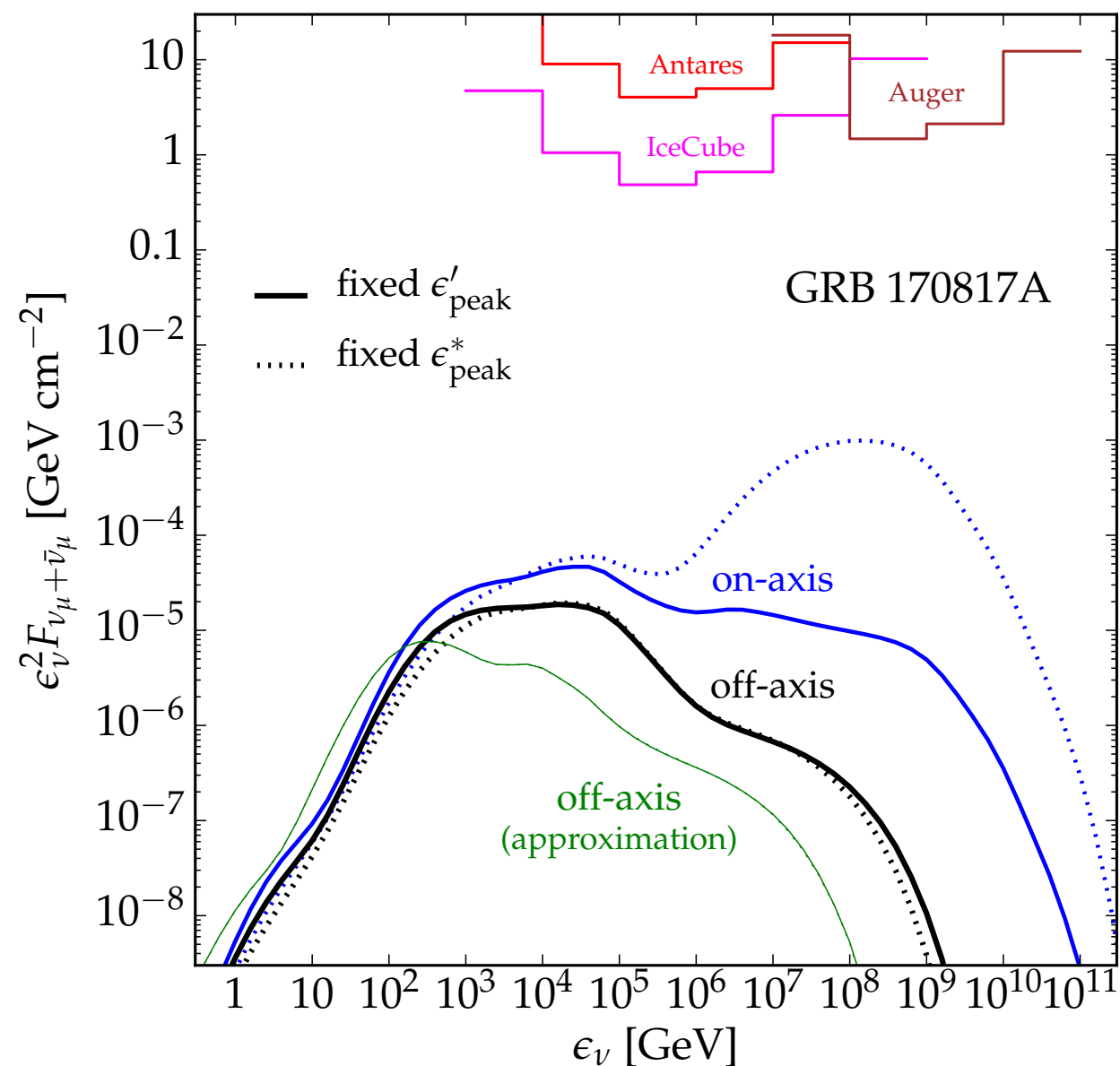
**Oscillations are
dampened for all
scenarios**



IceCube-170922A

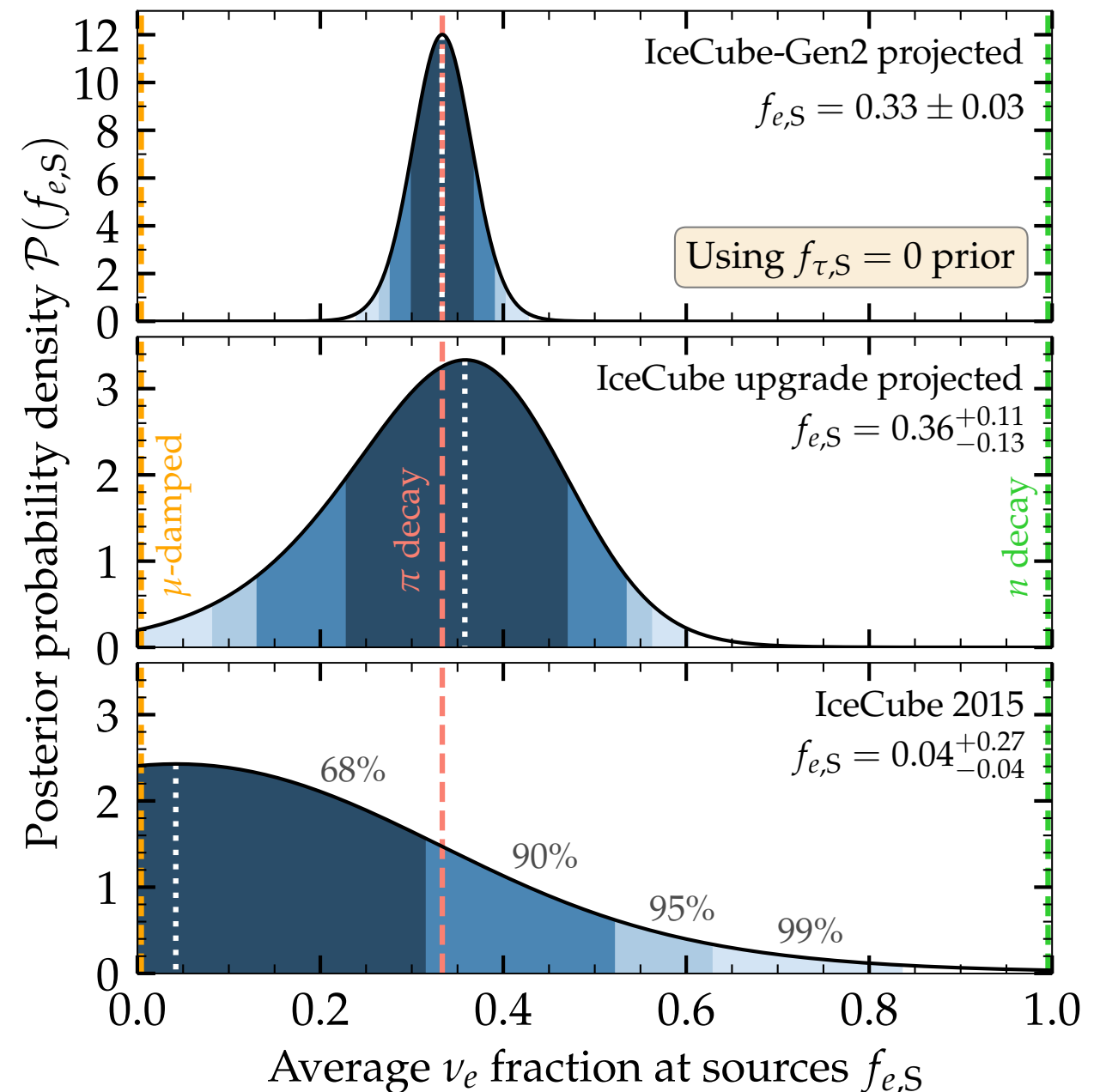


Probe of Astrophysics

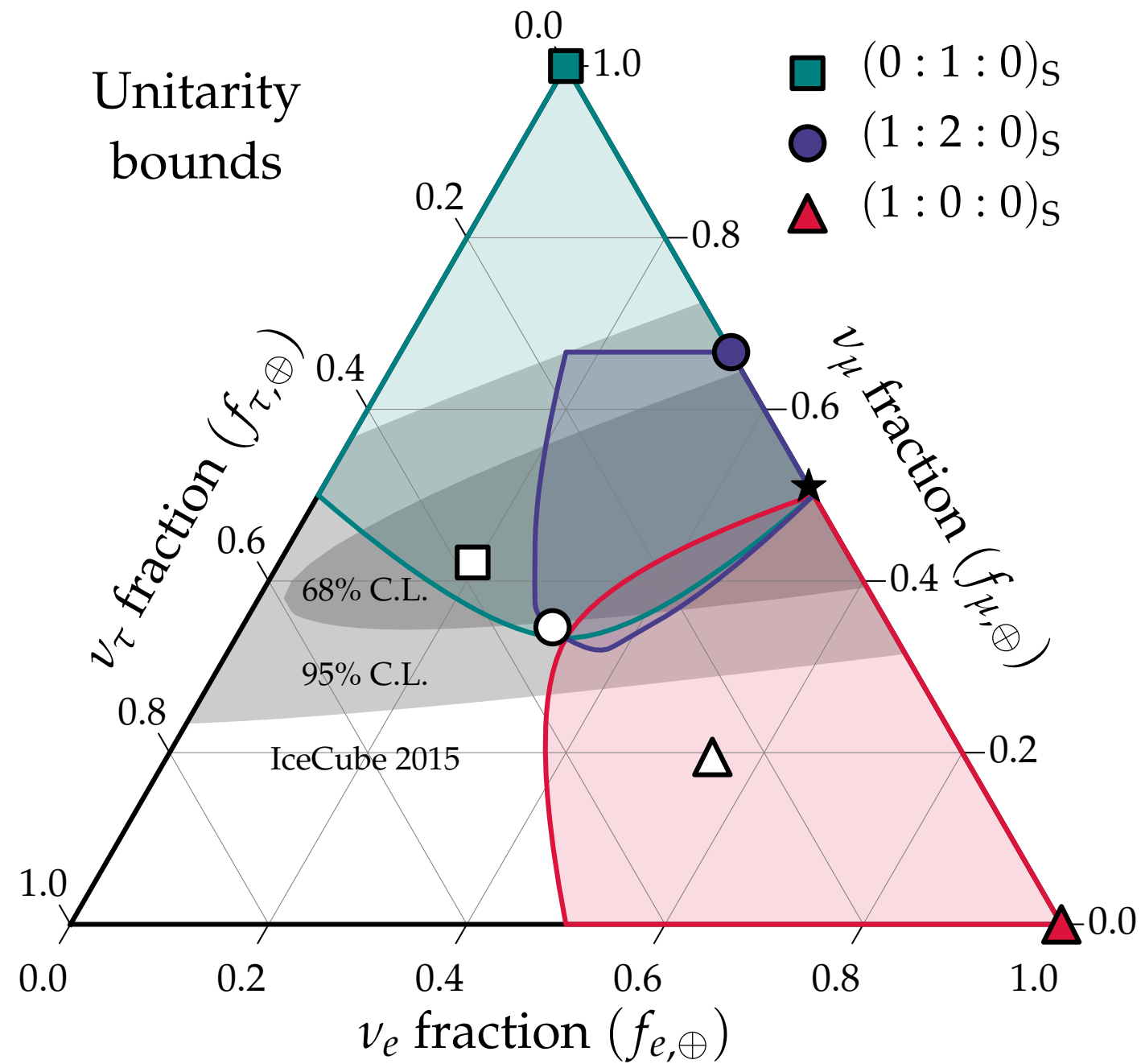


“Neutrino Fluence from Gamma-Ray Bursts: Off-Axis View of Structured Jets”
 [MA & Halser, **MNRAS** 490 (2019)]

“Inferring the flavor of high-energy astrophysical neutrinos at their sources”
 [Bustamante & MA, **PRL** 122 (2019)]



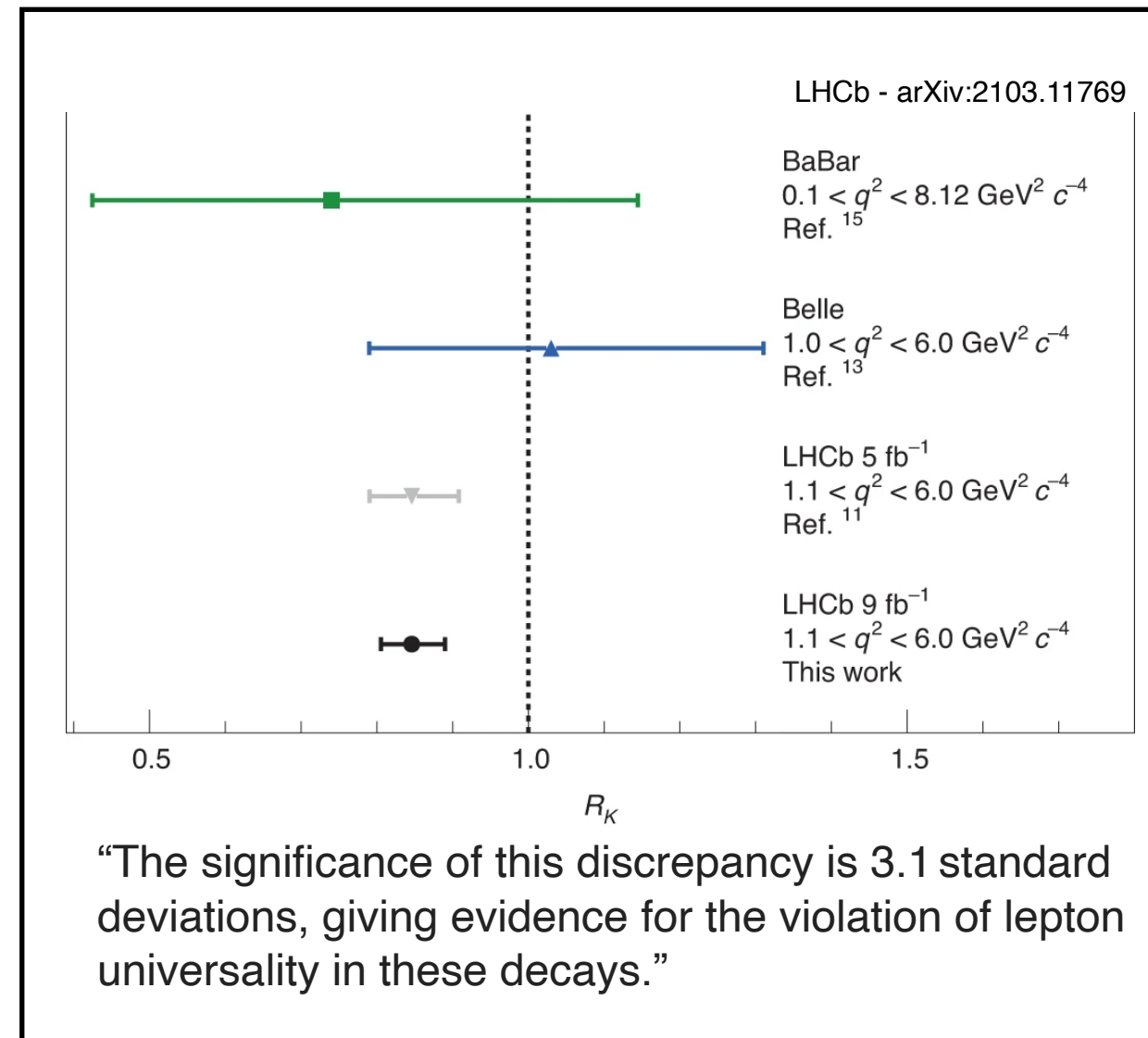
TeV+ Neutrino Unitarity



Lepton Universality

“2) it is questionable that the DeepCore detector itself can measure the tau neutrino appearance to a good degree of accuracy which will allow a scientifically reasonable test of the PMNS matrix’s unitarity, in particular in the situation that current neutrino oscillation data and precision electroweak data only tolerate the effects of possible unitarity violation at or below the one percent level”

**Grant rejection for IceCube tau neutrino oscillation unitarity focus*

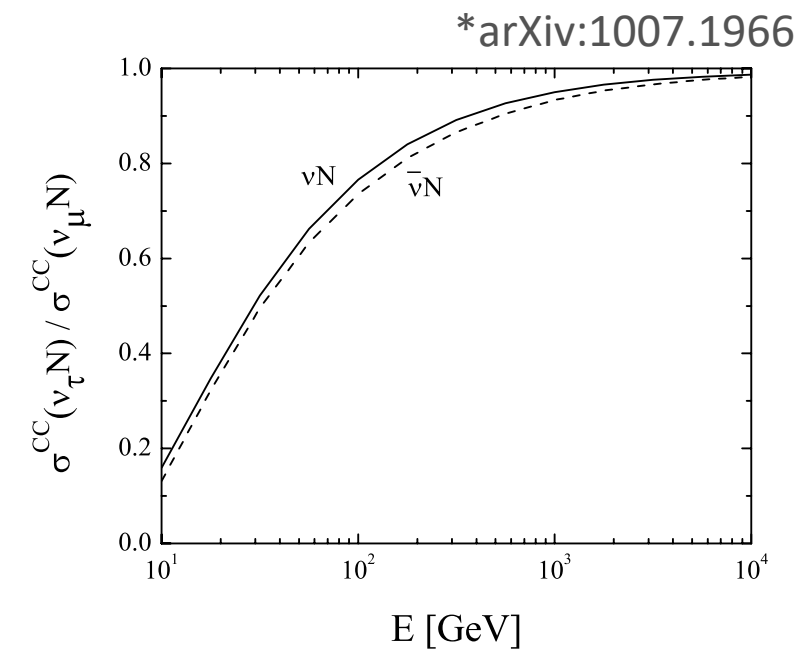
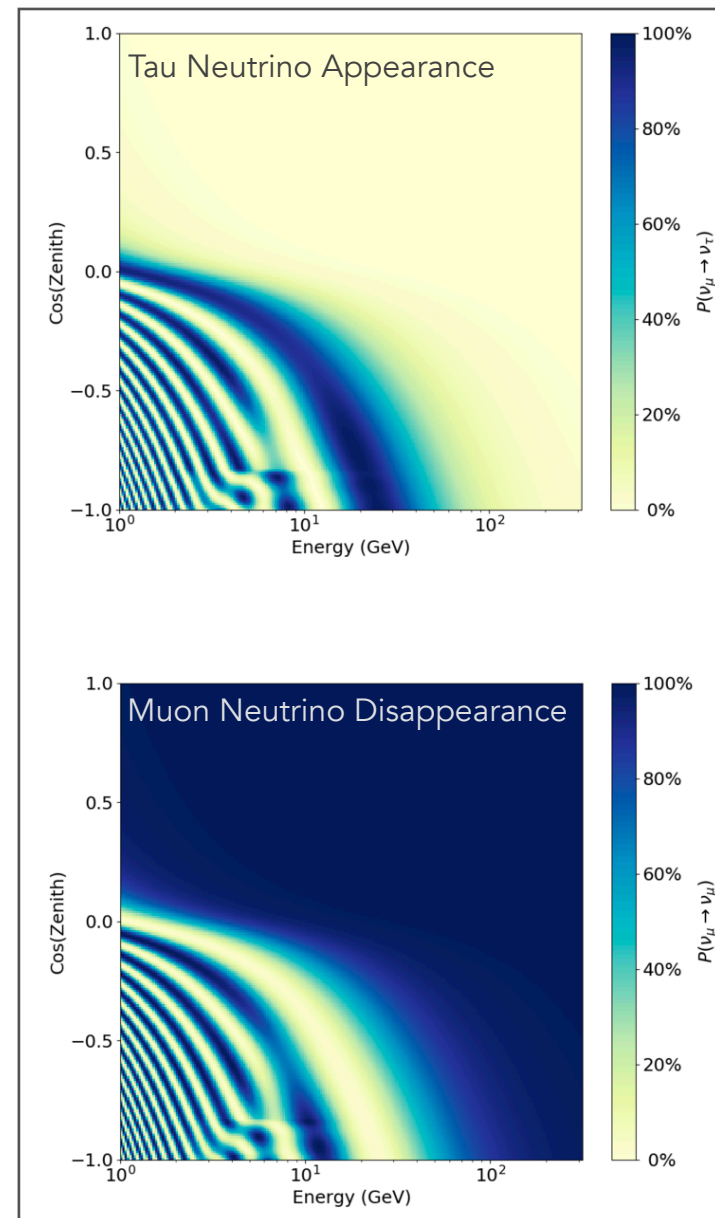
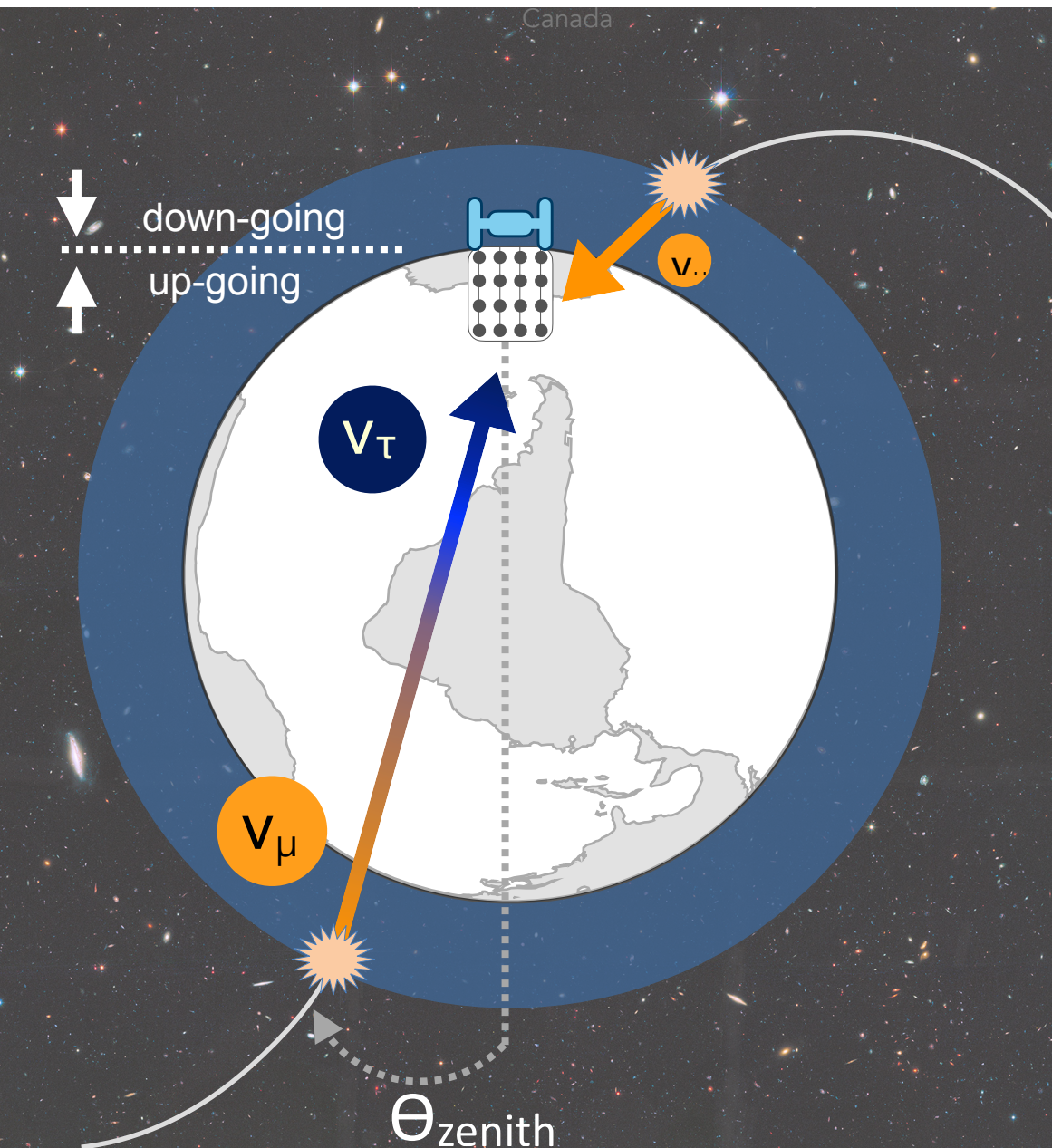


- Accelerator-based and astro-based particle physics distinctions are becoming artificial boundaries, and both hadron and lepton fields have positive (and negative) feedback loops

Why IceCube/DeepCore/Upgrade for Atmospheric ν_τ ?

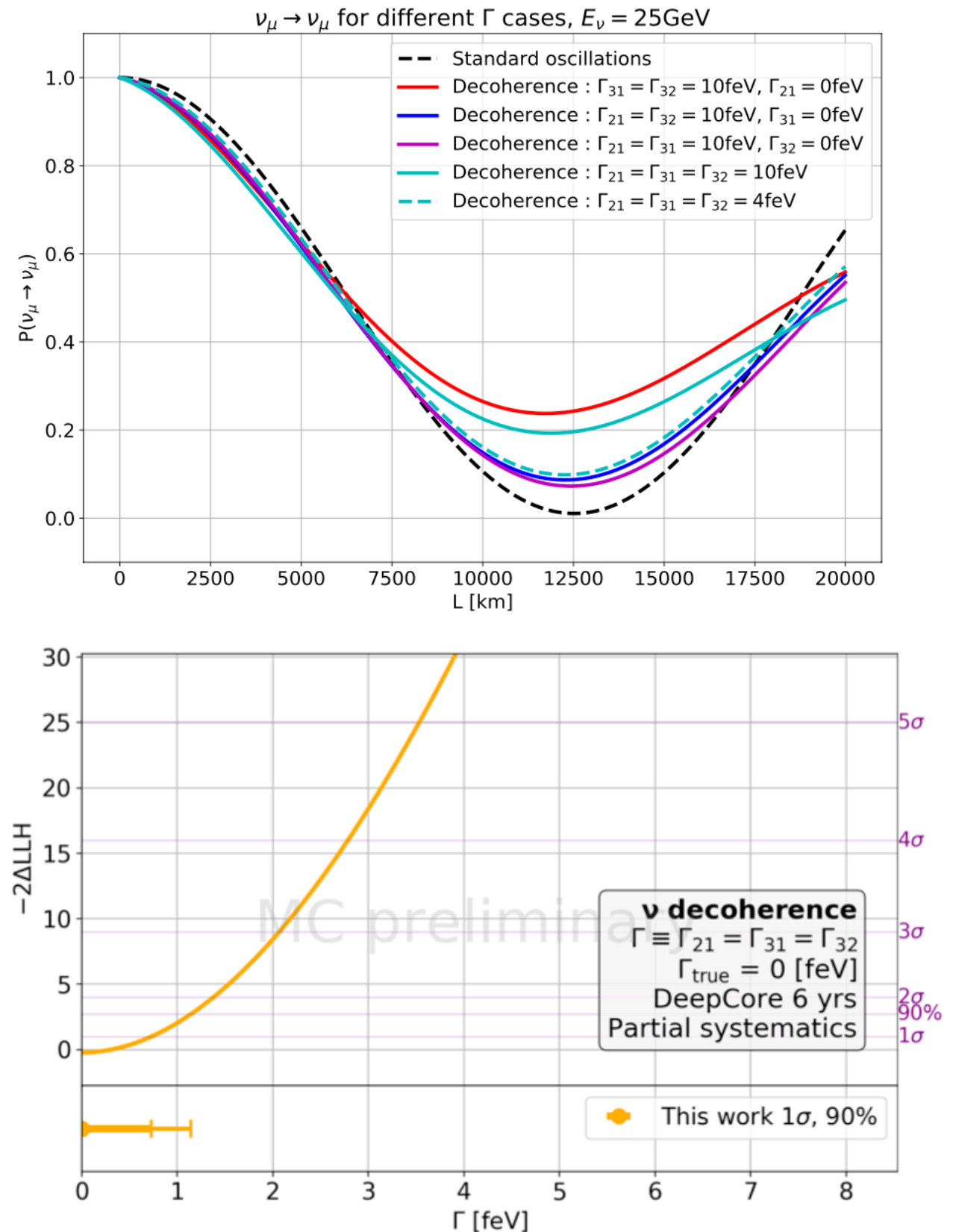
ν_τ ?

Beckett, S. Meneguolo, Royal Astronomical Society of Canada

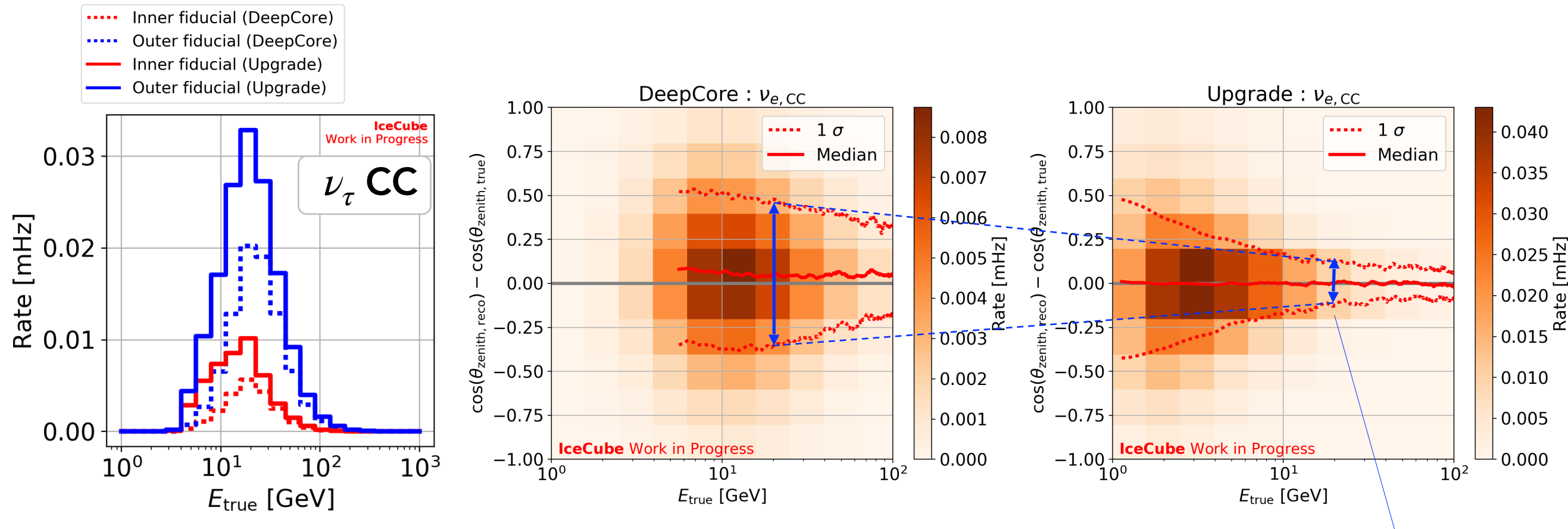


New Scales

- With tens of thousands of atmospheric neutrinos, IceCube is sensitive to planck scale physics
- Phenomenology and experimental analysis led by NBI IceCube researchers



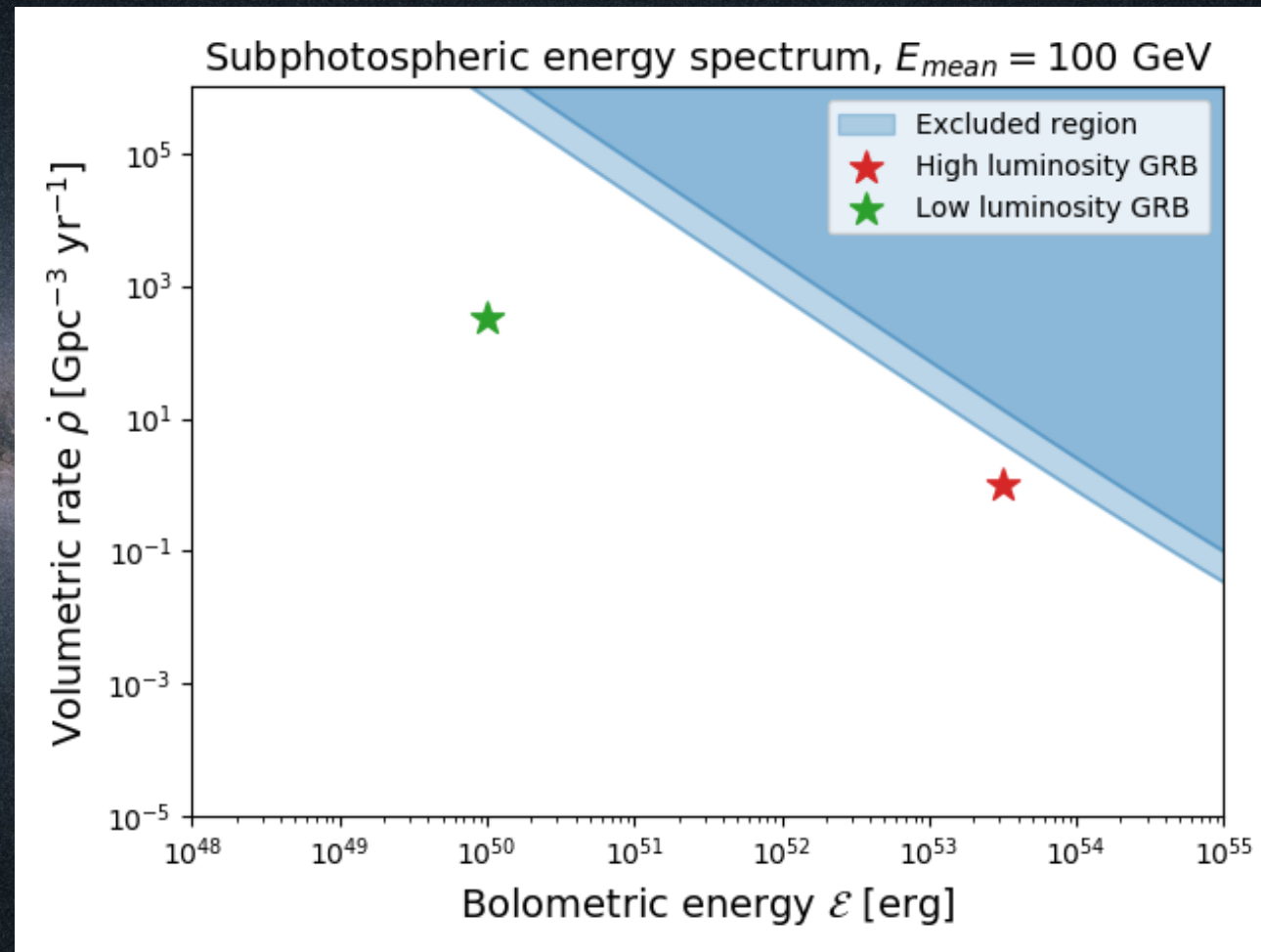
IceCube Upgrade



* ν_e CC and ν_τ CC both appear as cascades. ν_e are an easier proxy for cascade reconstruction development.

3x improvement in cascade resolution @ ν_τ appearance energies

Neutrino+ Astronomy



10 MeV

100 MeV

1 GeV

10 GeV

100 GeV

1 TeV

10 TeV

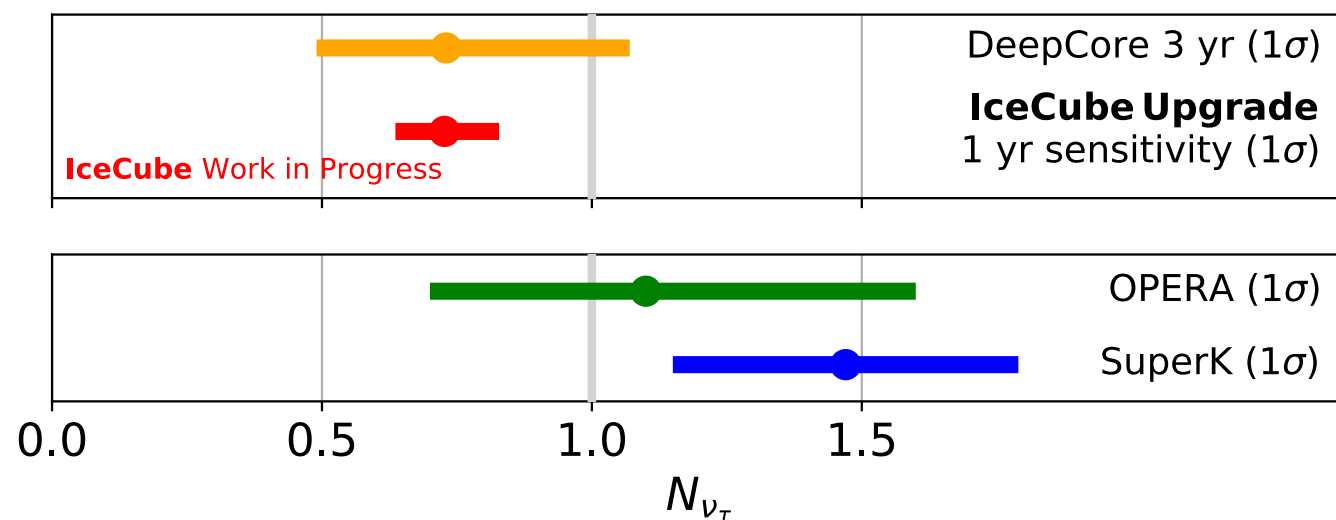
10 PeV

DeepCore

IceCube

IceCube Upgrade

- Conservative experimental choices still illustrate potential of IceCube Upgrade for physics
 - $\sim 10\%$ N_{ν_τ} resolution with 1-year of data
 - Excludes improvements from new reconstructions, better detector systematics, better flux treatment, and no combination of 10+ years of DeepCore data



Analysis Tools & Machine Learning

- IceCube is a sparsely instrumented and asymmetric detector
 - Will get more complicated and asymmetric with the IceCube Upgrade
 - Data is structured, but irregular

