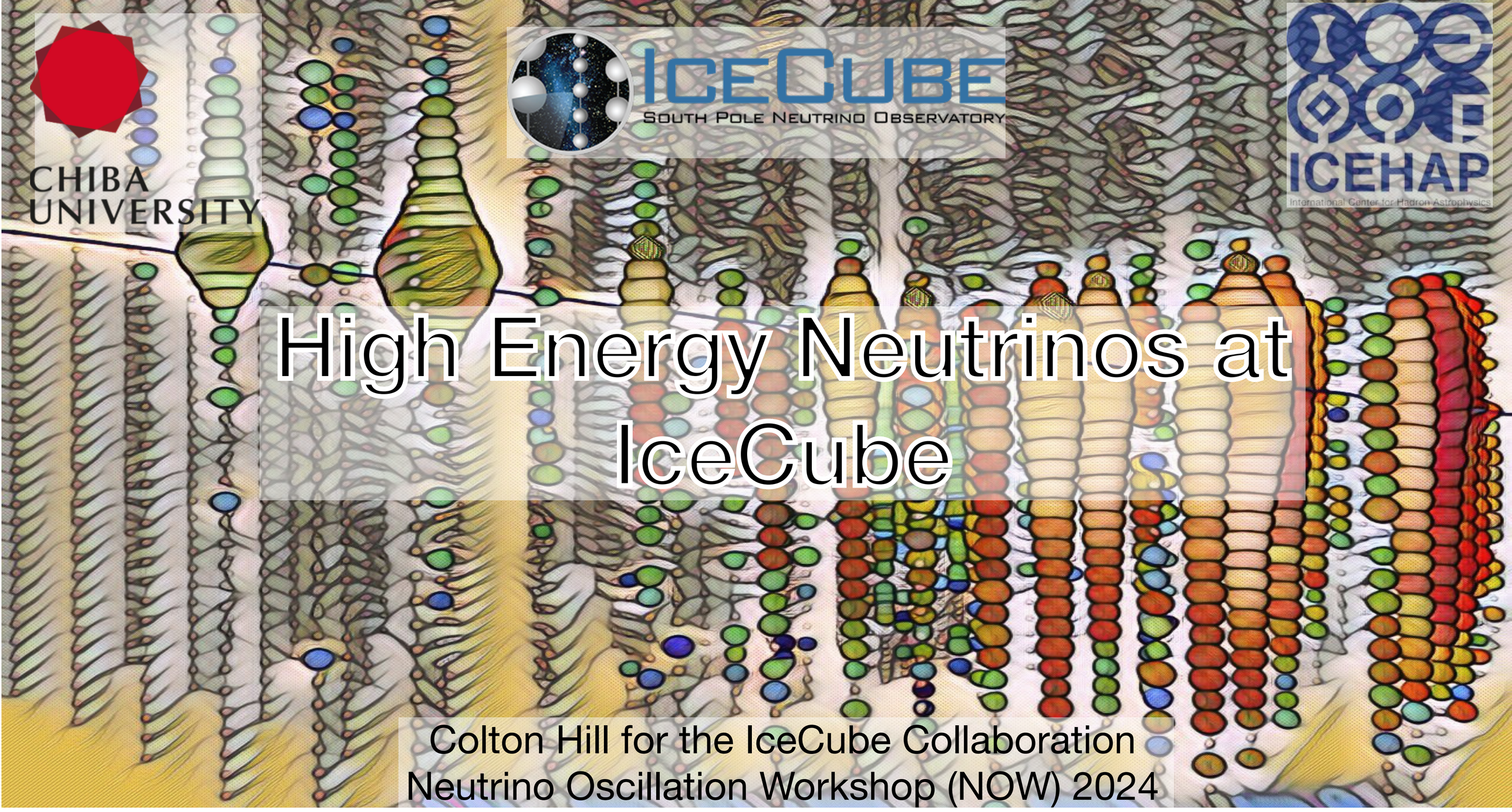


High Energy Neutrinos at IceCube

Colton Hill for the IceCube Collaboration

Neutrino Oscillation Workshop (NOW) 2024

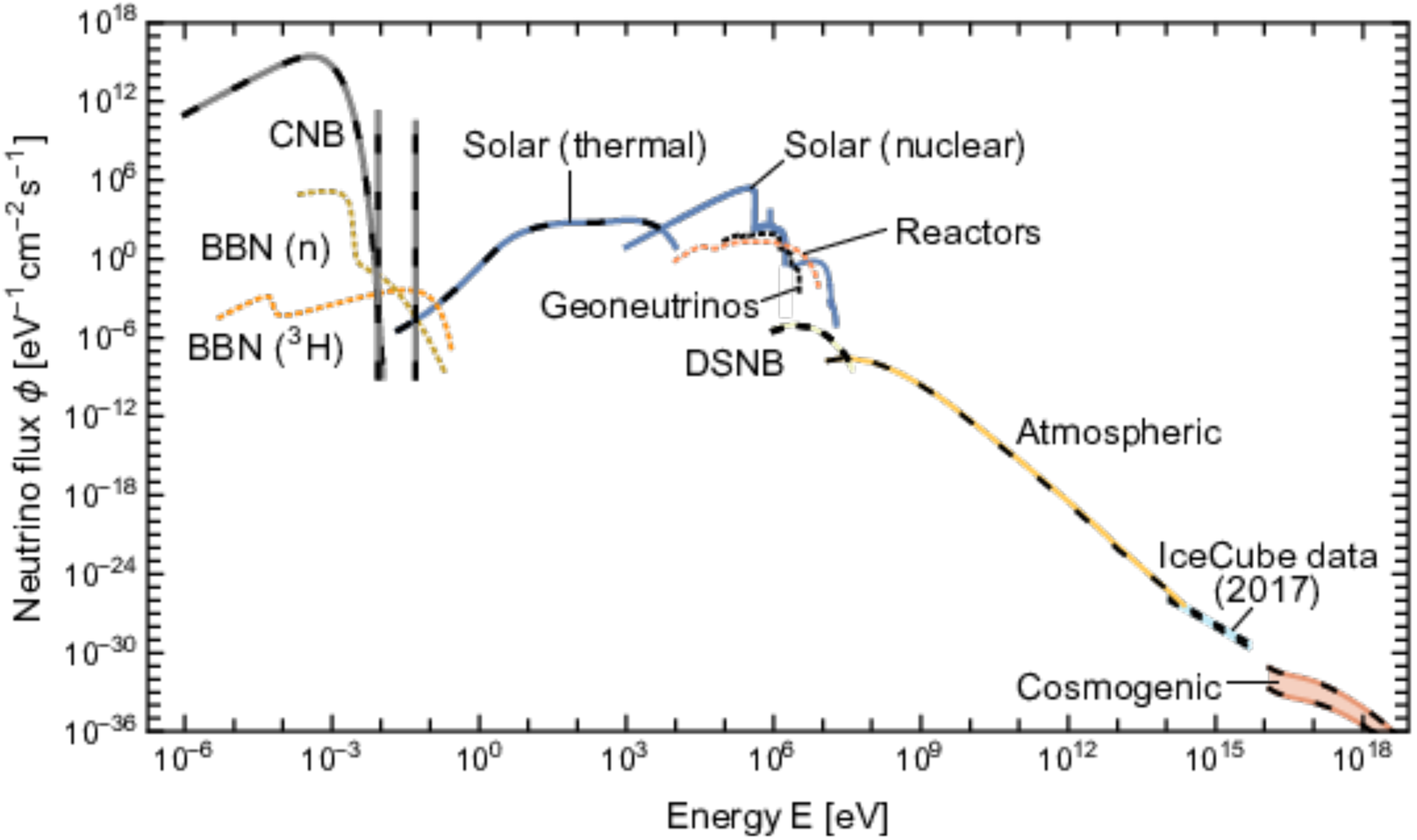
Contents

- Neutrinos & the Universe
- The IceCube Neutrino Observatory
- Neutrino Sources & Multi-messenger Astrophysics
- Extremely High Energies & IceCube Gen2

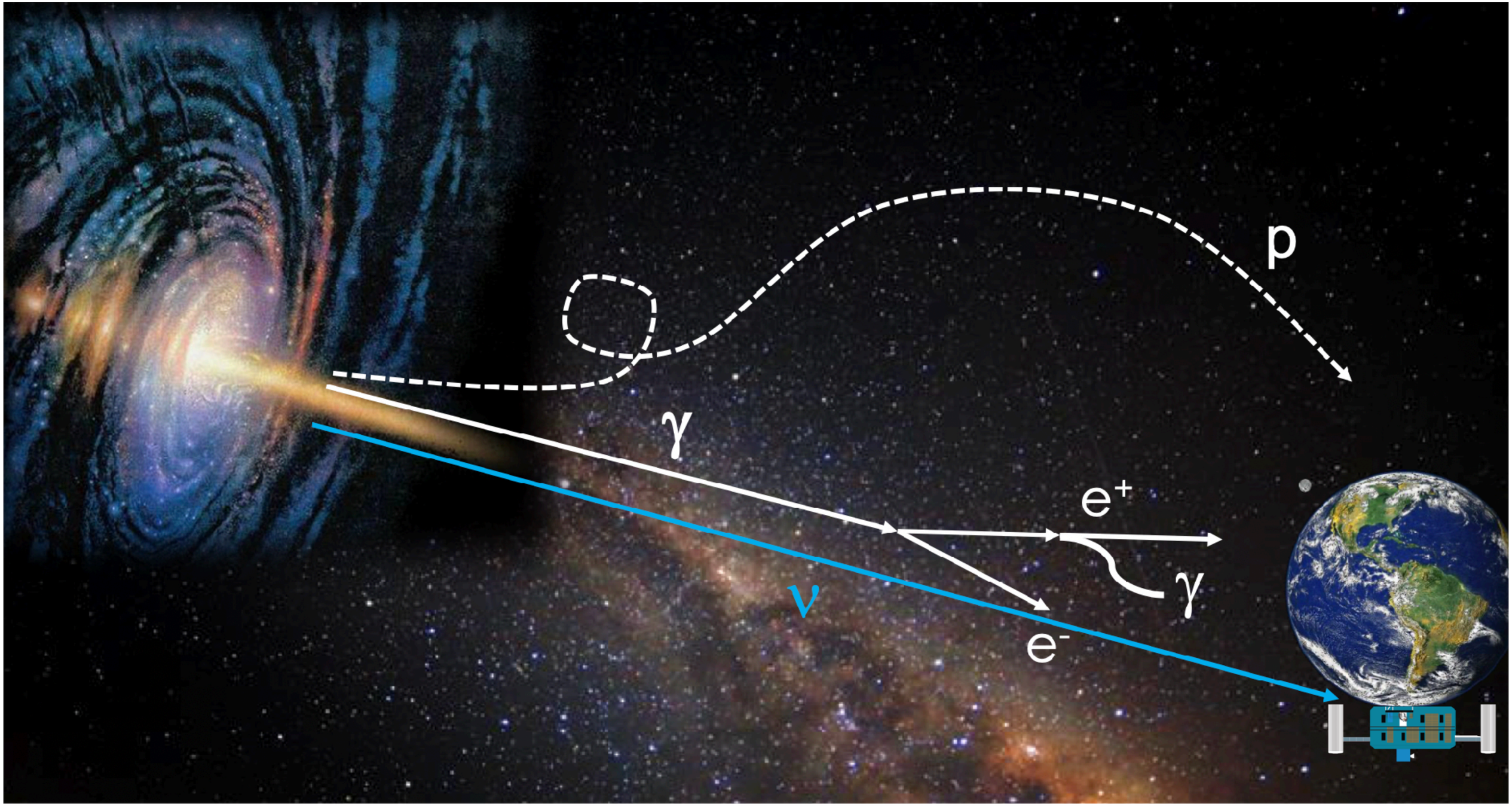
https://higgstan.com

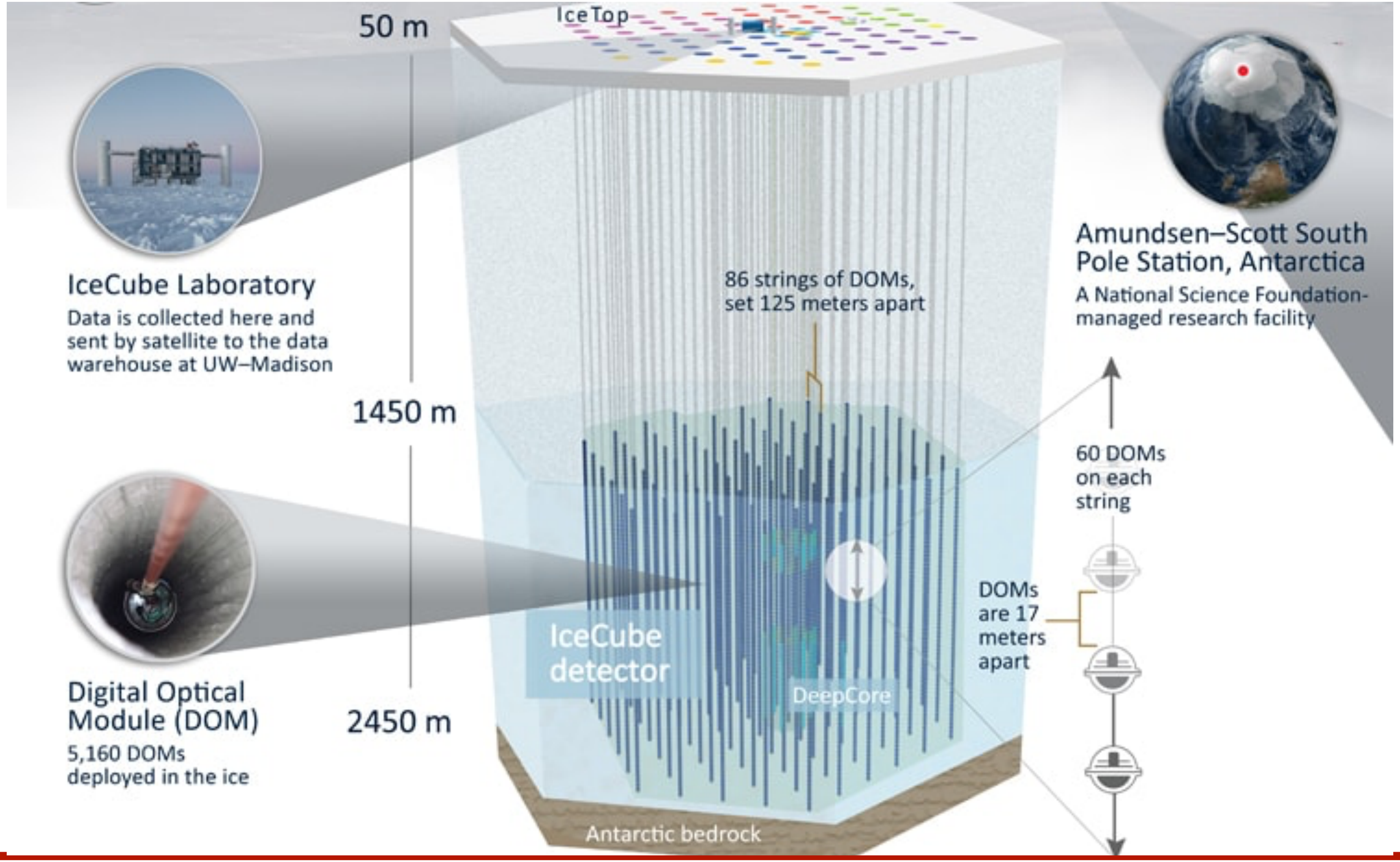
Neutrinos & The Universe

- Neutrino sources are varied and diverse - far away astrophysical sources, atmospheric neutrinos, supernovae.
- Large variety of sources covering a huge range of energies.
- Approaching higher energies, fluxes fall off - need very large detectors to probe fluxes beyond GeV-scale!
- Open questions related to the origins of these neutrinos, and their role in the universe.

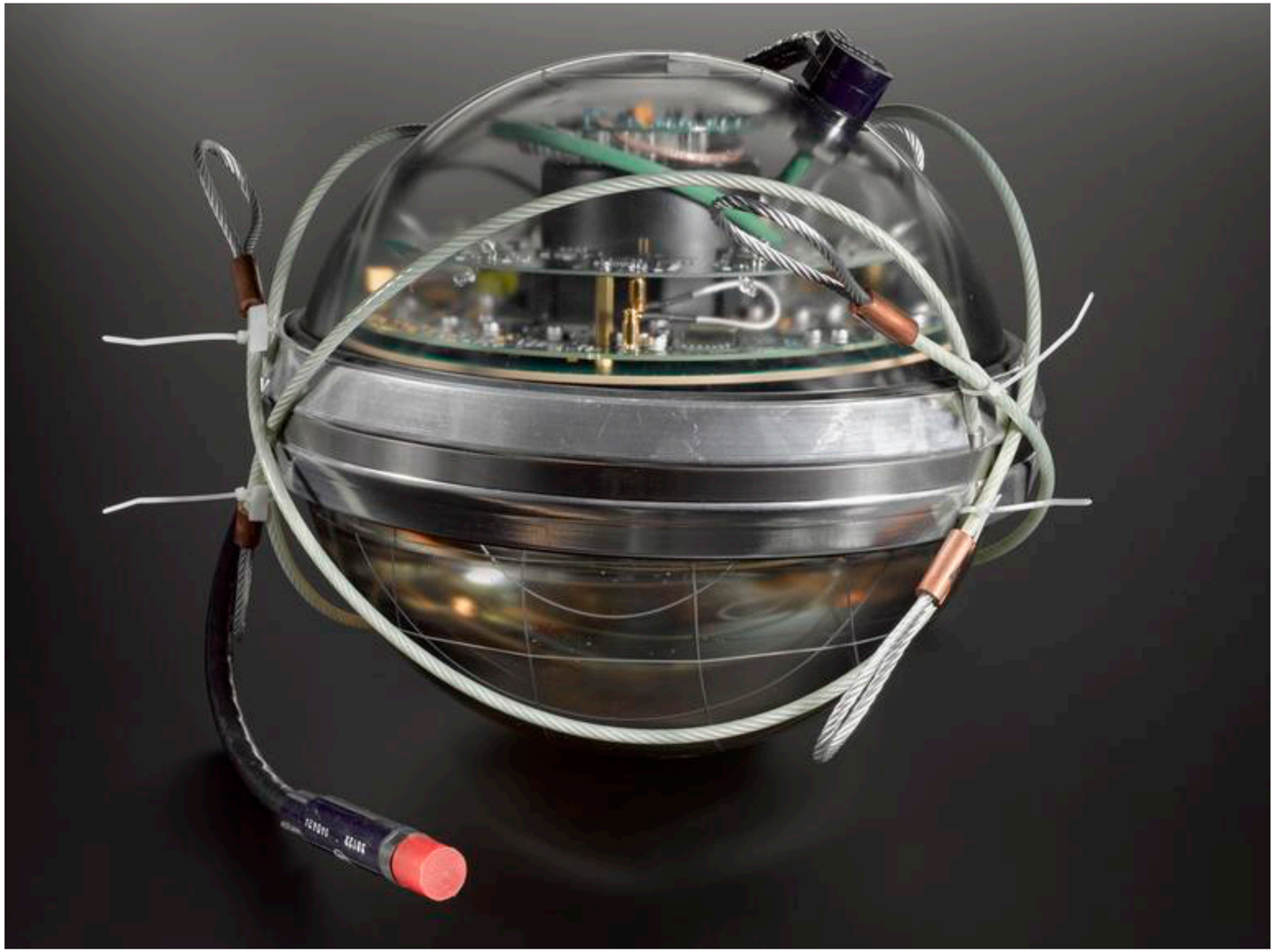


Snowmass Neutrino Frontier Report - Huber, Patrick *et al* - arXiv:2211.08641FERMILAB-FN-1215-ND-PPD-SCD

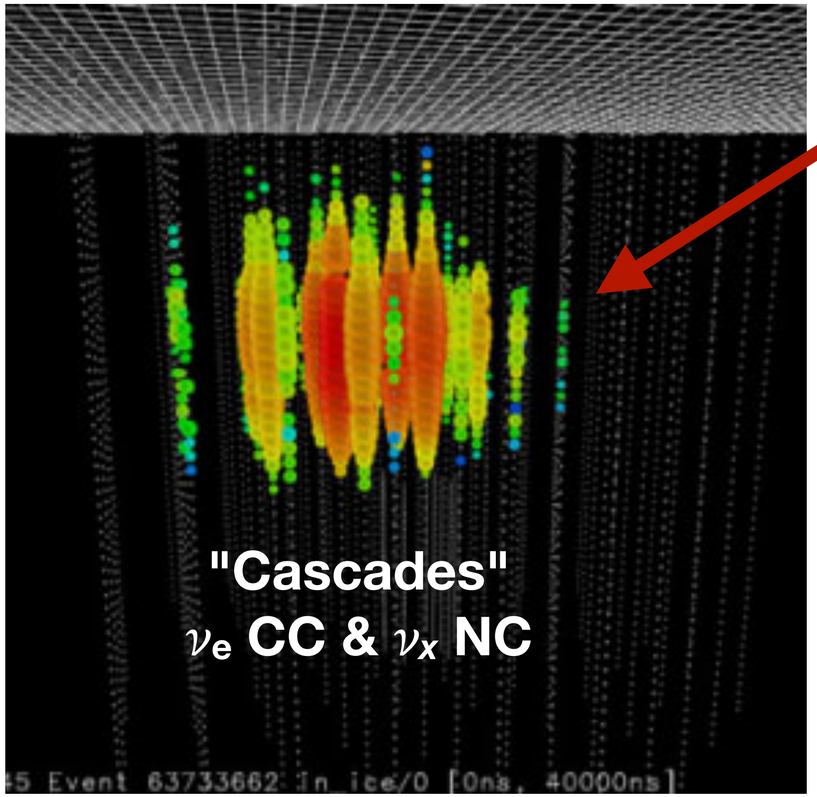

p
γ
e+
γ
ν
e-


50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube detector
DeepCore
2450 m
Antarctic bedrock

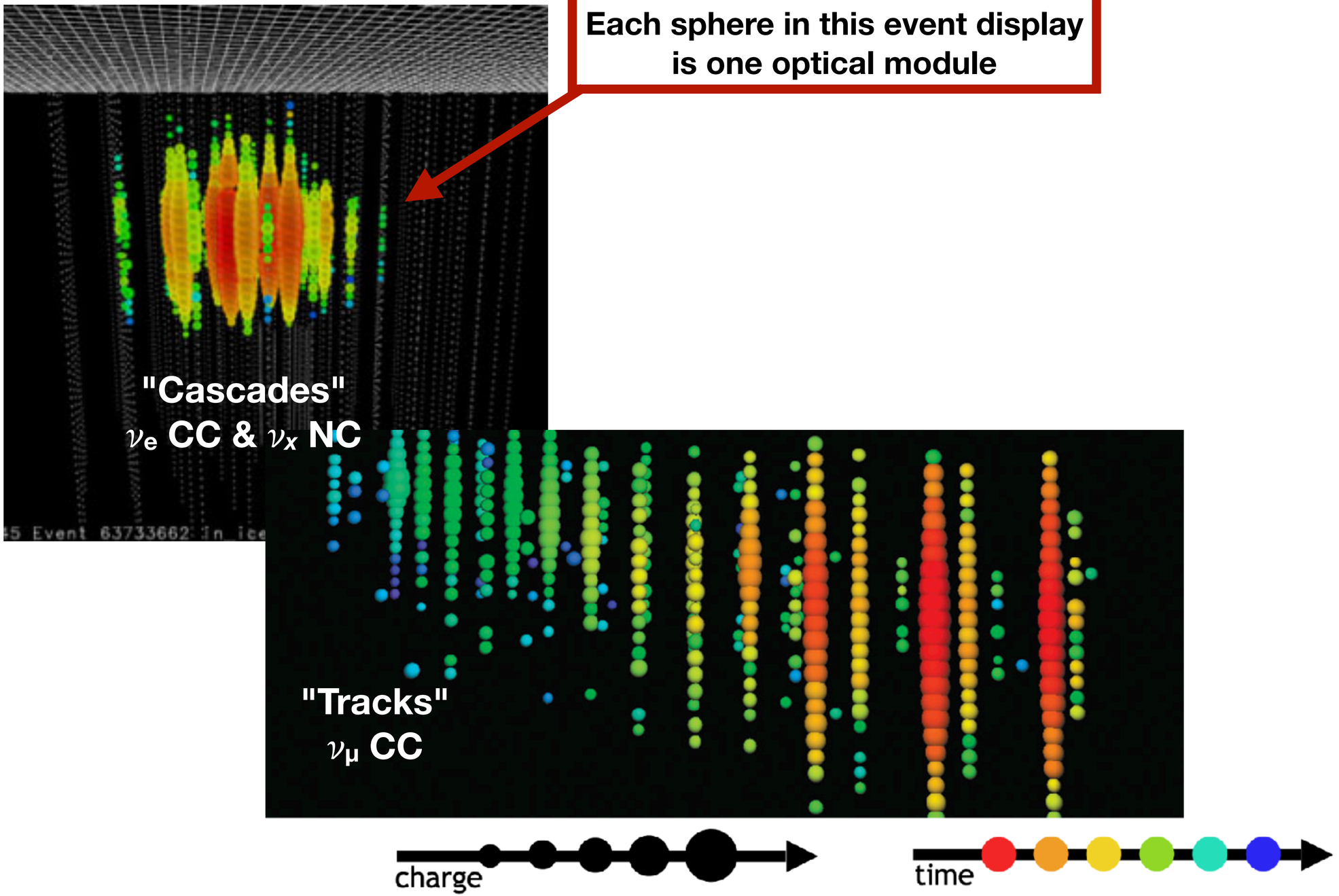
The IceCube DOM

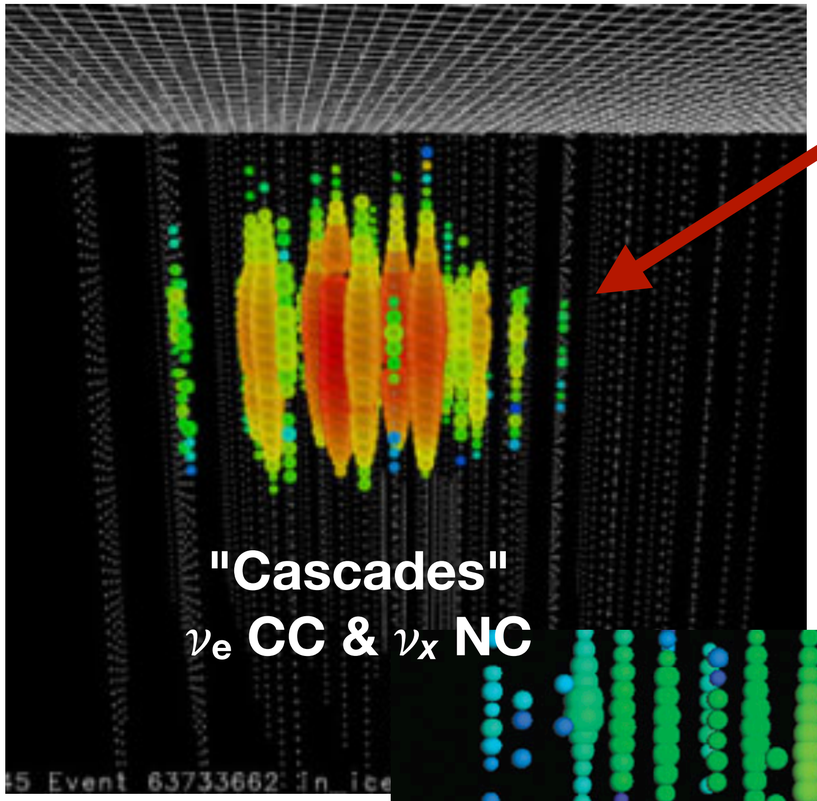


- 5160 Digital Optical Modules (DOMs) deployed into the Antarctic ice.
- Uses a single 10 inch downward-facing photomultiplier tube (PMT) to detect Cherenkov light.
- PMT & electronics sealed in a pressure-resistant glass housing.
- The Gen1 DOMs have been a very successful and robust design:
  - High detector up-time (98%+).
  - Low failure rate (<1%).



Each sphere in this event display is one optical module


Each sphere in this event display is one optical module
"Cascades"
ν_e CC & ν_x NC
"Tracks"
ν_μ CC
charge
time



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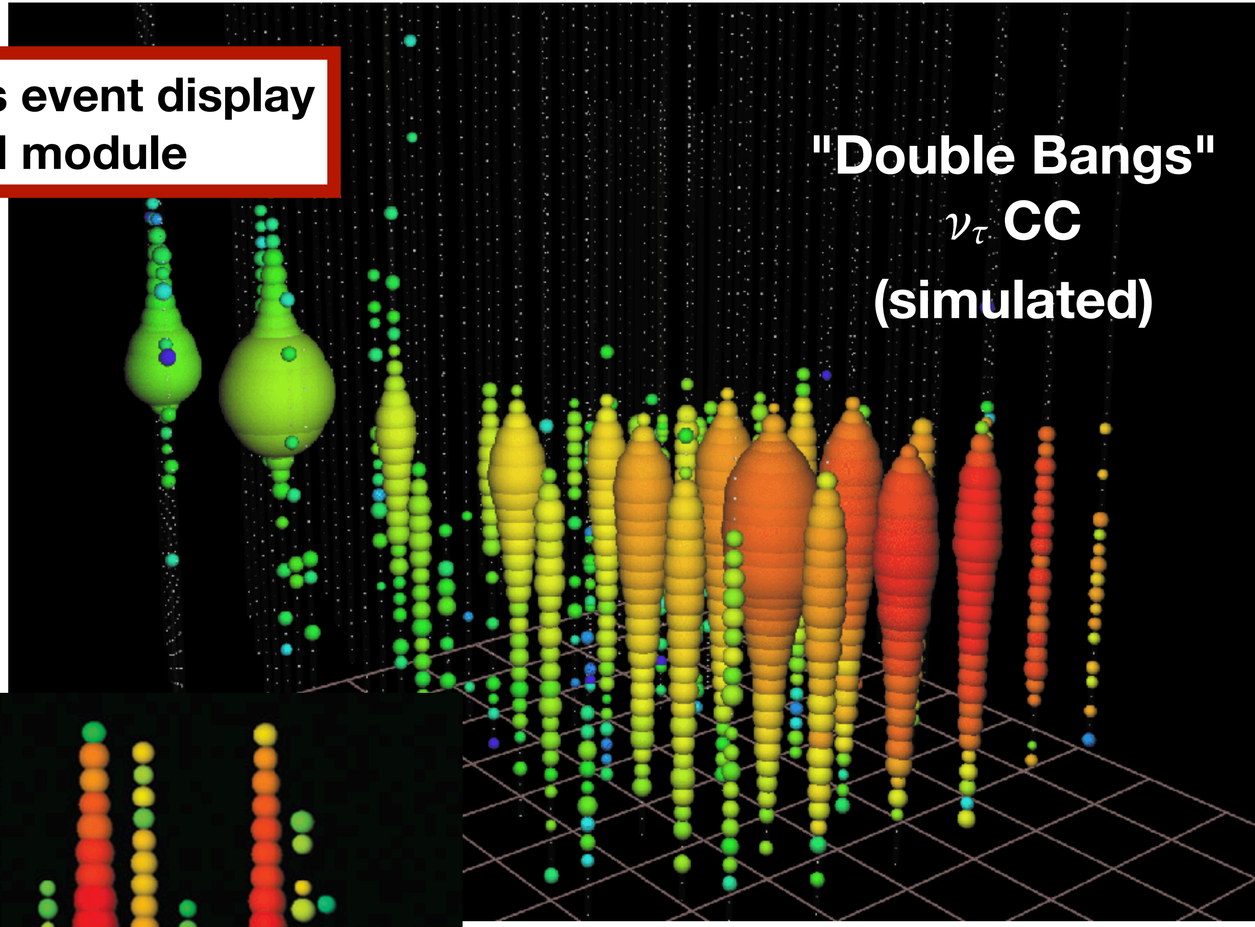
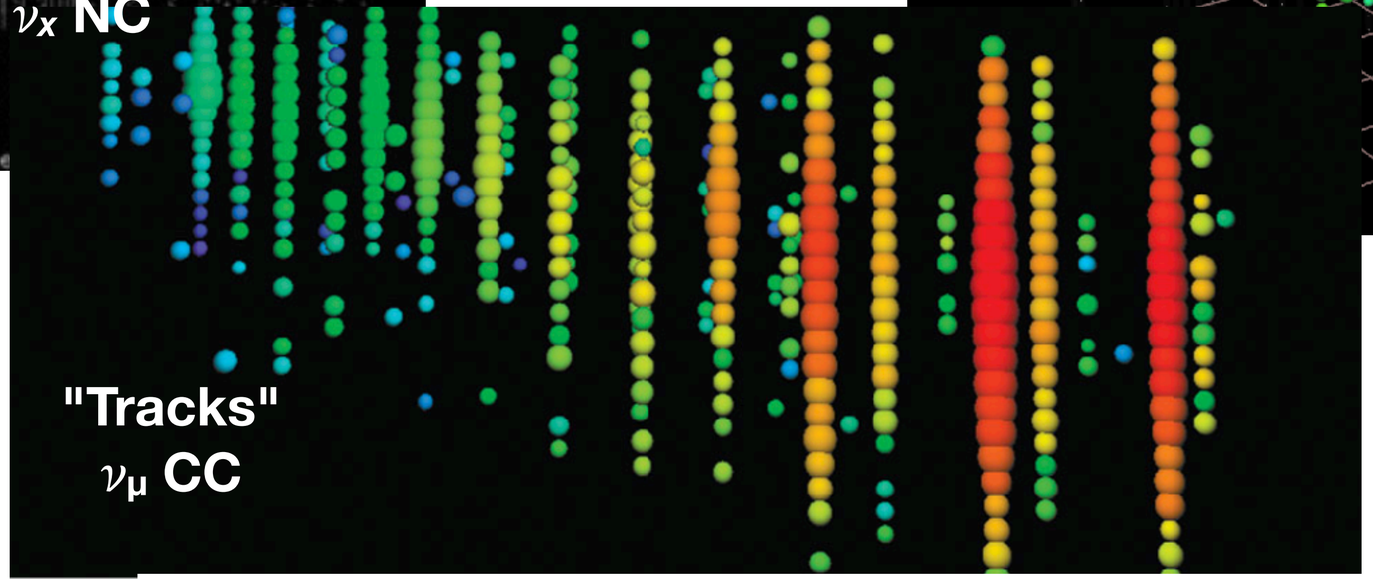
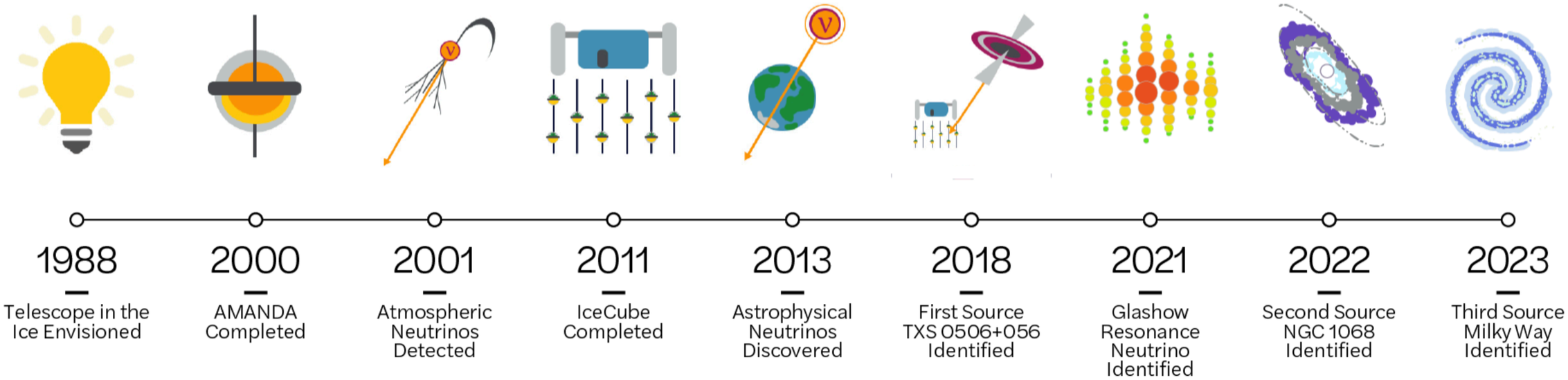
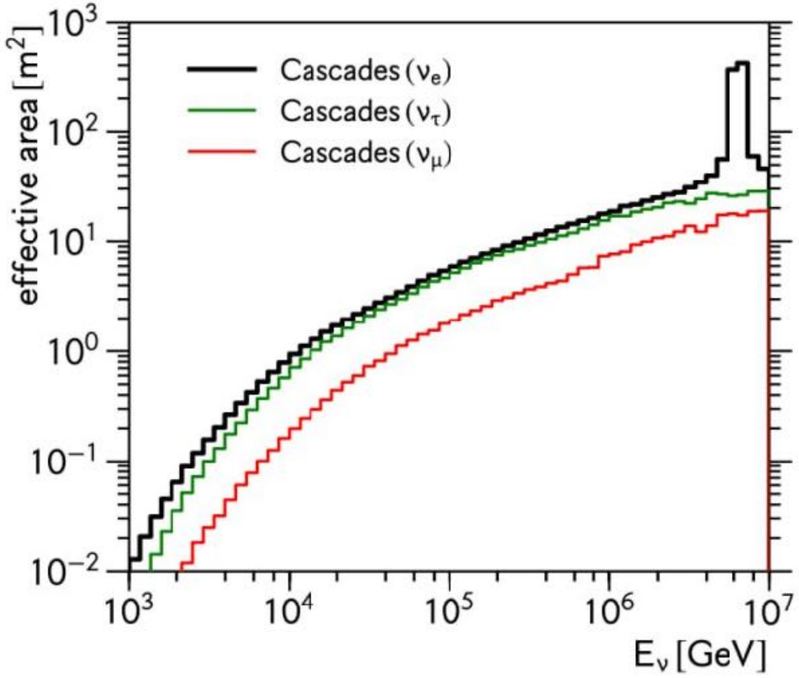


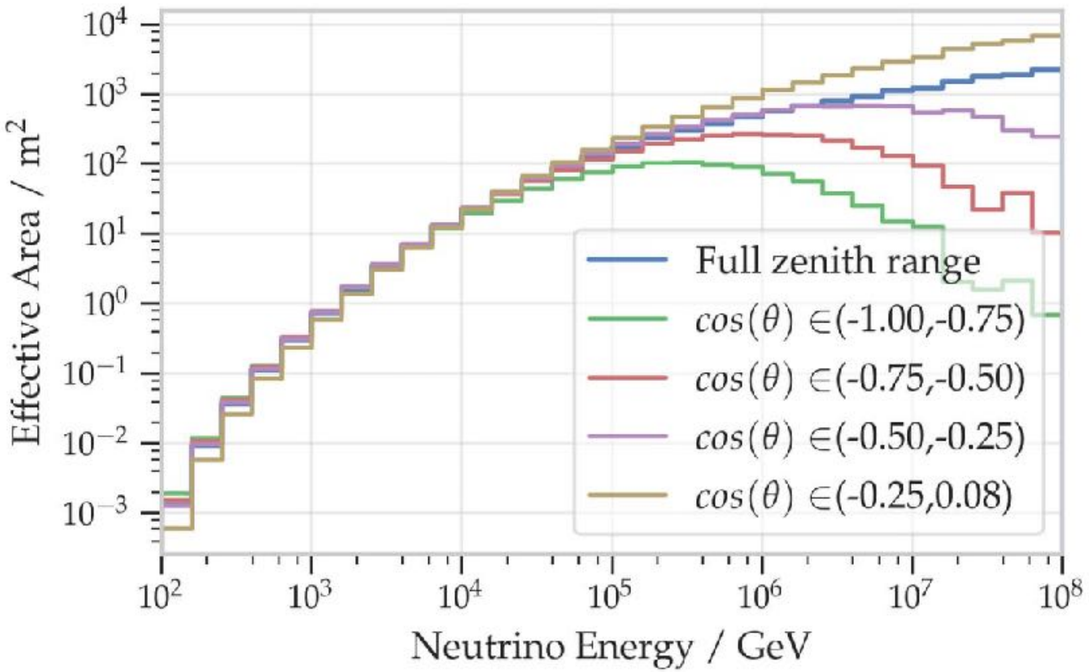


A History of Neutrino Astronomy in Antarctica

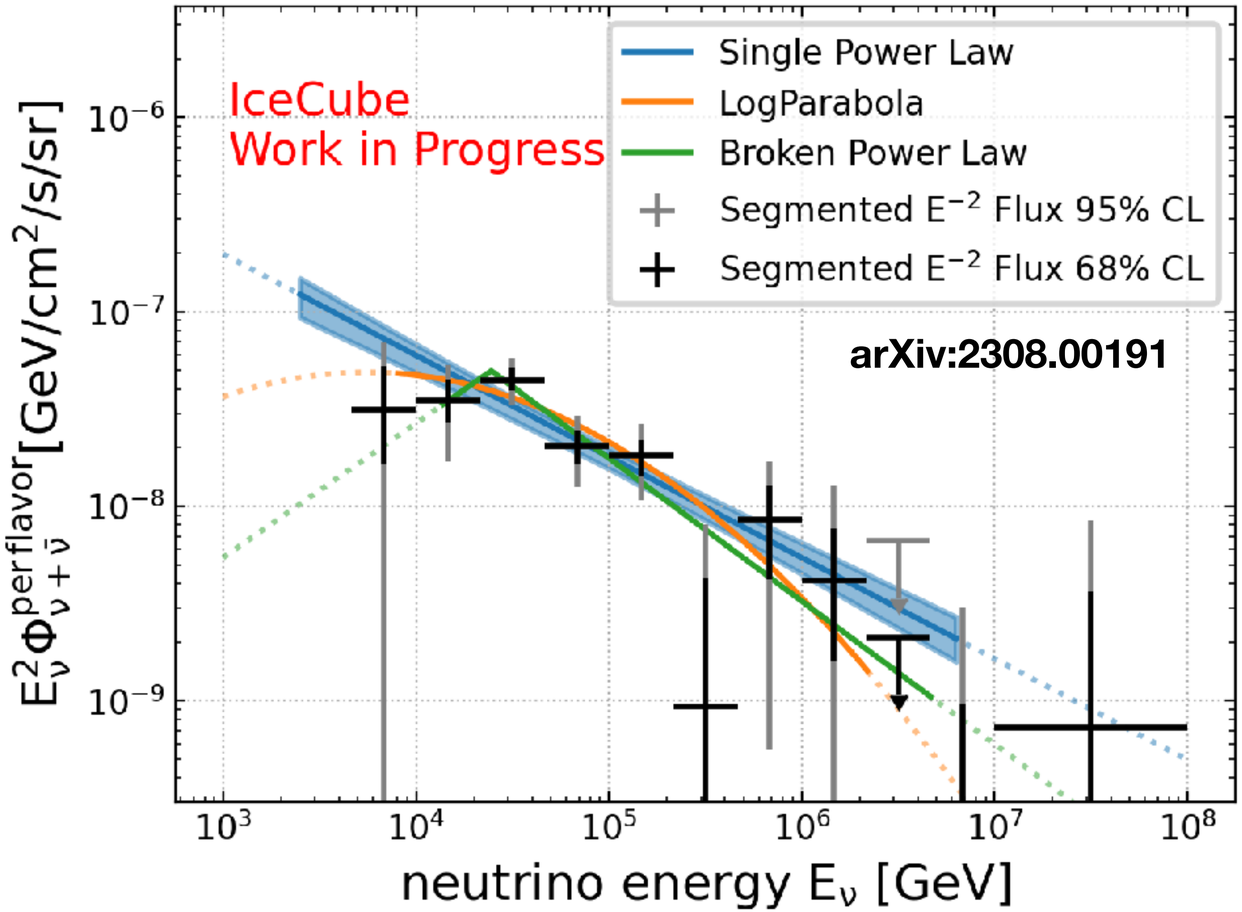


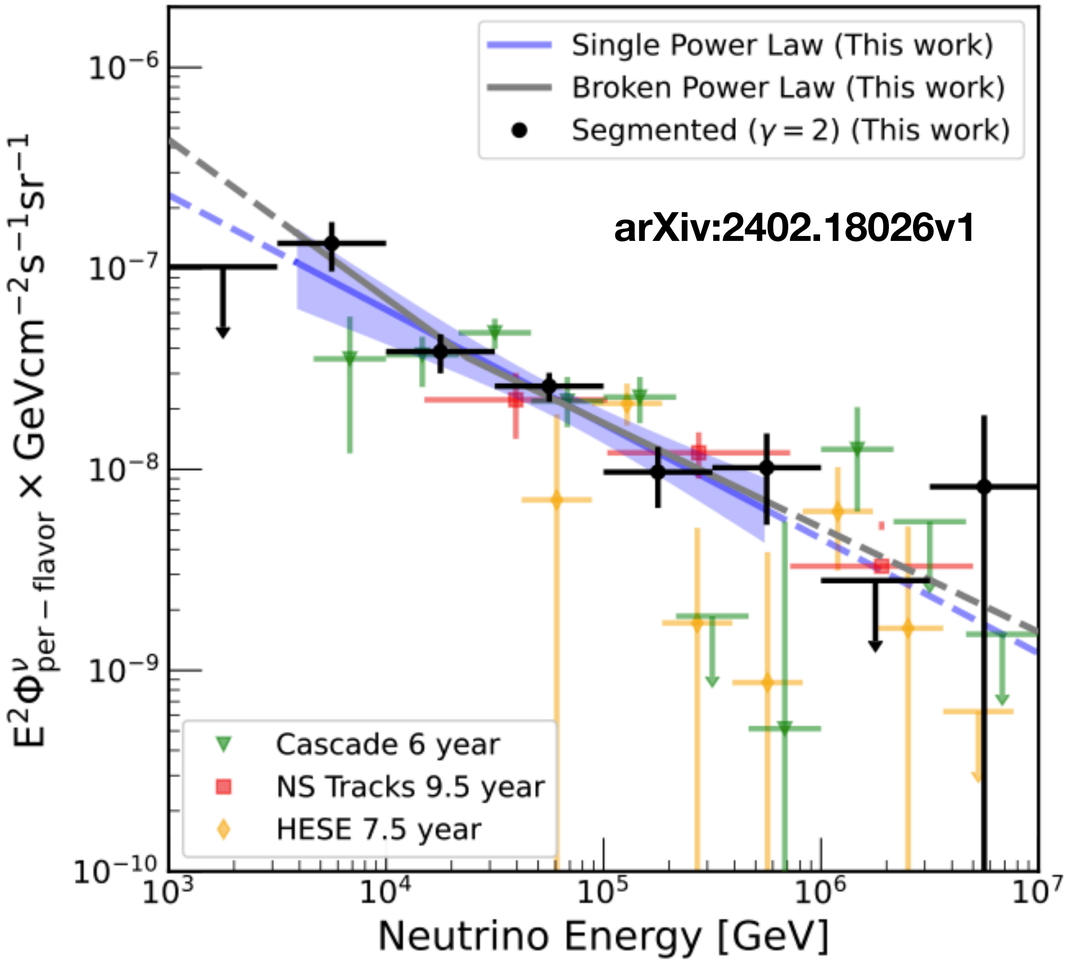
High Energy Performance



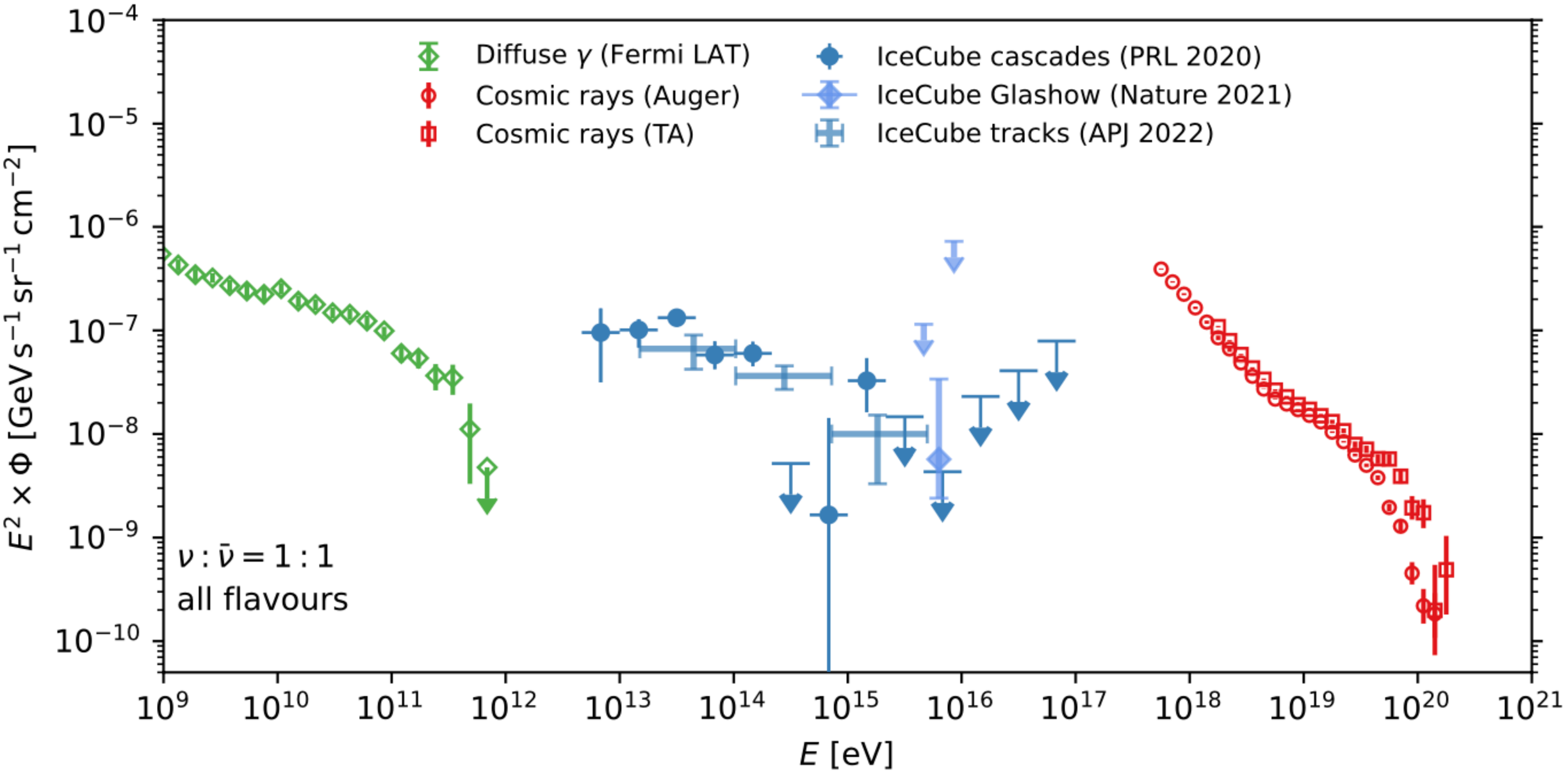


- IceCube's performance continues to climb into the PeV energy range! ("Diffuse" neutrino cascade & track samples).
- IceCube is ideal environment to investigate the high energy frontier in neutrino physics (TeV⇒EeV).
- What is the connection between astrophysical neutrinos & other sources?
- What does the flux reaching the Earth from these sources look like?





The all-sky characterisation of the astrophysical flux is being performed with unprecedented precision - but the exact shape of the flux is still in question!

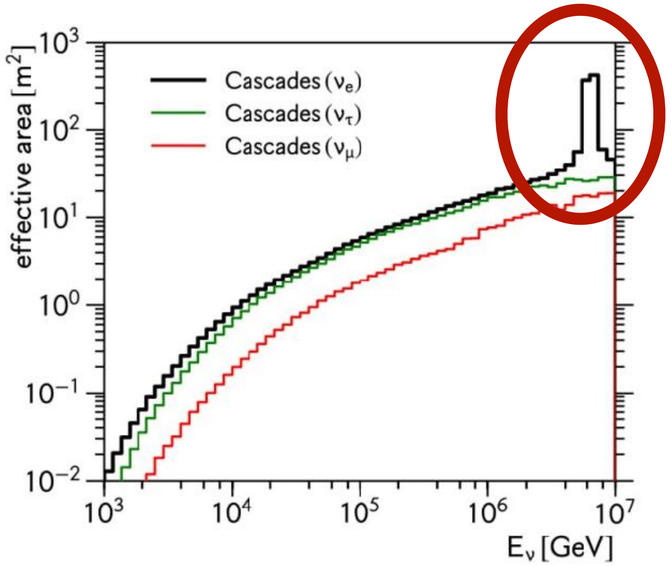


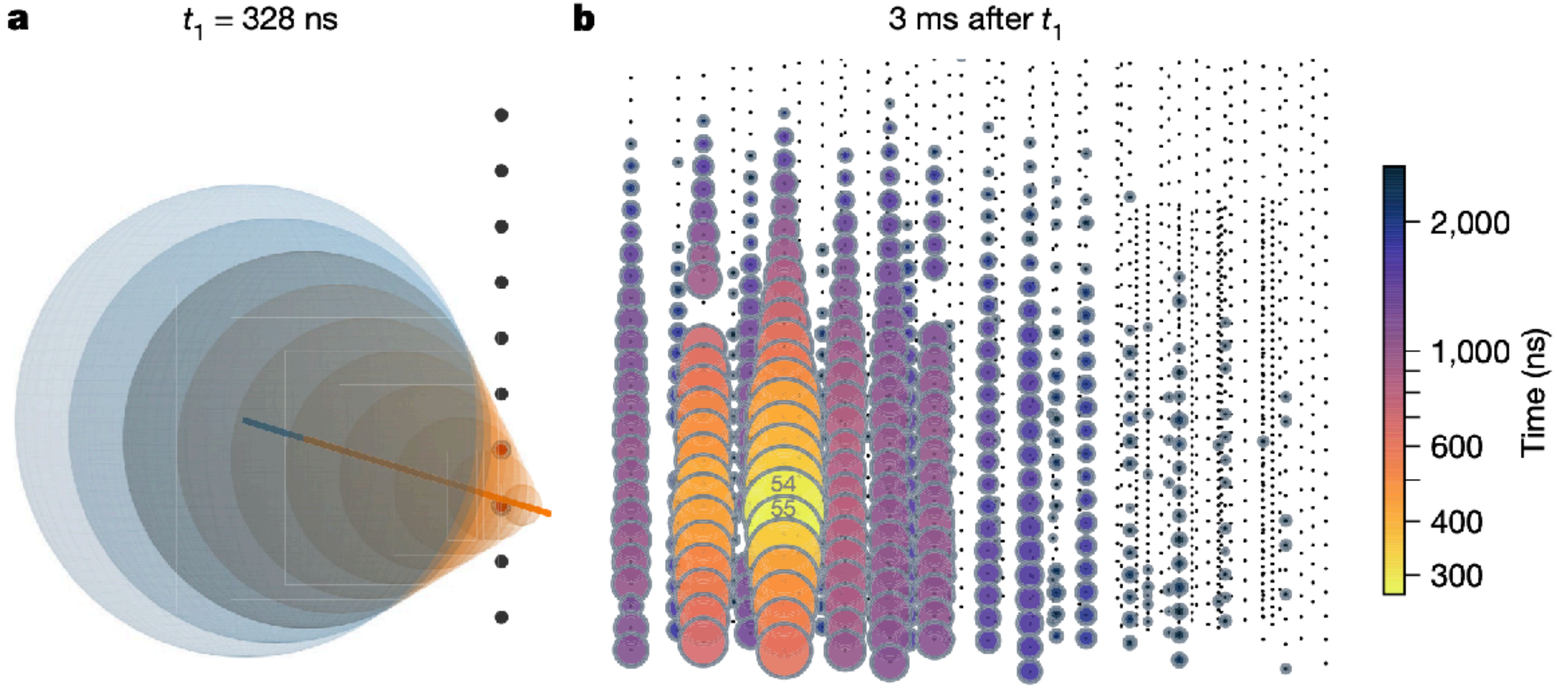
Multi-messenger astrophysics - bringing signals together.

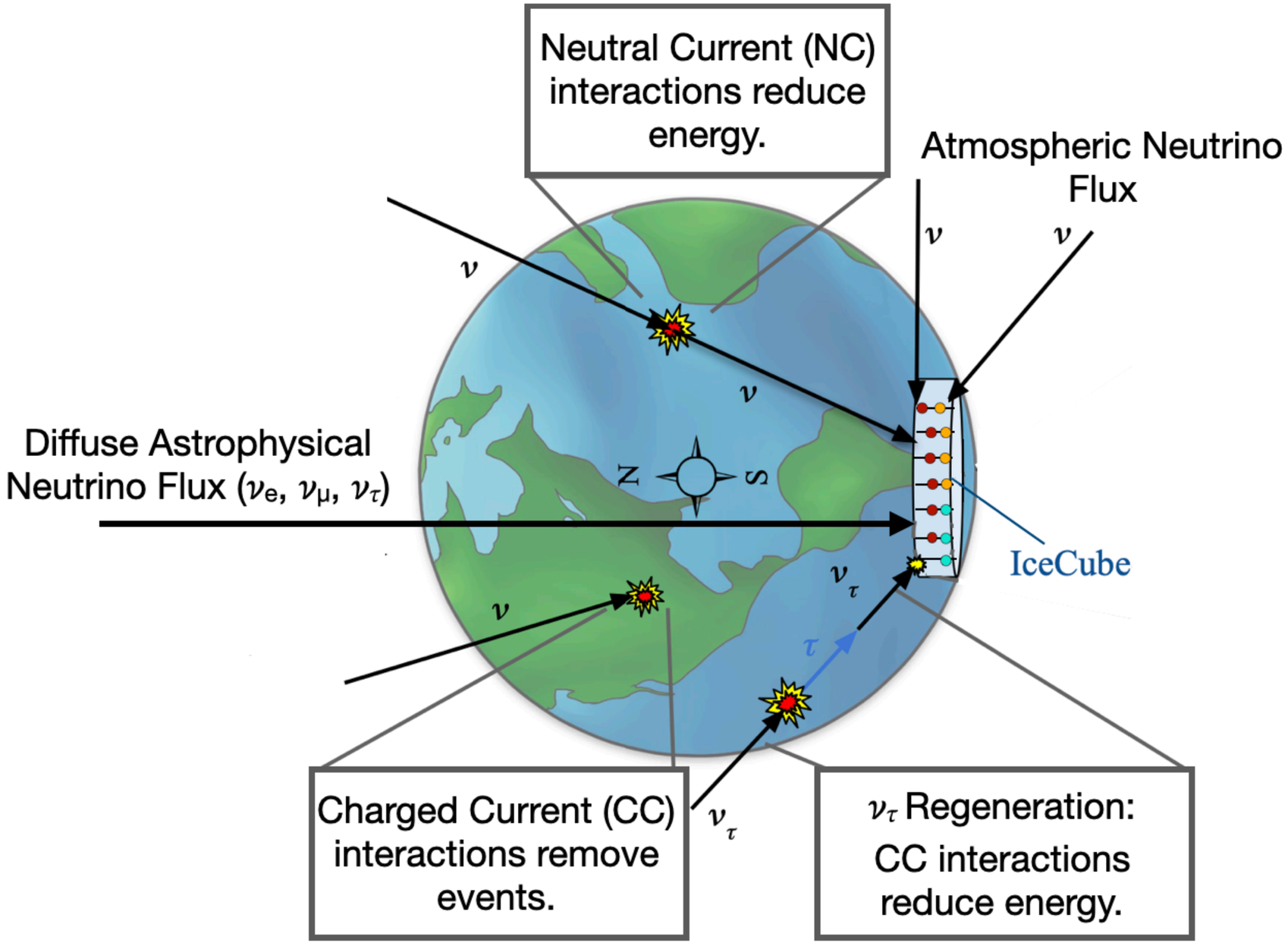
arXiv:2203.08096v2

Neutrino Interaction Physics

- At sufficiently high energies (6.3 PeV), $\overline{\nu_e}$ can perform an electroweak resonant production of a real *W*-boson*:* *($\overline{\nu_e}$ + e-).*
- IceCube observed a neutrino with energy consistent with production from *W*-boson decay - first ever Glashow Resonance candidate!
- Exciting for future studies of $\nu/\overline{\nu}$ ratios from astrophysical sources.



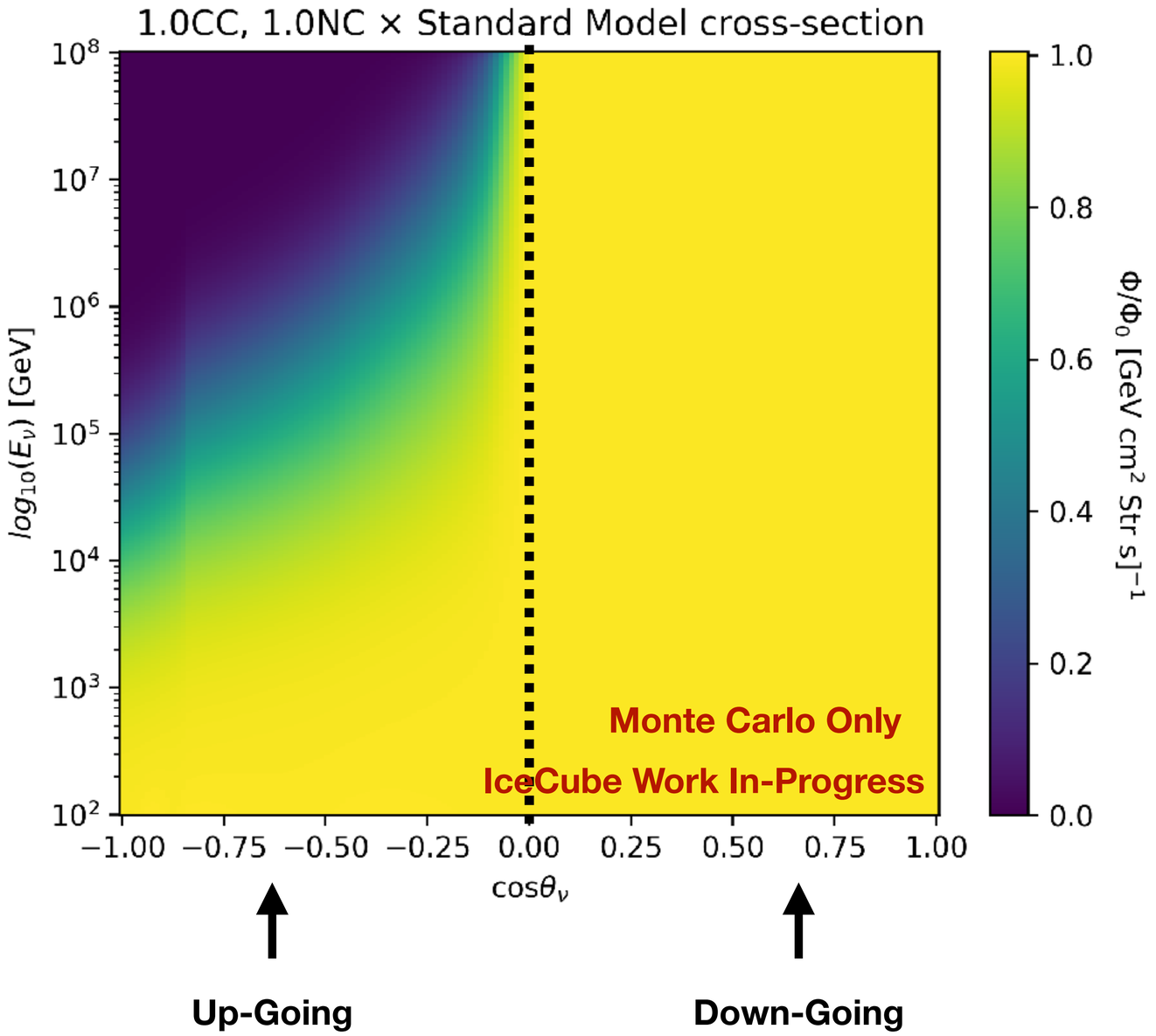


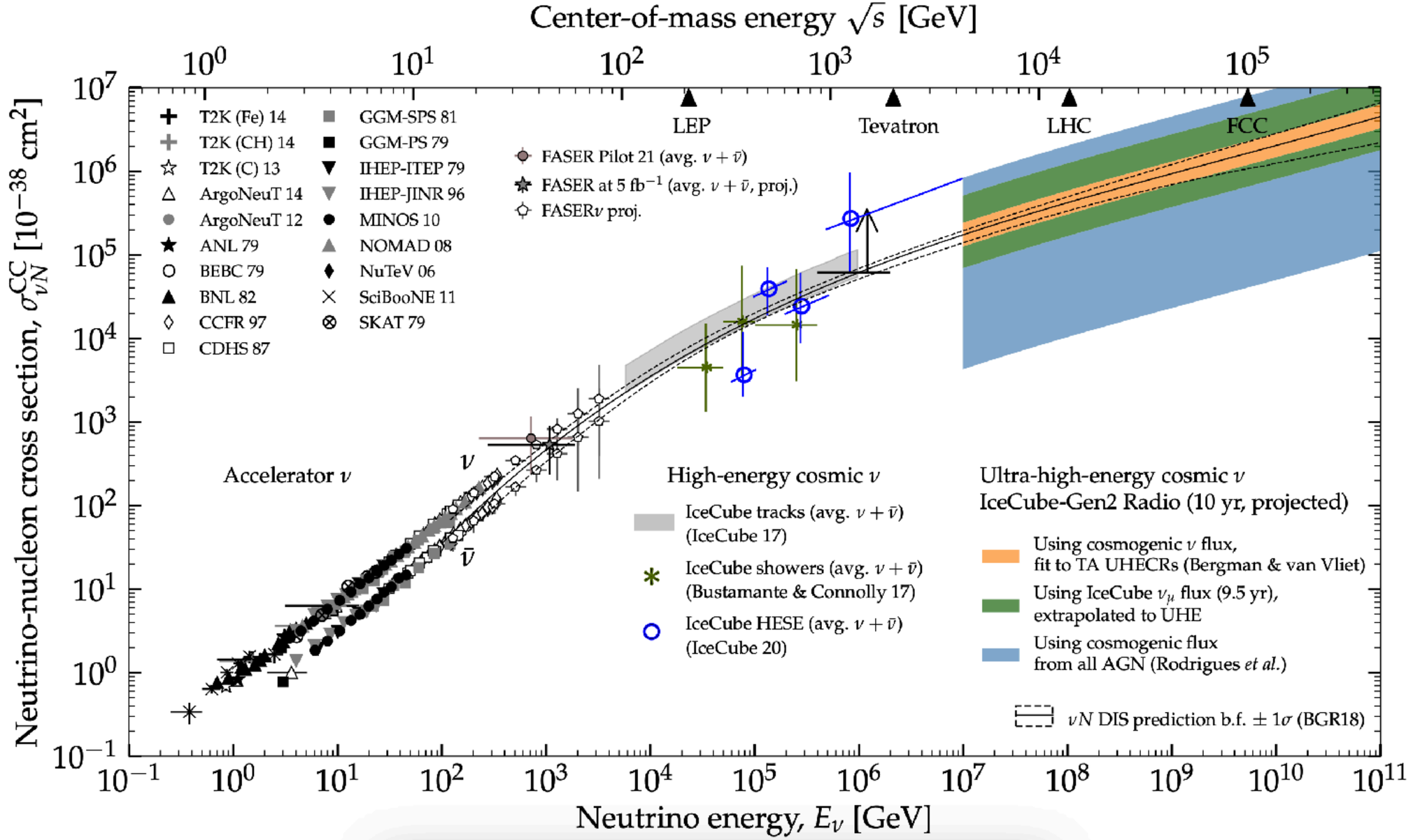


- Using the Earth as a shield against atmospheric μ, we're able to build high purity selections for "up-going" neutrinos.
- Most neutrinos travel unattenuated, but starting from TeV energies, the Earth starts to become opaque.
- We can use this to our advantage to probe interaction physics.

Neutrino Interaction Physics

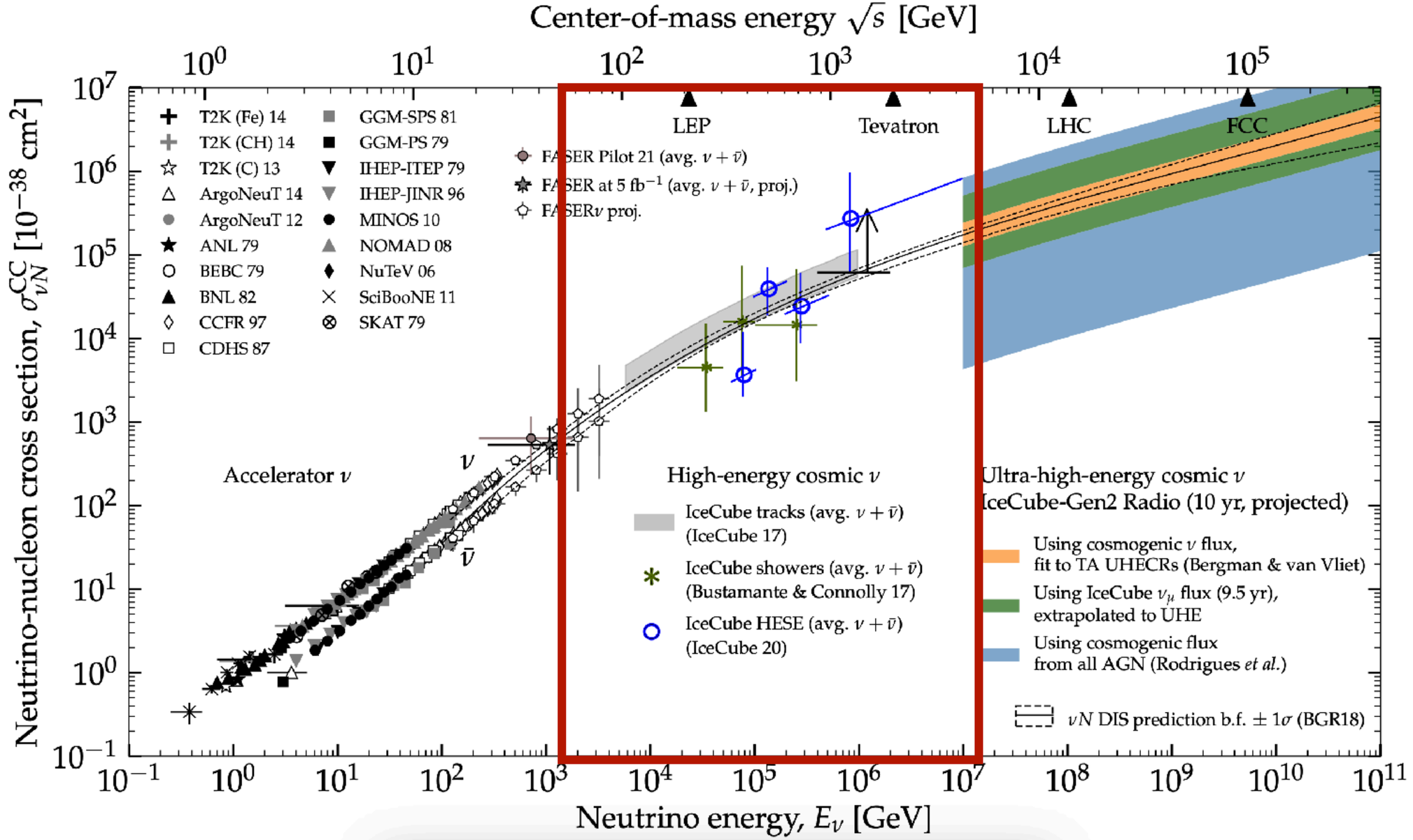
- As the neutrino cross section grows, more and more of the initial flux becomes attenuated.
- For up-going neutrinos at PeV+ energies, almost none reach IceCube un-attenuated.
- But this presents a unique opportunity to measure the neutrino cross section primarily at the TeV-scale.





Interactions in IceCube are almost exclusively in the Deep Inelastic Scattering region.
Measurements at TeV-Scale limited - IceCube & FASERν

arxiv:2008.04323
arXiv:2204.04237



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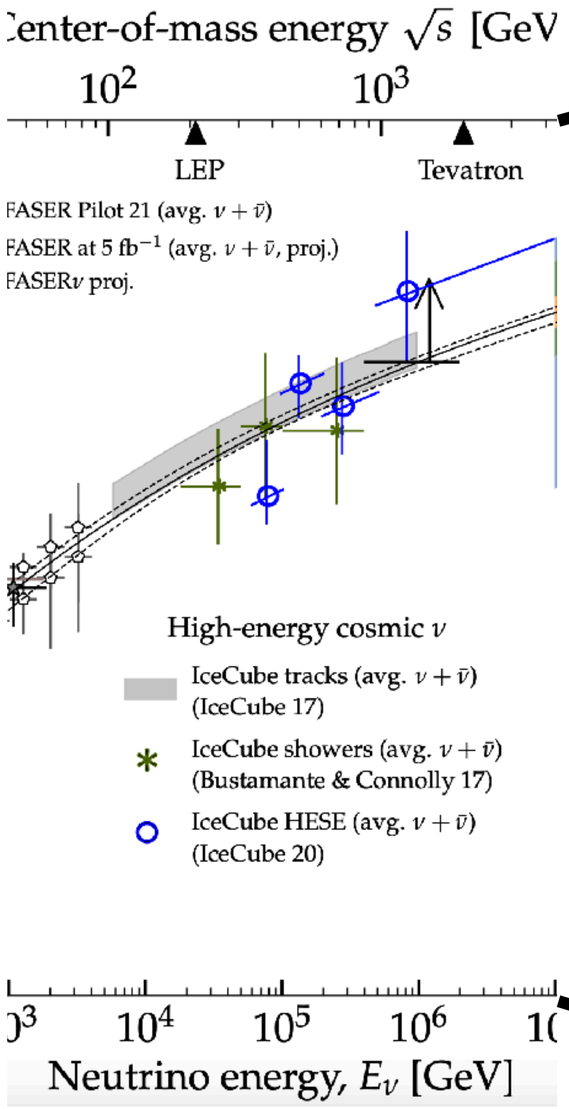
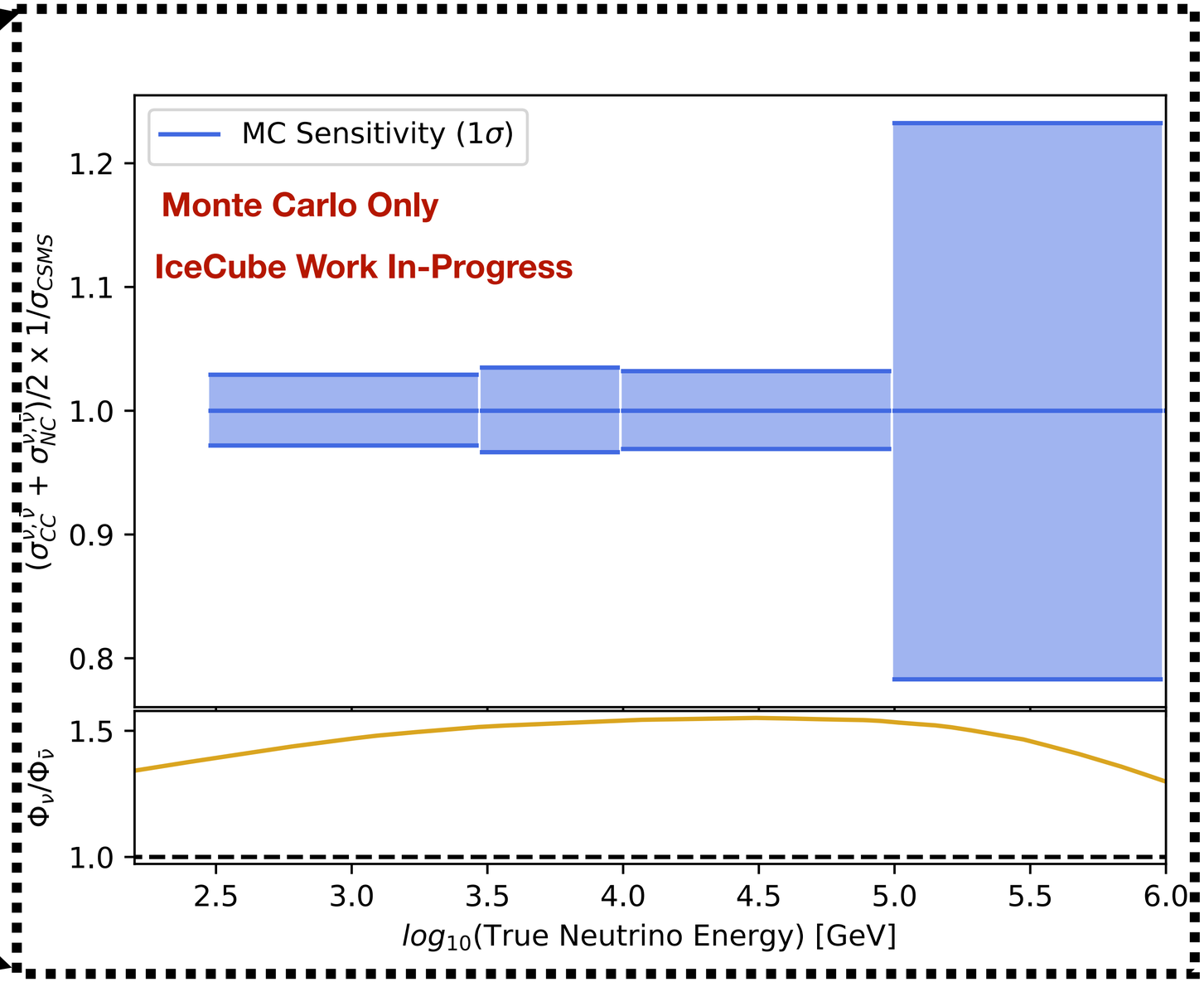
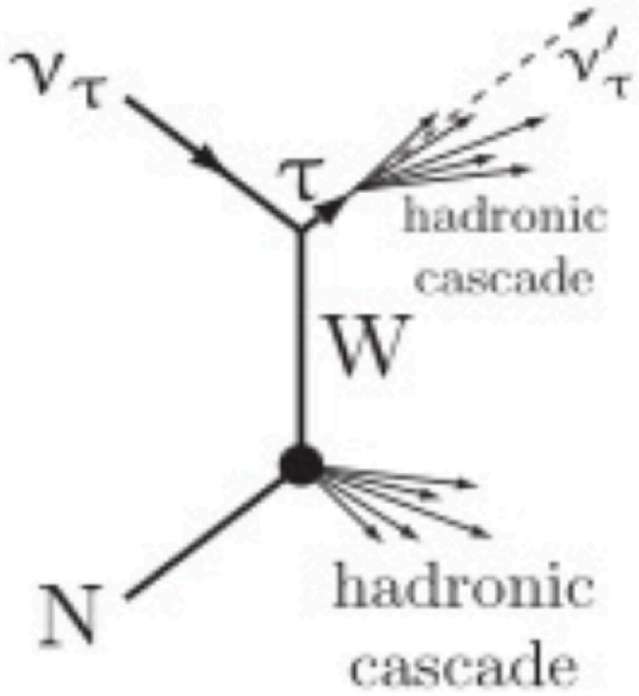
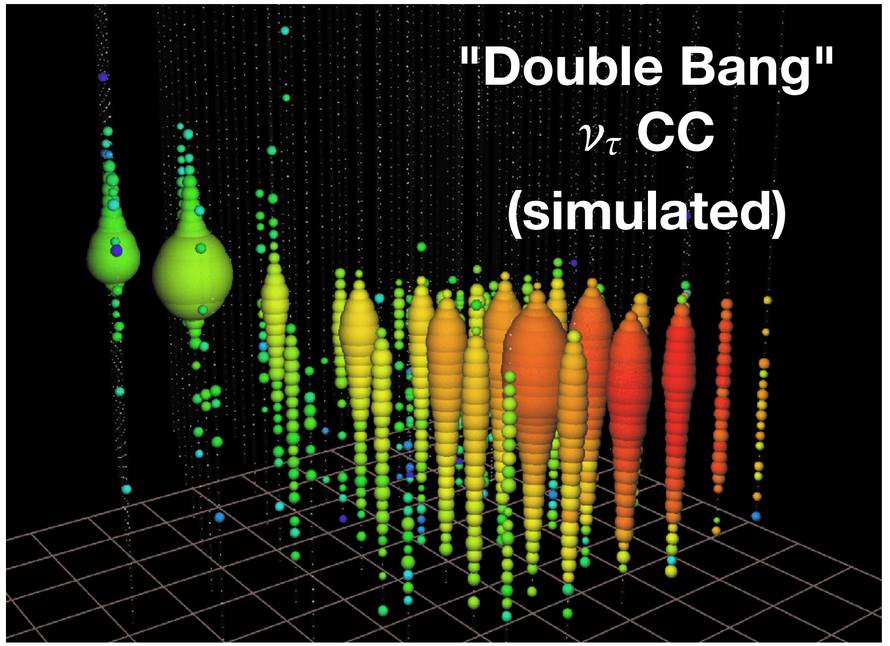




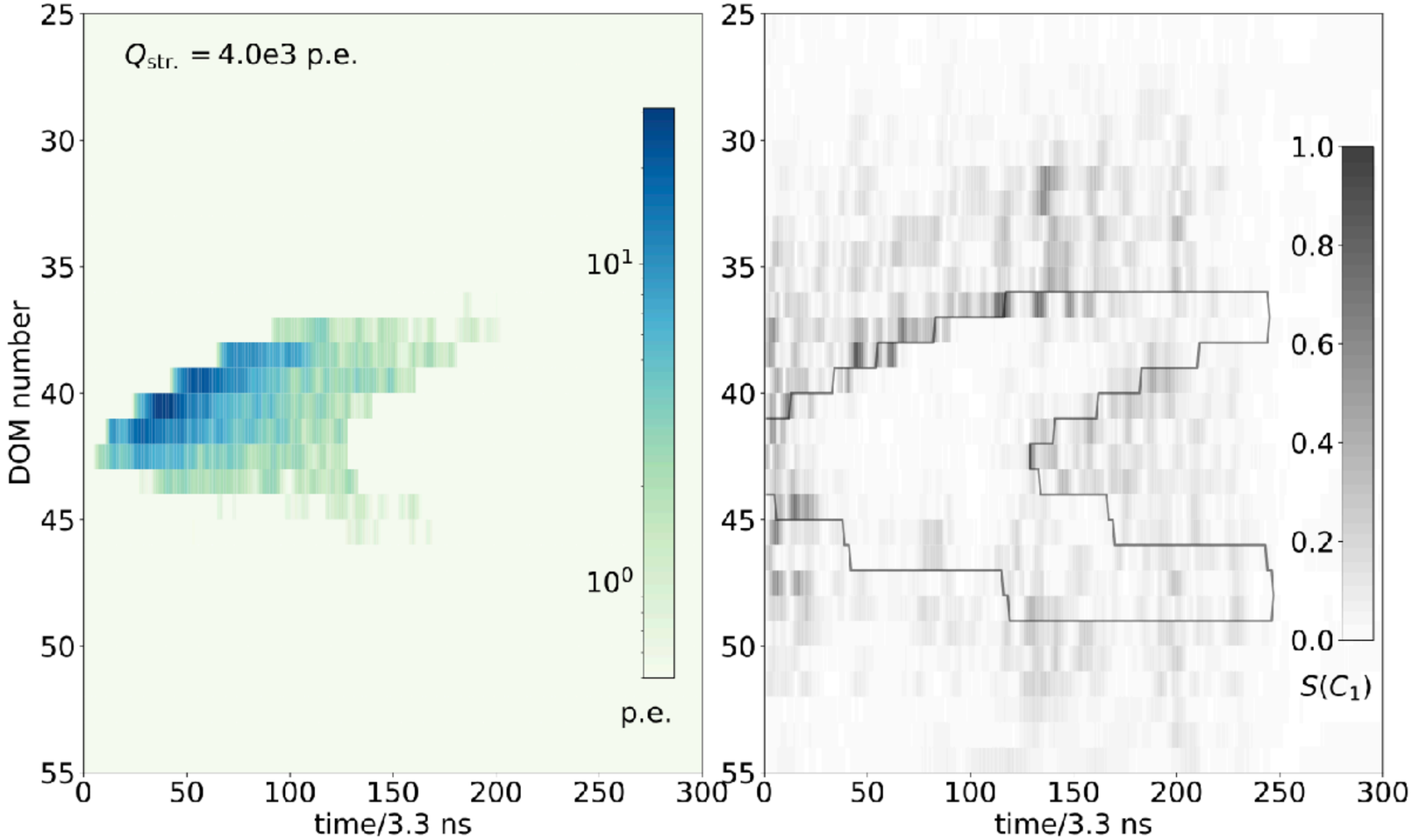
Continuing to improve on existing neutrino cross section results, incorporating newest detector knowledge and flux models.

- Data for ν_e & ν_μ are plentiful, but ν_τ has historically been elusive.
- Through oscillations over cosmic distances, the ratio of $\nu_e : \nu_\mu : \nu_\tau$ is expected to be roughly 1:1:1 at Earth.
- This means, the astrophysical neutrino flux provides opportunity to directly observe ν_τ events.
- These ν_τ events are able to CC interact thanks to their high energy, producing distinct signatures.
- Per 1 PeV in energy, the τ travels on average 50 m.





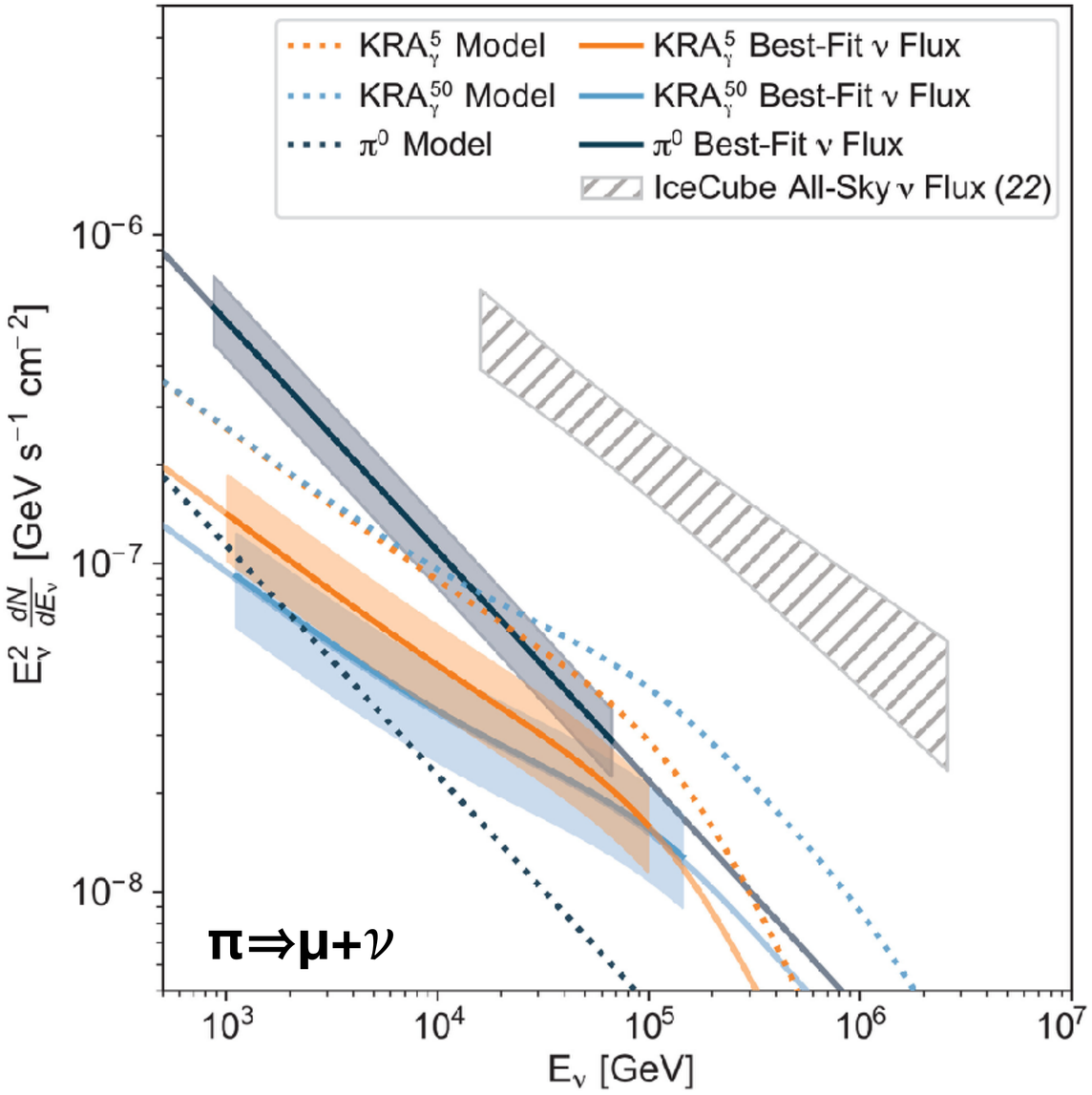
- With 10+ years of data, finally isolated a significant number of astrophysical ν_τ candidates.
- Leveraging power of CNN-based tools.
- Median energy of ~200 TeV.
- Absence of astrophysical ν_τ flux ruled-out with 5σ confidence.



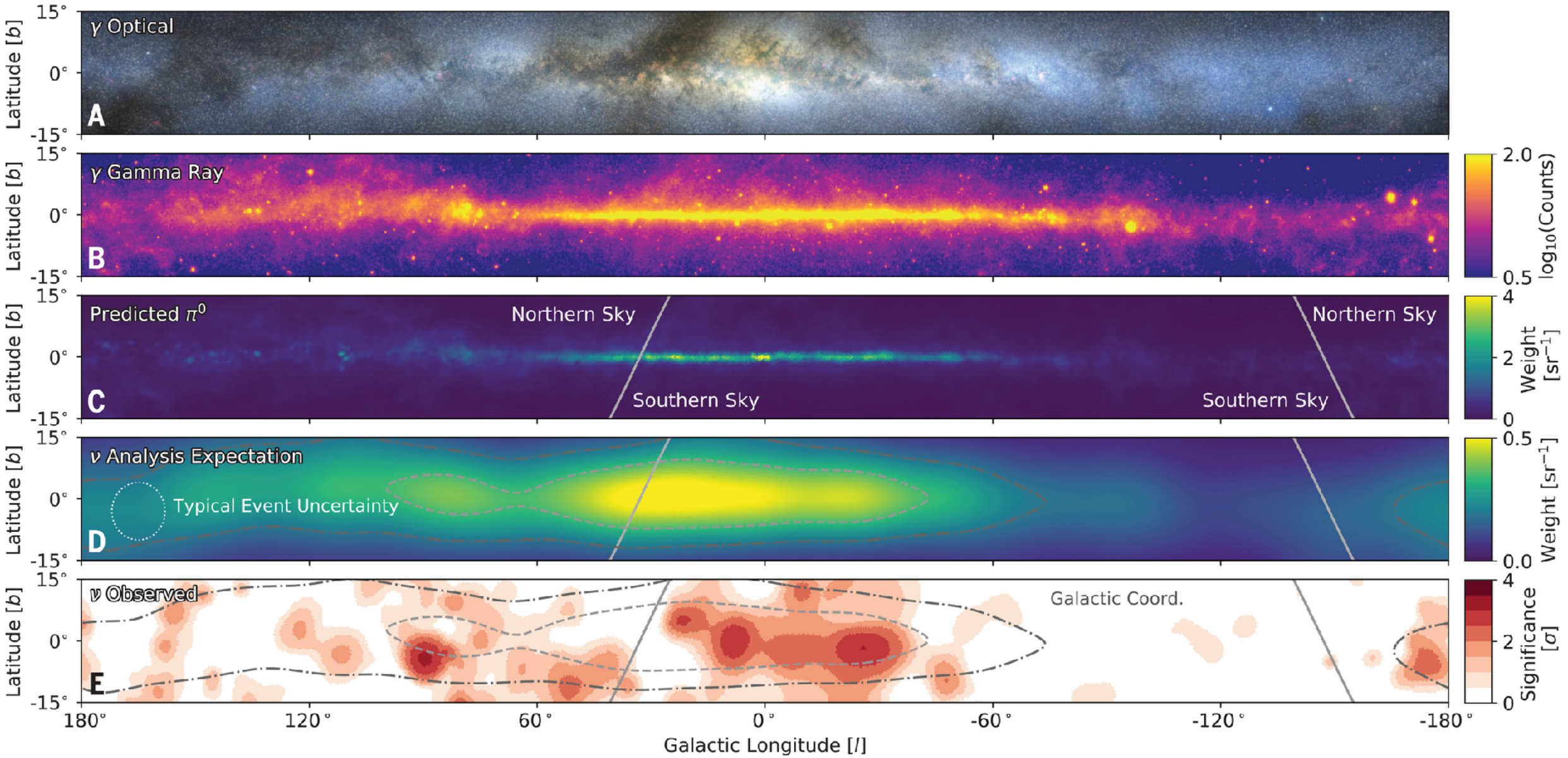
arXiv:2403.02516

Neutrino Sources

- Astrophysical neutrino flux is constructed from a huge number of individual sources.
- One such cluster of sources is the galactic plane - 4.5σ significance observation!
- This observation is consistent with our expectations based on charged π decays.
- Source models and characterisation of the flux the focus of the future studies.



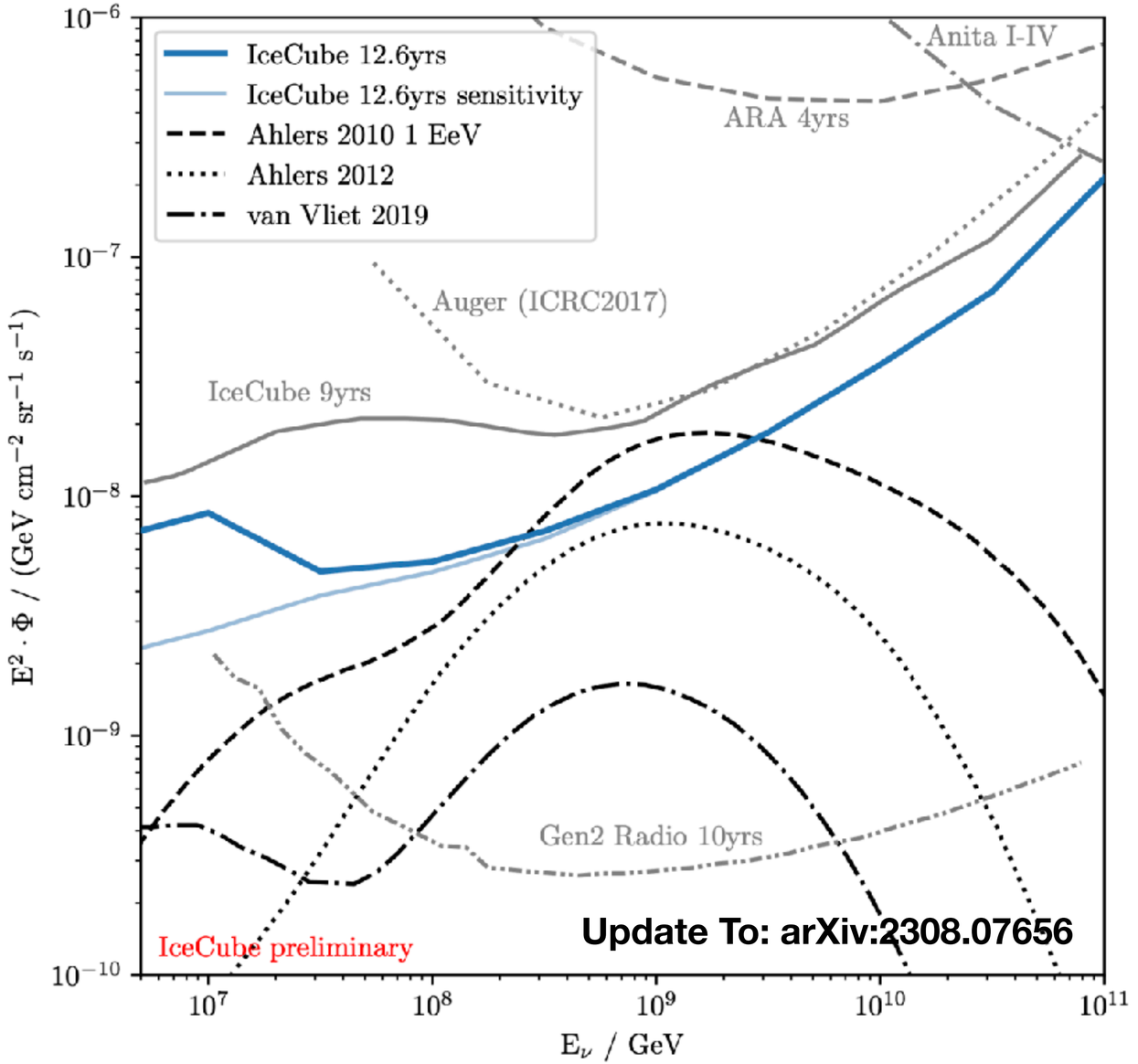
*Science***380**,1338-1343(2023)



arXiv:2307.04427

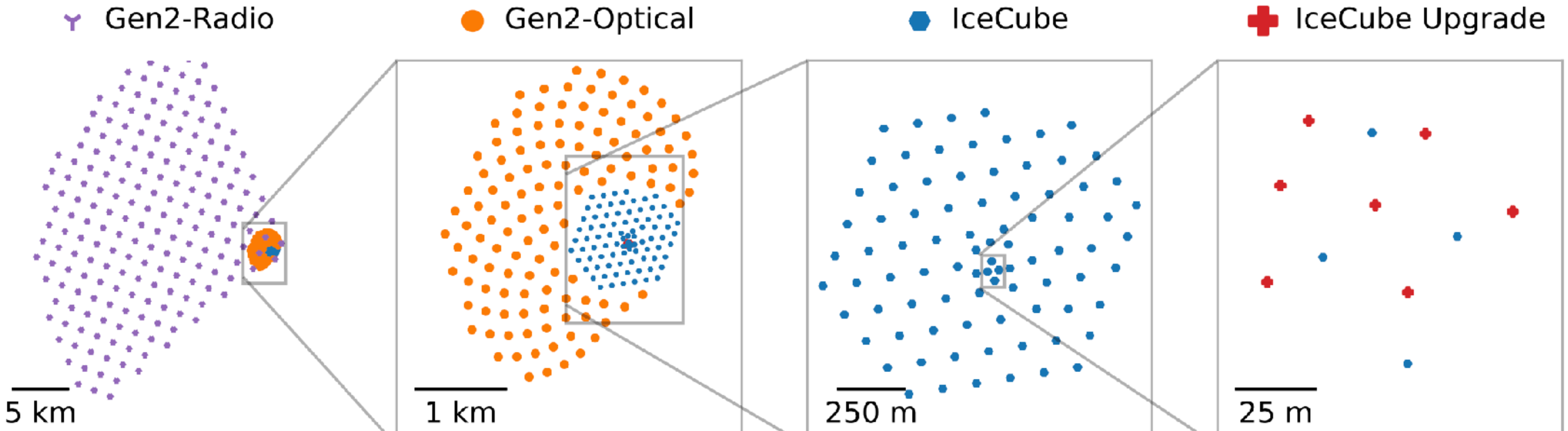
Extremely High Energy Neutrinos

- IceCube can also constrain the neutrino flux beyond PeV energies (EeV) - world-leading limit.
- These neutrinos originate from ultra-high energy cosmic rays interacting with the cosmic microwave background photons.
- Based on these new results, 100% proton fraction of cosmic rays strongly disfavoured.
- In combination with future results from IceCube-Gen2 radio, expected to strongly probe GZK flux models.



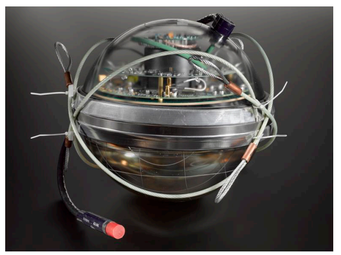

PeV-Scale Neutrino Event
Credit K. Mase

From IceCube to Upgrade to Gen2



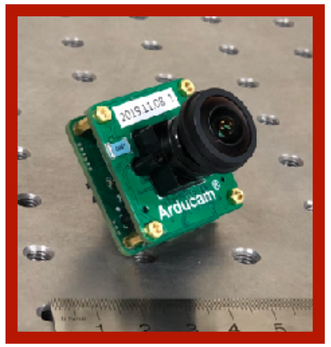
From ~2032

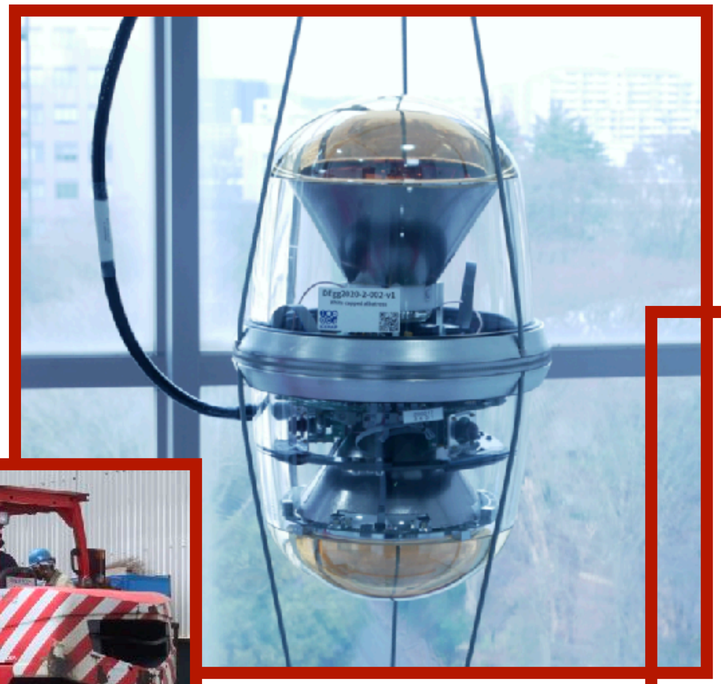
Since 2011



From 2026

The IceCube Upgrade

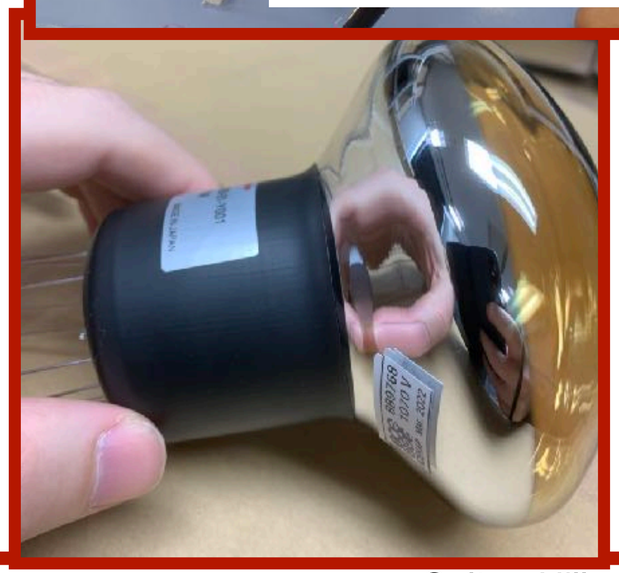


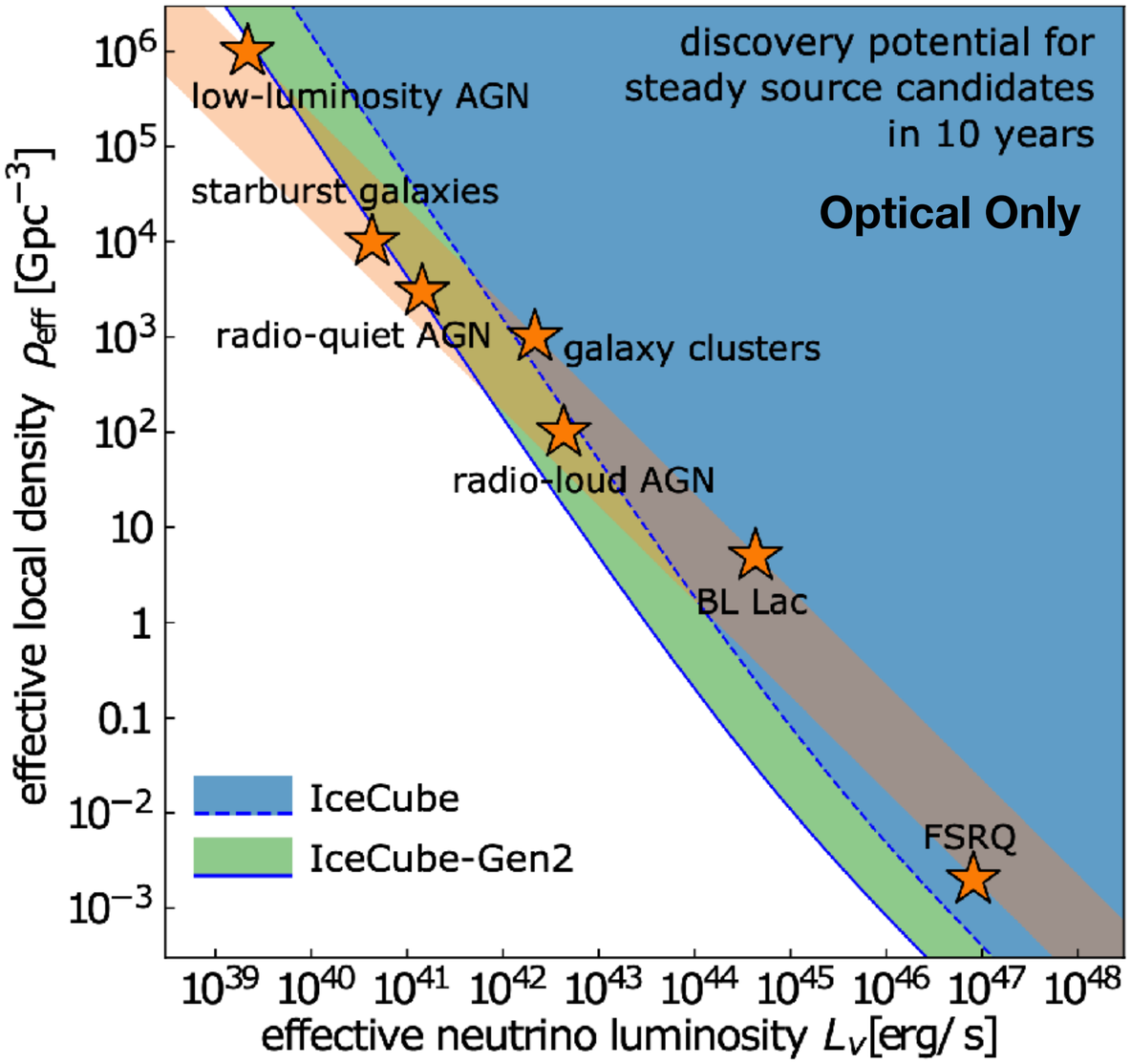


- Upgrade is primarily the GeV-scale extension to IceCube, but will be a testing-grounds for new optical modules & calibration subsystems.
- Modules already on their way to the South Pole for 2025/2026 deployment!

Gen2 Science Goals

- Resolving the high energy sky: TeV - EeV energies.
- Probing fundamental physics with high energy neutrinos.
- Understand highest energy cosmic accelerators through multi-messenger observations.
- Discover sources in the Milky Way and beyond.





Summary and Outlook

- Reaching high enough sensitivity to study specific astrophysical flux shapes - huge progress in the last 10 years!
- First detection of a candidate neutrino produced via the Glashow resonance.
- Continuing to improve on neutrino DIS cross section measurements critical for precision measurements of astrophysical neutrinos & beyond.

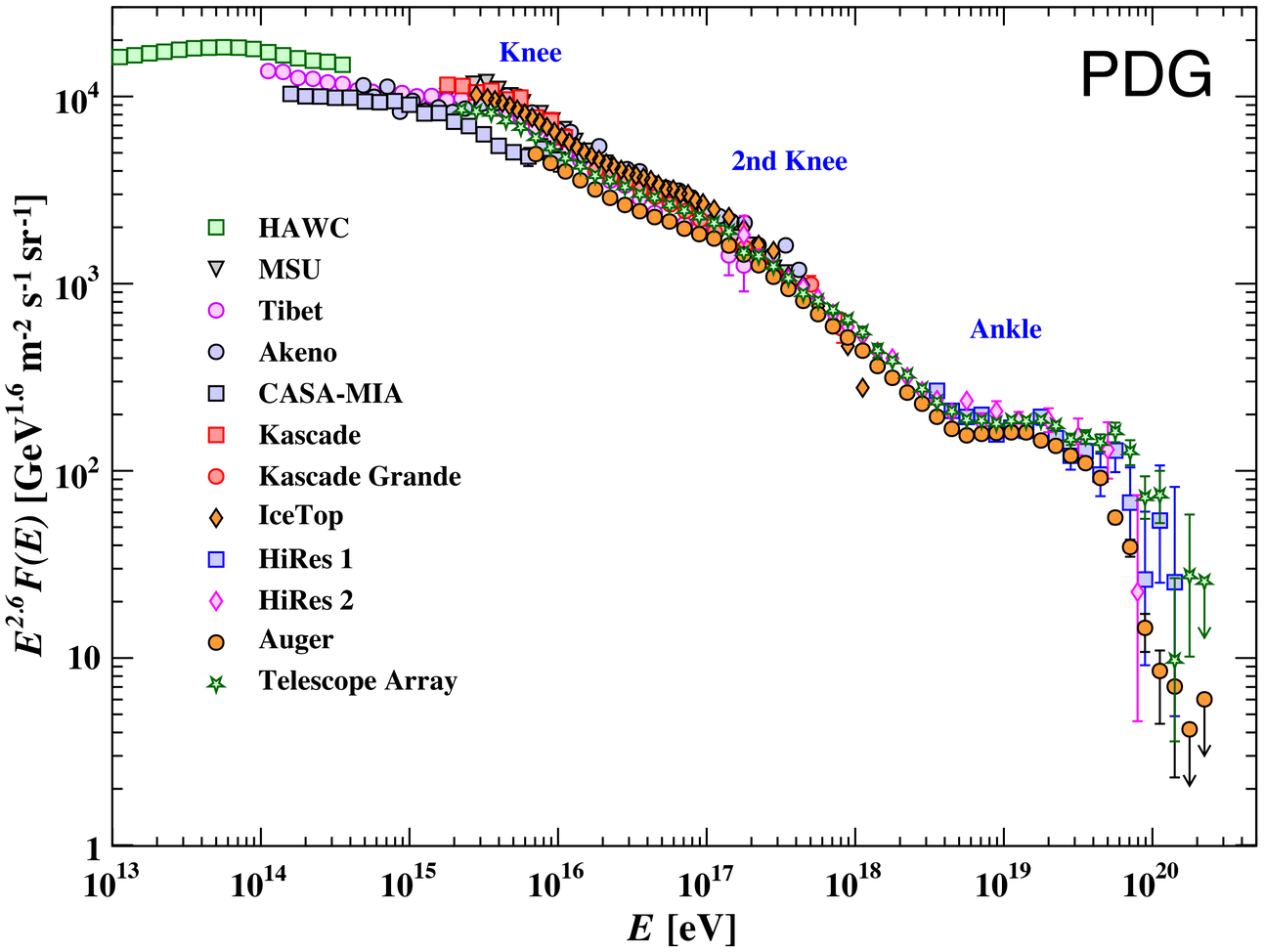
- Significant observation of neutrinos consistent with the galactic plane.
- Best limit EHE neutrino flux beginning to resolve aspects of the cosmic ray composition.
- IceCube Gen2 will unlock new measurements and be a leader in the growing multi-messenger astrophysics community.

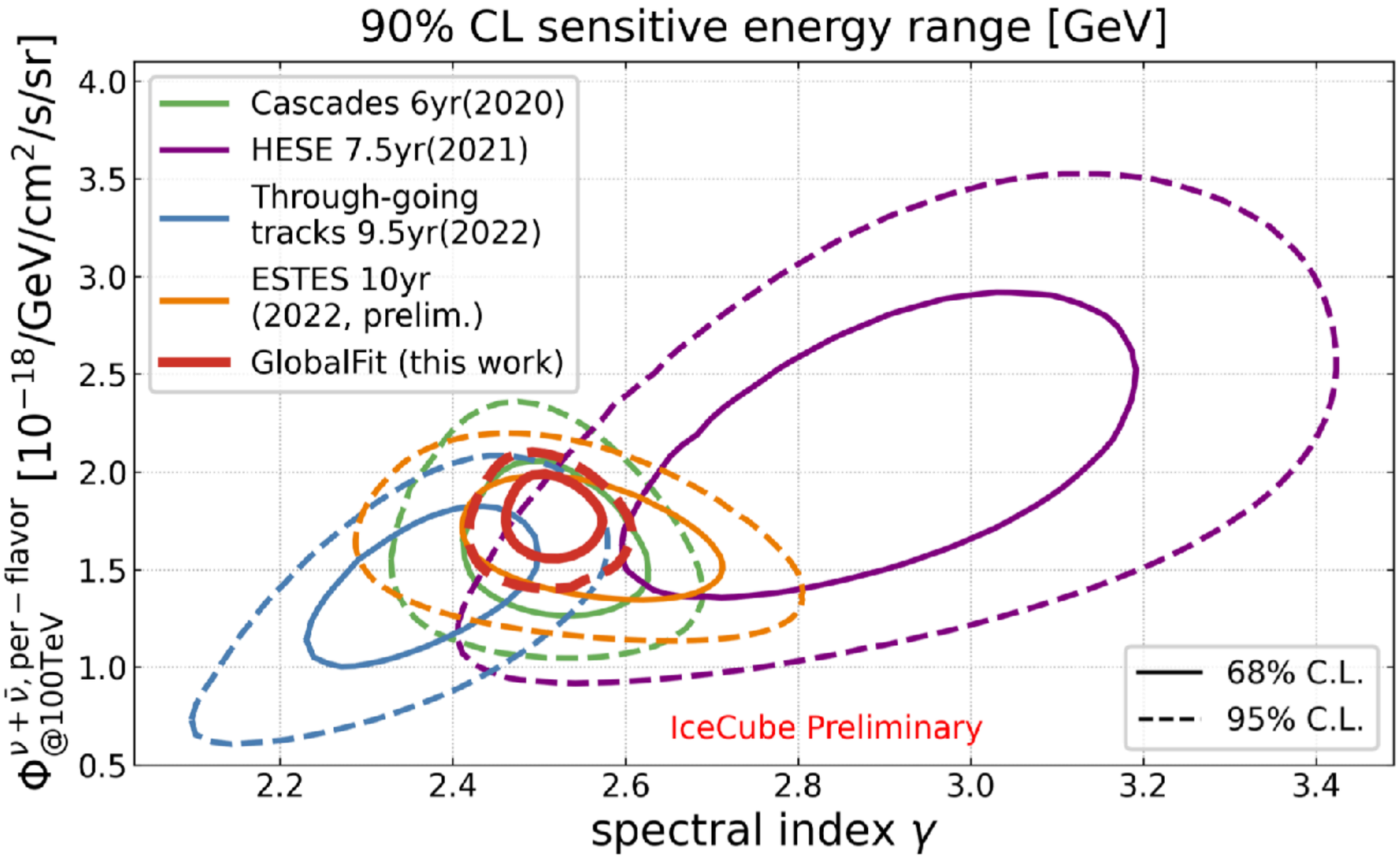
Thank You!

- Backup

Neutrinos & The Universe

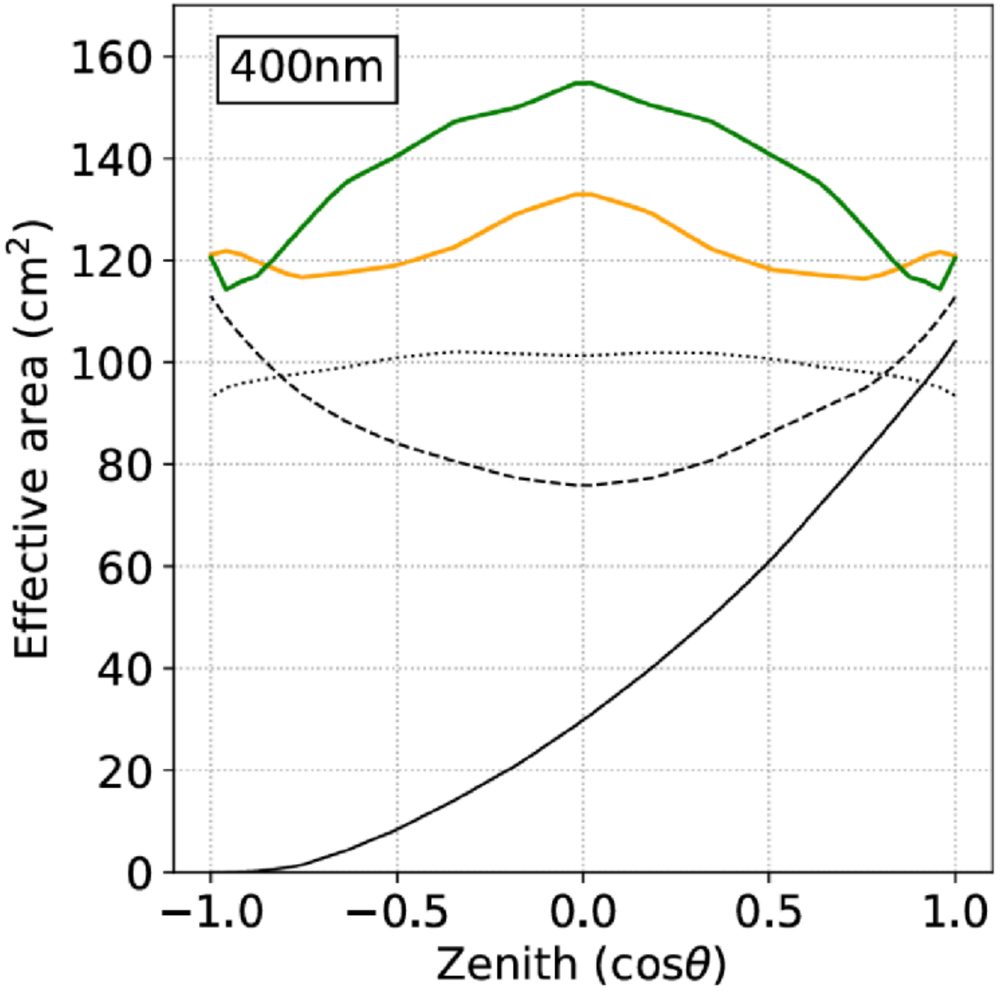
- Cosmic rays are accelerated up to immense energies beyond what we can produce on Earth.
- But our knowledge of these highest energy sources limited.
- The universe is filled with a variety of sources: Active Galactic Nuclei, Gamma Ray Bursts, Supernovae.
- These sources and their cosmic rays can produce neutrinos as primary or secondary particles.

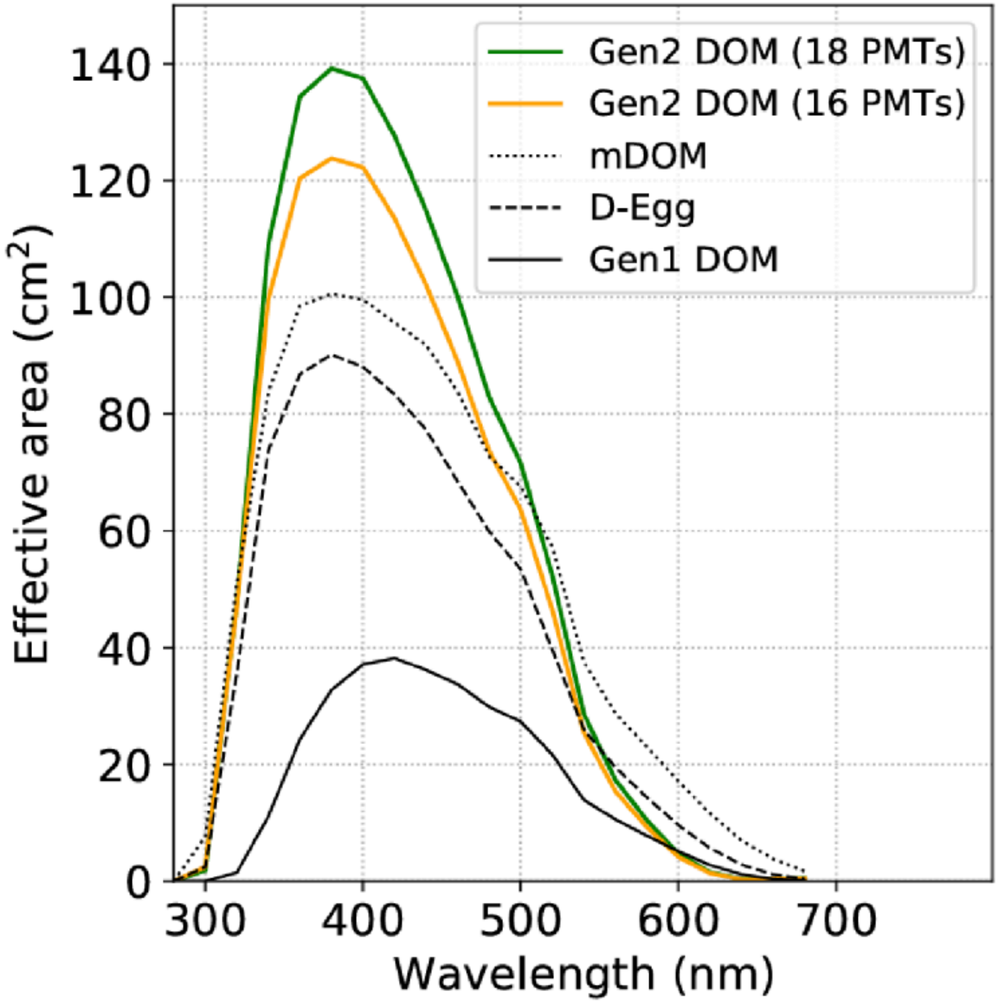




arXiv:2308.00191

IceCube Upgrade





IceCube Gen2 TDR

IceCube Upgrade

Planned 2025-

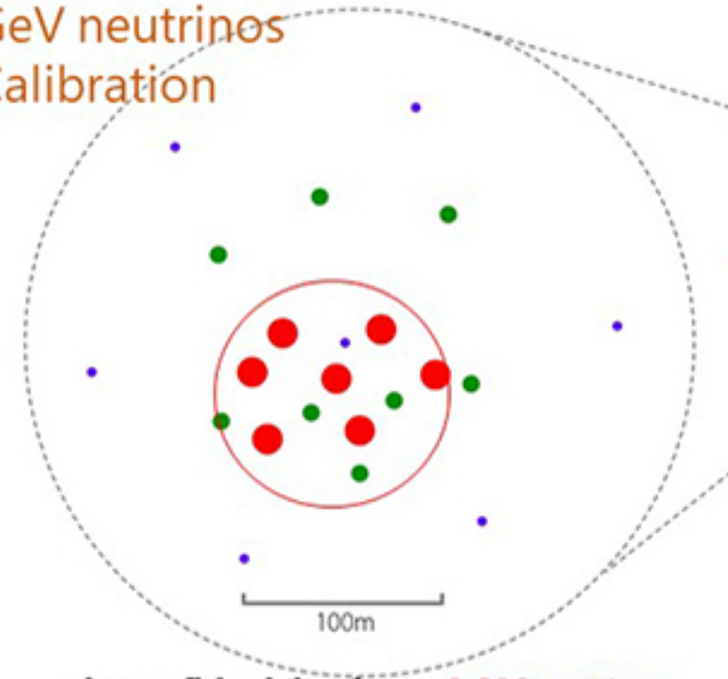
Optimized for
- GeV neutrinos
- Calibration

IceCube (2005-)

Optimized for
- Diffuse high energy cosmic neutrinos

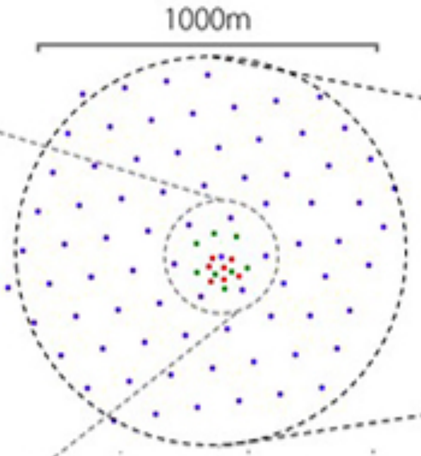
IceCube-Gen2 **Planned 2028-**

Optimized for
- Cosmic neutrino point sources

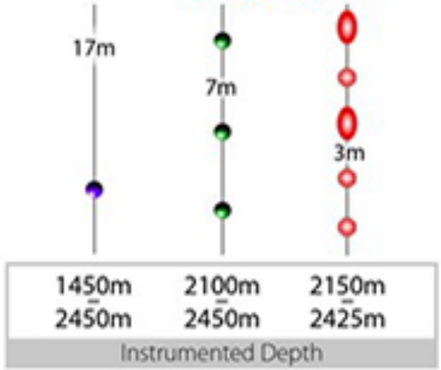


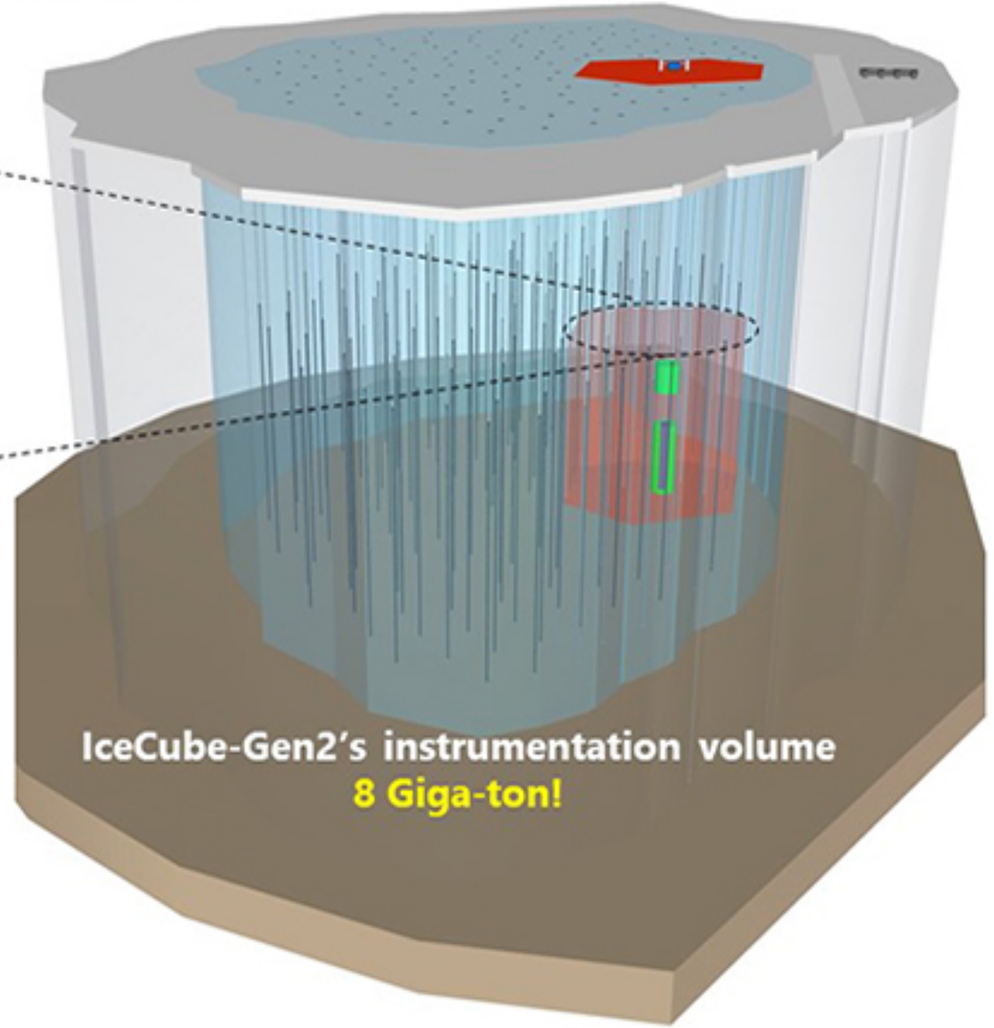
inner fiducial volume 2.2Mega-ton

IceCube DeepCore Upgrade



IceCube's instrumentation volume 1 Giga-ton



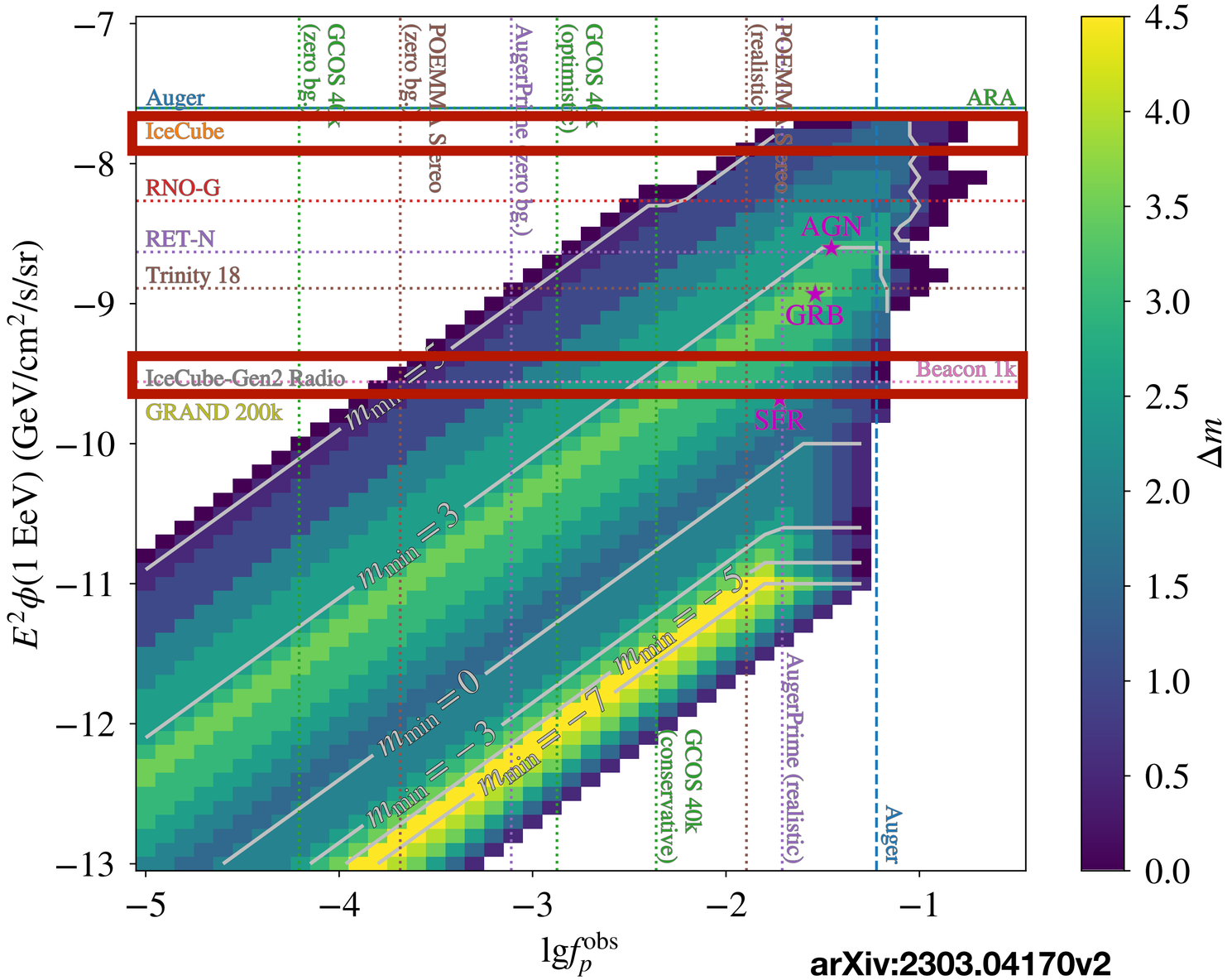


IceCube Gen2

- Gen2 EHE neutrino flux measurement + UHE cosmic ray flux composition ⇒

  constraints on the cosmic ray source evolution parameter *m*.

$$\phi(z) \in (1+z)^m$$



IceCube Gen2

- For detecting specific sources, Gen2 will lower the time a source needs to be active.
- This is extremely beneficial for multi-wavelength follow-ups from other experiments (IceCube has constant 4π sensitivity, most telescopes only a few degrees field of view).