IceCube

Presented by Nahee Park

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's UNIVERSITY

More than 300 people from 56 institutions in 14 countries

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Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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German Research Foundation (DFG)
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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)

IceCube South Pole Neutrino Observatory

icecube.wisc.edu

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South Dakota School of Mines and Technology
Southern University and A&M College
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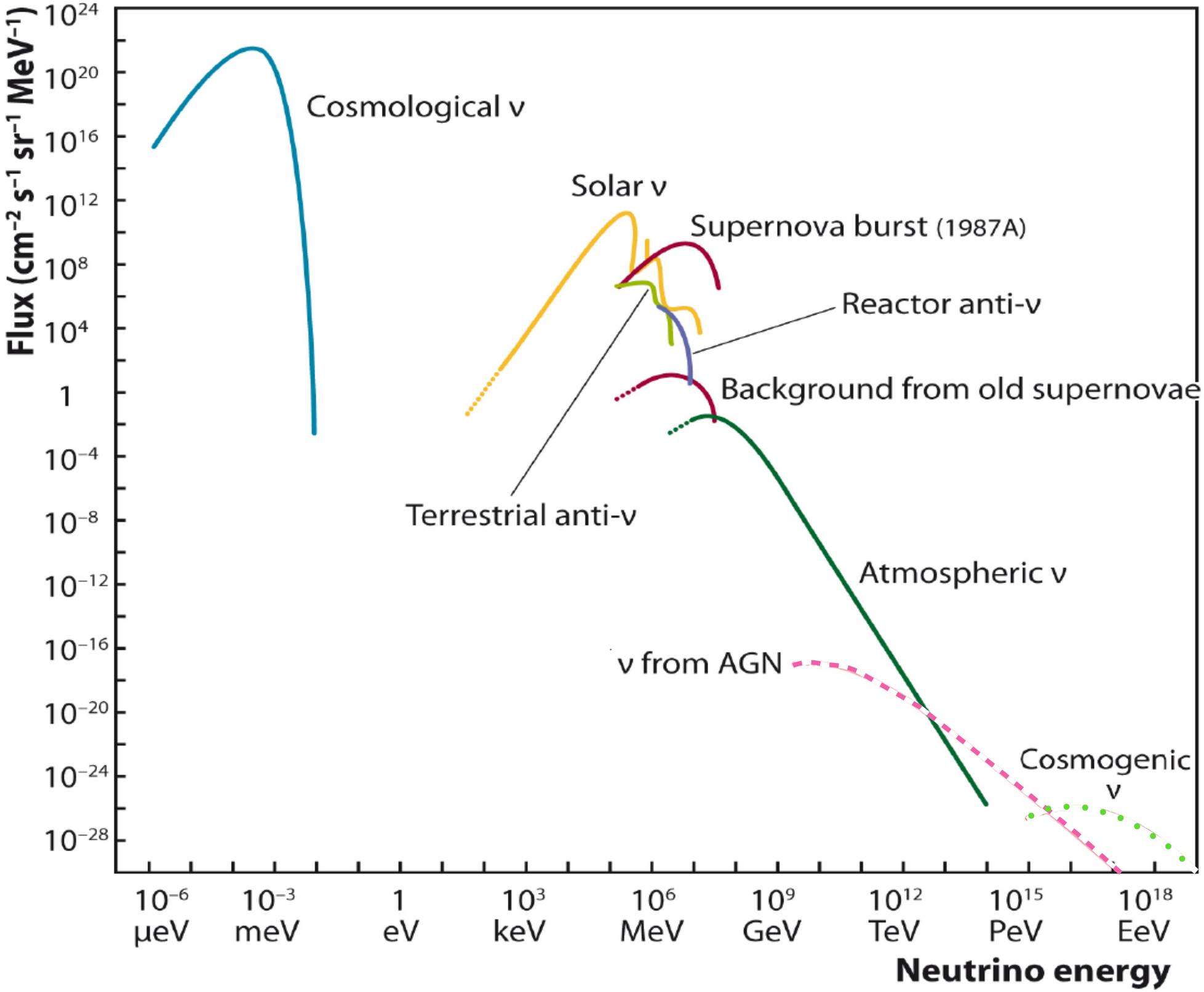
Neutrino Measurements of IceCube



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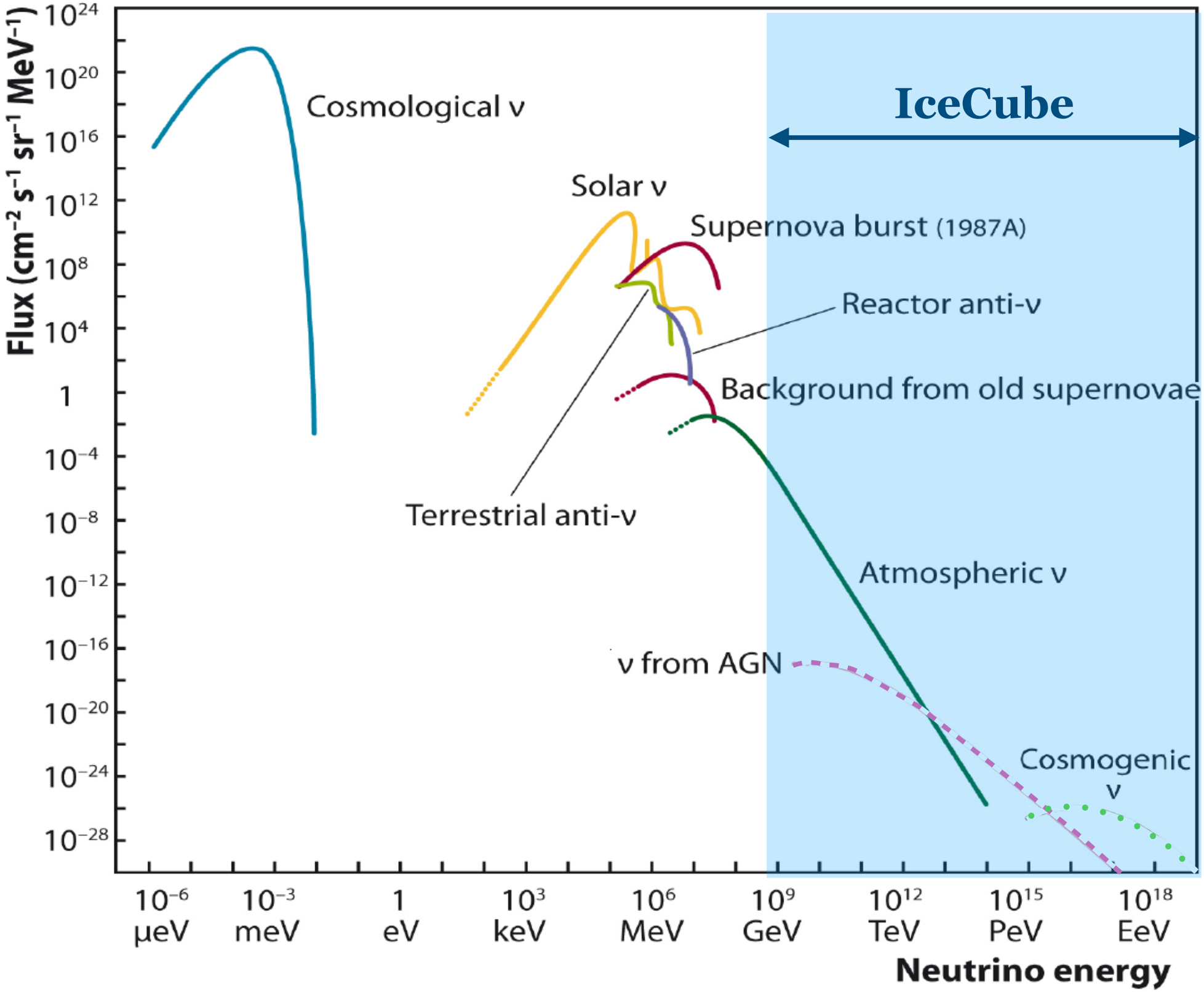
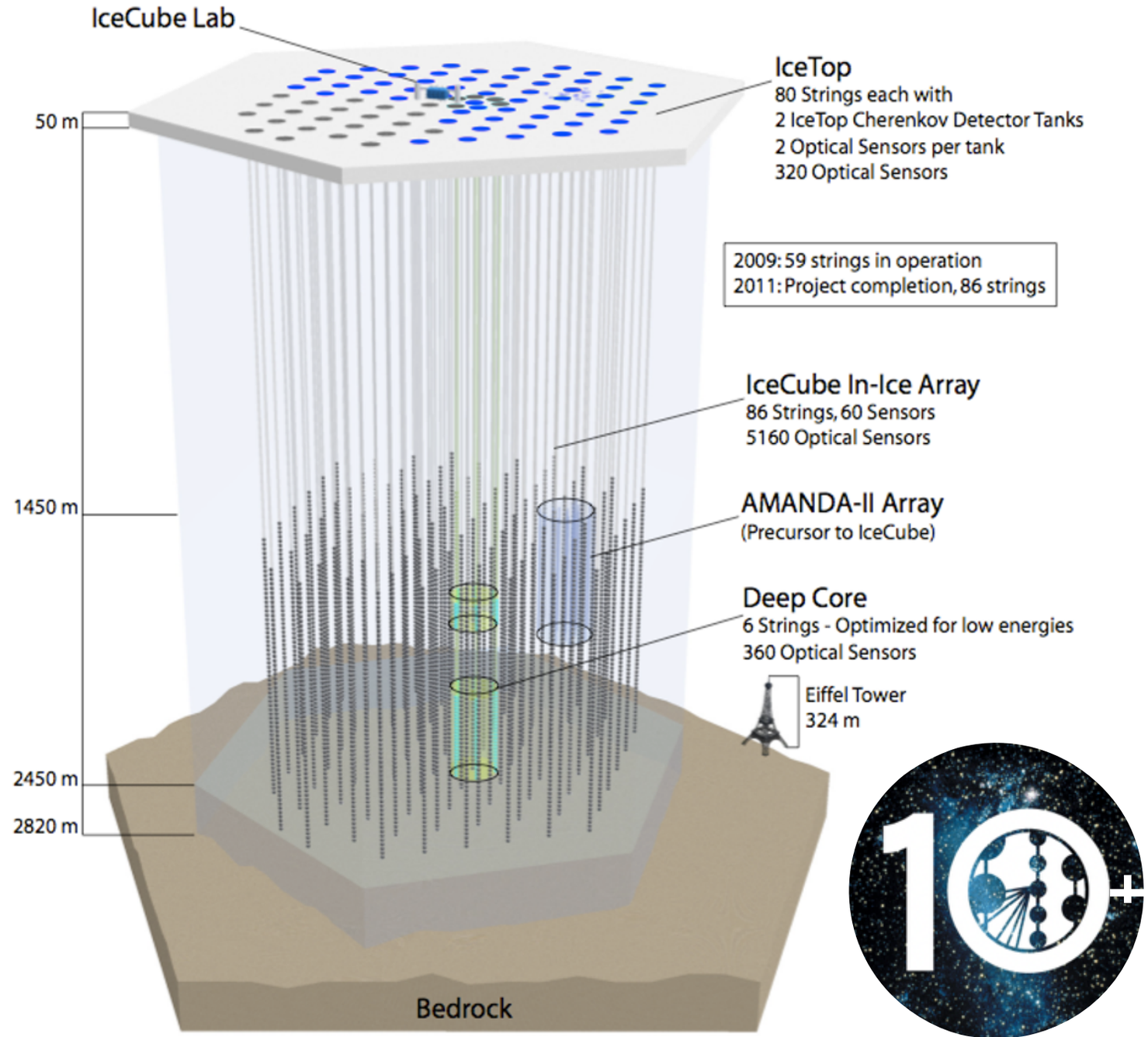
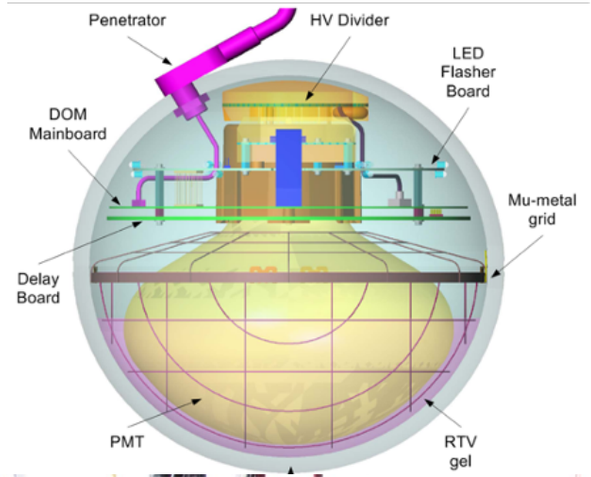


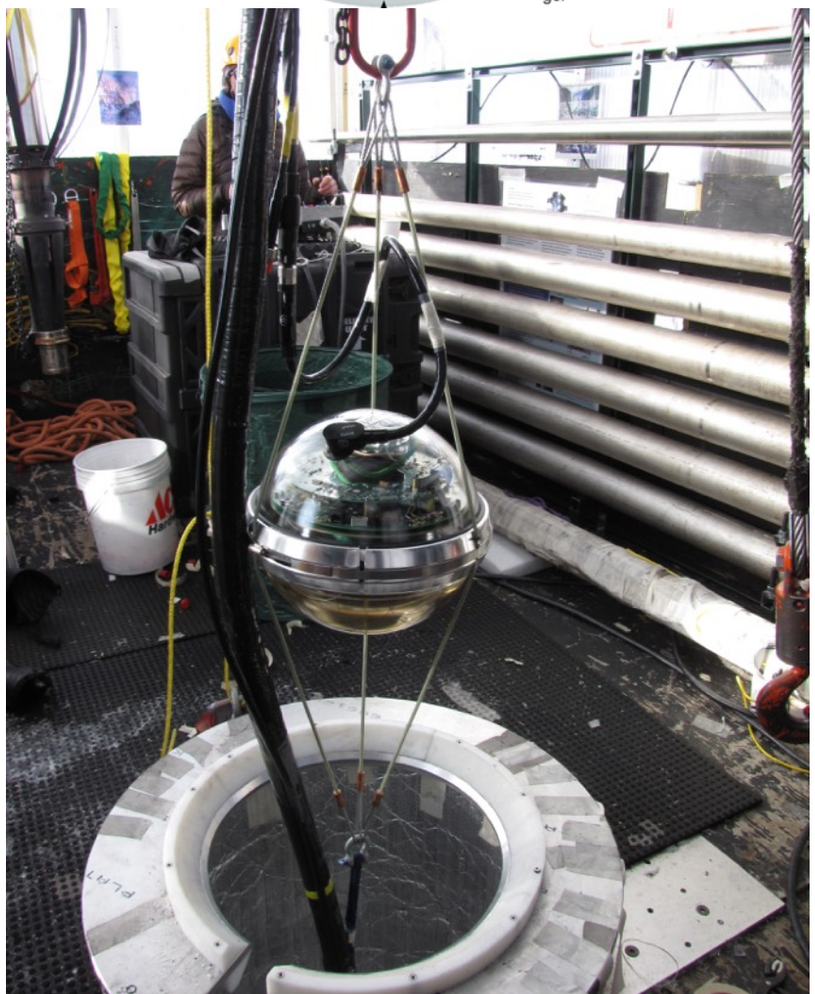
The IceCube Neutrino Observatory

High-energy neutrino observatory with a cubic kilometre located at 1.5 - 2.5 km under the South Pole

- Full deployment in Dec. 2010







Observed Neutrino Event Types

Track

CC ν_μ interactions

Cascade

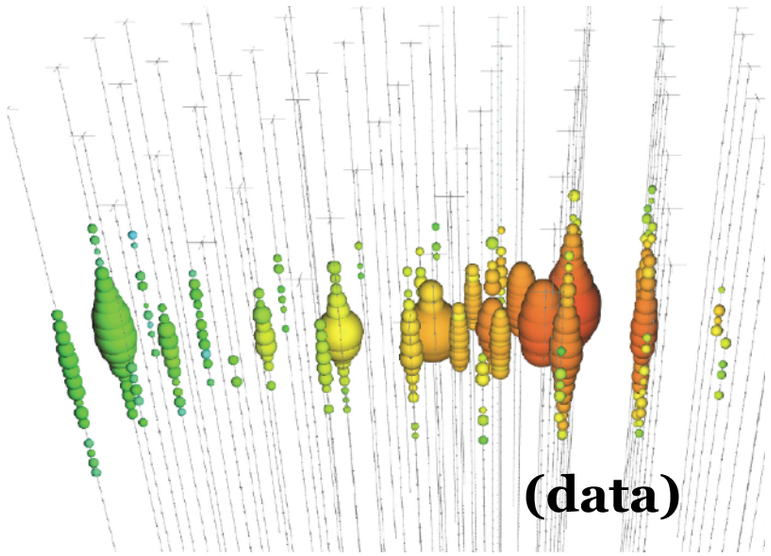
NC interactions

CC ν_e interactions

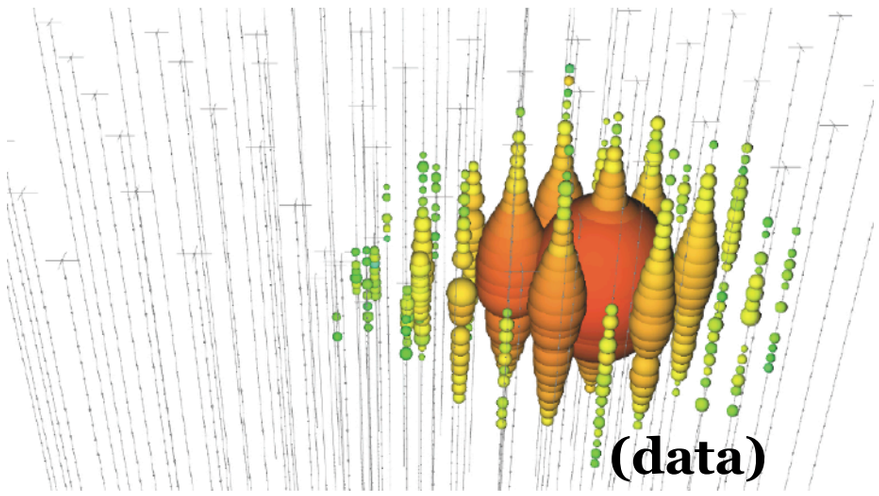
Most of CC ν_τ interactions

Double cascade

CC ν_τ interactions
(E_{dep} > 100 TeV)



(data)



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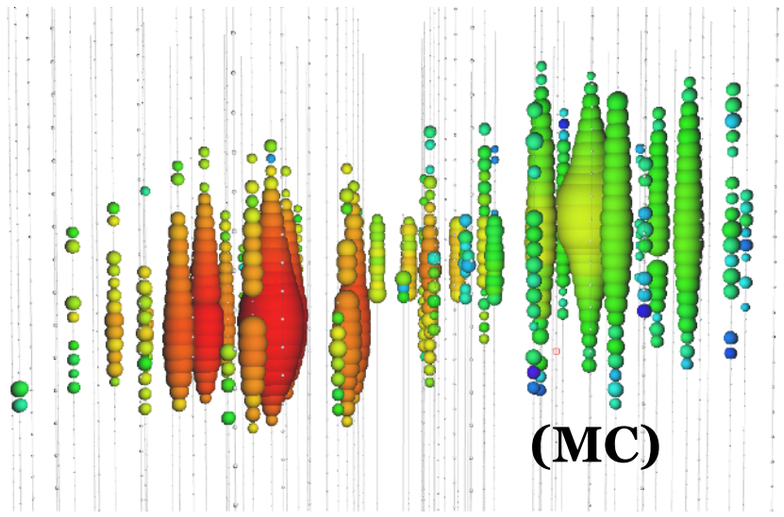


(MC)

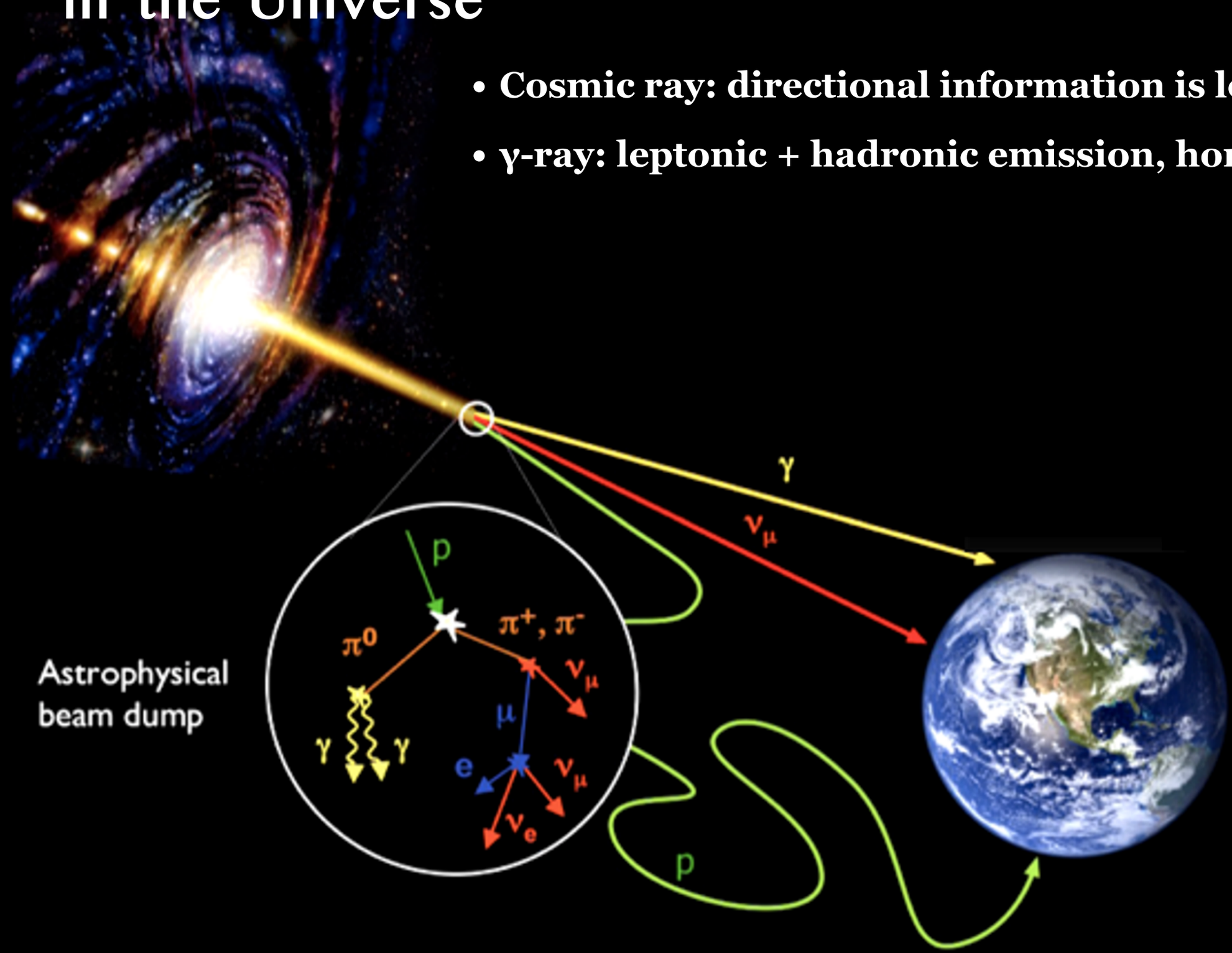
Earlier **Later**

Angular resolution ~ 0.2° ~ 1°
Energy resolution ~ factor of 2

Angular resolution ~ 10 °
Energy resolution ~ 15% (>100 TeV)

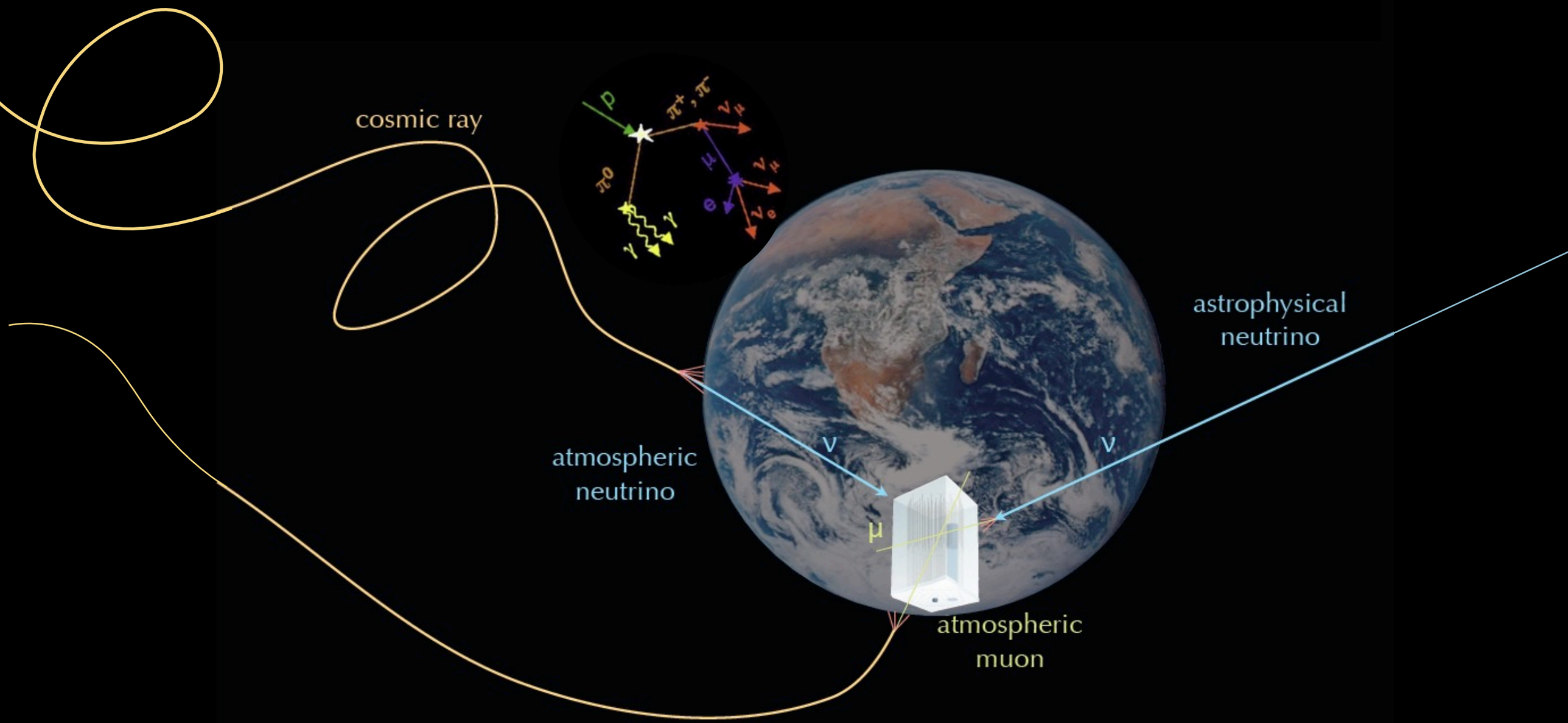
Neutrino is the best messenger to study the high-energy hadronic particle interactions in the Universe

- **Cosmic ray: directional information is lost**
- **γ-ray: leptonic + hadronic emission, horizon at z~1**



Background

- **Atmospheric muon: 10^{3} Hz**
- **Atmospheric neutrino: 10^{-3} Hz**
- **Astrophysical neutrino: 10^{-7} Hz**



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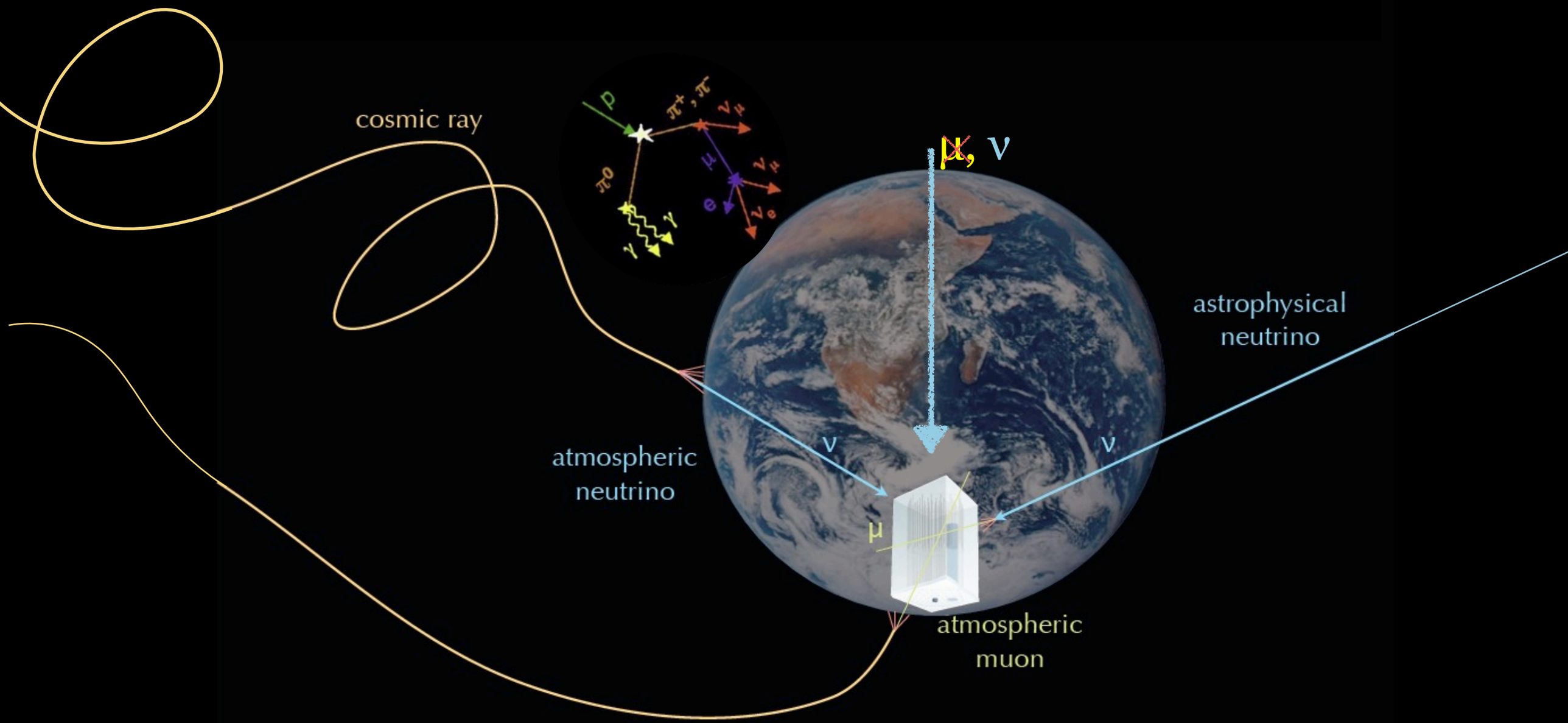

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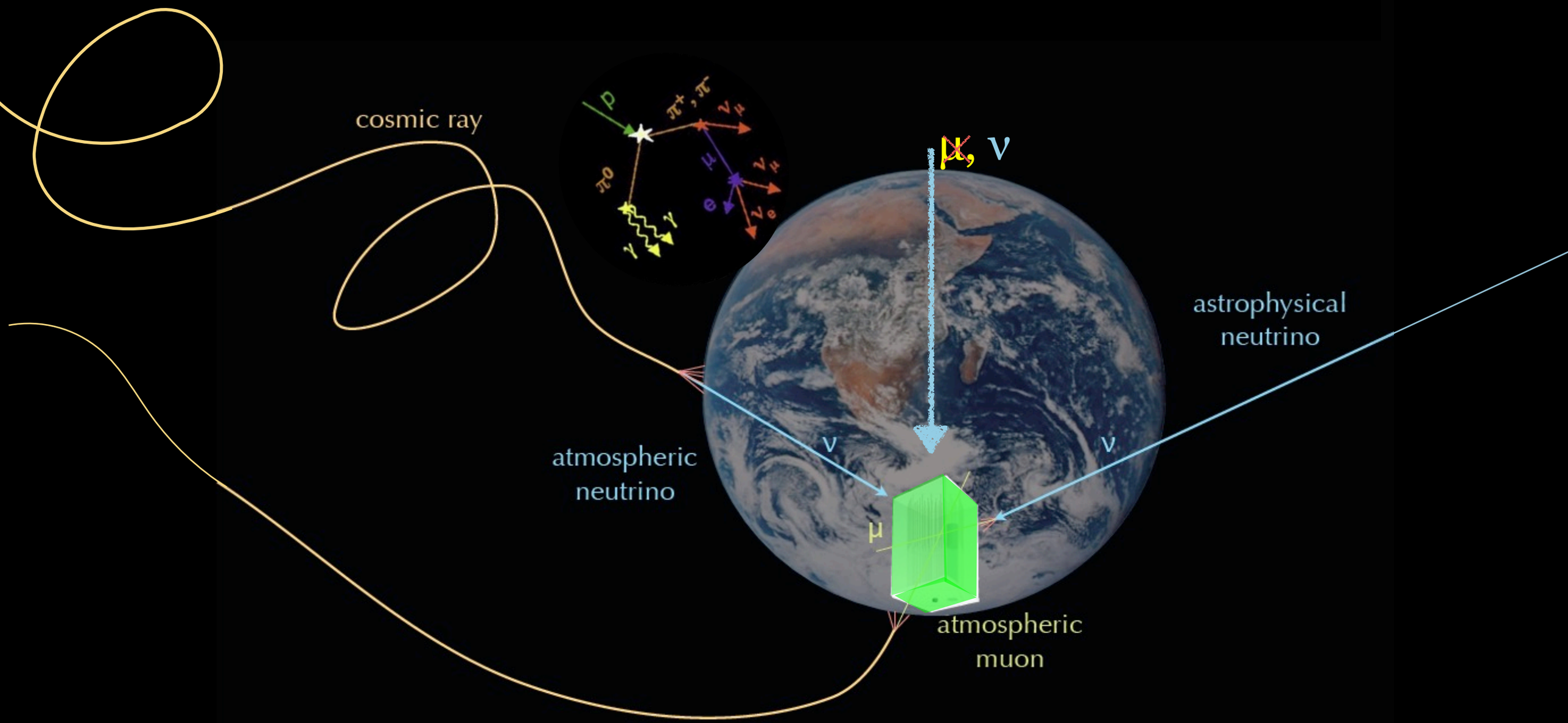

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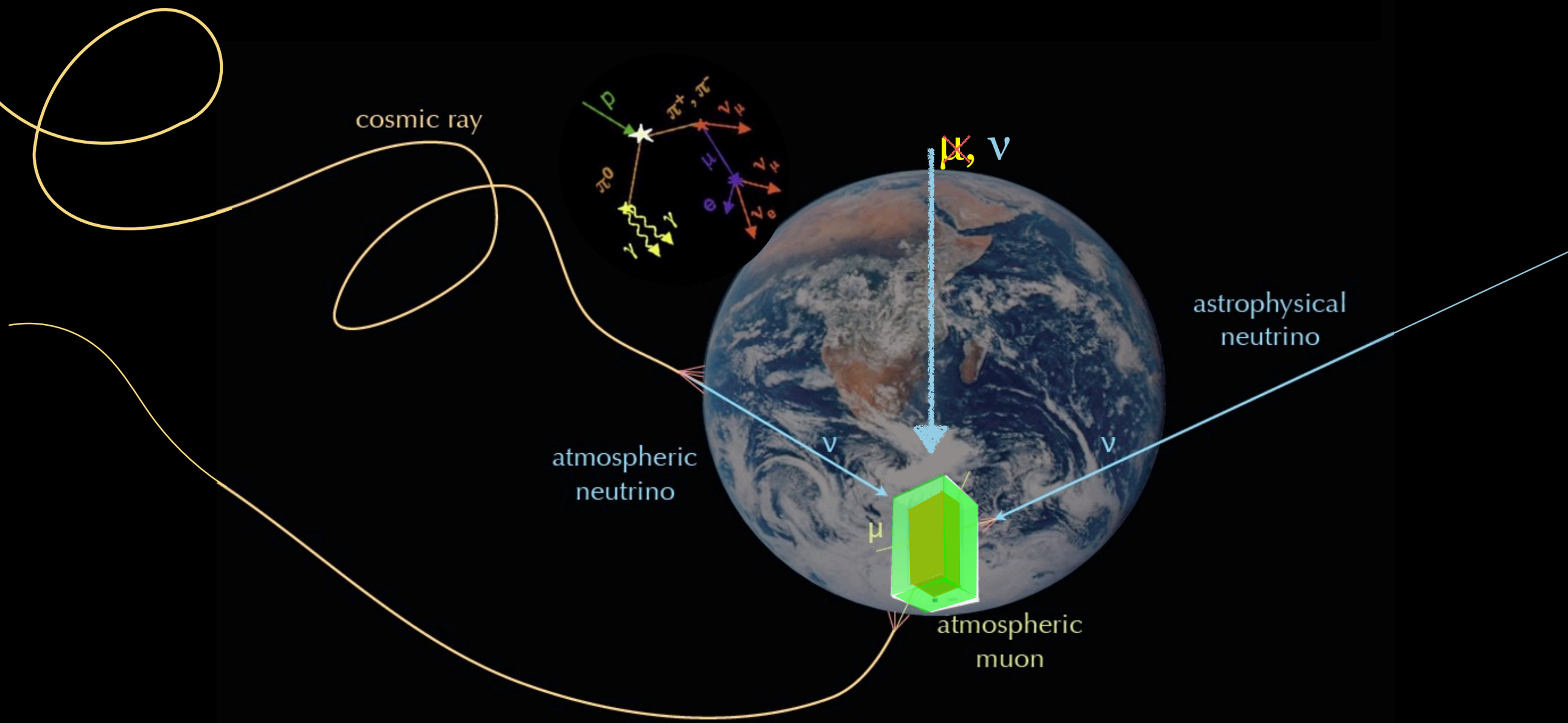

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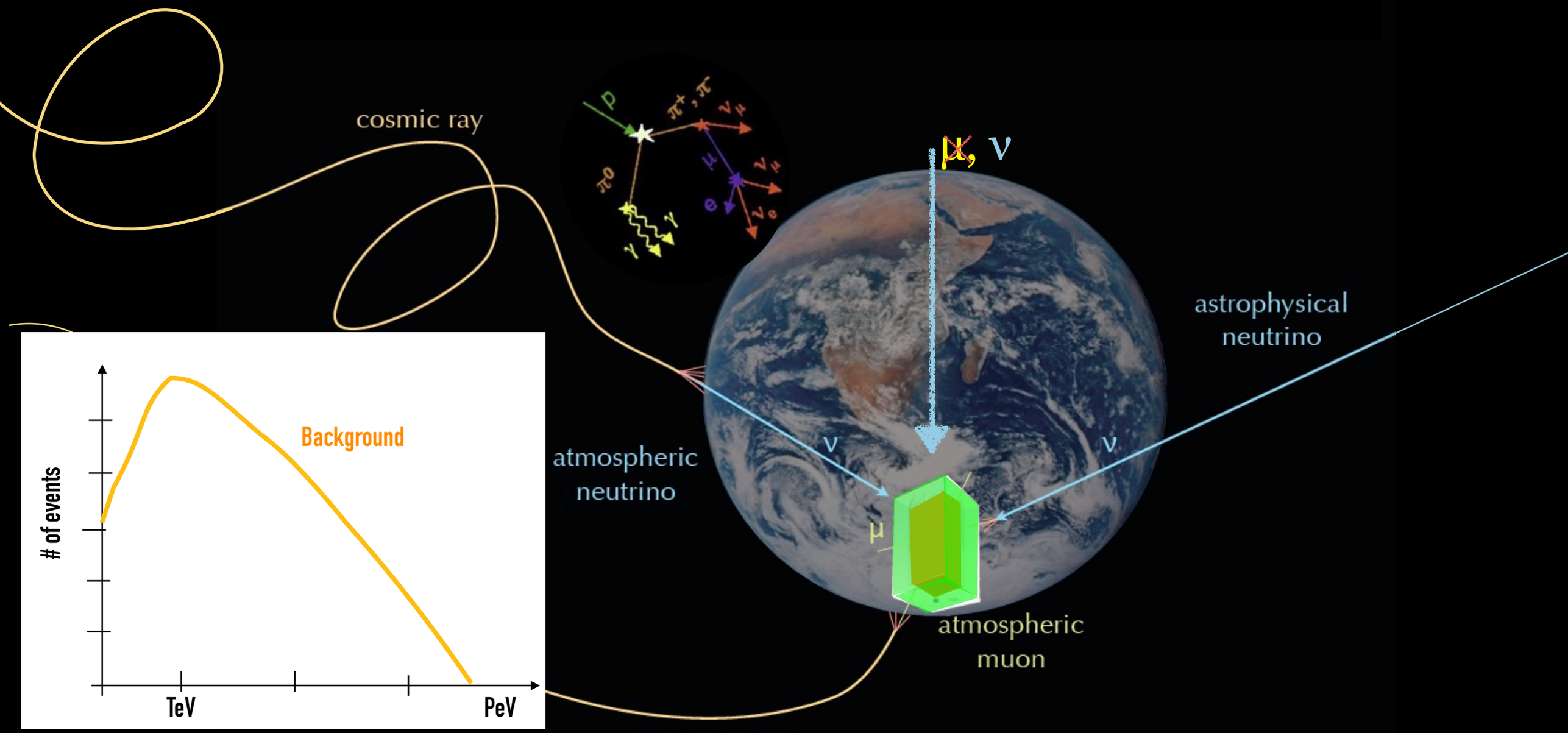

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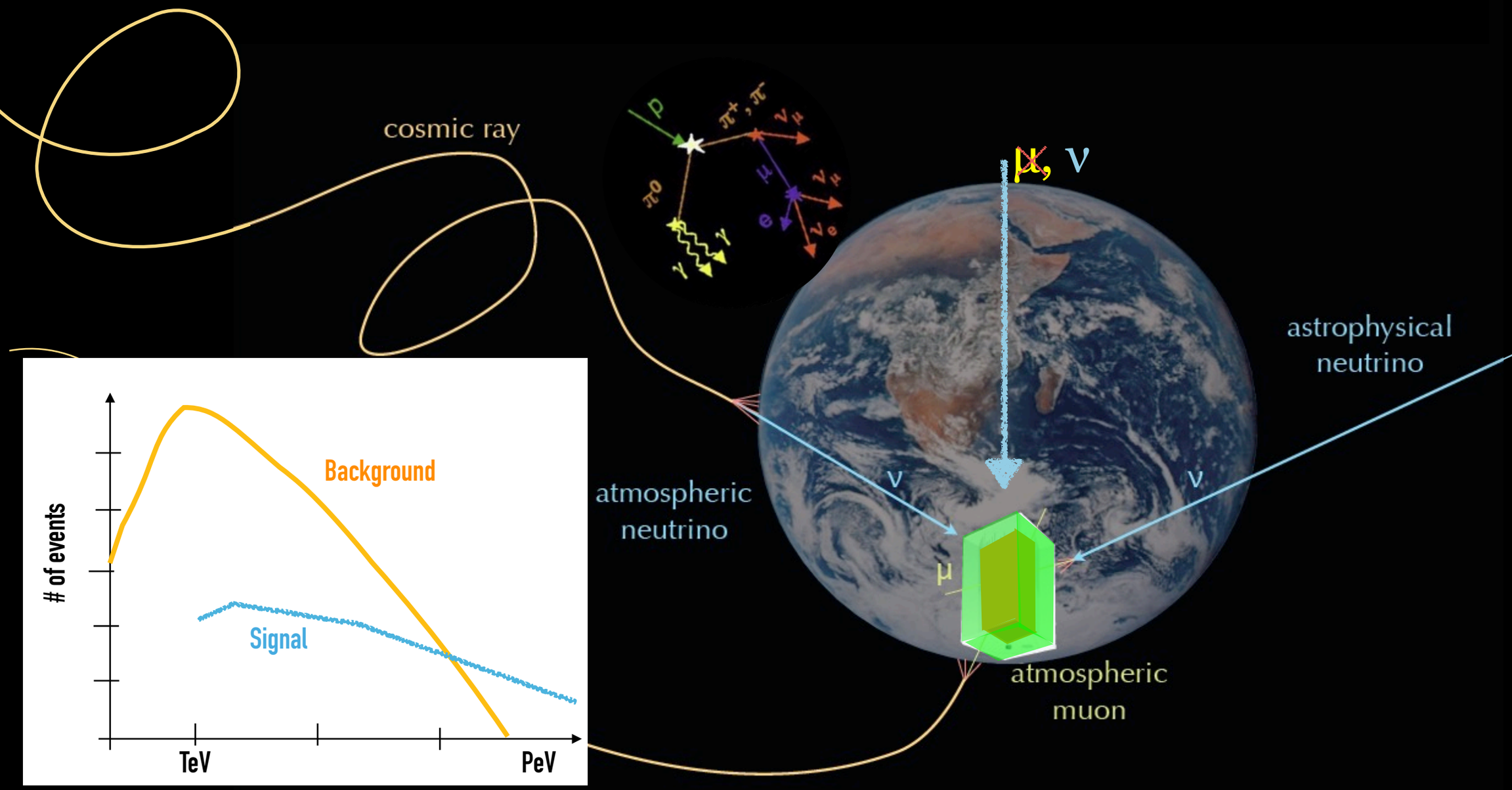

IceCube Science

- Diffuse Neutrino Study
- Neutrino Source Search
- Multi-messenger Astronomy
- Solar Physics

Neutrino Astrophysics

- Flavor Ratio

Neutrino Physics

- Neutrino Oscillation
- Sterile Neutrinos
- Non-standard Interactions

Cosmic Rays

- Anisotropy
- Elemental Composition
- Knee/2nd knee spectra
- Particle Interactions in Air shower

Beyond Standard Model

- Rare Interaction Studies
- Searches for Axions, monopole,..
- SUSY

Dark Matter

- Indirect Searches for Dark Matter

IceCube Science

UNIVERSITY OF ALBERTA

Queen's UNIVERSITY

Canadian Contributions

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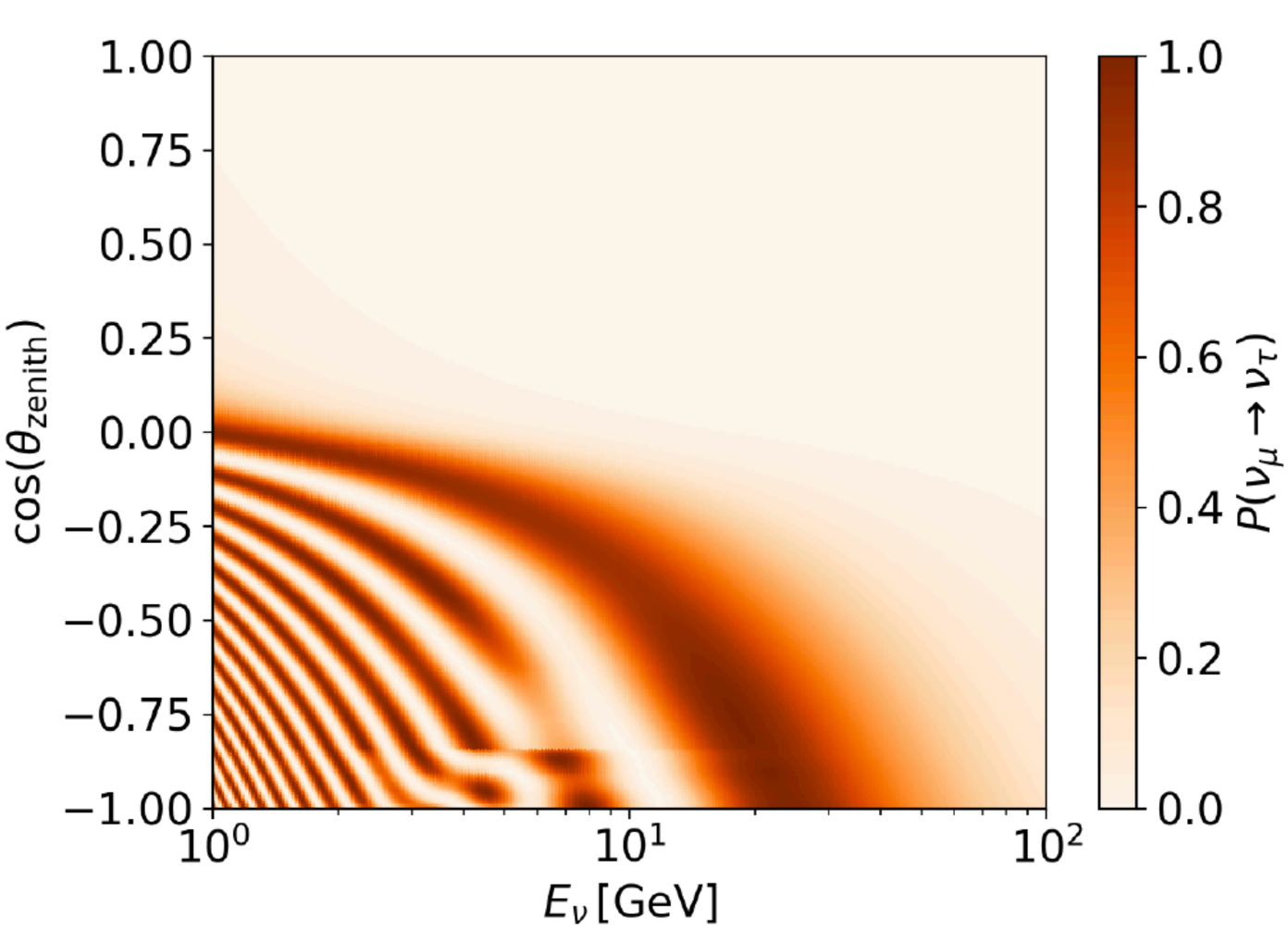
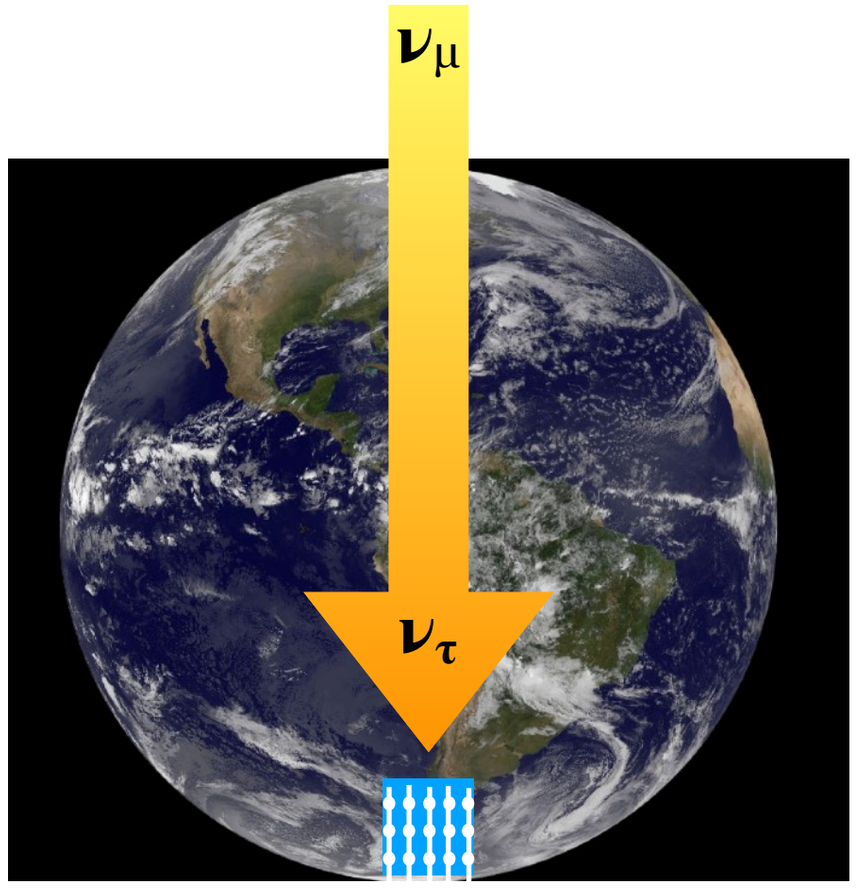
Neutrino Oscillation

Atmospheric neutrinos from ~5 GeV up to 100 GeV

- Atmospheric neutrinos: mixed composition of ν_μ and ν_e
- L varies between 20 km to 1.3×10^4 km
  - O (25 GeV) Earth-crossing ν_μ near maximally oscillates to ν_τ





Neutrino Oscillation

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- Atmospheric neutrinos: mixed composition of ν_μ and ν_e
- L varies between 20 km to 1.3×10^4 km
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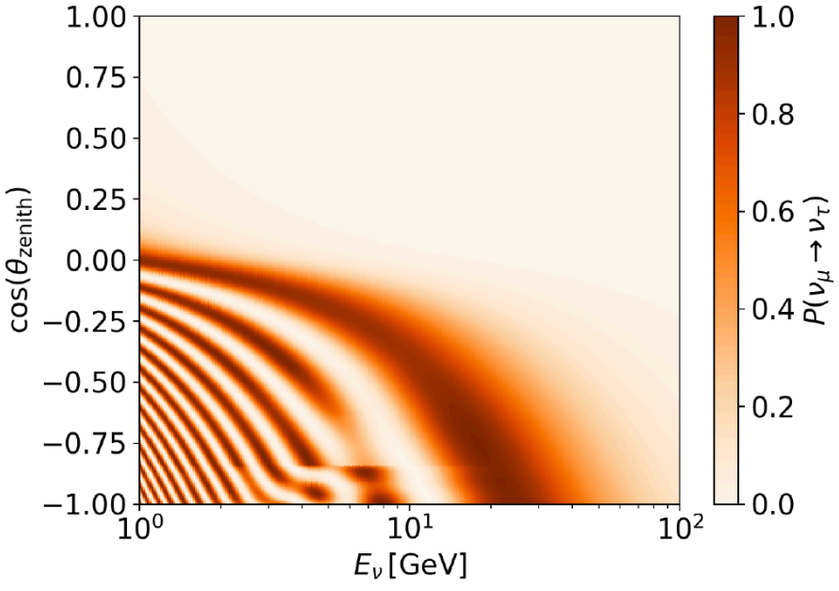
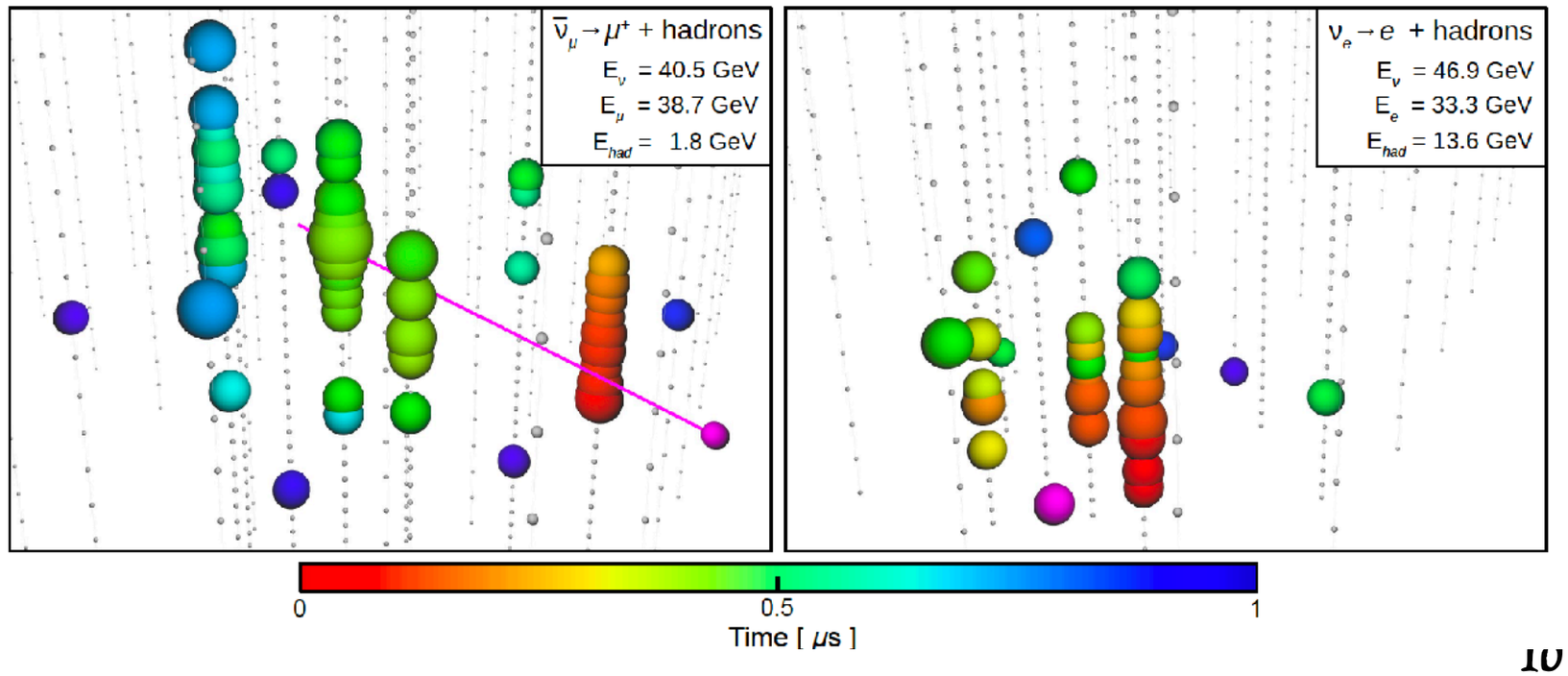
- Observe ν_μ disappearance and corresponding ν_τ appearance



“Track-like“:
ν_μ CC

“Cascade-like“:
NC interactions,
ν_e CC & ν_τ CC



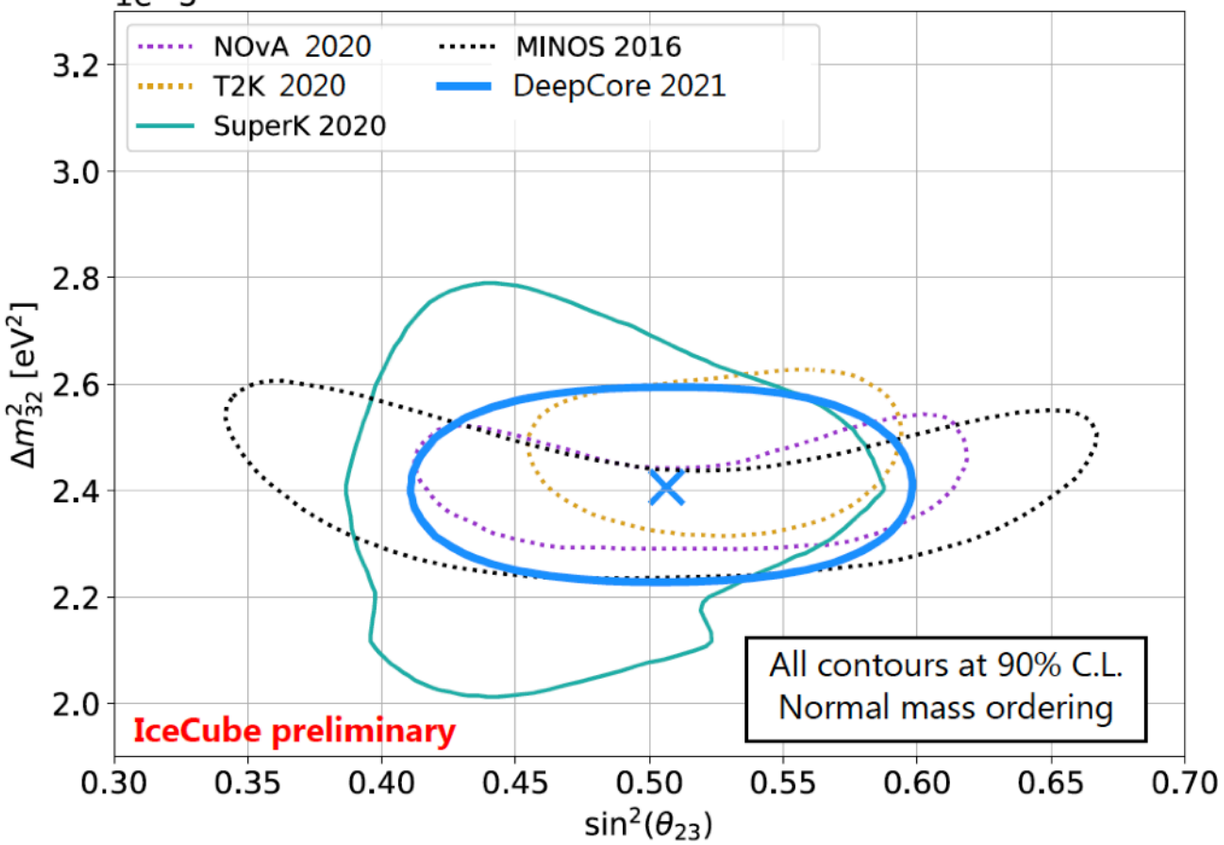
Neutrino Oscillation

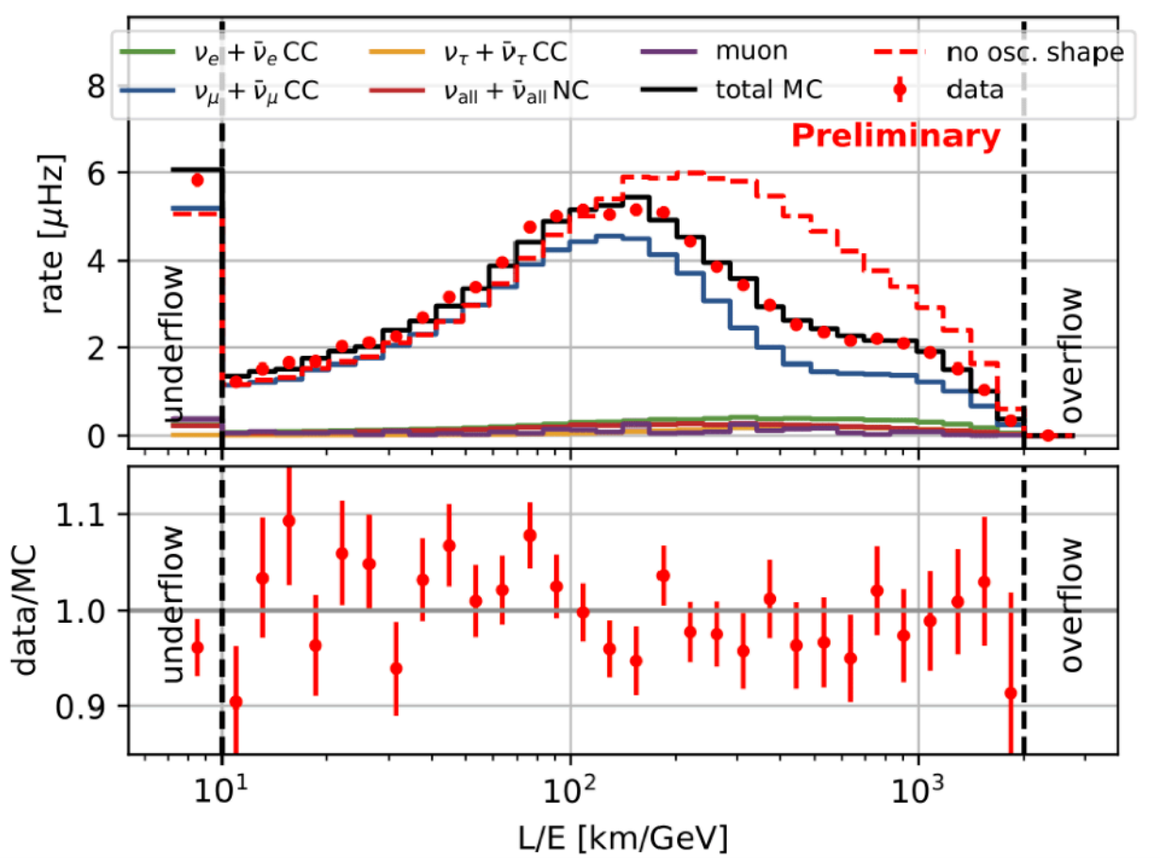
oscNext: New event selection with improved detector calibration and analysis methods

- Sensitivity of full data analysis is expected to be competitive to LBL

  -210,000 neutrinos (~9,700 $\nu_{\tau,cc}$) with 0.7% background

- Oscillation working group-wide effort with key aspects developed in Canada

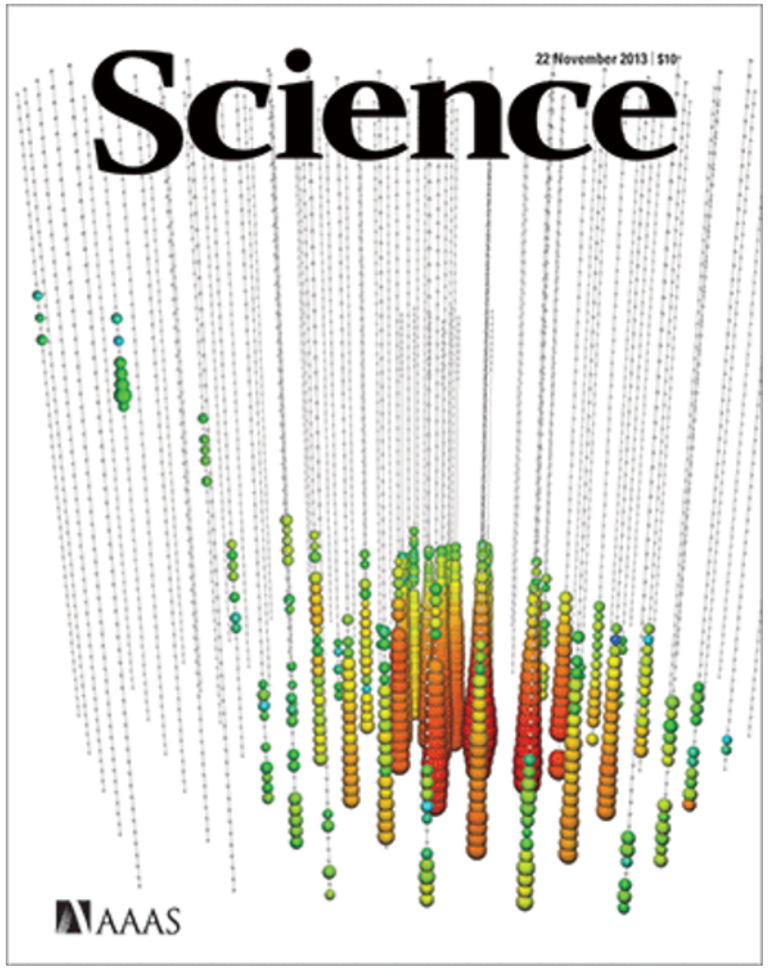


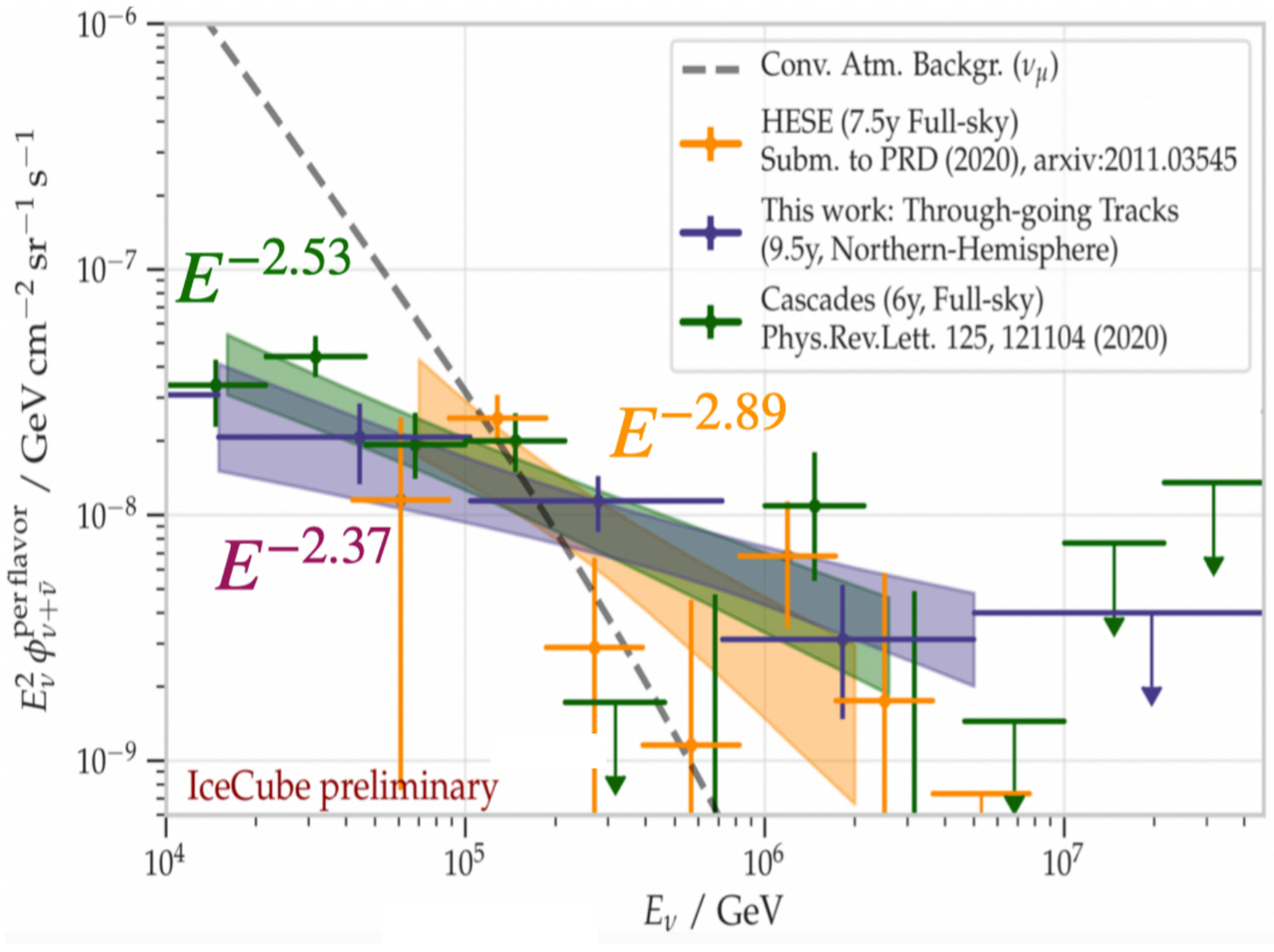


Discovery of high-energy neutrino flux

IceCube has measured the astrophysical neutrino flux with multiple independent analyses

- Through-going muon (ν_μ), Cascade (all flavor, $\nu_e + \nu_\tau$ dominant), high-energy starting event (HESE, all flavor, low background selection): all agree on the flux level





IceCube, PRL 111, 021103 (2013)
IceCube, Science 342, 1242856 (2013)
IceCube, PRL 113, 101101 (2014)

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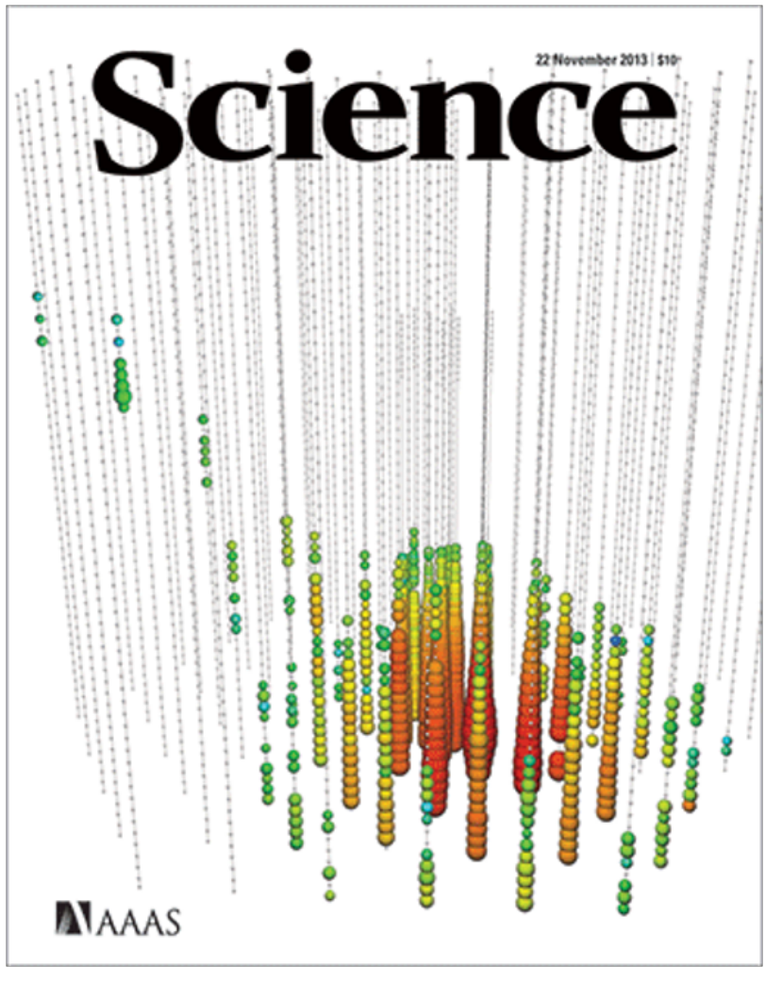

IceCube, PRL 111, 021103 (2013)
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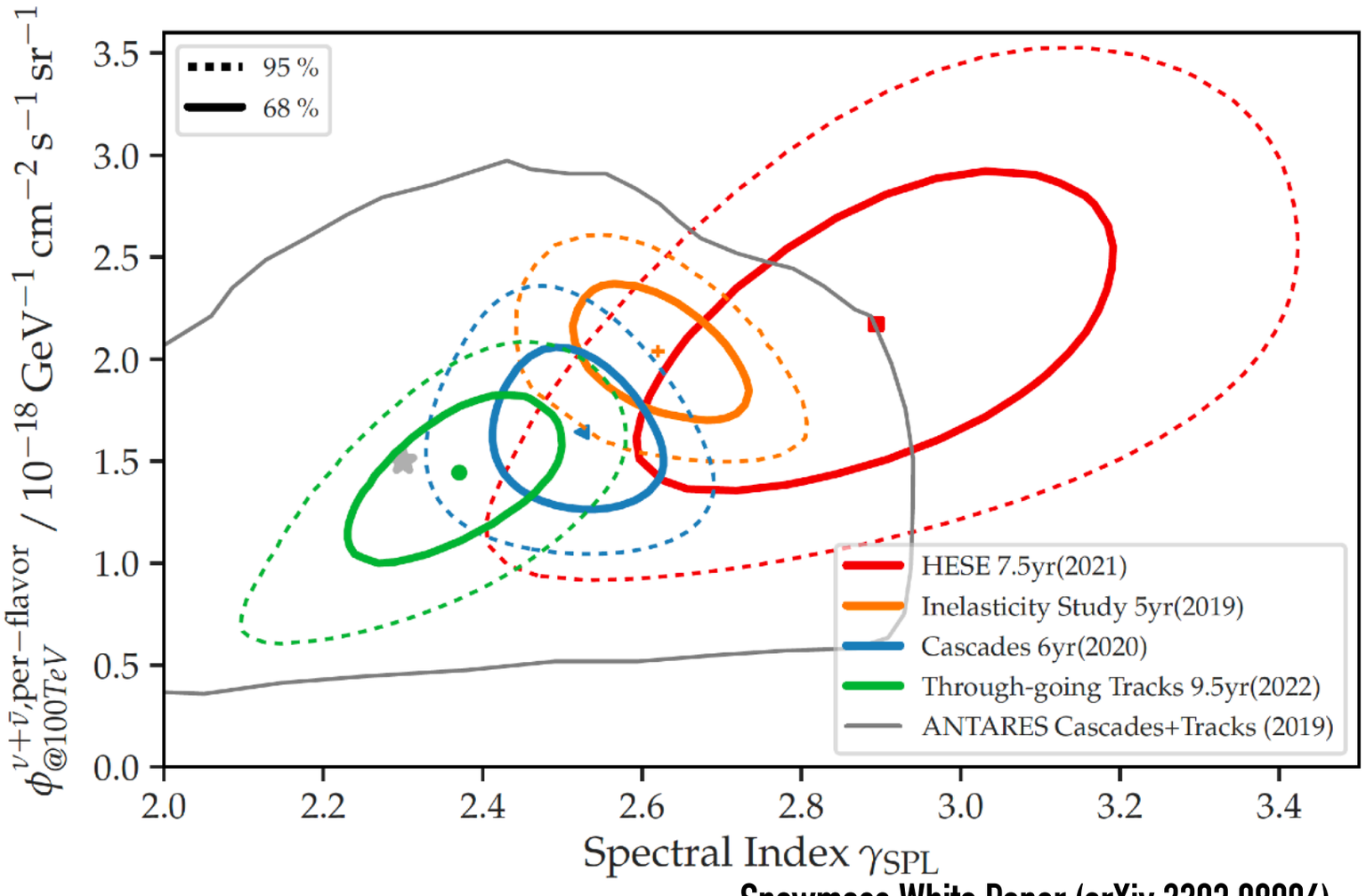
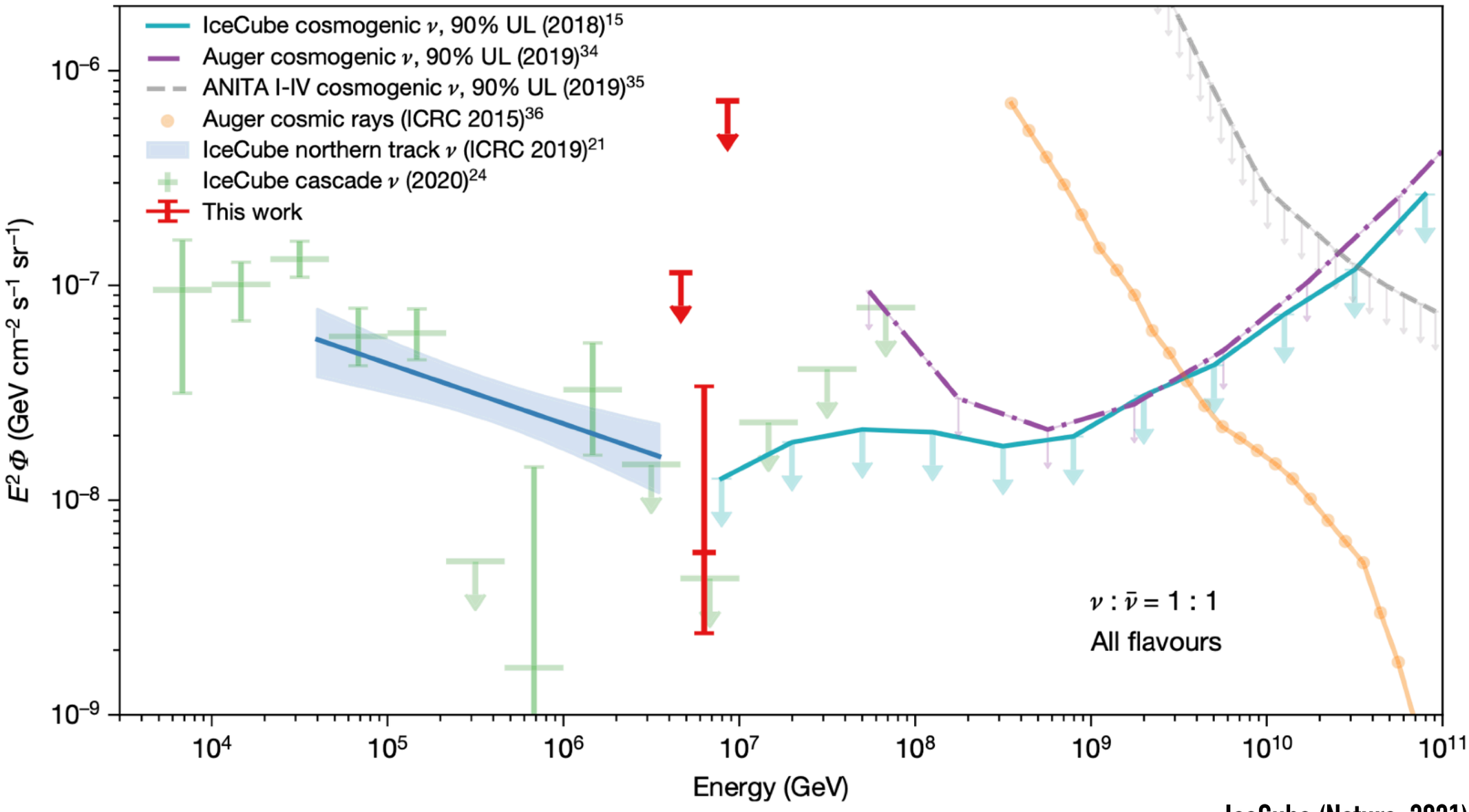
IceCube, PRL 113, 101101 (2014)



Snowmass White Paper (arXiv:2203.08096)

Glashow Resonance

IceCube detected a cascade event with an estimated energy of 6.05 ± 0.72 PeV consistent with the resonant formation of a W- boson predicted by Glashow



IceCube (Nature, 2021)

Particle Physic & BSM

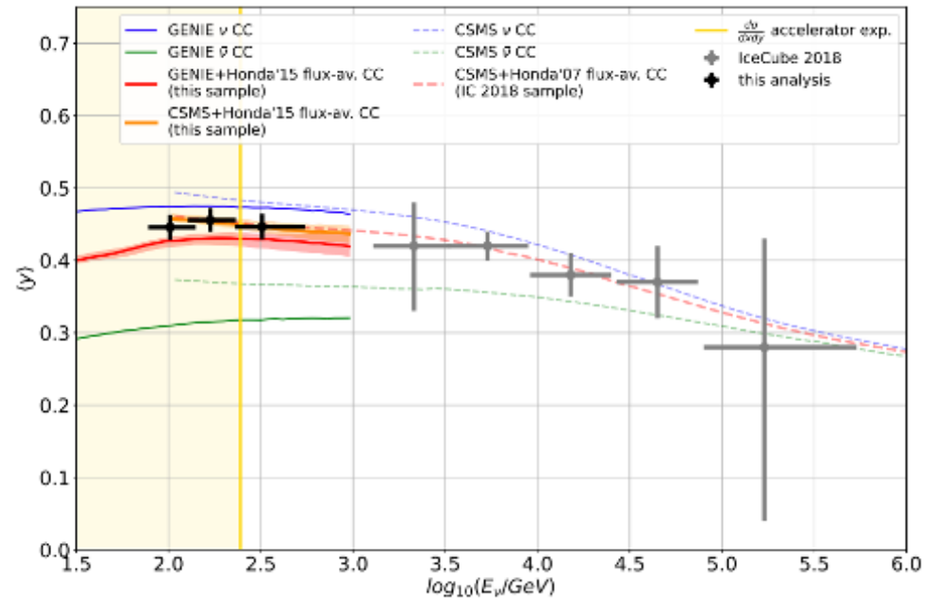
Canadian Contributions

Study of inelastic neutrino-nucleon scattering

- Using neutrinos with E>20 GeV, compare the observed level of "inelasticity" to theoretical expectations

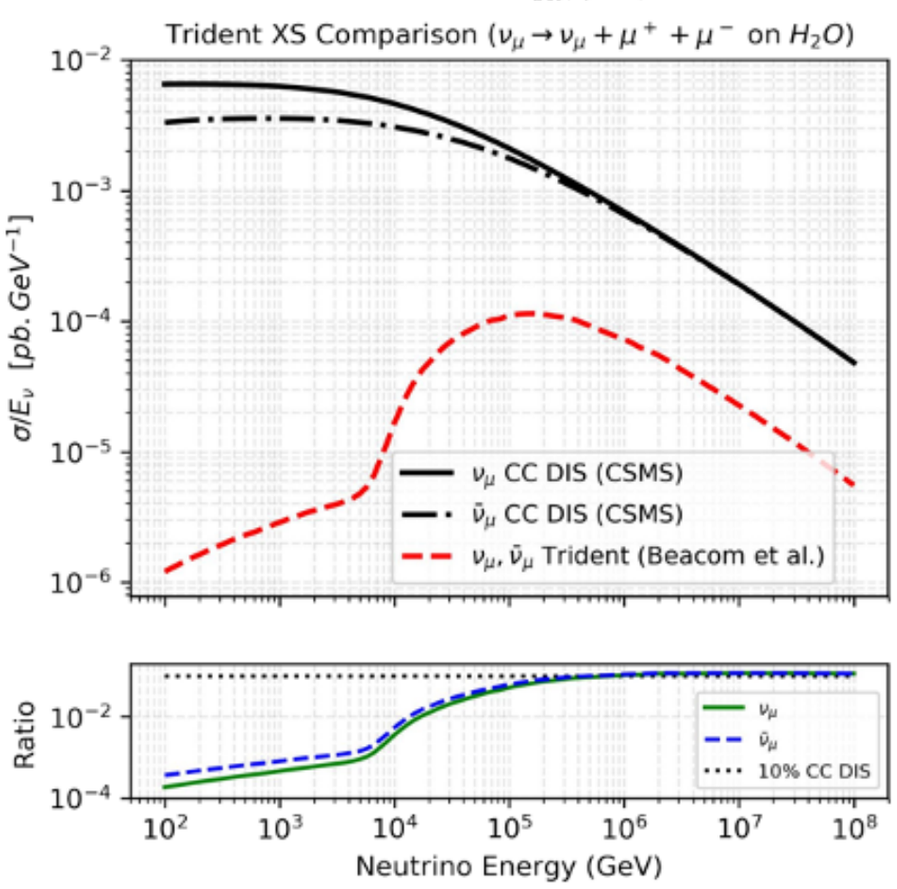
$$y = \frac{E_{hadr}}{E_\nu}$$

- Publication in preparation



Search for BSM processes

- Search for "Trident" events
  - Rate SM process with two muons in the final state
  - Can be enhanced by BSM
- Expect 2-3 σ sensitivity to SM, analysis close to approval

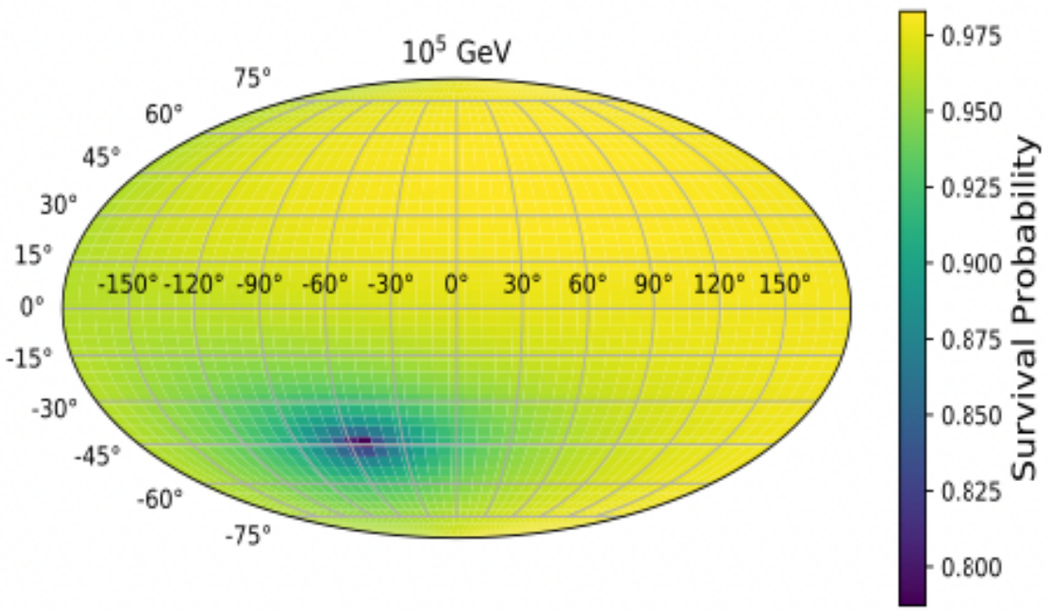


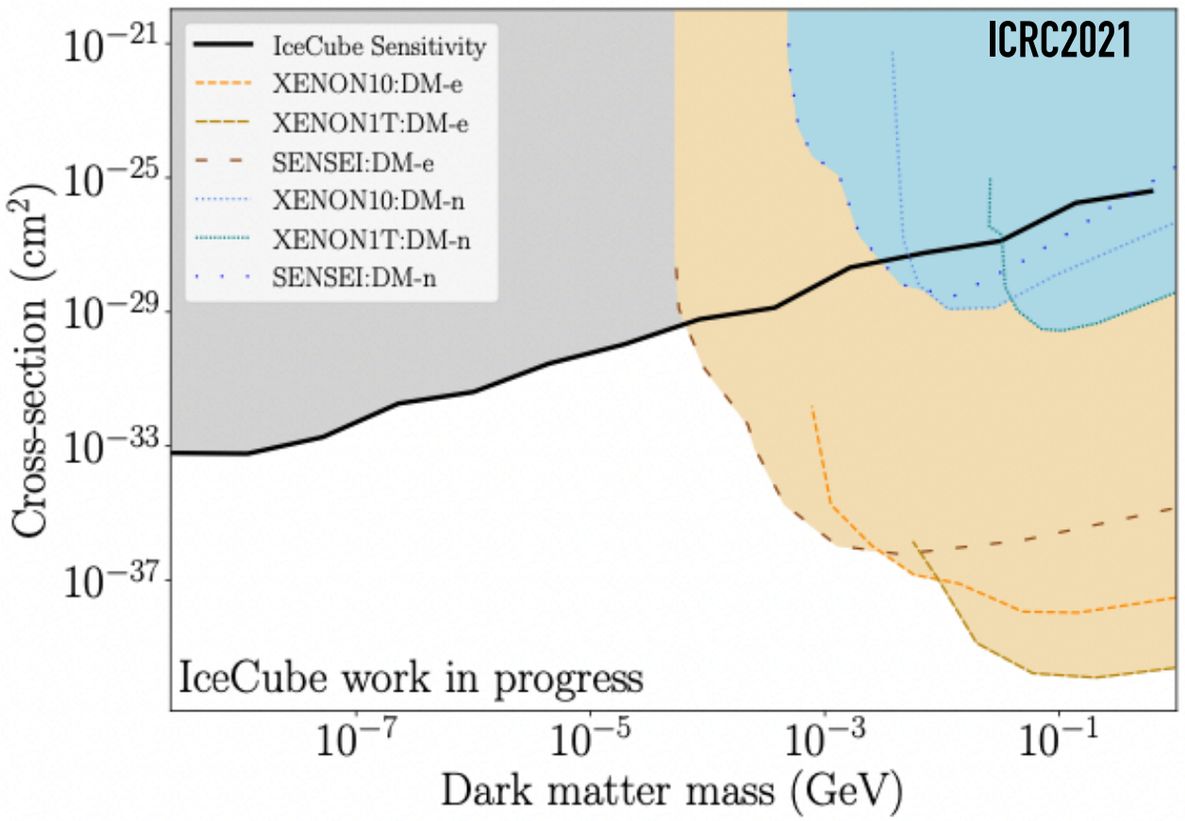
Dark Matter Search

Canadian Contributions

Dark matter neutrino scattering in the galactic center

- Search for the attenuation of isotropic high-energy neutrino flux by the elastic scattering of dark matter concentrated in the Galactic center





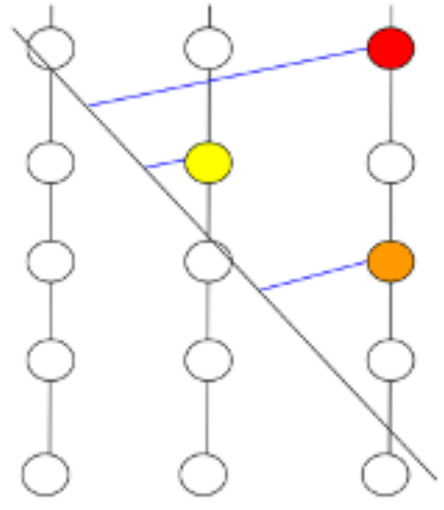
arXiv:2107.11491

Other Canadian Contributions...

Canadian Contributions

Detector Calibration with cosmic muons

- Study charge vs. distance to match optical efficiency
- Publication in preparation
  - -Analysis recognized by IceCube's Impact Award



IceCube Event Filter Updates

- Updating the "event" packaging filters and event classifiers
  - -Important step for the future analyses to potentially combine all event selections

Computing Resources

- CC/DRAC RPP support since 2017

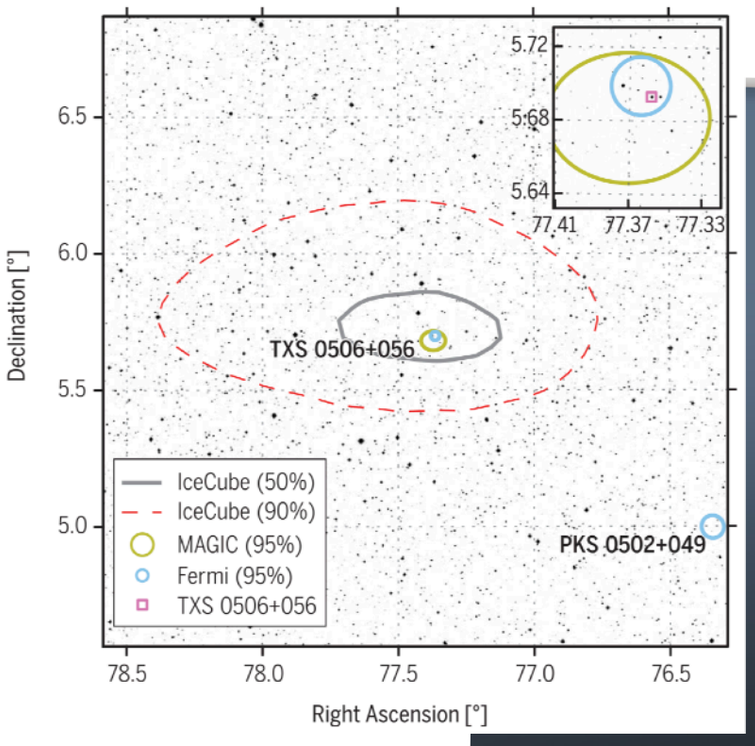
Canadian leaderships in IceCube

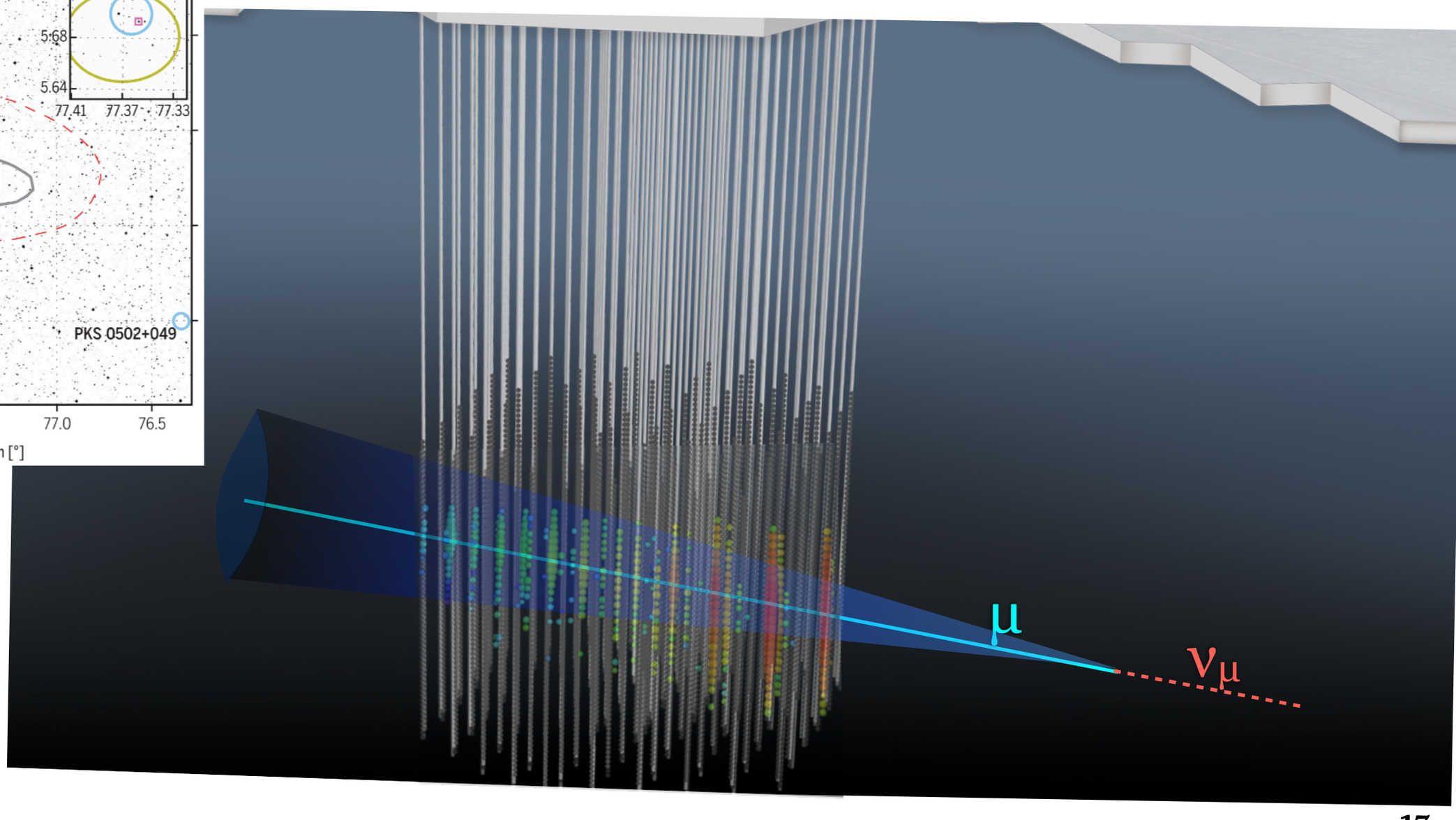
- Co-leads for the working groups
  - -Neutrino Sources (N. Park)
  - -Neutrino Oscillation (K. Clark, J. P. Yanez)

Evidence of Neutrino Source

Multi-messenger observations of IceCube-170922A coincident with flaring blazar TXS 0506+056

- Chance coincidence disfavored by 3σ

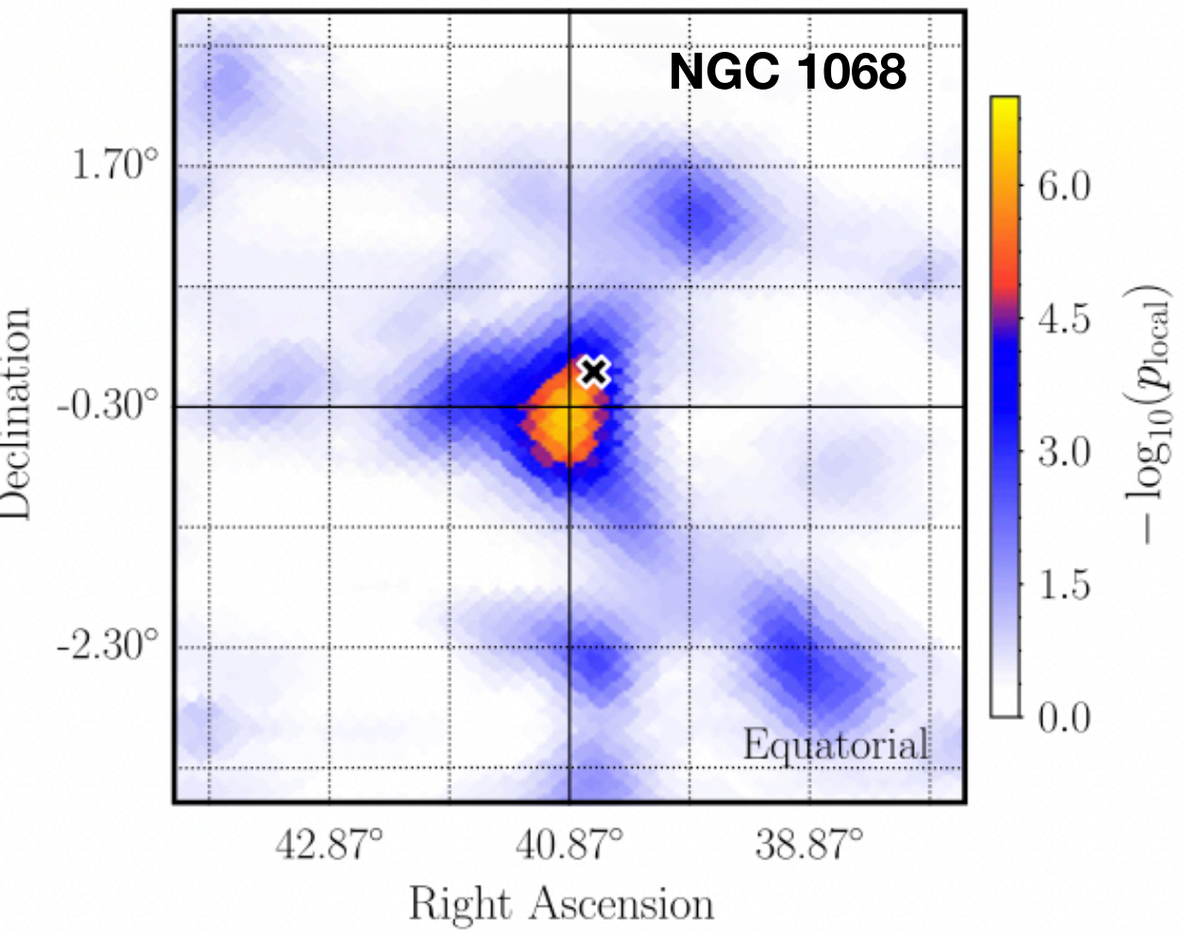


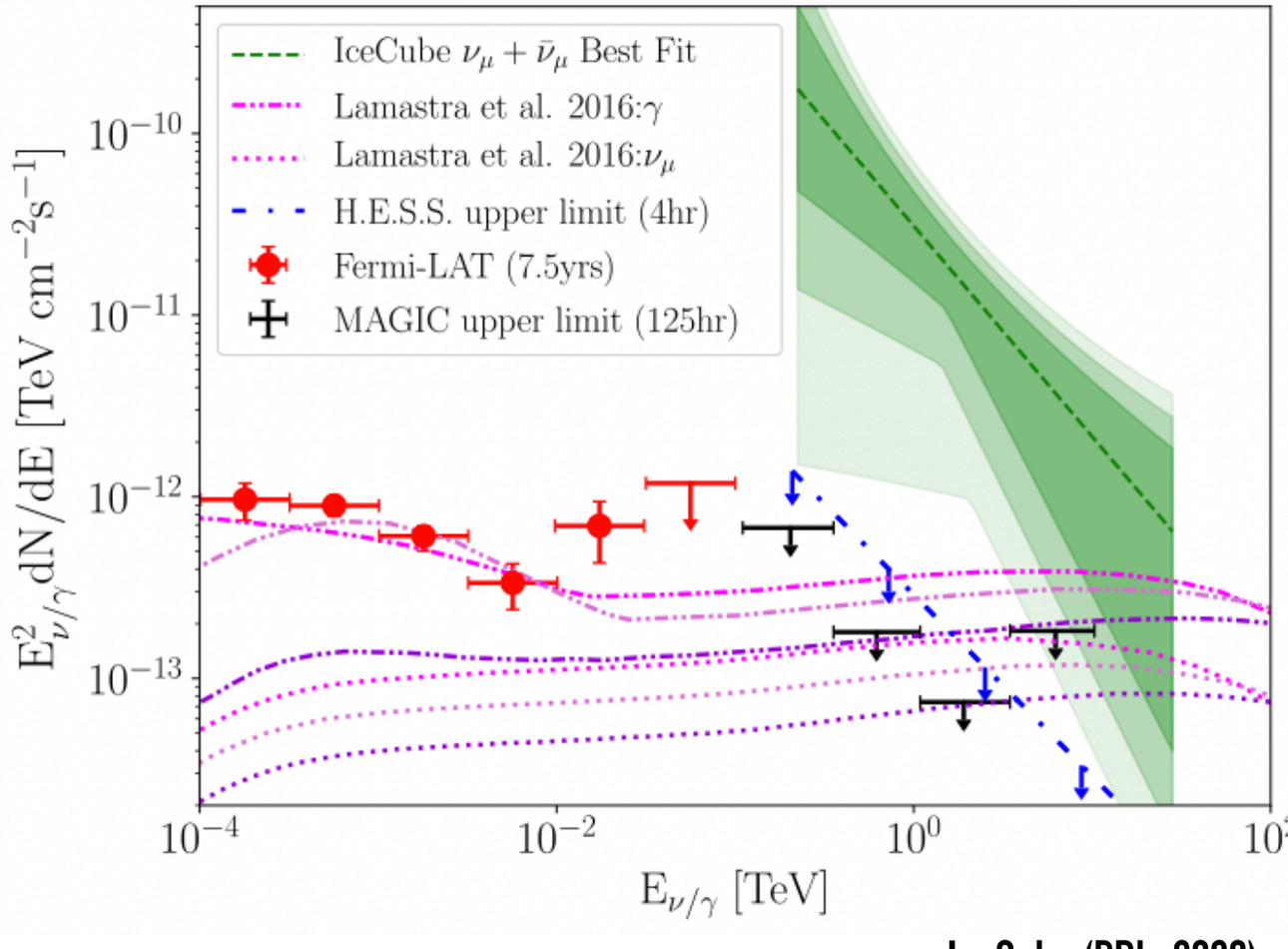


Astrophysical Source Search with IceCube

The most significant source in the Nothern hemisphere: nearby Seyfert galaxy NGC 1068 w/ significance of 2.9σ

- GeV gamma-ray based catalogue search inconsistent with background w/ 3.3σ



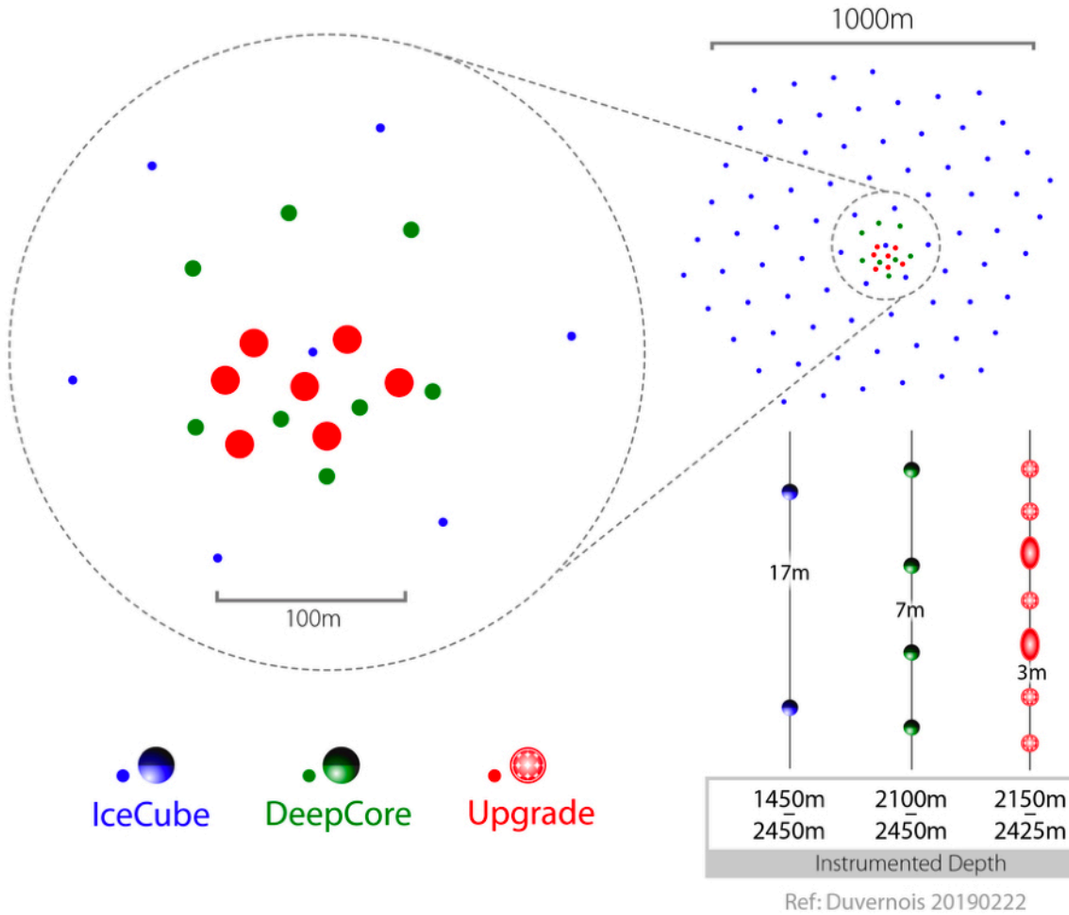


IceCube (PRL, 2020)

IceCube Upgrade: Near Future

IceCube Upgrade

- Precision oscillation measurements
- Improved detector calibration
- R&D for IceCube-Gen2
- Pandemic delayed the deployment.
  Now scheduled to start drilling
  in 2024-25
  String deployment in 2025-26



Ref: Duvernois 20190222

IceCube Upgrade: Near Future

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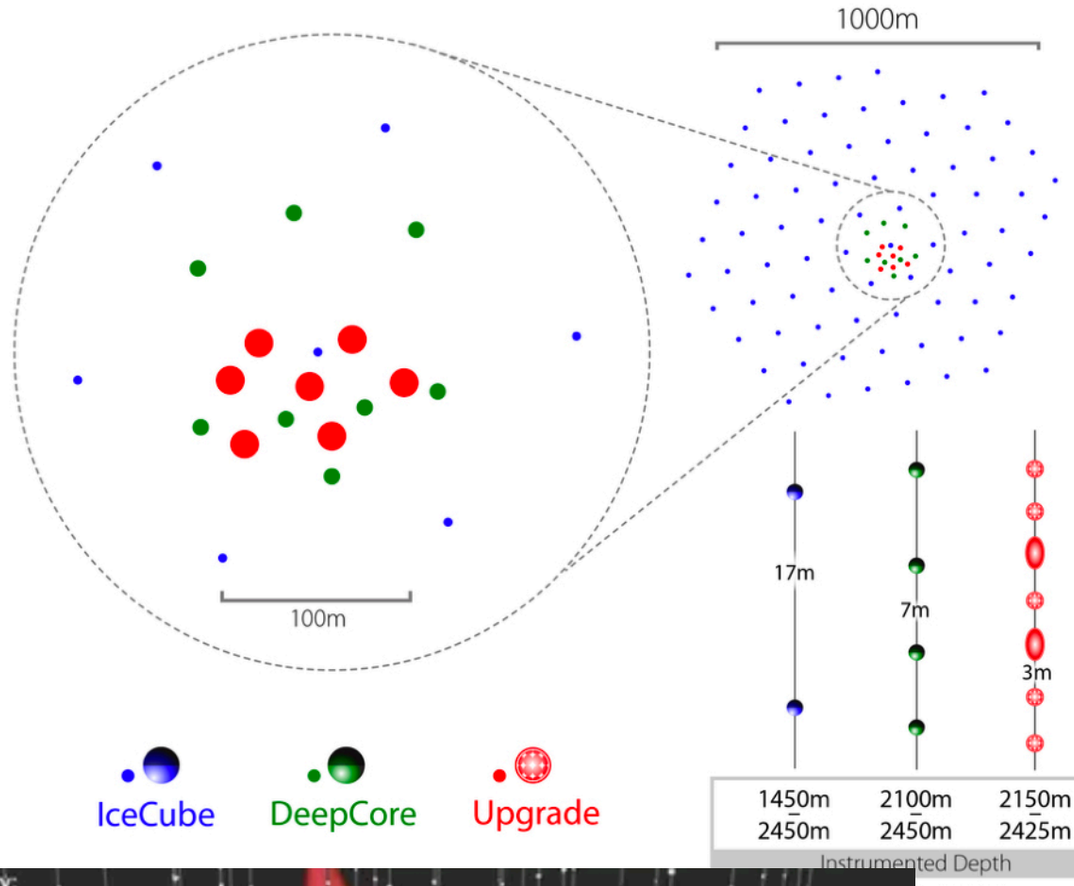
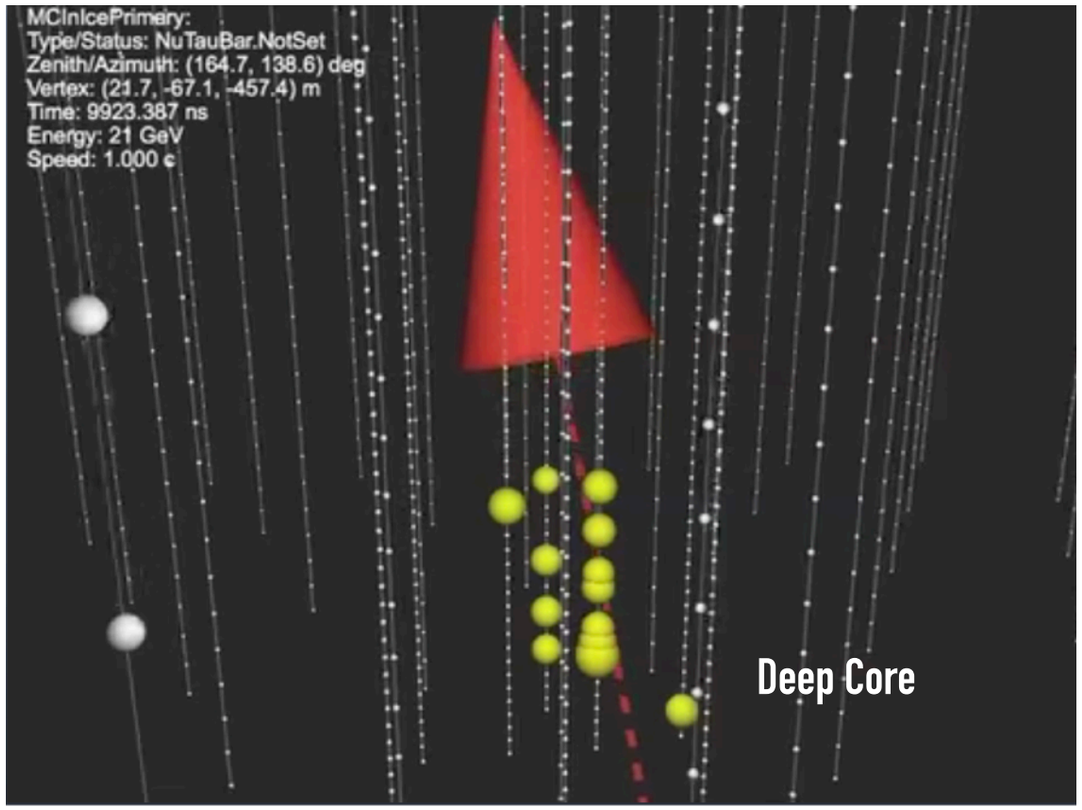
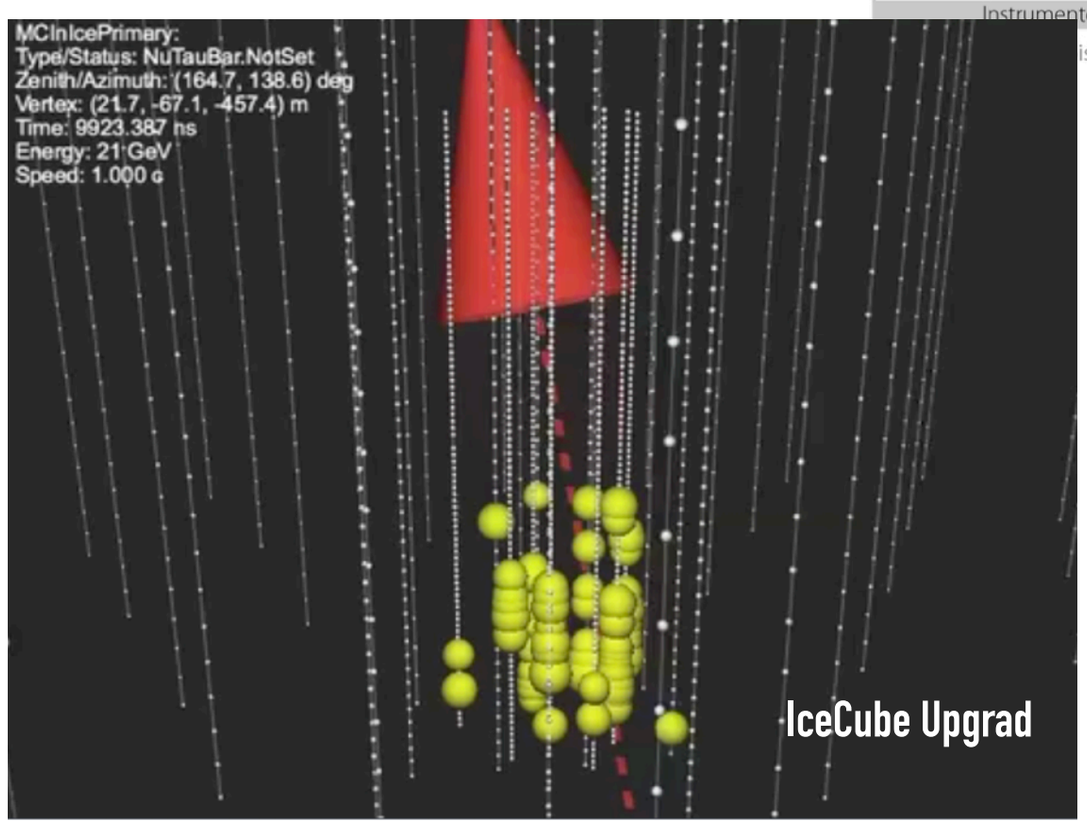
- Precision oscillation measurements
- Improved detector calibration
- R&D for IceCube-Gen2
- Pandemic delayed the deployment.
  Now scheduled to start drilling
  in 2024-25
  String deployment in 2025-26



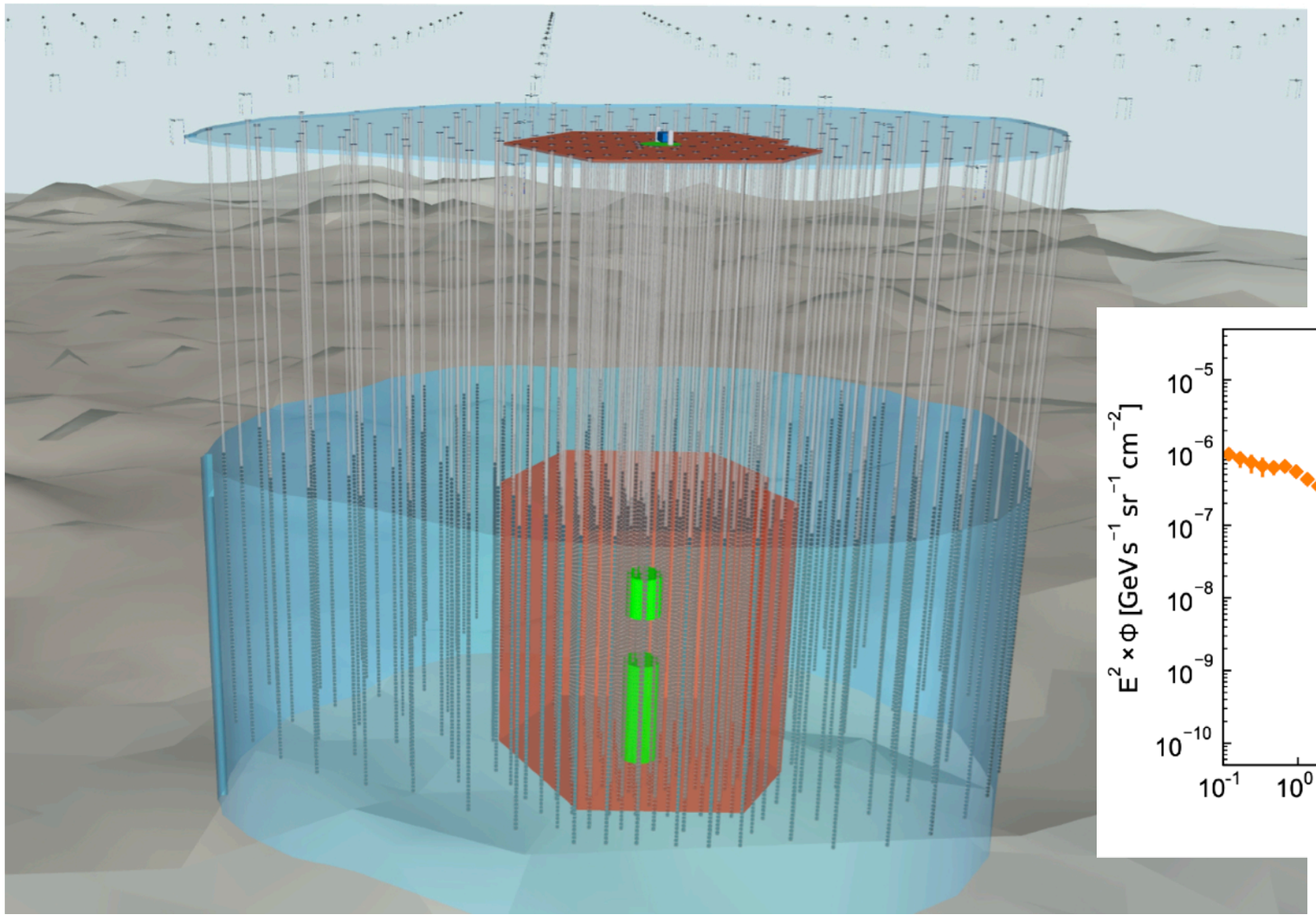


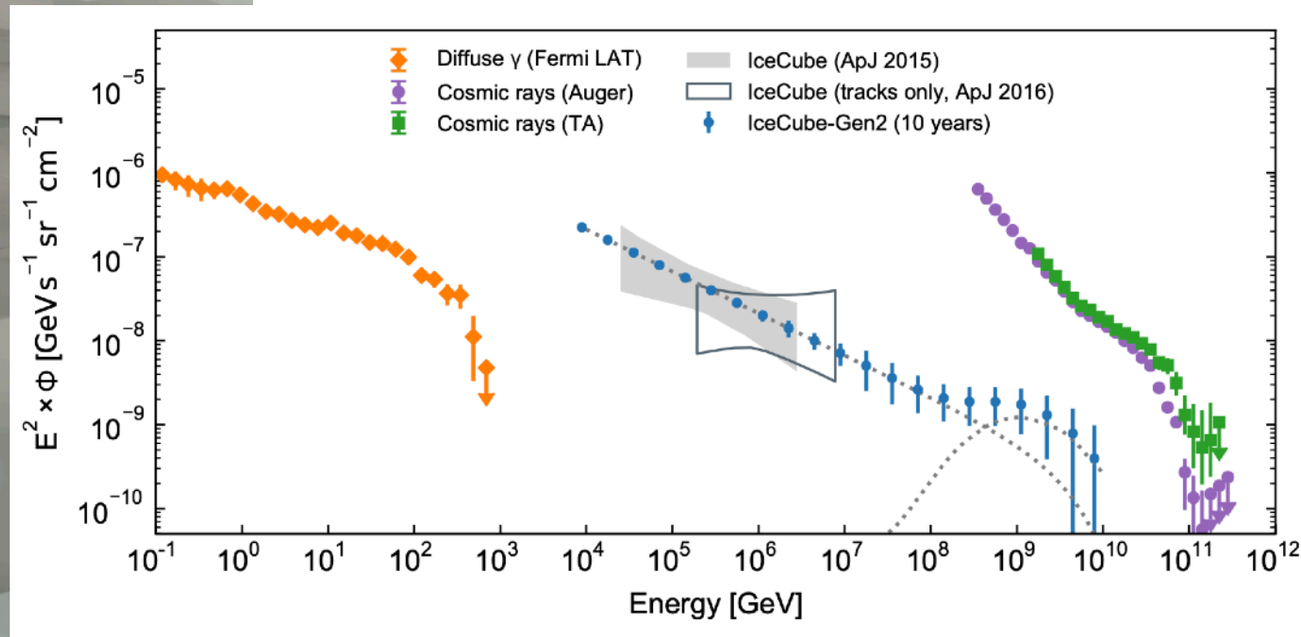


IceCube Gen-2: Future

Designed to achieve five times better sensitivity than IceCube array

- Optical array: Eight times larger active volume compared to IceCube
- Radio array: ~ 500 km² area of the antenna array for the detection of EeV neutrinos

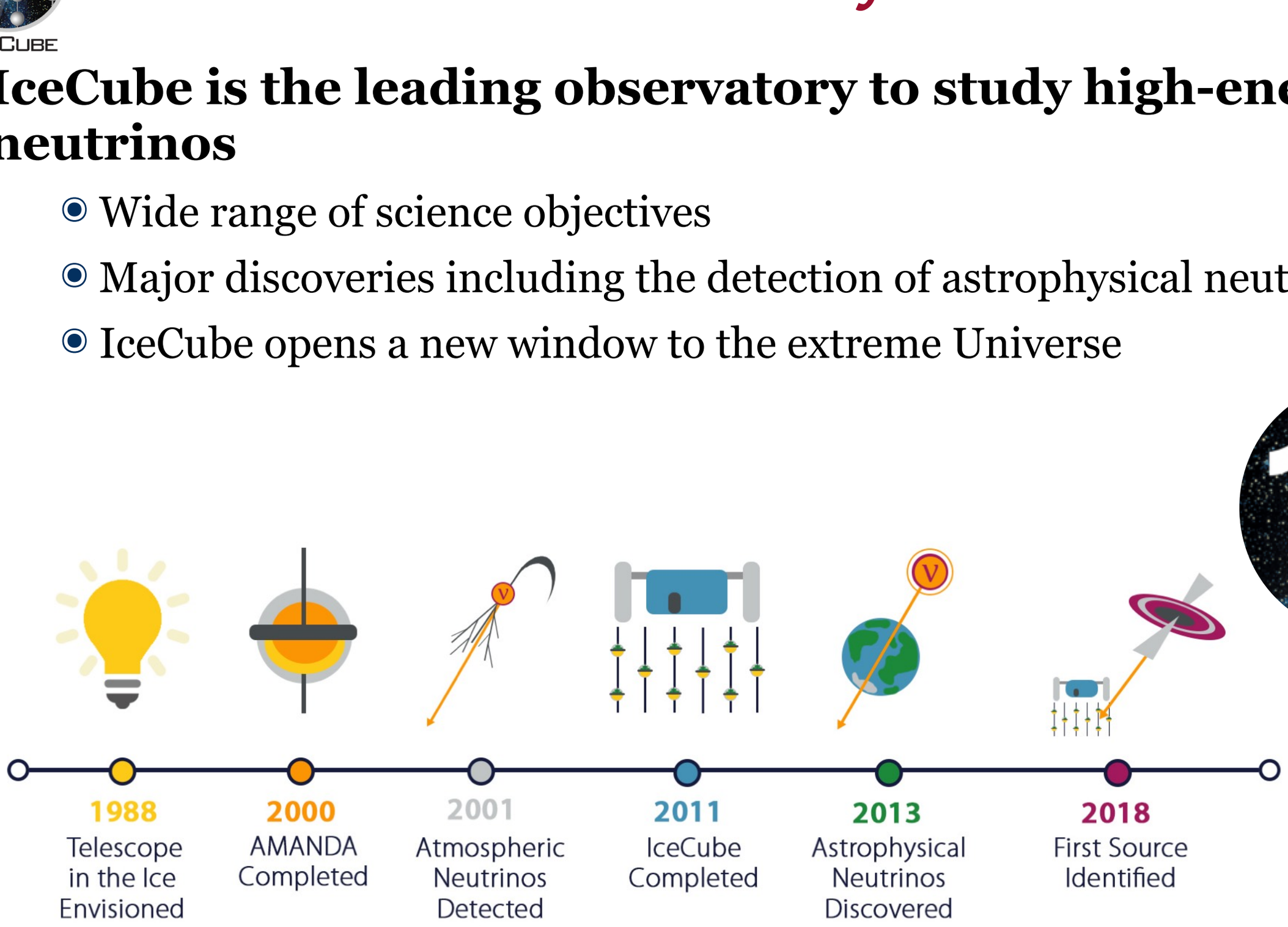




Summary

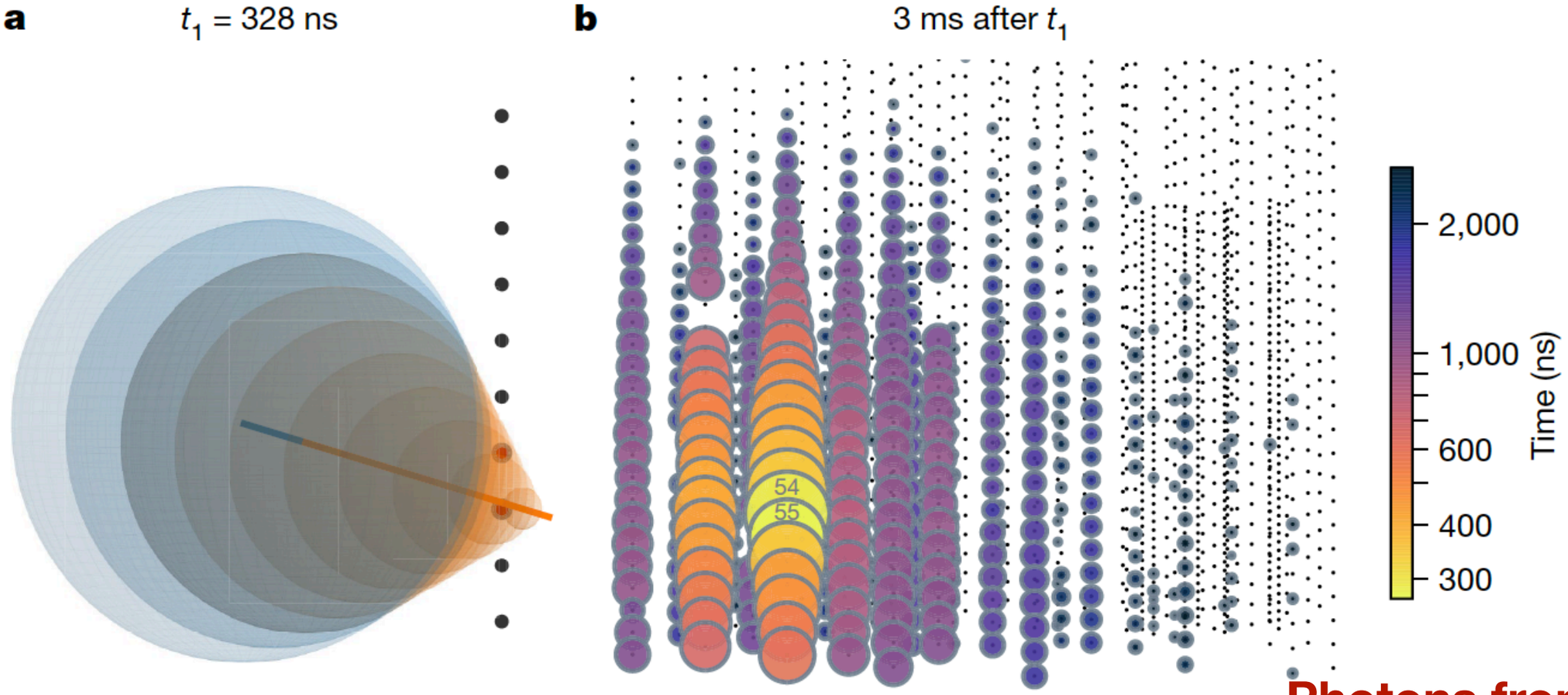
IceCube is the leading observatory to study high-energy neutrinos

- Wide range of science objectives
- Major discoveries including the detection of astrophysical neutrino flux
- IceCube opens a new window to the extreme Universe

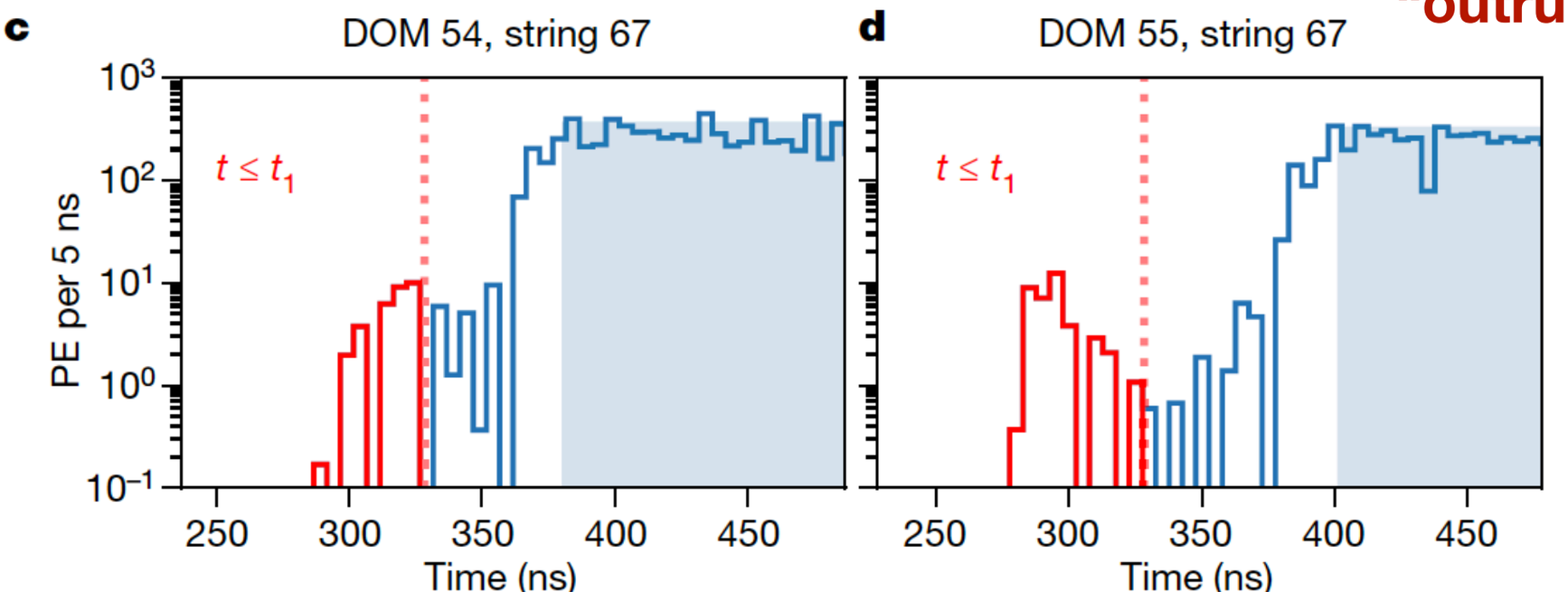


BACKUP

Hadronic Cascade Signature



Photons from early muons "outrunning" the cascade



IceCube (Nature, 2021)