



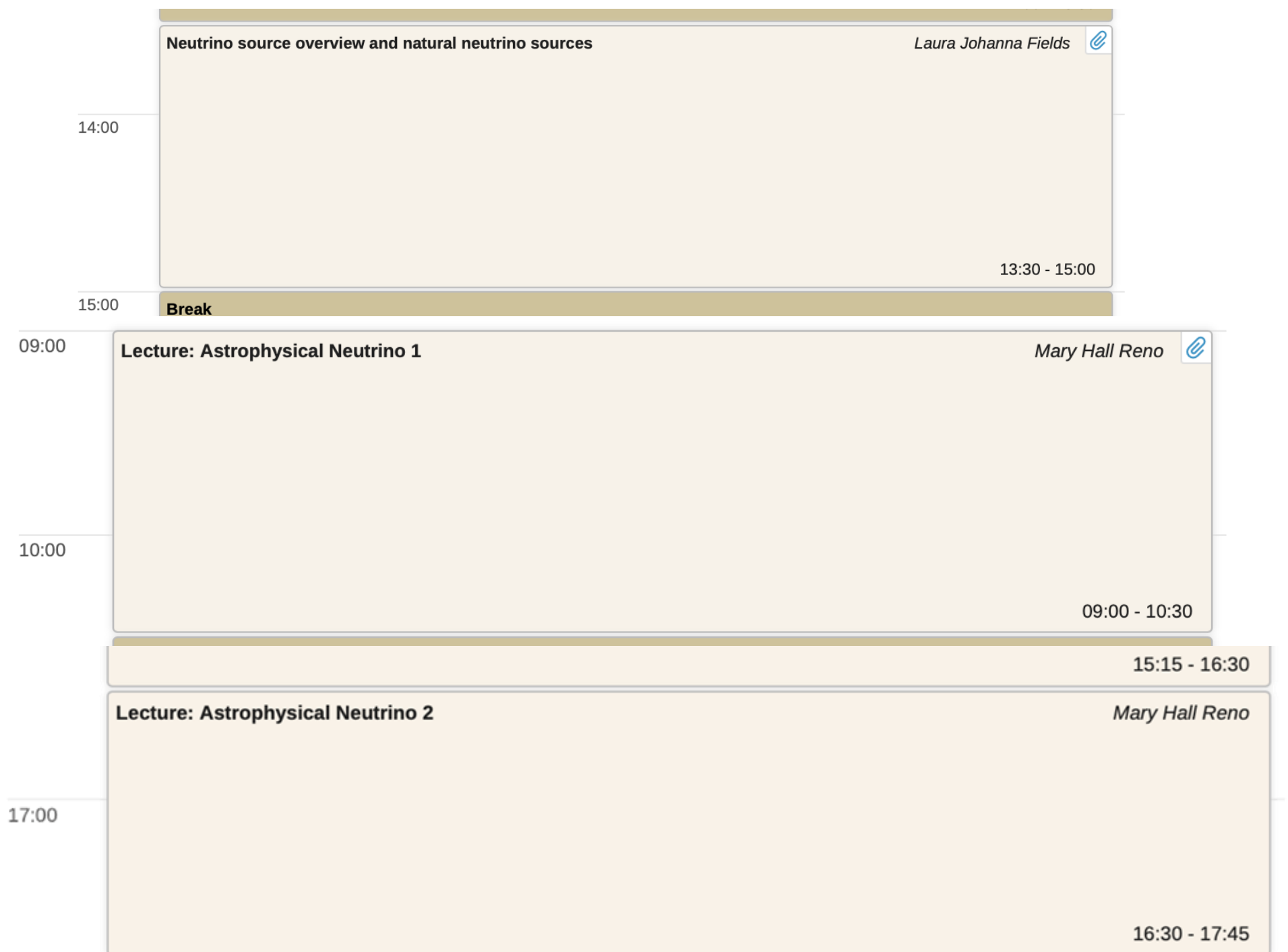
Atmospheric & Astrophysical Neutrino Detection

Lu Lu

University of Wisconsin-Madison



Related lectures



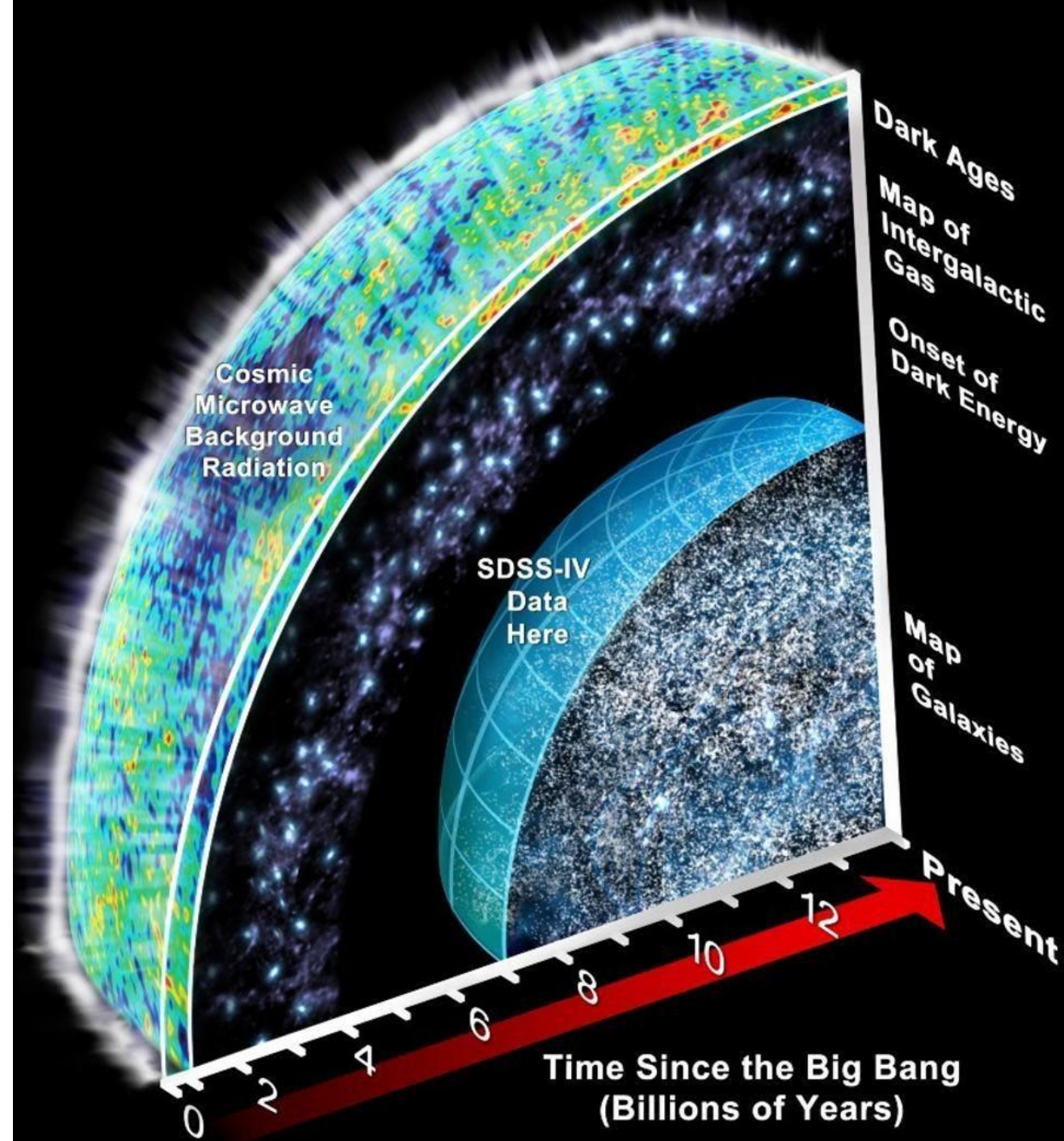
Diffuse



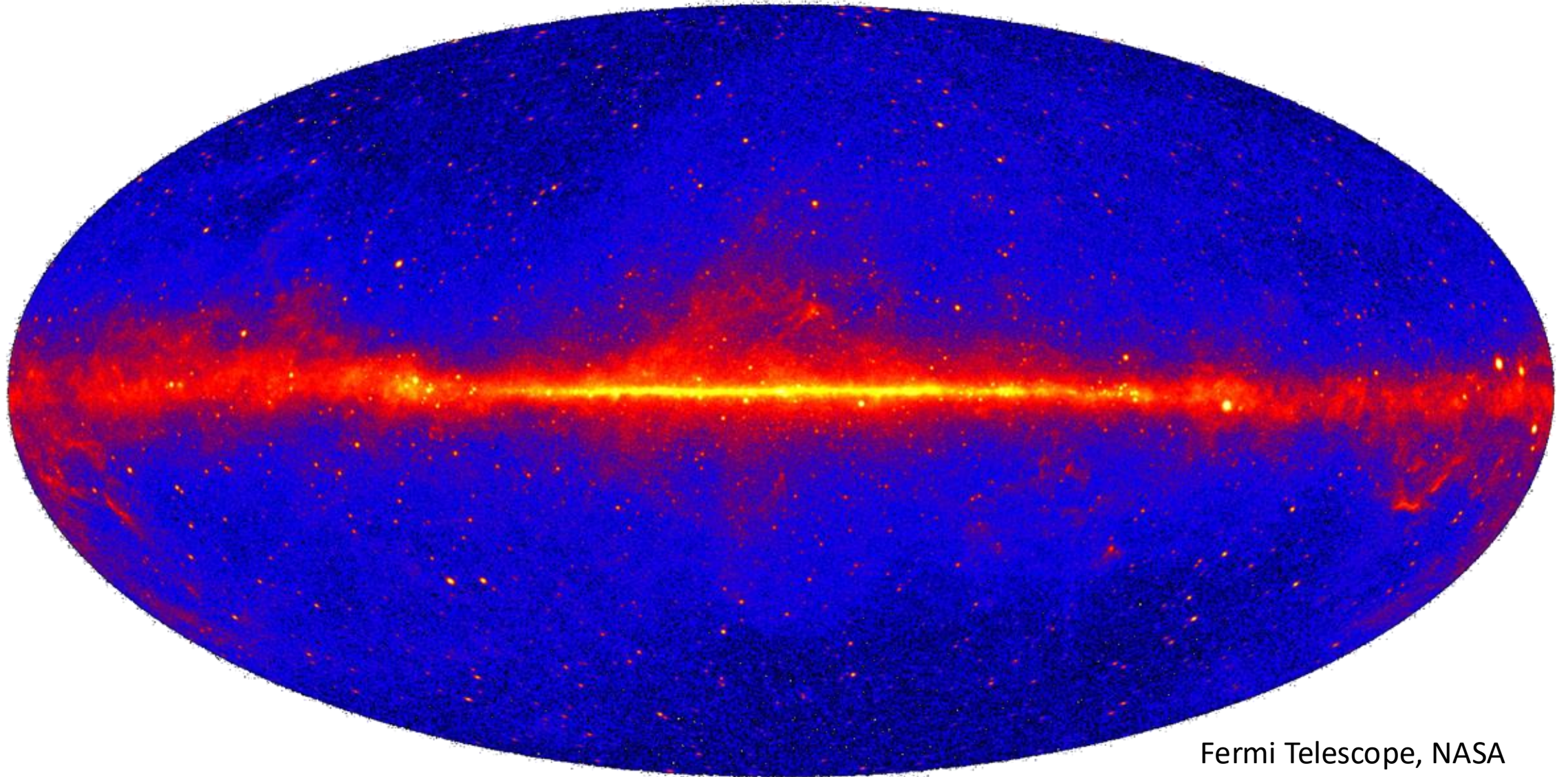
Point source



- A distant football field turns many lights into one glow
- The distant universe turns many cosmic accelerators into one diffuse neutrino flux

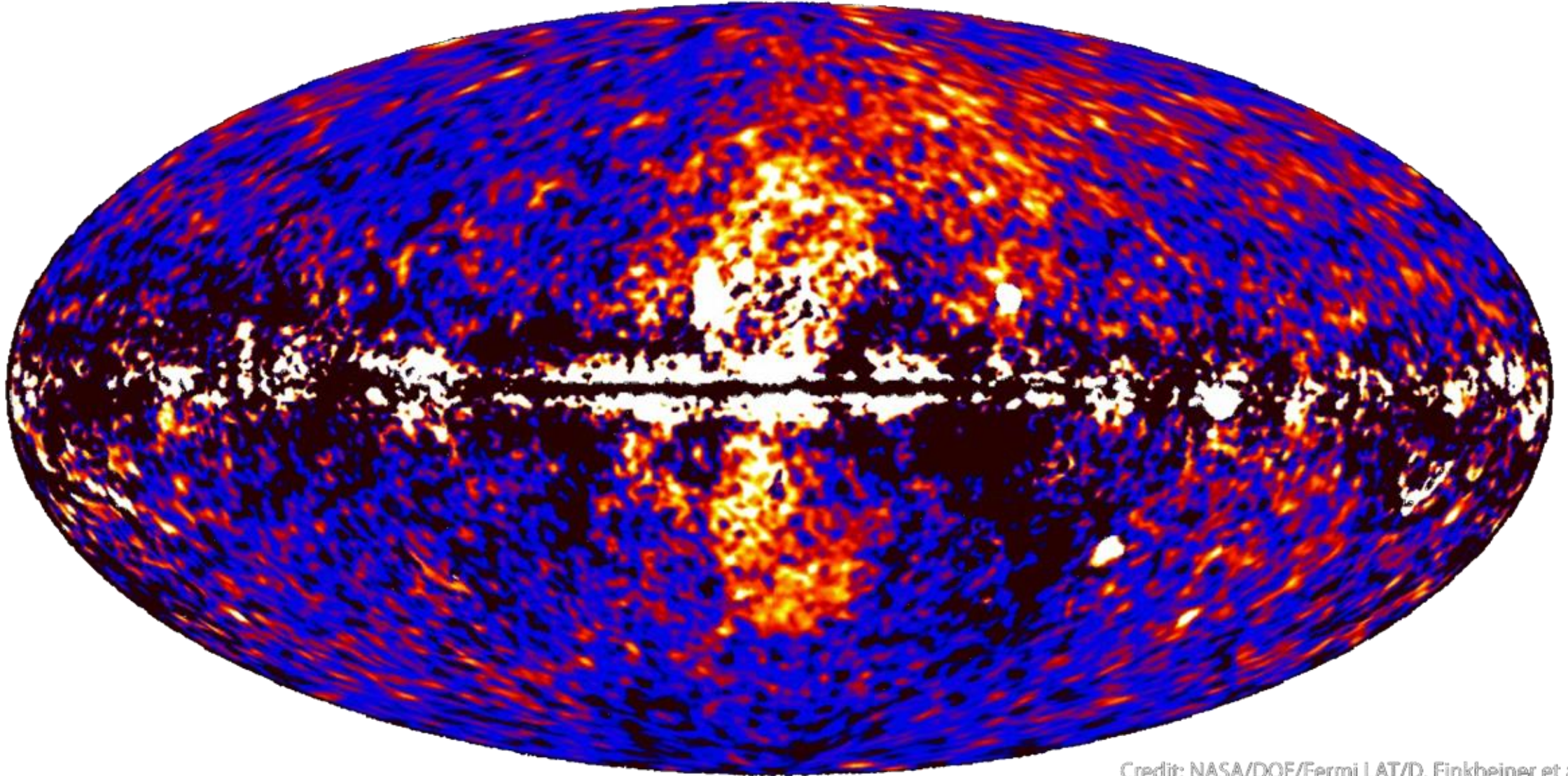


Point-source gamma-ray photons

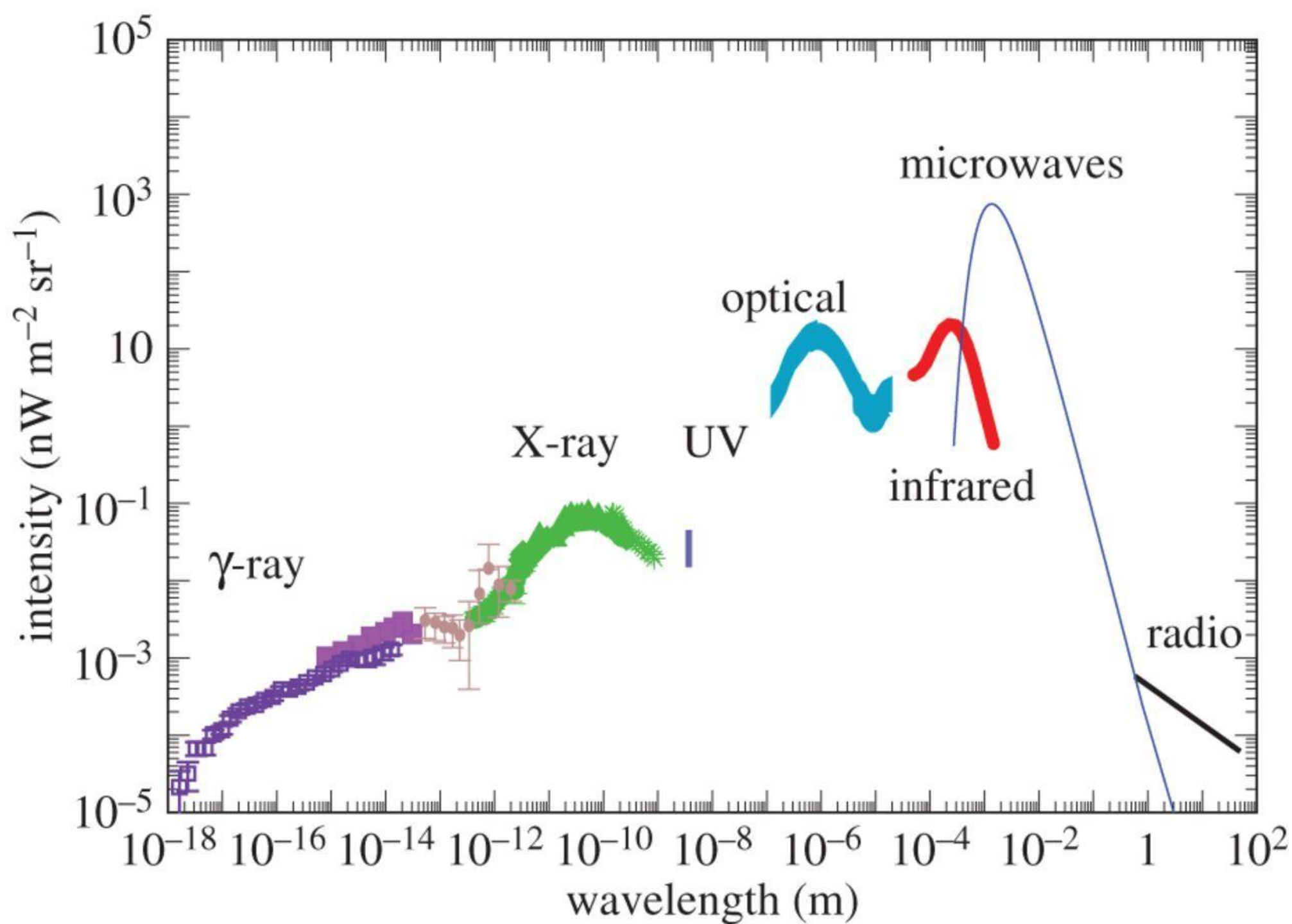


Fermi Telescope, NASA

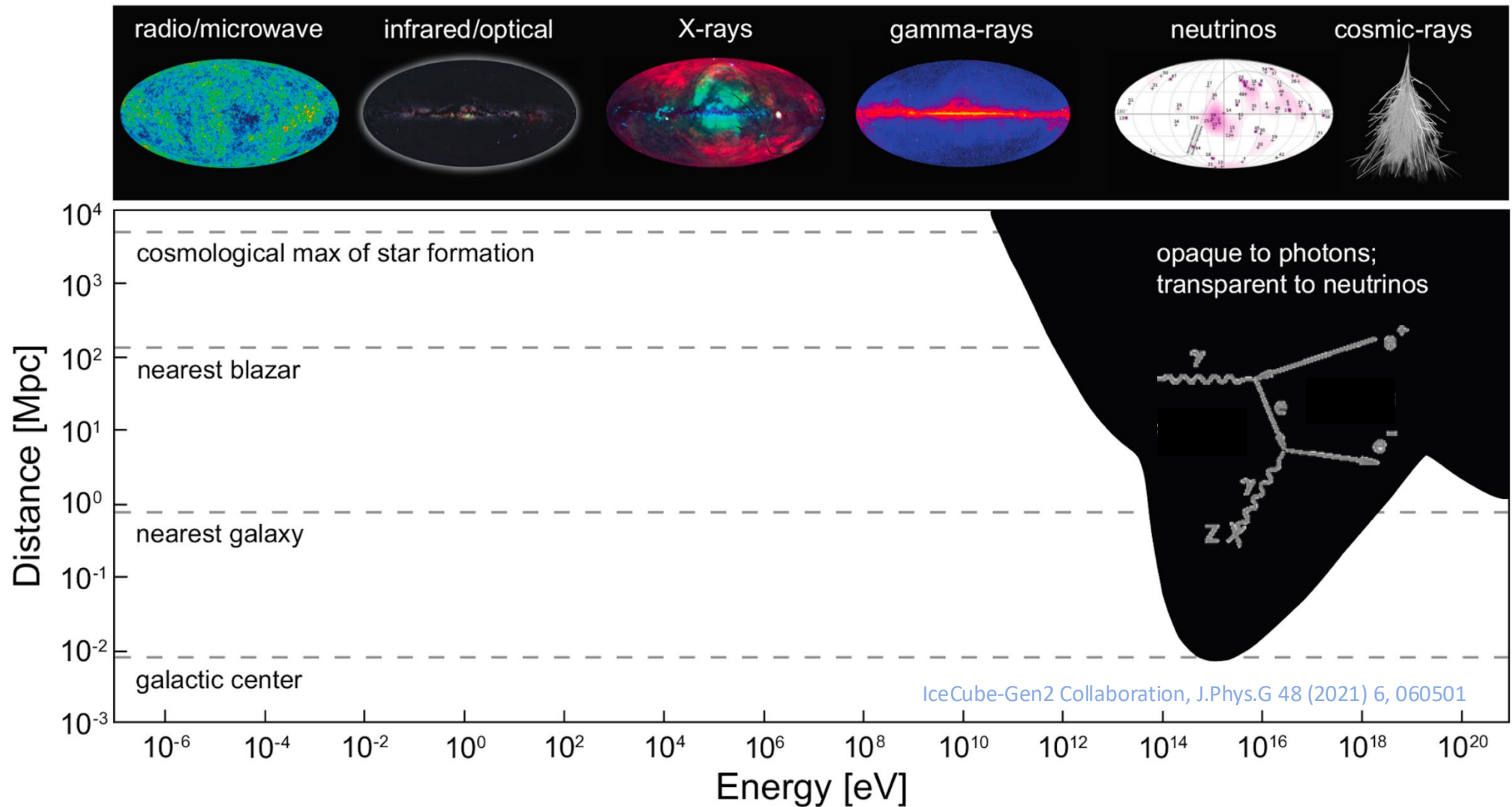
Diffuse gamma-ray photons

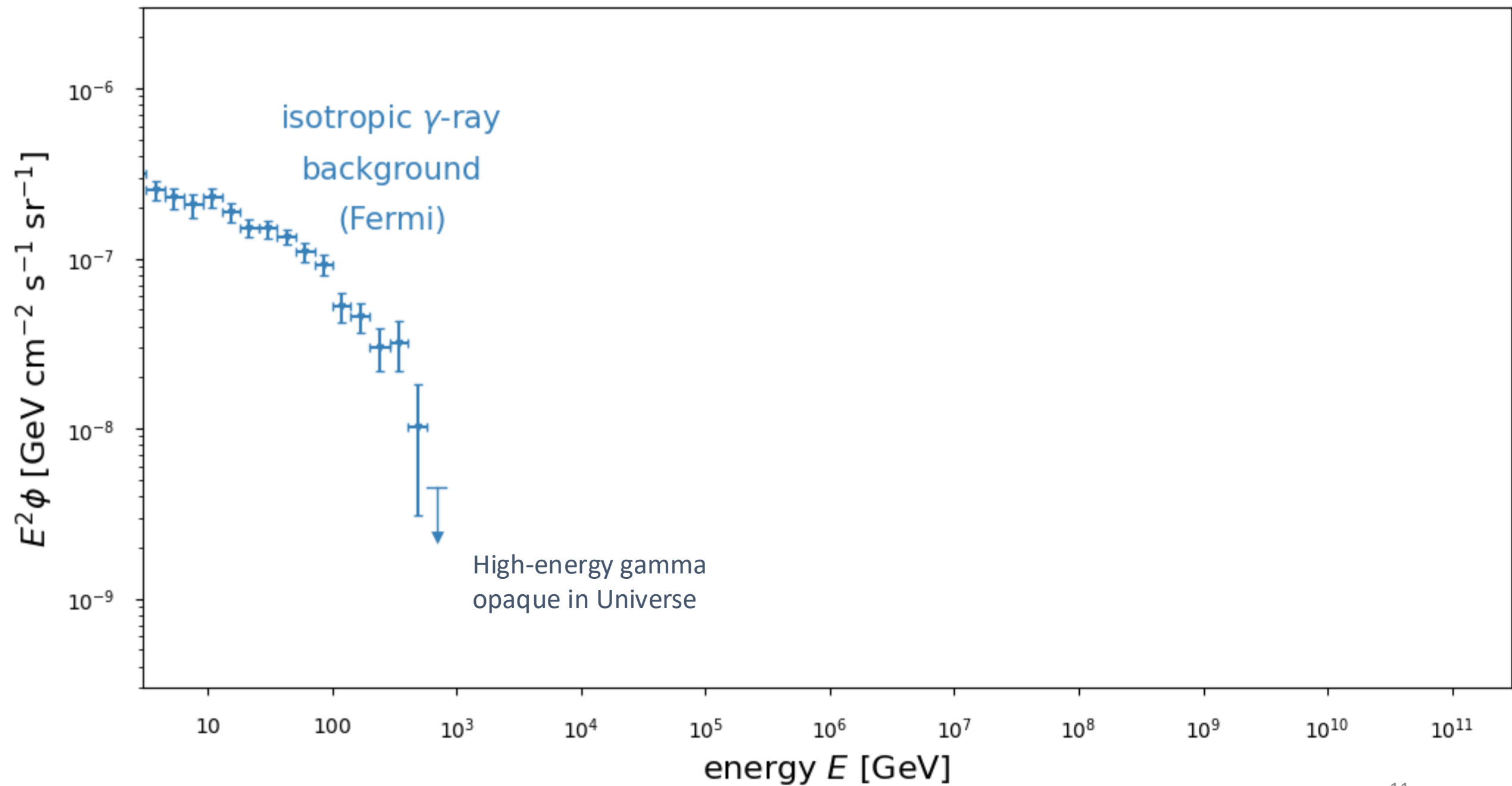


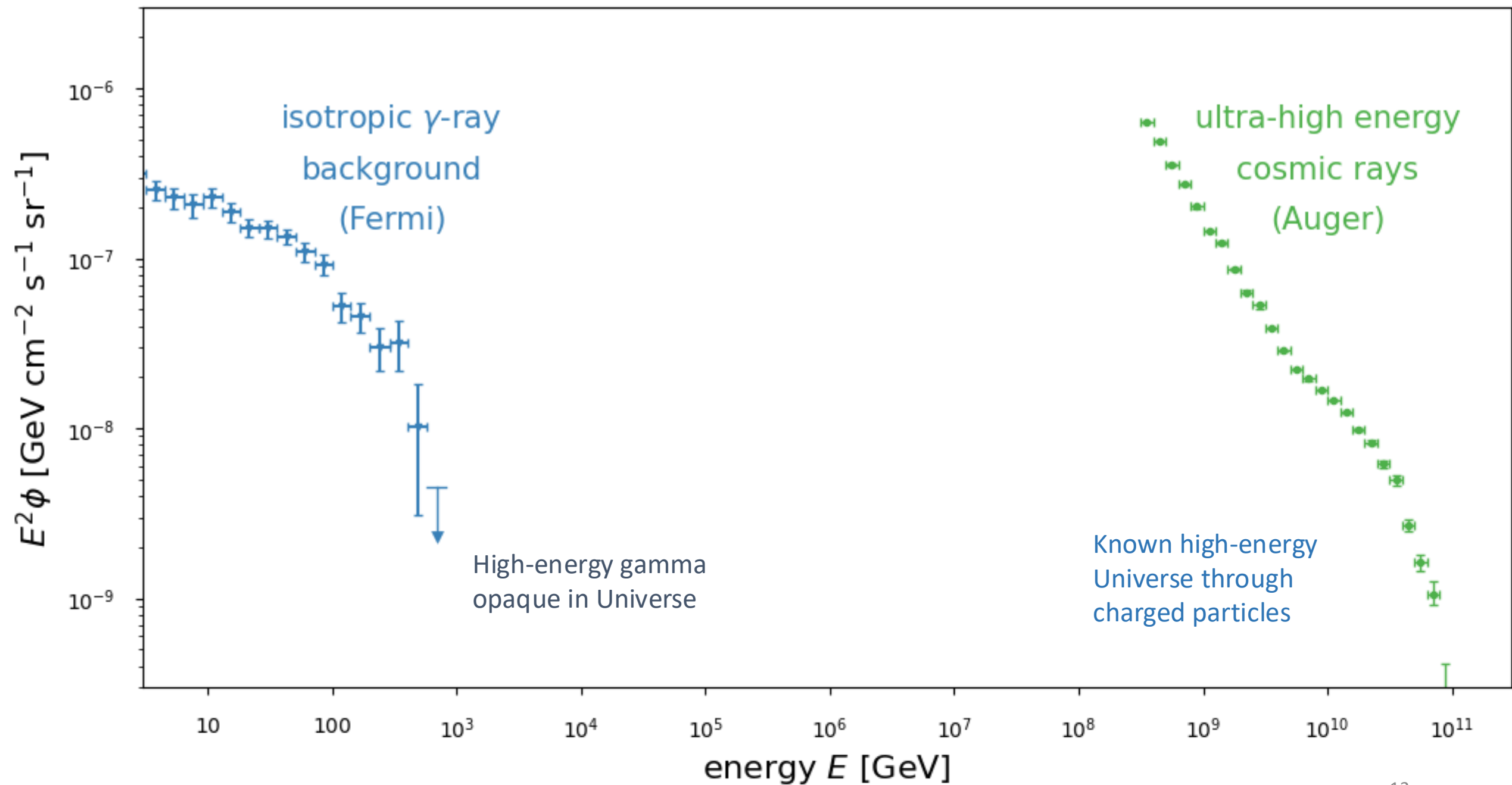
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

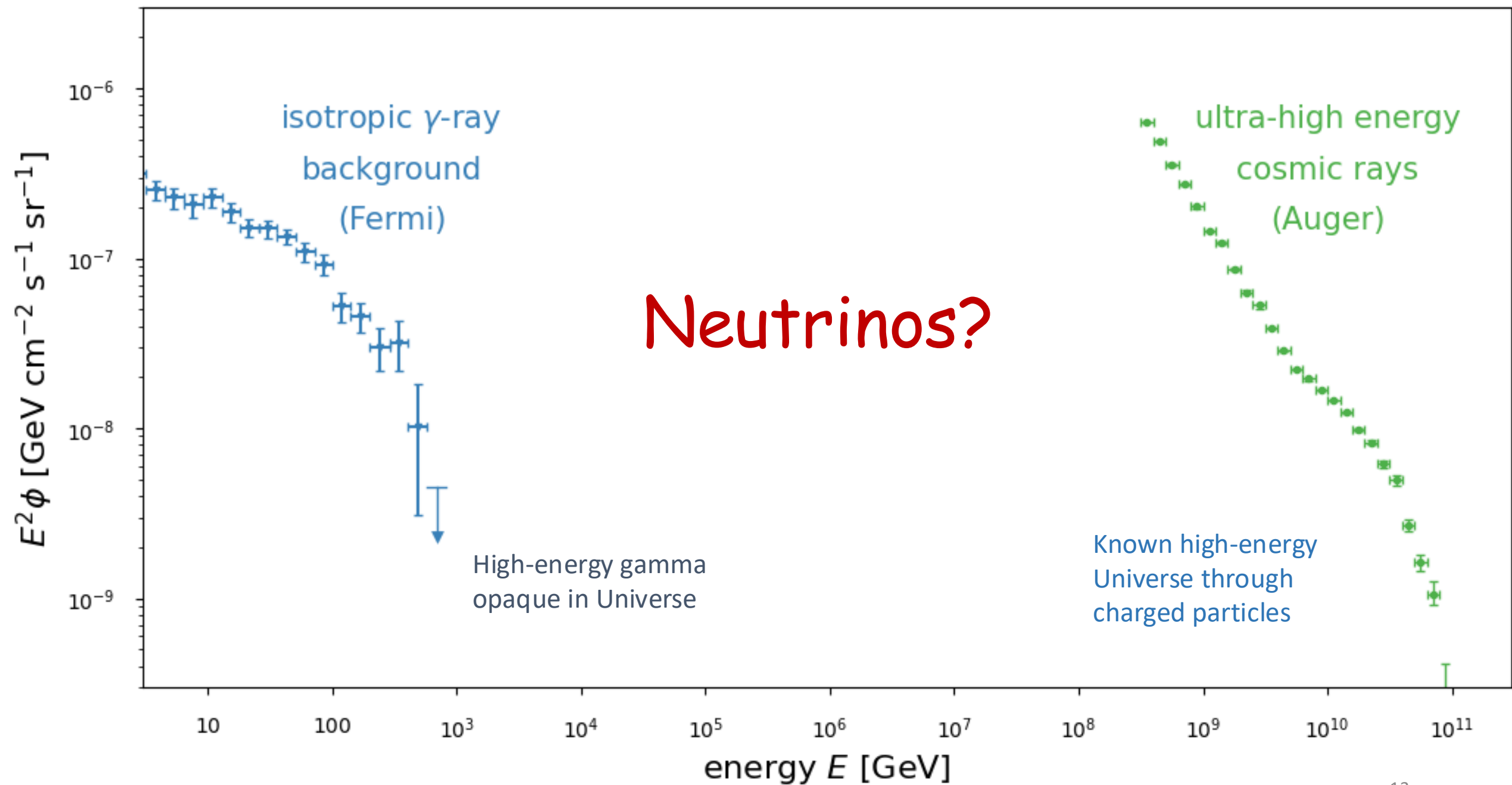


Photons attenuation at high energies









Is there physics beyond the collider frontier?

The only probe of ν interactions at $\sqrt{s}$ beyond the LHC — where sterile states and non-standard interactions would show up first.

Does coherence survive a billion light-years?

The oscillations you averaged over kilometres now run over gigaparsecs — testing ν lifetime, decoherence and Lorentz / CPT invariance.

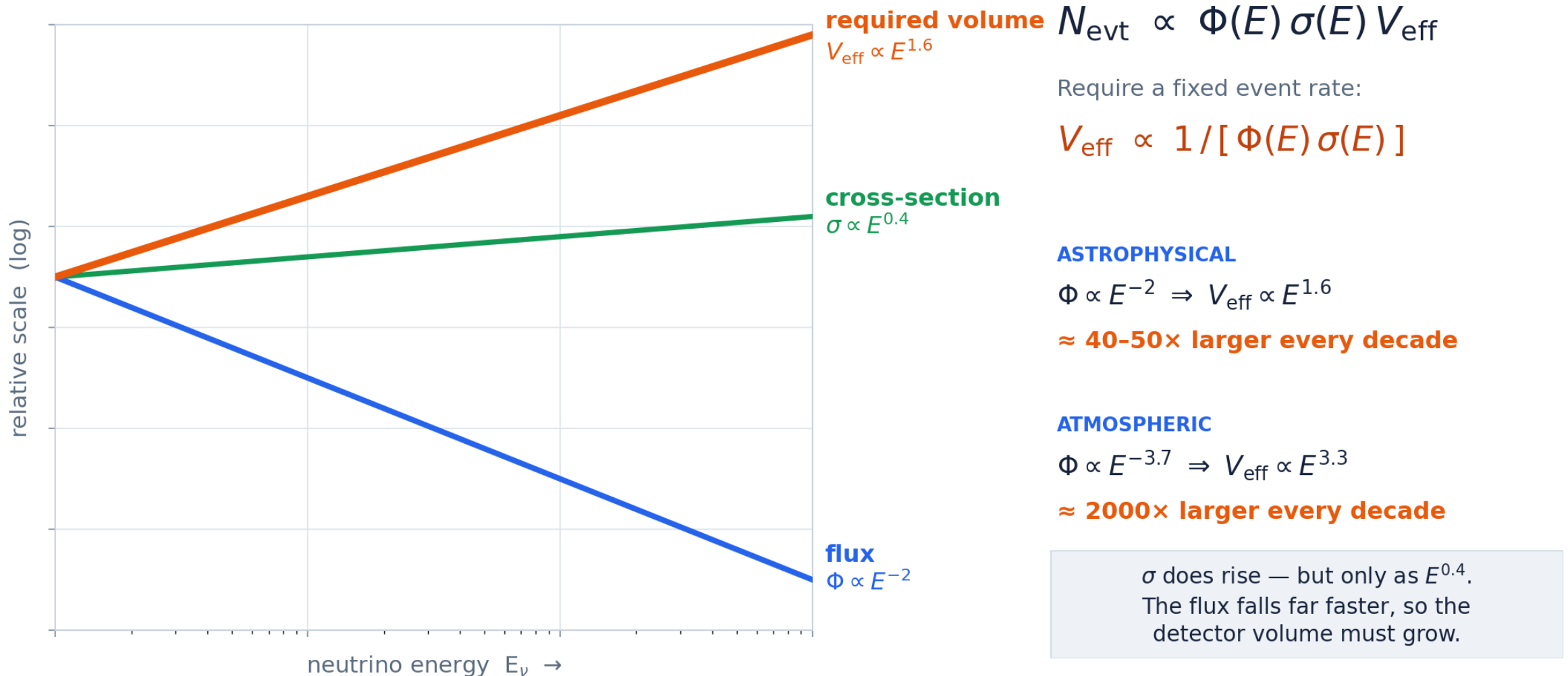
What accelerates the universe to 10^{20} eV?

A century-old mystery. The neutrino is the only neutral, penetrating, pointing messenger — it names the engines light cannot reveal.

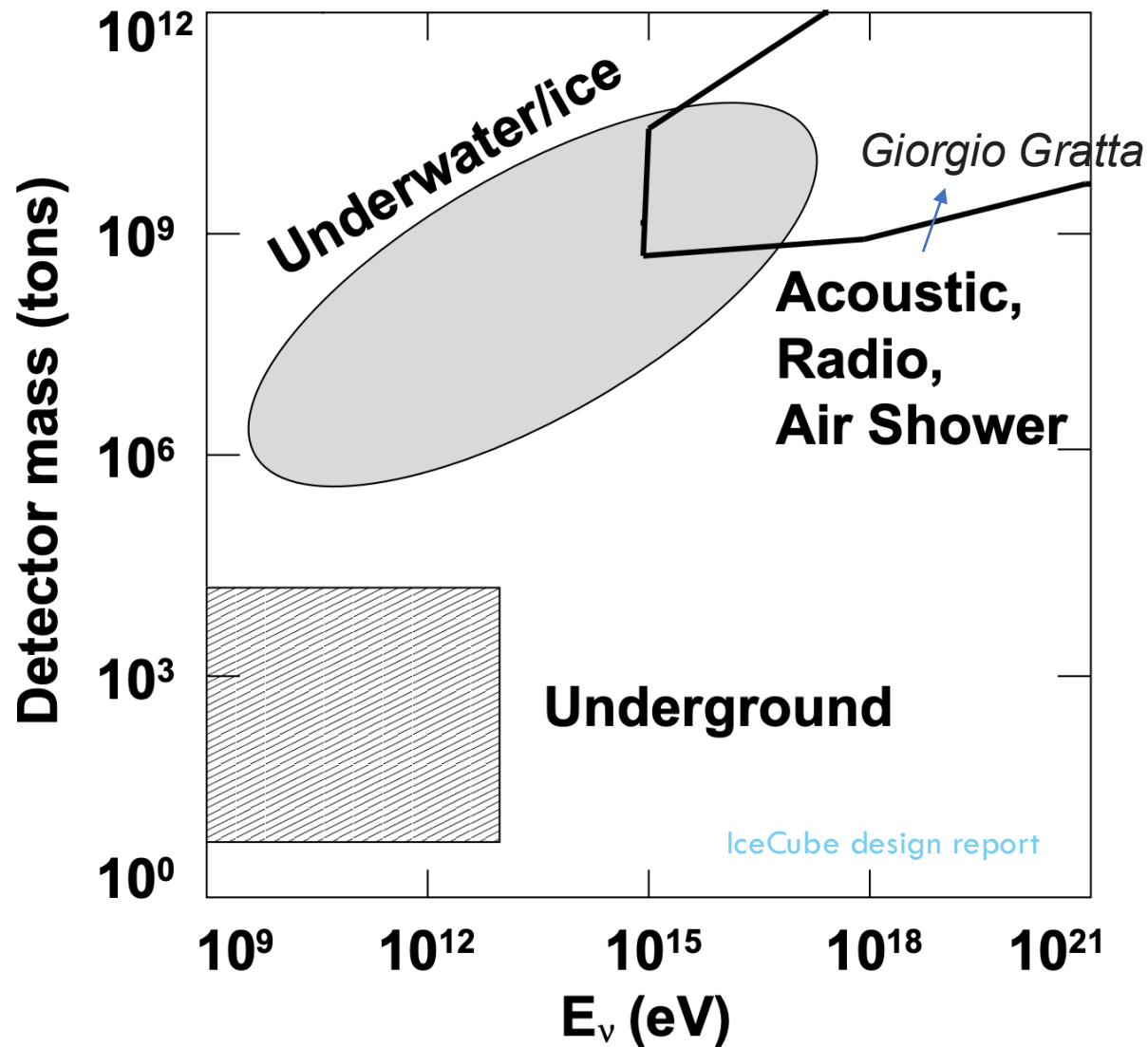
What stays hidden from light?

Neutrinos escape source cores and the young universe, carry dark-matter signatures, and turn the CMB itself into a beam dump.

How big does the detector needs to be?

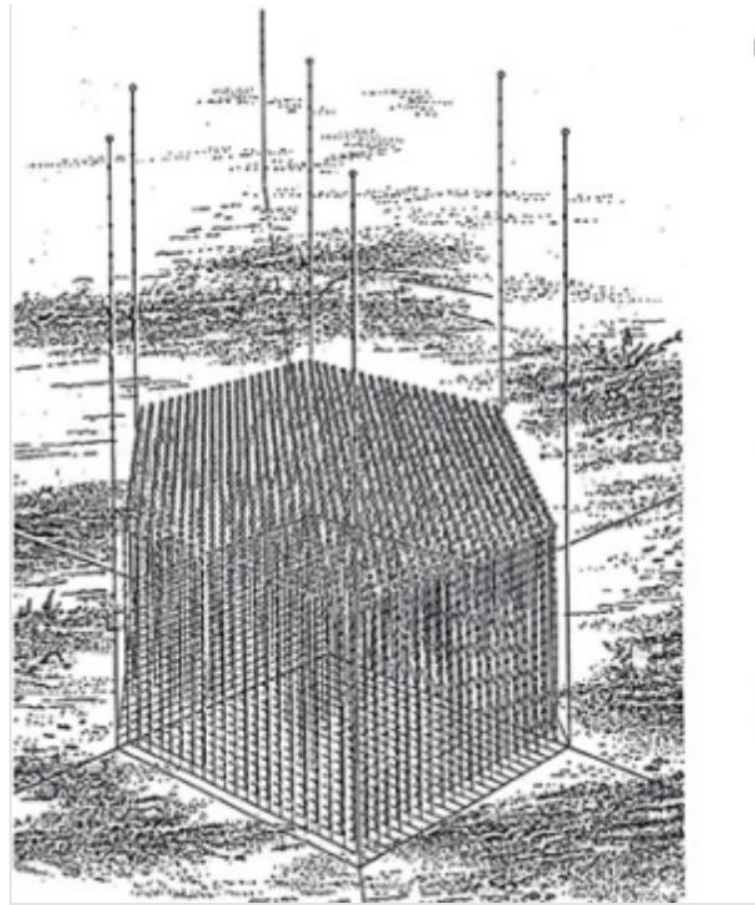


DETECTING NEUTRINOS FROM GEV TO EEV

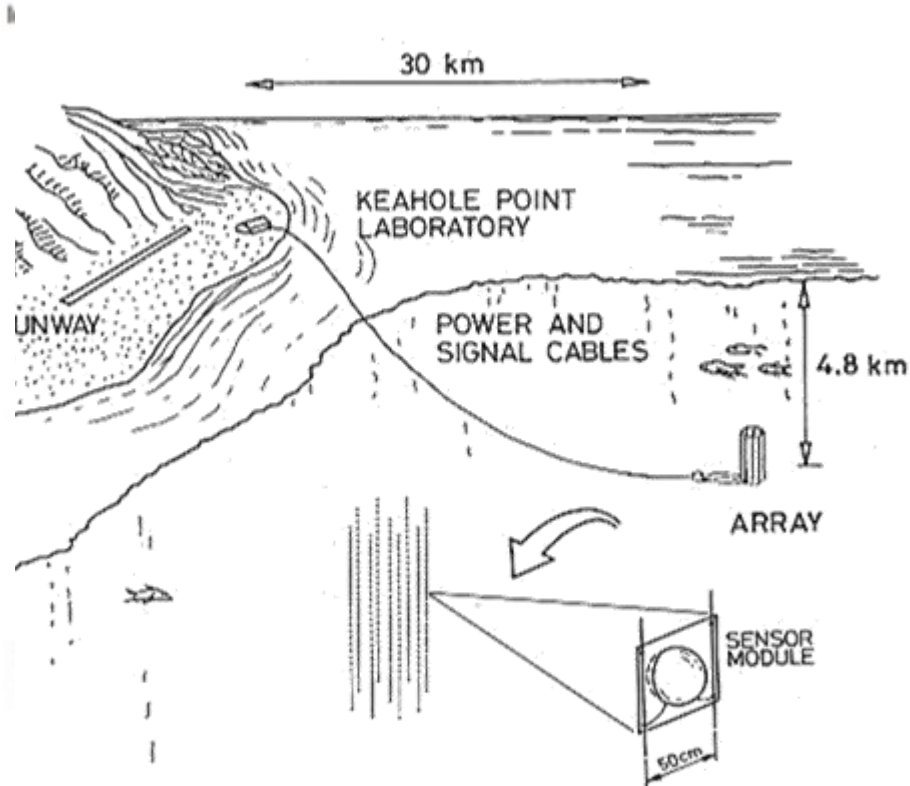


- Higher neutrino energy requires a larger instrumentation volume
- < 1 TeV: underground Cherenkov detector
- 1 TeV – 20 PeV Under water/ice Cherenkov detector
- > 20 PeV: radio, air shower, balloon, space-based, Earth-skimming ...

DUMAND: Deep Underwater Muon And Neutrino Detection (1973)



4800 m depth at Hawaii shore



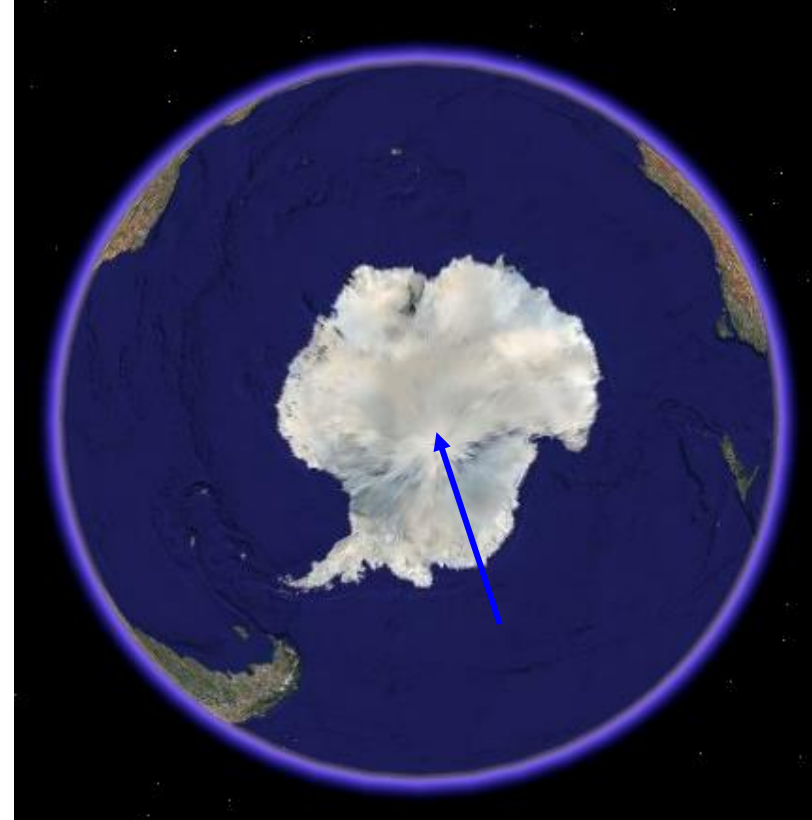
Why DUMAND failed

- Deep-sea technology was immature.
 - Salt-water corrosion, leaks and biofouling.
 - Ocean currents moved detector strings.
 - Expensive ship-based deployment.
 - Funding instability and repeated technical setbacks.
-
- DUMAND did not fail because the physics was wrong.
 - It failed because the engineering and logistics were decades ahead of available technology.
 - Legacy: optical modules, string architecture, timing calibration and the km³ concept all originated with DUMAND.

Earth's Abundant Transparent Medium: H₂O

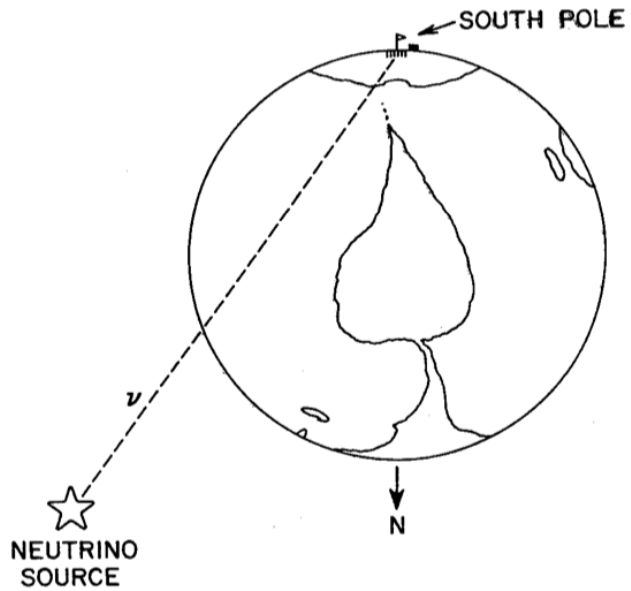


Mediterranean,
Lake Baikal



Antarctic ice sheet

Neutrino Detection in Ice: A Very Brief History



1988: Halzen and Learned propose a neutrino detector in ice



1990–92: tests in Greenland and South Pole to validate concept



1993–2000: AMANDA detector built at South Pole, detects neutrinos!

1999: *must go bigger!*

In conclusion, we suggest that field investigations begin as soon as possible to examine the relevant optical properties of deep Antarctic ice. It is amusing to envisage the Antarctic ice sheet as a giant neutrino telescope, with the whole earth as its rotating neutrino bandpass filter. While the South Pole may not be as pleasant as Hawaii, or as convenient as Arkansas, or even Lake Baykal, it may just turn out to be the best place to initiate high energy neutrino astrophysics.

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University of Wisconsin–River Falls
Yale University

THE ICECUBE COLLABORATION

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

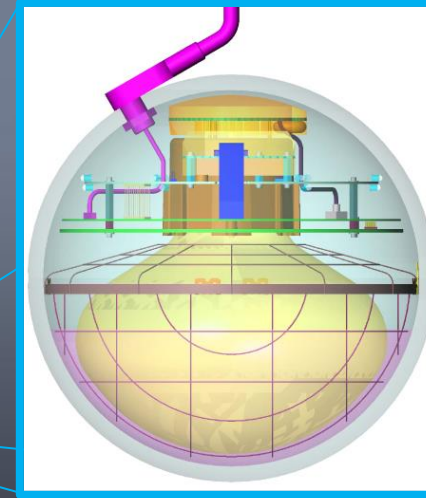
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

geographic South Pole

surface detectors ("IceTop")

The IceCube Detector

cables ("strings")

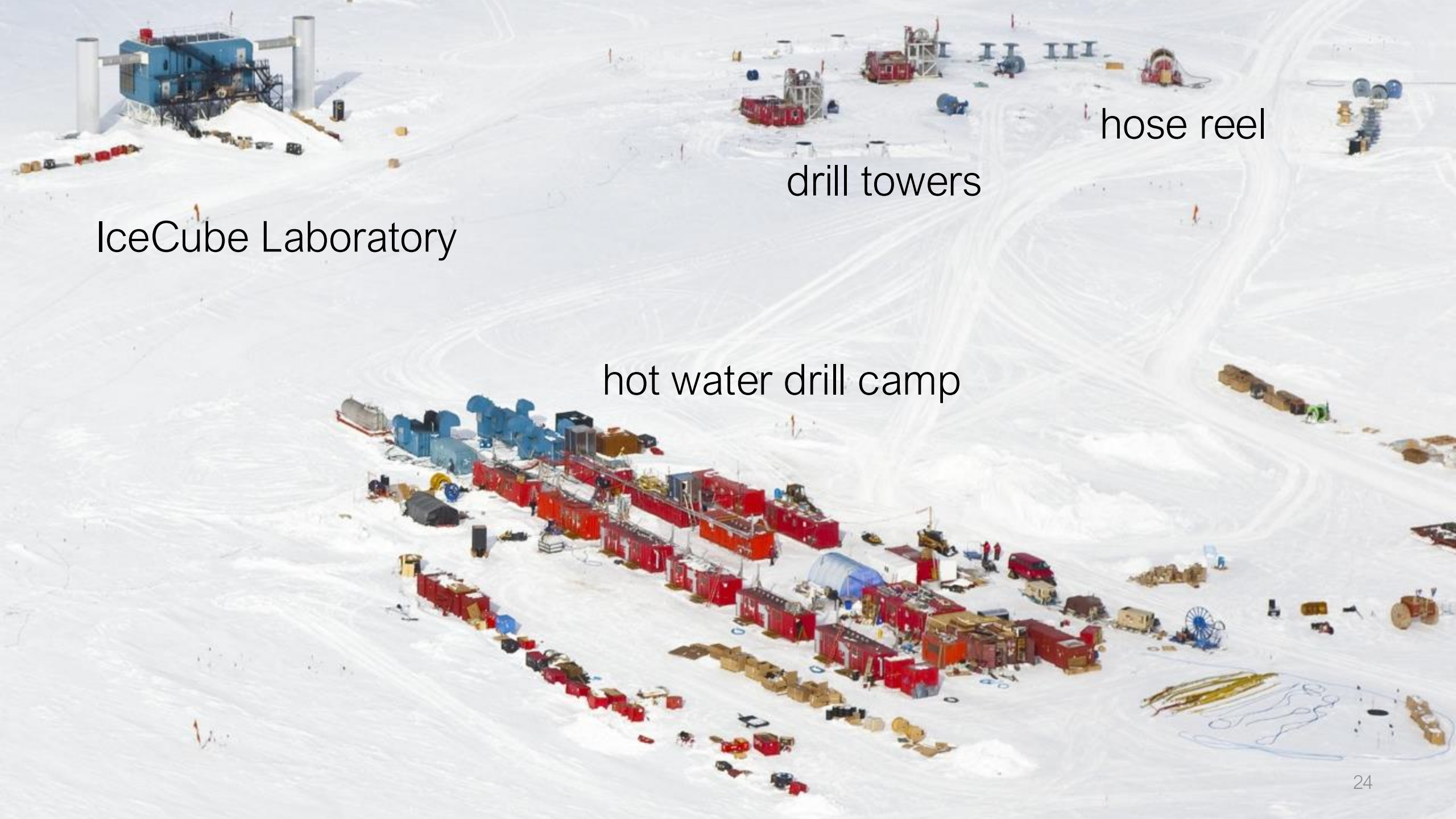


5160 digital optical modules (DOM)
to detect Cherenkov light

1.5 to 2.5 km deep
in ultra-clear ice

μ

ν_{μ}



IceCube Laboratory

hose reel

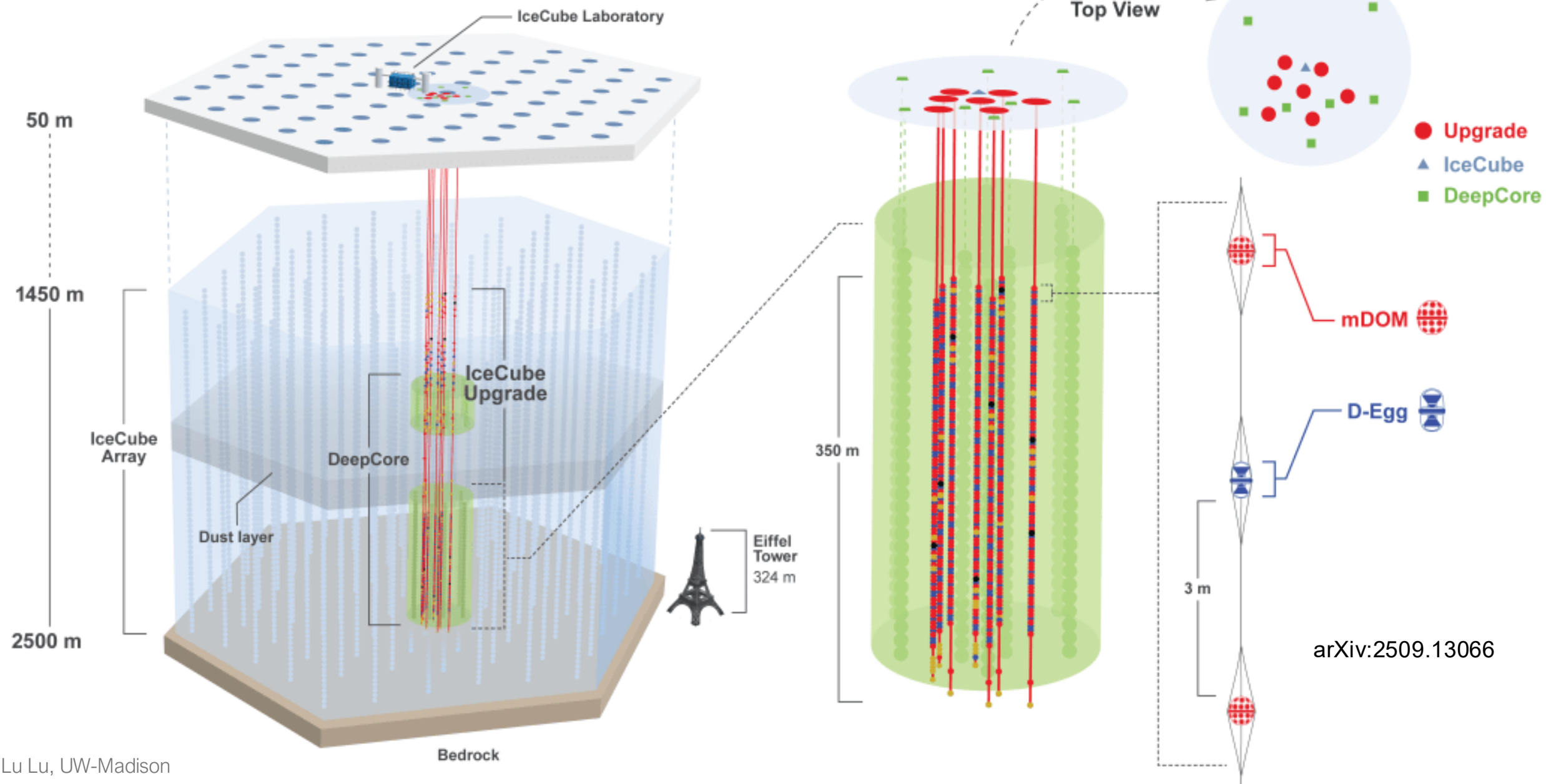
drill towers

hot water drill camp

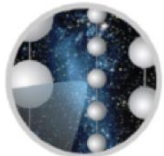
drill time: ~40h / hole
installation time: ~10h / string



IceCube-Upgrade (2026)



New sensors deployed during the upgrade



ICECUBE



IceCube DOM

10" PMT & dia. 33 cm

>98% still in operation



ICECUBE
UPGRADE

DEgg
Elongated vessel



Image Credit: N. Shimizu/CEHAP



Image Credit: S. Niedworok/
DESY



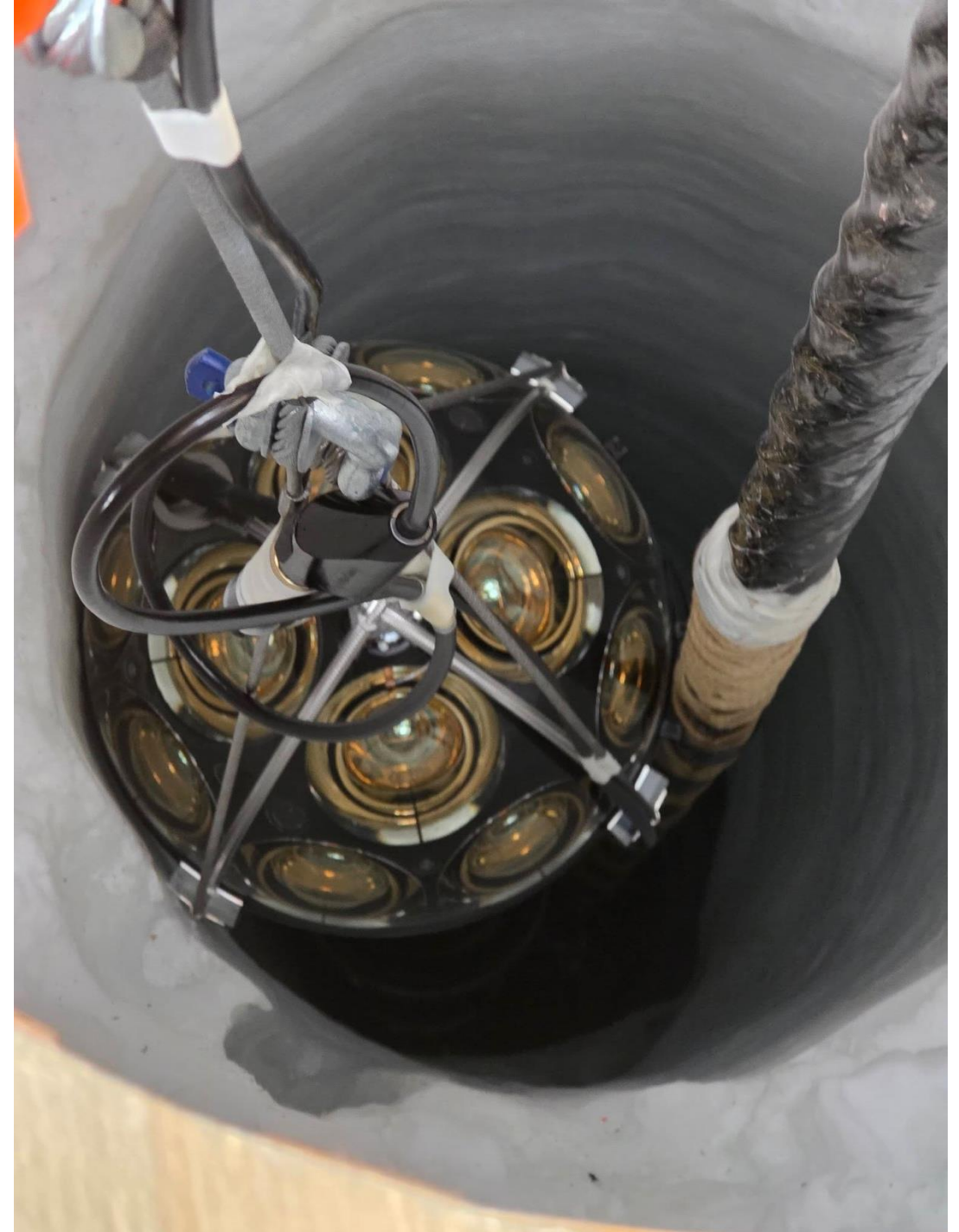
ICECUBE
GEN2



Image Credit: Y. Makino/WIPAC

Gen2-DOM
PMT segmentation with 4π angular
coverage in an elongated vessel



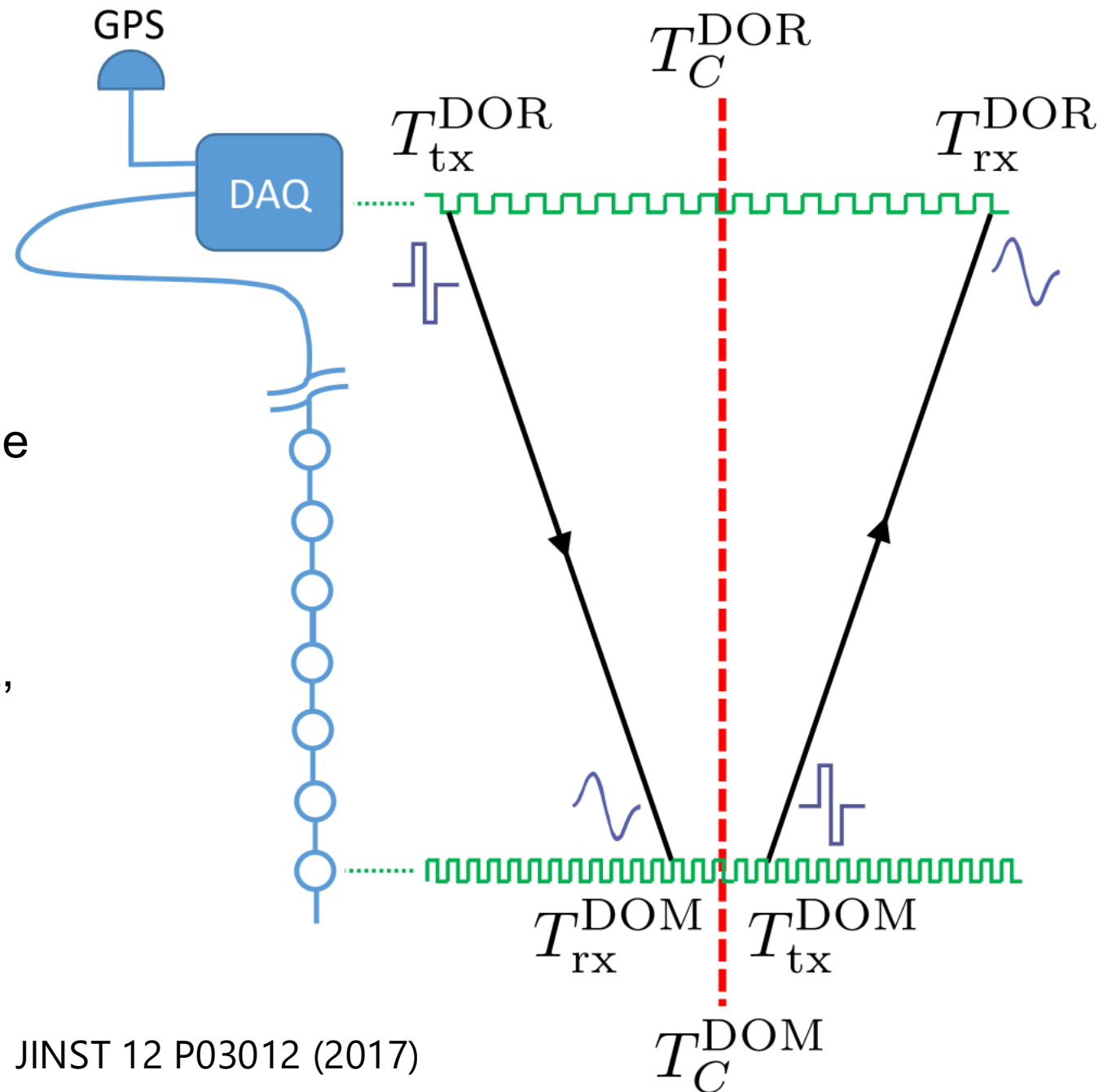




Time calibration

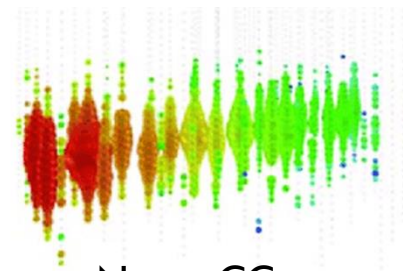
RAPCal:

- 5160 autonomous DOM clocks
- GPS-disciplined master clock at the surface
- RAPCal exchanges calibration pulses every ~ 1 s
- Measures cable delay, clock offset, and oscillator drift
- Global synchronization better than ~ 2 ns $\rightarrow$ precise event reconstruction

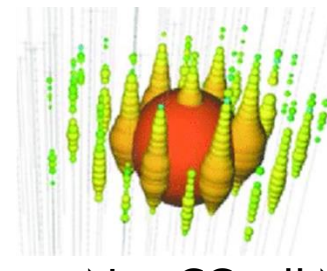


NEUTRINO INTERACTIONS

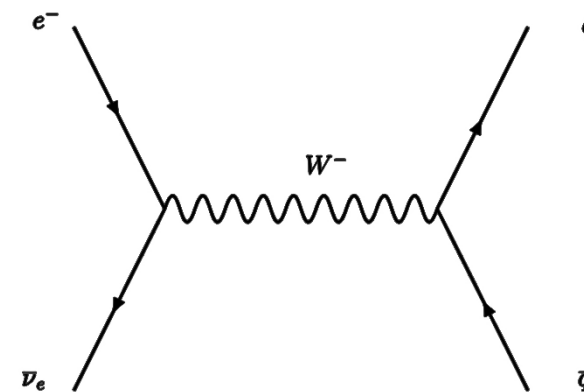
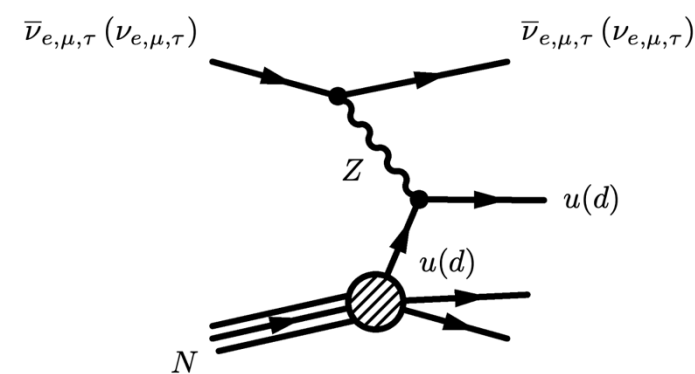
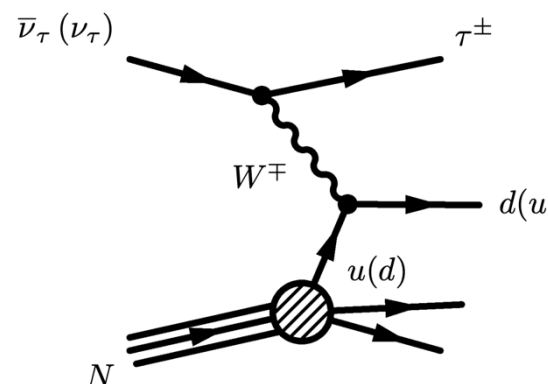
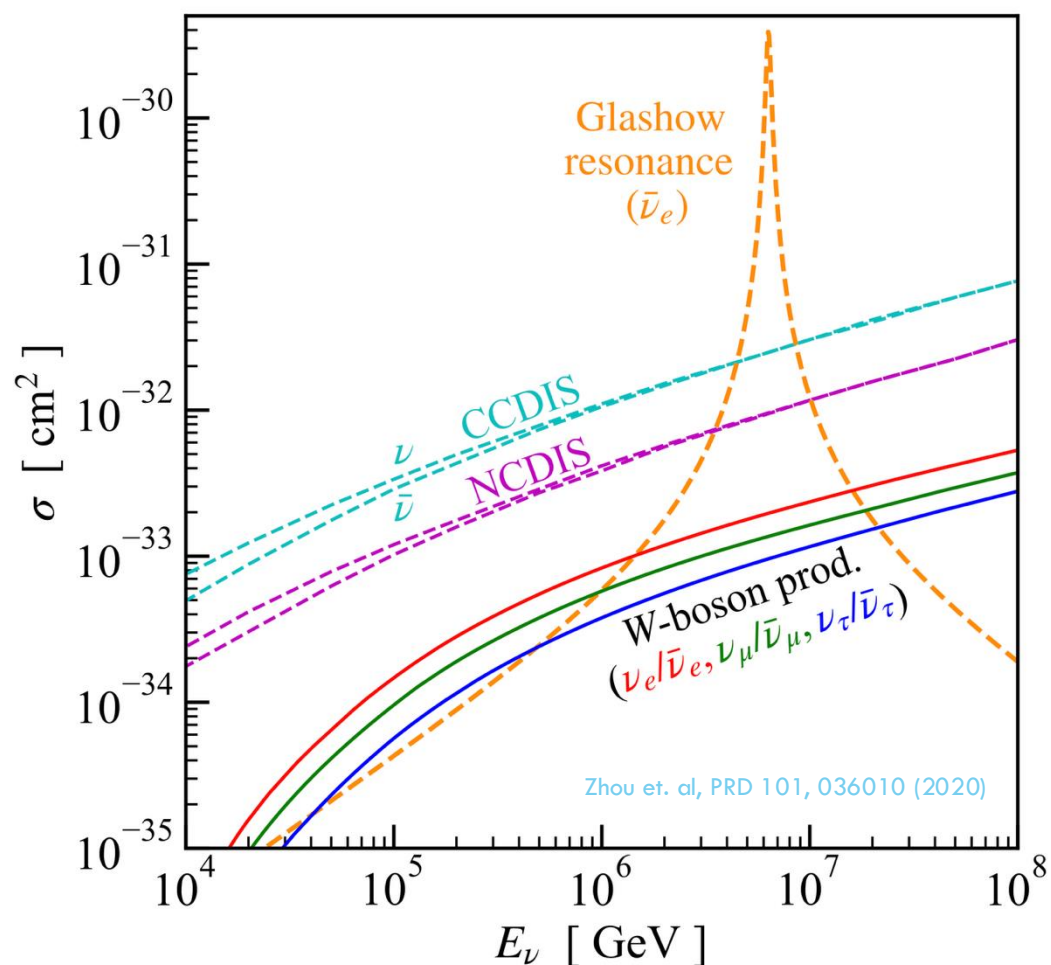
Detect Cherenkov radiation from secondary charged particles

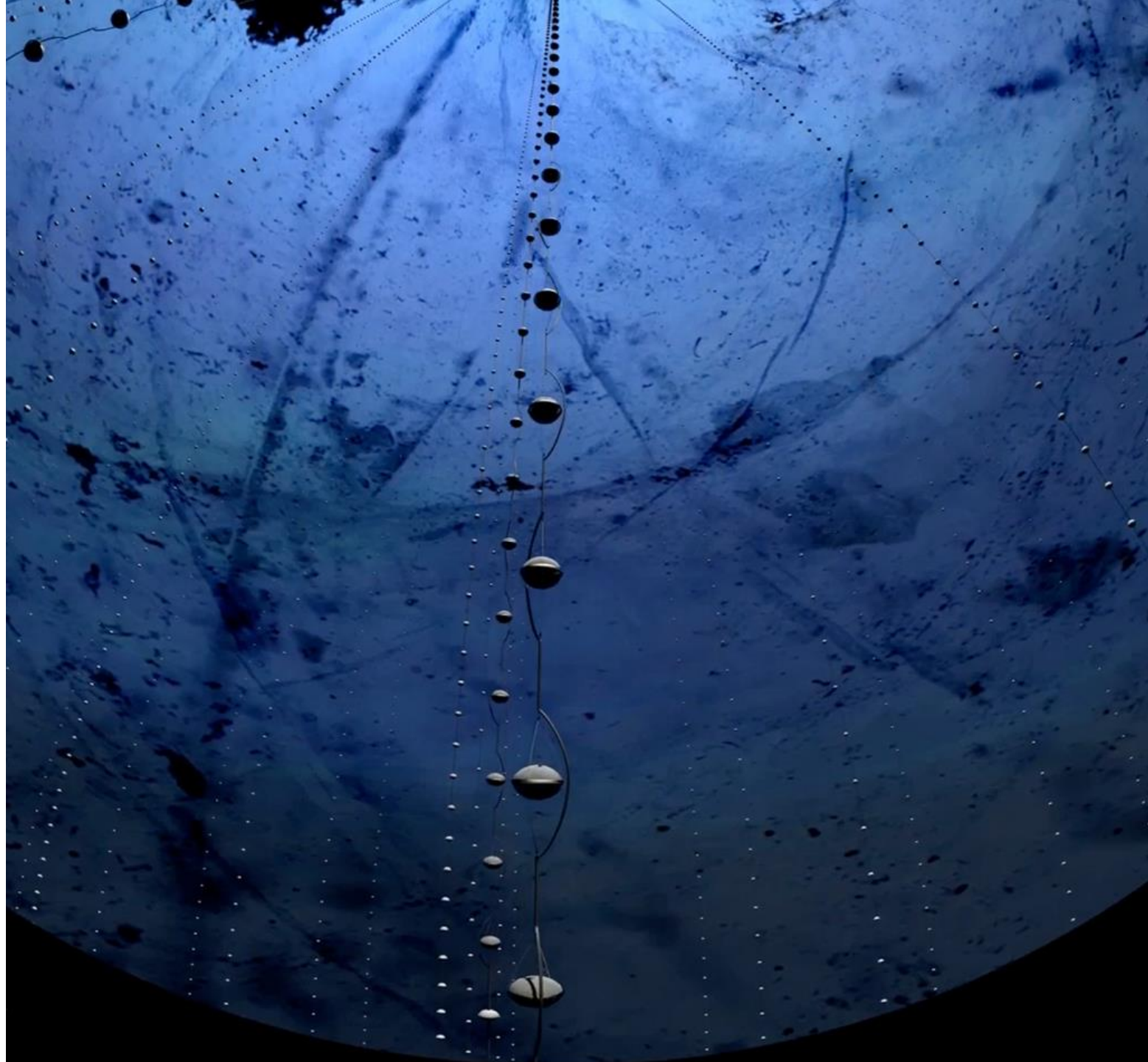


Numu CC

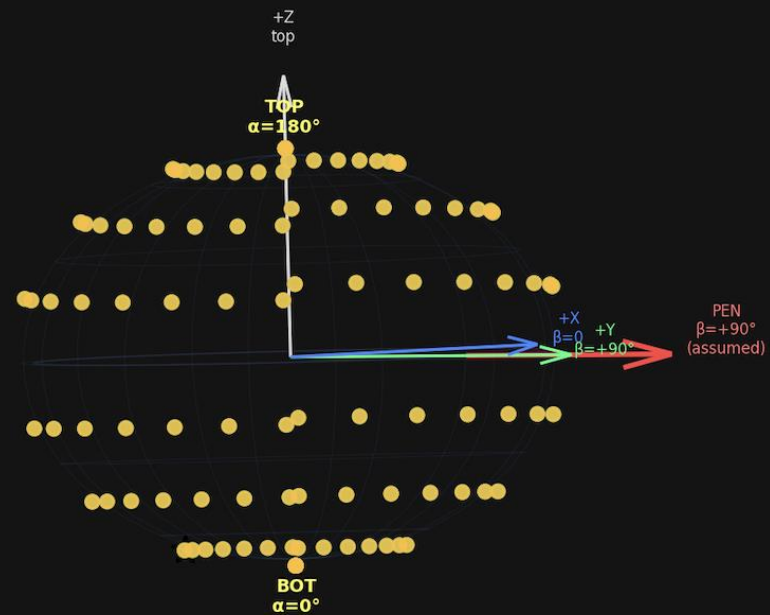


Nue CC, all NC





● fd_10s
 ● fd_4s



At (alpha,beta): 336 40

Video time: 00:37:24:000

Grid: ■=fd_10s ★=selected ·=missing ·dim = fd_4s [$\leftarrow \rightarrow$ = β step, $\uparrow \downarrow$ = α step, f = toggle focus]

$\alpha=0^\circ$	-38	-25	-12	+0	+1	+14	+27	+40	
$\alpha=24^\circ$	-38	-25	-12		+1	+14	+27	+40	
$\alpha=48^\circ$	-38	-25	-12		+1	+14	+27	+40	
$\alpha=72^\circ$	-38	-25	-12		+1	+14	+27	+40	
$\alpha=108^\circ$	-38	-25	-12		+1	+14	+27	+40	+53
$\alpha=132^\circ$	-38	-25	-12		+1	+14	+27	+40	+53
$\alpha=156^\circ$	-38	-25	-12		+1	+14	+27	+40	+53
$\alpha=180^\circ$	-38	-25	-12		+1	+14	+27	+40	+53
$\alpha=204^\circ$	-38	-25	-12		+1	+14	+27	+40	+53

Neutrino detection

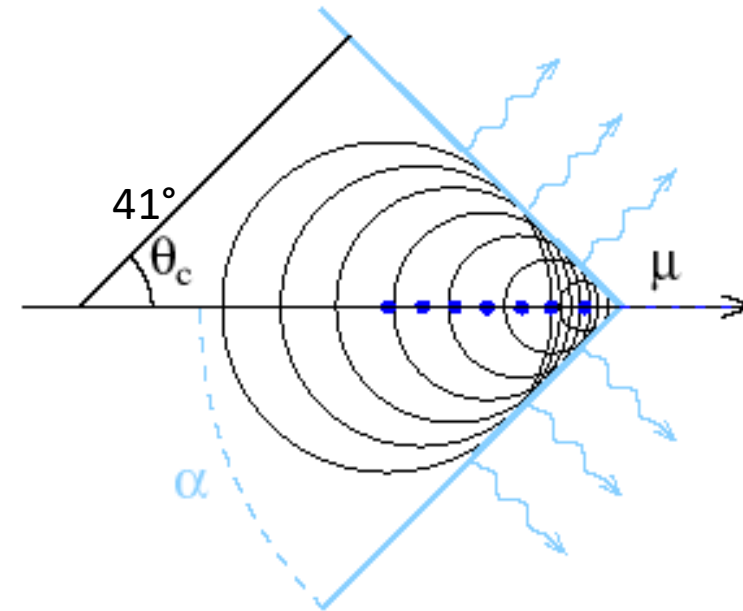
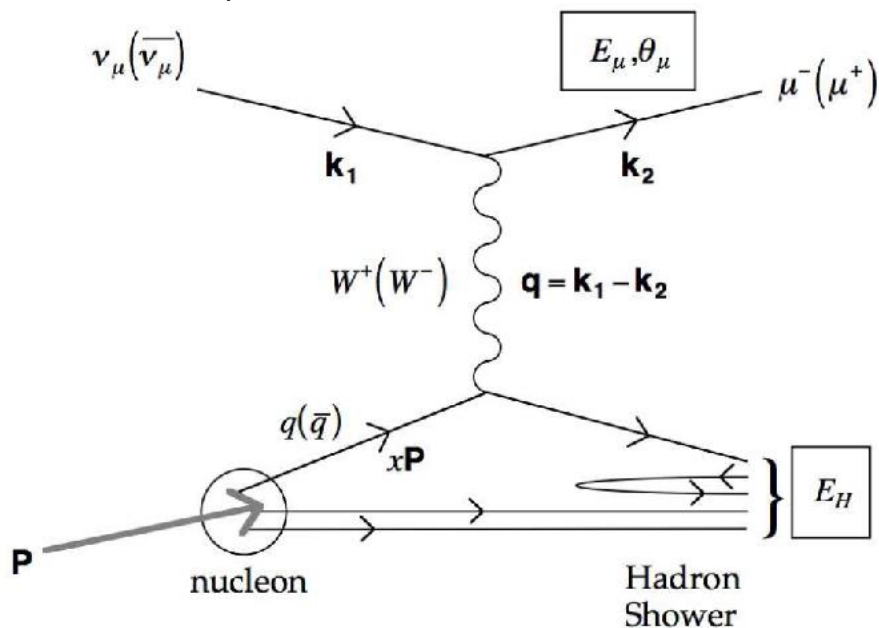
Neutrino interacts with targets in media such as ice and water

- At energies relevant for this talk, primarily DIS off nucleons
- W-boson resonance with atomic electrons at $E_\nu \sim 6.3$ PeV

Charged outgoing particles emit Cherenkov radiation detectable by PMTs

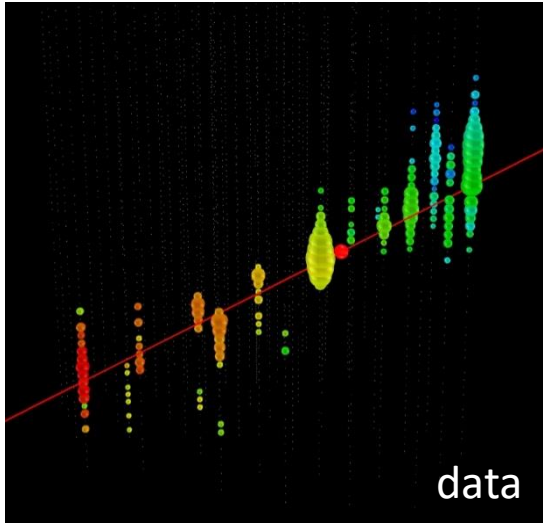
- Large boost factor $\rightarrow$ align with neutrino direction

Rev. Mod. Phys. 84, 1307



Neutrino event topologies

CC muon neutrino

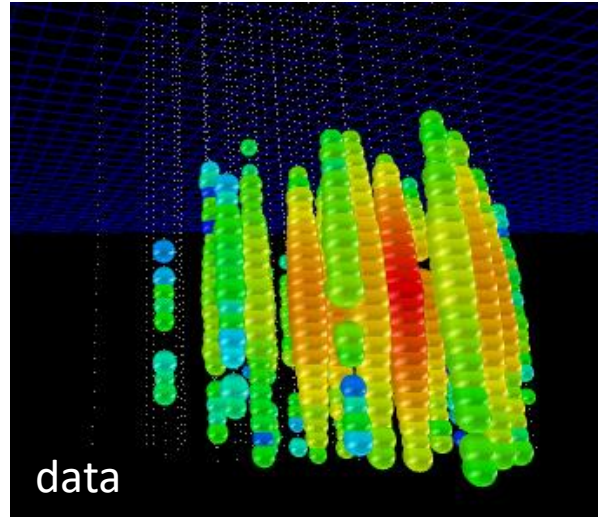


$$\nu_{\mu} + N \rightarrow \mu + X$$

track

angular resolution $\sim 0.5^{\circ}$
energy resolution $\sim \times 2$

NC or CC electron neutrino

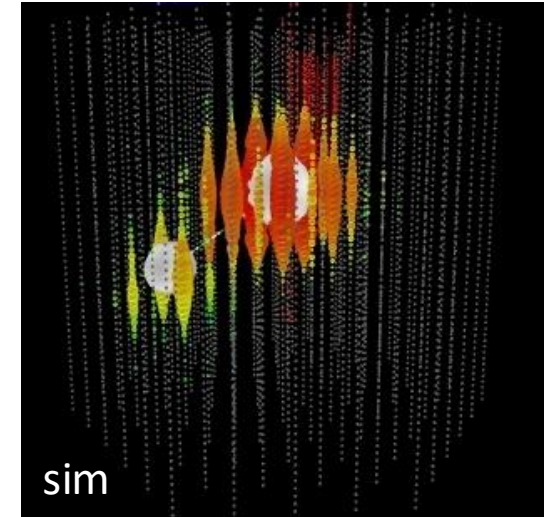


$$\begin{aligned}\nu_e + N &\rightarrow e + X \\ \nu_x + N &\rightarrow \nu_x + X\end{aligned}$$

cascade

angular resolution $\sim 4^{\circ}$
energy resolution $\sim 10\%$

CC tau neutrino

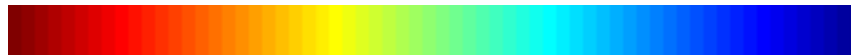


$$\nu_{\tau} + N \rightarrow \tau + X$$

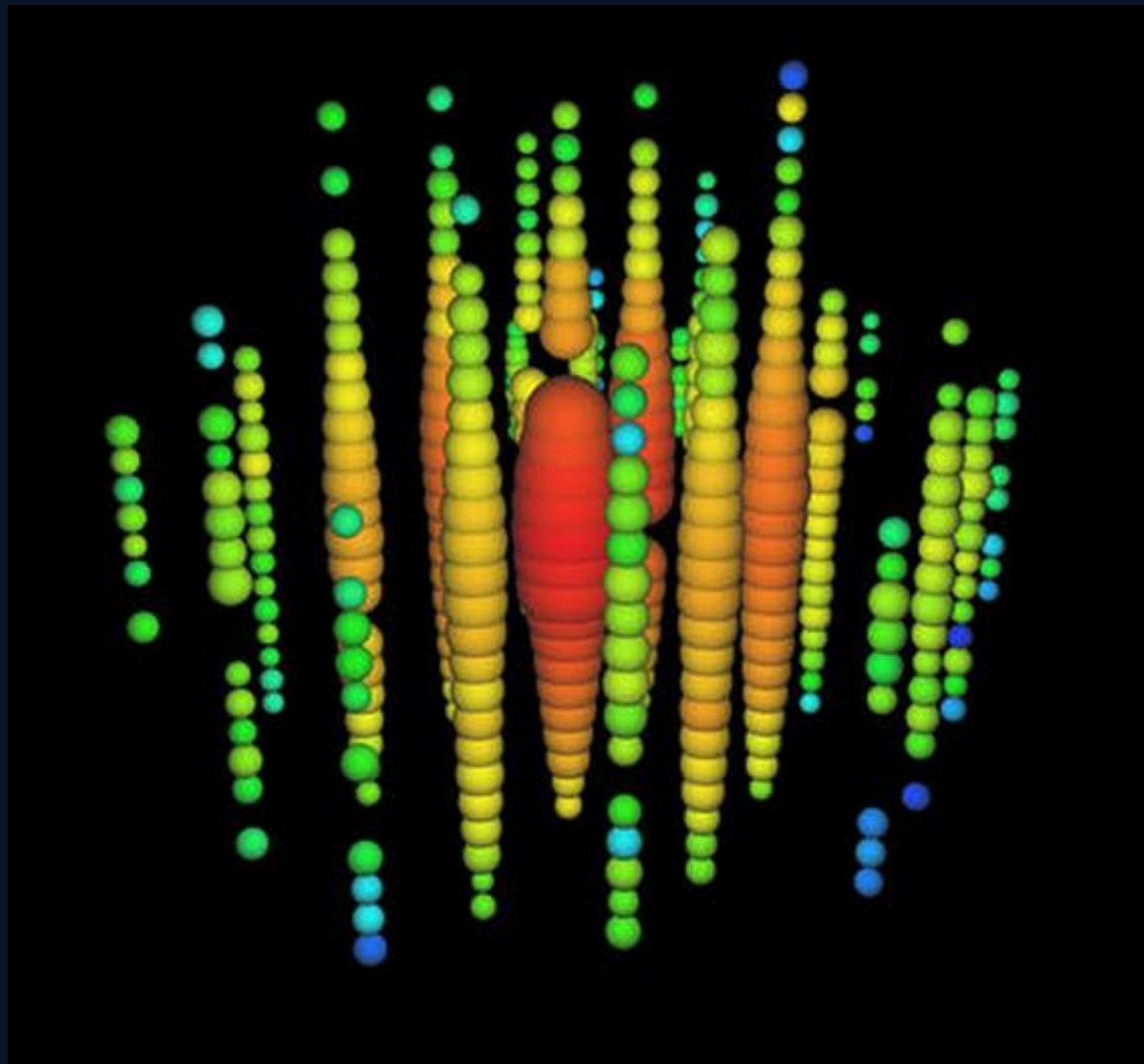
double cascade

~ 4 expected in 12 years

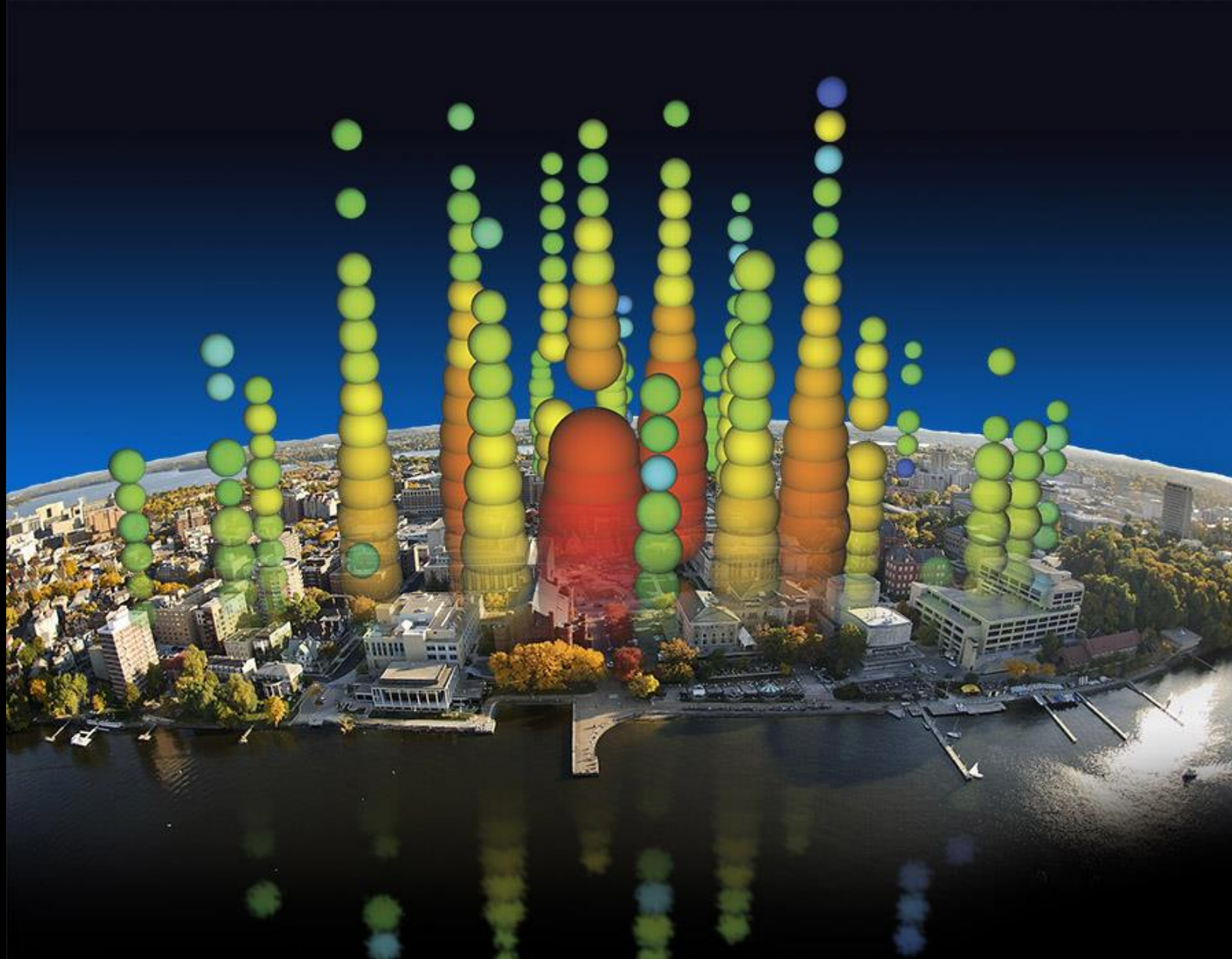
Earlier



Later

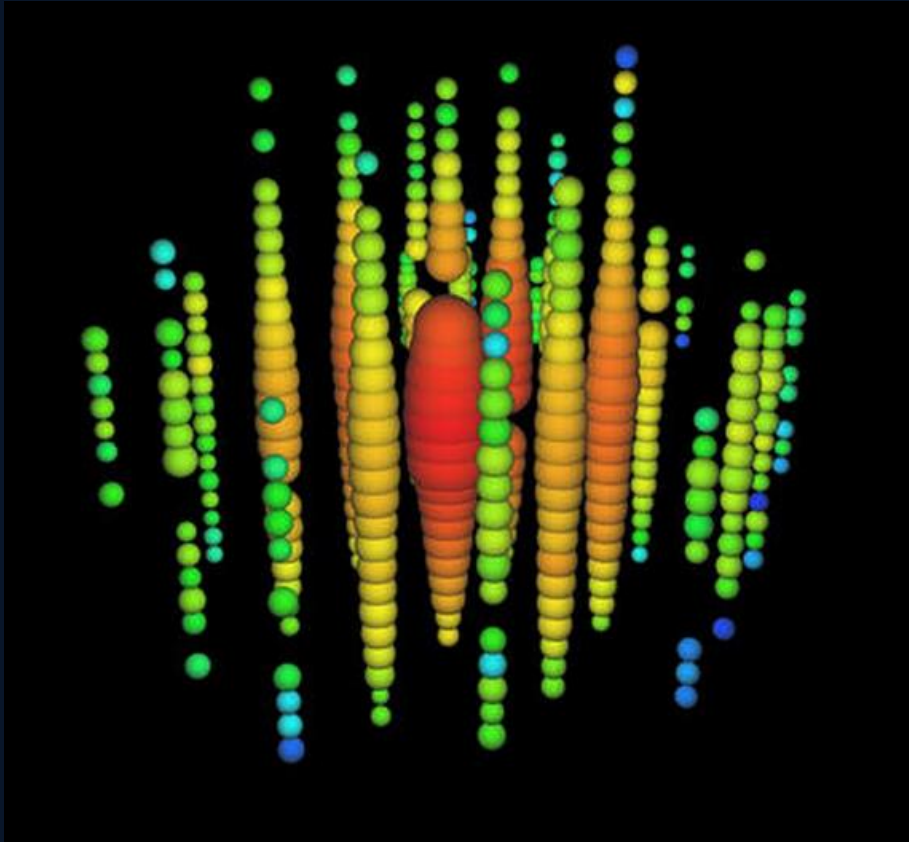


This is a particle physics event. Guess the size of what you're looking at.



Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

PeV electron neutrino shower



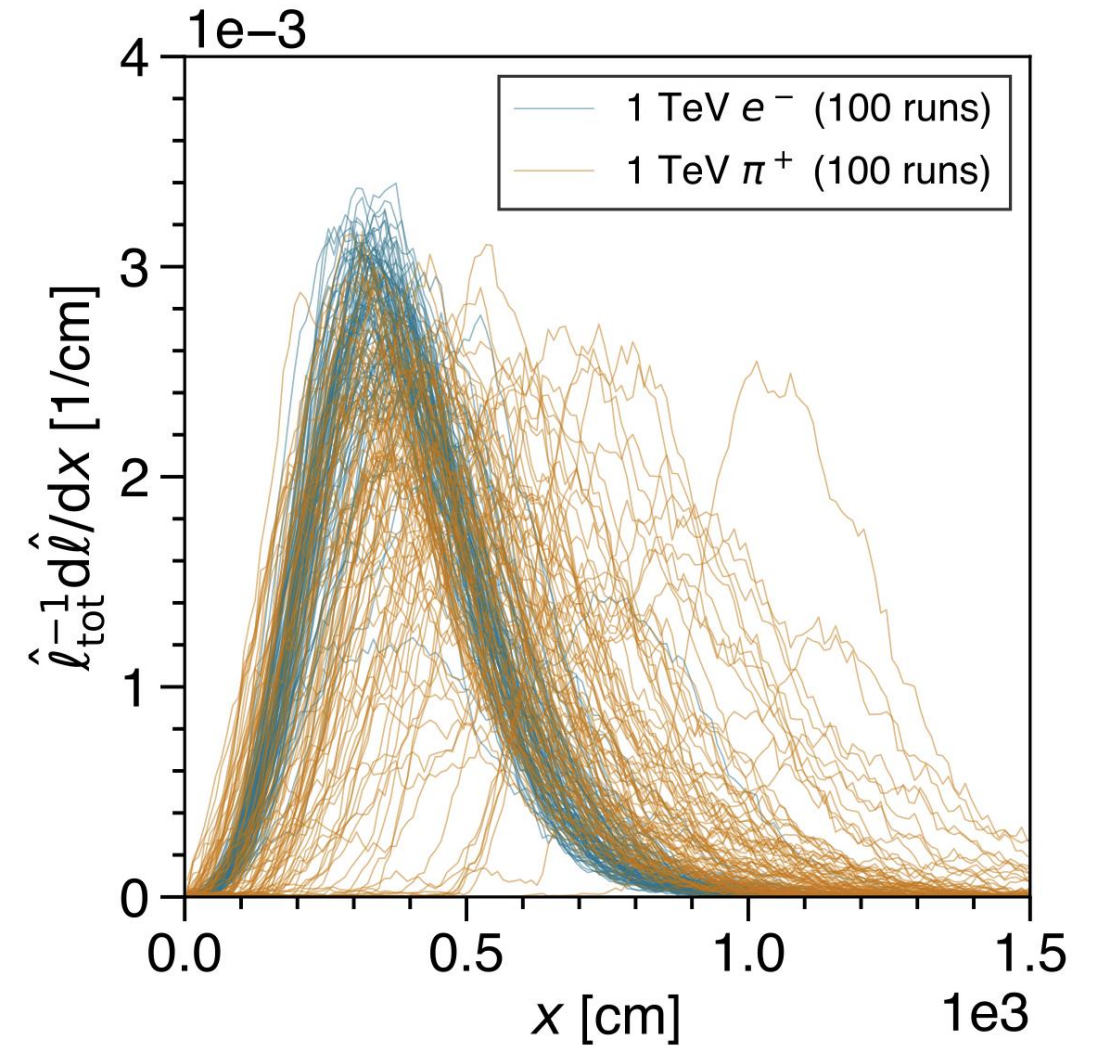
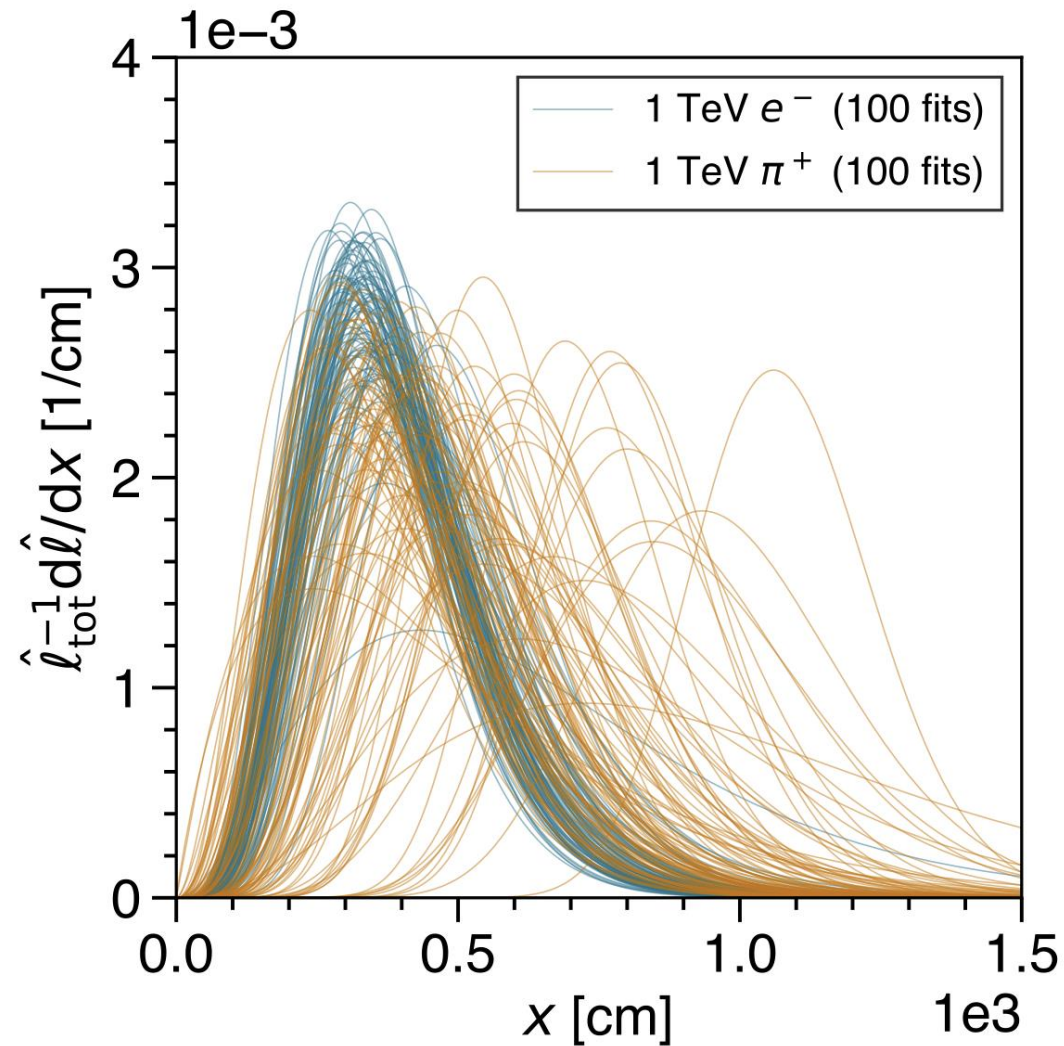
$\approx 500 \text{ m}$

diameter of the sphere of hit sensors — what you're looking at

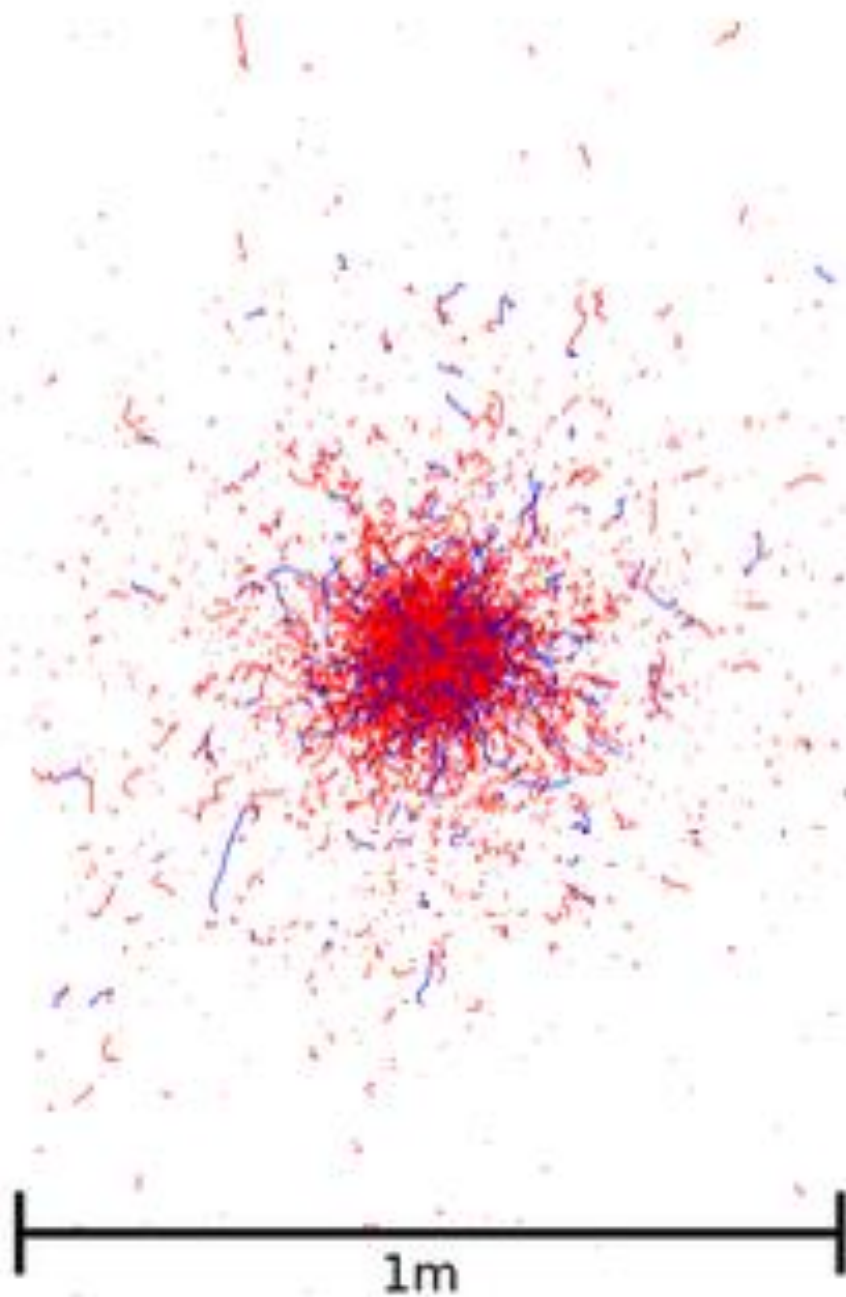
$\approx 10 \text{ m}$

length of the particle shower that actually made it

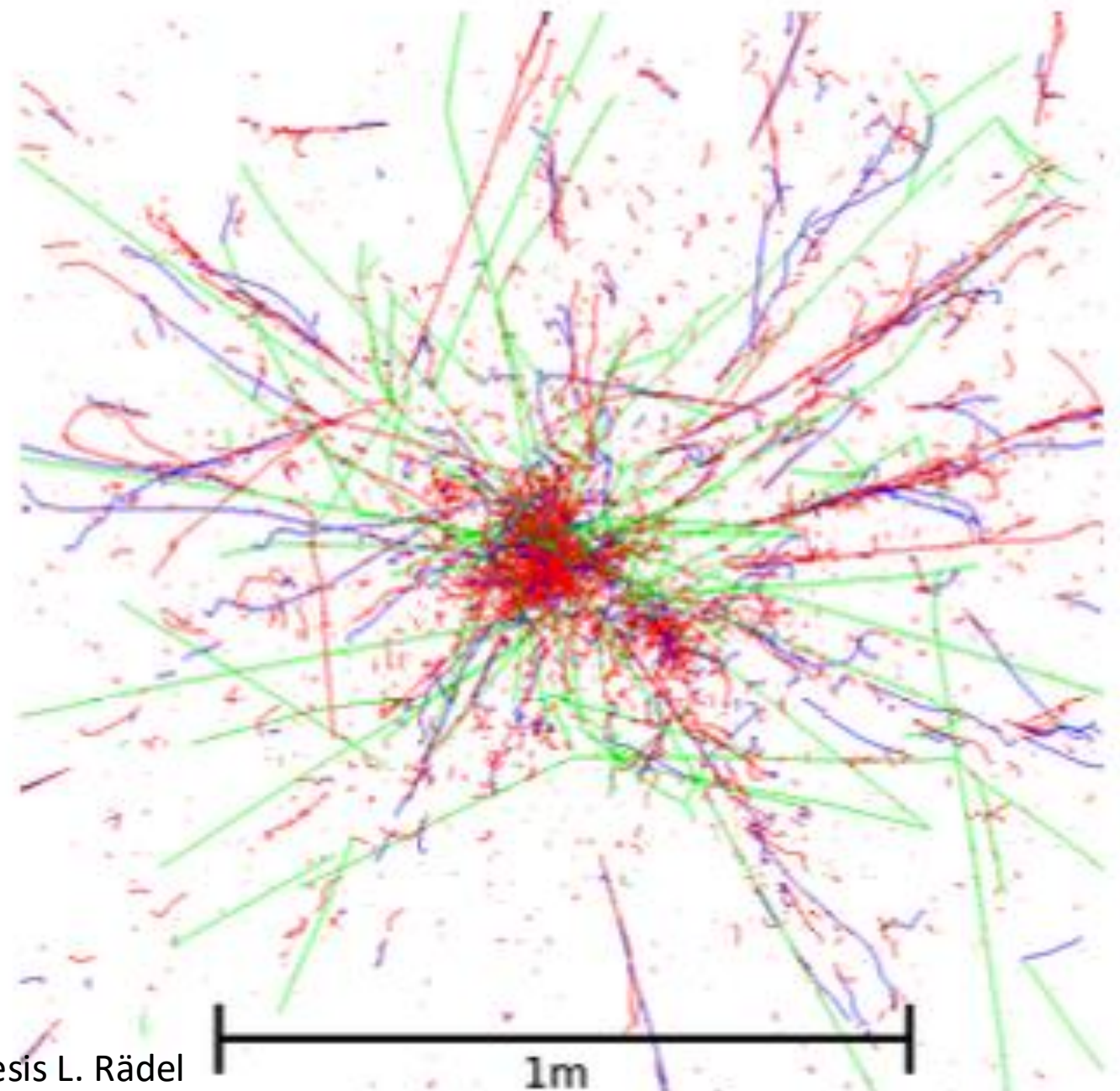
Shower profiles approximated with analytic approach



EM

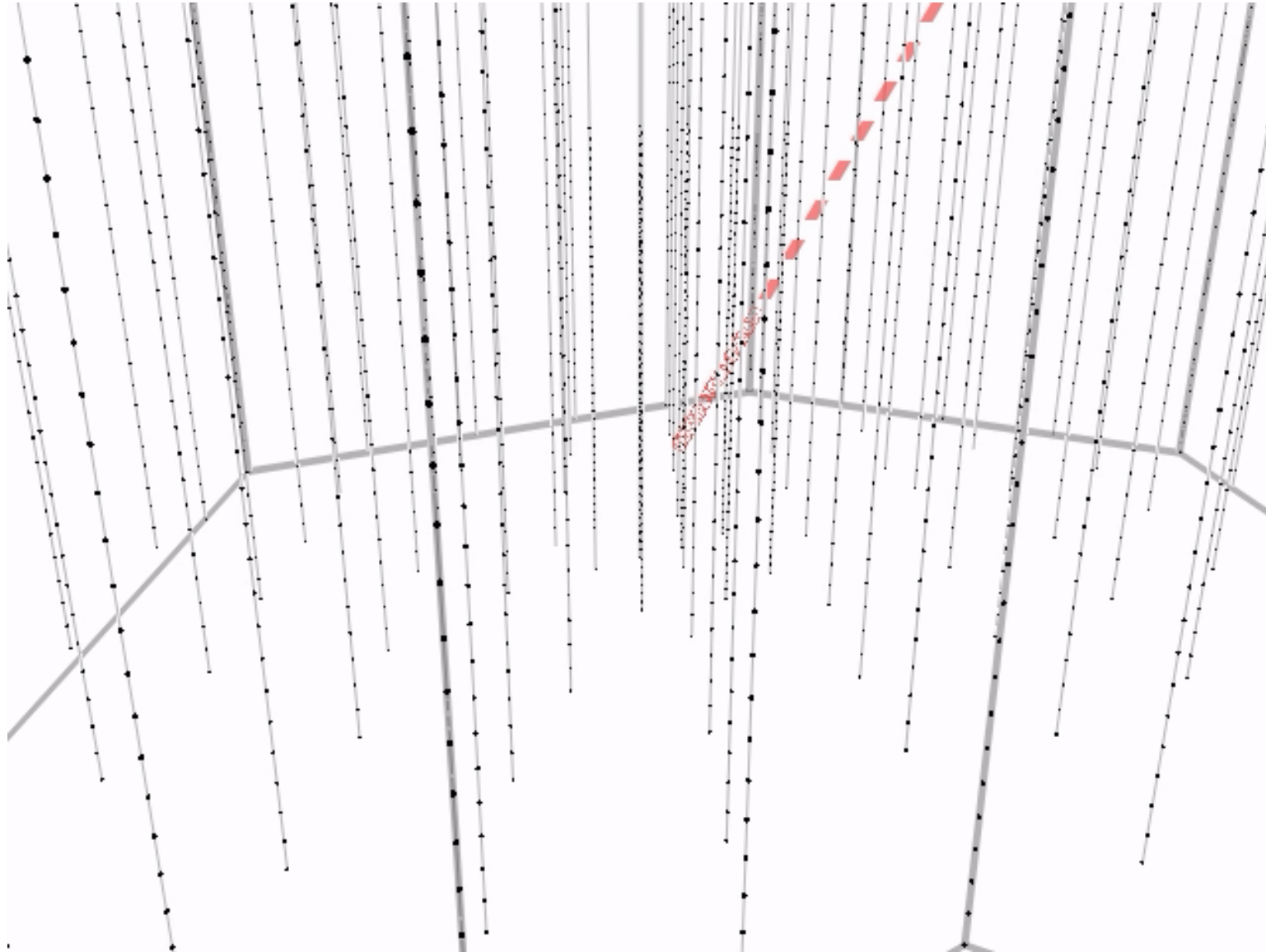


Hadron

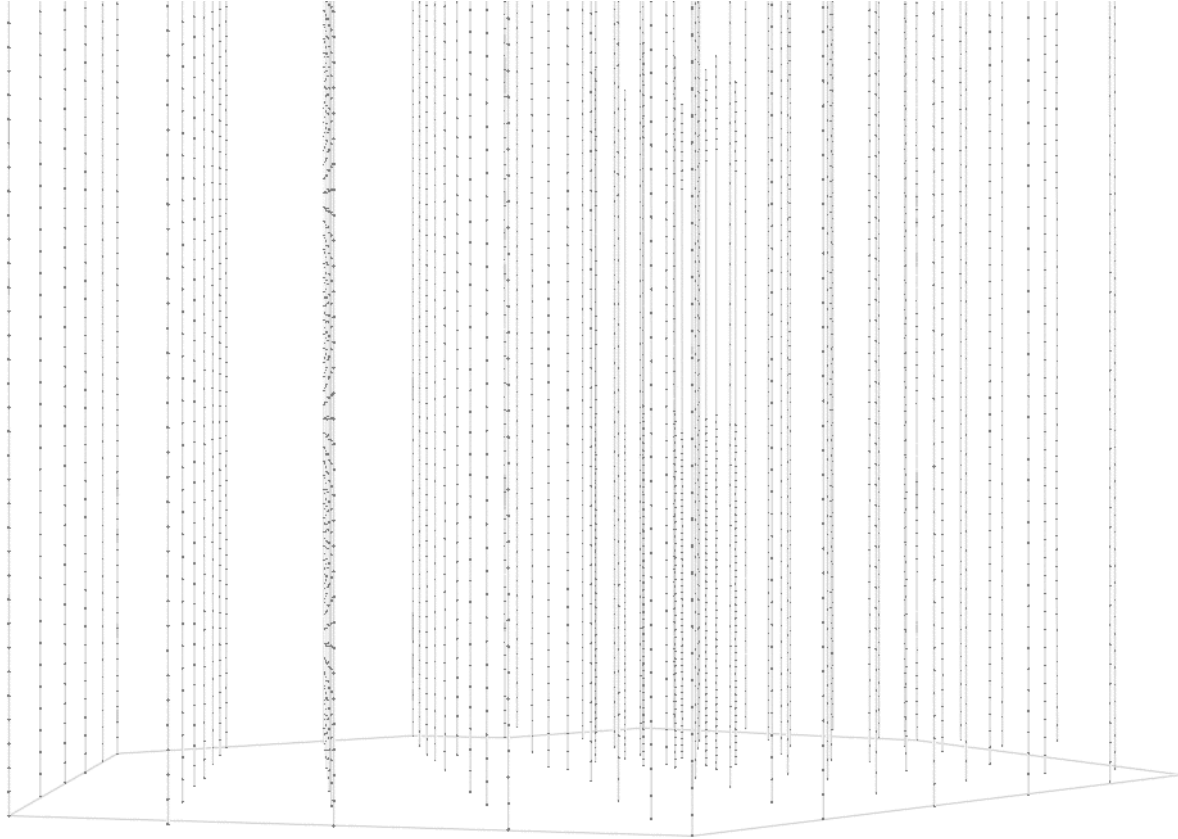


MSc's thesis L. Rädcl

Example: high-energy ν_τ



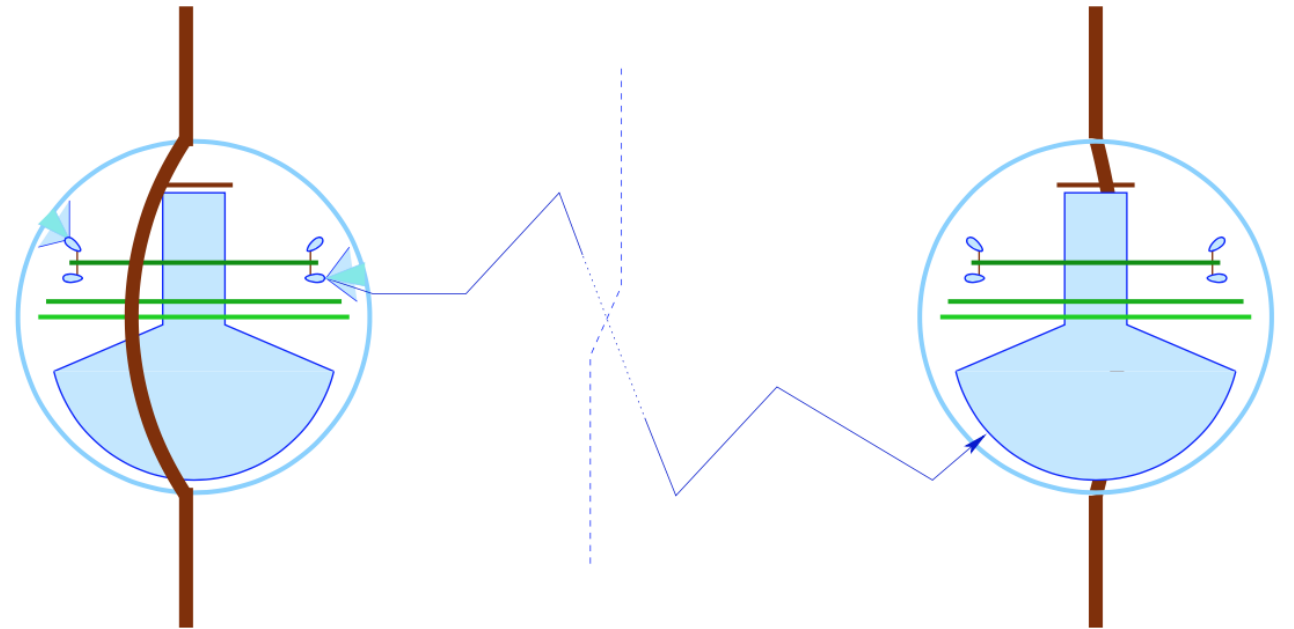
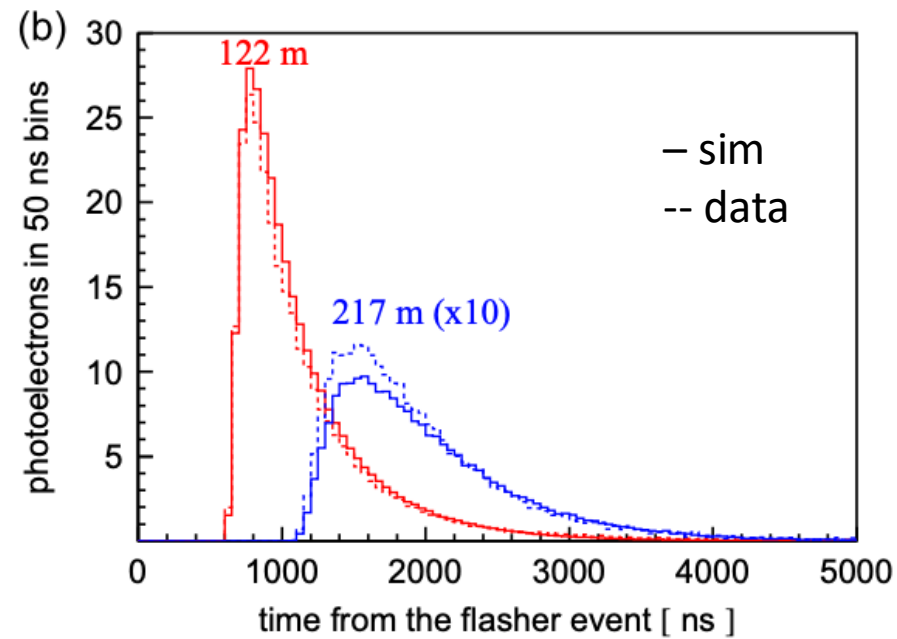
Example: high-energy ν_μ



Ice modeling

Six horizontal and six tilted LEDs on each DOM

Simulate on GPUs while fitting ice scattering, absorption, crystal density to flasher calibration data

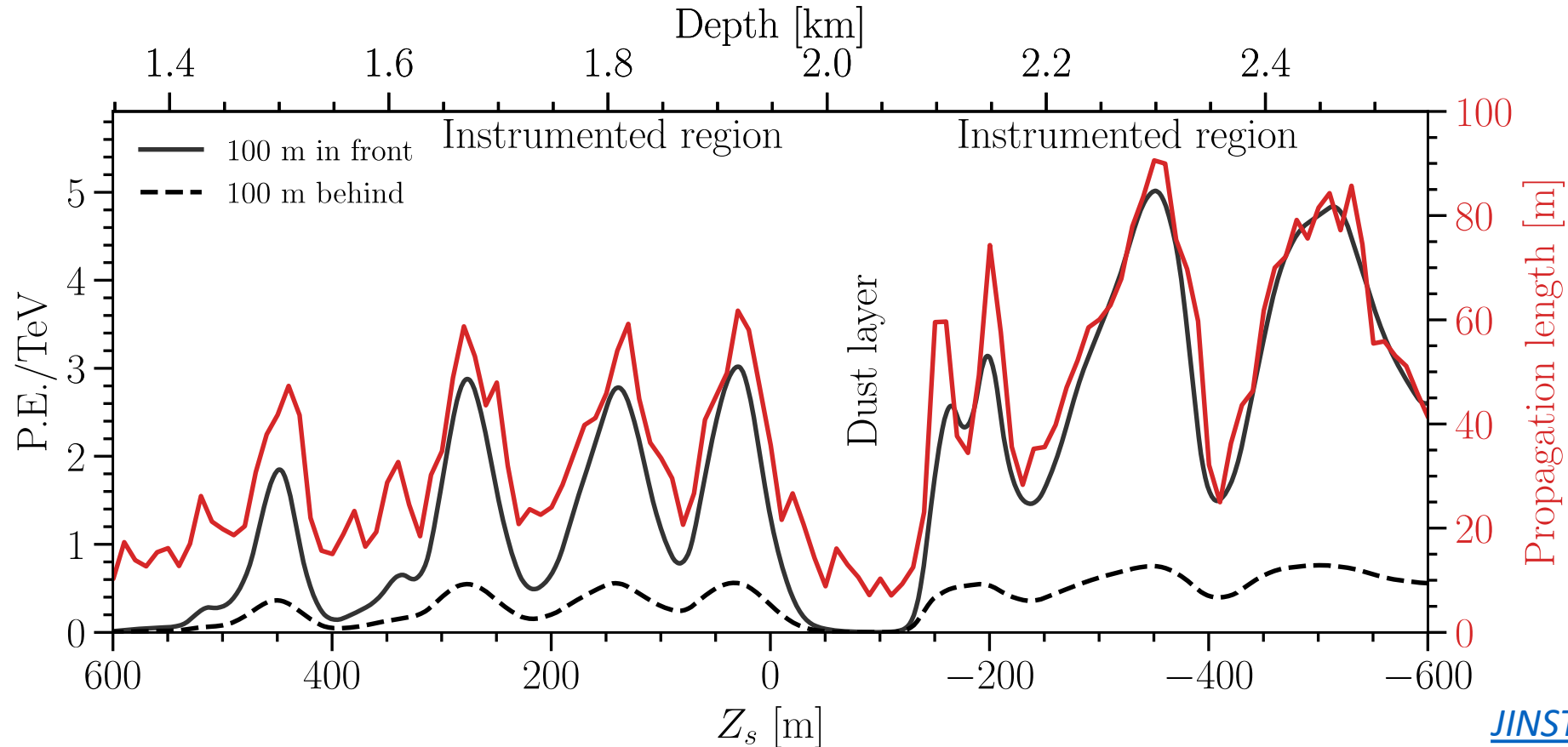


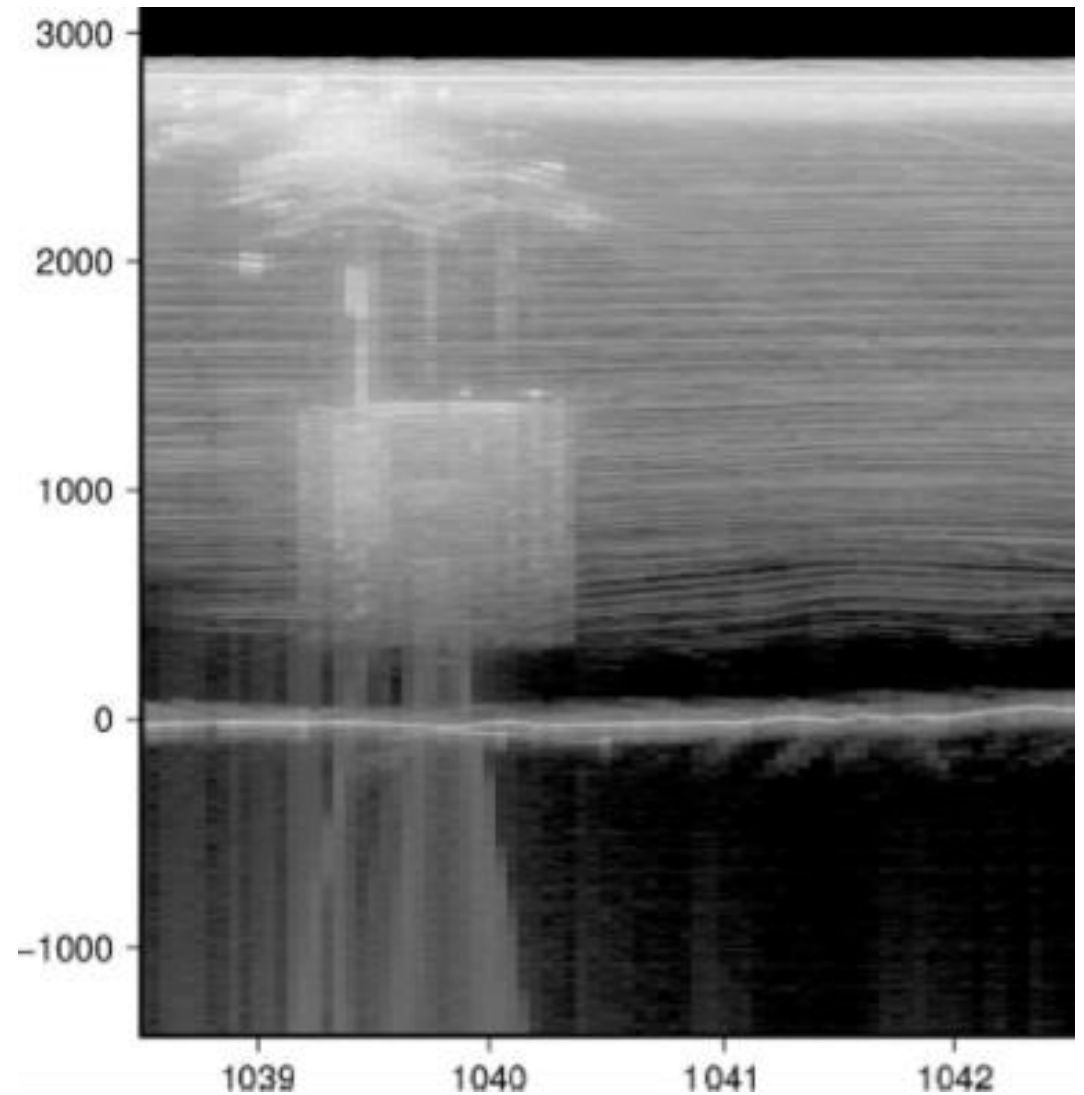
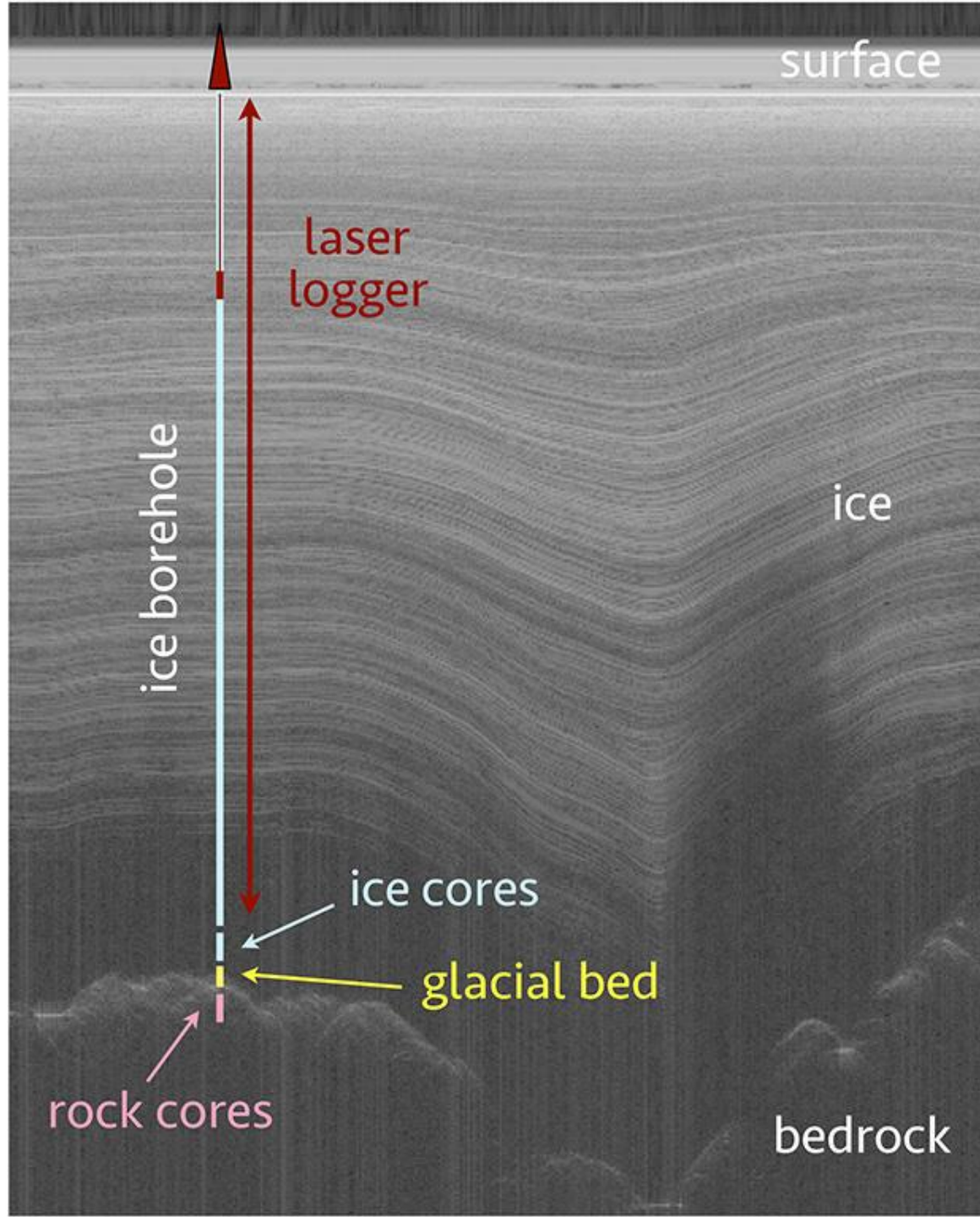
[J. NIMA 2013.01.054](#)

Detector (ice) calibration

Shown: time-integrated cascade photoelectron yields as a function of depth; receiver 100m in front of (solid) and behind (dashed) source

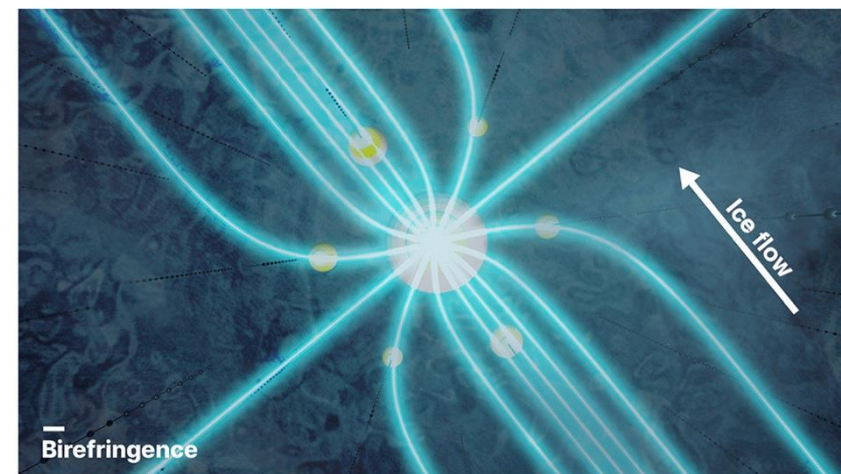
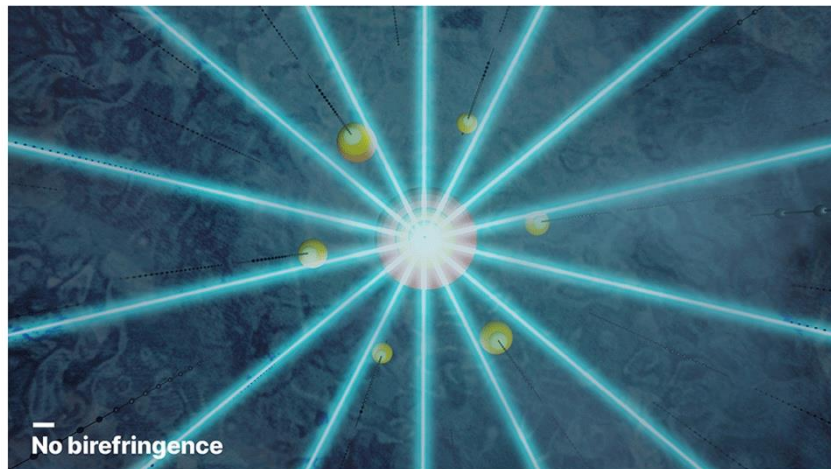
Strong correlation between **ice properties** and **light yield**



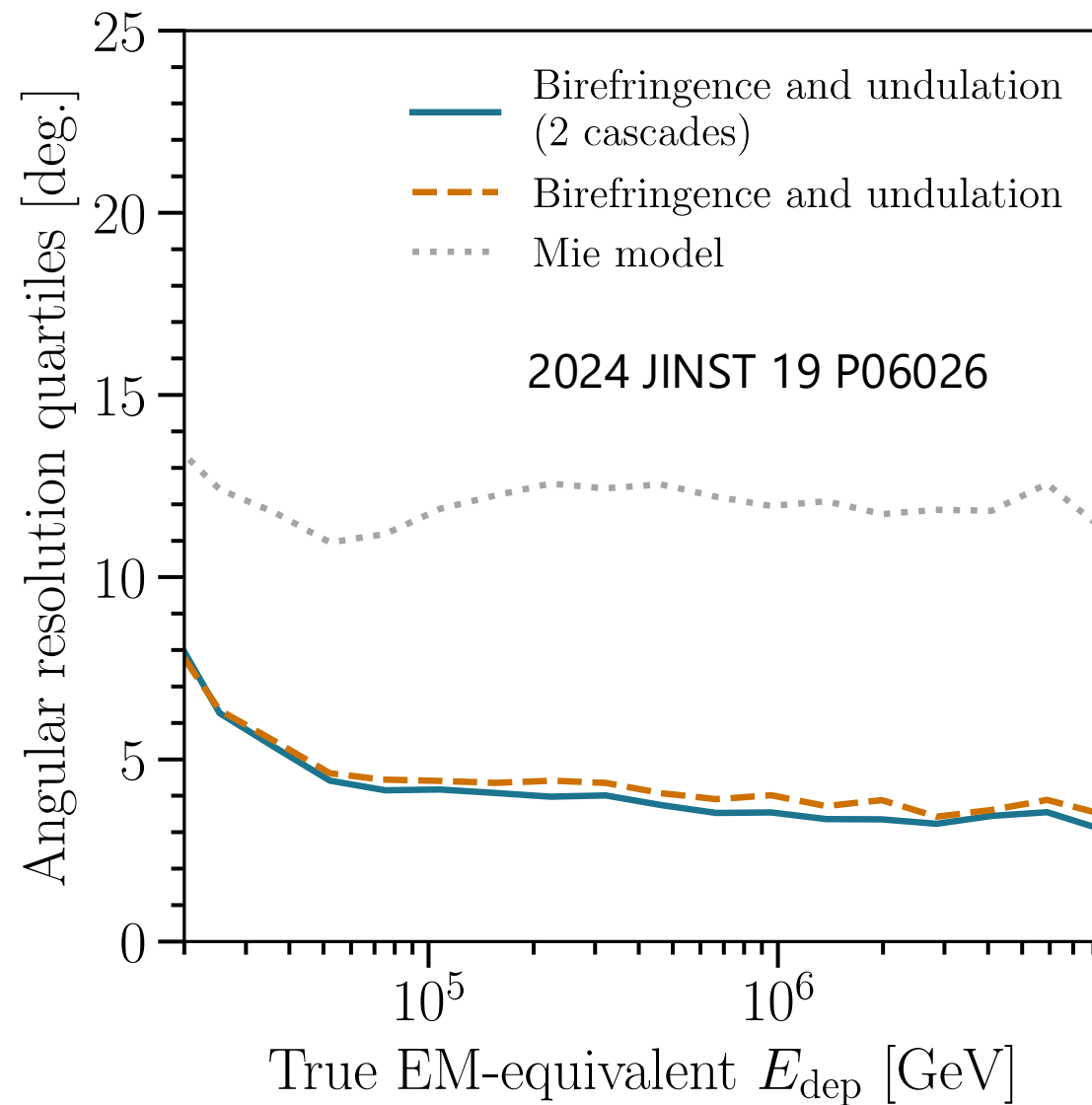


Birefringence is a property of every ice crystal. What makes Antarctic deep ice special is that the crystals become aligned by ice flow, so the entire ice sheet becomes birefringent on kilometer scales.

New result: improved ice modelling and reconstructions



The Cryosphere 18 (2024) 1

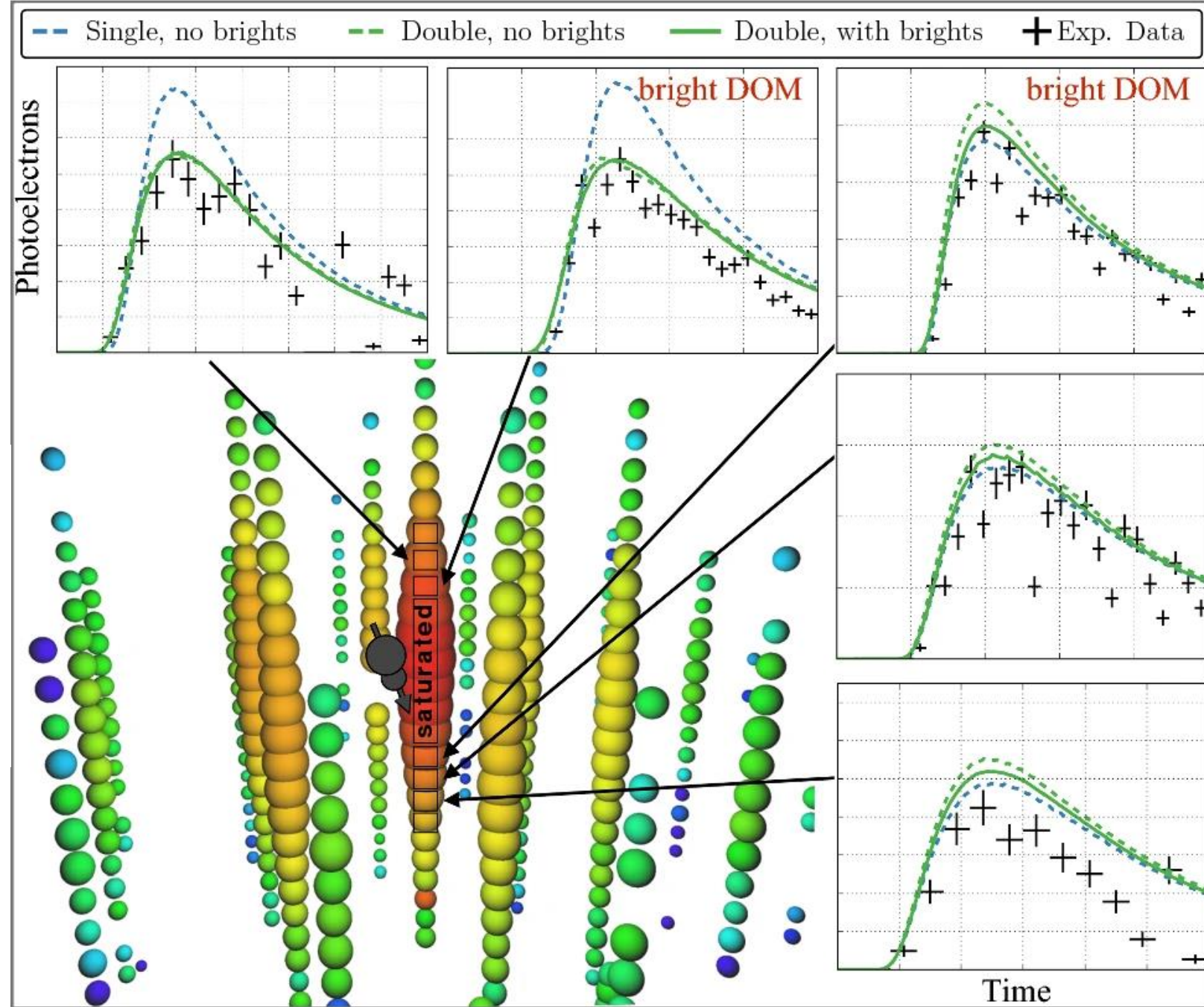


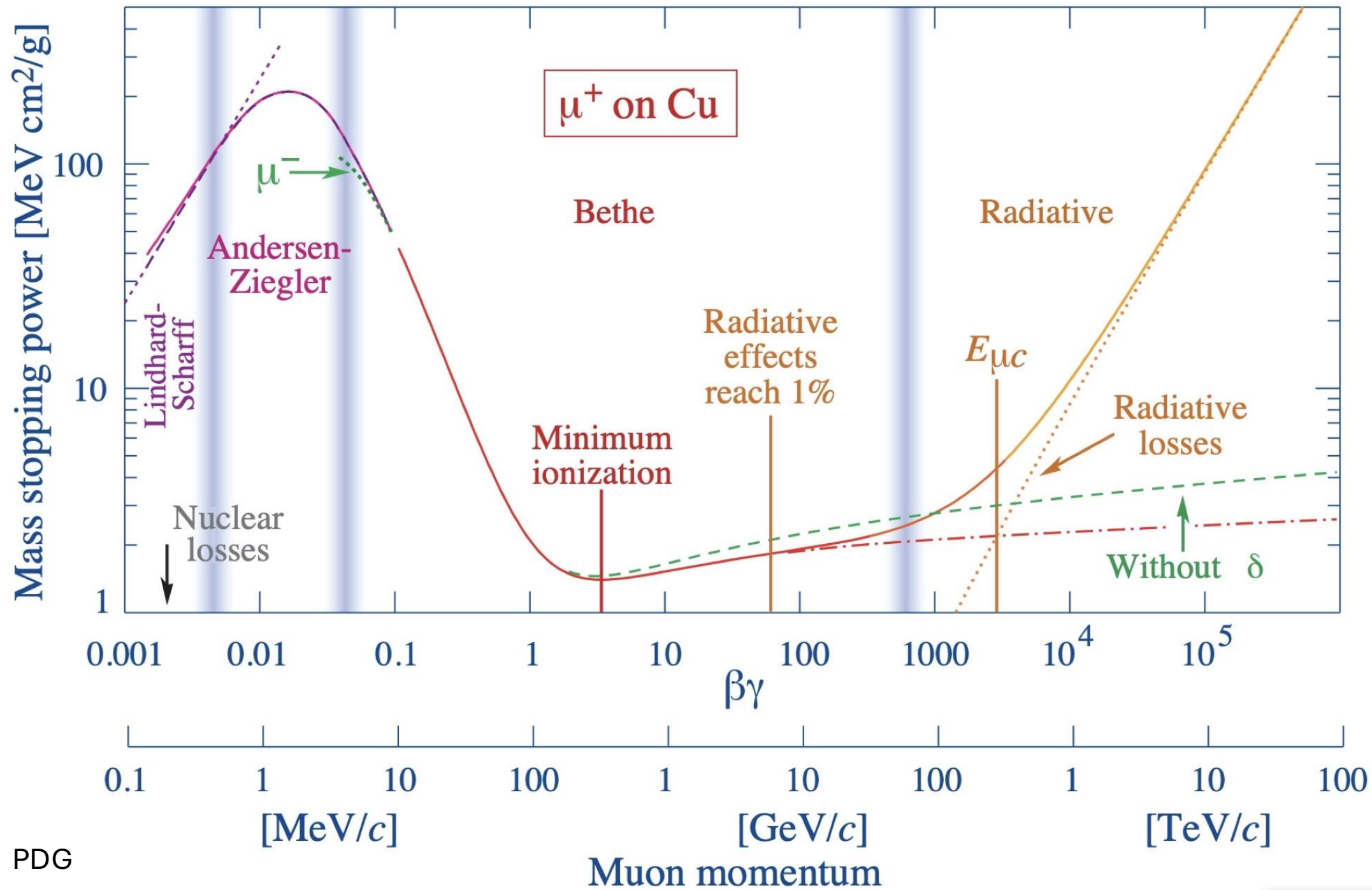
Reconstructing showers

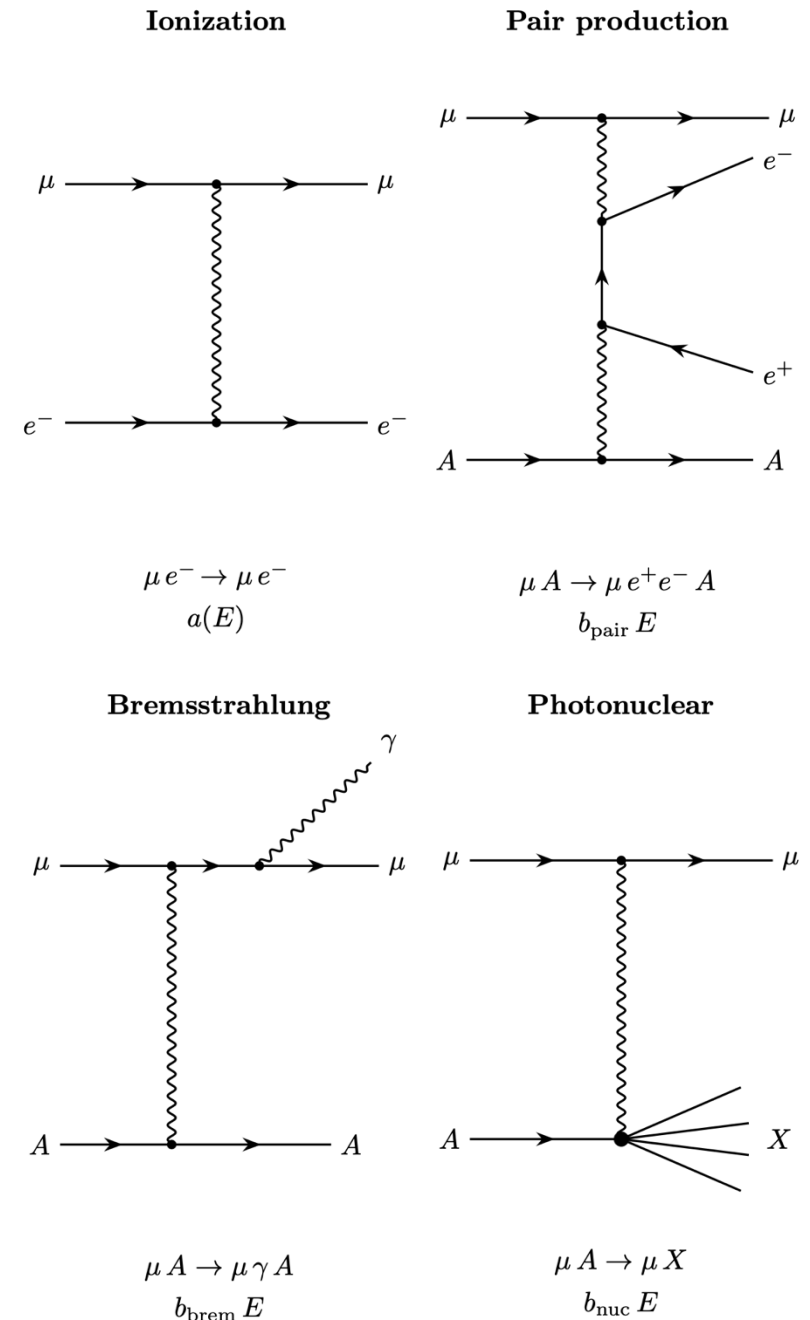
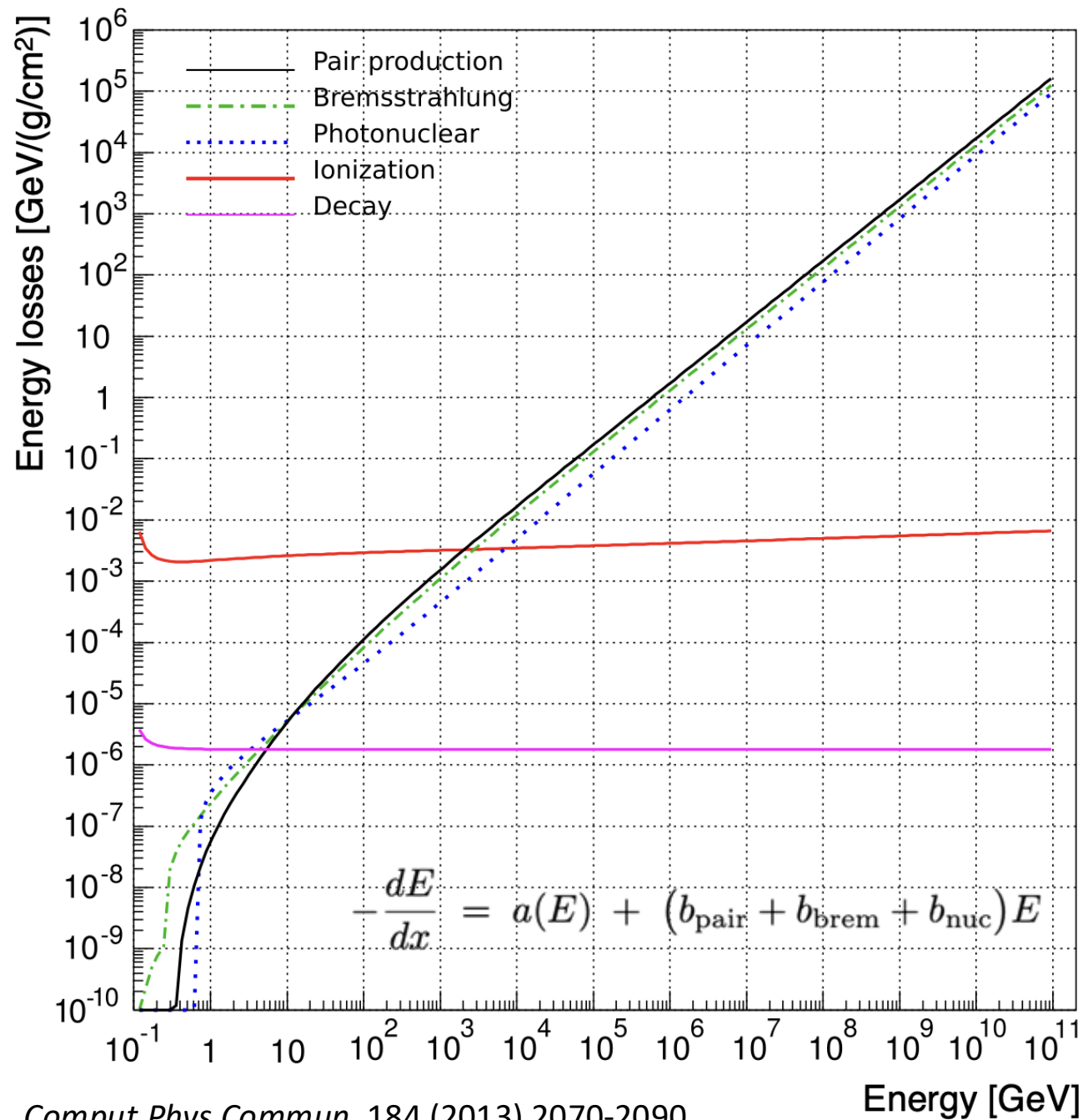
- Poisson likelihood

$$\mathcal{L} = \prod_{\text{DOMs}} P(\text{waveform}_i \mid \theta)$$

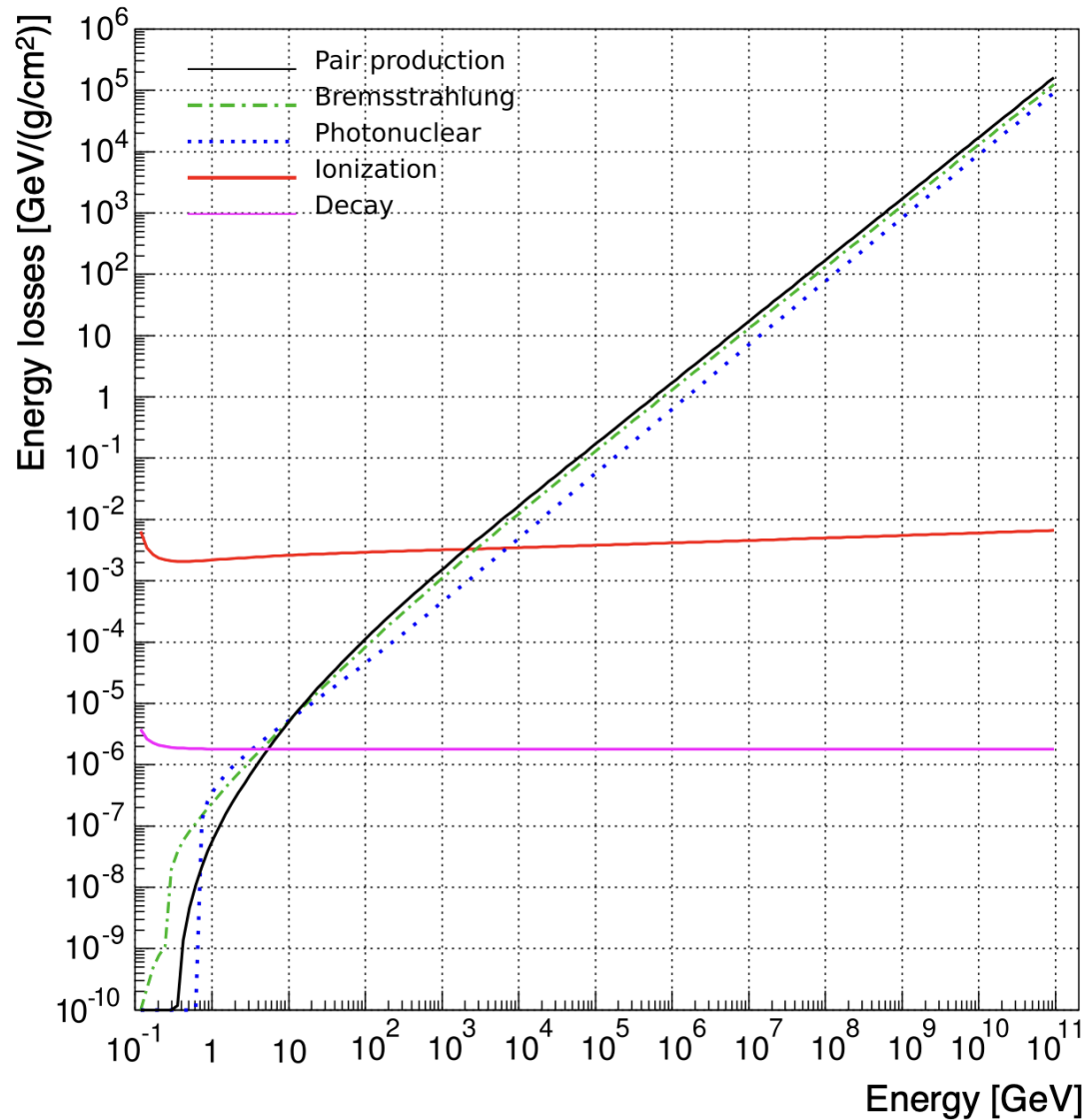
$$\theta = \{x, y, z, t, E, \vec{n}\}$$



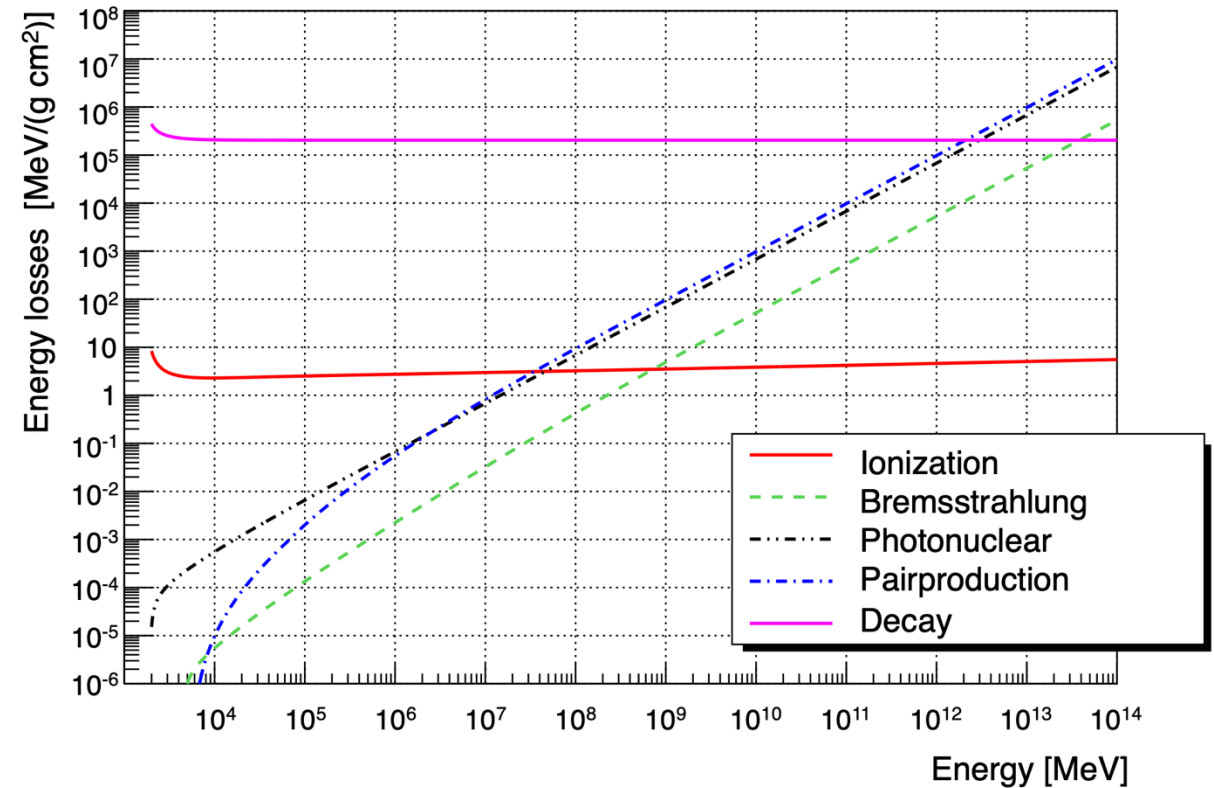


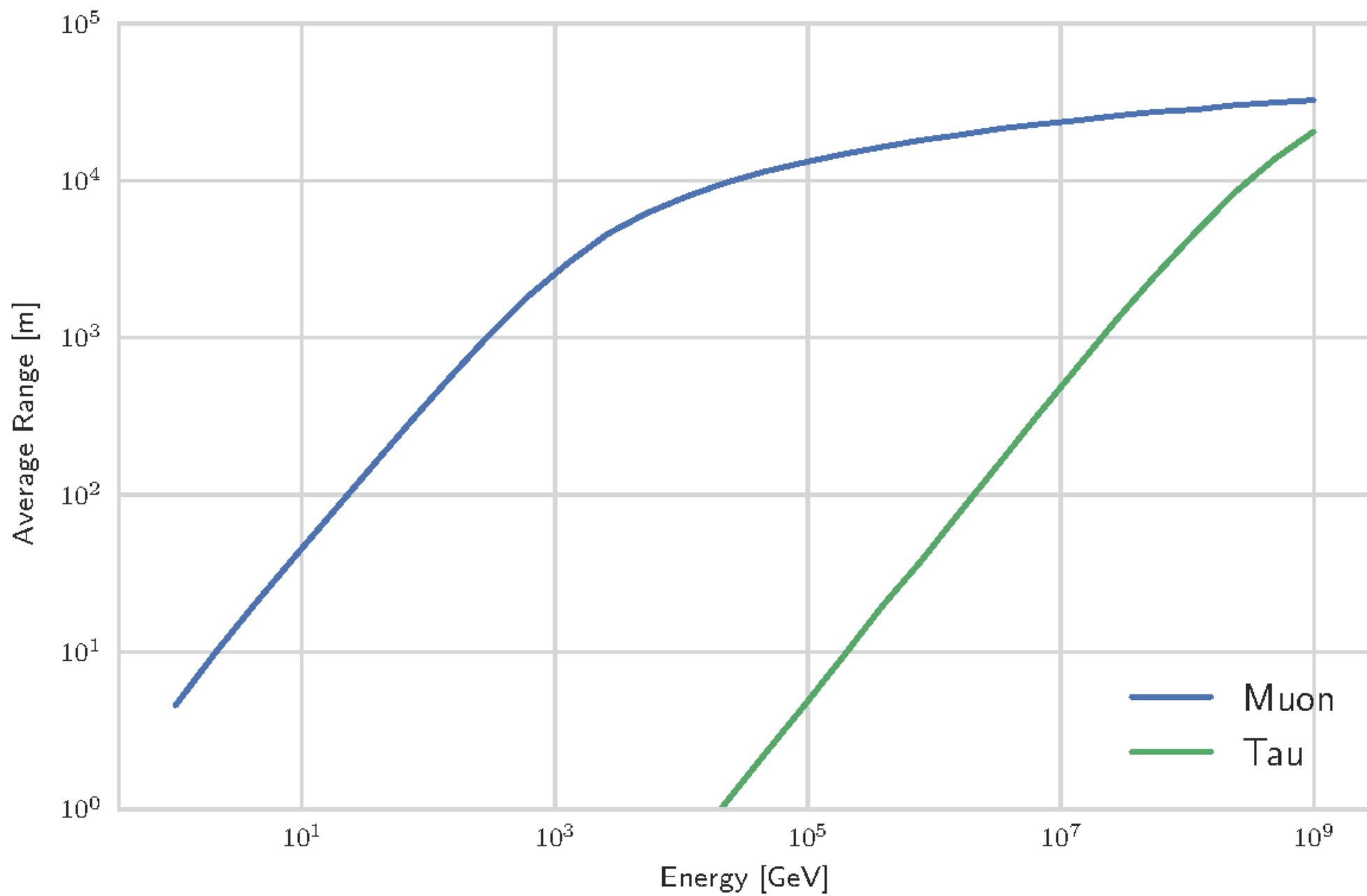


Mu vs tau



Muons interact, taus decay



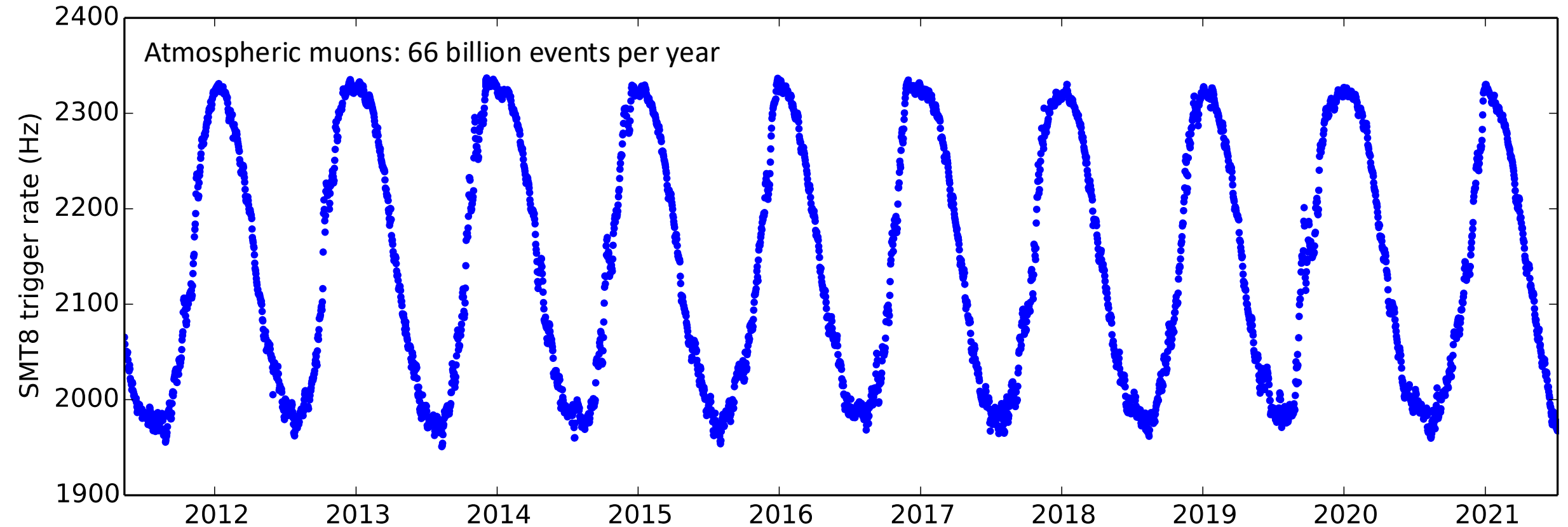




Background and signals

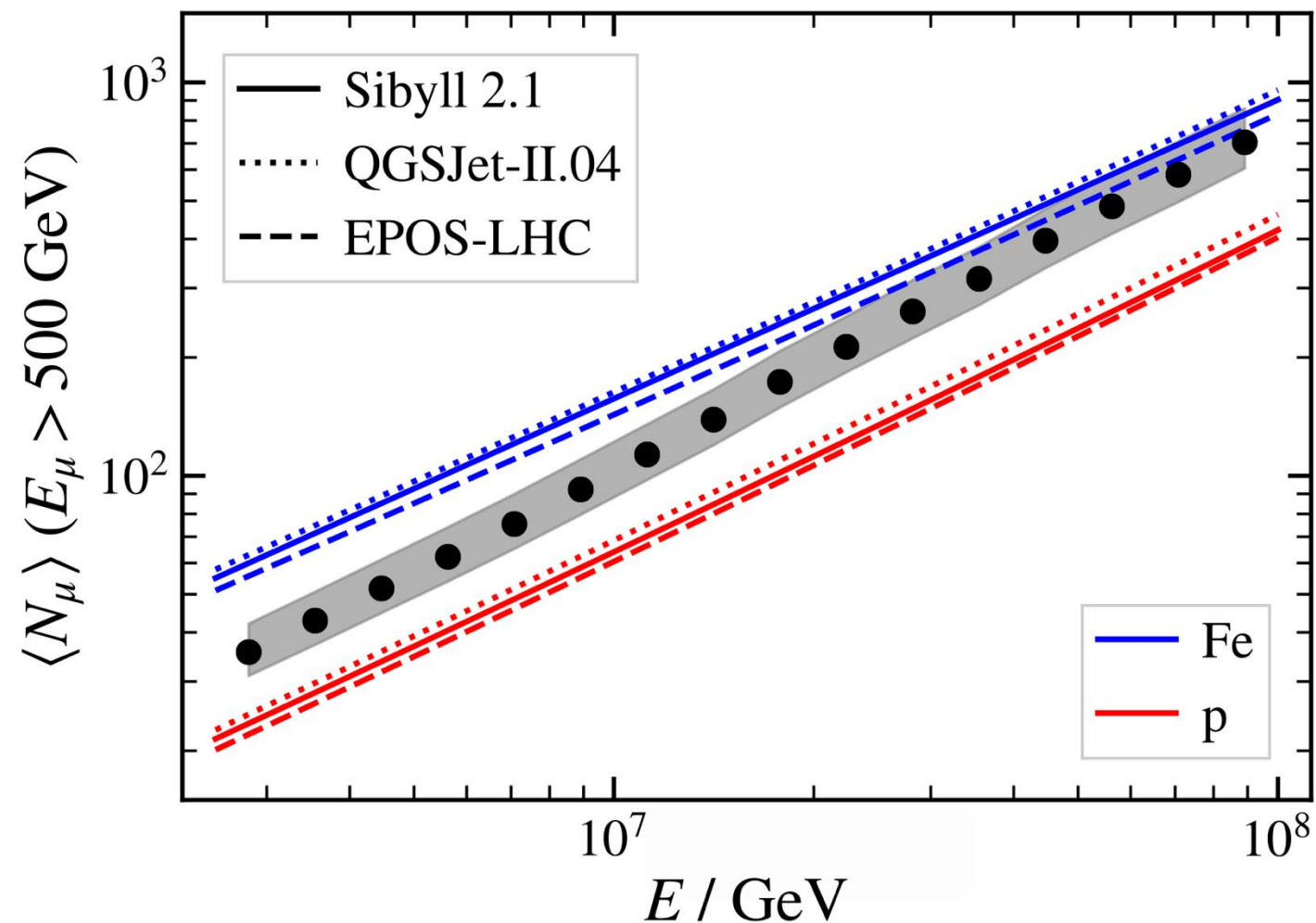
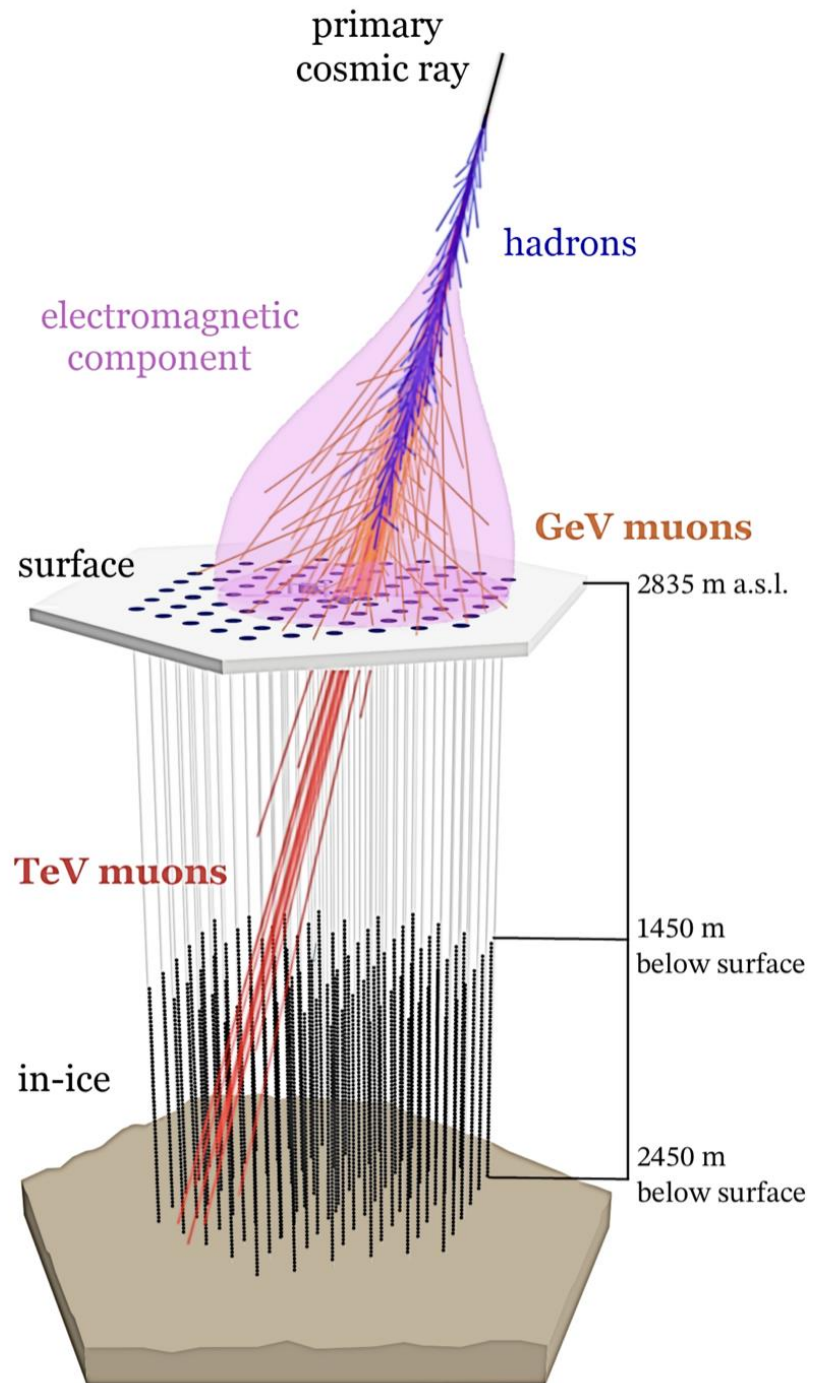
Over a decade of full-detector data taking

- Detector uptime > 99%, 98.5% of all DOMs still taking data



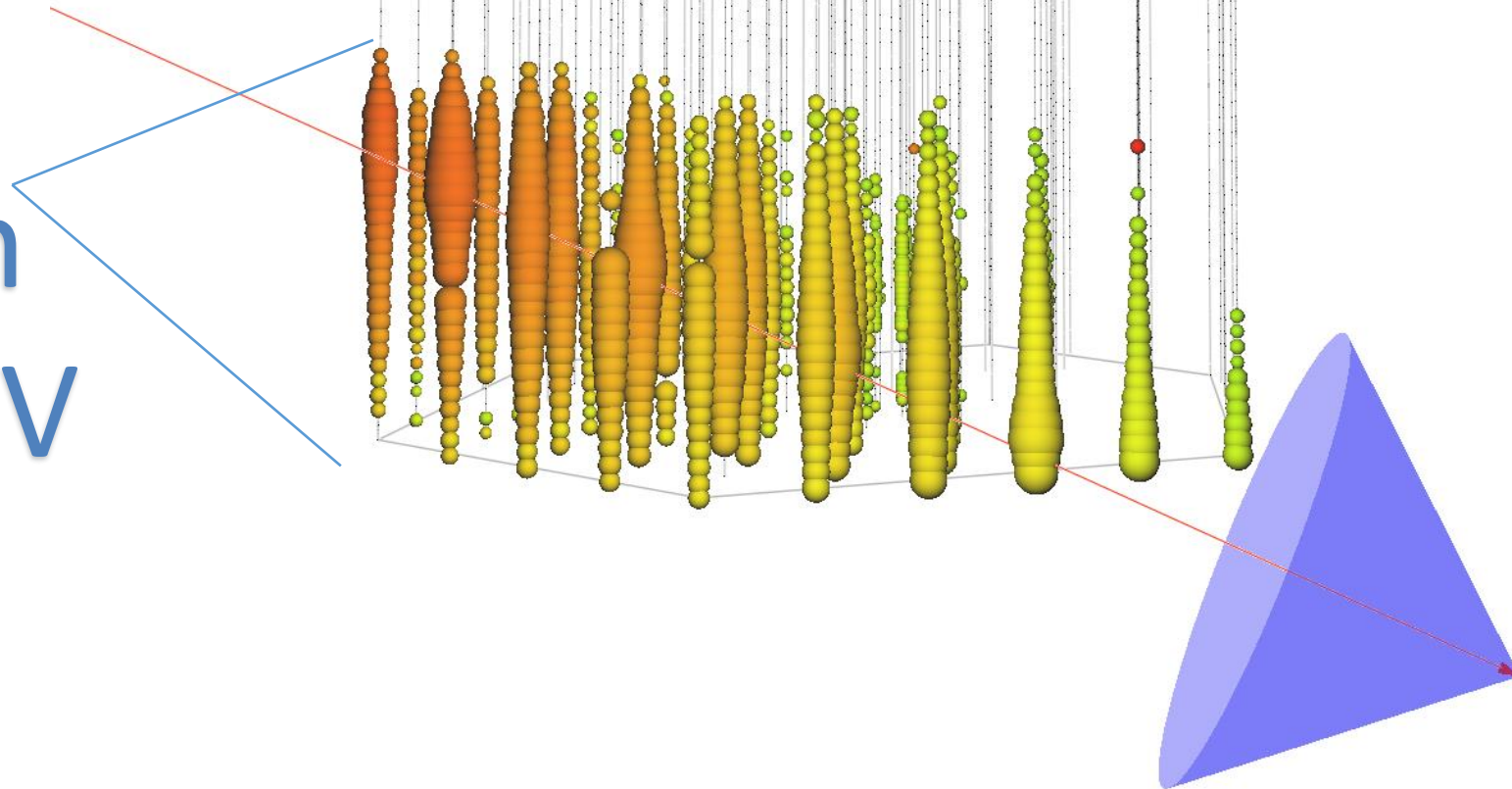
Cosmic-ray muon background

Phys. Rev. D 112, 082004 (2025)



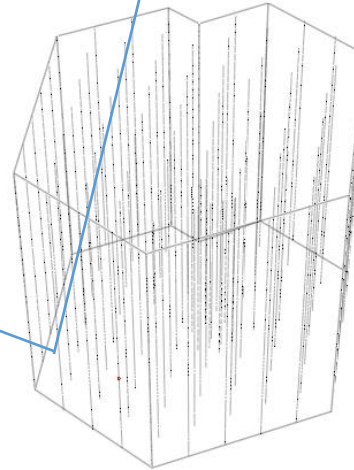
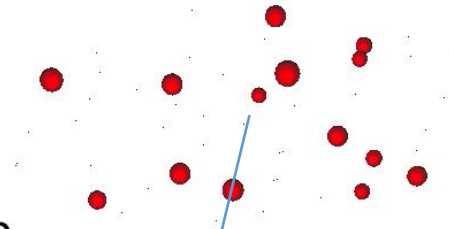
Event 140348/20002811-2
Time 2025-01-12 17:02:32 UTC
Duration 28122.0 ns

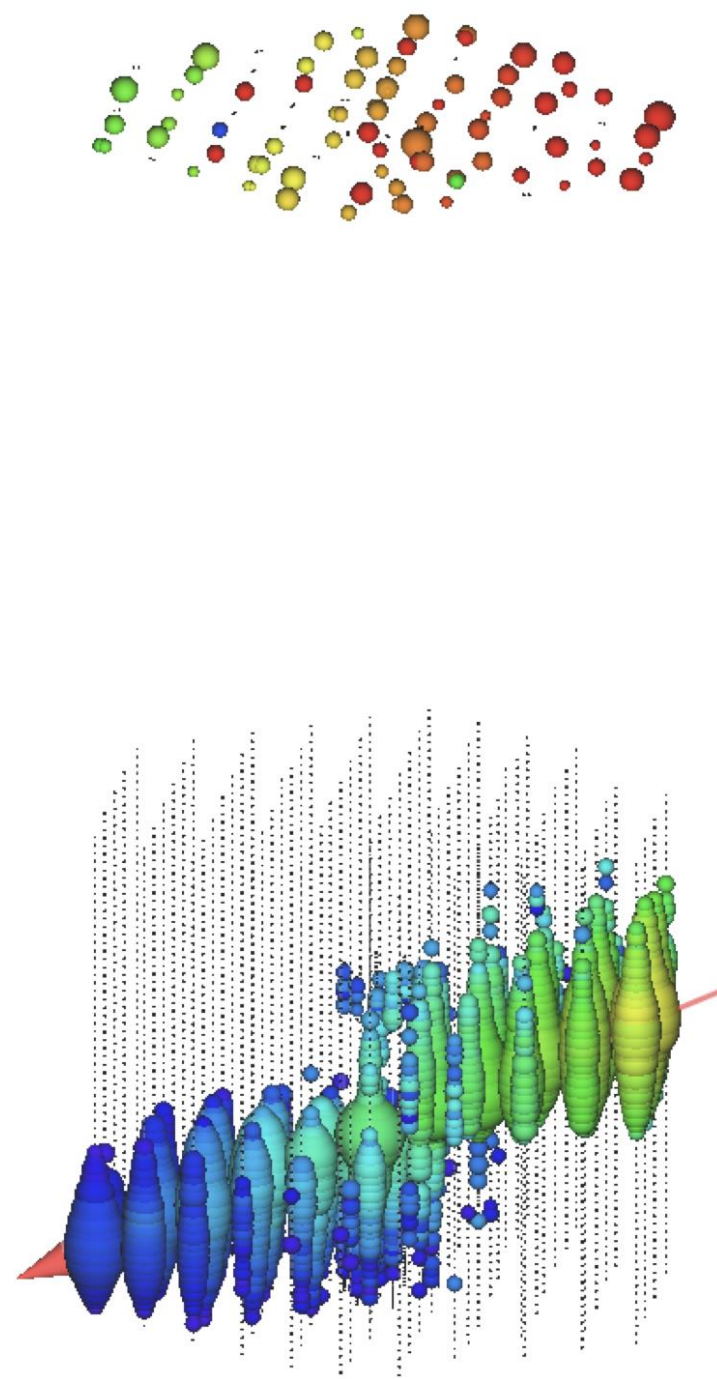
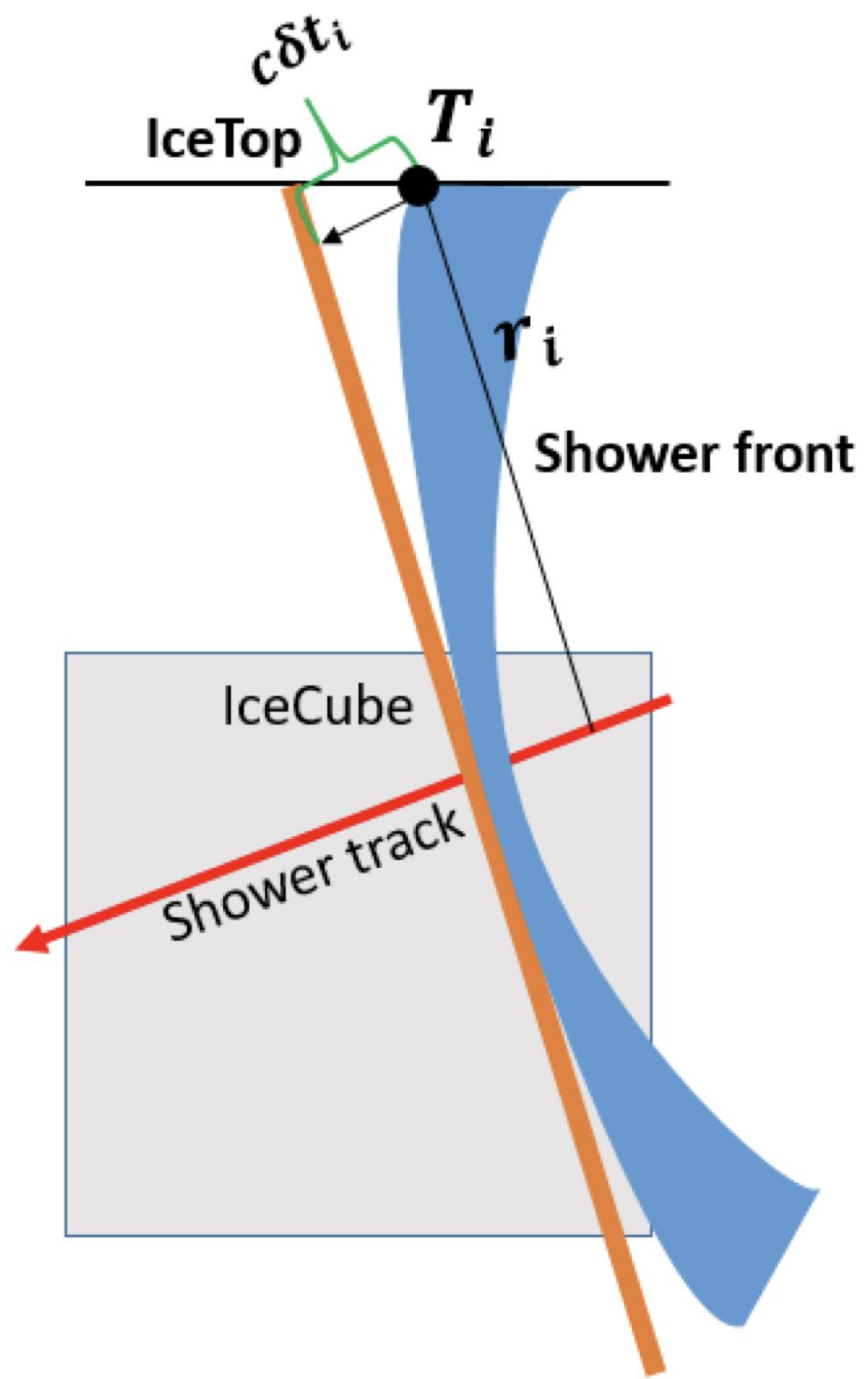
500 m
~35 PeV

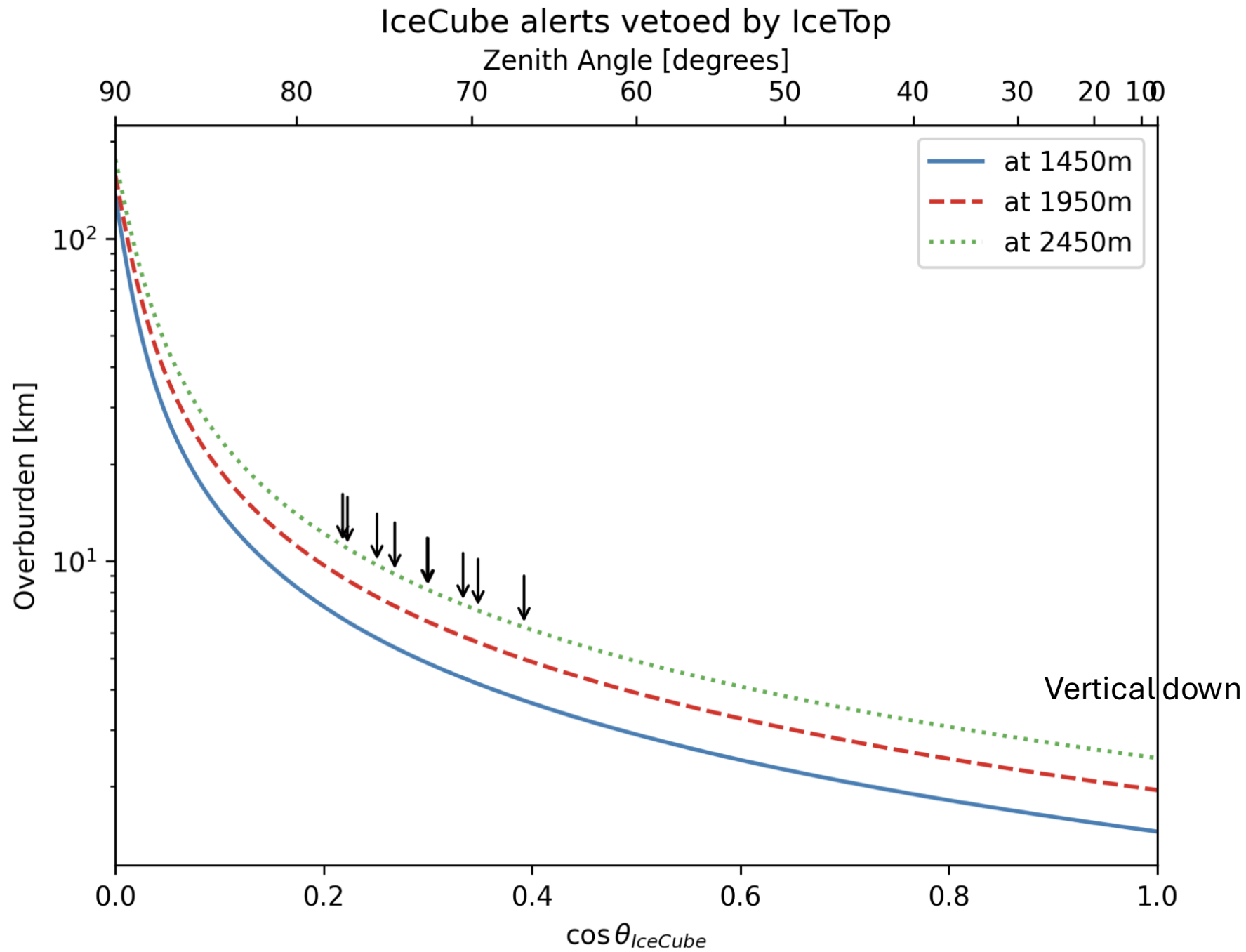


Event 140348/20002811-2
Time 2025-01-12 17:02:32 UTC
Duration 28122.0 ns

>3000 m



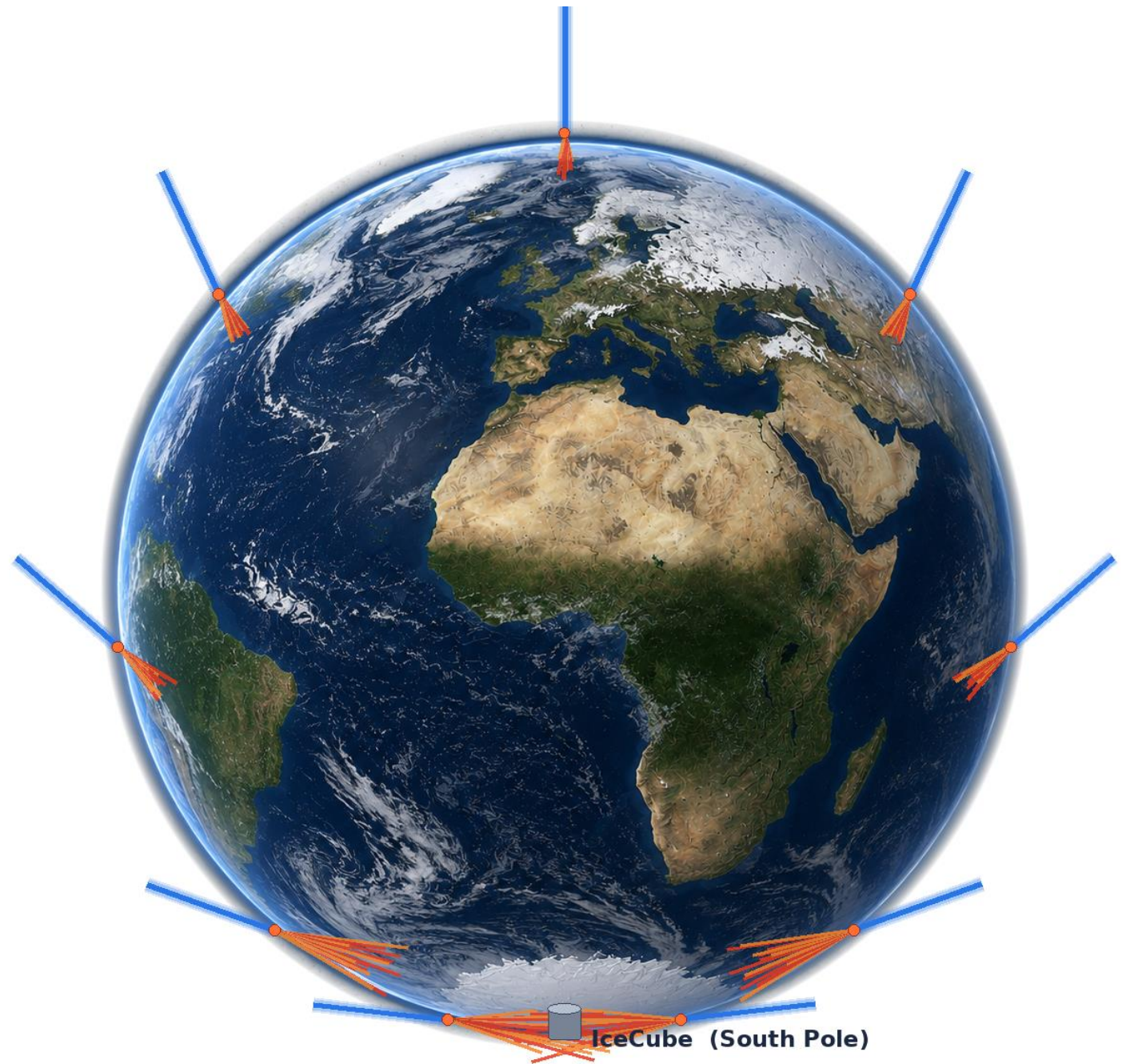


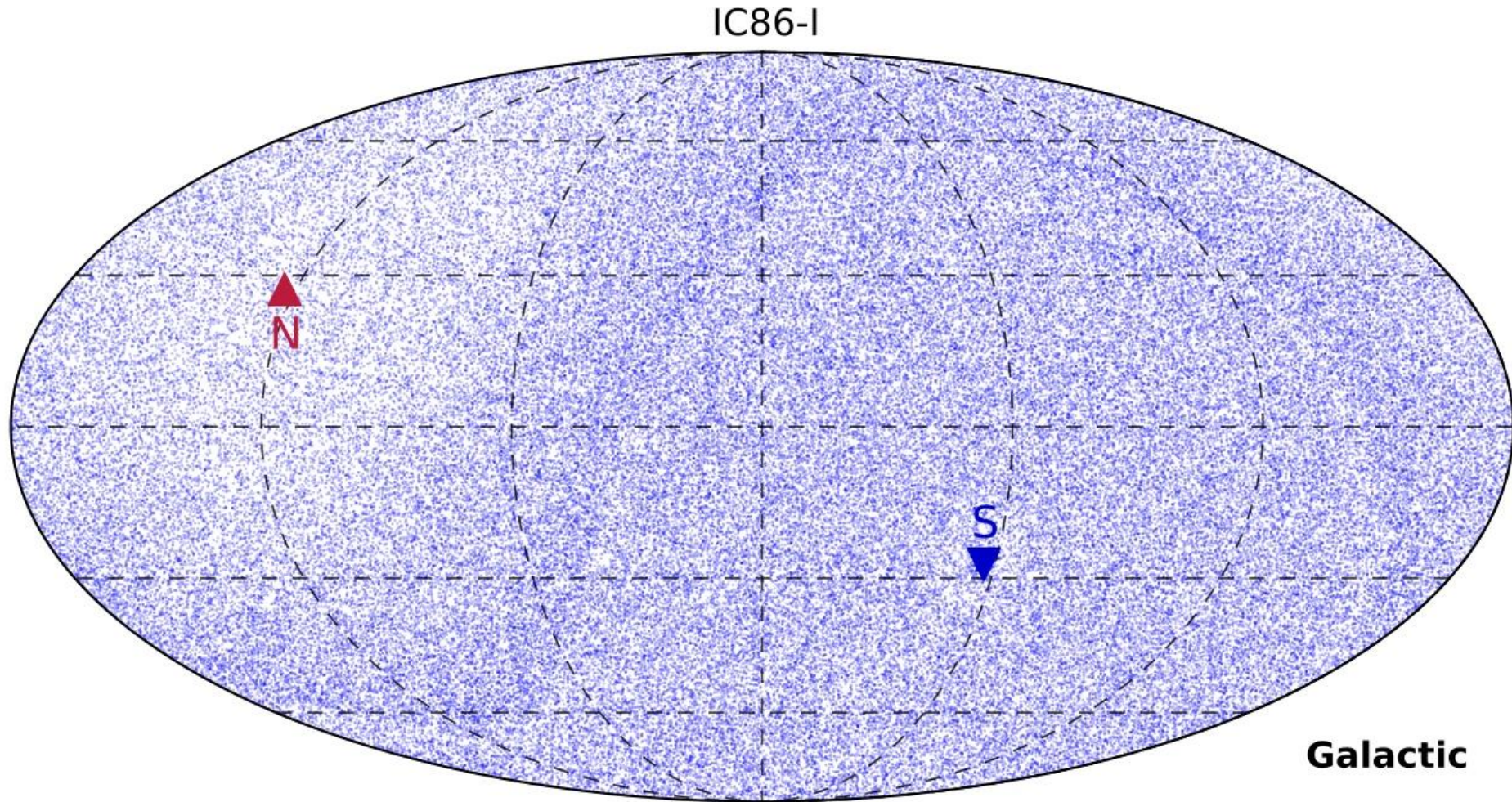


Cosmic-ray neutrino background

Use Earth as a shield to
selection neutrinos

For muons >99%
neutrino pure





138322 neutrino candidates in one year
>120 cosmic neutrinos (depending on the spectrum)
~12 separated from atmospheric background with $E > 60$ TeV

Neutrinos from north

>1TeV

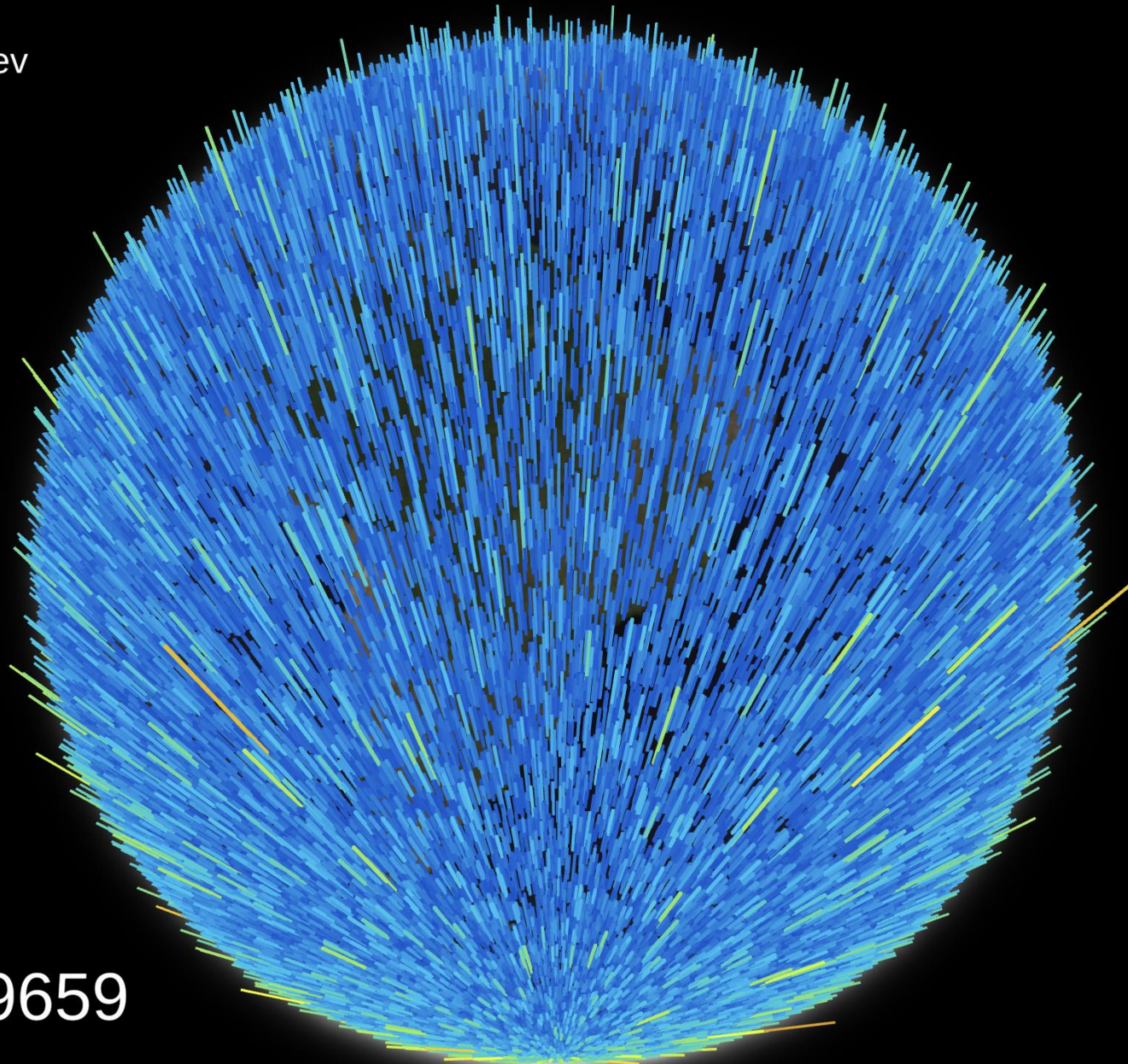
>10TeV

>100TeV

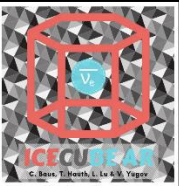
NGC1068

https://user-web.icecube.wisc.edu/~lulu/globe_AR/webcity/ngc1068/

21.1752 -167.9659



FPS:55



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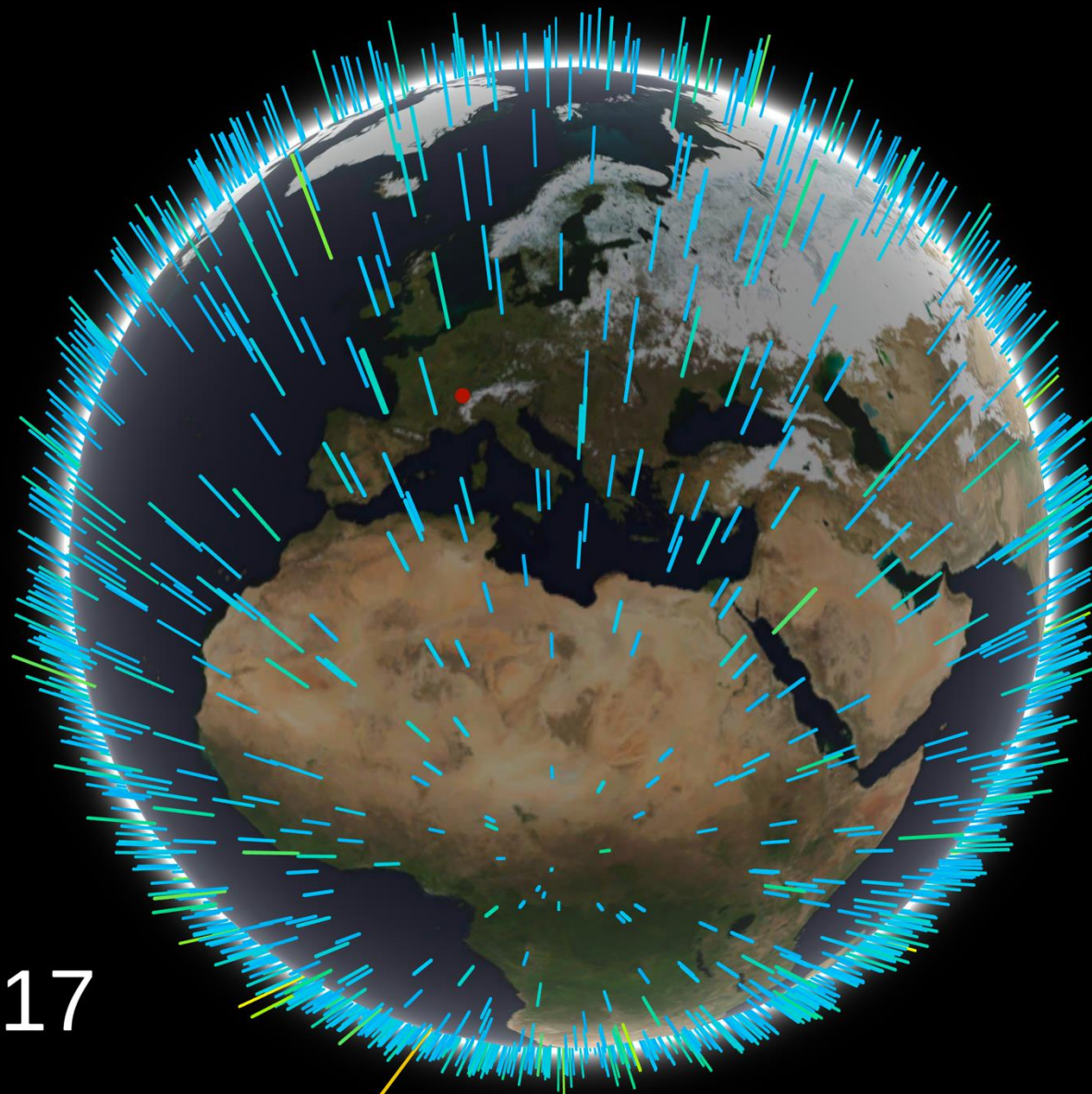
By: Lu Lu, Yugov Seva

Origins of icecube neutrinos?

FPS:60



Geneva,
Switzerland



>1Tev

>10Tev

>100Tev

NGC1068

https://user-web.icecube.wisc.edu/~lulu/globe_AR/webcity/ngc1068/

46.4771 6.2017

By: Lu Lu, Yugov Seva

Earth absorption

FPS:60



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>1TeV

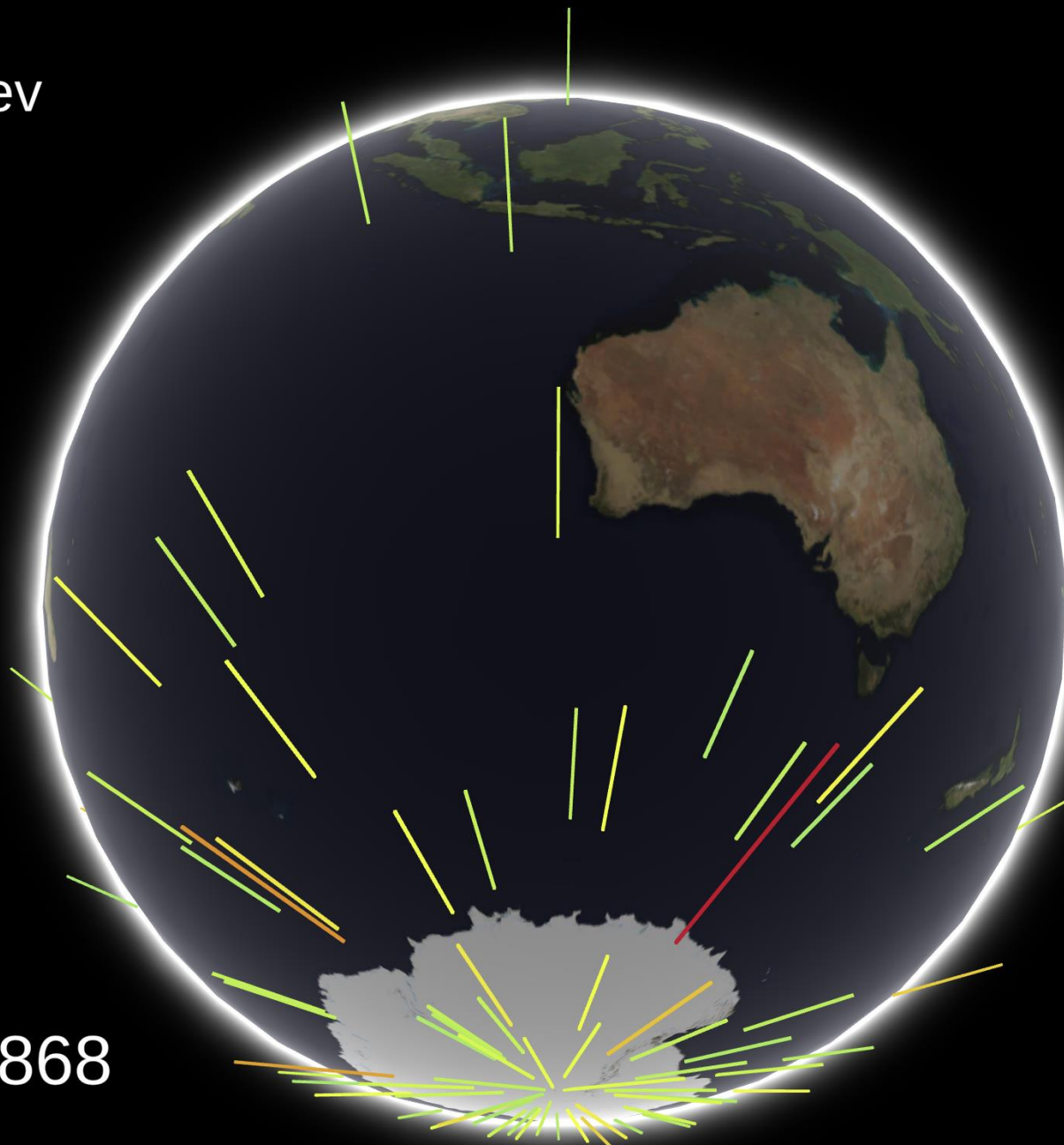
>10TeV

>100TeV

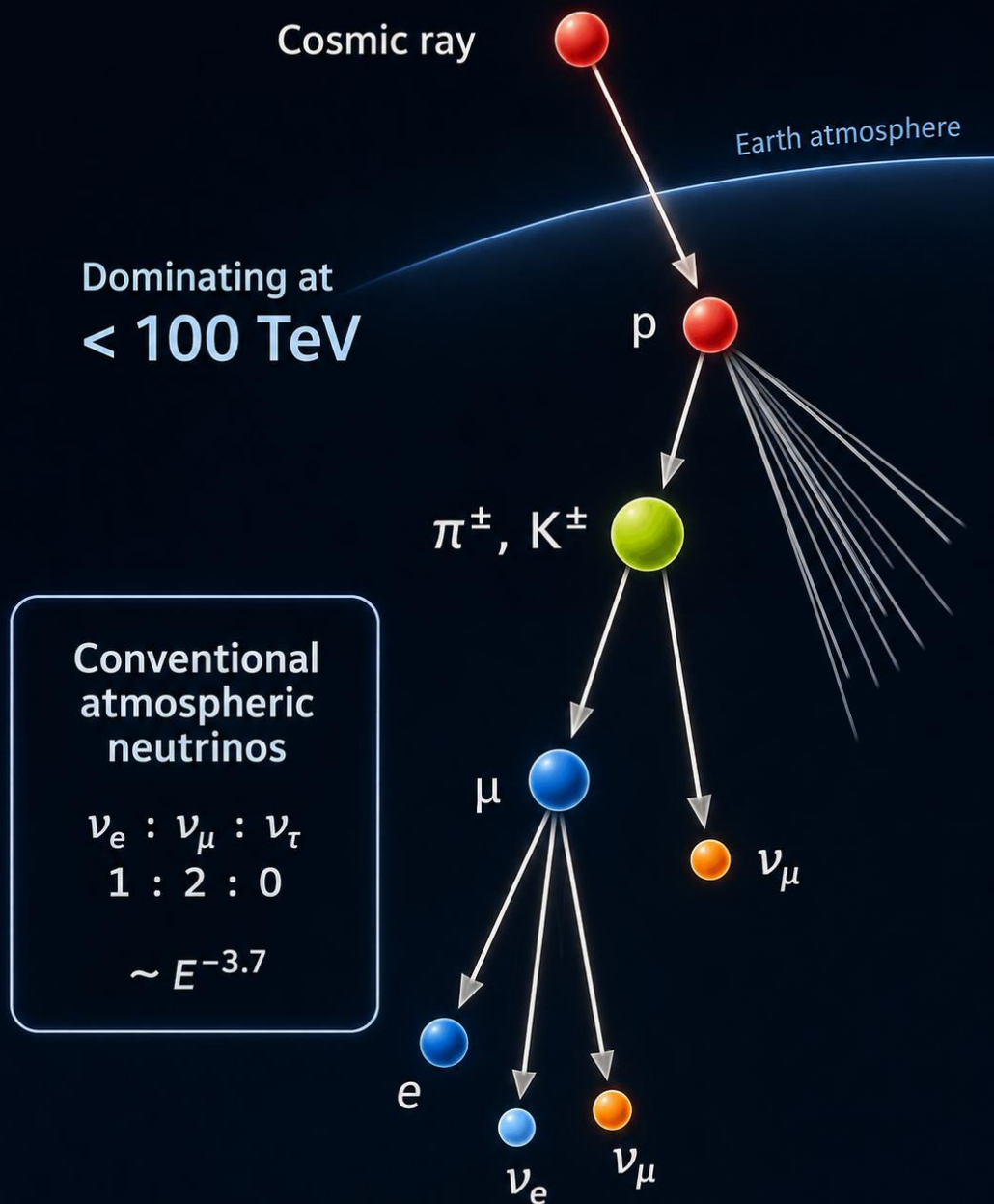
NGC1068

https://user-web.icecube.wisc.edu/~lulu/globe_AR/webcity/ngc1068/

-37.5022 155.8868



By: Lu Lu, Yugov Seva



Conventional ν_μ

dominant charged-meson chain

Conventional ν_e at low energy

from the daughter muon

Conventional ν_e at high energy

semileptonic kaon decays

Rare high-energy conventional

short-lived kaon contribution

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$$

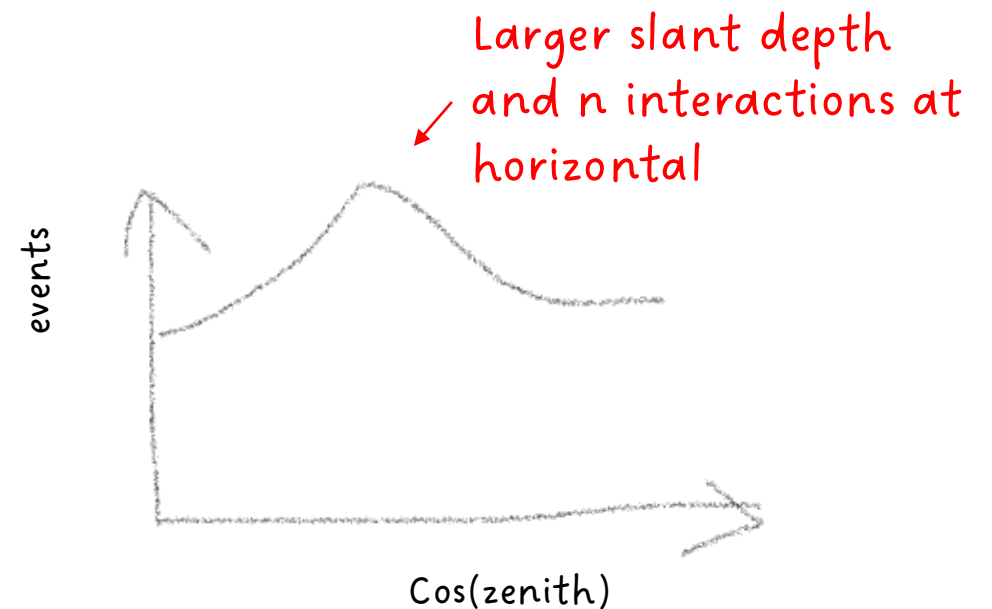
$$K^\pm \rightarrow \mu^\pm + \nu_\mu$$

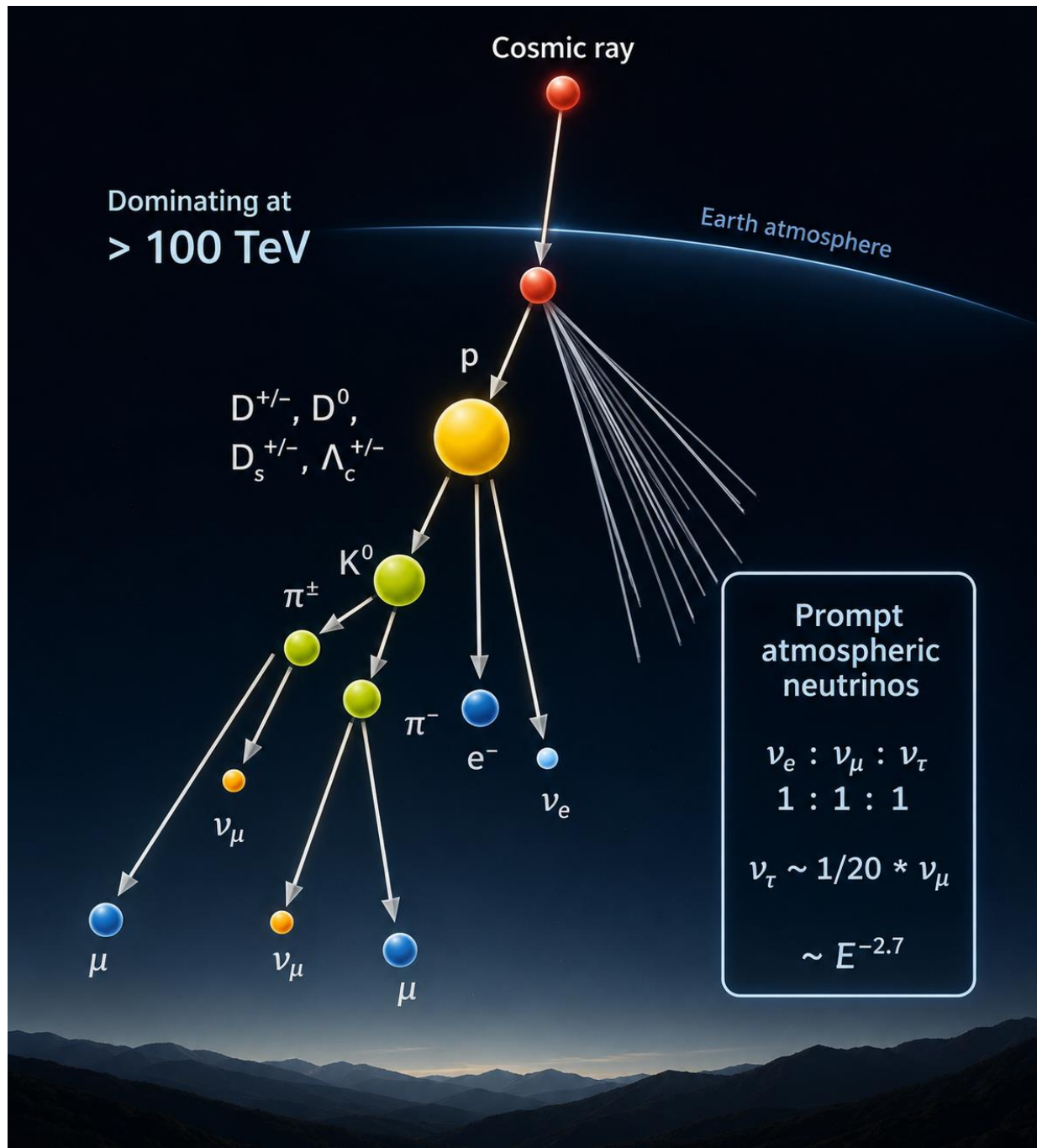
$$\pi/K \rightarrow \mu \rightarrow e + \nu_e + \nu_\mu$$

$$K^\pm \rightarrow \pi^0 + e^\pm + \nu_e$$

$$K_L^0 \rightarrow \pi + e + \nu_e$$

$$K_S^0 \rightarrow \pi + e + \nu_e$$



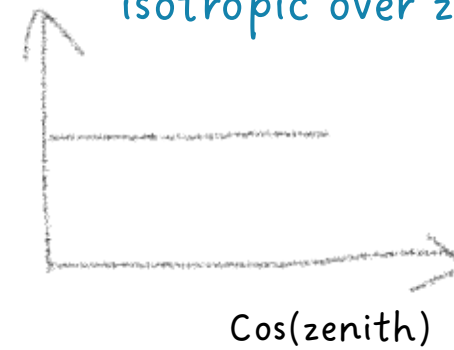


Prompt

charm and other very short-lived parents

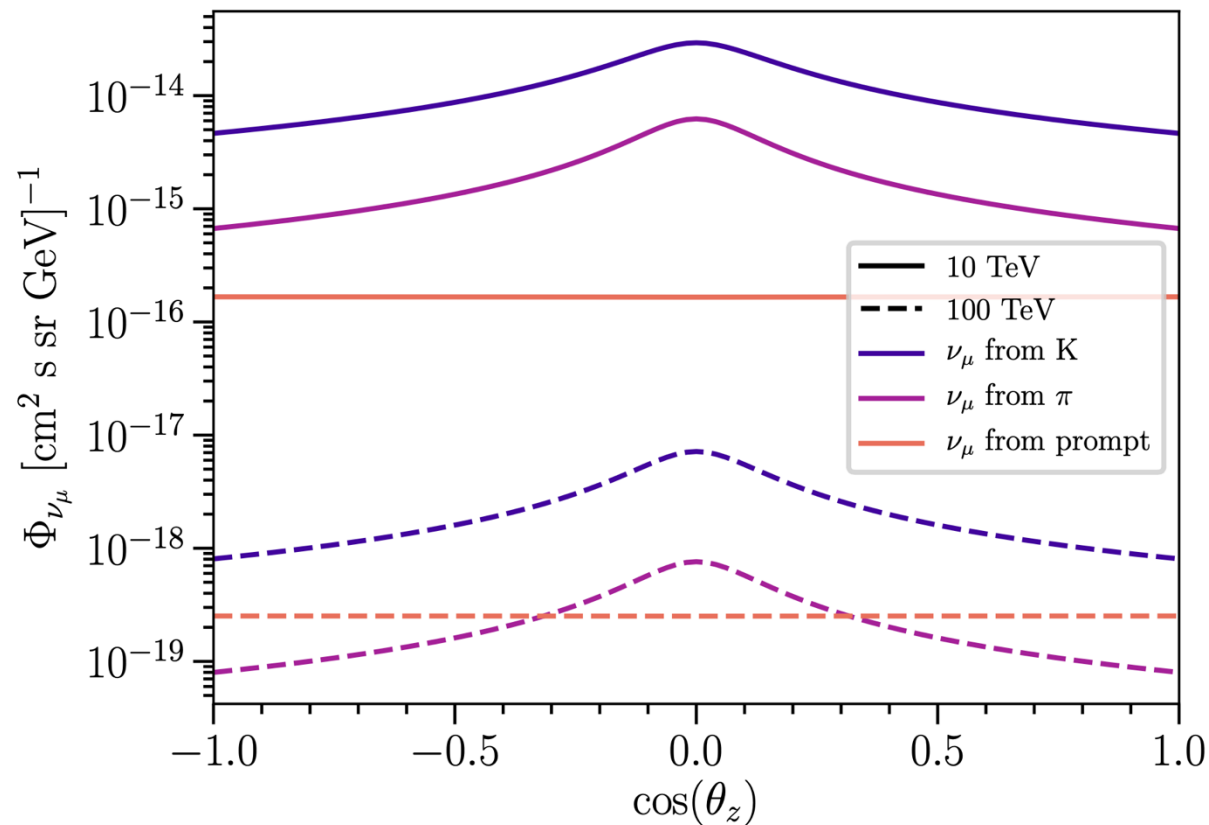
$$D, \Lambda_c, \dots \rightarrow \ell + \nu + X$$

Decays before interaction
isotropic over zenith



!! Same with Astrophysical

ATMOSPHERIC NEUTRINO FLUX DEPEND ON ZENITH ANGLE

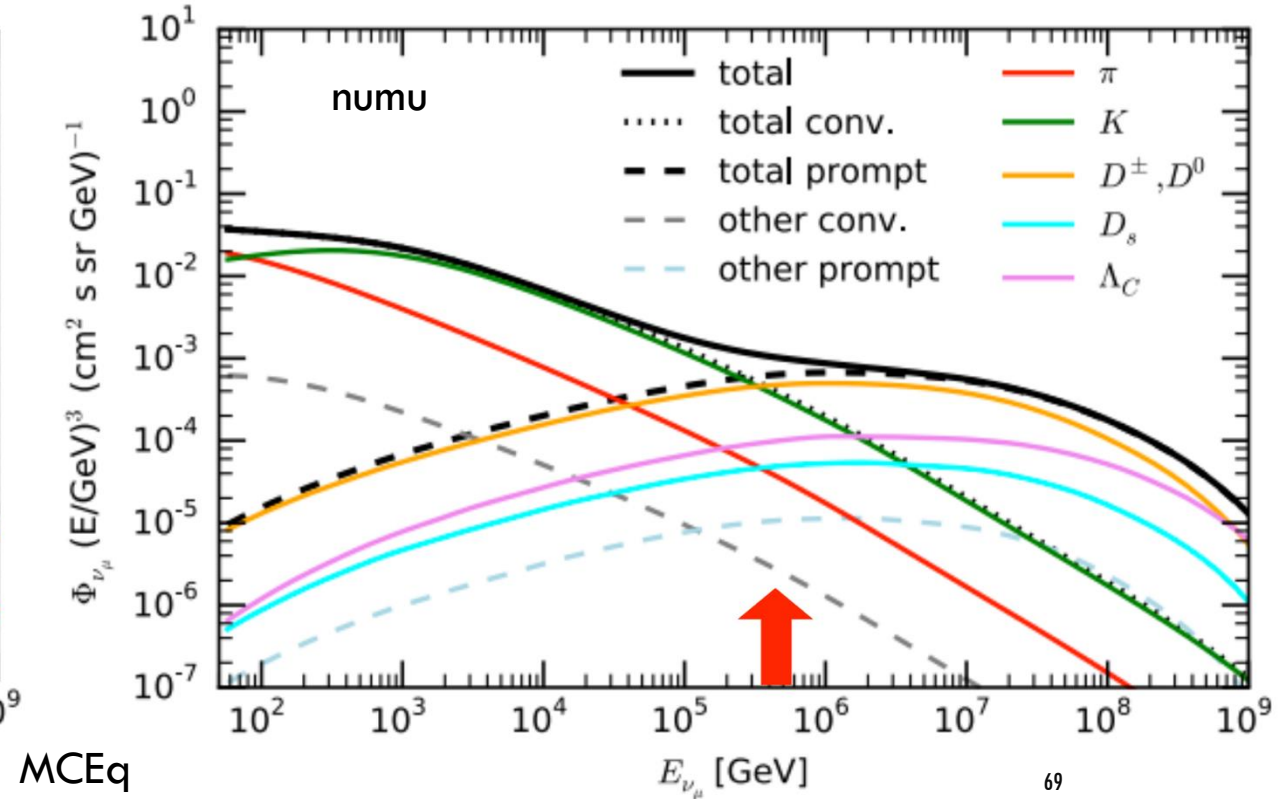
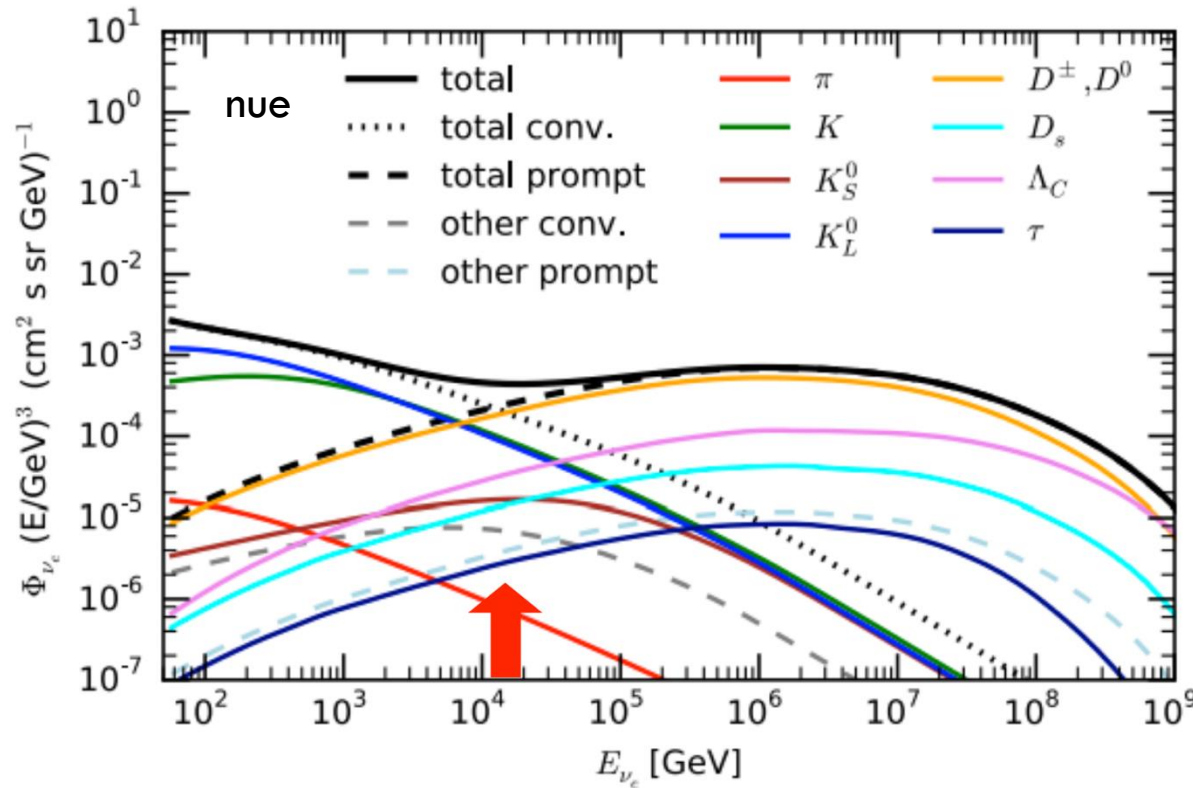


- prompt is isotropic over zenith
- degenerate from extragalactic diffuse flux (signal)
- conventional peaks at horizon
- ν_μ production dominated by kaon decay

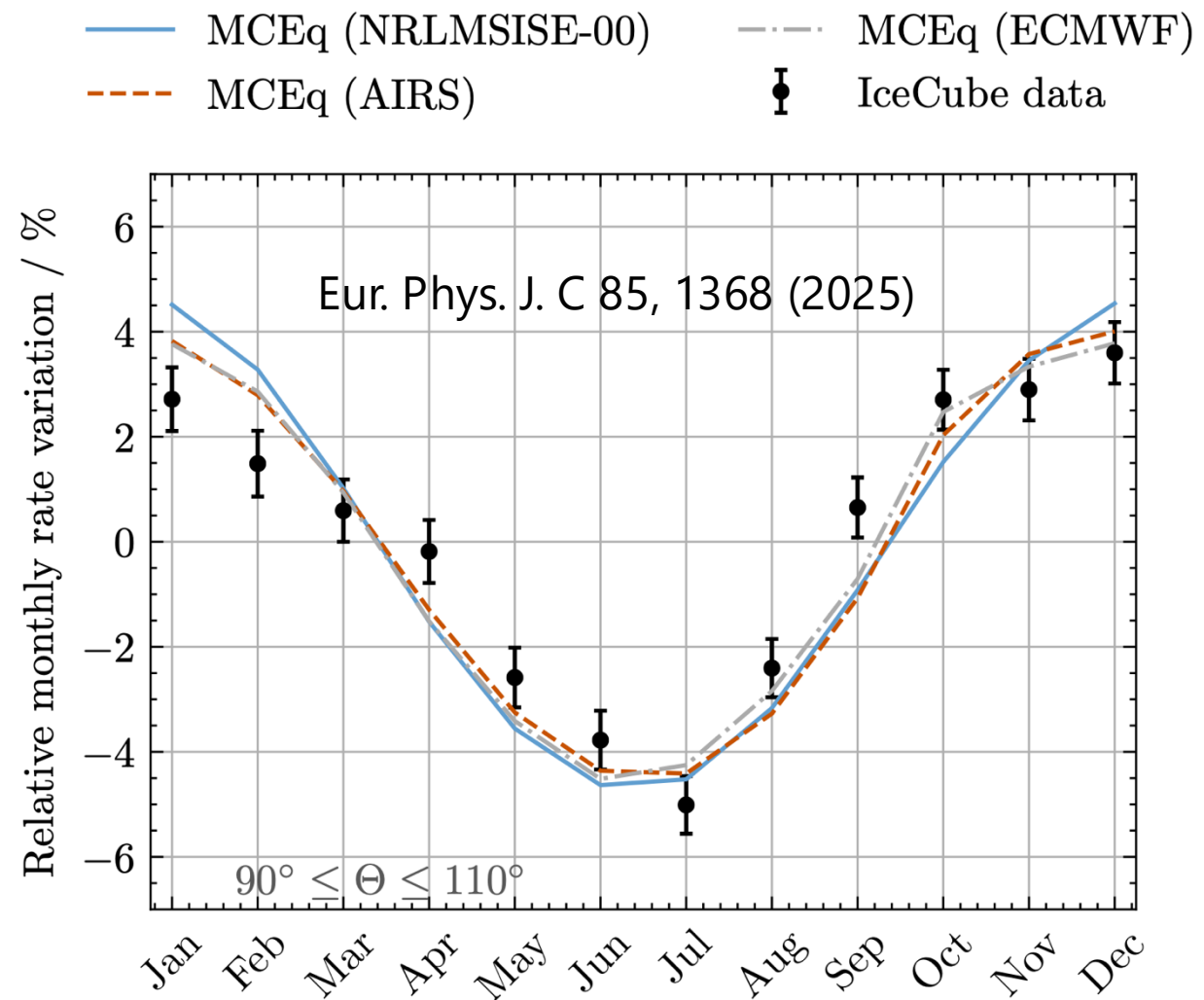
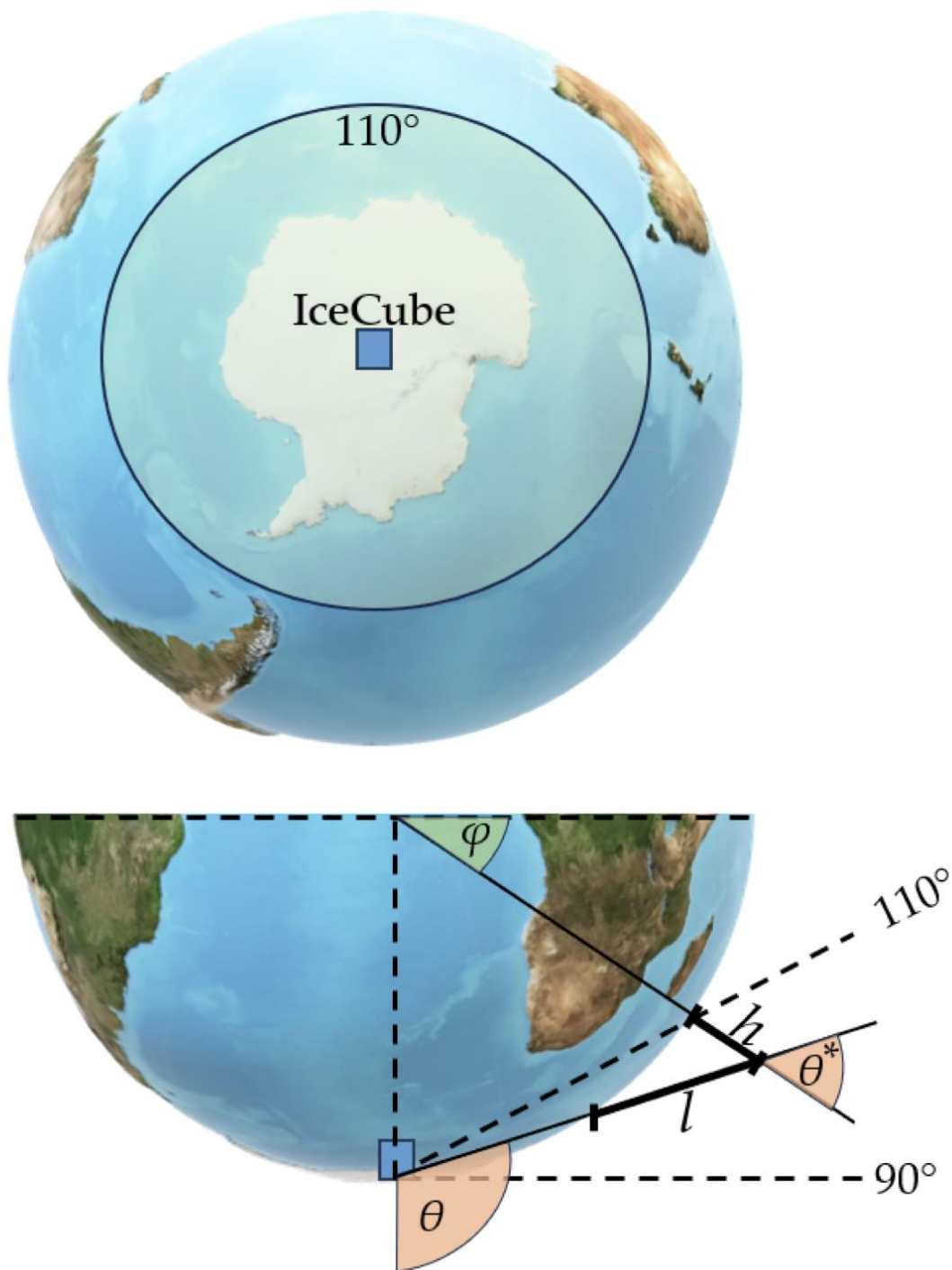
ATMOSPHERIC NEUTRINO FLUX DEPEND ON ENERGY AND FLAVOUR

Nue: prompt overtakes conventional at ~20 TeV

Numu: prompt overtakes conventional at ~200 TeV

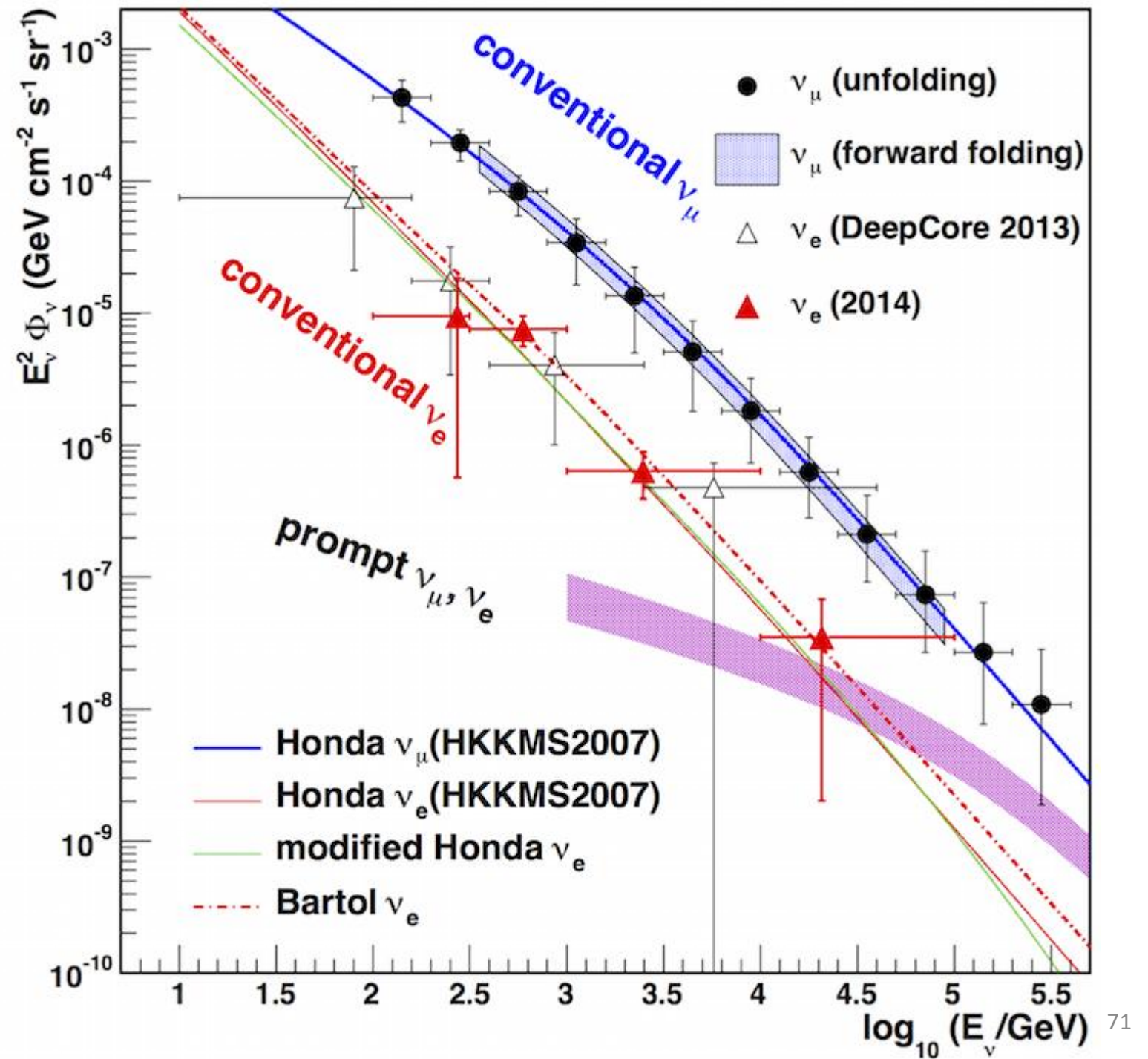


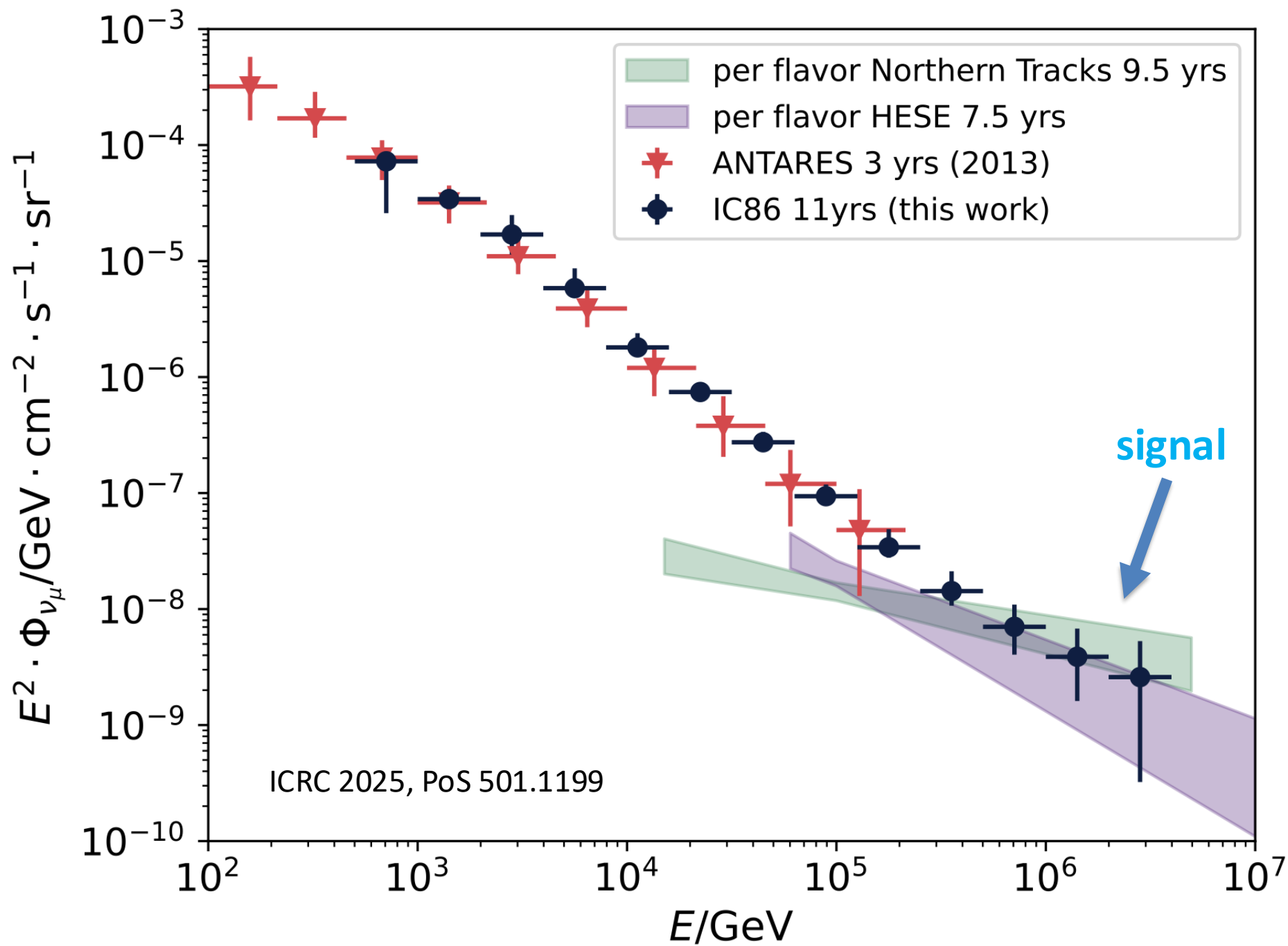
Atmospheric neutrino: seasonal variations



Atmospheric neutrino unfolding

PRD 91 (2015) 122004



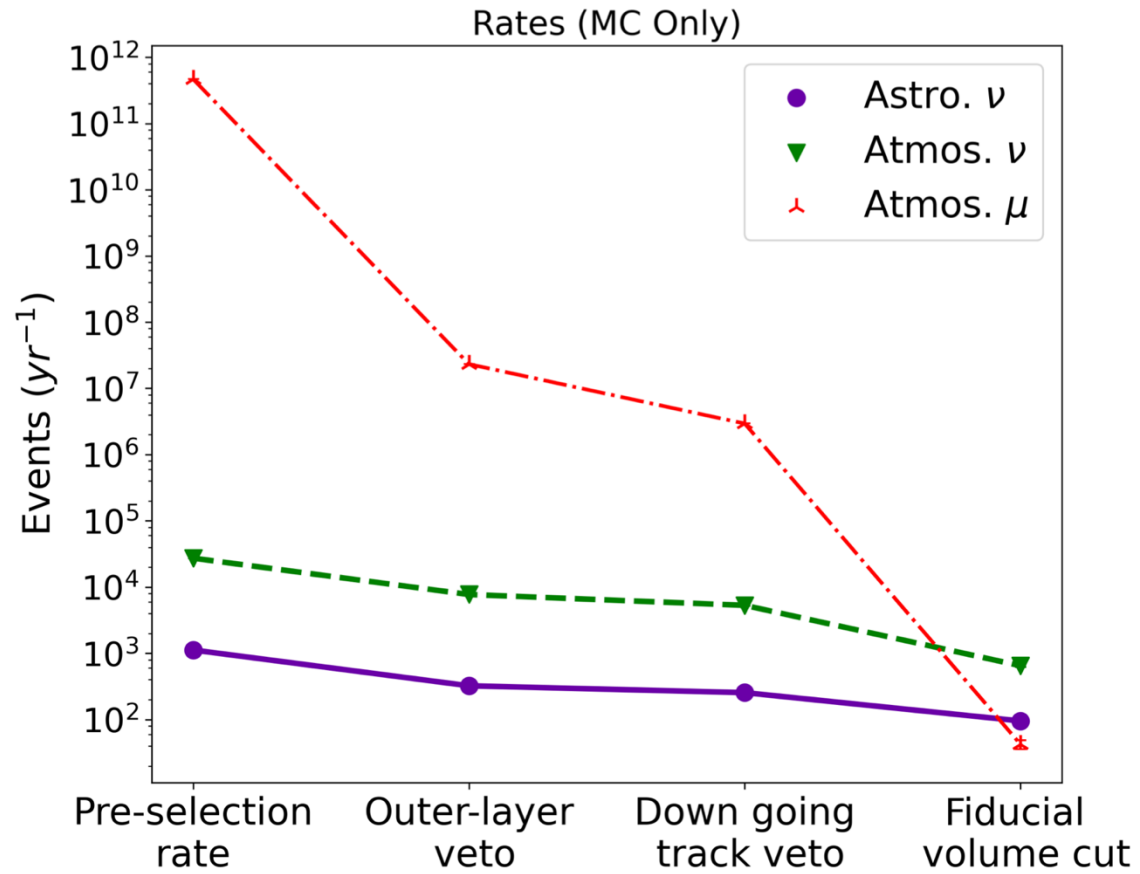


Astrophysical neutrinos?

- Raw atmospheric-muon triggers:
 $\sim 10^{11}$ / yr
- Atmospheric neutrinos:
 $\sim 10^5$ / yr
- Astrophysical neutrinos:
 $\sim 10\text{--}100$ / yr
- Neutrinos with energies > 5 PeV:
3 in 12 yr (data)



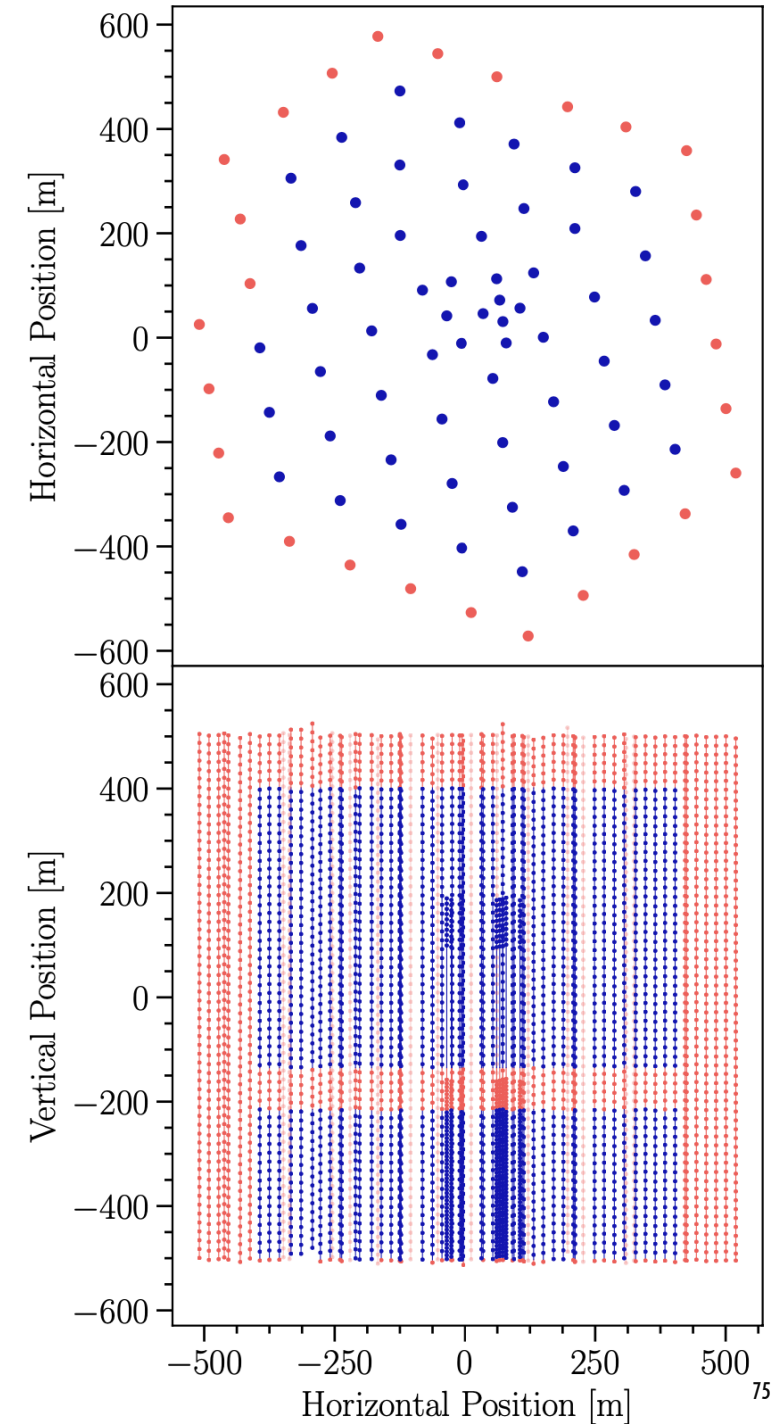
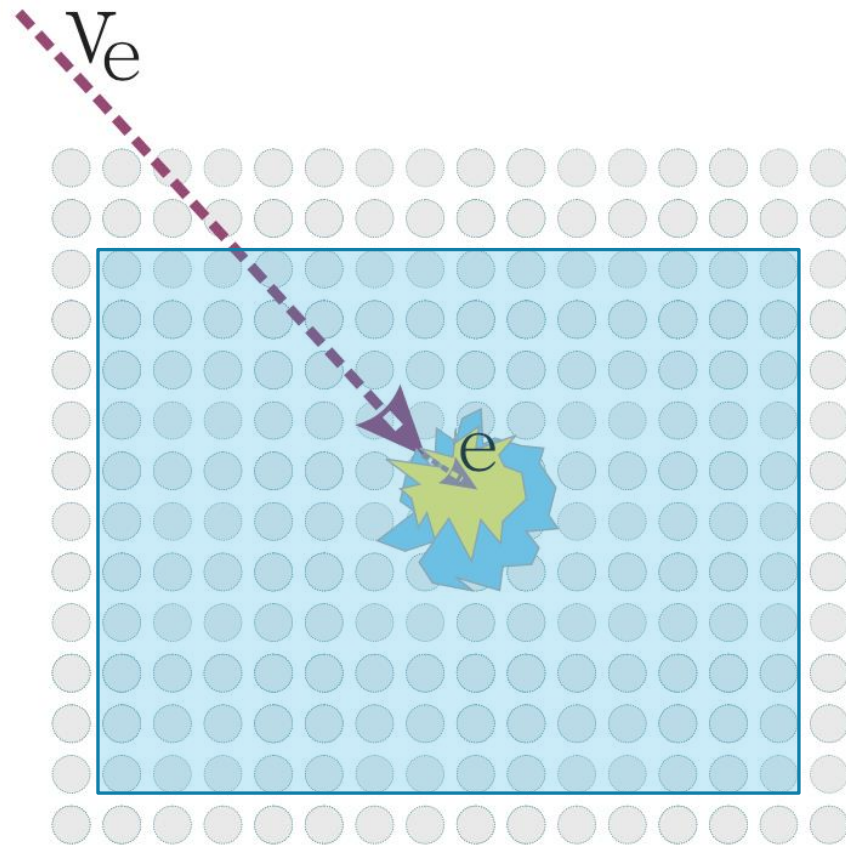
Astrophysical neutrinos?



HIGH ENERGY STARTING EVENTS (HESE)

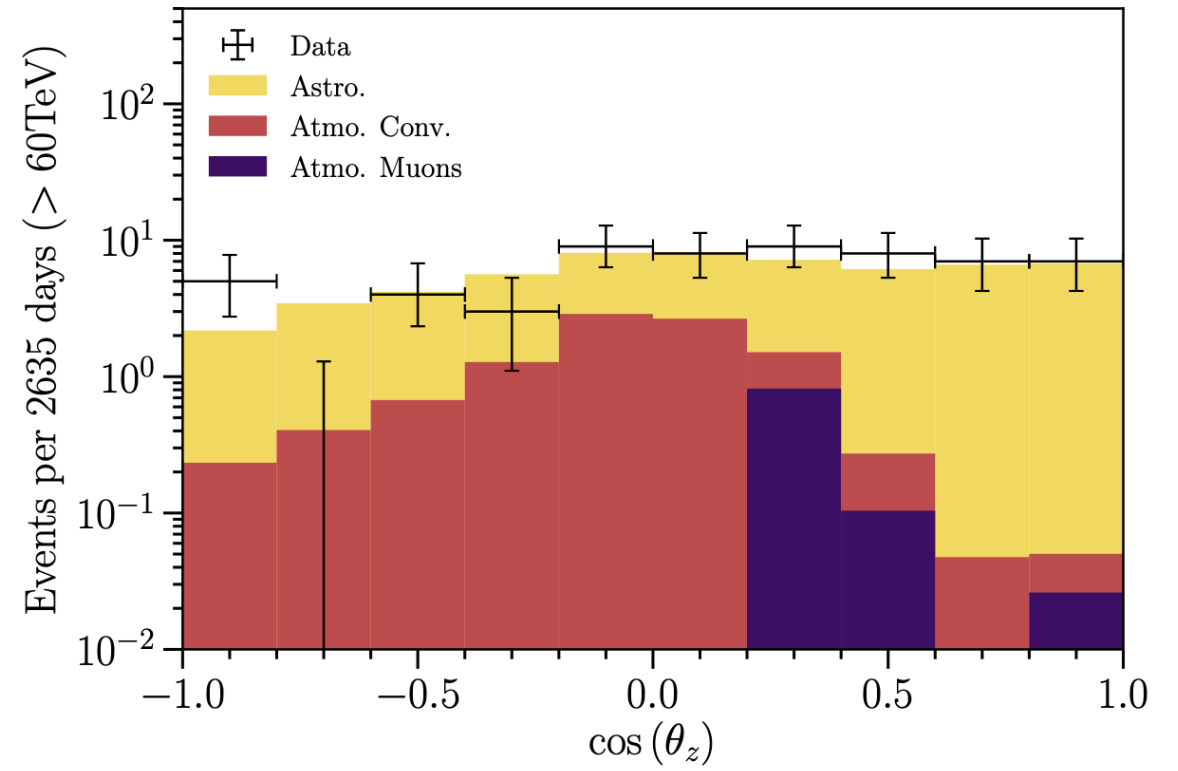
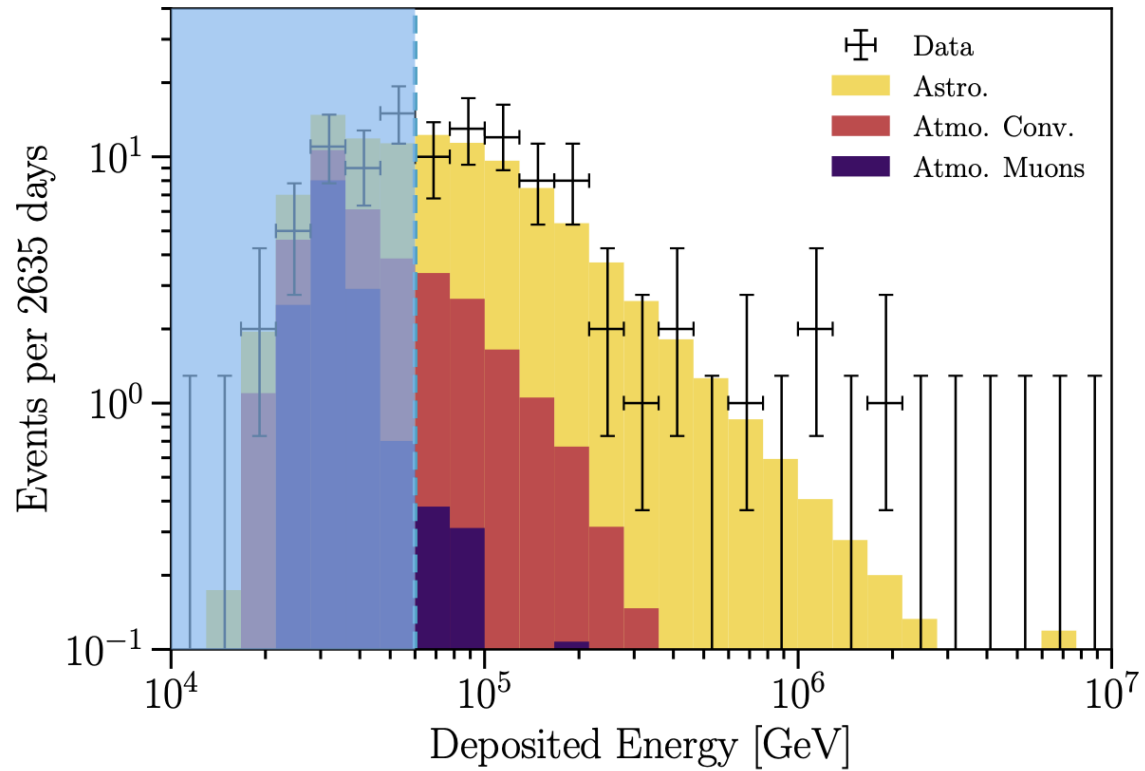
PRD 104, 022002 (2021)

Veto layer to select pure neutrino events



FORWARD FITTING

Observed events = astrophysical signal + atmospheric neutrinos
+ atmospheric muons



FORWARD FITTING: POISSON BINNED LIKELIHOOD

$$\Phi_{\text{astro}}(E_\nu) = \Phi_0 \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma},$$

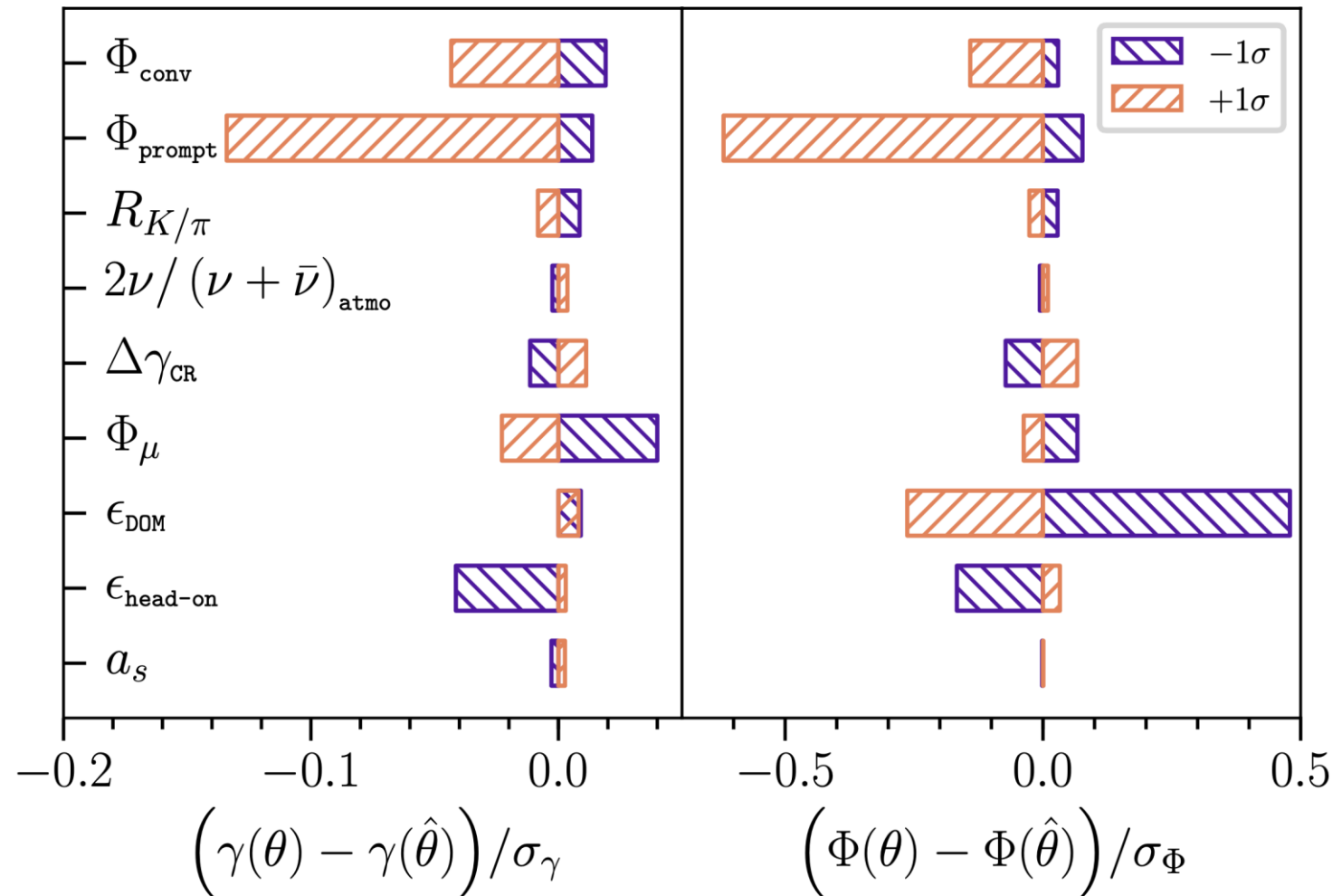
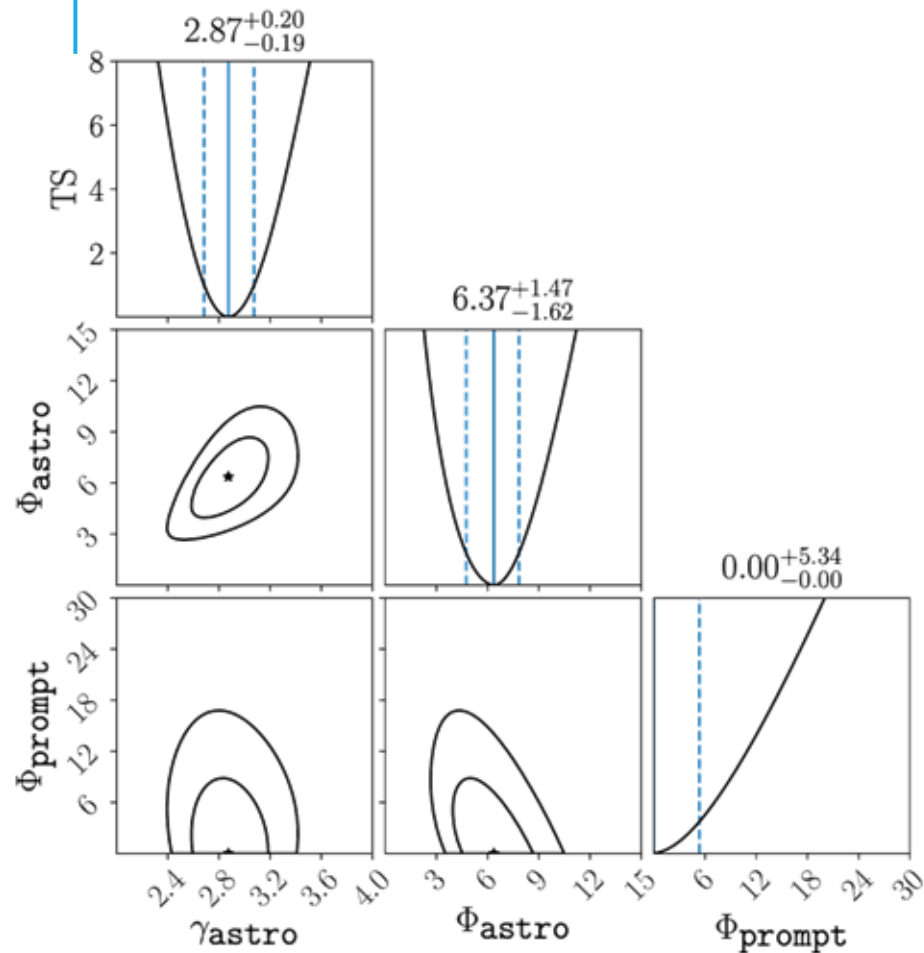
$$\mu_i^{\text{astro}} = T \int dE_\nu d\Omega \Phi_{\text{astro}}(E_\nu) A_{\text{eff}}(E_\nu, \Omega) P_i(E_\nu, \Omega),$$

$$\mu_i = \mu_i^{\text{astro}} + \mu_i^{\text{conv}} + \mu_i^{\text{prompt}} + \mu_i^{\mu\text{atm}},$$

$$\mathcal{L} = \prod_i \text{Poisson}(n_i \mid \mu_i) \times \prod_k \pi_k(\eta_k).$$

HESE: RESULTS

$$\phi_{\nu}^{\text{atm}} = \Phi_{\text{conv}} \left(\phi_{\nu}^{\pi} + R_{K/\pi} \phi_{\nu}^K \right) \left(\frac{E_{\nu}}{E_0^c} \right)^{-\Delta\gamma_{CR}} + \Phi_{\text{prompt}} \phi_{\nu}^p \left(\frac{E_{\nu}}{E_0^p} \right)^{-\Delta\gamma_{CR}}$$

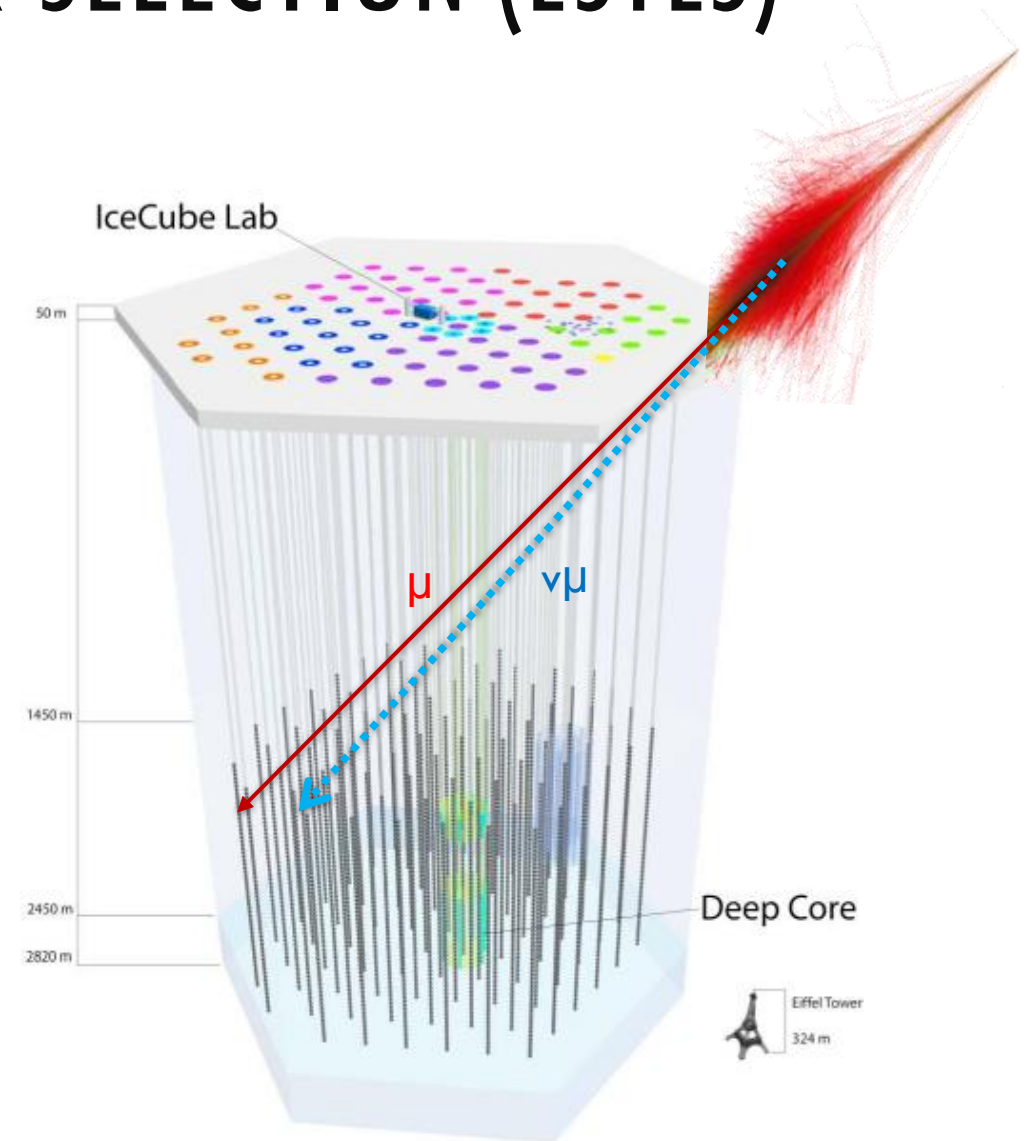
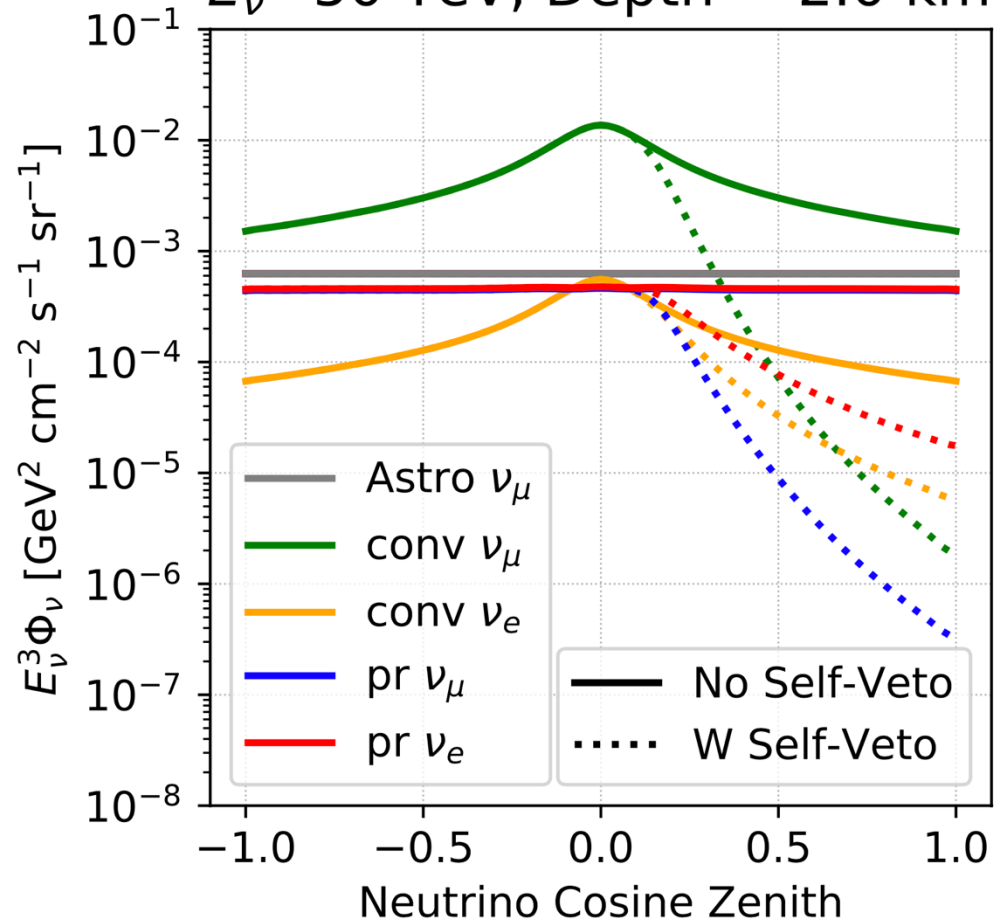


Prompt is bounded at 0

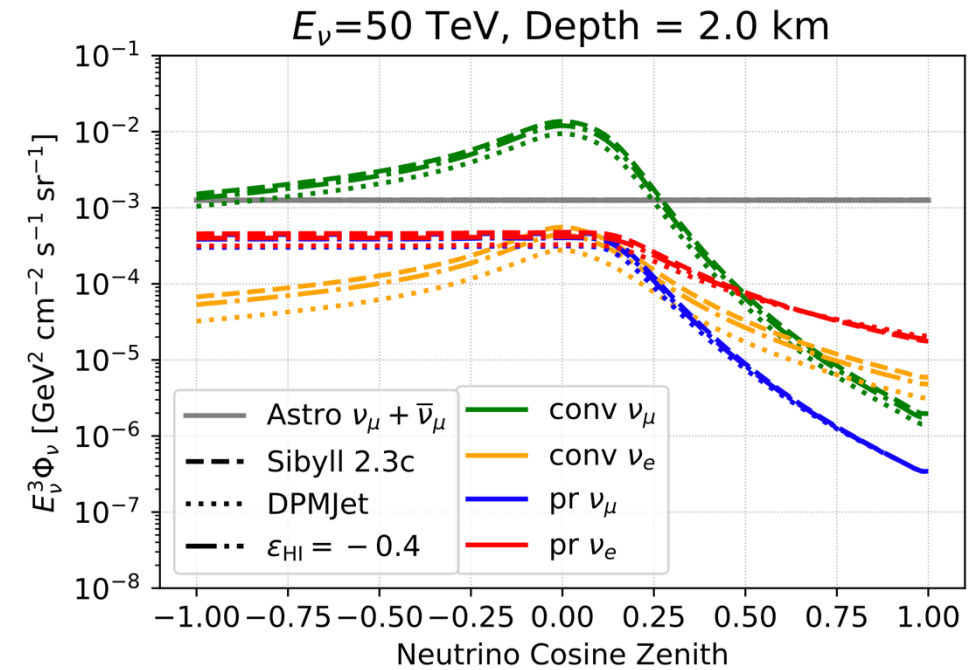
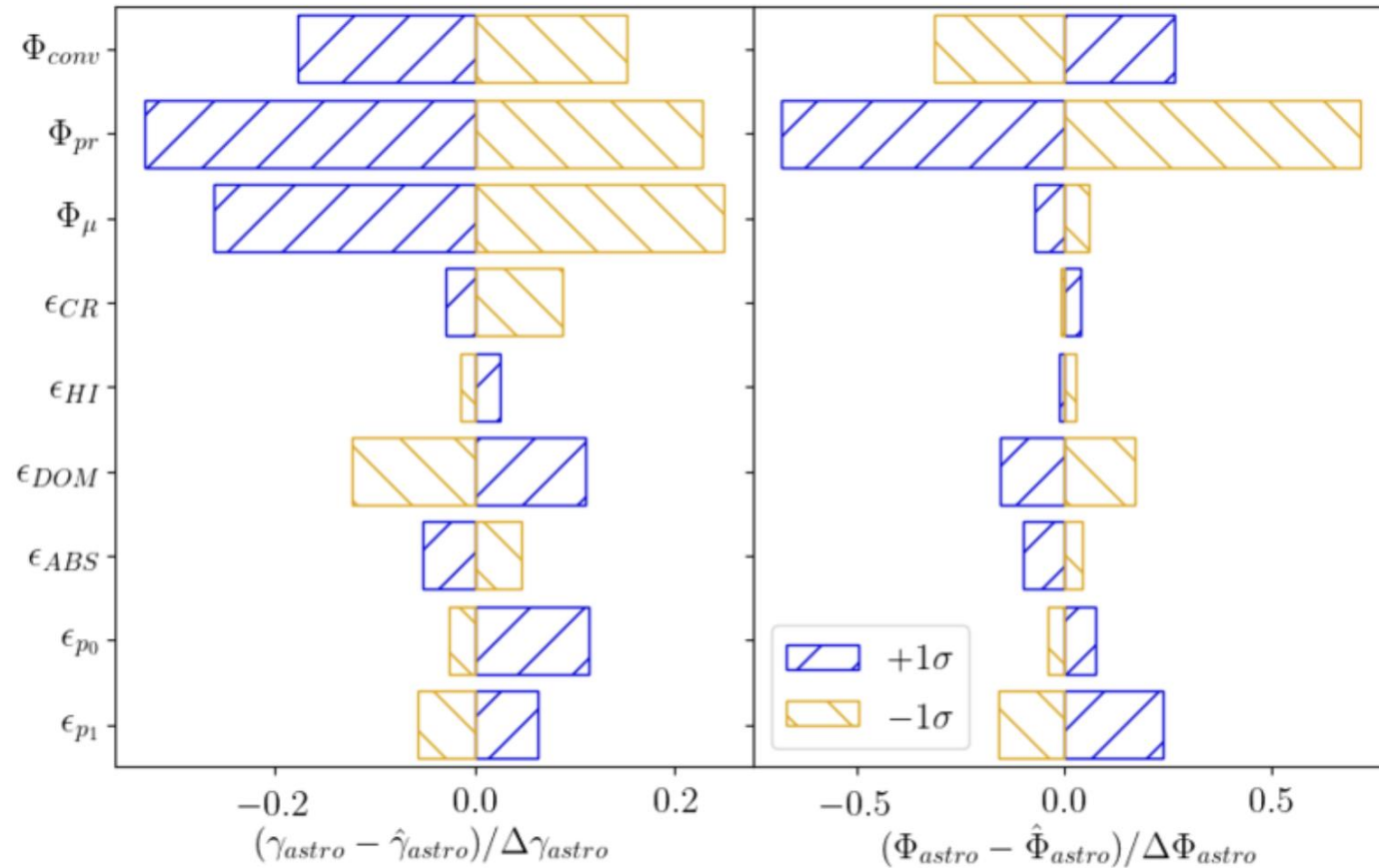
ENHANCED STARTING TRACK SELECTION (ESTES)

Breaking degeneracy of prompt: self-veto

$E_\nu = 50$ TeV, Depth = 2.0 km



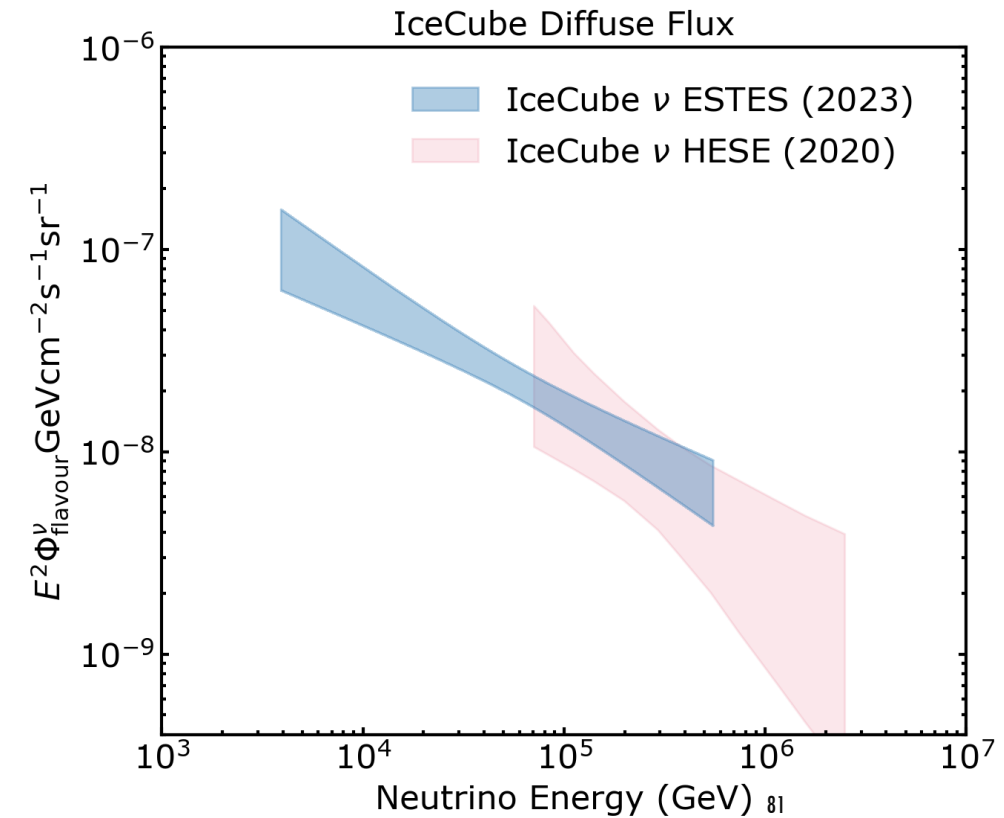
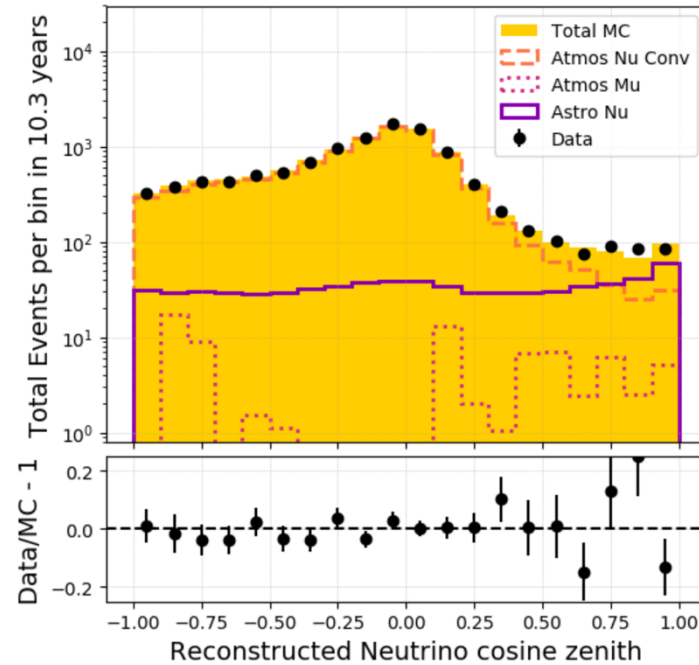
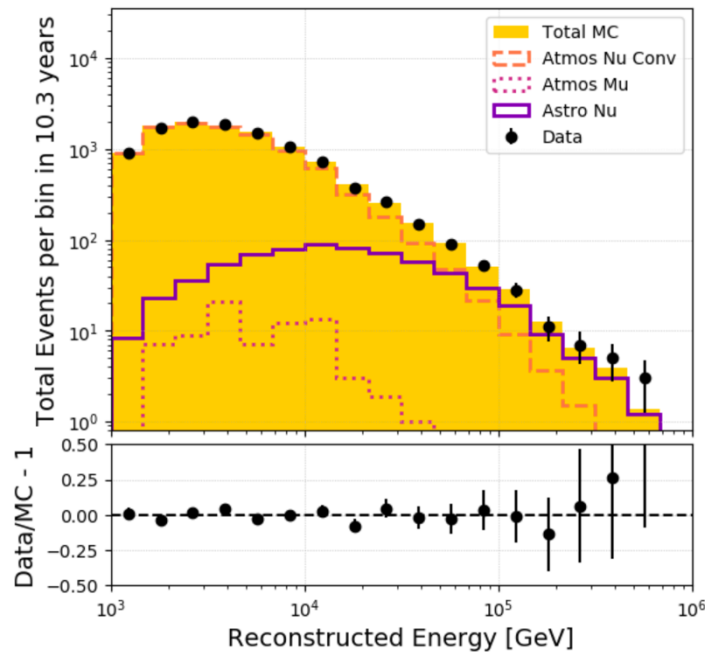
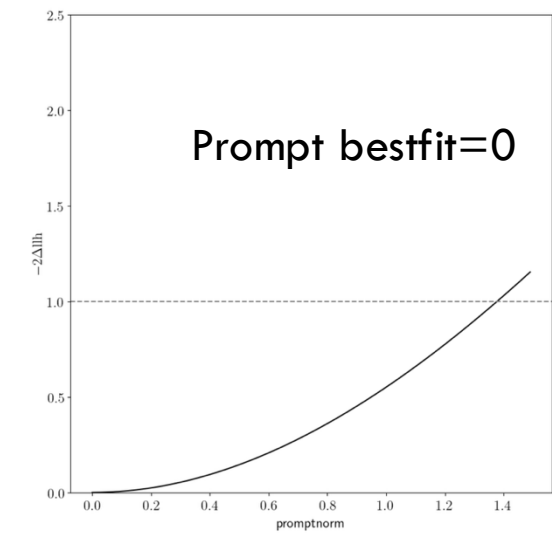
ESTES: PROMPT IMPACT ACCORDING TO ASIMOV TEST



ESTES: DATA RESULTS

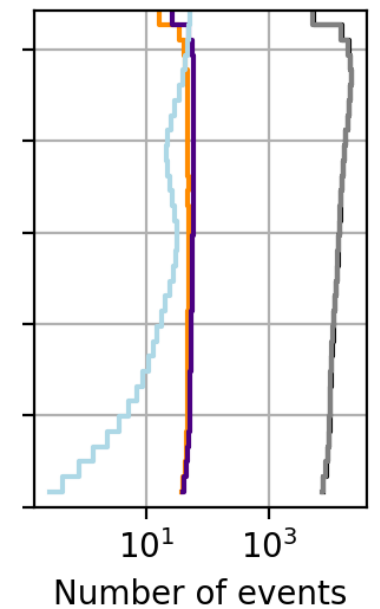
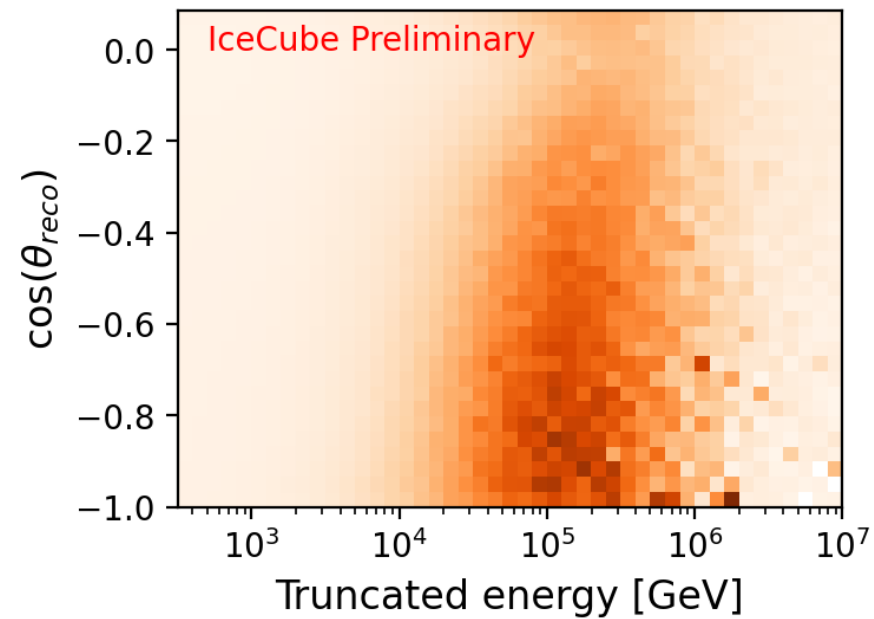
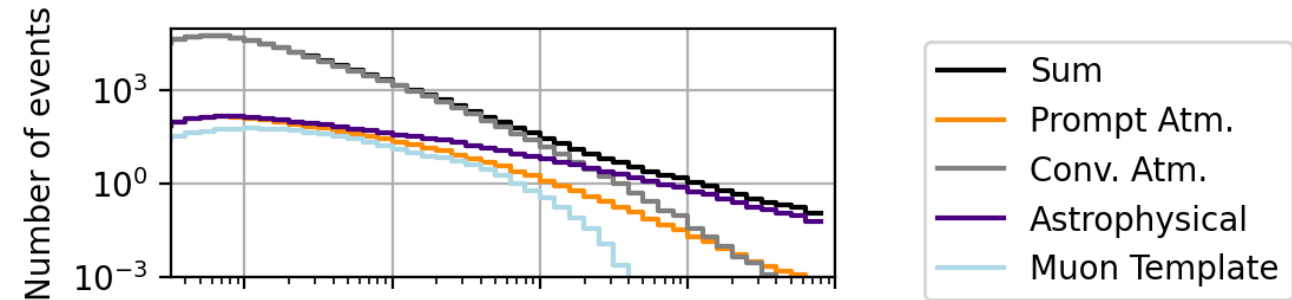
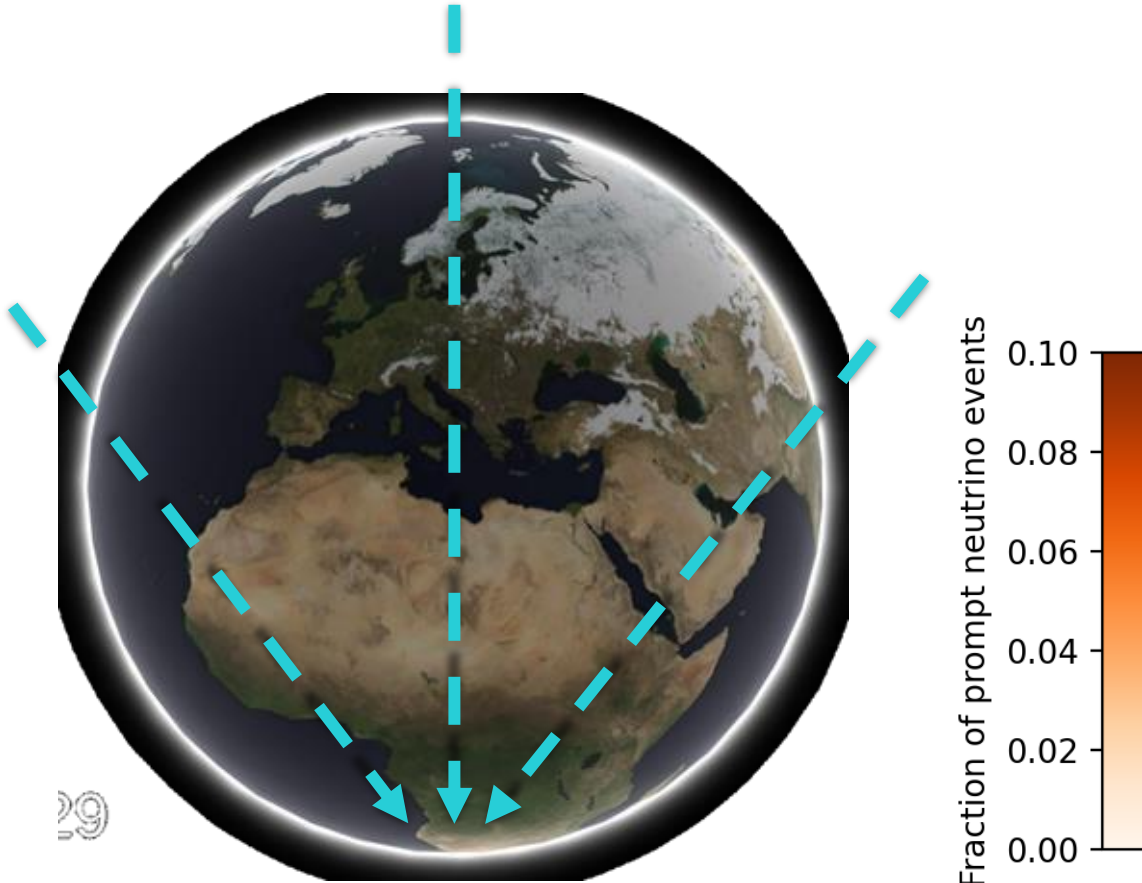
Extended the original HESE measurement to lower energies

Data prefers 0 prompt



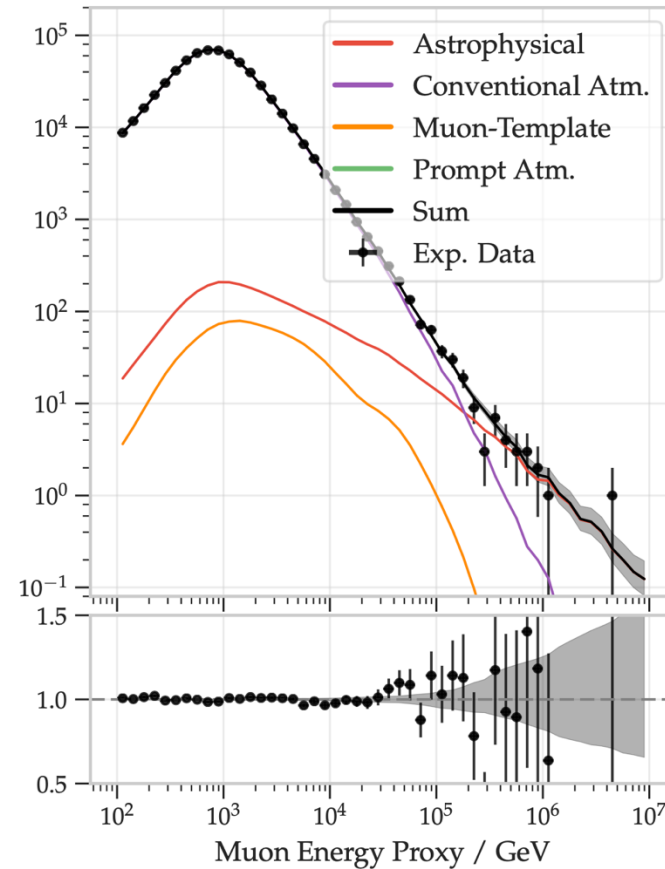
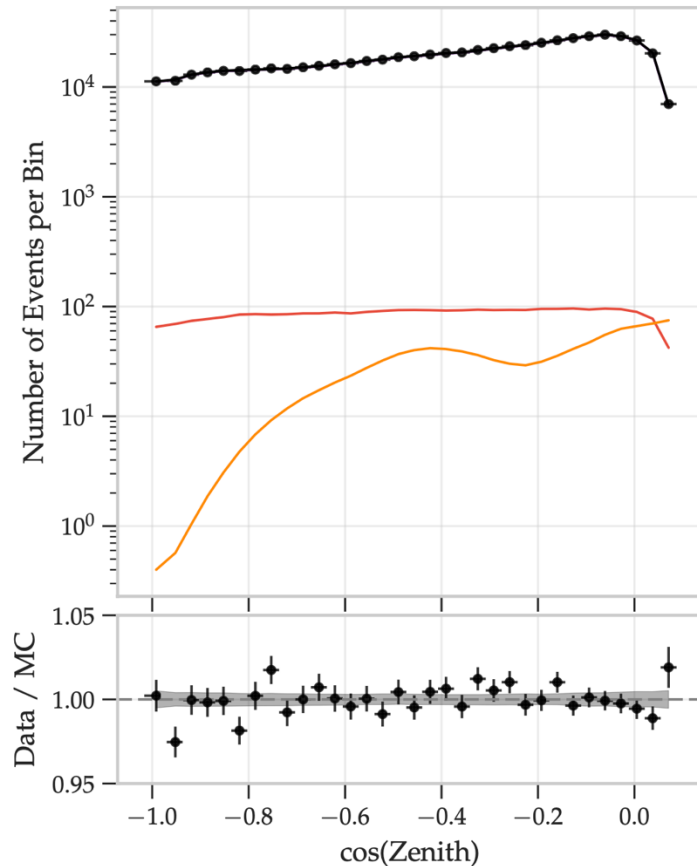
NORTHERN TRACKS

Use Earth as a shield

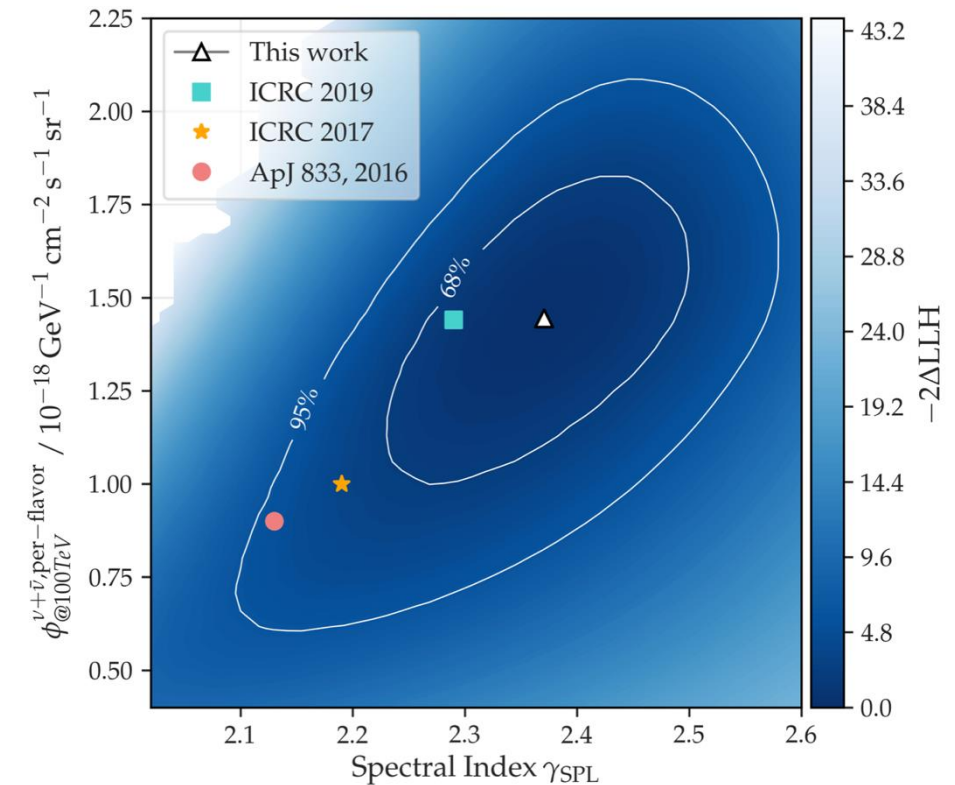


NORTHERN TRACKS

- Hadronic interaction model switched to Barr parameters
- Atmospheric predictions now produced with MCEq

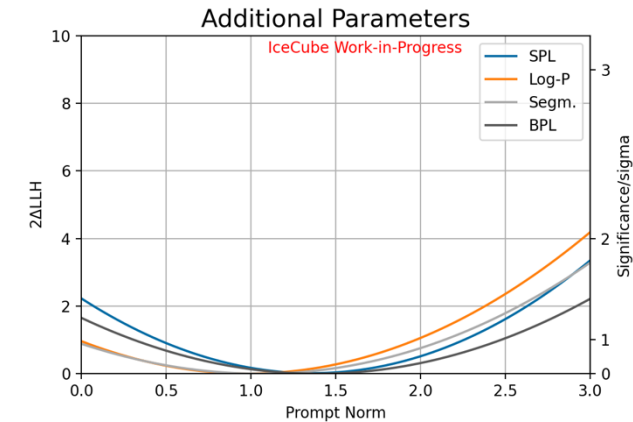


$$\Phi_{\text{astro.}}^{\nu_{\mu} + \bar{\nu}_{\mu}}(E_{\nu}) = \phi_{\text{astro.}} \times \left(\frac{E_{\nu}}{100 \text{ TeV}} \right)^{-\gamma_{\text{SPL}}}$$

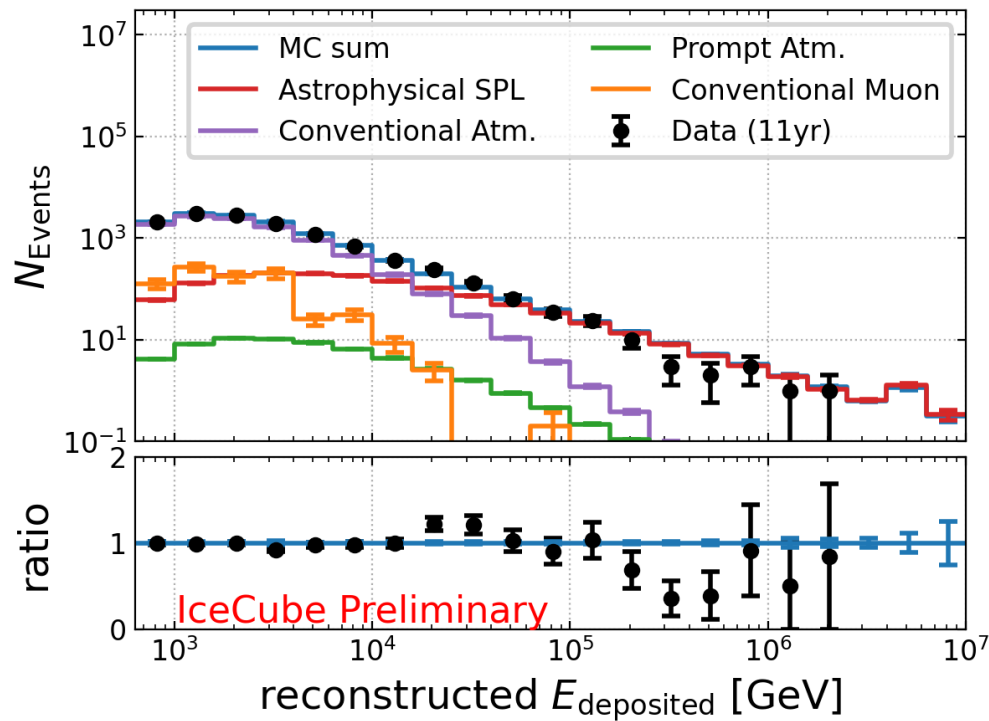


COMBINED FIT: TRACKS AND CASCADES

- * high statistics of tracks to constrain conv., self-veto from cascades for prompt
- * single power law no longer describes data & prompt bestfit non zero

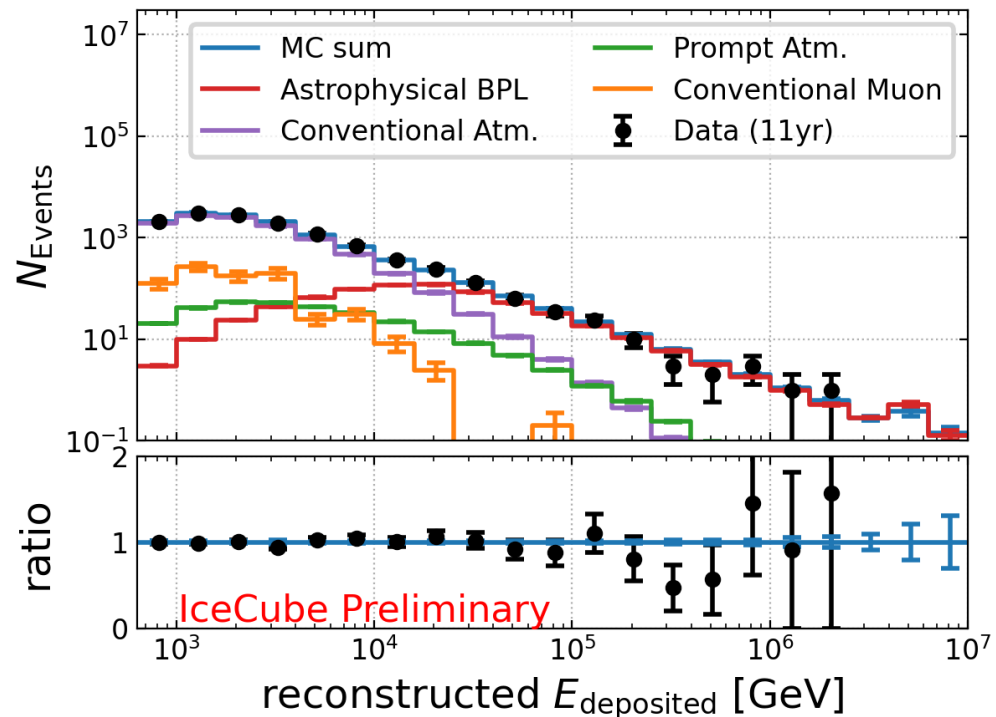


Cascade histogram



Single power law

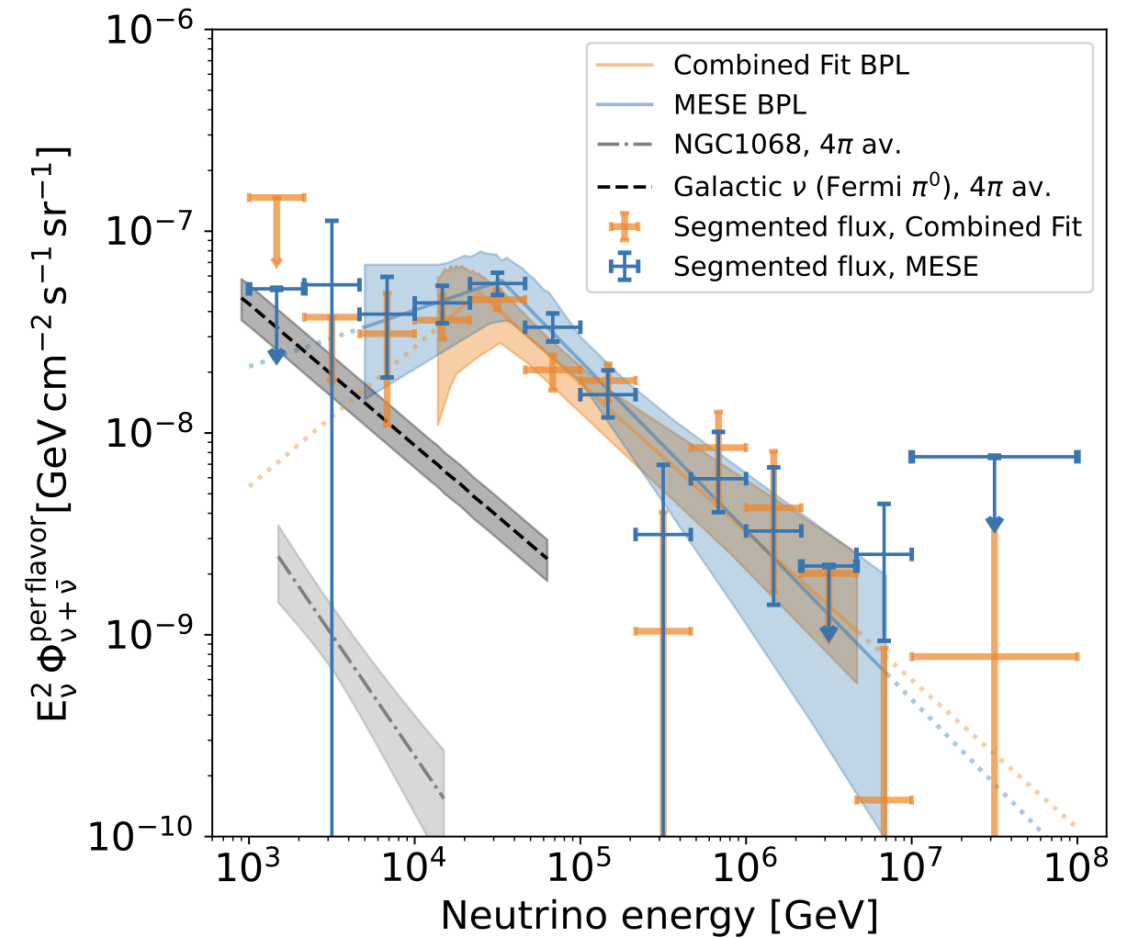
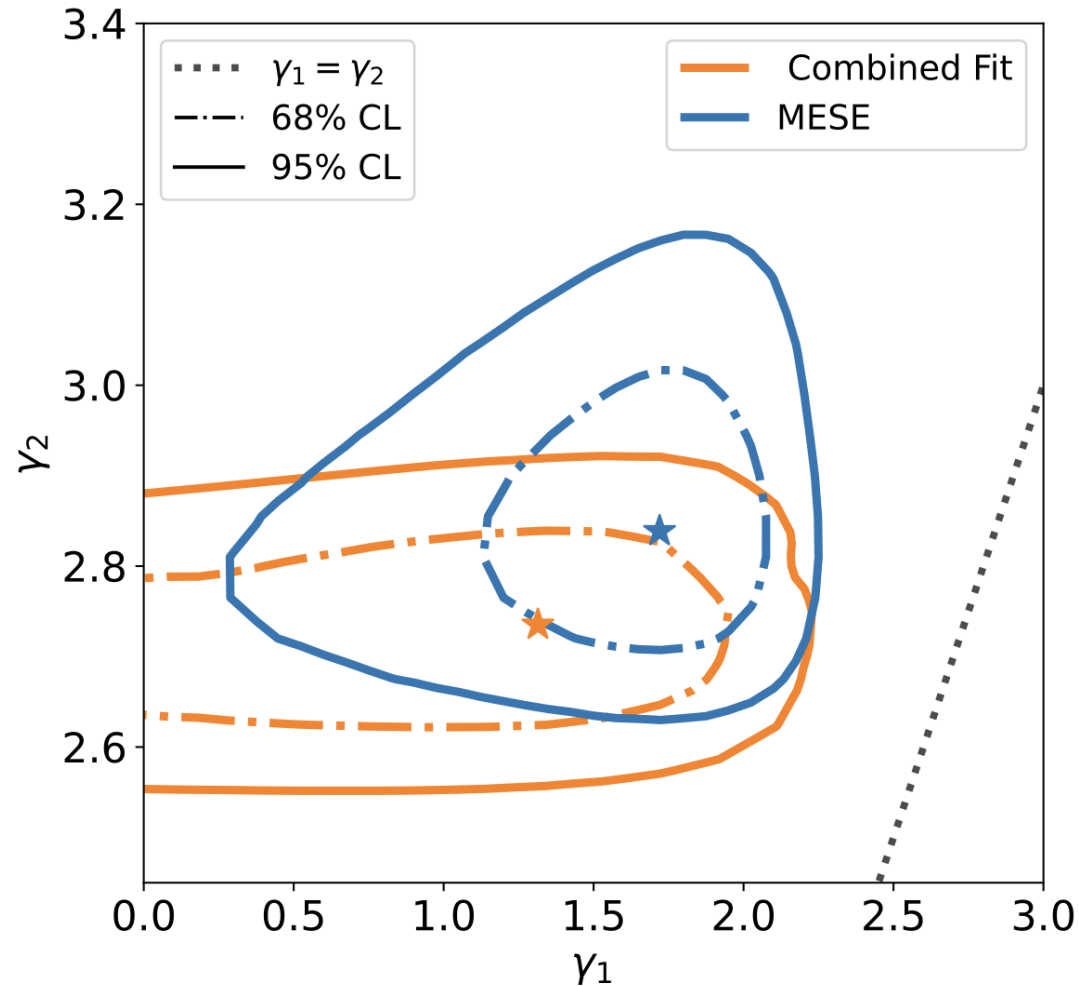
Cascade histogram



Broken power law

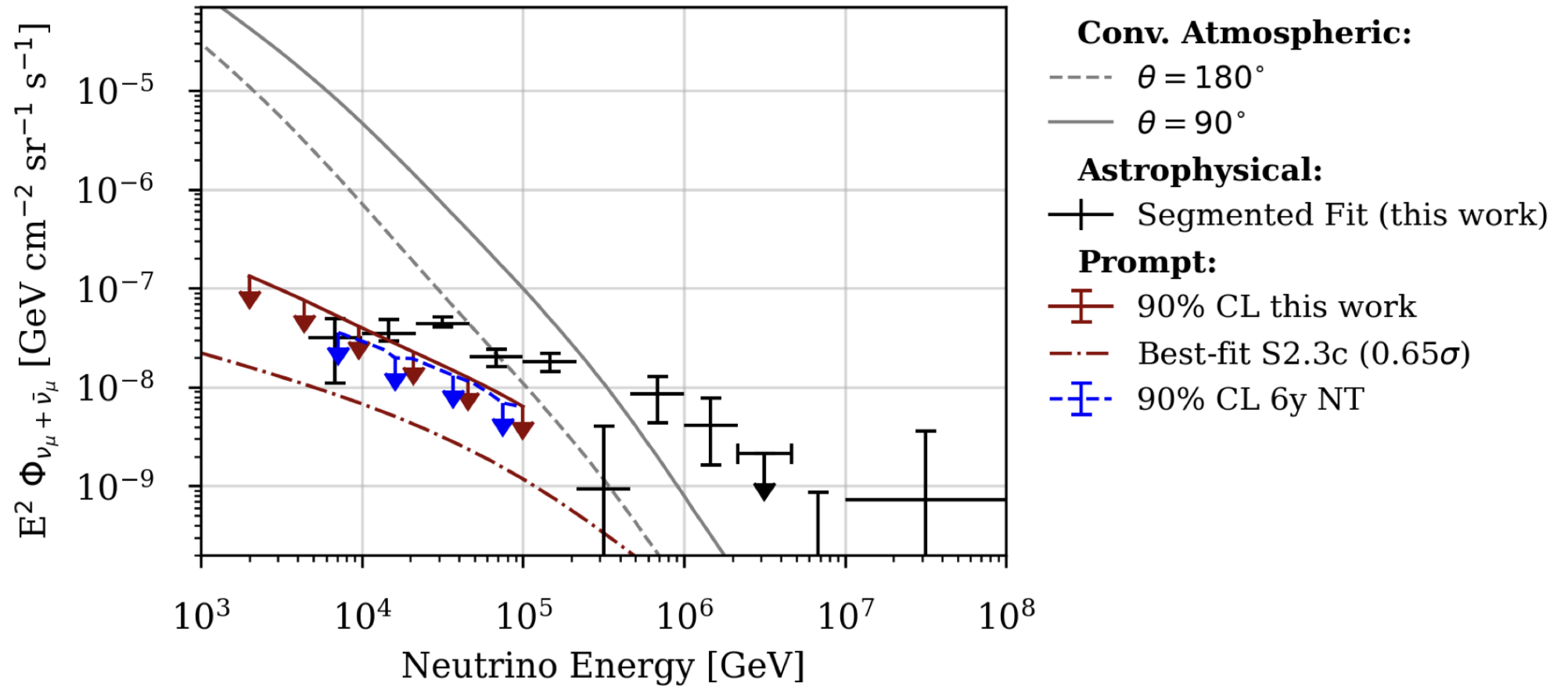
REJECTION OF SINGLE POWER LAW ≥ 4 SIGMA

PRL 136, 121002 (2026)

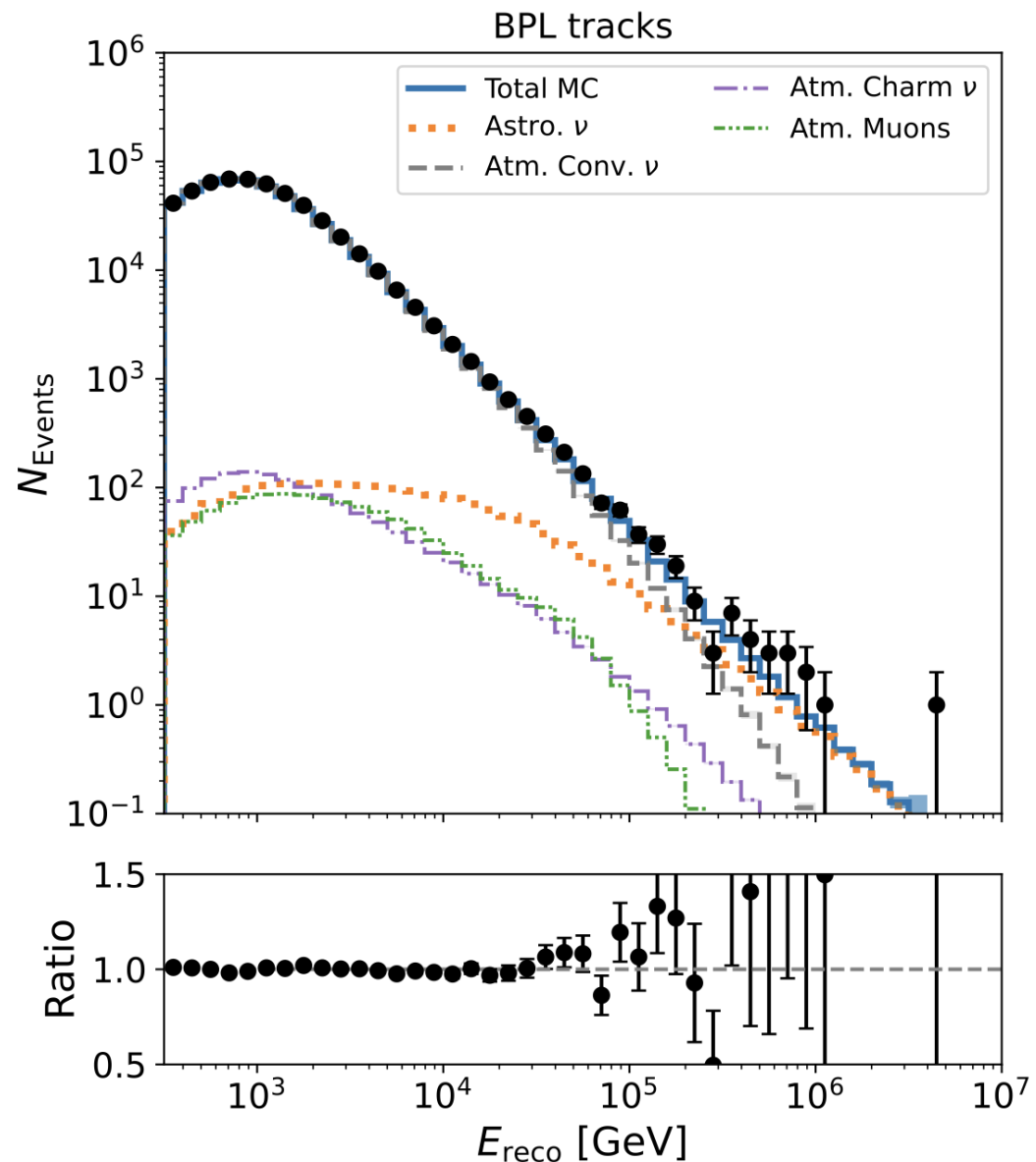
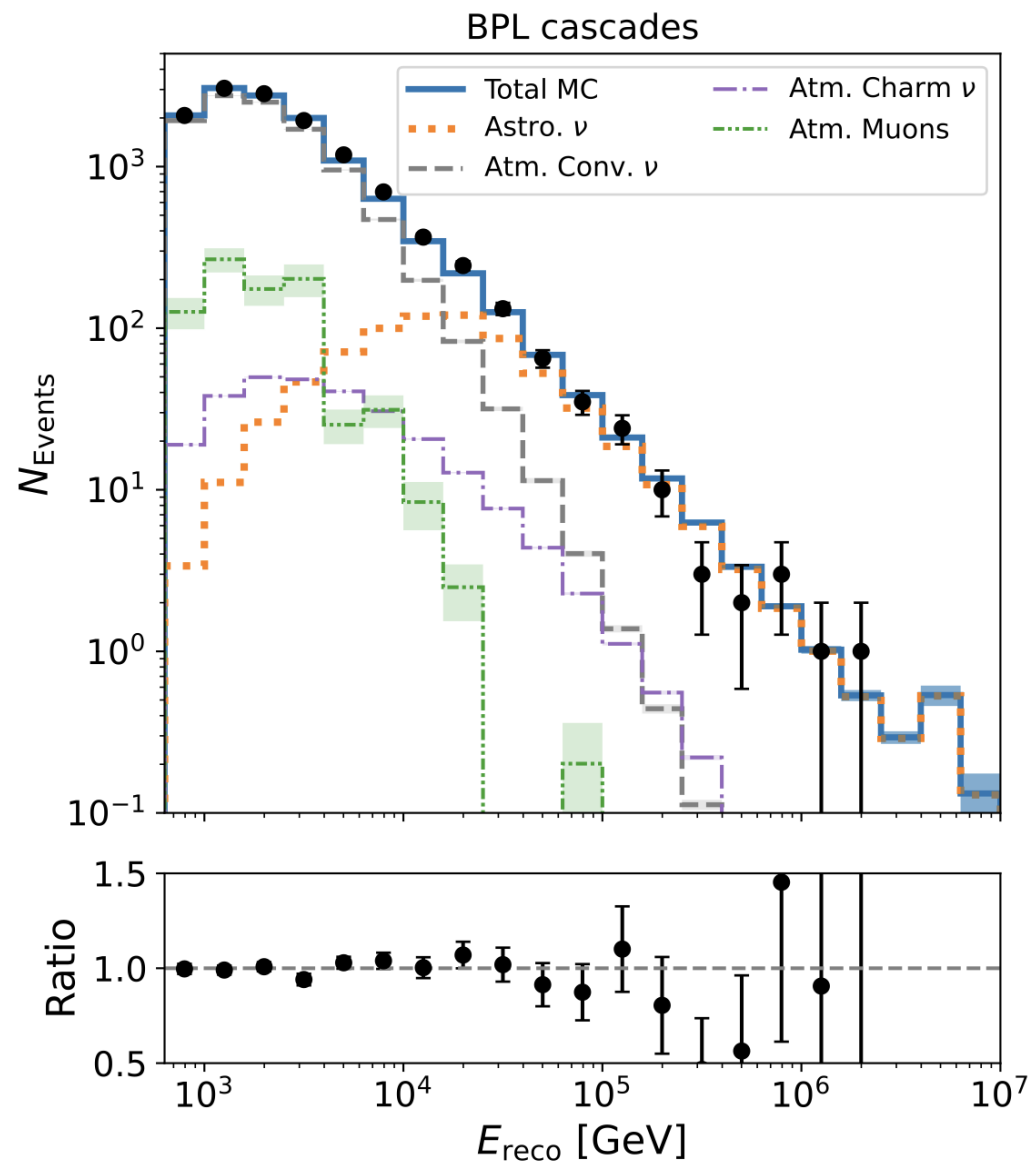


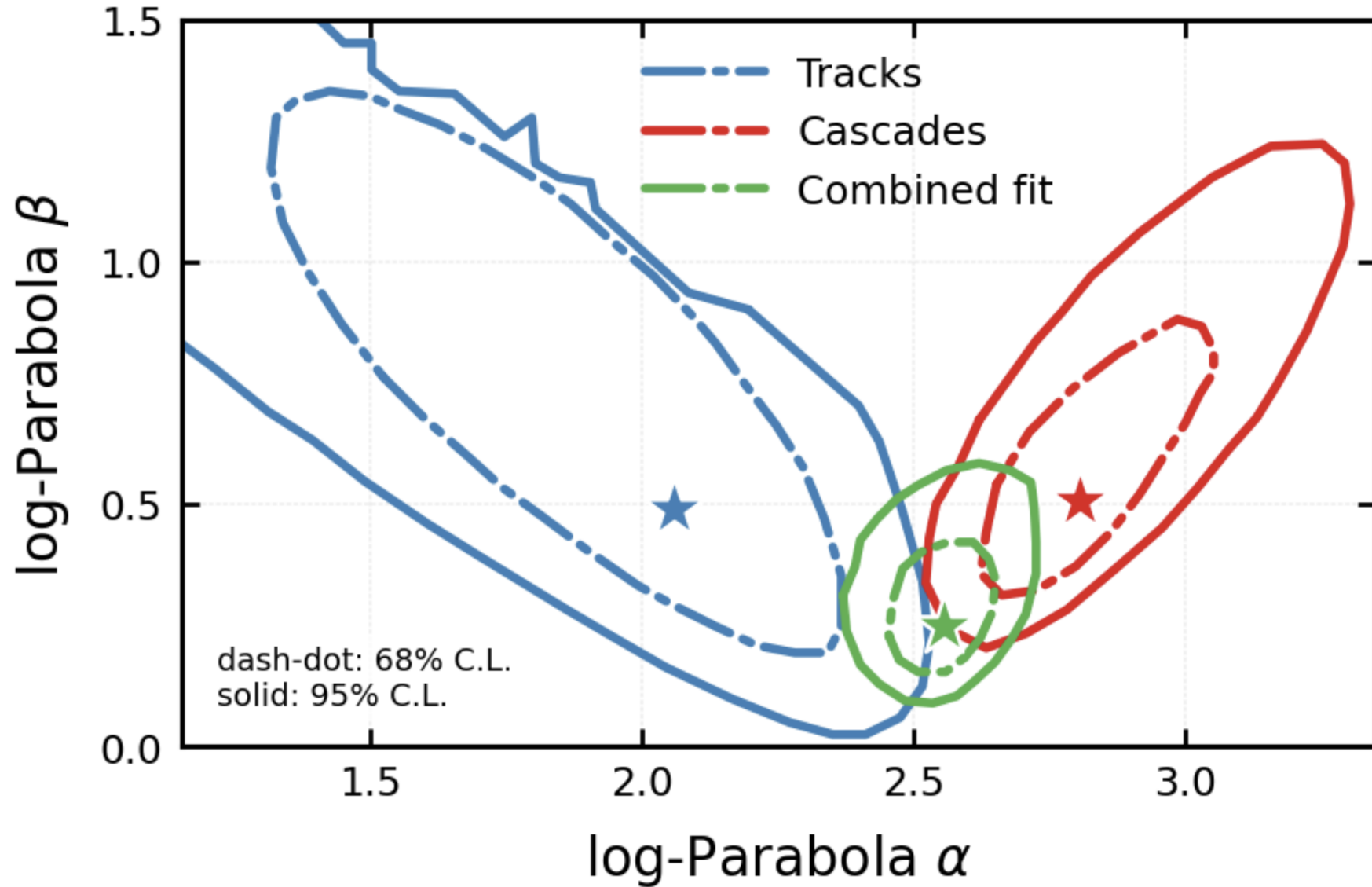
TRACK+CASCADE FIT

Prompt neutrino flux

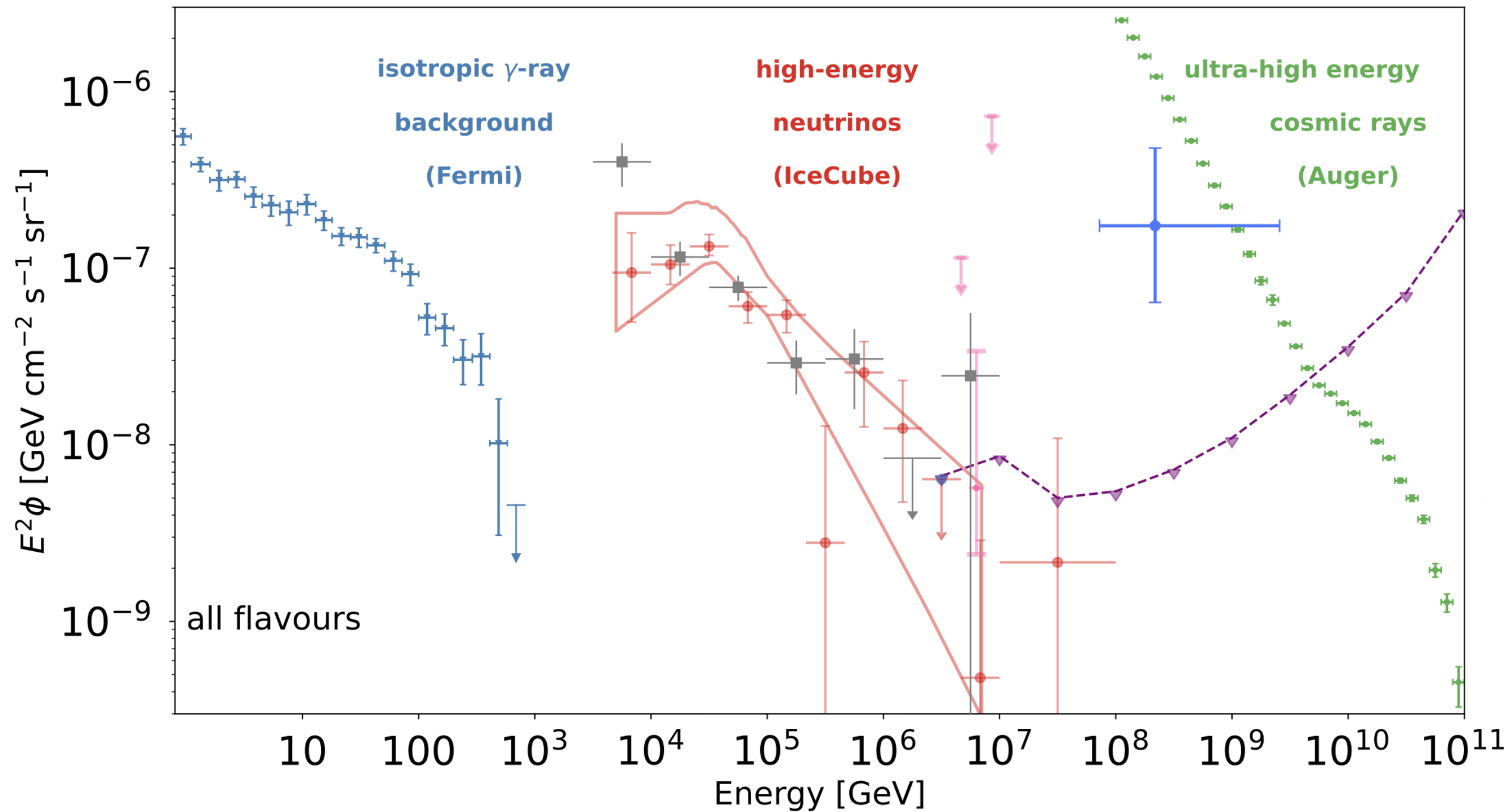


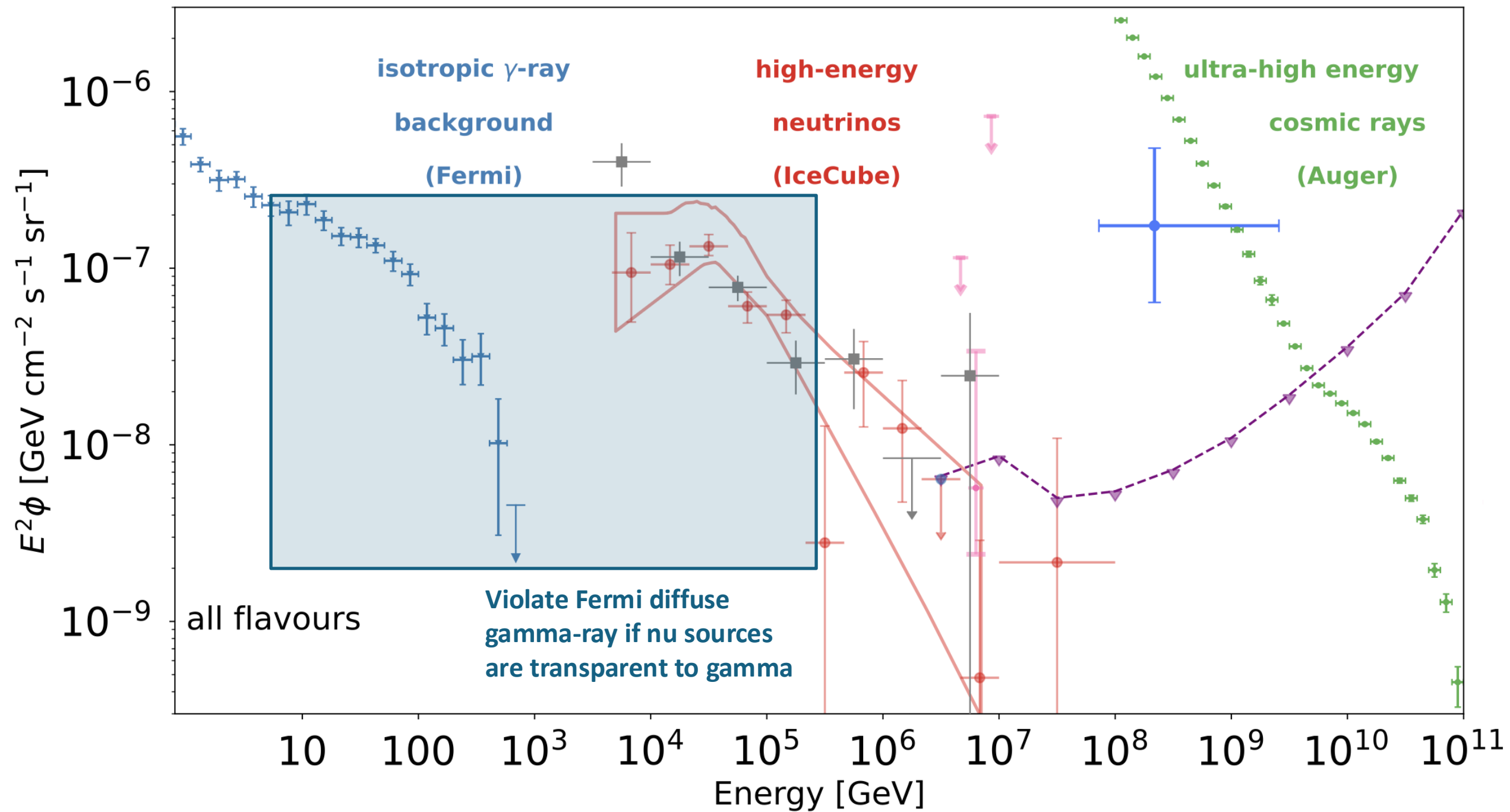
TRACK AND CASCADES: DO THEY AGREE?





Broken power law is only evident for cascade/shower events

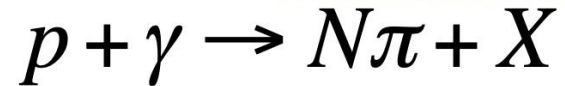
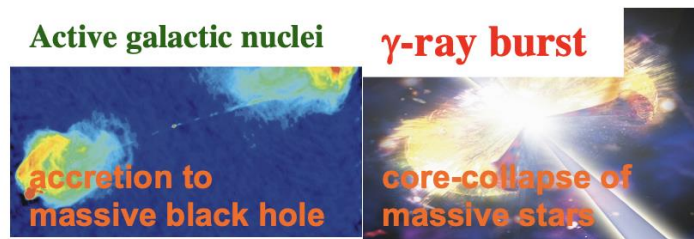




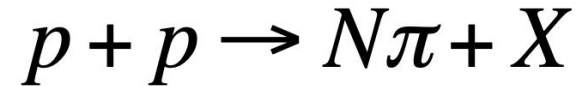
Astrophysical Extragalactic Scenarios

$E_\nu \sim 0.04 E_p$: PeV neutrino $\Leftrightarrow$ 20-30 PeV CR nucleon energy

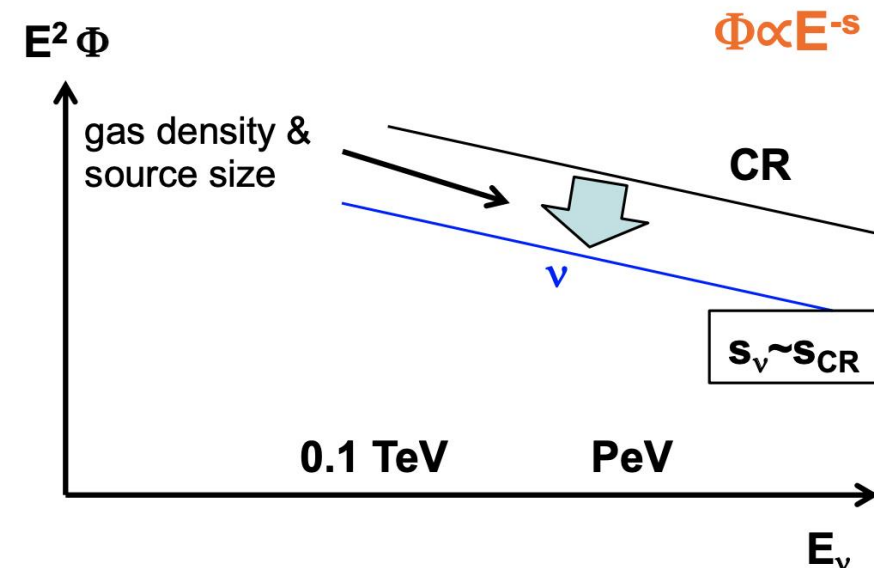
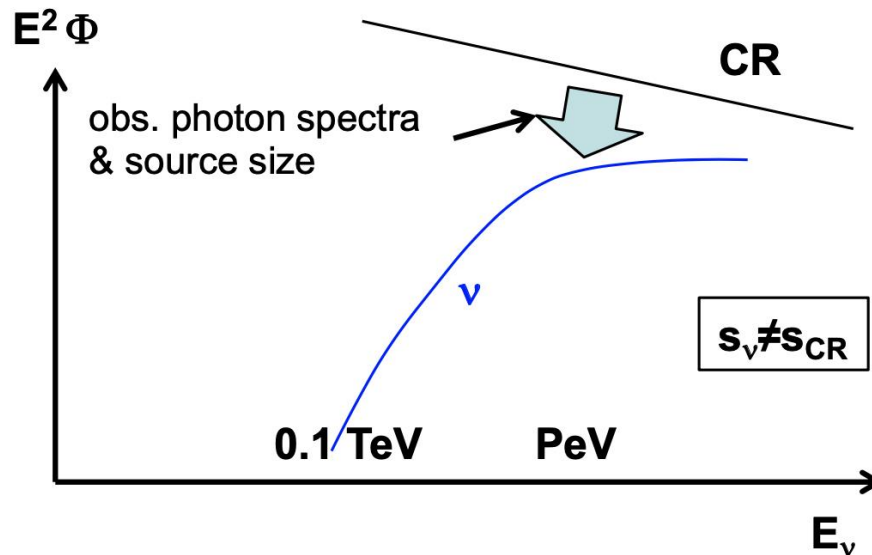
Cosmic-ray Accelerators
(ex. UHECR candidate sources)

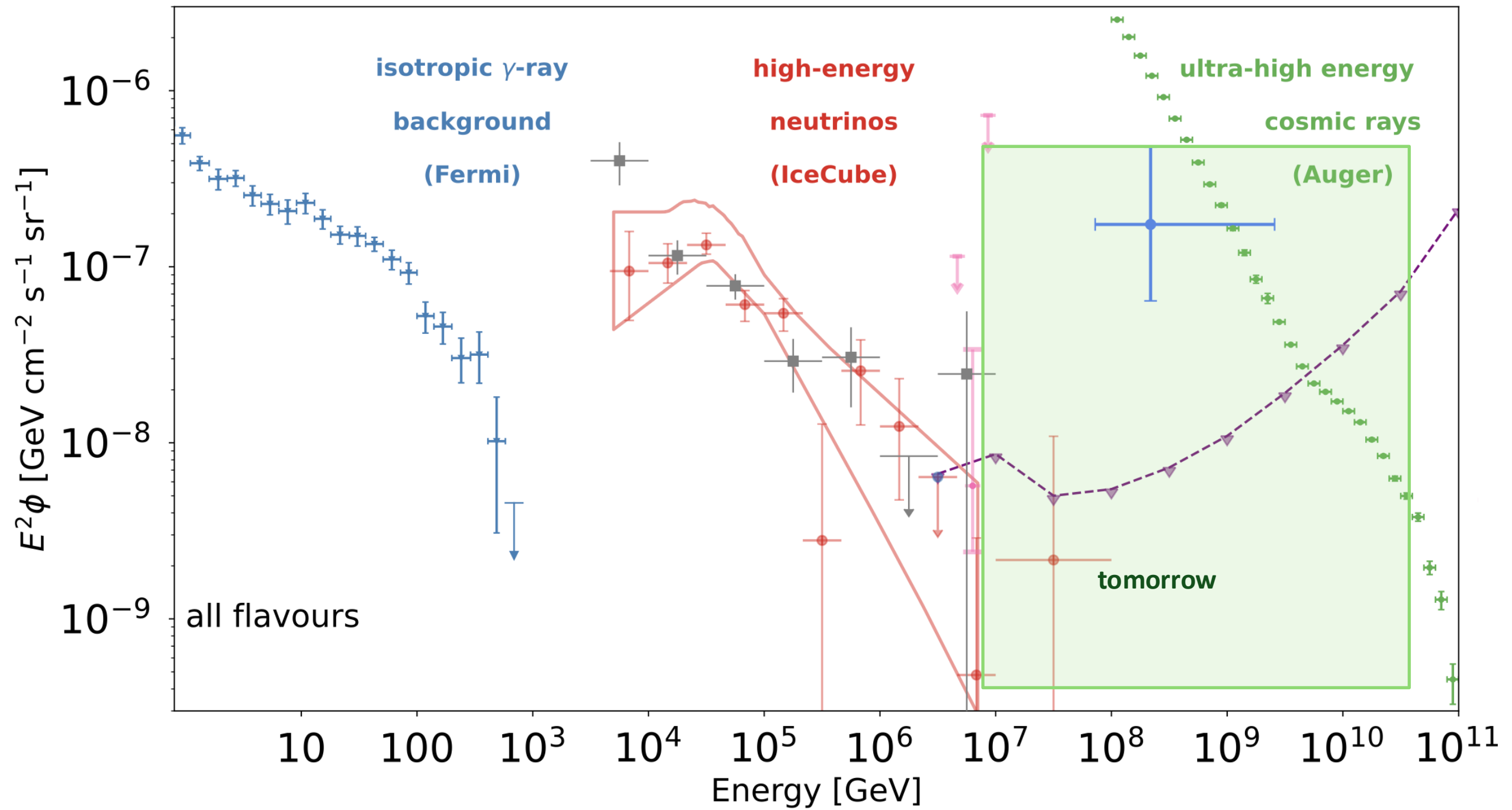


Cosmic-ray Reservoirs

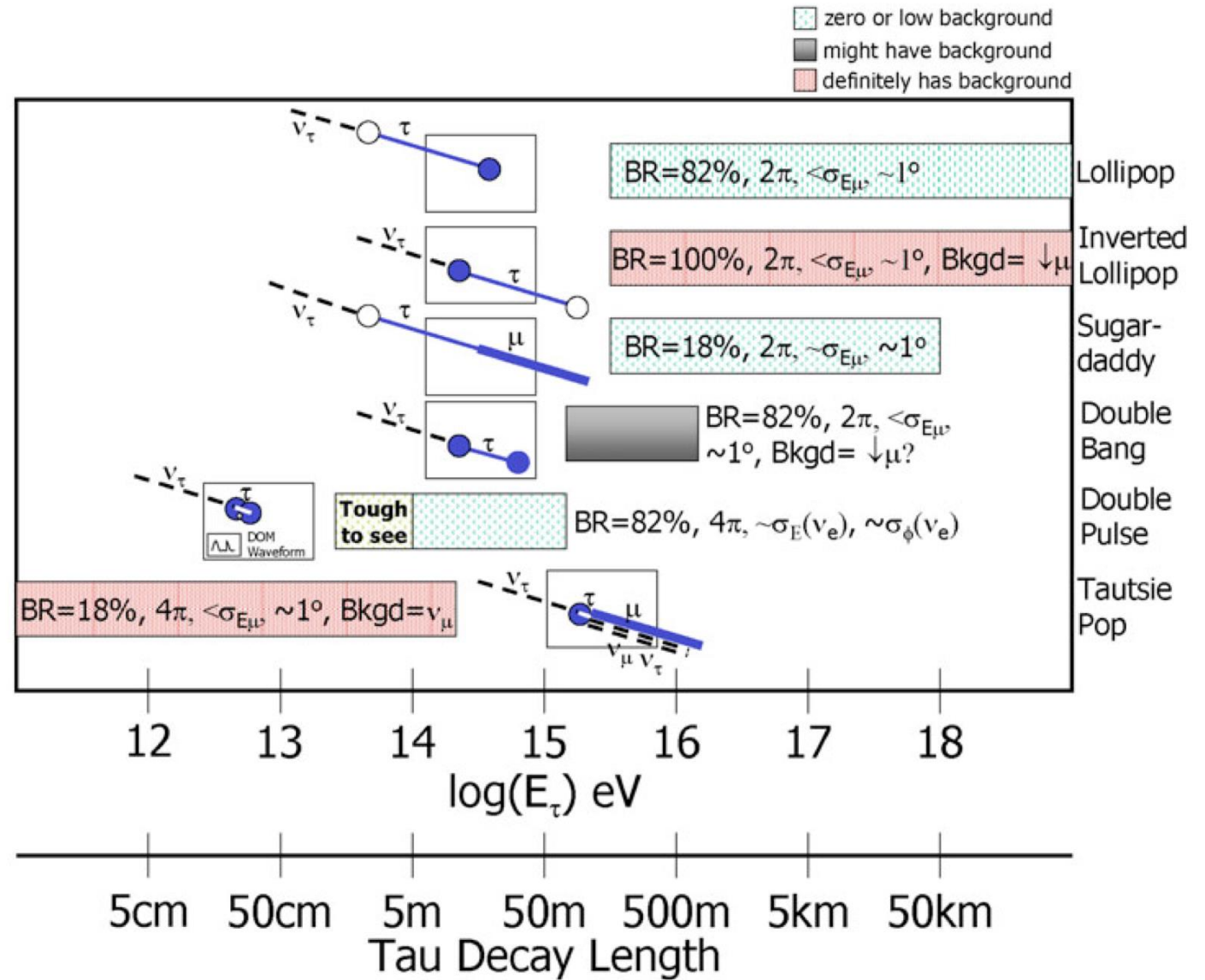


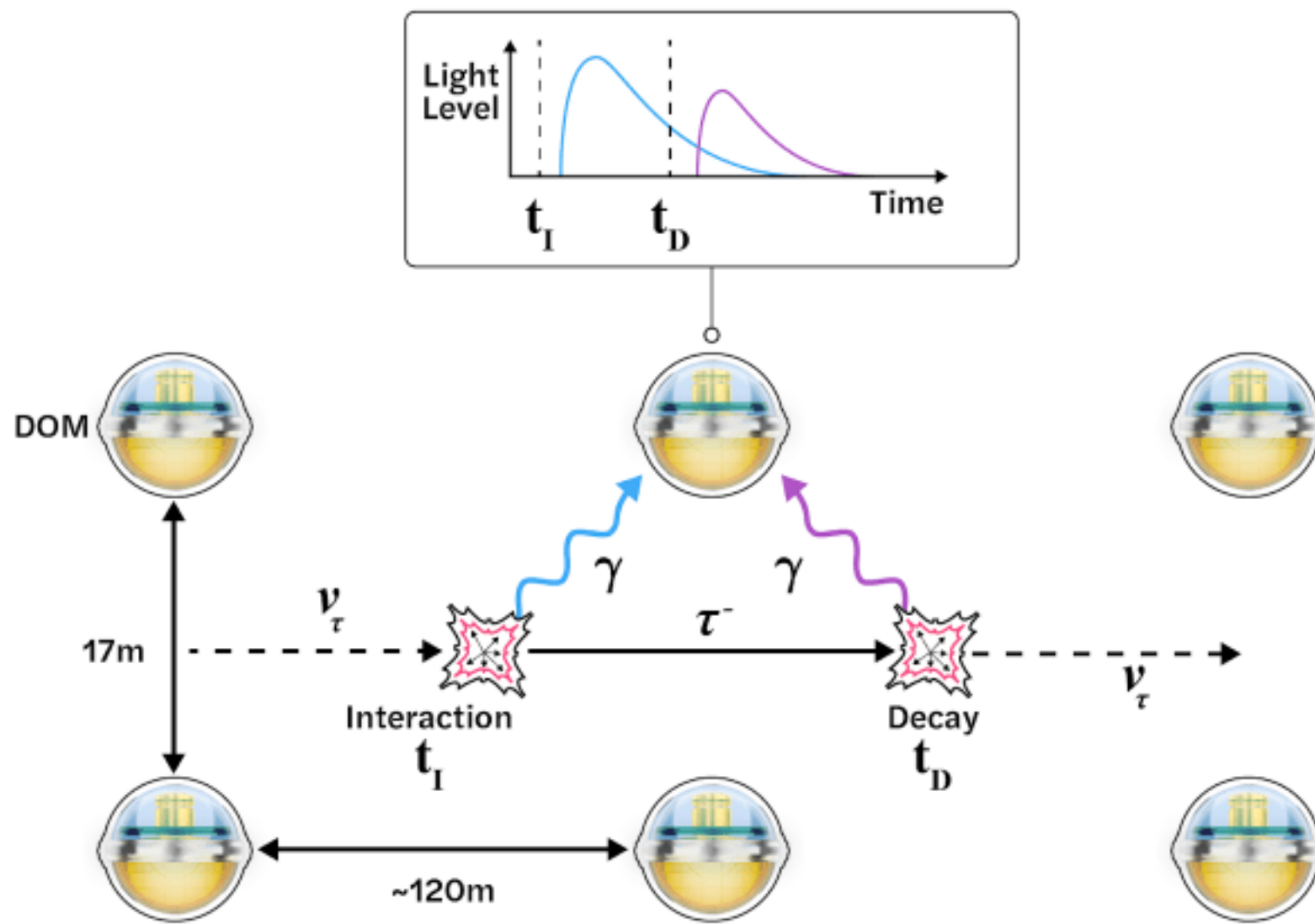
Slide from
Kohta Murase

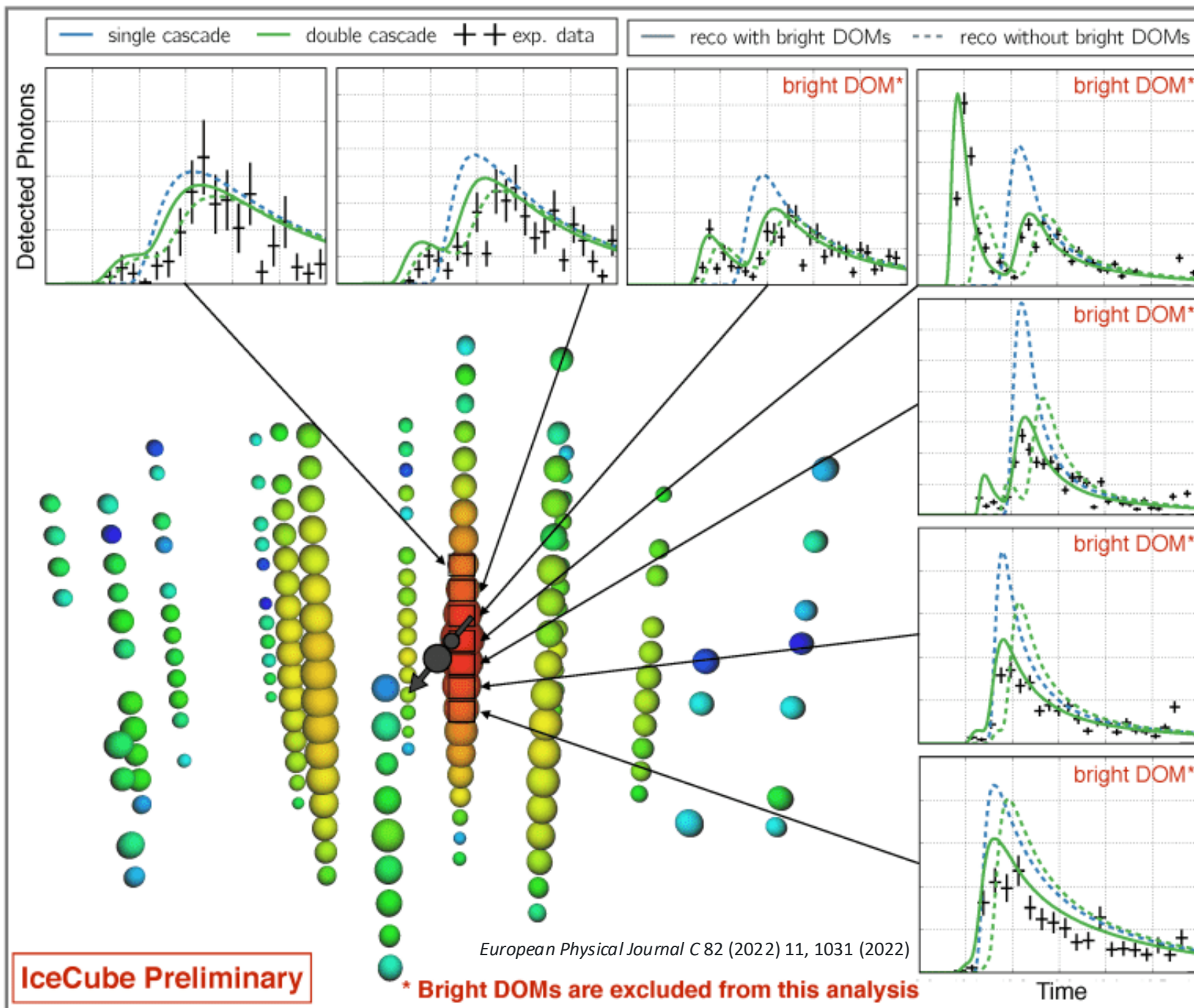


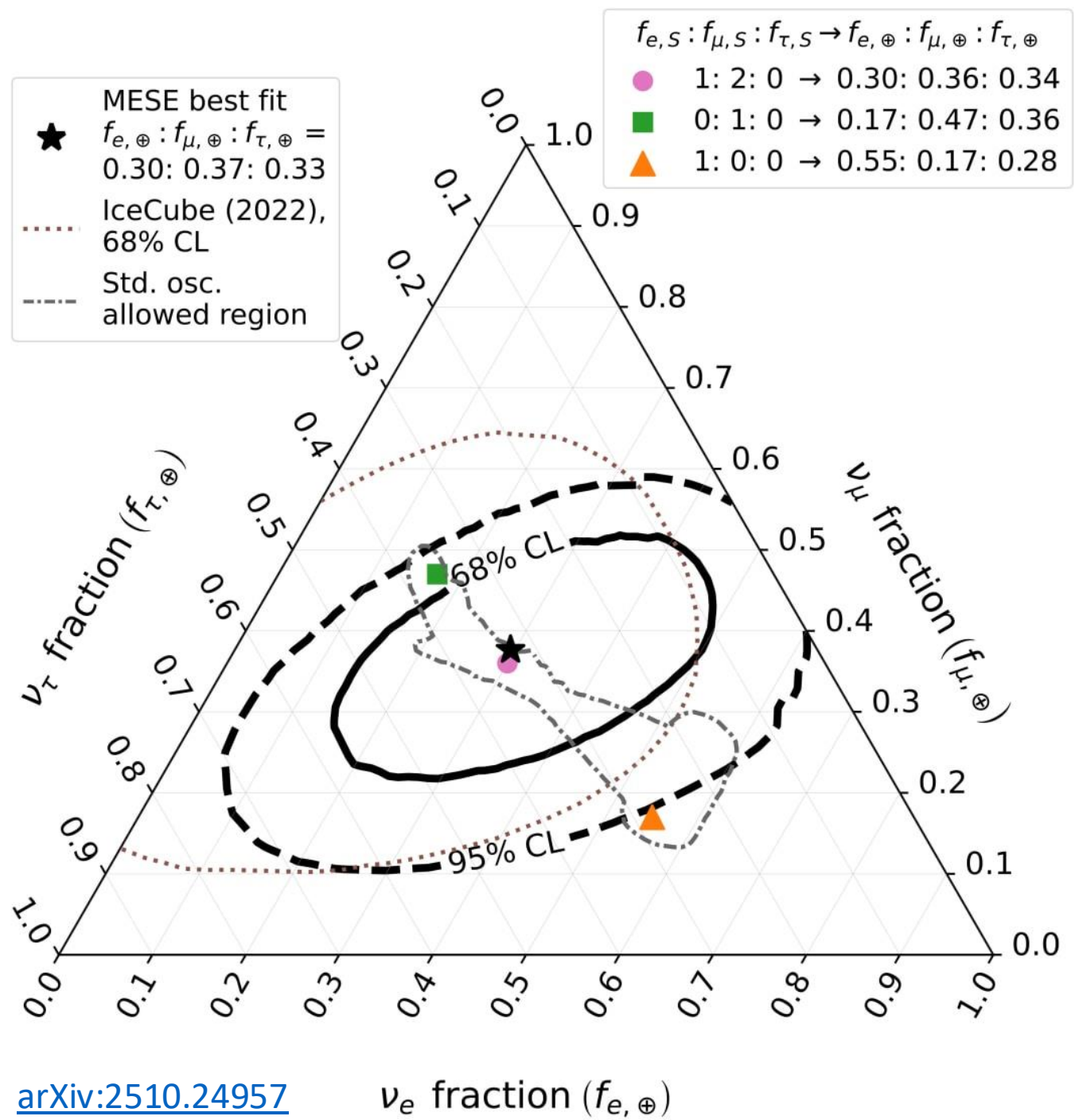


Tau neutrinos?









https://user-web.icecube.wisc.edu/~lulu/Osc_game/



Neutrino Oscillation Journey

Explore how neutrino flavors change with distance, energy, and source.

Explore Mode

Classroom Mode

Research Sandbox

Print / White Background

Science Accuracy Notes

JUMP TO AN EXPERIMENT

Free exploration

WORLD

World 2 · Through the Earth

Scan for a hidden signal

INITIAL FLAVOR

ve

$\nu\mu$

$\nu\tau$

☐ Antineutrino mode ($\delta_{CP} \rightarrow -\delta_{CP}$)

NEUTRINO ENERGY

Energy 0.60 GeV

Higher energy stretches the oscillation wavelength (fewer wiggles over the same distance).

BASELINE

Max baseline 1,000 km

Detector at 635 km

PATH THROUGH EARTH

Crust skimmer (~1,000 km)

☐ Matter effect

Simplified educational approximation: constant average density ($\rho \approx 2.7 \text{ g/cm}^3$) modifies θ_{13} only. Not a full layered-Earth solver.

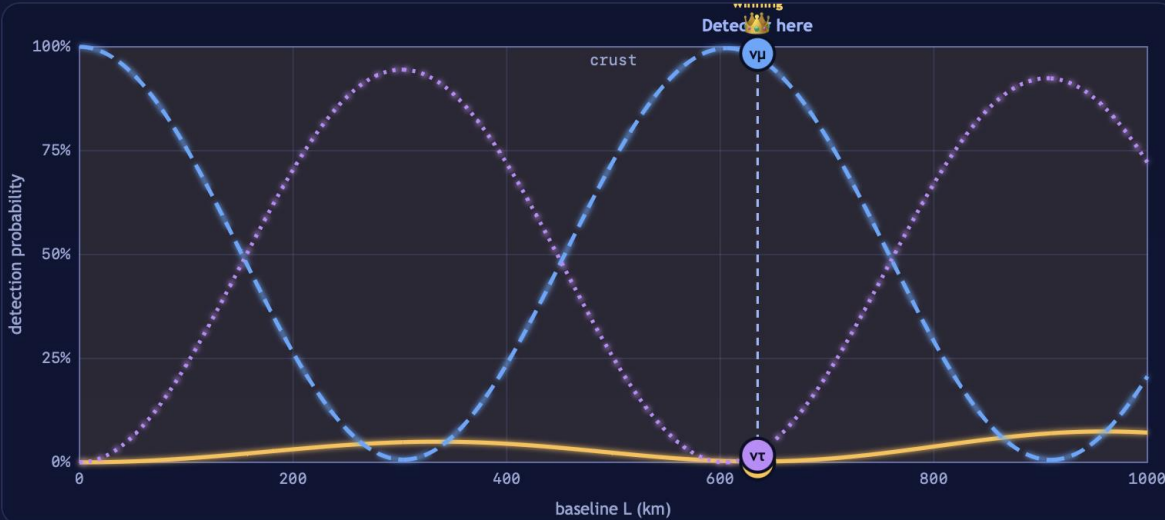
Flavor Race

Δ Flavor Triangle

+ BSM Cosmos

OSCILLATION RACE TRACK

Drag on the graph to move the detector.



Legend: — ve electron neutrino - - - $\nu\mu$ muon neutrino ···· $\nu\tau$ tau neutrino

Annotations: crust, **winning** $\nu\mu$ here, $\nu\tau$

● **$\nu\mu$ is way ahead! ve is disappearing!**

① This graph does **not** mean the neutrino splits into three pieces — it shows the **chances** of which flavor a detector would record.

ve

0.2%

$\nu\mu$

97.5%

$\nu\tau$

2.3%

Record Event

MISSIONS — WORLD 2 · THROUGH THE EARTH

Crust skimmer

Ride the crust path (detector past 85%).

Claim

NEUTRINO JOURNAL

I was born as a muon neutrino — quantum mixing gives me hidden νe and $\nu\tau$ possibilities.

After 635 km at 0.60 GeV, $\nu\mu$ is currently the most likely detection (97.5%).

DISCOVERIES

Badge: Night-side neutrino — Earned in World 2 — Through the Earth.

Badge: Core diver — Earned in World 2 — Through the Earth.

Badge: $\nu\tau$ climbs high — Earned in World 1 — Earth Oscillation Lab.

Badge: The vanishing $\nu\mu$ — Earned in World 1 — Earth Oscillation Lab.

QUICK QUIZ

Which three flavors do neutrinos have?

Red, green, and blue

Proton, neutron, electron

Up, down, and strange

Electron, muon, and tau



Neutrino Oscillation Journey

Explore how neutrino flavors change with distance, energy, and source.

Explore Mode

Classroom Mode

Research Sandbox

JUMP TO AN EXPERIMENT

Free exploration

WORLD

World 2 · Through the Earth



Scan for a hidden signal

INITIAL FLAVOR

ν_e

ν_μ

ν_τ



Antineutrino mode ($\delta_{CP} \rightarrow -\delta_{CP}$)

NEUTRINO ENERGY

Energy



1.00 GeV

Higher energy stretches the oscillation wavelength (fewer wiggles over the same distance).

BASELINE

Max baseline



12,740 km

Detector at



4,810 km

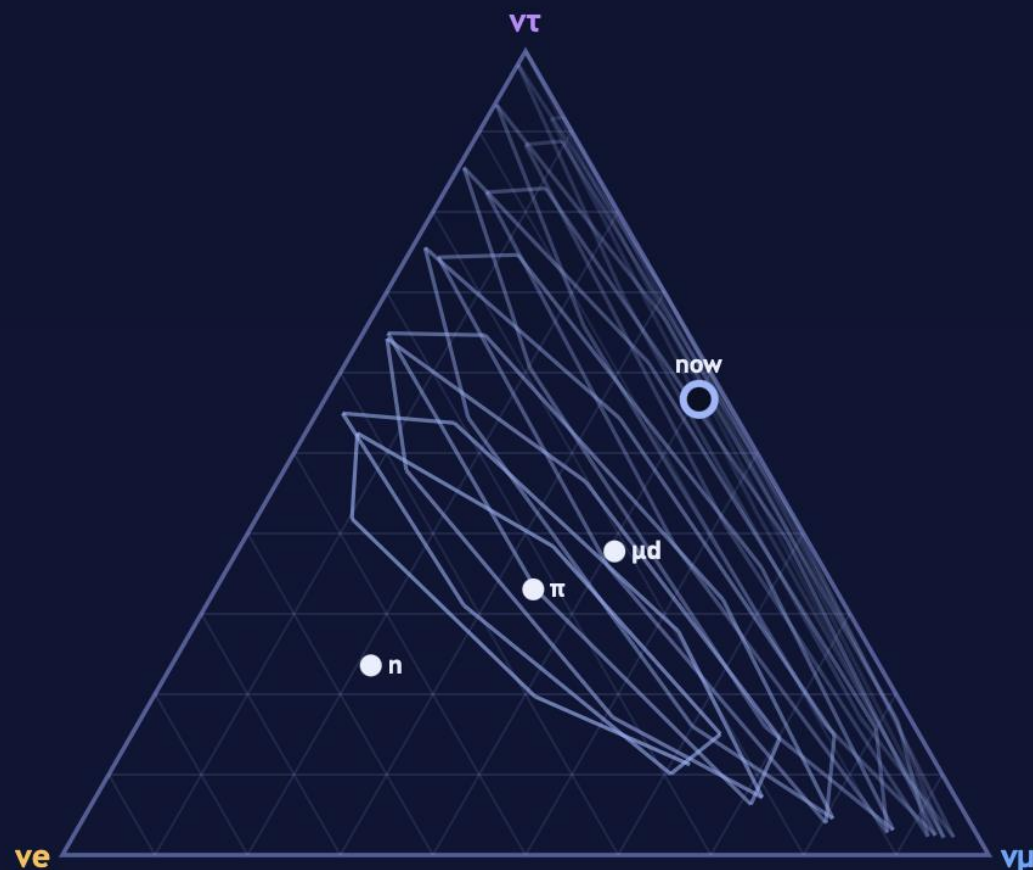
Flavor Race

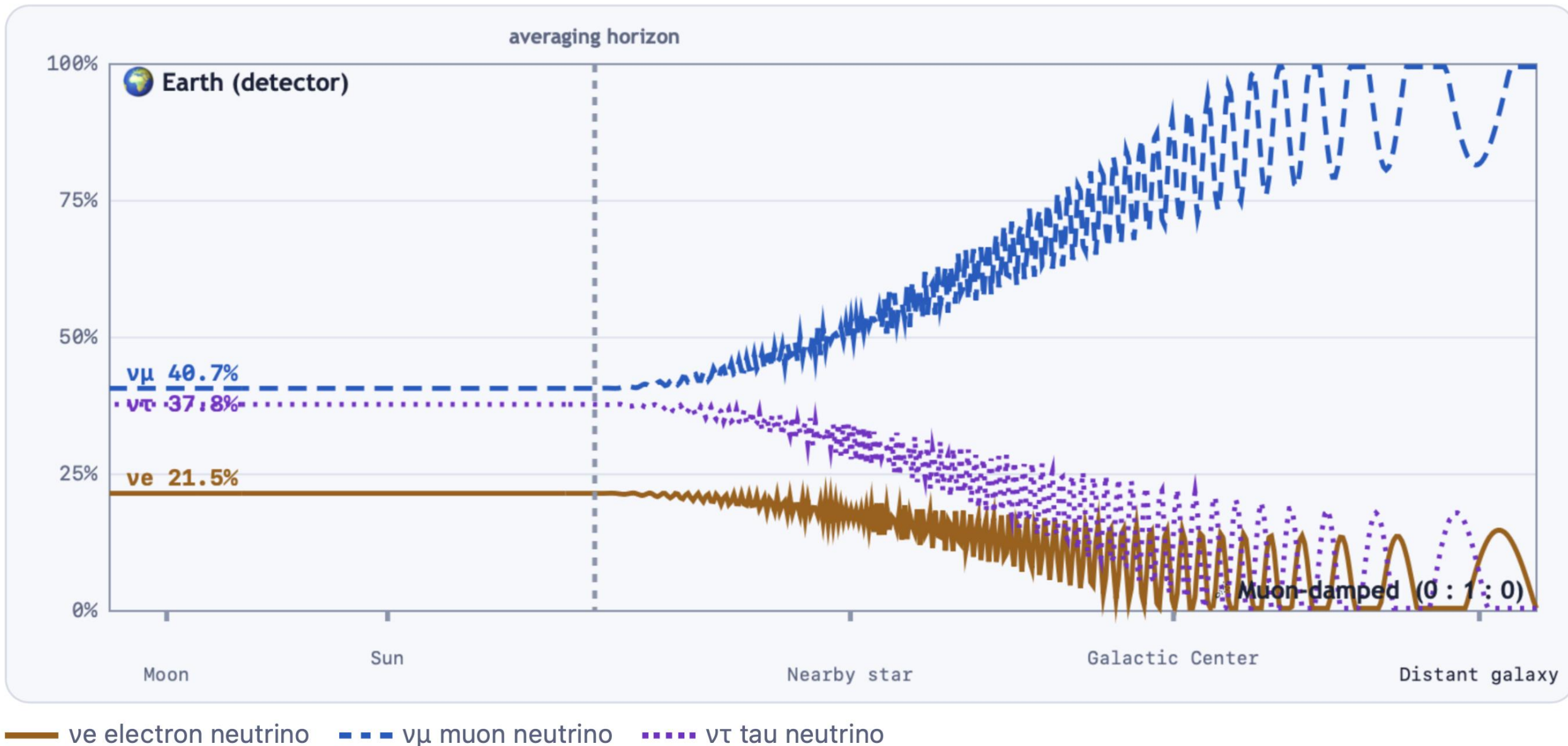
Δ Flavor Triangle

+ BSM Cosmos

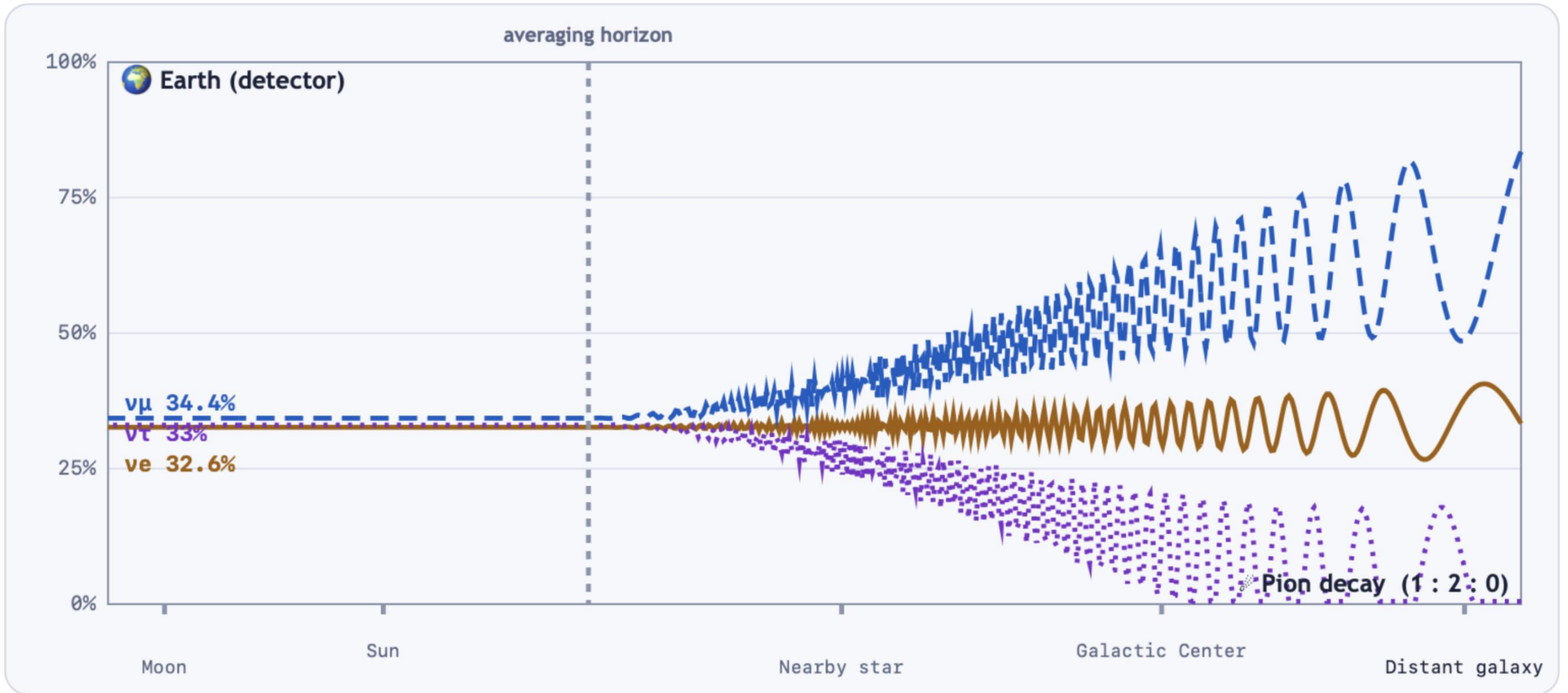
FLAVOR TRIANGLE — THE SCIENTIST MAP

Each point is a mix of $\nu_e : \nu_\mu : \nu_\tau$ (corners = pure flavors).



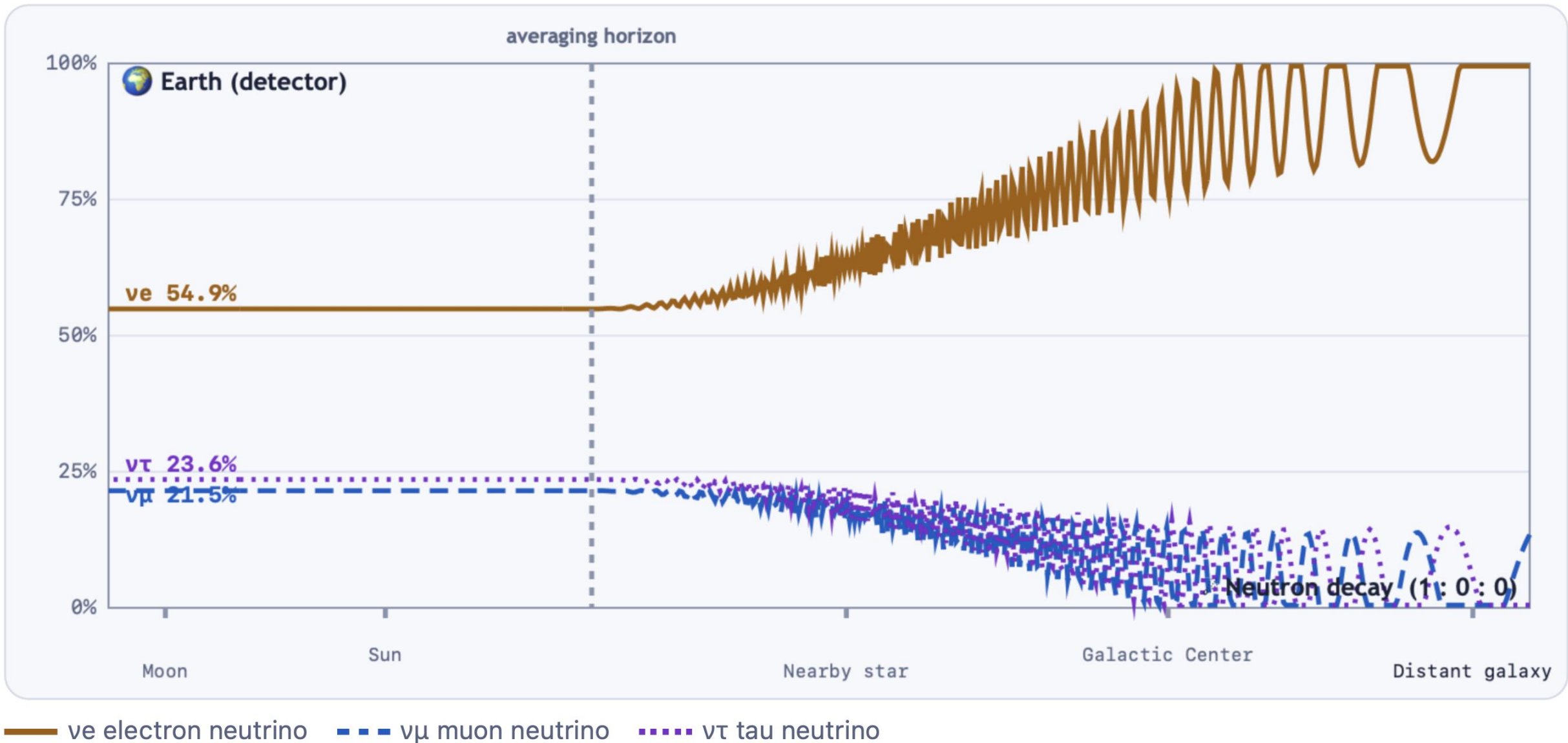


● Muon-damped → averaged across the Distant galaxy distance — ν_μ arrives most often.



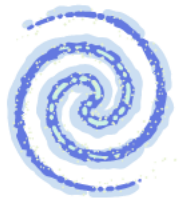
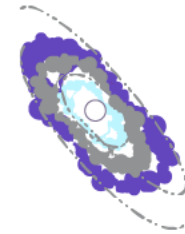
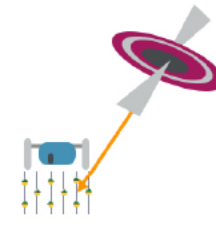
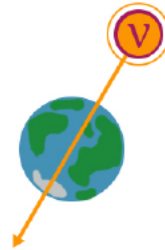
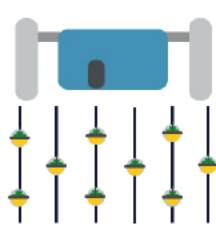
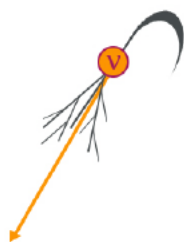
— ν_e electron neutrino - - - ν_μ muon neutrino ν_τ tau neutrino

● Pion decay → averaged across the Distant galaxy distance — ν_μ arrives most often.



- Neutron decay → averaged across the Distant galaxy distance — ve arrives most often.

A History of Neutrino Astronomy in Antarctica



1988

Telescope in the
Ice Envisioned

2000

AMANDA
Completed

2001

Atmospheric
Neutrinos
Detected

2011

IceCube
Completed

2013

Astrophysical
Neutrinos
Discovered

2018

First Source
TXS 0506+056
Identified

2021

Glashow
Resonance
Neutrino
Identified

2022

Second Source
NGC 1068
Identified

2023

Third Source
Milky Way
Identified