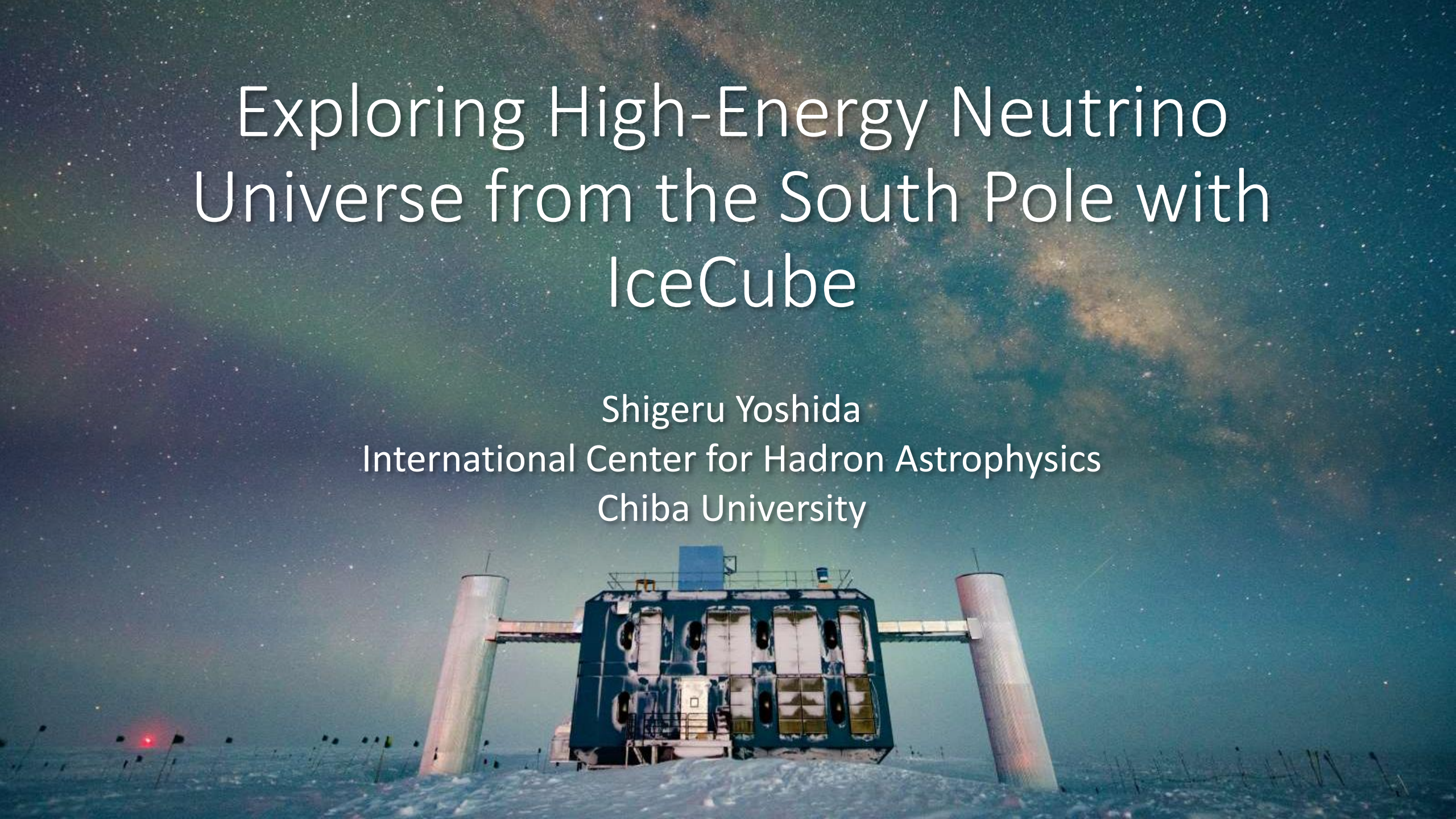
Exploring High-Energy Neutrino Universe from the South Pole with IceCube

Shigeru Yoshida
International Center for Hadron Astrophysics
Chiba University




THE ICECUBE COLLABORATION
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Universiteit Gent
Vrije Universiteit Brussel
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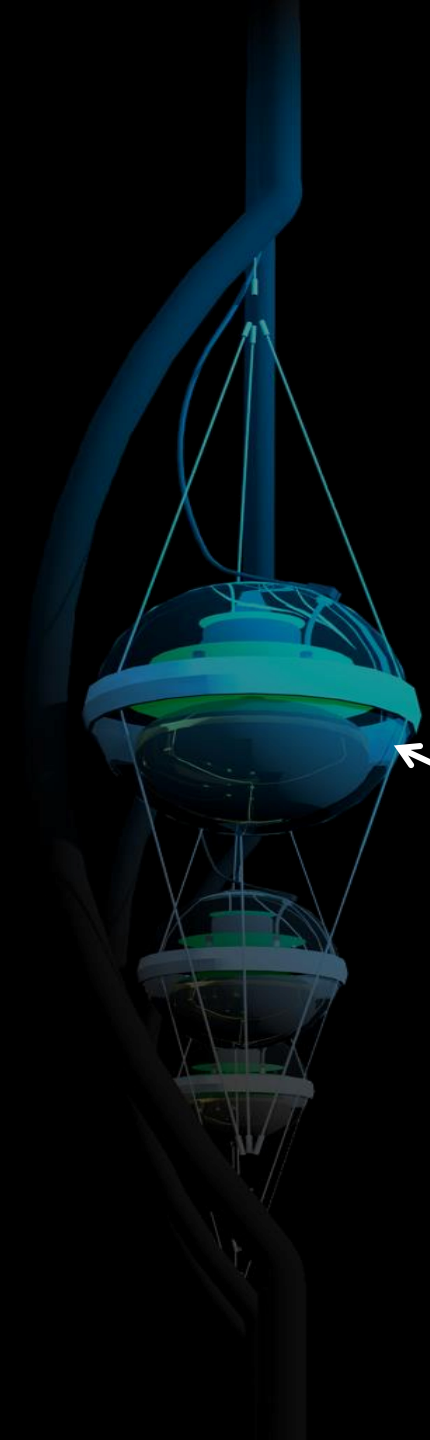
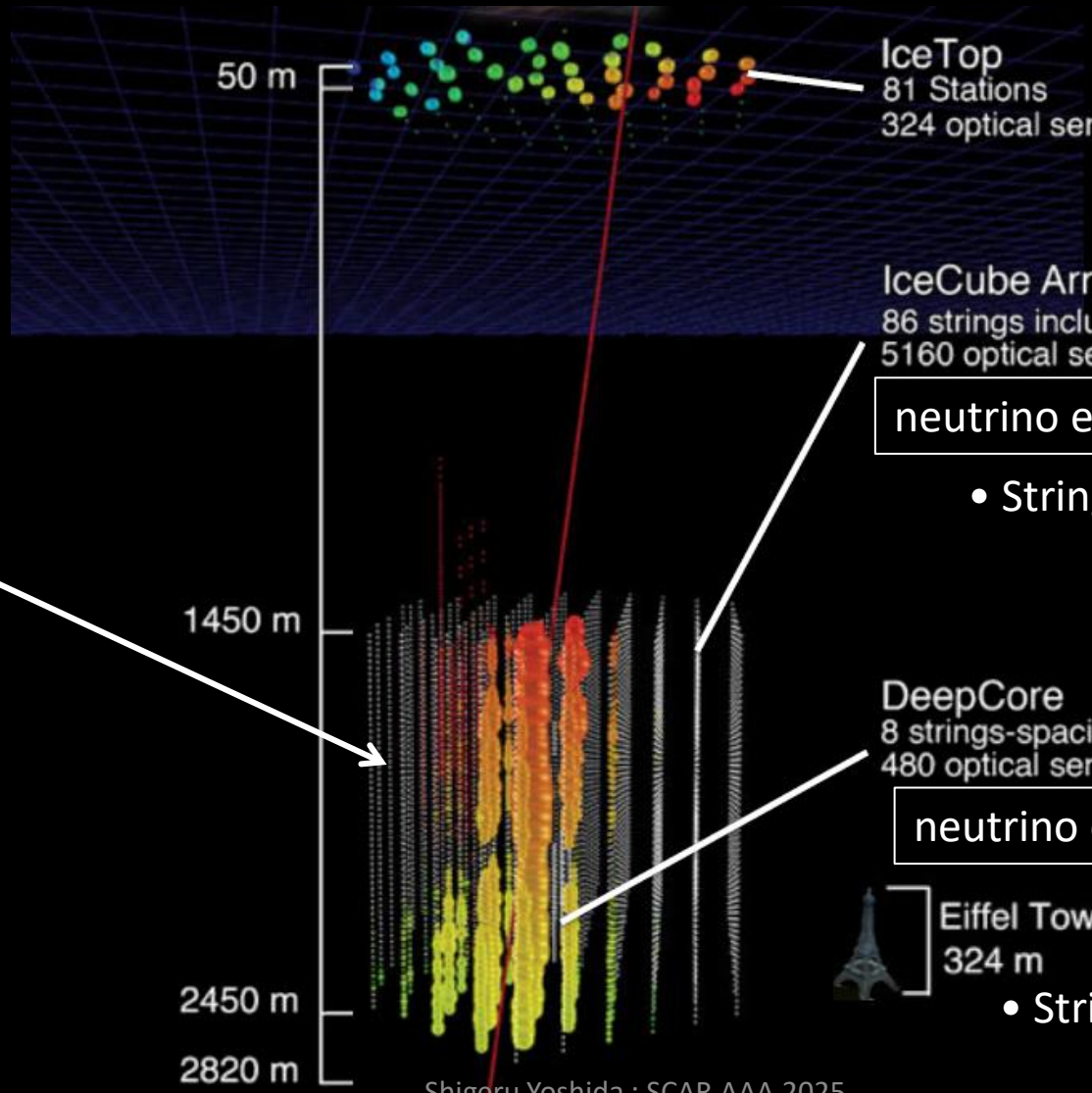
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

The IceCube Detector





IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

neutrino energy: 1TeV-100EeV

- String spacing 125 m, DOM spacing of 17 m

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

neutrino energy: 5GeV-100GeV

Eiffel Tower
324 m

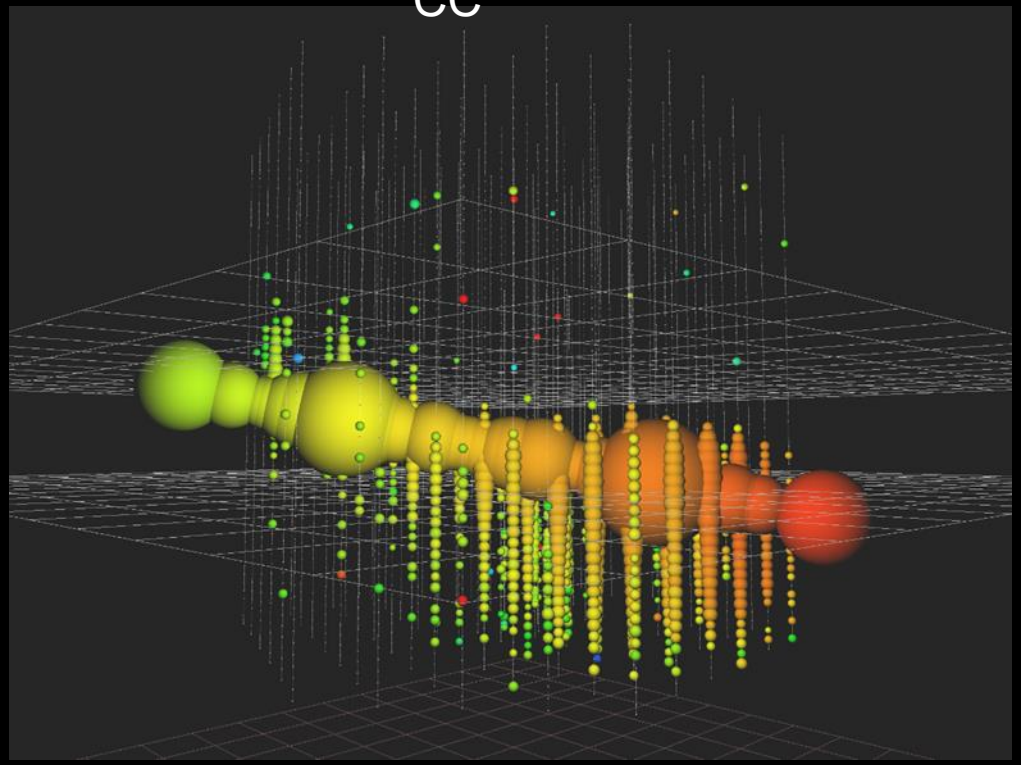
- String spacing ~70 m, DOM spacing of 7 m

IceCube Event Topology

Track

$\nu_\mu \xrightarrow[CC]{} \mu$

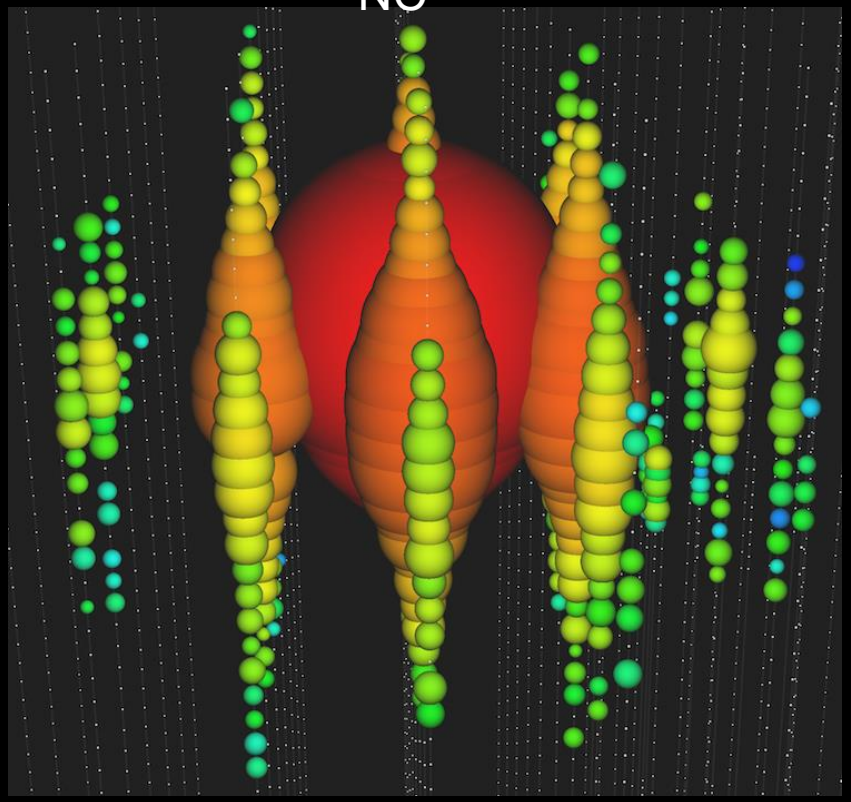
$\nu_\tau \xrightarrow[CC]{} \tau$ (only at ultra-high energies)



Cascade (shower)

$\nu_e \xrightarrow[CC]{} e + X$

$\nu_x \xrightarrow[NC]{} x + X$ x=e, μ, τ



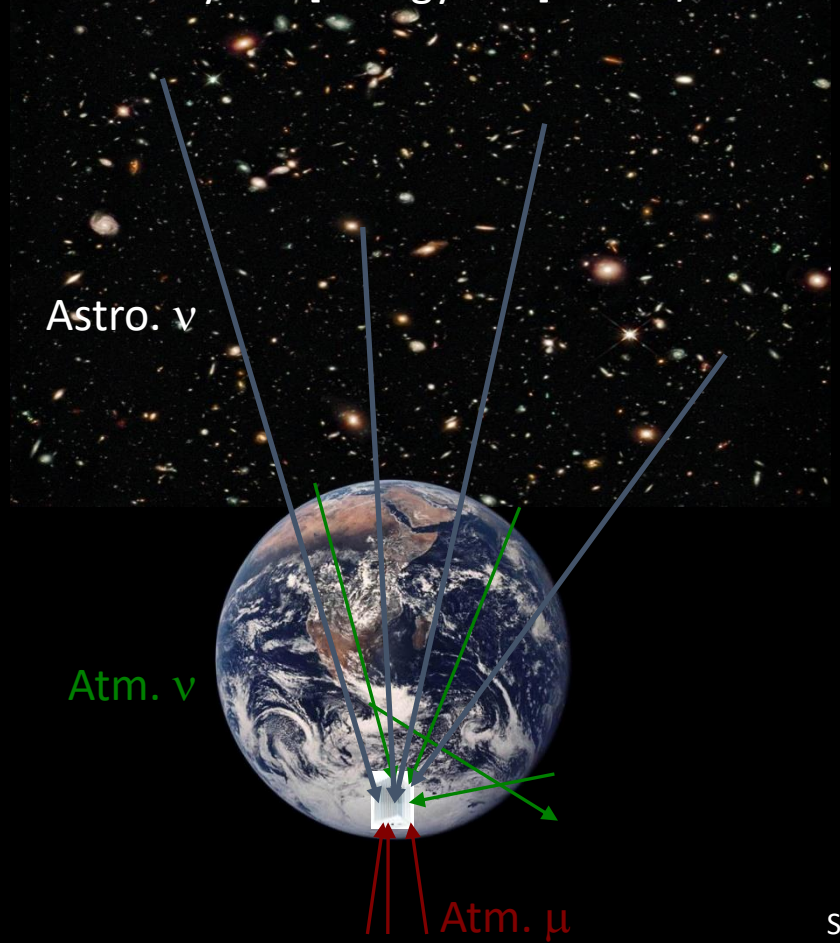
Concepts of the Cosmic fluxes

cosmic background flux

= sum from all (**likely unresolved**) extraterrestrial sources from all-sky

[flux] = /cm^2 s str

"luminosity" or [energy flux] = GeV/cm^2 s str



Point-source Flux = flux from a (resolved) astronomical object (including an *extended source*)

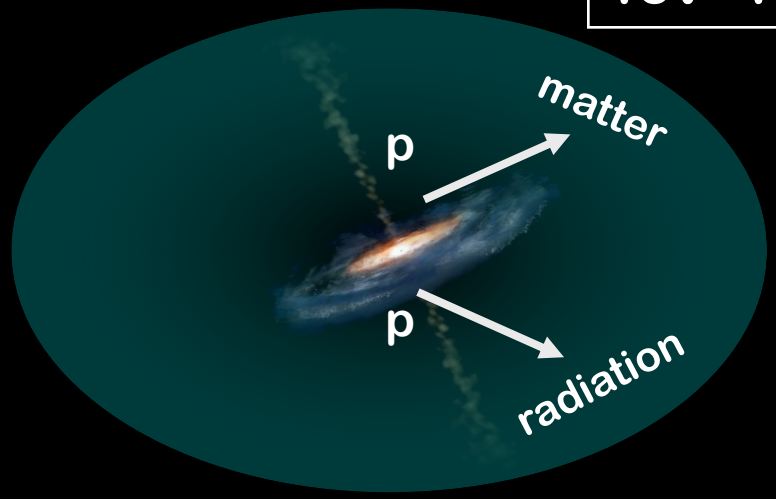
[flux] = /cm^2 s

"energy flux" or [sed] = erg (or TeV) /cm^2 s

The Cosmic Neutrinos
Production Mechanisms

"On-source" ν

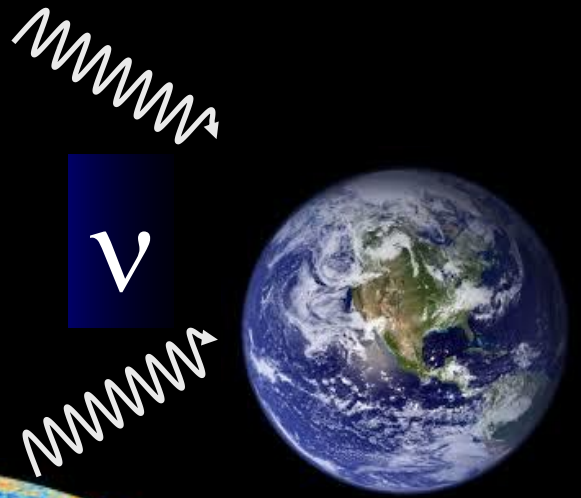
TeV - PeV



$pp \rightarrow \pi \rightarrow \nu$

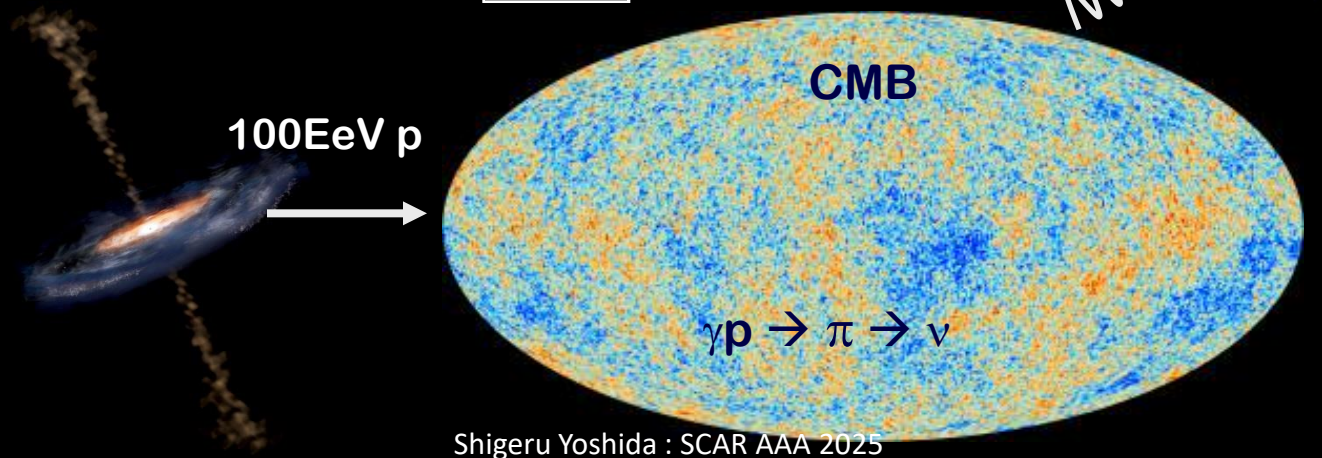
$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production



"GZK" cosmogenic ν

EeV

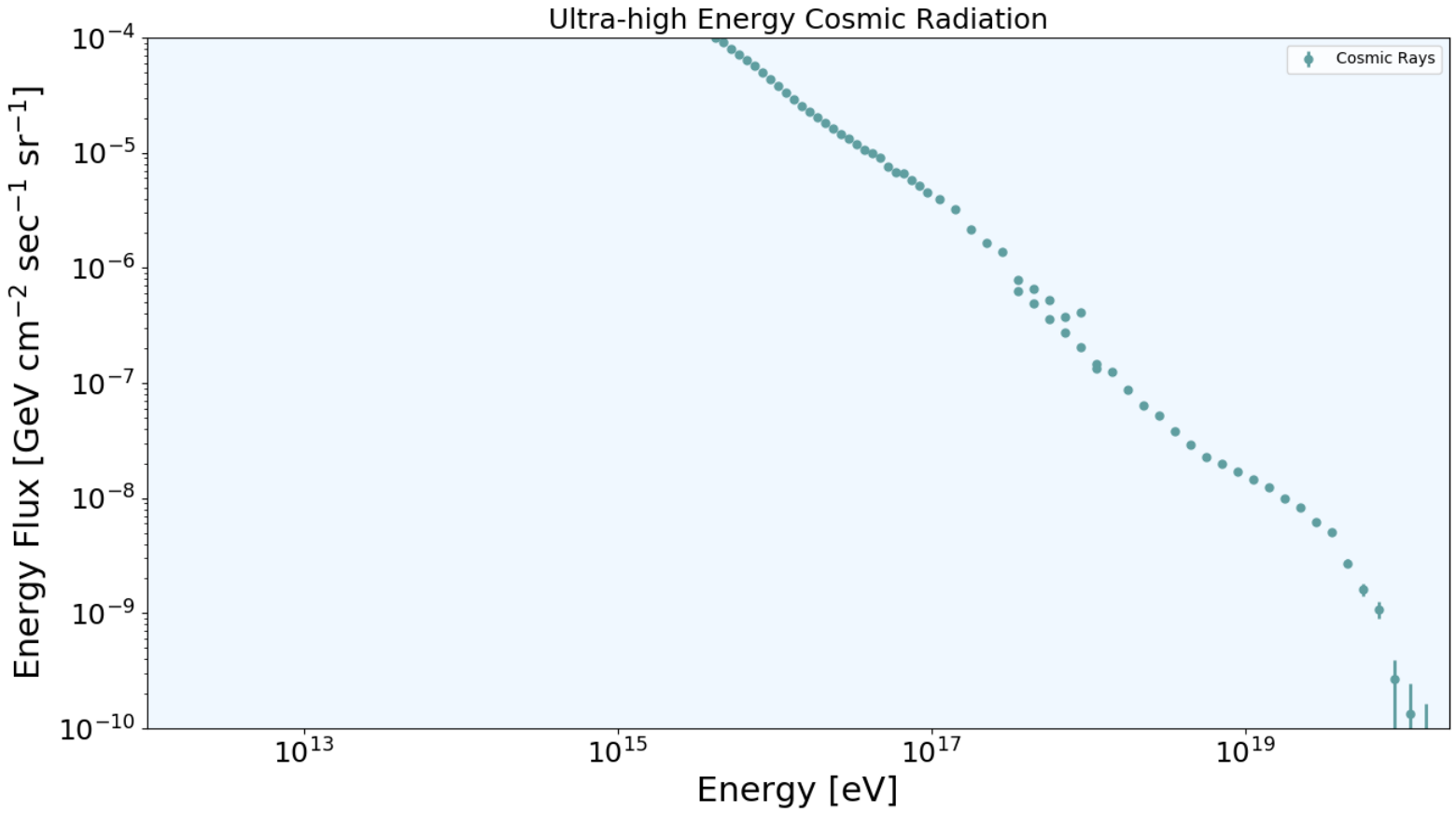


TeV PeV EeV

The UHE Cosmic Background Radiations

The UHE Cosmic Ray **Energy** Flux

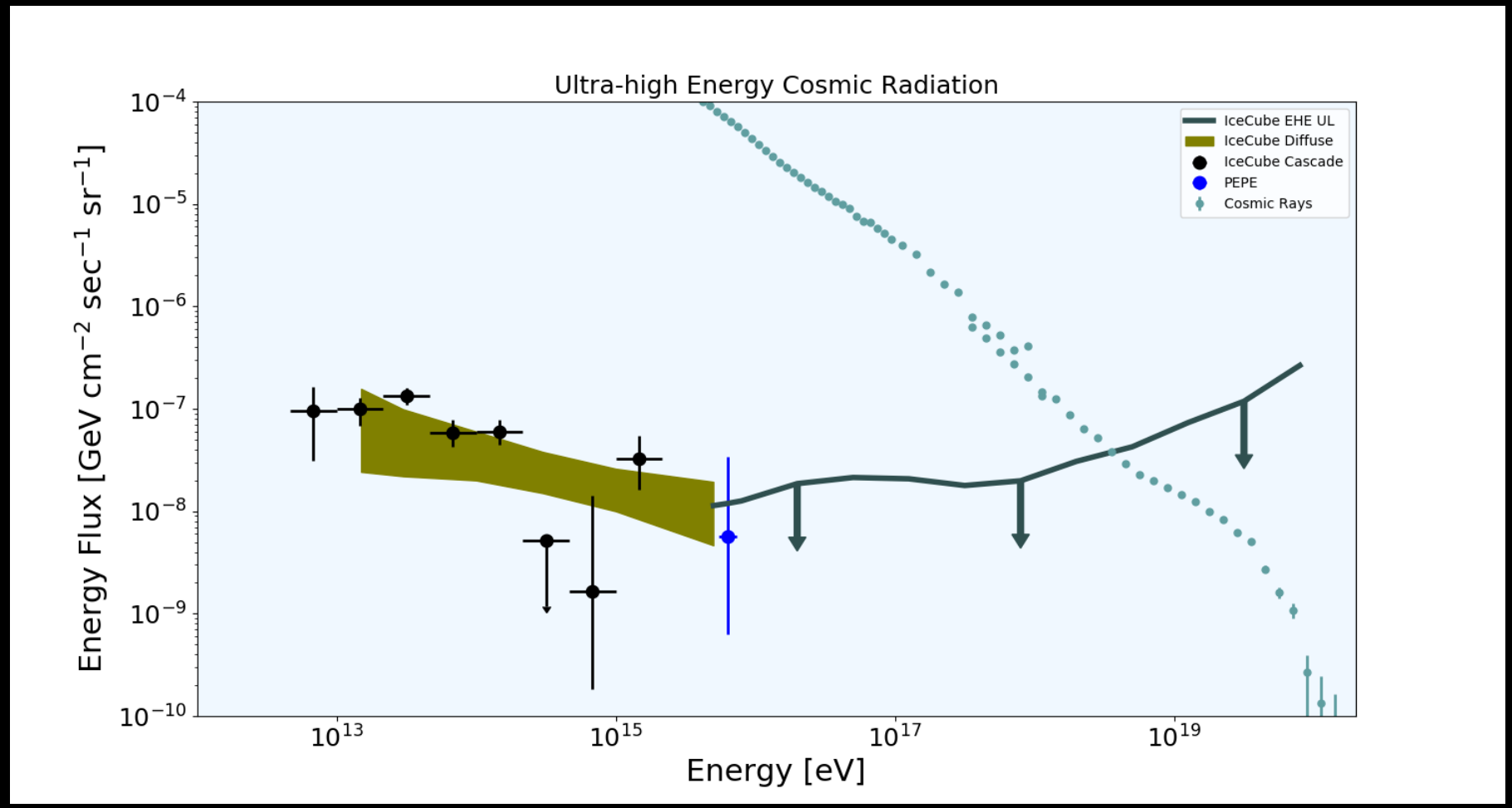
[energy]/[area][time][solid angle]



TeV PeV EeV

The UHE Cosmic Background Radiations

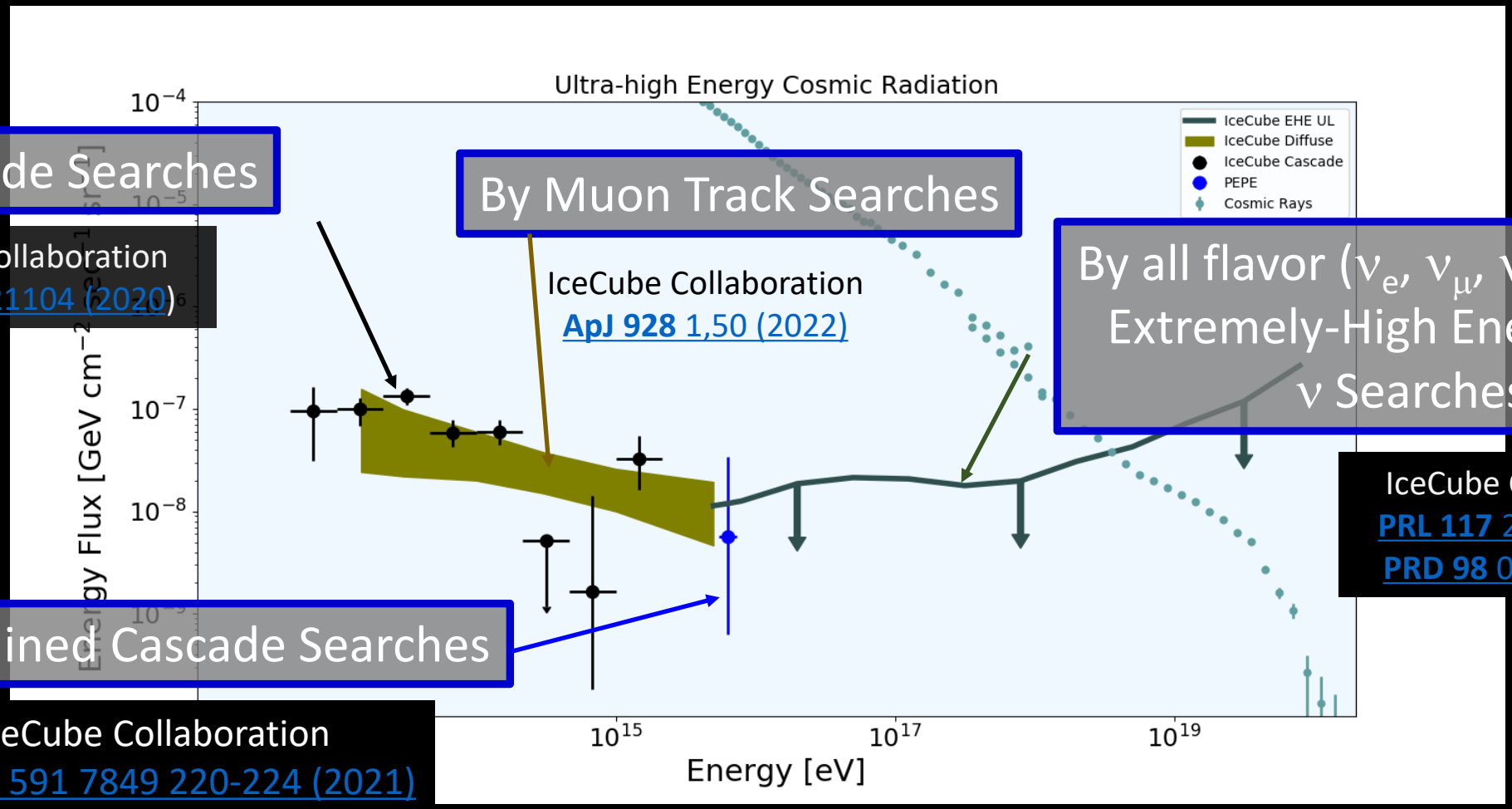
The UHE Cosmic Ray + **Neutrino** **Energy** Fluxes



TeV PeV EeV

The UHE Cosmic Background Radiations

The UHE Cosmic Ray + **Neutrino** **Energy** Fluxes



By Cascade Searches

IceCube Collaboration
PRL 125 121104 (2020)

By Muon Track Searches

IceCube Collaboration
ApJ 928 1,50 (2022)

By all flavor (ν_e, ν_μ, ν_τ) sensitive Extremely-High Energy (EHE) ν Searches

IceCube Collaboration
PRL 117 241101 (2016)
PRD 98 062003 (2018)

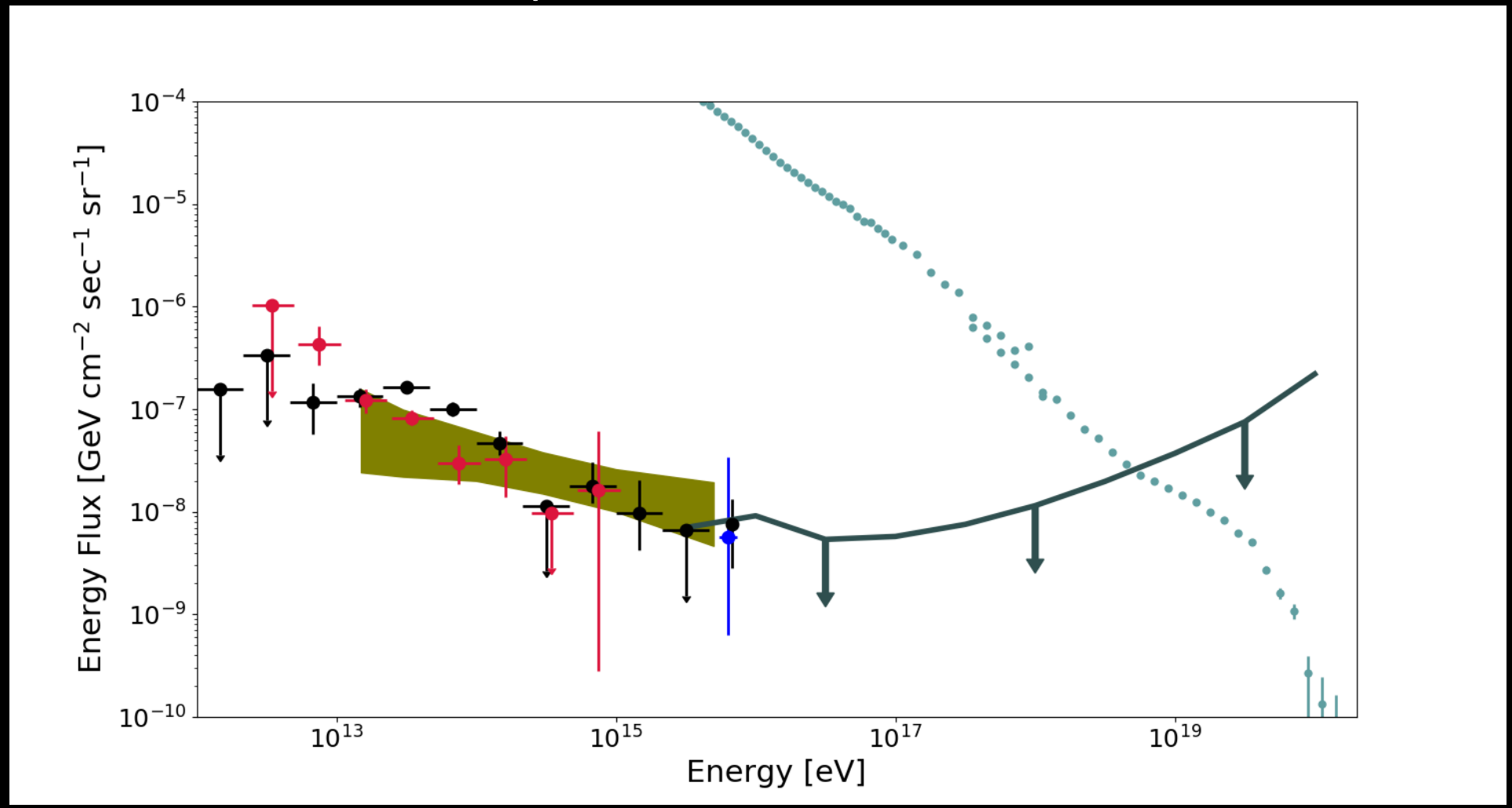
By Uncontained Cascade Searches

IceCube Collaboration
Nature 591 7849 220-224 (2021)

TeV PeV EeV

The UHE Cosmic Background Radiations

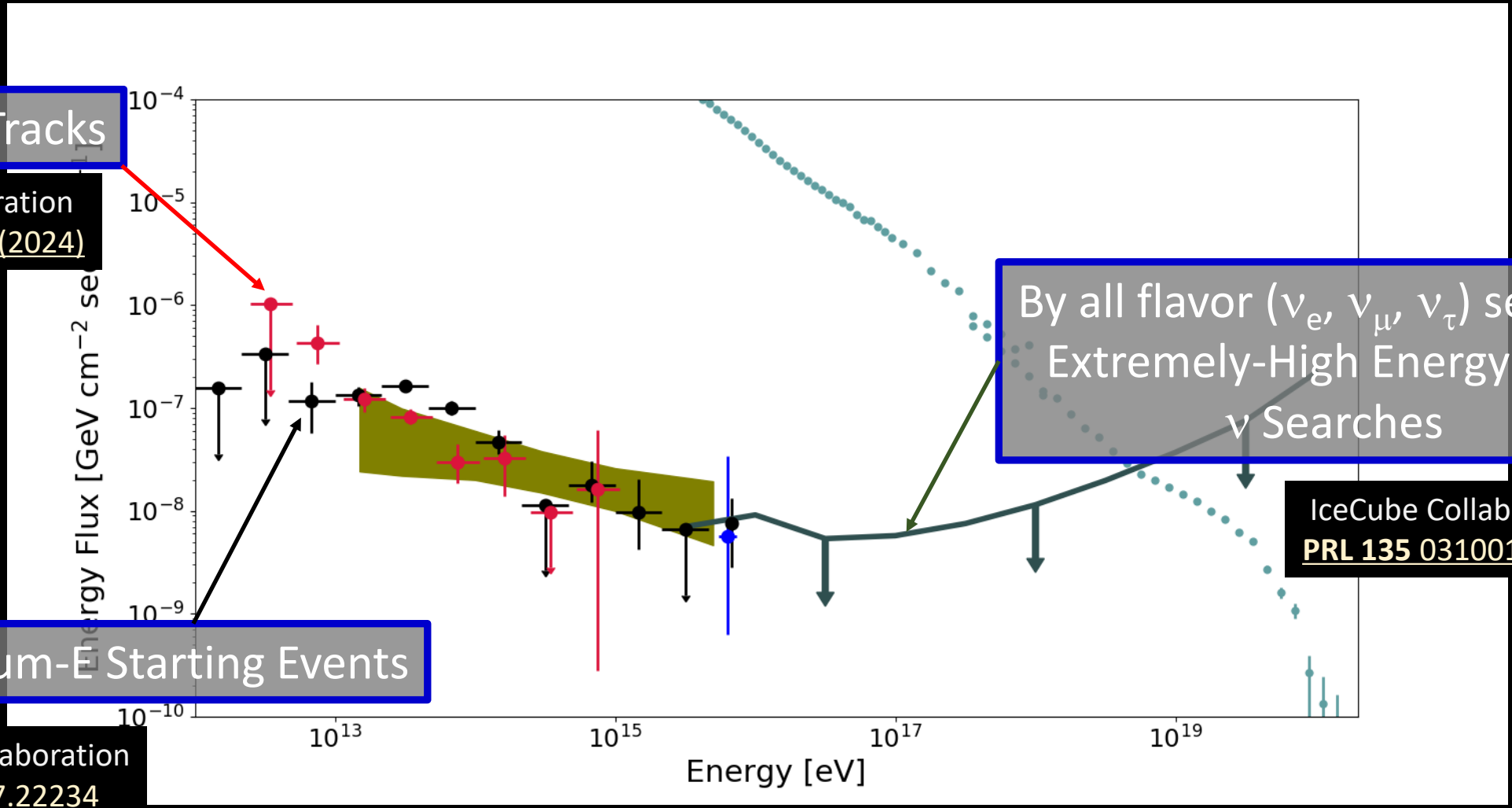
Updated : as of 2025



TeV PeV EeV

The UHE Cosmic Background Radiations

Updated : as of 2025



By Starting Tracks

IceCube Collaboration
PRD 110 022001 (2024)

By all flavor (ν_e, ν_μ, ν_τ) sensitive Extremely-High Energy (EHE) ν Searches

IceCube Collaboration
PRL 135 031001 (2025)

By Medium-E Starting Events

IceCube Collaboration
arXiv:2507.22234
arXiv:2507.22234

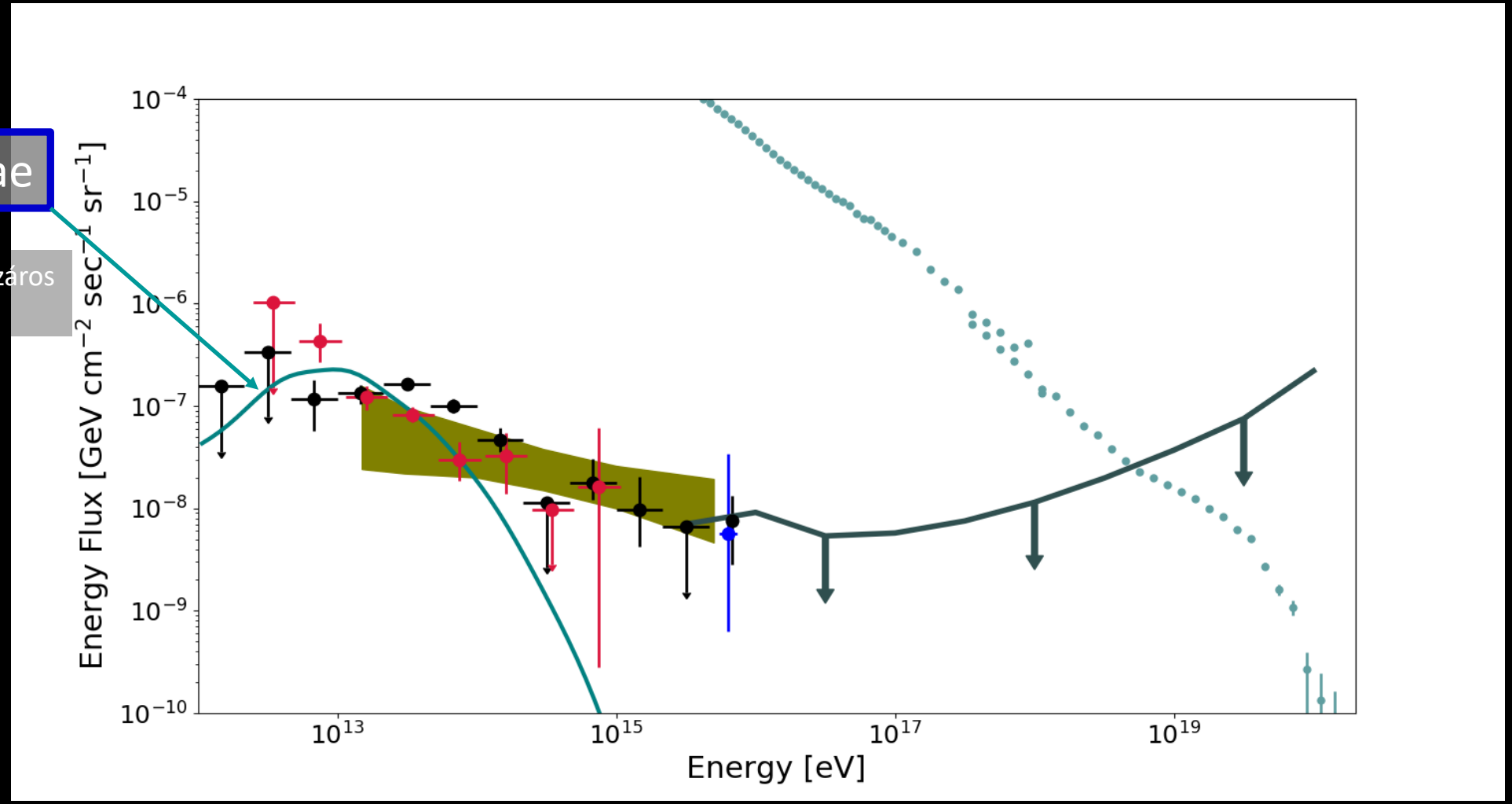
TeV PeV EeV

The UHE Cosmic Background Radiations

Explainable? A possible scenario

AGN Coronae

Murase, Kimura, Mészáros
PRL (2020)

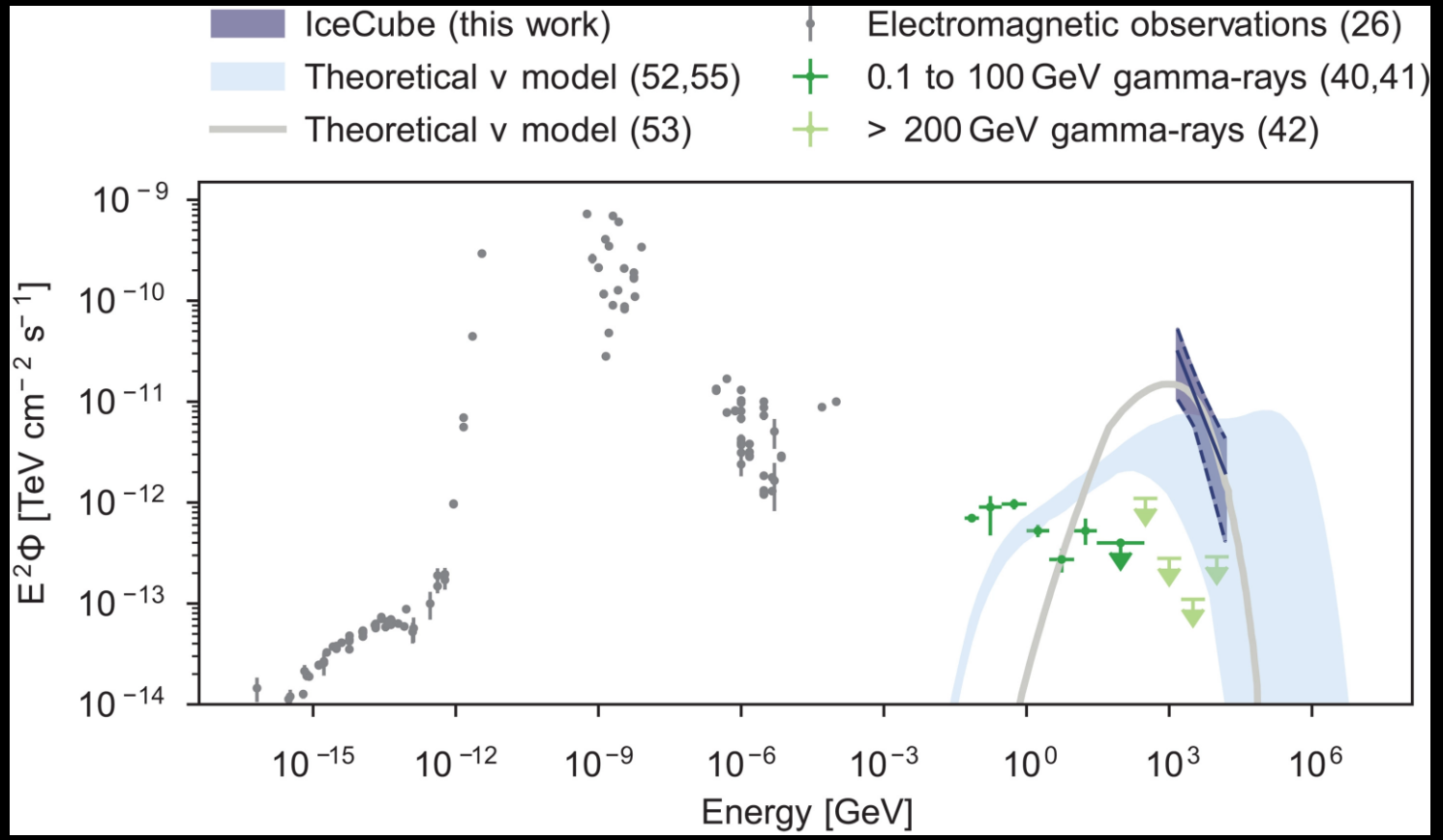


TeV PeV EeV

TeV ν sky

IceCube Collaboration
Science **378** 538 (2022)

Seyfert II Galaxy NGC 1068



TeV PeV EeV

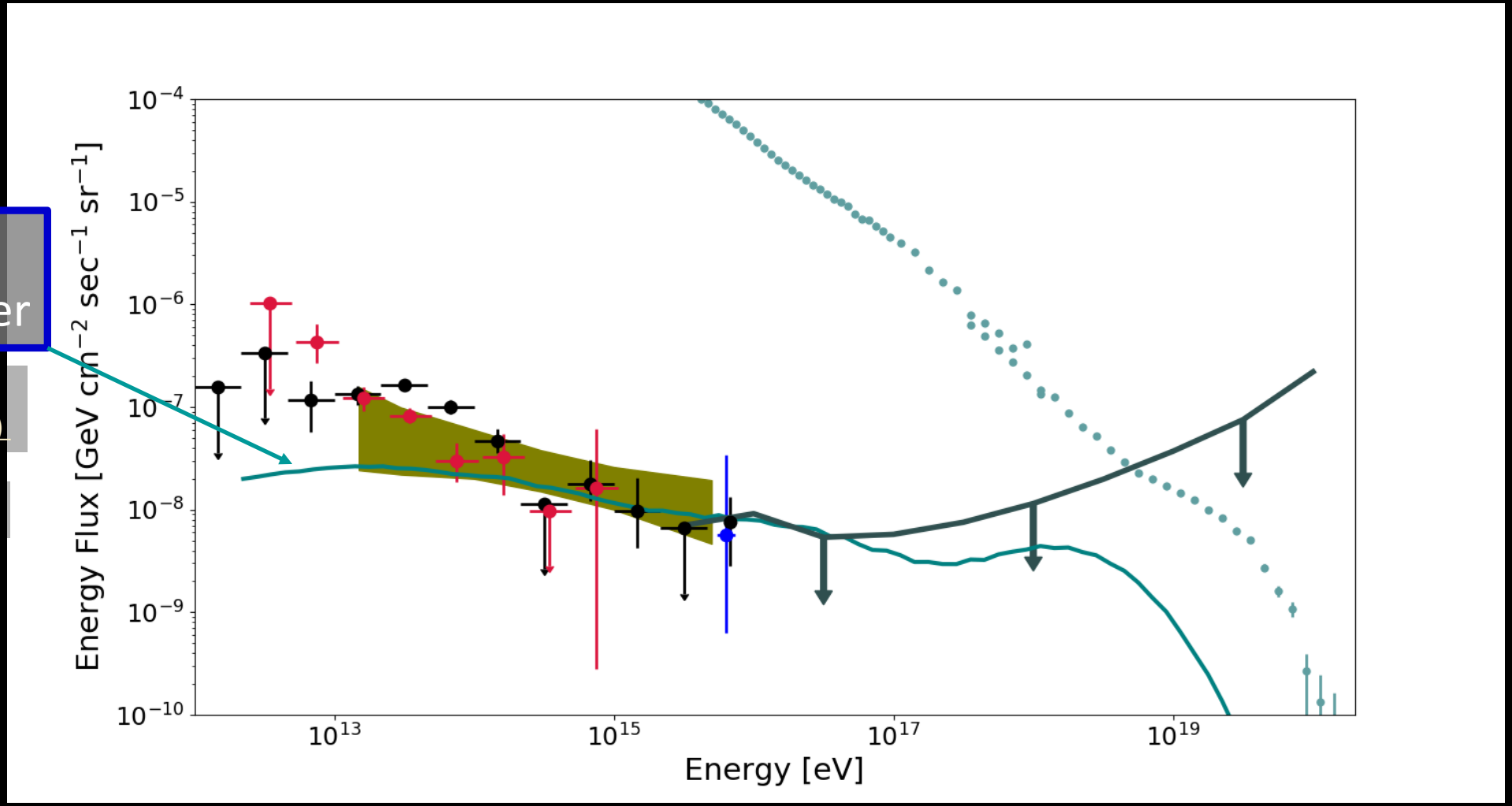
The UHE Cosmic Background Radiations

Explainable? A possible scenario

AGN in a galaxy cluster

Fang, Murase
Nature Phys (2018)

"Cosmic reservoir"



TeV PeV EeV

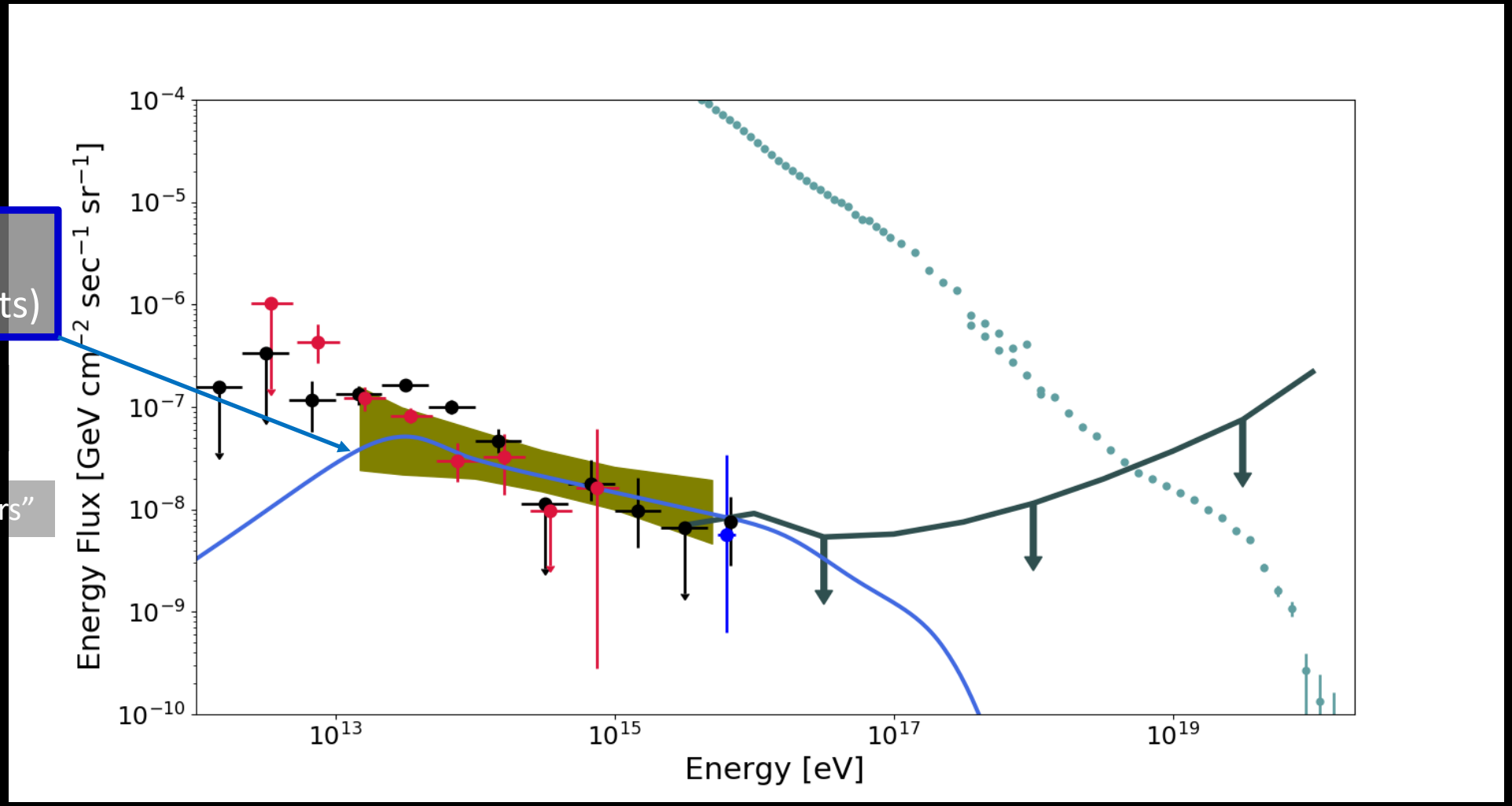
The UHE Cosmic Background Radiations

Explainable? A possible scenario

LL GRBs
(X-ray transients)

Yoshida, Murase
PRD (2024)

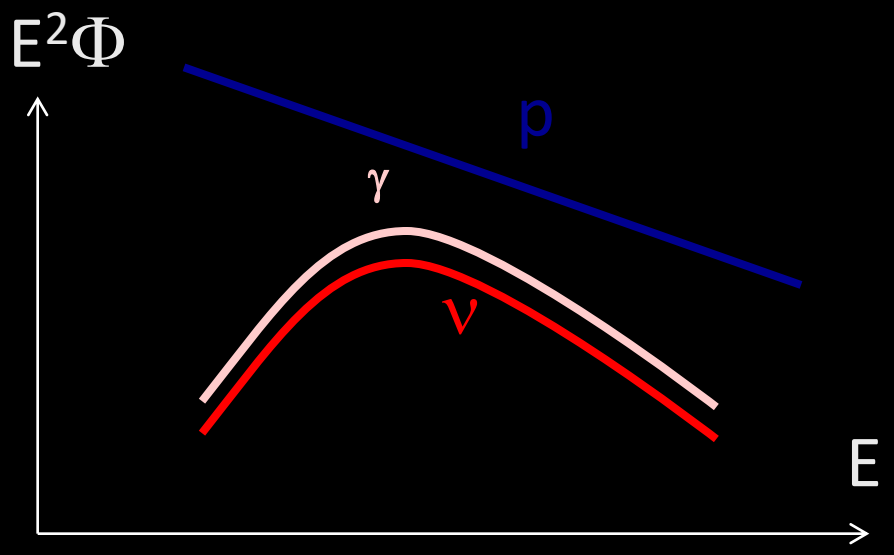
"Cosmic accelerators"

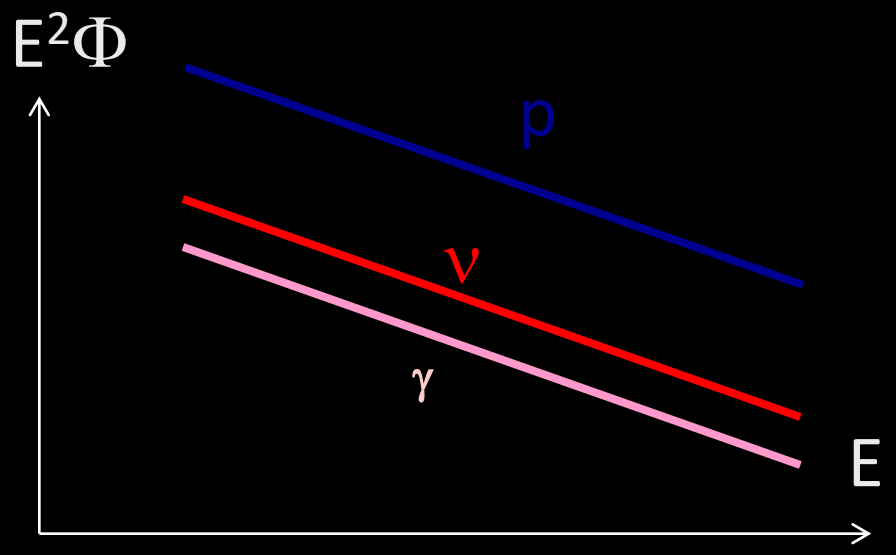


γp? or pp?

$$p + \gamma \rightarrow N\pi + X$$

$$p + p \rightarrow N\pi + X$$





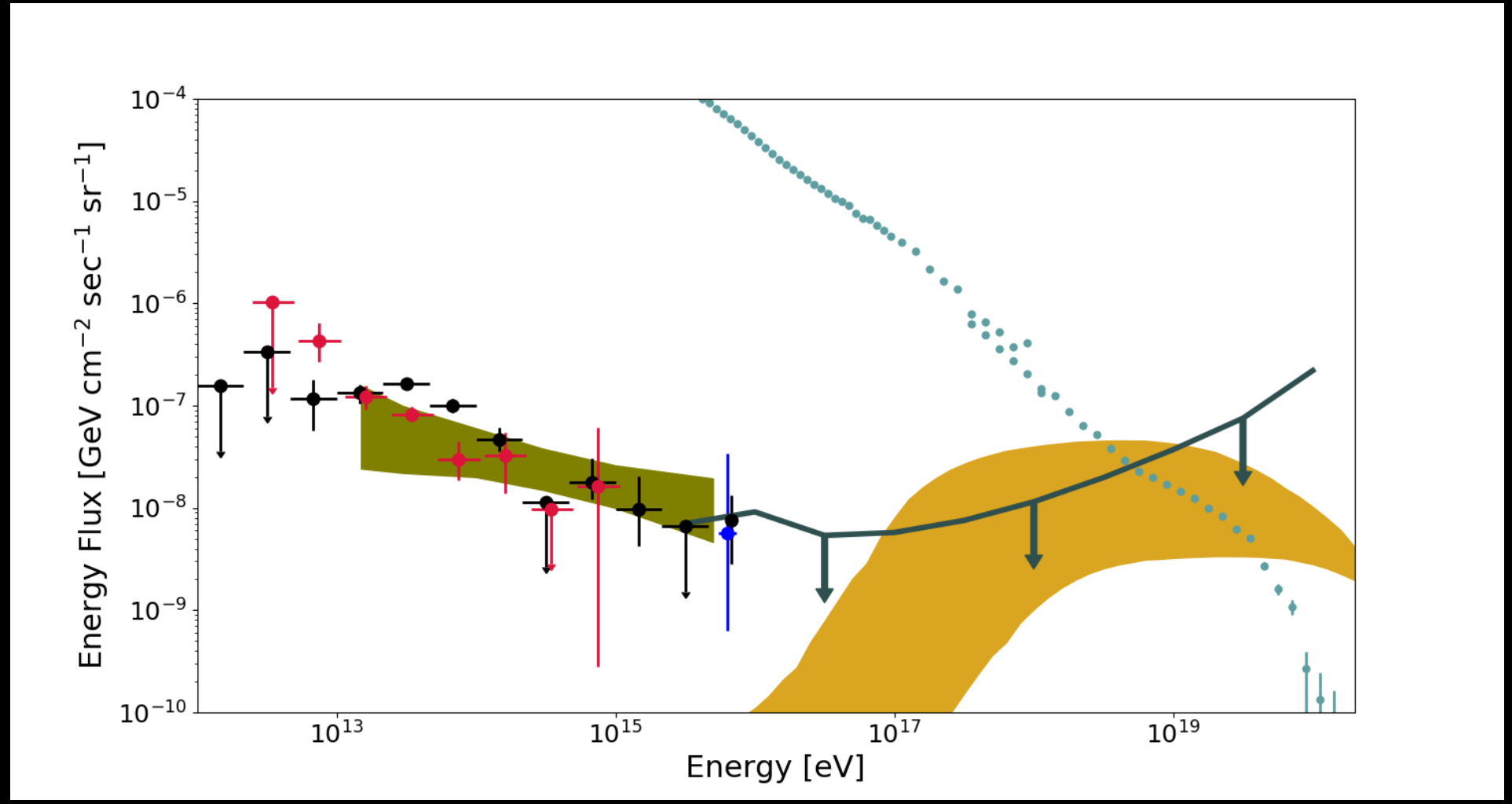
Convolute target γ spectrum

Copy p spectrum

TeV PeV EeV

The UHE Cosmic Background Radiations

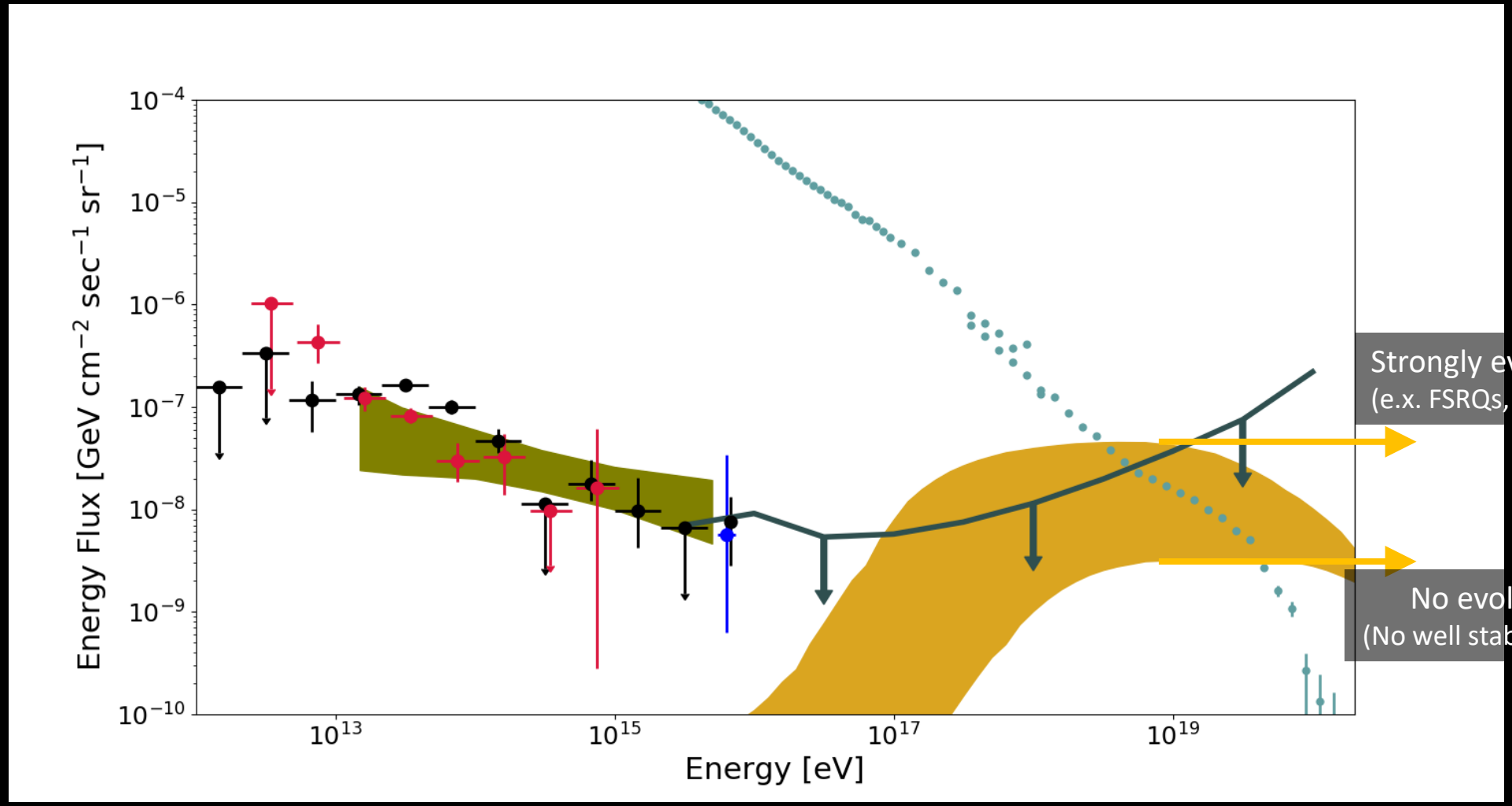
Constraints on ultra-high energy cosmic ray sources



TeV PeV EeV

The UHE Cosmic Background Radiations

Constraints on ultra-high energy cosmic ray sources



Multimessenger approaches

List of known X-ray/Gamma-ray sources

Hard X-ray AGNs
(NGC1068, NGC4151,…)

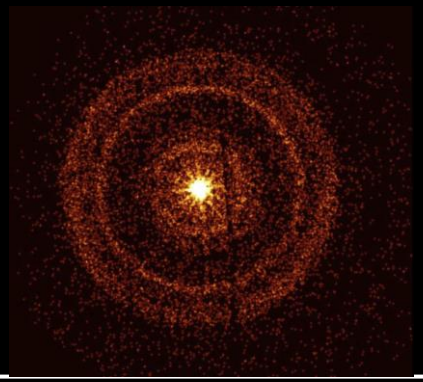
IceCube Collaboration ApJ (2025)

Blazars < 10% of the all sky ν flux

non-Blazars : <100% (statistical limit)

GRBs

IceCube Collaboration ApJ (2024) ApJ (2022)

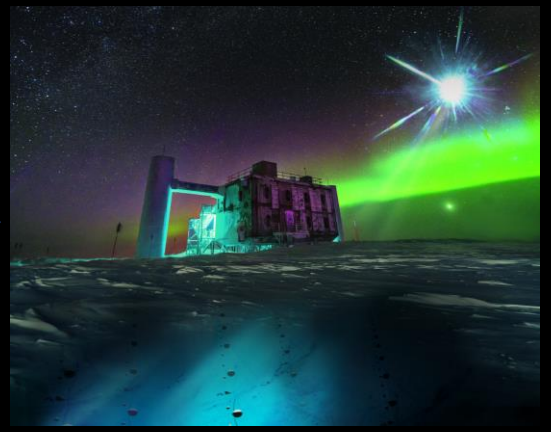


No detection from the BOAT GRB

prompt GRB emission < 1% of the all sky ν flux

~10^4 sec emission < 24%

IceCube



Multimessenger approaches

Look for (unknown) X-ray/Optical transients

X-ray monitors/observatories

Optical/NIR telescopes

published results

NMRAS (2023)

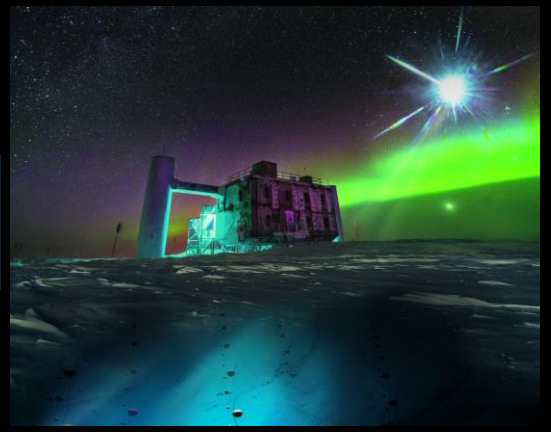
arXiv:2504.04741

arXiv:2584.08355

ApJ (2019)

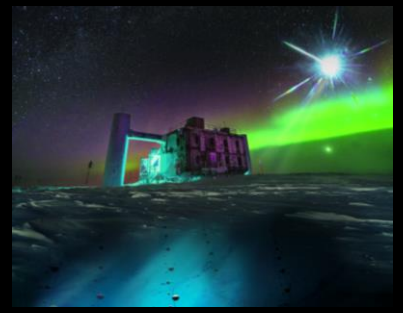
public alerts/
archival data

IceCube



The claimed neutrino-TDE associations are now in question

IceCube

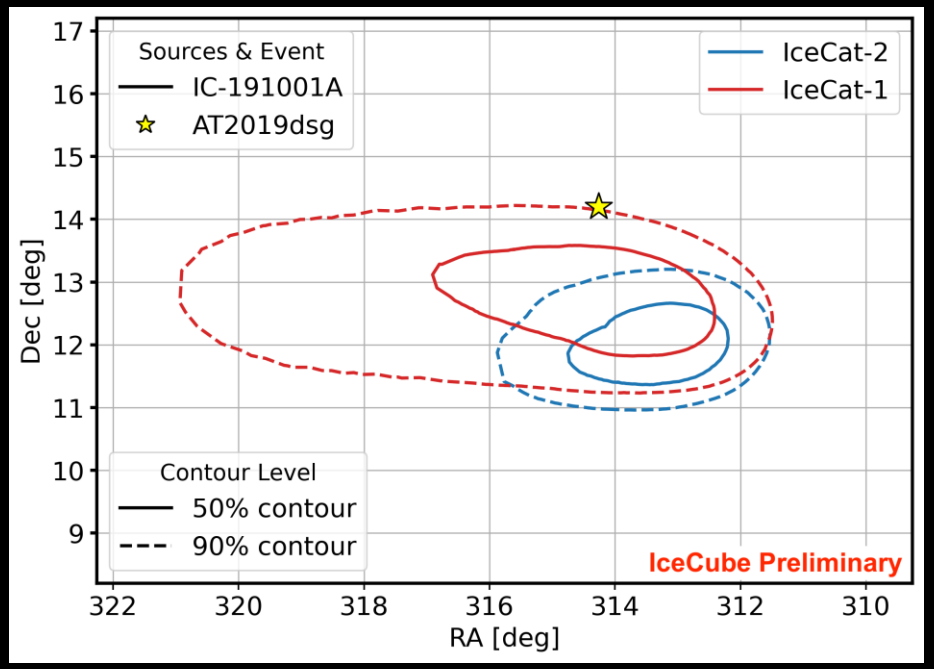


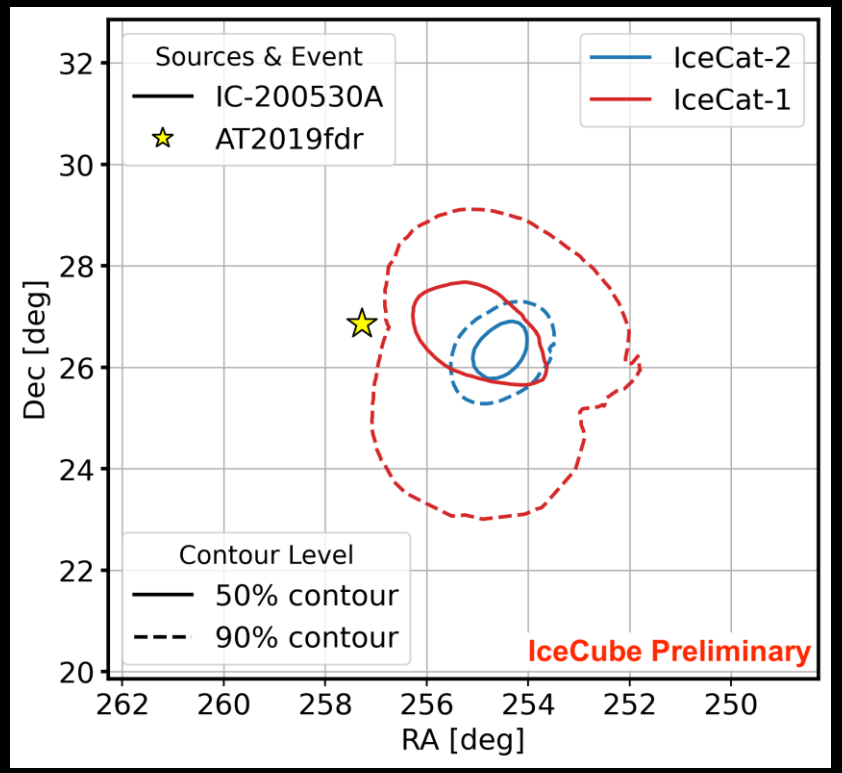
ZWICKY TRANSIENT FACILITY

AT2019dsg Stein et al Nature Astronomy (2021)

AT2019fdr Reusch et al PRL (2022)

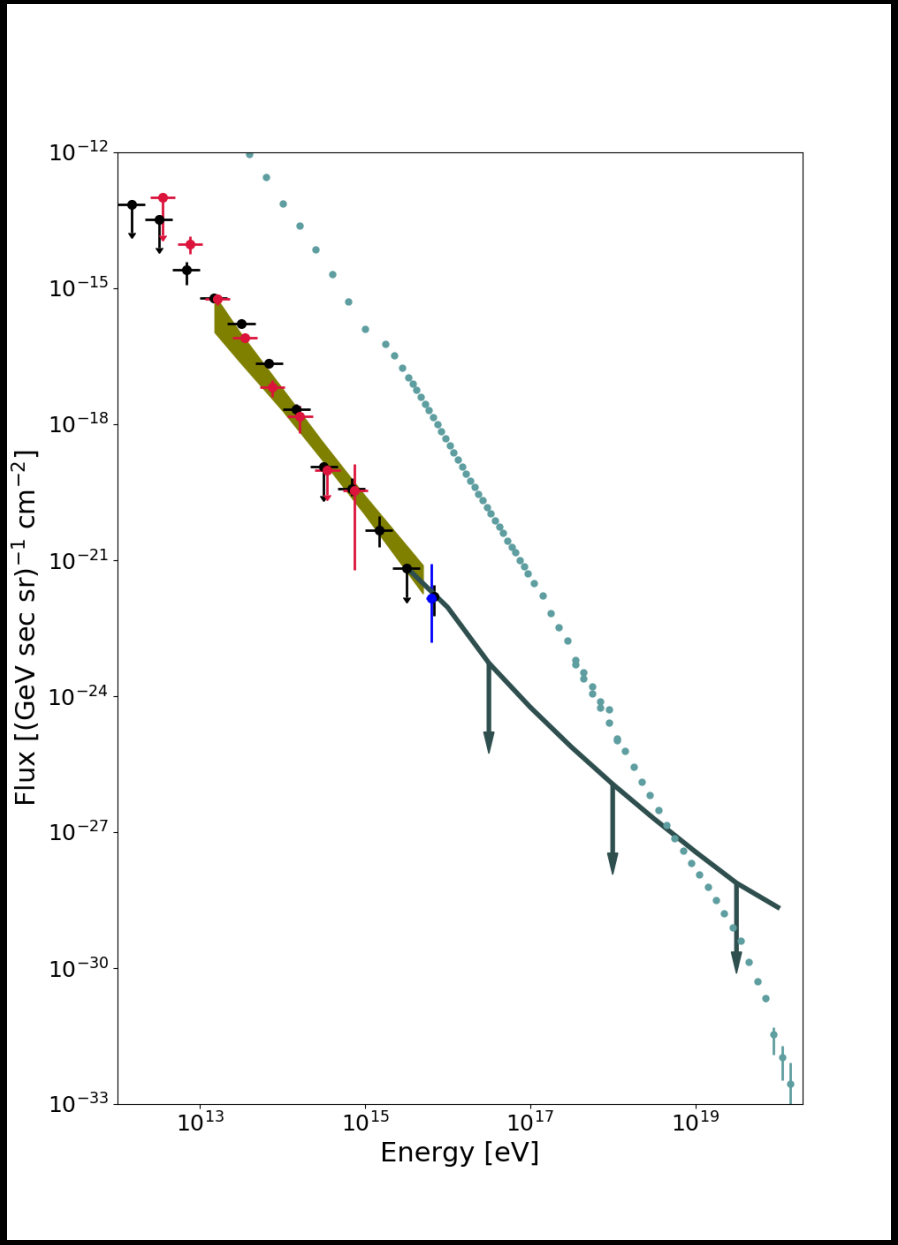
Angela Zegarelli+ for IceCube Collaboration: arXiv:2507.06176



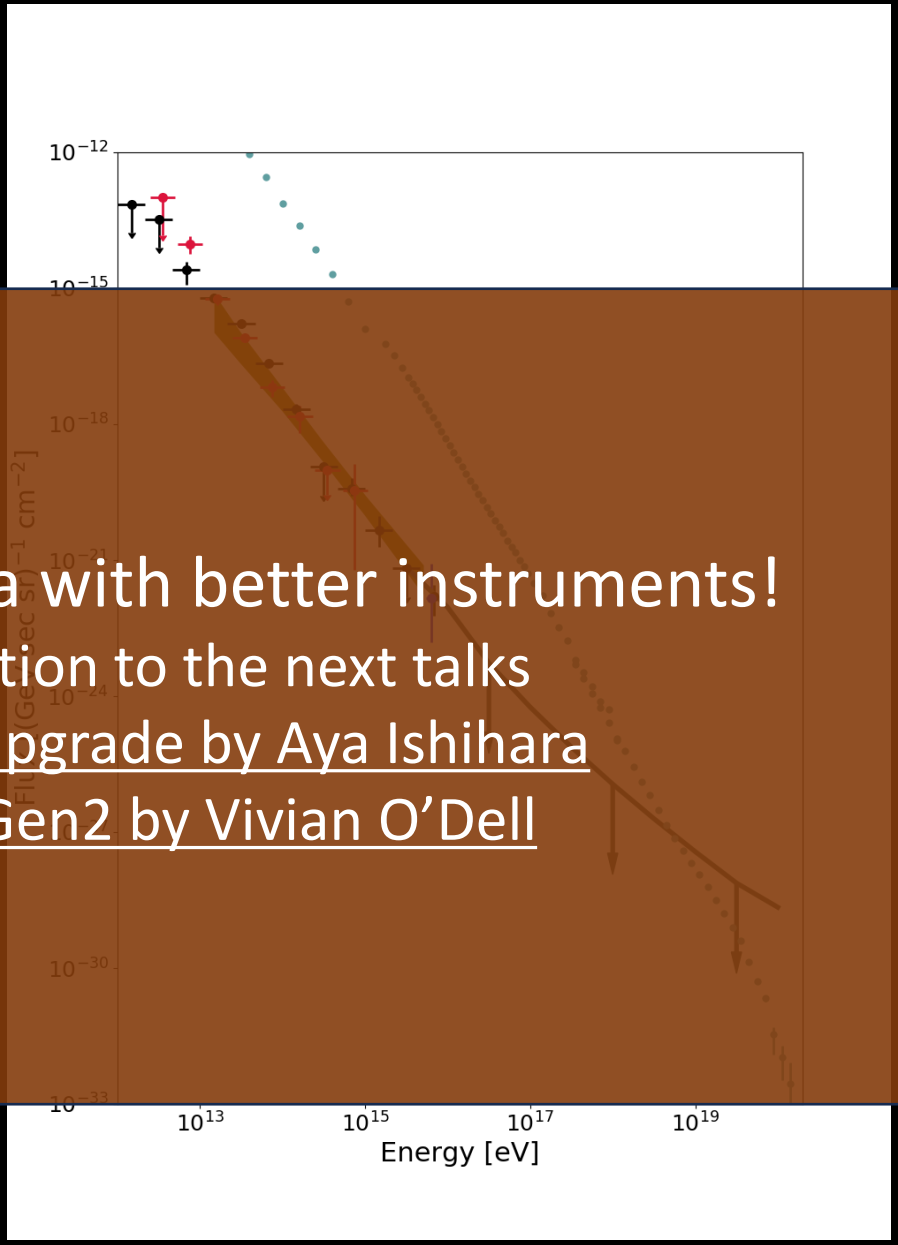


Neutrino Flux spans the huge range

15 orders of magnitude!!



Neutrino Flux spans the huge range



Needs more data with better instruments!

pay attention to the next talks

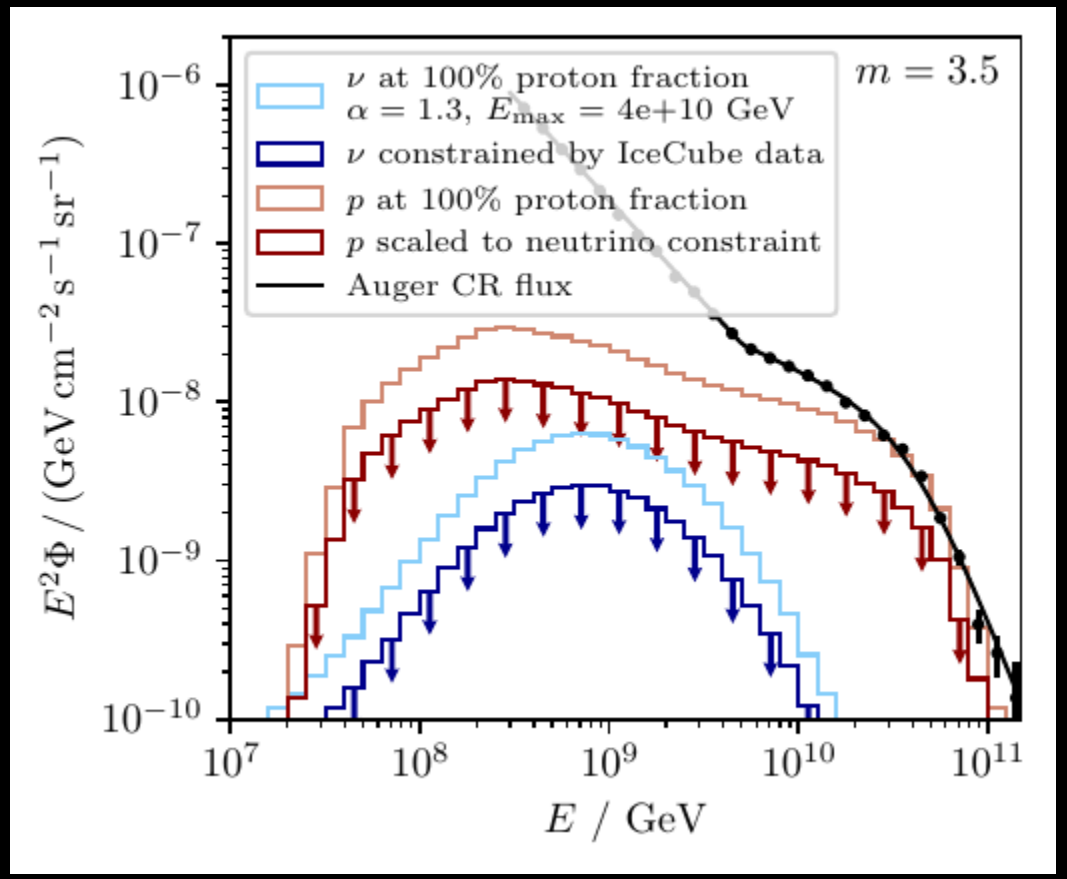
IceCube – Upgrade by Aya Ishihara

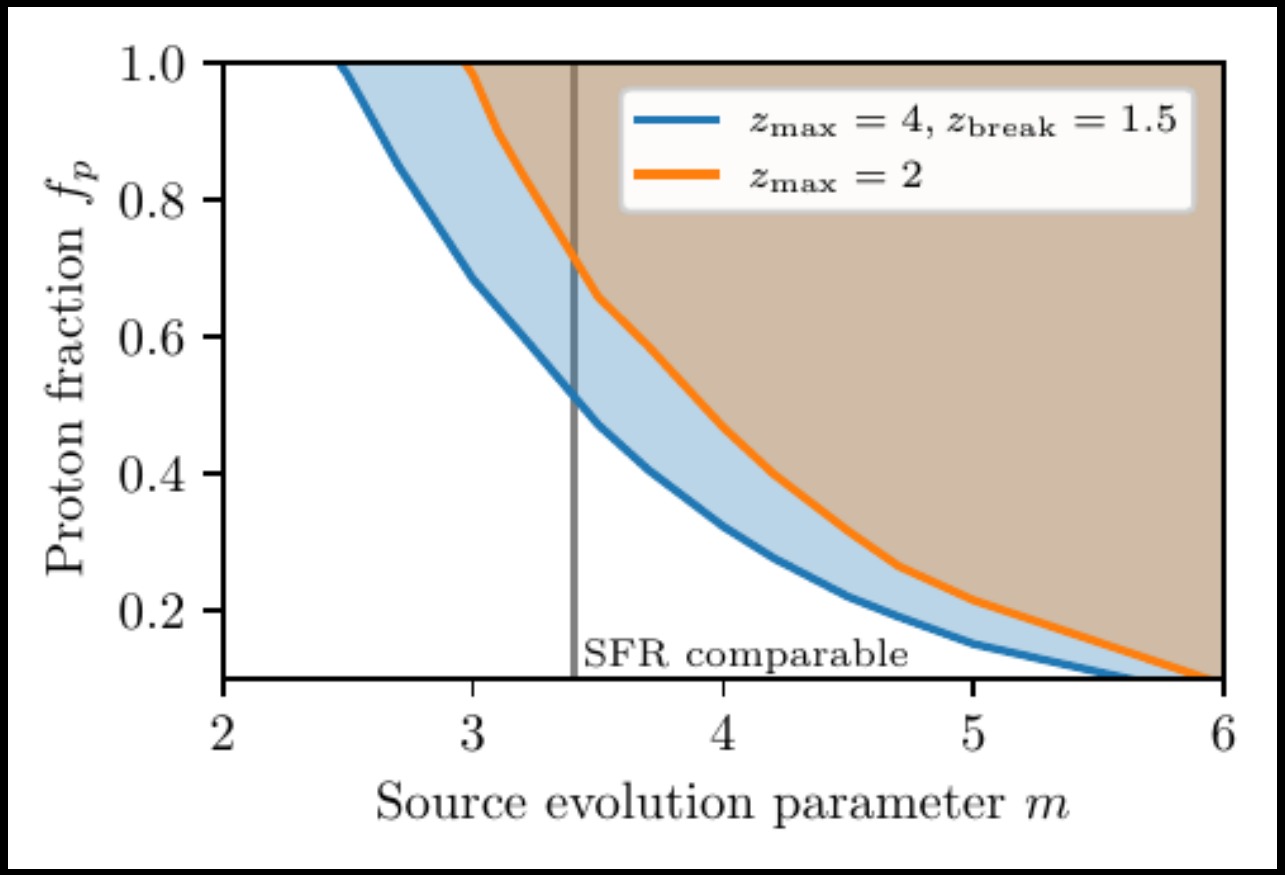
IceCube-Gen2 by Vivian O'Dell

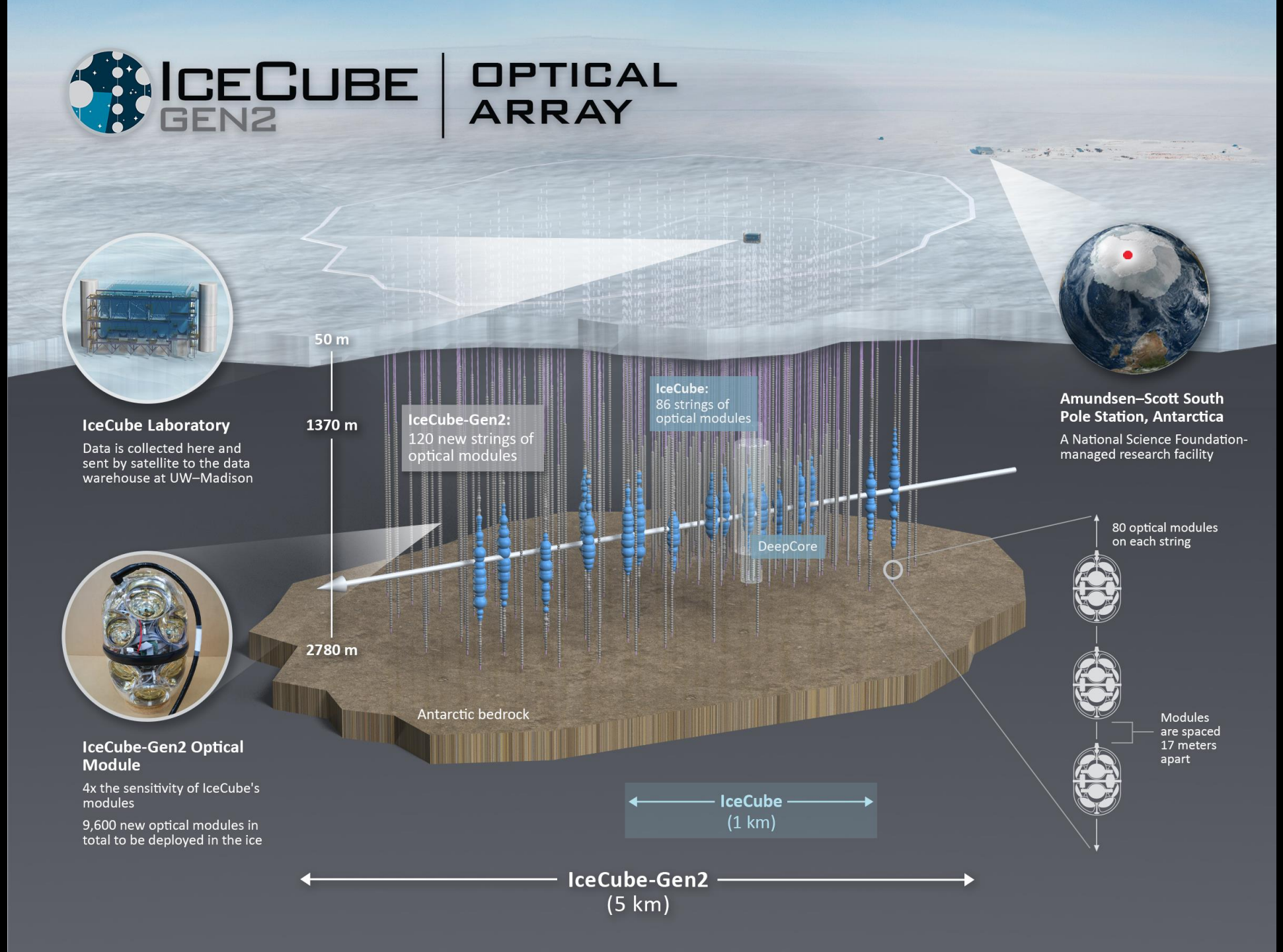
backups

TeV PeV EeV

Neutrino observations tell cosmic ray compositions






ICECUBE GEN2 | OPTICAL ARRAY
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
50 m
1370 m
2780 m
IceCube-Gen2:
120 new strings of optical modules
IceCube:
86 strings of optical modules
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
80 optical modules on each string
Modules are spaced 17 meters apart
IceCube Gen2 Optical Module
4x the sensitivity of IceCube's modules
9,600 new optical modules in total to be deployed in the ice
IceCube
(1 km)
IceCube-Gen2
(5 km)