Diffuse neutrinos from 1 TeV to 1 EeV

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IceCube Summer School 2026

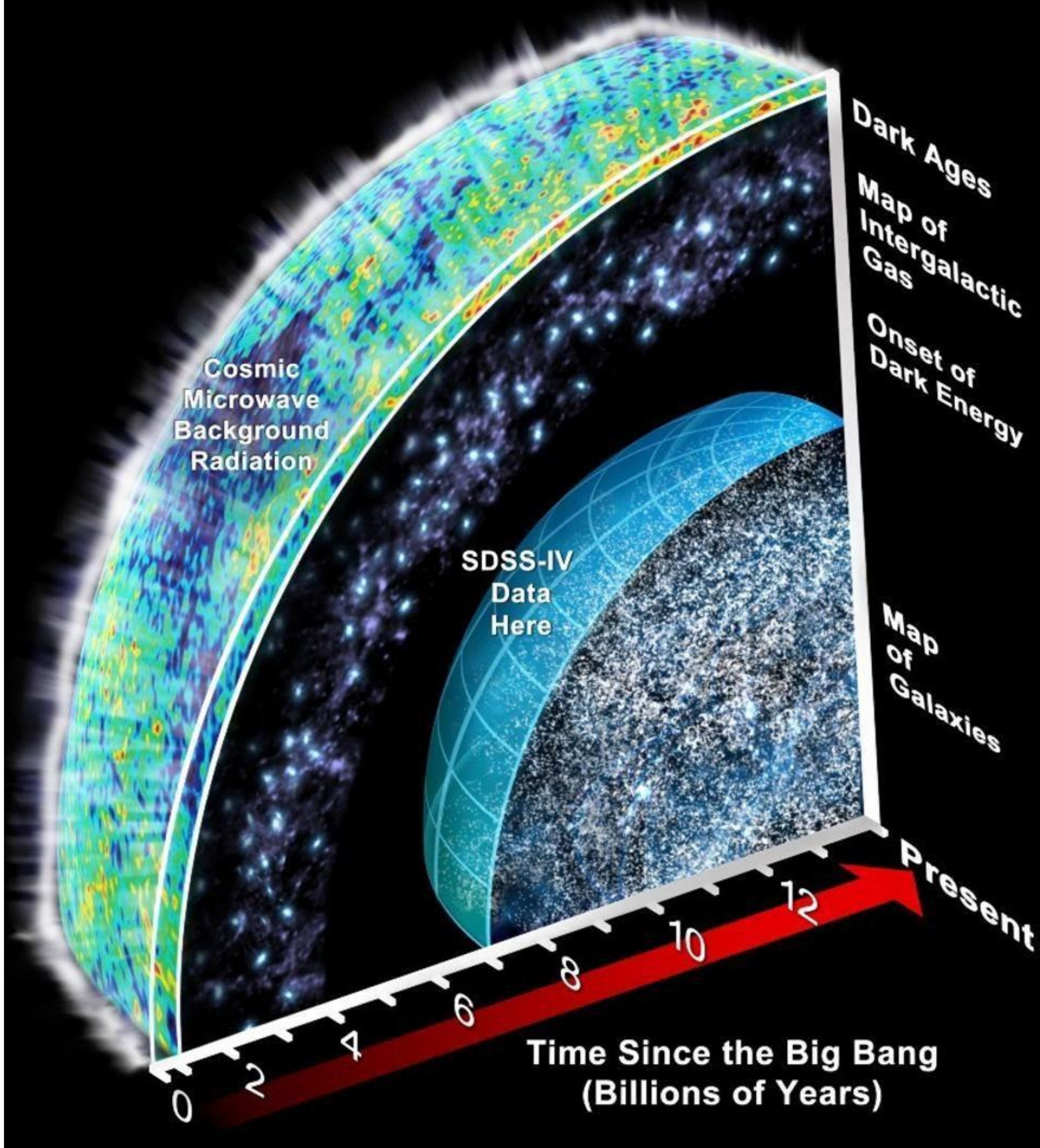
FROM FAR AWAY:

The city appears
as a diffuse glow.
Individual streetlights
cannot be seen.

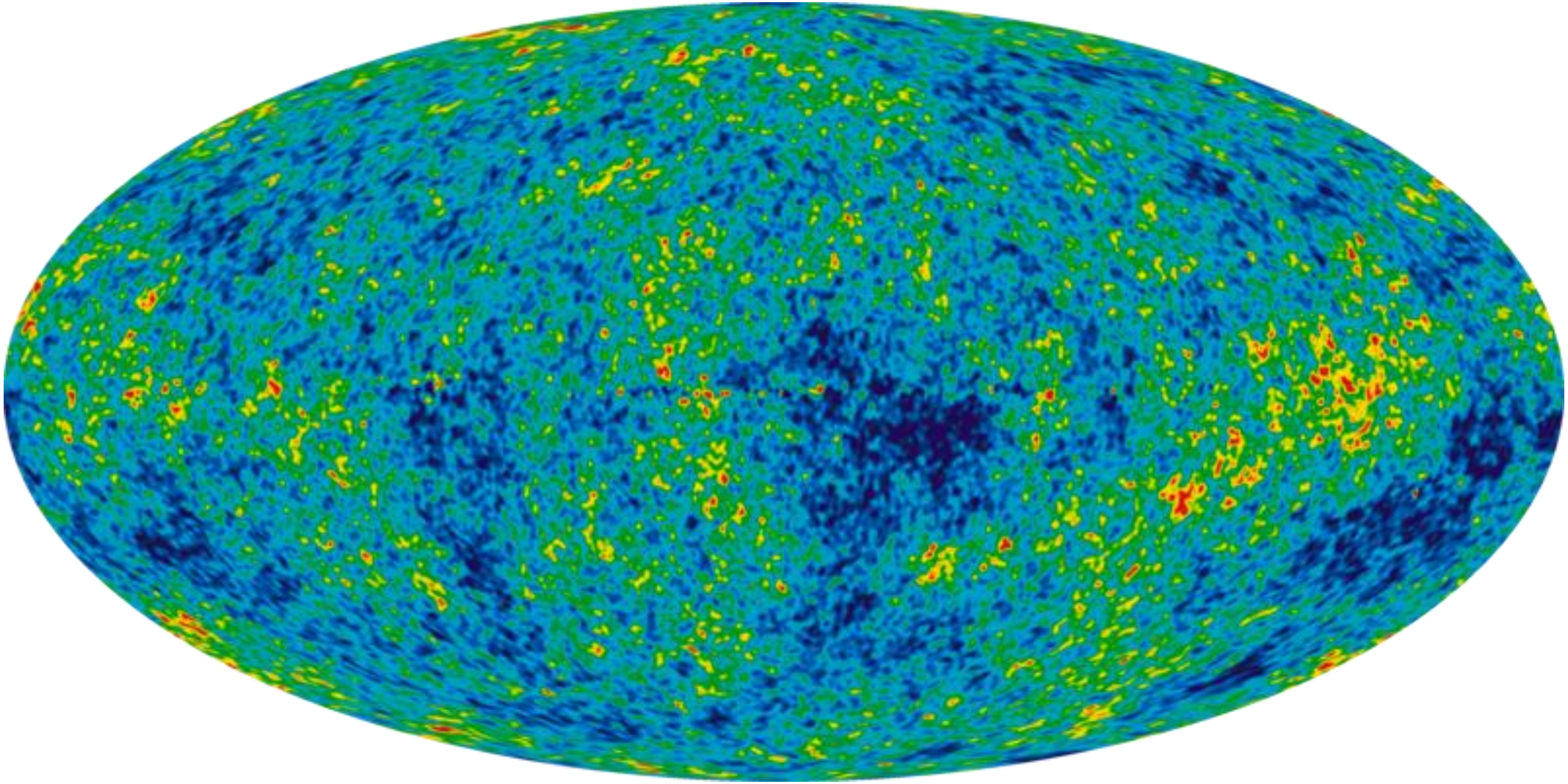
UP CLOSE:

Individual streetlights
and buildings
become visible.

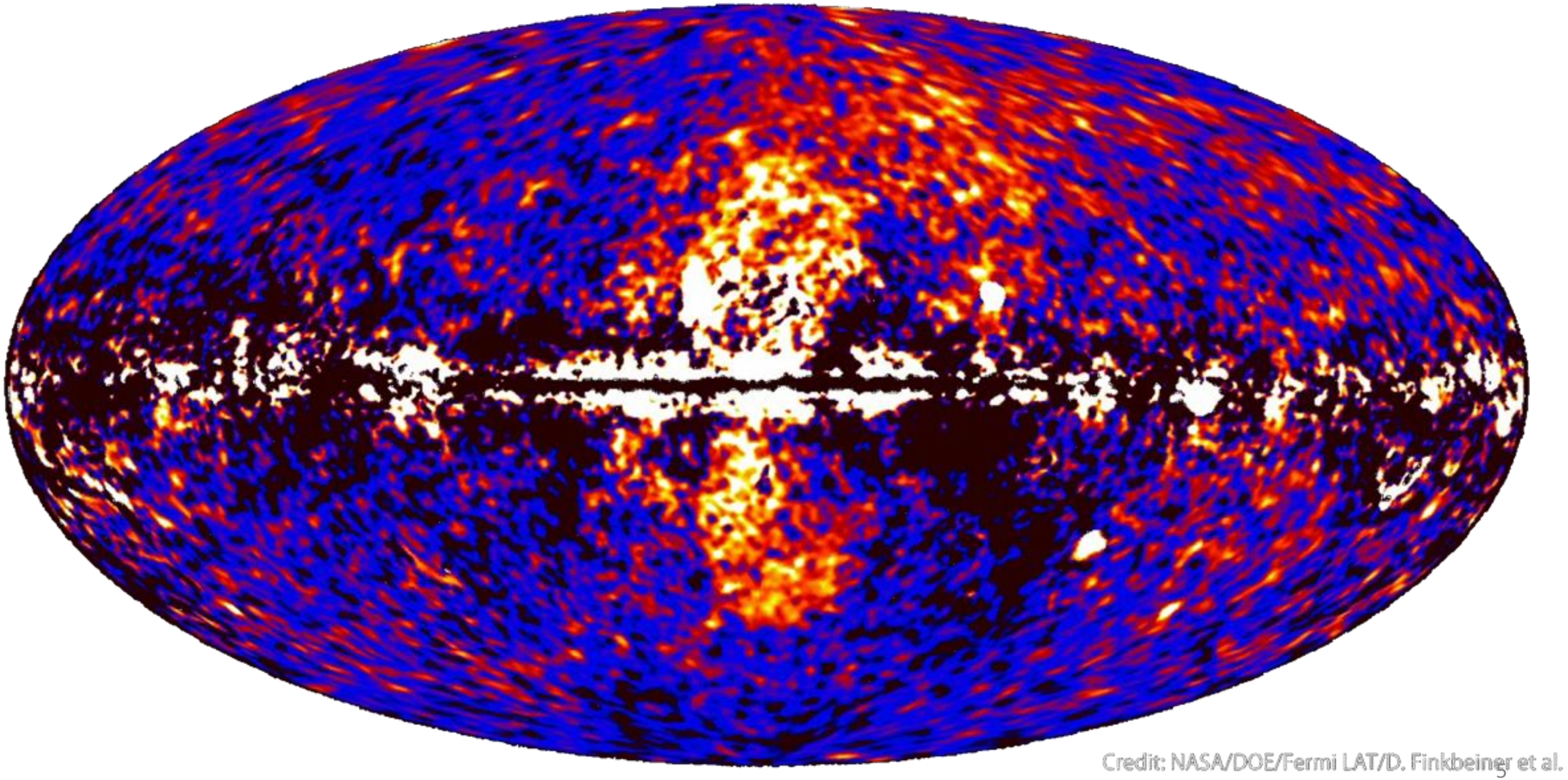
- A distant city turns many streetlights into one glow
- The distant universe turns many cosmic accelerators into one diffuse neutrino flux

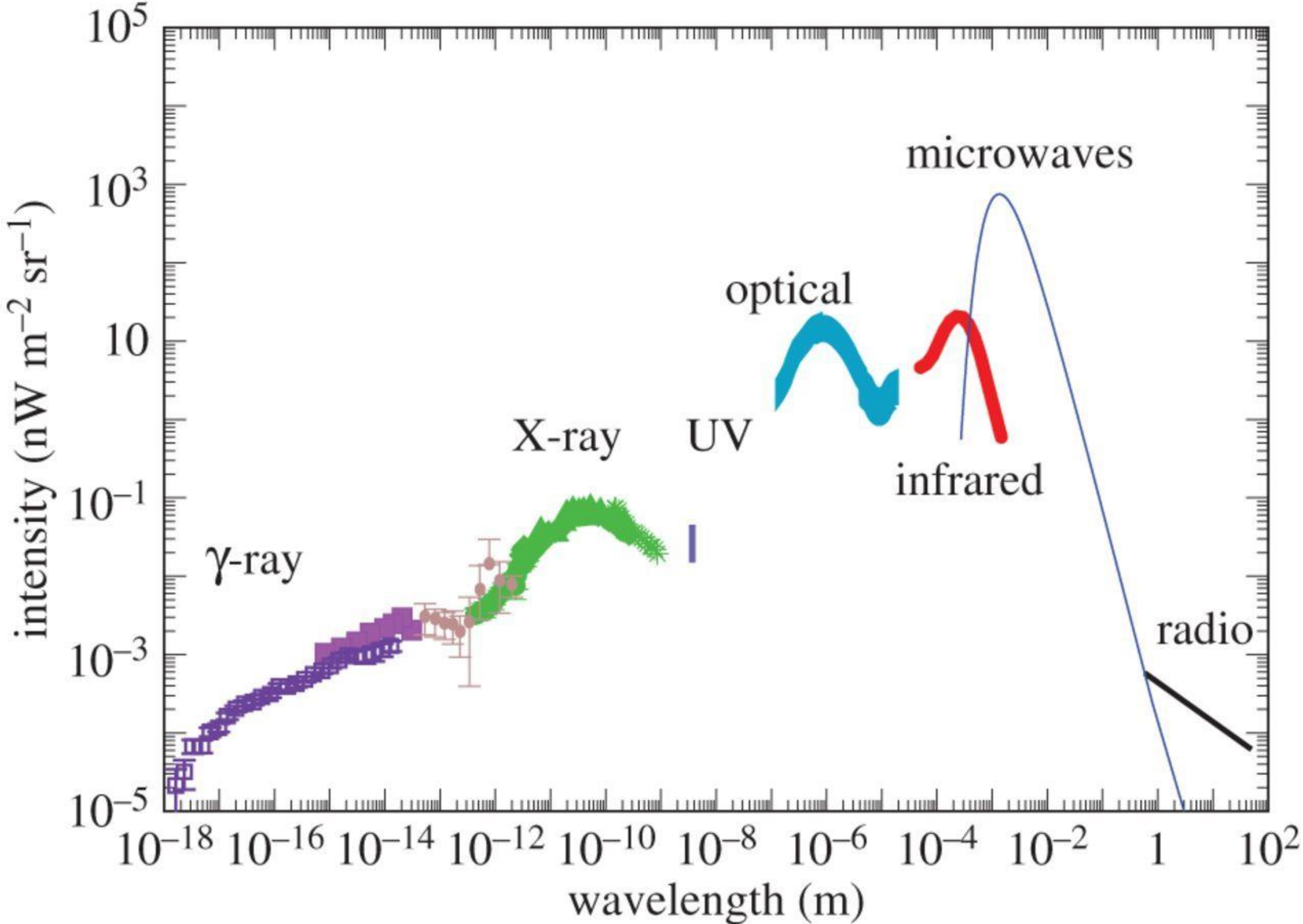


Diffuse microwave photons

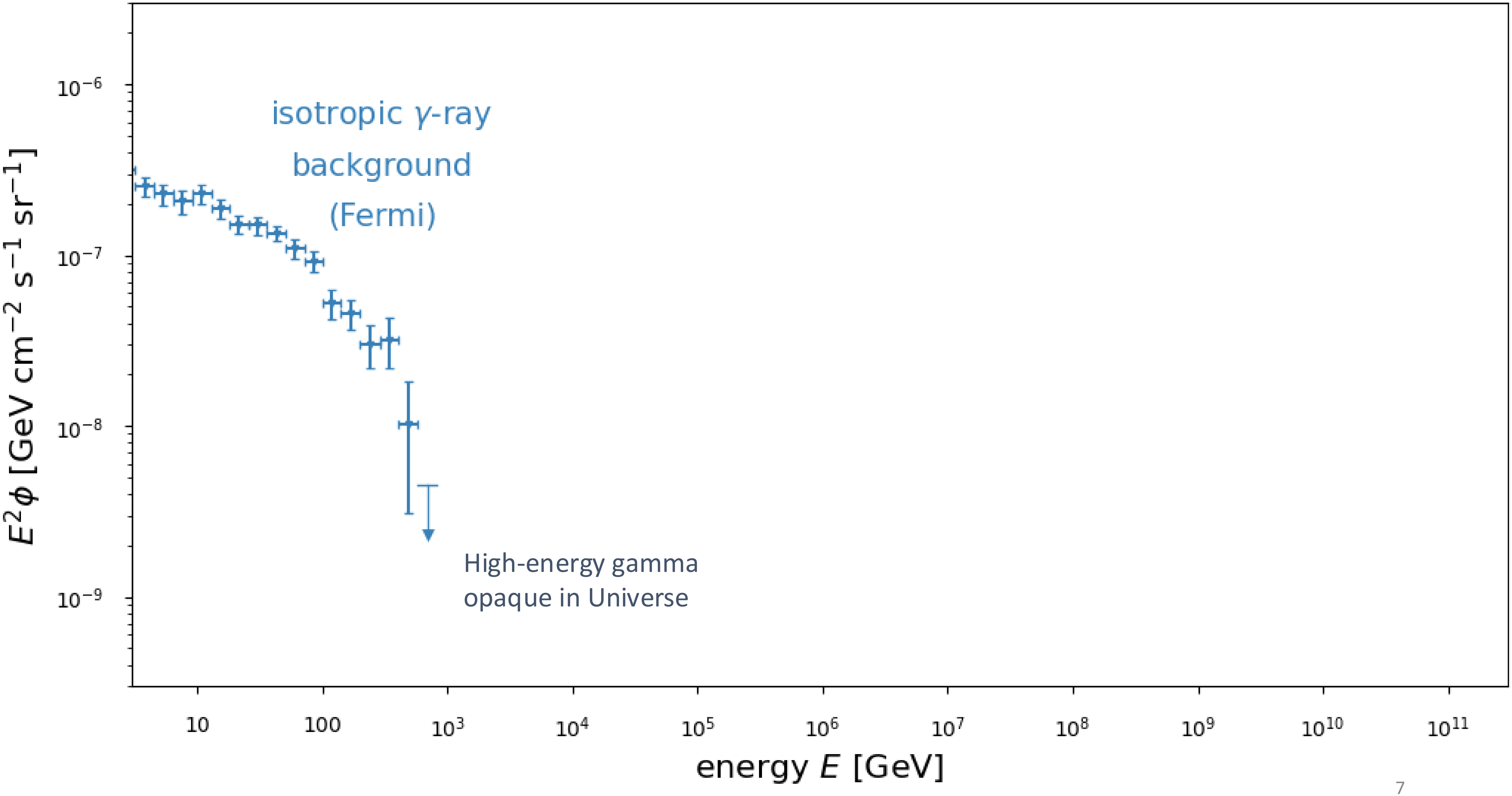


Diffuse gamma-ray photons

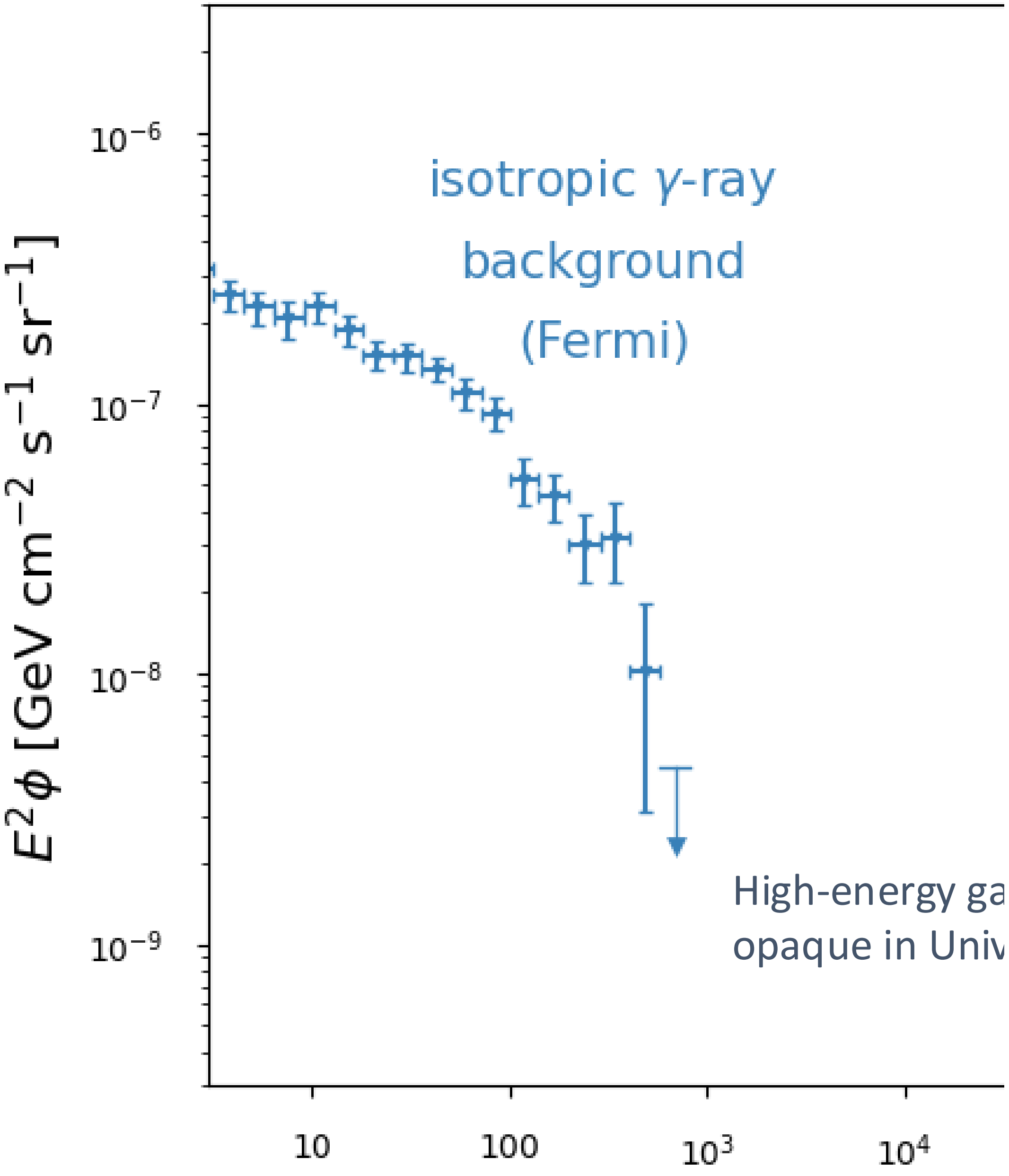


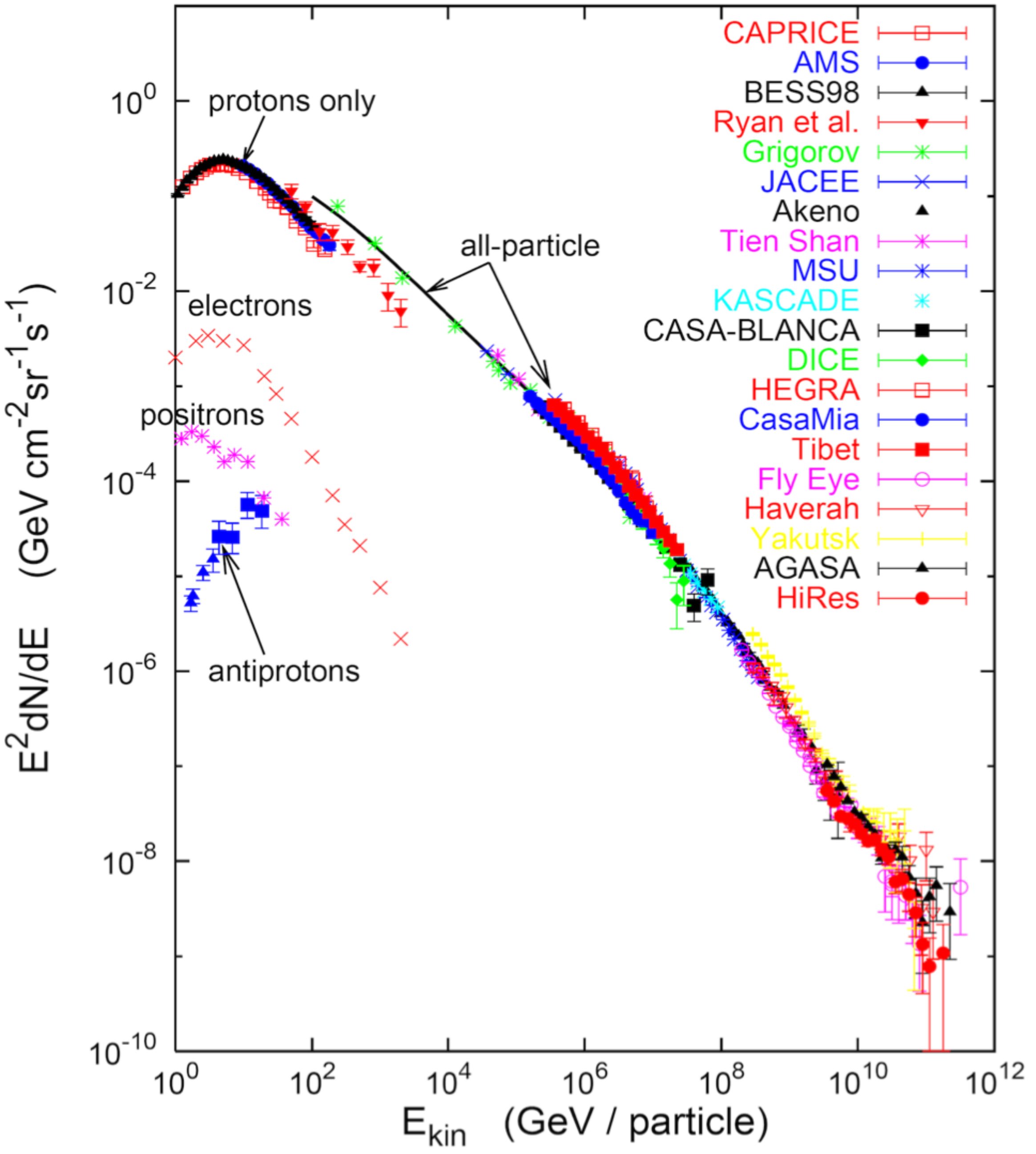


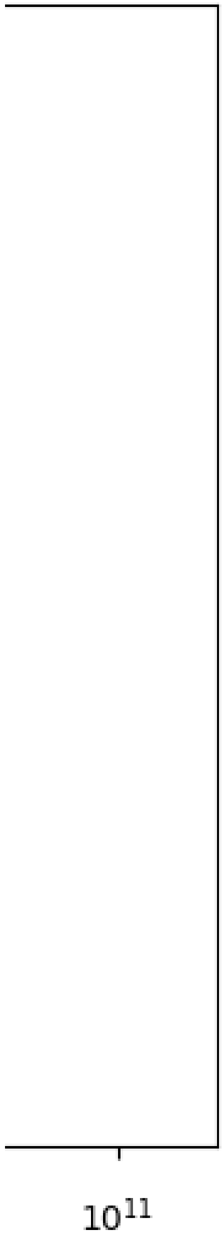
intensity (nW m⁻² sr⁻¹)
wavelength (m)
γ-ray
X-ray
UV
optical
infrared
microwaves
radio

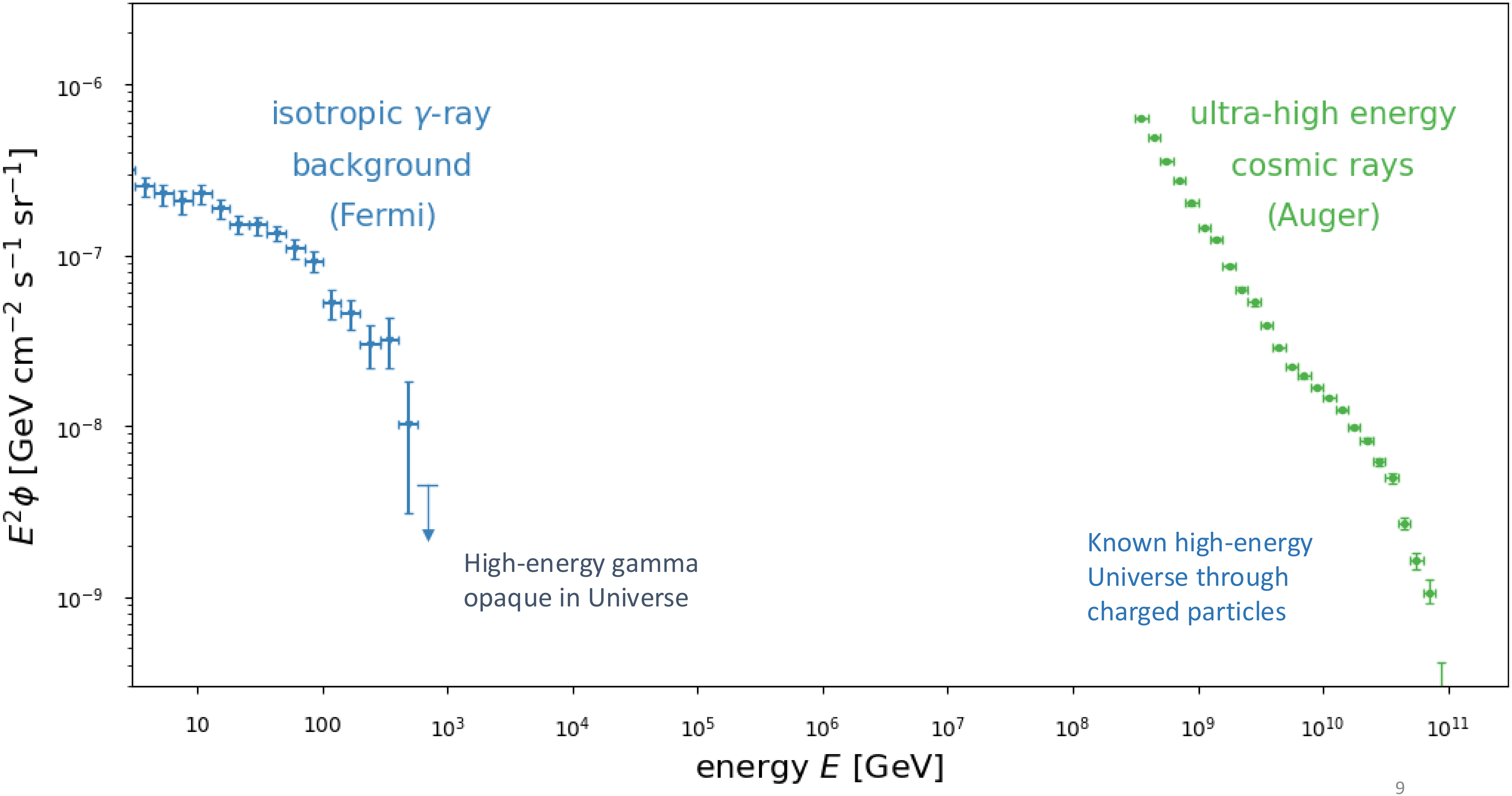


isotropic γ-ray
background
(Fermi)
High-energy gamma
opaque in Universe
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
energy E [GeV]


isotropic γ-ray
background
(Fermi)
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
High-energy ga
opaque in Univ

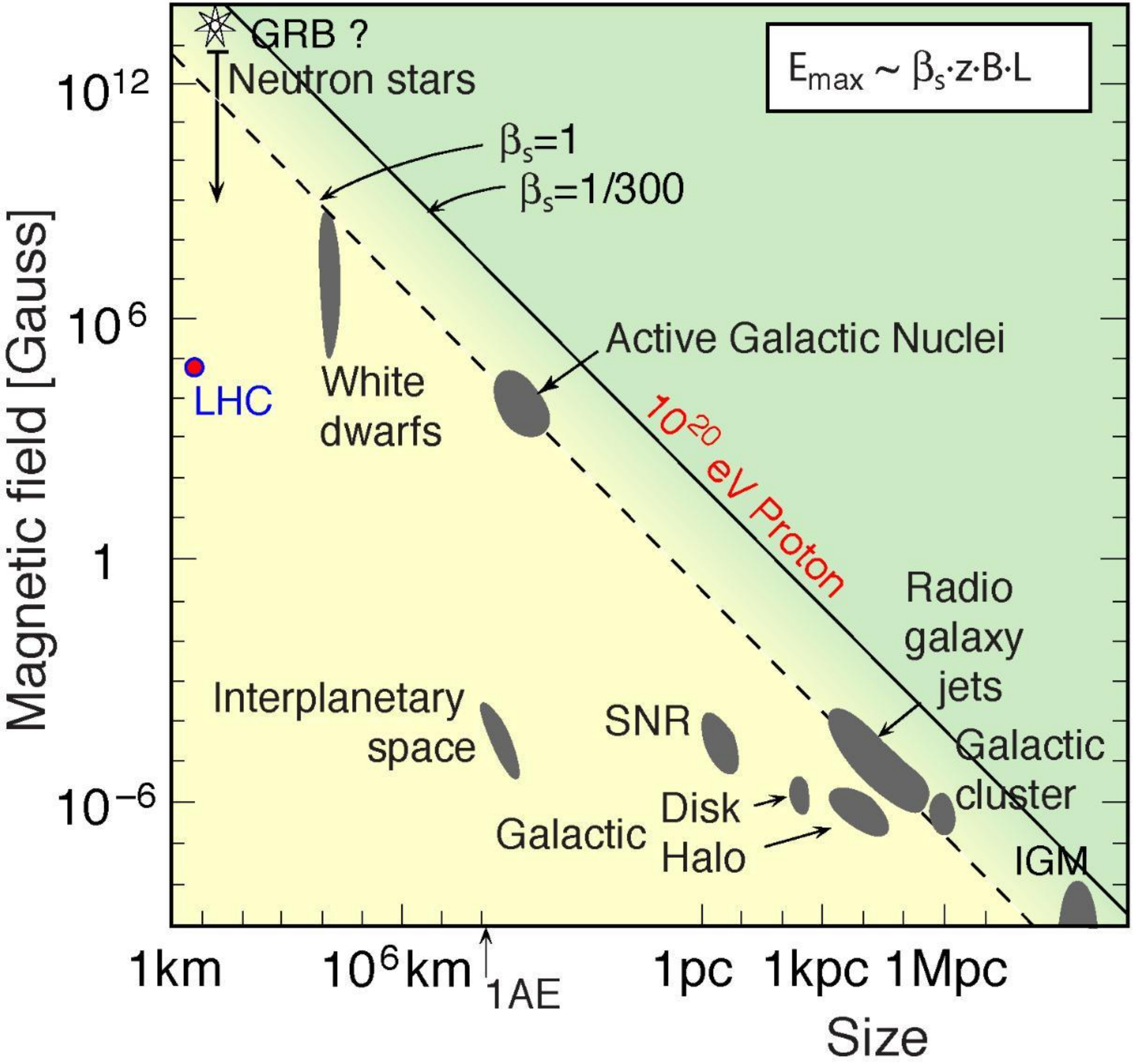

protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
E^2dN/dE (GeV cm^{-2}sr^{-1}s^{-1})
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
E_{kin} (GeV / particle)


10^{11}



isotropic γ-ray
background
(Fermi)
ultra-high energy
cosmic rays
(Auger)
High-energy gamma
opaque in Universe
Known high-energy
Universe through
charged particles
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
energy E [GeV]

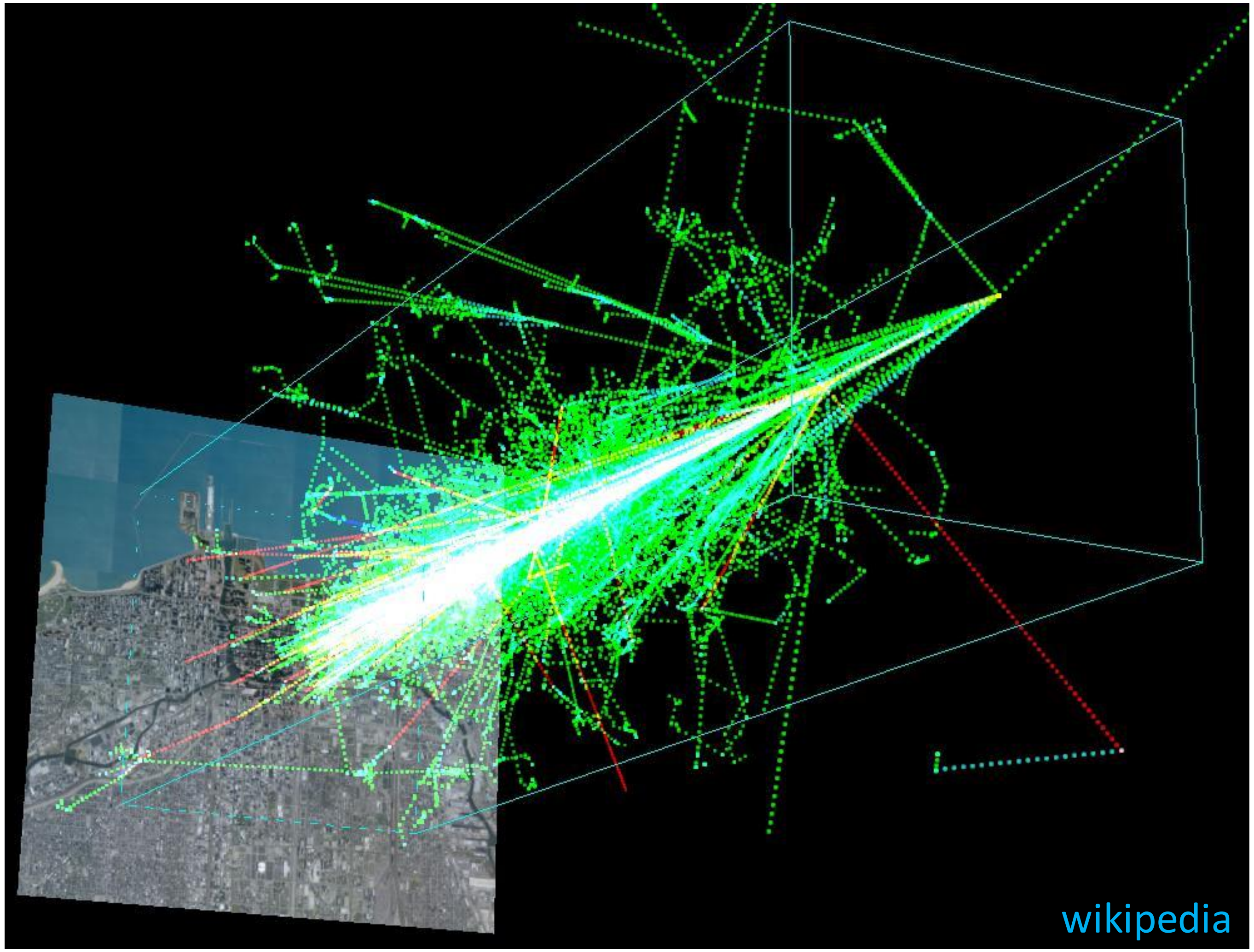
Hillas plot

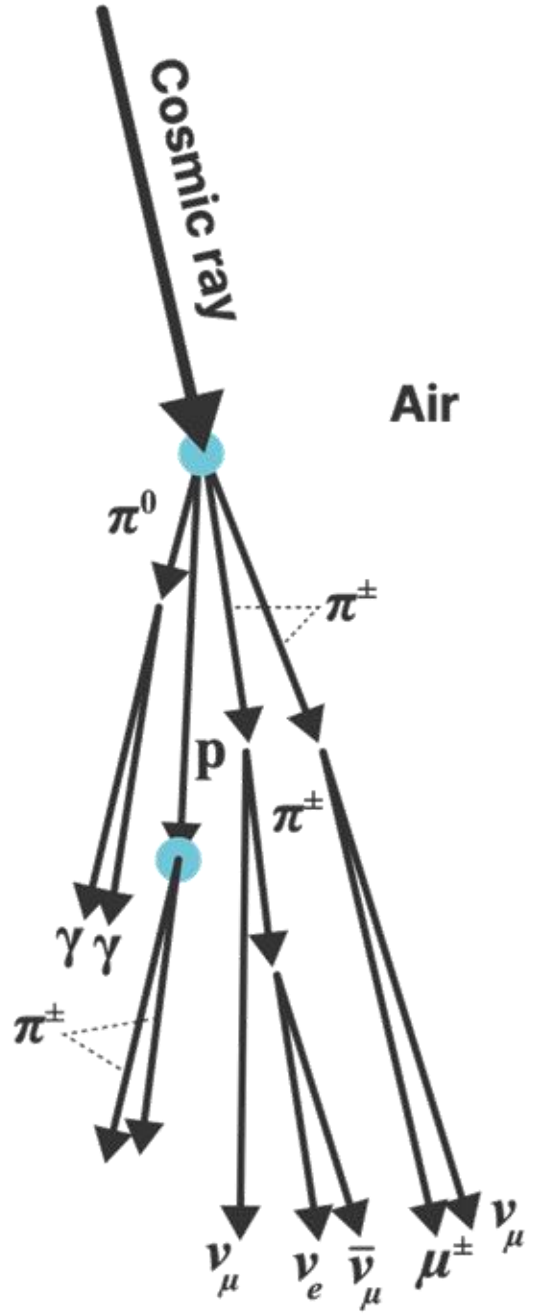


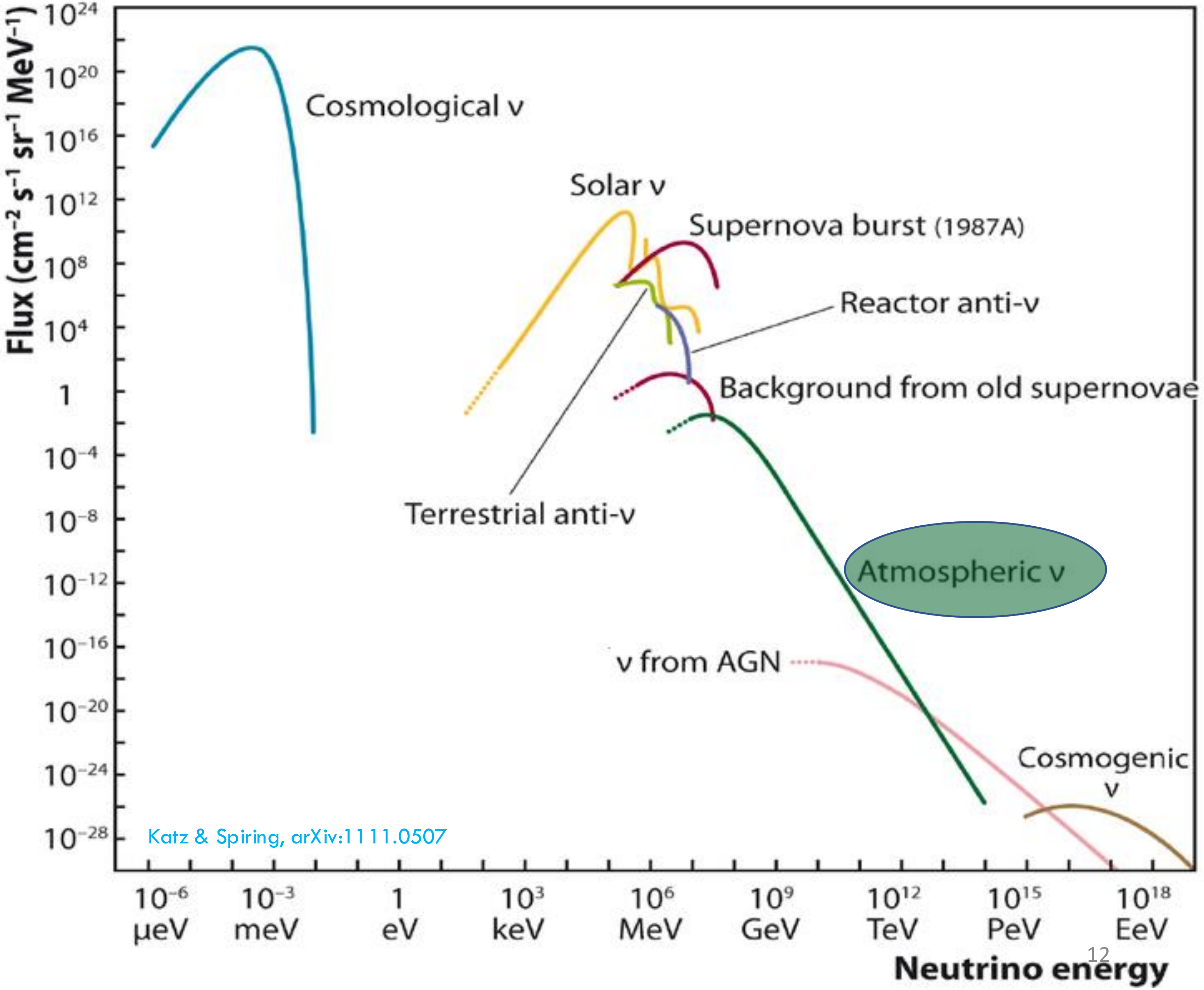
$E_{max} \sim \beta_s \cdot z \cdot B \cdot L$
GRB ?
Neutron stars
β_s=1
β_s=1/300
White dwarfs
LHC
Active Galactic Nuclei
10^{20} eV Proton
Radio galaxy jets
Interplanetary space
SNR
Galactic cluster
Disk
Galactic
Halo
IGM
Magnetic field [Gauss]
10^{12}
10^{6}
1
10^{-6}
1km
10^6km
1AE
1pc
1kpc
1Mpc
Size

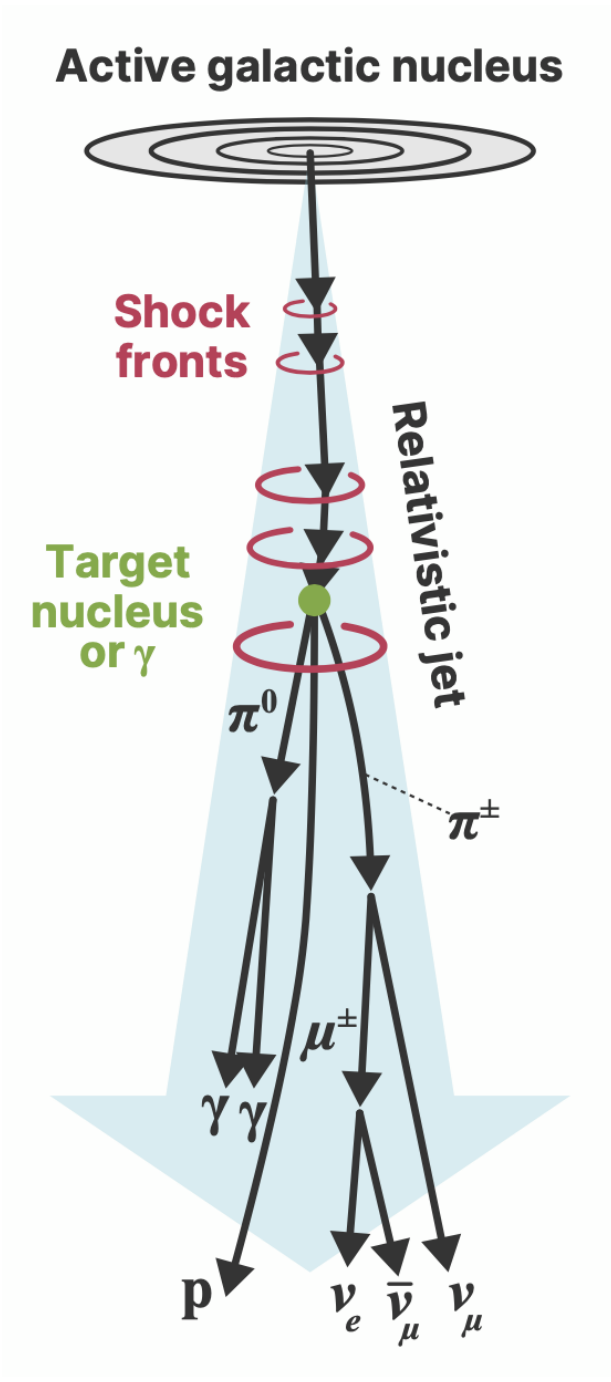
FROM CLOUD CHAMBERS TO EXTENSIVE AIR SHOWERS

Particle shower universality: fundamental laws at over 10 orders of magnitude in energy

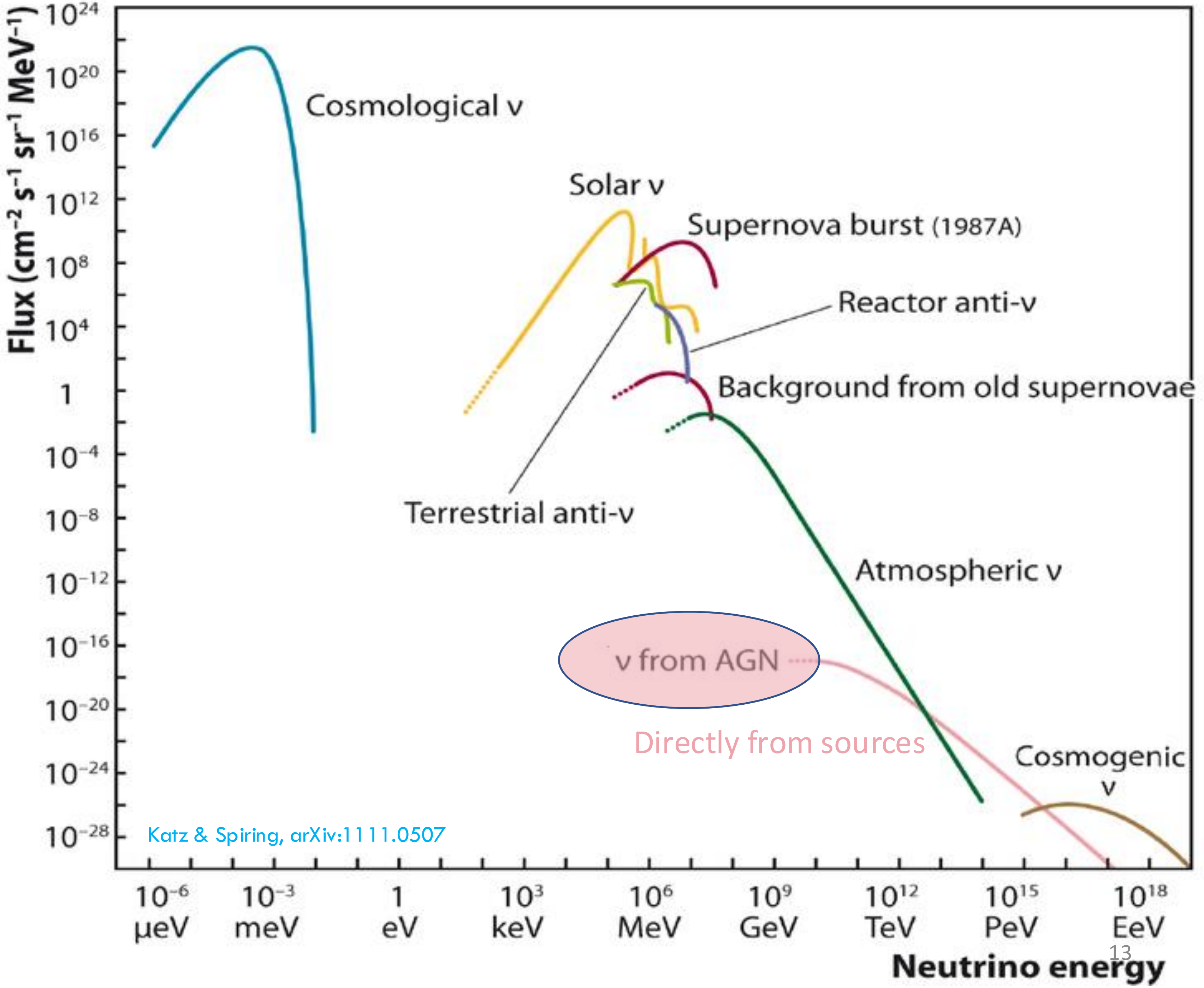



Cosmic ray
Air
π^0
$\pi^\pm$
p
$\pi^\pm$
γ γ
$\pi^\pm$
ν_μ
ν_e
$\bar{\nu}_\mu$
$\mu^\pm$
ν_μ

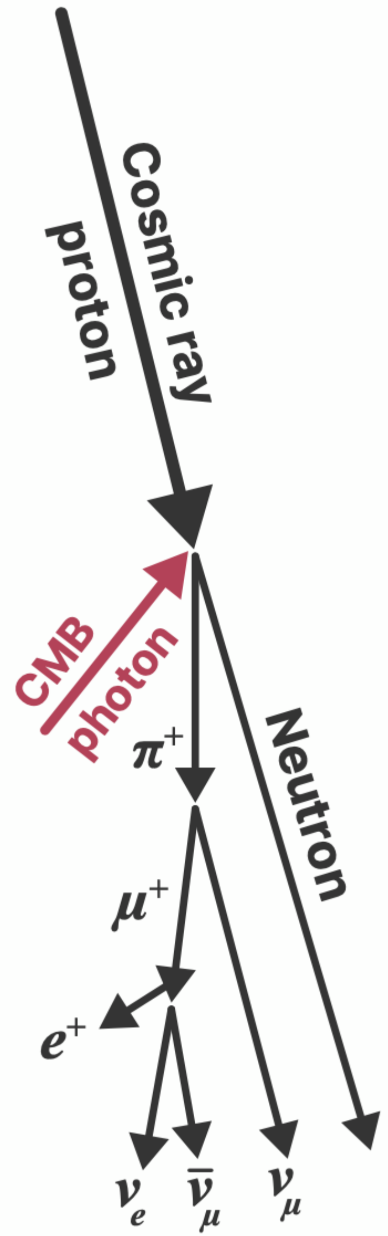

Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiring, arXiv:1111.0507
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

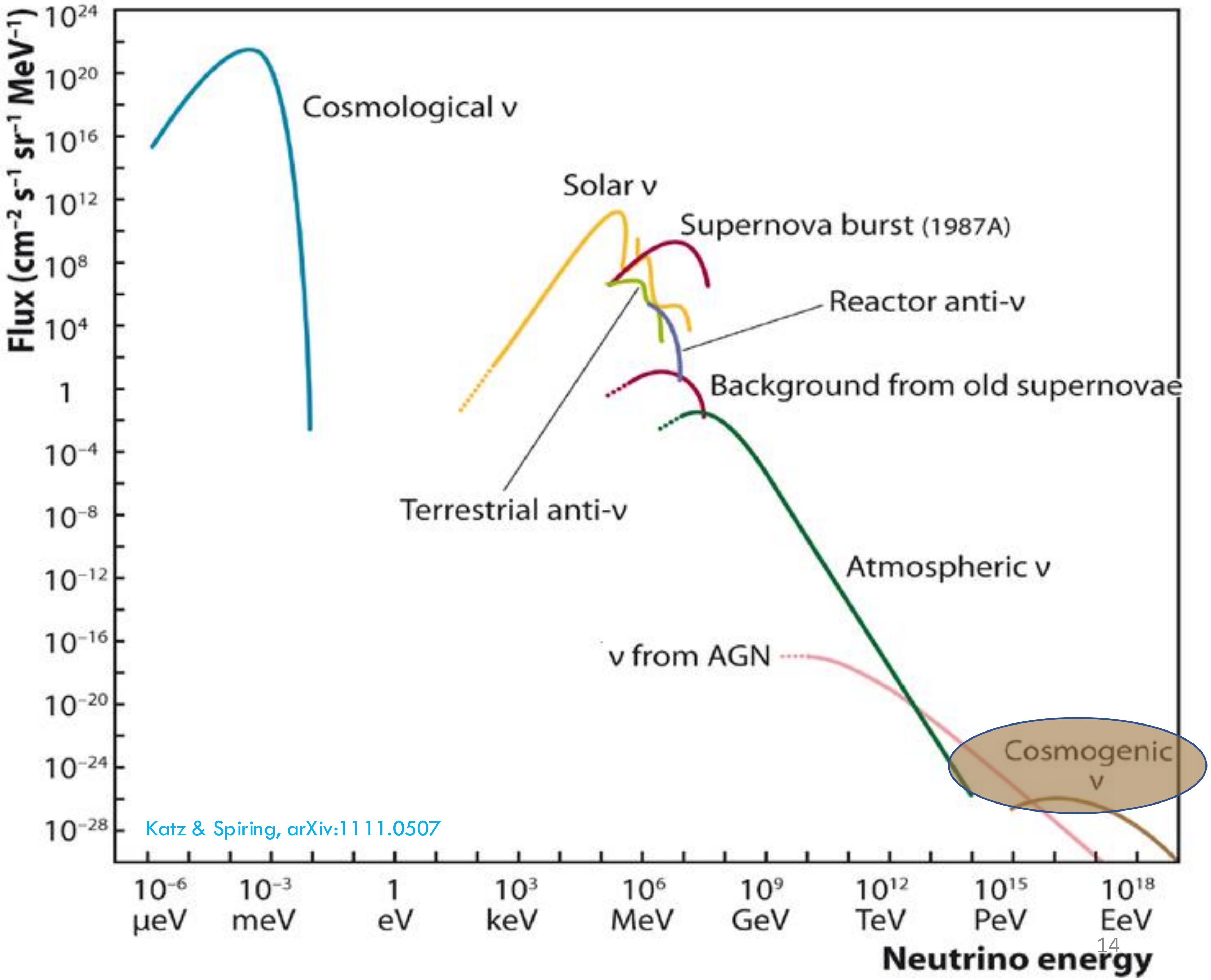


Active galactic nucleus
Shock fronts
Relativistic jet
Target nucleus or γ
π0
π±
γ γ
μ±
p
νe
ν̄μ
νμ



Flux (cm-2 s-1 sr-1 MeV-1)
1024
1020
1016
1012
108
104
1
10-4
10-8
10-12
10-16
10-20
10-24
10-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Directly from sources
Cosmogenic ν
Katz & Spiring, arXiv:1111.0507
10-6 μeV
10-3 meV
1 eV
103 keV
106 MeV
109 GeV
1012 TeV
1015 PeV
1018 EeV
Neutrino energy

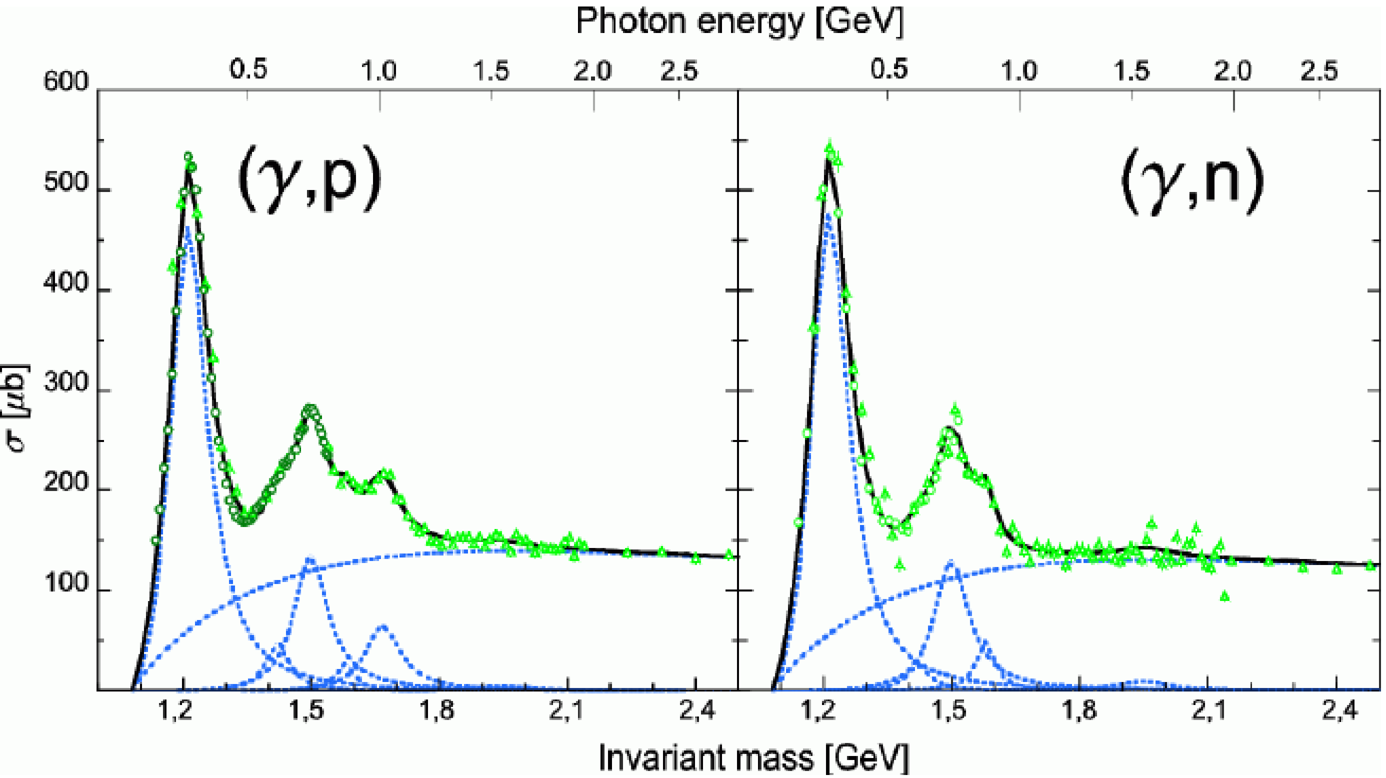

Cosmic ray proton
CMB photon
Neutron
π^+
μ^+
e^+
ν_e
$\bar{\nu}_\mu$
ν_μ

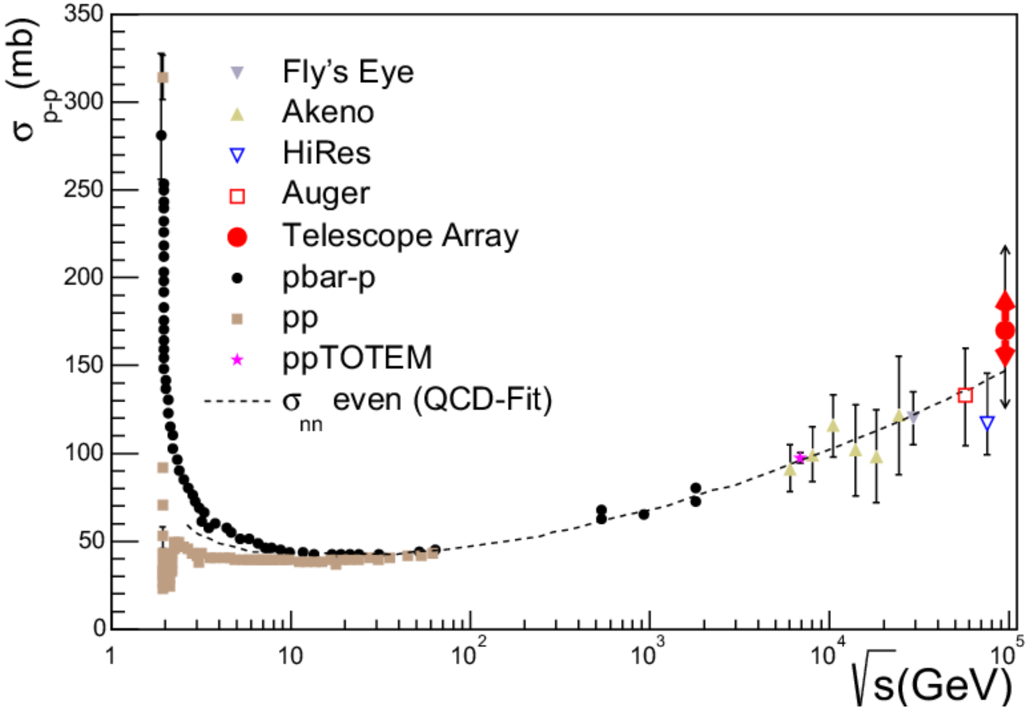

Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiring, arXiv:1111.0507
Neutrino energy
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV

A Universal Particle Shower Problem

- A high-energy particle initiates a cascade.
- At each stage, energy is partitioned among EM particles, muons, neutrinos, and hadrons.
- Whether mesons decay, reinteract, or cool determines the neutrino output.
- This same logic governs atmospheric backgrounds, astrophysical sources, and flavor signatures.

- Hadronic and photohadronic interactions initiate the cascade
- Inelastic collision → secondary hadrons: π±, K±, π^0, and heavier mesons





- A primary (CR, proton, γ-ray) hits a target (air nucleus, CMB photon, gas cloud)
- Inelastic collision → secondary hadrons: π±, K±, π^0, and heavier mesons
- Each secondary faces three fates: decay | re-interaction | energy loss (cooling)
- Neutrinos only emerge from decay — they cannot be created by EM or hadronic cooling
- The neutrino yield is set by the competition between these three rates

```
Γ_dec = 1/γτ              (decay rate)
Γ_int = n σ_inel c         (interaction rate)
Γ_cool = -dE/dt / E       (cooling rate)
P(decay) = Γ_dec / (Γ_dec + Γ_int + Γ_cool)
```

How inelastic collisions divide energy among secondary species

$\pi^0 \rightarrow \gamma\gamma$

~1/3 of pions are neutral
Decay instantly (cτ ~ 25 nm)
All energy → EM cascade
Feed gamma-ray luminosity

$\pi^\pm \rightarrow \mu\nu \rightarrow e\nu\nu$

~2/3 of pions are charged
2 neutrinos + 1 muon per decay
Muon carries ~75% of π± energy
Soft ν_e from subsequent μ decay

Muons

Long-lived (cτ ~ 660 m)
Lose energy by ionisation
At high E: may be absorbed
before decaying → ν_μ suppressed

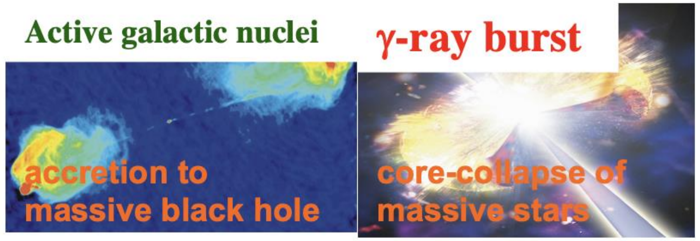
Hadronic re-interaction

Higher multiplicity, lower ⟨E⟩
Feeds next cascade generation
Inelasticity K ~ 0.5
Fraction (1-K) continues as leading p

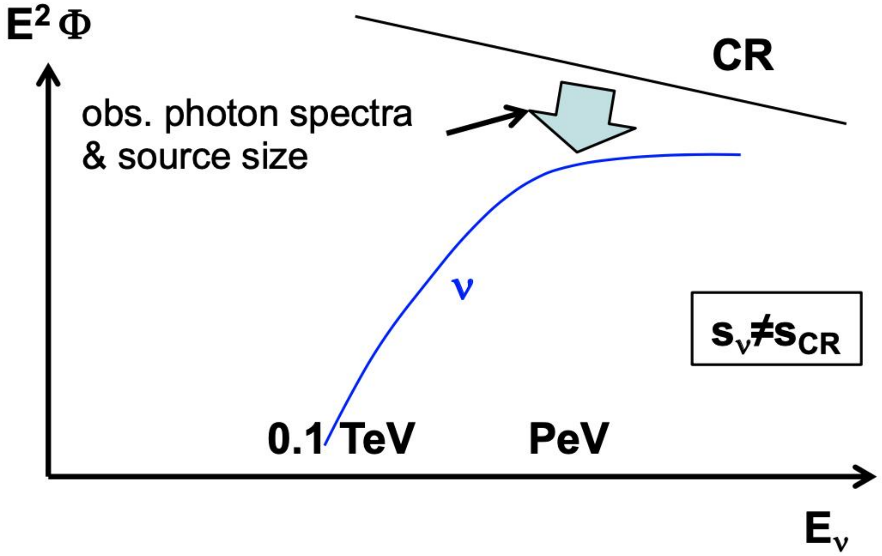
Astrophysical Extragalactic Scenarios

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

Cosmic-ray Accelerators (ex. UHECR candidate sources)

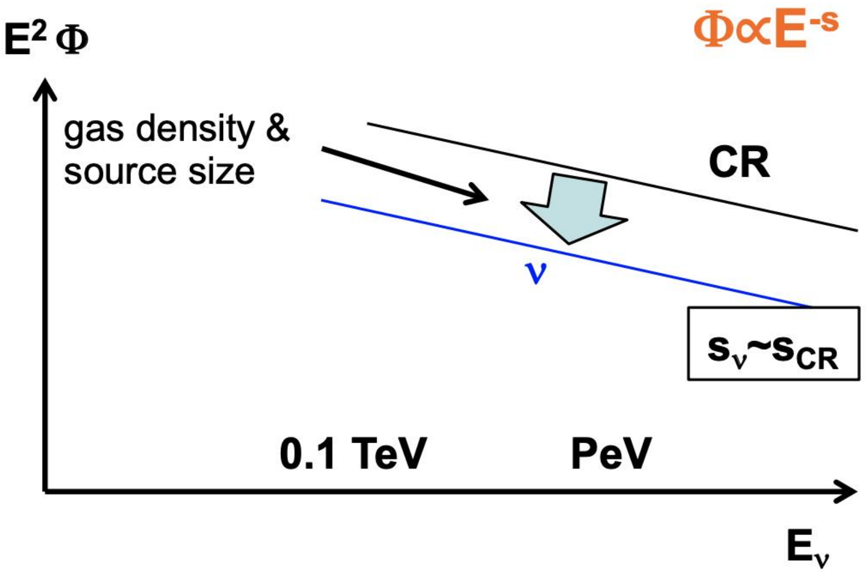


$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs

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

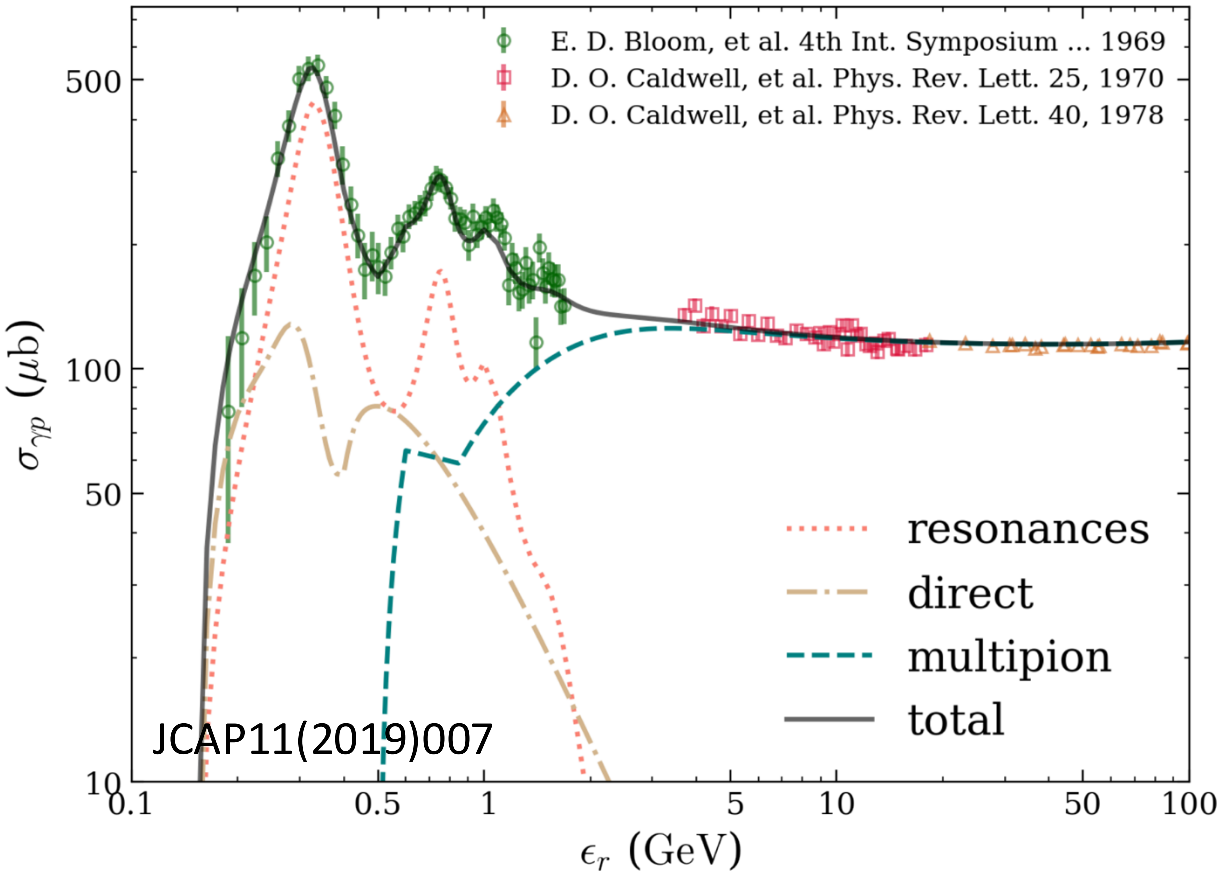


Slide from Kohta Murase

Why X-rays are important?

- Pion productions

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$



Threshold photon energy in proton's rest frame

$$\epsilon'_\gamma = \frac{(s_\Delta - m_p^2)}{2m_p}$$

Observed photon energy required for pion production with PeV protons

$$\epsilon_\gamma = 15 \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\epsilon_p}{1\ \mathrm{PeV}}\right)^{-1} \ \mathrm{keV}$$

bulk Lorentz factor Γ of the relativistic plasma (jets) 1~100 in GRB, AGN, TDE…

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\epsilon_\nu \approx 50\,\mathrm{TeV} \times \left(\frac{\epsilon_p}{1\,\mathrm{PeV}}\right)$$

~50 TeV neutrinos from p–gamma jetted sources are expected to be accompanied by X-rays

Atmospheric nu

$\pi^{\pm}\ K^{\pm} \rightarrow\ \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$ (63.5% for K)

$\quad \hookrightarrow e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_{\mu}(\nu_{\mu})$

→ E_{ν} ~ 100/cosθ GeV

$K^{\pm} \rightarrow \pi^0 e \nu_e$ (5%)

$K_L^0 \rightarrow \pi e \nu_e$ (40%)

Conv.

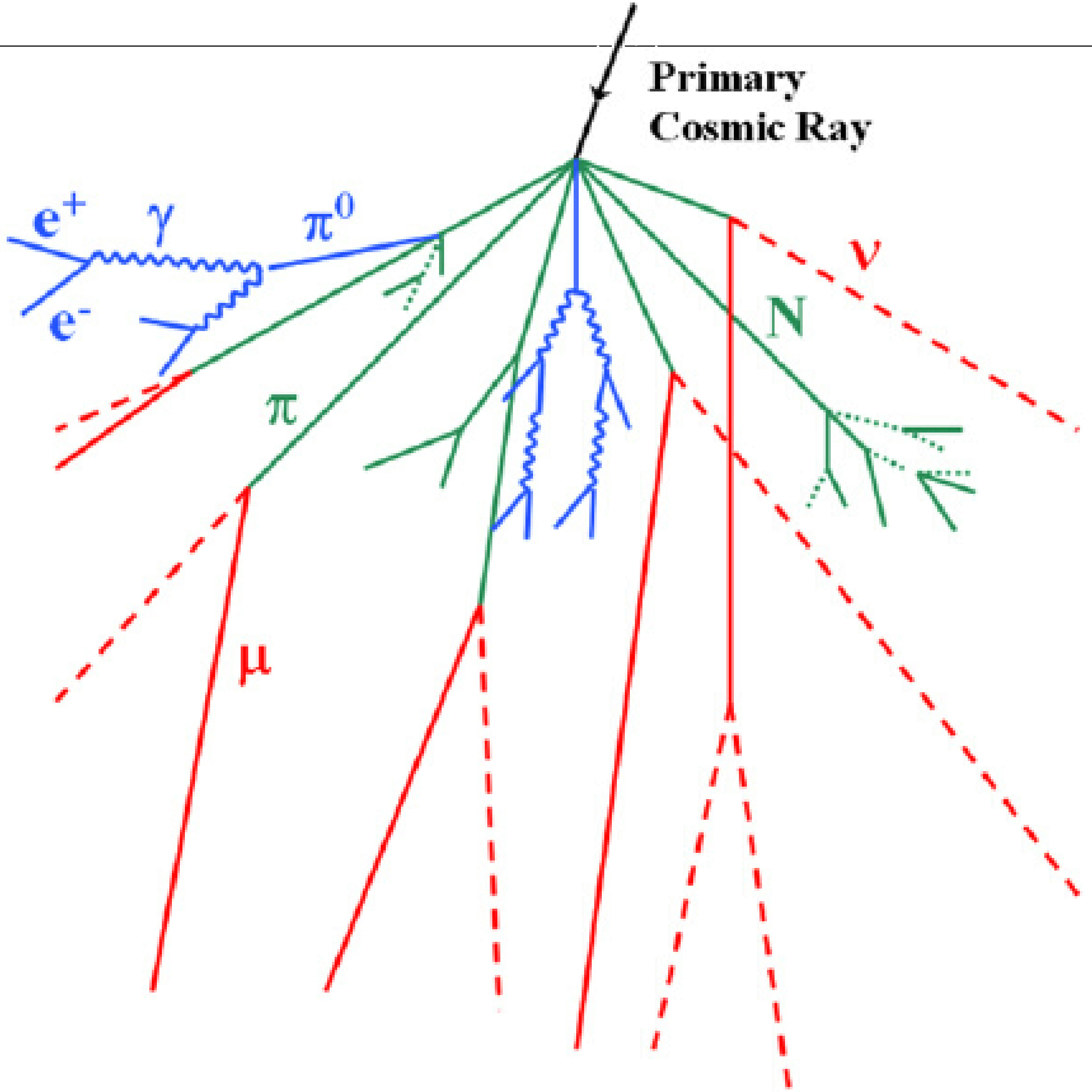
→ E_{ν} ~ 100/cosθ TeV

$K_S^0 \rightarrow \pi e \nu_e$ (Gaisser & Klein 2014) (0.07%)

prompt

$D, \Lambda_c \rightarrow \ell + \nu_{\ell} + \ldots$ (order %)

$\eta, \eta' \rightarrow \mu^+ \mu^-$



Air showers: the Atmospheric neutrino factory

Earth's atmosphere is a natural hadron calorimeter producing conventional neutrinos

- Cosmic ray (mostly proton/He nucleus) strikes air nucleus at ~15 km altitude
- Inelastic collision: NN → $\pi^\pm$, π^0, K±, … with multiplicity ∝ ln s
- Neutral pions decay promptly (cτ = 25 nm) → gamma-ray sub-shower (EM component)
- Charged pions propagate in air: decay OR re-interact, depending on energy vs. ε_π
- **Below critical energy ε_π: decay dominates → conventional atmospheric neutrinos**
- **Above ε_π: interaction dominates → pions are absorbed → flux suppressed**

```
l_dec = γcτ = (E/m)cτ
[meson decay length]
l_int = 1/(n σ_inel)
[interaction length in air]
Decay dominates when
l_dec < l_int
```

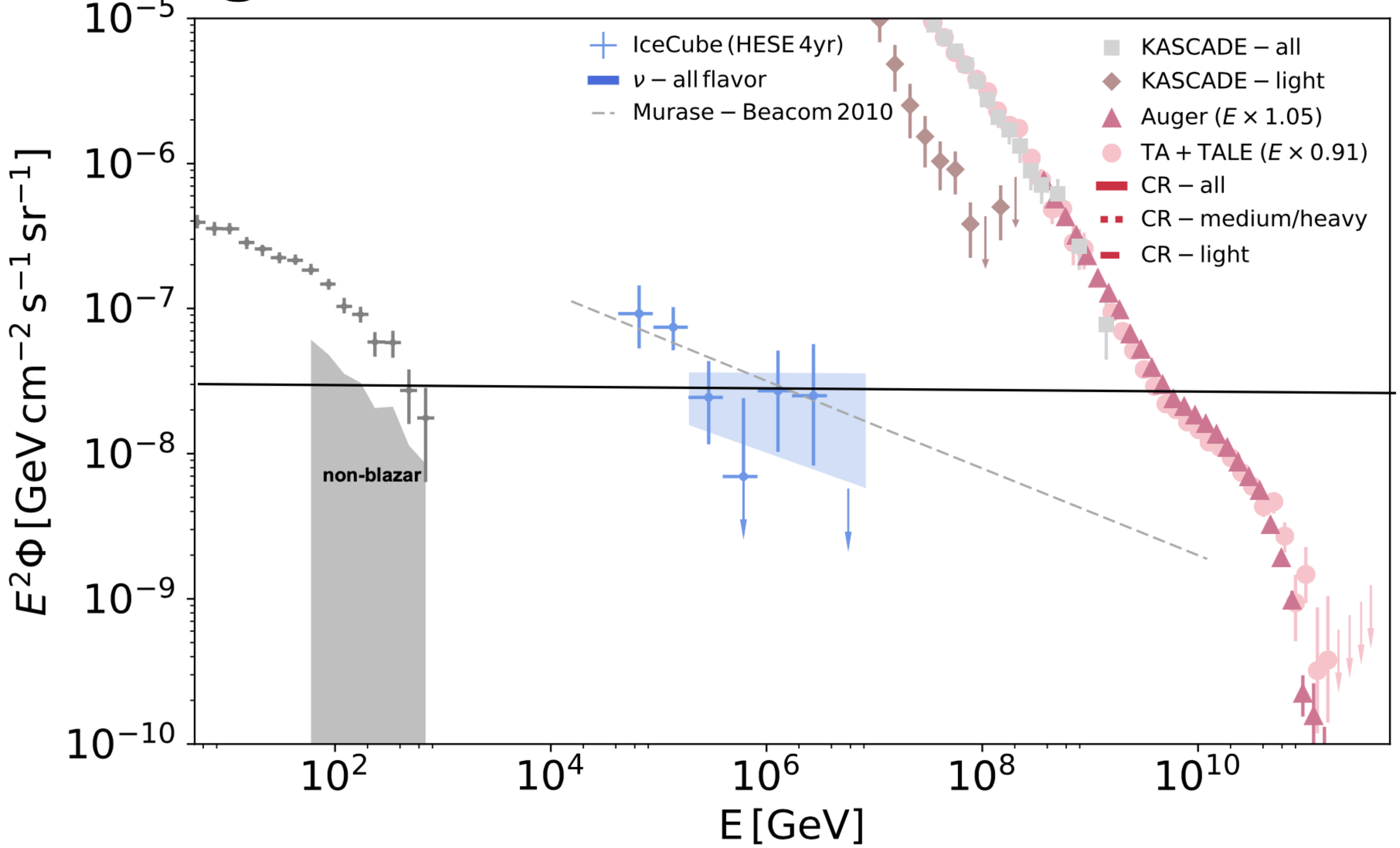
Critical energy

- Define critical energy ε: where l_dec = l_int, i.e., decay rate = interaction rate in air
- **For E ≫ ε, flux is suppressed by factor ~ε/E — the spectrum steepens by one power**
- For E ≪ ε, the meson decays freely → neutrino flux tracks primary CR flux ($E^{-2.7}$)
- **Kaons have shorter lifetimes AND smaller cross sections → larger ε_K vs ε_π**
- At E > ε_π ~ 115 GeV: pion contribution suppressed; kaon contribution still alive
- At E > ε_K ~ 850 GeV: kaon contribution also suppressed; both conventional components steep

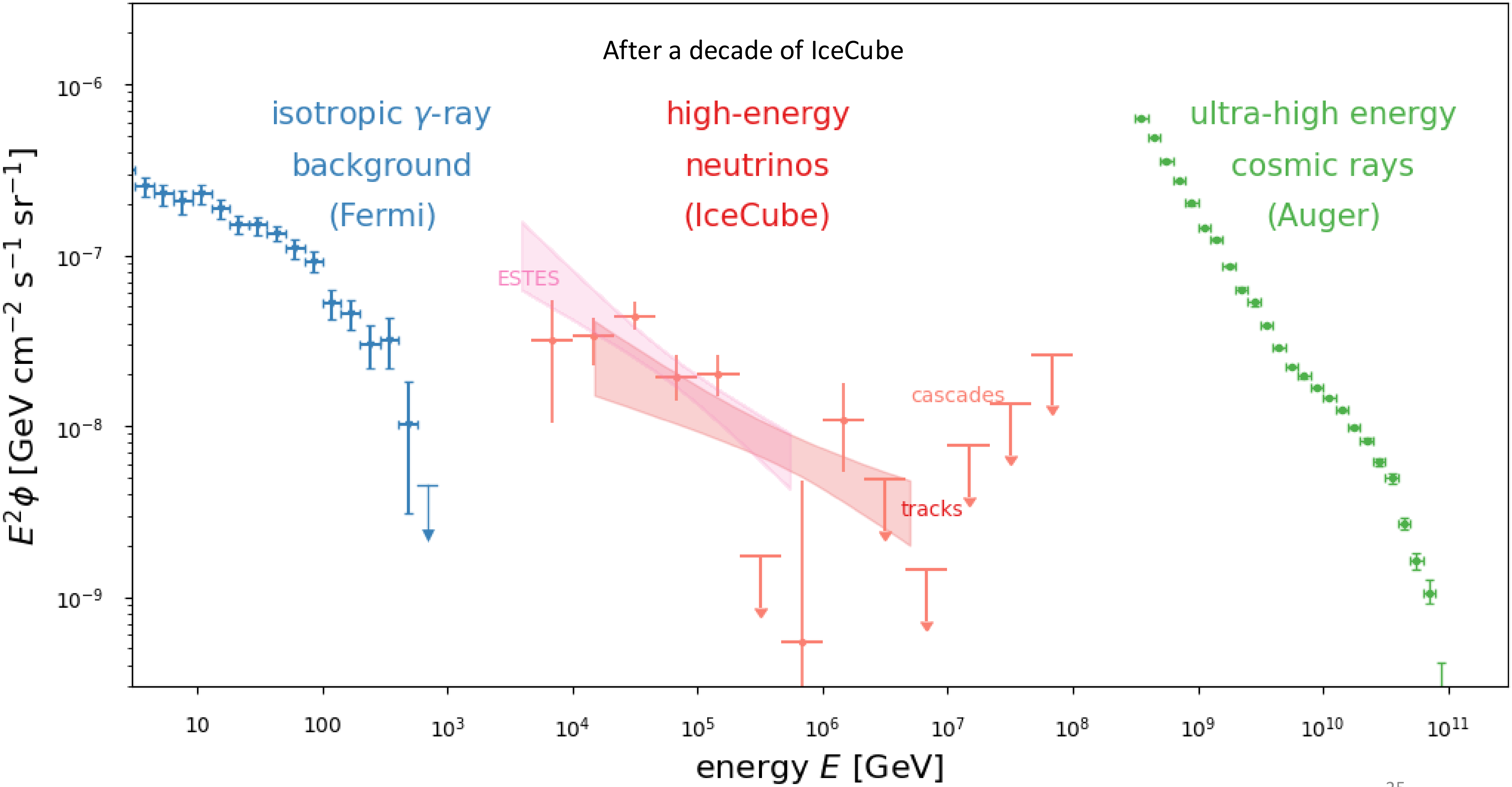
Meson	cτ (m)	mass (MeV)	ε_crit
π±	7.80 m	139.6	~115 GeV
K±	3.71 m	493.7	~850 GeV
D±	0.31 mm	1869	~4×10⁷ GeV

```
Flux suppression above ε:
dΦ/dE ∝ E⁻(γ+1)  (steepens by 1 power)
vs.  ∝ E⁻γ below ε
```

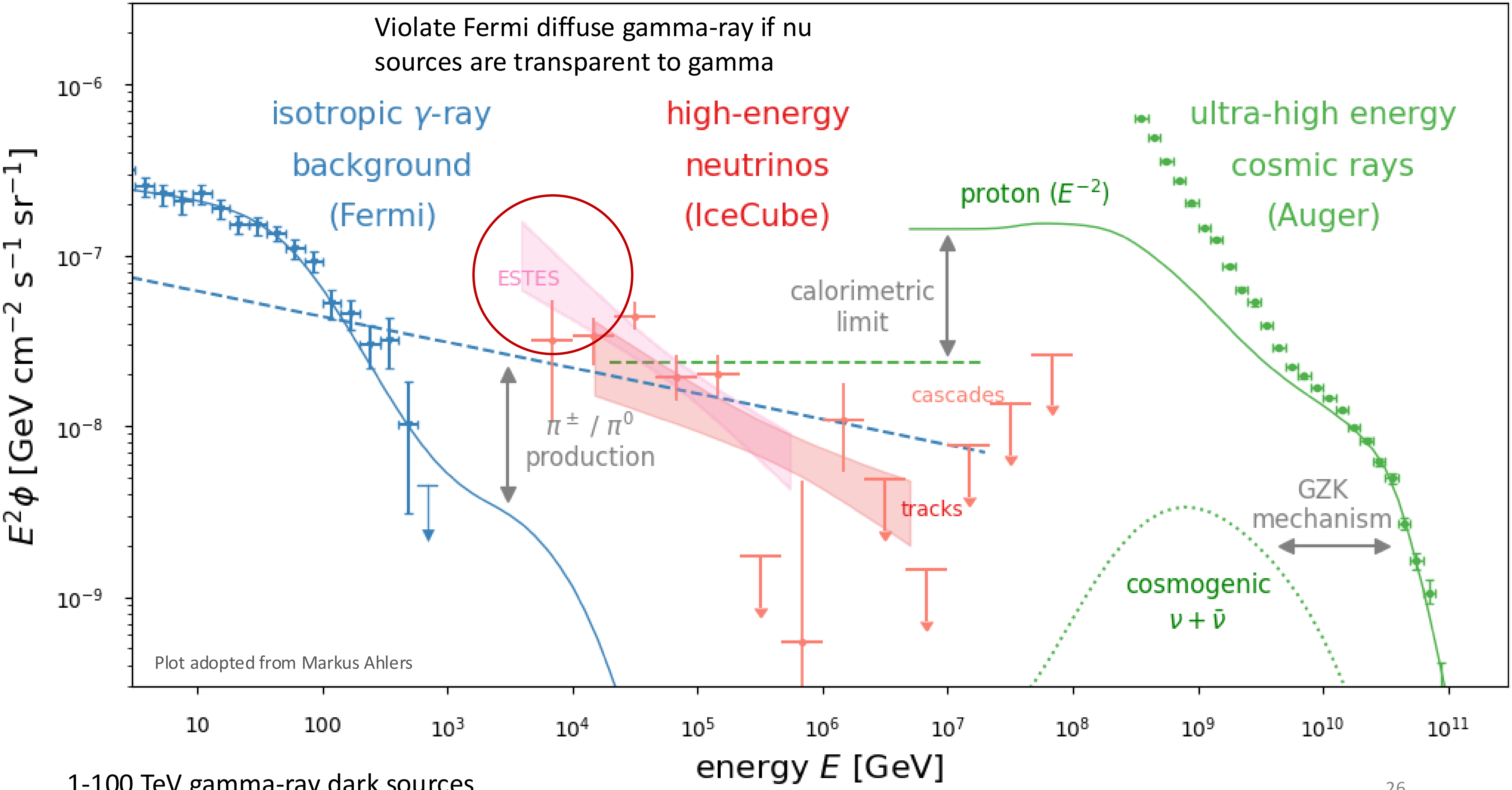
gamma neutrino UHECR



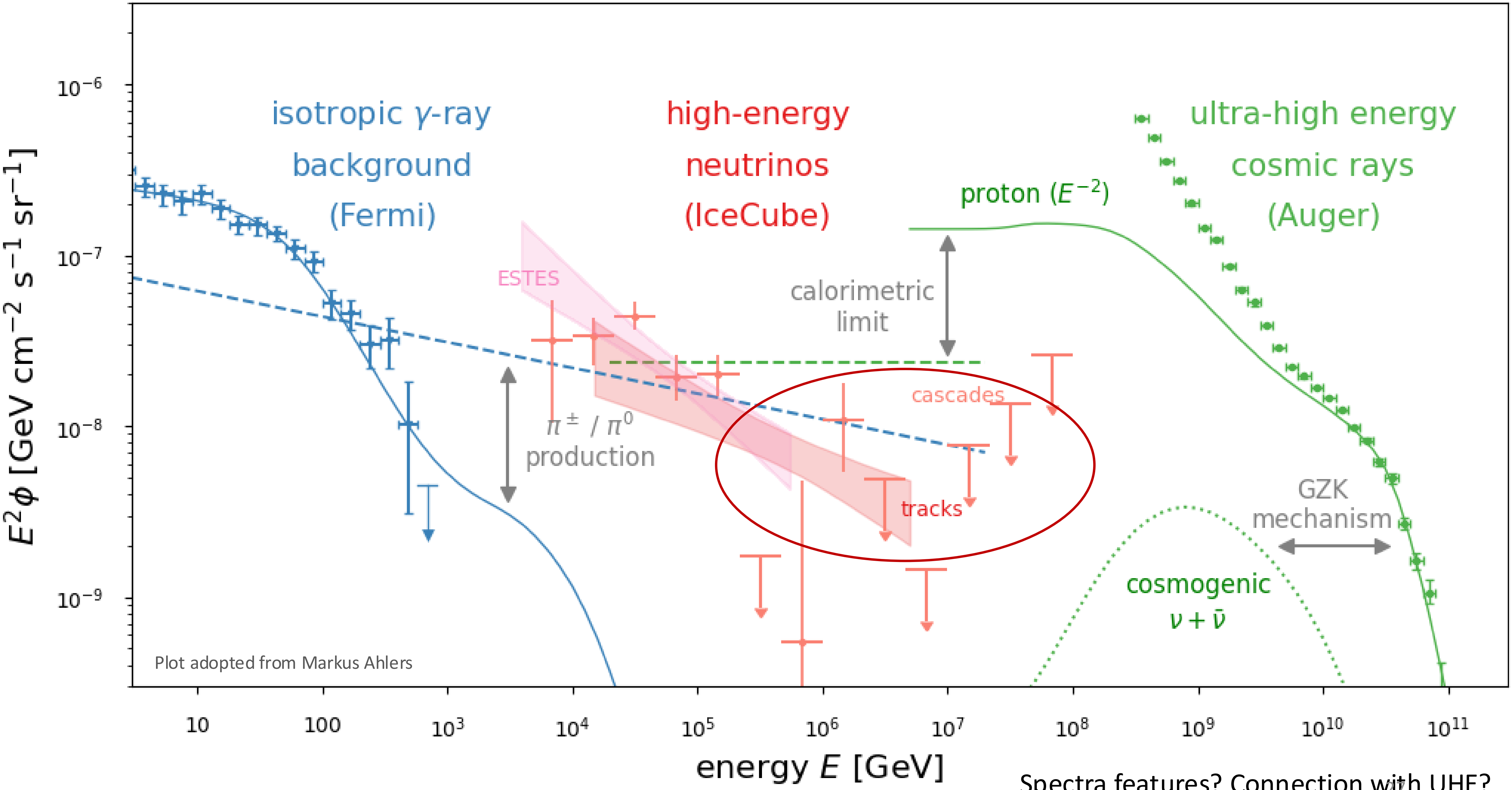
Energy generation rates are all comparable to a few x 10^{43} erg Mpc^{-3} yr^{-1}


After a decade of IceCube
isotropic γ-ray background (Fermi)
high-energy neutrinos (IceCube)
ultra-high energy cosmic rays (Auger)
ESTES
cascades
tracks
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
energy E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

Violate Fermi diffuse gamma-ray if nu sources are transparent to gamma



1-100 TeV gamma-ray dark sources



Spectra features? Connection with UHE?

Highest-energy KM3Net/ARCA21 event

Partially constructed array in Mediterranean

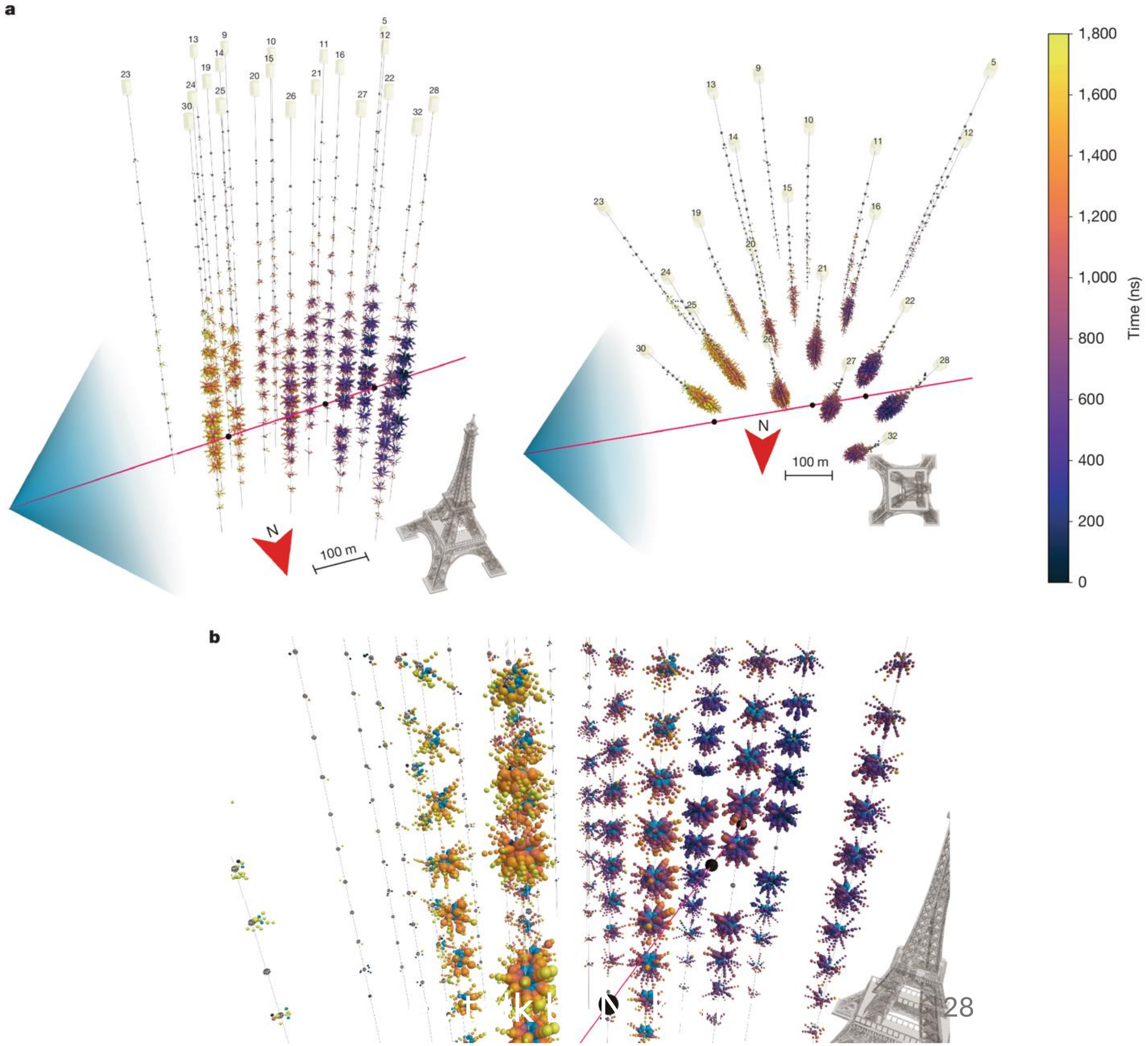
Unique, high charge event detected

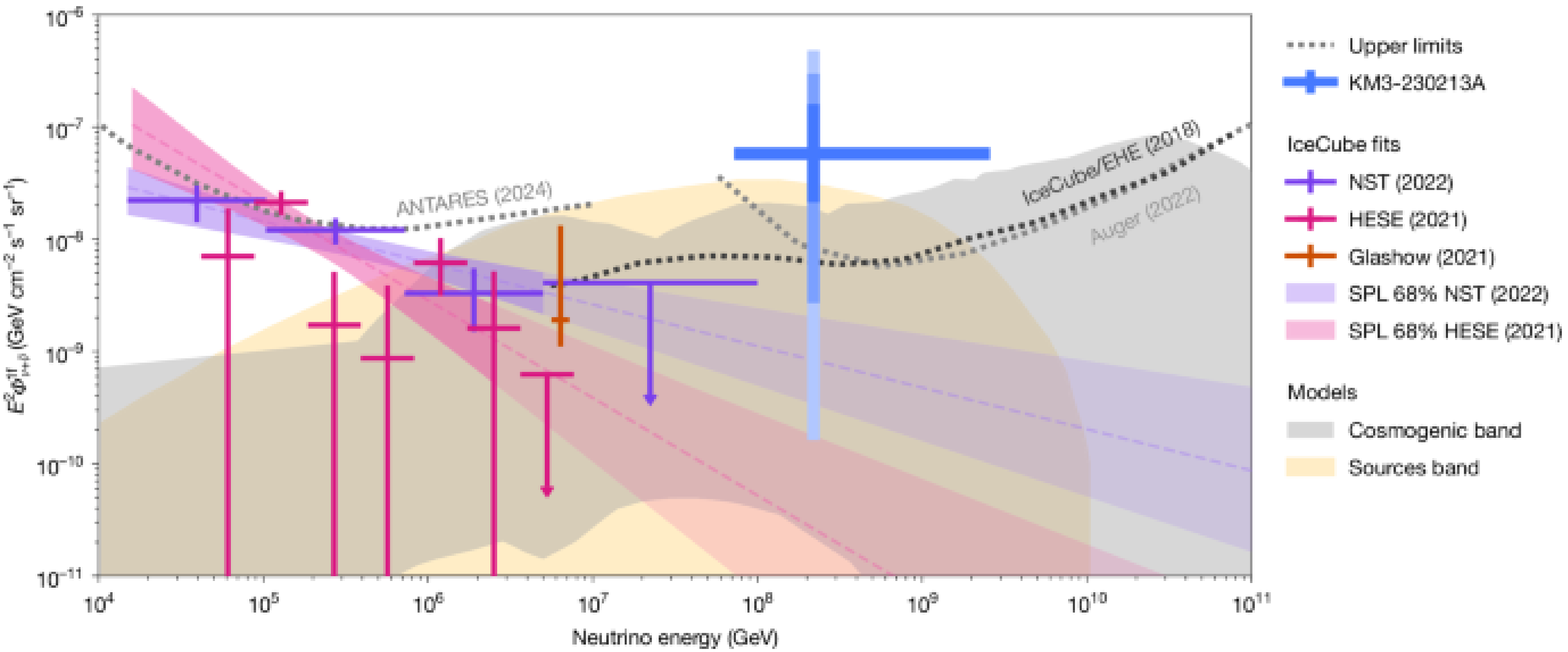
Assuming E^{-2} spectrum:

→ $E_\nu = 220^{+570}_{-110}$PeV

→ Strong prior dependence, large energy uncertainty

Nature **638**, 376–382 (2025)

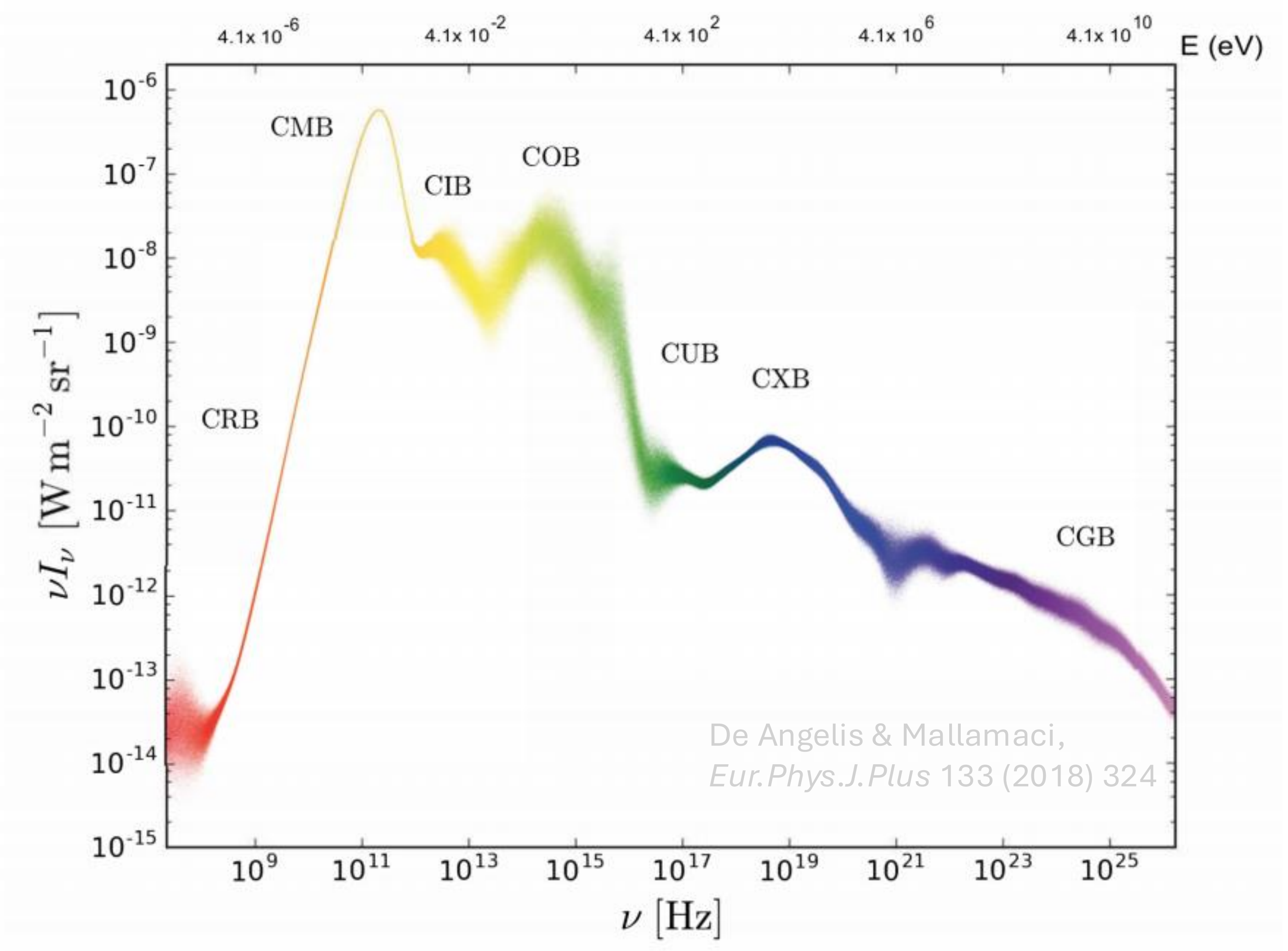




Nature **volume 638**, pages376–382 (2025)

UHE neutrinos: a smoking gun signature

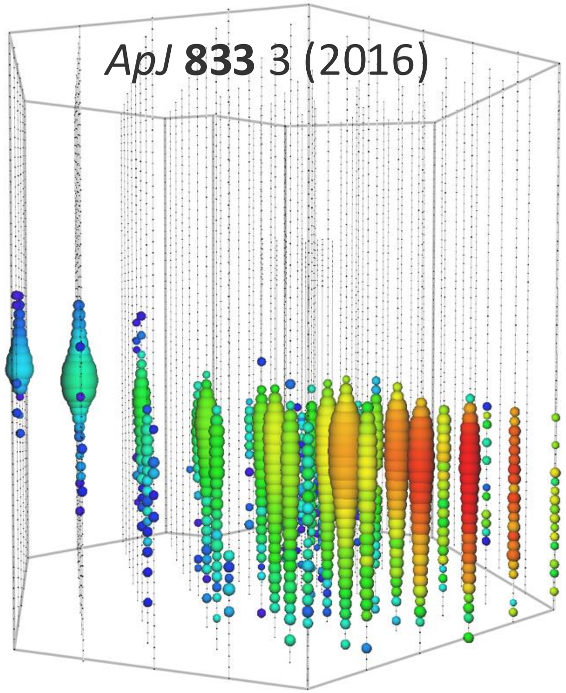
- Photopion produced neutrinos have 1/20 the primary energy-per-nucleon
- CMB target: $10^{19.7}$ eV energy threshold => EeV energy neutrinos
- CIB target: 10^{18} eV energy threshold => **O(10 PeV)** neutrinos
  - **Ambient photons** in **source** can also serve as target



The highest energy neutrinos

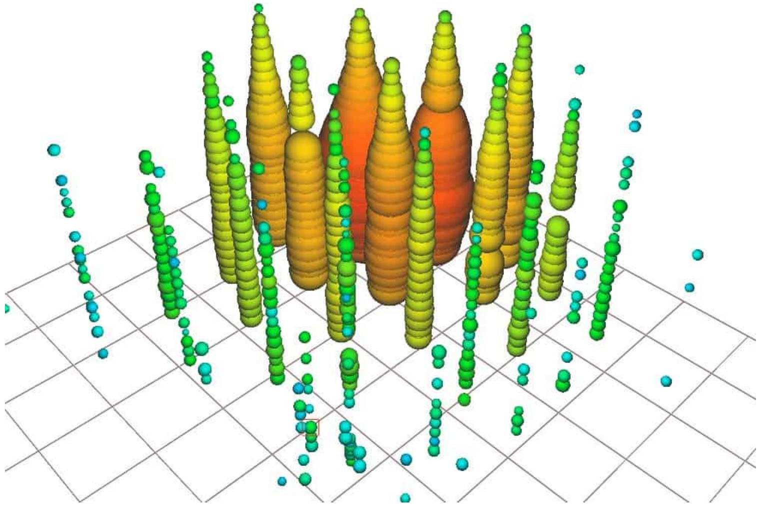
- 3 events with neutrino energy > 5 PeV over a decade of data taking

ApJ **833** 3 (2016)



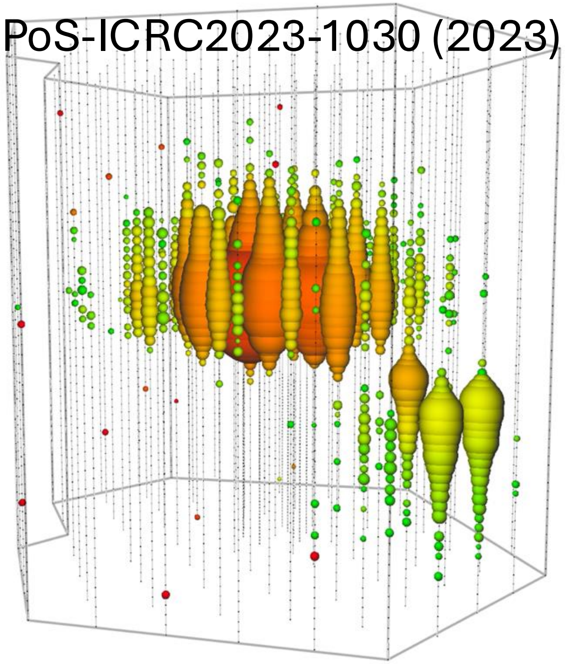
Muon energy: 4.5±1.2 PeV
Nu energy ~ 9 PeV

Nature **591**, 220–224 (2021)



Deposited energy: 6.05 ±0.72 PeV
Nu energy ~6.3 PeV

PoS-ICRC2023-1030 (2023)

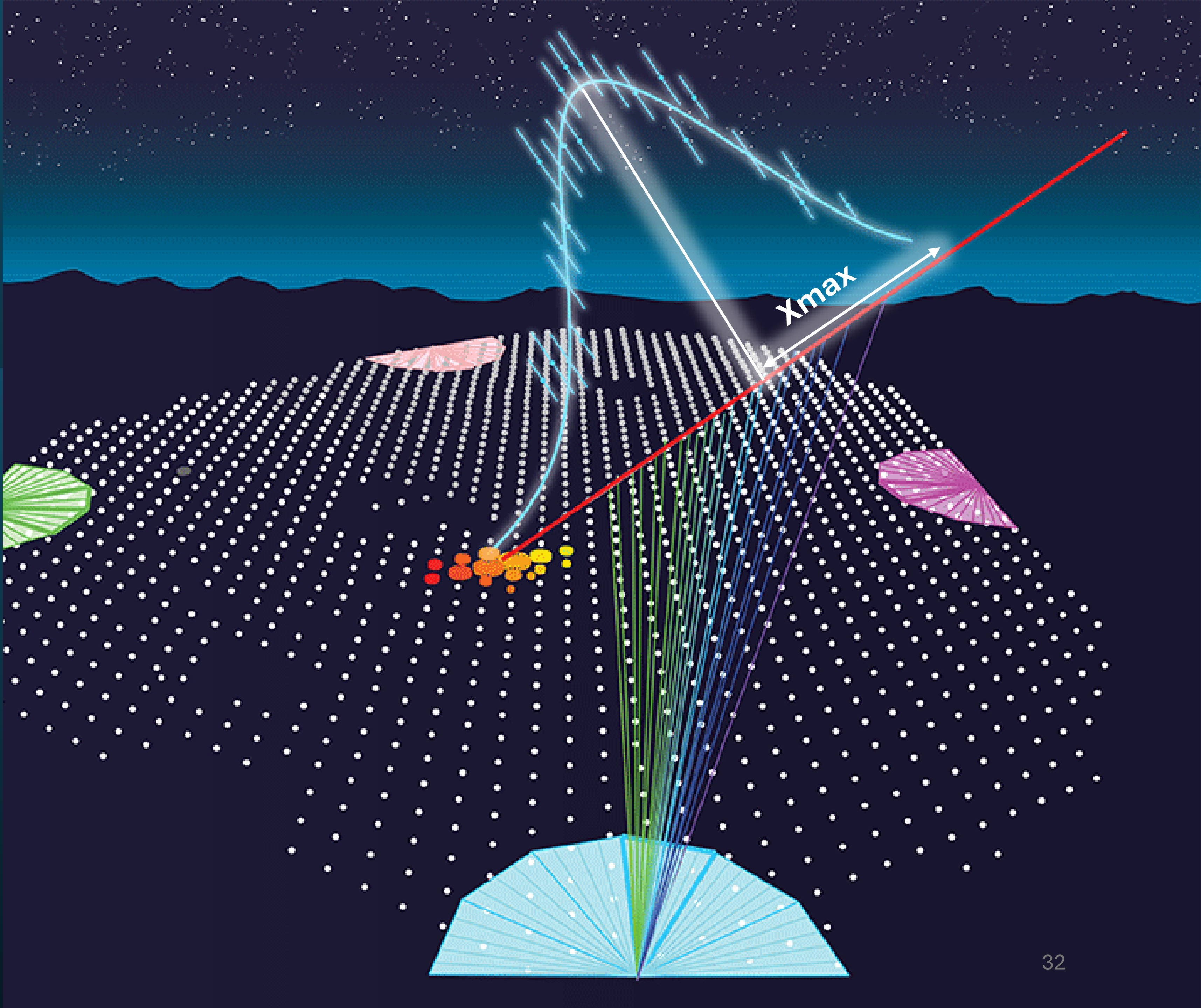


Nu energy ~11.4±2.5 PeV

Hybrid air shower detections from the Pierre Auger Observatory (2004 to now)

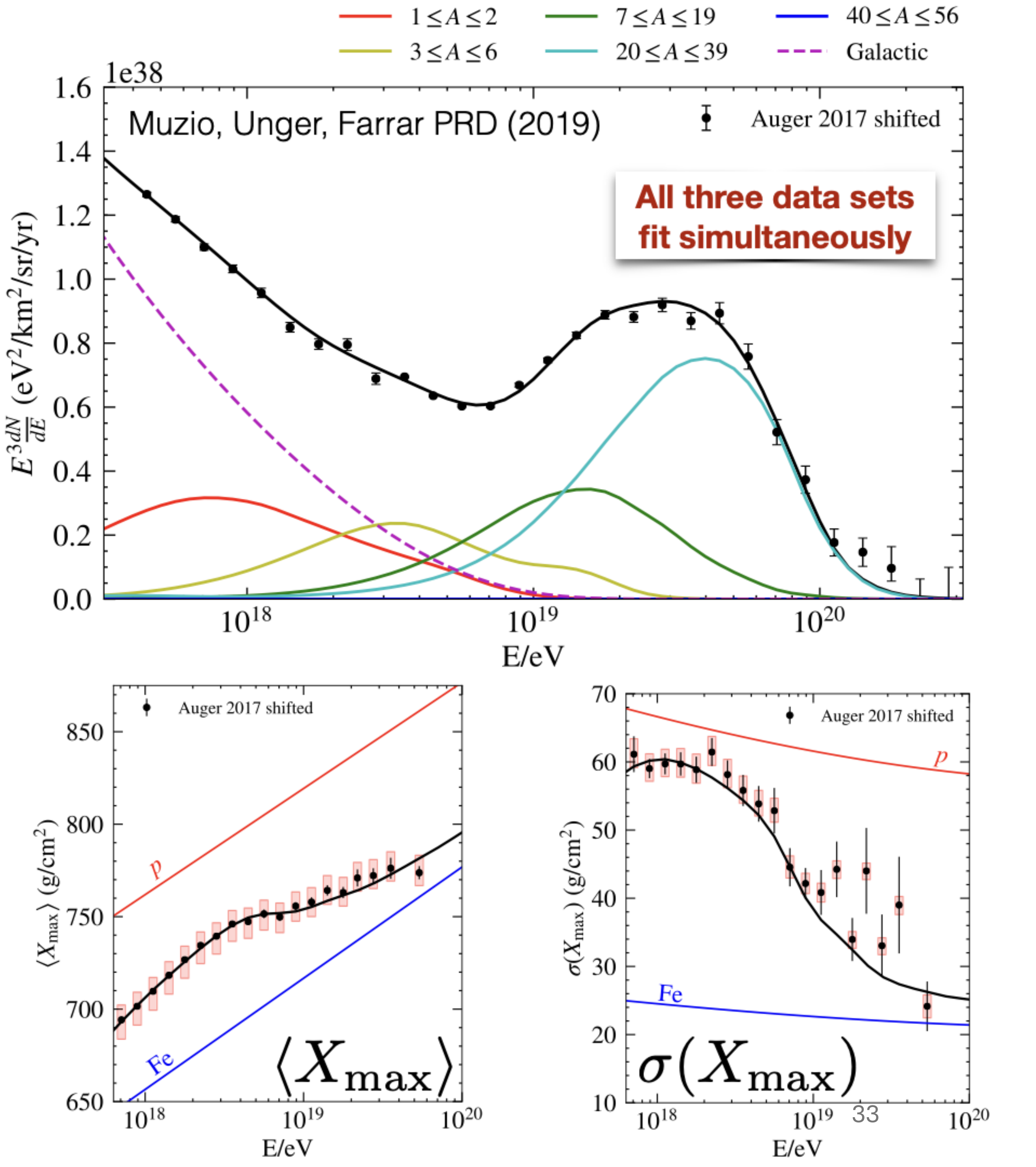
The highest energy cosmic rays

Observables: cosmic ray flux; mass composition via Xmax



CR Source Model

- Unger-Farrar-Anchordoqui model (UFA, 2015 PRD):
    1. Inject CRs into source environment
    2. **CRs processed by *photon* interactions**
    3. CRs escape source environment
    4. CRs propagate to Earth
- Accounts for observed spectrum (>$10^{17.5}$ eV) & composition (>$10^{17.8}$ eV)



Joint UHECR-neutrino likelihood maximization

- High energy neutrinos**
  - Poisson distribution in energy-zenith-flavor bins >5 PeV**
  - Non-observation of neutrinos >15 PeV**

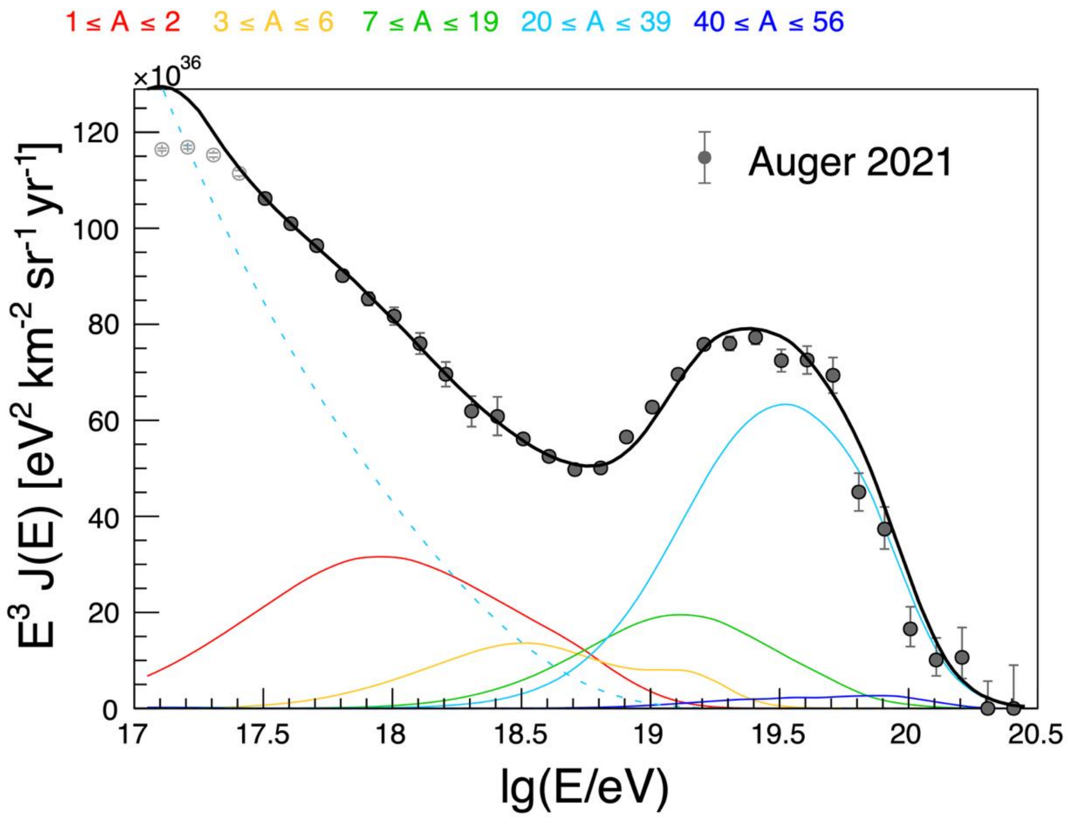
- Ultra high energy cosmic rays
  - Flux $>10^{17.5}$ eV
  - Full Xmax distributions $>10^{18.6}$ eV**
    - Rather than fitting only first two moments

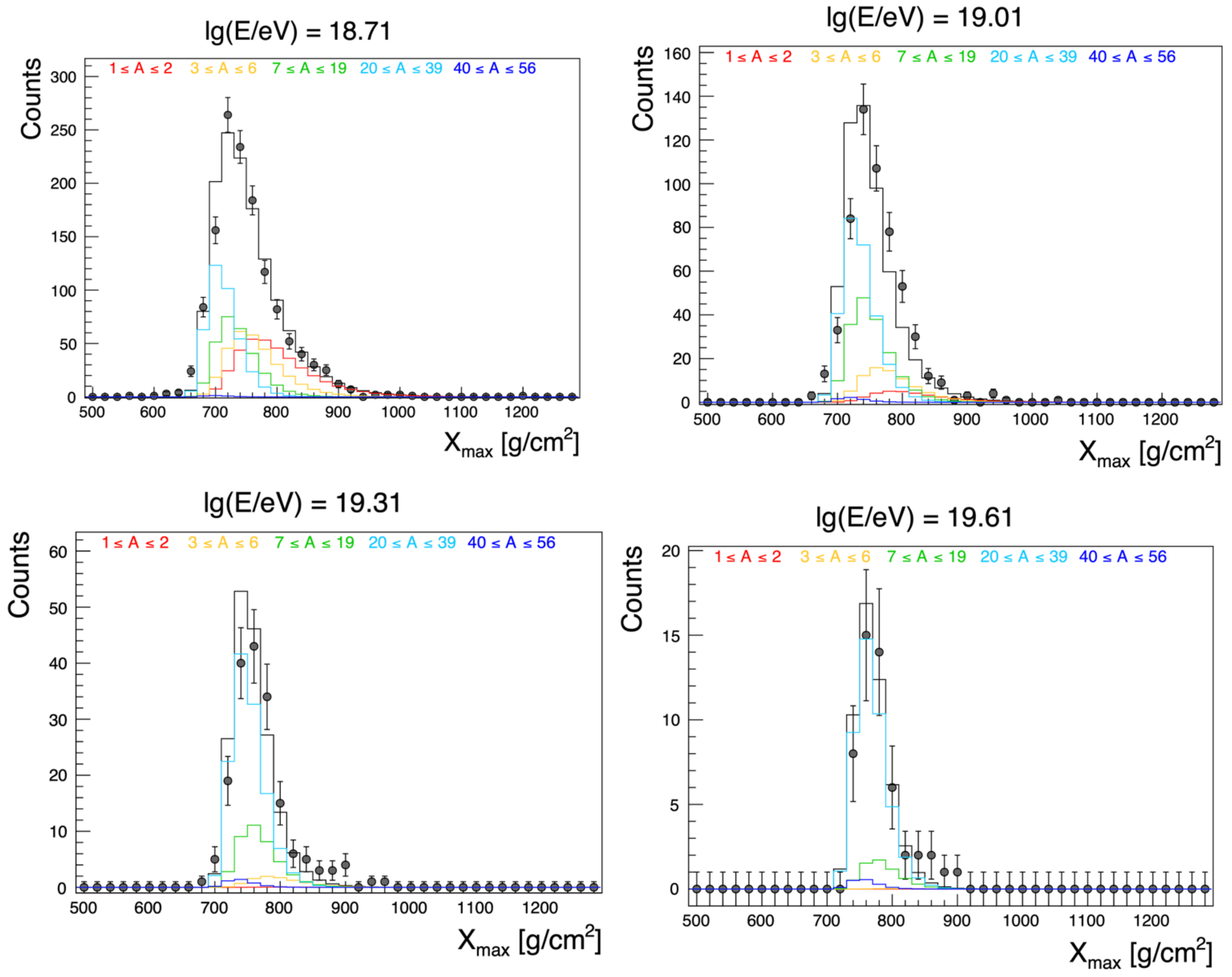
****NEW THIS ANALYSIS**

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{UHECR}} + \ln \mathcal{L}_{\nu}$$

Assumptions: standard sources, SFR source evolution, mixed composition injection, Sibyll2.3d hadronic interaction model,
Auger energy scale shifted by +1σ, Xmax scale by -1σ

Result: UHECR parameters



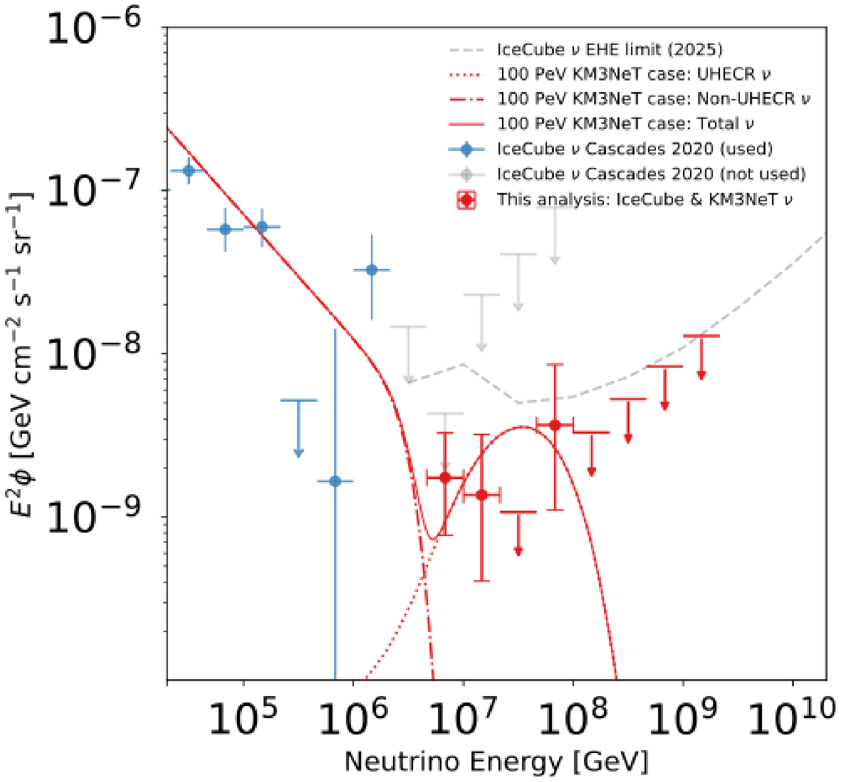


Common origin with UHECR?

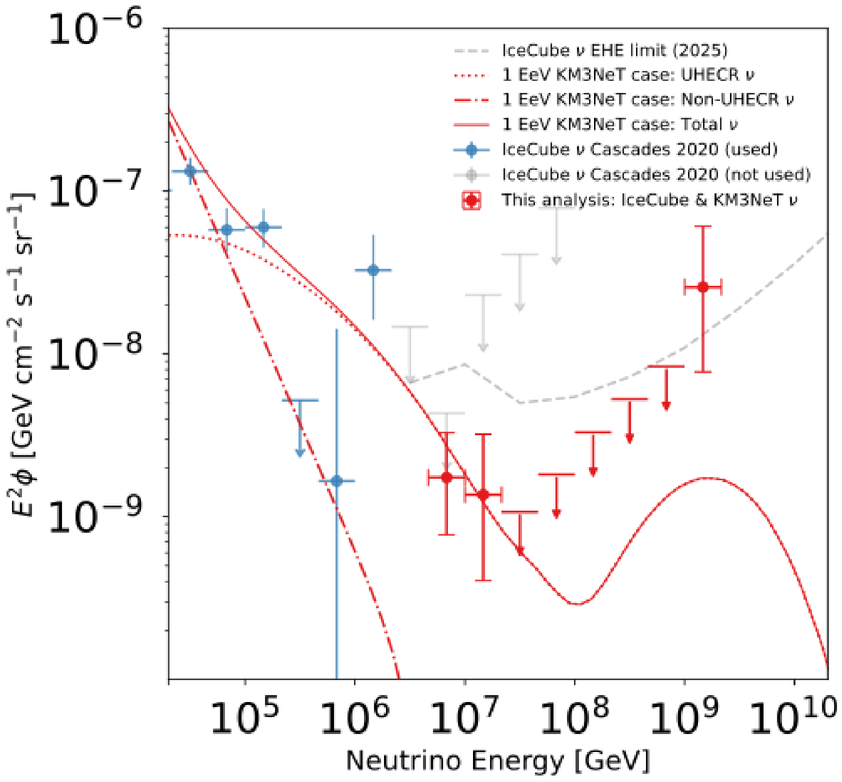
Muzio, Yuan, Lu
arXiv:2502.06944

Assume KM3Net/ARCA exposure is ~2% of IceCube NT

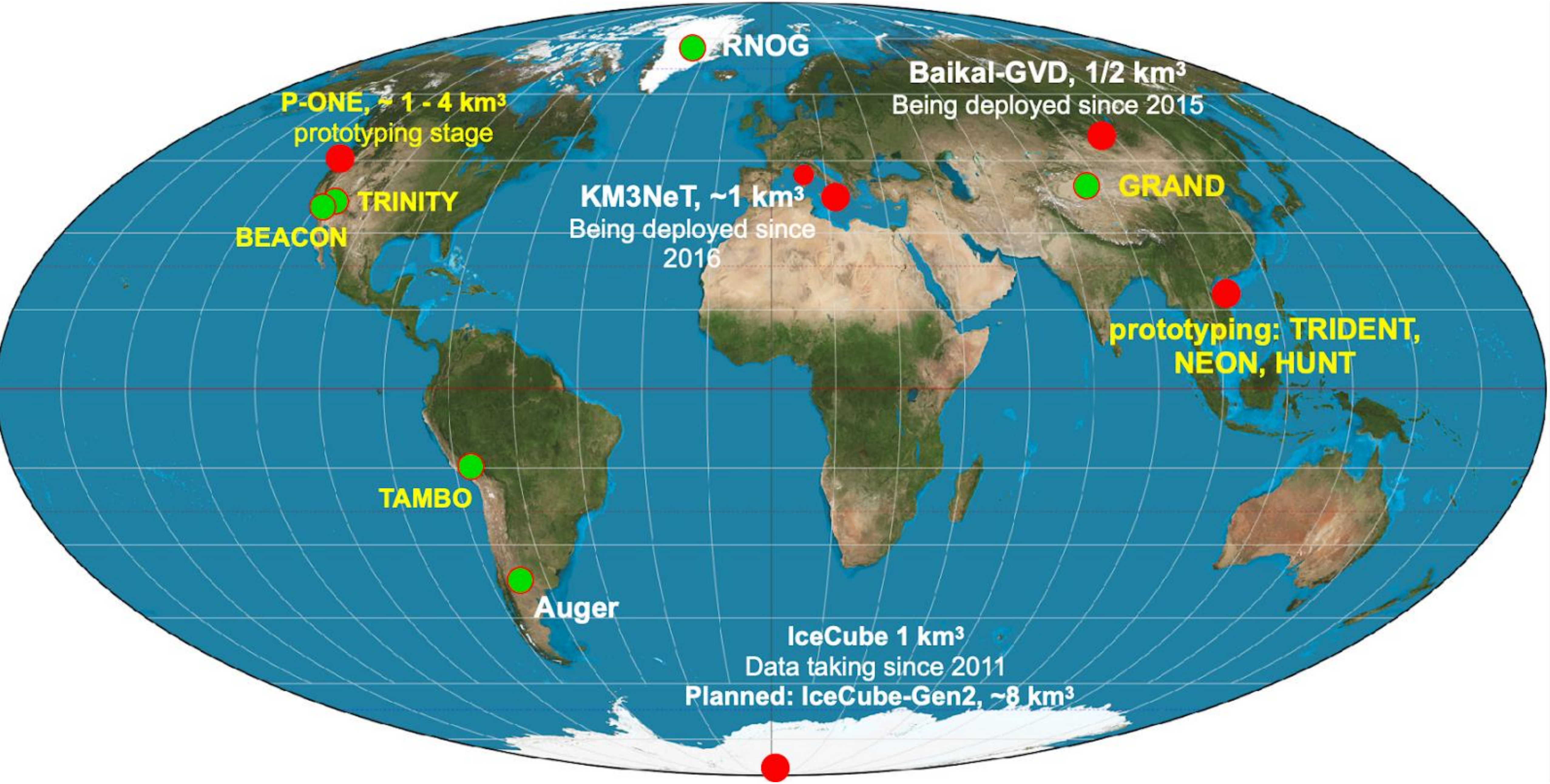
Test 100 PeV and 1 EeV+additional proton component as two distinct scenarios // combined fit with Auger mass/flux



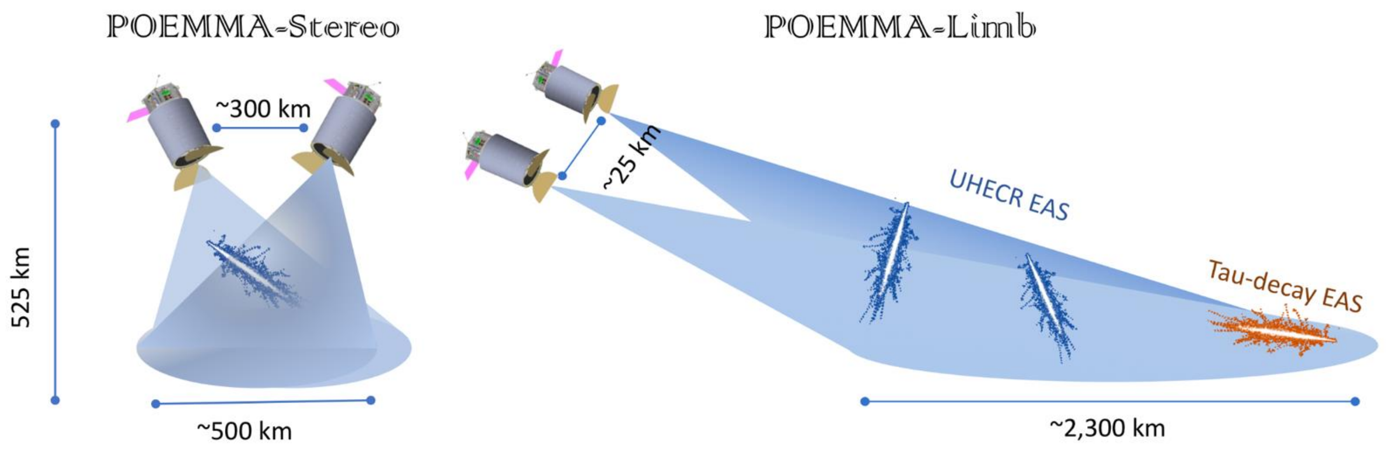
100 PeV scenario
Possible recovery at 30 PeV from UHECR

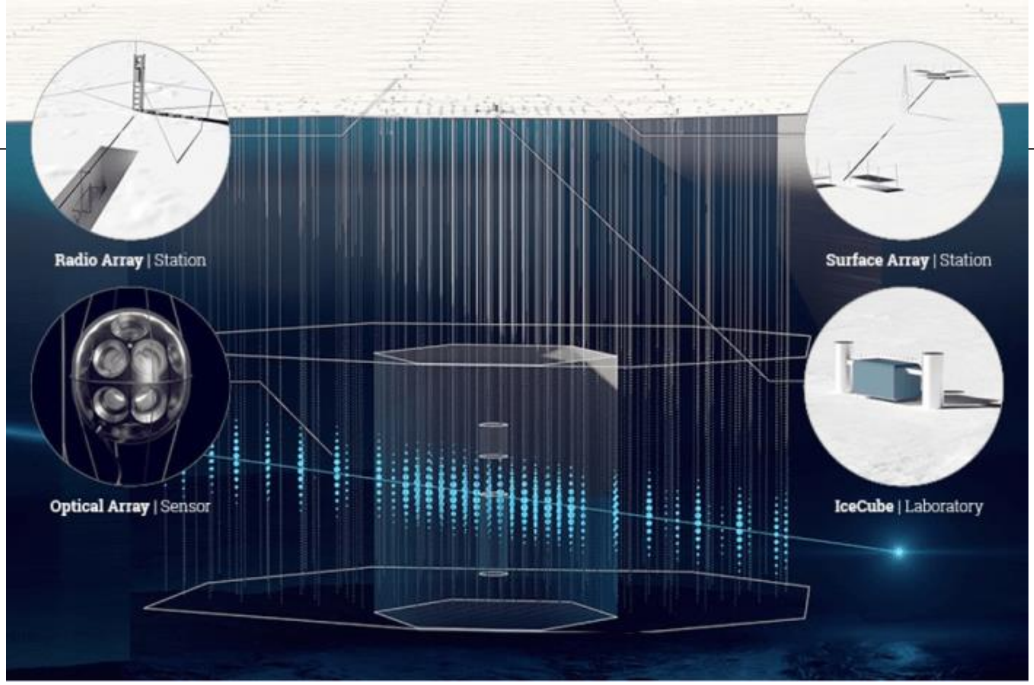


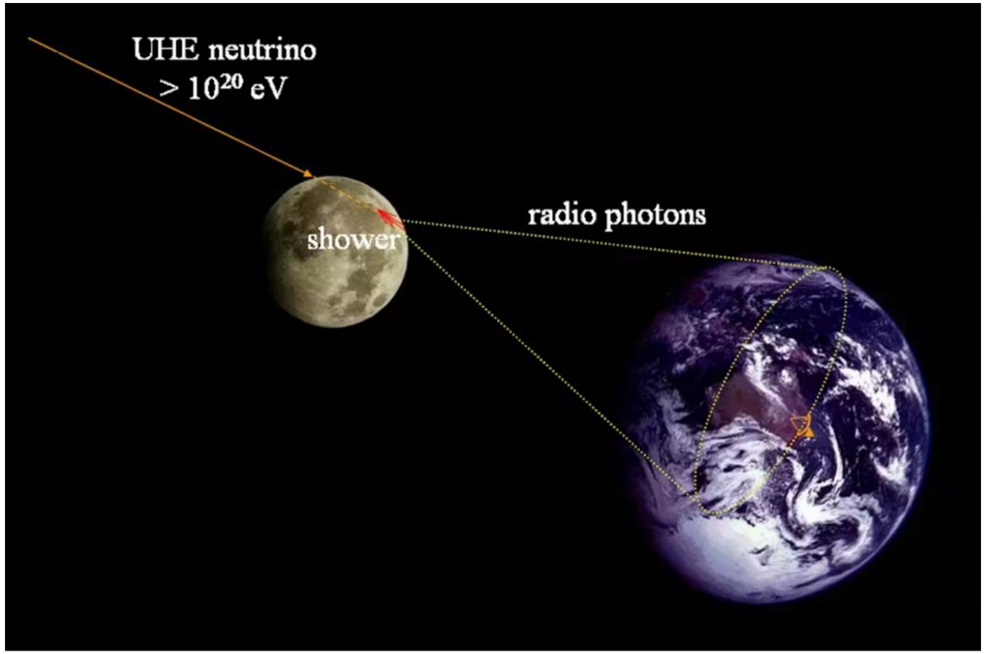
1 EeV + pure proton component scenario
Possibly a cosmogenic neutrino via GZK mechanism

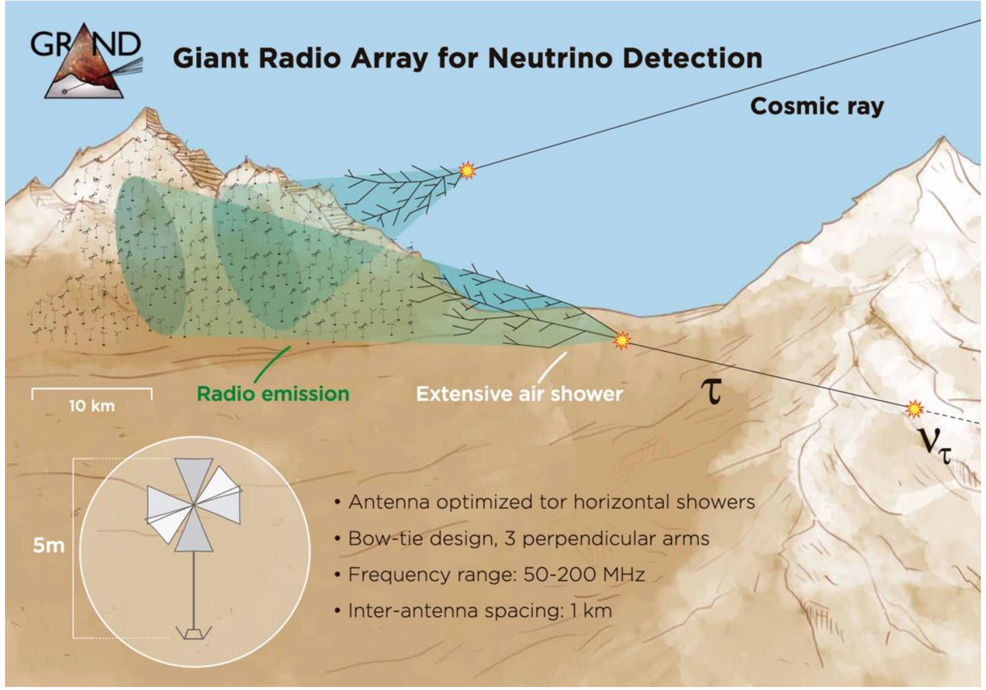

RNOG
Baikal-GVD, 1/2 km³
Being deployed since 2015
P-ONE, ~ 1 - 4 km³
prototyping stage
GRAND
TRINITY
KM3NeT, ~1 km³
Being deployed since 2016
BEACON
prototyping: TRIDENT, NEON, HUNT
TAMBO
Auger
IceCube 1 km³
Data taking since 2011
Planned: IceCube-Gen2, ~8 km³

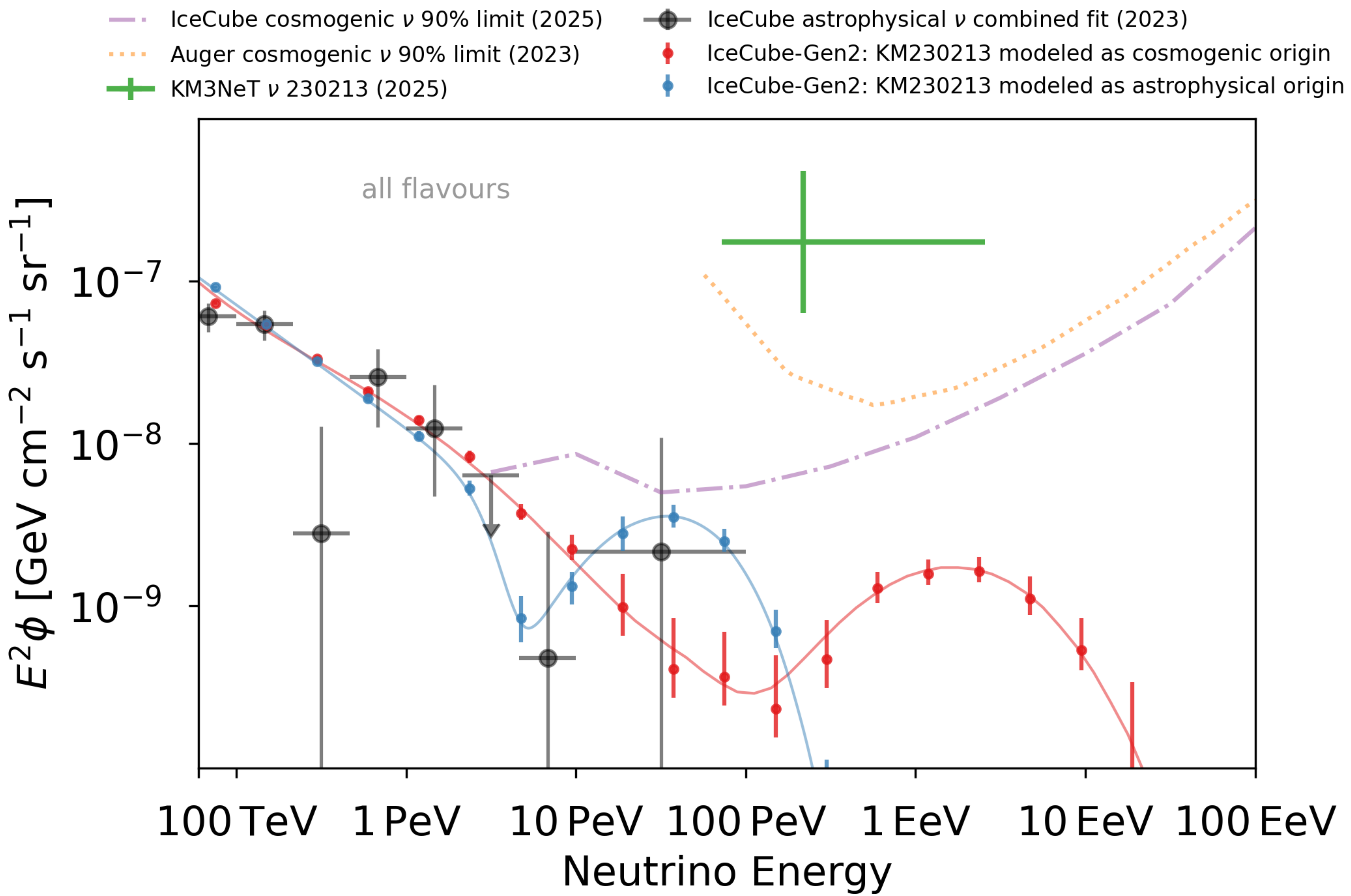
Future neutrino telescopes











IceCube cosmogenic ν 90% limit (2025)
Auger cosmogenic ν 90% limit (2023)
KM3NeT ν 230213 (2025)
IceCube astrophysical ν combined fit (2023)
IceCube-Gen2: KM230213 modeled as cosmogenic origin
IceCube-Gen2: KM230213 modeled as astrophysical origin
all flavours
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
100 TeV
1 PeV
10 PeV
100 PeV
1 EeV
10 EeV
100 EeV
Neutrino Energy

- Read about future neutrino detectors

https://cerncourier.com/a/discovering-the-neutrino-sky/

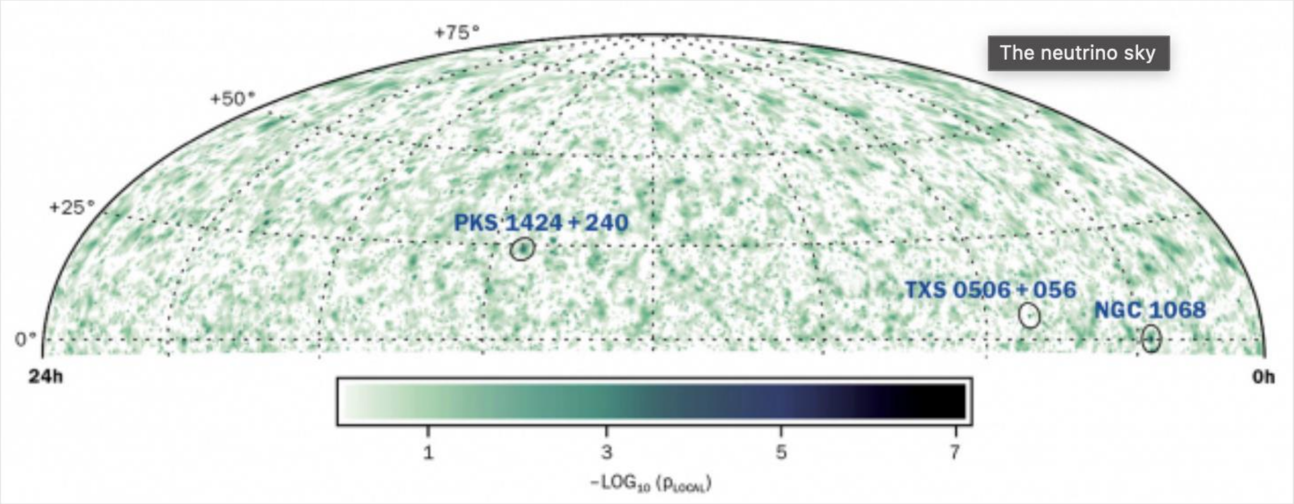
CERNCOURIER Reporting on international high-energy physics

NEUTRINOS | FEATURE

Discovering the neutrino sky

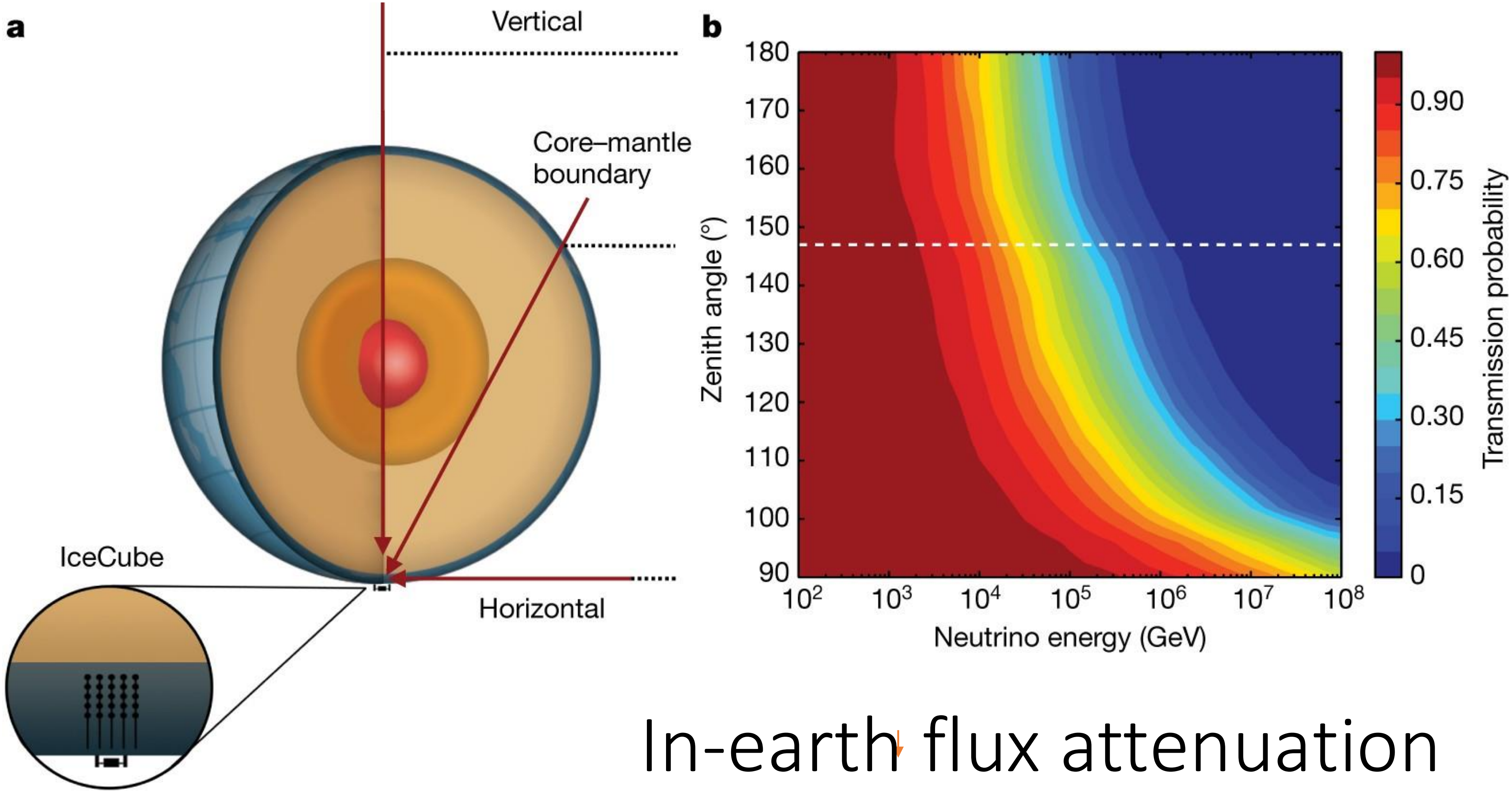
19 May 2025

Lu Lu looks forward to the next two decades of neutrino astrophysics, exploring the remarkable detector concepts needed to probe ultra-high energies from 1 EeV to 1 ZeV.



The neutrino sky IceCube selects neutrinos by using the Earth as a cosmic-ray veto. This map, where 0° is the projection of the Earth's equator onto the sky, shows point-source candidates in the northern hemisphere observed by the IceCube detector at the South Pole. The colour scale represents the statistical significance that a signal is not just a random background. The hottest spot in the northern sky is NGC 1068: a barred spiral galaxy 47 million light-years away that hosts a supermassive black hole surrounded by gamma-ray-attenuating gas and dust. Credit: IceCub Collab. 2022 *Science* **378** 538

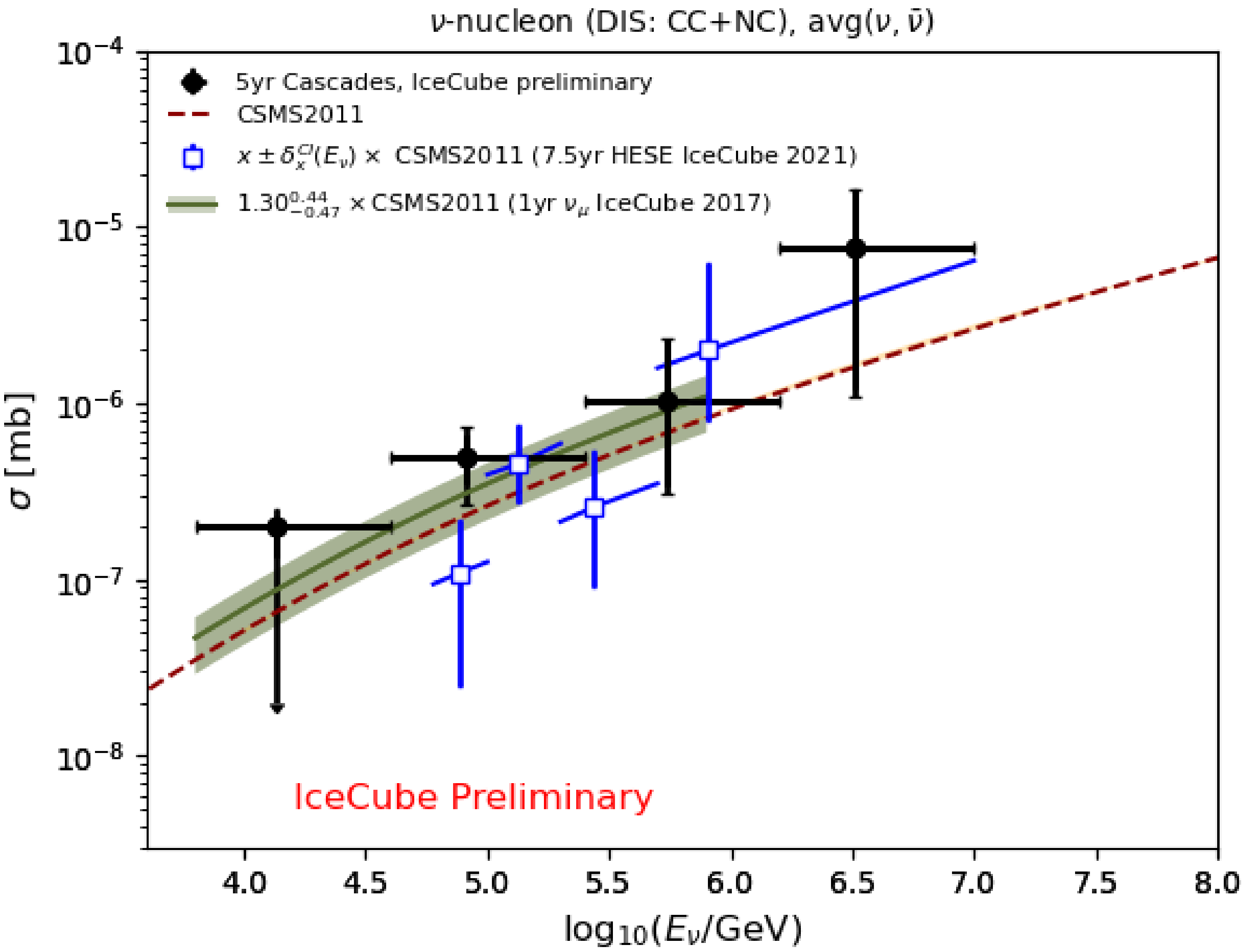
Cross section measurement using Earth as the target



In-earth flux attenuation

Cross section

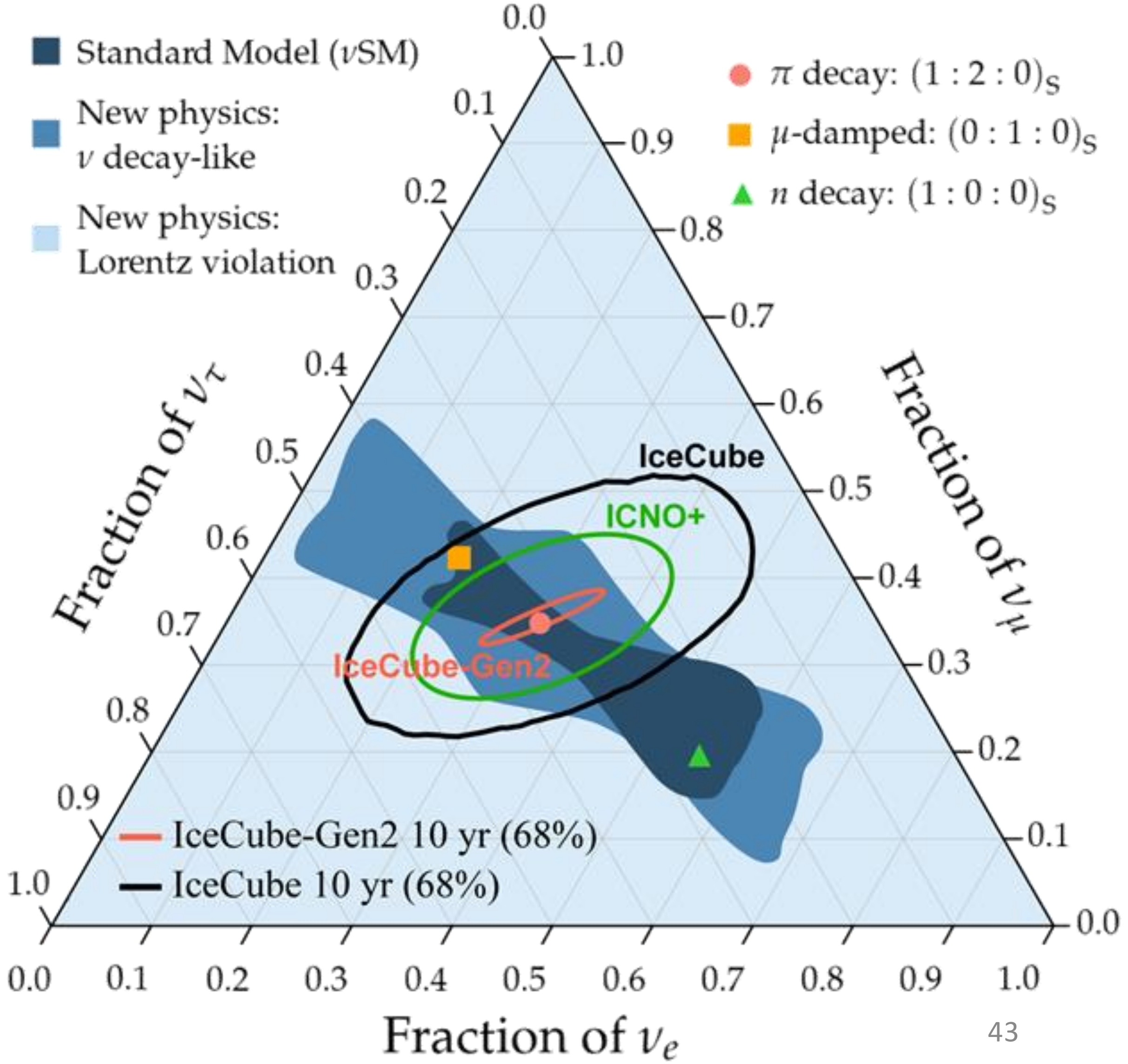
- Both tracks and cascades
- Reaching energies beyond accelerators

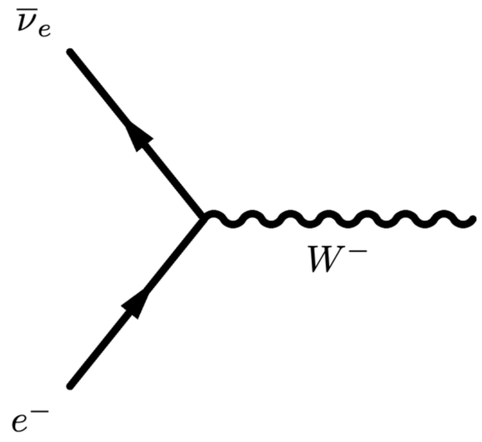


Neutrino oscillations over cosmic baselines

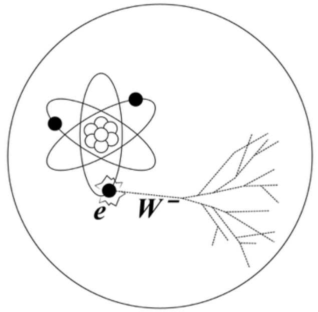
- For the first time tau candidates in data

- Observed high-energy tau neutrinos mainly due to neutrino oscillations through astronomical distances.
- Sensitive probe for physics beyond the Standard Model





Neutrino-electron scattering



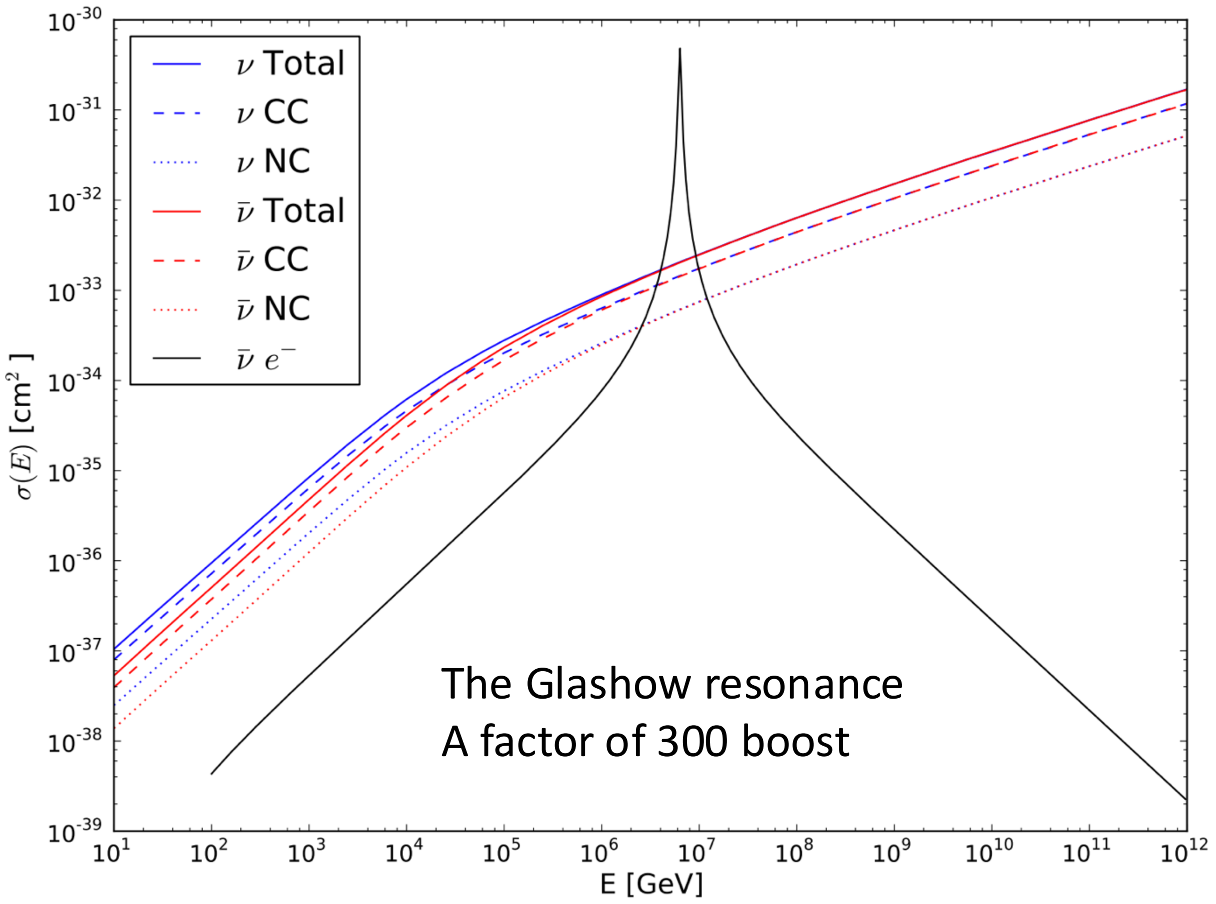
at a neutrino energy of 6.3 PeV, the centre-of-mass energy (80.5 GeV) is large enough to produce a real W boson

$$\sigma(s) = 24\pi\Gamma_W^2 B_{W^- \to \bar{\nu}_e + e^-} \frac{s/M_W^2}{(s - M_W^2)^2 + \Gamma_W^2 M_W^2}$$

$$\overline{\nu_e} + e \quad \to W^- \to \quad \overline{\nu_l} + l$$

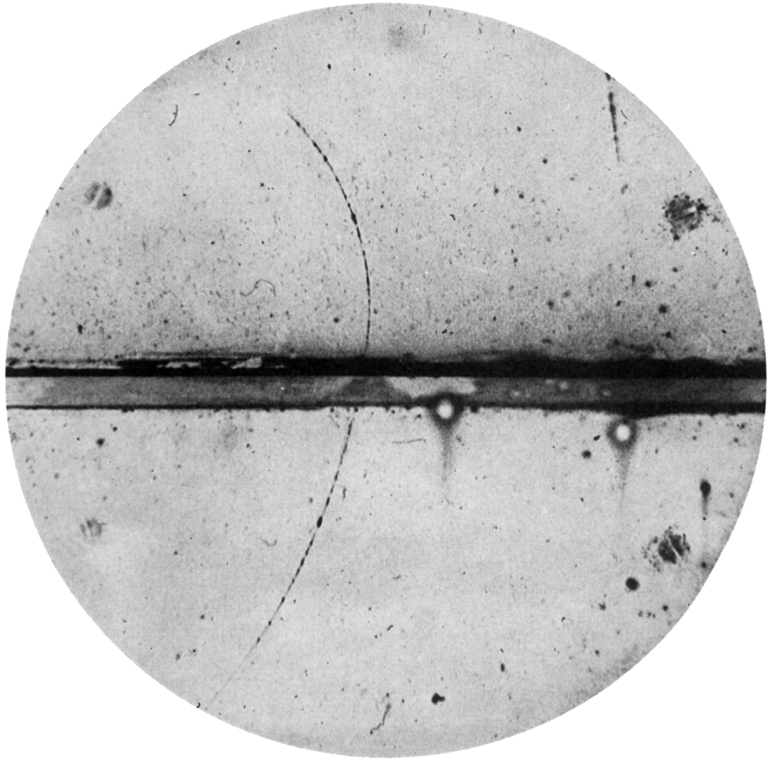
$$\overline{\nu_e} + e \quad \to W^- \to \quad X \quad ,$$

$$E_{\rm R} = M_W^2/(2m_e) = 6.32 \text{PeV}$$

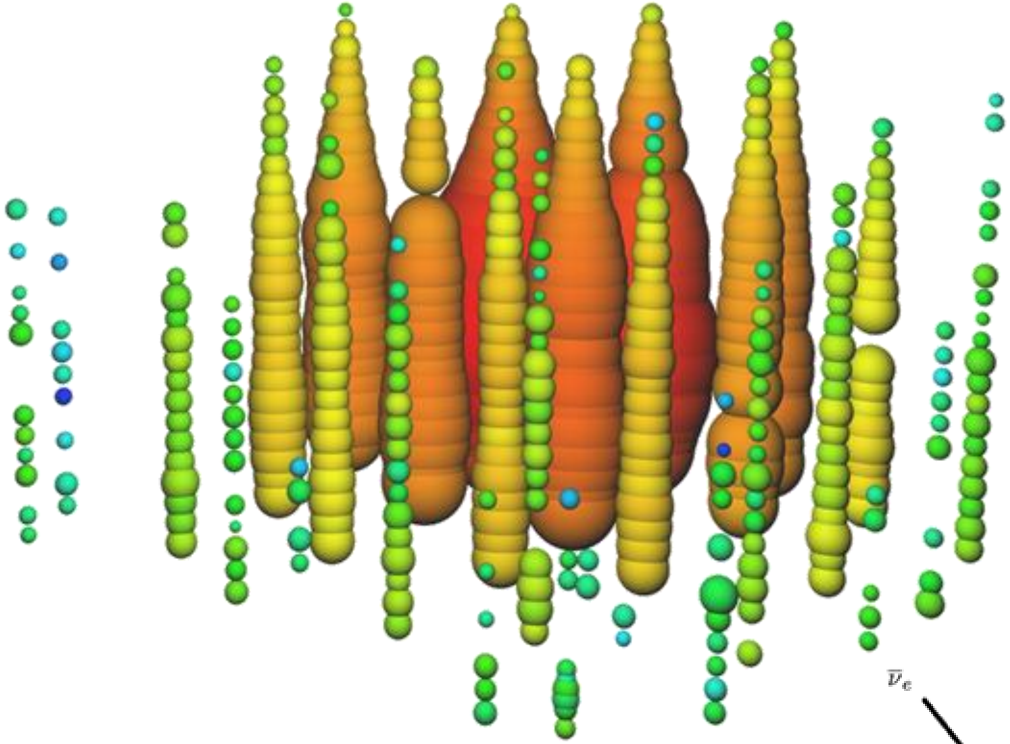


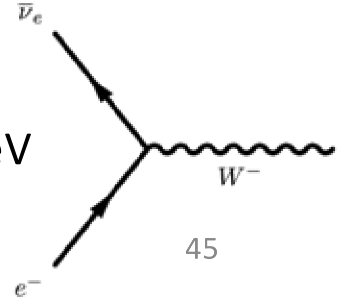
W boson (Glashow) resonance – first hint of electron anti-neutrino

Nature **591,** 220–224 (2021)

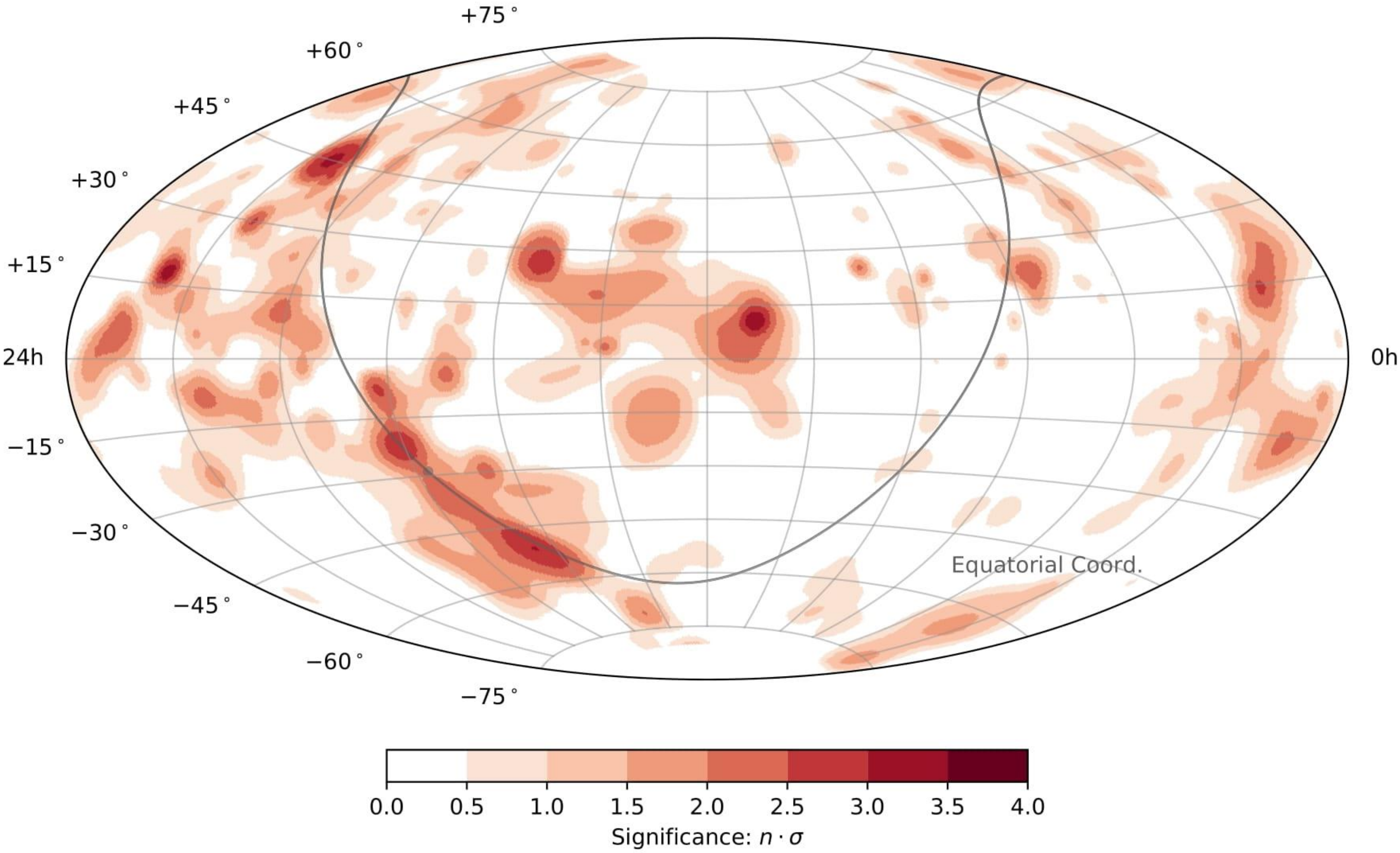


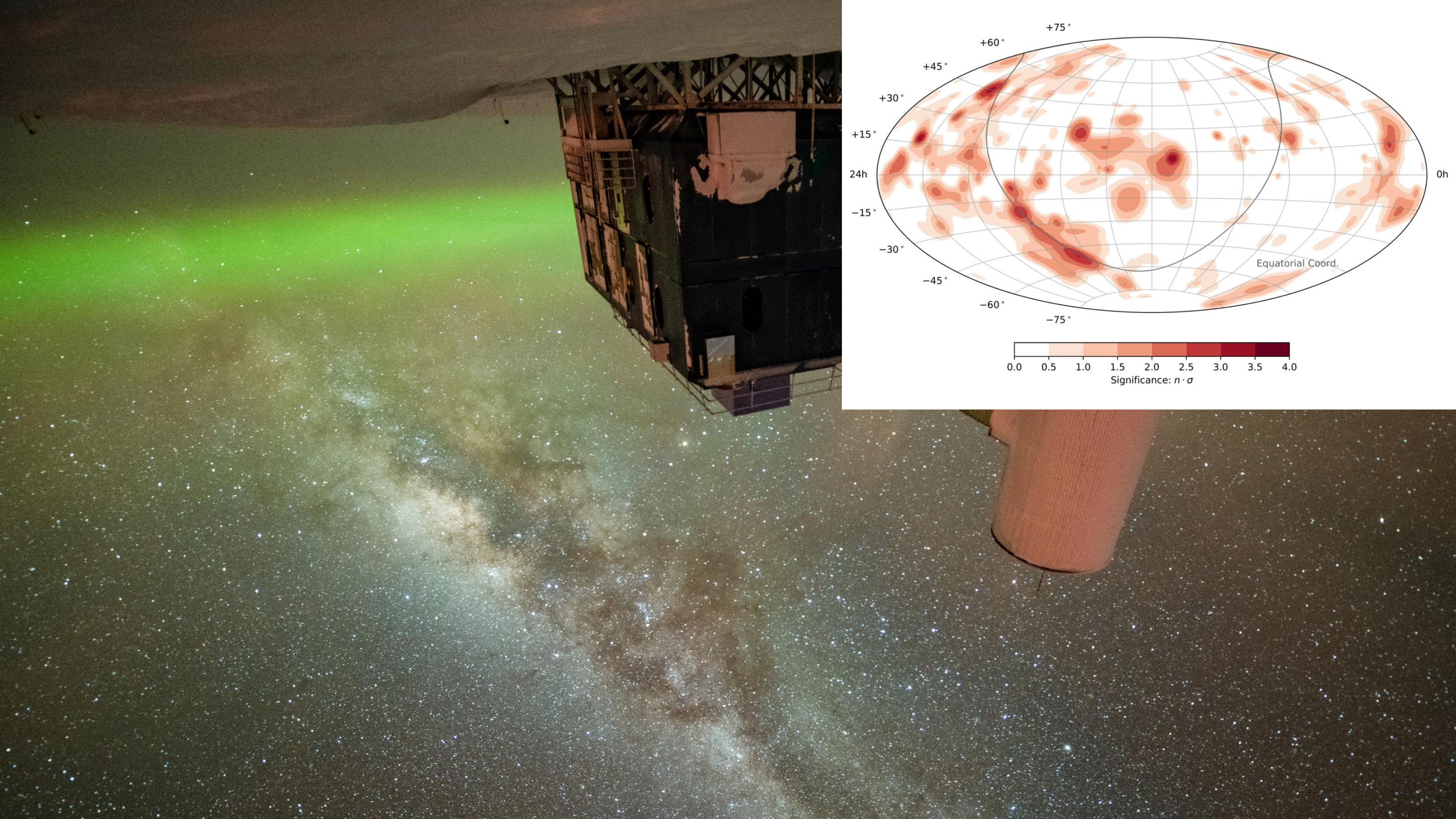
Discovery of antimatter, positron
Carl Anderson via cloud chamber, 1932





W boson resonance , nuebar 6.3 PeV
IceCube, 2021


+75°
+60°
+45°
+30°
+15°
24h
0h
−15°
−30°
−45°
−60°
−75°
Equatorial Coord.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Significance: $n \cdot \sigma$

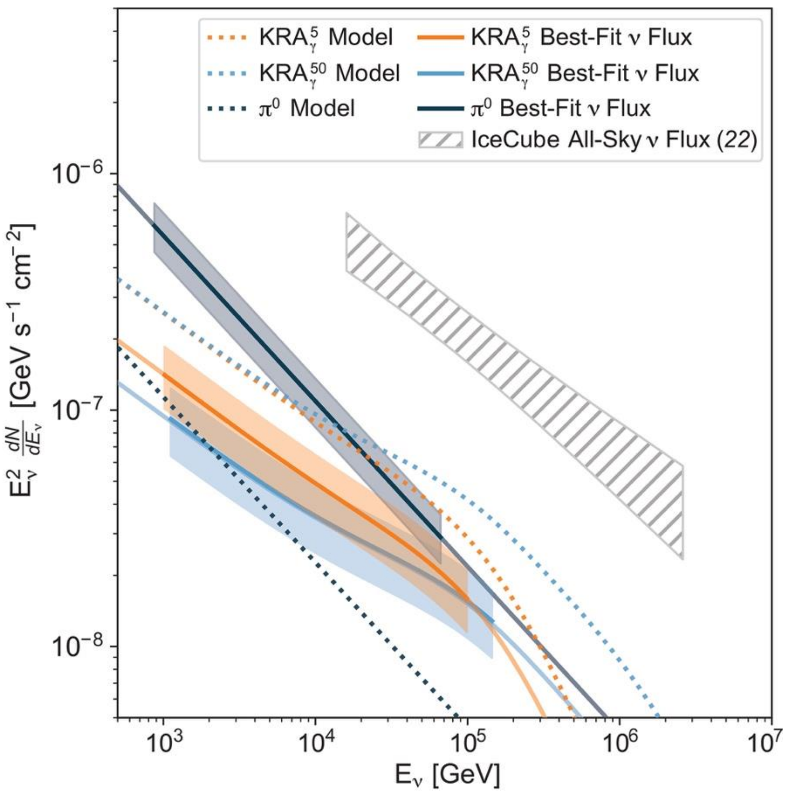


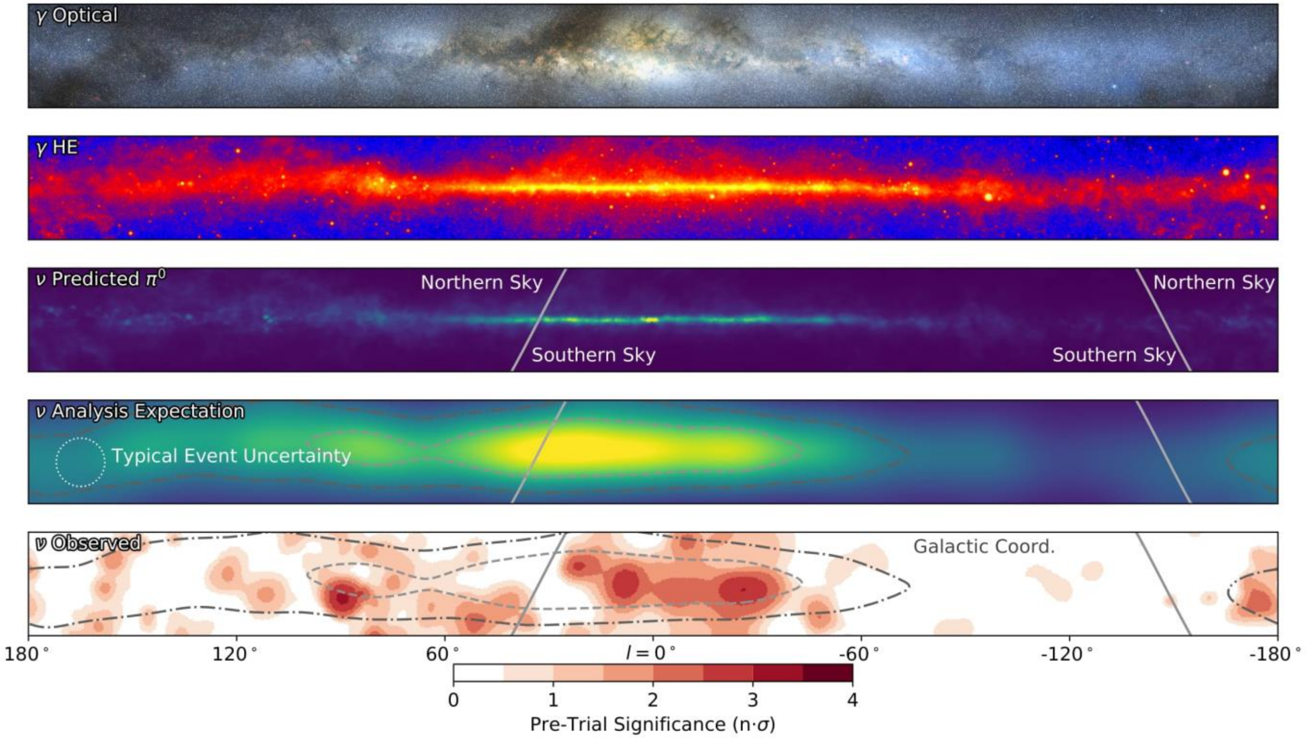
+75°
+60°
+45°
+30°
+15°
24h
−15°
−30°
−45°
−60°
−75°
0h
Equatorial Coord.
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Significance: n · σ

Neutrino flux from the galactic plane

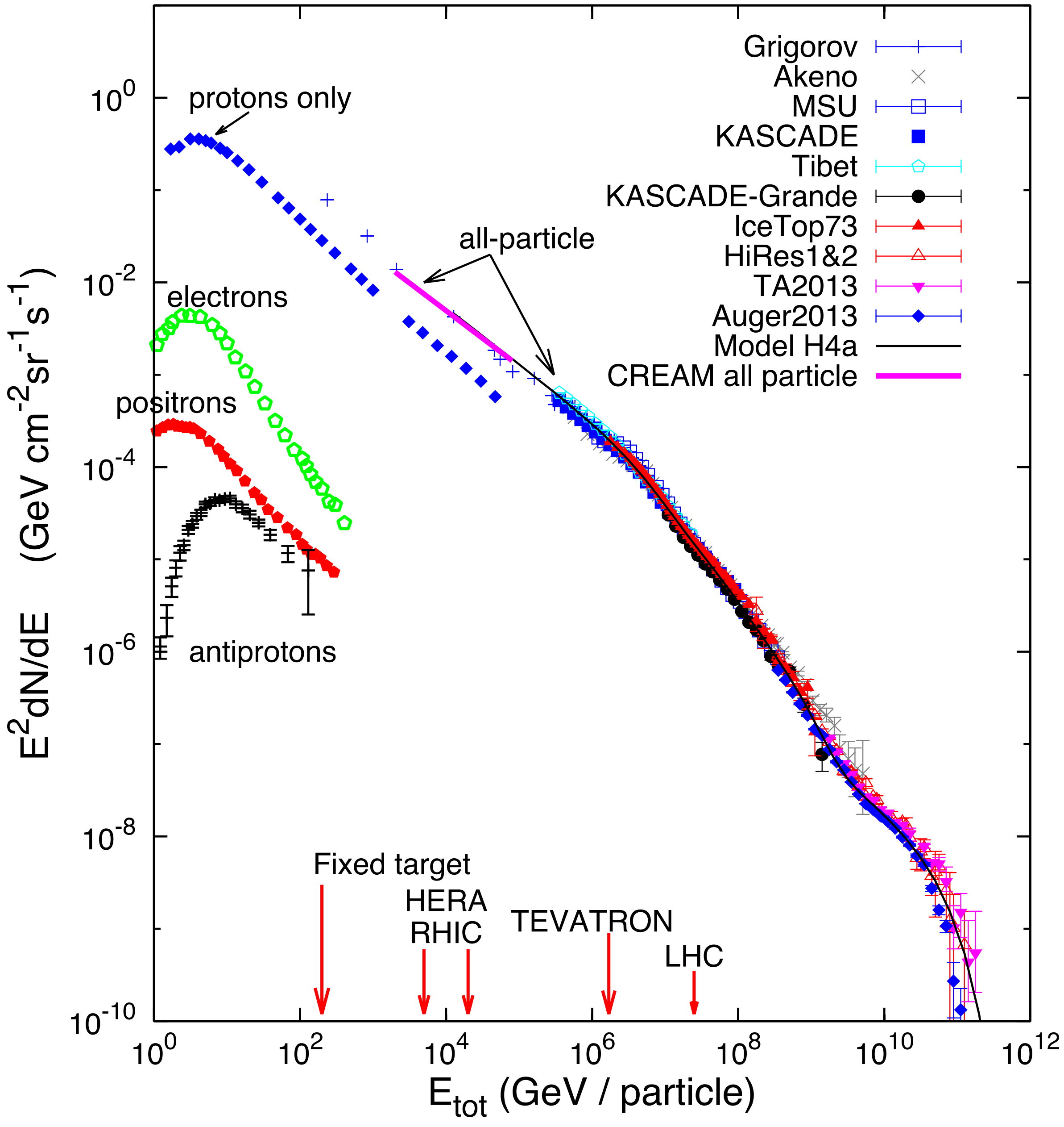
Trials correcting for the three different templates → $\mathbf{4.48\sigma}$ **global p-value**

Contribution of ~6-13% to the total neutrino flux at 30 TeV





Science 380 6652 (2023)

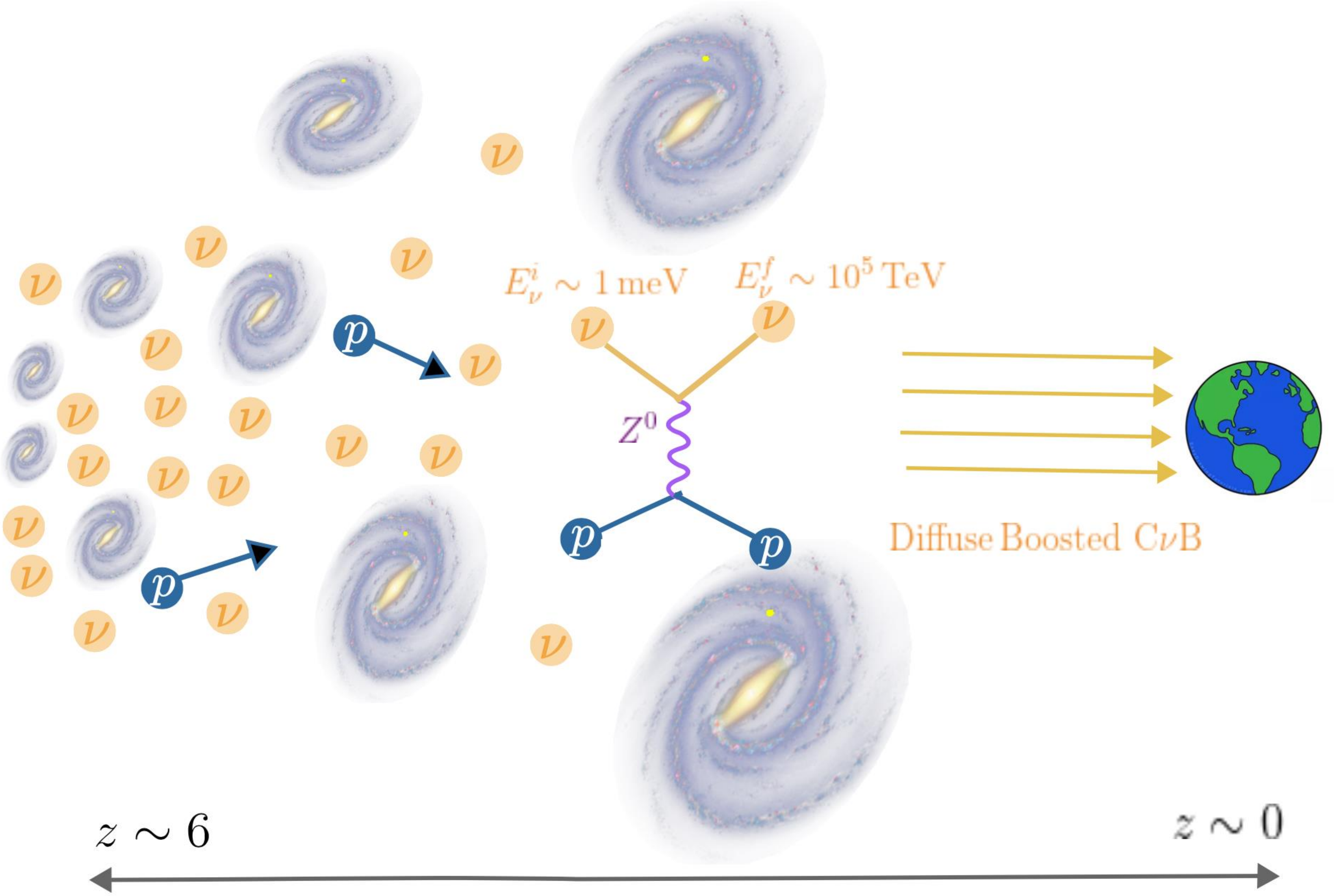


See talk on cosmic rays

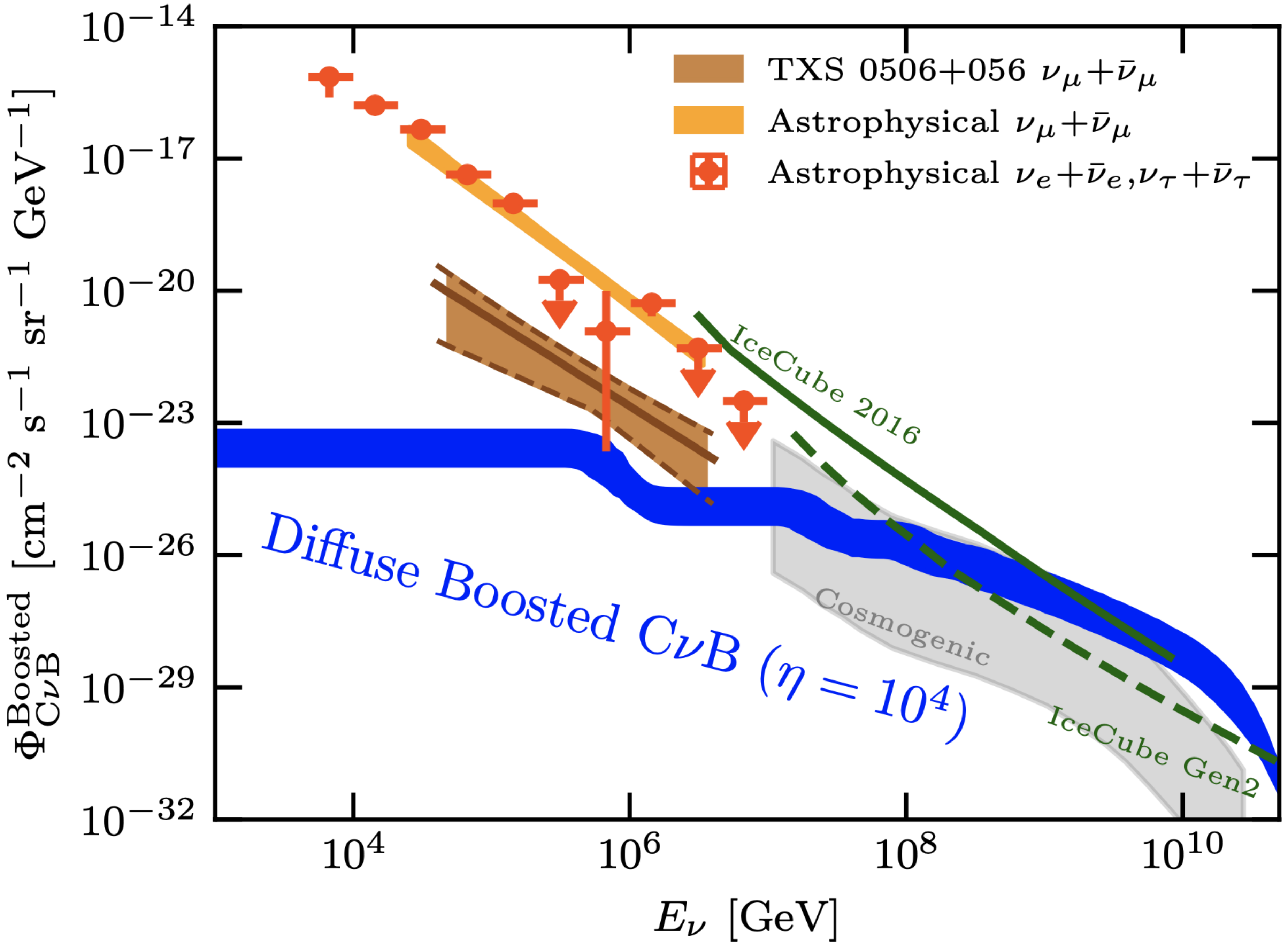
Cosmogenic neutrinos

- 1956 discovery of neutrinos
- 1962 discovery of UHECR 10^20 eV
- 1964 discovery of CMB
- 1969 theory cosmogenic neutrinos

$$p + \gamma_{\rm CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma, \text{ and}$$
$$p + \gamma_{\rm CMB} \rightarrow n + \pi^+ \rightarrow p + \nu_{e,\mu}.$$



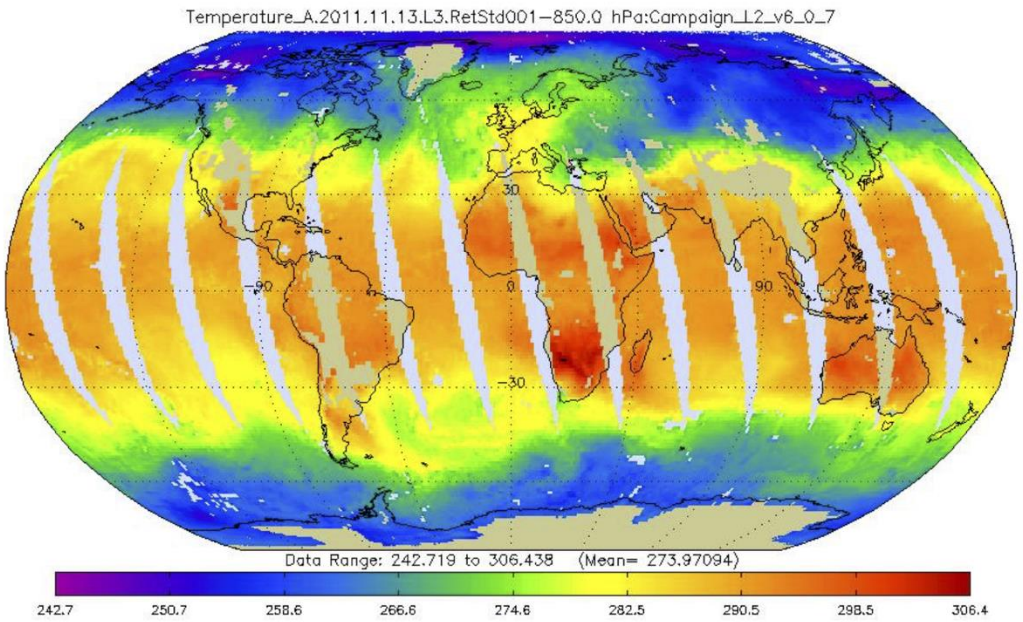
$E_\nu^i \sim 1\,\mathrm{meV}$
$E_\nu^f \sim 10^5\,\mathrm{TeV}$
Z^0
Diffuse Boosted CνB
$z \sim 6$
$z \sim 0$

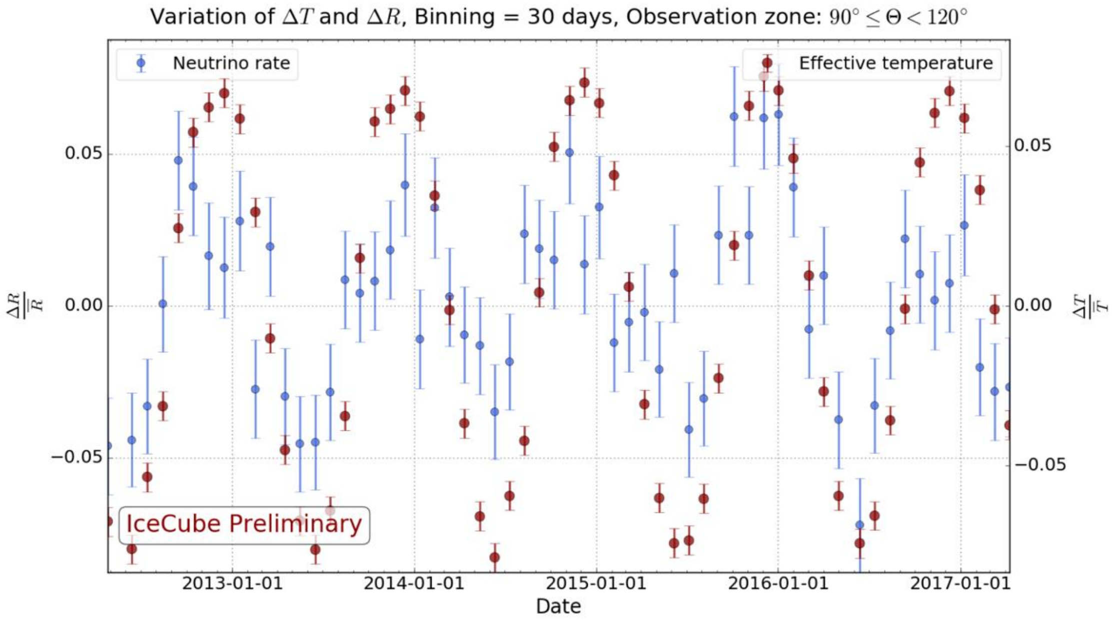


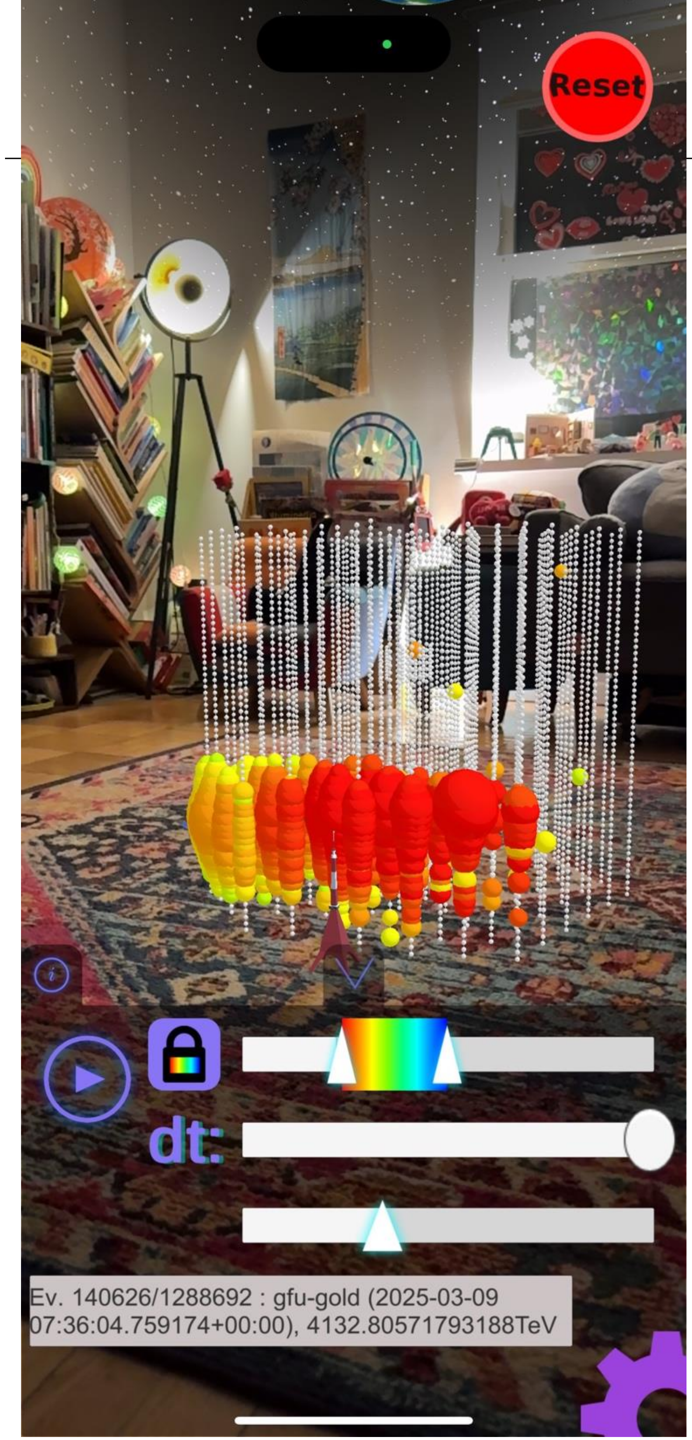
TXS 0506+056 $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_e+\bar{\nu}_e, \nu_\tau+\bar{\nu}_\tau$
IceCube 2016
Cosmogenic
IceCube Gen2
Diffuse Boosted CνB ($\eta = 10^4$)
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^4
10^6
10^8
10^{10}
$\Phi_{C\nu B}^{\rm Boosted}$ [cm^{-2} s^{-1} sr^{-1} GeV-1]
E_ν [GeV]

(atmospheric) Neutrino weather!

Lead by Aachen group







Receive IceCube alerts

- GCN notice and circular
- Extradentary events also Atel
- The Astrophysical Multimessenger Observatory Network (AMON)
- Augmented Reality app (ICEcuBEAR) on Android and iOS.