Diffuse neutrinos from 1 TeV to 1 EeV

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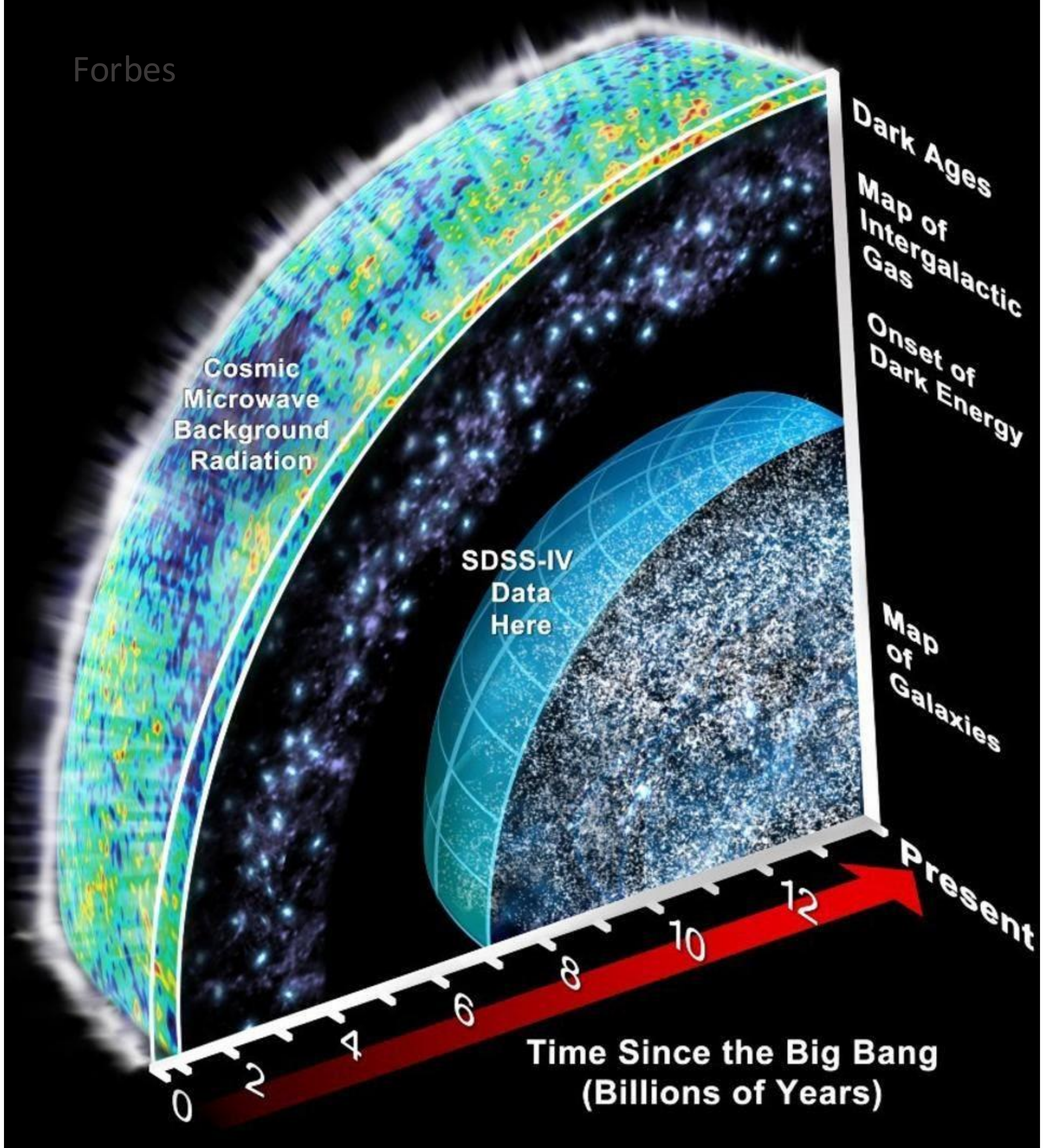
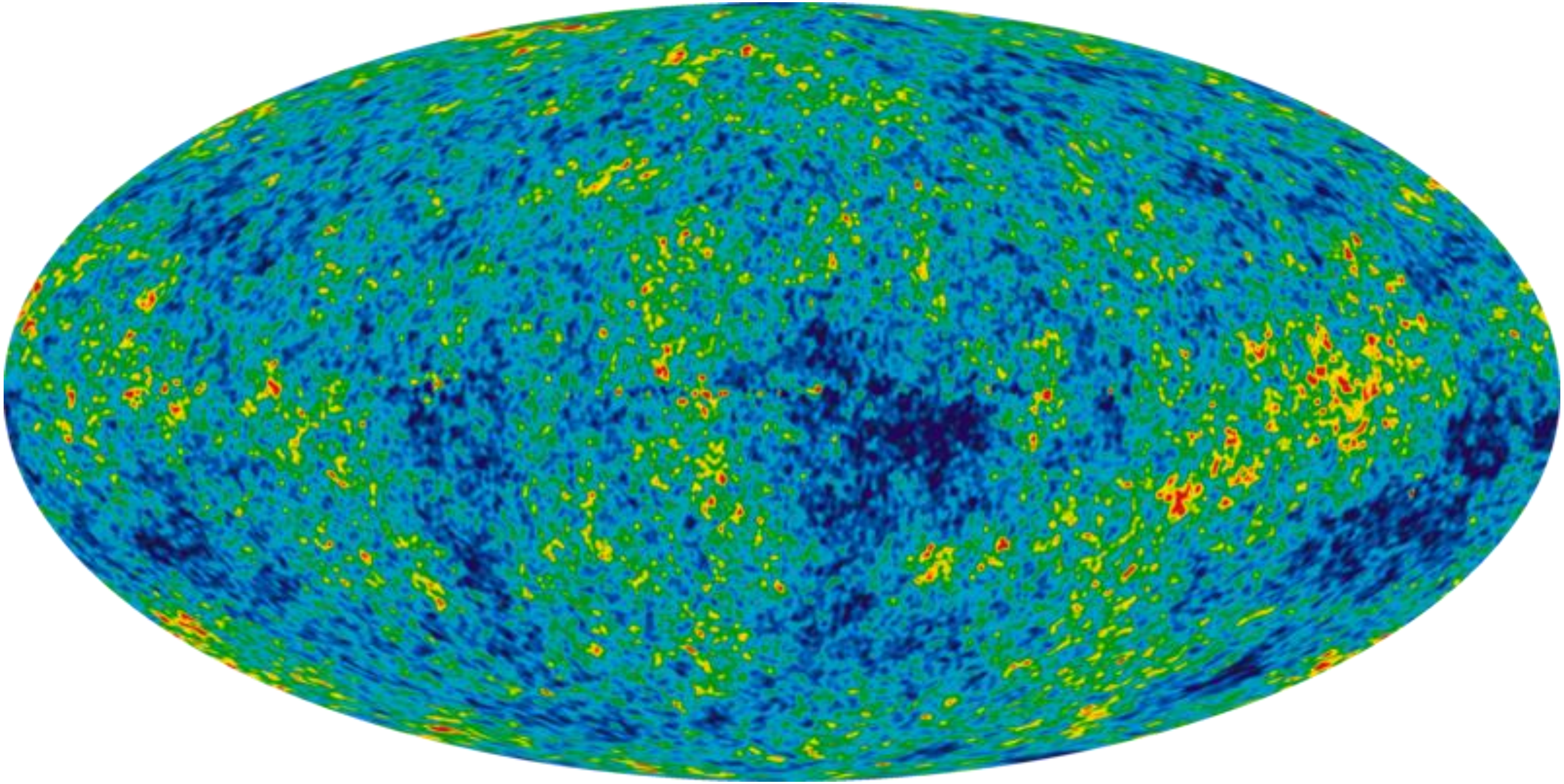
IceCube Summer School 2025

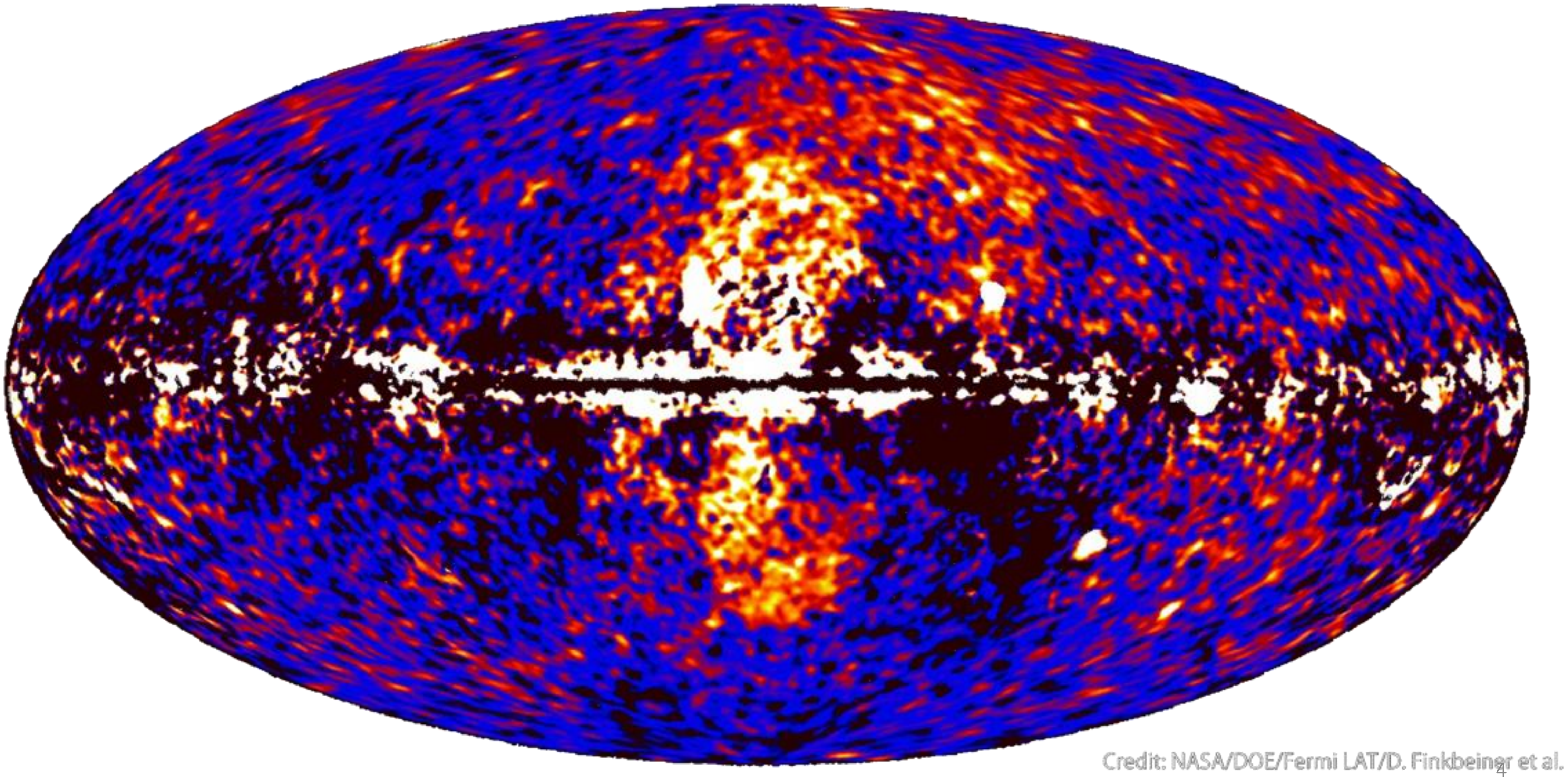
Forbes

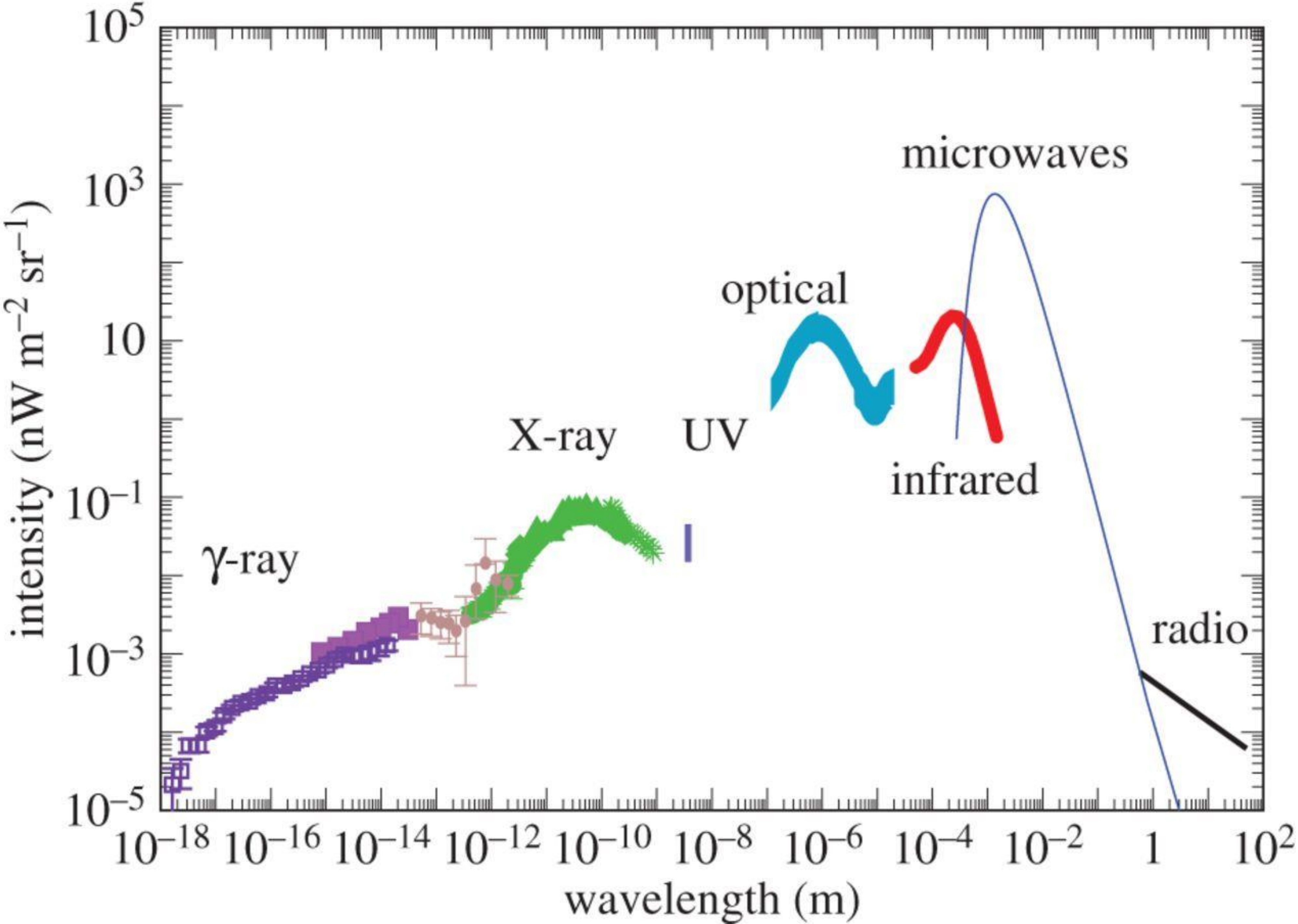

Dark Ages
Map of Intergalactic Gas
Onset of Dark Energy
Map of Galaxies
Cosmic Microwave Background Radiation
SDSS-IV Data Here
Present
0
2
4
6
8
10
12
Time Since the Big Bang
(Billions of Years)

Diffuse microwave photons

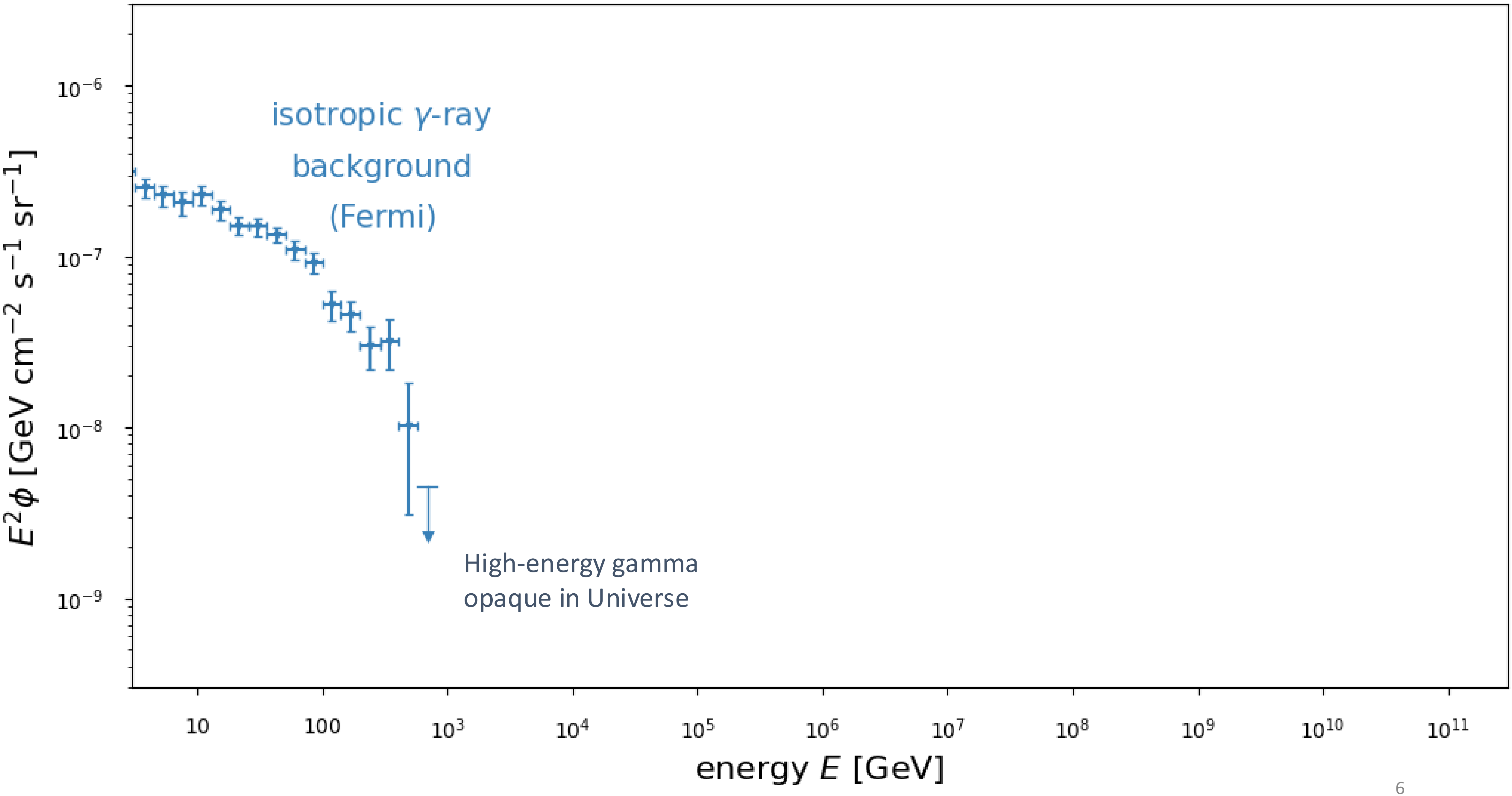


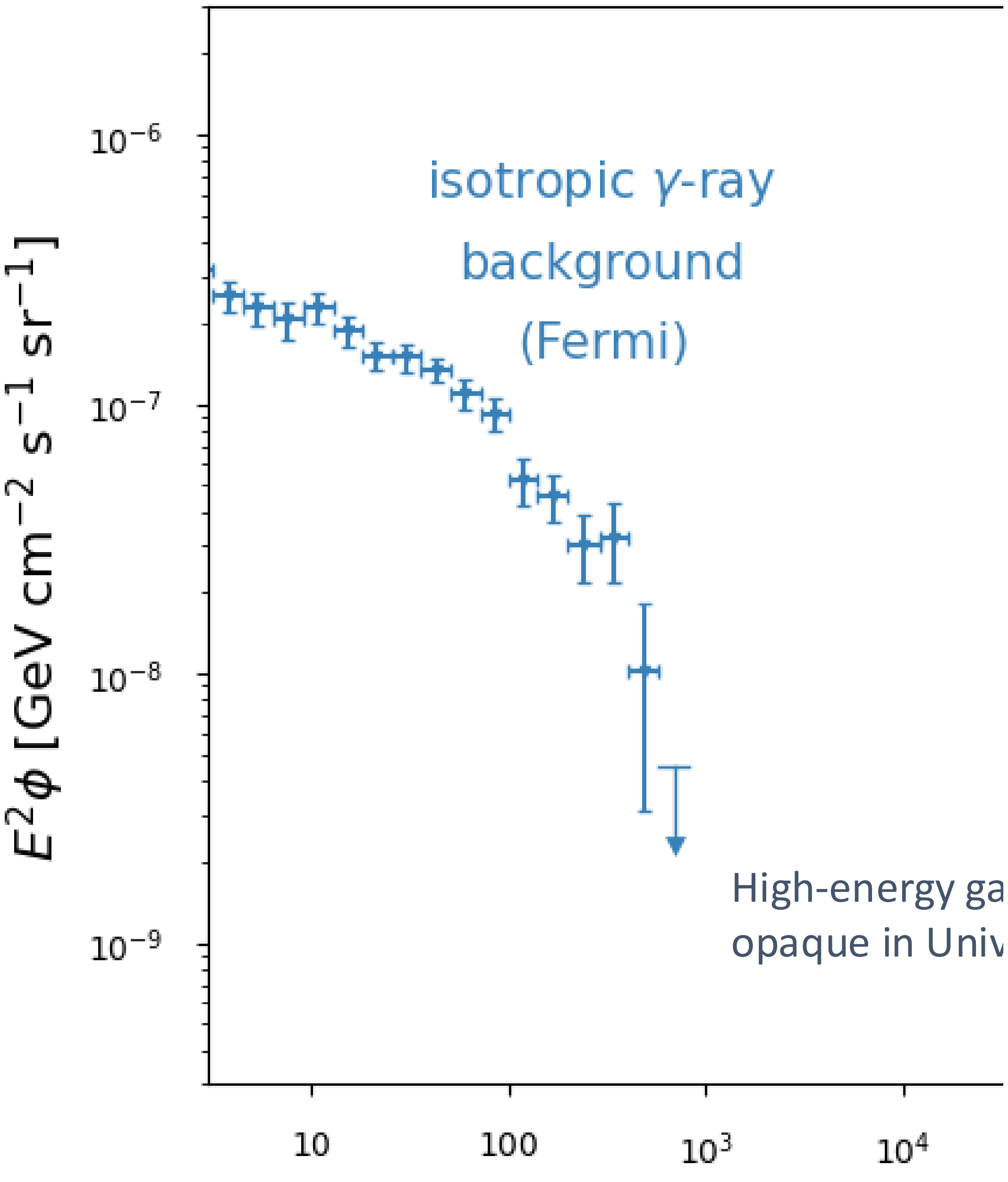
Diffuse gamma-ray photons

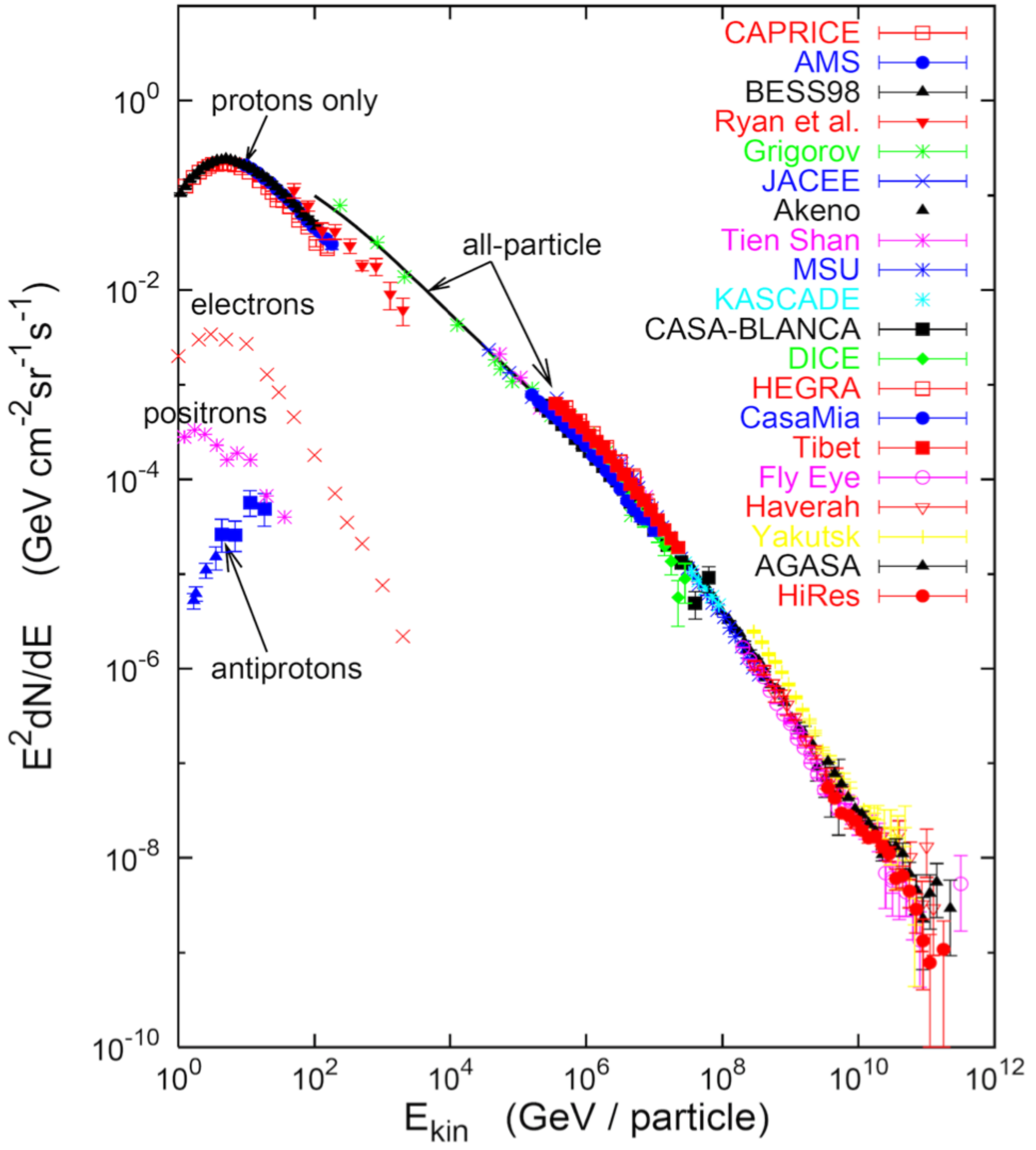


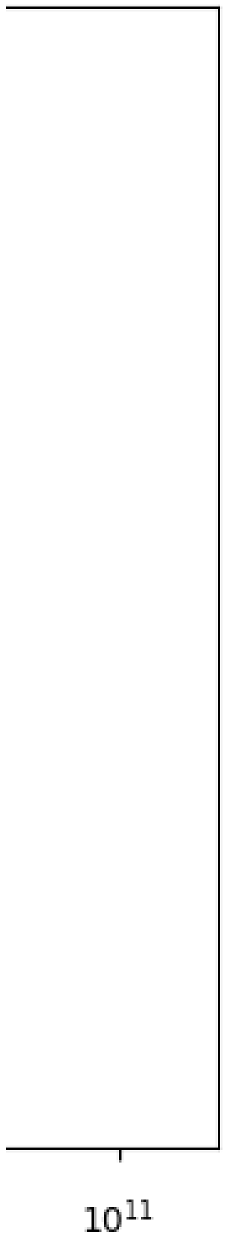


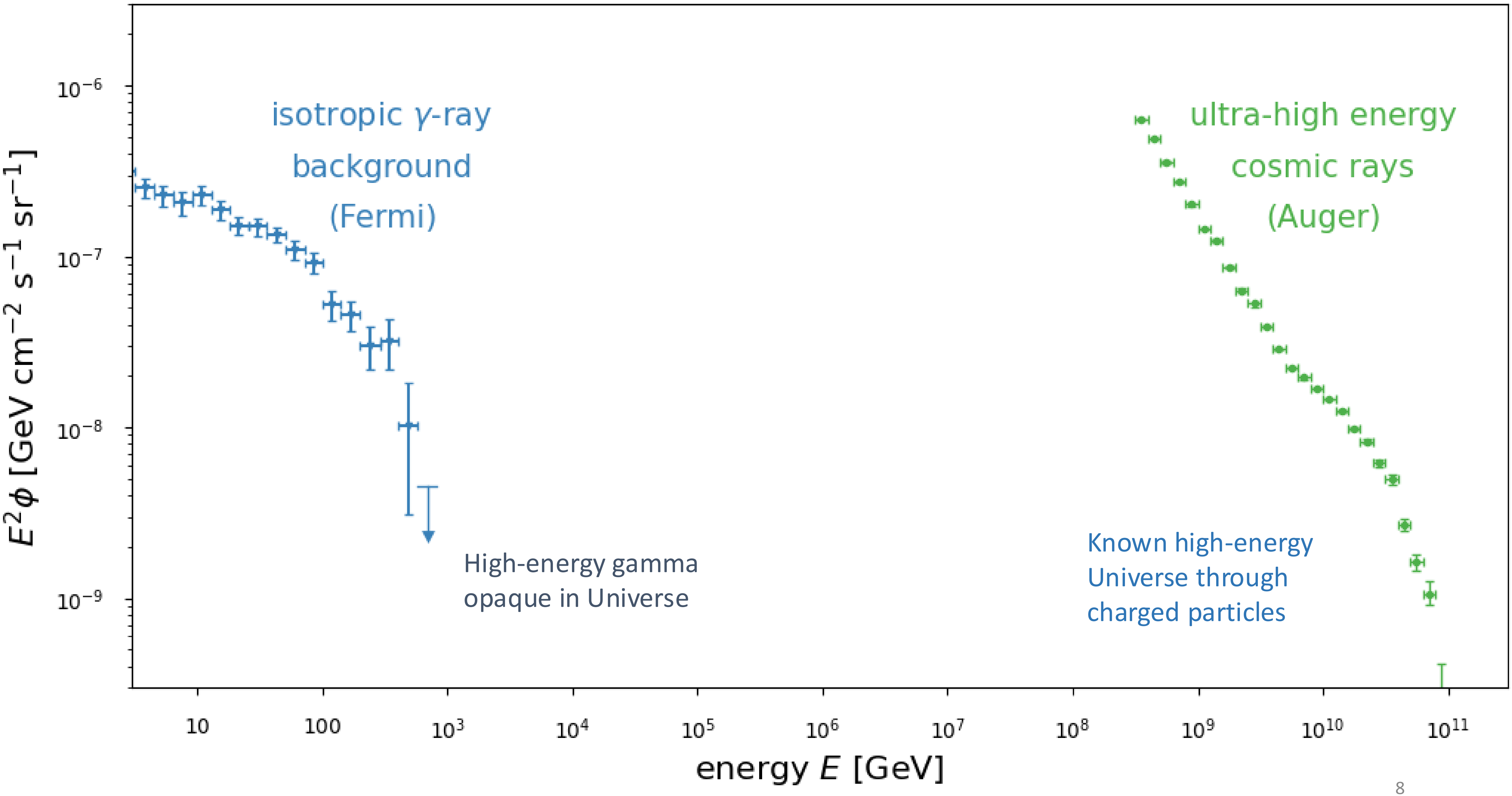
microwaves
optical
UV
X-ray
infrared
γ-ray
radio
intensity (nW m−2 sr−1)
10^5
10^3
10
10^−1
10^−3
10^−5
10^−18
10^−16
10^−14
10^−12
10^−10
10^−8
10^−6
10^−4
10^−2
1
10^2
wavelength (m)


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

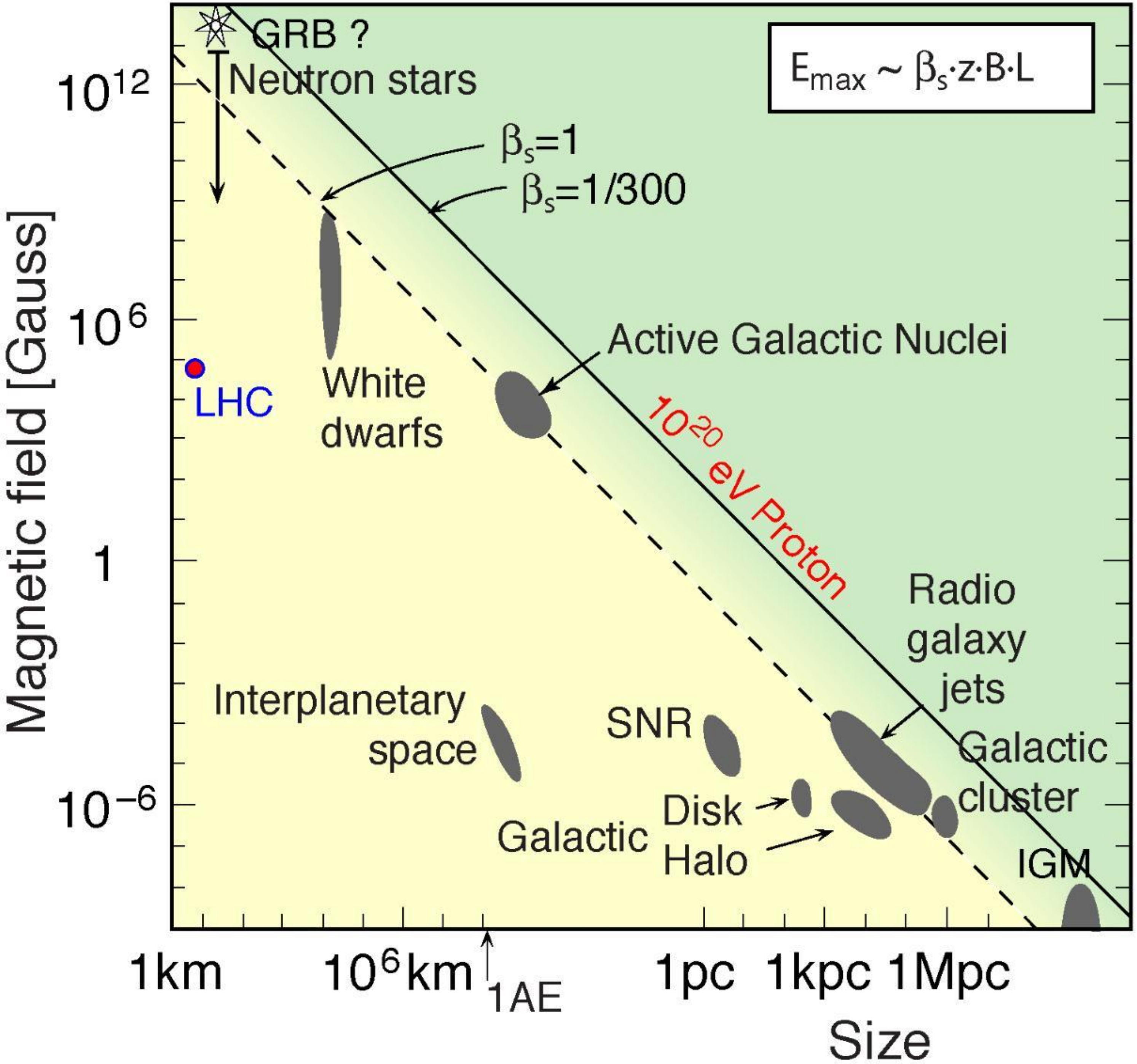

isotropic γ-ray
background
(Fermi)
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
High-energy ga
opaque in Univ


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}]
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}

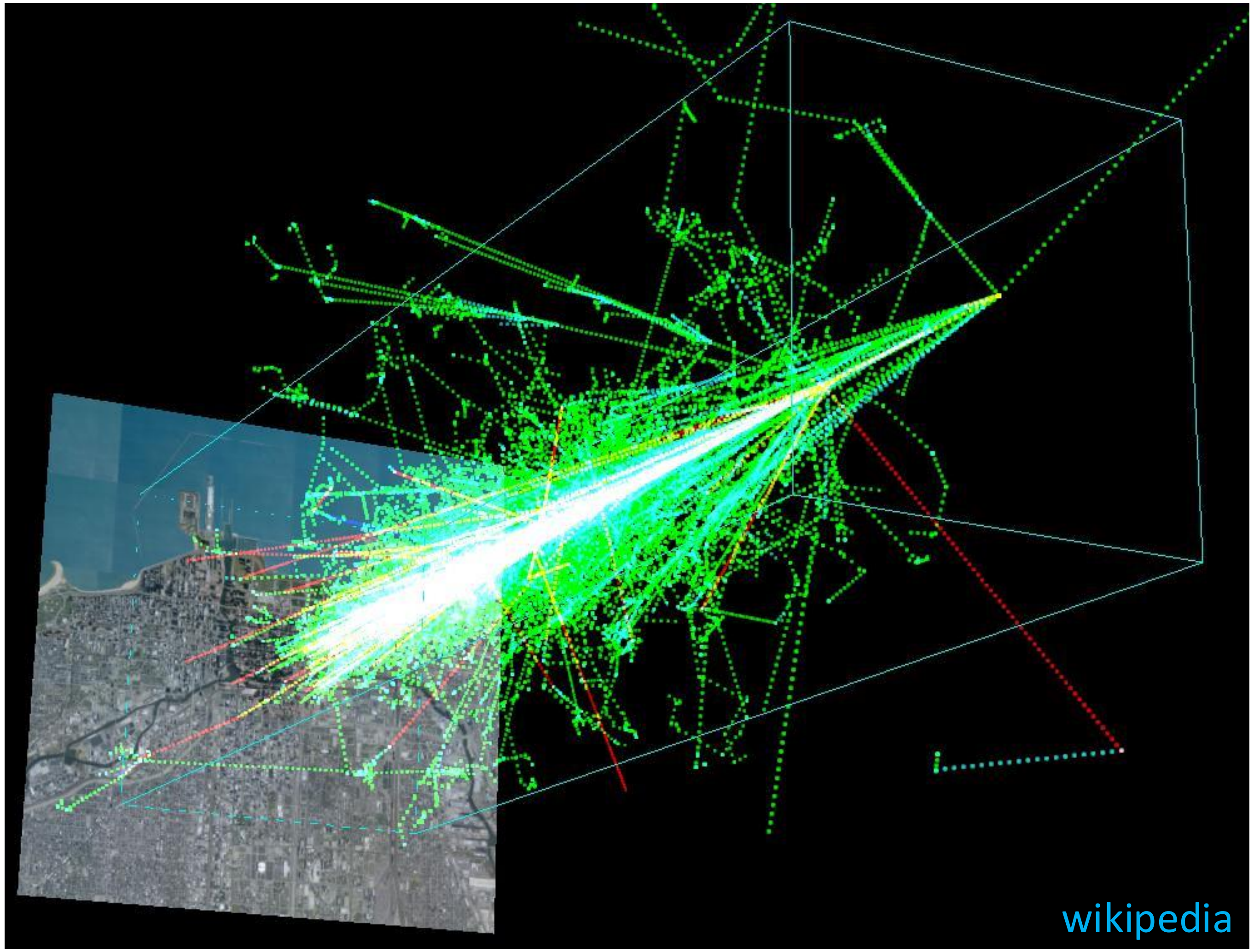
Hillas plot

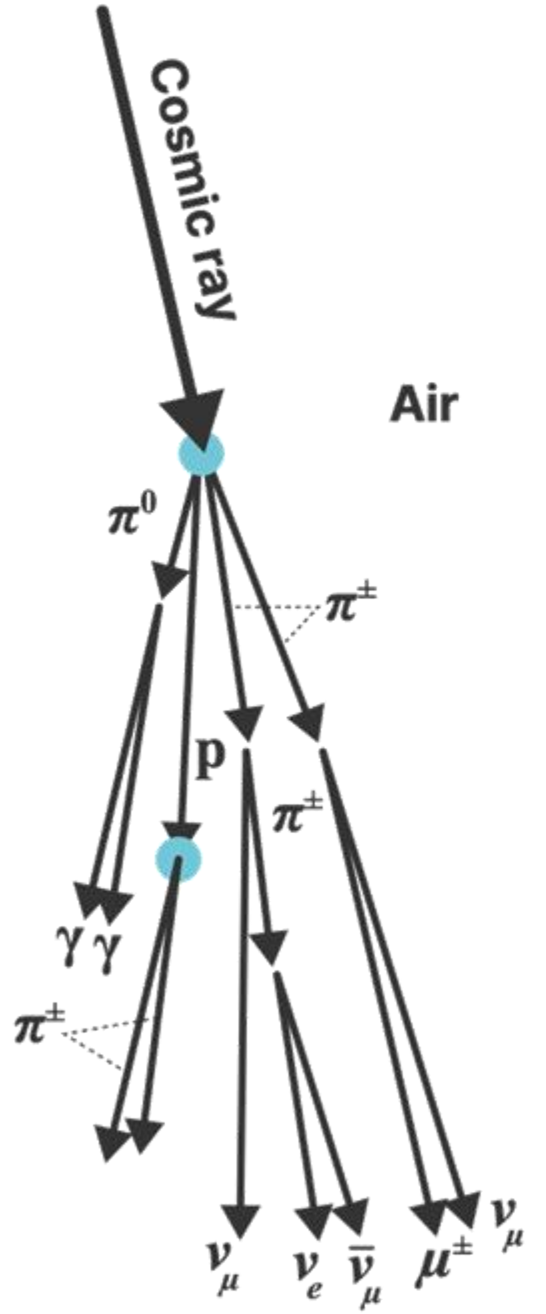


GRB ?
Neutron stars
$E_{max} \sim \beta_s \cdot z \cdot B \cdot L$
β_s=1
β_s=1/300
10^{12}
10^6
1
10^{-6}
Magnetic field [Gauss]
LHC
White dwarfs
Active Galactic Nuclei
10^{20} eV Proton
Radio galaxy jets
Interplanetary space
SNR
Galactic cluster
Disk
Halo
Galactic
IGM
1km
10^6km
1AE
1pc
1kpc
1Mpc
Size

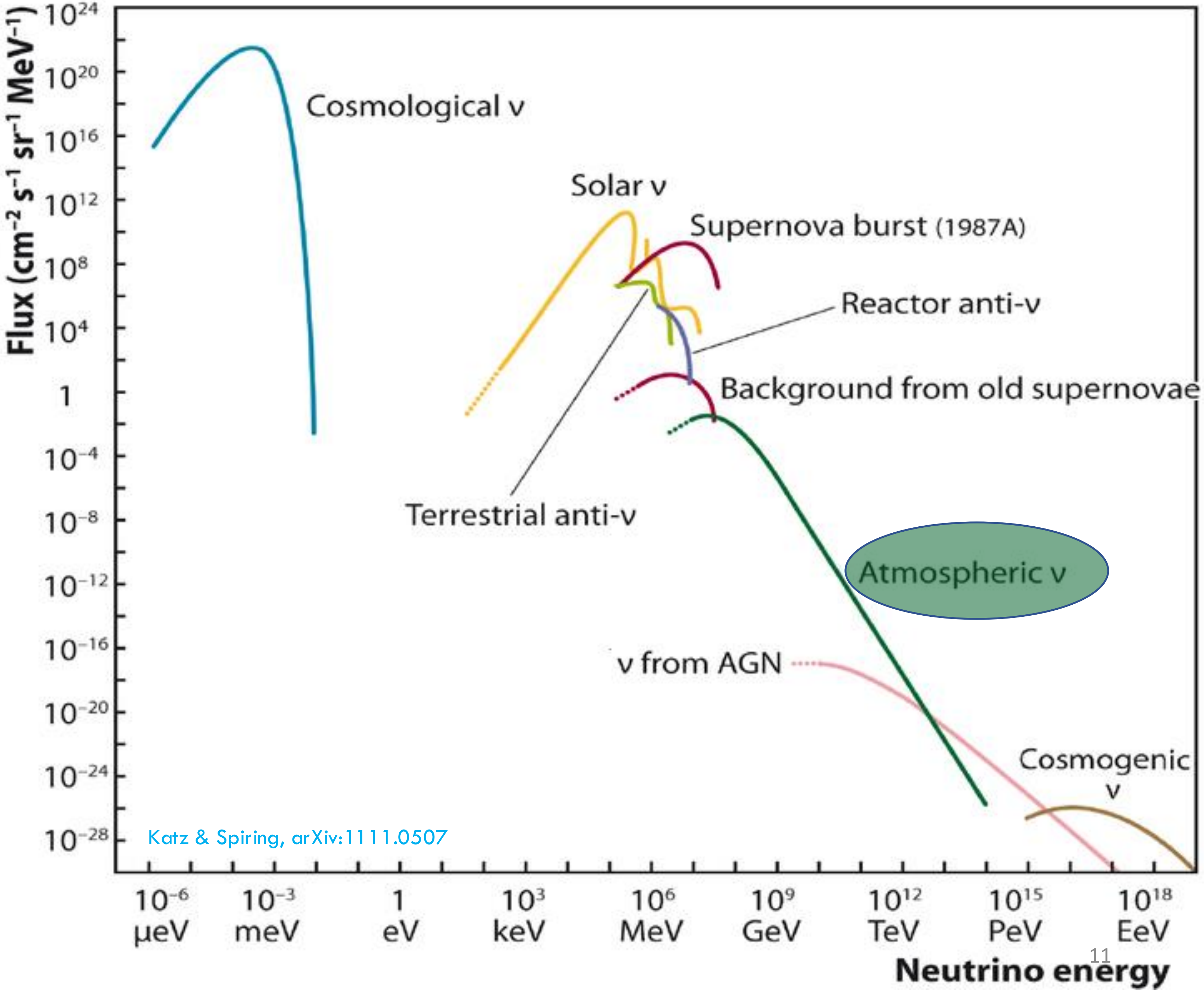
FROM CLOUD CHAMBERS TO EXTENSIVE AIR SHOWERS

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

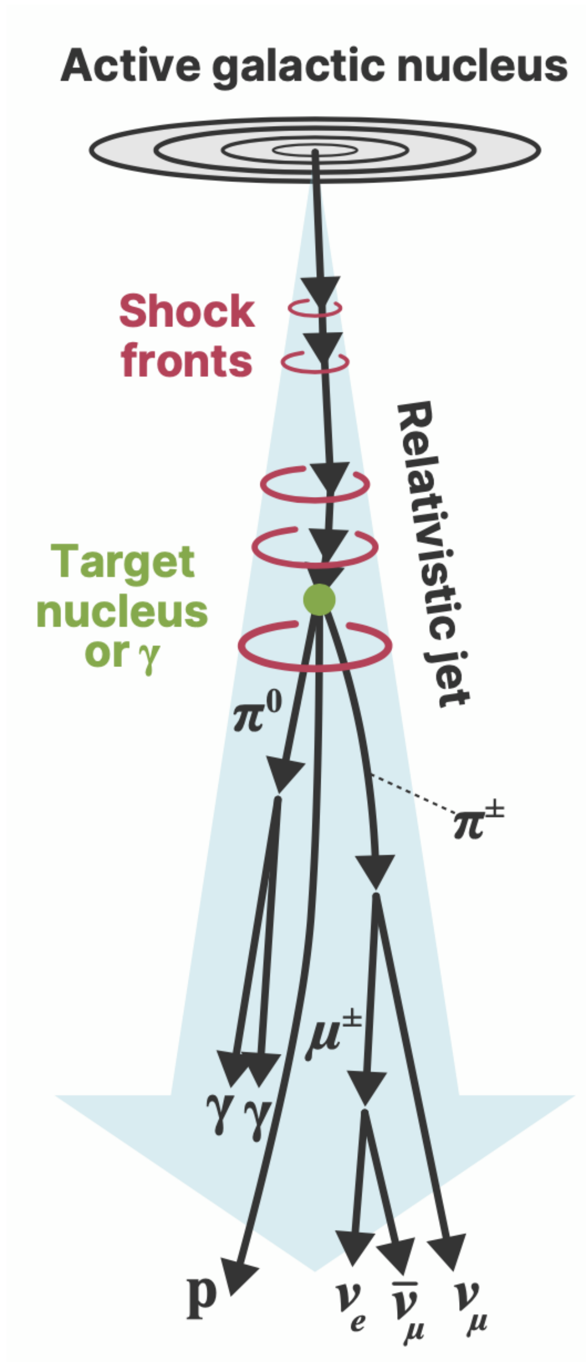


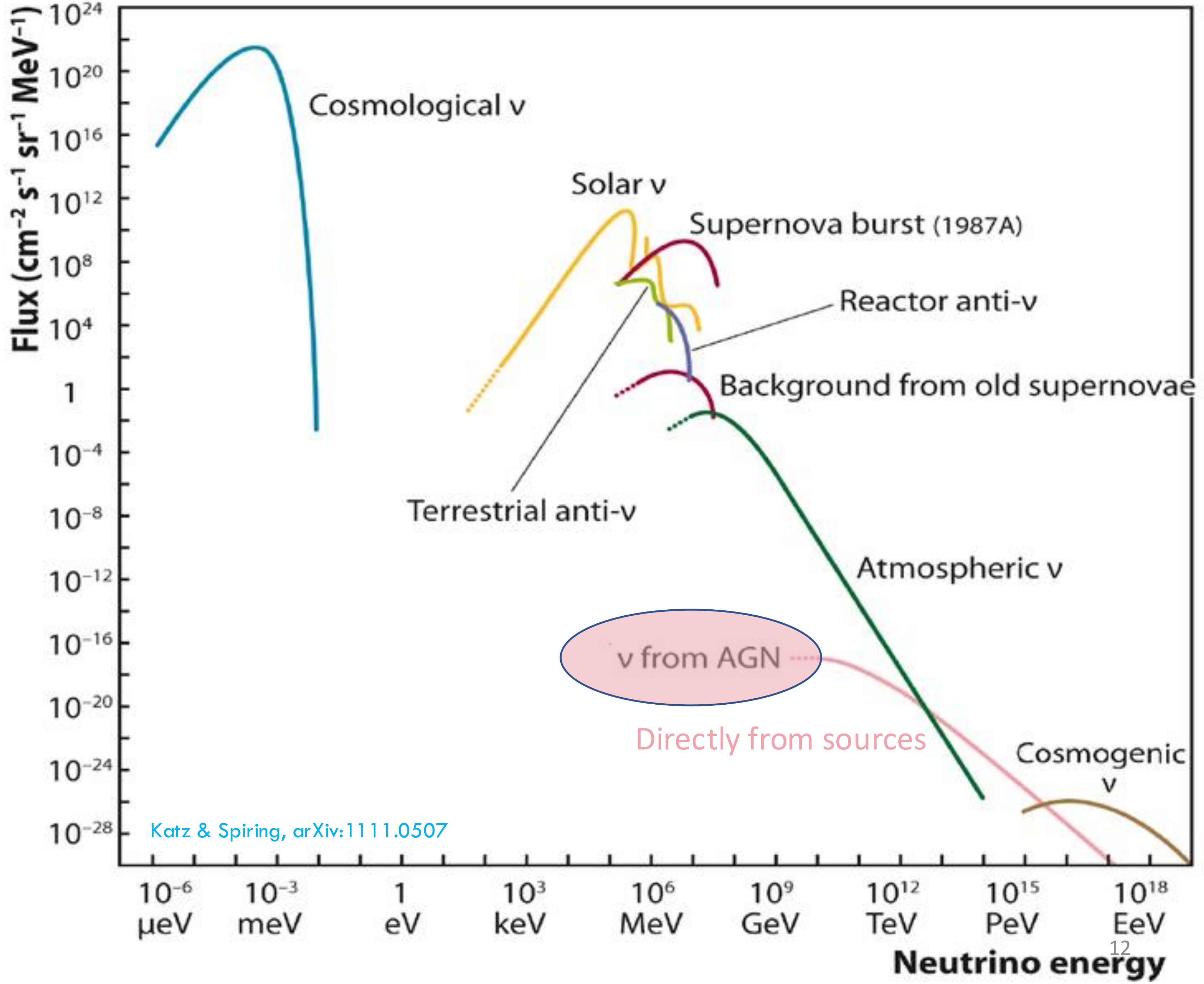


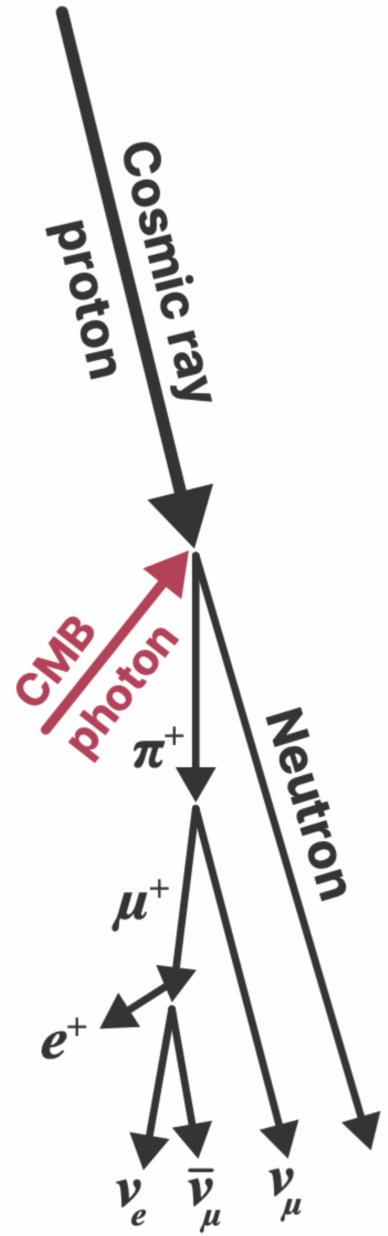
Cosmic ray
Air
π^0
$\pi^\pm$
p
$\pi^\pm$
γ γ
$\pi^\pm$
ν_μ
ν_e
$\bar{\nu}_\mu$
$\mu^\pm$
ν_μ

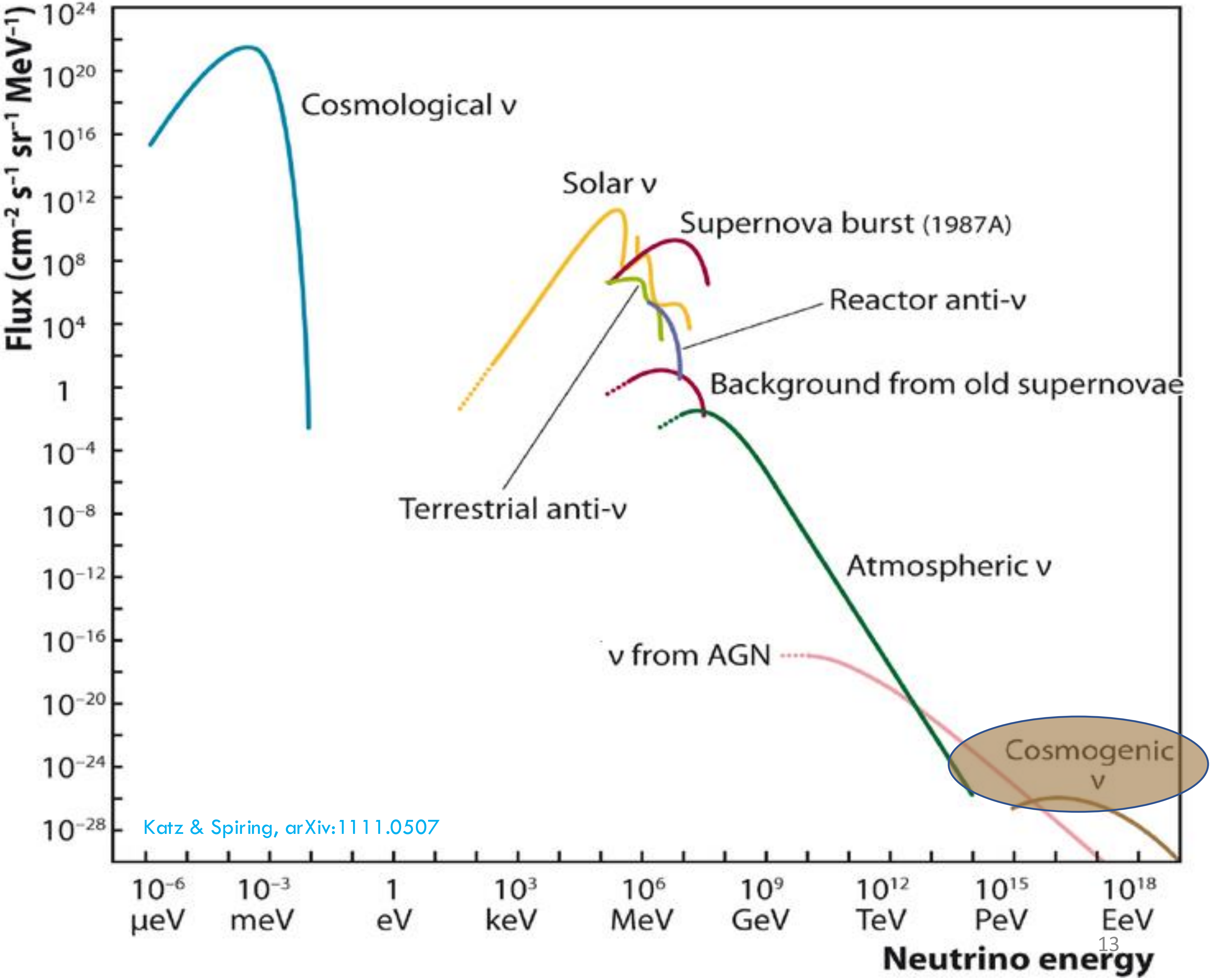


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiring, arXiv:1111.0507
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy


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


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
Directly from sources
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

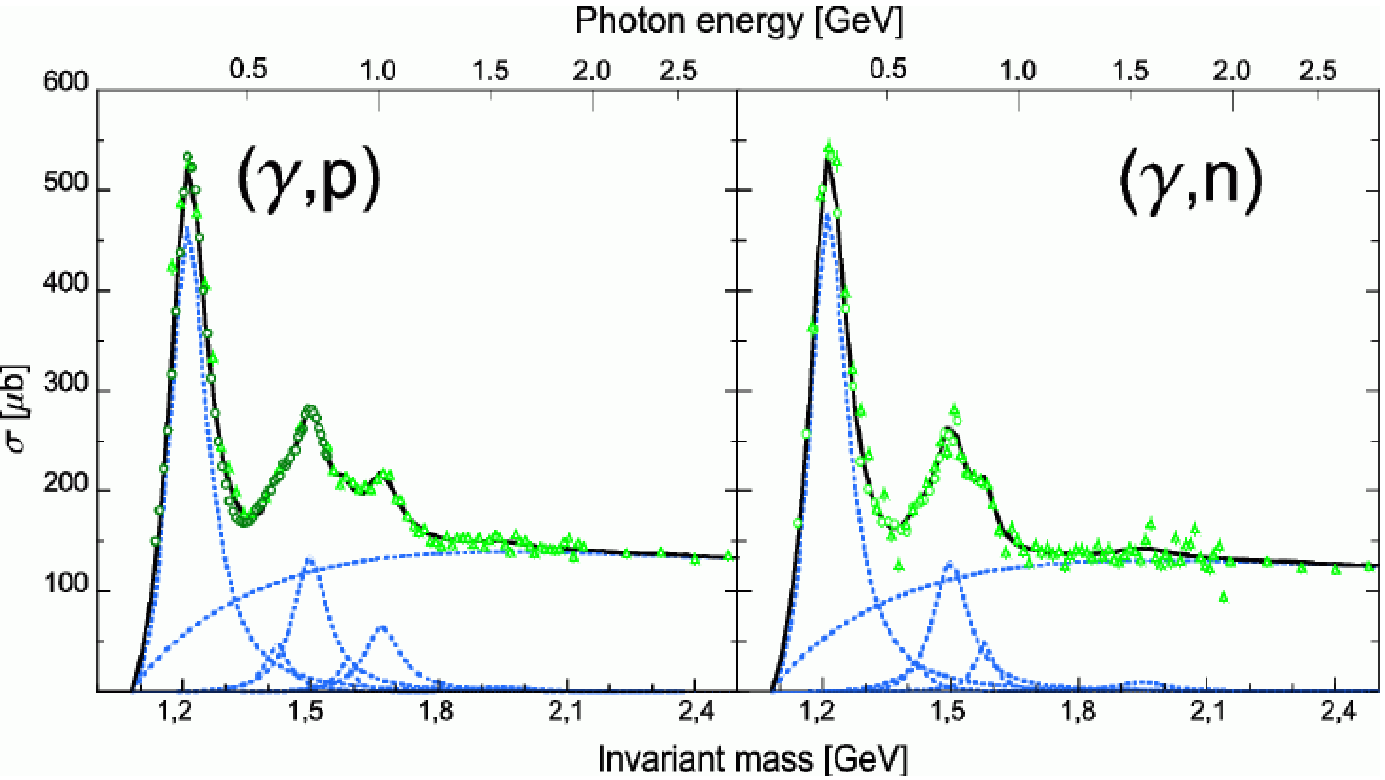


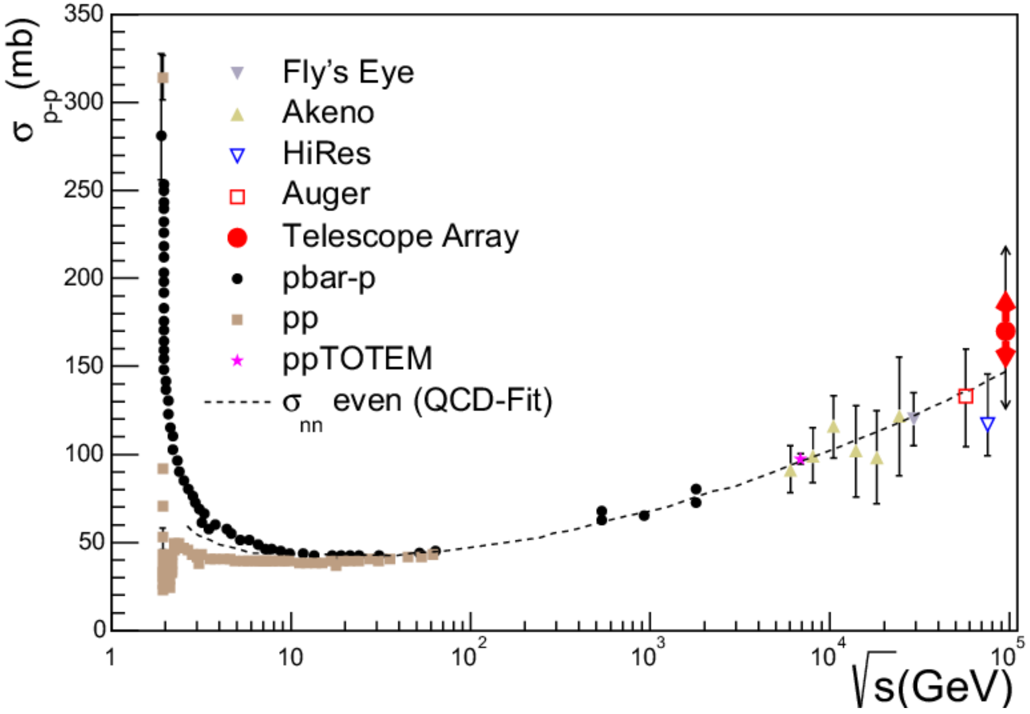


Katz & Spiring, arXiv:1111.0507

Neutrino productions at accelerator sites

- P-gamma vs pp

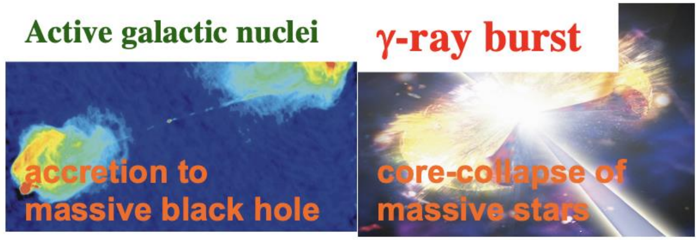




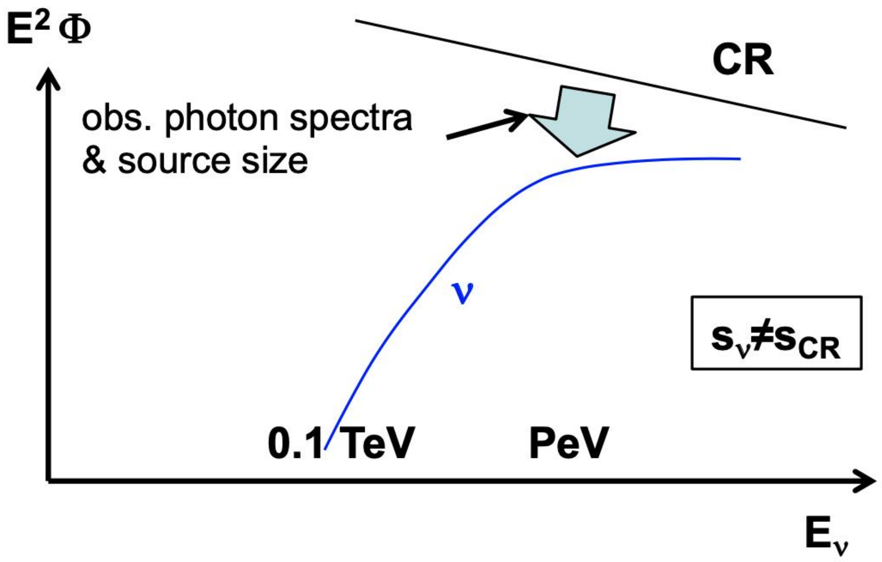
Astrophysical Extragalactic Scenarios

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

Cosmic-ray Accelerators (ex. UHECR candidate sources)



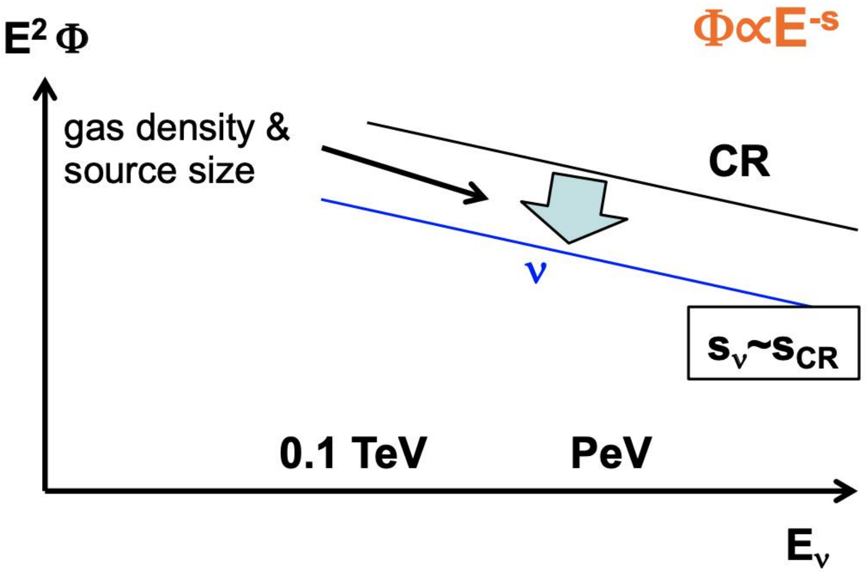
$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs

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

$\Phi \propto E^{-s}$

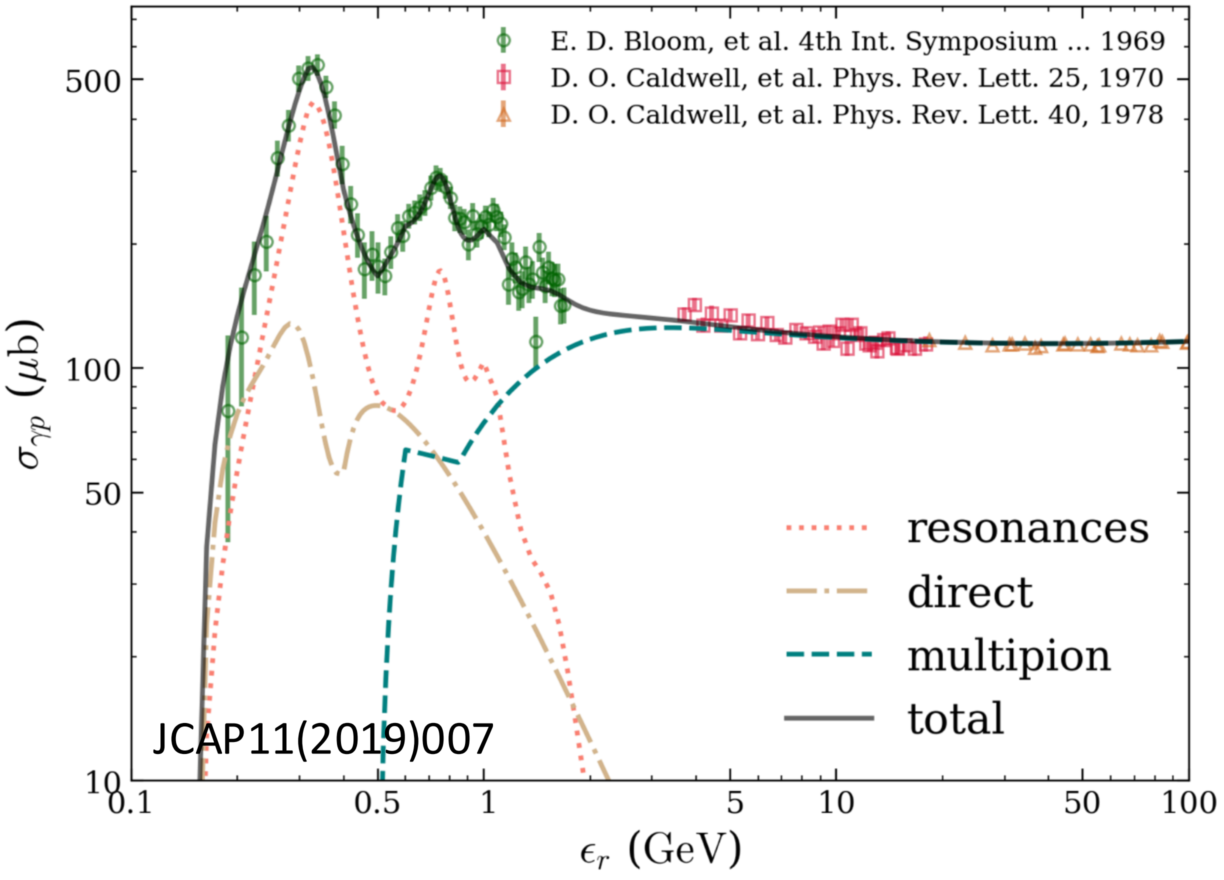


Slide from Kohta Murase

Why X-rays are important?

- Pion productions

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



JCAP11(2019)007

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

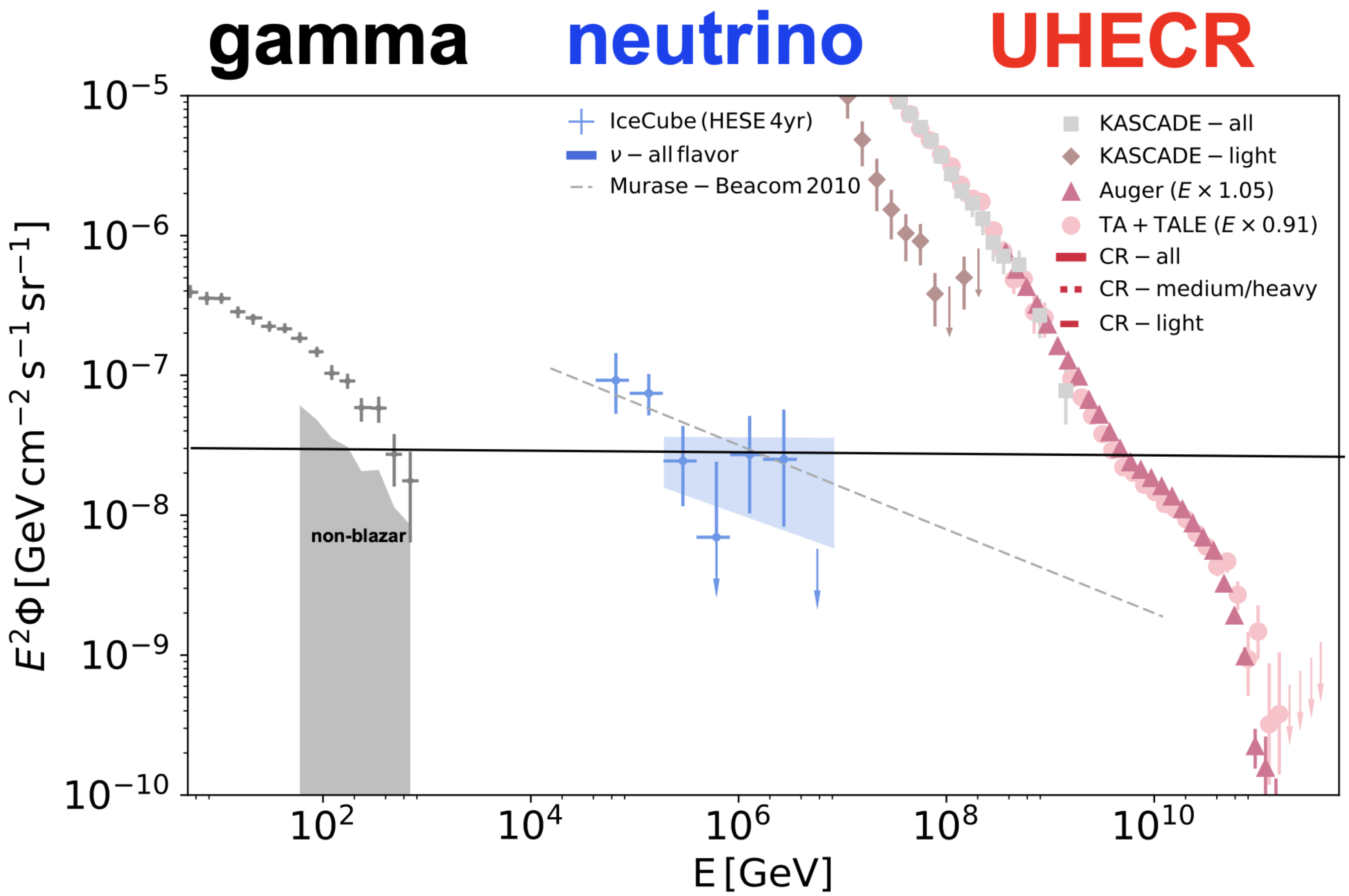
$$\epsilon_\gamma = 15 \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\epsilon_p}{1\ \mathrm{PeV}}\right)^{-1} \mathrm{keV}$$

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

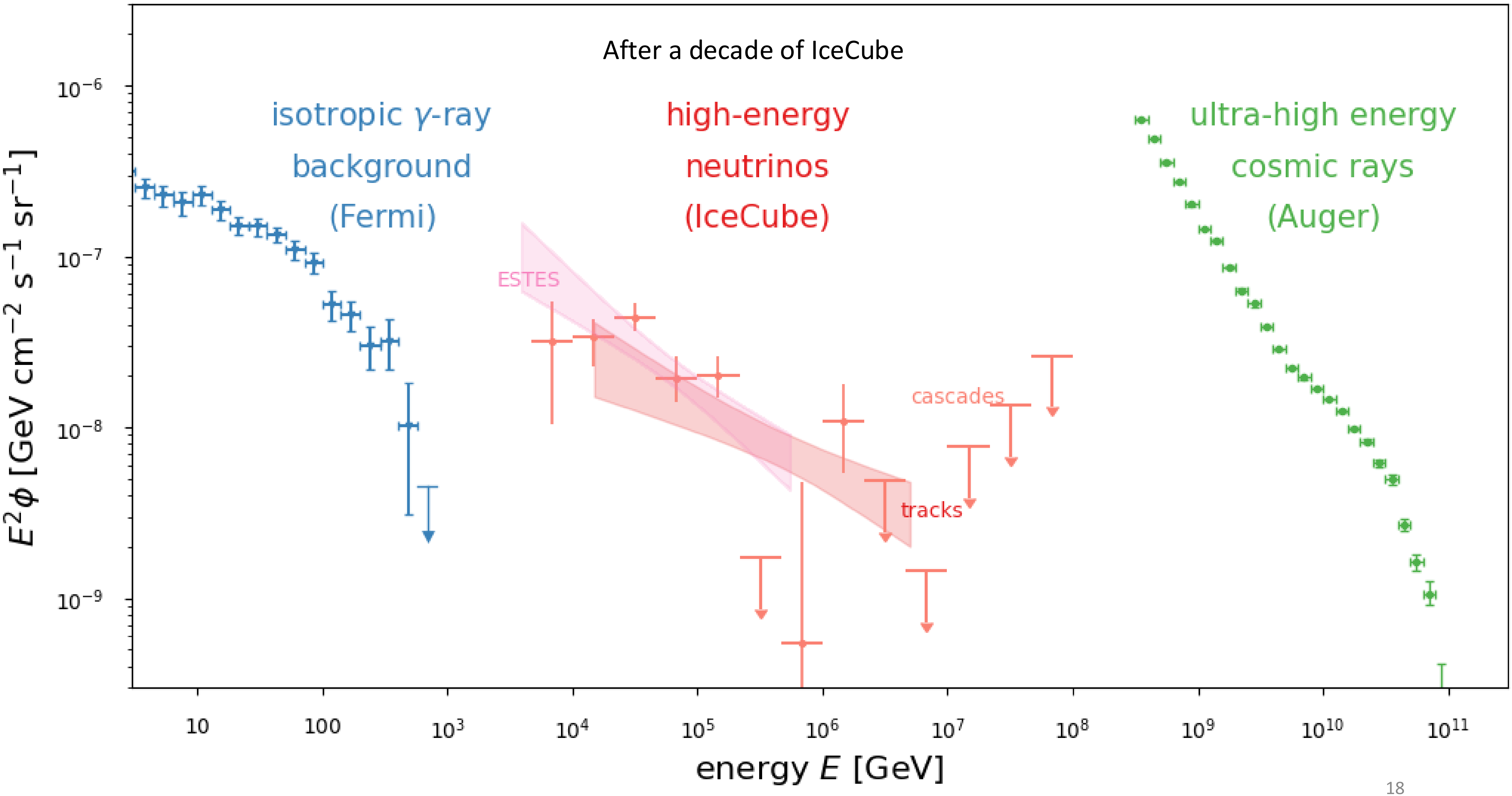
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

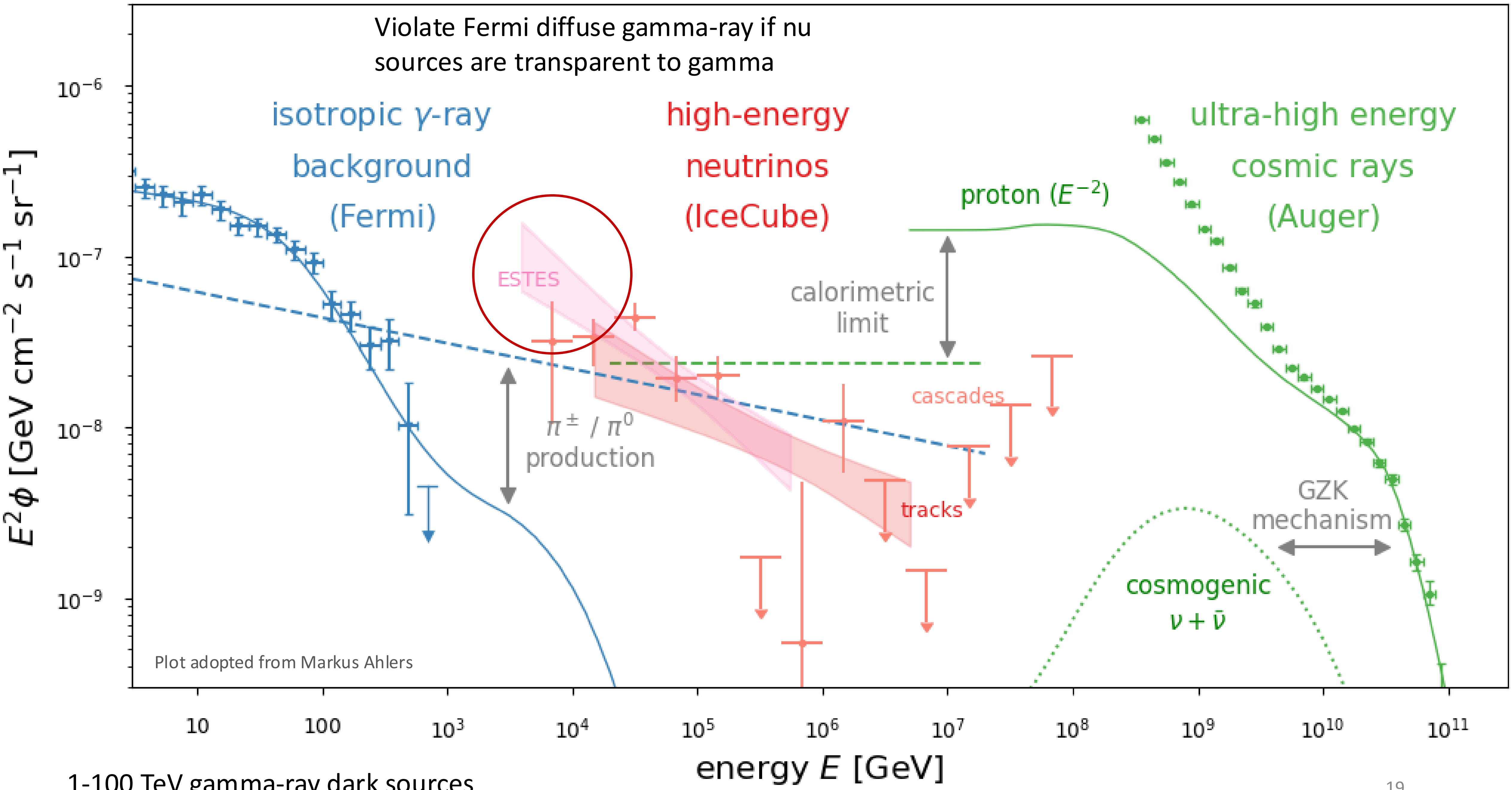


Energy generation rates are all comparable to a few x 10^{43} erg $\mathrm{Mpc^{-3}\,yr^{-1}}$

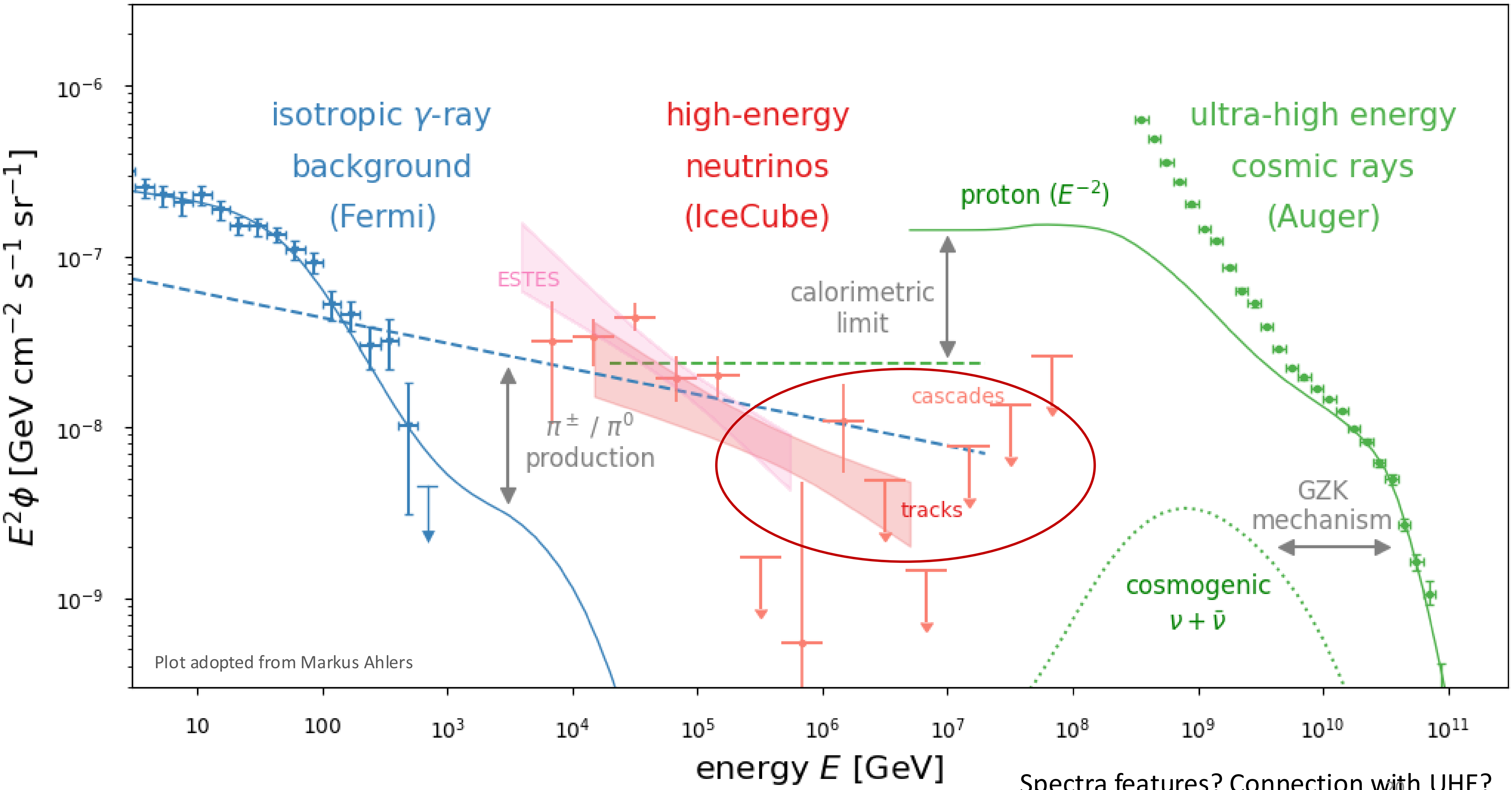


After a decade of IceCube
isotropic γ-ray
background
(Fermi)
high-energy
neutrinos
(IceCube)
ultra-high energy
cosmic rays
(Auger)
ESTES
cascades
tracks
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
energy E [GeV]

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

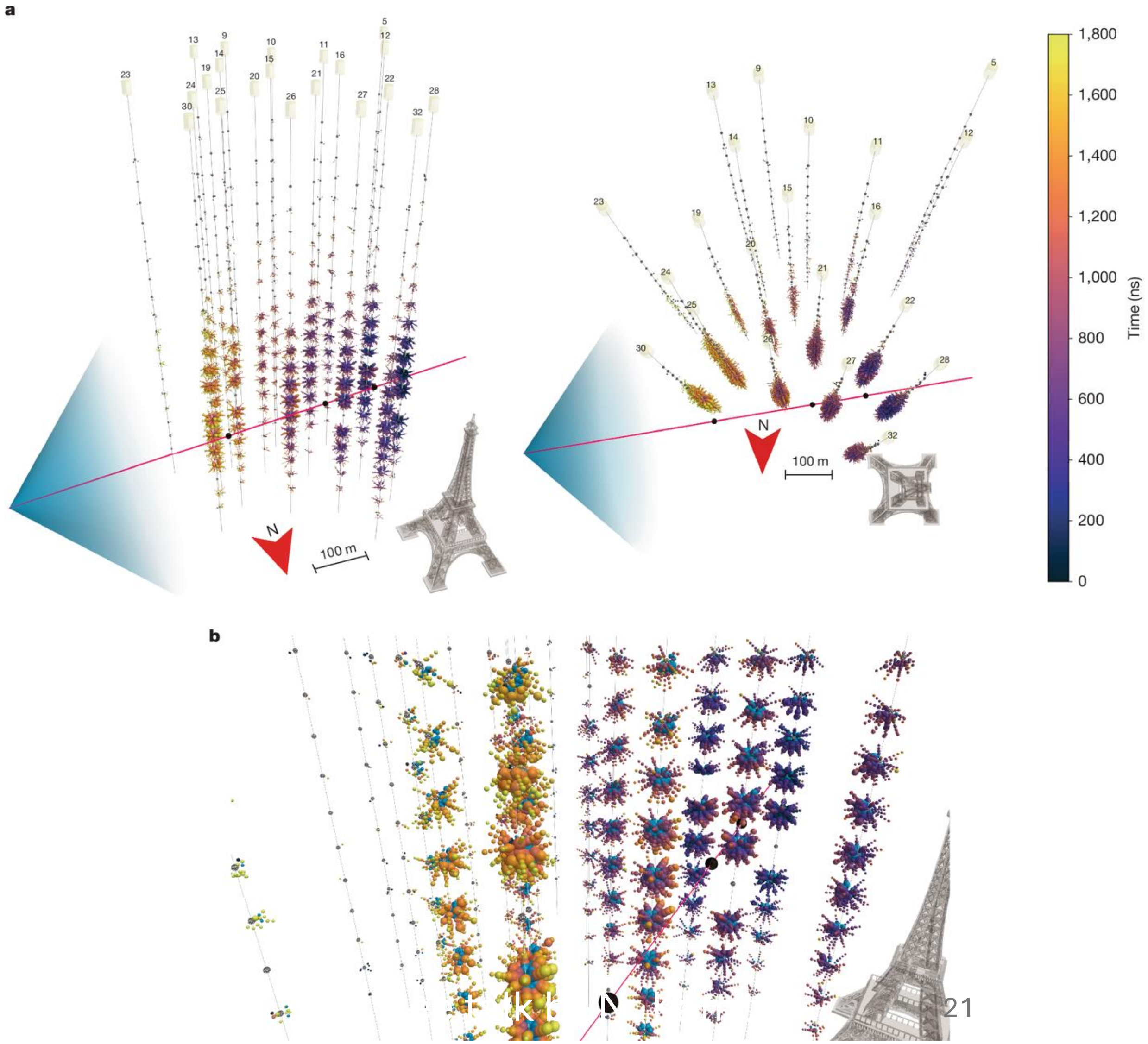
Unique, high charge event detected

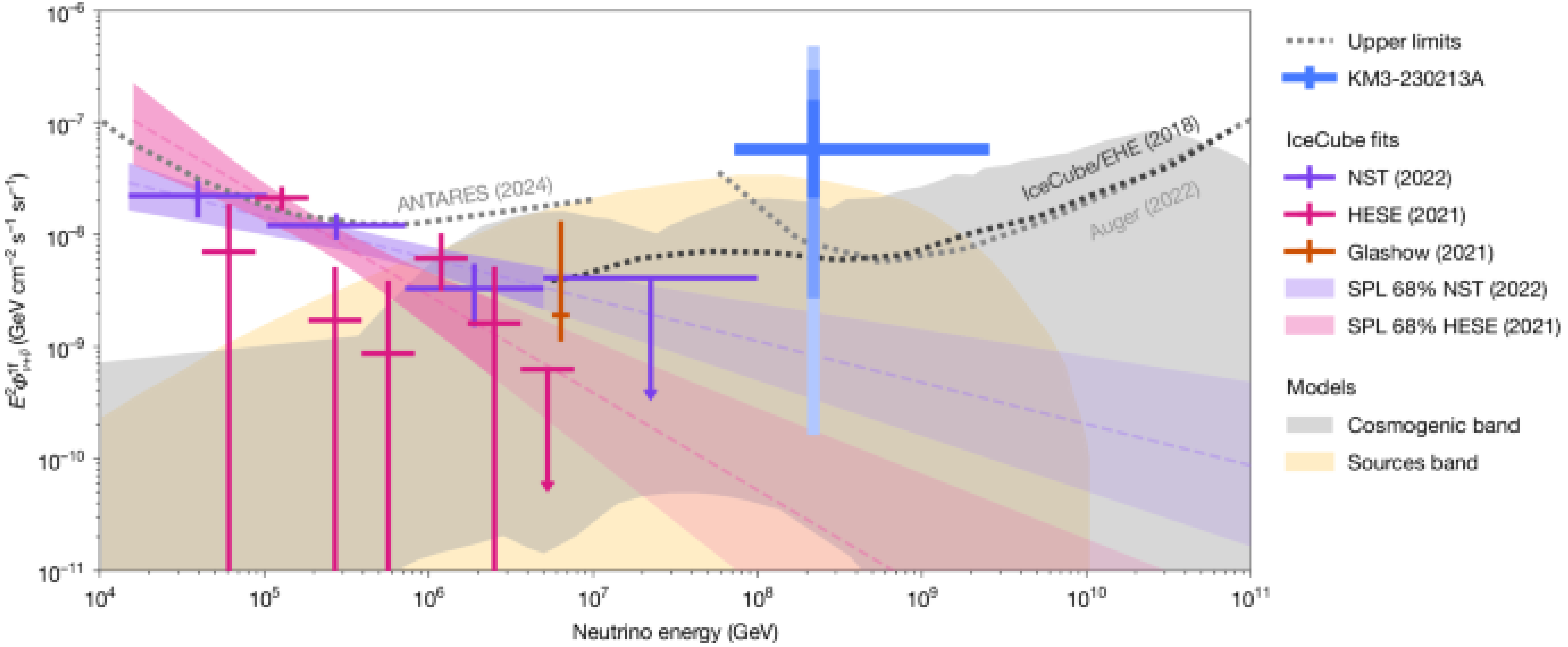
Assuming E^{-2} spectrum:

→ $E_\nu = 220^{+570}_{-110}$PeV

→ Strong prior dependence, large energy uncertainty

Nature **638**, 376–382 (2025)

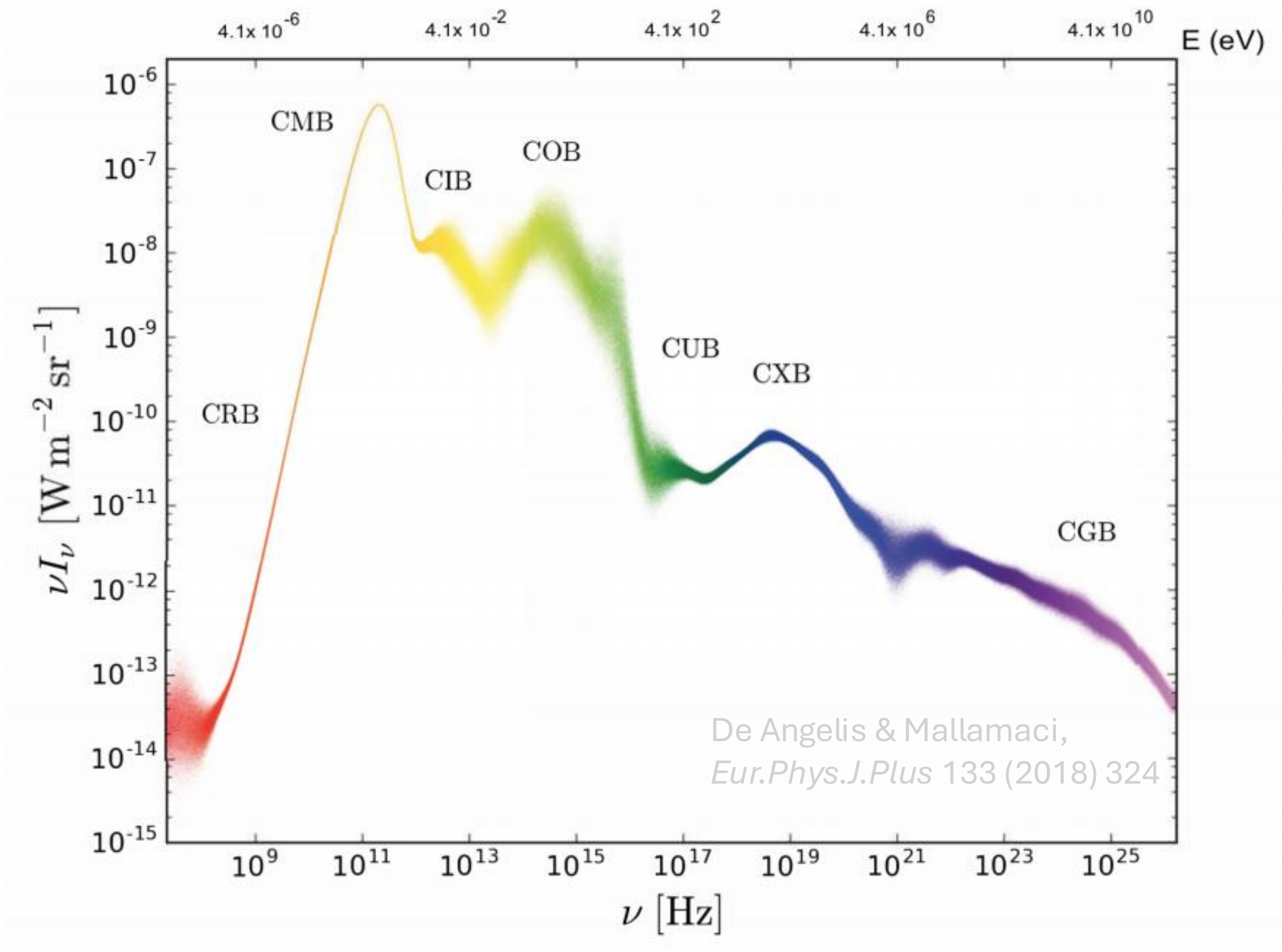




Nature **volume 638**, pages376–382 (2025)

UHE neutrinos: a smoking gun signature

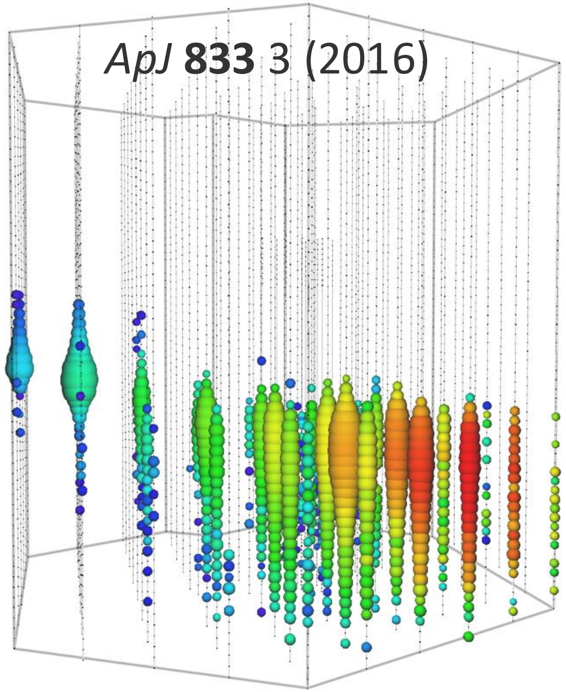
- Photopion produced neutrinos have 1/20 the primary energy-per-nucleon
- CMB target: $10^{19.7}$ eV energy threshold => EeV energy neutrinos
- CIB target: 10^{18} eV energy threshold => **O(10 PeV)** neutrinos
  - **Ambient photons** in **source** can also serve as target



The highest energy neutrinos

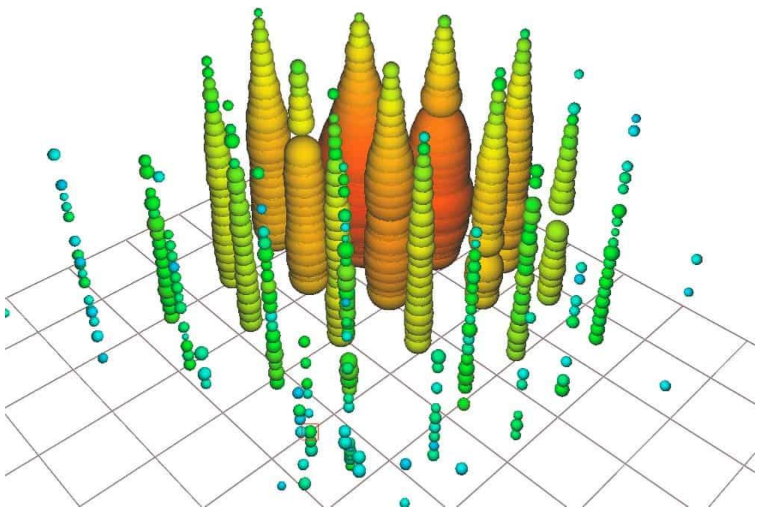
- 3 events with neutrino energy > 5 PeV over a decade of data taking

ApJ **833** 3 (2016)



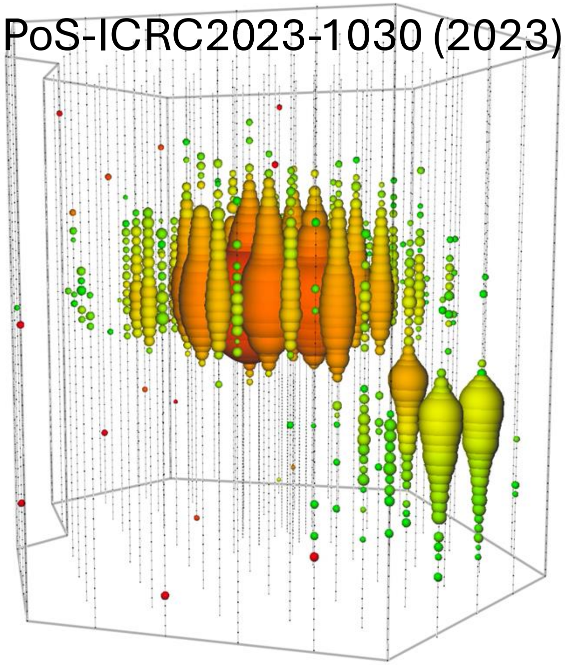
Muon energy: 4.5±1.2 PeV
Nu energy ~ 9 PeV

Nature **591**, 220–224 (2021)



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

PoS-ICRC2023-1030 (2023)

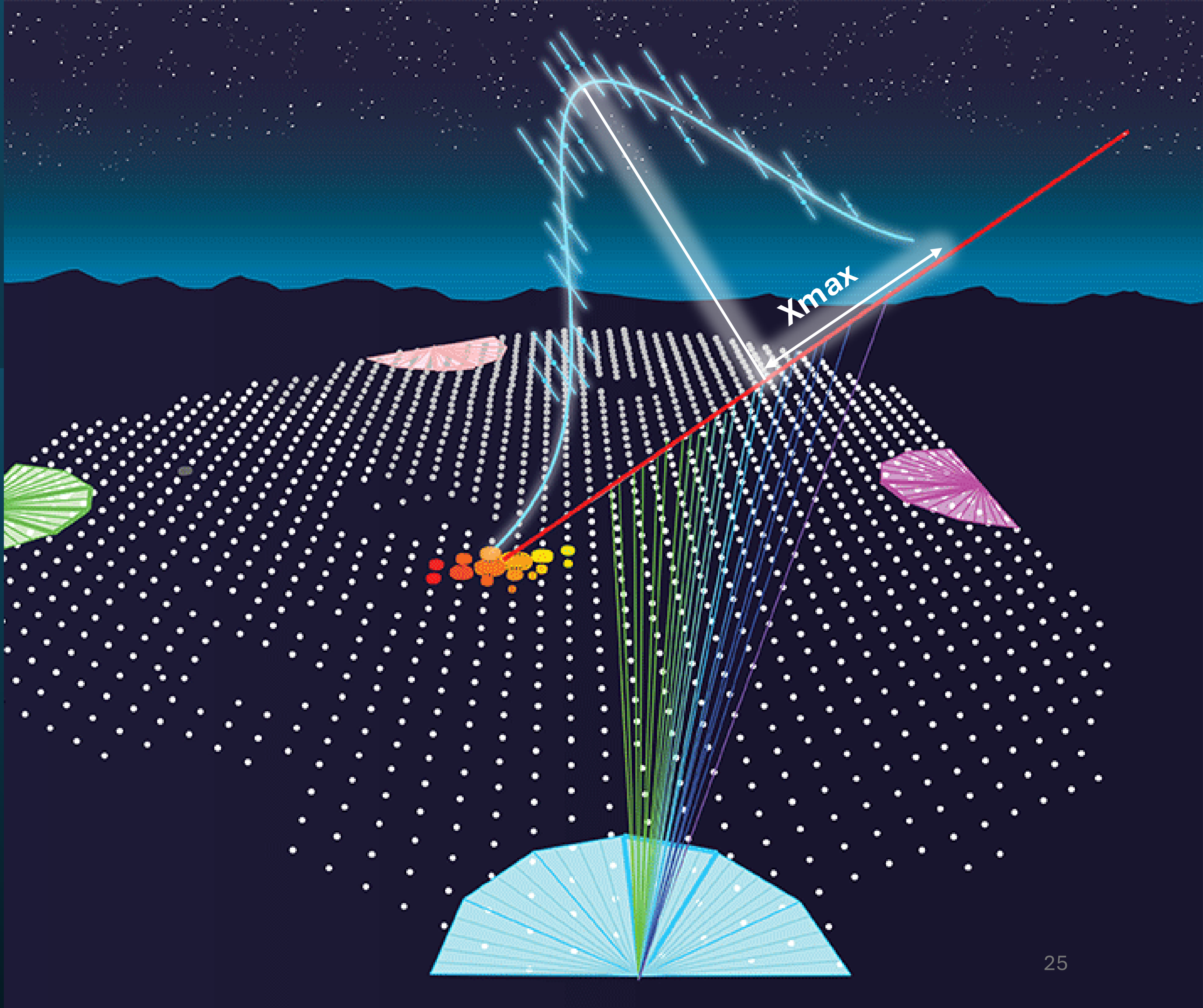


Nu energy ~11.4±2.5 PeV

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

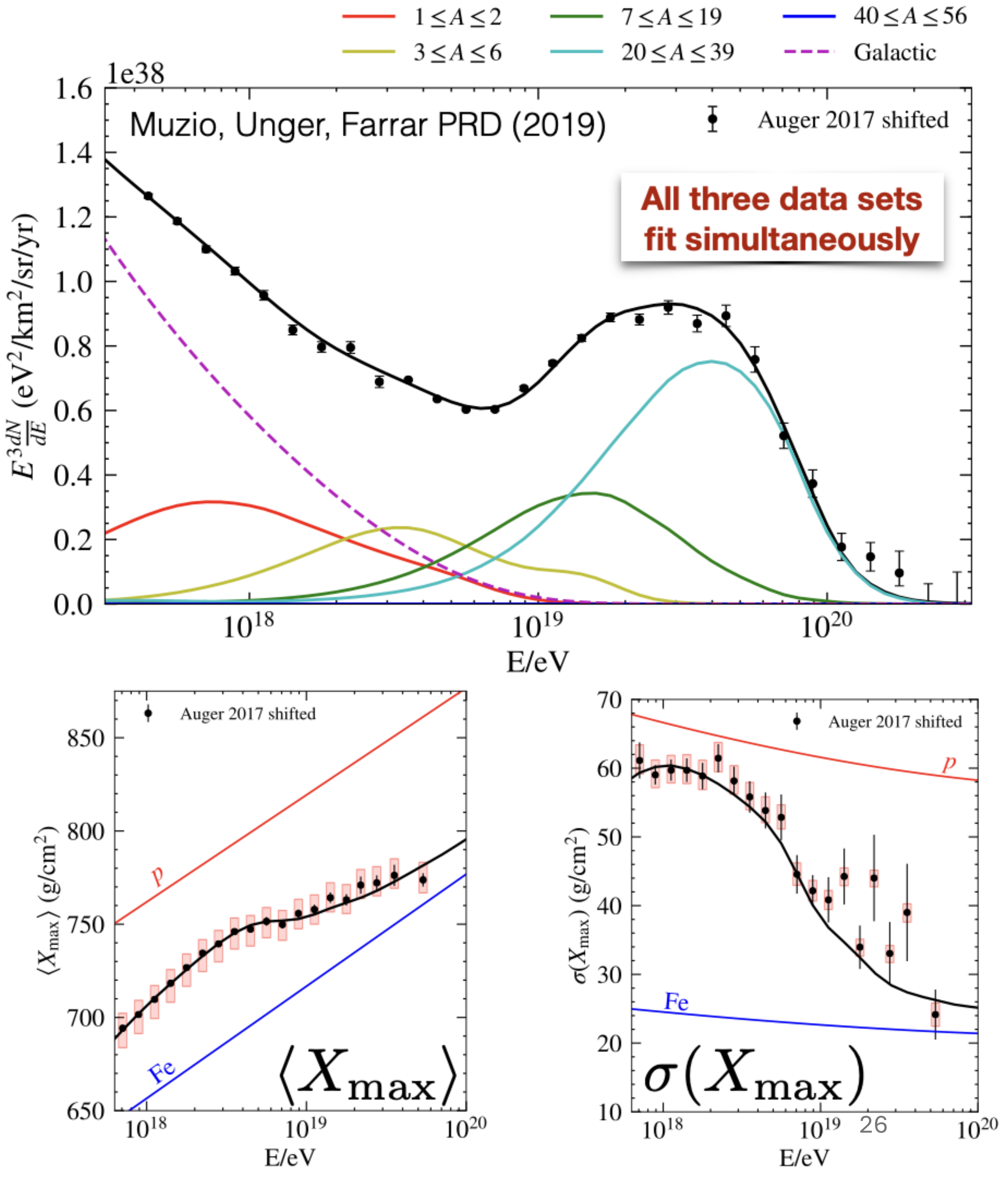
The highest energy cosmic rays

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**

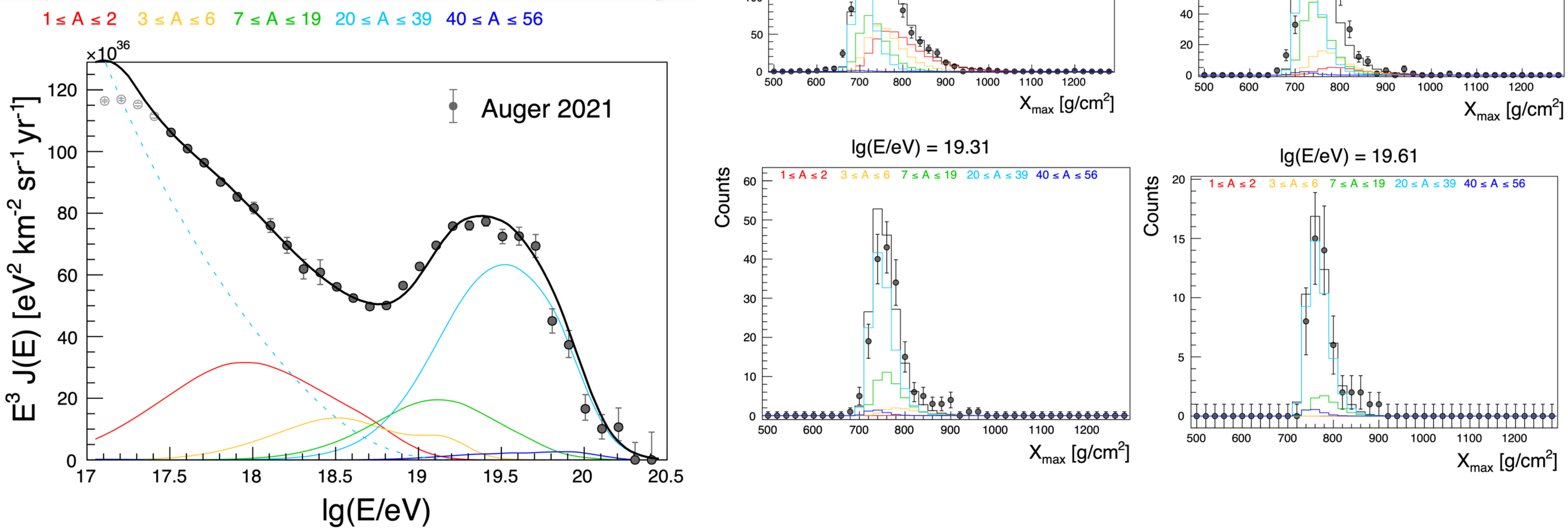
- Ultra high energy cosmic rays
  - Flux $>10^{17.5}$ eV
  - Full Xmax distributions $>10^{18.6}$ eV**
    - Rather than fitting only first two moments

****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 $+1\sigma$, Xmax scale by -1σ

Result: UHECR parameters

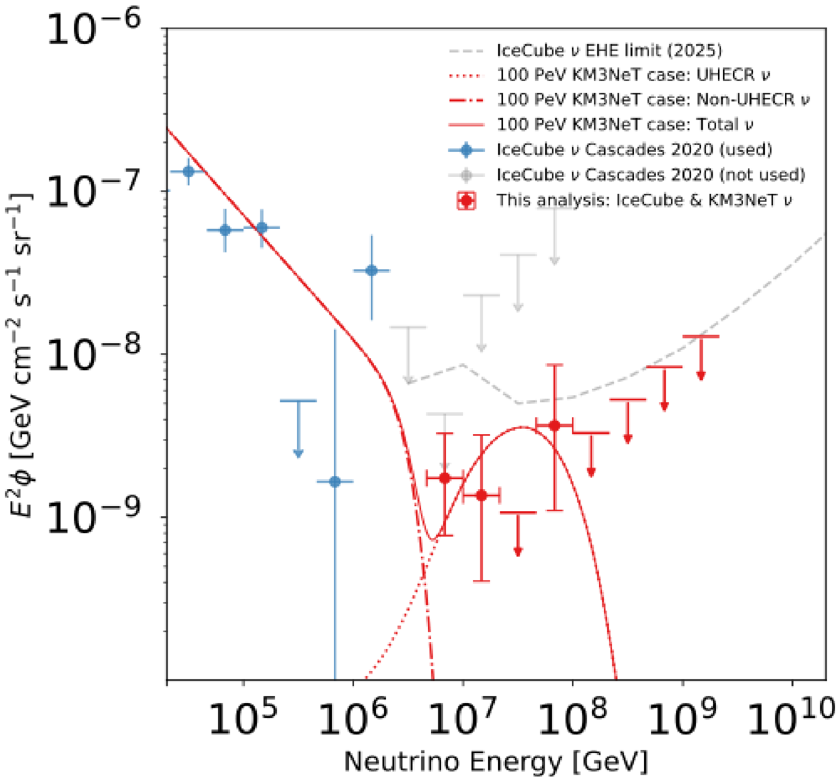


Common origin with UHECR?

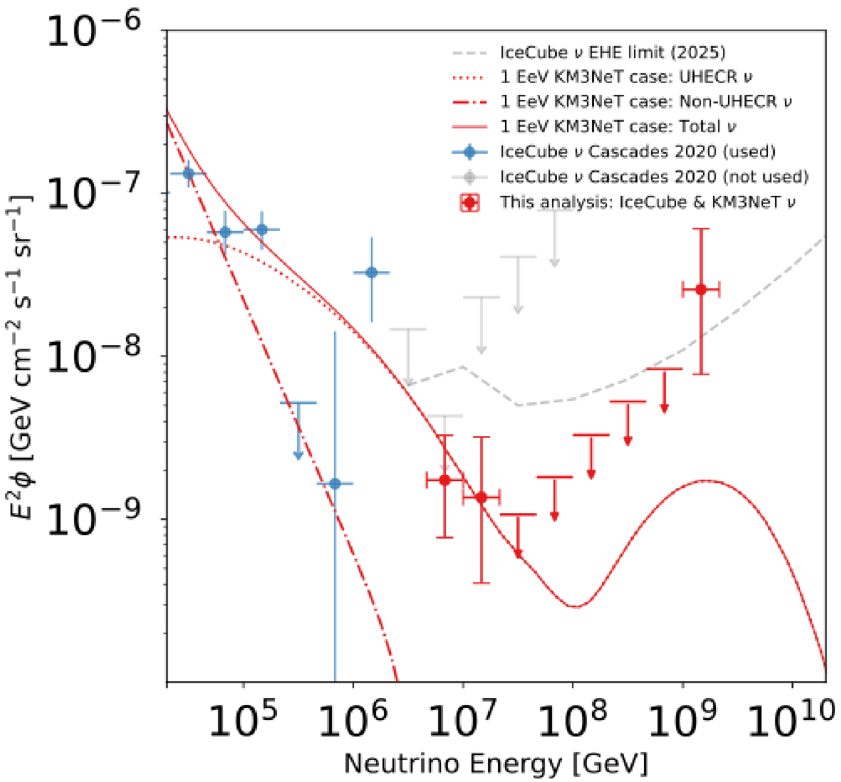
Muzio, Yuan, Lu
arXiv:2502.06944

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

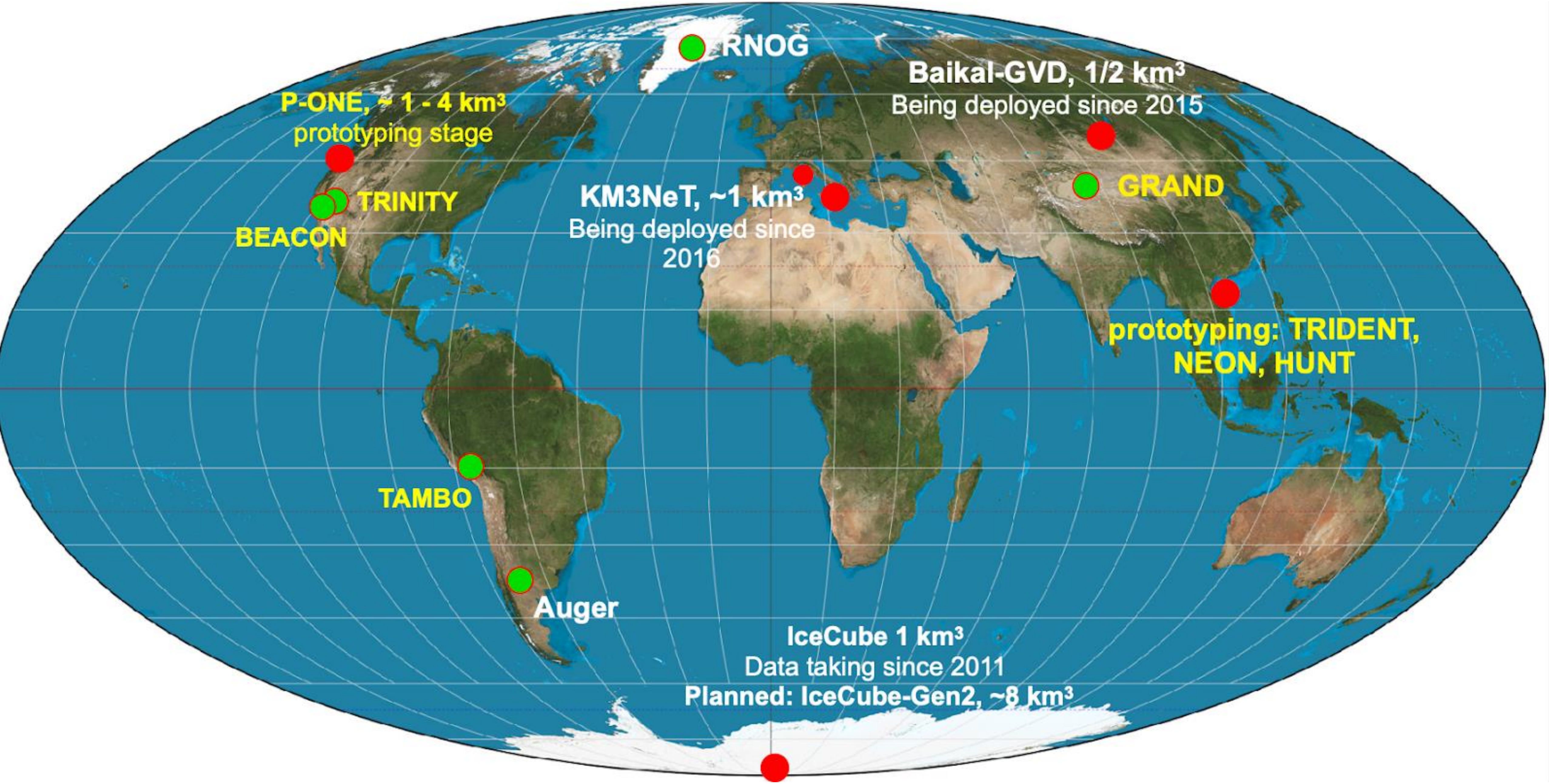
Test 100 PeV and 1 EeV+additional proton component as two distinct scenarios // combined fit with Auger mass/flux



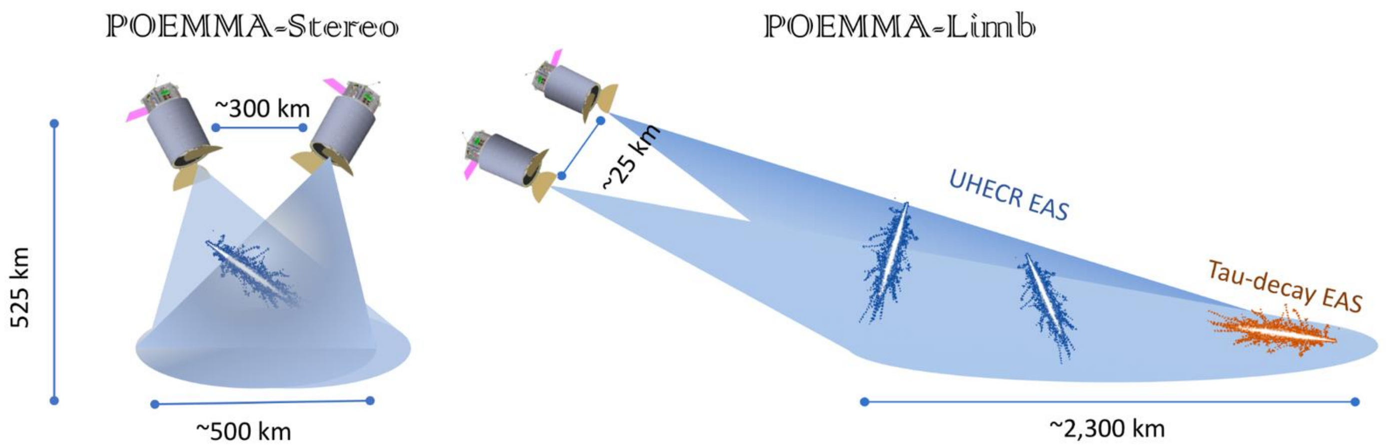
100 PeV scenario
Possible recovery at 30 PeV from UHECR

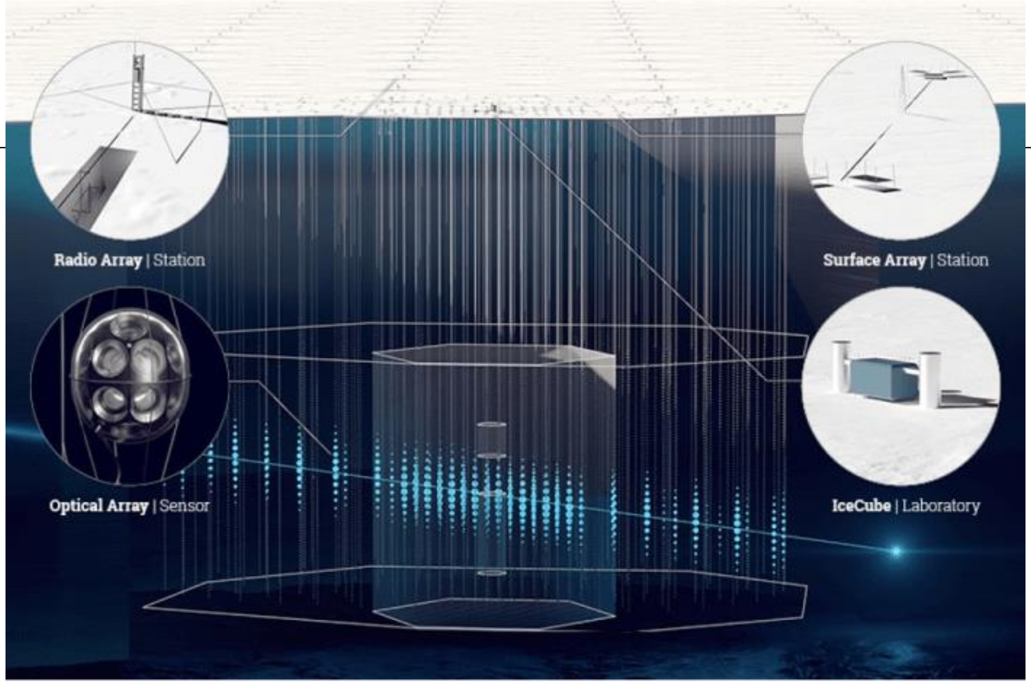


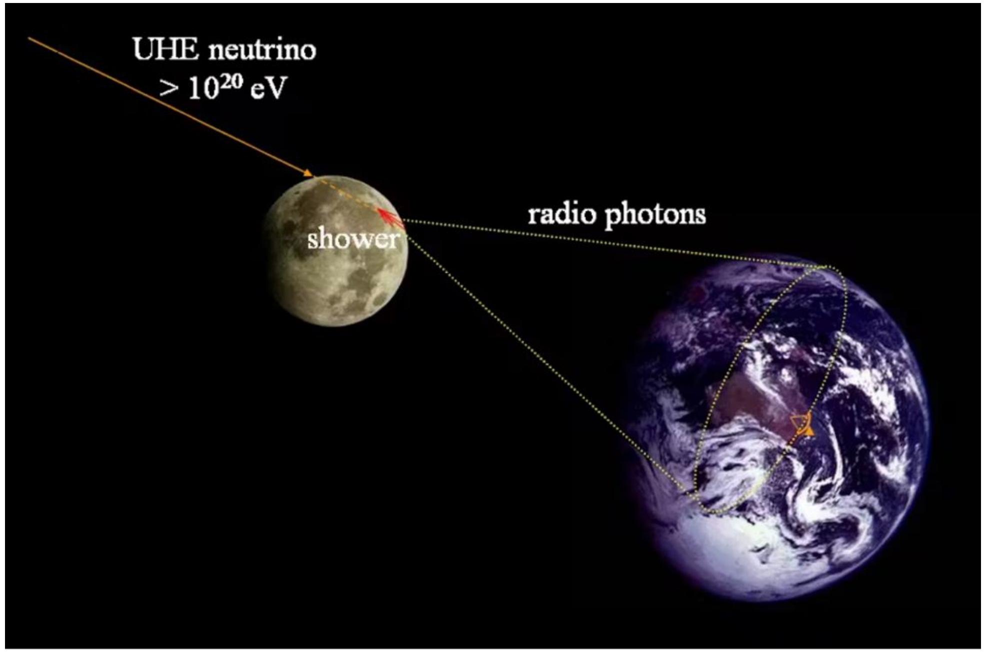
1 EeV + pure proton component scenario
Possibly a cosmogenic neutrino via GZK mechanism

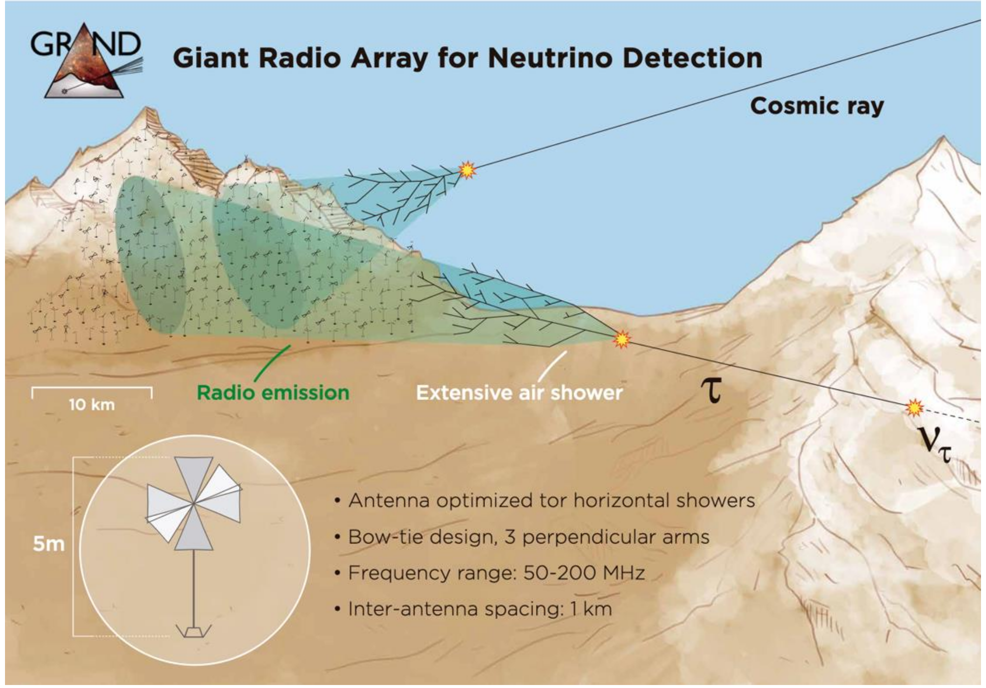

RNOG
Baikal-GVD, 1/2 km³
Being deployed since 2015
P-ONE, ~ 1 - 4 km³
prototyping stage
GRAND
TRINITY
KM3NeT, ~1 km³
BEACON
Being deployed since 2016
prototyping: TRIDENT, NEON, HUNT
TAMBO
Auger
IceCube 1 km³
Data taking since 2011
Planned: IceCube-Gen2, ~8 km³

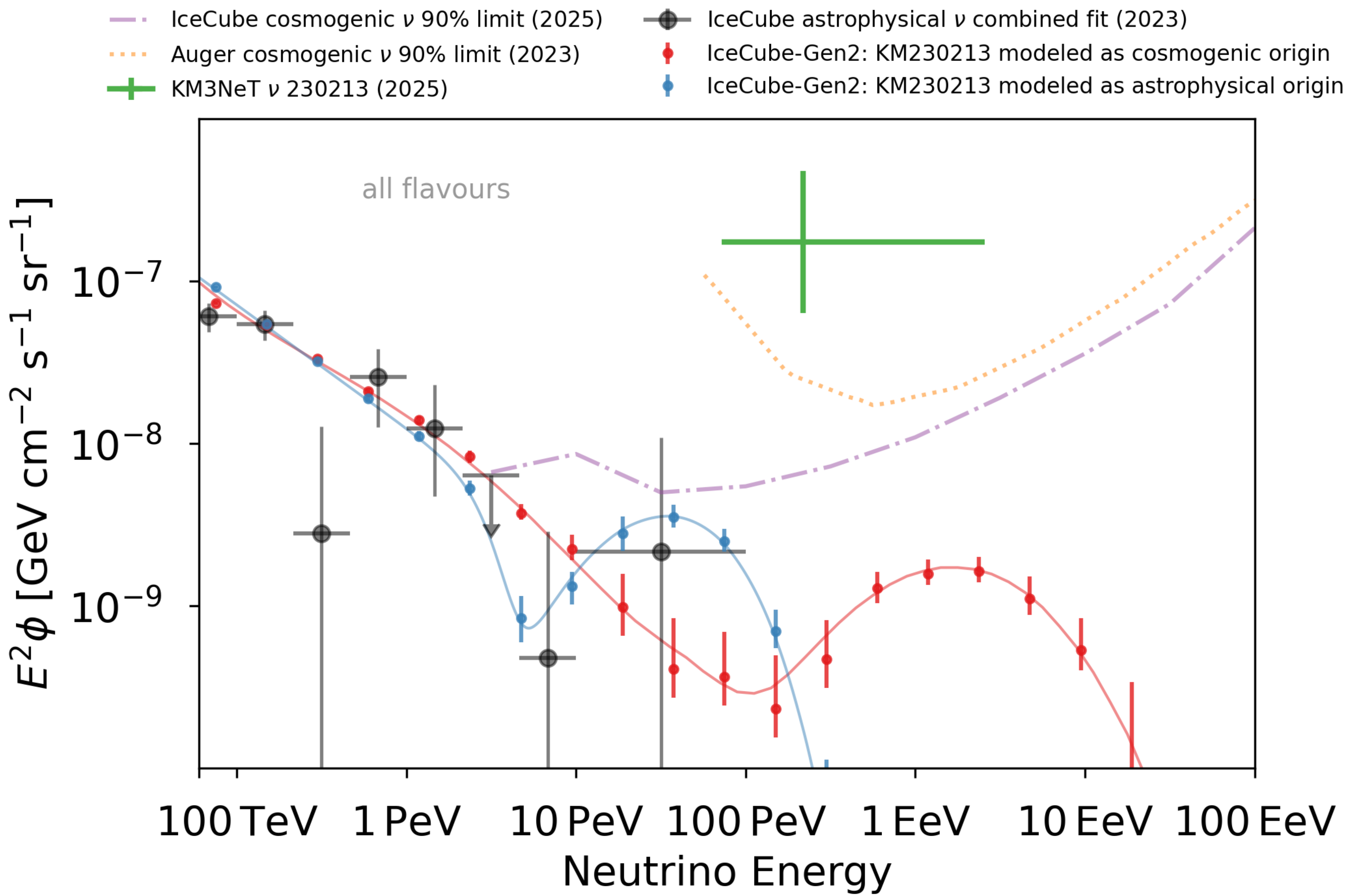
Future neutrino telescopes











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/

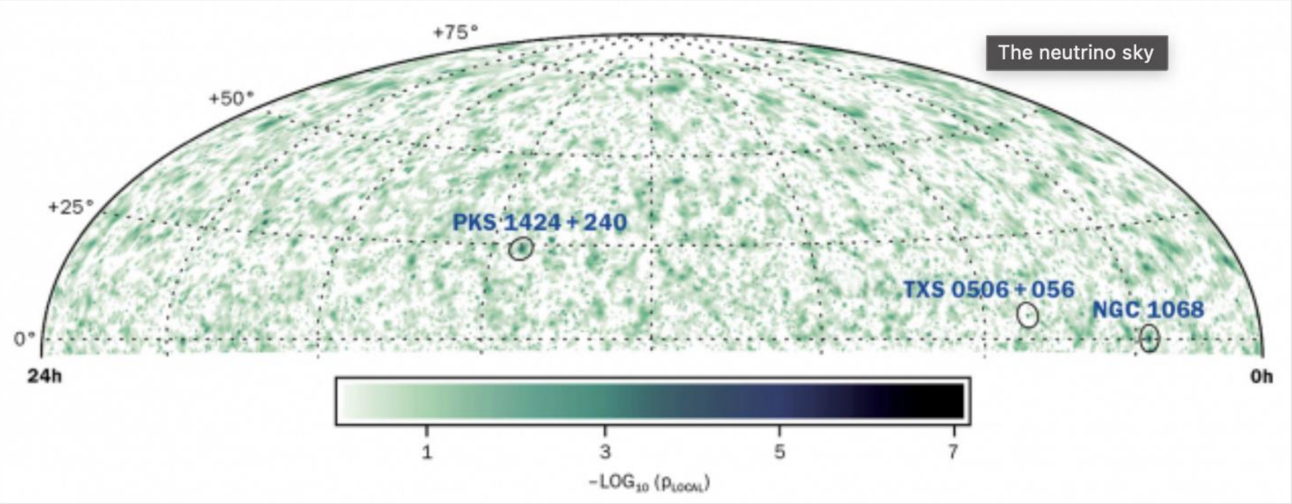
CERNCOURIER | Reporting on international high-energy physics

NEUTRINOS | FEATURE

Discovering the neutrino sky

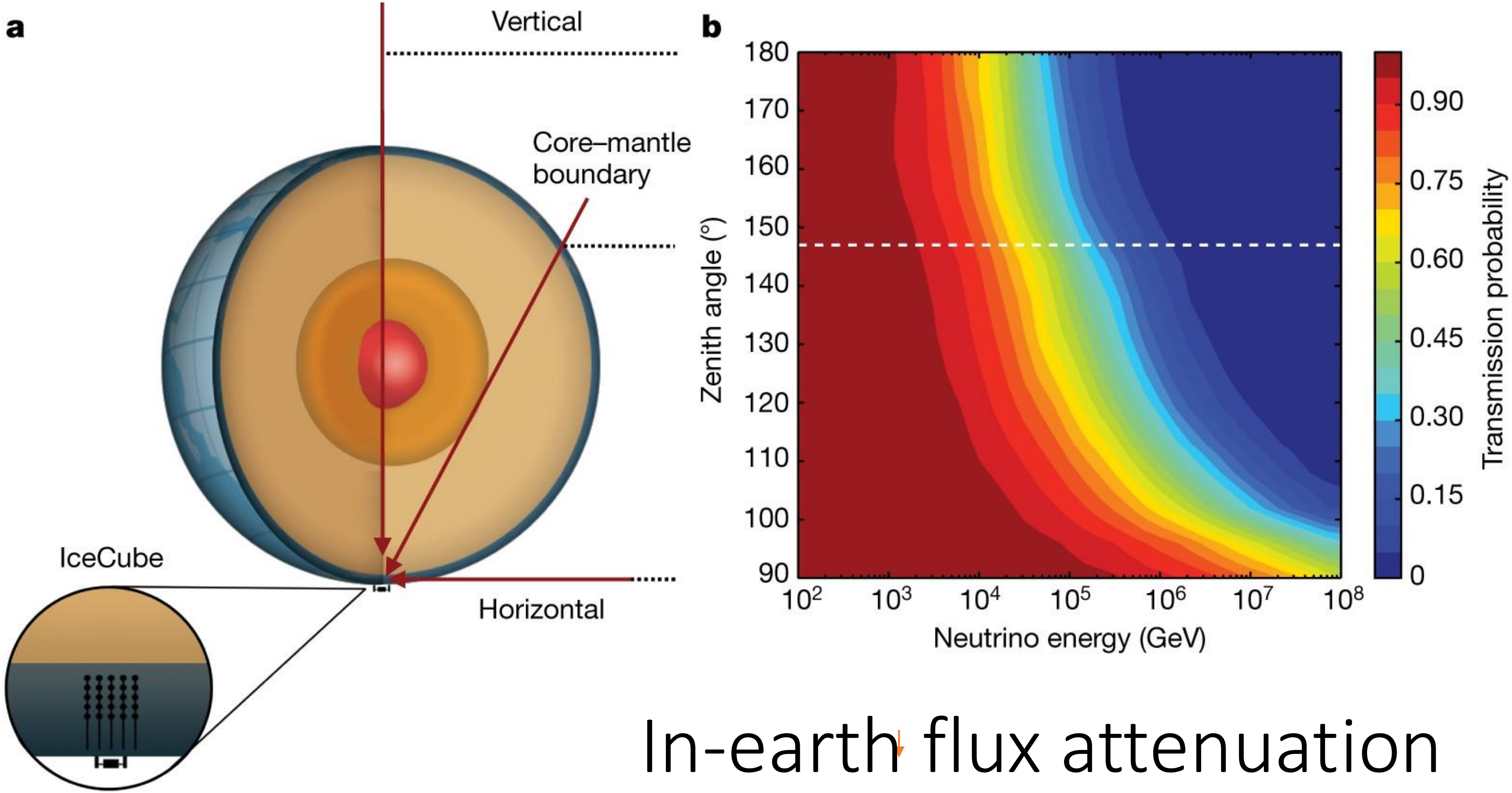
19 May 2025

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

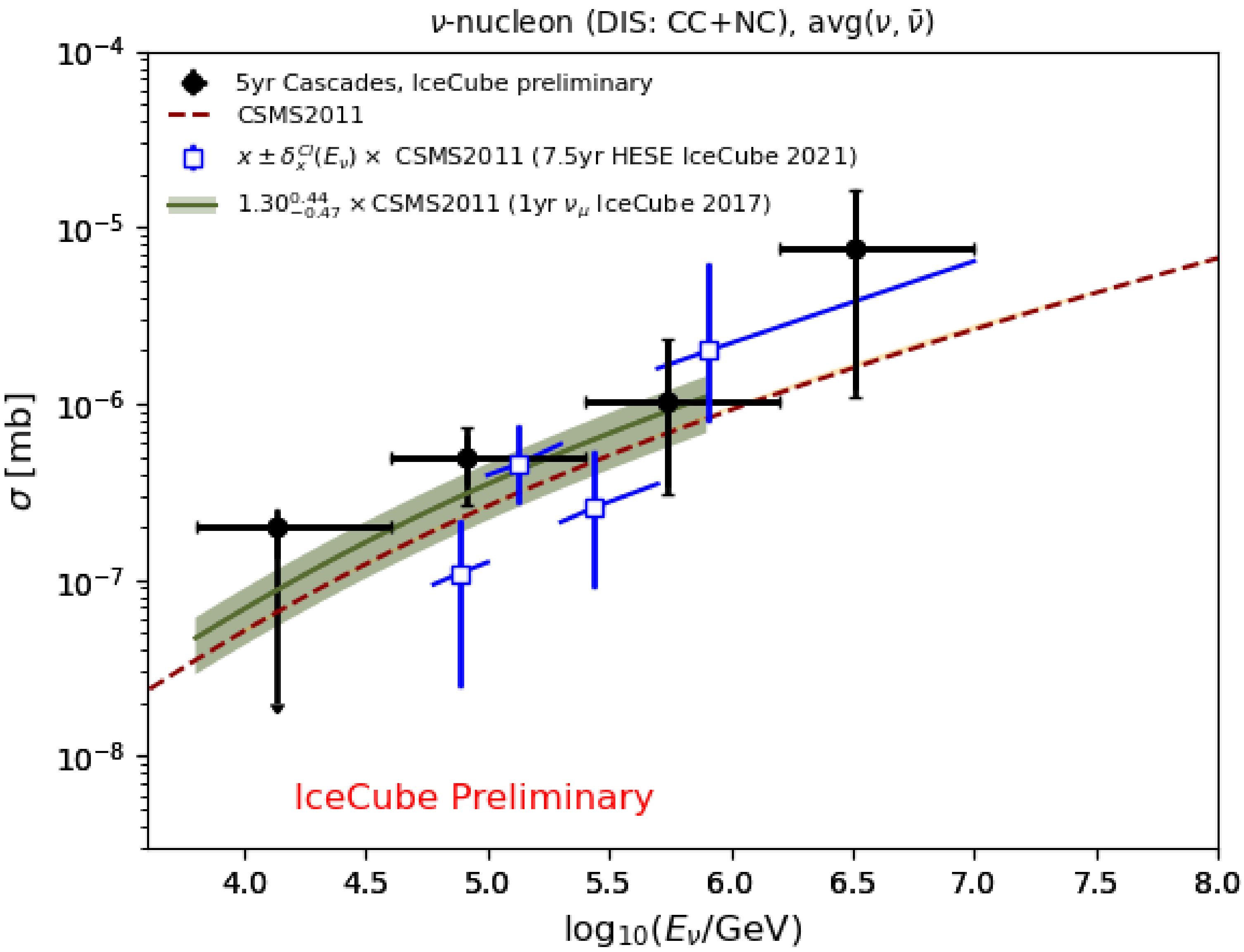
Cross section measurement using Earth as the target



In-earth flux attenuation

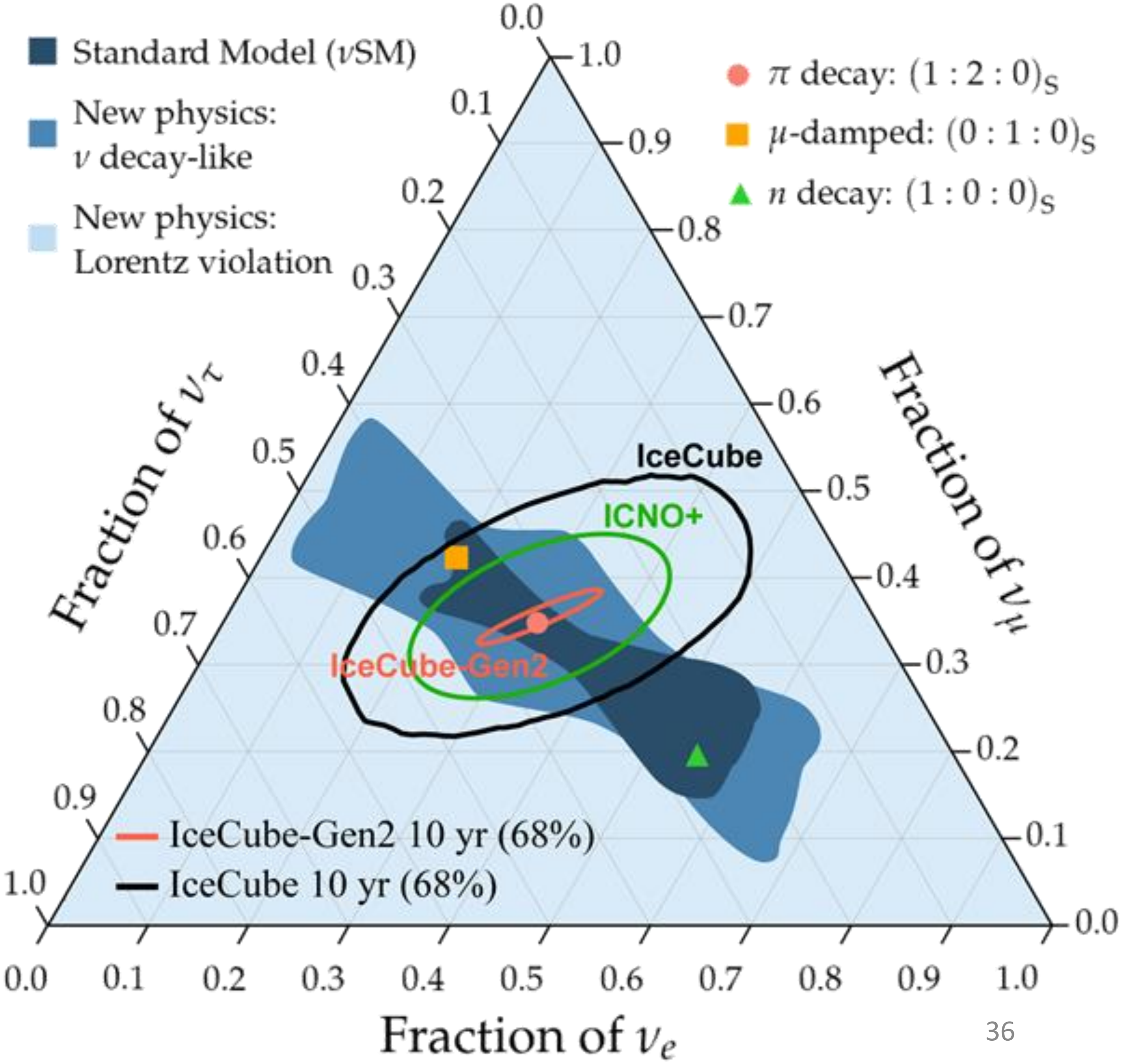
Cross section

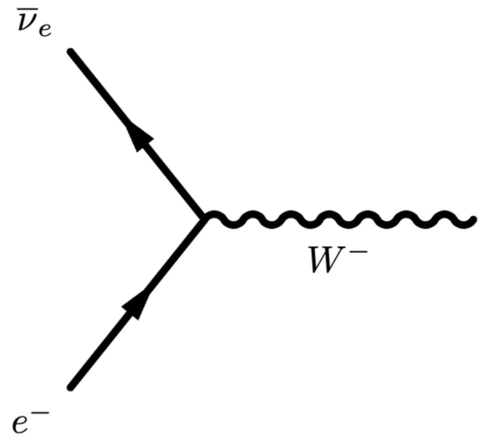
- Both tracks and cascades
- Reaching energies beyond accelerators



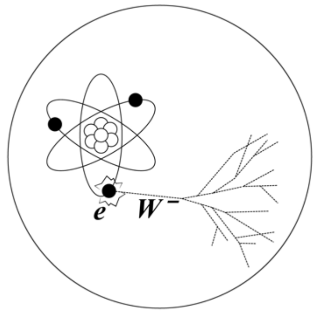
Neutrino oscillations over cosmic baselines

- 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



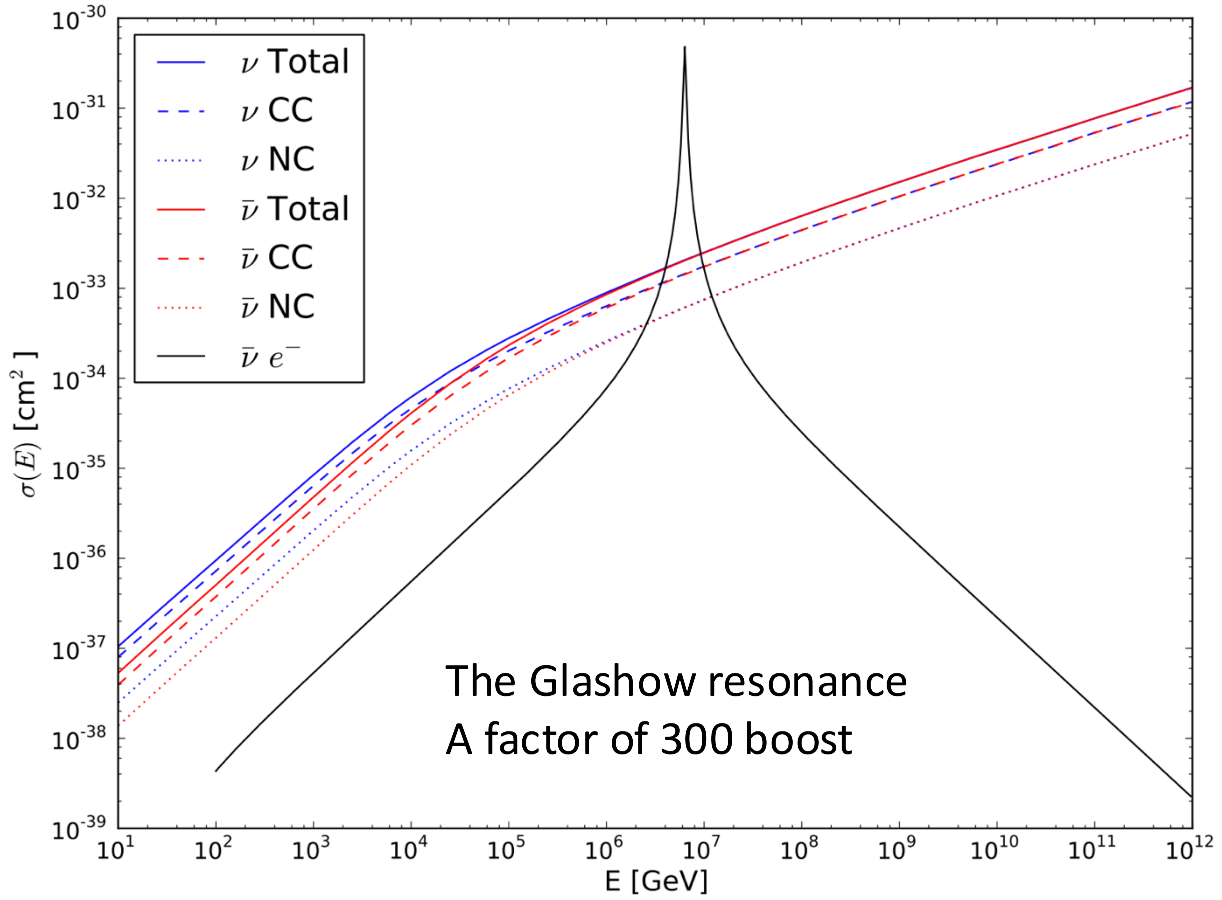
at a neutrino energy of 6.3 PeV, the centre-of-mass energy (80.5 GeV) is large enough to produce a real W boson

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

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

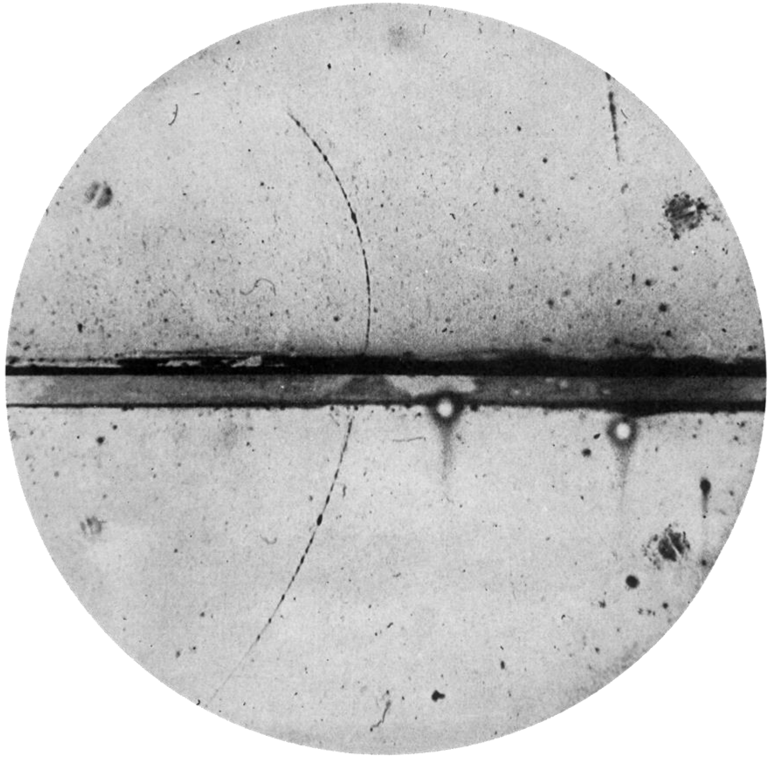
$$\overline{\nu_e} + e \quad \to W^- \to \quad X \quad ,$$

$$E_R = M_W^2/(2m_e) = 6.32\text{PeV}$$

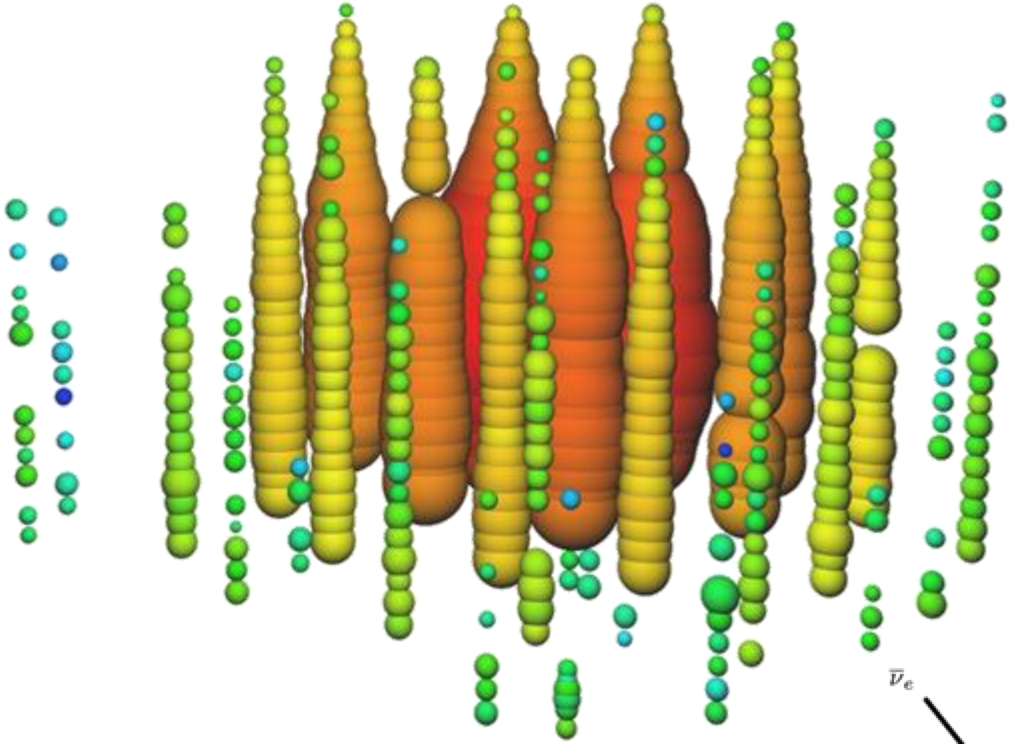


W boson (Glashow) resonance – first hint of electron anti-neutrino

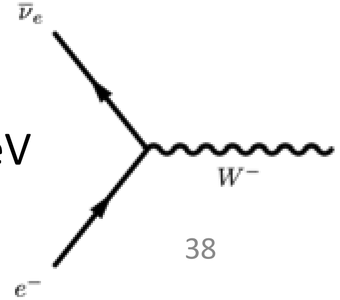
Nature **591,** 220–224 (2021)

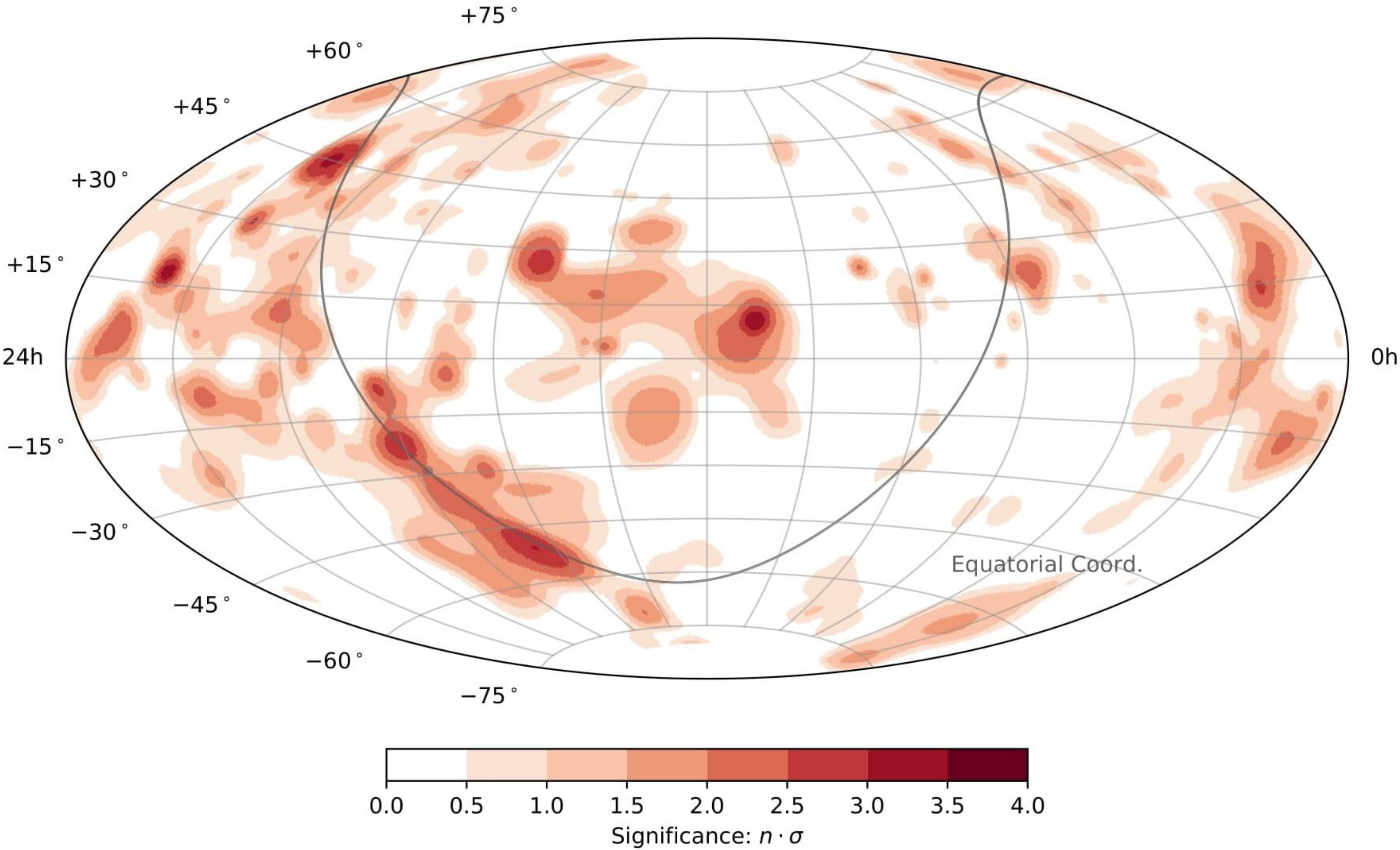


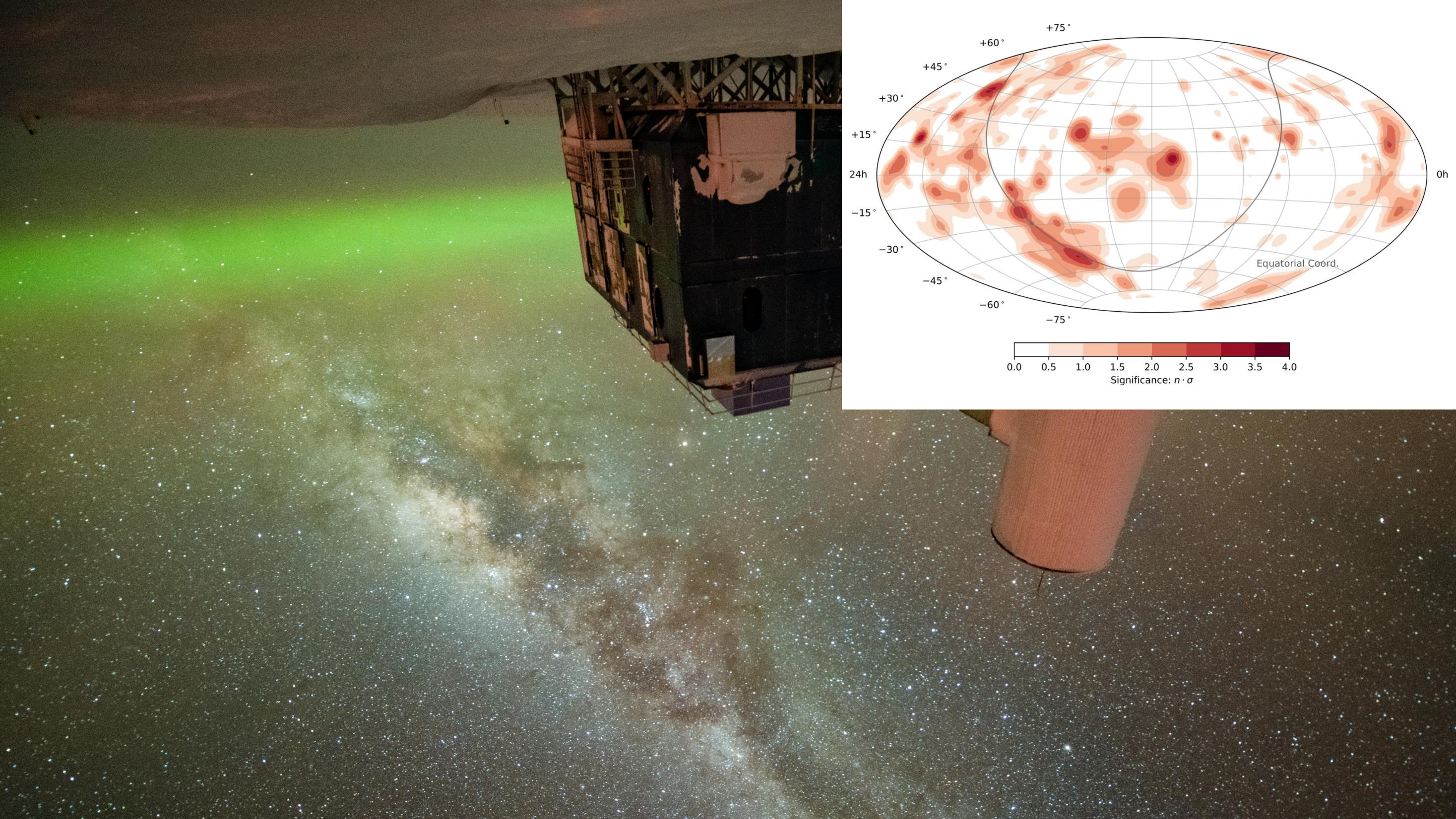
Discovery of antimatter, positron
Carl Anderson via cloud chamber, 1932



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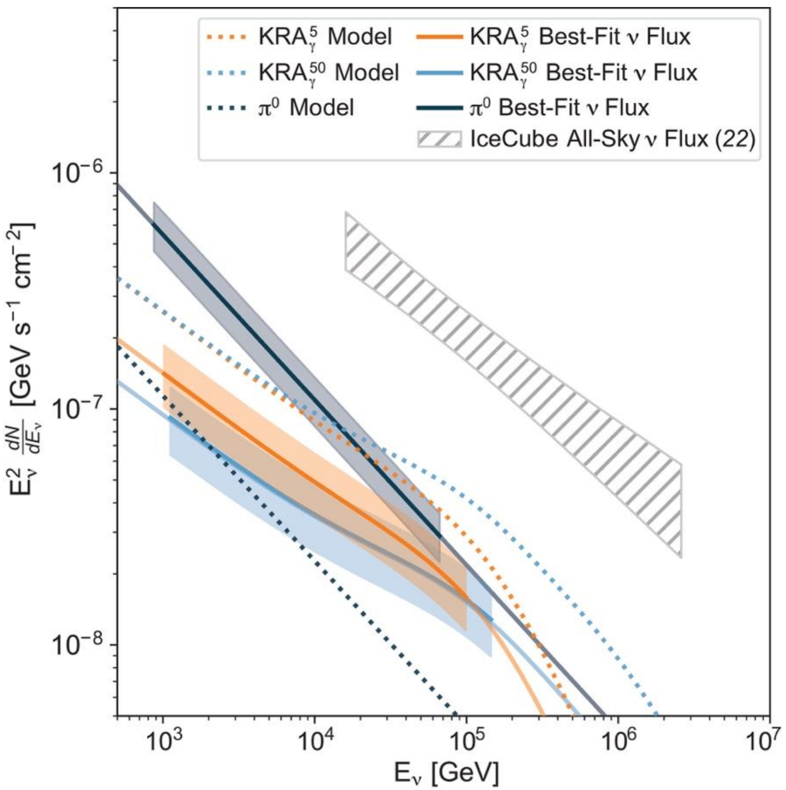
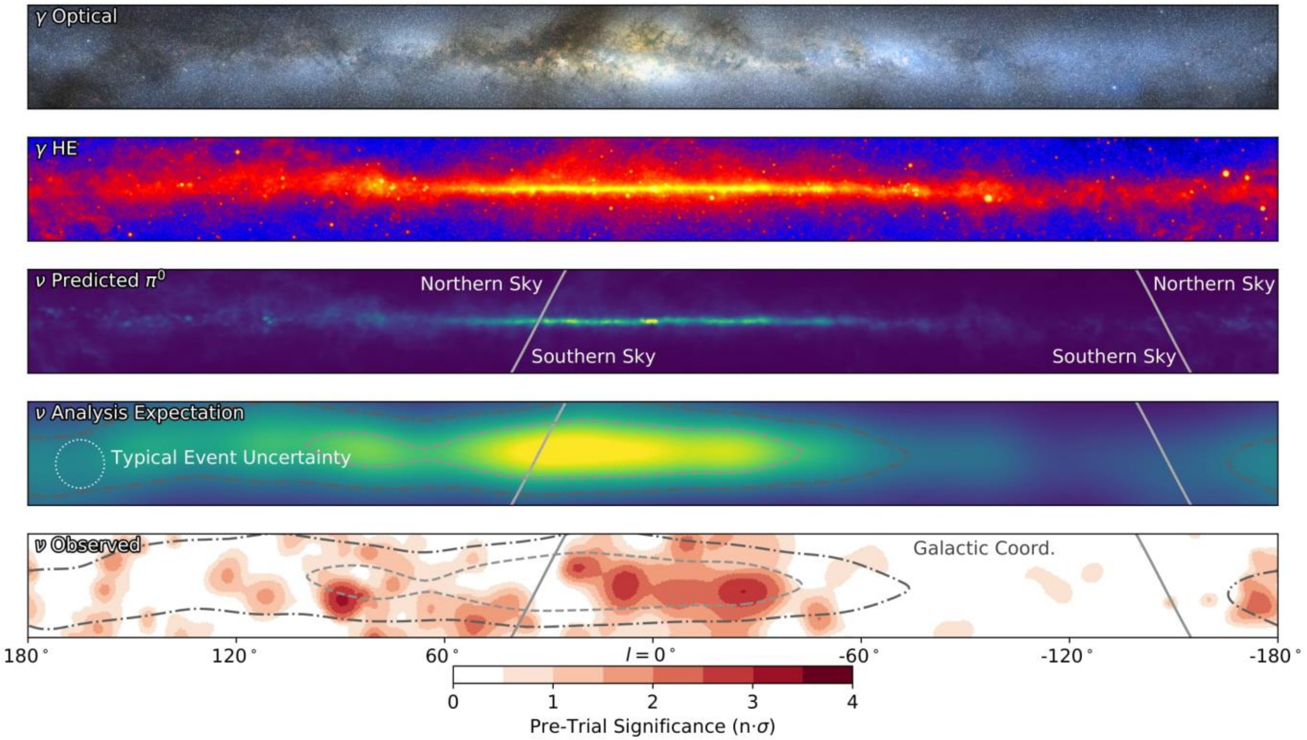
−45°
−60°
−75°
Equatorial Coord.
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Significance: $n \cdot \sigma$

Neutrino flux from the galactic plane

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

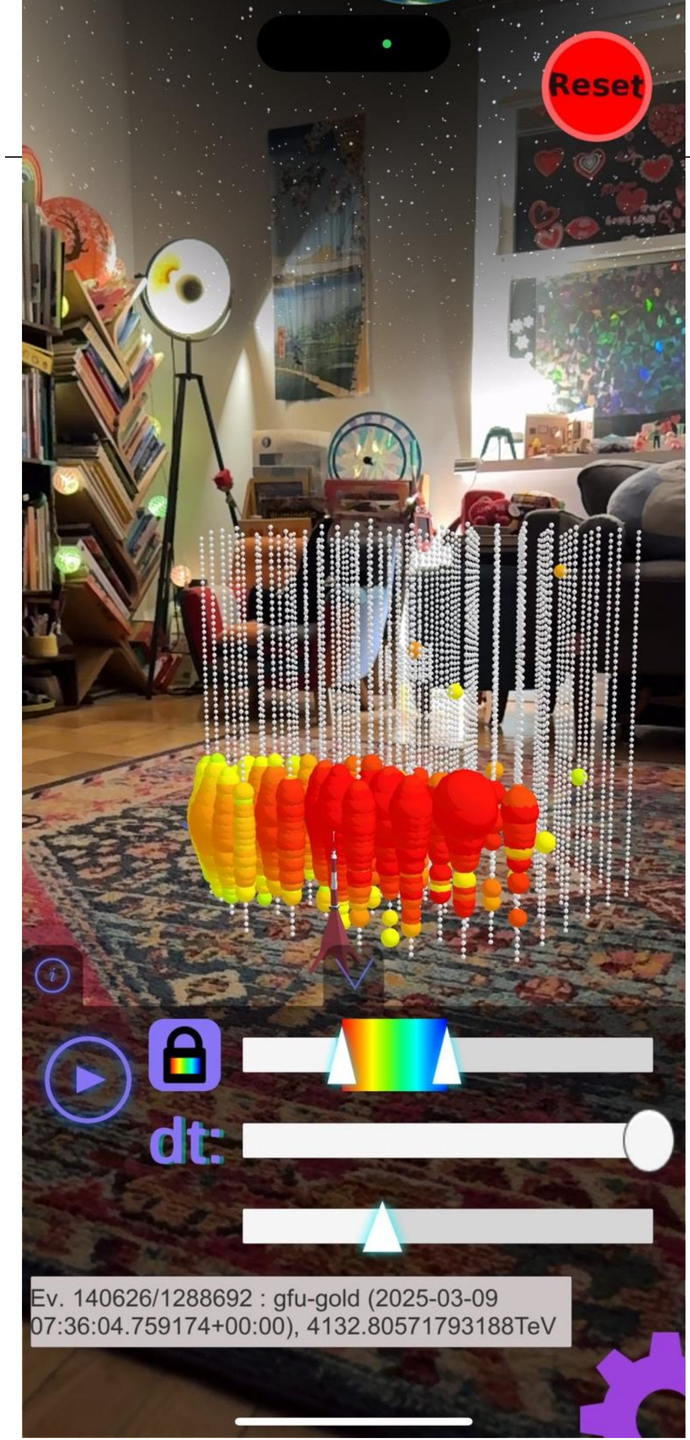
Contribution of ~6-13% to the total neutrino flux at 30 TeV



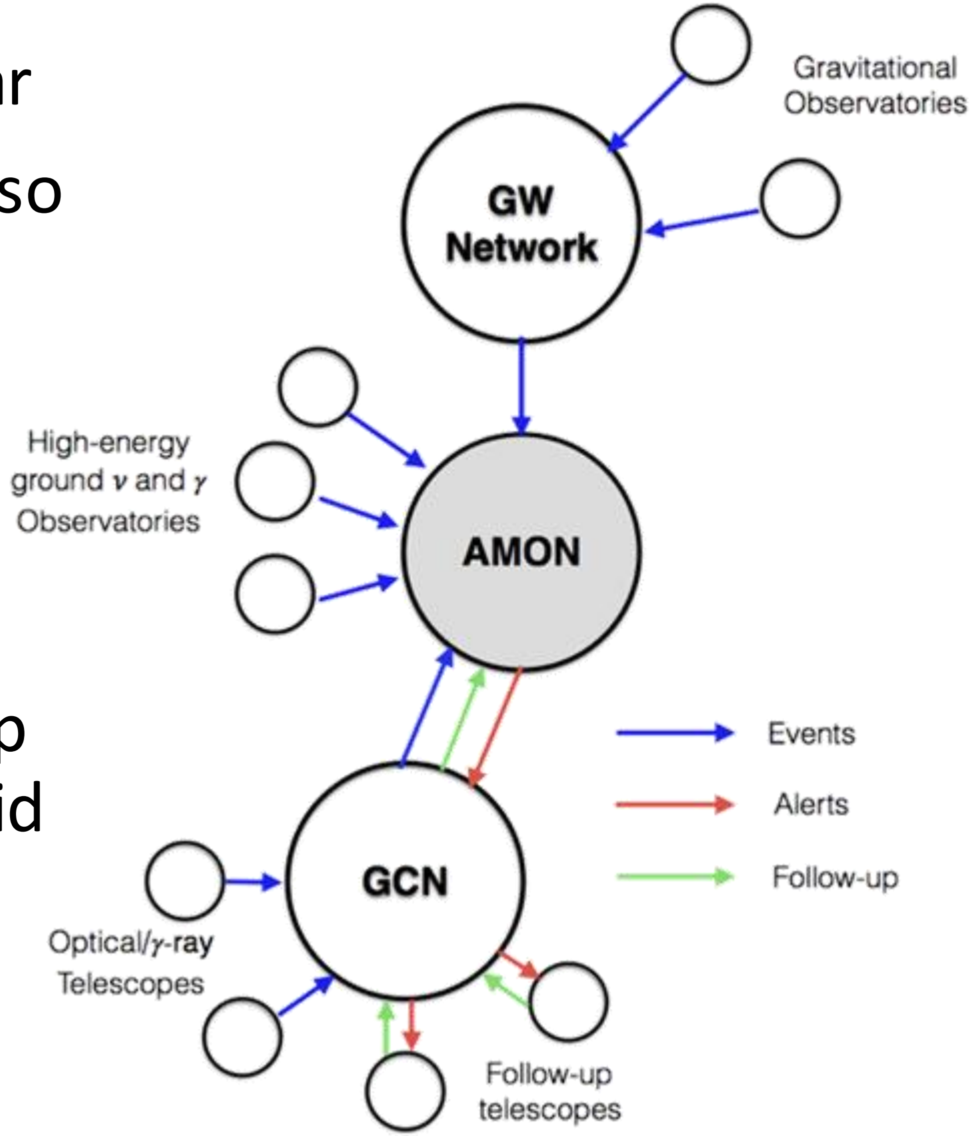


Science 380 6652 (2023)

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.



Atmospheric nu

From Paolo's talk

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

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

→ E_ν ~ 100/cosθ GeV

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

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

Conv.

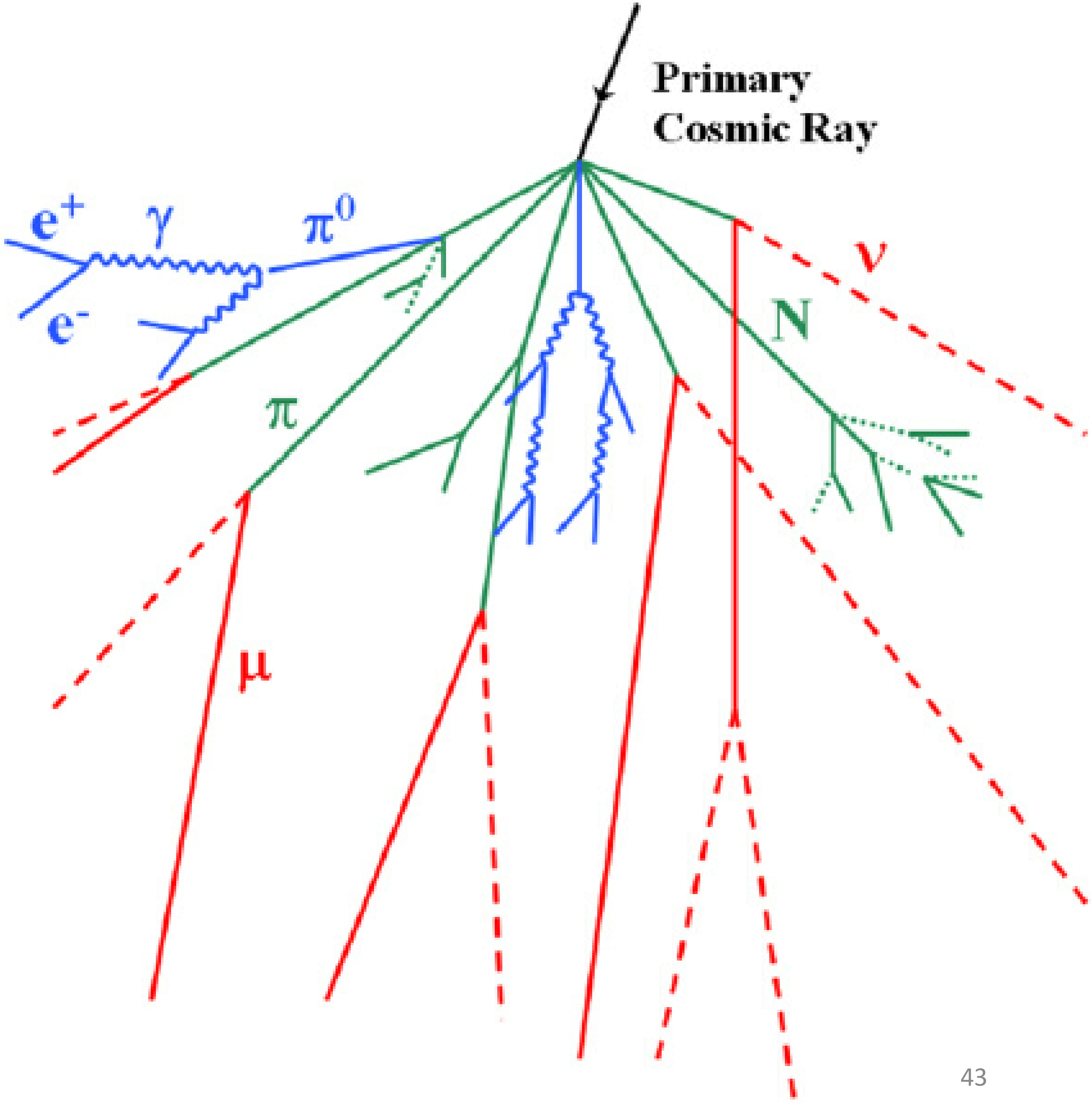
→ E_ν ~ 100/cosθ TeV

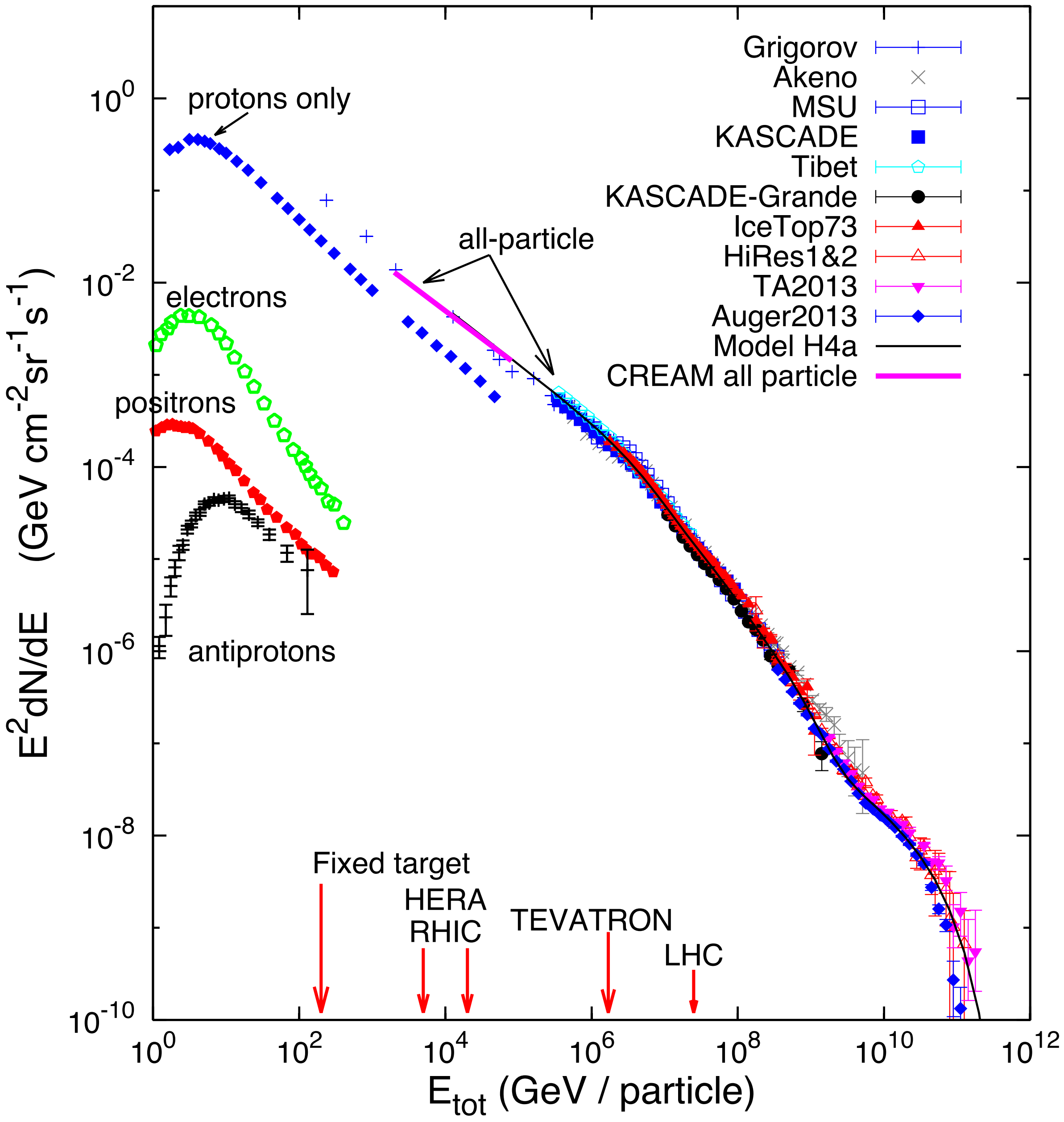
$K_S^0 \to \pi e \nu_e$ (Gaisser & Klein 2014) (0.07%)

prompt

$D, \Lambda_c \to \ell + \nu_\ell + \ldots$ (order %)

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



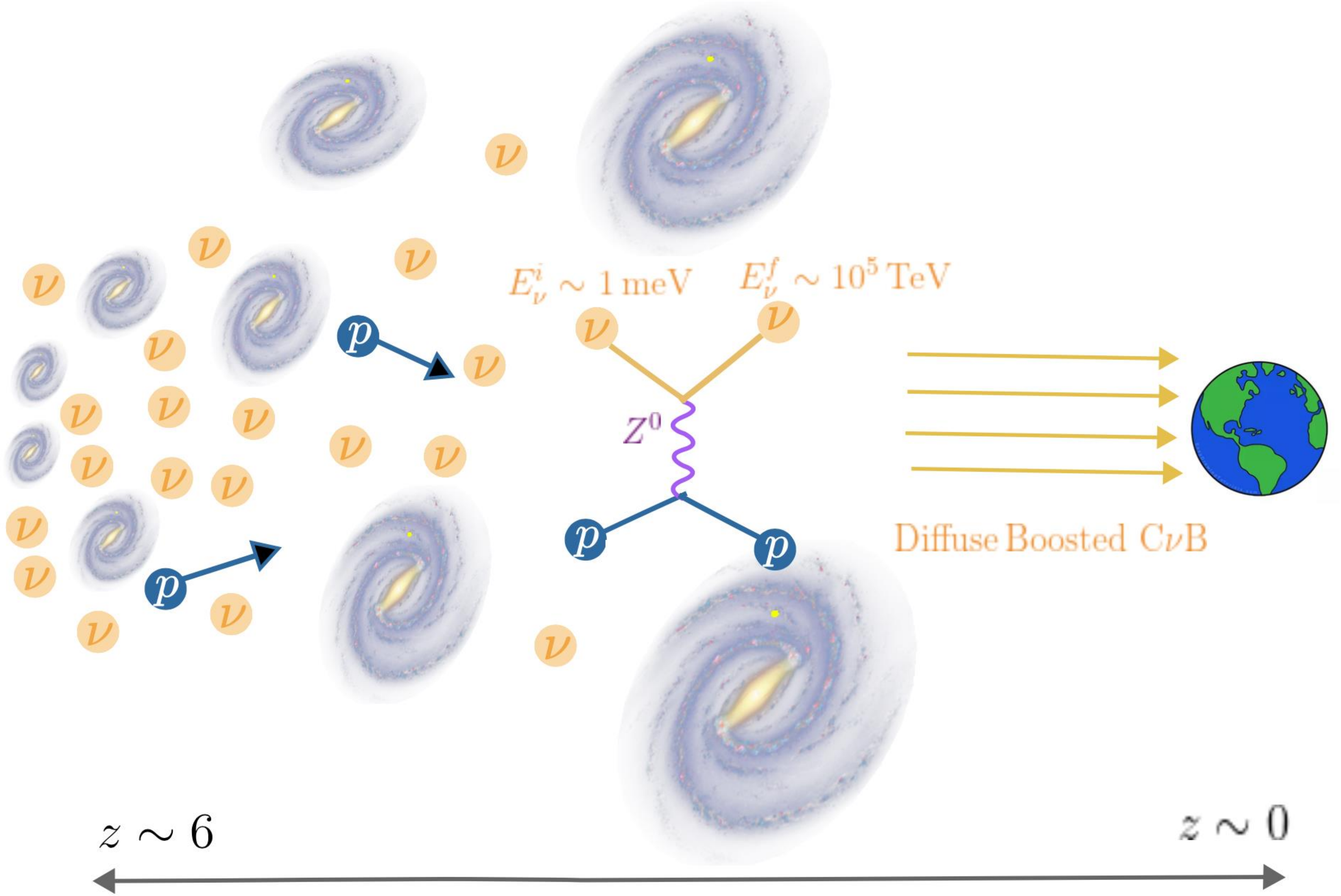


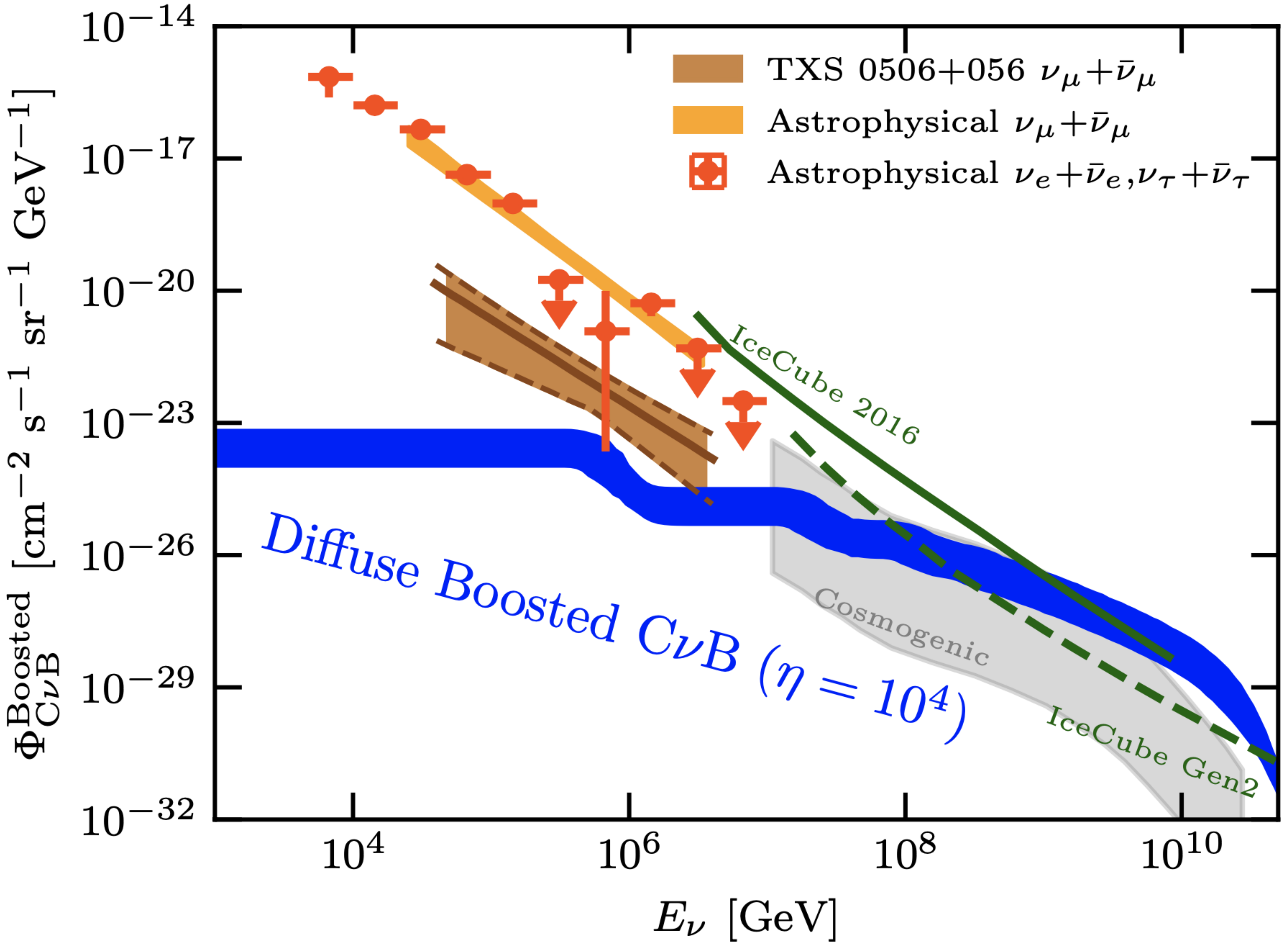
See talk on cosmic rays

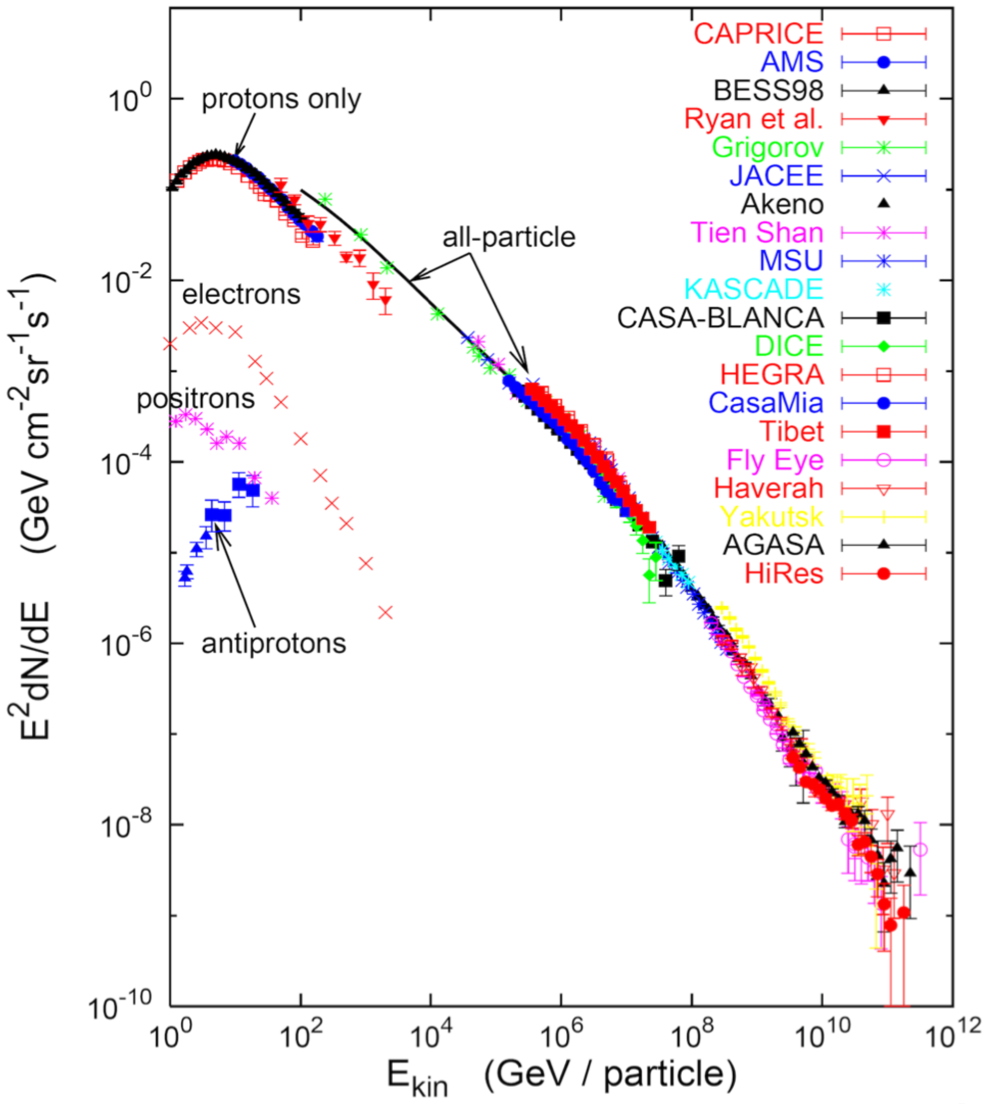
Cosmogenic neutrinos

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

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


$E_\nu^i \sim 1\,\mathrm{meV}$
$E_\nu^f \sim 10^5\,\mathrm{TeV}$
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
Diffuse Boosted CνB ($\eta = 10^4$)
Cosmogenic
IceCube Gen2
$\Phi^{\mathrm{Boosted}}_{\mathrm{C}\nu\mathrm{B}}$ [cm^{-2} s^{-1} sr^{-1} GeV-1]
E_ν [GeV]
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^4
10^6
10^8
10^{10}



Energy density of Galactic cosmic rays

$$I(E) \approx 1.8 \times 10^4 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-2.7} \frac{\mathrm{nucleons}}{\mathrm{m^2\ s\ sr\ GeV}}$$

$$\Phi(E) = \int_\Omega \mathrm{d}\Omega I(E) = 4\pi I(E)$$

$$n(E) = \frac{4\pi}{v} I(E)$$

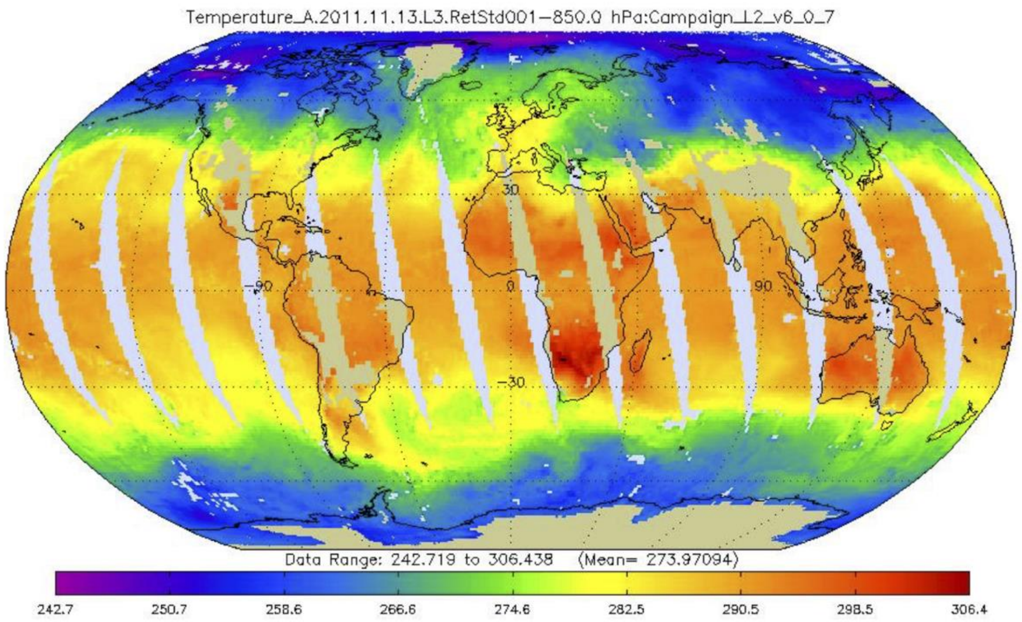
$$\rho_{CR} = \int E n(E) \mathrm{d}E = 4\pi \int \frac{E}{v} I(E) \mathrm{d}E$$

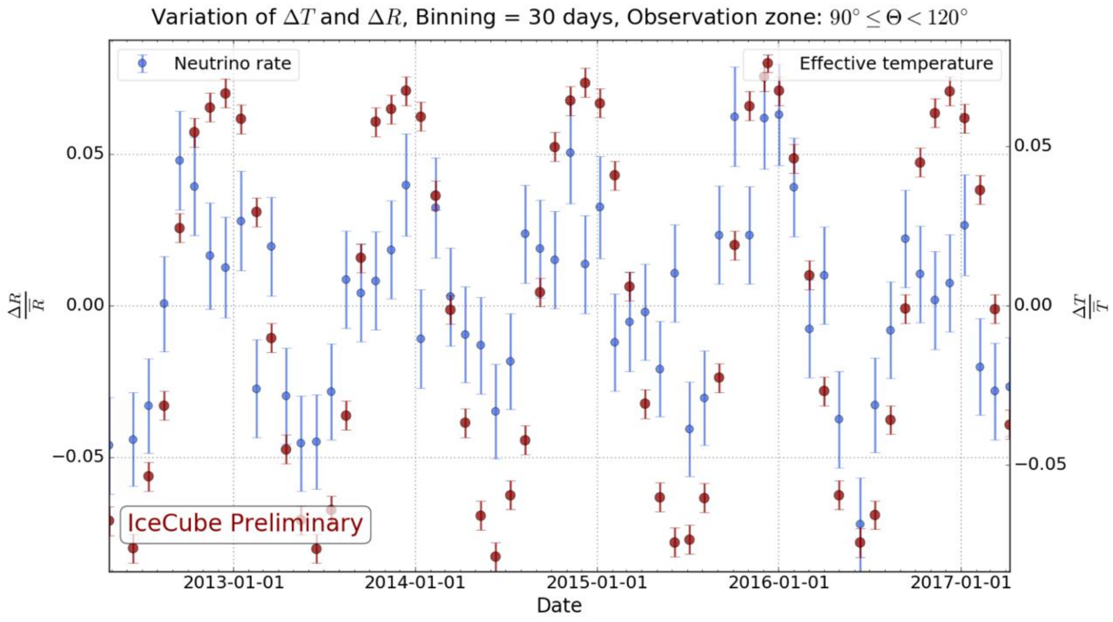
$$\rho_{CR} = \frac{4\pi}{c} \frac{1.8}{1-1.7} \left[\left(\frac{E_{max}}{1\ \mathrm{GeV}}\right)^{1-1.7} - \left(\frac{E_{min}}{1\ \mathrm{GeV}}\right)^{1-1.7}\right] \approx 1\ \mathrm{ev\ cm^{-3}}$$

CMB $\rho_{CMB} \approx 0.25$ eV/cm^3

(atmospheric) Neutrino weather!

Lead by Aachen group





In photon-proton interactions (γ + p → X), the **invariant mass** W of the final state is related to the incoming **photon lab energy** E_γ by:

$$W = \sqrt{m_p^2 + 2m_p E_\gamma}$$

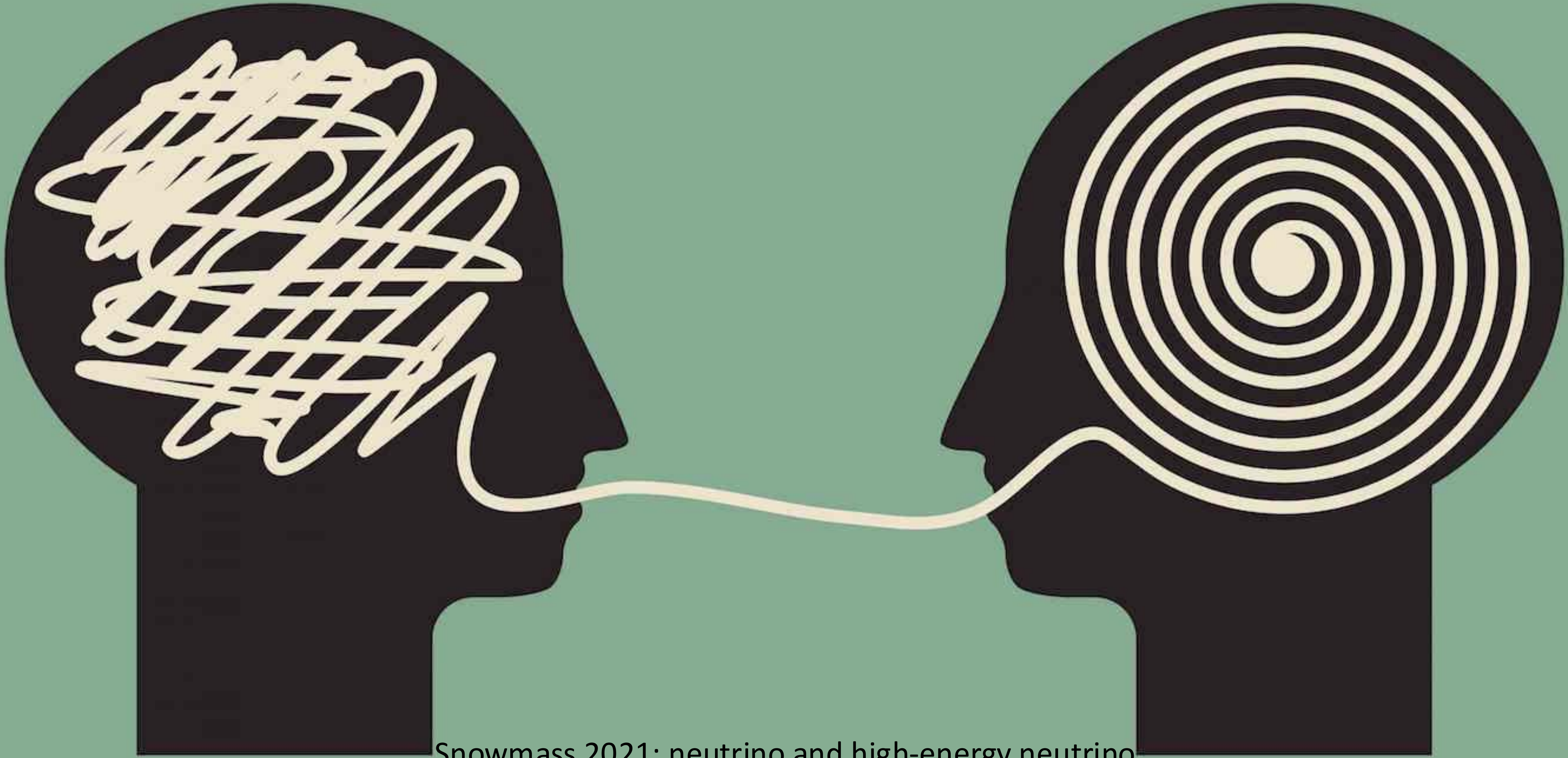
Where:

- m_p is the proton mass ≈ **0.938 GeV**
- E_γ is the photon energy in the **lab frame**
- W is the invariant mass of the system (center-of-mass energy)

Solve for E_γ:

$$E_\gamma = \frac{W^2 - m_p^2}{2m_p} = \frac{(1.232)^2 - (0.938)^2}{2 \cdot 0.938} = \frac{1.518 - 0.88}{1.876} \approx 0.34 \text{ GeV}$$

I hope ‘diffuse’ makes sense to you now



Snowmass 2021: neutrino and high-energy neutrino
https://cds.cern.ch/record/2806792?ln=en