Diffuse neutrinos from 1 TeV to 1 EeV

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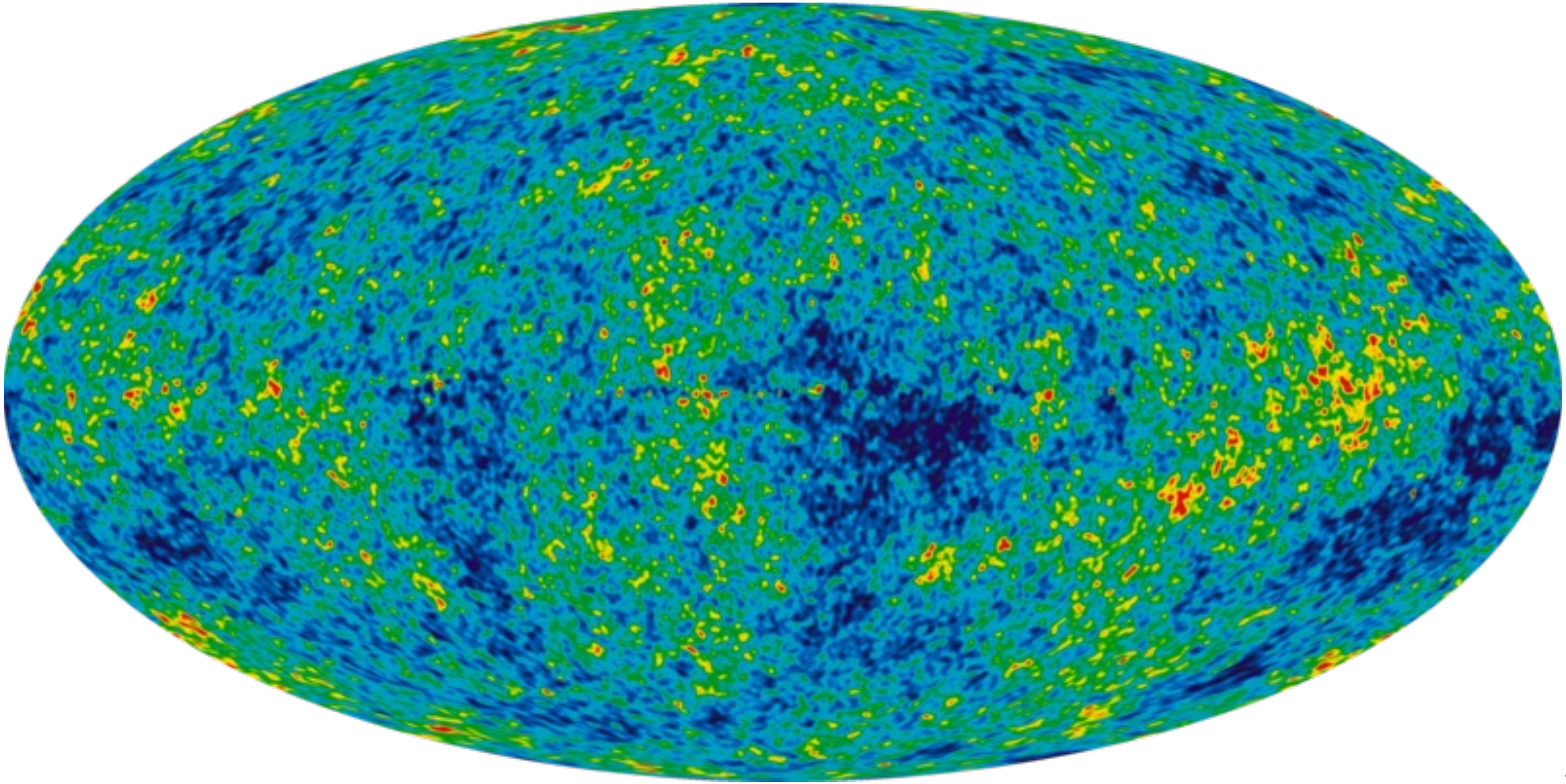
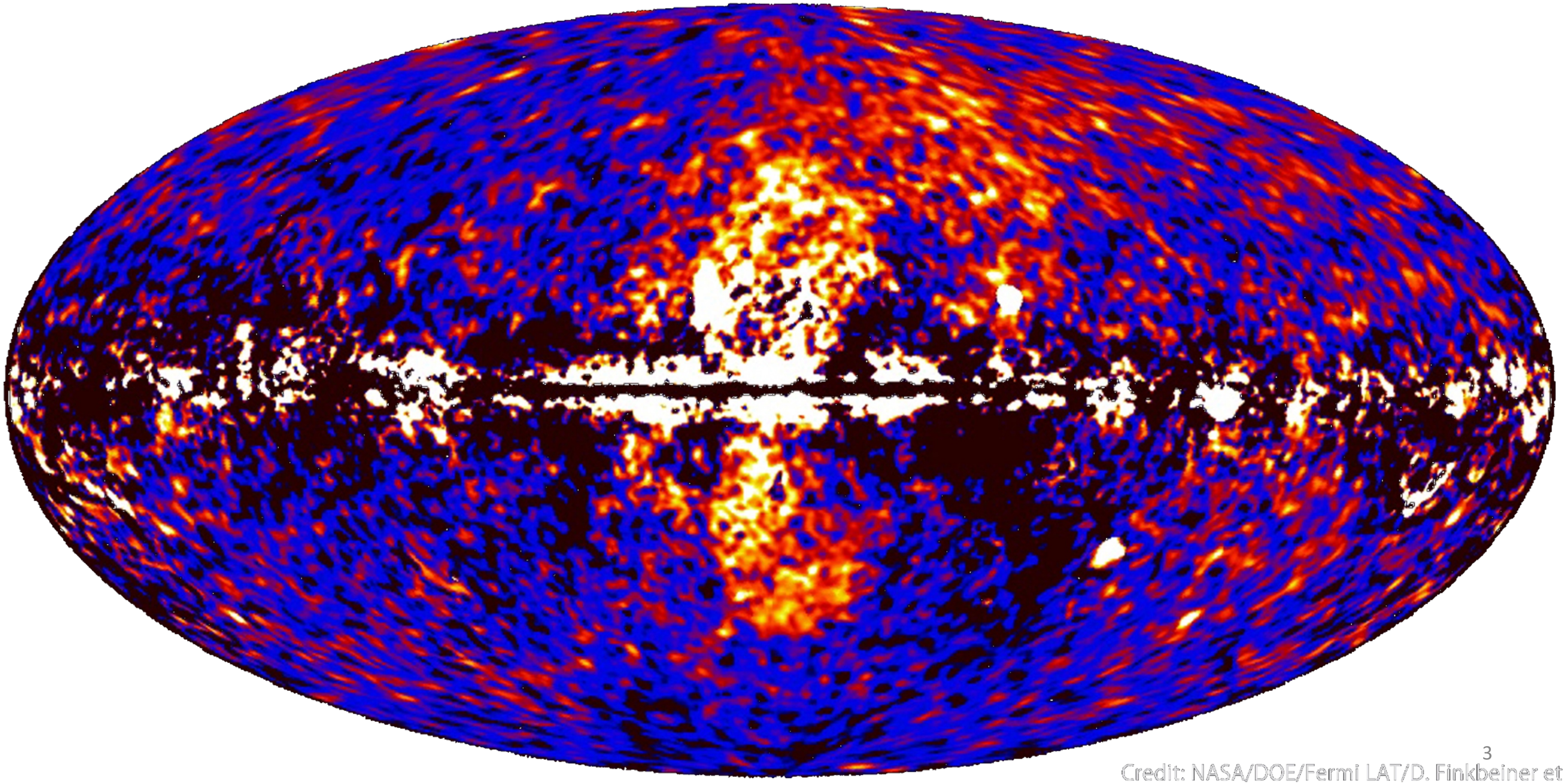
University of Wisconsin-Madison

IceCube Summer School 2023

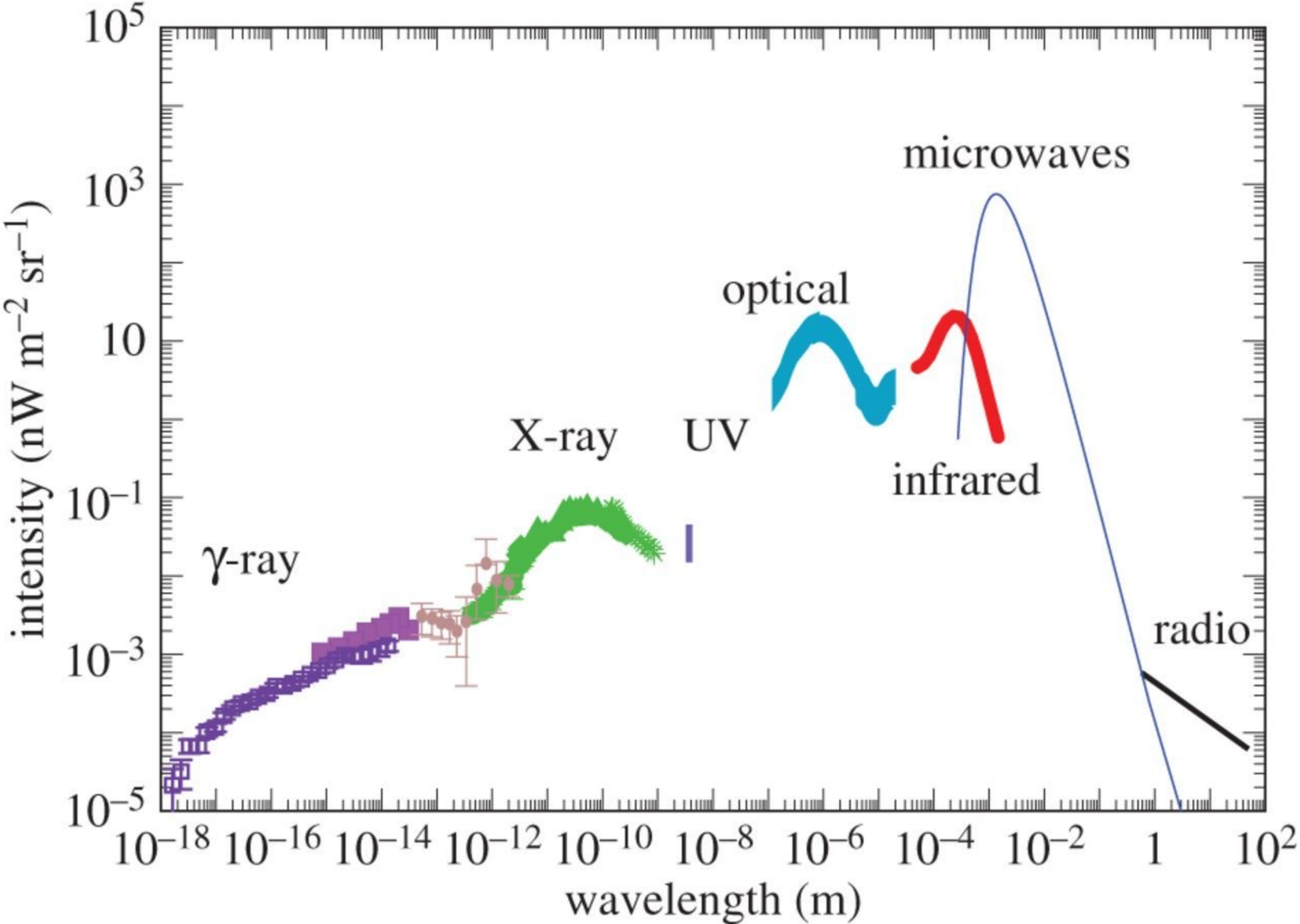
Diffuse microwave photons



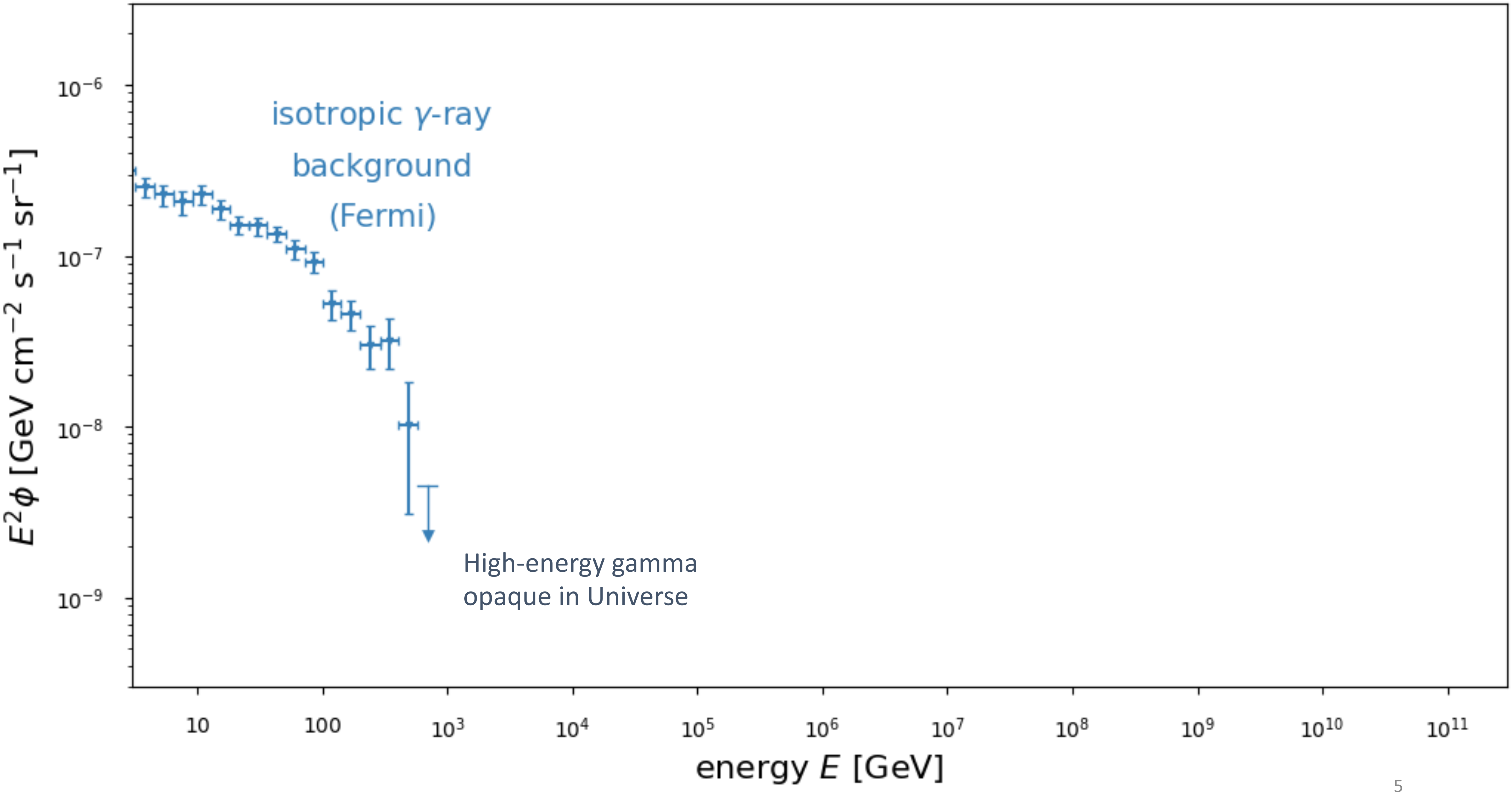
Diffuse gamma-ray photons

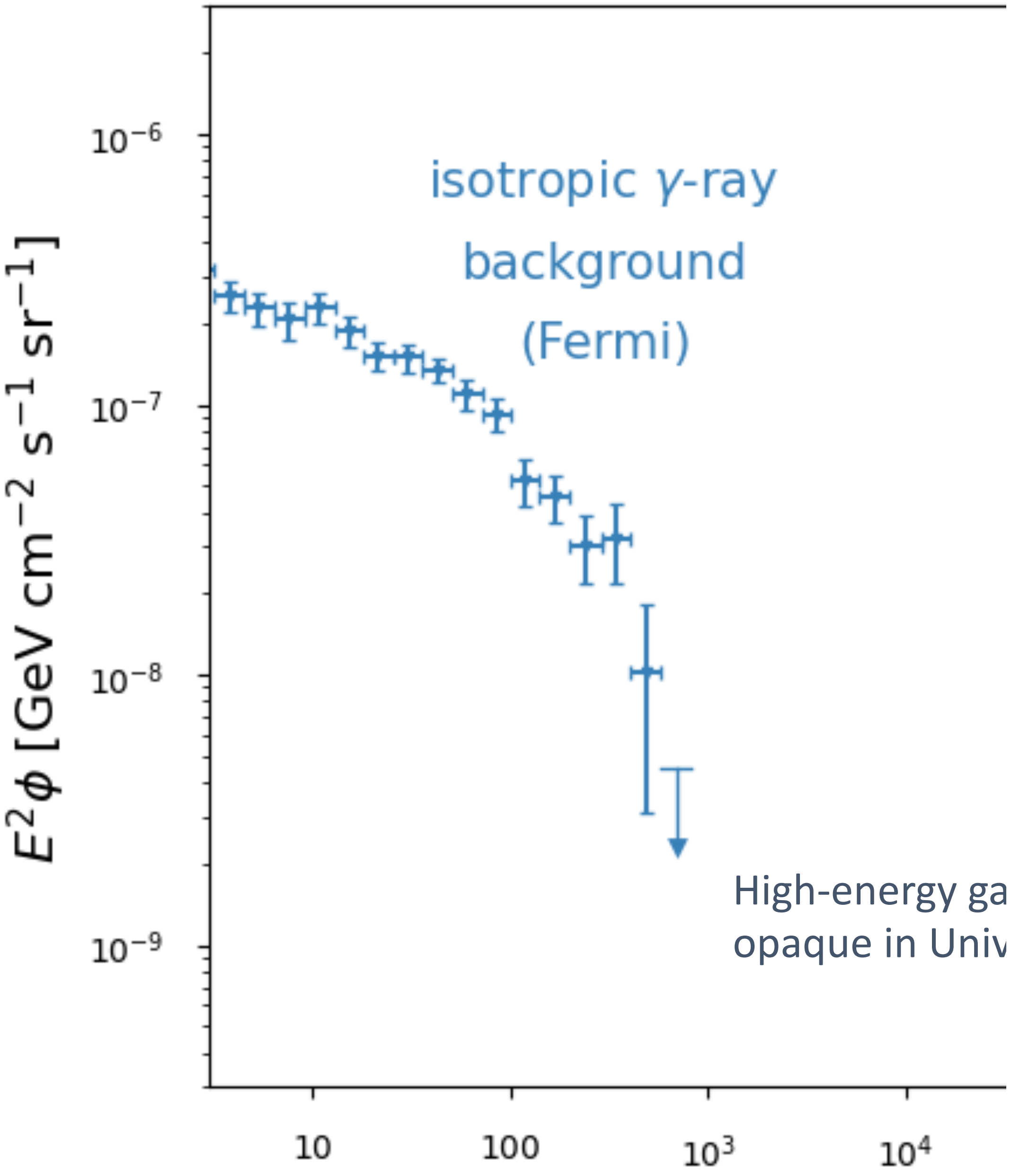


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

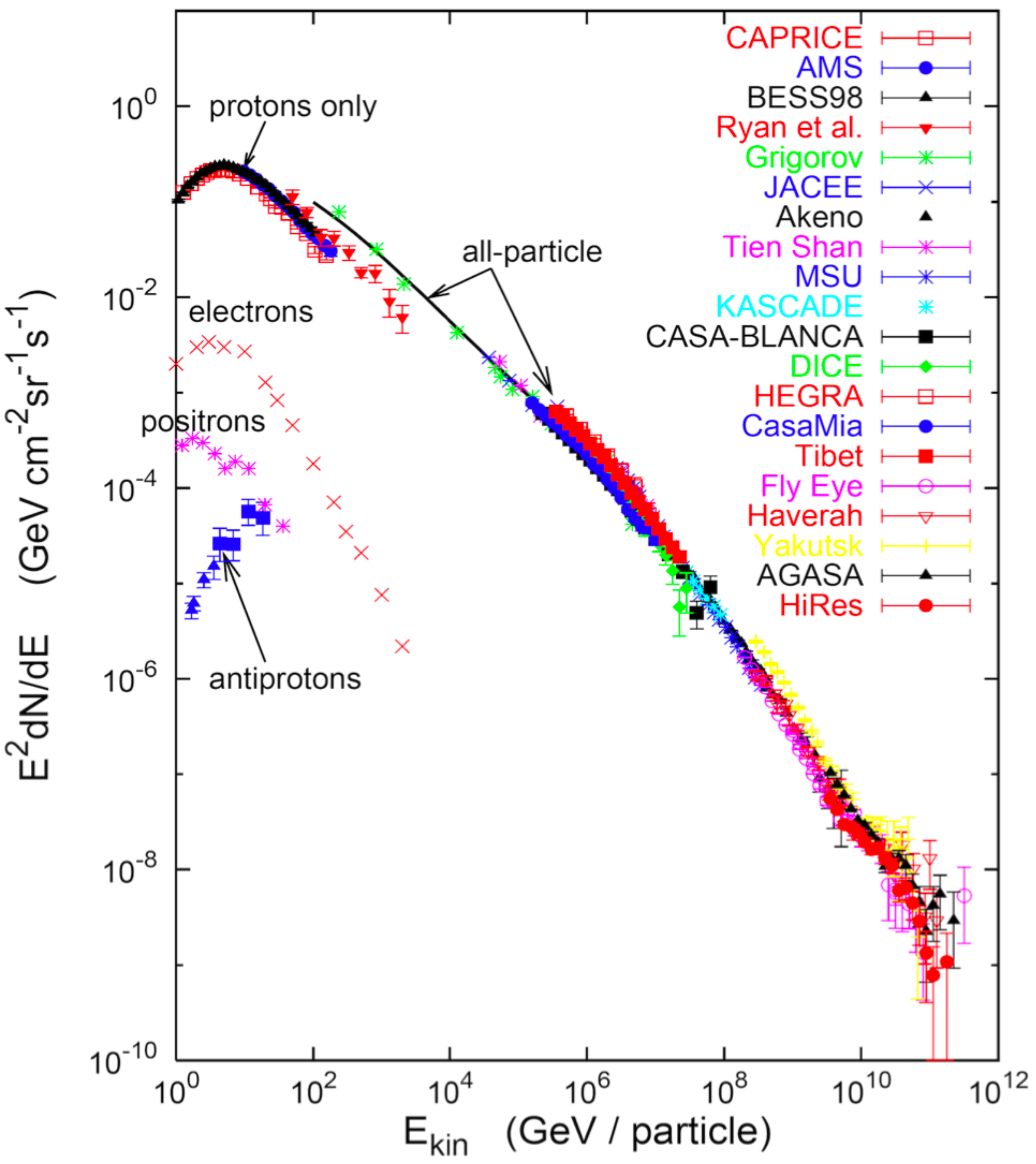


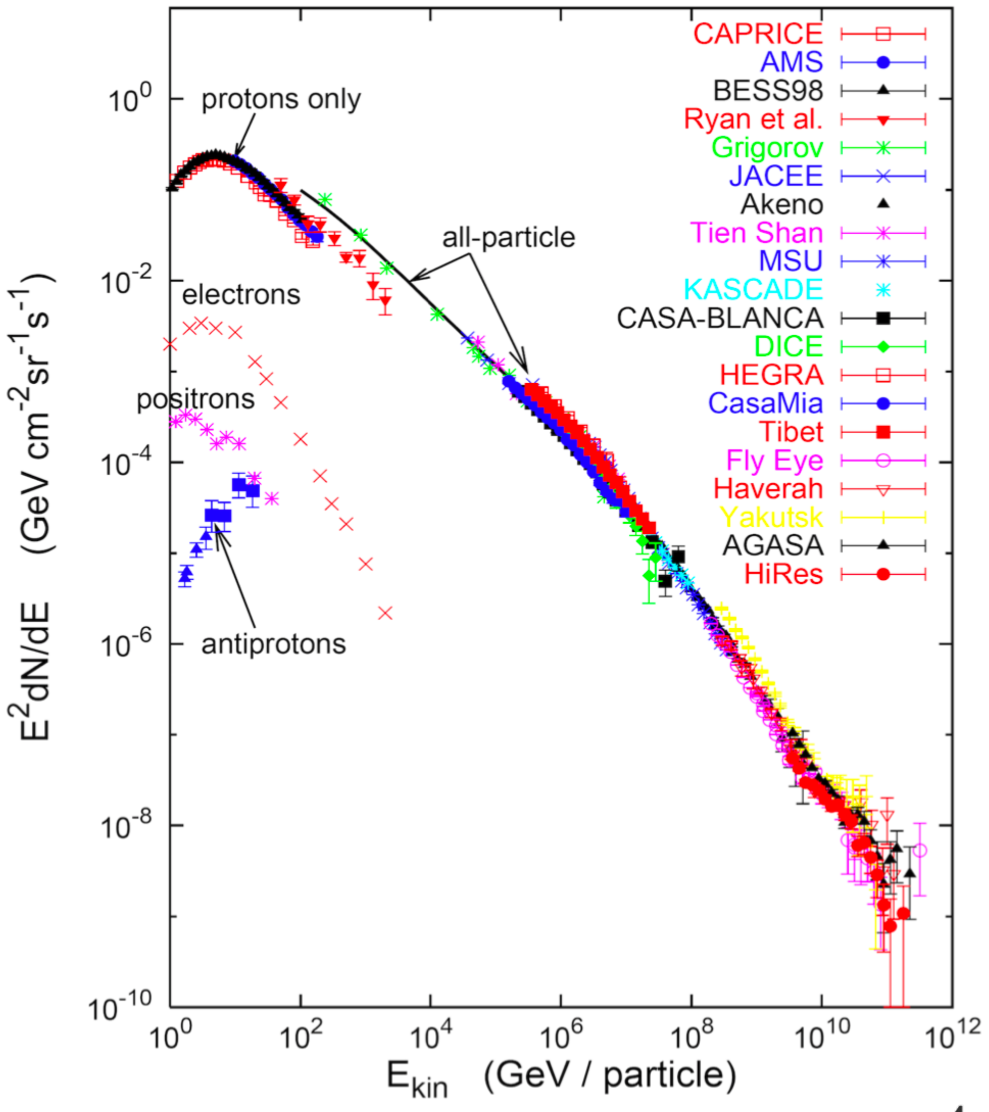
intensity (nW m^{-2} sr^{-1})
10^5
10^3
10
10^{-1}
10^{-3}
10^{-5}
microwaves
optical
X-ray
UV
infrared
γ-ray
radio
10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^2
wavelength (m)


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]



High-energy ga
opaque in Univ





Energy density of Galactic cosmic rays

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

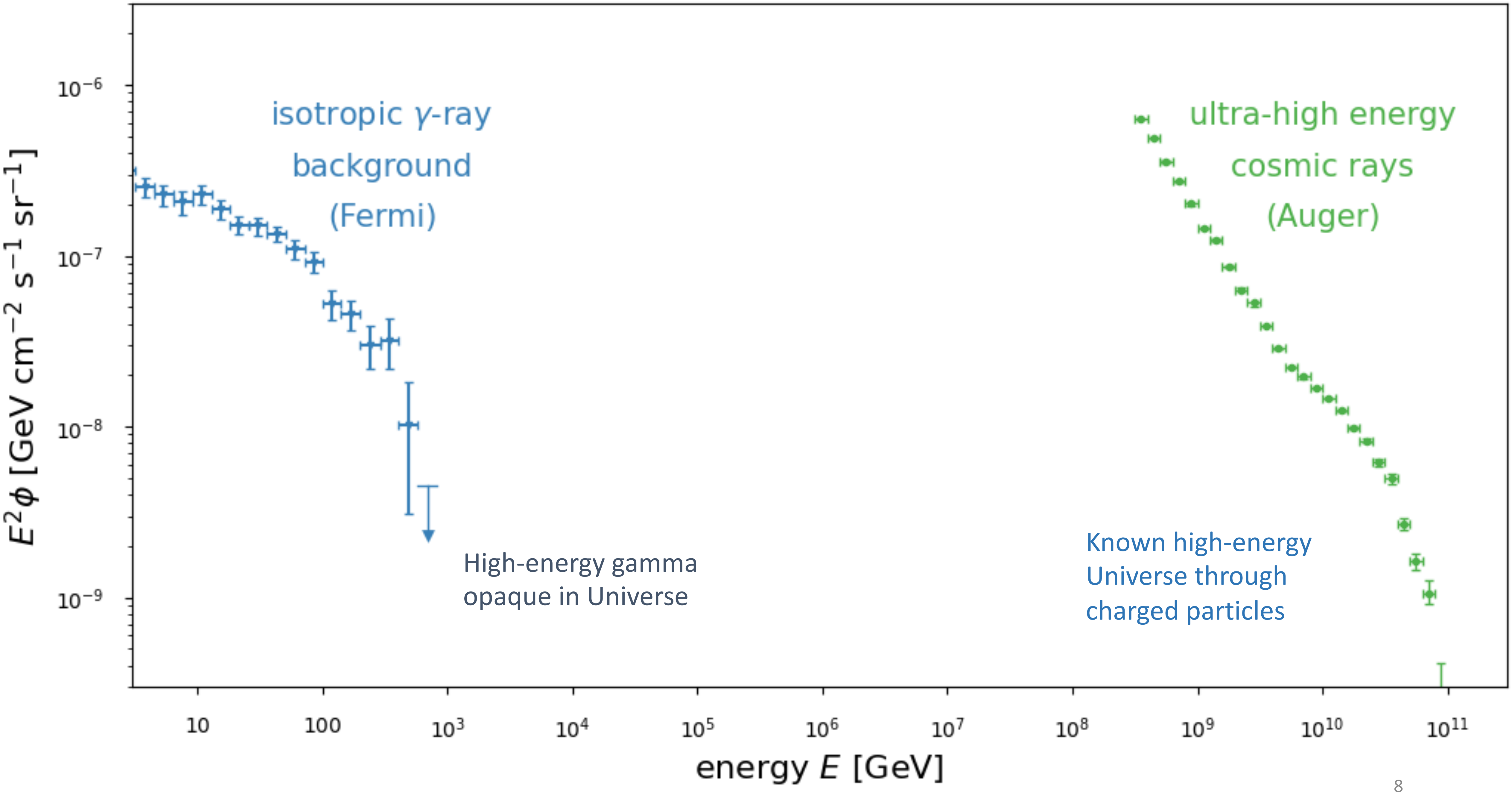
$$\Phi(E) = \int_\Omega \mathrm{d}\Omega I(E) = 4\pi I(E)$$

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

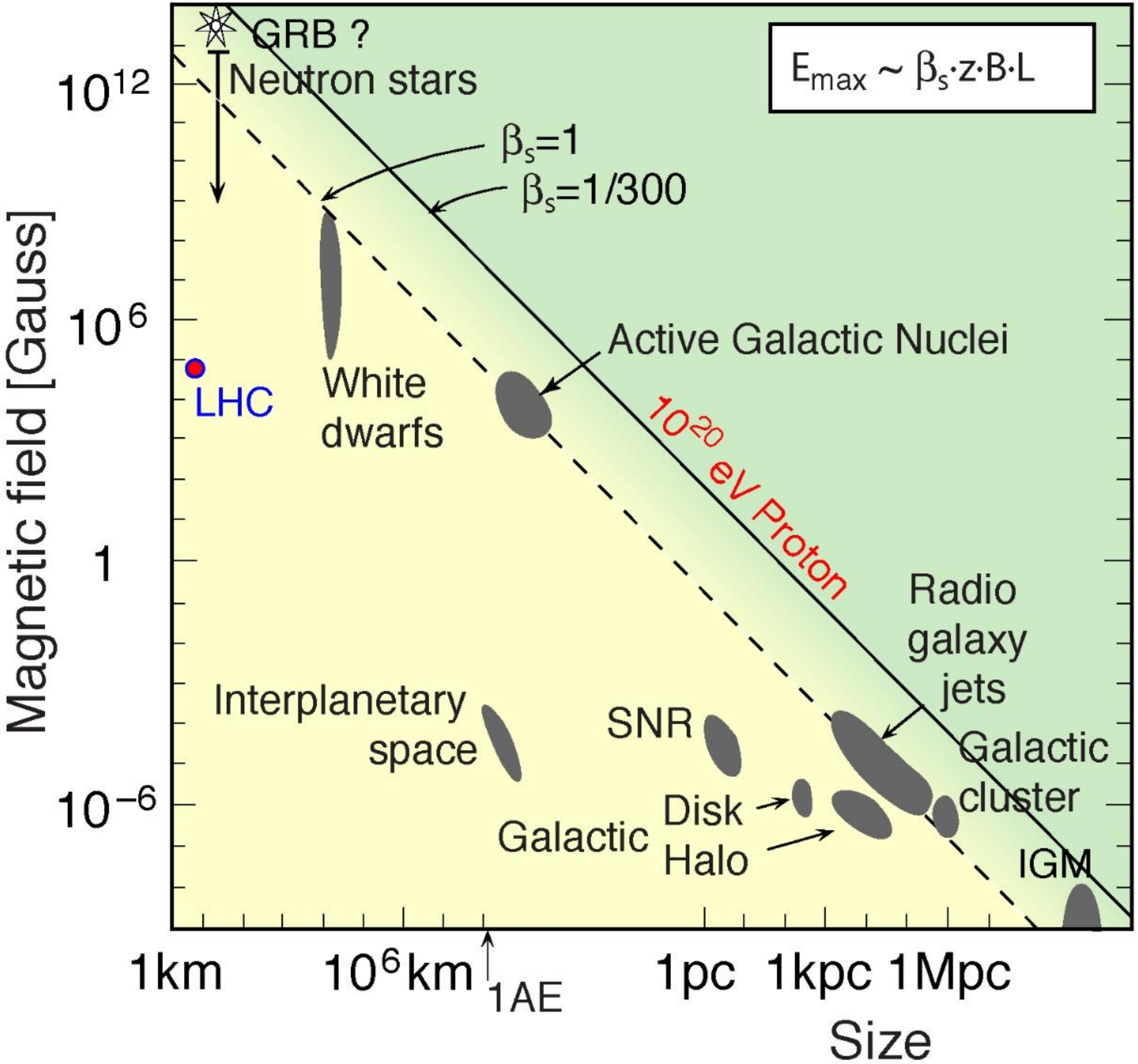
$$\rho_{CR} = \int E n(E) \mathrm{d}E = 4\pi \int \frac{E}{v} I(E) \mathrm{d}E$$

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

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


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]

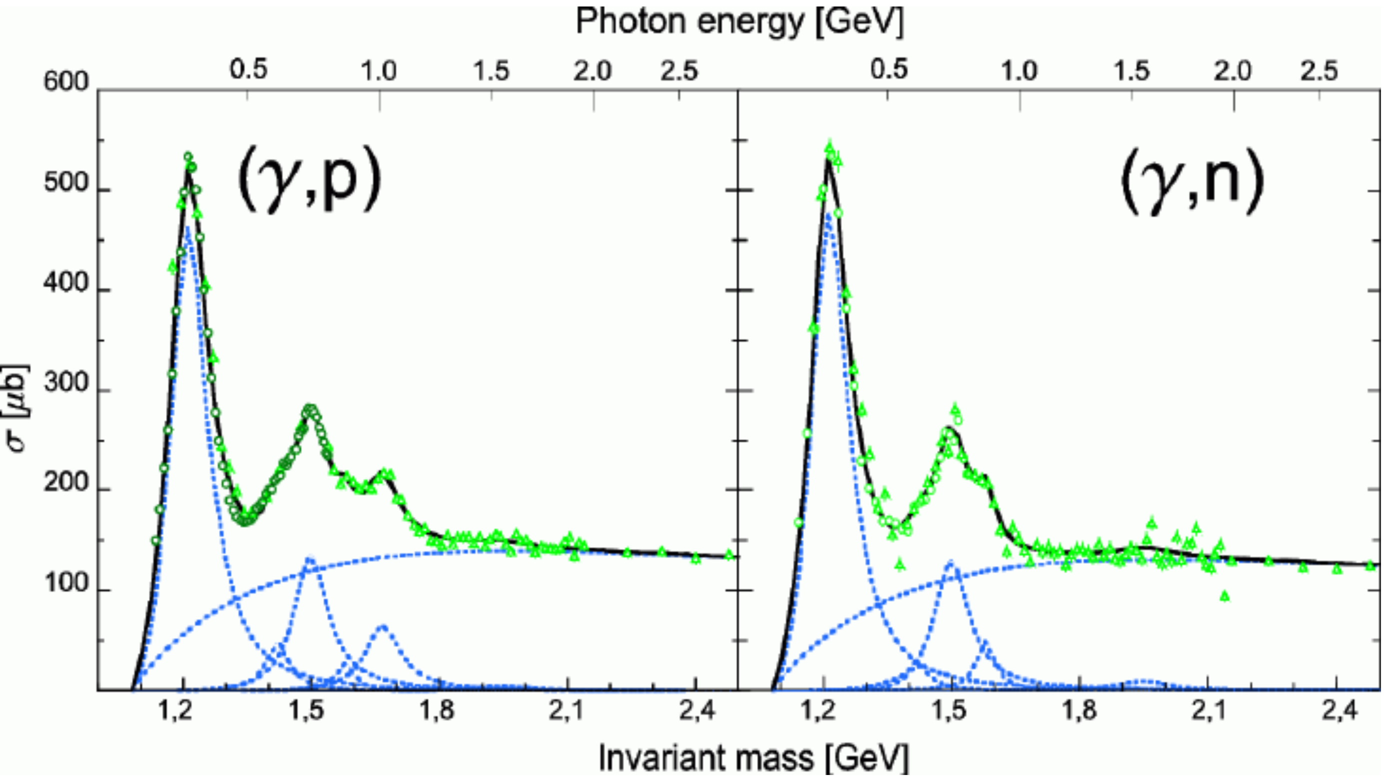
Hillas plot

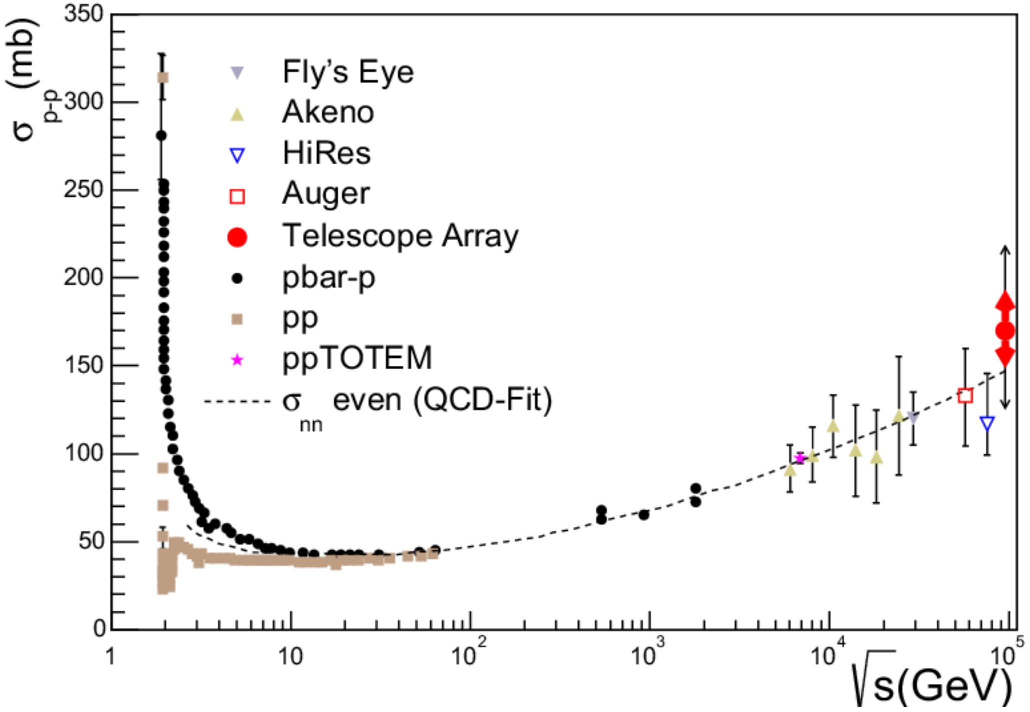


GRB ?
Neutron stars
$E_{max} \sim \beta_s \cdot z \cdot B \cdot L$
$\beta_s=1$
$\beta_s=1/300$
Active Galactic Nuclei
10^{20} eV Proton
White dwarfs
LHC
Radio galaxy jets
Interplanetary space
SNR
Galactic cluster
Disk
Halo
Galactic
IGM
Magnetic field [Gauss]
10^{12}
10^{6}
1
10^{-6}
1km
10^{6}km
1AE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

Neutrino productions at accelerator sites

- P-gamma vs pp

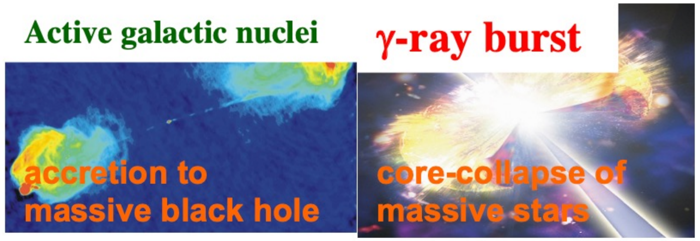




Astrophysical Extragalactic Scenarios

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

Cosmic-ray Accelerators (ex. UHECR candidate sources)

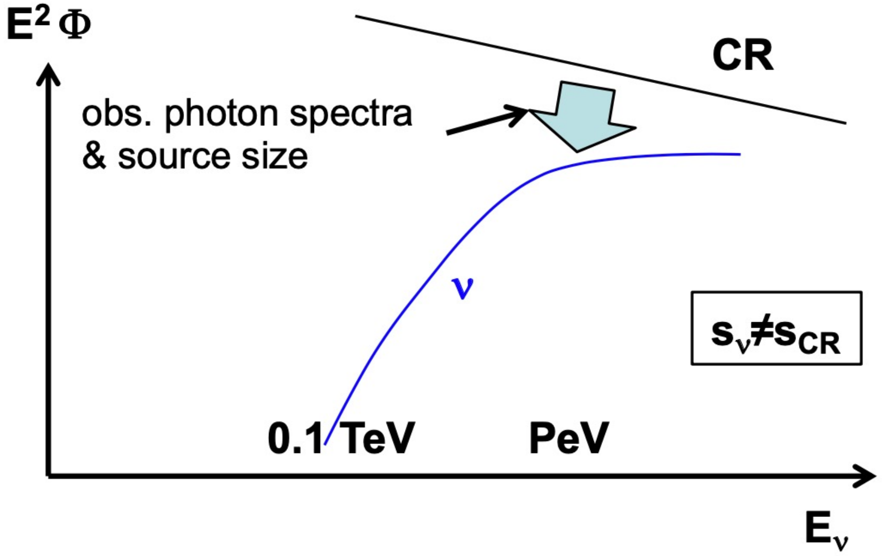


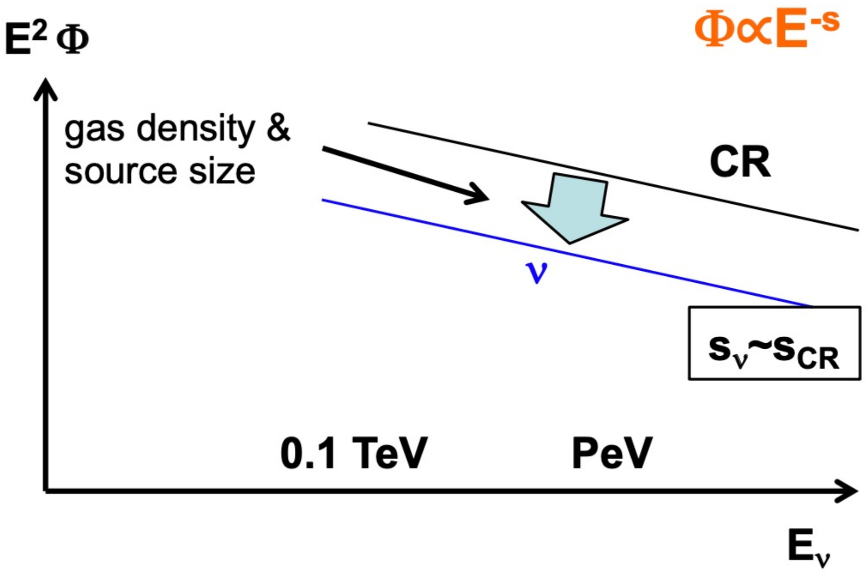
$$p + \gamma \rightarrow N\pi + X$$

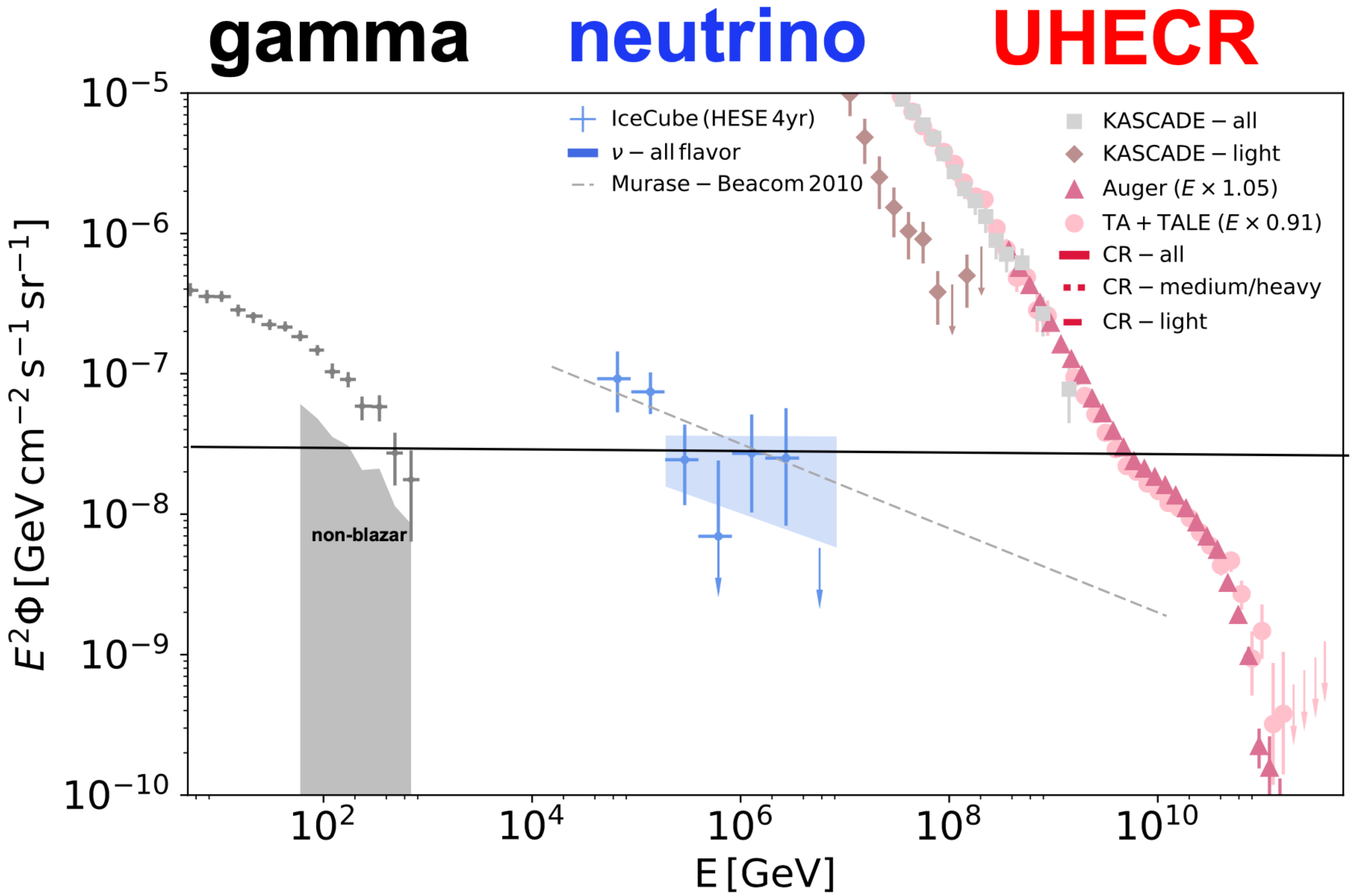
Cosmic-ray Reservoirs

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

Slide from Kohta Murase

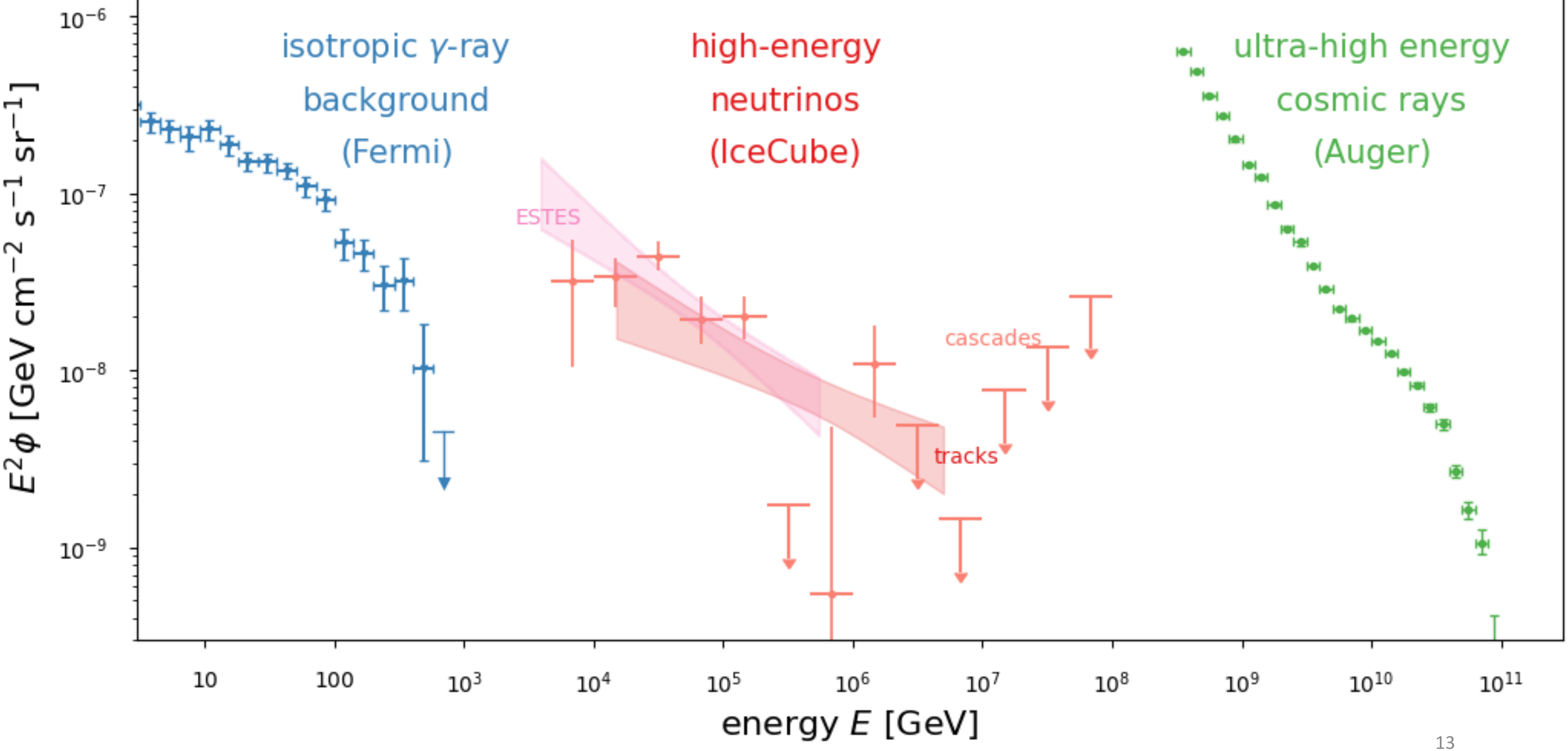




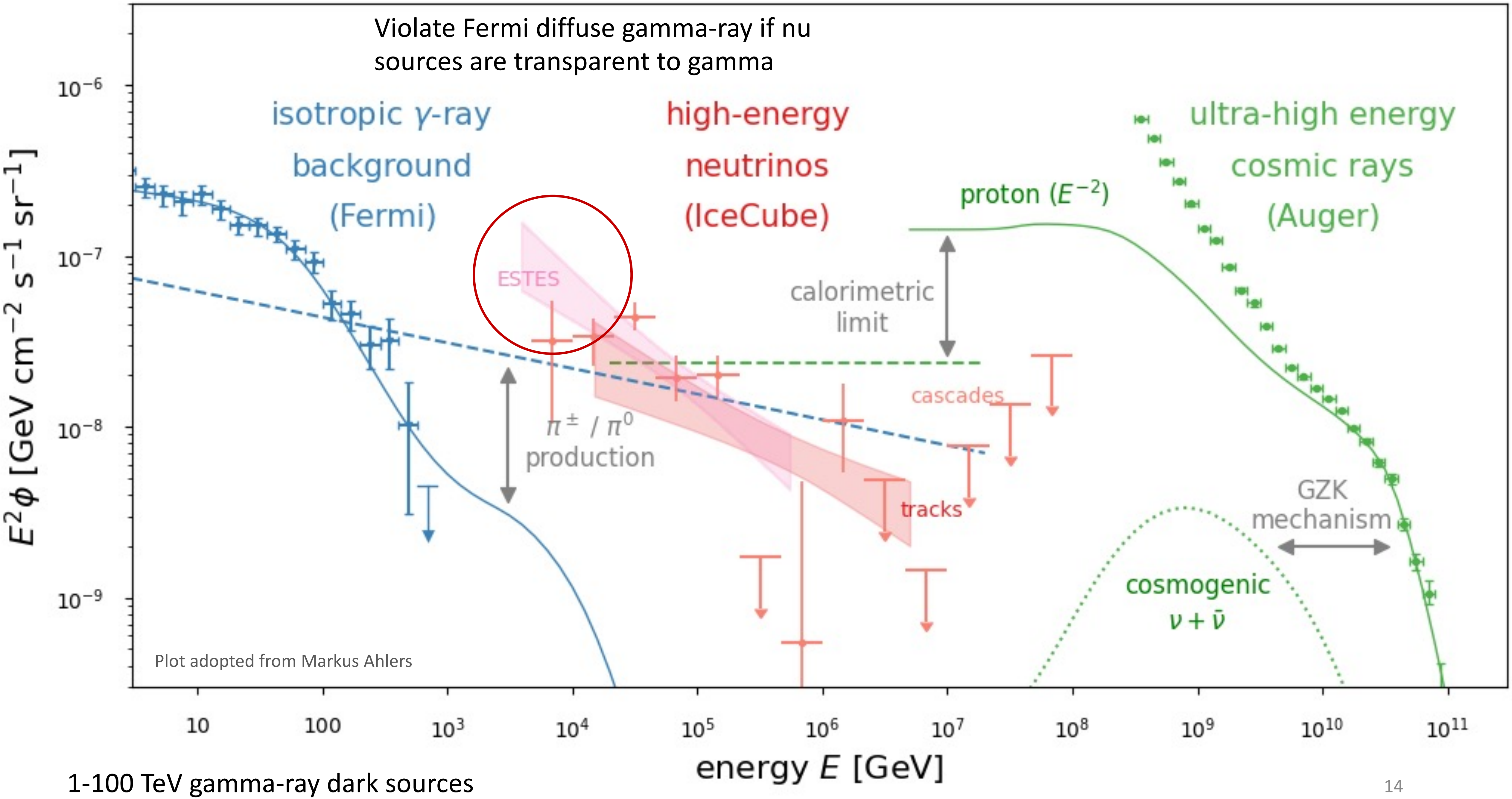


Energy generation rates are all comparable to a few x 10^{43} erg Mpc^{-3} yr^{-1}

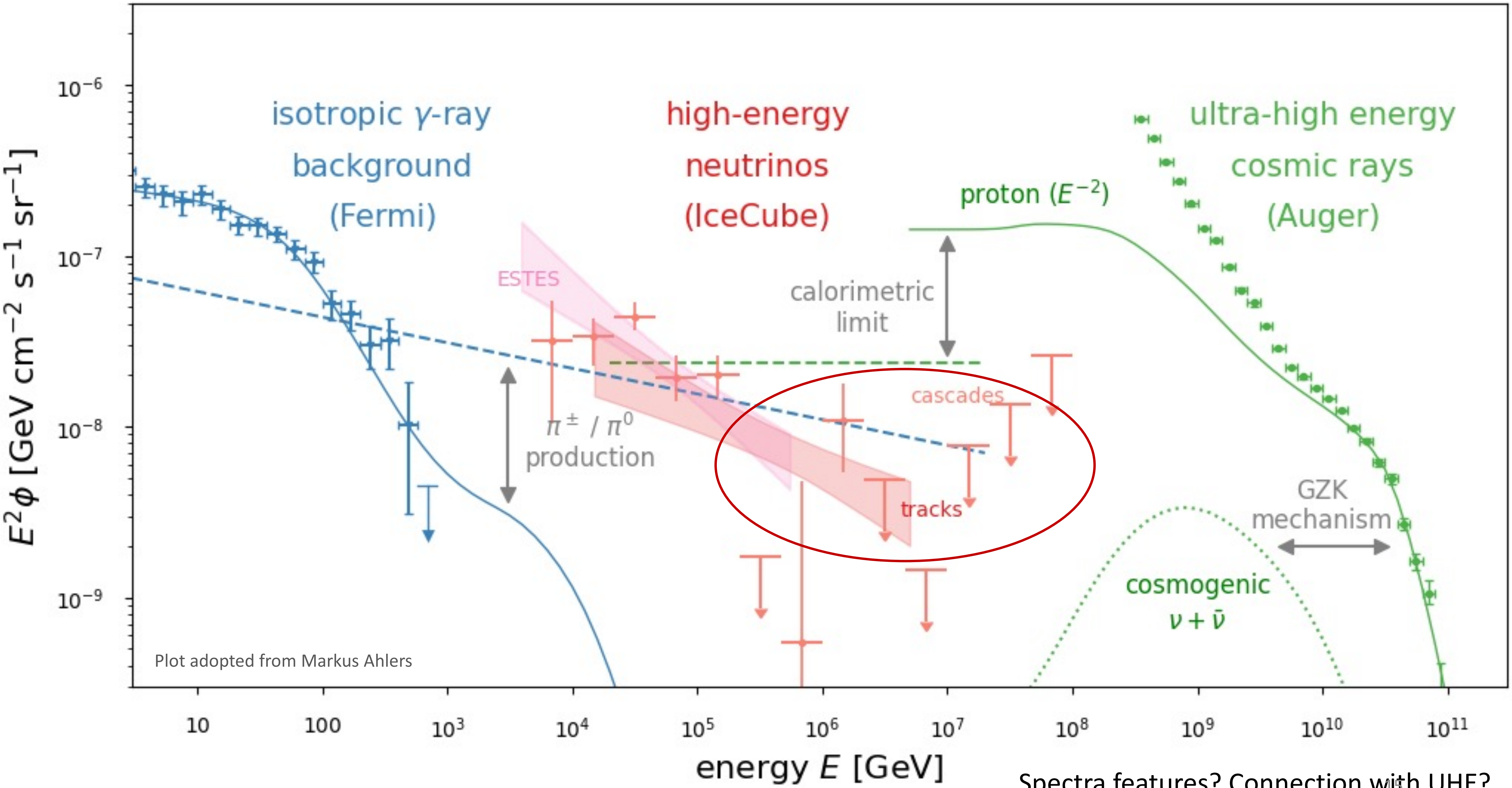
After a decade of IceCube



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



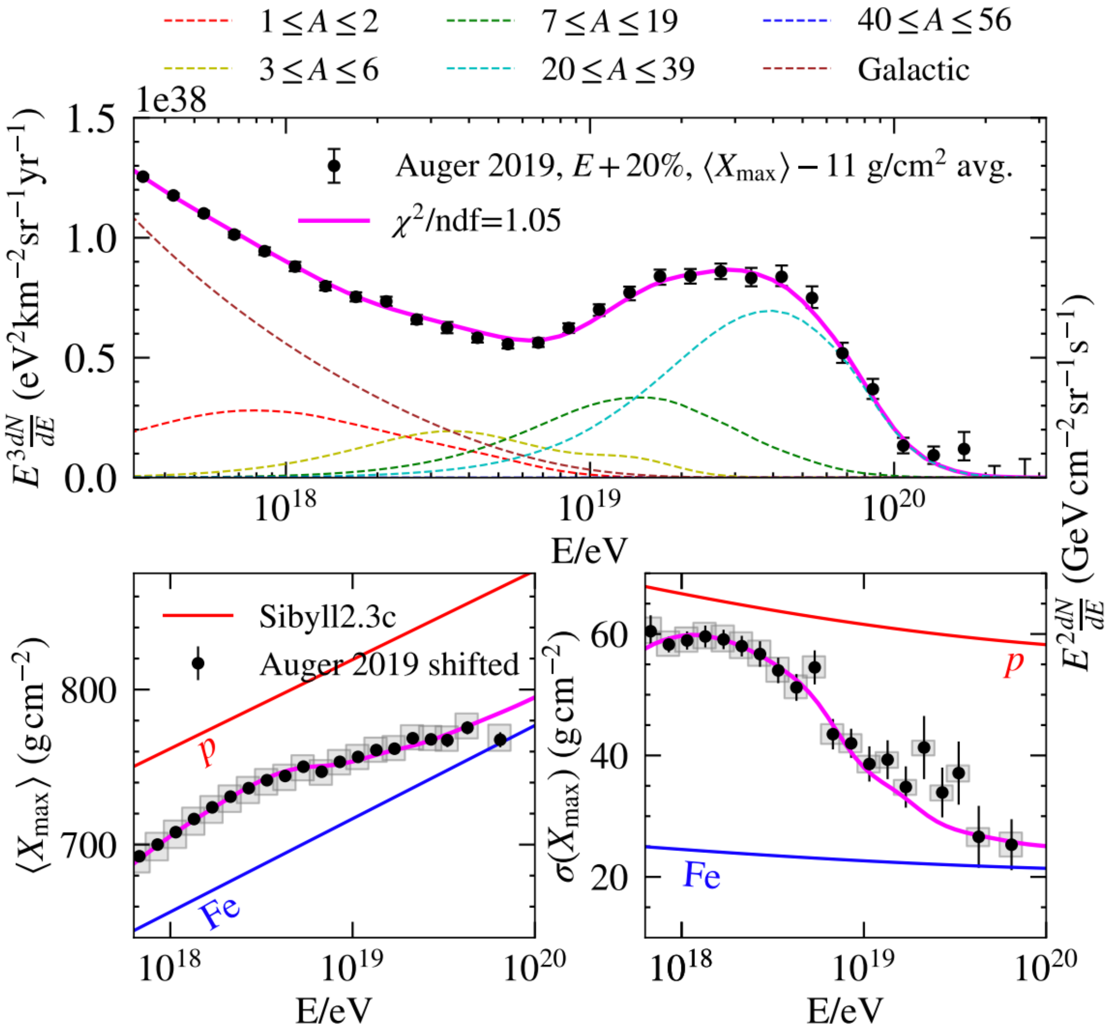
1-100 TeV gamma-ray dark sources

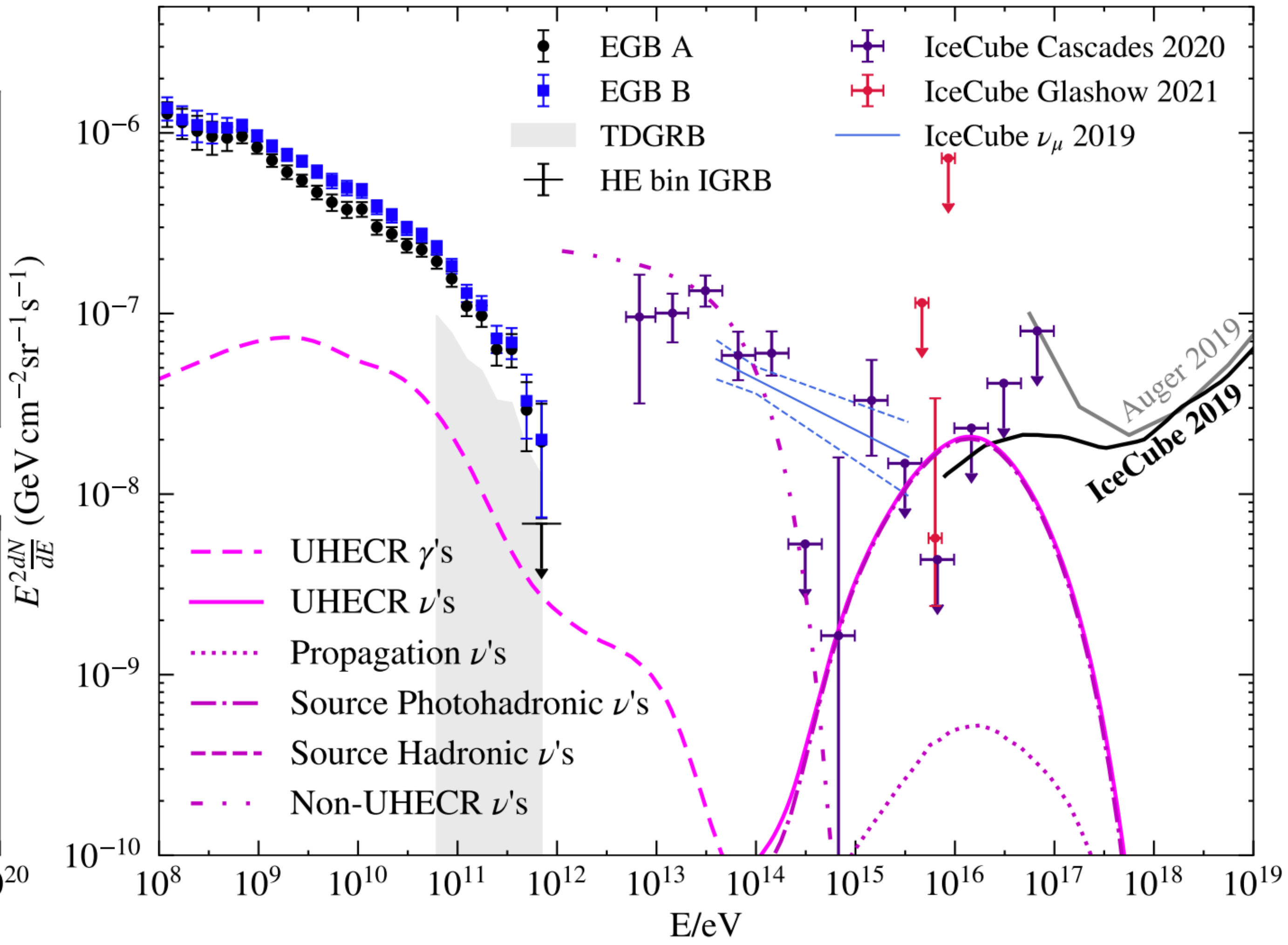


Spectra features? Connection with UHE?

Muzio et al

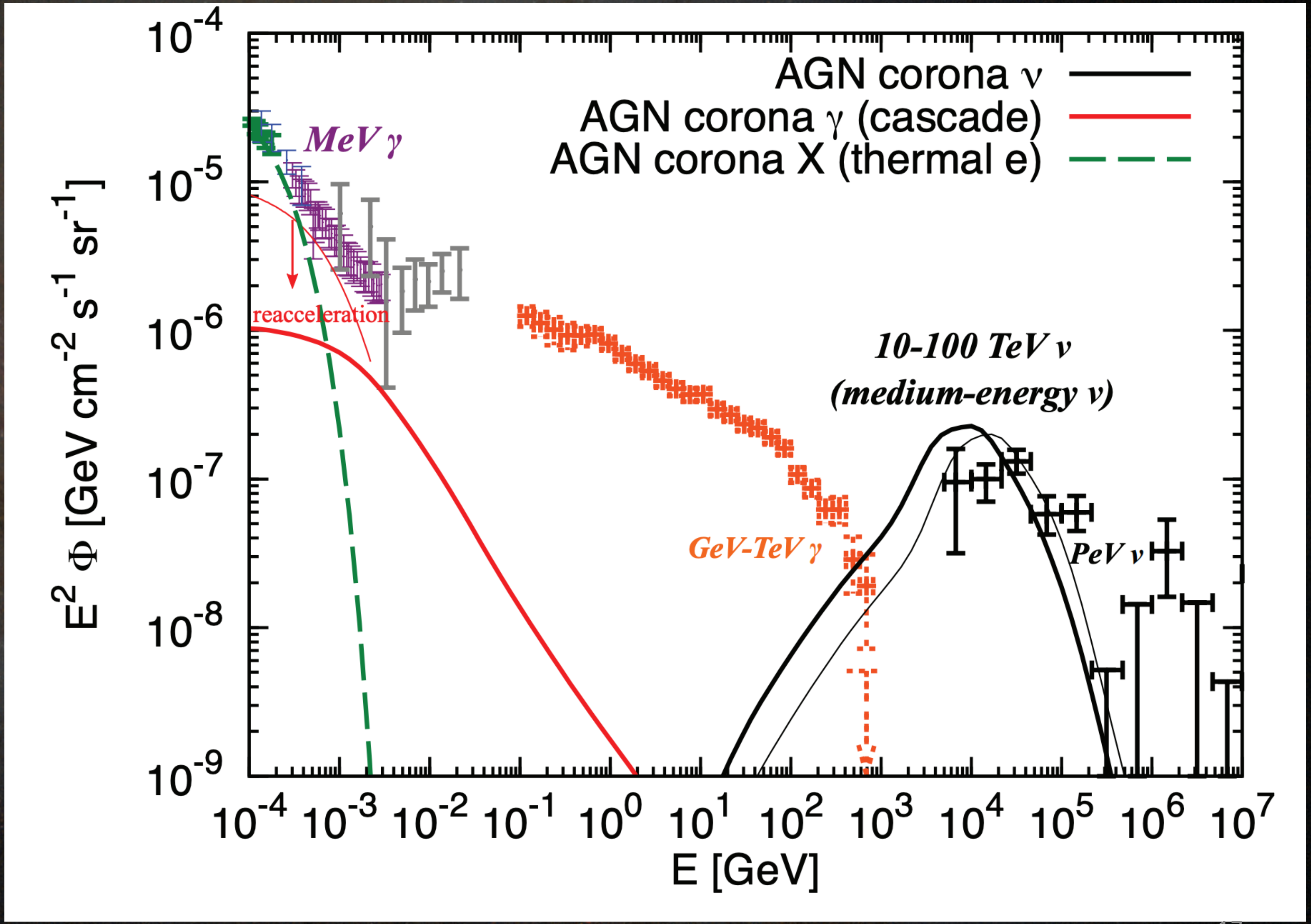
Unification of UHE vs IceCube nu



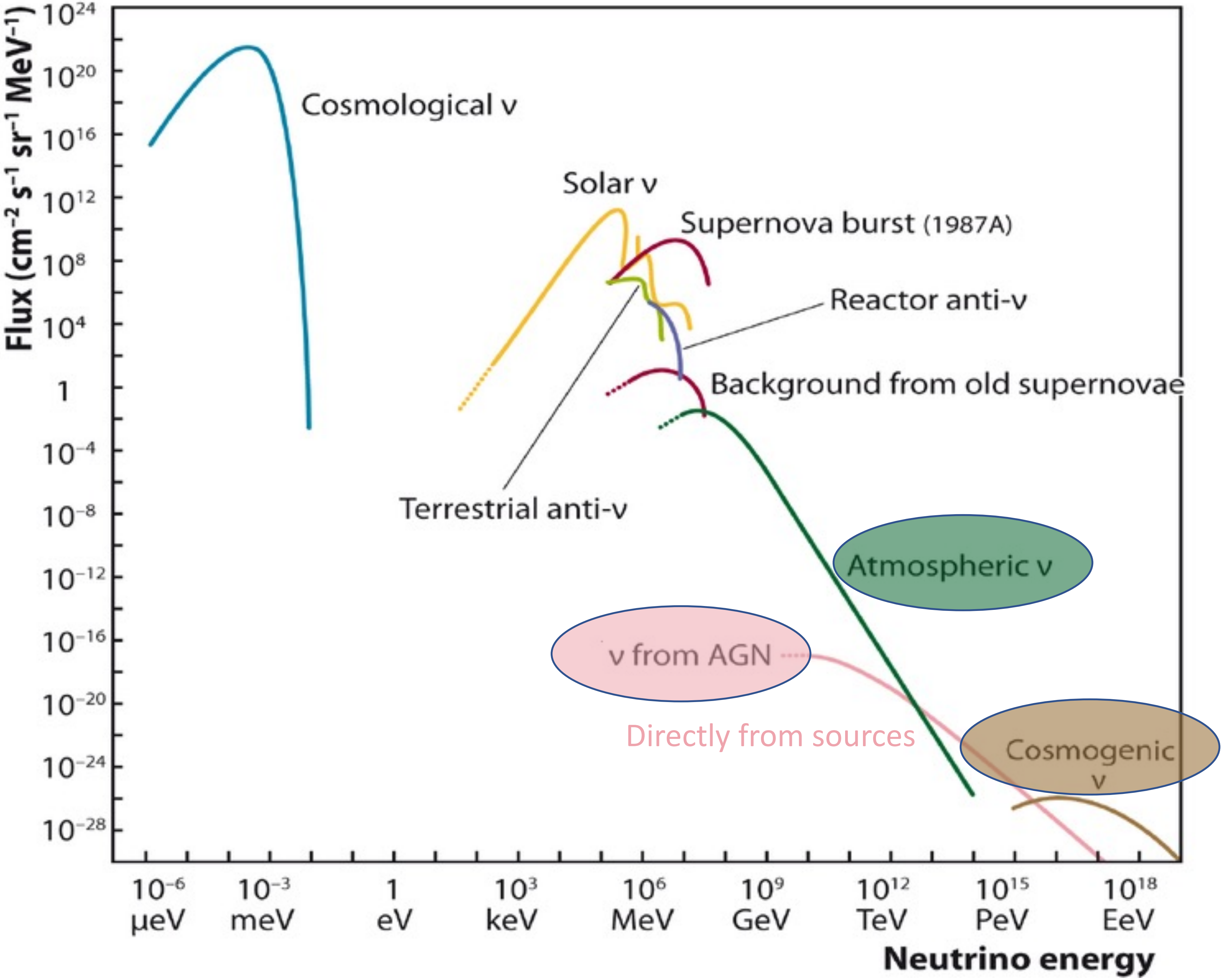


Murase et al

NGC1068



Zoom out - Diffuse flux



Atmospheric nu

From Paolo's talk

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

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

→ $E_\nu \sim 100/\cos\theta$ GeV

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

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

Conv.

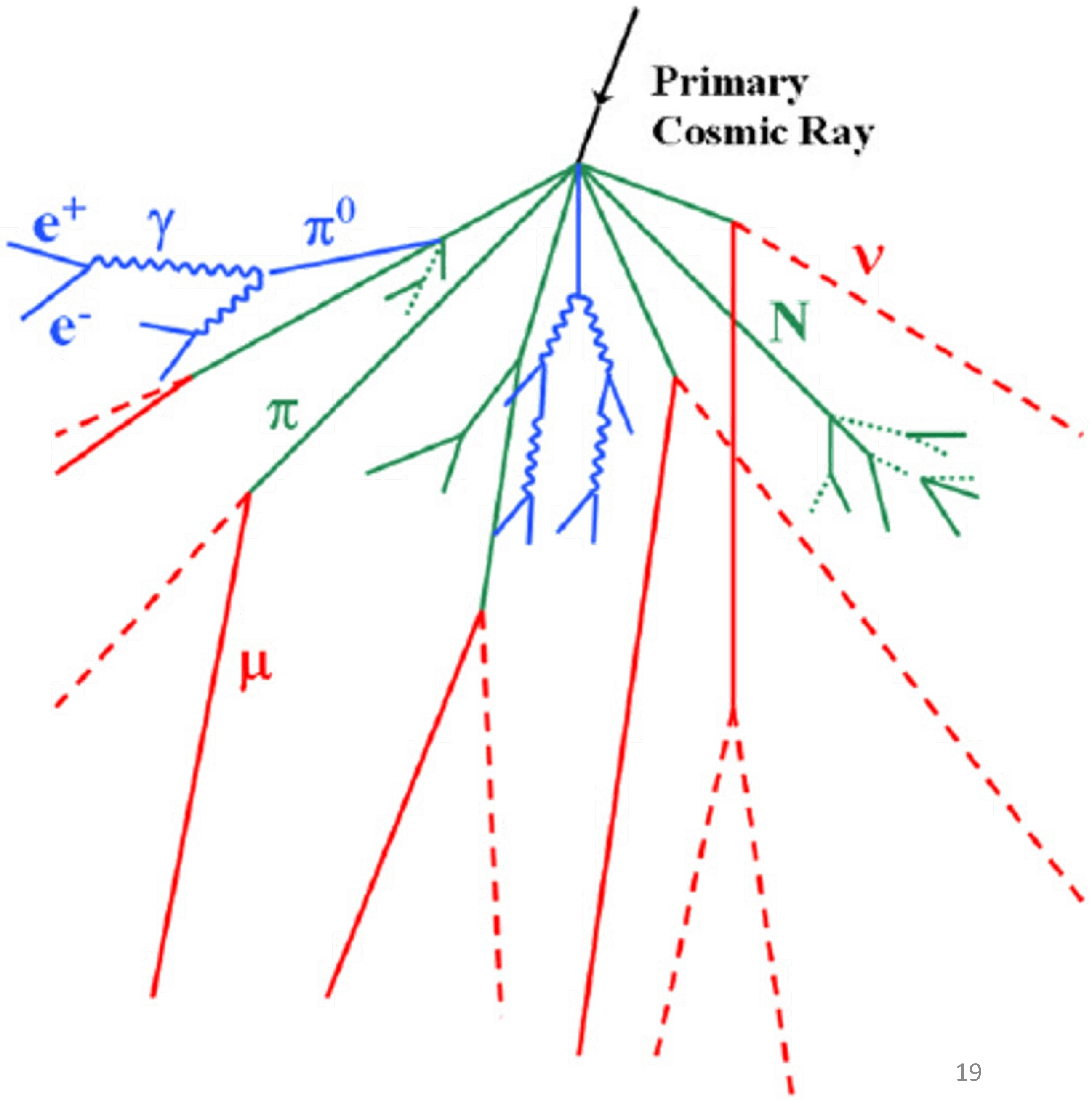
→ $E_\nu \sim 100/\cos\theta$ TeV

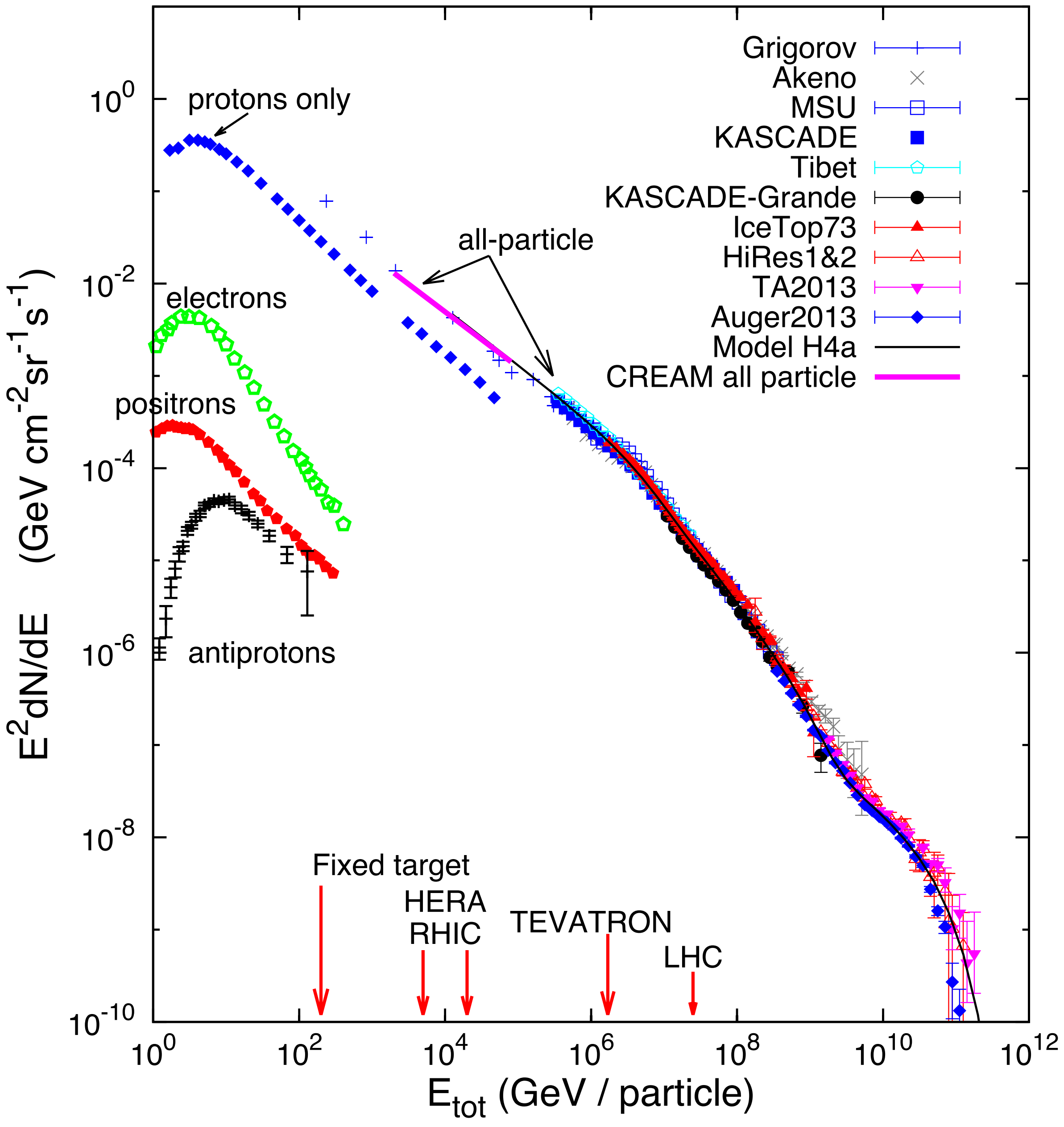
$K^0_S \rightarrow \pi e \nu_e$ (Gaisser & Klein 2014) (0.07%)

prompt

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

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





See Paolo's talk on cosmic rays

Cosmogenic neutrinos

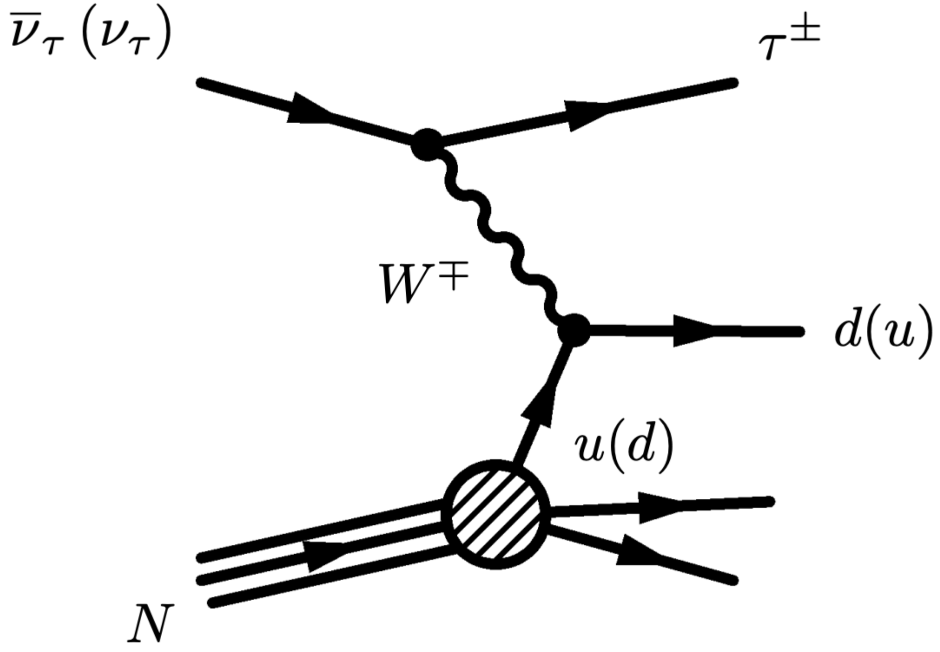
- 1956 discovery of neutrinos
- 1962 discovery of UHECR 10^20 eV
- 1964 discovery of CMB
- 1969 theory cosmogenic neutrinos

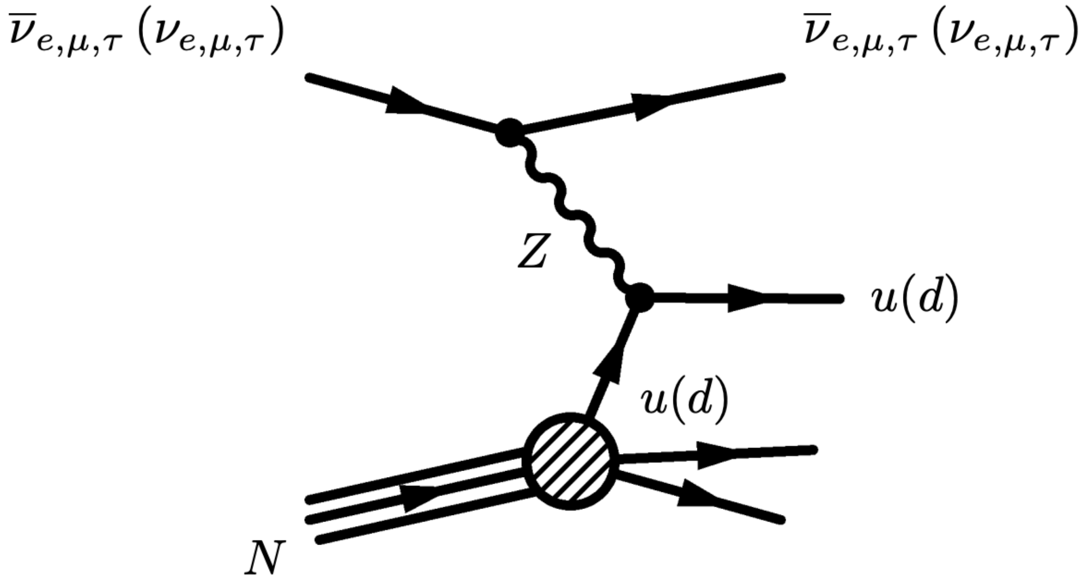
$$p + \gamma_{\rm CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma, \text{ and}$$
$$p + \gamma_{\rm CMB} \rightarrow n + \pi^+ \rightarrow p + \nu_{e,\mu}.$$

What we observe – secondaries of neutrino interactions with matter

Deep inelastic neutrino-nucleon scattering

- Charged current and neutral current interactions





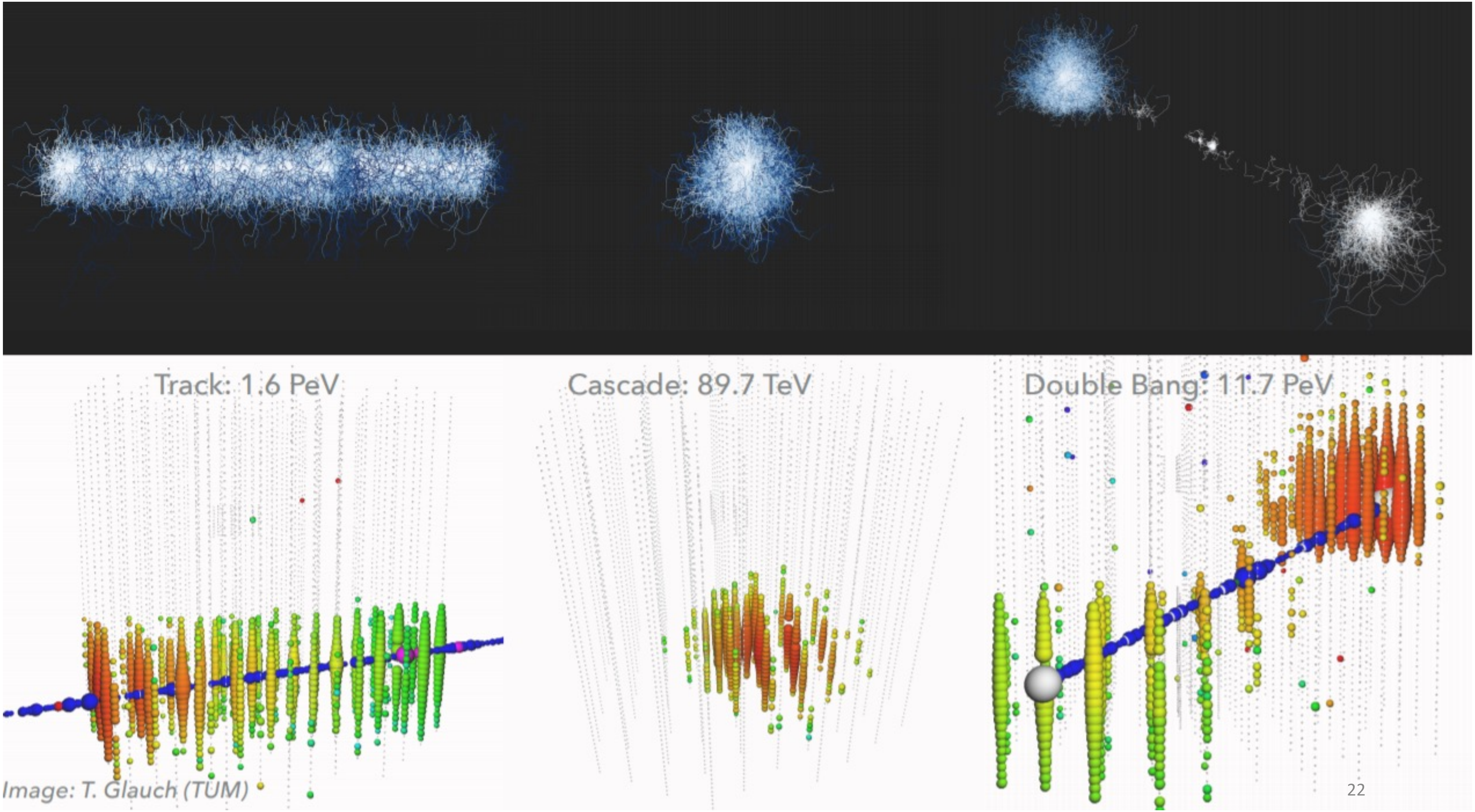
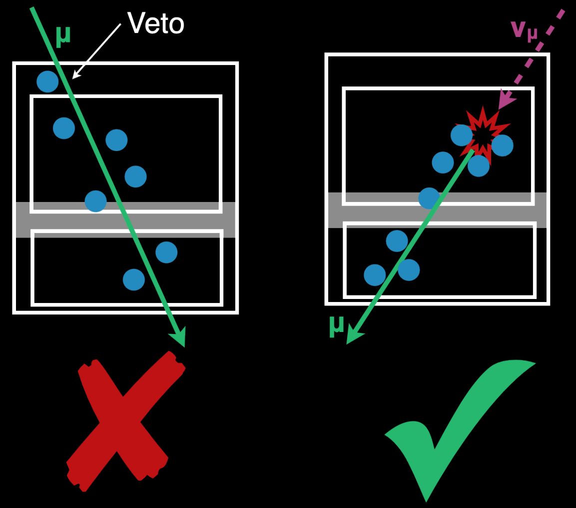


Image: T. Glauch (TUM)

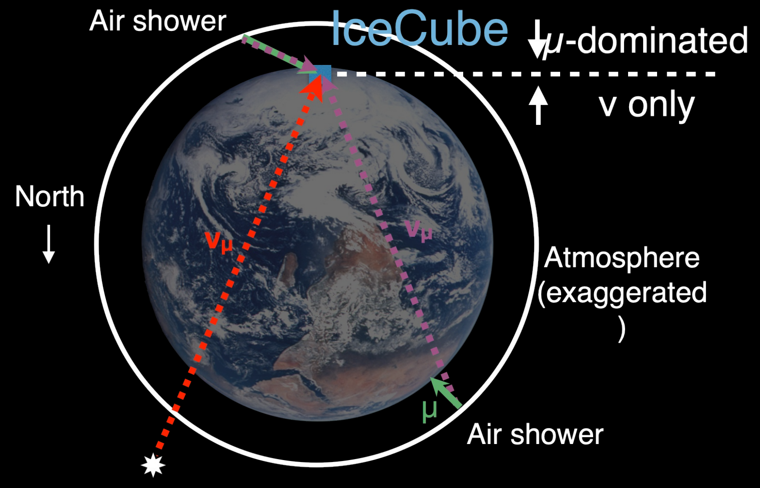
Signal:Background~1:10million

Active veto



Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

Up-going tracks



Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to “half” the sky

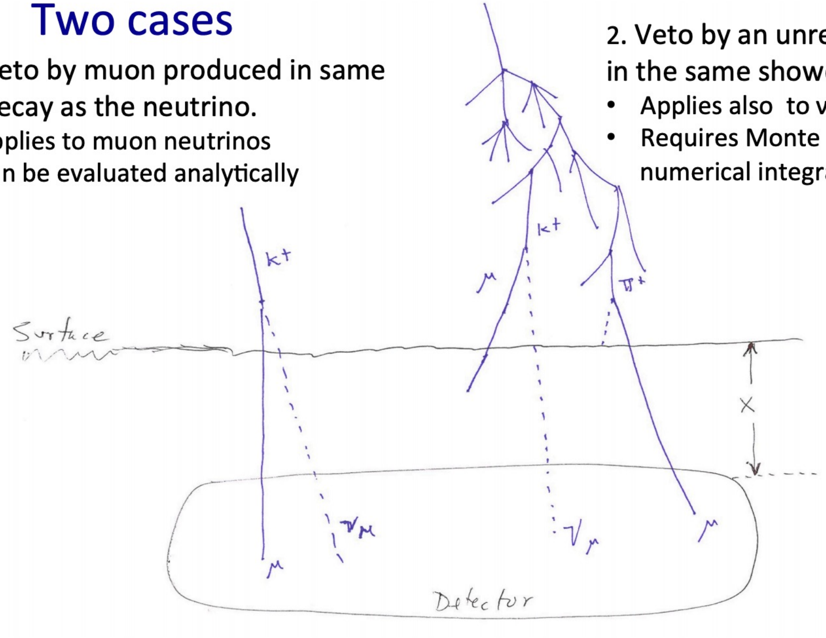
Southern sky advantage: self-veto (slide from Tom Gaisser)

Atmospheric neutrino self veto

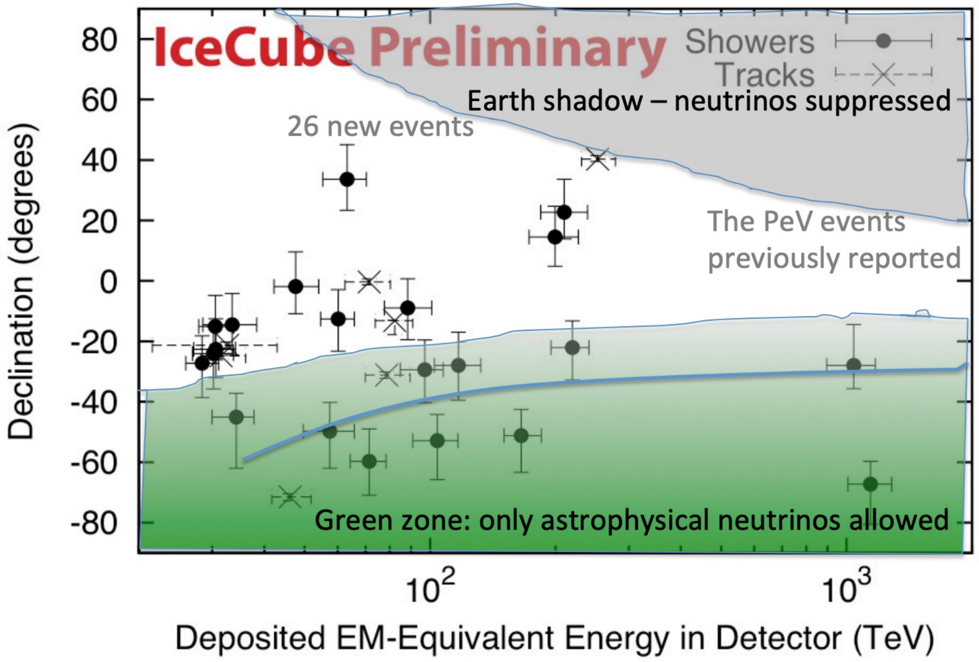
Two cases

1. Veto by muon produced in same decay as the neutrino.
   - Applies to muon neutrinos
   - Can be evaluated analytically

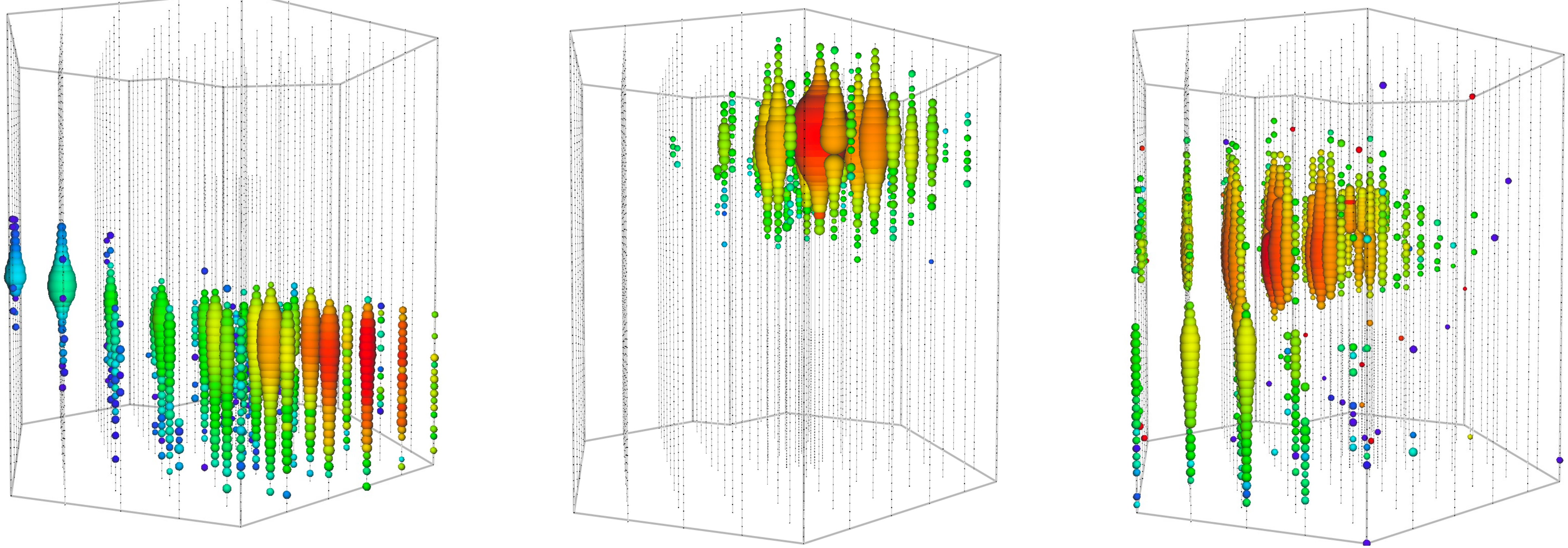
2. Veto by an unrelated μ in the same shower
   - Applies also to ν_e
   - Requires Monte Carlo or numerical integration



Results revisited

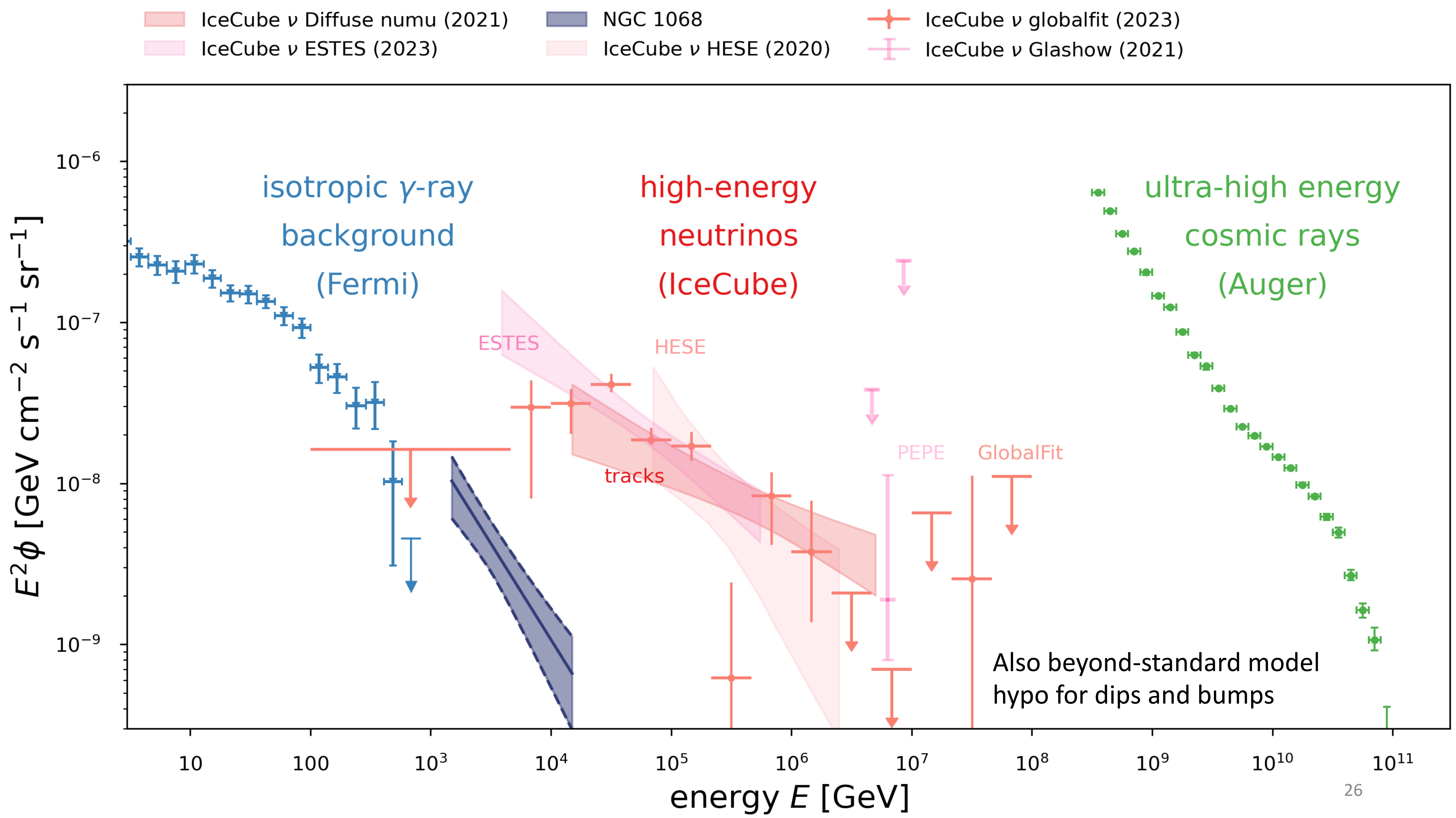


Argument applied to HESE, MESE, ESTES, cascade etc diffuse measurements



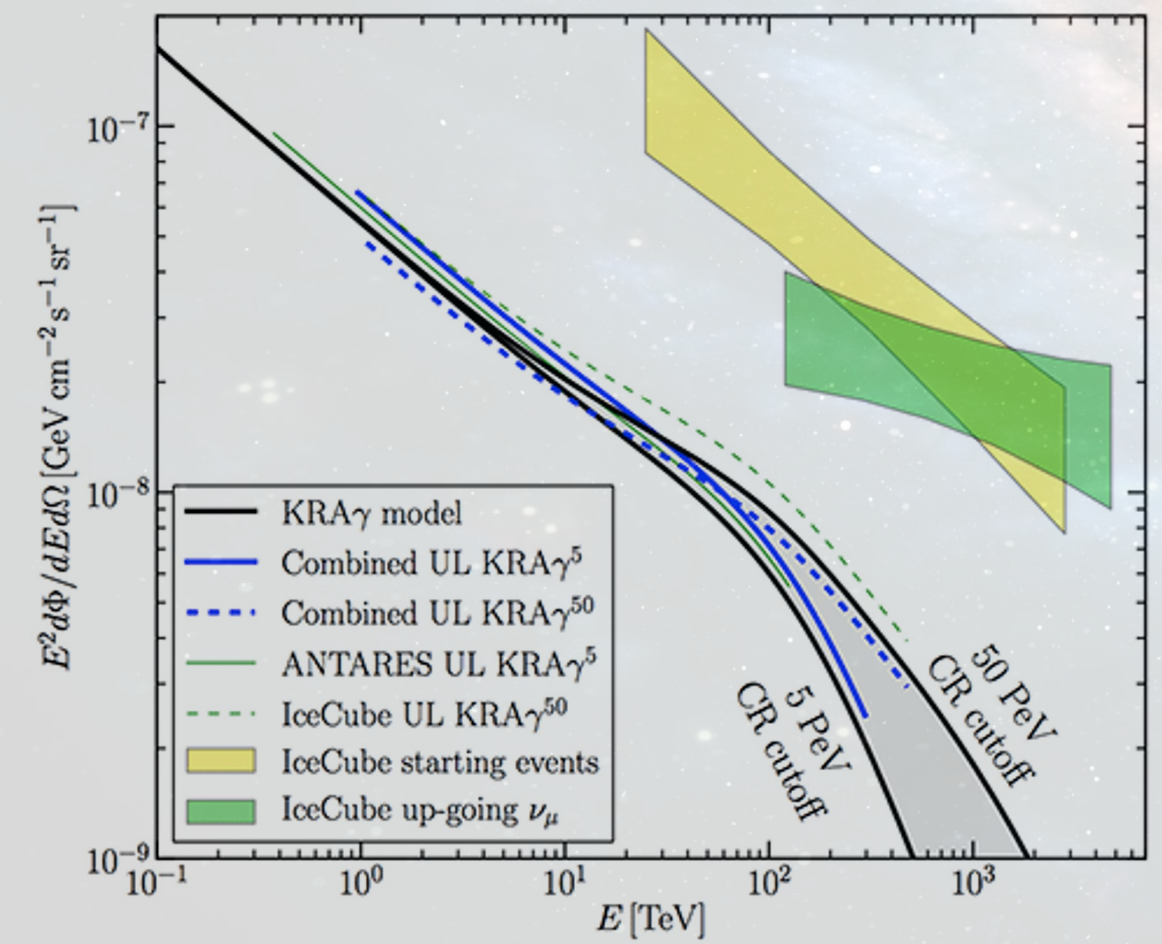
6 events > PeV

-> IceCube Gen2 (see Albrecht’s talk on Friday)

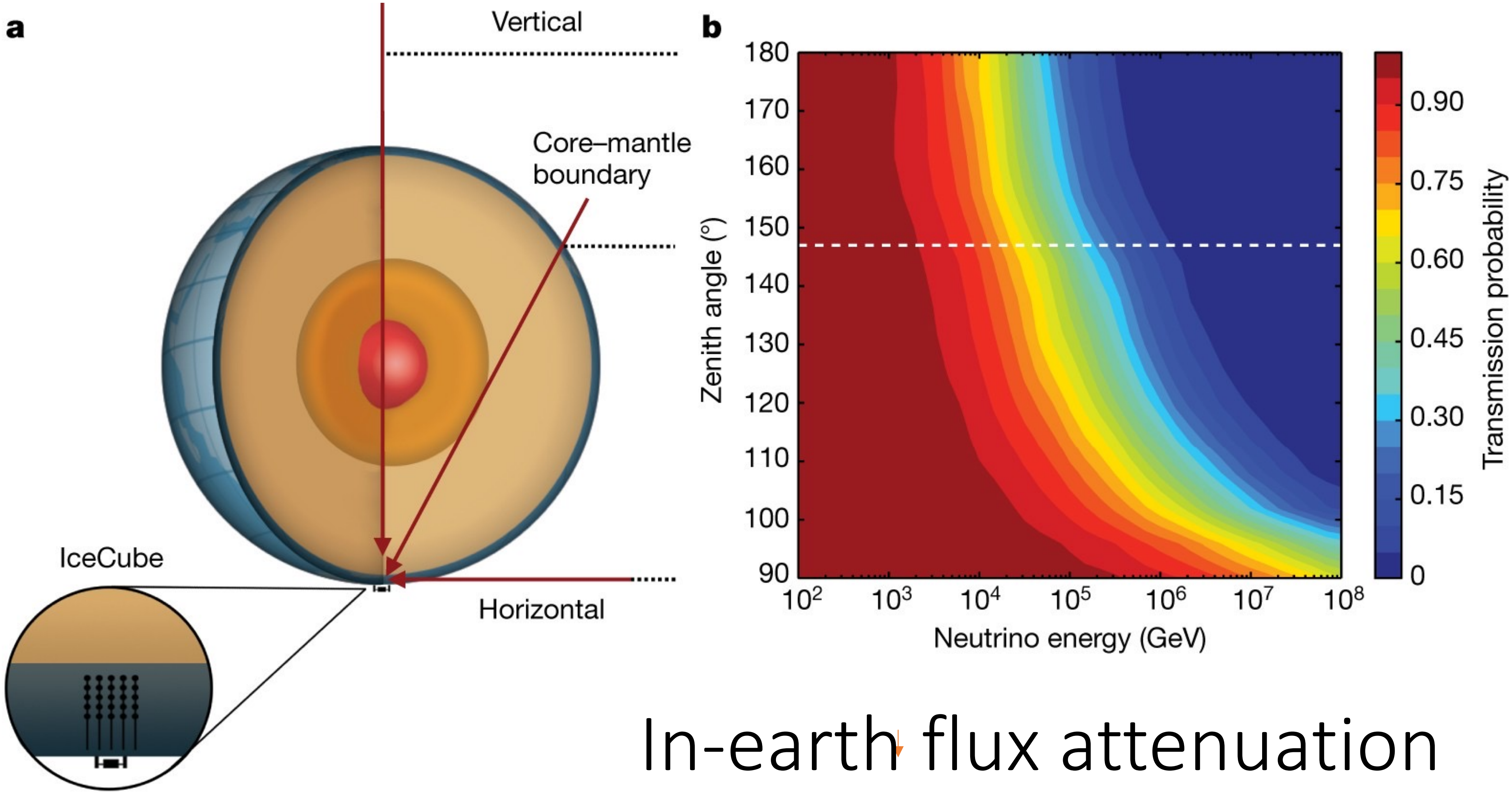


IceCube ν Diffuse numu (2021)
IceCube ν ESTES (2023)
NGC 1068
IceCube ν HESE (2020)
IceCube ν globalfit (2023)
IceCube ν Glashow (2021)
isotropic γ-ray background (Fermi)
high-energy neutrinos (IceCube)
ultra-high energy cosmic rays (Auger)
ESTES
HESE
tracks
PEPE
GlobalFit
Also beyond-standard model hypo for dips and bumps
$E^2\phi$ [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}

Galactic plane



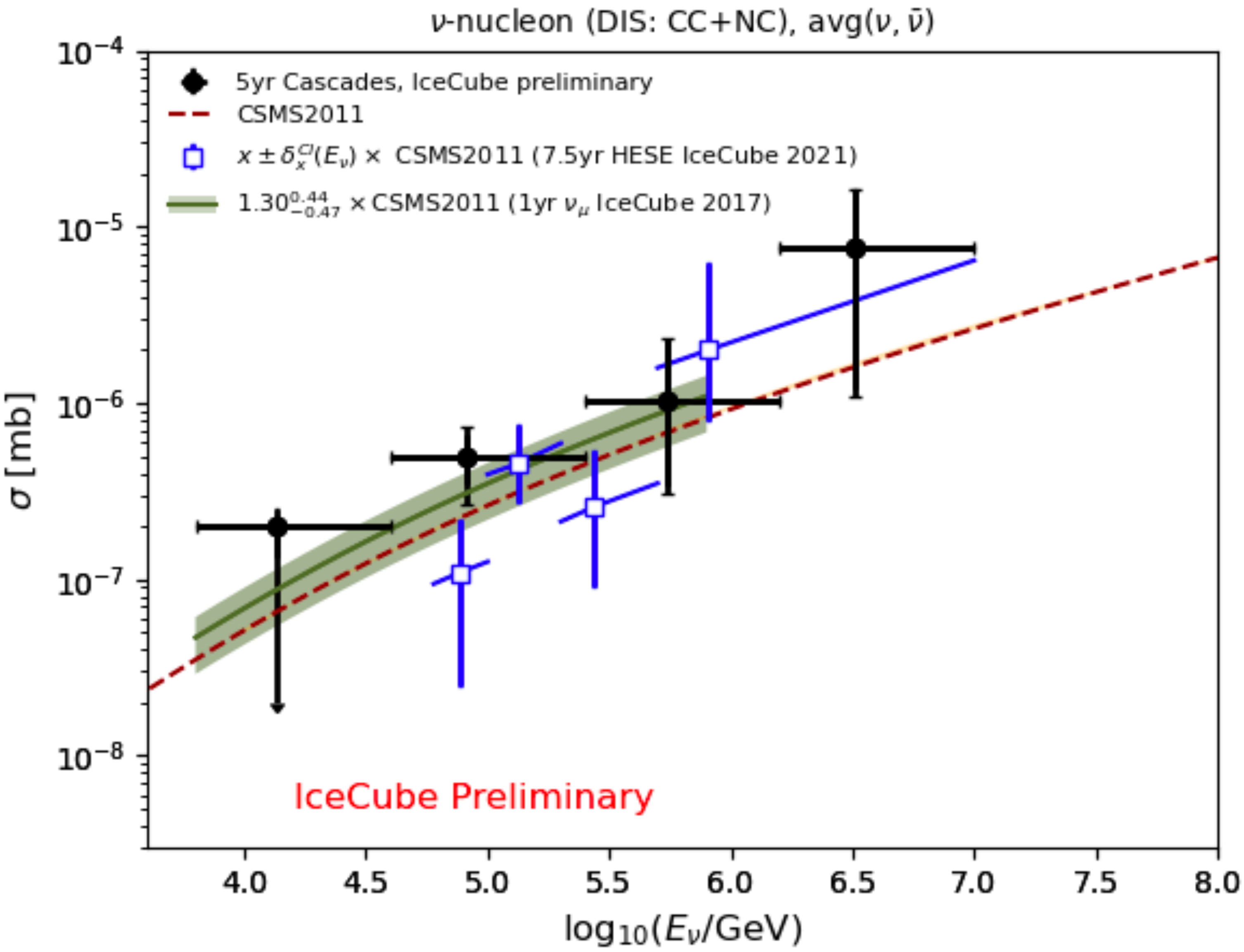
Cross section measurement using Earth as the target



In-earth flux attenuation

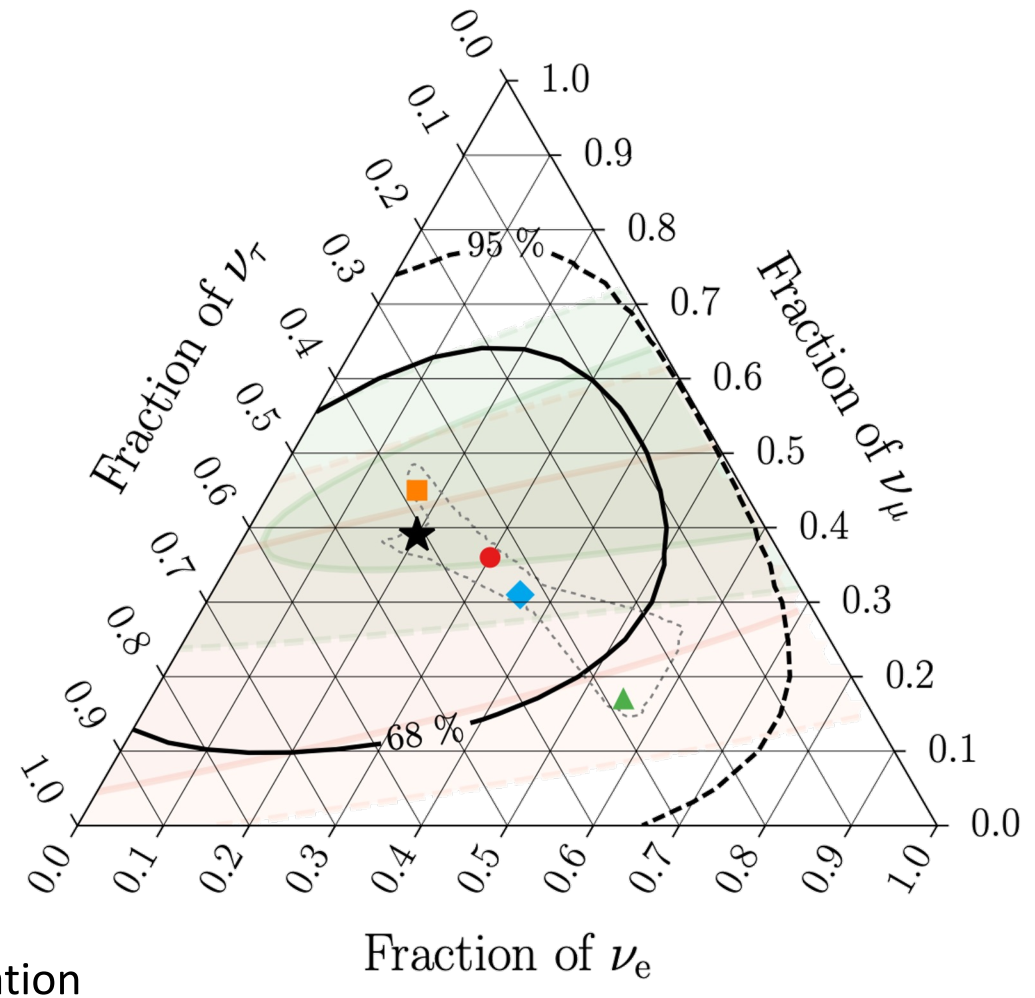
Cross section

- Both tracks and cascades
- Reaching energies beyond accelerators

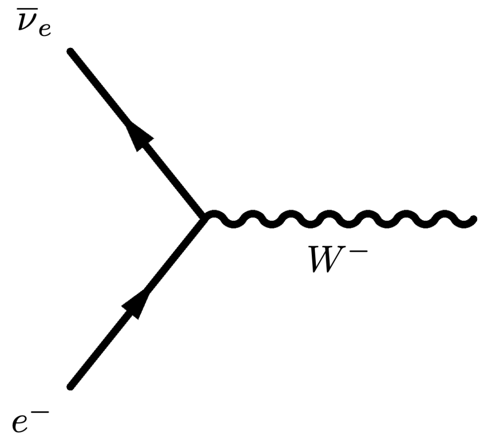


Neutrino oscillations over cosmic baselines

- 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



https://arxiv.org/abs/2011.03561, publication in preparation



Neutrino-electron scattering

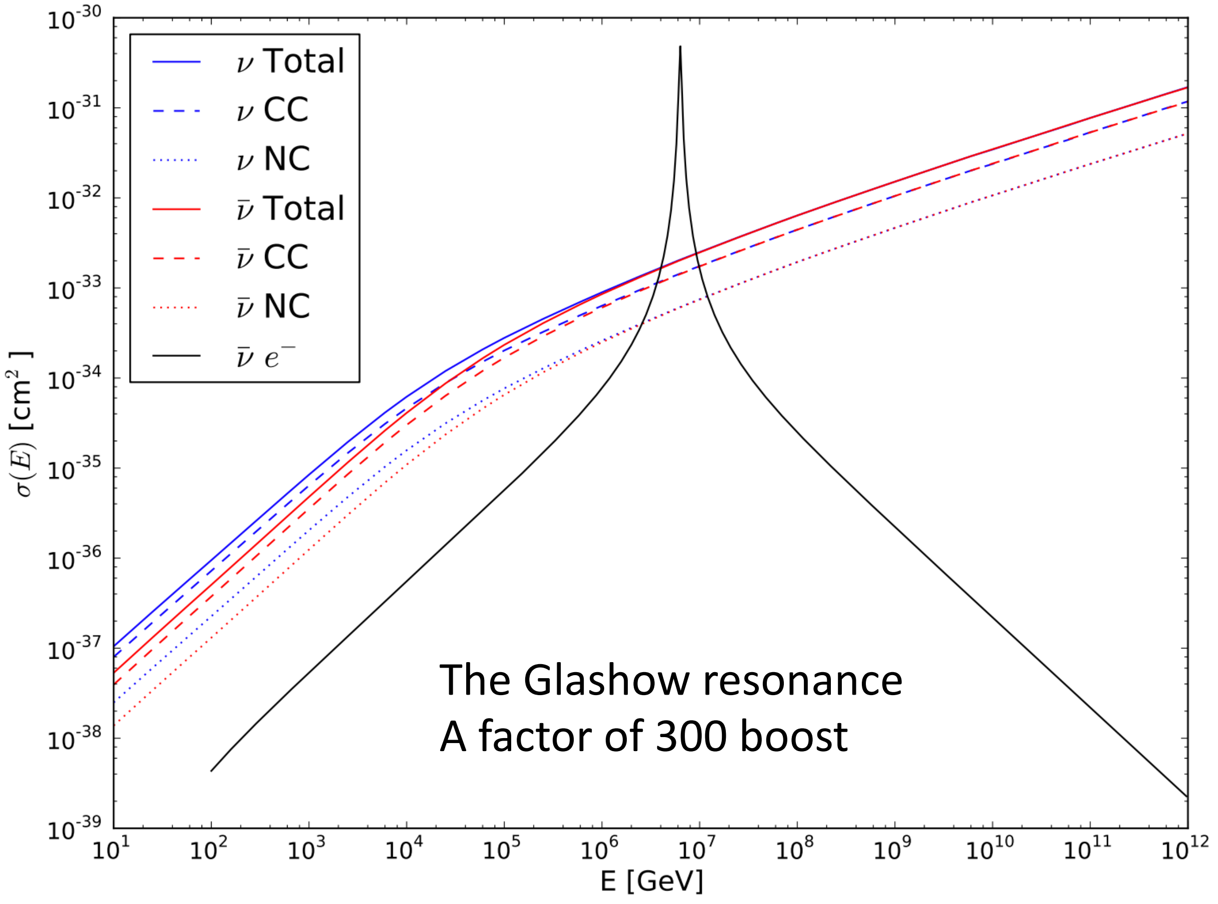
at a neutrino energy of 6.3 PeV, the centre-of-mass energy (80.5 GeV) is large enough to produce a real W boson

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

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

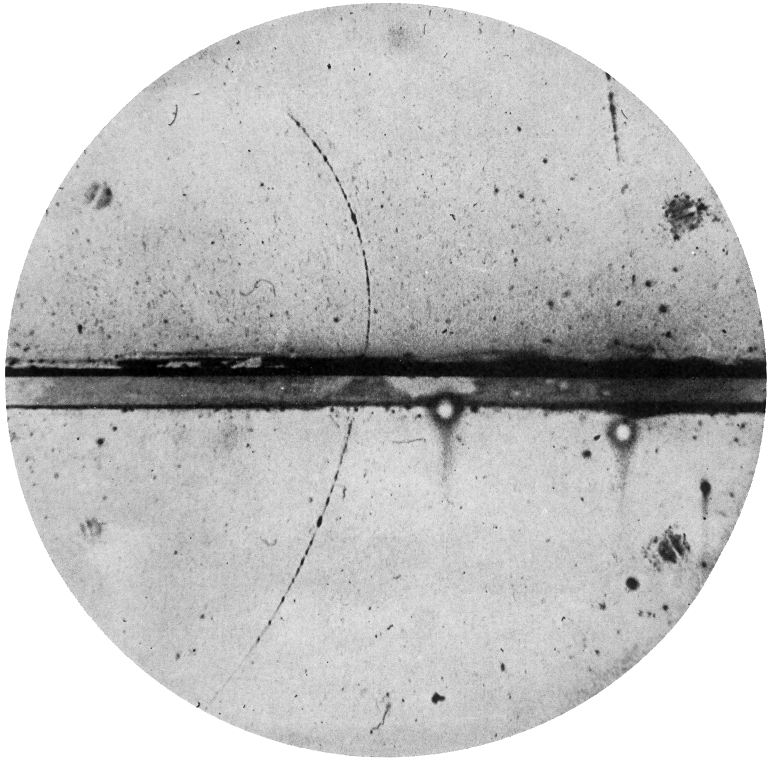
$$\overline{\nu_e} + e \quad \to W^- \to \quad X \quad ,$$

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

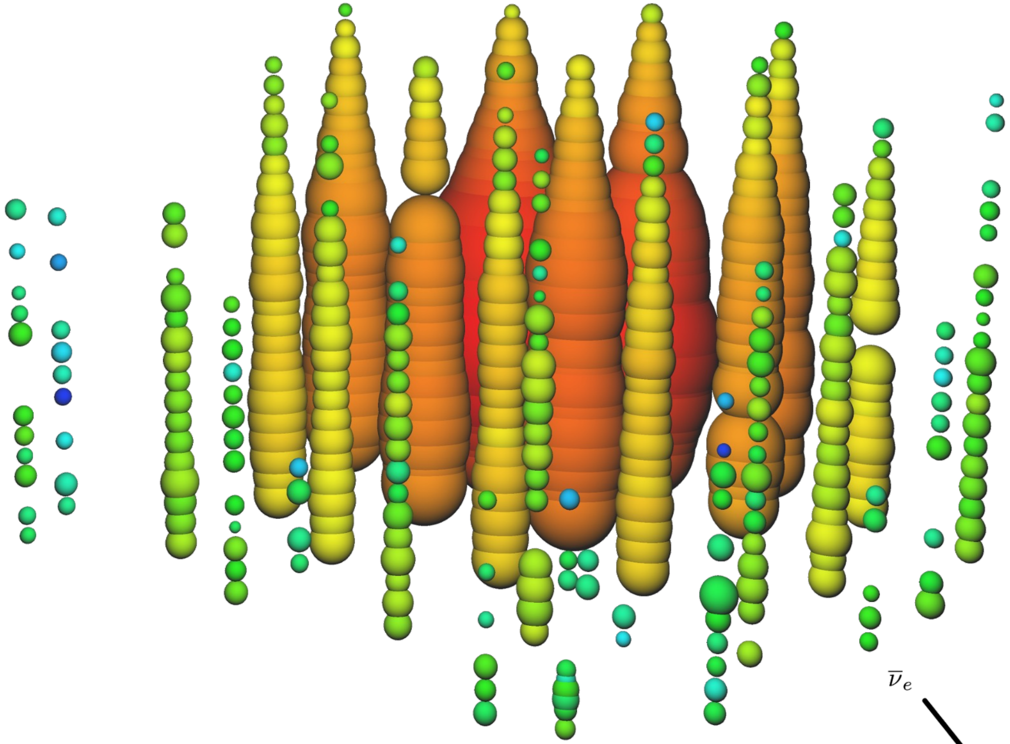


W boson (Glashow) resonance – first hint of electron anti-neutrino

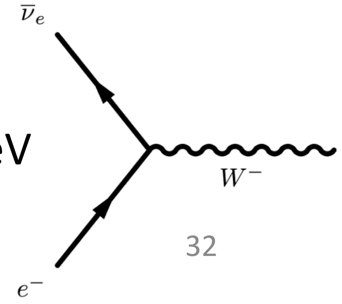
Nature **591,** 220–224 (2021)



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

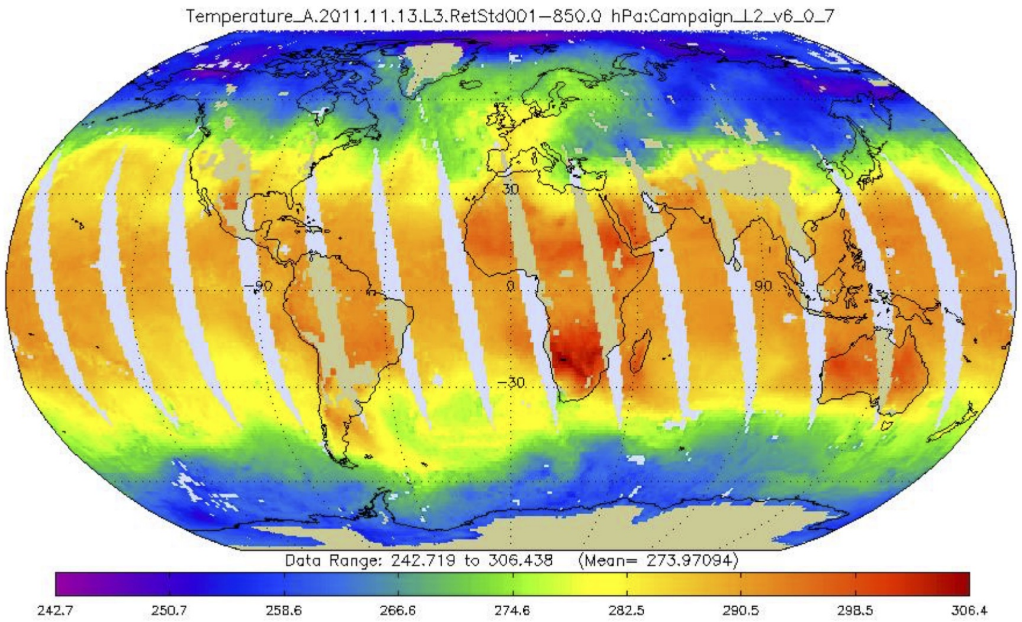


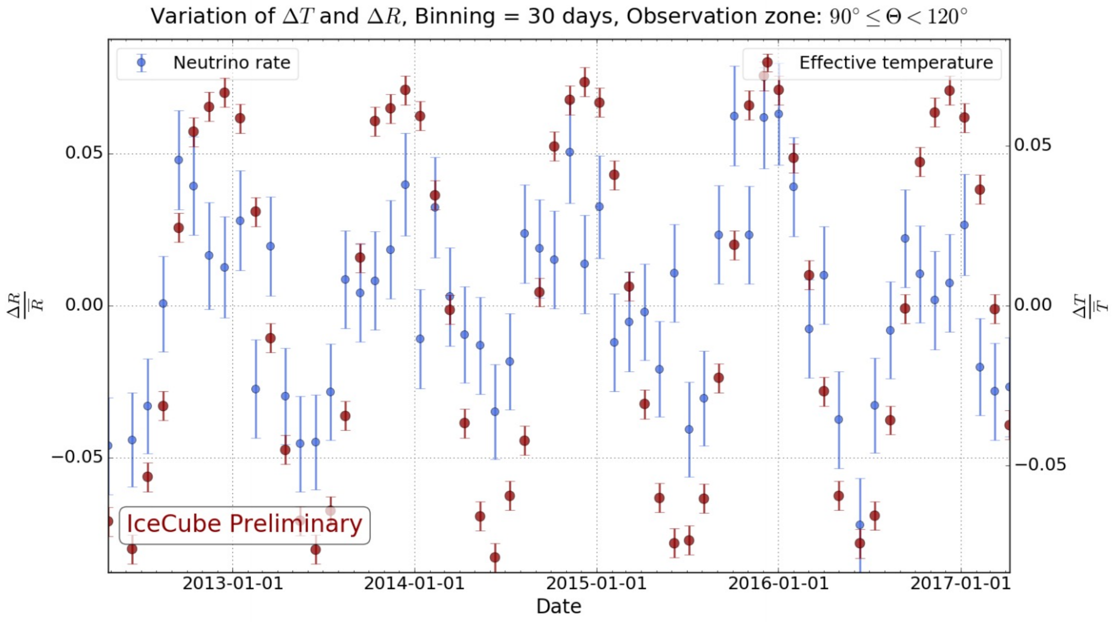
W boson resonance , nuebar 6.3 PeV
IceCube, 2021



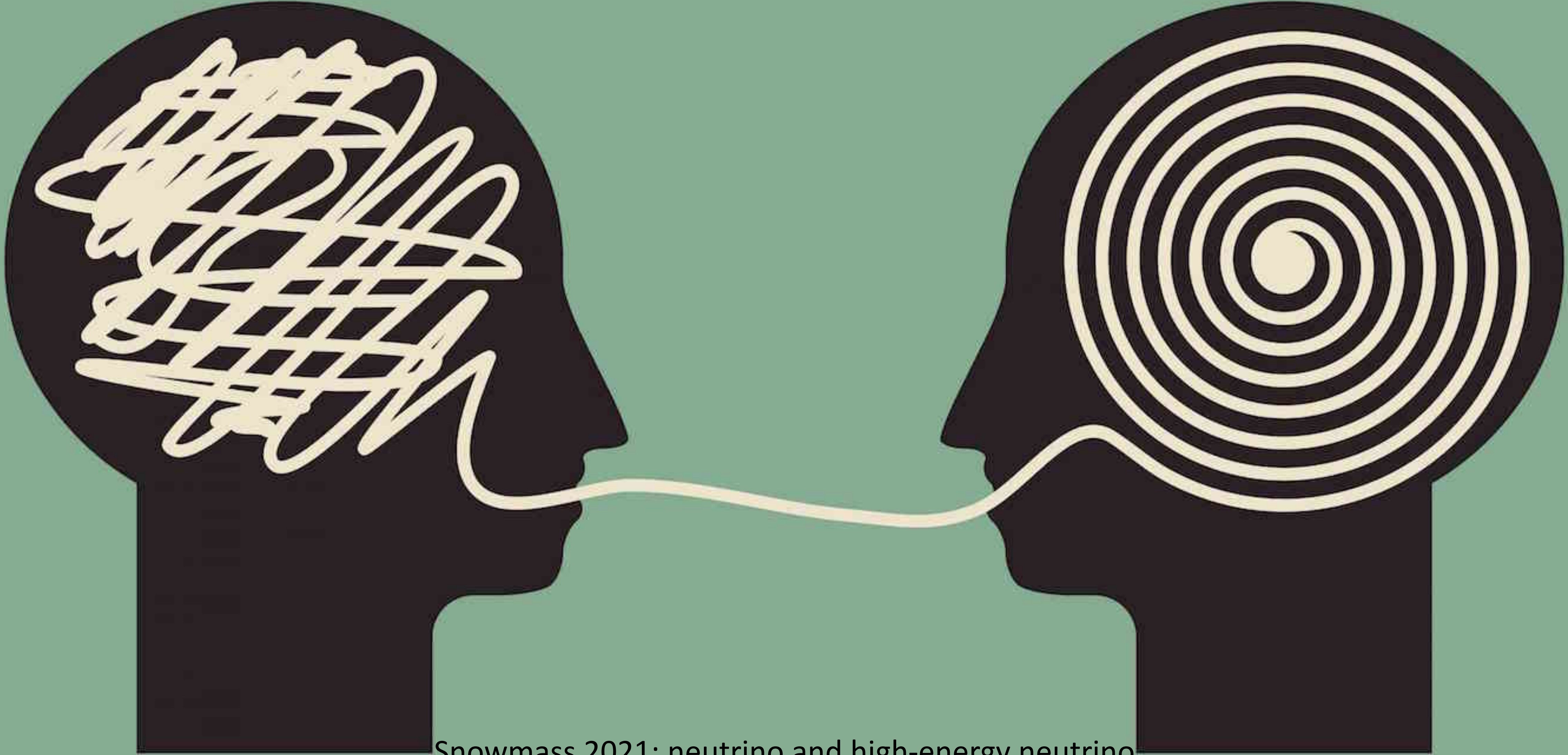
(atmospheric) Neutrino weather!

Lead by Aachen group





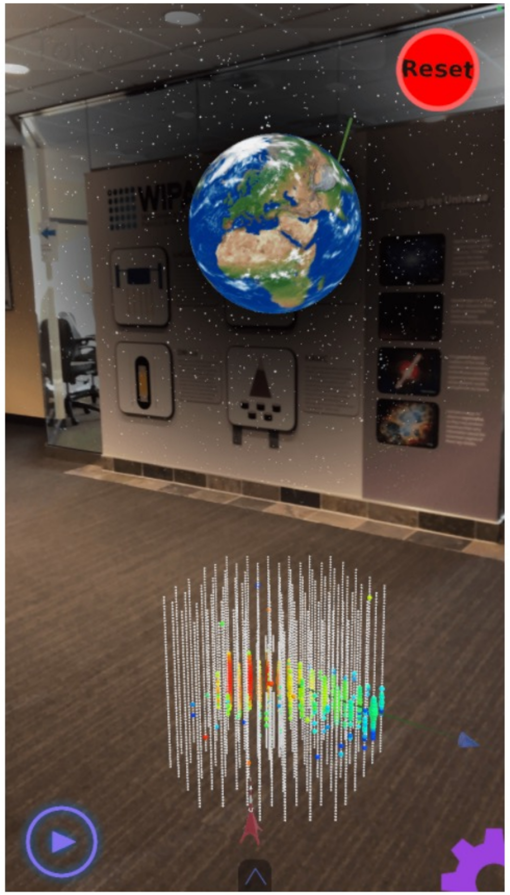
I hope 'diffuse' makes sense to you now



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

From outer space, to the South Pole, to your phone: A new AR app for IceCube

Posted on October 8, 2020 by Madeleine O'Keefe



A screenshot from the IceCubeAR app.

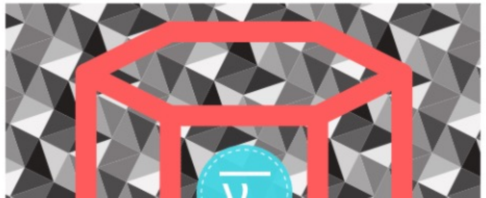
Located in the frigid desert that is the South Pole, the IceCube Neutrino Observatory isn't your typical telescope. It doesn't have an observatory dome or satellite dish. In fact, if you were standing at the South Pole looking at IceCube, you would see nothing but a small building in a vast, barren, snowy landscape.

That's because the IceCube detector is *underground*. It comprises an array of 5,160 optical sensors that are frozen beneath a cubic kilometer of ice a mile beneath the surface. These sensors pick up signals left behind by mysterious particles called neutrinos.

Now, thanks to a new augmented reality (AR) app, anyone in the world can see what's happening under the ice at the South Pole. And when a neutrino candidate sails through the detector, users will find out in real time!

Introducing IceCubeAR, aka IceBear.

Neutrinos are fundamental particles that travel through the cosmos. They come from myriad sources on Earth and in our solar system—but many are from outside our galaxy, known as astrophysical neutrinos, and



https://icecube.wisc.edu/news/outreach/2020/10/from-outer-space-to-south-pole-to-your-phone-new-ar-app-for-icecube/

ICEcuBEAR