# Diffuse neutrinos from 1 TeV to 1 EeV

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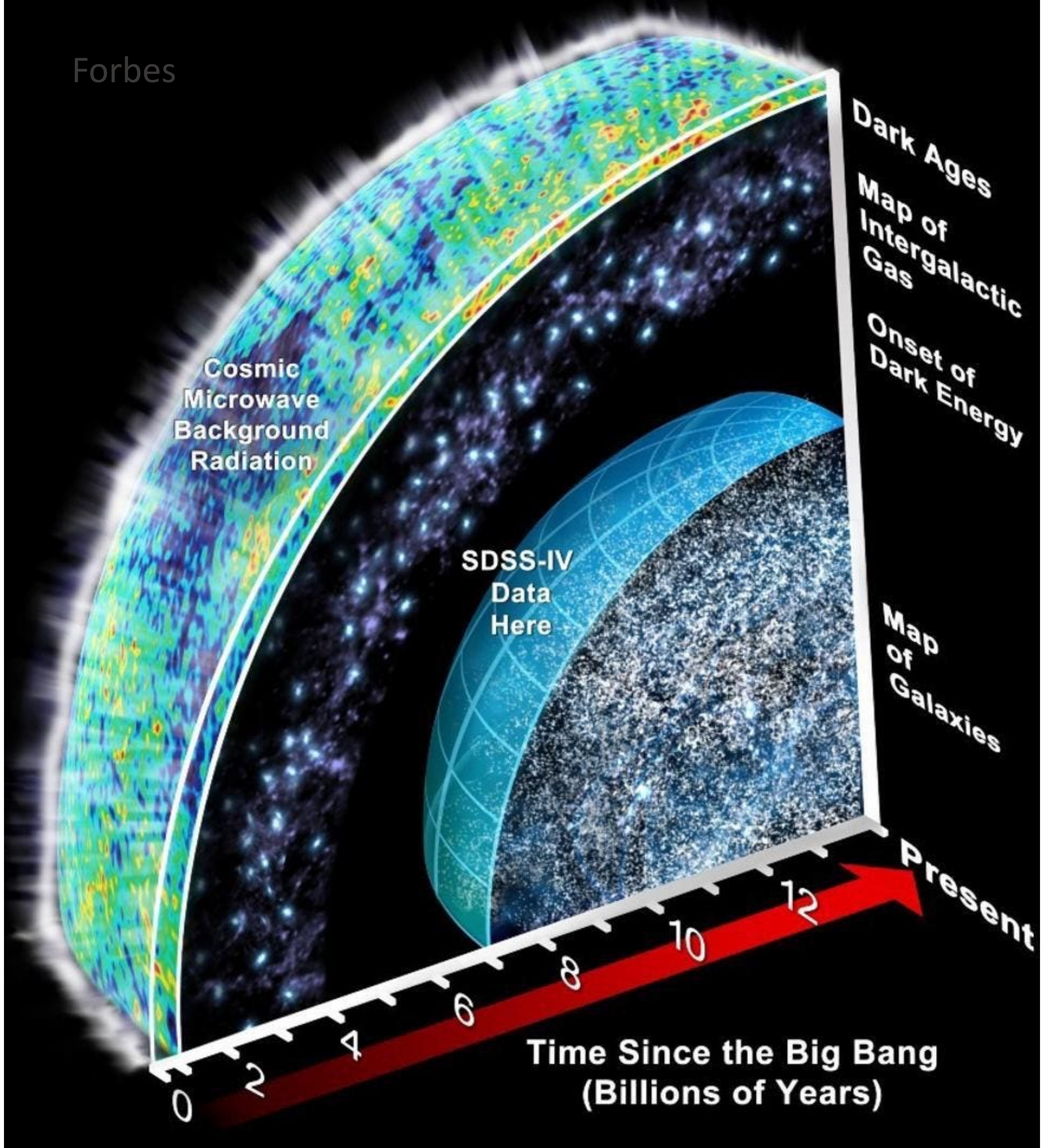
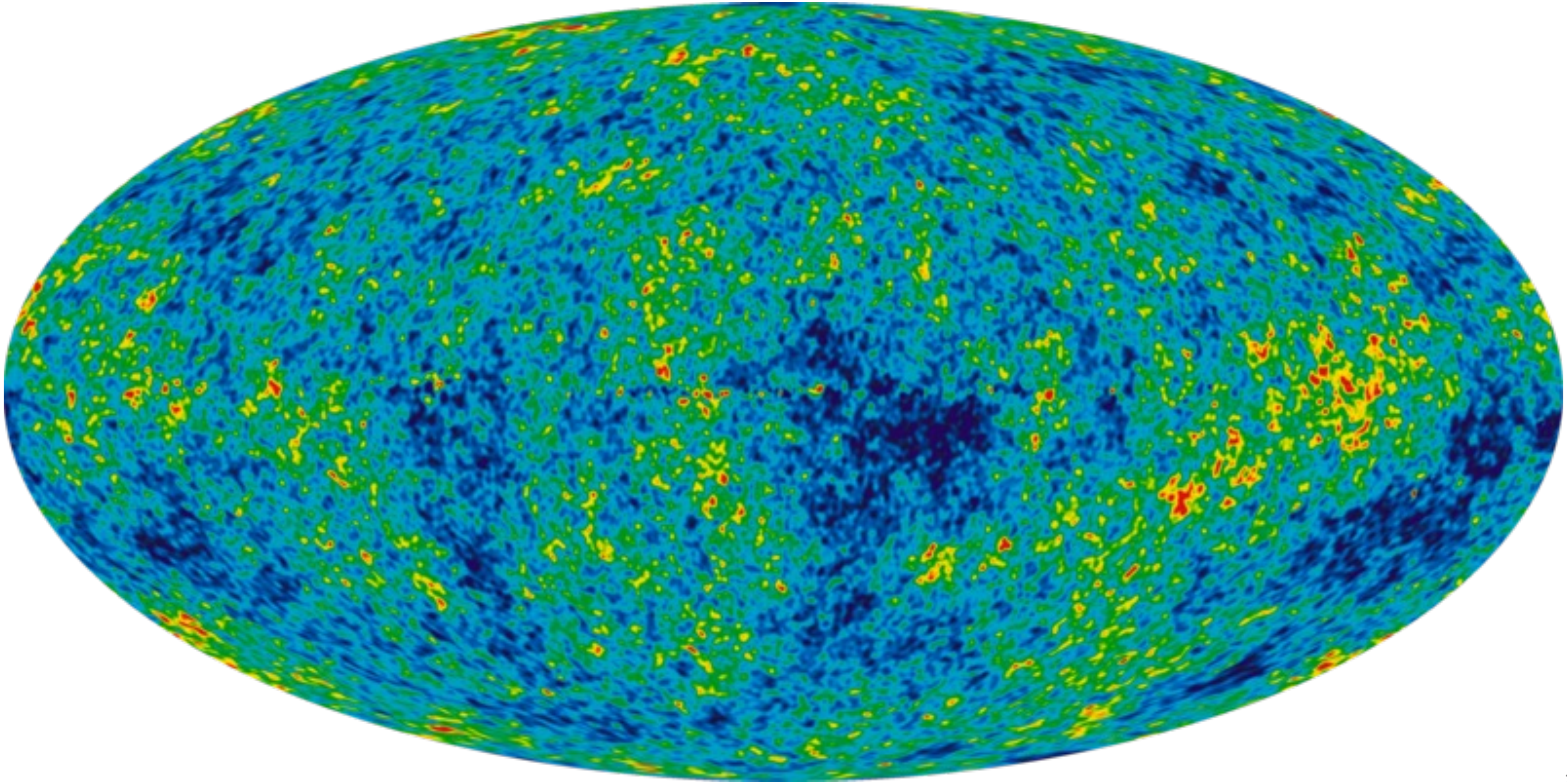
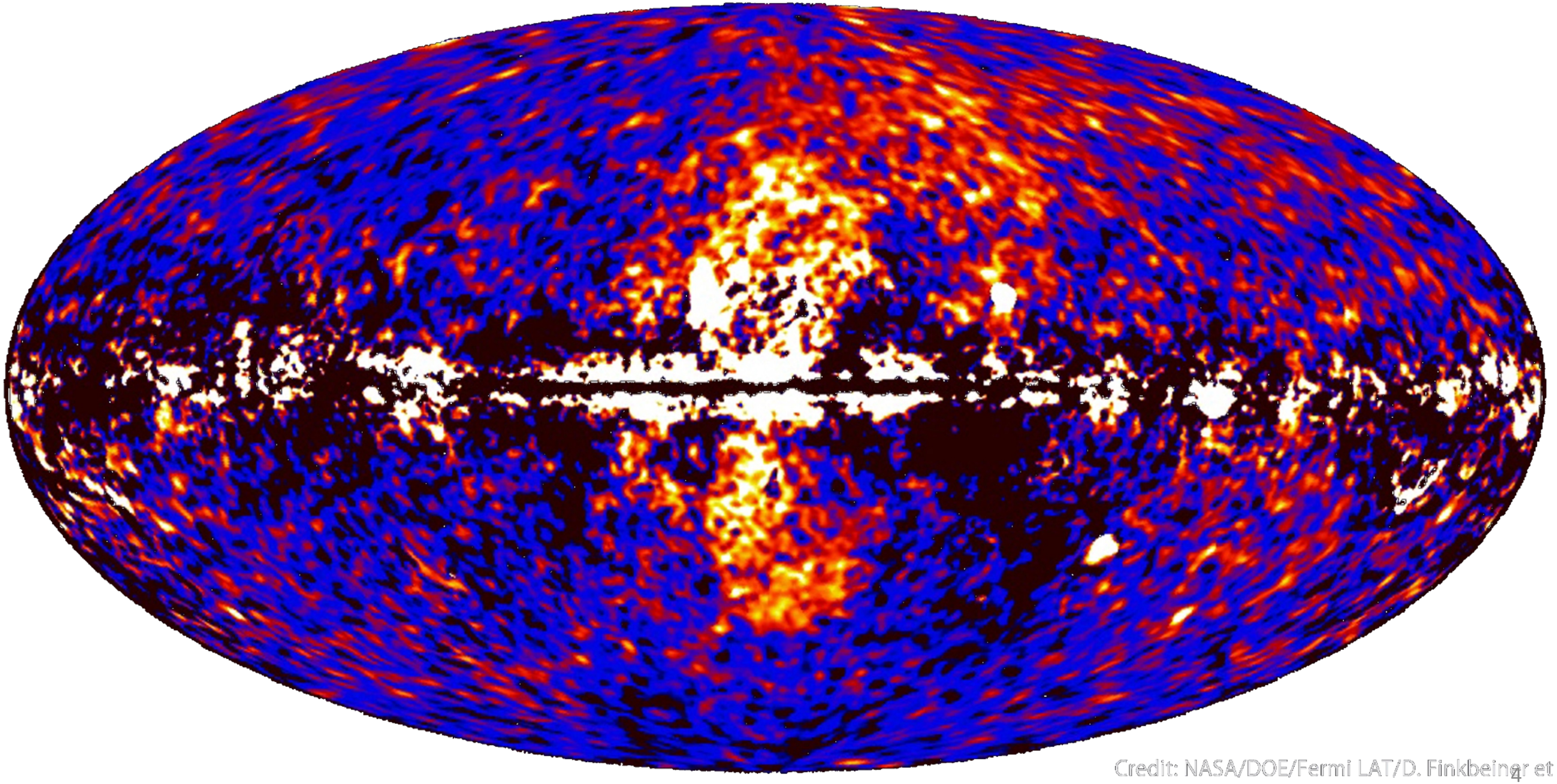
IceCube Summer School 2024


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

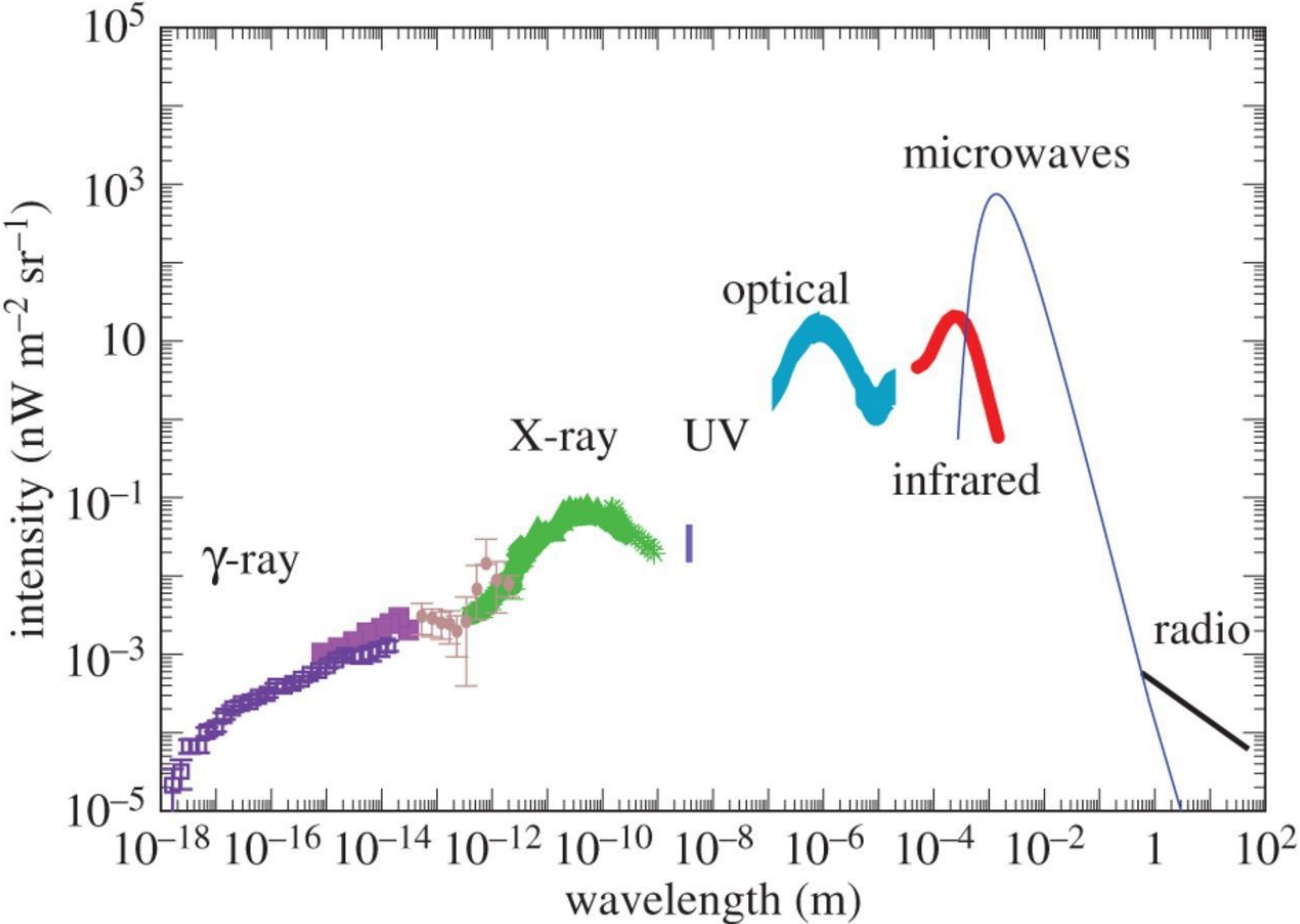
# Diffuse microwave photons



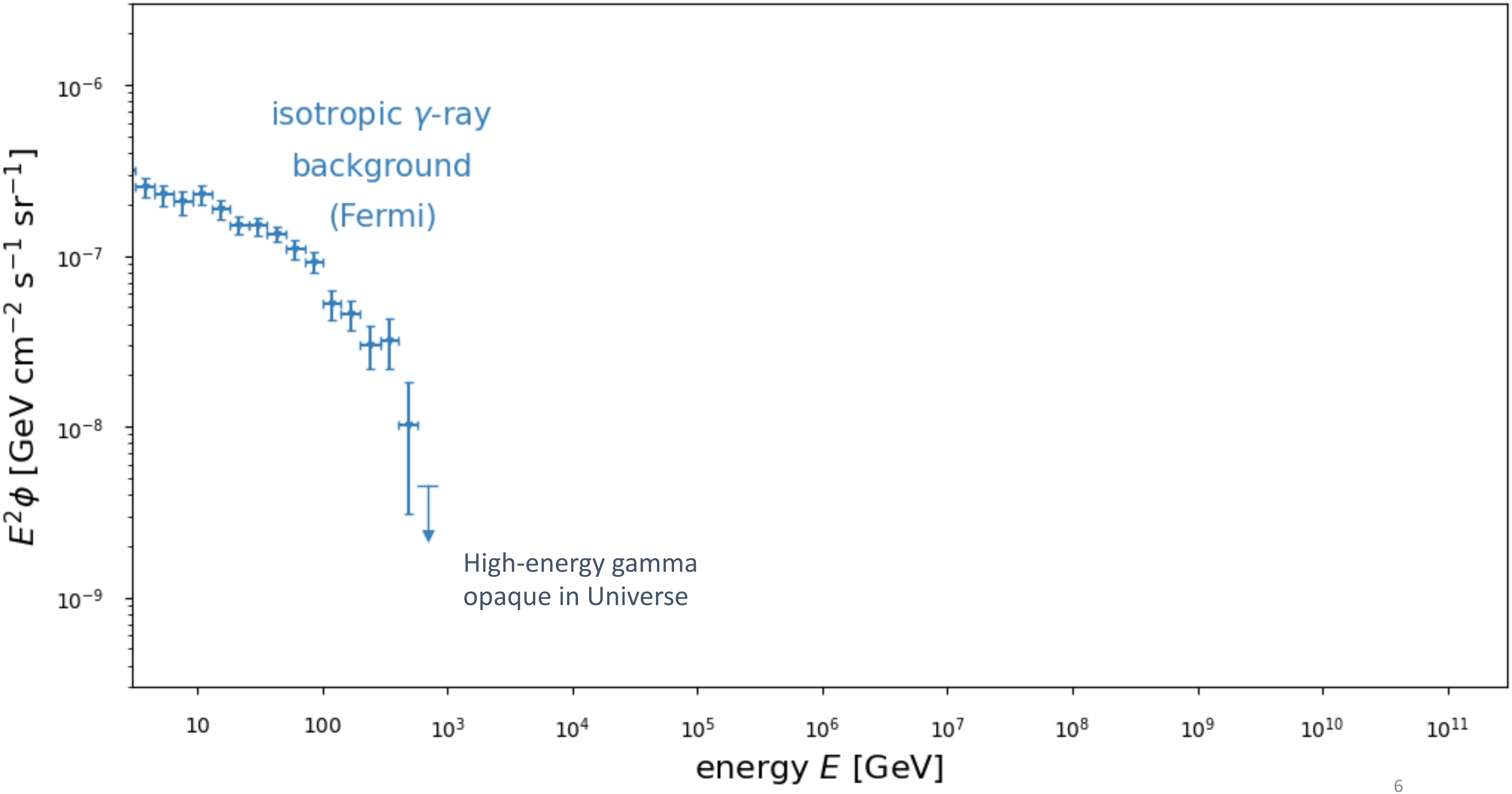
# Diffuse gamma-ray photons



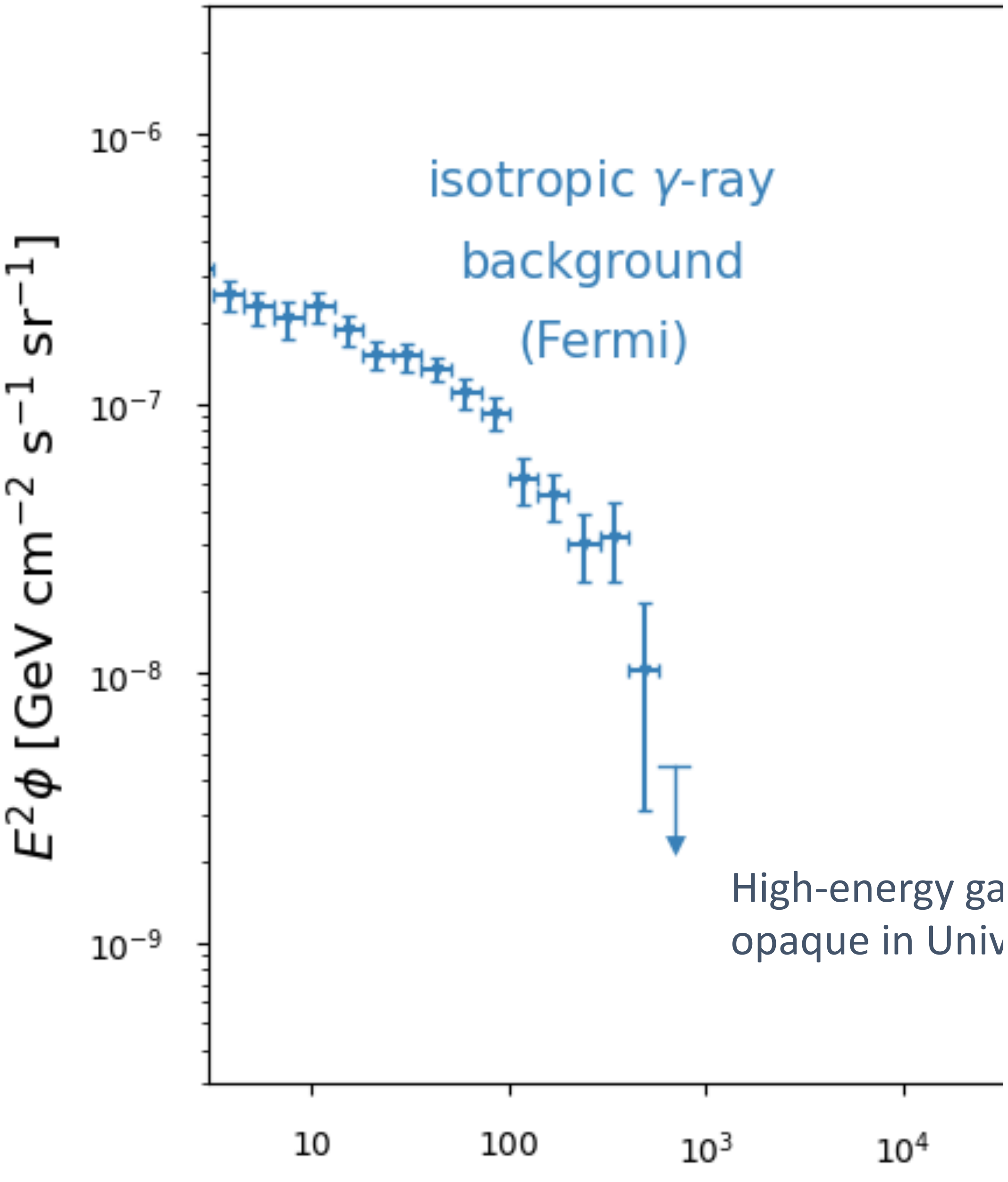
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.



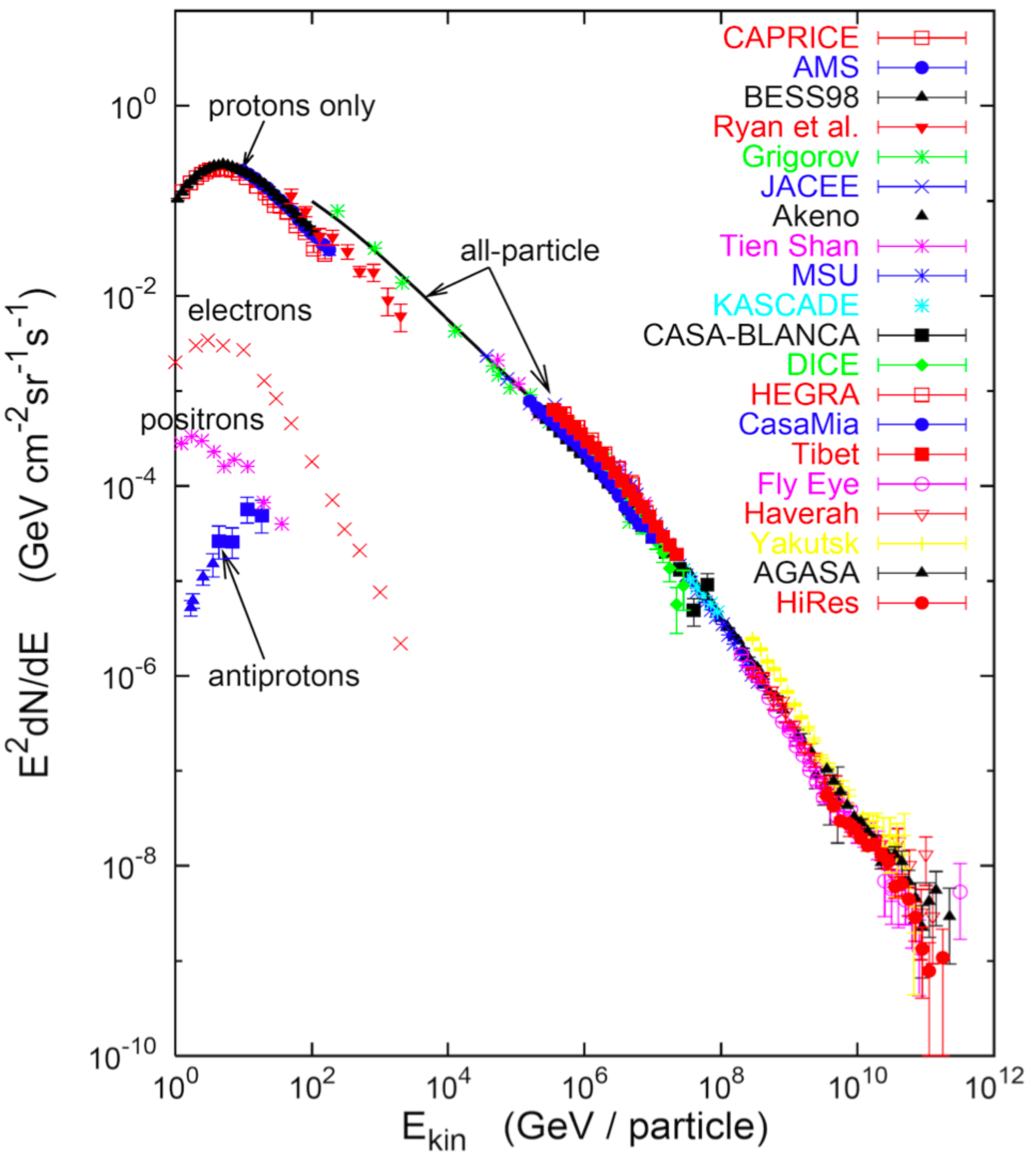
intensity (nW m$^{-2}$ sr$^{-1}$)
$10^5$
$10^3$
10
$10^{-1}$
$10^{-3}$
$10^{-5}$
microwaves
optical
infrared
X-ray
UV
γ-ray
radio
$10^{-18}$ $10^{-16}$ $10^{-14}$ $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ 1 $10^2$
wavelength (m)



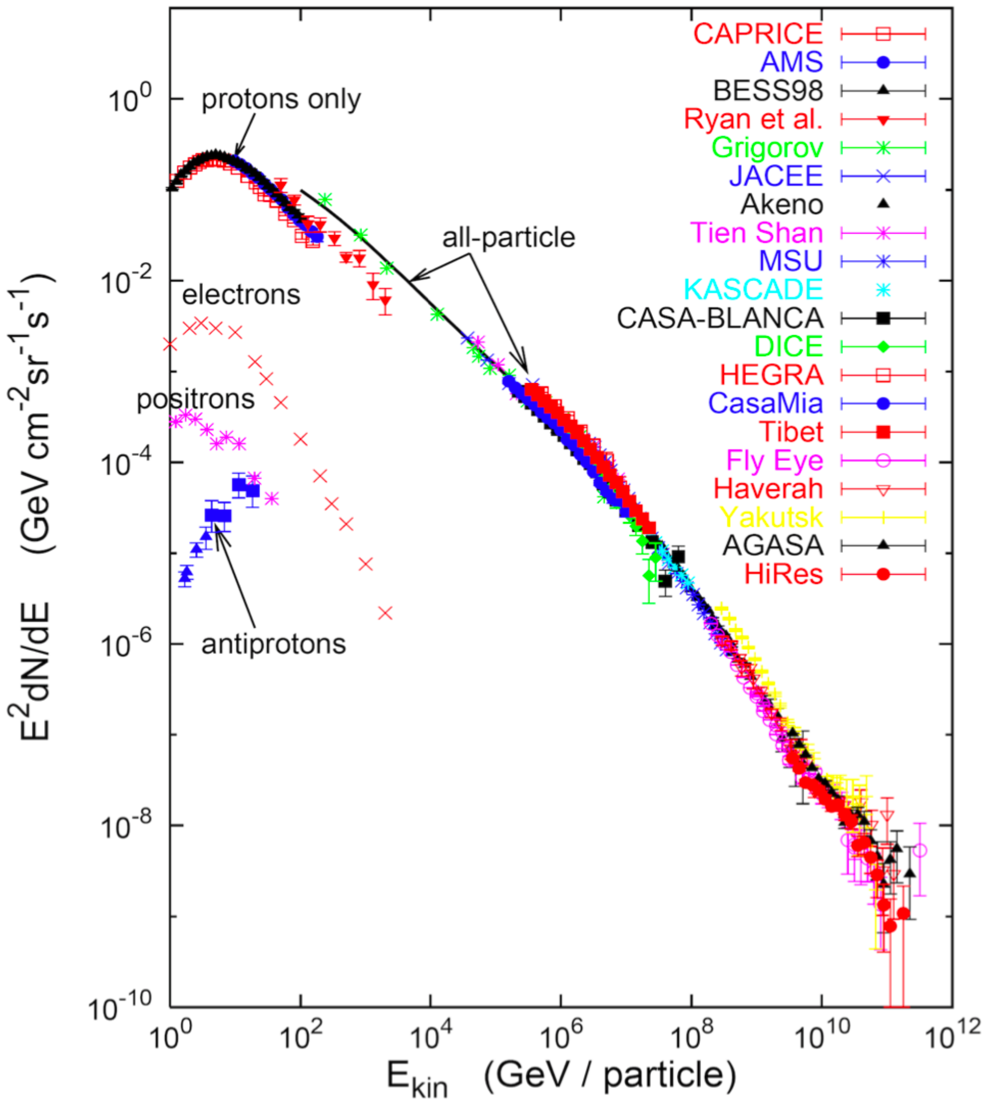
isotropic γ-ray
background
(Fermi)
High-energy gamma
opaque in Universe
$E^2\phi$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
10
100
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$10^9$
$10^{10}$
$10^{11}$
energy $E$ [GeV]




High-energy ga
opaque in Univ



Energy density of Galactic cosmic rays




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

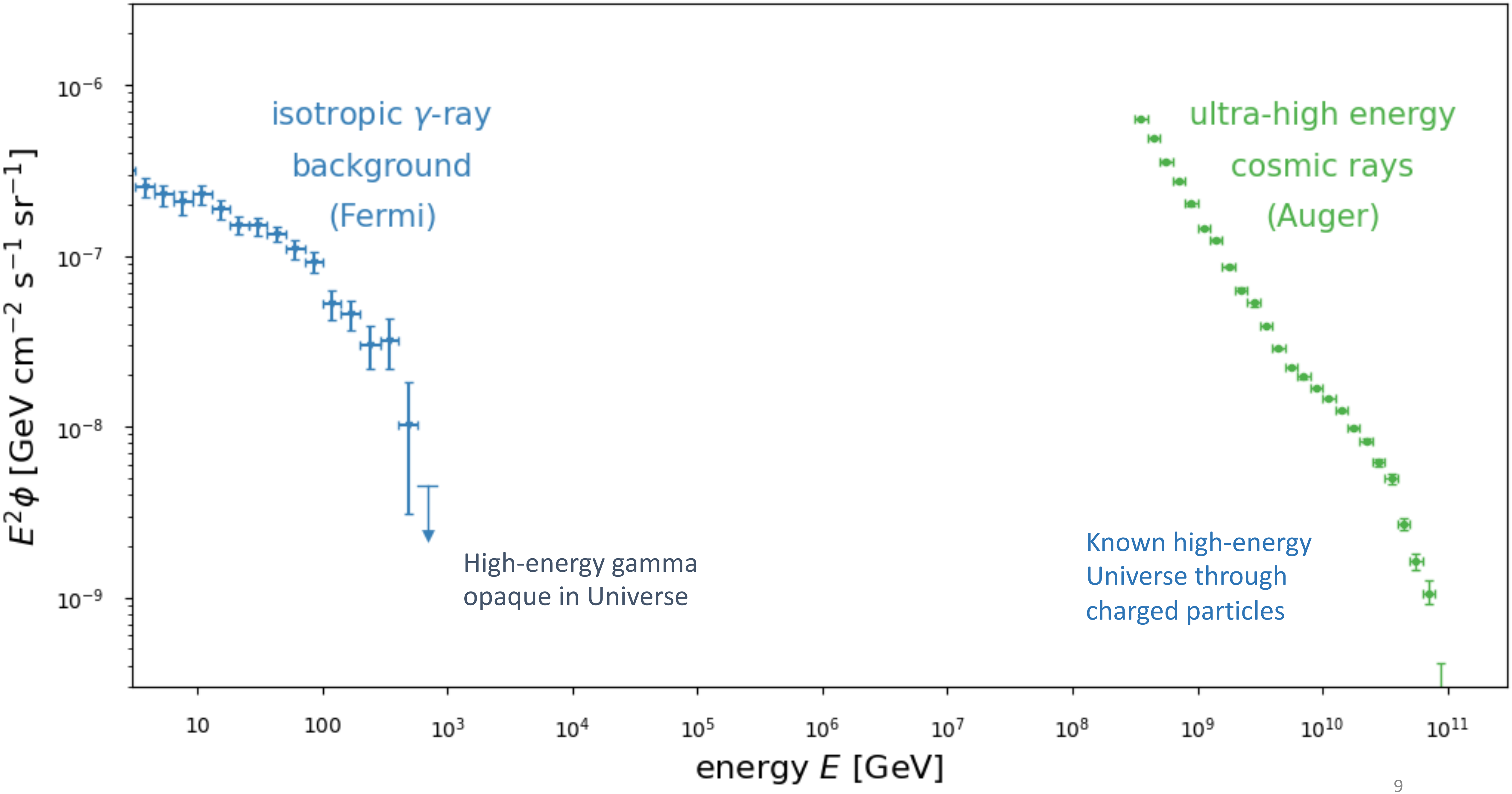
$$\Phi(E) = \int_\Omega \mathrm{d}\Omega I(E) = 4\pi I(E)$$

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

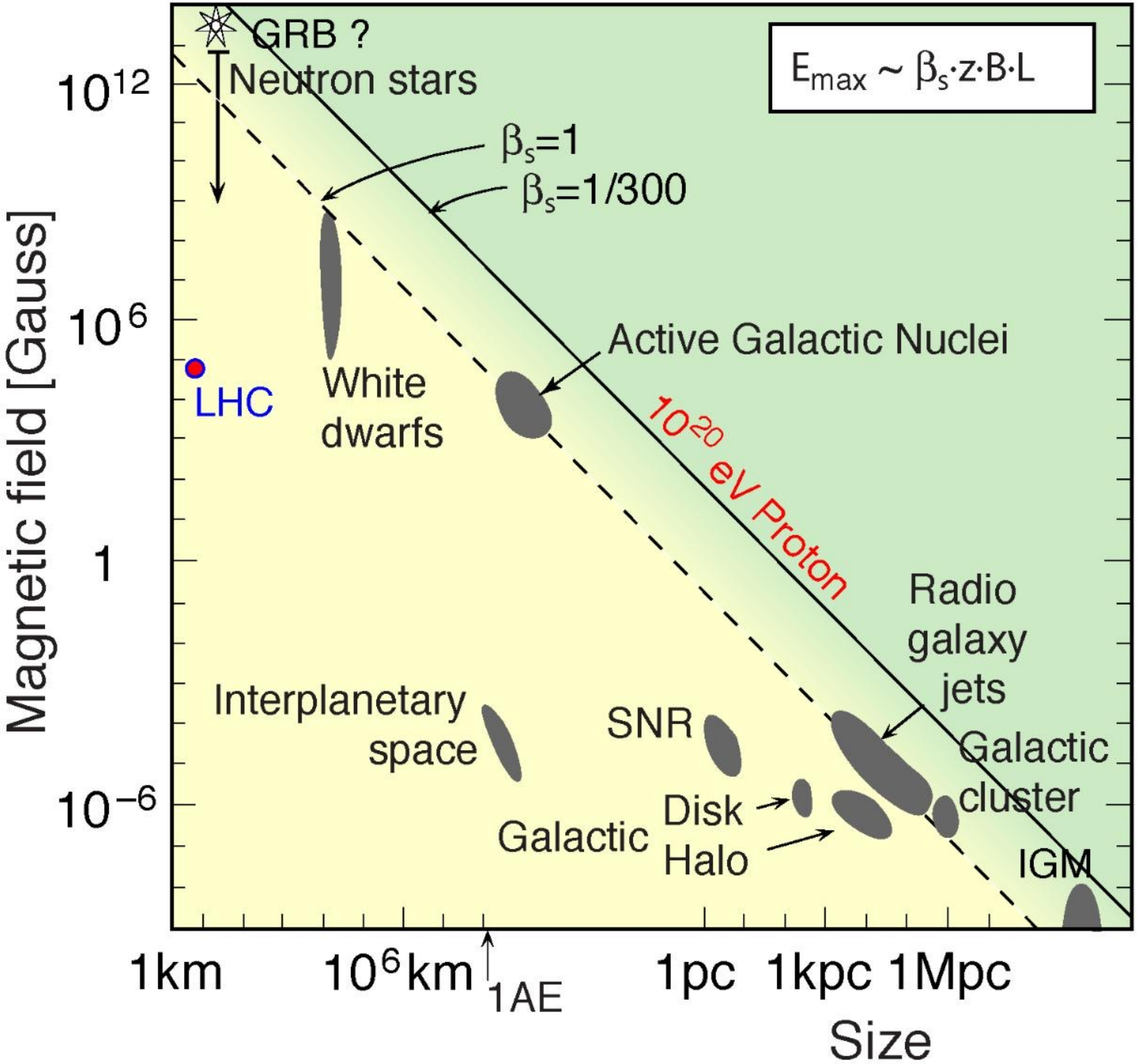
$$\rho_{CR} = \int E n(E) \mathrm{d}E = 4\pi \int \frac{E}{v} I(E) \mathrm{d}E$$

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

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]

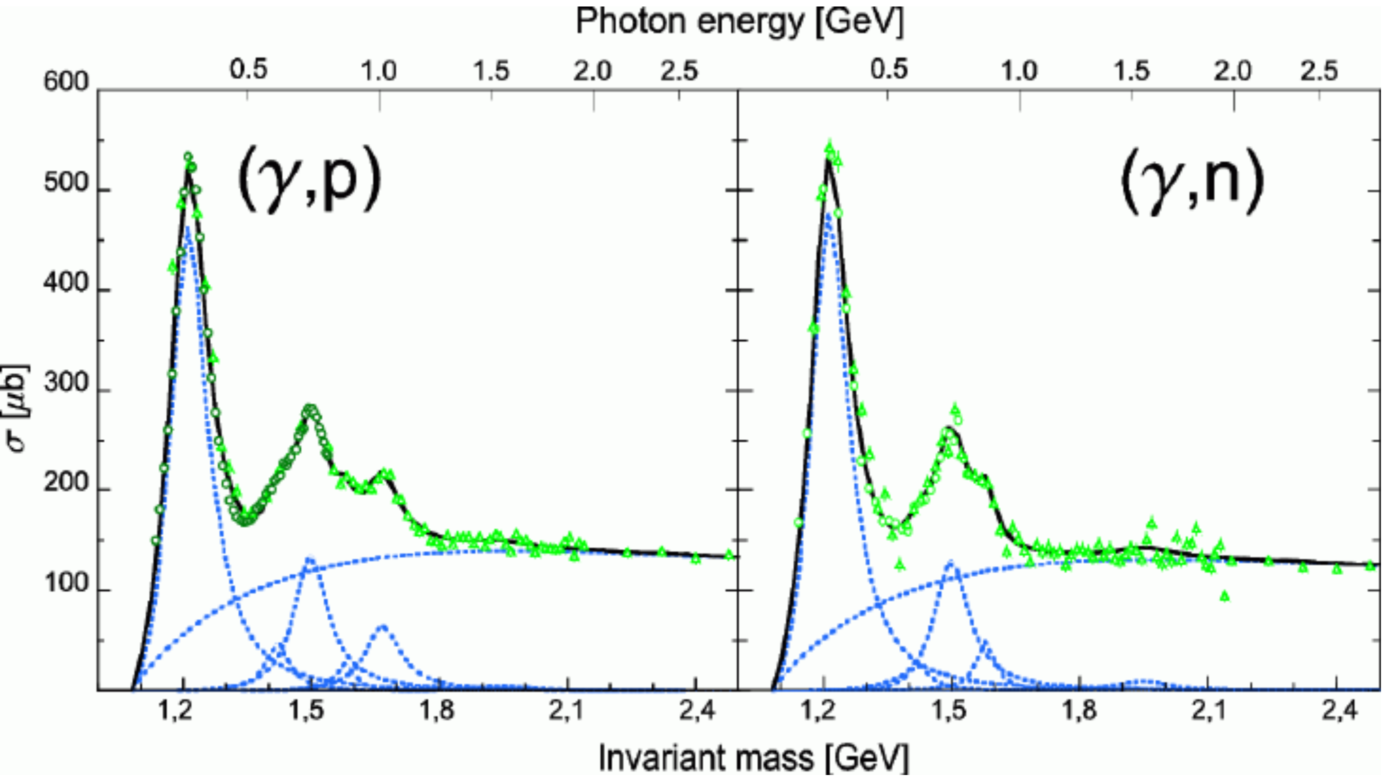
# Hillas plot

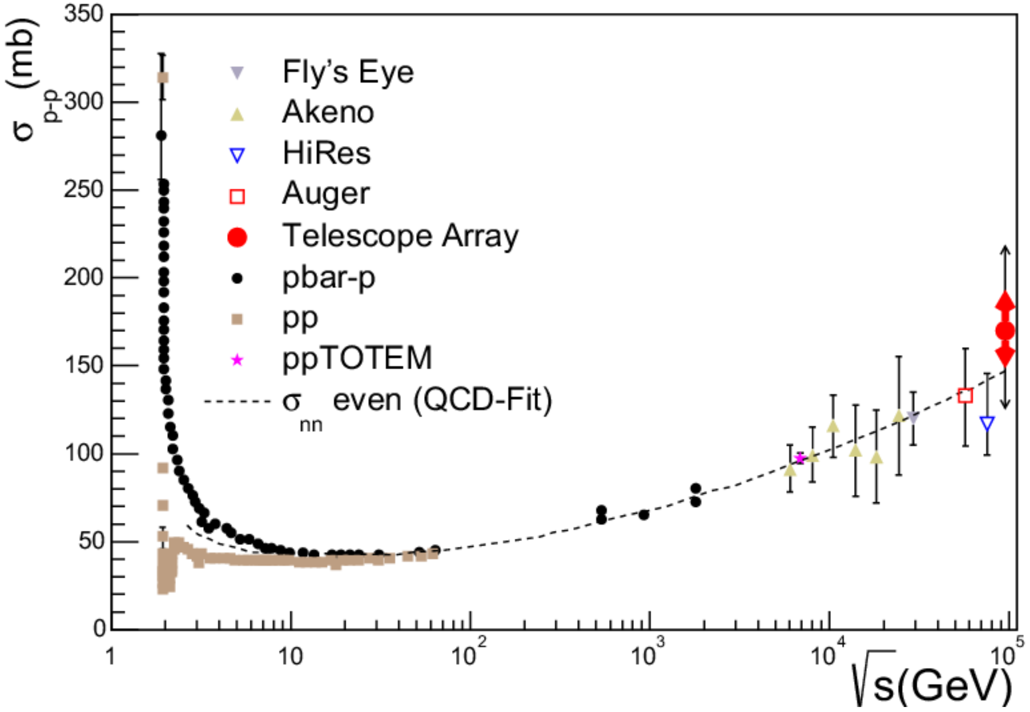


GRB ?
Neutron stars
$E_{max} \sim \beta_s \cdot z \cdot B \cdot L$
$\beta_s$=1
$\beta_s$=1/300
Active Galactic Nuclei
$10^{20}$ eV Proton
White dwarfs
LHC
Radio galaxy jets
Interplanetary space
SNR
Galactic cluster
Disk
Halo
Galactic
IGM
Magnetic field [Gauss]
$10^{12}$
$10^{6}$
1
$10^{-6}$
1km
$10^6$km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

# Neutrino productions at accelerator sites

- P-gamma vs pp

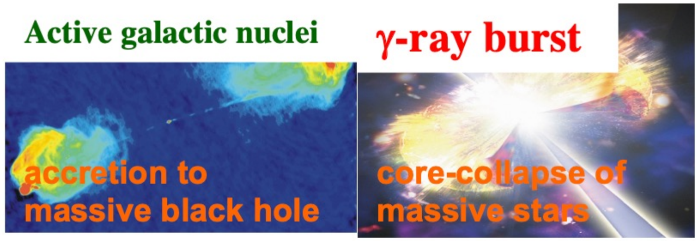


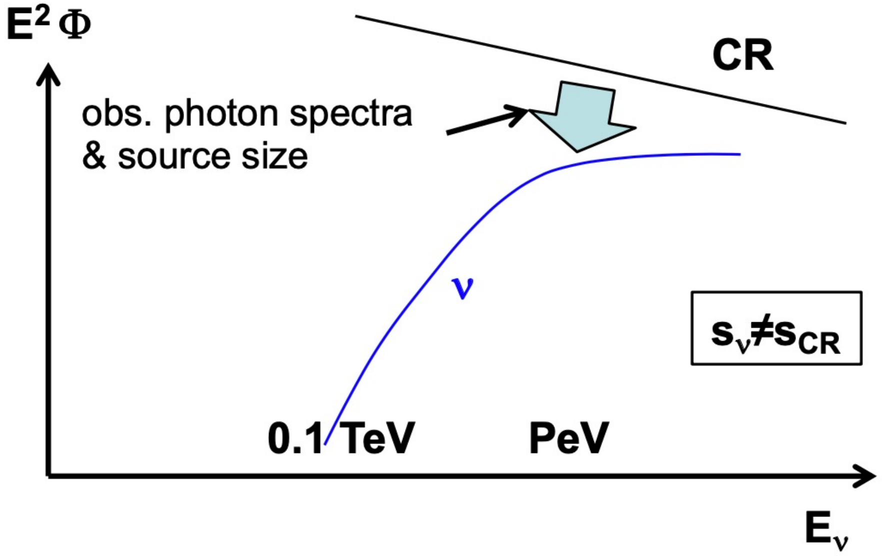
# Astrophysical Extragalactic Scenarios

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

### Cosmic-ray Accelerators (ex. UHECR candidate sources)

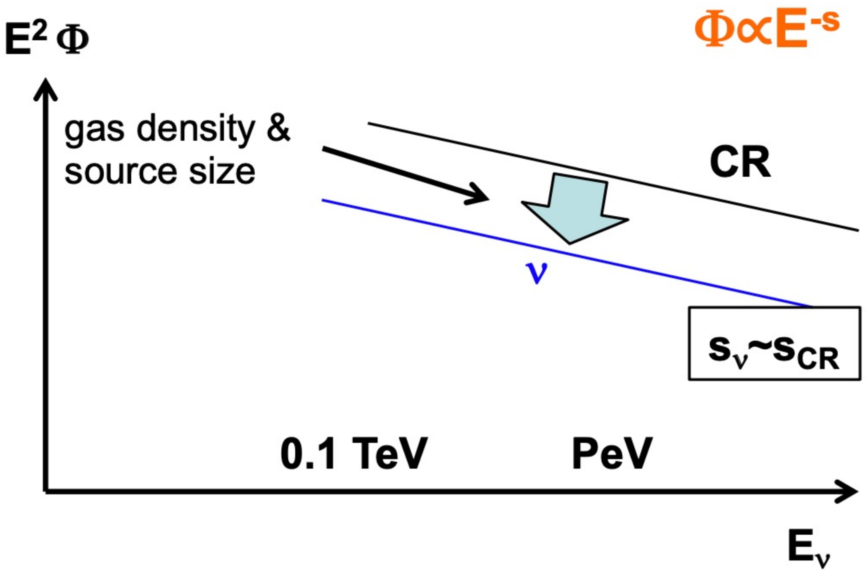



$$p + \gamma \rightarrow N\pi + X$$



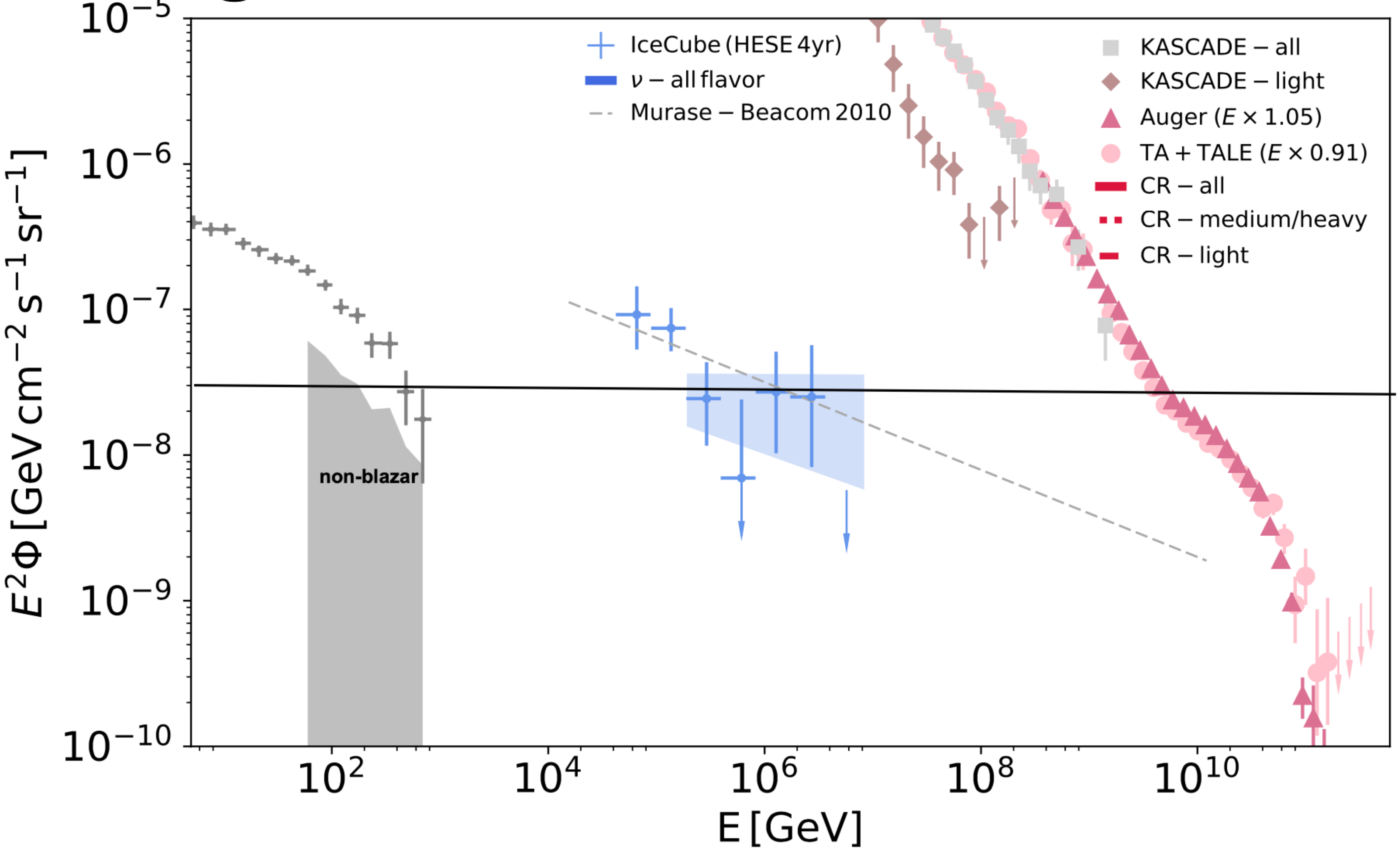

### Cosmic-ray Reservoirs


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

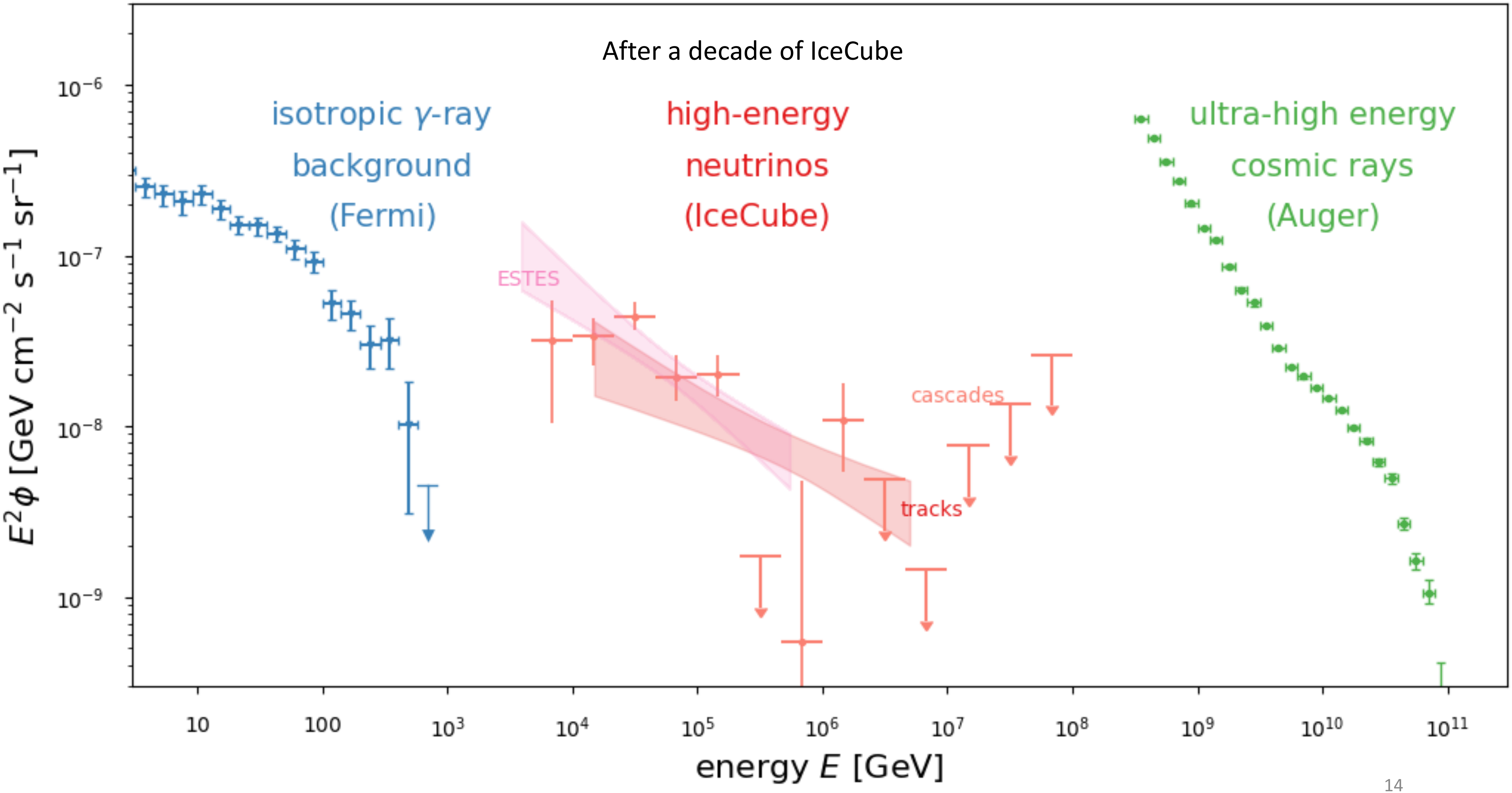



Slide from Kohta Murase

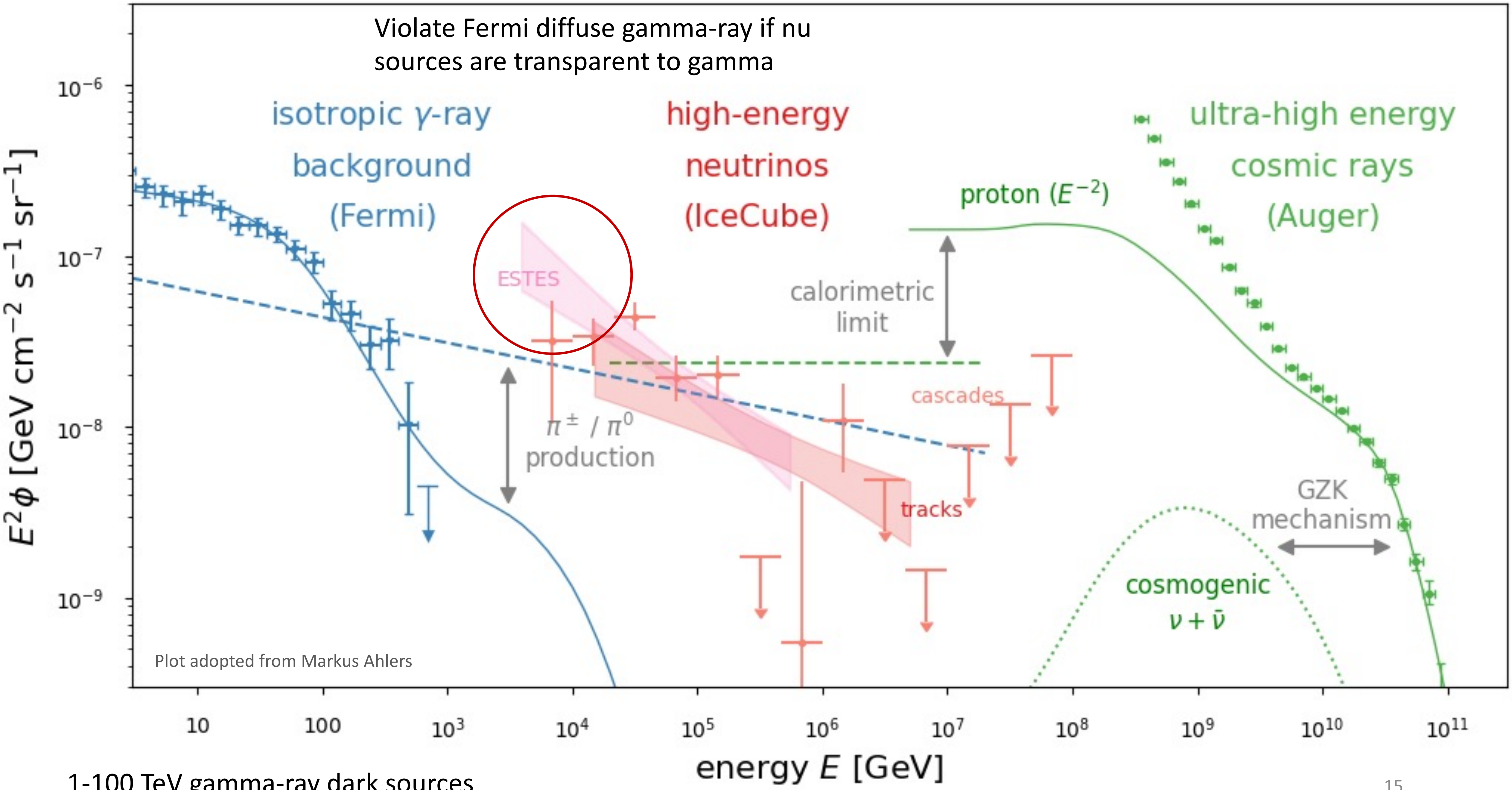
# gamma neutrino UHECR



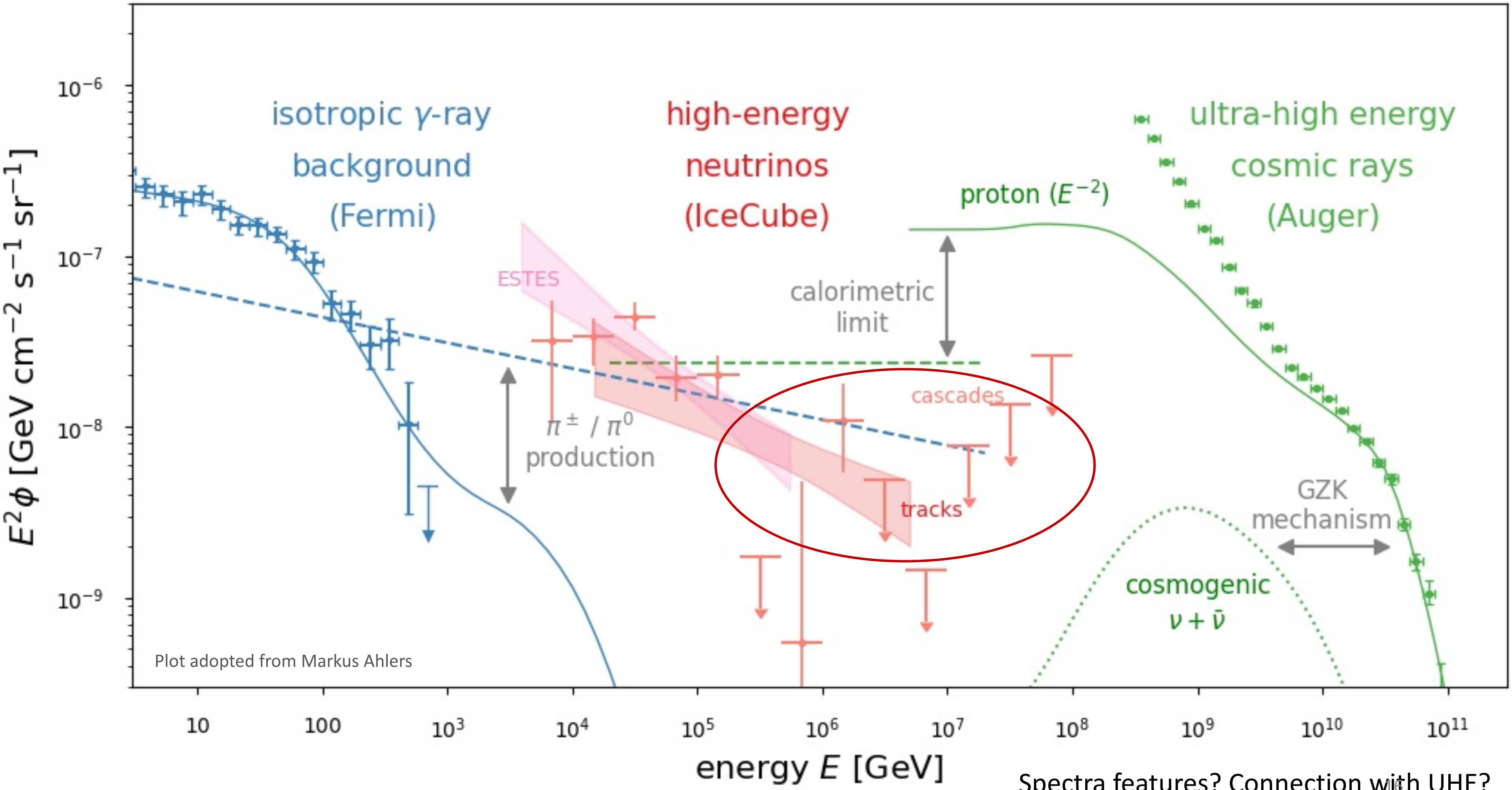

Energy generation rates are all comparable to a few x $10^{43}$ erg $Mpc^{-3}$ $yr^{-1}$


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$^{-1}$]
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
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



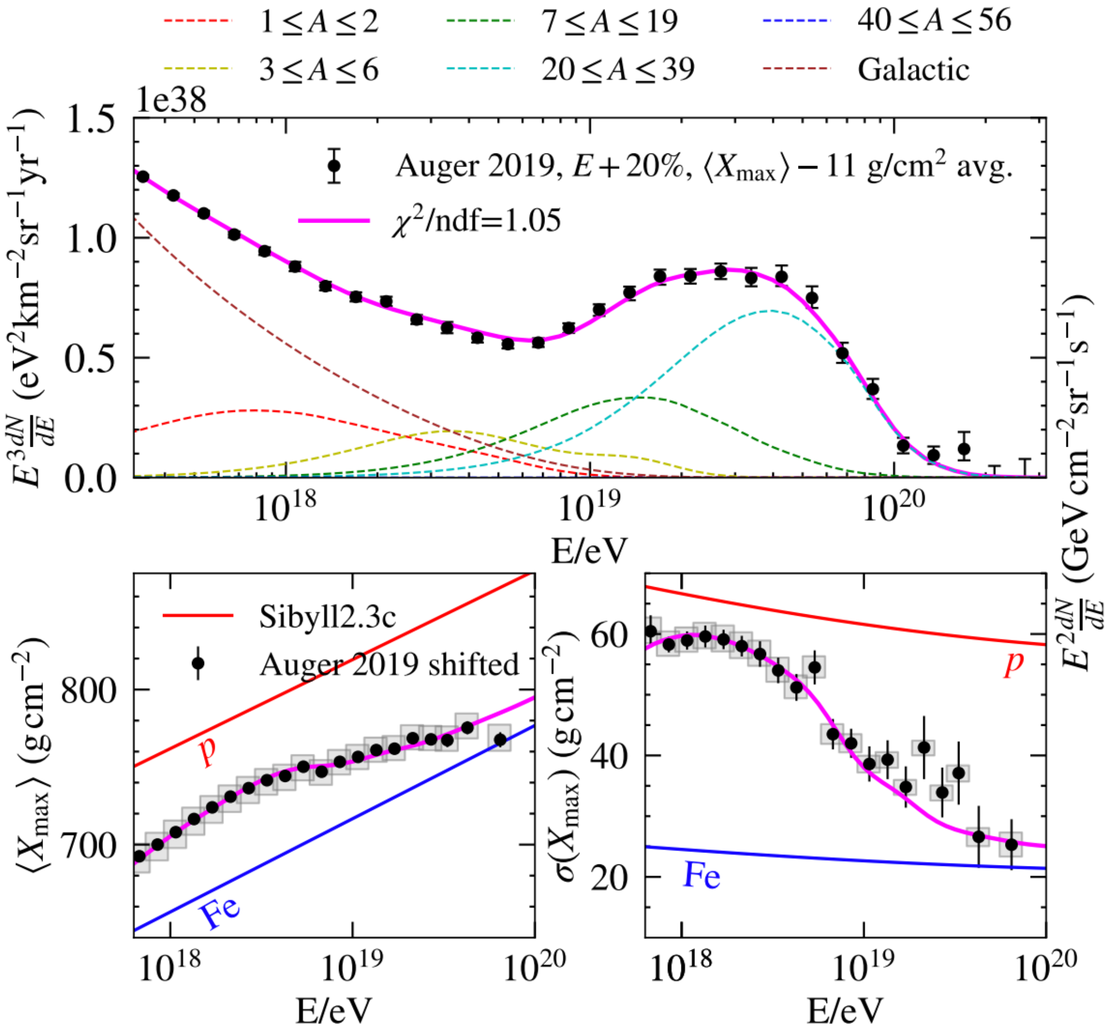

1-100 TeV gamma-ray dark sources

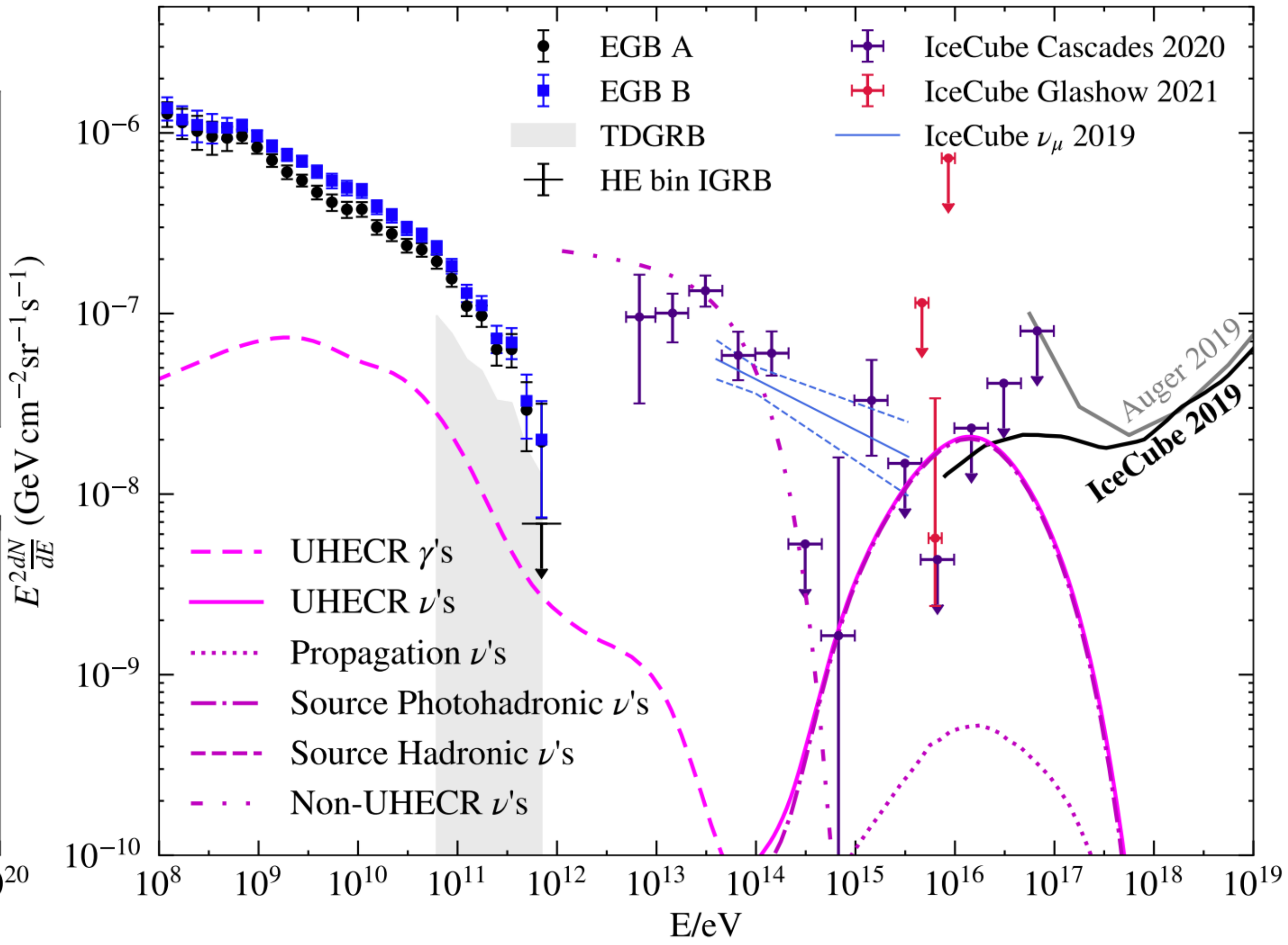



Spectra features? Connection with UHE?

Muzio et al

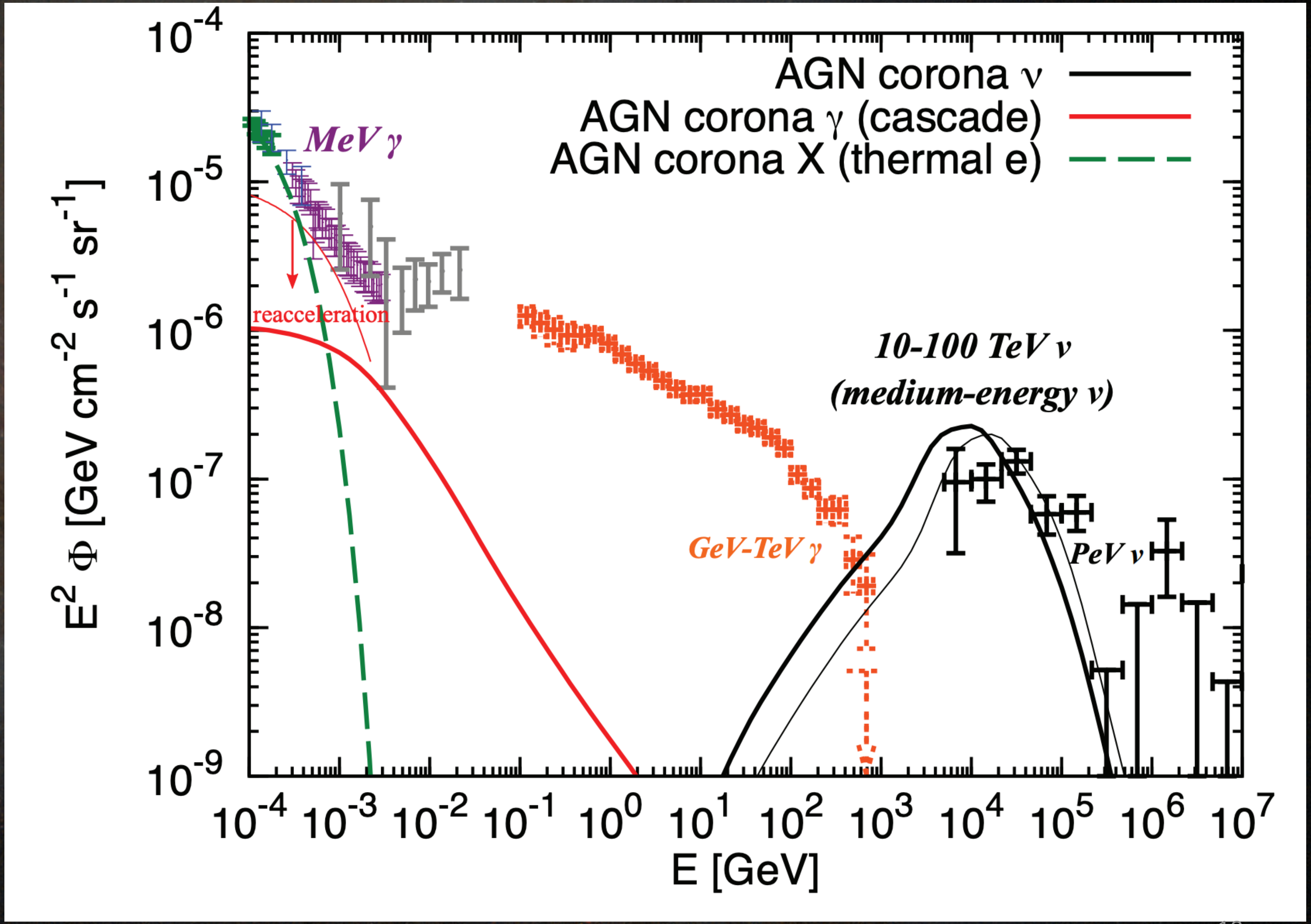
Unification of UHE vs IceCube nu



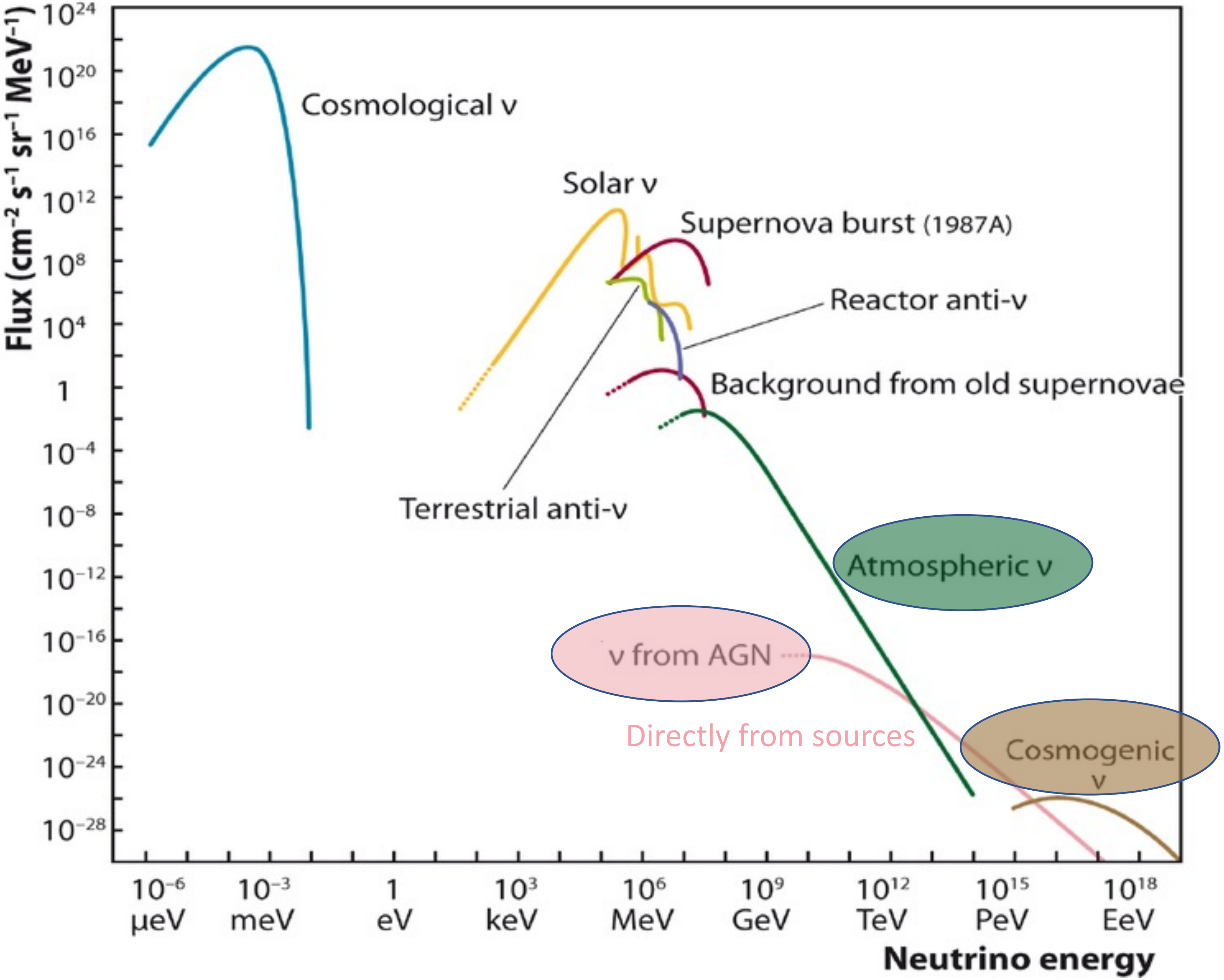



Murase et al

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)**

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

**→ $E_\nu$ ~ 100/cosθ GeV**

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

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

Conv.

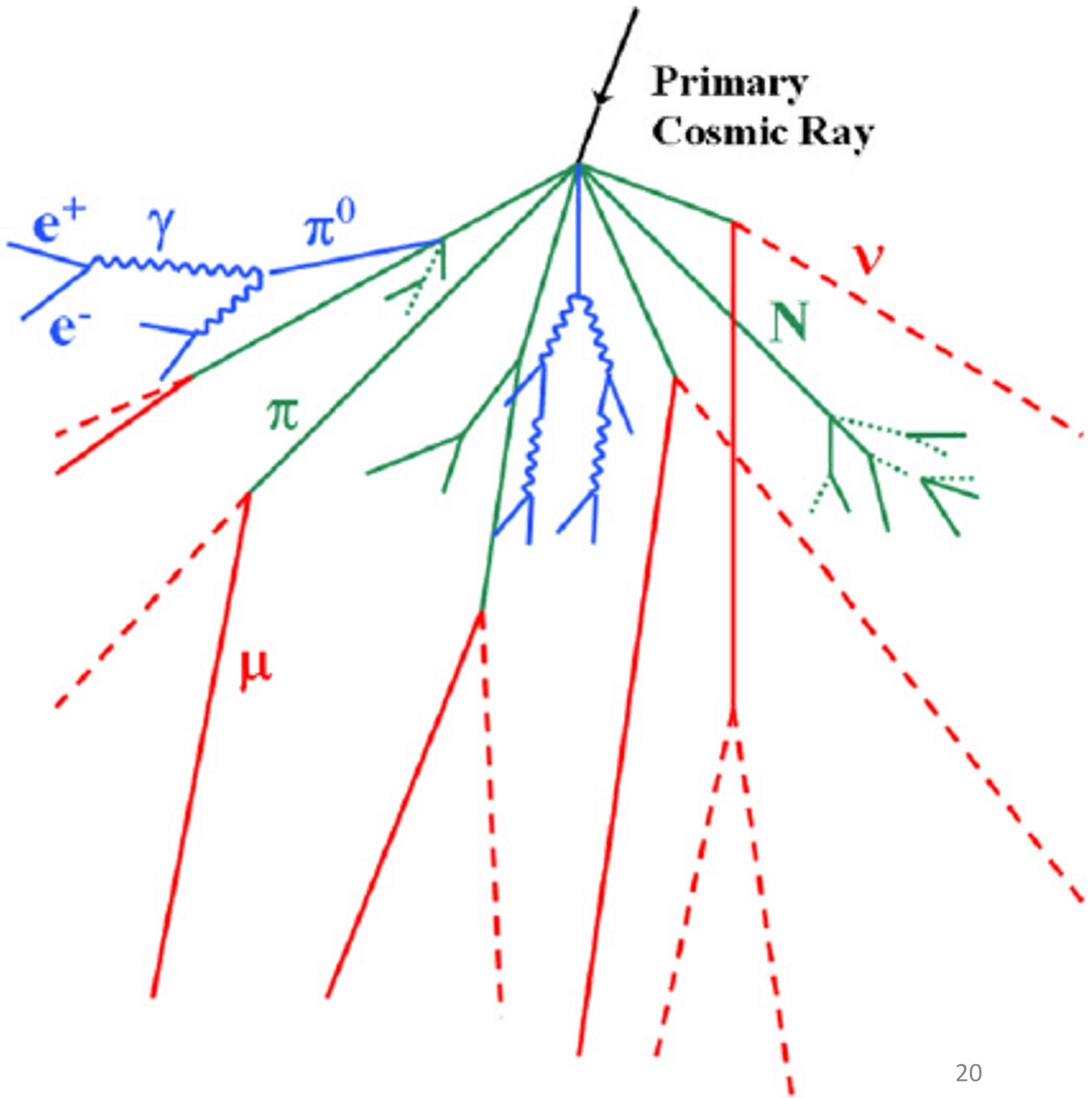
**→ $E_\nu$ ~ 100/cosθ TeV**

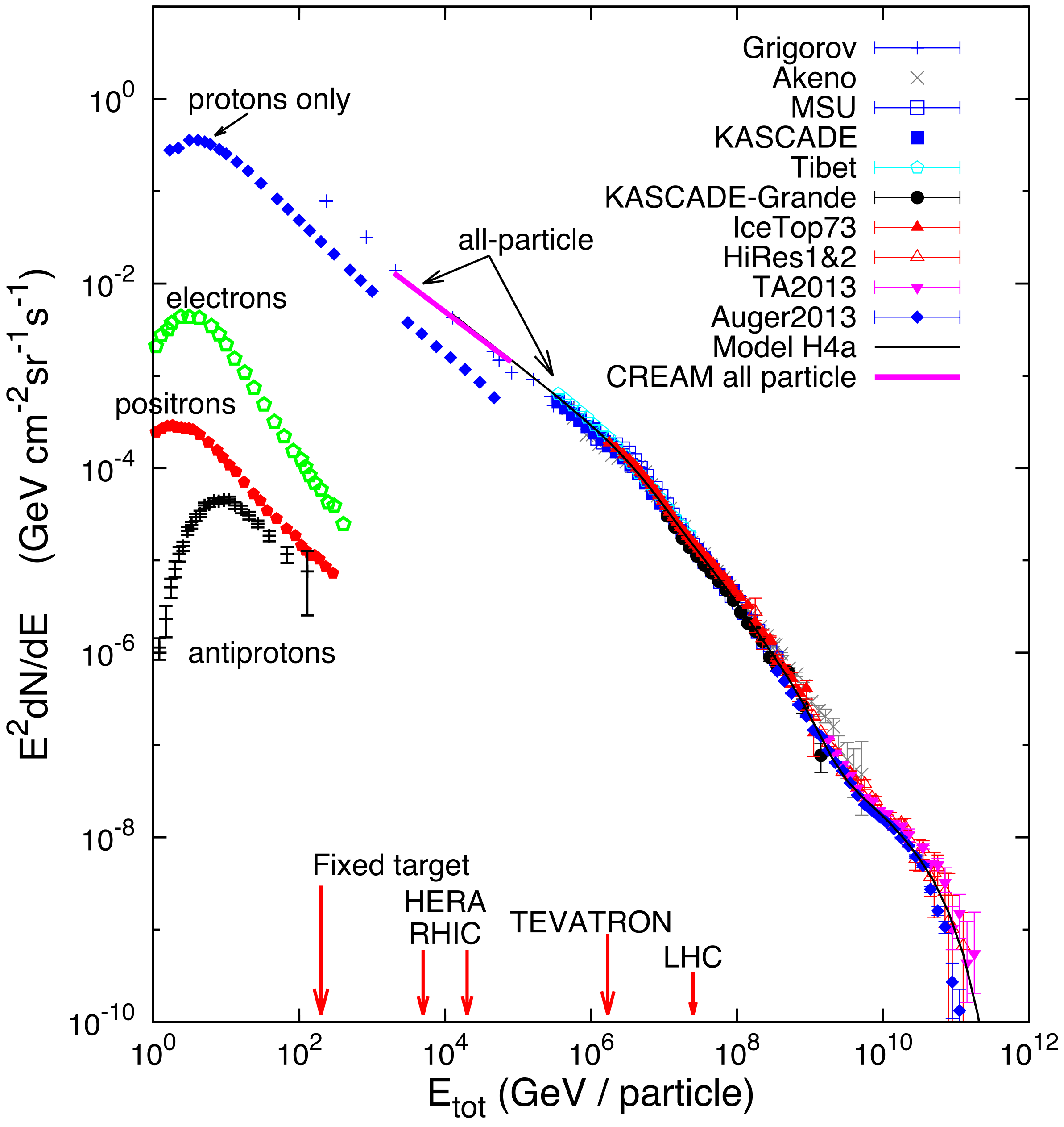
$K^0_S \rightarrow \pi e \nu_e$ (Gaisser & Klein 2014) **(0.07%)**

prompt

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

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



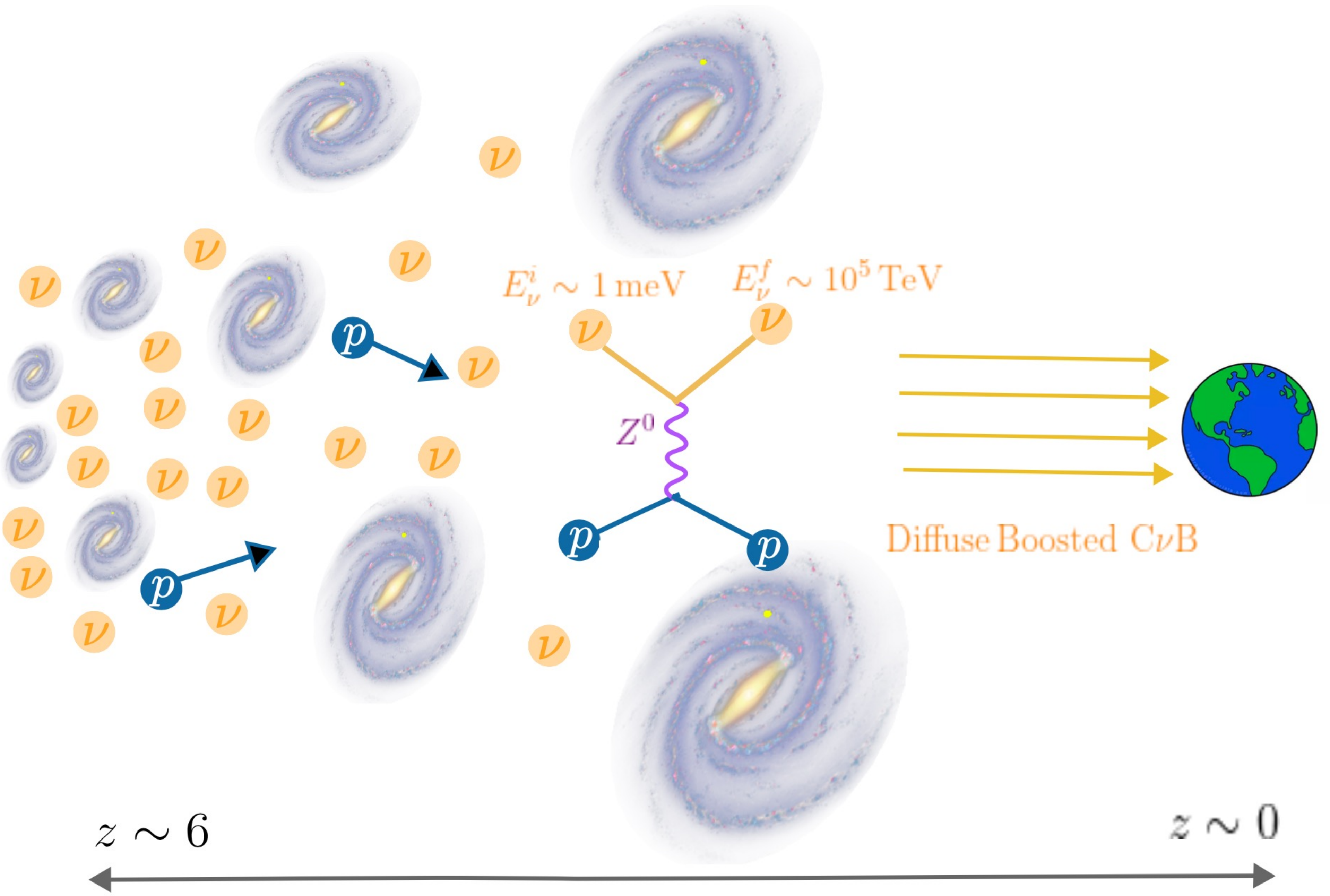



See Paolo's talk on cosmic rays

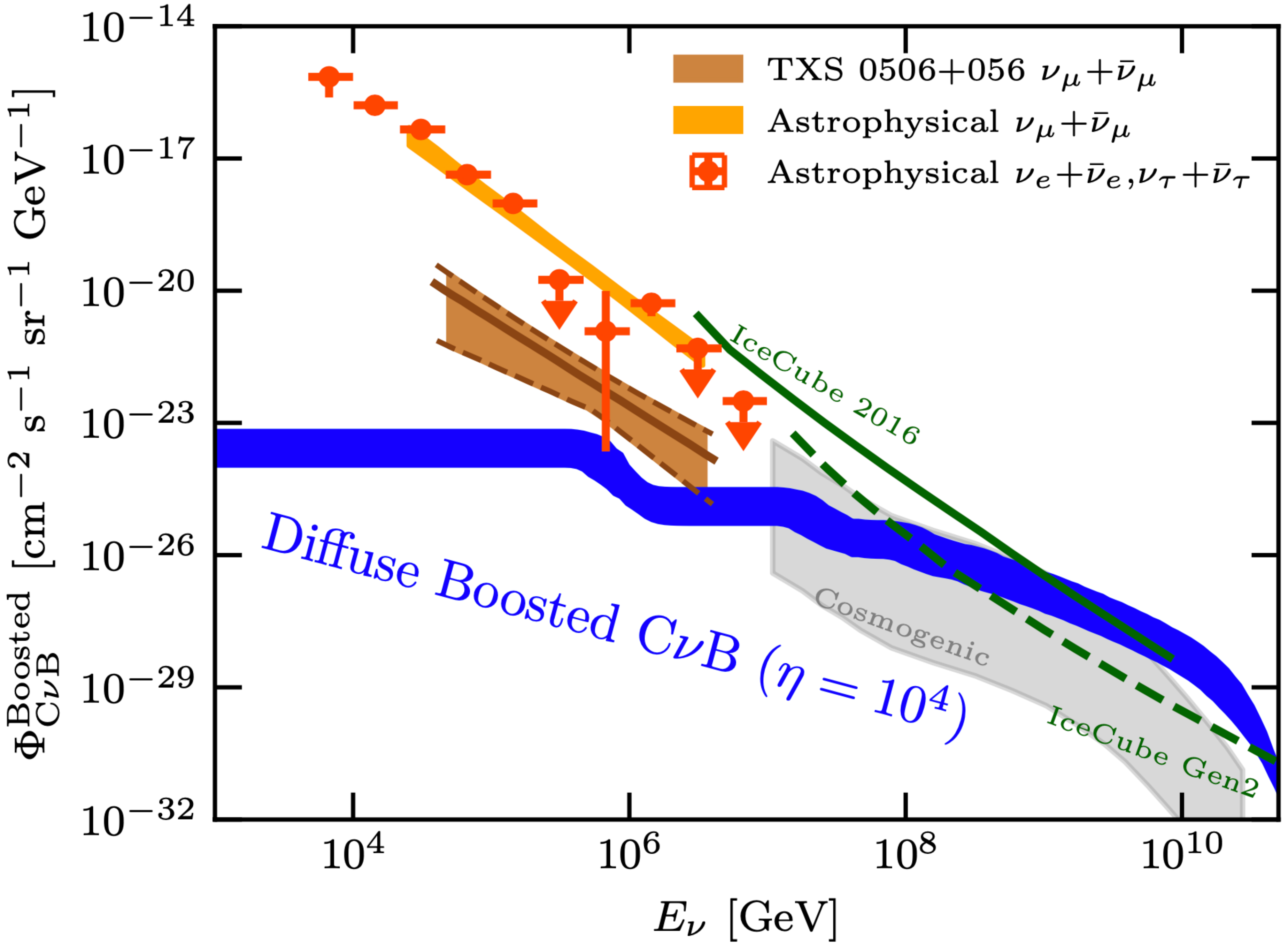
Cosmogenic neutrinos

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

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



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

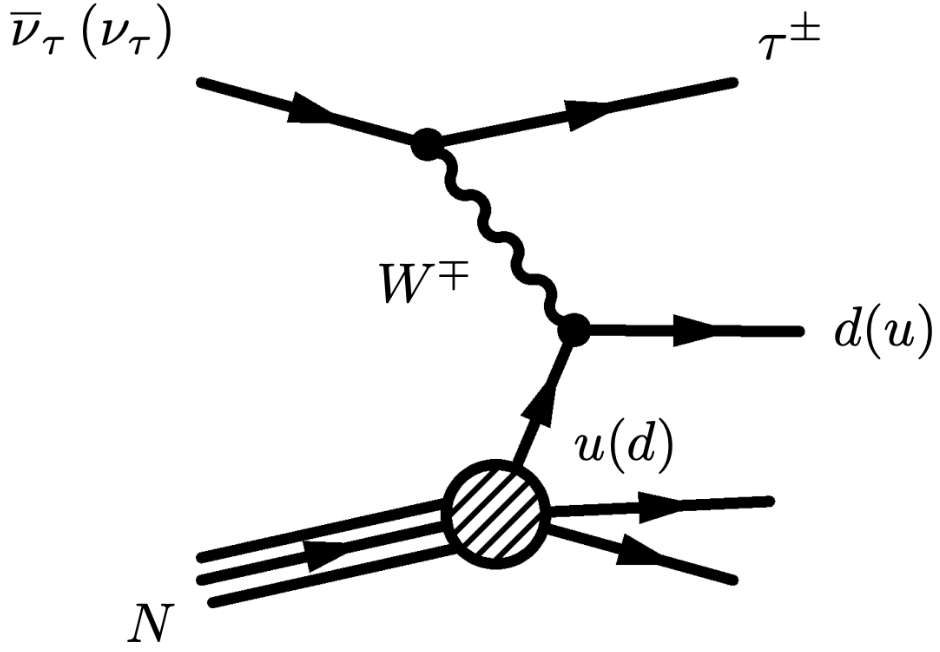


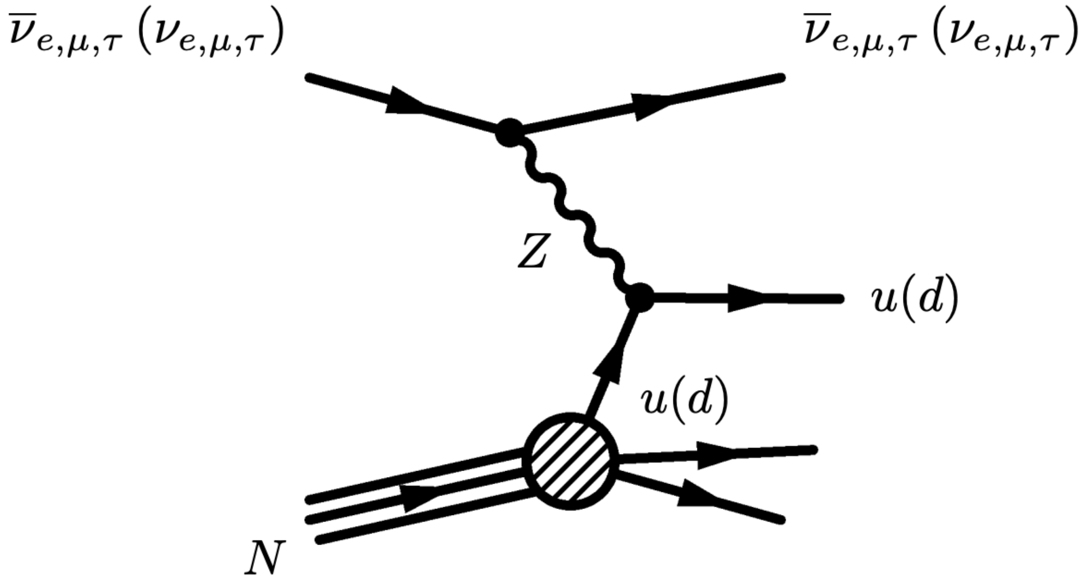
TXS 0506+056 $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_e+\bar{\nu}_e,\nu_\tau+\bar{\nu}_\tau$
IceCube 2016
IceCube Gen2
Cosmogenic
Diffuse Boosted C$\nu$B ($\eta = 10^4$)
$\Phi_{C\nu B}^{Boosted}$ [cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$]
$E_\nu$ [GeV]
$10^{-14}$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

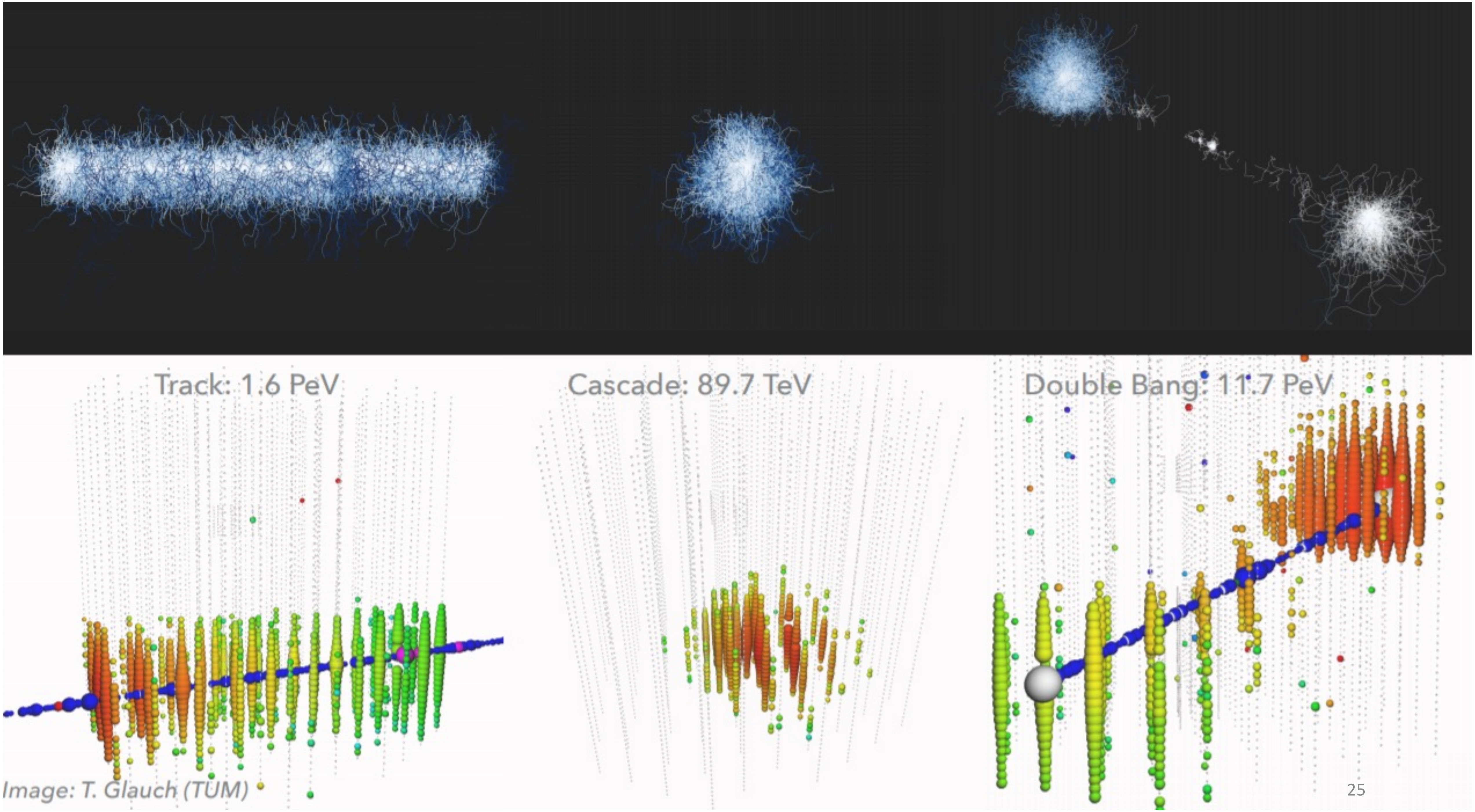
# What we observe – secondaries of neutrino interactions with matter

Deep inelastic neutrino-nucleon scattering

- Charged current and neutral current interactions

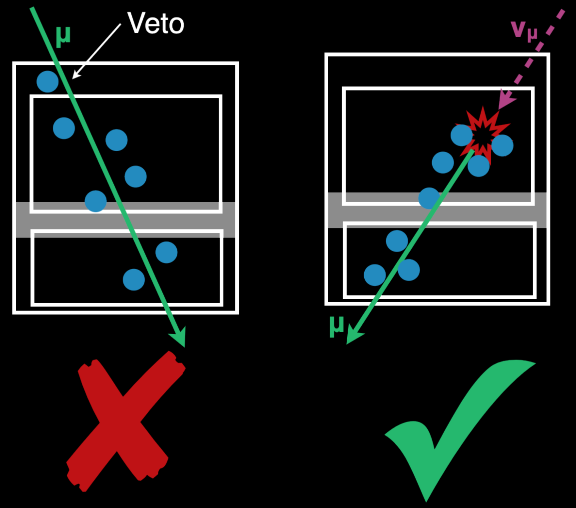



Track: 1.6 PeV
Cascade: 89.7 TeV
Double Bang: 11.7 PeV
Image: T. Glauch (TUM)

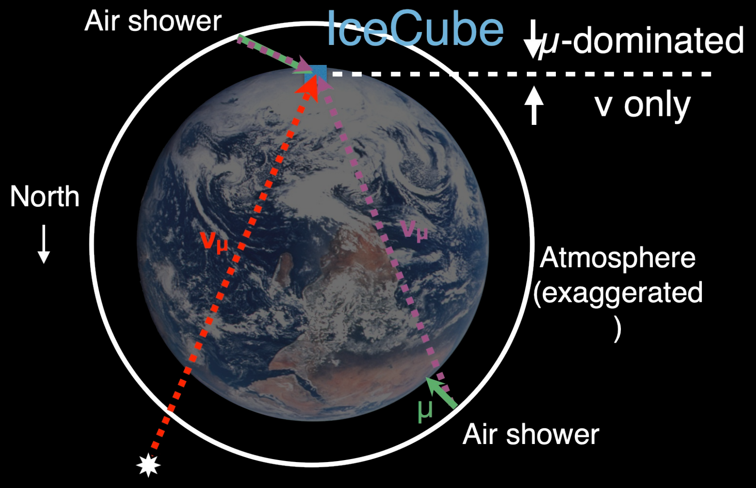
# Signal:Background~1:10million

## 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 $\nu_\mu$ only
Sensitive to “half” the sky

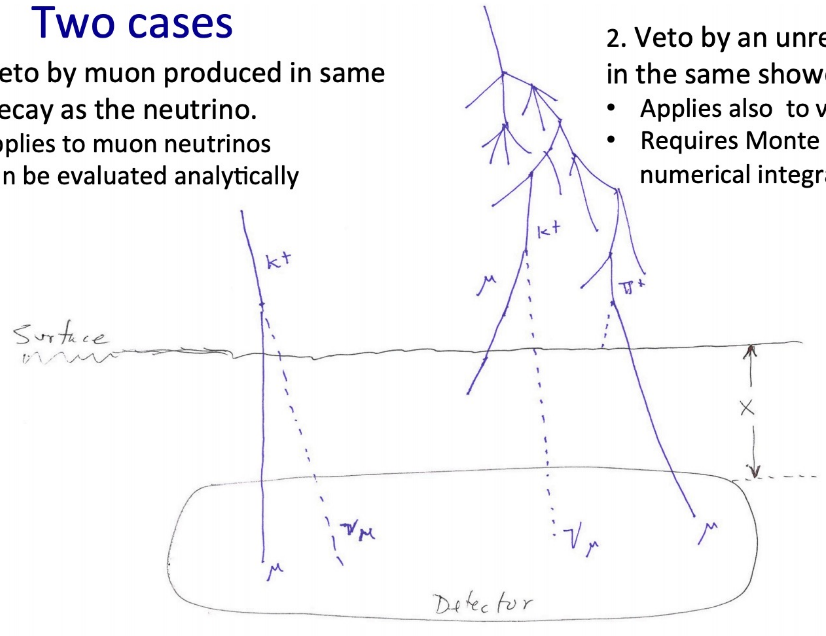
# Southern sky advantage: self-veto (slide from Tom Gaisser)

## Atmospheric neutrino self veto

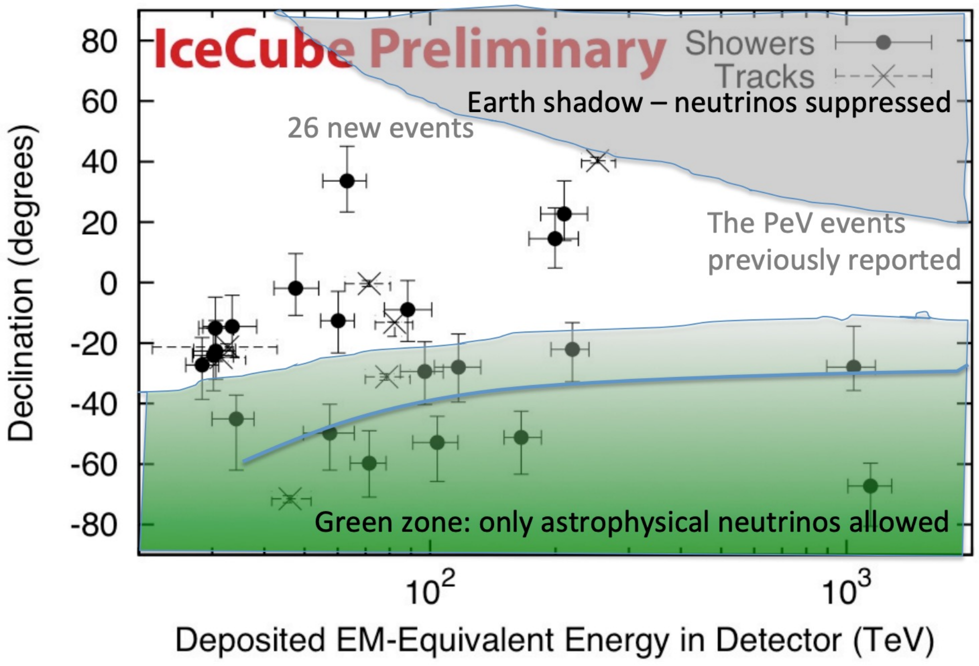
### Two cases

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

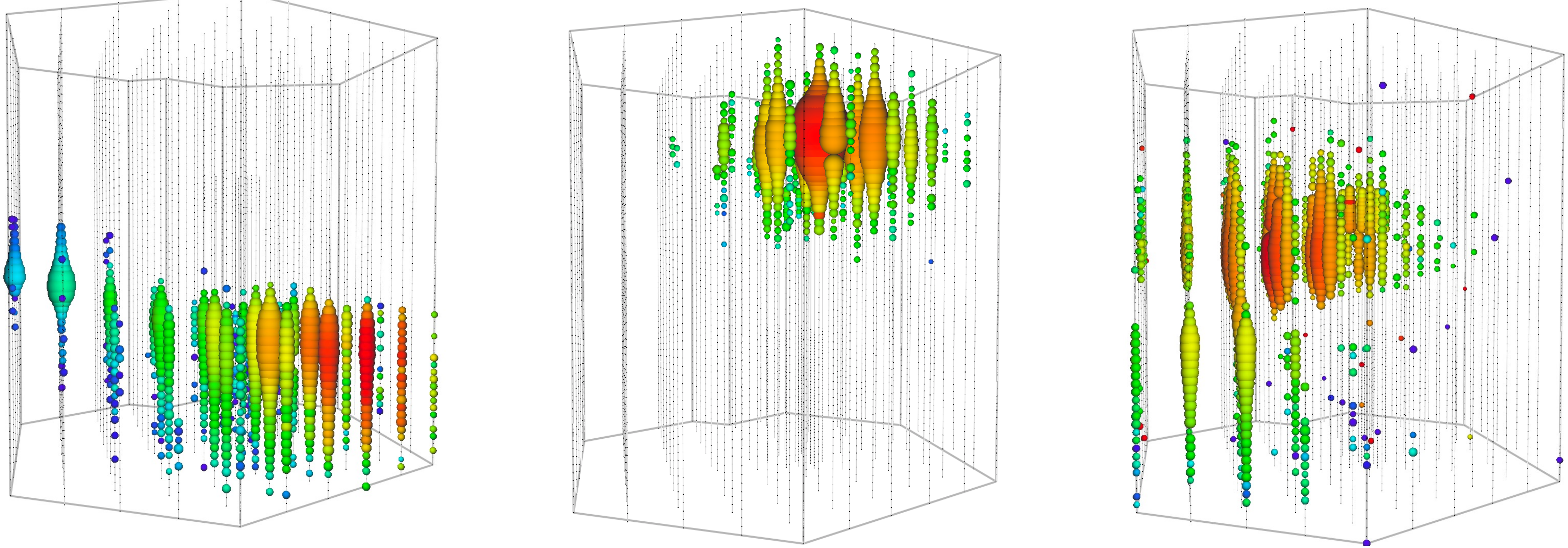
2. Veto by an unrelated μ in the same shower
   - Applies also to $\nu_e$
   - Requires Monte Carlo or numerical integration




## Results revisited

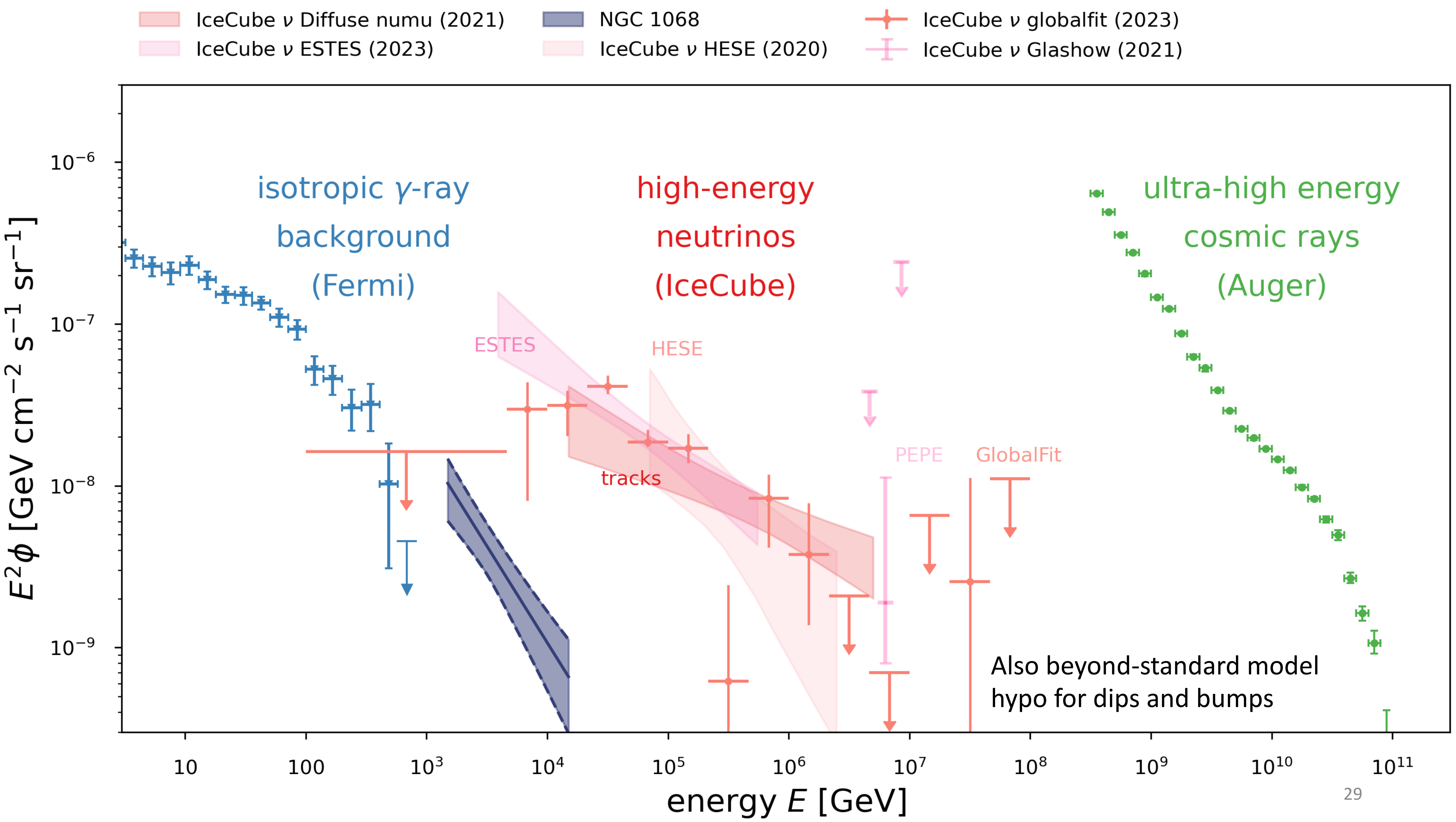



Argument applied to HESE, MESE, ESTES, cascade etc diffuse measurements



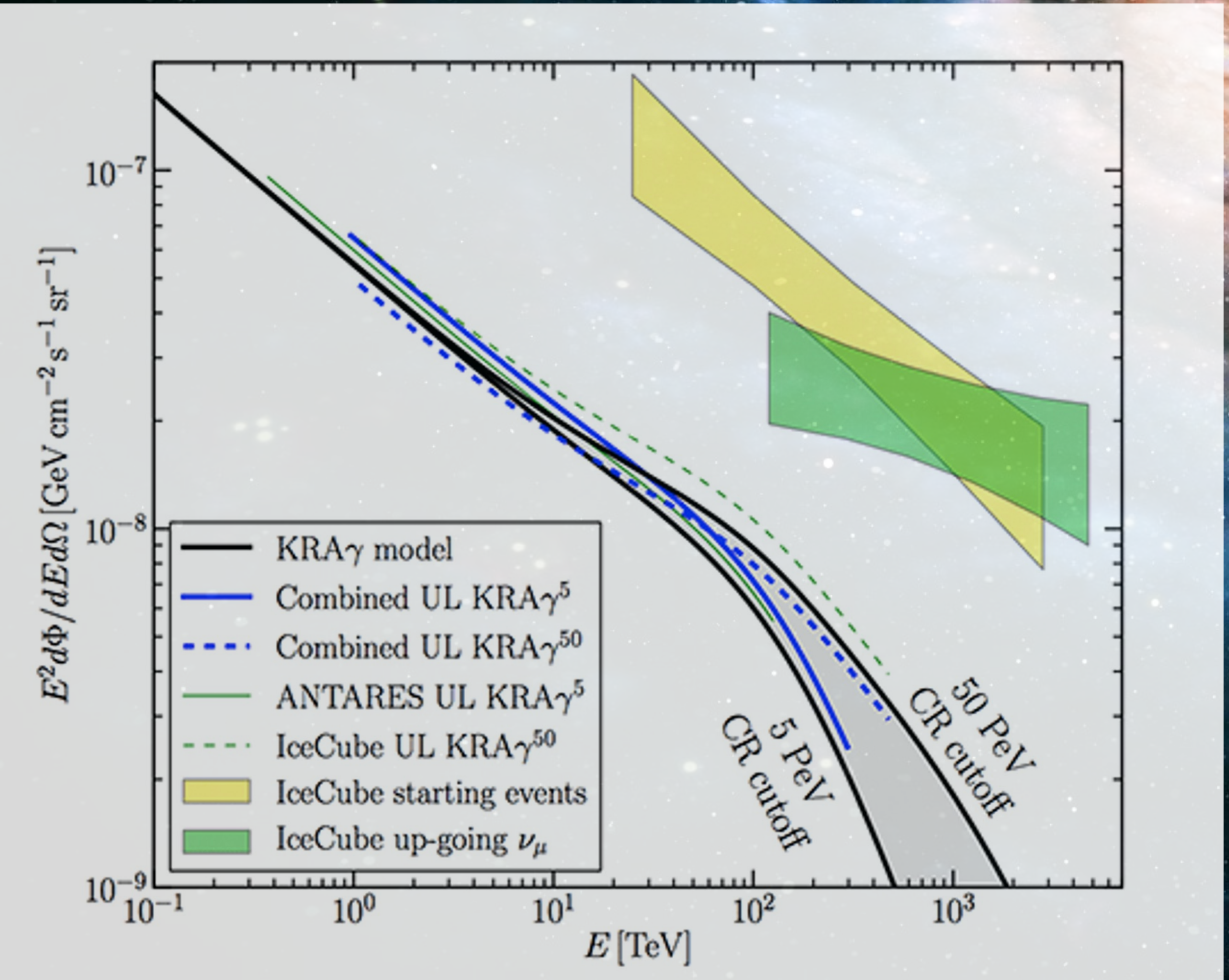
6 events > PeV

-> IceCube Gen2 (see Yuya Makino's talk)

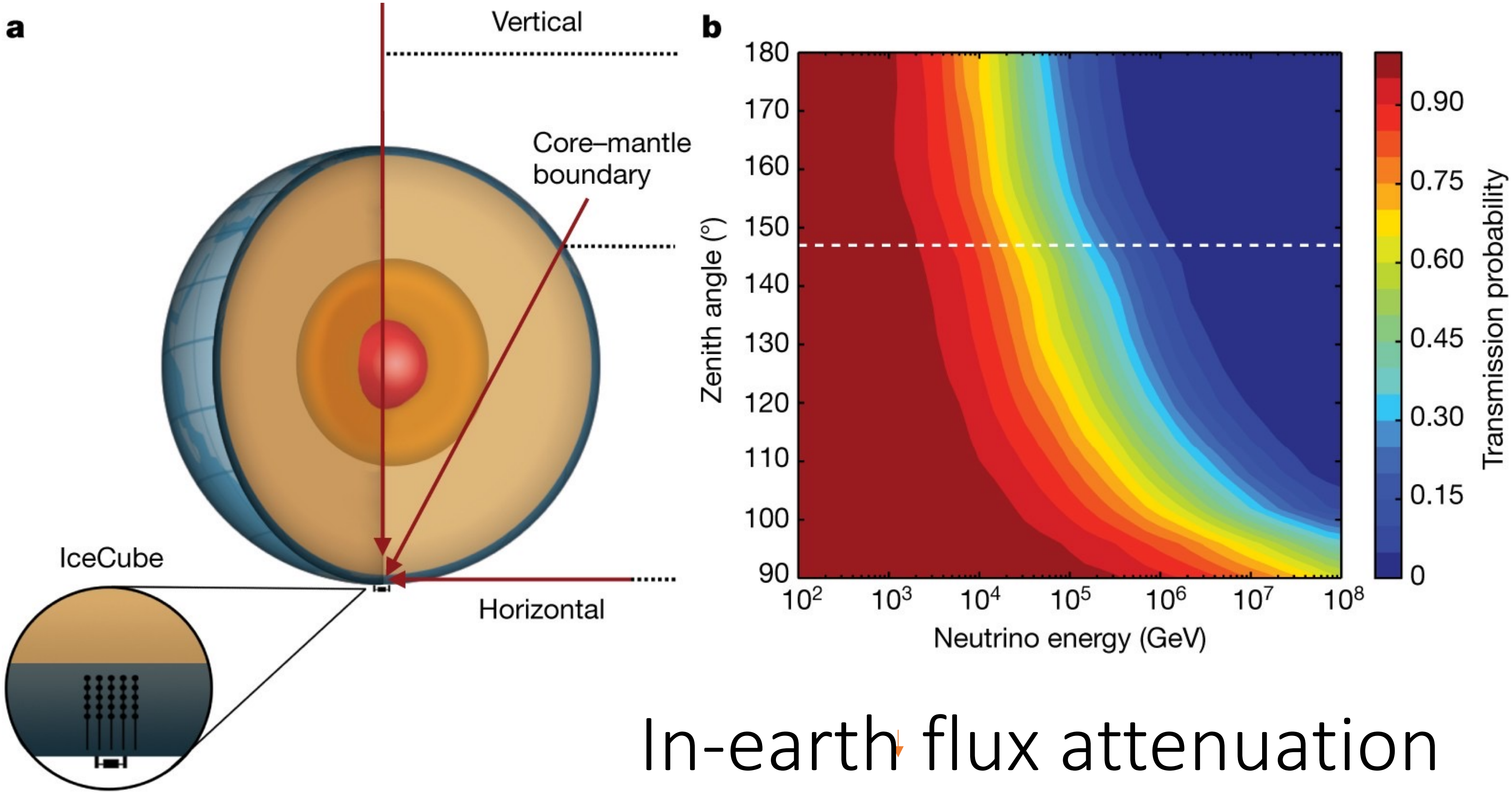


IceCube ν Diffuse numu (2021)
IceCube ν ESTES (2023)
NGC 1068
IceCube ν HESE (2020)
IceCube ν globalfit (2023)
IceCube ν Glashow (2021)
isotropic γ-ray background (Fermi)
high-energy neutrinos (IceCube)
ultra-high energy cosmic rays (Auger)
ESTES
HESE
tracks
PEPE
GlobalFit
Also beyond-standard model hypo for dips and bumps
$E^2\phi$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
energy $E$ [GeV]

# Galactic plane



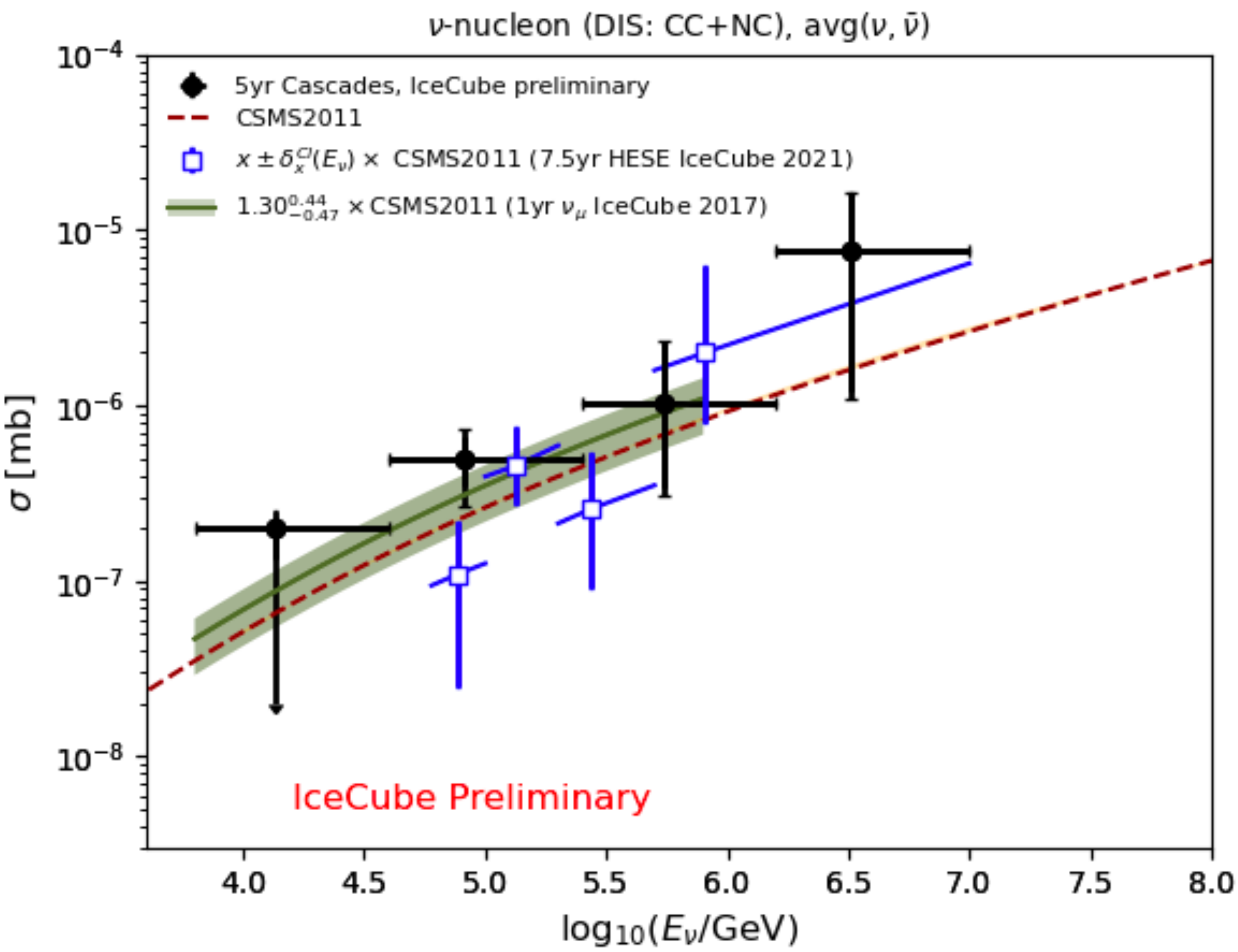
# Cross section measurement using Earth as the target




In-earth flux attenuation

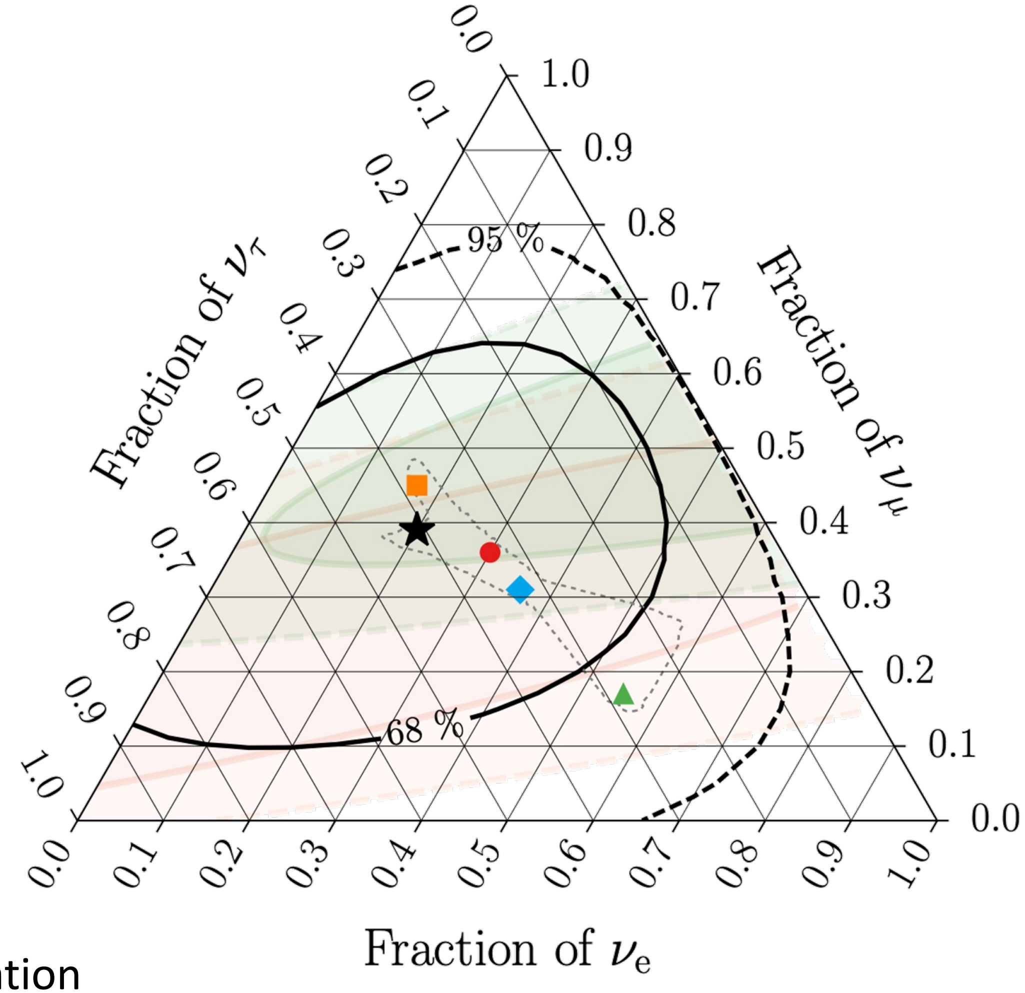
# Cross section

- Both tracks and cascades
- Reaching energies beyond accelerators

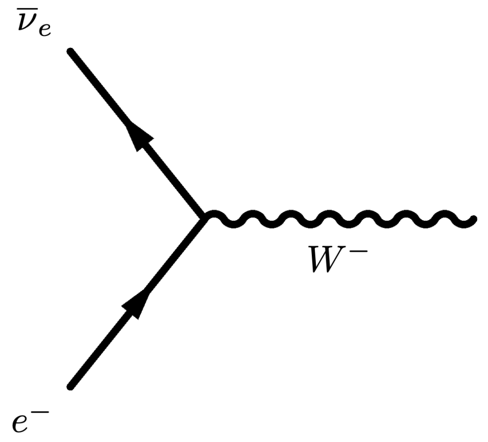


# Neutrino oscillations over cosmic baselines

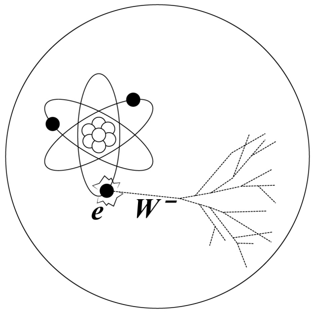
- For the first time tau candidates in data
- Observed high-energy tau neutrinos mainly due to neutrino oscillations through astronomical distances.
- Sensitive probe for physics beyond the Standard Model




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




# Neutrino-electron scattering



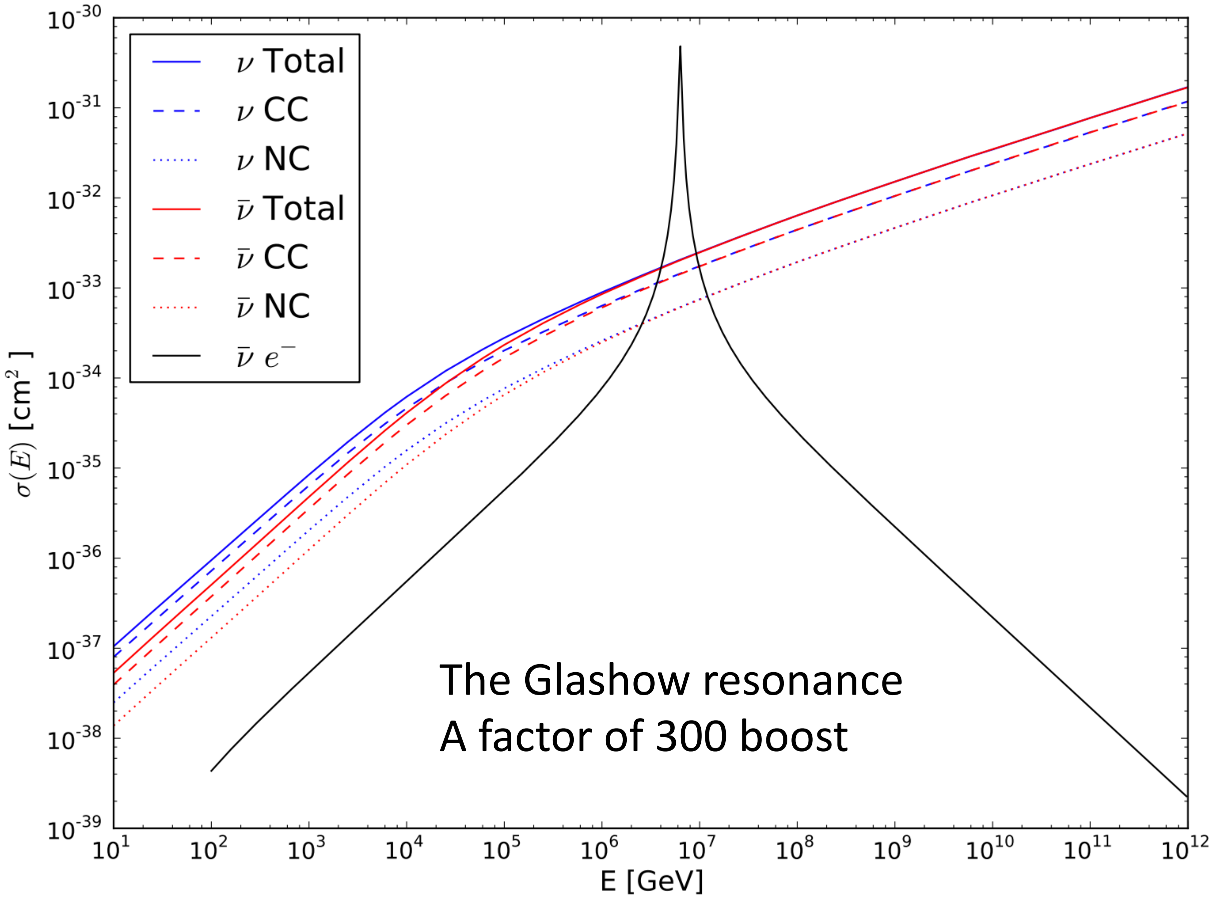

at a neutrino energy of 6.3 PeV, the centre-of-mass energy (80.5 GeV) is large enough to produce a real W boson

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

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

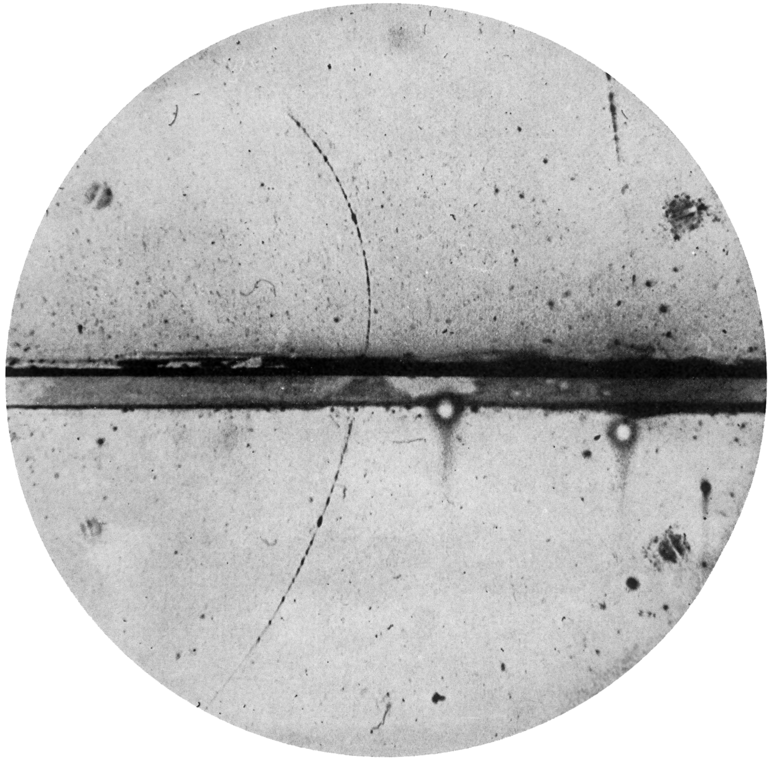
$$\overline{\nu_e} + e \quad \to W^- \to \quad X \quad ,$$

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

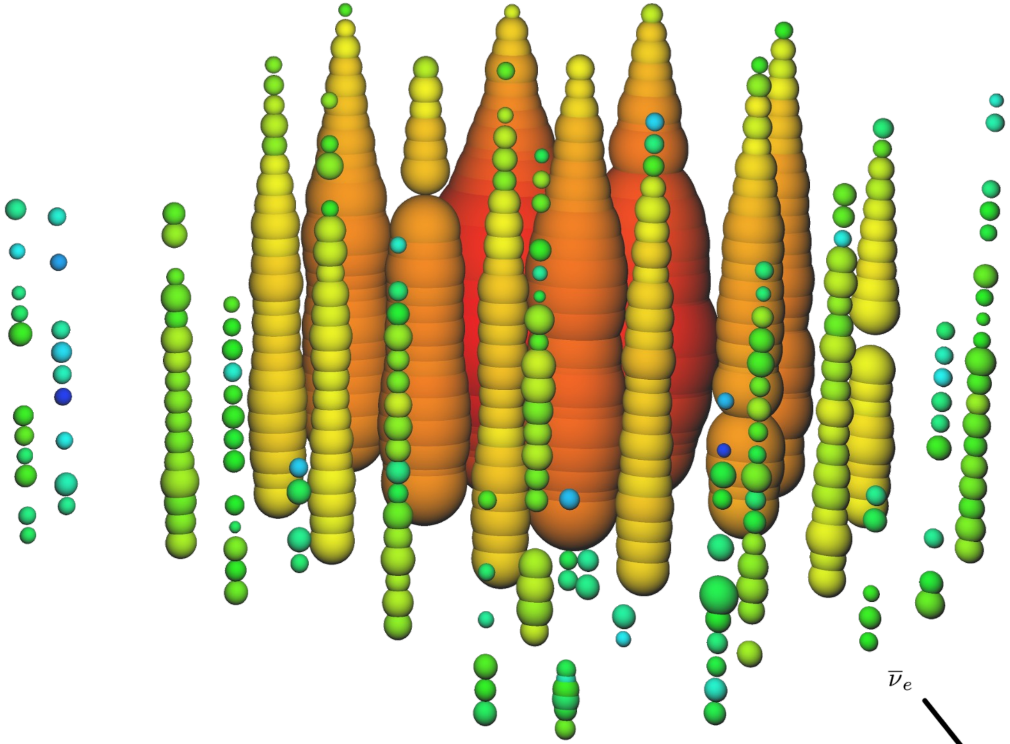


# W boson (Glashow) resonance – first hint of electron anti-neutrino

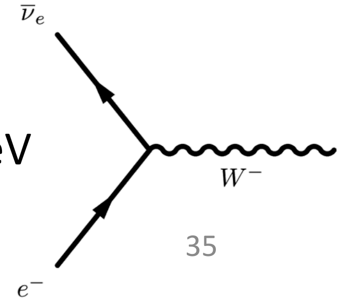
*Nature* **591,** 220–224 (2021)



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

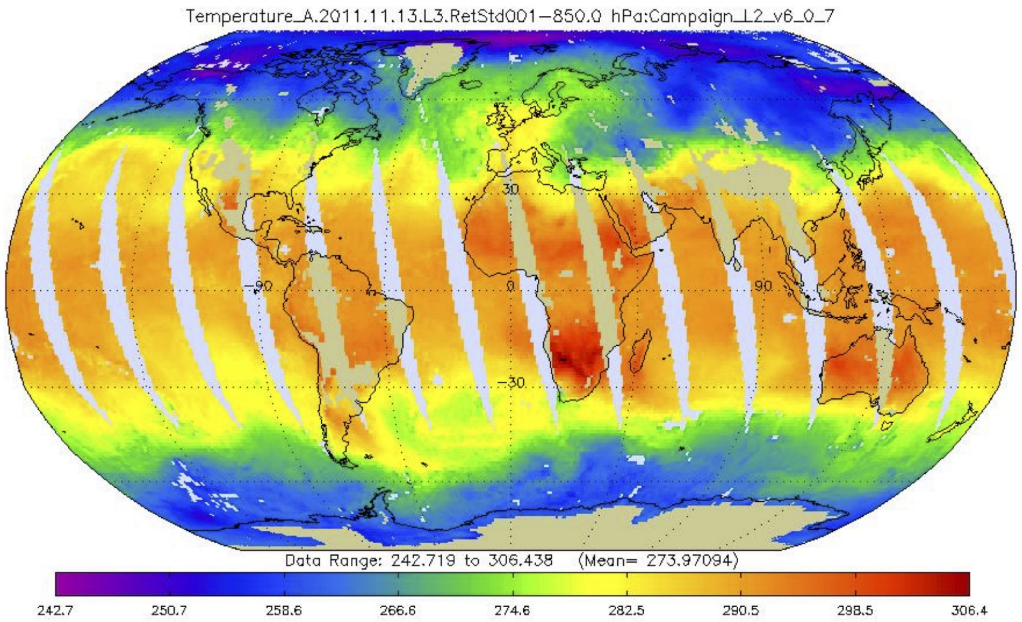


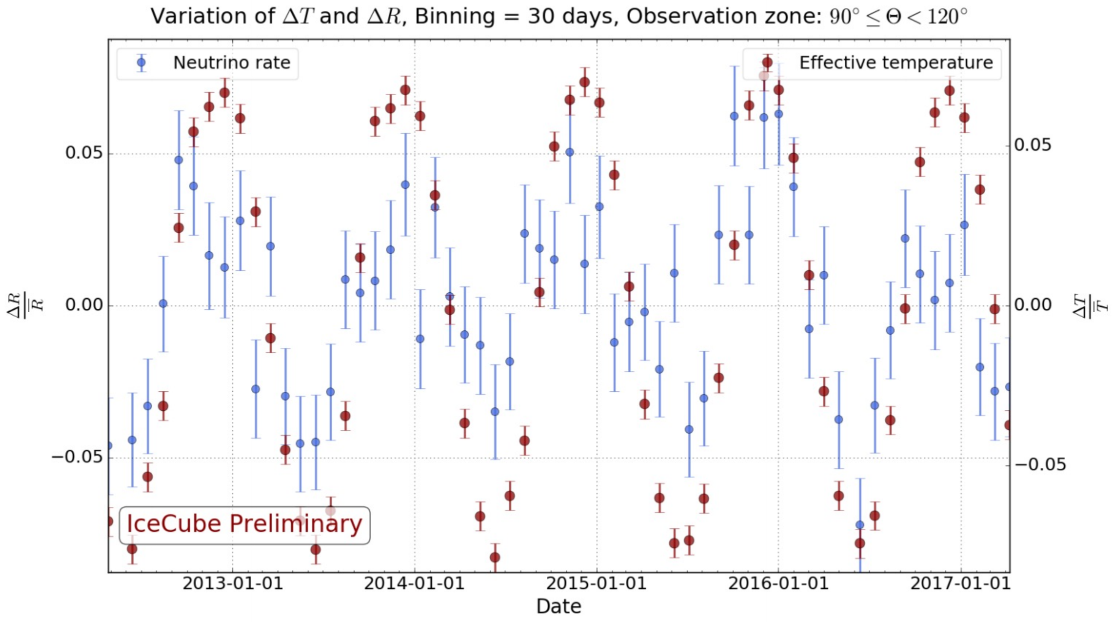
W boson resonance , nuebar 6.3 PeV
IceCube, 2021



# (atmospheric) Neutrino weather!

Lead by Aachen group



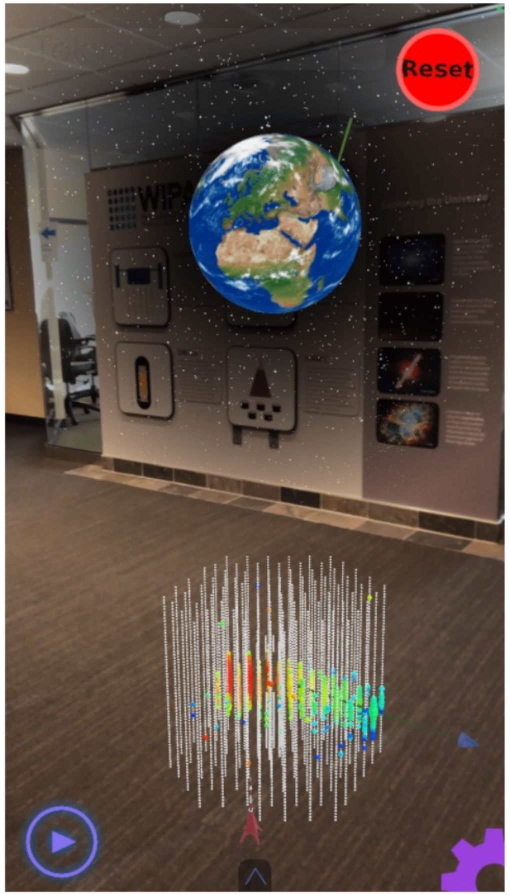



I hope 'diffuse' makes sense to you now

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



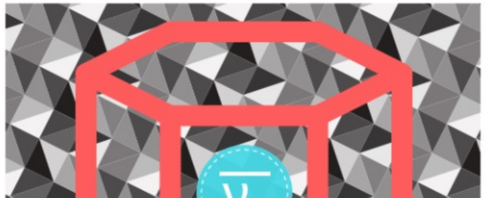

*A screenshot from the IceCubeAR app.*

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

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