A relook at the GZK effect

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Greisen, PRL (1966), Zatsepin and Kuzmin, JETP Letters (1966)

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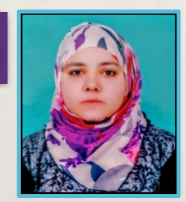
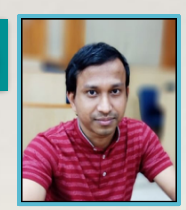


Sheeba Shafaq (2022)

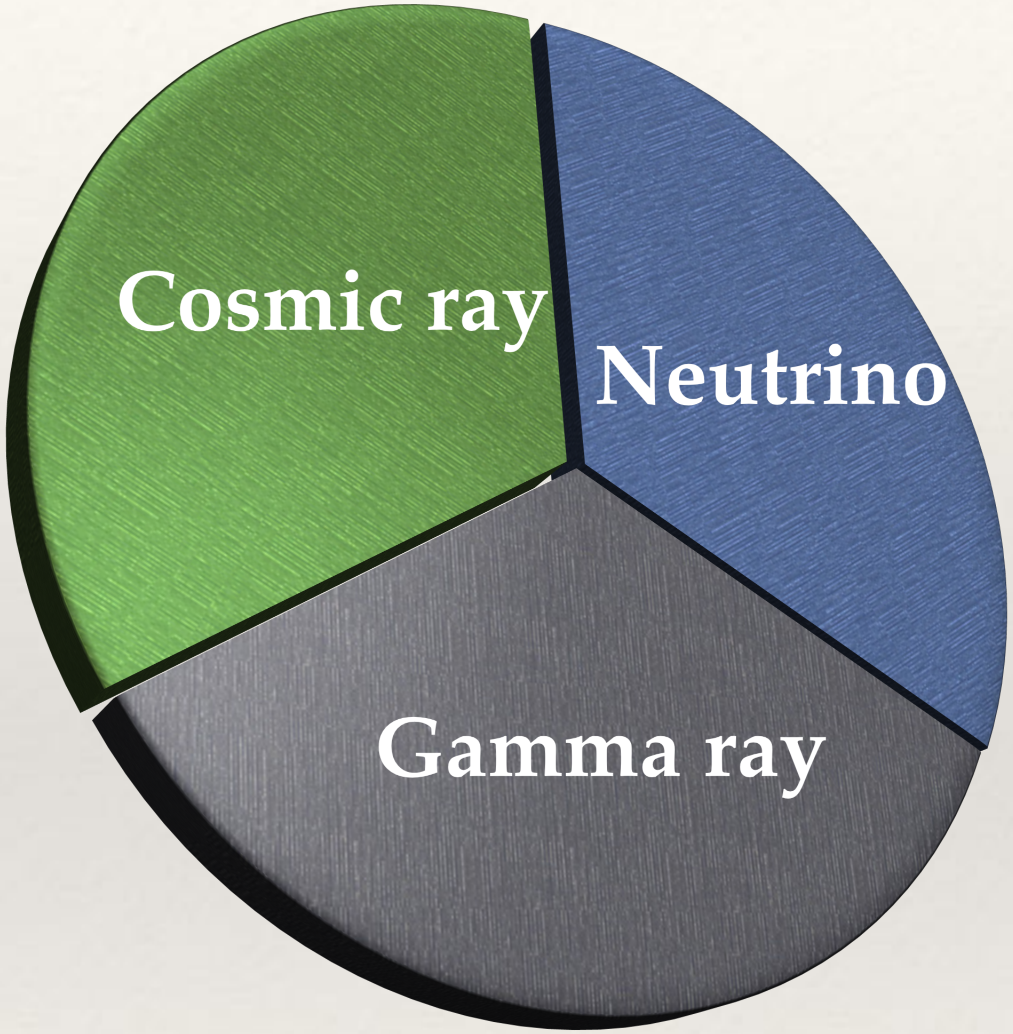
Samiran Roy (2020)



JNU-HBNI MoU

Jogesh Rout (2020)

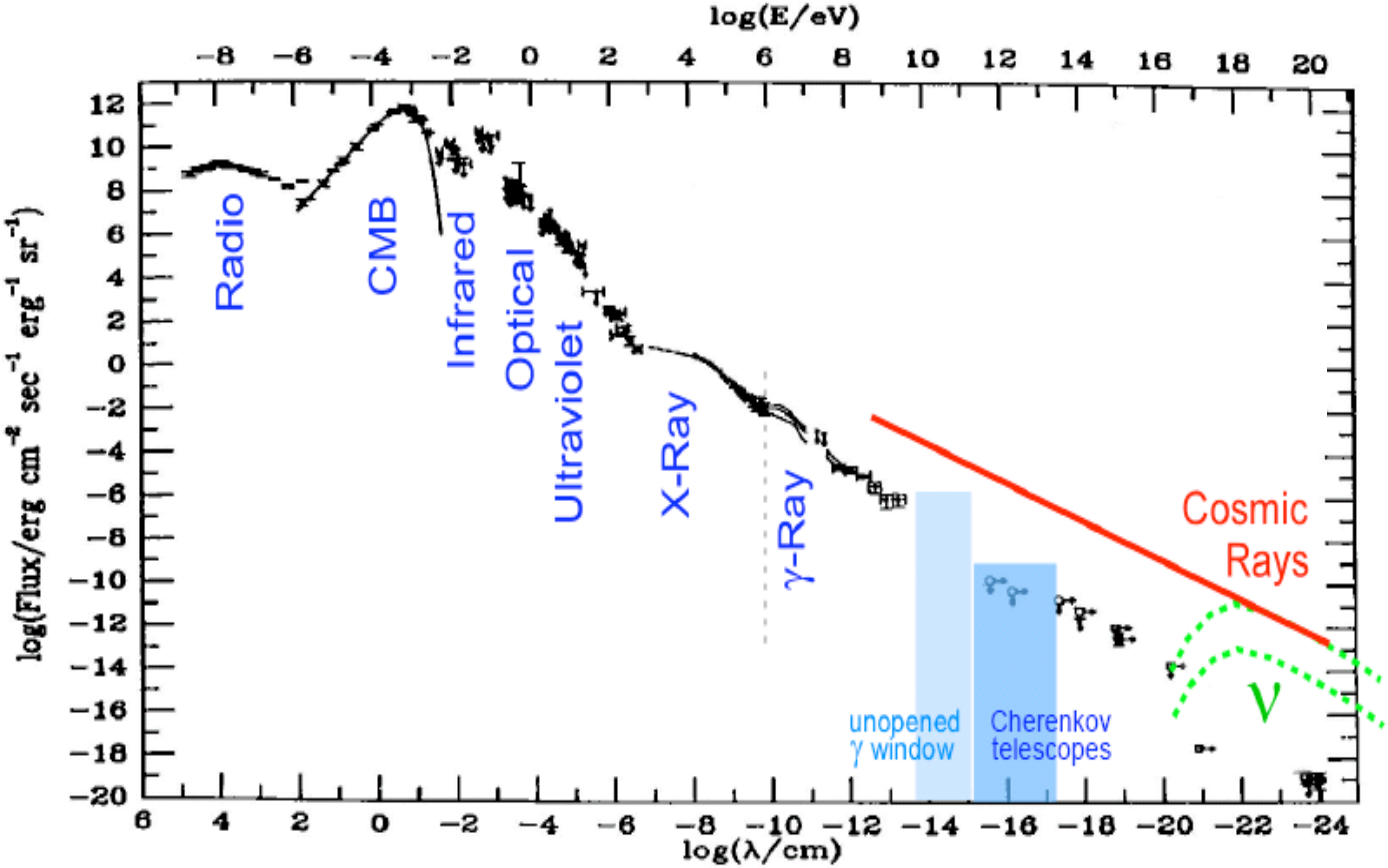
The three messengers at extreme energies



work with Prantik Sarmah and Sovan Chakraborty (IIT Guwahati),

JCAP 01, 058 (2024)

We cannot see the deep universe at energies > few TeV, since photons are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on cosmic radiation backgrounds



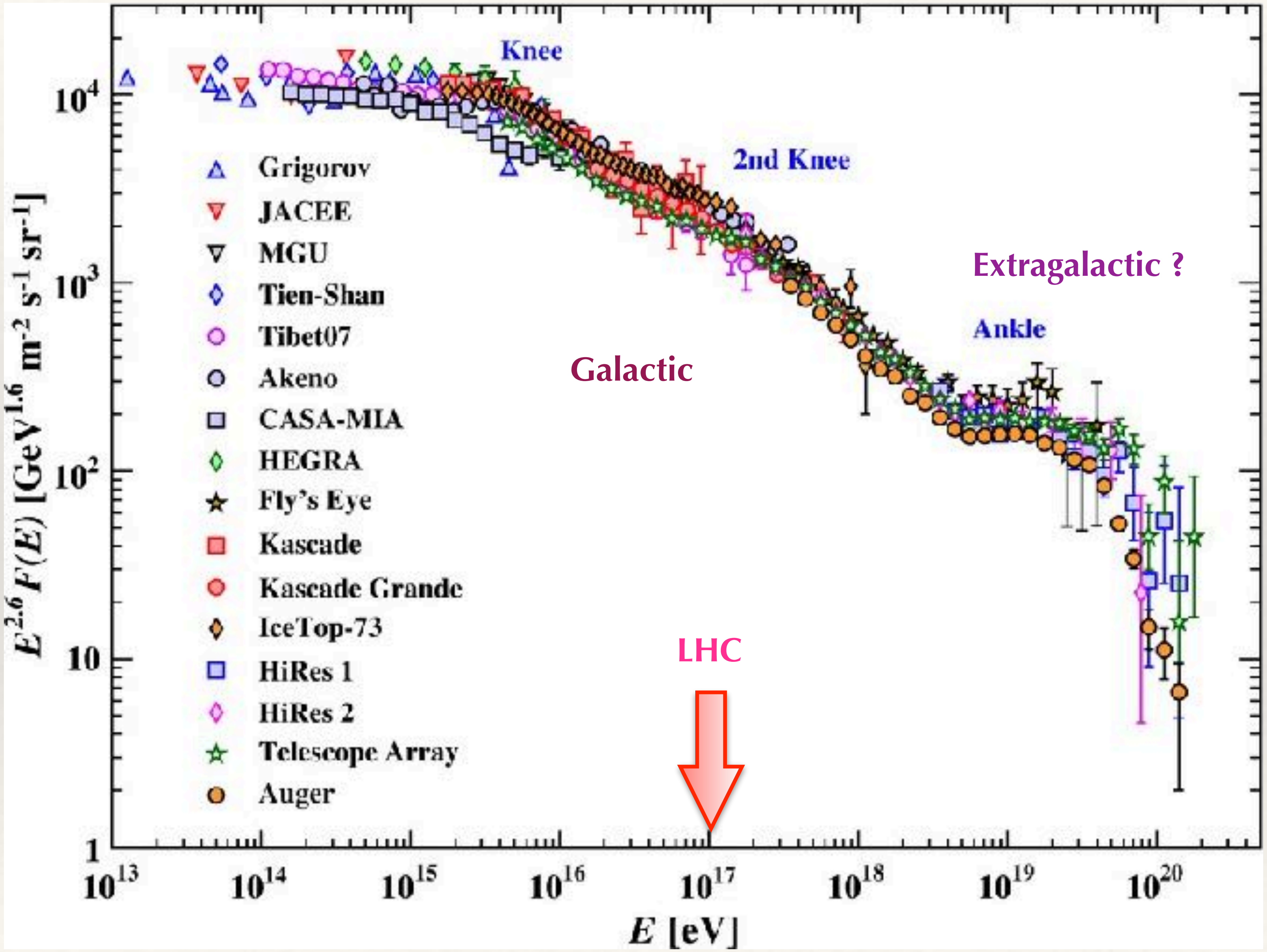
Courtesy : Subir Sarkar

But using cosmic rays we can 'see' up to ~ 6 x 10^{10} GeV before they get attenuated through photopion interactions on the CMB

… and the universe is ~transparent to neutrinos at effectively all energies

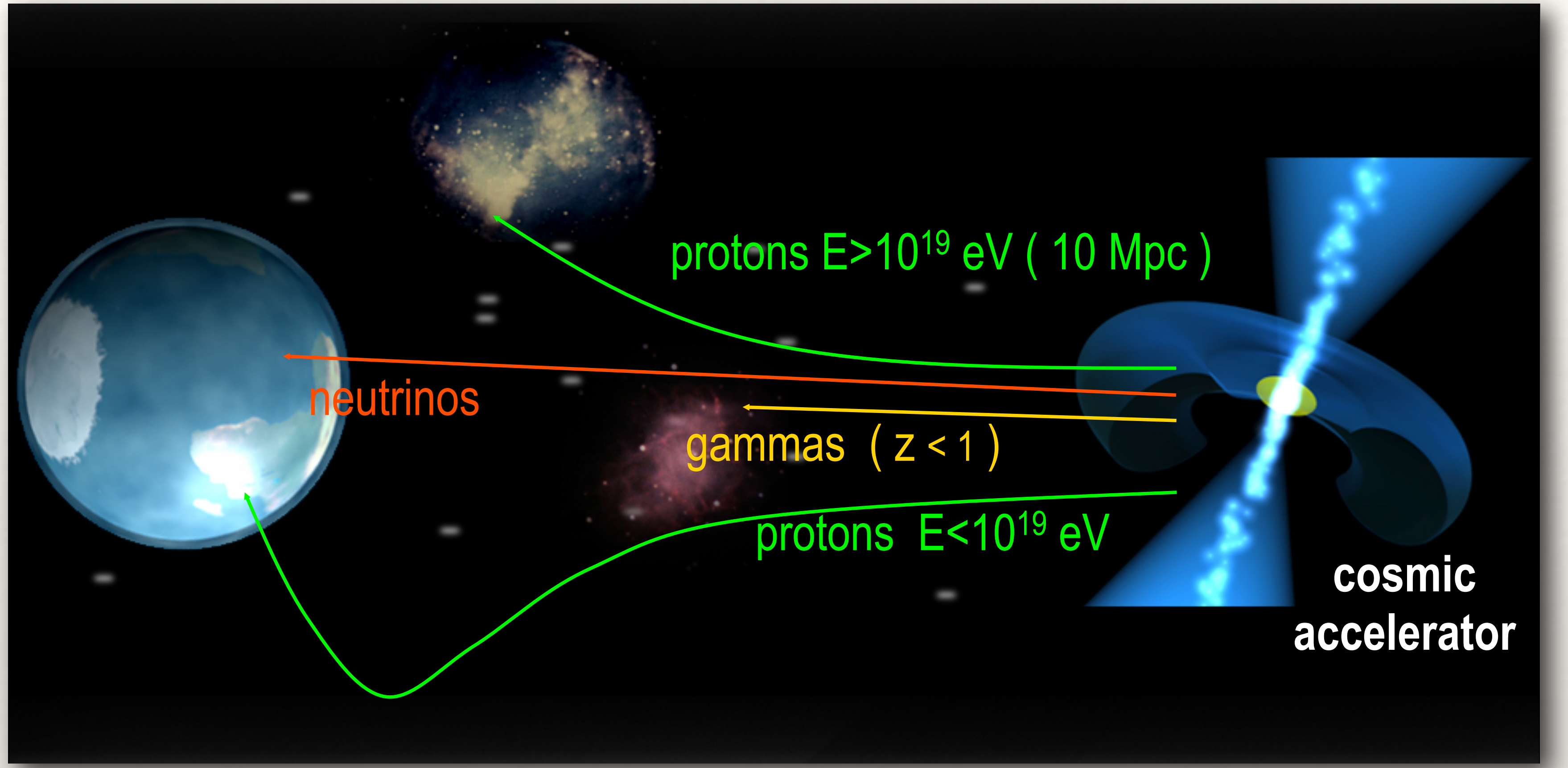
Cosmic ray spectrum

Courtesy : Subir Sarkar



Cosmic accelerators

Courtesy : Montaruli, SSI 2010

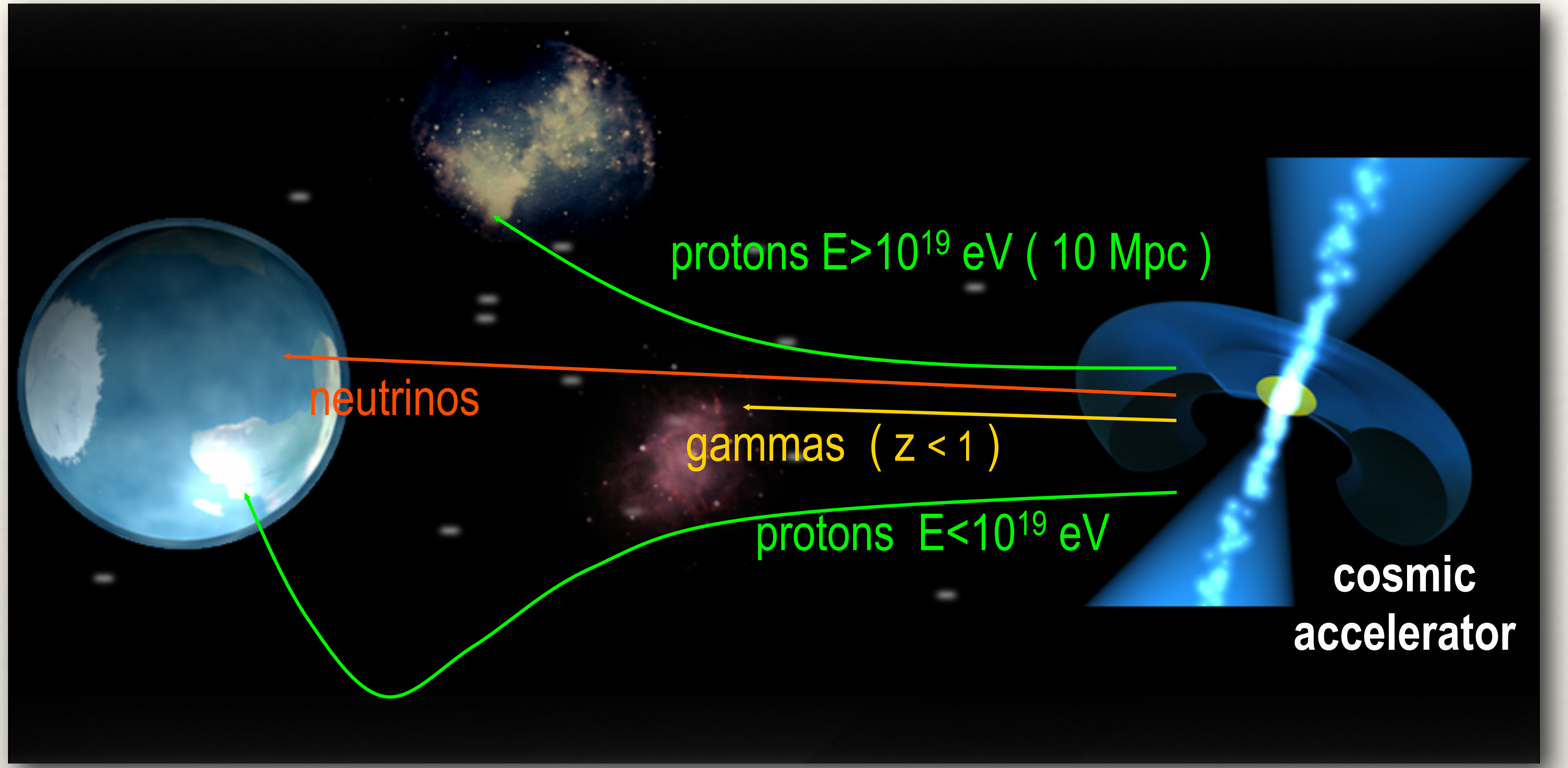


- protons/nuclei: deflected by magnetic fields, absorbed on radiation (GZK)
- photons: absorbed on radiation/dust; reprocessed at source
- neutrinos: neither absorbed nor bent, straight path from source

$1pc = 3.1 \times 10^{13}\ km$

Cosmic accelerators

Courtesy : Montaruli, SSI 2010



Neutrinos : can reliably lead to the discovery of such point sources

$$\gamma + \gamma_{2.7K}$$

$$l_\gamma = \frac{1}{\sigma_{p-\gamma_{2.7K}} \times n_\gamma} \sim \frac{1}{5 \times 10^{-28} cm^2 \times 400 cm^{-3}} = 10 Mpc$$

$$\nu + \nu_{1.95K} \rightarrow Z + X$$

$$l_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{-31} cm^2 \times 112 cm^{-3}} = 6 Gpc$$

A typical cosmic accelerator

Pion photoproduction

$$p + \gamma \rightarrow \Delta_{1232} \rightarrow p + \pi^0 \quad \text{BR=2/3}$$

$$p + \gamma \rightarrow \Delta_{1232} \rightarrow n + \pi^+ \quad \text{BR=1/3}$$

Weak decays

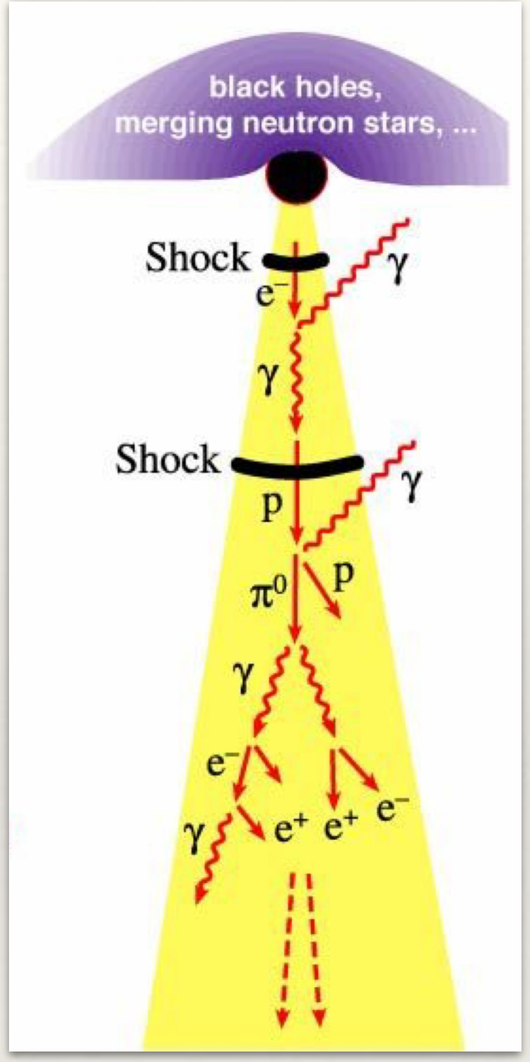
1:2:0

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

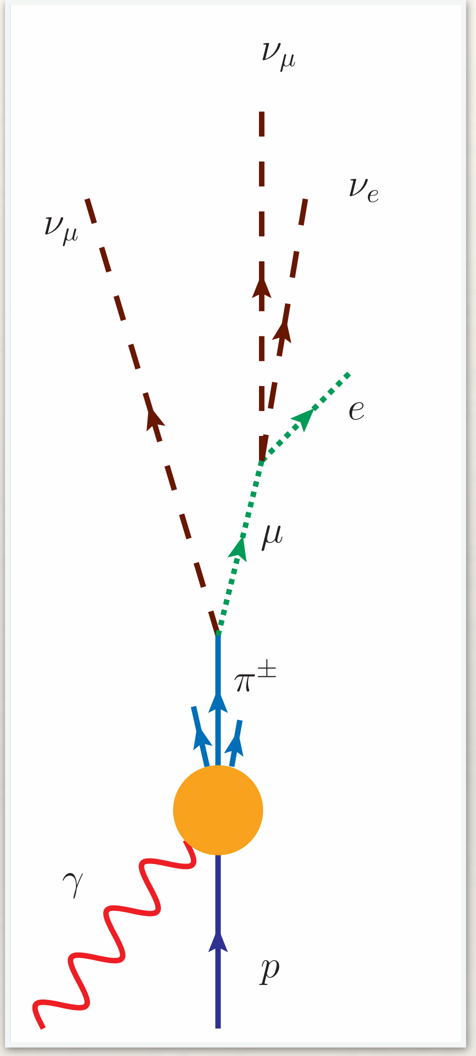
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

If n exits the source

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Ref: Halzen, ICRC'07



Hadron-hadron interactions

$$p + p \rightarrow \pi^\pm$$

A typical cosmic accelerator

Pion photoproduction

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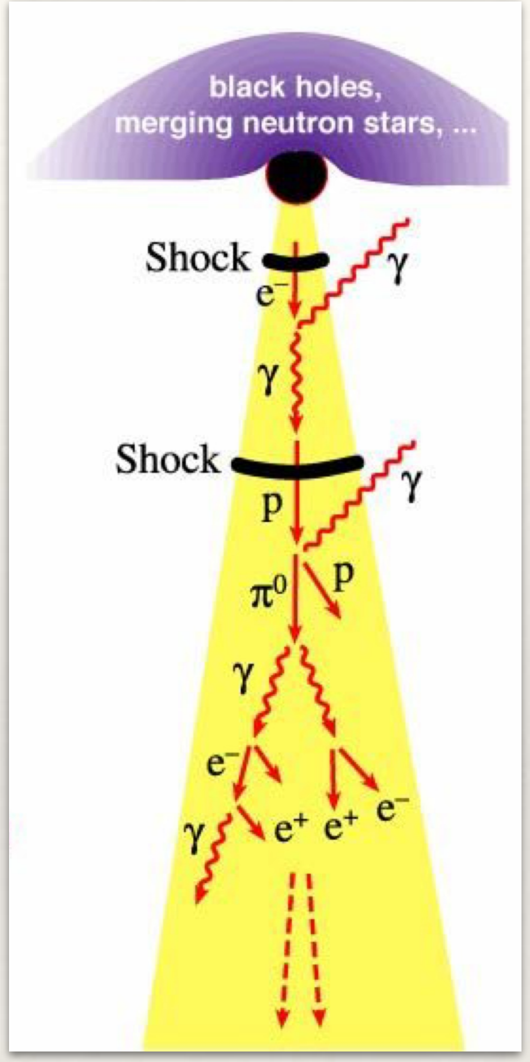

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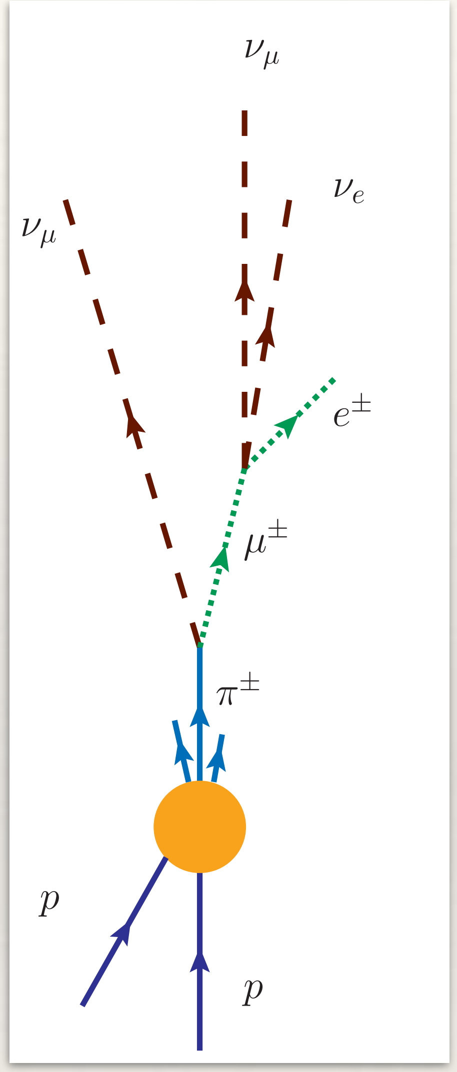


Hadron-hadron interactions

$$p + p \to \pi^\pm$$

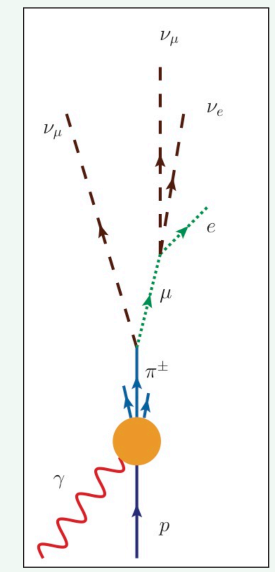
Flavor composition

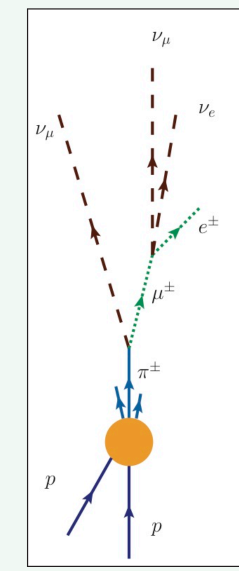
Classification of sources

Pakvasa, MPLA23, 1313 (2008) , talk@Nusky2011 A relativistic jet [credits : Zhang and Woosley]

Source Candidates : AGN, GRB, SNR, MQ

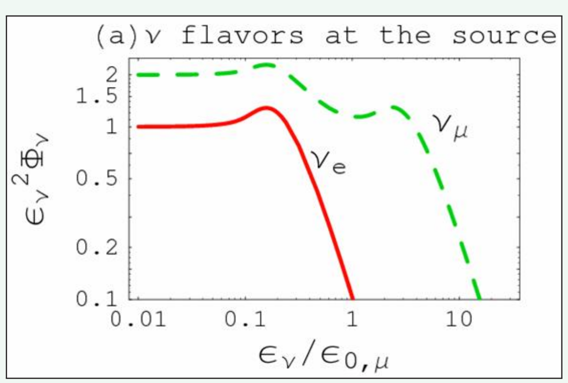
1. Conventional pion beam source :
   Cosmic rays (assumed to be p) interact with γ or p and produce charged mesons (pions, kaons) which decay to give neutrinos via the $\pi \to \mu \to e$ decay chain :
   $p\gamma$: $p + \gamma \to \pi^{\pm} + \text{all}$; pp : $p + p \to \pi^{\pm} + \text{all}$
2. Damped muon source : Muons lose energy prior to decay (depends on E)
3. Muon decay : Muons from damped muon source decay at lower E
4. Prompt : Decay of short-lived heavy flavors (pions interact and do not decay)
5. Neutron decay : Photodisintegration of heavy nuclei



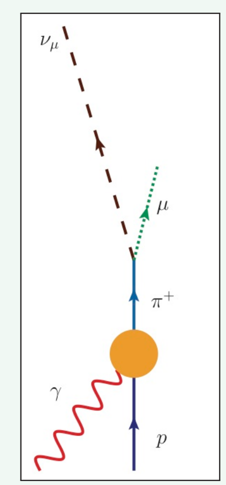


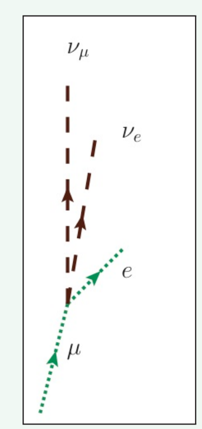
- Source type can be characterized by $\widehat{X} = \Phi_e^0/\Phi_\mu^0$ (since Φ_τ^0 is negligible)
- However same source can mimic different source types as a function of E i.e. $\widehat{X}(E)$

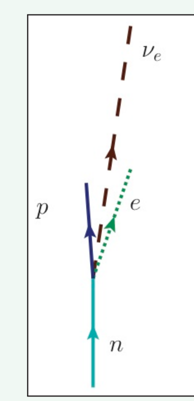
Kashti and Waxman, PRL95, 181101 (2005)



Source	$\widehat{X}$	$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0$
Pion beam	0.5	1:2:0
Neutron decay	>> 1	1:0:0
Muon decay/Prompt	1	1:1:0
Damped muon	0	0:1:0







Astrophysical parameter space

- Hillas criterion for acceleration and confinement :

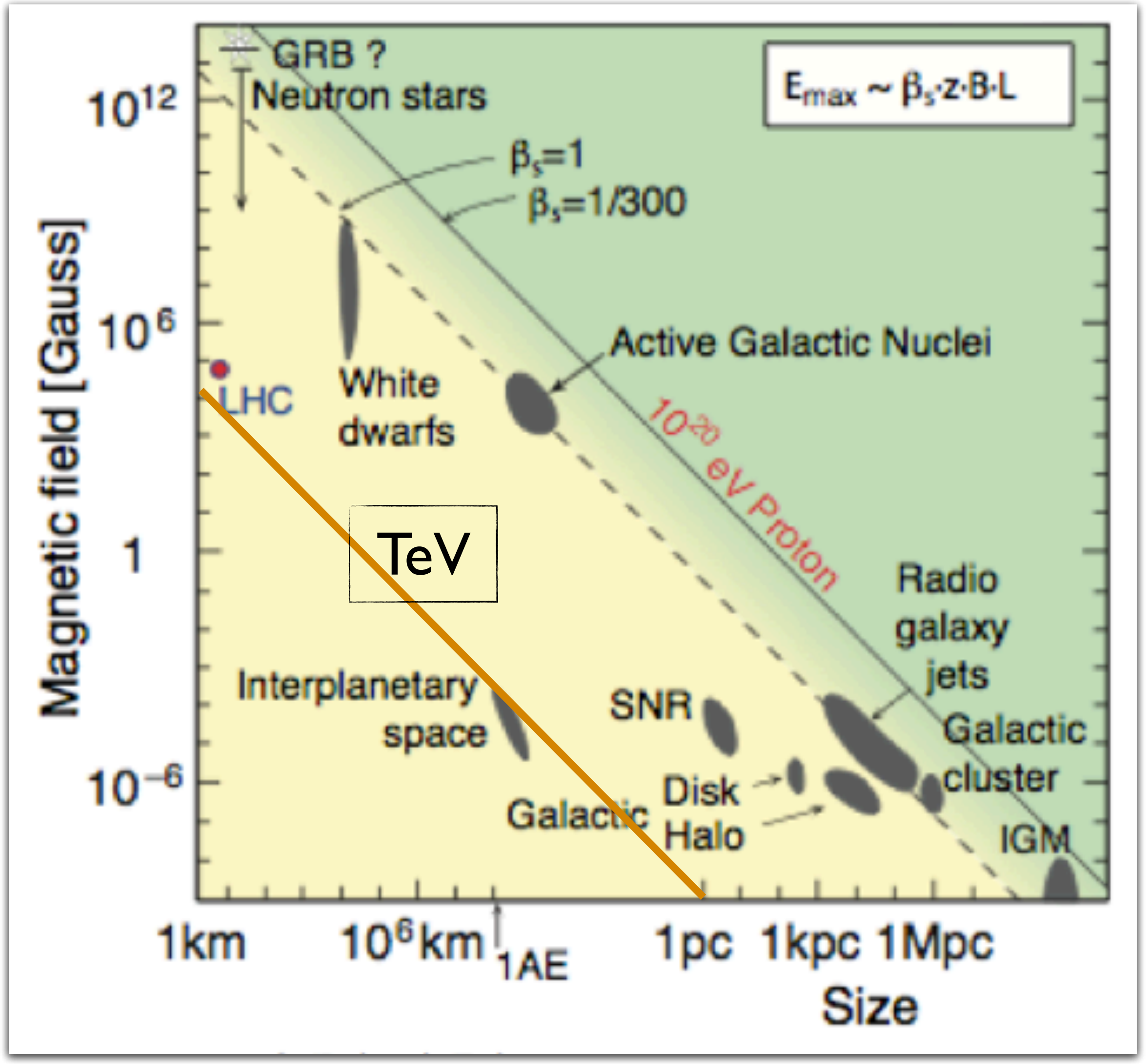
$$r_L < R$$

Larmor radius size of accelerator

$$E \leq E_{max} = qBR$$

- constraint on B and R

Ref: Hillas (1984), Boratav (2001), Hummer et al. (2010)



- Call sources as "test points" in order to discuss E-dependent effects at source

The GZK mechanism

Pion photoproduction

$$p + \gamma_{CMB} \rightarrow \Delta_{1232} \rightarrow n + \pi^+ (E_{\rm th} \sim 5 \times 10^{19} eV)$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

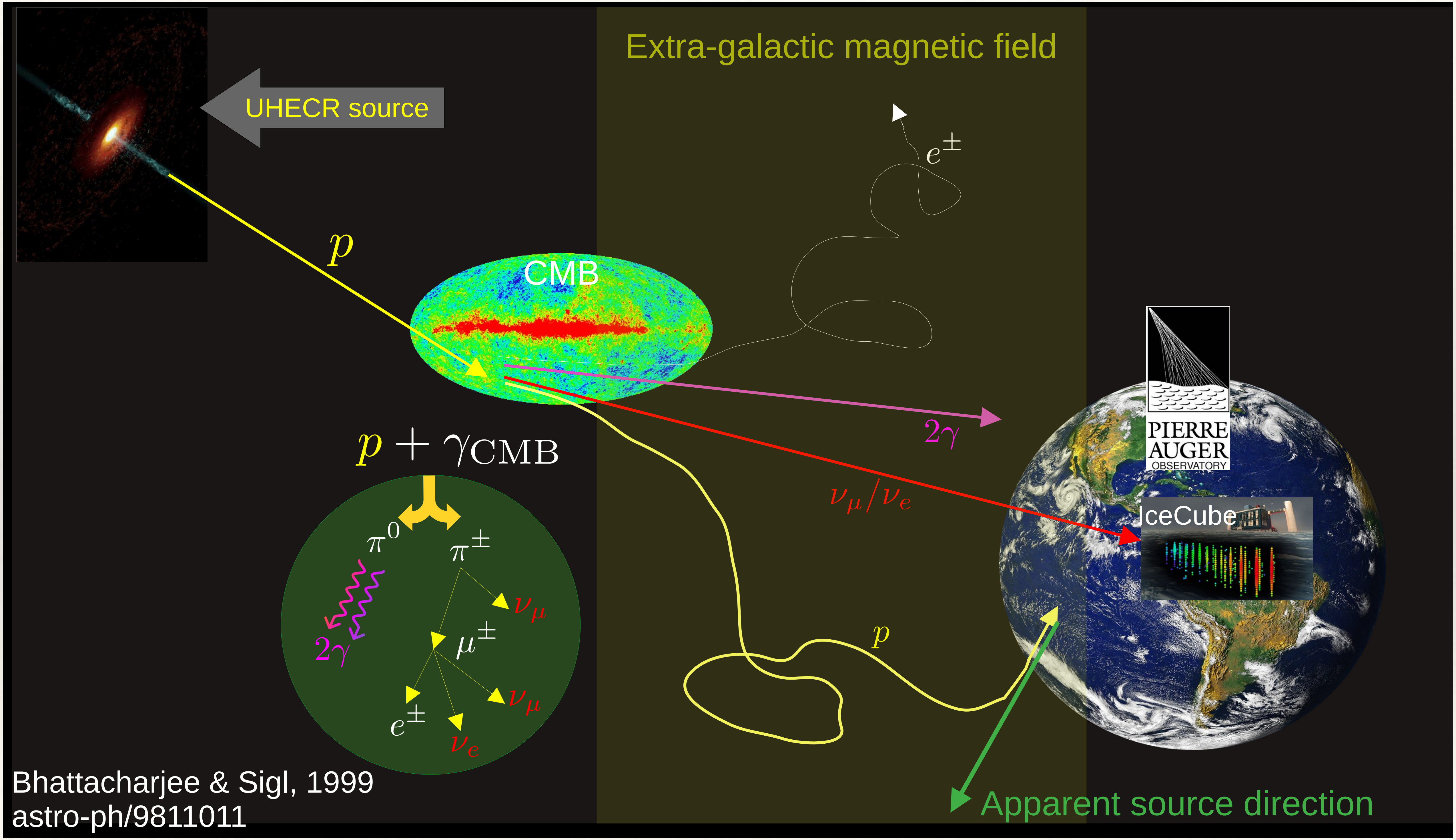
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Predicts that the spectrum should be cut-off…

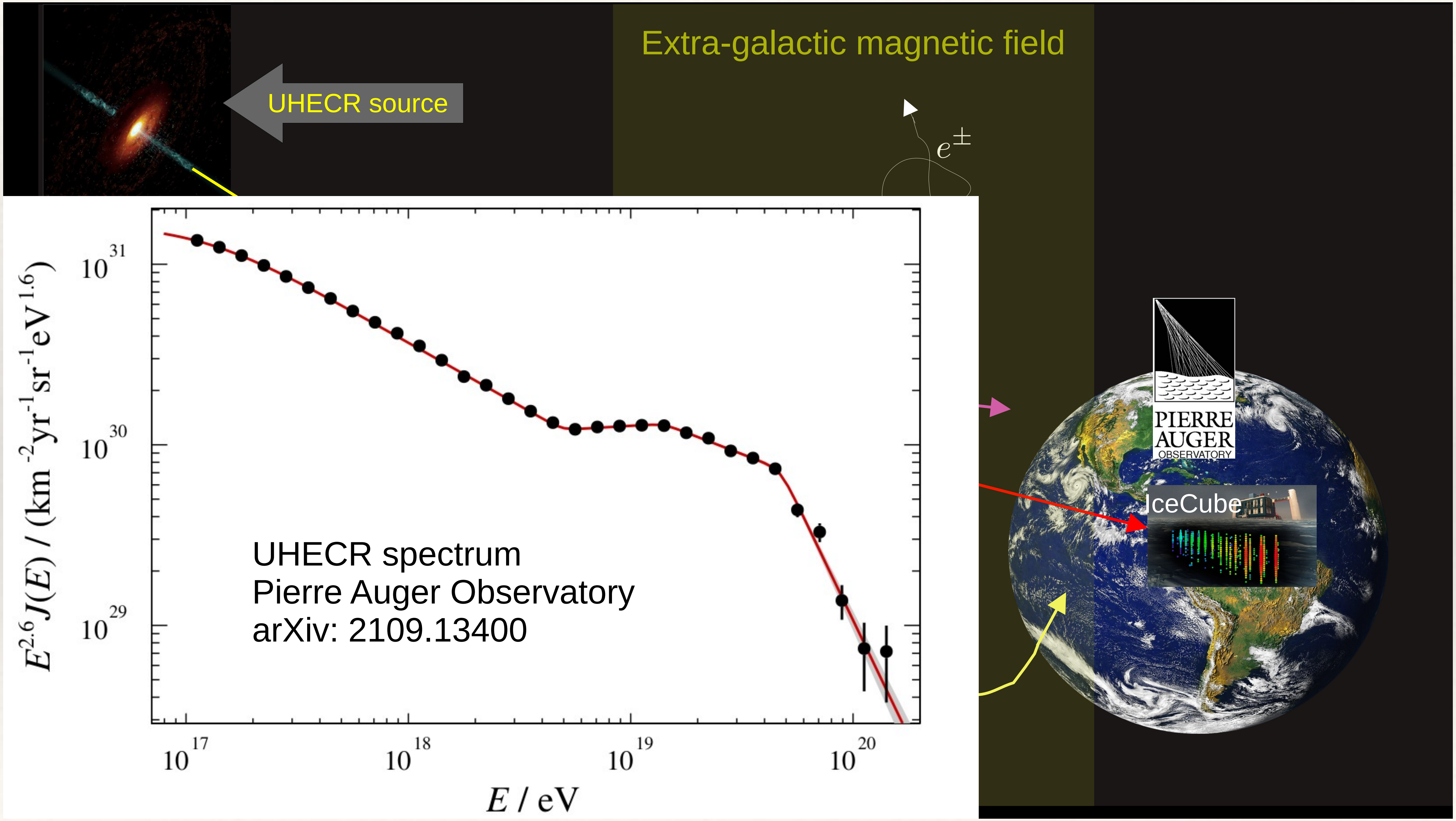
Telescope Array (SD) have seen a recent event at 244 EeV, so naturally questions arise about its origin…

R. U. Abbasi et al. (Telescope Array), Science 382, abo5095 (2023), arXiv:2311.14231 [astro-ph.HE].
(See also P. Sarmah, N. Das, D. Borah, .S Chakraborty and P. Mehta arXiv:2406.03174 [hep-ph])

UHECR propagation & GZK process

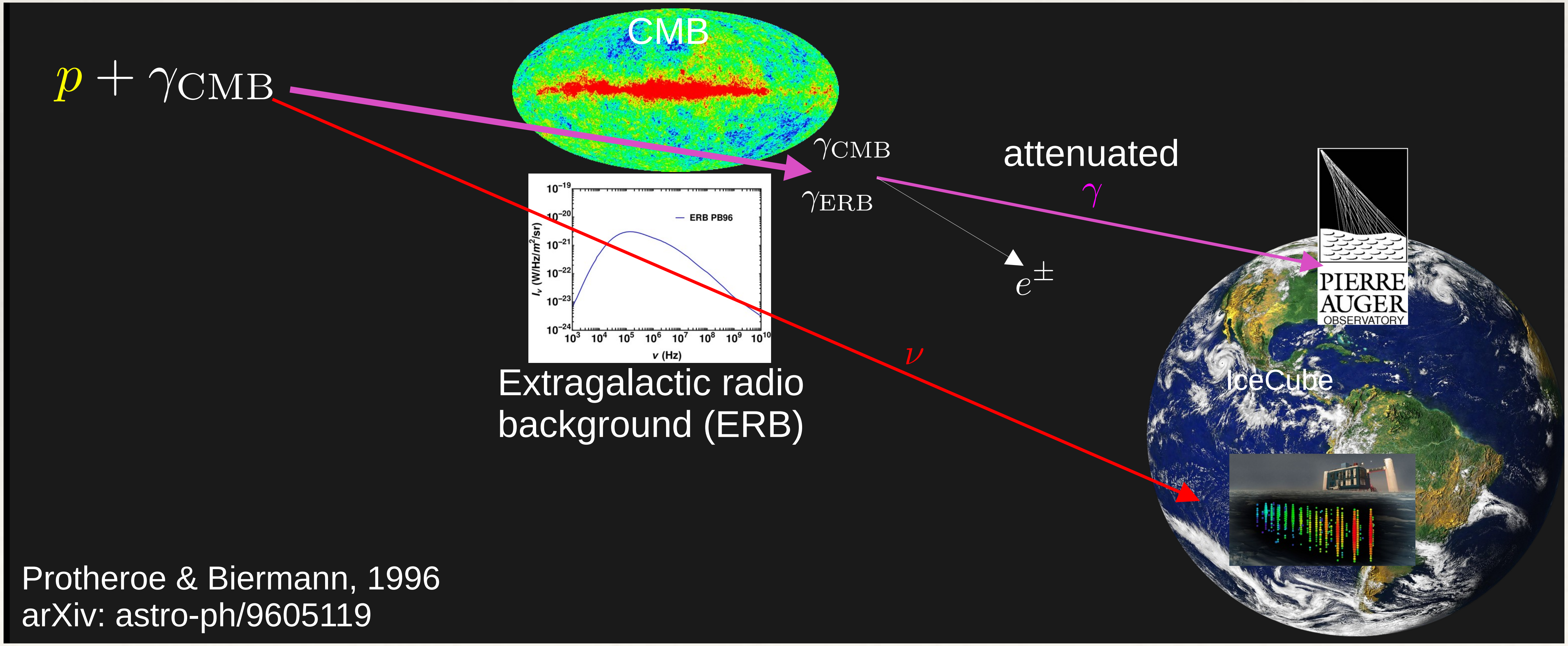


The GZK process



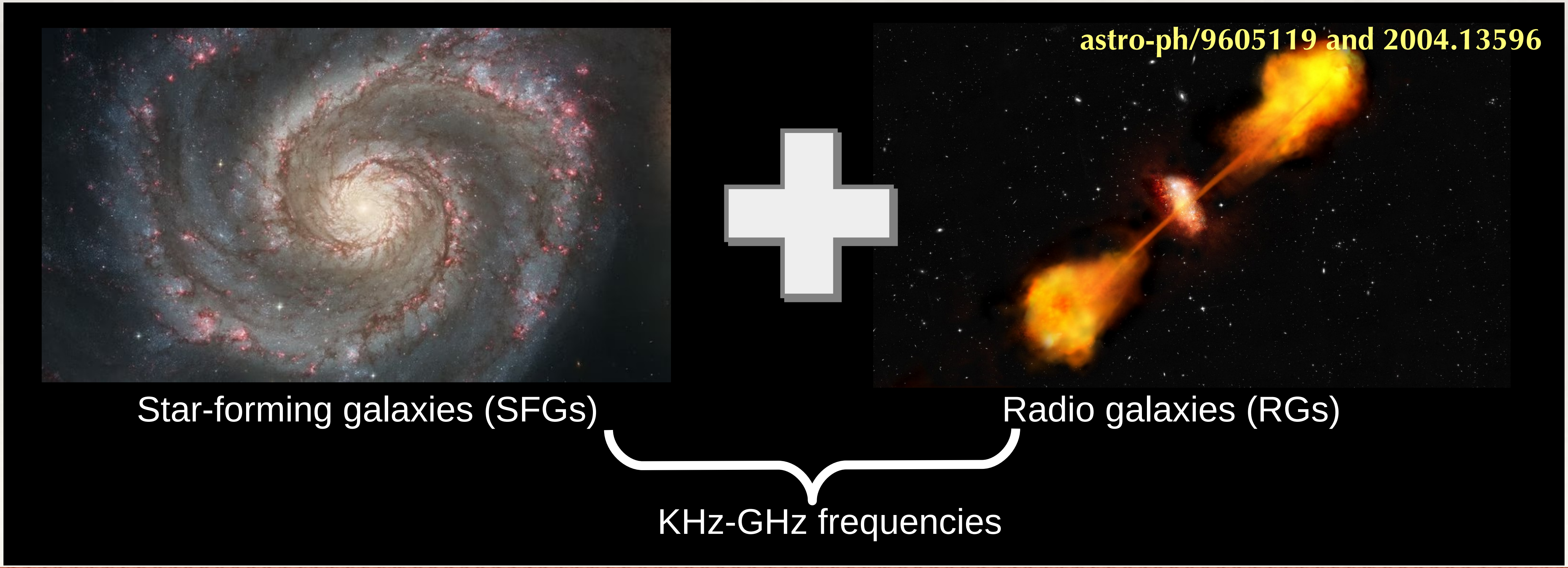
The GZK photon flux

- Also affected by inverse Compton, double pair production, em cascades
- Need precise estimates of CMB and ERB
- While CMB spectrum is well measured, the ERB has large uncertainties



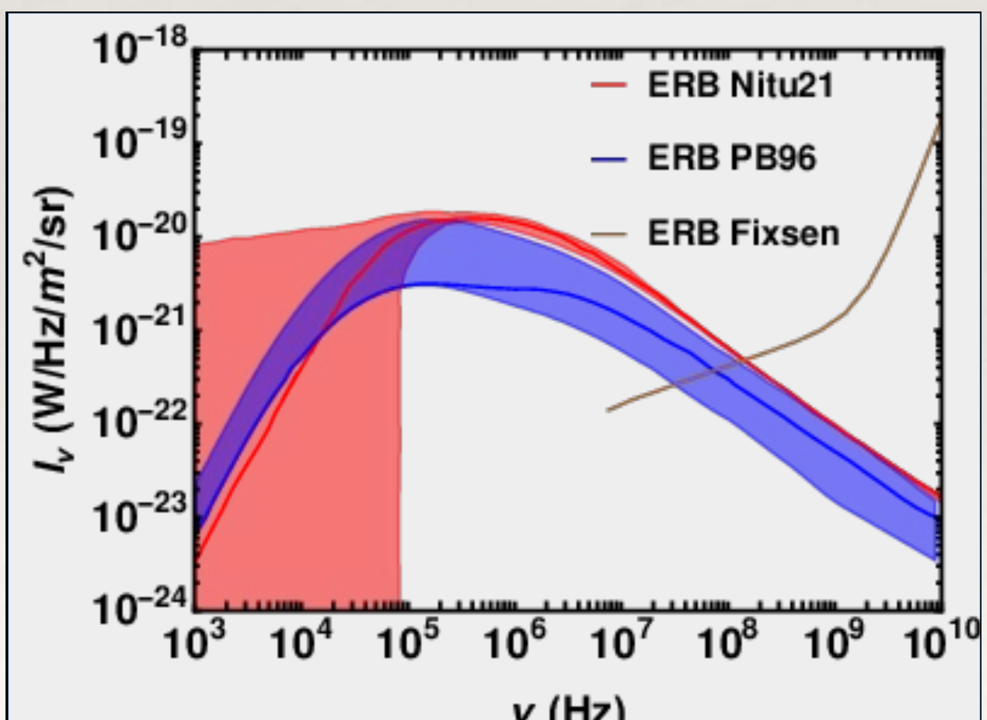
Extragalactic Radio Background

- Free-free emission in SFGs & synchrotron radiation in RGs
- SFG contribution dominates at low frequencies (below ~100 MHz)
- RG dominates at higher frequencies
- 2 Models : Protheroe and Biermann 1996 (PB96) & Nitu et al 2021 (Nitu21)



Extragalactic Radio Background

- The ARCADE2 (Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission) measured radiometric temperature at 3-90 GHz.
- Analysis (Fixsen et. al. 2011) showed an excess of temperature of about $24.1 (\nu/310\ \mathrm{MHz})^{-2.59}$ K over the CMB temperature ~ 2.73 K
- May be due to unresolved radio sources or simplistic geometry adopted for galactic radio emission.



astro-ph/9605119, 2004.13596, 0901.0555

These uncertainties can impact the GZK photon flux prediction

GZK flux & UHECR Source properties

- UHE Primary spectrum

$$E^{-\alpha} \exp\left(\frac{-E}{E_{\rm cut}}\right)$$

$$\alpha : 2.2 - 2.7$$

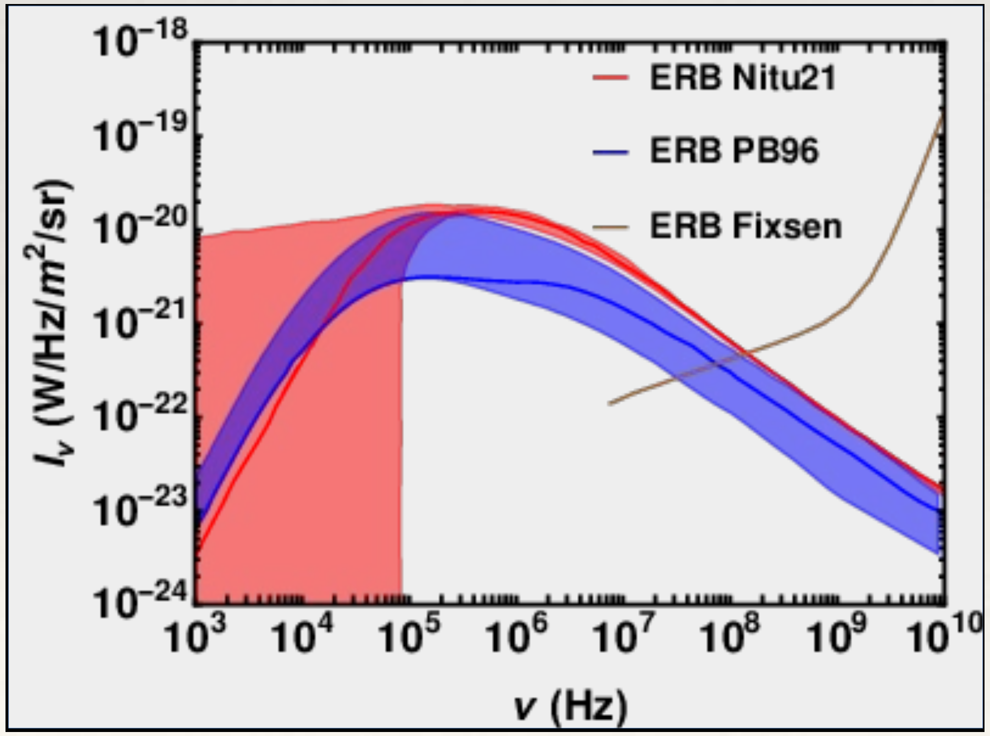
$$E_{\rm cut} : 5 \times 10^{20} - 10^{22} \mathrm{eV}$$

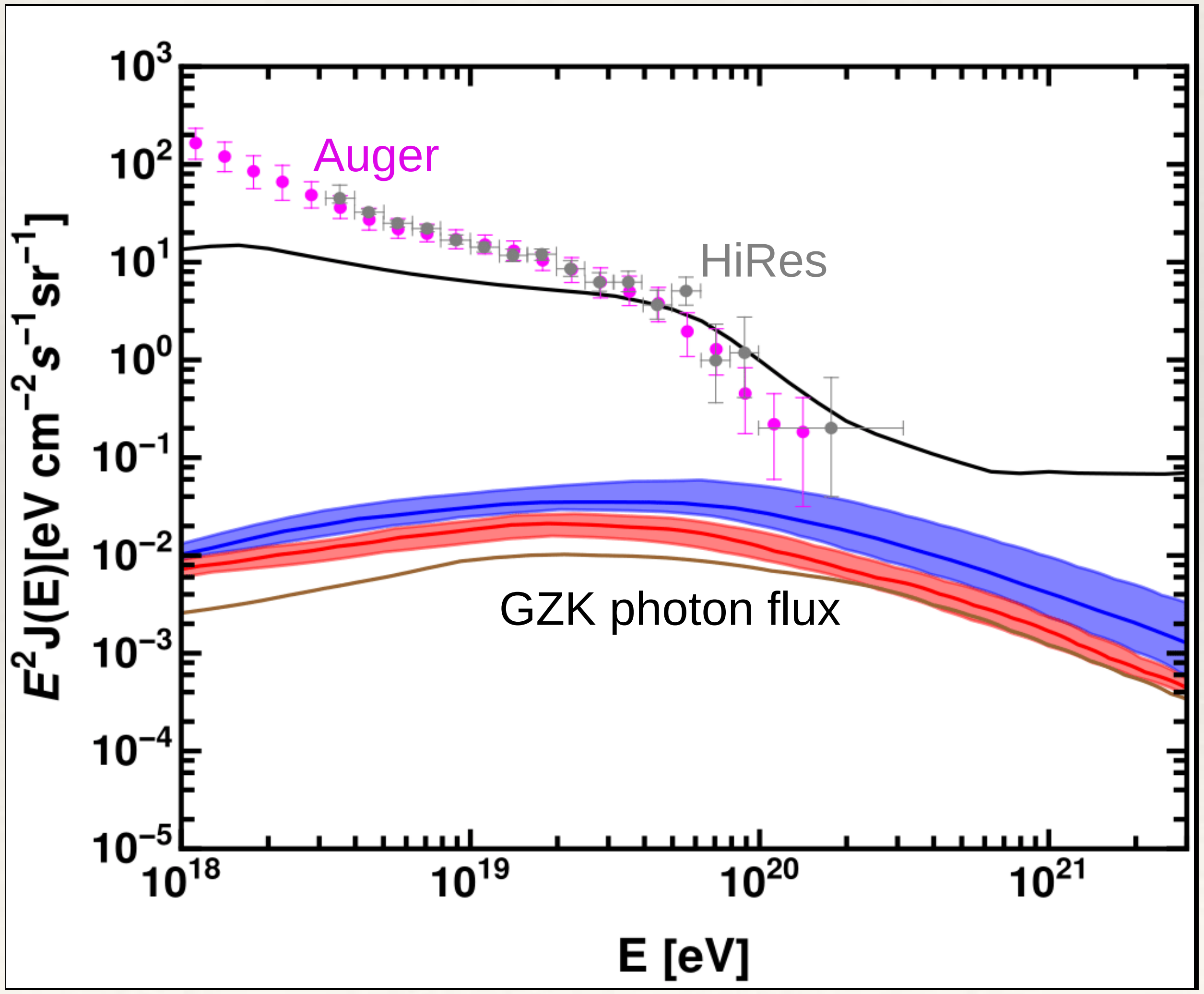
- Composition : protons and heavy elements suggested by observations
- We take 2 extreme cases : 100% proton and 100% iron primary
- How far are the sources : 0.1 kpc to 100 Mpc

Impact of ERB uncertainties

- ERB uncertainties give rise to about an order of magnitude of uncertainties in the GZK photon flux.
- ARCADE 2 radio excess becomes significant at lower energies for GZK photons.

astro-ph/9605119, 2004.13596, 0901.0555





Present and Future experiments

GZK Neutrinos

Pierre Auger Observatory (Auger)

Giant Radio Array for Neutrino Detection (GRAND)

IceCube, IceCube-Gen2

Antarctic Impulsive Transient Antenna (ANITA)

Askaryan Radio Array (ARA)

Square Kilometre Array (SKA)

GZK Photons

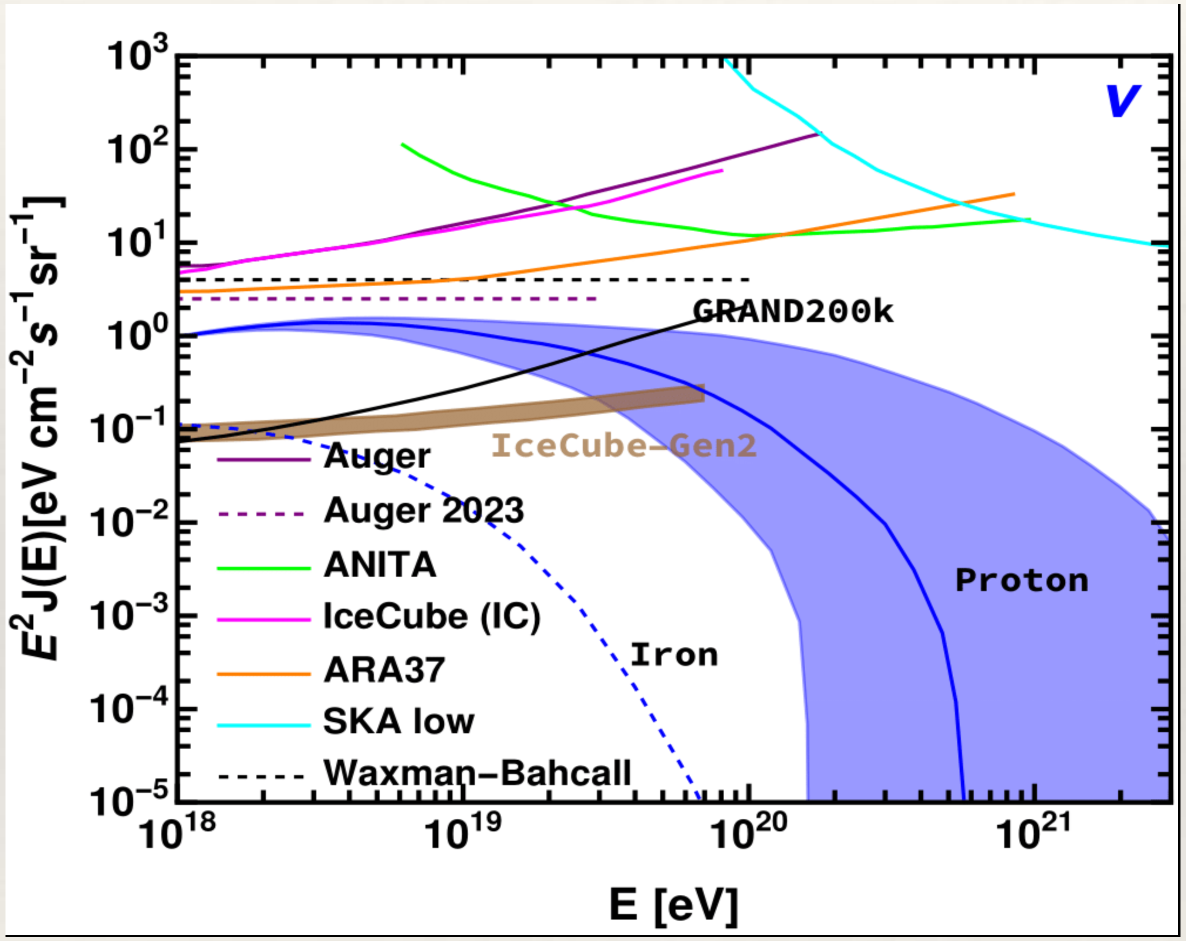
Auger

GRAND

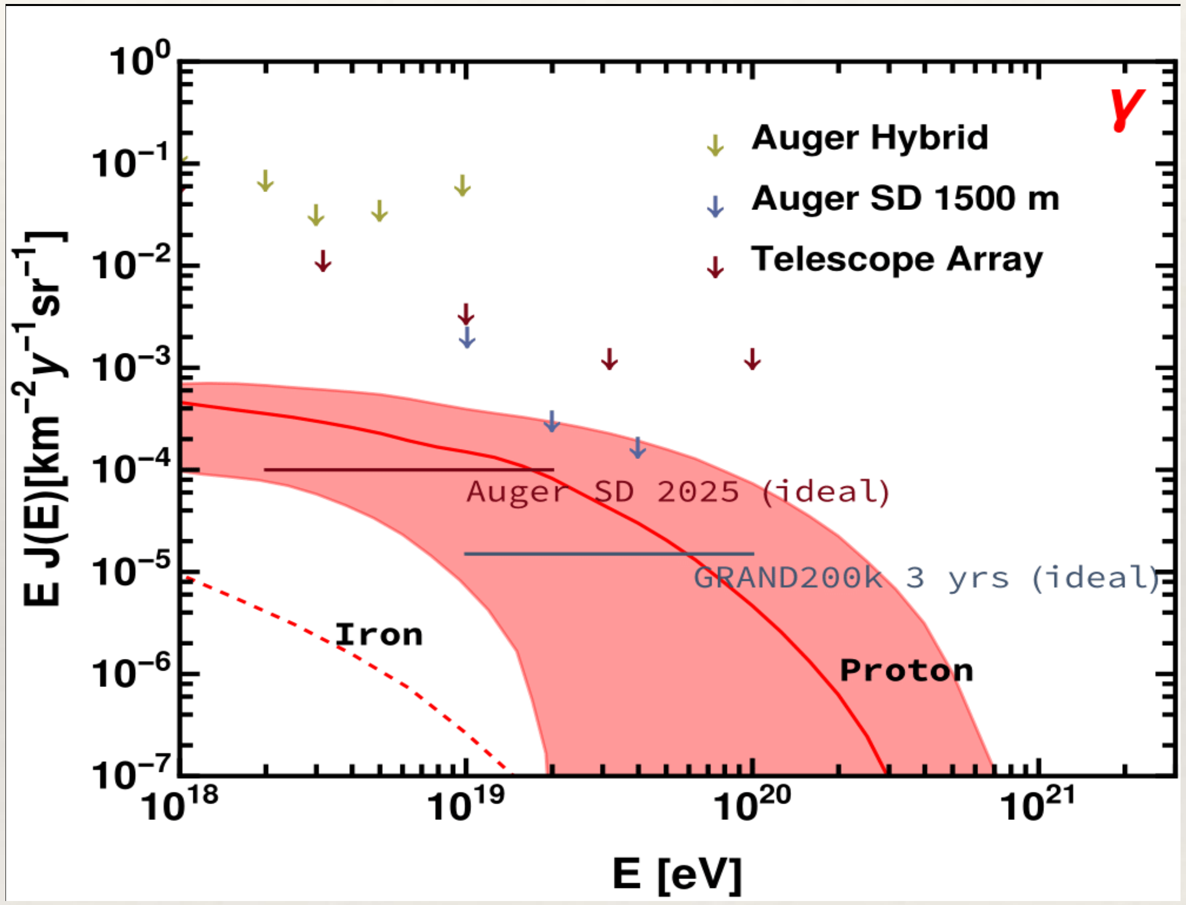
Telescope Array (TA)

Detection Prospects

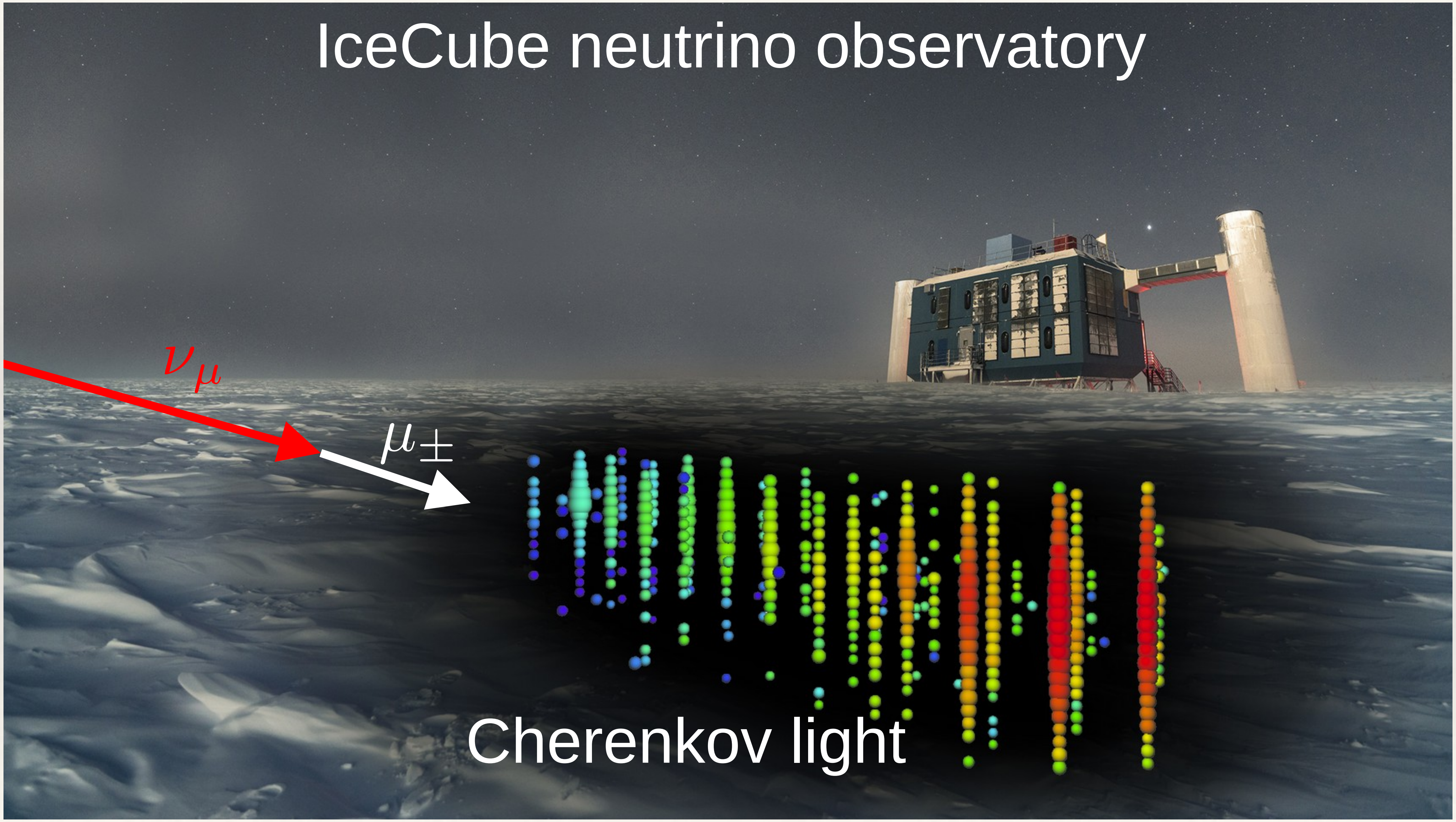
GZK Neutrinos



GZK Photons

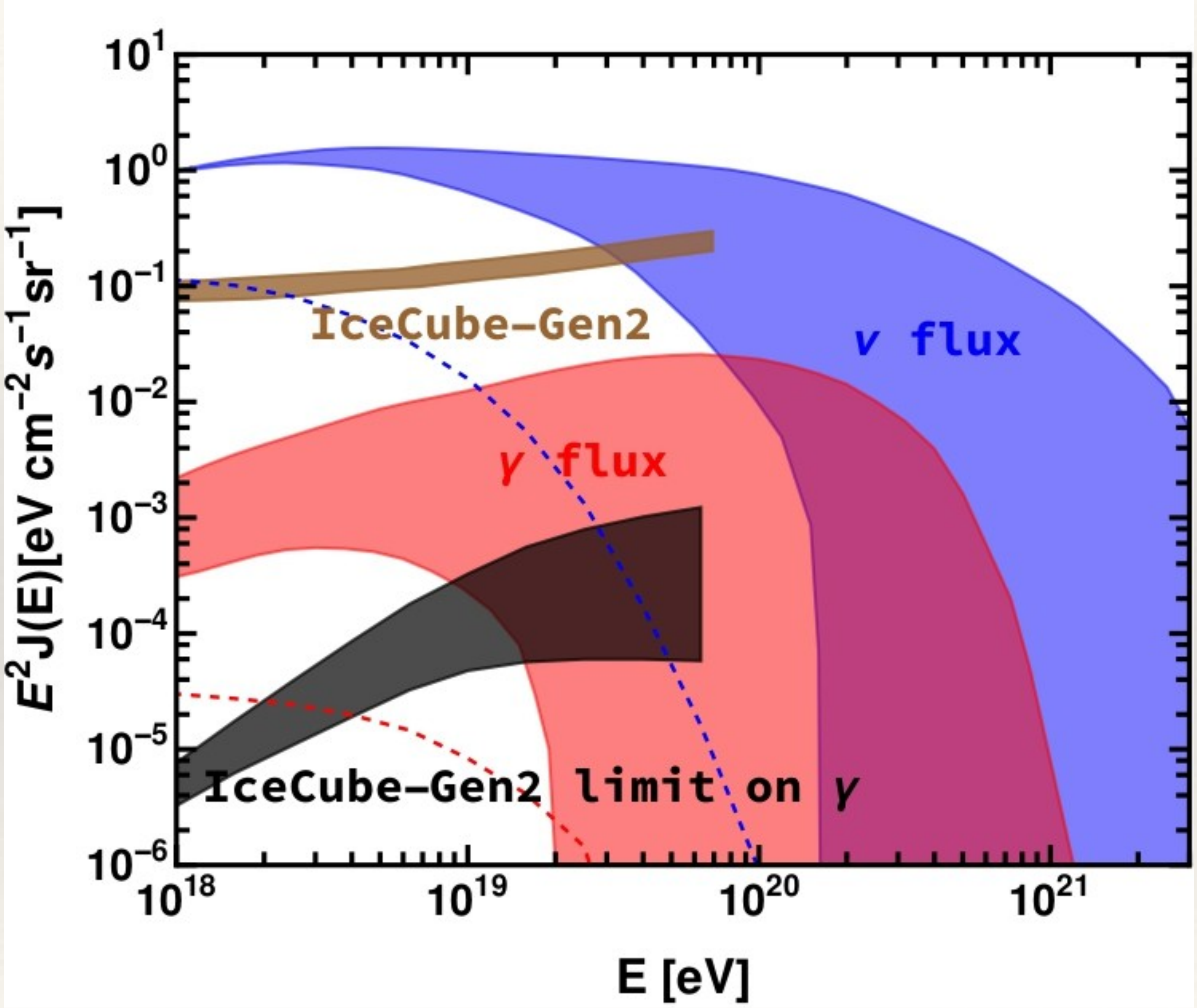


Multi-messenger constraints from IceCube-Gen2



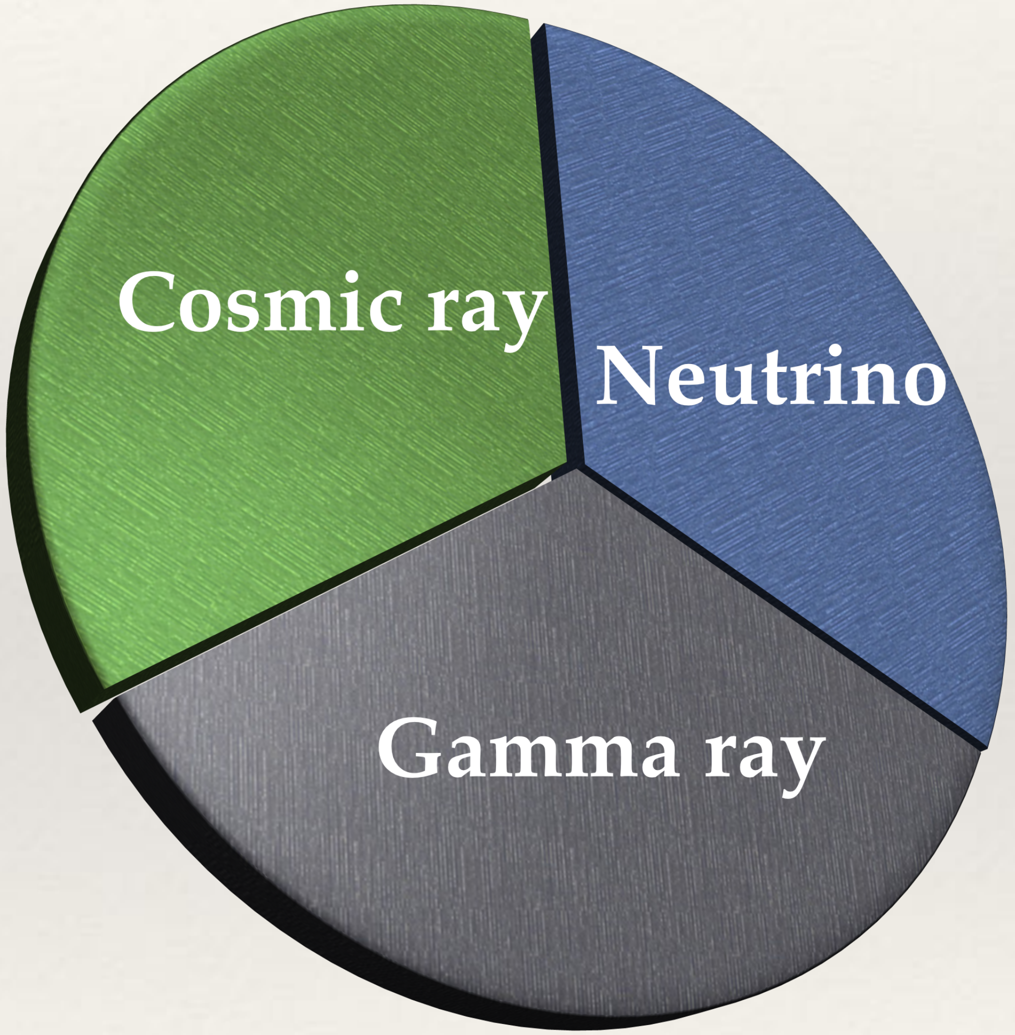
Multi-messenger constraints from IceCube-Gen2

- GZK Photon flux limit (black band) corresponding to the IceCube-Gen2 sensitivity
- If GZK neutrinos are detected, we can expect GZK photon flux above the black band.
- Non-detection - tension b/w GZK process and UHECR data.



The future…

- GZK ?
- Better model of ERB, Role of SKA ?
- Sources of UHECR ?
- Power of multi-messenger astronomy!



Thanks for your attention!