Does the Amaterasu particle point to superheavy dark matter decay in Milky Way ?

Based on arXiv: 2406.03174

From Big Bang to Now : A Theory-Experiment Dialogue@SRM University AP, Andhra Pradesh

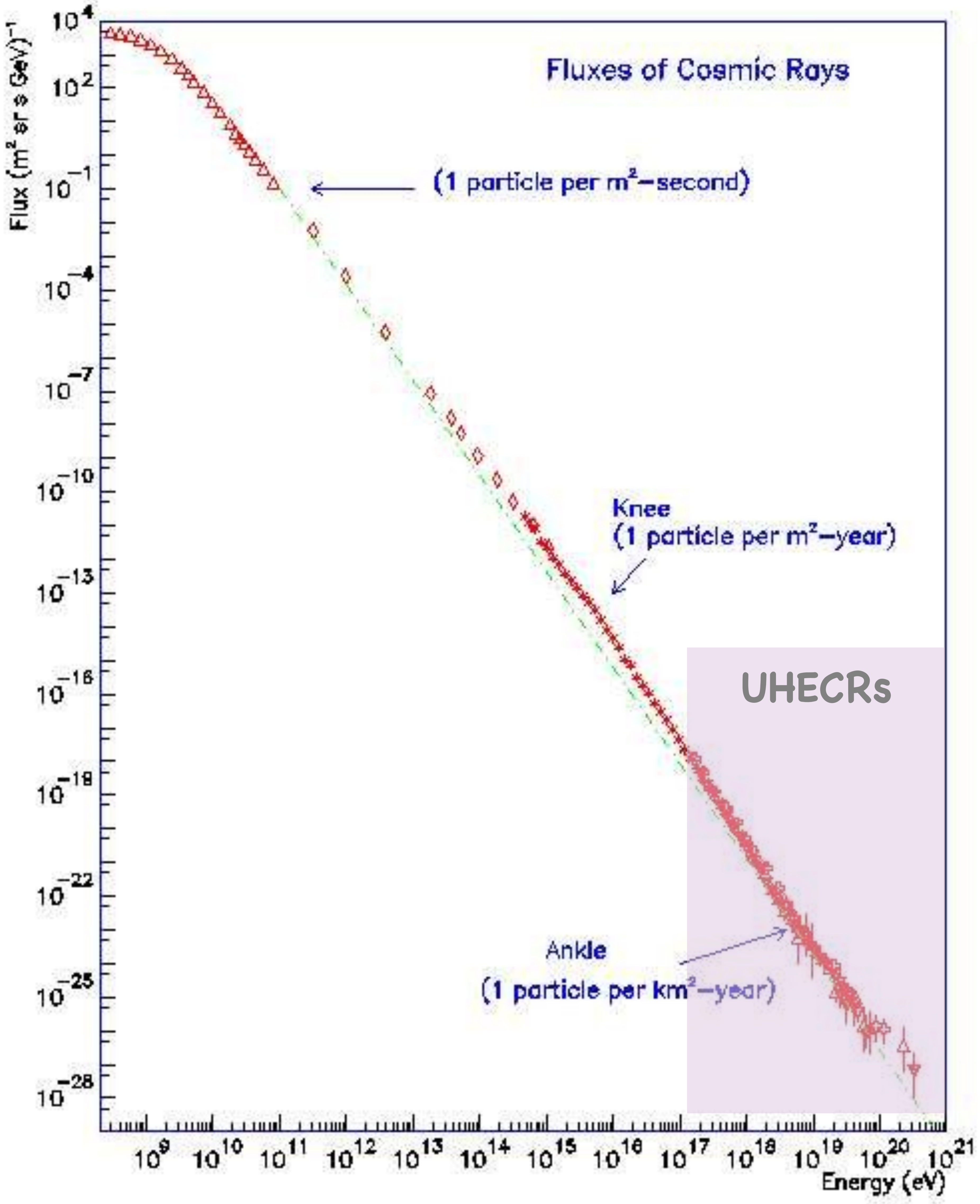
Prantik Sarmah
prantiksarmah@ihep.ac.cn

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Outline

- Ultra-high energy cosmic rays
- The Amaterasu event
- Superheavy dark matter as the origin of the Amaterasu ? 
- Multi-messenger constraints and future predictions
- Summary

Ultra-high energy cosmic rays



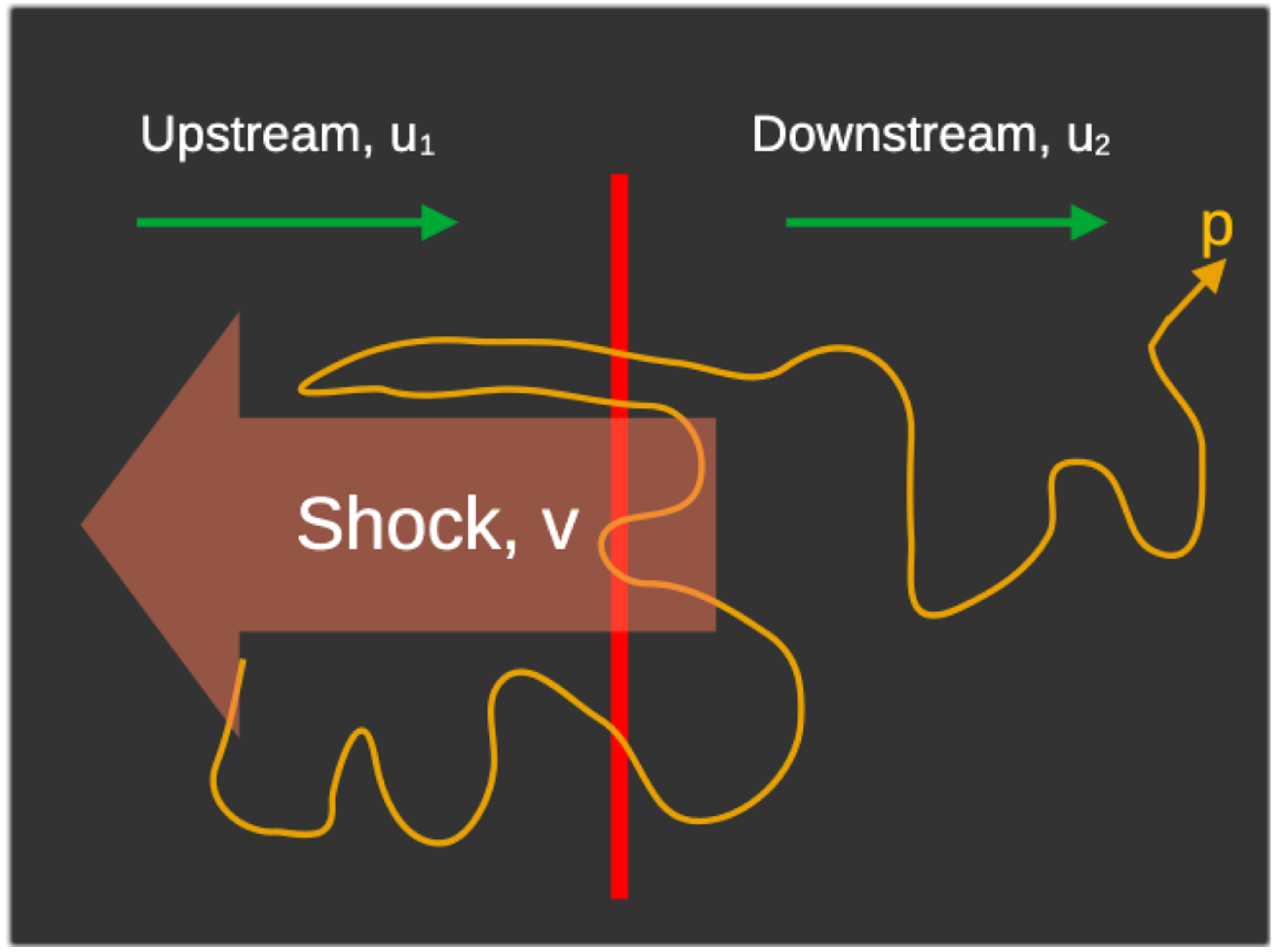
- Cosmic rays (CRs) are mostly protons (about 90%), alpha particles (9%), and other heavy elements.
- CR spectrum spans over a vast energy range from 1 GeV to 10^{11} GeV.
- Galactic origin upto the knee (10^6 GeV).
- Extra-galactic above the ankle (10^9 GeV): Ultra-high energy cosmic rays (UHECRs).

Book byT. K. Gaisser, Review by Bhattacharjee and Sigl, 1999

Origin of UHECRs

Diffusive shock acceleration

- Active galactic nuclei such as blazers, quasars…



Energy gain:

$$\Delta E = E\frac{(u_2 - u_1)}{v}$$

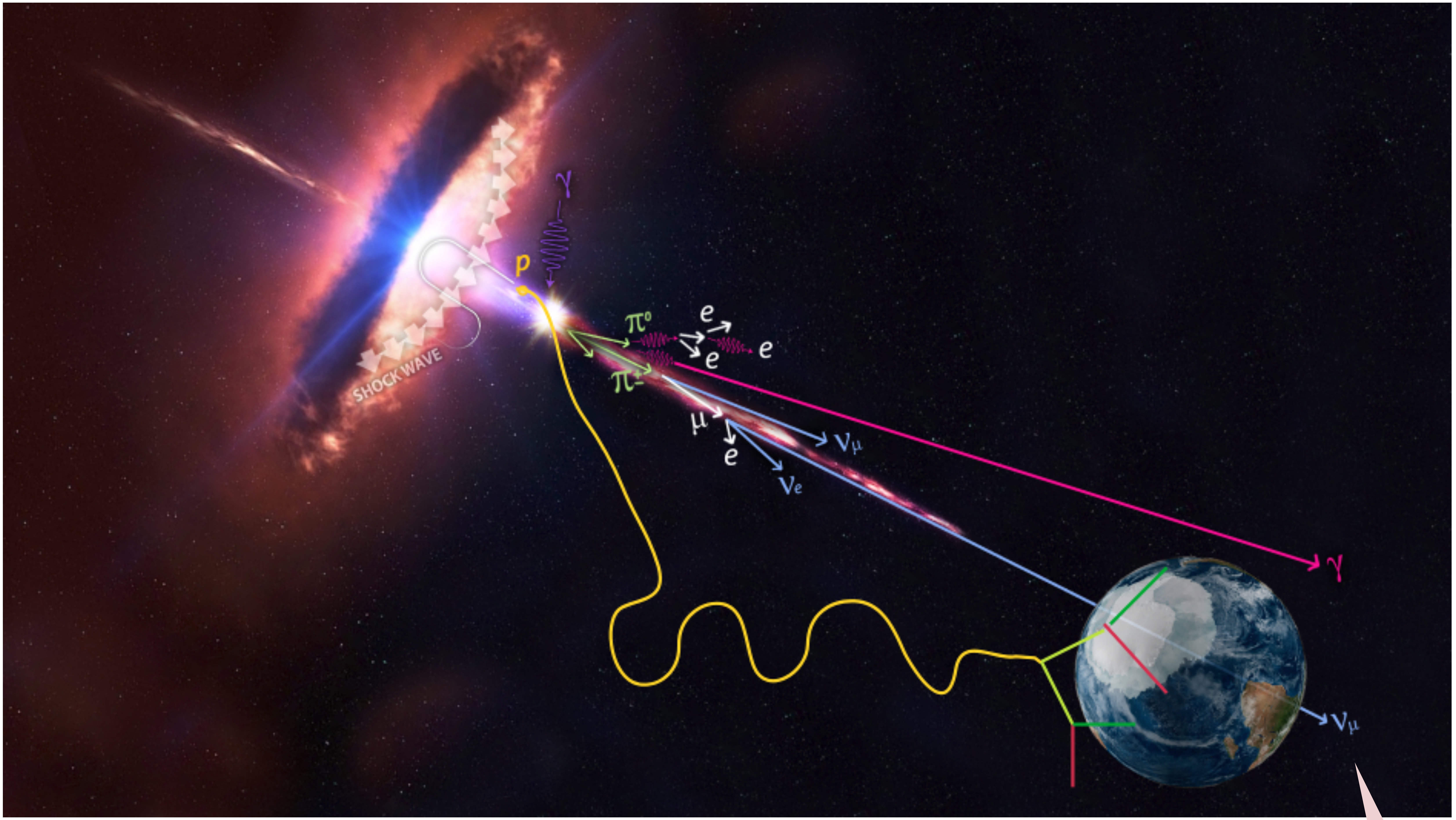
Fermi's 1st order accleration

Power law spectrum $\propto E^{-2}$

Exotic processes

- Dark matter decay or annihilation, cosmic strings, topological defects…..
- Expected to produce more photons than nucleons.
- Observations: more nucleons than photons.
- Tightly constrained.

Propagation of UHECRs: The GZK processs

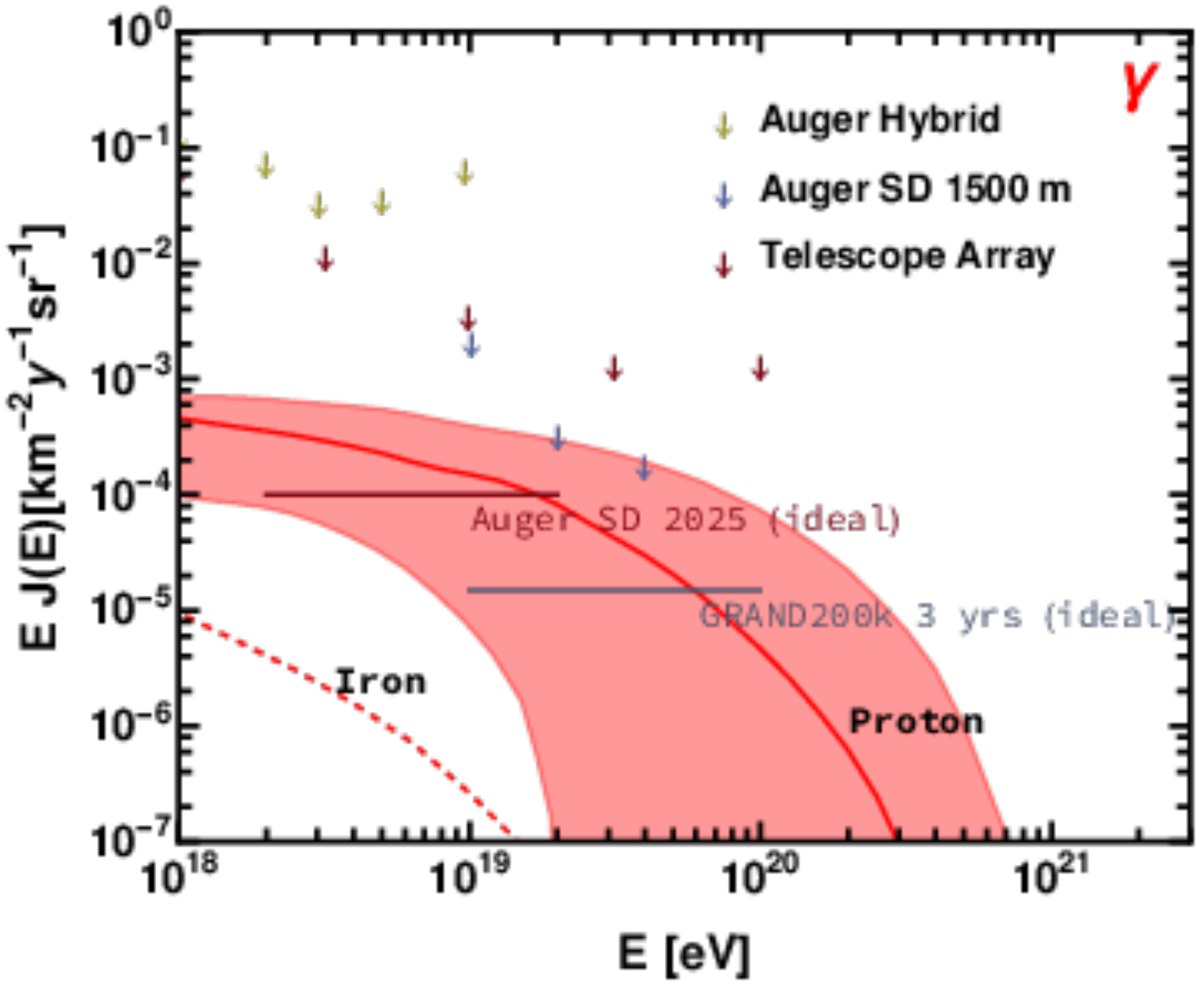


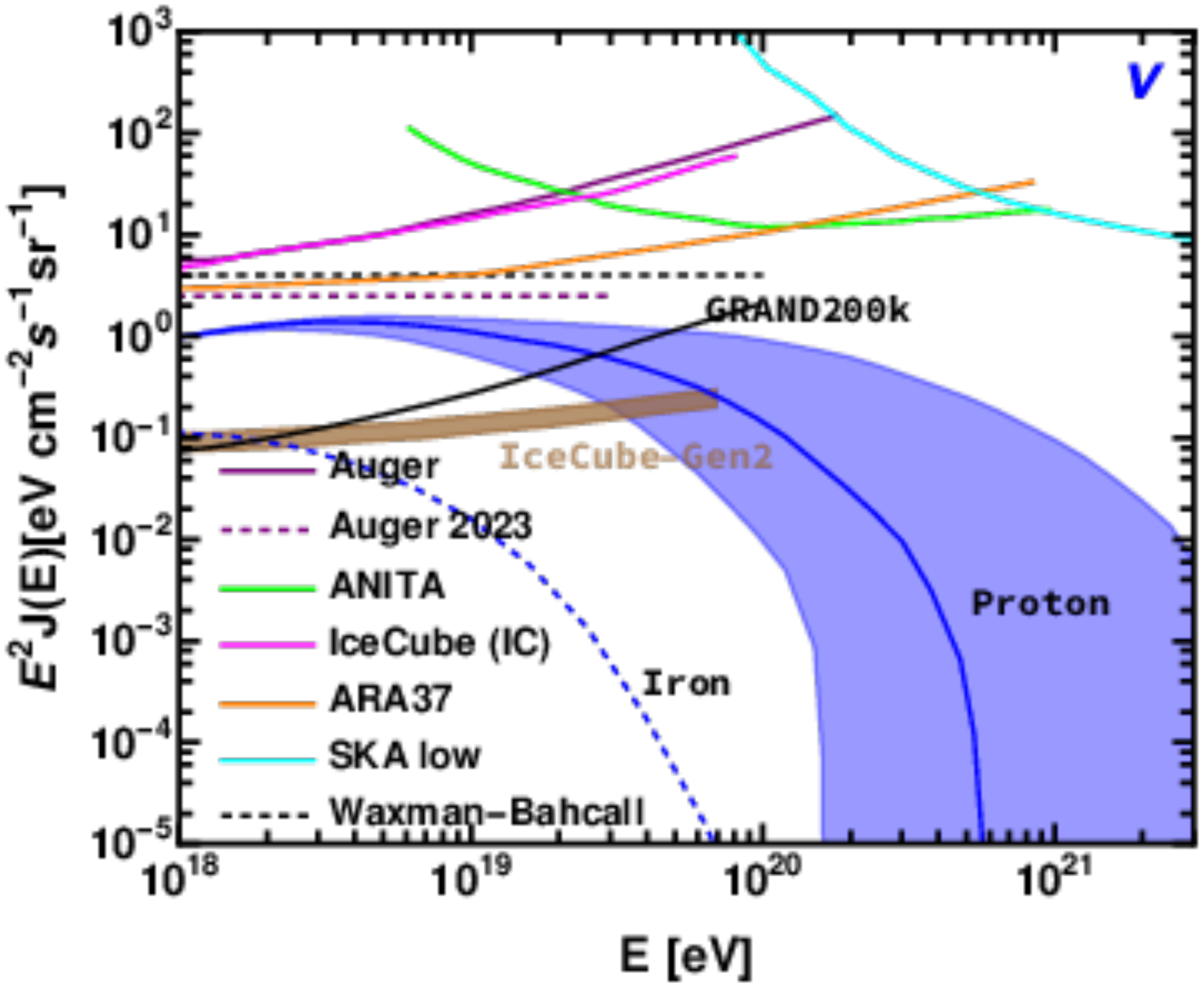
- UHECRs + Cosmic Microwave Background.
- Threshold energy of protons: GZK cut-off ($\sim 5 \times 10^{10}$ GeV).
- Mean free path $\sim$ 10 Mpc.
- CR spectrum falls rapidly beyond the GZK cut-off.

Multi-messenger signals

Greisen, PRL. 16 (1966) 748; Kuzmin and Zatsepin, SJETPL, 4 (1966) 78

GZK photon and neutrino flux

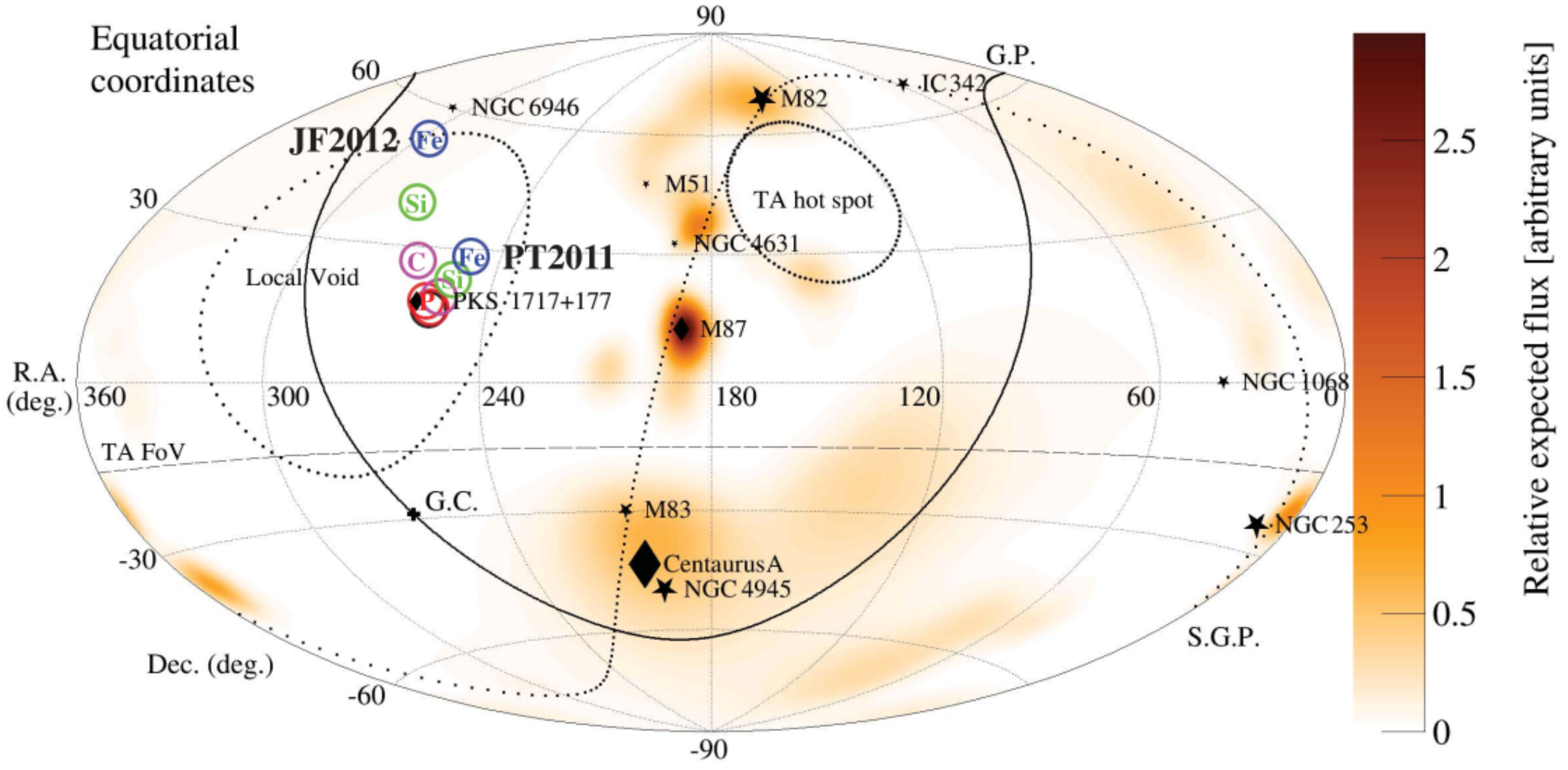




Chakraborty, Mehta, PS, *JCAP* 01 (2024) 058

The Amaterasu event

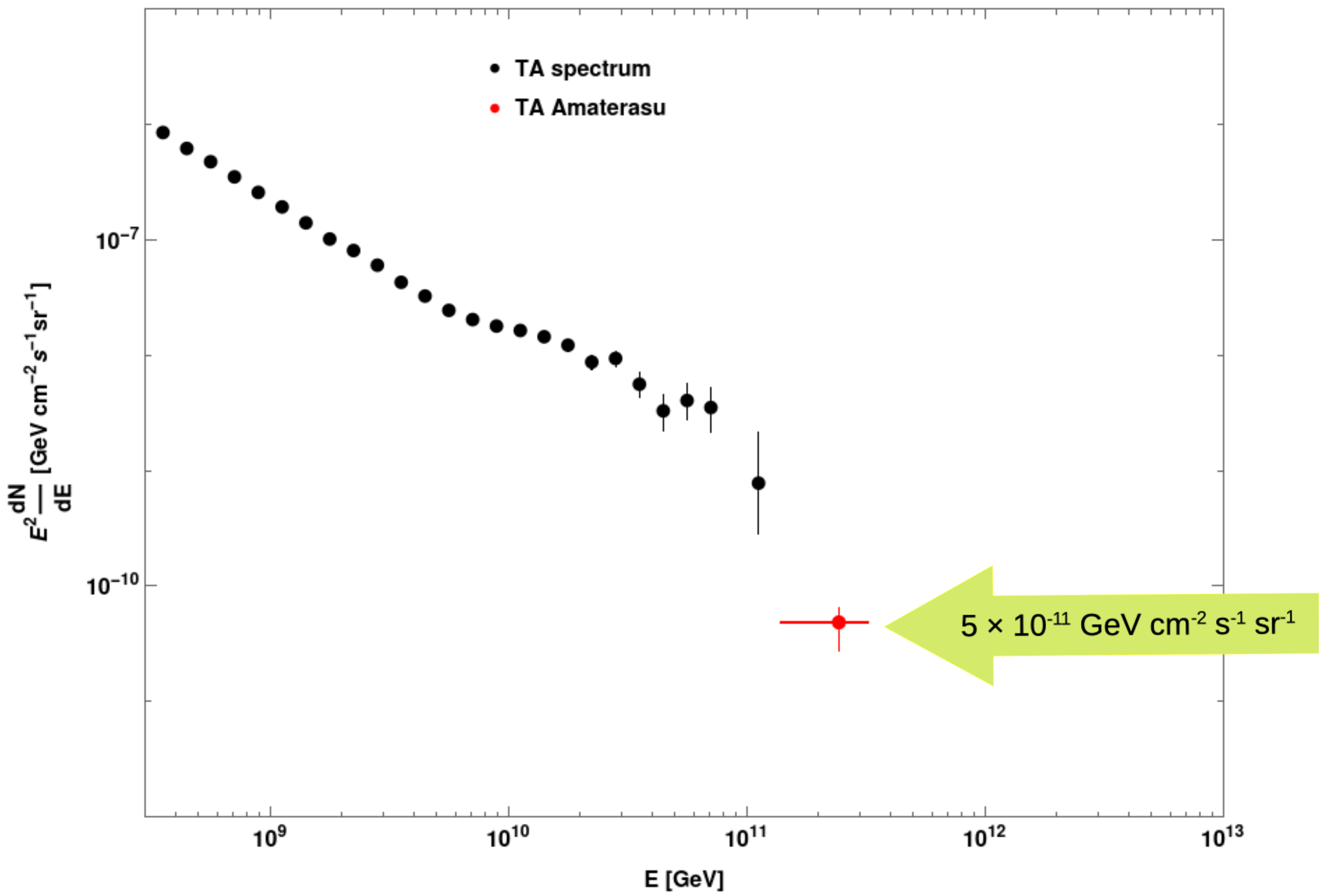
- UHECRs detected by the Telescope Array experiment, about 45 degrees away from the Galactic centre.
- Third most energetic (2.44×10^{11} GeV) CR particle ever detected.
- Due to the GZK process, the source should be within about 30 Mpc.
- No possible sources within this distance.
- What could be the origin ?



Science 382 (2023) 903-907

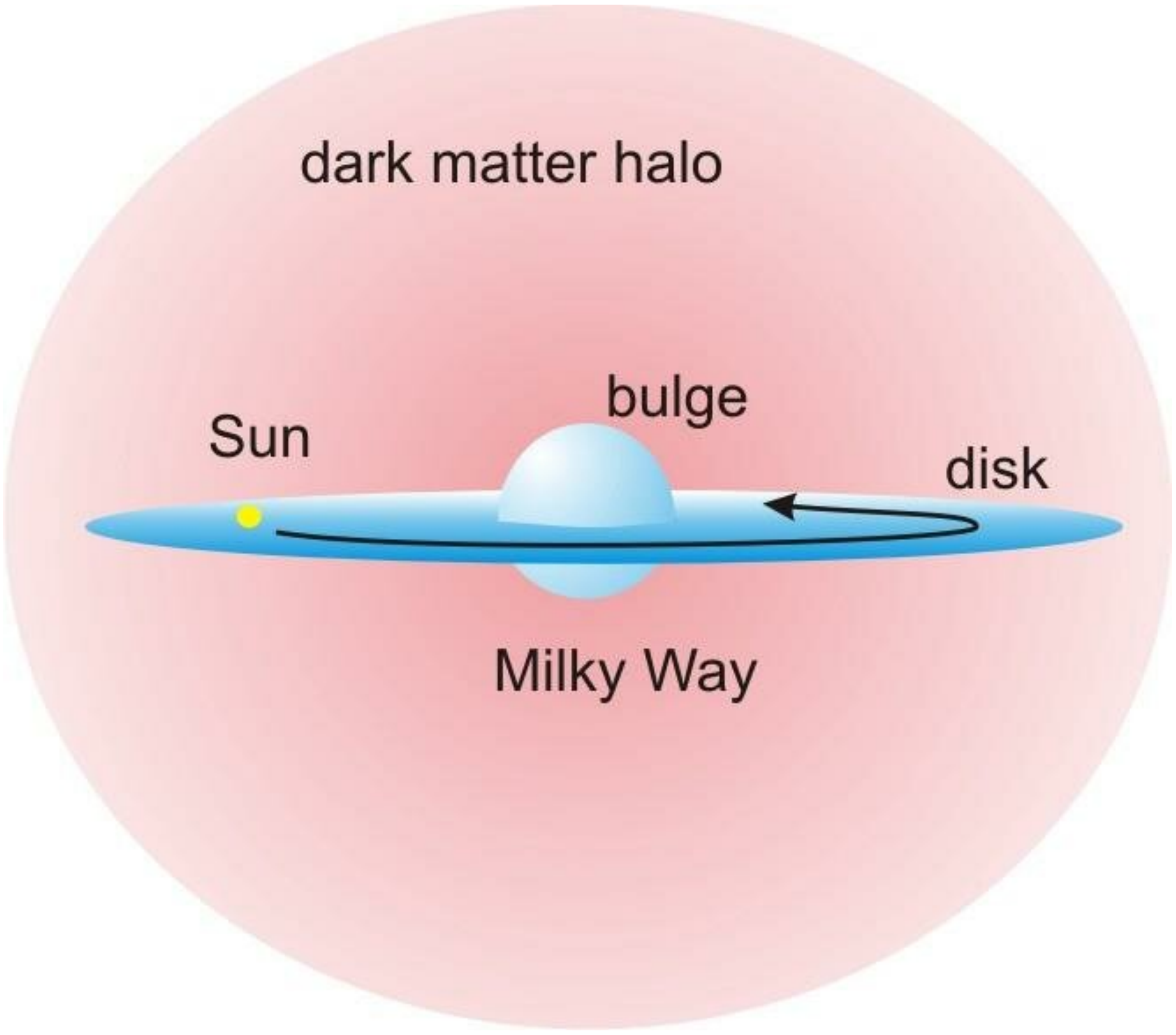
The Amaterasu event

- Possible explanations:
  - Could be heavy elements like Iron, deflected by the Inter-galactic magnetic field ?
  - Electroweak monopole ?
  - Superheavy dark matter (SHDM) decay or annihilation in Milky Way ?



2312.13273, 2311.14628, 2405.17409, 2312.08115, 2401.00560, 2403.12322

SHDM decay as the origin of the UHECRs/Amaterasu



$$\chi \to b\bar{b} \begin{cases} p + \bar{p} \\ \nu + \bar{\nu} \text{ (any flavour)} \\ 2\gamma \end{cases}$$

It can decay to any standard model particle and anti-particle pairs.

Diffuse flux:
UHECRs,
UHE γ-rays,
UHE νs.

List of experiments

Present

- Pierre Auger Observatory (PAO) and Telescope Array (TA).
- Can detect all three signals.

Future

- Giant Radio Array for Neutrino Detection (GRAND 200k), PAO upgrade, and IceCube-Gen2.

2007.15001

Estimation of UHECRs flux from SHDM decay

$$\Phi_i(E) = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_i(E)}{dE} \int^{\text{line of sight}} \rho_\chi(l) dl$$

$i = p,\ \gamma,\ \nu$

Differential energy spectra → HDMSpectra (2007.15001)

Milky Way DM density

Free parameters

- Flux depends on DM mass (m_χ), lifetime (τ_χ) and differential energy spectra.
- Differential energy spectra depends on the specific decay channel, e.g., $\chi \rightarrow b\bar{b}$ or $\chi \rightarrow e^- e^+$.

1206.2595, 2302.02993

Milky Way DM profile

Navarro-Frenk-White (NFW):

$$\rho_{\rm NFW}(R_{\rm GC}) = \frac{\rho_c}{(R_{\rm GC}/R_c)(1+R_{\rm GC}/R_c)^2}$$

astro-ph/9611107

Einesto:

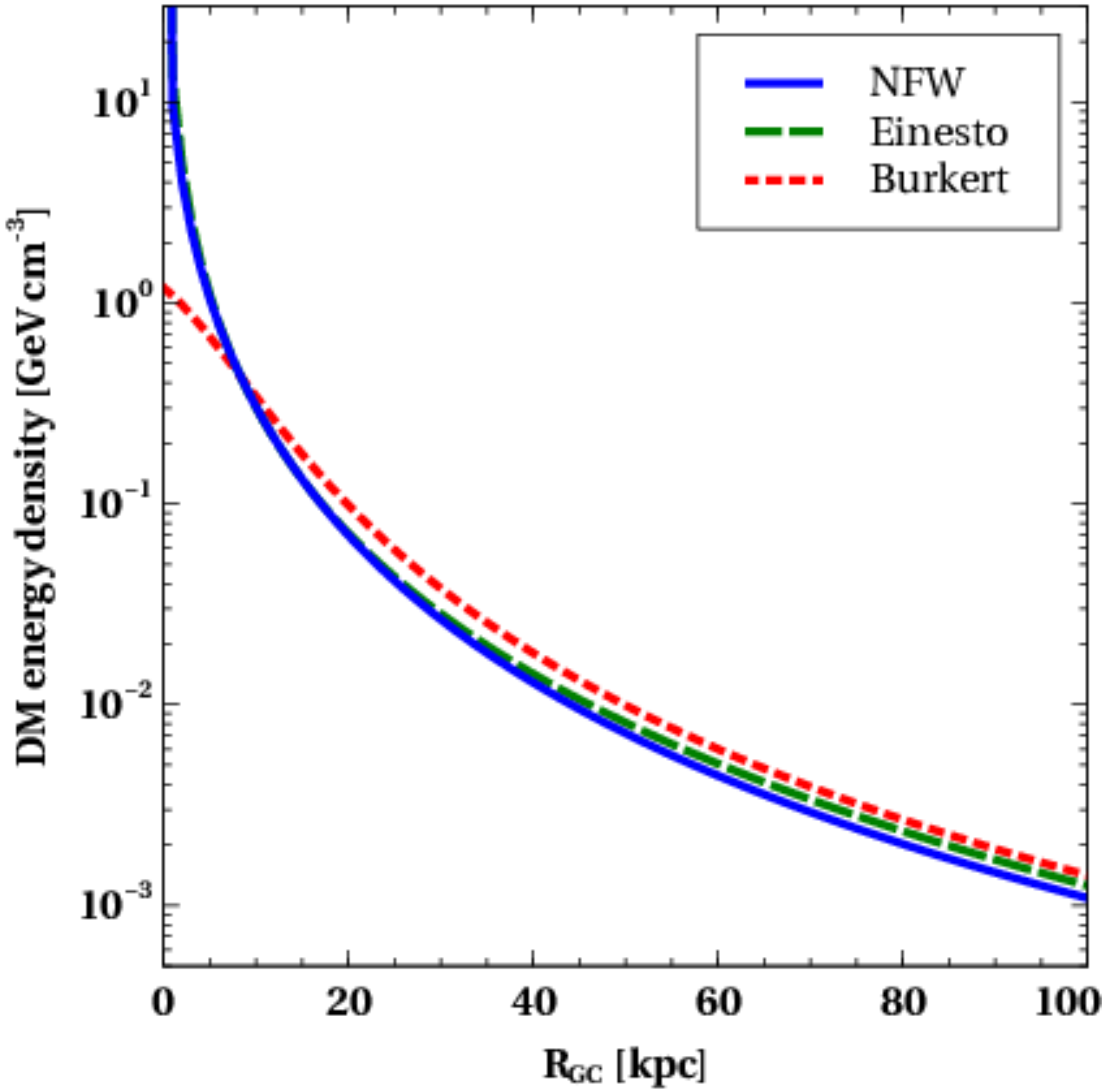
$$\rho_{\rm Ein}(R_{\rm GC}) = \rho_c \exp\left[-12.5\left(\left(\frac{R_{\rm GC}}{R_C}\right)^{0.16} - 1\right)\right]$$

AAP 223, 89 (1989)

Burkert:

$$\rho_{\rm Bur}(R_{\rm GC}) = \frac{\rho_c R_c^3}{(R_{\rm GC}+R_c)(R_{\rm GC}^2+R_c^2)}$$

astro-ph/9504041

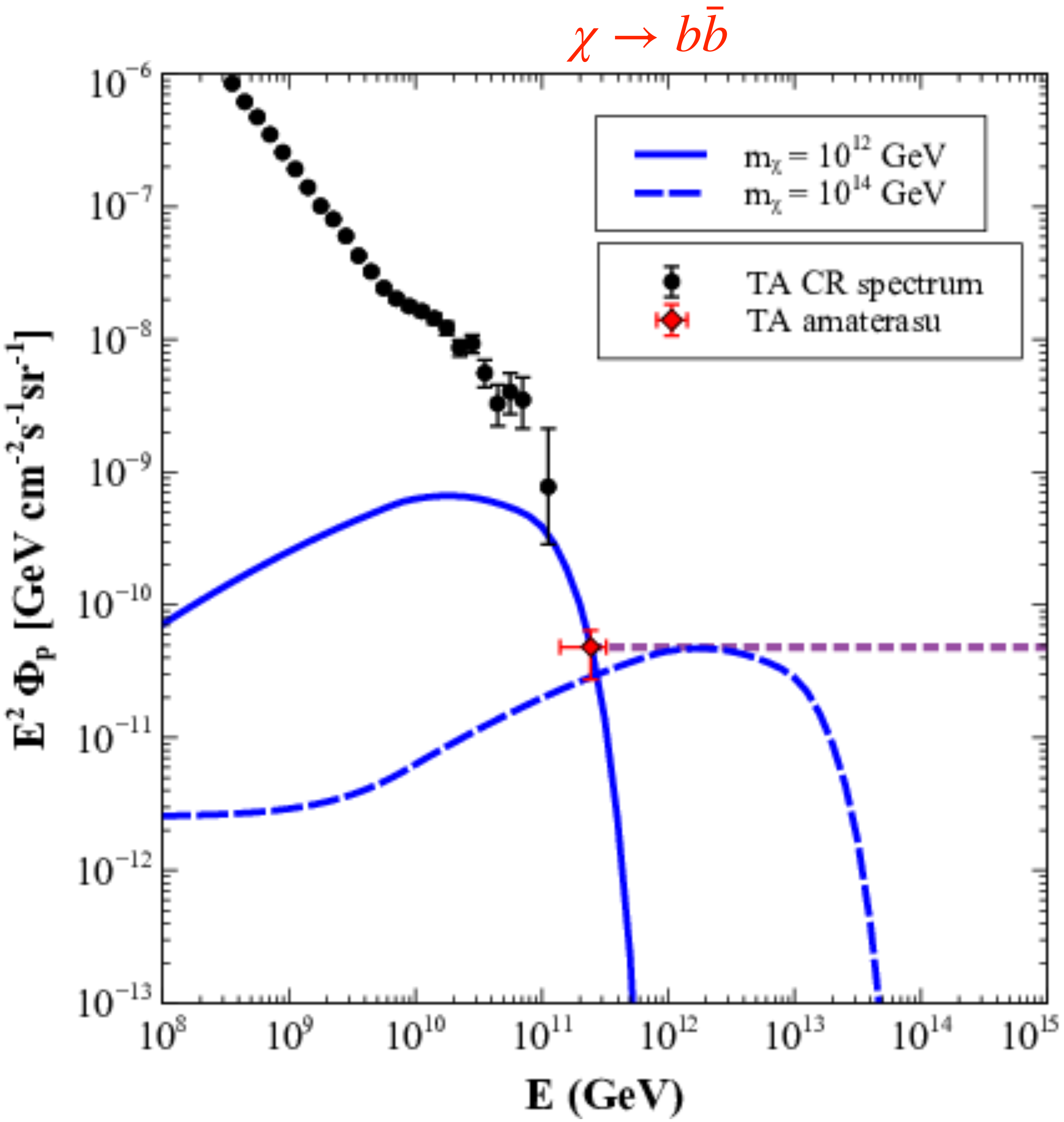


R_{GC} : Galactocentric radius, R_c : 11 kpc, ρ_c : characteristic DM density.

UHECRs flux from SHDM decay

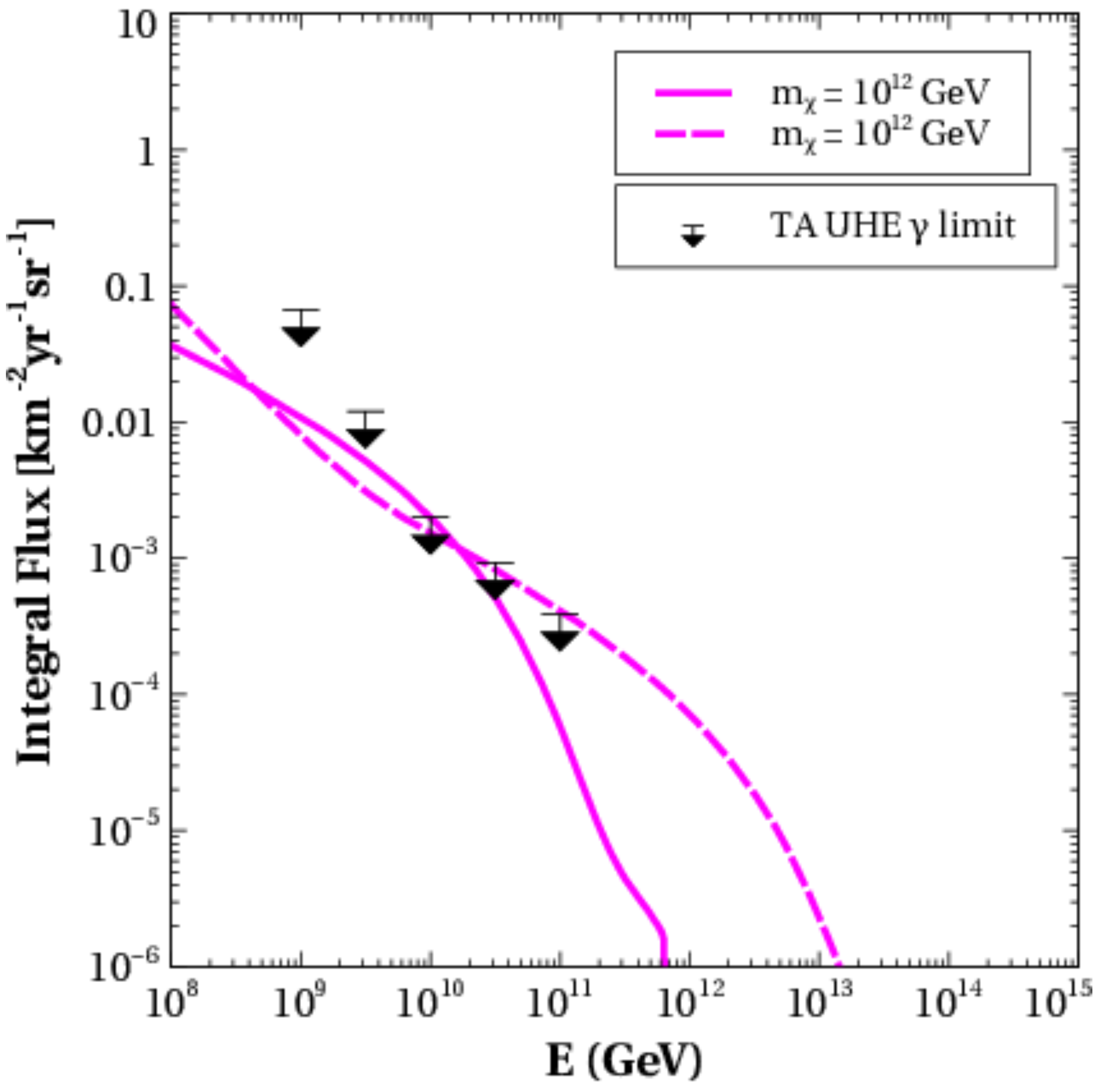
$$\Phi_i(E) = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_i(E)}{dE} \int^{\text{line of sight}} \rho_\chi(l)dl$$

- Free parameters: m_χ and τ_χ.
- Obtained by normalising the flux to the data.
- UHECR flux above the Amaterasu energy is assumed constant.
- $m_\chi = 10^{12}$ GeV, $\tau_\chi = 5.5 \times 10^{28}$ s and $m_\chi = 10^{14}$ GeV, $\tau_\chi = 7.5 \times 10^{29}$ s.
- Probable $m_\chi \sim (10^{12} - 10^{14})$ GeV.



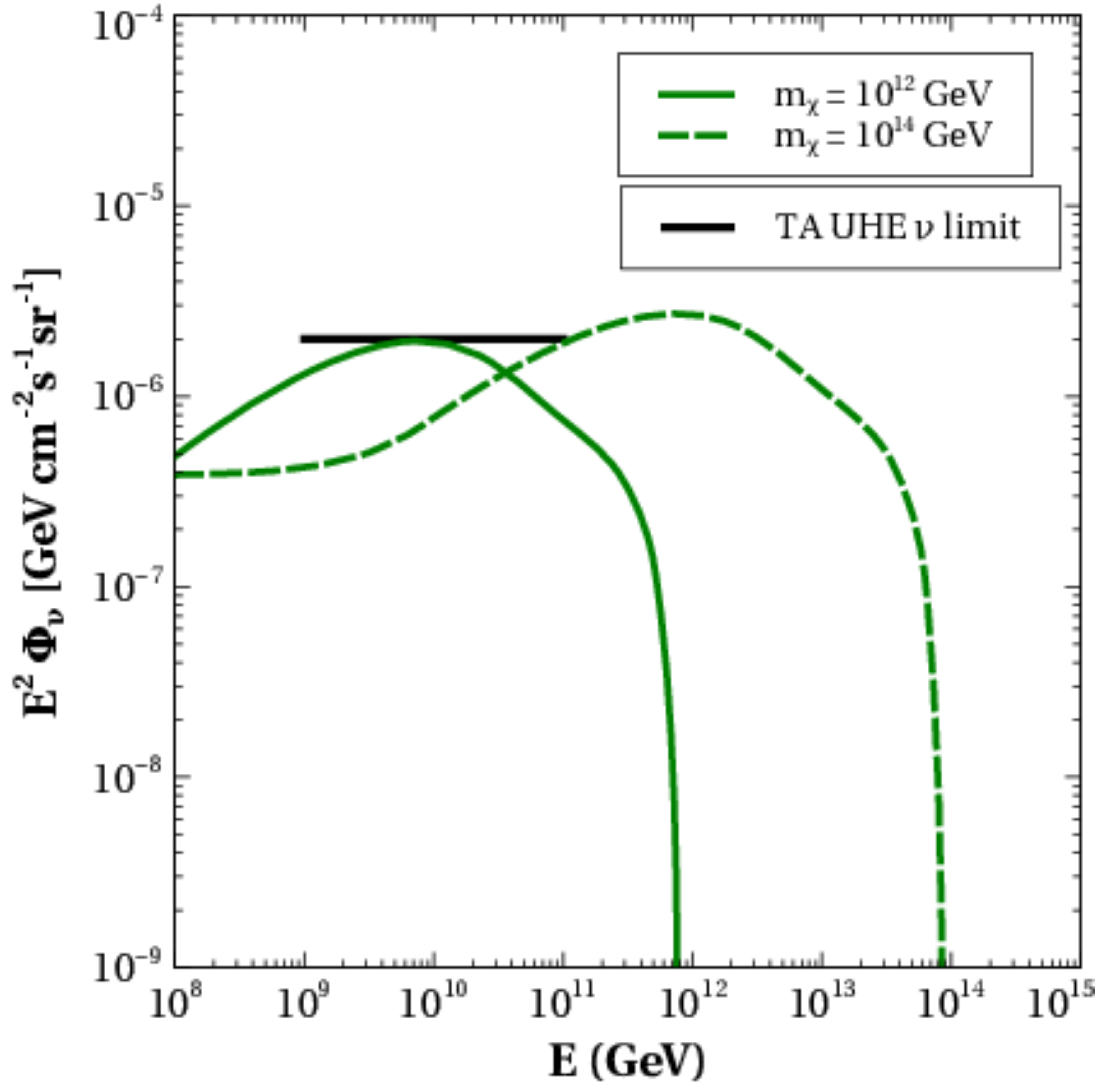
UHE photons and neutrinos from SHDM decay

$\chi \to b\bar{b}$



For $m_\chi = 10^{12}$ GeV, $\tau_\chi = 3.0 \times 10^{30}$ s
and $m_\chi = 10^{14}$ GeV, $\tau_\chi = 8.0 \times 10^{29}$ s.

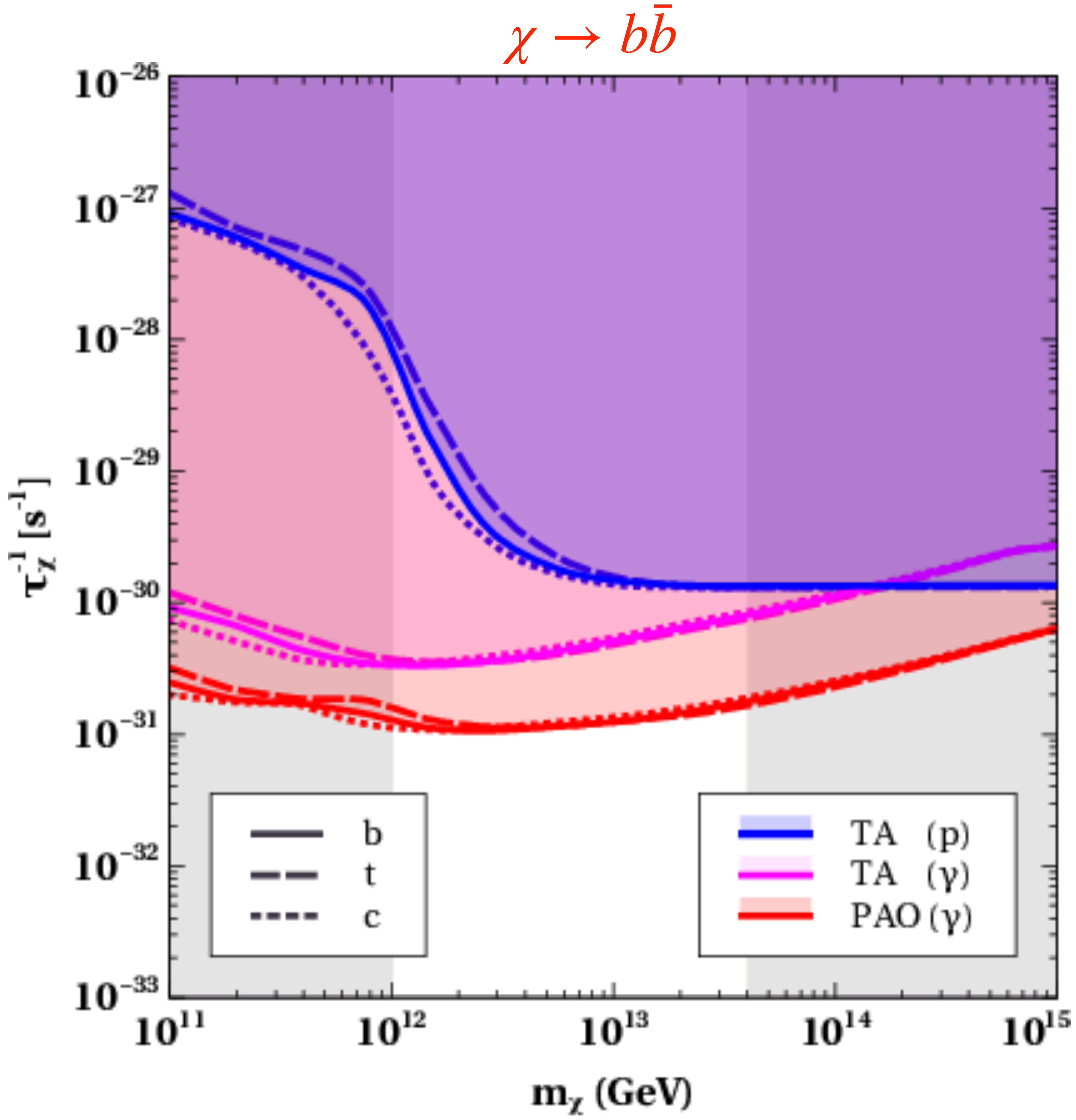
$\chi \to b\bar{b}$



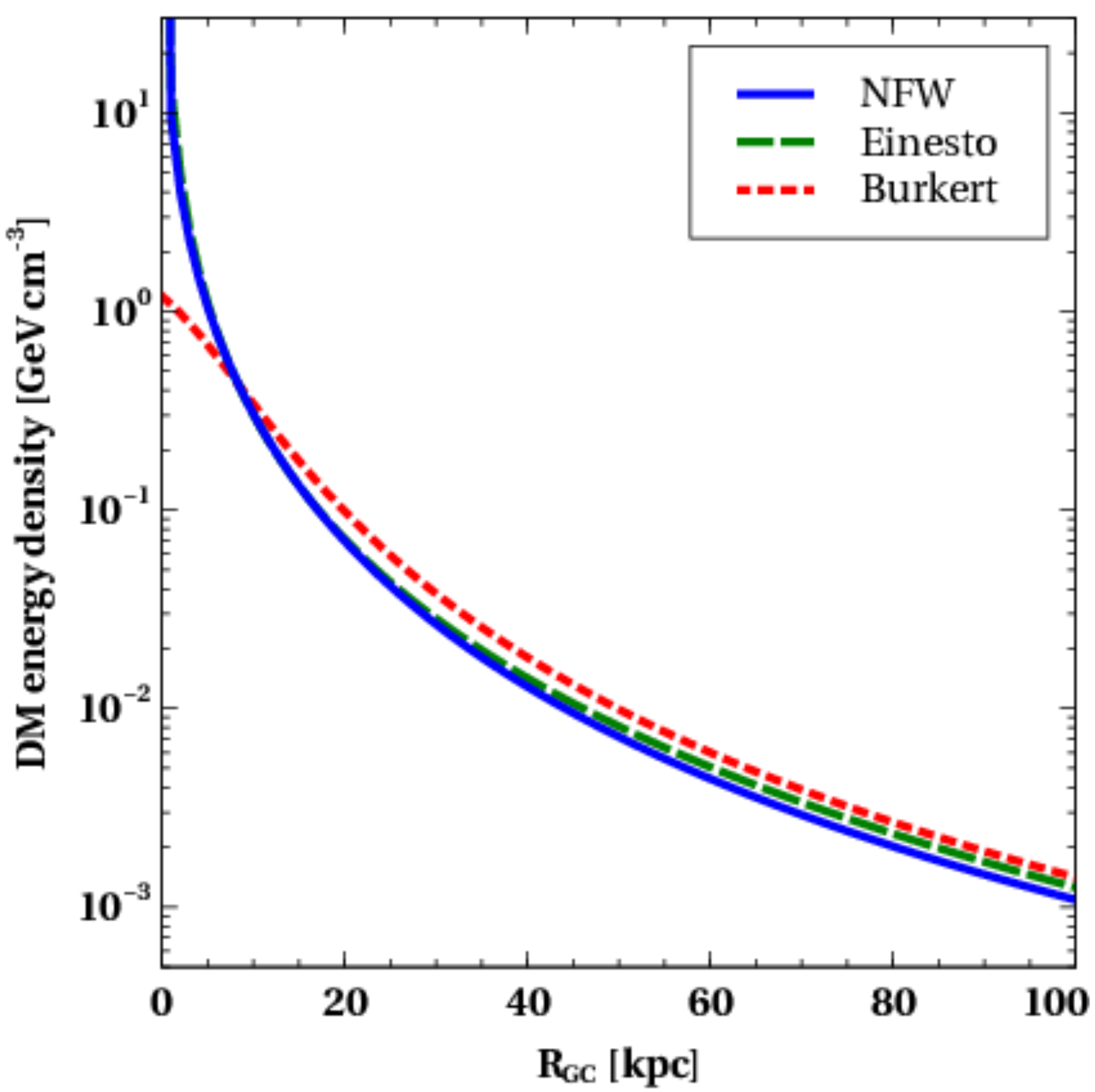
For $m_\chi = 10^{12}$ GeV, $\tau_\chi = 7.0 \times 10^{25}$ s
and $m_\chi = 10^{12}$ GeV, $\tau_\chi = 4.8 \times 10^{25}$ s.

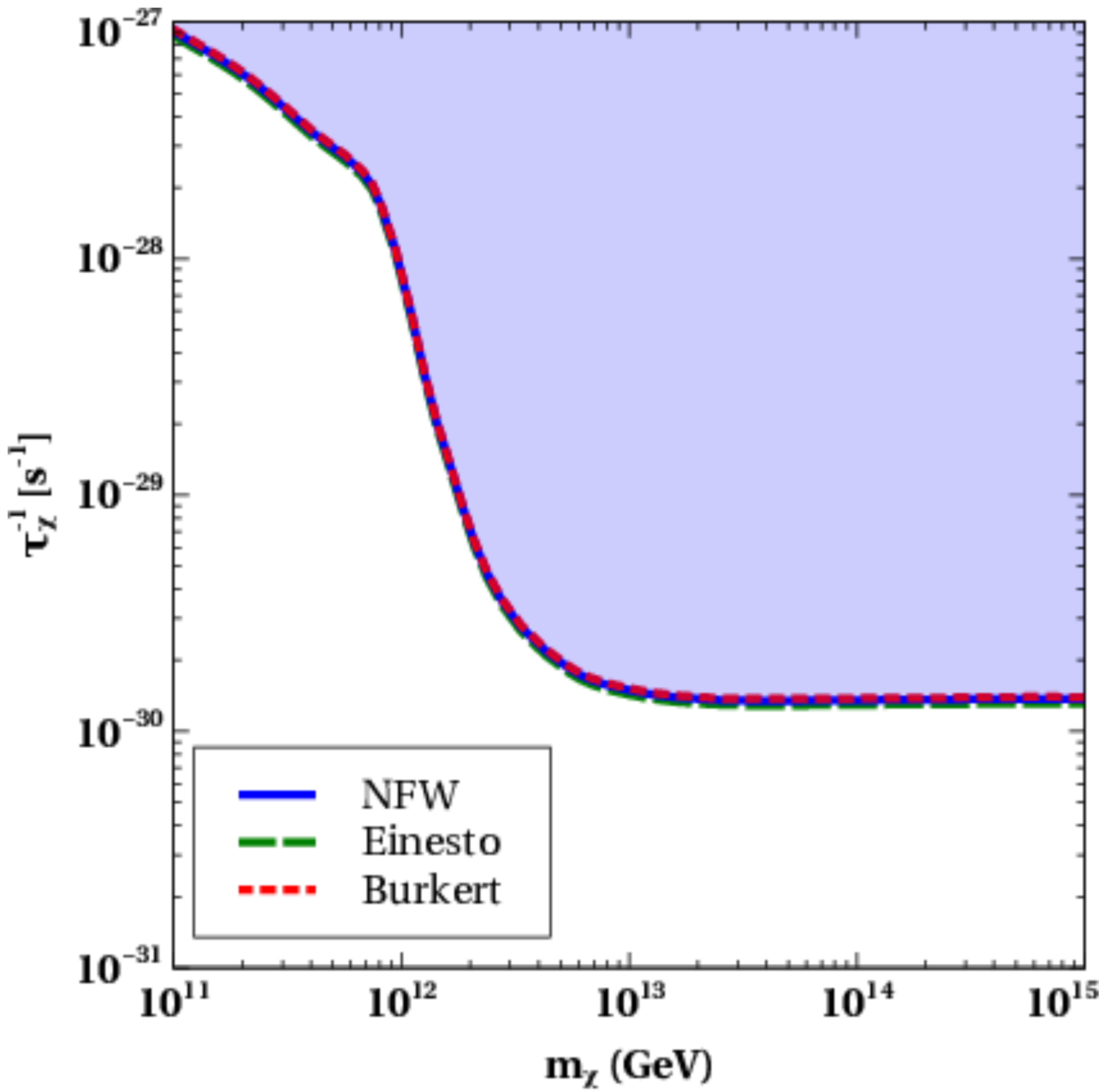
Multi-messenger constraints

- Bound on SHDM lifetime from UHECRs $\sim 10^{30}$ s.
- Bounds on SHDM lifetime from γ-ray non-observation are strongest, $(10^{30} - 10^{31})$ s.
- The Amaterasu particle is unlikely to have any SHDM origin.



Dependence on DM profiles

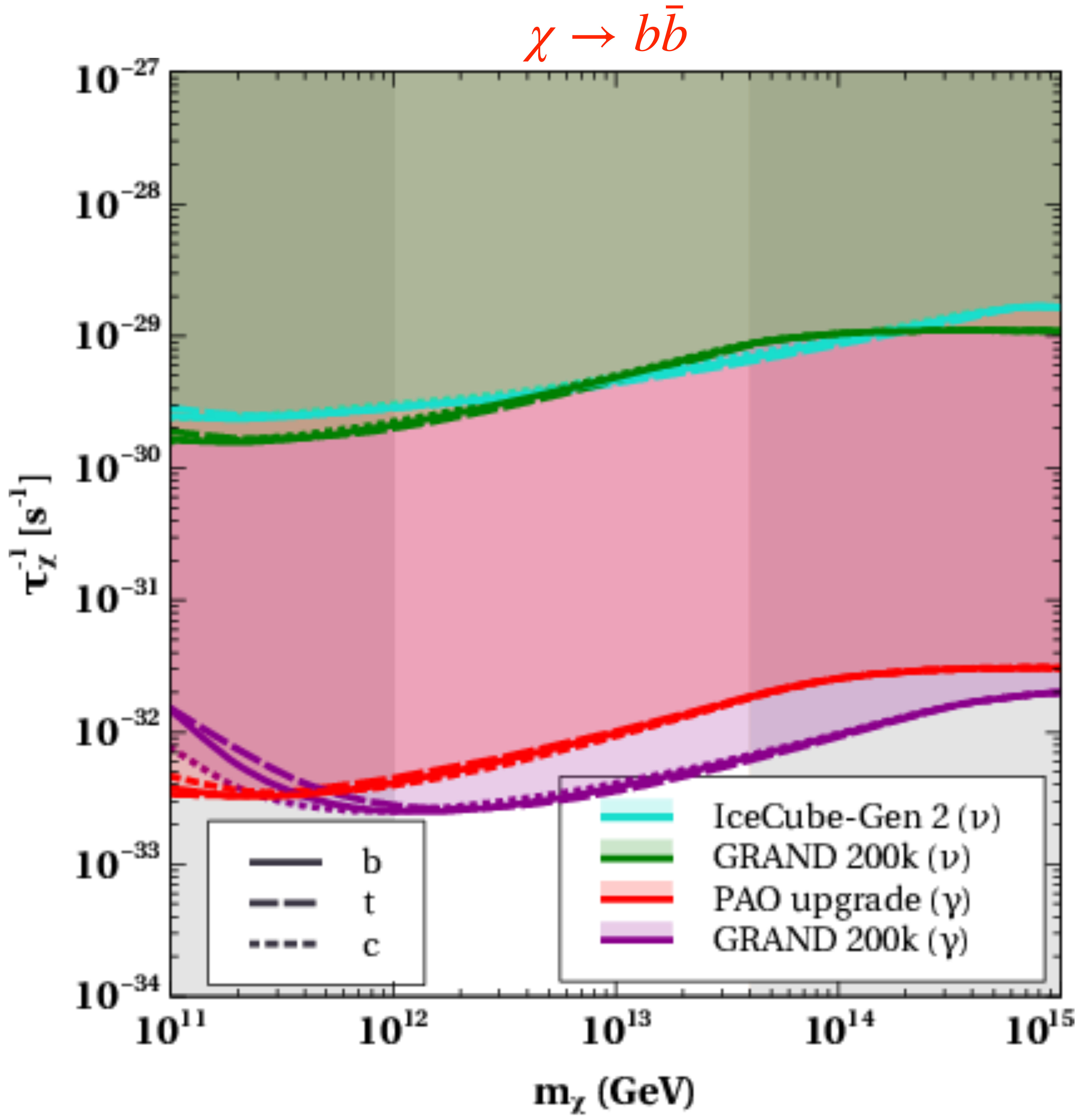




Dependence of DM profile is negligible.

Future predictions

- Bounds from future neutrino telescopes $(10^{29} - 10^{30})$ s.
- Future γ-ray telescopes may probe beyond 10^{32} s.



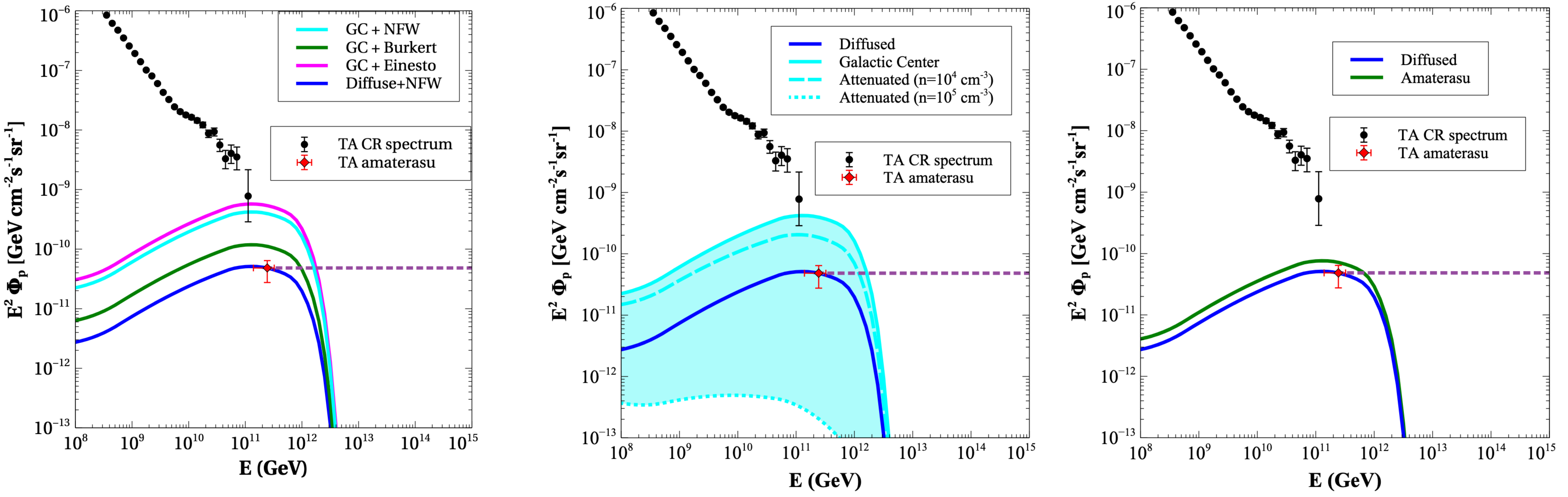
Summary

- Briefly discussed about origin and propagation of UHECRs.
- Discussed why the origin of the Amaterasu event detected by TA experiment is not known.
- Analysed SHDM as a possible origin.
- UHE Gamma-ray constraints from PAO and TA being stronger than those from UHECRs disfavour the SHDM origin for the Amaterasu event.
- Future UHE gamma-ray experiments such as GRAND 200k and PAO upgrade will improve the bounds on the SHDM lifetime.

Thank you!

Backup slides

Constraints from the galactic centre



Backup slides

Constraints from all decay modes