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

Based on arXiv: 2406.03174

21st Rencontres du Vietnam
Theory meeting experiments: particle astrophysics and cosmology
@ICISE, Quy Nhon, Vietnam

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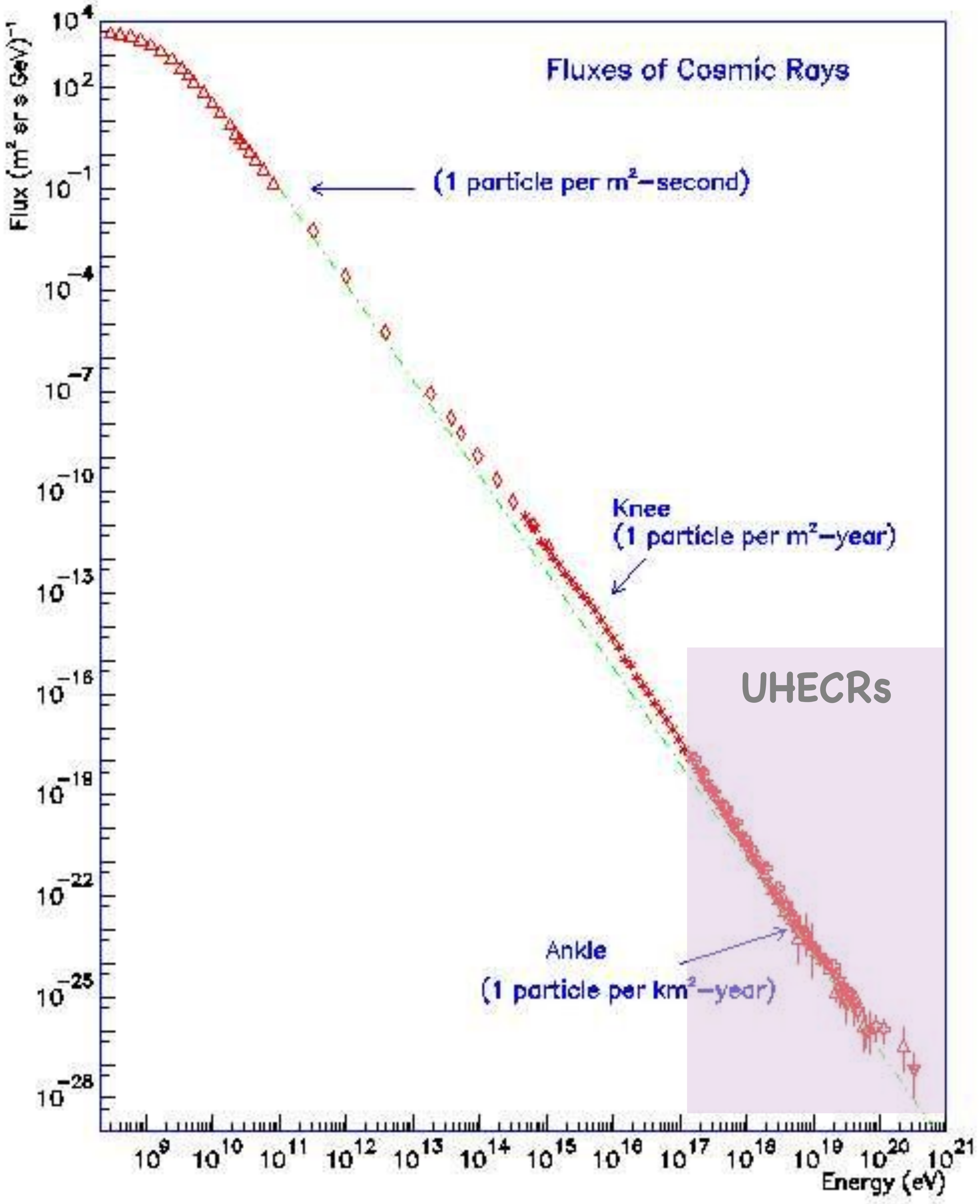
Outline

- 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



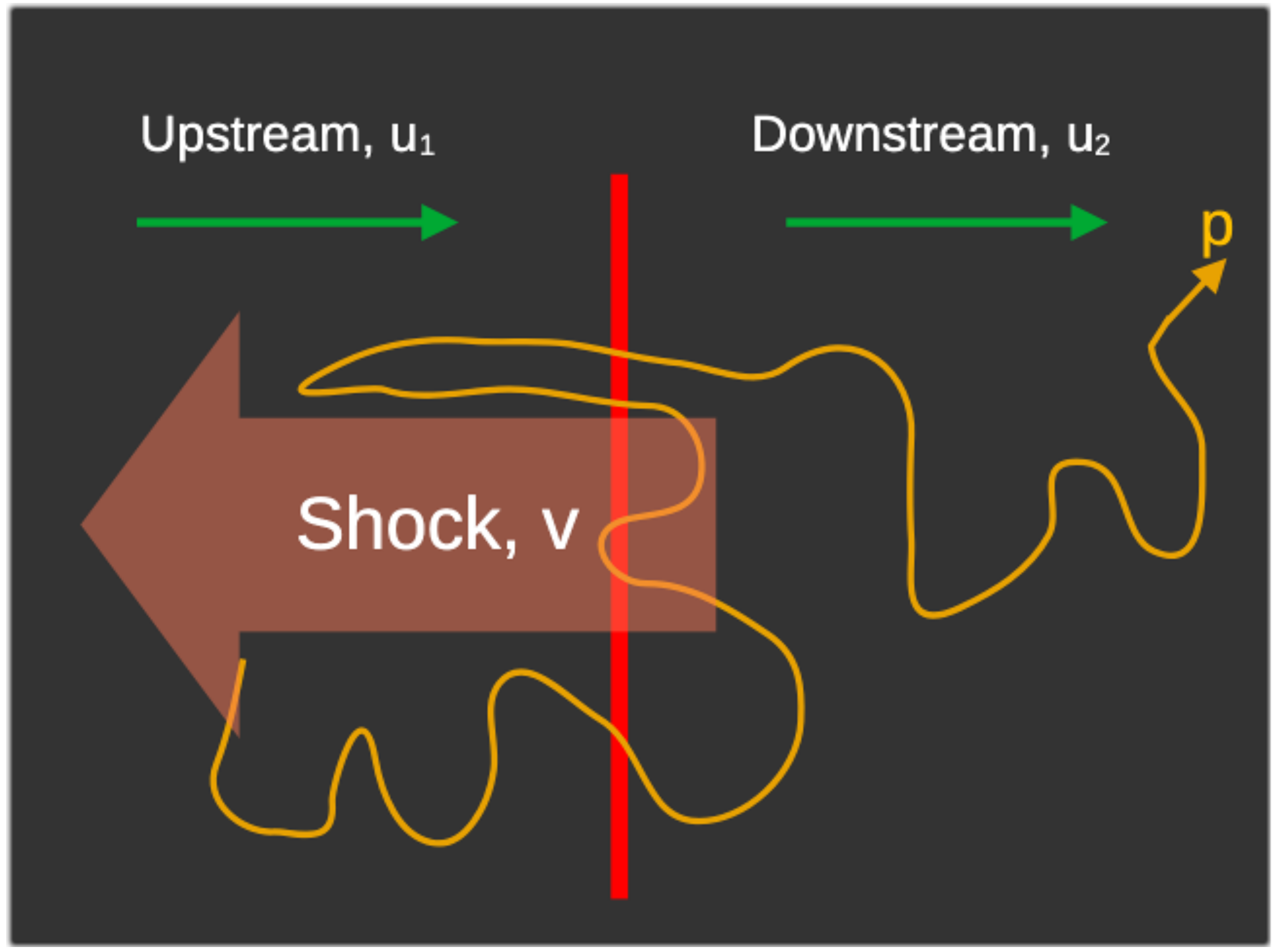
- Cosmic rays (CRs) are mostly protons (about 90%), alpha particles (9%), and other heavy elements.
- CR spectrum spans over a vast energy range from 1 GeV to 10^{11} GeV.
- Galactic origin upto the knee (10^6 GeV).
- Extra-galactic above the ankle (10^9 GeV): Ultra-high energy cosmic rays (UHECRs).

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:

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

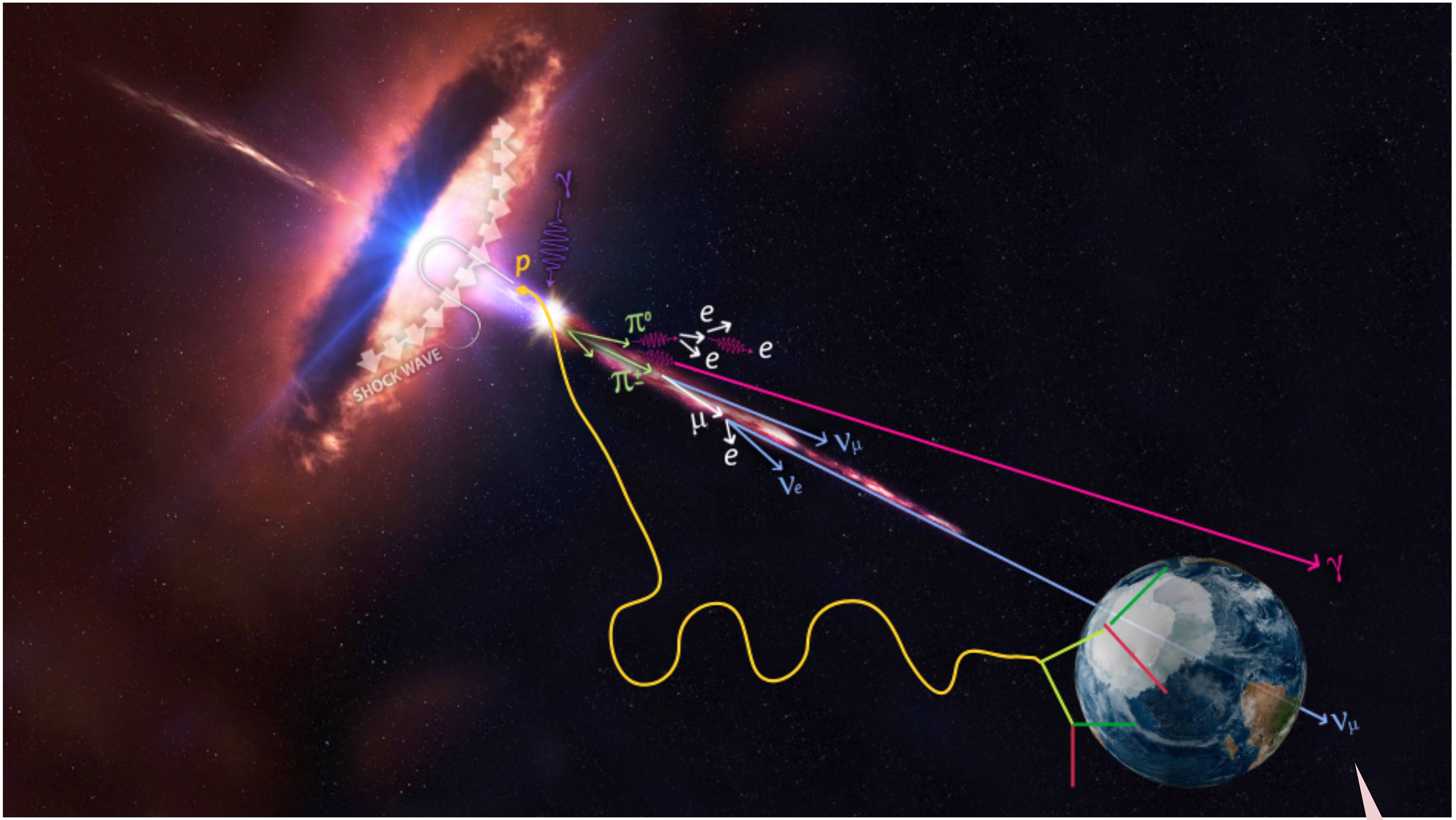
Fermi's 1st order accleration

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

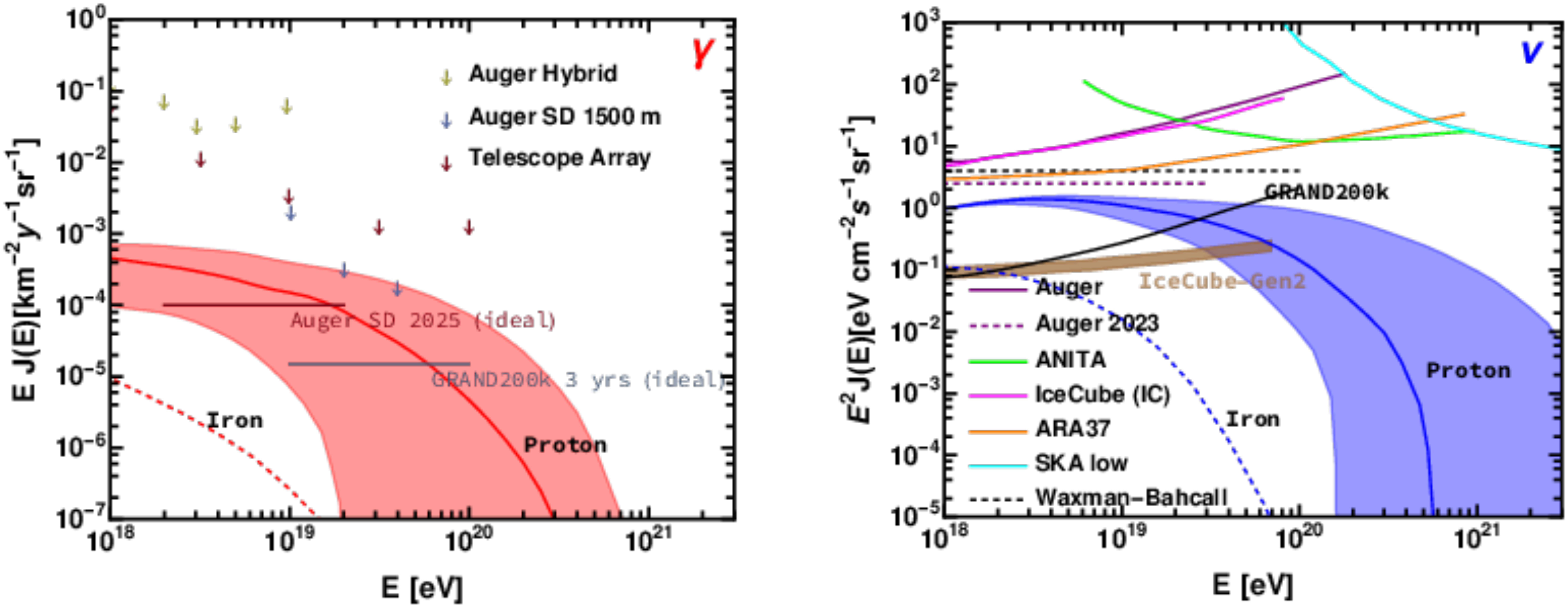


- UHECRs + Cosmic Microwave Background.
- Threshold energy of protons: GZK cut-off ($\sim 5 \times 10^{10}$ GeV).
- Mean free path $\sim$ 10 Mpc.
- CR spectrum falls rapidly beyond the GZK cut-off.

Multi-messenger signals

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

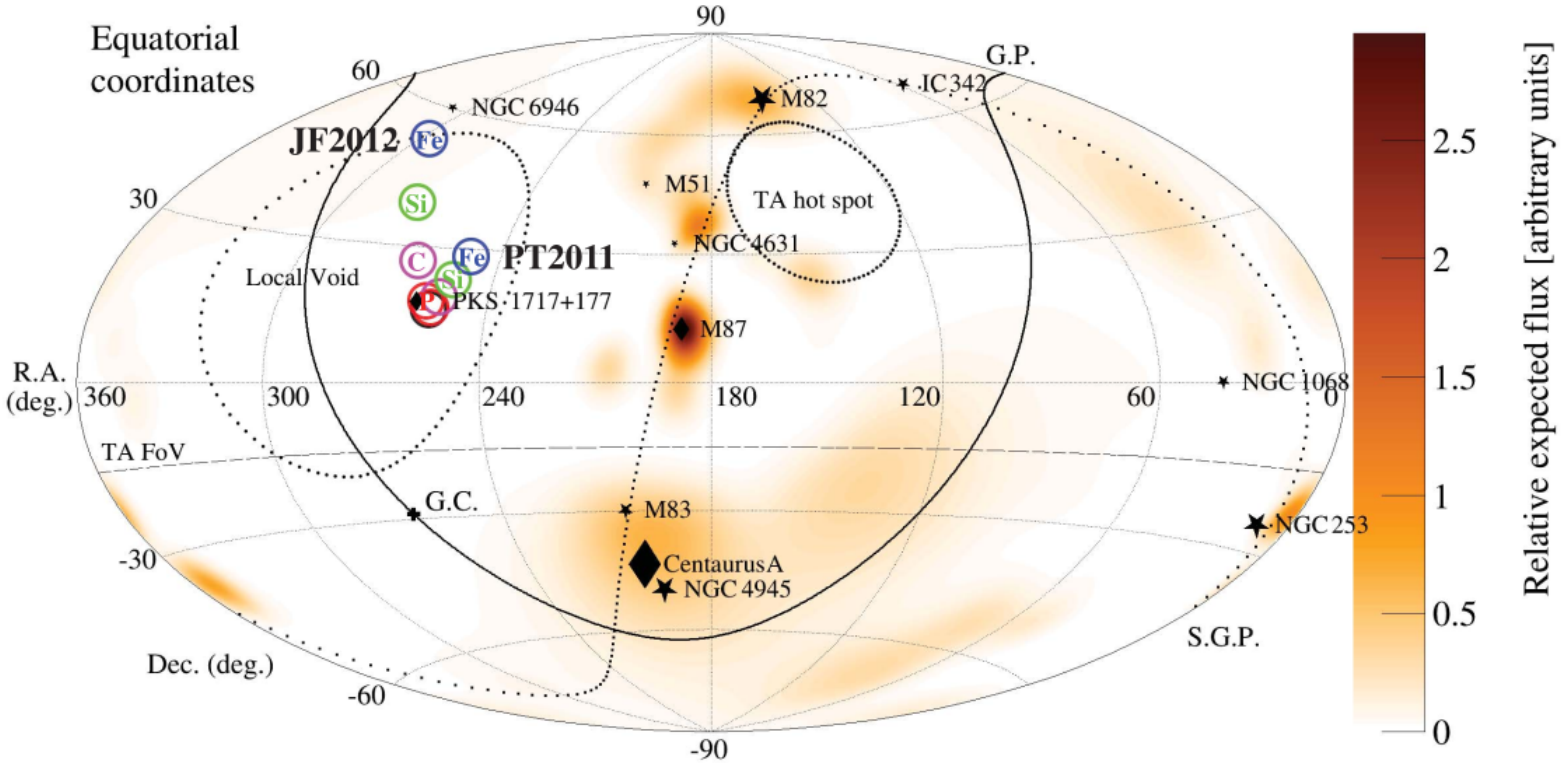
GZK photon and neutrino flux



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

The Amaterasu event

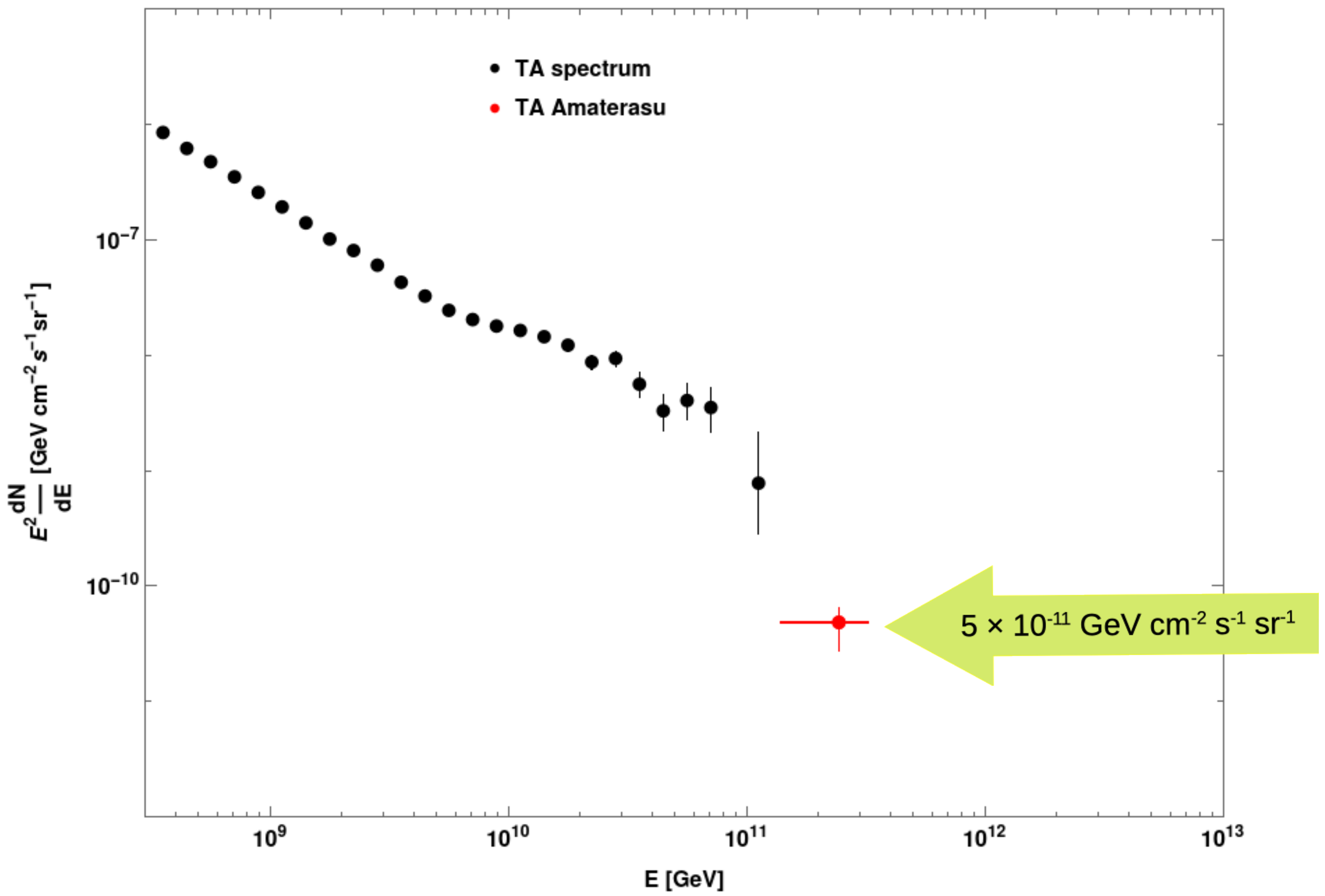
- UHECRs detected by the Telescope Array experiment, about 45 degrees away from the Galactic centre.
- Third most energetic (2.44×10^{11} GeV) CR particle ever detected.
- Due to the GZK process, the source should be within about 30 Mpc.
- No possible sources within this distance.
- What could be the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



Science 382 (2023) 903-907

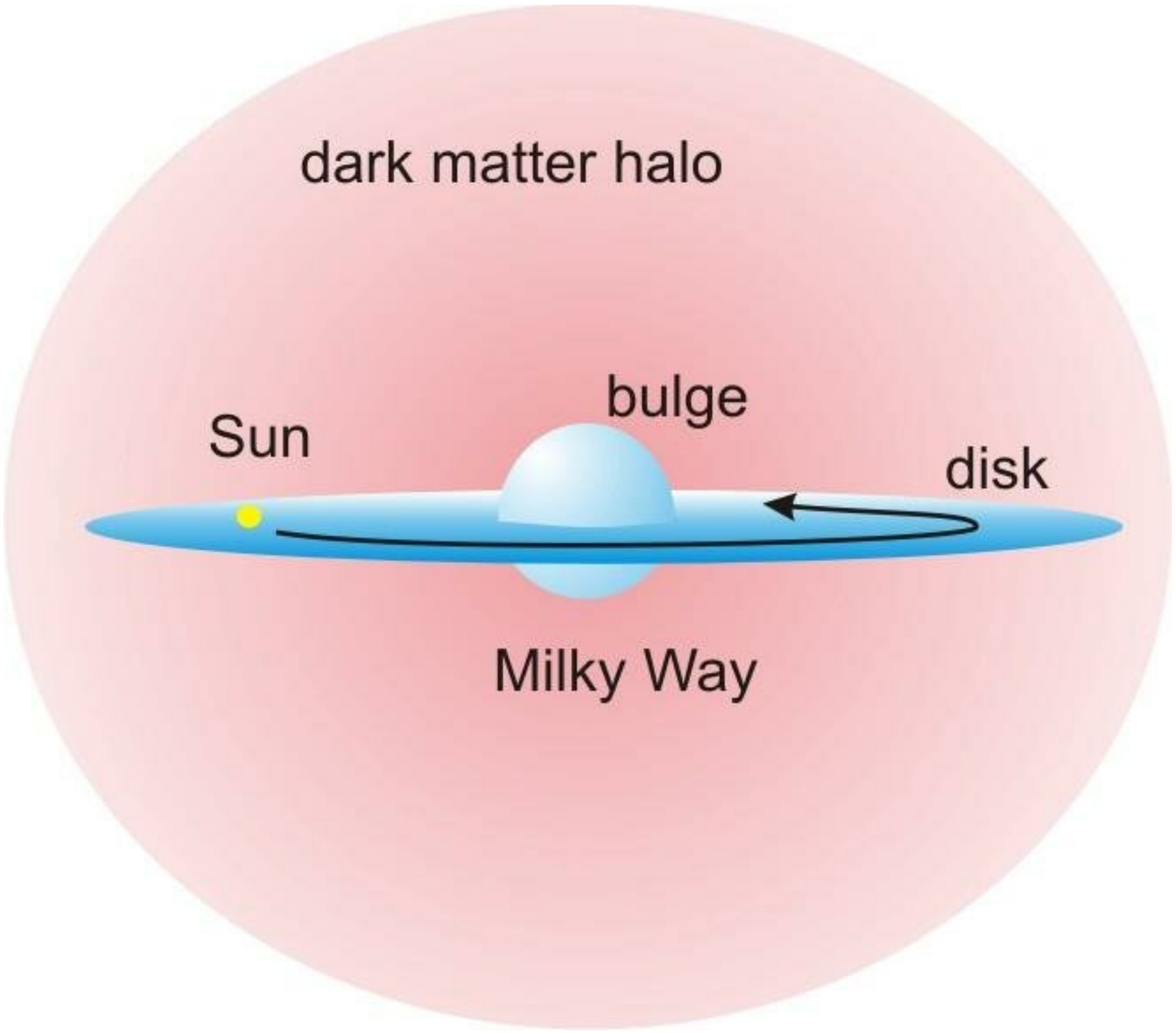
The Amaterasu event

- 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



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

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., $\chi \to b\bar{b}$ or $\chi \to e^- e^+$.

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:

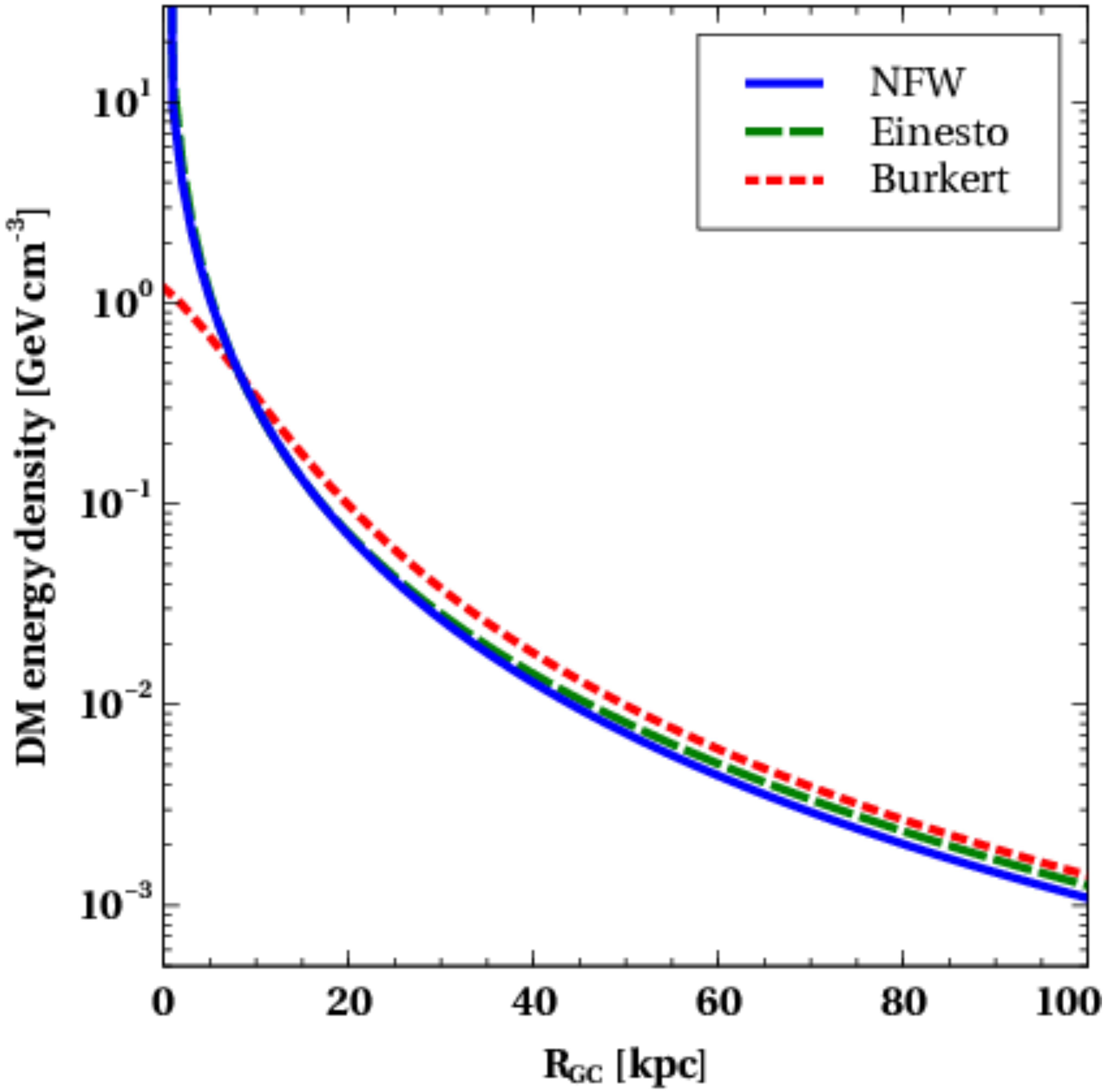
$$\rho_{\rm Ein}(R_{\rm GC}) = \rho_c \exp\left[-12.5\left(\left(\frac{R_{\rm GC}}{R_C}\right)^{0.16} - 1\right)\right]$$

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



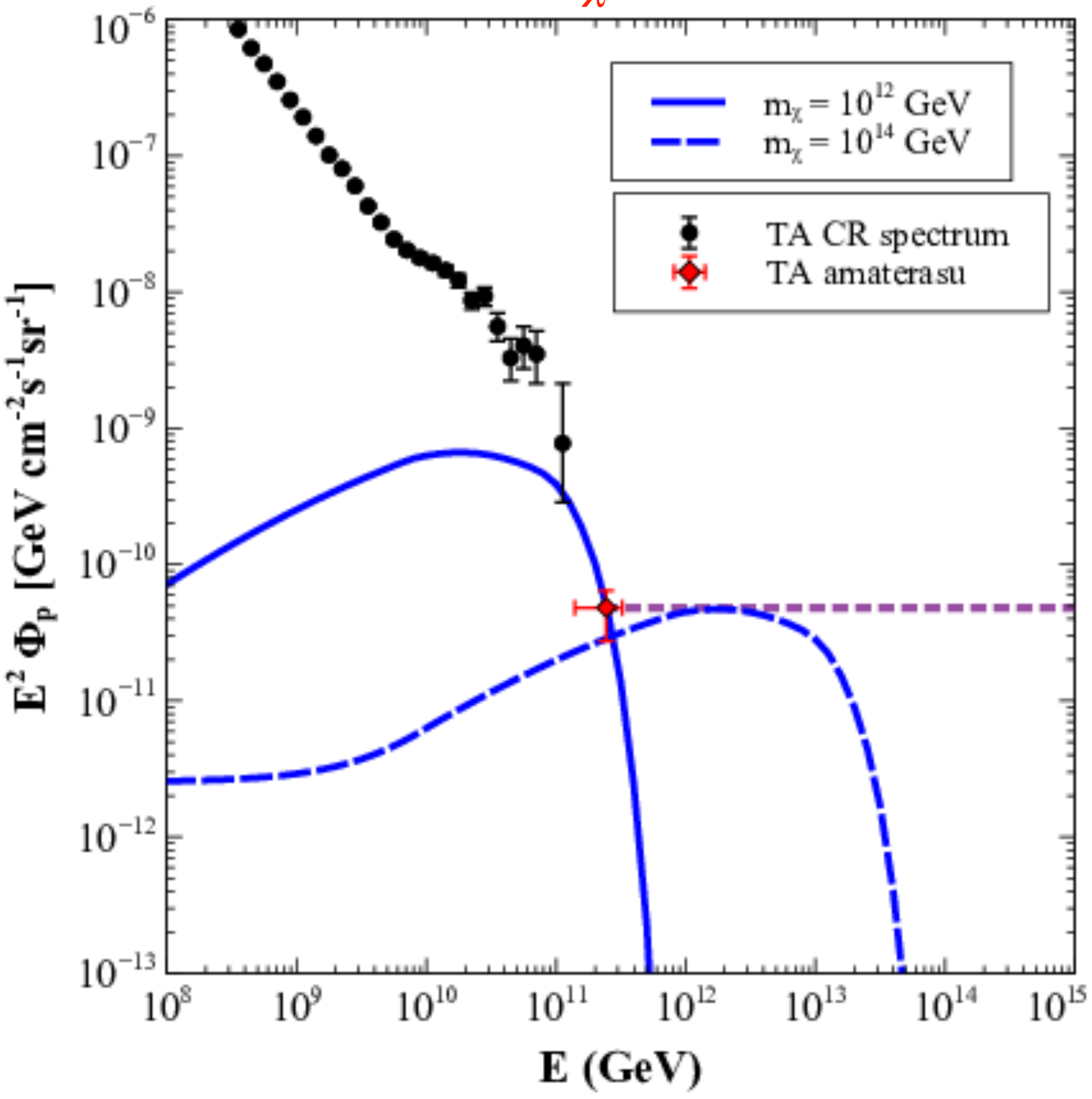
R_{GC} : Galactocentric radius, R_c : 11 kpc, ρ_c : characteristic DM density.

UHECRs flux from SHDM decay

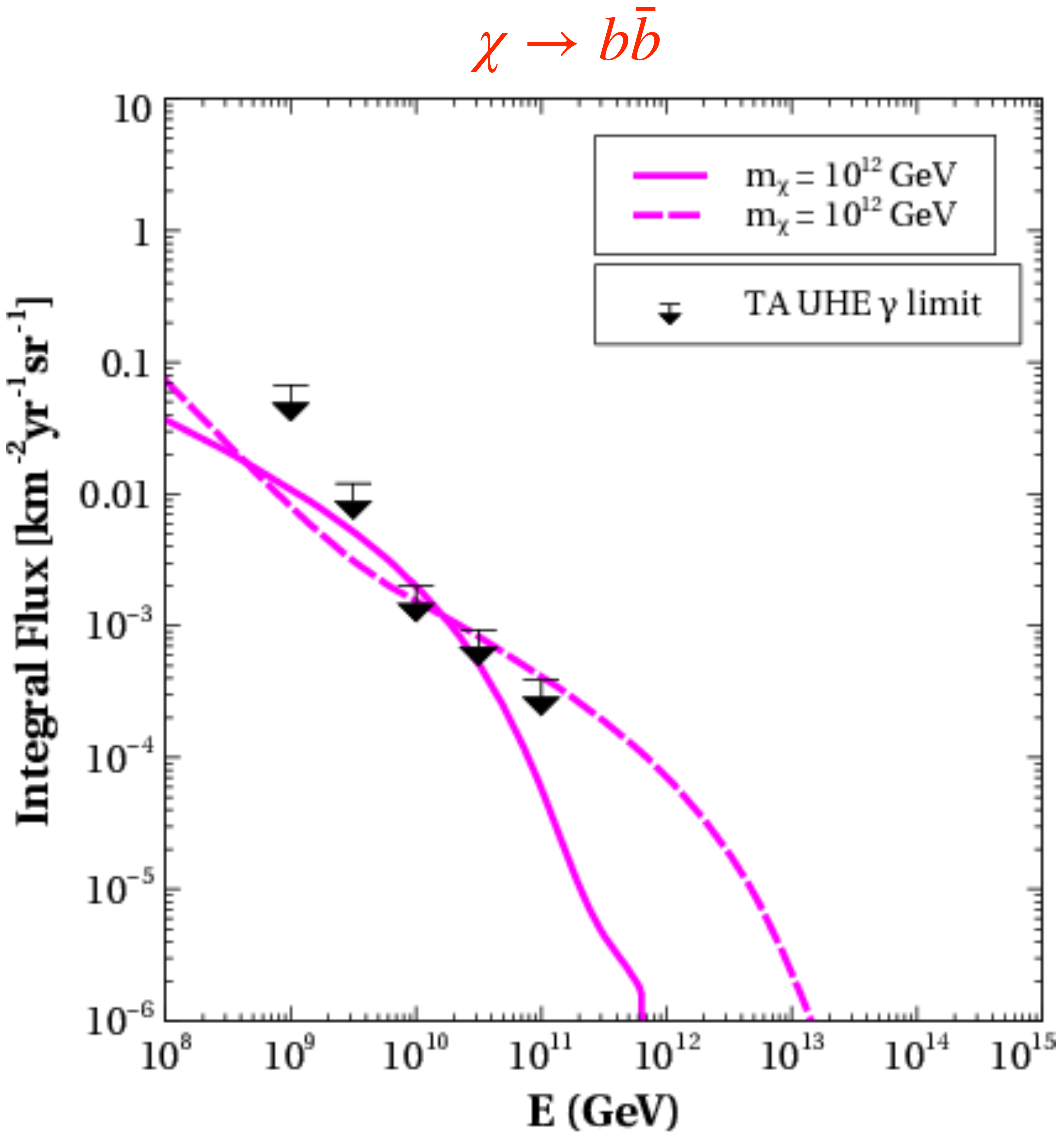
$$\Phi_i(E) = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_i(E)}{dE} \int^{\text{line of sight}} \rho_\chi(l)dl$$

- 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.

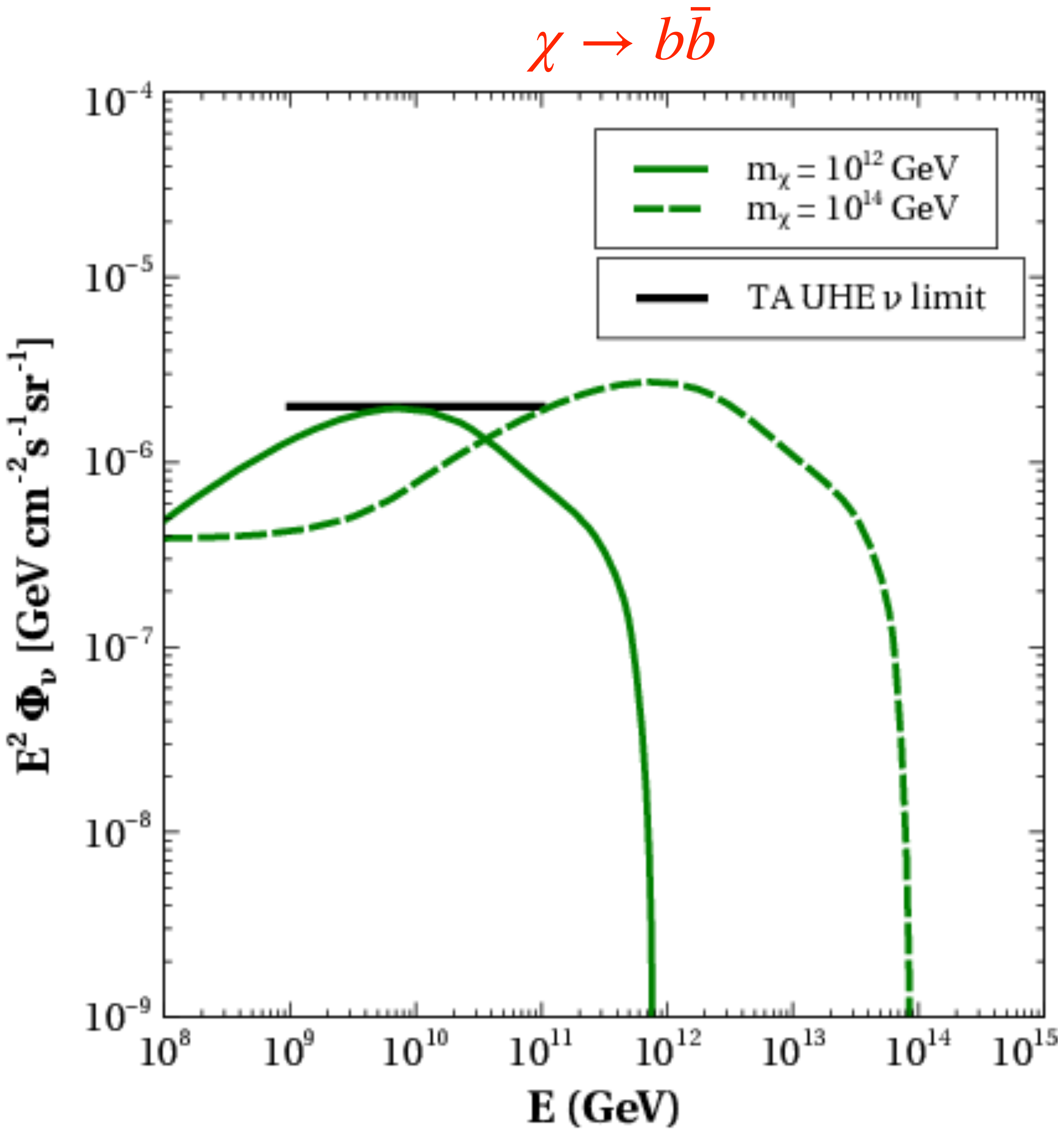
$\chi \to b\bar{b}$



UHE photons and neutrinos from SHDM decay



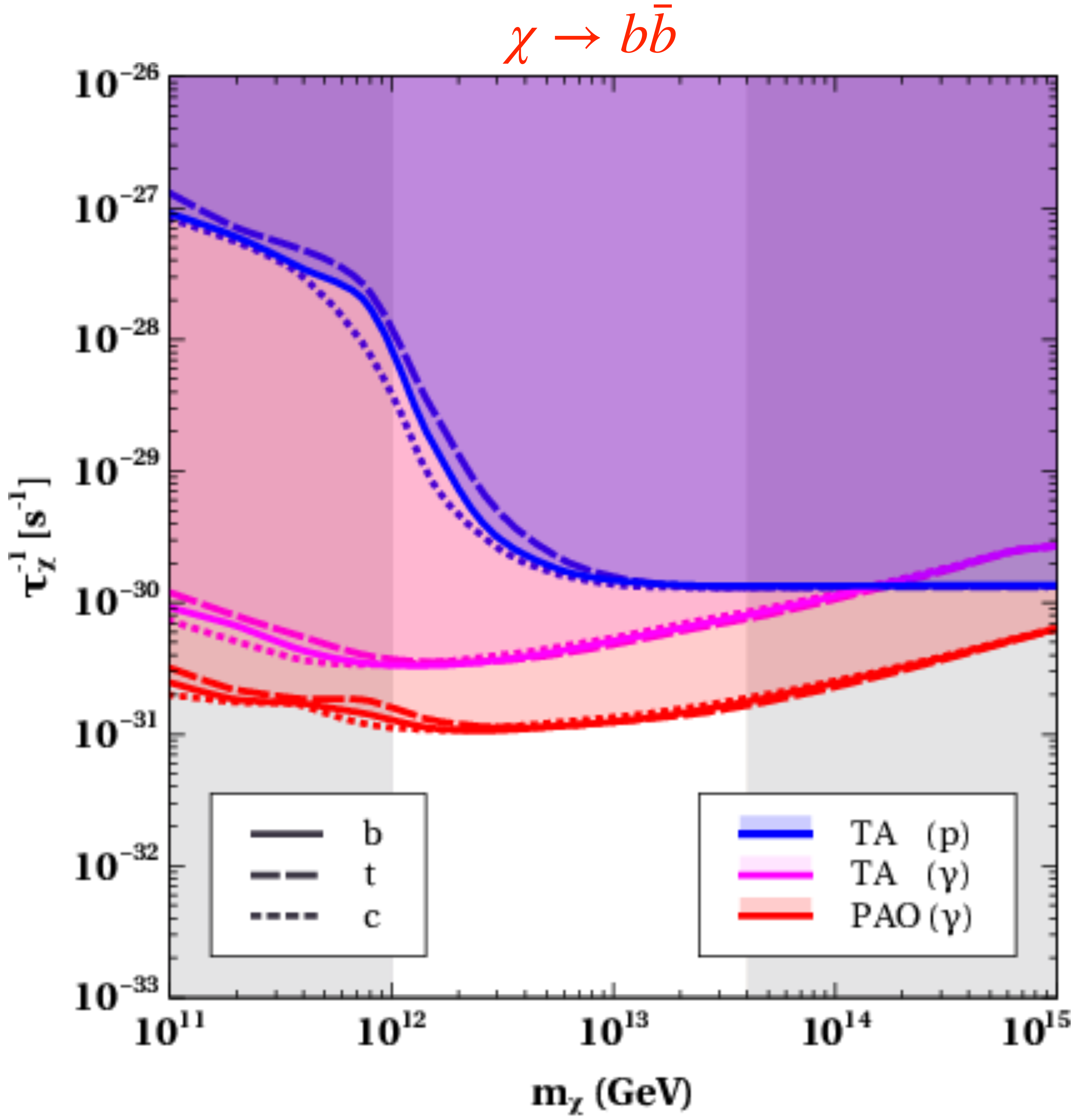
For $m_\chi = 10^{12}$ GeV, $\tau_\chi = 3.0 \times 10^{30}$ s and $m_\chi = 10^{14}$ GeV, $\tau_\chi = 8.0 \times 10^{29}$ s.



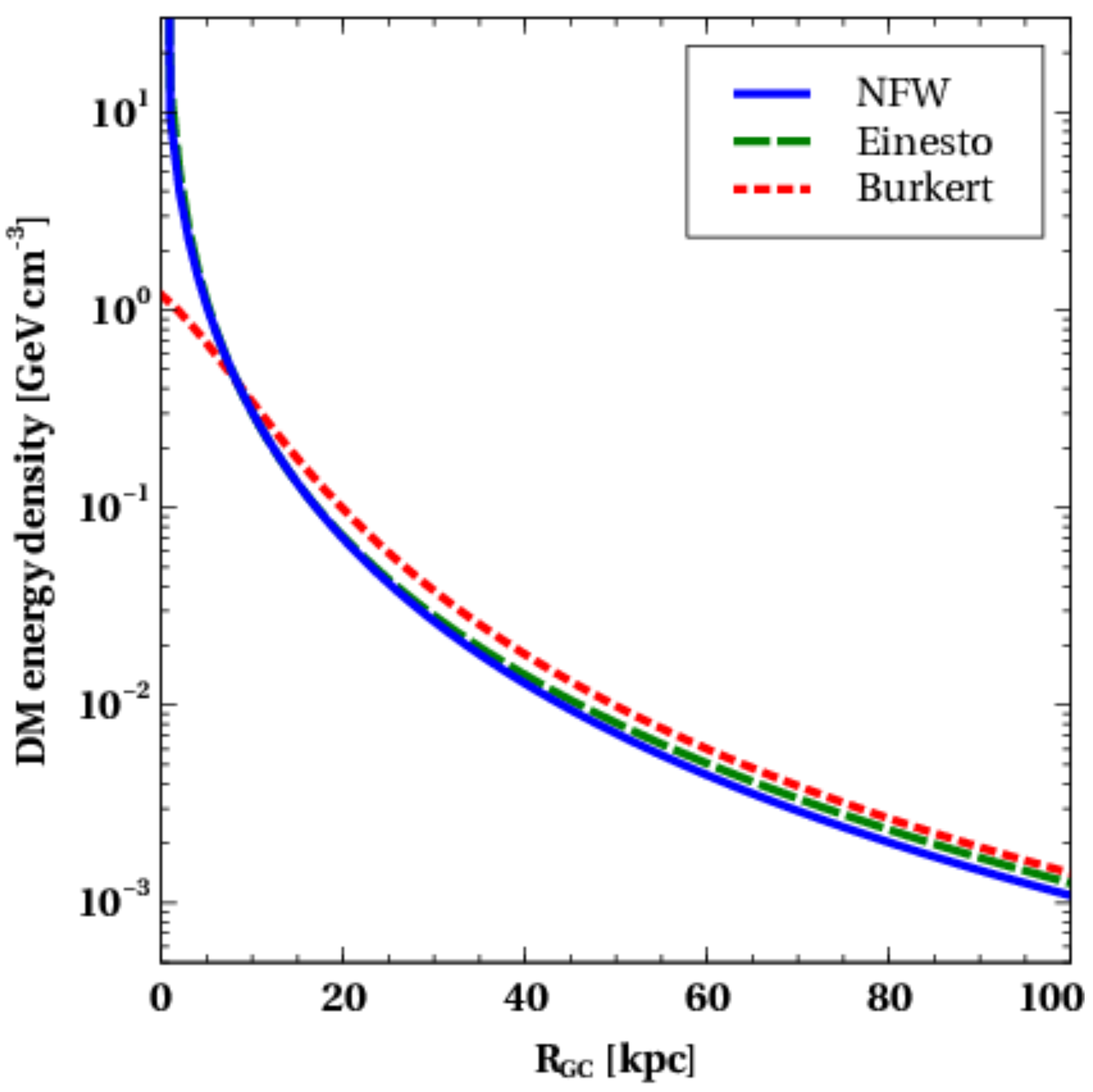
For $m_\chi = 10^{12}$ GeV, $\tau_\chi = 7.0 \times 10^{25}$ s and $m_\chi = 10^{12}$ GeV, $\tau_\chi = 4.8 \times 10^{25}$ s.

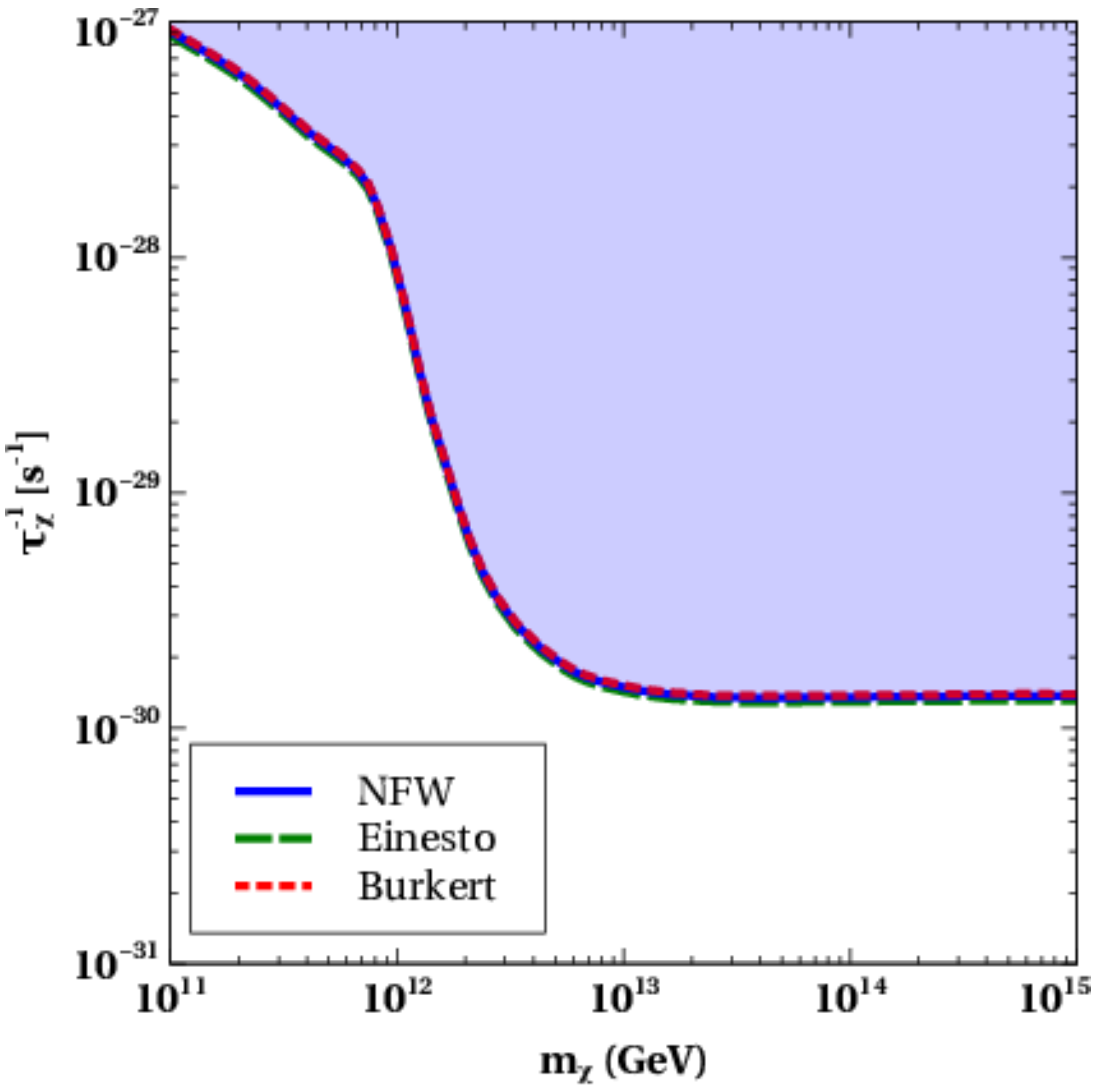
Multi-messenger constraints

- 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

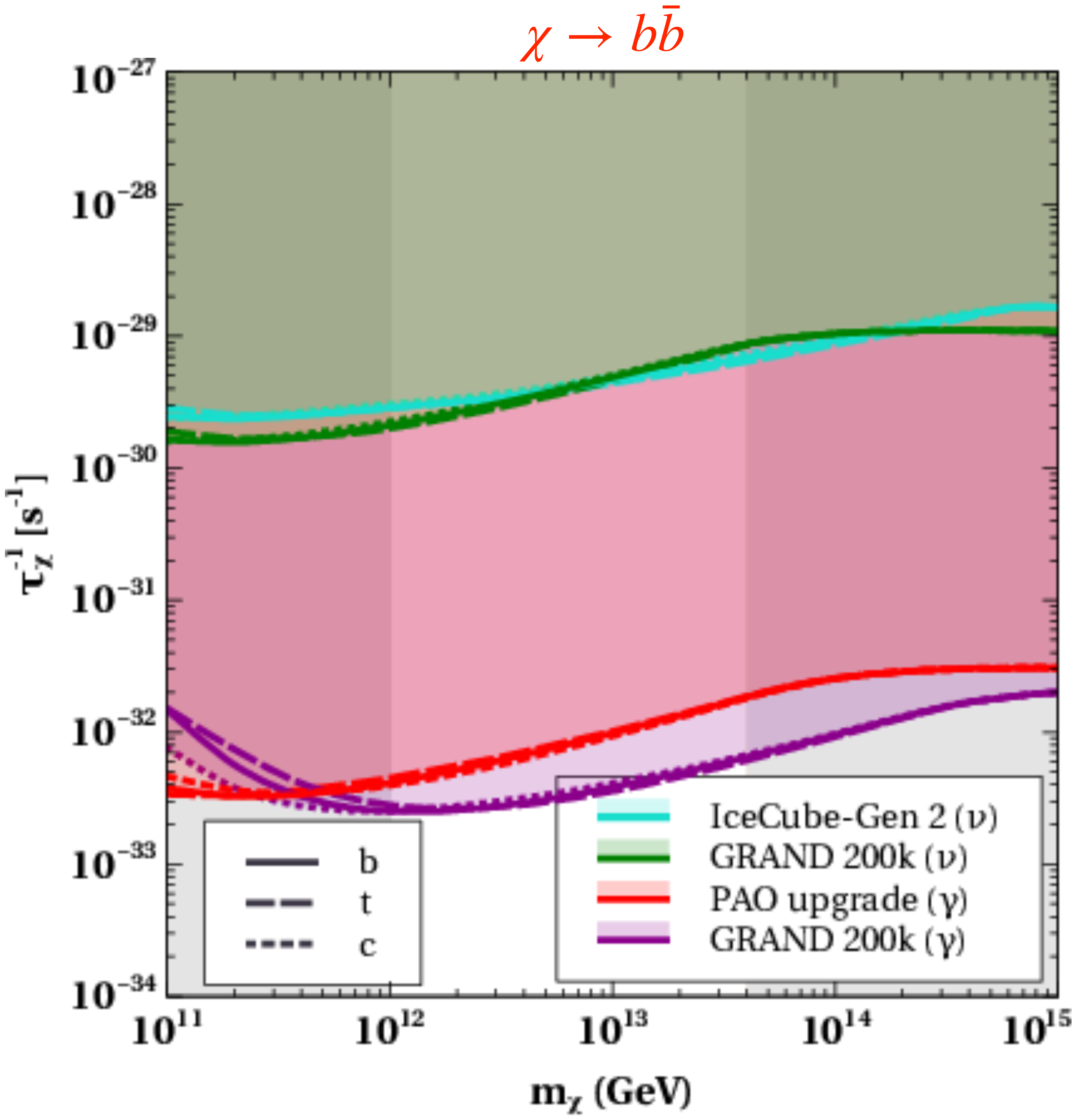




Dependence of DM profile is negligible.

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!