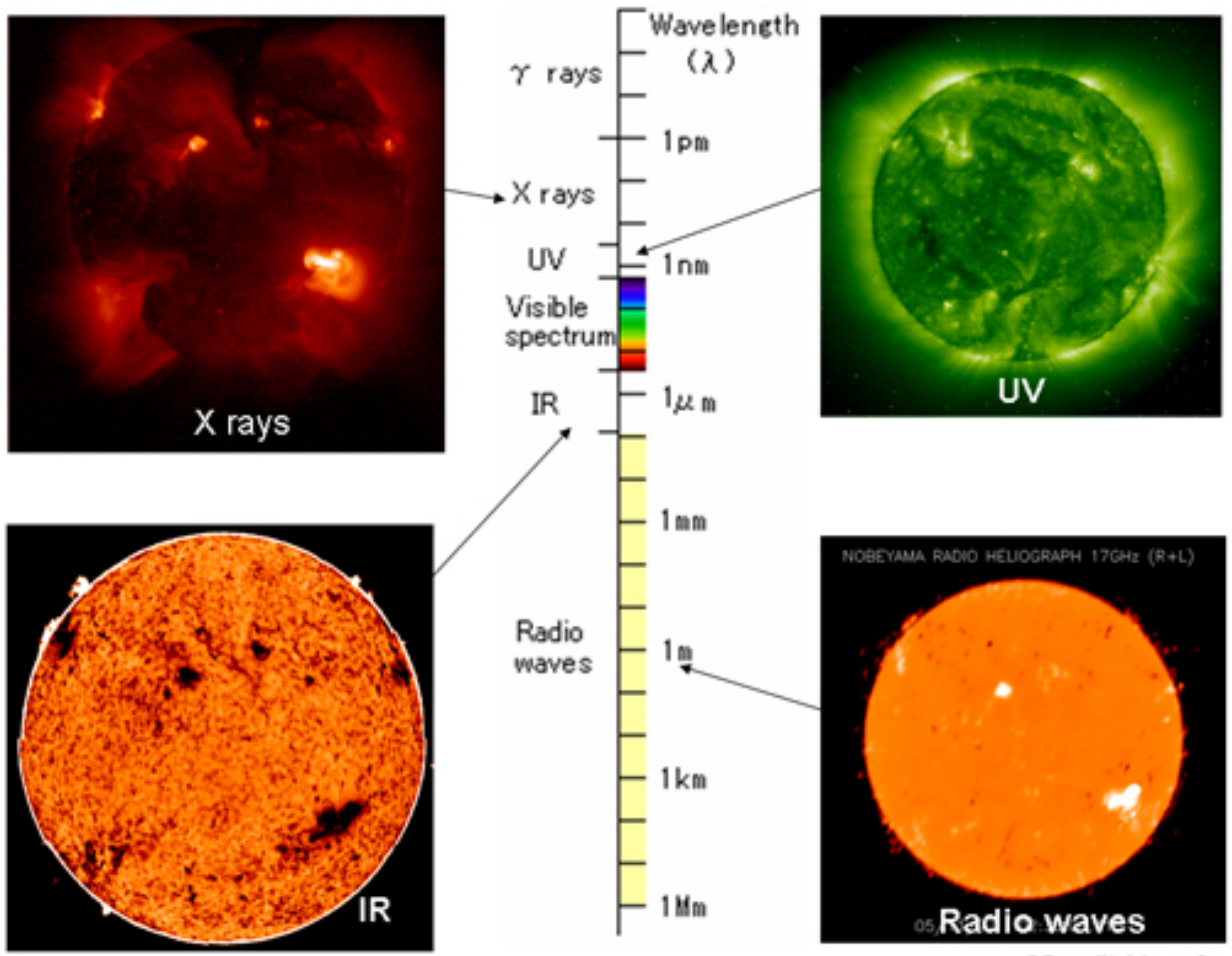
CTAO-KM3NeT Community Day
Nikhef, Amsterdam
8 September 2025

TeV Gamma Rays (and Neutrinos) as a Probe of Solar Magnetic Fields

Shin'ichiro Ando
University of Amsterdam

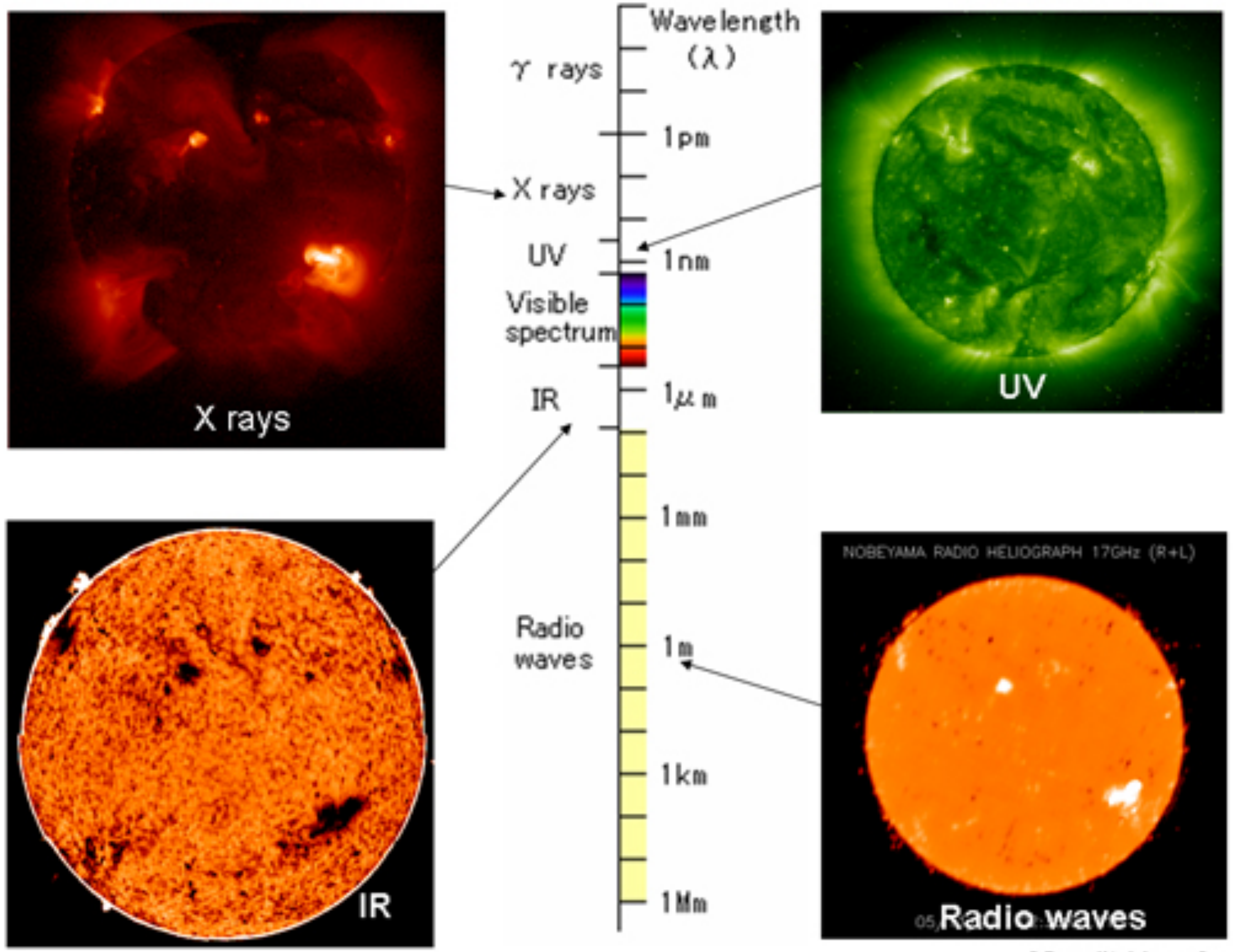
Based on: Kenny Ng, Andrew Hillier, Shin'ichiro Ando, *Phys. Rev. Lett.* (to appear) [arXiv:2405.17549 [astro-ph.SR]]

Multi-messenger images of the Sun



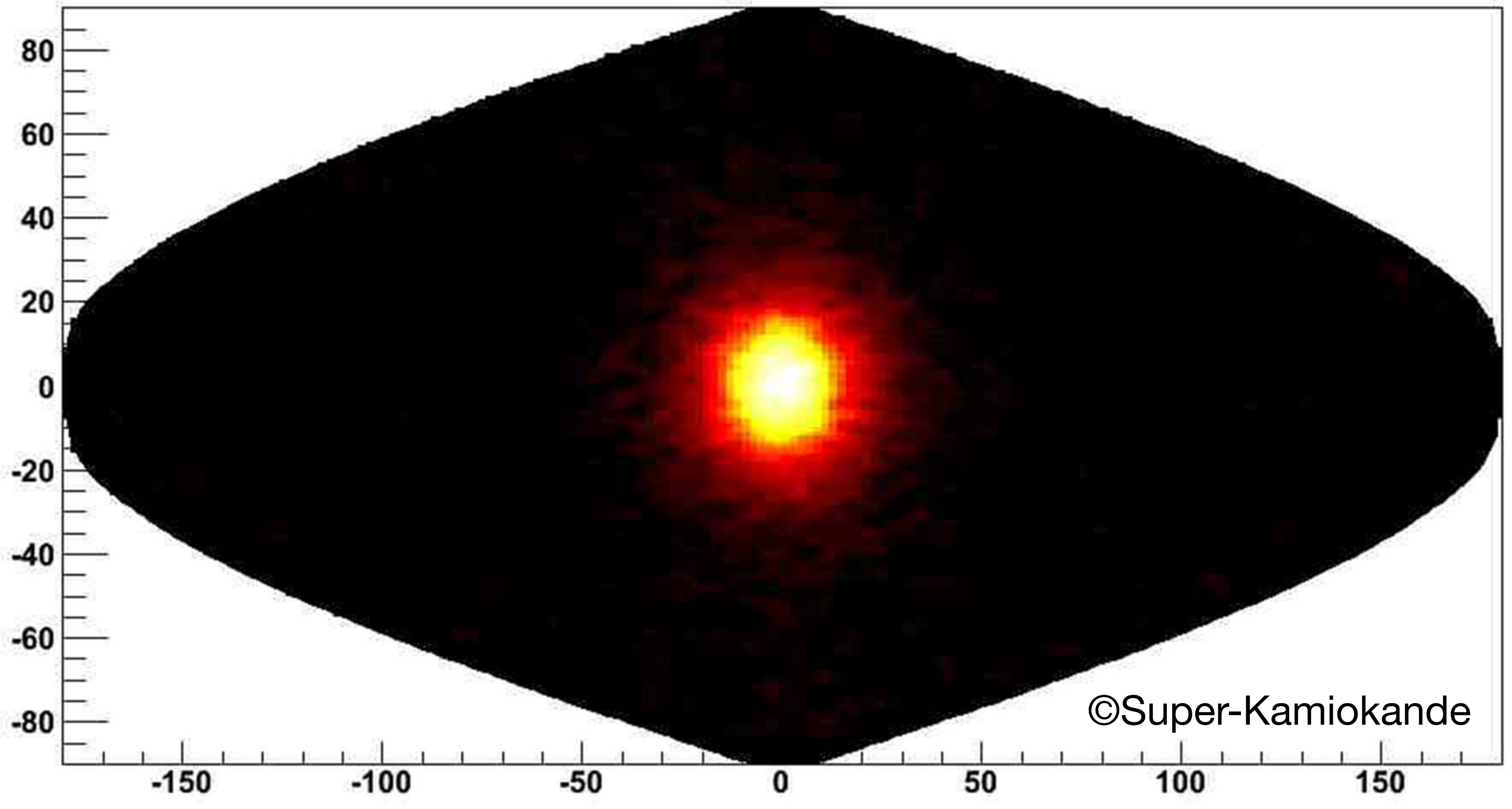
[Credit:Nasa]

Multi-messenger images of the Sun

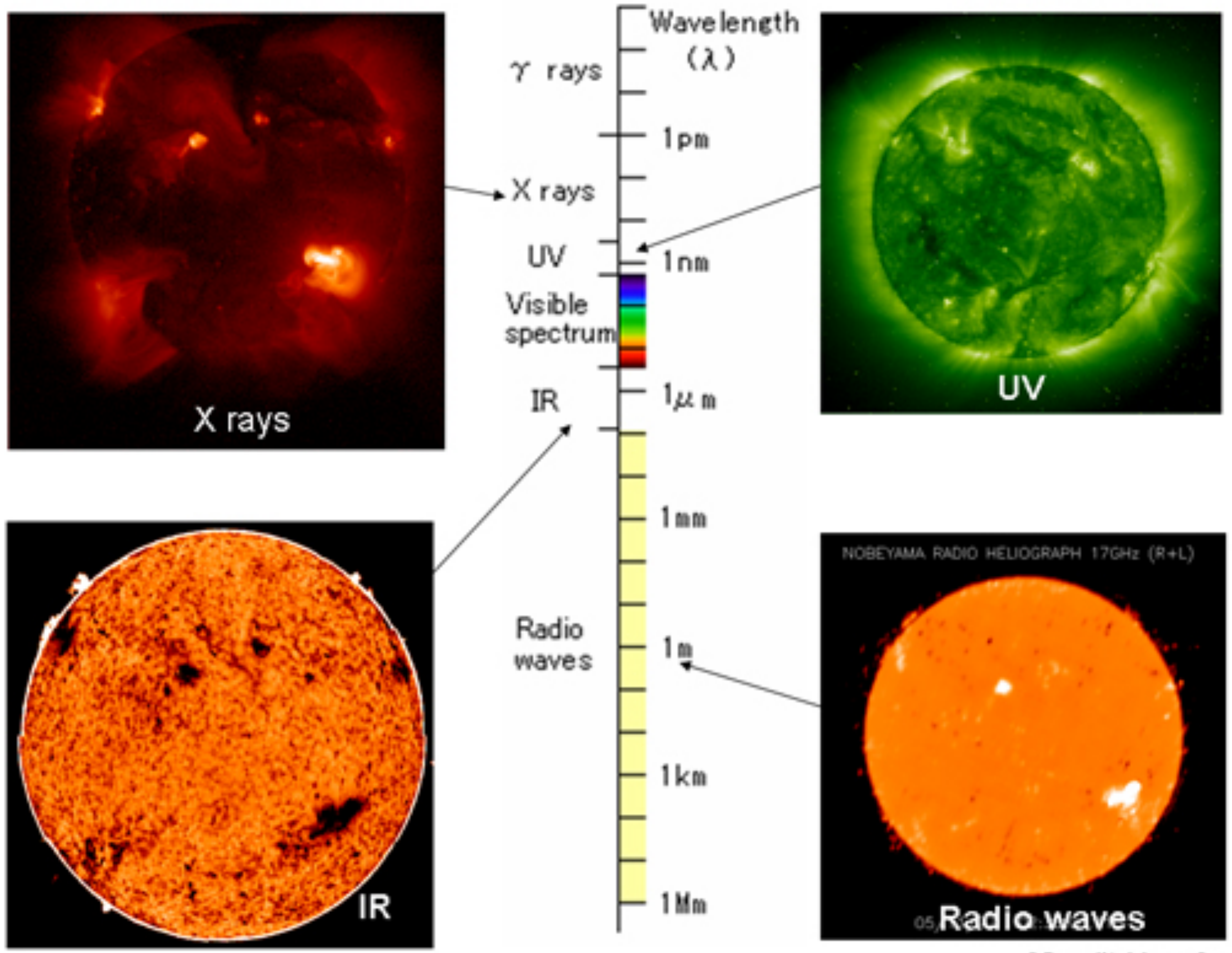


[Credit:Nasa]

MeV neutrinos

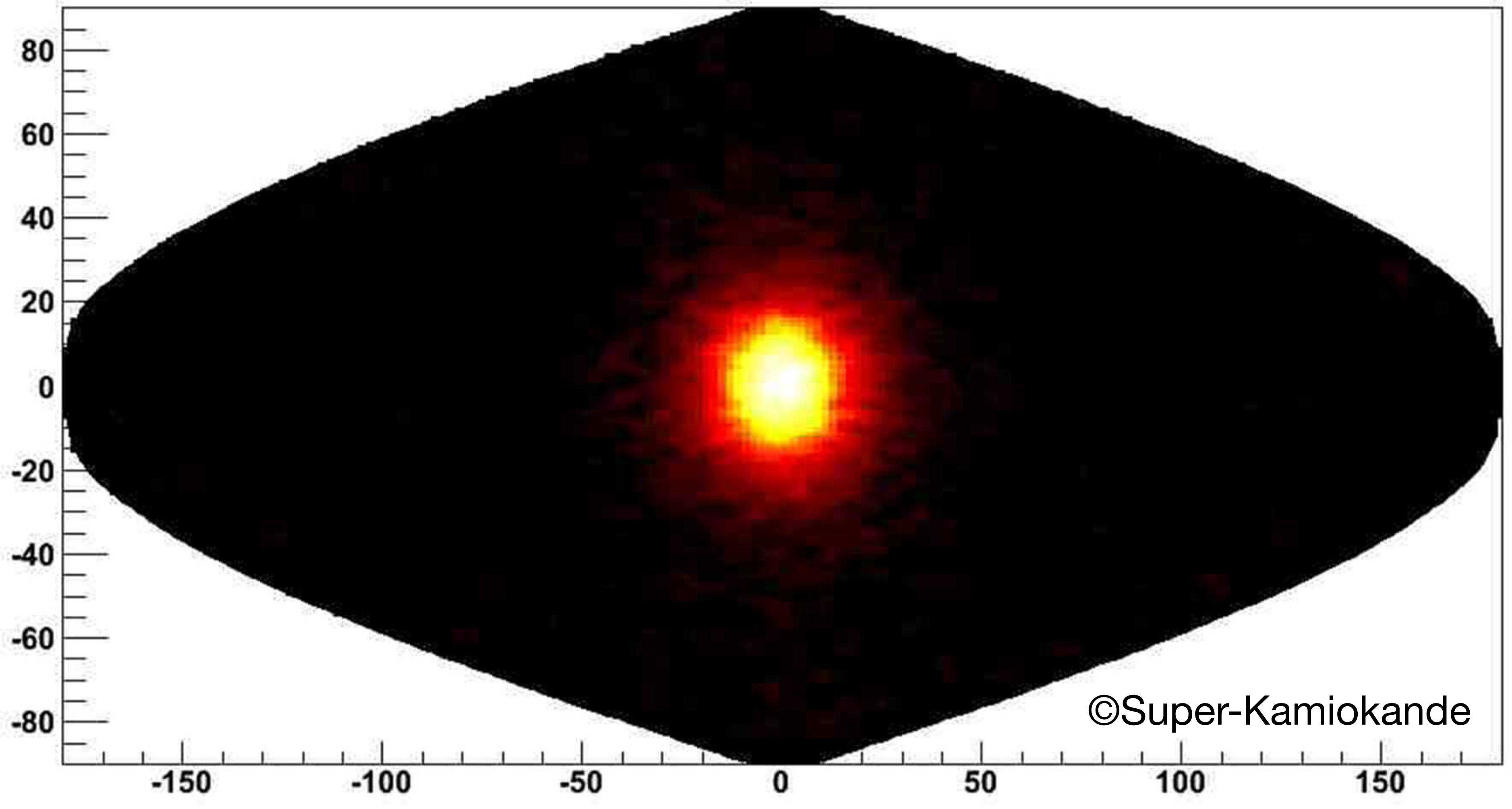


Multi-messenger images of the Sun



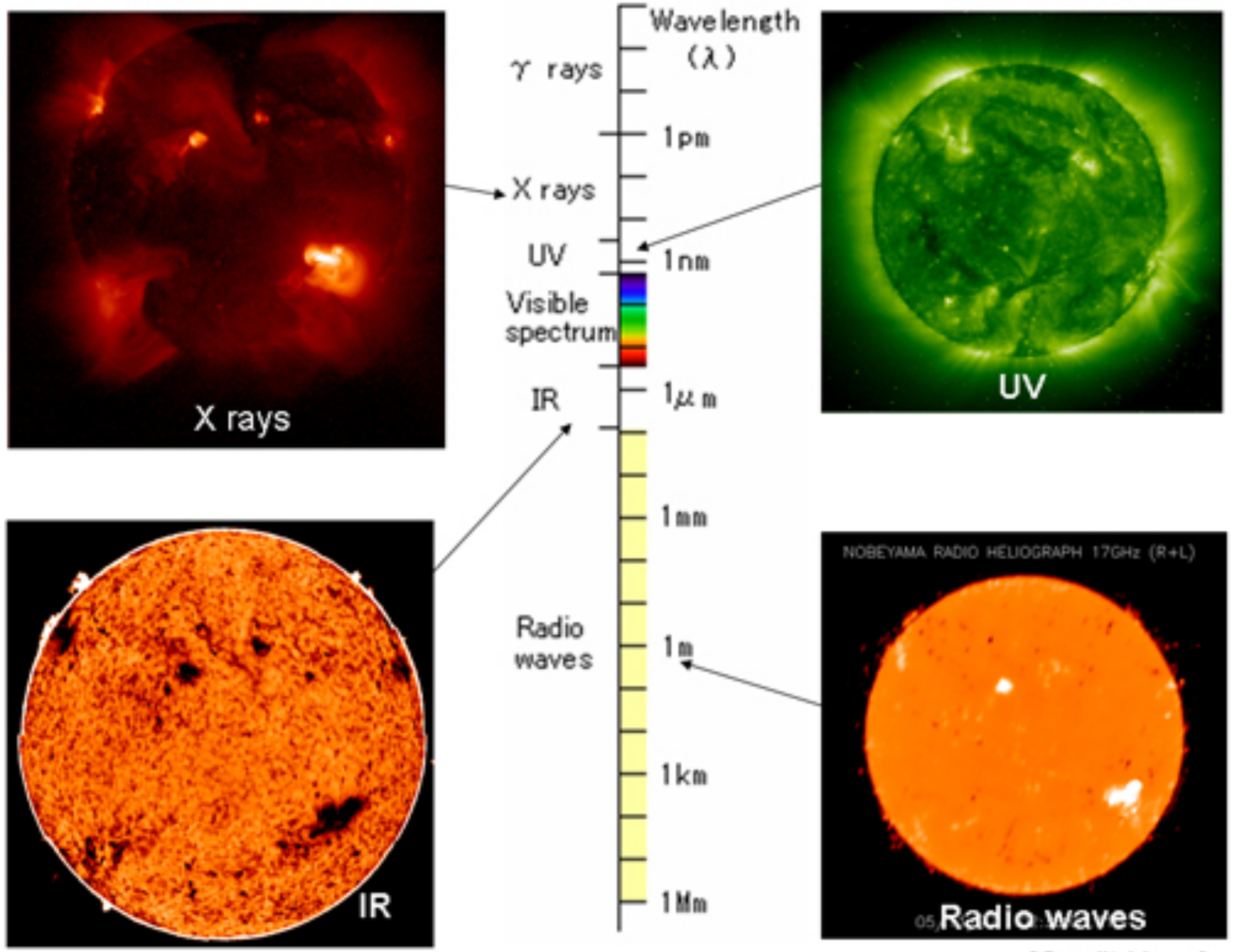
[Credit:Nasa]

MeV neutrinos



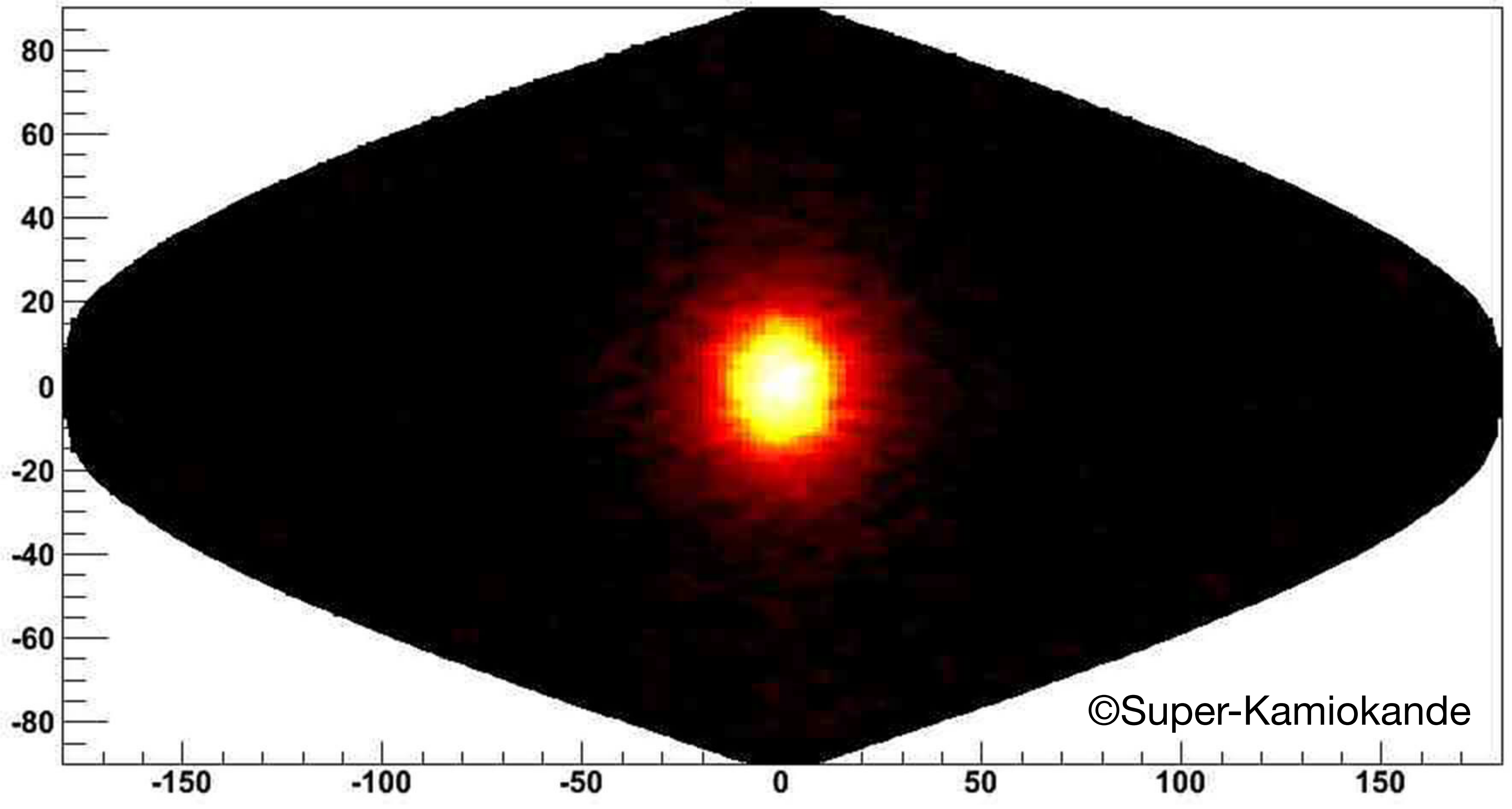
> GeV???

Multi-messenger images of the Sun



[Credit:Nasa]

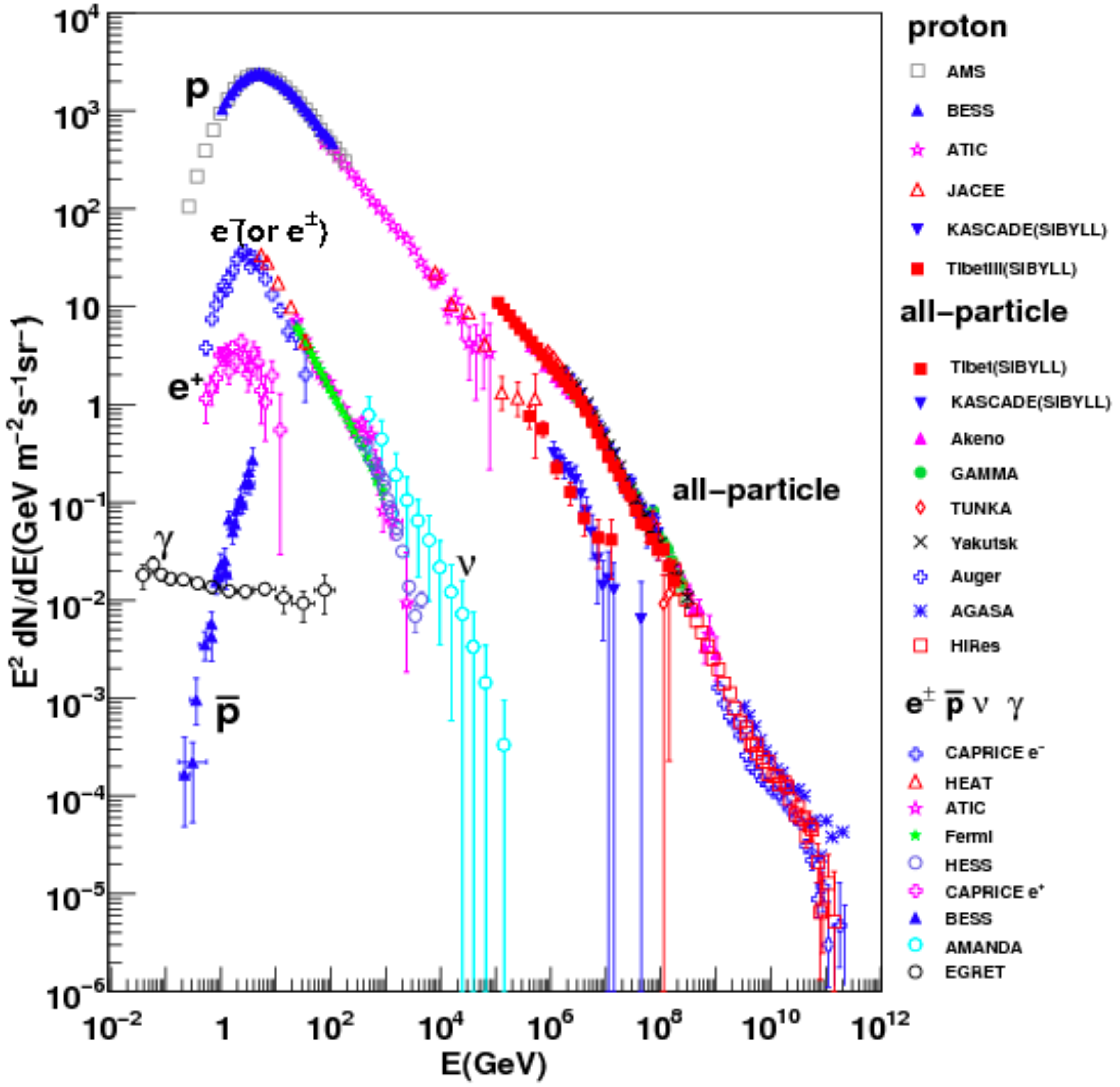
MeV neutrinos



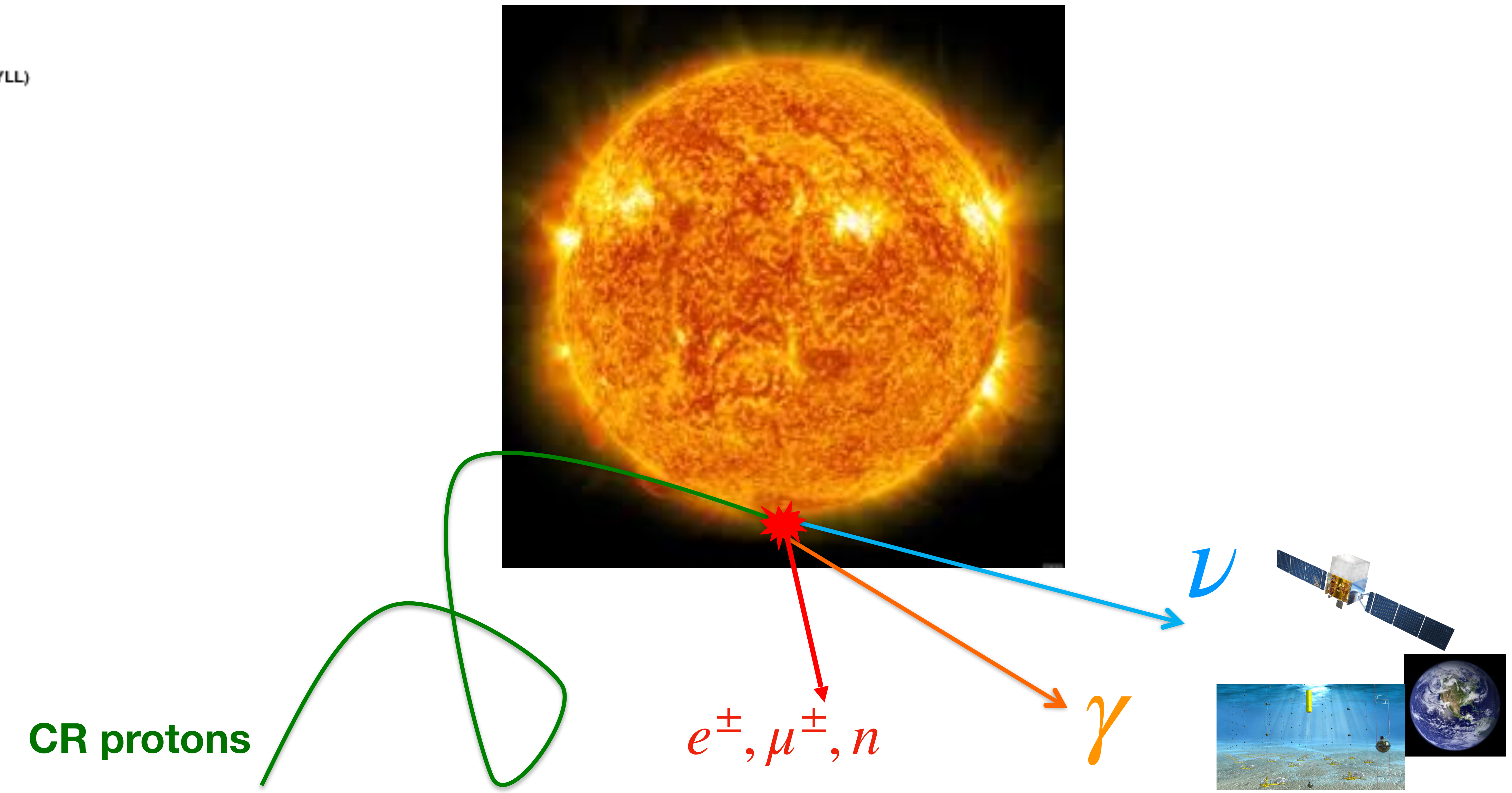
> GeV???

➡ *The Sun is not hot enough!*

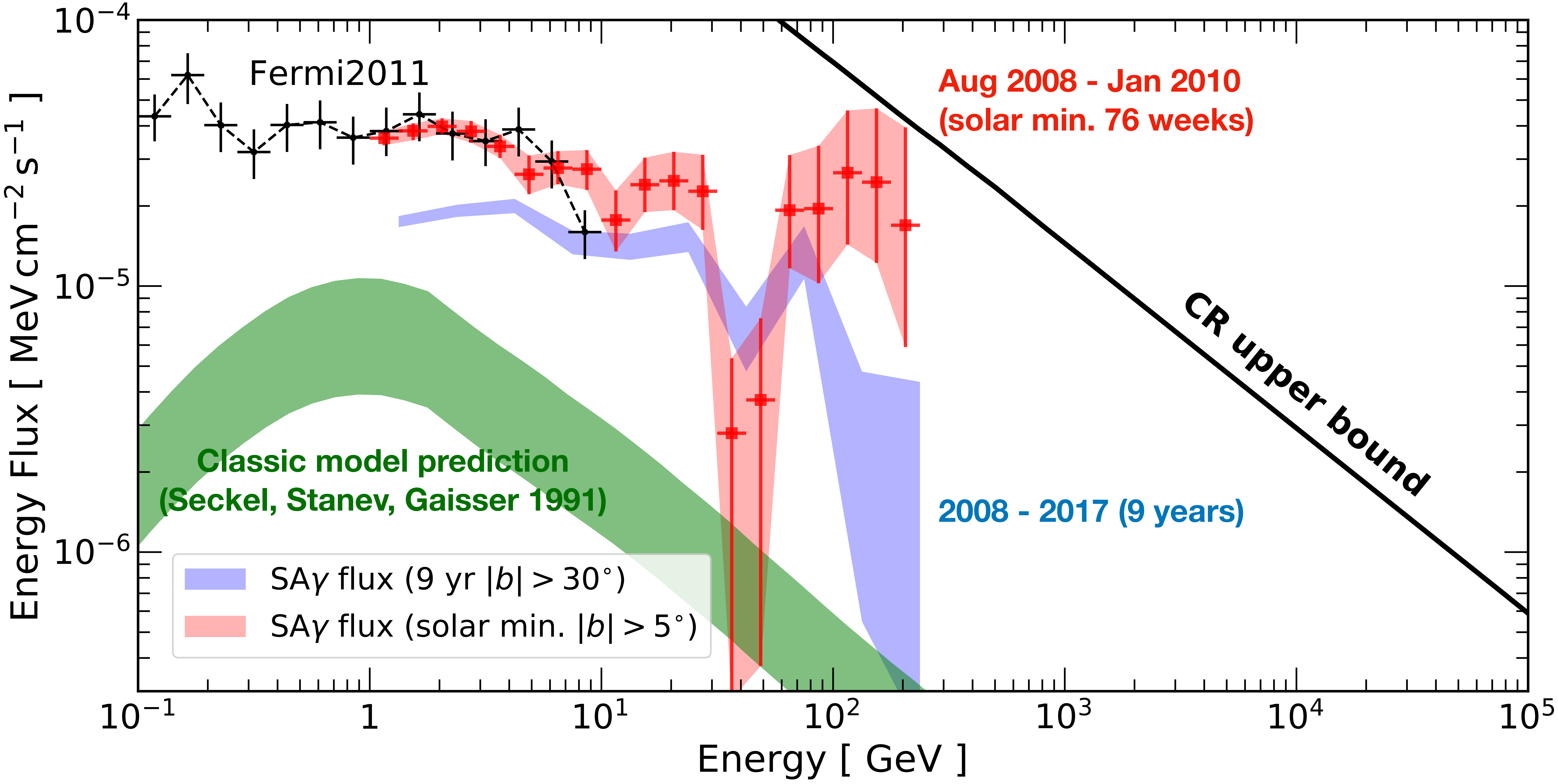
Cosmic rays production of solar atmospheric gamma rays



$$p + p \rightarrow \pi^0/\pi^\pm + X$$
$$\pi^0 \rightarrow \gamma + \gamma,$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu/\nu_\mu + \nu_e/\bar{\nu}_e$$



Observations: solar gamma rays

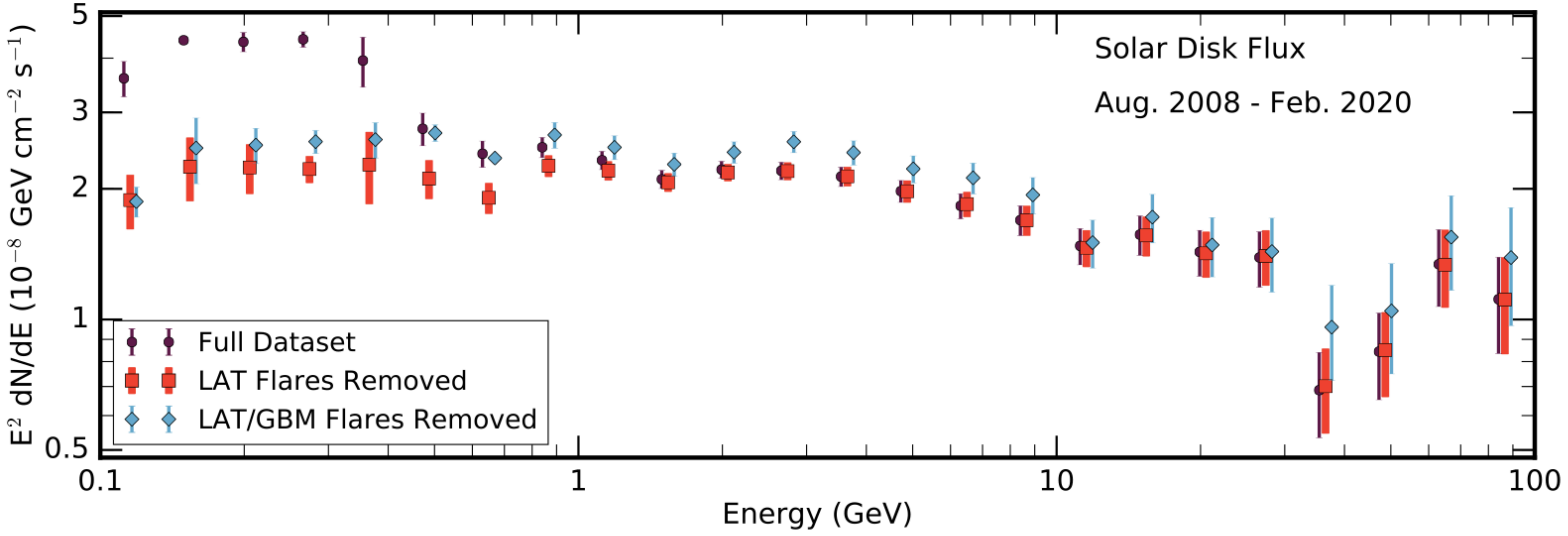


Tang et al. *Phys. Rev. D* (2018)

Anti-correlated with the solar activity

Surprisingly hard spectrum

Linden et al. (2022)



Hard spectrum up to ~100 GeV

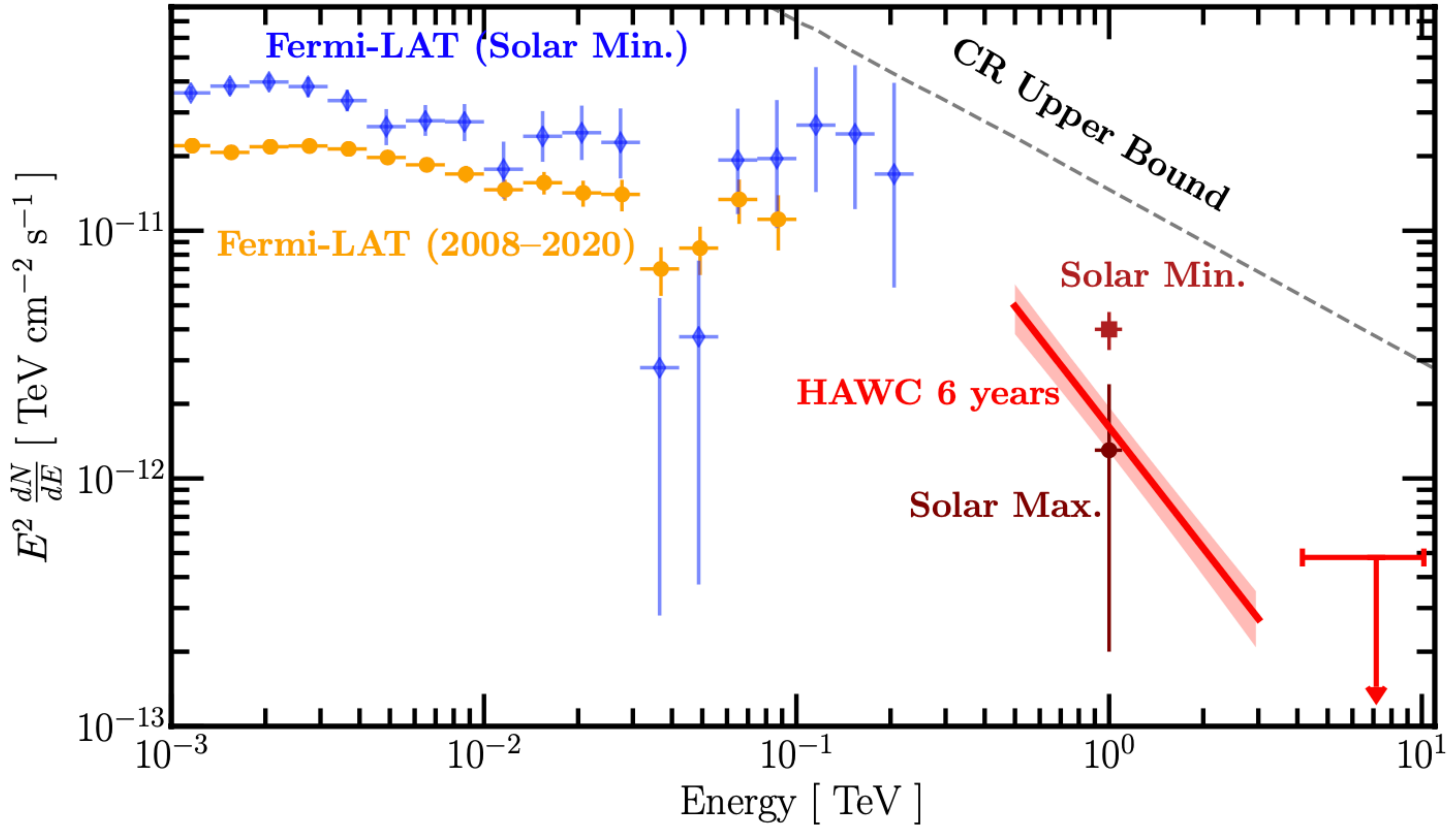
- Magnetic enhancement works for protons of ~TeV
- Enhancement becomes increasingly efficient! Close to upper bound at high energies

$$F(E) \propto \sigma_{pp} \times \Phi_p(E) \times \epsilon(E)$$

$$\sim E^{-2.2} \qquad \sim E^{0} \qquad \sim E^{-2.7} \qquad \sim E^{+0.5}$$

Magnetic efficiency factor

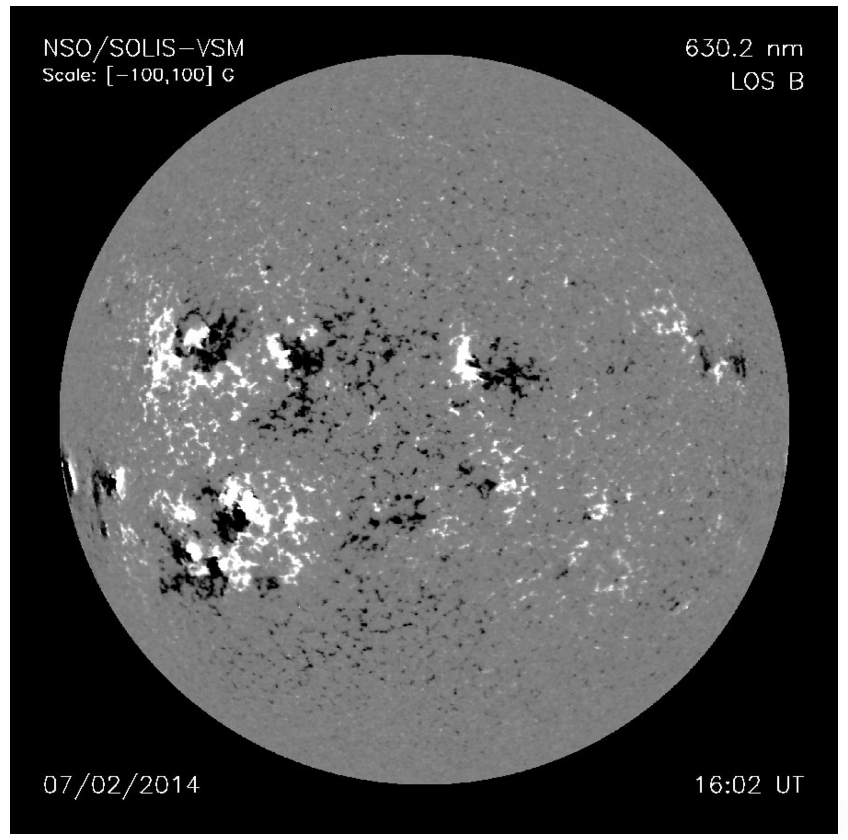
TeV solar gamma-ray spectrum



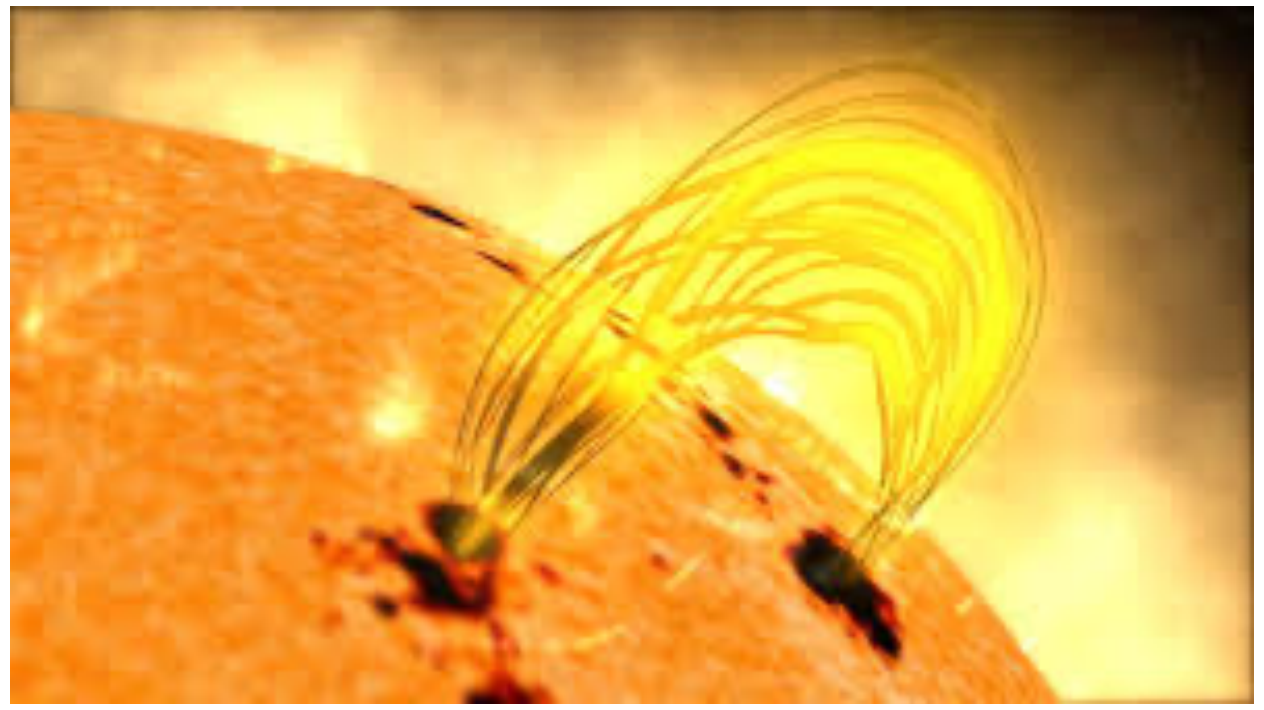
HAWC, *Phys. Rev. Lett.* **131**, 051201 (2023)

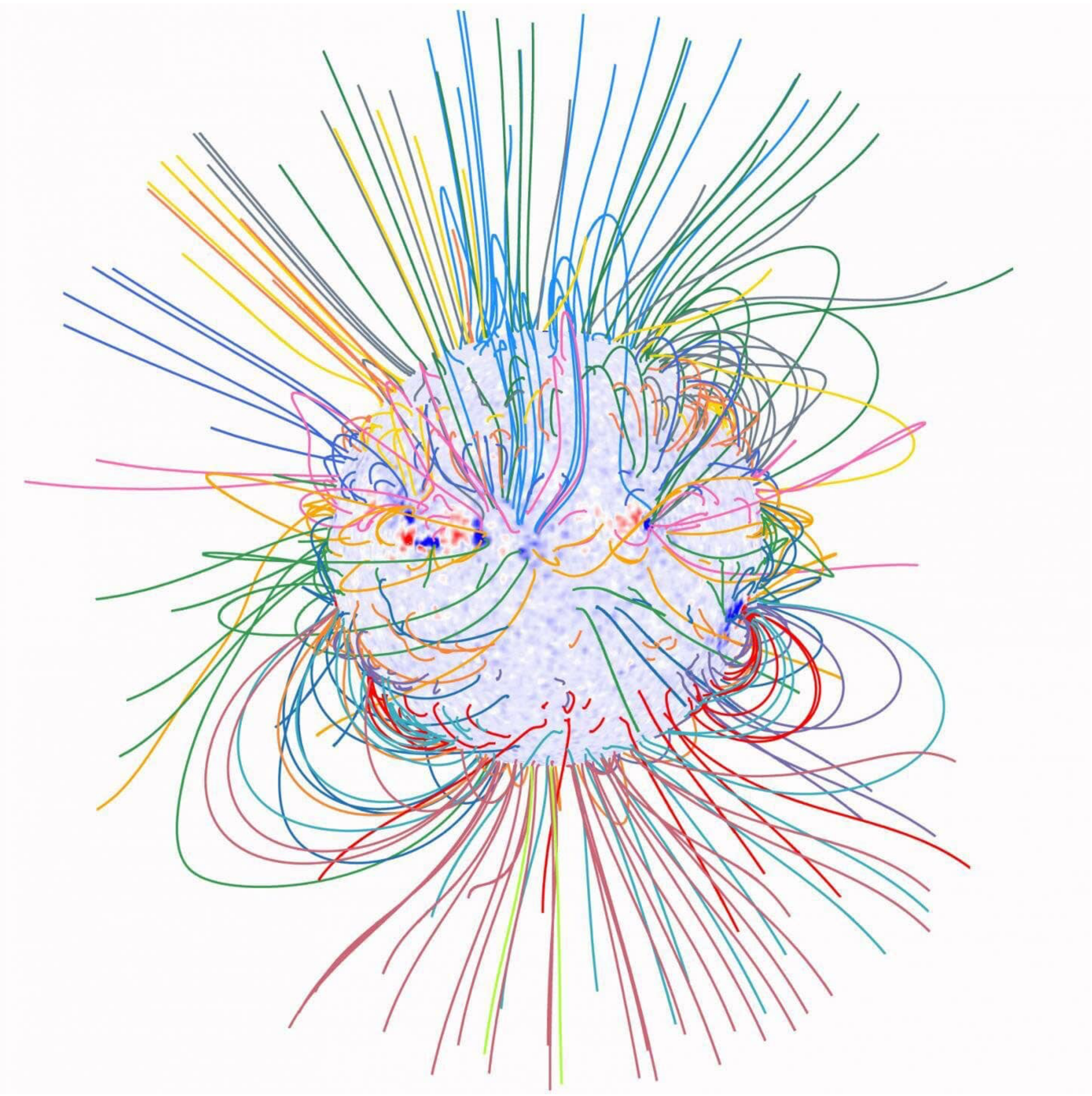
- Spectral index changes around TeV
- A sign that the magnetic field effect is decreasing?

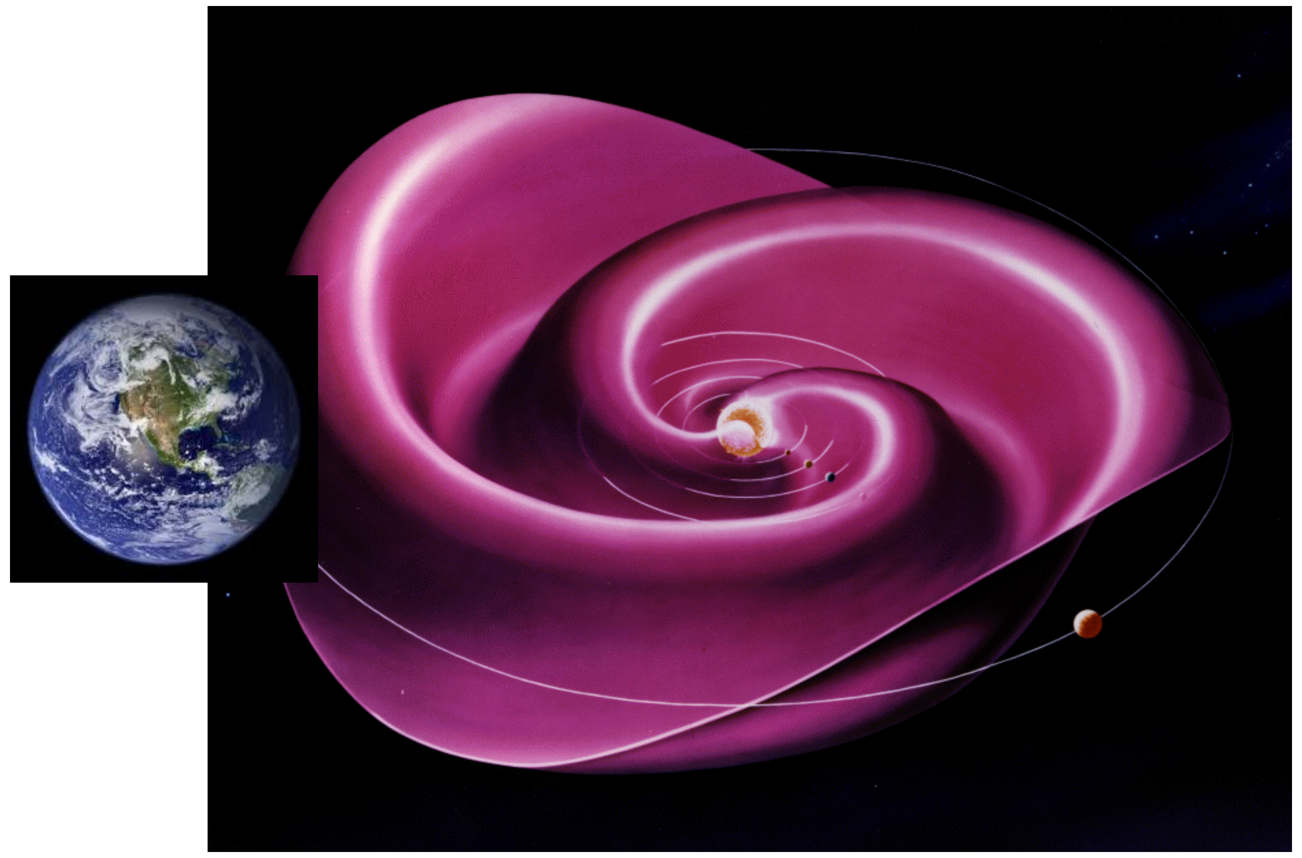
Theoretical interpretation



Best observational B-filed data comes from optical data ***at the photosphere***







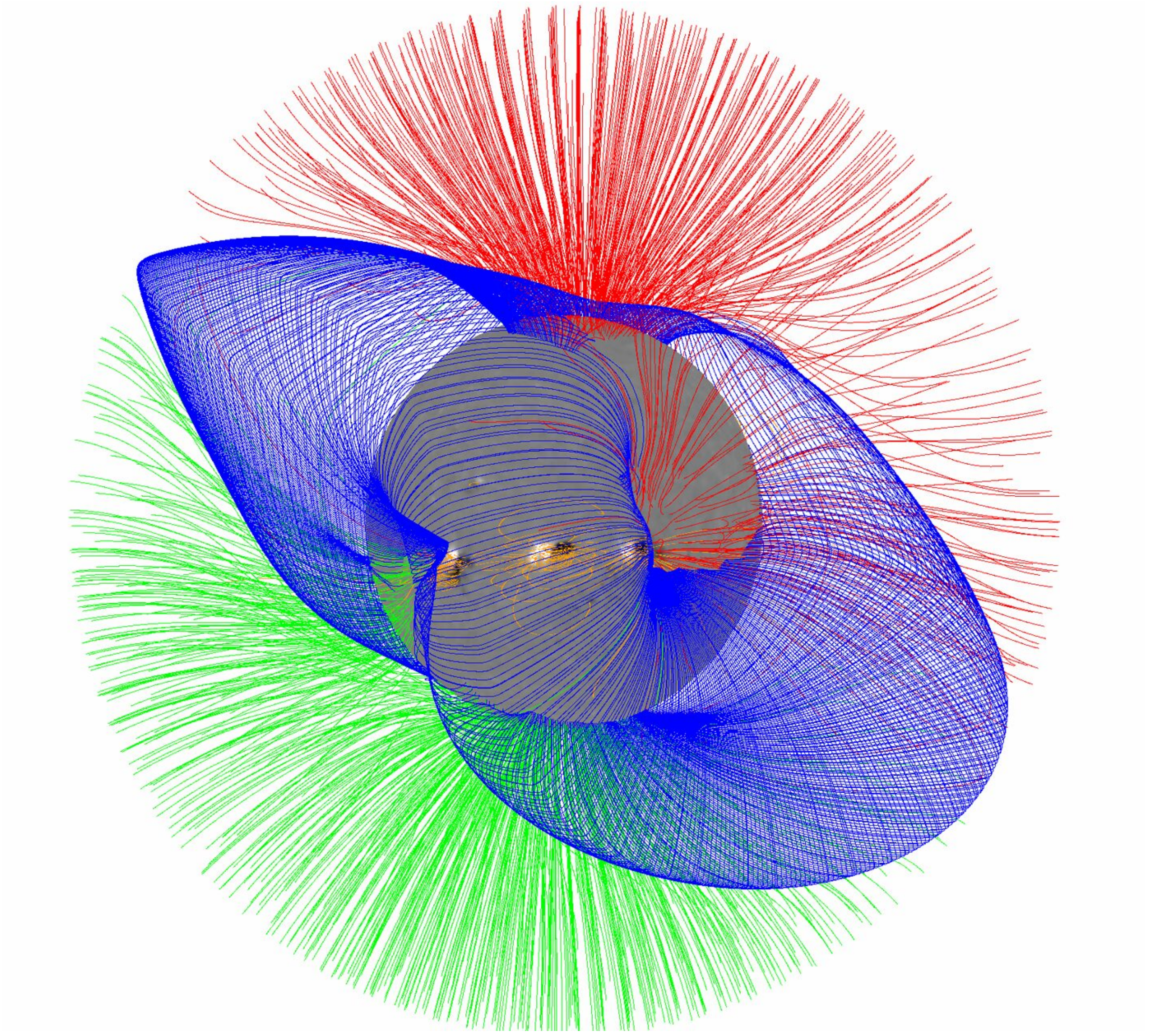
Photosphere B-field
$<R_{sun}$ to R_{sun}

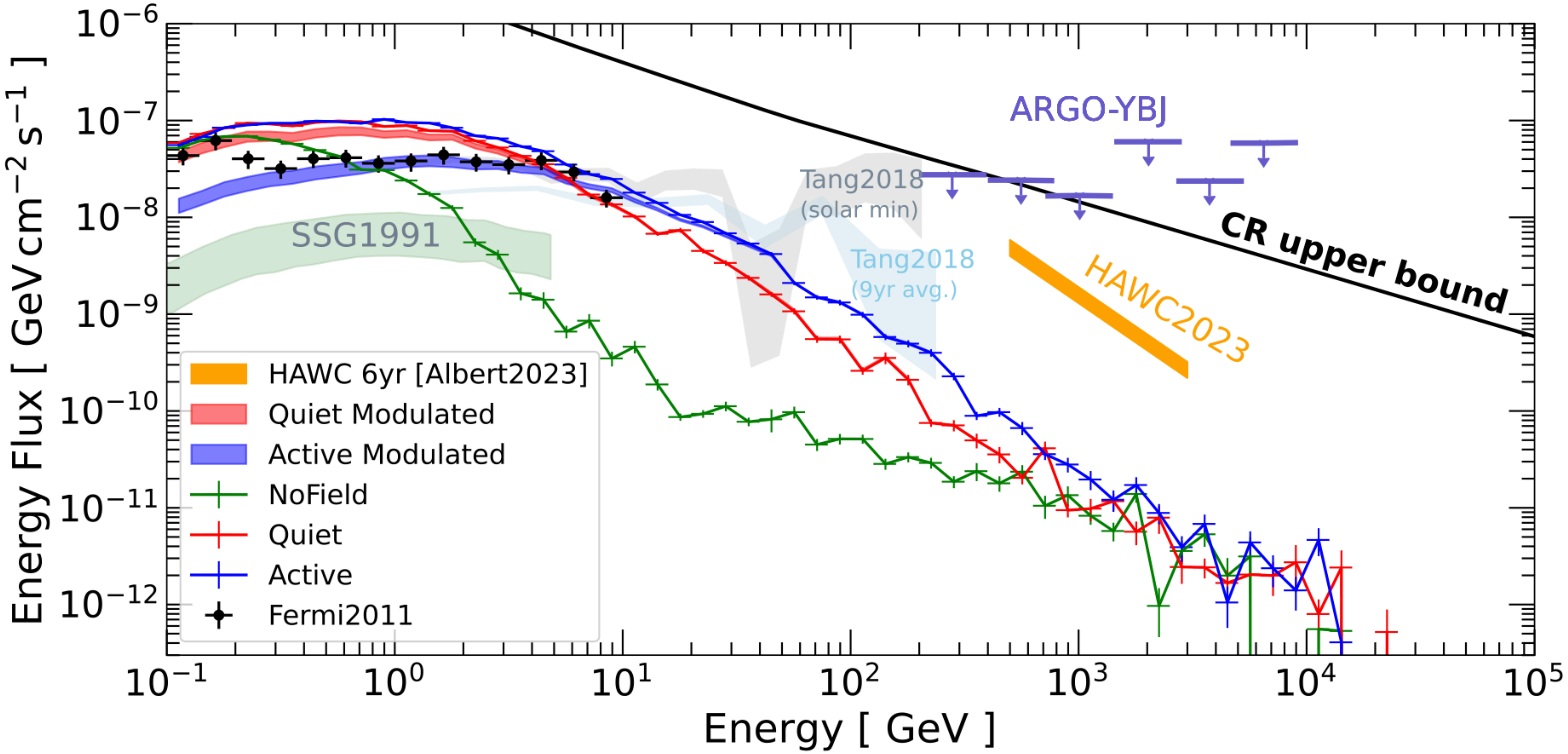
Coronal B-field
R_{sun} to $10R_{sun}$

Interplatnetary B-field
10 R_{sun} to inteplanetary space

Simulating solar gammas with coronal fields

Li et al. *Chinese Phys. C* **48**, 045101 (2024)

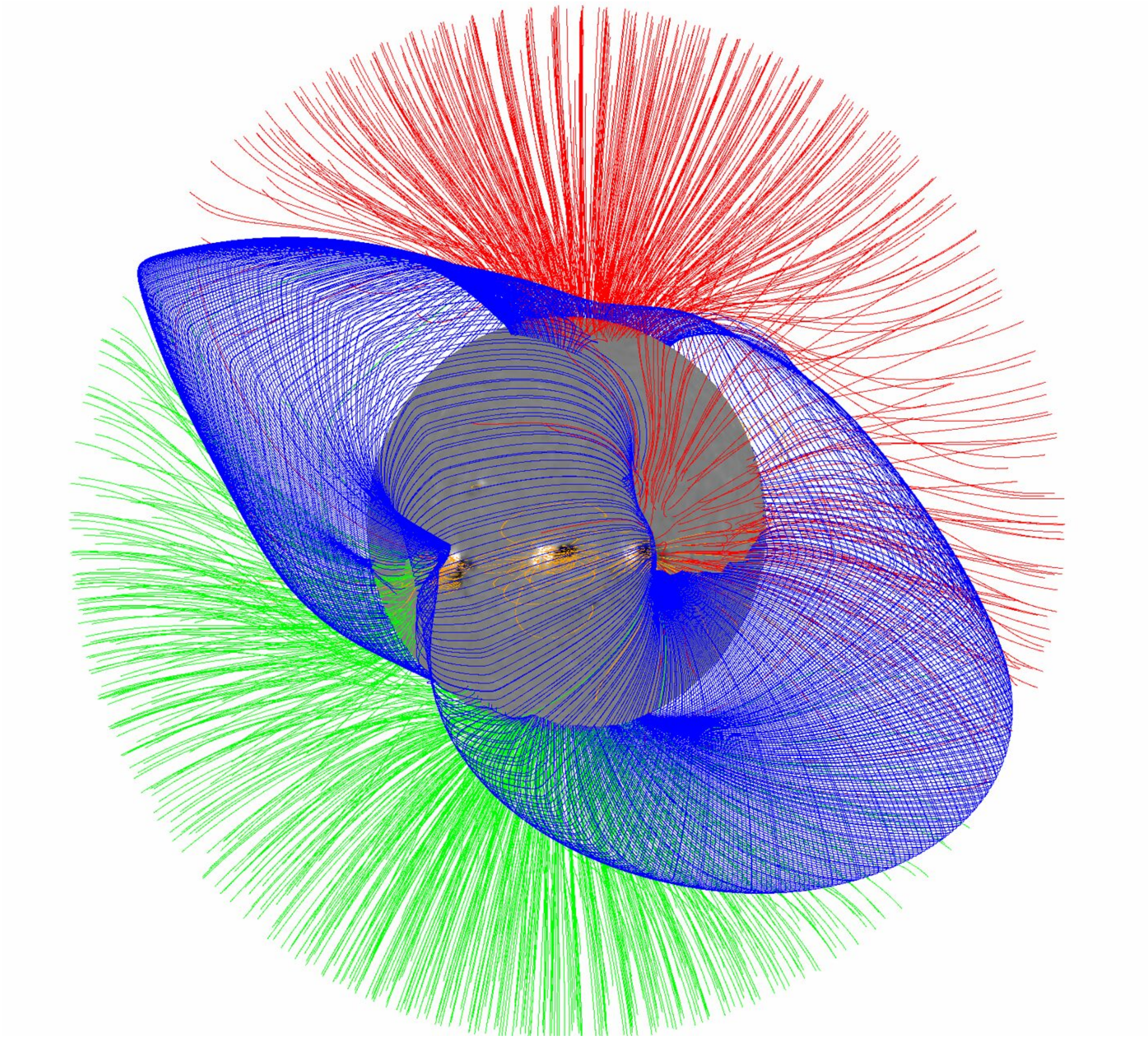


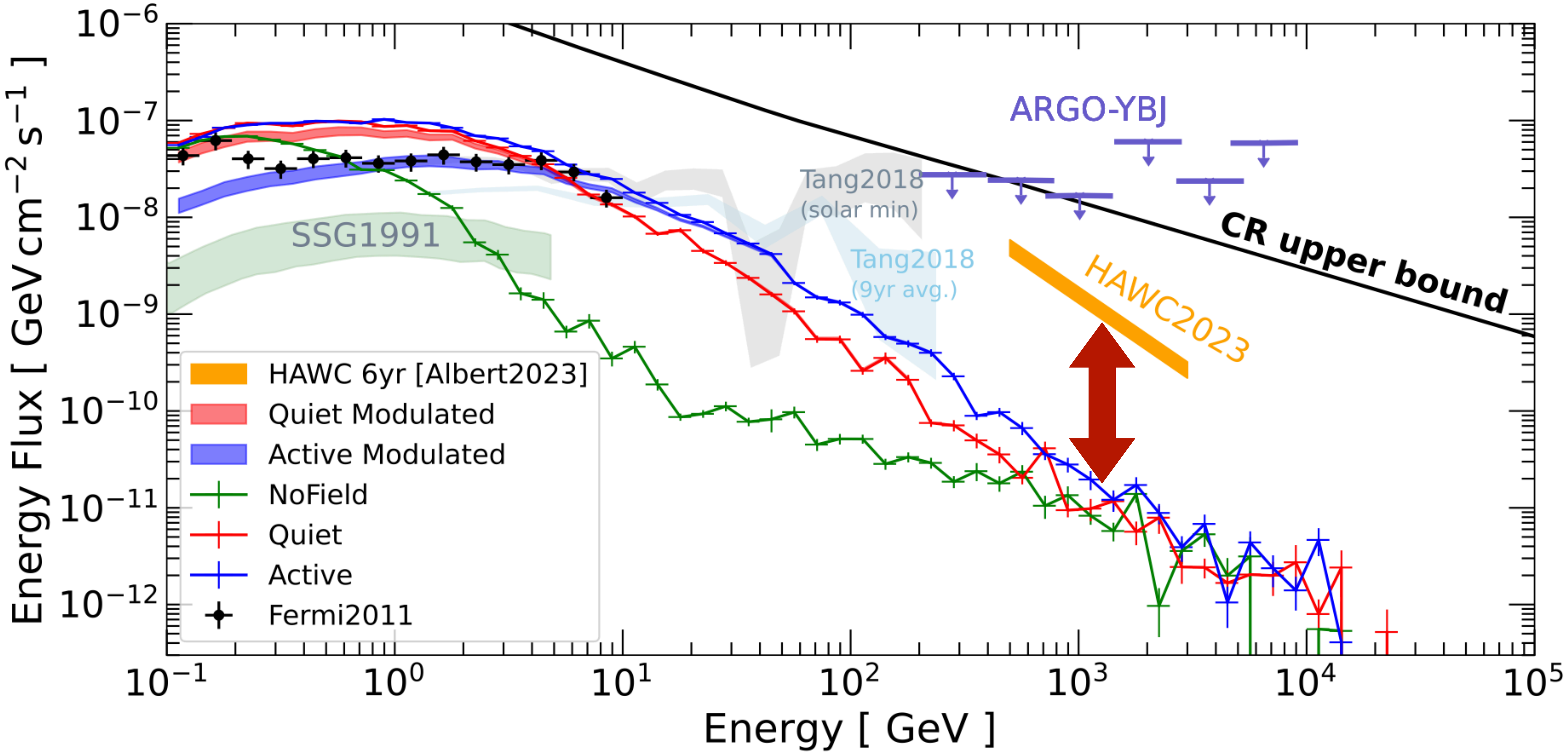


- Effects important for <100 GeV
- Under-prediction at TeV

Simulating solar gammas with coronal fields

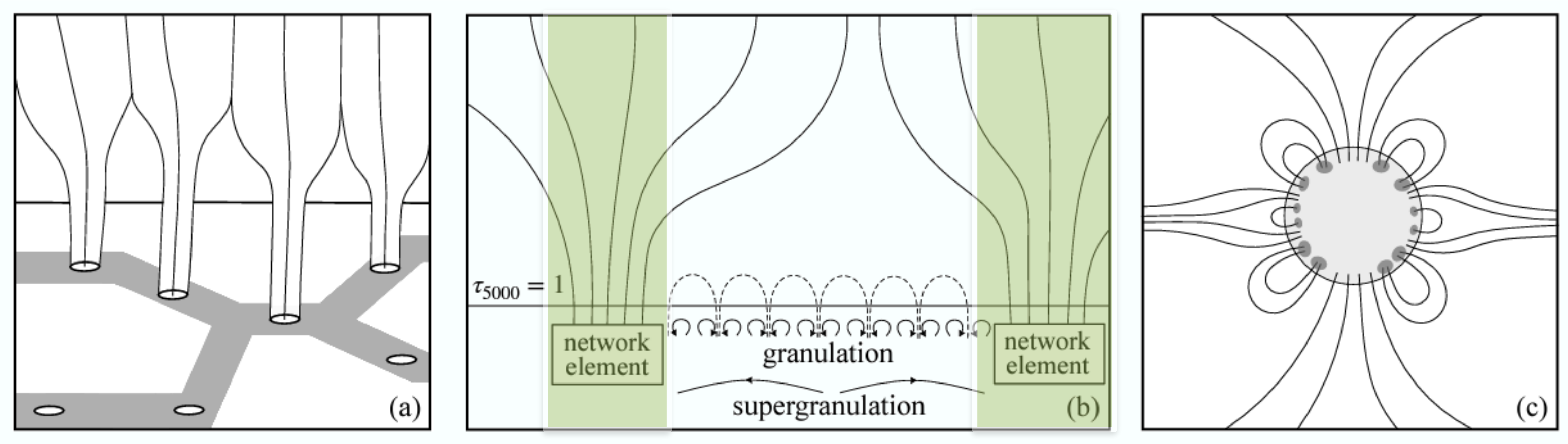
Li et al. *Chinese Phys. C* **48**, 045101 (2024)





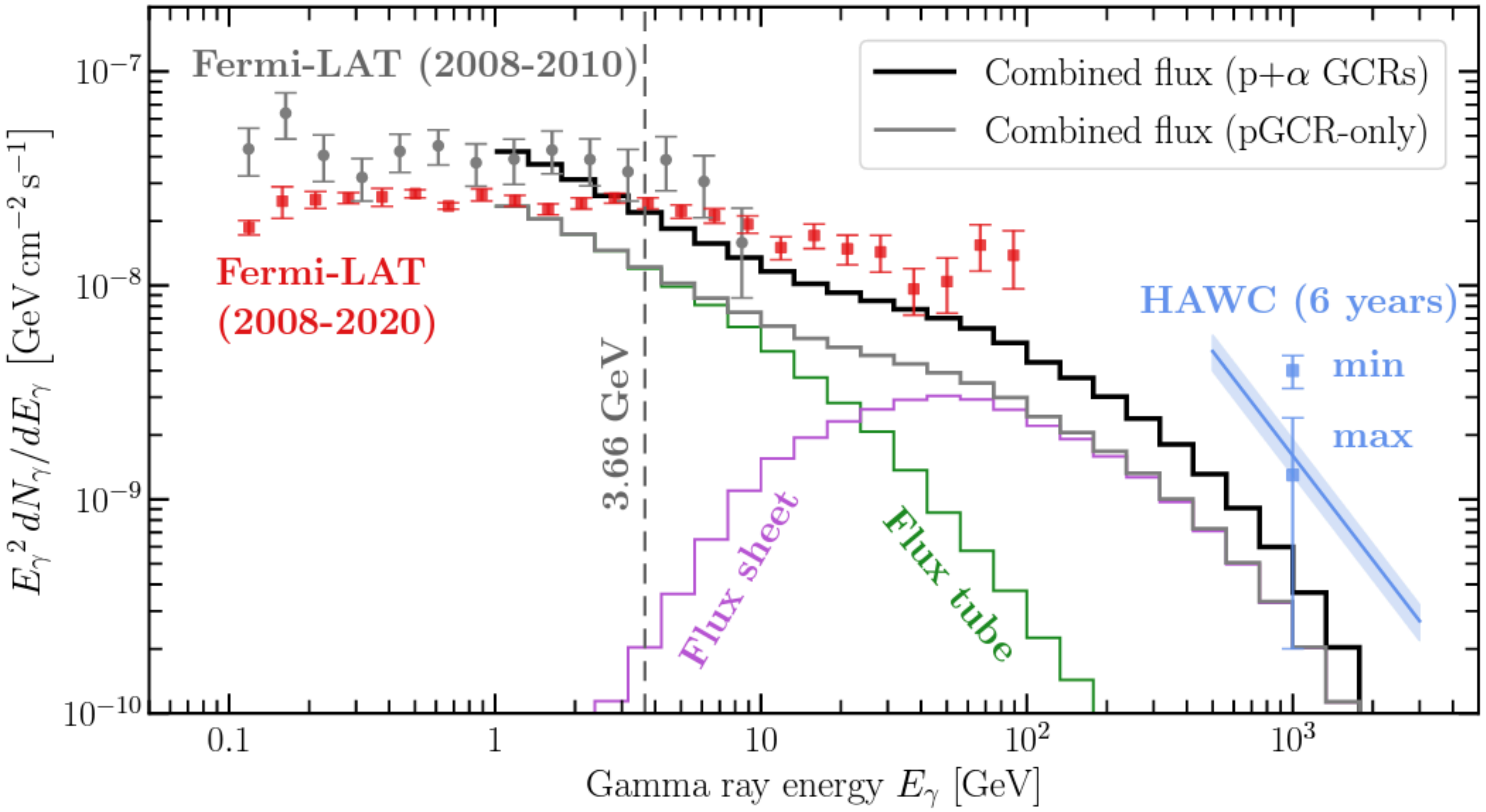
- Effects important for <100 GeV
- Under-prediction at TeV

Solar gammas from network fields

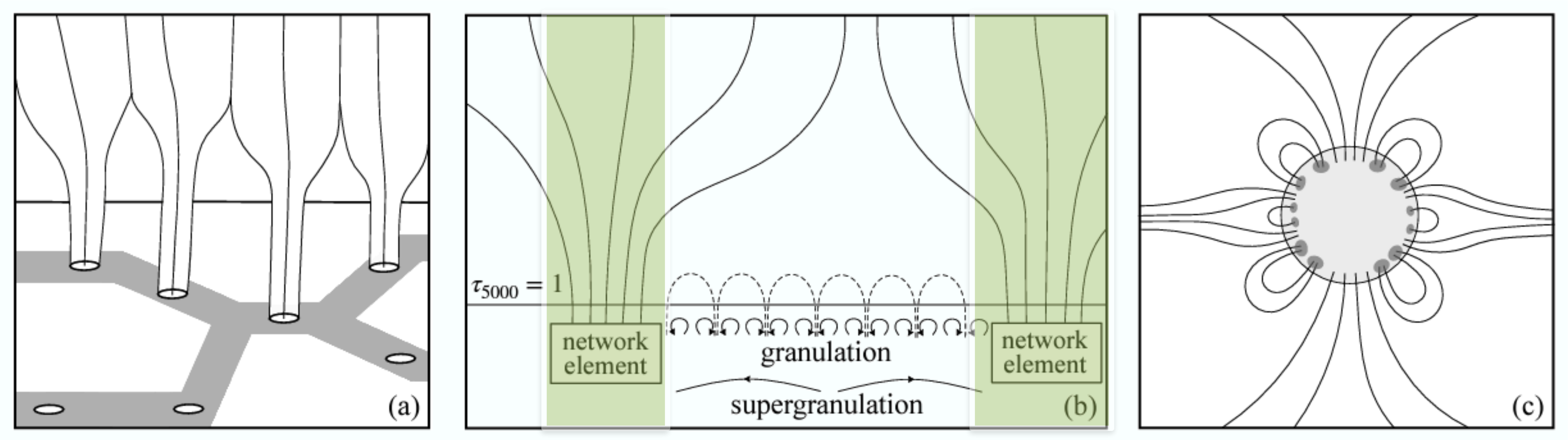


Li et al. *Astrophys. J.* **961**, 167 (2024)

- Significant below 50 GeV
- Effect decreases above 100 GeV

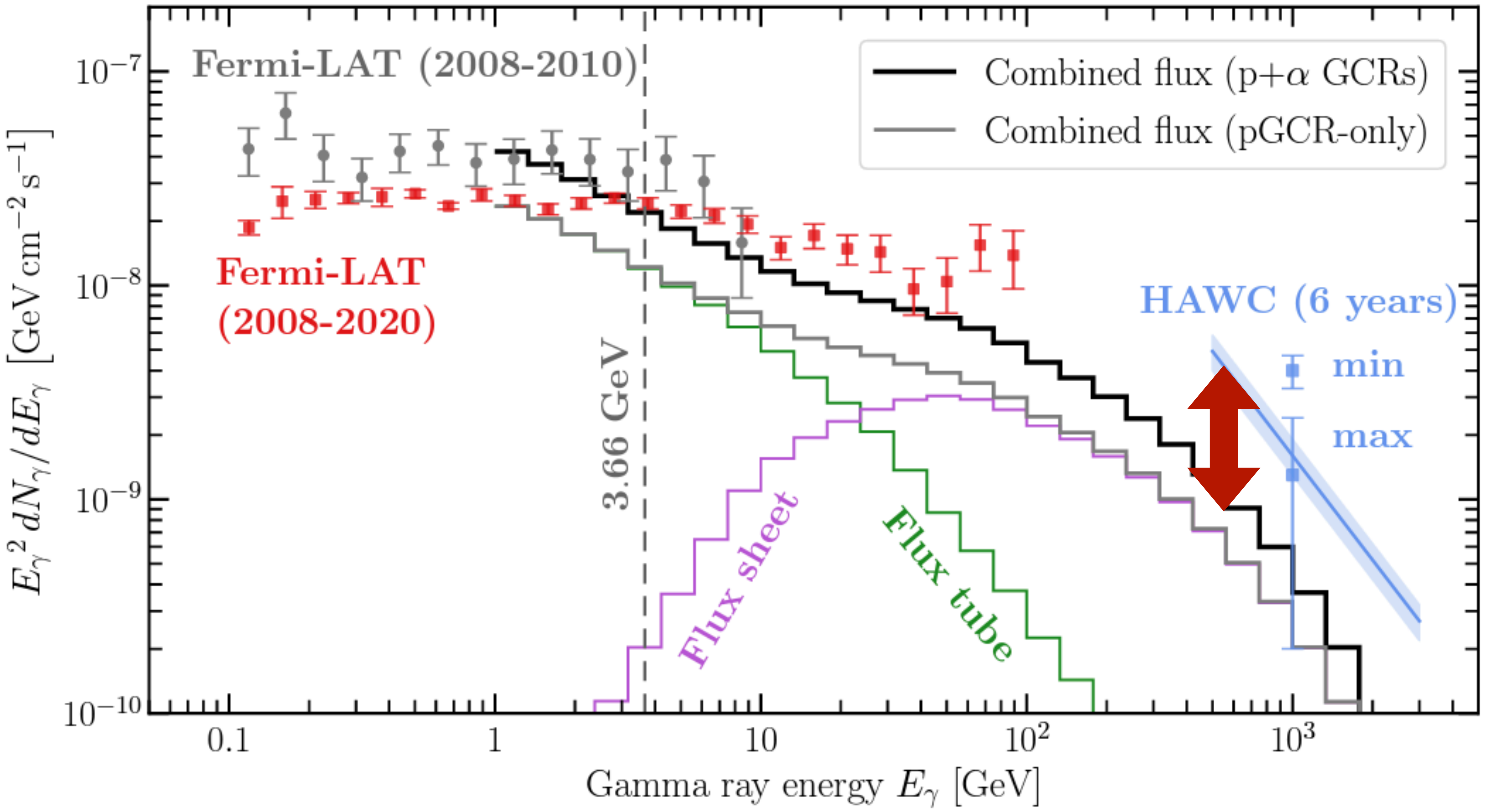


Solar gammas from network fields



Li et al. *Astrophys. J.* **961**, 167 (2024)

- Significant below 50 GeV
- Effect decreases above 100 GeV



What do we need to explain TeV data?

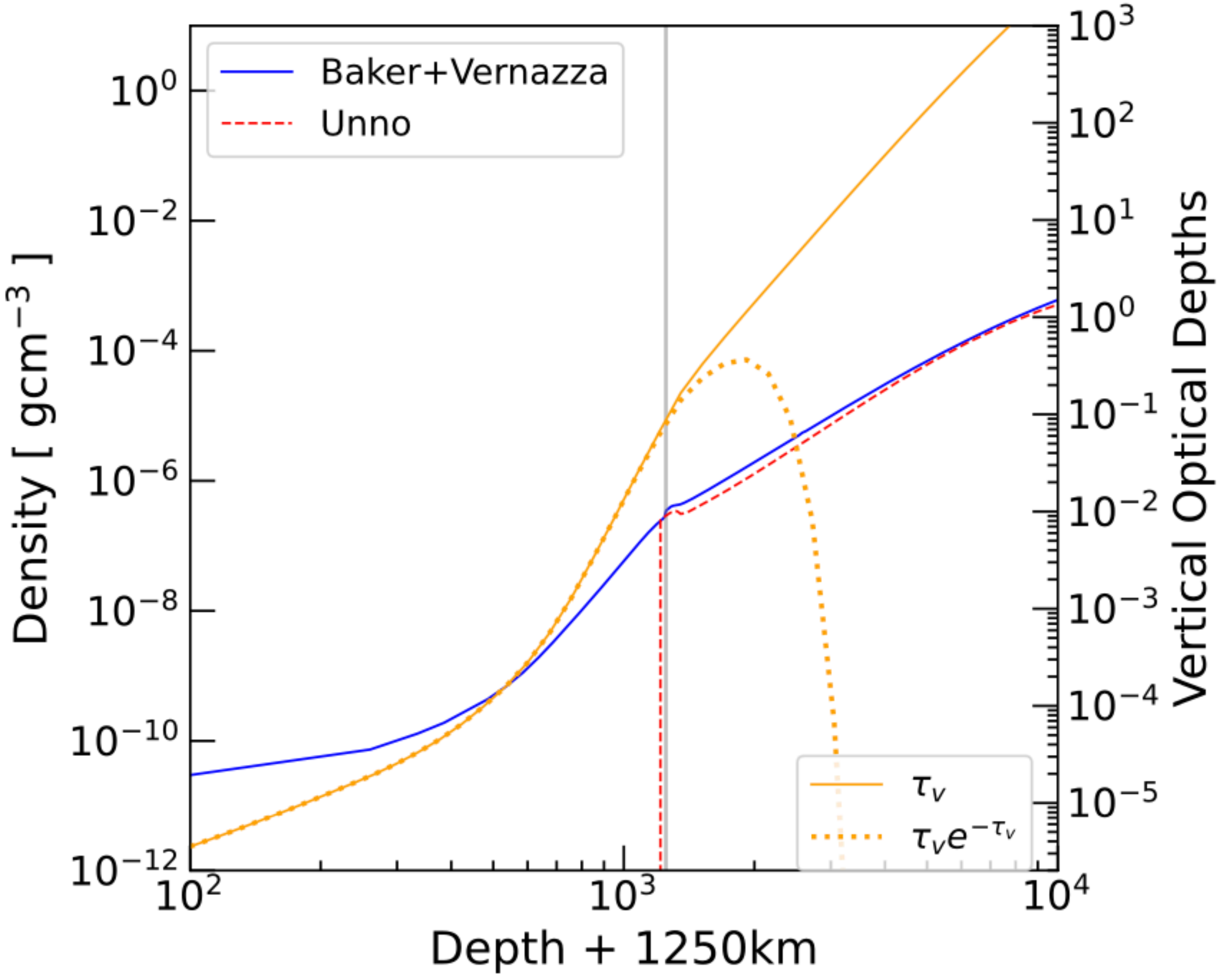
- Larmor radius required to reflect 20 TeV proton:

$$\frac{E}{20\ \text{TeV}} \simeq \frac{L}{10^3\ \text{km}} \frac{B}{\text{kG}}$$

What do we need to explain TeV data?

- Larmor radius required to reflect 20 TeV proton:

$$\frac{E}{20\ \mathrm{TeV}} \simeq \frac{L}{10^3\ \mathrm{km}} \frac{B}{\mathrm{kG}}$$



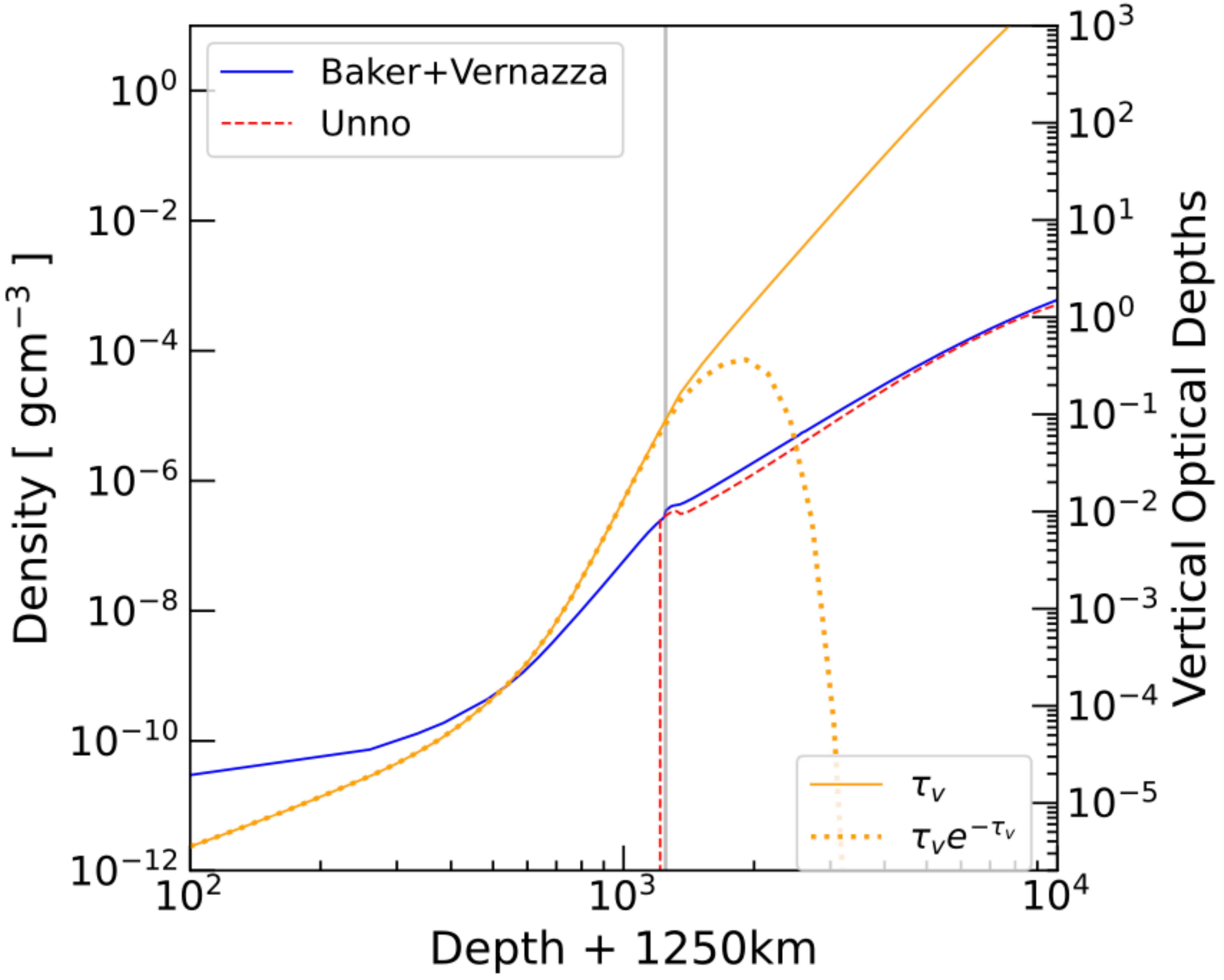
Ng, Hillier, Ando, arXiv:2405.17549 [astro-ph.SR]

What do we need to explain TeV data?

- Larmor radius required to reflect 20 TeV proton:

$$\frac{E}{20\ \mathrm{TeV}} \simeq \frac{L}{10^3\ \mathrm{km}} \frac{B}{\mathrm{kG}}$$

- Opacity for protons ~ 1 at
    - 600 km below photosphere
    - At density $\sim 10^{-6}\,\mathrm{g\,cm^{-3}}$



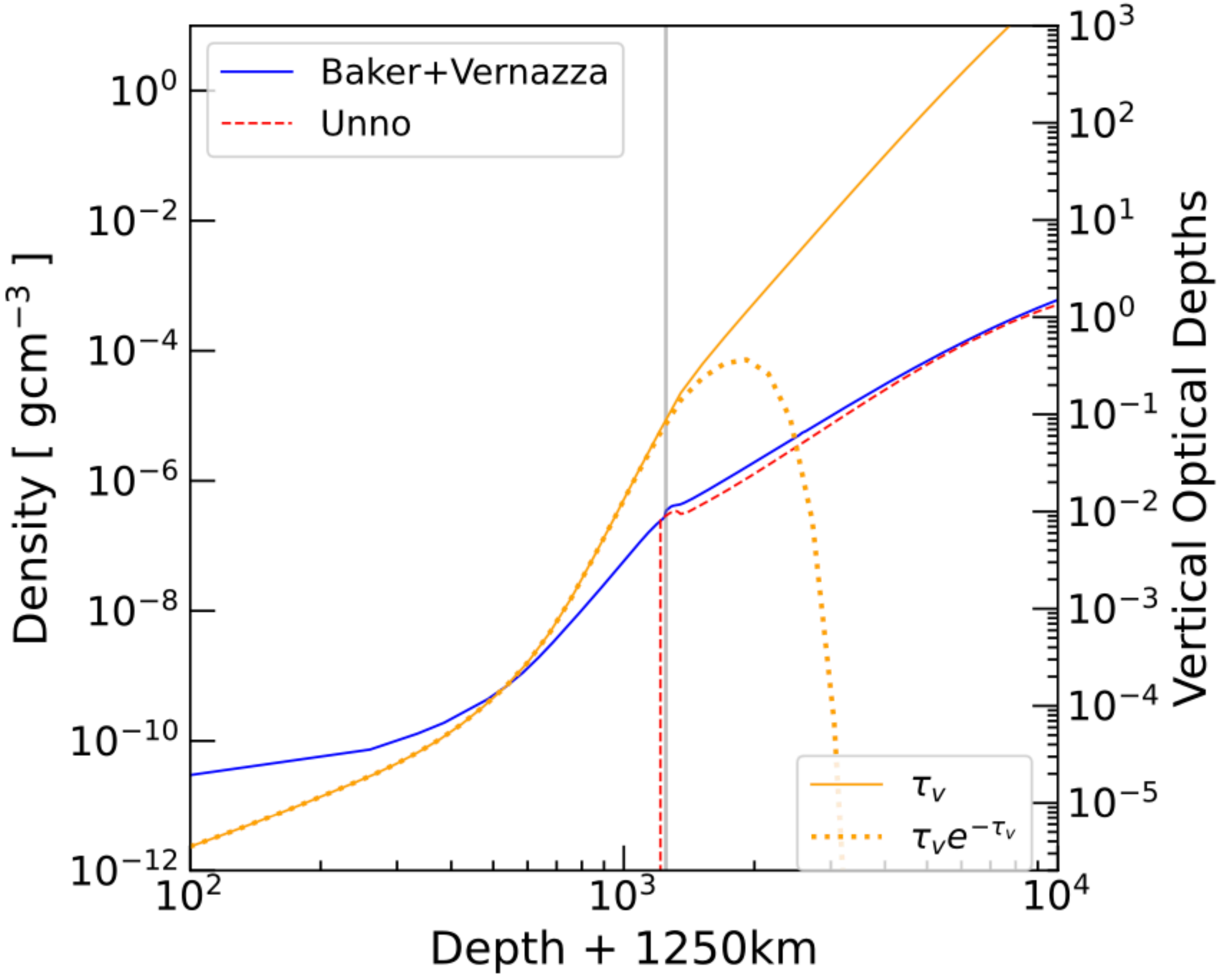
Ng, Hillier, Ando, arXiv:2405.17549 [astro-ph.SR]

What do we need to explain TeV data?

- Larmor radius required to reflect 20 TeV proton:

$$\frac{E}{20\ \mathrm{TeV}} \simeq \frac{L}{10^3\ \mathrm{km}} \frac{B}{\mathrm{kG}}$$

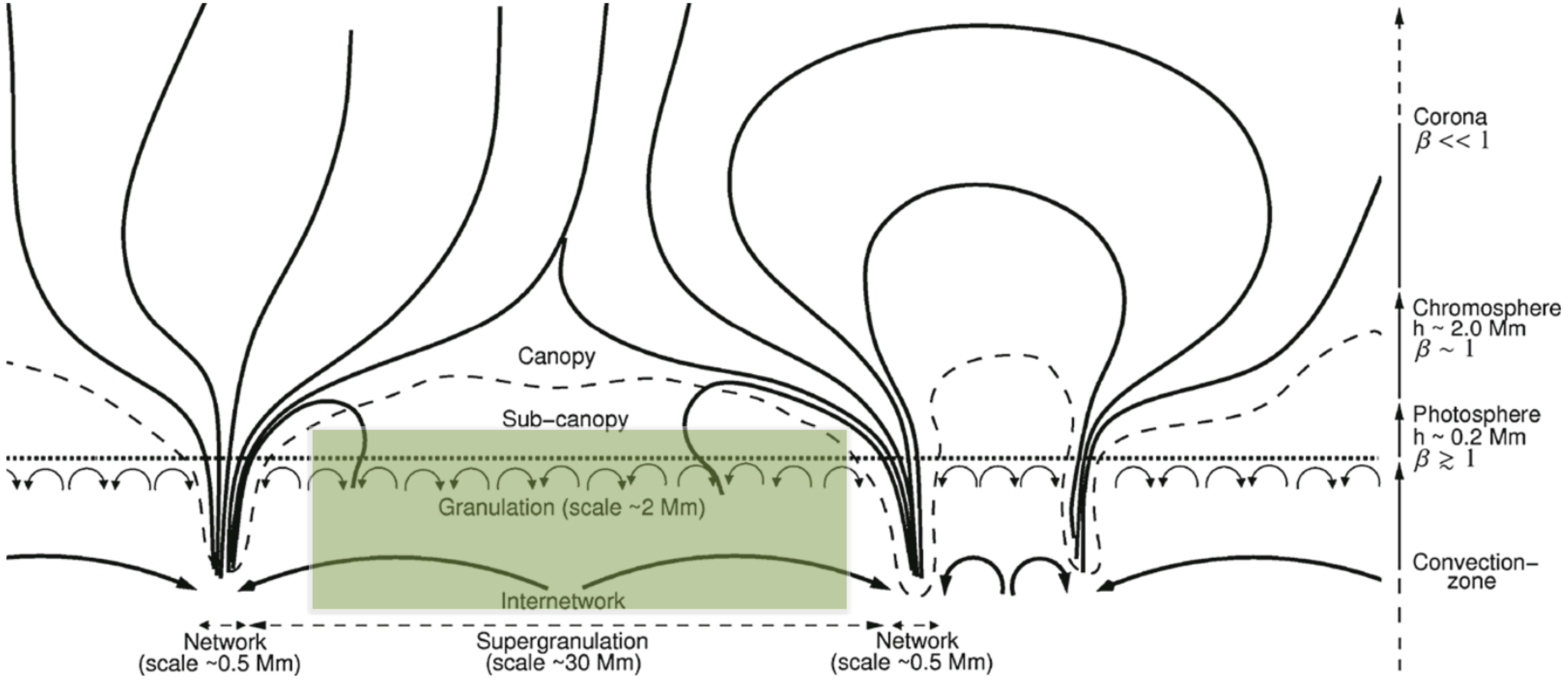
- Opacity for protons ~ 1 at
  - 600 km below photosphere
  - At density $\sim 10^{-6}\,\mathrm{g\,cm^{-3}}$
- kG field at 1000 km below photosphere could reflect 20 TeV protons



Ng, Hillier, Ando, arXiv:2405.17549 [astro-ph.SR]

Horizontal internetwork fields

Ng, Hillier, Ando, arXiv:2405.17549 [astro-ph.SR]



- TeV gamma rays produced by ~10 TeV protons
- Need strong (~kG) magnetic fields
- Internetwork magnetic fields
- Assumptions:
  - Horizontal **below the photosphere**
  - Cover a large part of the solar surface

Horizontal internetwork fields

Ng, Hillier, Ando, arXiv:2405.17549 [astro-ph.SR]

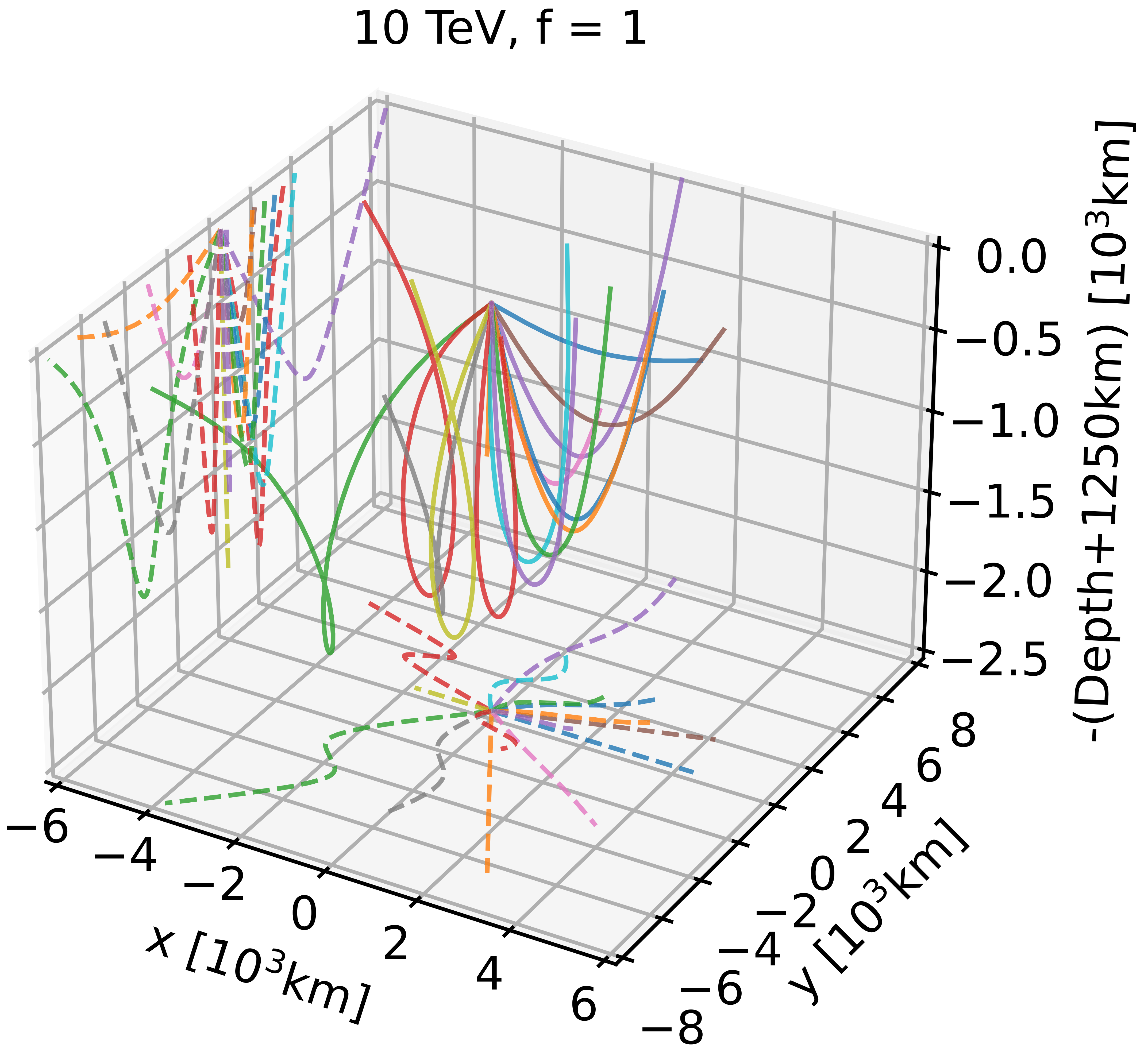
- Horizontal **below the photosphere**

- Infer magnetic field energy from kinetic energy

$$|B(r)| = f\sqrt{4\pi\rho(r)v^2(r)}$$

- Velocity amplitude from Unno et al. (1985)

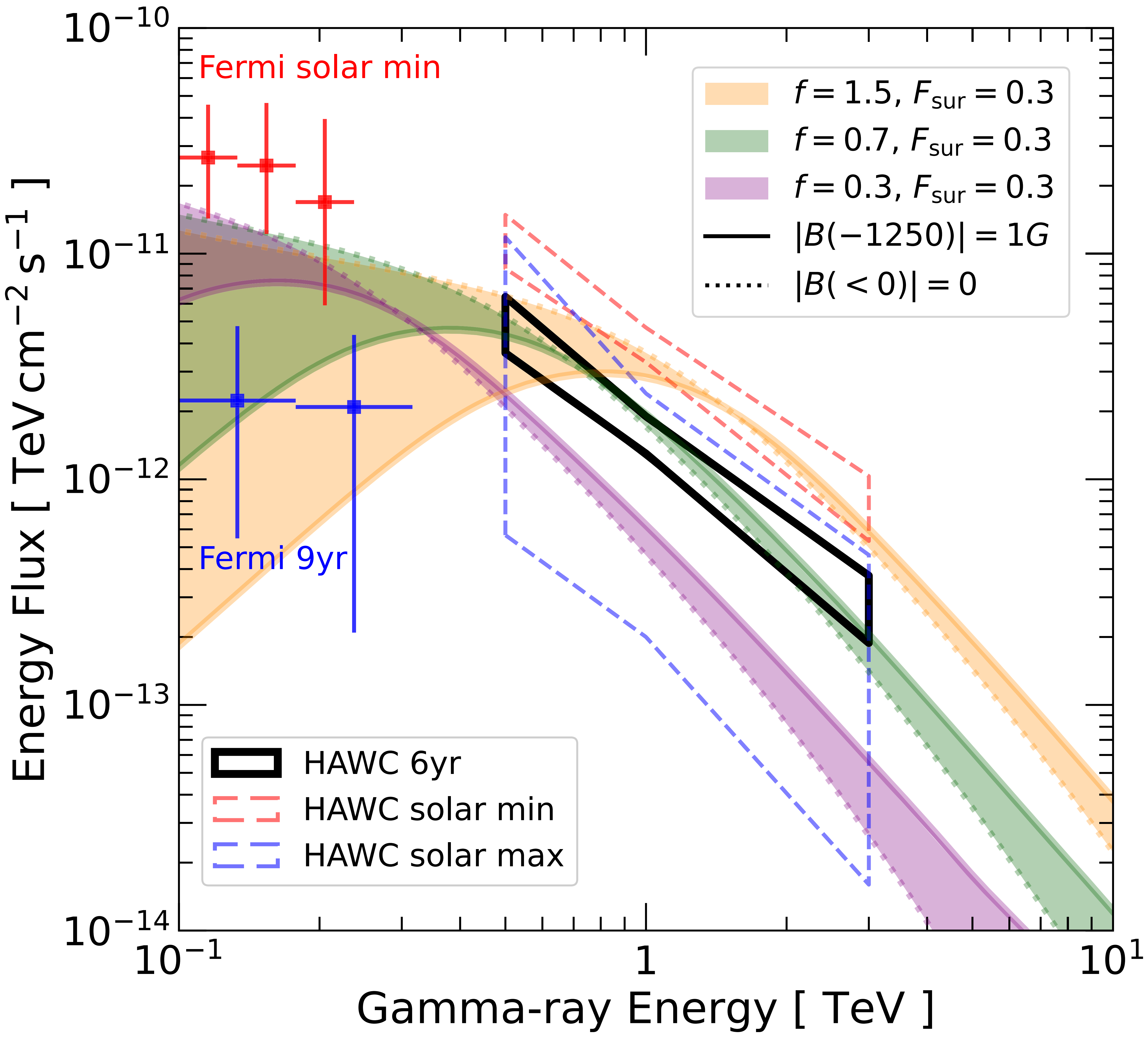
- Gamma-ray production $\propto \tau e^{-\tau}$ (τ: interaction opacity)



Horizontal internetwork fields

Ng, Hillier, Ando, arXiv:2405.17549 [astro-ph.SR]

- The horizontal internetwork fields could explain HAWC with reasonable choice of parameters: $f = 0.7,\ F_{\rm sur} = 0.3$
  - Change of these parameters might explain time variation
- In the quiet solar phase, are the fields mostly horizontal?
- **Solar gamma rays as a new way for studying solar magnetism**



Summary and outlook

- Sun is a bright source of >GeV gamma rays, detected by both Fermi-LAT and HAWC
- Both coronal and network magnetic fields can explain low-energy (<100 GeV) gamma rays, but underpredicts >TeV data
- Horizontal internetwork fields (strength ~1 kG, length ~1000 km) could explain the HAWC data
- Promising possibility for future gamma-ray and neutrino telescopes to probe internal conditions of the Sun
- Sun is also an important calibration source for neutrino telescopes through its cosmic ray shadow (and so is Moon)