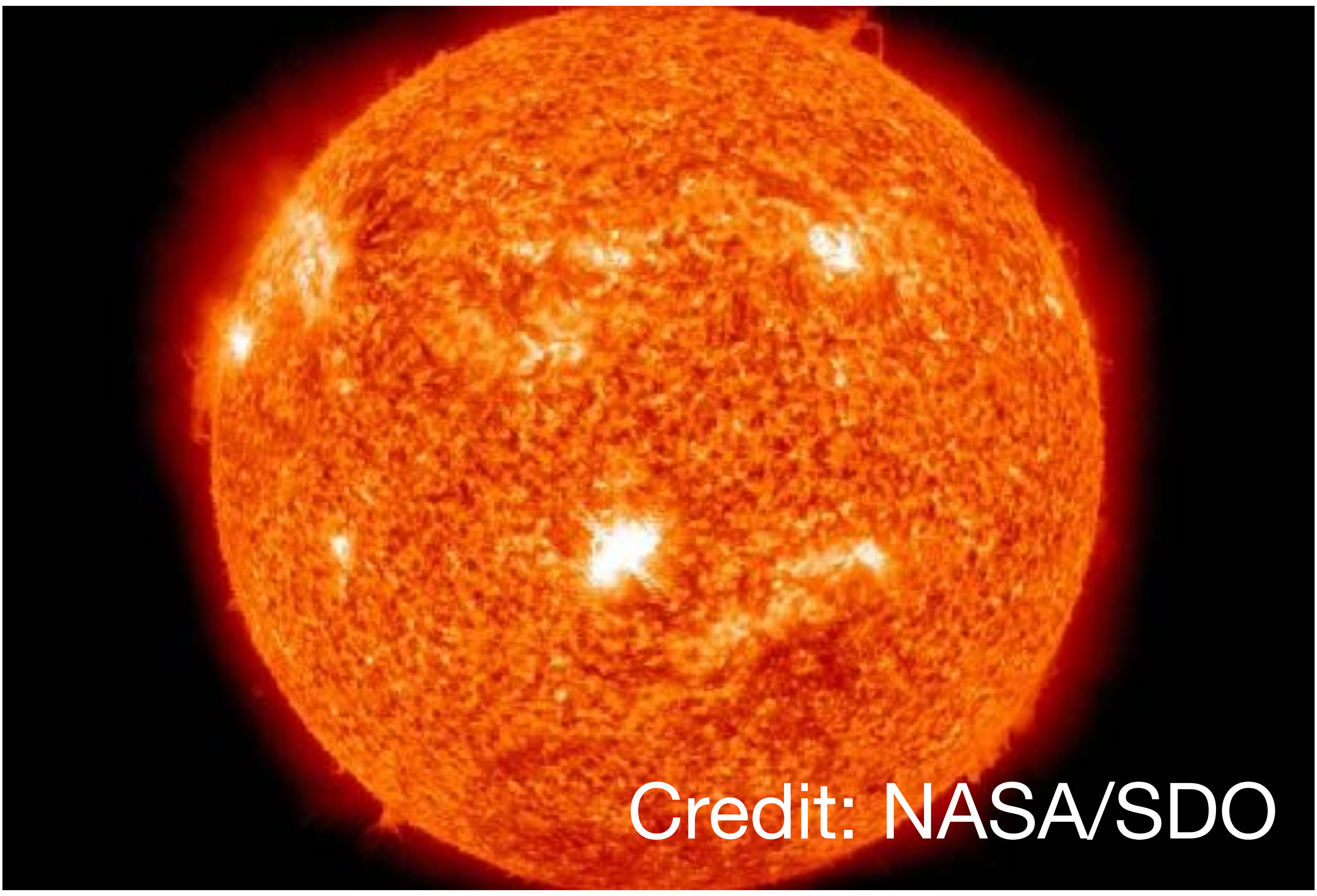
Small-Scale Magnetic Fields are Critical to Shaping Continual Solar Gamma-Ray Emission


Credit: NASA/SDO

Jung-Tsung Li
(Ohio State University)

CCAPP Symposium 2023

Collaborators: John Beacom, Spencer Griffith, and Annika Peter

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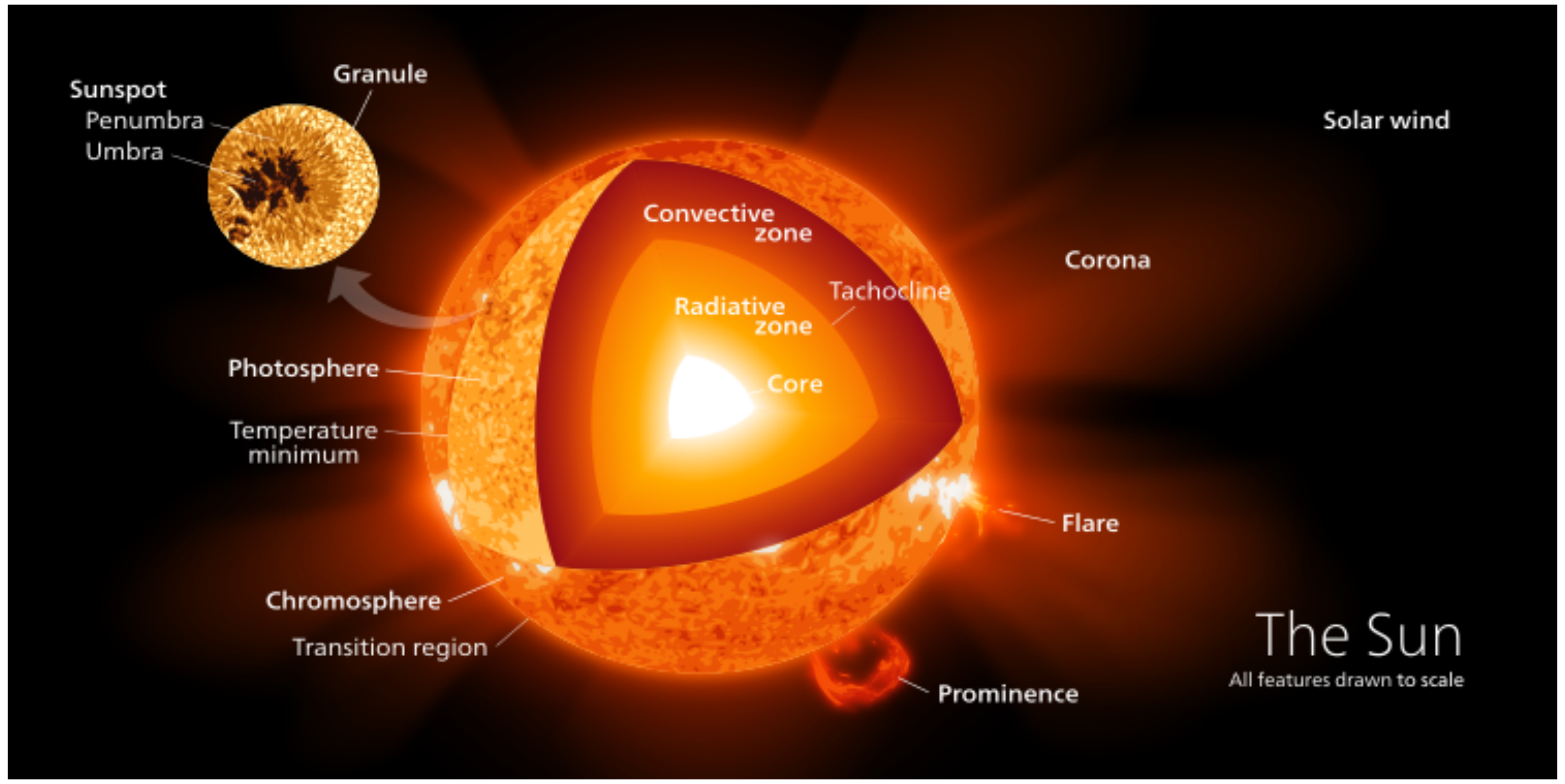
Why is *continual* solar gamma-ray emission interesting?

(Because the Sun itself doesn't emit continual gamma rays)



- Photosphere temperature is 6000 Kelvin — visible light (~1 eV)
- Corona temperature can reach as high as 4 million Kelvin
  - EUV and X-ray ($\lesssim 1$ keV)
  - Heating due to wave-driven turbulence and reconnection
- Solar flare and coronal mass ejection emit gamma rays up to few GeV
  - Due to non-thermal particle acceleration from shock-like structures
  - Signals are transient — can be removed out from continual emission

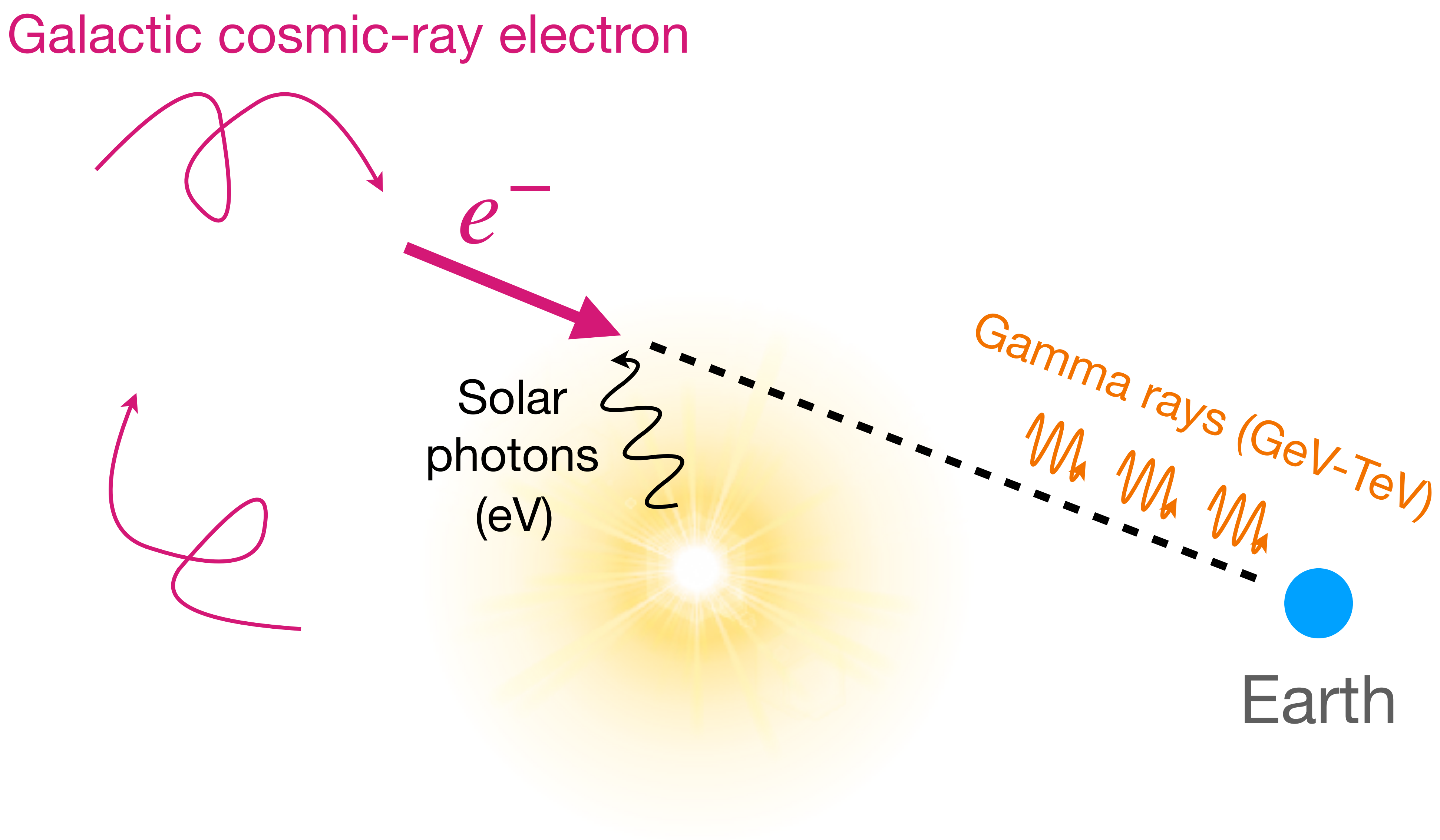
Continual gamma rays from solar halo

(Not the focus of this talk)

Inverse-Compton scattering in the solar halo

$$e^- + \gamma \rightarrow e^- + \gamma$$

See Moskalenko, Porter & Diego 2006;
Orlando & Strong 2007;
Abdo et al 2011



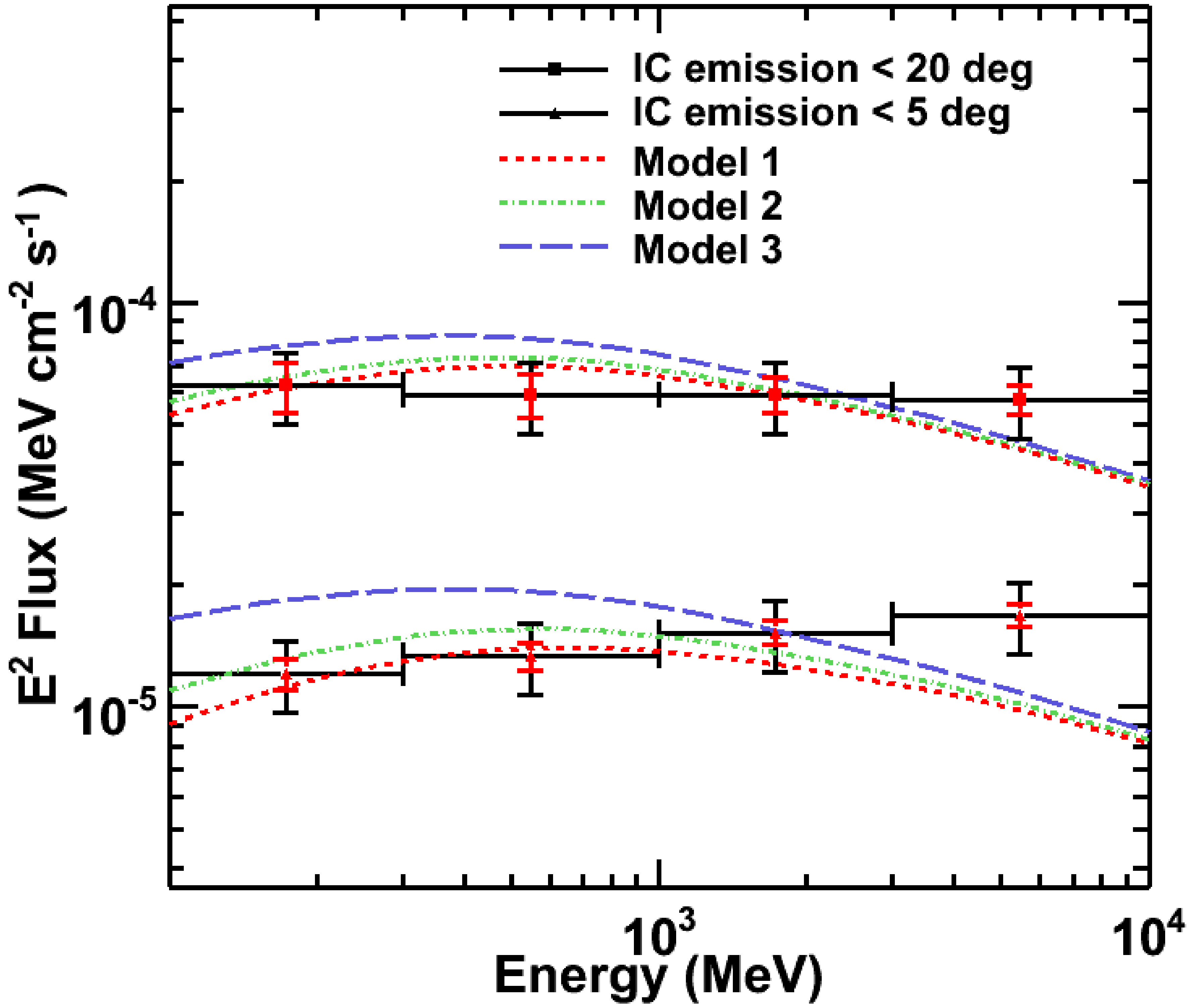
Galactic cosmic-ray electron

e^-

Solar photons (eV)

Gamma rays (GeV-TeV)

Earth



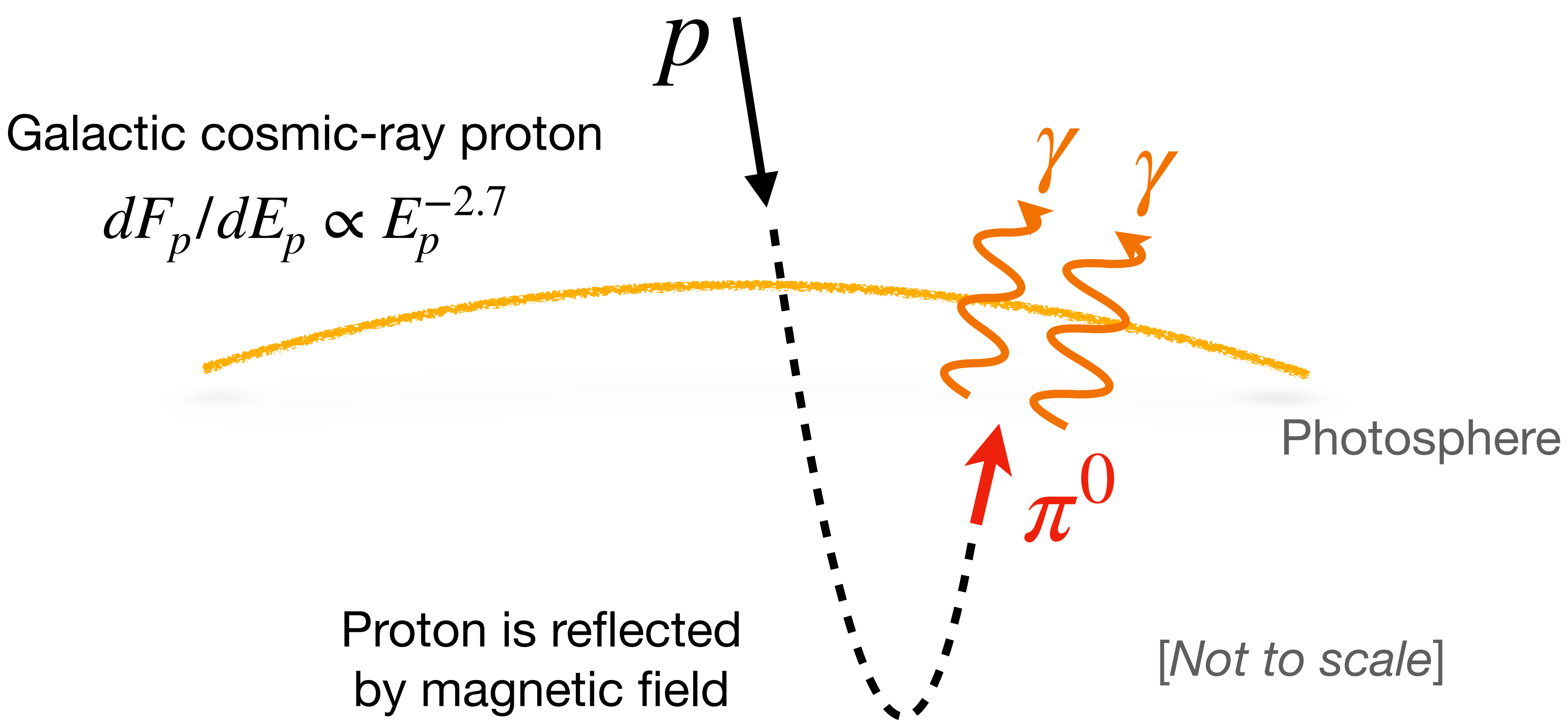
(Fermi Collaboration; Abdo et al 2011)

Continual gamma rays from solar disk

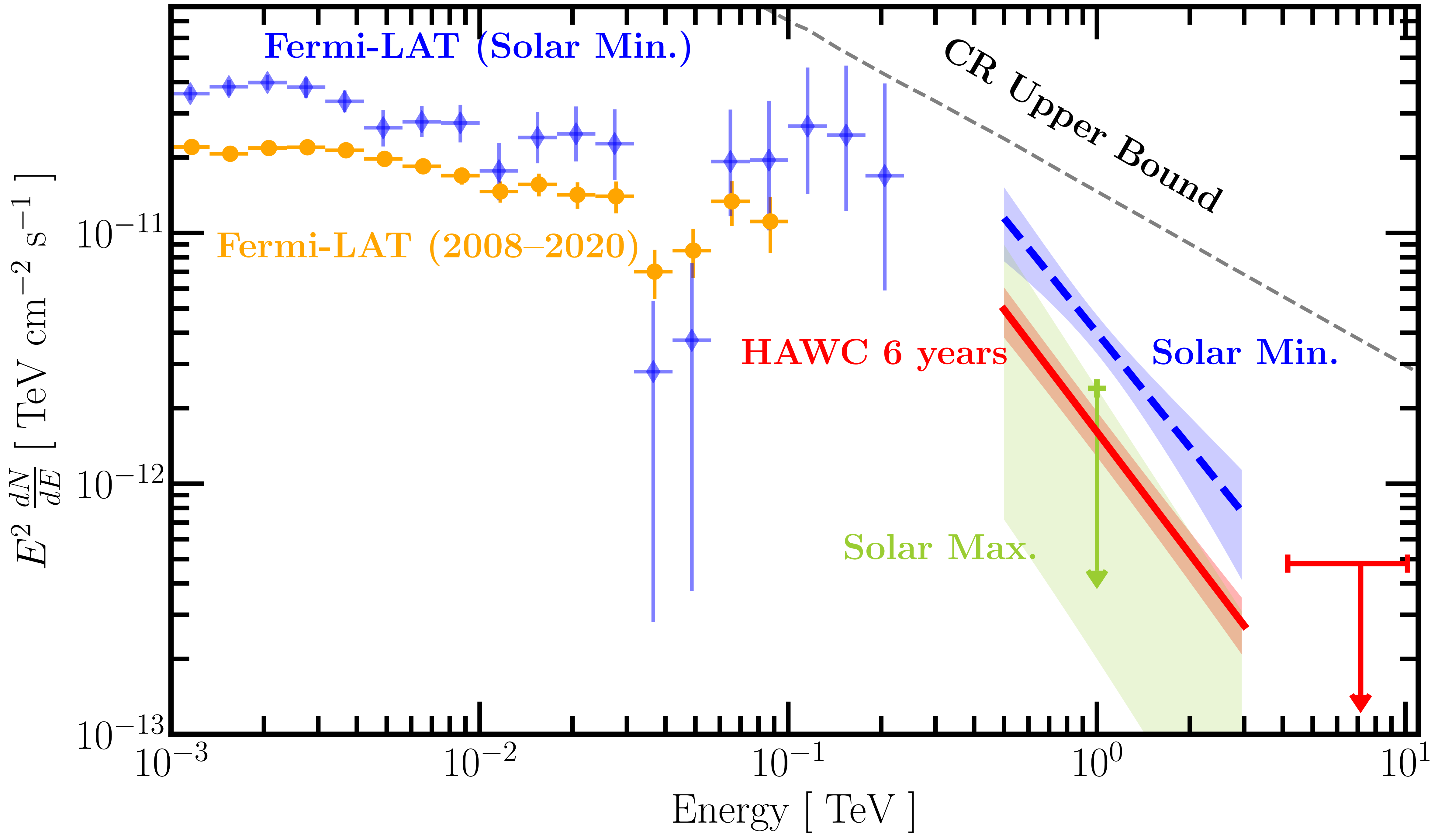
Hadronic scattering
in the solar disk

$$p + p \rightarrow p + p + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

(See Seckel, Stanev & Gaisser 1991)

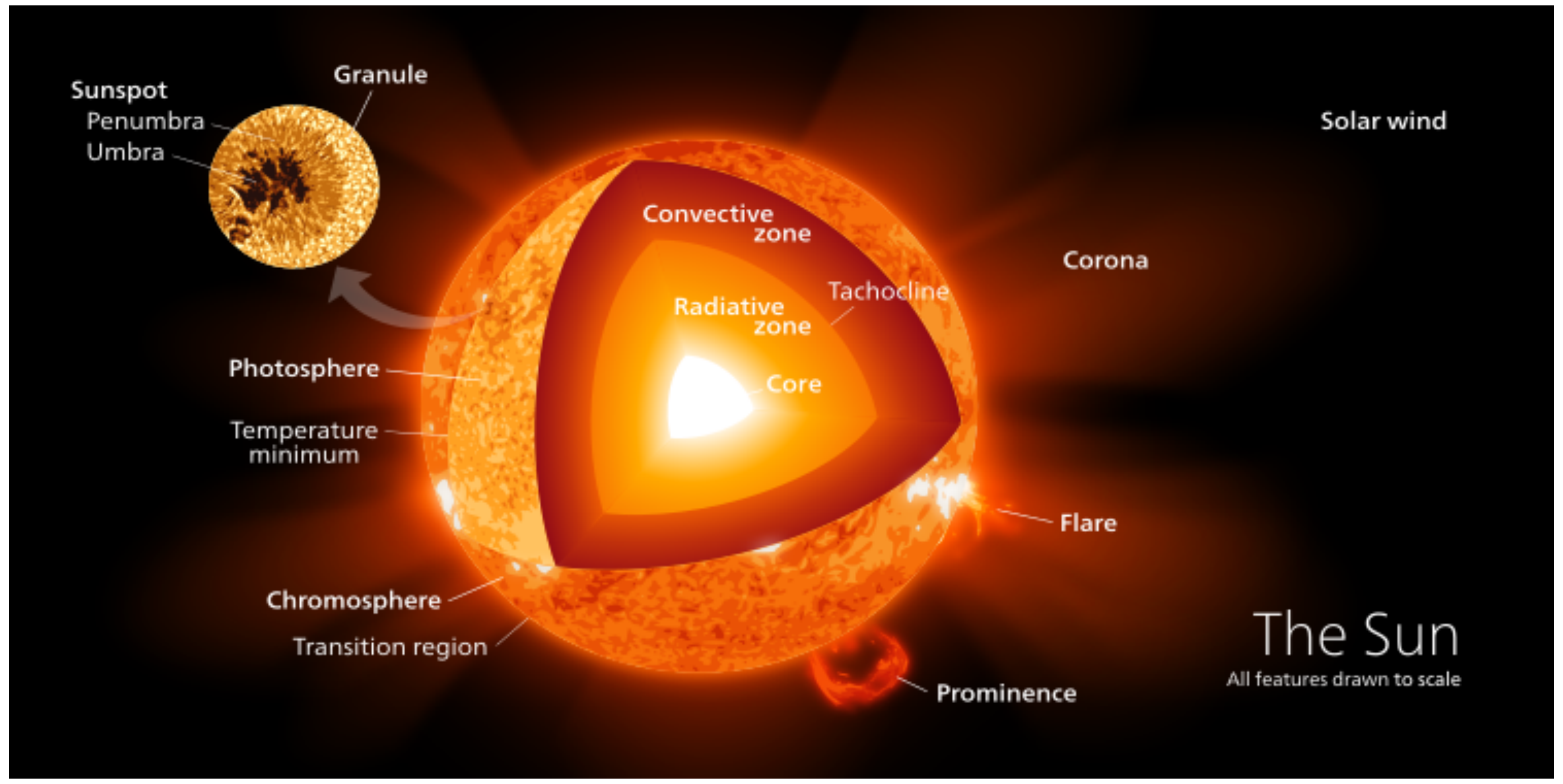


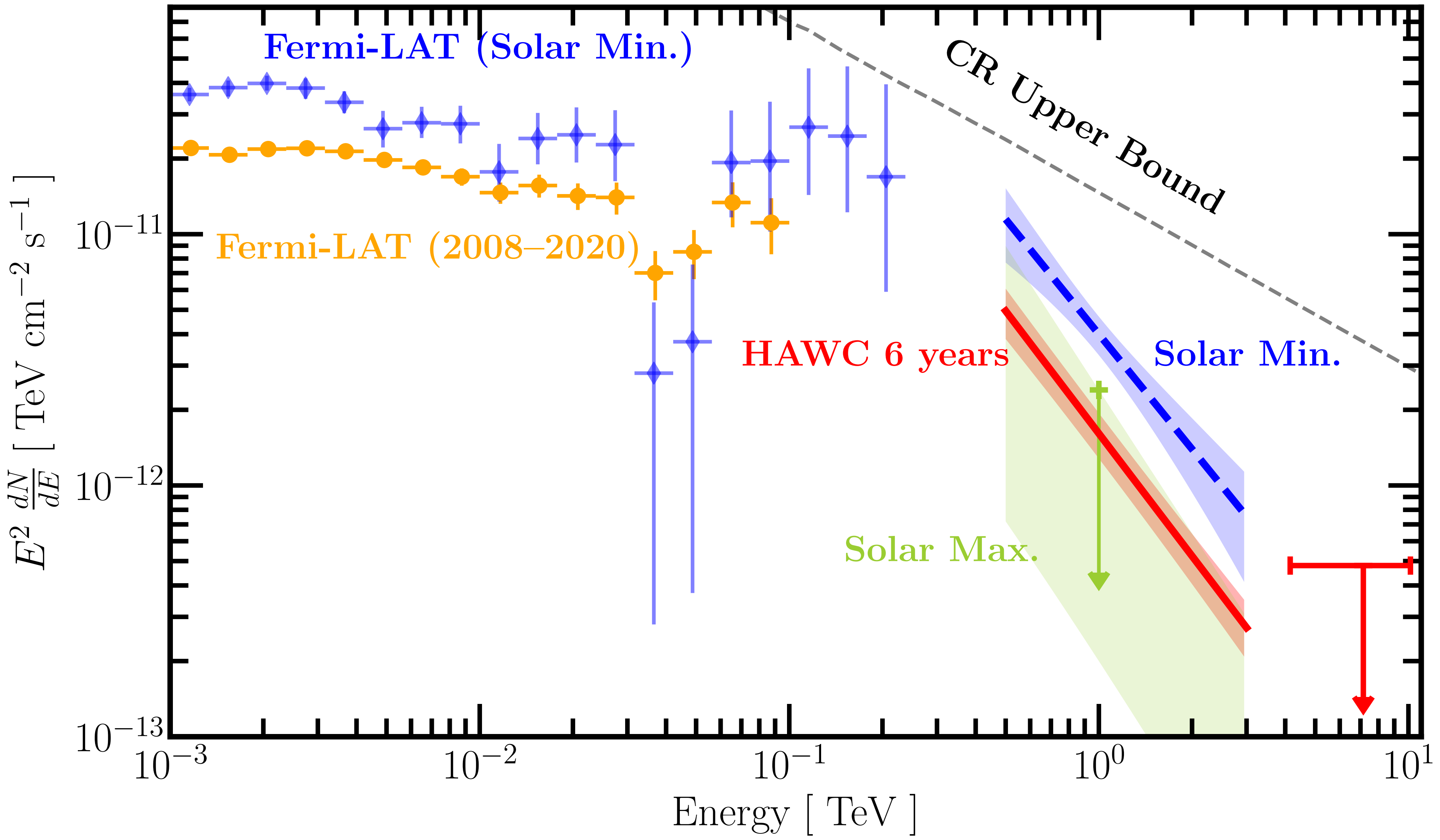
Focus of this talk!



(HAWC Collaboration; Albert et al 2023)

Theoretical challenges for solar disk emission

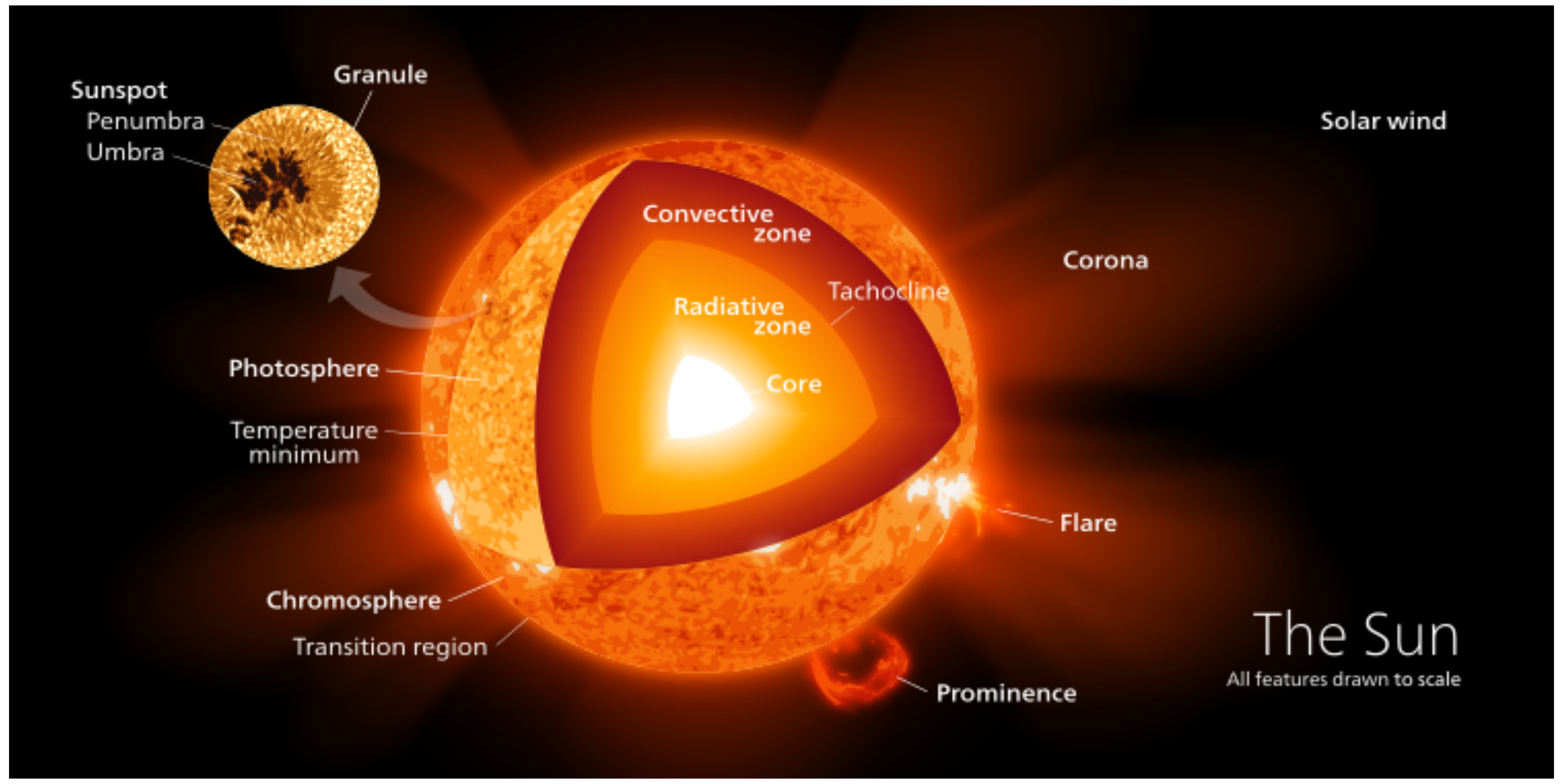


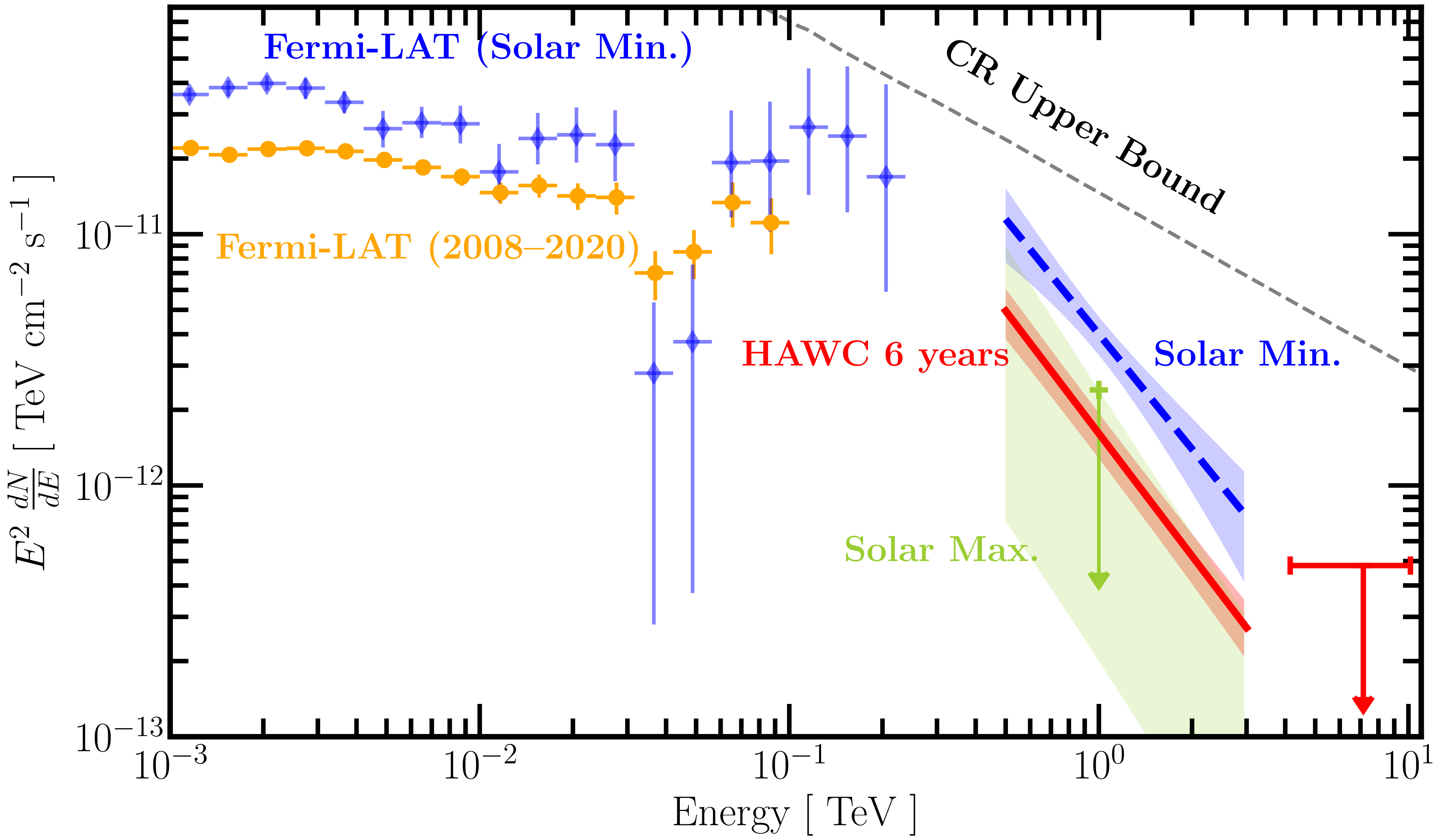


(HAWC Collaboration; Albert et al 2023)

1. Magnetic field structures determining the observed gamma-ray spectrum
   - Solar magnetic field is multi-scale. How do we think this problem?
2. Spectral shape
   - Hard spectrum for $\lesssim$ 200 GeV ($dN_\gamma/dE_\gamma \sim E_\gamma^{-2.2}$)
   - Soft spectrum at $\sim$ 1 TeV ($dN_\gamma/dE_\gamma \sim E_\gamma^{-3.6}$)
3. Gamma-ray emission anti-correlated with solar activity
   - Higher gamma-ray flux at solar min
   - GCR Transport? Active region activity? Small-scale convection at quiet photosphere?

Theoretical challenges for solar disk emission





(HAWC Collaboration; Albert et al 2023)

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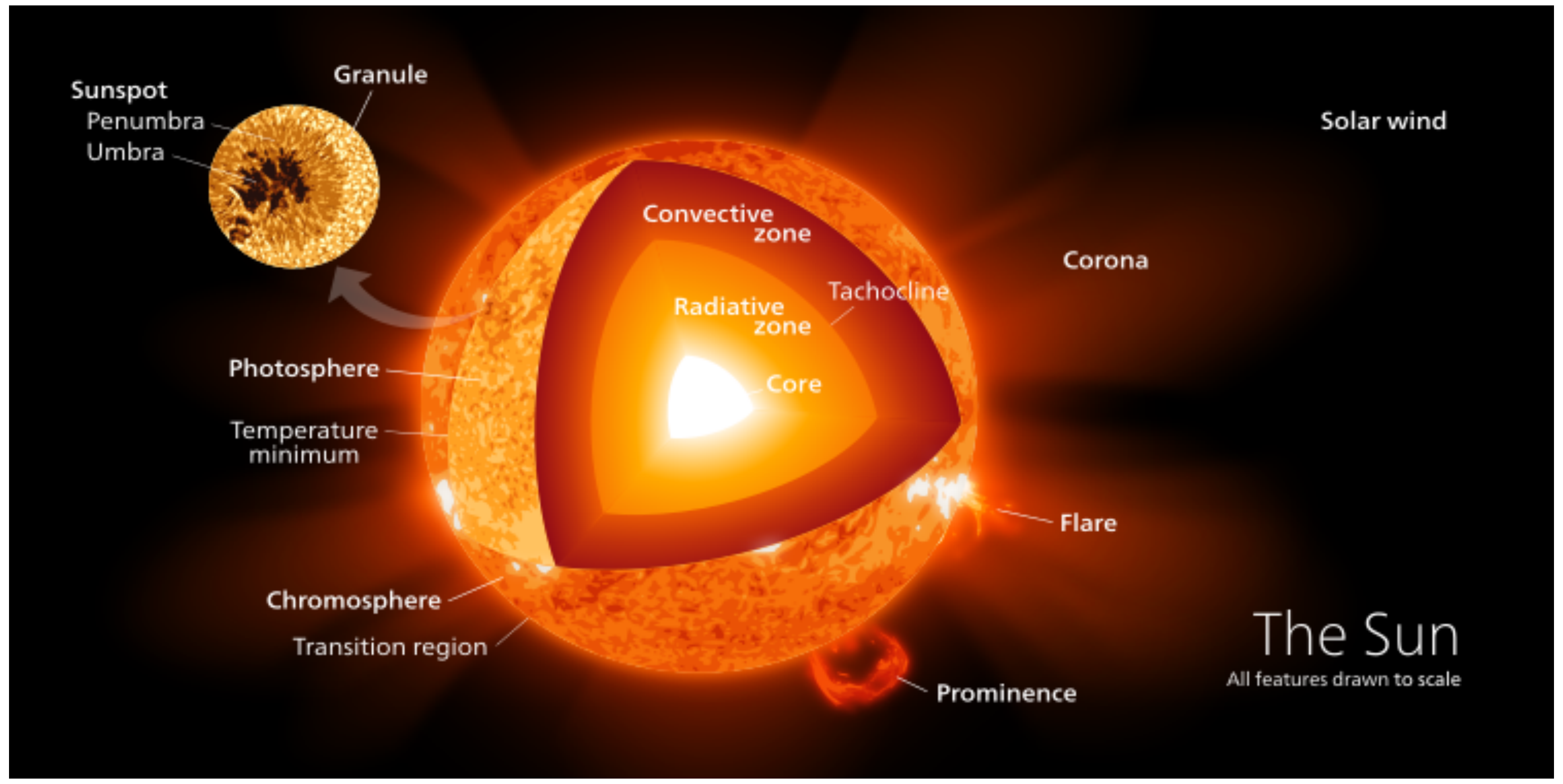
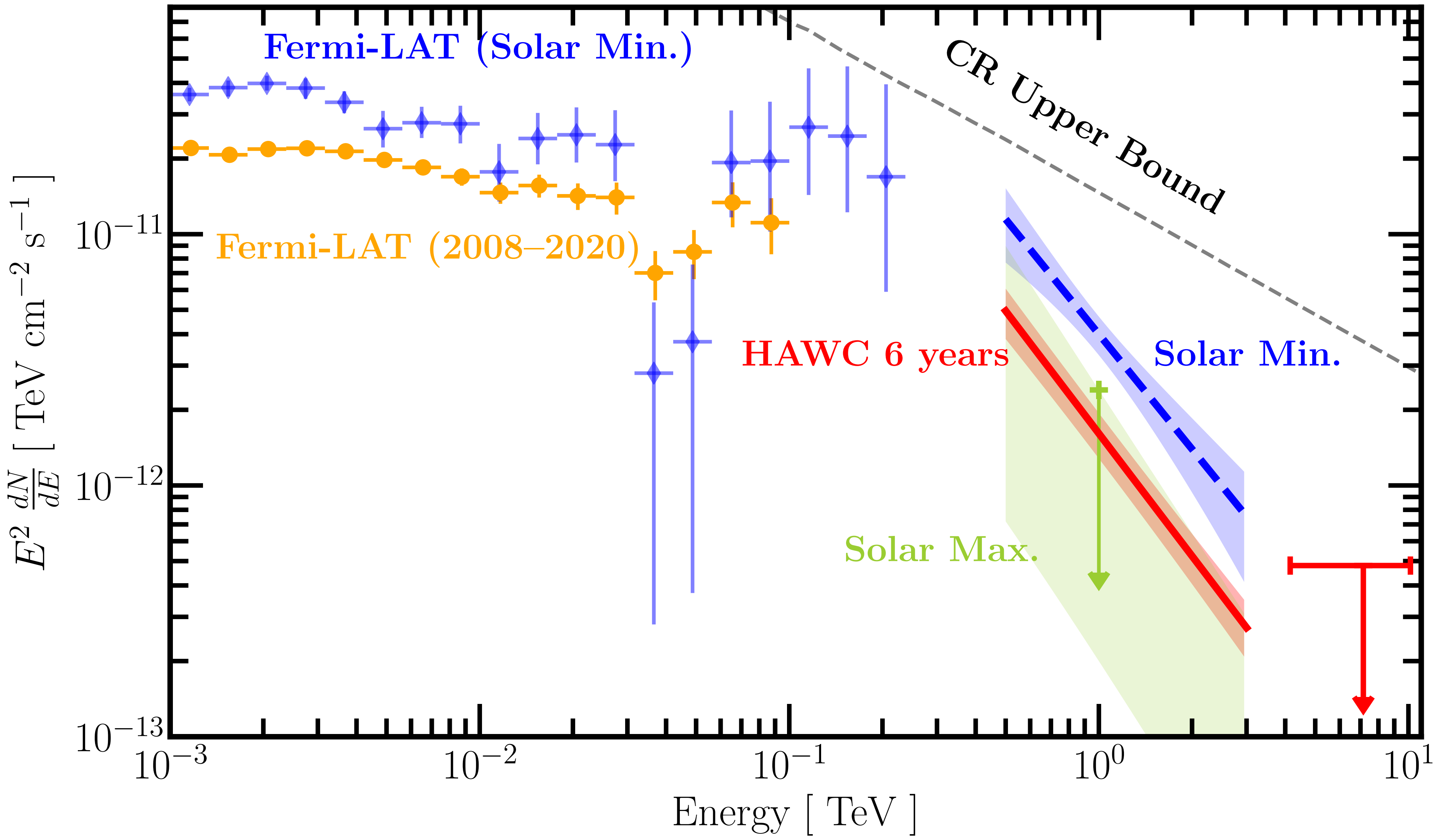
Theoretical challenges for solar disk emission





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The Sun’s magnetic structure is complex

- It is impractical to consider all structures at all scales in one study
- The goal is understand the nature of the problem: What critical magnetic structures should we consider?

In this work

- We consider quiet region of the Sun that forms the network field and open magnetic field lines
- Open field lines extends to interplanetary space and become the interplanetary magnetic fields

Two Stages

Stage 1

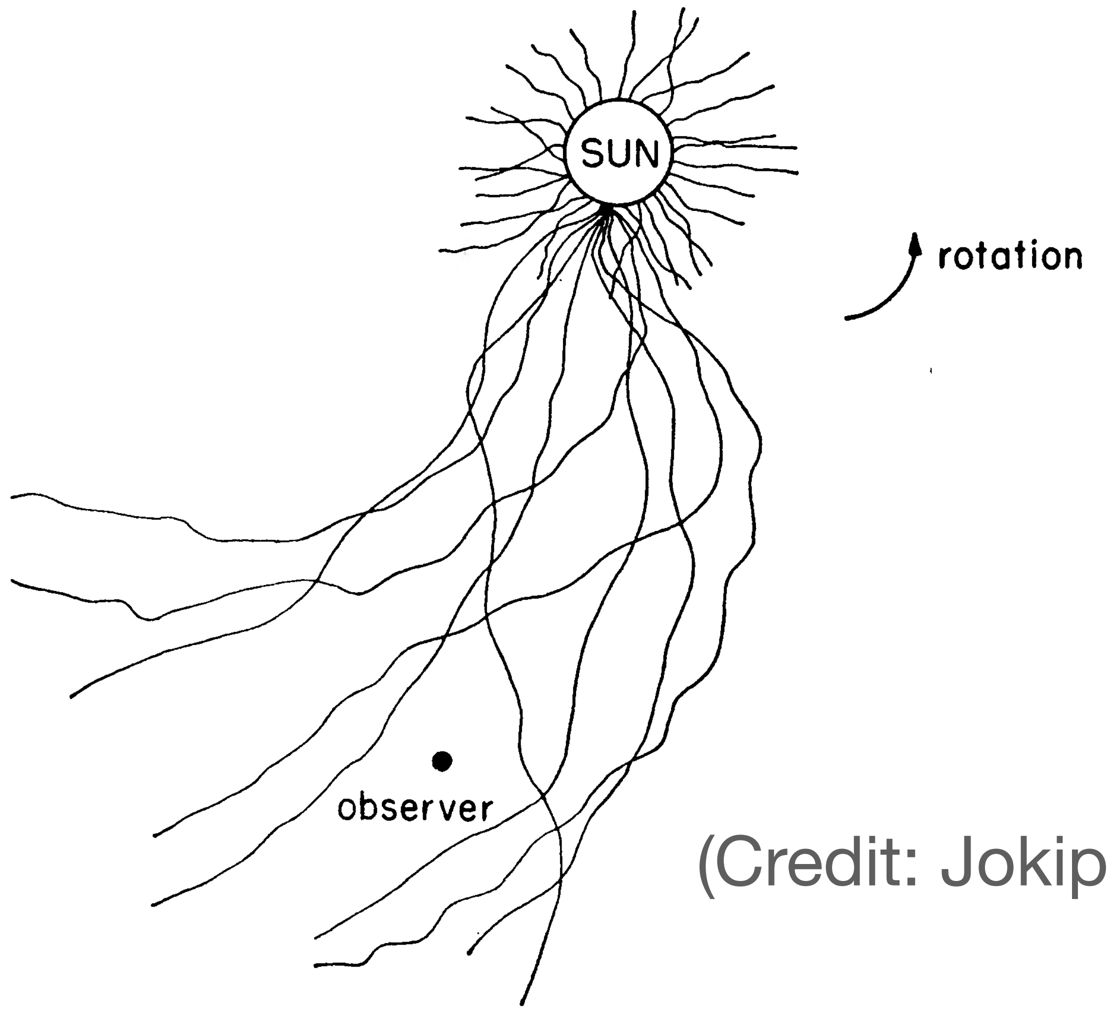
Solar modulation

- Evaluate galactic cosmic ray intensity in the inner heliosphere (< 1 AU), especially at above photosphere.

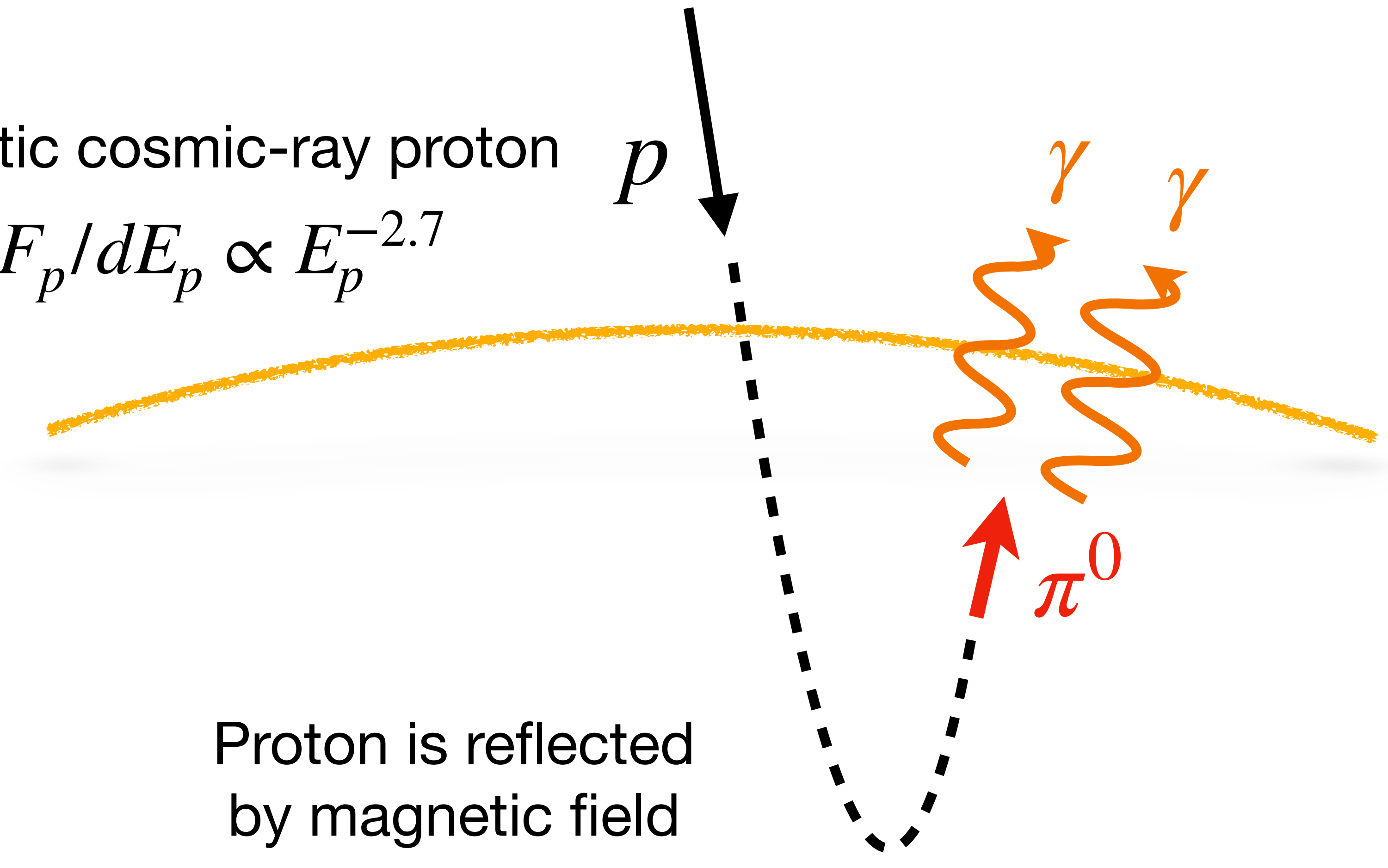
Stage 2

Particle reflection in photosphere

- Magnetic field structure in photosphere and uppermost convection zone
- Proton galactic cosmic ray reflection



(Credit: Jokipii & Parker 1969)



Galactic cosmic-ray proton

$dF_p/dE_p \propto E_p^{-2.7}$

Photosphere

Proton is reflected
by magnetic field

Stage 1: Solar Modulation

Using Force-Field Model

- Full cosmic ray transport equation, in the solar system frame (Parker 1965; Gleeson & Webb 1978)

$$\frac{\partial U_p}{\partial t} + \nabla\cdot\left(C\mathbf{V}_{\rm sw}U_p\right) - \nabla\cdot\left(\kappa\cdot\nabla U_p\right) + v_{\rm D}\cdot\nabla U_p + \frac{1}{3}\frac{\partial}{\partial p}\left(p\mathbf{V}_{\rm sw}\cdot\nabla U_p\right) = 0$$

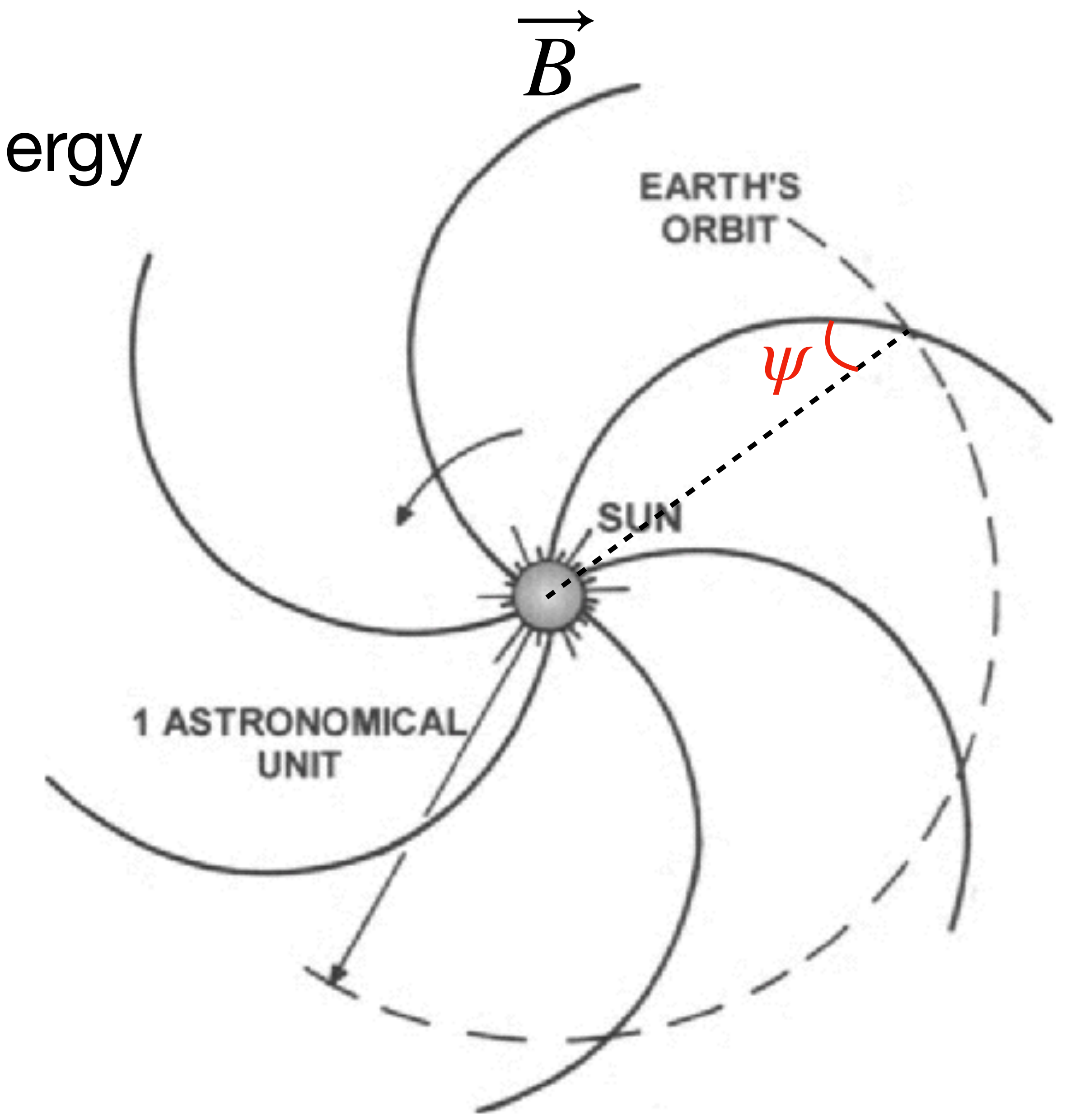
Rate change
Convection
Diffusion
Drift
Momentum loss

- 1D force-field model: convection flux balances diffusion flux (Gleeson & Axford 1966)

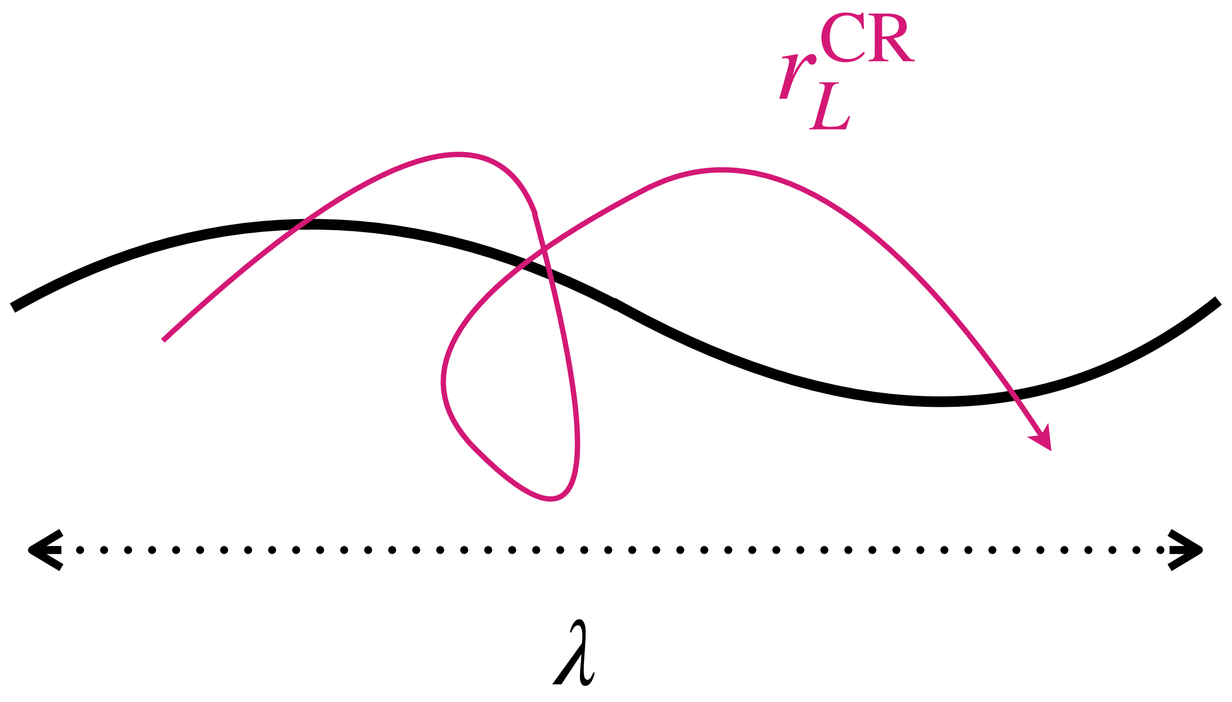
1. Force-field solution $\frac{J_E\left(E,r_1\right)}{E^2-E_0^2} = \frac{J_E\left(E+\Delta\Phi,r_2\right)}{(E+\Delta\Phi)^2-E_0^2}$ where $\Delta\Phi$ is modulation potential energy
2. Characteristic eqn $\frac{dE}{dr} = \frac{V_{\rm sw}}{3\kappa_{rr}}\frac{\left(E^2-E_0^2\right)}{E}$

$\kappa_{rr} = \kappa_{\parallel}\cos^2\psi + \kappa_{\perp}\sin^2\psi$ in the plane, with $\kappa_{\parallel} \gg \kappa_{\perp}$ in the inner heliosphere

$\kappa_{\parallel}$ is determined from CR resonant interaction with magnetic turbulence



Quasi-Linear Theory (QLT)



- Quasi-linear theory describes the slow evolution of the particle distribution in a weak turbulent plasma back to a marginally stable state.

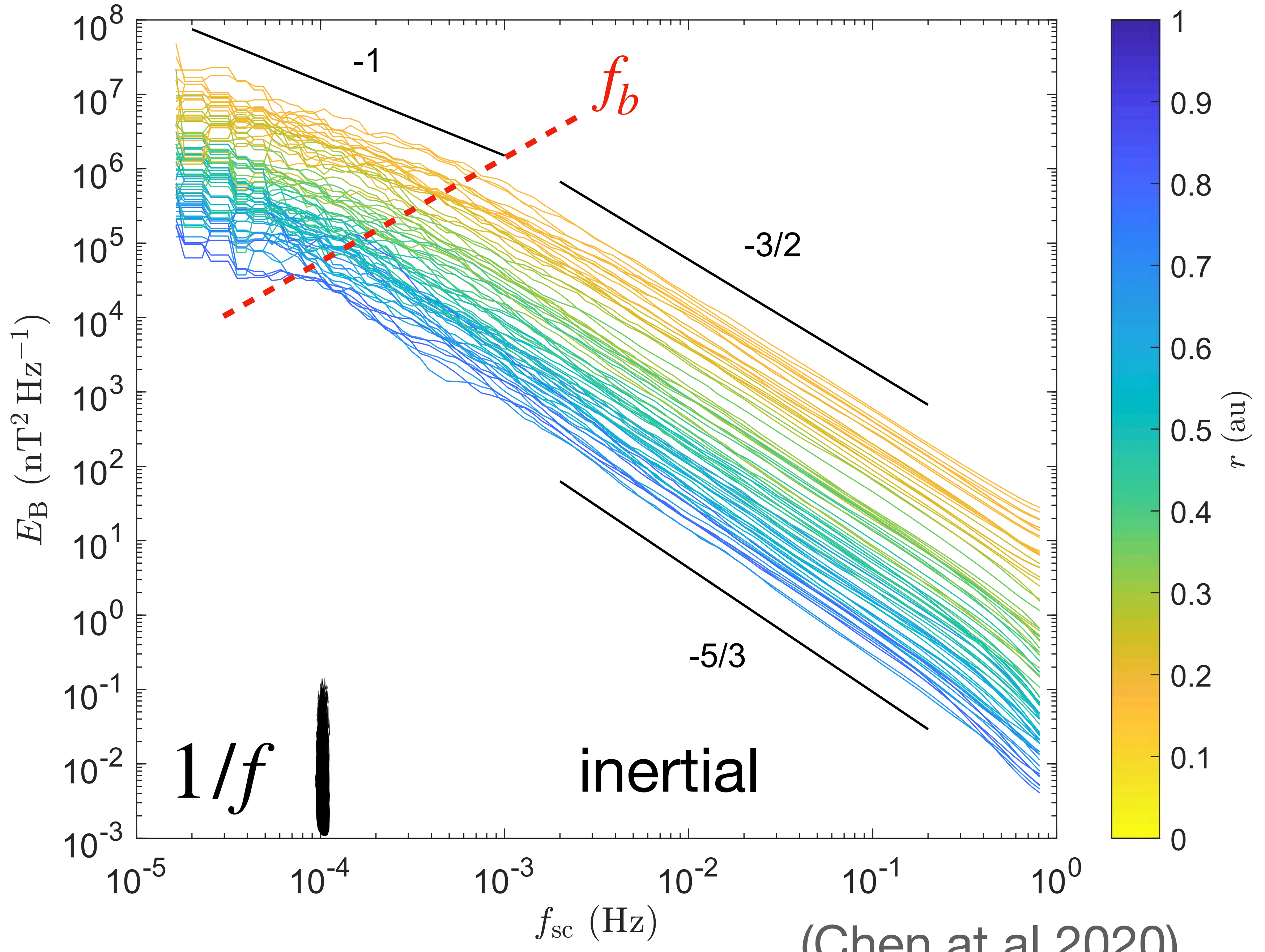
$$\kappa_{\|} = \frac{v^2}{4}\int_{\mu_{\mathrm{min},s}}^{1} \frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}} d\mu \qquad D_{\mu\mu} = \frac{1-\mu^2}{2|\mu|v}\left(\frac{\Omega_{0,s}}{|\langle \mathbf{B} \rangle|}\right)^2 V_{\mathrm{sw}}(r)\, E_{\mathrm{B},xx}\left(f_{\mathrm{res}}, r\right)$$

(Jokipii 1966)

μ: cosine of pitch angle

E_{B}: magnetic power spectrum

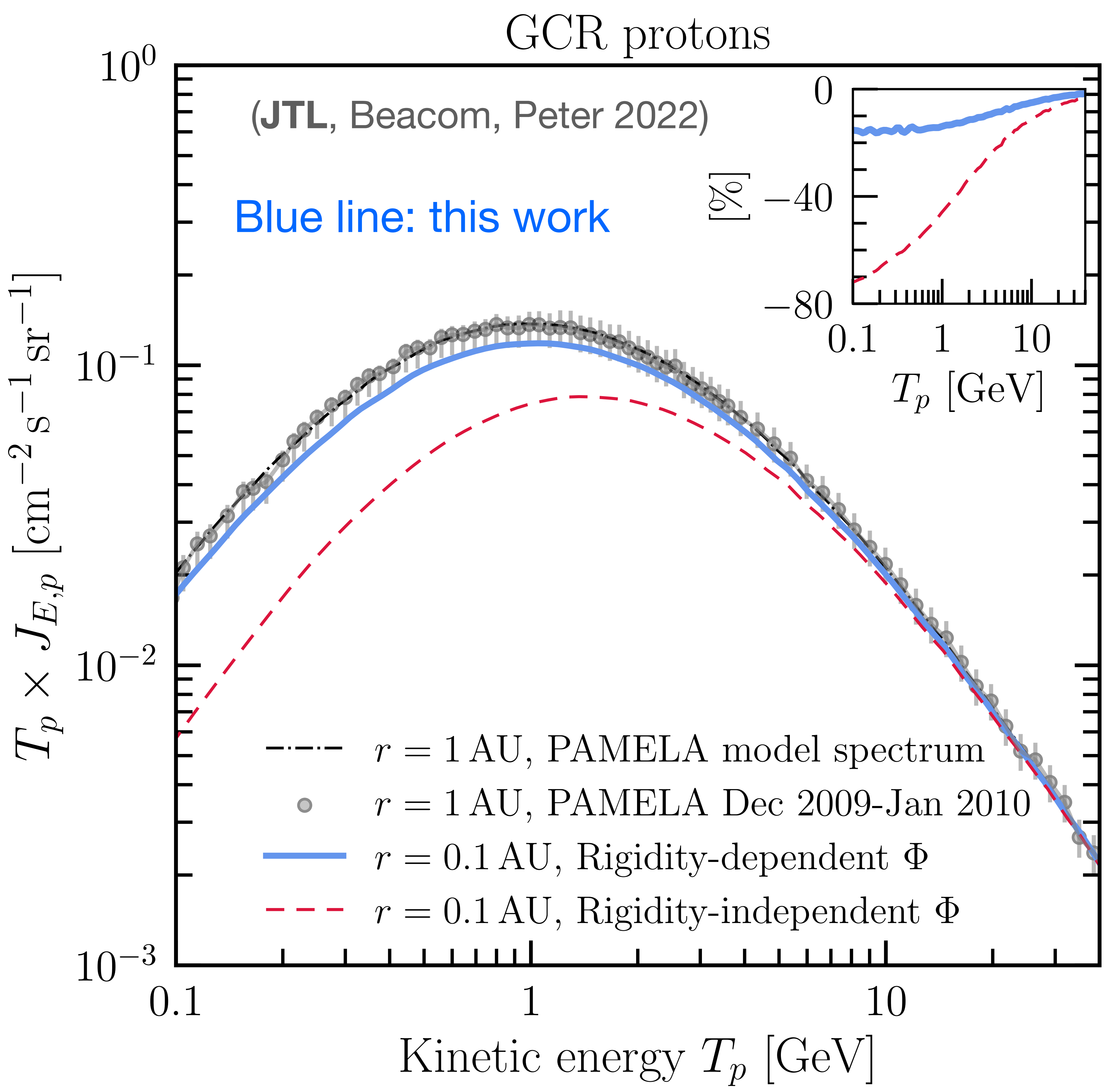
f_b: frequency break



(Chen at al 2020)

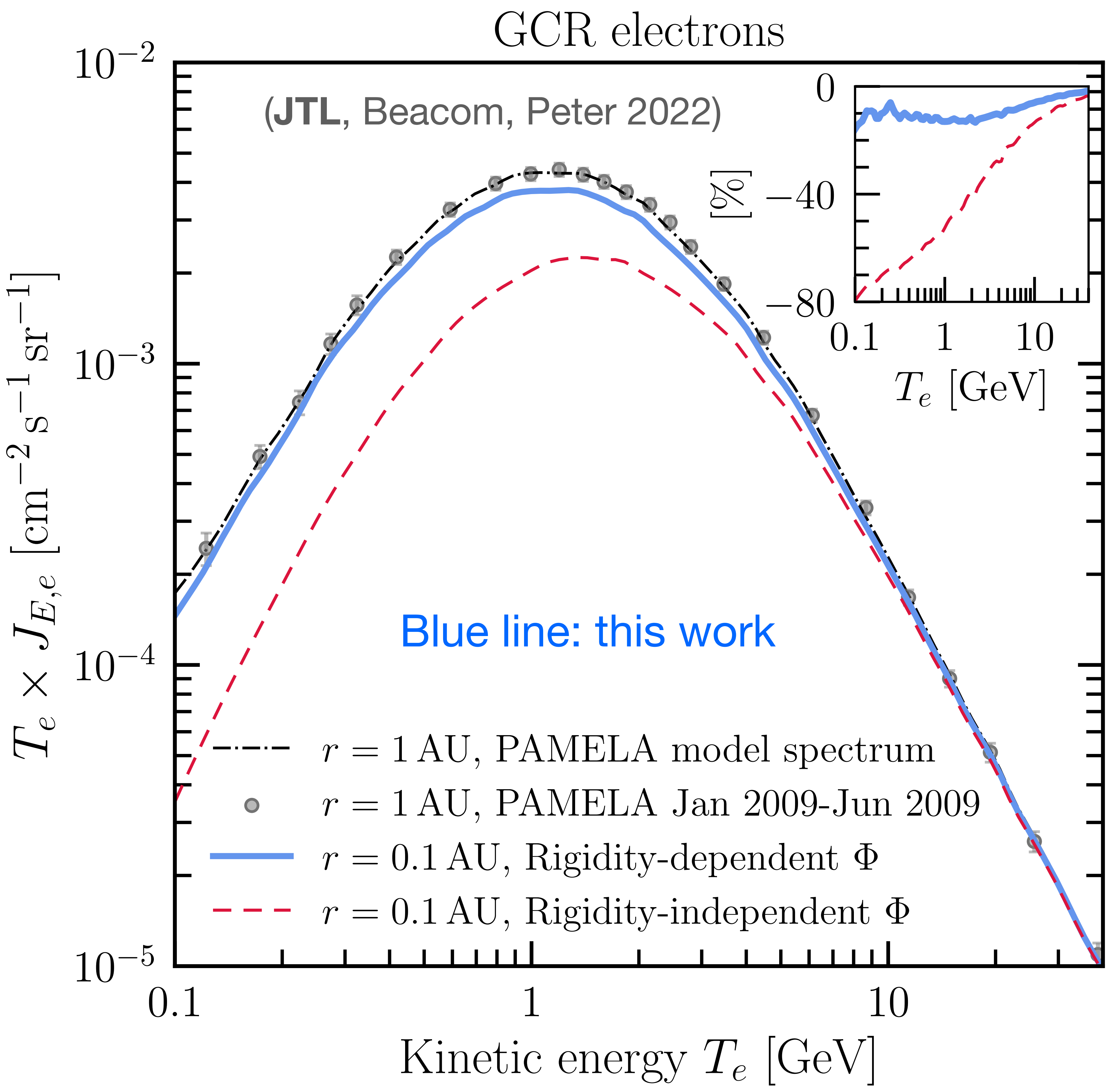
- PSP measurement of magnetic power spectrum (Chen et al 2020)
  - A. Turbulence evolution down to 0.17 AU
  - B. Frequency break f_b which separates $1/f$ range and inertial range turbulence

Cosmic-Ray Energy Spectrum at 0.1 AU


GCR protons

(**JTL**, Beacom, Peter 2022)

Blue line: this work


GCR electrons

(**JTL**, Beacom, Peter 2022)

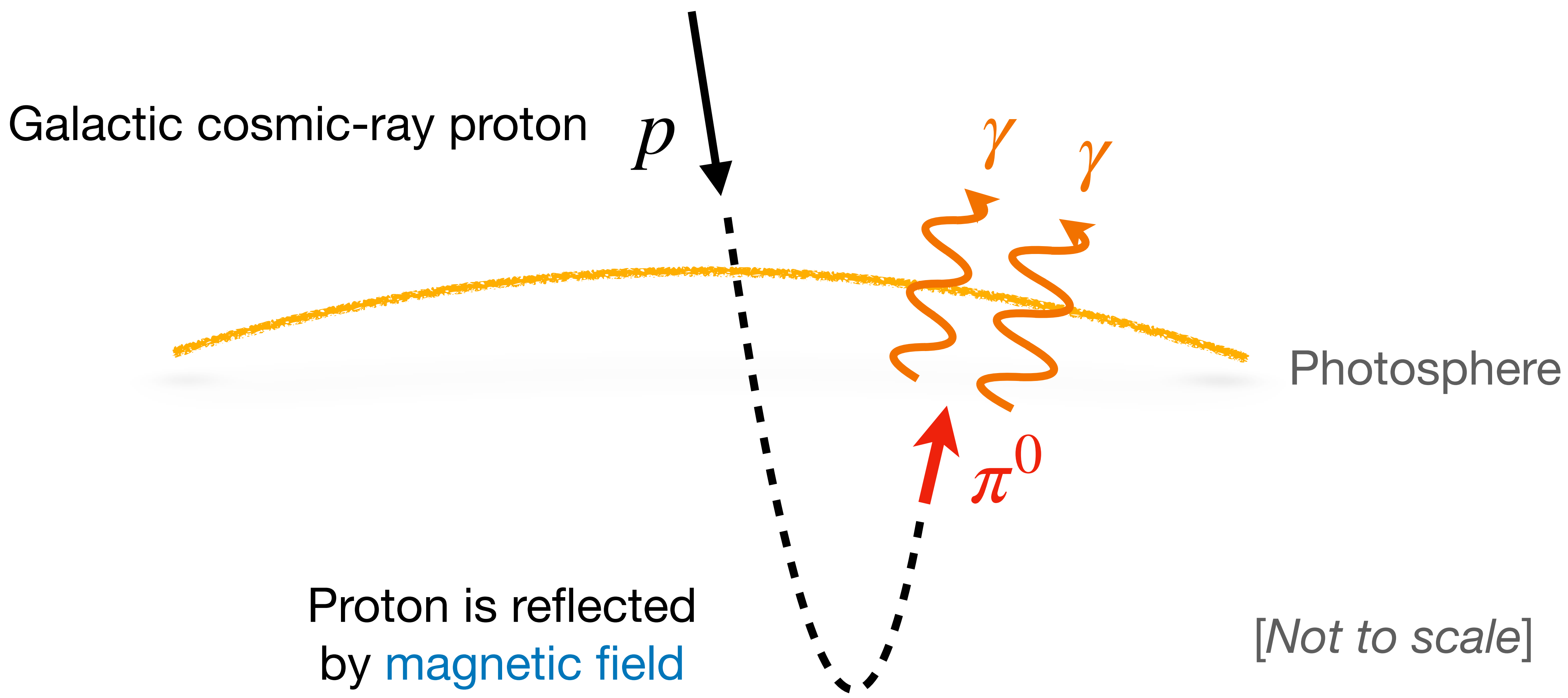
Blue line: this work

Modulation in the inner heliosphere is modest

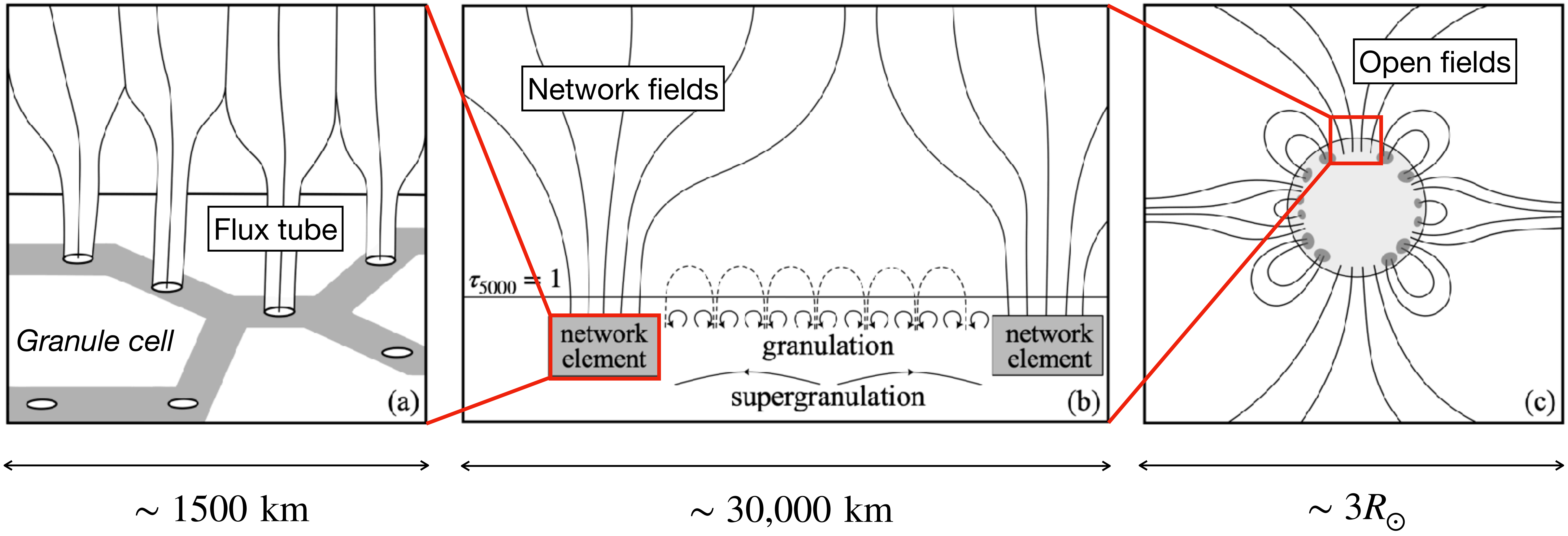
≈ 10 % reduction of intensity from 1 AU to 0.1 AU

JTL, Beacom, Peter 2022
ApJ 937, 27

Stage 2: Particle reflection in flux tube & flux sheet

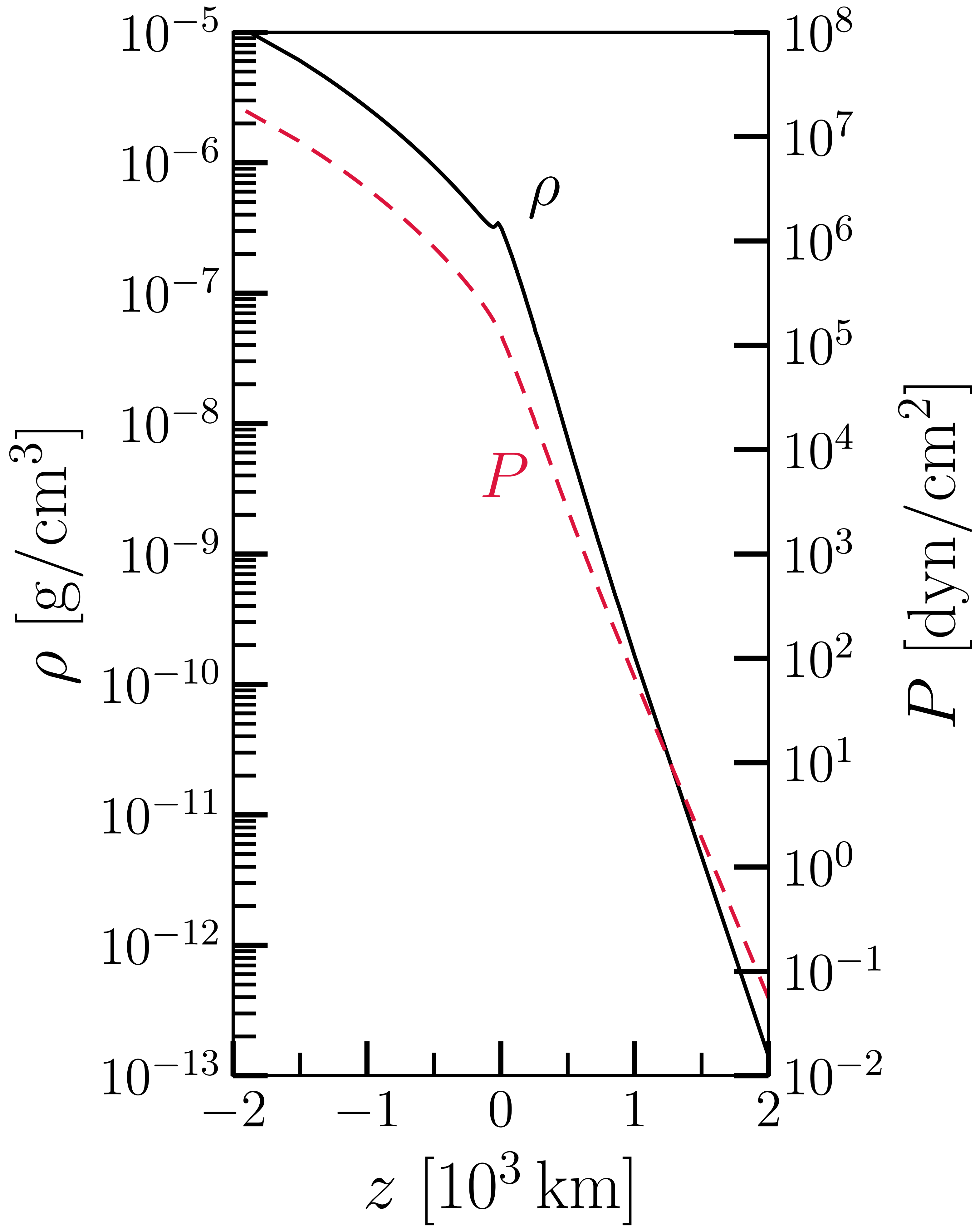


Overview of Coronal-hole Open Field Lines & Magnetic Network Fields (Quiet Photosphere Region)



JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

Depths of Interest



- Magnetic field structure is multi-scale — need to identify the Depth of interest for gamma-ray production

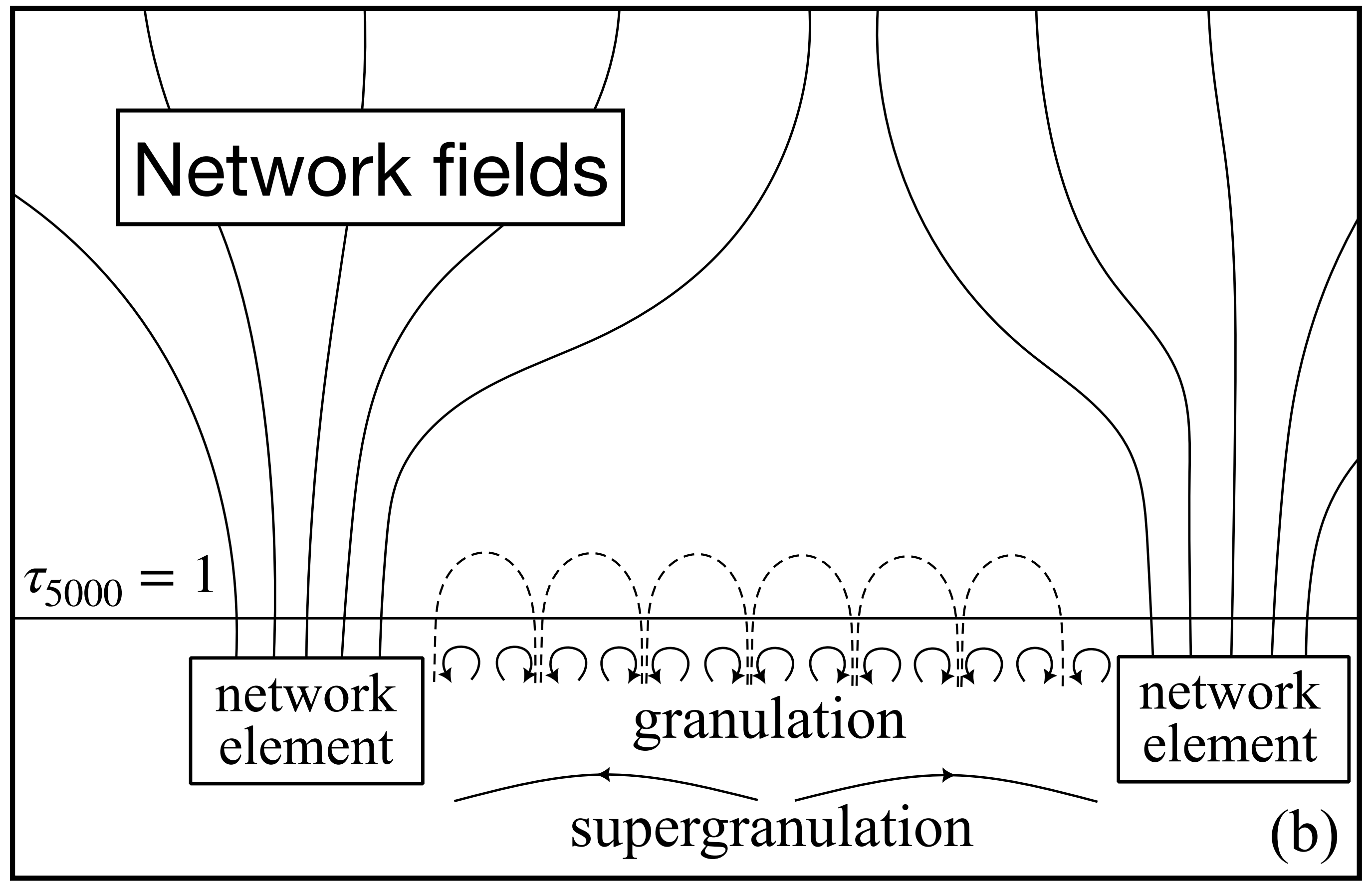
- Estimates of proton GCR absorption in the Sun
  - One absorption from *pp* interaction

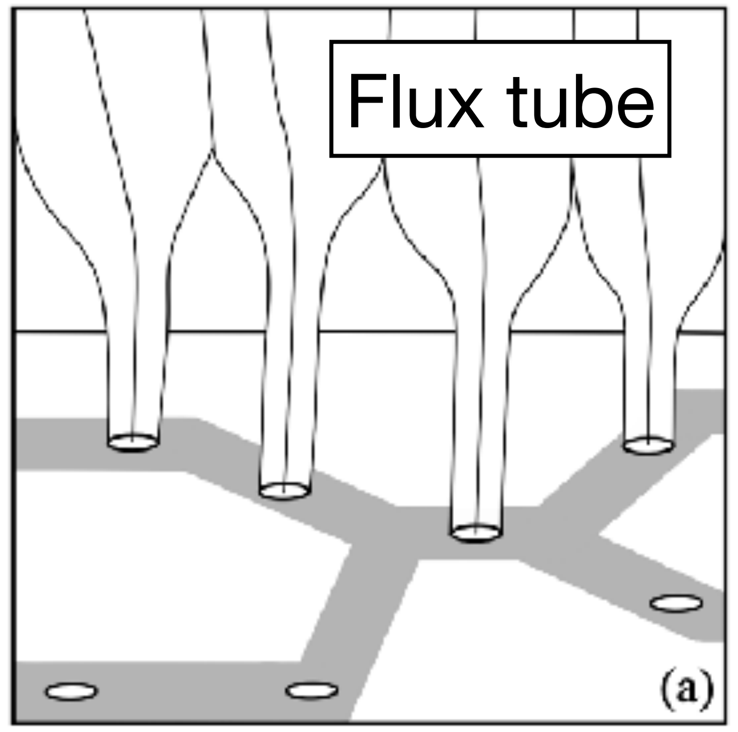
$$\int n_{\text{gas}}(z)\,\sigma_{\text{pp}}dz \sim 1$$

  - *pp* interaction occurs within ~ few 100 km below solar surface.
  - Surface (z=0) is defined as $\tau_{500\,\text{nm}} = 1$

- Gamma rays are emitted in *photosphere* and *uppermost convection zone*

Our Model Assumptions





JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

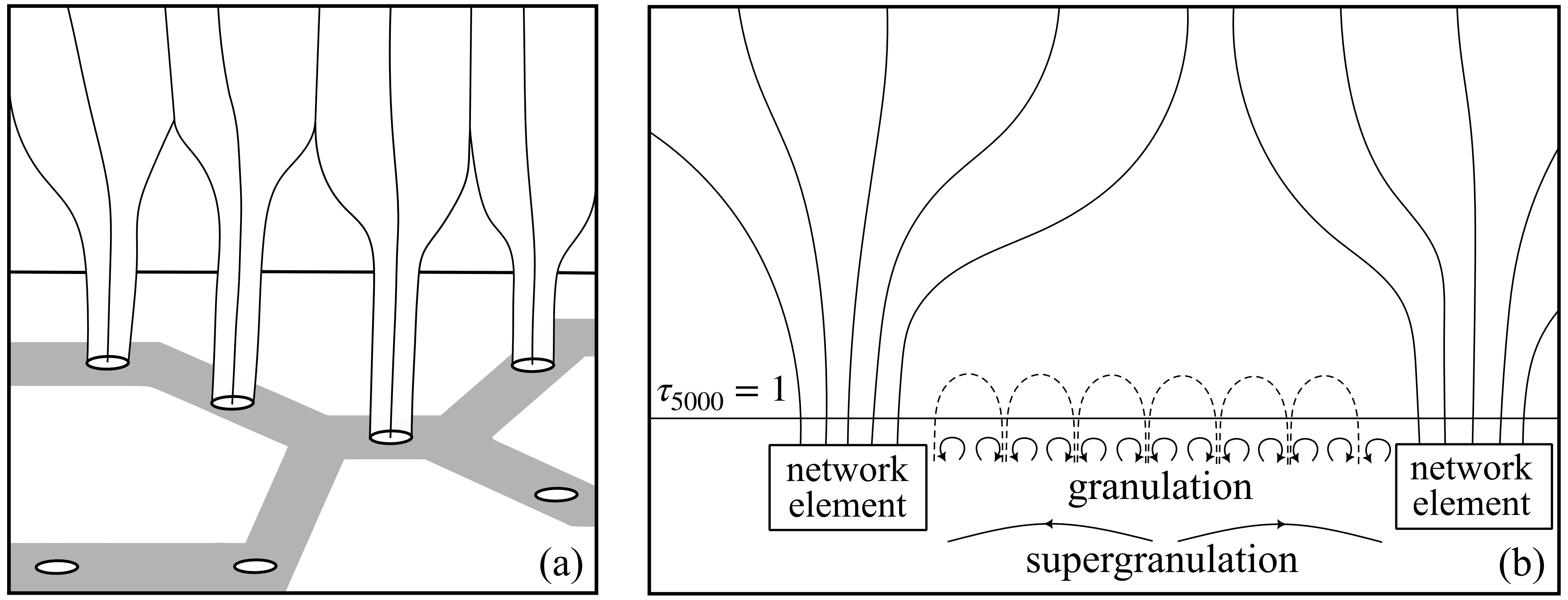
- GCRs propagate along open field lines, entering network elements

- Simulation starts at the merging height of tubes (at z=1600 km)
    - i.e., we consider chromosphere, photosphere, uppermost convection zone

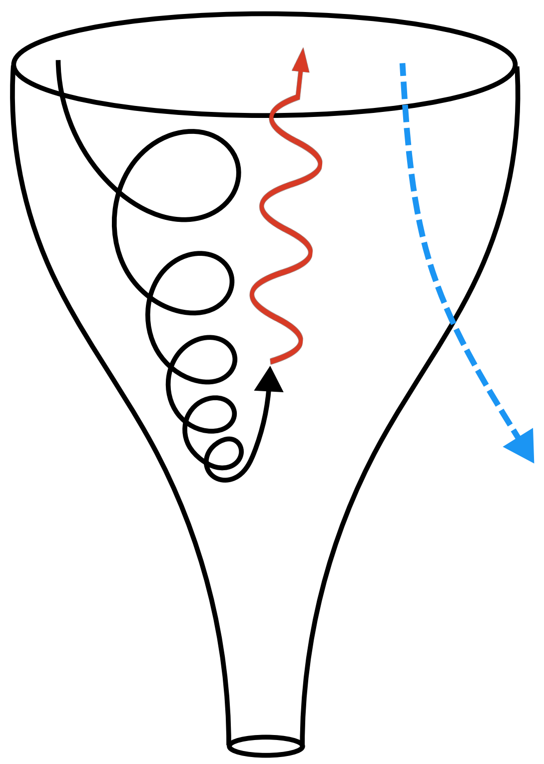
- GCR intensity taken from AMS + CREAM measurement at 1 AU
    - Using Parker Solar Probe result on magnetic power spectrum, GCR flux reduction is $\lesssim 10\,\%$ from 1 AU to 0.1 AU (see **JTL** et al 2022: ApJ **937** 27)
    - Solar modulation from 1 AU to solar surface is not considered

- Inject GCRs into tube isotropically
    - Those high-energy GCRs passing through tube surface enters internetwork regions consisting of sheets

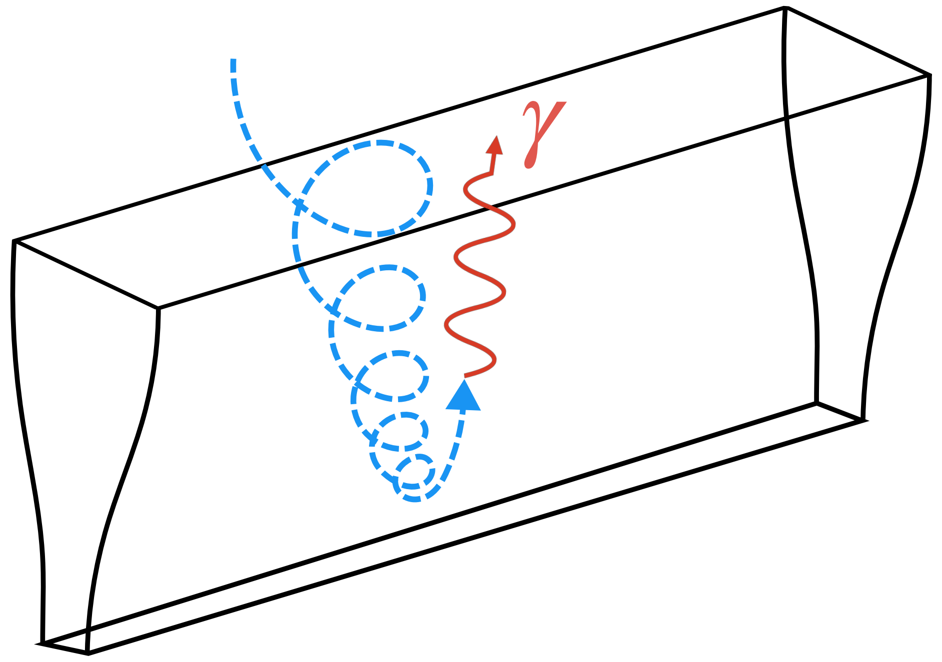
Schematics of Our Model: Flux Tube + Flux Sheet



- One flux tube and one flux sheet
  - Tube represents network element
  - Sheet represents granule sheet



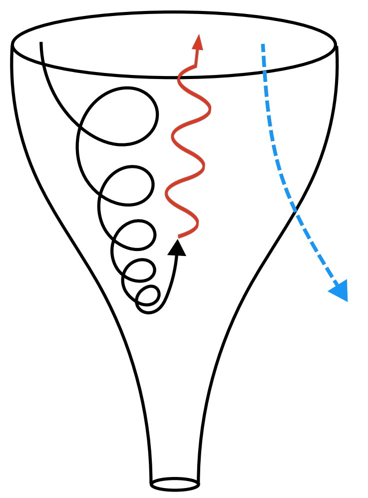
Flux tube



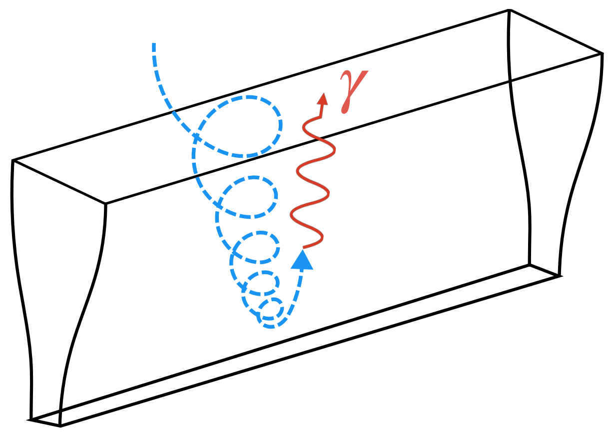
Flux sheet

- Particles are reflected via magnetic bottle (magnetic mirroring) effect
  - Increasing B makes pitch angle approaching 90°
  - Radial field imparts a kick at 90°
  - Particle starts spiraling upward

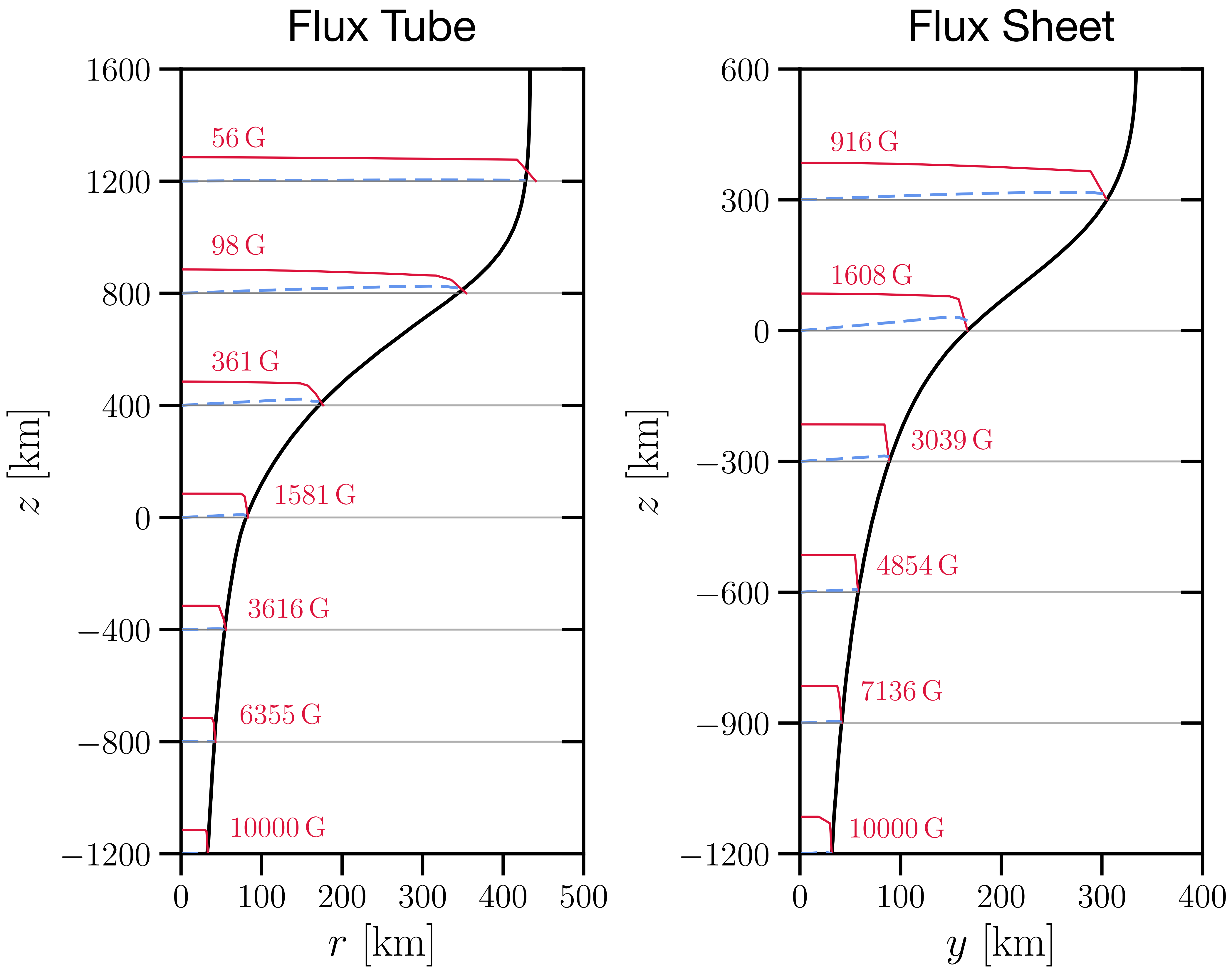
Magneto-Hydrostatic Equilibrium



Flux tube



Flux sheet



- Magneto-hydrostatic equilibrium with the surrounding gas

- Following Grad-Shafranov equations
  - Flux tube:

$$\frac{\partial^2\Psi}{\partial r^2} - \frac{1}{r}\frac{\partial\Psi}{\partial r} + \frac{\partial^2\Psi}{\partial z^2} = -4\pi r J$$

$$B_r = -\frac{1}{r}\frac{\partial\Psi}{\partial z}, \quad B_z = \frac{1}{r}\frac{\partial\Psi}{\partial r}, \quad B_\phi = 0$$

  - Flux sheet:

$$\frac{\partial^2\Psi}{\partial y^2} + \frac{\partial^2\Psi}{\partial z^2} = -4\pi J$$

$$B_y = -\frac{\partial\Psi}{\partial z}, \quad B_z = \frac{\partial\Psi}{\partial y}, \quad B_x = 0$$

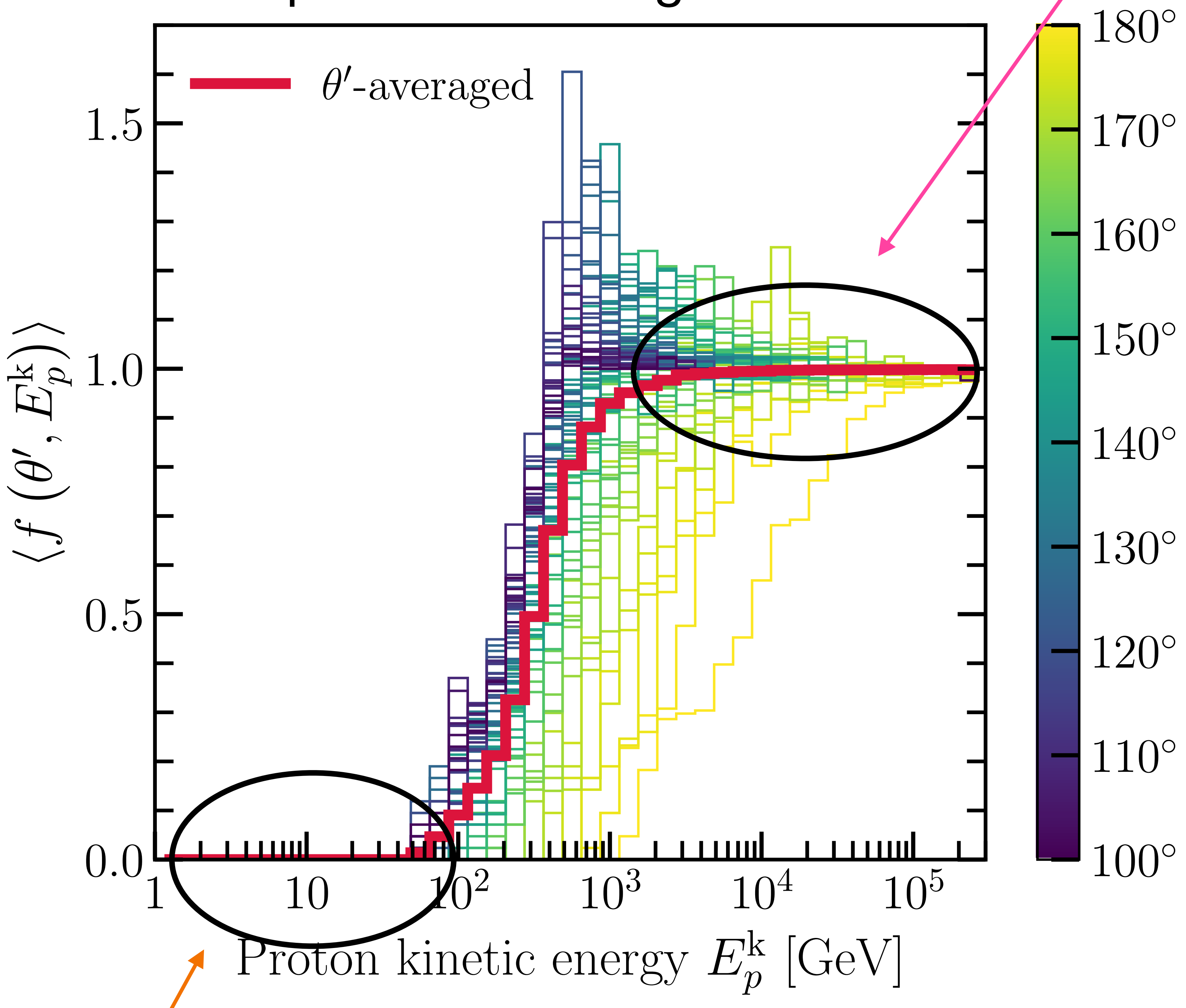
- Internal magnetic flux structure is critical for magnetic bottle effect!

JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

Angular Distribution of Proton GCR Escaping Flux Tube

Higher-energy proton GCR passing through the flux tube, entering flux sheet

Fraction of proton GCR
penetrate through flux tube

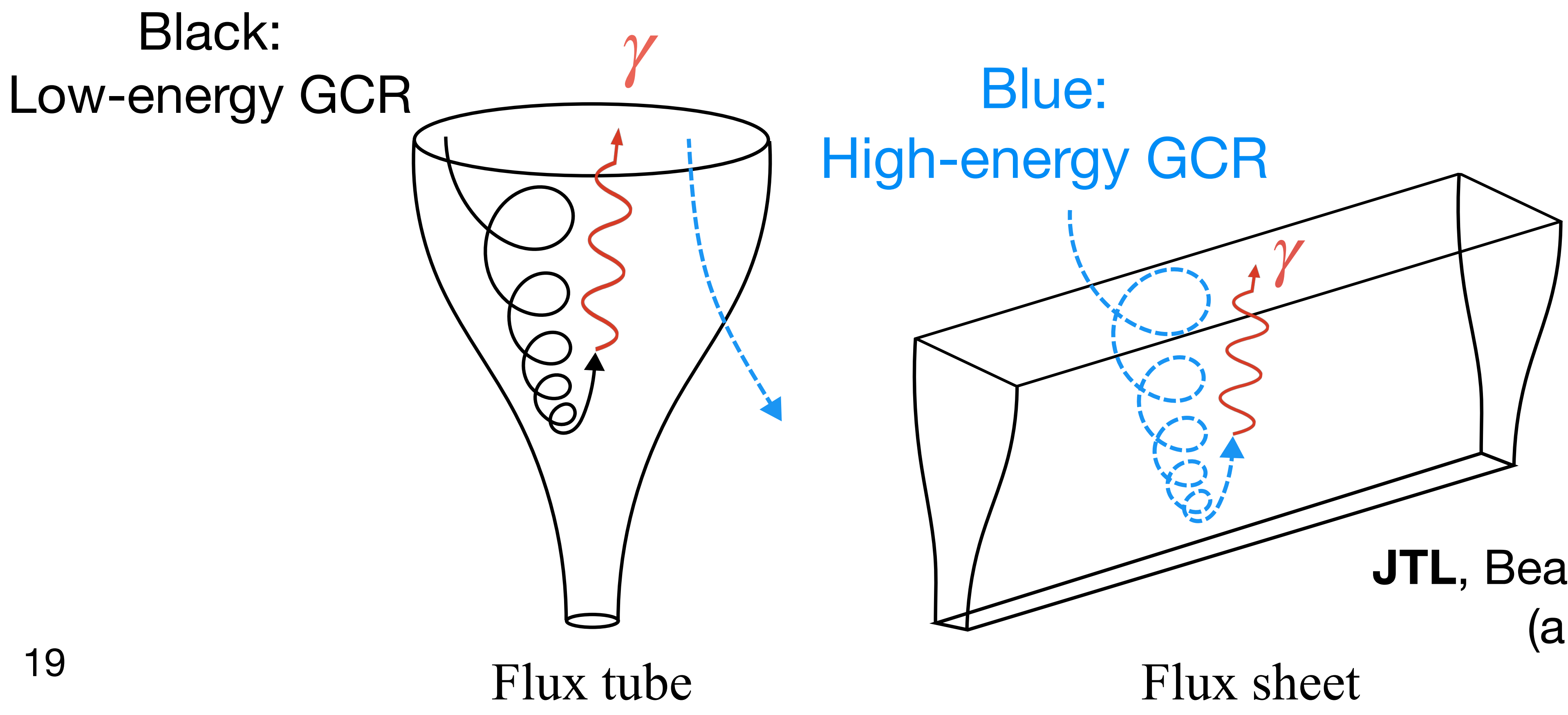


Lower-energy proton GCR bounded by the flux tube

- Angular distribution: fraction of pGCR passing through flux tube, entering into flux sheet

- Low energy GCRs are tightly bounded by magnetic field lines in the tube
  - Cannot penetrating through tube

- High-energy GCRs are NOT bounded by magnetic field lines in the tube
  - Penetrating through tube, entering into internetwork regions (sheets)



JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

Calculation of Gamma-Ray Emission

- Main gamma-ray production channel: $p + p \to p + p + \pi^0, \qquad \pi^0 \to \gamma + \gamma$

- Gamma-ray flux

$$\frac{dN_\gamma}{dE_\gamma} = \int_{\Omega_0}\int_{E_\gamma}^{\infty}\int_0^{\bar{\chi}_p} F_\gamma\left(E_\gamma, E_p\right)\ \Phi_p\left(E_p\right)\cos\theta_0\ \frac{dP_{\mathrm{abs}}\left(\chi_p, E_p\right)}{d\chi_p}\ \zeta\left(\boldsymbol{r}\right)\ d\chi_p\,\frac{dE_p}{E_p}\,d\Omega_0$$

GCR measurement at 1 AU
AMS02 + CREAM

Gamma rays transmitted
out from the solar gas

$$\frac{dN}{dE_\gamma} \sim (\#\ \text{of}\ \gamma\ \text{per interaction}) \times (\text{GCR flux}) \times (\text{GCR absorption prob.}) \times (\gamma\ \text{transmission prob.})$$

Gamma-ray yield only
available for $E_\gamma \gtrsim 3\ \mathrm{GeV}$
In the literature

Kelner et al 2006
(PRD **74**, 034018)

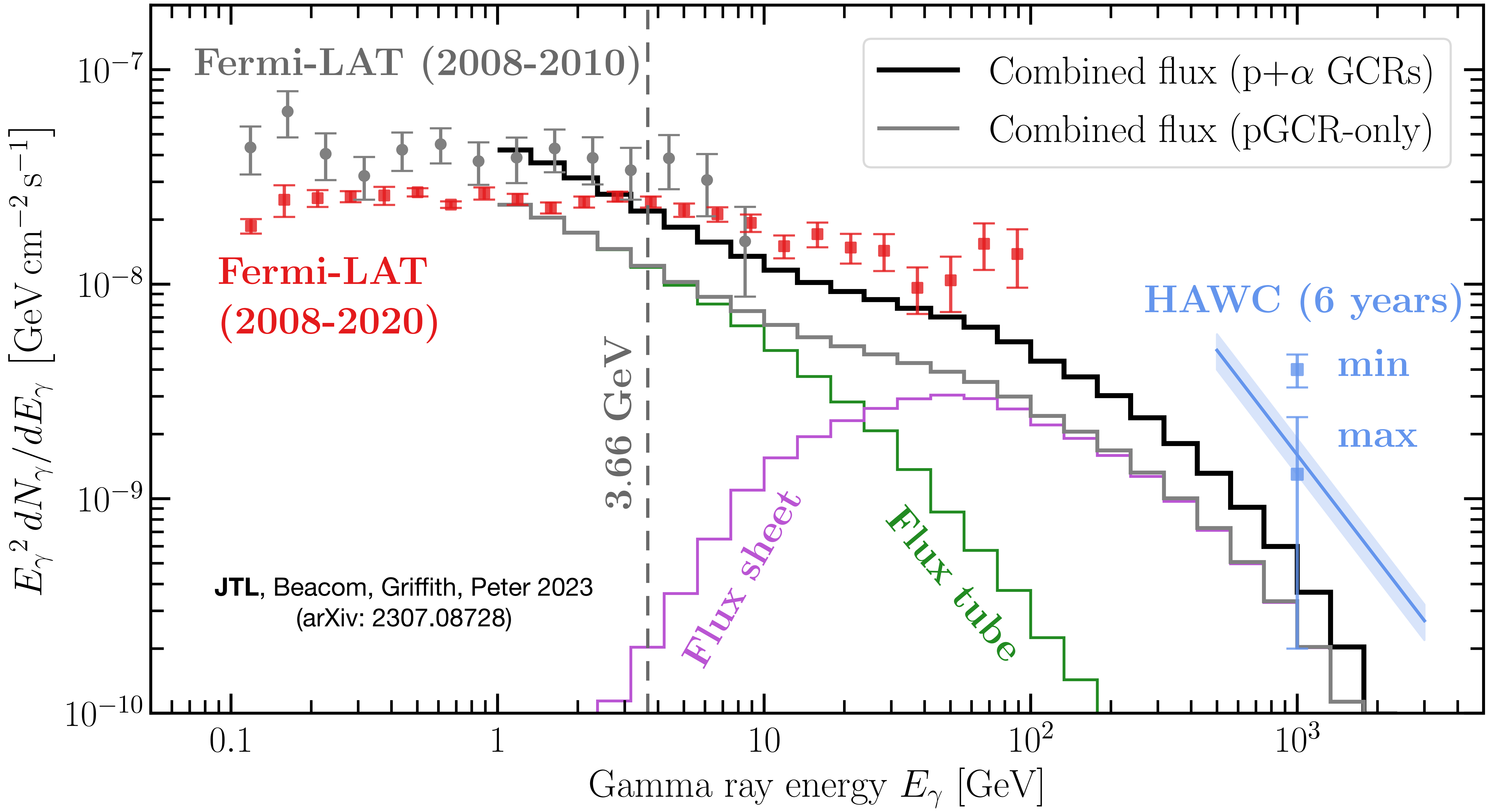
Numerical calculation of
GCR trajectory

Our Result: Gamma-Ray Spectrum

- Lower-energy ($\lesssim 10\ \mathrm{GeV}$) gamma rays are produced from flux tube (forming the network element)

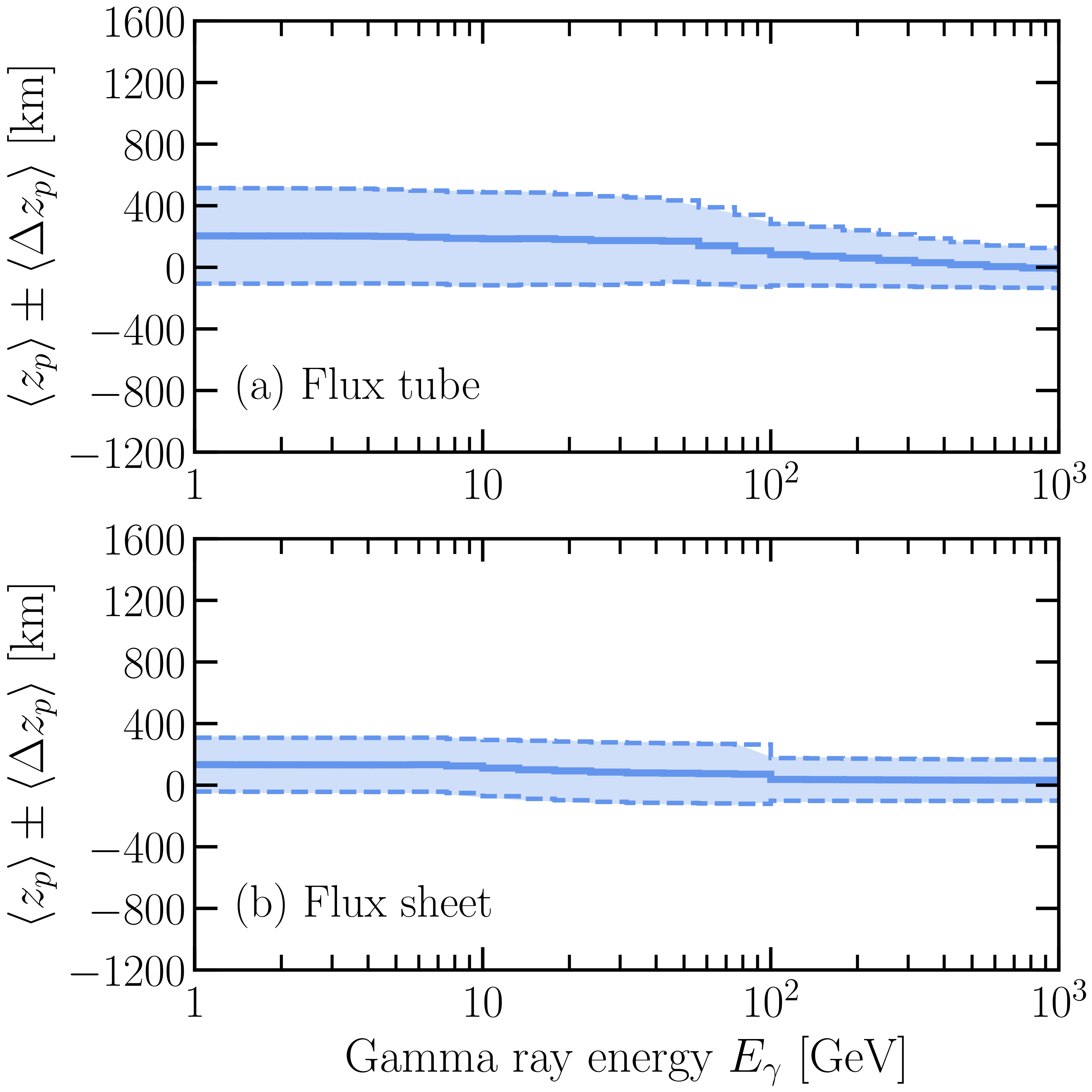
- Mid-energy ($1\ \mathrm{GeV} \lesssim E_\gamma \lesssim 100\ \mathrm{GeV}$) gamma rays are produced from the combination of flux tube and flux sheet
  - — Convective cell plays critical role!

- Higher-energy ($\gtrsim 100\ \mathrm{GeV}$) gamma rays produced from flux sheet (between granular convective cells)
  - — GCR isotropically bombard internetwork regions



JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

Average Emission Height



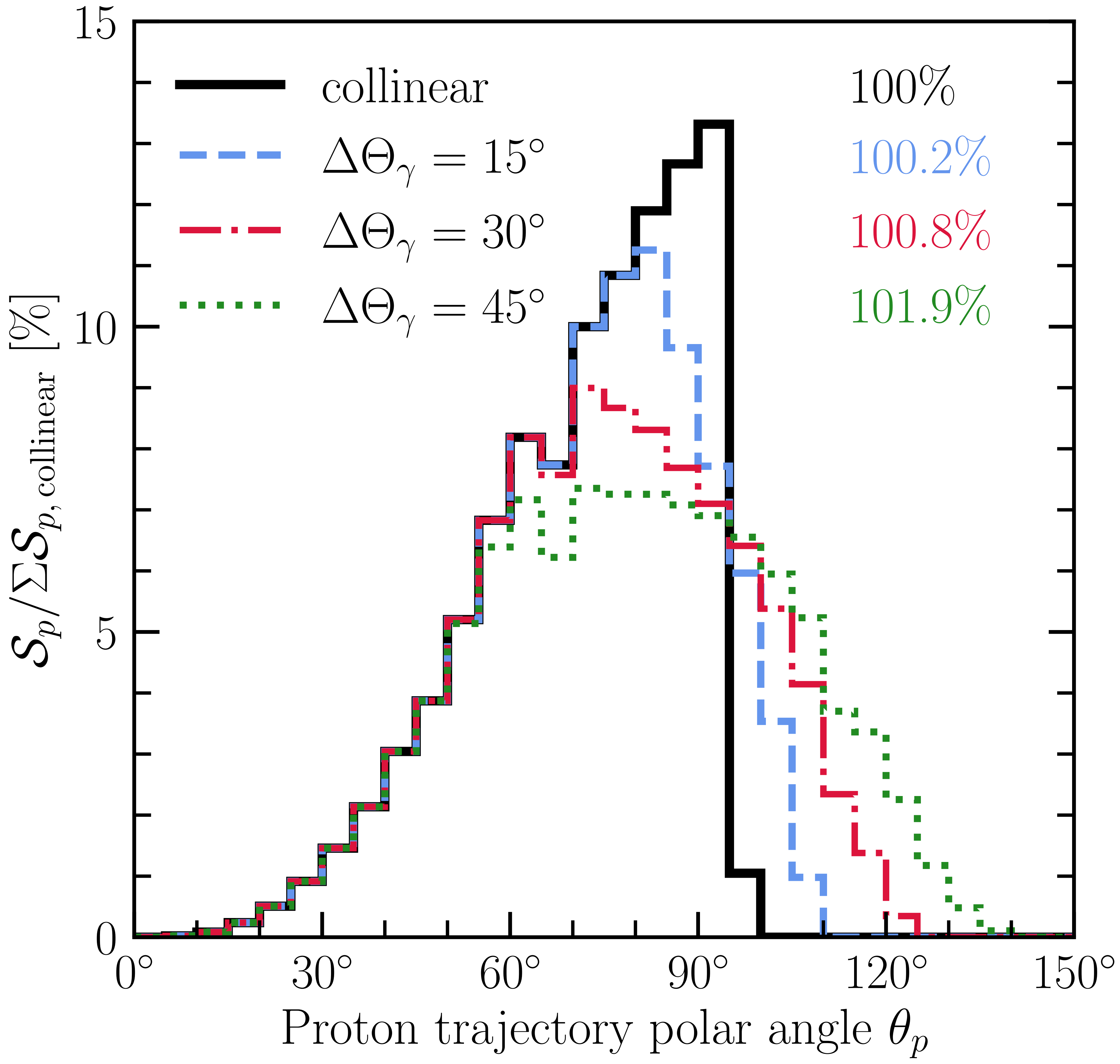
- Emission occurs primarily in the chromosphere, photosphere, and upper-most convection zone (~100 km)

JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

Conclusions and Outlook

- A simple model consisting of one tube and one sheet
    - Gamma-ray observation data is explained reasonably well (within a factor 2)
    - Ineffectiveness of capturing high-energy GCRs causes the steep gamma spectrum at ~ TeV (HAWC)
- What causes the anti-correlation between gamma-ray flux and solar cycle?
    - Coronal holes? Active regions? Small-scale dynamo? GCR transport?
- How does turbulence from the convective flow affect GCR transport in the photosphere and uppermost convection zone?

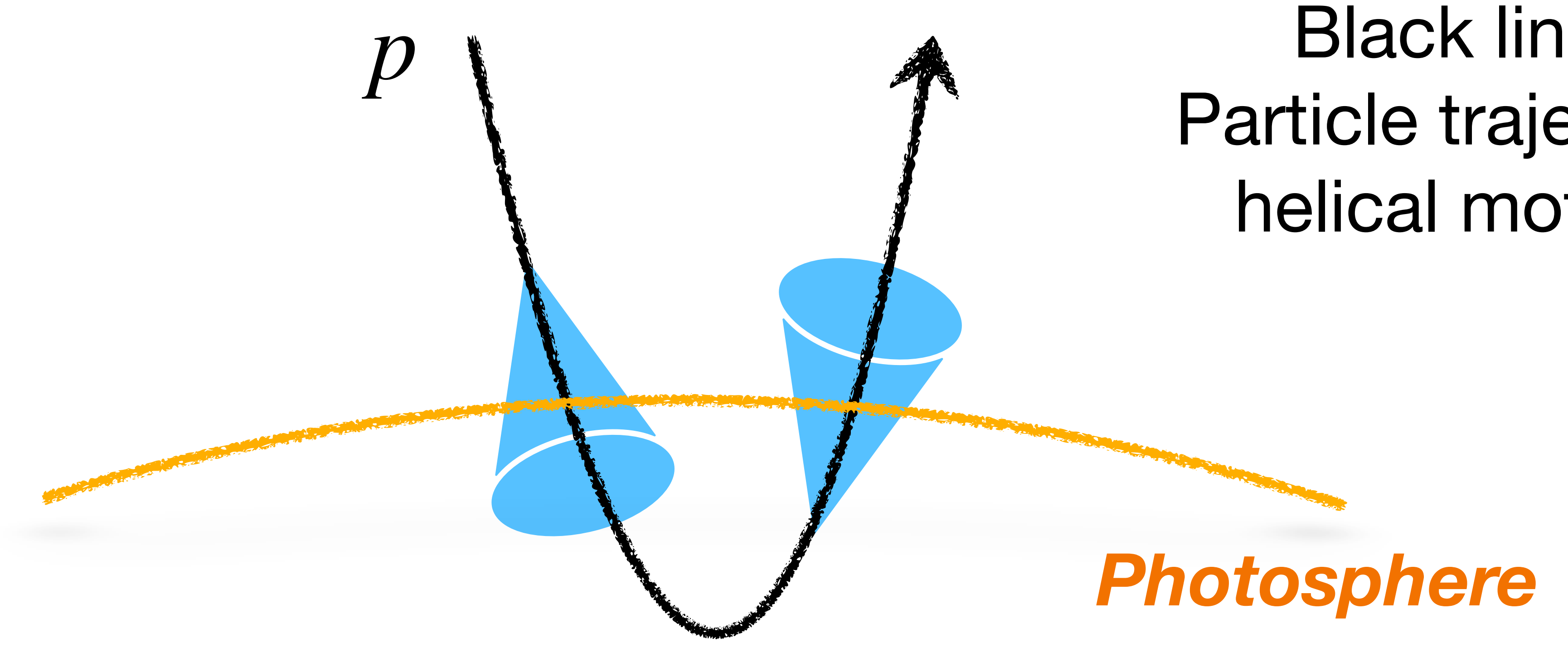
Finite-Sized Emission Cone (*for each pp interaction*)



$$\mathcal{S}_p = \int_0^{\bar{\chi}_p} \frac{dP_{\mathrm{abs}}\left(\chi_p, E_p\right)}{d\chi_p} \; \zeta(\mathbf{r}) \; d\chi_p$$

= proton GCR absorption probability

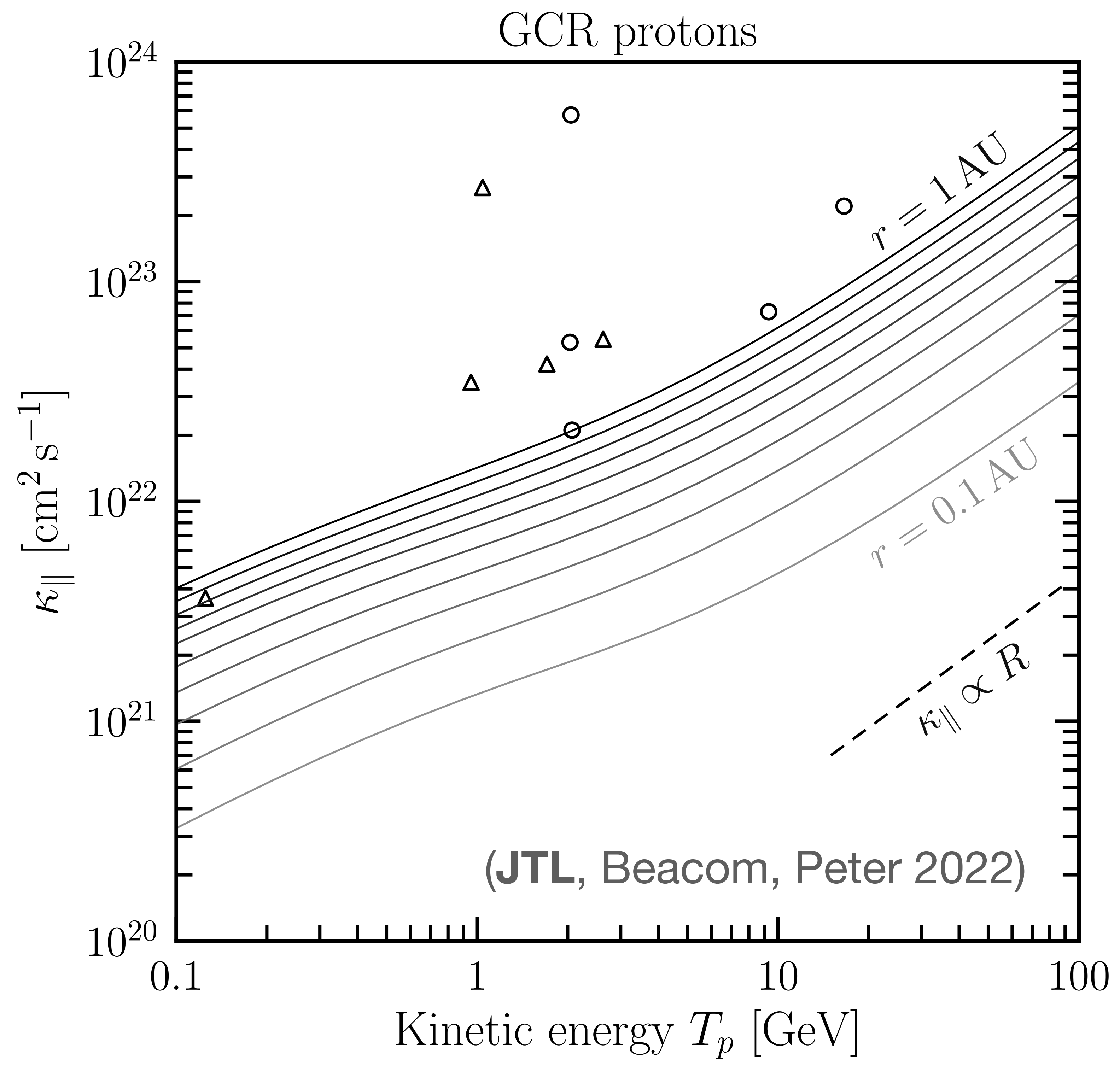
× gamma absorption probability

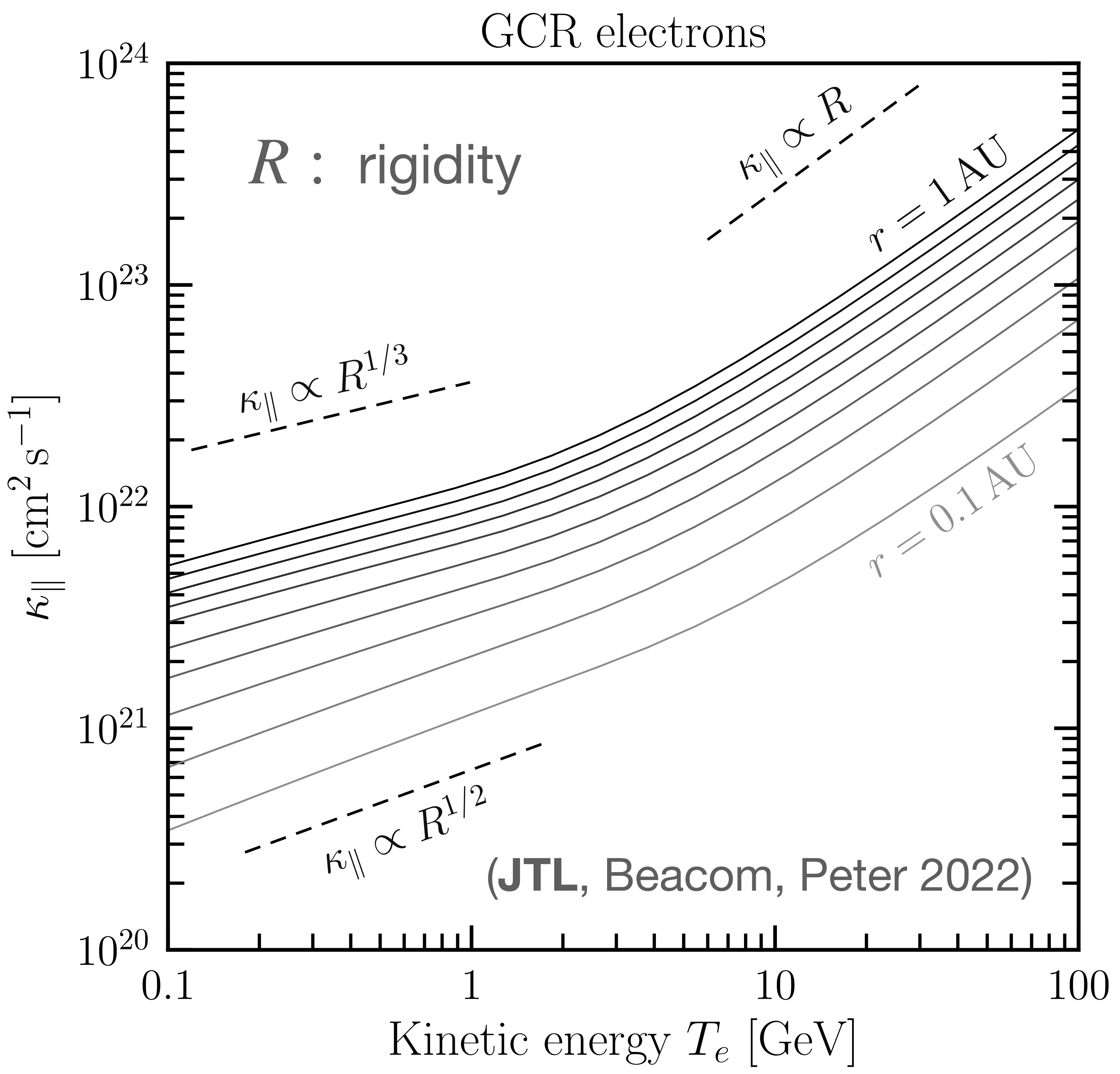


Black line:
Particle trajectory
helical motion

JTL, Beacom, Griffith, Peter 2023
(arXiv: 2307.08728)

Diffusion Coefficients



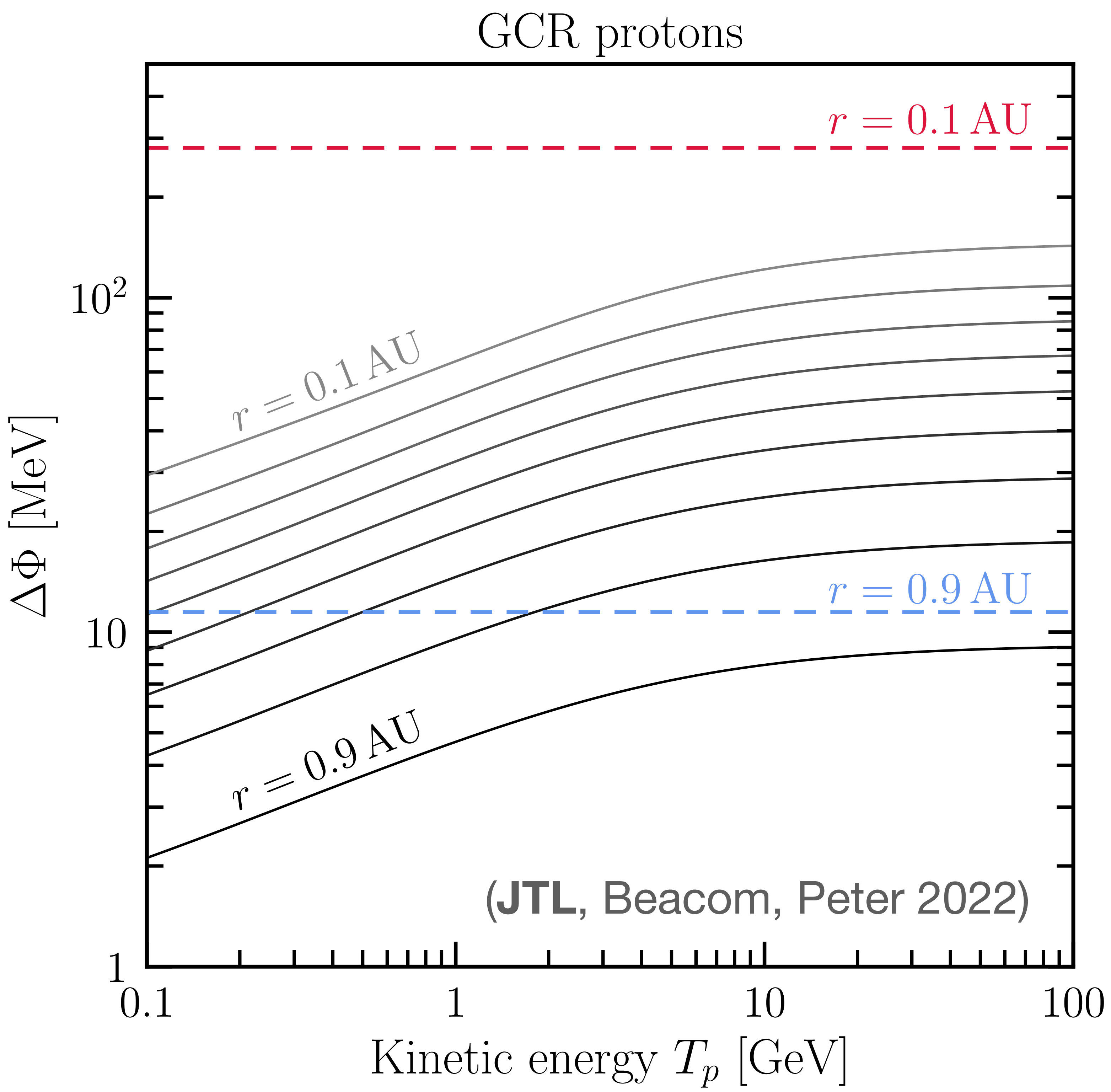


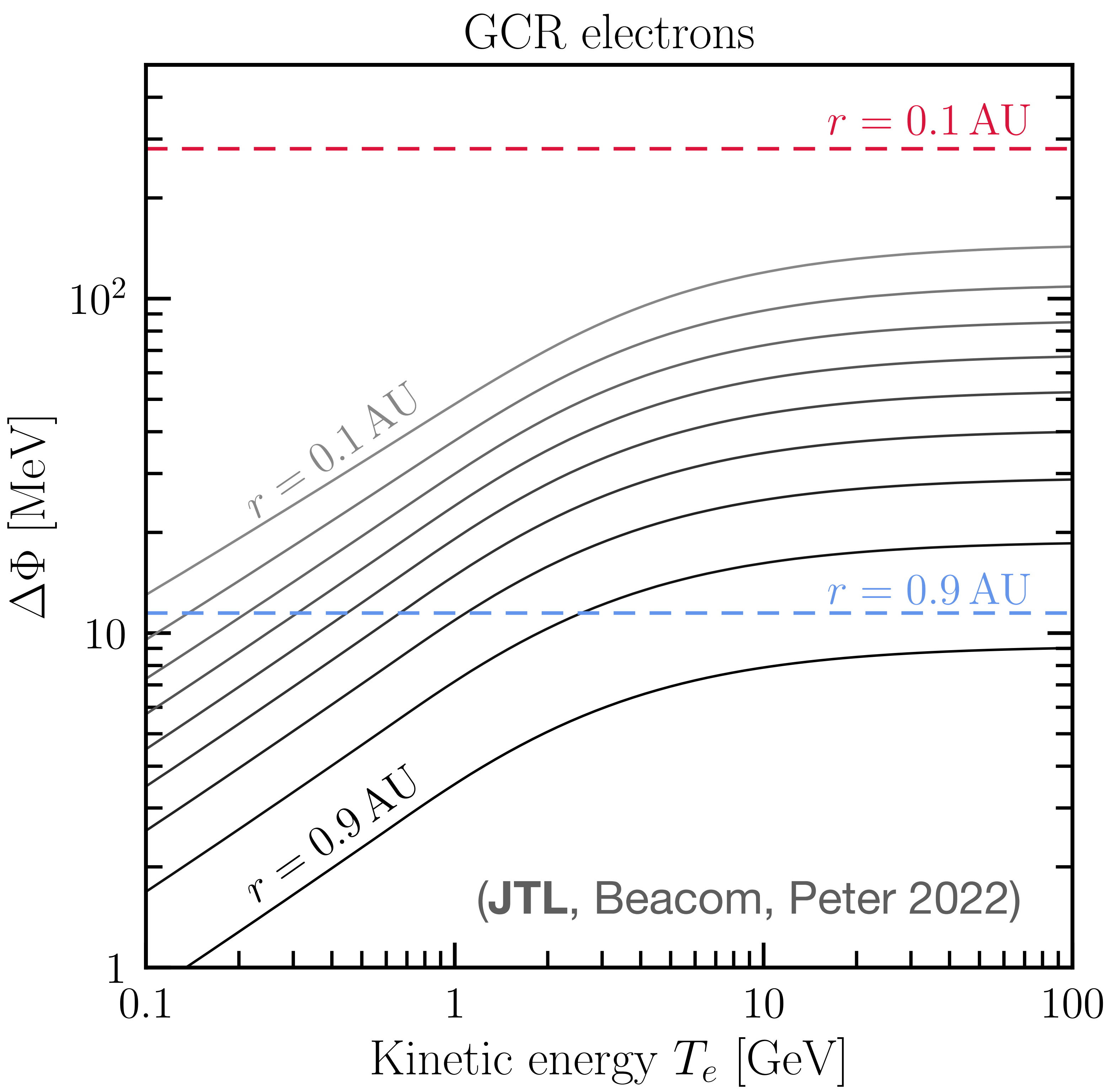
Circle and triangle: measurements of CR proton, from Palmer 1982

Measured mean free path is approximately 2 times
higher than QLT result, known as Palmer consensus

JTL, Beacom, Peter 2022
ApJ 937, 27

Modulation Potential Energy





Small modulation potential increase for $E_{\mathrm{kin}} \lesssim 10\ \mathrm{GeV}$

Magnetic spectrum ($1/f$ v.s. inertial range) matters

JTL, Beacom, Peter 2022
ApJ 937, 27