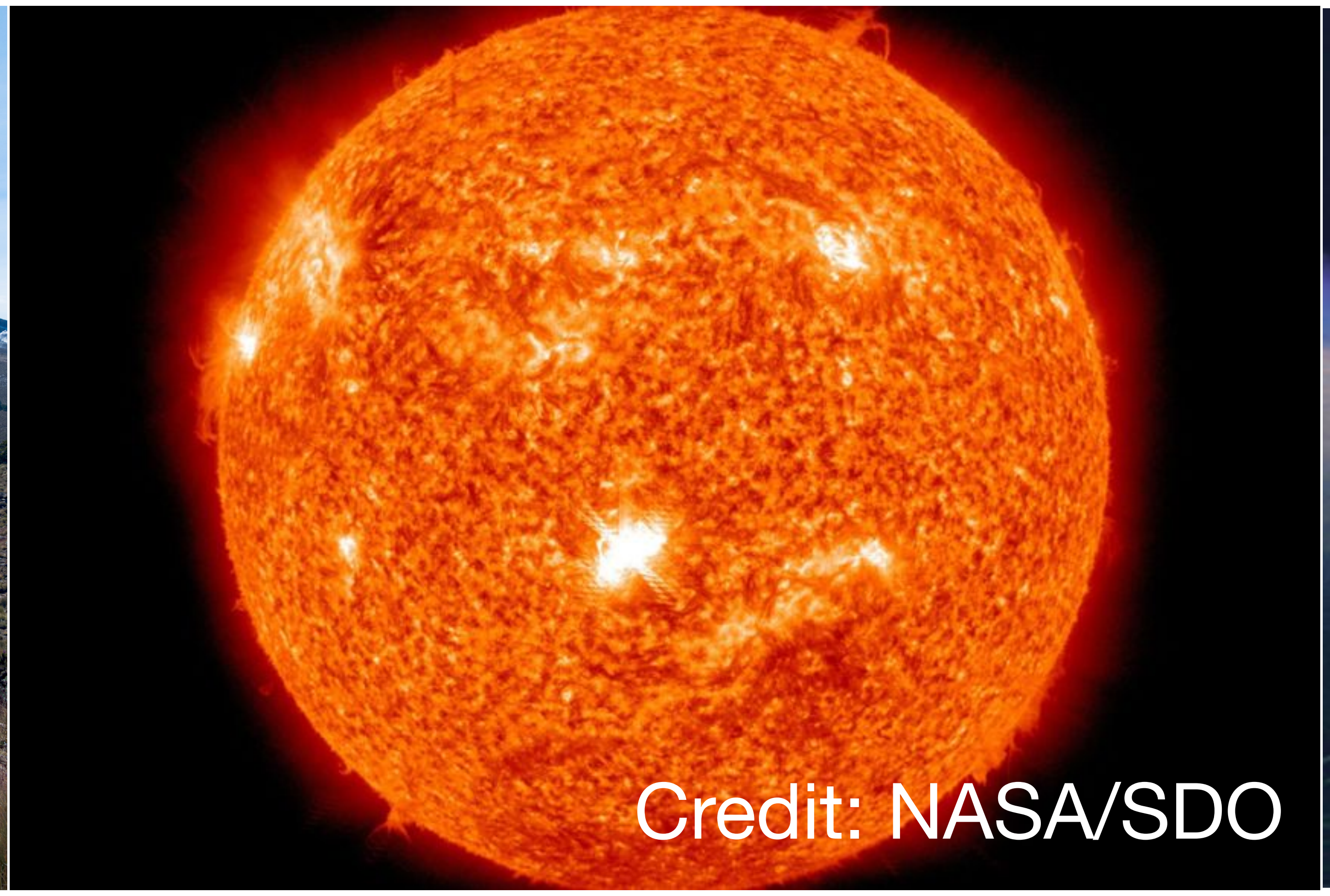
The Solar Gamma Rays as A New Probe of Solar Magnetism



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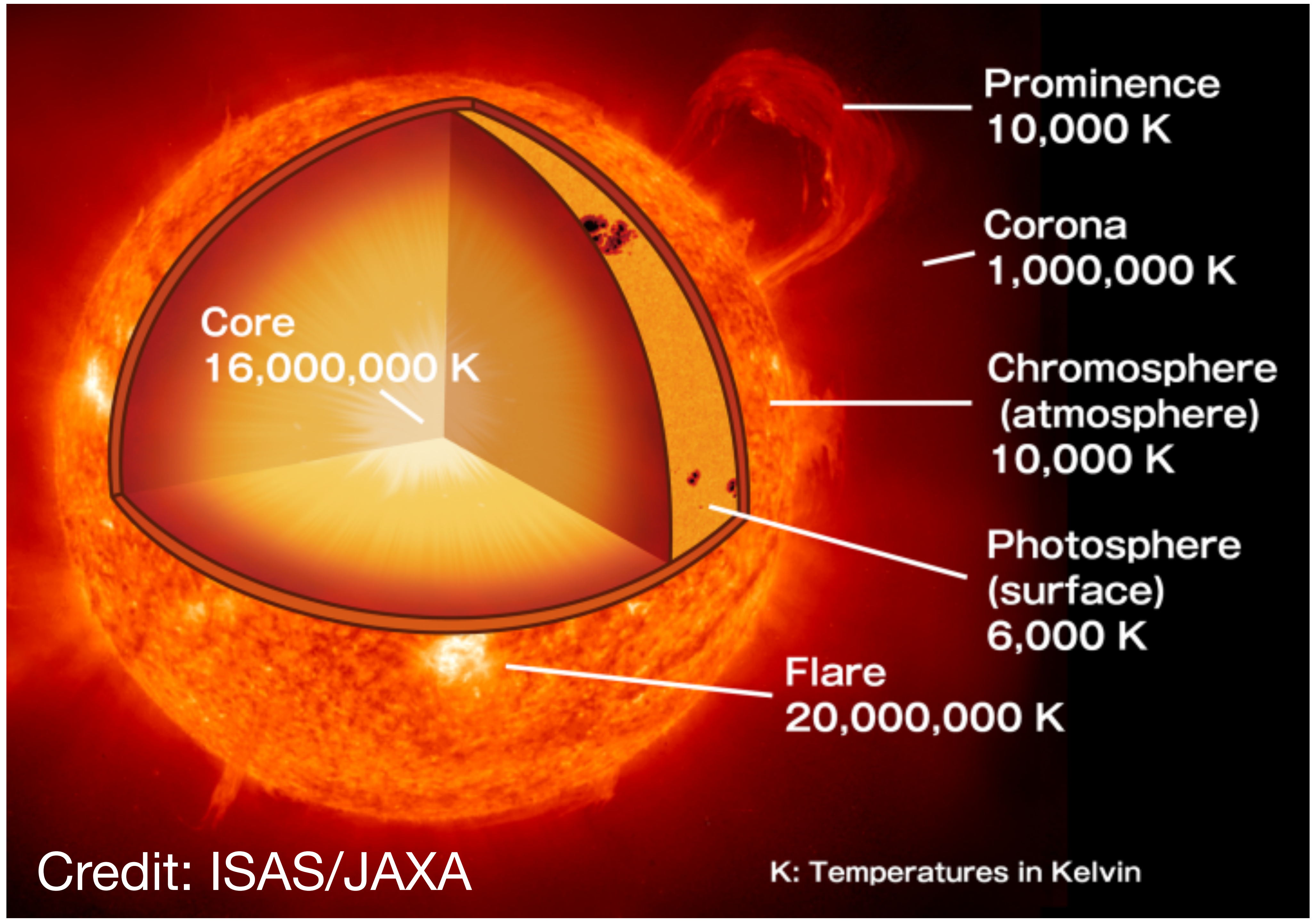
THE OHIO STATE UNIVERSITY

Why are *continual* GeV-TeV gamma rays surprising?

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



- Photosphere & chromosphere is 6,000-10,000 Kelvin, visible light (~1 eV)
- Corona is million Kelvin, EUV and X-ray ($\lesssim 1$ keV)
  - Wave-driven turbulence and reconnection
- Large solar flares produce nonthermal particles and gamma rays up to few GeV
  - Transient signal — can be removed from data

How does the Sun produce gamma rays?

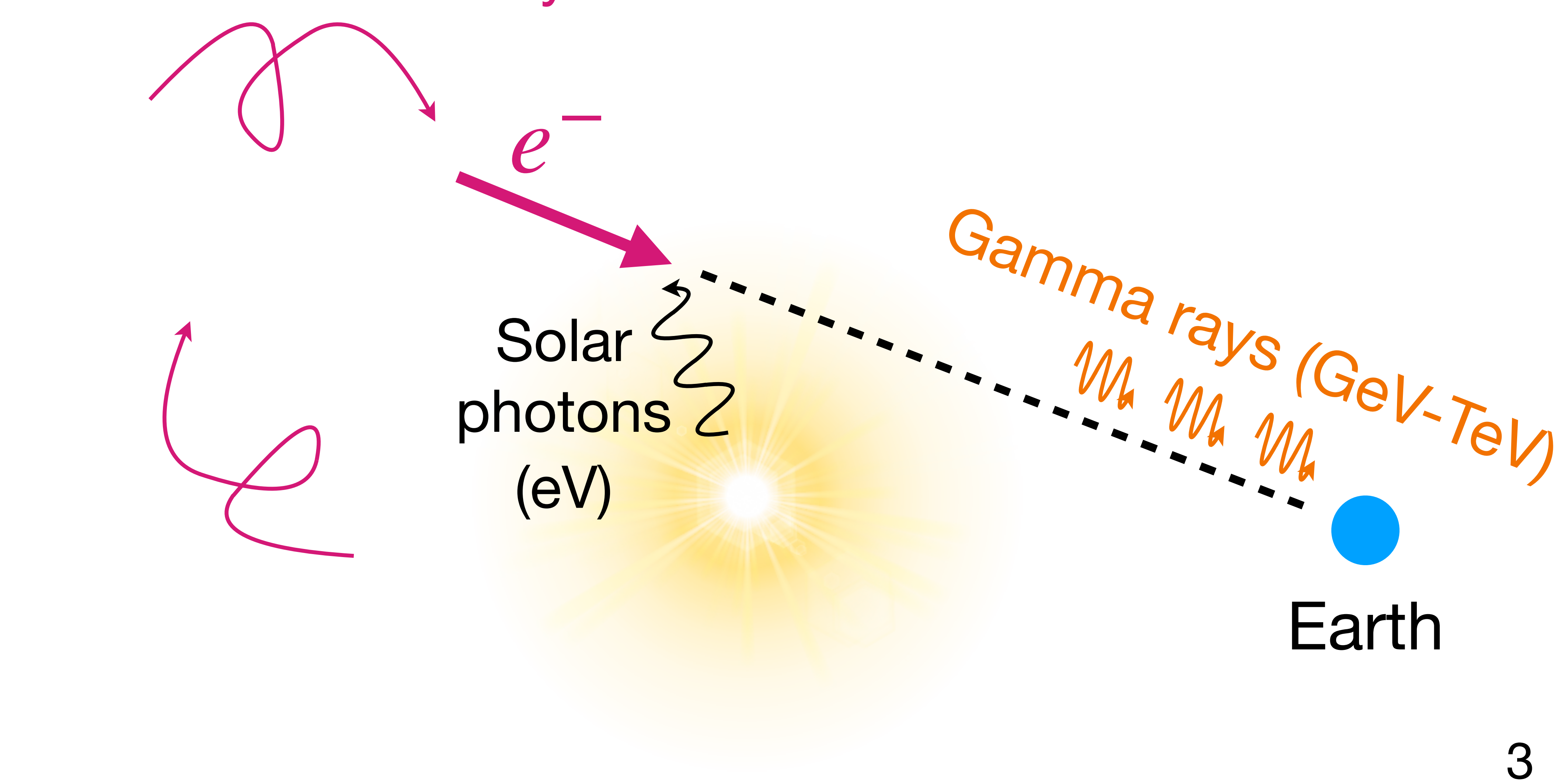
From galactic cosmic-ray (GCR) **bombardment**!

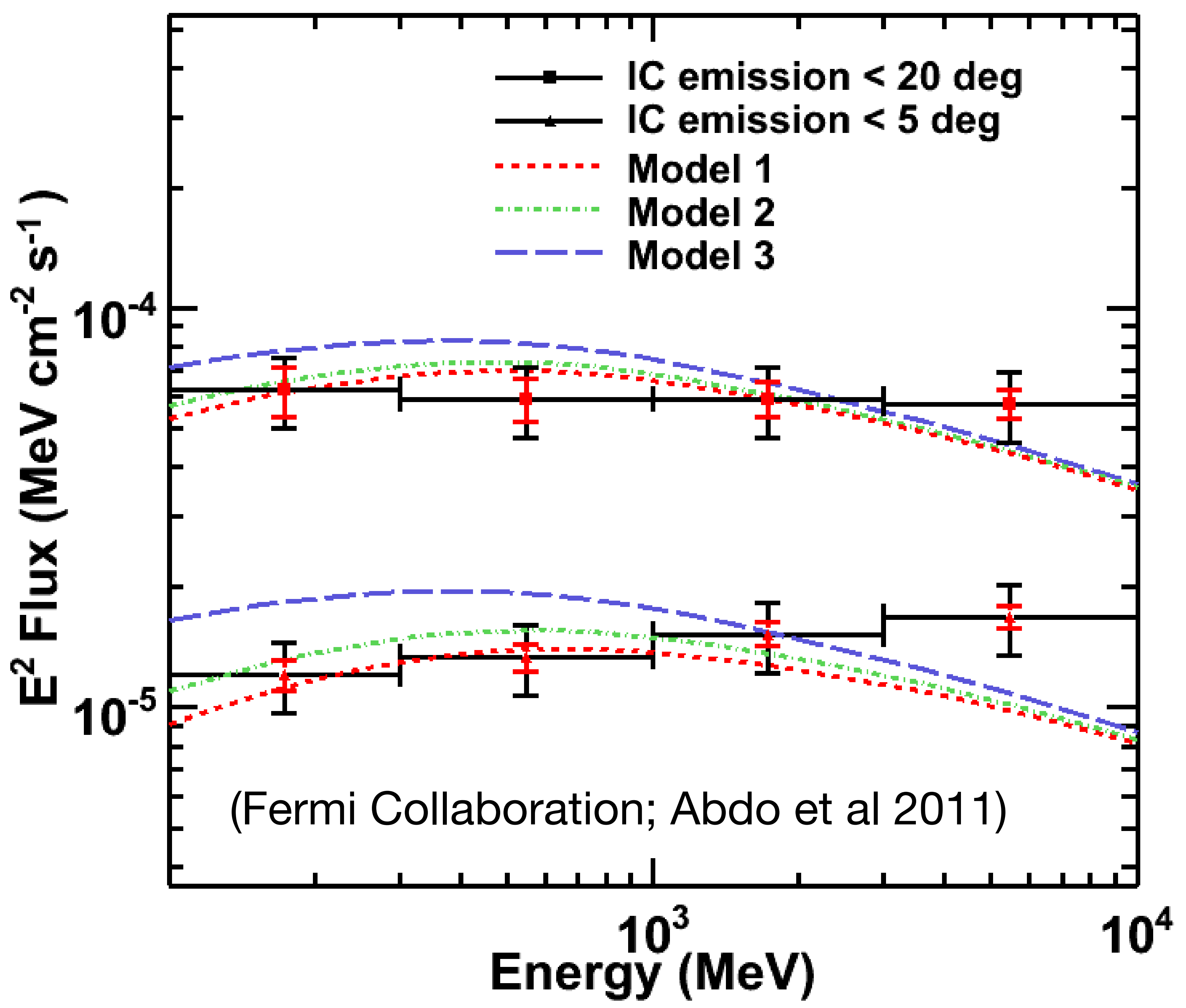
Continual gamma rays from solar halo *(Not the focus of this talk)*

Inverse-Compton scattering in the solar halo

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

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





Potentially a new way to probe electron cosmic ray transport in the inner heliosphere

Linden, **JTL**, + (in preparation)

Continual gamma rays from solar disk

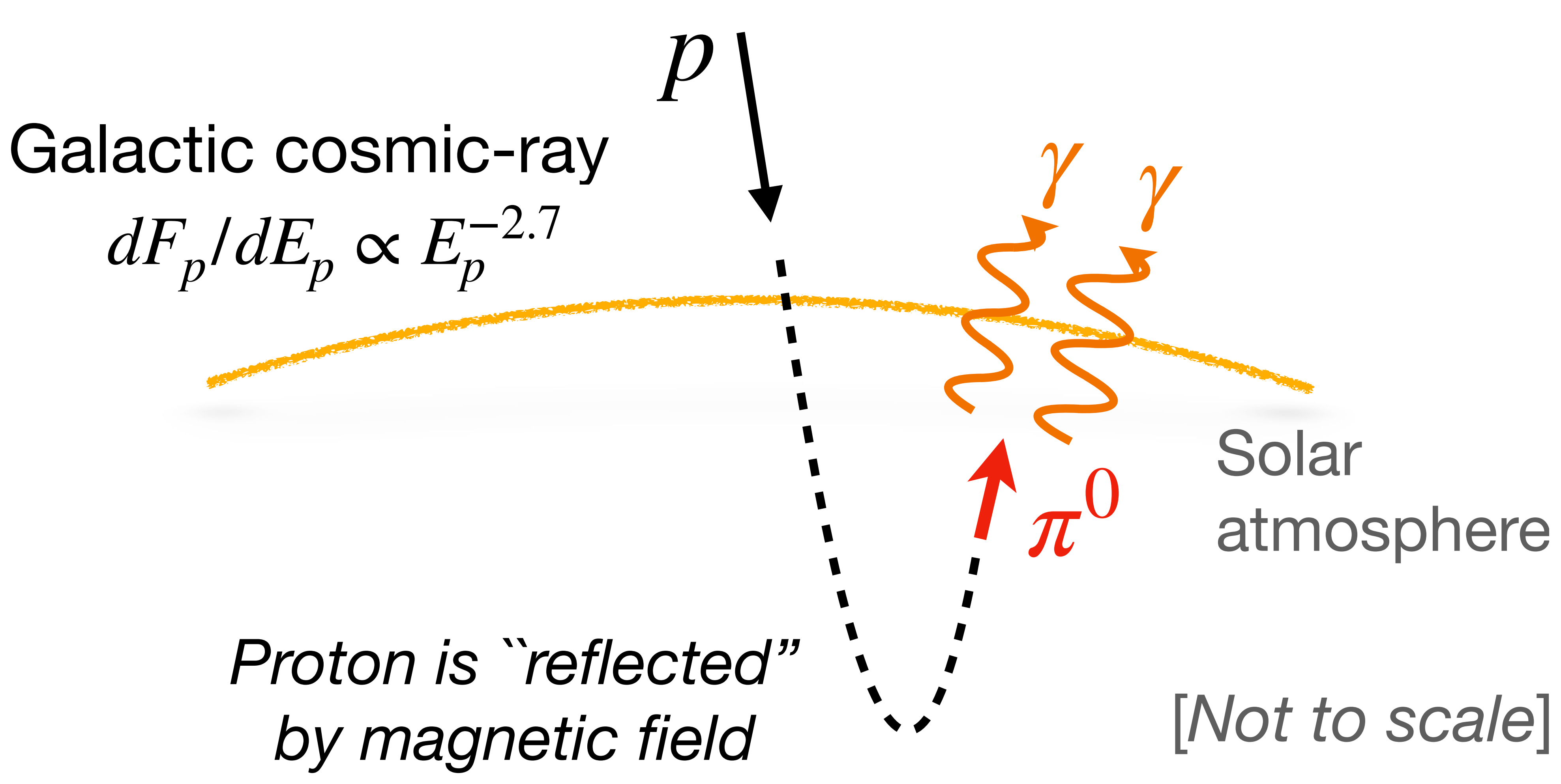
Focus of this talk!

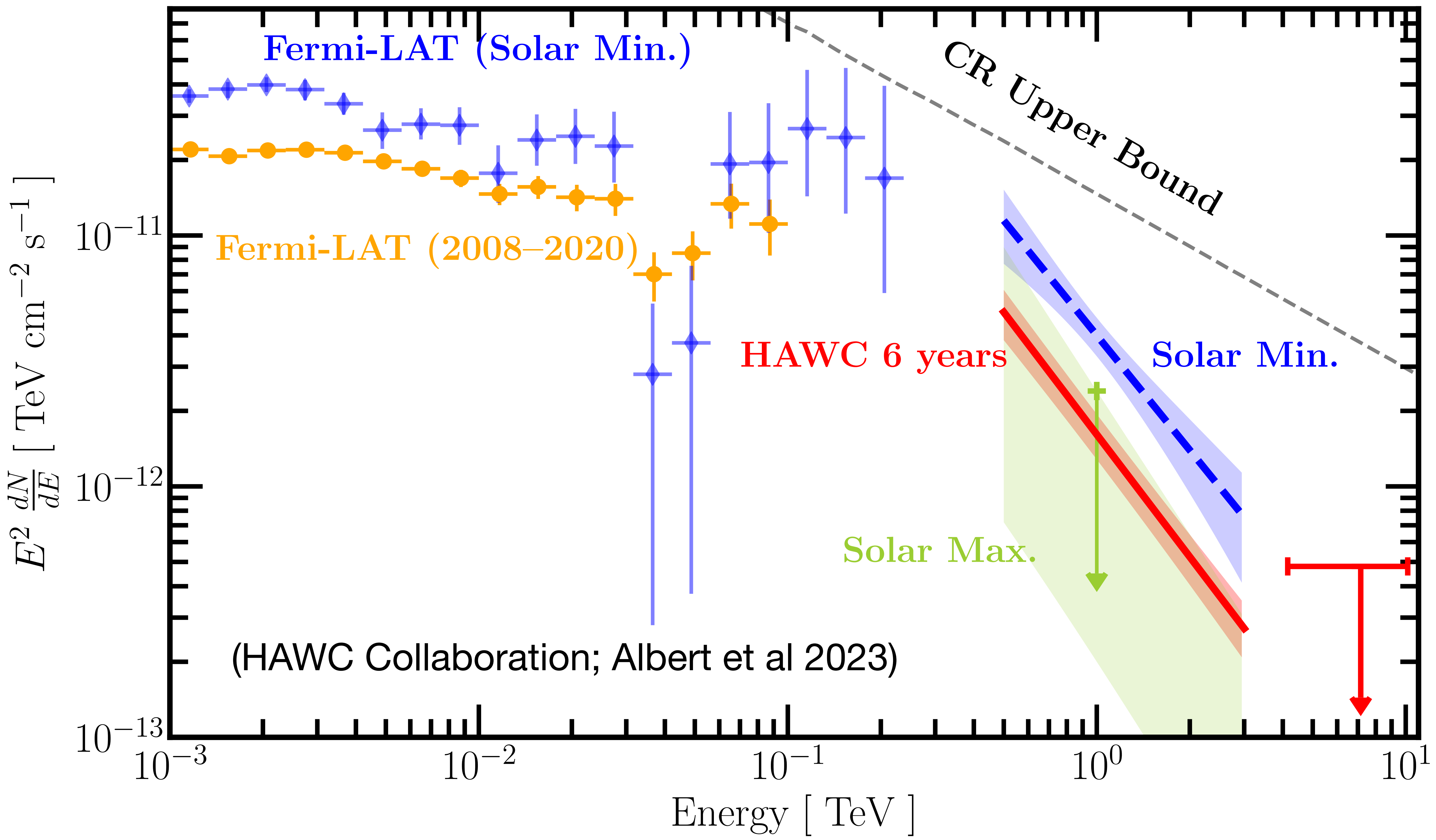
Hadronic scattering

in the solar disk

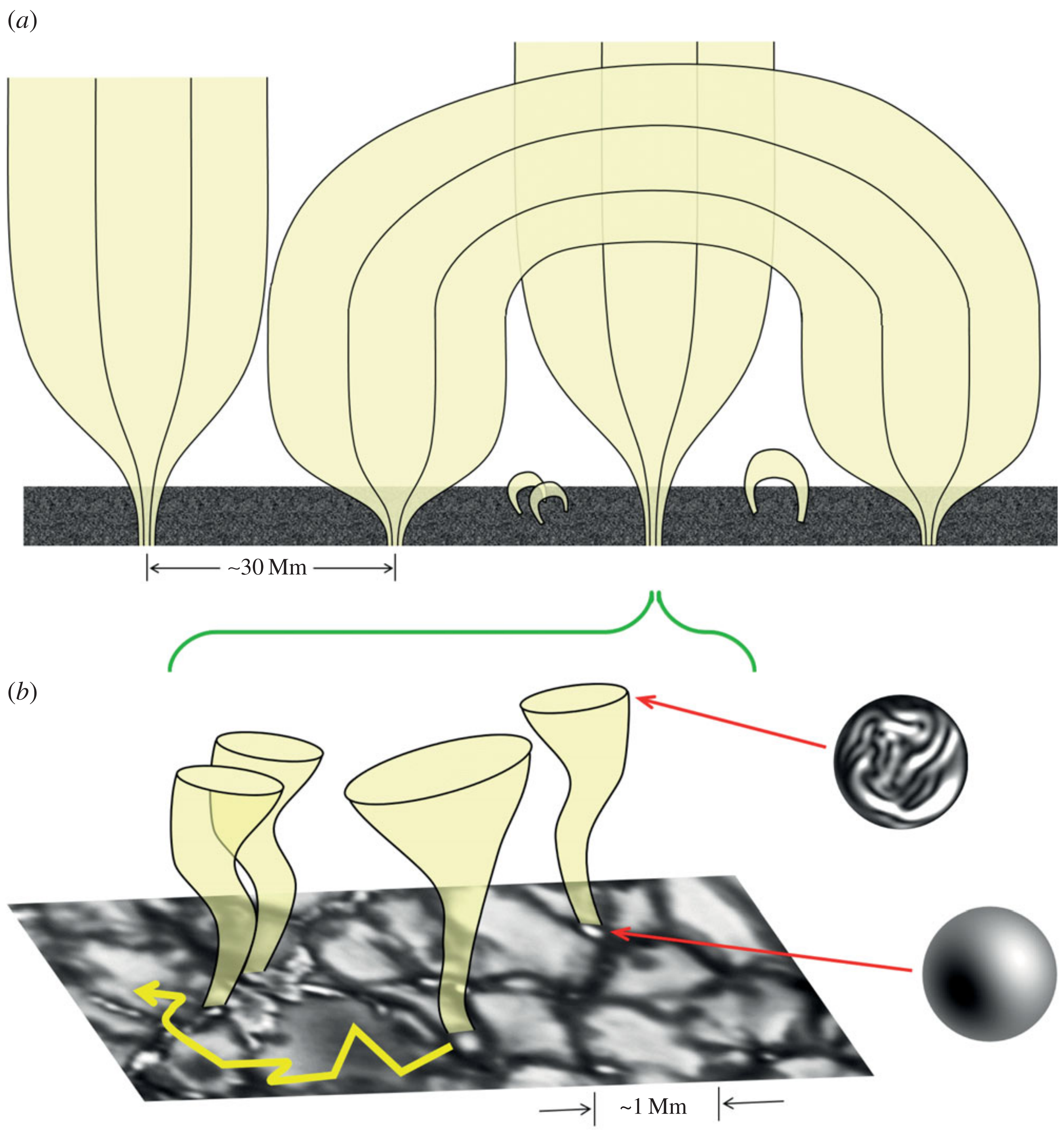
$$p + p \rightarrow p + p + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

(See Seckel, Stanev & Gaisser 1991)





What needs to be answered? (#1)

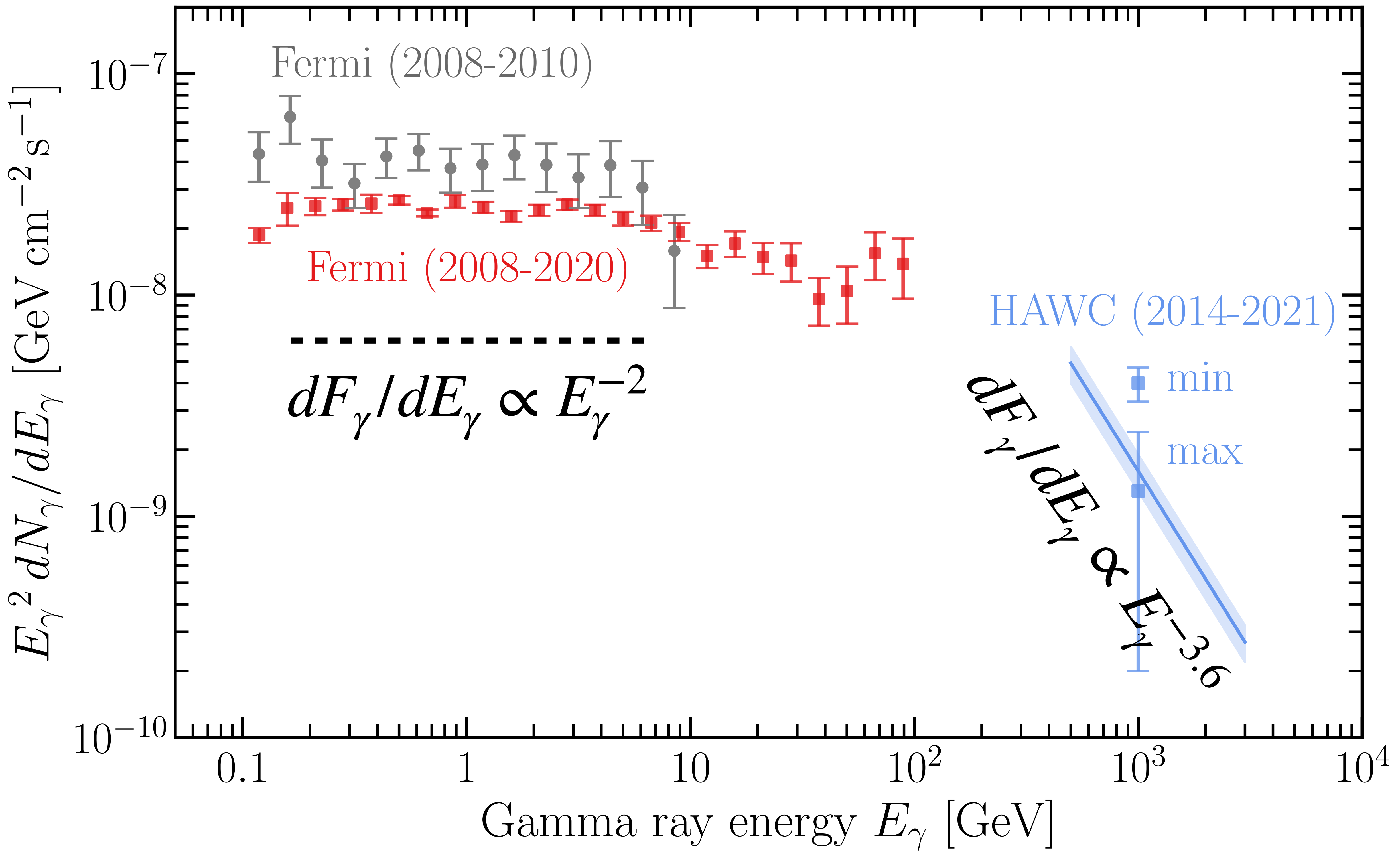


Credit: Cranmer et al. 2015

1. Solar magnetic field is multi-scale, how do we think this problem? Today ✔
2. Spectral shape:
   - Hard spectrum $\sim E_\gamma^{-2}$ below 200 GeV
   - Soft spectrum $\sim E_\gamma^{-3.6}$ at ~ 1 TeV
3. Anti-correlation between gamma-ray flux and solar cycle
4. Anisotropic emission:
   1. Polar flux: relatively constant across solar cycle
   2. Equatorial flux: anti-correlate with solar cycle

What needs to be answered? (#2)

** *Galactic cosmic-ray proton* $dF_p/dE_p \propto E_p^{-2.7}$



1. Solar magnetic field is multi-scale, how do we think this problem? Today ✔
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   - Hard spectrum $\sim E_\gamma^{-2}$ below 200 GeV Today ✔
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3. Anti-correlation between gamma-ray flux and solar cycle
4. Anisotropic emission:
   1. Polar flux: relatively constant across solar cycle
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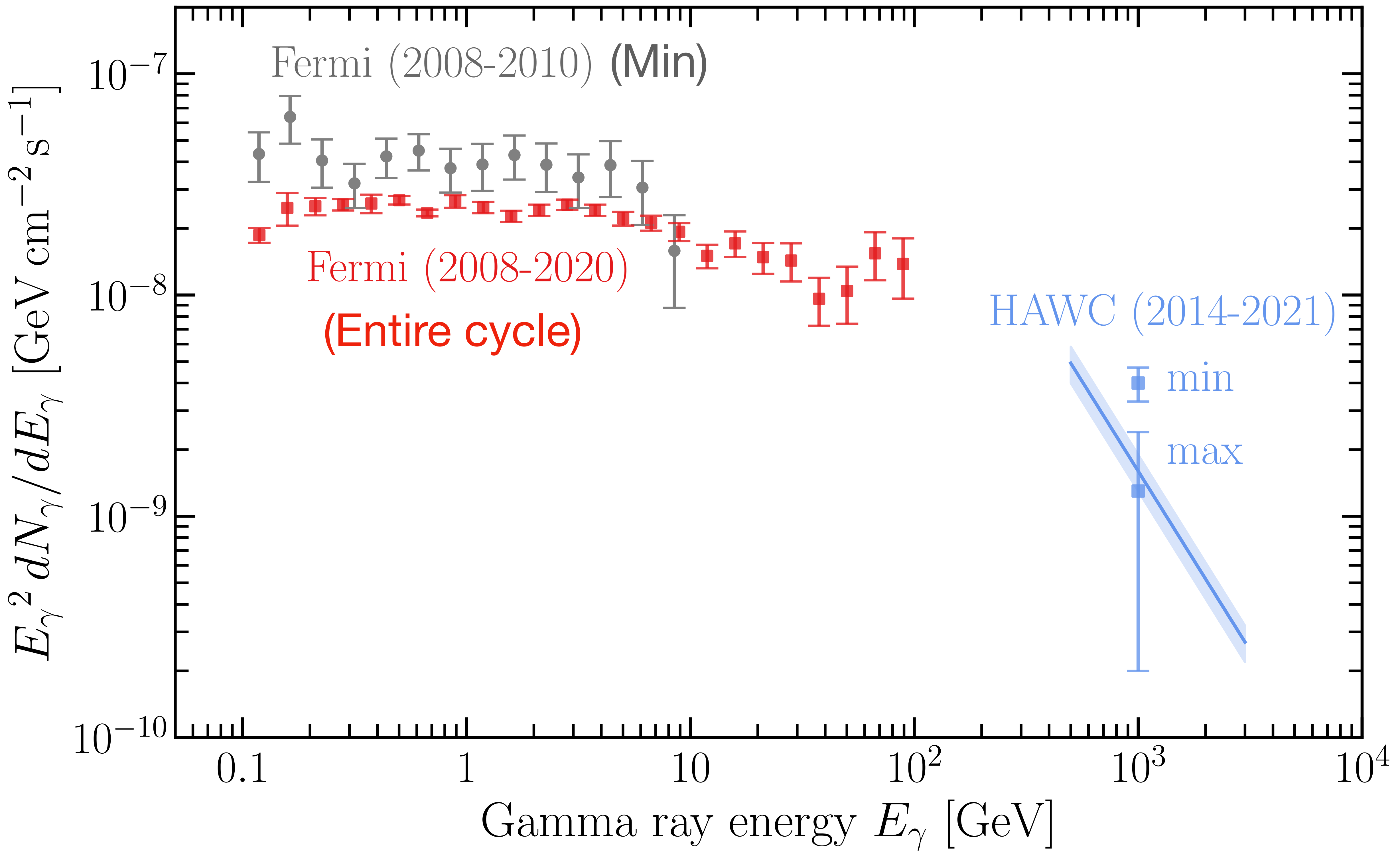
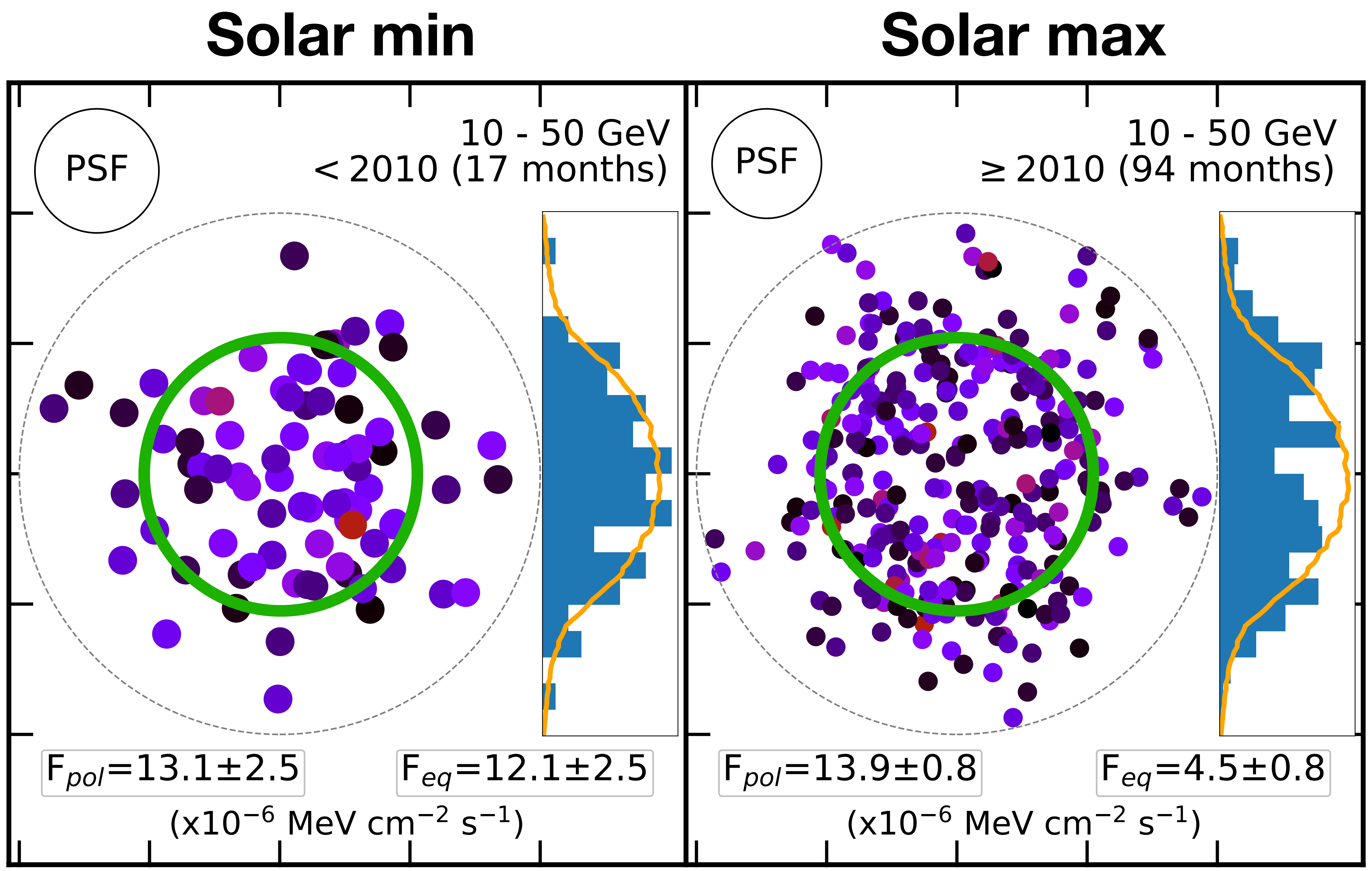
What needs to be answered? (#3)



1. Solar magnetic field is multi-scale, how do we think this problem? Today ✓
2. Spectral shape:
   - Hard spectrum $\sim E_\gamma^{-2}$ below 200 GeV Today ✓
   - Soft spectrum $\sim E_\gamma^{-3.6}$ at ~ 1 TeV Today ✓
3. Anti-correlation between gamma-ray flux and solar cycle *Unknown*
4. Anisotropic emission:
   1. Polar flux: relatively constant across solar cycle
   2. Equatorial flux: anti-correlate with solar cycle

What needs to be answered? (#4)



** Green circle: Solar disk

** Dotted circle: 0.5° region of interest

Credit: Linden et al. 2018

1. Solar magnetic field is multi-scale, how do we think this problem? Today ✓
2. Spectral shape:
   - Hard spectrum $\sim E_{\gamma}^{-2}$ below 200 GeV Today ✓
   - Soft spectrum $\sim E_{\gamma}^{-3.6}$ at ~ 1 TeV Today ✓
3. Anti-correlation between gamma-ray flux and solar cycle *Unknown*
4. Anisotropic emission: *Unknown*
   1. Polar flux: relatively constant across solar cycle
   2. Equatorial flux: anti-correlate with solar cycle

Qualitative: At what depth is $p + p \to \pi^0 \to \gamma + \gamma$ produced?

- Absorption from proton-proton interaction

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

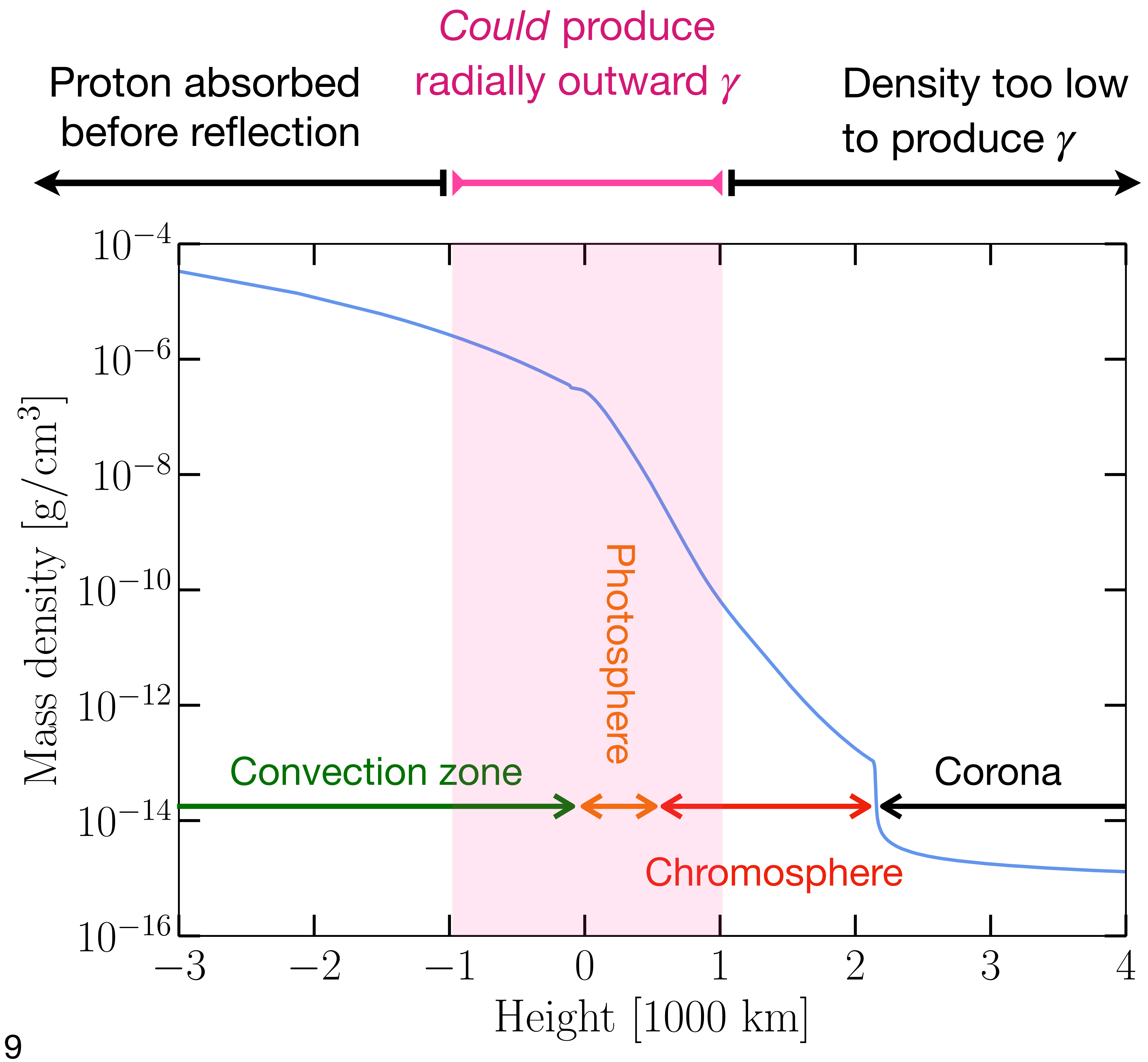
  - Interacting at -1000 km to 1000 km

- Gamma rays from

  Uppermost convection zone

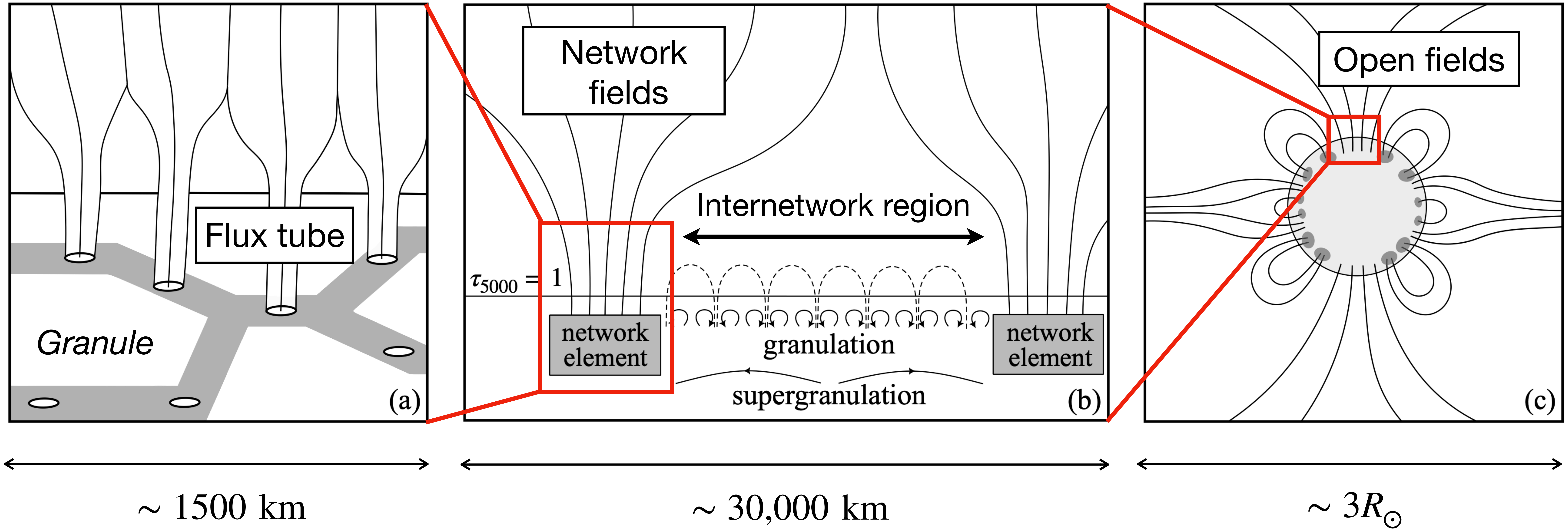
  Photosphere

  Lower chromosphere



Coronal-hole Network Field & Open Field Lines

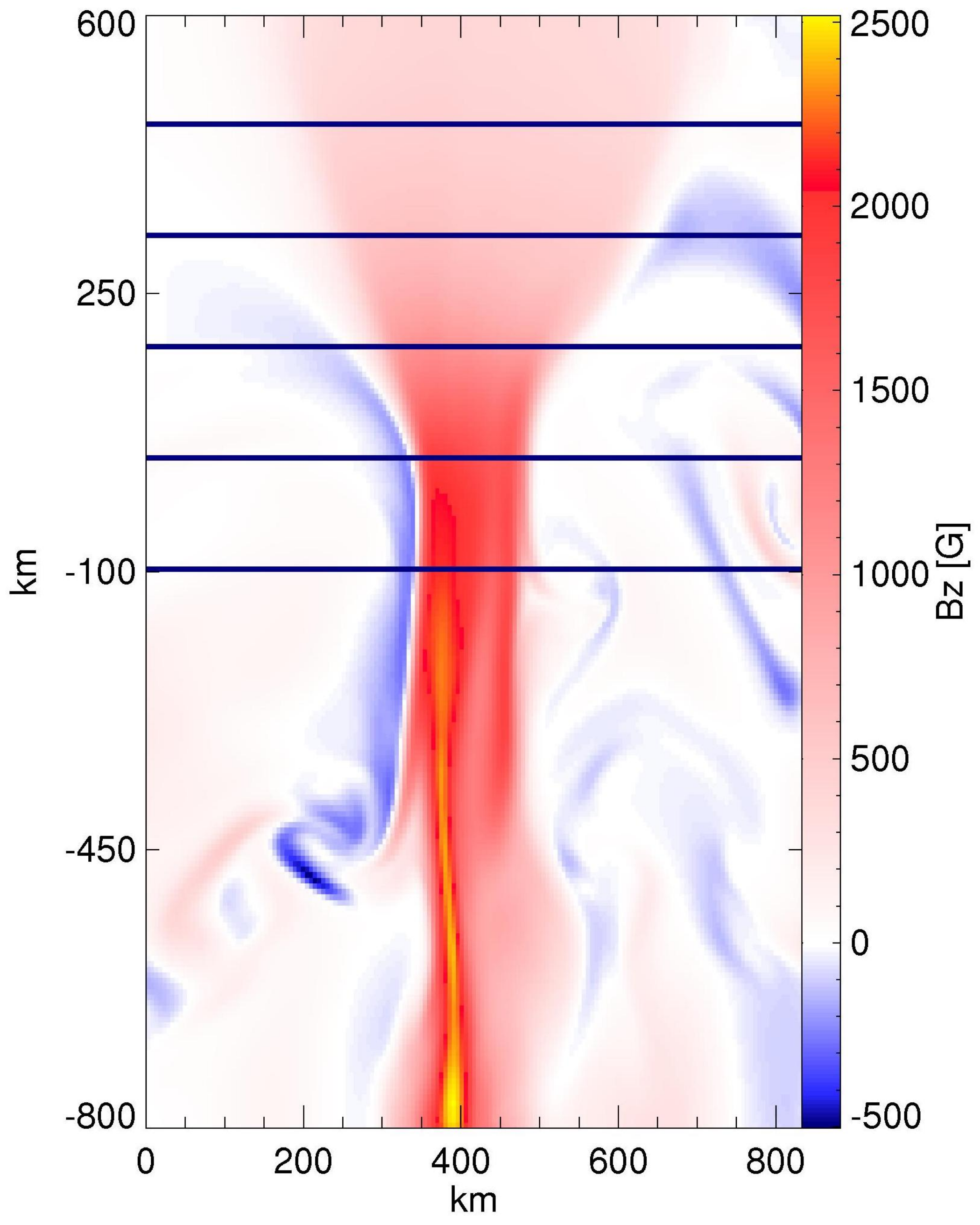
We consider proton cosmic rays following **open** magnetic fields, entering solar surface.



Redrawn illustration from Cranmer & van Ballegooijen 2005 and Wedemeyer-Bohm et al 2008

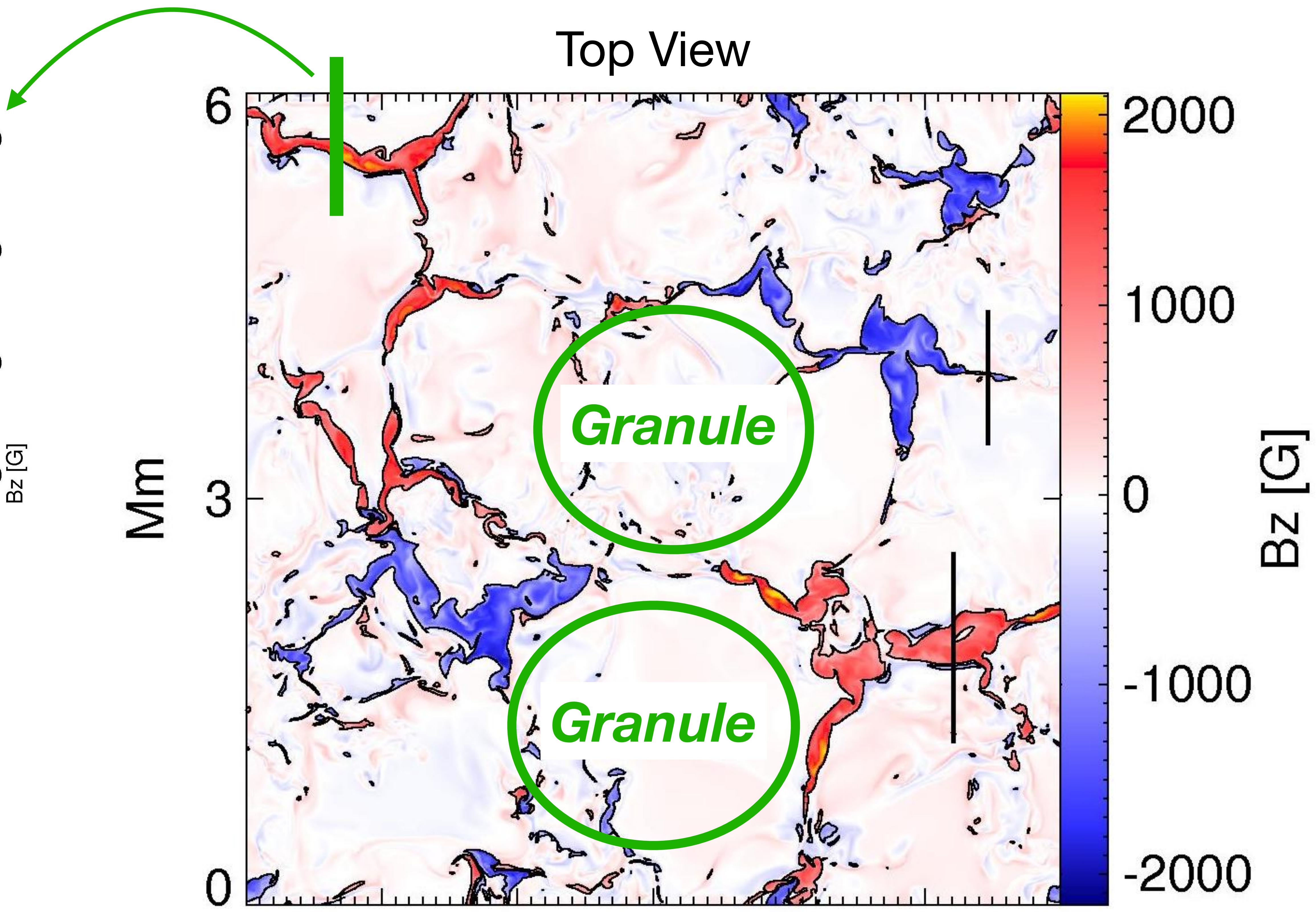
Thin Magnetic Sheets in the Intergranular Lanes

Side View



Yelles et al. 2009
(MURaM simulation)

Top View

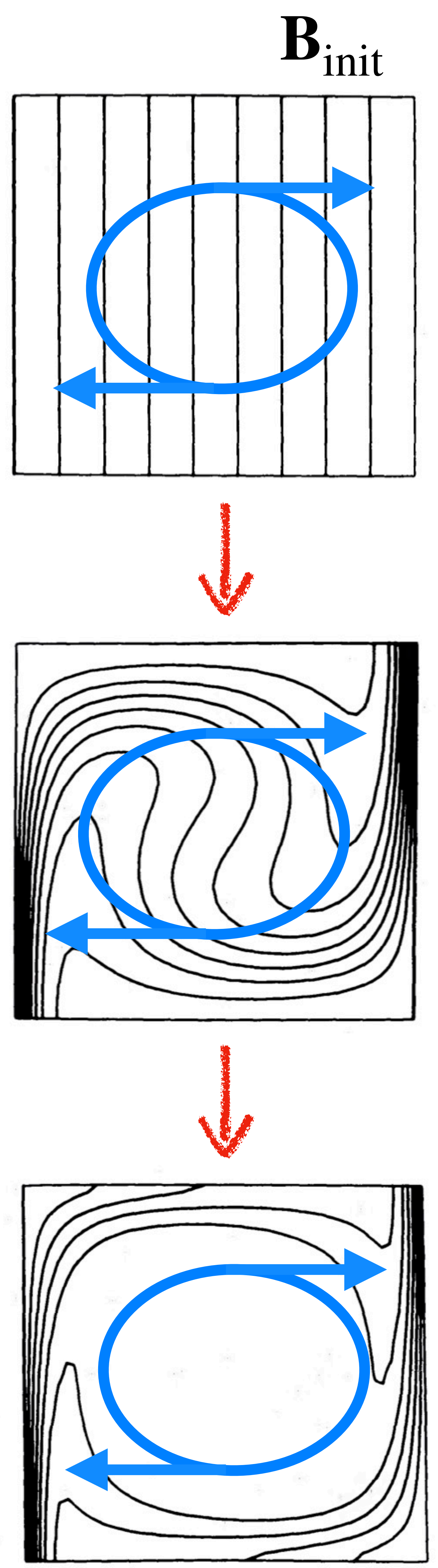


Volger et al. 2005 (MURaM simulation)

Intergranular lanes contain high intensity magnetic sheets
due to flux expulsion (Weiss 1966, Volger et al. 2005)

Flux Expulsion

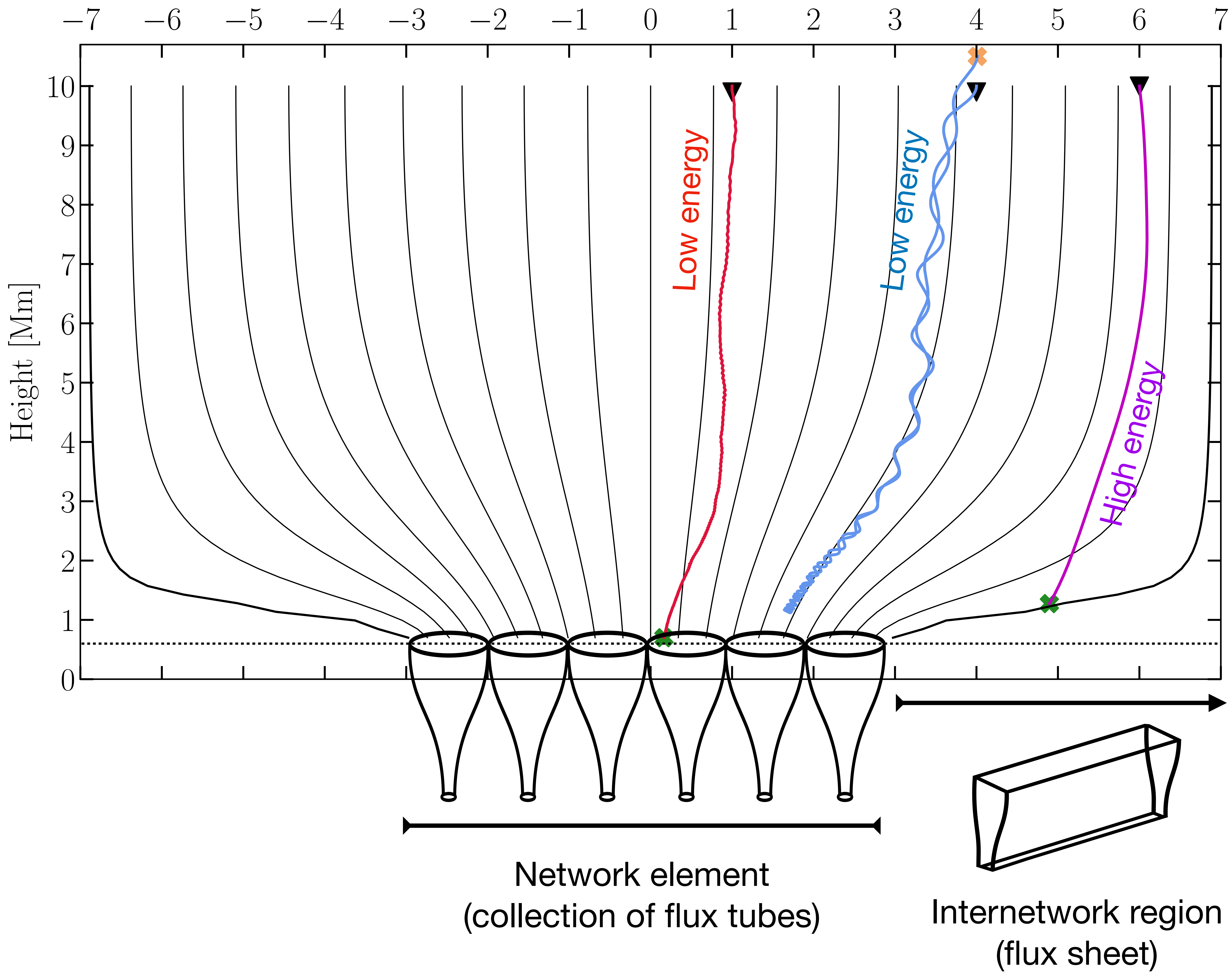
- Magnetic fields wound up due to eddy motion (Weiss 1966)
- For magnetic Reynolds number $\mathrm{Rm} \sim vL/\eta \gg 1$, magnetic fields are "expelled" to boundary layer of eddy
- At surface of the Sun:
  - Granular cell at solar surface is eddy of size ~ 1000 km
  - kG magnetic fields formed at granular lane (e.g., Volger et al. 2005)



$\mathrm{Rm} \sim vL/\eta \gg 1$

Credit: Galloway & Weiss 1981

Main ideas of our model: flux tube + flux sheet



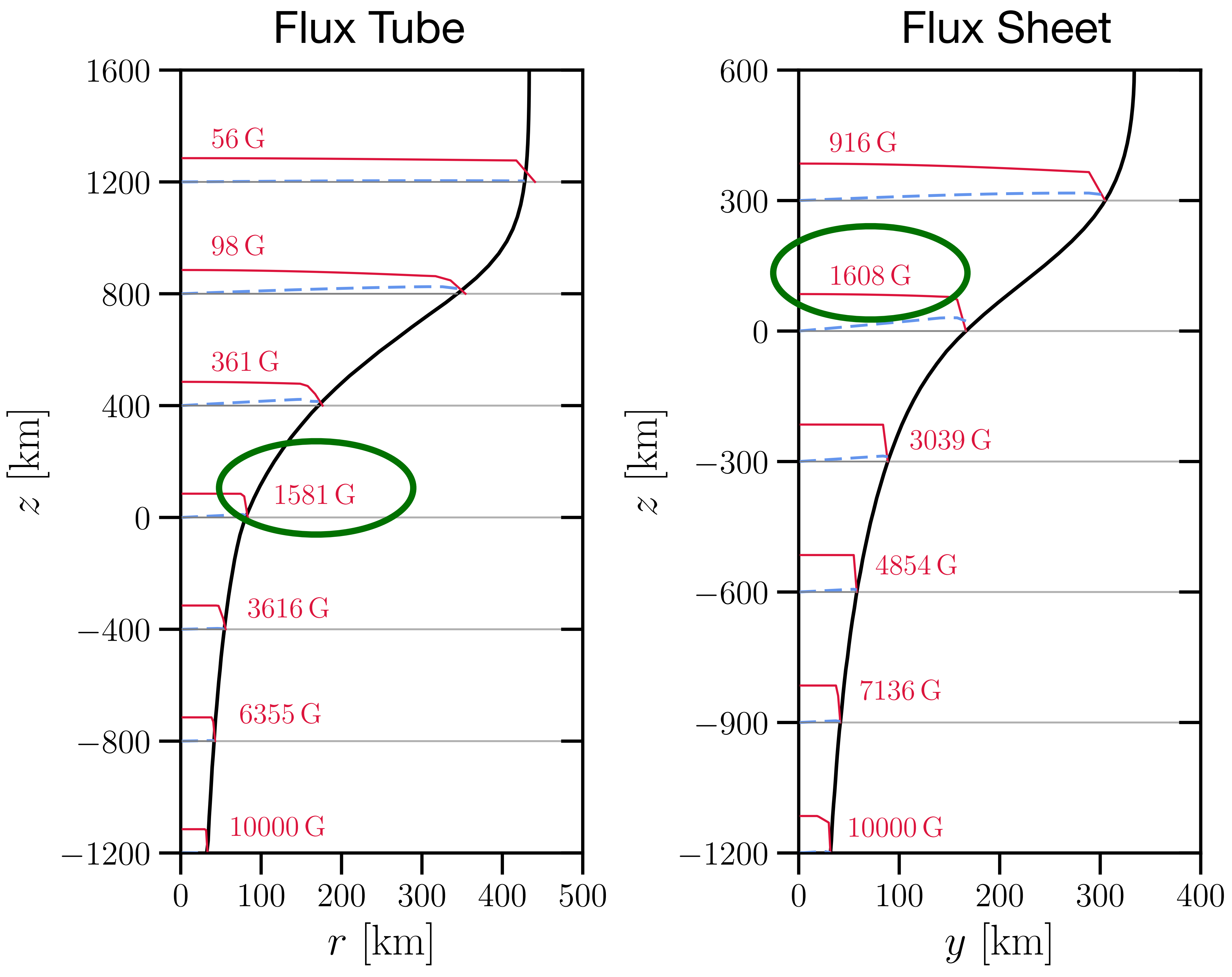
- Step-1:
  Inject GCR protons at 10 Mm from surface
- Step-2:
  Particles reaching the network element are injected into a flux tube
- Step-3:
  Particles reaching the internetwork region are injected into a flux sheet

Two important ingredients:

1. Finite-sized flux geometry
2. Magnetic turbulence

Ingredient 1: Flux Geometry

(Magneto-hydrostatic Equilibrium)



$$\mathbf{B} \cdot \left[\nabla P - \rho \mathbf{g}\right] = 0$$ Hydro-equilibrium parallel to $\mathbf{B}$

$$\mathbf{J} = \frac{1}{B^2}\mathbf{B} \times \left[\nabla P - \rho \mathbf{g}\right]$$ Balancing net hydro-force perp. to $\mathbf{B}$

$$\nabla \times \left(\nabla \times \mathbf{A}\right) = 4\pi \mathbf{J}$$ Ampere's law

Tube: $$\frac{\partial^2 \Psi}{\partial r^2} - \frac{1}{r}\frac{\partial \Psi}{\partial r} + \frac{\partial^2 \Psi}{\partial z^2} = -4\pi r J$$ (Grad-Shafranov eqn)

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

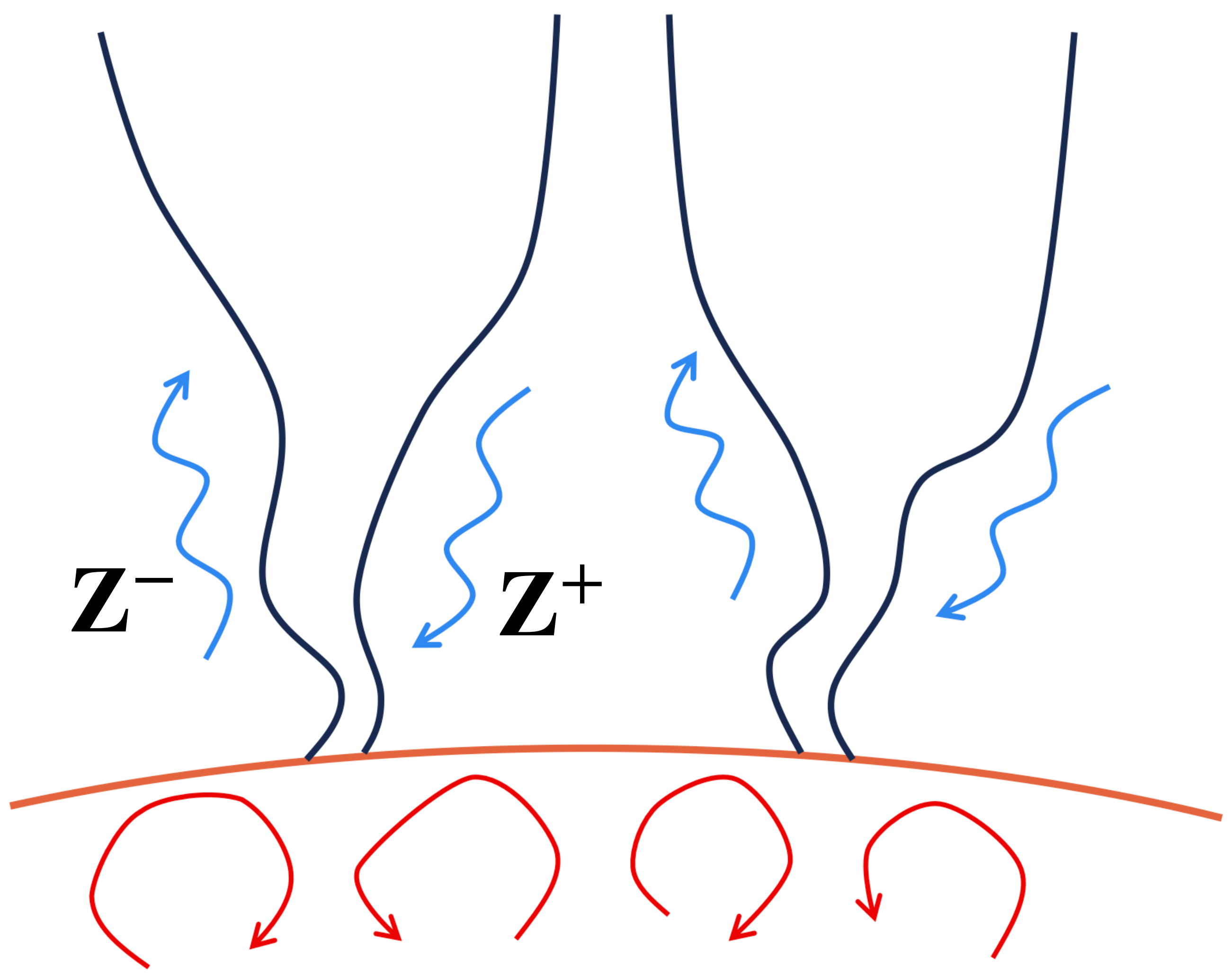
At z=0 km, $|B| \approx 1500\ \mathrm{G}$ (Stenflo 1973)

JTL et al. 2024 (ApJ 961, 167)

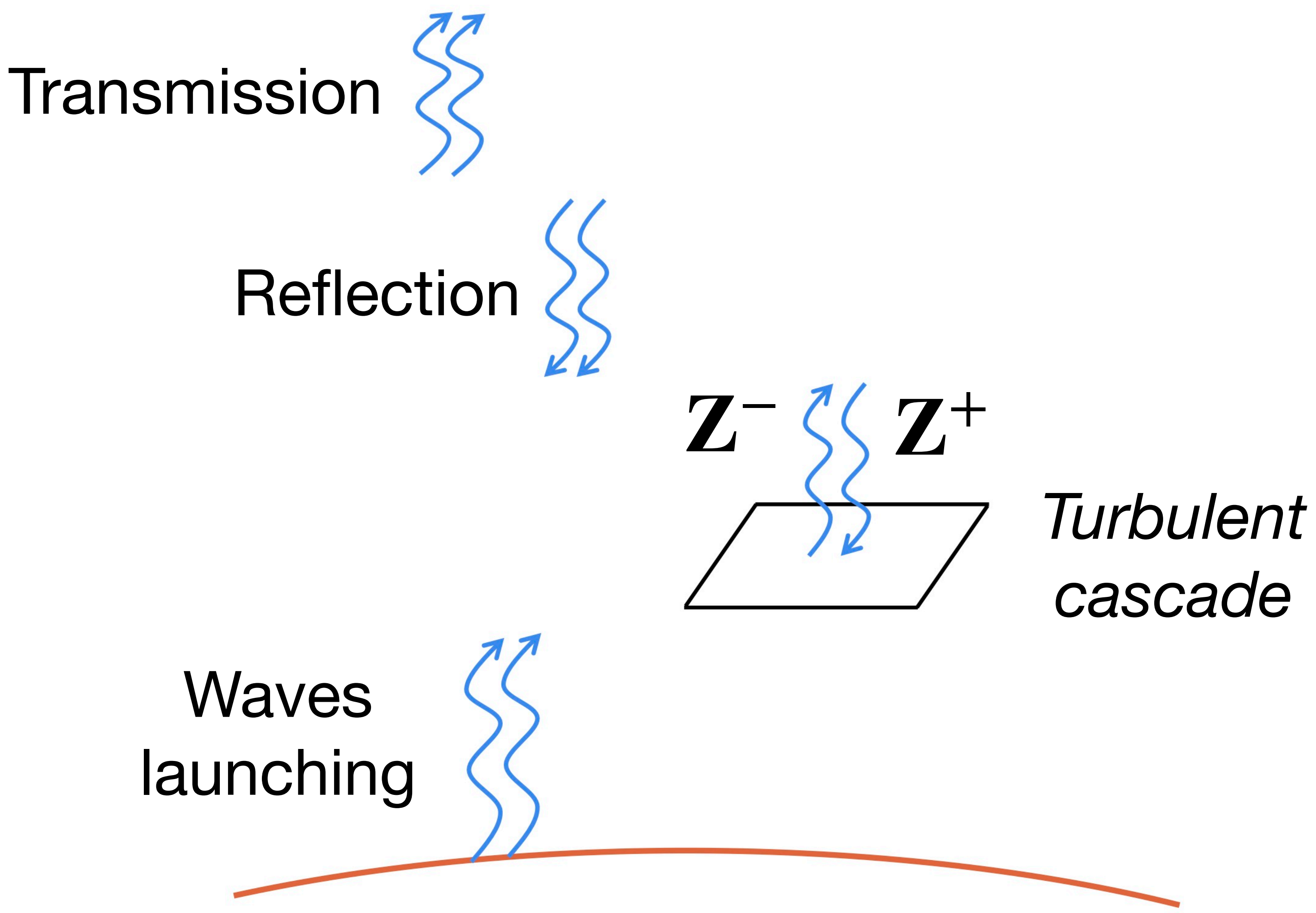
Ingredient 2: Magnetic Turbulence

Magnetic bottle effect vs. Pitch-angle scattering

- Alfvenic fluctuations ($\mathbf{Z}^-$) from buffeting of granules
- Waves are partially reflected ($\mathbf{Z}^+$) due to density and field gradients
- Counter-propagating waves trigger turbulent cascade, creating smaller scales
- Magnetic energy dissipates to kinetic energy — causing the coronal heating



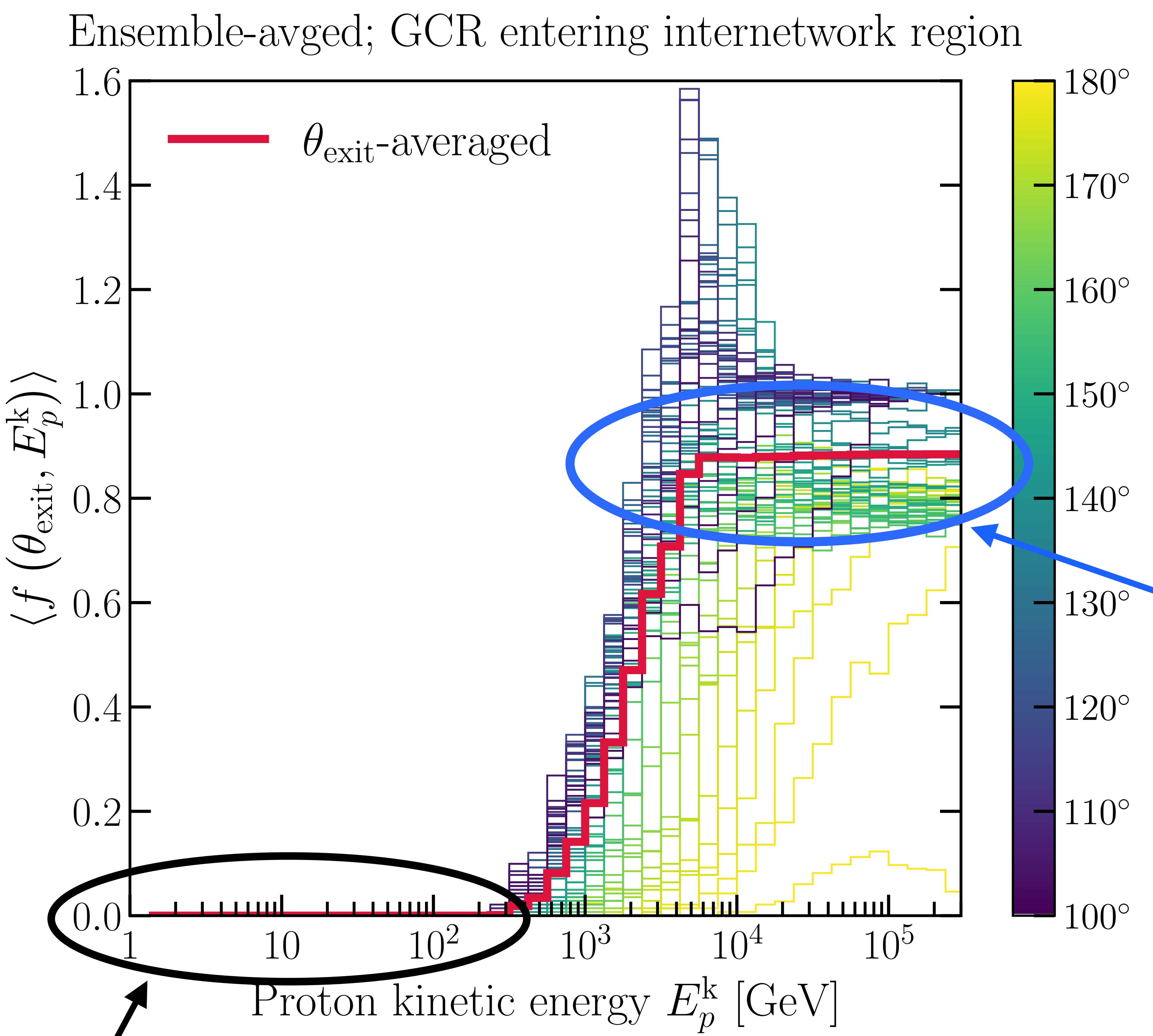
Credit: S. Cranmer



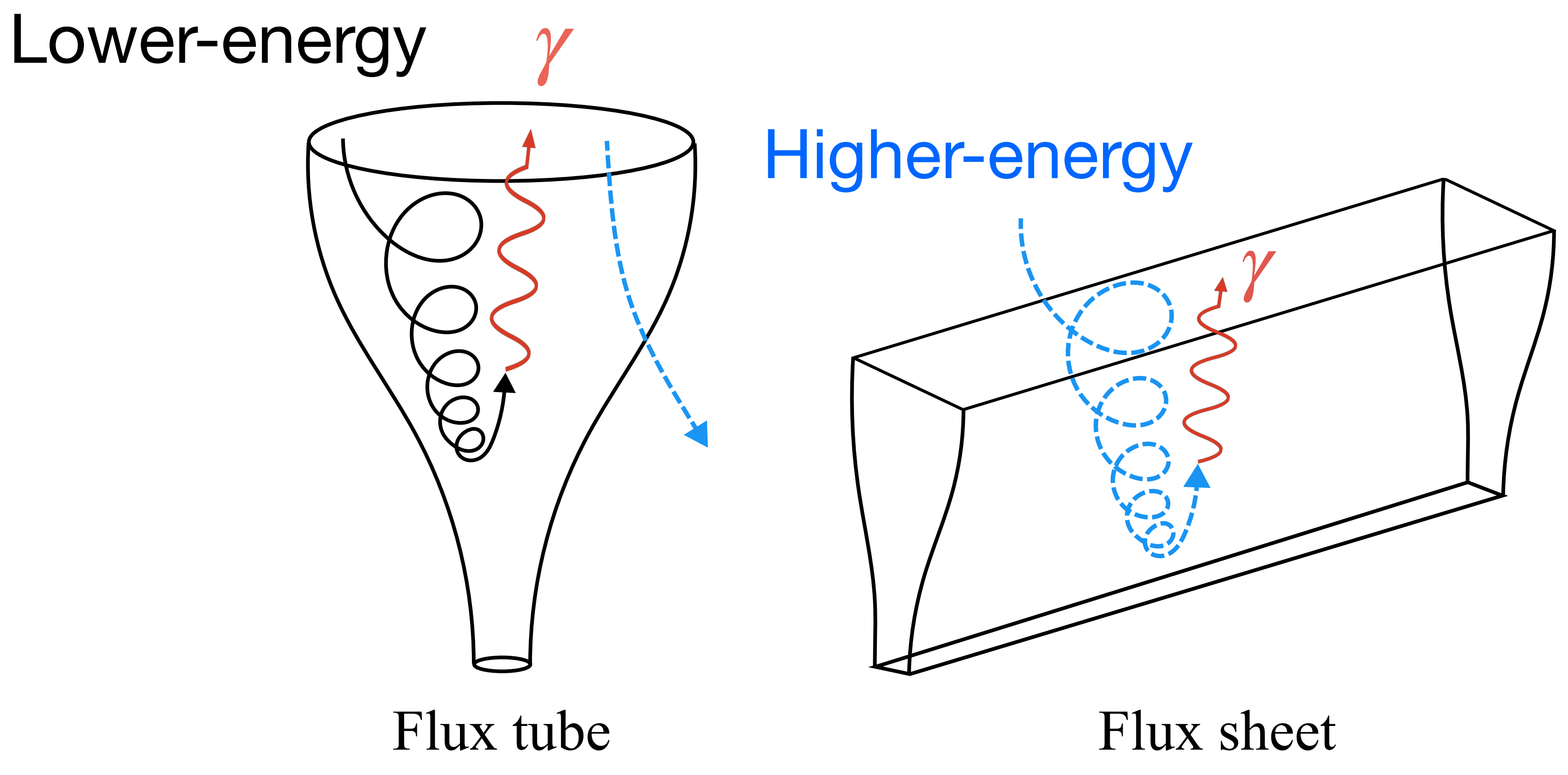
See Matthaeus et al 1999

Our Result #1: Fraction of GCR Penetrating Network Field

Y-axis:
Fraction of GCR penetrating network field



Lower-energy ($\lesssim 100$ GeV) bounded by network field



Higher-energy ($\gtrsim 1$ TeV) passing through network field, entering intergranular sheet

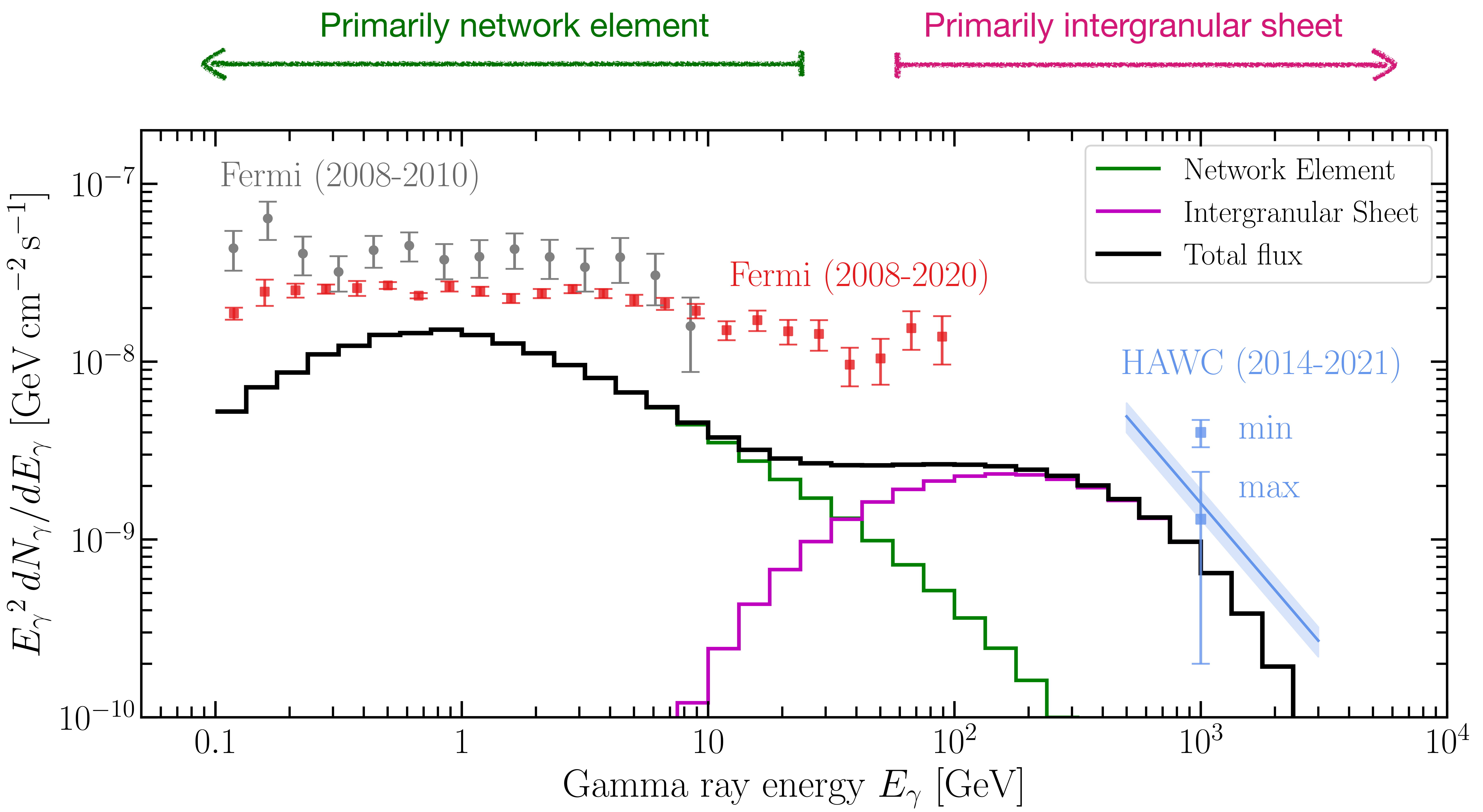
Using $E_\gamma \sim 0.1\, E_p$ rule:

- Tube produces γ for $E_\gamma \lesssim 10$ GeV
- Sheet produces γ for $E_\gamma \gtrsim 100$ GeV

JTL et al. 2024b, in preparation

JTL et al. 2024a (ApJ 961, 167)

Our Result #2: Gamma-Ray Spectrum

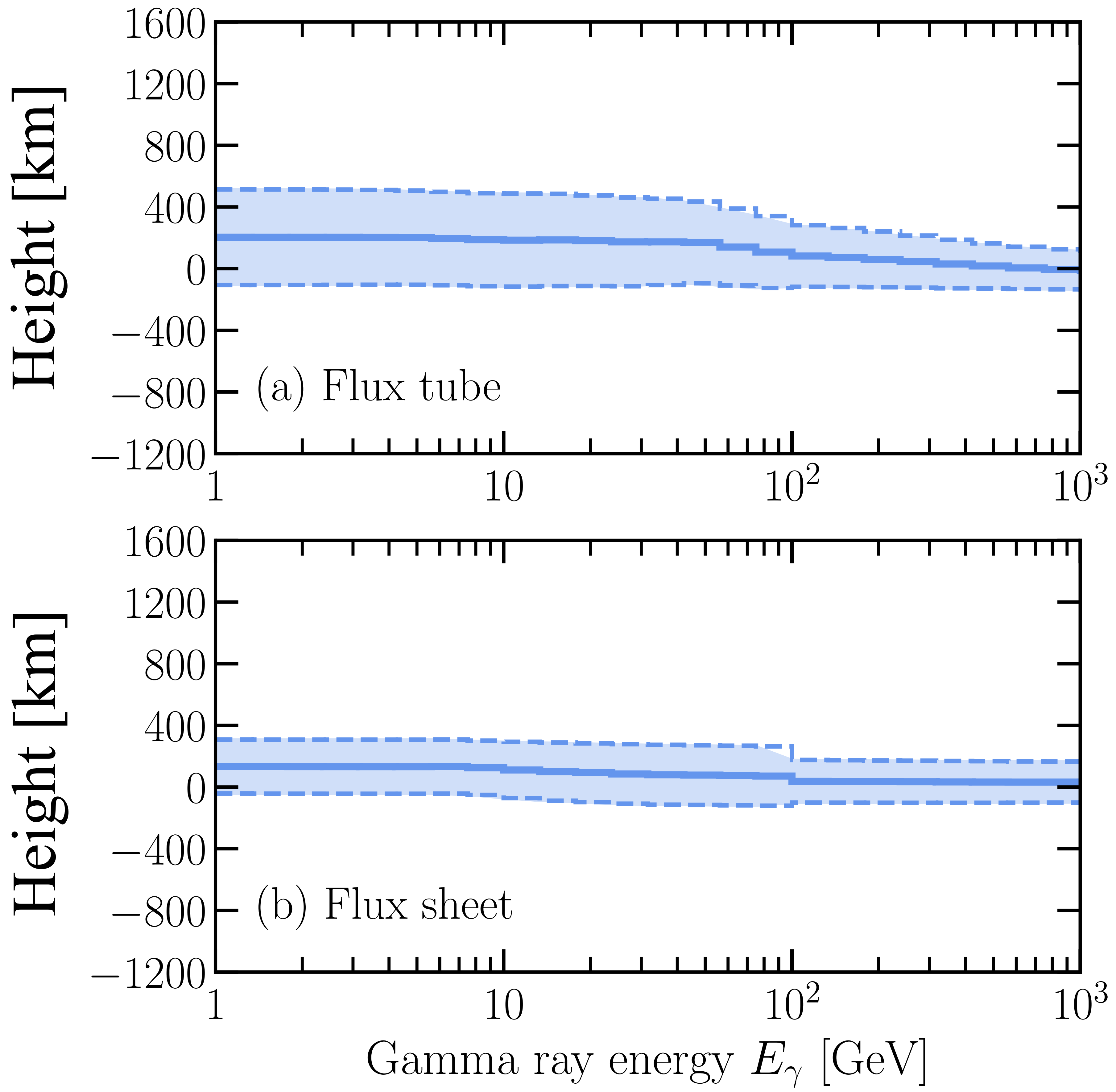


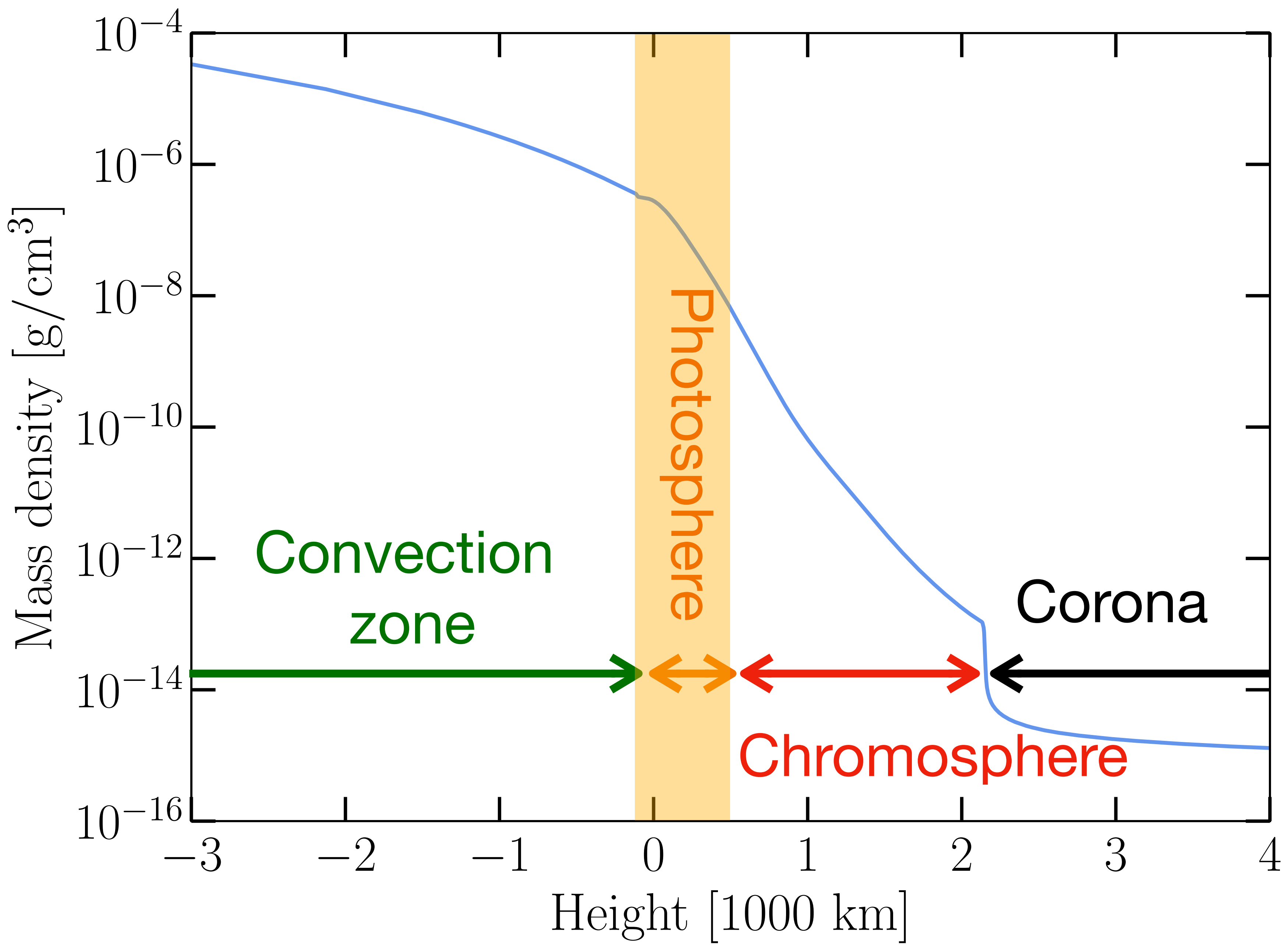
Finite-sized structure is the key!

JTL et al. 2024b, in preparation

JTL et al. 2024a (ApJ 961, 167)

Our Result #3: Average Emission Height





- Emission mainly happens in height $z = -100$ km to 400 km, corresponding to **photosphere** & **uppermost convection zone**

- A new tool to probe photospheric magnetism

JTL et al. 2024b, in preparation

JTL et al. 2024a (ApJ 961, 167)

Conclusions and Outlook

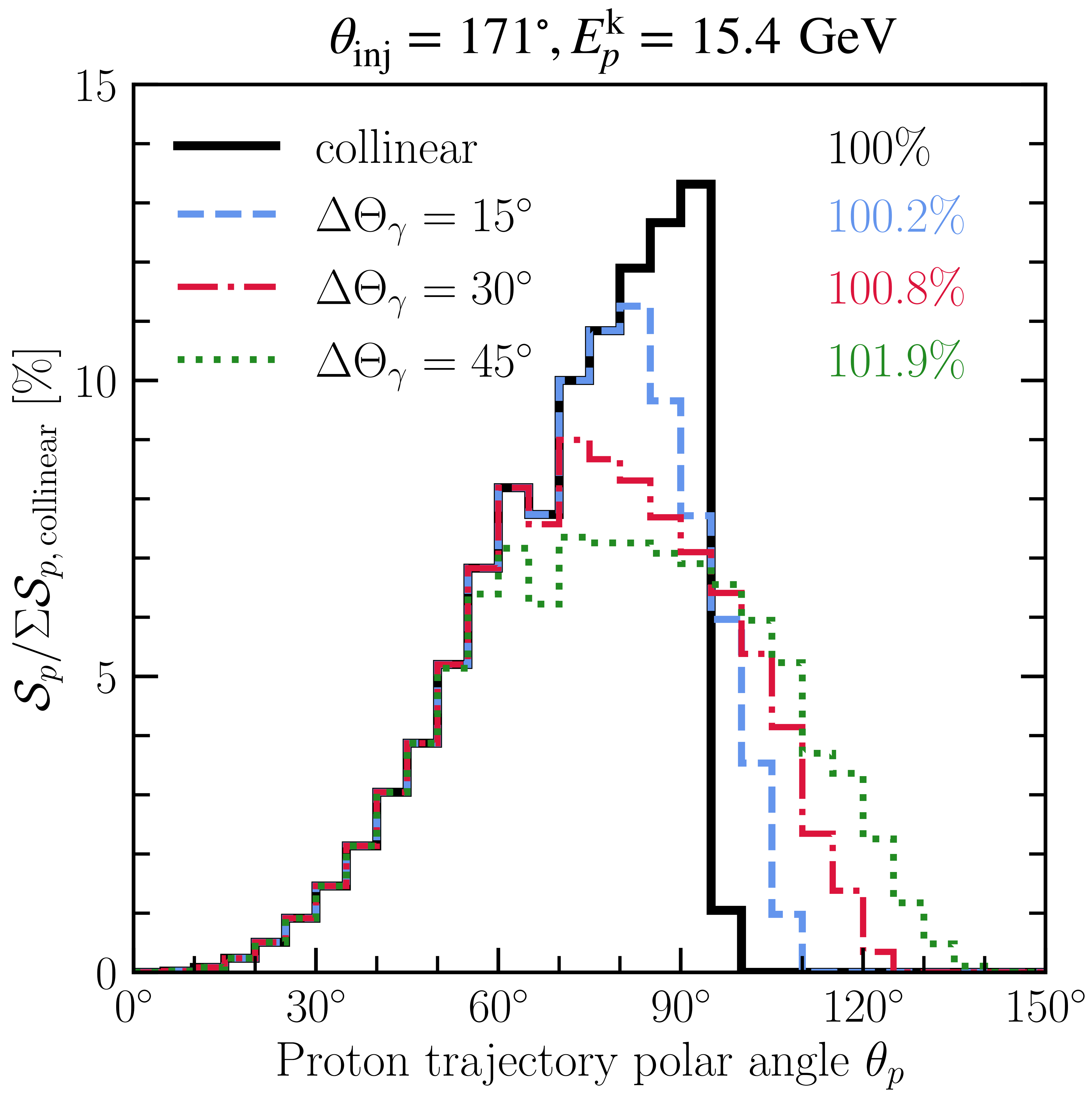
- A simple model consisting of network element and intergranular sheet:
    - Lower-energy γ from network elecment, higher-energy γ from intergranular sheet
    - Finite-sized flux sheet results in ineffectiveness of capturing higher-energy GCRs
        - steep γ spectrum at $\sim \mathrm{TeV}$ seen by HAWC.

- What causes the anti-correlation between γ flux and solar cycle?
    - Quiet vs. active regions? Magneto-convection? GCR transport?

- Exciting opportunities ahead!
    - Solar-disk probe of γ to reveal small-scale magnetic fields at photospheric surface:
        — Small-scale dynamo vs. magneto-convection

Backup slides

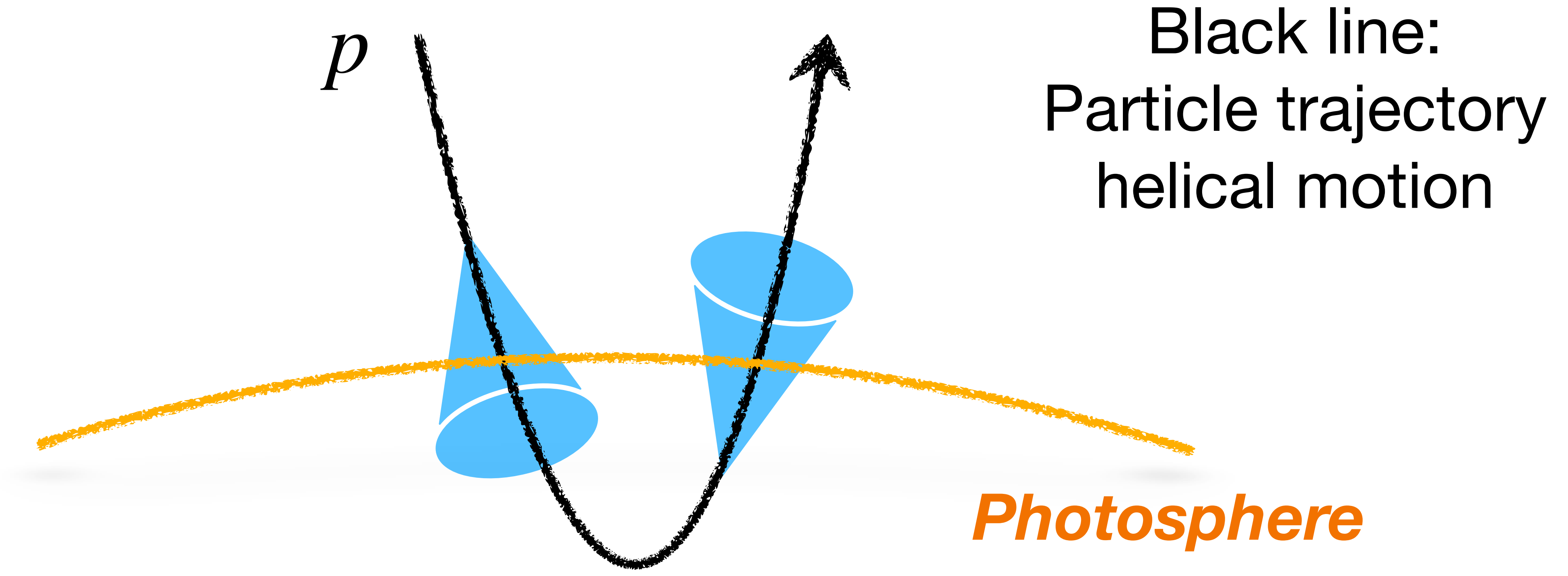
Finite-Sized Emission Cone (*for each pp interaction*)



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

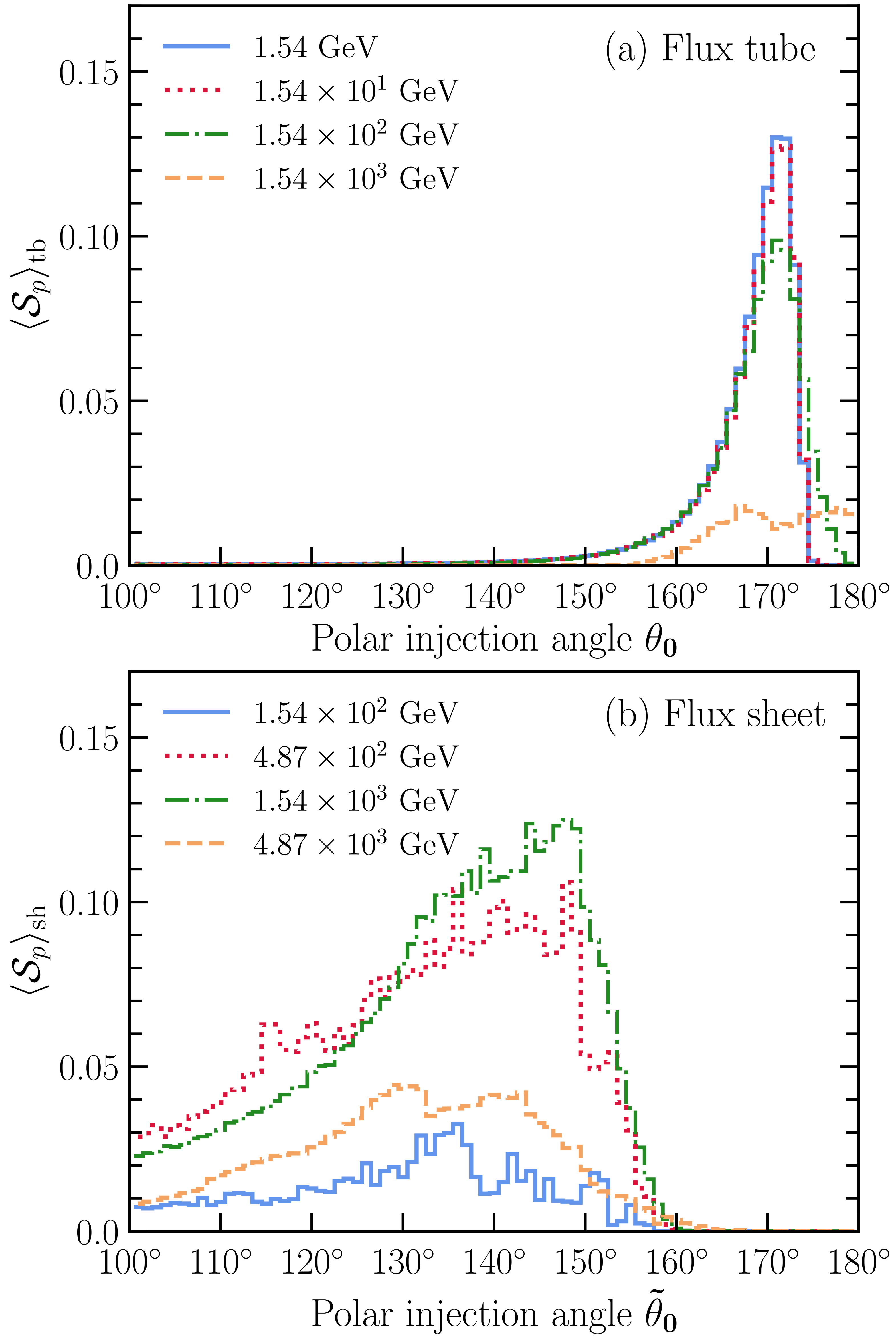
= proton GCR absorption probability

× gamma transmission probability

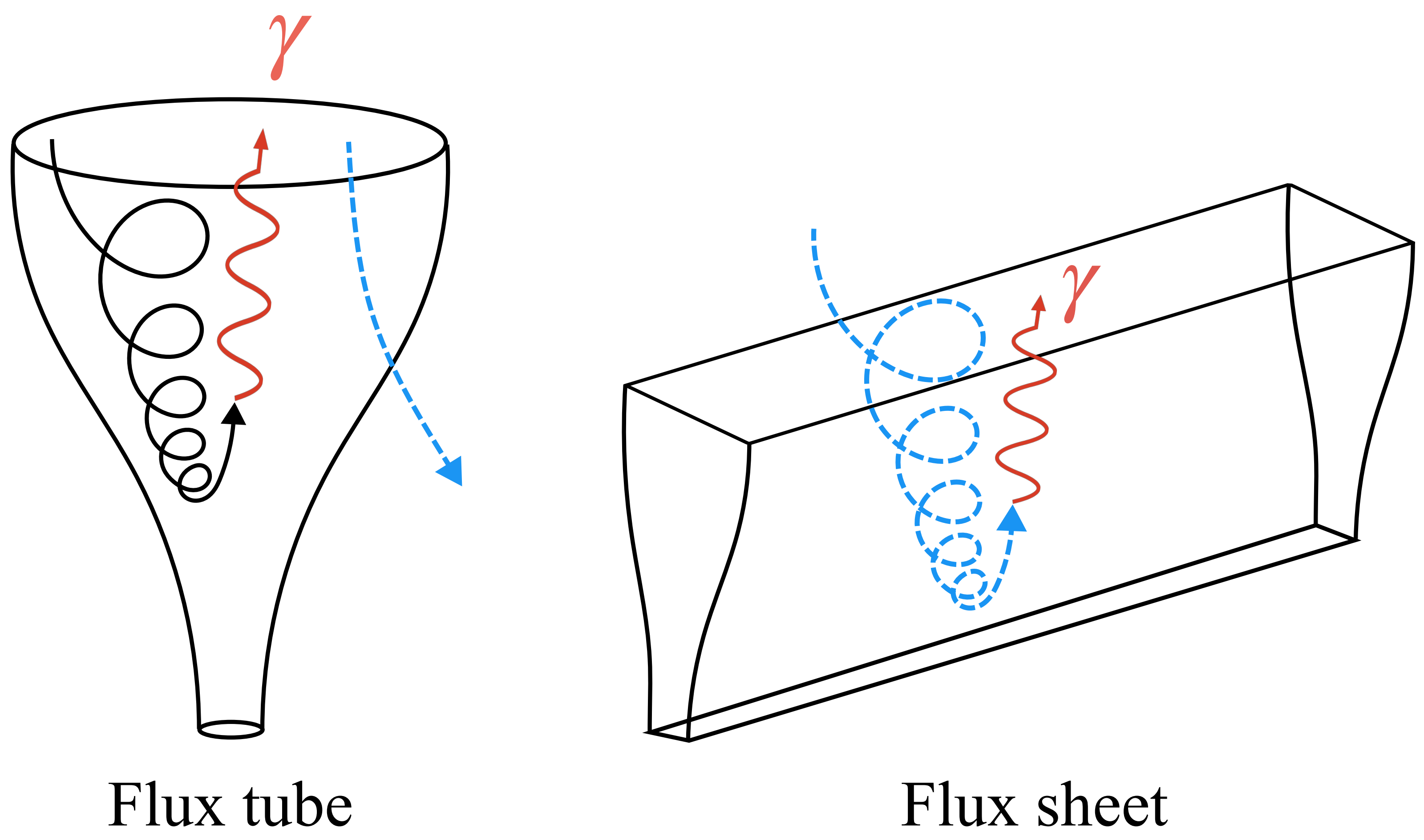


JTL et al. 2024 (ApJ 961, 167)

Results: Optimal Injection Angle



** Polar angle θ_0 is angle relative to $\hat{z}$-axis



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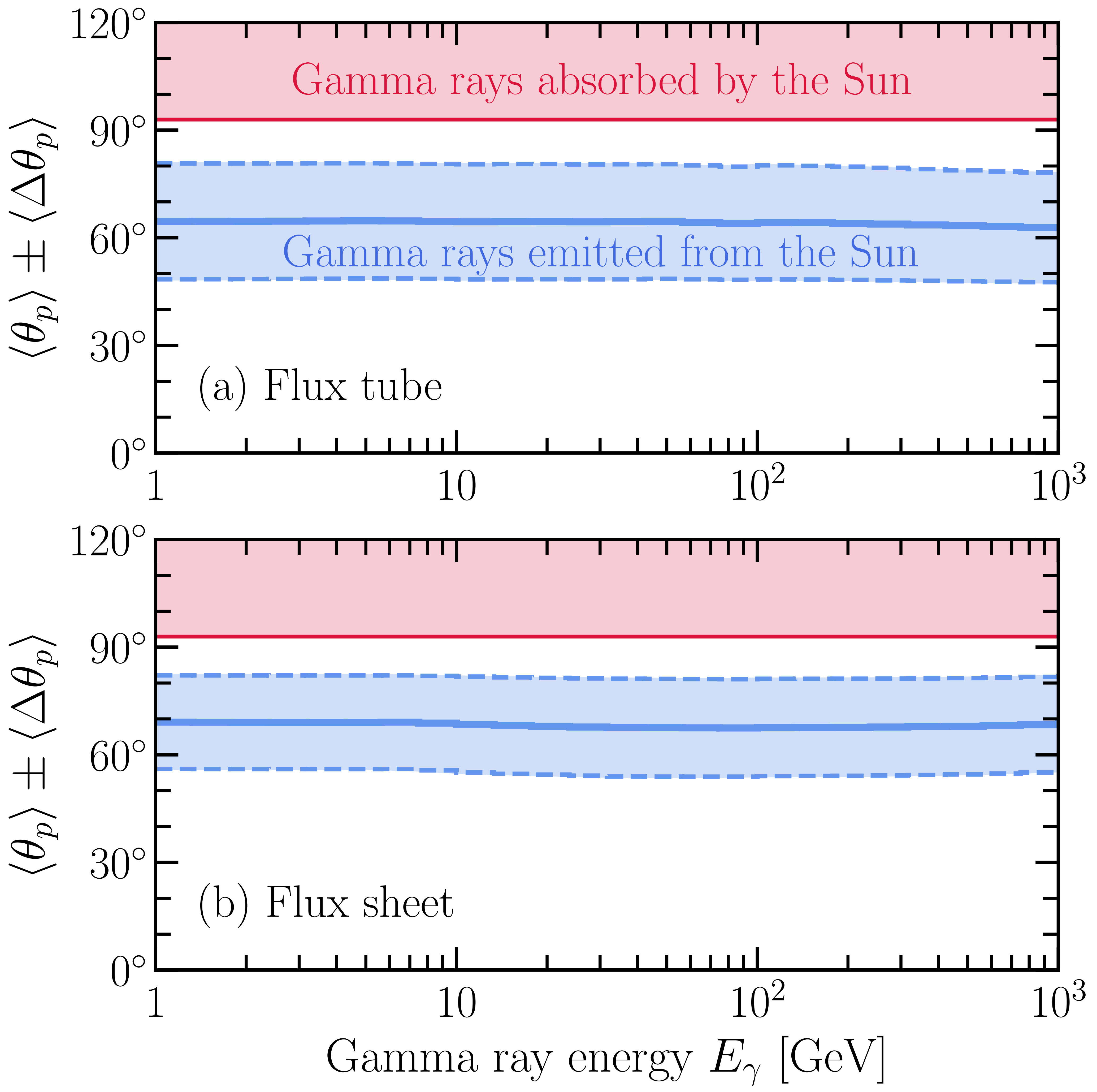
Our Result: Average Emission Angle

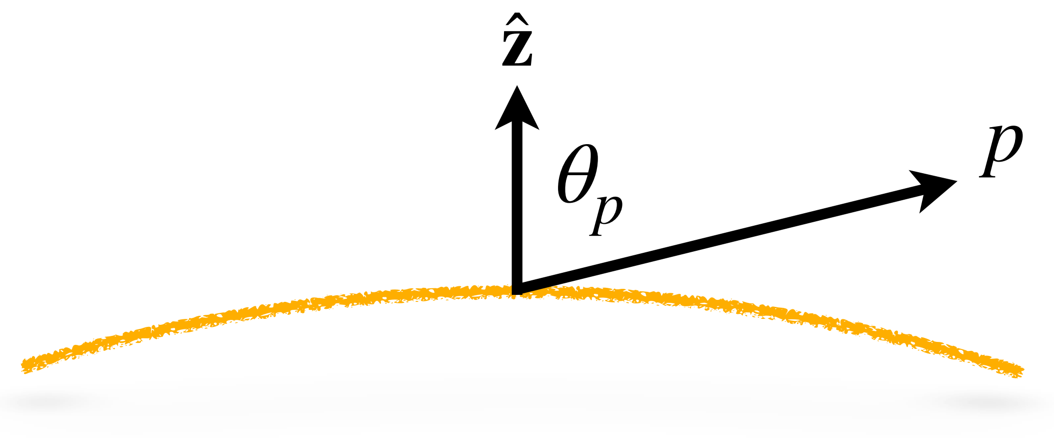


Our result:

- Locally, emission angle is $50° \lesssim \theta_p \lesssim 80°$ due to highest gas density at reflection point where pitch angle is $90°$

Fermi-LAT observation:

- Emission can happen at center of disk ($\theta_p \sim 0°$), which cannot be explained by our model



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