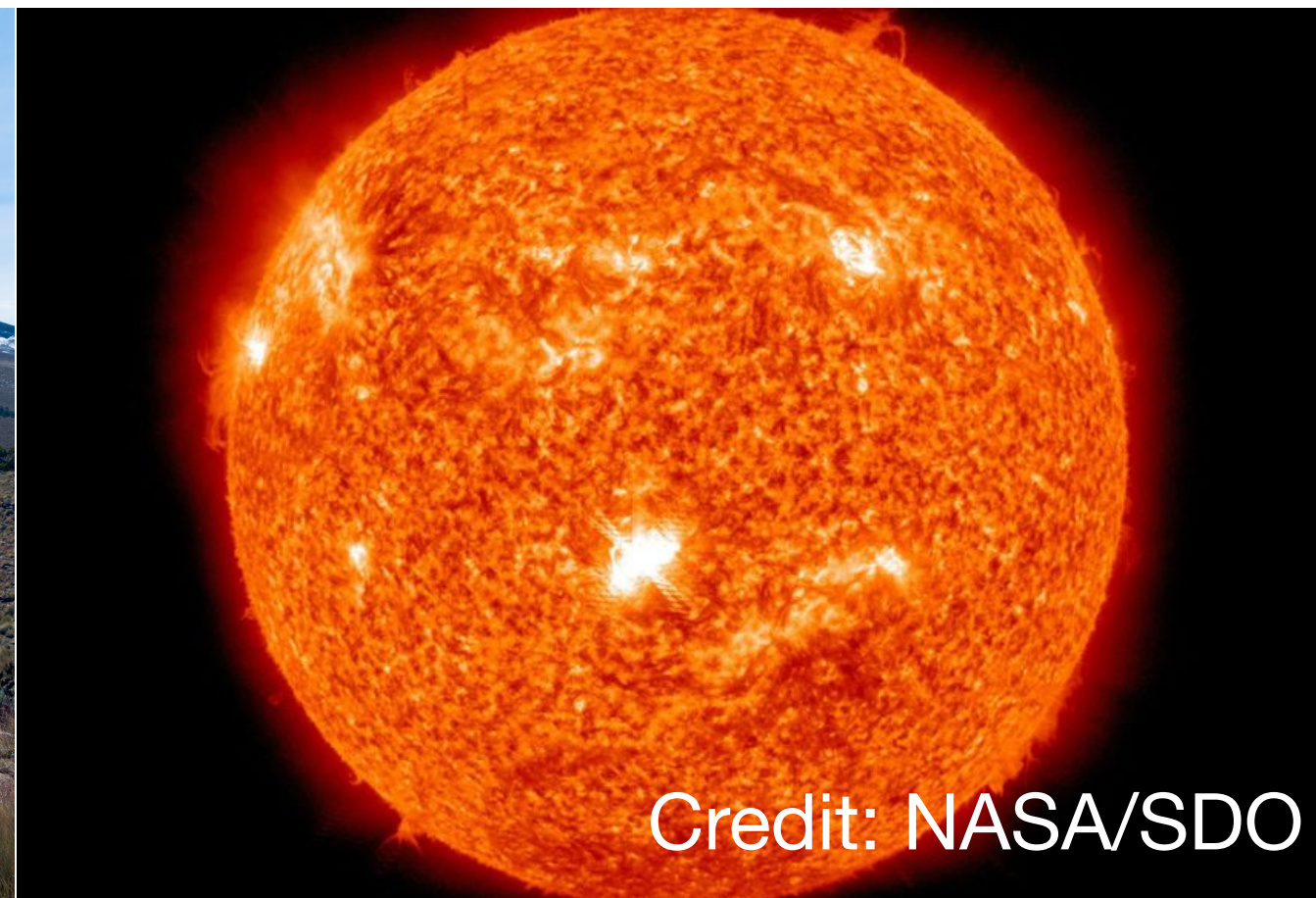


Small-Scale Magnetic Fields are Critical to Shaping Continual Solar Gamma-Ray Emission



HAWC



Credit: NASA/SDO



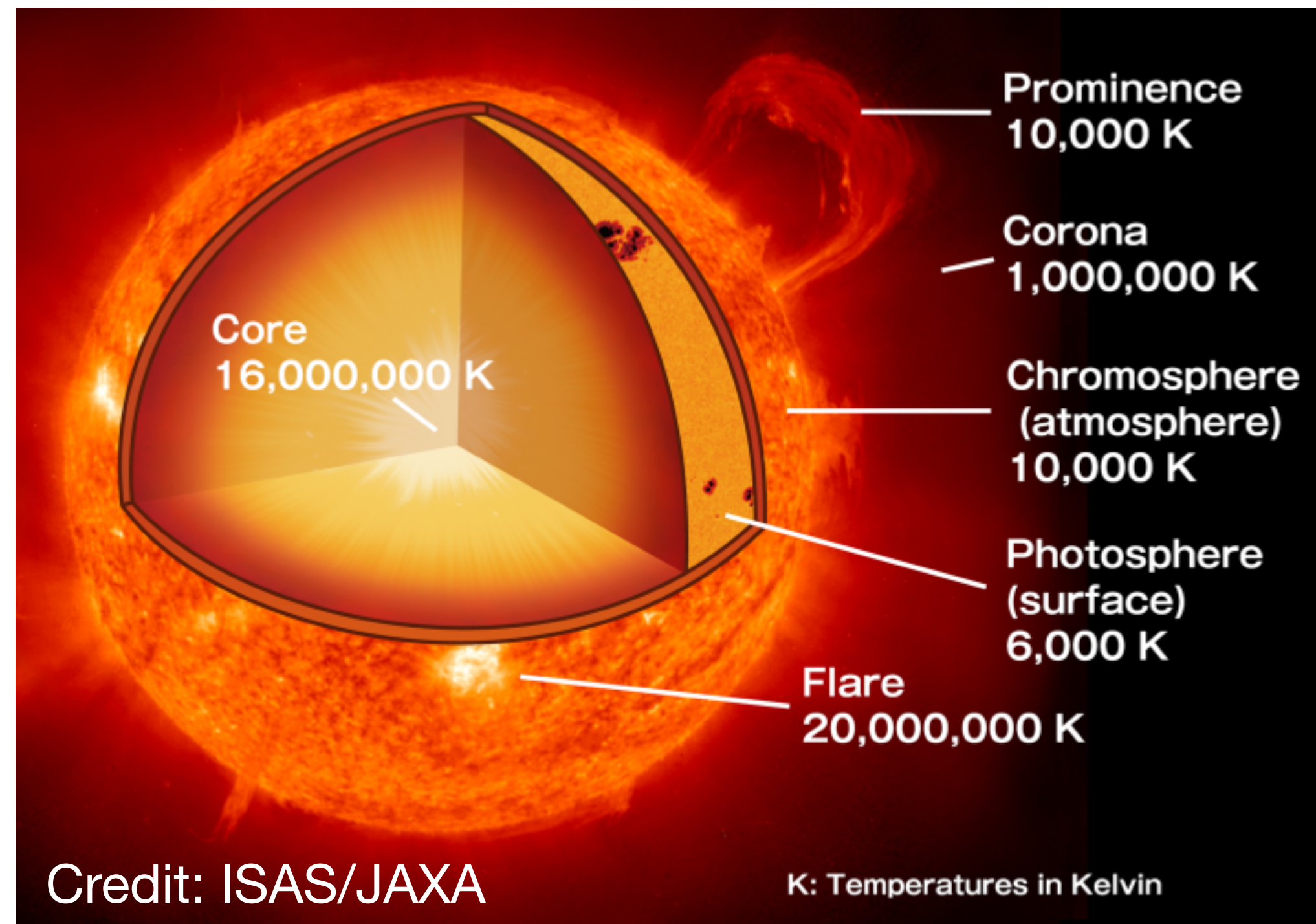
Fermi-LAT

Jung-Tsung Li
(Ohio State University)

COSPAR 2024, Busan
July 18, 2024

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!**

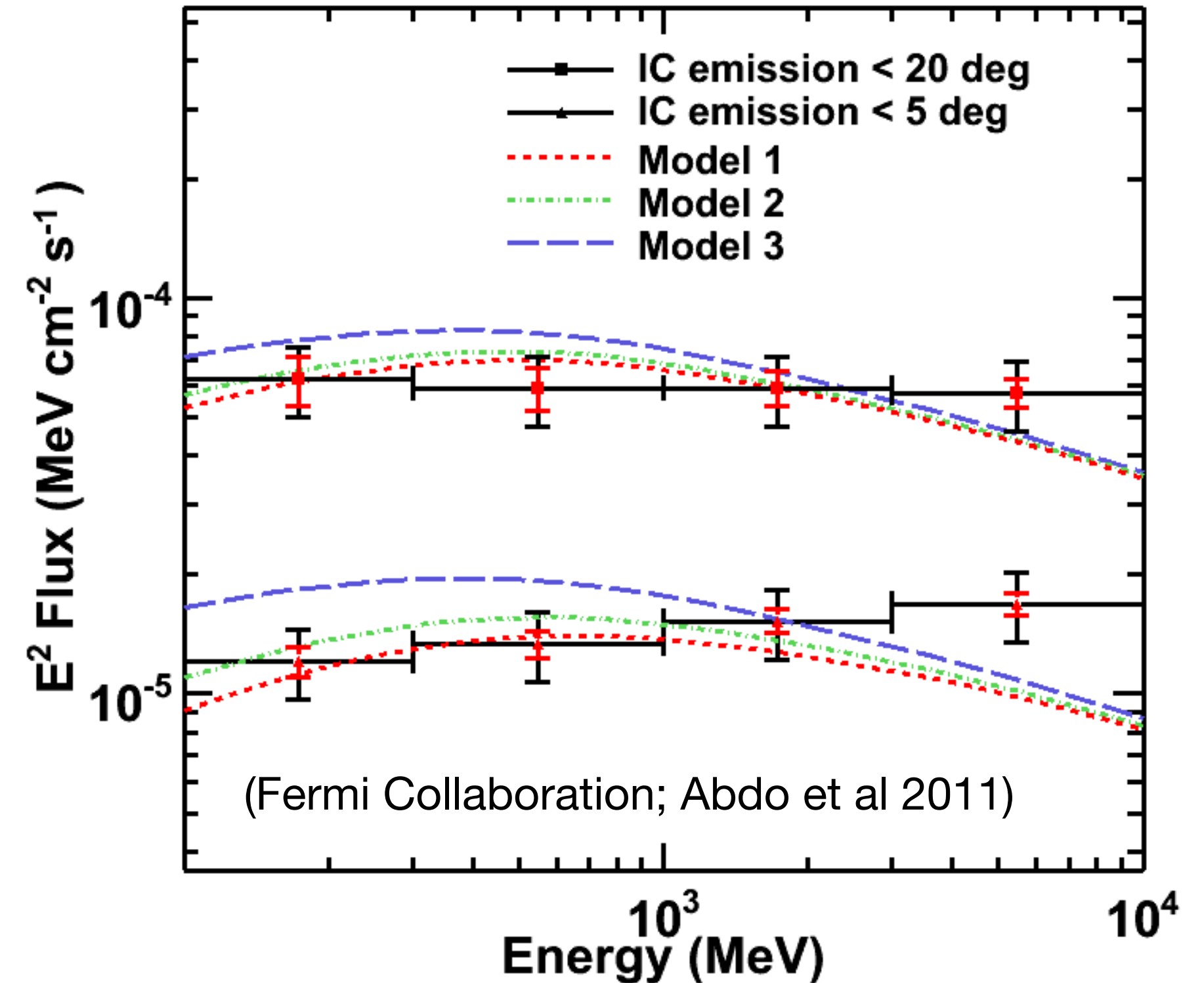
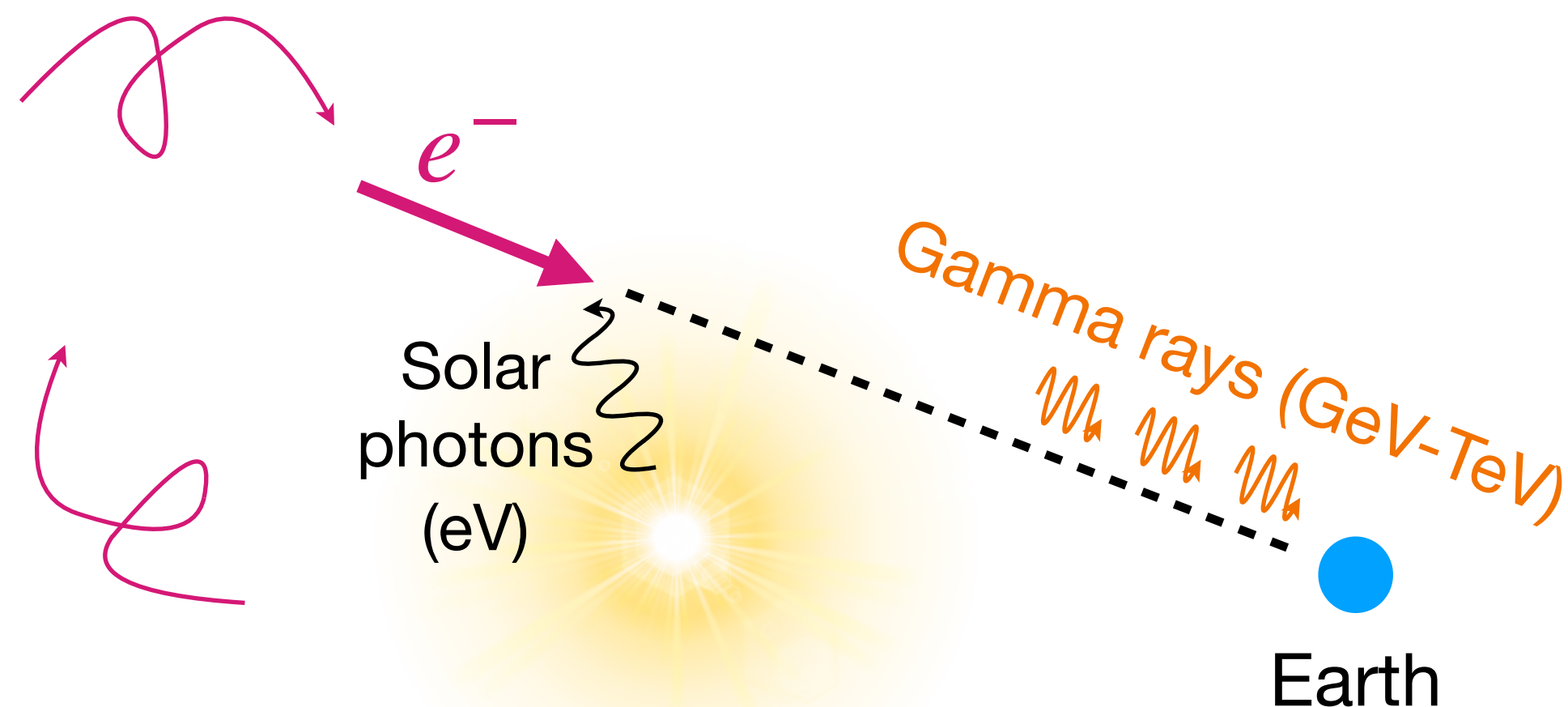
Continual gamma rays from solar halo *(Not the focus of this talk)*

Inverse-Compton scattering in the solar halo

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

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

Galactic cosmic-ray electron

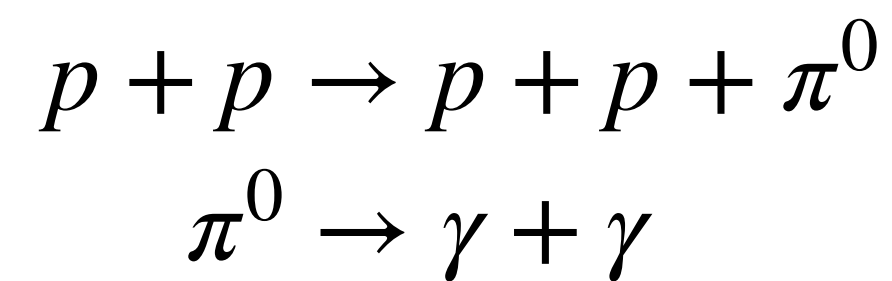


*Potentially a new way to probe
electron cosmic ray transport
in the inner heliosphere*

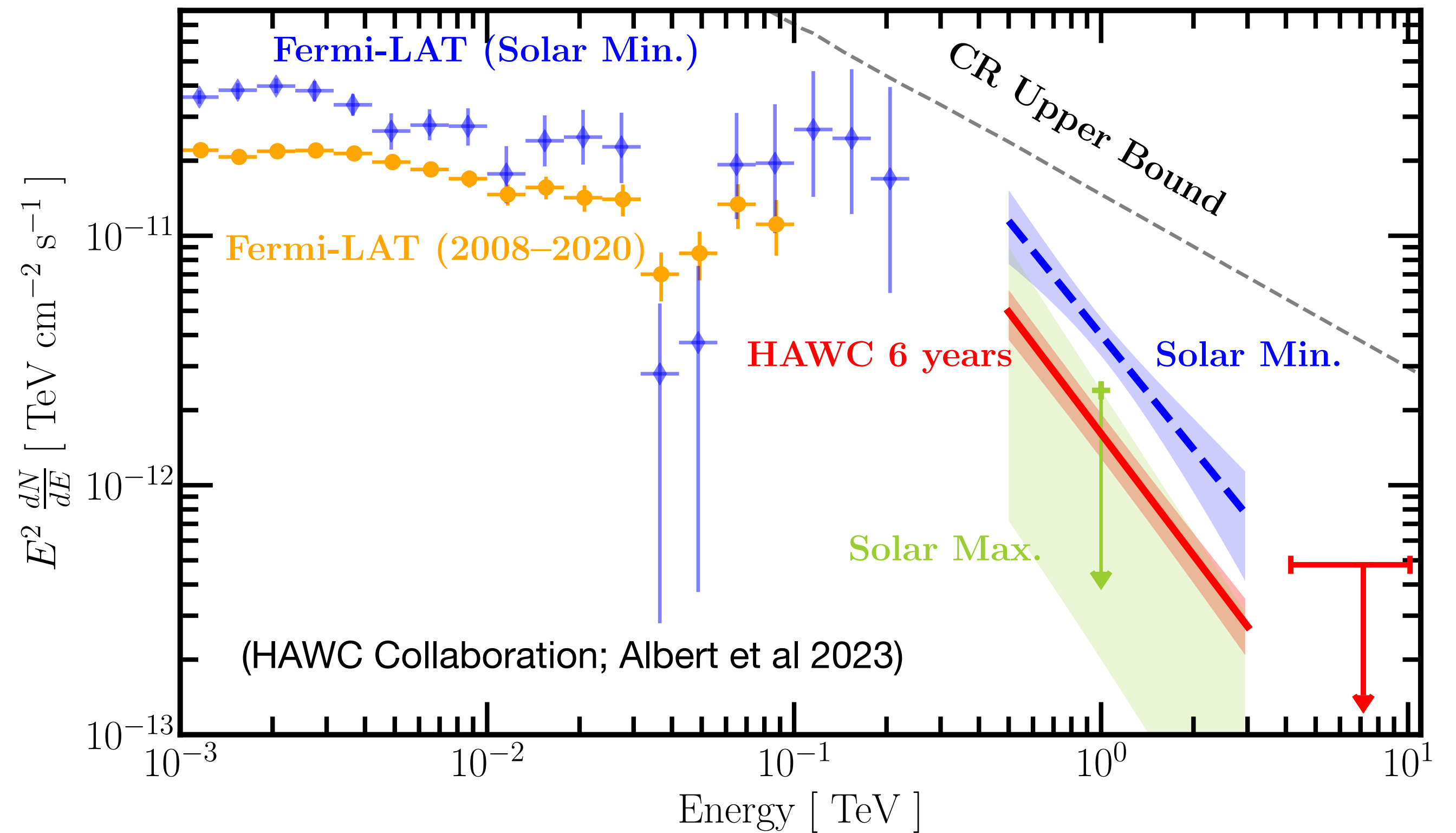
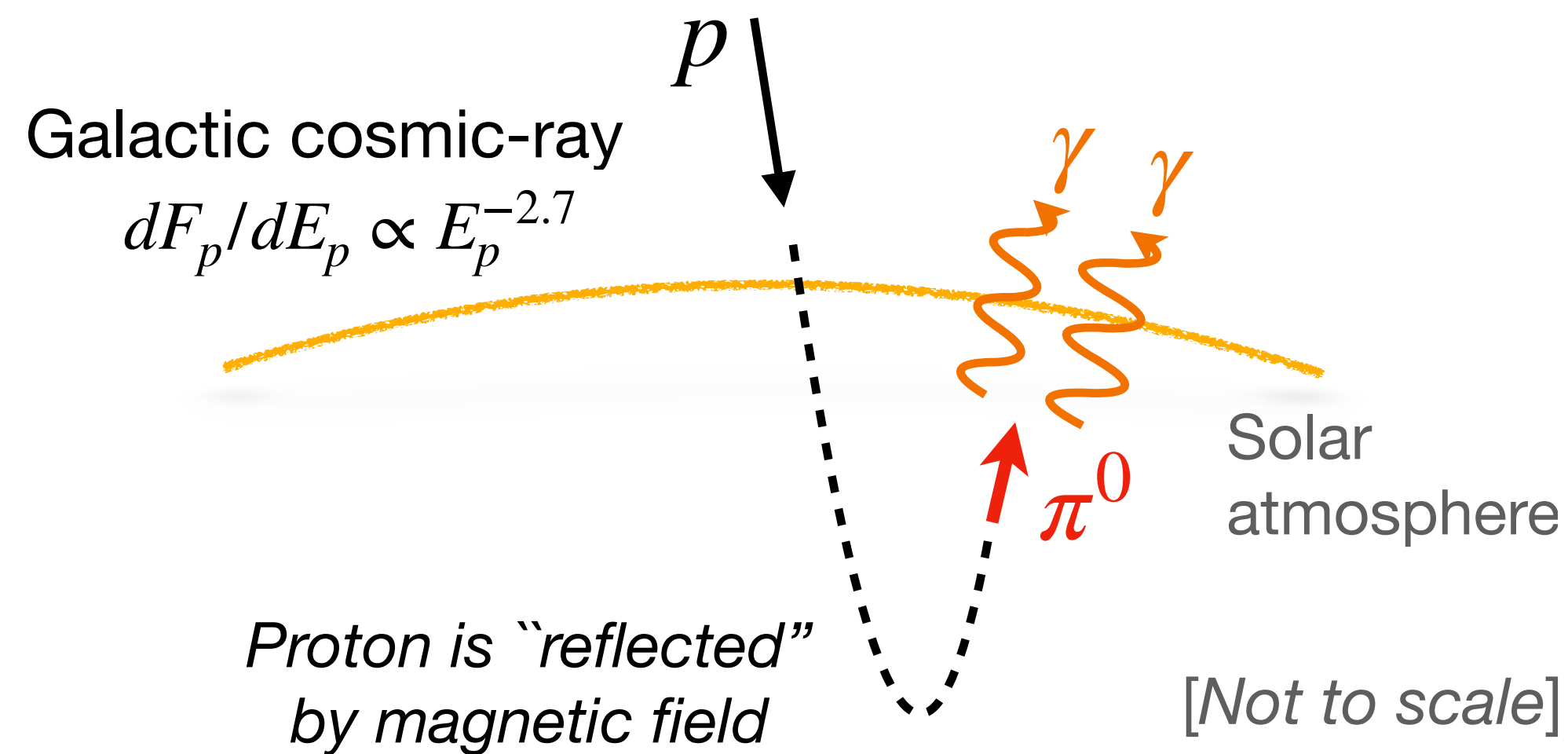
Continual gamma rays from solar disk

Focus of this talk!

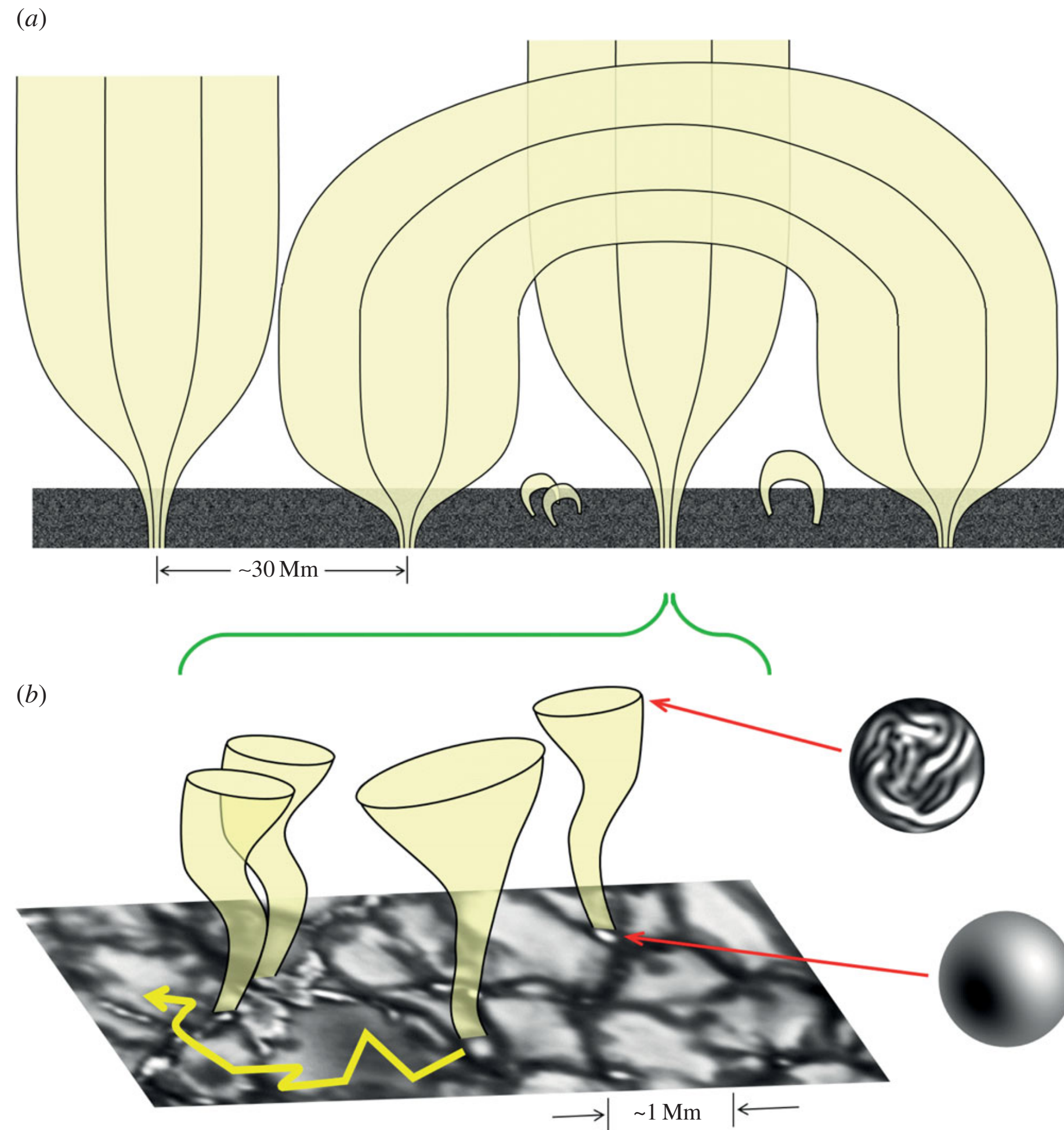
Hadronic scattering in the solar disk



(See Seckel, Stanev & Gaisser 1991)



What needs to be answered? (#1)

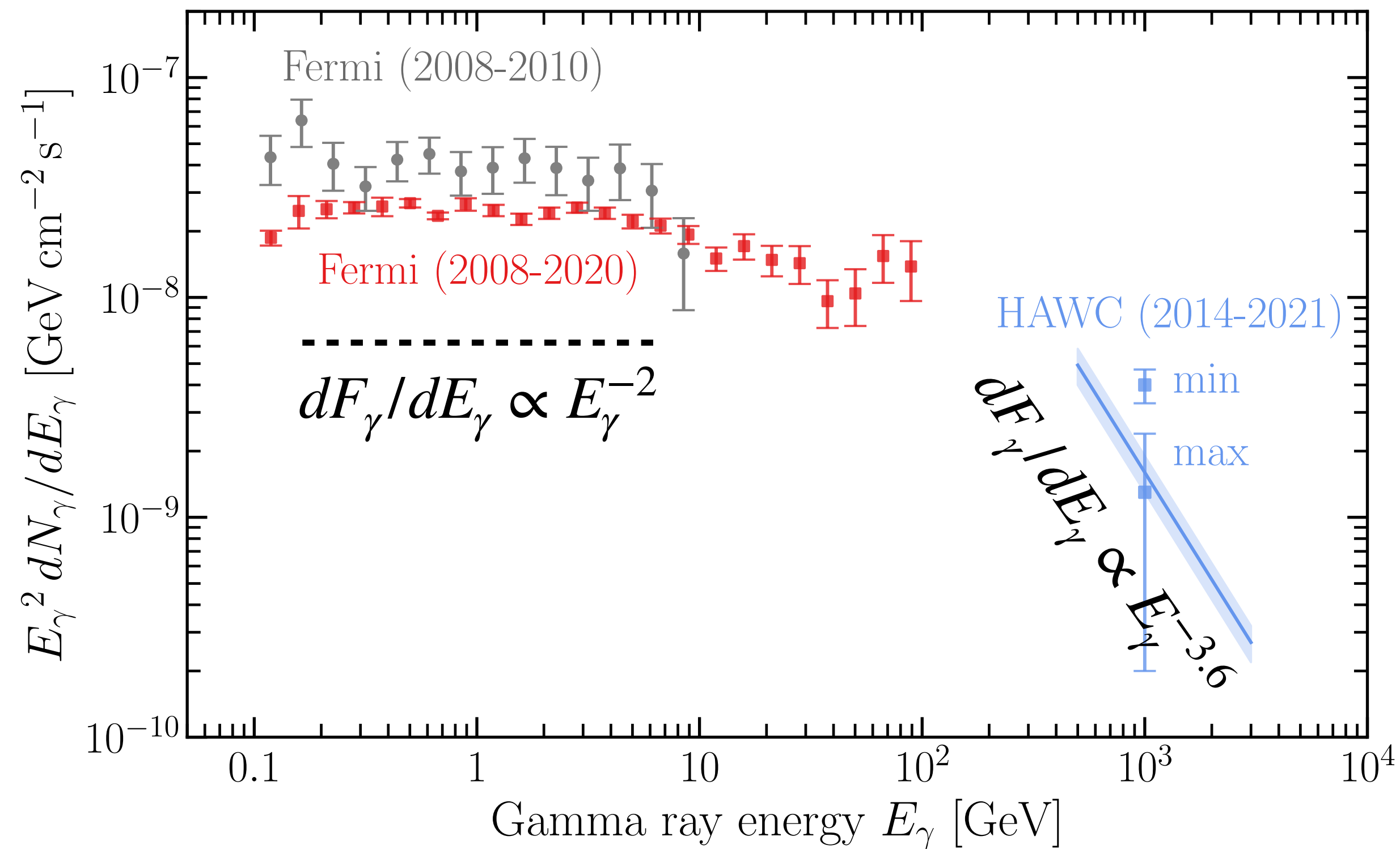


Credit: Cranmer et al. 2015

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** ✓

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

4. Anisotropic emission:

1. Polar flux: relatively constant across solar cycle

2. Equatorial flux: anti-correlate with solar cycle

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** ✓

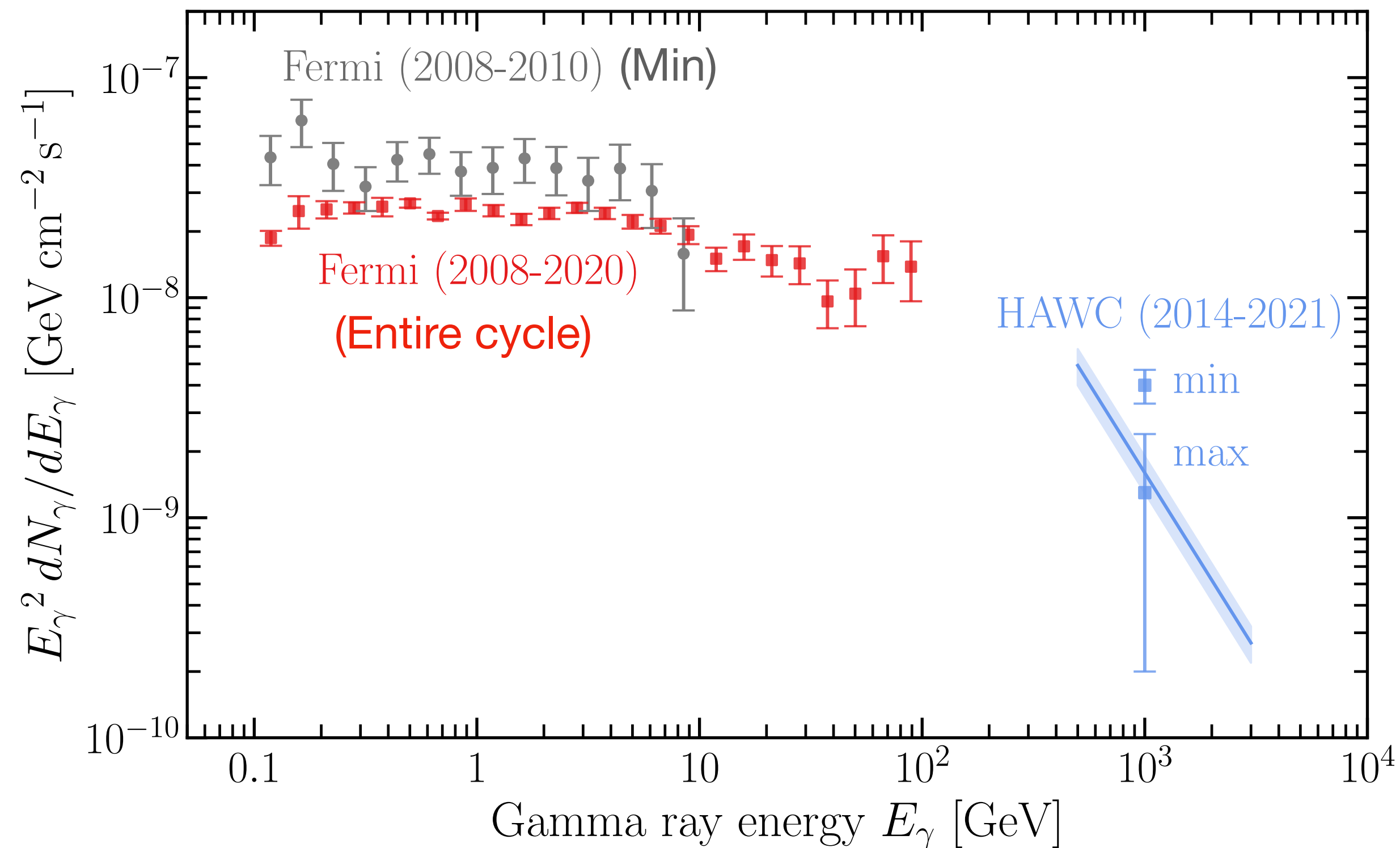
○ Soft spectrum $\sim E_\gamma^{-3.6}$ at ~ 1 TeV **Today** ✓

3. Anti-correlation between gamma-ray flux and solar cycle **Unknown**

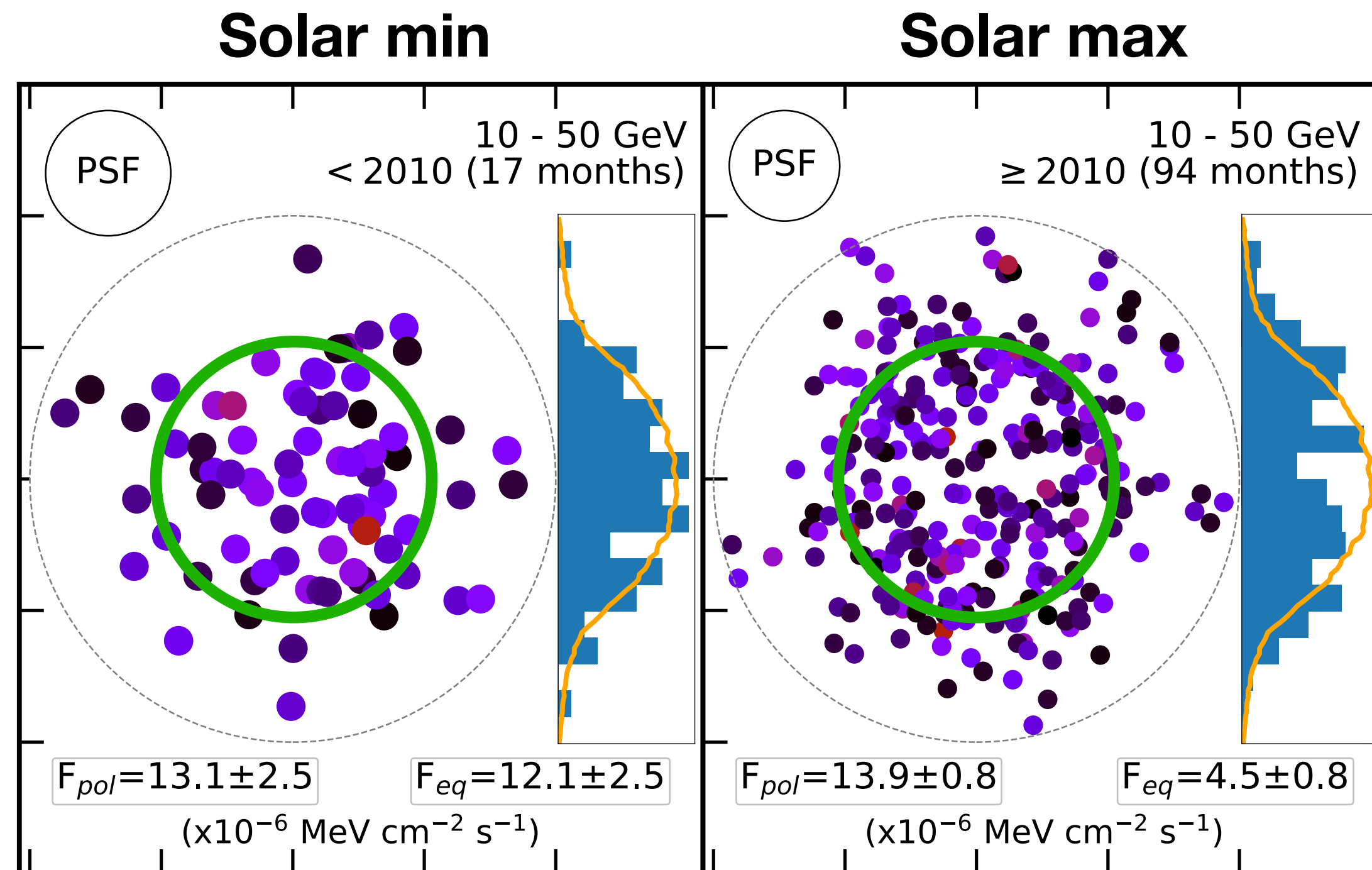
4. Anisotropic emission:

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

- Absorption from proton-proton interaction

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

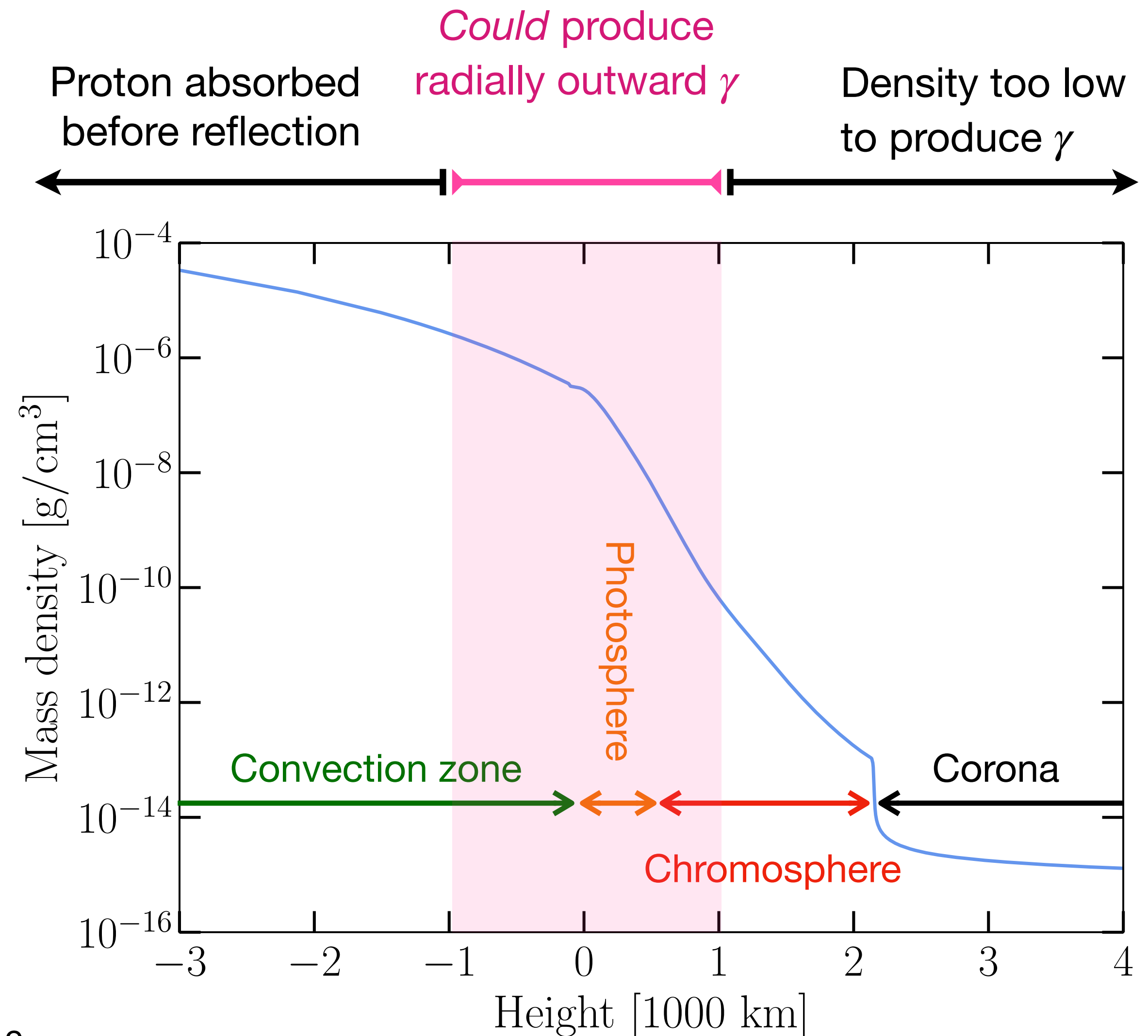
- Interacting at -1000 km to 1000 km

- Gamma rays from

Uppermost convection zone

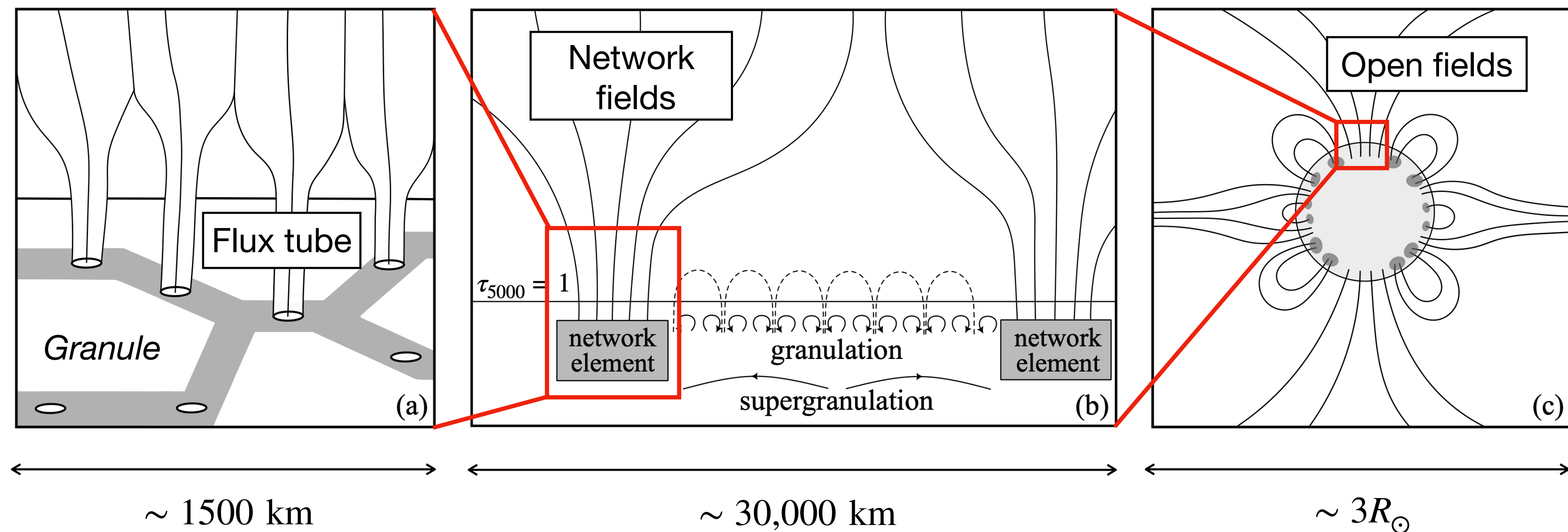
Photosphere

Lower chromosphere



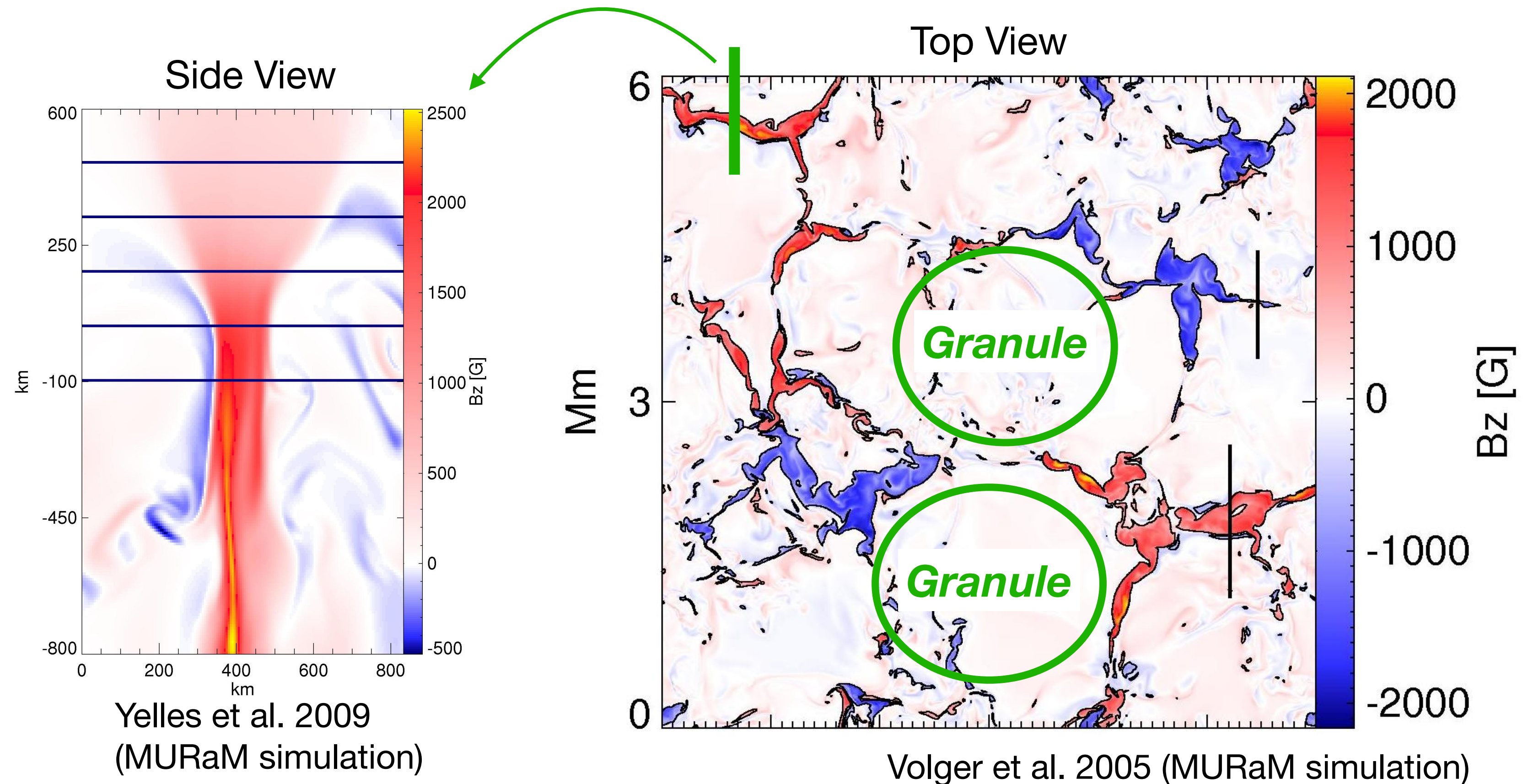
Coronal-hole Network Field & Open Field Lines

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



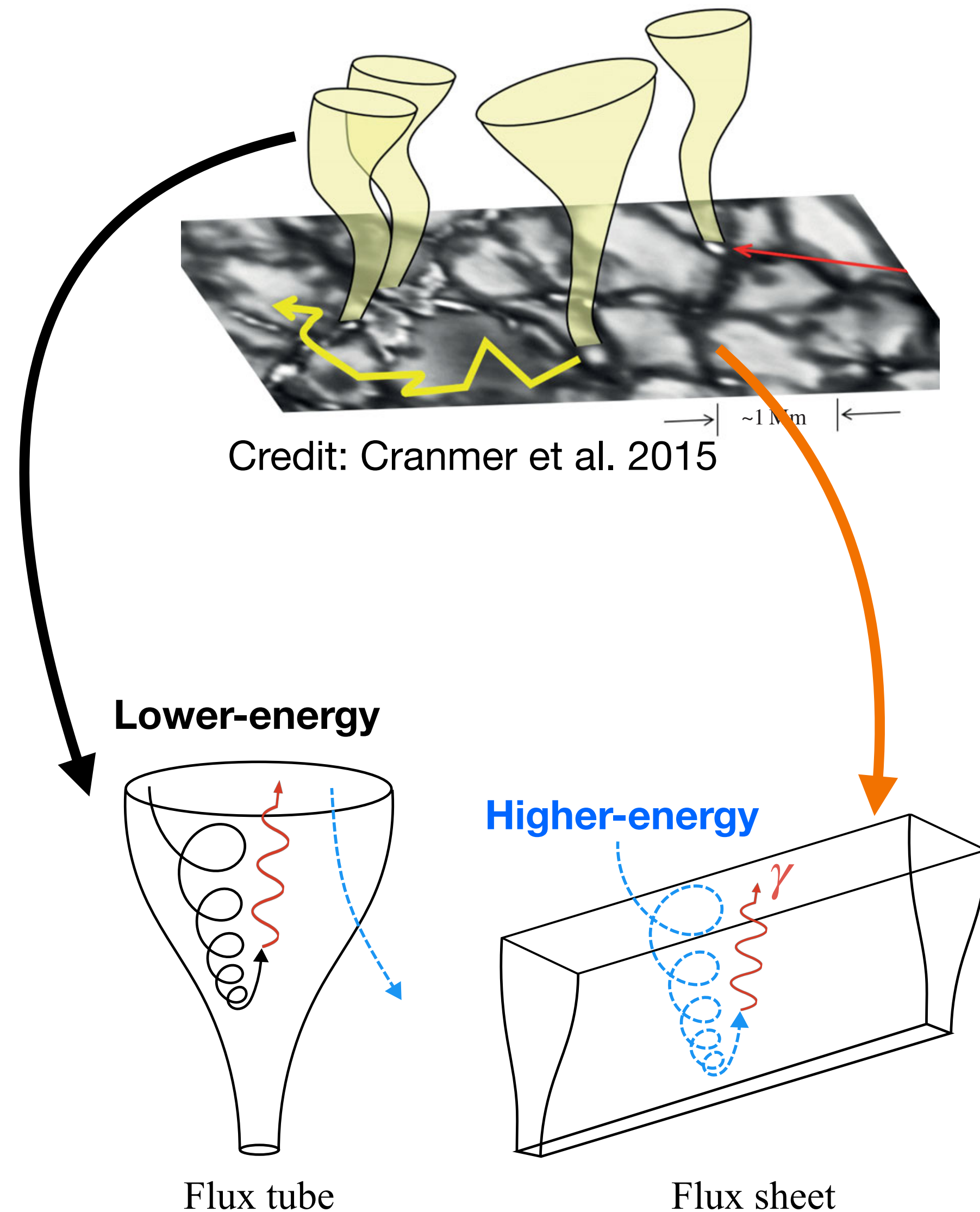
Redrawn illustration from Cranmer & van Ballegooijen 2005
and Wedemeyer-Bohm et al 2008

Thin Magnetic Sheets in the Intergranular Lanes



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

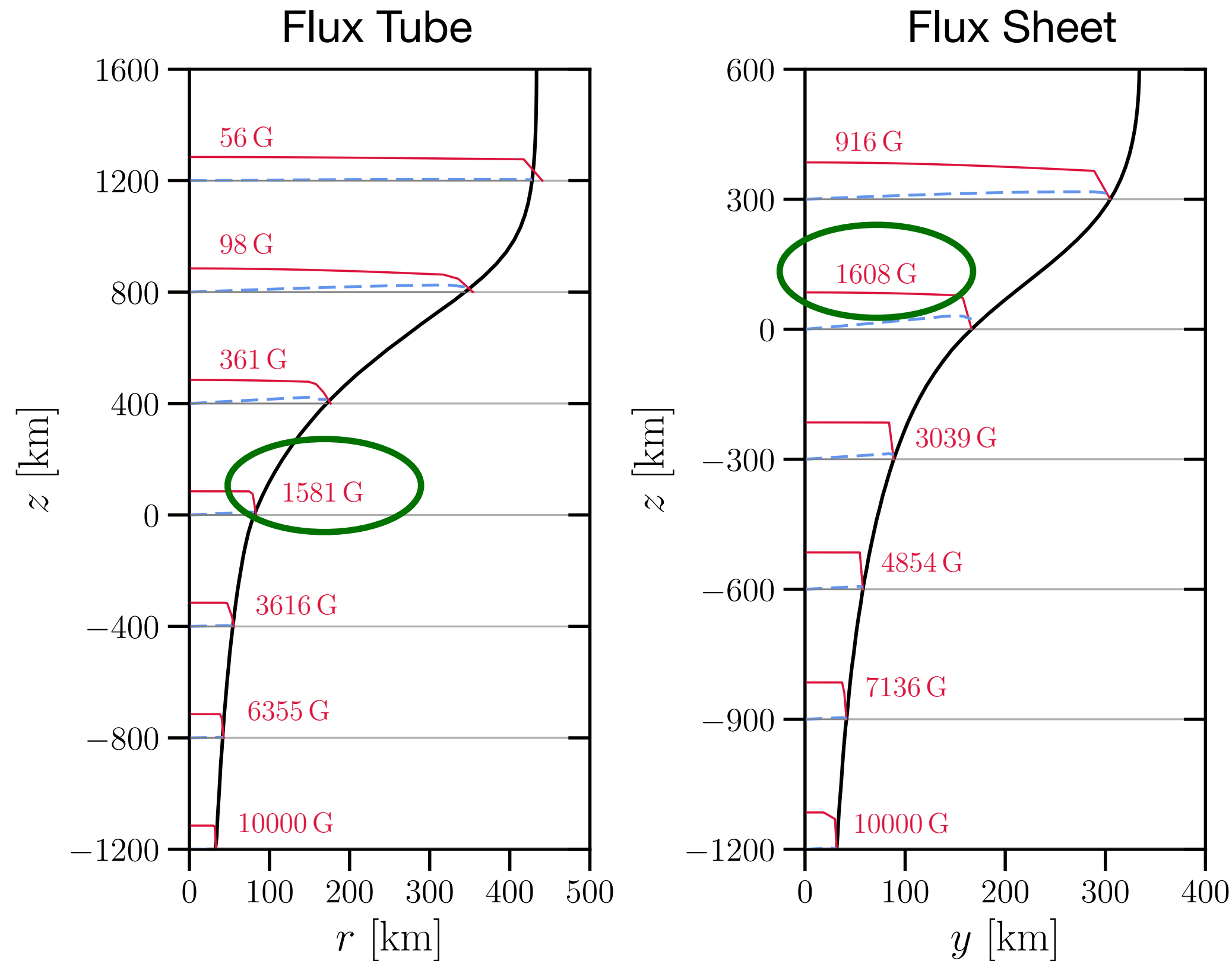
Main ideas of our model: flux tube + flux sheet



- One flux tube and repeating flux sheets
 - Tubes builds up **network element**
 - Sheet represents **intergranular sheet**
 - Sheet spacing 1200 km (size of one granule)
- GCR injection into tube at $z=1600$ km
 - **Lower-energy** GCRs bounded by tube
 - **Higher-energy** GCRs pass through tube; Some enter sheet

We numerically track 250,000 particle trajectories.

Magneto-hydrostatic Equilibrium



$$\mathbf{B} \cdot [\nabla P - \rho \mathbf{g}] = 0$$

Hydro-equilibrium parallel to $\mathbf{B}$

$$\mathbf{J} = \frac{1}{B^2} \mathbf{B} \times [\nabla P - \rho \mathbf{g}]$$

Balancing net hydro-force perp. to $\mathbf{B}$

$$\nabla \times (\nabla \times \mathbf{A}) = 4\pi \mathbf{J}$$

Ampere's law

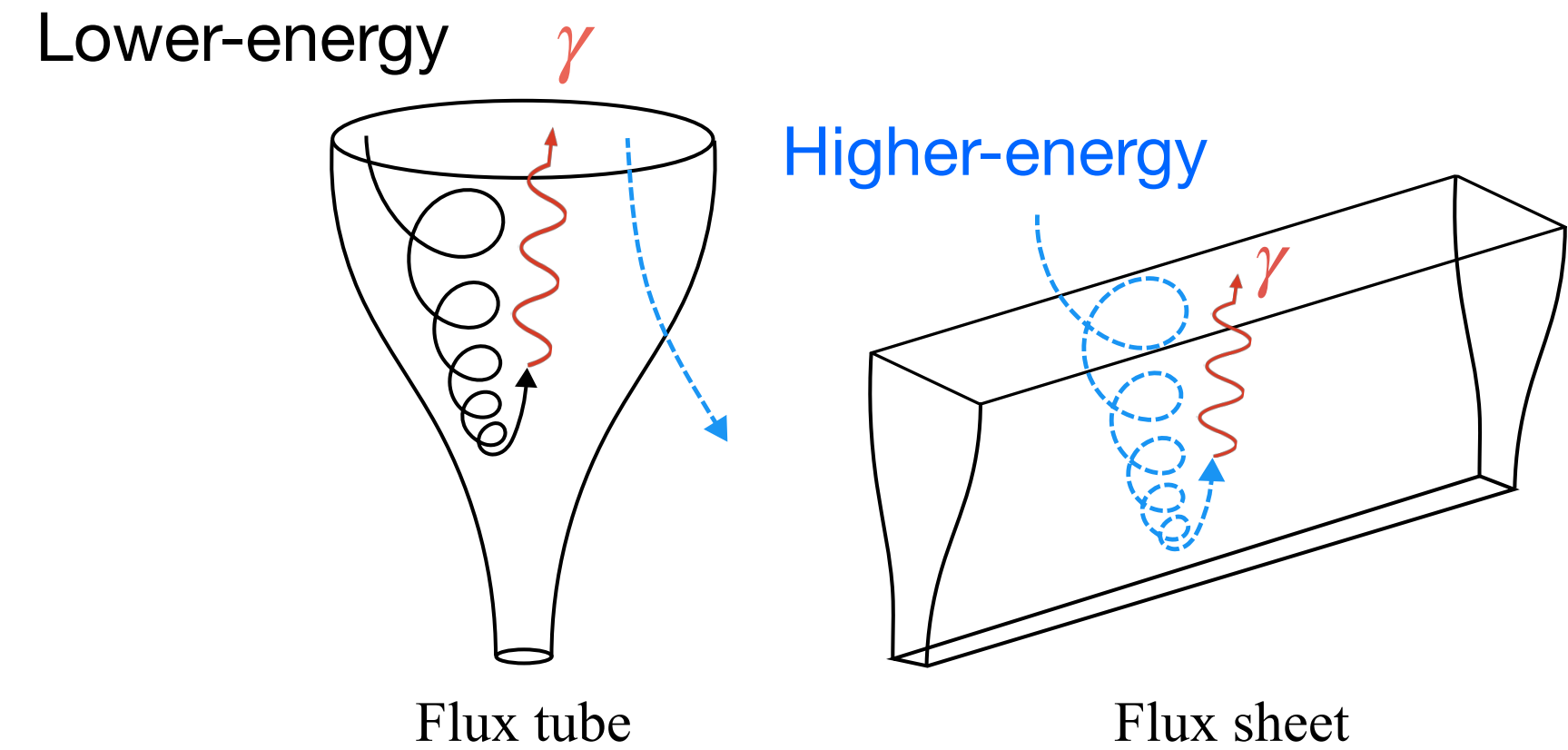
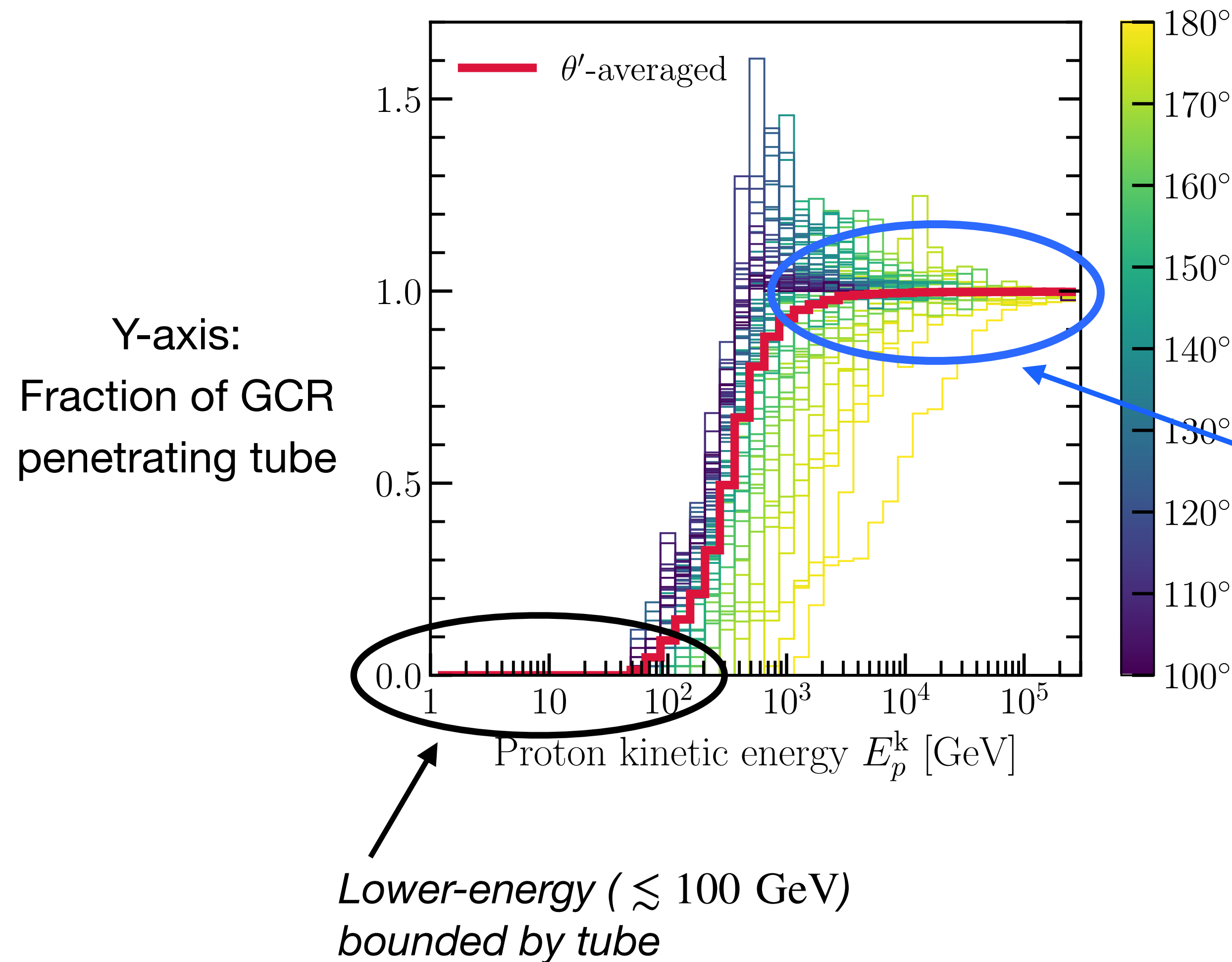
Tube
$$\frac{\partial^2 \Psi}{\partial r^2} - \frac{1}{r} \frac{\partial \Psi}{\partial r} + \frac{\partial^2 \Psi}{\partial z^2} = -4\pi r J$$
 (Grad-Shafranov eqn)

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

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

** Magnetic turbulence not considered here.

Our Result #1: Fraction of GCR Penetrating Tube

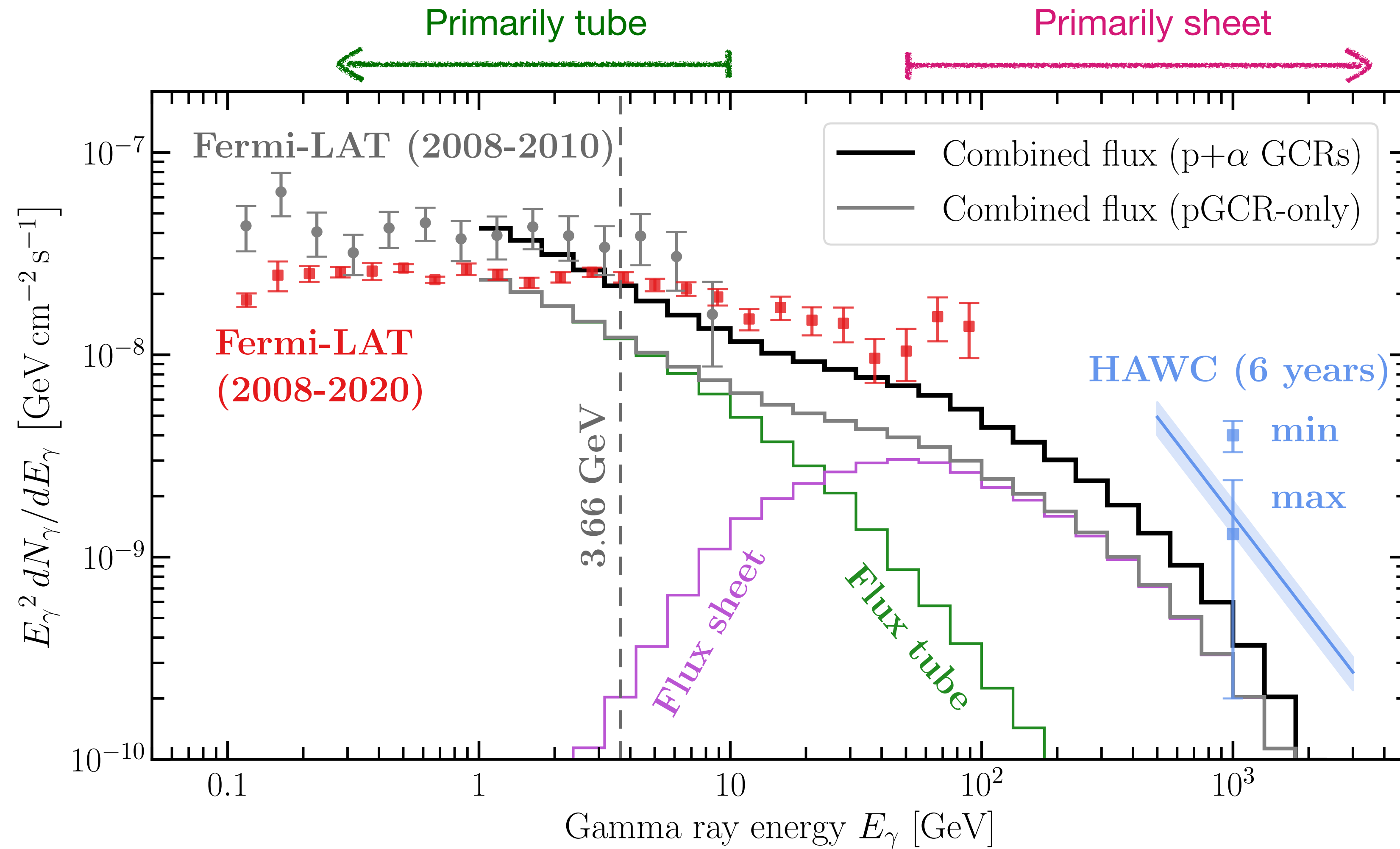


Higher-energy ($\gtrsim 500$ GeV) passing
through tube, some entering flux sheet

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

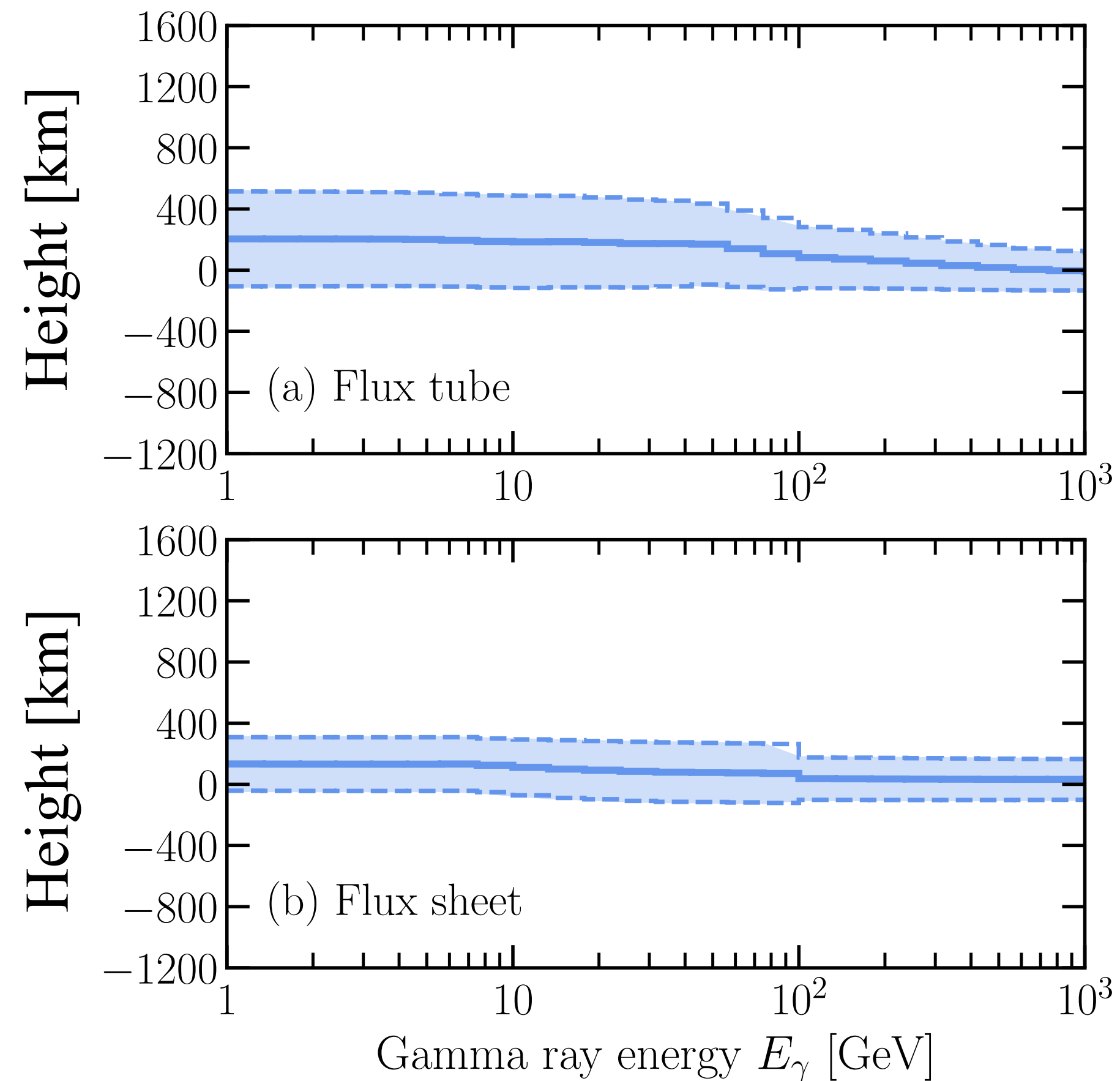
- Tube produces γ for $E_\gamma \lesssim 10$ GeV
- Sheet produces γ for $E_\gamma \gtrsim 50$ GeV

Our Result #2: Gamma-Ray Spectrum

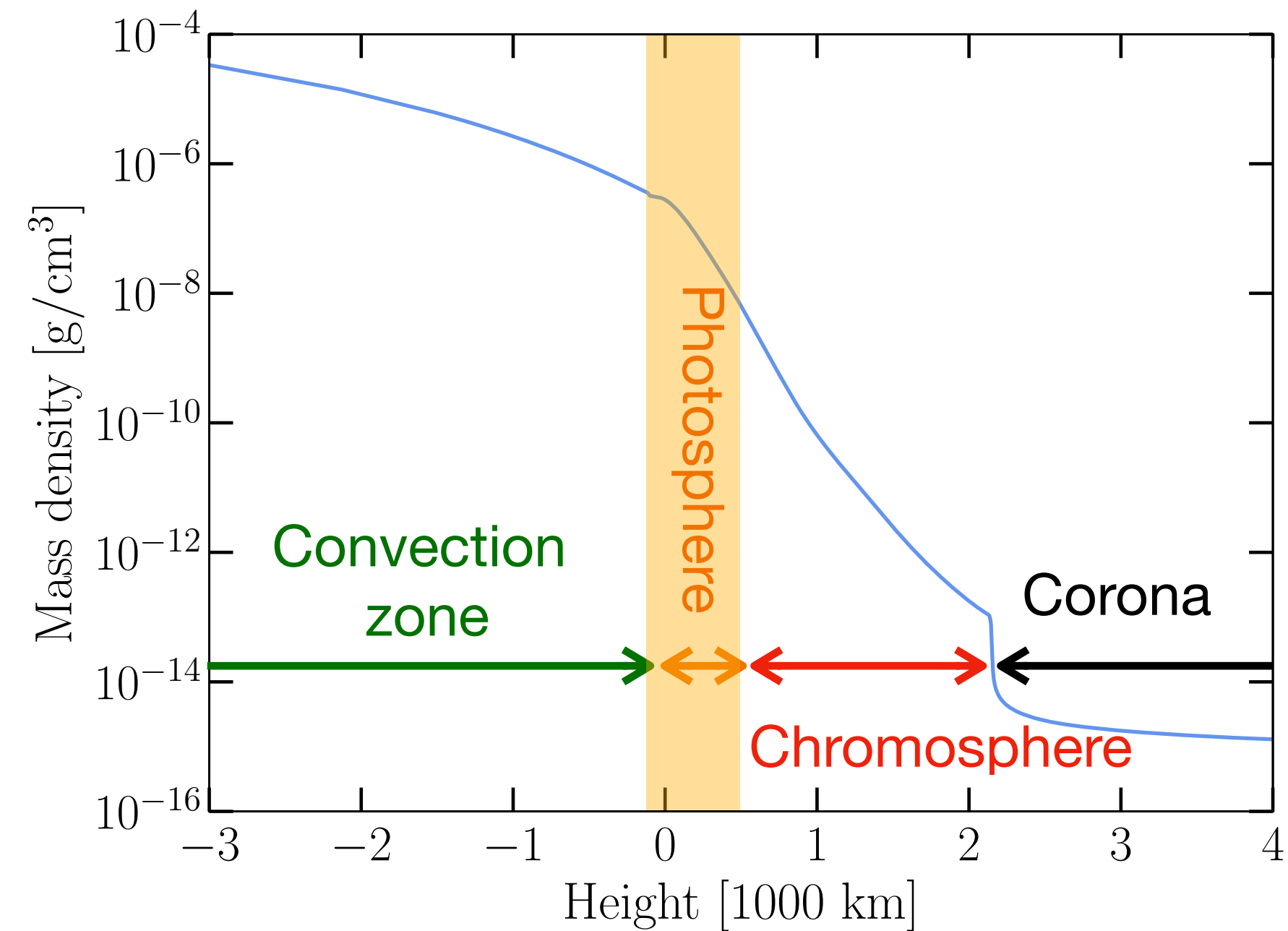


Finite-sized structure is the key!

Our Result #3: Average Emission Height



JTL et al. 2024 (ApJ 961, 167)



- Emission mainly happens in height $z = -100$ km to 400 km, corresponding to **photosphere & uppermost convection zone**
- A new tool to probe photospheric magnetism

Conclusions and Outlook

- A simple model consisting of **one tube** and **one sheet** in the -1000 km to 1600 km height range
 - Lower-energy gamma rays from flux tube, higher-energy gamma rays from intergranular sheet
 - Finite-sized flux sheet results in ineffectiveness of capturing higher-energy GCRs
 - steep gamma spectrum at $\sim$ TeV seen by HAWC.
- The **anti-correlation** between gamma-ray flux and solar cycle?
 - Quiet vs. active regions? Magneto-convection? GCR transport?
- Exciting opportunities ahead!
 - **Solar-disk probe** of gamma rays to reveal small-scale magnetic fields at solar surface:
 - Small-scale dynamo vs. magneto-convection