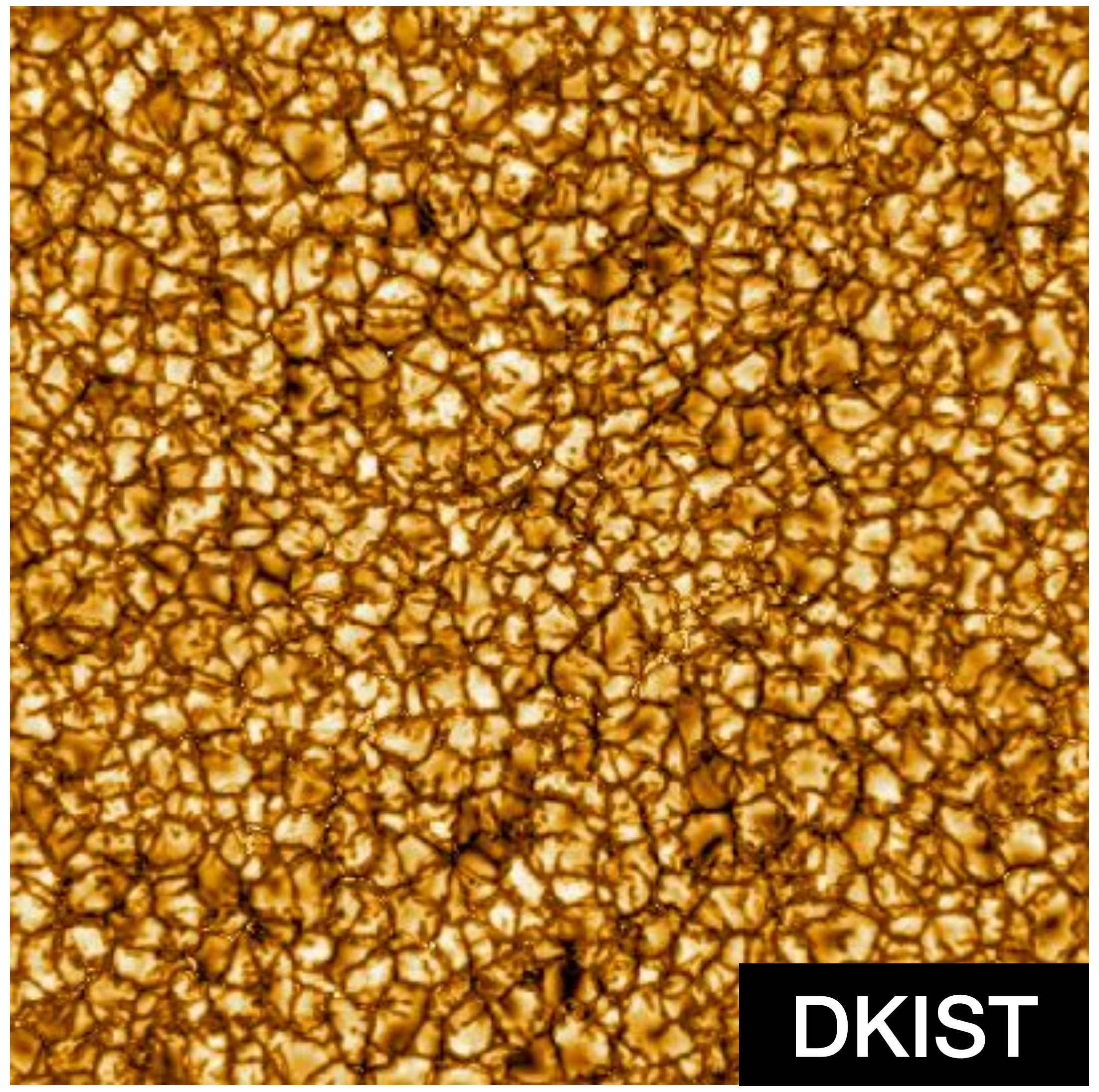
Flux Expulsion
&
Gamma-Ray Emission From the Sun



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In collaboration with

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CCAPP Symposium

September 18, 2025

CCAPP

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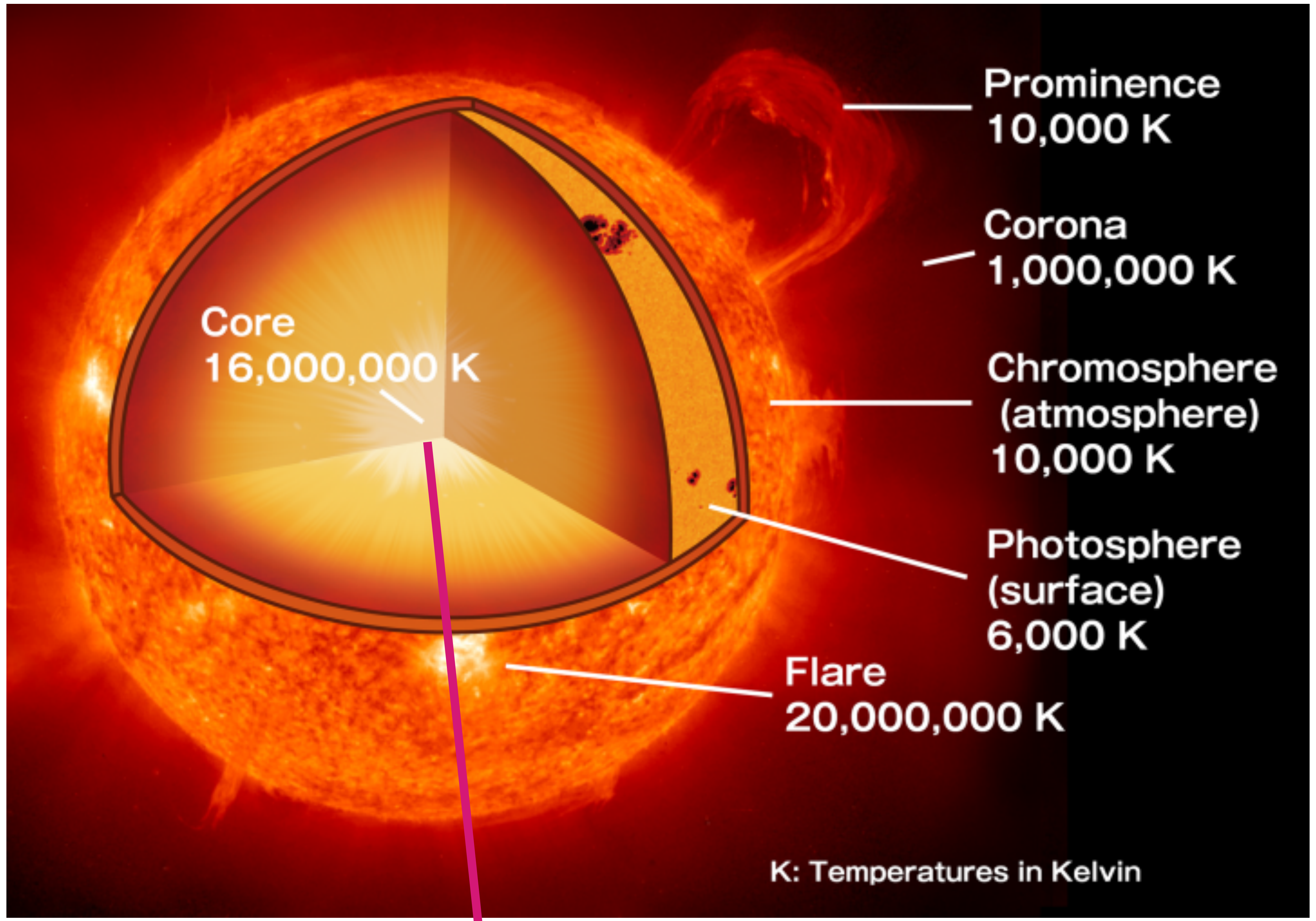
The Ohio State University

Solar Atmosphere is “*hotter*” than we think

(Let’s start from Introduction of the Sun 101)



See Melanie’s poster for using $^{8}\mathrm{B}$ (Boron 8) neutrinos to probe the solar interior structure.

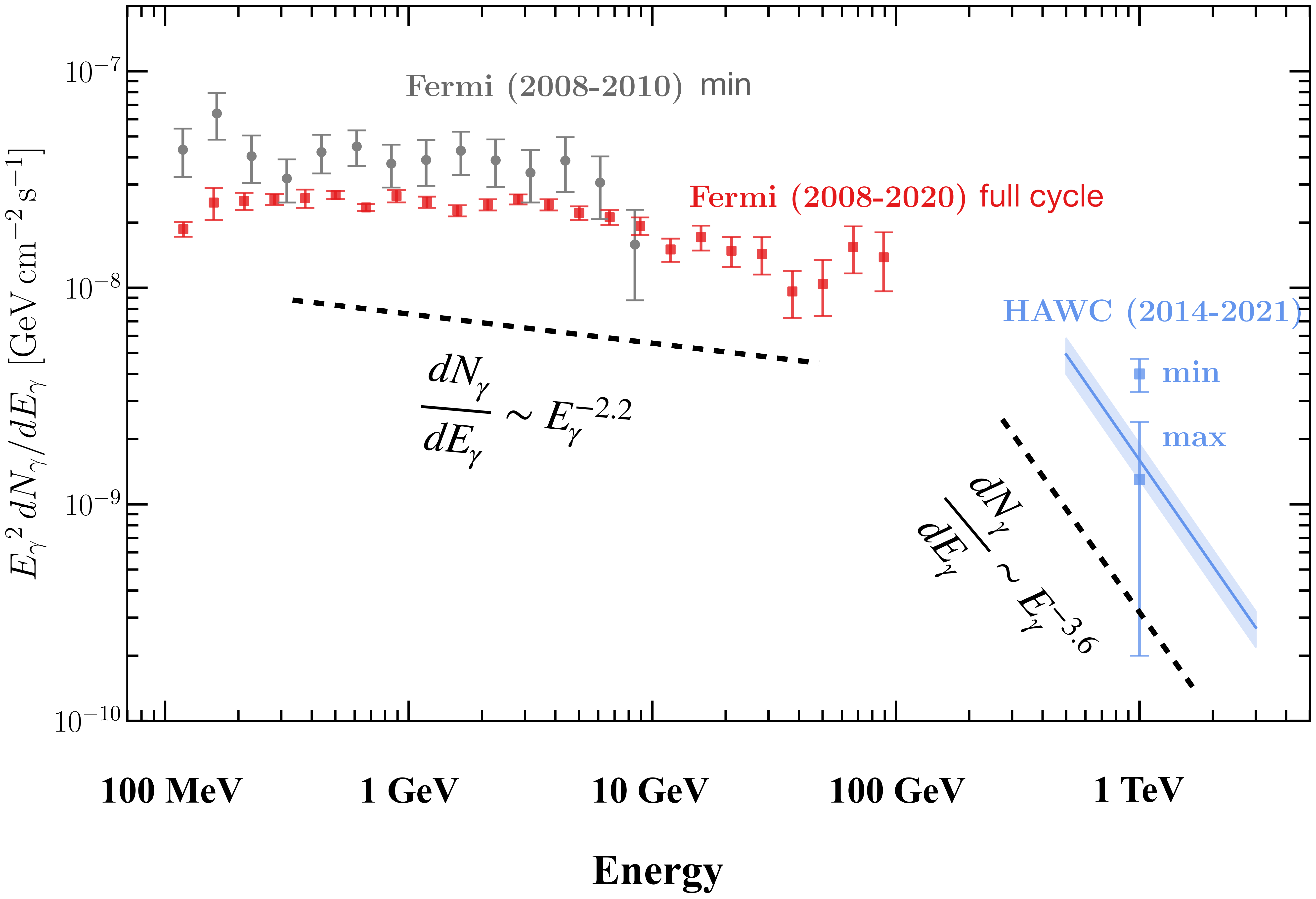
- Photosphere & chromosphere is 6,000-10,000 Kelvin, visible light ($\sim$1 eV)
- Corona is million Kelvin, EUV and X-ray ($\lesssim 1$ keV)
  - Wave-driven turbulence and reconnection
- Large solar flares produce nonthermal particles and gamma rays up to few GeV
  - Transient signal — can be removed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

Surprisingly, gamma-ray observatories see *continual* GeV—TeV emission from the Sun!

Fermi-LAT and HAWC see GeV—TeV γ-rays

Fermi-LAT

- Space-based detector
- 20 MeV to 200 GeV



HAWC

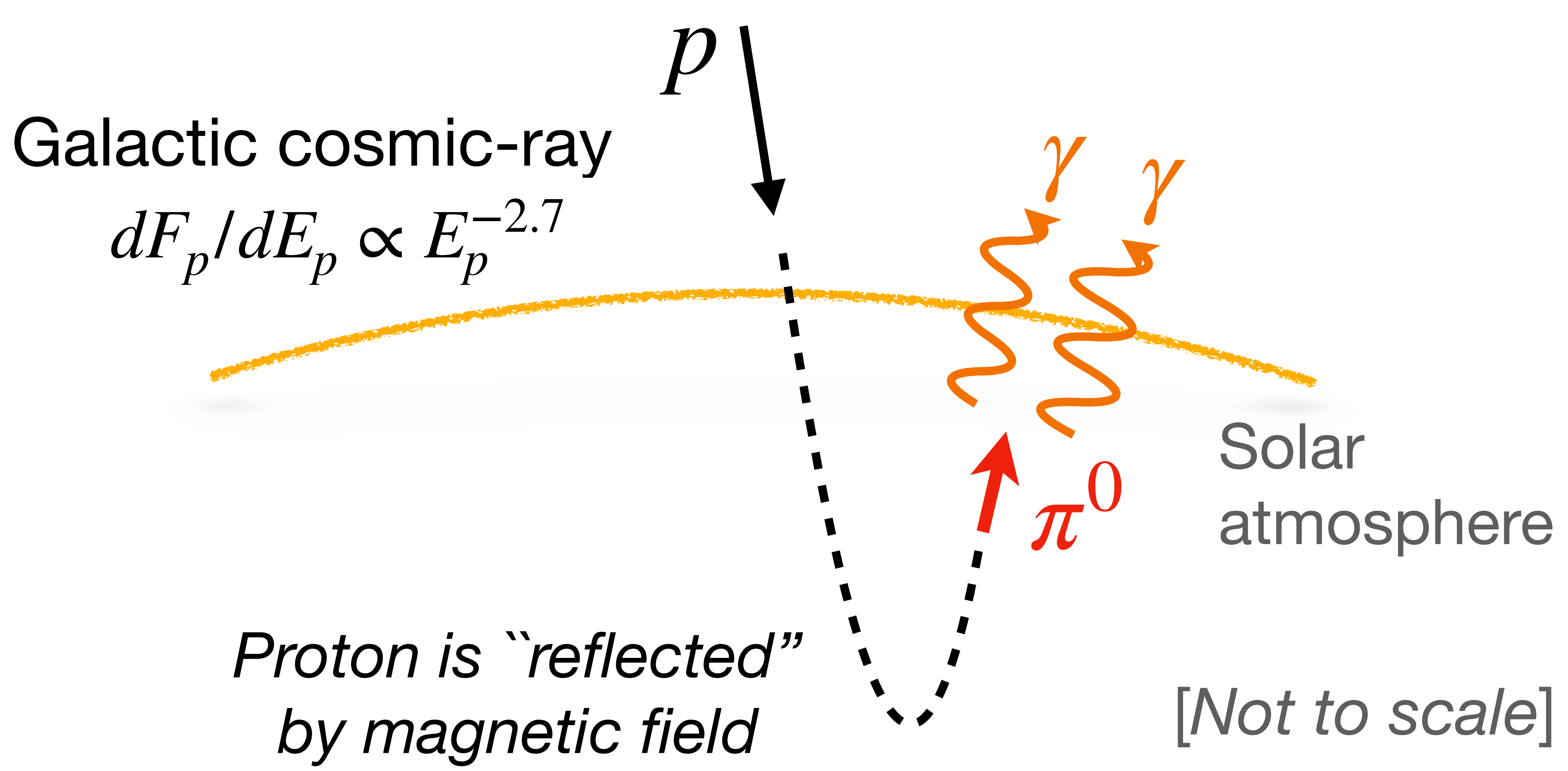
- Ground-based Cherenkov detector in Mexico
- multi-TeV gamma rays and cosmic rays

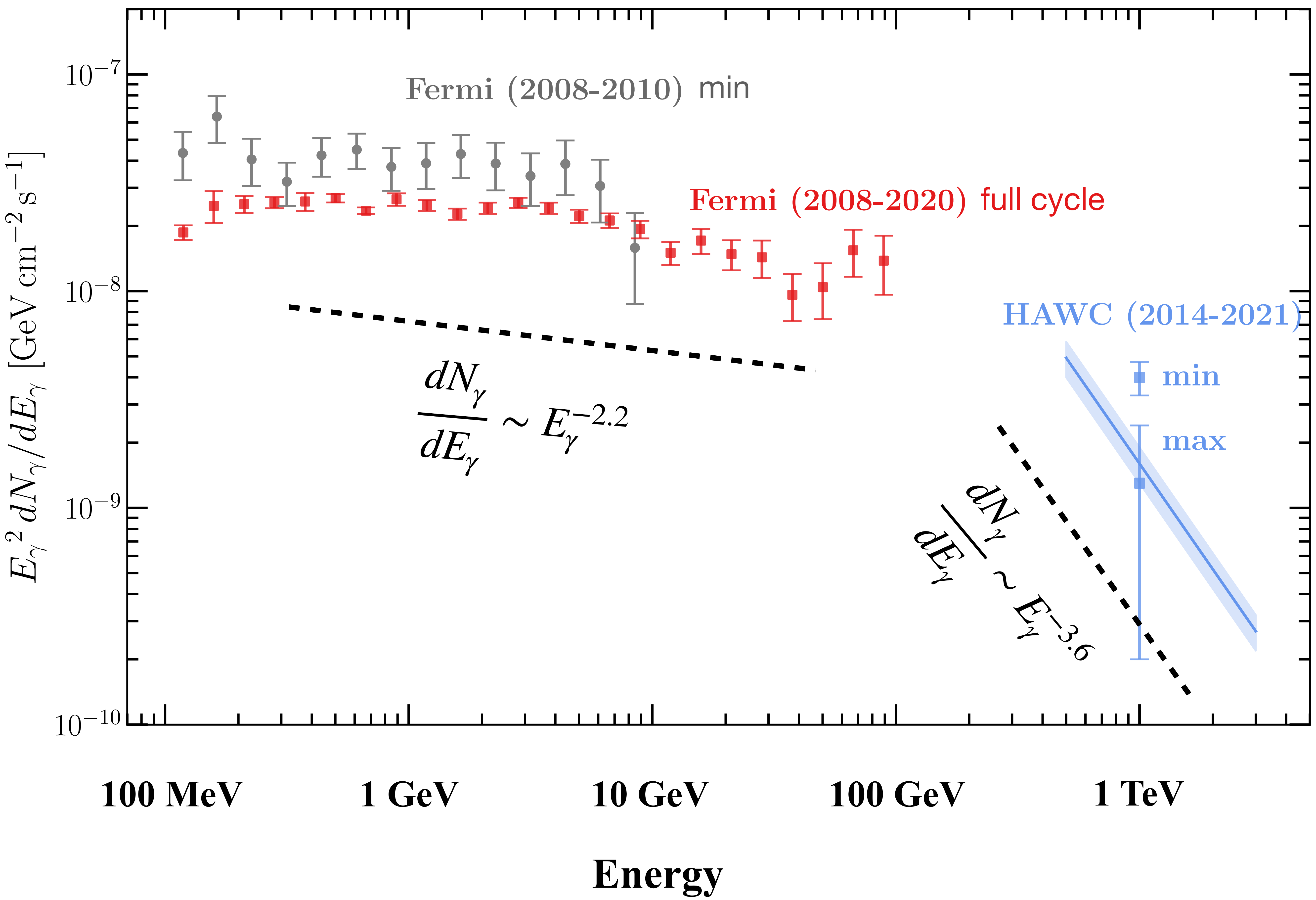
Channel 1: Continual Emission from Solar Disk

Focus of this talk!

Hadronic scattering in the solar disk

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



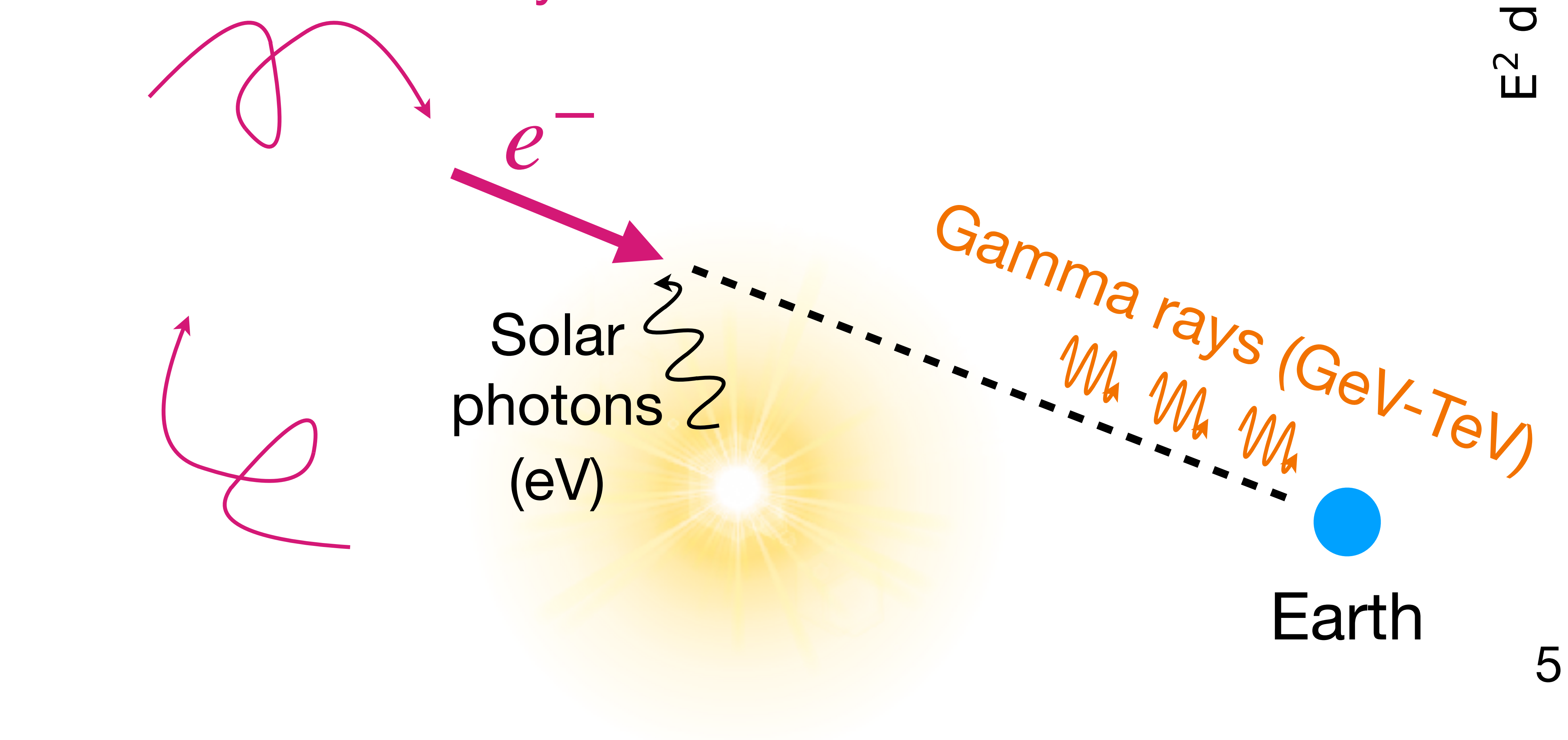


Channel 2: Continual Emission from Solar Halo

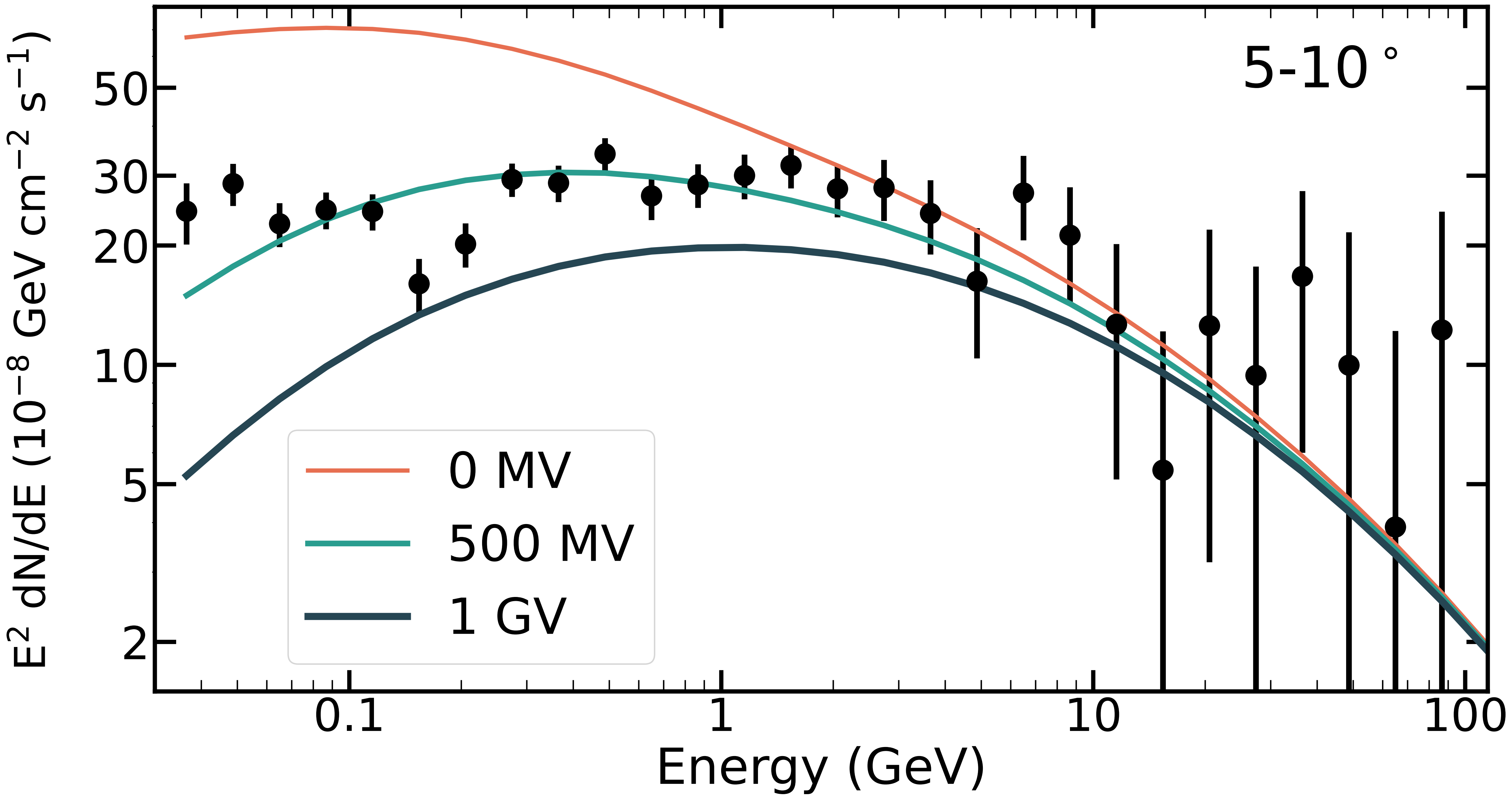
(Not the focus of this talk)

Inverse-Compton scattering in the solar halo

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

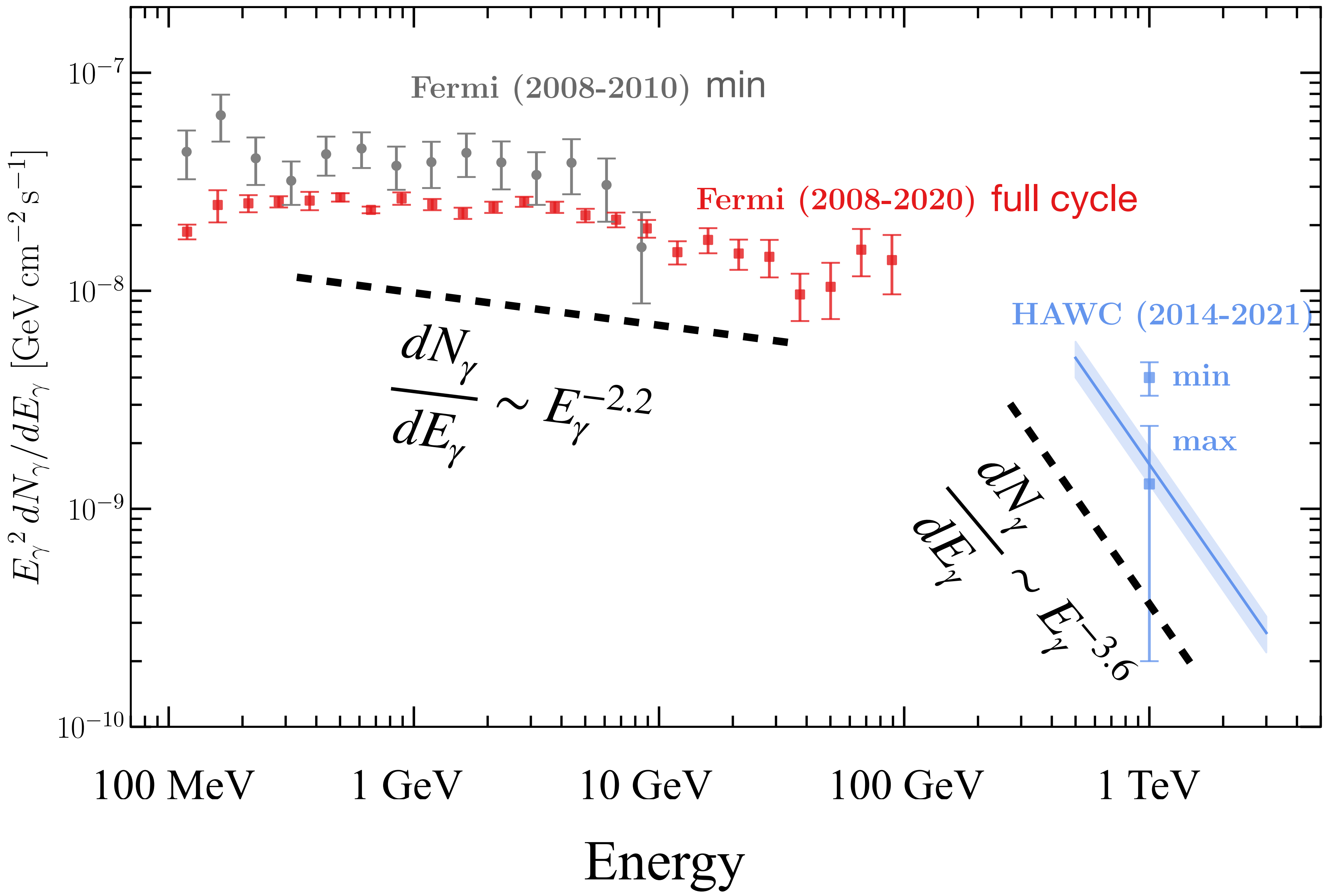


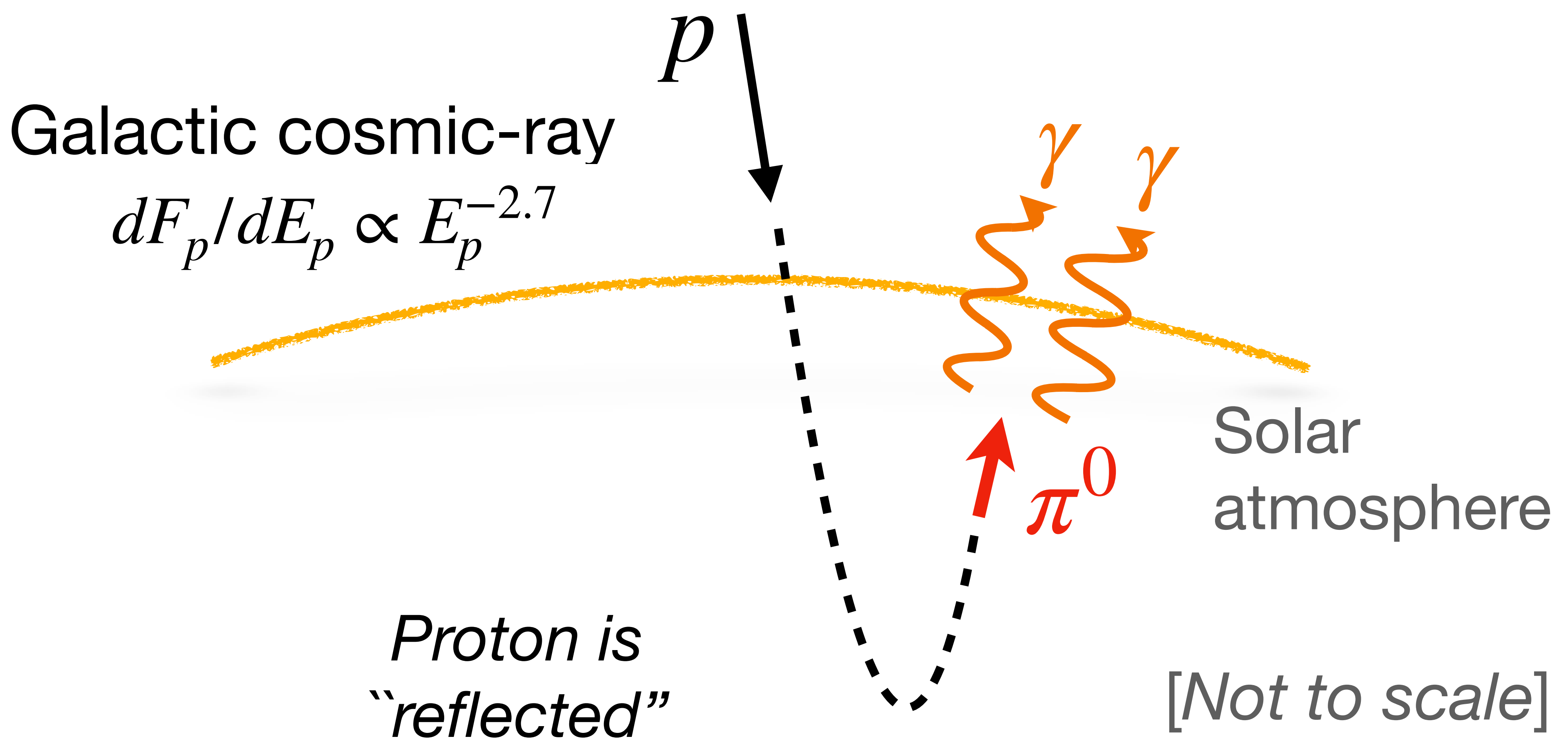
T. Linden, **JTL**, et al 2025



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

Why Study *Solar-Disk* Gamma-Ray Emission?



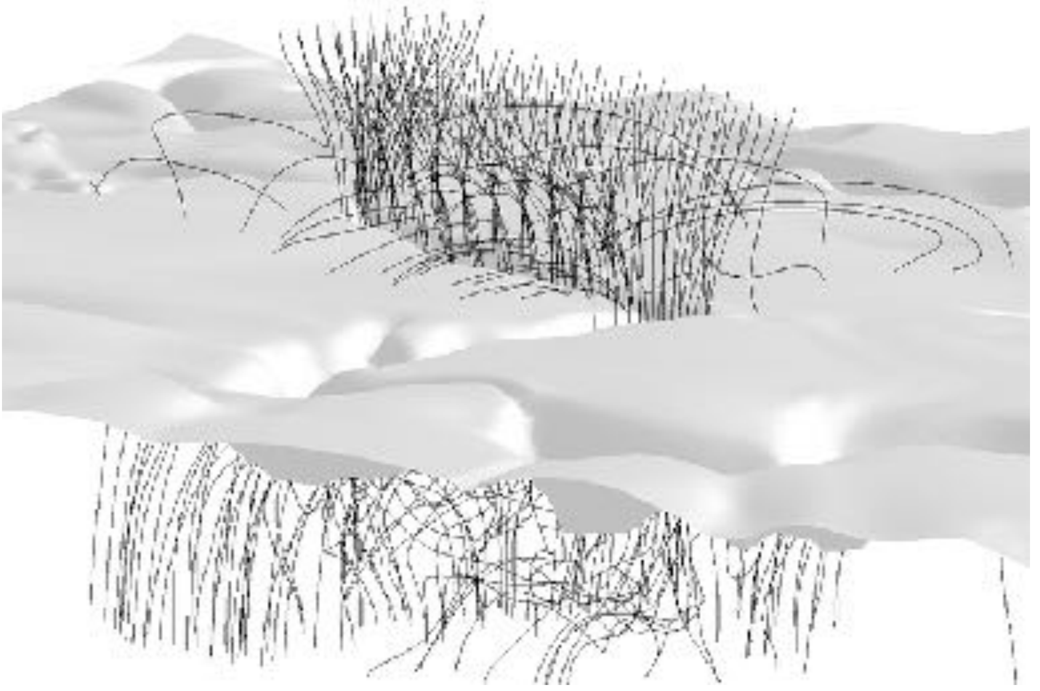


Ideally, solar-disk gamma-ray data tells us:

1. Transport of relativistic protons deep in the solar atmosphere where *in situ* spacecrafts cannot reach
   - Indirectly probing particle transport — for both Galactic Cosmic Rays and Solar Energetic Particles
   - Solar weather prediction

2. Mapping photospheric magnetic fields

Where are we now?



Challenges:

1. Poor angular resolution from Fermi-LAT and HAWC
2. Long observation time (2-14 years), whereas topology of magnetic field changes every few days or weeks

Pratical Approach:

1. Use theory to understand the limited γ-ray data
   - Spectral slope and spectral break
   - Anti-correlation between γ emission and solar cycle
   - Rules out incorrect magnetic field modeling
2. Solar weather prediction 20-30 years later?

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

- Absorption from proton-proton interaction

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

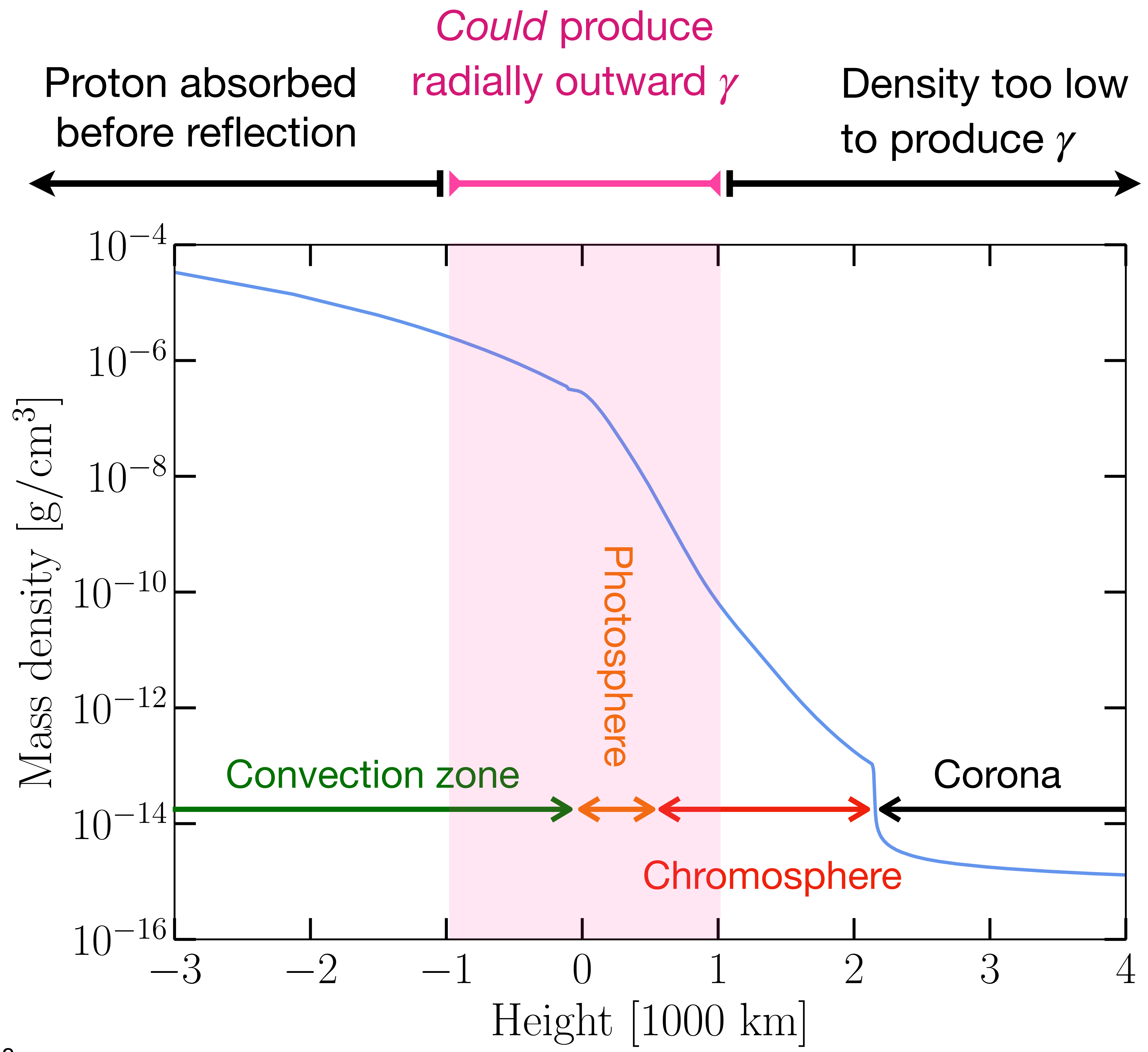
  - Interacting at -1000 km to 1000 km

- Gamma rays from

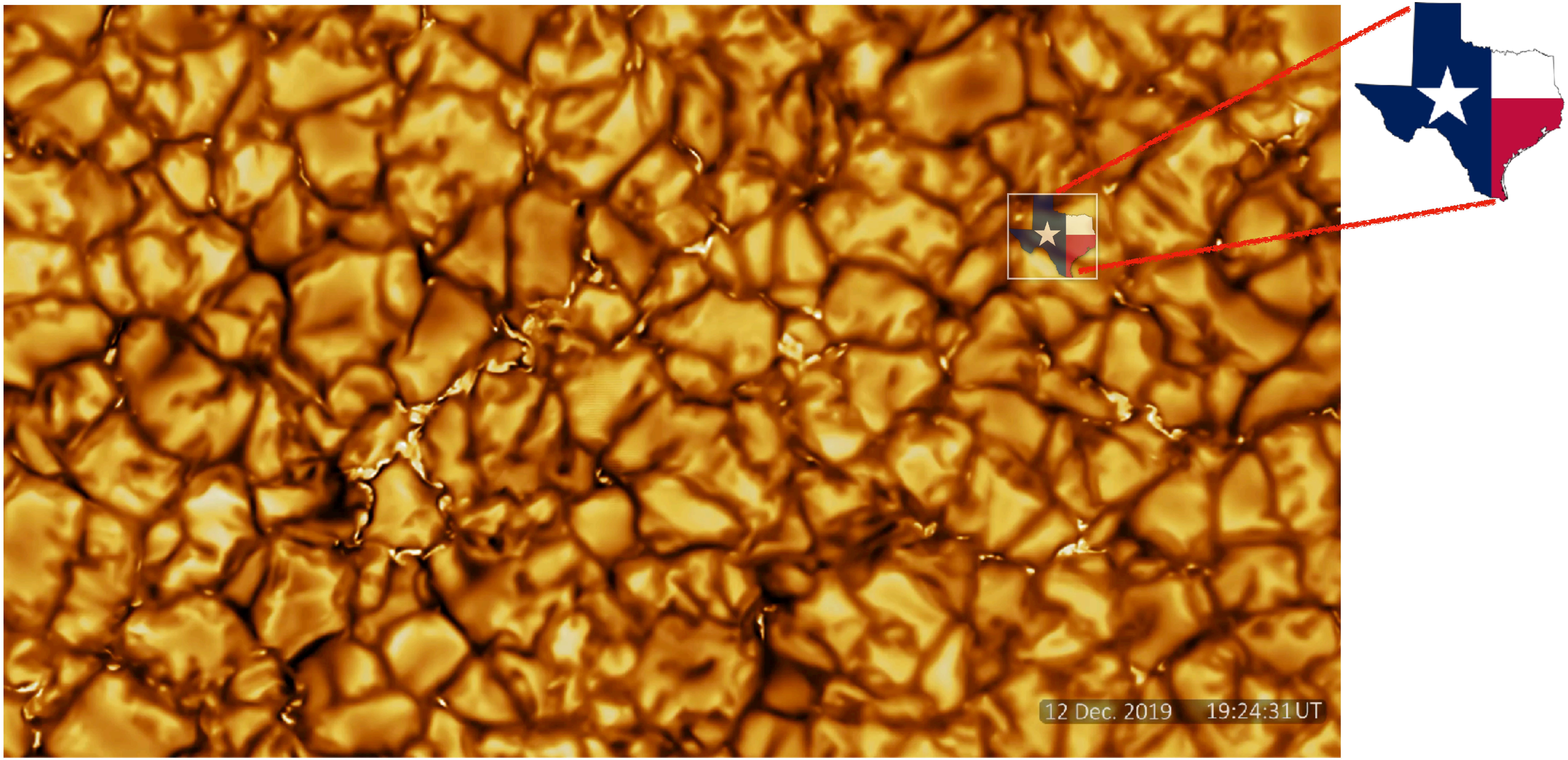
  Uppermost convection zone

  Photosphere

  Lower chromosphere



DKIST Image of Photospheric Surface

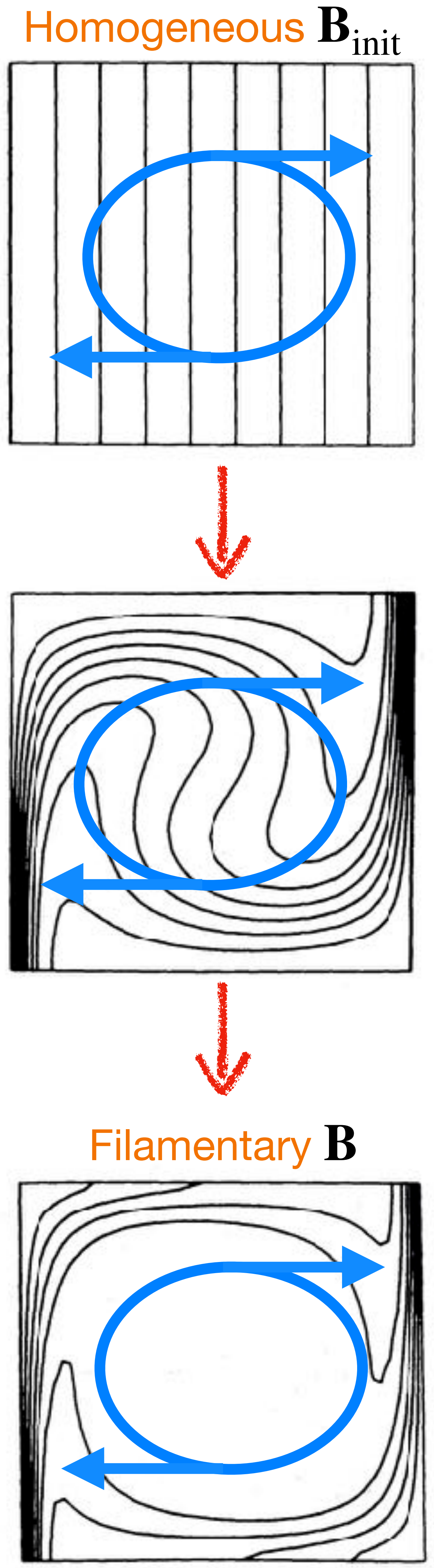


Movie Credit: DKIST

Flux Expulsion & Homogenization

- Pioneered by the late Nigel Weiss in 1966
- Large magnetic Reynolds number, $\mathrm{Rm} \gg 1$
- Convection cell winds up and fold the magnetic field
- Fields are expelled to boundary layer (cell edge)
  - Hence “flux expulsion”
- Inside the convection cell: $\mathbf{B} \to 0, \quad A \to \mathrm{const}\,.$
  - Hence “Homogenization”

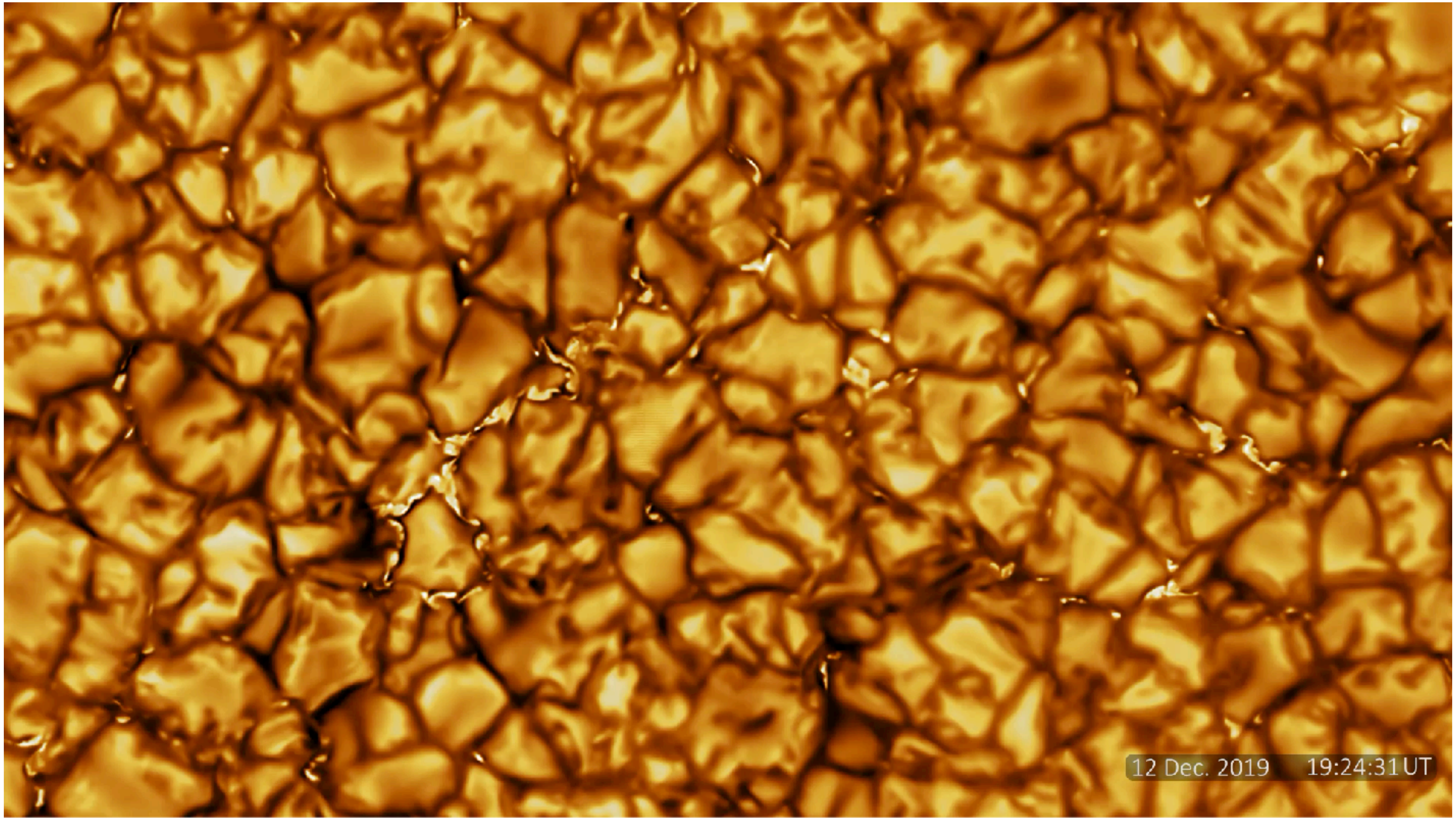
- At surface of the Sun:
  - Granular cell at solar surface is eddy of size ~ 1000 km
  - kG magnetic fields formed at granular lane (e.g., Volger et al. 2005)



(1936-2020)

Image Credit:
Galloway & Weiss 1981

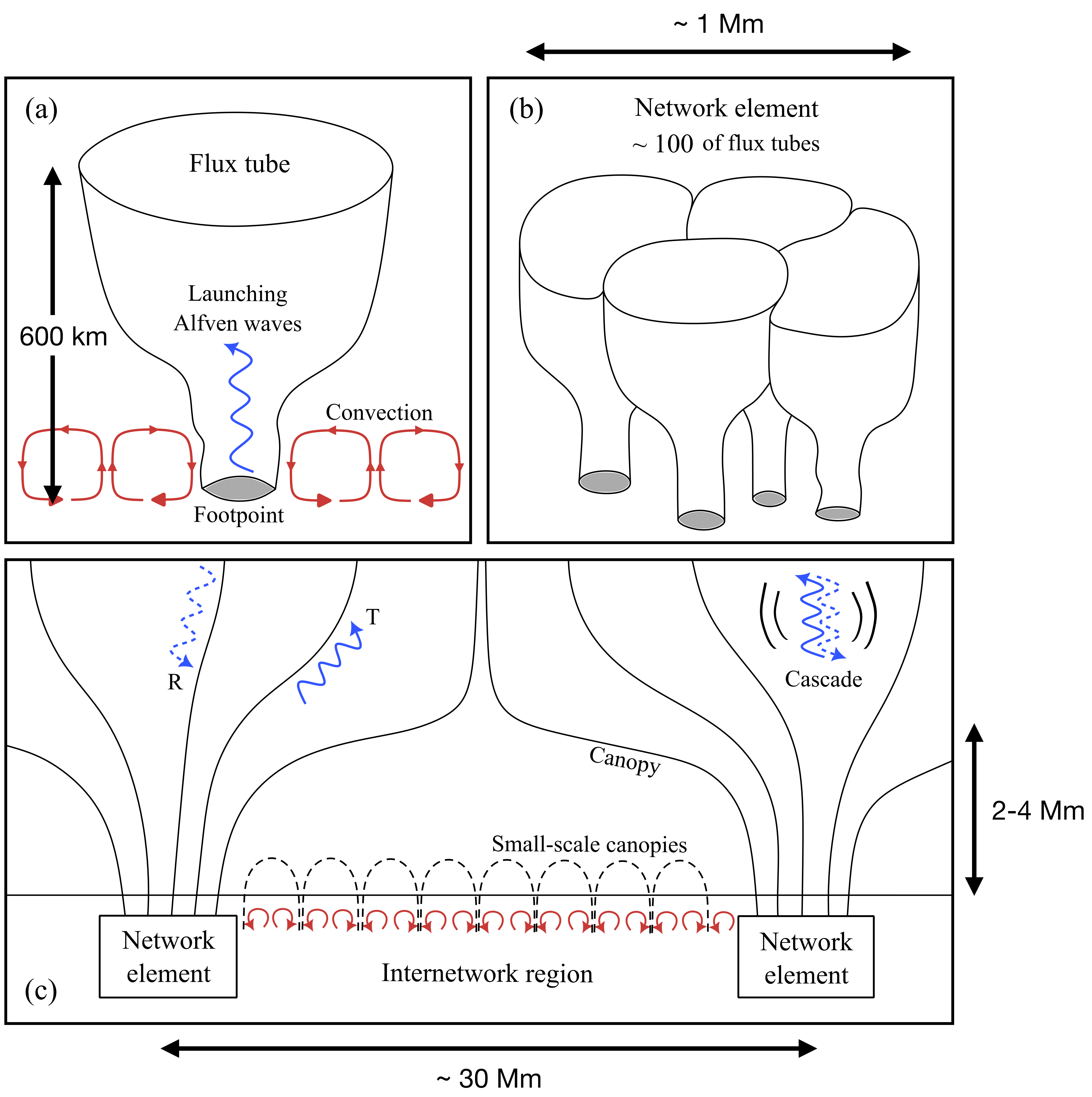
Filamentary Magnetic Fields at Dark Lanes



Movie Credit: DKIST

Spatial Scales

1. Volume-filling magnetic fields above z = 2-4 Mm
2. Filamentary fields below z = 2-4 Mm
   - Due to convection and flux expulsion
   - ~ few x 100 km wide tubes and sheets at photosphere
3. Alfven wave turbulence scale below ~ 10 km



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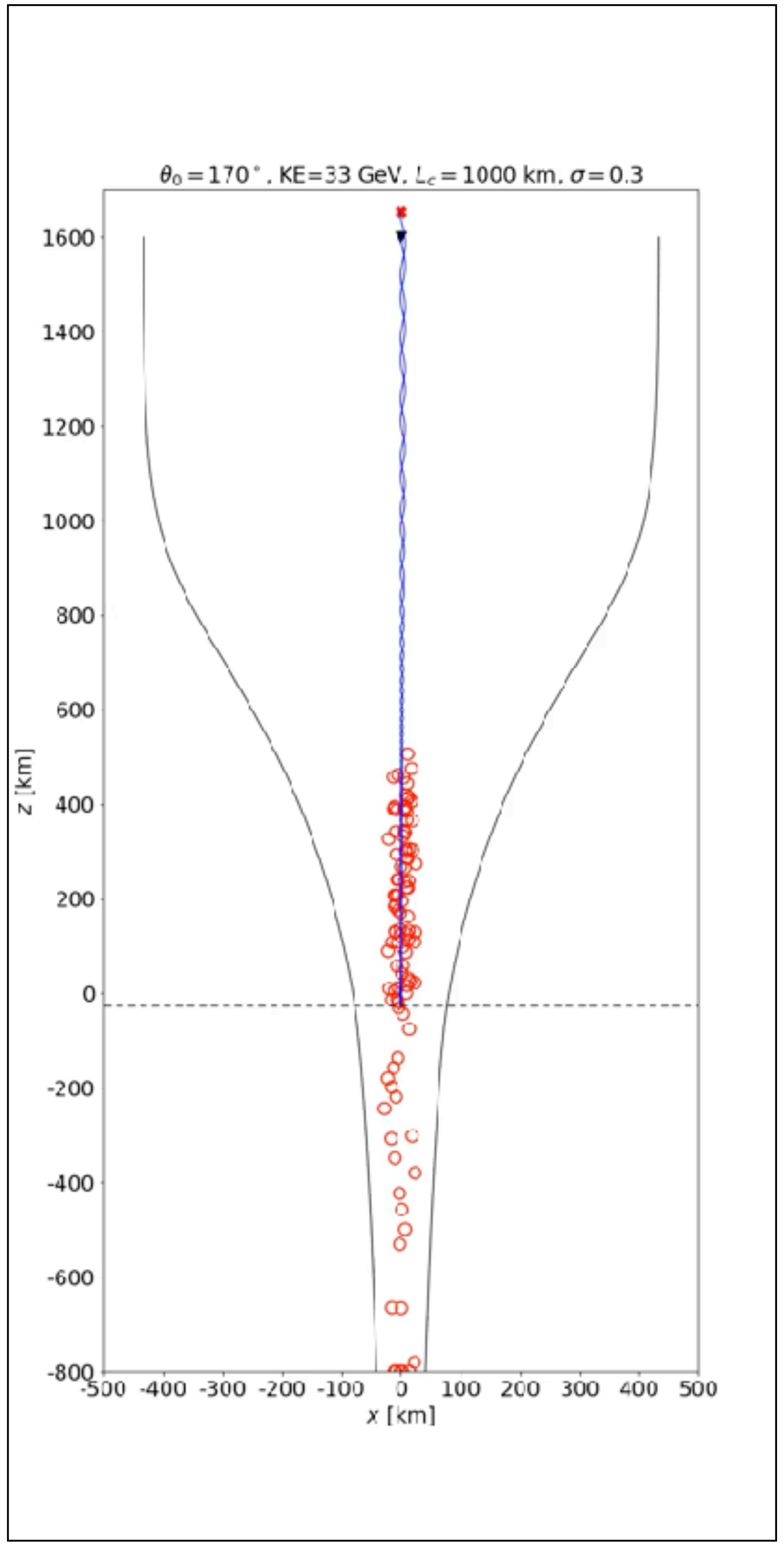
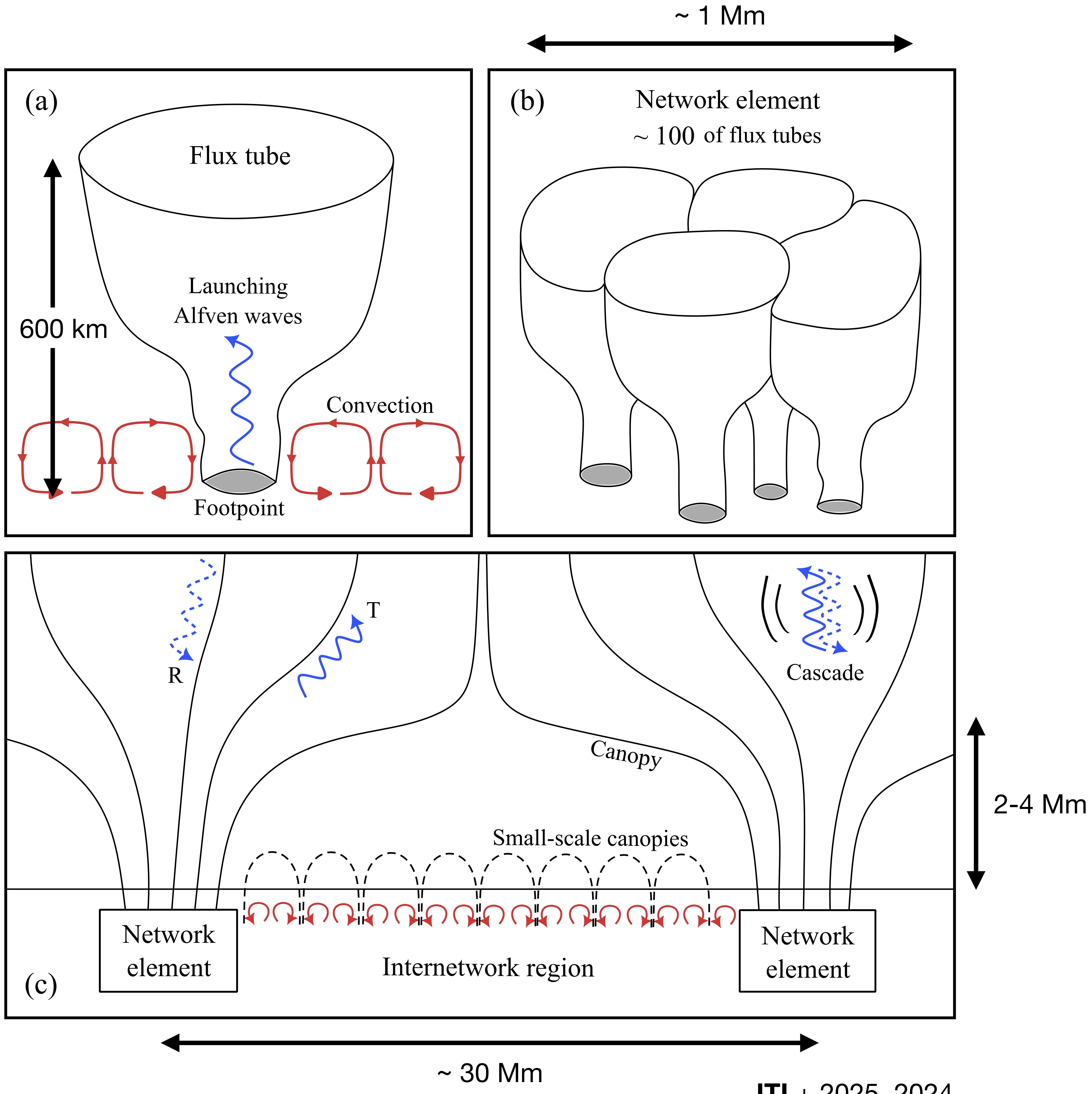
Magnetic Mirroring

** Bottle squeezes out charged particles





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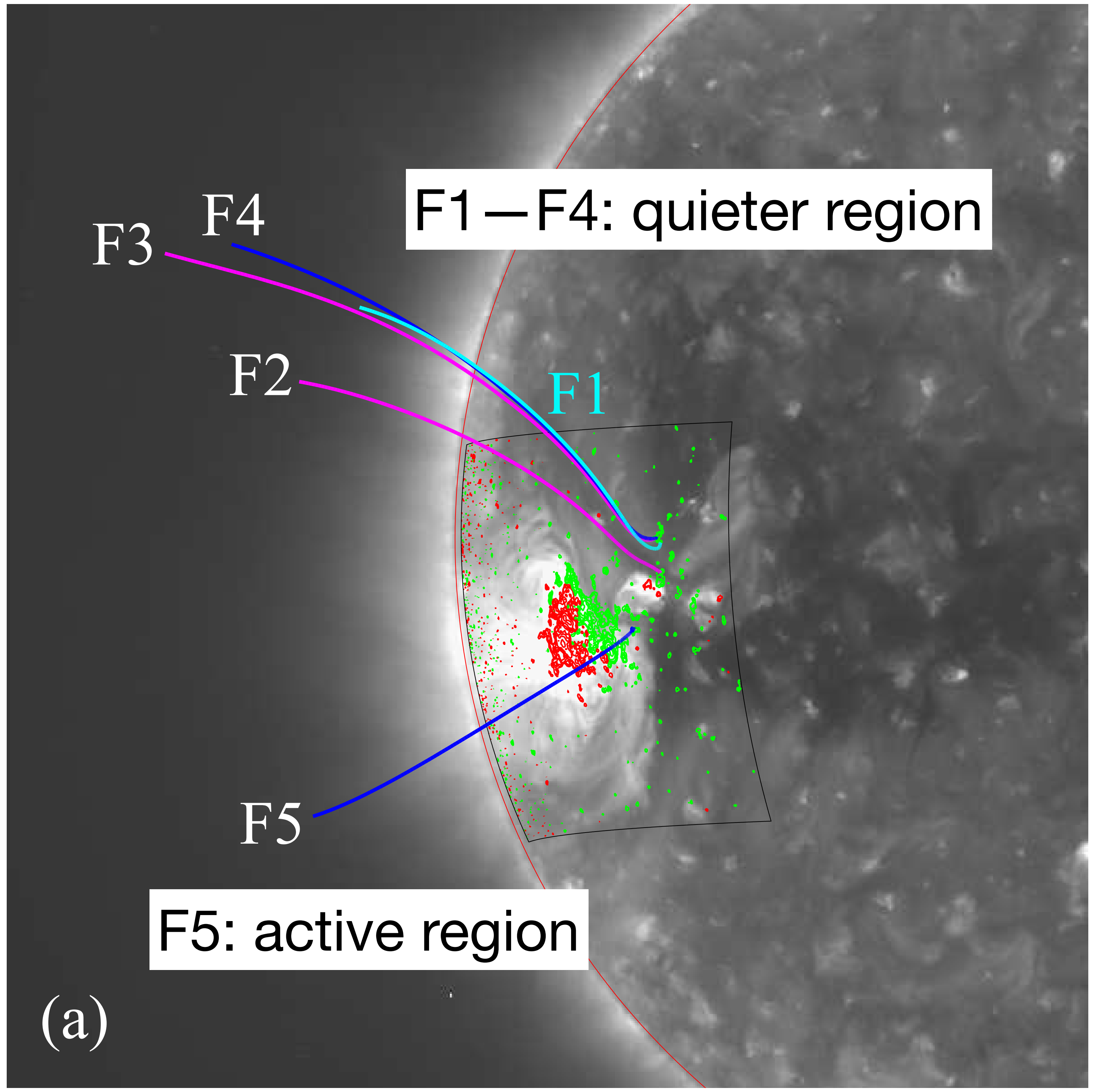
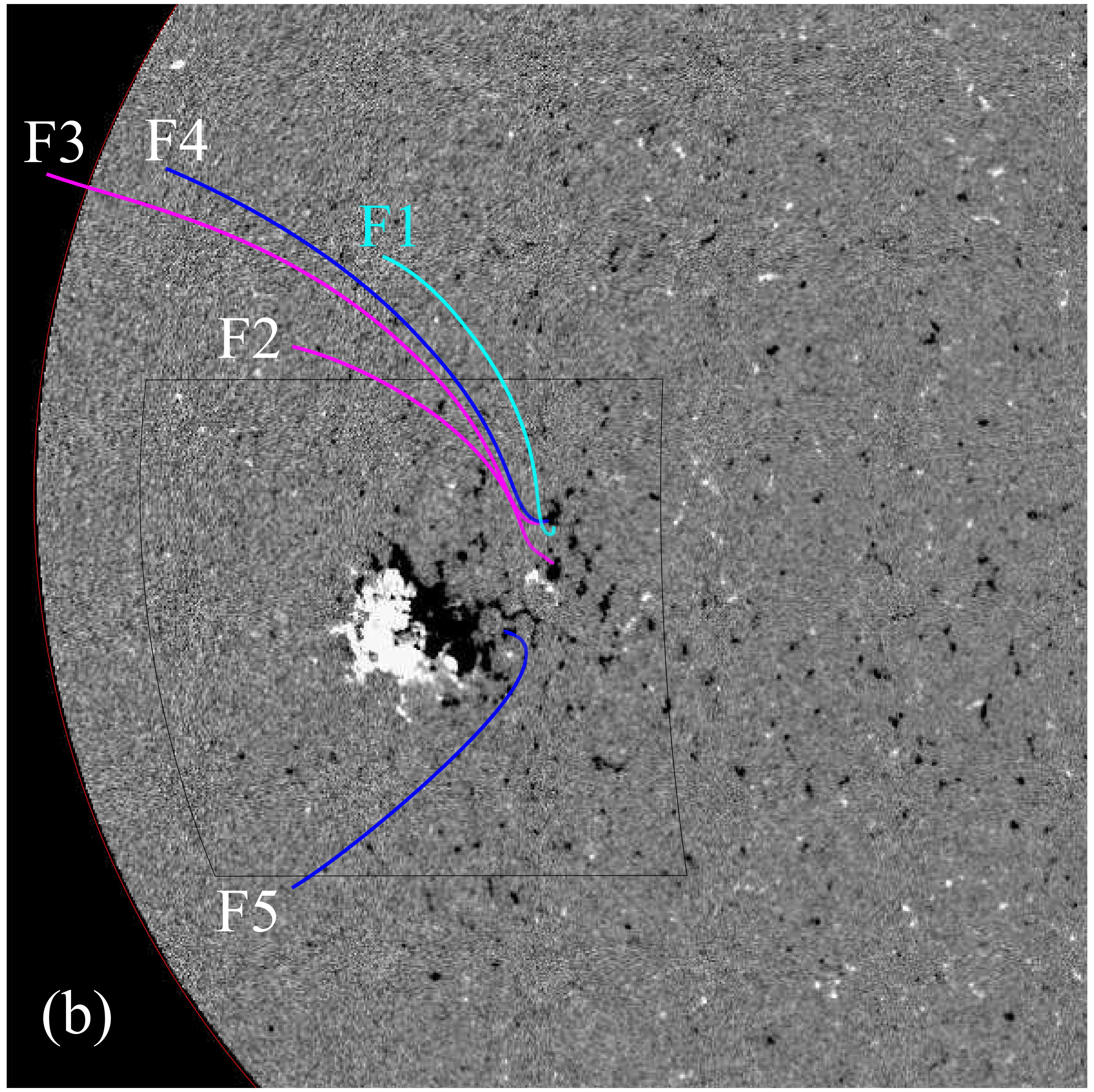
Five Field Lines: Quiet vs. Active

STEREO-A (195Å)



Magnetogram



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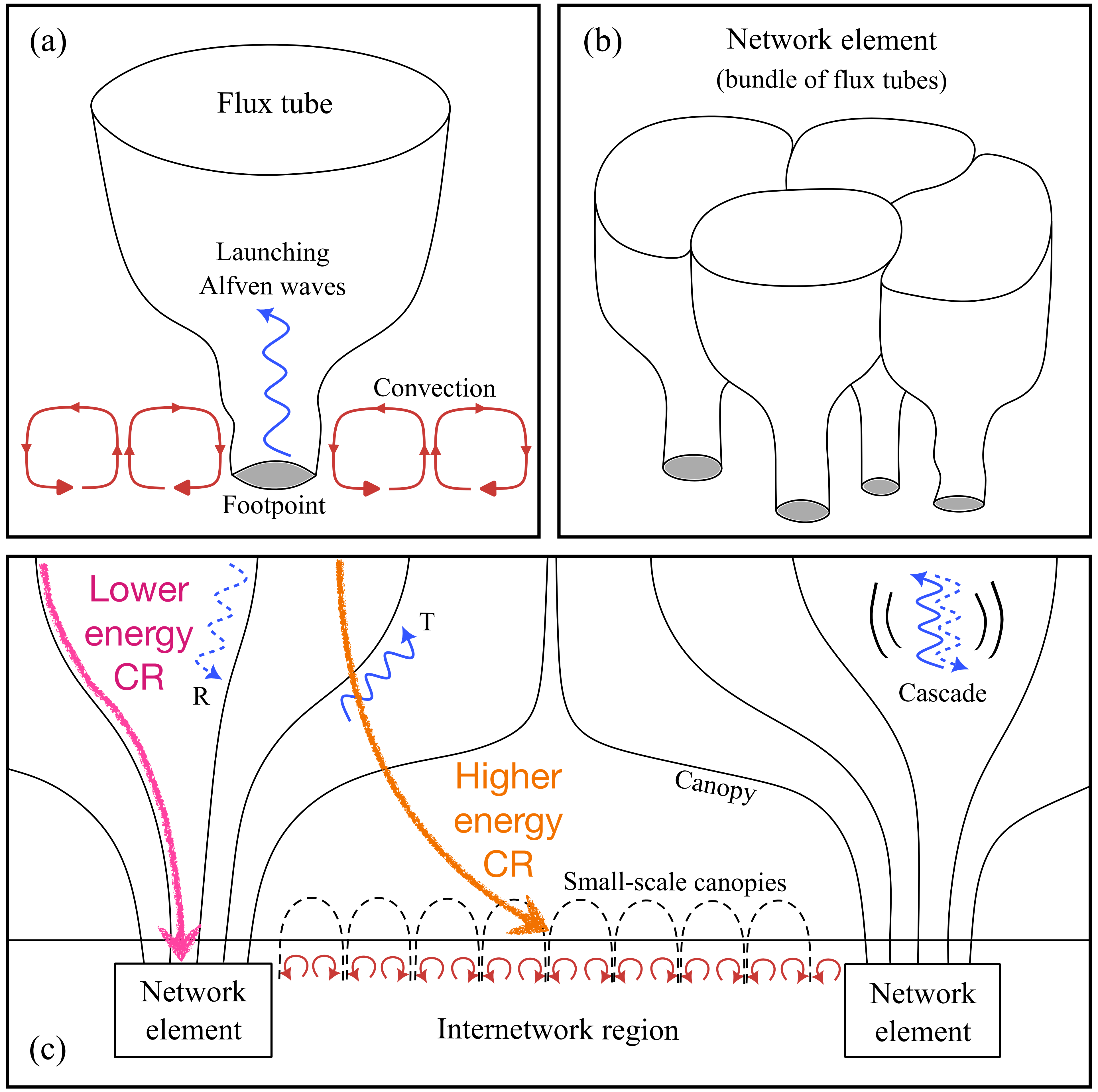
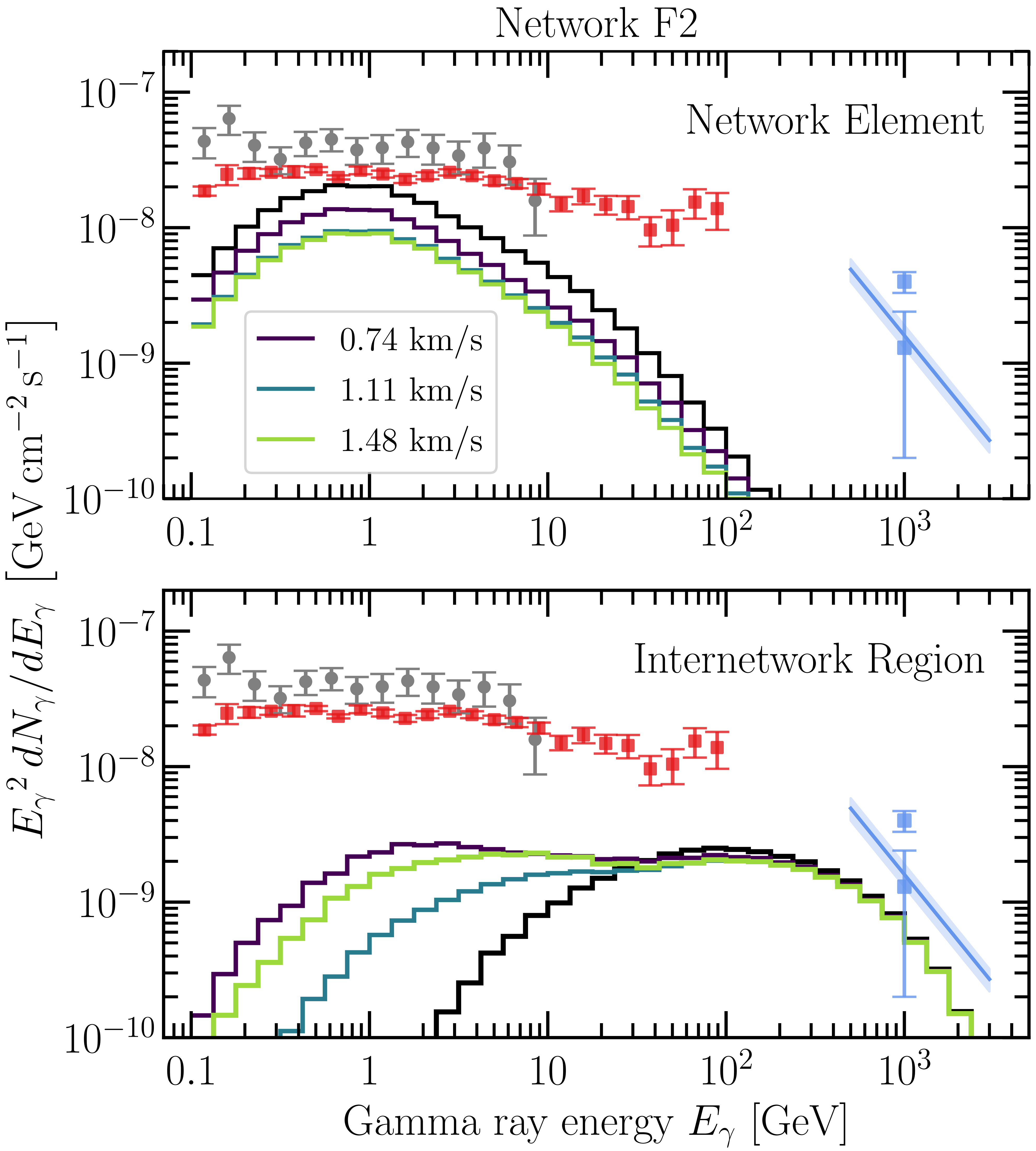
Result 1: Predicted Spectrum





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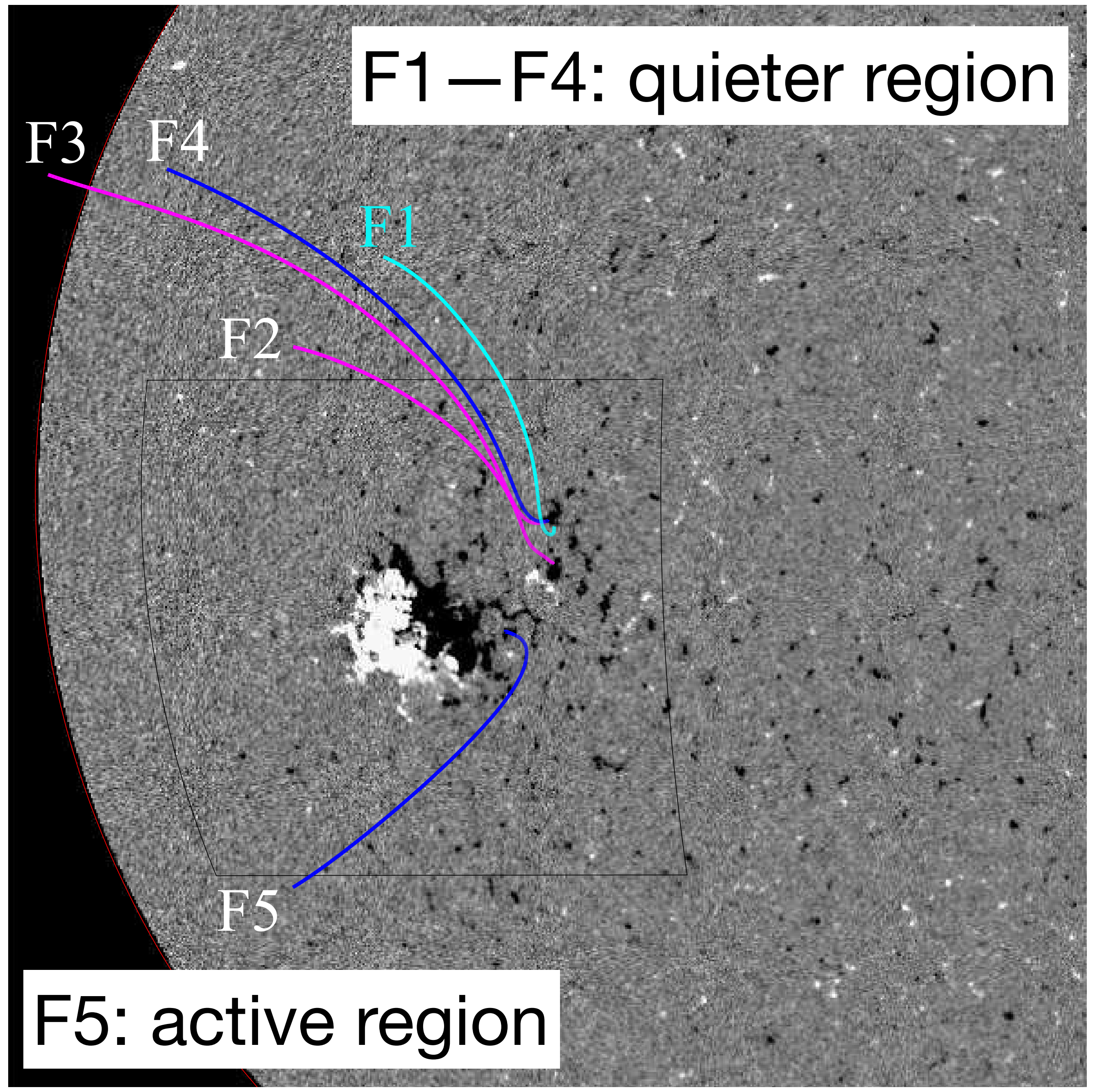
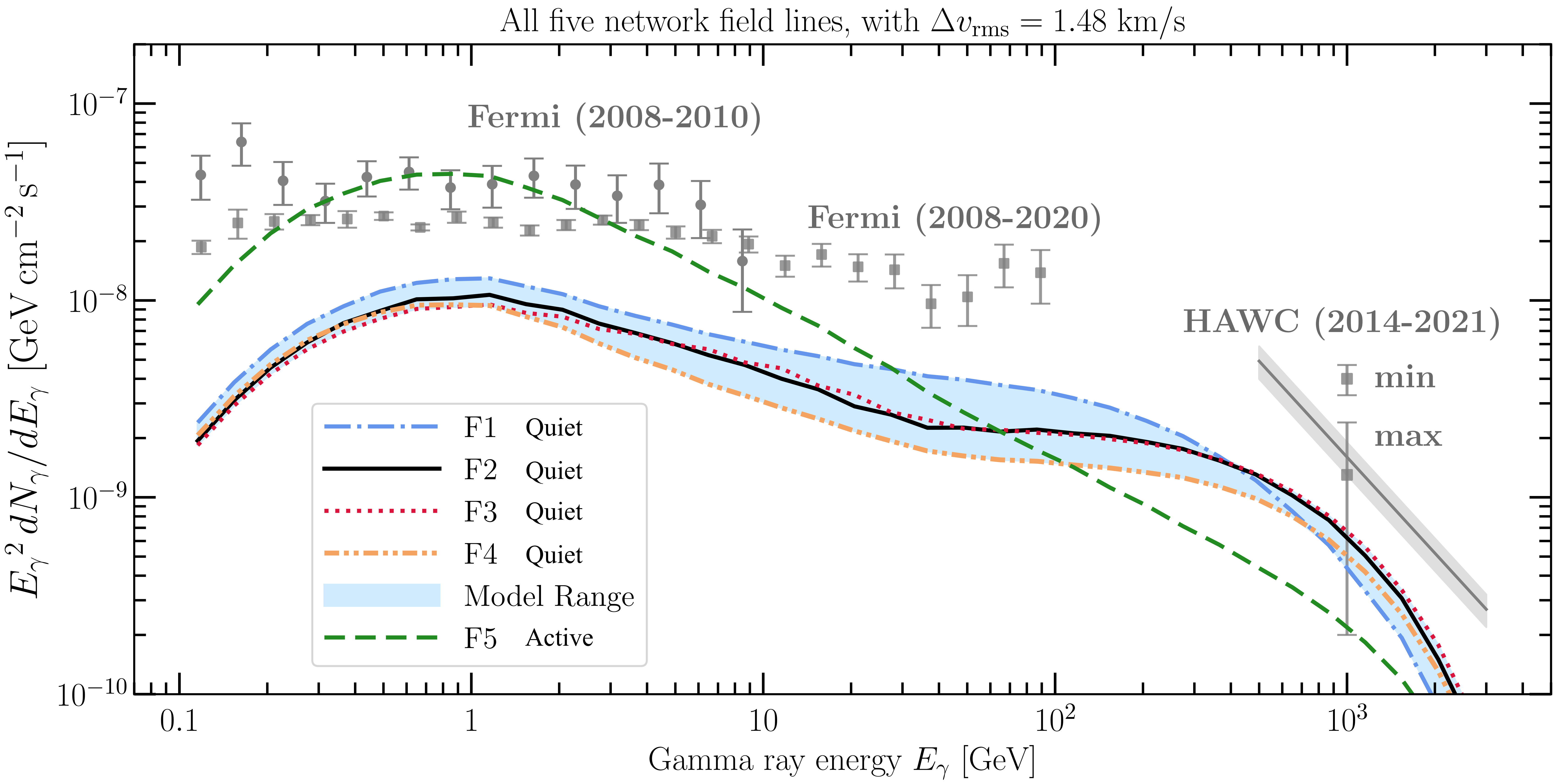
Result 2: Predicted Spectrum





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Conclusions and Outlook

- Multi-scale implies:
  - CR spectrum slope $\neq$ gamma spectrum slope (vice versa)
  - CR spectrum slope $\neq$ neutrino spectrum slope (vice versa)

- Exciting opportunities ahead!
  1. Solar-disk probe of gamma rays to reveal magnetic fields and particle transport deep into solar atmosphere
  2. Solar-halo probe of gamma rays to reveal electron CR transport in the inner heliosphere

Backup slides

Fermi-LAT detects multi-GeV gamma rays

Fermi-LAT

- Space-based detector
- 20 MeV to 200 GeV

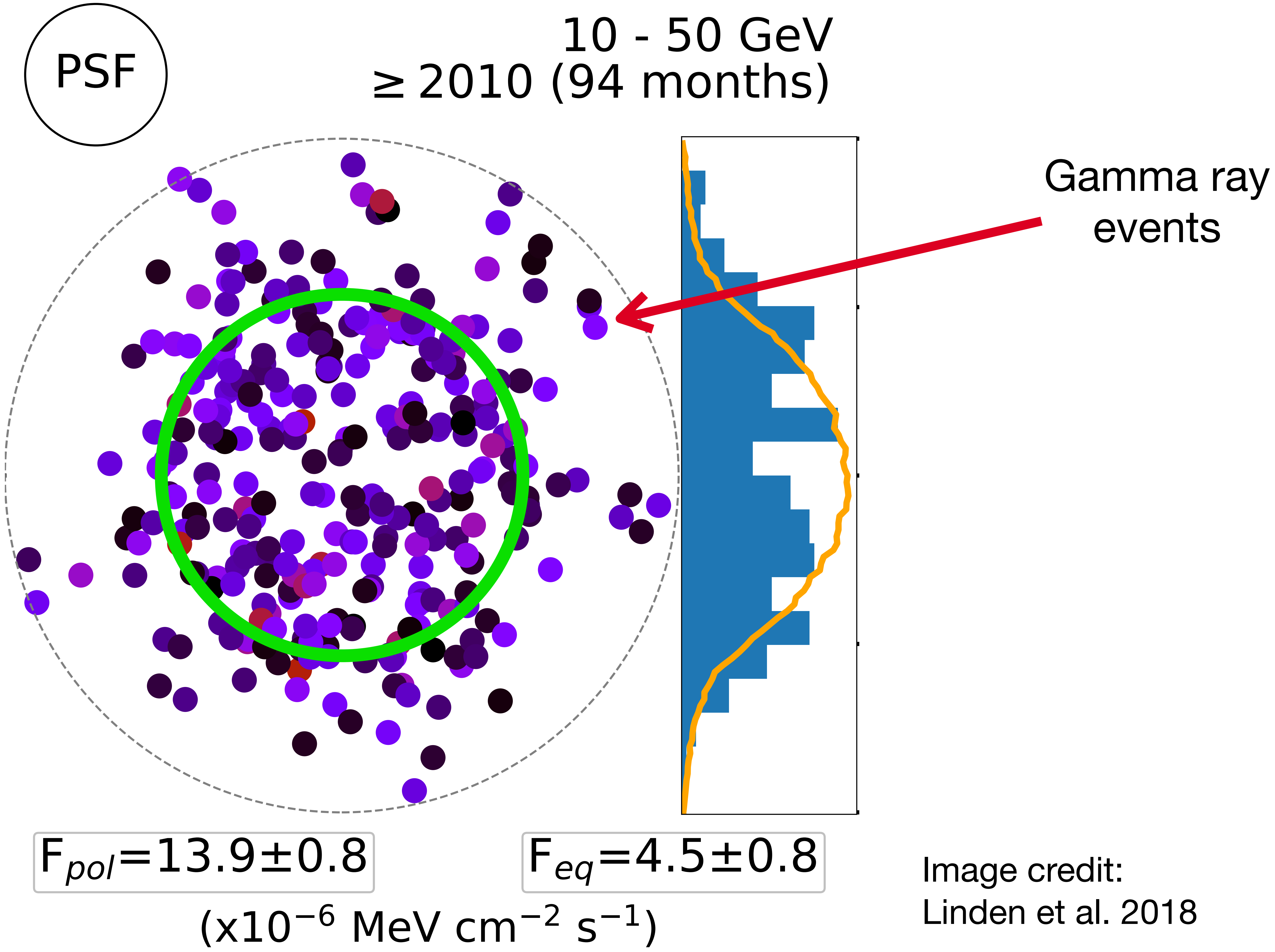
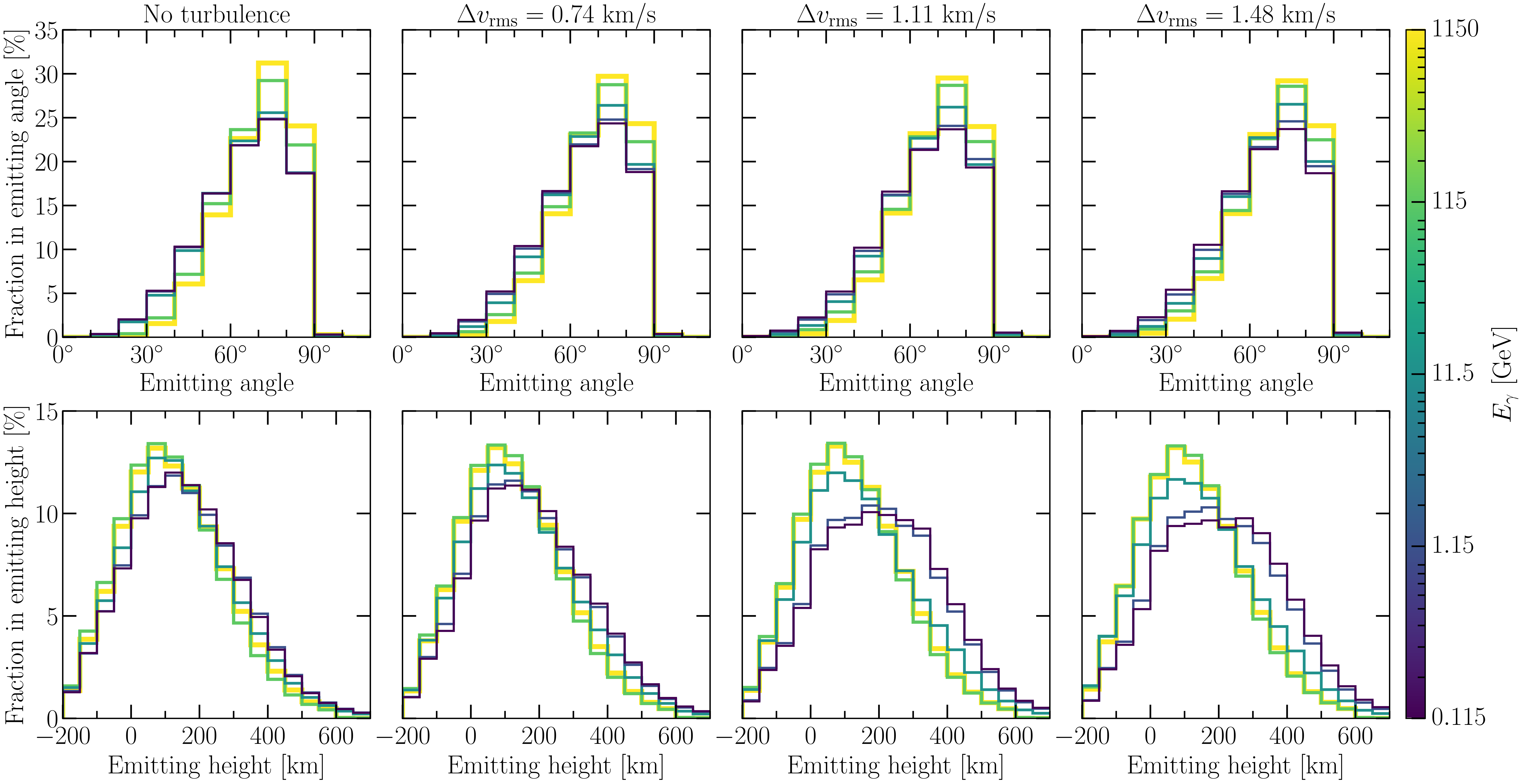
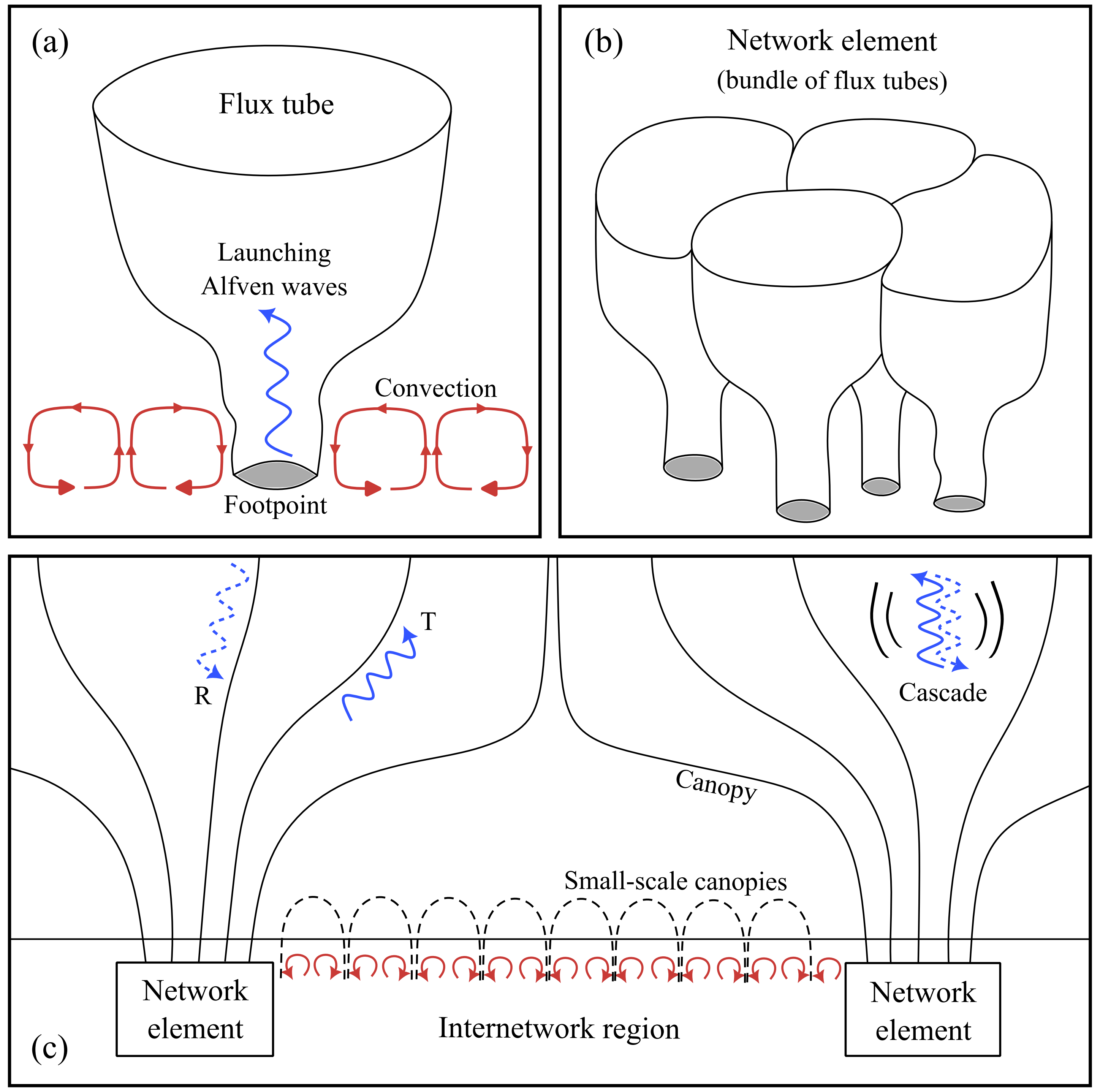


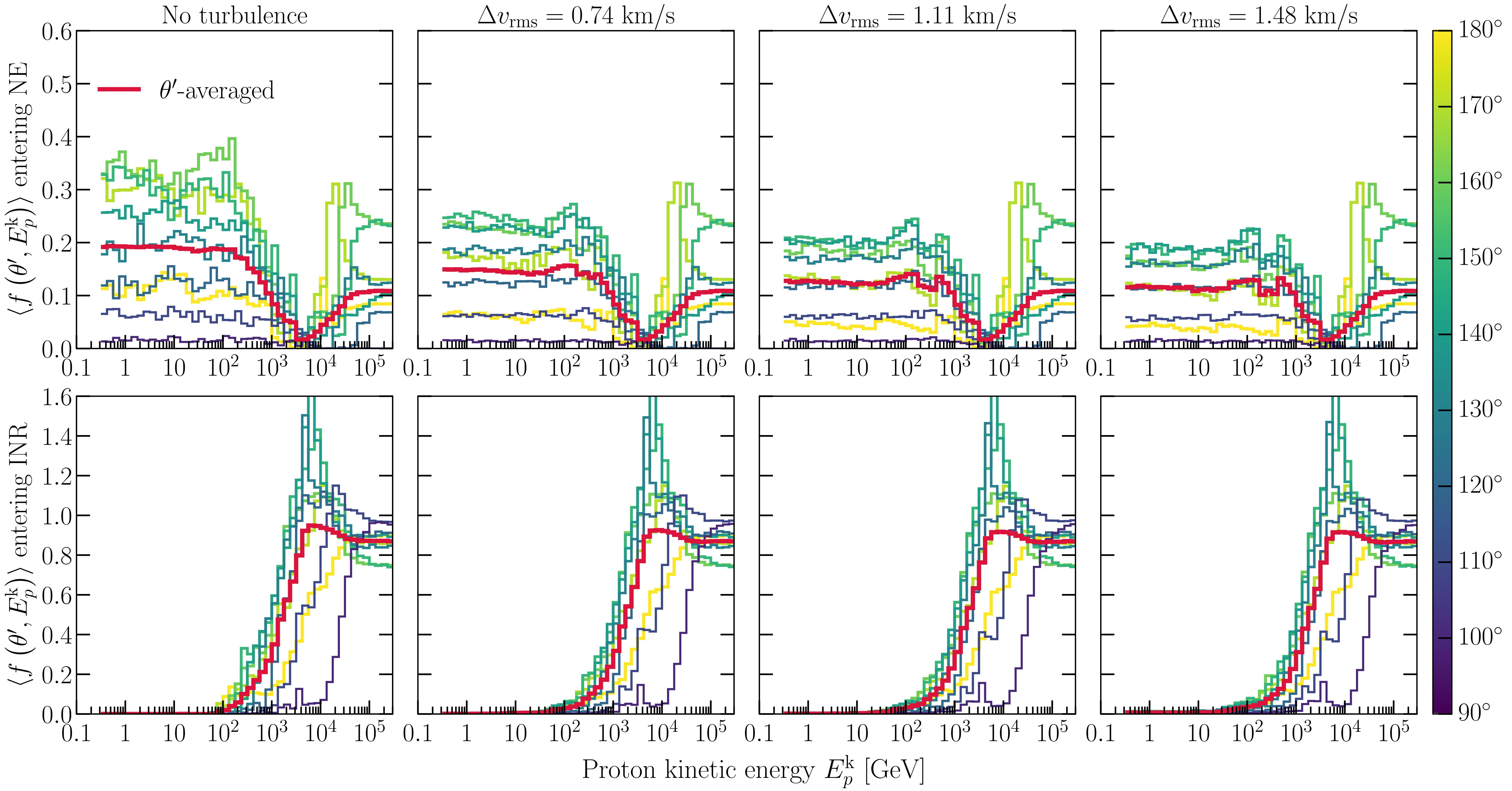
Image credit:
Linden et al. 2018

Result 3: Emission Height



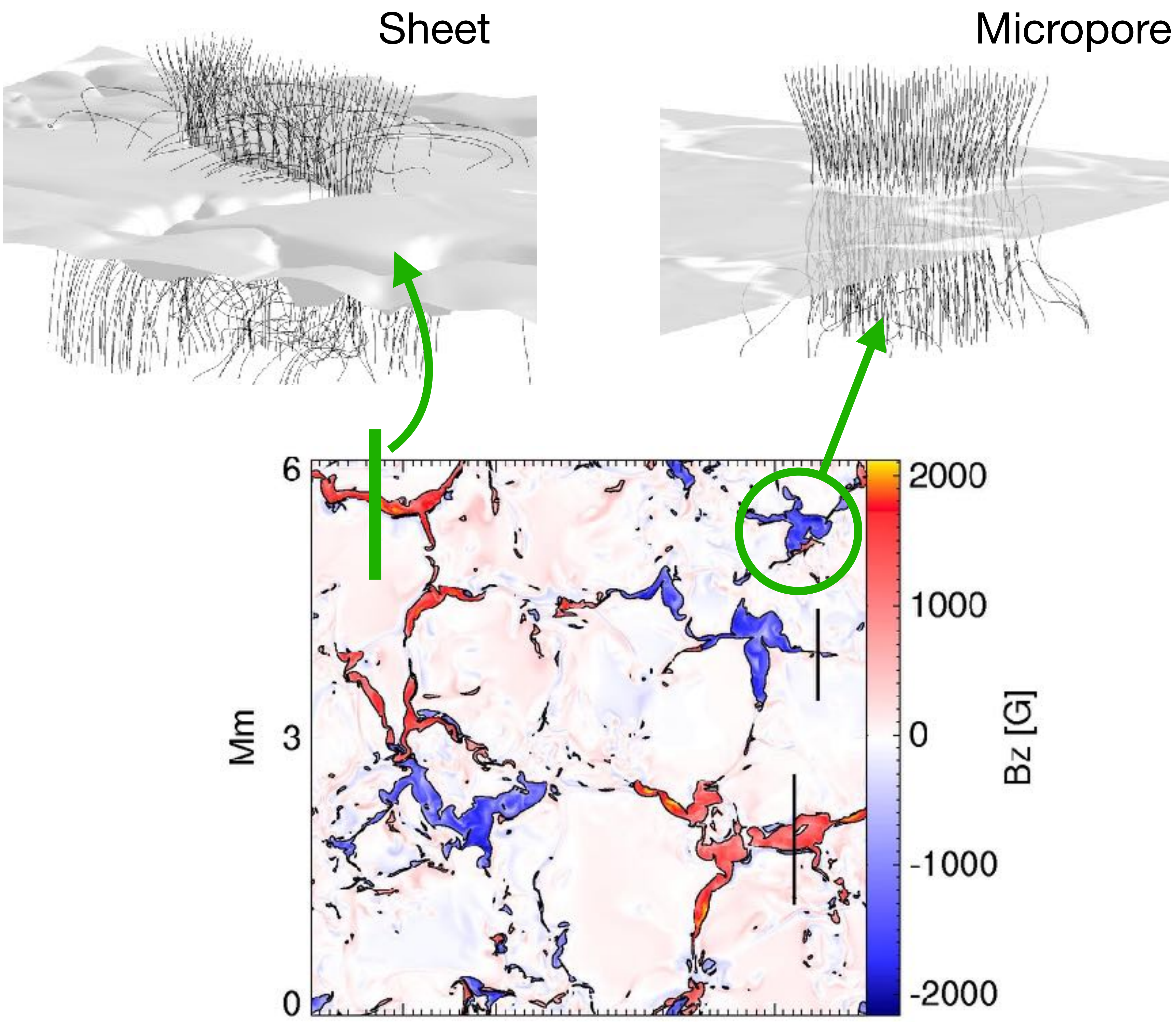
Result4: Where Proton GCR lands





Realistic Magneto-convection from MURaM

- Our previous work is *magneto-static*
  - What is the effect of convection motion to large-scale sheet structures
- Realistic field structure:
  - Particle transport in a realistic sheet using numerical magneto-convection simulation (e.g. MURaM, BIFROST)



Credit: Volger et al. 2005 (MURaM simulation)