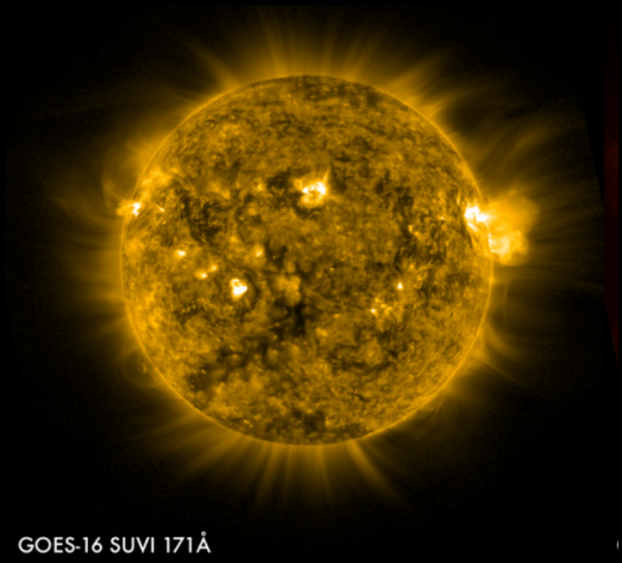
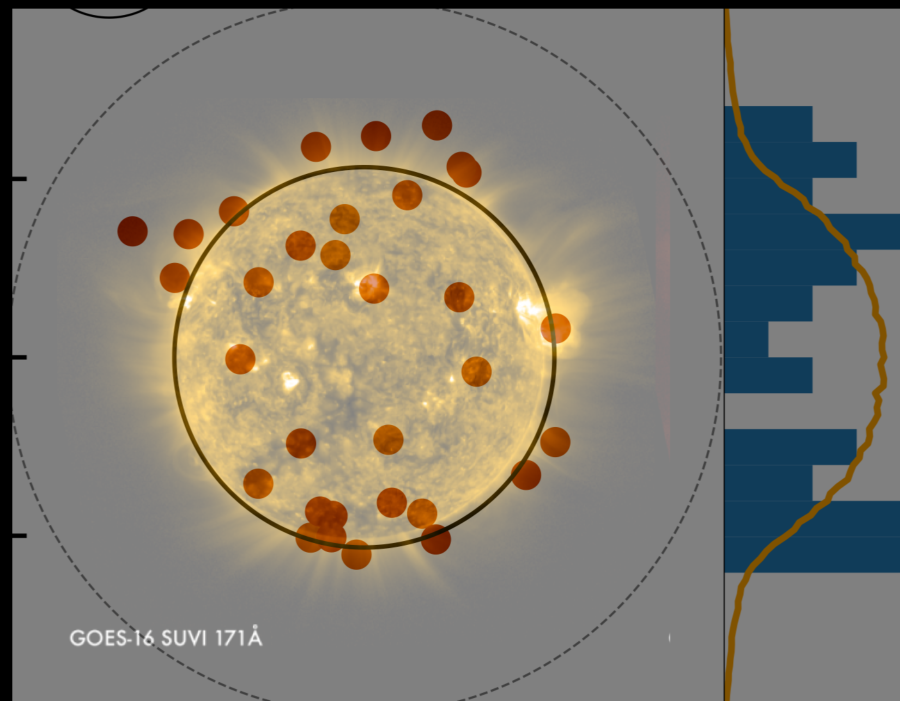
Exploring the Sun-Galaxy connection with GeV gamma rays



Annika Peter
Center for Cosmology and AstroParticle Physics
The Ohio State University

Exploring the Sun-Galaxy connection with GeV gamma rays



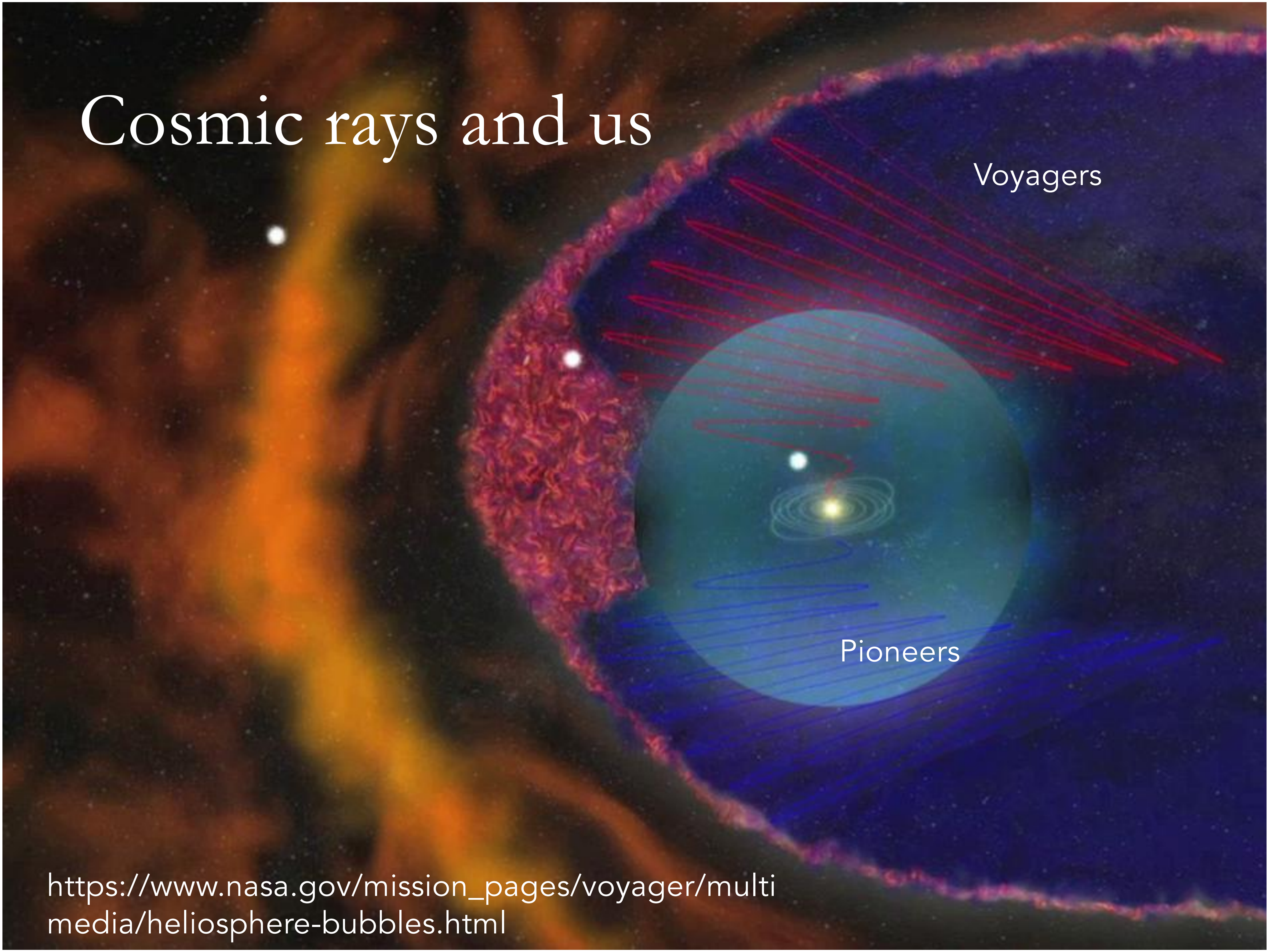
>50 GeV

Annika Peter

Center for Cosmology and AstroParticle Physics

The Ohio State University

Cosmic rays and us



https://www.nasa.gov/mission_pages/voyager/multimedia/heliosphere-bubbles.html

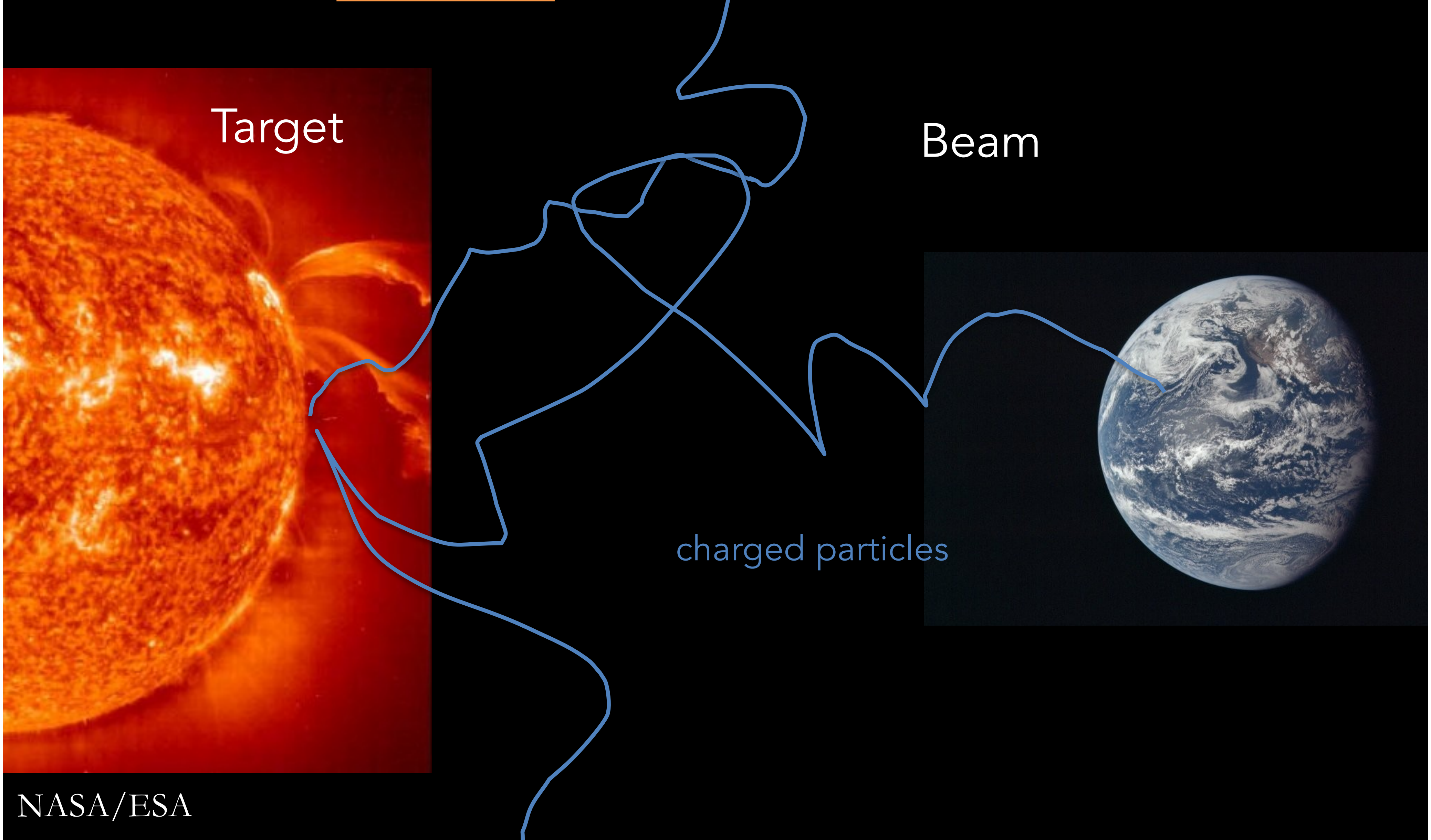
Questions

- What does the magnetic field structure in the (inner) solar system really look like, and why?

- How do cosmic rays propagate through the (inner) solar system?

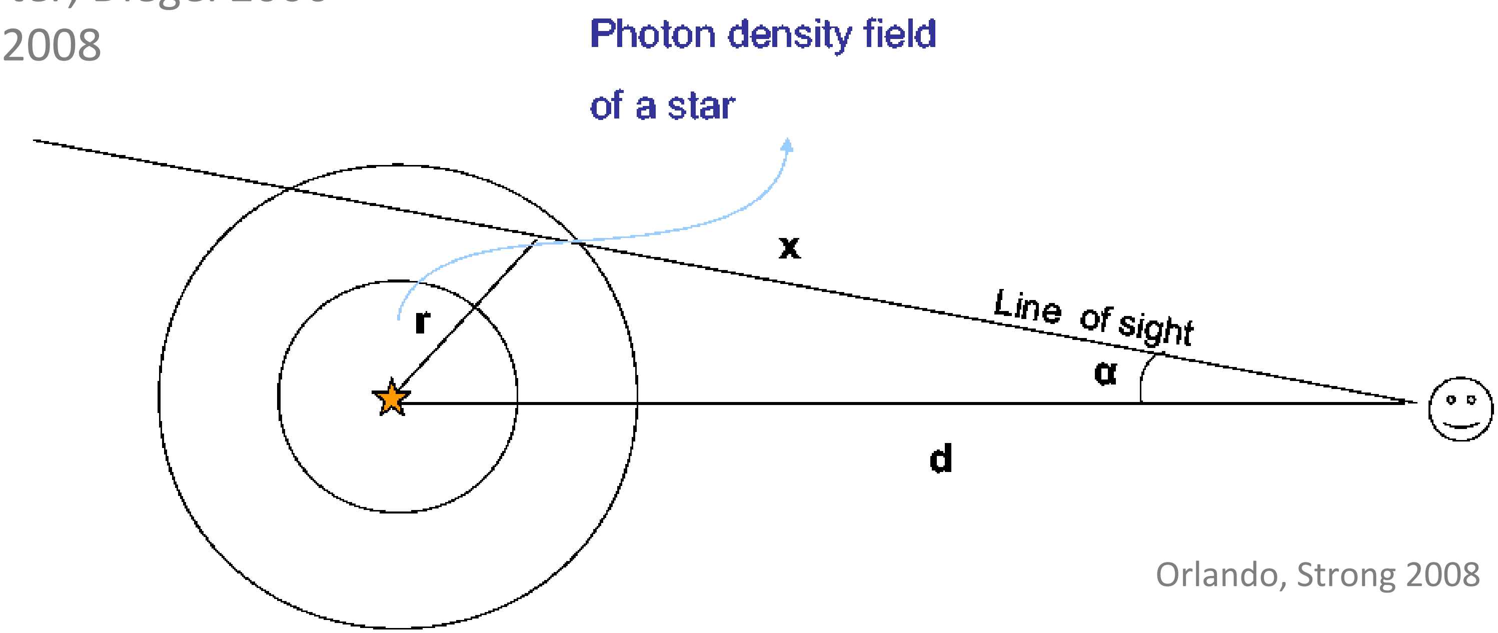
(Maps onto two Scientific Goals from the 2013 Decadal Survey in Solar and Space Physics)

Sun as a detector of (Galactic) cosmic rays



Leptonic Cosmic Rays: Inverse Compton (IC)

Moskalenko, Porter, Diegel 2006
Orlando, Strong 2008

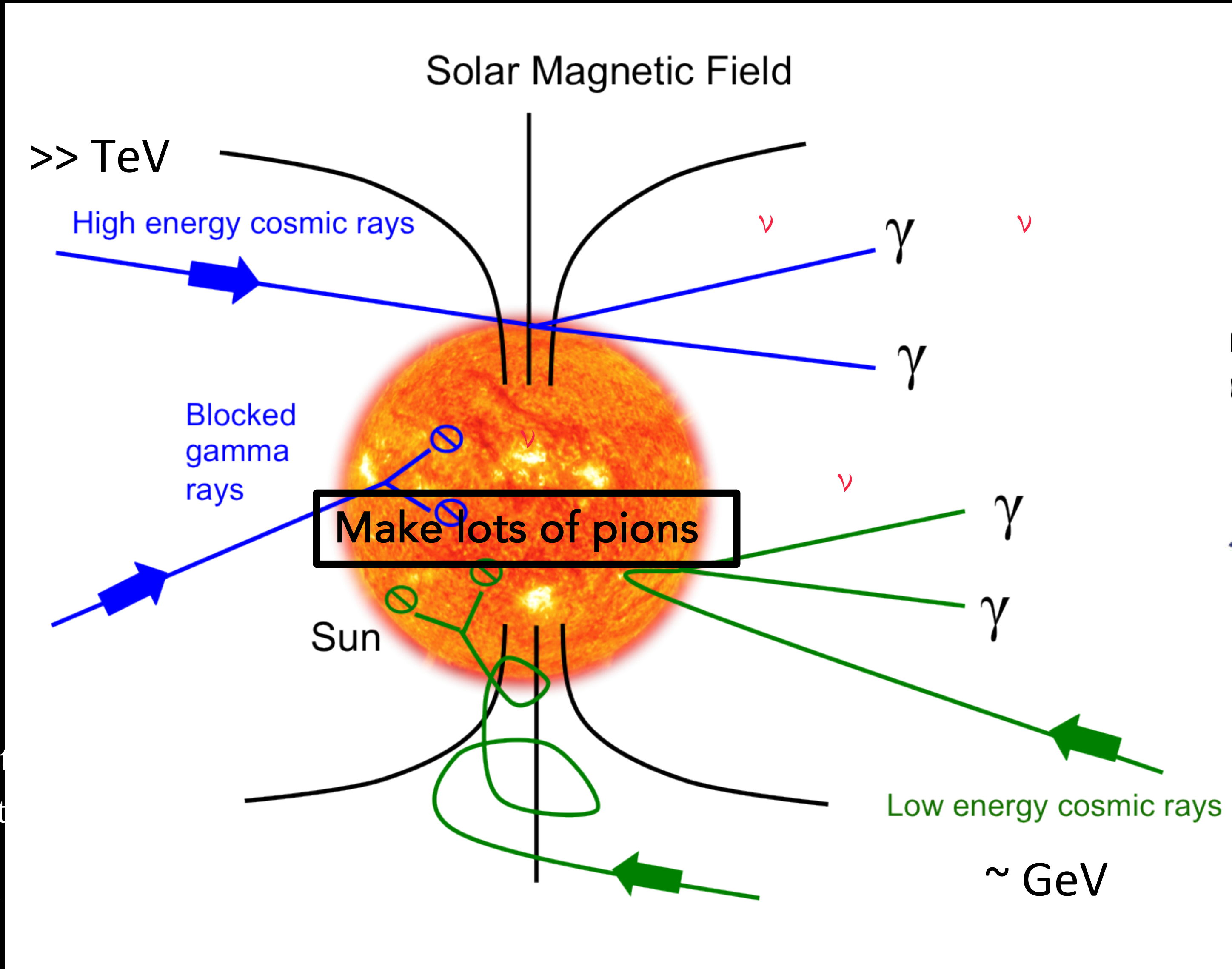


Orlando, Strong 2008

- Photons only
- Extended
- 1 GeV-range peak comes from: E ~$\gamma^2 E_{\odot,photon}$

Hadronic Cosmic Rays

Seckel, Stanev, Gaisser (SSG) 1991



Gamma-ray energy ~1/10th of primary

For neutrinos, see Gerrit Roellinghoff's IceCube t WIN2021 this week: https://indico.fnal.gov/ 2/

Picture by Kenny Ng

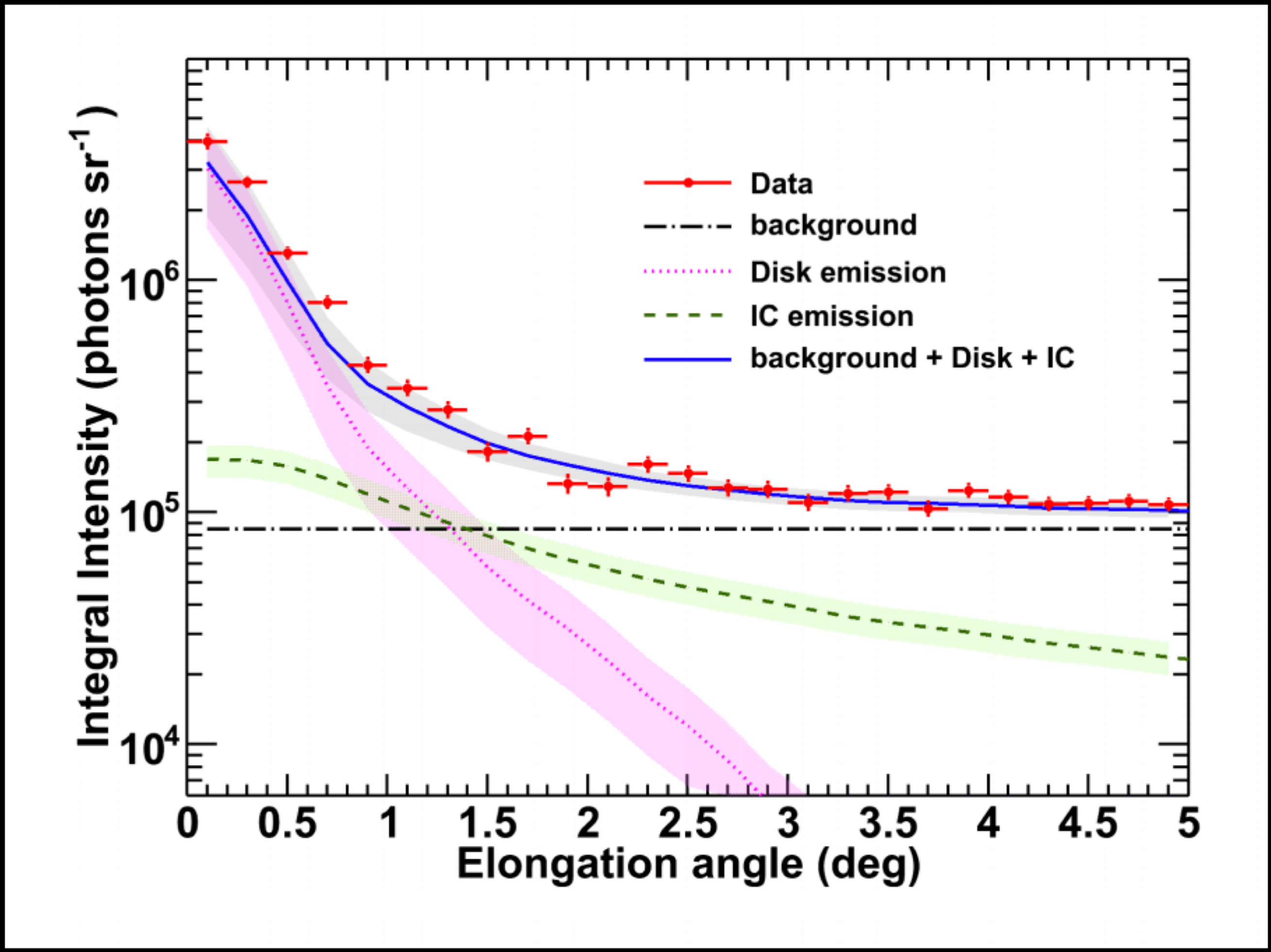
What are the observations telling us?

What new questions do the observations raise?

Peeling the first onion layer: IC

First 18 months of Fermi mission, Cycle 23/24 solar minimum

Inner heliosphere

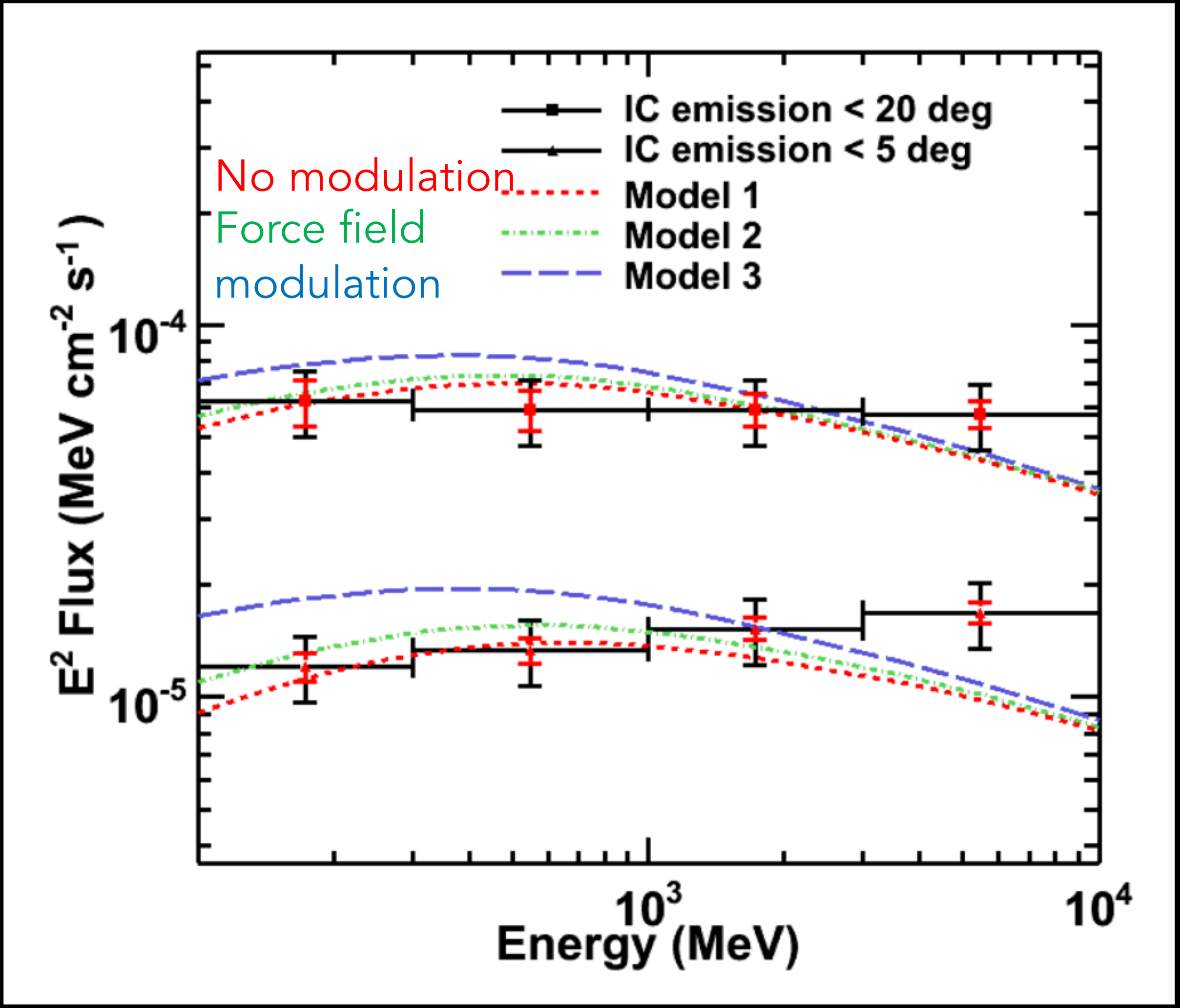


Abdo+ 1104.2093 Fermi-LAT collaboration

Peeling the first onion layer: IC

Inner heliosphere

First 18 months of Fermi mission, Cycle 23/24 solar minimum

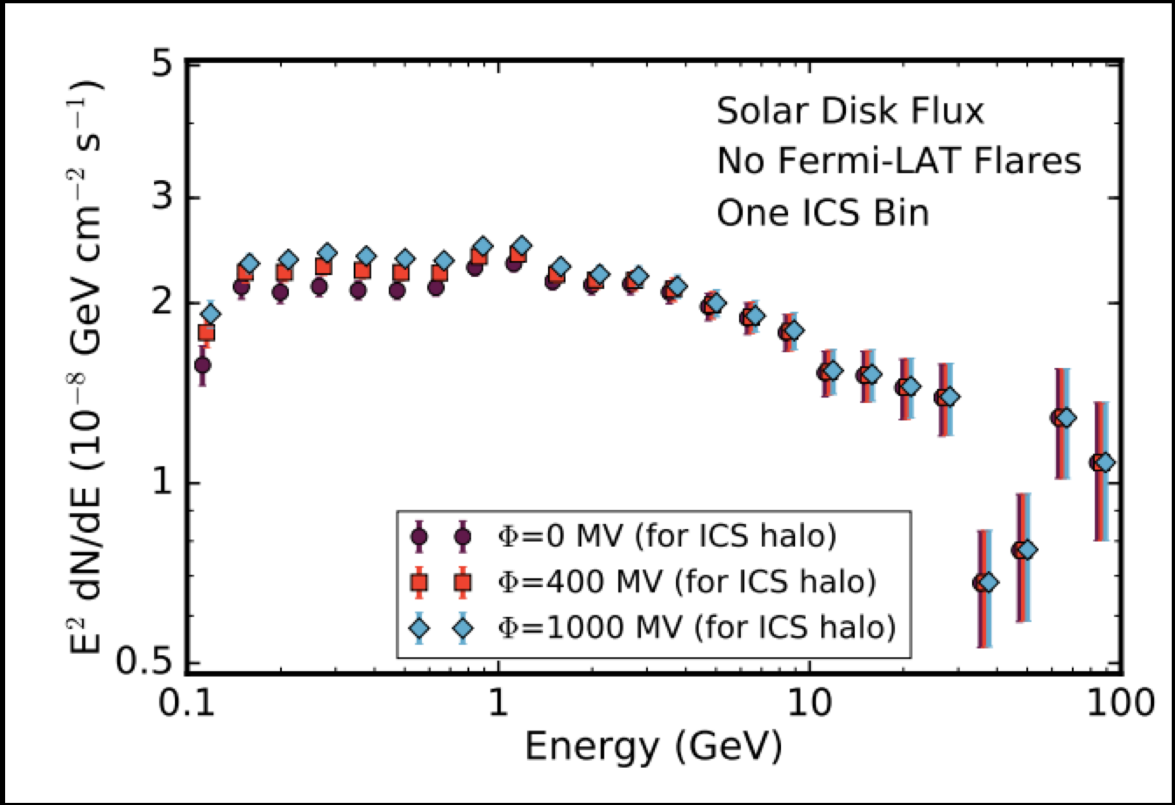


Abdo+ 1104.2093 Fermi-LAT collaboration

Peeling the first onion layer: IC

11 years of Fermi-LAT data

Inner heliosphere



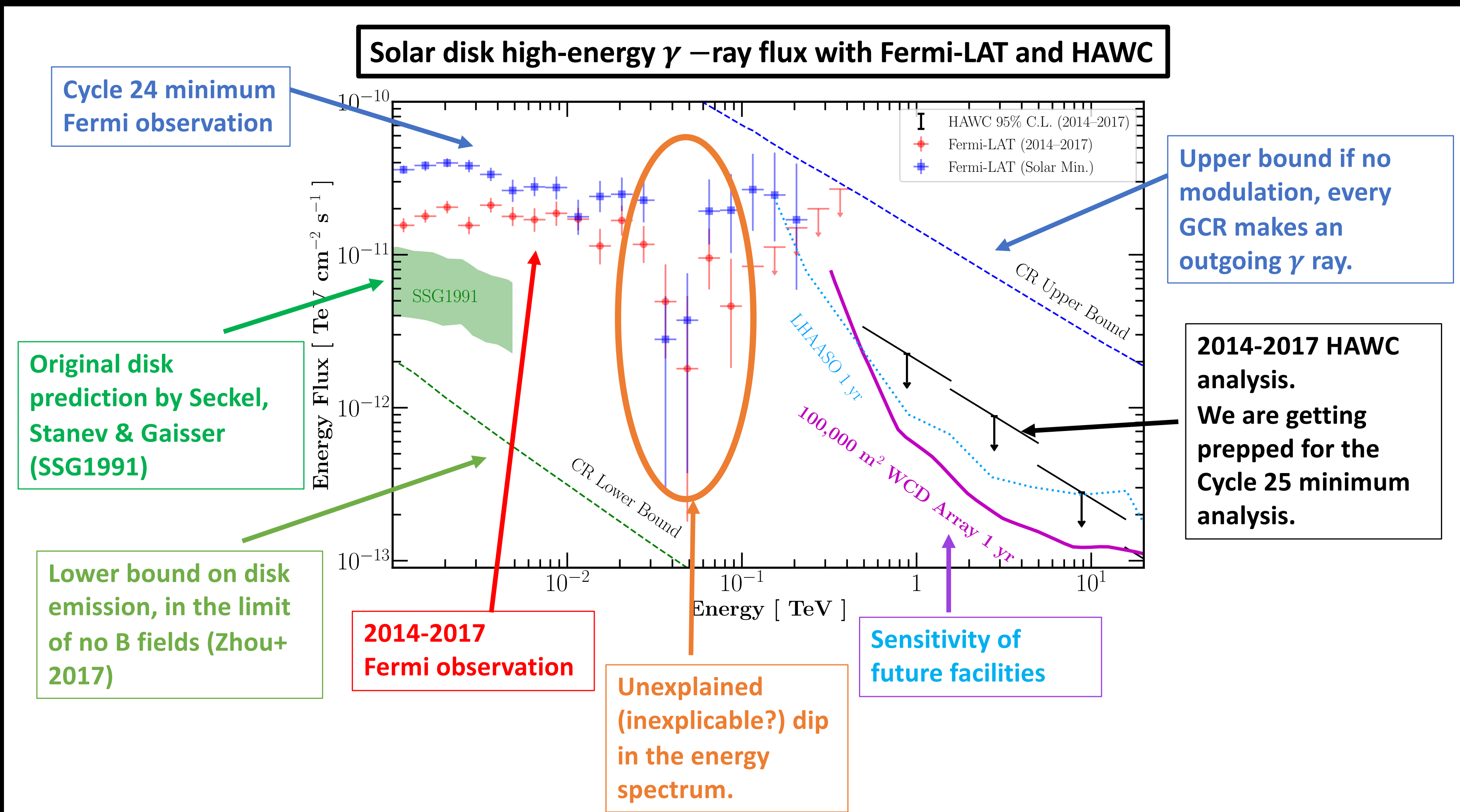
E < 1 GeV prefer LARGE modulation

E > 1 GeV prefer NO modulation

Stay tuned.

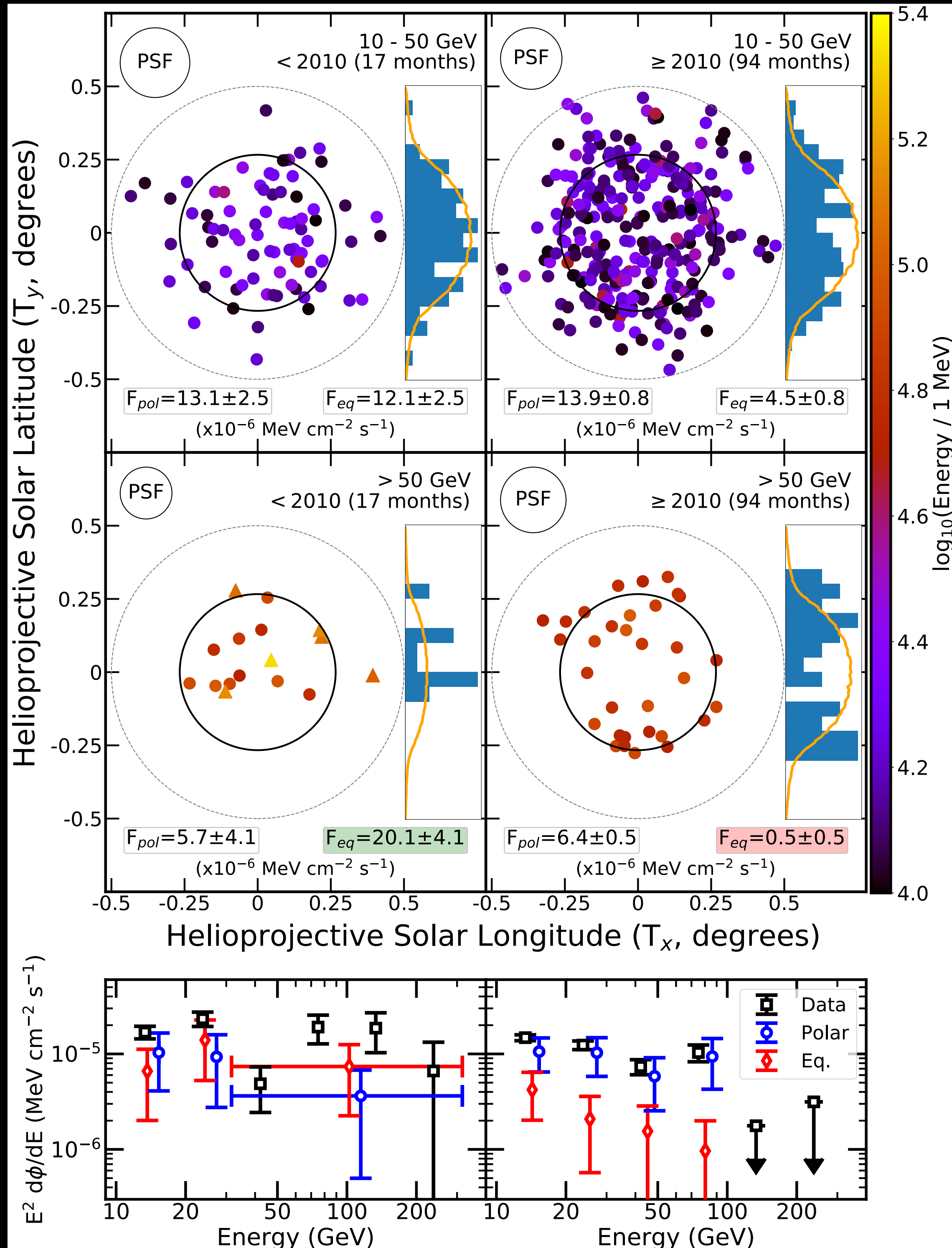
Linden+ 2012.04654

The center: hadronic observations



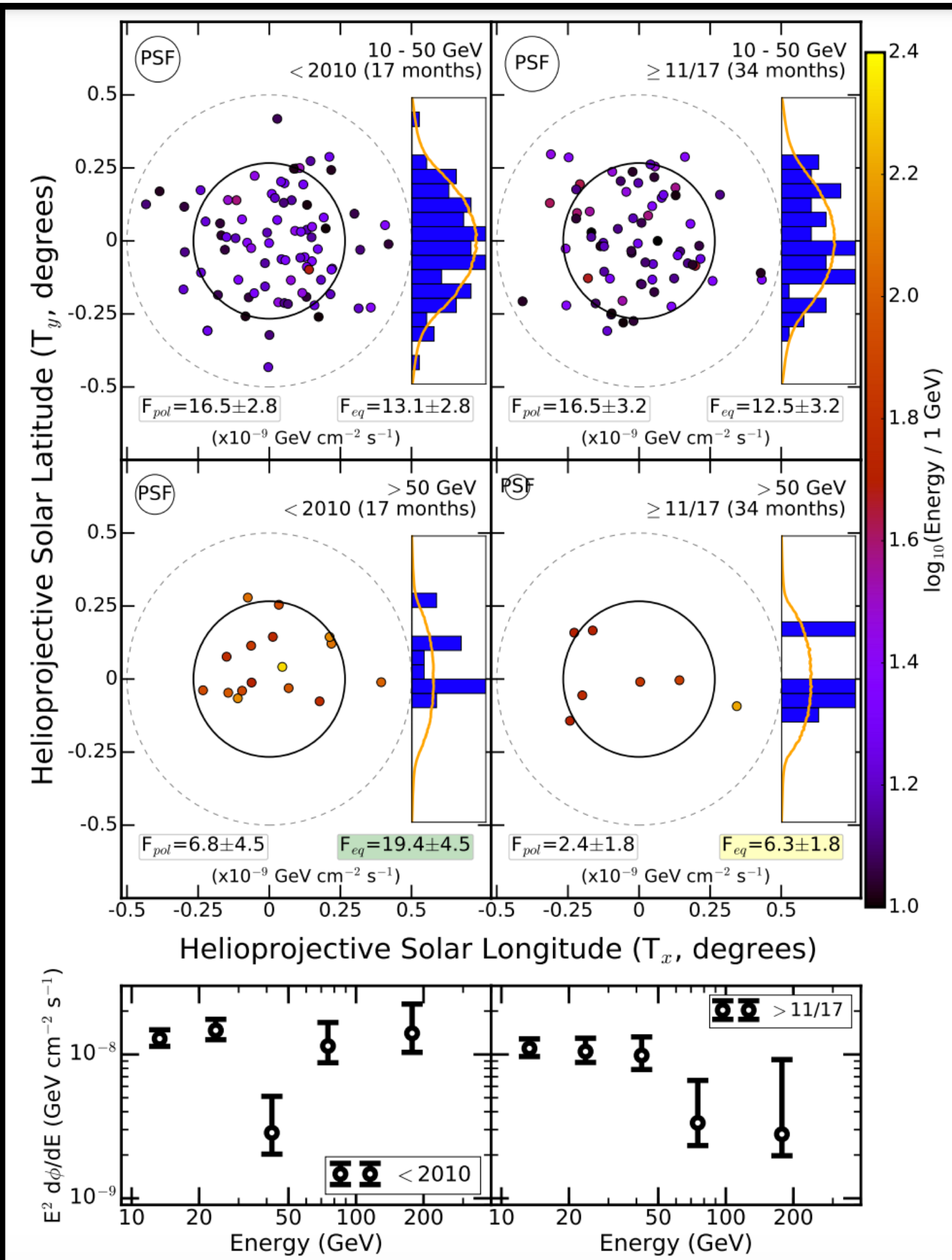
Modified from Nisa+ 1903.06349

The center: hadronic observations



Linden et al. 1803.05436

The center: hadronic observations

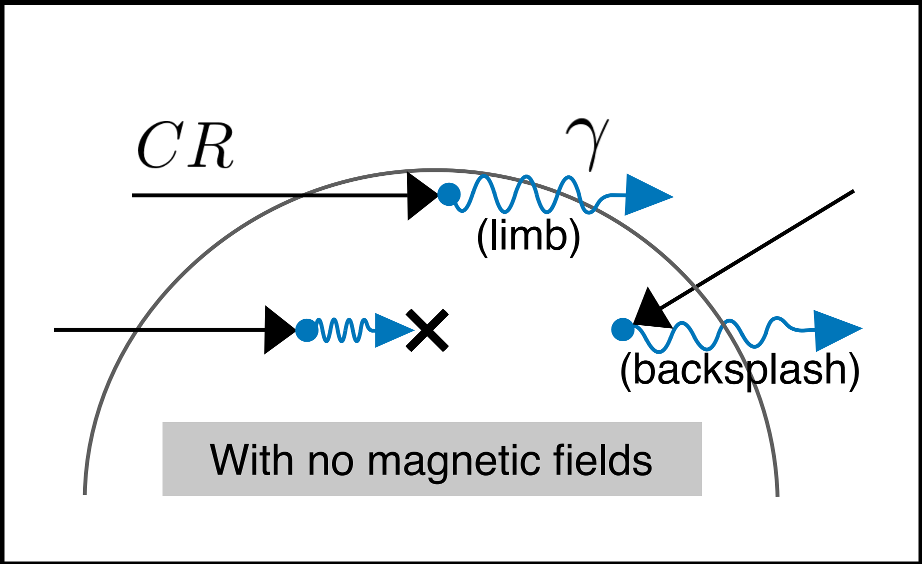


Linden+ 2012.04654

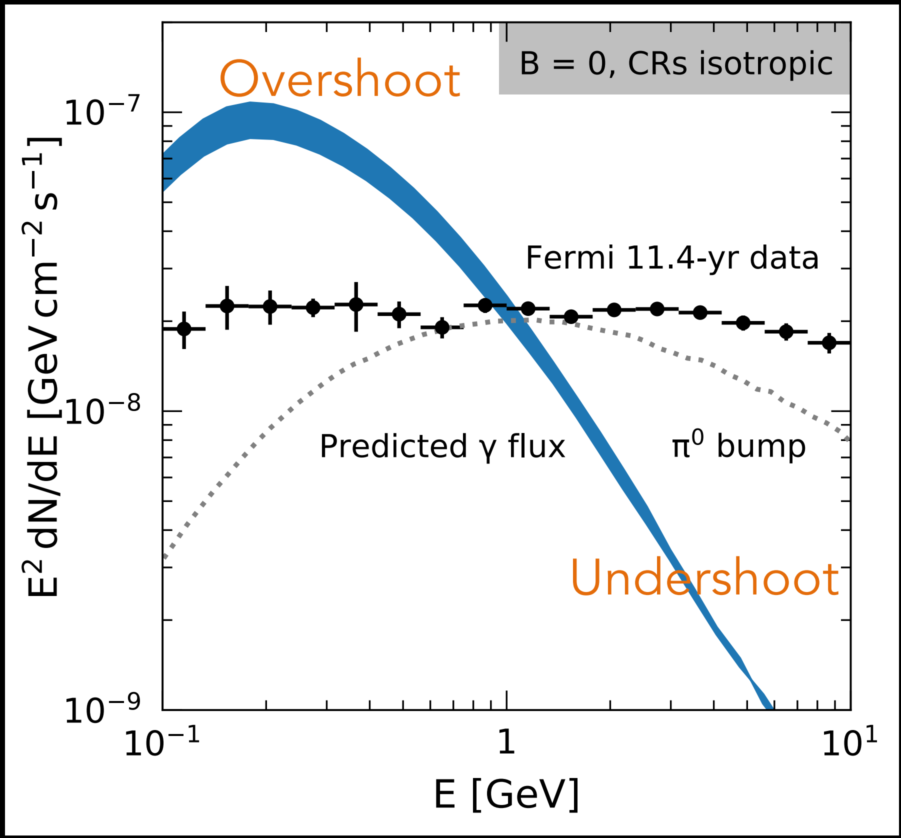
The center: hadronic predictions

- No magnetic fields.
- No photospheric fields but include the corona.
- Include the photospheric fields but not the corona above 1000 km.

No magnetic fields

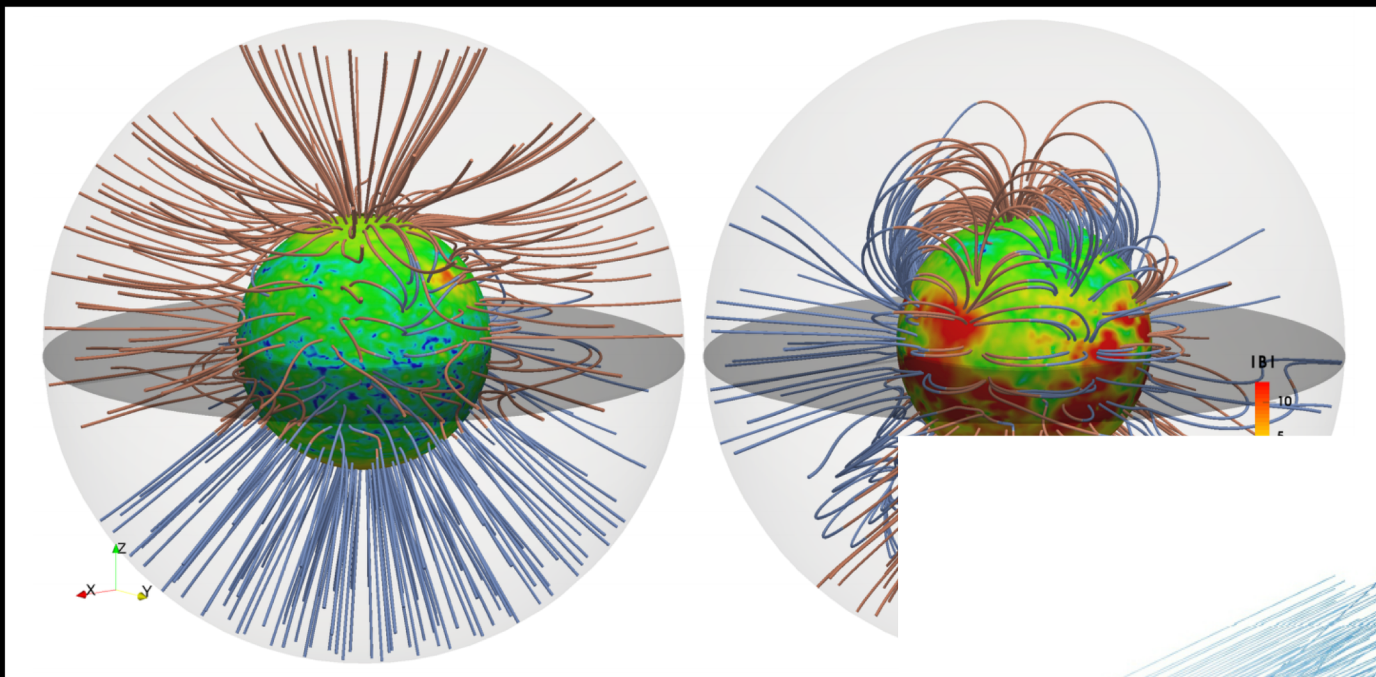


Zhu et al., in prep.

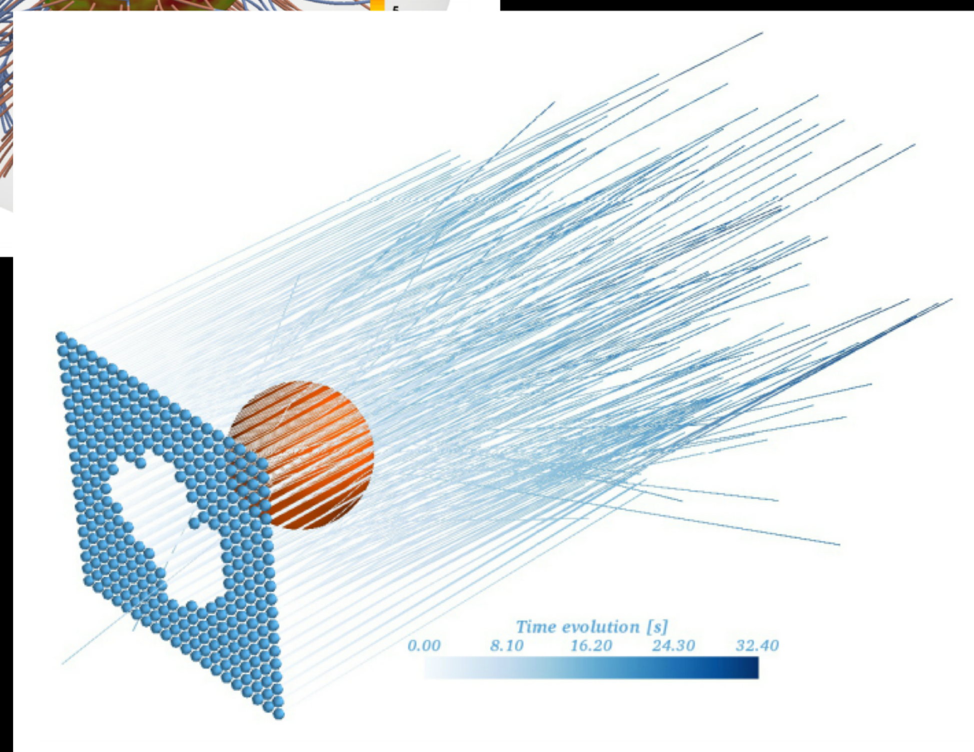


Fermi data points from Linden+ 2012.04654

w/corona but no photosphere

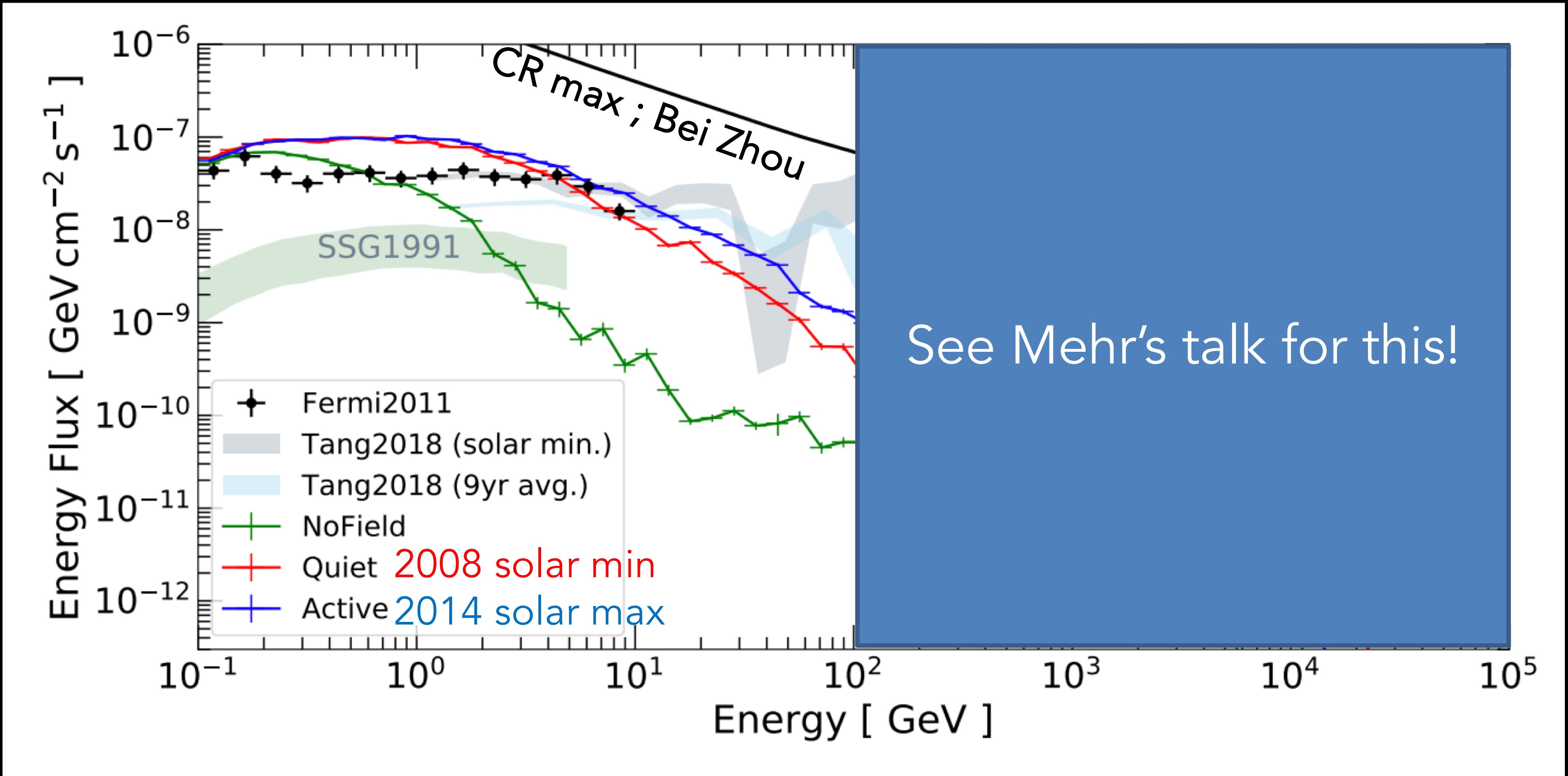


PFSS model during solar min and solar max



Becker Tjus+ 1903.12638

w/corona but no photosphere



Li+ 2009.03888

w/photosphere B but no corona

Propagation and interaction in chromo/photosphere

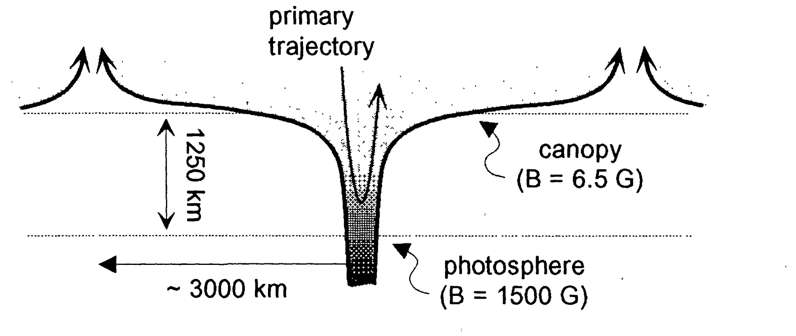
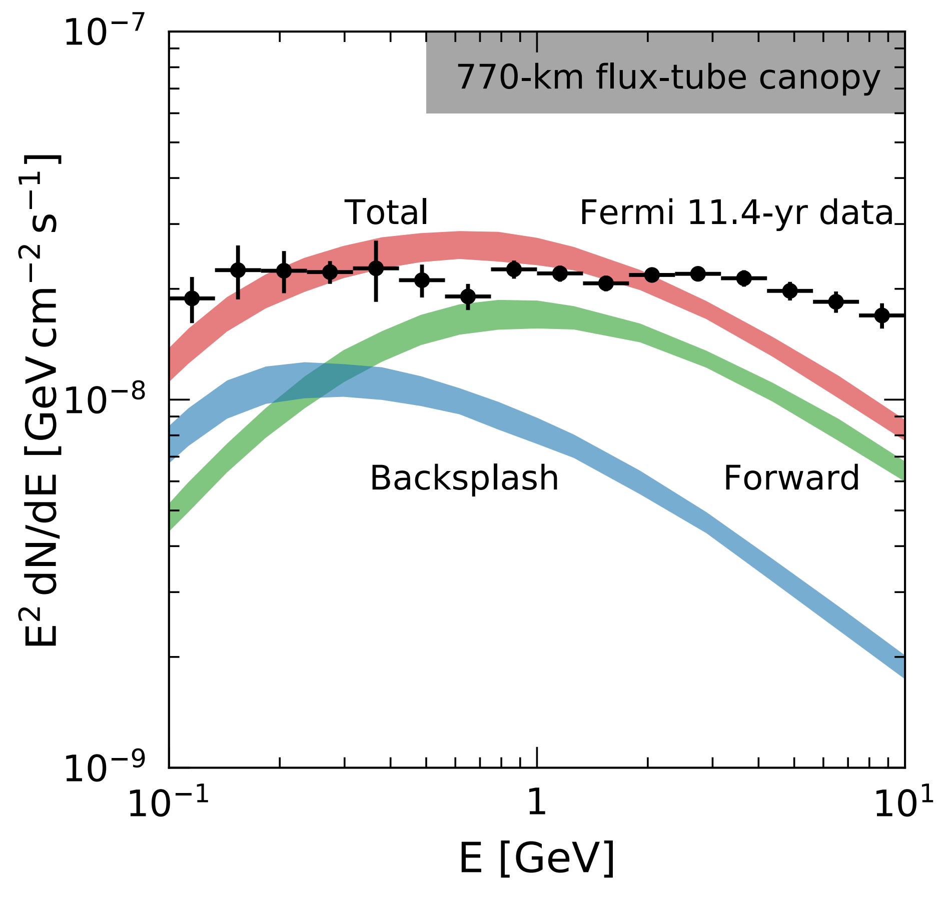


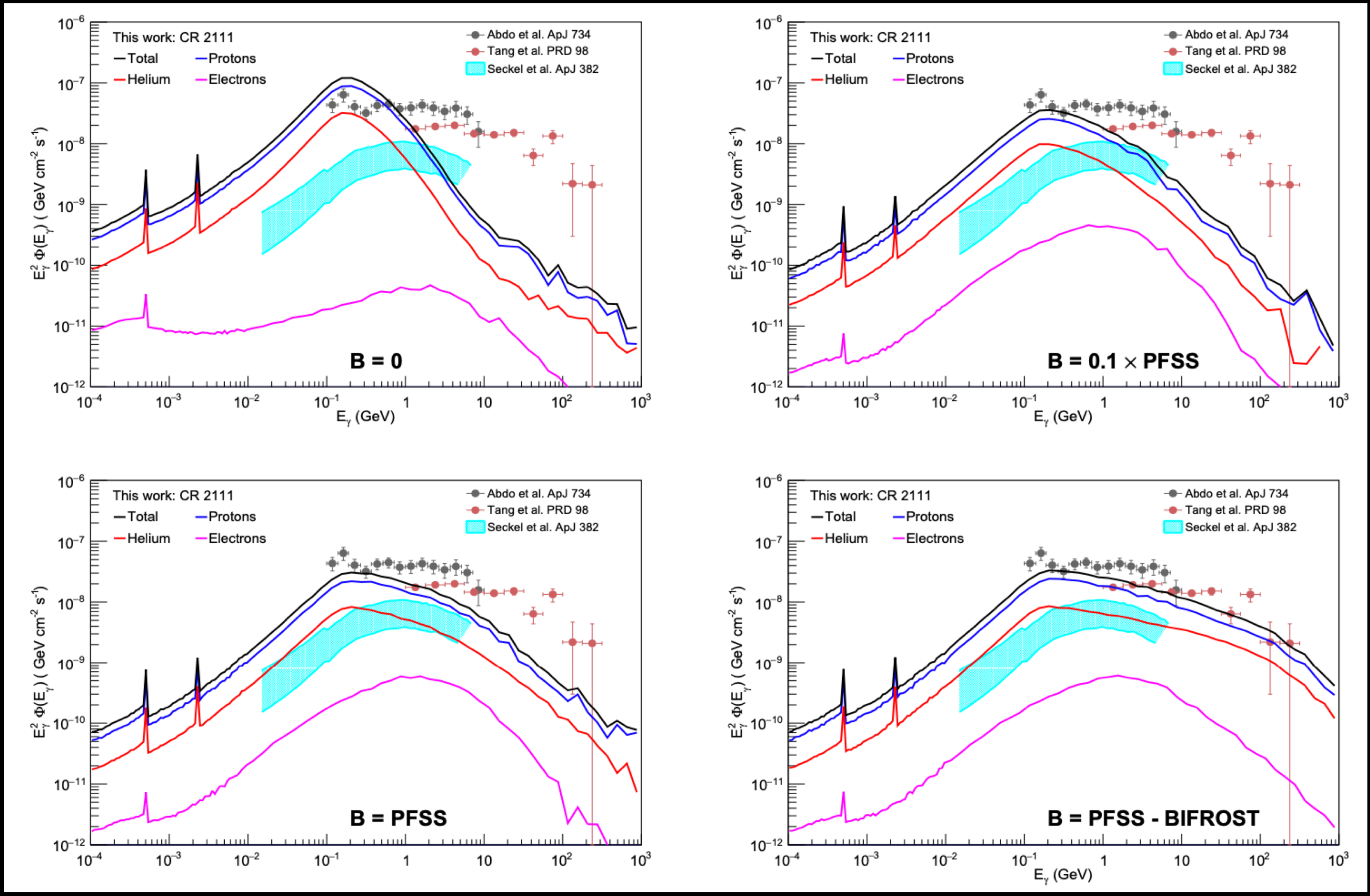
Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

Seckel, Stanev, 1992



Zhu et al., in prep.

Hints with corona + photosphere together



Mazziotta+ 2001.09933

Summary of weird stuff we can't explain

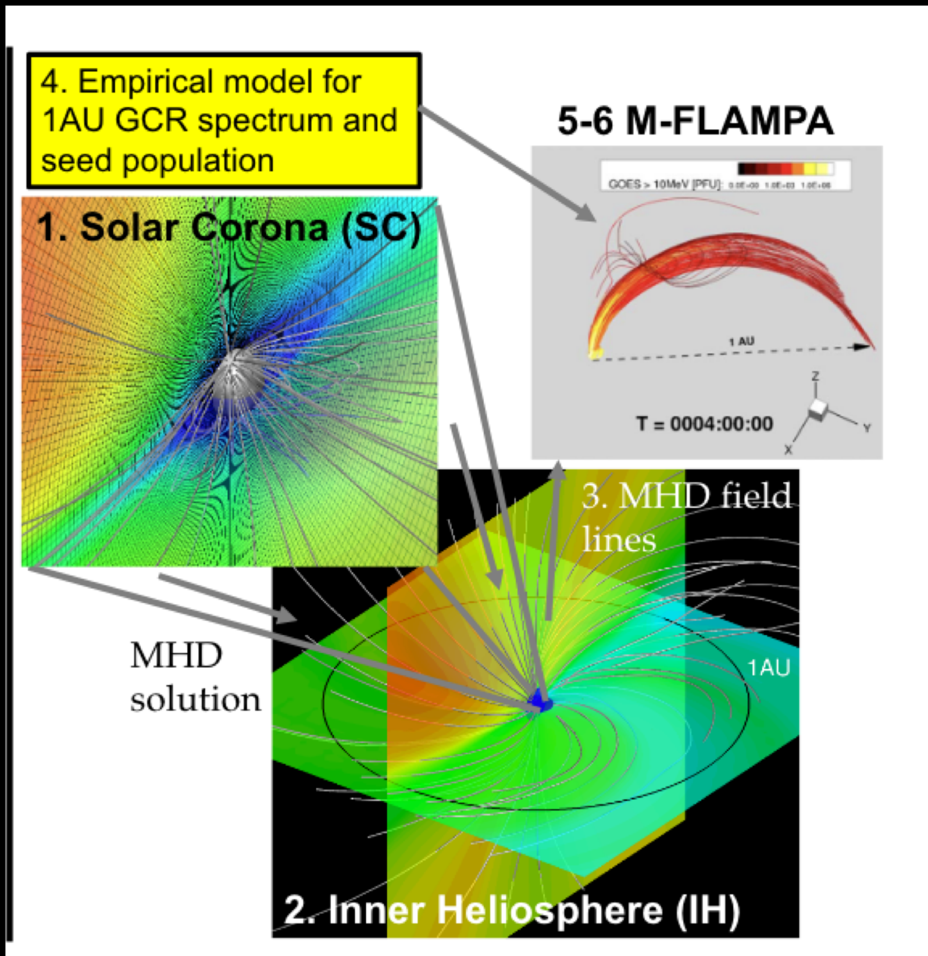
(because no predictions fully work)

- Why IC prefers different force-field modulation at different energies.
- ``Dip" in gammas at ~40 GeV (hadrons).
- The overall hardness of the energy spectrum but for the dip.
- Time variability of the energy spectrum.
- Spatial morphology of gamma-ray emission.
- Differences in last two solar minima?

Going forward

Probably B fields at all scales (inner heliosphere, corona, solar atmosphere, photosphere) matter to more-or-less similar degrees to explain the observed properties.

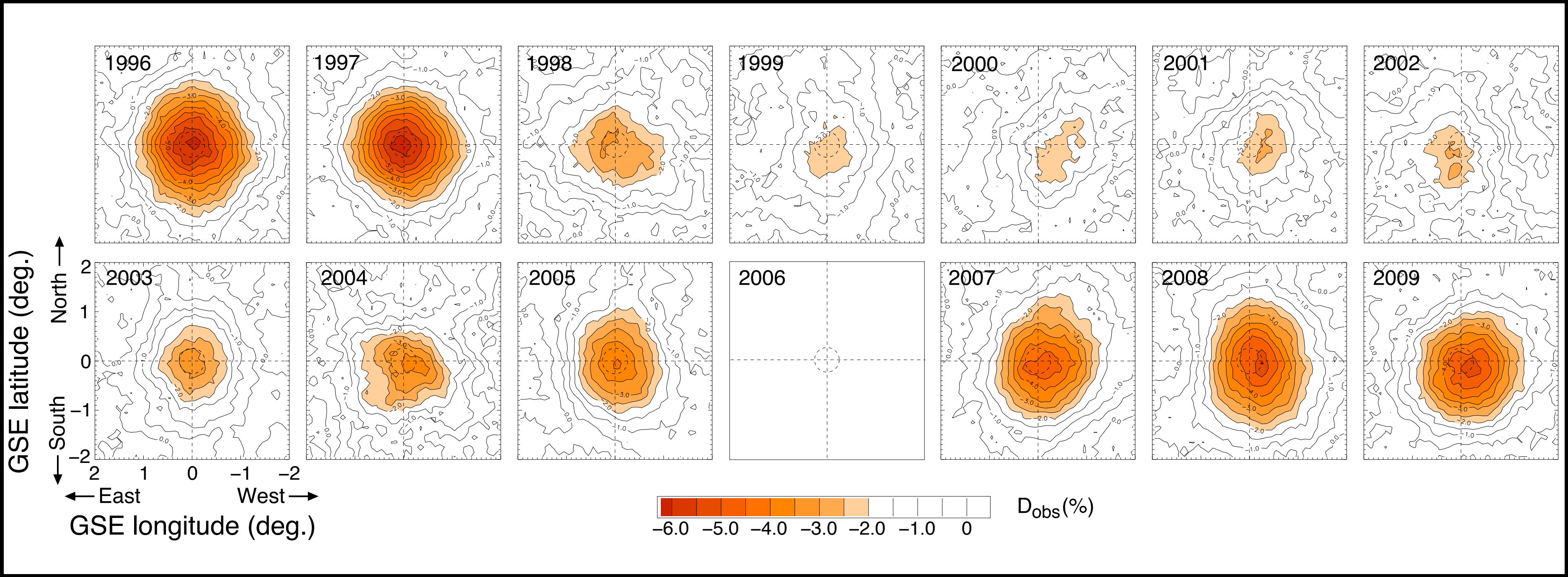
New collab with solar/space physicists (Cohen, Sokolov) + our OSU-based team.



From Ofer Cohen

Cosmic ray shadow

Protons 0.3-100 TeV



Tibet Air Shower array
1306.3009

More w/HAWC and Tibet coming soon.