The Remarkable Influence of Corona Field on Solar Gamma Ray

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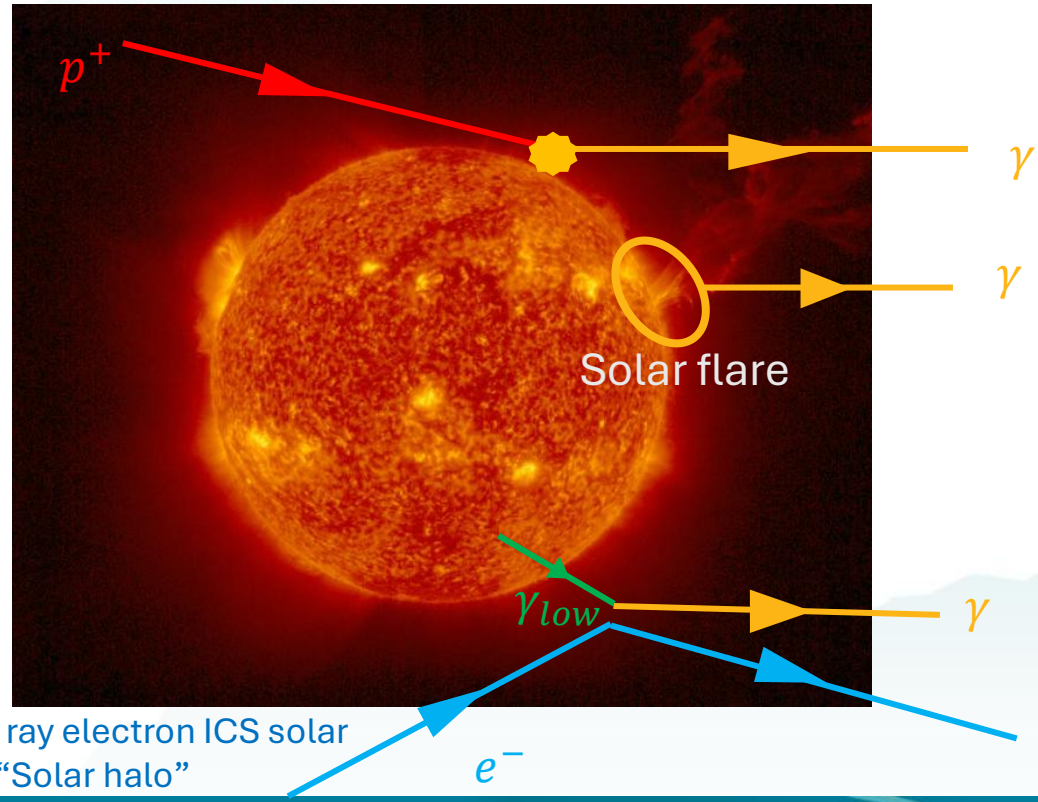
XICHANG
SICHUAN, CHINA
2025.8.24 - 8.30
TAUP XICHANG

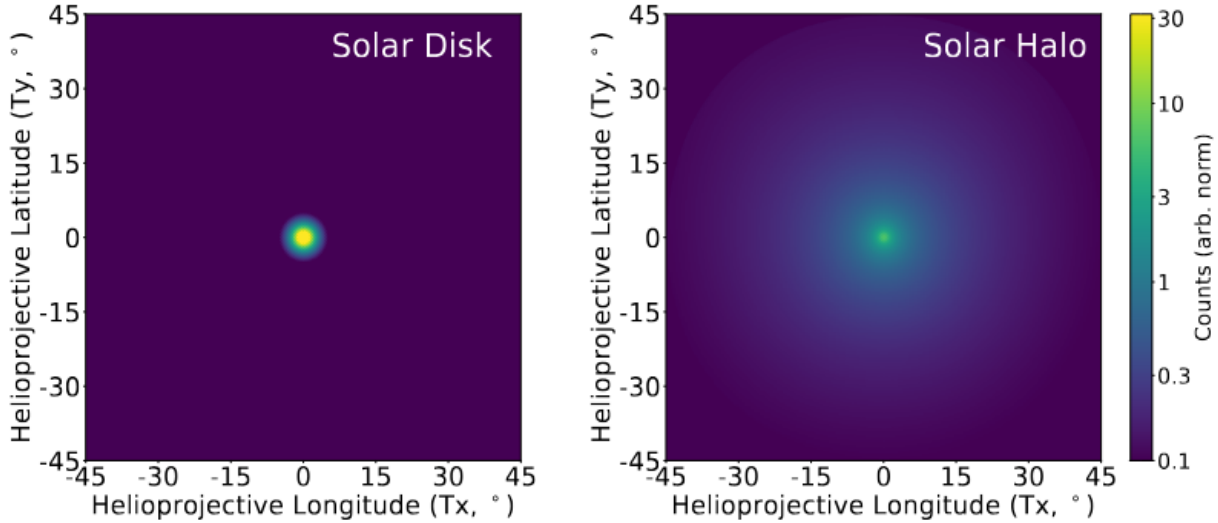
Sun as a Gamma Ray Source

Cosmic ray proton + solar atmosphere -> “Solar disk”



Cosmic ray electron ICS solar photon “Solar halo”

T. Linden et al., 2025
arxiv: 2505.04625



- Easily distinguishable from one another
- We focus on solar disk gamma ray here

Cosmic Ray's Journey to Gamma Ray

Galactic Cosmic Ray
- 1 AU & beyond
- Isotropic

→ **Inter-planetary space**
- Heliospheric field modulation

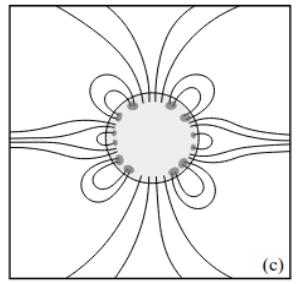
→ **Inner heliosphere**
- Coronal Field

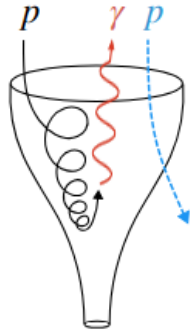
→ **Photosphere**
- Proton interactions
- Bent by sub-surface field in the Sun

→ **Gamma ray**

In this work, we consider these elements

- Importance:
  - Probe solar magnetic field.
  - Laboratory of high energy particle.
  - Potential for new physics.





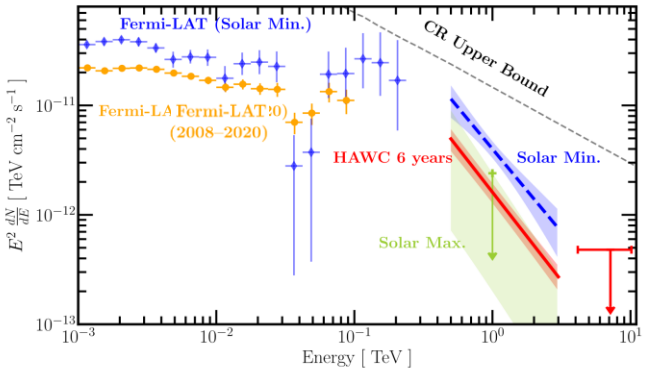
$$p + p \rightarrow \pi^0 + \mathrm{X}$$
$$\pi^0 \rightarrow \gamma\gamma$$

Li et, al 2023
arxiv:2307.08728

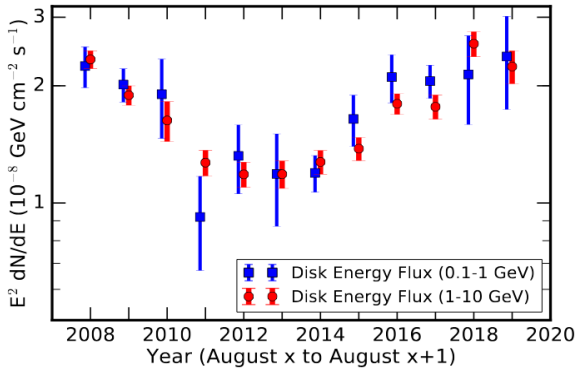
Observation Puzzles

The complete theory for solar disk gamma ray needs to explain all of these!

HAWC Collaboration, 2022
arxiv:2212.00815

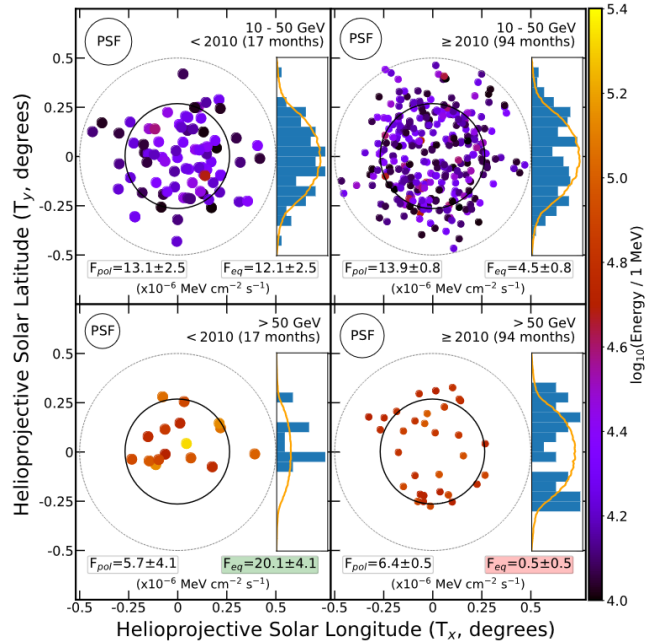


Linden et, al 2020
arxiv:2012.04654



- *Flux:*
  - Flat up to 200 GeV
  - 6x higher than early estimate
- *Time Variation:*
  - Anti-correlates with solar cycle

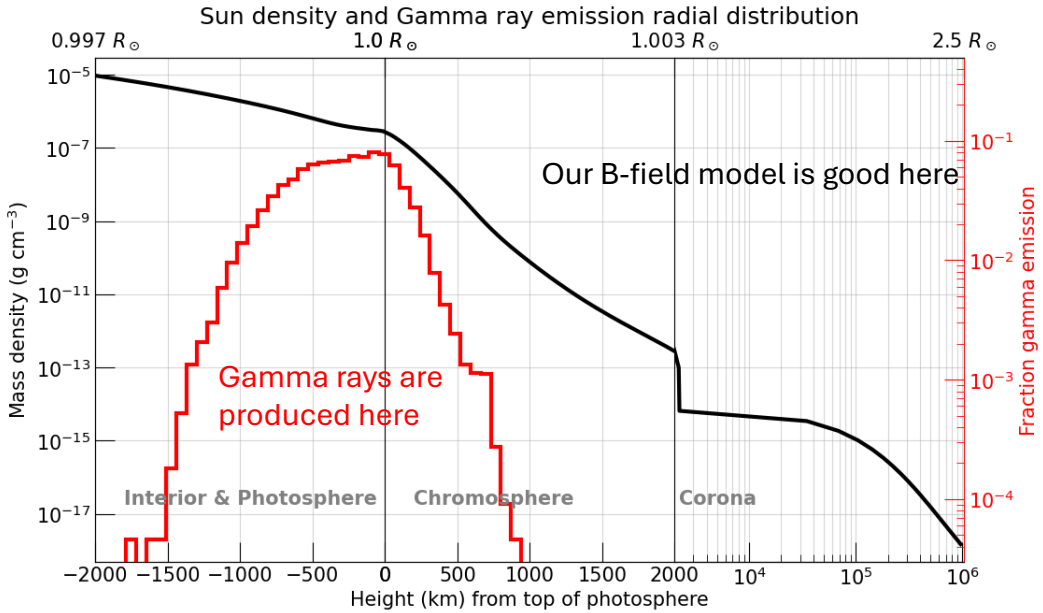
Quiet Active

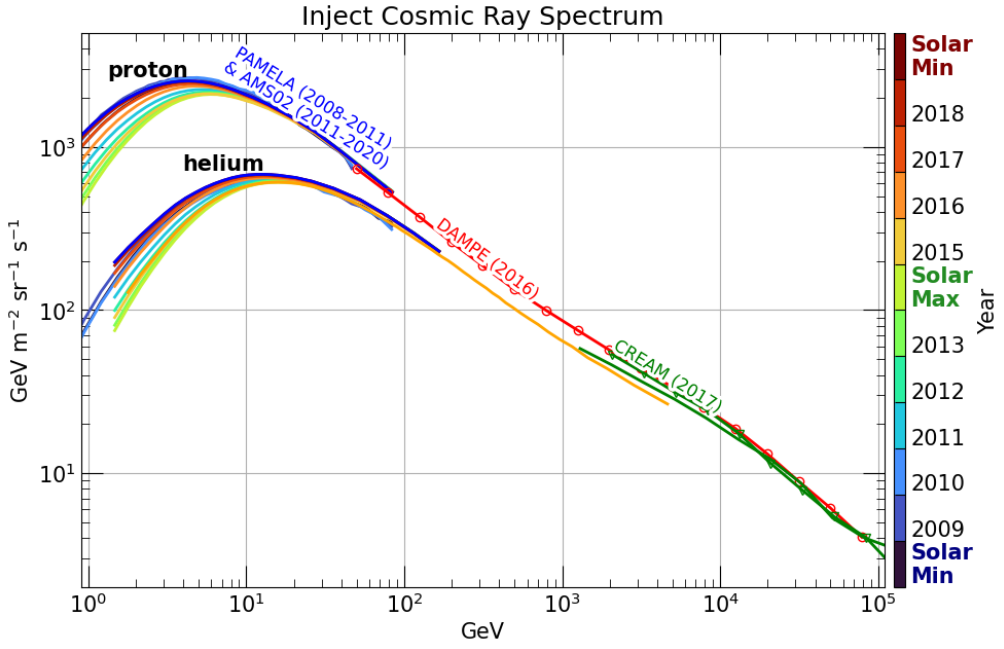


Linden et, al 2018
arxiv:1803.05436

- *Morphology:*
  - Energy and time dependent
    - Quiet:
      - Low energy: uniform
      - High energy: equator focus
    - Active:
      - More polar emission (low and high)

Simulation Toolkit G4SOLAR2.0

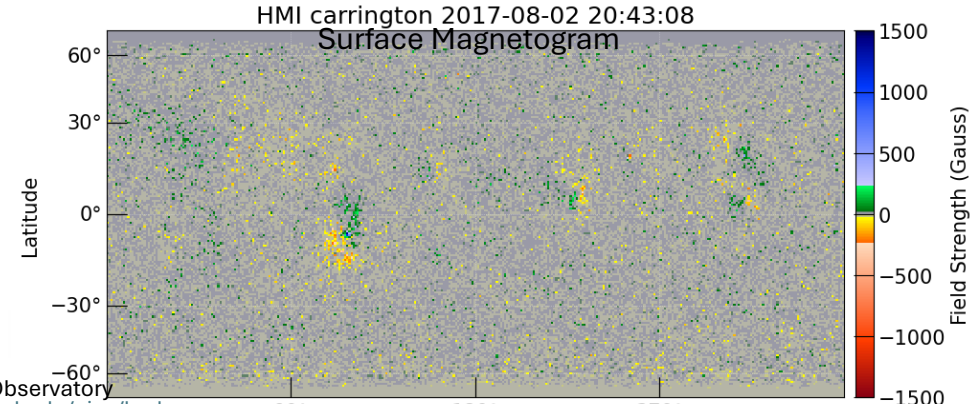




tools.ssdc.asi.it/CosmicRays/

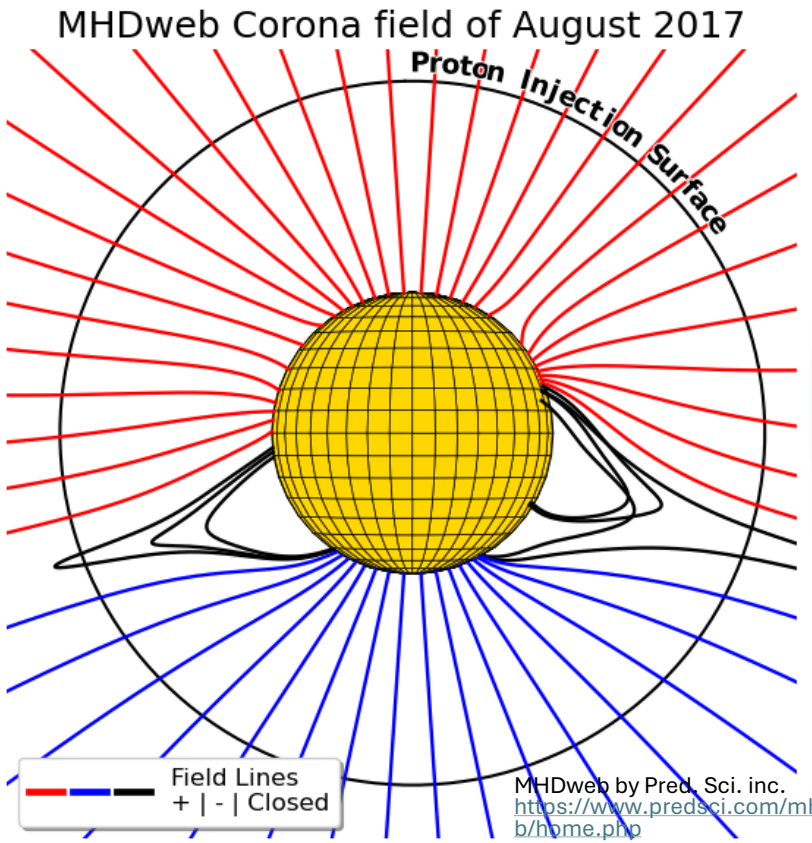
- Written in Geant4, first developed by Zhe Li (2009.03888)
- Simulation volume:
  - [(R_sun - 2000km), 2.5 R_sun]
- Isotropic inject Cosmic Ray, normalize to 1 AU flux
  - Proton & Helium, with solar cycle variation

Corona Field Model



Solar Dynamics Observatory
http://jsoc.stanford.edu/ajax/lookdata.html?ds=hmi.pfss_synop

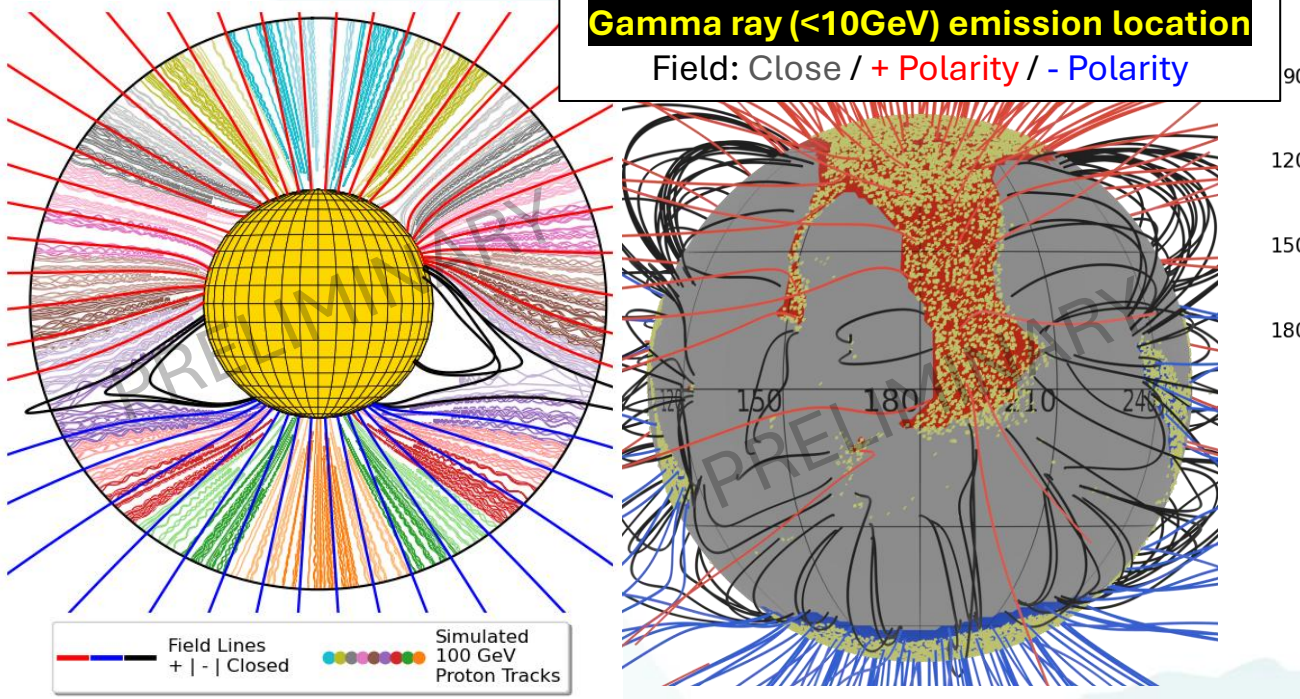
- Magneto-Hydrodynamic (MHD) corona model solutions, calculated by Predictive Science Inc. (PSI)
  - Boundary condition: observed photosphere field
  - Require full surface magnetogram, available only after full Sun rotation



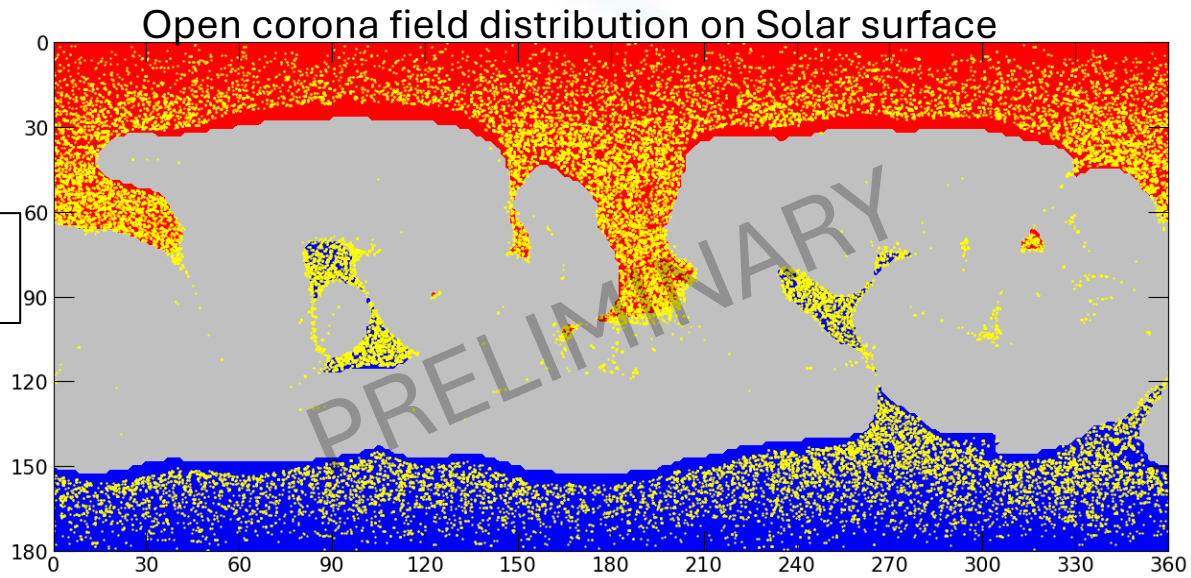
MHDweb by Pred. Sci. inc.
https://www.predsci.com/mhdweb/home.php

- We simulate gamma ray flux in field models from different periods of solar cycle, across 11 years

Cosmic Ray Affected by Corona Field

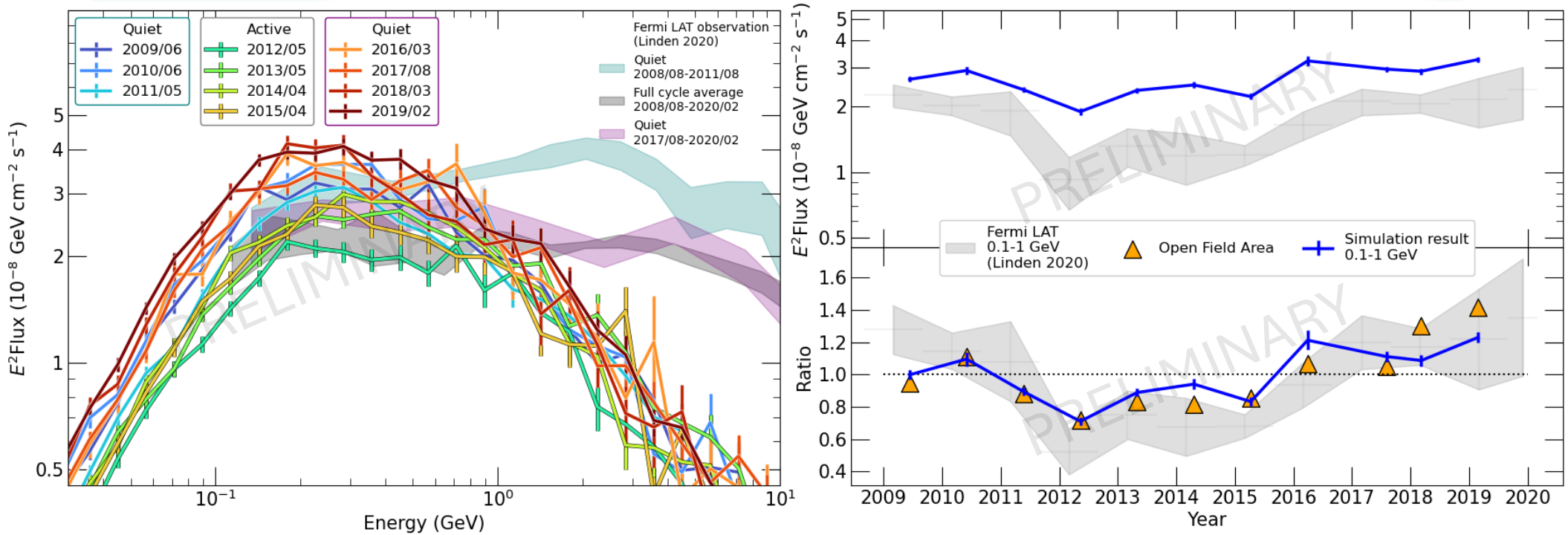


- We trace individual cosmic ray (CR) propagation and interaction



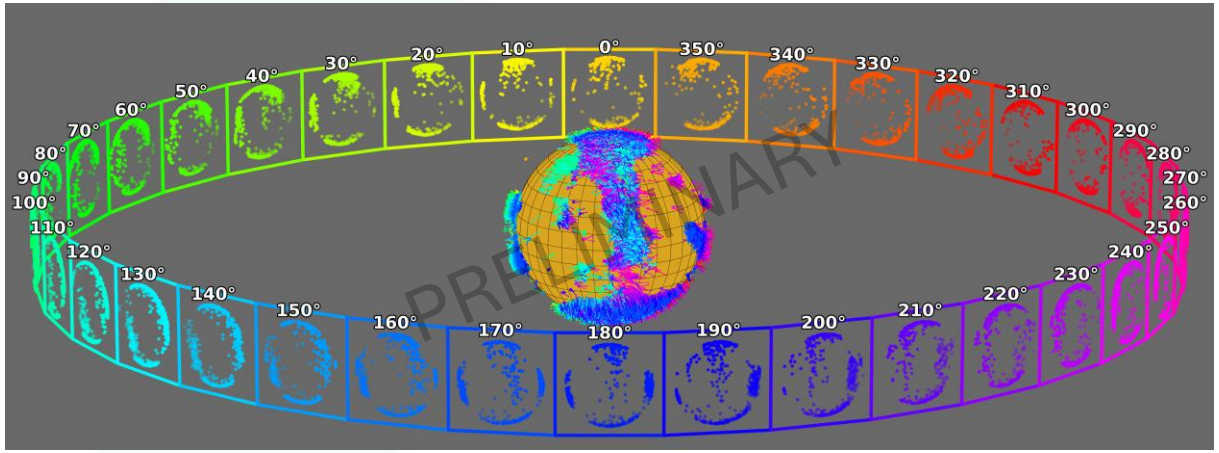
- CR < 100 GeV is heavily influenced by corona B field.
  - To reach solar surface, CR must follow open field lines
  - Close field lines reflects CR
- *The area of open field directly decides low E gamma ray flux*

Time Varying 0.1-1 GeV Gamma Flux

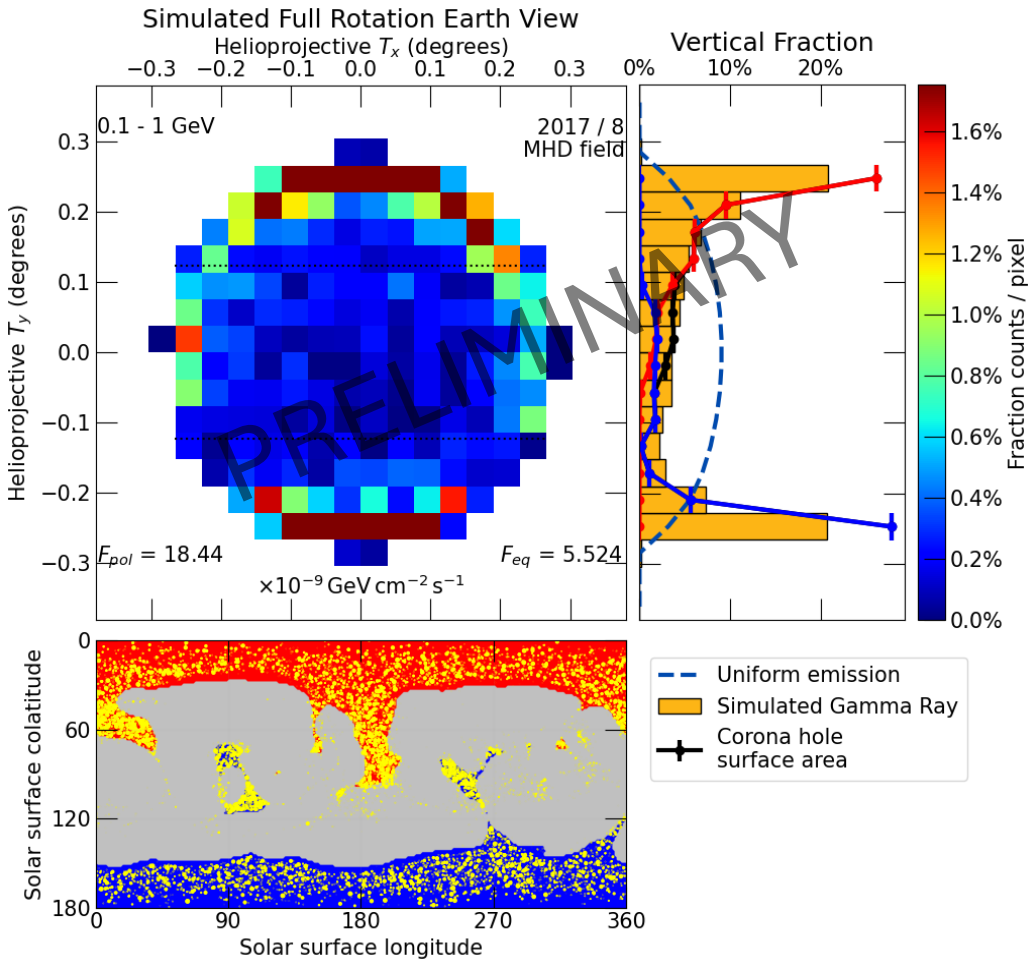


- Gamm flux time variation is consistent with changes in open corona field
- *First study to find a cause for solar gamma time variation: open corona field!*

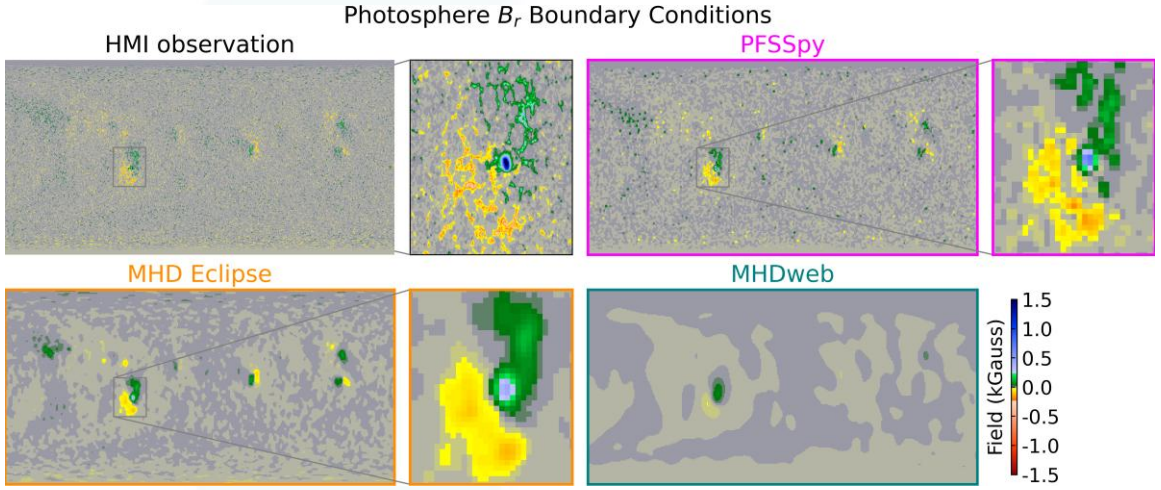
Gamma Ray Morphology



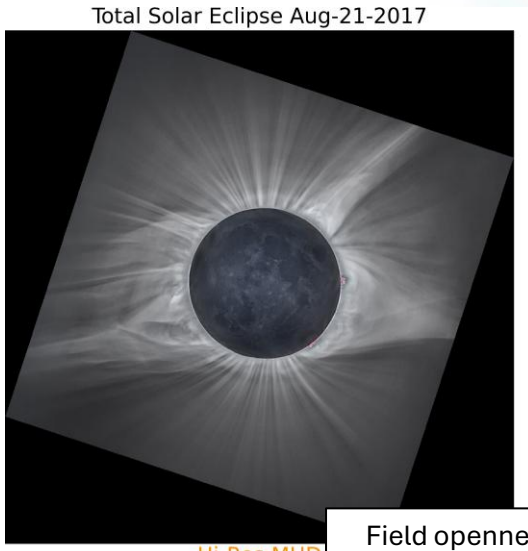
- Tiny "screens" around the Sun, represent observer near Earth orbit
- Corona open field dependance is observable in gamma morphology
  - Specific time: 2D image
  - Time integrated over rotation: vertical fraction

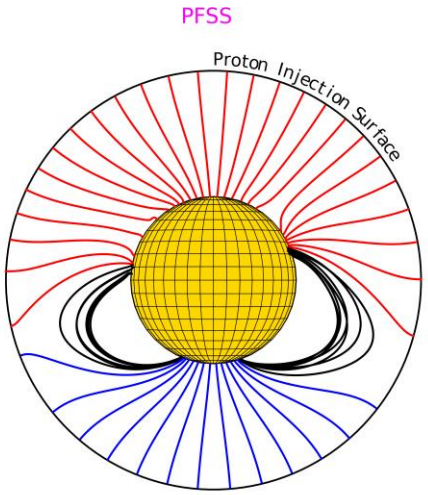


Comparing Corona Models

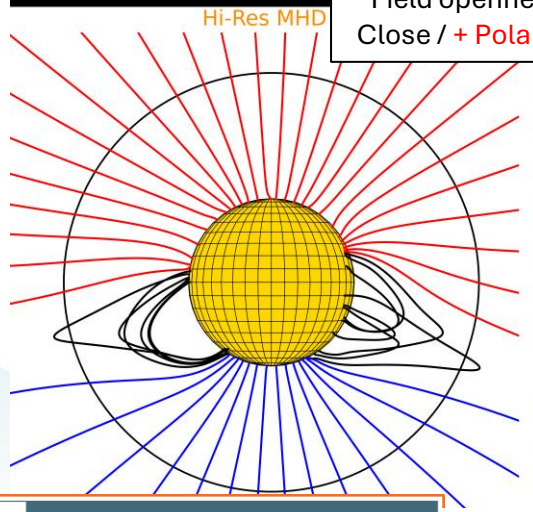


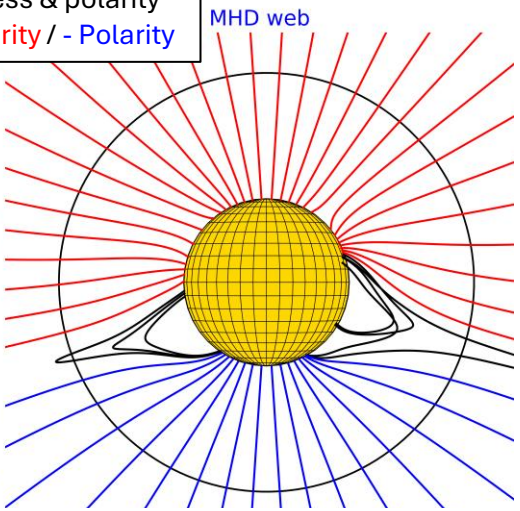
- 3 models:
  - PFSS, MHD, High resolution MHD for eclipse
- All came from the same HMI observation
  - Varying precision & resolution

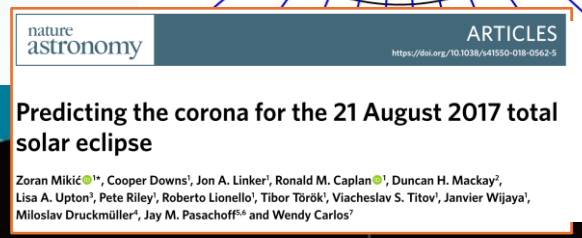




Field openness & polarity
Close / + Polarity / - Polarity






nature astronomy ARTICLES
https://doi.org/10.1038/s41550-018-0562-5

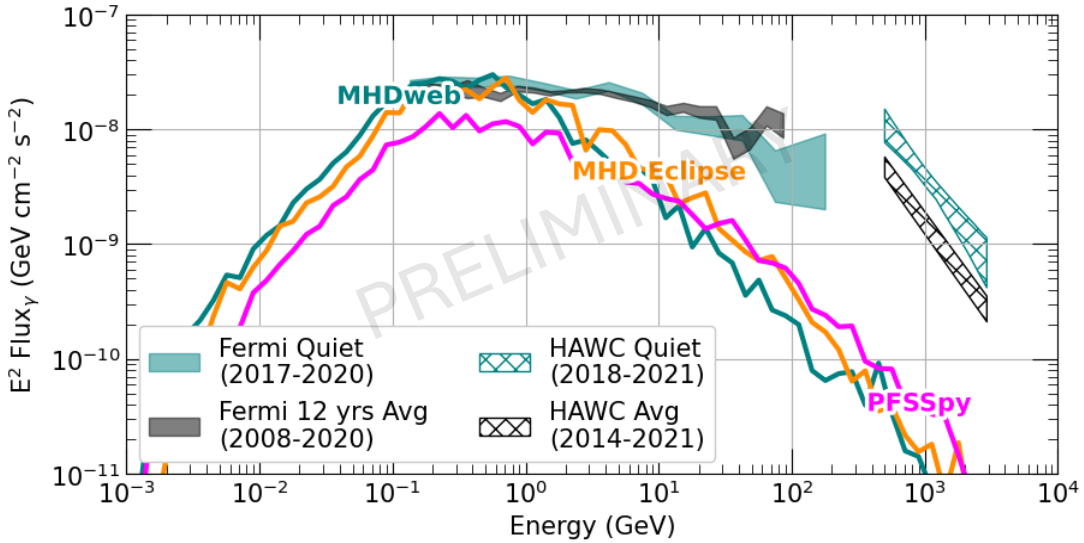
Predicting the corona for the 21 August 2017 total solar eclipse

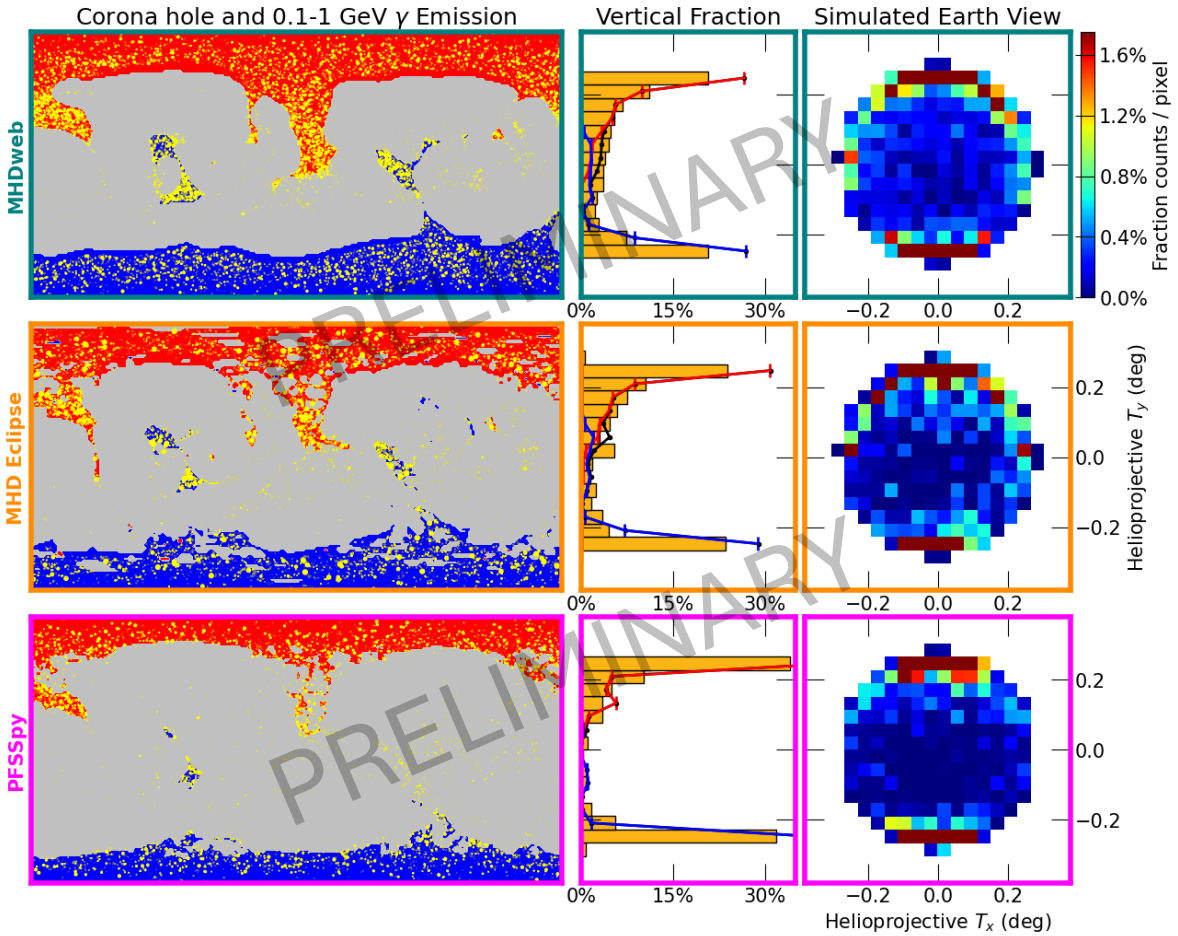
Zoran Mikić[1]*, Cooper Downs[1], Jon A. Linker[1], Ronald M. Caplan[1], Duncan H. Mackay[2], Lisa A. Upton[3], Pete Riley[1], Roberto Lionello[1], Tibor Török[1], Viacheslav S. Titov[1], Janvier Wijaya[1], Miloslav Druckmüller[4], Jay M. Pasachoff[5,6] and Wendy Carlos[7]

PFSSpy by David Standsby
https://pfsspy.readthedocs.io/en/latest/
Predicting the corona for the 21 August 2017 total solar eclipse. *Nat Astron* **2**, 913–921 (2018).
https://www.nature.com/articles/s41550-018-0562-5
MHDweb by Pred. Sci. inc.
https://www.predsci.com/mhdweb/home.php

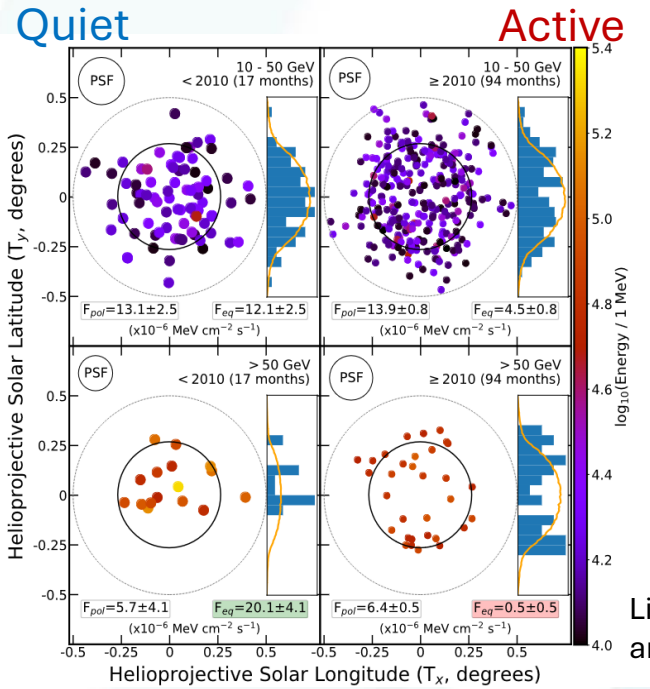
Observable Effects Due to Corona Field

- Different corona model predicts different 1 AU observed morphology.
- Low E solar gamma ray could be used to test corona model



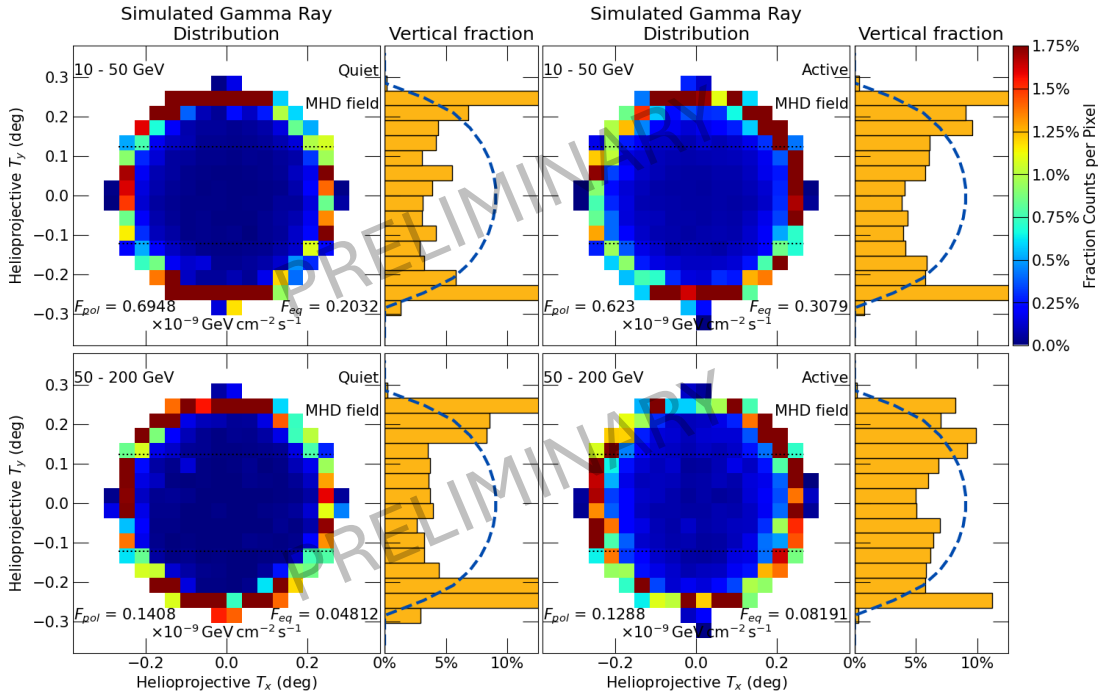


Compare to Fermi Morphology



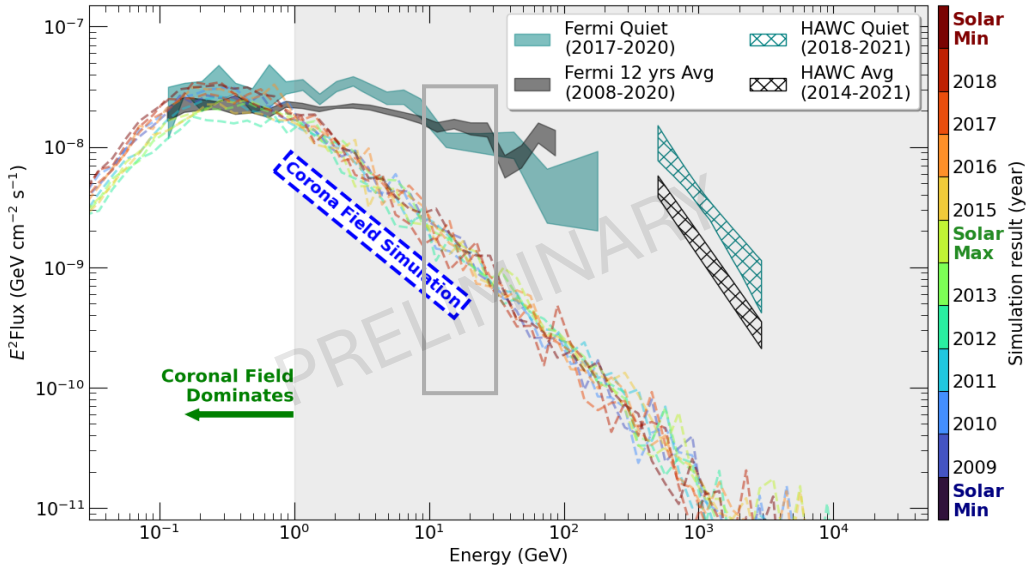
Linden et, al 2018
arxiv:1803.05436

- Fermi LAT only has morphology above 10 GeV, where our flux result is wrong

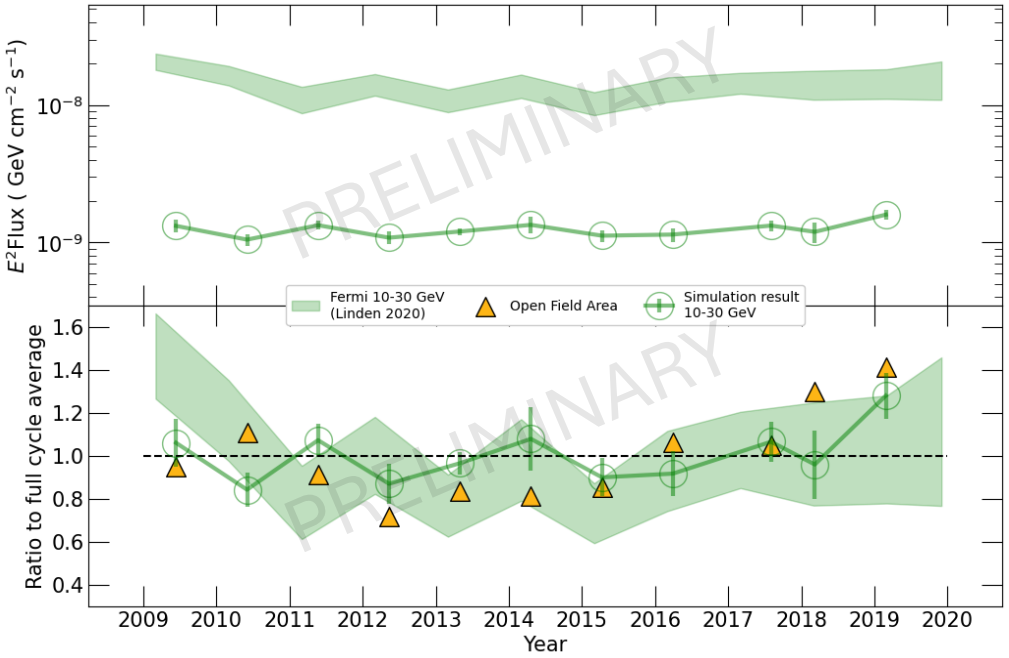


- Observed morphology:
  - More uniform, favors equator at quiet
  - Energy dependent
- Simulation:
  - Heavily favors edge
  - Mostly energy independent

Test Photosphere Field

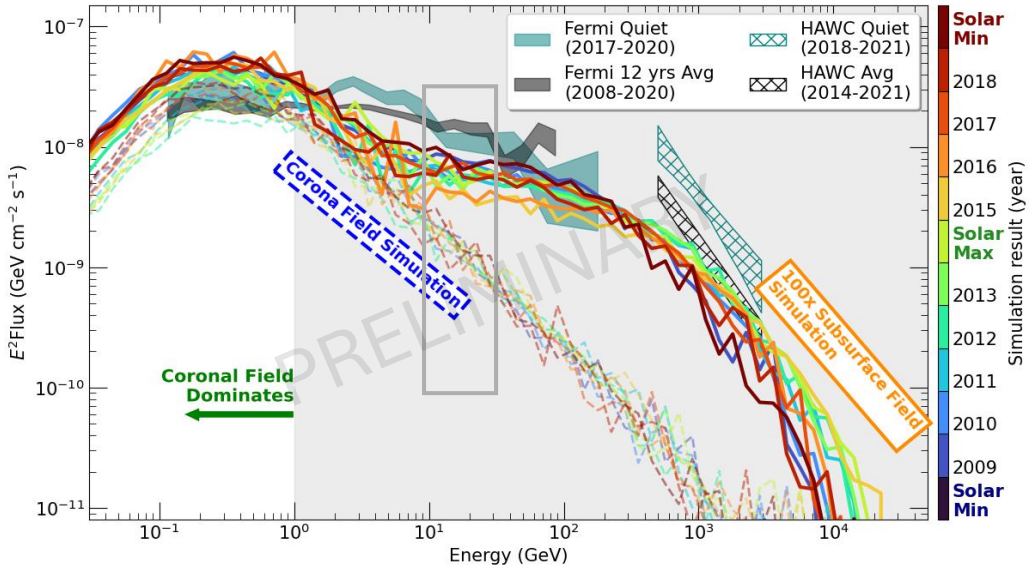


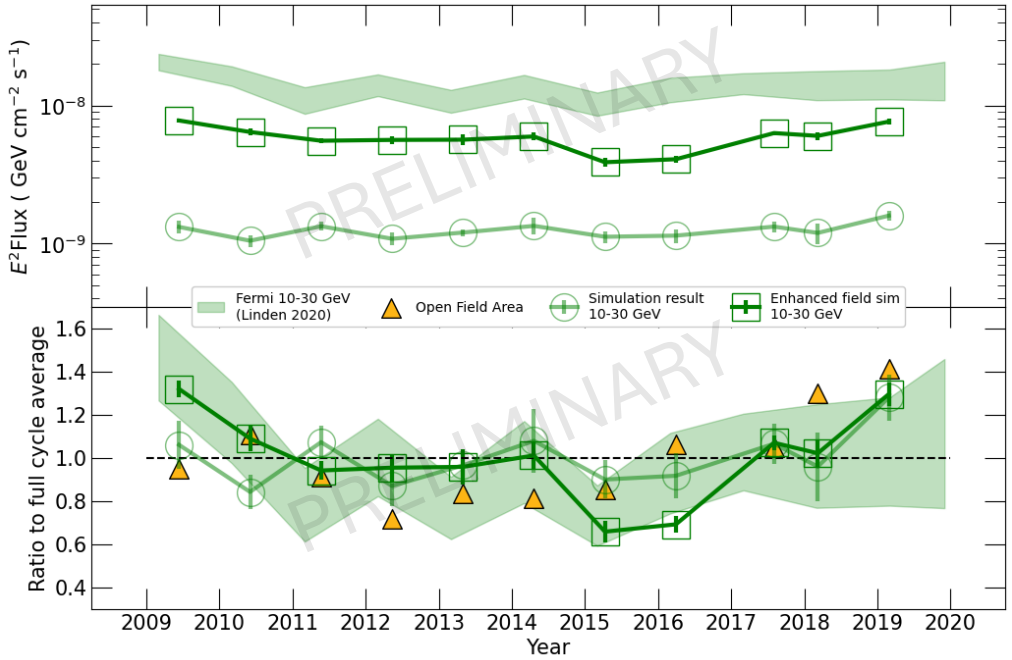
- We put in "toy model" photosphere field to investigate the effect
  - 100x field strength, same structure
- Almost no effect on low energy result



- Enhances high energy flux
  - Could not create time variation in high energy Fermi and HAWC observation
- *Low and high energy gamma ray are caused by different solar magnetic field components!*

Test Photosphere Field





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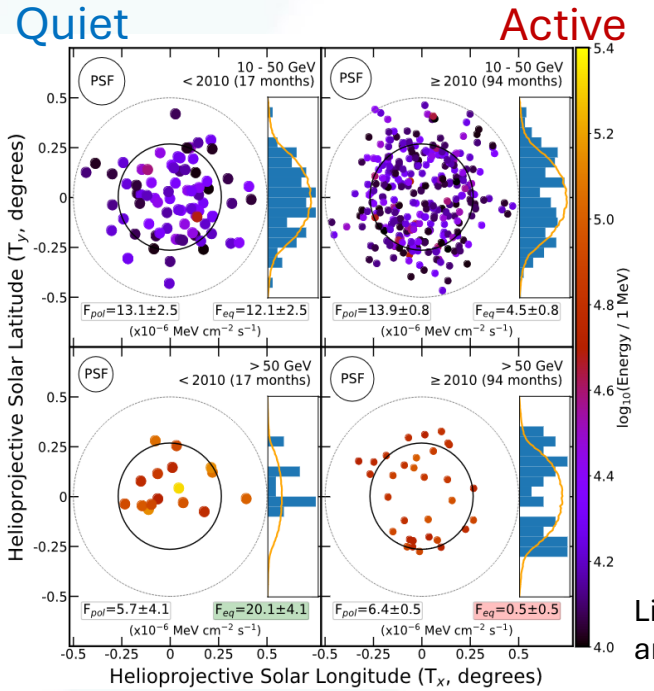
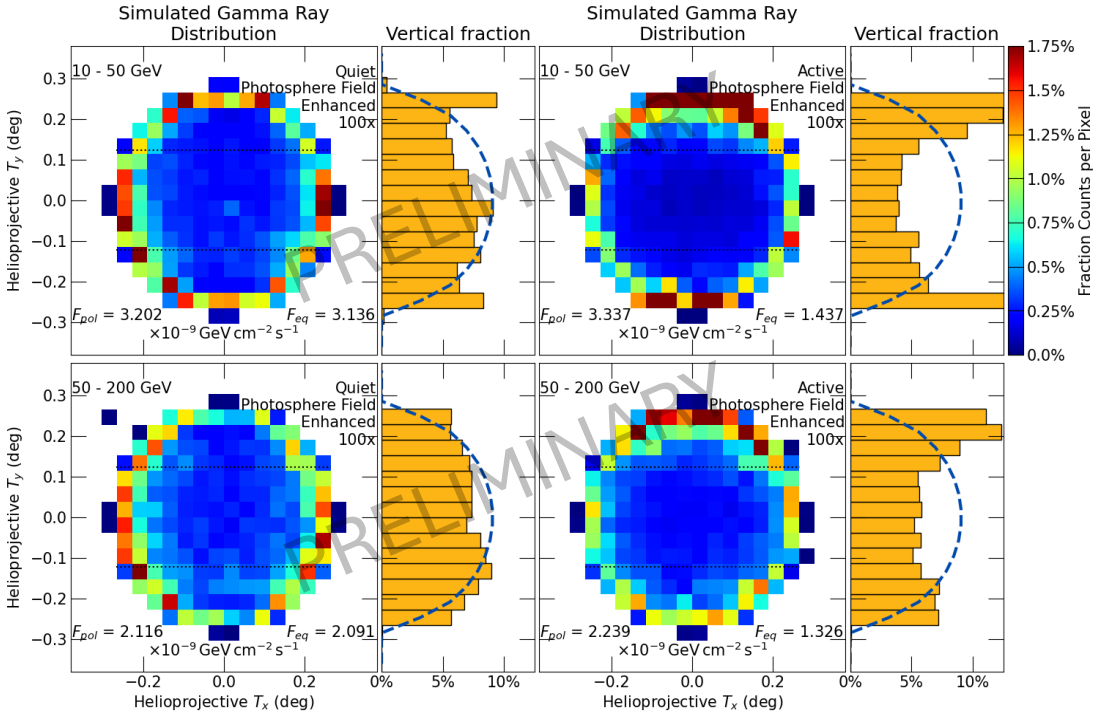
Test Photosphere Field Morphology



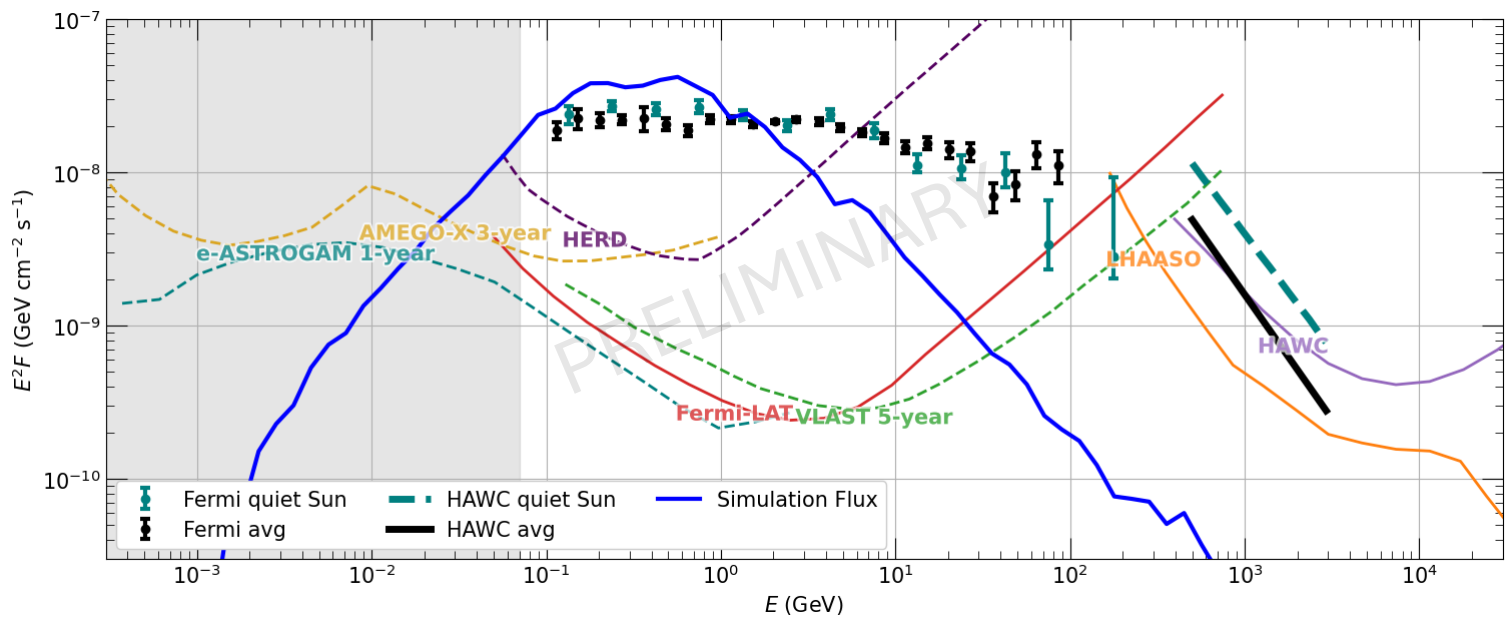
Linden et, al 2018
arxiv:1803.05436

- Still favor ring like morphology
- Cannot reproduce quiet Sun



- Our toy photosphere field changes high energy flux and morphology, still cannot reproduce observation
  - and that's okay

The Future of Solar Gamma is Bright



- Many planned future gamma ray missions can observe > MeV solar gamma
  - Better angular resolution and sensitivity
  - eASTROGAM, AMEGO-X, HERD, VLAST …

Conclusions

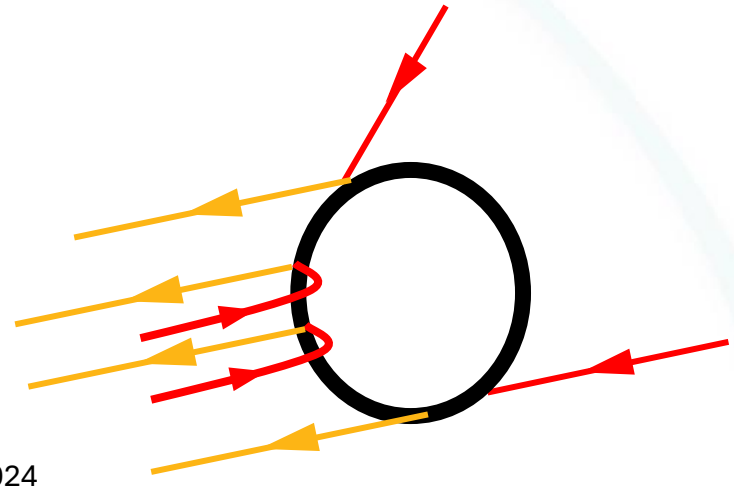
- Corona field has significant effect on low energy cosmic ray and gamma ray
  - MHD model result matches observed flux and time variation < 1 GeV
- Our full Sun simulation allows us to study morphology of gamma ray, which can verify corona models
- Exercise in photosphere field shows high energy gamma are influenced by field inside the Sun
- Many current and future gamma ray missions can study solar disk gamma

Questions?

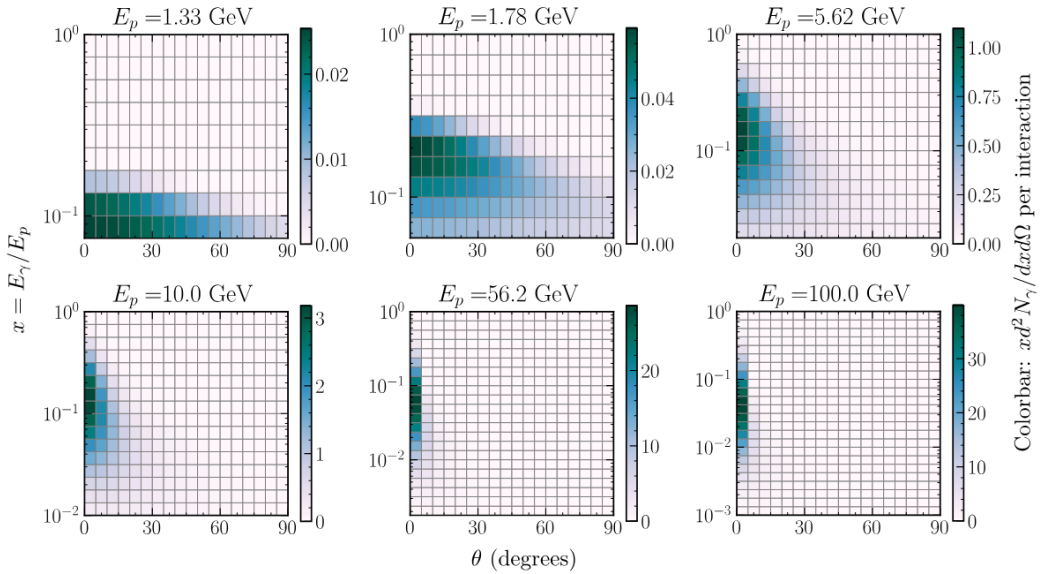
Appendix

Why low energy gamma ray doesn't require strong surface field?

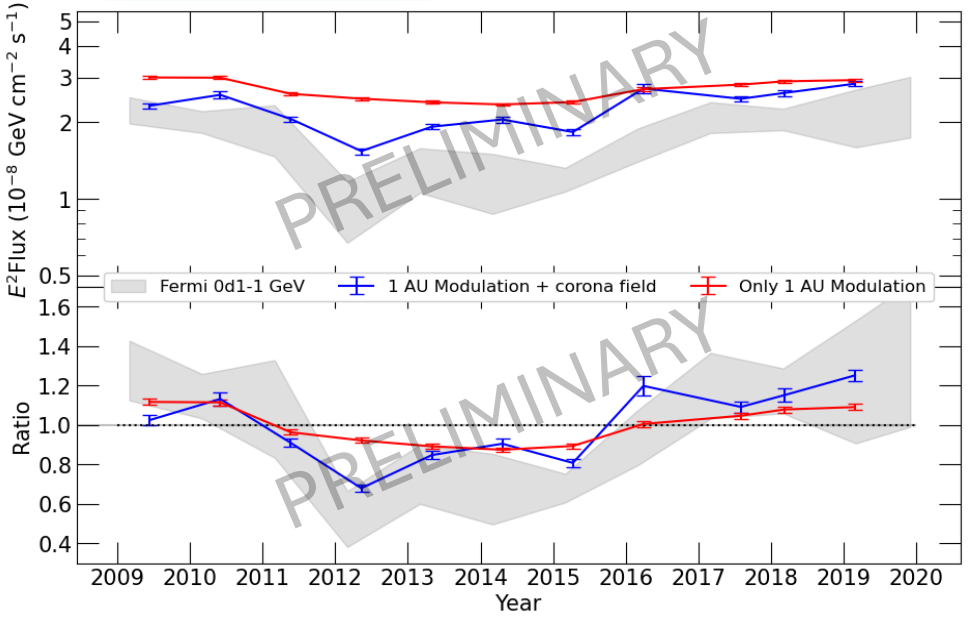
- After proton hit the Sun, the observable gamma must be able to escape, which requires either:
  - Proton graze through atmosphere
    - Ring like, low flux
  - The gamma ray emission direction doesn't follow original cosmic ray direction
    - Can only happen for low energy
  - The original proton is reflected by field to point outward
    - High energy gamma require this!

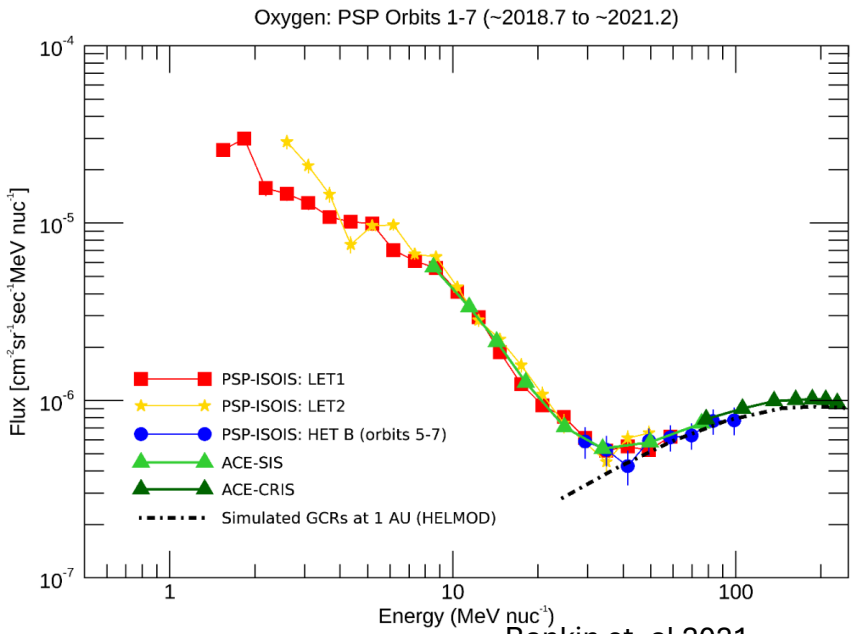


Griffith et al., 2024
arxiv: 2412.08726



Interplanetary Modulation?



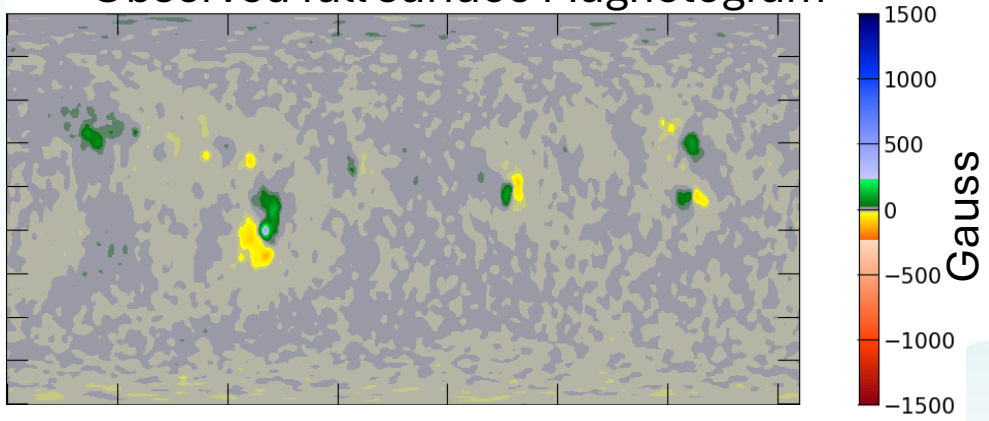


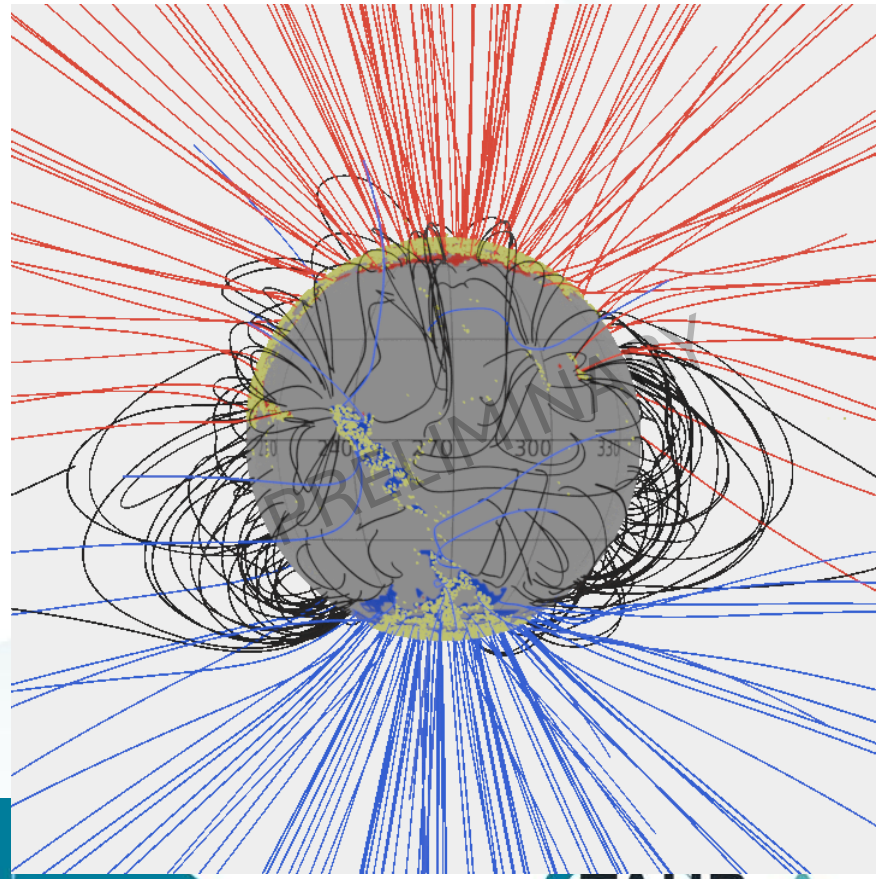
Rankin et, al 2021
arxiv:2110.03601

- Is interplanetary modulation the more dominant effect?
- Only using 1 AU CR modulation: result doesn't look good

- Also, PSP result shows no additional modulation at 0.1 AU in oxygen

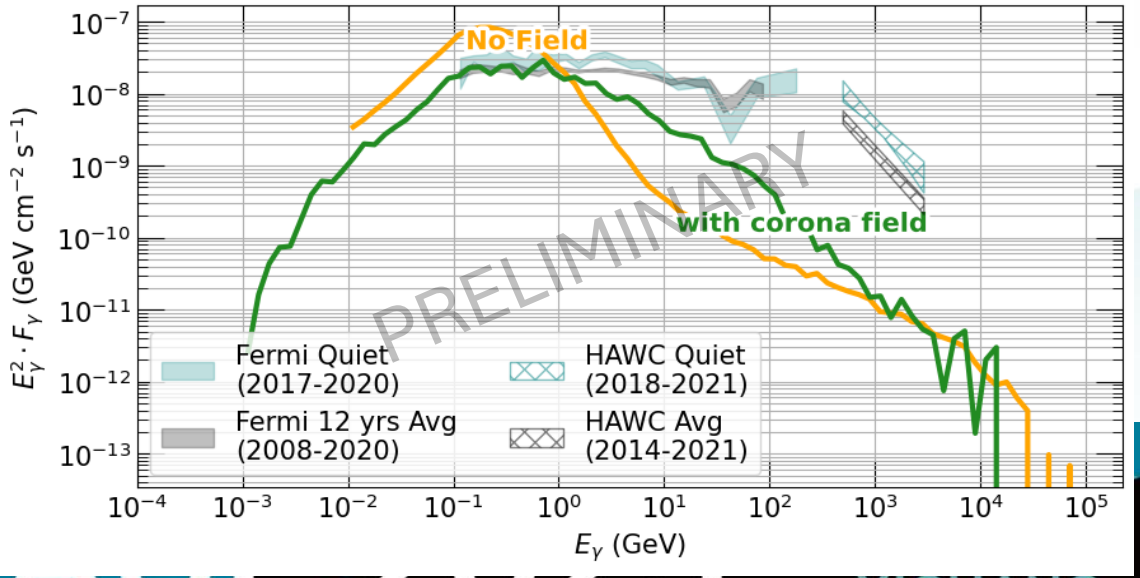
Observed full surface Magnetogram

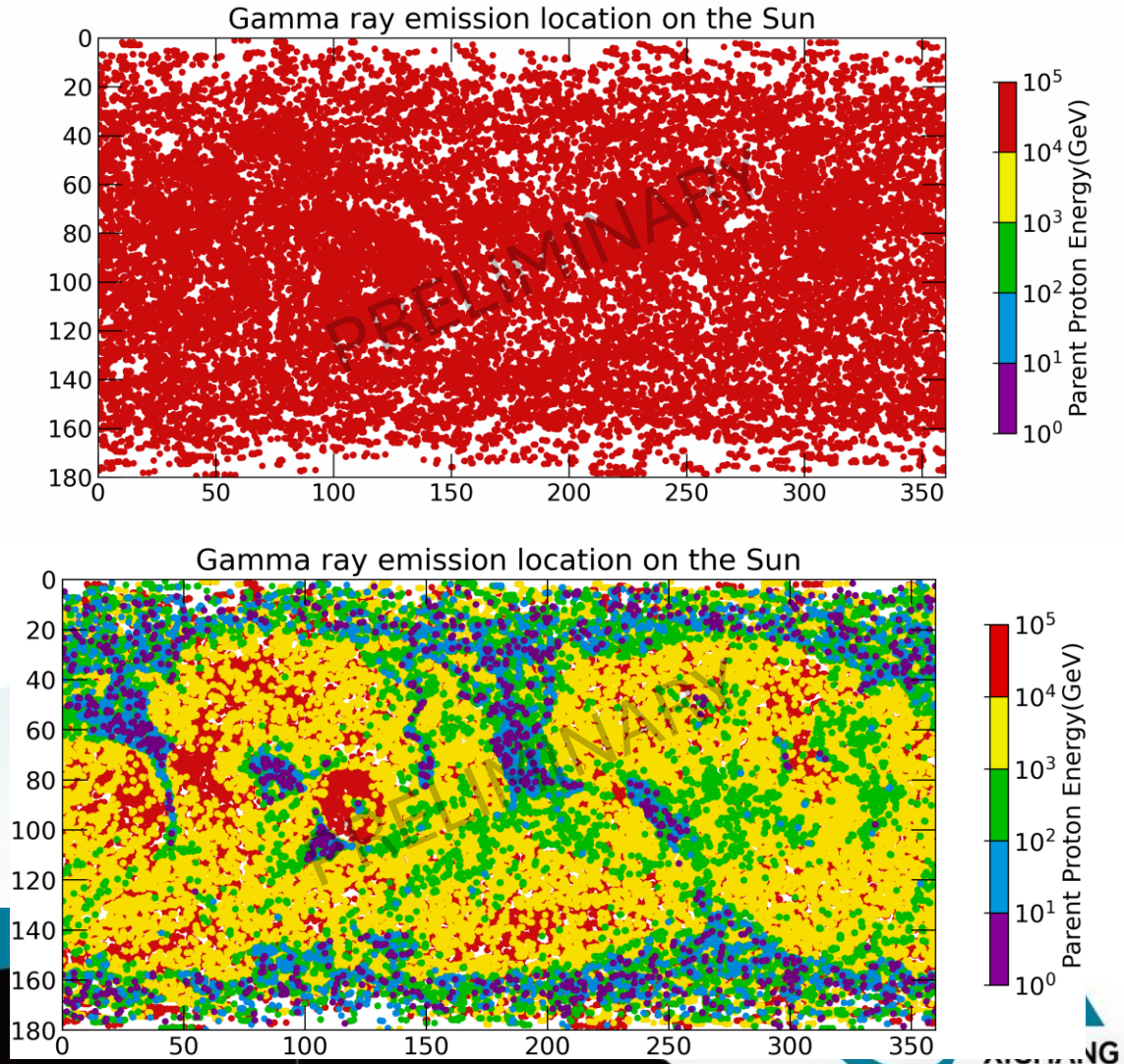




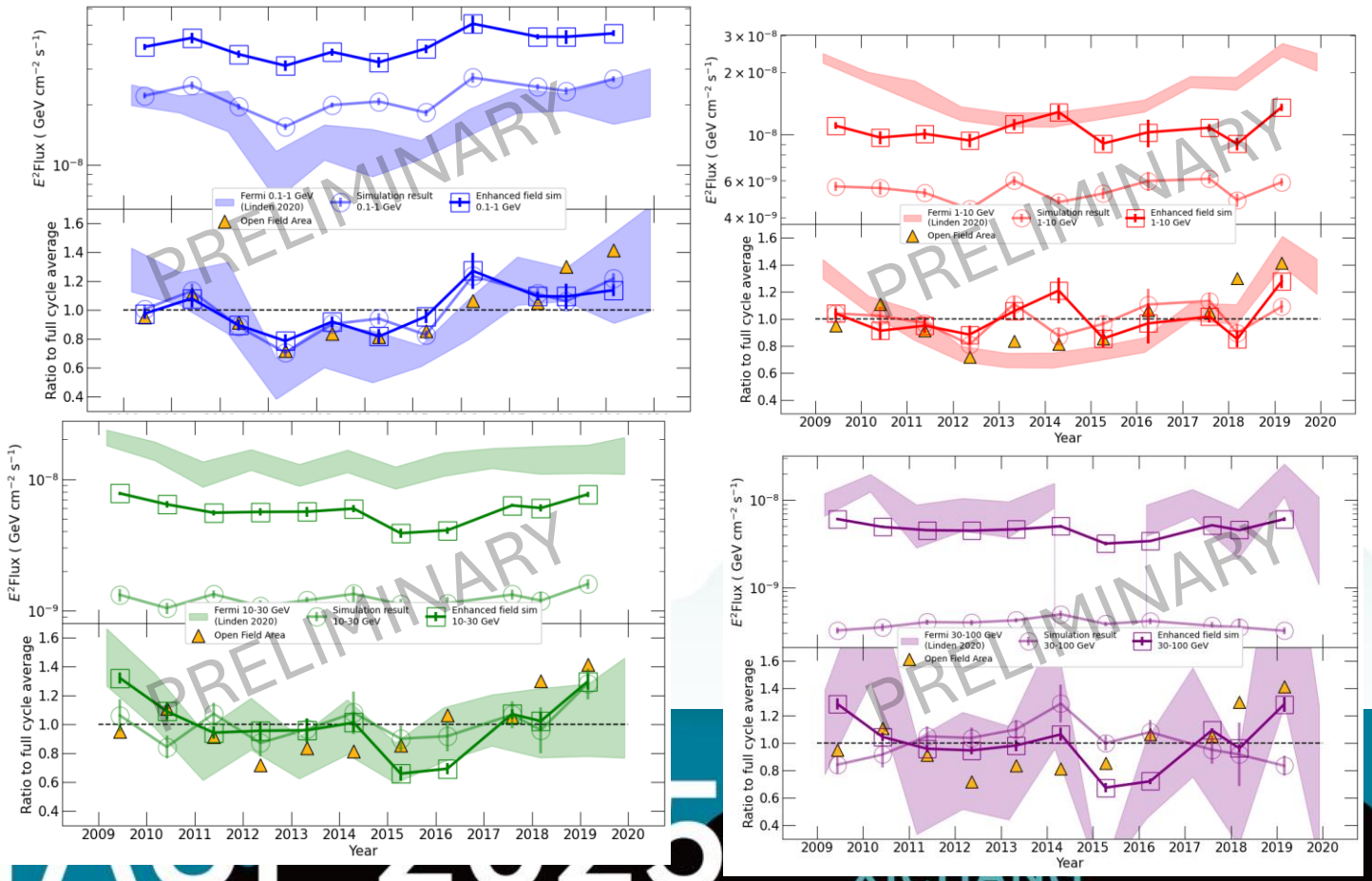
Where the Corona field Stopped being effective

- At higher energy, the corona field is not the dominant effect, and the gamma ray flux behaves as if there's no field.

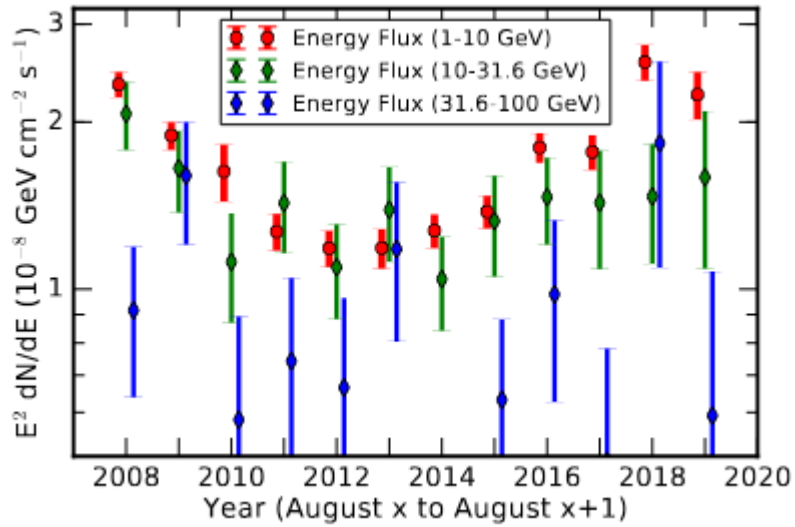




Time Variation in All Fermi Energy Range

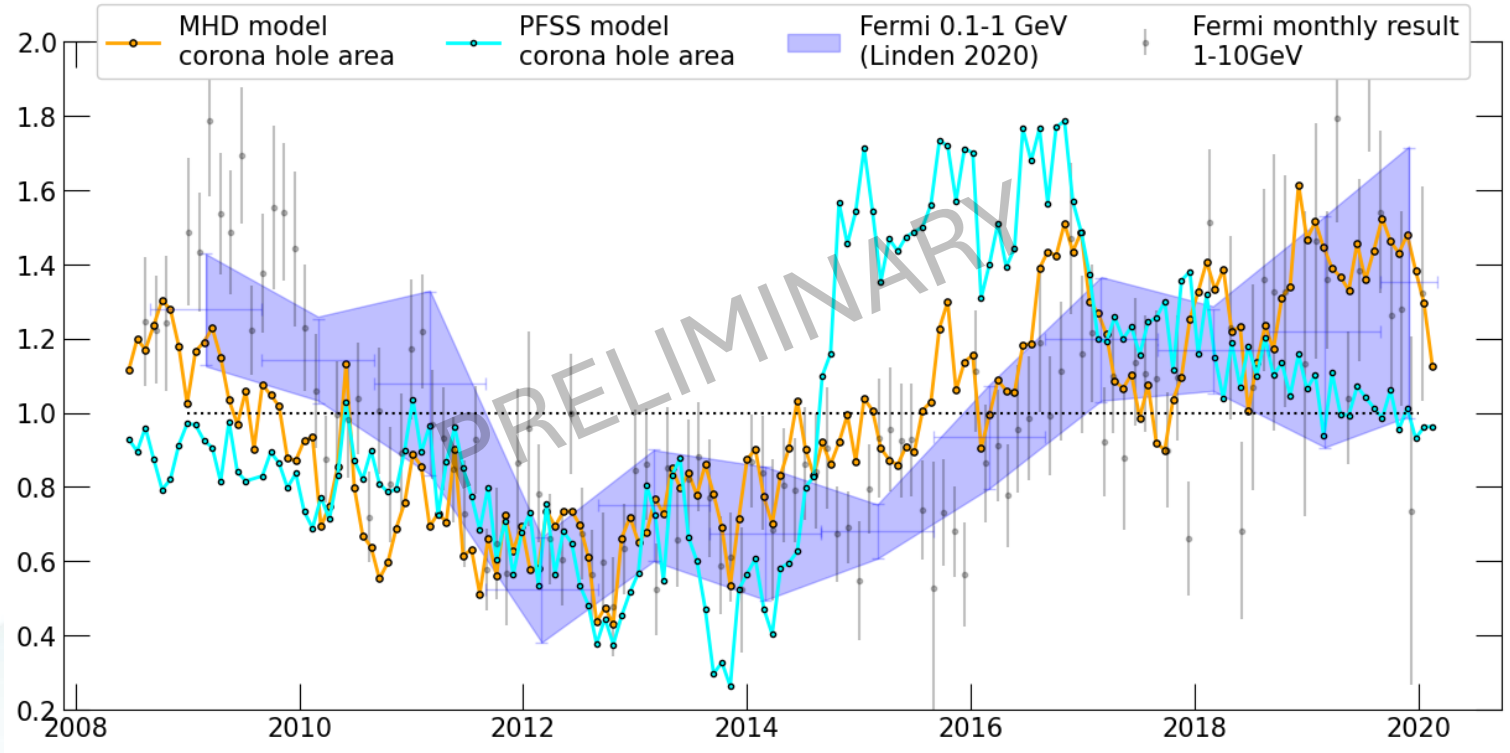


Linden et, al 2020
arxiv:2012.04654



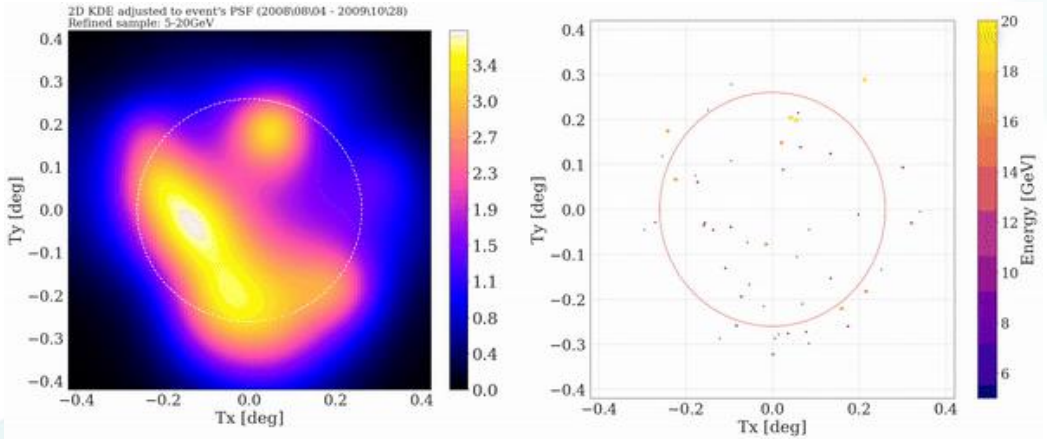
Full cycle, monthly time evo (MHD & PFSS)

- Both models show anti-correlation in monthly result.
- MHD matches better than PFSS



Morphology through time

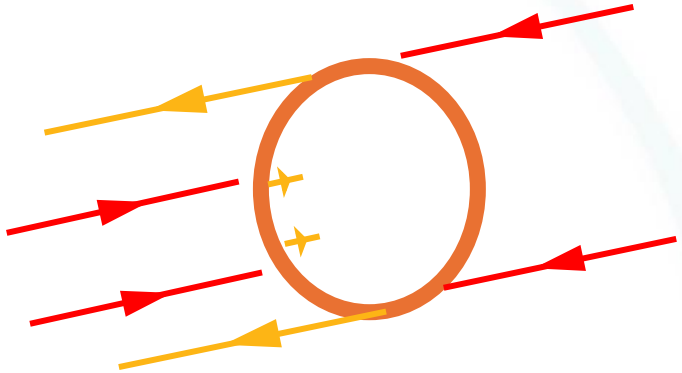
- Year by year asymmetry
- We could not explain this in either enhanced field or just corona field

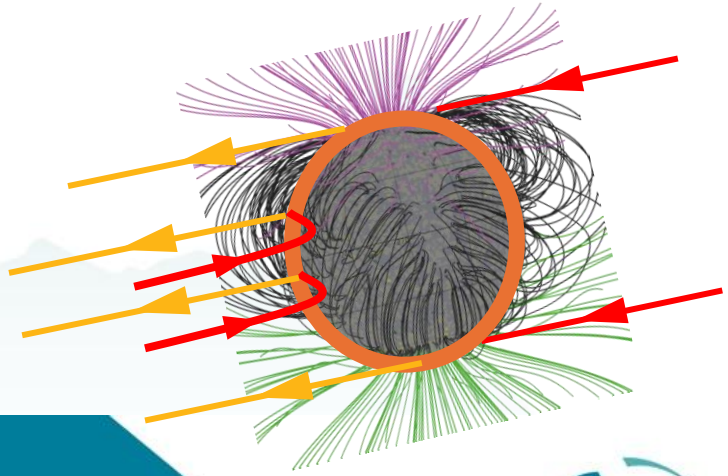


Arsioli & Orlando, 2024

Lower / Upper gamma limit & Importance of B Field

- $\frac{dF}{dE_\gamma}(E_\gamma) = \Phi_{CR} \cdot \frac{dN_\gamma}{dE_\gamma}(E_\gamma, E_p) \cdot \Delta\Omega_\odot \cdot f_{int}$
- Lower bound: Thin ring of gamma ray $f_{int} = 0.1\%$
- Upper bound: All incoming reflected $f_{int} = 100\%$
- Analytical model: Magnetic mirroring $f_{int} \sim 1\%$ (Seckel Stanev Gaisser 1991)
  - Transition energy to ignore magnetic field: $E_p \sim 10^4 GeV(B/1G)\left(L/R_\odot\right), E_\gamma = 1\,TeV$





Cosmic Ray in All Field Models

- Below 100 GeV cosmic rays are trapped and diverted by field lines
  - Therefore, CR collision location and gamma ray emission traces open field lines on the Sun's surface
- Higher energy protons impact more isotropic on solar surface
- Consistent behavior regardless of models