Coronal Magnetic Field Modulates GeV Solar Disk Gamma Ray

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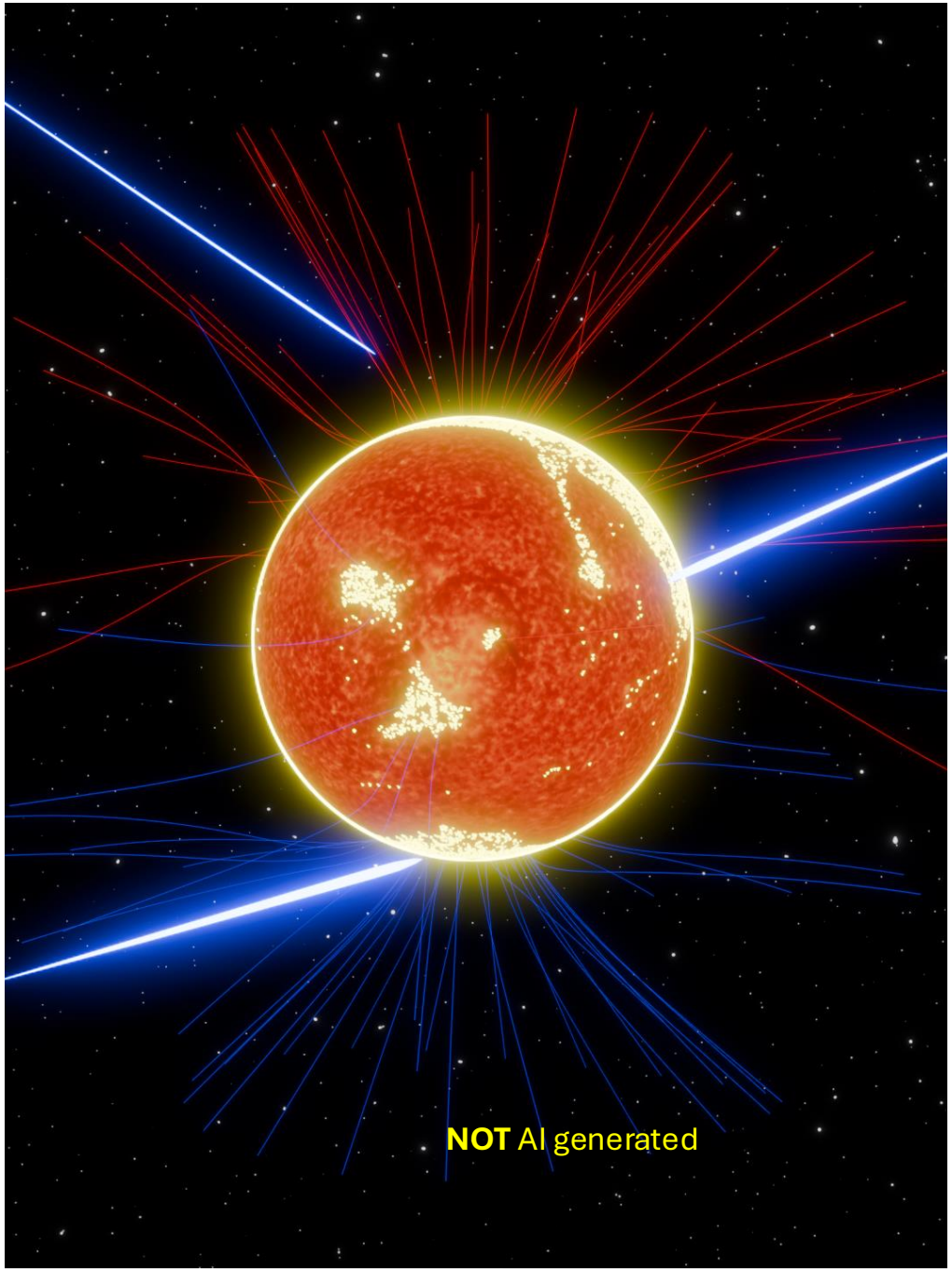


Cosmic Ray to Solar Gamma Ray

Galactic Cosmic Ray → Inter-planetary Space

Primary consideration

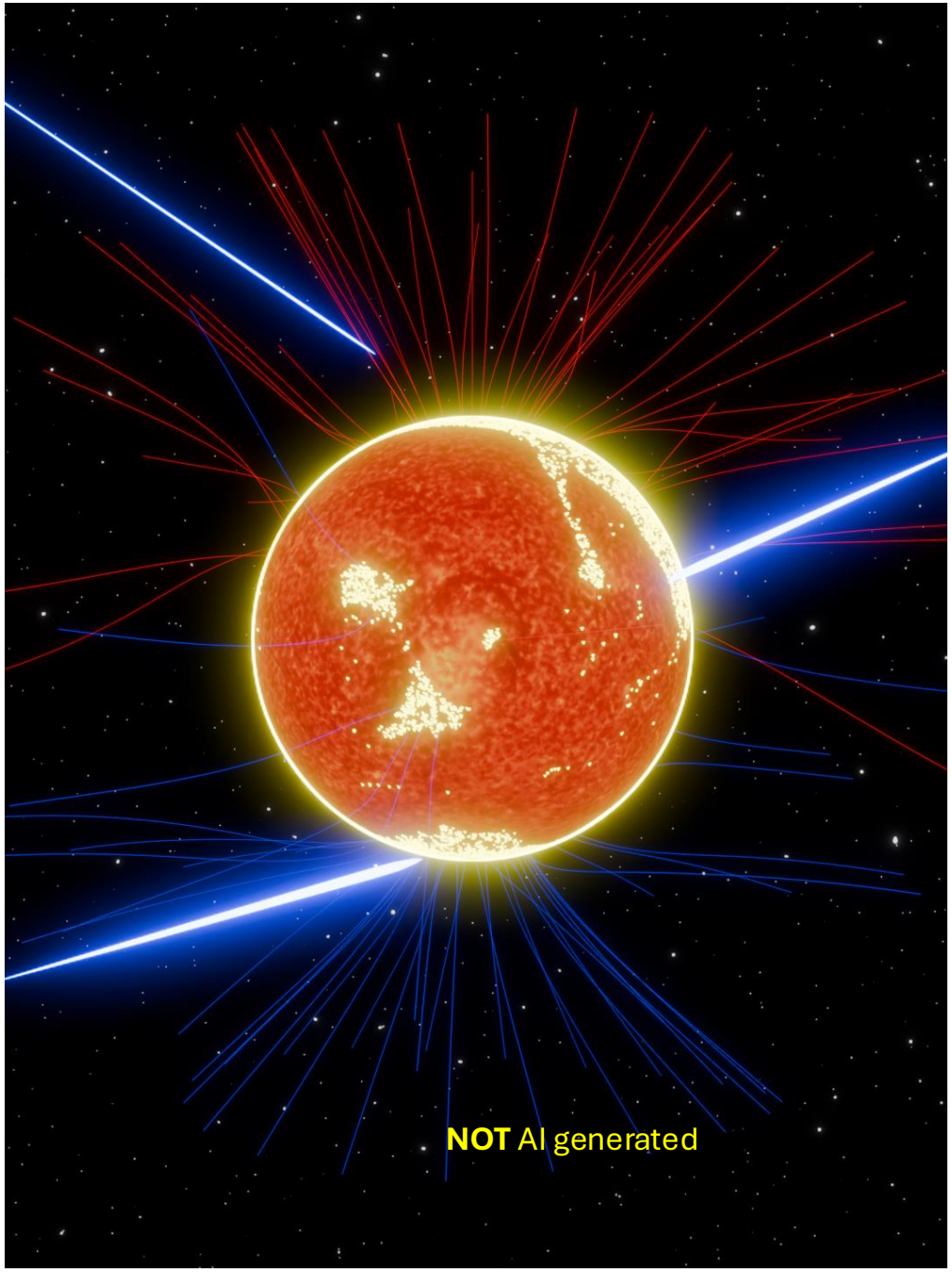
$$p + p \rightarrow \pi^0 + \mathrm{X}$$

$$\pi^0 \rightarrow \gamma\gamma$$

Coronal Field

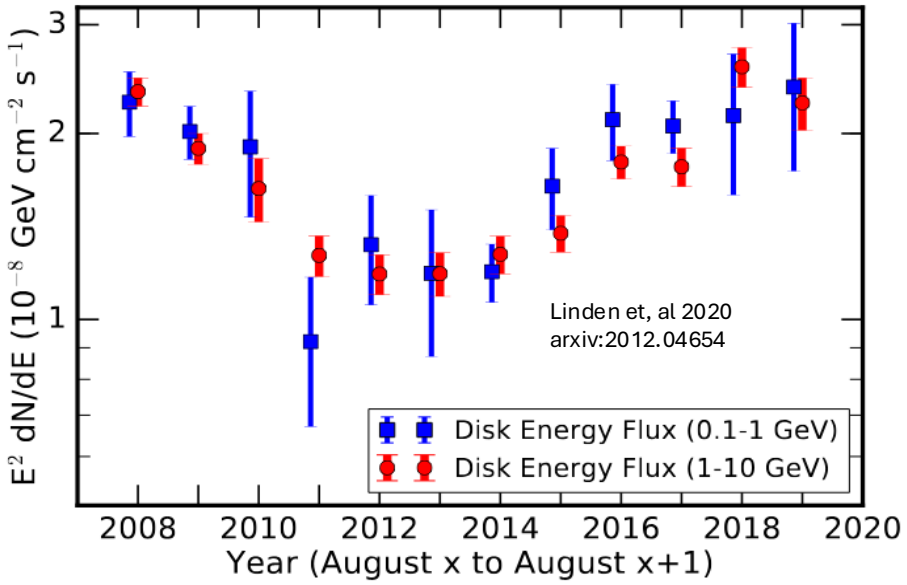
Photosphere
- Field in the Sun

Gamma Ray

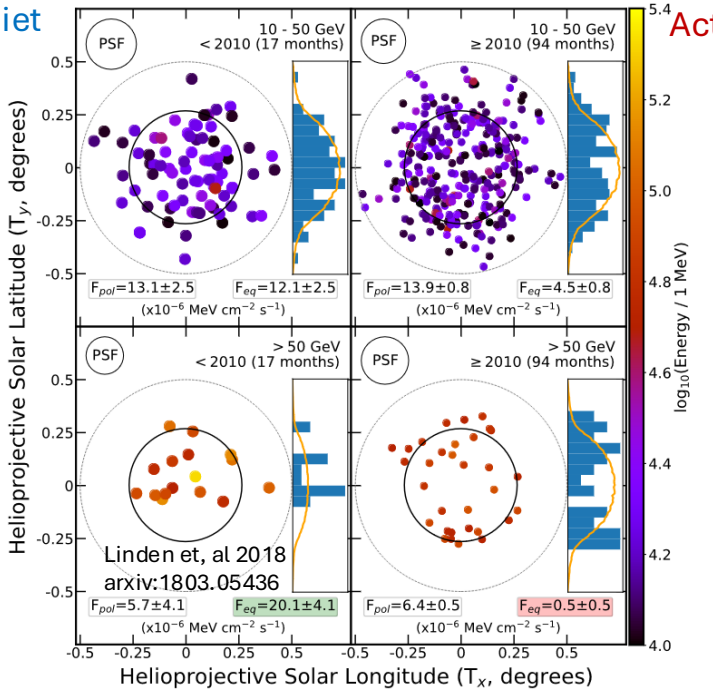


Observation Puzzles

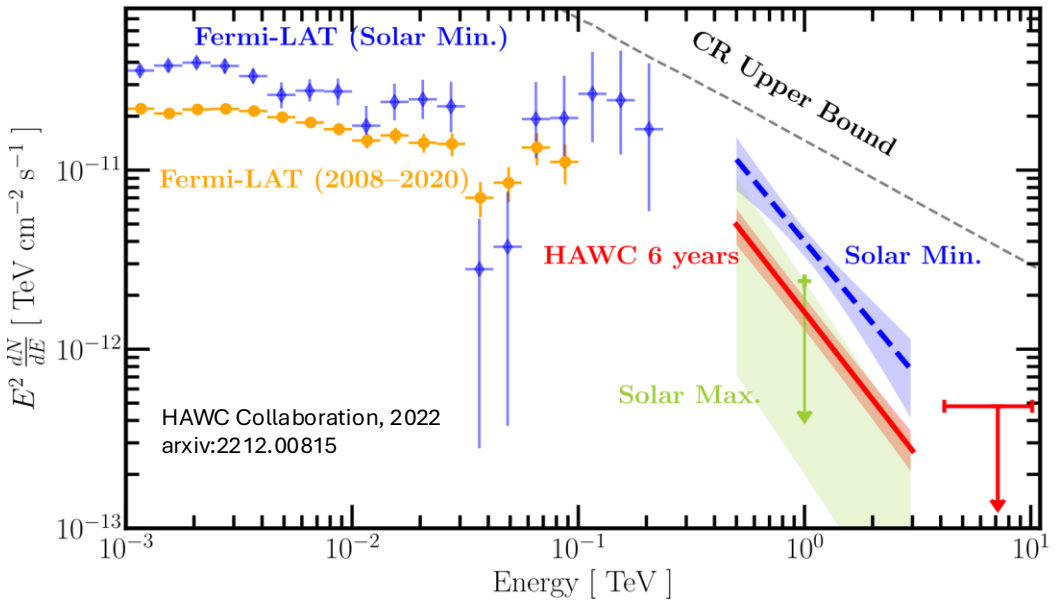
- High flux, flat spectral index
- Anti-correlation with solar activity cycle
- Energy and time dependent Morphology



Quiet



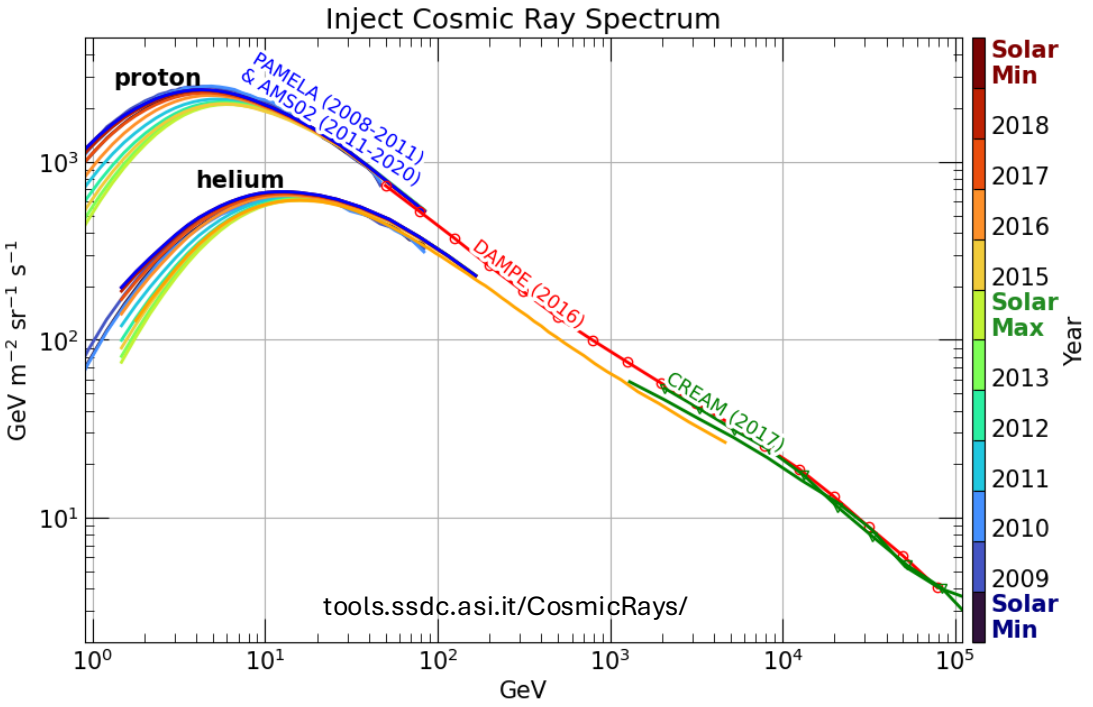
Active

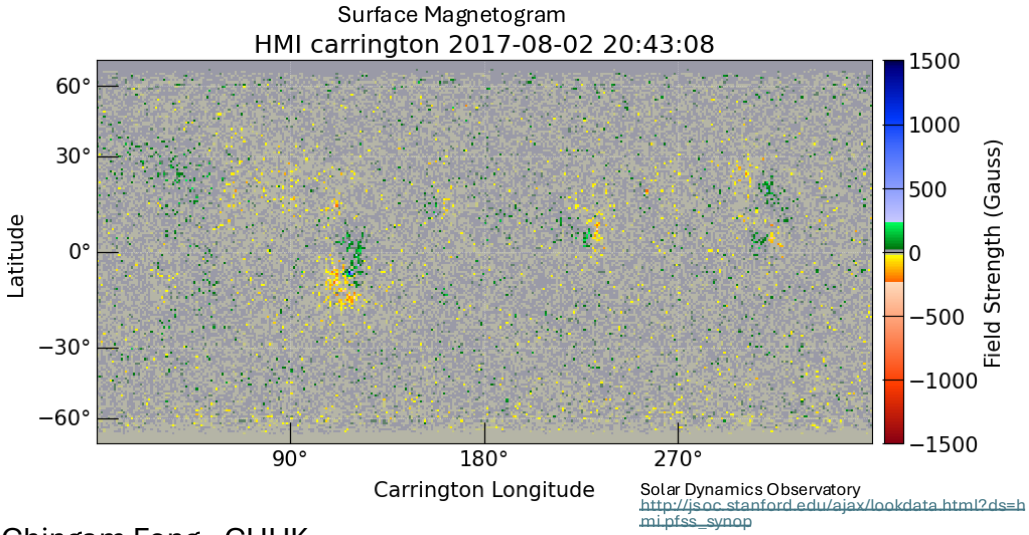


Full overview in K. C. Y. Ng's talk on Monday

Simulation Toolkit G4SOLAR

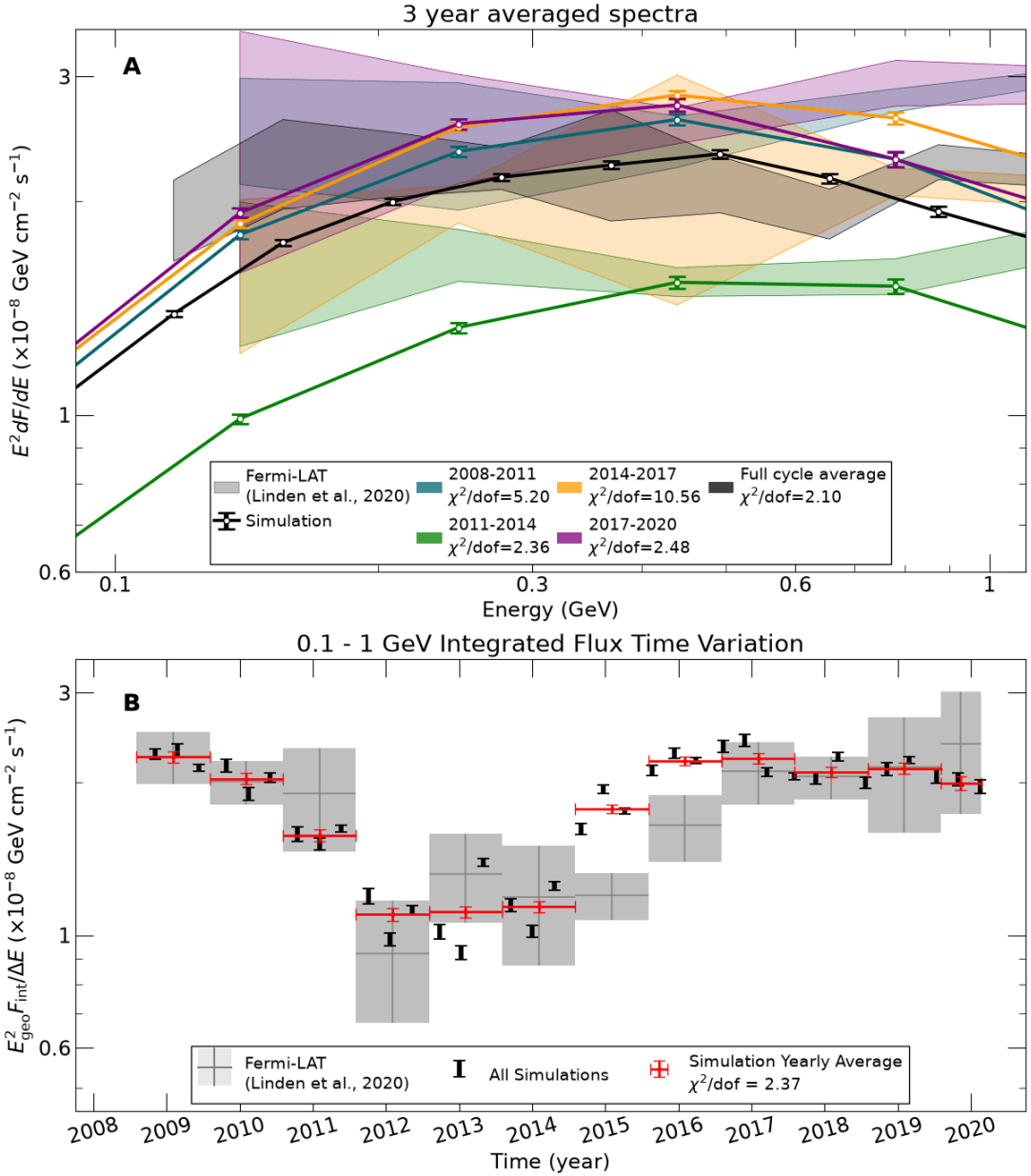
- Written in Geant4, developed by Zhe Li (2009.03888)
- Isotropic inject Cosmic Ray (p & He)
- 36 MHD field models, entire solar cycle
  - Previous works: only a few PFSS field (Mazziotta et al 2020, Dörner et al 2026)
- Assume: field inside the Sun same as the surface





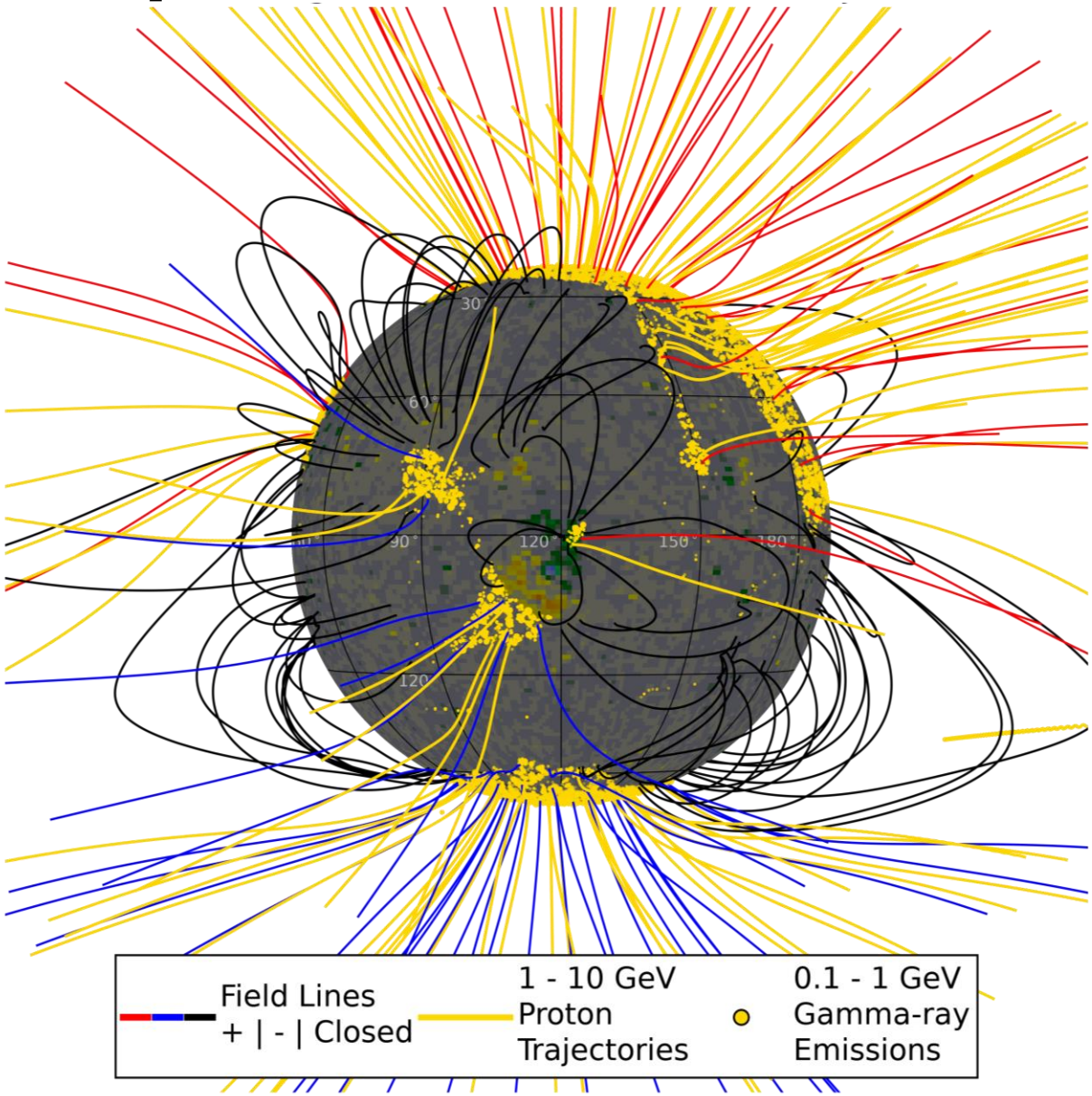
Time Varying 0.1 – 1 GeV Flux

- From simulation we calculate spectral flux at Earth
- Between 0.1 - 1 GeV, simulation *matches observation*, in flux, spectral shape, and time varying behavior
- *First study pointing out corona field as a cause of solar time variation!*

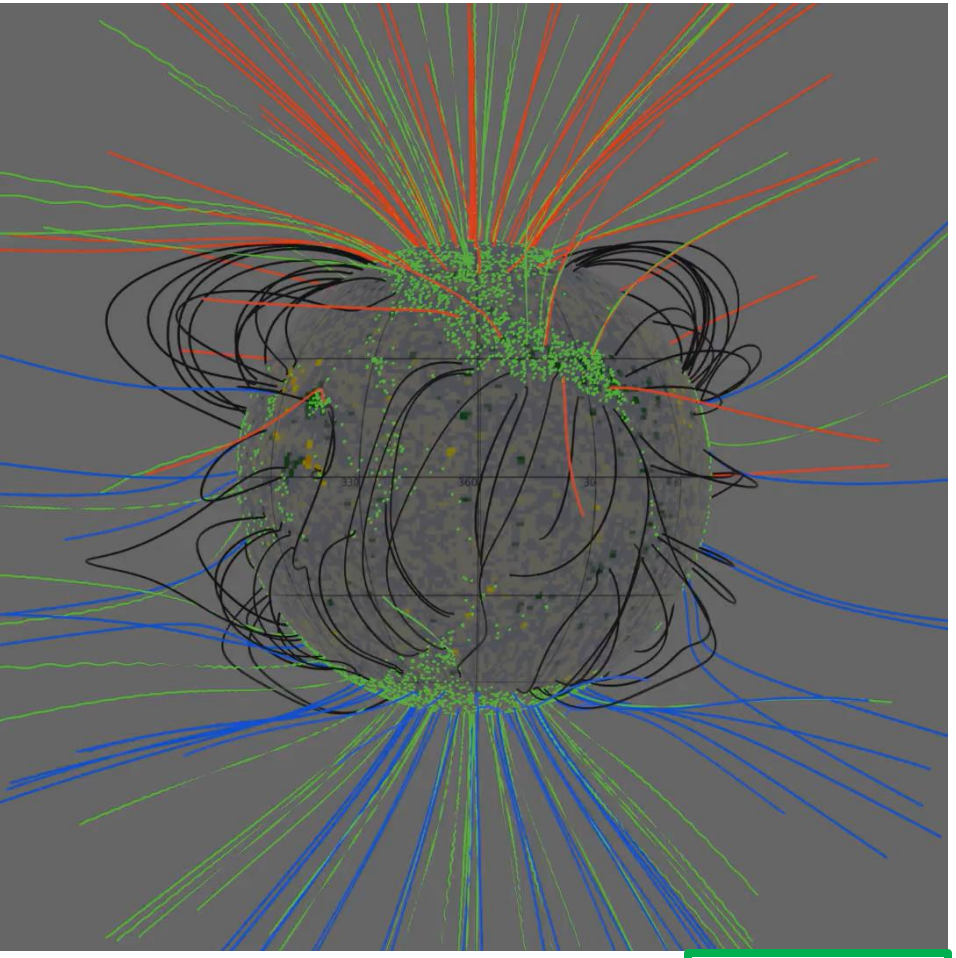


Critical Role of Open Corona Field

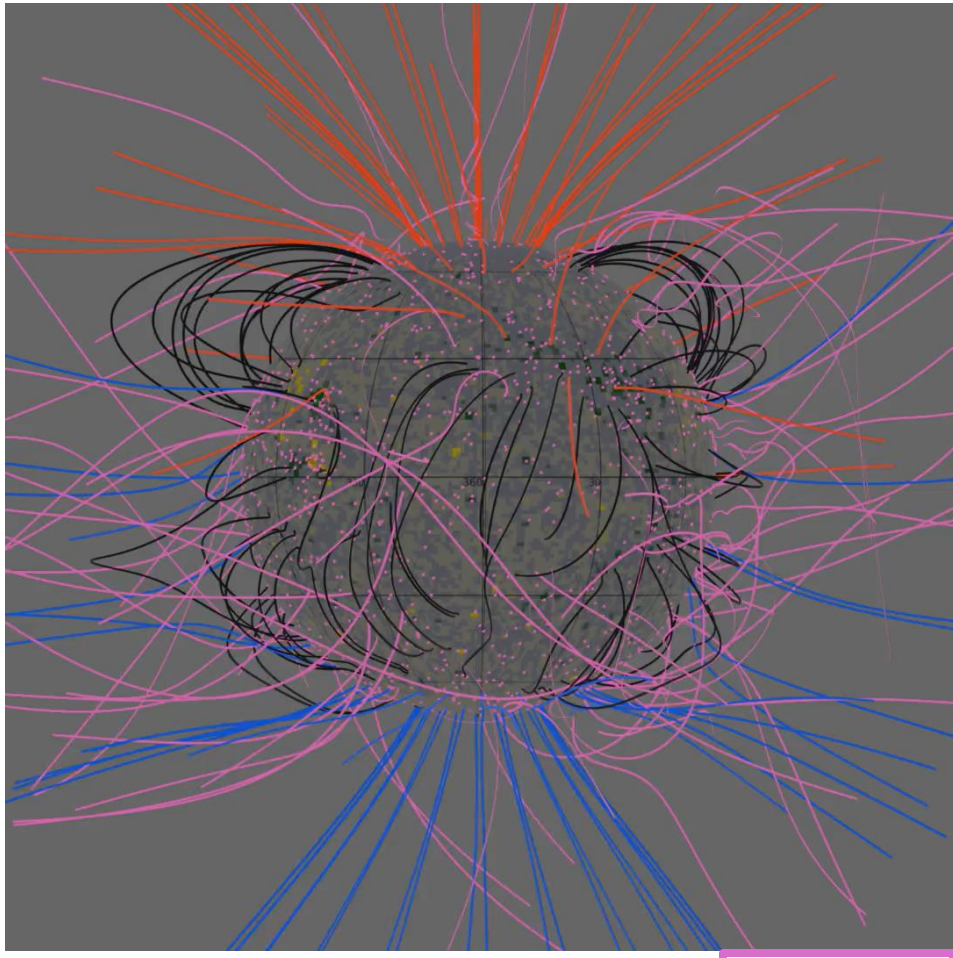
- We trace cosmic ray (CR) propagation and interaction, as well as magnetic field lines
- CR < 10 GeV (yellow) must follow open field lines (red and blue)
  - ***Area of open field regions directly decides GeV gamma ray flux***



Low Energy Trajectories vs High Energy



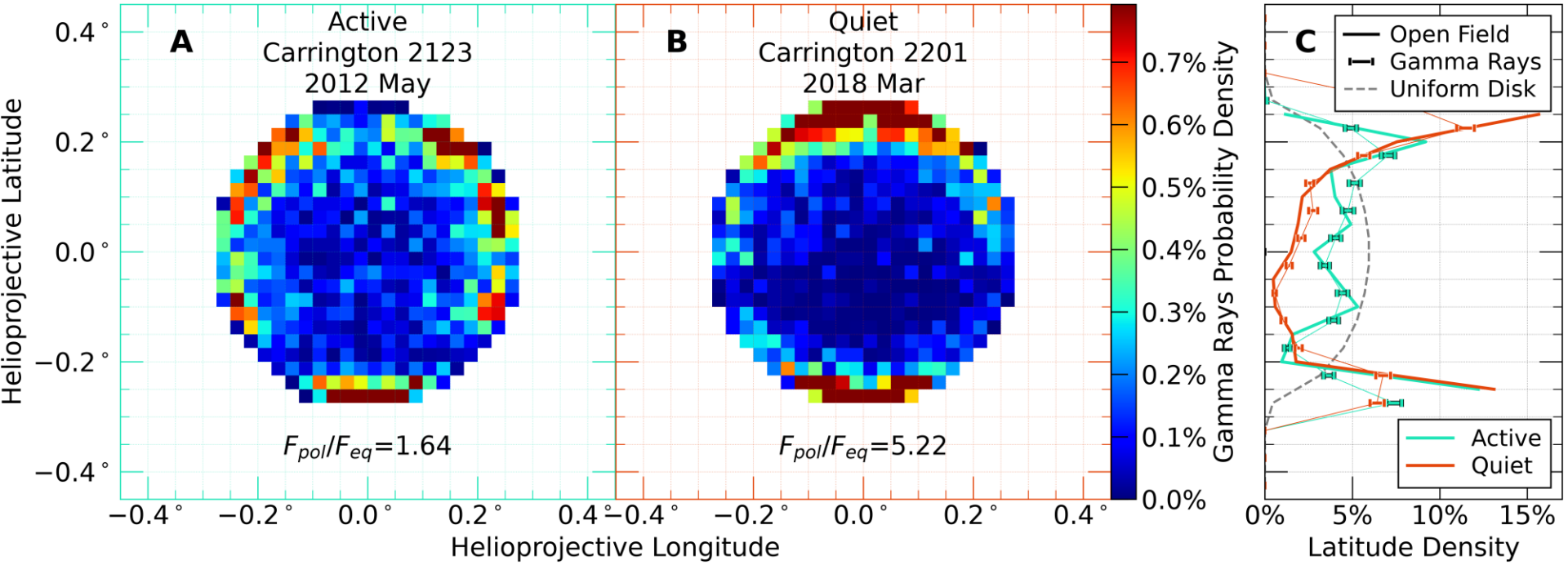
10 GeV proton



1 TeV proton

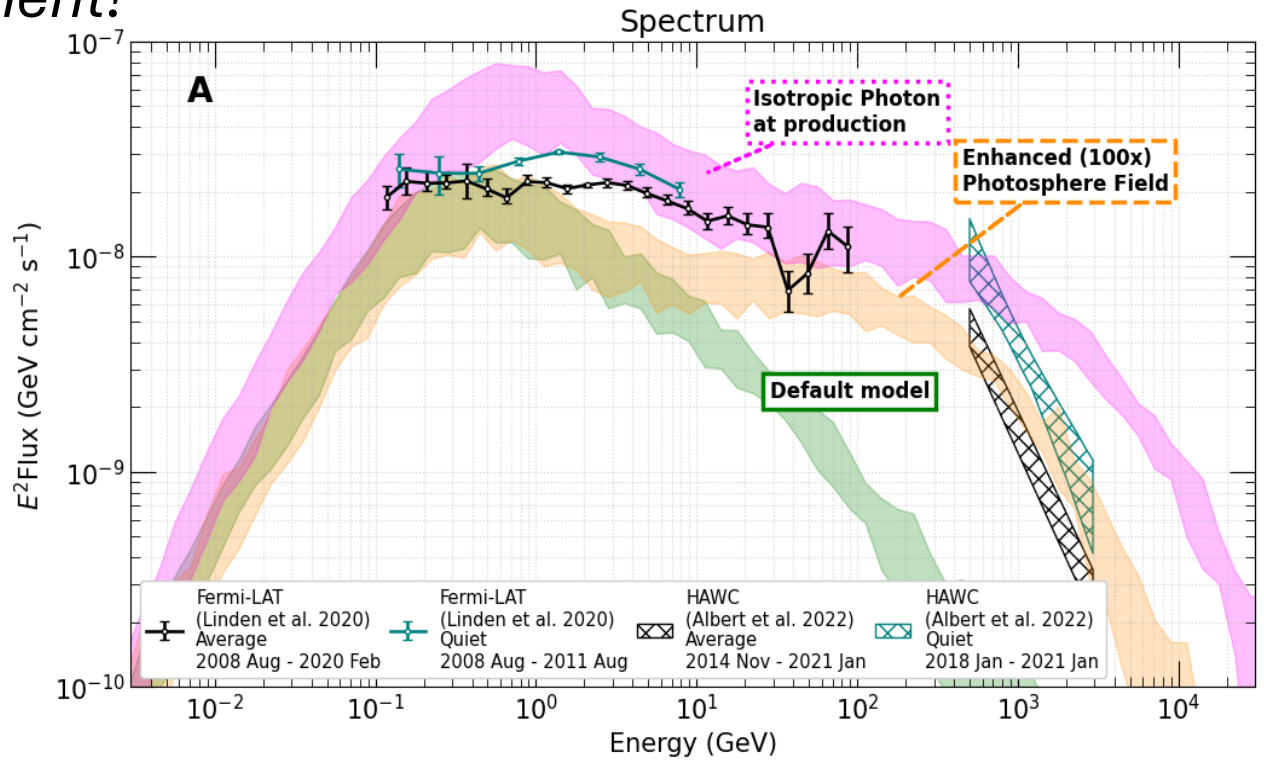
Implication for Observed Morphology

- We make predictions of 1 GeV gamma ray morphology
- The coronal field – flux connection is very pronounced.
- *Gamma ray morphology is a powerful tool to probe coronal field*



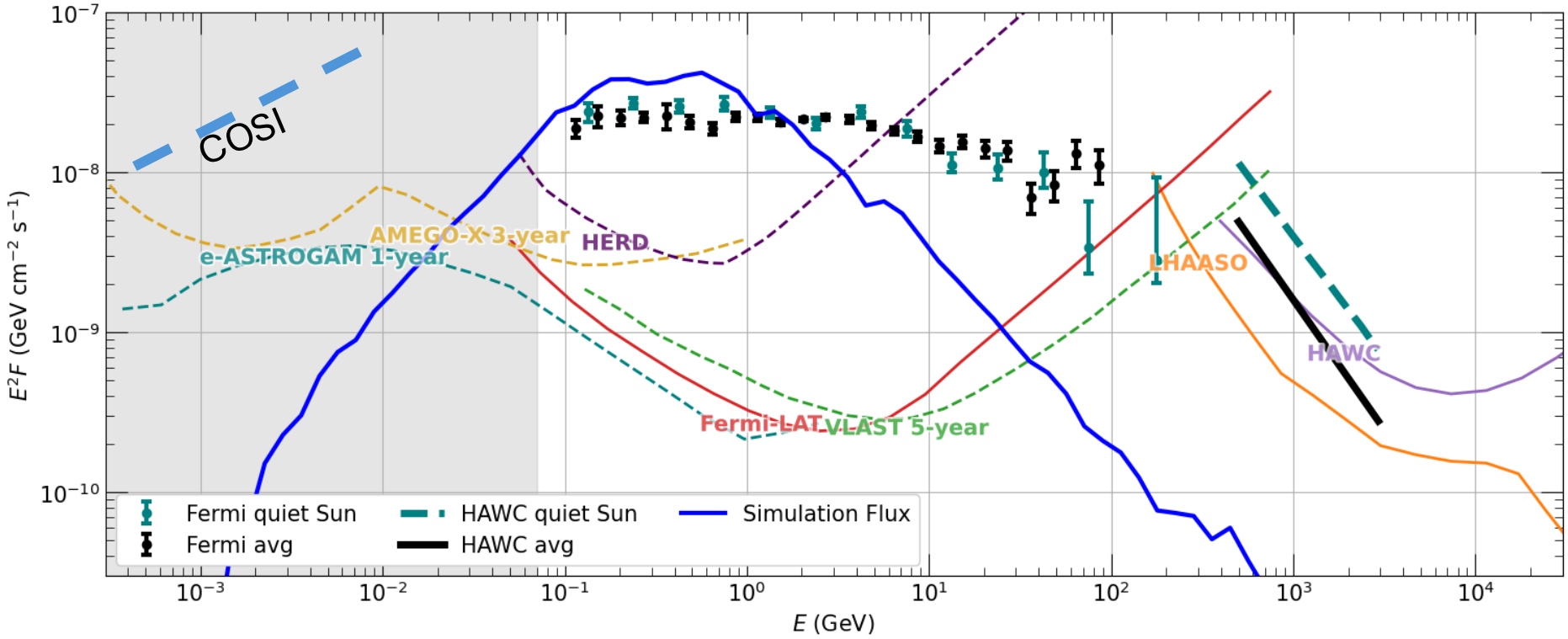
Testing Photosphere Field Effect

- We test 2 different "toy models" photosphere field: 1. 100x field strength, 2. isotropic photon production
- Almost no effect on low energy flux, enhances high energy flux
  - *High energy gamma-ray caused by different magnetic field component!*



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 propagation near the Sun and solar gamma ray
  - Simulation 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

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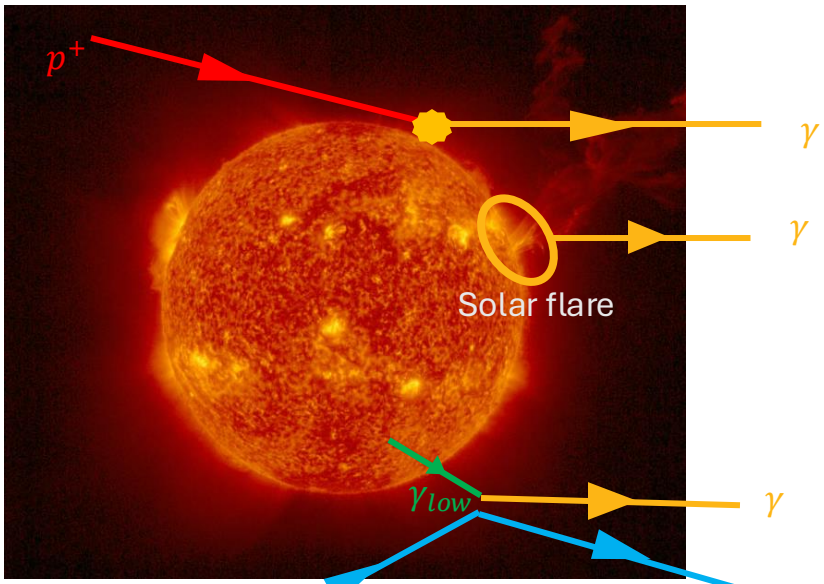
Questions?

Backup slides

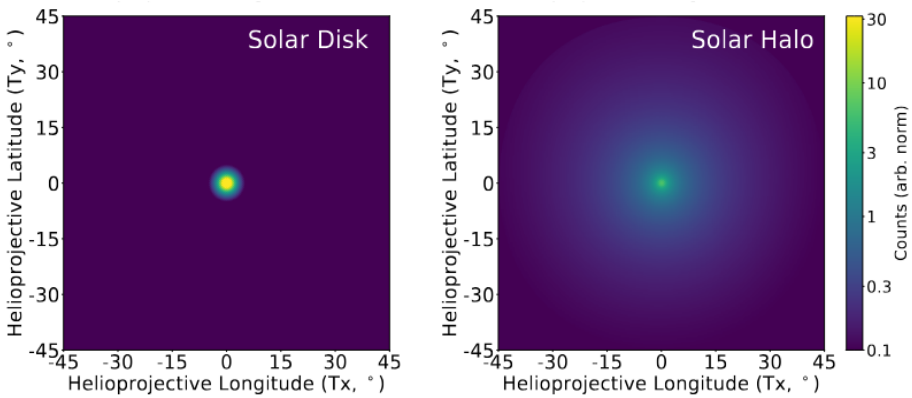
Sun as a Gamma Ray Source

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



Cosmic ray electron ICS with photon -> “Solar halo”

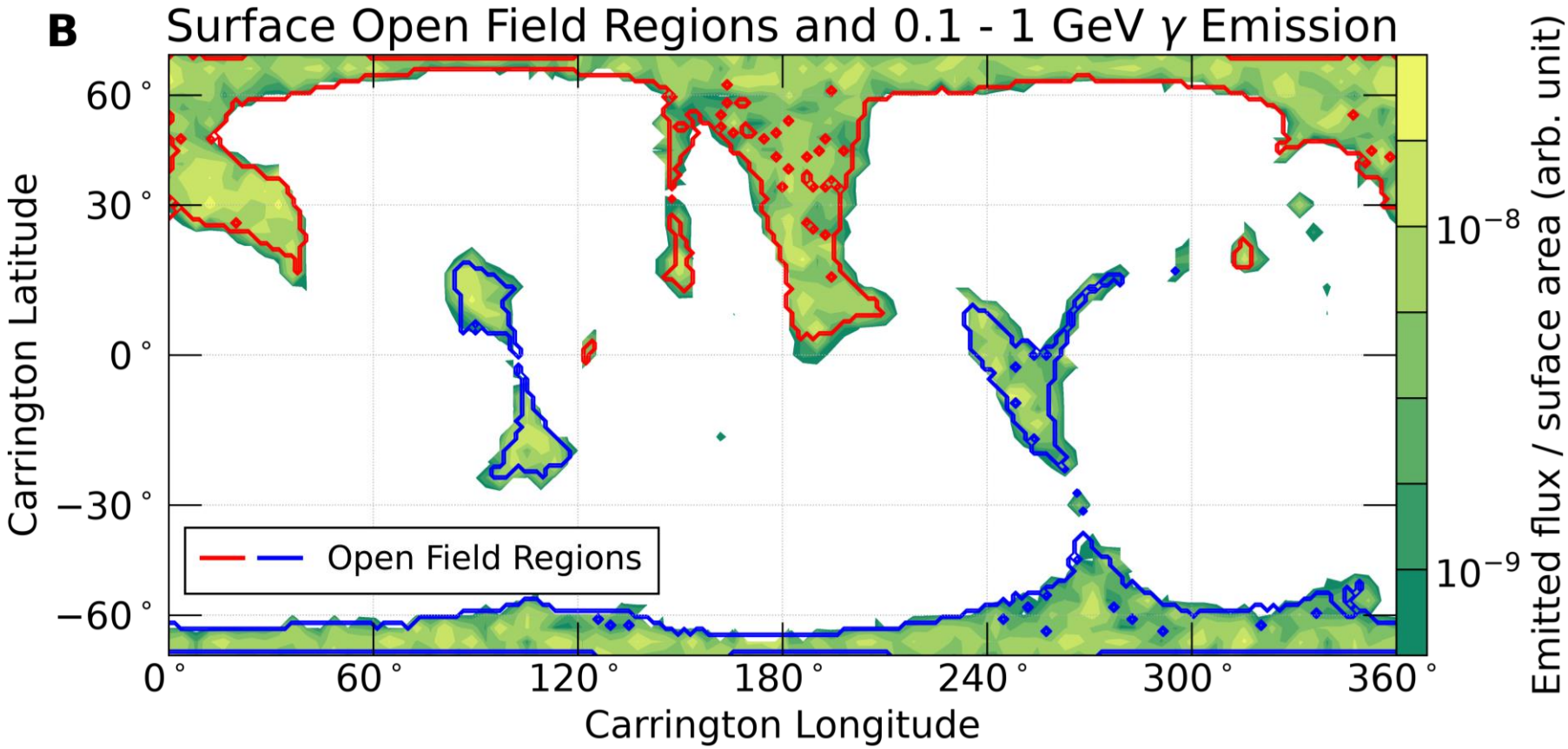
T. Linden et al., 2025
arxiv: 2505.04625



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

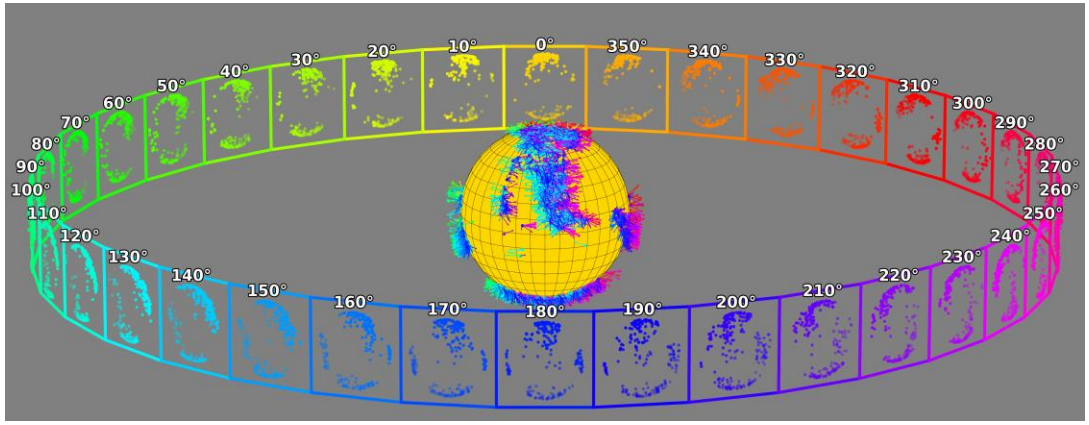
Surface Emission Map

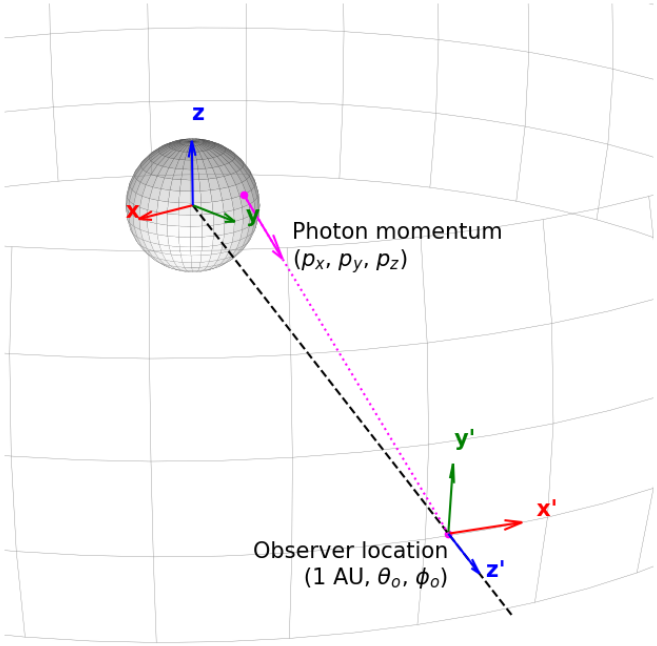
- Tracing field lines to surface, open field regions correlate with gamma emission



More Detail about Morphology Calculation

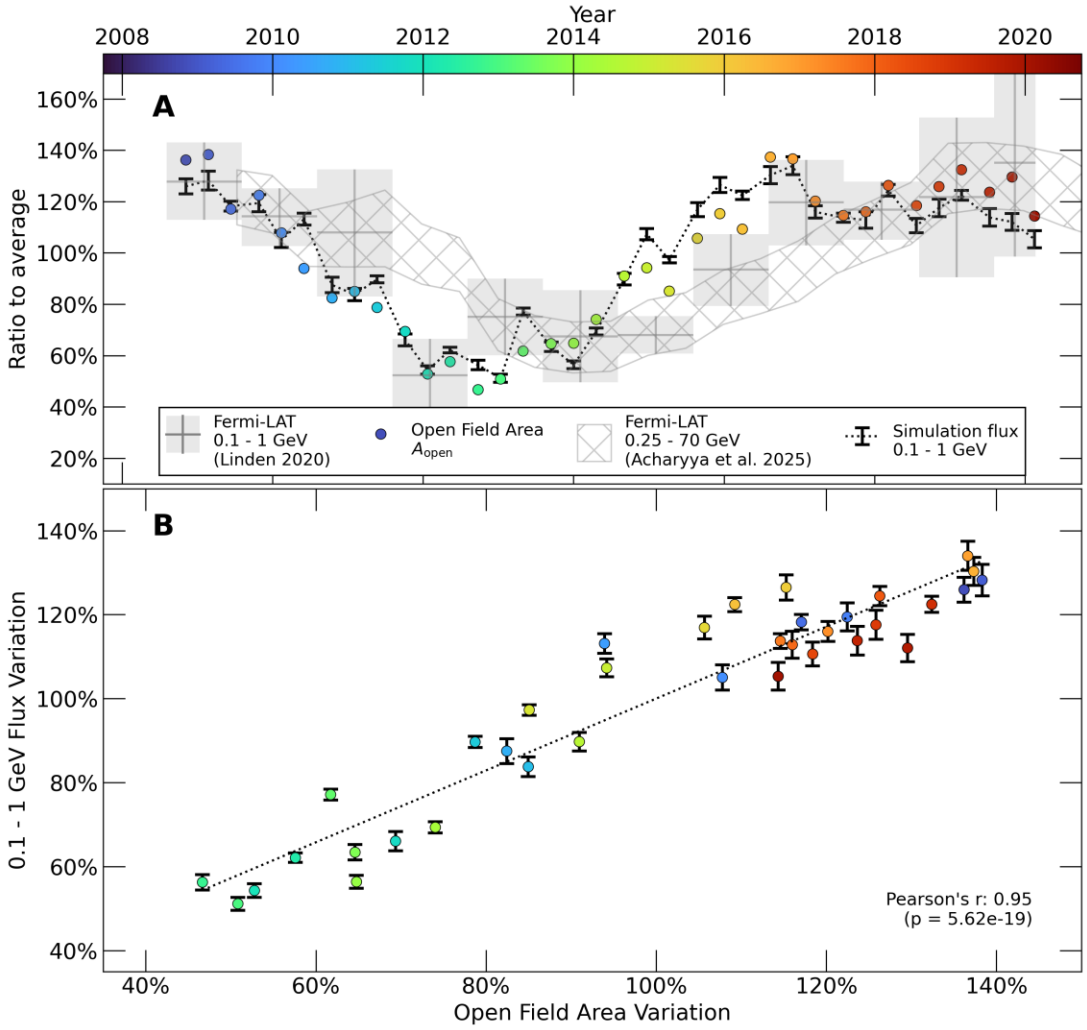
- We project gamma ray onto Earth perspective, based on emission location and direction, thus getting collected gamma ray morphology at specific points in time
- Integrated over entire orbit -> time averaged gamma ray morphology





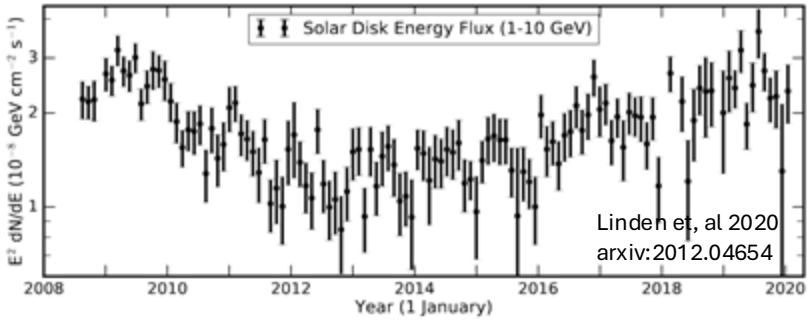
Open Field Modulates Solar Gamma Rays

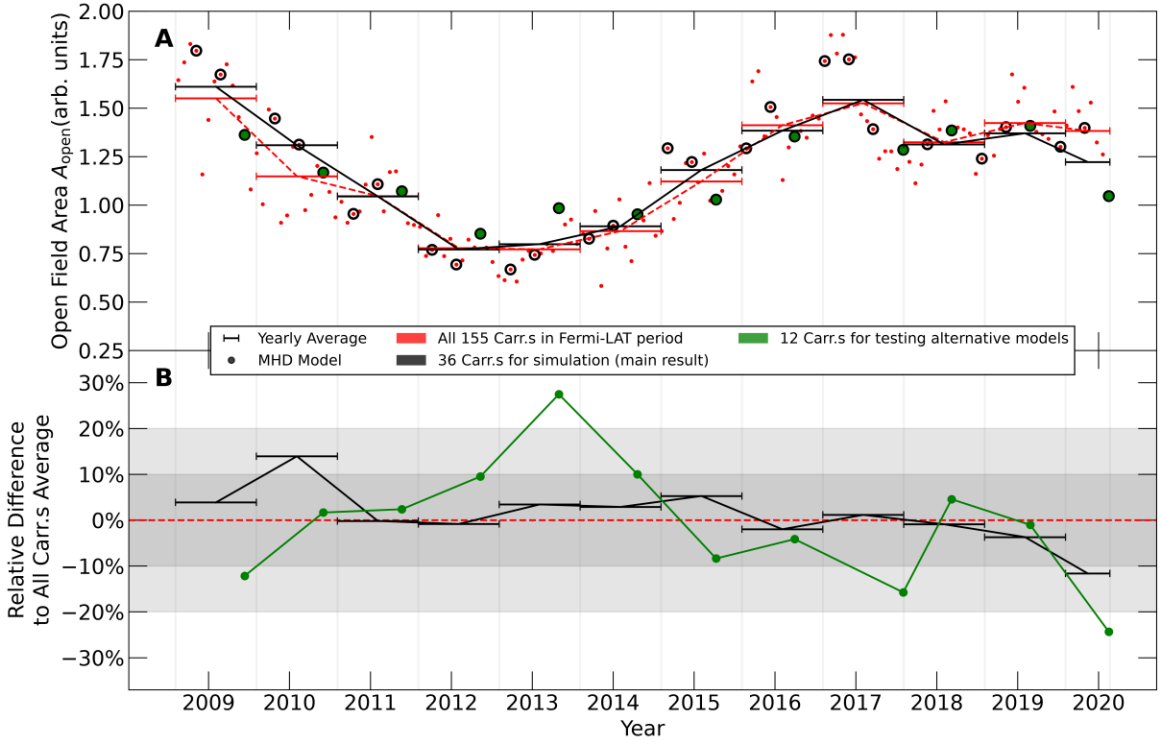
- Throughout solar cycle, the open field area on the Sun changes by factor of 2, causing gamma ray variation
  - Strong correlation in long-term trend



Higher order periodicity

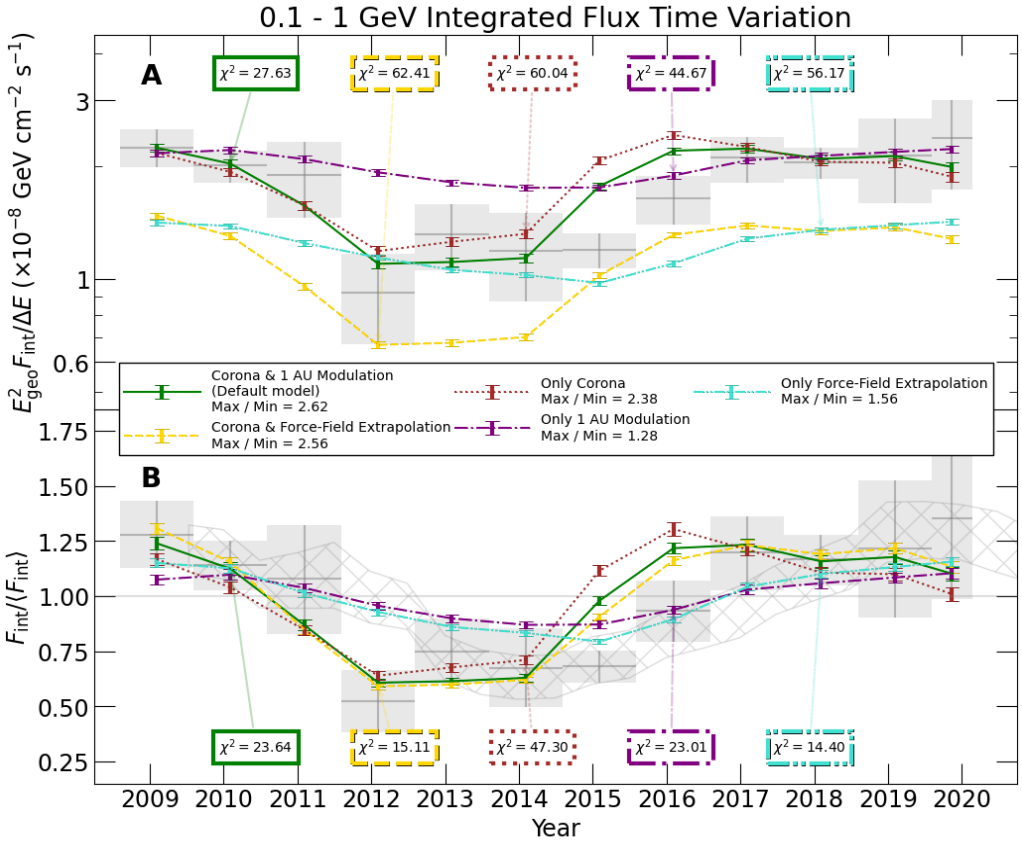
- All cycle, open field area predicted by coronal field follow the same trend

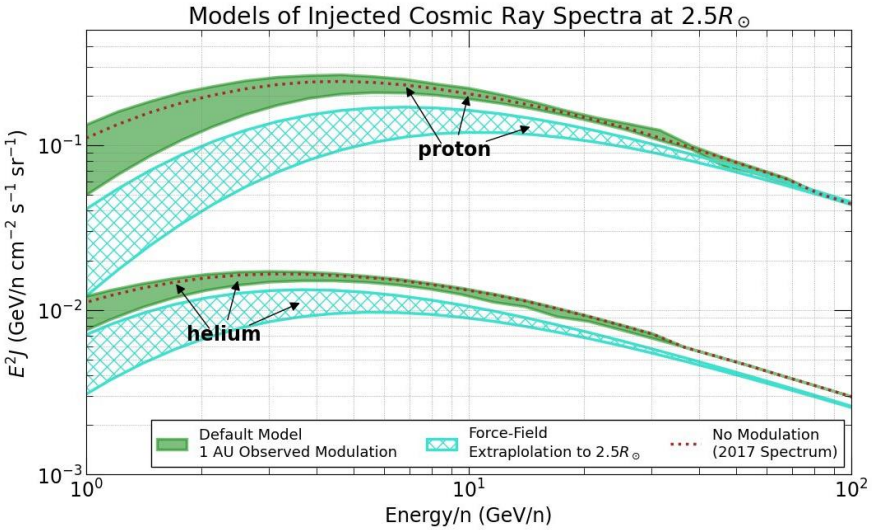




Alternative CR Flux Models

- Main analysis: 1 AU flux = corona flux
- To compare IMF effect, force field approximation
- Corona field effect dominates over force field approximation





Morphology Under Enhanced Field

- More turbulence -> concentrated center emission