Solar disk gamma-rays emission via synthetic magnetic field from photosphere to low corona

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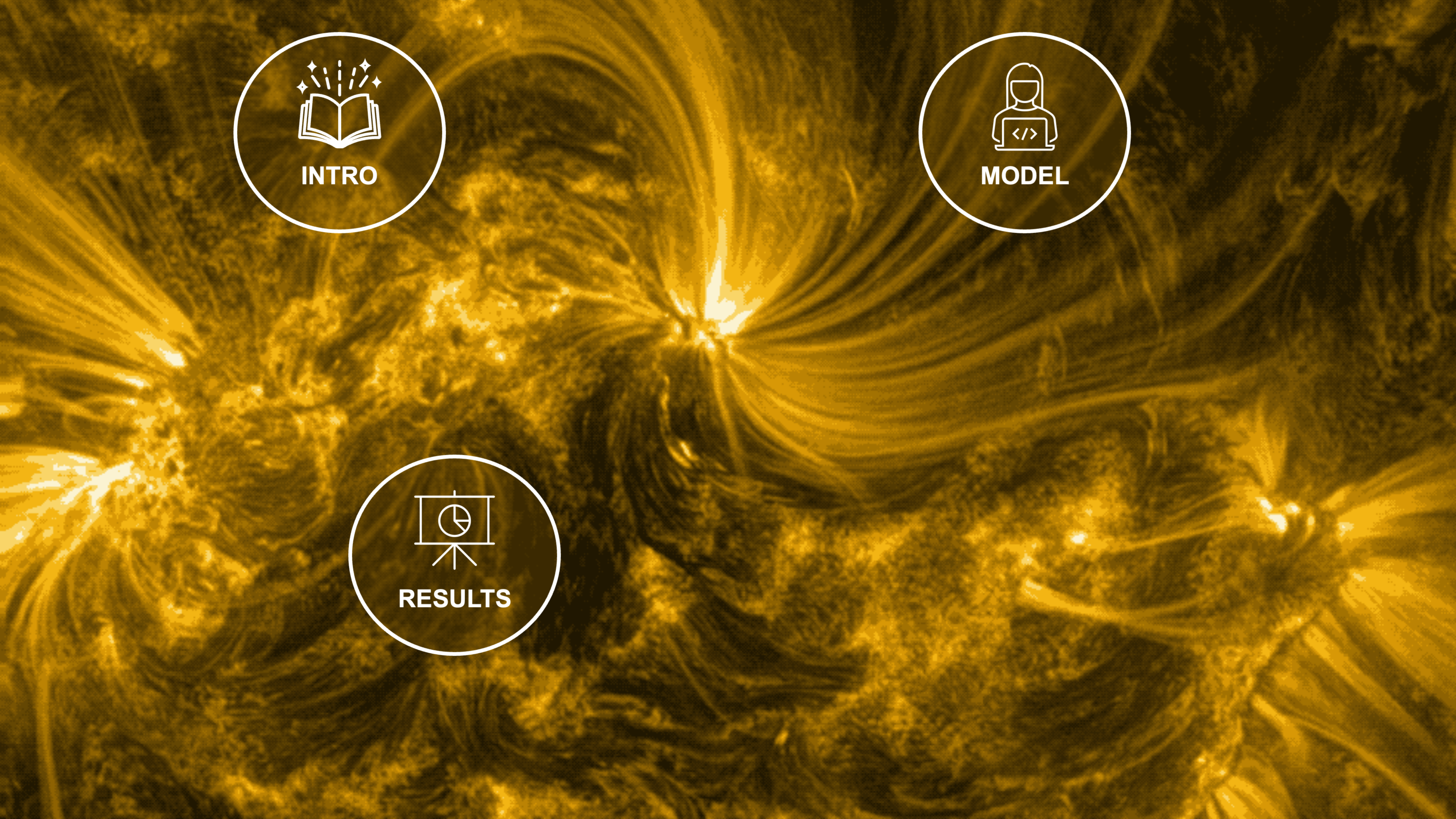
Atelier "Physique cinétique des plasmas astrophysiques"

Project supported by

Grant 80NSSC22K0040

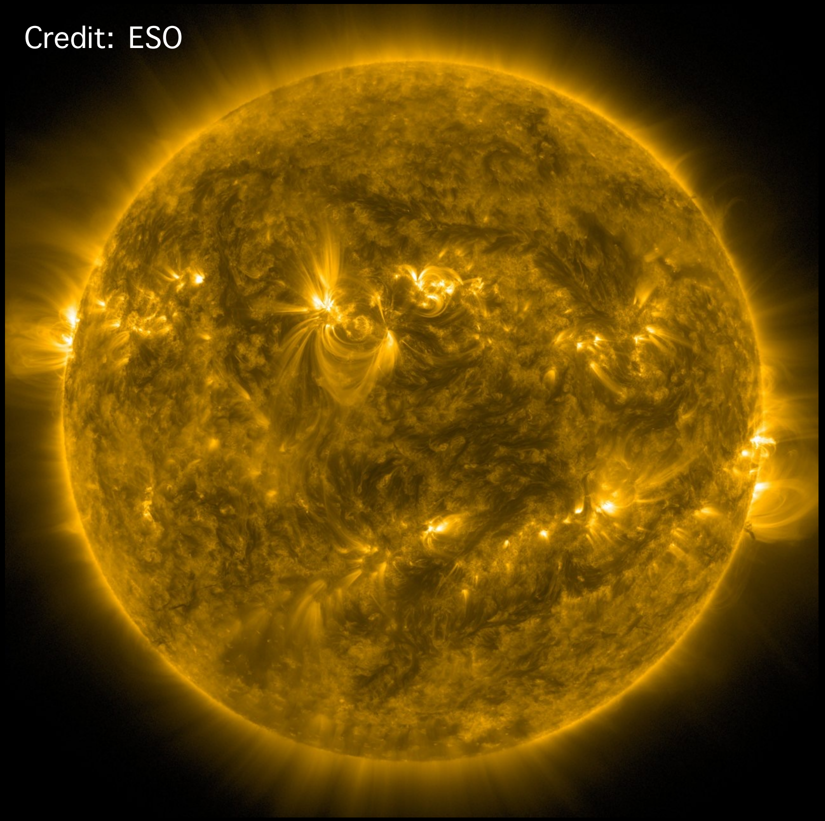

INTRO
MODEL
RESULTS

INTRO

INTRO

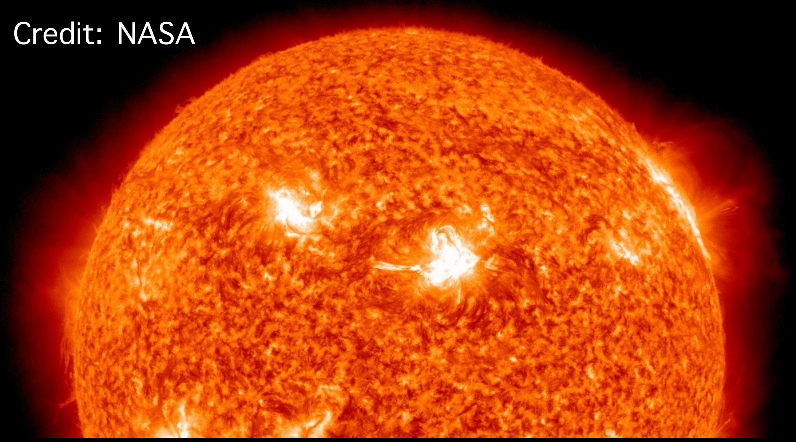
SOLAR EMISSION MECHANISMS

Credit: ESO



- **Inverse-Compton scattering**: cosmic-ray electrons interacting with solar photons (solar halo)
- **Bombardment by hadronic cosmic rays** (mostly protons) interacting with solar gas (solar disk)
- **Solar flares and coronal mass ejections**

Credit: NASA



GAMMA-RAYS PRODUCTION

Credit: Scott Wiessinger

INTRO

THE EXISTING THEORETICAL MODEL

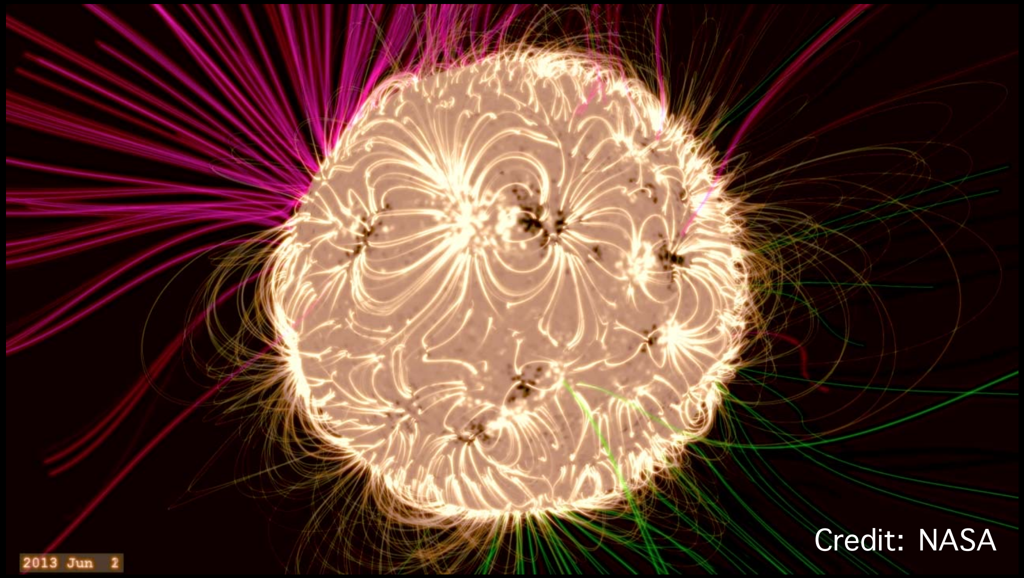
Magnetic fields are crucial!

Seckel, Stanev, and Gaisser model (1991)

Magnetic flux tubes can reverse incoming protons deep within the solar atmosphere, where they have an appreciable probability of producing outgoing γ-rays.

↓

γ-ray flux is greatly enhanced!

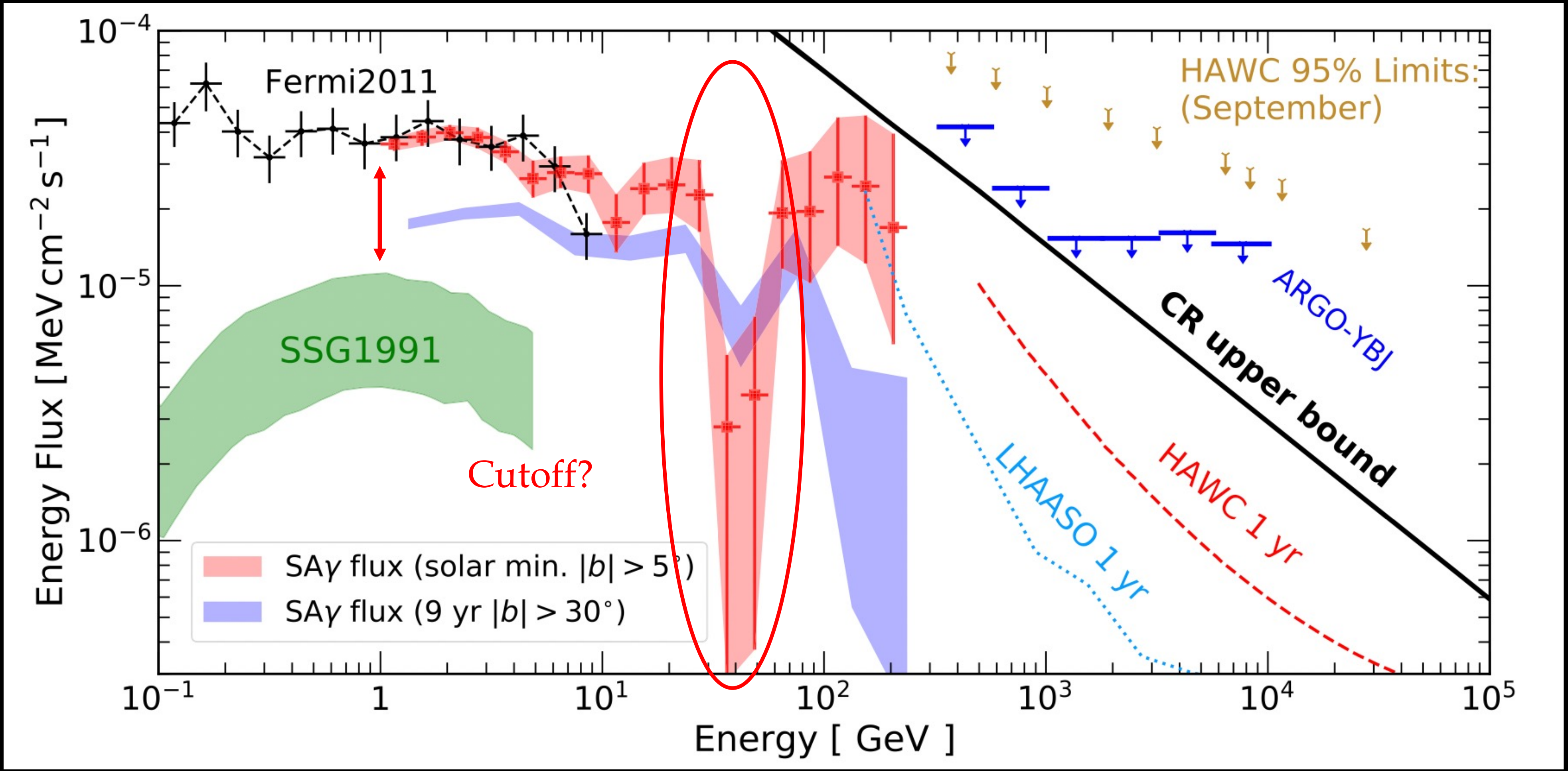


"Current technology is improving to the point that such a flux of GeV γ-rays should be detectable by the EGRET instrument of the Gamma Ray Observatory (GRO)"

- Fermi Gamma-ray Space Telescope
- High-Altitude Water Cherenkov Gamma-ray Observatory (HAWC)

INTRO

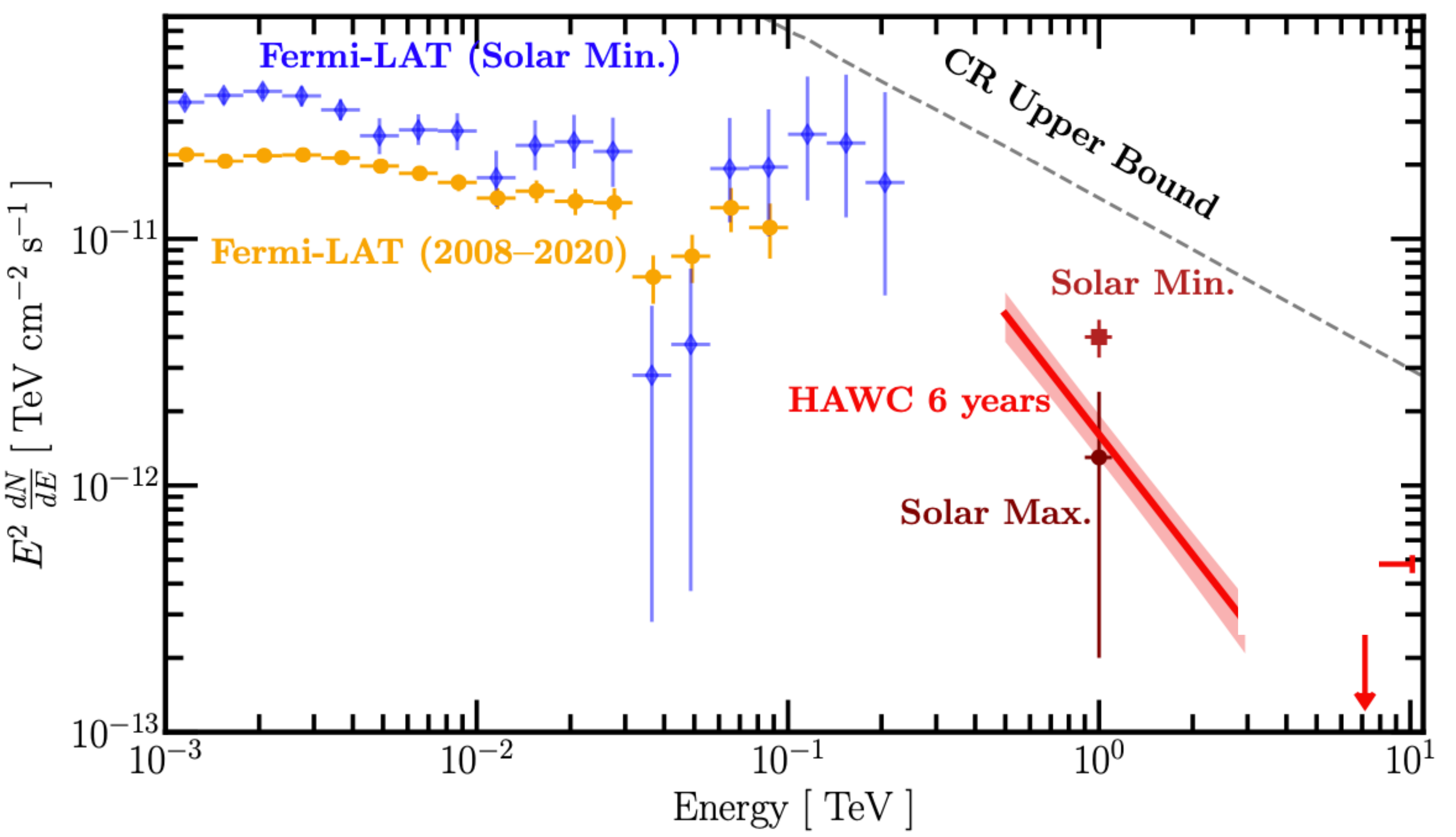
MODEL VS OBASERVATIONS



Credits: Tang et al. 2018

INTRO

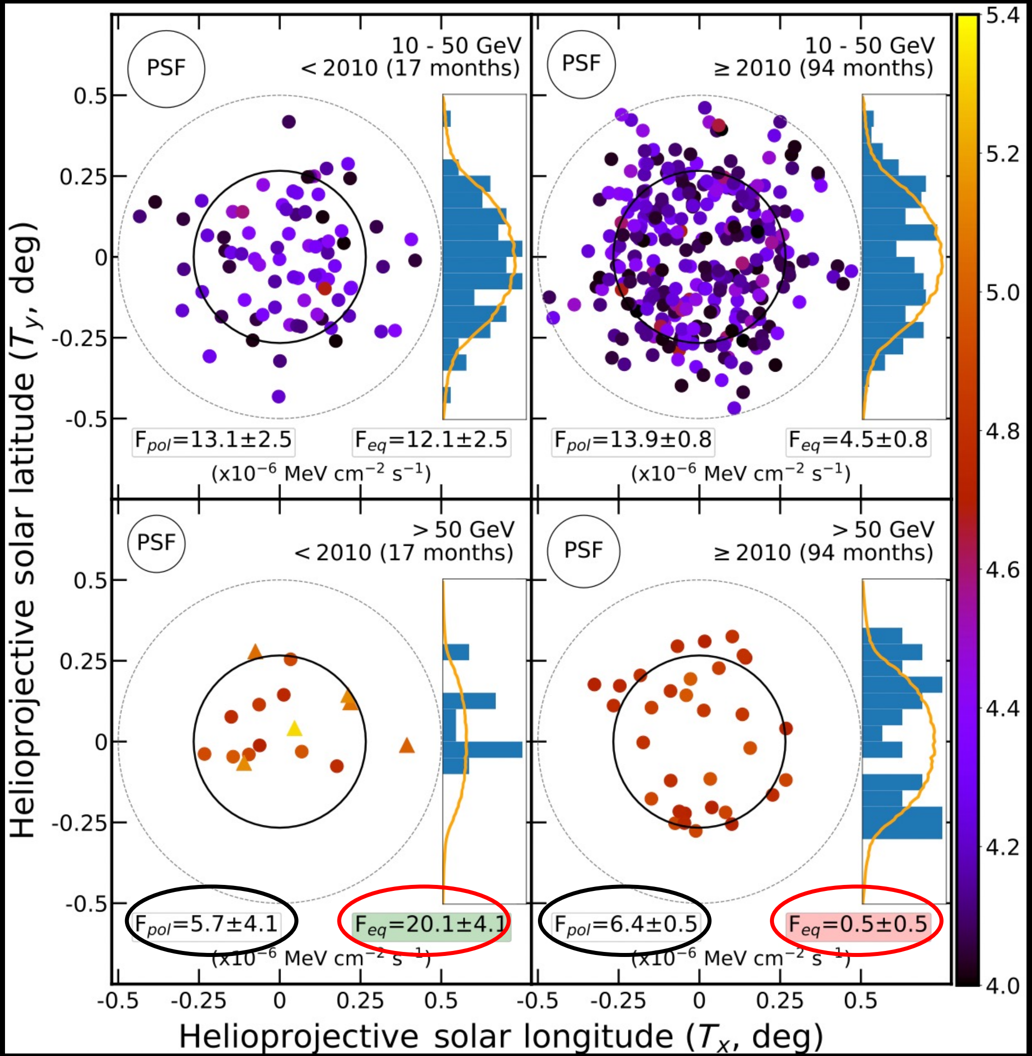
MODEL VS OBASERVATIONS



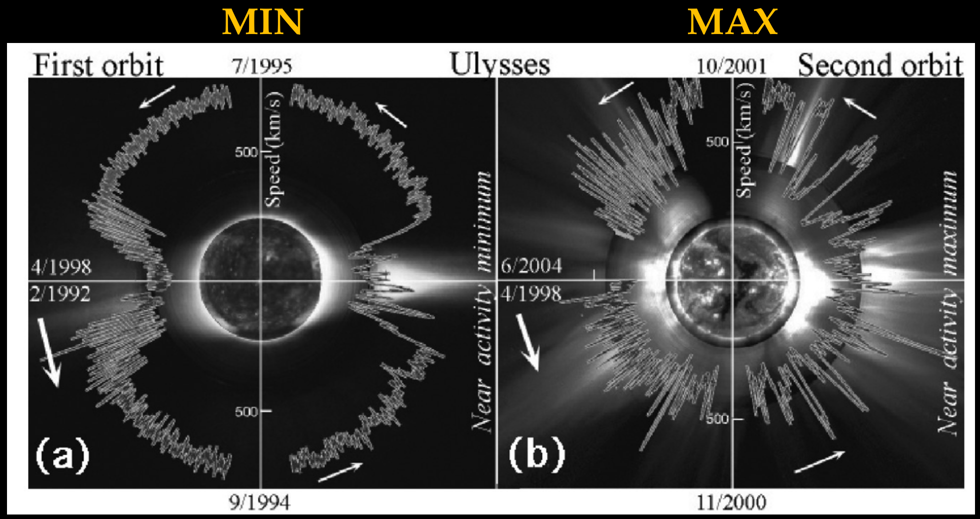
Credits: HAWC Collaboration (2022)

INTRO

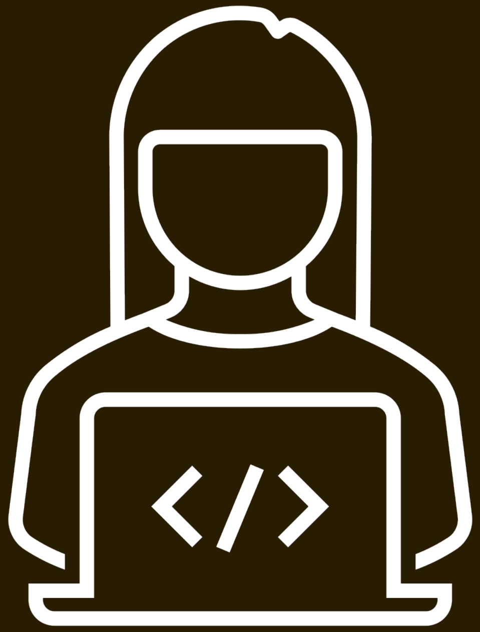
SOLAR CYCLE DEPENDENCE



Credits: Linden et al. 2018



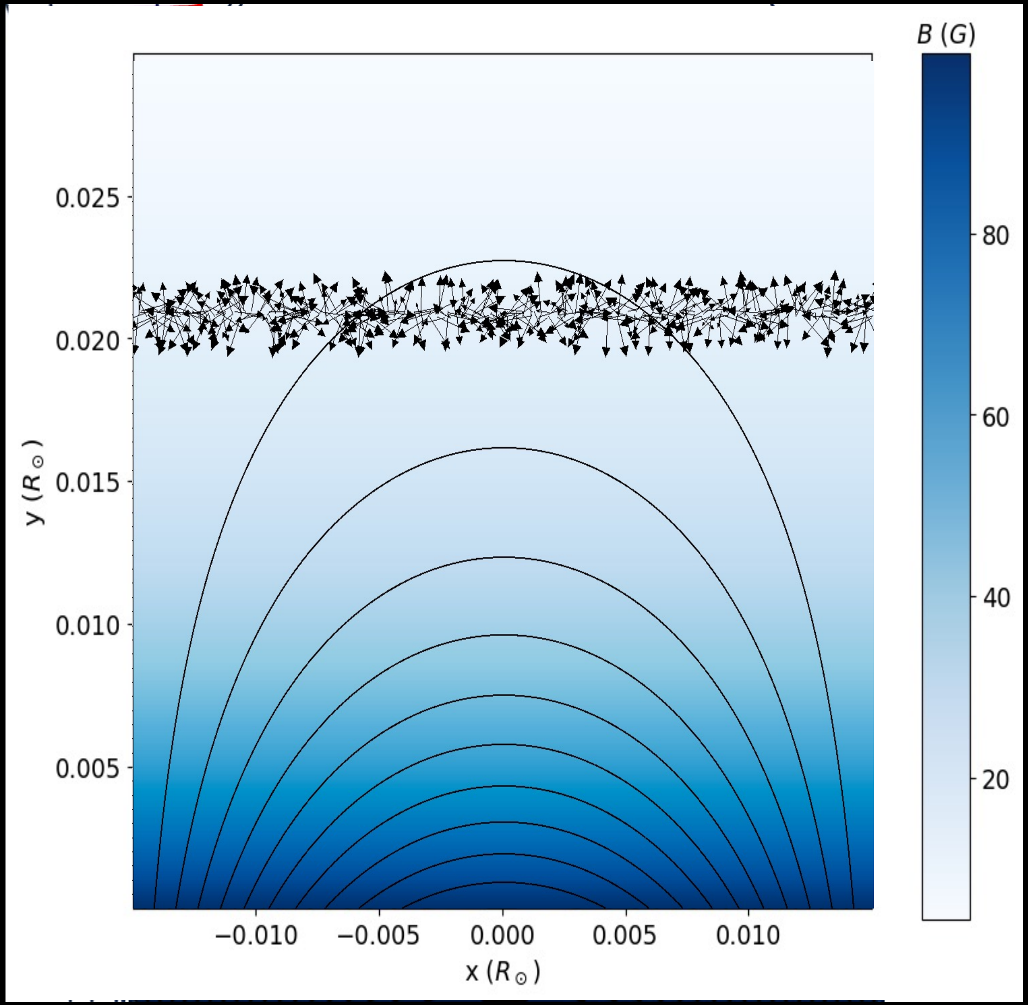
Credits: Priest 2012



MODEL

MODEL

PREVIOUS WORK



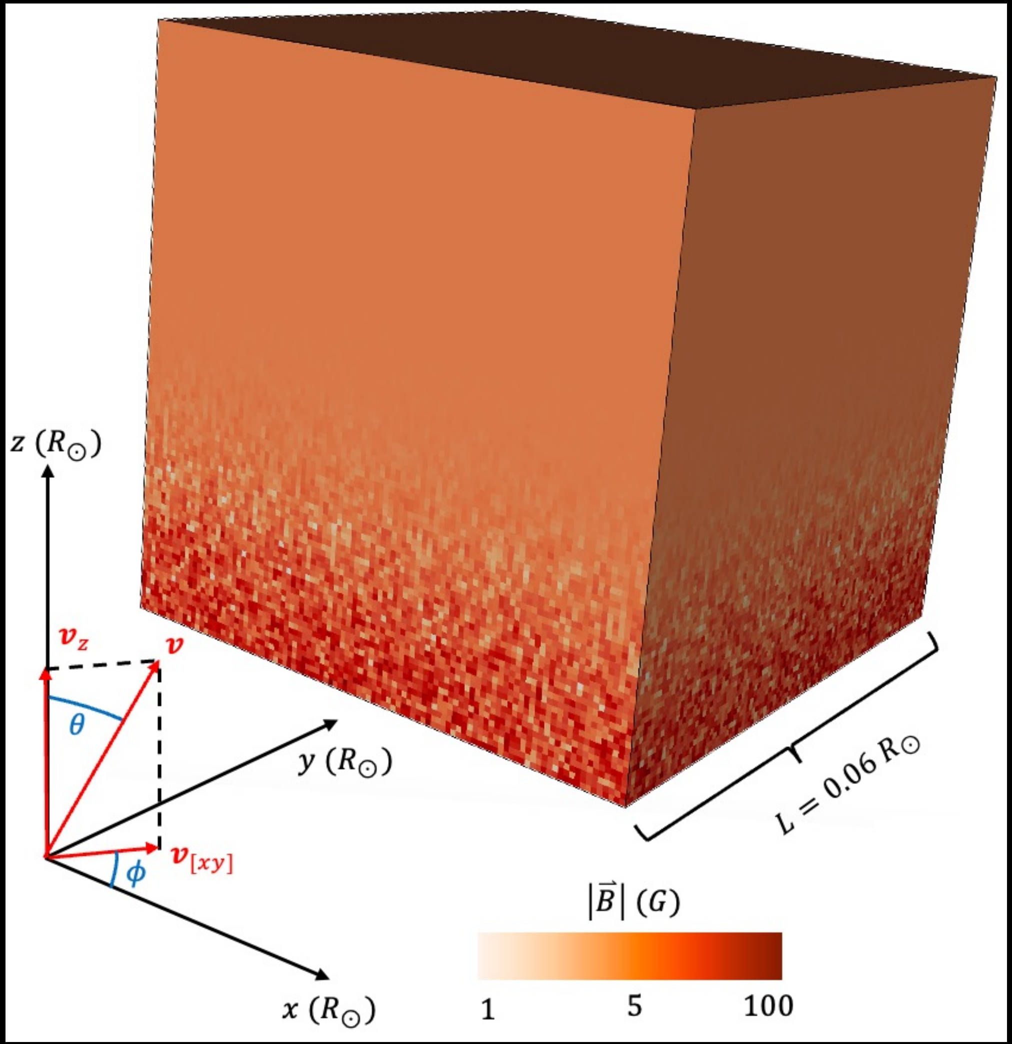
Credits: Puzzoni et al. 2024

"Role of Magnetic Arcades in Explaining the Puzzle of the Gamma-Ray Emission from the Solar Disk"

SCAN ME

MODEL

SYNTHETIC MAGNETIC FIELD



$$\mathbf{B}(x, y, z) = B_0 \hat{\mathbf{k}} + \nabla \times [f(z)\mathbf{S}(x, y, z)]$$

$B_0 = 5$ Gauss $\quad f(z) = e^{-\left(\frac{z}{\Lambda}\right)^2} \quad \Lambda \sim 10^{-2} R_\odot$

Credits: Giacalone 2021

$$\mathbf{S}(x, y, z) = \sum_{n=1}^{N_m} \frac{A_n}{k_n} \left(\sin \alpha_n \widehat{x_n'} + i \cos \alpha_n \widehat{y_n'}\right) e^{i k_n z_n' + i \beta_n}$$

$$\delta\mathbf{B}(x, y, z) = \nabla \times \mathbf{S}(x, y, z)$$

Credits: Giacalone & Jokipii 1999

$$\delta\mathbf{B}(x, y, z) = \sum_{n=1}^{N_m} A_n \left(\cos \alpha_n \widehat{x_n'} + i \sin \alpha_n \widehat{y_n'}\right) e^{i k_n z_n' + i \beta_n}$$

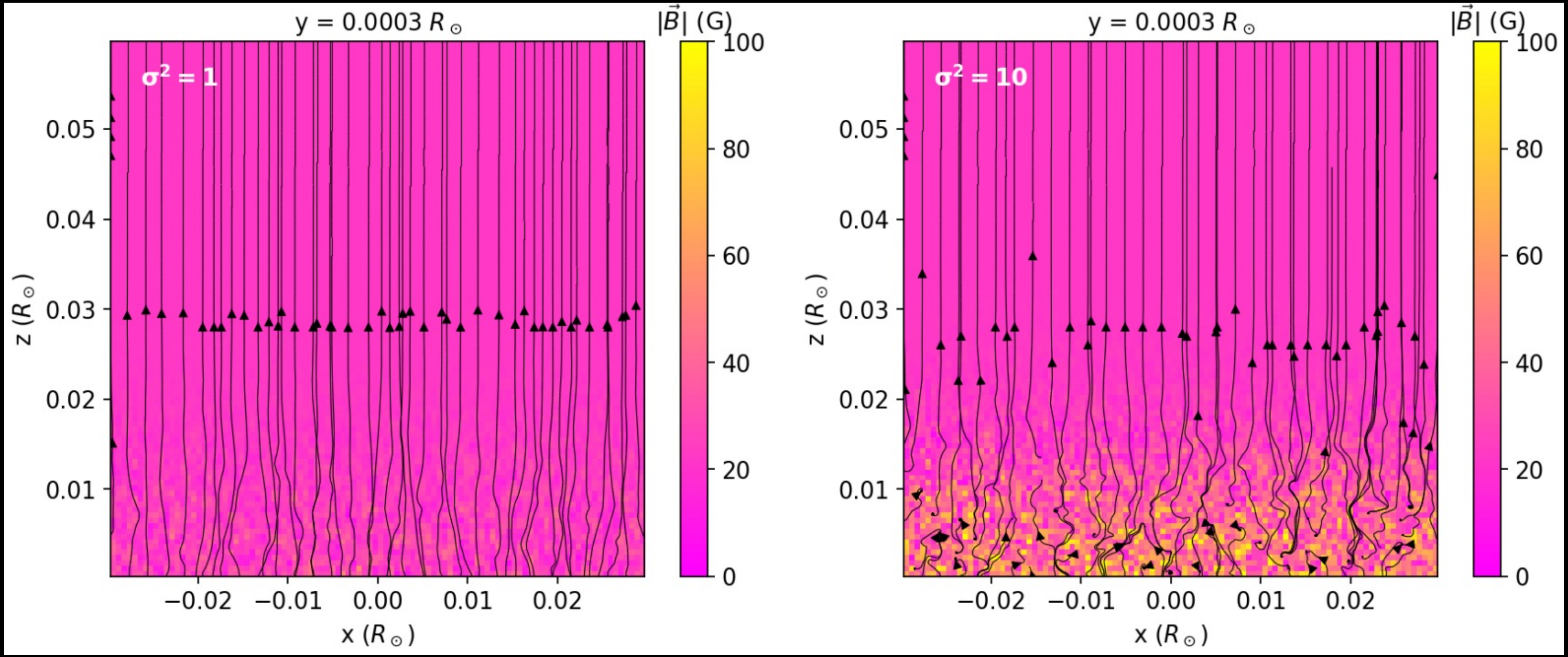
Credits: Puzzoni et al. 2025 (submitted to ApJL)

MODEL

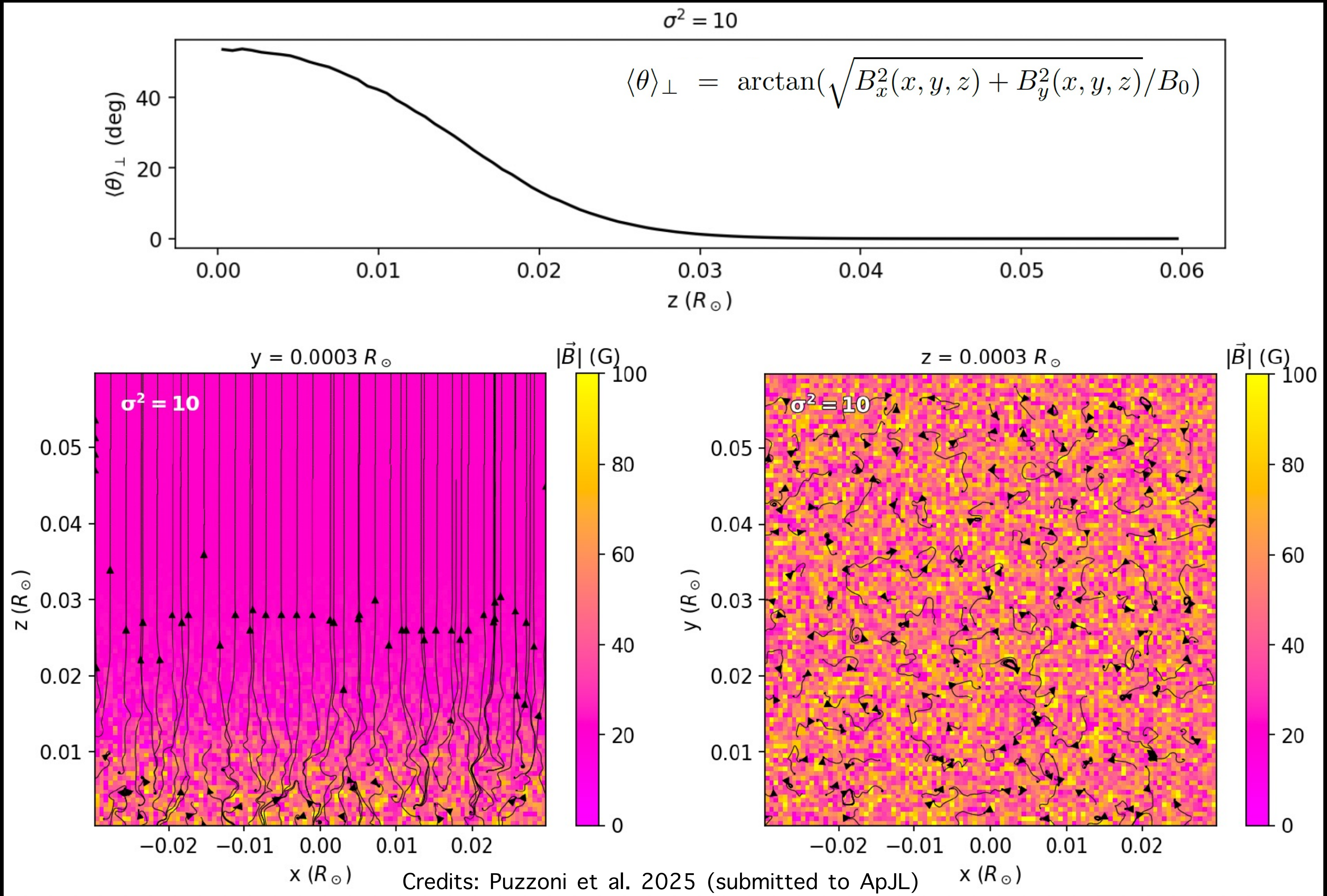
$L_s = 0.003\ R_\odot \sim 2\ \mathrm{Mm}$ $\quad L_{min} = 10^{-3} R_\odot$ $\quad L_{max} = 0.06\ R_\odot$

$$\sigma^2 = \frac{\sigma'^2}{B_0^2} = 0.1, 1.0, 10$$

Credits: Puzzoni et al. 2025 (submitted to ApJL)



MODEL

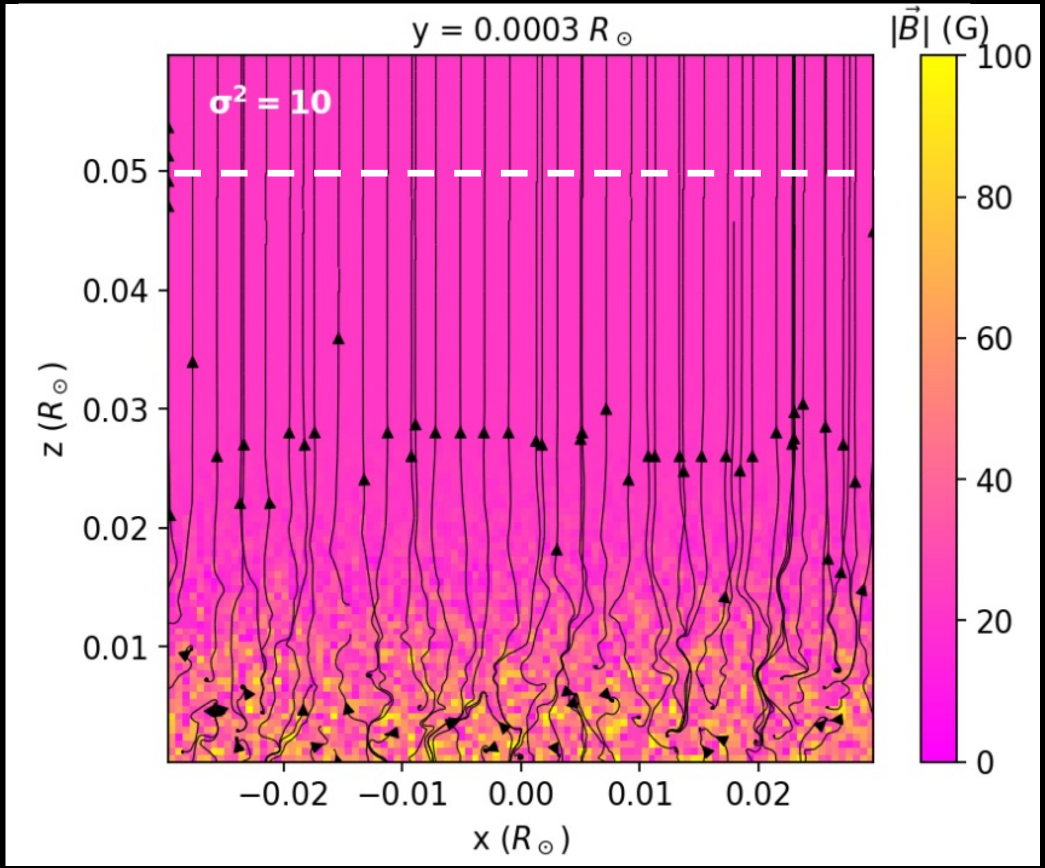


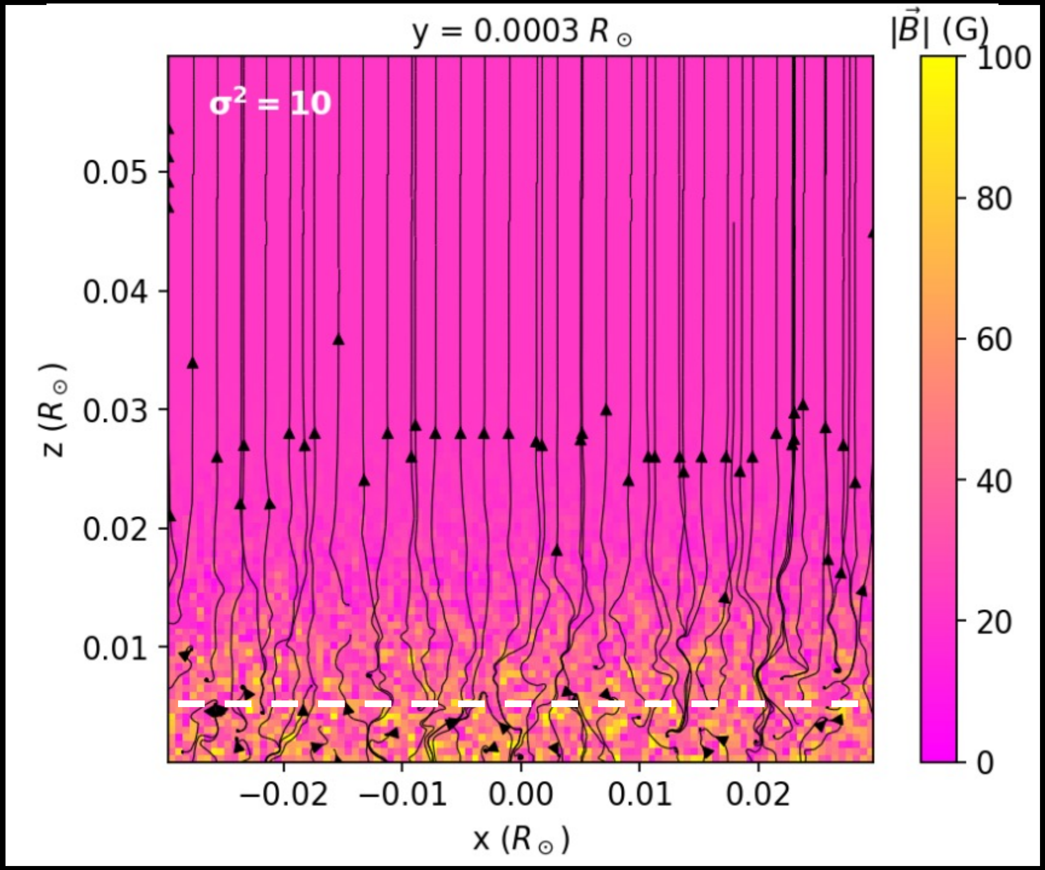
Credits: Puzzoni et al. 2025 (submitted to ApJL)

MODEL

TEST-PARTICLES INITIALIZATION

- Initialized with an isotropic velocity distribution
- Magnetic field configuration reshuffled every 100 particles





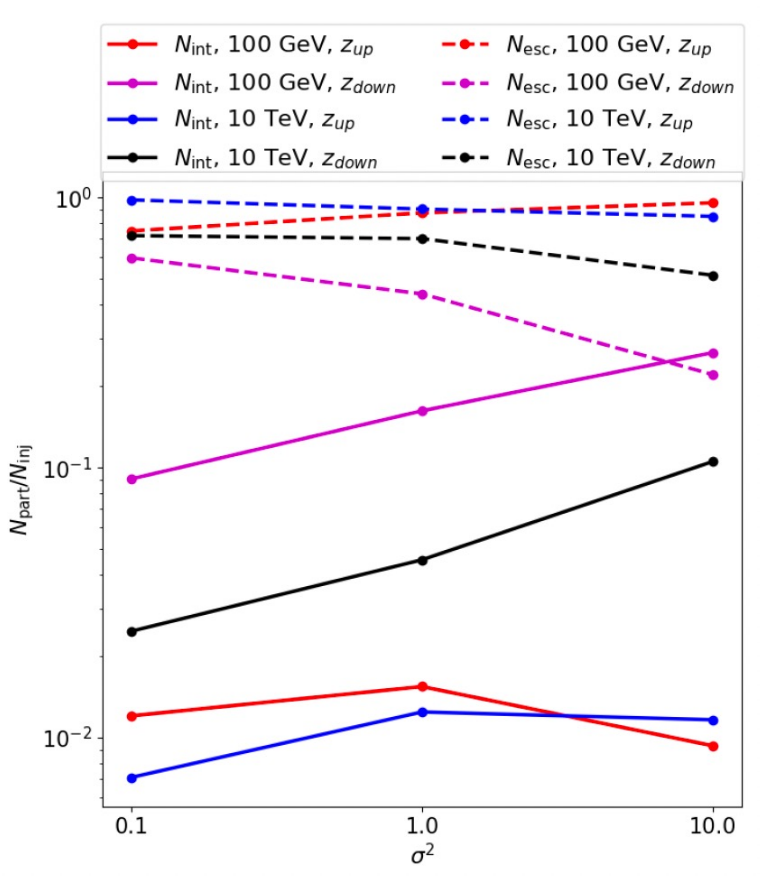
RESULTS

RESULTS

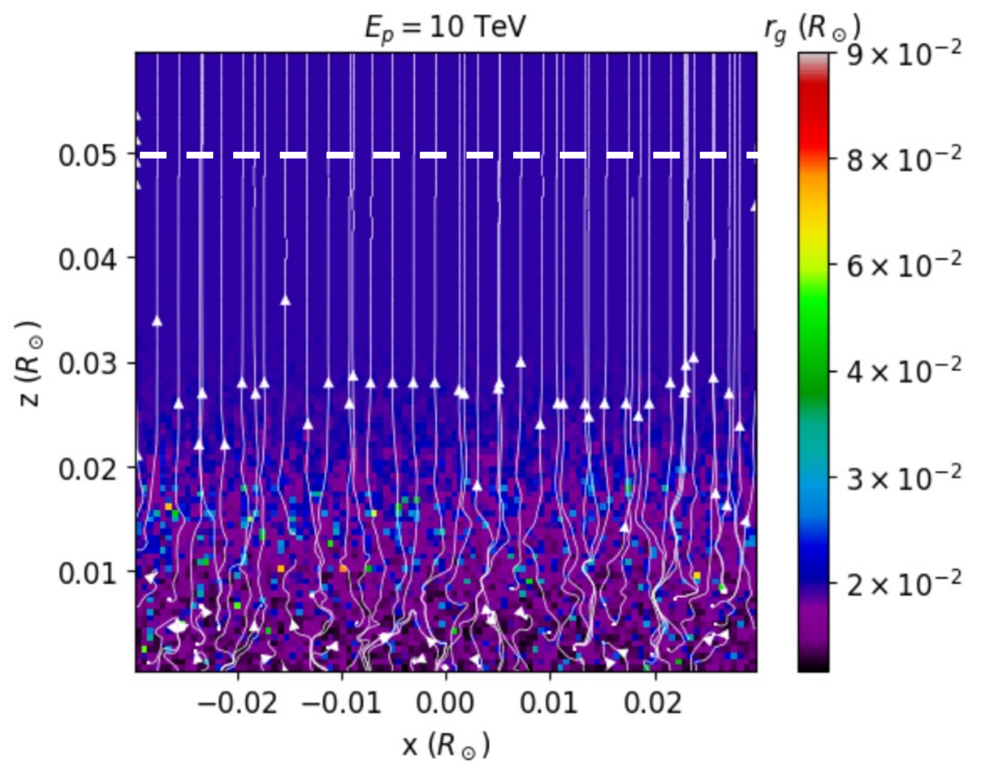
INTERACTING GCR PROTONS

$$\frac{\Delta t}{t_{int}} = \int_{t_i}^{t_f} \frac{dt}{t_{int}(z)} = \sigma_{pp} v \int_{t_i}^{t_f} n[z(t)]dt > 1 \qquad v_z > 0$$

(Focus: protons escaping from the Sun as they can produce gamma−rays observed at Earth)



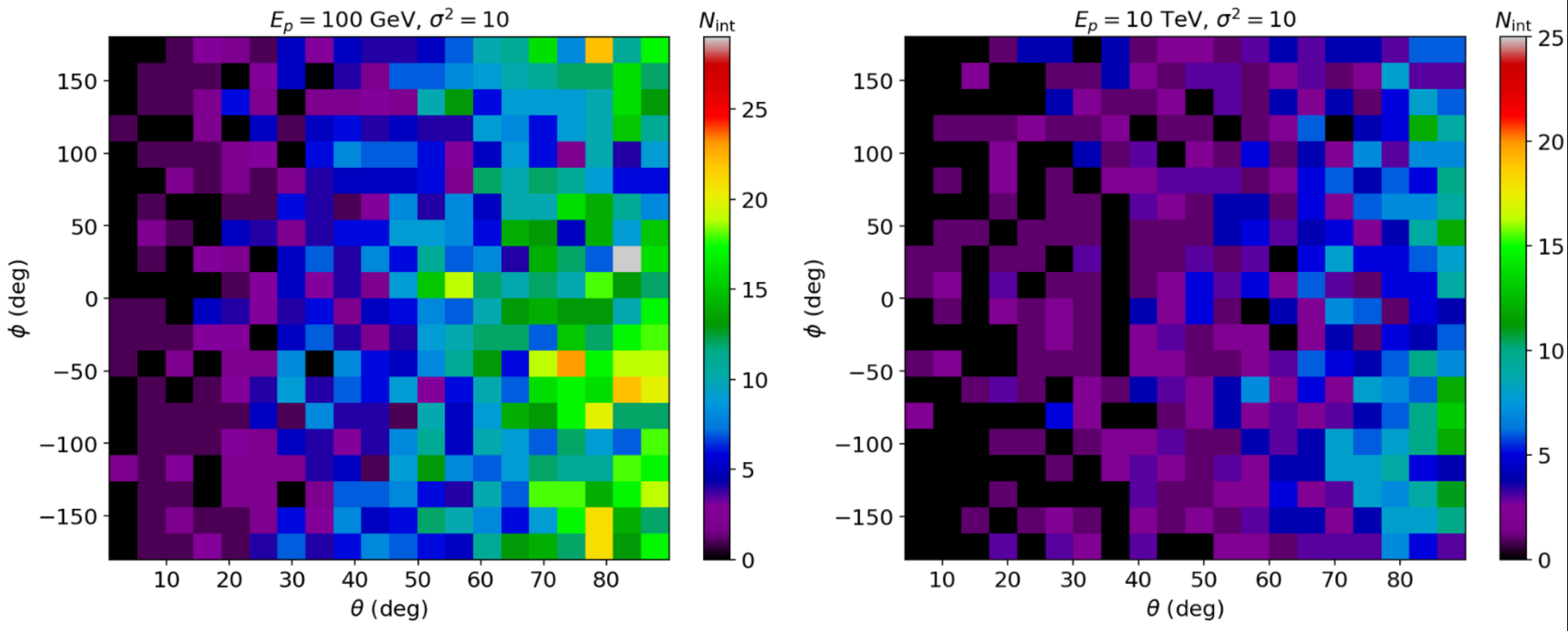
Credits: Puzzoni et al. 2025 (submitted to ApJL)

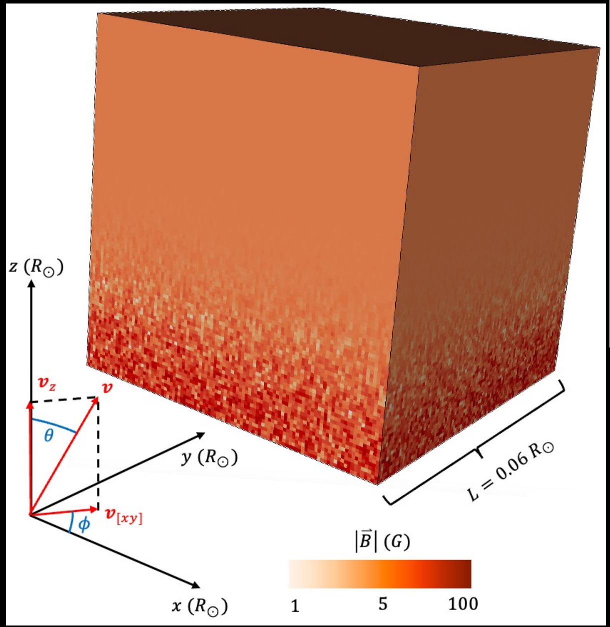


RESULTS

γ-RAYS EMISSION DIRECTION

Credits: Puzzoni et al. 2025 (submitted to ApJL)

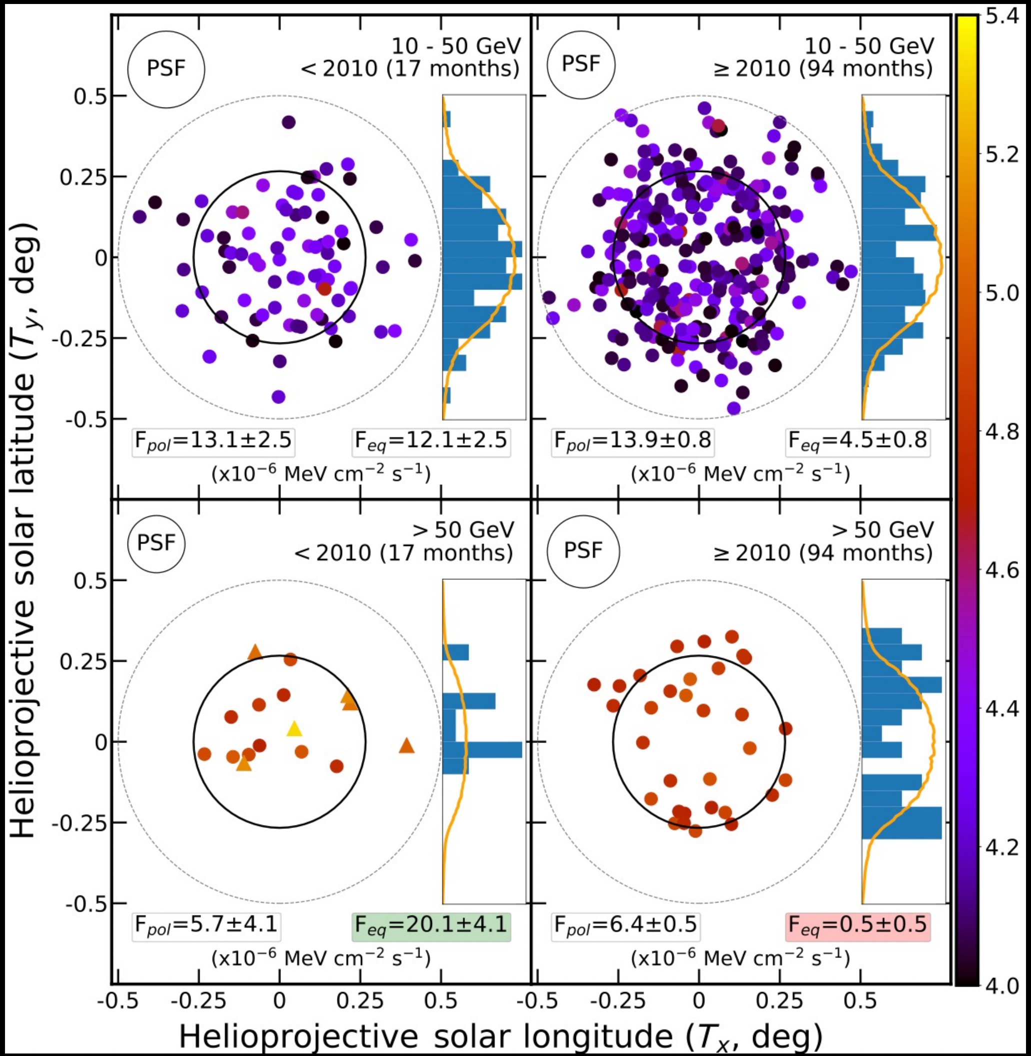




- θ range broadens to $\approx 40°$
- $70° \lesssim \theta \lesssim 90°$

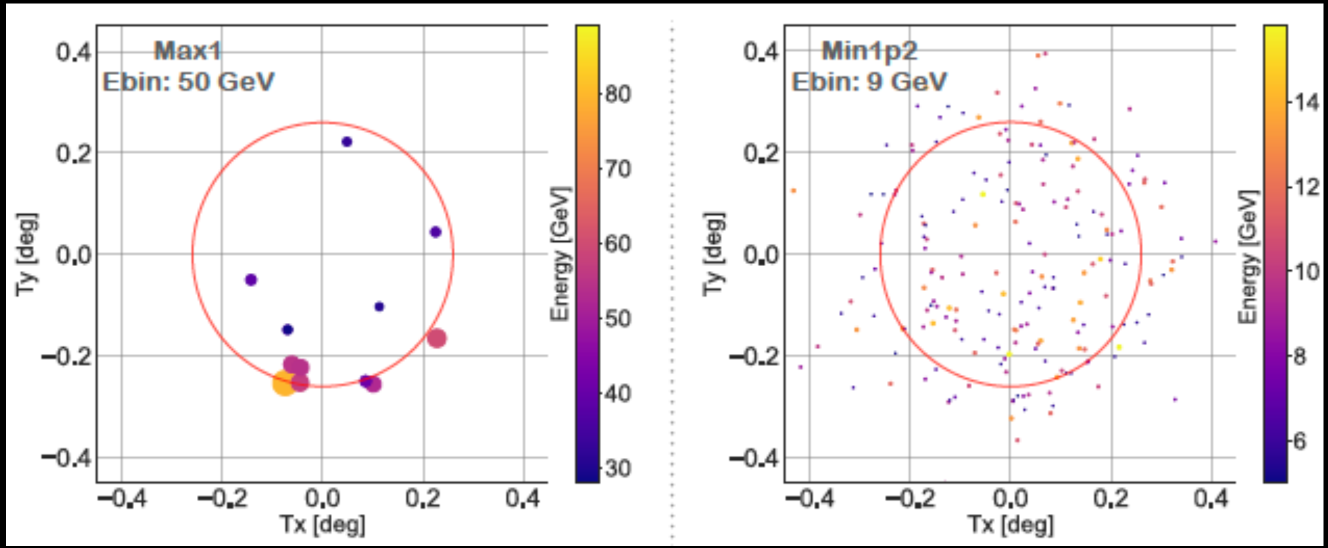
Anisotropic gamma-ray emission pattern

RESULTS



Credits: Linden et al. 2018

Credits: Arsioli & Orlando 2024



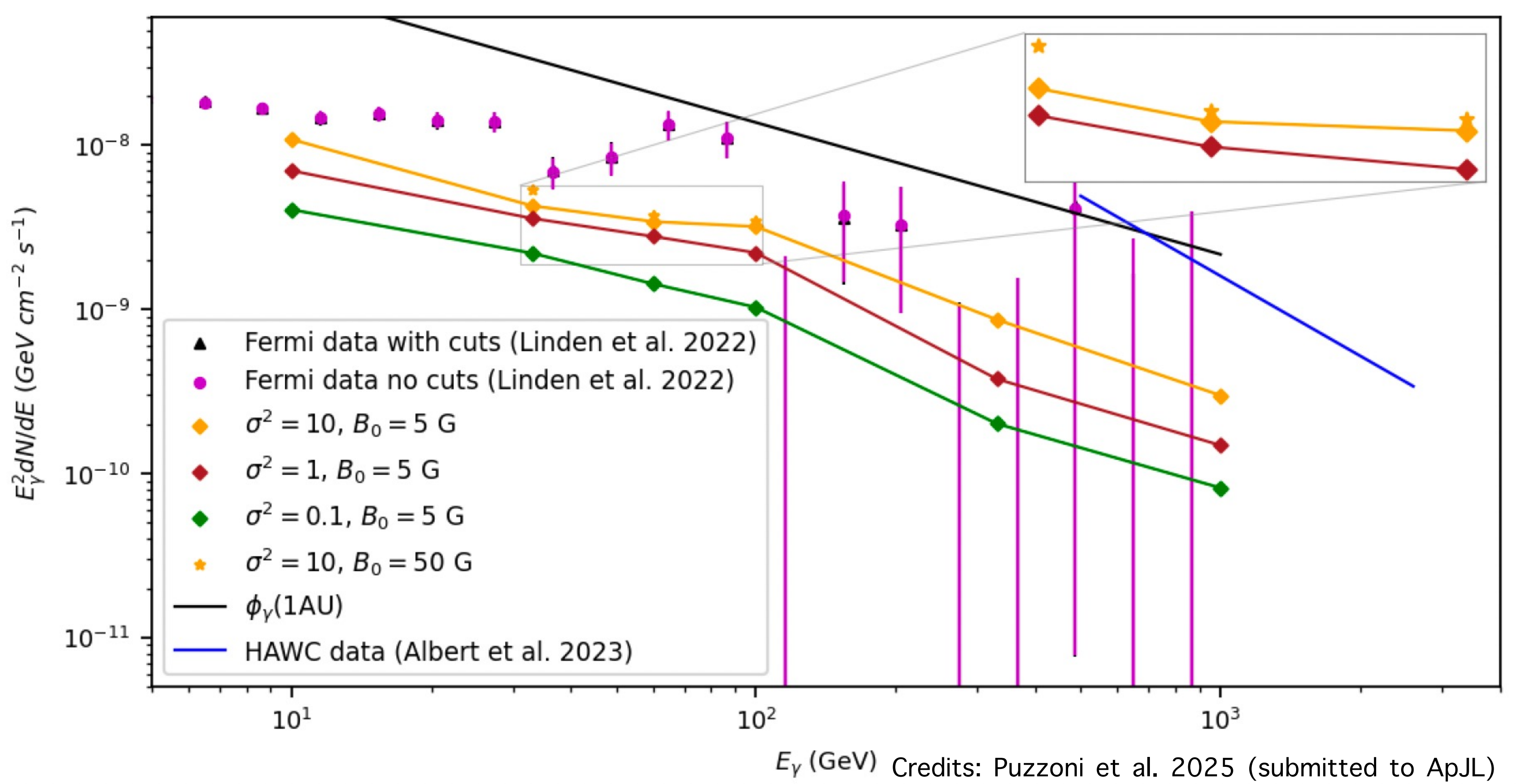
Anisotropic gamma-ray emission pattern

RESULTS

γ-RAYS FLUX

Credits: Kelner et al. 2006

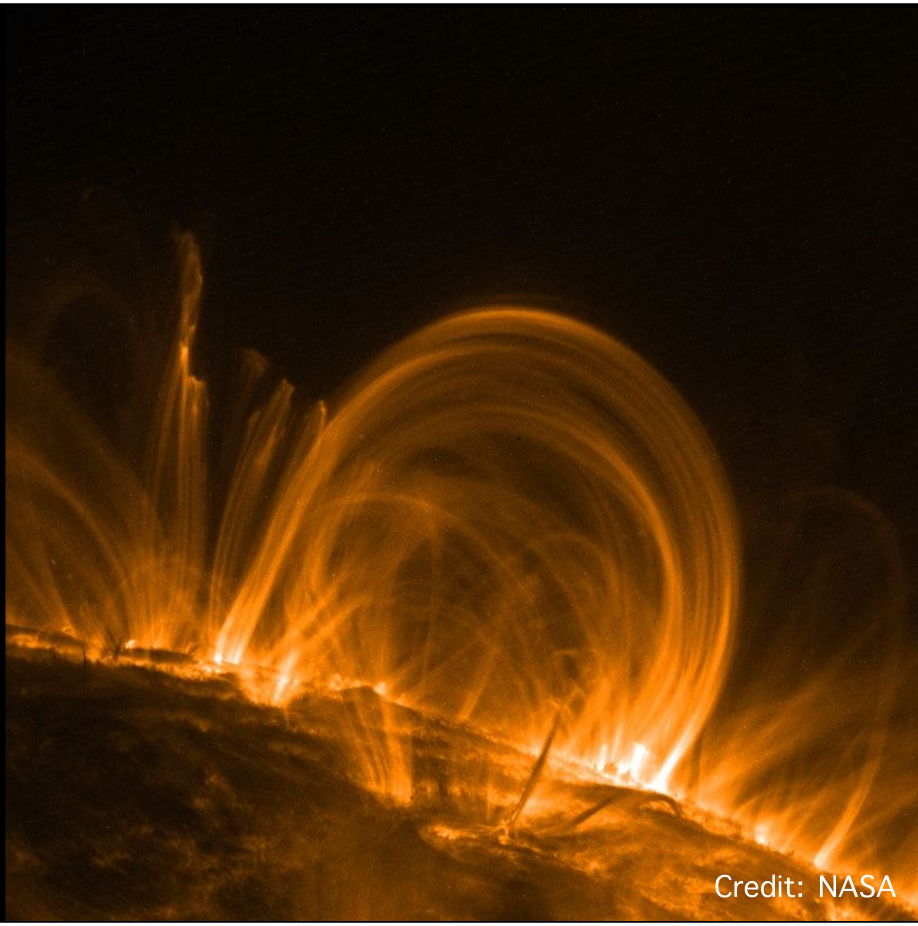
$$\Phi_\gamma(E_\gamma) = \frac{dN_\gamma}{dE_\gamma} = c n_p \int_{E_\gamma}^{\infty} \sigma_{pp}(E_p) J_p(E_p) F_\gamma\left(\frac{E_\gamma}{E_p}, E_p\right) \frac{dE_p}{E_p} \times \frac{2\pi R_\odot^2}{(L\times L) R_\odot^2} \left(\frac{R_\odot^2}{R_{1AU}}\right)^2$$



Credits: Puzzoni et al. 2025 (submitted to ApJL)

future works

- **Synthetic** model reproduces **overall trend** and **order of magnitude** of γ-ray flux both in **Fermi-LAT** and **HAWC** energy range
- **Flatness** of γ-ray flux in the **spectral dip region** increases with $\boldsymbol{\sigma^2}$
- Effect of **interchange reconnection** on γ-ray flux



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MODEL EQUATIONS

Credits: Giacalone and Jokipii 1999

$$\delta \boldsymbol{B}(x, y, z) = \sum_{n=1}^{N_m} A(k_n) \hat{\boldsymbol{\xi}}_n \exp\left(i k_n z'_n + i\beta_n\right), \quad (3)$$

where

$$\hat{\boldsymbol{\xi}}_n = \cos\alpha_n \hat{\boldsymbol{x}}'_n + i \sin\alpha_n \hat{\boldsymbol{y}}'_n \quad (4)$$

and

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\theta_n \cos\phi_n & \cos\theta_n \sin\phi_n & -\sin\theta_n \\ -\sin\phi_n & \cos\phi_n & 0 \\ \sin\theta_n \cos\phi_n & \sin\theta_n \sin\phi_n & \cos\theta_n \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}. \quad (5)$$

$$A^2(k_n) = \sigma^2 G(k_n) \left[\sum_{n=1}^{N_m} G(k_n)\right]^{-1}, \quad (6)$$

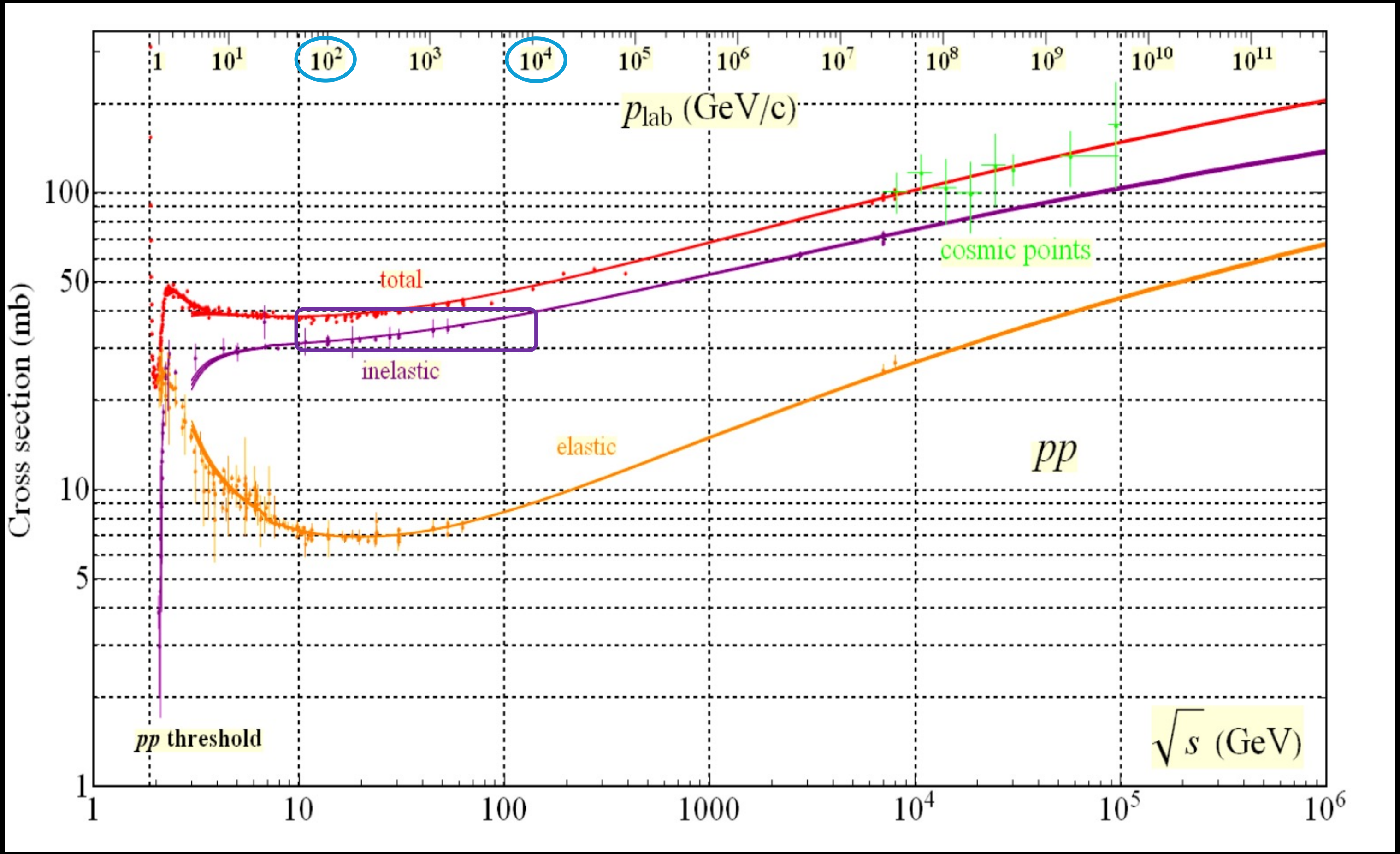
where

$$G(k_n) = \frac{\Delta V_n}{1 + (k_n L_c)^\gamma}. \quad (7)$$

P – P INELASTIC CROSS SECTION

Credits: Kafexhiu et al. 2014

$$\sigma_{pp} = \left[30.7 - 0.96\log\left(\frac{T}{T^{th}}\right) + 0.18\log^2\left(\frac{T}{T^{th}}\right)\right] \times \left[1 - \left(\frac{T^{th}}{T}\right)^{1.9}\right]^3 mb$$

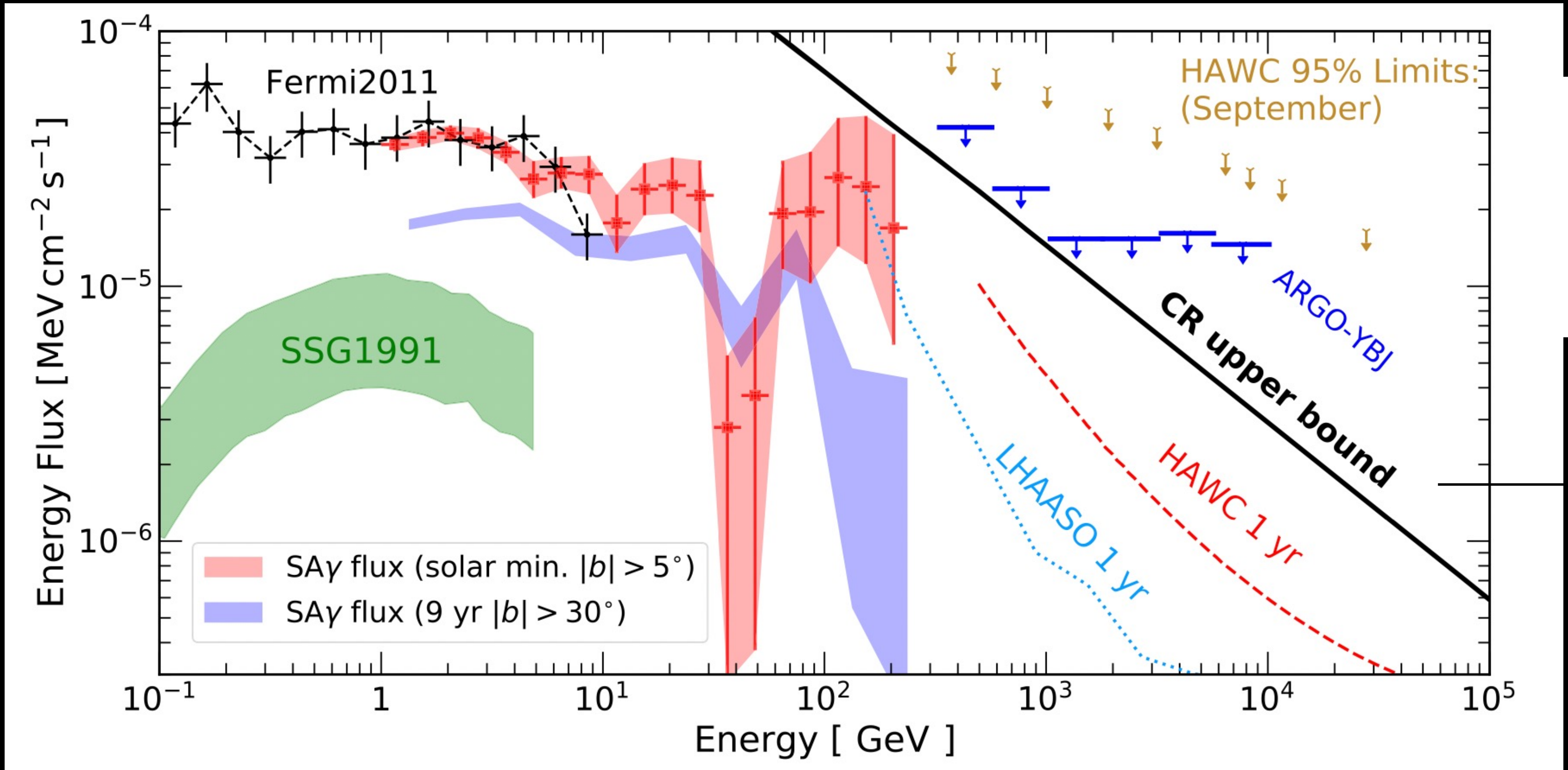


T: proton kinetic energy in the laboratory frame

$T^{th} = 0.2797$ GeV: threshold kinetic energy for the production of neutral and charged pions

Credits: Tanabashi et al. 2018

FERMI DATA



- Fermi 2011
- Fermi solar minimum 2008-2010
- Fermi 9 years 2008-2017

Theoretical maximum gamma-ray flux the Sun can produce with cosmic rays

DENSITY PROFILE

Credits: Morton et al. 2023