Semi-analytical Model of Solar Atmospheric Gamma Rays with PFSS Model

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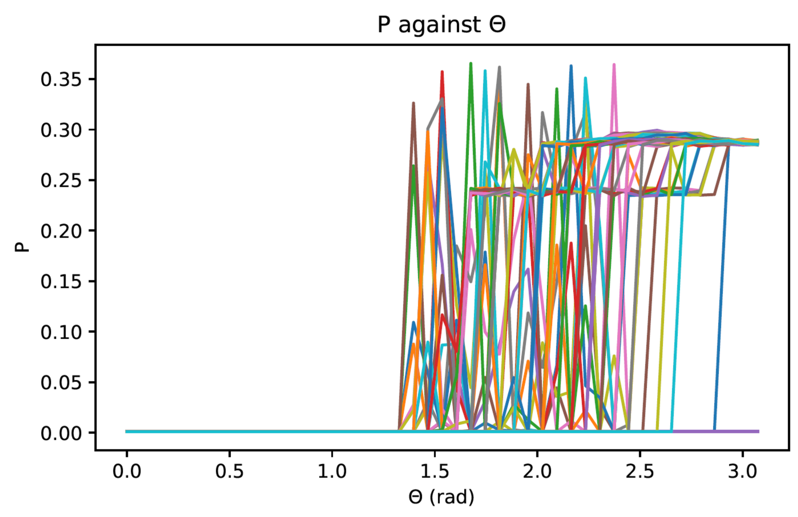
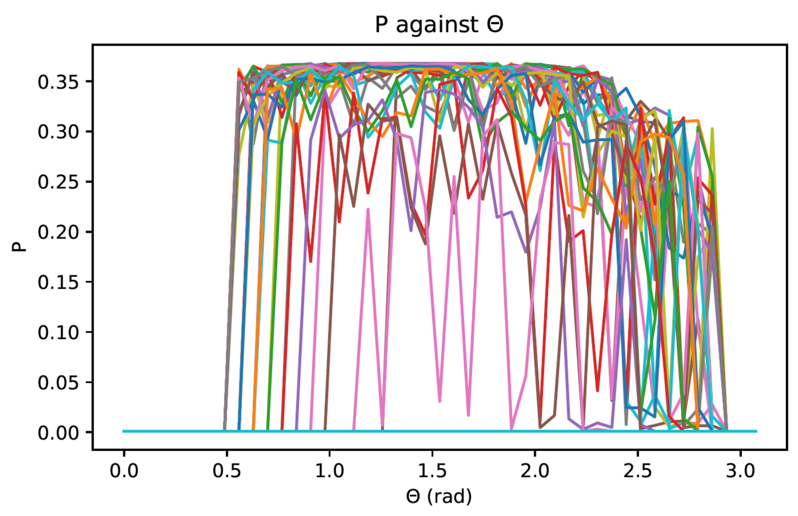
Motivation

- The solar atmospheric gamma ray (SAγ) flux has been a major unsolved problem in astroparticle physics
- Observations made with Fermi-LAT shows wide range of features that show cosmic rays interaction at solar atmosphere must be significantly affected by solar magnetic field
- Previous works (Li, 2020) used full simulation to produce SAγ flux under the influence of solar magnetic field
- However it was tedious and required weeks of time to perform one full simulation
- In this project, we use semi-analytical method to reproduce the result of Li
- We use PFSS model to simulate cosmic rays proton trajectory inside the Sun, but we use analytical method to solve for particle interaction
- It hugely shortens the time to get results

Method



(PFSS Model April 2014, R_s = 2.5 $R_\odot$)

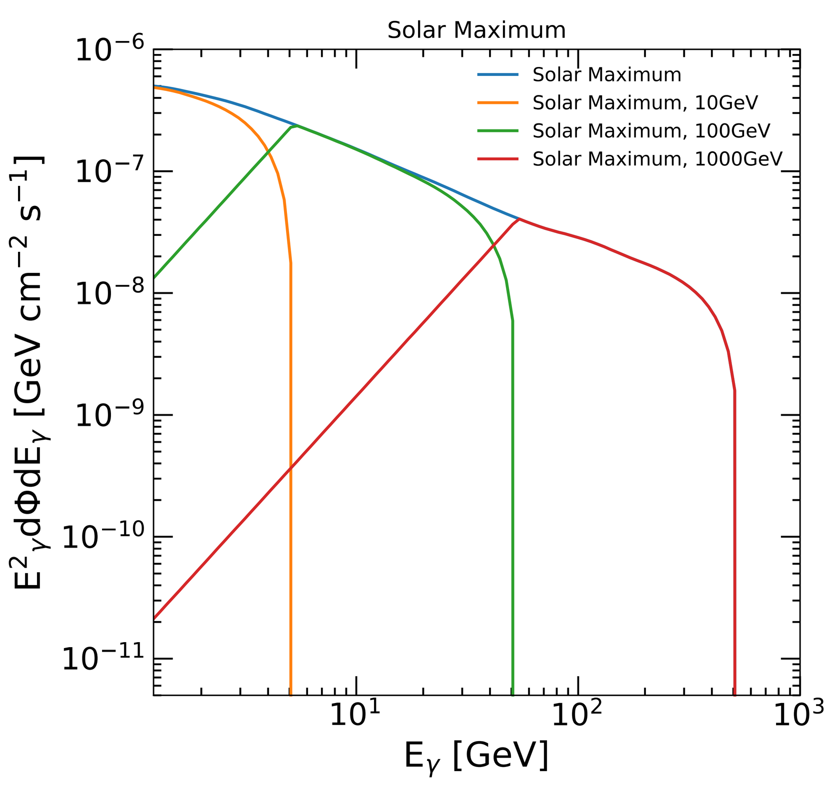


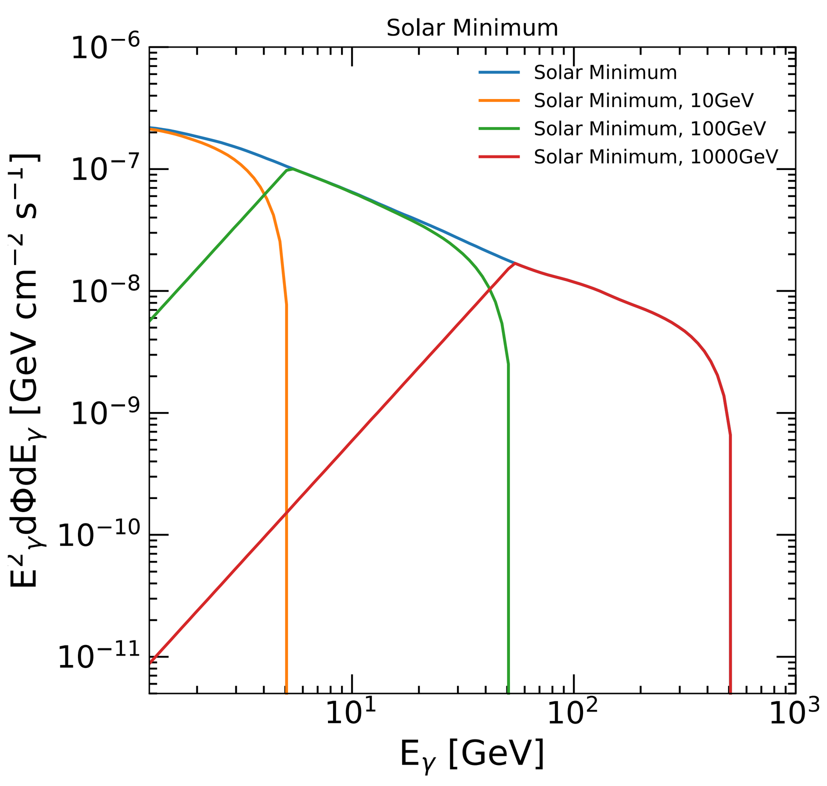
(PFSS Model May 2019, R_s = 1.6 $R_\odot$)

- The graphs indicated the emission probability of gamma ray P against the θ component of the initial momentum of the injected protons. There are 90 φ uniformly distributed in [0, 2π], for each φ, one P against θ is plotted.
- In the simulation, a total of 4050 protons were injected in (R_0 + 3000, 0.5π, 0.5π), with direction of initial momentum uniformly distributed in $0 \le \theta \le \pi$, $0 \le \varphi \le 2\pi$.
- We take the average P over solid angle (⟨P⟩ below)
- We calculate the flux using the equation below:

$$\frac{dF}{dE} = \frac{1}{4\pi D^2} \int_S dA \, \langle P \rangle \cos\alpha \, \frac{2\tilde{n}}{K_\pi} \int dE_\pi \frac{J_p}{\sqrt{E_\pi^2 - m_\pi^2}}$$

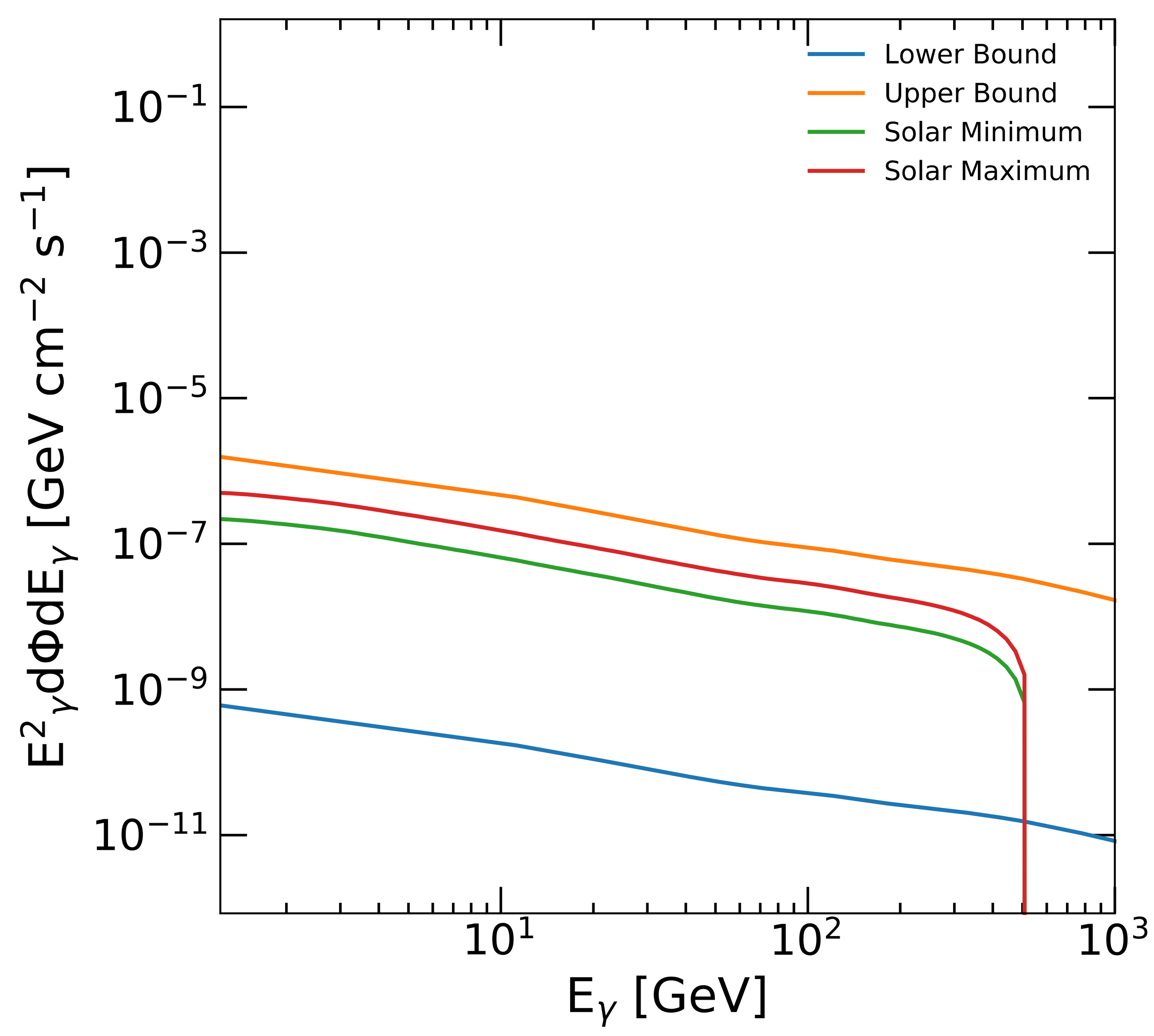
- where D is Sun-Earth distance, α is zenith angle





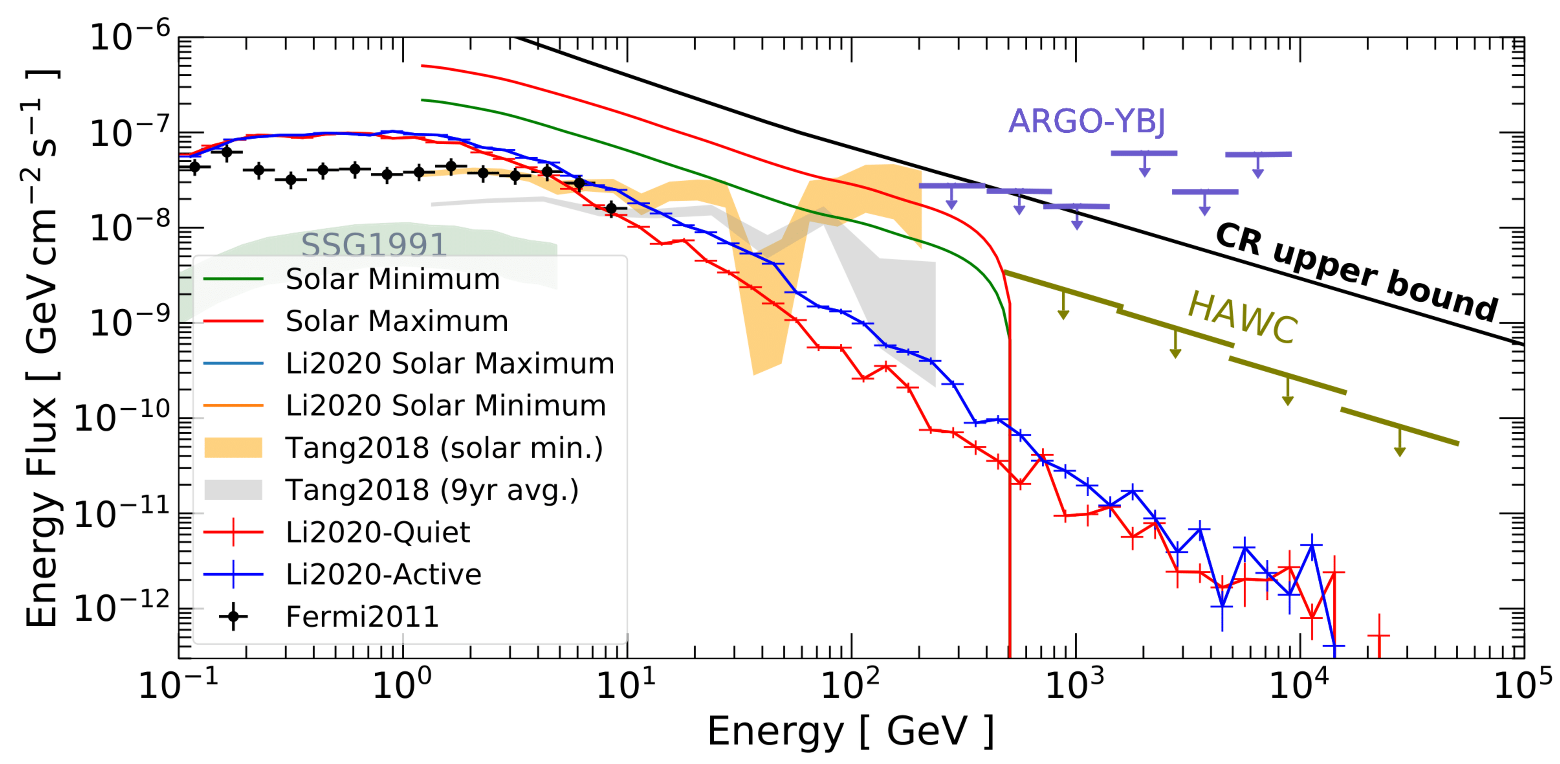
- We simulated with 3 different energies carried by the injected cosmic ray protons (10, 100, 1000GeV)
- We then add up the flux of each energy to obtain the total flux
- These plots show the contribution from each proton energy to the total flux at both solar minimum and solar minimum
- No flux at energy larger than that of the injected protons

Results



- The plot shows the flux against energy for the theoretical upper and lower bound (without the influence of solar magnetic field), as well as the flux at solar minimum and maximum (with the influence of magnetic field).
- The flux for solar maximum and minimum stay within the theoretical upper and lower bound
- During solar maximum the flux being slightly higher than at solar minimum

Discussion



- Our flux for Solar Maximum and Solar Minimum is an order of magnitude higher than previous full simulation works (Li, 2020)
- Also, the cut-off at about 500GeV is due to limited energies of injected protons in simulation (we use 10, 100, 1000GeV only for simplicity)
- It means plenty of rooms for improvements
- Possible future improvements include:
  - Simulating with more energies with PFSS model
  - Simulating at different location at solar surface
  - Simulating with more injection angles
  - Extrapolate PFSS field below the photosphere

Reference List

[1] Z. Li, K. C. Y. Ng, S. Chen, Y. Nan, and H. He, (2020), arXiv:2009.03888 [astro-ph.HE]

[2] Q. Tang, K. C. Y. Ng, T. Linden, B. Zhou, J. F. Beacom, and A. H. G. Peter, (2018), arXiv:1804.06846 [astro-ph.HE].