Advances in Modeling High-Energy Astrophysical Sources
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Solar-system gamma-ray sources with Fermi-LAT

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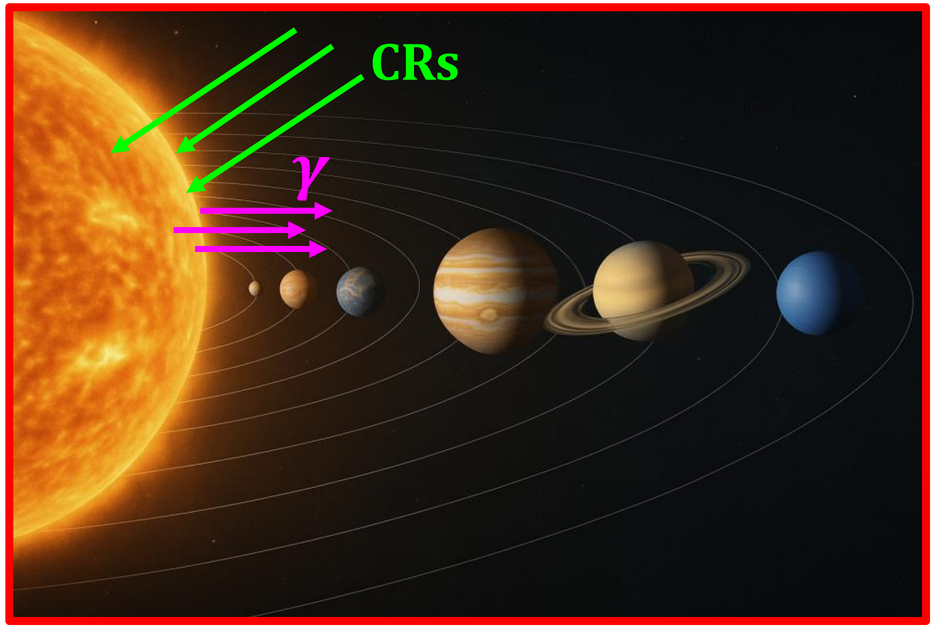
Gamma-ray sources in the Solar system: the Moon and the Sun

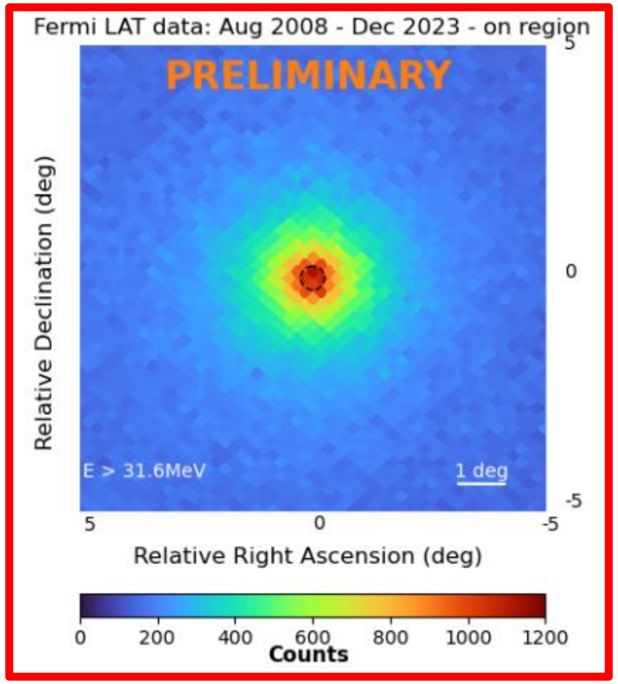
- **Moon** and **Sun** among the brightest sources in the sky → **Detected by Fermi LAT in its early years** of operation
- **Gamma rays are secondary products** of inelastic collisions of galactic **cosmic-ray nuclei (CRs)** with matter (e.g. in the atmosphere of the Sun or at the surface of the Moon).
- Gamma rays are **also** originated by **bremsstrahlung of CR electrons**
- The **Sun has an additional leptonic** component, due to **inverse Compton scattering of CR electrons** on solar photons
- In flaring state, the Sun can be an active source of gamma-ray photons up to few GeVs due to local acceleration of electrons and protons



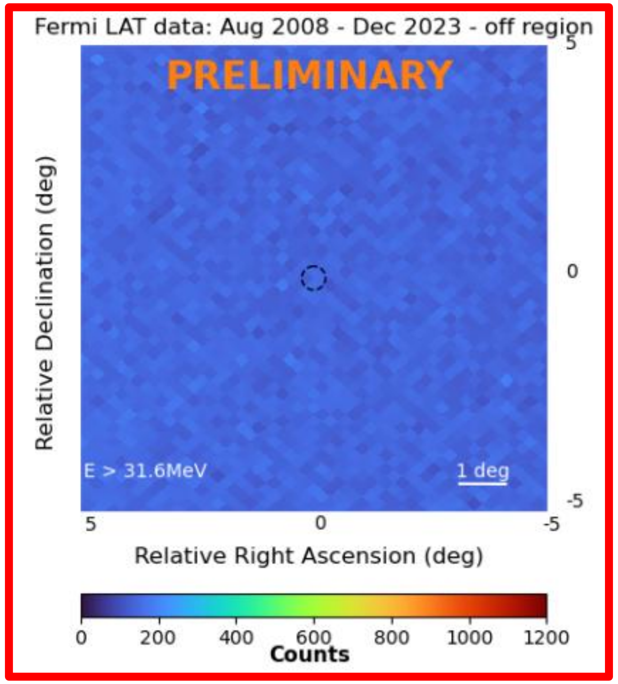
Observations of the Moon and the Sun as moving sources

- **Moon and Sun are moving sources** in the Sky
  → $\sim 13^{o}/day$ for the Moon, $\sim 1^{o}/day$ for the Sun
- **ROIs** for the analysis of these sources **must follow their drift** [1][3]
- Typical selection criteria of *good-time intervals* include:
  - Fermi-LAT in standard science operation and outside the SSA
  - ROI cone outside Earth's limb
  - ROI observed with small off-axis angles by LAT
  - ROI far from the galactic plane
  - Far from any bright source in Fermi catalogs ($\text{Flux} \gtrsim 10^{-7} \text{ph}/\text{cm}^2\text{s}$)
- **Background estimation** using the ***ON-OFF* method**:
  - **"Fake Moon" or "Fake Sun" ROIs** that move in the sky along the **same path of real sources**, but
    → **With a time shift** to ensure *large enough* separation from real source ROI
  - Same data selection applied to the "real source" and "fake source" ROIs
    → Same background is sampled

Moon-centered count map



"Fake Moon" count map



Plots from a recent analysis of Fermi-LAT data:
F. Loparco, Fermi Symposium 2024

Fermi-LAT observations of the Moon

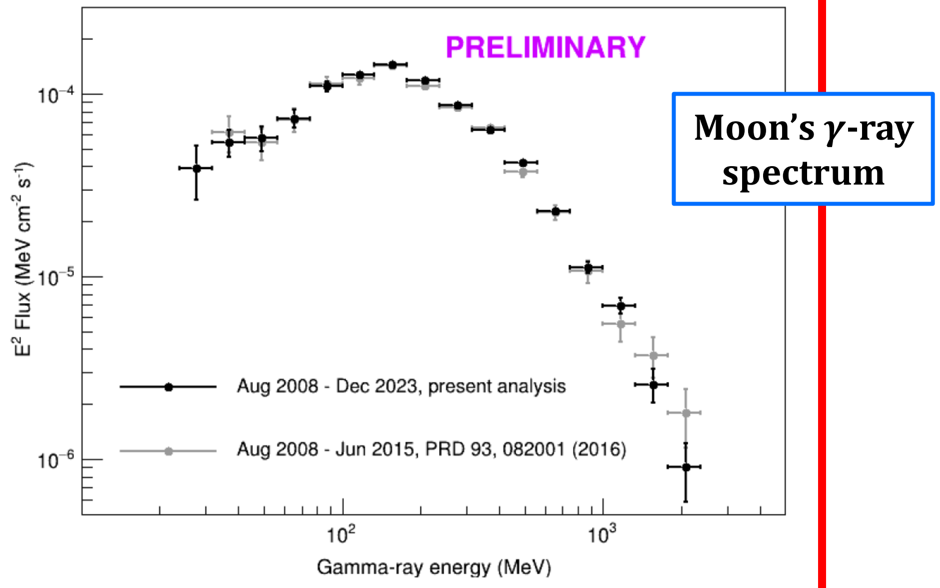
- The **gamma-ray fluxes $\vec{\phi}_s$, $\vec{\phi}_b$ evaluated** from the counts in the signal and in background ROIs $\vec{n}_s, \vec{n}_b$ by **maximizing a Poisson likelihood function** [1]:

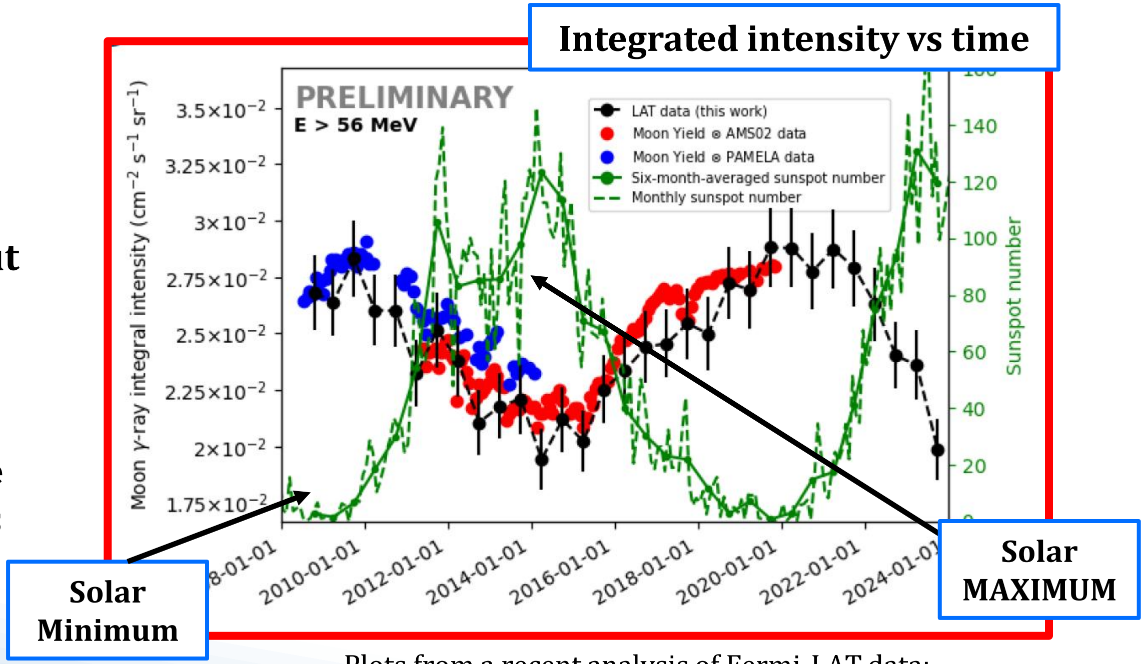
$$\mathcal{L}(\vec{\phi}_s, \vec{\phi}_b | \vec{n}_s, \vec{n}_b) = \prod_i e^{-\mu_s(E_i)} \frac{\mu_s(E_i)^{n_s(E_i)}}{n_s(E_i)!} \prod_i e^{-\mu_b(E_i)} \frac{\mu_b(E_i)^{n_b(E_i)}}{n_b(E_i)!}$$

$$\mu_s(E_i) = \sum_j P_s(E_i|E_j)[\phi_s(E_j) + \phi_b(E_j)] \cdot \Delta E_j \cdot A \cdot t_s$$

$$\mu_b(E_i) = \sum_j P_b(E_i|E_j) \cdot \phi_b(E_j) \cdot \Delta E_j \cdot A \cdot t_b$$

- The **spectral energy distribution $E^2\phi_s(E)$** is **peaked at about 150 MeV** and drops as a power-law with an index ~2
- Same analysis can be carried out in 6-months temporal bins
- Energy-integrated intensity exhibits **anti-correlation with the solar activity and correlation with measured CR intensities**
- The **anti-correlation** tends to **disappear at the higher energies**.





Plots from a recent analysis of Fermi-LAT data:
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Modeling of the Moon with Monte Carlo simulations

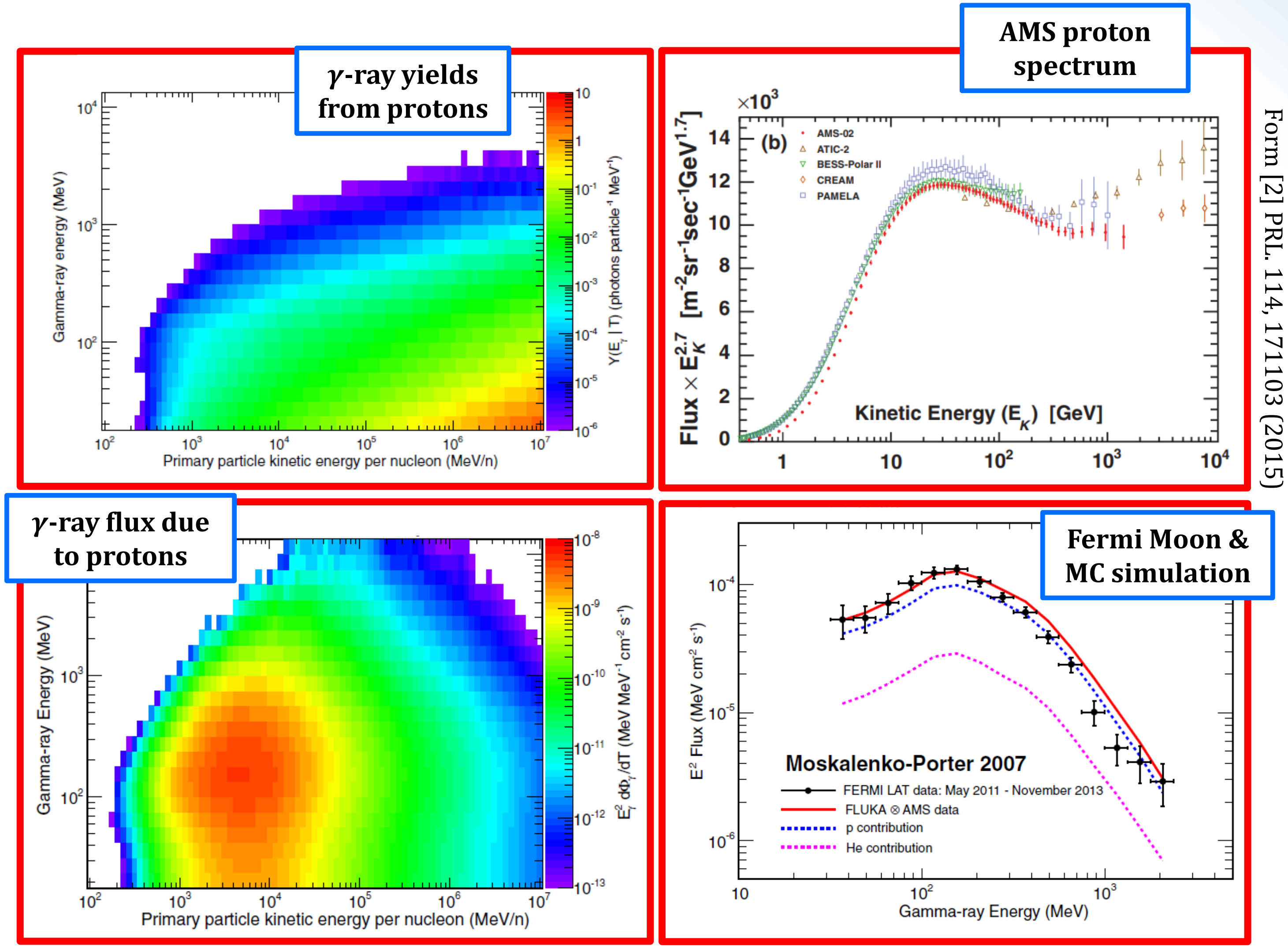
- Modeling carried out with a **MC simulation** approach [1] that can be extended to the Sun and other Solar System bodies
- Main inputs:
  1. Composition and density of the lunar regolith
  2. Model of hadronic interactions (embedded in the FLUKA code)
- Primary p and He generated with isotropic & uniform distribution over the lunar surface. Energy range: 10 MeV/n to 10TeV/n
- The gamma-ray **yields** from primary species i:

$$Y_{i\rightarrow\gamma}(E_\gamma|E_i) = \frac{N_{\gamma,i}(E_\gamma|E_i)}{N_{gen,i}(E_i)\Delta E_\gamma}$$

- **Flux of γ-rays** calculated by **folding the yields with intensities of p and He measured by AMS** [2]:

$$I_{i\rightarrow\gamma}(E_\gamma|E_i) = Y_{i\rightarrow\gamma}(E_\gamma|E_i)\, I_i(E_i)$$

$$\phi_\gamma(E_\gamma) = \frac{\pi R^2}{d^2} \sum_{i=p,\,He} \int I_{i\rightarrow\gamma}(E_\gamma|E_i)\, dE_i$$



Form [2] PRL. 114, 171103 (2015)

From[1]: PRD 93, 082001 (2016)

Where R = radius of the Moon, d = distance Moon-LAT

The two-component solar γ-ray emission observed by Fermi-LAT

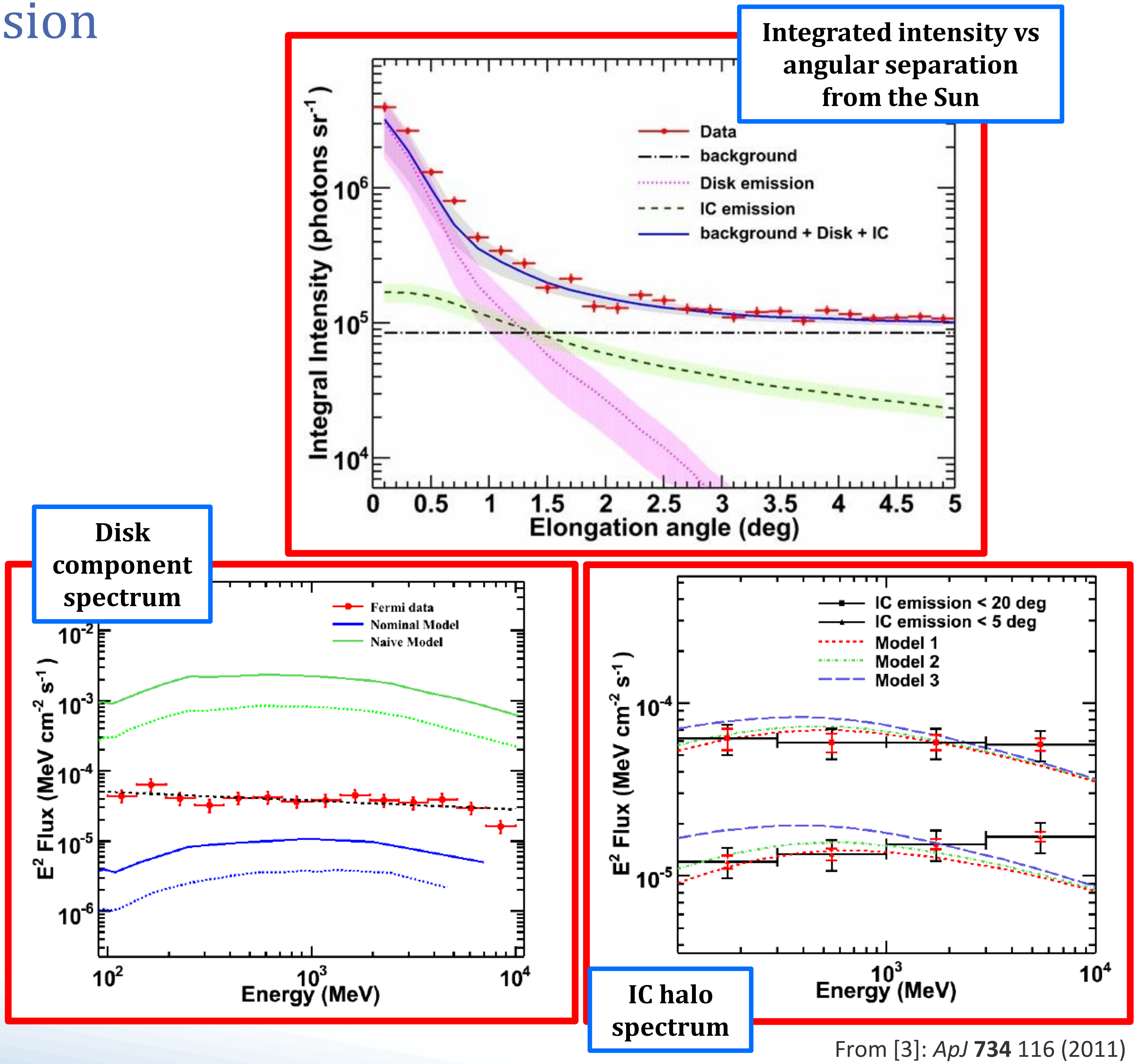
Components of solar γ-ray emission distinguished by Fermi-LAT in 2011 analysis [3] :

«Disk»:

- **Due to CR nuclei** inelastic interactions with solar atmosphere
- Modeled as a point source
- Unexpectedly bright
- Spectrum approx. $\propto E^{-2}$ in the 100 MeV – 10 GeV range

Extended IC halo:

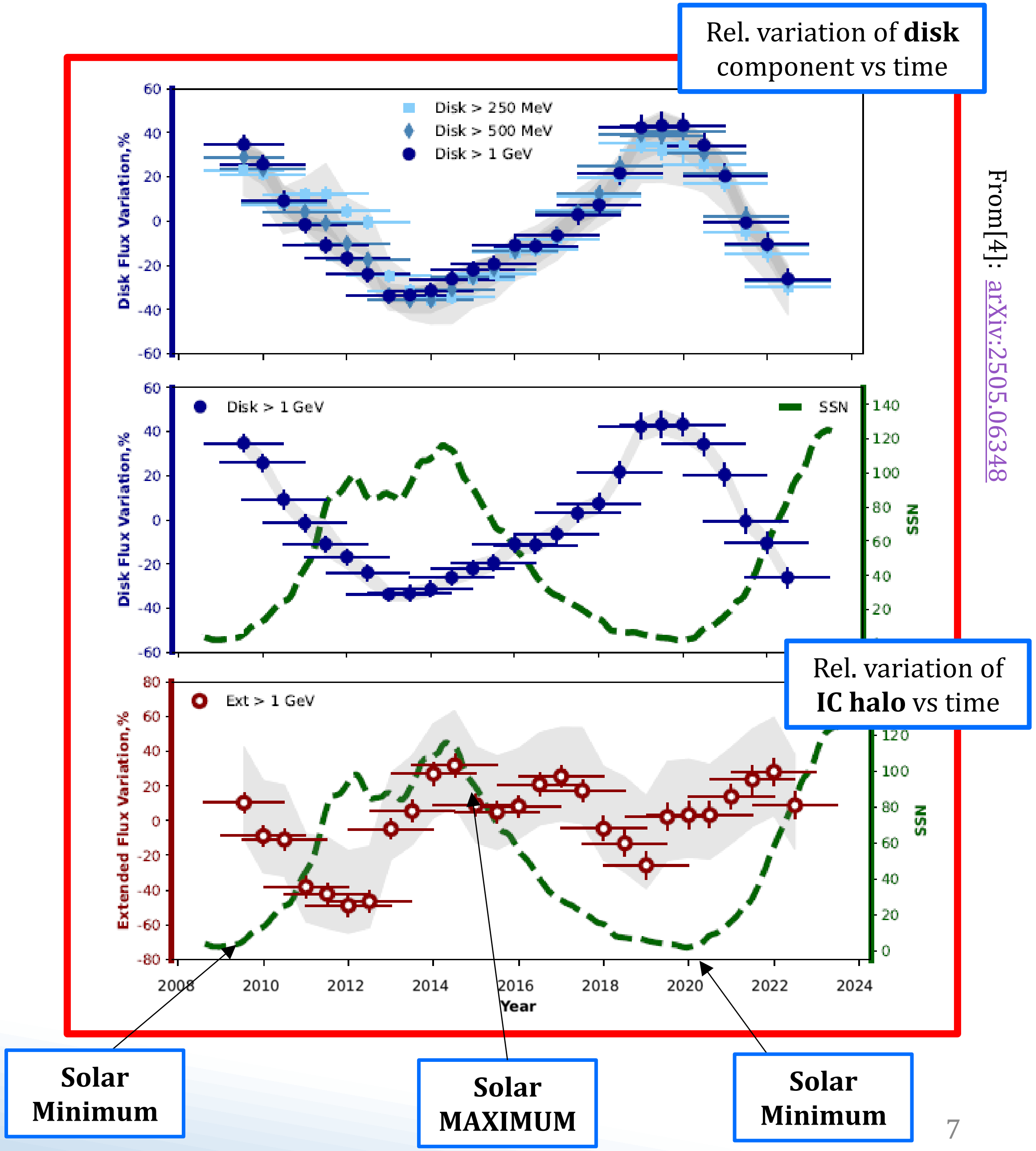
- **Due to CR electrons** scattering off the solar blackbody photon field, via inverse-Compton
- Modeled by subdividing the Sun-centered ROI in nested rings
- Detected up to 20° away from the position of the Sun
- Globally brighter than disk
- Can be used to investigate CR electrons modulation in the heliosphere



From [3]: *ApJ* **734** 116 (2011)

Further observational features of γ rays from the Sun and open questions

- The spectrum of the **disk** component, approximately proportional to E^{-2}, is **harder than the CR spectrum** ($\propto E^{-2.7}$) that origniates it
- From more recent studies of Fermi-LAT data**, in a solar cycle** the disk integral flux subject to $\sim \pm$ **40% variation** with respect to average.
  It is strongly anti-corrlated with solar activity [4]
- But the **variability is mostly energy-independent**, while more pronounced modulation are expected at the lower energies
- The **inverse Compton** component is surprisingly **anti-correlated** with solar activity **only until mid 2012** [4]

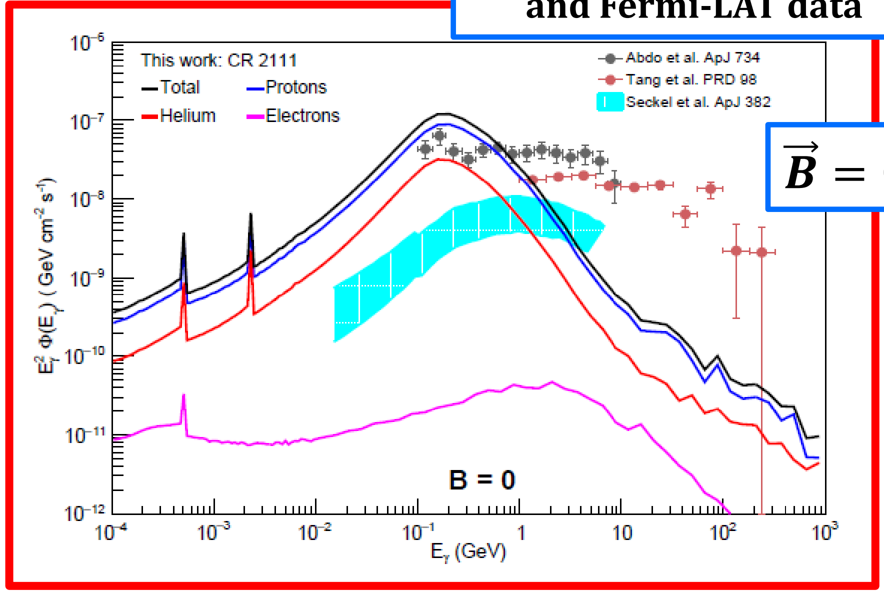


From[4]: arXiv:2505.06348

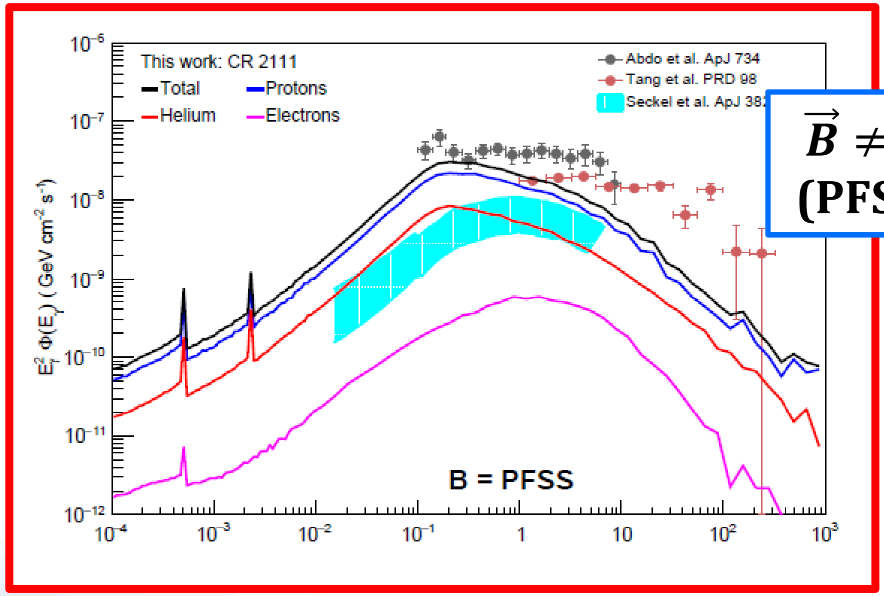
Modeling of the solar disk emission

- The solar gamma-ray emission can be investigated with a **MC simulation setup** that follows similar principles as the one for the Moon [5], based on the FLUKA code
- Key aspects:
  1. **Detailed description** of composition + density/temperature/pressure profiles **of the interior** of the Sun
  2. Realistic **modeling of magnetic fields** in the vicinity of the sun (**PFSS** from solar magnetograms for $r < 2.5R_{\odot}$)
  3. **Parker magnetic field model** in the interplanetary space
  4. **CR intensities measured at 1 AU rescaled** to account for transport in the B-field (HelioProp software)
- This simulation setup shows:
  - The **fundamental role of the solar magnetic field**
  - It **reduces the gamma-ray flux at $E \lesssim 1GeV$** by partially blocking low energy CRs, before they reach the Sun
  - **Enhances flux at higher energy** due to an increase of the average length of the trajectories in the solar atmosphere

Simulated disk spectrum and Fermi-LAT data



$\vec{B} = 0$



$\vec{B} \neq 0$ (PFSS)

From [5]: PRD 101, 083011 (2020)

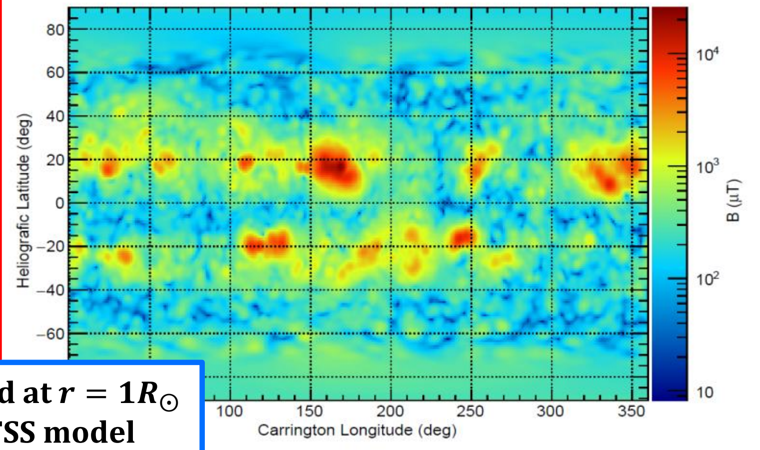
Modeling of the Solar IC emission

The **solar B-field** is also expected to affect the IC component:

- Electrons move along curved trajectories
- Their length determines the interaction probability with sunlight

A custom 3D MC simulation has already been developed [6], considering anisotropic IC-scattering and assuming a simplified geometry for the Sun. The Parker model was used for the EM-fields
→ IC spectral shape is affected and and the gamma-ray flux enhanced

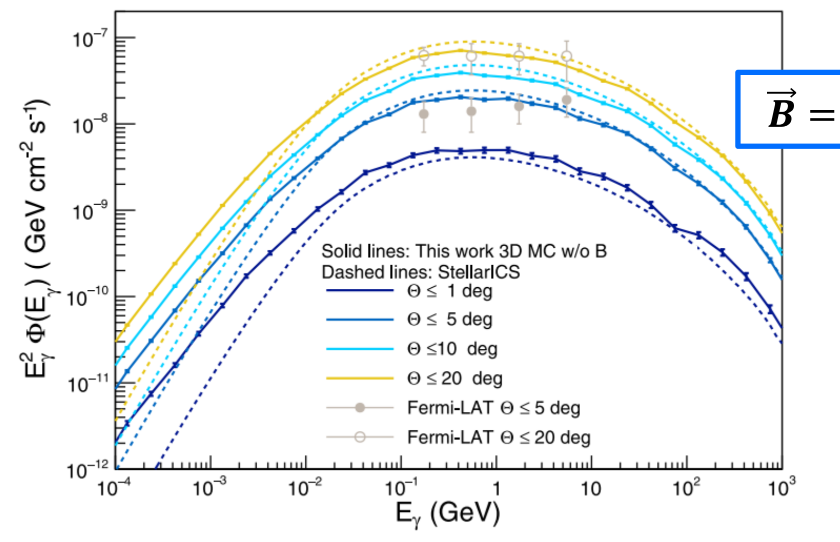
This study can be extended, including realistic models for the solar atmosphere and complex B-field configurations, derived from measurements of the field on the photosphere.



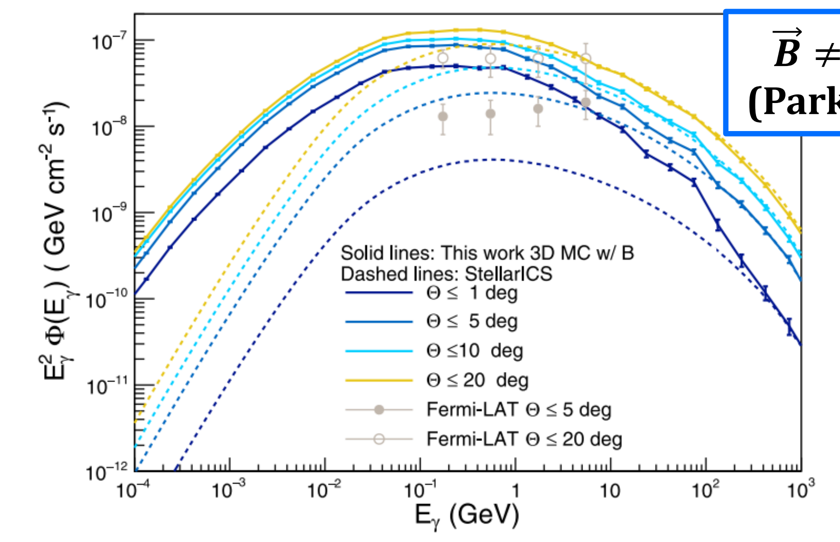
B field at $r = 1R_\odot$
PFSS model

From [5]: PRD 101, 083011 (2020)

IC halo $E_\gamma{}^2\phi_\gamma(E_\gamma)$



$\vec{B} = 0$



$\vec{B} \neq 0$
(Parker)

From [6]: PRD 111, 123011 (2025)

Conclusions

- During its early years of operation, Fermi-LAT has observed the Moon and the quiet Sun as bright sources of gamma rays
- The Moon's observations are in agreement with predictions obtained by folding the measured intensities of CR protons and He nuclei with gamma-ray yields derived from Monte Carlo simulations
- While the basic mechanism of the solar disk gamma-ray emission is understood, several of its features remain unexplained
- The extended component also shows unexpected variability over time
- Detailed simulation studies of gamma-ray emission from the Sun in presence of magnetic fields may give new insights into the aspects that are not yet fully understood

References

[1] M. Ackermann et al. (Fermi-LAT Collaboration), “Measurement of the high-energy γ-ray emission from the Moon with the Fermi Large Area Telescope”, Phys. Rev. D 93, 082001 (2016), published 8 April 2016. DOI: 10.1103/PhysRevD.93.082001

[2] M. Aguilar et al., “Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station”, Phys. Rev. Lett. 114, 171103 (2015), DOI: https://doi.org/10.1103/PhysRevLett.114.171103

[3] A. A. Abdo et al. (Fermi-LAT Collaboration), “Fermi large area telescope observations of two gamma-ray emission components from the quiescent sun” , ApJ 734 116 (2011), DOI 10.1088/0004-637X/734/2/116

[4] A. Acharyya et al., "Surprising Variation of Gamma Rays from the Sun over the Solar Cycle Revealed with Fermi-LAT." arXiv preprint arXiv:2505.06348 (2025)

[5] M. N. Mazziotta et al., “Cosmic-ray interactions with the Sun using the FLUKA code”, Phys. Rev. D 101, 083011 (2020) DOI: https://doi.org/10.1103/PhysRevD.101.083011

[6] M. N. Mazziotta, " 3D Monte Carlo calculation of the inverse Compton emission from the Sun and stars in the presence of magnetic and electric fields", Phys. Rev. D 111, 123011(2025), DOI: https://doi.org/10.1103/zs82-fktf