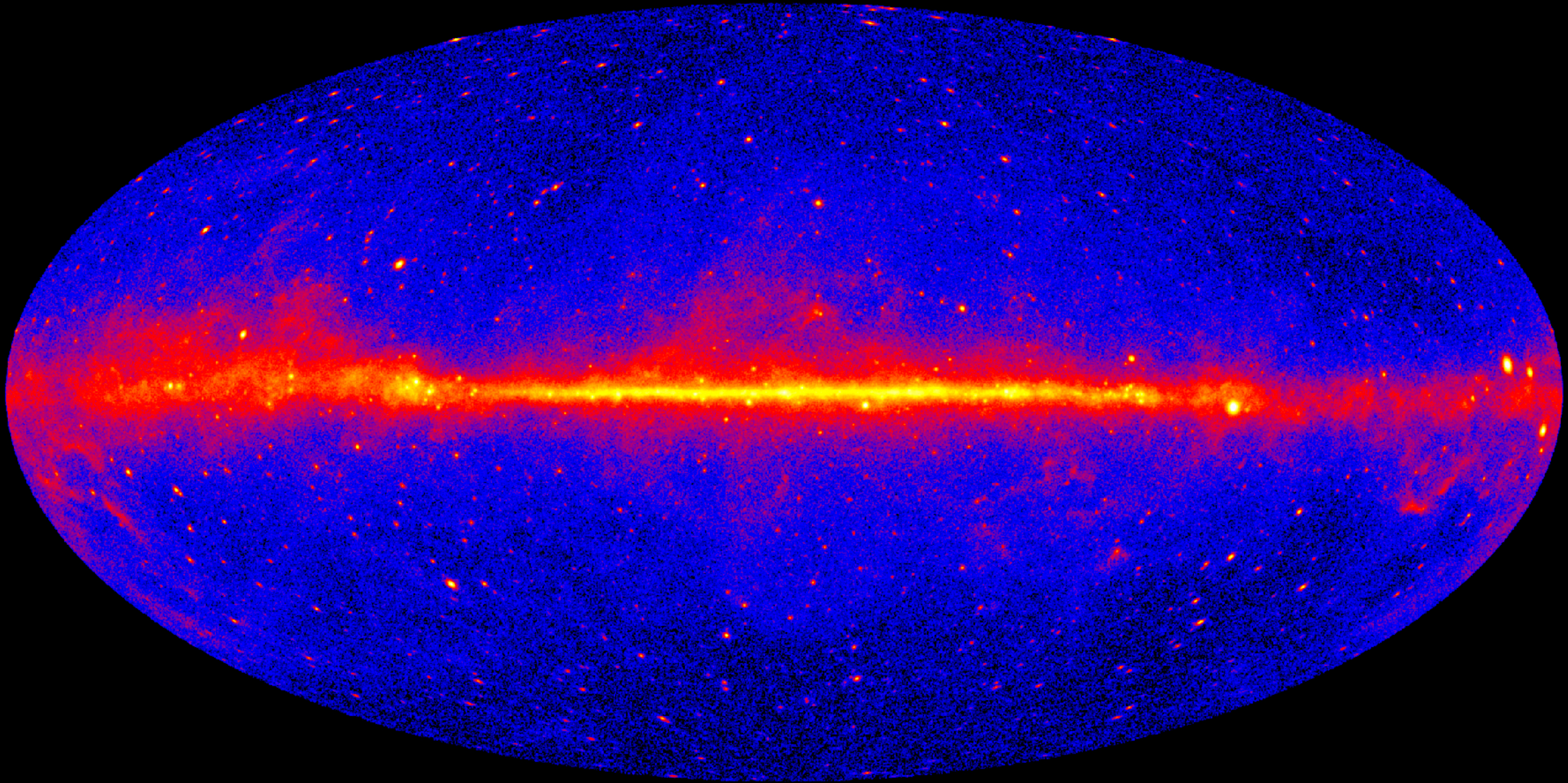
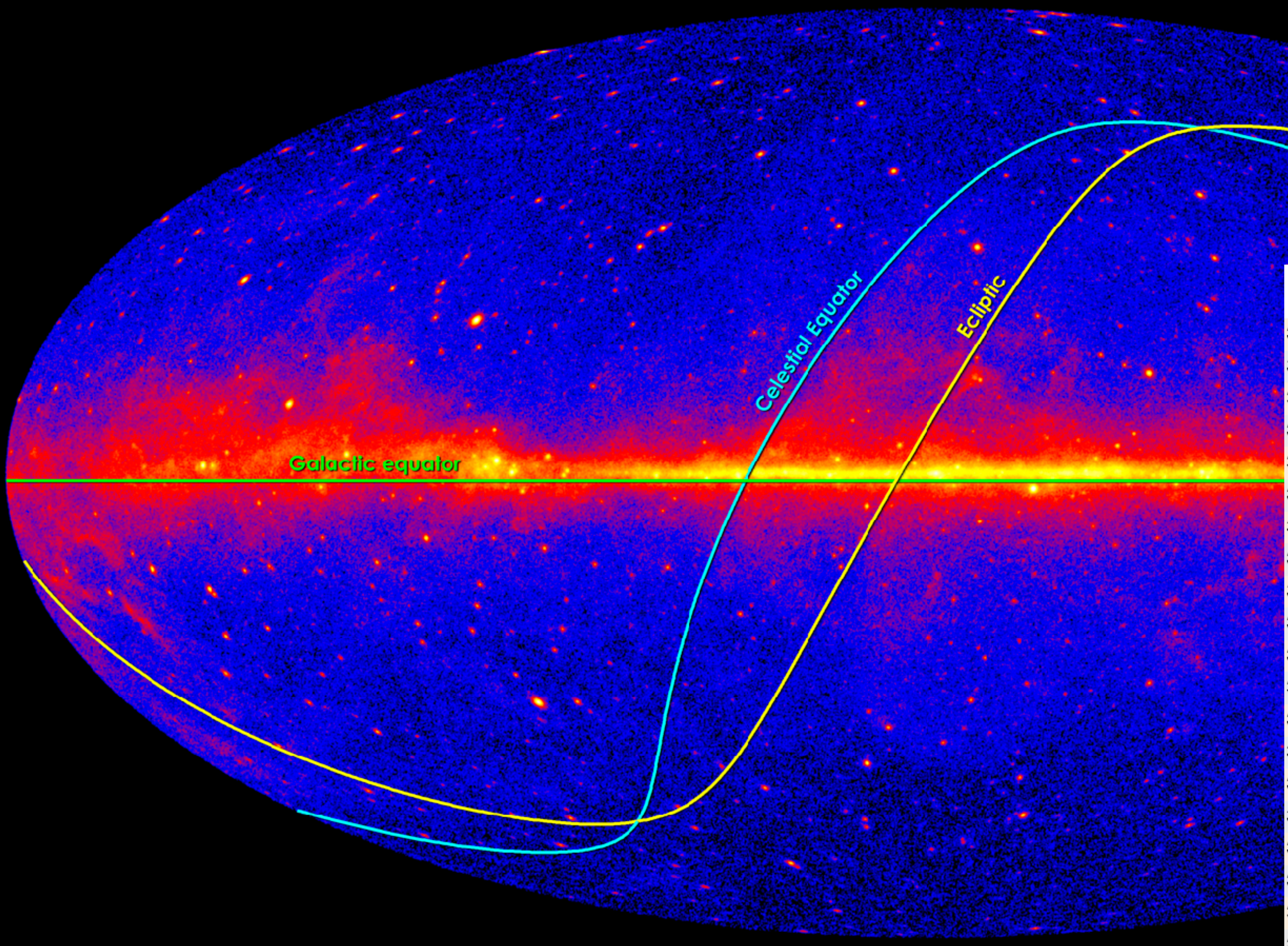
TIM LINDEN

16 October 2023

Evidence for a New Component of Solar Gamma-Ray Emission

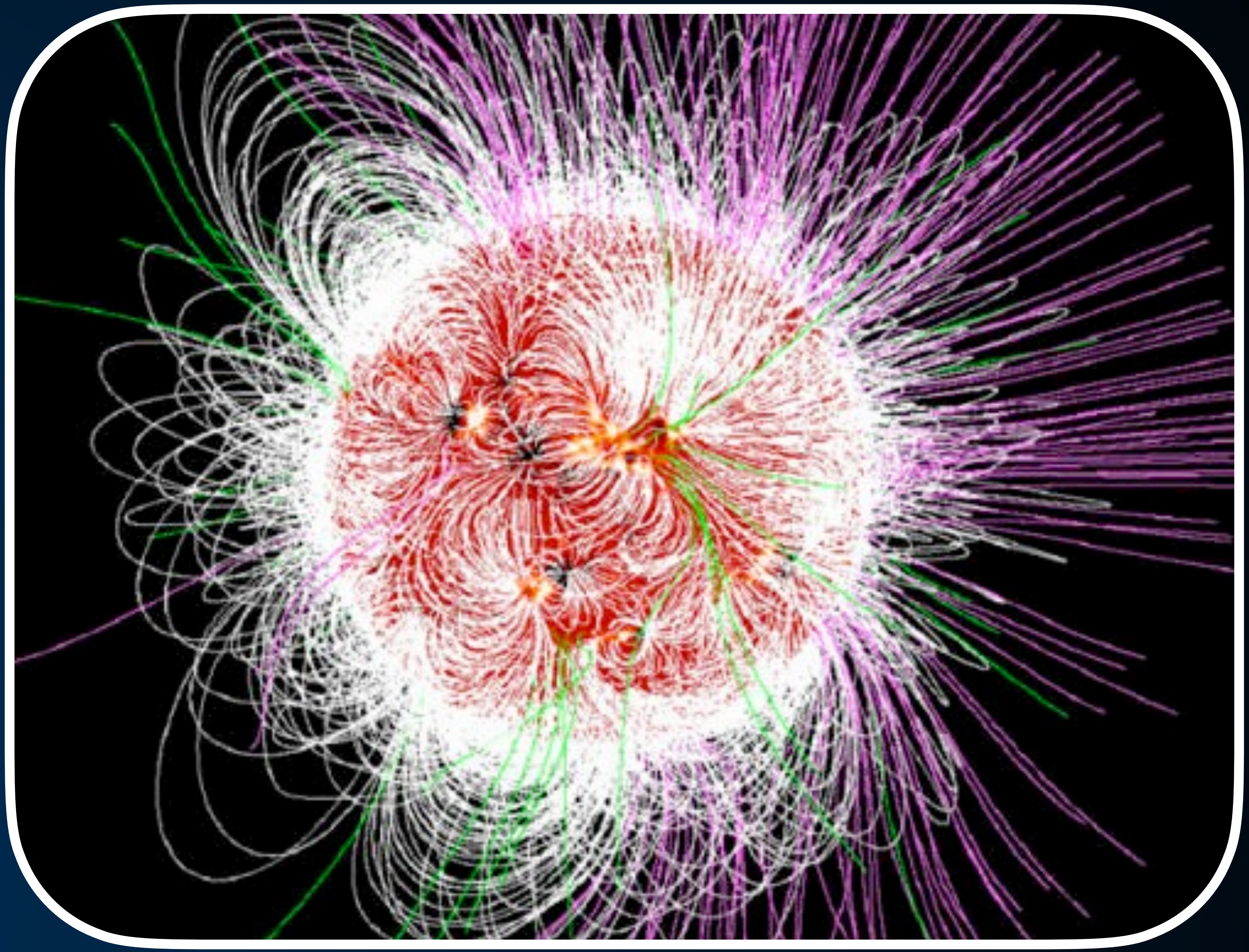
Stockholms universitet





name	assoc name 1	energy flux [erg/cm^2/s]	assoc name 2
3FGL J0835.3-4510	PSR J0835-4510	8.93008e-09	Vela
3FGL J0633.9+1746	PSR J0633+1746	4.15261e-09	Geminga
3FGL J0534.5+2201	PSR J0534+2200	1.47178e-09	Crab
3FGL J1709.7-4429	PSR J1709-4429	1.31463e-09	
3FGL J2254.0+1608	3C 454.3	1.23418e-09	
3FGL J2021.5+4026	LAT PSR J2021+4026	8.83261e-10	
3FGL J2028.6+4110e	Cygnus Cocoon	6.57388e-10	
3FGL J1836.2+5925	LAT PSR J1836+5925	5.98187e-10	
3FGL J1855.9+0121e	W44	5.35680e-10	
3FGL J2021.1+3651	PSR J2021+3651	5.03626e-10	
3FGL J0617.2+2234e	IC 443	5.02055e-10	
3FGL J1512.8-0906	PKS 1510-08	4.92754e-10	
3FGL J0240.5+6113	LS I+61 303	4.72665e-10	
3FGL J1809.8-2332	PSR J1809-2332	4.47994e-10	
3FGL J0007.0+7302	LAT PSR J0007+7303	4.25538e-10	
3FGL J1801.3-2326e	W28	4.15501e-10	
3FGL J1826.1-1256	LAT PSR J1826-1256	4.14665e-10	
3FGL J0534.5+2201i	Crab	3.92571e-10	
3FGL J1104.4+3812	Mkn 421	3.82949e-10	
3FGL J1923.2+1408e	W51C	3.45801e-10	
3FGL J1907.9+0602	LAT PSR J1907+0602	3.19051e-10	
3FGL J1418.6-6058	LAT PSR J1418-6058	3.10352e-10	

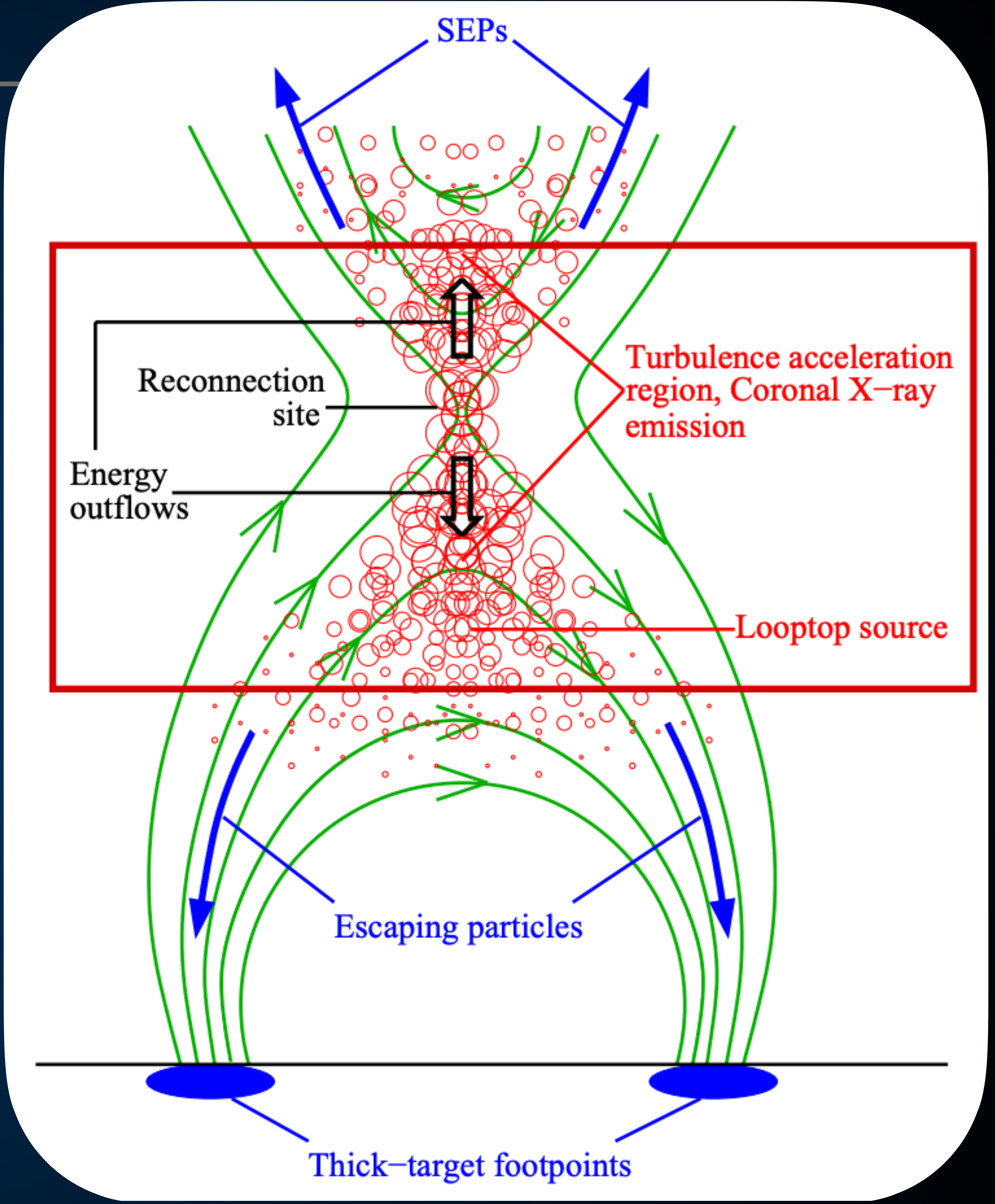
Why Gamma-Rays?



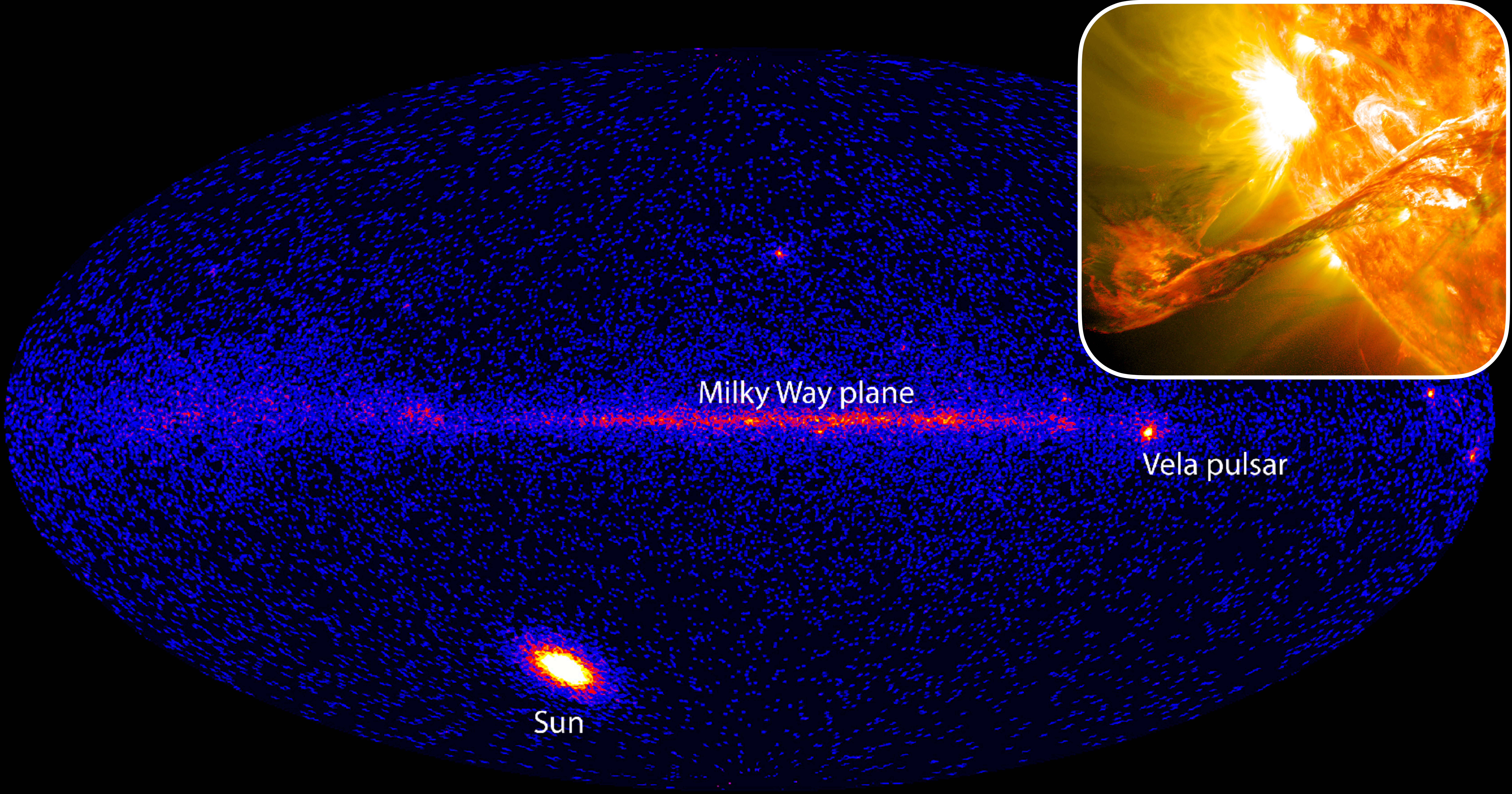
How are solar gamma-rays produced?

Gamma Rays - How?

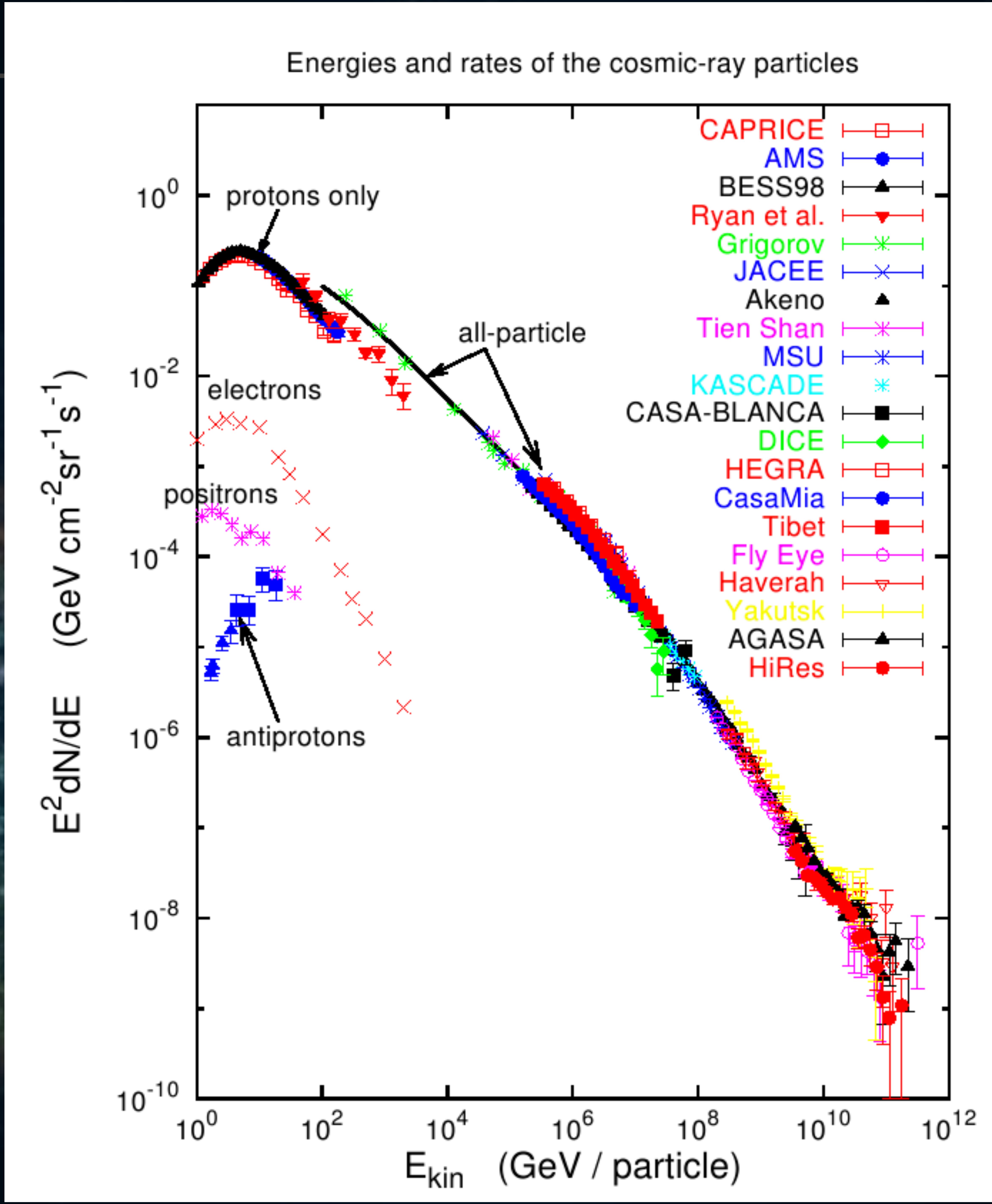
- **Solar Flares and Reconnection events.**



Petrosian (2016; 1605.04022)

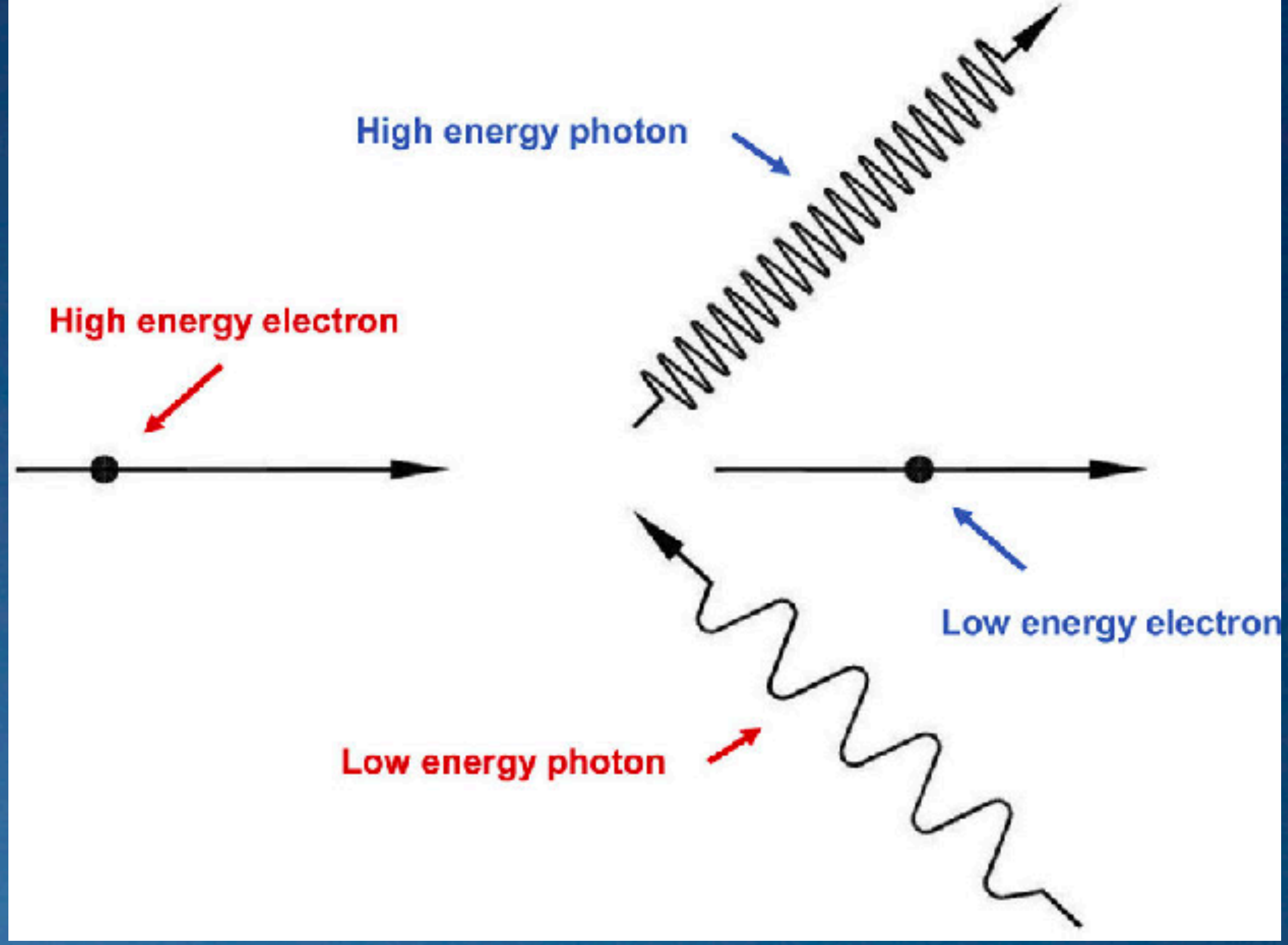


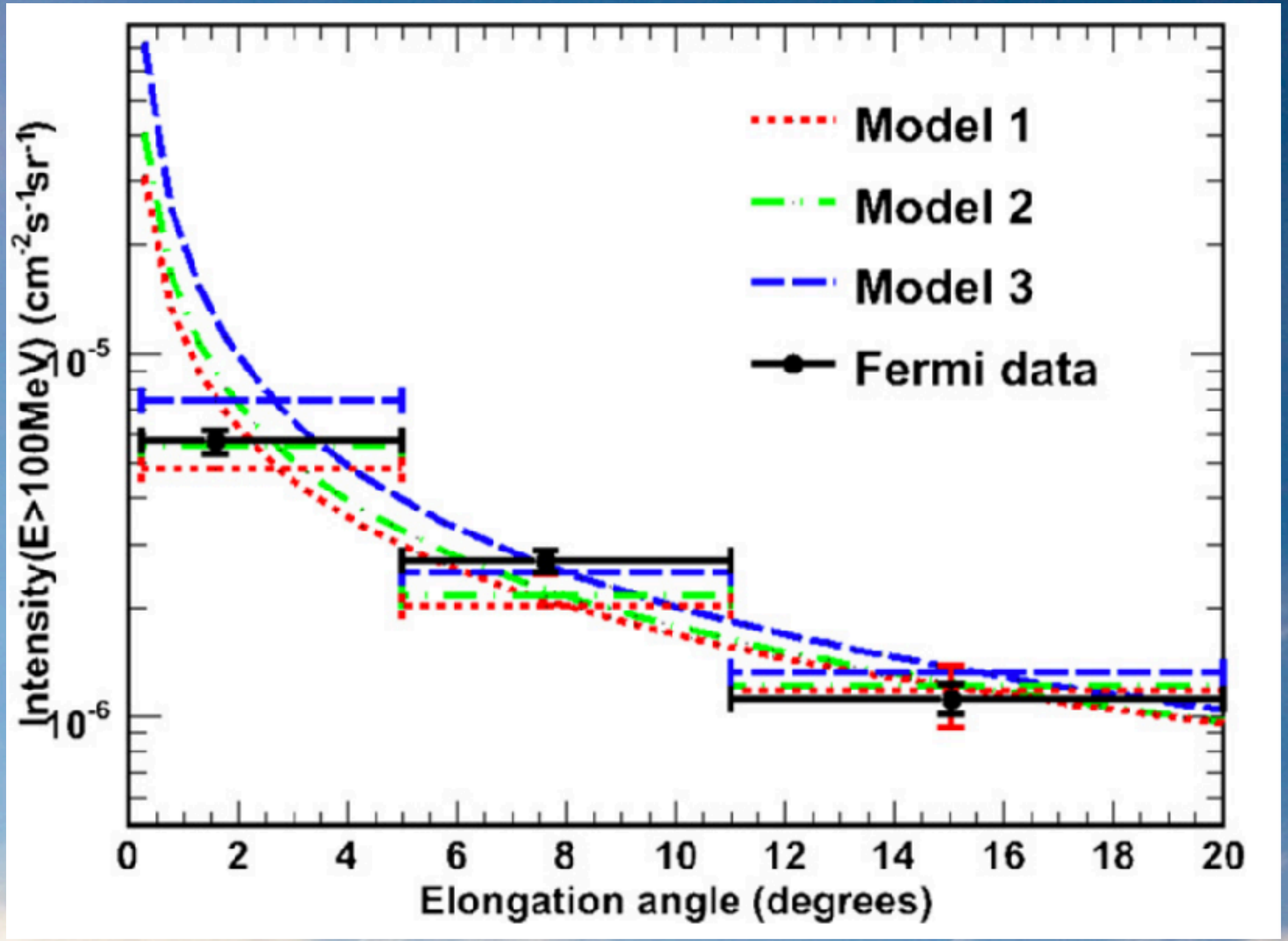
Solar Flare gamma-rays are low energy (E_{max} = 4 GeV)

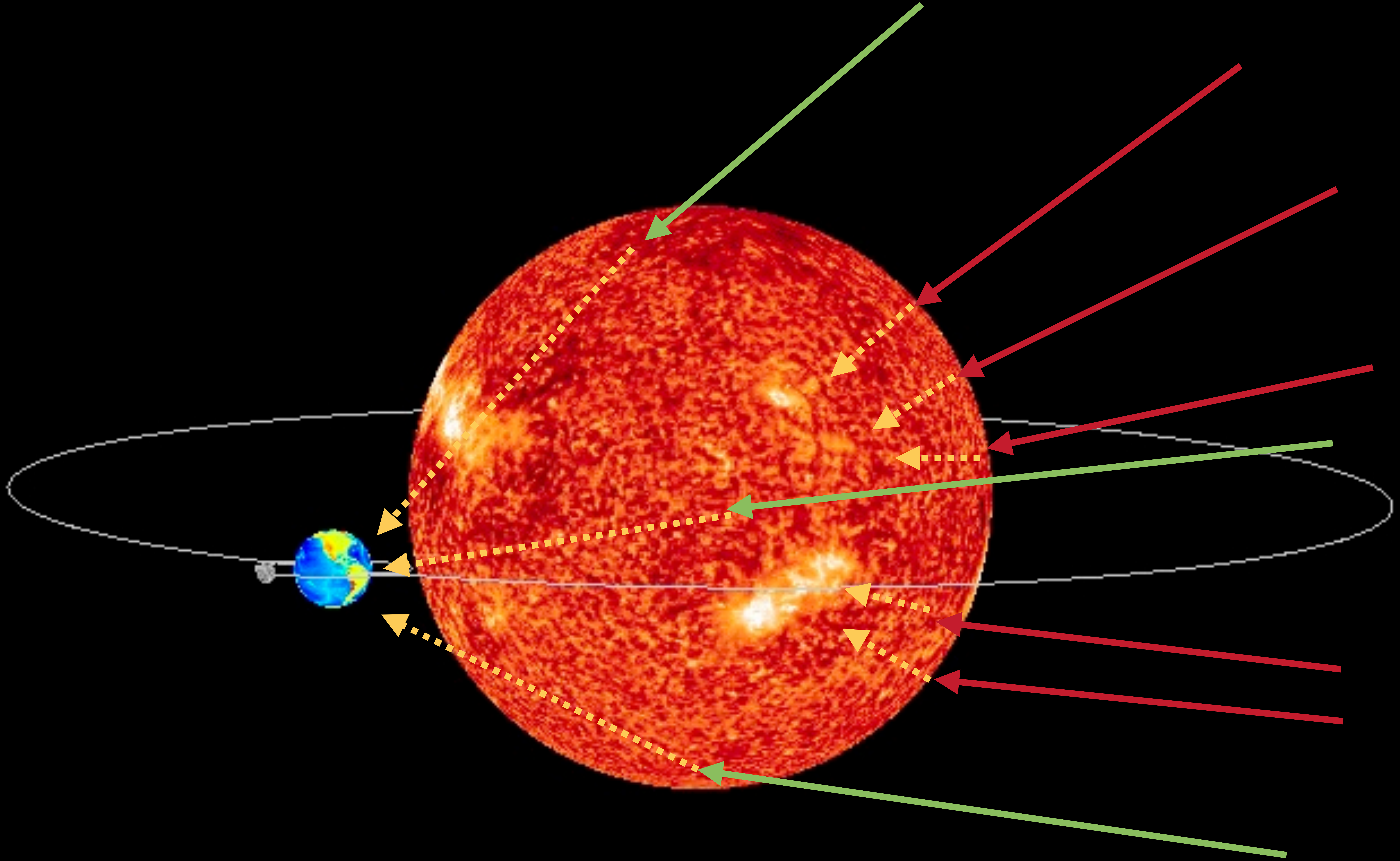


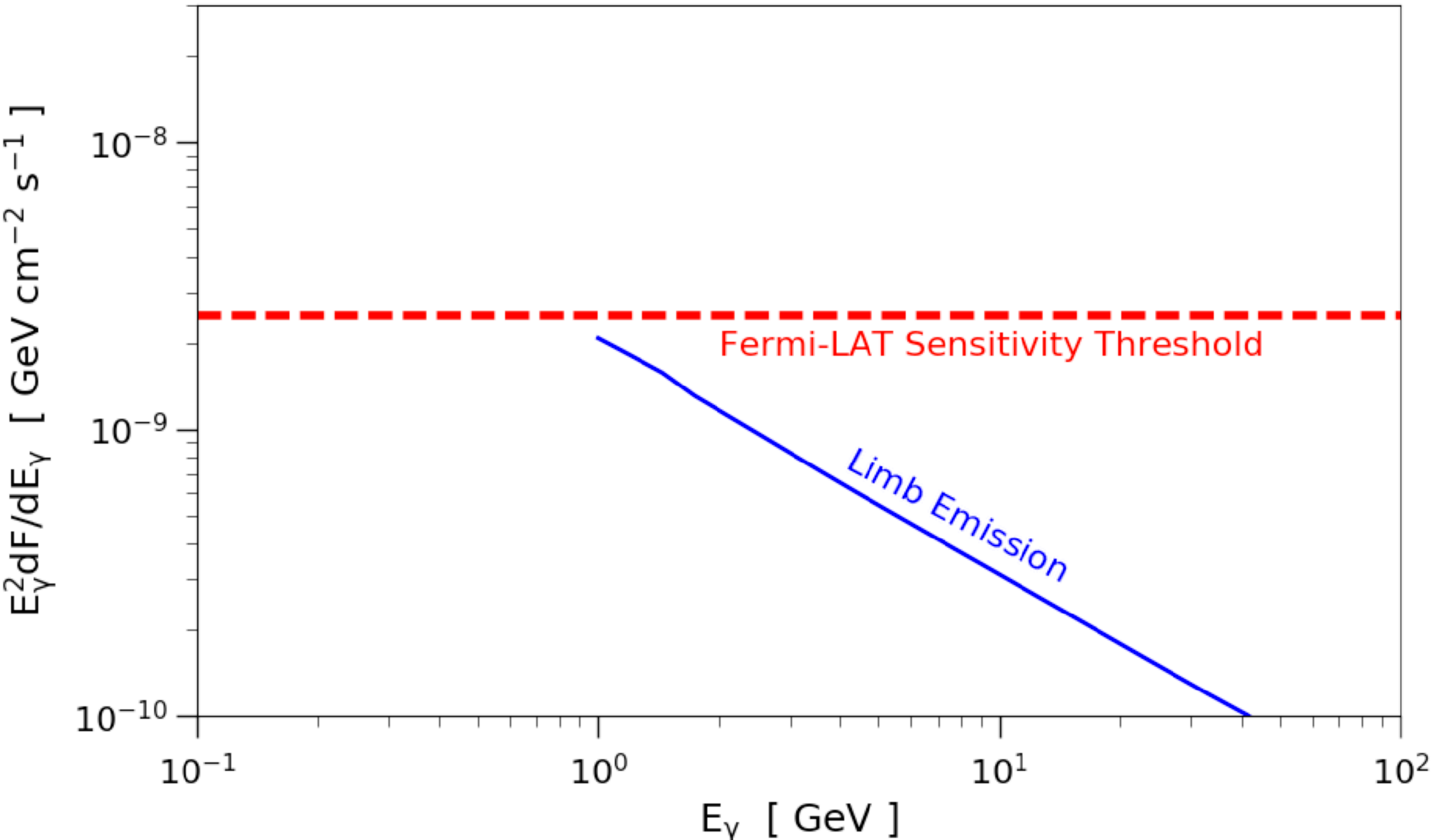
Energies and rates of the cosmic-ray particles
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
E^2dN/dE (GeV cm^{-2}sr^{-1}s^{-1})
E_{kin} (GeV / particle)


Heliosphere
Interstellar space
Heliopause
Voyager-1
Sun
Solar wind
Termination shock
Cosmic rays

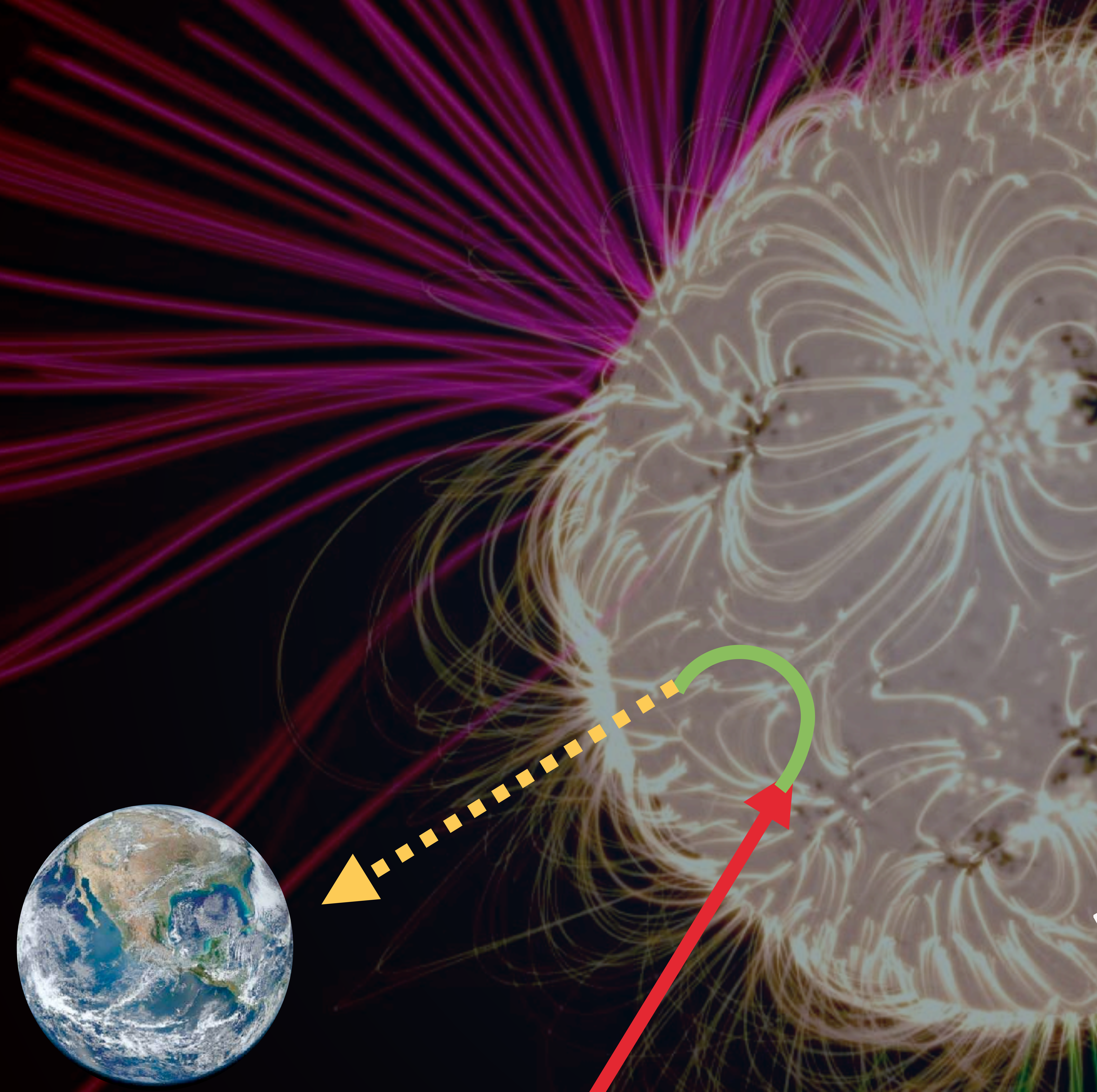

High energy photon
High energy electron
Low energy electron
Low energy photon


Model 1
Model 2
Model 3
Fermi data
Intensity(E>100MeV) (cm^{-2}s^{-1}sr^{-1})
10^{-5}
10^{-6}
0 2 4 6 8 10 12 14 16 18 20
Elongation angle (degrees)





$E_\gamma^2 dF/dE_\gamma$ [GeV cm^{-2} s^{-1}]
10^{-8}
10^{-9}
10^{-10}
Fermi-LAT Sensitivity Threshold
Limb Emission
10^{-1}
10^{0}
10^{1}
10^{2}
E_γ [GeV]



THE ASTROPHYSICAL JOURNAL, 382:652–666, 1991 December 1

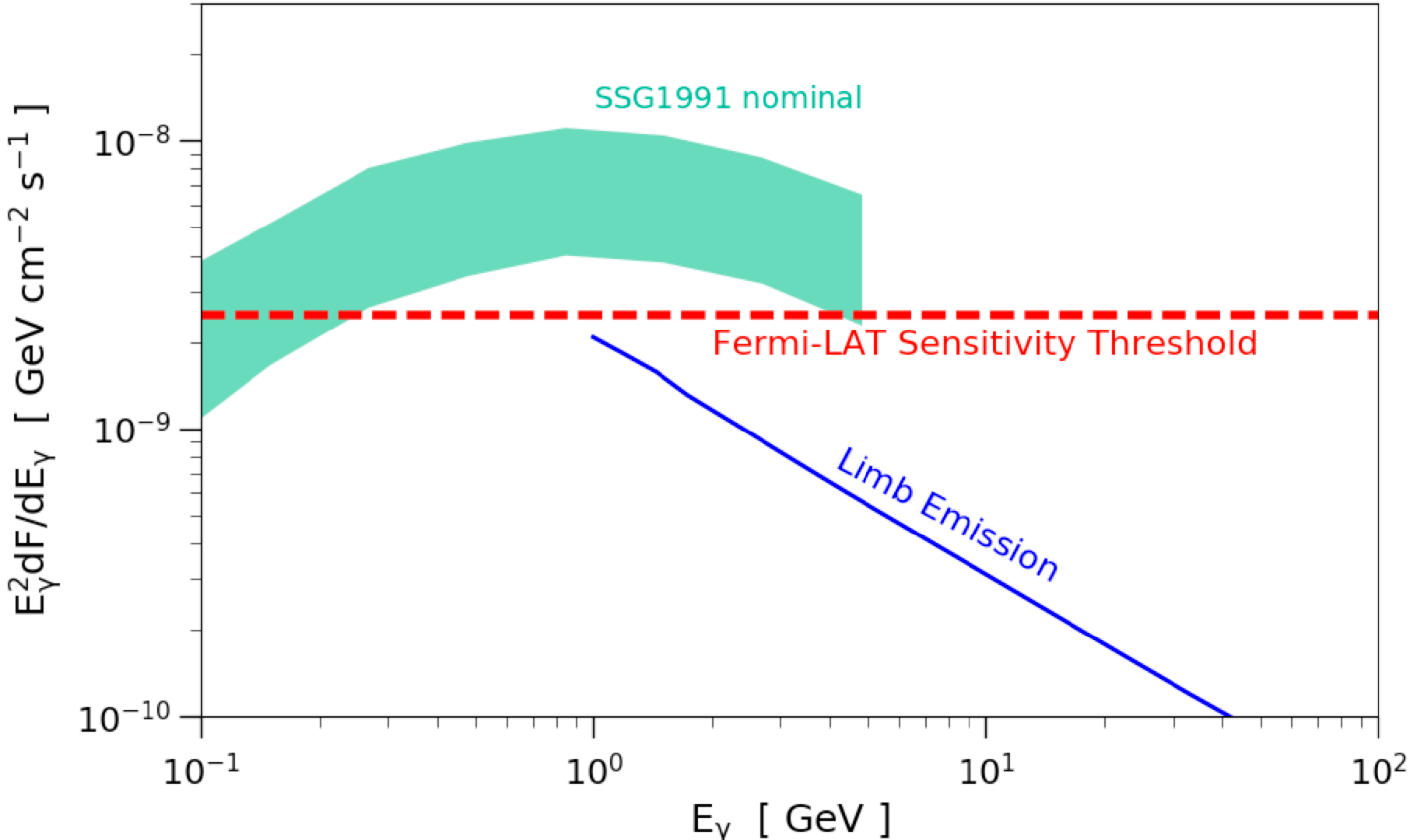
SIGNATURES OF COSMIC-RAY INTERACTIONS ON THE SOLAR SURFACE

D. SECKEL, TODOR STANEV, AND T. K. GAISSER
Bartol Research Institute, University of Delaware, Newark, DE 19716
Received 1991 March 21; accepted 1991 June 5

ABSTRACT

We estimate the fluxes of neutrinos, gamma rays, antiprotons, neutrons, and antineutrons that
...ions of high-energy Galactic cosmic rays with the solar atmosphere. The results are sensitive
...ut cosmic-ray transport in the magnetic fields of the inner solar system. The high-energ
...rvable by the Gamma Ray Observatory. The neutrino flux should produce less
...t generation of neutrino telescopes. The antiproton flux is unobservable a
...eutron and antineutron fluxes are detectable only if neutrons prod
...discriminated against.
...neral — gamma rays: general — neutrinos — Sun: activ

$$r_g/\text{meter} = 3.3 \times \frac{(\gamma mc^2/\text{GeV})(v_\perp/c)}{(|q|/e)(B/\text{Tesla})}$$



SSG1991 nominal
Fermi-LAT Sensitivity Threshold
Limb Emission
$E_\gamma^2 dF/dE_\gamma$ [GeV cm^{-2} s^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-1}
10^{0}
10^{1}
10^{2}
E_γ [GeV]

First Observation of Time Variation in the Solar-Disk Gamma-Ray Flux with Fermi

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(Dated: 7 November 2015)

The solar disk is a bright gamma-ray source. Surprisingly, its flux is about one order of magnitude higher than predicted. As a first step toward understanding the physical origin of this discrepancy, we perform a new analysis in 1–100 GeV using 6 years of public Fermi-LAT data. Compared to the previous analysis by the Fermi Collaboration, who analyzed 1.5 years of data and detected the solar disk in 0.1–10 GeV, we find two new and significant results: 1. In the 1–10 GeV flux (detected at $> 5\sigma$), we discover a significant time variation that anticorrelates with solar activity. 2. We detect gamma rays in 10–30 GeV at $> 5\sigma$, and in 30–100 GeV at $> 2\sigma$. The time variation strongly indicates that solar-disk gamma rays are induced by cosmic rays and that solar atmospheric magnetic fields play an important role. Our results provide essential clues for understanding the underlying gamma-ray production processes, which may allow new probes of solar atmospheric magnetic fields, cosmic rays in the solar system, and possible new physics. Finally, we show that the Sun is a promising new target for ground-based TeV gamma-ray telescopes such as HAWC and LHAASO.

PACS numbers: 95.85.Pw, 96.50.S-, 13.85.Qk, 96.50.Vg

I. INTRODUCTION

The Sun is well studied and understood with a broad set of messengers at different energies. For example, the optical photon and MeV neutrino spectra confirm a de-

angular size of the Sun ($\simeq 0.5°$); we denote it (plus any potential non-cosmic-ray contribution) as the solar-disk component.

Theoretical estimation of both components requires taking into account the effects of solar magnetic activity.

Unexpected Dip in the Solar Gamma-Ray Spectrum

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(Dated: 9th May 2018)

The solar disk is a bright source of multi-GeV gamma rays, due to the interactions of hadronic cosmic rays with the solar atmosphere. However, the underlying production mechanism is not understood, except that its efficiency must be greatly enhanced by magnetic fields that redirect some cosmic rays from ingoing to outgoing before they interact. To elucidate the nature of this emission, we perform a new analysis of solar atmospheric gamma rays with 9 years of Fermi-LAT data, which spans nearly the full 11-year solar cycle. We detect significant gamma-ray emission from the solar disk from 1 GeV up to $\gtrsim$ 200 GeV. The overall gamma-ray spectrum is much harder ($\sim E_\gamma^{-2.2}$) than the cosmic-ray spectrum ($\sim E_{\rm CR}^{-2.7}$). We find a clear anticorrelation between the solar cycle phase and the gamma-ray flux between 1–10 GeV. Surprisingly, we observe a spectral dip between ∼30–50 GeV in an otherwise power-law spectrum. This was not predicted, is not understood, and may provide crucial clues to the gamma-ray emission mechanism. The flux above 100 GeV, which is brightest during the solar minimum, poses exciting opportunities for HAWC, LHAASO, IceCube, and KM3NeT.

I. INTRODUCTION

particles accelerated during energetic solar events, such as solar flares and coronal mass ejections [11], can pro-

Evidence for a New Component of High-Energy Solar Gamma-Ray Production

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The observed multi-GeV gamma-ray emission from the solar disk — sourced by hadronic cosmic rays interacting with gas, and affected by complex magnetic fields — is not understood. Utilizing an improved analysis of the Fermi-LAT data that includes the first resolved imaging of the disk, we find strong evidence that this emission is produced by two separate mechanisms. Between 2010–2017 (the rise to and fall from solar maximum), the gamma-ray emission is dominated by a polar component. Between 2008–2009 (solar minimum) this component remains present, but the total emission is instead dominated by a new equatorial component with a brighter flux and harder spectrum. Most strikingly, although 6 gamma rays above 100 GeV are observed during the 1.4 years of solar minimum, none are observed during the next 7.8 years. These features, along with a 30–50 GeV spectral dip which will be discussed in a companion paper, were not anticipated by theory. To understand the underlying physics, Fermi and HAWC observations of the imminent Cycle 25 solar minimum are crucial.

The Sun is a bright source of multi-GeV γ-rays, with emission observed both from its halo — due to cosmic-rays electrons interacting with solar photons — and its disk — due to hadronic cosmic rays (mostly protons) interacting with solar gas. (Emission from solar particle acceleration is only bright during flares and has not been observed above 4 GeV [1–8].) Although the halo emission [9] agrees with theory [10–12], the disk emission does not, and hence is our focus.

Until recently, the most extensive analysis of solar disk

is detected up to $\sim$30 GeV. Most significantly, we discover a spectral dip between 30–50 GeV. This dip is unexpected and its origin is unknown. Here we extend the analyses of Refs. [13, 17] by going to higher energies, studying the time variation in a new way, and performing the first analysis of flux variations across the resolved solar disk. In the following, we detail our methodology, highlight key discoveries, and discuss their possible theoretical implications.

The importance of this work is manifold. Because the disk

First Observations of Solar Disk Gamma Rays over a Full Solar Cycle

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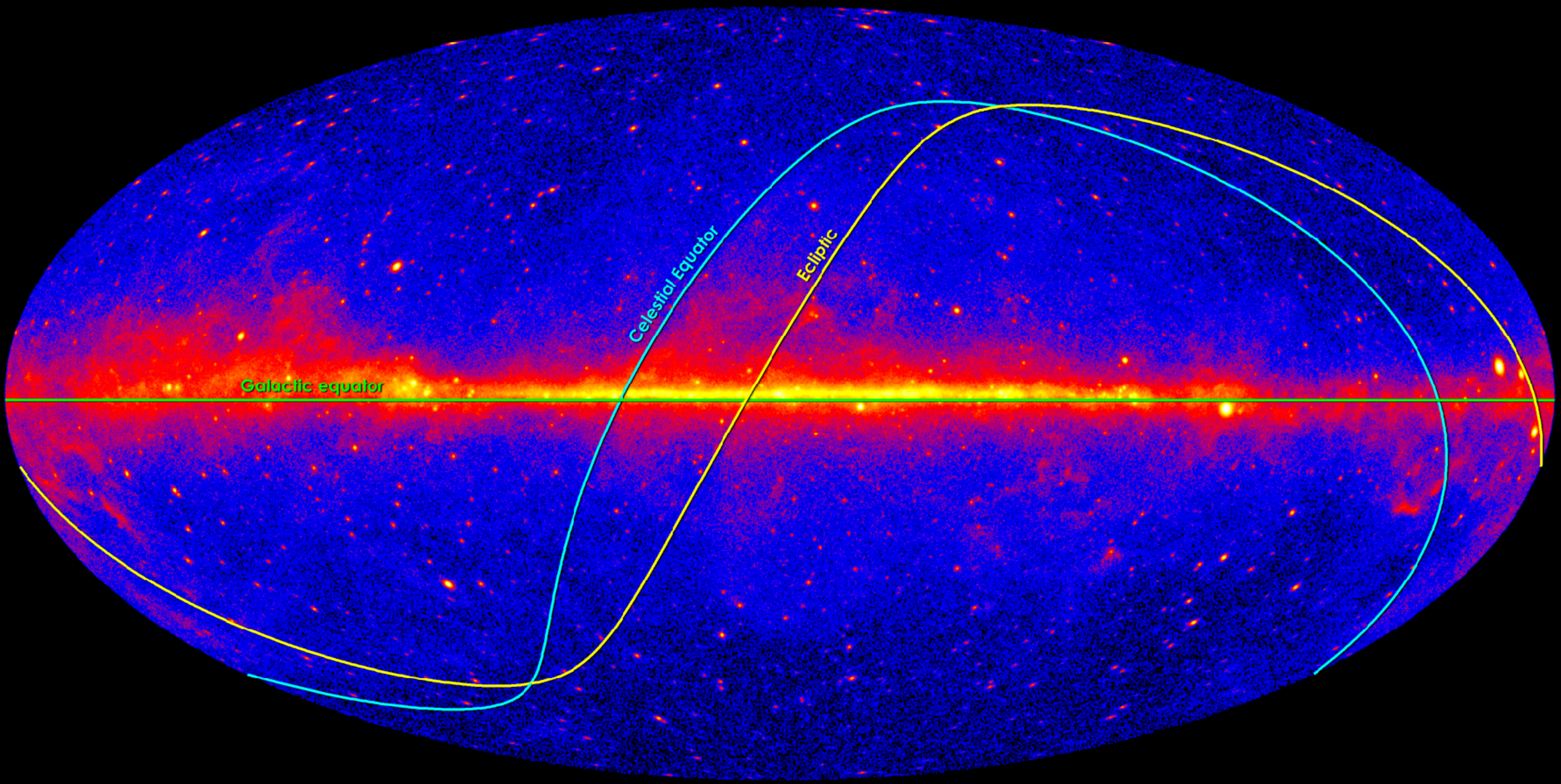
[5]*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA*

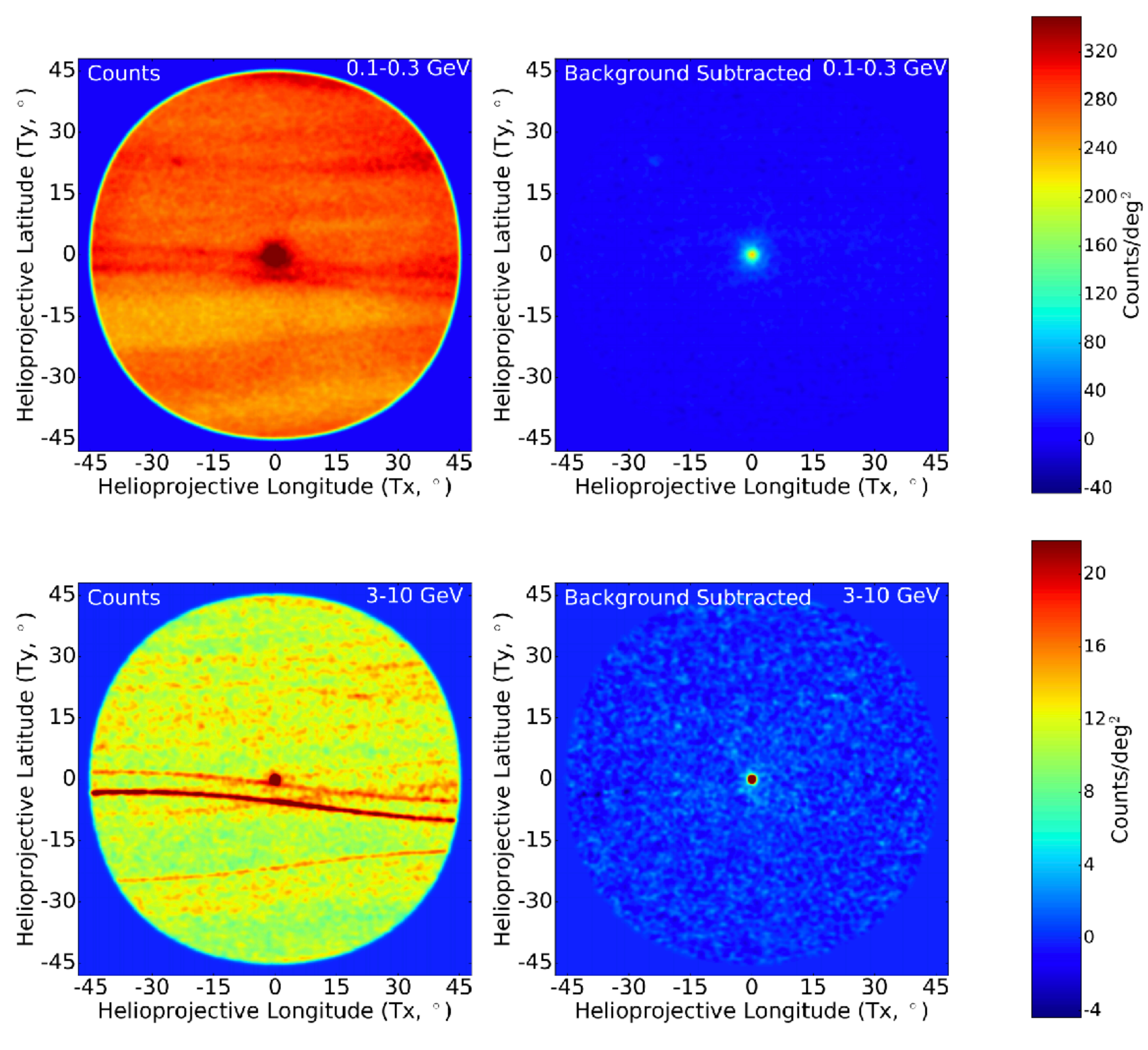
The solar disk is among the brightest γ-ray sources in the sky. It is also among the most mysterious. No existing model fully explains the luminosity, spectrum, time variability, and morphology of its emission. We perform the first analysis of solar-disk γ-rays over a full 11-year solar cycle, utilizing a powerful new method to differentiate solar signals from astrophysical backgrounds. We produce: (i) a robustly measured spectrum from 100 MeV to 100 GeV, reaching a precision of several percent in the 1–10 GeV range, (ii) new results on the anti-correlation between solar activity and γ-ray emission, (iii) strong constraints on short-timescale variability, ranging from hours to years, and (iv) new detections of the equatorial and polar morphologies of high-energy γ-rays. Intriguingly, we find no significant energy dependence in the time variability of solar-disk emission, indicating that strong magnetic-field effects close to the solar surface, rather than modulation throughout the heliosphere, must primarily control the flux and morphology of solar-disk emission.

I. INTRODUCTION

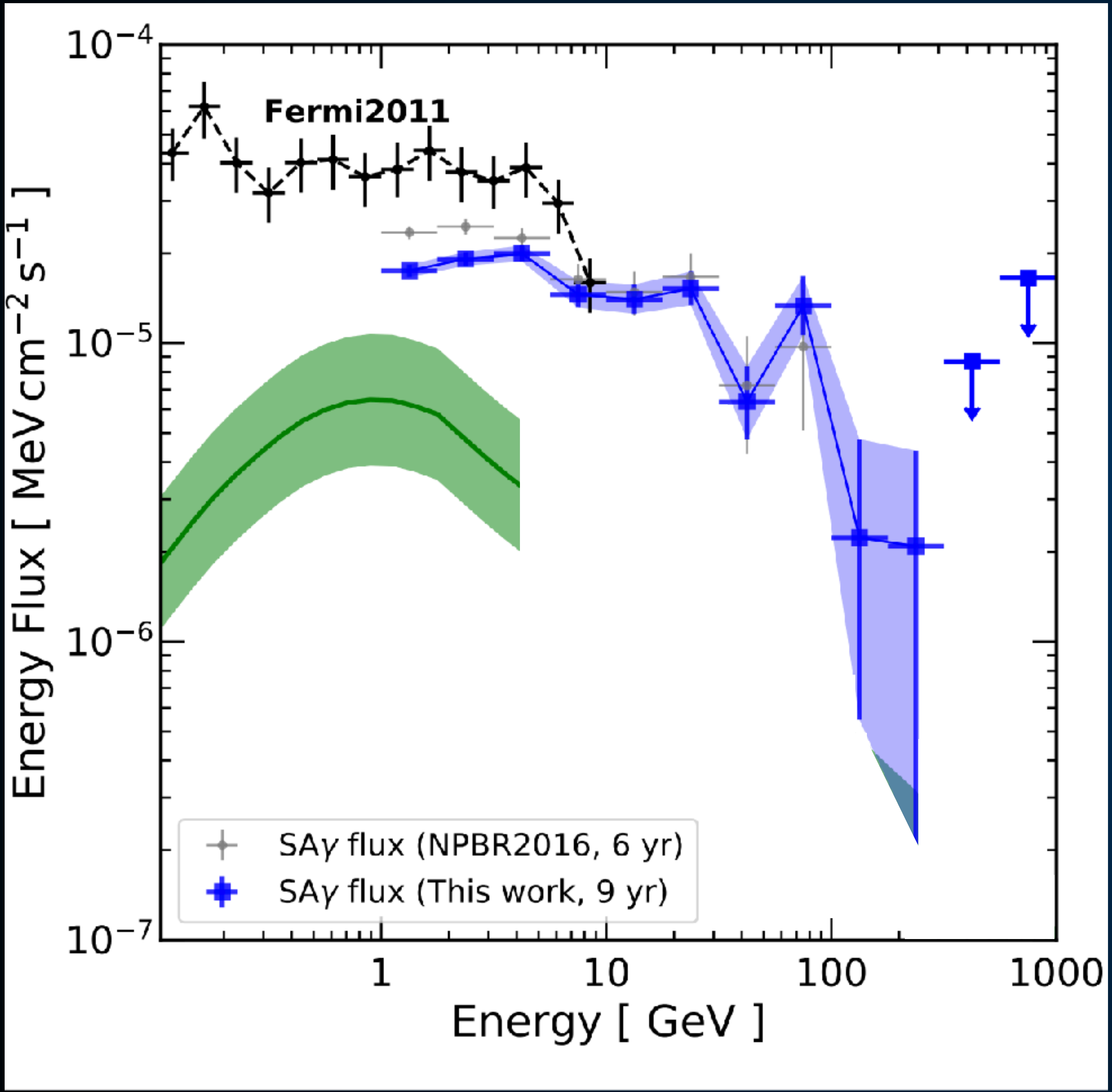
The Sun is a special astrophysical source. Its close proximity allows detailed studies critical to understanding other stars. The ability to spatially resolve solar emission is especially important for probing high-energy, nonthermal processes, which can be highly local. These processes reveal charged-particle

The Sun's γ-ray emission is dramatically affected by its magnetic fields. Without magnetic fields, the disk emission would have two components. At energies above $\sim$1 GeV, the γ-ray direction increasingly follows that of the parent cosmic ray. Accordingly, only cosmic rays that graze the solar surface can interact and have the γ-rays escape [14]. The corresponding emission from the solar limb is too faint to be observed


Celestial Equator
Ecliptic
Galactic equator


Counts
0.1-0.3 GeV
Background Subtracted
0.1-0.3 GeV
Counts
3-10 GeV
Background Subtracted
3-10 GeV
Helioprojective Latitude (Ty, °)
Helioprojective Longitude (Tx, °)
45
30
15
0
-15
-30
-45
Counts/deg^2
320
280
240
200
160
120
80
40
0
-40
20
16
12
8
4
0
-4

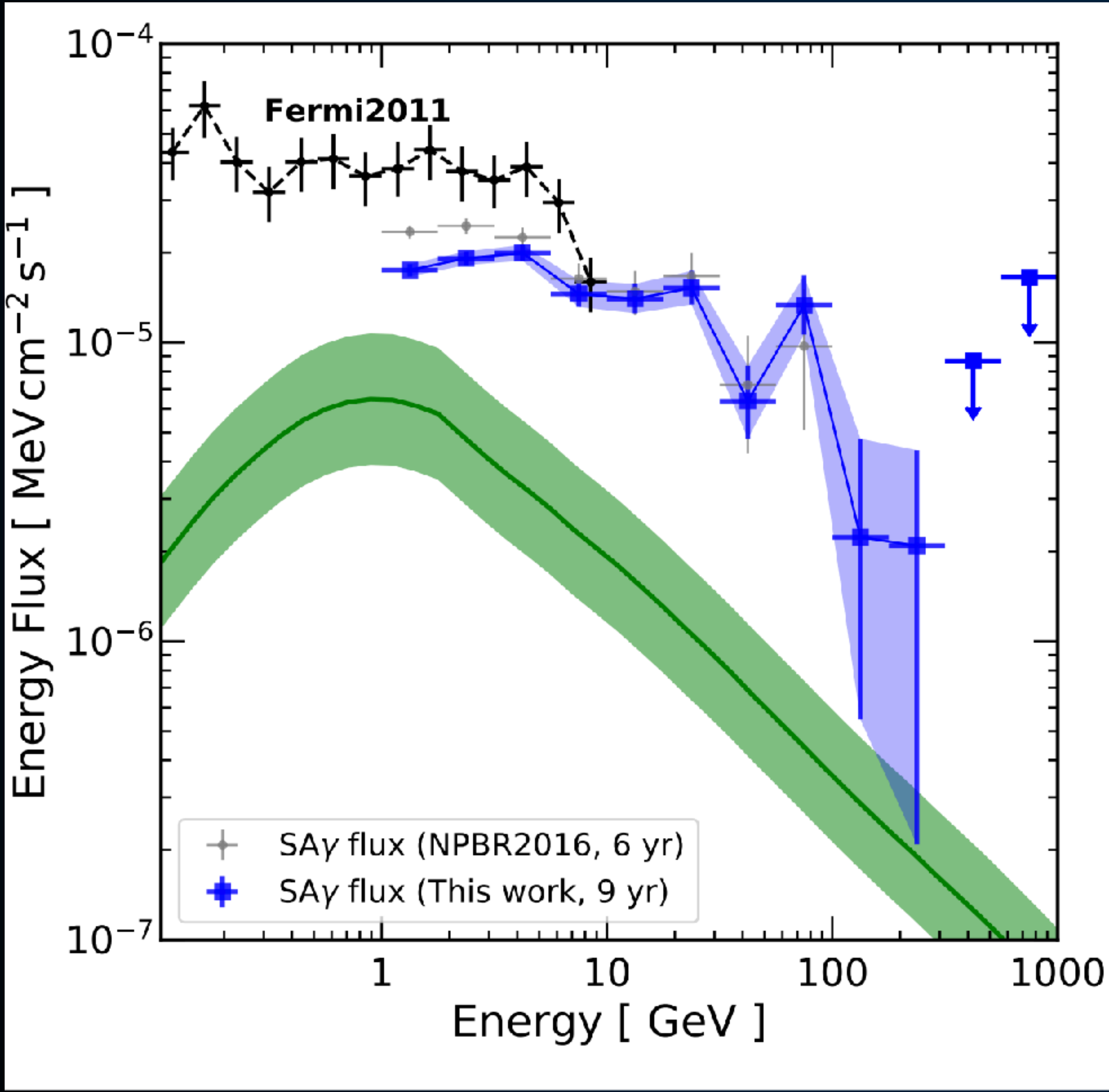
Our Limited Knowledge



Intensity

X

Our Limited Knowledge



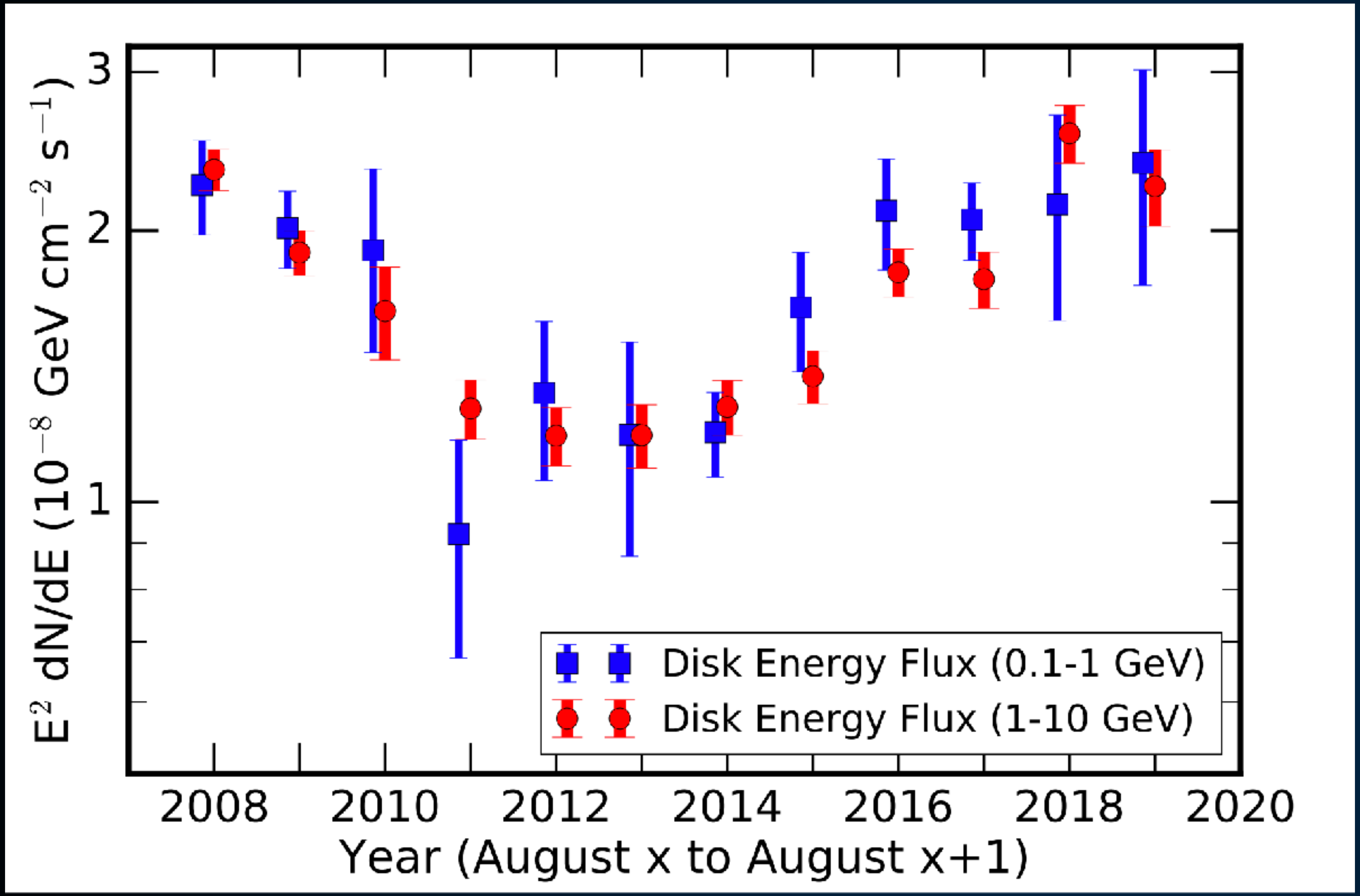
Intensity X

Spectrum X

Spectrum

Low-Energy Spectrum does not cut off either!

Our Limited Knowledge

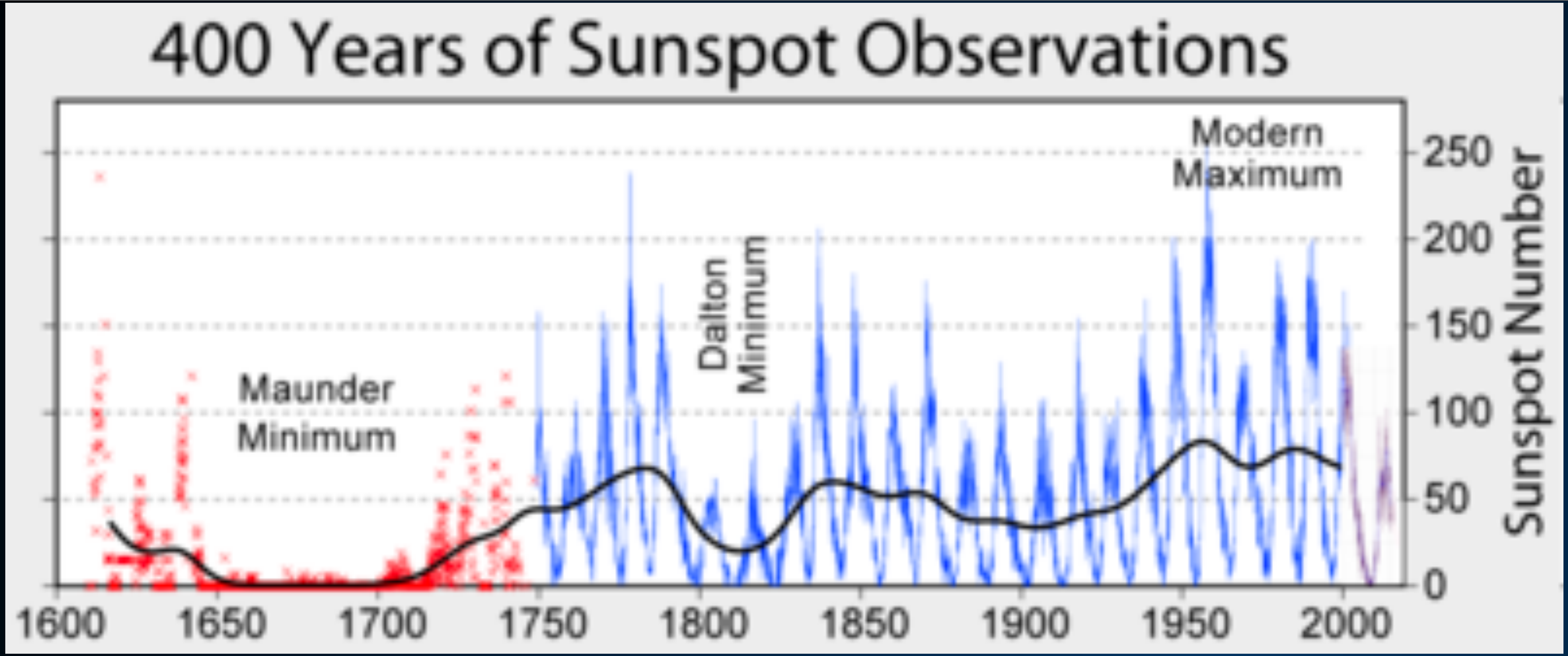


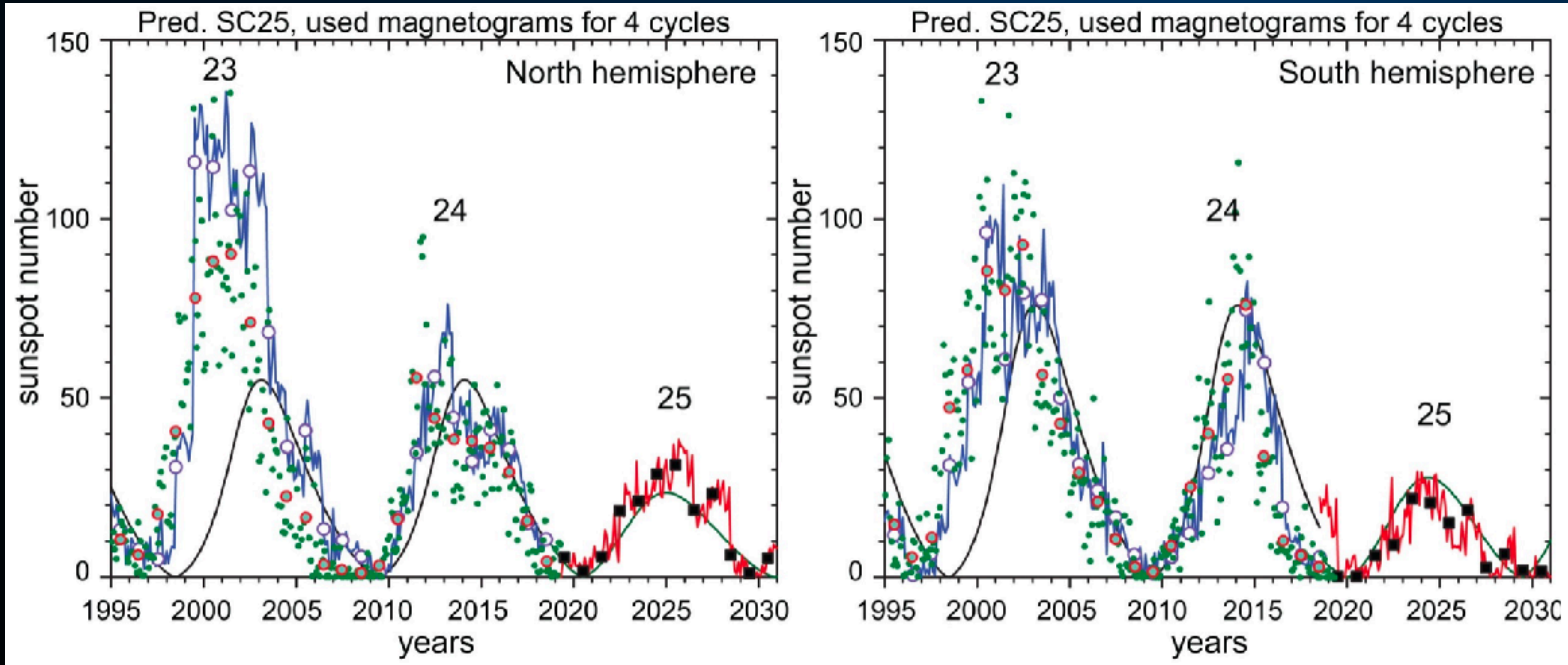
Intensity X

Spectrum X

Time Variability X

Our Limited Knowledge



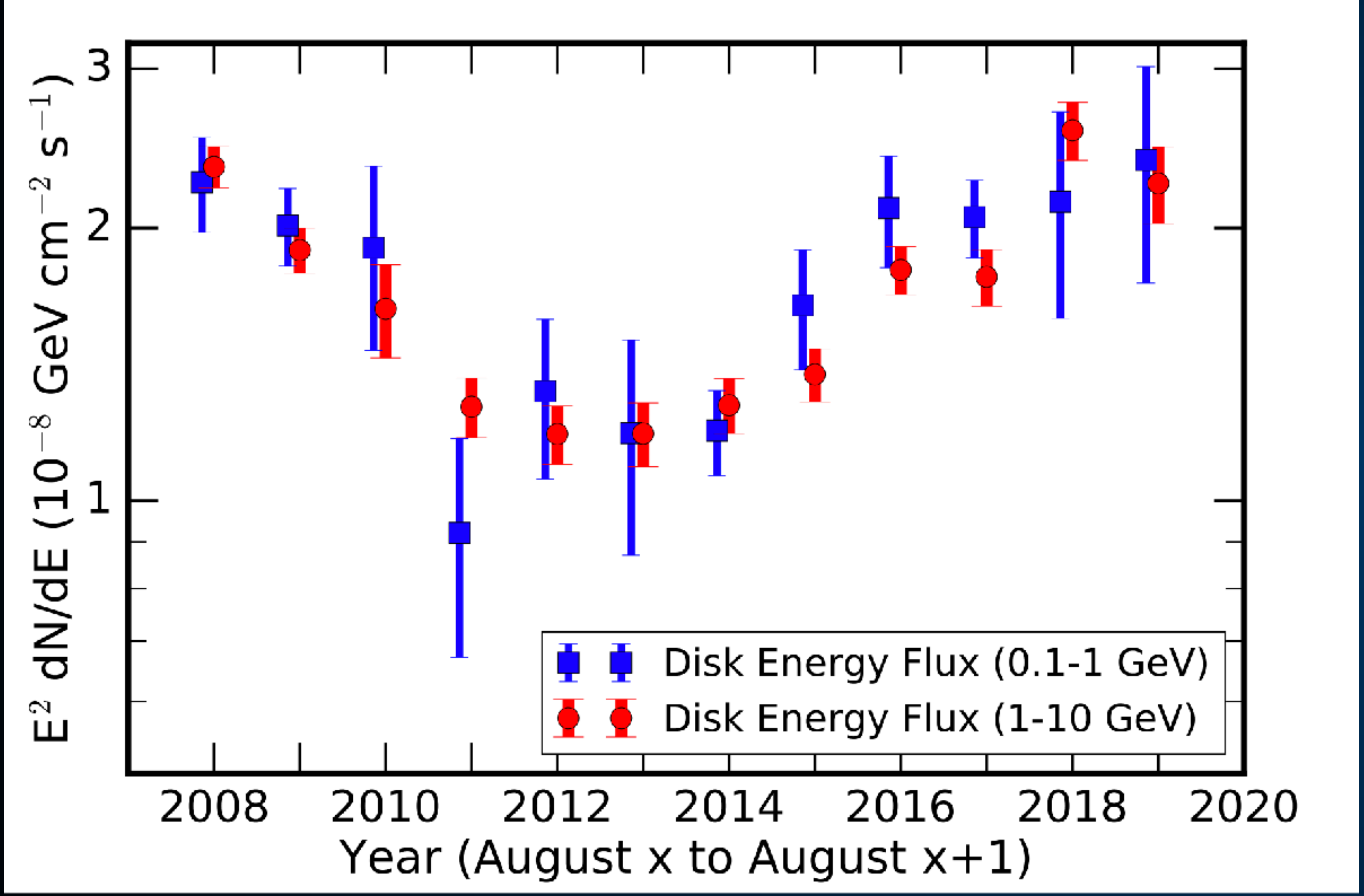


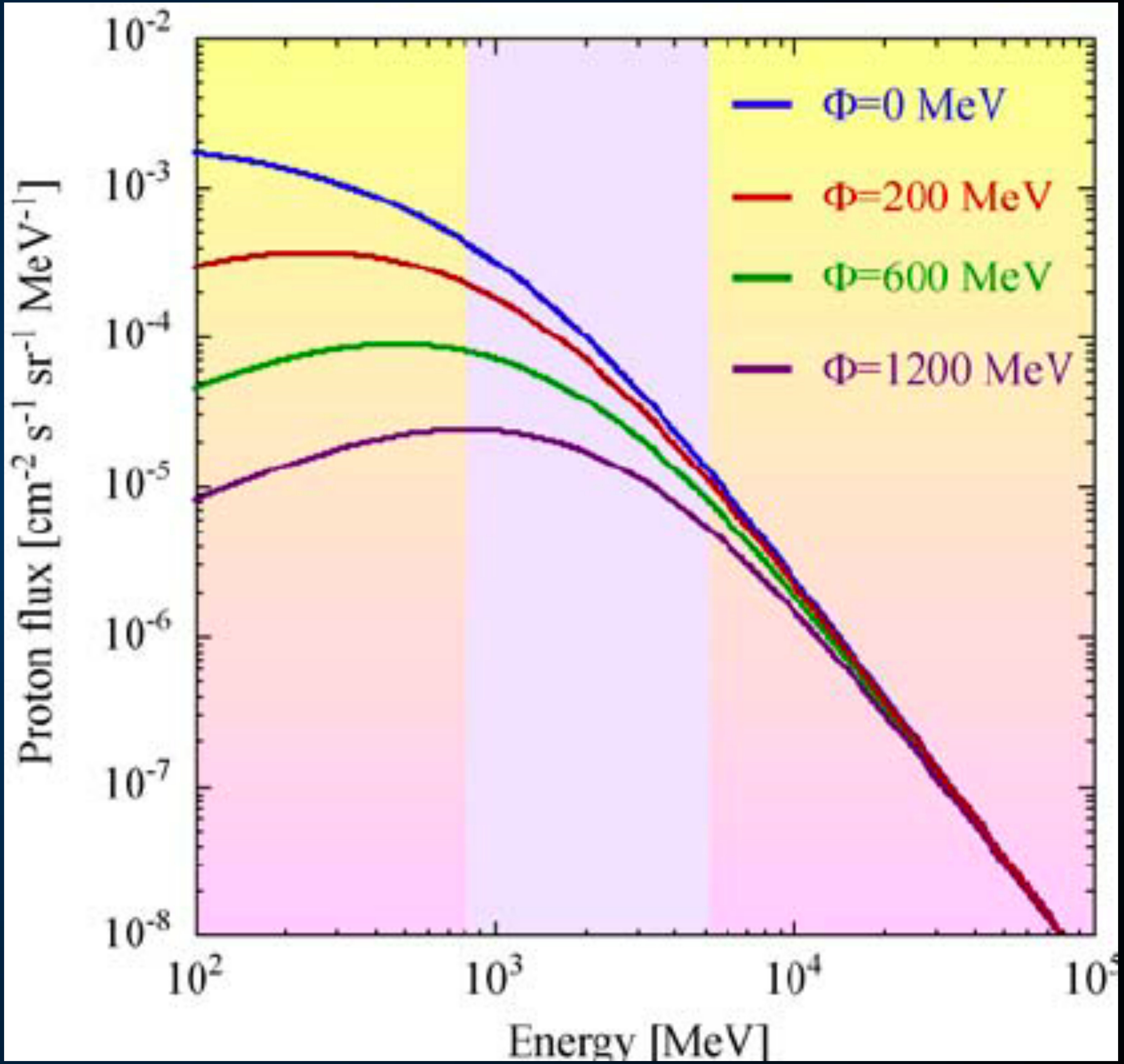
Intensity X

Spectrum X

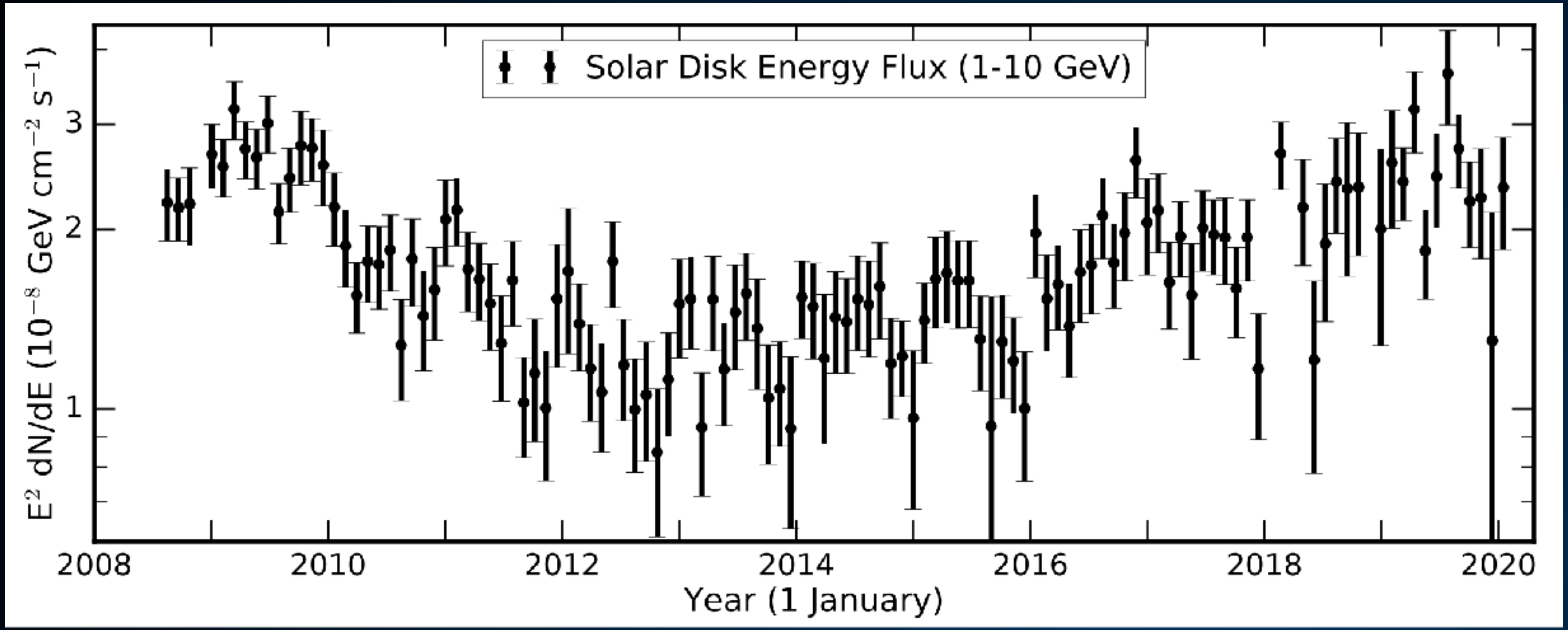
Time Variability X

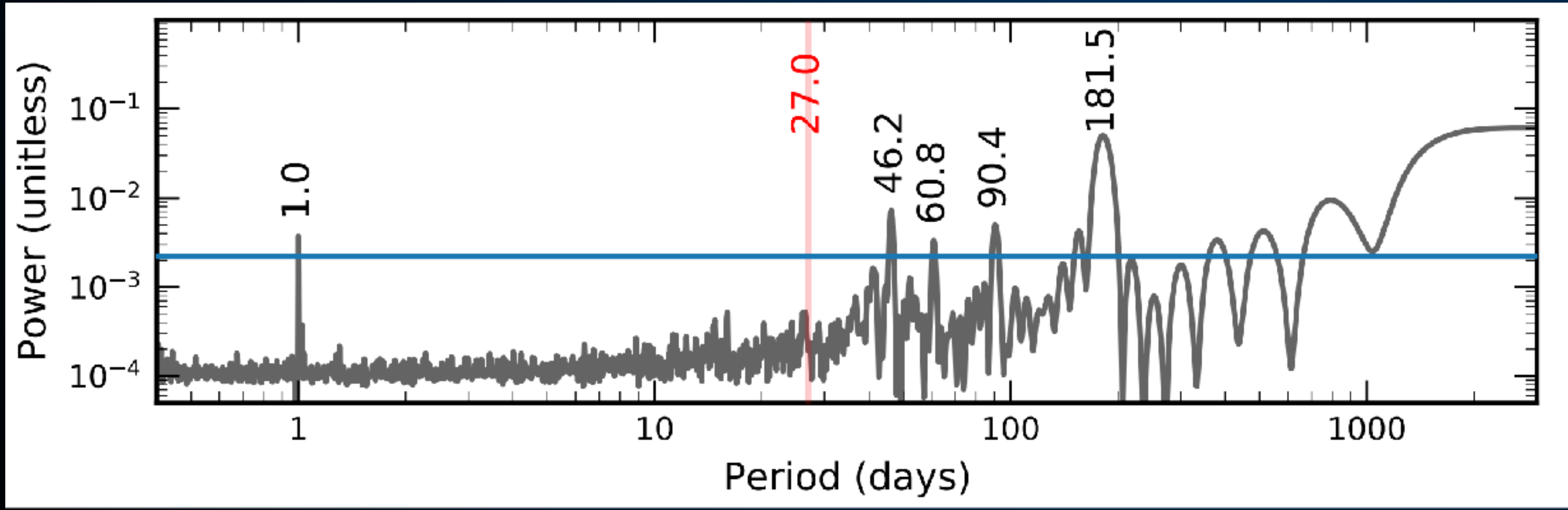
Our Limited Knowledge





Our Limited Knowledge



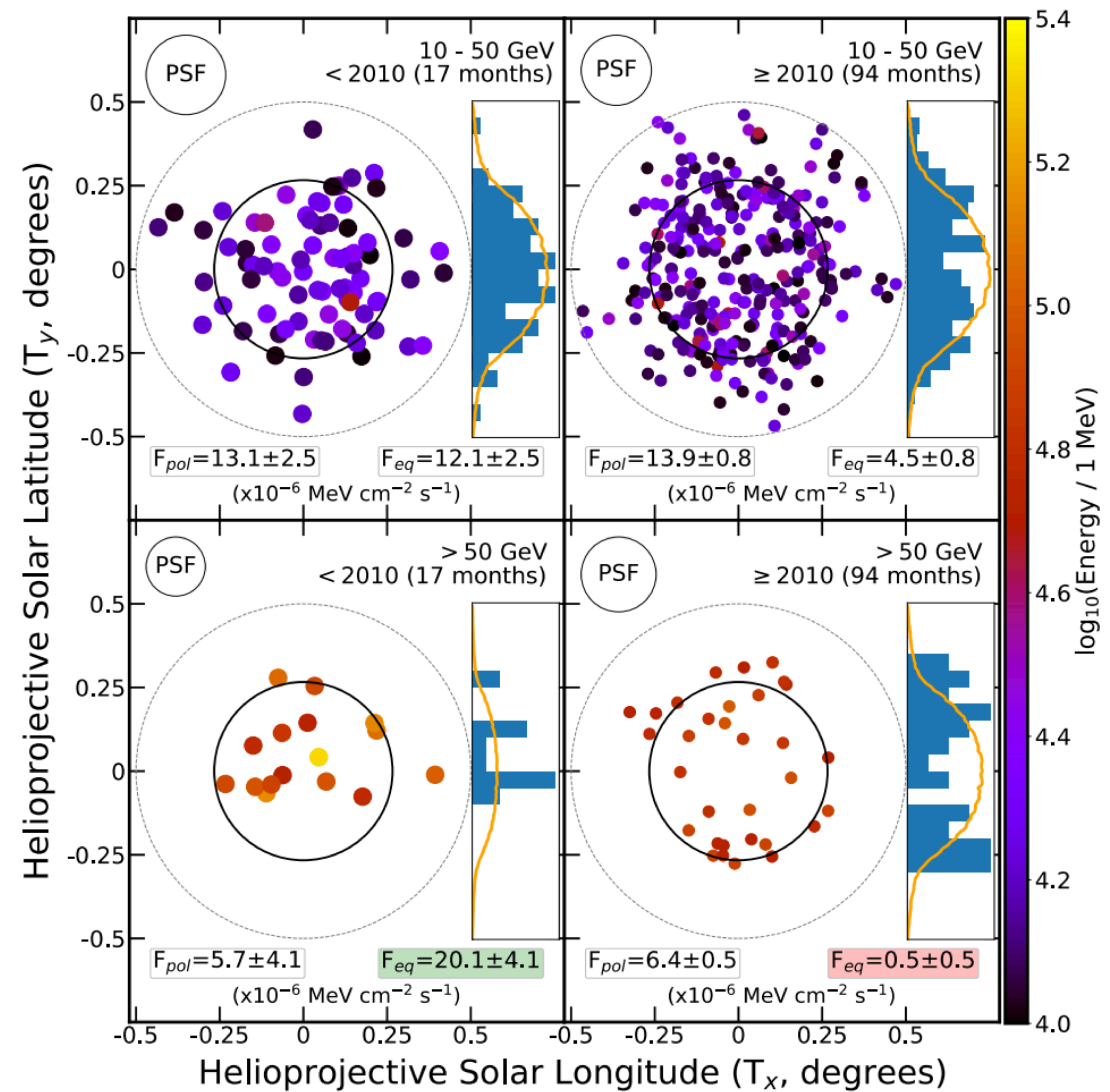


Intensity X

Spectrum X

Time Variability X

Our Limited Knowledge



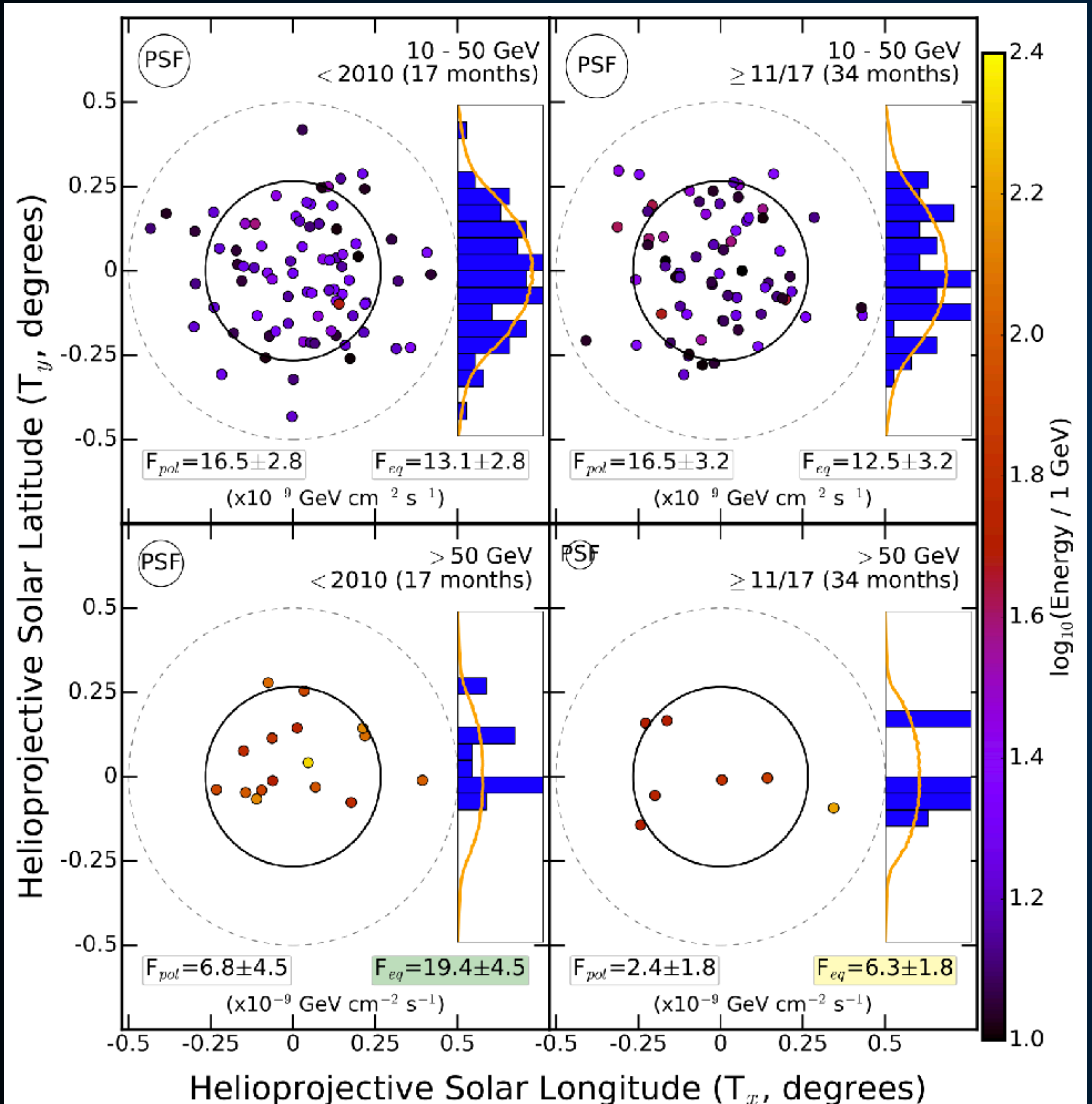
Intensity X

Spectrum X

Time Variability X

Morphology X

Our Limited Knowledge



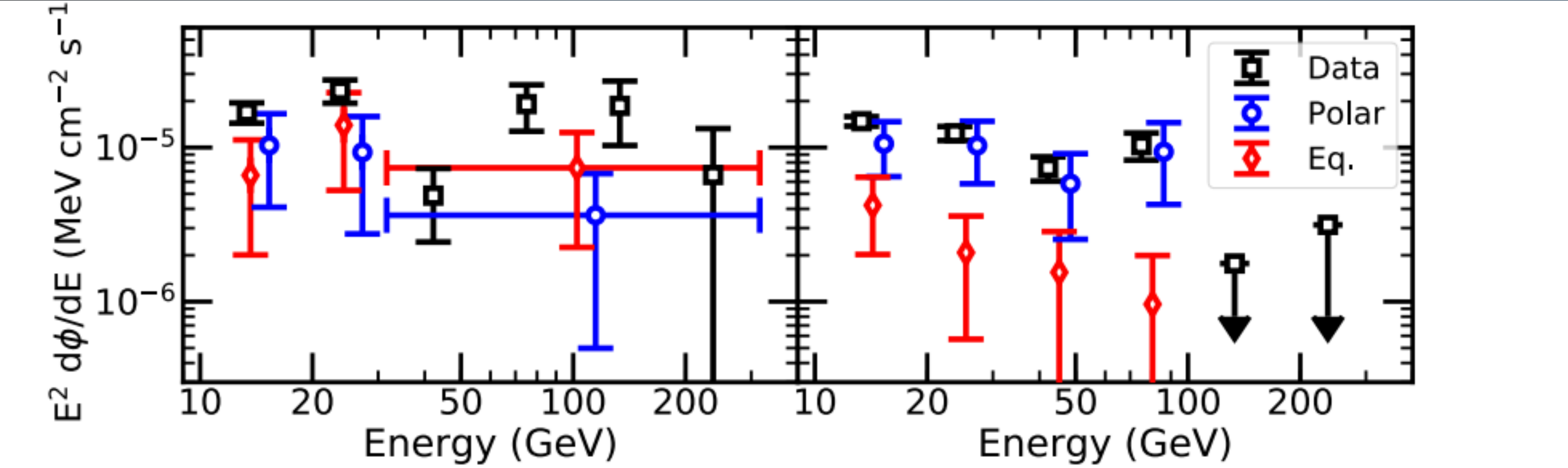
Intensity X

Spectrum X

Time Variability X

Morphology X

Our Limited Knowledge



Time (UTC)	Energy	R.A.	Dec	Solar Distance	Event Class	PSF Class	Edisp Class	P6	P7	BG Contribution
2008-11-09 03:47:51	212.8 GeV	224.497	-16.851	0.068°	UltraCleanVeto	PSF0	EDISP3	✓	✓	0.00050
2008-12-13 03:25:55	139.3 GeV	260.707	-23.243	0.126°	UltraCleanVeto	PSF2	EDISP1	X	X	0.00038
2008-12-13 07:04:07	103.3 GeV	260.346	-23.102	0.399°	UltraCleanVeto	PSF0	EDISP2	X	X	0.00052
2009-03-22 08:43:13	117.2 GeV	1.337	0.703	0.255°	UltraCleanVeto	PSF1	EDISP3	✓	✓	0.00027
2009-08-15 01:14:17	138.5 GeV	144.416	14.300	0.261°	UltraCleanVeto	PSF2	EDISP3	✓	✓	0.00021
2009-11-20 07:55:20	112.6 GeV	235.905	-19.473	0.288°	UltraCleanVeto	PSF1	EDISP1	X	X	0.00020
2008-12-24 05:41:53	226.9 GeV	272.899	-23.343	0.069°	UltraClean	PSF1	EDISP3	X	X	0.00128
2009-12-20 08:06:31	467.7 GeV	268.046	-23.177	0.338°	UltraCleanVeto	PSF1	EDISP0	X	X	0.00208

Intensity X

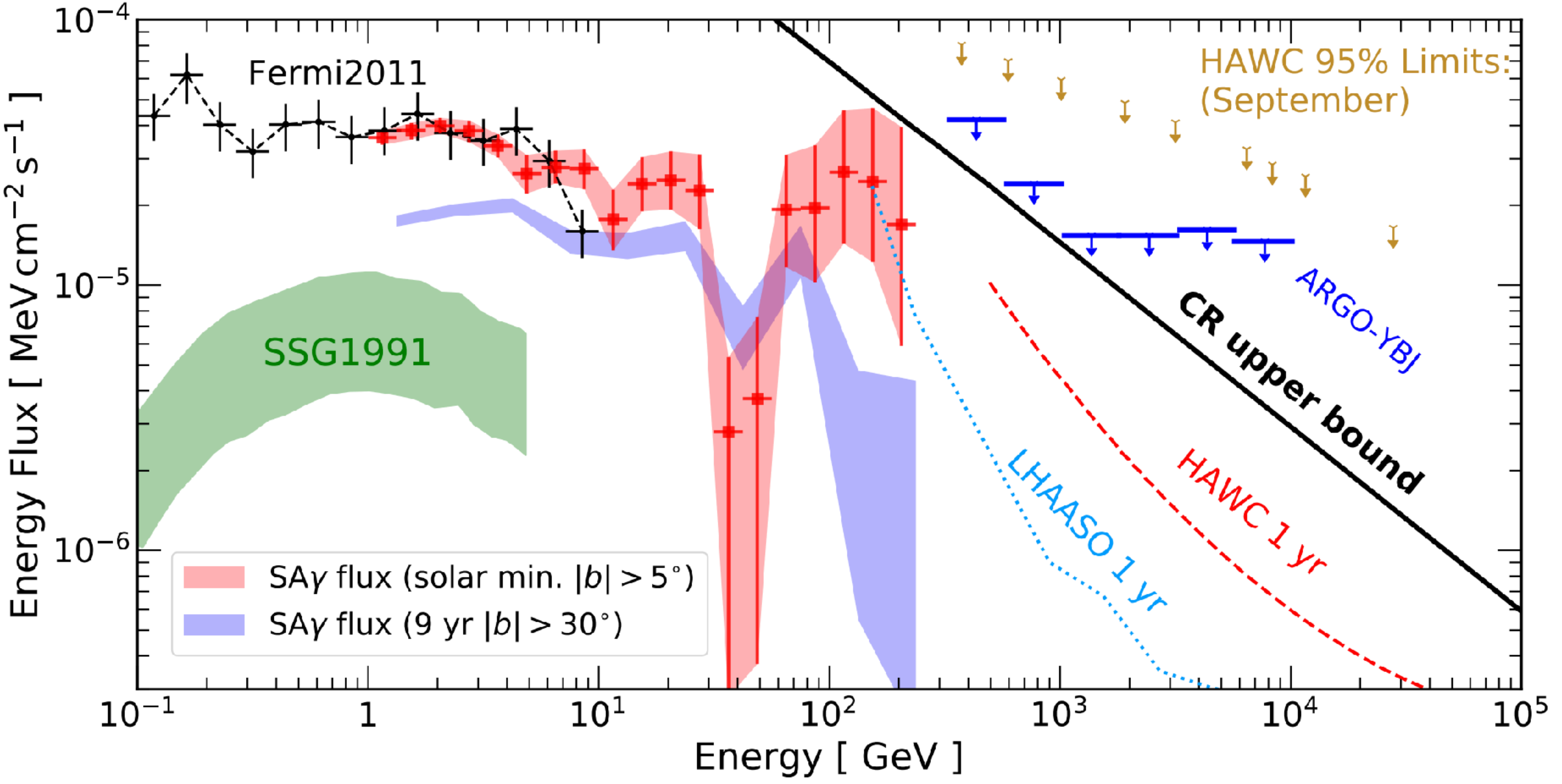
Spectrum X

Time Variability X

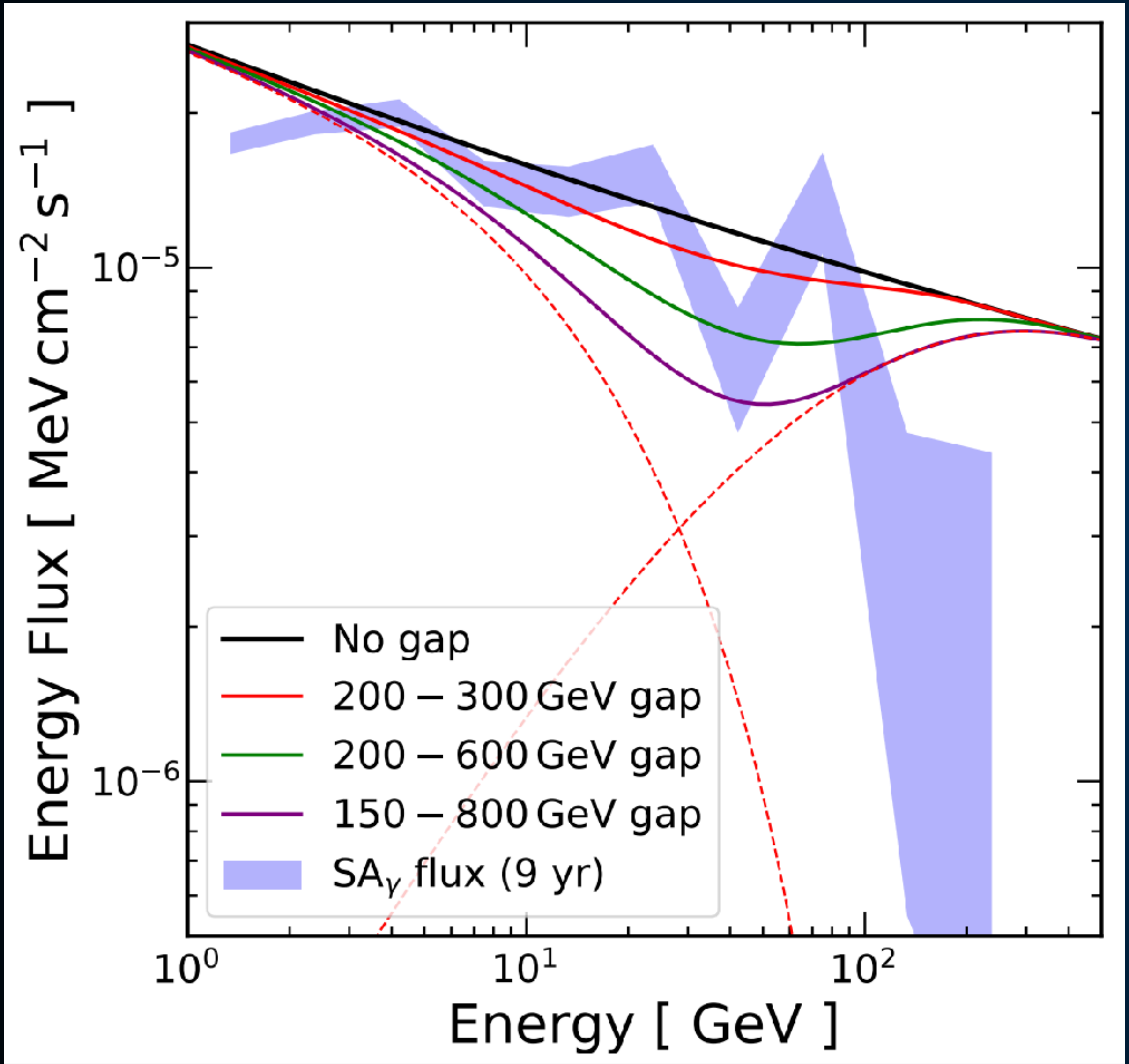
Morphology X

Spectral Variability X

Our Limited Knowledge

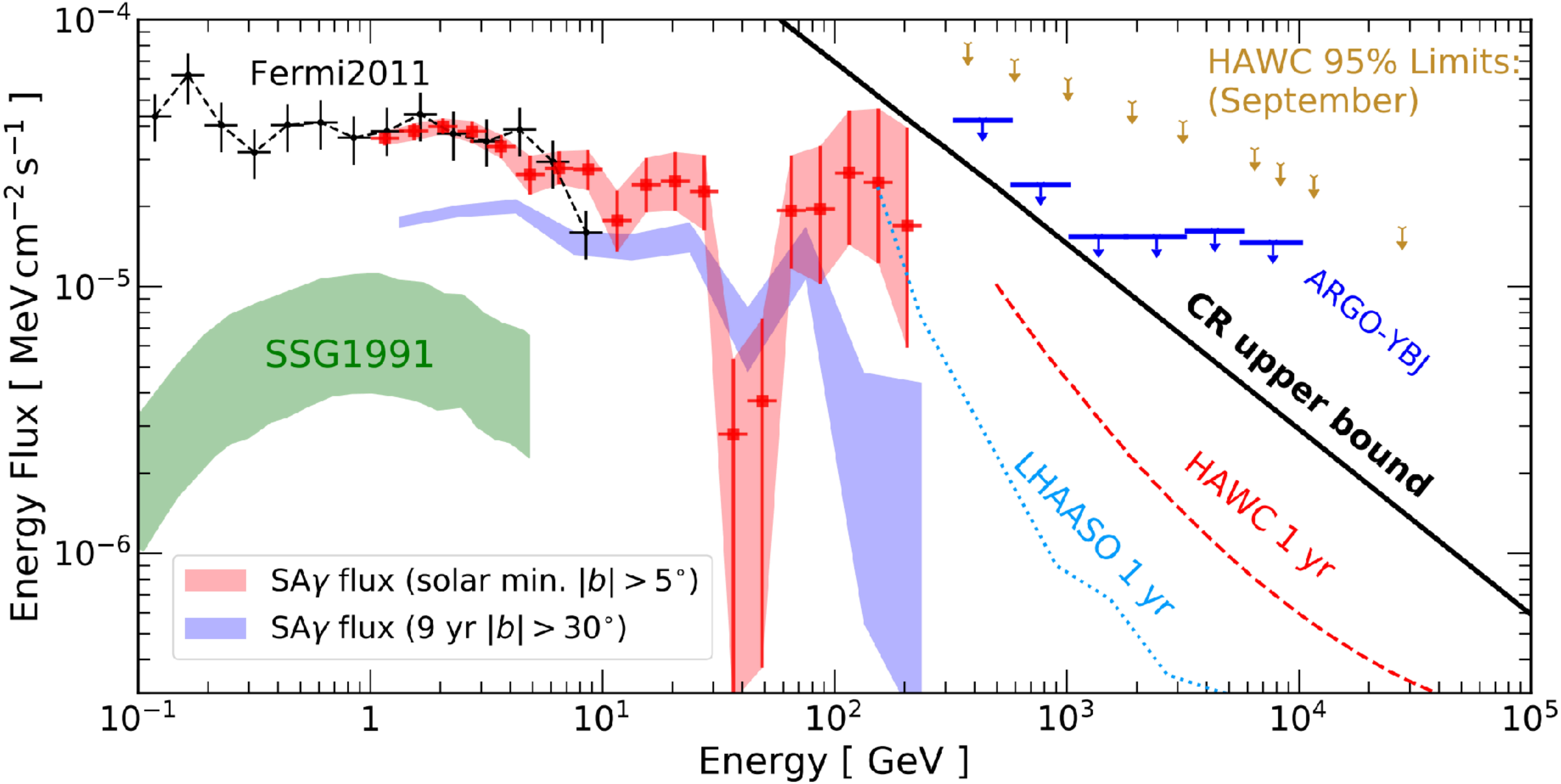


Our Limited Knowledge



Intensity	X
Spectrum	X
Time Variability	X
Morphology	X
Spectral Variability	X
Spectral Dip	X

The Whole Picture



Fermi Solar Panel


May 30, 2018

Fermi Status Update

Both instruments aboard NASA's Fermi Gamma-ray Space Telescope have resumed science observations. The spacecraft itself is functioning well despite the March 16 failure of a mechanism that drives one solar panel, an event that triggered an automatic "safe hold" that powered down Fermi's instruments.

The Gamma-ray Burst Monitor (GBM) was powered back up on March 28 and has resumed normal science operations, detecting more than two dozen gamma-ray bursts since. The GBM sees the entire sky not blocked by Earth.

Fermi's primary instrument, the Large Area Telescope (LAT), was powered up on April 2 and allowed to reach its nominal temperature before observations resumed on April 8.

Currently, the observatory is using a slightly different strategy for viewing the sky. This strategy is still being optimized while the engineering team continues to study the cause of the anomalous solar panel behavior.

Since its return to duty, the LAT has detected numerous flares from active galaxies powered by supermassive black holes and saw two novas — stellar explosions occurring on white dwarf stars in our own galaxy.

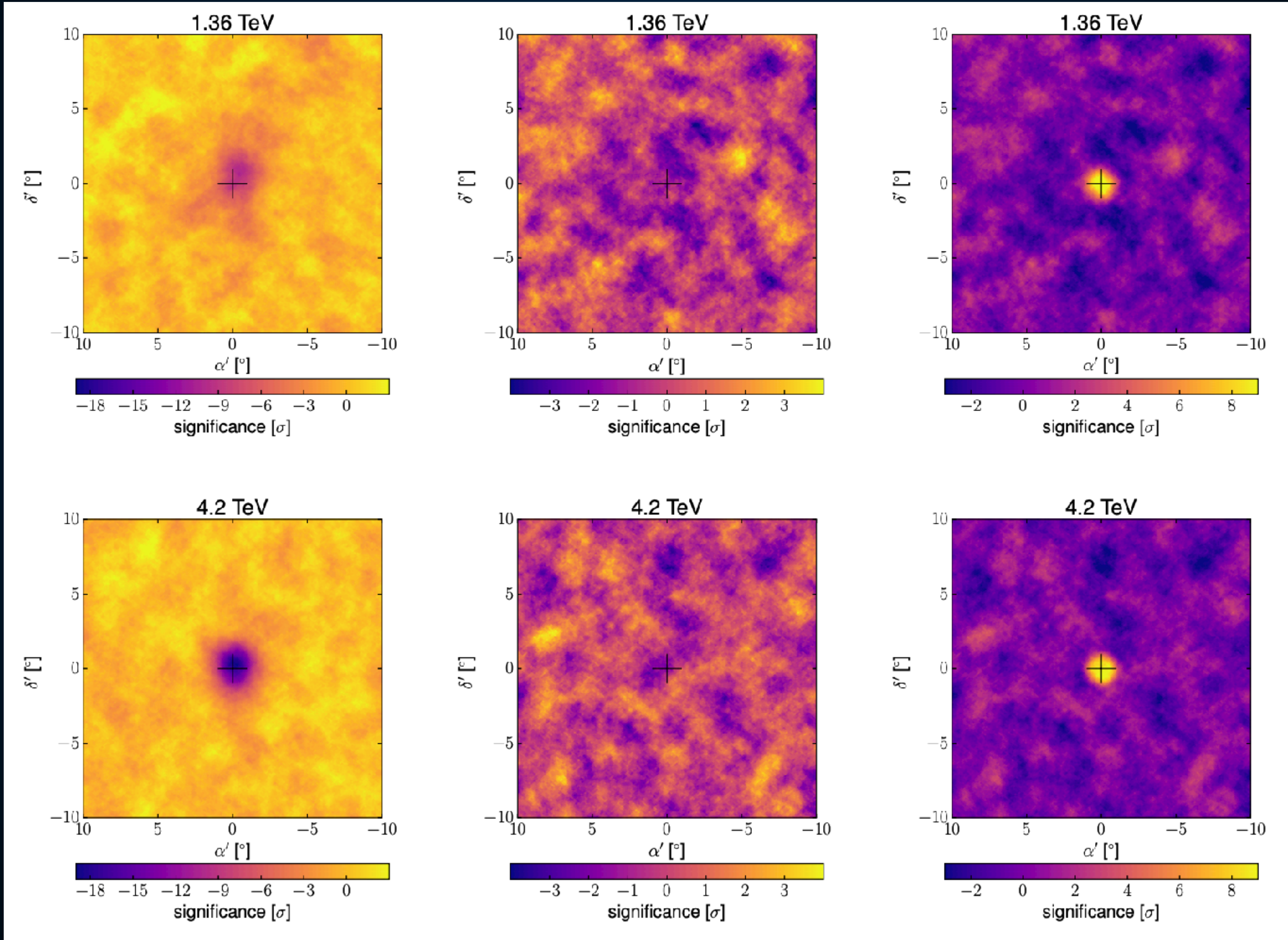
"The gamma-ray sky has been quite active lately, so we're glad the LAT is back on the job," said Fermi Project Scientist Julie McEnery at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

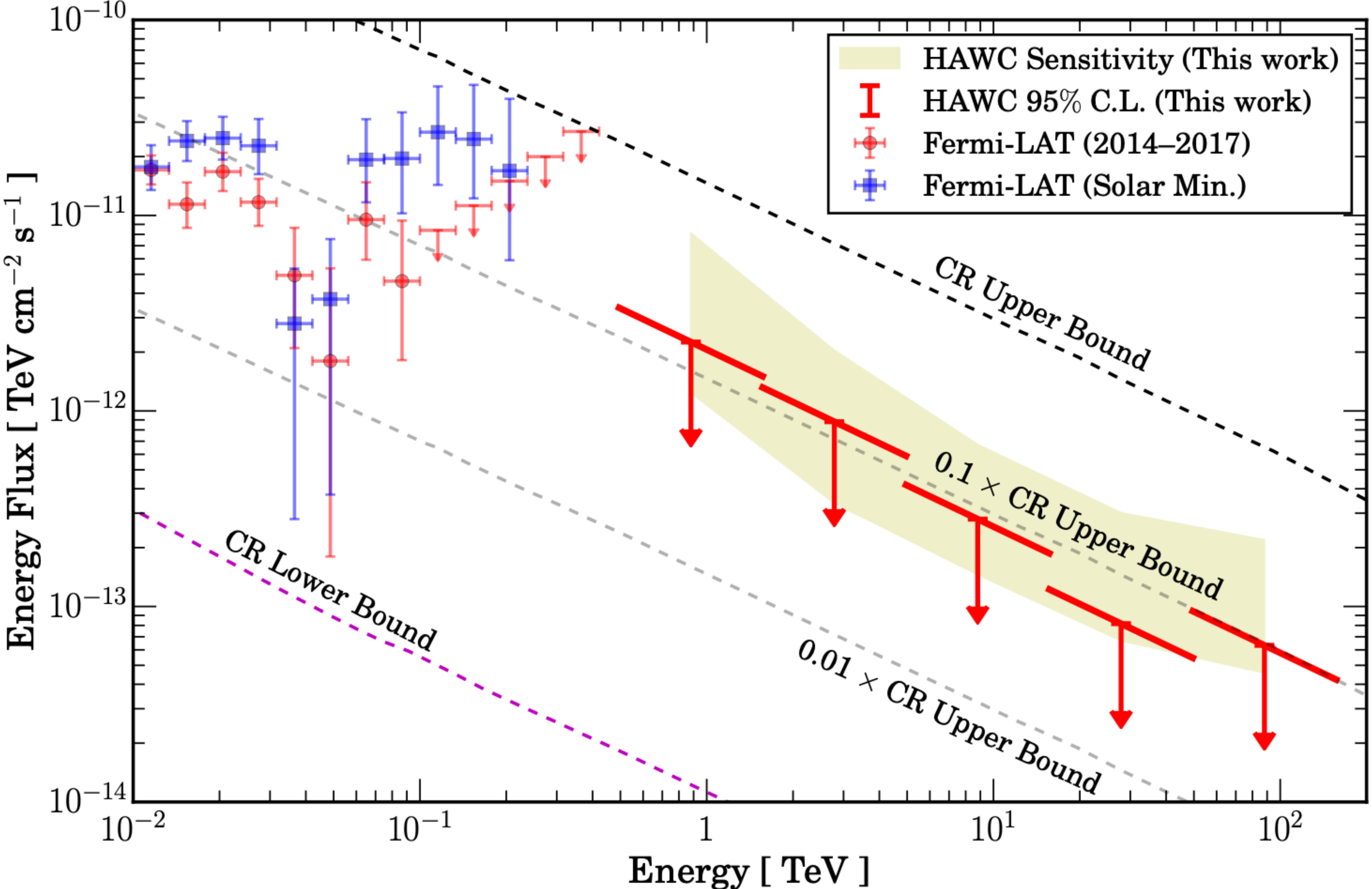
Media Contact: Felicia Chou, NASA Headquarters


V2
V1

TEV OBSERVATIONS OF THE SUN

HAWC Collaboration (including TL) (2018; 1808.05624)





HAWC Sensitivity (This work)
HAWC 95% C.L. (This work)
Fermi-LAT (2014–2017)
Fermi-LAT (Solar Min.)
CR Upper Bound
0.1 × CR Upper Bound
0.01 × CR Upper Bound
CR Lower Bound
Energy Flux [TeV cm^{-2} s^{-1}]
Energy [TeV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-2}
10^{-1}
1
10^{1}
10^{2}

The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC

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(HAWC Collaboration)

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Difficulty in Hadron Separation Makes Analysis Much More Difficult for HAWC

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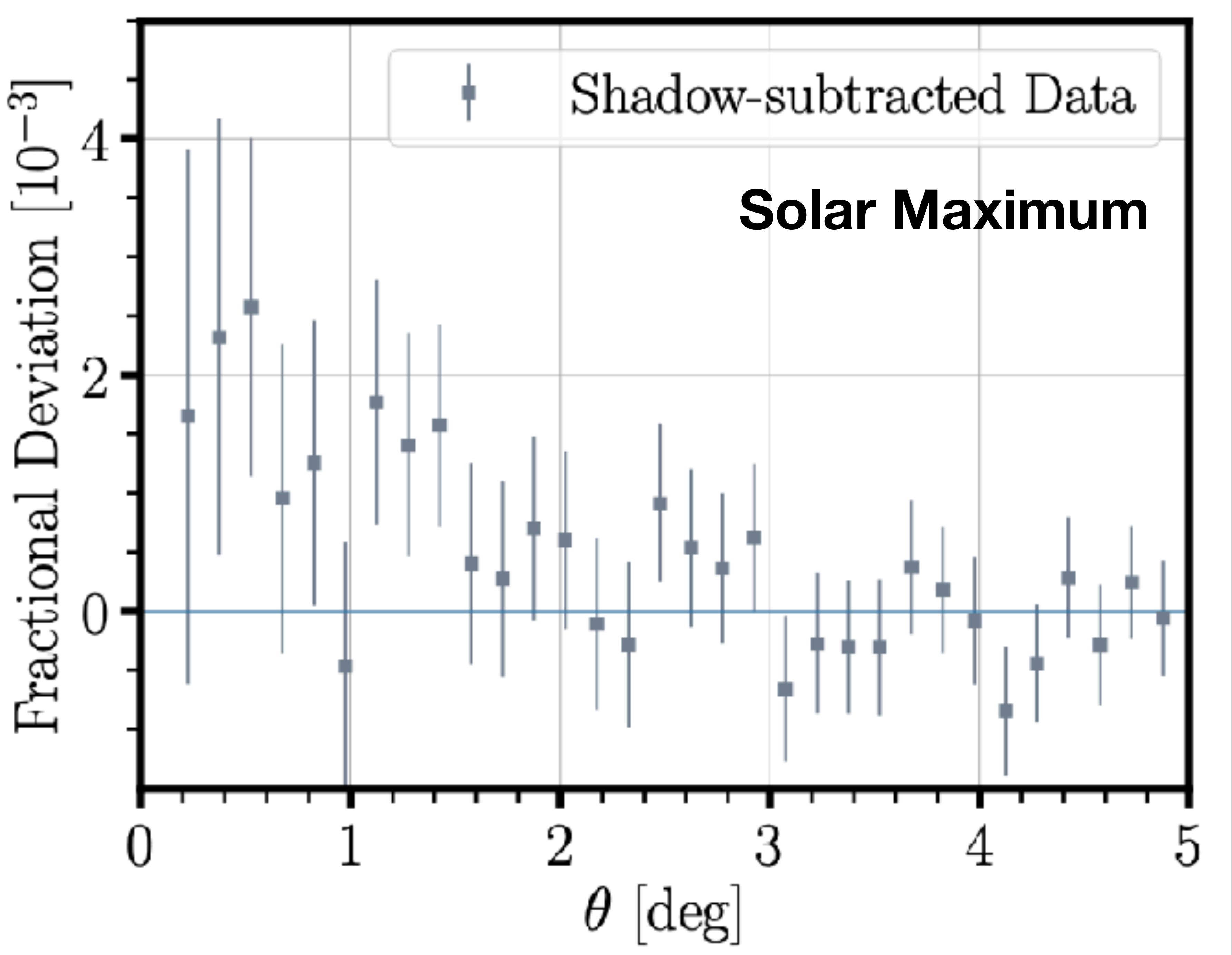
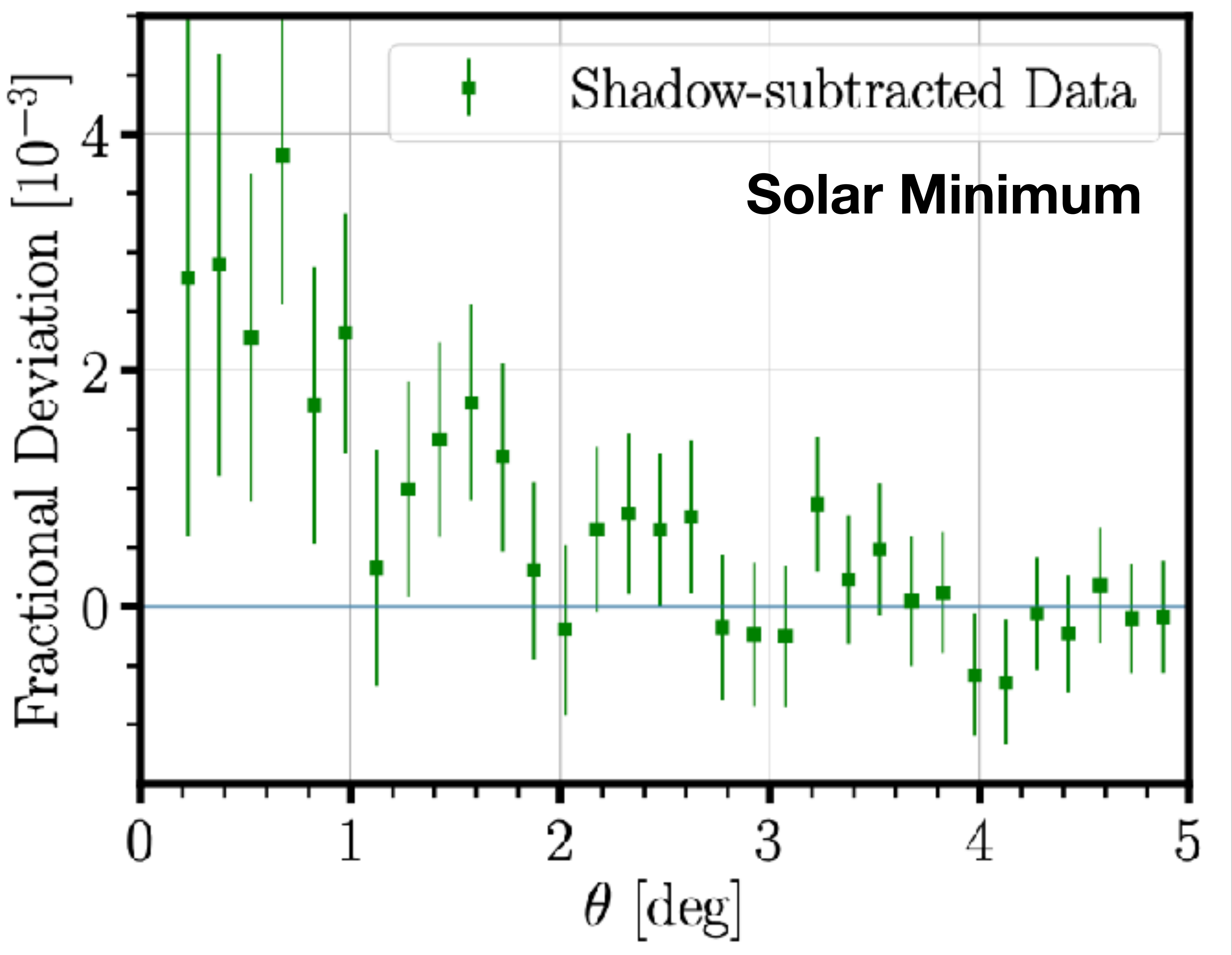
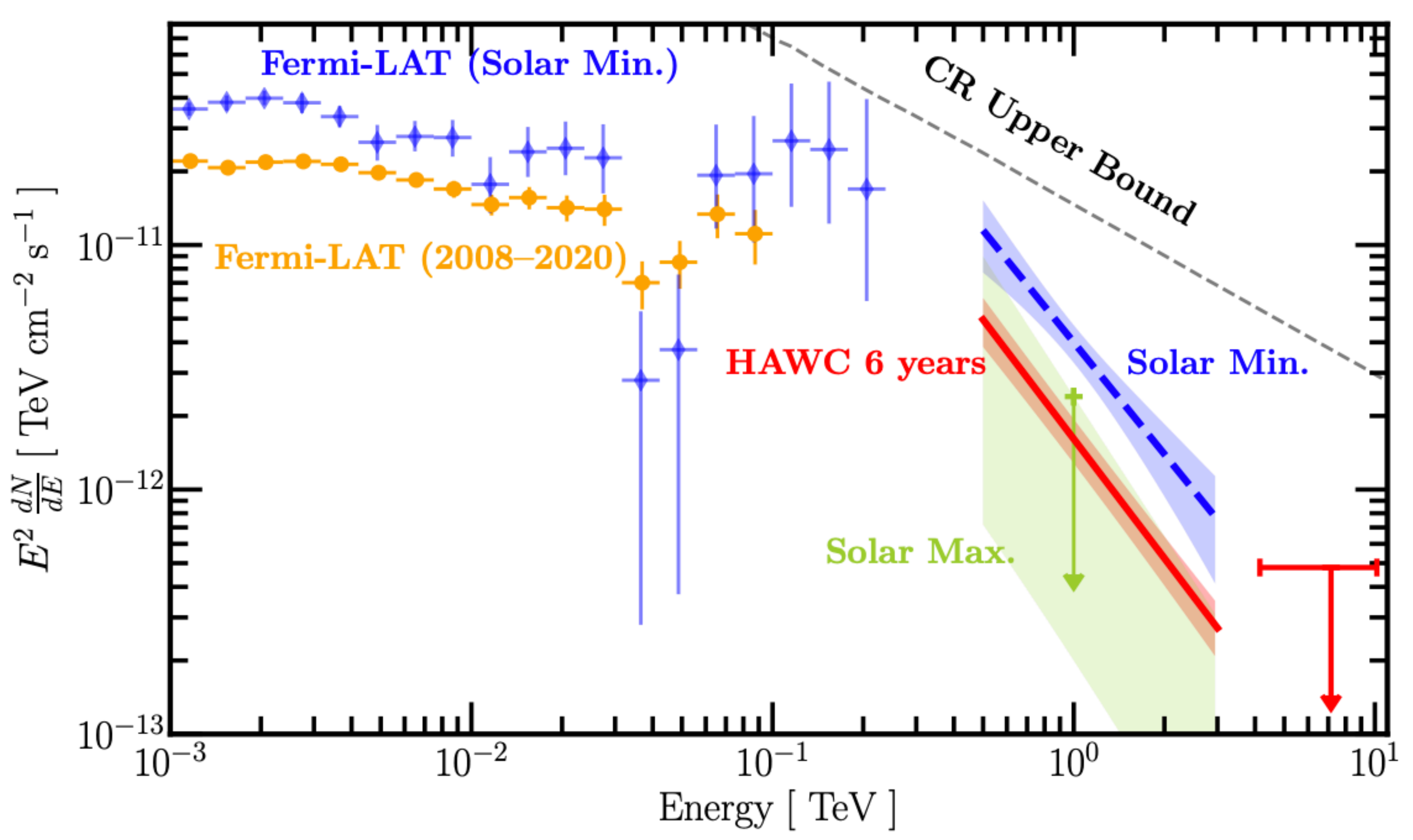
HAWC Verifies Variability over Solar Cycle

Flux only robustly detected during solar minimum.

Similar exposure in both datasets.







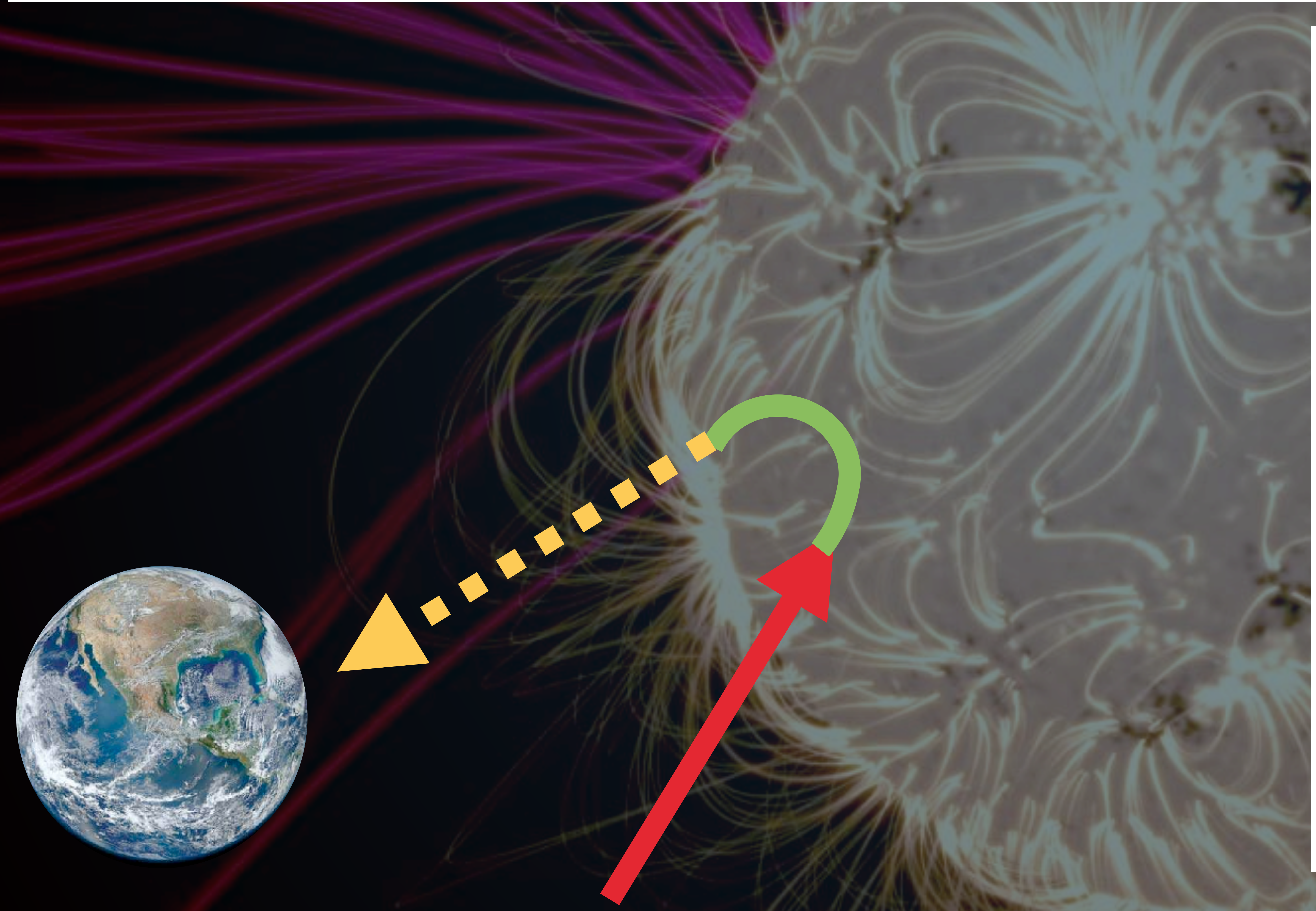
Fermi-LAT (Solar Min.)
CR Upper Bound
Fermi-LAT (2008–2020)
HAWC 6 years
Solar Min.
Solar Max.
$E^2 \frac{dN}{dE}$ [TeV cm^{-2} s^{-1}]
10^{-11}
10^{-12}
10^{-13}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Energy [TeV]

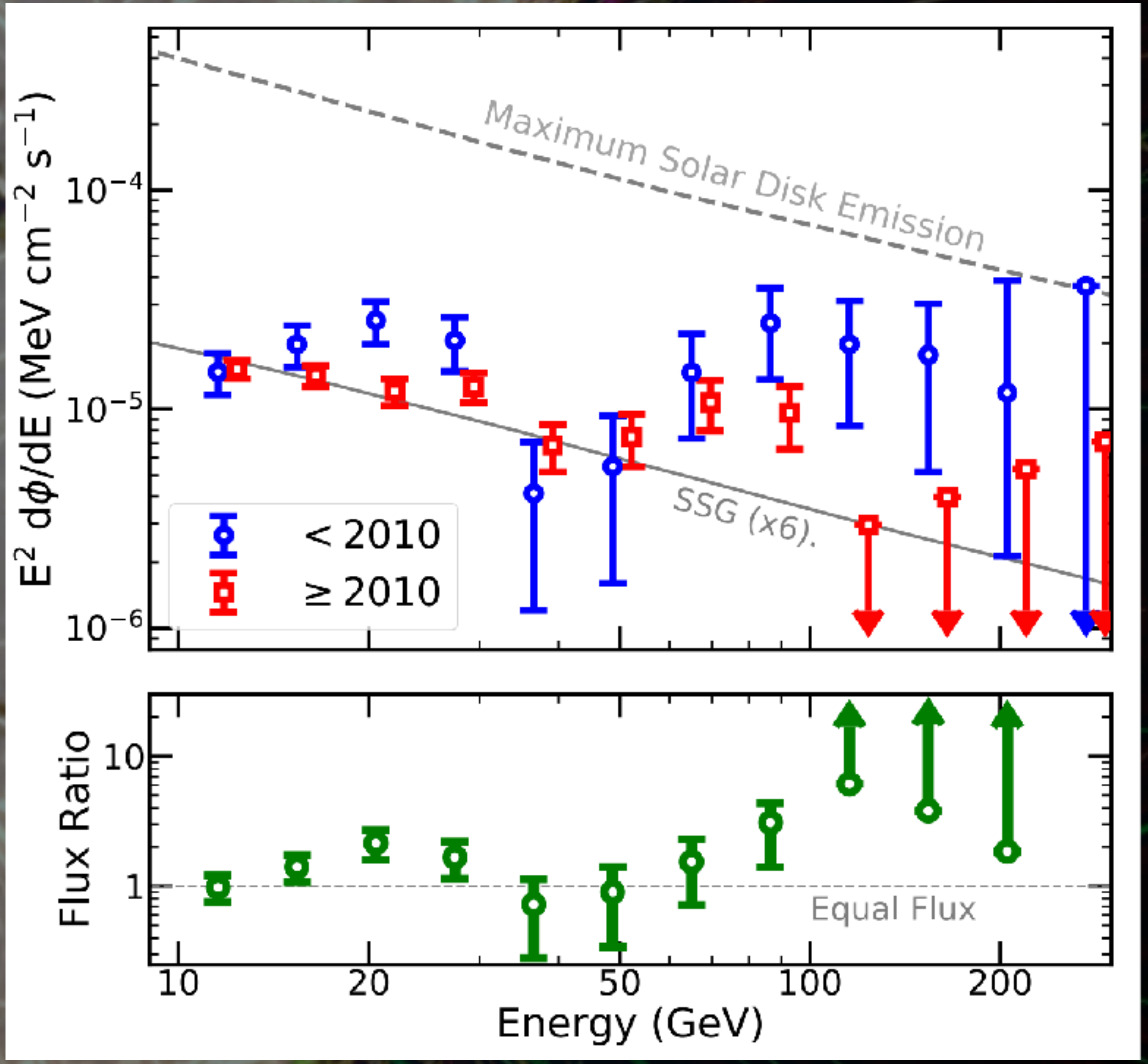
So basically everything is wrong….

How do we model this?

Gamma-Ray Emission much brighter than expected

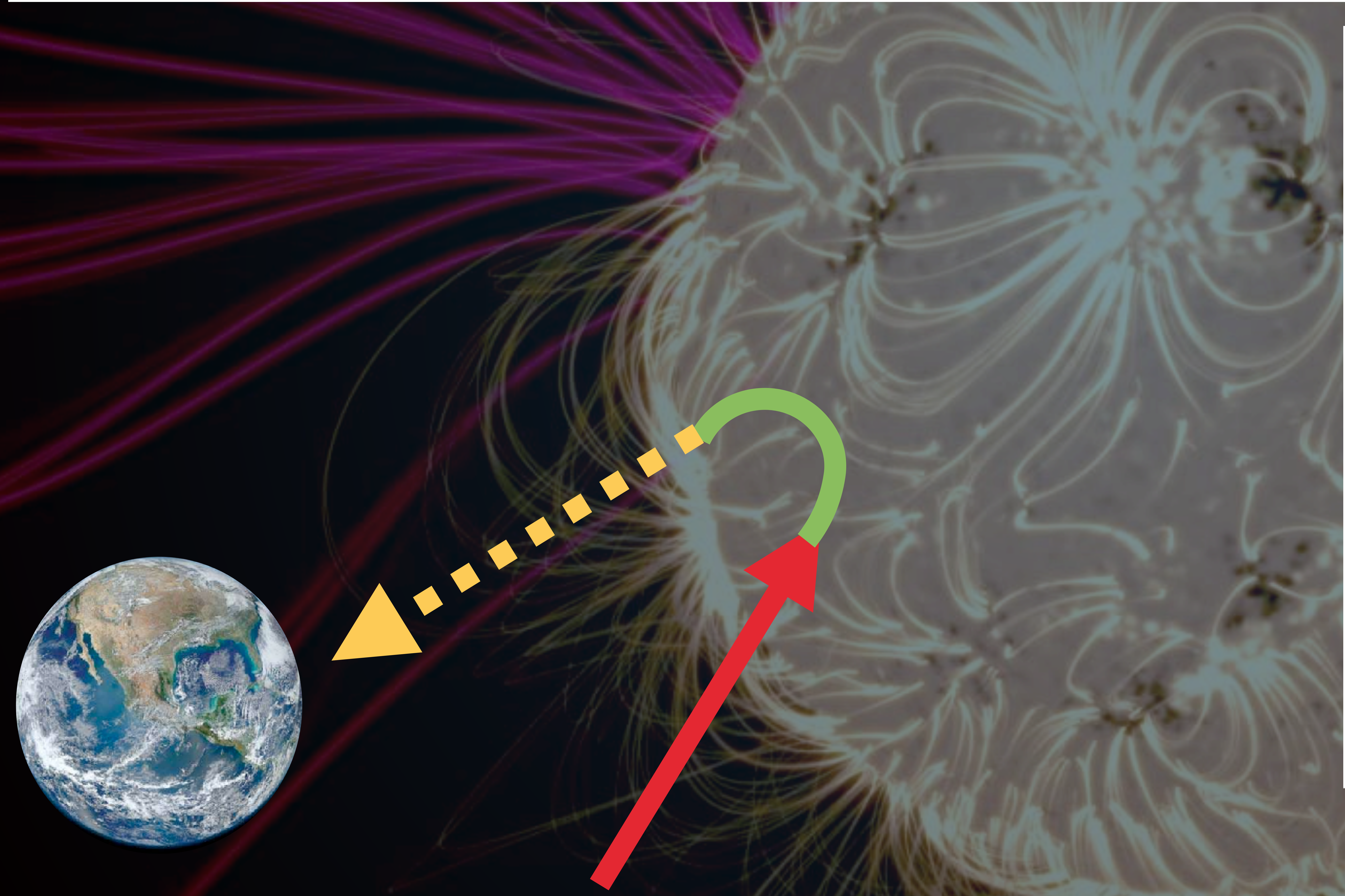
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

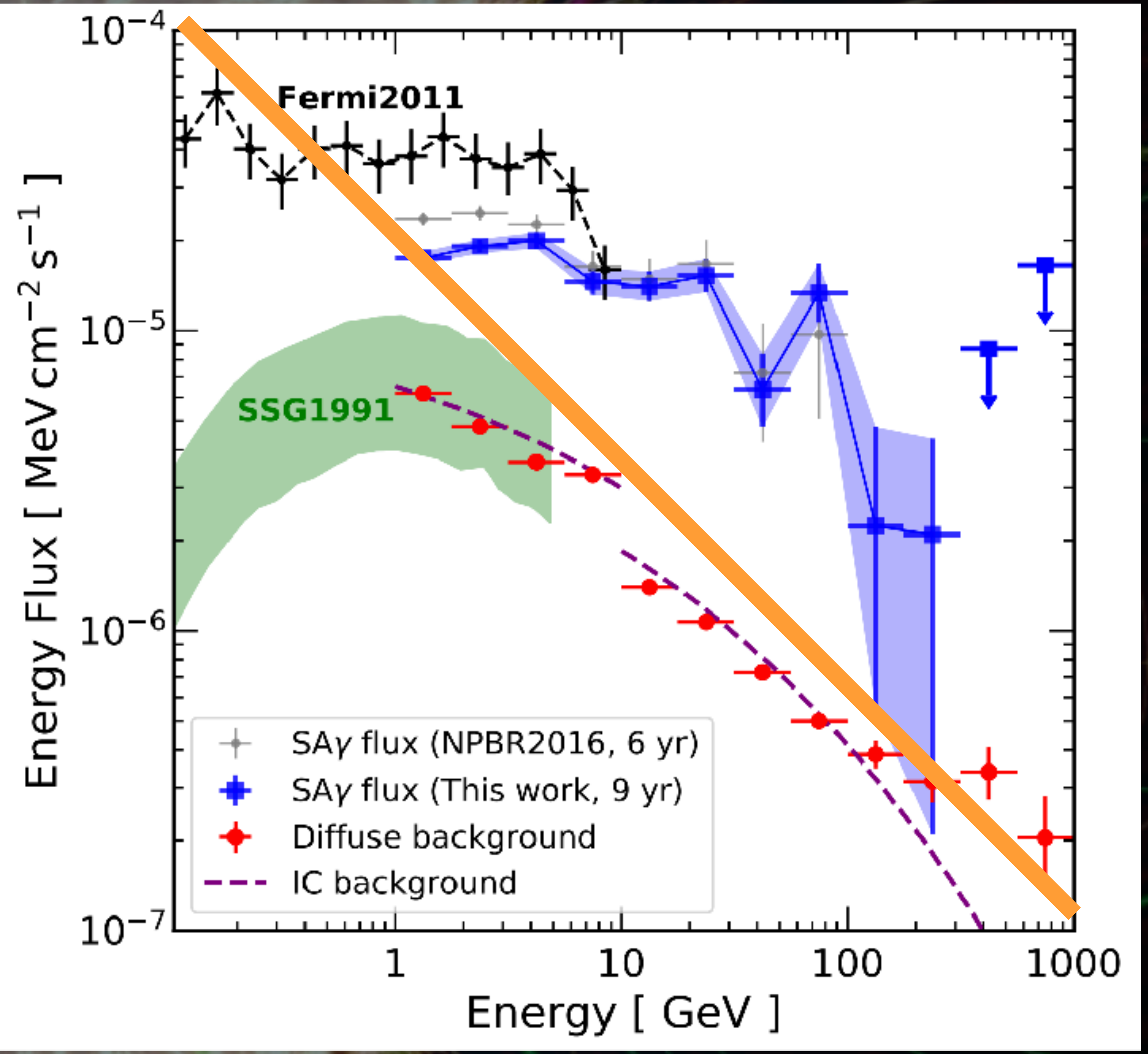




Gamma-Ray Spectrum Harder than Expected

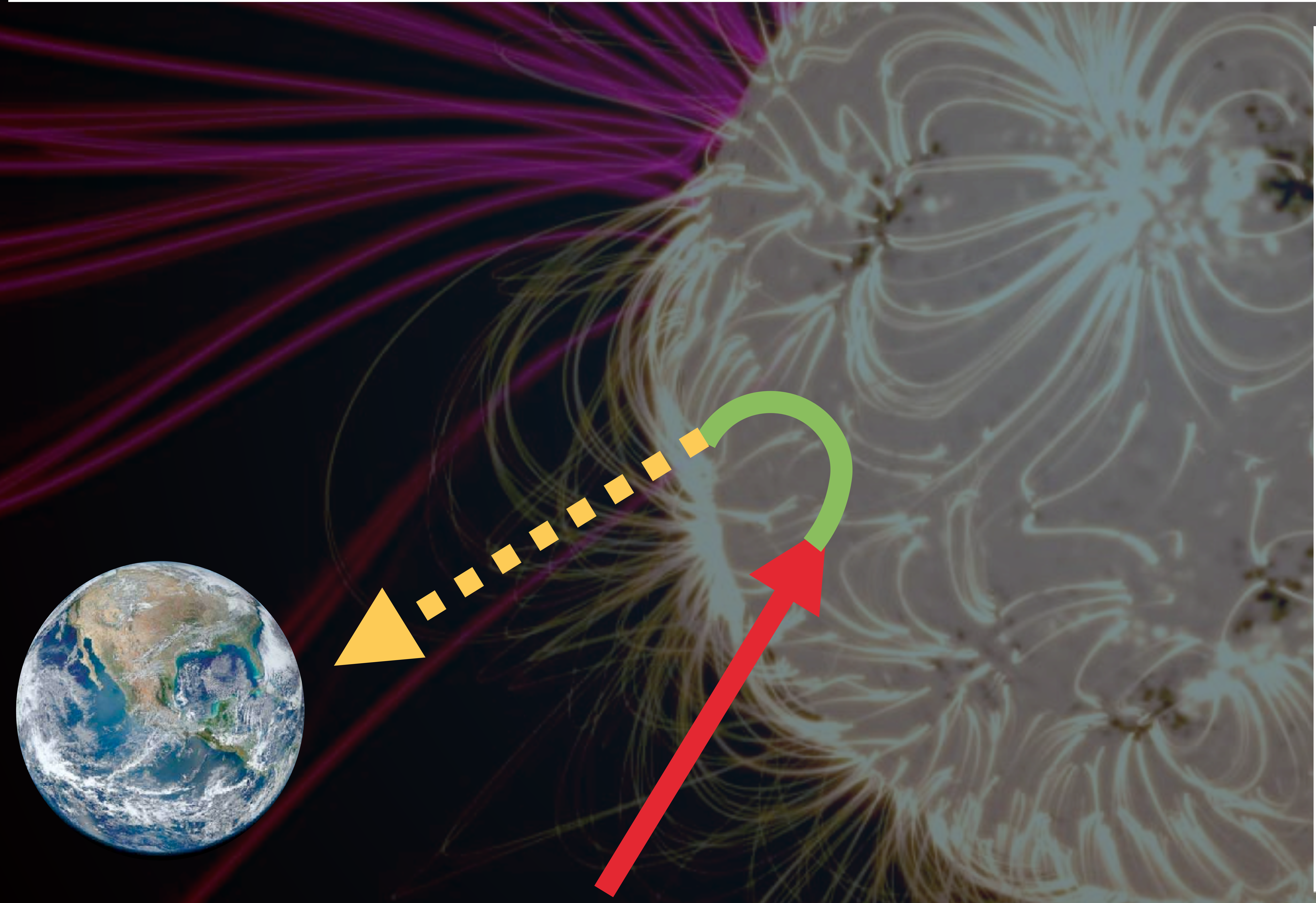
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

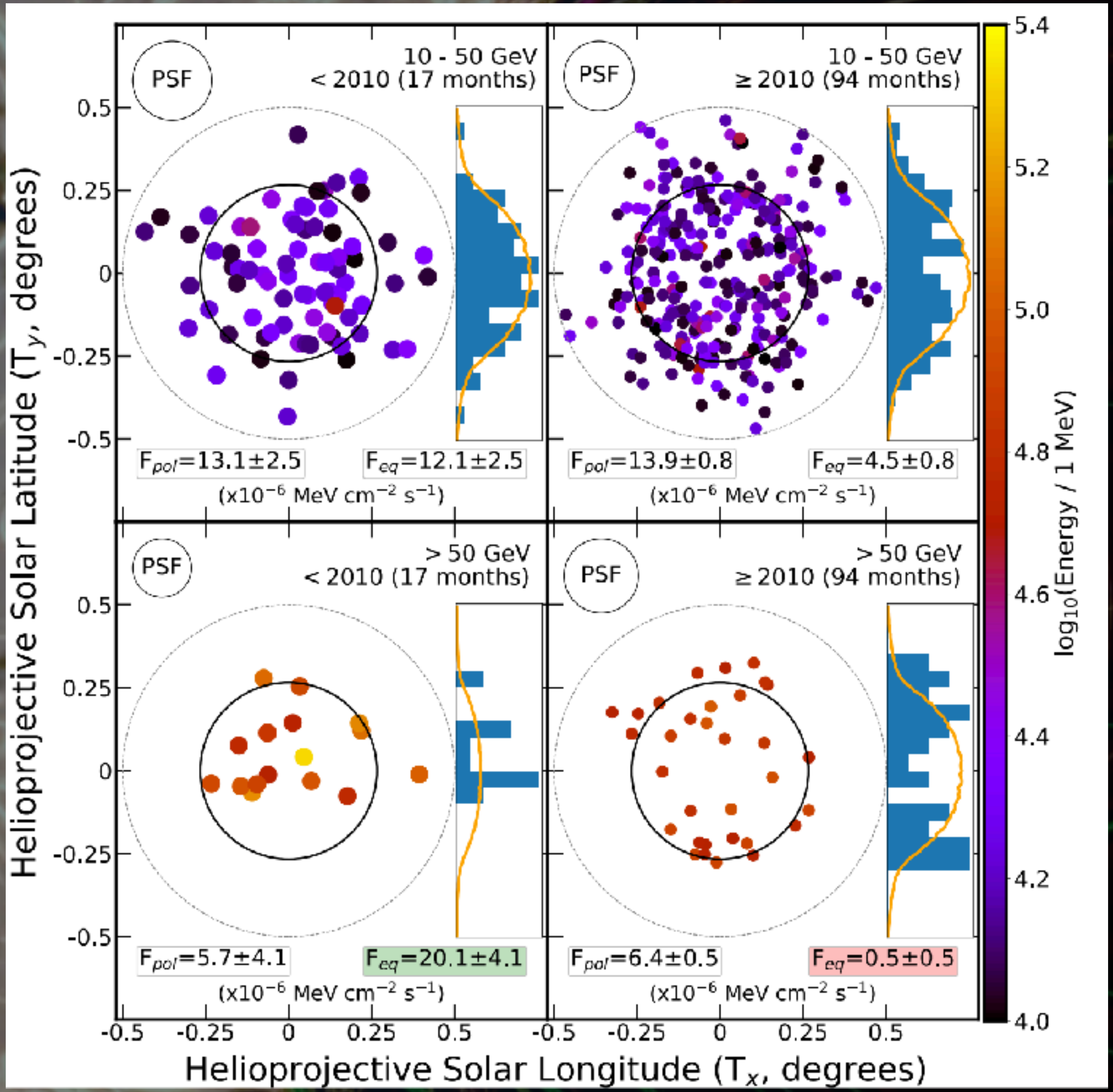




Gamma-Ray Emission Not Uniform

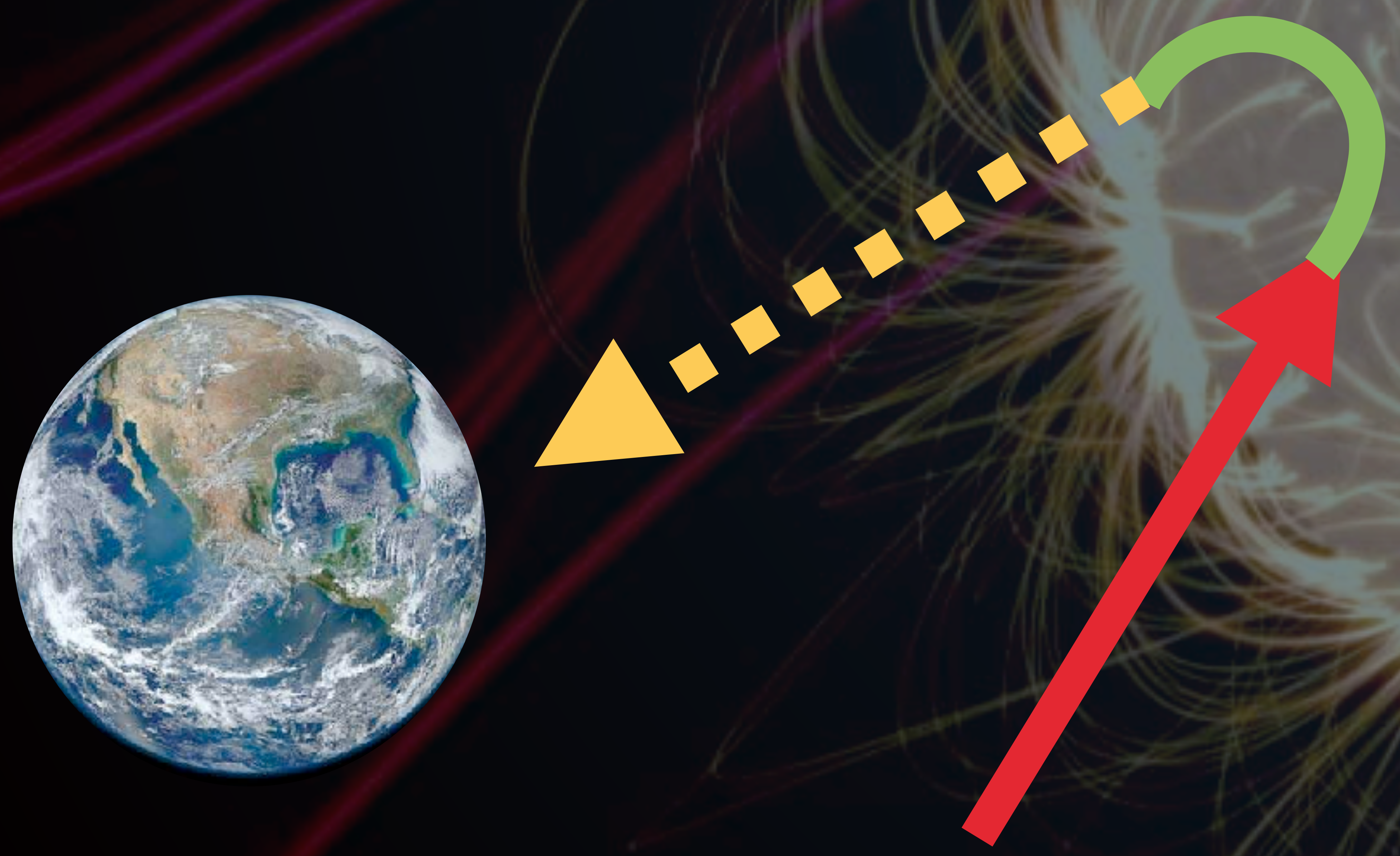
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

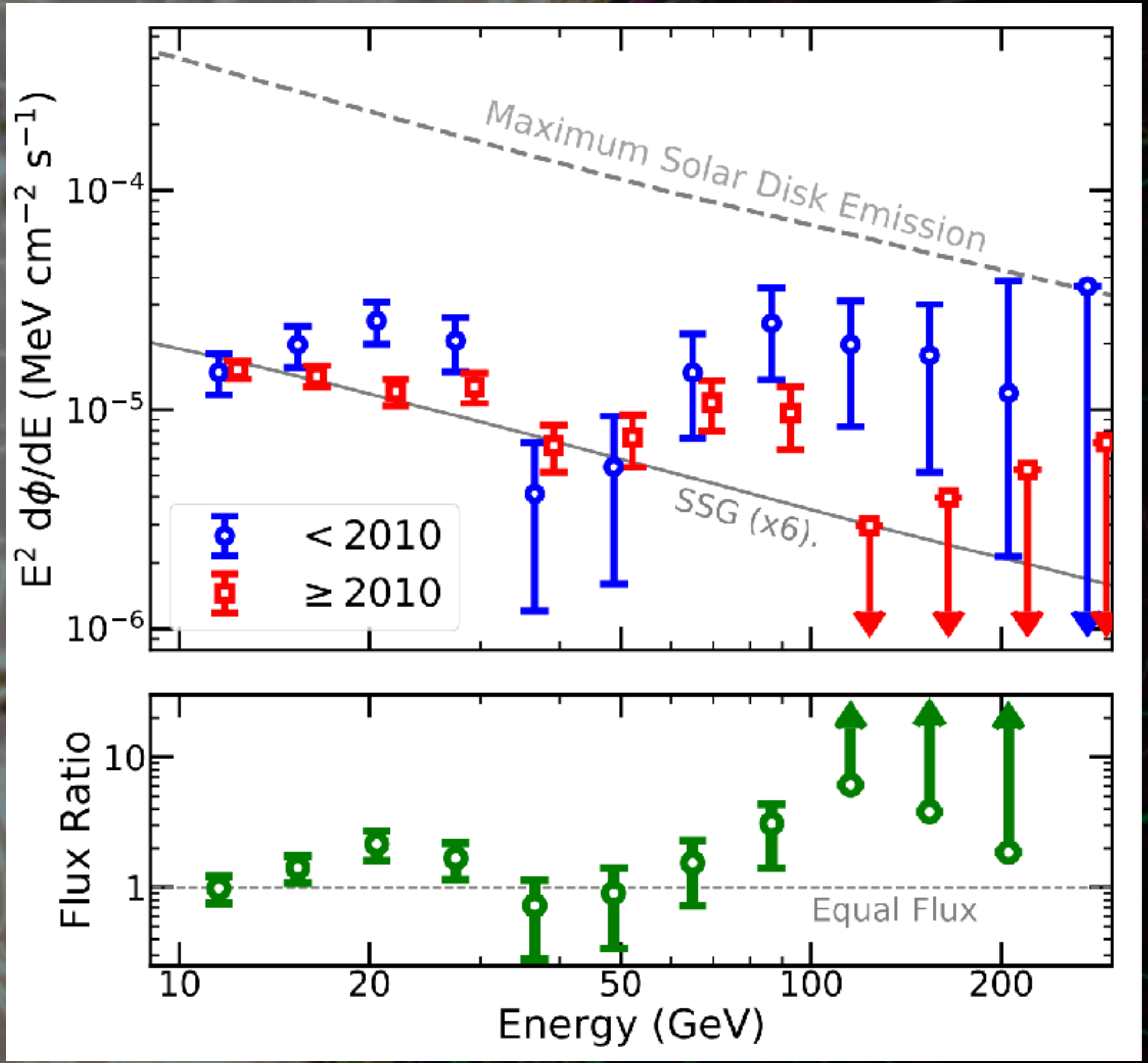




Two Different Emission Mechanisms?

$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$





Conclusions

We see, but we don't understand.

Help?

Solar gamma-rays provide a new handle into fundamental questions in solar magnetohydrodynamics.

Huge Potential For Cross-Correlations with other wavelengths