TIM LINDEN

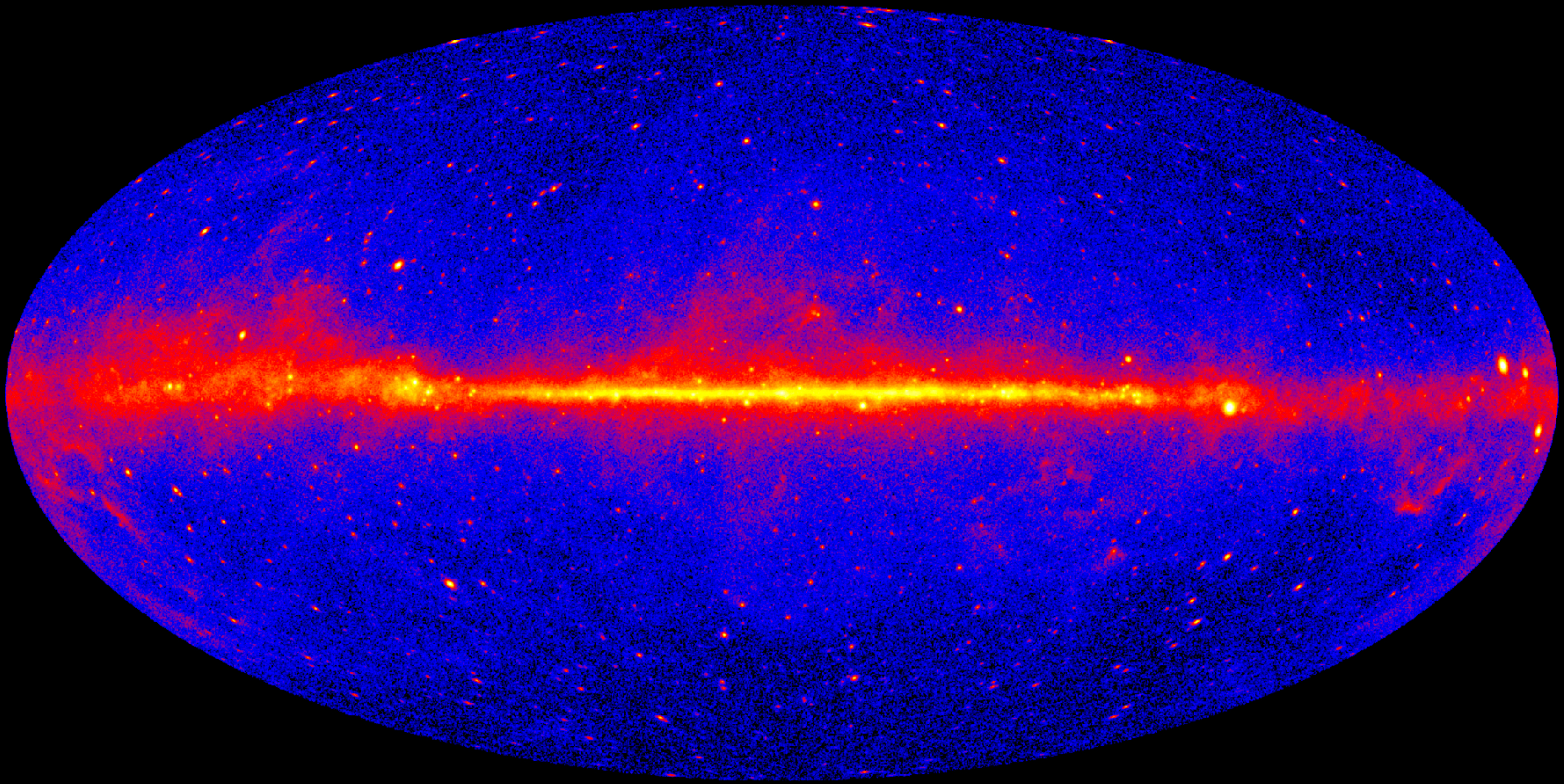
Hebrew University of Jerusalem, 2021

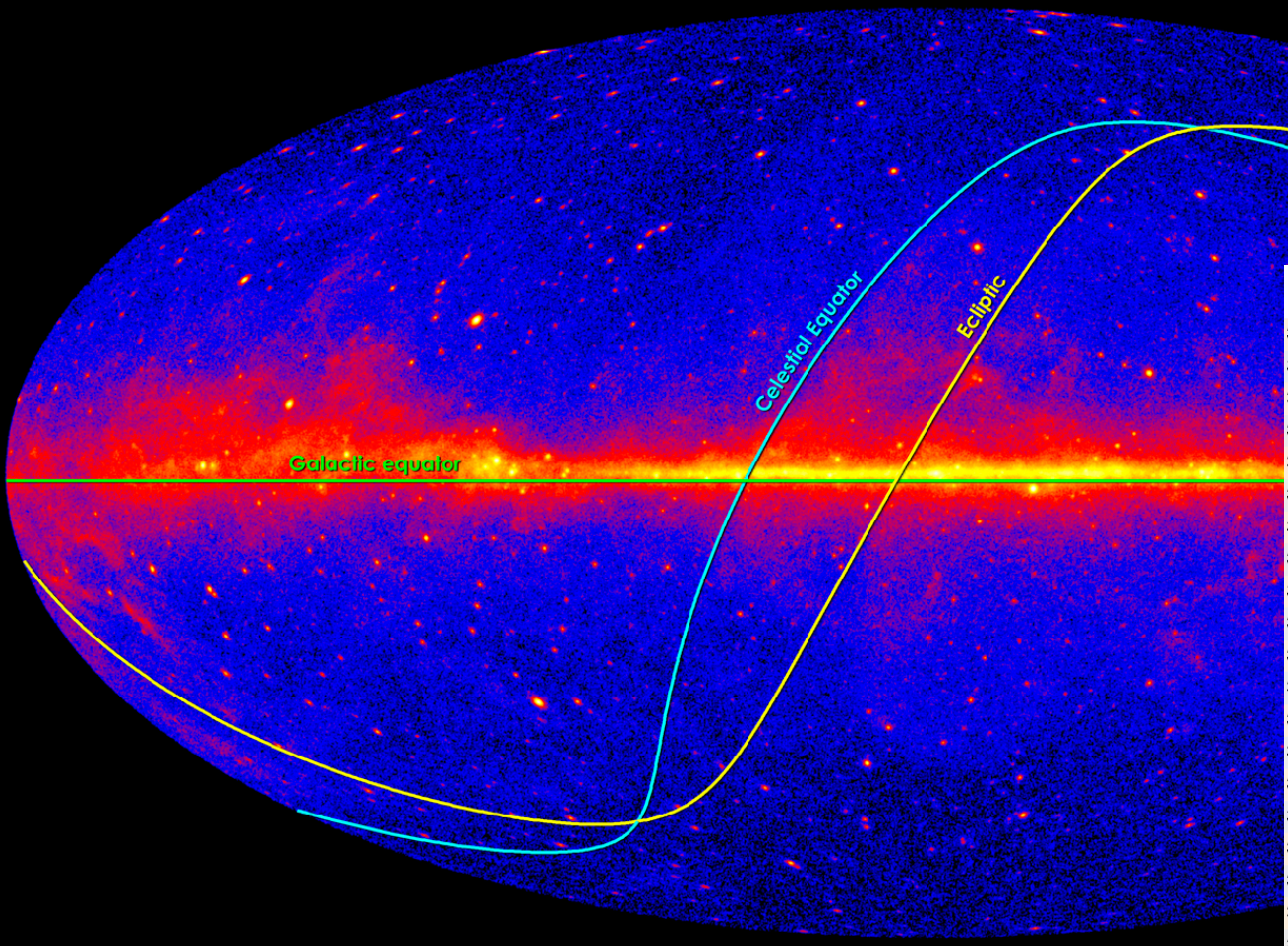
Evidence for a New Component of Solar Gamma-Ray Emission

Stockholms universitet


SUN
EARTH
MARS
JUPITER
SATURN
NAPTUNE
PLUTO
PROXIMA CENTAURI
AU
1
10^1
10^2
10^3
10^4
10^5
10^6

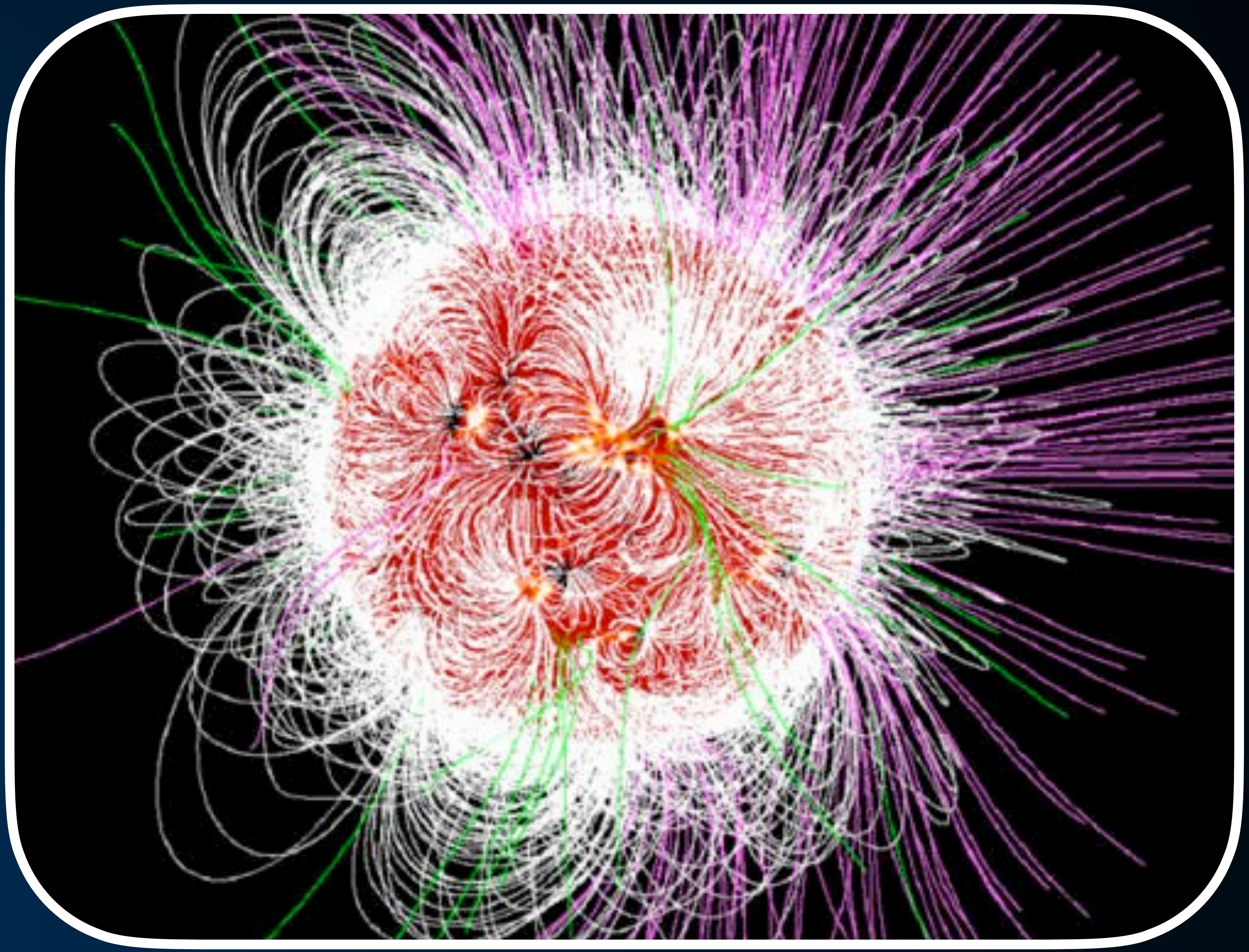

Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause





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?

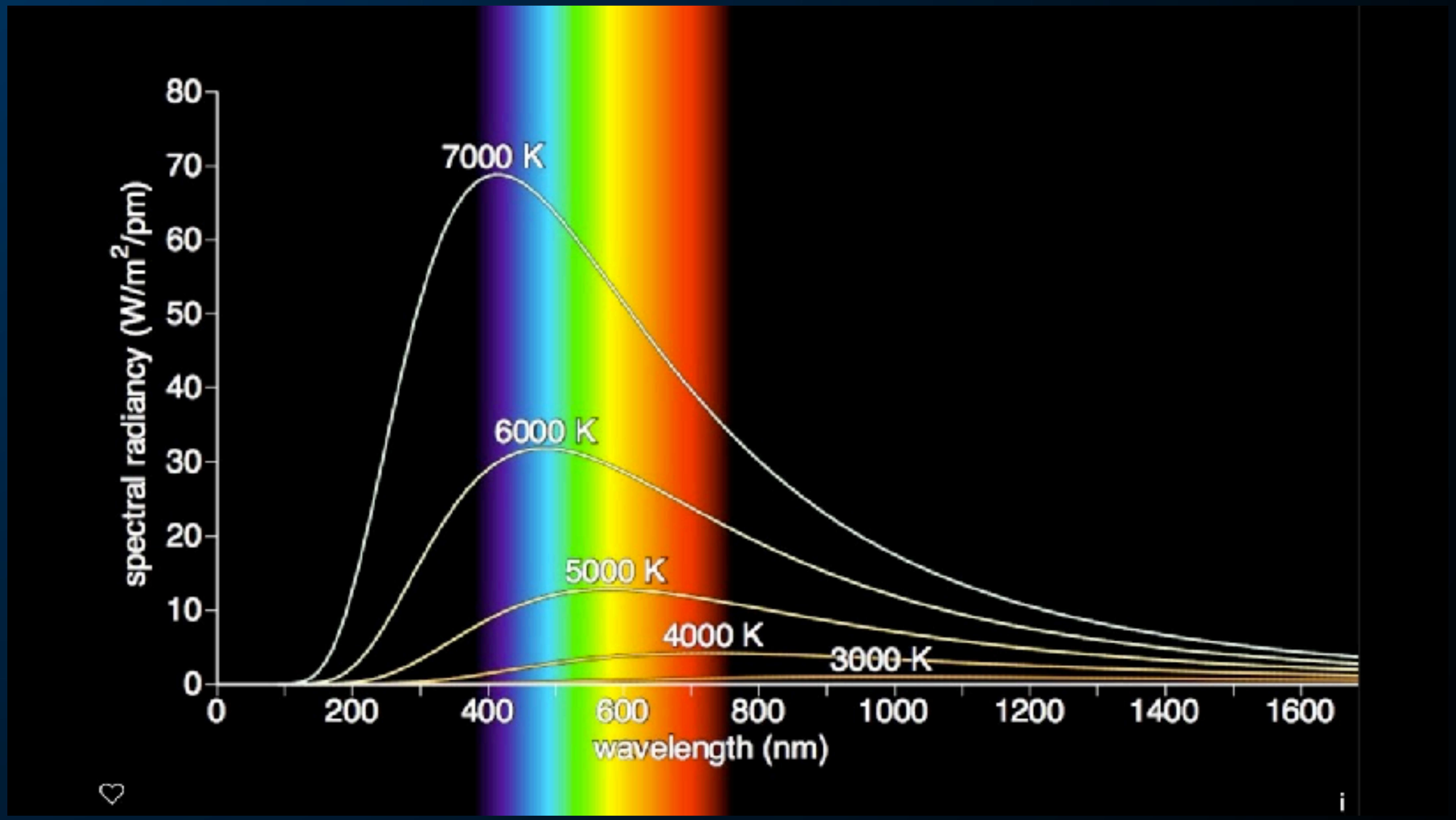


How are solar gamma-rays produced?

Gamma Rays - How?

$$T_\odot = 6000\ \text{K} = 0.5\ \text{eV}$$

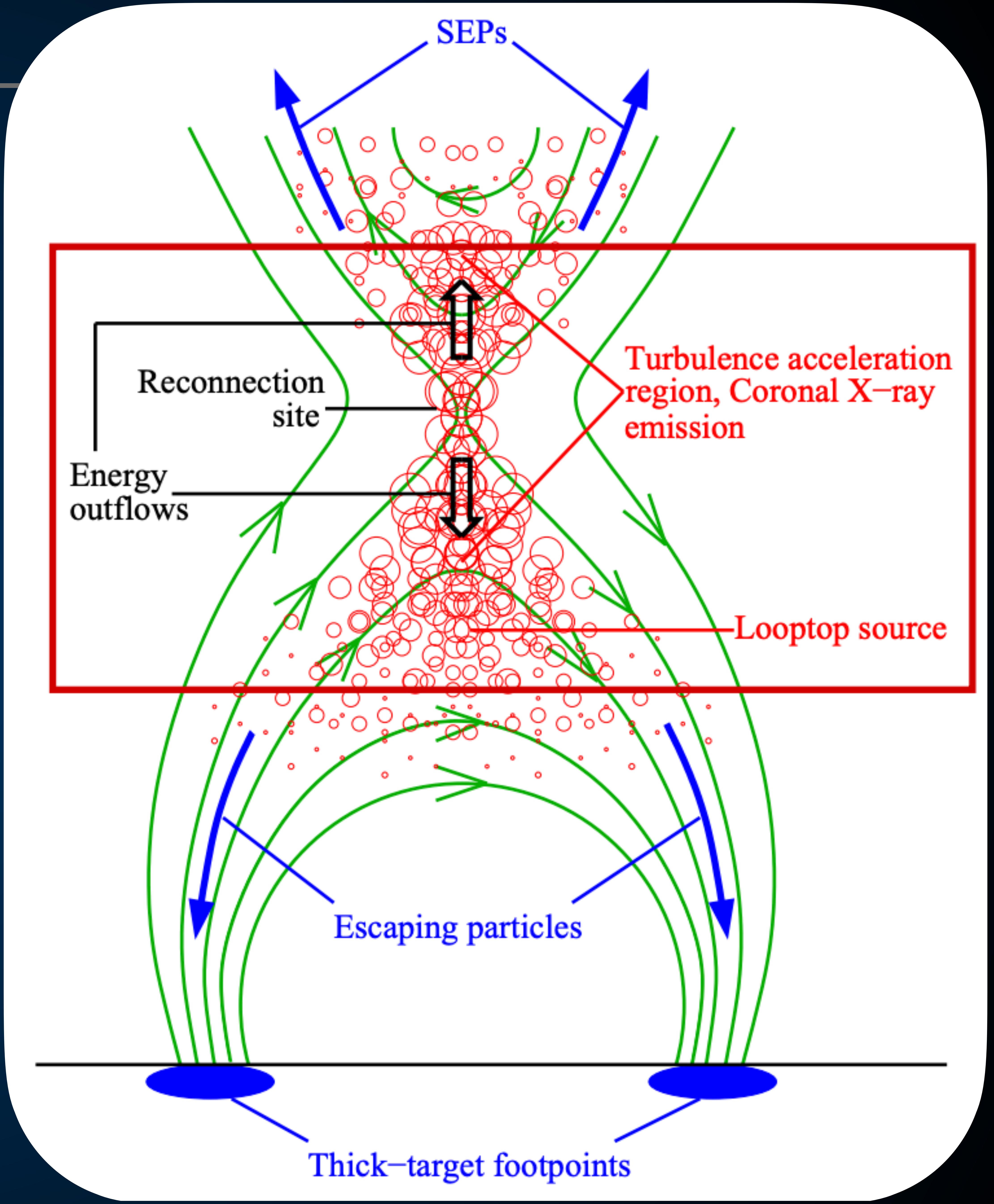
$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



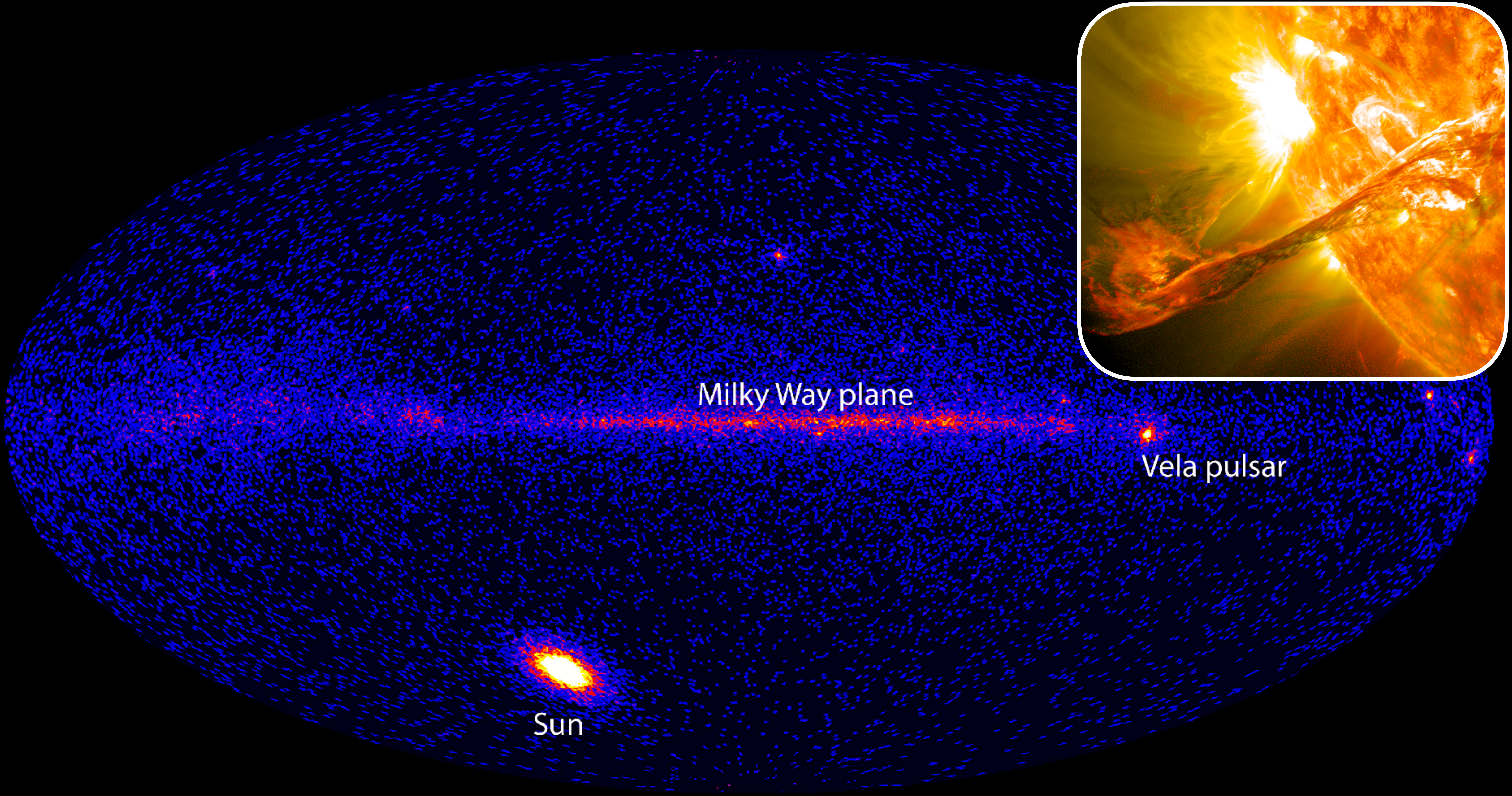
Thermal production of gamma-rays is suppressed by exp[-10⁹] = 0

Gamma Rays - How?

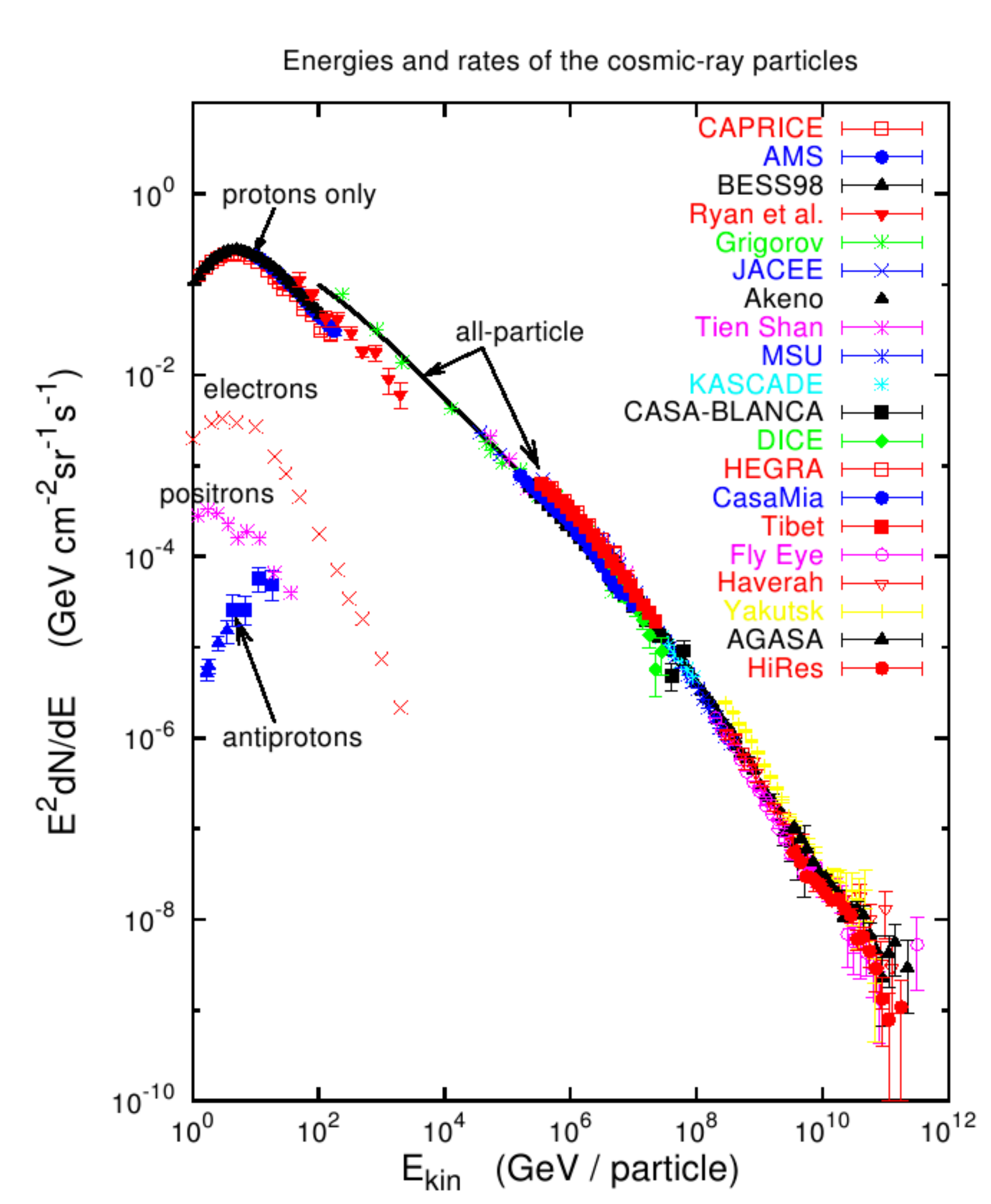
- **Solar Flares and Reconnection events.**



Petrosian (2016; 1605.04022)

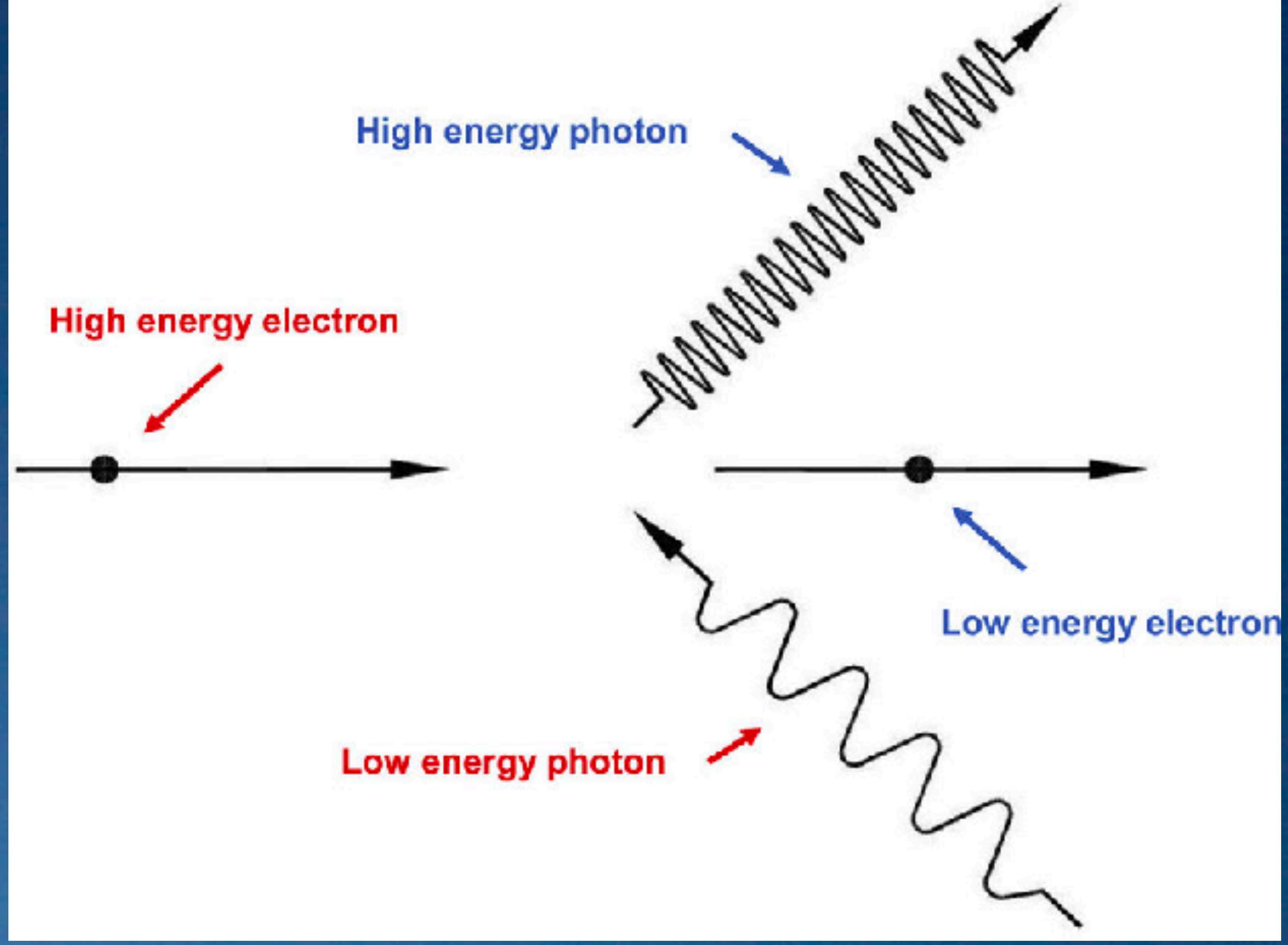


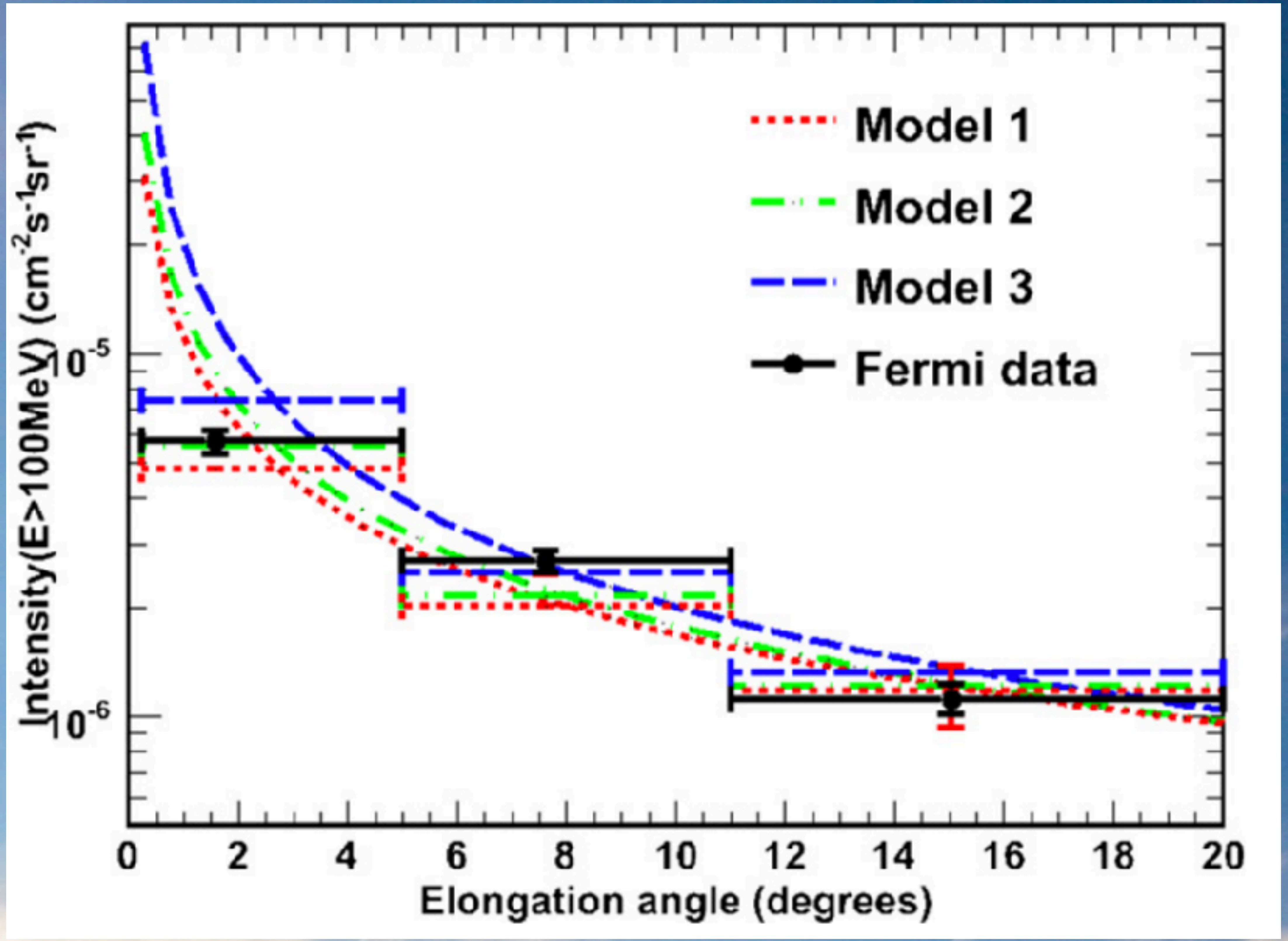
Solar Flare gamma-rays are low energy (E_{max} = 4 GeV)

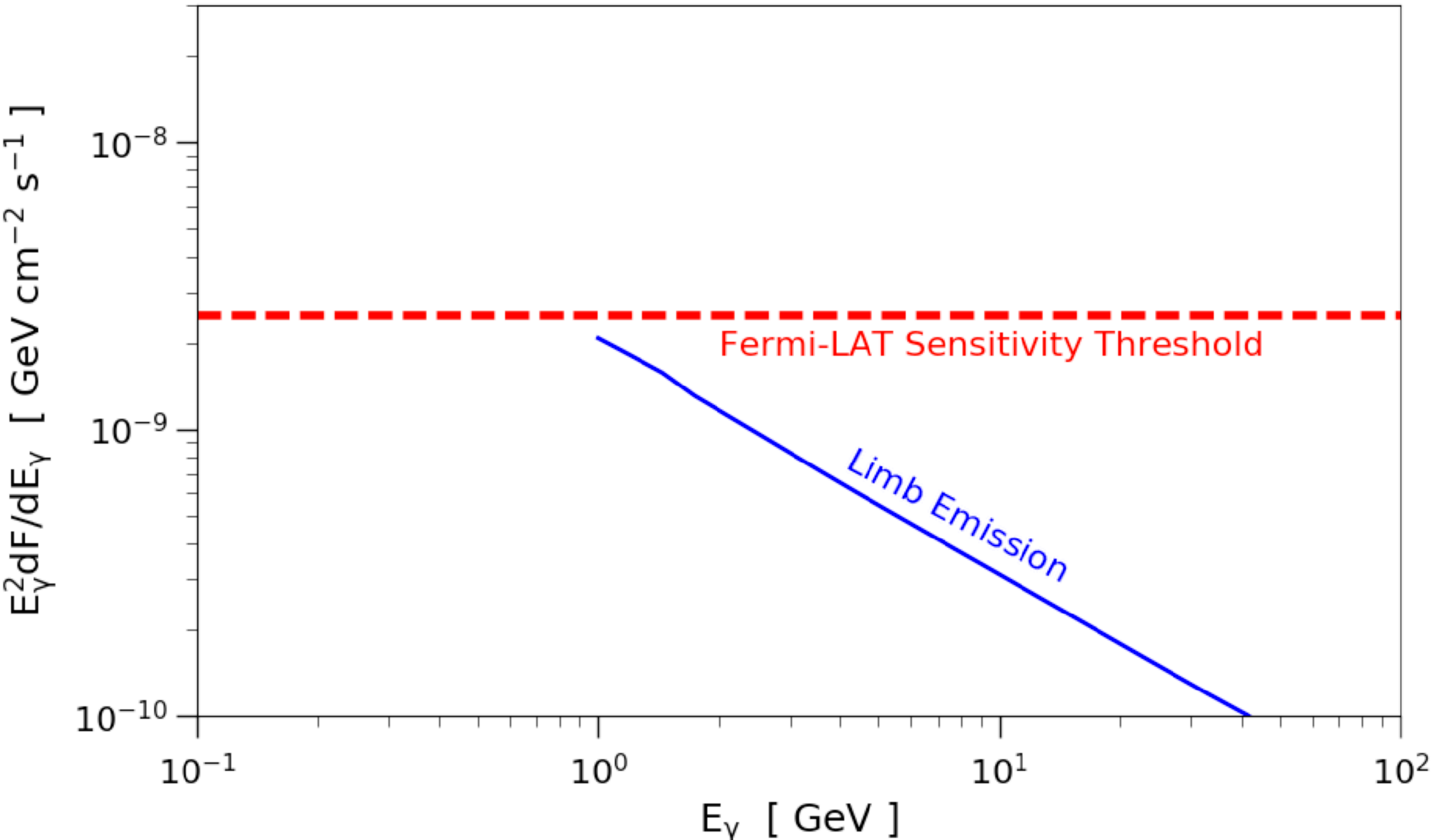


Energies and rates of the cosmic-ray particles
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
E^2dN/dE (GeV $cm^{-2}sr^{-1}s^{-1}$)
E_{kin} (GeV / particle)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^2
10^4
10^6
10^8
10^{10}
10^{12}

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


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


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



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


1991ApJ...382..652S
The Astrophysical Journal, 382:652–666, 1991 December 1
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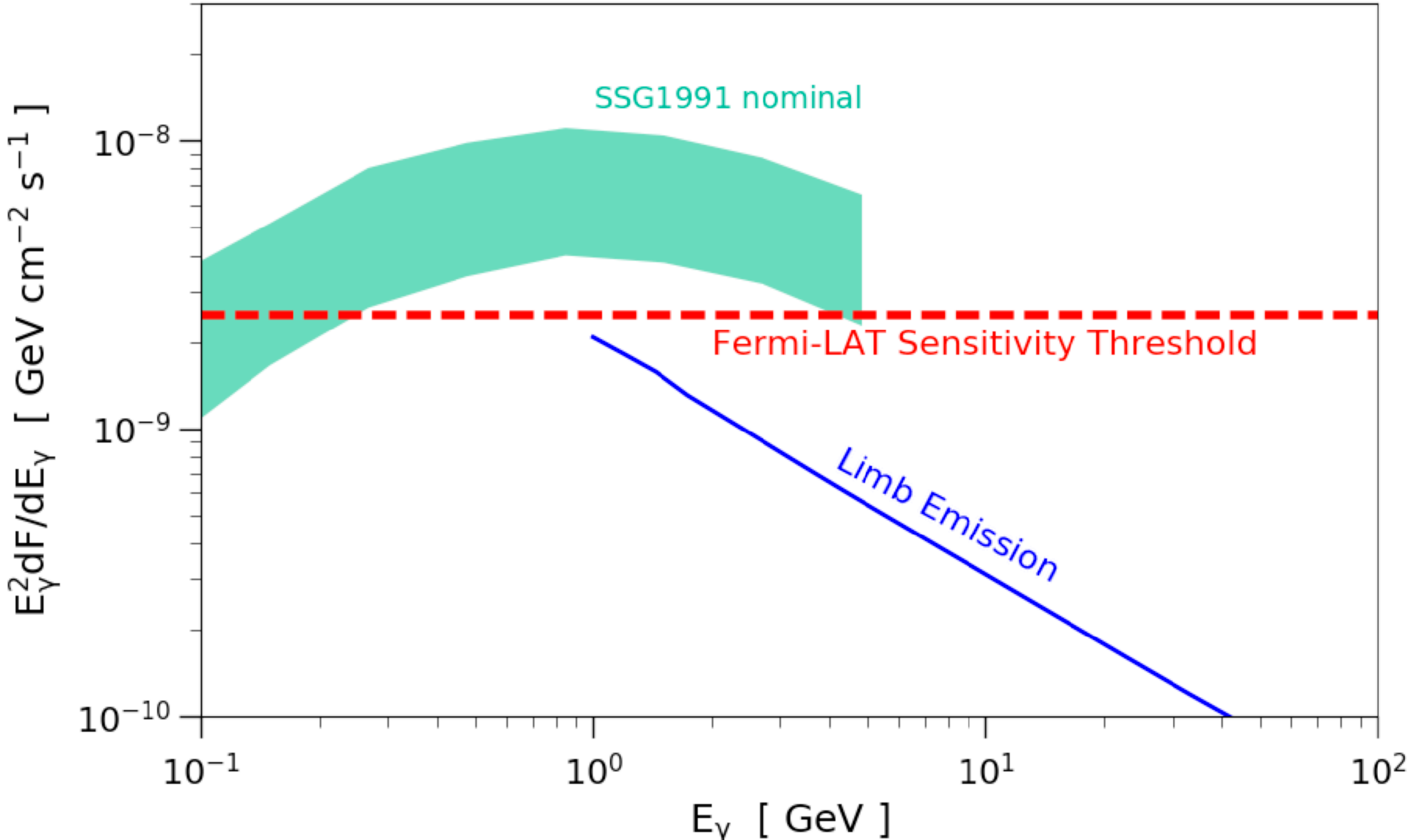
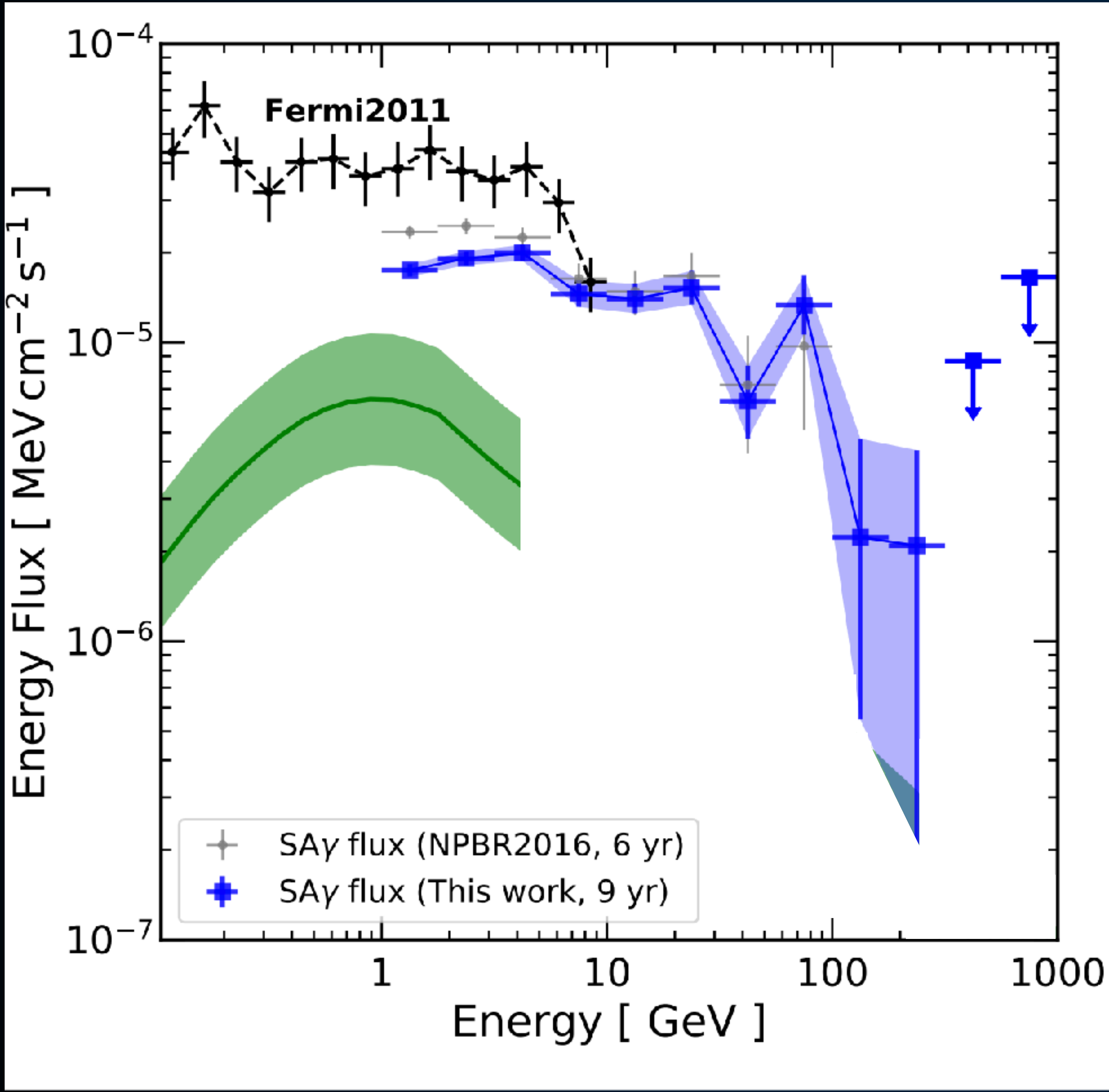
SIGNATURES OF COSMIC-RAY INTERACTIONS ON THE SOLAR SURFACE
D. Seckel, Todor Stanev, and T. K. Gaisser
Bartol Research Institute, University of Delaware, Newark, DE 19716
Received 1991 March 21; accepted 1991 June 5
ABSTRACT
We estimate the fluxes of neutrinos, gamma rays, antiprotons, neutrons, and antineutrons that
of high-energy Galactic cosmic rays with the solar atmosphere. The results are sensitive
cosmic-ray transport in the magnetic fields of the inner solar system. The high-energ
by the Gamma Ray Observatory. The neutrino flux should produce less
generation of neutrino telescopes. The antiproton flux is unobservable
and antineutron fluxes are detectable only if neutrons prod
discriminated against.
gamma rays: general — neutrinos — Sun: activ
appropriate thickness
without reabsorbing them
would then be suppresse

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


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

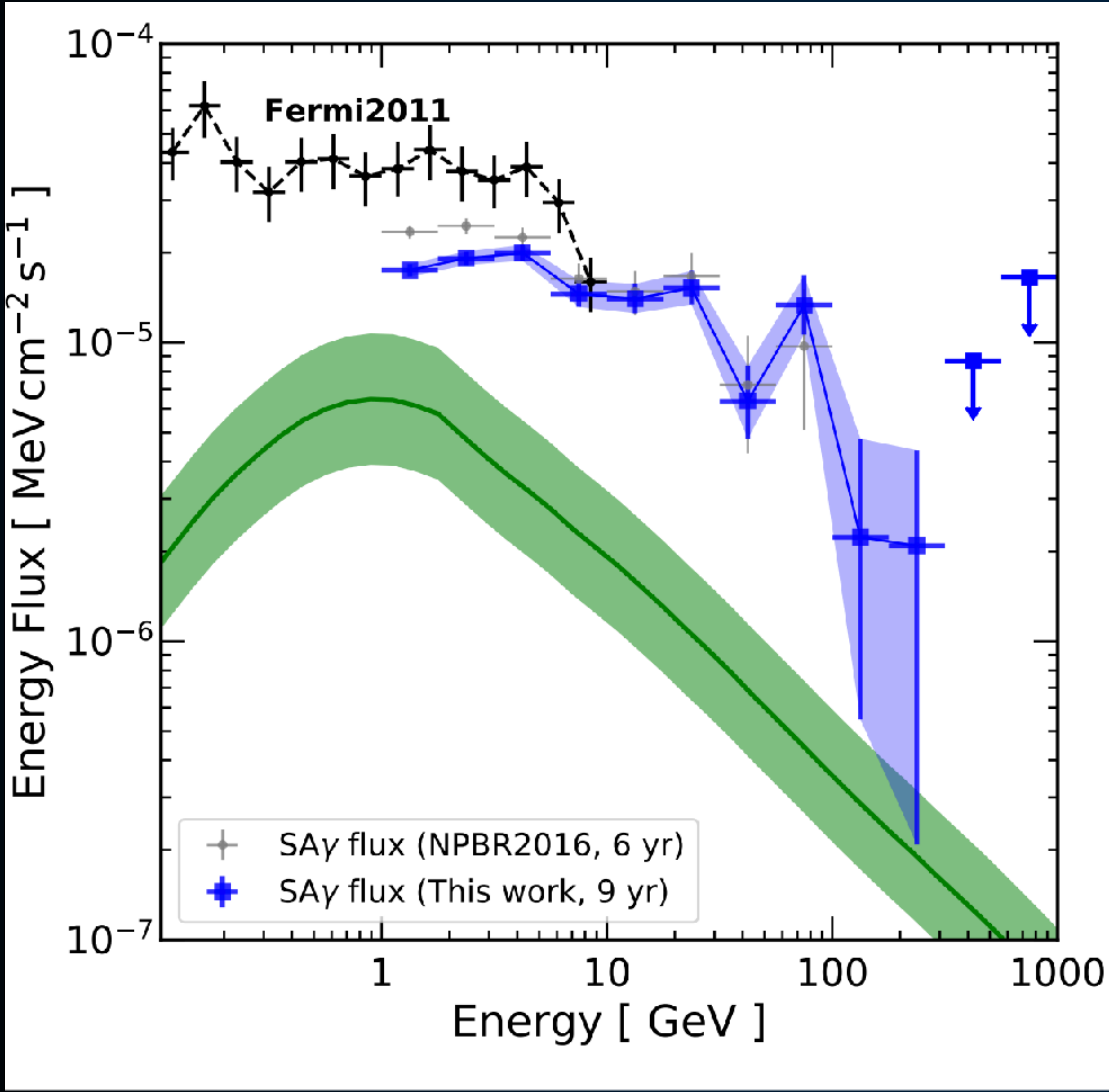
Our Limited Knowledge



Intensity

X

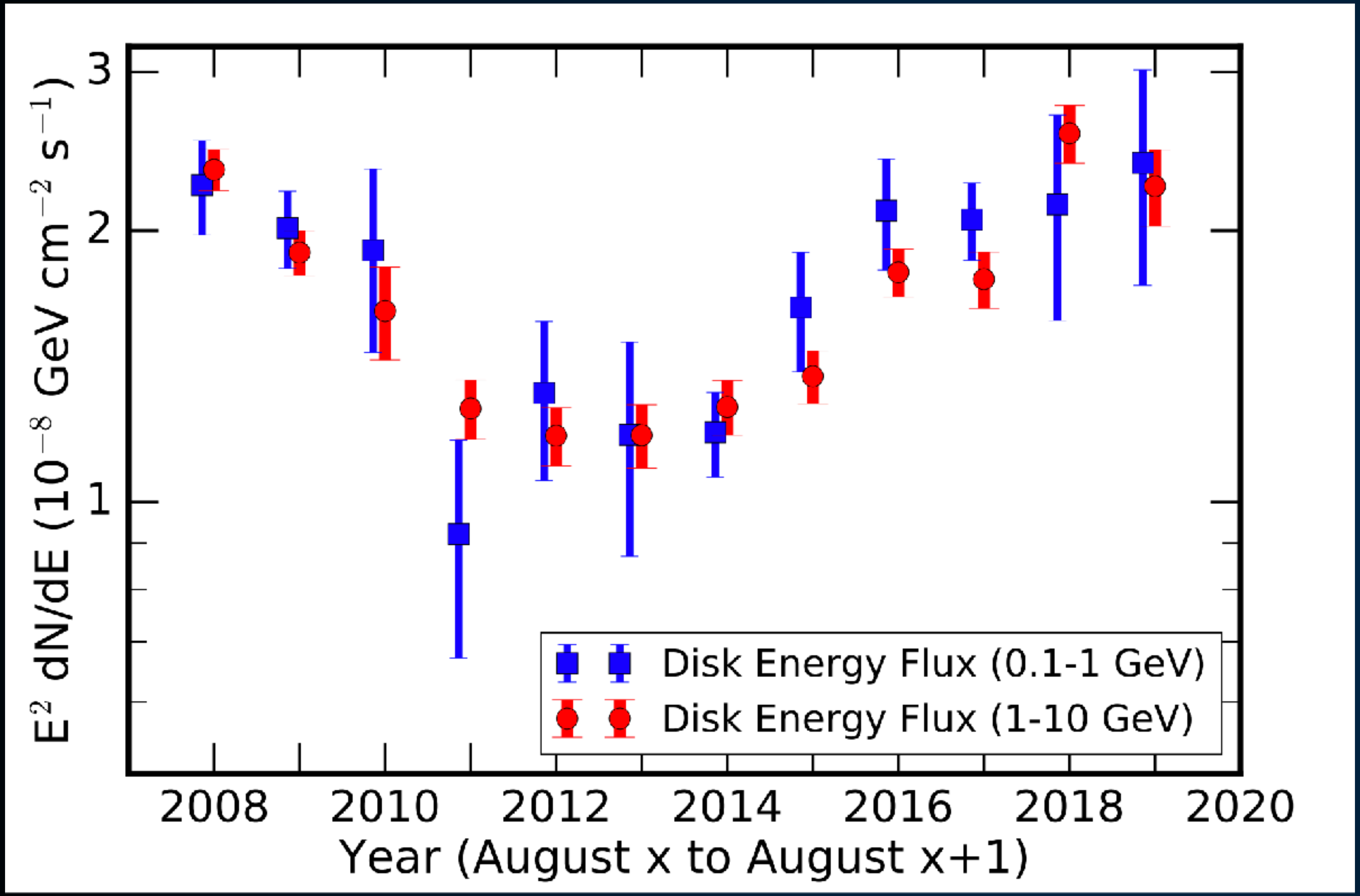
Our Limited Knowledge



Intensity X

Spectrum X

Our Limited Knowledge

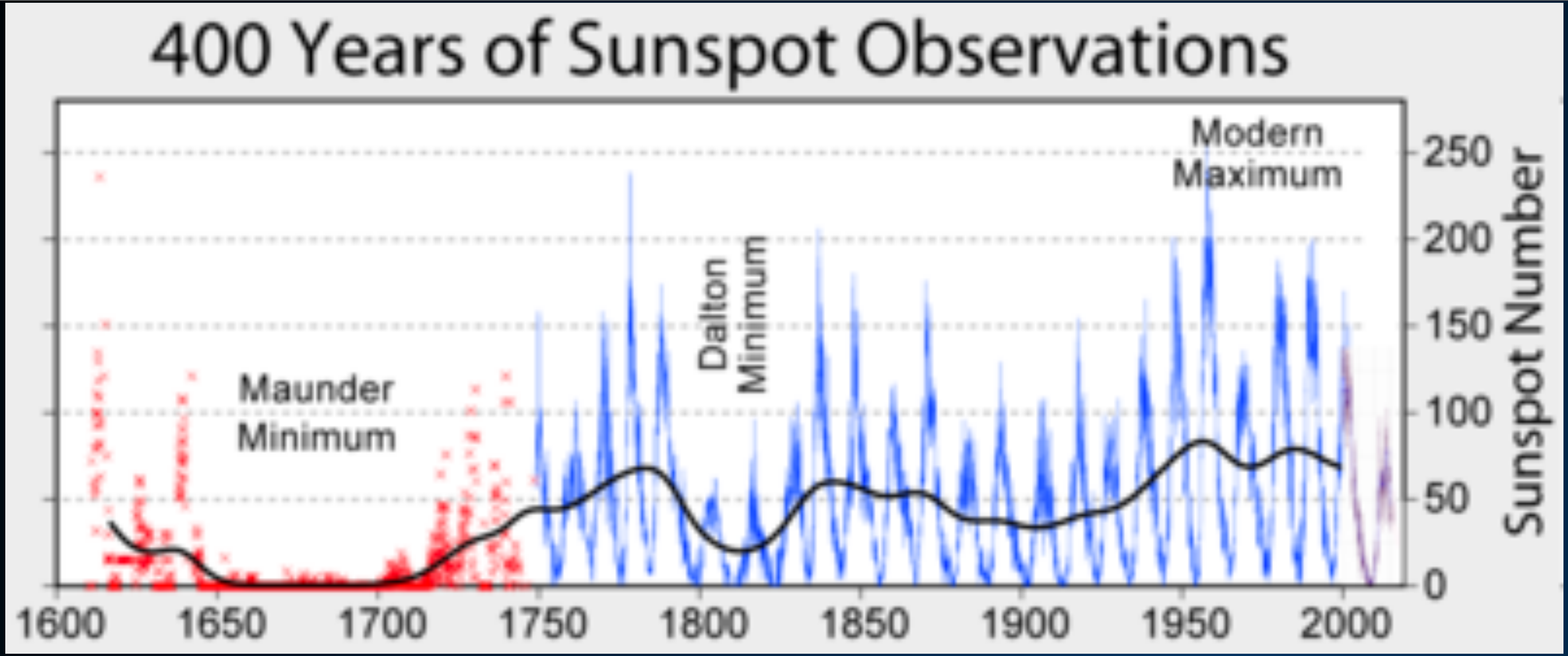


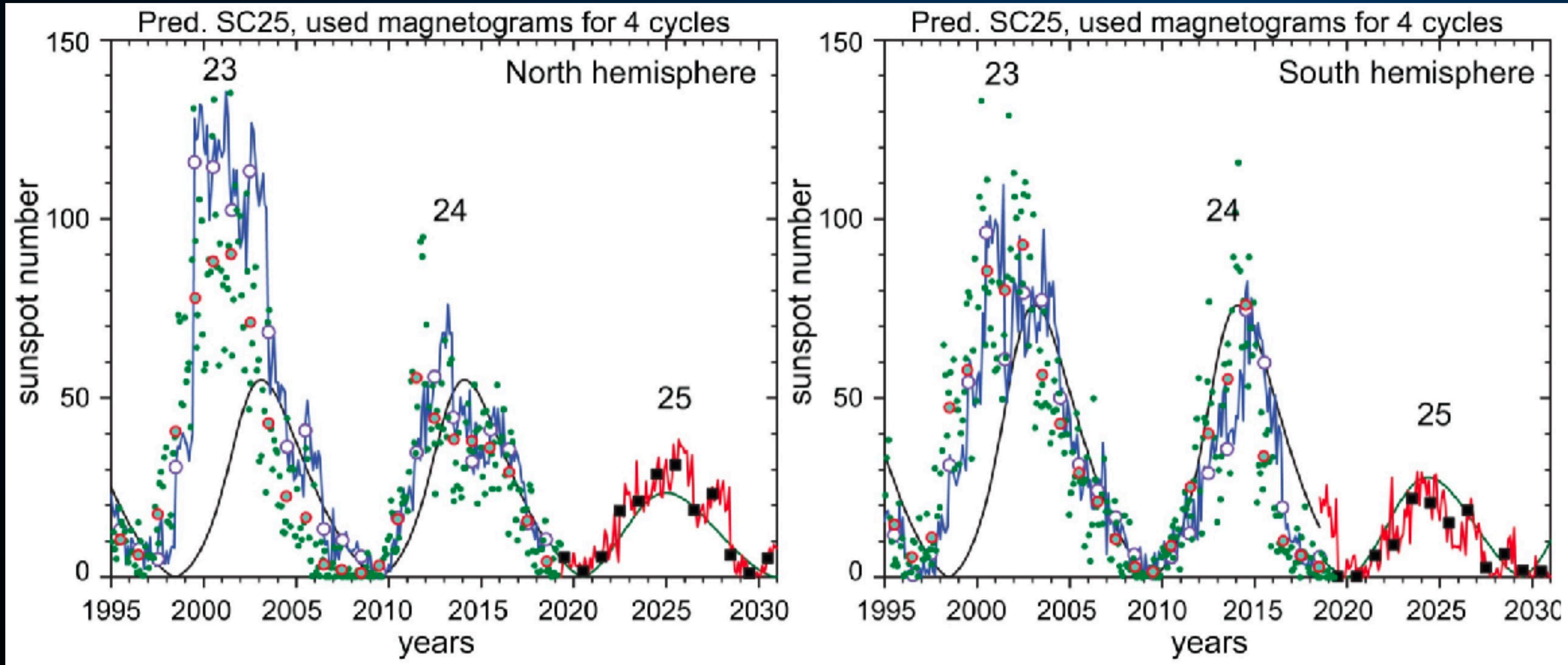
Intensity X

Spectrum X

Time Variability X

Our Limited Knowledge



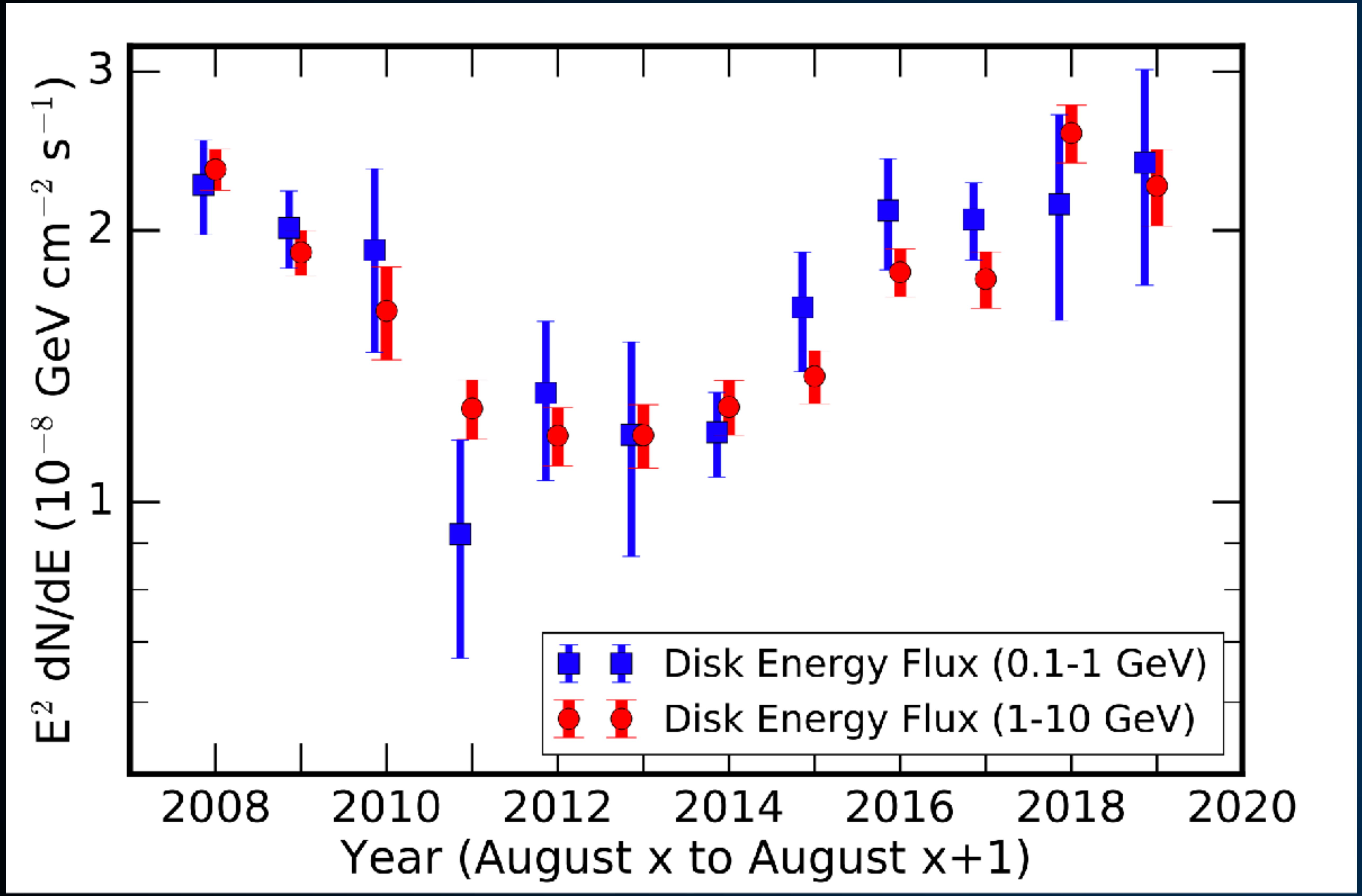


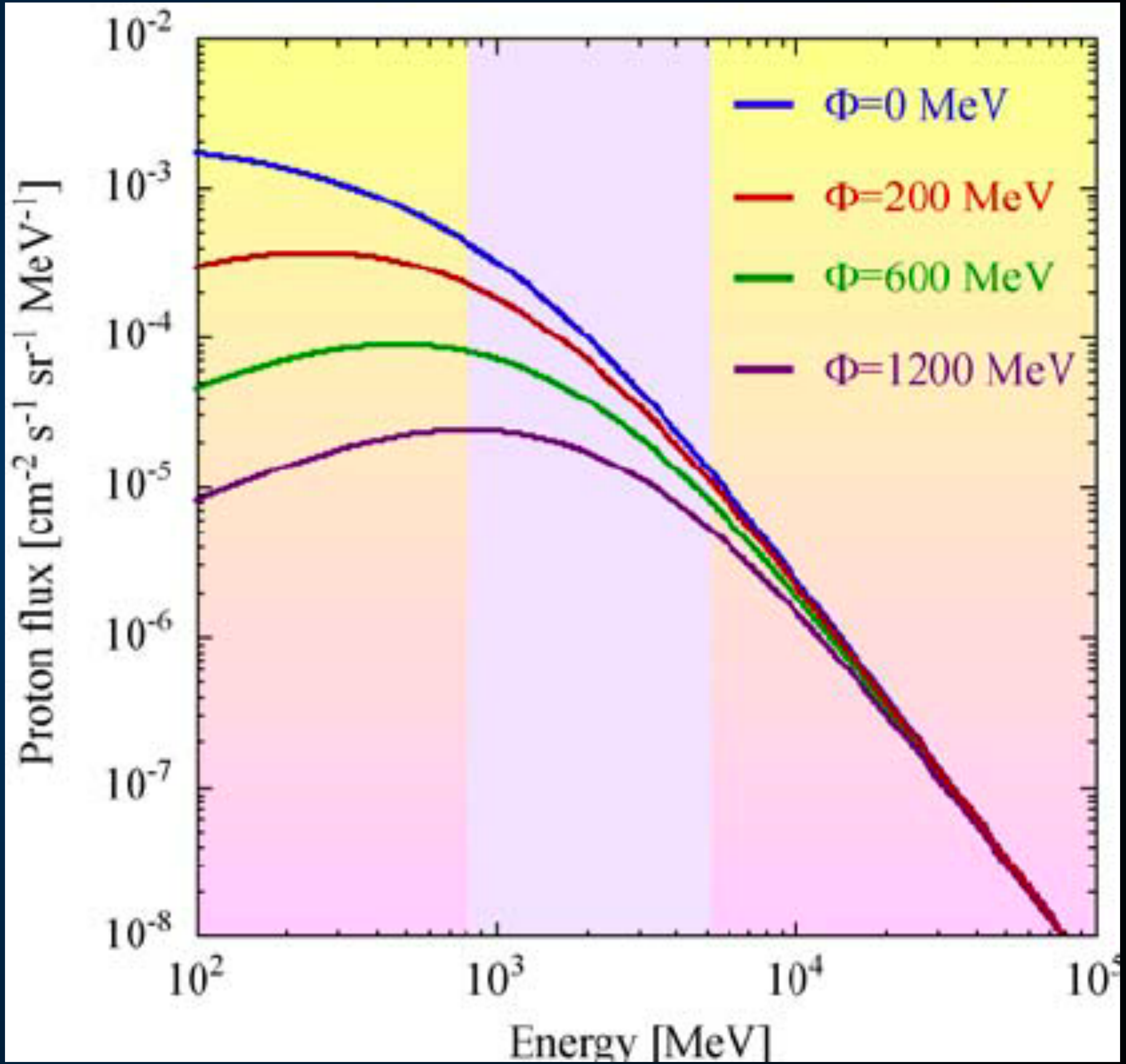
Intensity X

Spectrum X

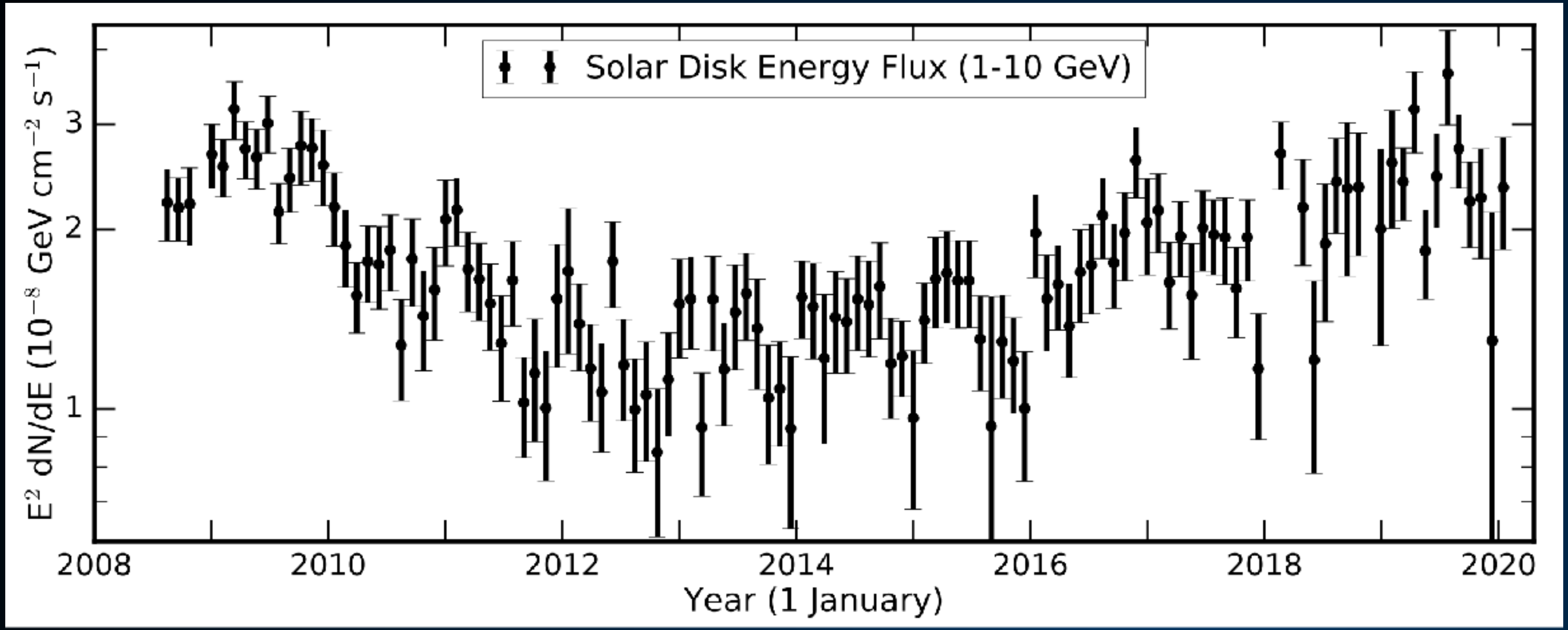
Time Variability X

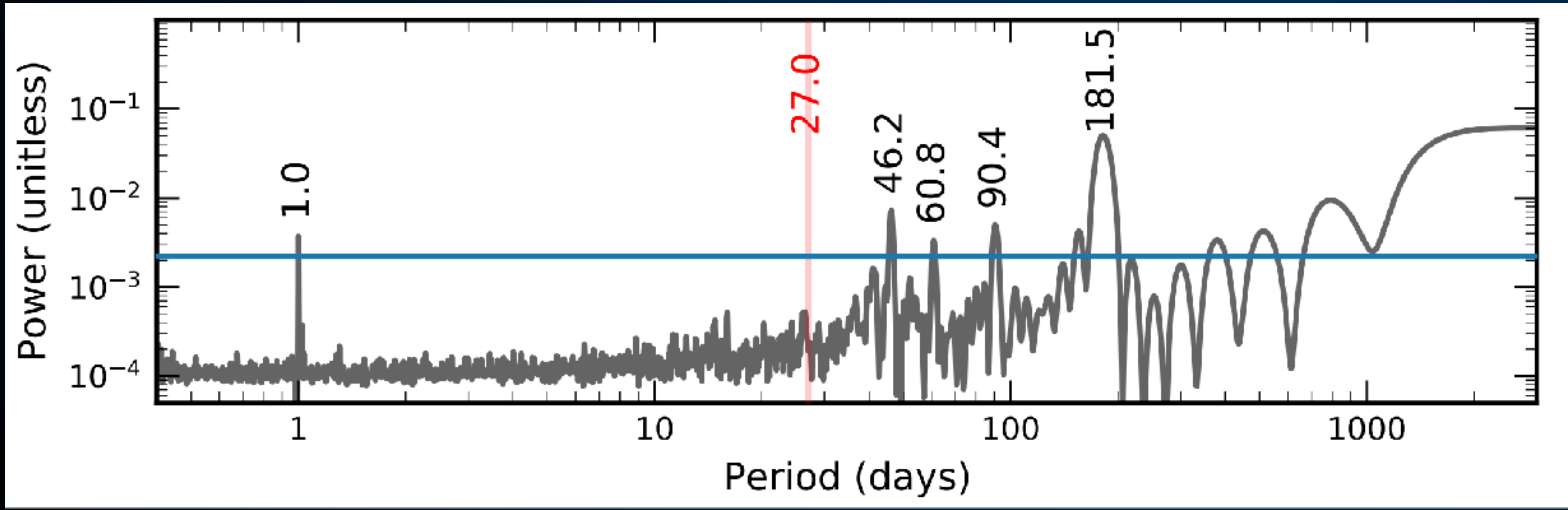
Our Limited Knowledge





Our Limited Knowledge



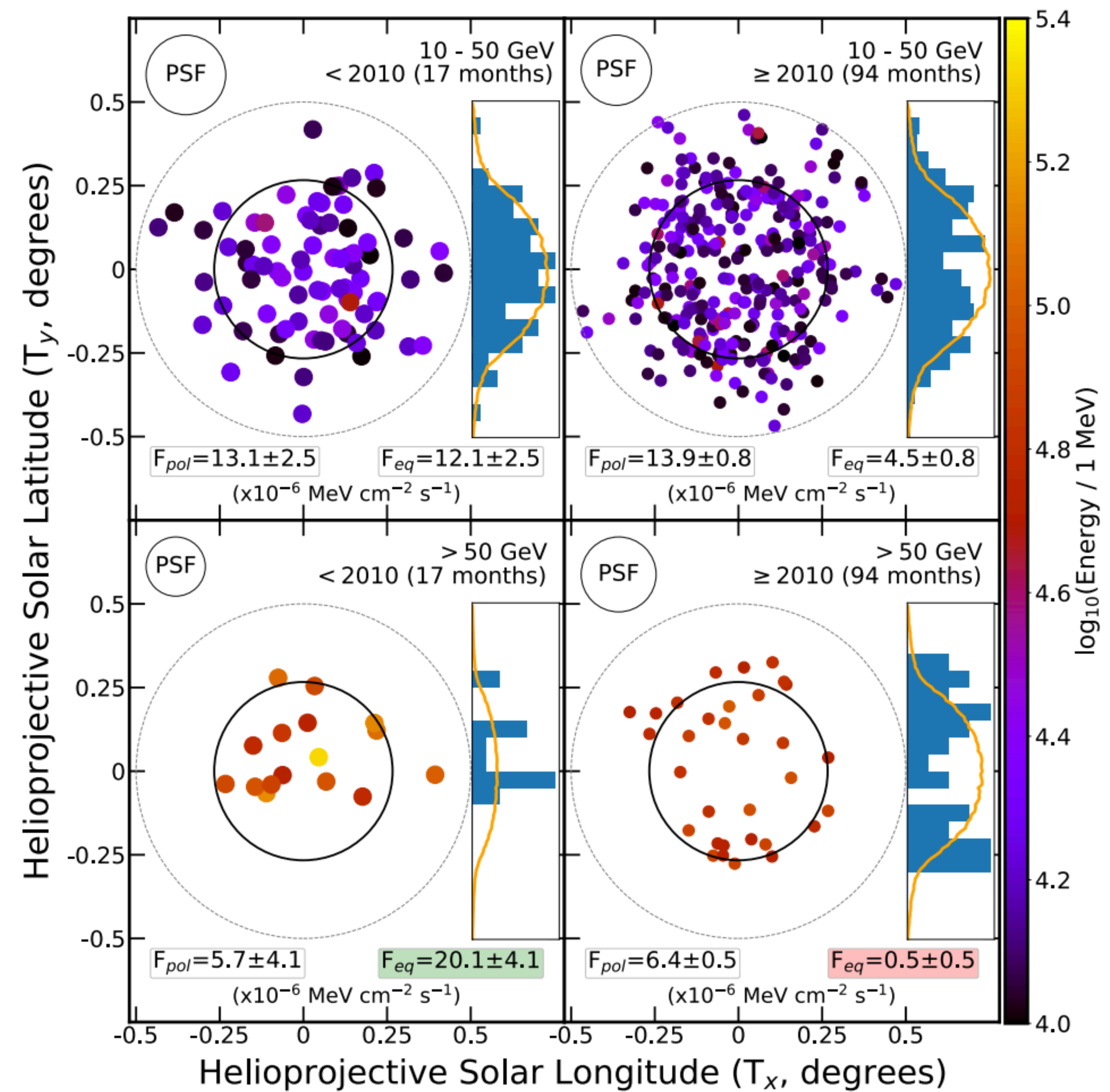


Intensity X

Spectrum X

Time Variability X

Our Limited Knowledge



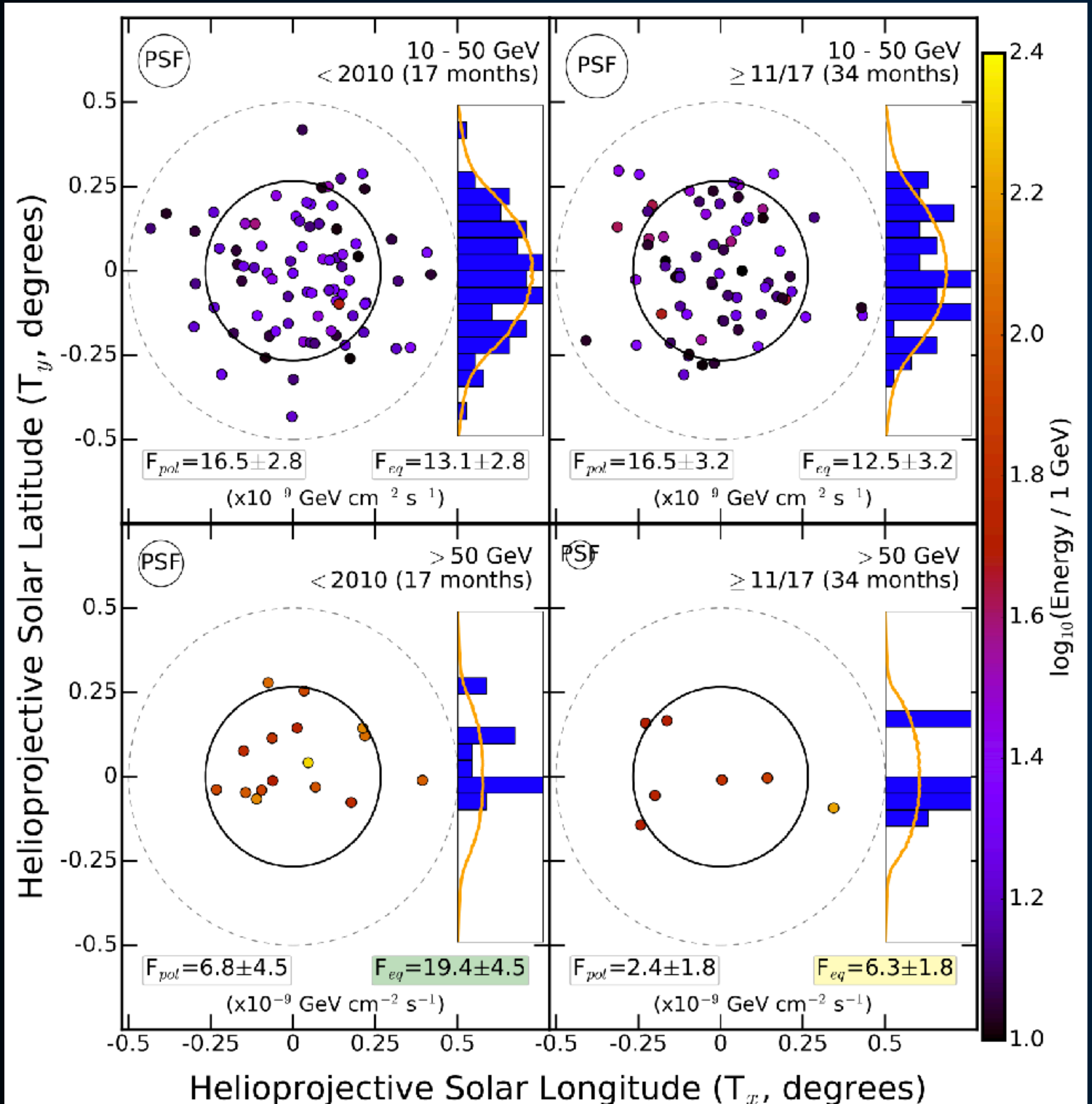
Intensity X

Spectrum X

Time Variability X

Morphology X

Our Limited Knowledge



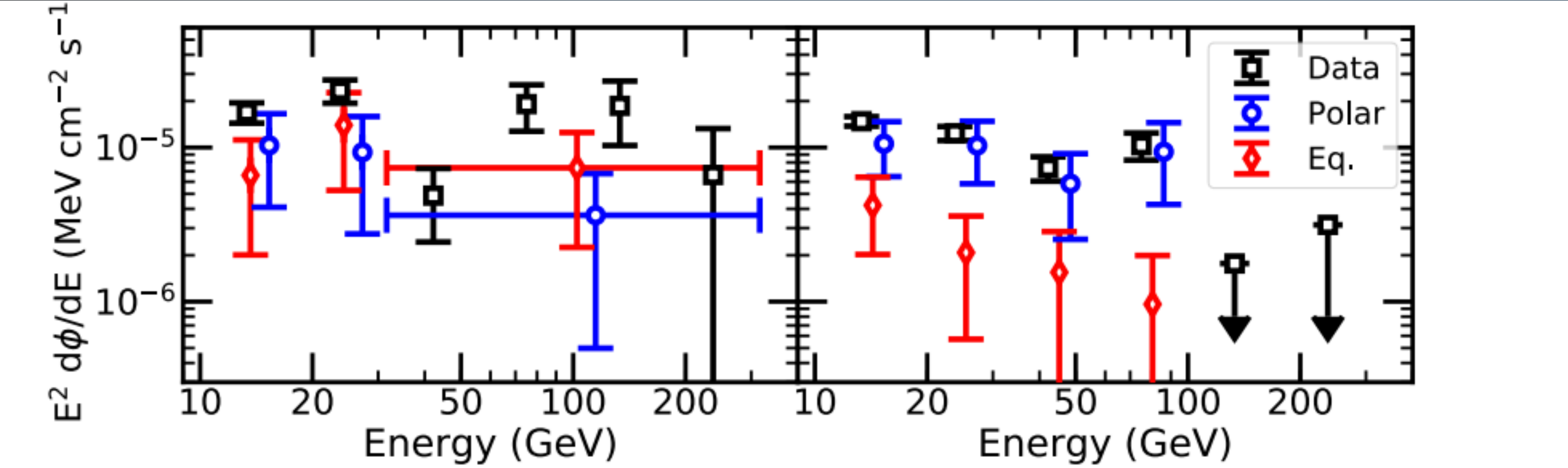
Intensity X

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

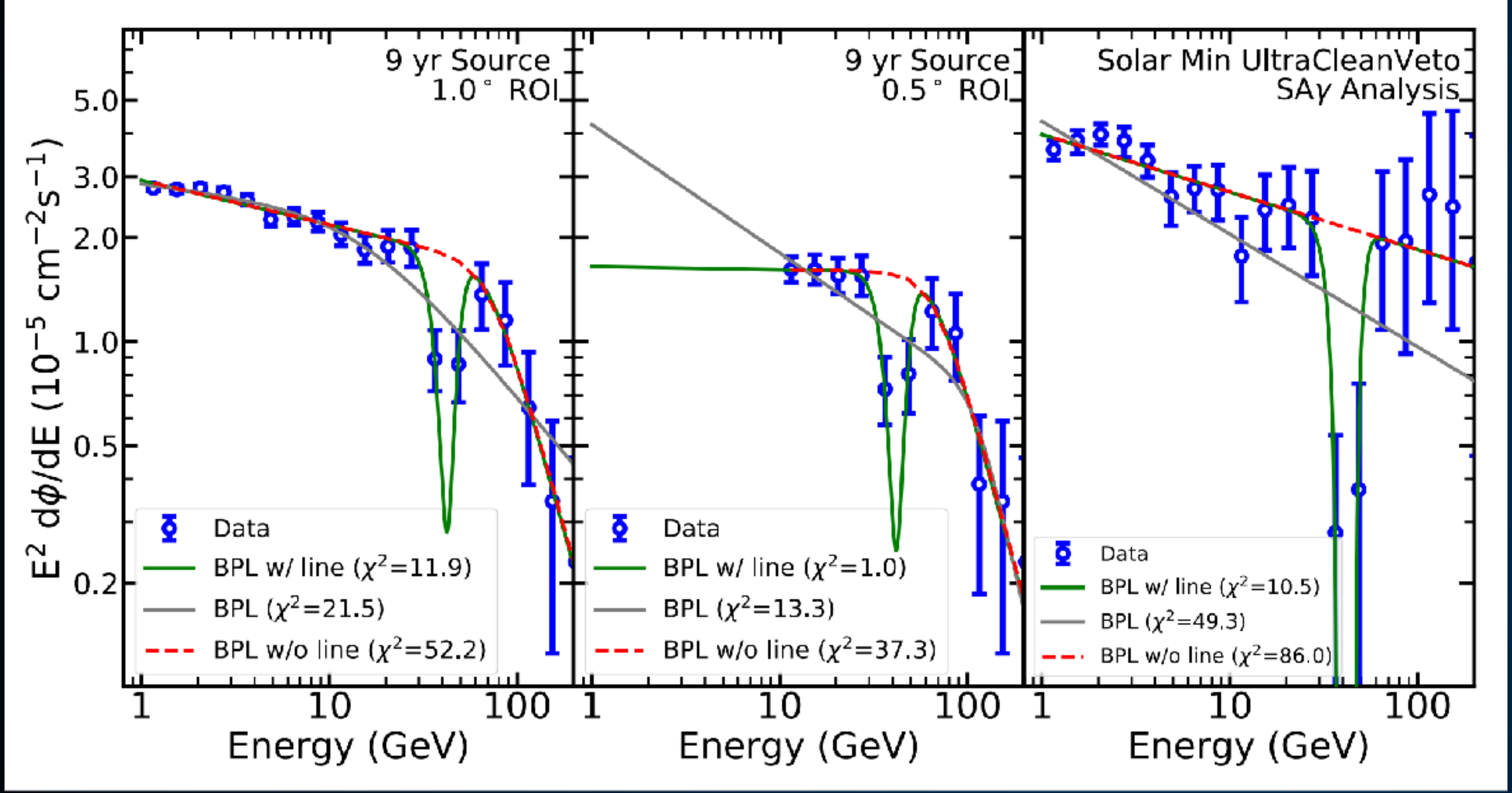
Spectrum X

Time Variability X

Morphology X

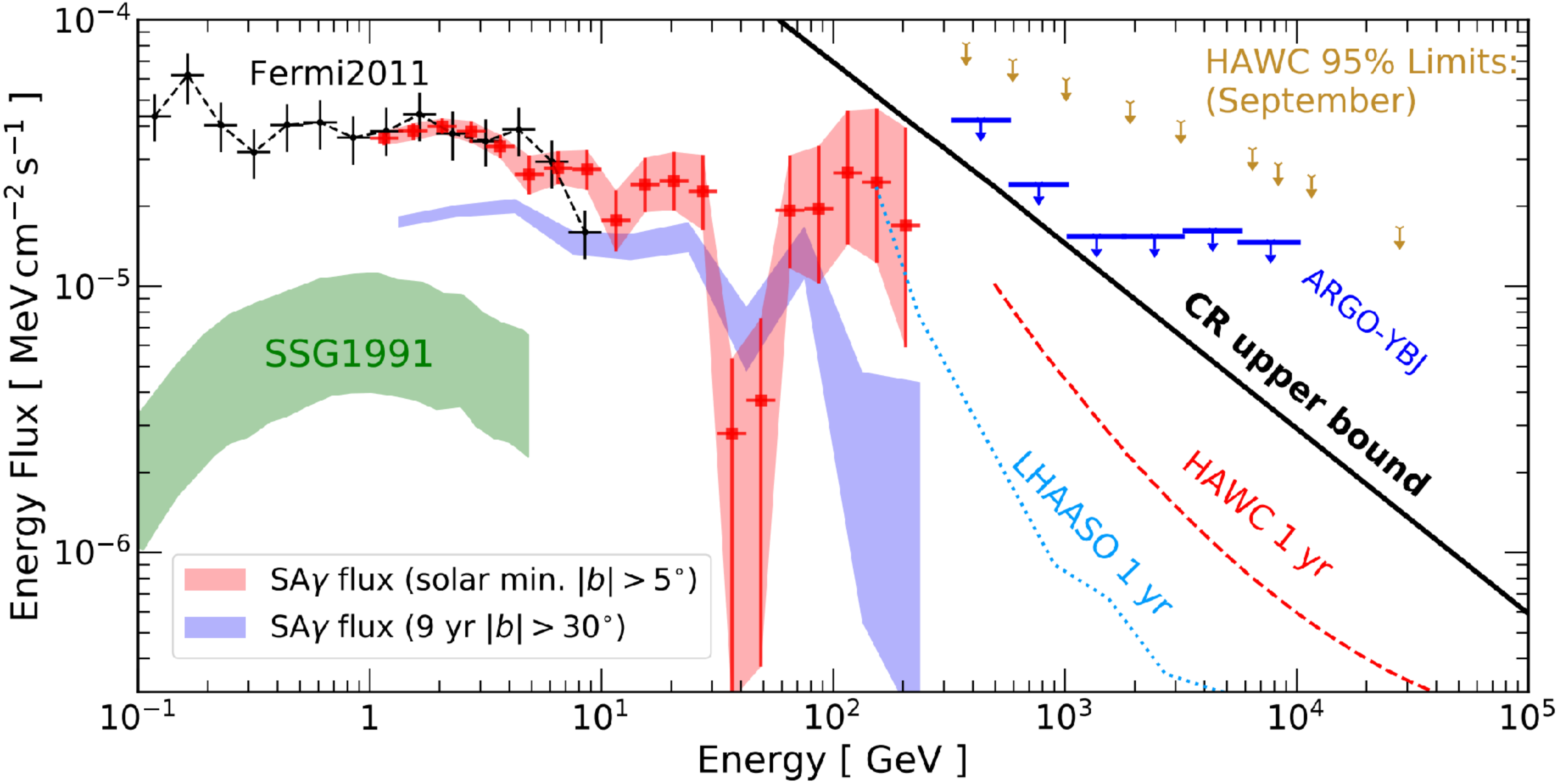
Spectral Variability X

Our Limited Knowledge



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

The Whole Picture

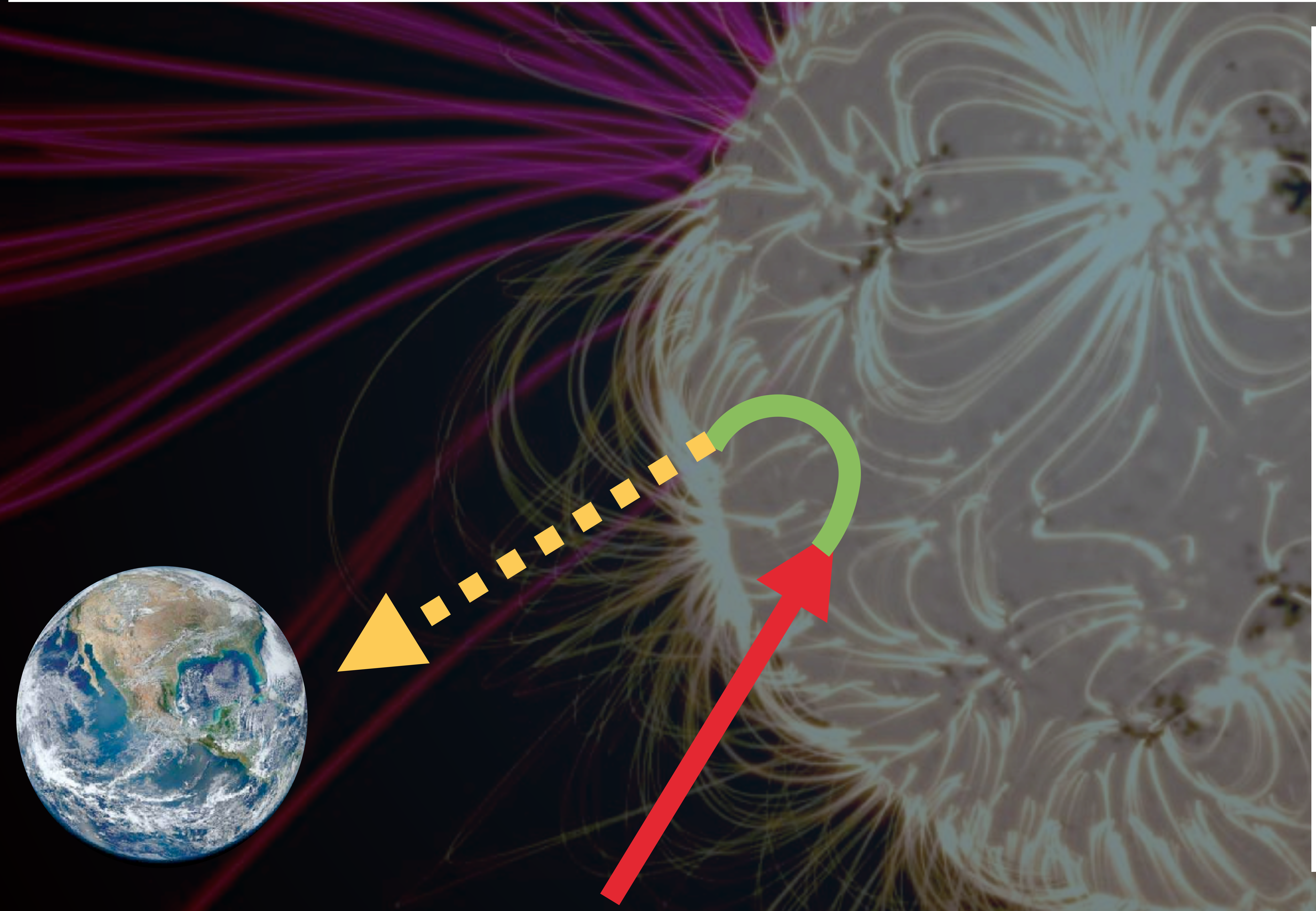


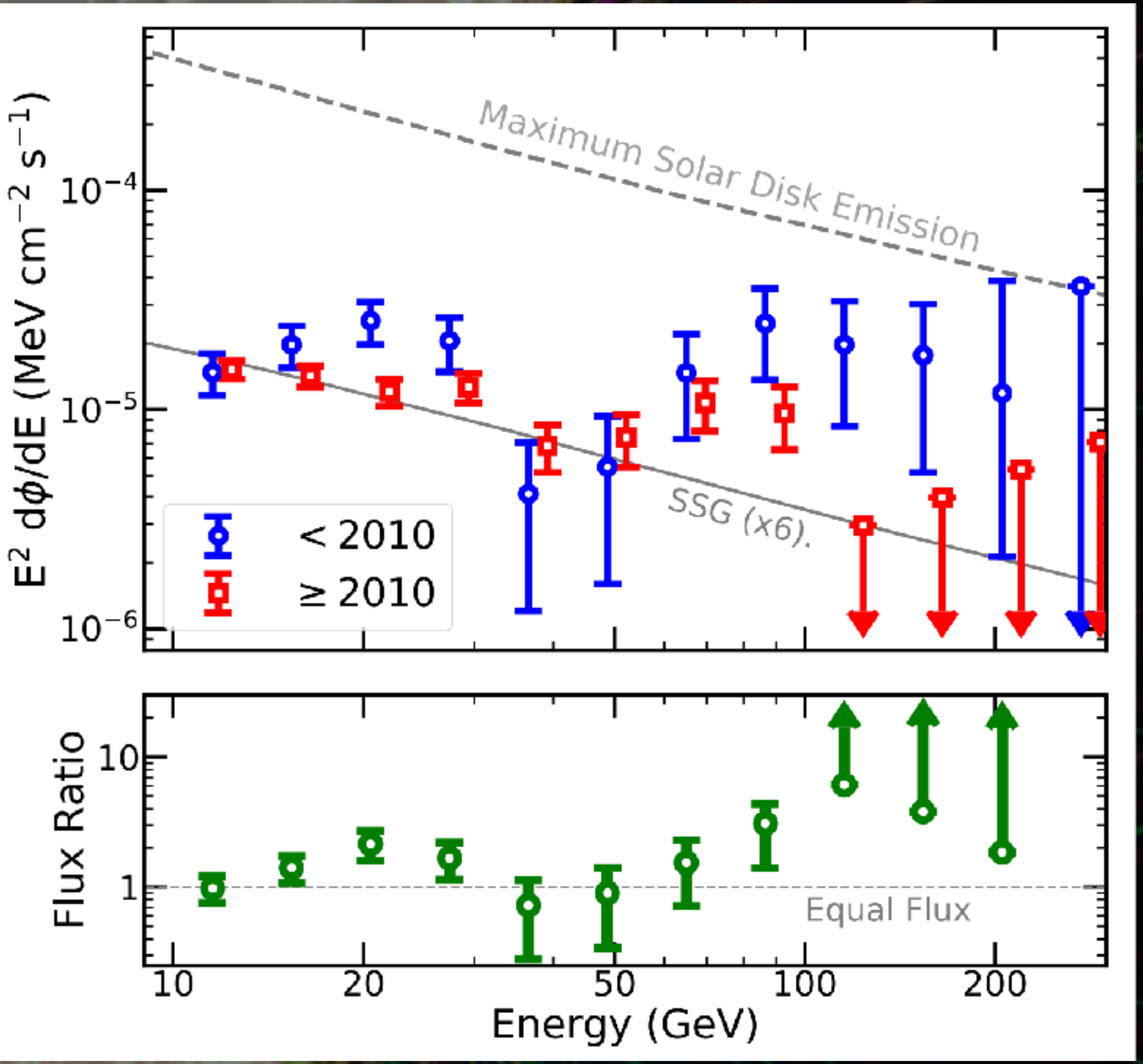
So basically everything is wrong….

How do we model this?

Gamma-Ray Emission much brighter than expected

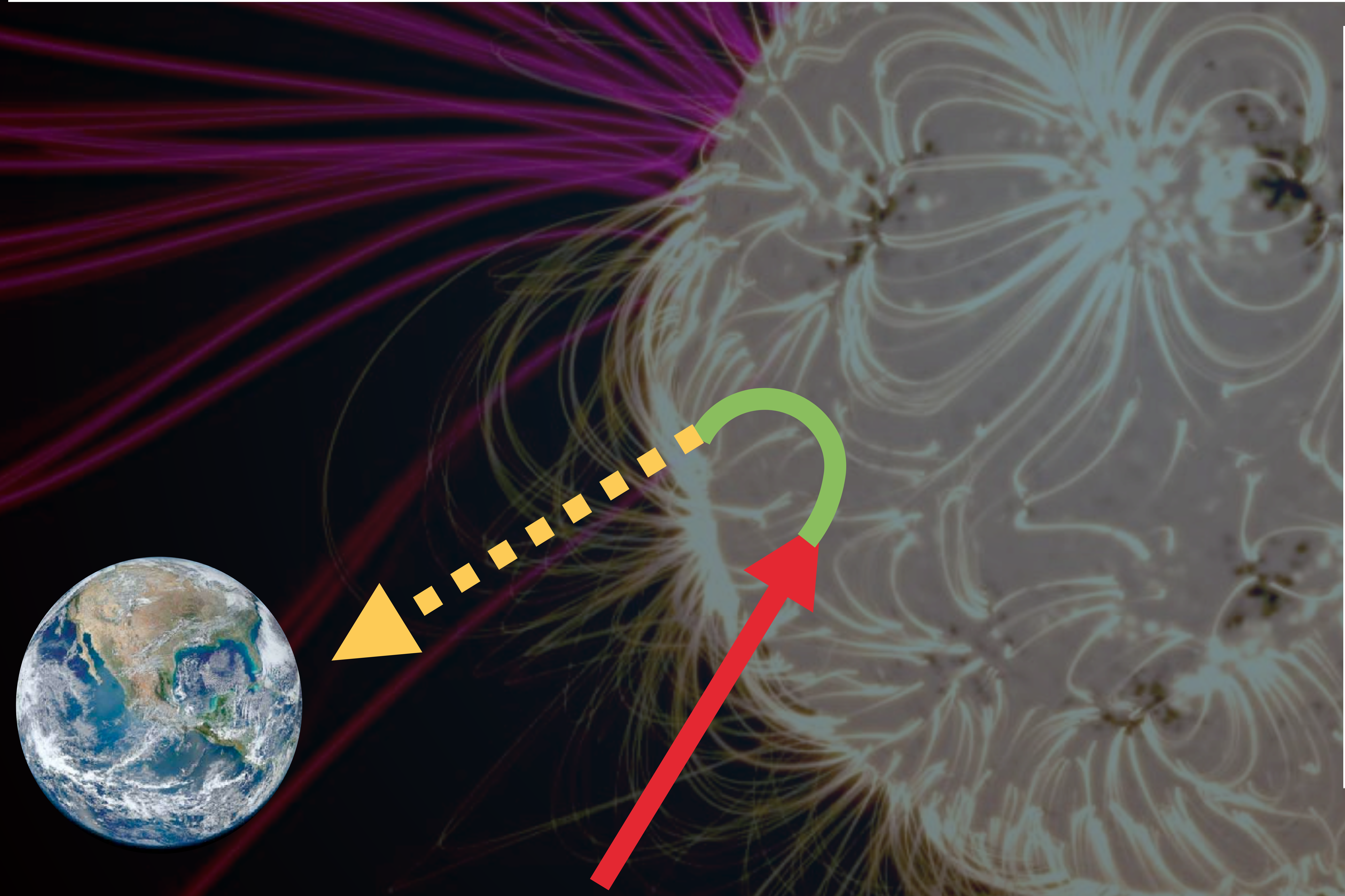
$$\Phi_{\odot}(E_\gamma) = \pi R_{\odot}^2 \Phi_{\mathrm{CR}}(E_{\mathrm{CR}}) C(E_\gamma, E_{\mathrm{CR}}) f_{\mathrm{sur}} f_{\mathrm{turn}} f_{\mathrm{int}}$$

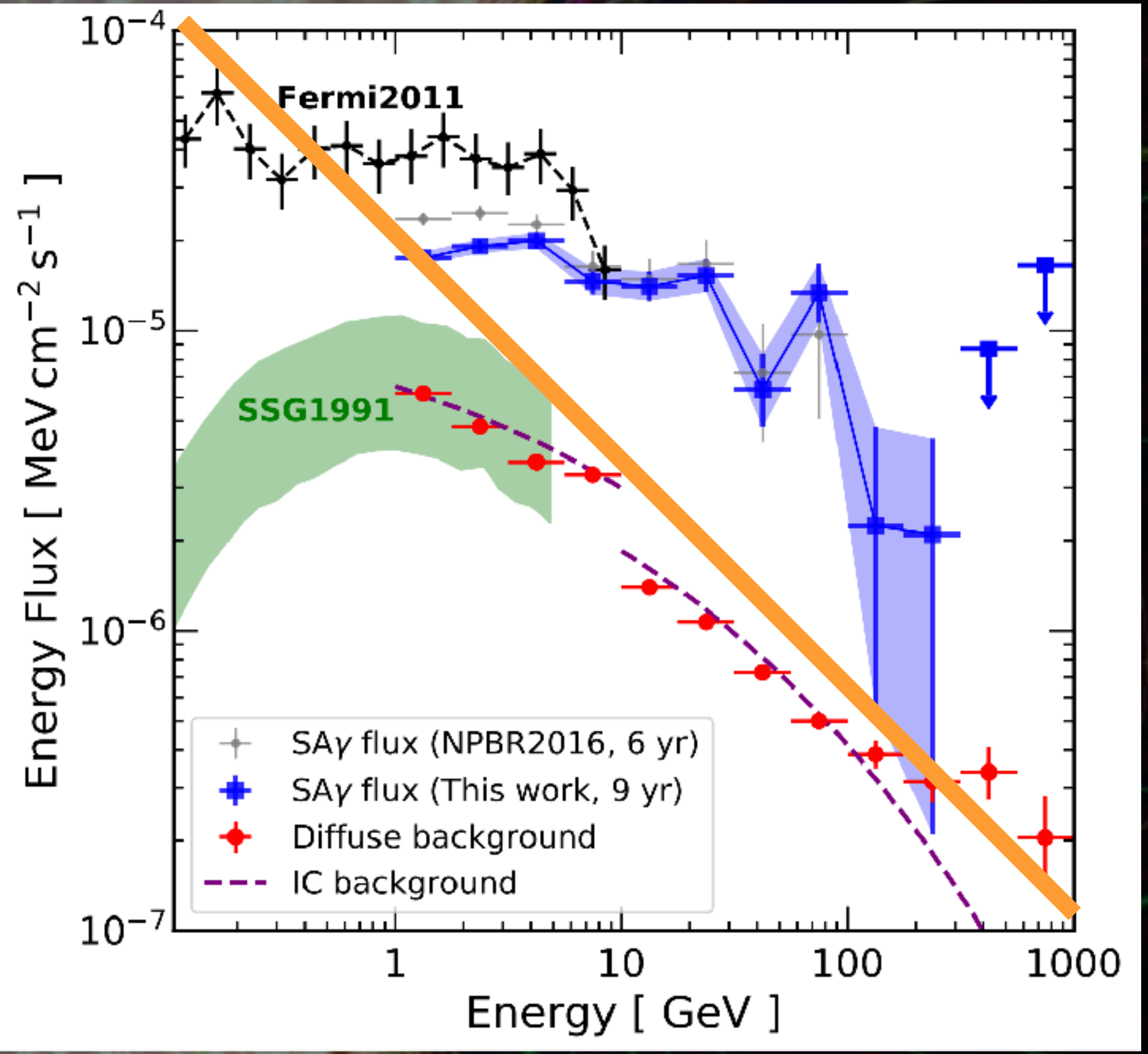




Gamma-Ray Spectrum Harder than Expected

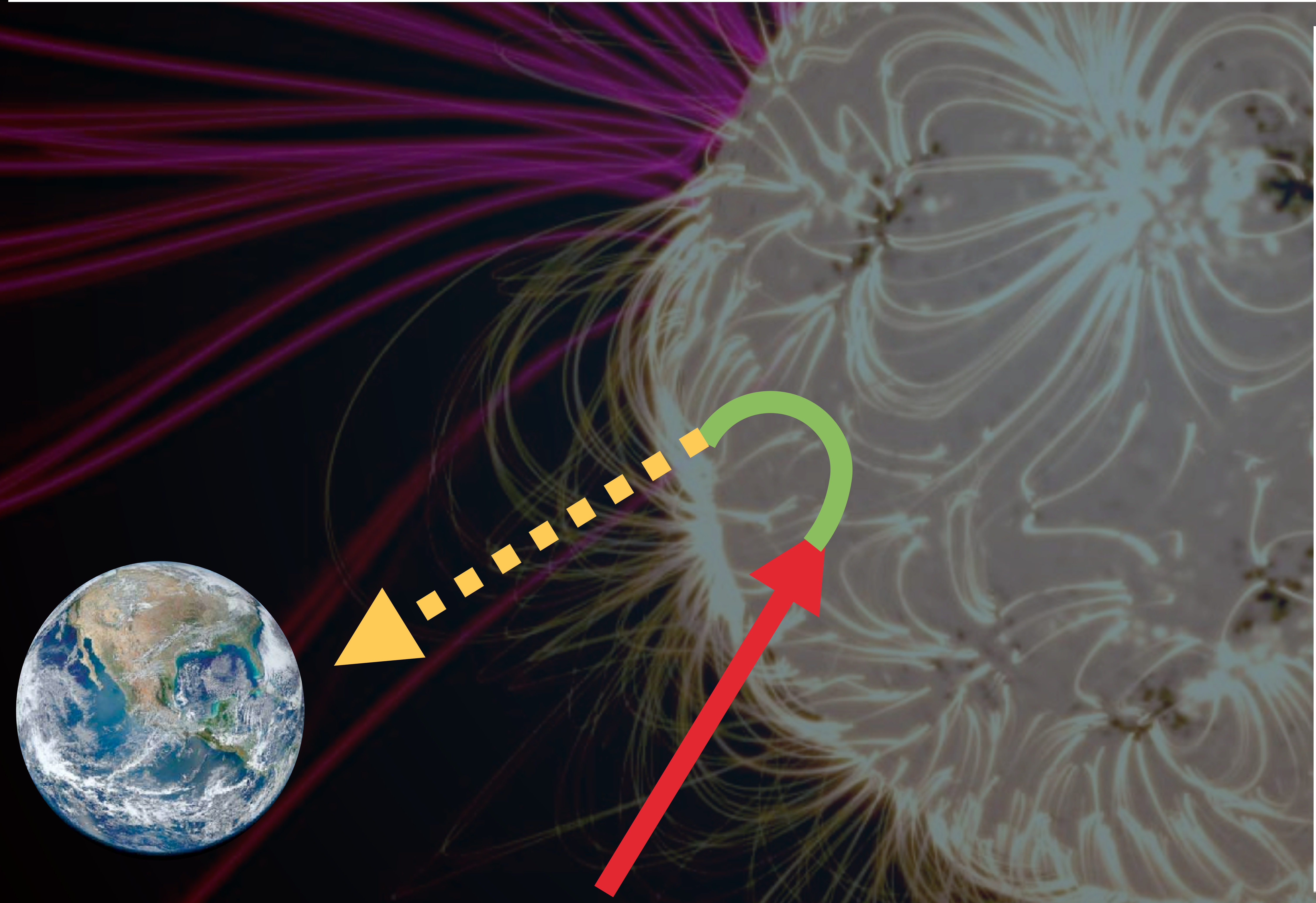
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

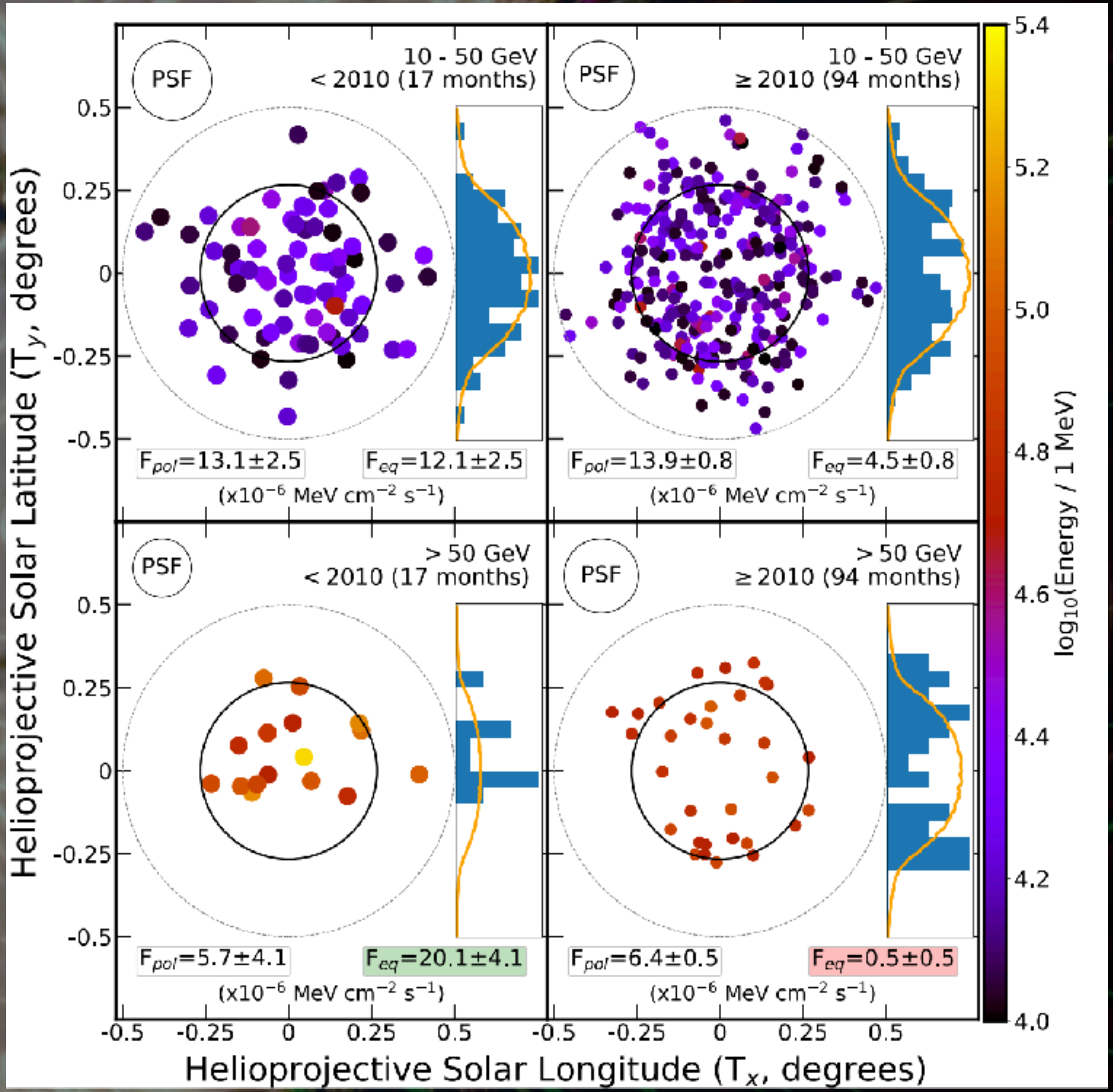




Gamma-Ray Emission Not Uniform

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





Two Different Emission Mechanisms?

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

How?

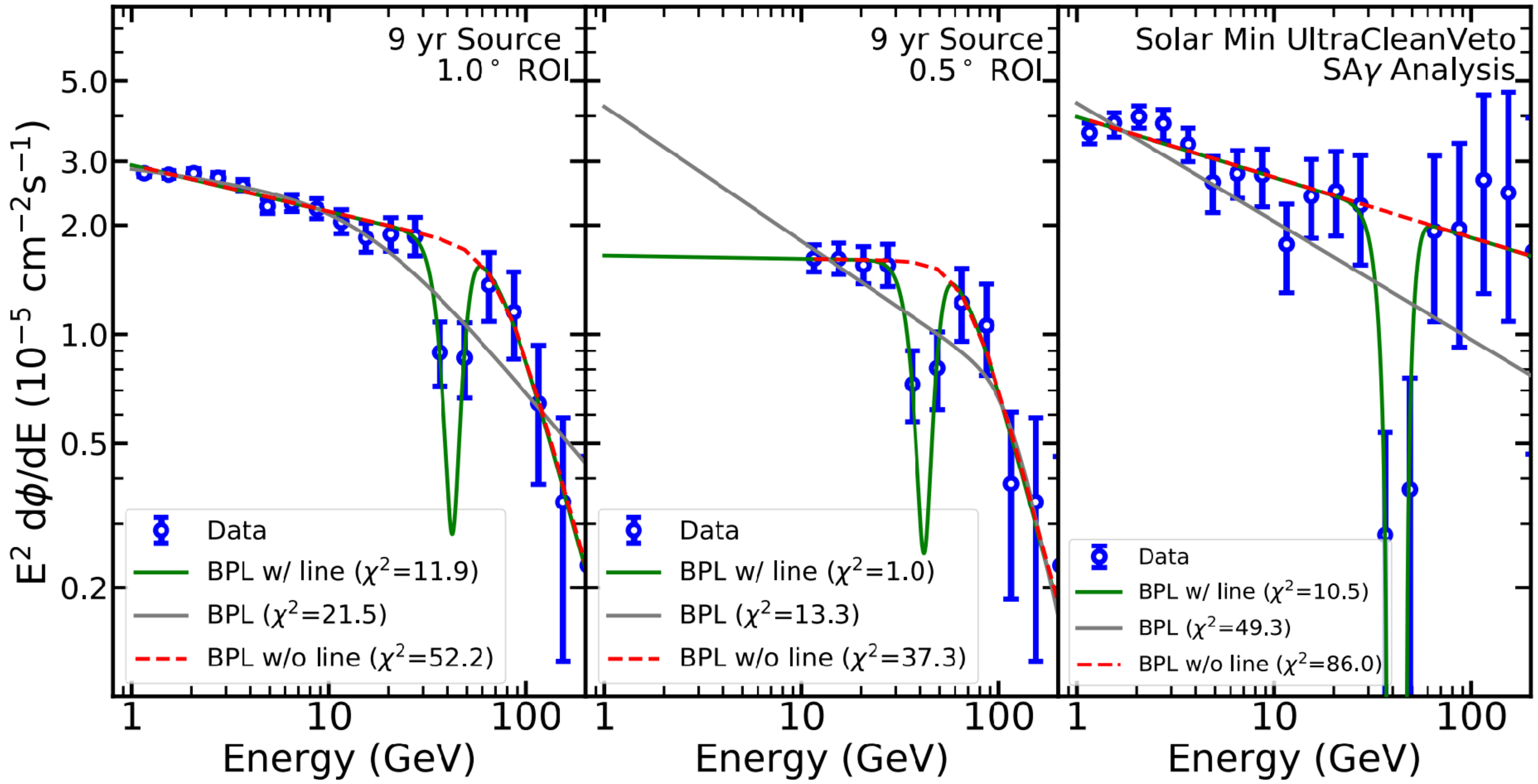
- Possibilities
  - Anisotropic gamma-ray emission
  - Cosmic-Ray Storage

What About this spectral dip?

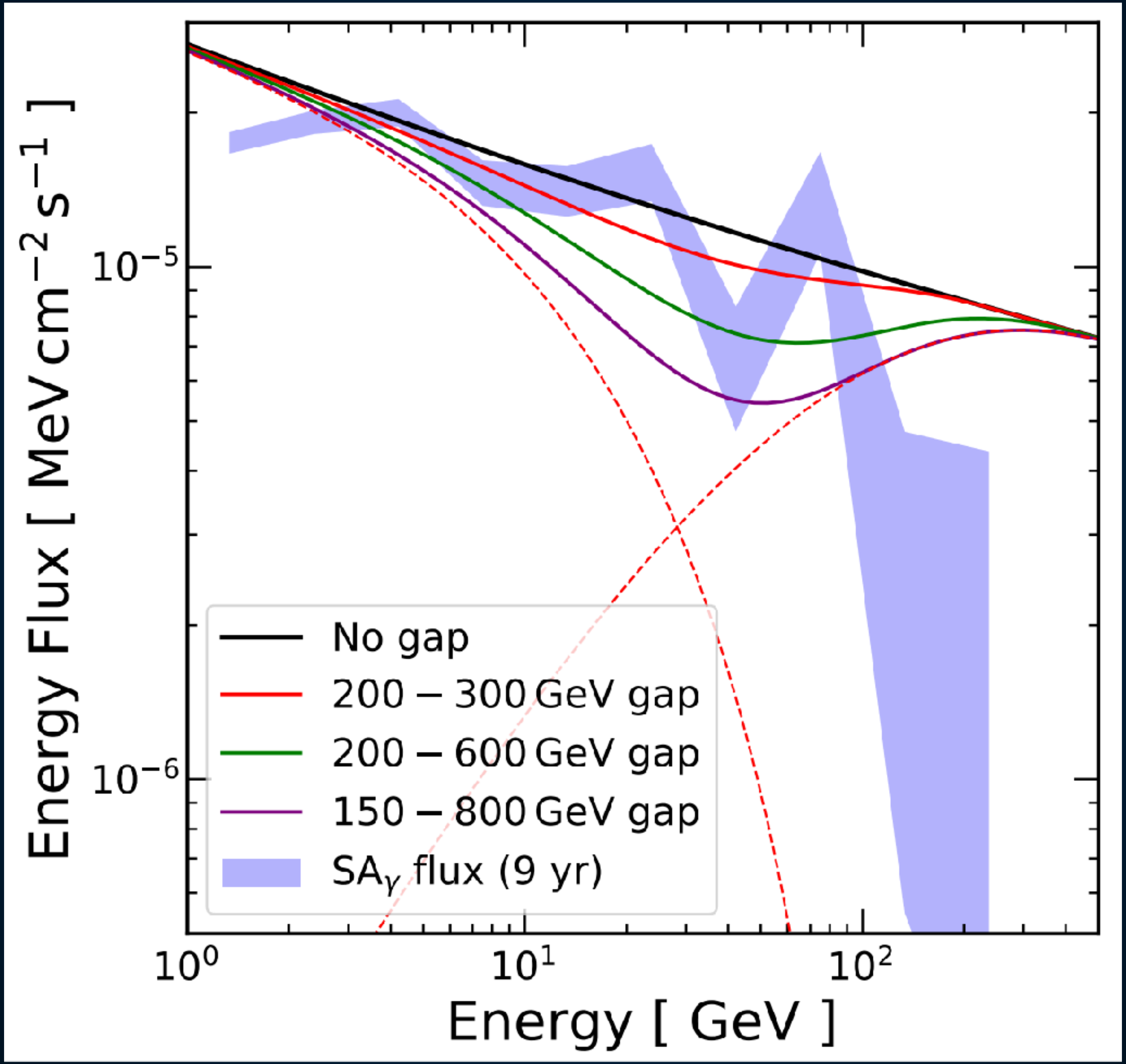
How?

?

The Spectral Dip



How?



Energy Flux [MeV cm^{-2} s^{-1}]
10^{-5}
10^{-6}
10^0
10^1
10^2
Energy [GeV]
No gap
200 – 300 GeV gap
200 – 600 GeV gap
150 – 800 GeV gap
SA$_\gamma$ flux (9 yr)

Fermi Solar Panel

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

Tim Linden,[1,*] Bei Zhou,[1,2,†] John F. Beacom,[1,2,3,‡] Annika H. G. Peter,[1,2,3,§] Kenny C. Y. Ng,[4,¶] and Qing-Wen Tang[1,5,**]

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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.

03.05436v1 [astro-ph.HE] 14 Mar 2018

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 γ-ray emission was based on Fermi-LAT data from 2008–2014 [13] (for earlier work, see Refs. [9, 14]), and produced three results. First, the flux is bright, e.g., at 10 GeV, it exceeds the flux expected from Earth-directed cosmic rays interacting with the solar limb by a factor $\gtrsim$50 [15]. Second, it continues to 100 GeV, requiring proton energies $\sim$1000 GeV. Third, the 1–10 GeV flux is anti-correlated with solar activity, and is $\sim$2.5× larger at solar minimum than maximum. The *only* theoretical model of disk emission is the 1991 paper of Seckel, Stanev, and Gaisser (SSG) [16], which proposes that magnetic flux tubes can reverse incoming protons deep within the solar atmosphere, where they have an appreciable probability of

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 γ-ray emission is brighter and more mysterious than expected, it motivates new searches with Fermi [18], the higher-energy HAWC γ-ray experiment [19], and the IceCube neutrino observatory [20]. The results will yield valuable insights on the complex, dynamic solar magnetic environment, from cosmic-ray modulation in the solar system to the fields deep within the photosphere. They will also advance searches for new physics [21–29]. Most generally, these searches provide the highest-energy data available in the program to understand the Sun as an example of other stars.

Methodology.— We utilize front and back Pass 8 Source

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

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

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[3]*Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
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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.

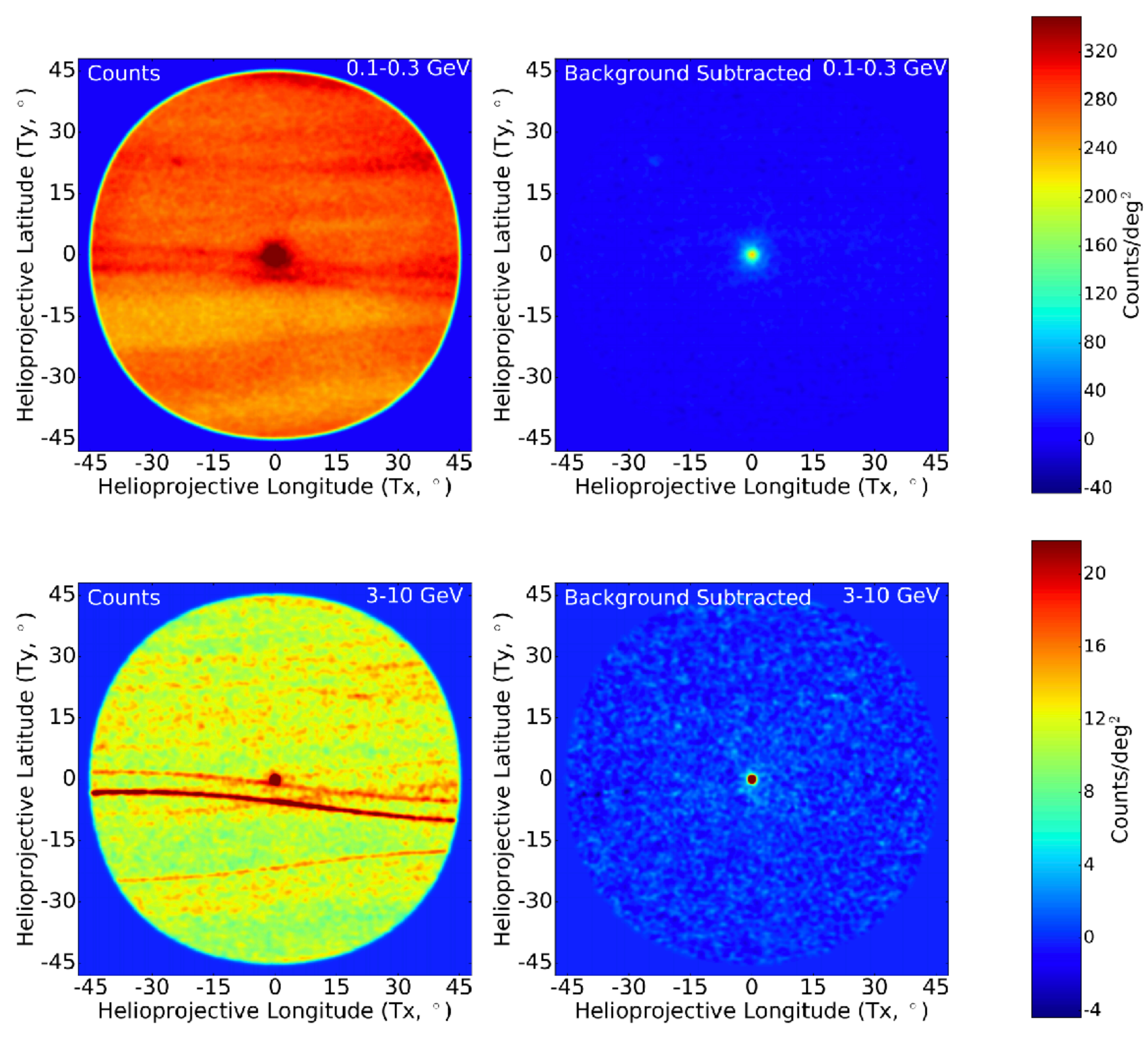
I. INTRODUCTION

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 acceleration and interactions in the Sun's complex, dynamic magnetic fields. In addition, the "space weather" induced by these processes affects Earth's atmosphere and our technological infrastructure, giving these studies practical as well as scientific importance [1].

The highest-energy processes are revealed by γ-ray observations up to $\sim$200 GeV, which correspond to charged par-

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 by the Fermi Gamma-Ray Space Telescope (Fermi). Near 1 GeV, there is also a "backsplash" component from the whole disk, as kinematics allow low-energy γ-rays to be emitted at a large angle relative to the parent cosmic ray [15].

Of course, the Sun does have magnetic fields. Seckel, Stanev, and Gaisser (SSG [16]) hypothesized that surface fields allow emission from the full disk even at high energies.



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
320
280
240
200
160
120
80
40
0
-40
Counts/deg^2
20
16
12
8
4
0
-4
Counts/deg^2

Spectrum

Solar Disk Flux
Aug. 2008 - Feb. 2020
Full Dataset
LAT Flares Removed
LAT/GBM Flares Removed
E^2 dN/dE (10^{-8} GeV cm^{-2} s^{-1})
Energy (GeV)
0.1
1
10
100
0.5
1
2
3
5

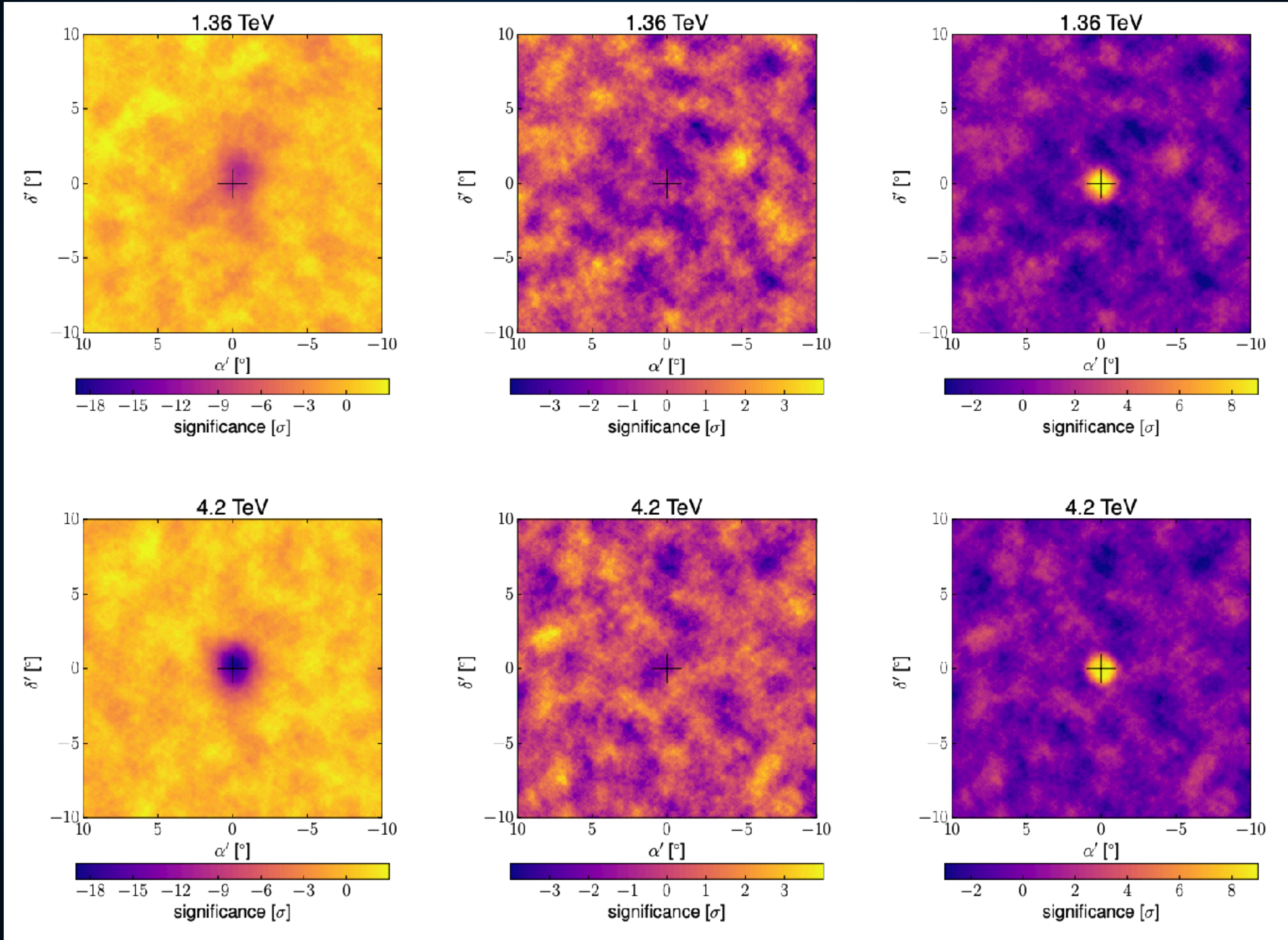
Spectrum

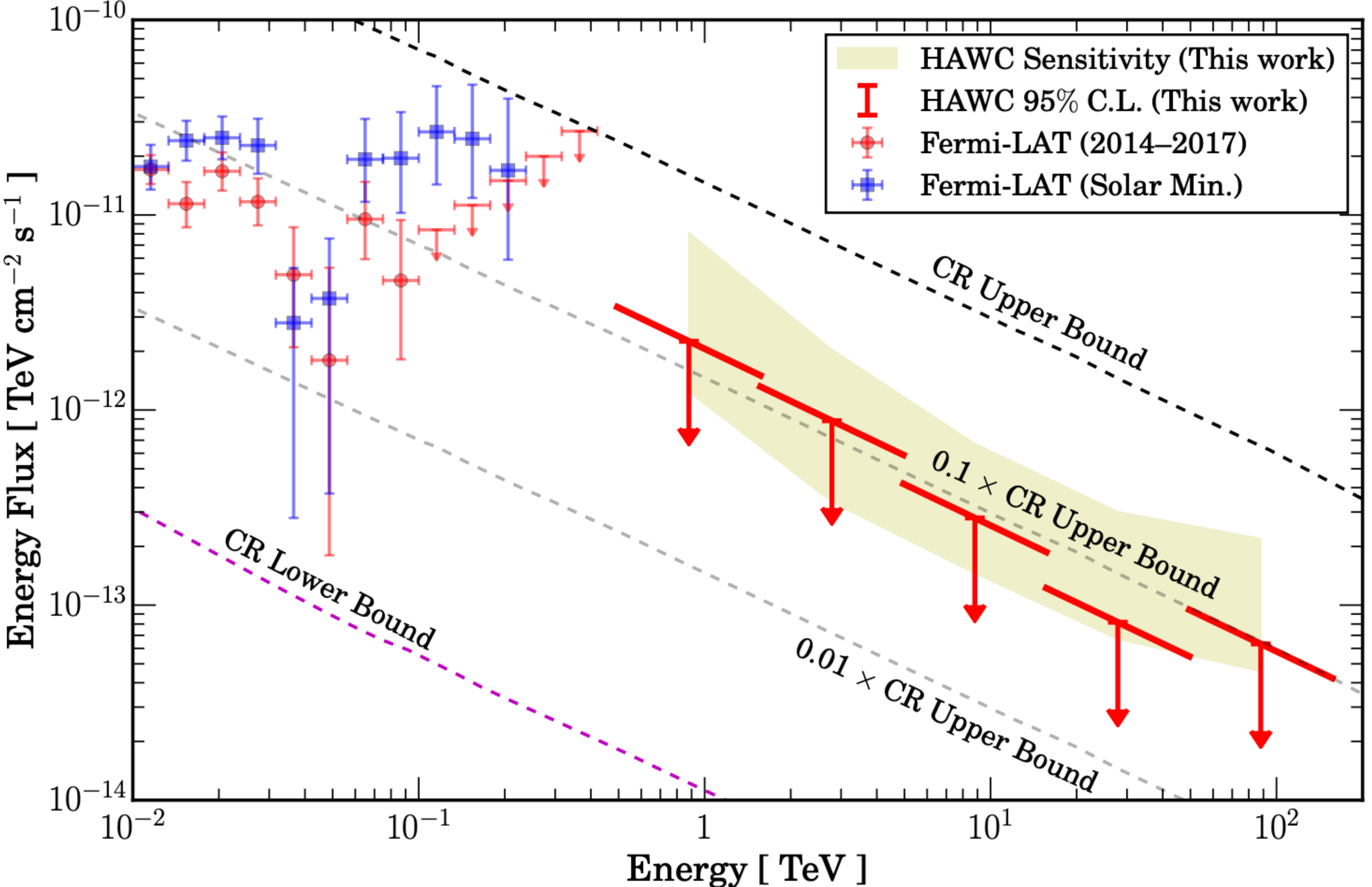
E^2 dN/dE (10^{-8} GeV cm^{-2} s^{-1})
5
3
2
1
0.5
0.1
1
10
Energy (GeV)
Full Solar Cycle (This Paper)
Fermi 2011 (Solar Min)
Solar Min (This Paper)


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}

Conclusions - Astrophysics

We see, but we don't understand.

Help?

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