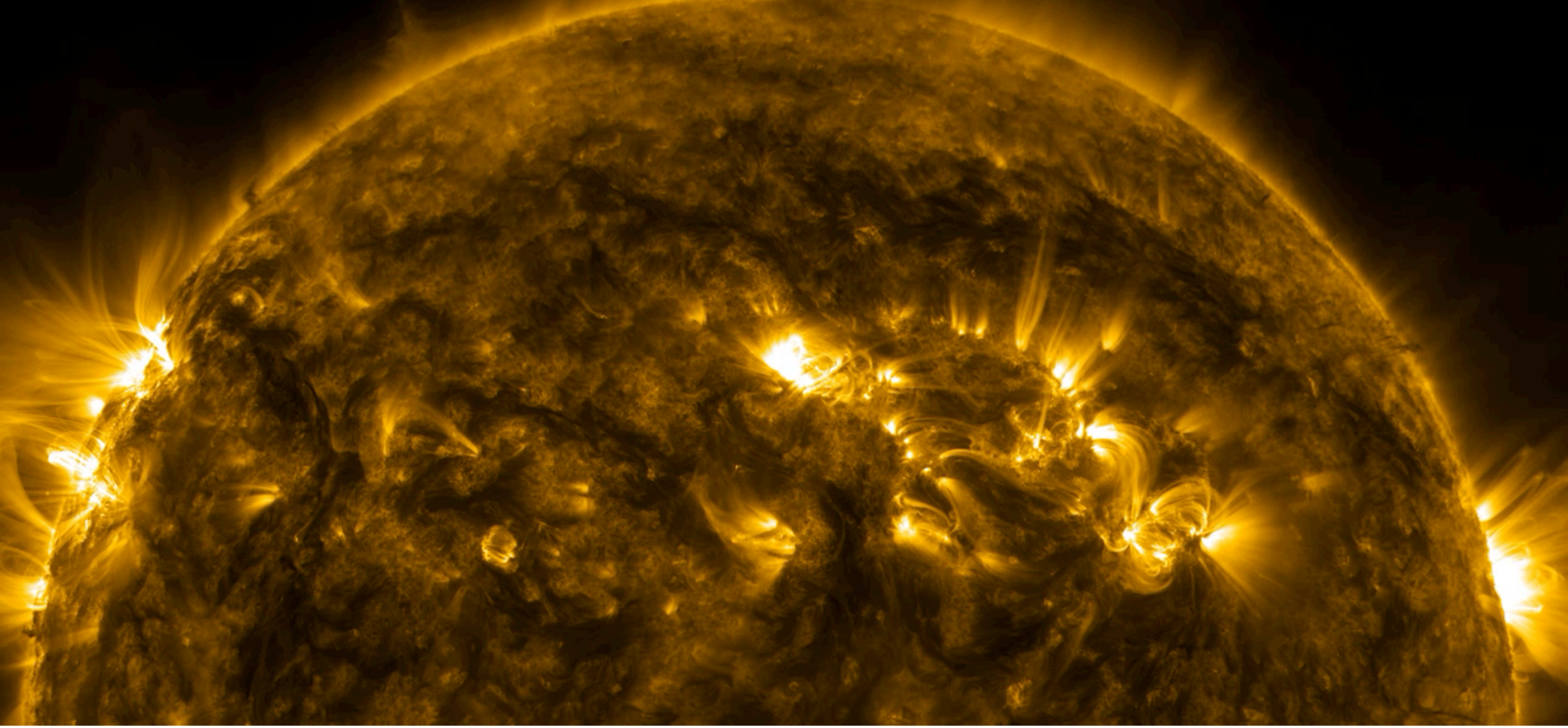
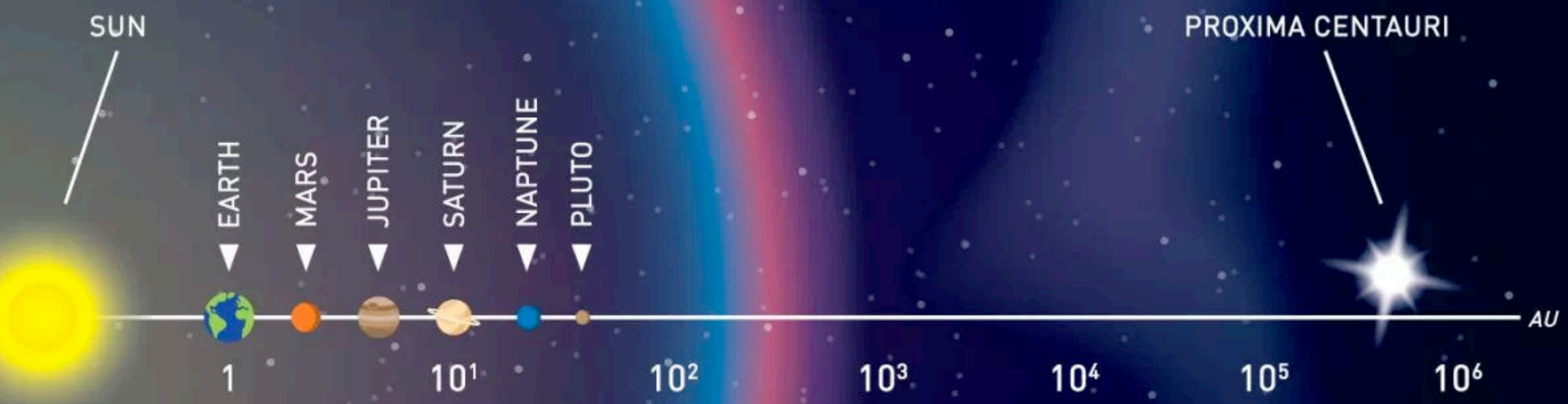


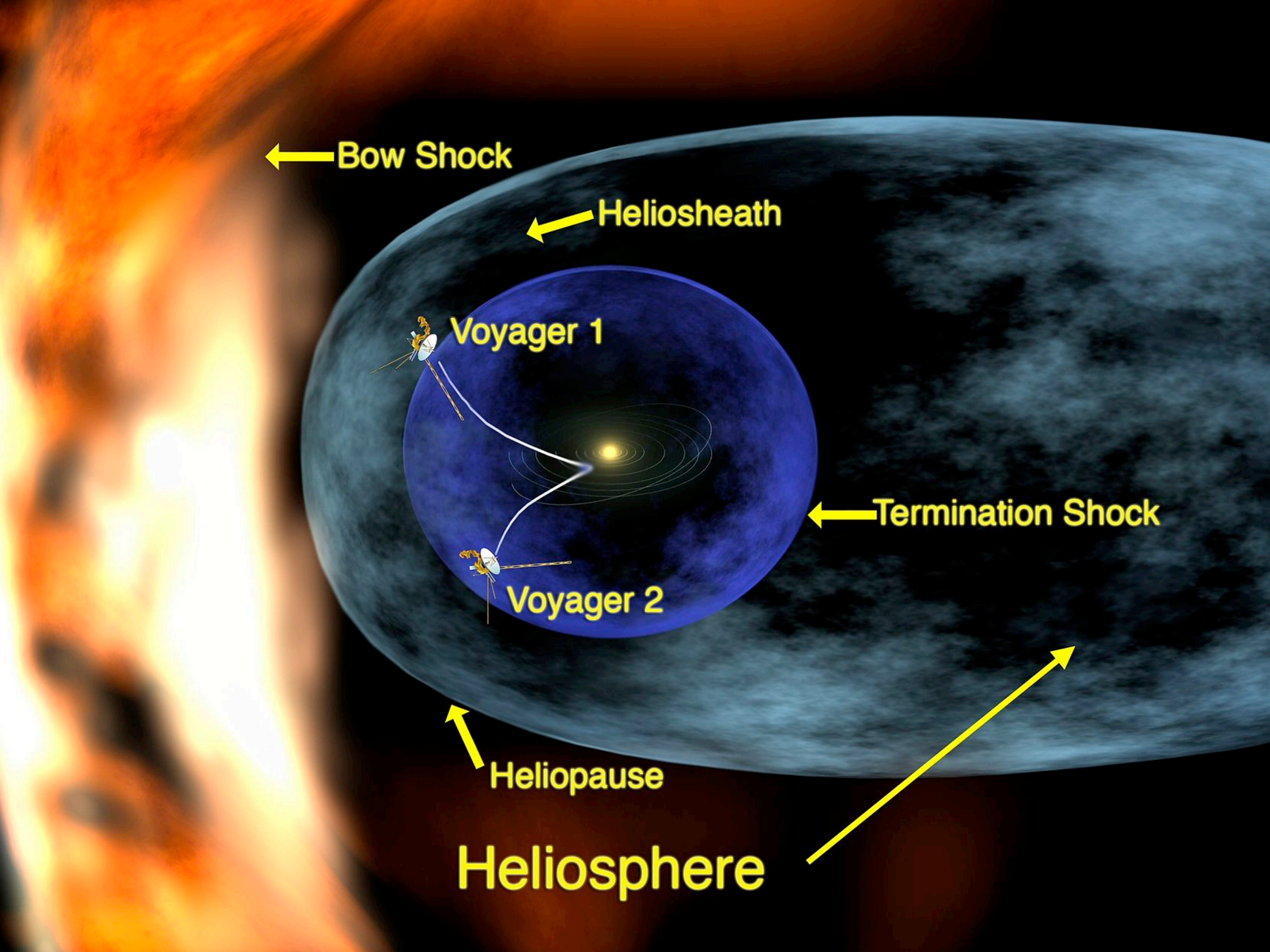
TIM LINDEN

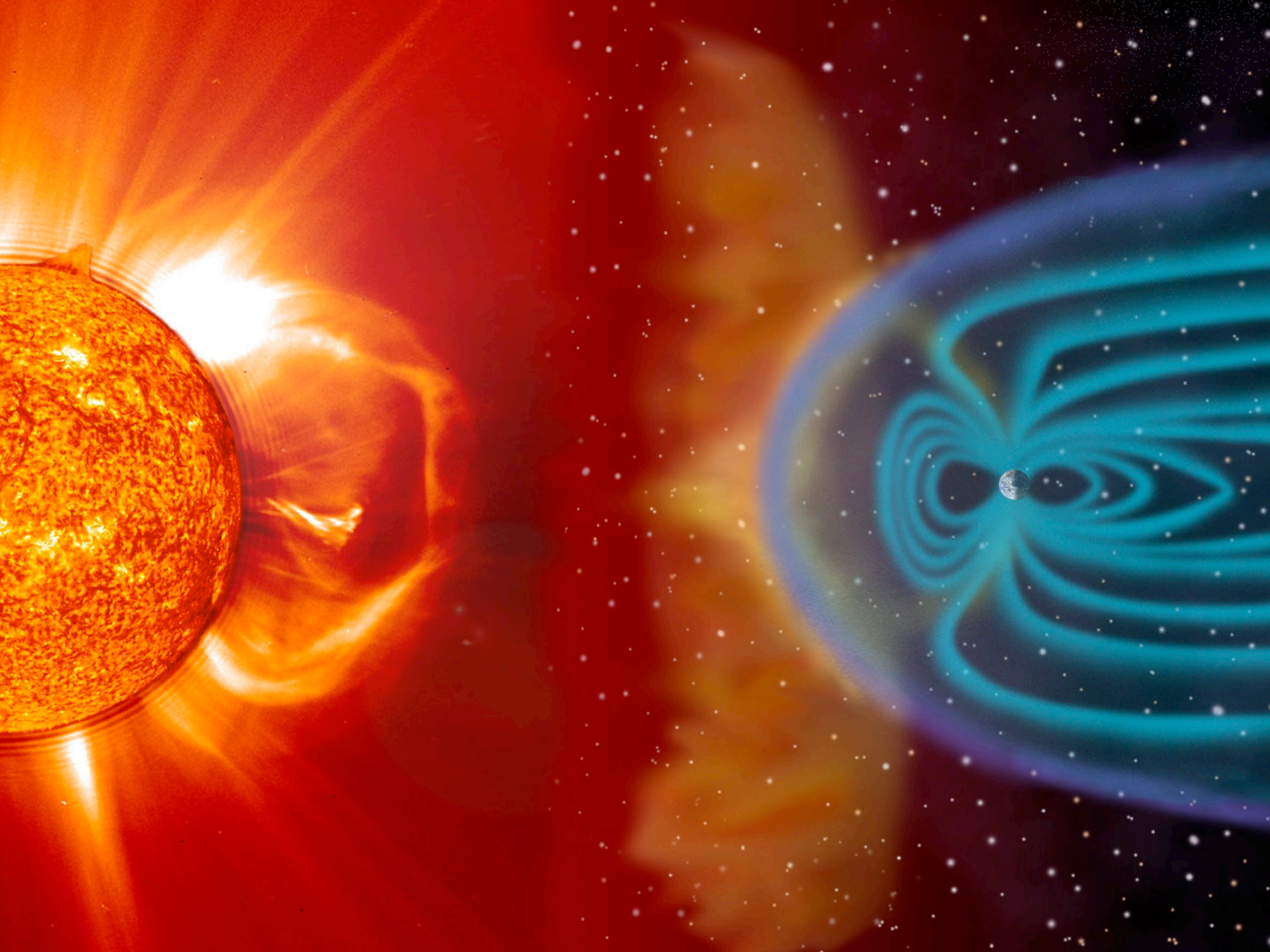
THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

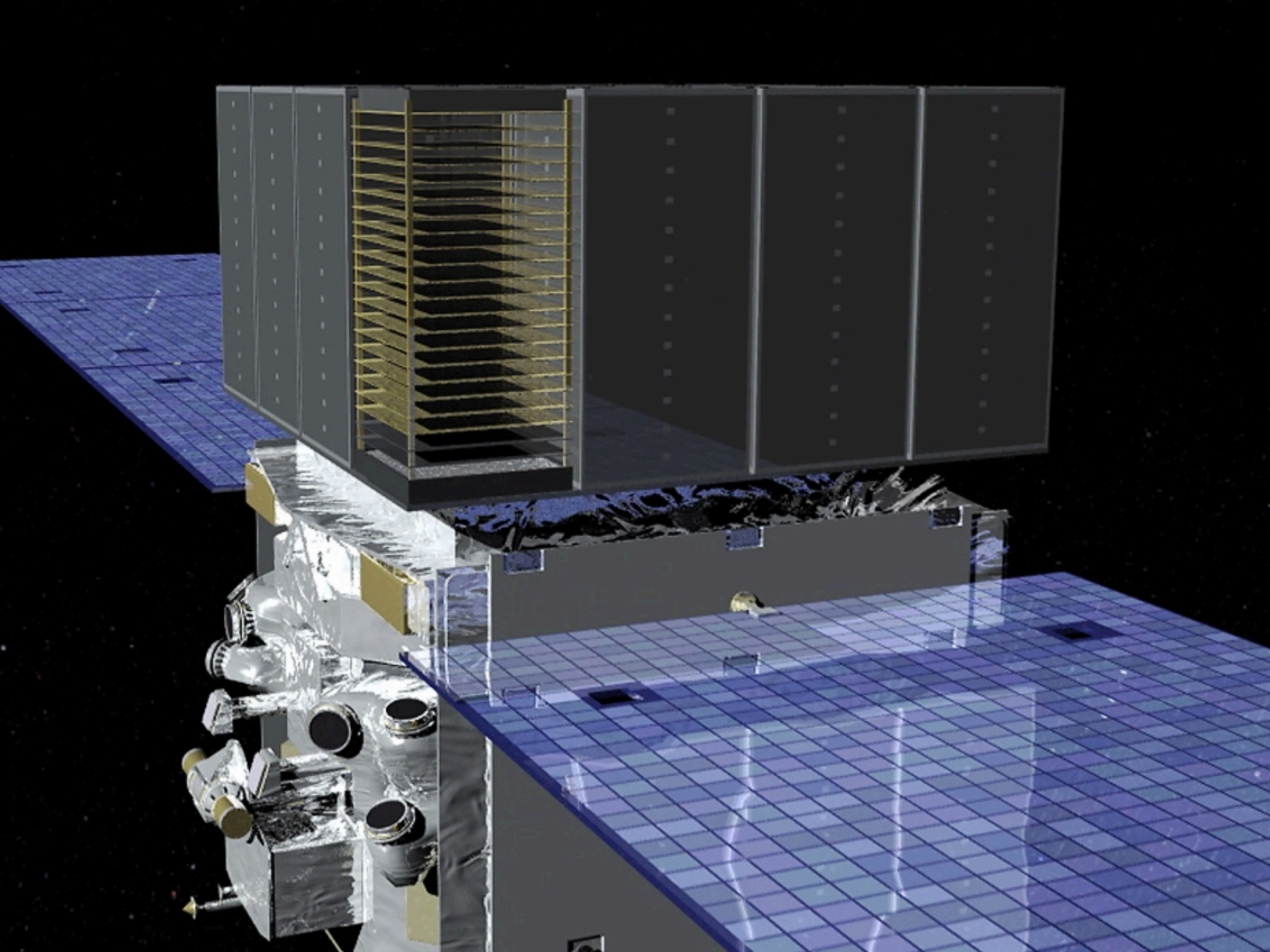
Photon 2019
Frascati, Italy
4 June 2019

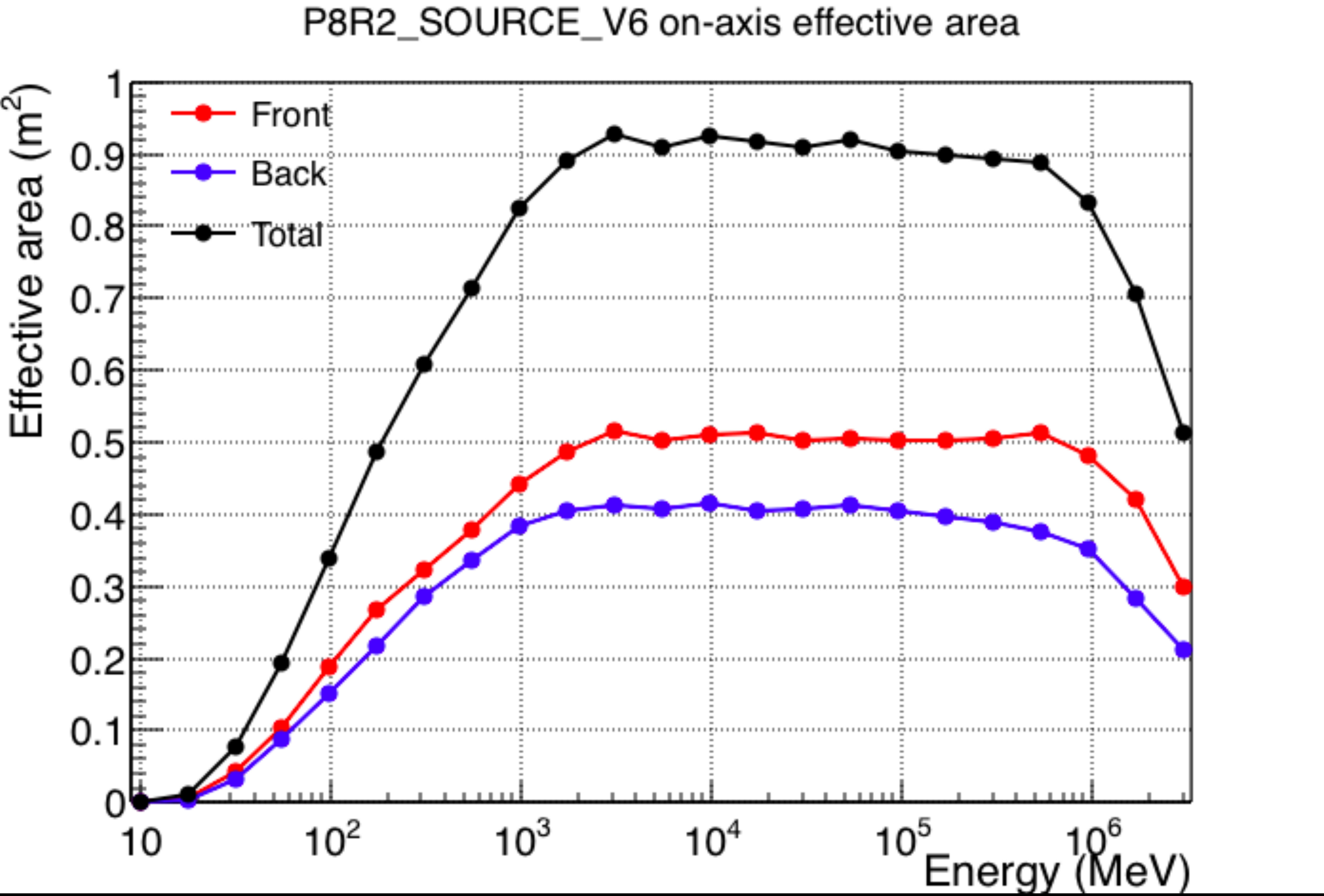


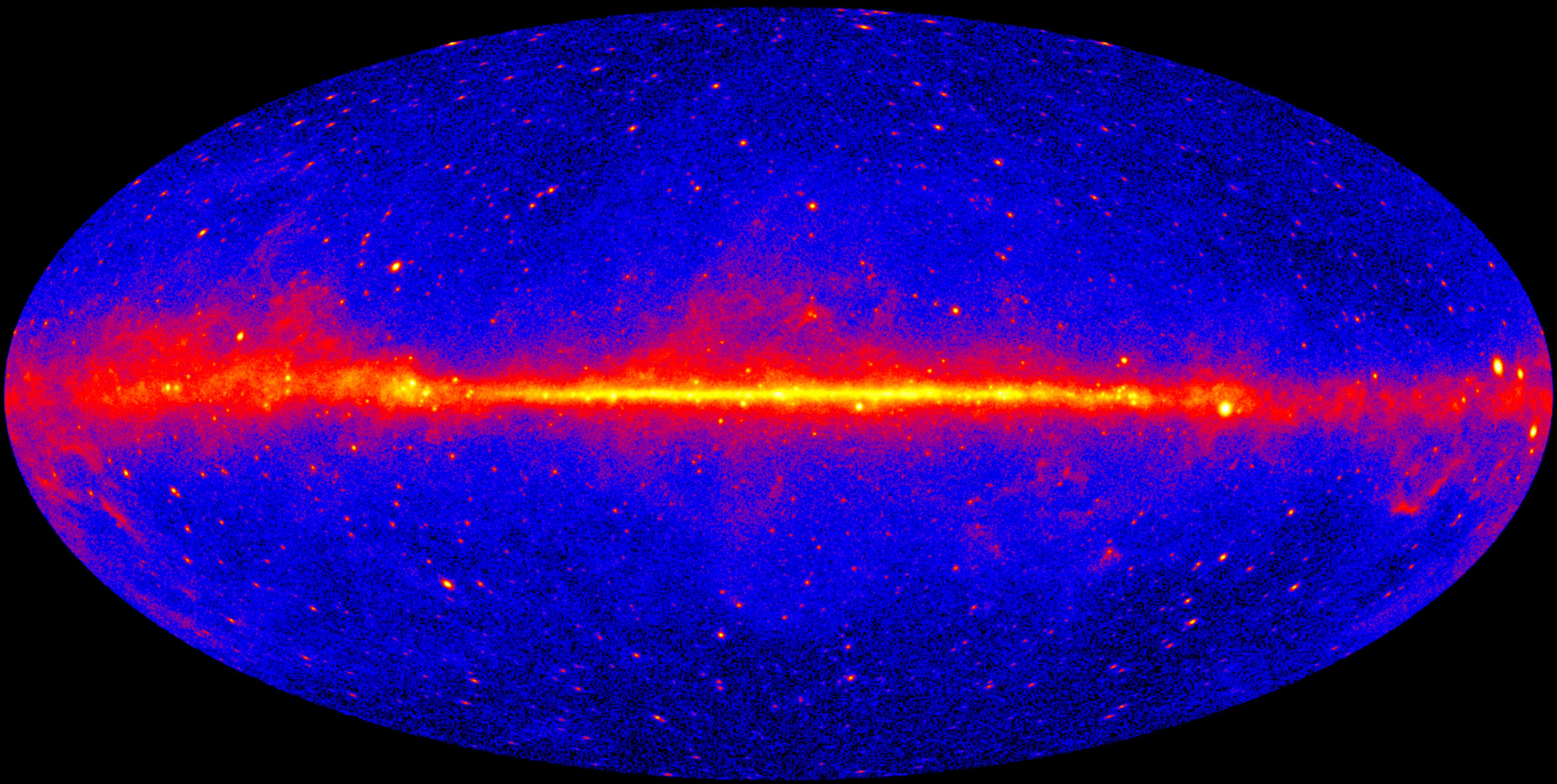
$$\left(\frac{d_{\alpha Cen}}{d_{\odot}}\right)^2 = 7 \times 10^{10}$$

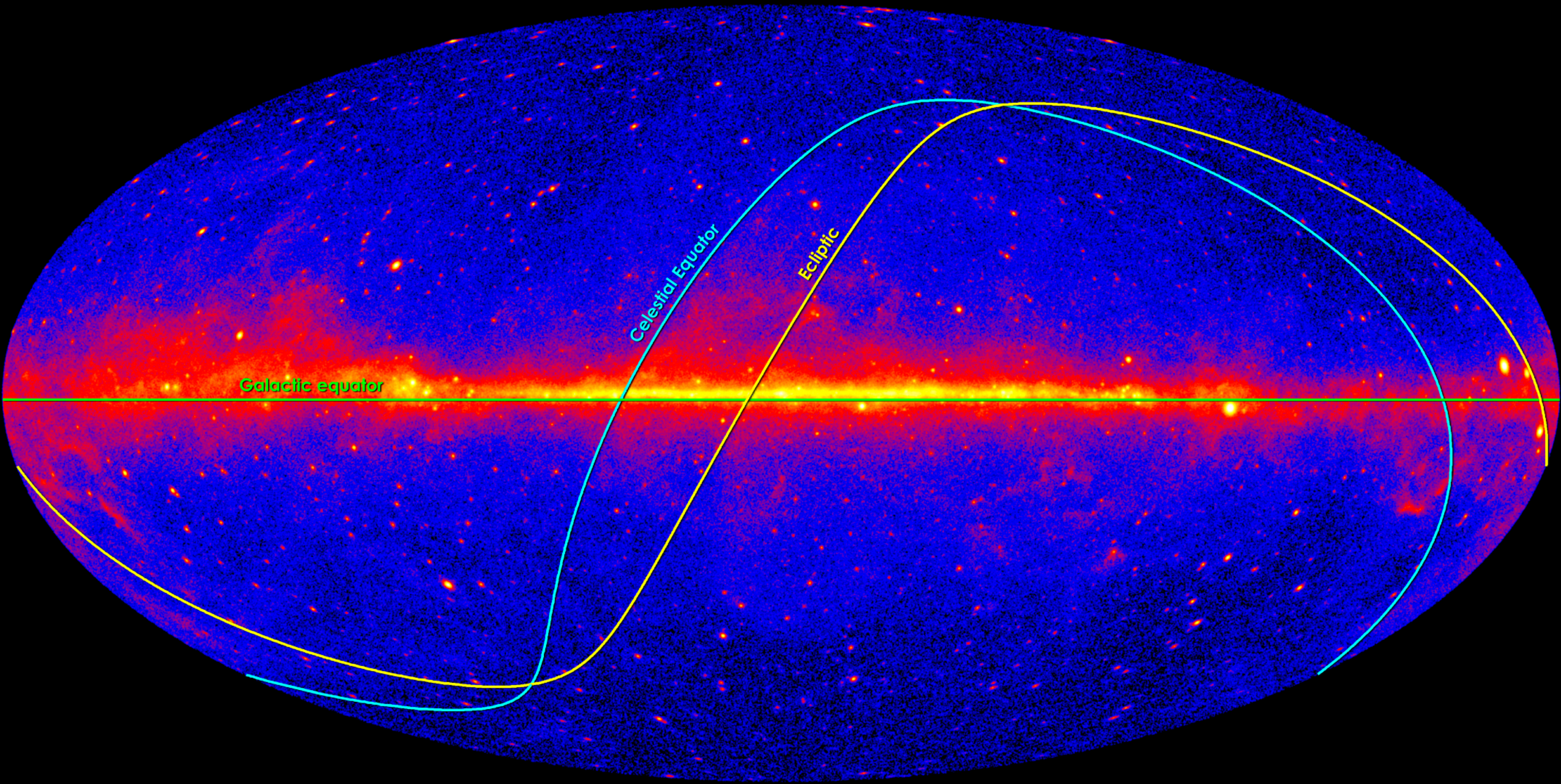

Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere






P8R2_SOURCE_V6 on-axis effective area
Effective area (m^2)
Energy (MeV)
Front
Back
Total
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10
10^2
10^3
10^4
10^5
10^6




Celestial Equator
Ecliptic
Galactic equator

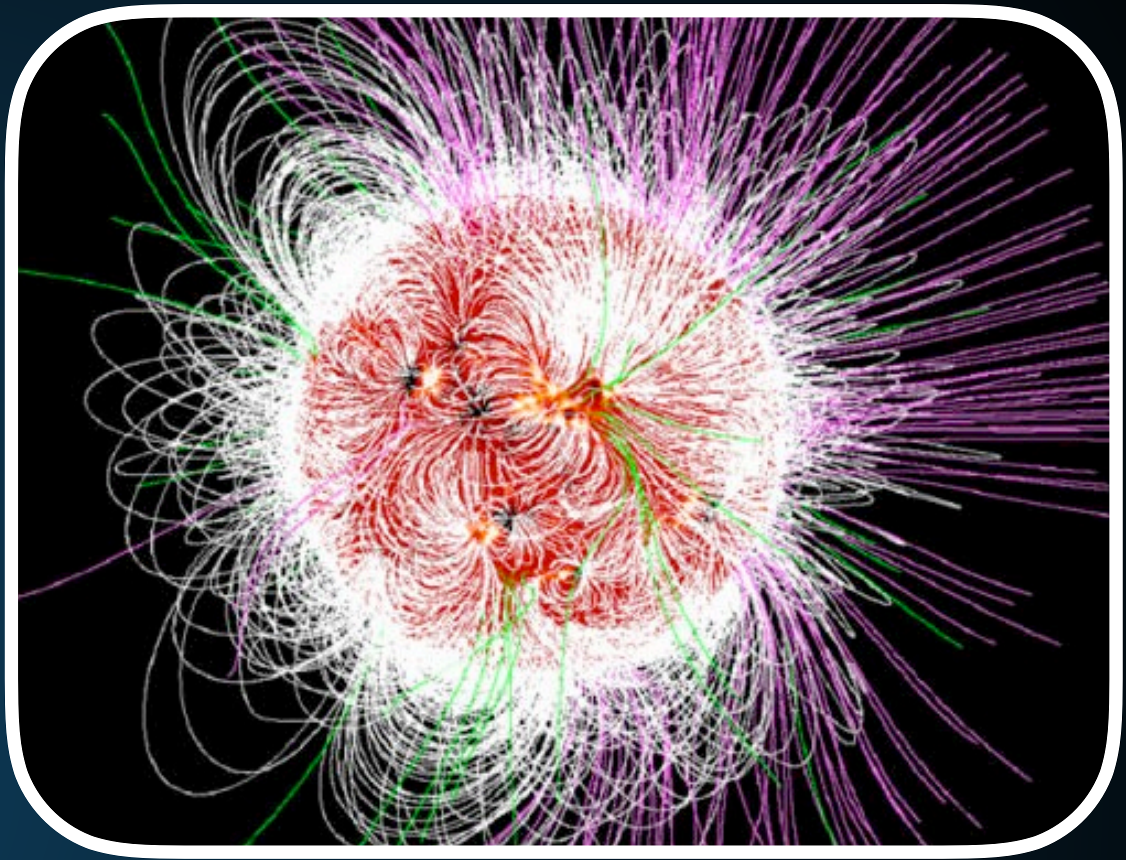
CRAZY FINE TUNING

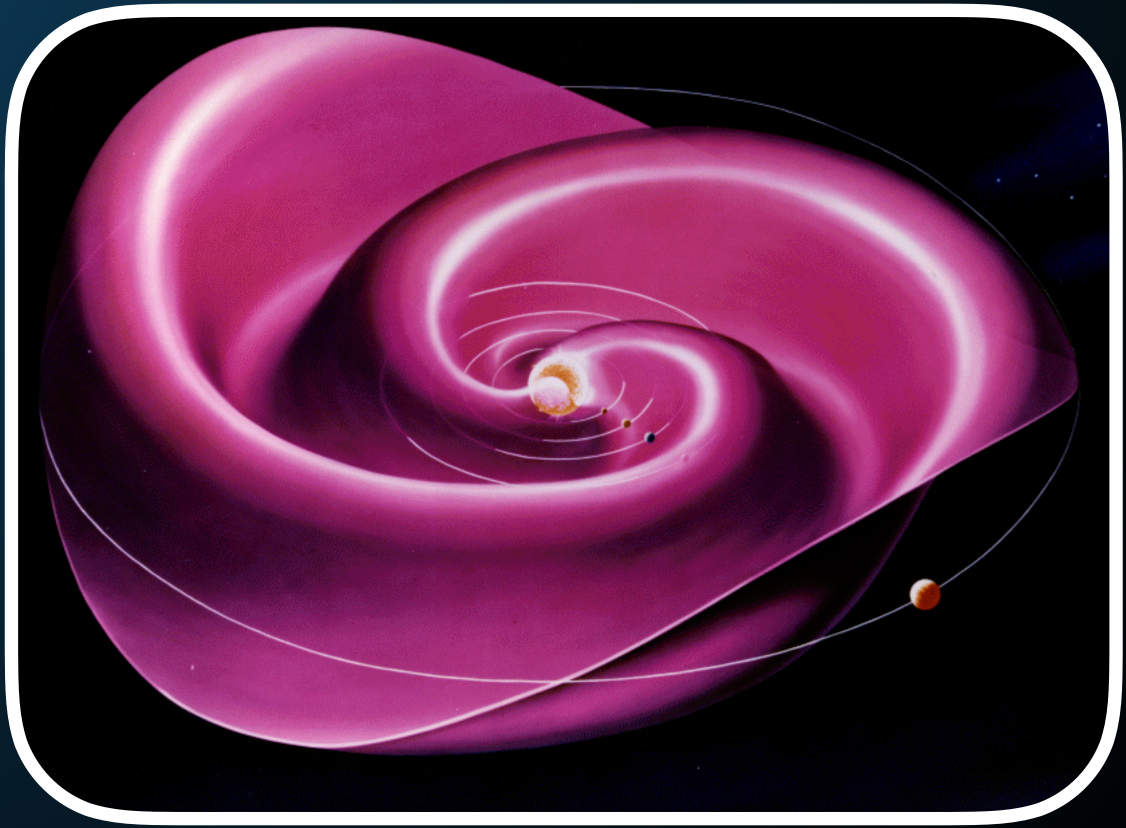
- **Solar gamma-ray flux is approximately:**

$$3 \times 10^{-10}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$$

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	

GAMMA-RAYS - WHY?

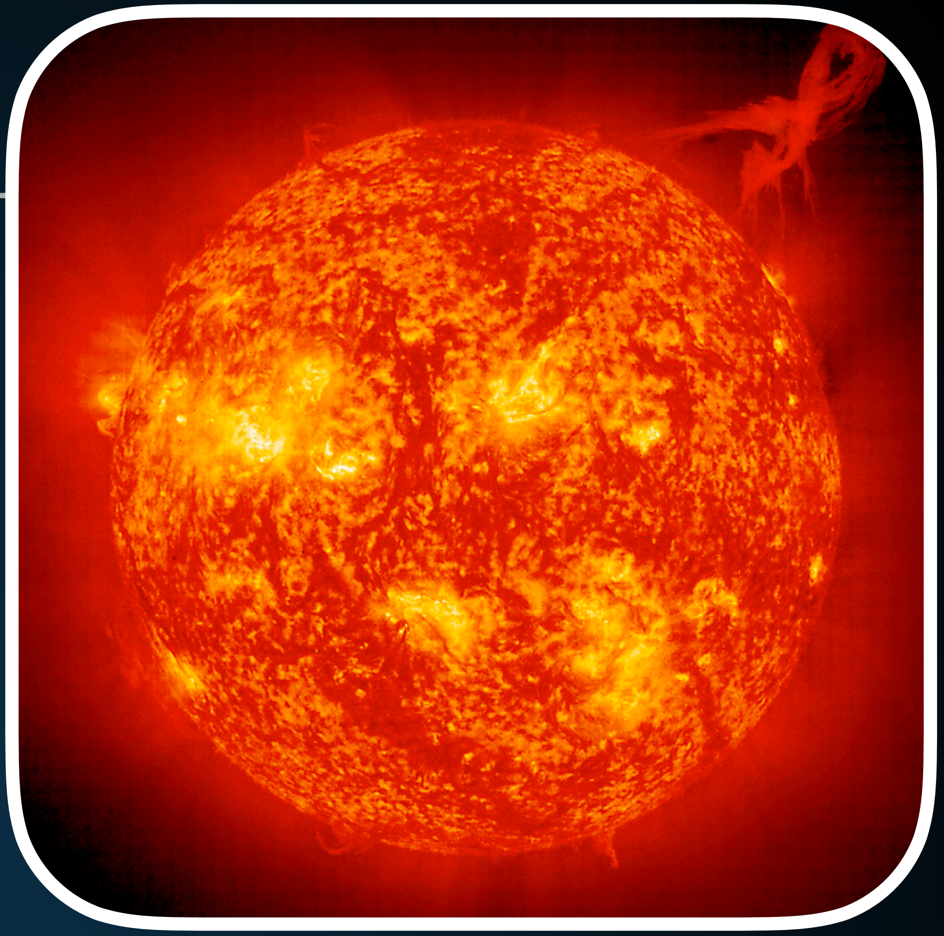




How are these gamma rays produced?

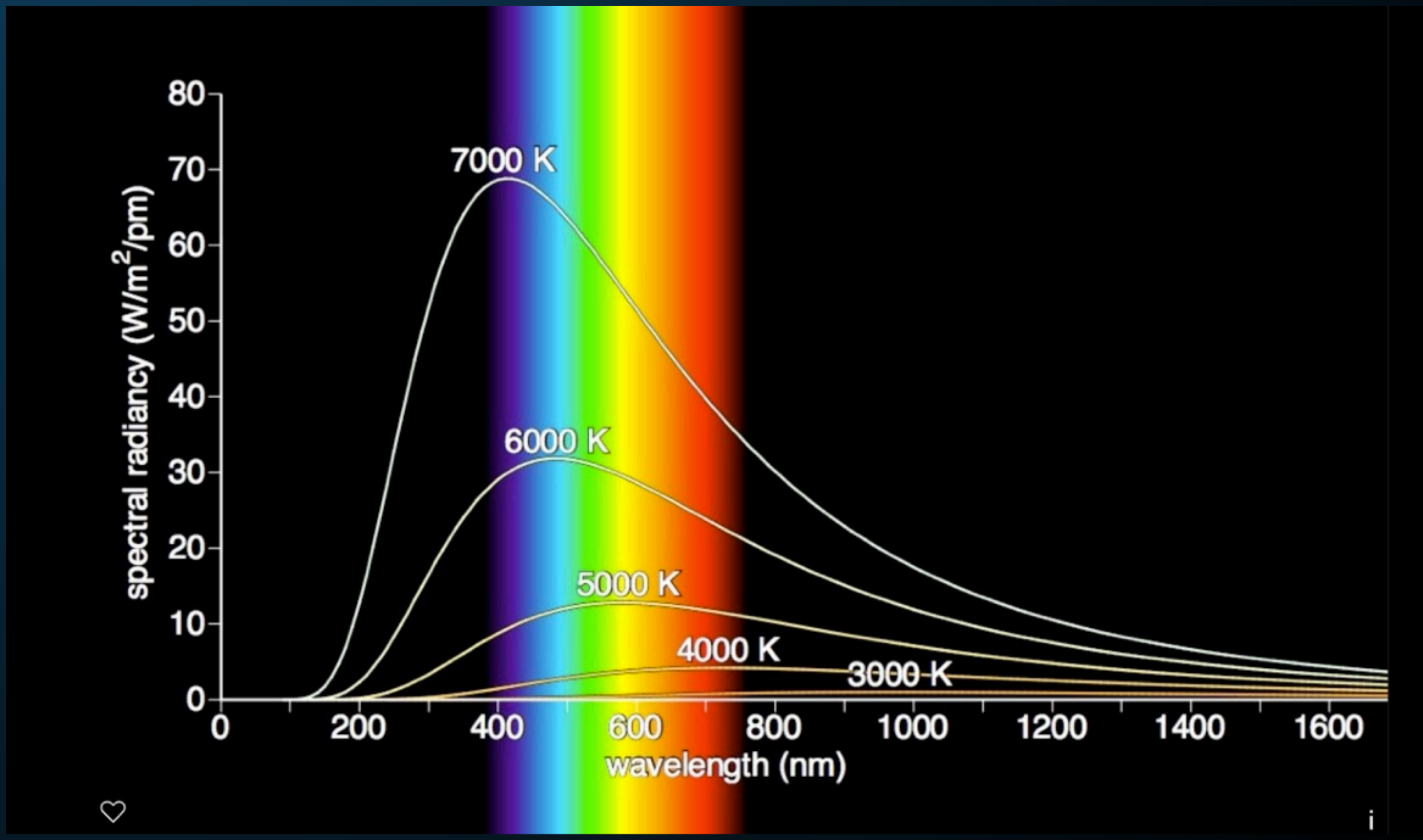
GAMMA-RAYS - HOW?

THERMAL MECHANISMS



$T_\odot$ = 6000 K = 0.5 eV

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



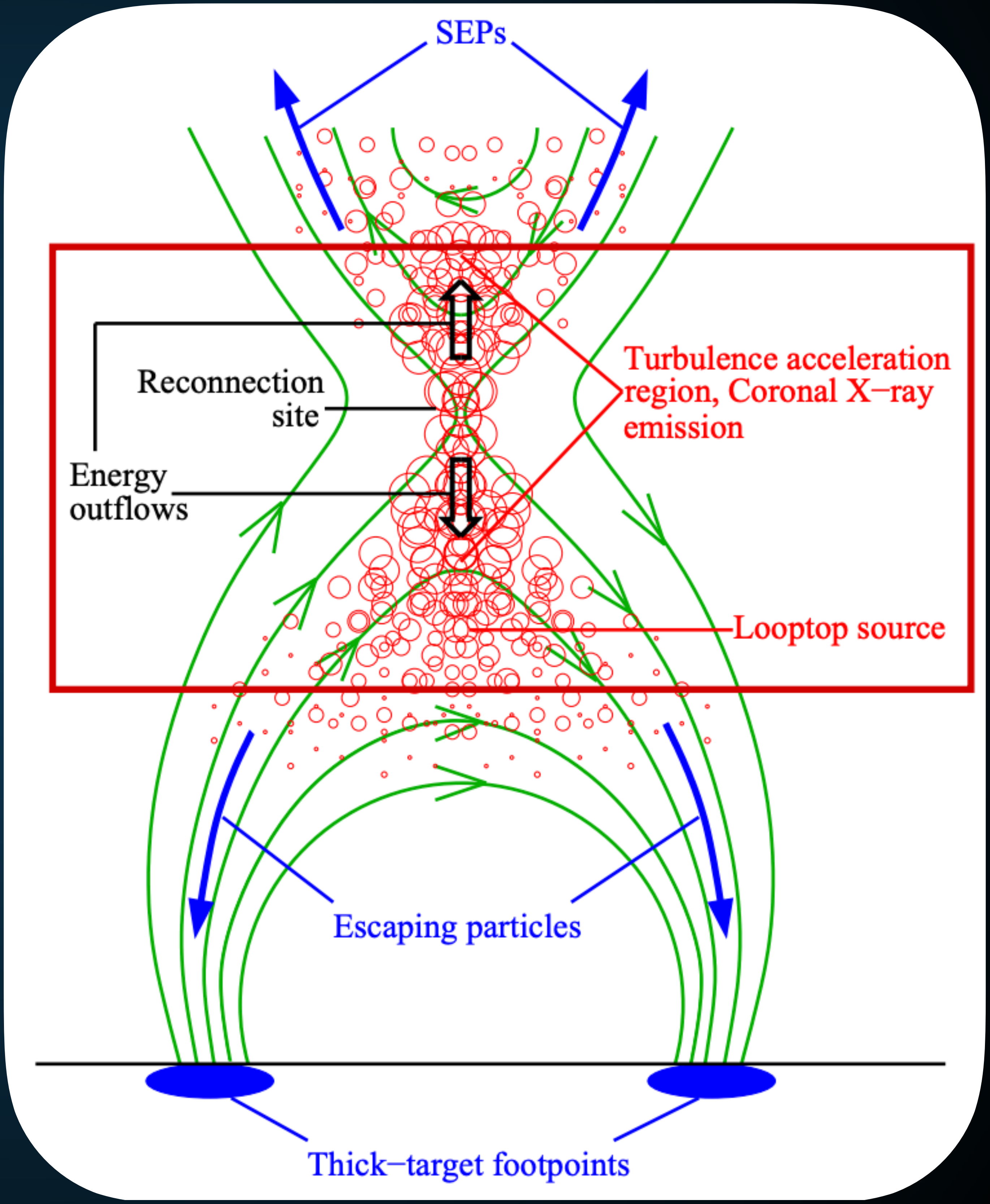
Thermal production of gamma-rays is suppressed by exp[-10⁹] = 0

GAMMA-RAYS - HOW?

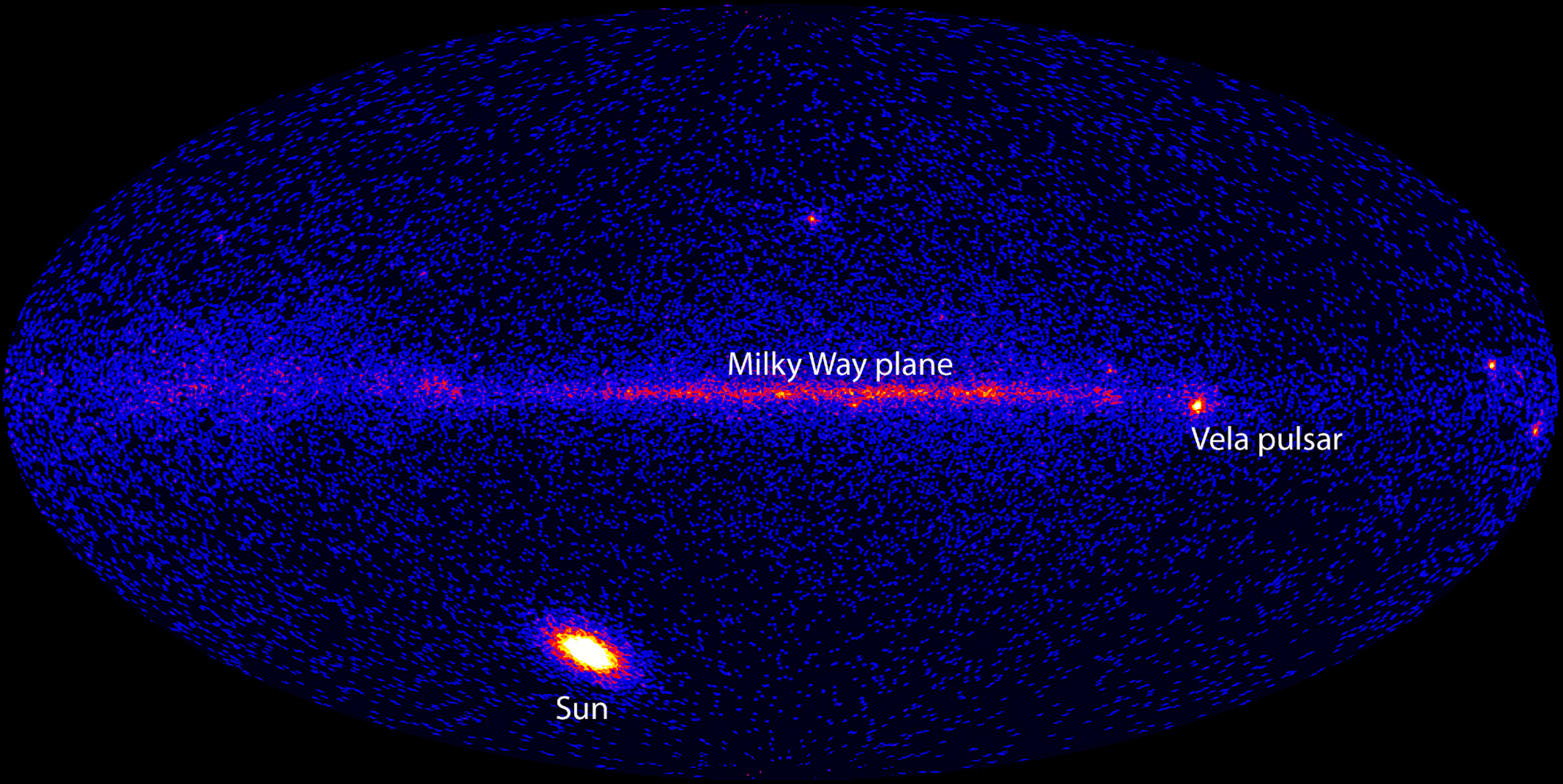
NON-THERMAL MECHANISMS

GAMMA-RAYS - HOW?

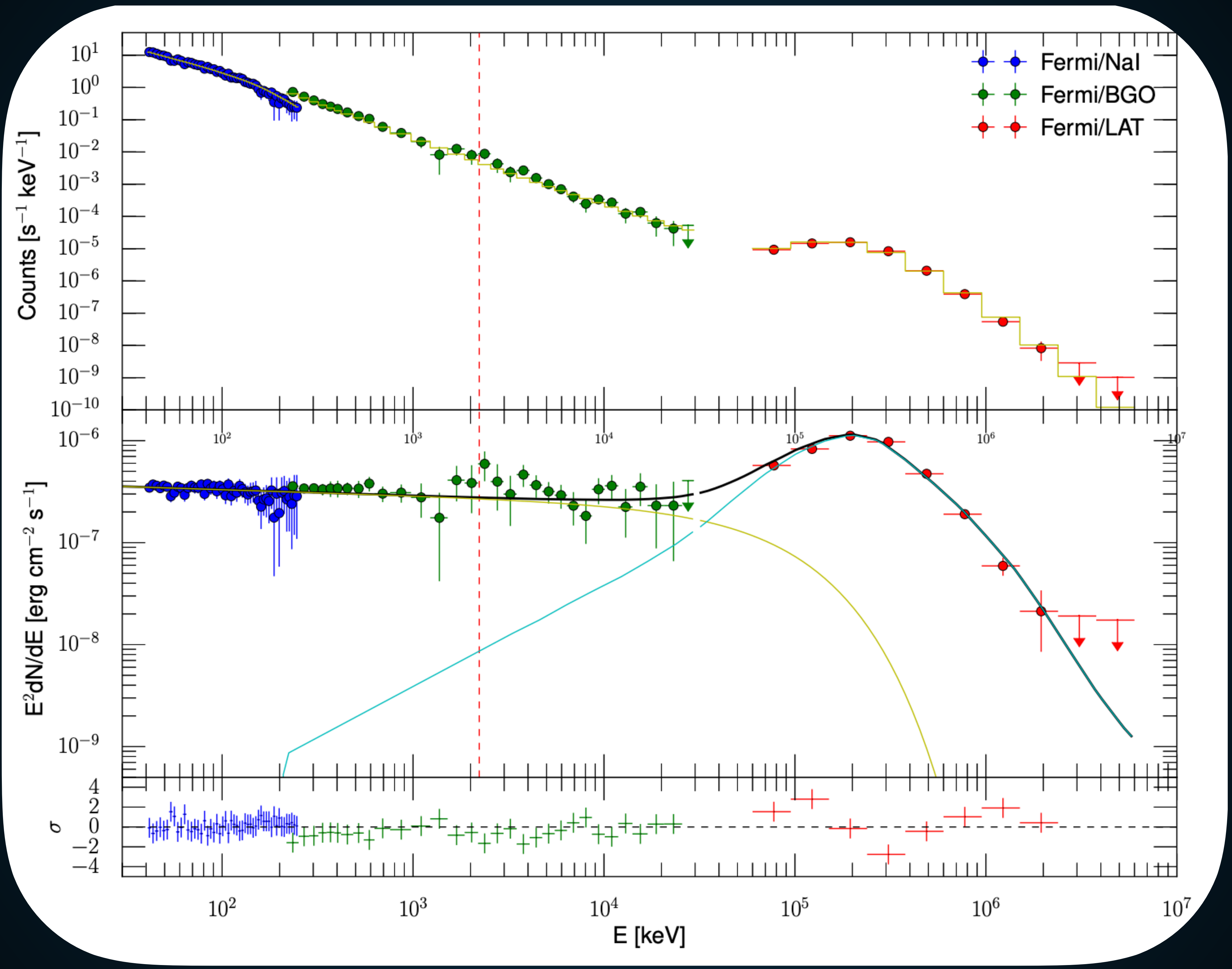
- **Solar Flares and Reconnection events.**



Petrosian (2016; 1605.04022)

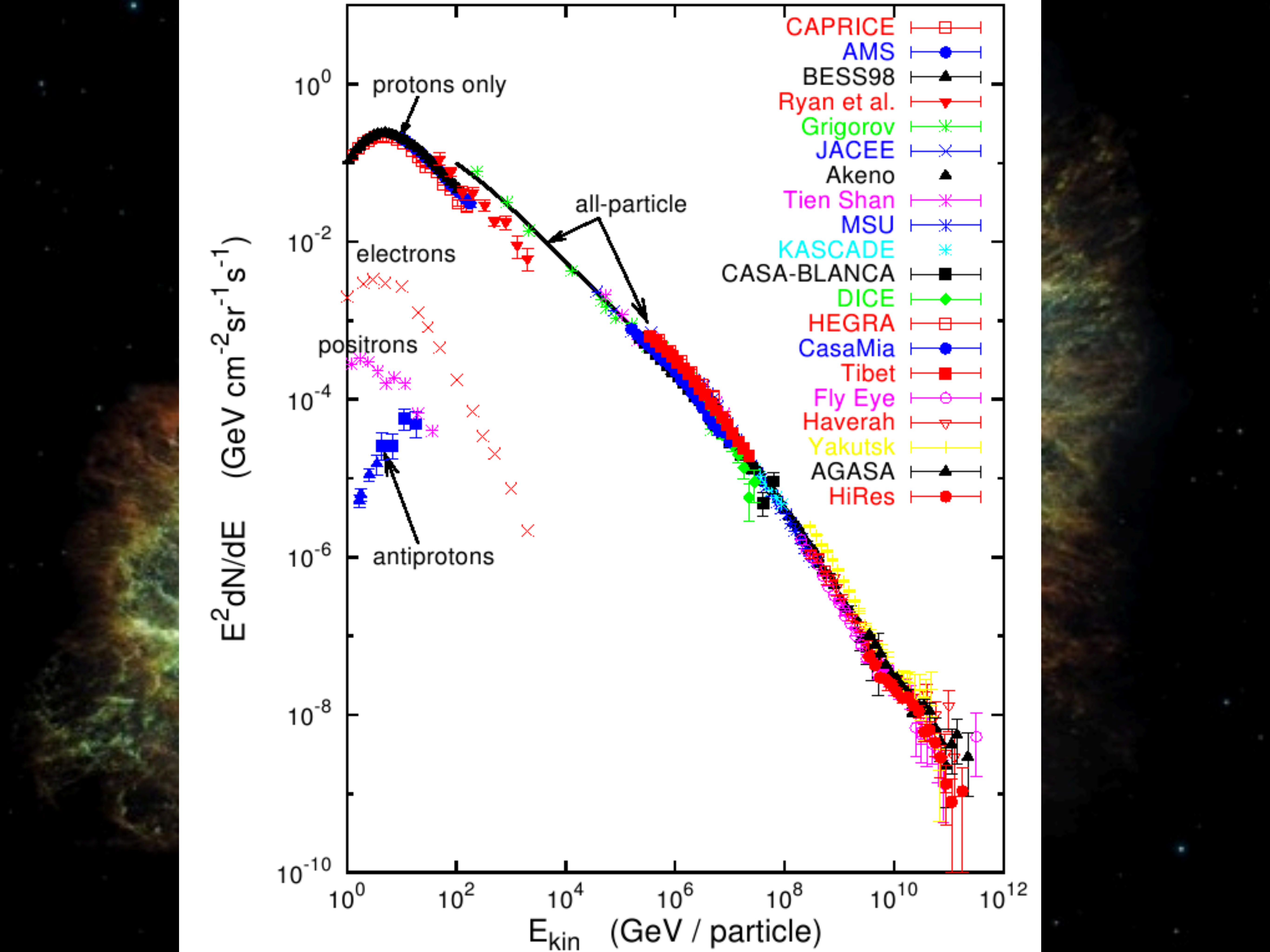

Milky Way plane
Vela pulsar
Sun

GAMMA-RAYS - HOW?



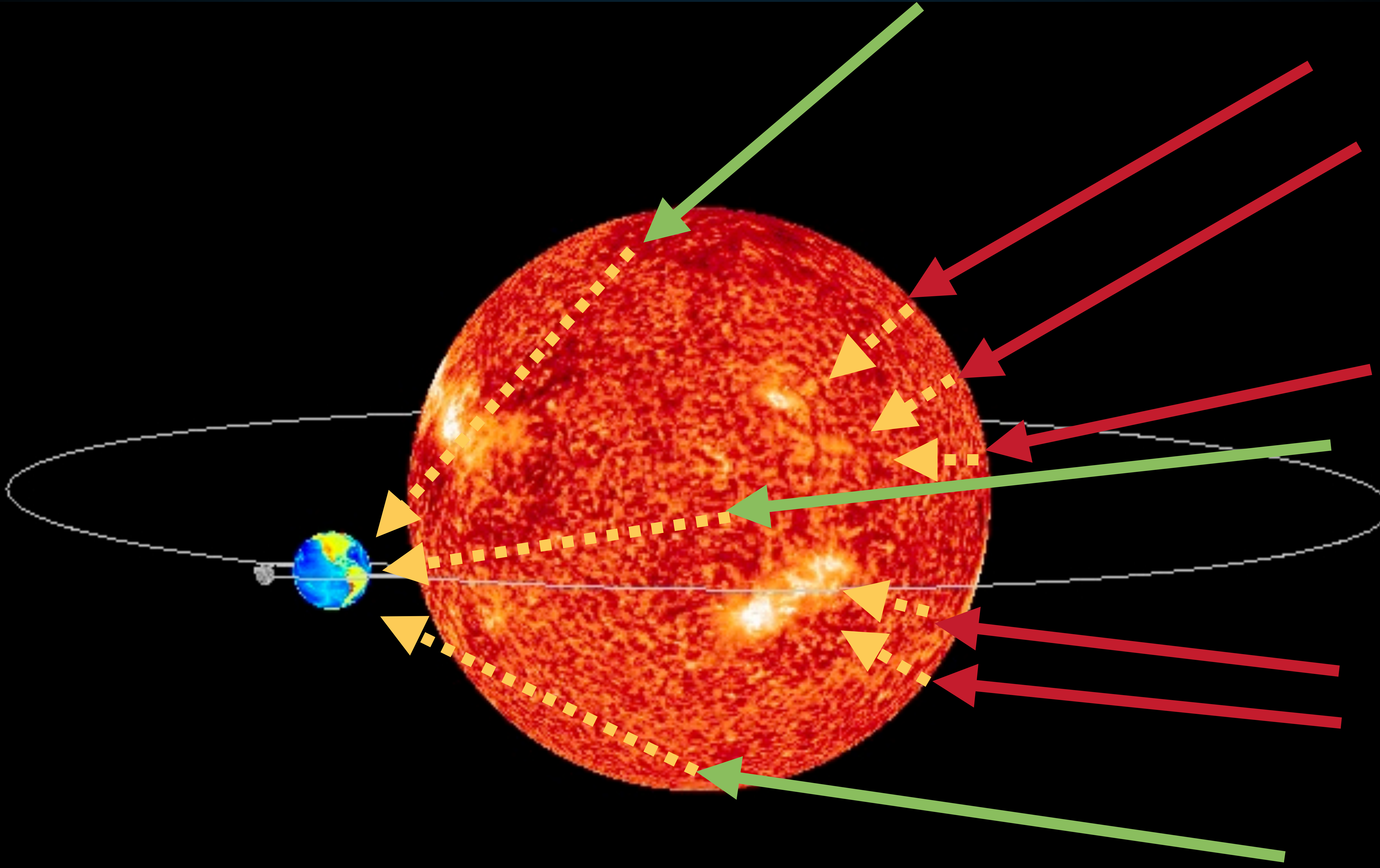
- **Solar Flare gamma-rays are low energy (E_{max} = 4 GeV)**

Exploiting the Energy of Galactic Cosmic-Rays



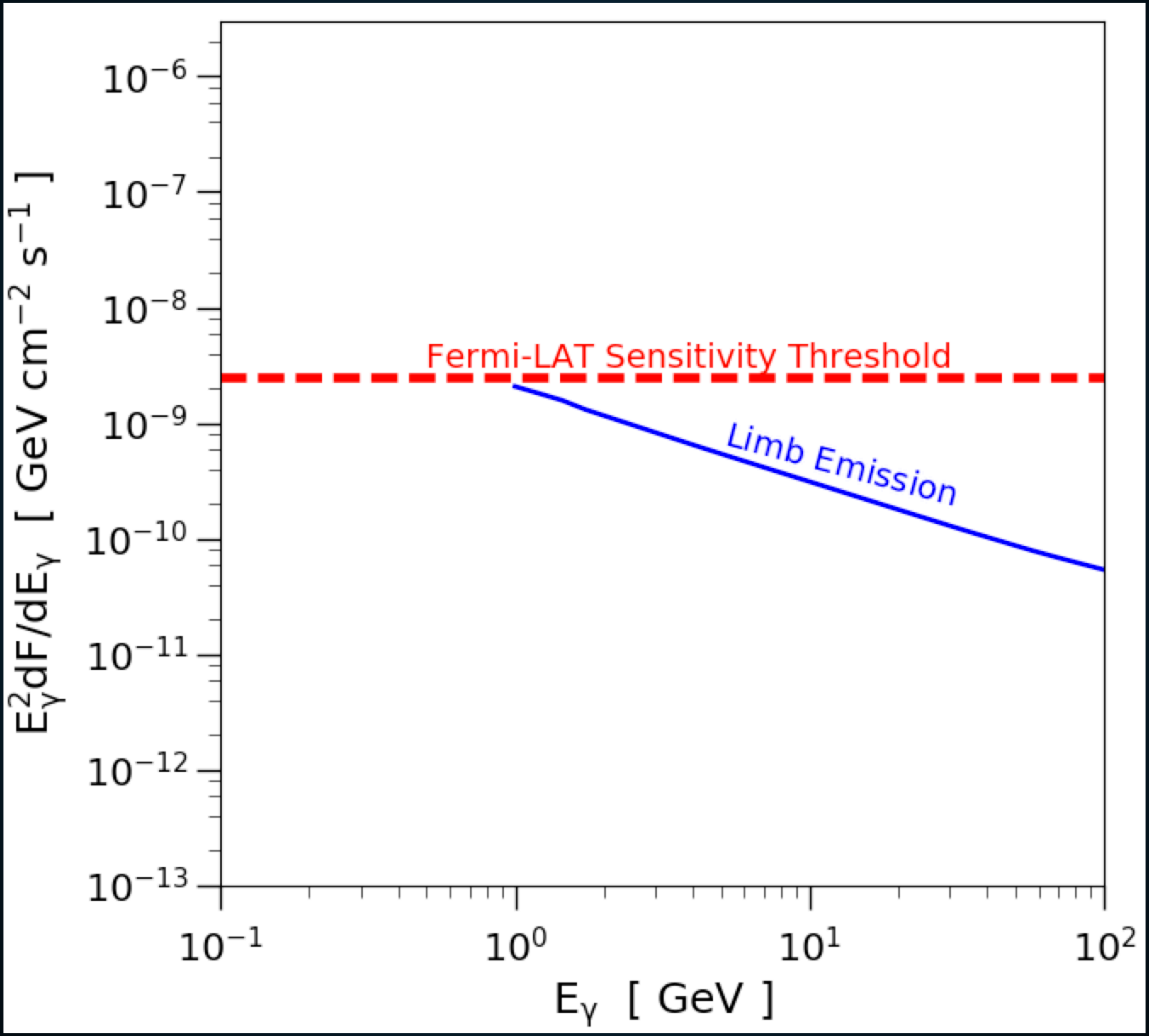
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
protons only
all-particle
electrons
positrons
antiprotons
E^2dN/dE (GeV cm^{-2}sr^{-1}s^{-1})
E_{kin} (GeV / particle)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}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

HADRONIC GAMMA-RAYS - HOW?



HADRONIC GAMMA-RAYS - HOW?

HADRONIC GAMMA-RAYS - HOW?



HADRONIC GAMMA-RAYS - HOW?

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 result from collisions of high-energy Galactic cosmic rays with the solar atmosphere. The results are sensitive to assumptions about cosmic-ray transport in the magnetic fields of the inner solar system. The high-energy photon flux should be observable by the Gamma Ray Observatory. The neutrino flux should produce less than one event per year in the next generation of neutrino telescopes. The antiproton flux is unobservable against the Galactic background. The neutron and antineutron fluxes are detectable only if neutrons produced in terrestrial cosmic-ray events may be discriminated against.

Subject headings: cosmic rays: general — gamma rays: general — neutrinos — Sun: activity

1. INTRODUCTION

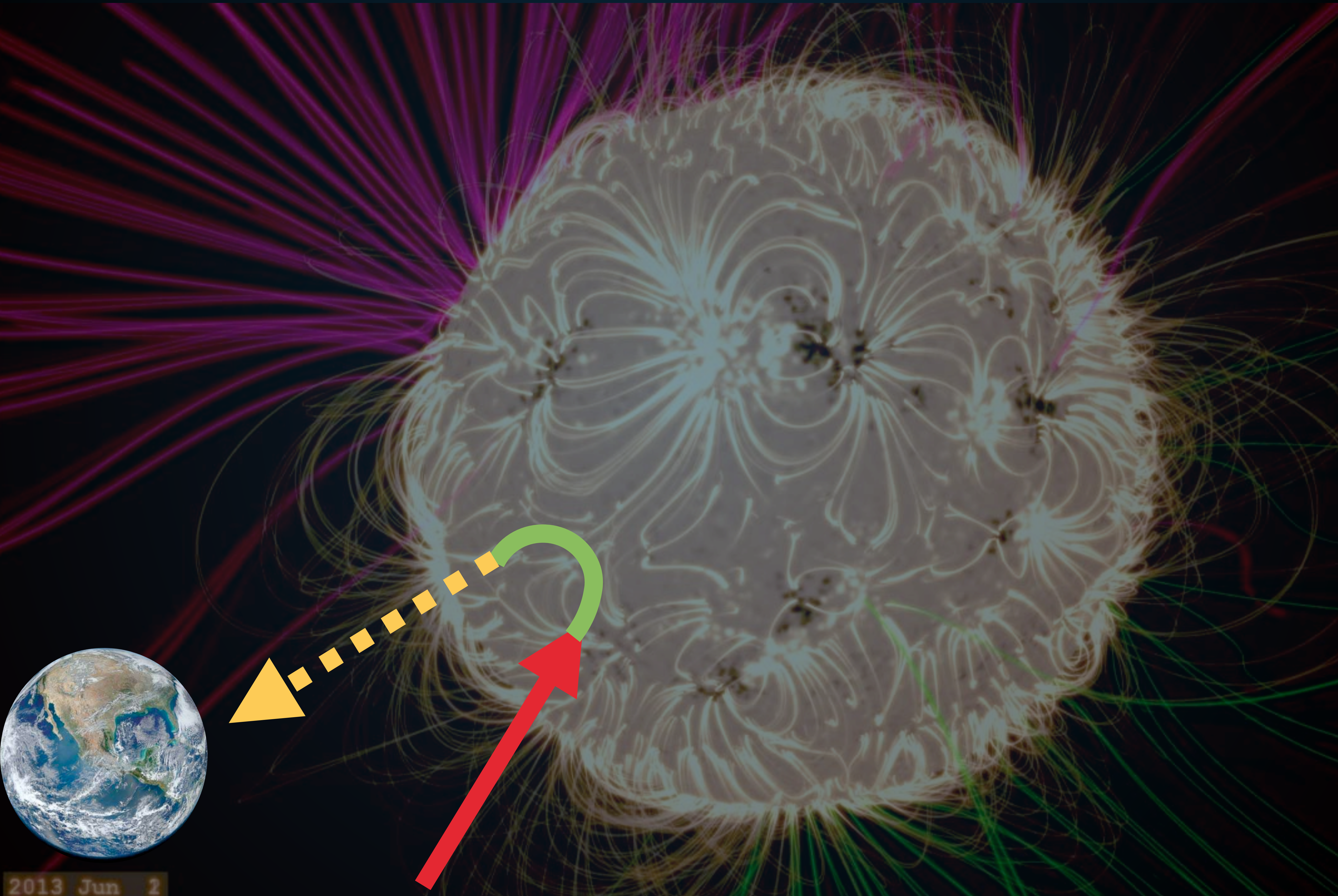
The interactions of high-energy cosmic-ray nuclei with matter have been studied in a variety of settings. In our own atmosphere, these interactions produce cascades which include, or in turn produce, detectable fluxes of electrons, positrons, muons, gamma rays, Čerenkov light, neutrons and other nuclear fragments, and neutrinos. Interactions with interstellar gas are thought to produce the observed Galactic flux of γ-rays (Mayer-Hasselwander et al. 1982; Fichtel & Kniffen 1984; Fichtel et al. 1977) with energies above $\sim$500 MeV, antiprotons (Stephens & Golden 1987), and positrons (Protheroe 1982). In this paper we explore another place where interactions between cosmic-ray nuclei and gas may produce observ-

appropriate thickness to generate high-energy photons without reabsorbing them. The high-energy cascade products would then be suppressed from the naive value by an amount of order $h_\oplus/R_\oplus \sim 10^{-3}$, where $h_\oplus$ is the scale height of Earth's atmosphere, and $R_\oplus$ is Earth's radius. Although we will argue otherwise, one might worry that a similar suppression occurs for the Sun.

Third, to calculate fluxes from the Sun, one must take into account the details of the solar atmosphere. For example, typical cascades will take place in a less dense environment than for Earth, and that increases the yields of some byproducts.

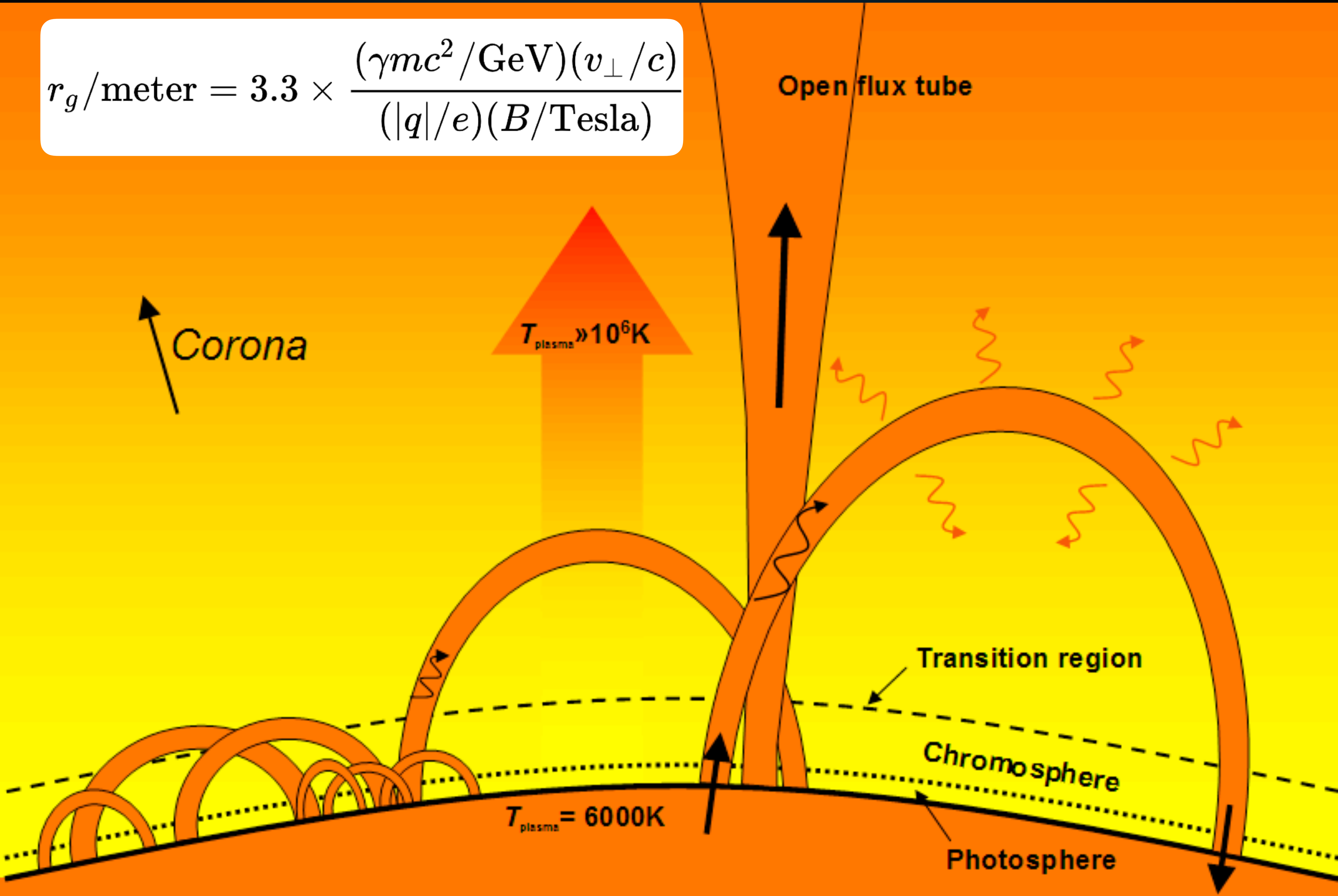
Despite these uncertainties, it is possible to make some quick

HADRONIC GAMMA-RAYS - HOW?

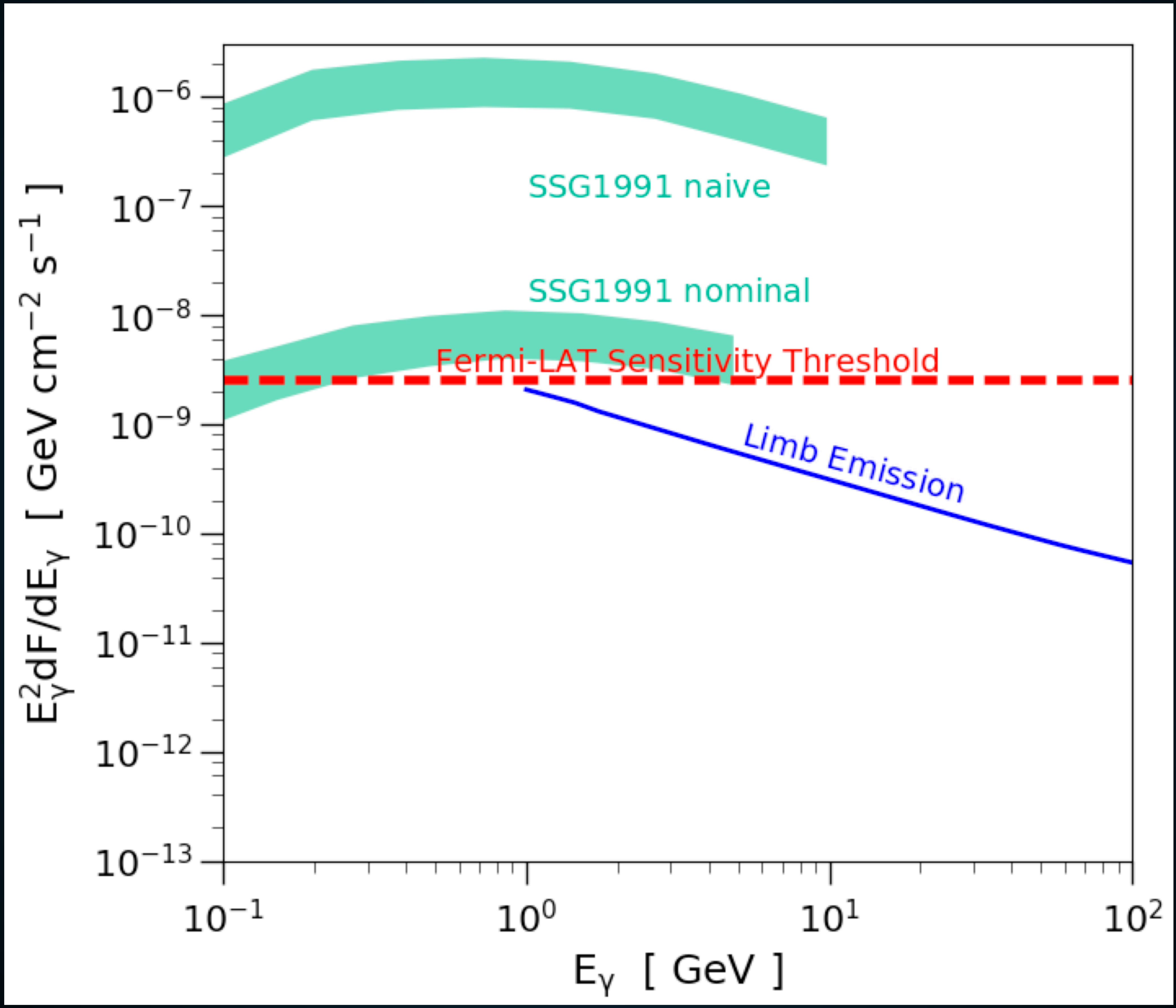


HADRONIC GAMMA-RAYS - HOW?

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



HADRONIC GAMMA-RAYS - HOW?

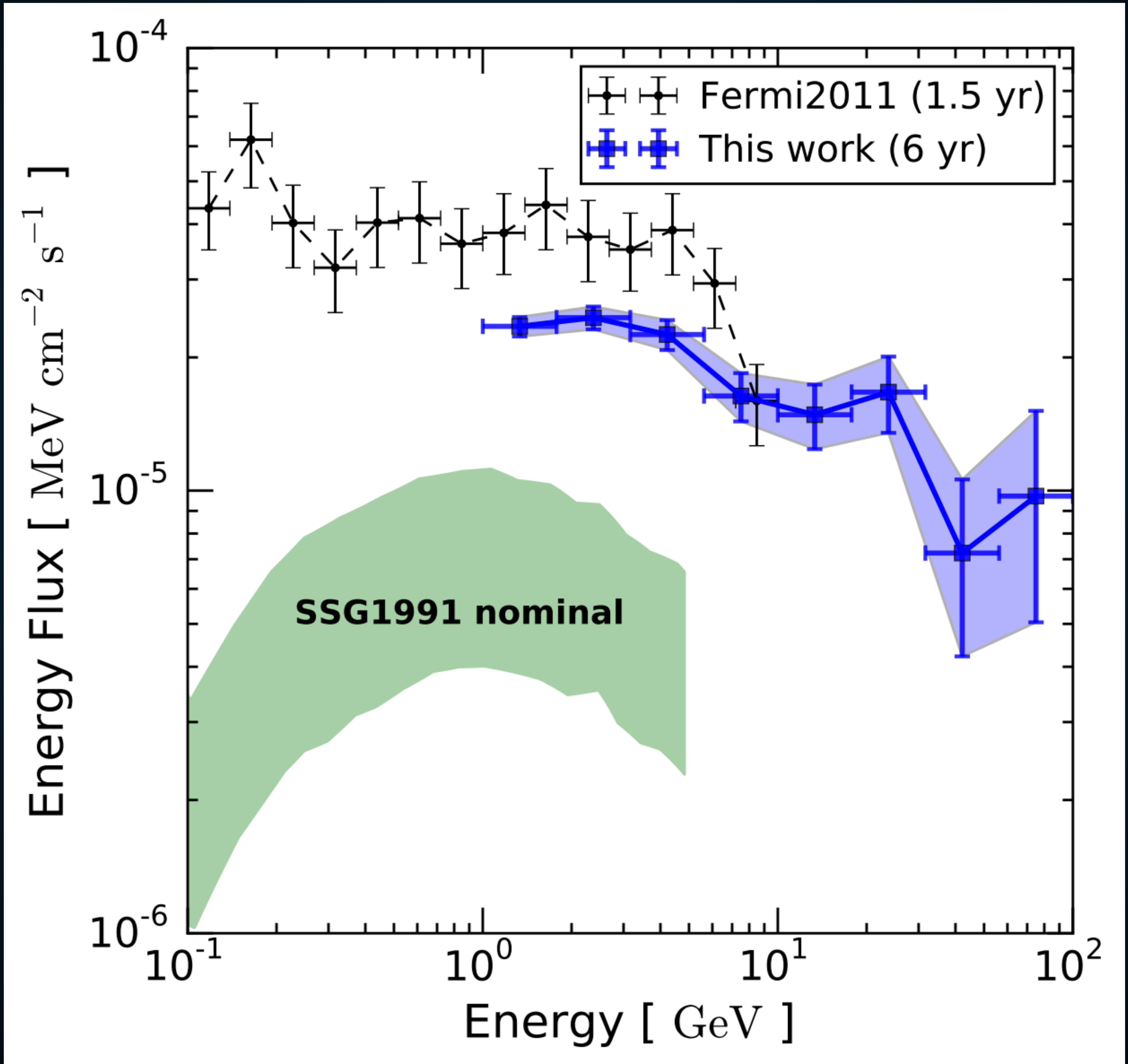


Let the observations be your guide…

GAMMA-RAYS - WHAT?

OBSERVATIONS - INTENSITY

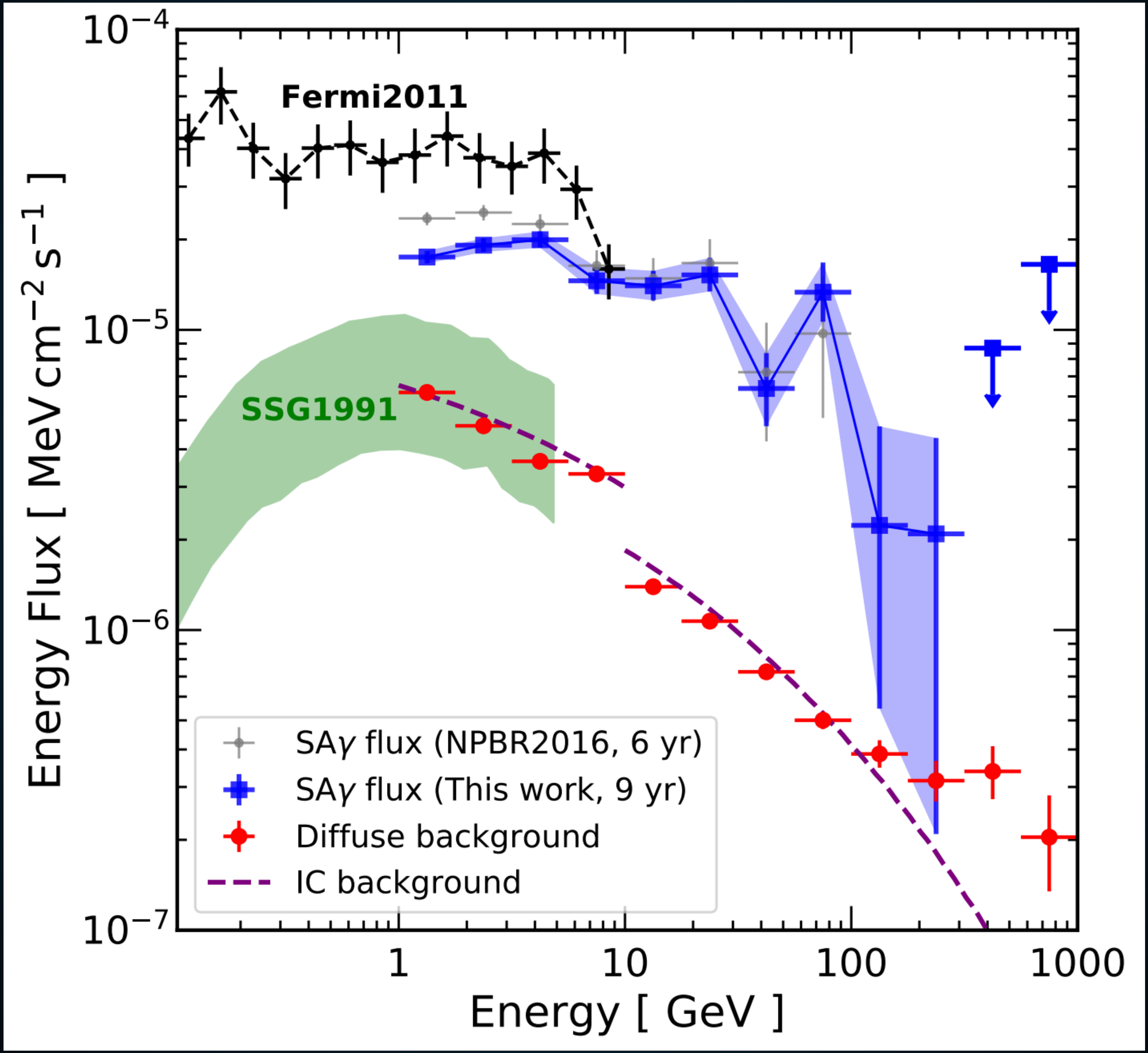
Ng et al. 2016 (1508.06276)



Intensity **X**

OBSERVATIONS - SPECTRUM

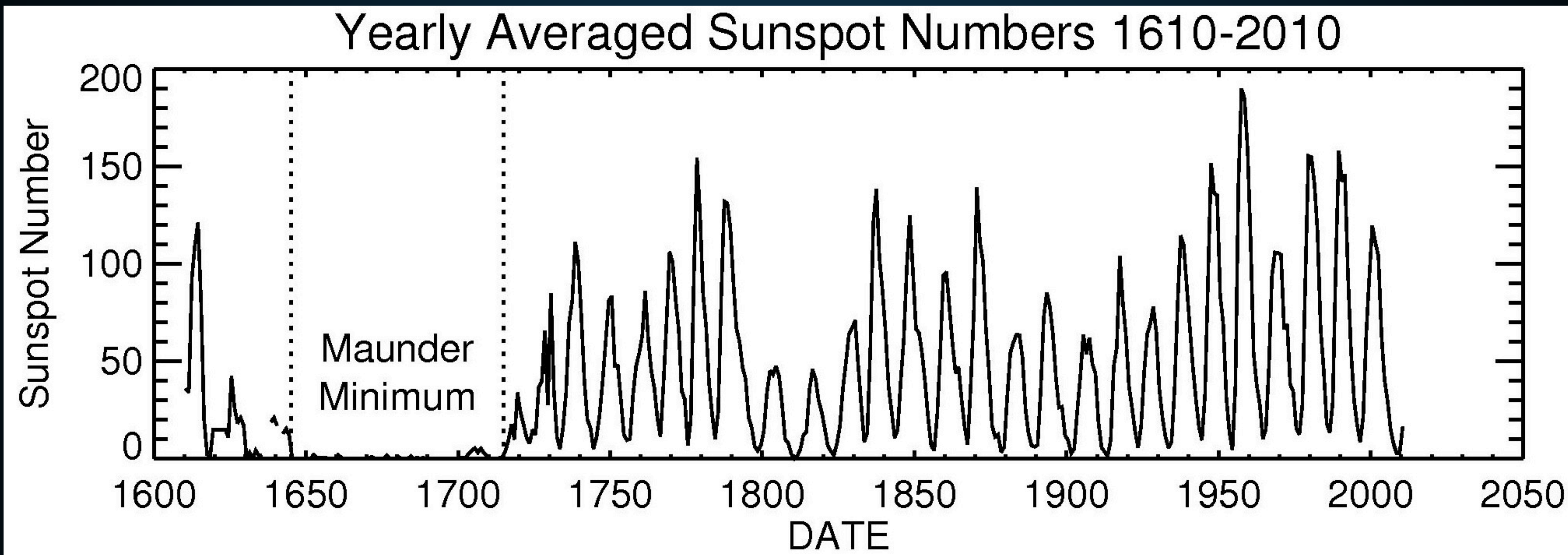
Tang et al. 2018 (1804.06846)



Intensity X

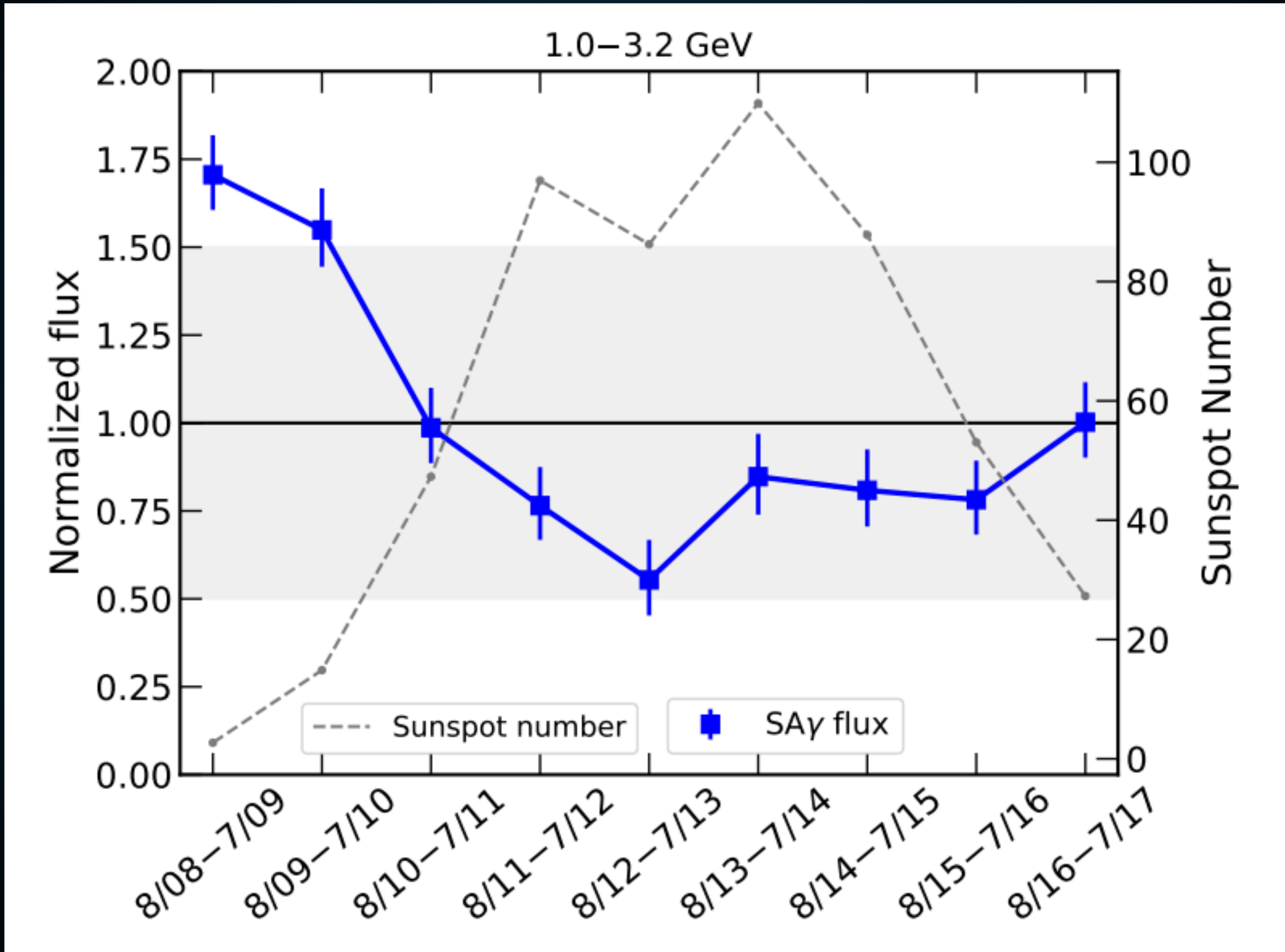
Spectrum X

OBSERVATIONS - TIME VARIABILITY



OBSERVATIONS - TIME VARIABILITY

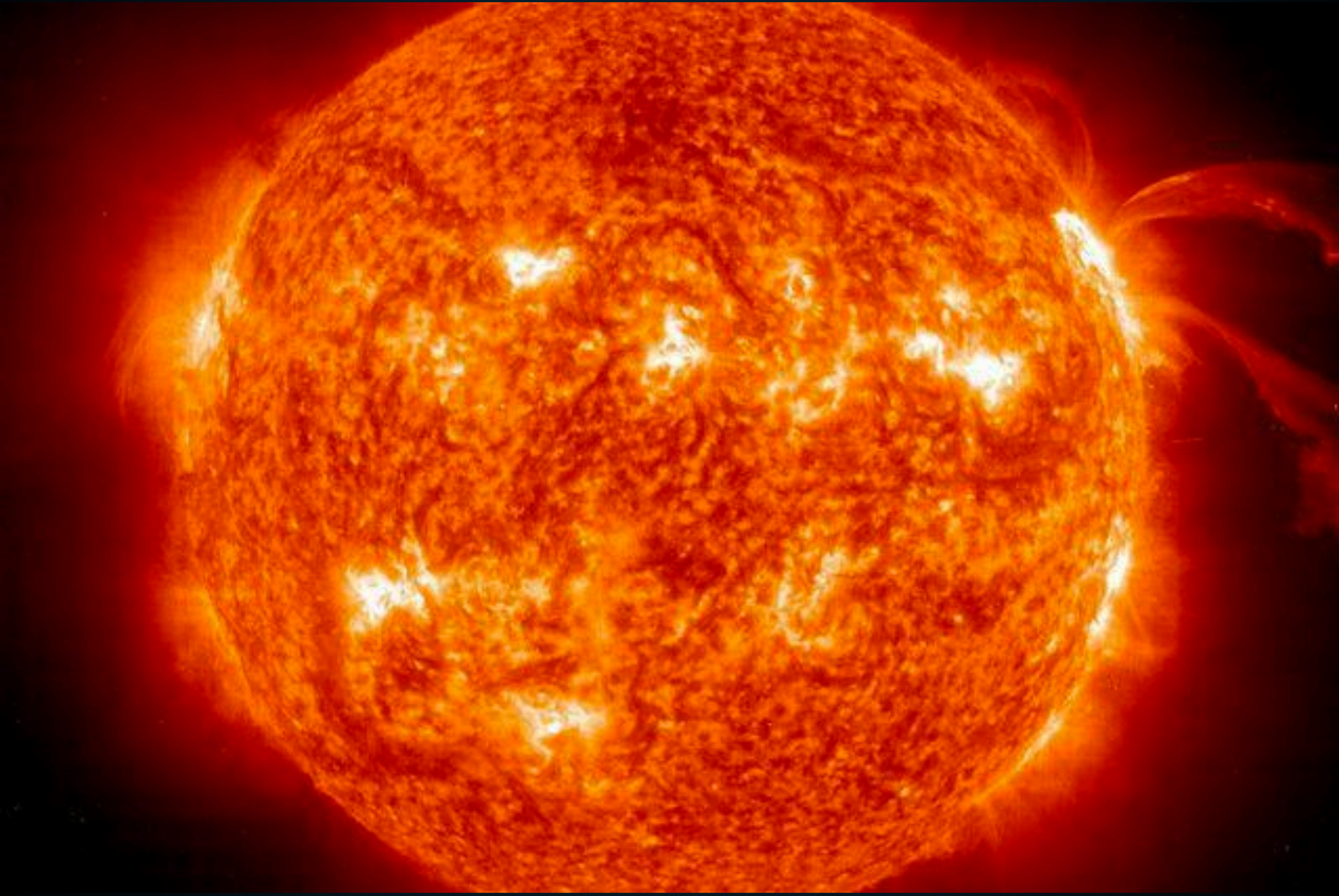
Tang et al. 2018 (1804.06846)



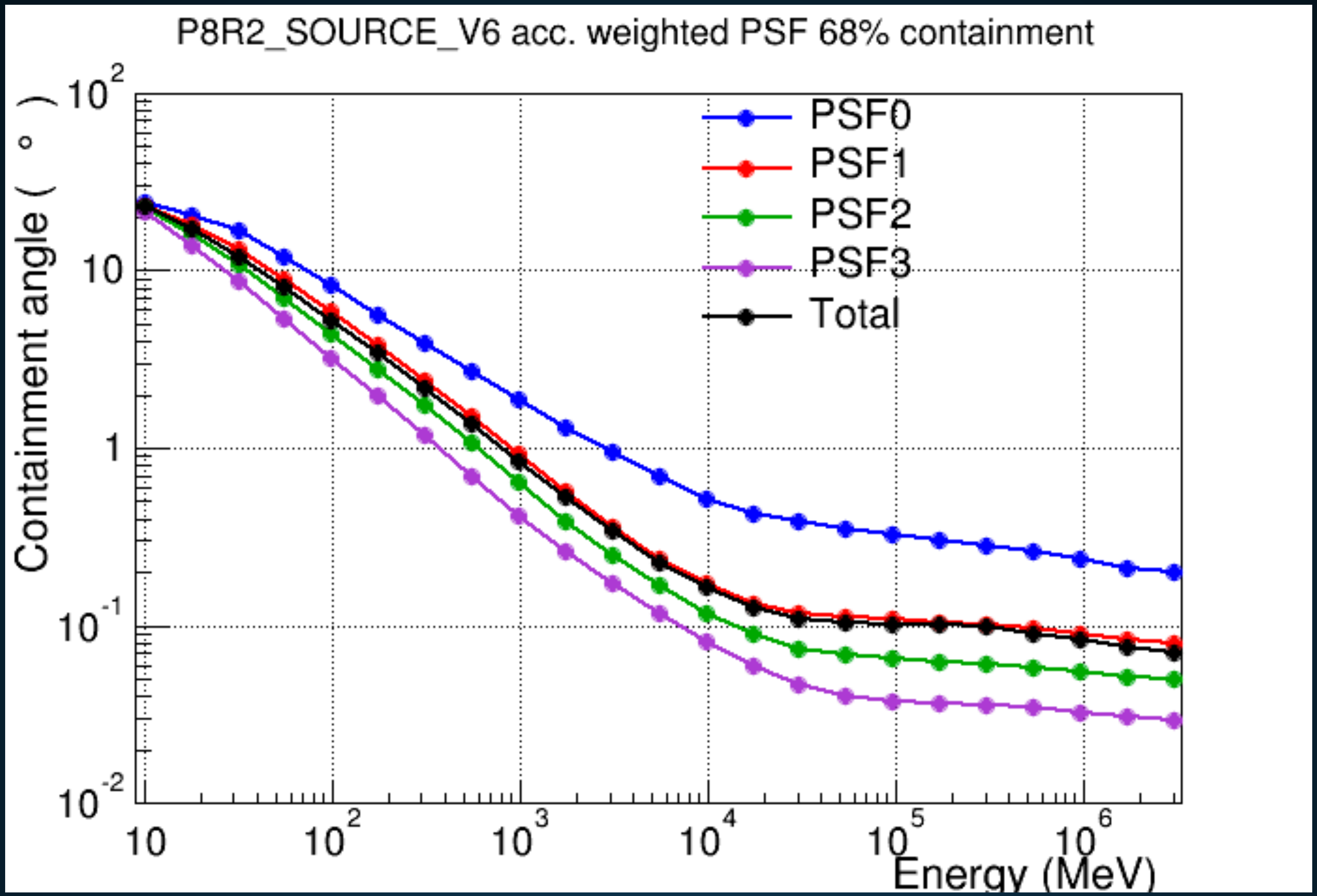
GAMMA-RAYS - WHAT?

Intensity	X
Spectrum	X
Time Variability	X

A MORPHOLOGICAL STUDY

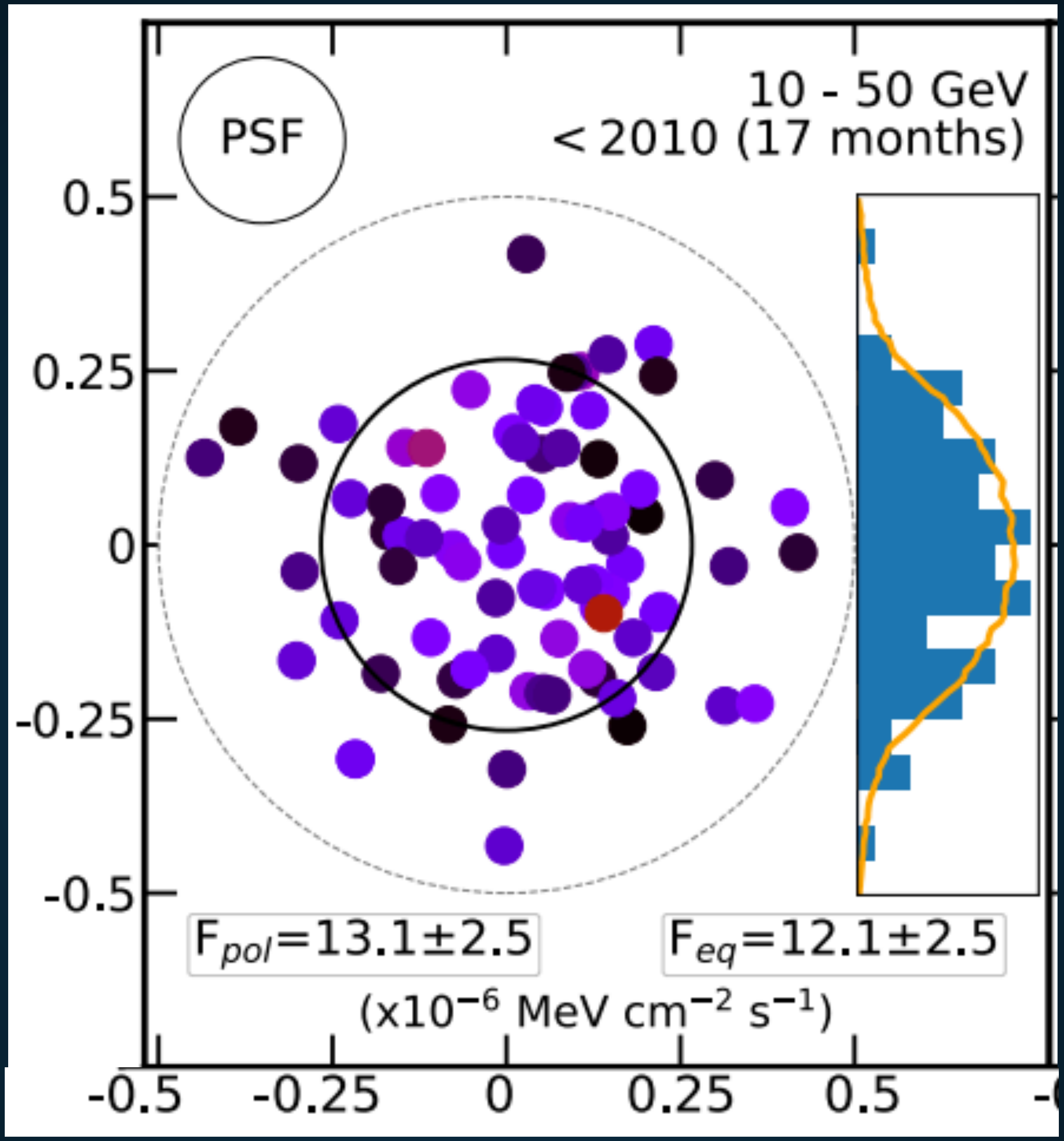


A MORPHOLOGICAL STUDY



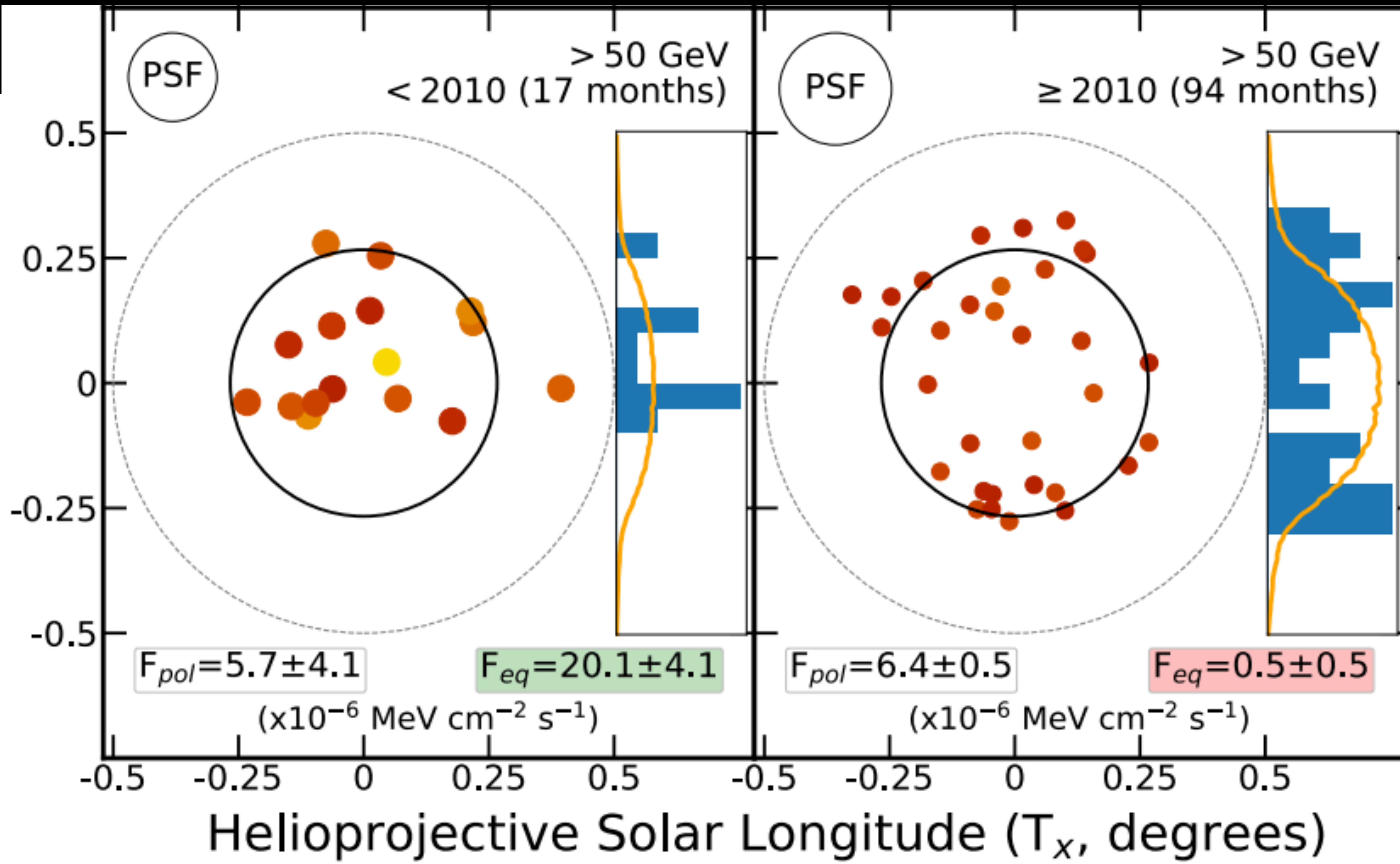
- **Examine 9 years of gamma-ray data.**
- **Re-map each photon into Helioprojective Coordinates to conserve solar rotation and position.**
- **Examine events >10 GeV, where PSF < Θ_o.**

A MORPHOLOGICAL STUDY



- **The entire disk is luminous.**
- **The limb does not appear bright.**

A MORPHOLOGICAL STUDY



GAMMA-RAYS - WHAT?

Intensity	X
Spectrum	X
Time Variability	X
Morphology	X

SPECTRAL VARIABILITY

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

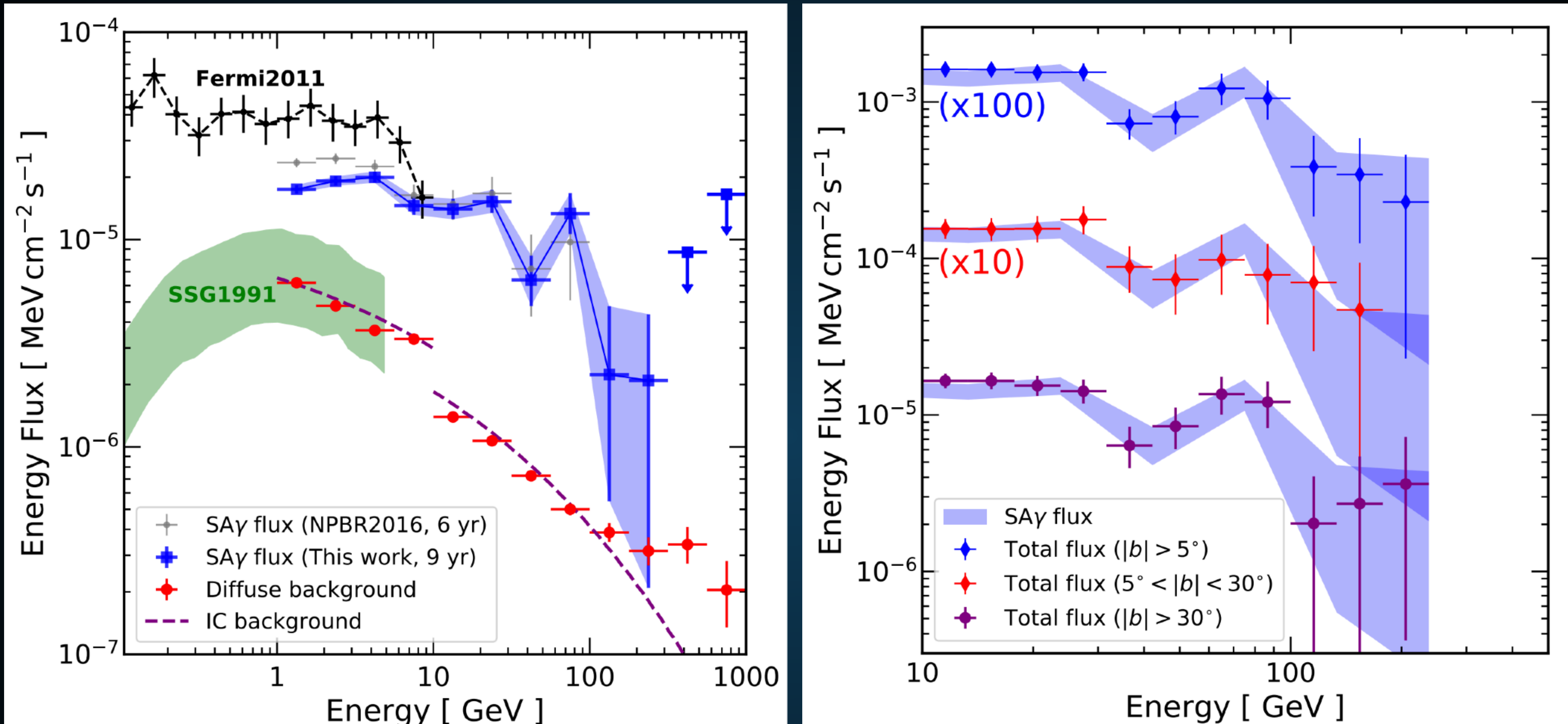
- **The spectrum also appears to change when moving from solar minimum to solar maximum.**
- **The polar component has a constant spectrum, the equatorial component does not.**

GAMMA-RAYS - WHAT?

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

GAMMA-RAYS - SPECTRAL DIP

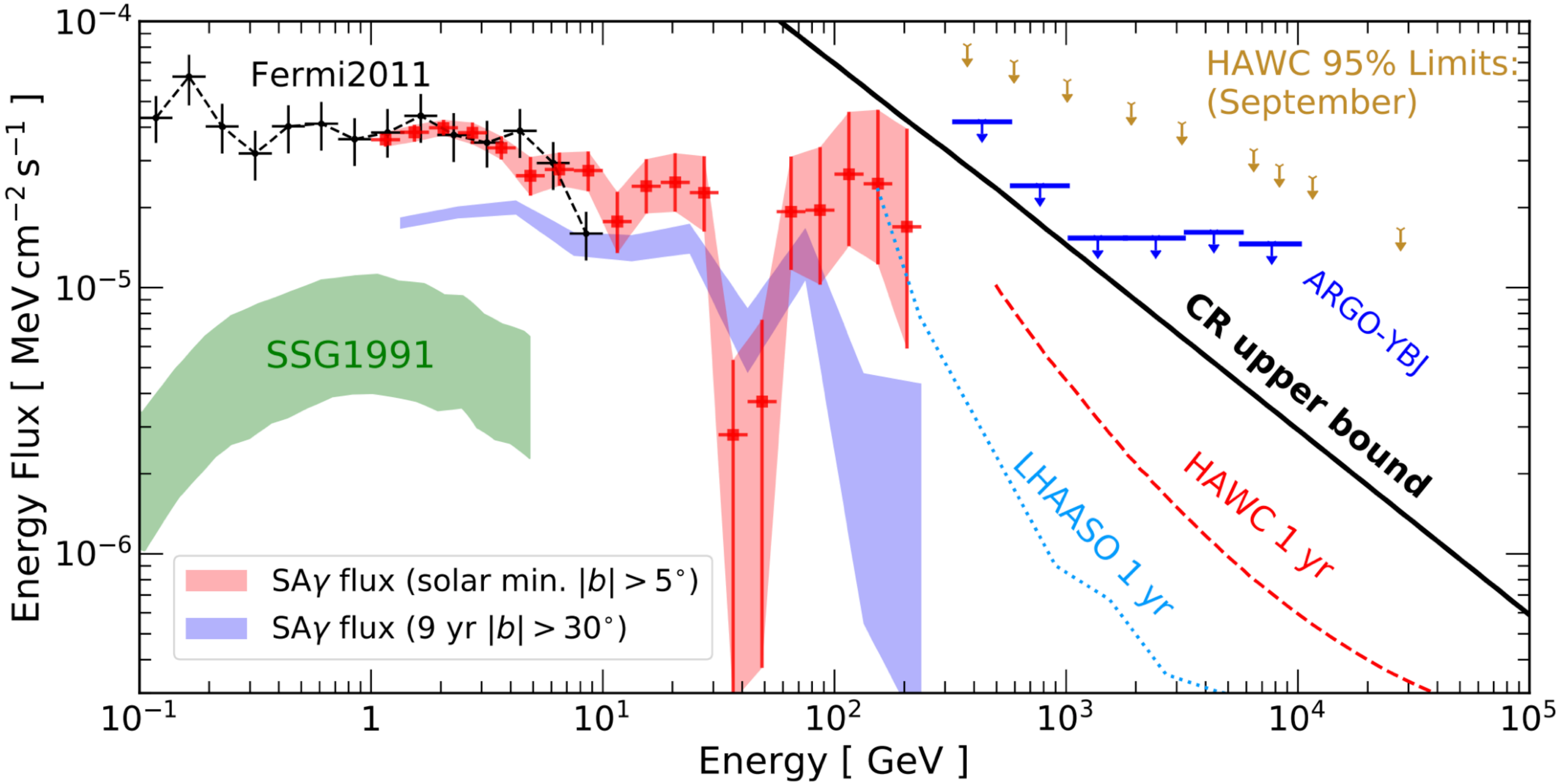
Tang et al. 2018 (1804.06846)



- **Significant dip in the gamma-ray spectrum between 30-50 GeV.**

GAMMA-RAYS - SPECTRAL DIP

Tang et al. 2018 (1804.06846)



GAMMA-RAYS - WHAT?

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

Oh wait… that’s basically everything.

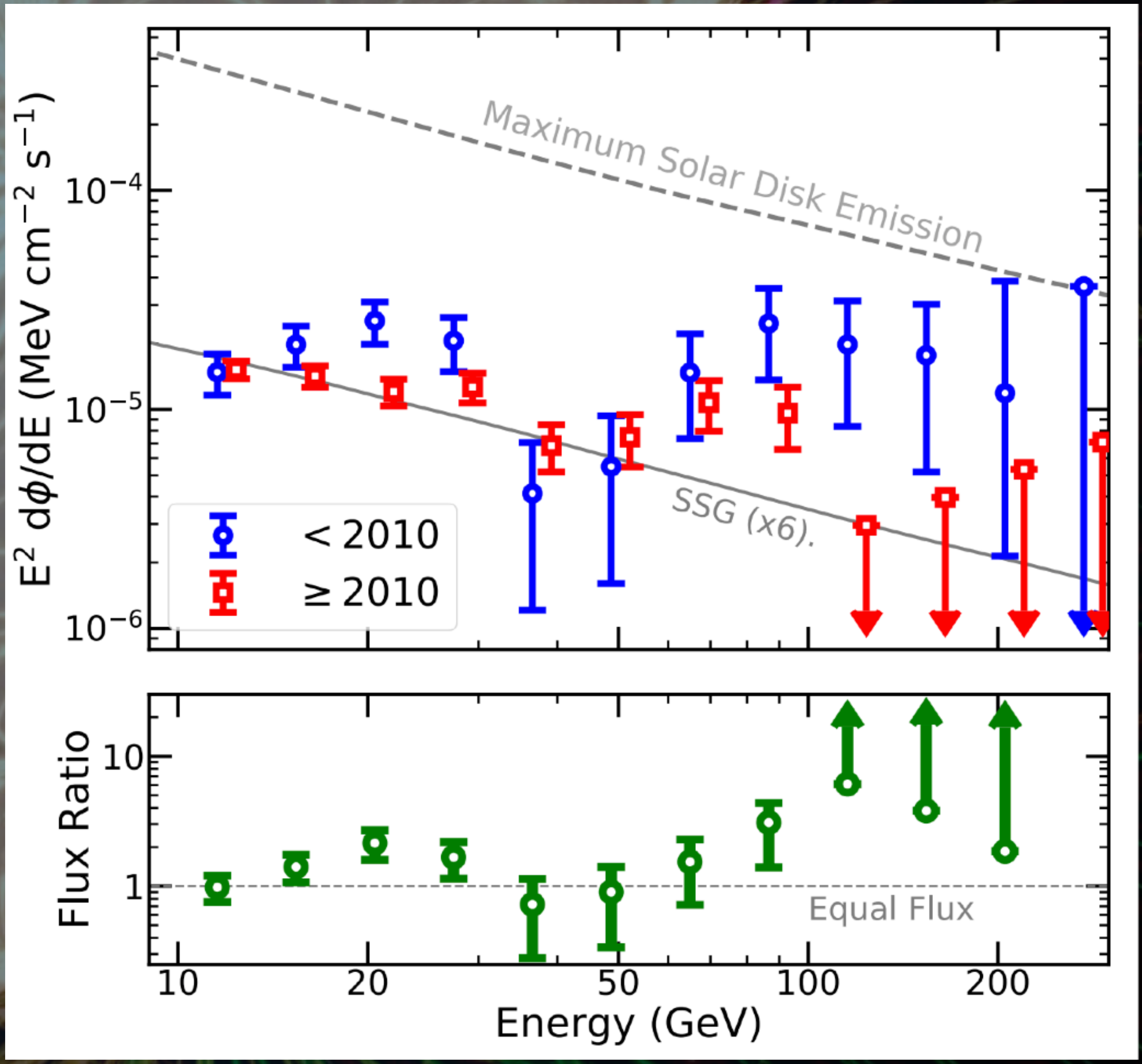
Oh wait… that's basically everything.

How do we model this?

GAMMA-RAYS - HOW?

- **Gamma-Ray Emission much brighter than expected**

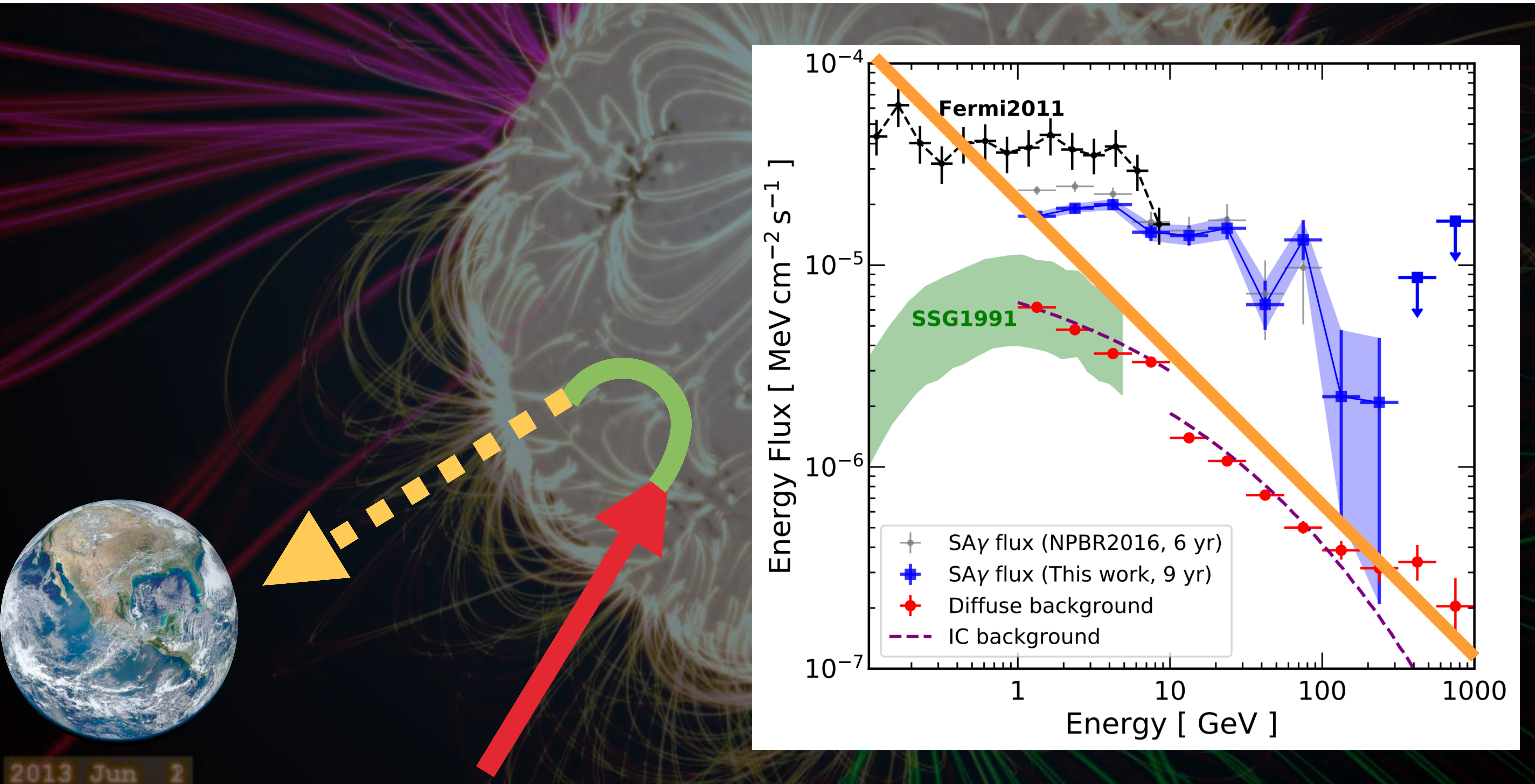
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$



2013 Jun 2

- **Gamma-Ray spectrum much harder than expected**

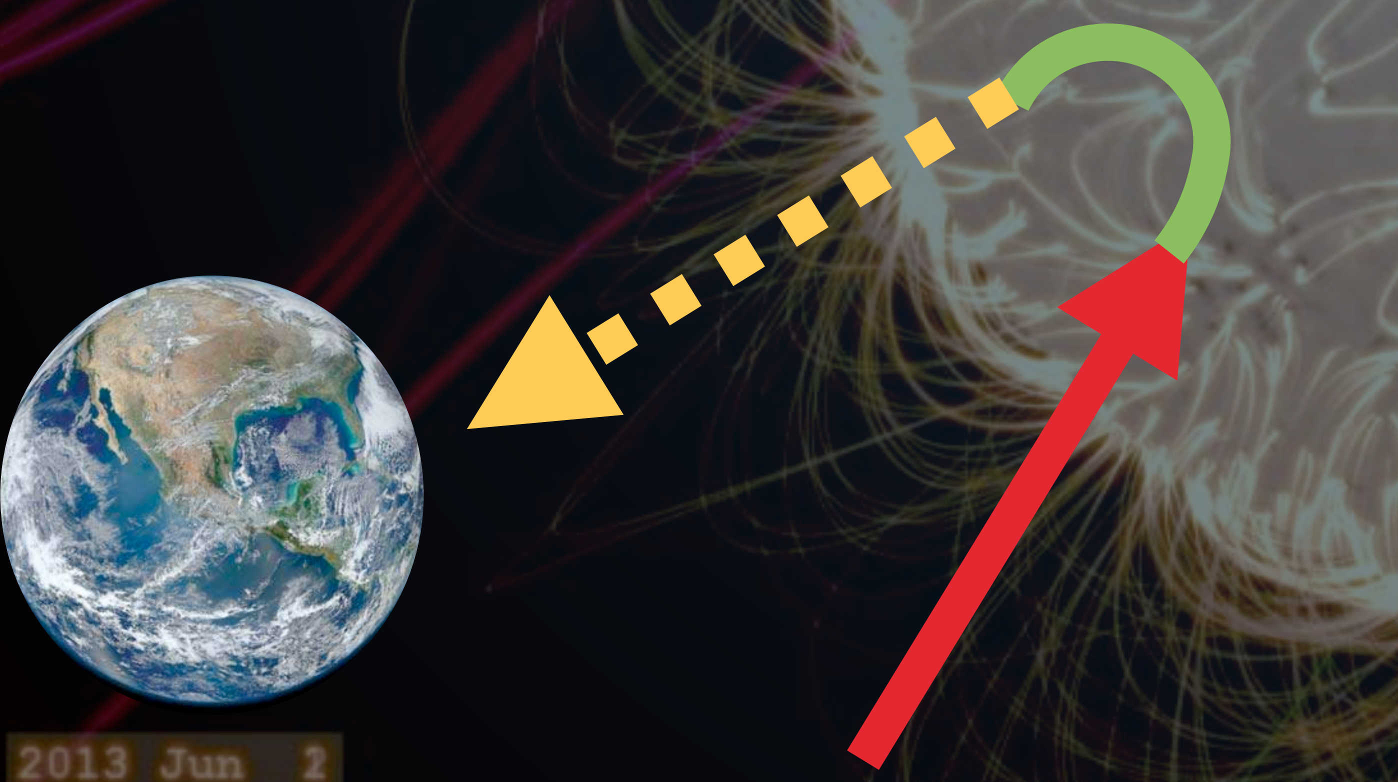
$$\Phi_{\odot}(E_{\gamma}) = \pi R_{\odot}^{2} \Phi_{\mathrm{CR}}(E_{\mathrm{CR}}) C(E_{\gamma}, E_{\mathrm{CR}}) f_{\mathrm{sur}} f_{\mathrm{turn}} f_{\mathrm{int}}$$

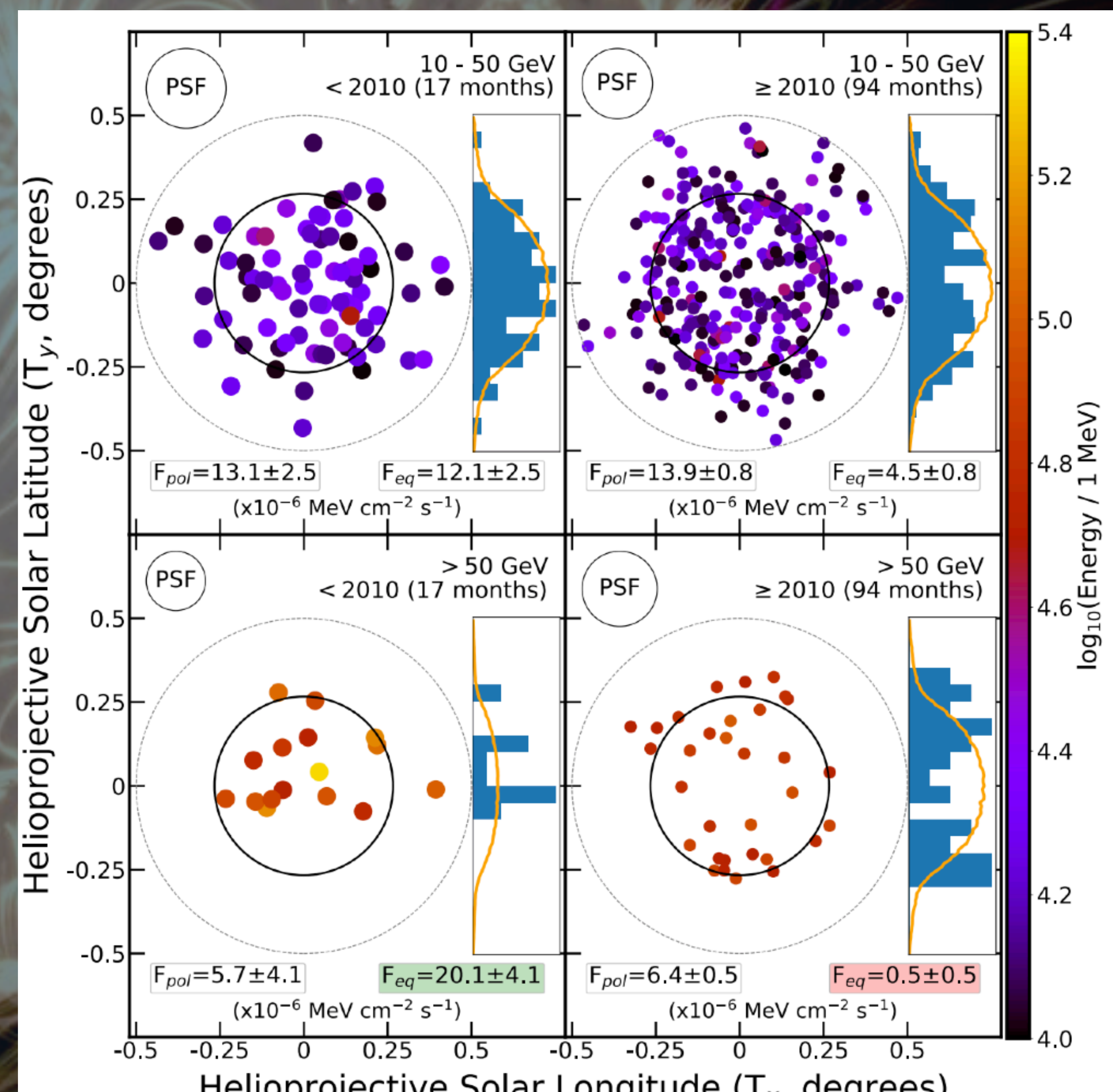


GAMMA-RAYS - HOW?

- **Gamma-Ray morphology not uniform**

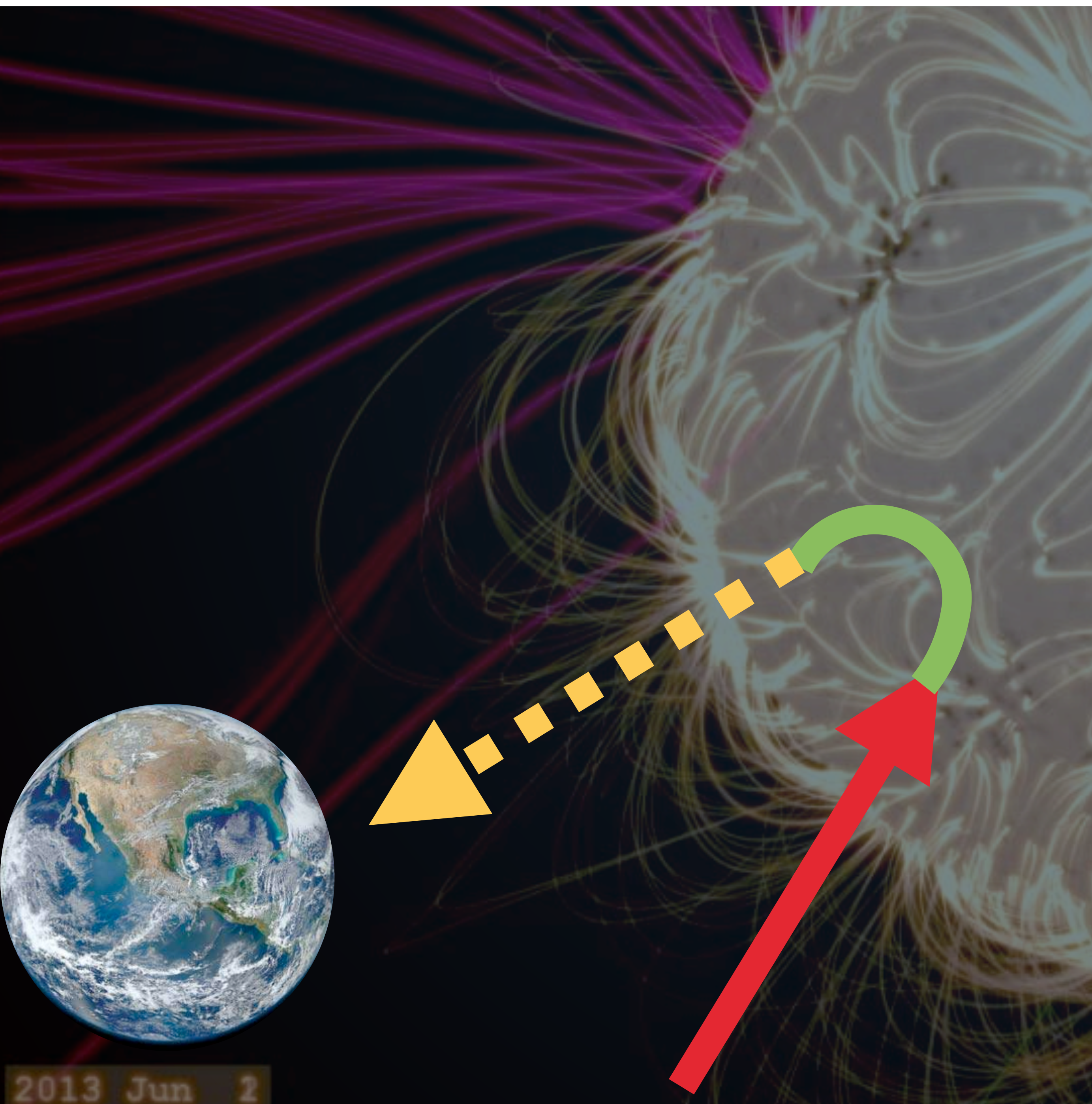
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

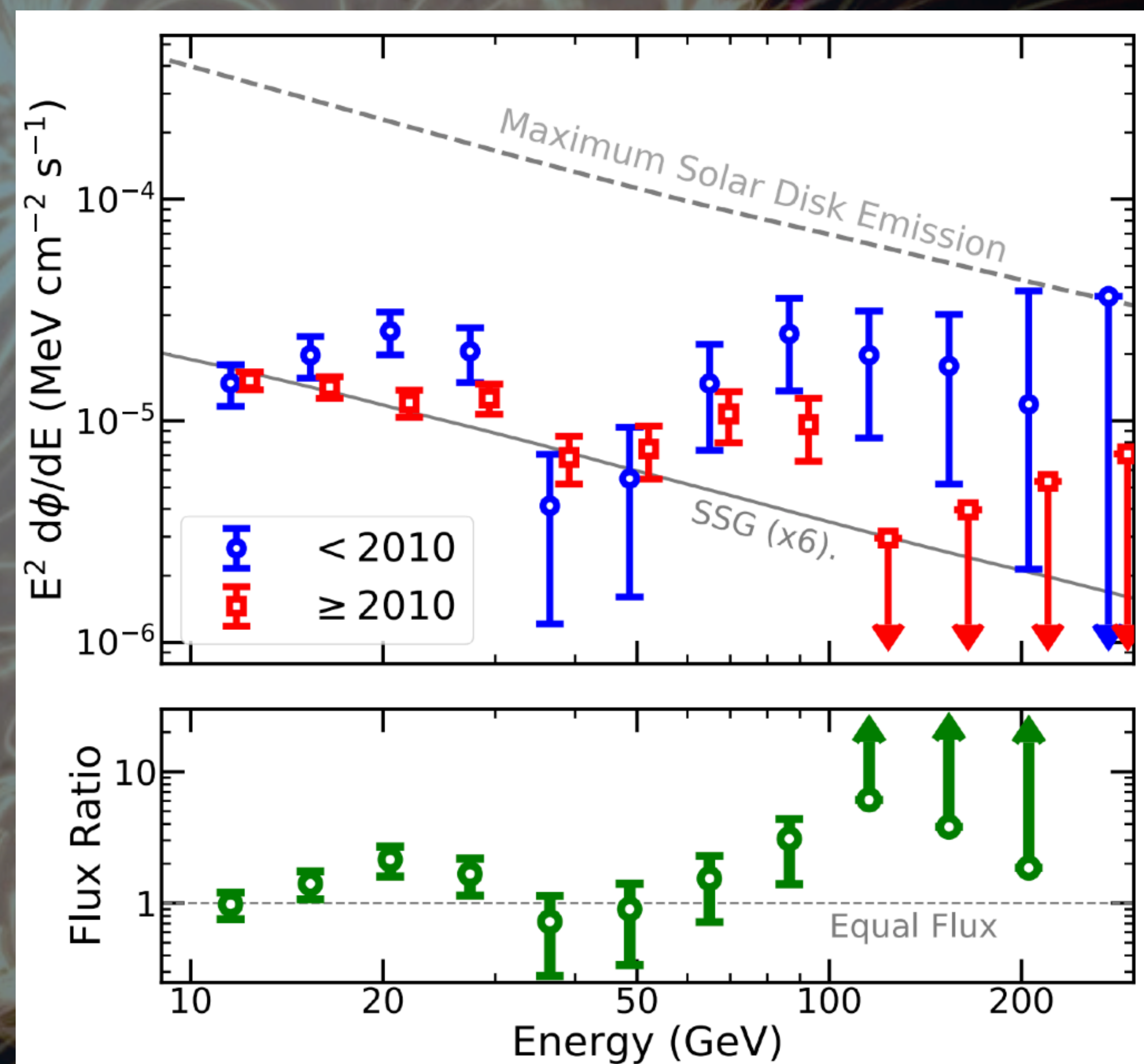




- **Evidence for two different emission mechanisms?**

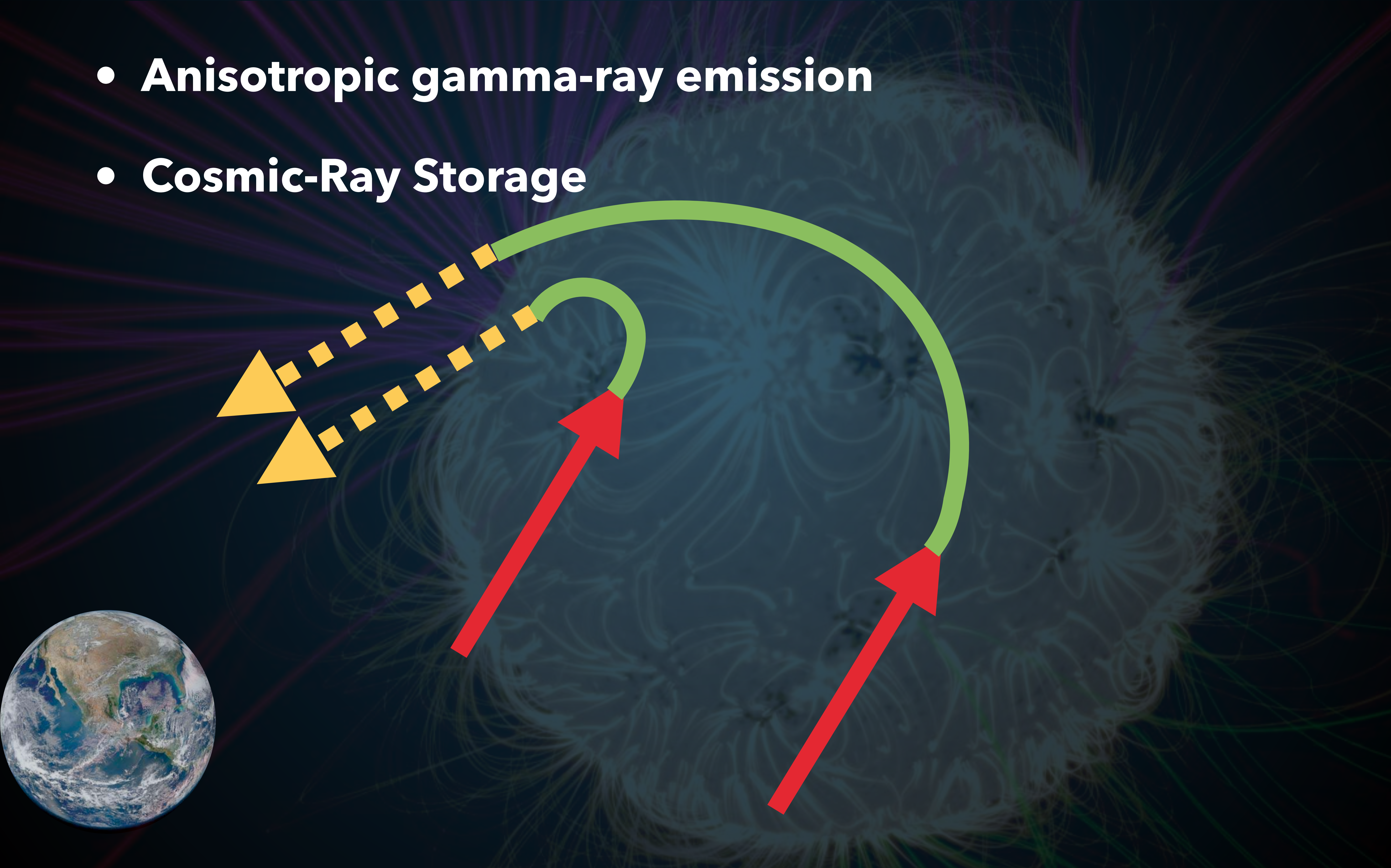
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\mathrm{CR}}(E_{\mathrm{CR}}) C(E_\gamma, E_{\mathrm{CR}}) f_{\mathrm{sur}} f_{\mathrm{turn}} f_{\mathrm{int}}$$





GAMMA-RAYS - HOW?

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

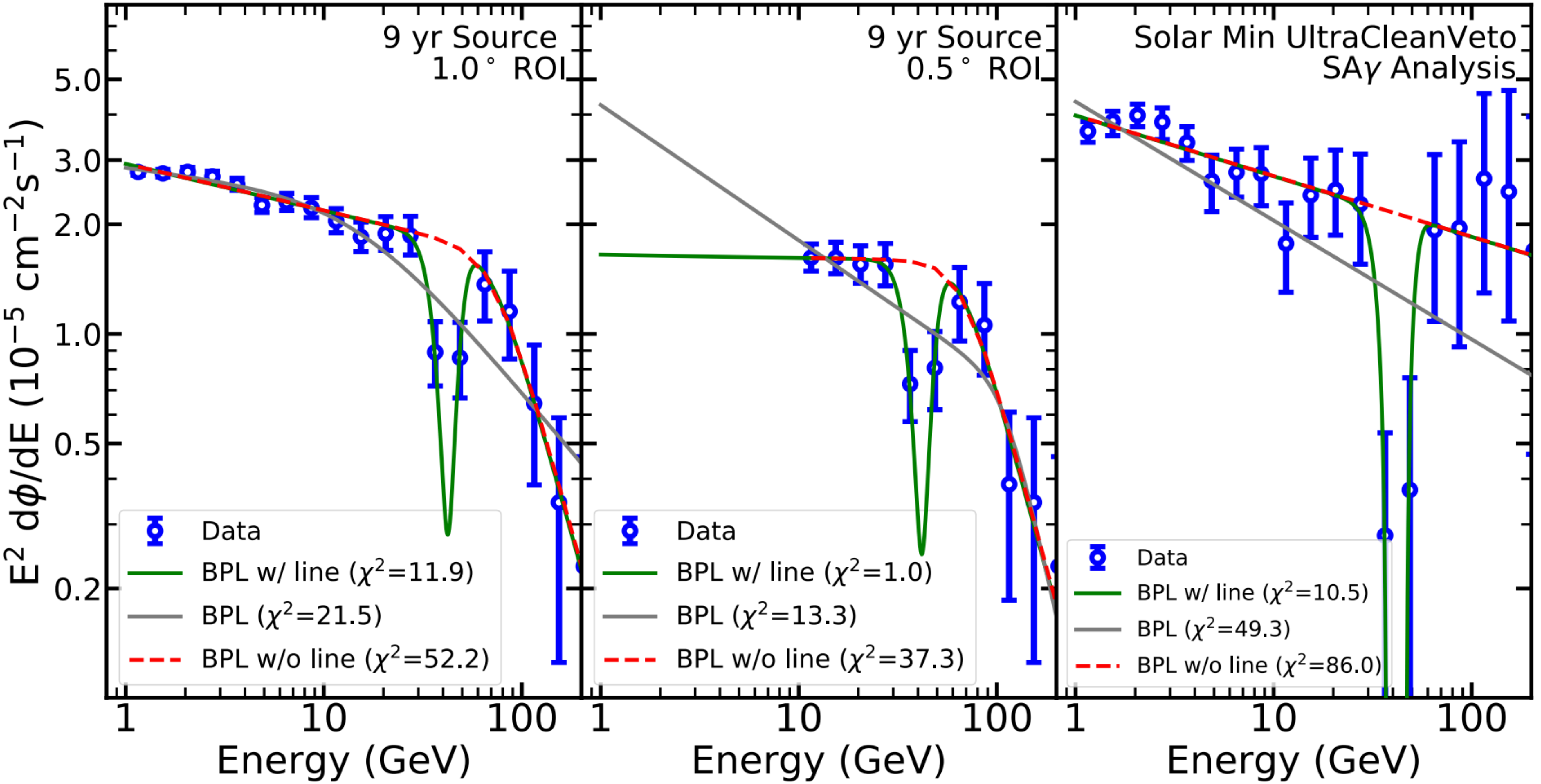


What About this spectral dip?

GAMMA-RAYS - HOW?

?

THE SPECTRAL DIP?

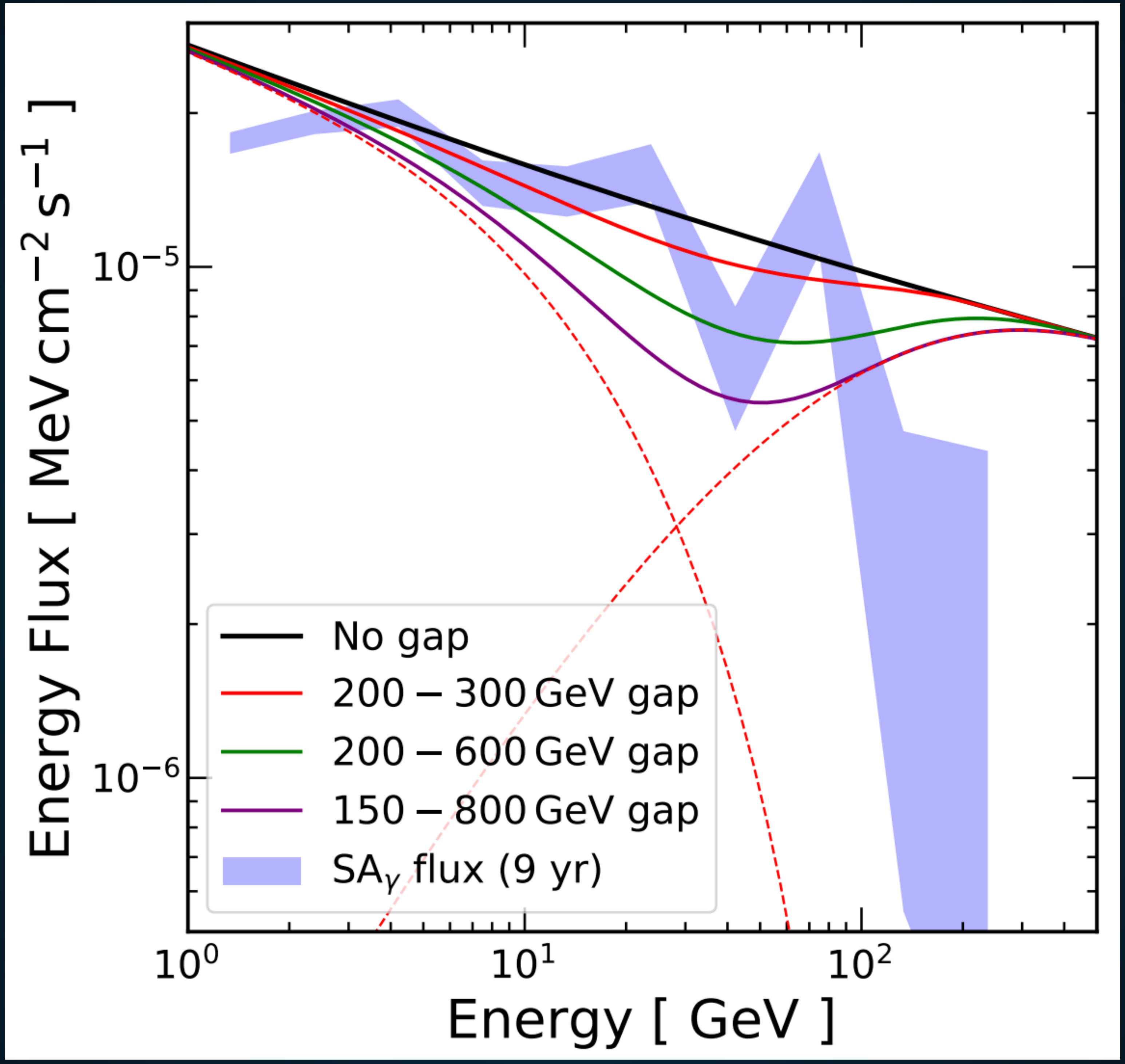


THE SPECTRAL DIP?

- **Possibilities:**

1. **Hadronic Physics**
2. **Gamma-ray Absorption**
3. **Instrumental Artifacts**

THE SPECTRAL DIP?

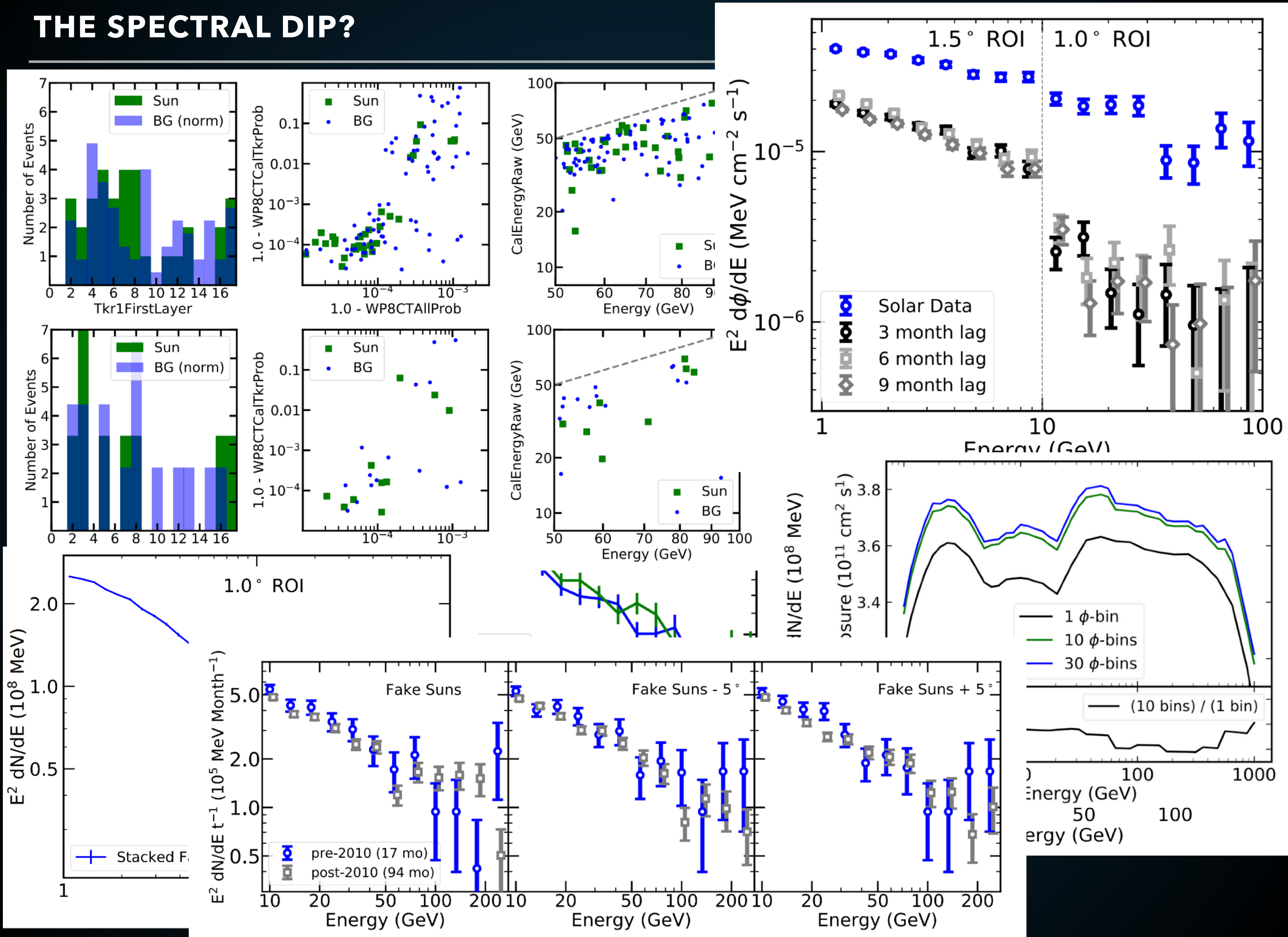


- **Hadronic processes cannot produce the amplitude and width of the spectral dip.**

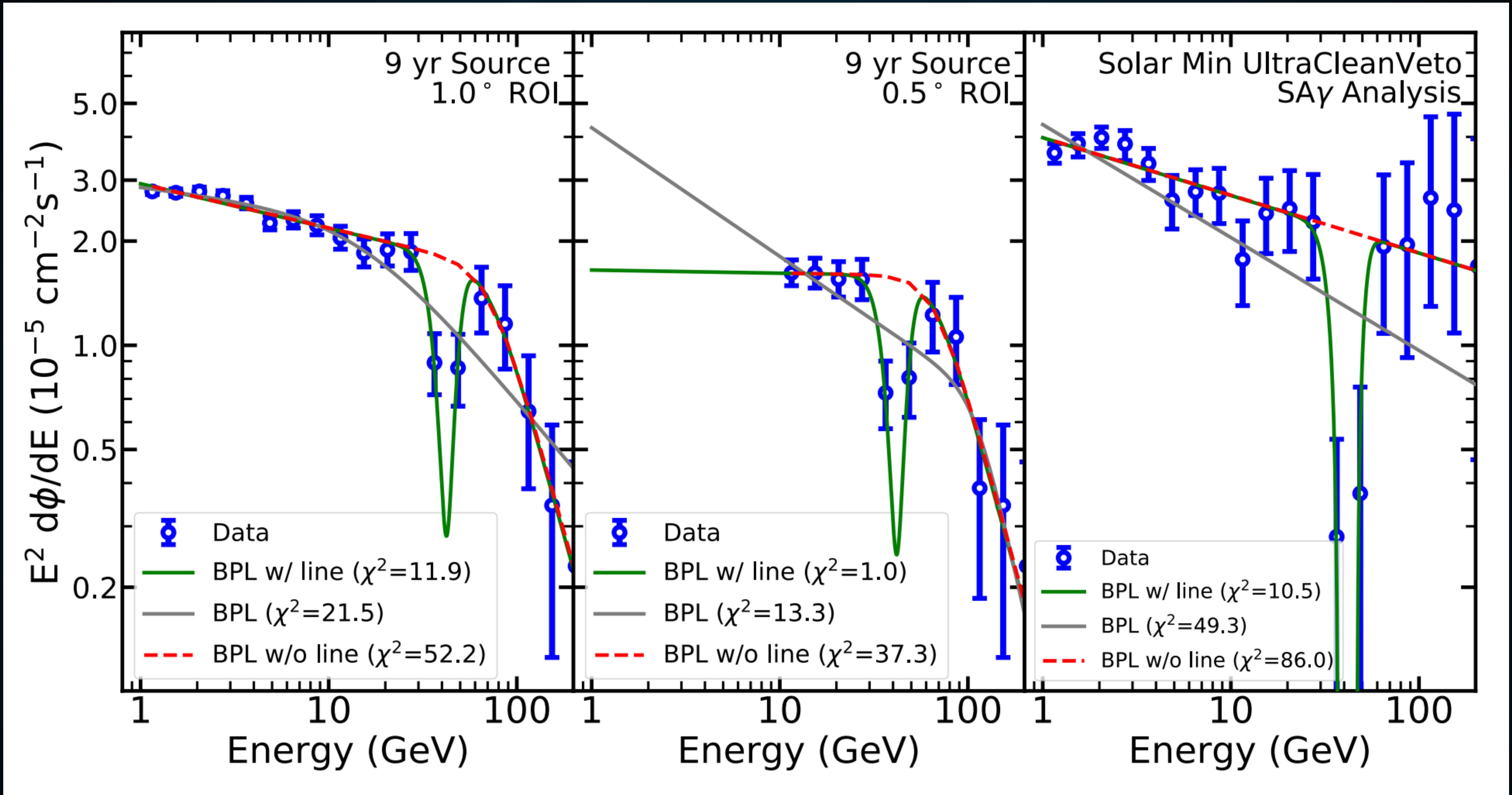
THE SPECTRAL DIP?

- **No clear mechanism for how energy-dependent photon absorption would work…**

THE SPECTRAL DIP?



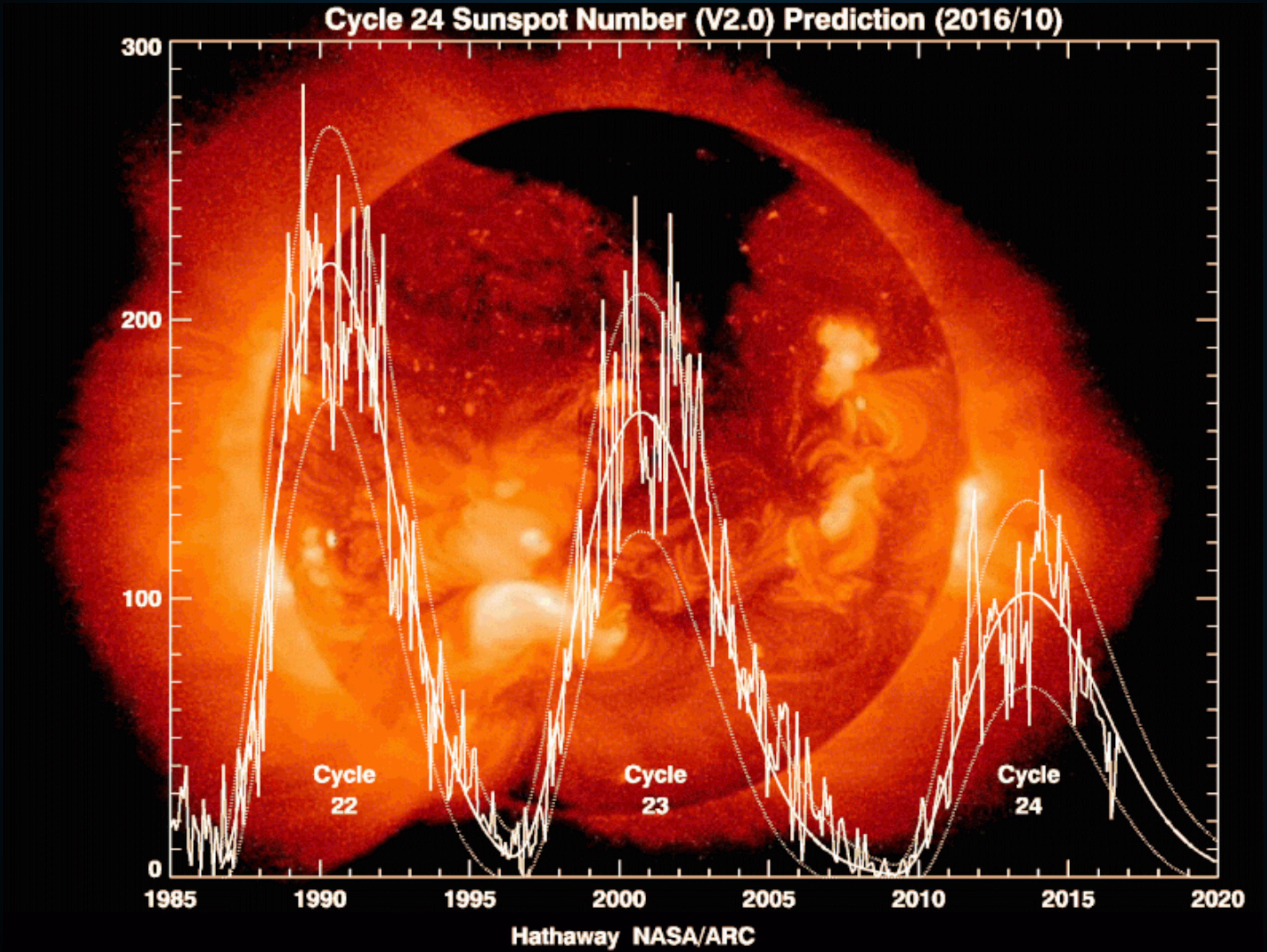
AN INSTRUMENTAL WORKING HYPOTHESIS



- **Or maybe new physics?**

HOW DO WE RESOLVE THESE ISSUES?

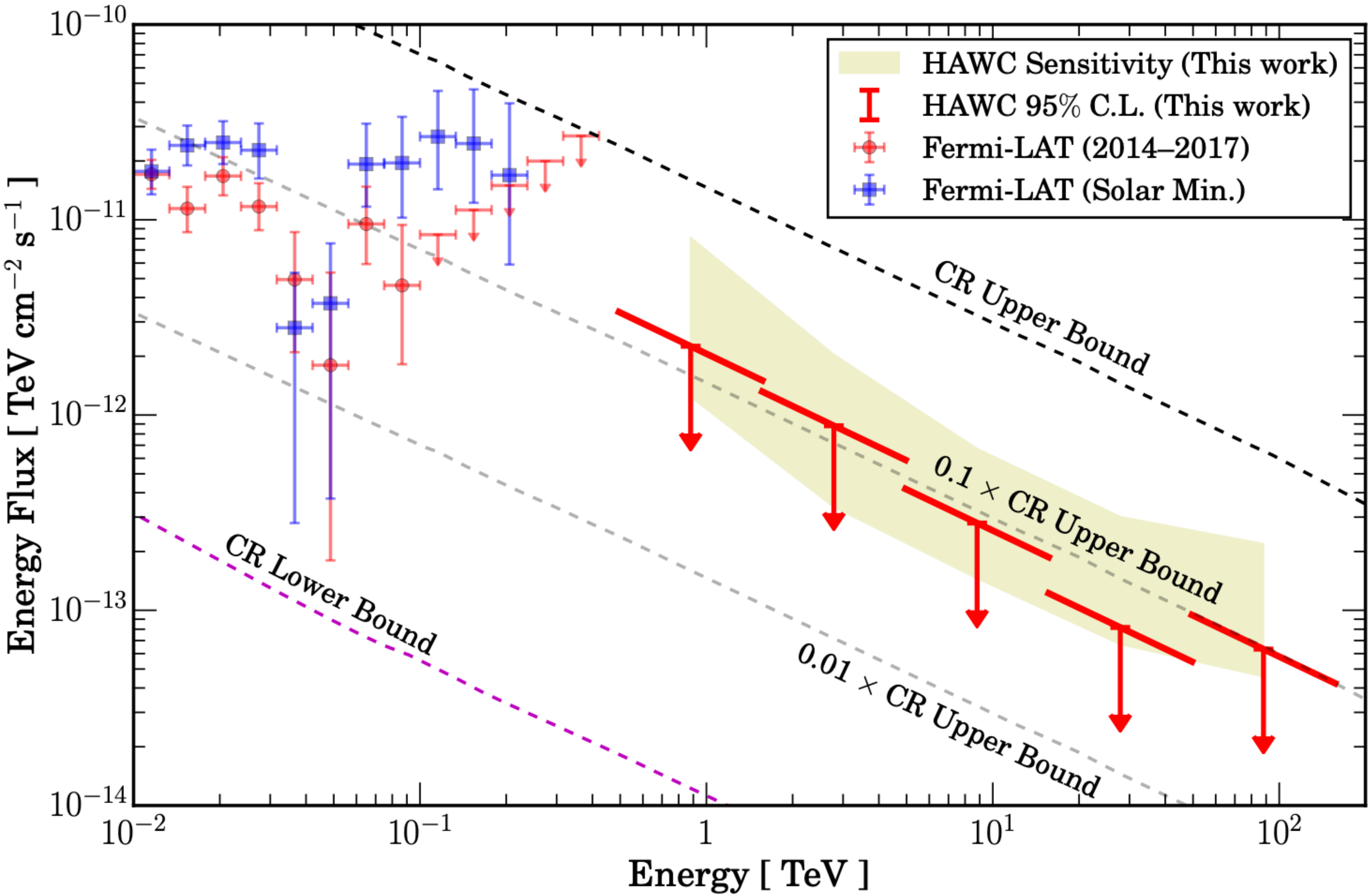
HOW DO WE RESOLVE THESE ISSUES?



TEV OBSERVATIONS OF THE SUN

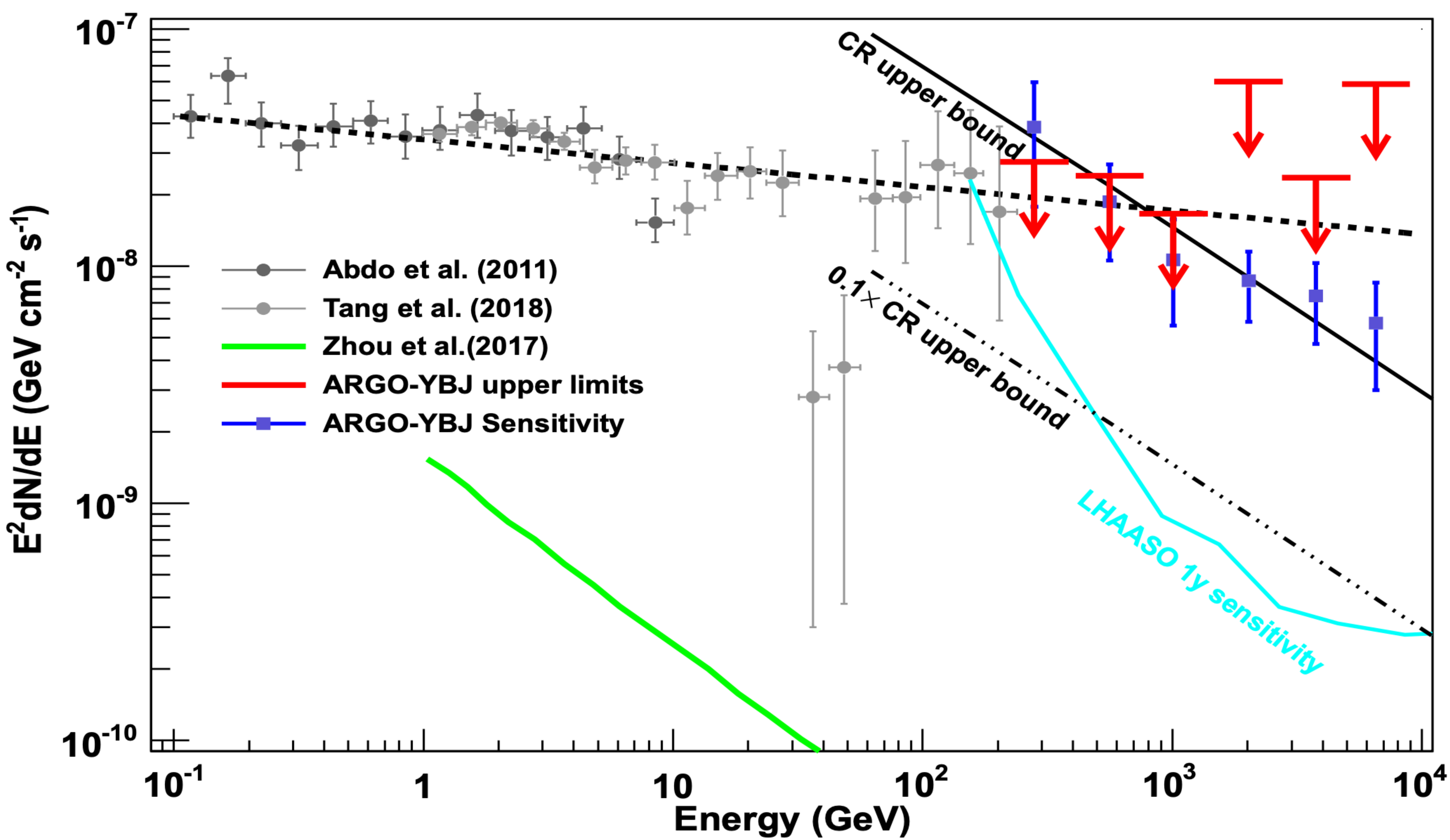
TEV OBSERVATIONS OF THE SUN

HAWC Collaboration (including TL) (2018; 1808.05620)



TEV OBSERVATIONS OF THE SUN

ARGO-YBJ Collaboration (2019; 1901.04201)

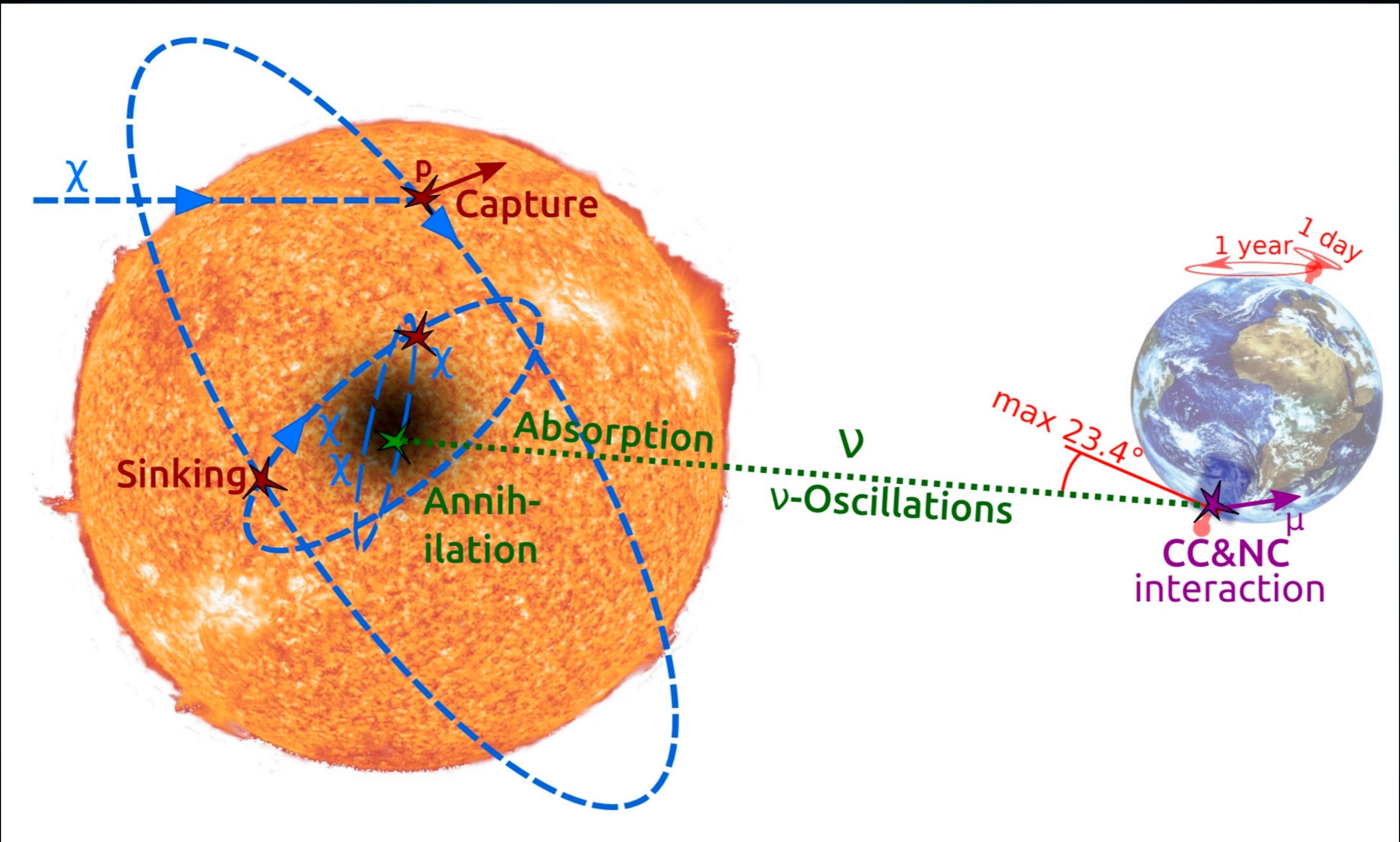


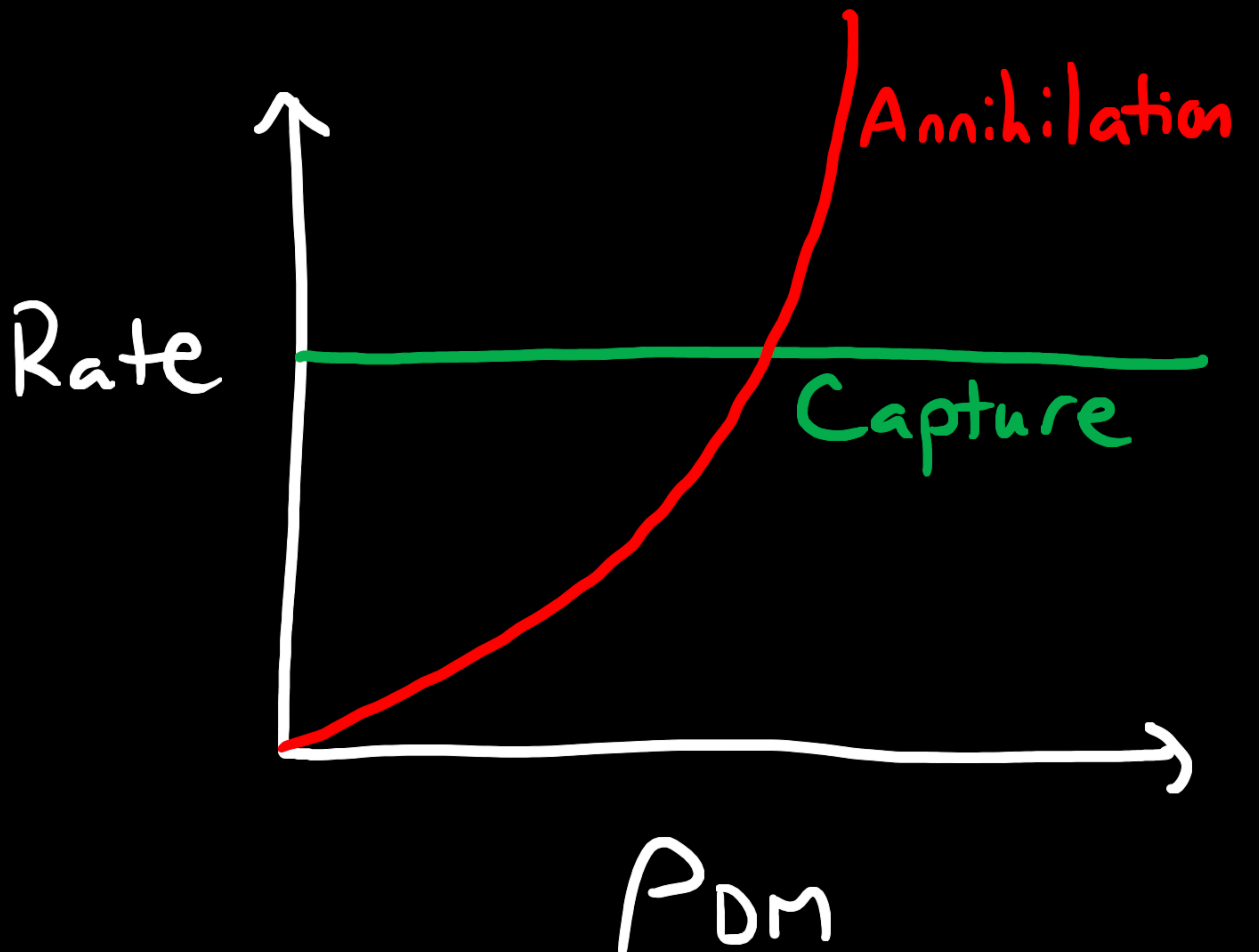
CONCLUSIONS

- We see - but we don't understand (solar gamma-ray emission).
- More work is needed:
  - Joint-Analysis of gamma-ray and magnetohydrodynamic data.
  - Detailed models of cosmic-ray propagation below the photosphere
- Opportunity to make fundamental advancements in our understanding of cosmic-ray propagation and solar physics.

A DARK-MATTER CONNECTION

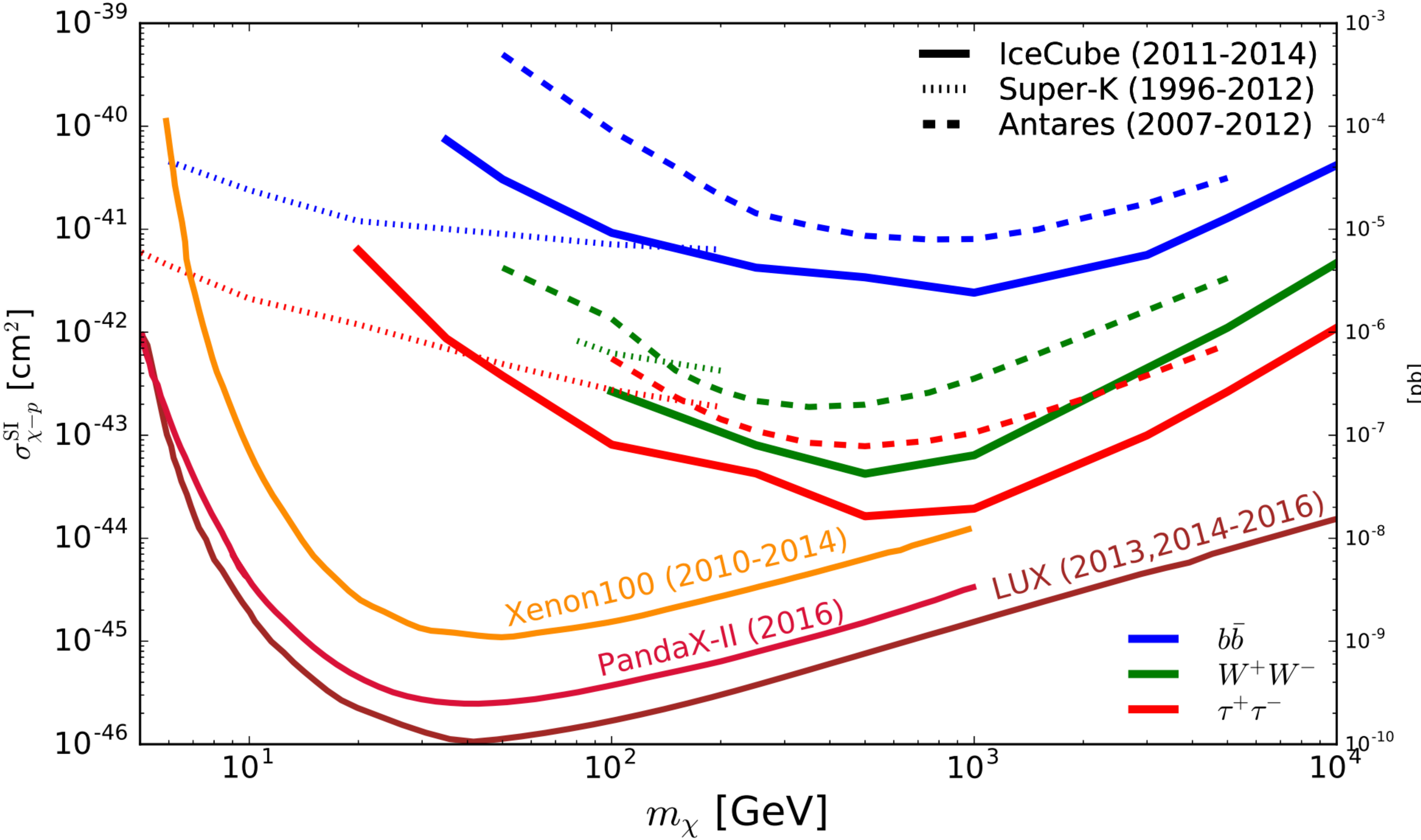
IceCube Collaboration (2016; 1612.05949)




Rate
Annihilation
Capture
ρ_{DM}

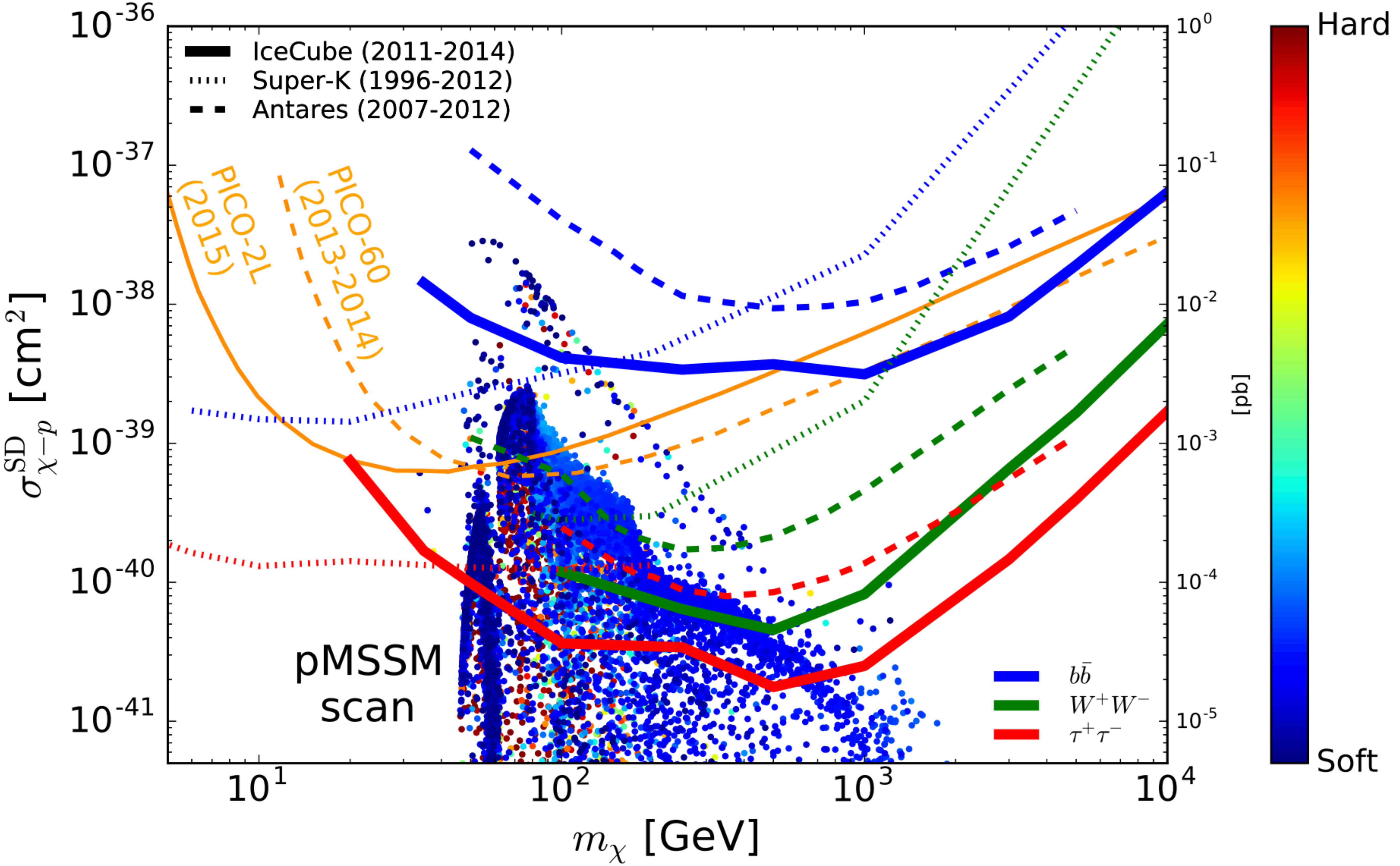
A DARK-MATTER CONNECTION

IceCube Collaboration (2016; 1612.05949)

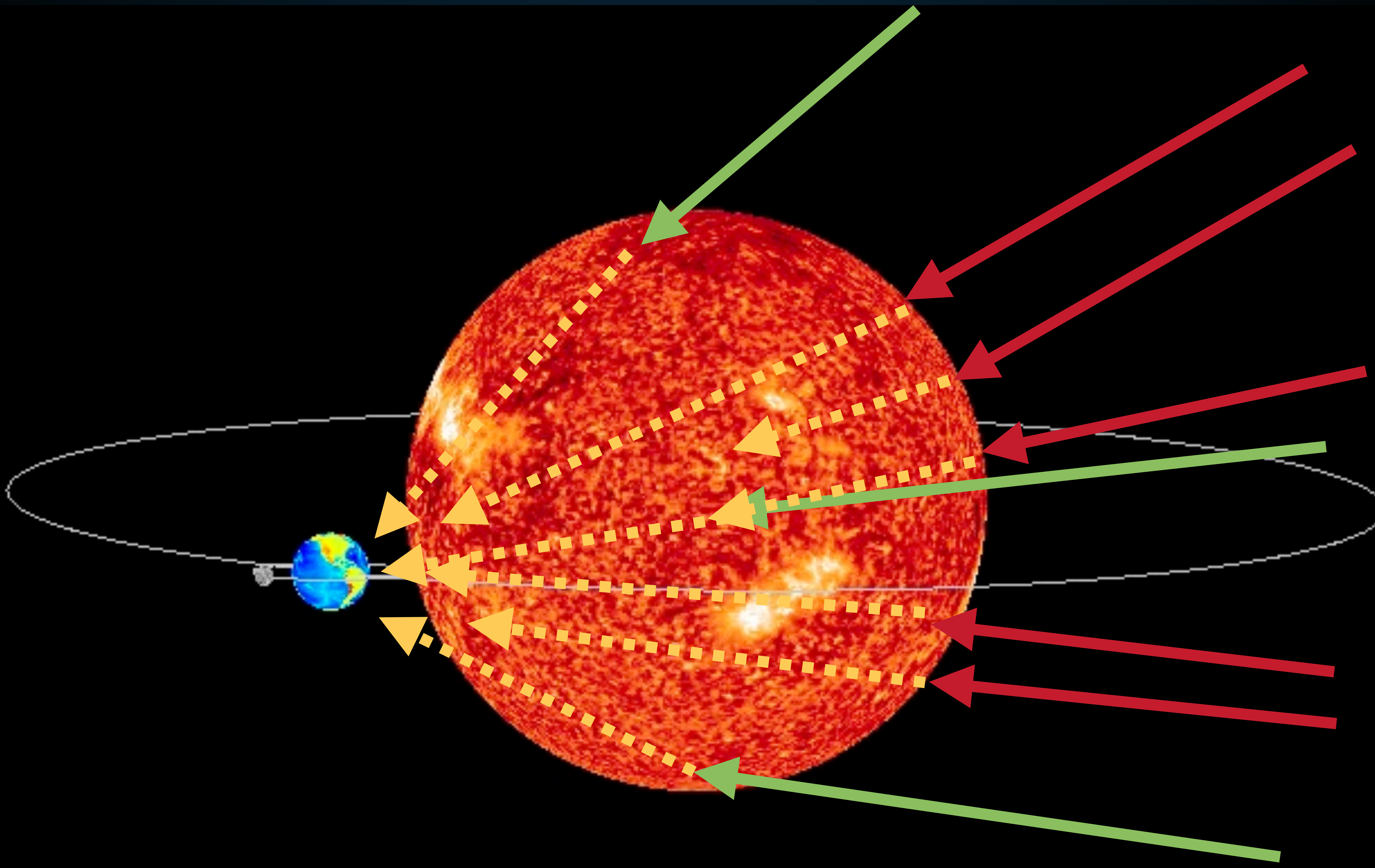


A DARK-MATTER CONNECTION

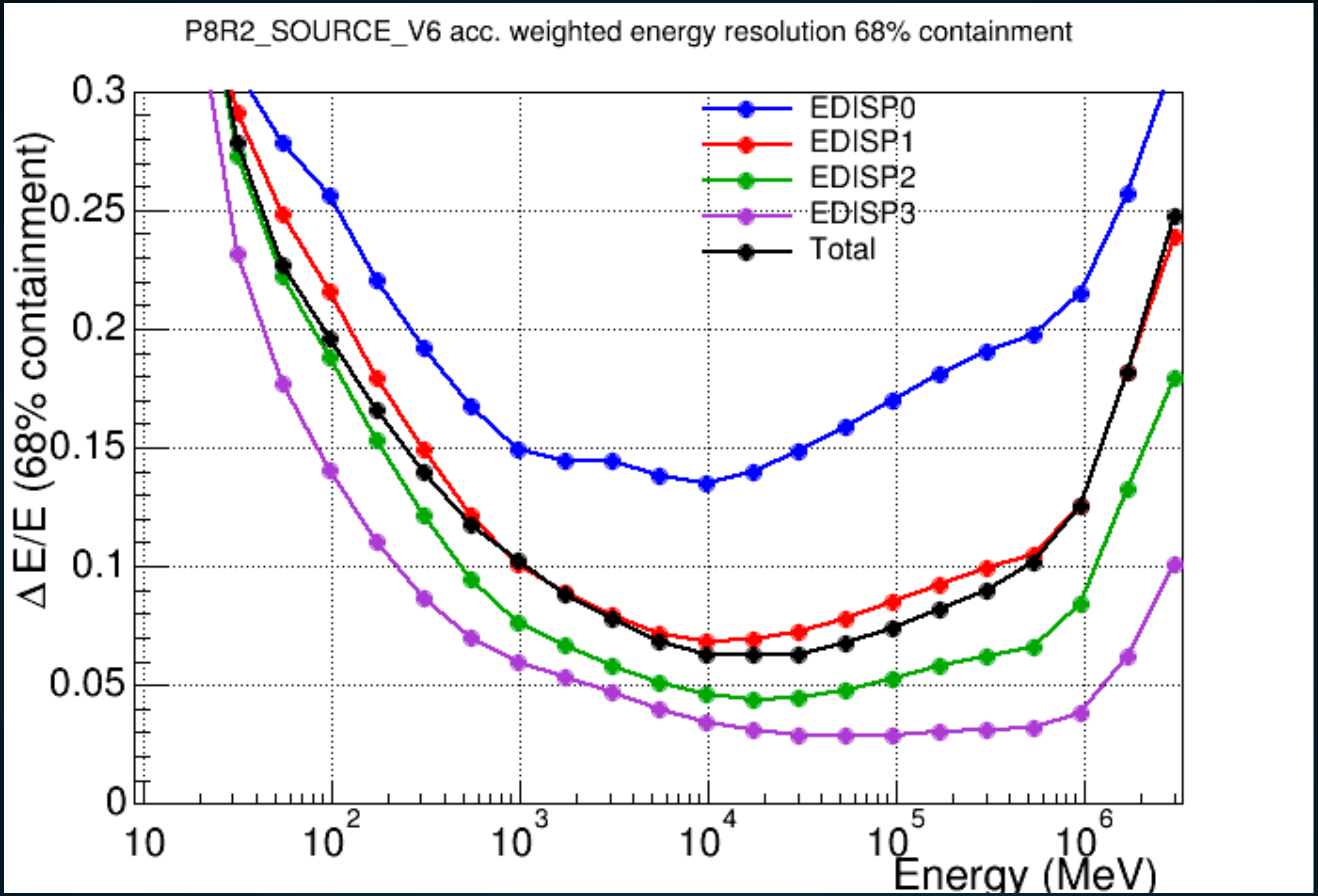
IceCube Collaboration (2016; 1612.05949)



HADRONIC GAMMA-RAYS - HOW?



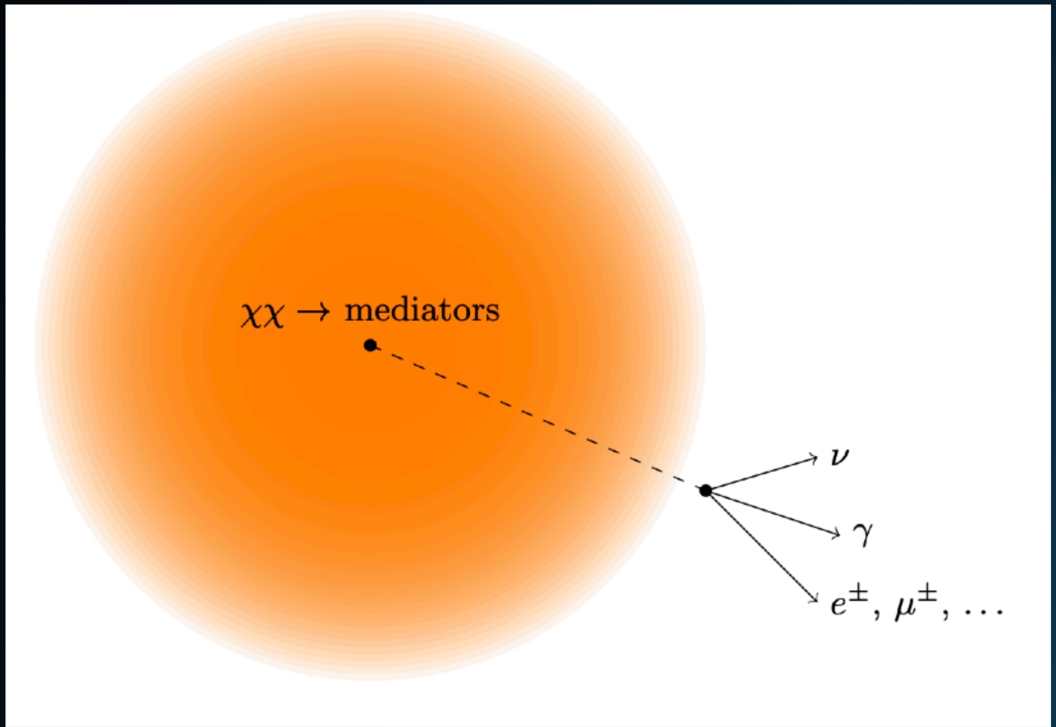
A SPECTRAL STUDY



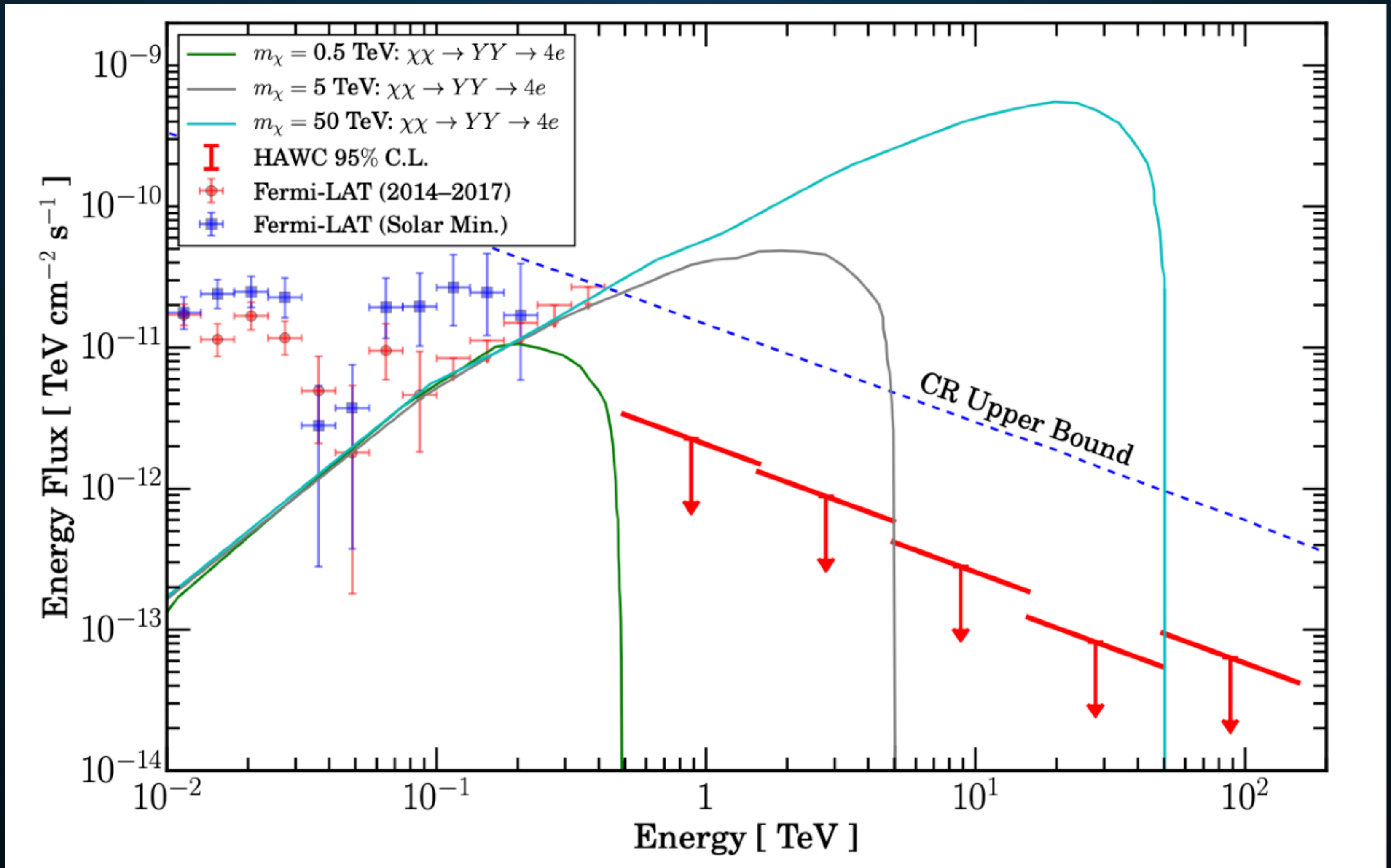
- **Examine 9 years of gamma-ray data.**
- **Utilize all events more than 5º from the Galactic plane**
- **Convolve each event with a best-fit energy dispersion.**

A DARK-MATTER CONNECTION

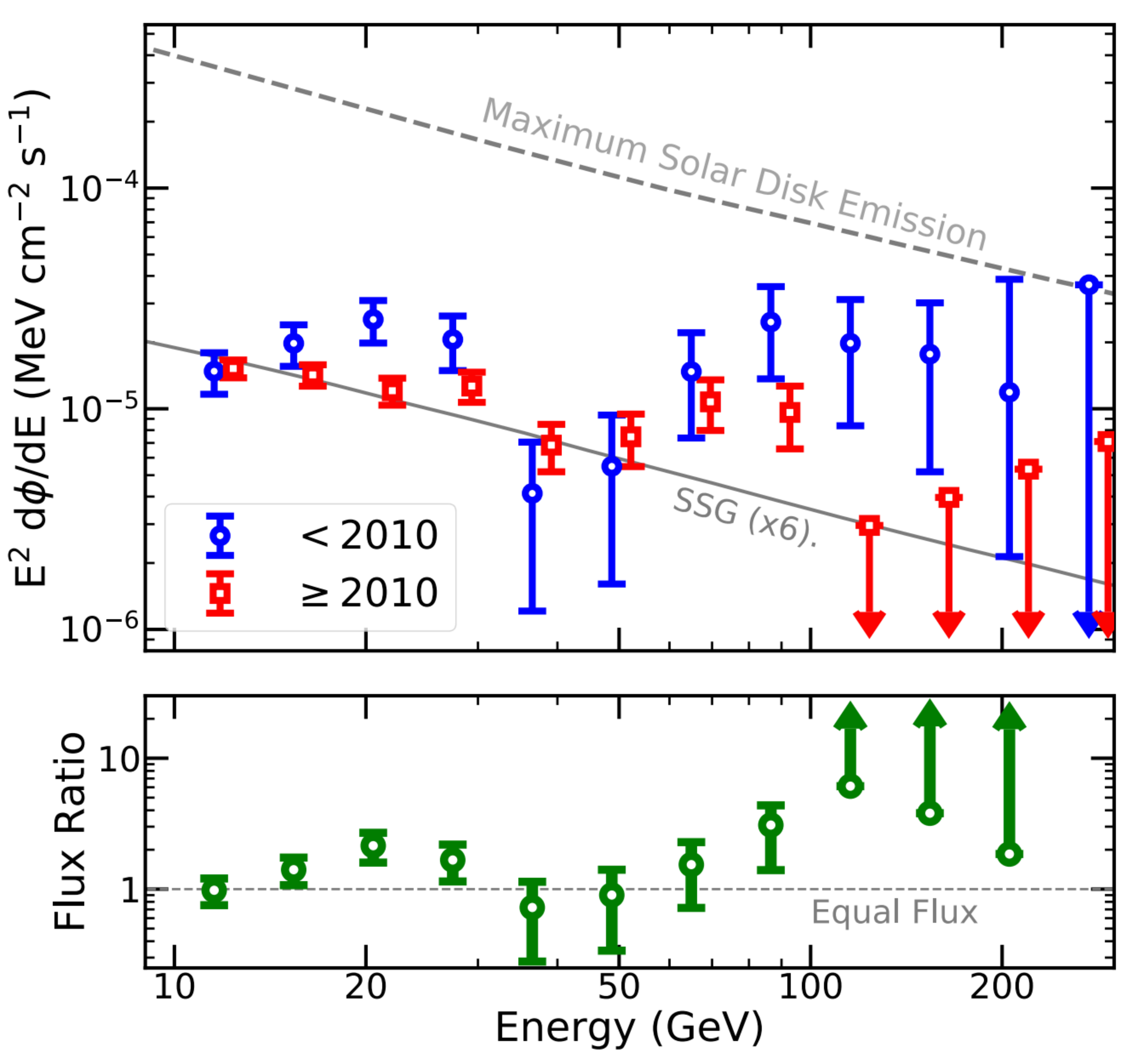
HAWC Collaboration (including TL) (2018; 1808.05624)



- **Can set limits on the gamma-ray signal, if annihilation goes to long-lived mediators.**



- **Gamma-Ray Emission much brighter than expected**



A DARK-MATTER CONNECTION

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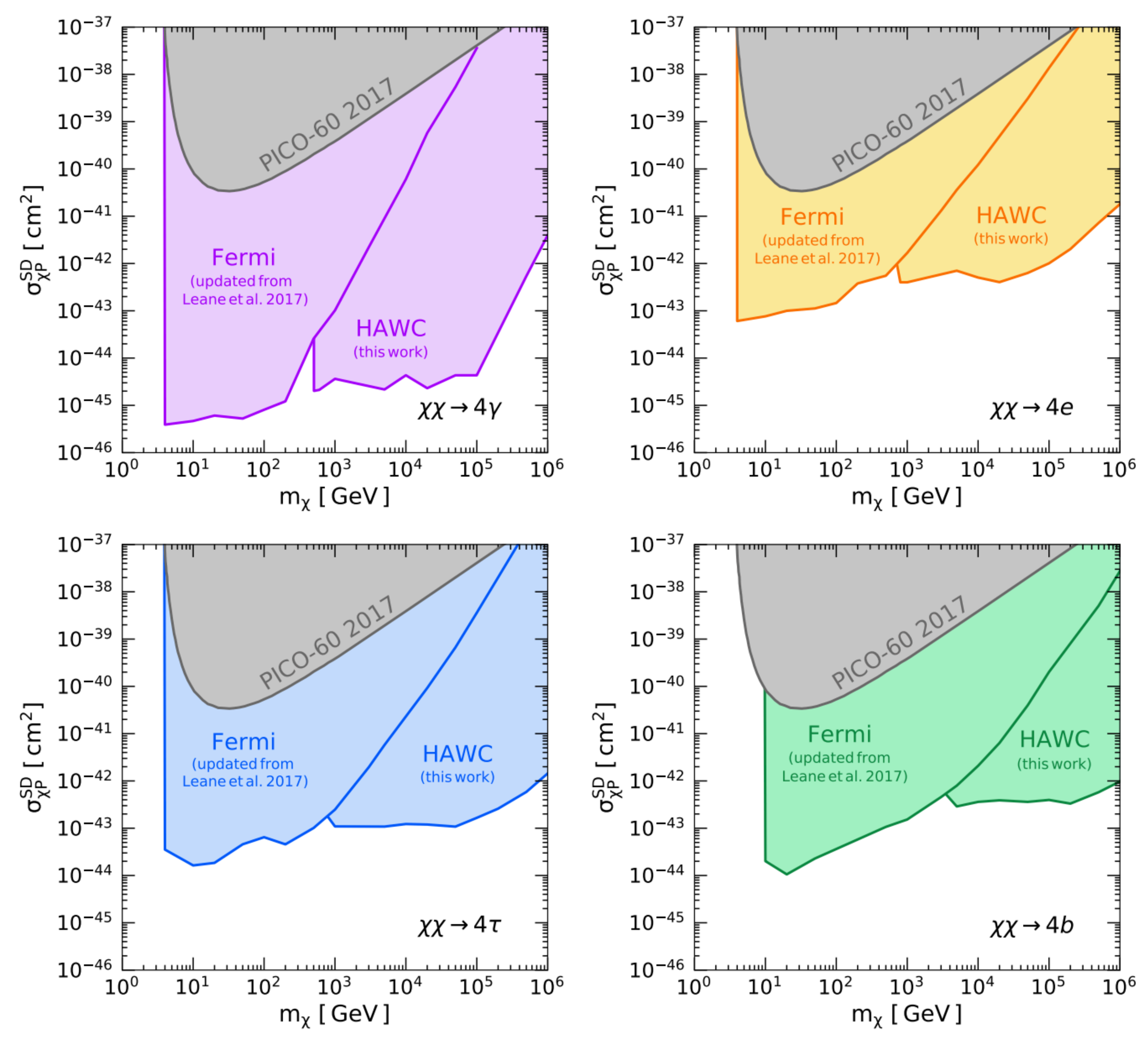
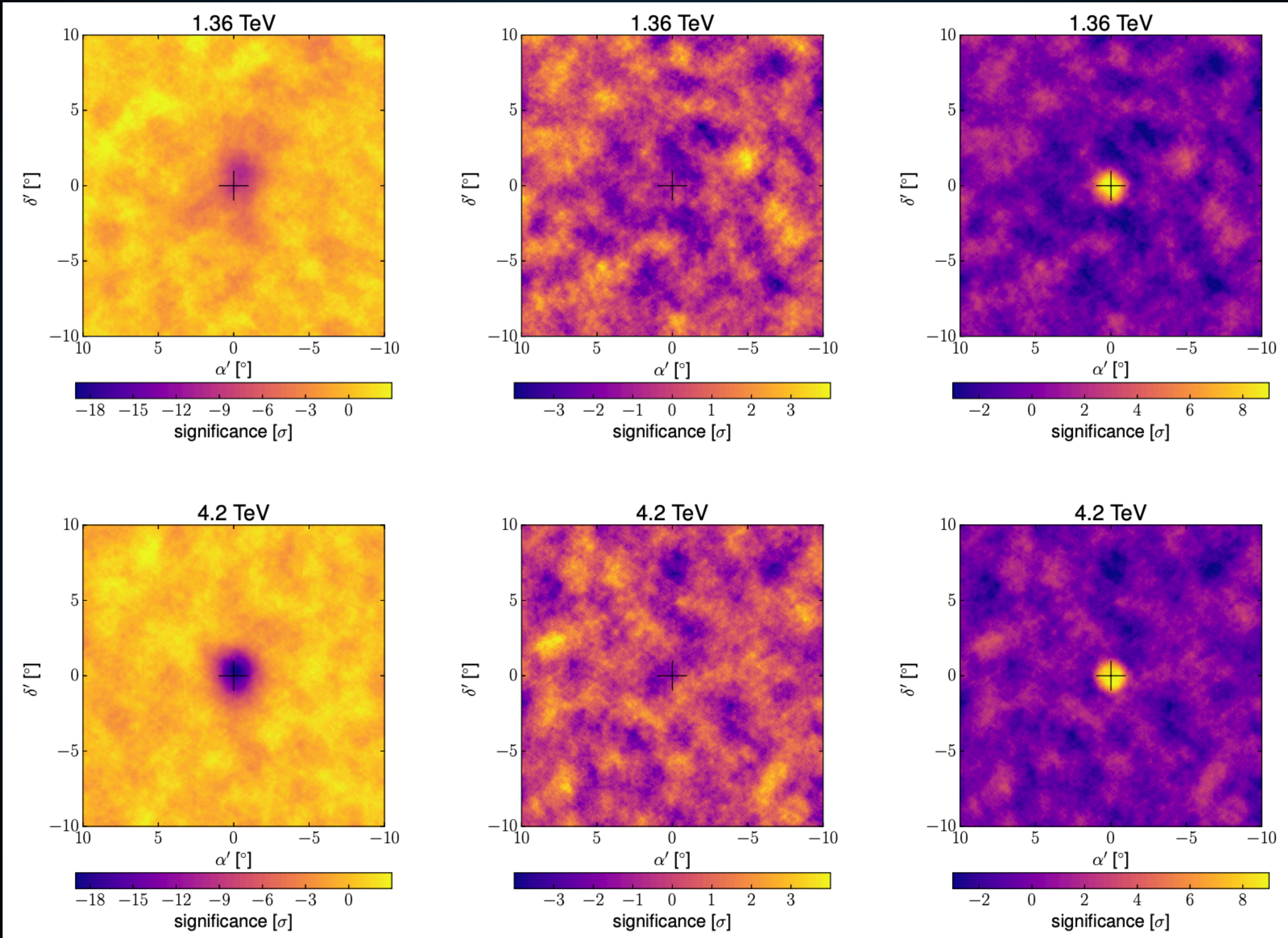
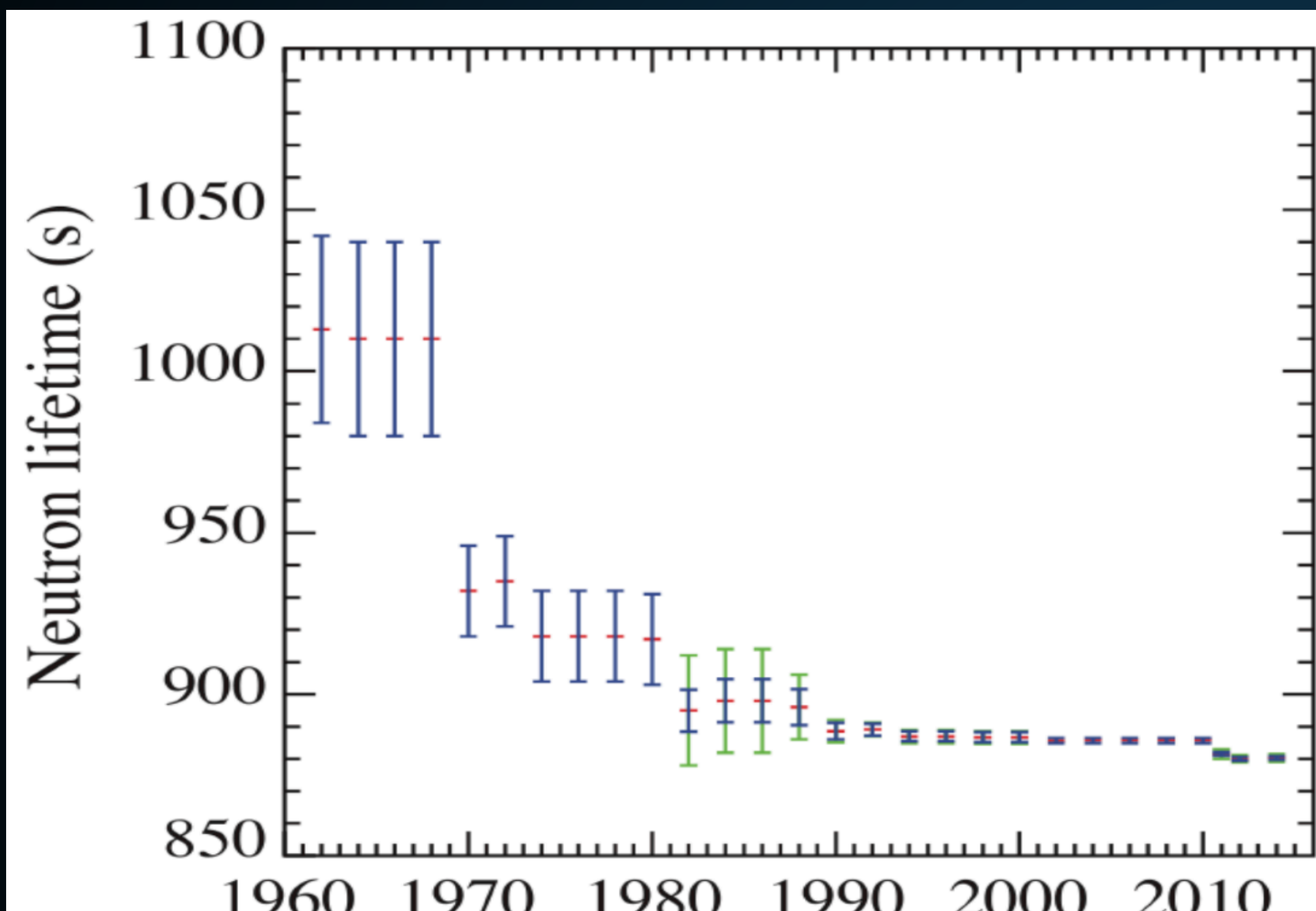


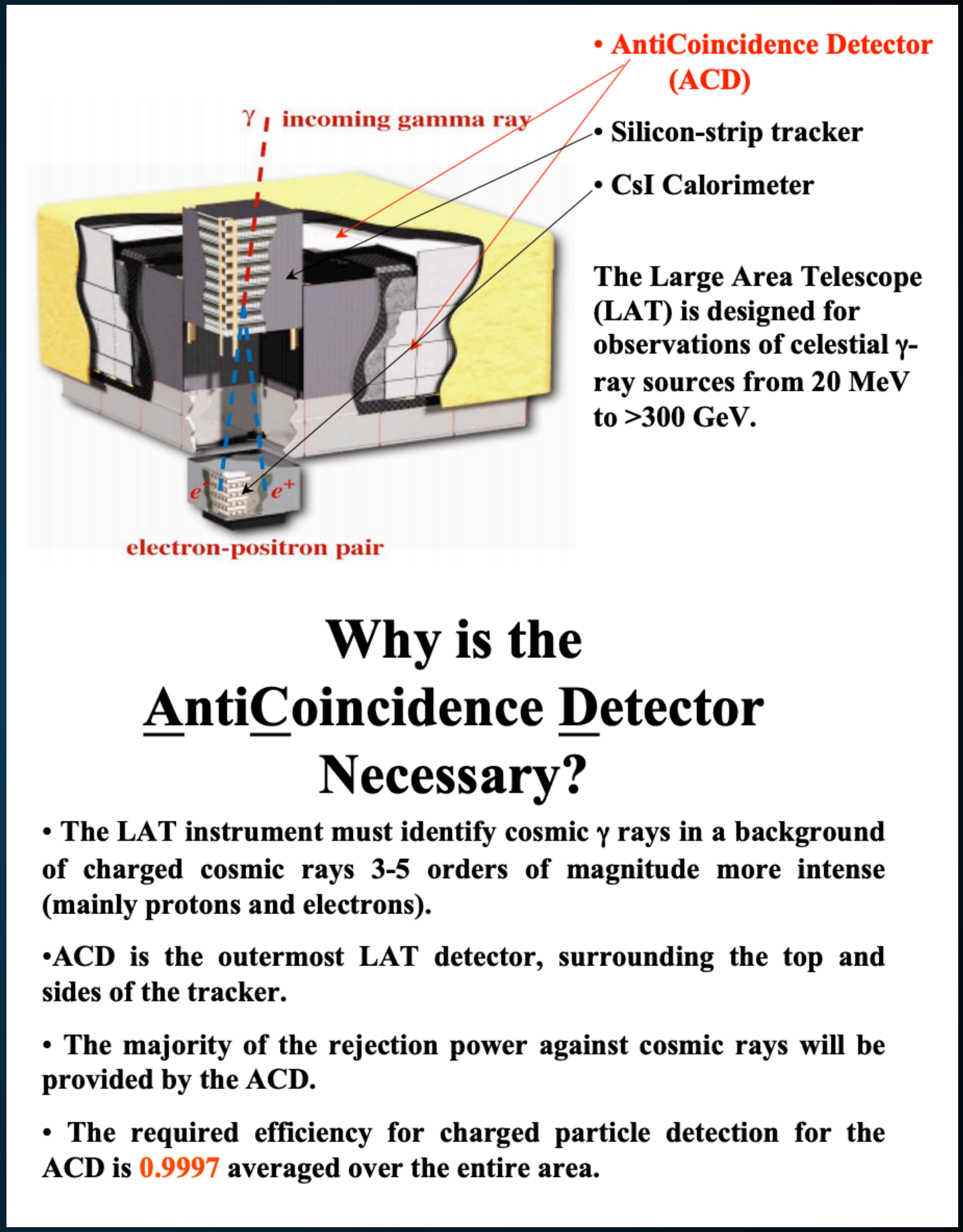
TEV OBSERVATIONS OF THE SUN

HAWC Collaboration (including TL) (2018; 1808.05620)



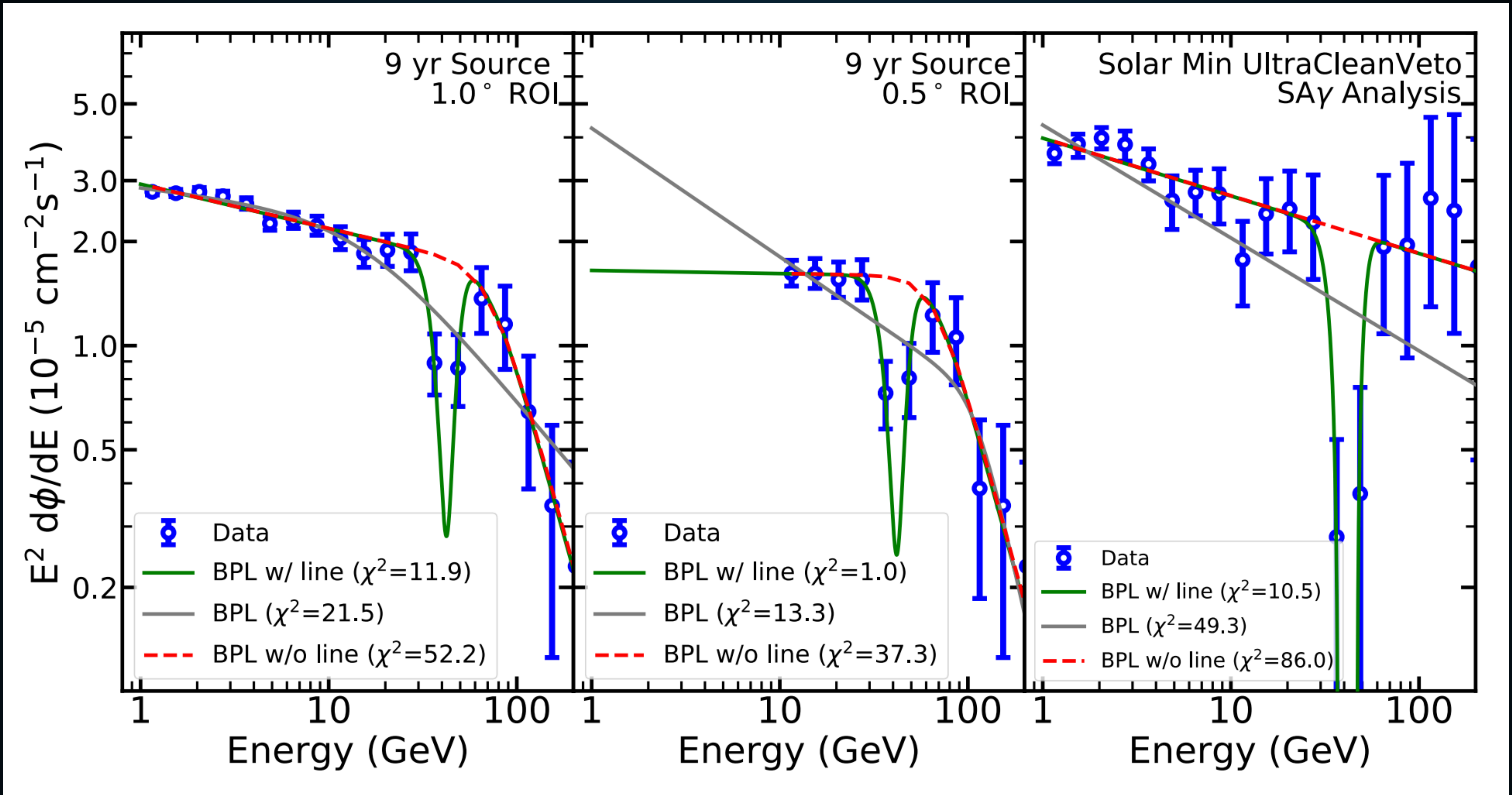
AN INSTRUMENTAL WORKING HYPOTHESIS





- **Neutrons from the Sun could be miscalibrated?**

AN INSTRUMENTAL WORKING HYPOTHESIS



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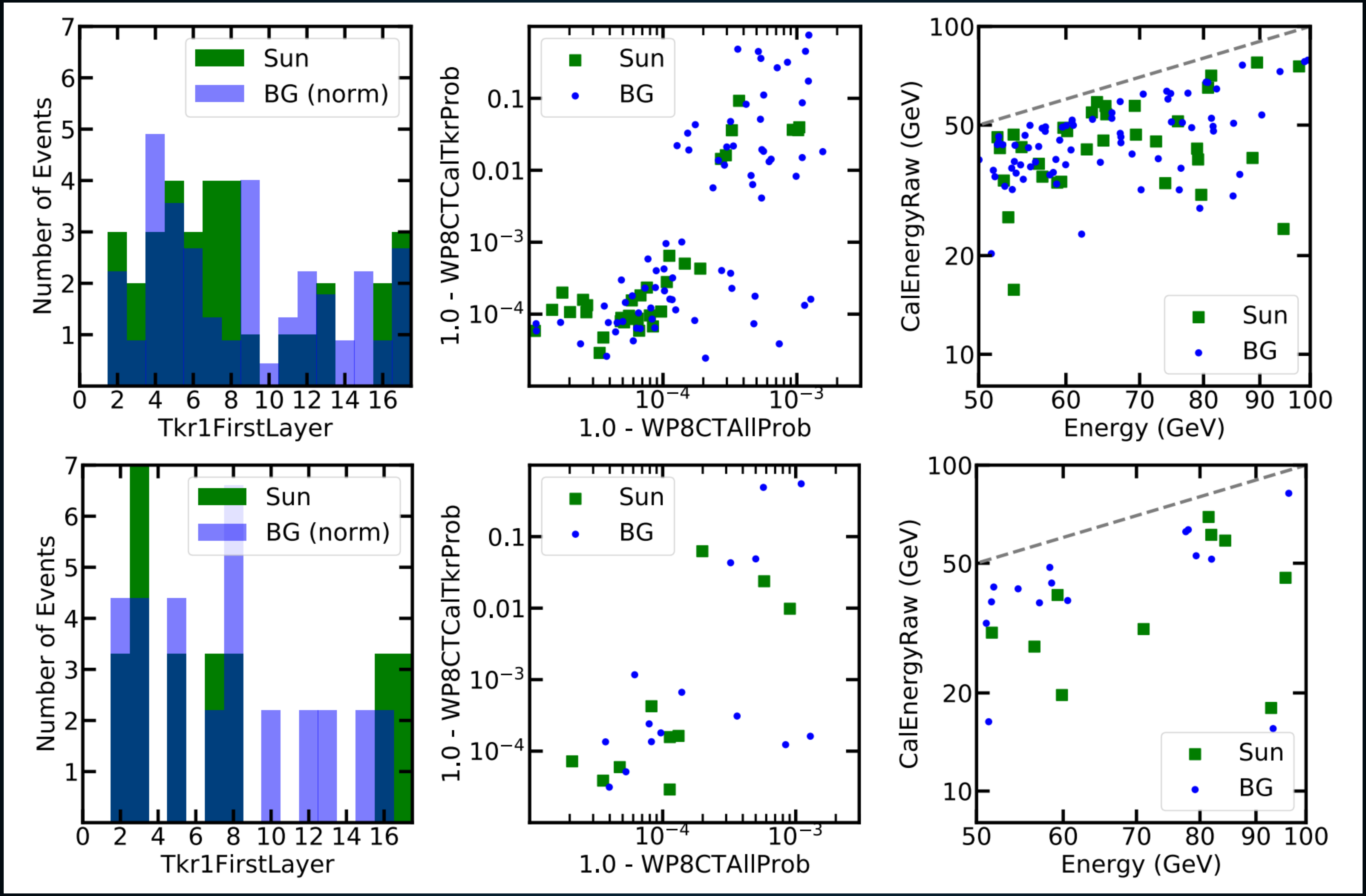
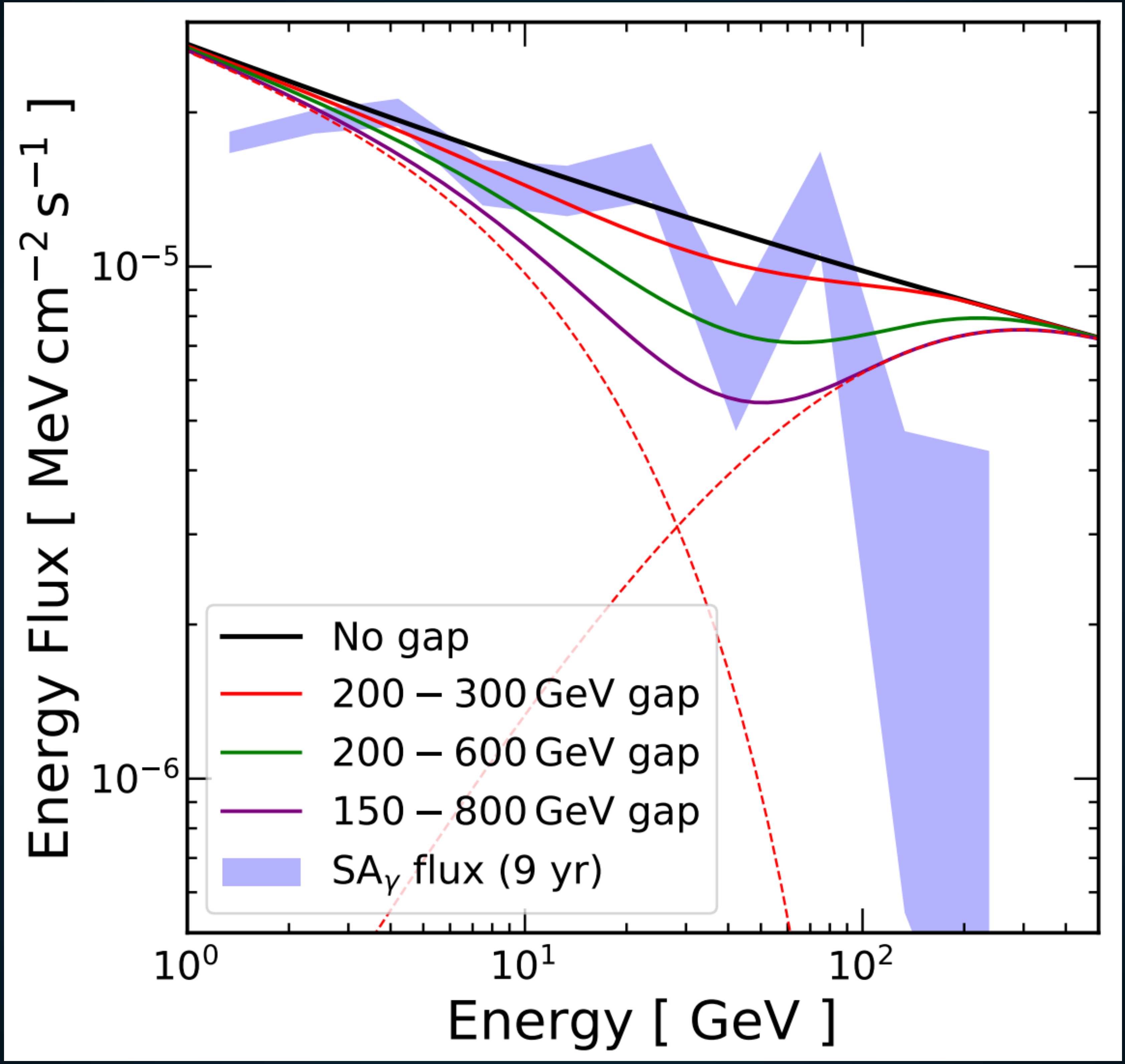
AN INSTRUMENTAL WORKING HYPOTHESIS



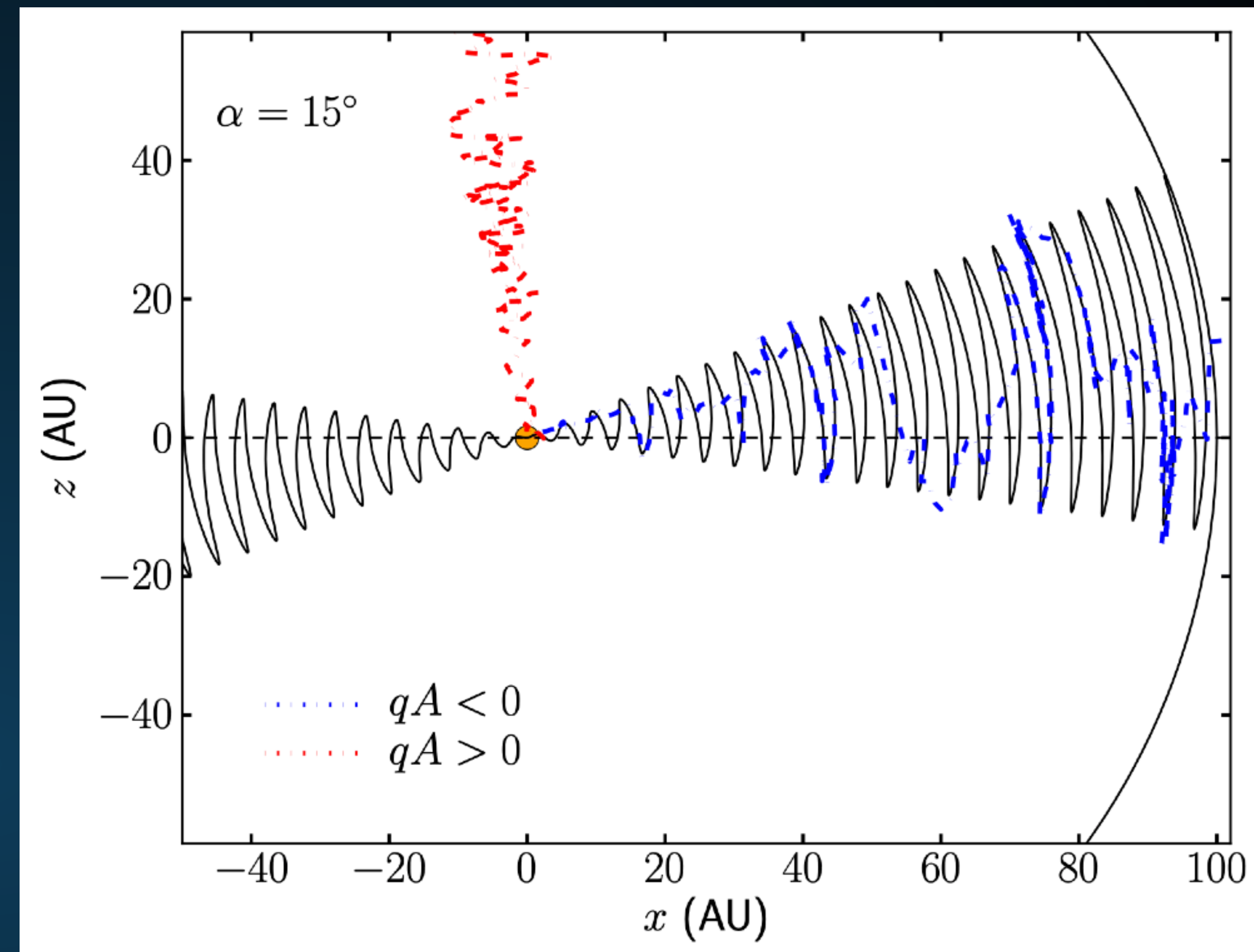
- **Neutrons from the Sun could be miscalibrated?**

AN INSTRUMENTAL WORKING HYPOTHESIS



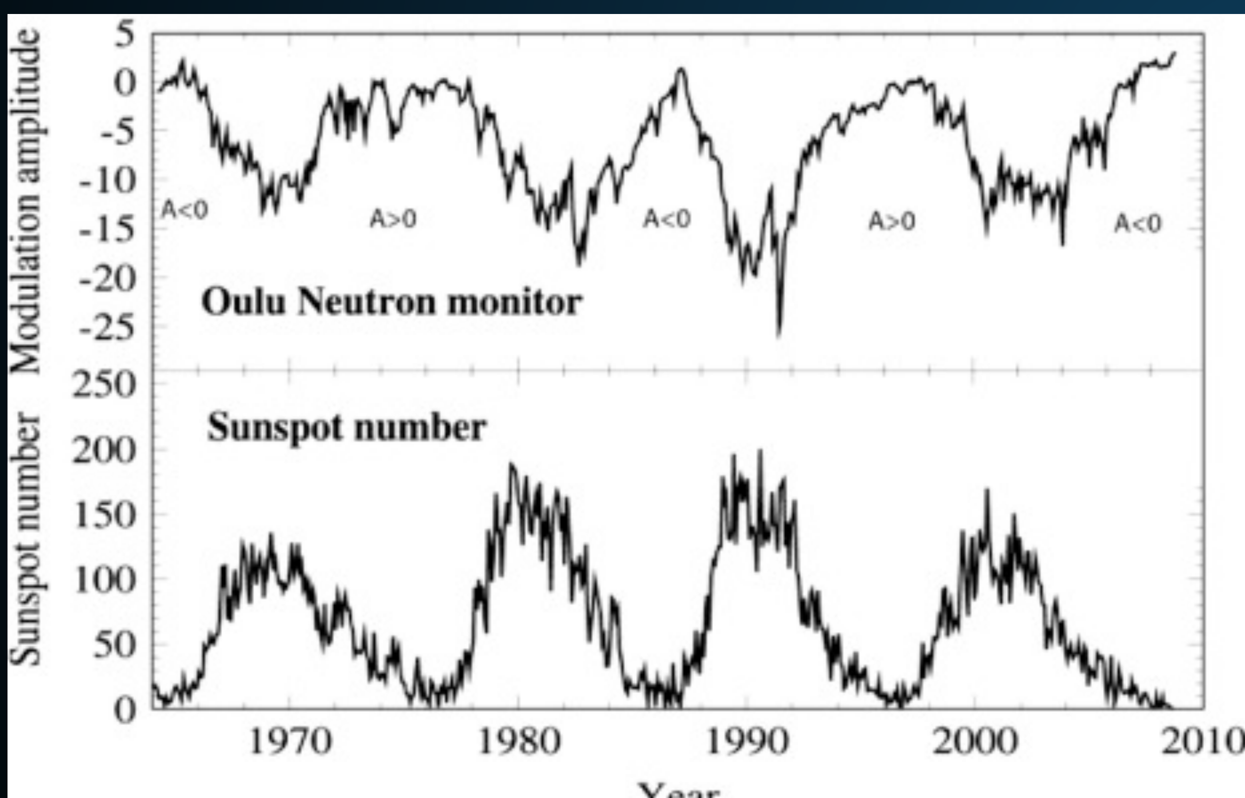
- **A combination of a real dip and low statistics?**

Cholis, Hooper, TL (2016; 1511.01507)



- **Cosmic-Rays must first fight the heliospheric potential to arrive at the Sun.**

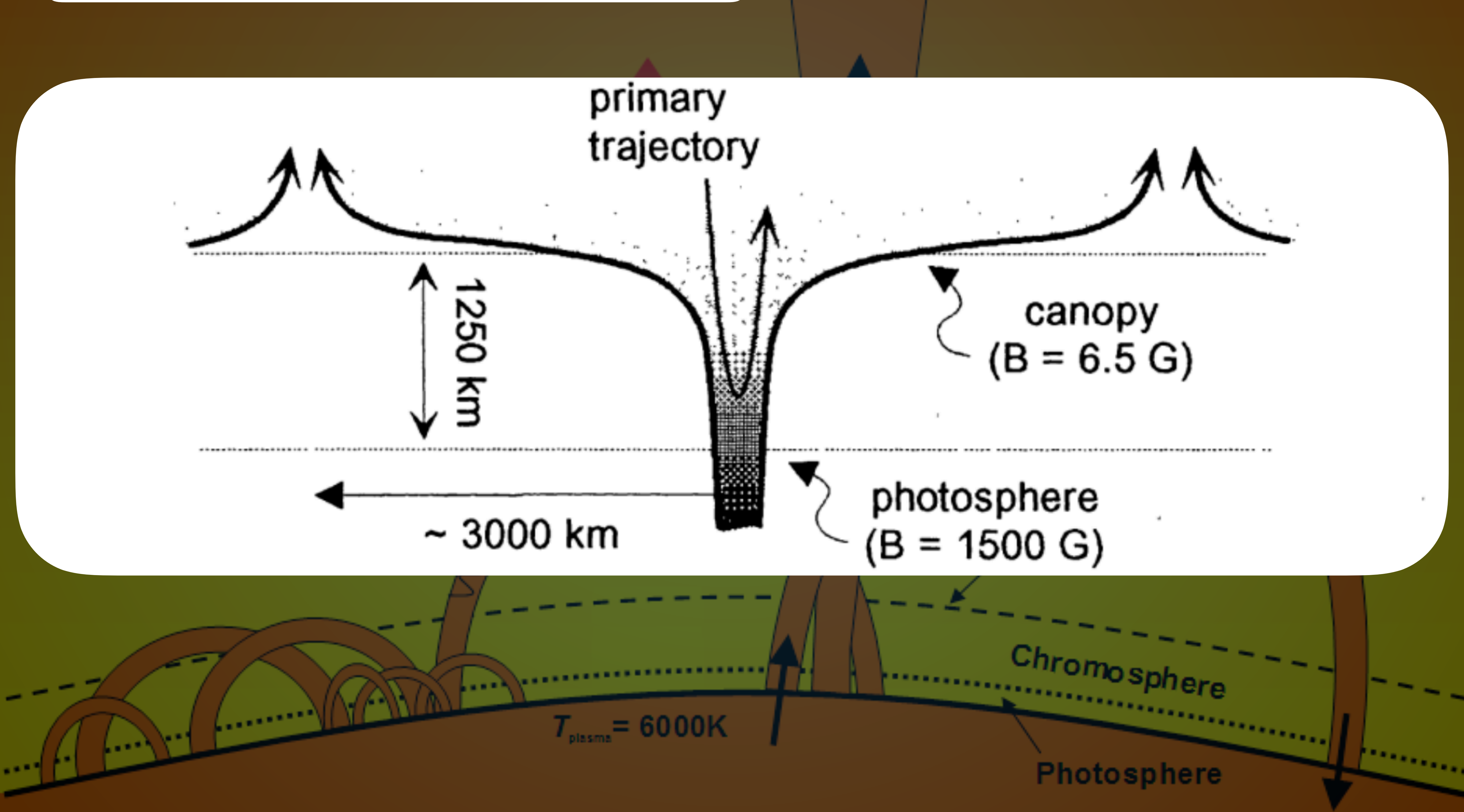
Valdes-Galicia & Gonzalez (2016)



$$\Phi(R,t) = \phi_0 \left(\frac{|B_{\rm tot}(t)|}{4\,\rm nT}\right) + \phi_1\, H(-qA(t)) \left(\frac{|B_{\rm tot}(t)|}{4\,\rm nT}\right) \left(\frac{1+(R/R_0)^2}{\beta(R/R_0)^3}\right) \left(\frac{\alpha(t)}{\pi/2}\right)^4$$

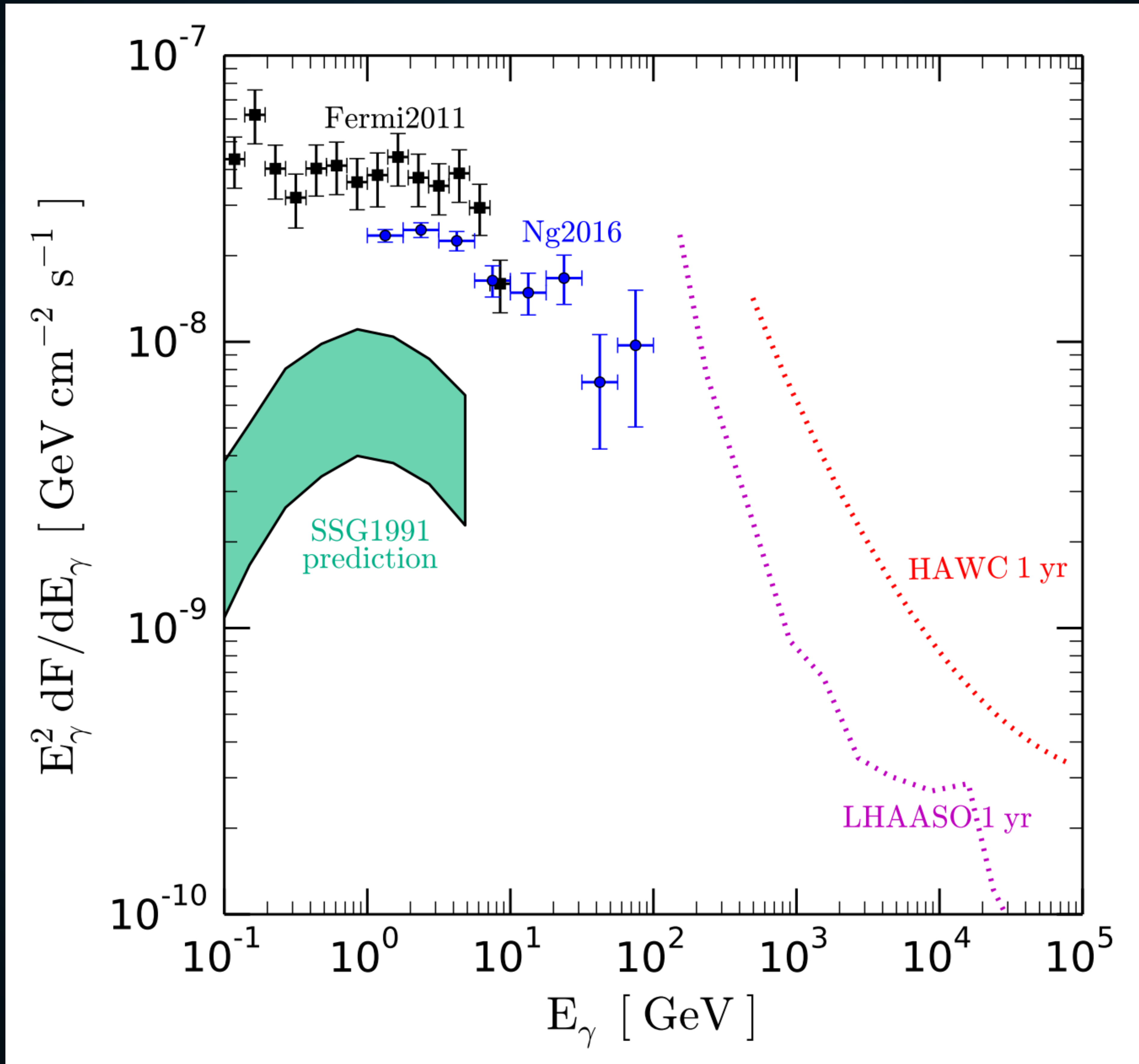
HADRONIC GAMMA-RAYS - HOW?

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

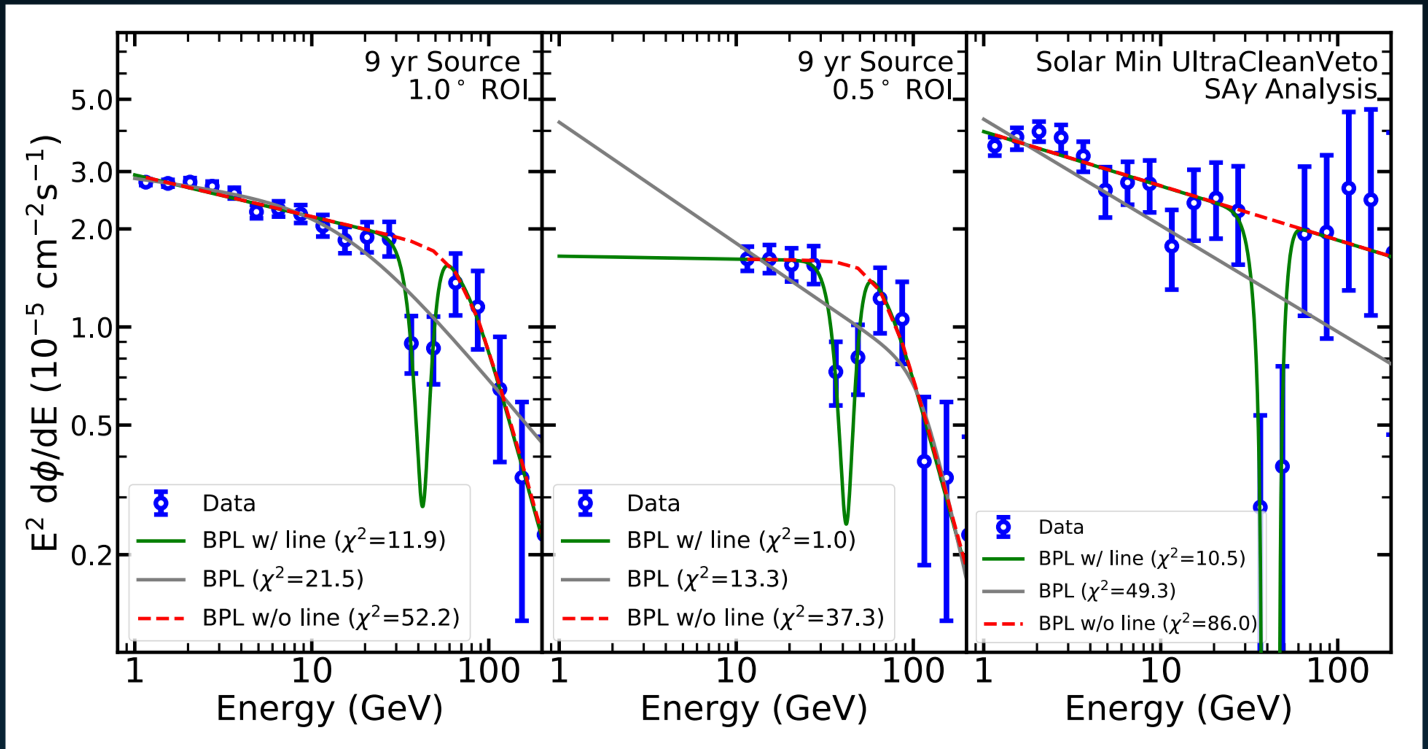


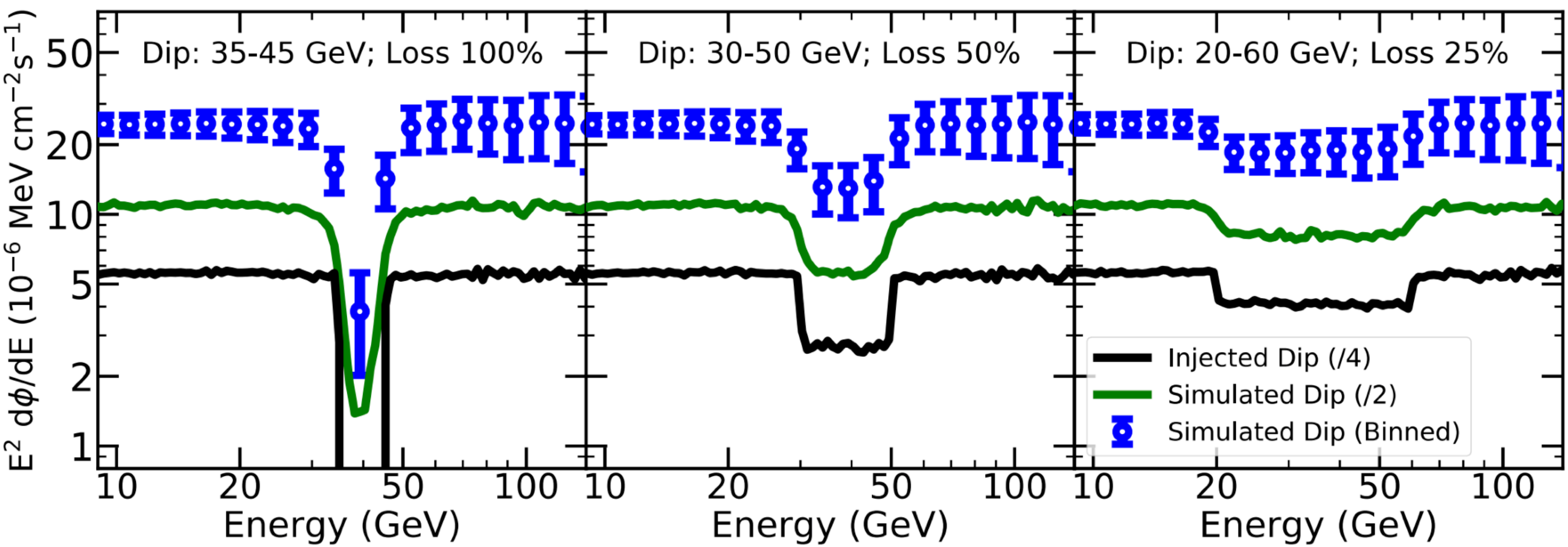
GAMMA-RAYS - SPECTRAL DIP

Zhou et al. (1612.02420)



THE SPECTRAL DIP?

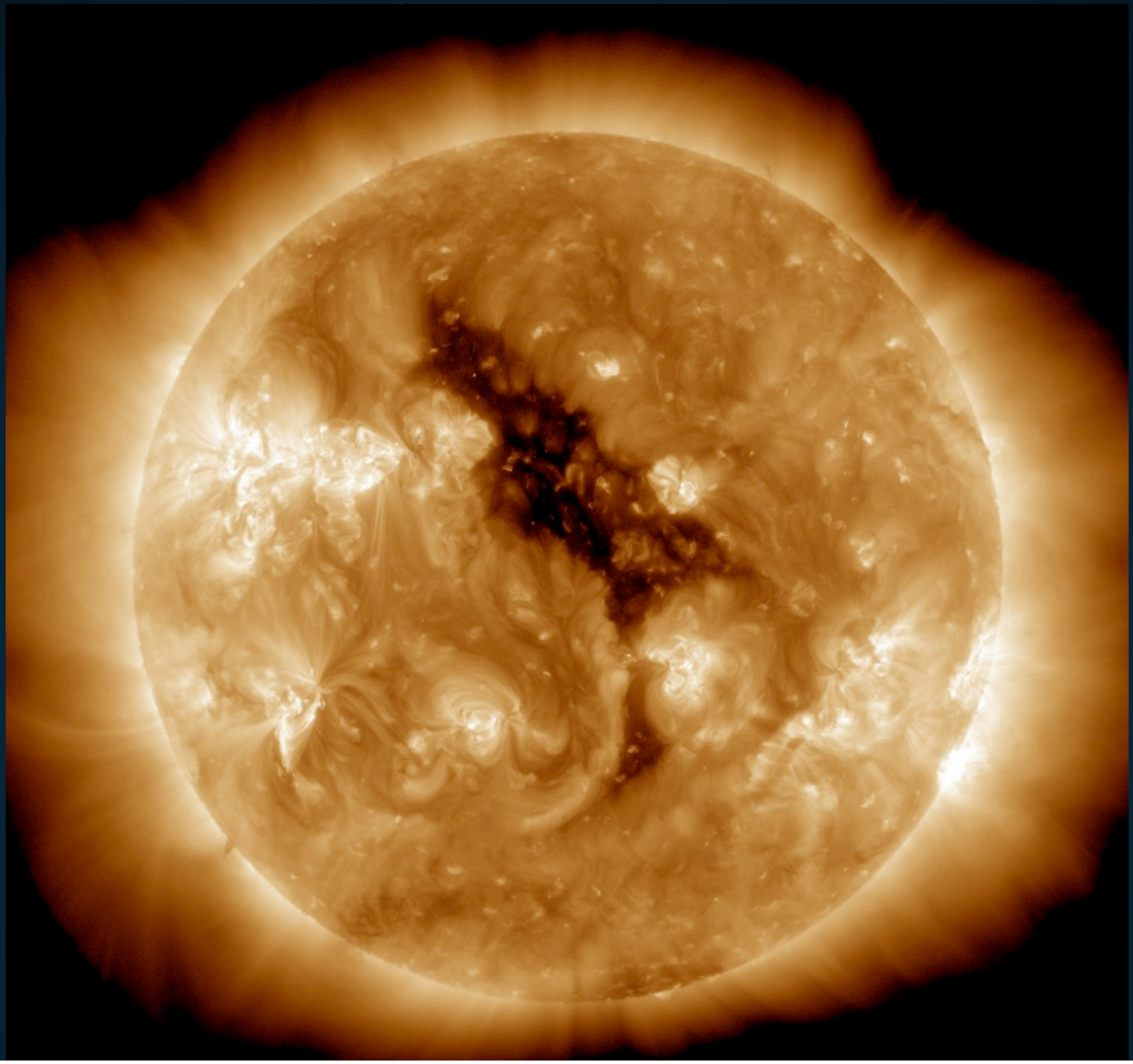




GAMMA-RAYS - HOW?

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

GAMMA-RAYS - HOW?



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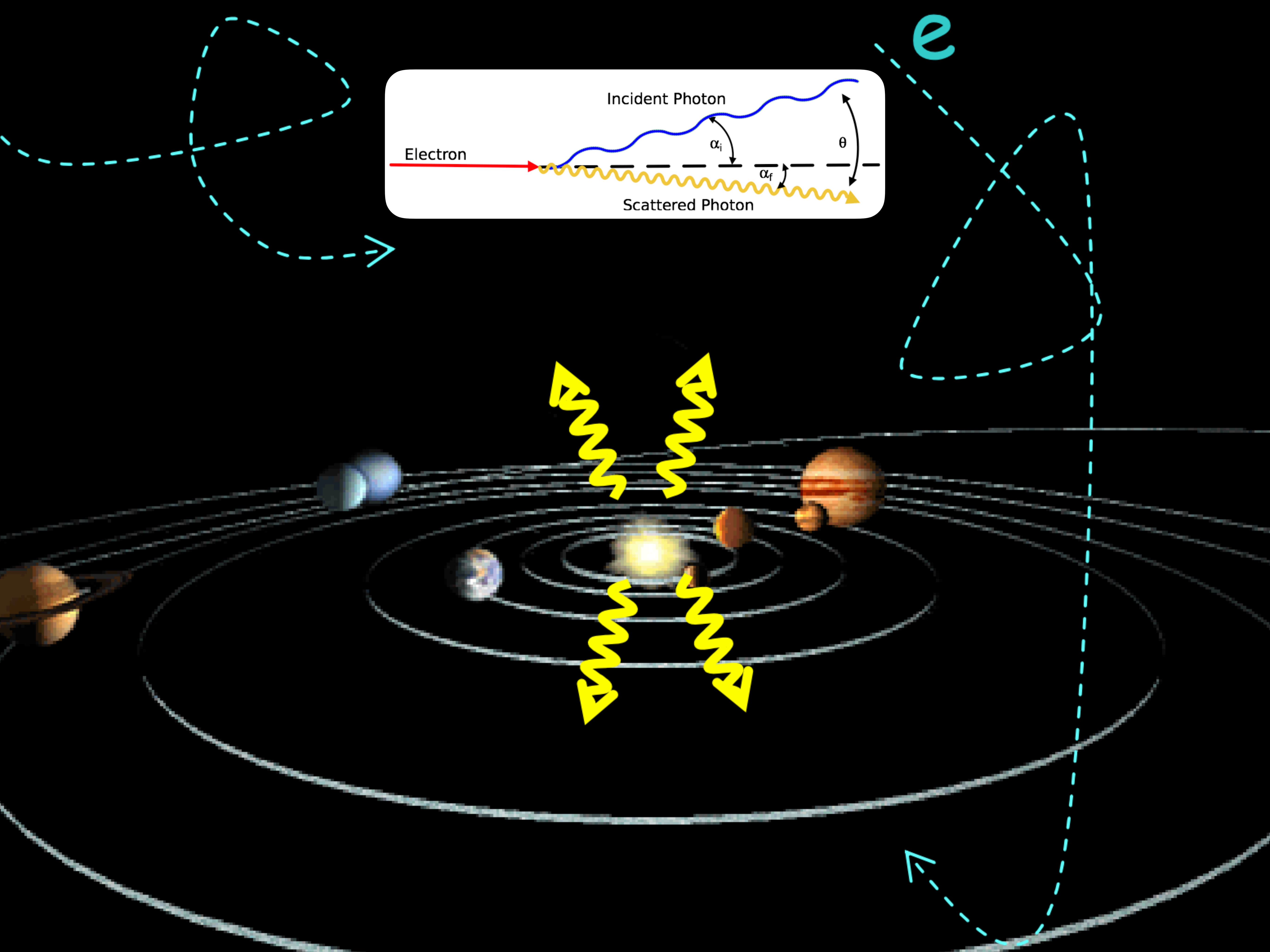
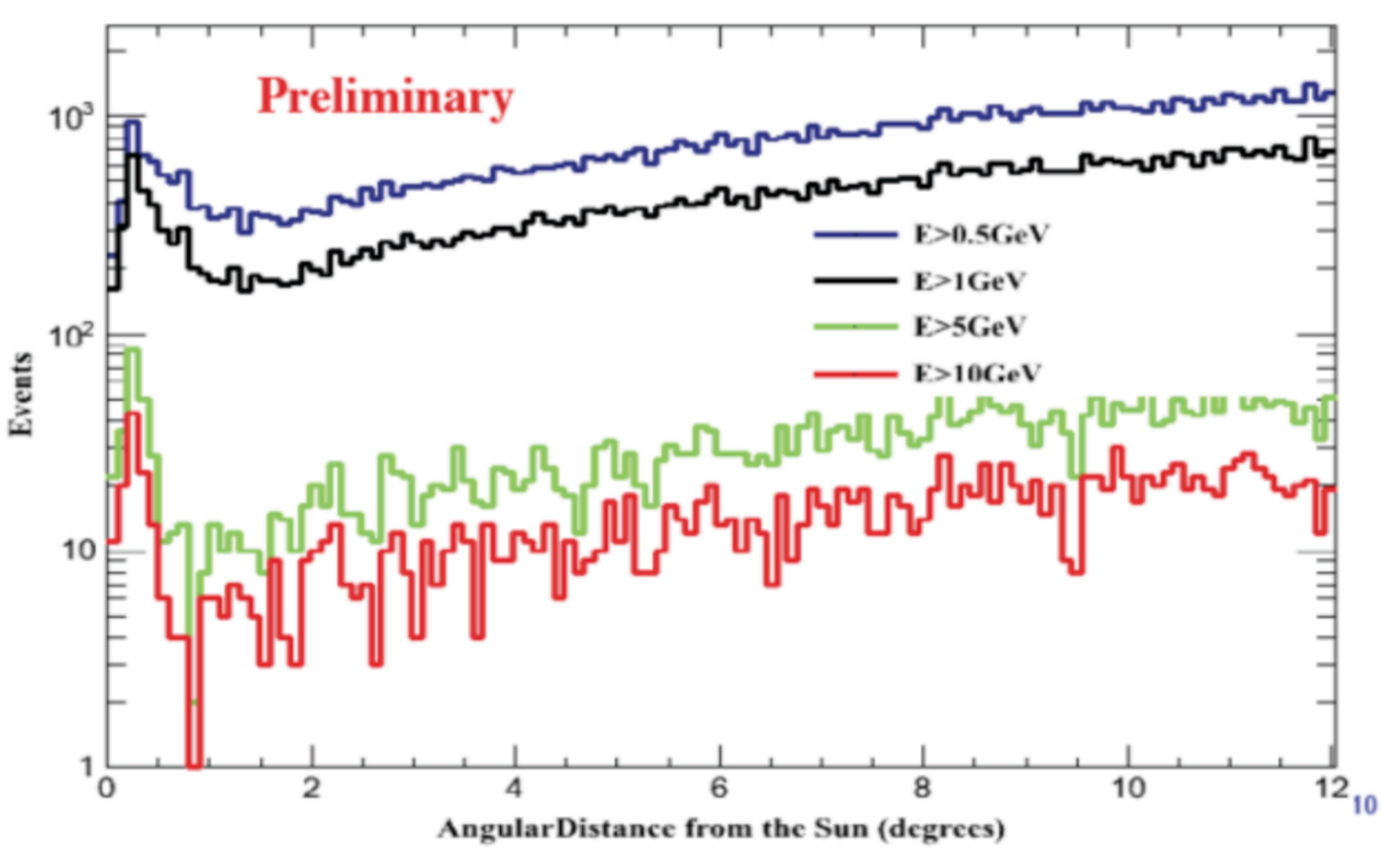
2008-12-24 05:41:53	226.9 GeV	272.899	-23.343	0.069°	UltraClean	PSF1	EDISP3	X	X	0.00128
2009-12-20 08:06:31	467.7 GeV	268.046	-23.177	0.338°	UltraCleanVeto	PSF1	EDISP0	X	X	0.00208

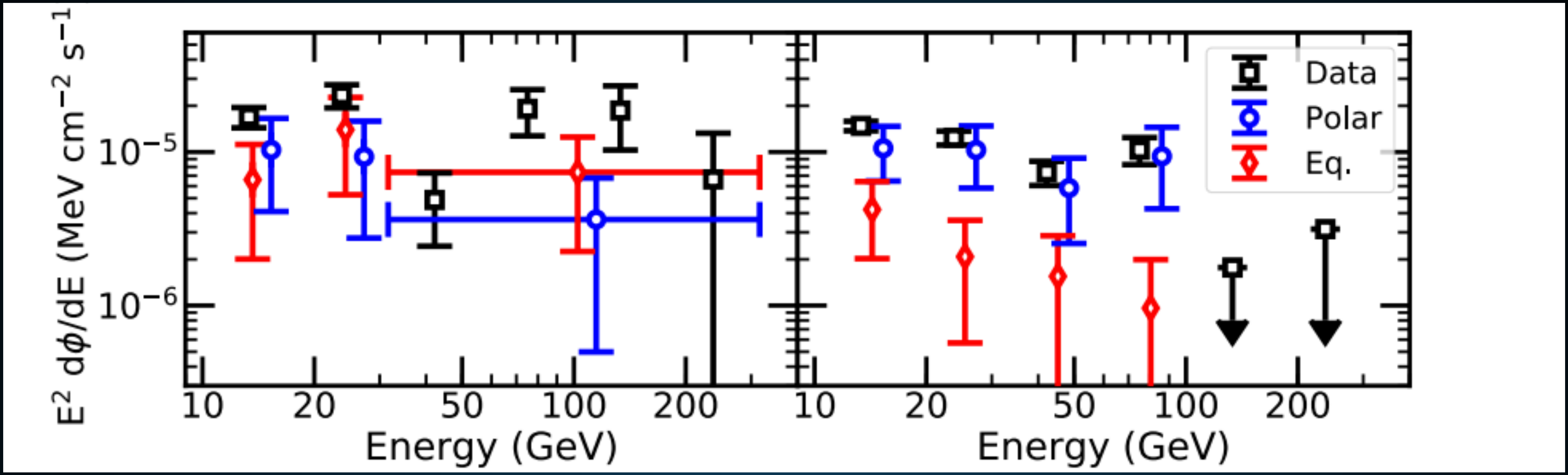

e
Incident Photon
Electron
α_i
θ
α_f
Scattered Photon

GAMMA-RAYS - INVERSE COMPTON SCATTERING

Raino et al. (2018)



SPECTRAL VARIABILITY



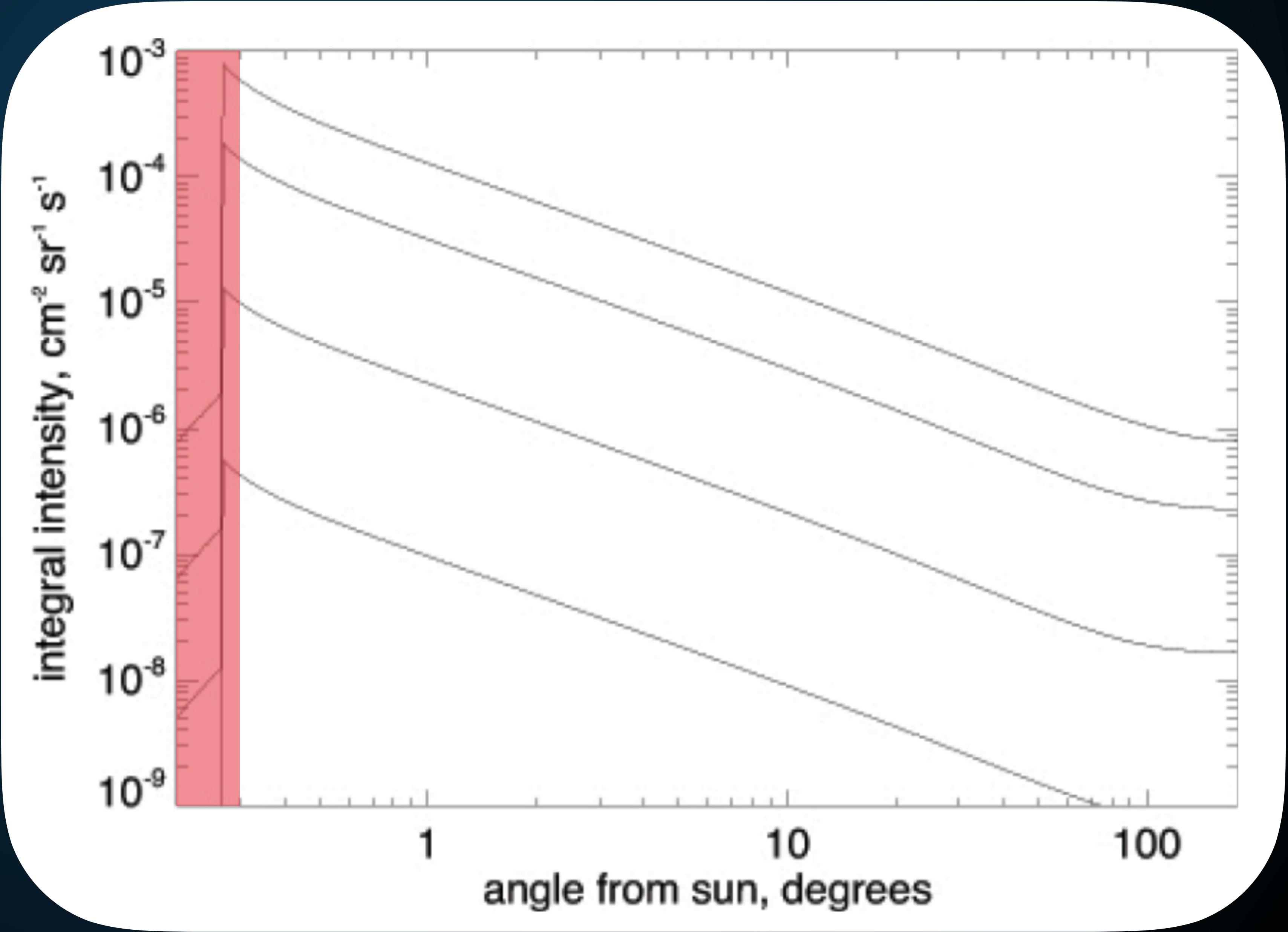
- **The spectrum also appears to change when moving from solar minimum to solar maximum.**
- **The polar component has a constant spectrum, the equatorial component does not.**

GAMMA-RAYS - HOW?

$$\frac{d\sigma_{\rm exact}}{d\Omega_1' d\epsilon_1'} = \frac{1}{2} r_0^2 \left(\frac{\epsilon_1'}{\epsilon'}\right)^2 \left(\frac{\epsilon'}{\epsilon_1'} + \frac{\epsilon_1'}{\epsilon'} - \sin^2\theta_1'\right) \delta\left(\epsilon_1' - \frac{\epsilon'}{1 + (\epsilon'/mc^2)(1 - \cos\theta_1')}\right)$$

$$\approx \frac{1}{2} r_0^2 (1 + \cos^2\theta_1') \left(1 - \frac{2\epsilon'}{mc^2}(1 - \cos\theta_1')\right) \delta\left[\epsilon_1' - \epsilon'\left(1 - \frac{\epsilon'}{mc^2}(1 - \cos\theta_1')\right)\right]$$

- **Inverse Compton Scattering is Kinematically suppressed across the solar disk**

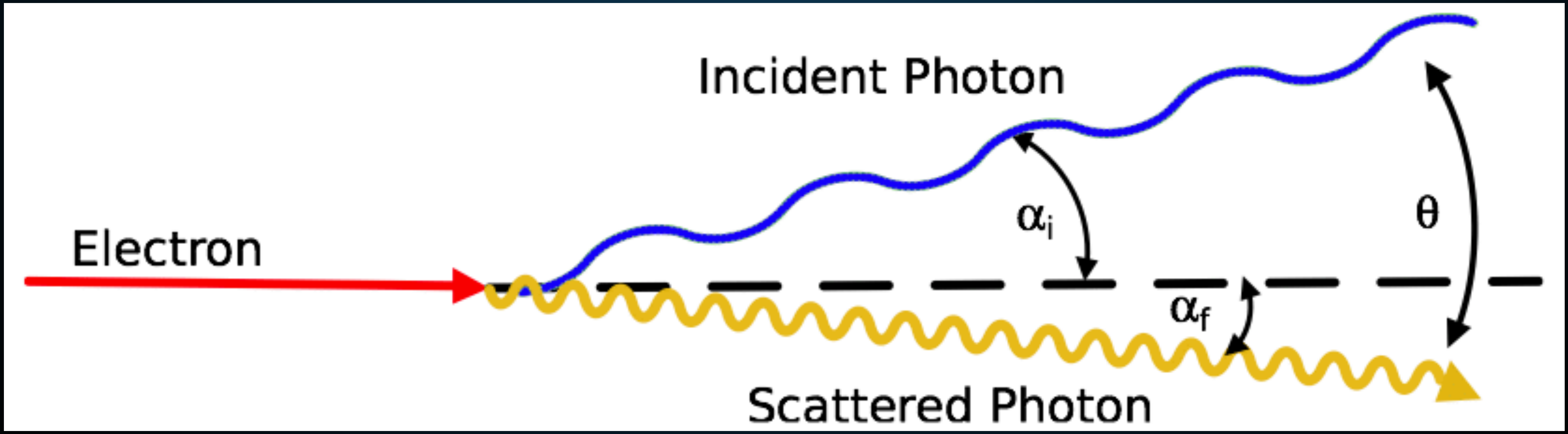


What about the solar disk itself?

WHAT IS THE ENERGY SCALE?

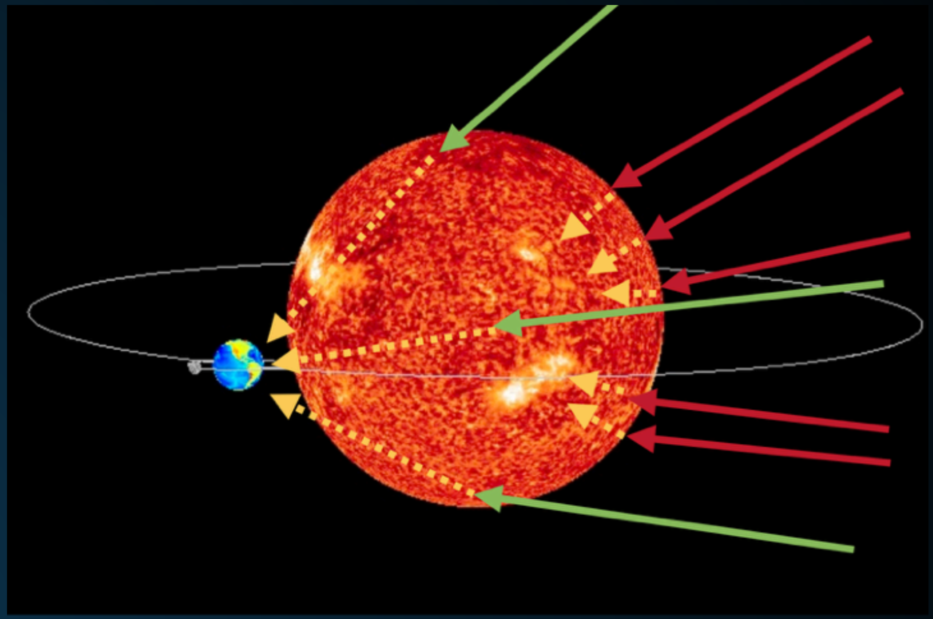
Hadronic Interactions

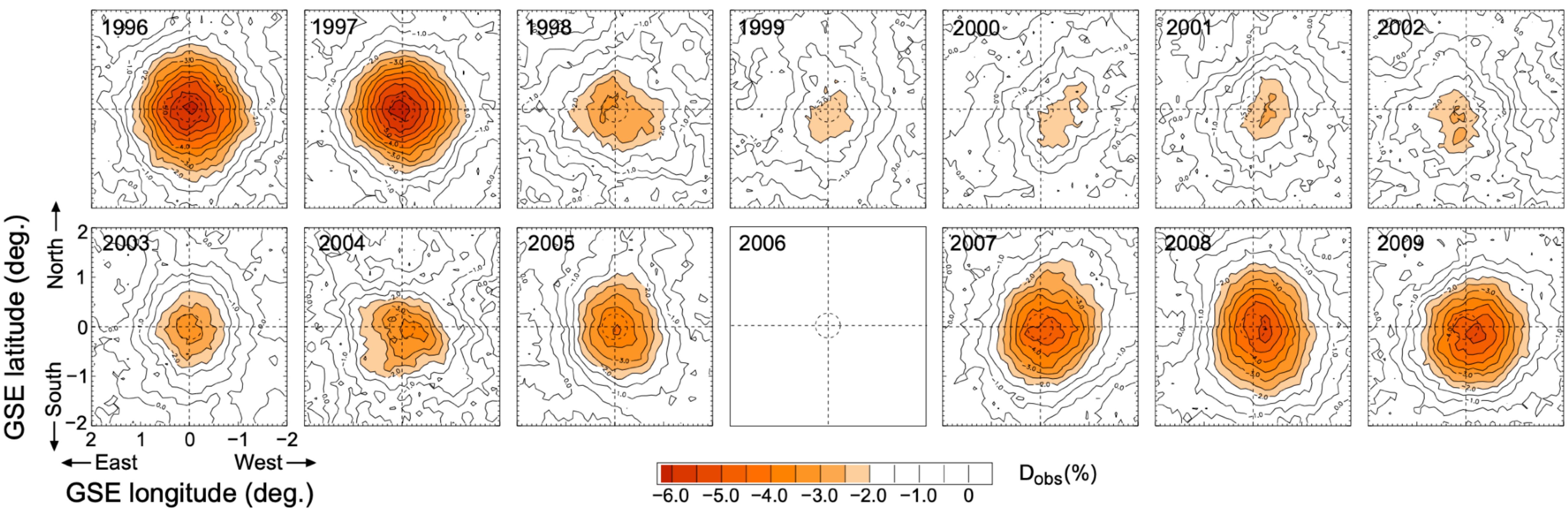
inverse-Compton Scattering



Tibet Array (2013; 1306.3009)

- **Possibilities**
  - **Solar Magnetic Fields Draw in Cosmic-Rays**





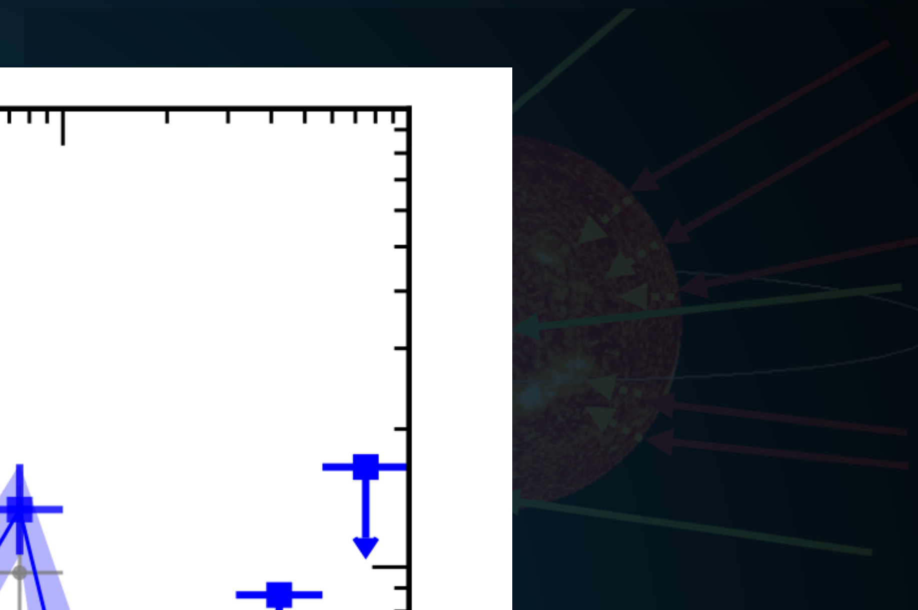
SPECTRAL VARIABILITY

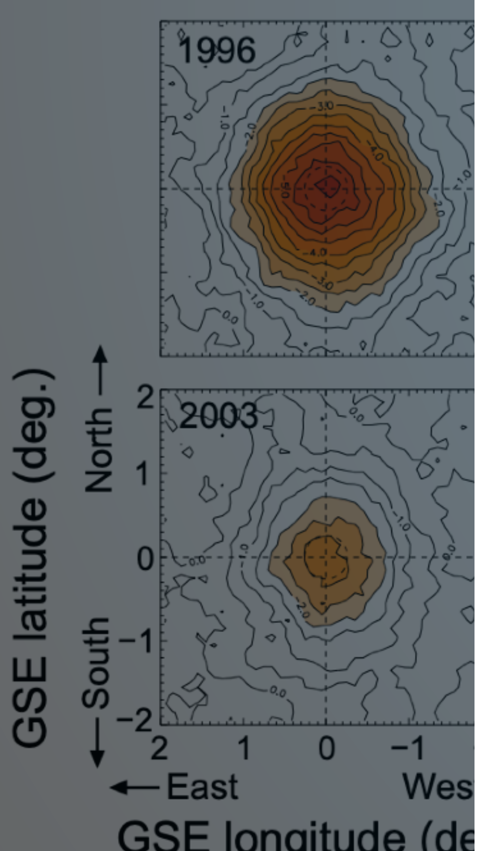
A New Event!—While finalizing this letter, we found a new >100 GeV event. Observed on February 13, 2018 at 17:49:15 UTC, the event has an energy of 162 GeV, is located 0.36° from the solar center, passes the UltraCleanVeto event selection, and belongs to the PSF0 and EDISP3 event classes. As we re-enter solar minimum, this is the first >100 GeV event recorded within 0.5° of the sun since 2009. The event may be connected to a Earth-bound CME observed on February 12, 2018.[1] Preliminary work indicates that this event increases the significance of the >100 GeV time variability above 5σ, and provides evidence that the upcoming solar minimum will provide a substantial flux of high-energy events.

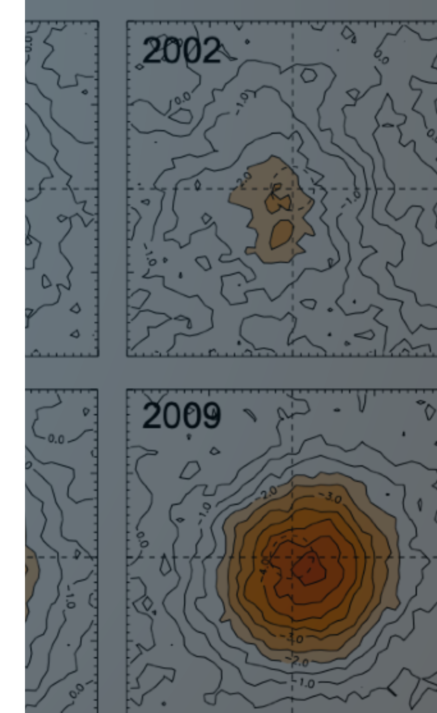
GAMMA-RAYS - HOW?

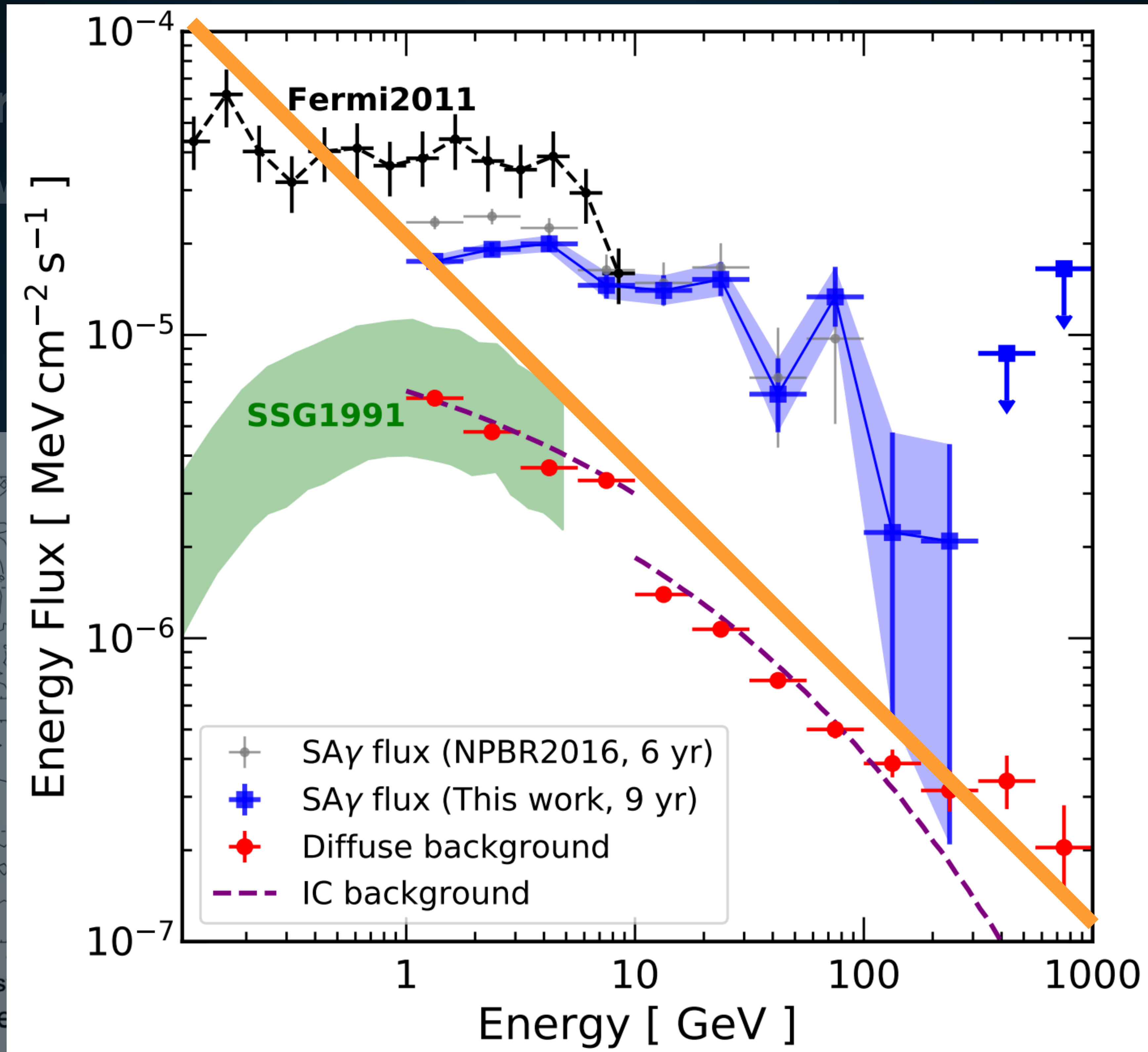
Tibet Array (2013; 1306.3009)

- Possibilities
  - Solar
    Draw









GAMMA-RAYS - HOW?

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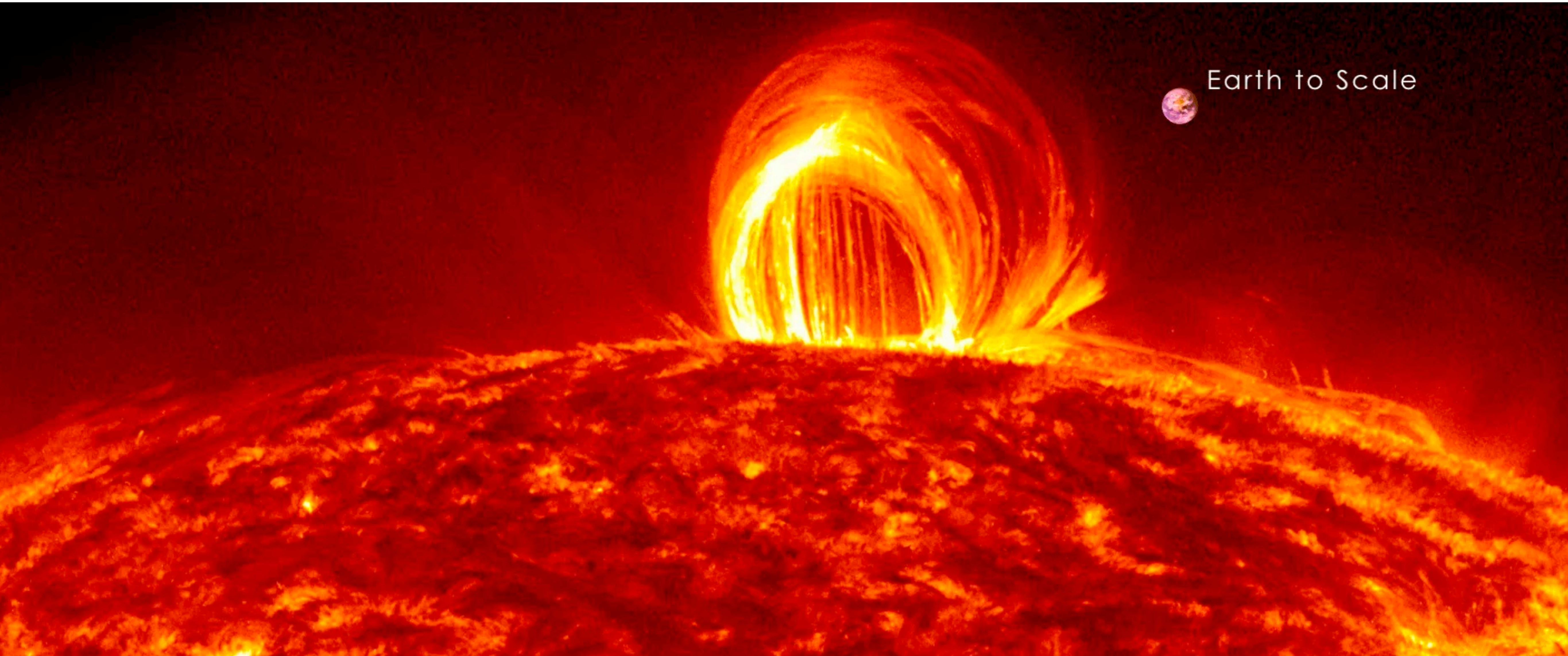

GAMMA-RAYS - WHY?