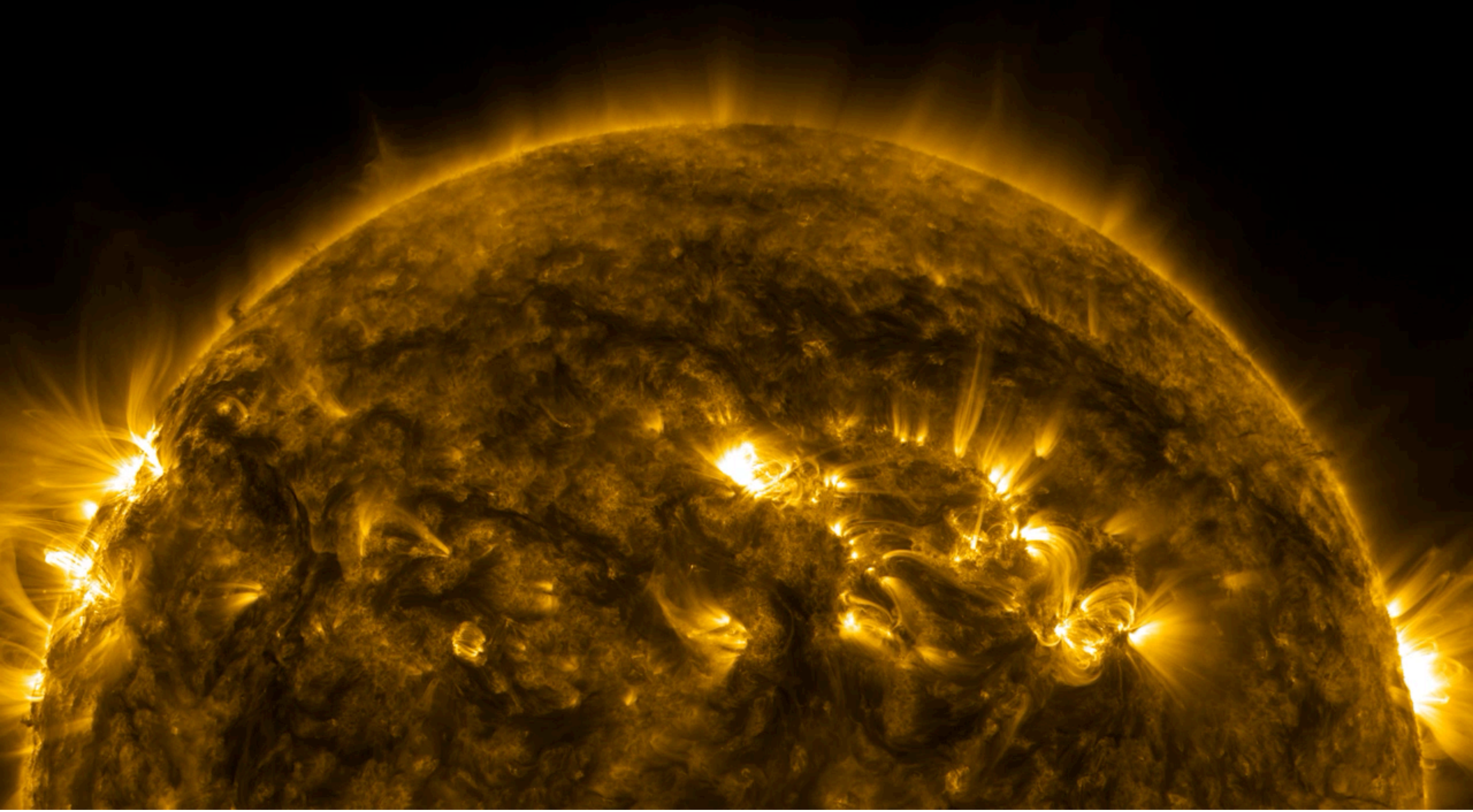


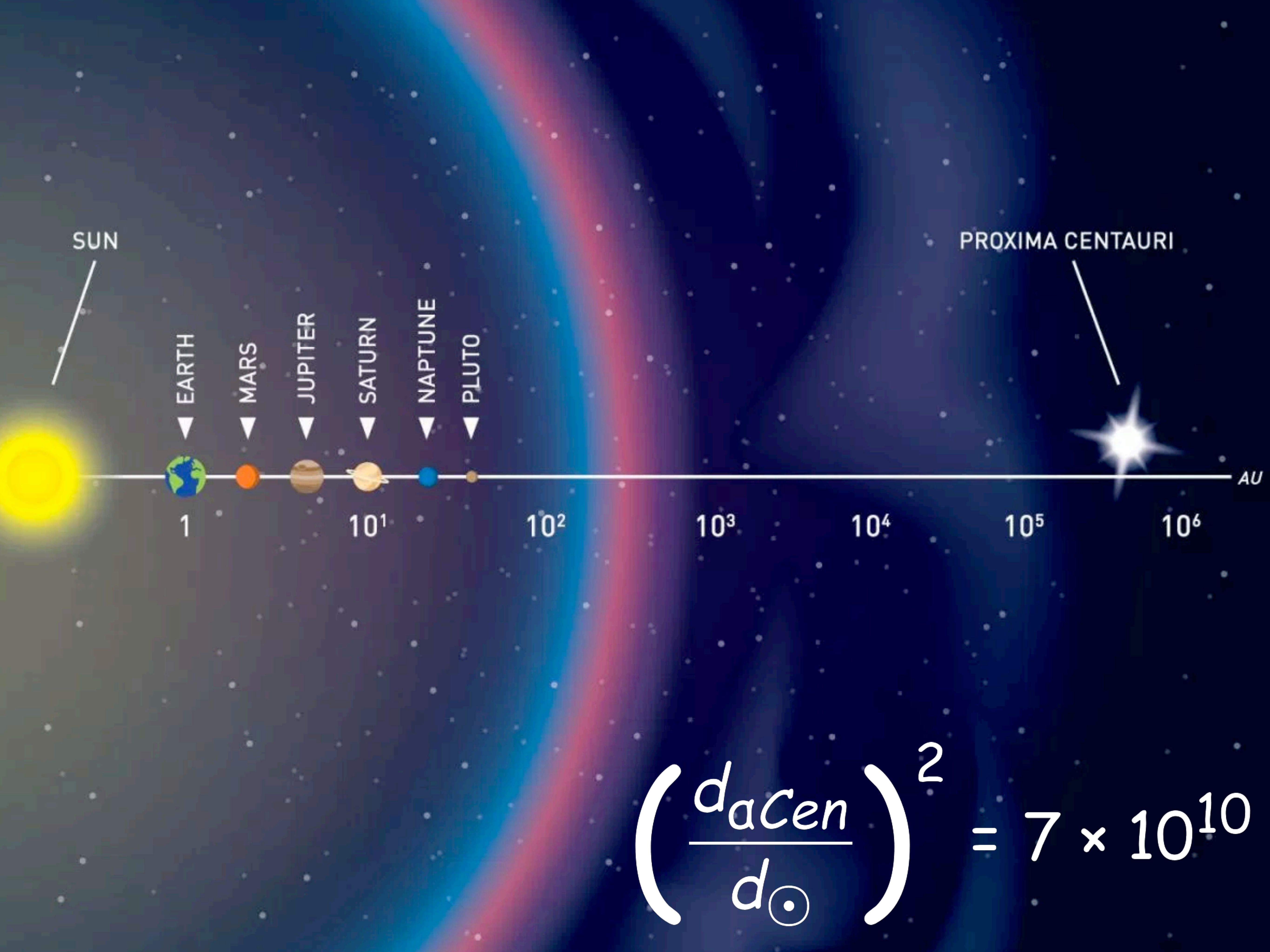
TIM LINDEN

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

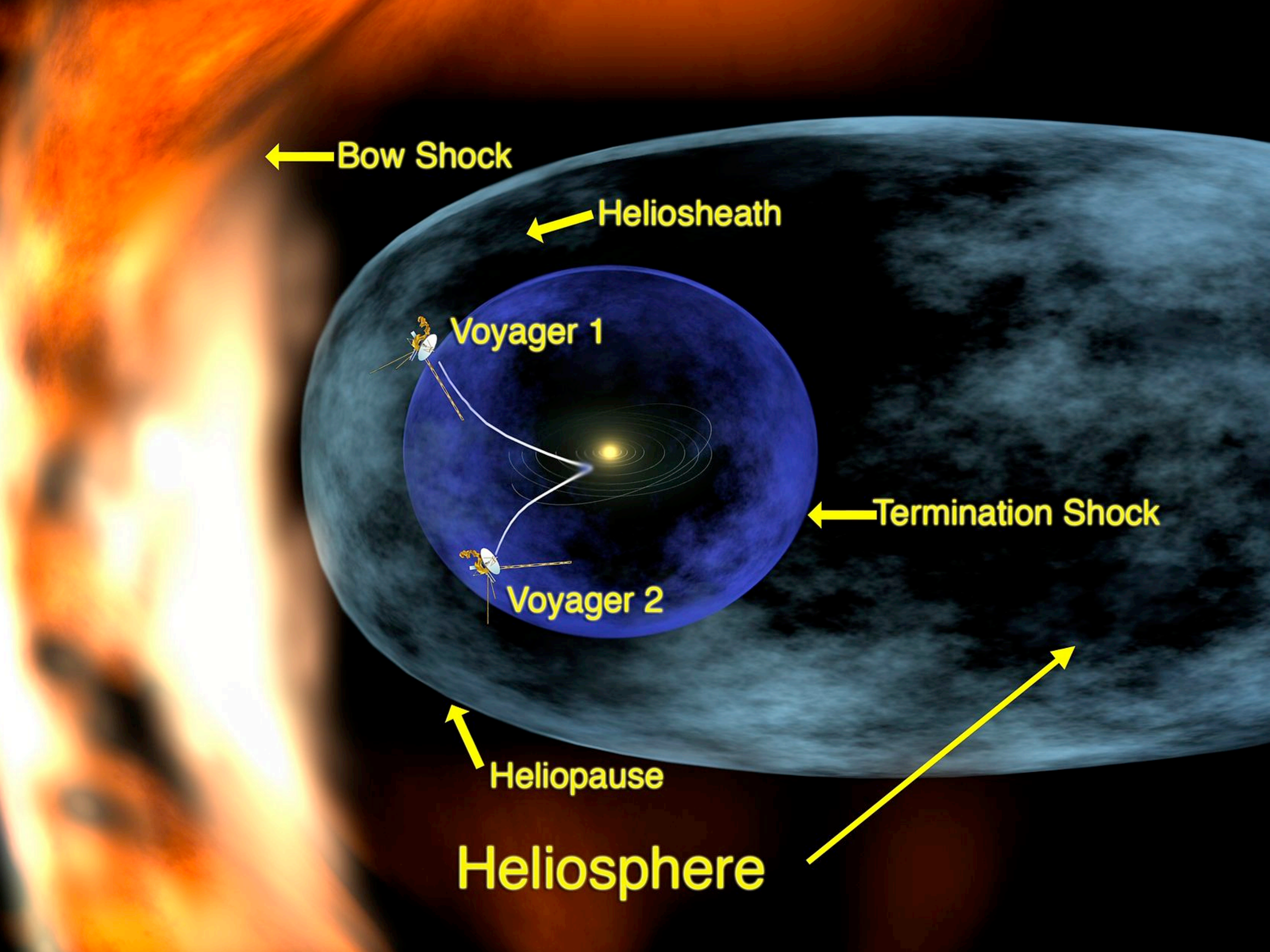
Michelson Postdoctoral Prize Lectures

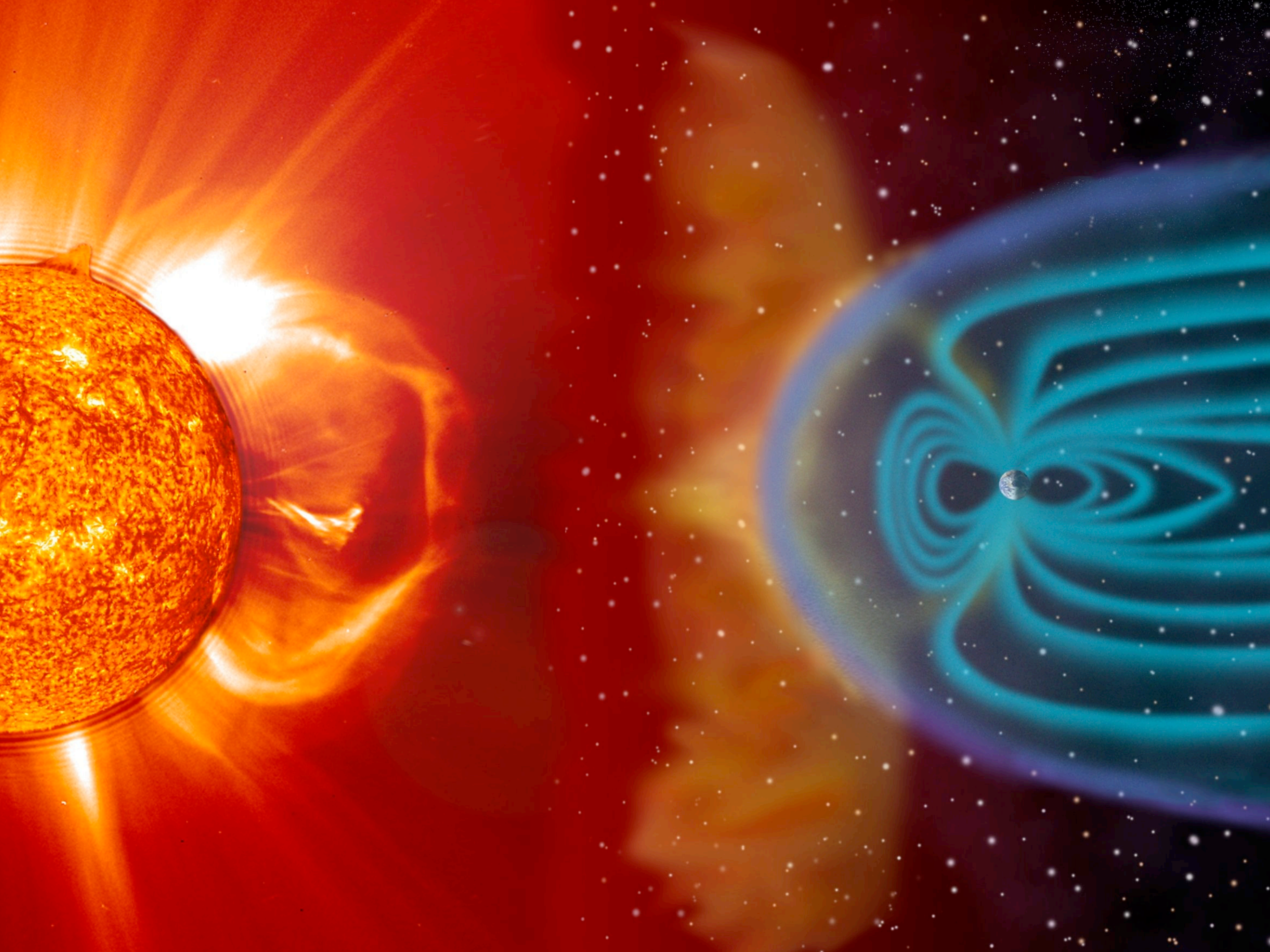
Case Western Reserve University

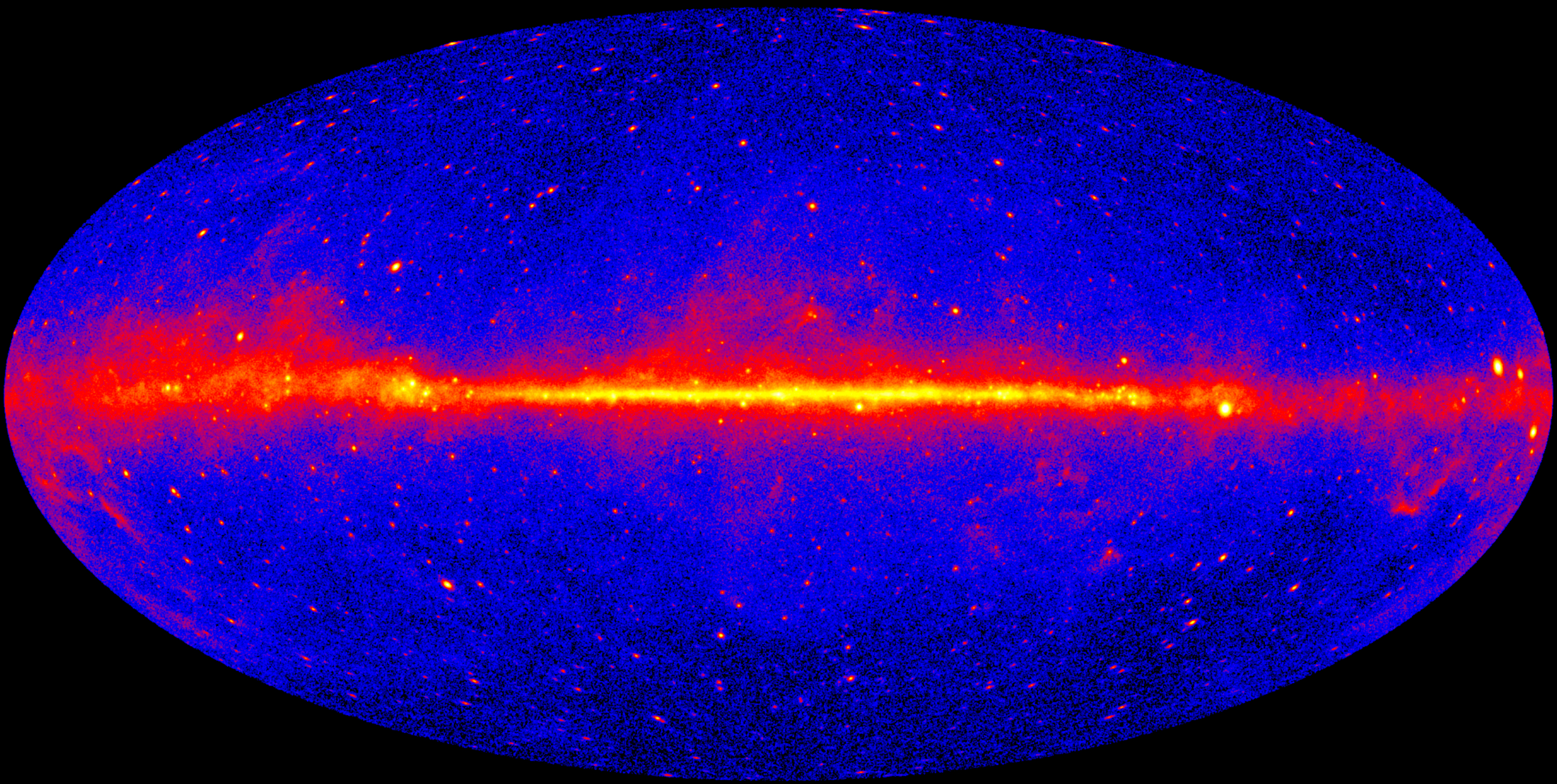
October 5, 2018



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


Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere





CRAZY FINE TUNING

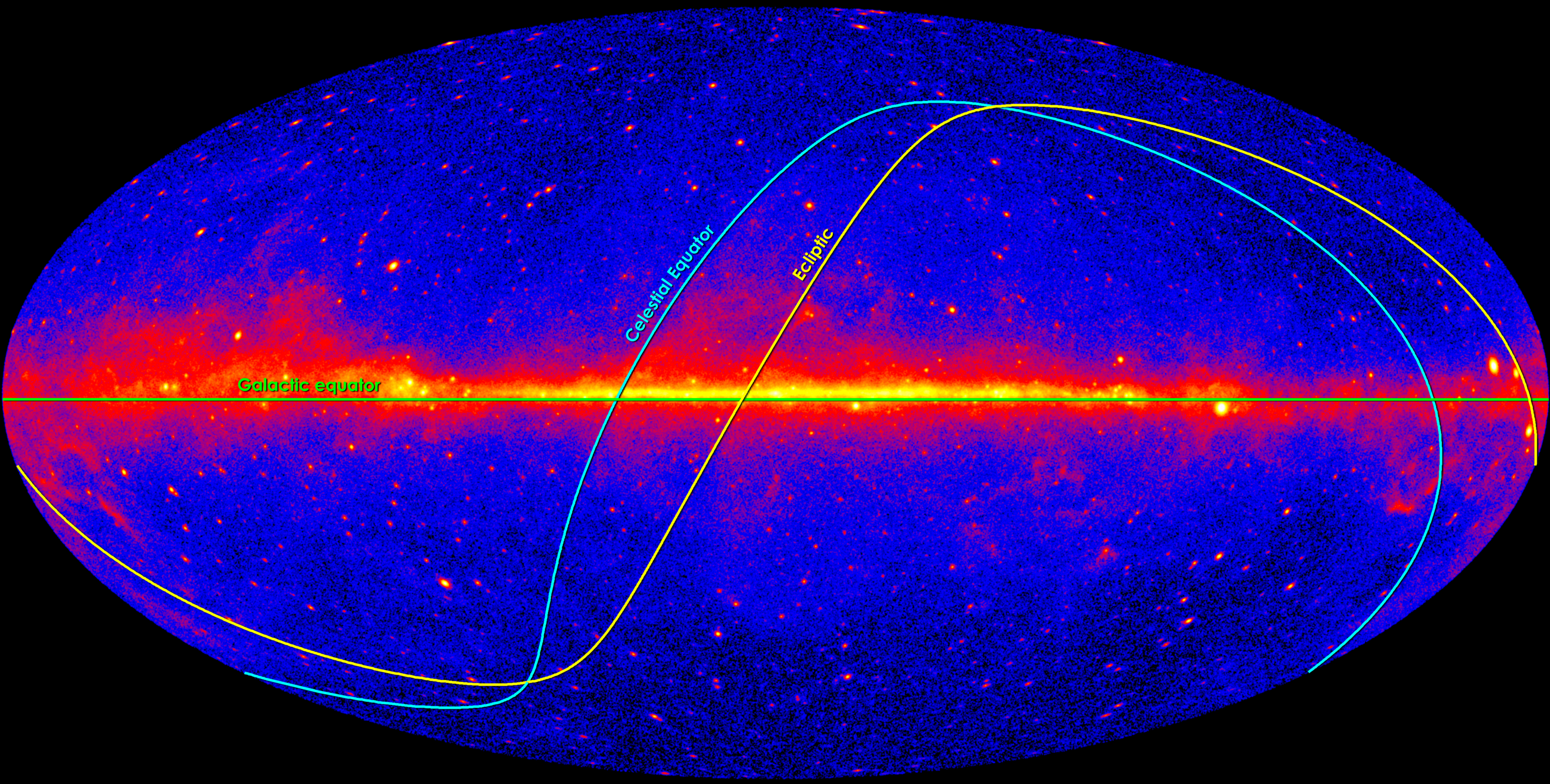
- **Solar gamma-ray flux is approximately:**

3×10^{-10} erg cm^{-2} s^{-1}

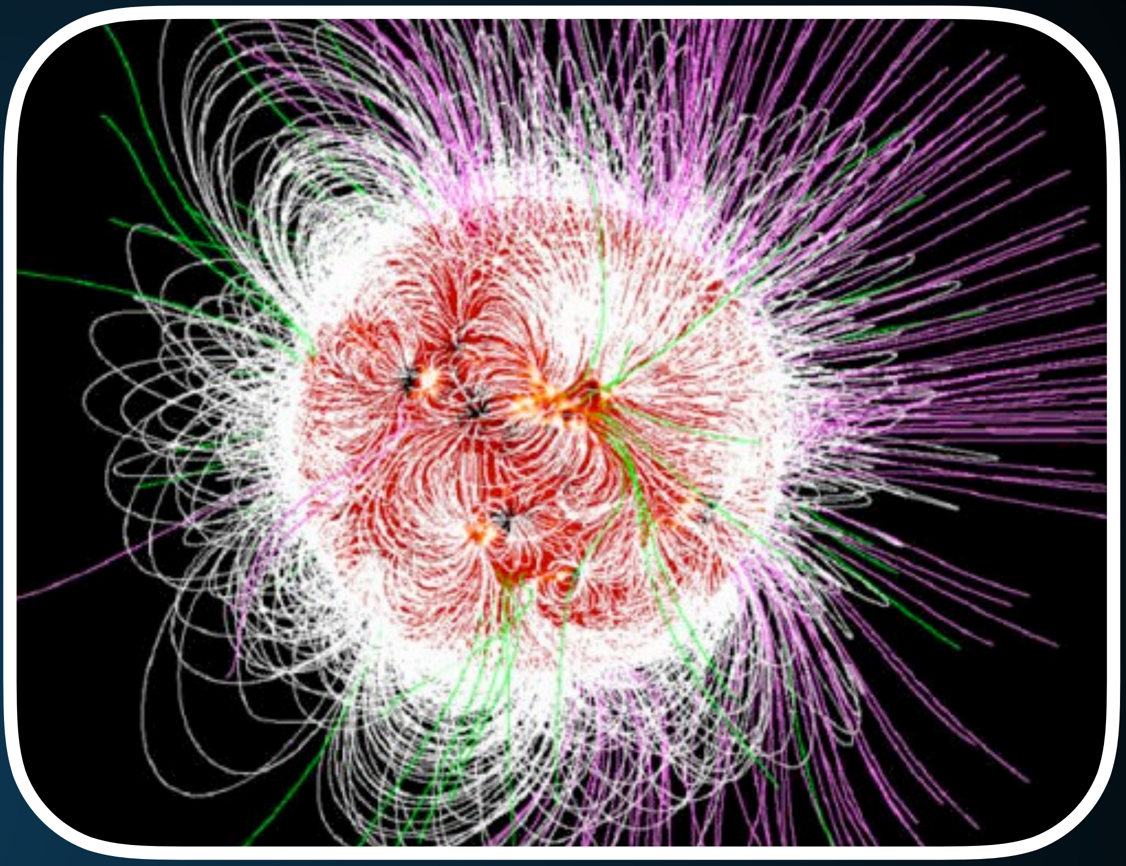
- **Solar disk gamma-ray flux:**

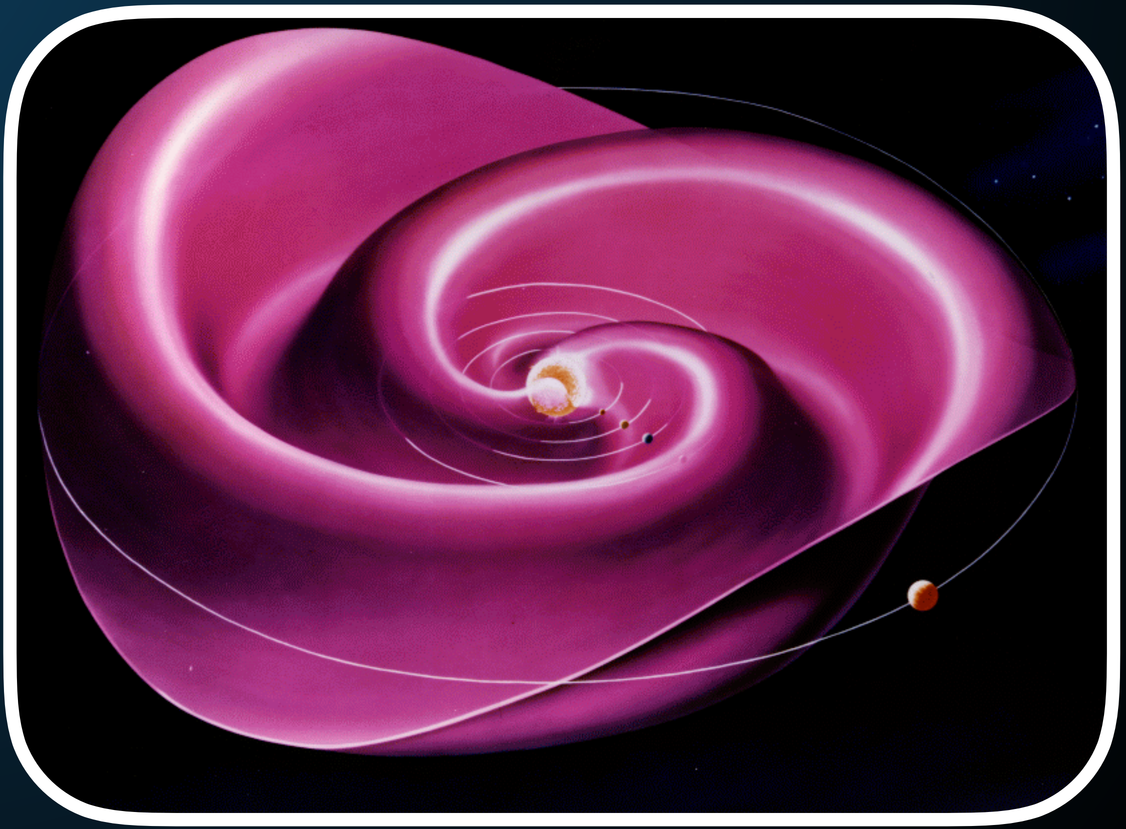
6×10^{-11} erg cm^{-2} s^{-1}

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	

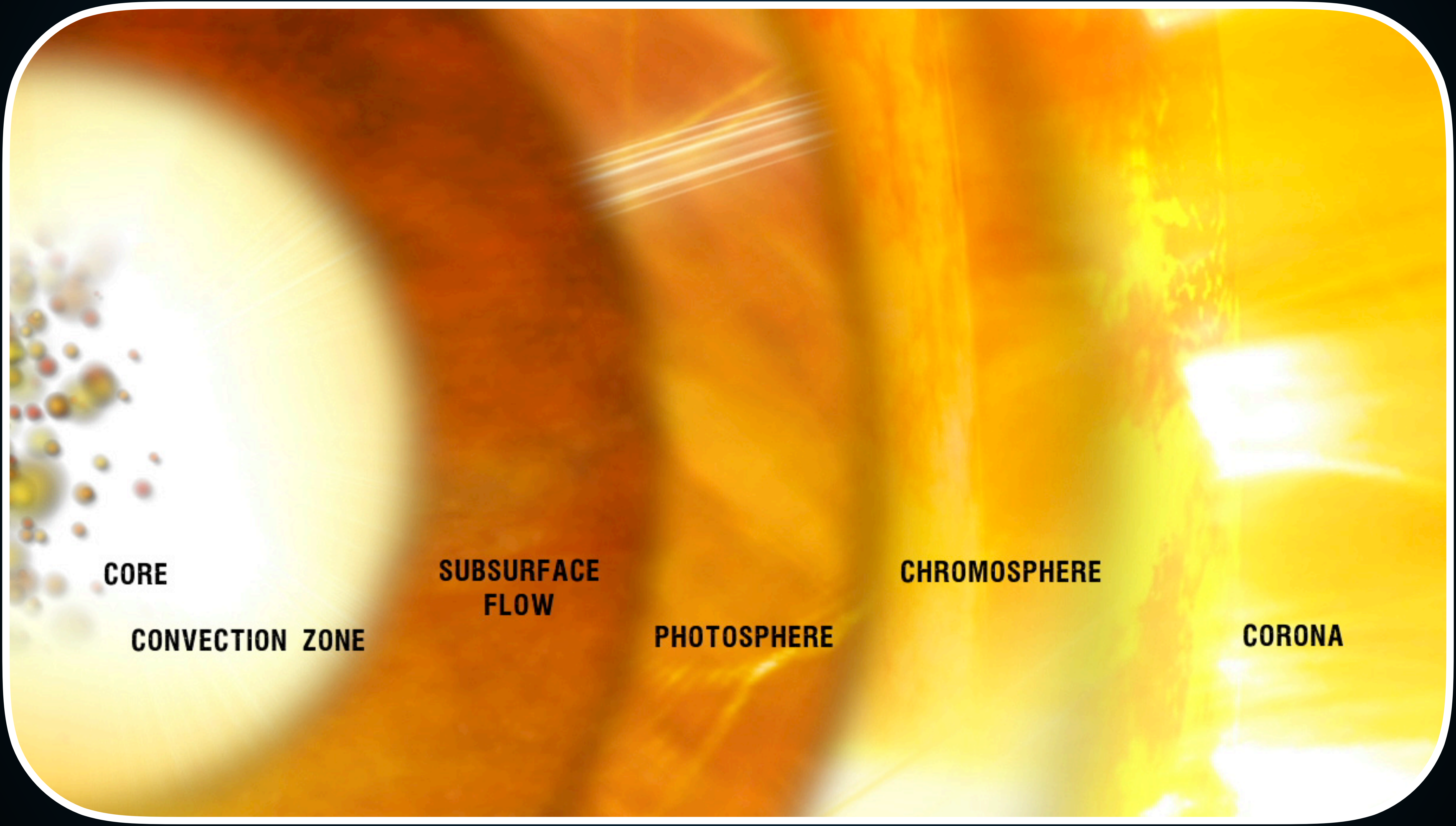

Celestial Equator
Ecliptic
Galactic equator

GAMMA-RAYS - WHY?





GAMMA-RAYS - WHY?



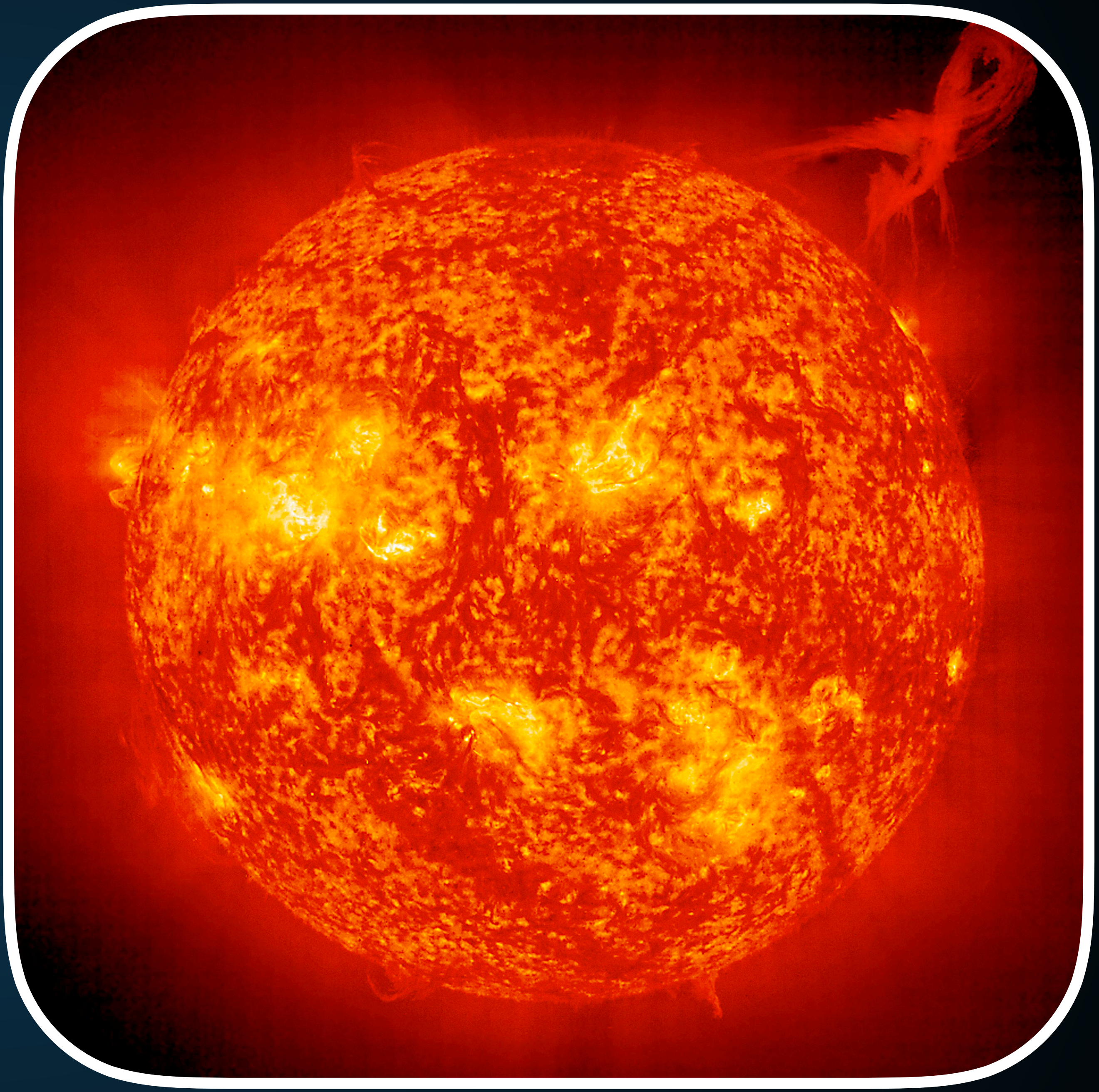
How are these gamma rays produced?

GAMMA-RAYS - HOW?

$T_\odot$ = 6000 K = 0.5 eV

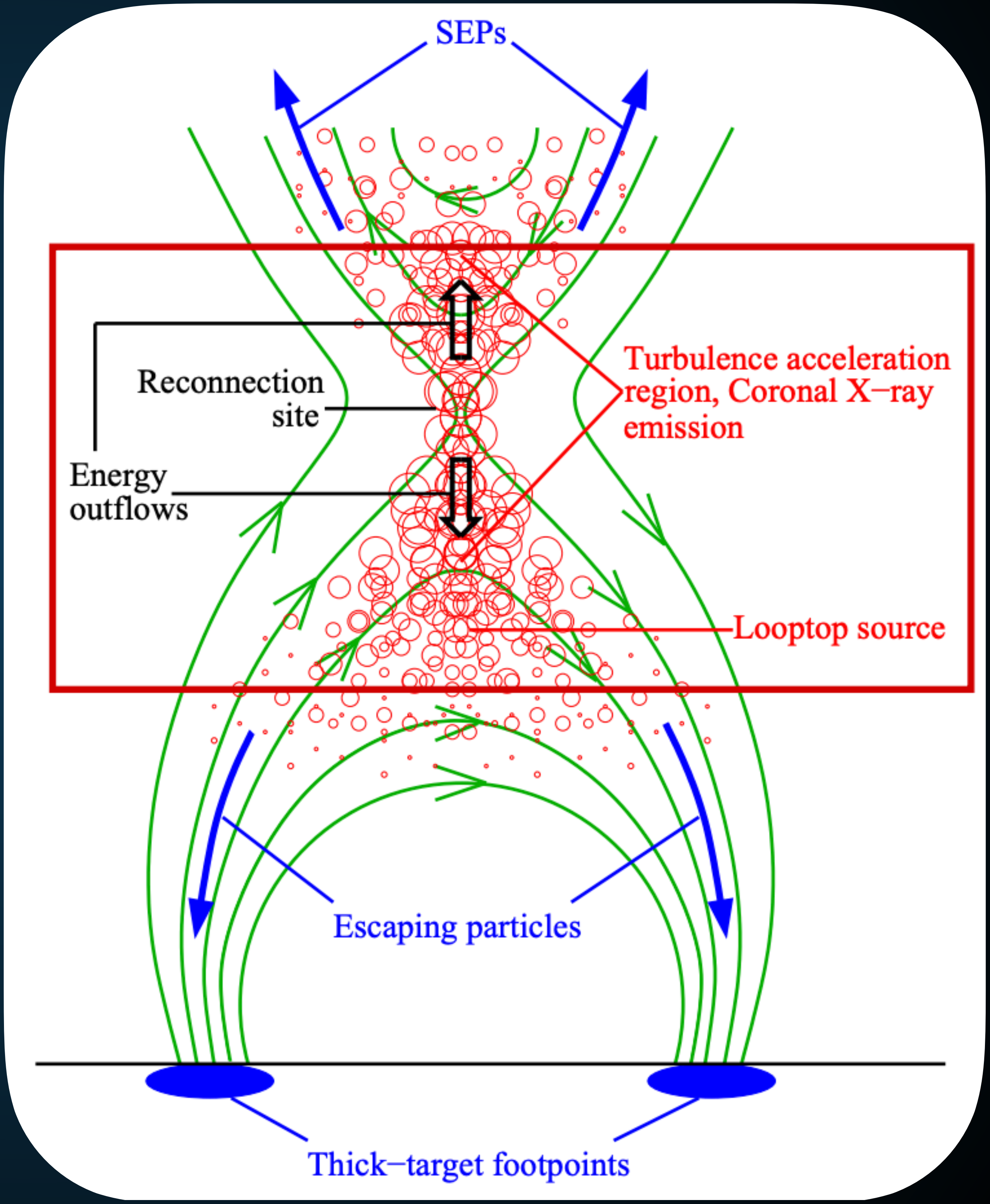
$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

- **Thermal production of GeV gamma-rays is suppressed by exp[-2 x 10^9] = 0**



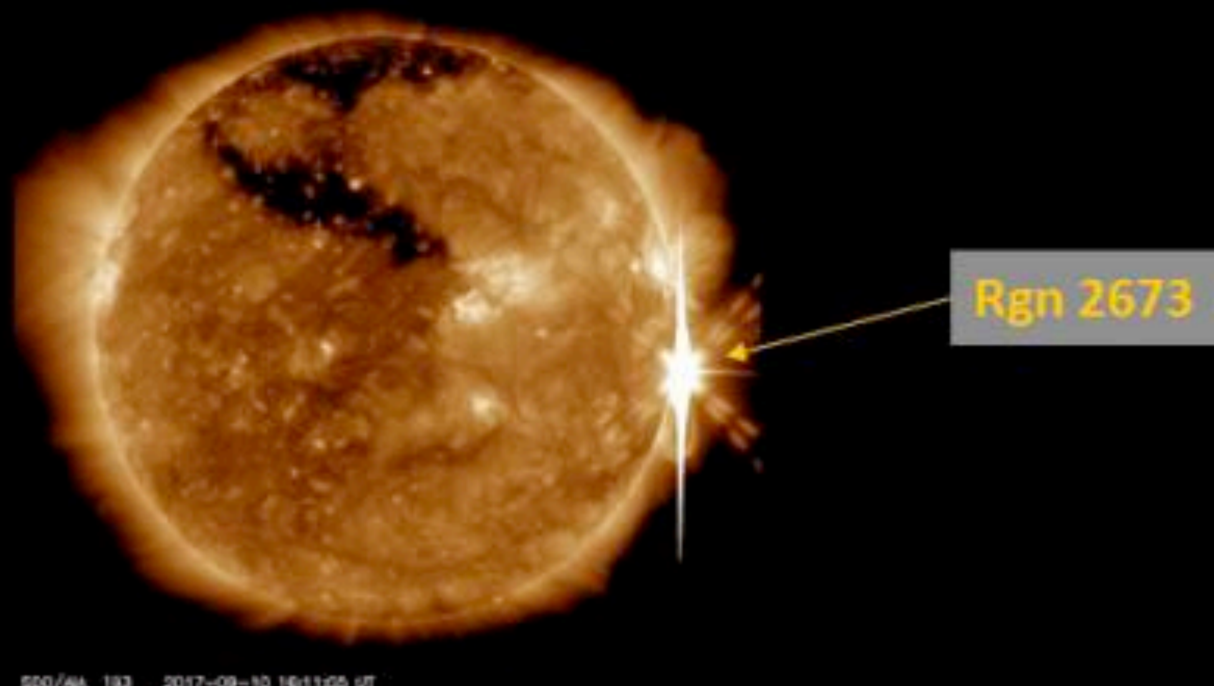
GAMMA-RAYS - HOW?

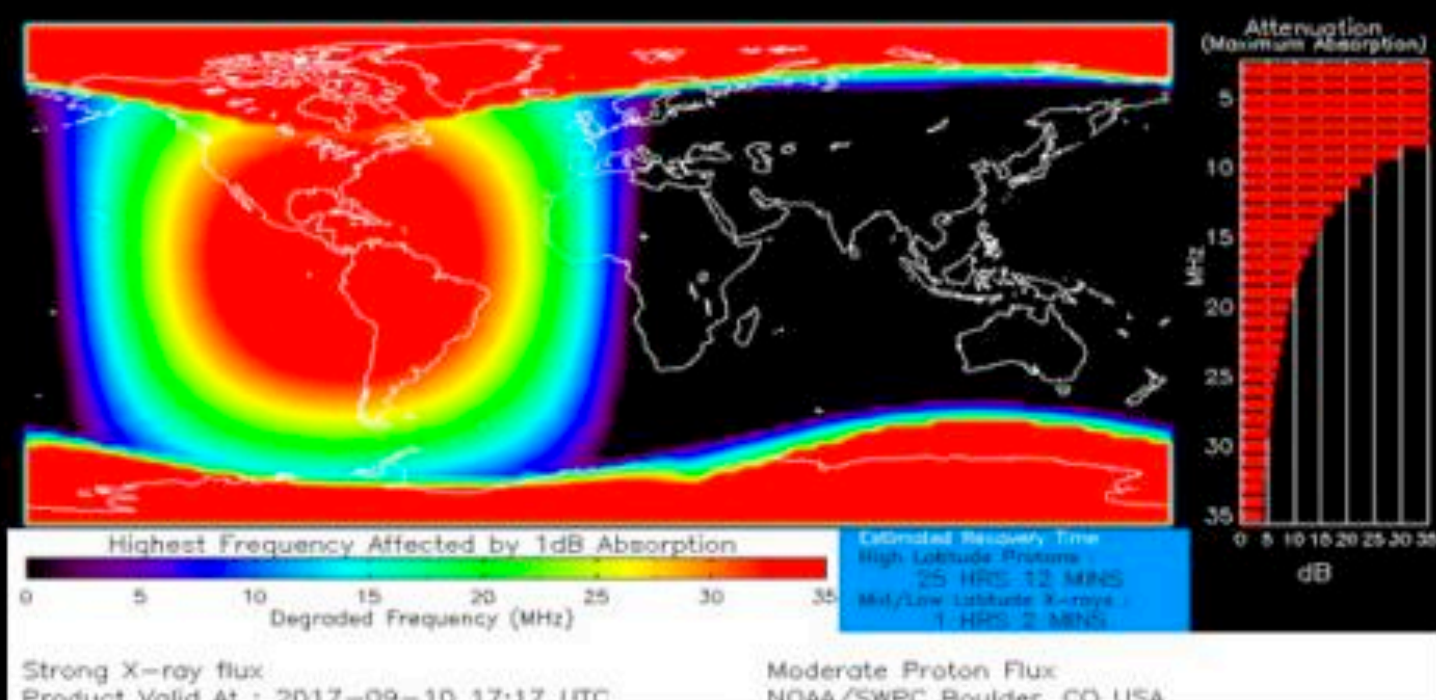
- Solar Flares and Reconnection events.



Petrosian (2016; 1605.04022)

Strong Radio Blackout 10 Sep 17 at 1606 UTC





R3

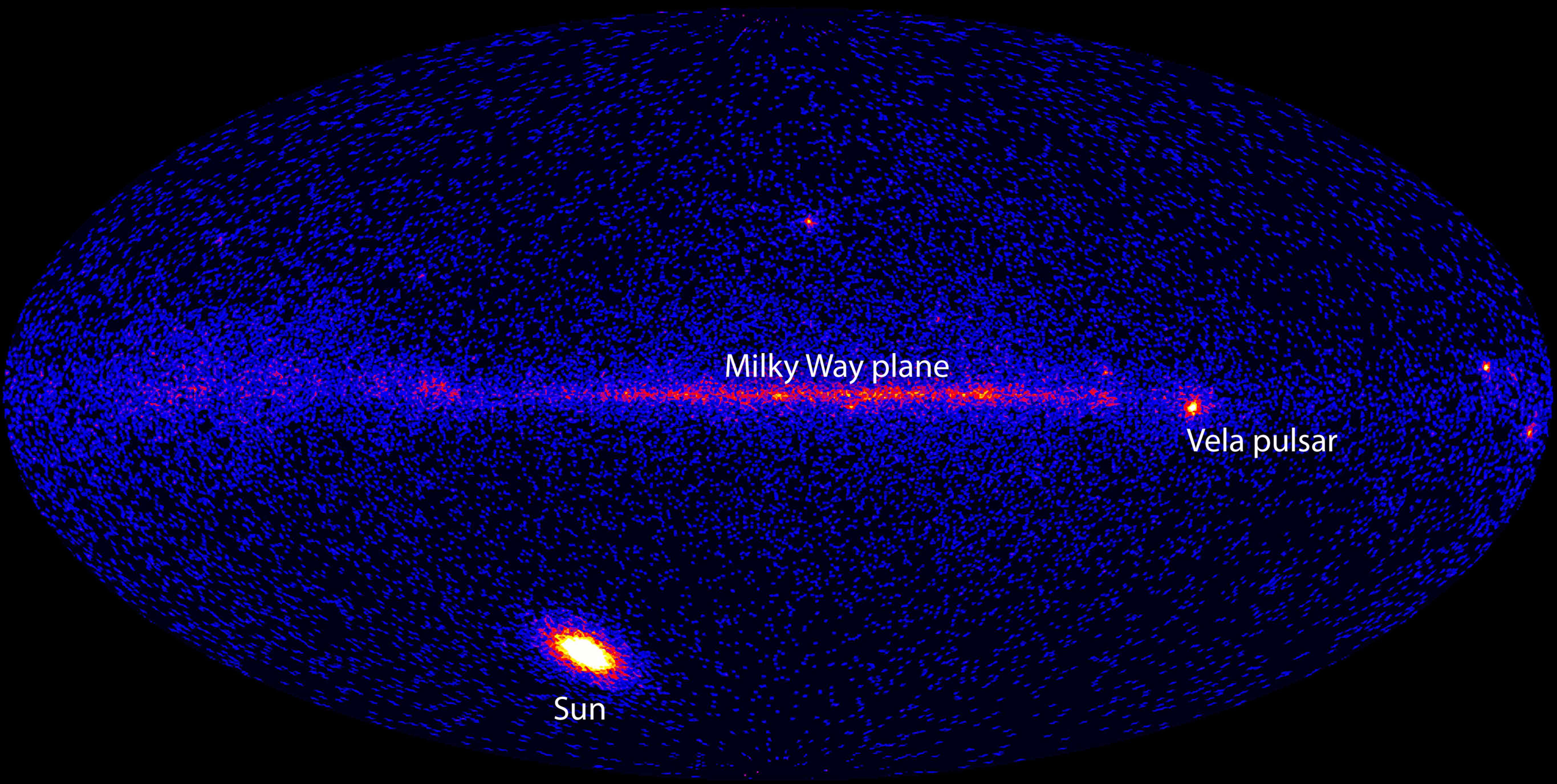
PRIMARY AREA of IMPACTS

Large portions of sunlit side of Earth

POSSIBLE EFFECTS

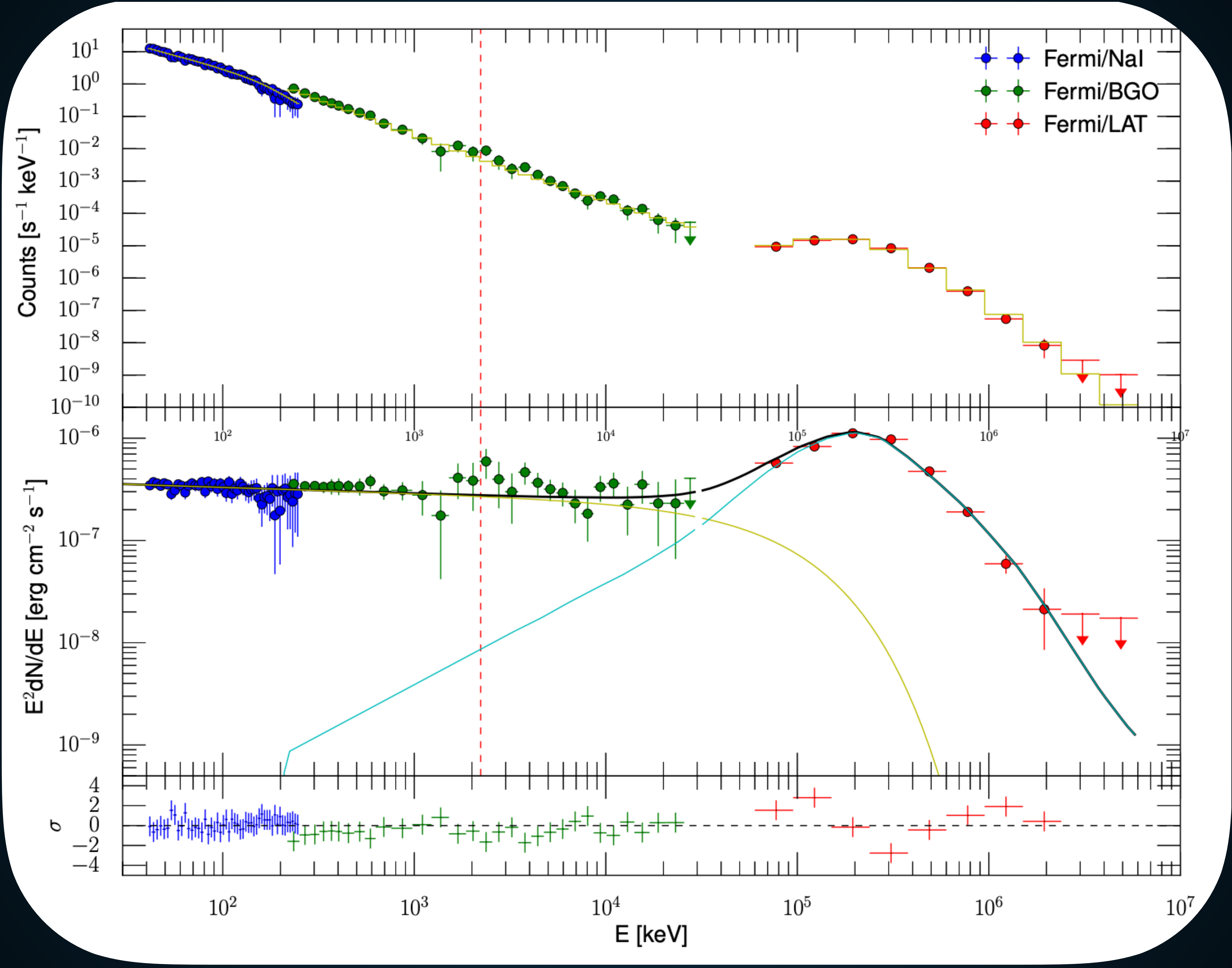
HF Radio: Wide area of blackouts; loss of contact for up to an hour over sunlit side of Earth

Navigation: Low frequency communication degraded for about an hour

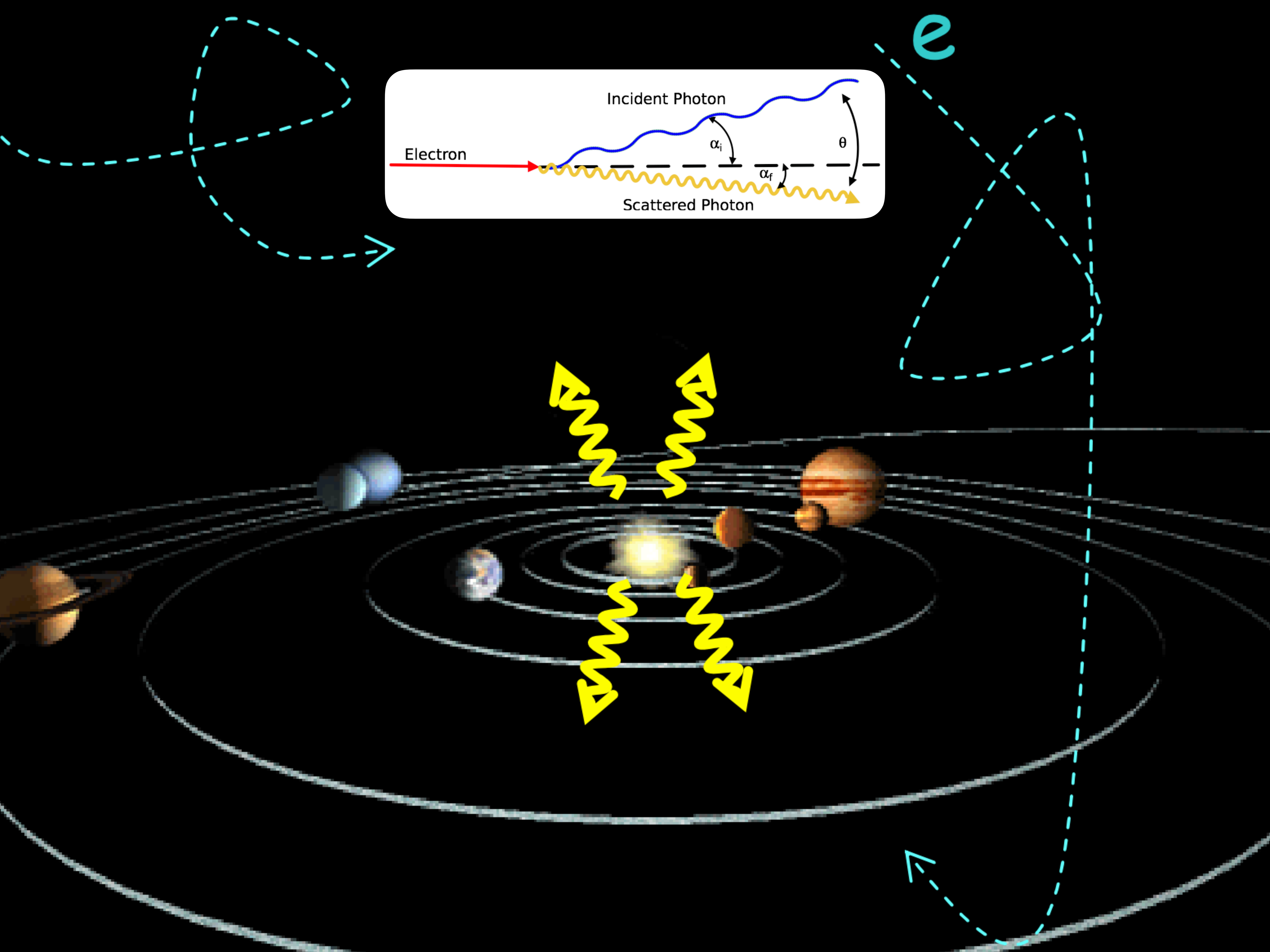


Milky Way plane
Vela pulsar
Sun

GAMMA-RAYS - HOW?



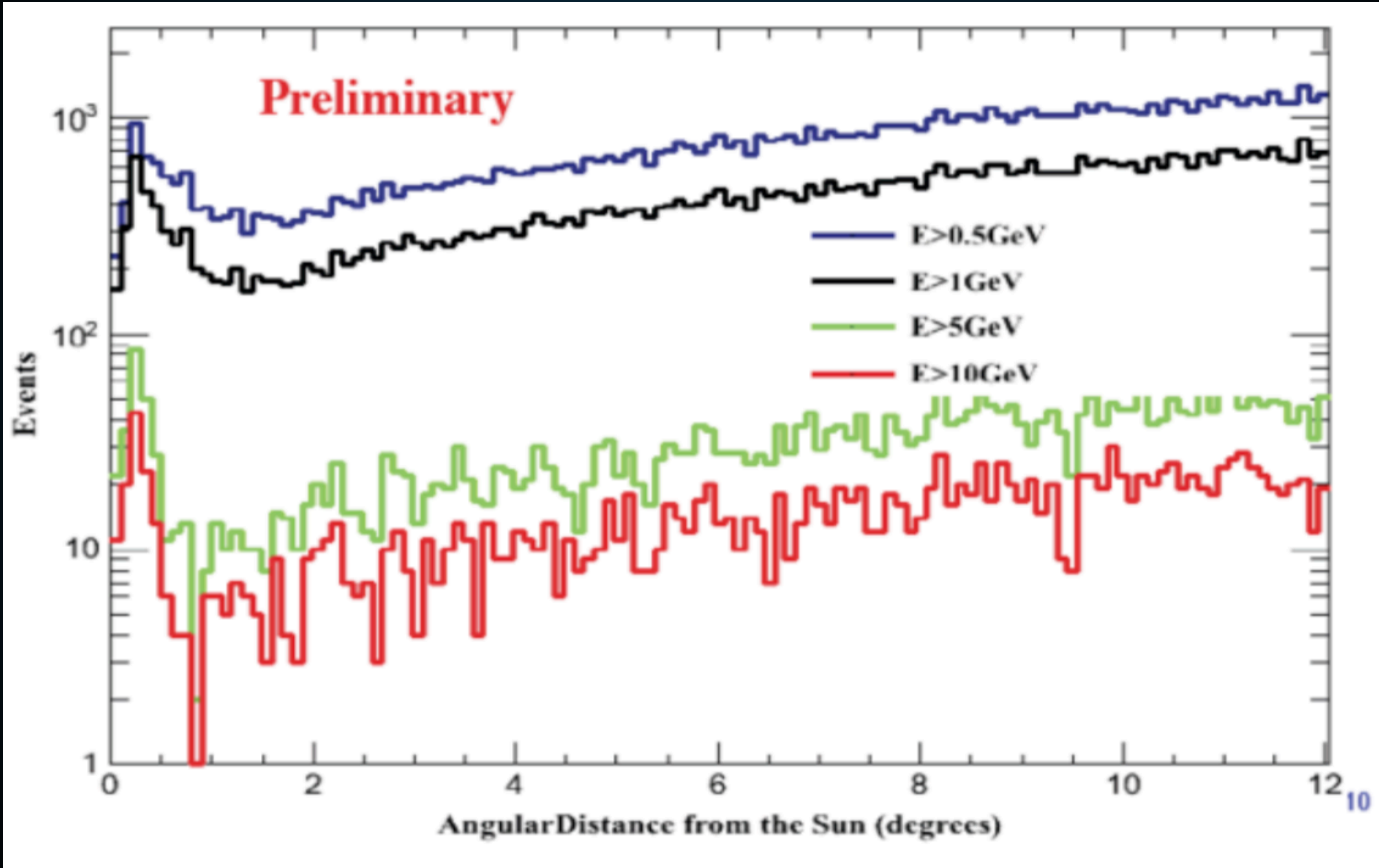
- **Solar Flare gamma-rays are low energy (E_{max} = 4 GeV)**



e
Incident Photon
Electron
Scattered Photon
α_i
α_f
θ

GAMMA-RAYS - INVERSE COMPTON SCATTERING

Raino et al. (2018)

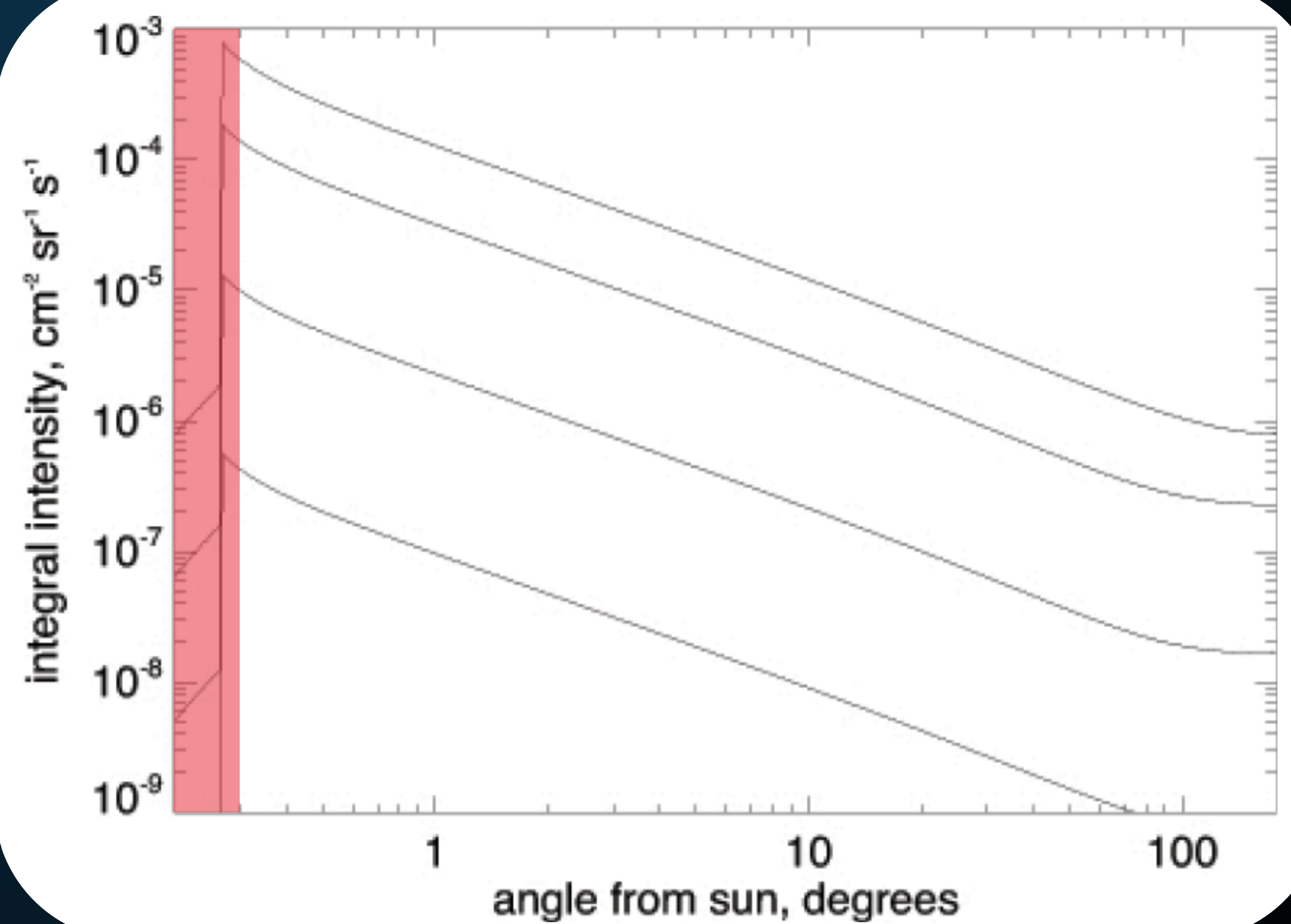


GAMMA-RAYS - HOW?

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

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

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

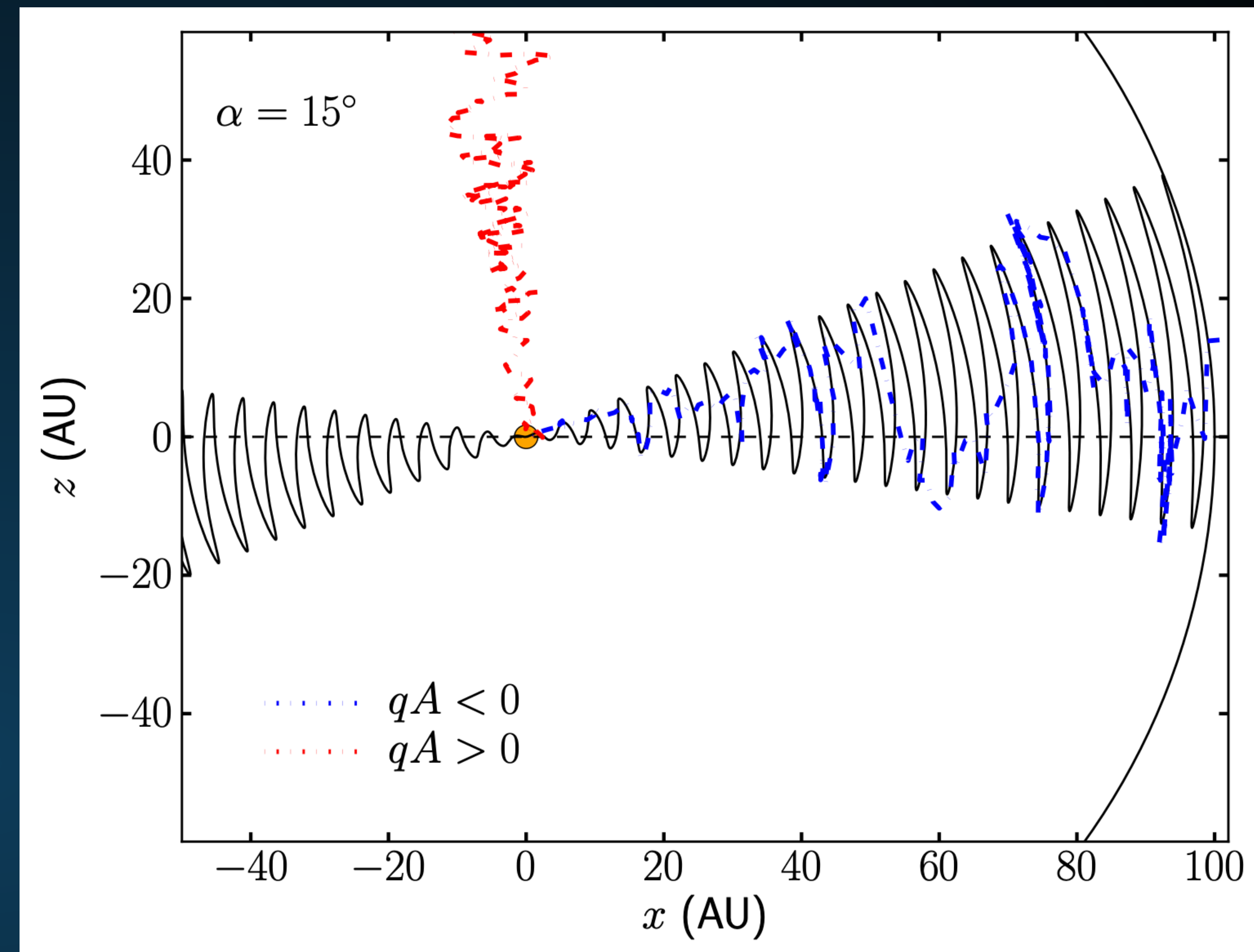


What about the solar disk itself?

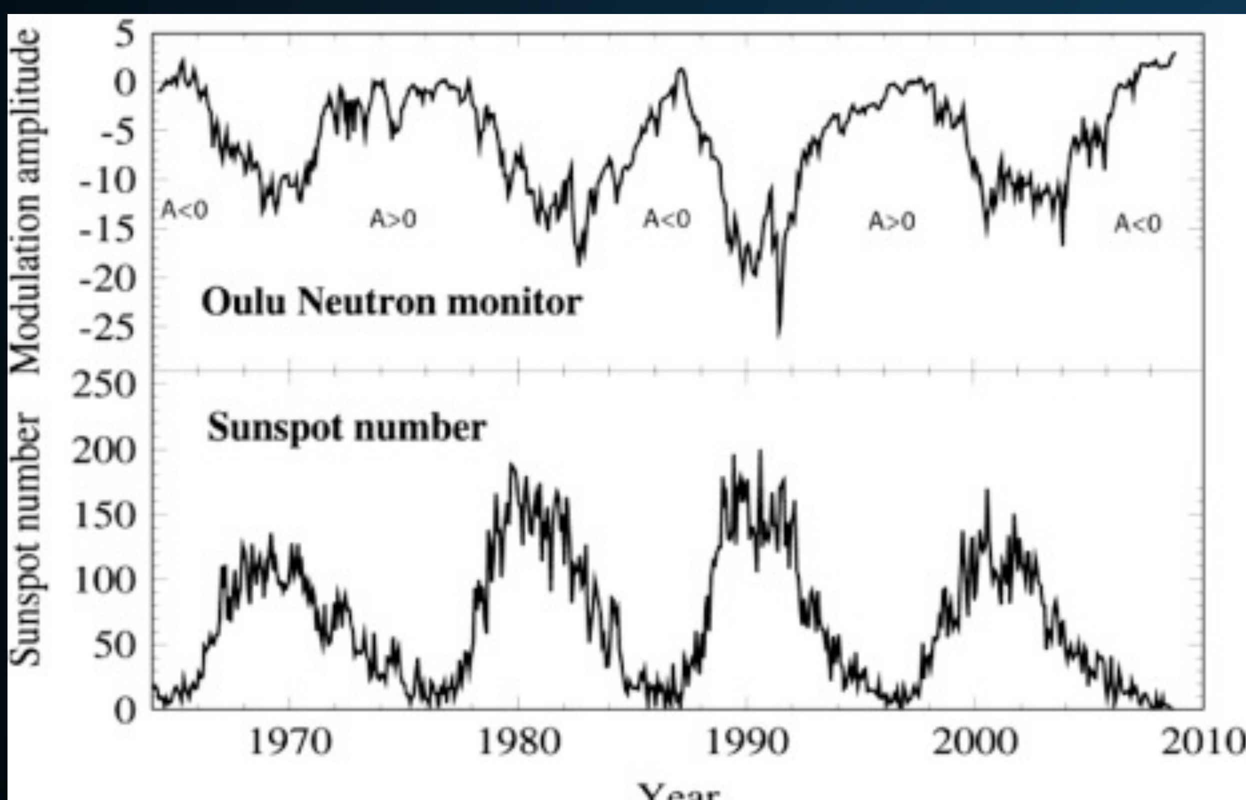
HADRONIC GAMMA-RAYS - HOW?

Cholis, Hooper, TL (2016; 1511.01507)

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

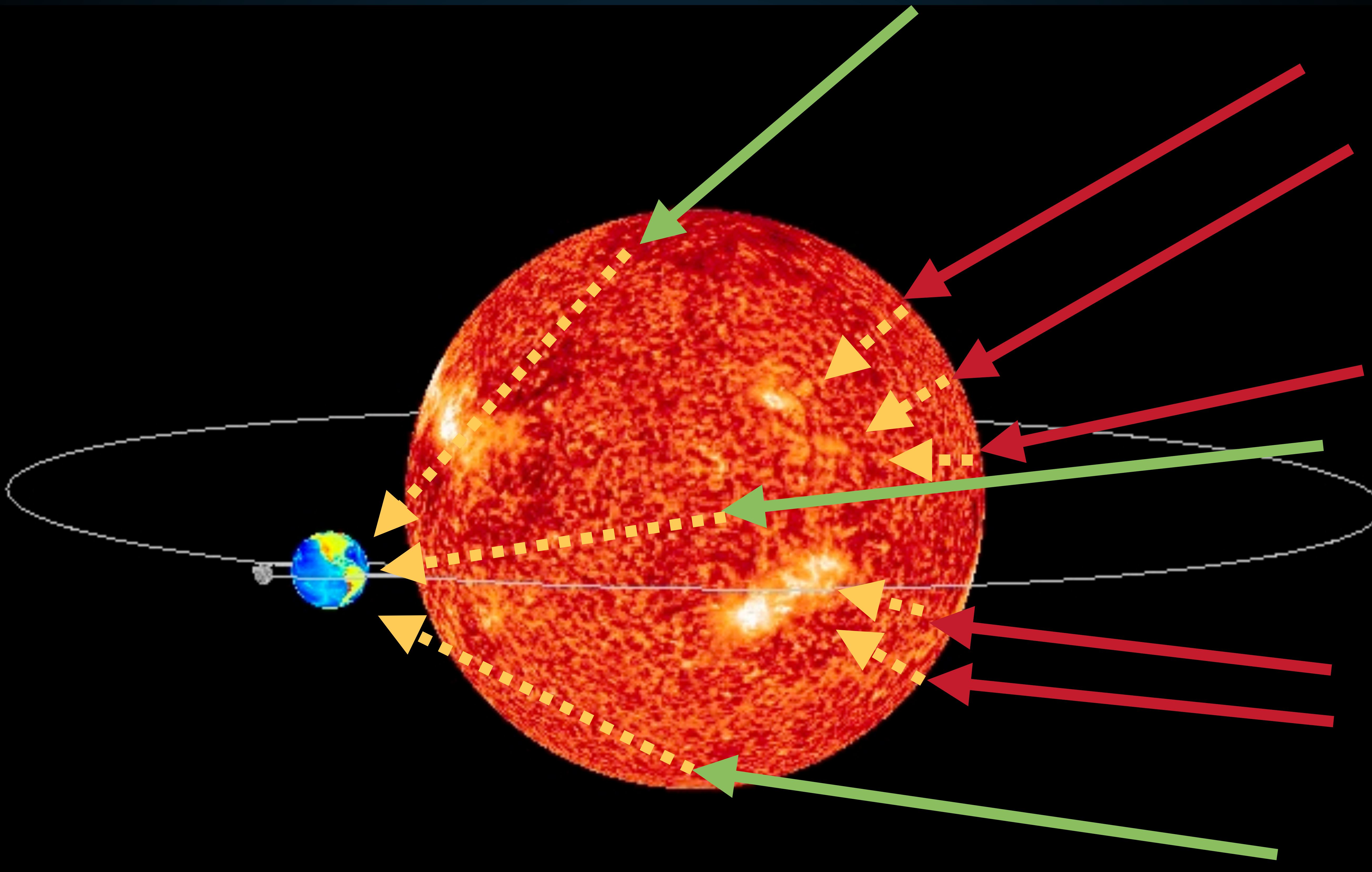


Valdes-Galicia & Gonzalez (2016)



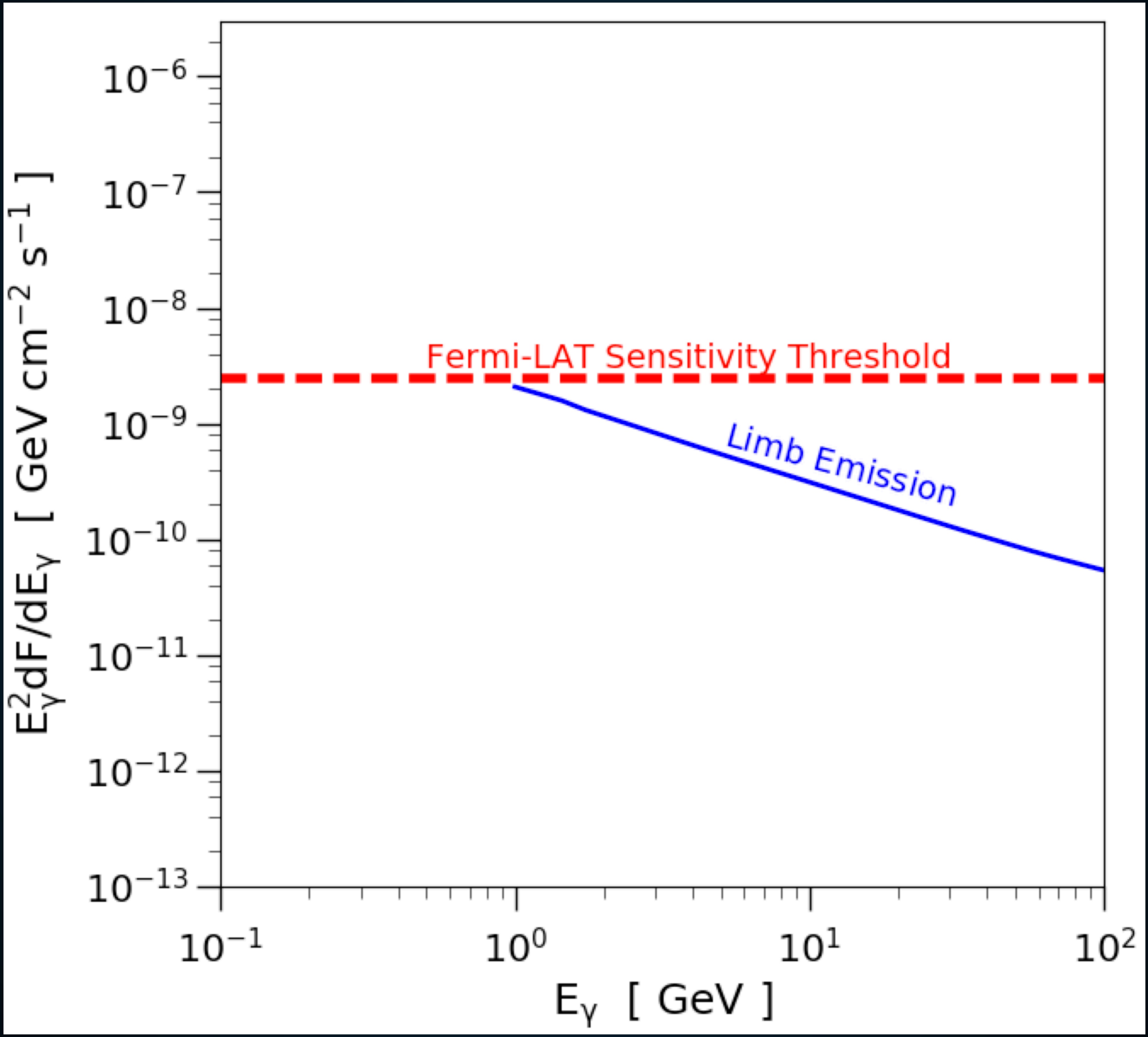
$$\Phi(R,t) = \phi_0 \left(\frac{|B_{\rm tot}(t)|}{4\,{\rm nT}}\right) + \phi_1\, H(-qA(t)) \left(\frac{|B_{\rm tot}(t)|}{4\,{\rm nT}}\right) \left(\frac{1+(R/R_0)^2}{\beta(R/R_0)^3}\right) \left(\frac{\alpha(t)}{\pi/2}\right)^4$$

HADRONIC GAMMA-RAYS - HOW?



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

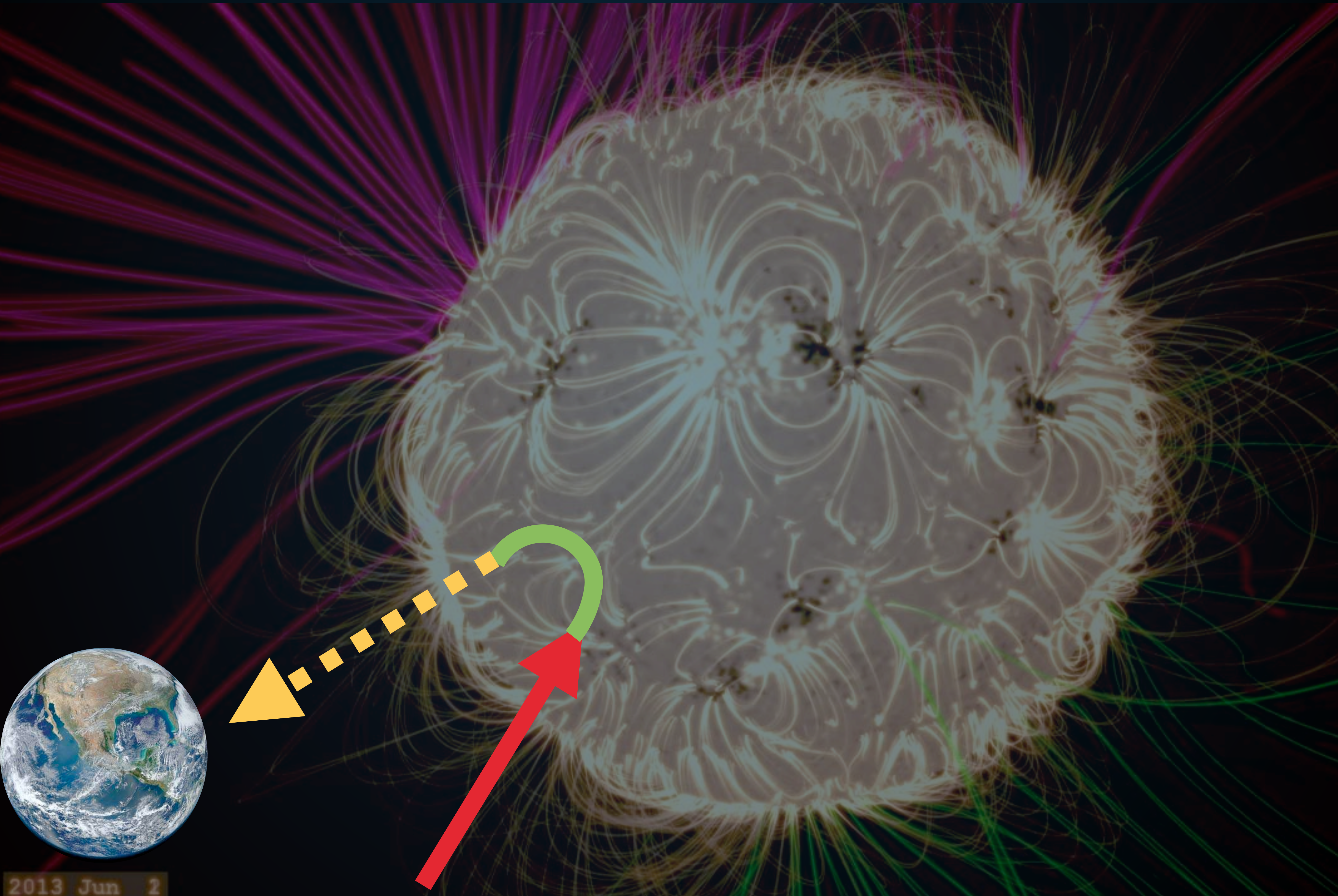
The interactions of high-energy cosmic-ray nuclei with matter have been studied in a variety of settings. In our own atmosphere, these interactions produce cascades which include, or in turn produce, detectable fluxes of electrons, positrons, muons, gamma rays, Čerenkov light, neutrons and other nuclear 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?



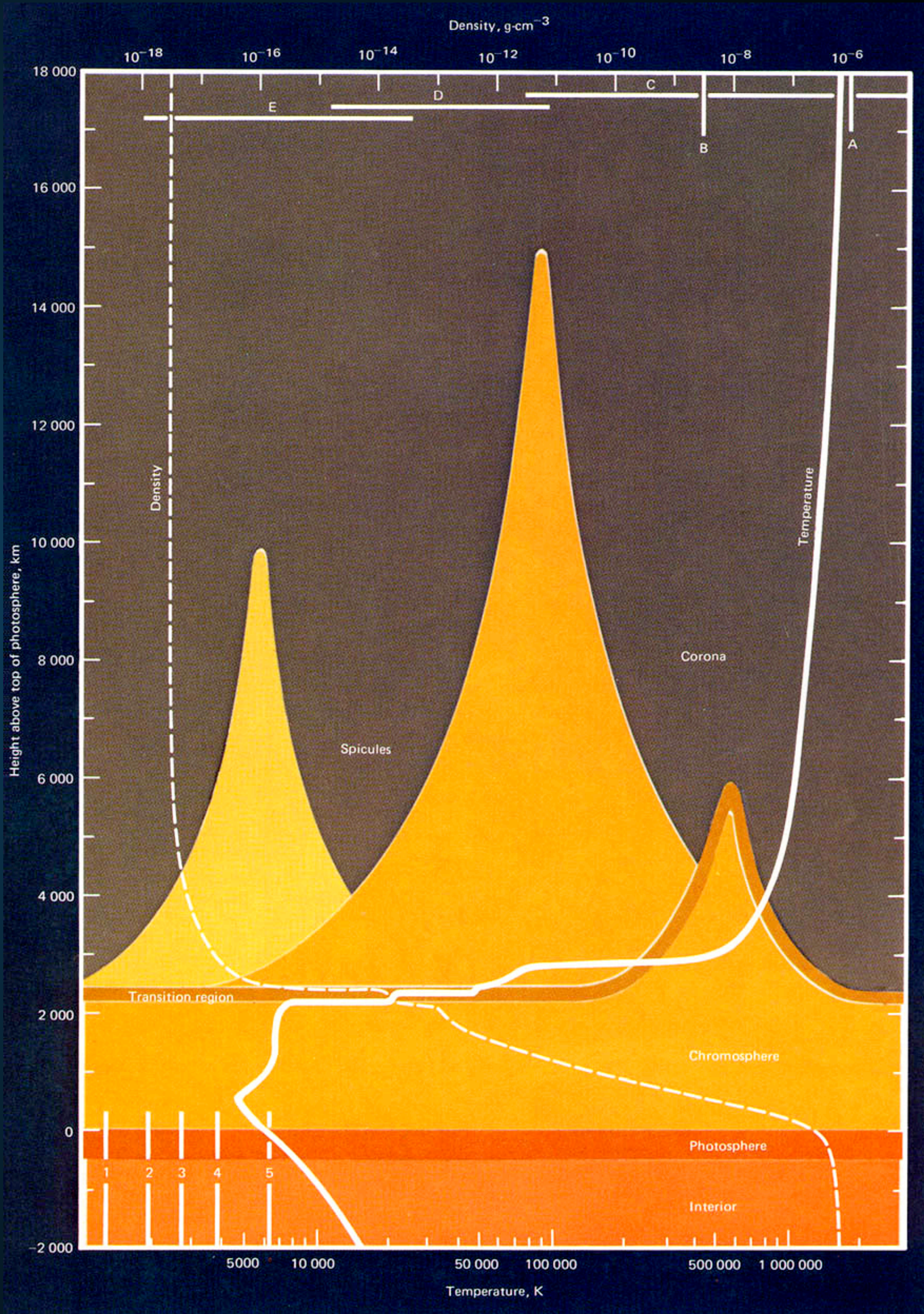
HADRONIC GAMMA-RAYS - HOW?

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

Photosphere Magnetic Field: **1-10 G**

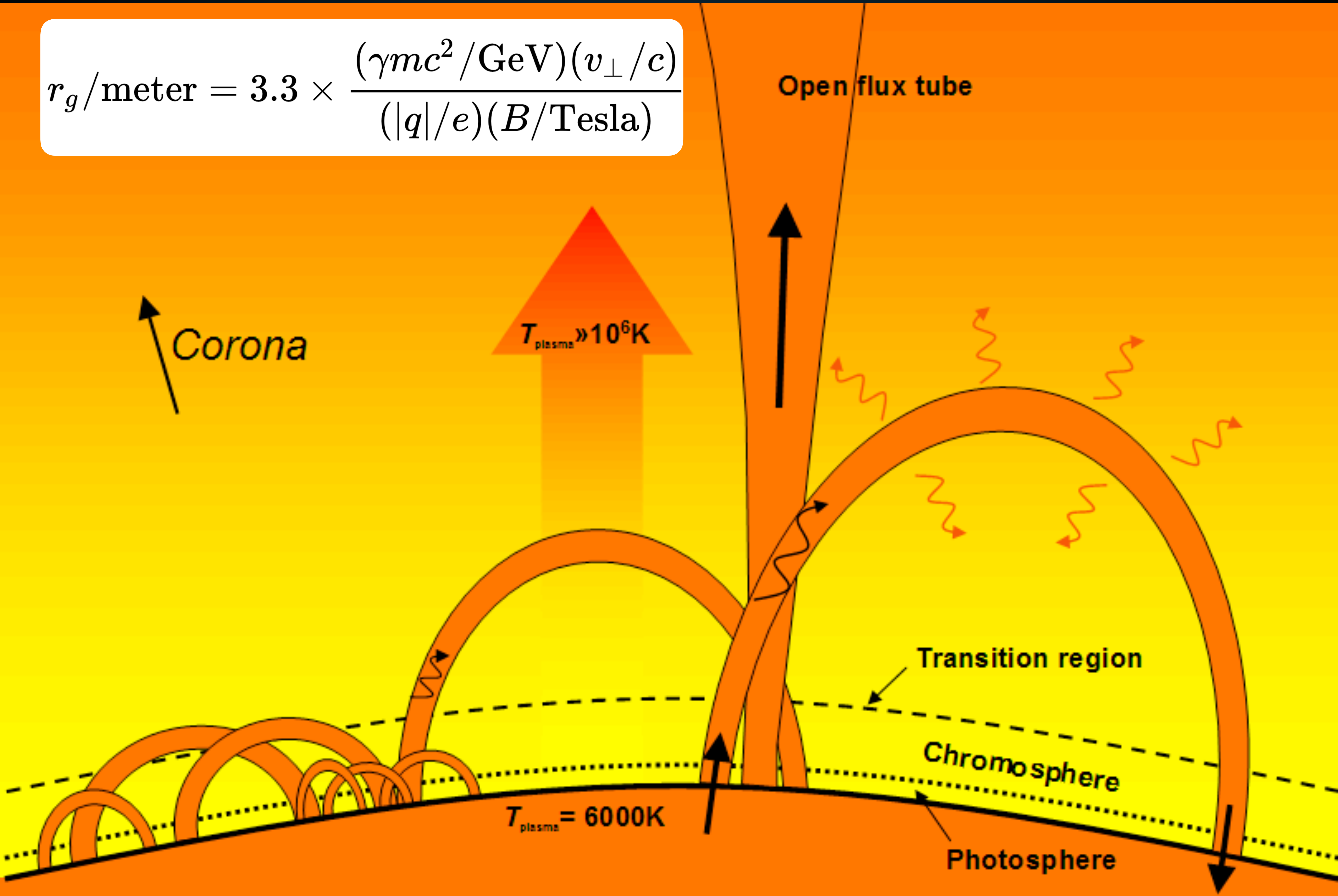
Gyroradius (100 GeV): **3300 km**

- **Cosmic rays encounter a grammage of 330 g cm^{-2}**
- **Cosmic rays die before reflecting within the solar surface.**



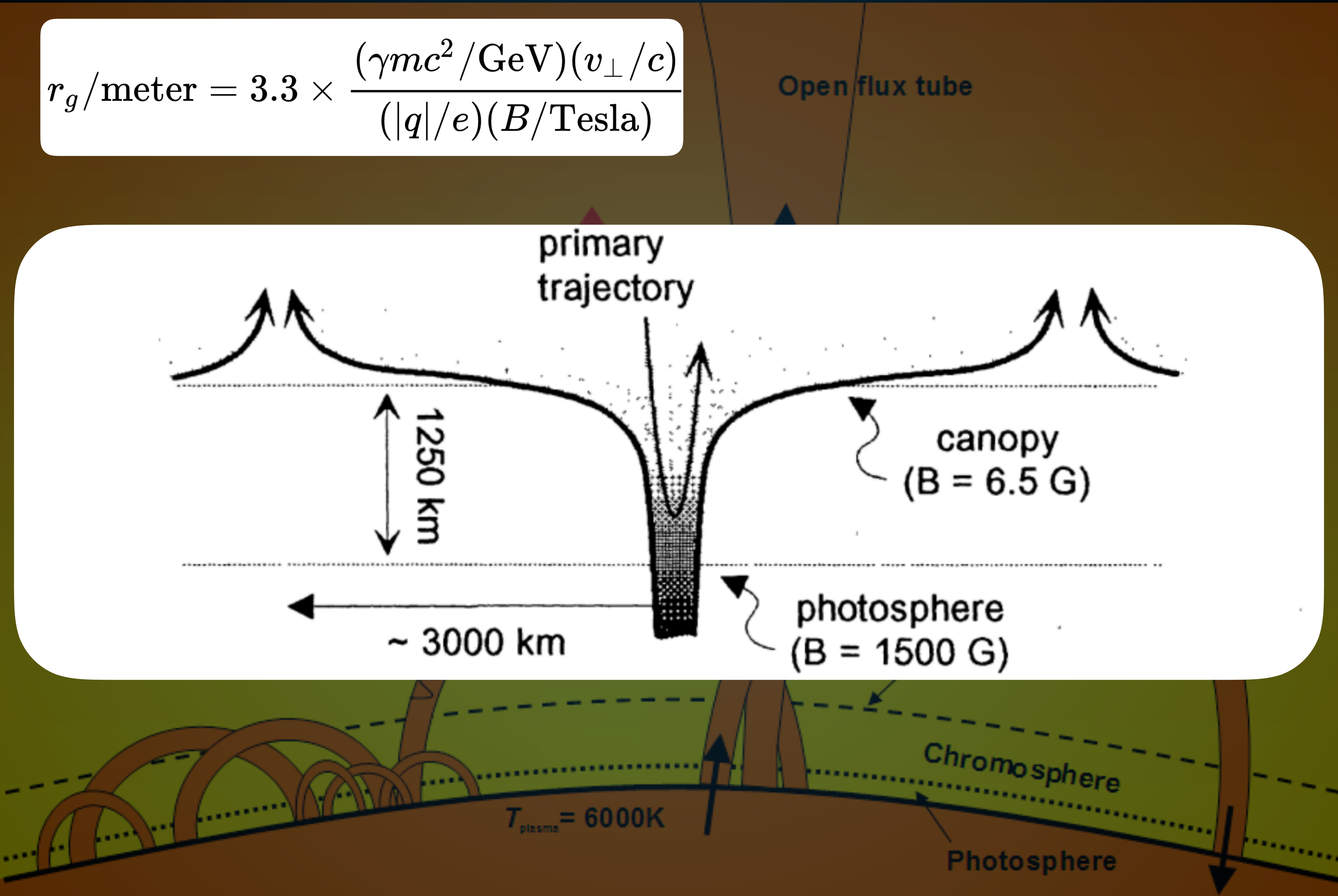
HADRONIC GAMMA-RAYS - HOW?

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

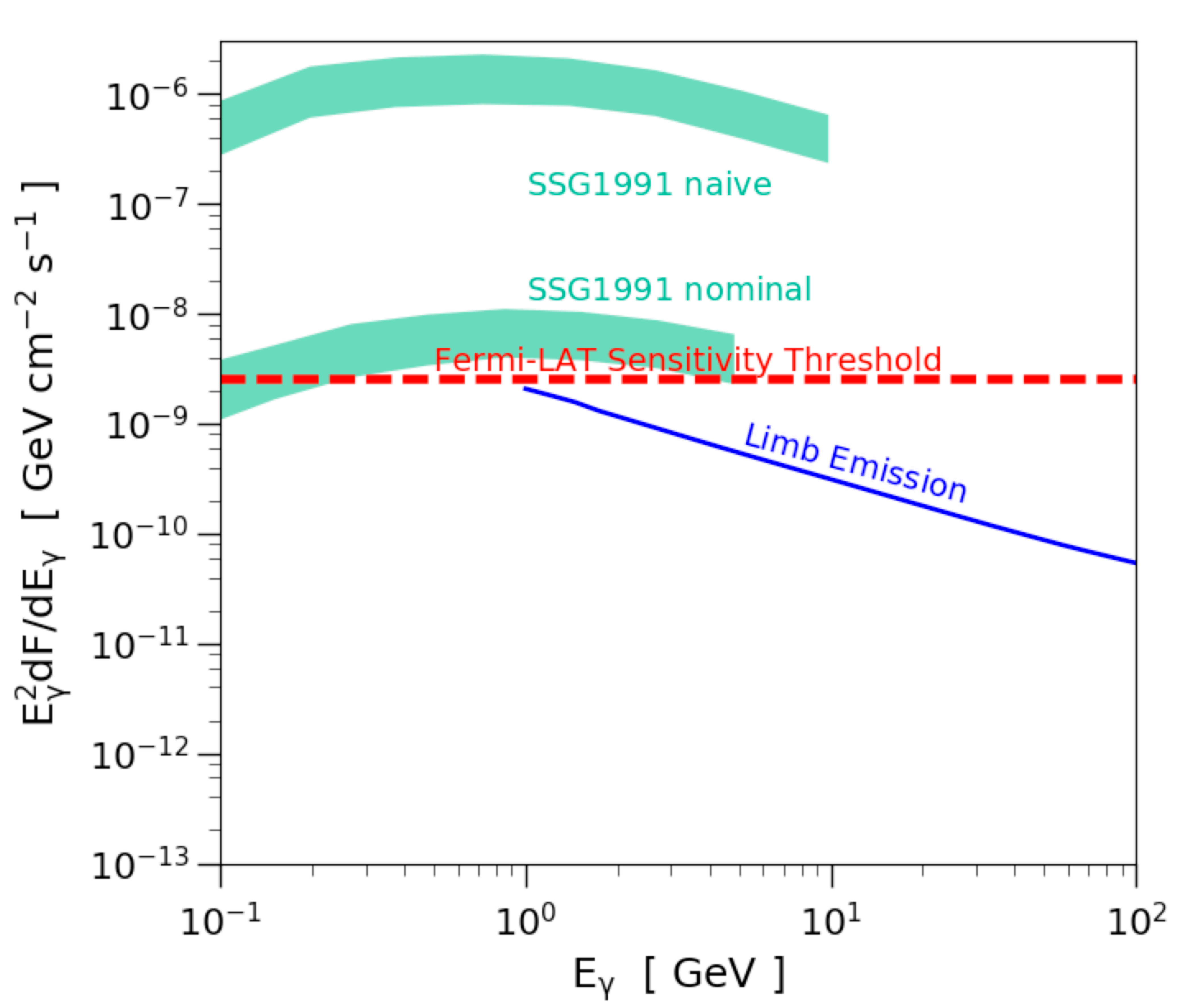


HADRONIC GAMMA-RAYS - HOW?

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



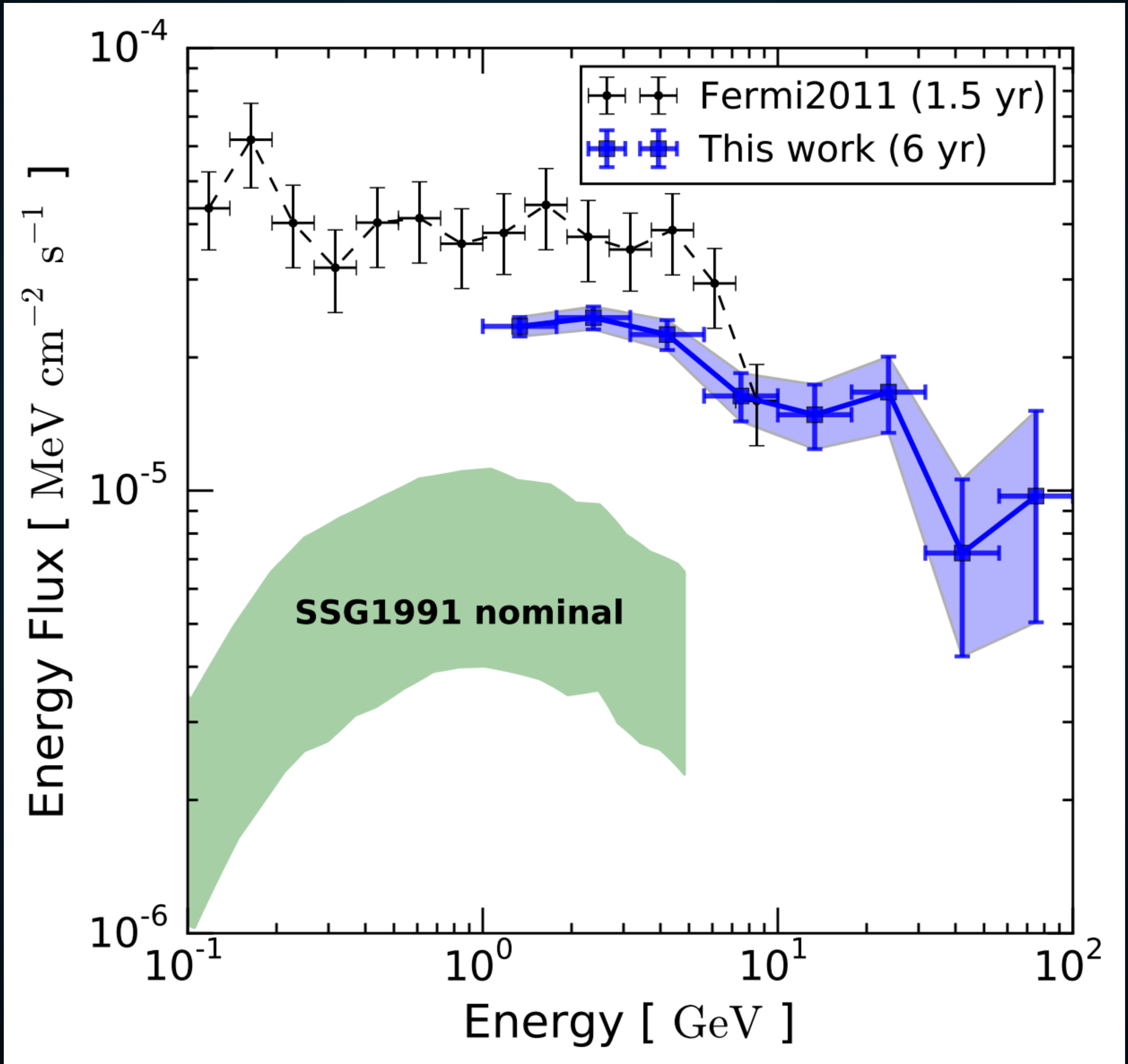
HADRONIC GAMMA-RAYS - HOW?



GAMMA-RAYS - WHAT?

OBSERVATIONS - INTENSITY

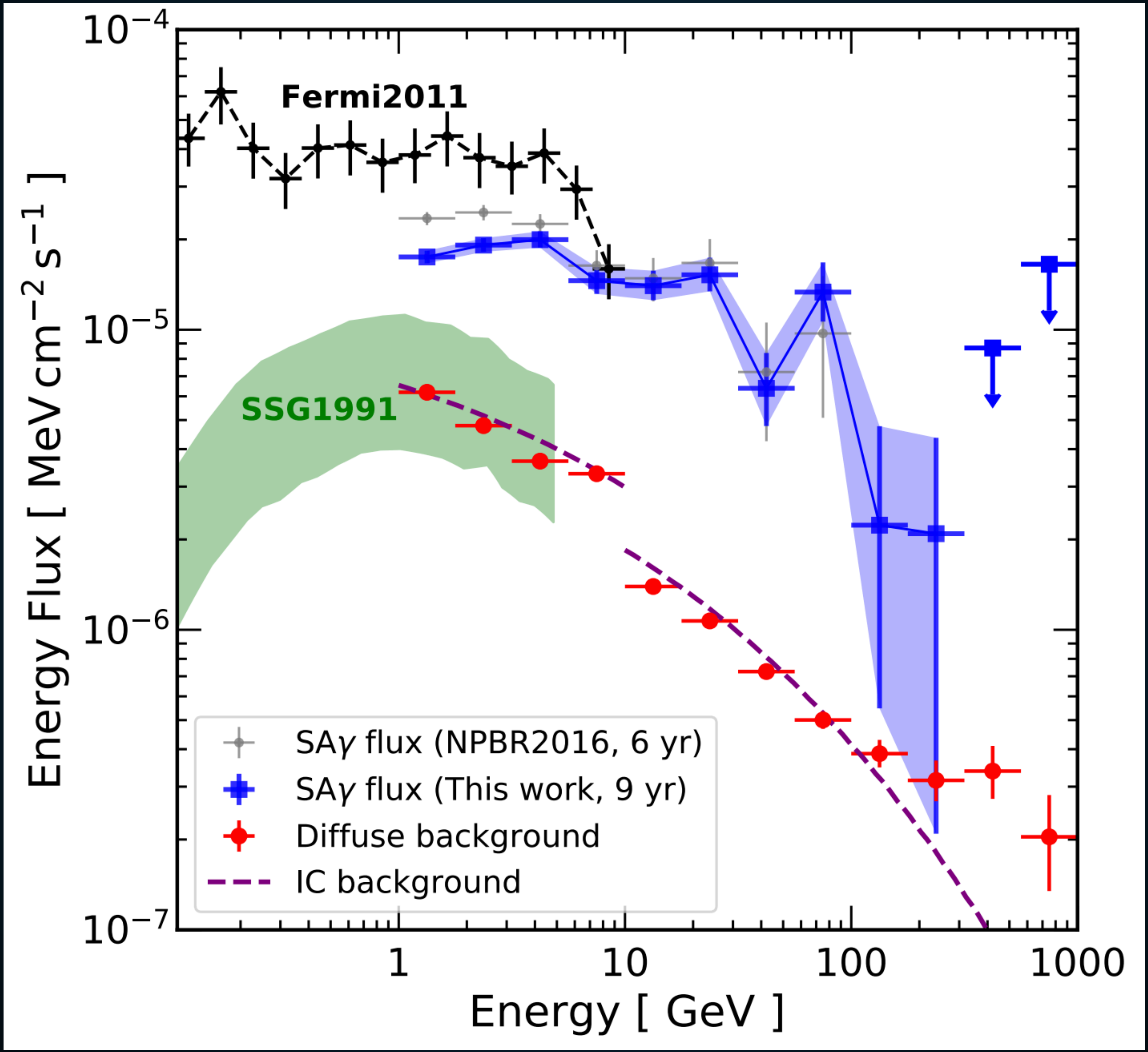
Ng et al. 2016 (1508.06276)



Intensity **X**

OBSERVATIONS - SPECTRUM

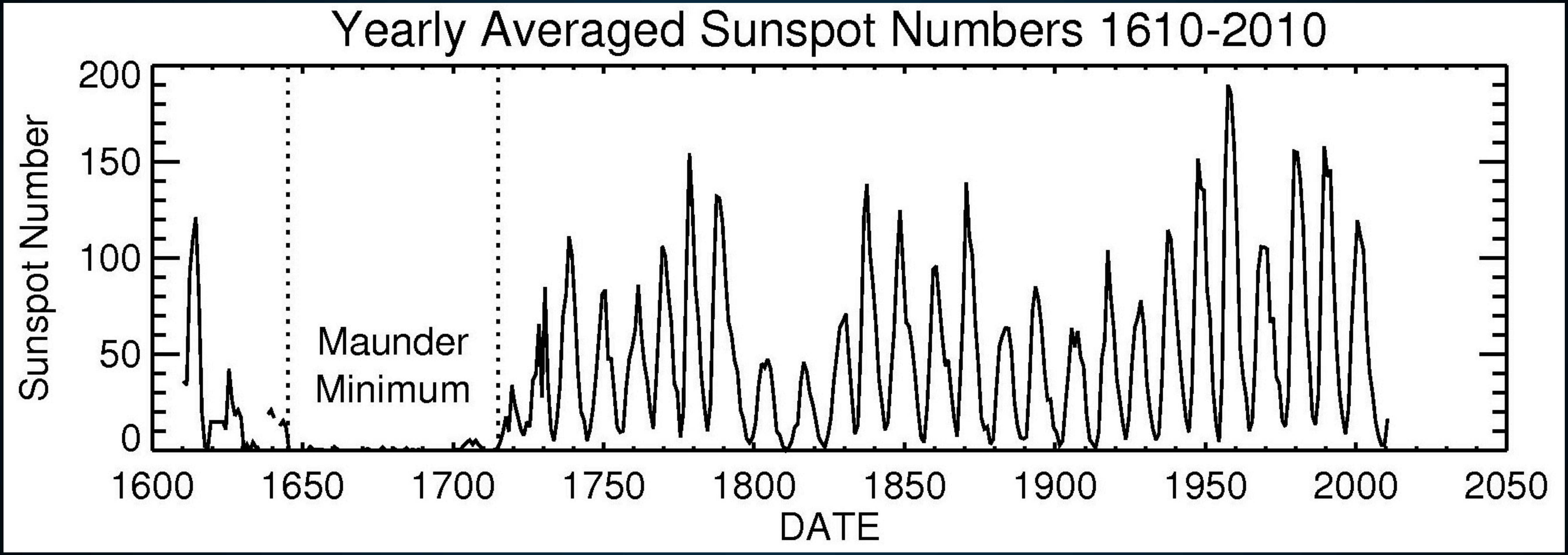
Tang et al. 2018 (1804.06846)



Intensity X

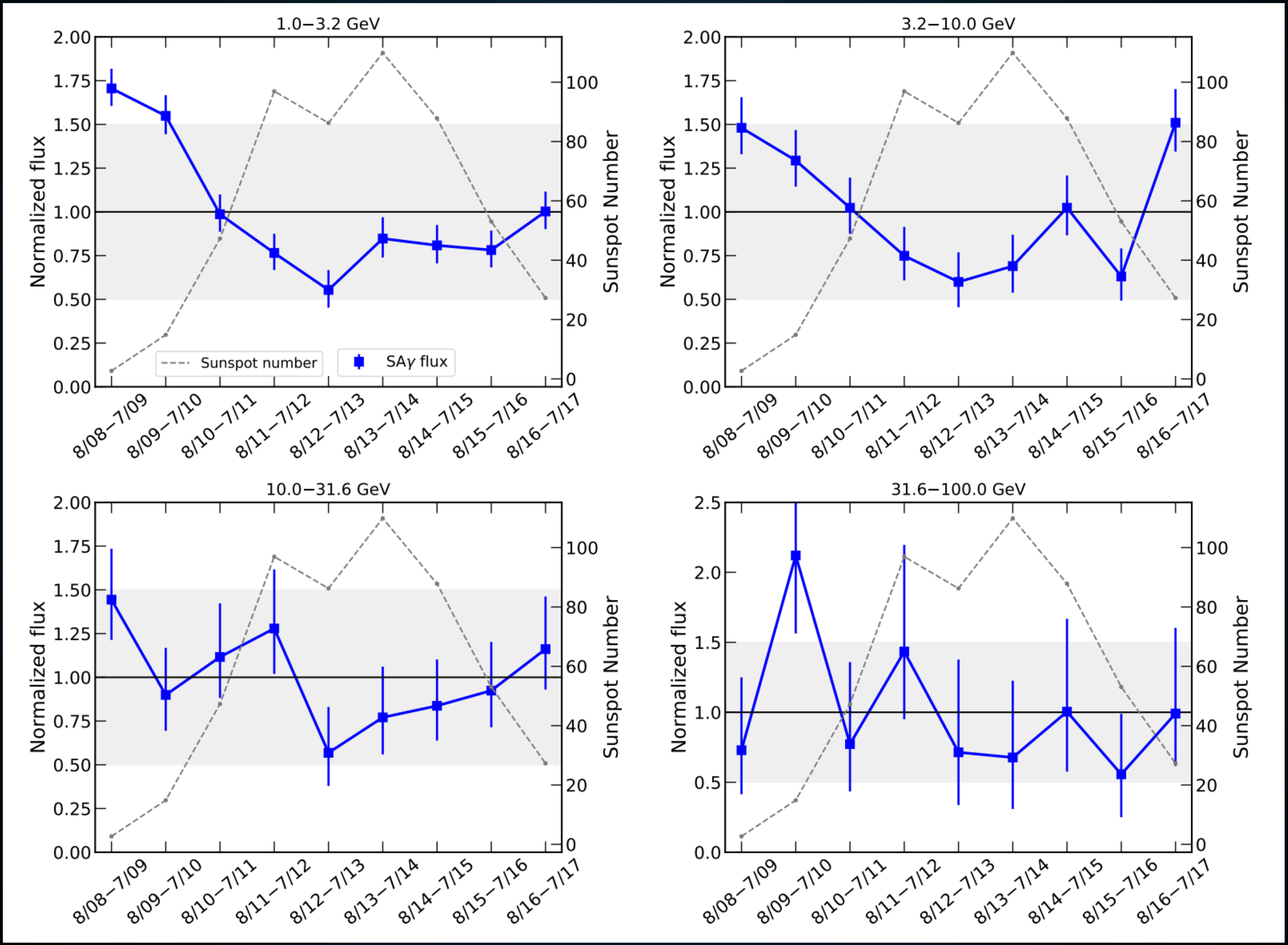
Spectrum X

OBSERVATIONS - TIME VARIABILITY



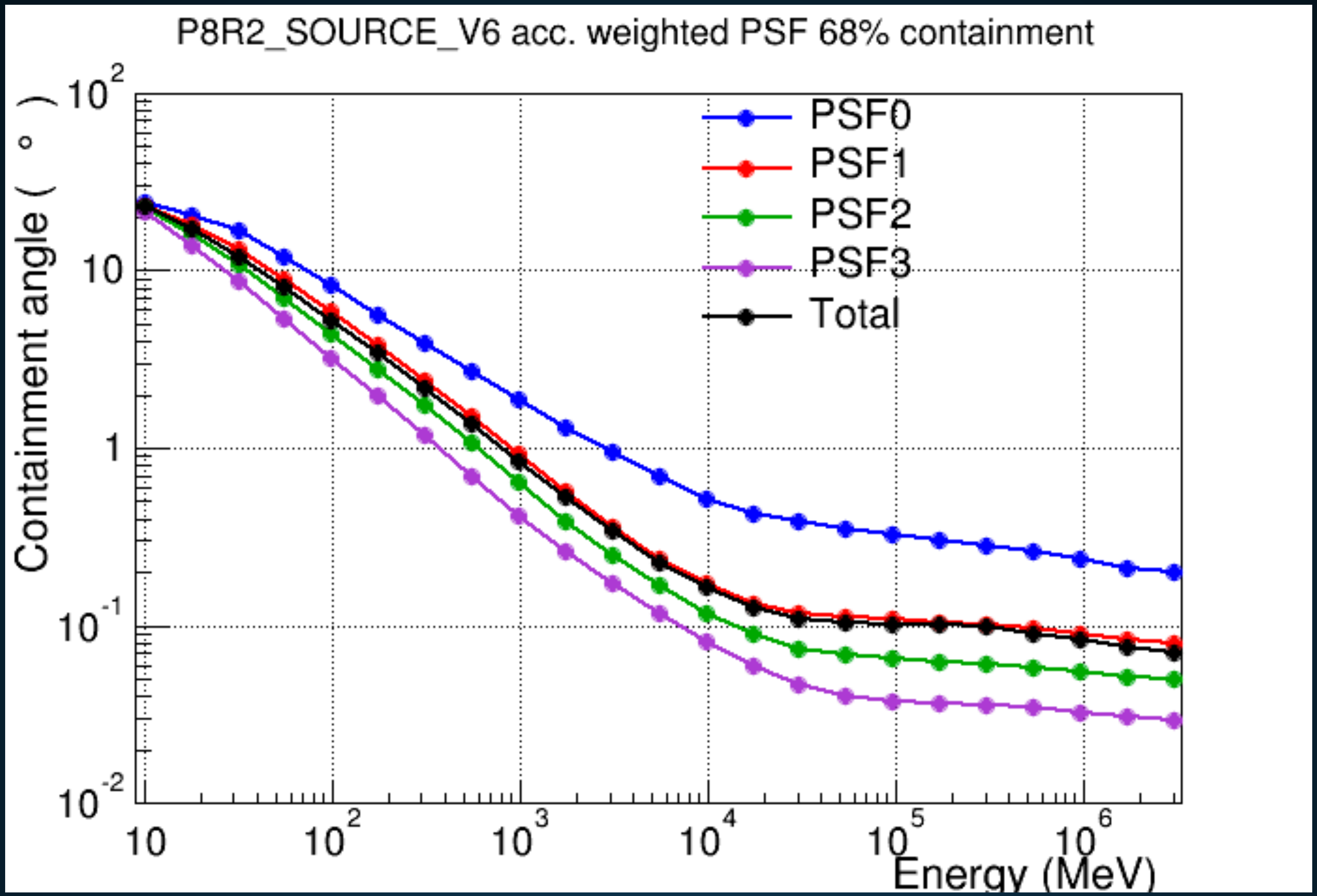
OBSERVATIONS - TIME VARIABILITY

Tang et al. 2018 (1804.06846)



Intensity	X
Spectrum	X
Time Variability	X

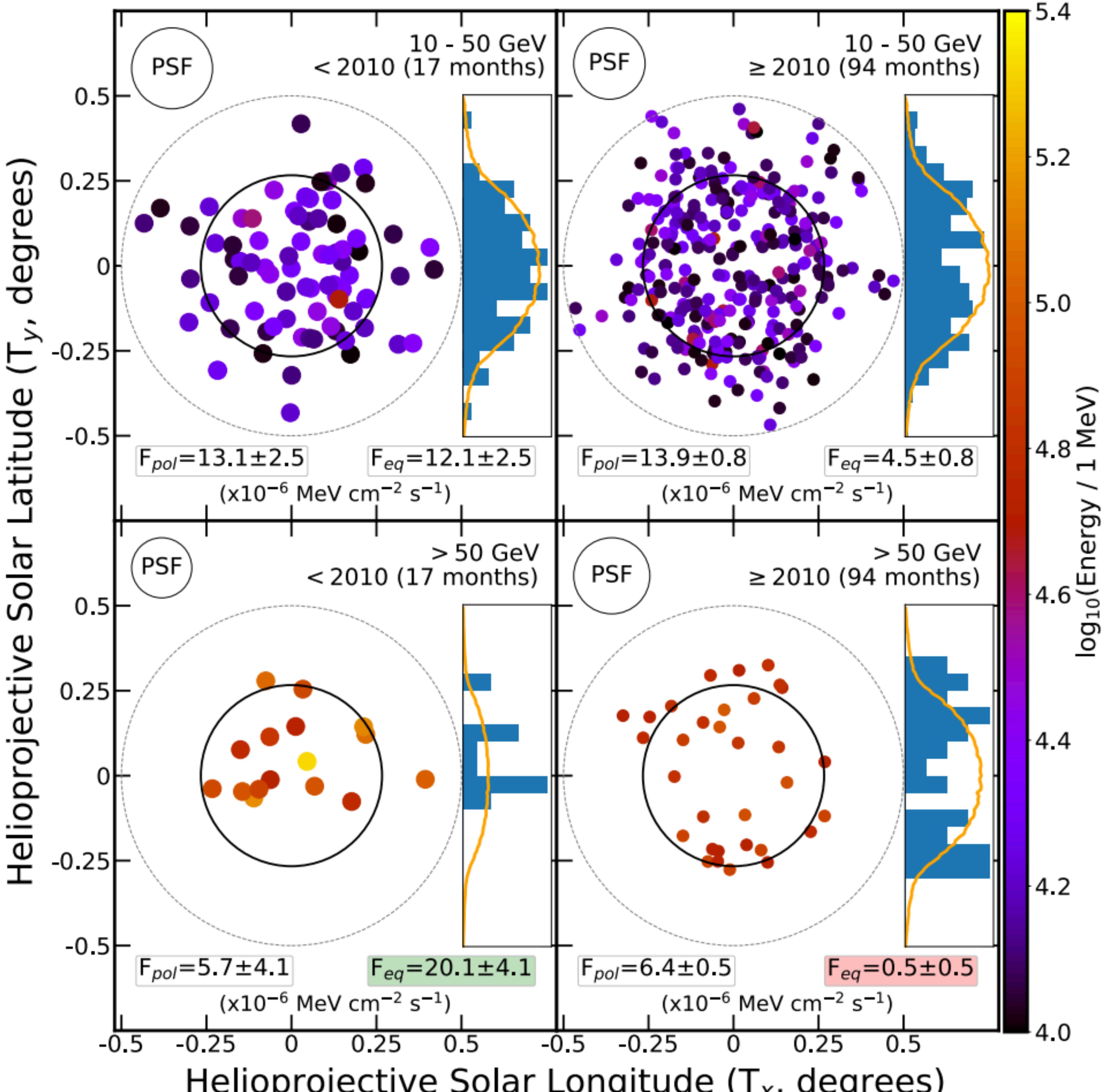
A MORPHOLOGICAL STUDY



- **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.**

[redacted]

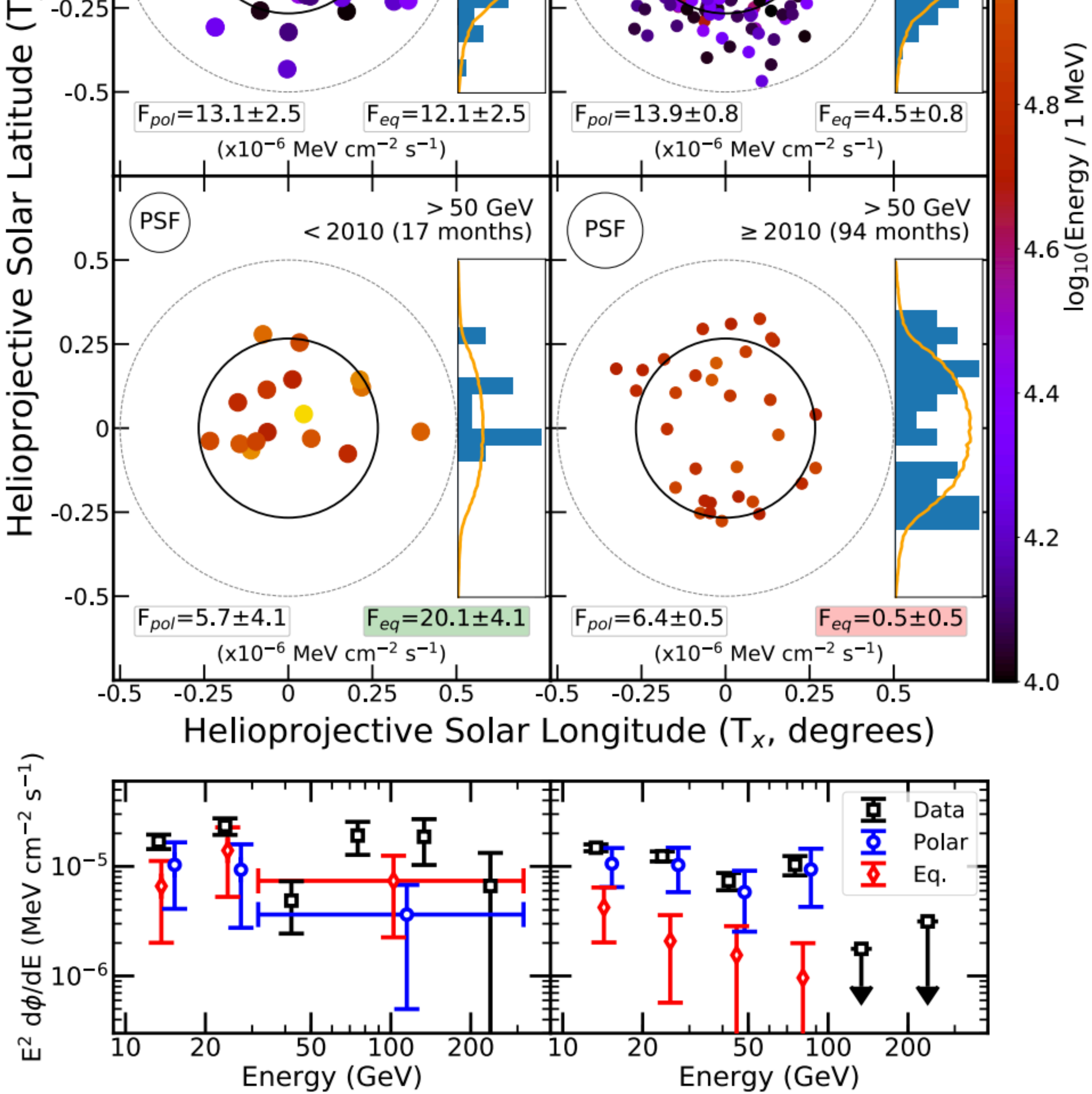
[redacted]



GAMMA-RAYS - WHAT?

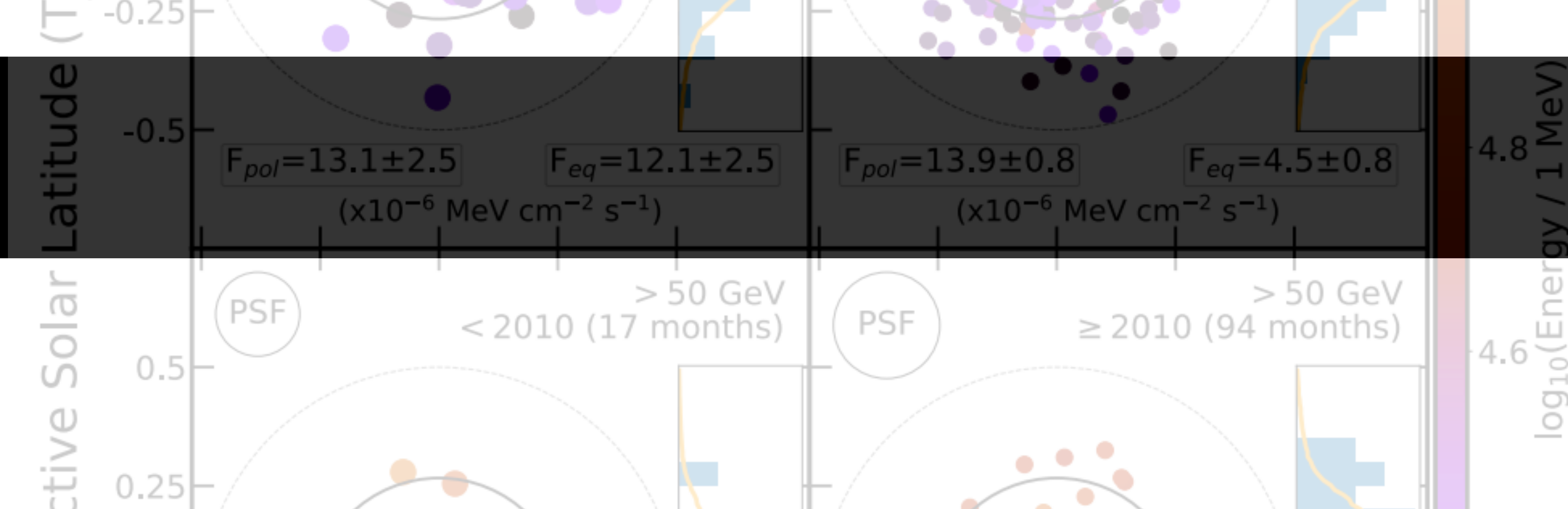
Intensity	X
Spectrum	X
Time Variability	X
Morphology	X

[redacted]

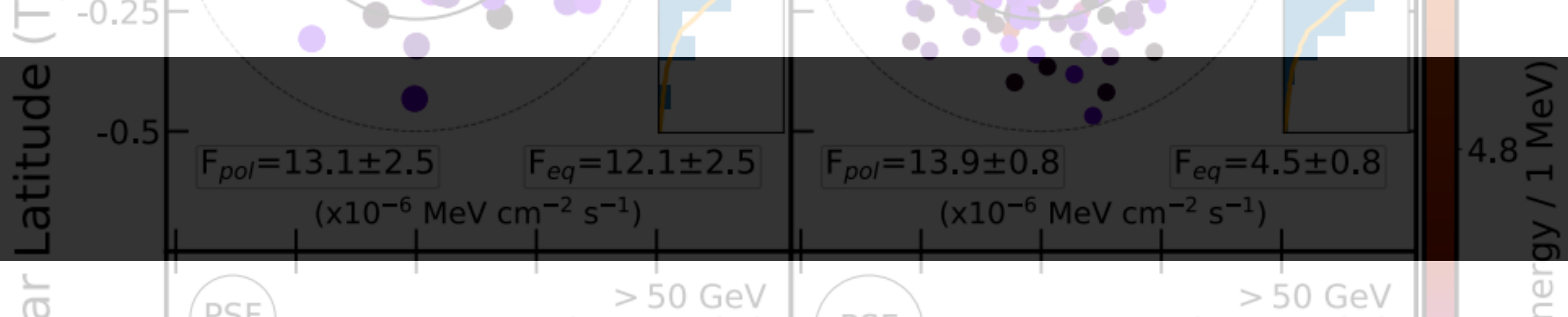


[redacted]

[redacted]



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



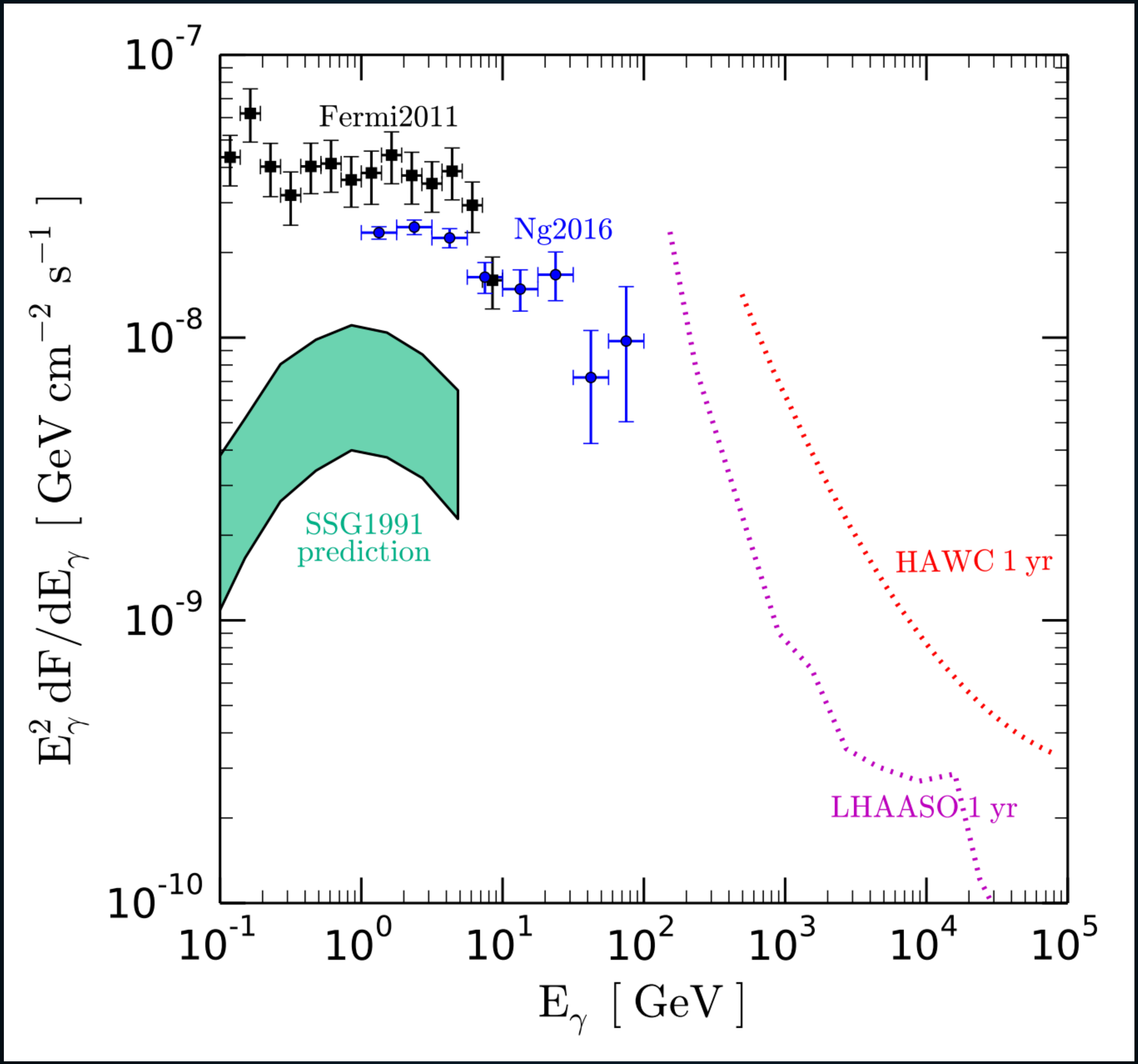
A New Event!—While finalizing this letter, we found a new >100 GeV event. Observed on February 13, 2018 at 17:49:15 UTC, the event has an energy of 162 GeV, is located 0.36° from the solar center, passes the UltraCleanVeto event selection, and belongs to the PSF0 and EDISP3 event classes. As we re-enter 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 - WHAT?

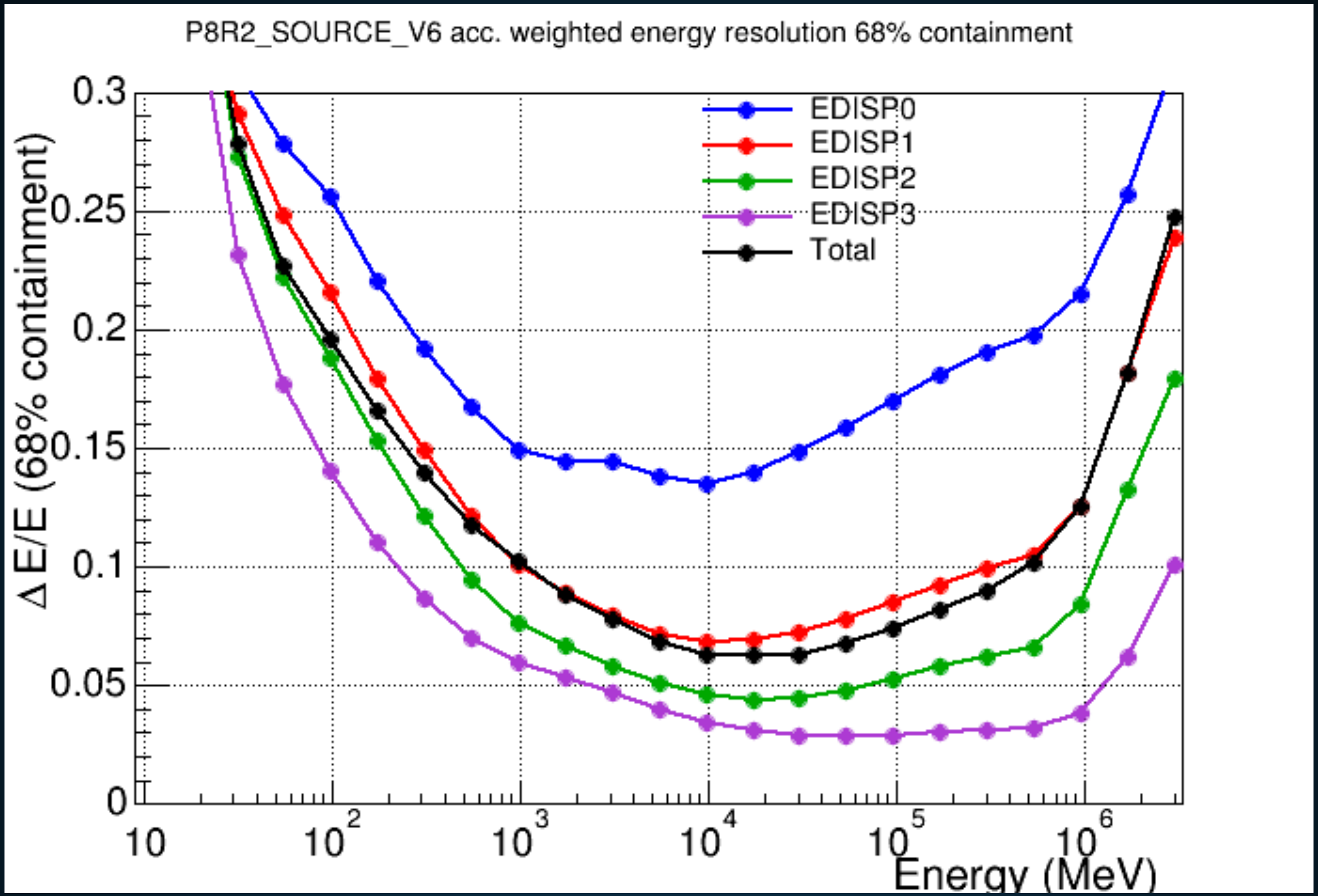
Intensity	X
Spectrum	X
Time Variability	X
Morphology	X
Spectral Variability	X

GAMMA-RAYS - SPECTRAL DIP

Zhou et al. (1612.02420)



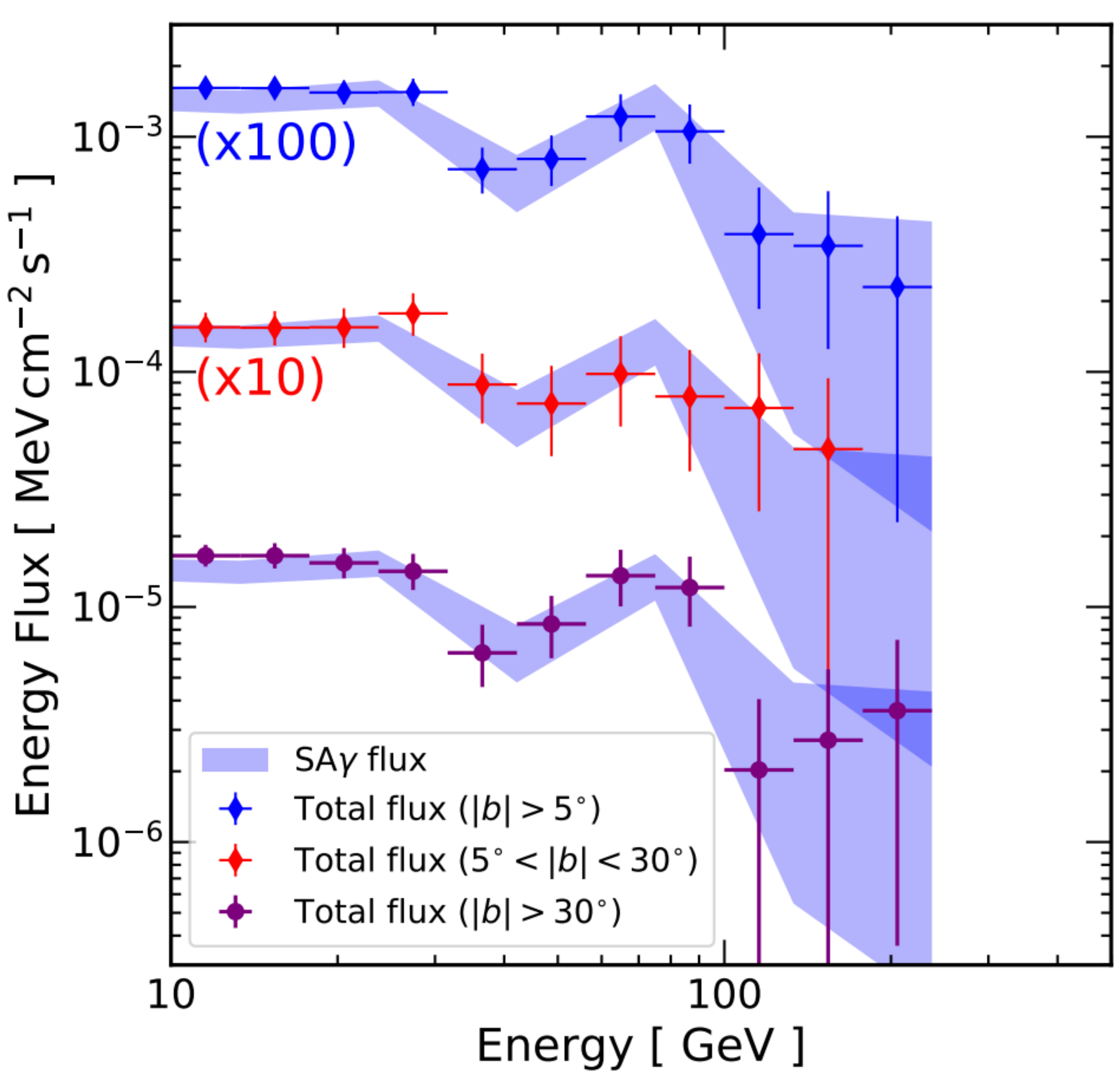
A SPECTRAL STUDY

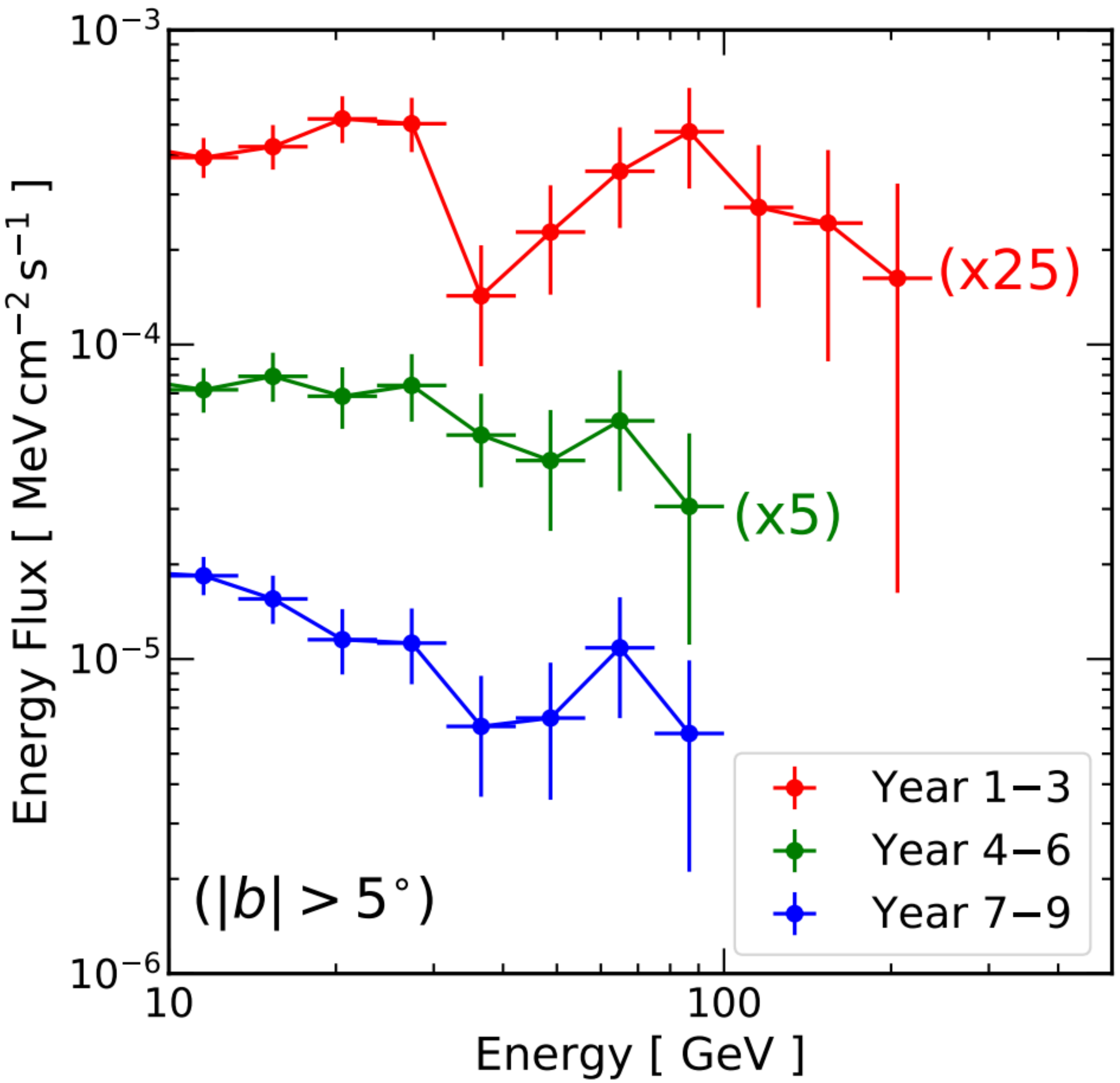


- **Examine 9 years of gamma-ray data.**
- **Utilize all events more than 5º from the Galactic plane**
- **Convolve each event with a best-fit energy dispersion.**

GAMMA-RAYS - SPECTRAL DIP

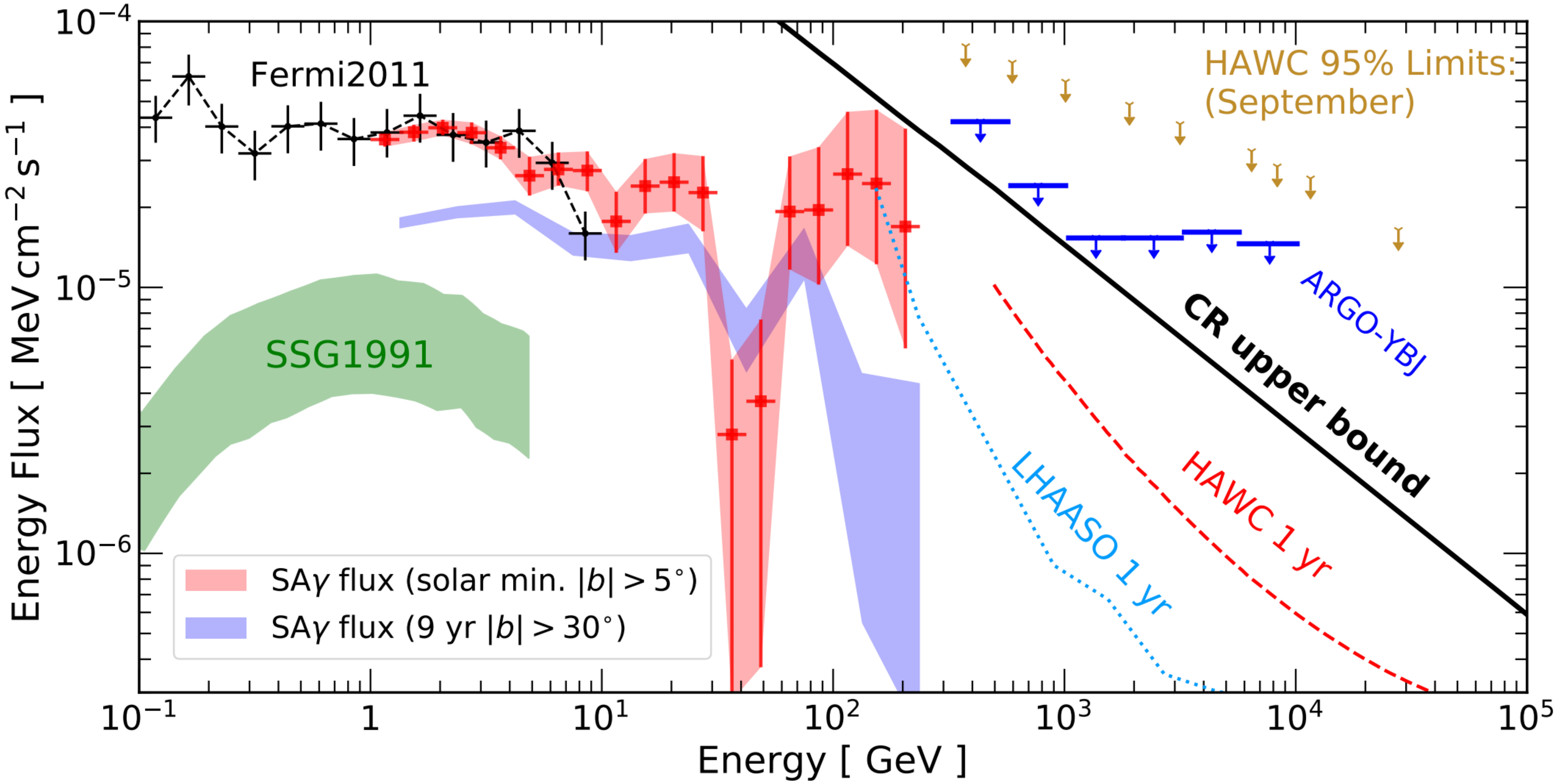
Tang et al. 2018 (1804.06846)





GAMMA-RAYS - SPECTRAL DIP

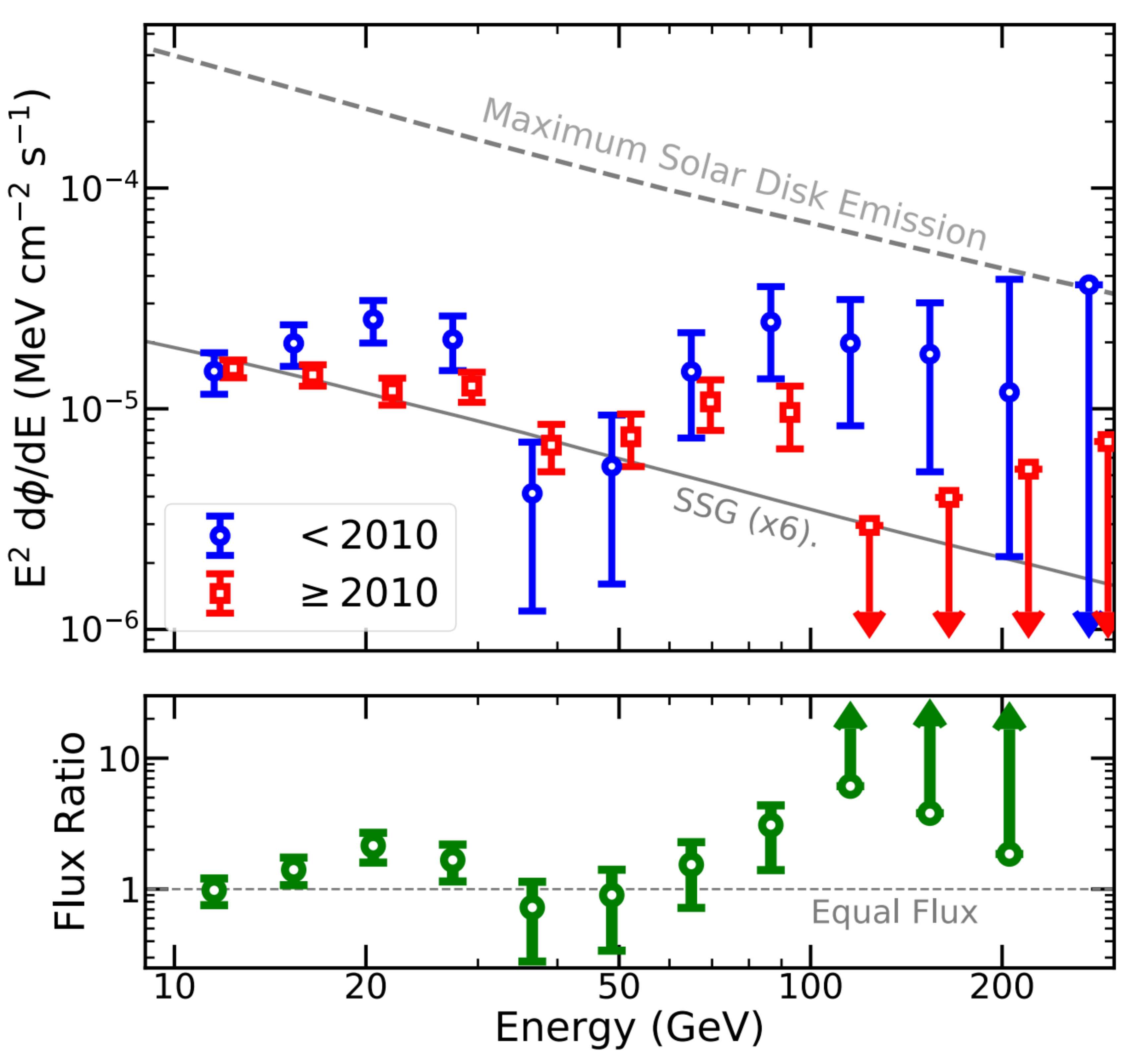
Tang et al. 2018 (1804.06846)



GAMMA-RAYS - WHAT?

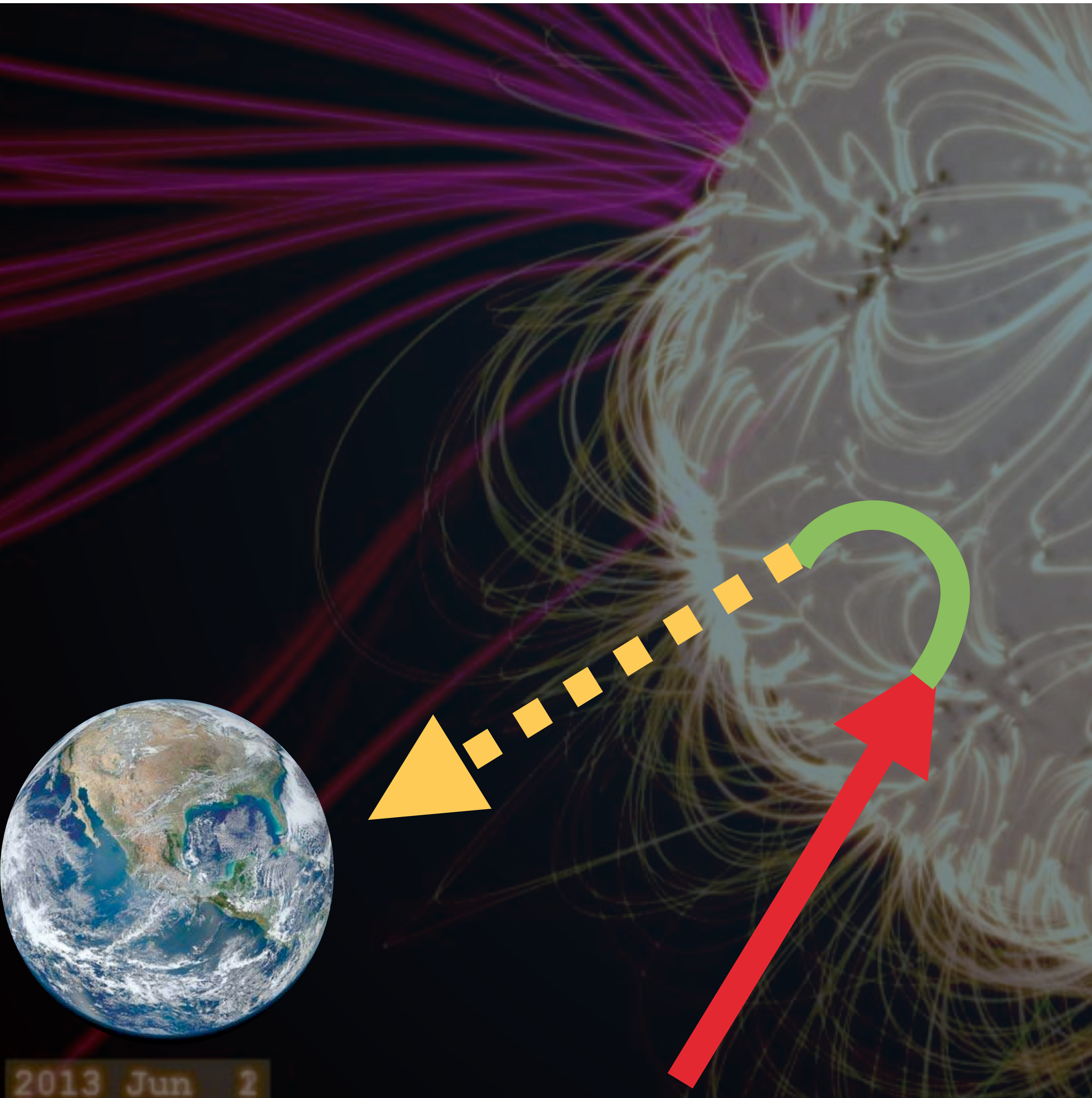
Intensity	X
Spectrum	X
Time Variability	X
Morphology	X
Spectral Variability	X
Spectral Dip?	X

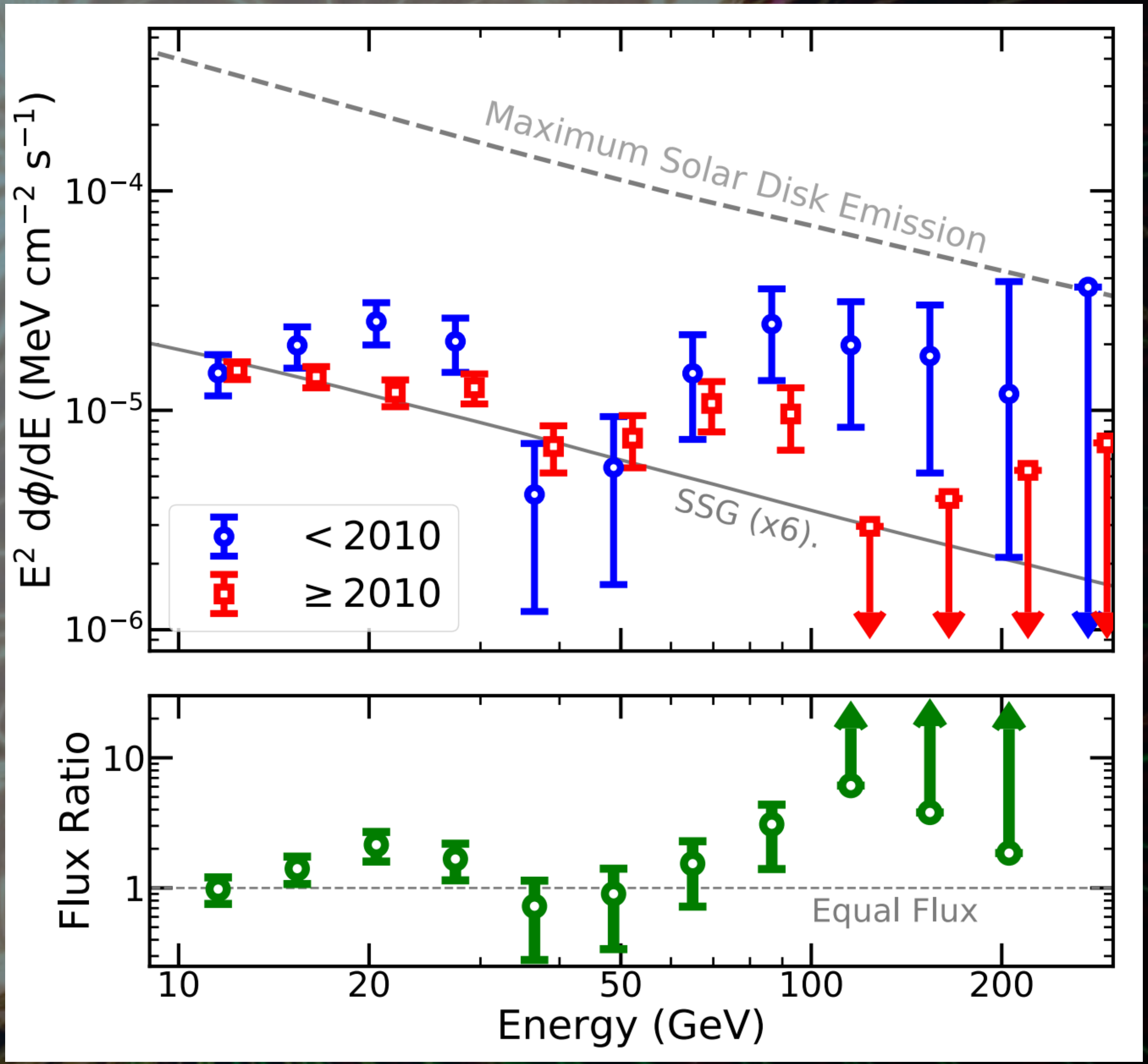
- **Gamma-Ray Emission much brighter than expected**



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

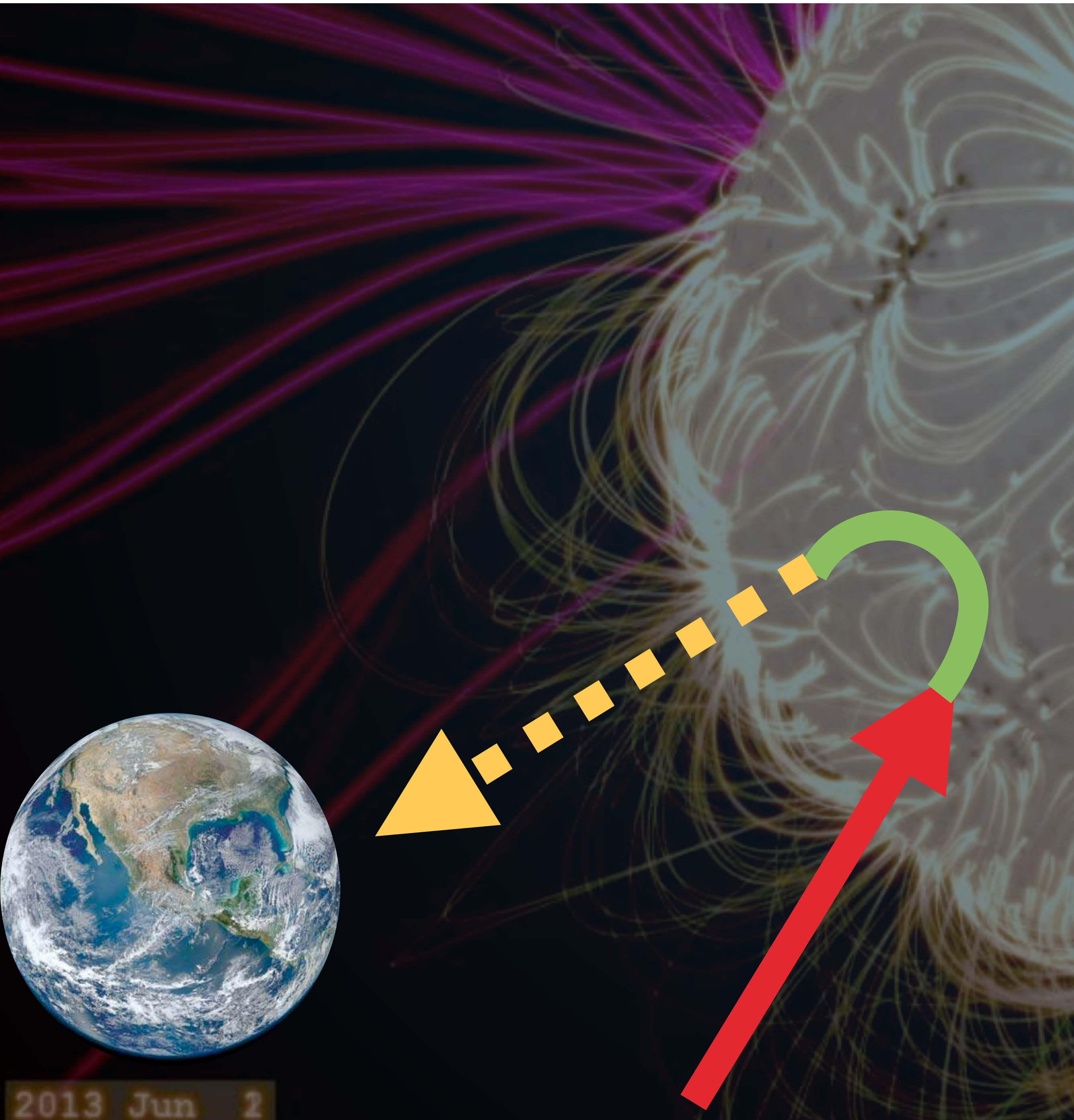
$$\Phi_\odot(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

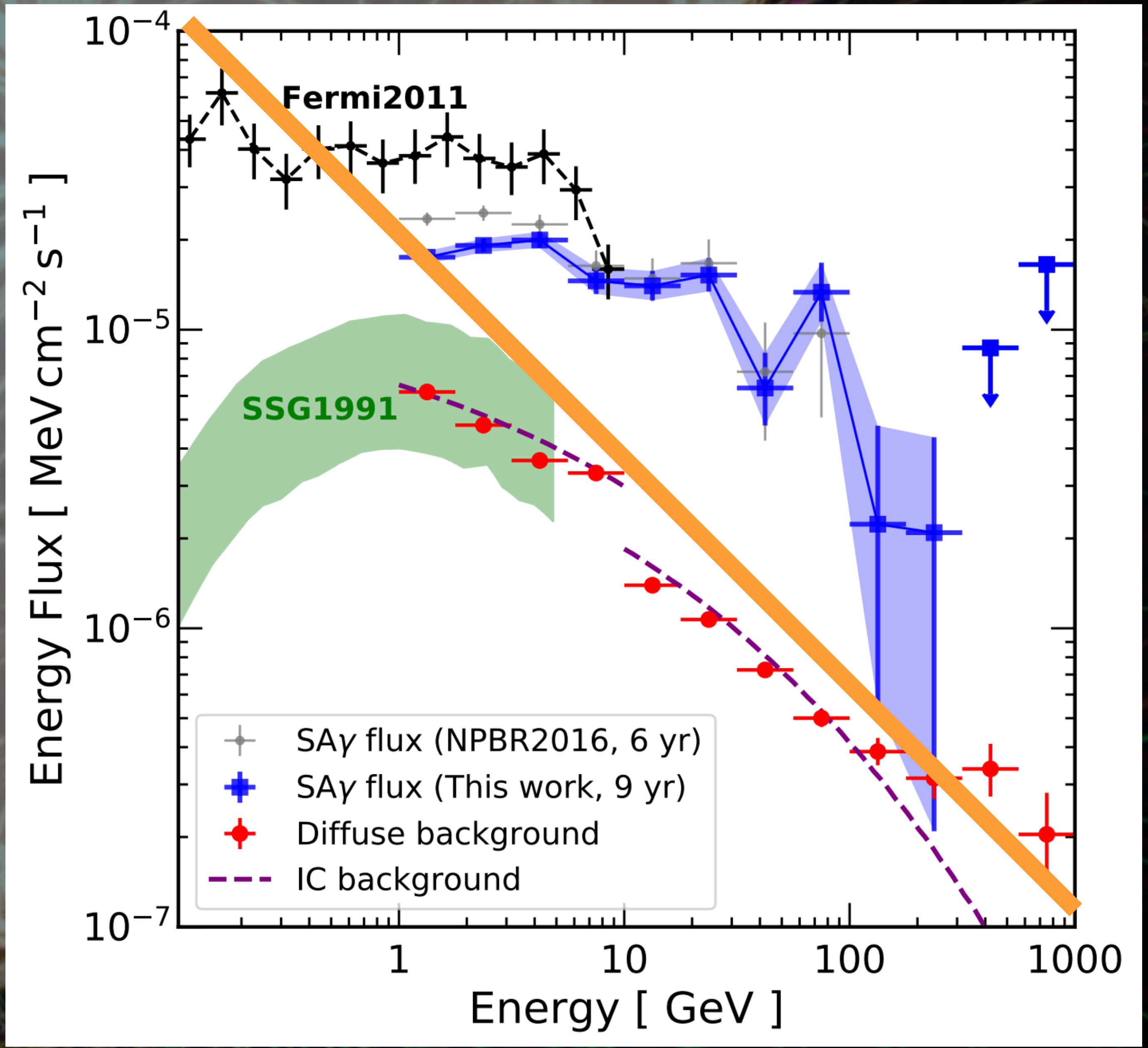




- **Gamma-Ray spectrum much harder than expected**

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

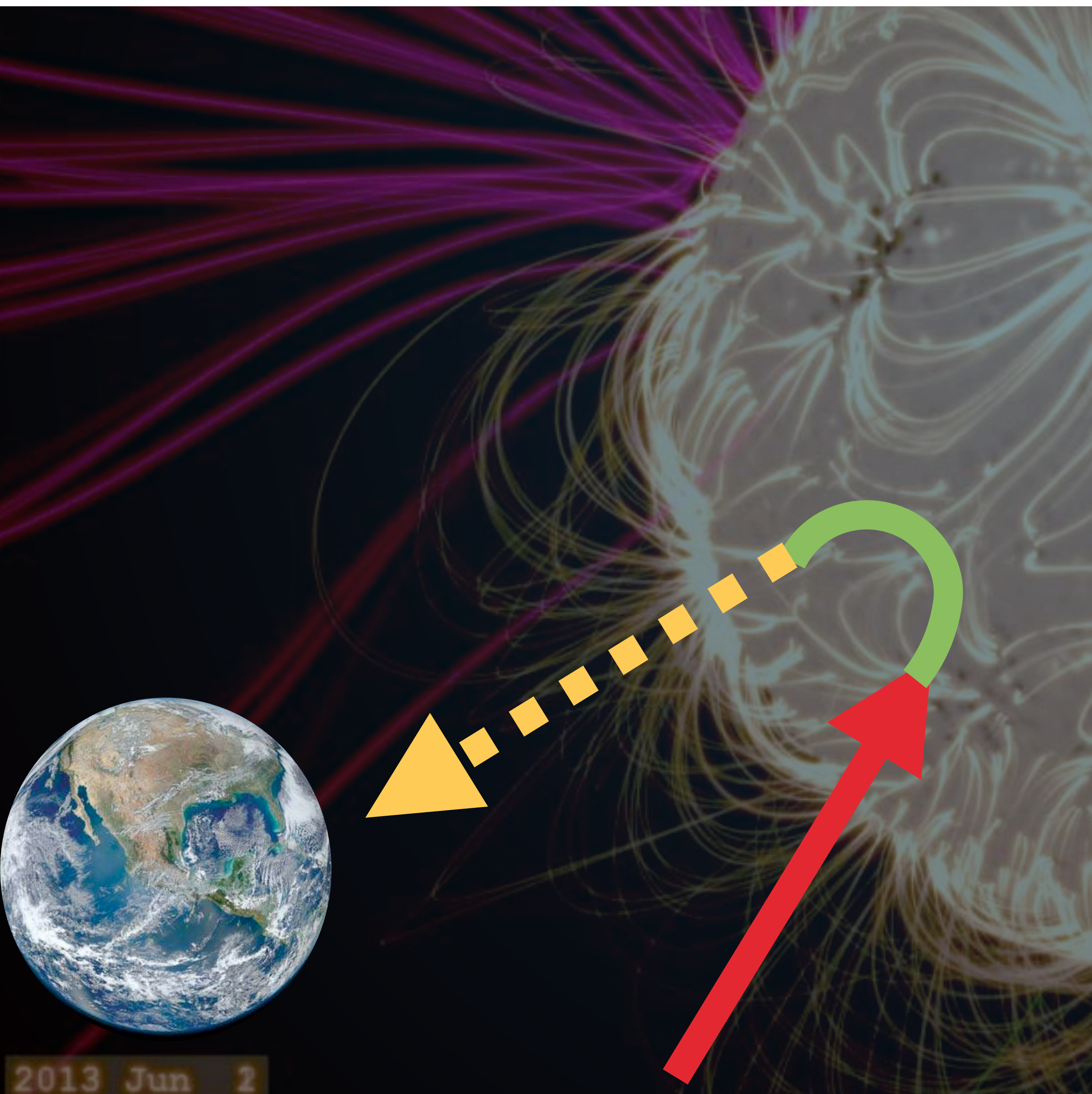


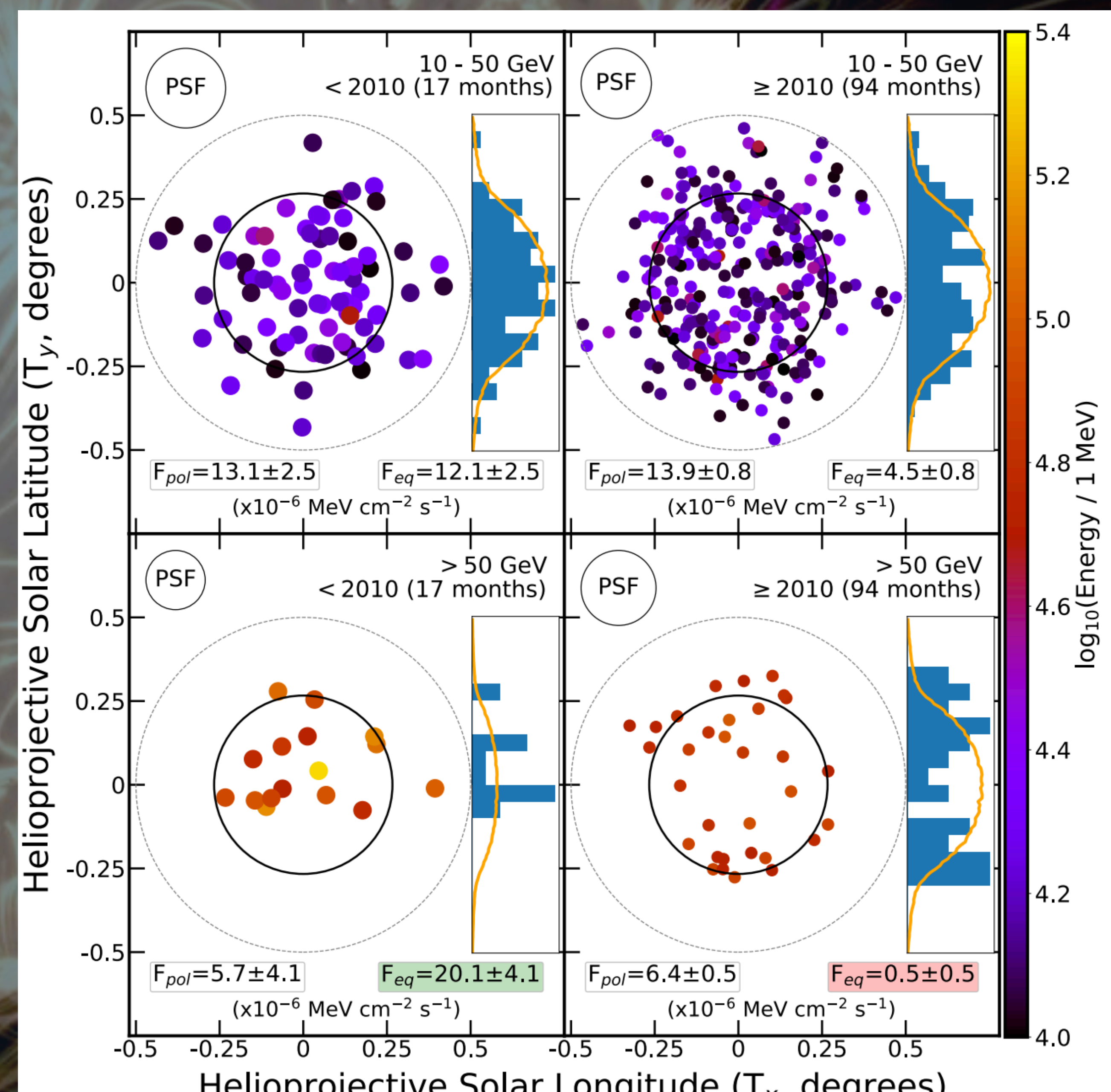


GAMMA-RAYS - HOW?

- **Gamma-Ray morphology not uniform**

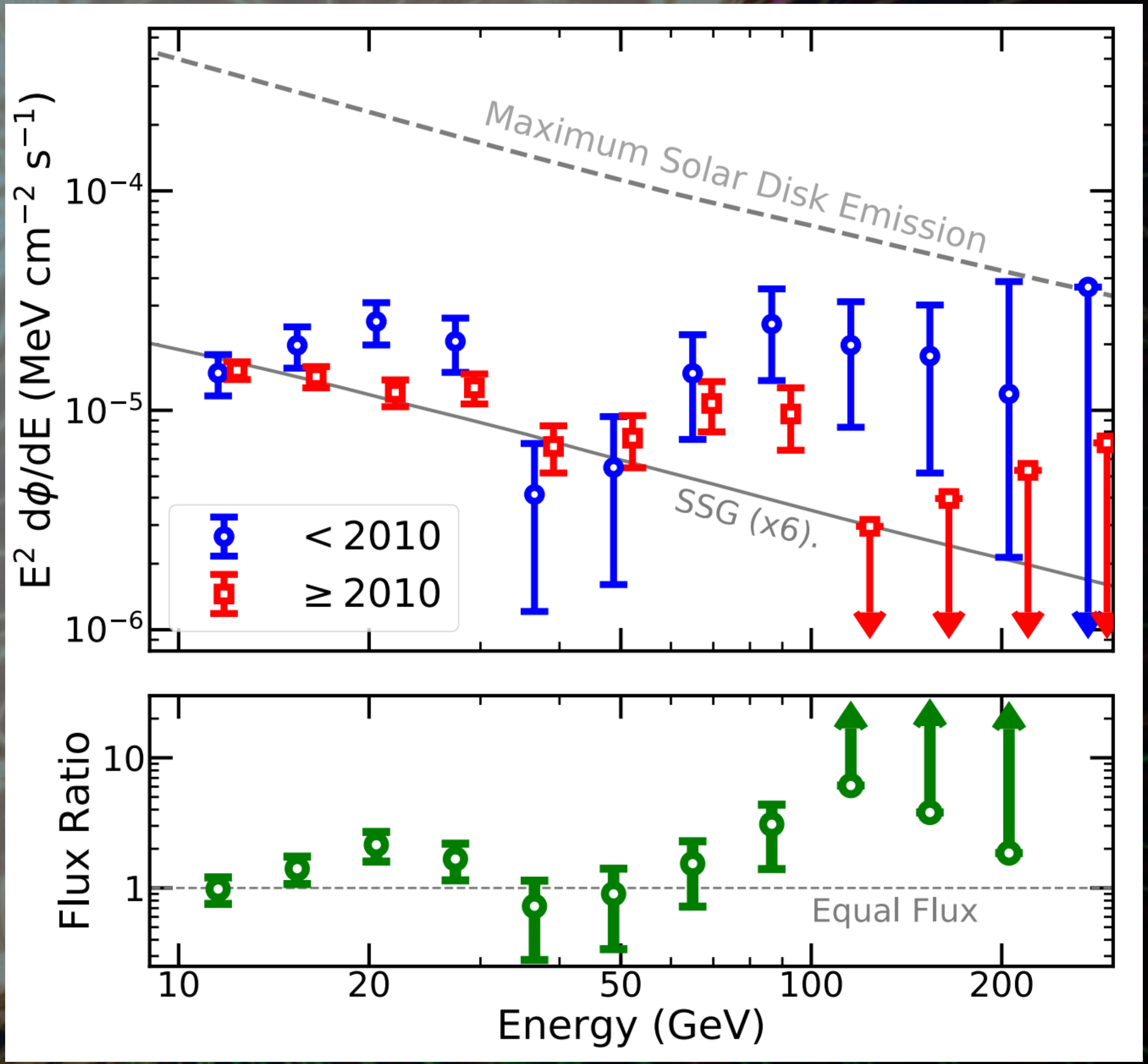
$$\Phi_{\odot}(E_\gamma) = \pi R_{\odot}^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$

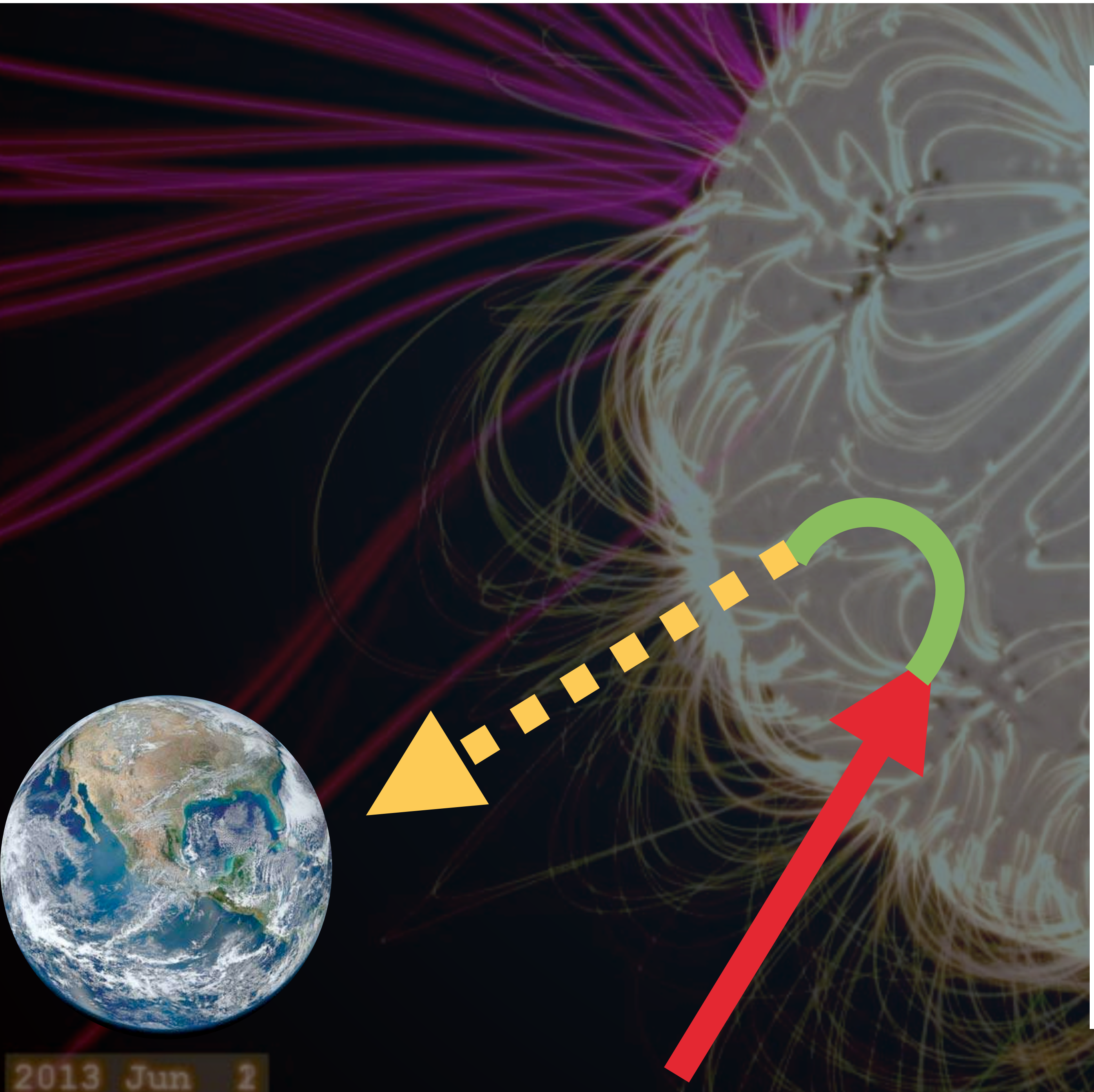




- **Evidence for two different emission mechanisms?**

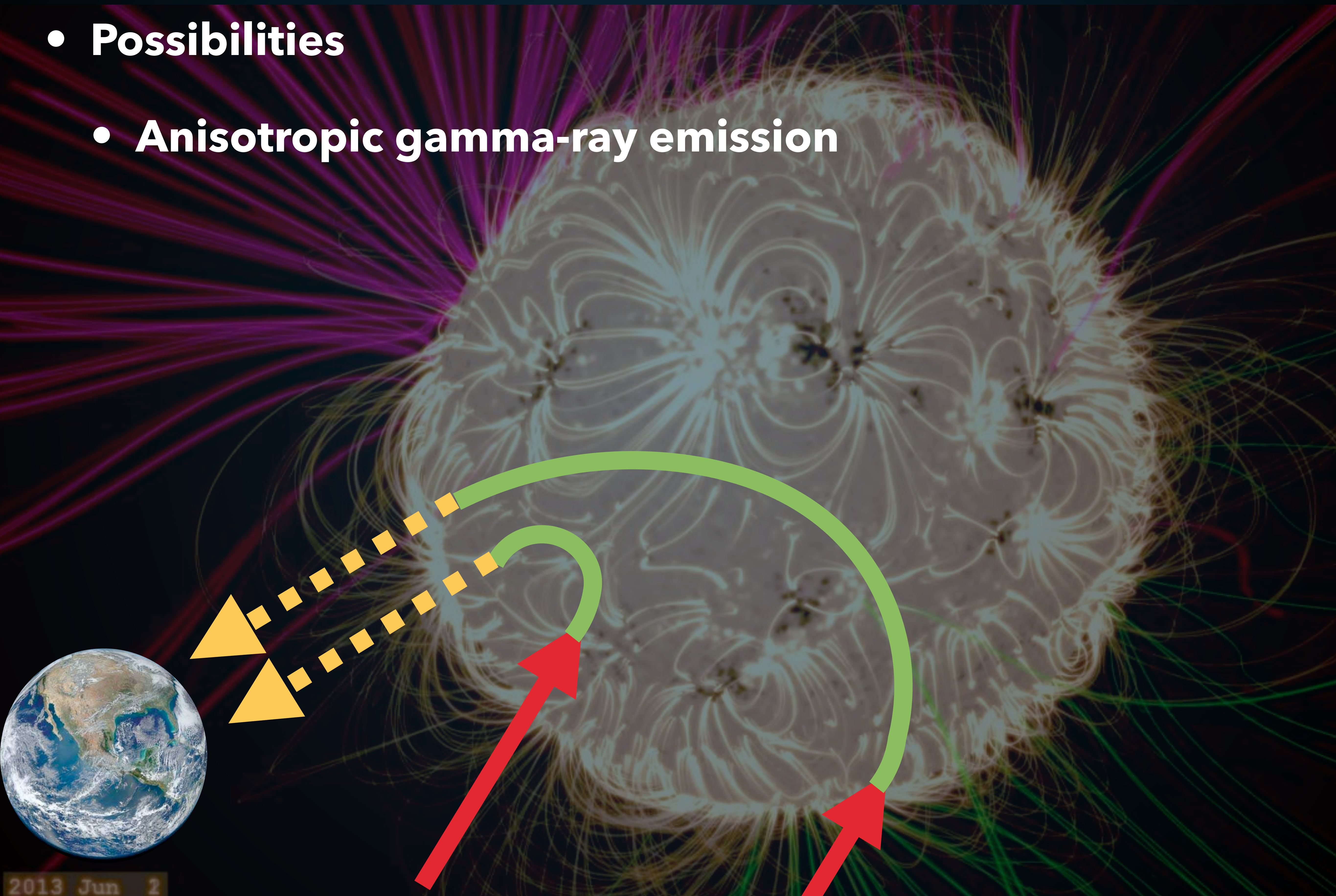
$$\Phi_{\odot}(E_\gamma) = \pi R_\odot^2 \Phi_{\rm CR}(E_{\rm CR}) C(E_\gamma, E_{\rm CR}) f_{\rm sur} f_{\rm turn} f_{\rm int}$$



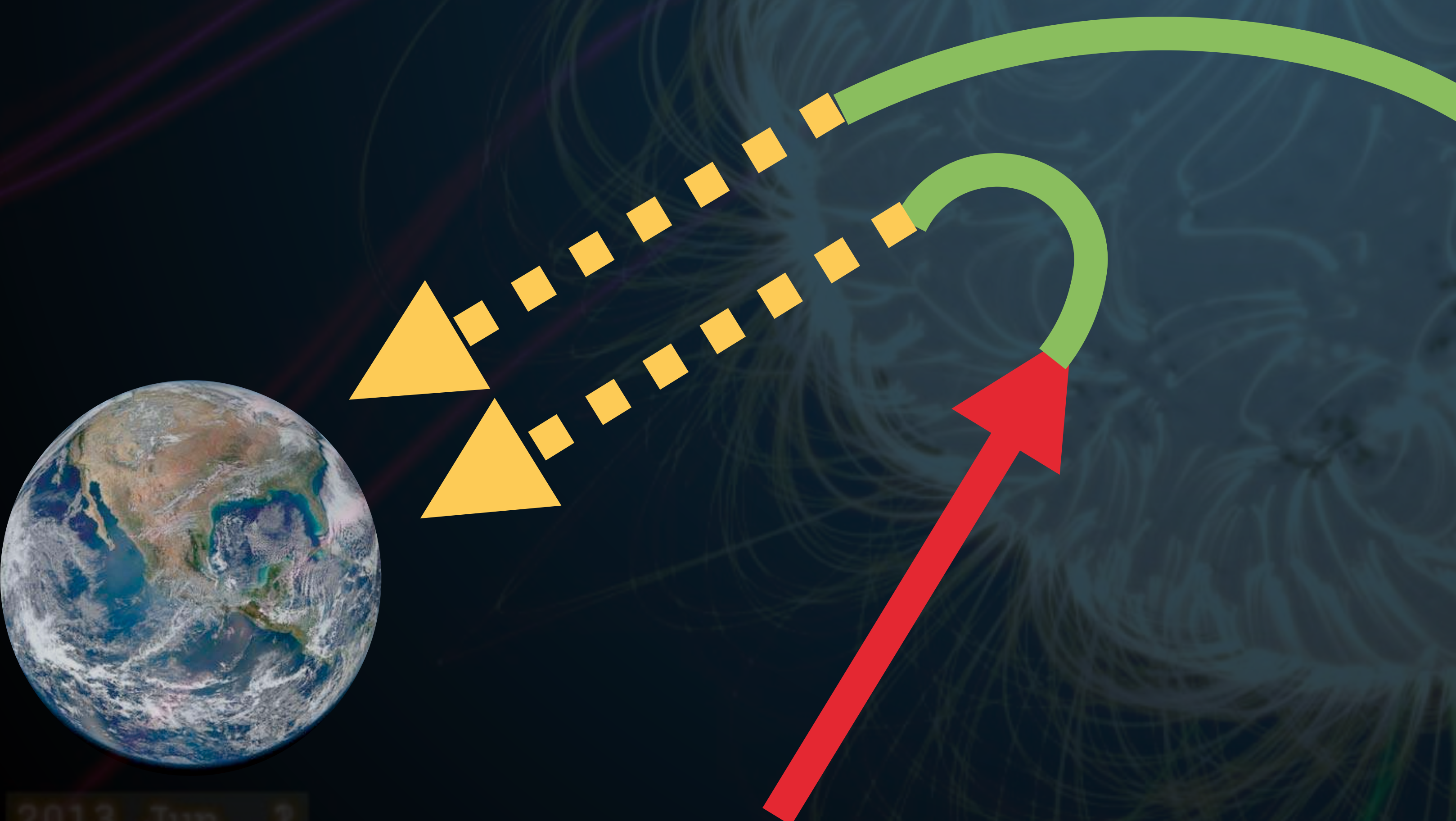


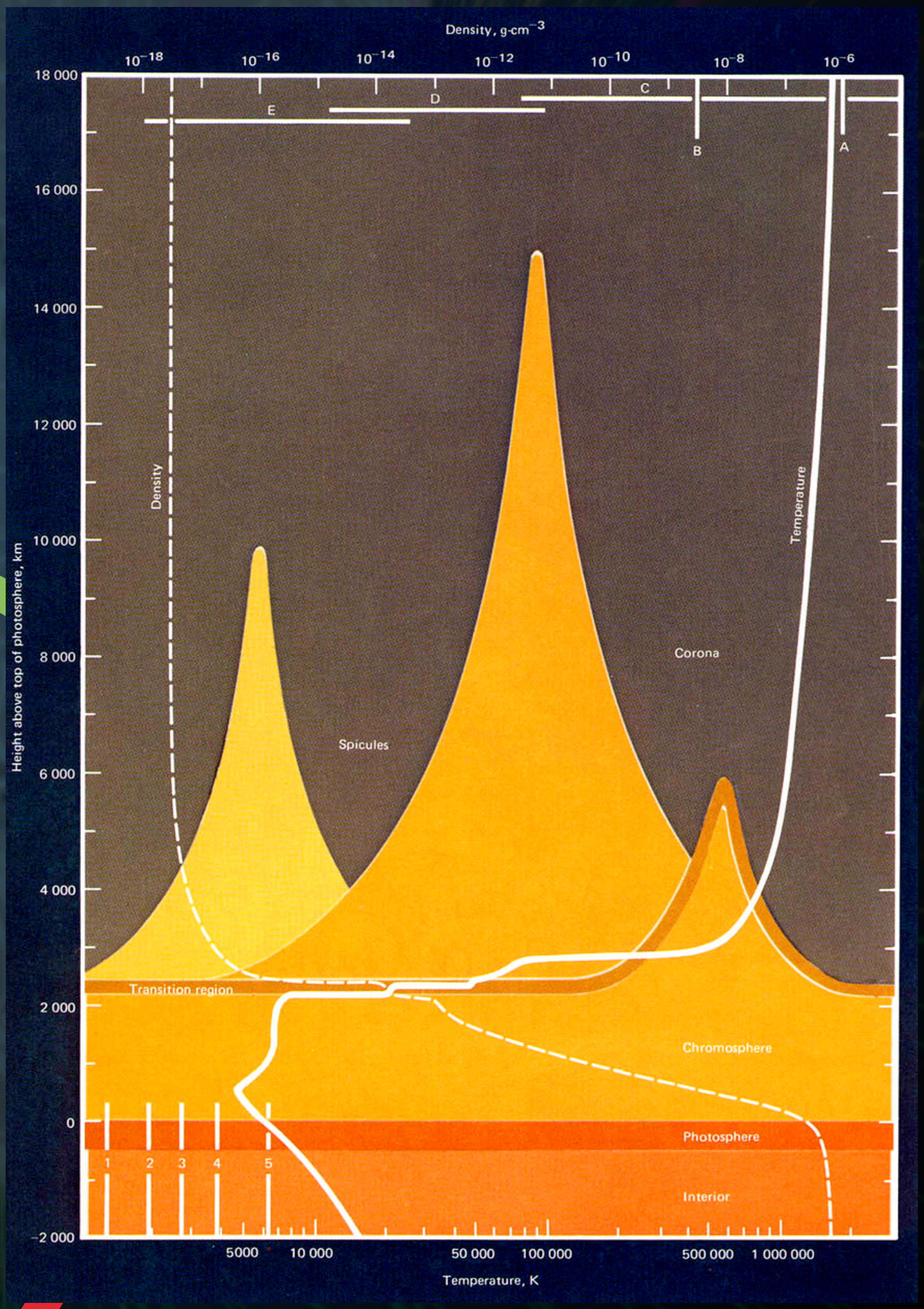
GAMMA-RAYS - HOW?

- **Possibilities**
  - **Anisotropic gamma-ray emission**

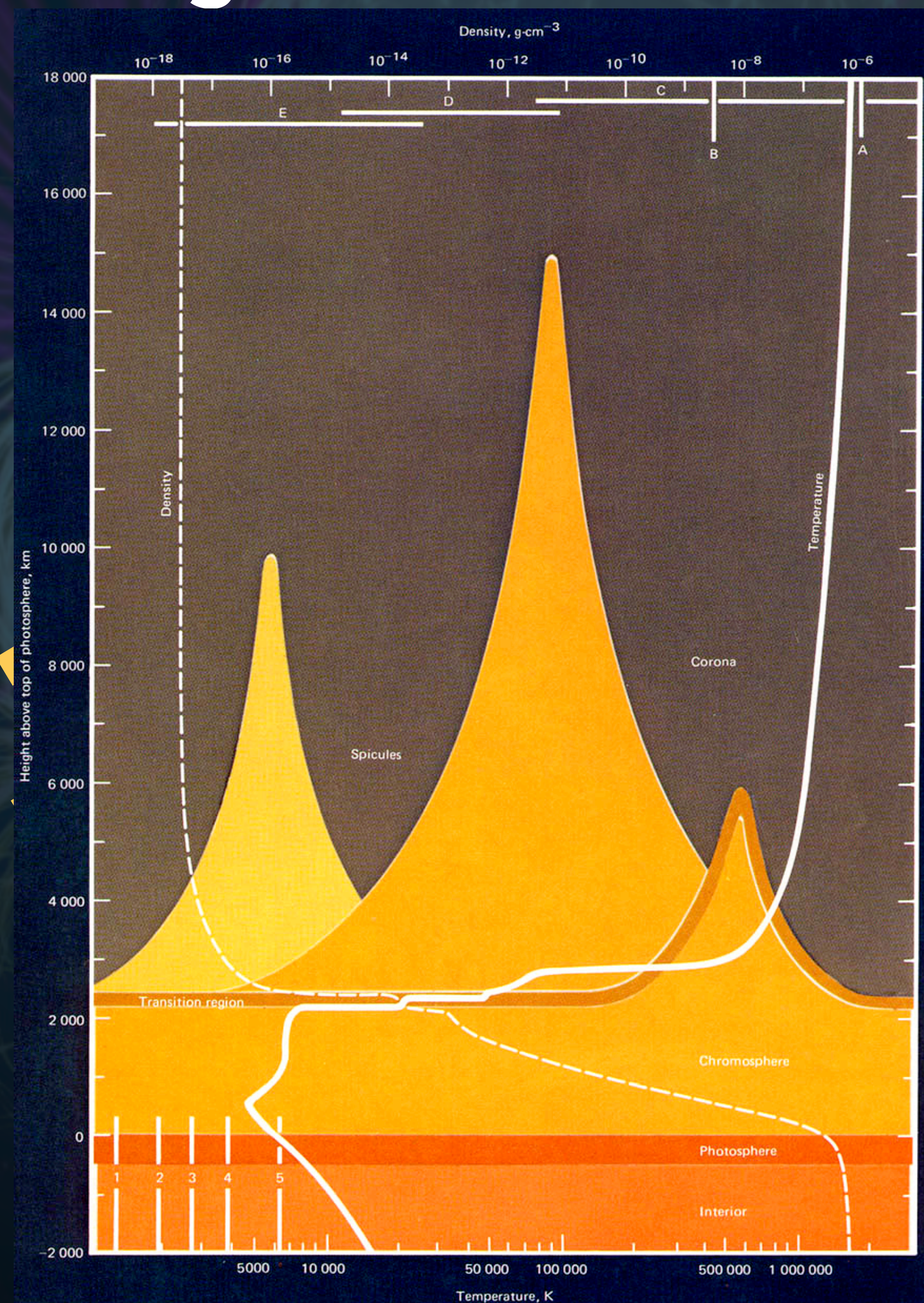


- Possibilities
  - Anisotropic gamma-ray emission



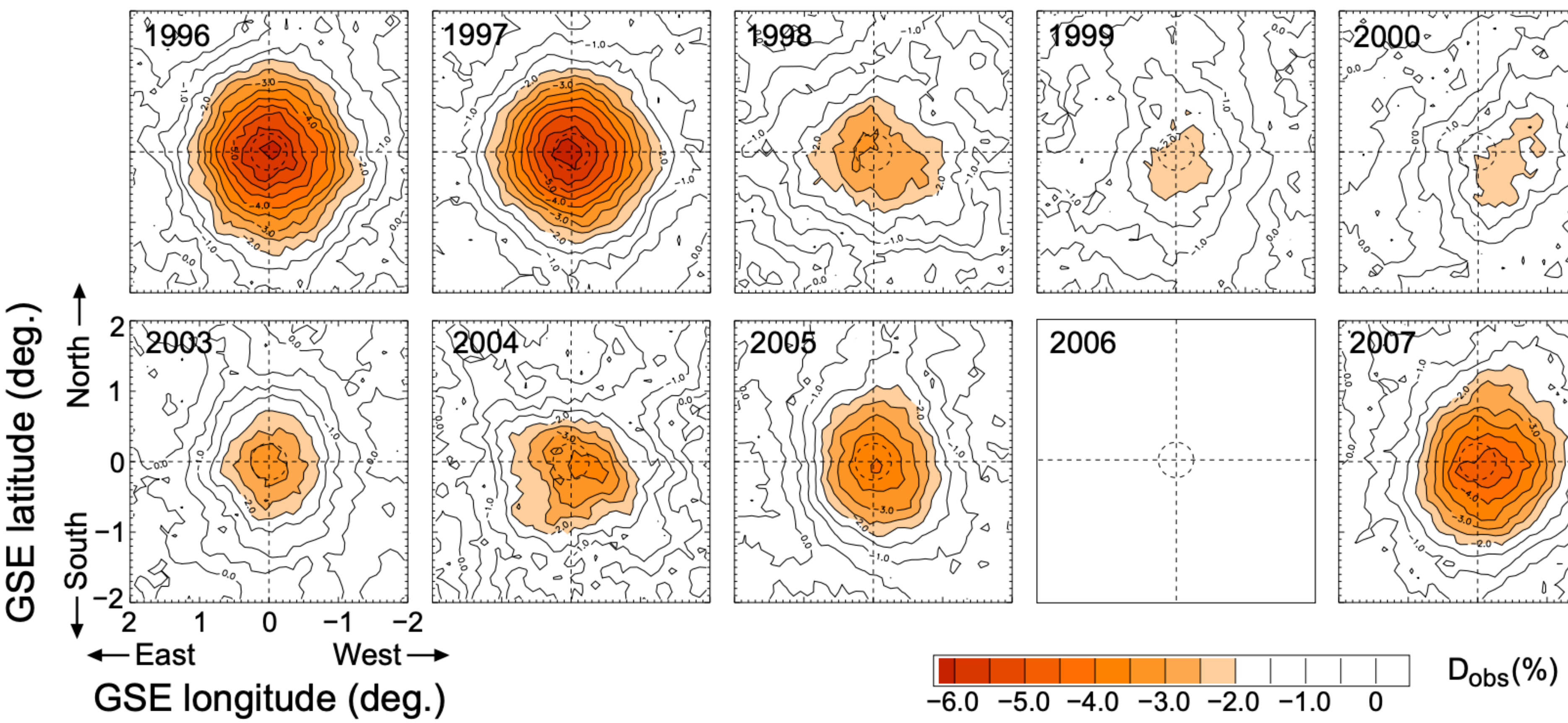


- **Possibilities**
  - **Cosmic-Ray Storage**

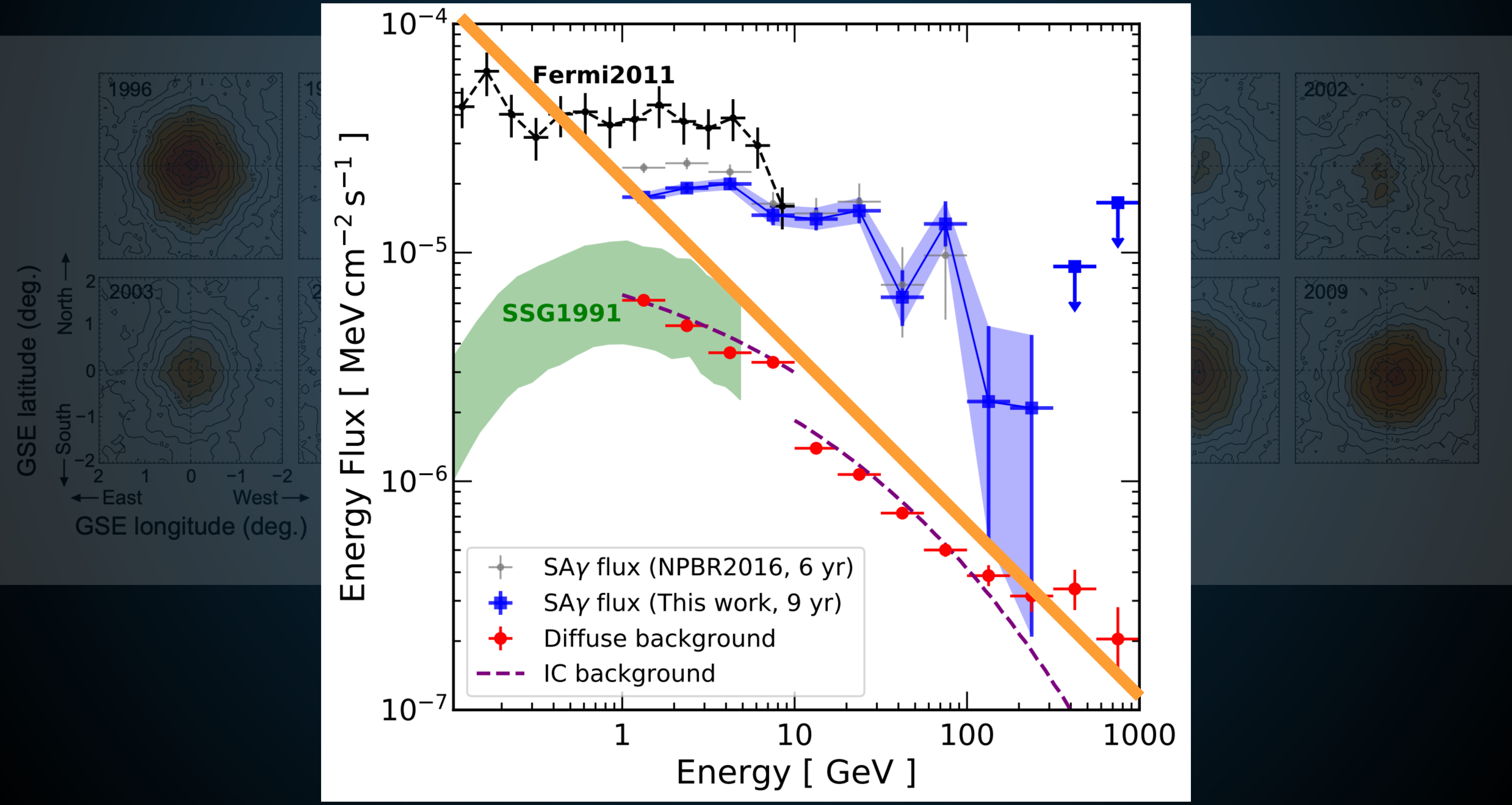


Tibet Array (2013; 1306.3009)

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

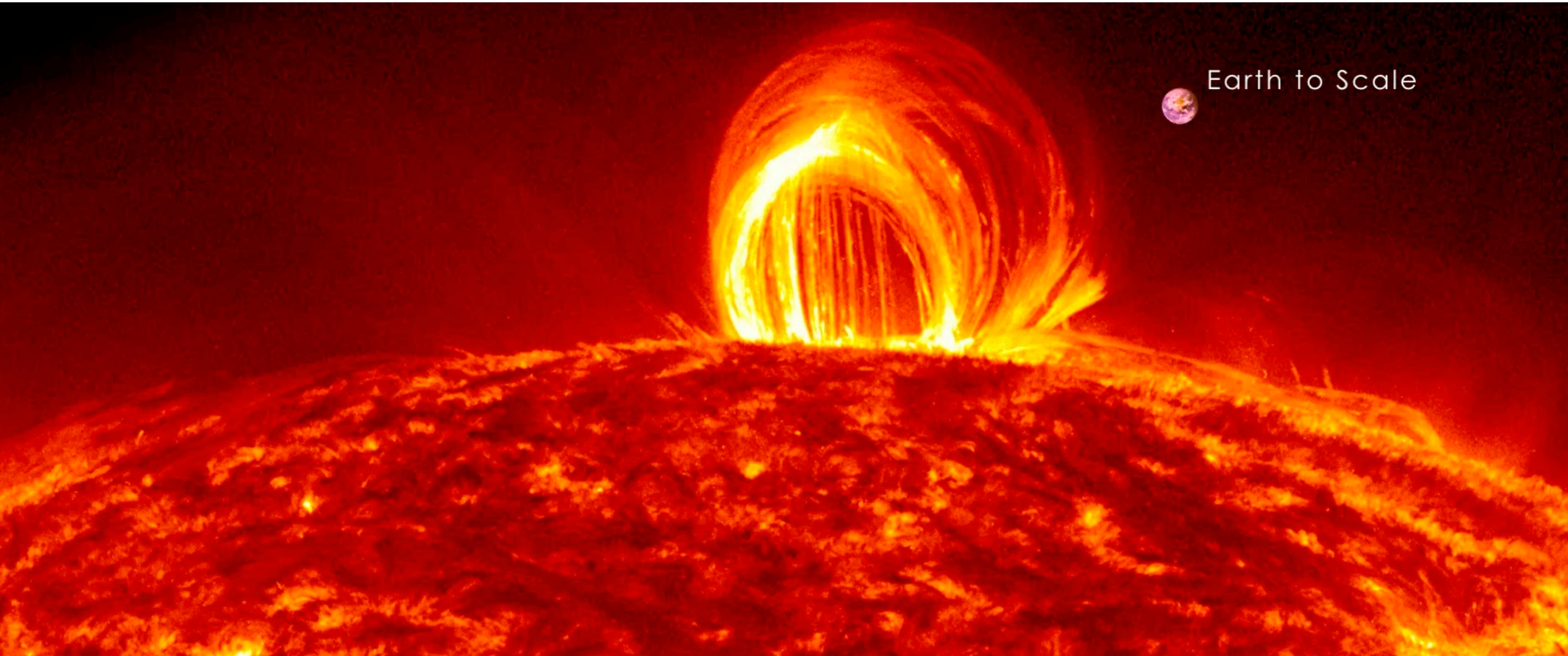


- **Possibilities**
  - **Solar Magnetic Fields Draw in Cosmic-Rays**

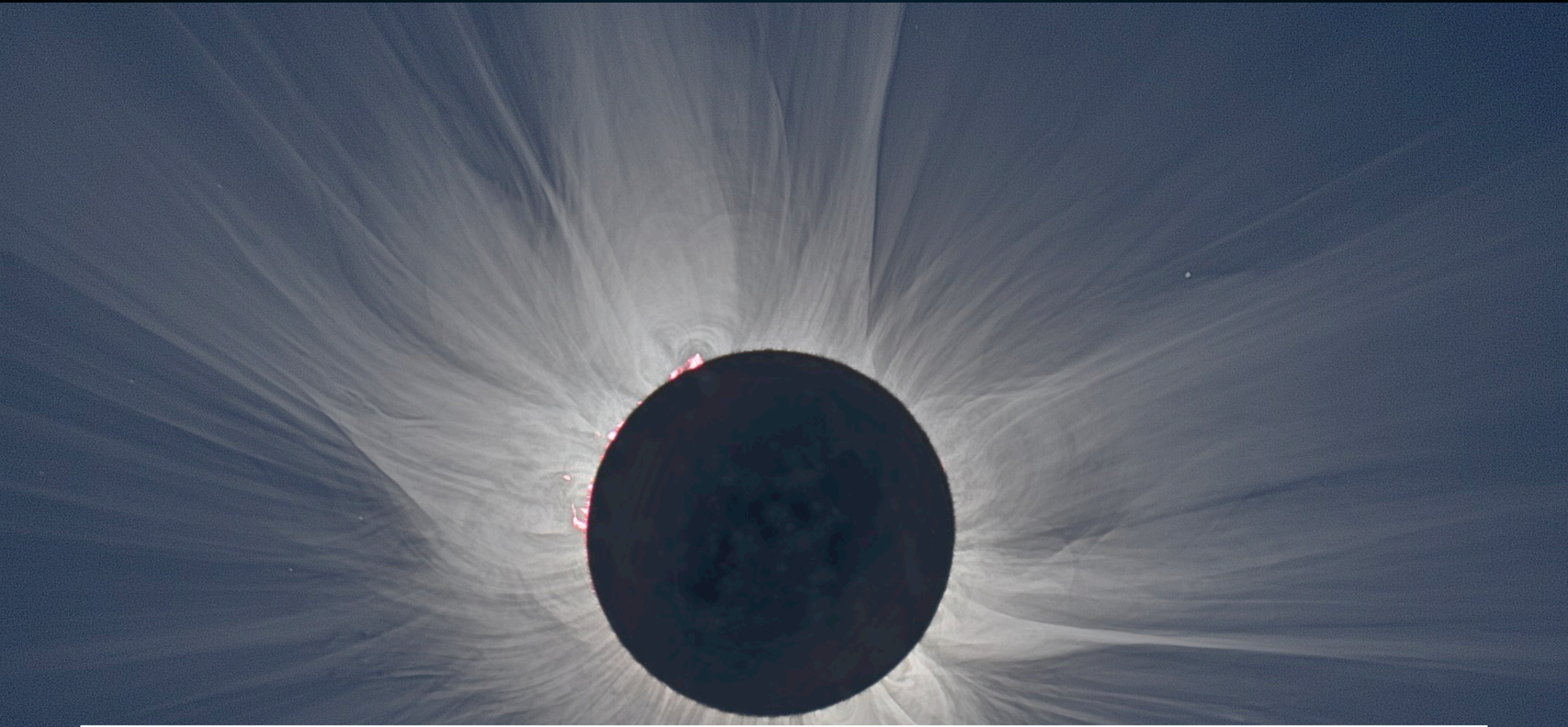


GAMMA-RAYS - HOW?

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

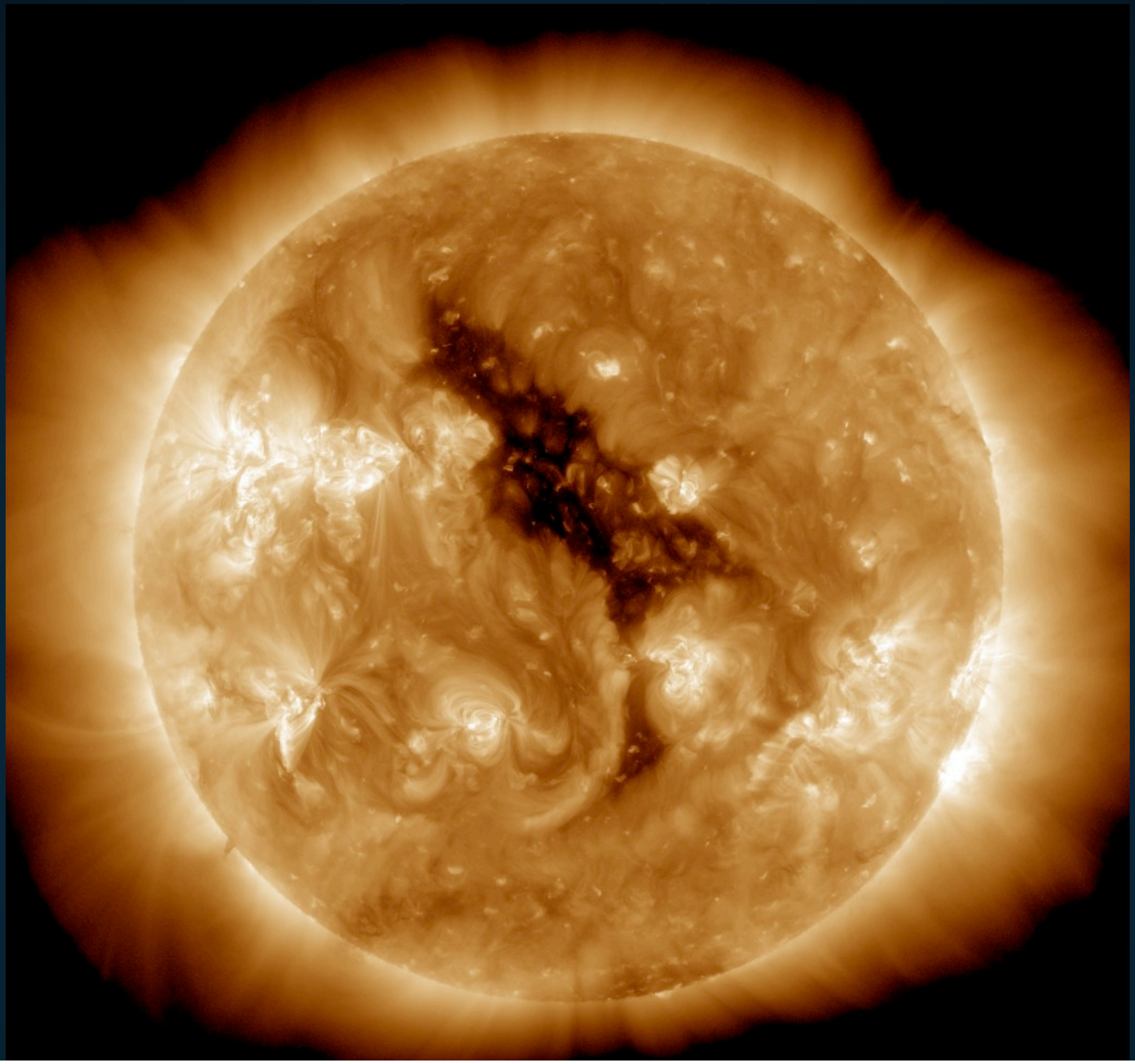


GAMMA-RAYS - HOW?



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?



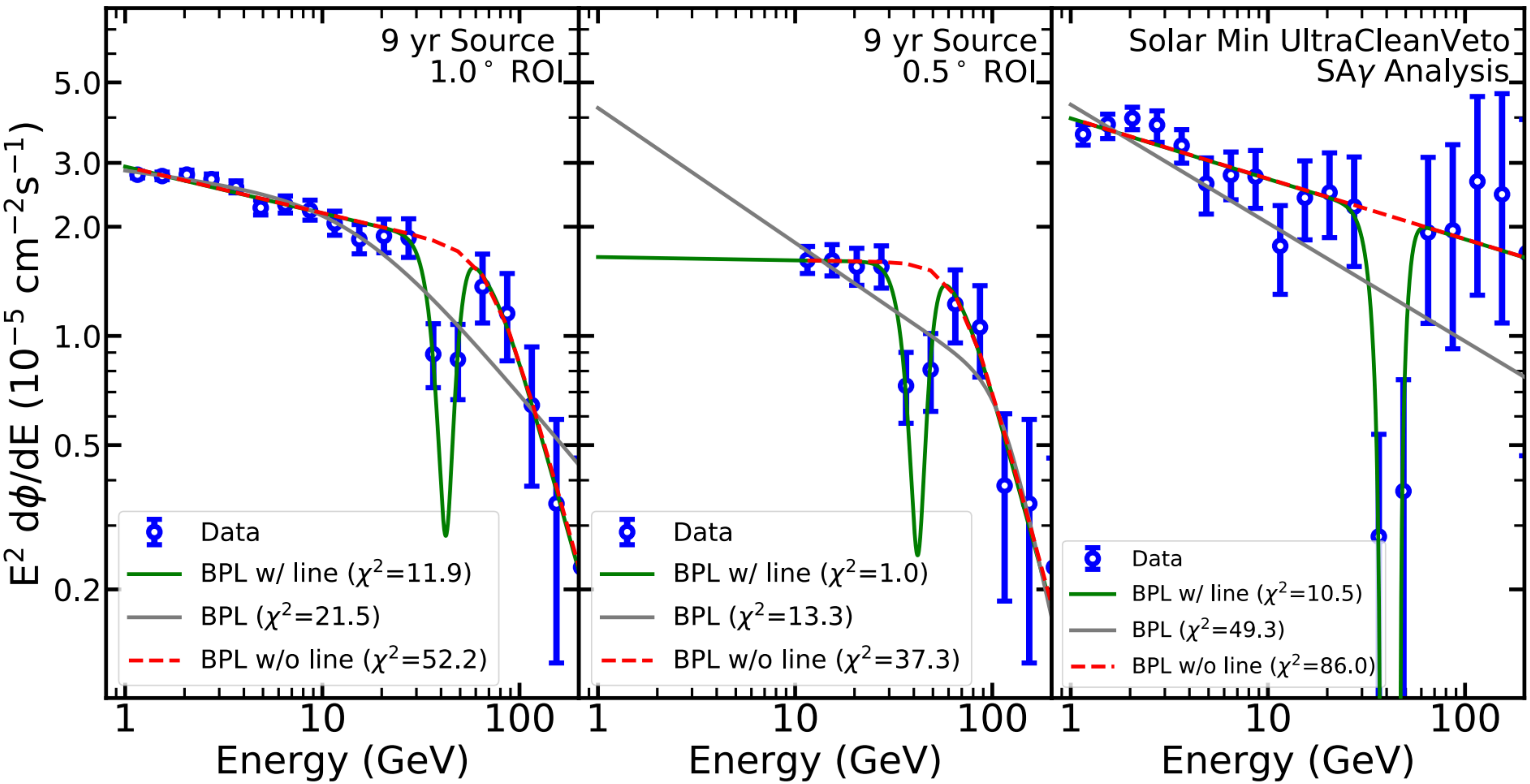
Time (UTC)	Energy	R.A.	Dec	Solar Distance	Event Class	PSF Class	Edisp Class	P6	P7	BG Contribution
2008-11-09 03:47:51	212.8 GeV	224.497	-16.851	0.068°	UltraCleanVeto	PSF0	EDISP3	✓	✓	0.00050
2008-12-13 03:25:55	139.3 GeV	260.707	-23.243	0.126°	UltraCleanVeto	PSF2	EDISP1	X	X	0.00038
2008-12-13 07:04:07	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

What About this spectral dip?

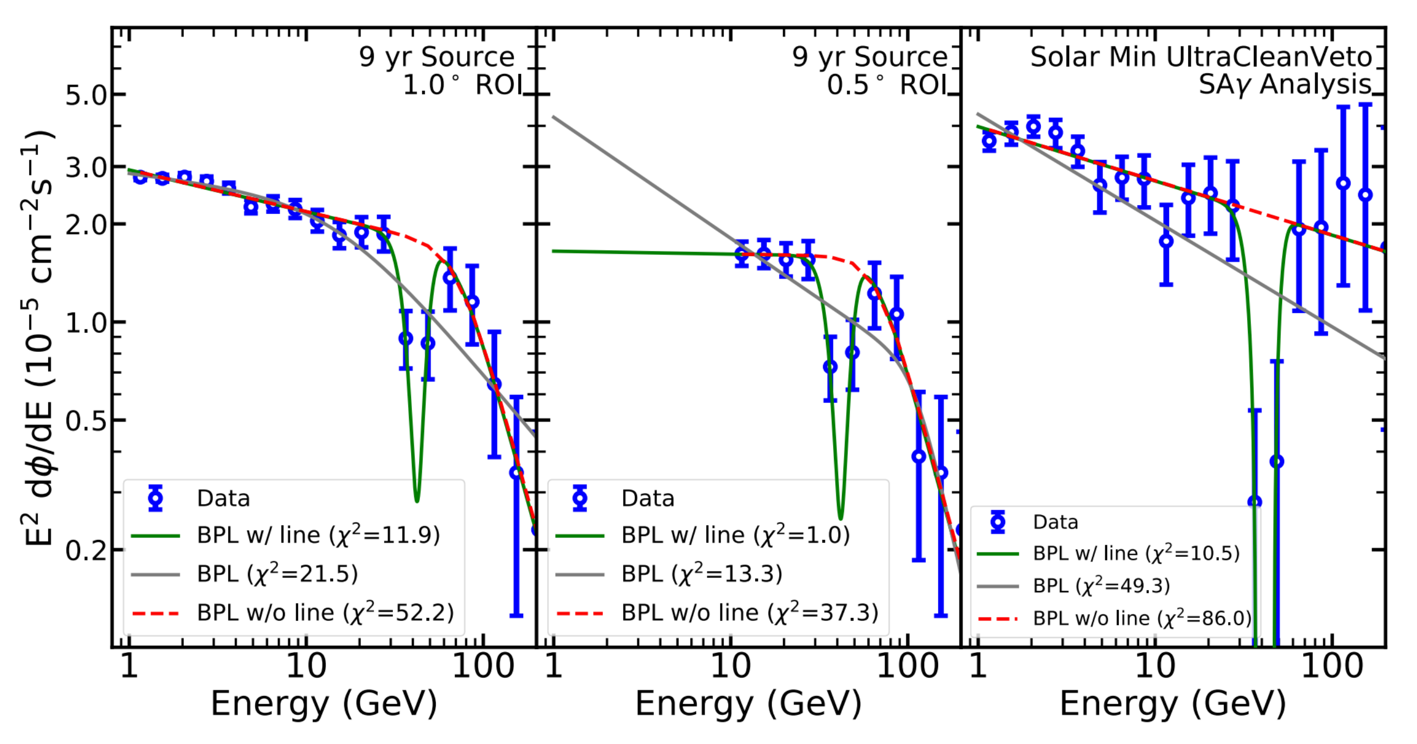
GAMMA-RAYS - HOW?

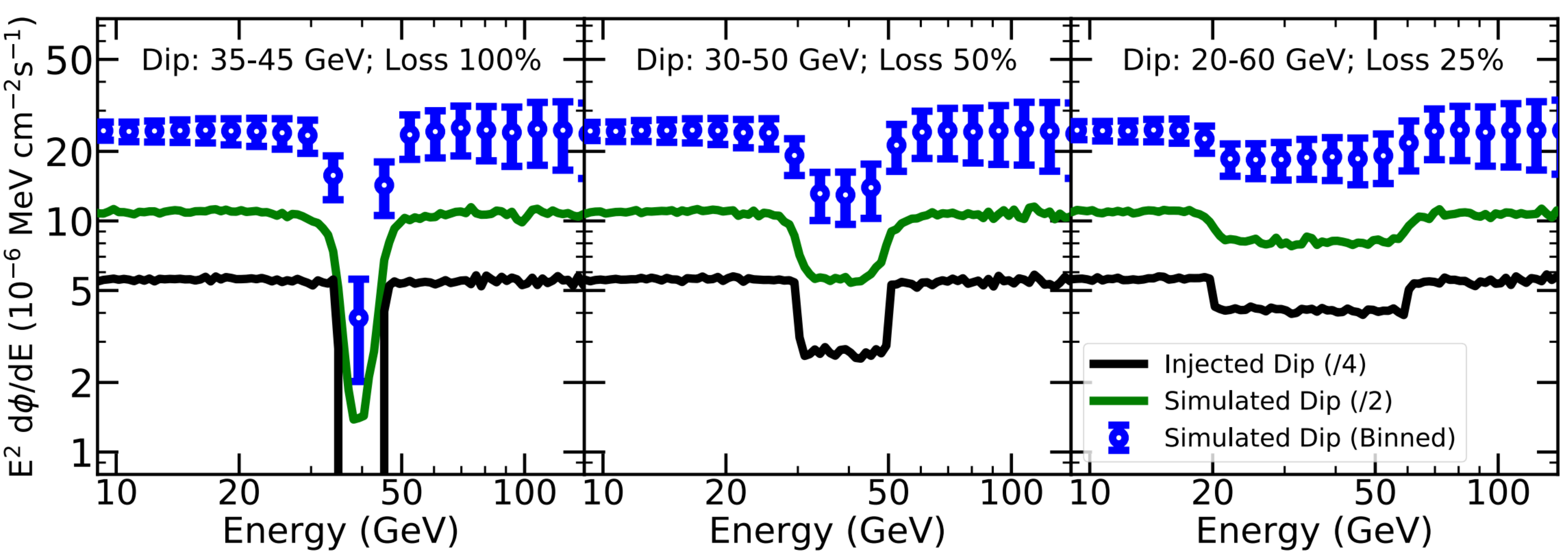
?

THE SPECTRAL DIP?



THE SPECTRAL DIP?



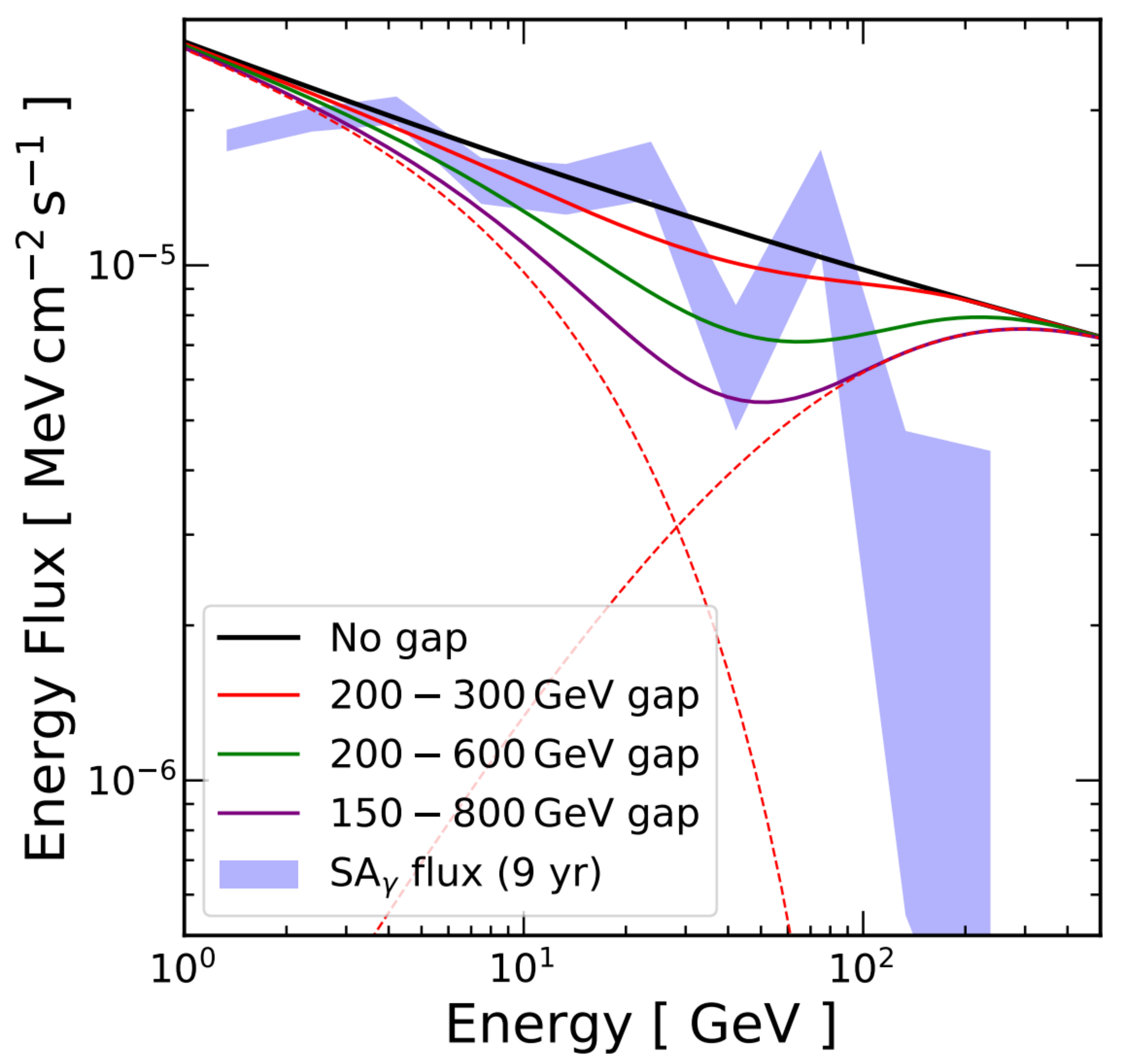


THE SPECTRAL DIP?

- **Possibilities:**

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

THE SPECTRAL DIP?

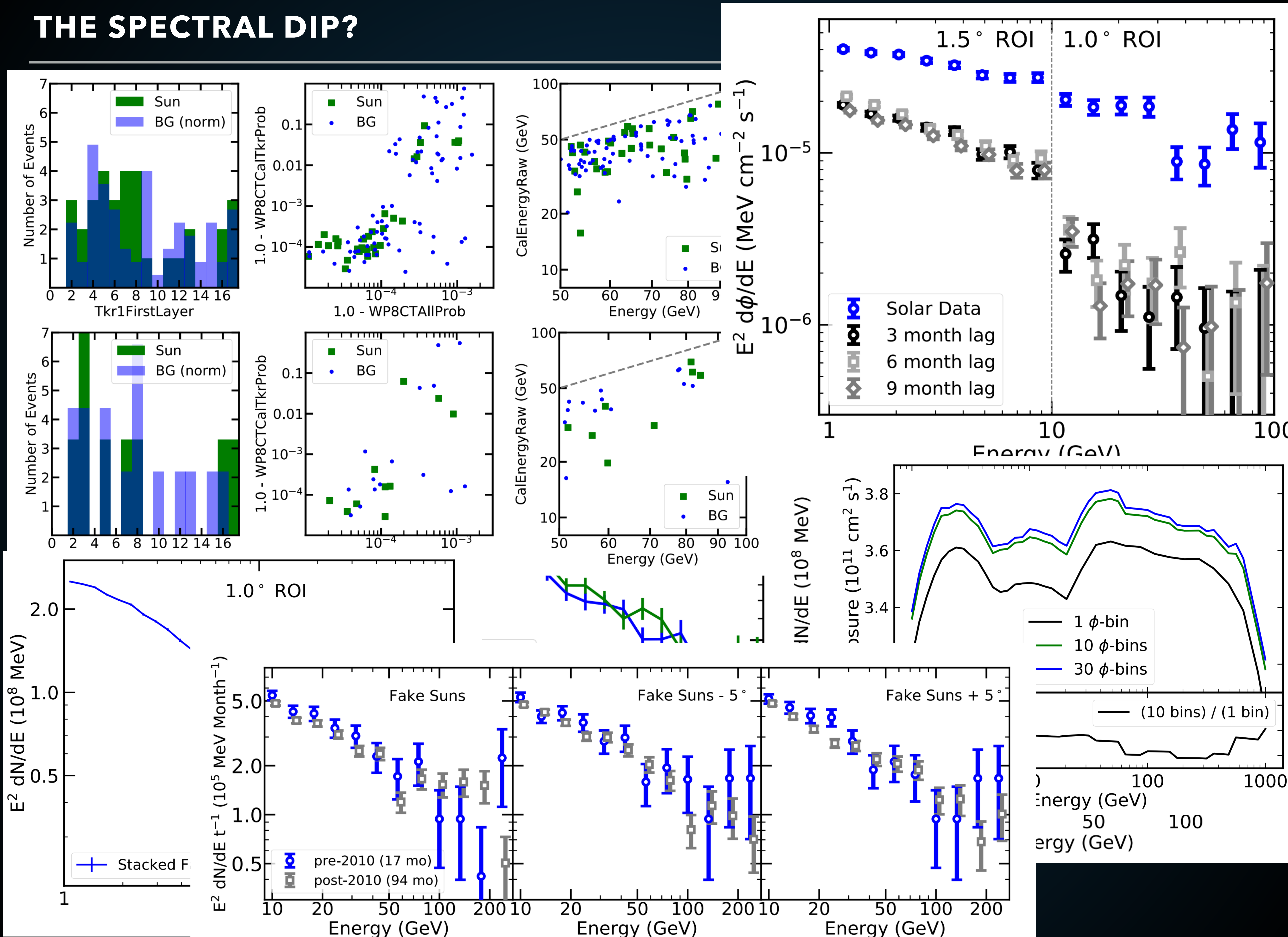


- **Hadronic processes cannot produce the amplitude and width of the spectral dip.**

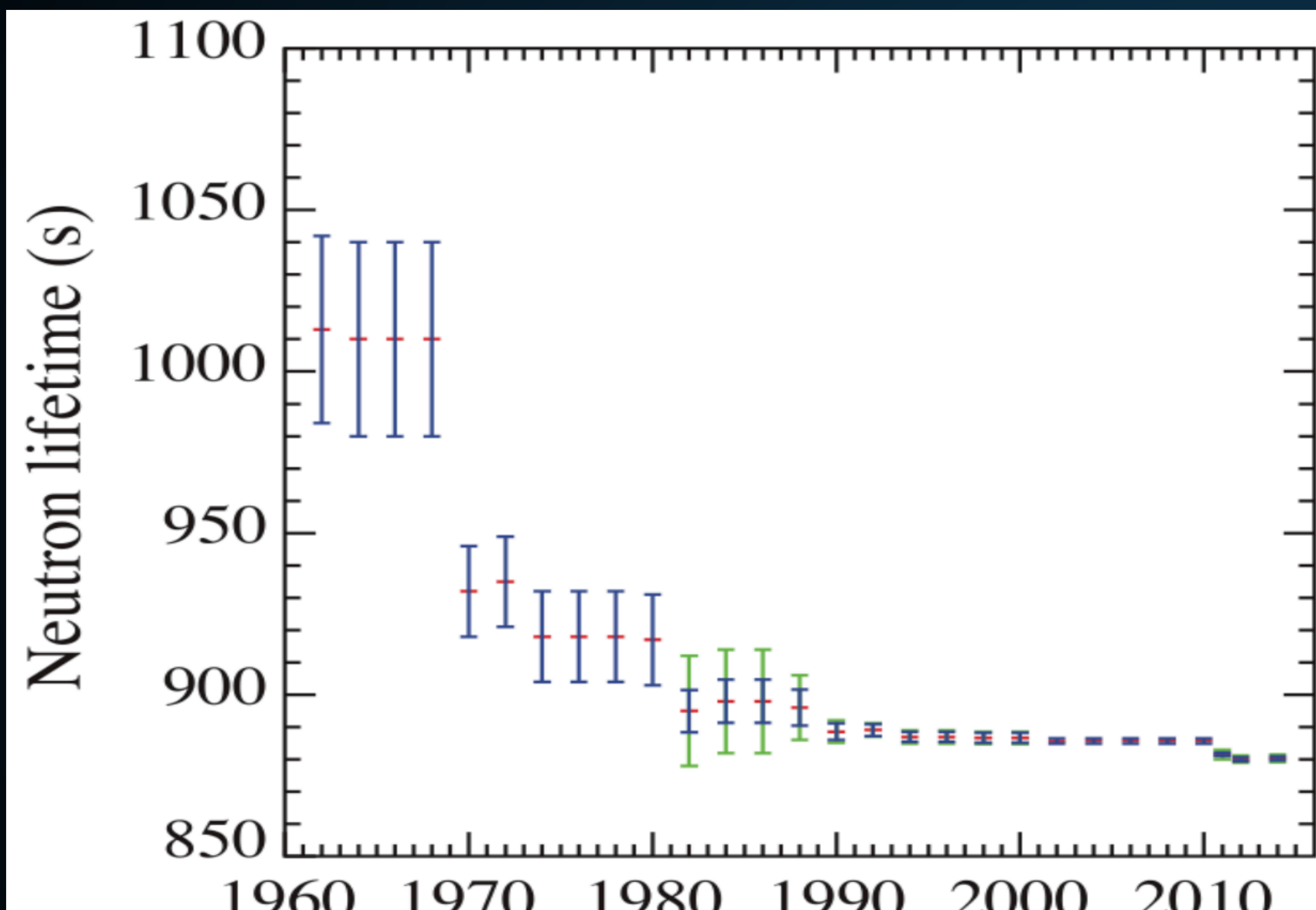
THE SPECTRAL DIP?

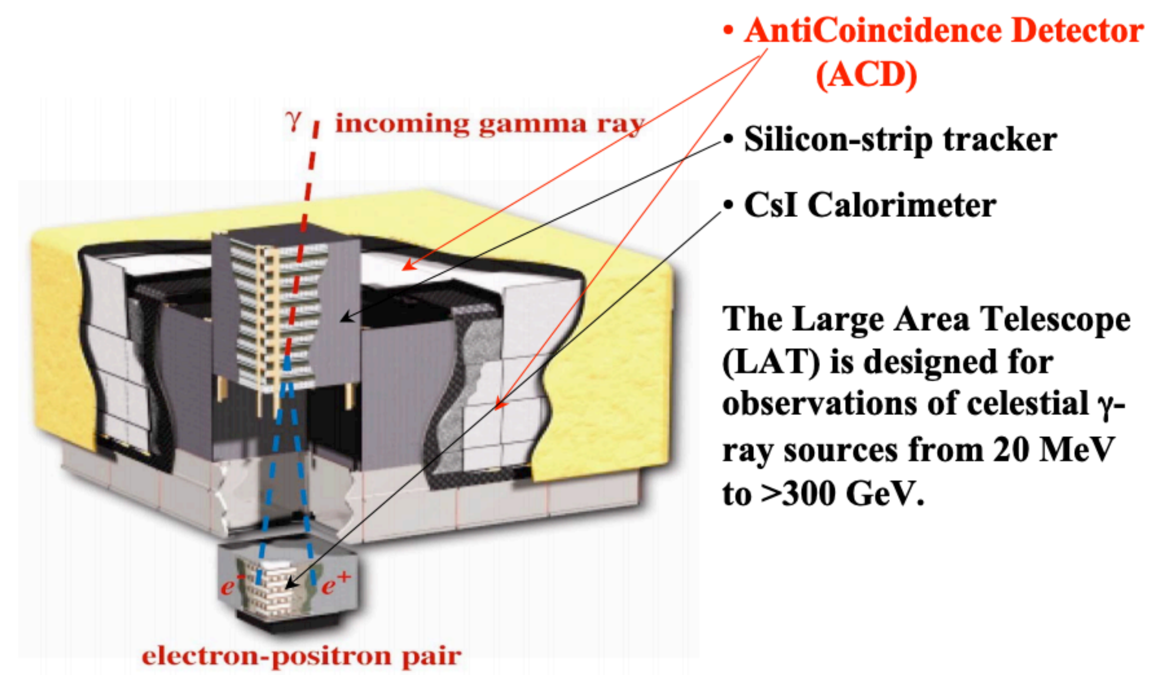
- **No clear mechanism for how energy-dependent photon absorption would work…**

THE SPECTRAL DIP?



AN INSTRUMENTAL WORKING HYPOTHESIS





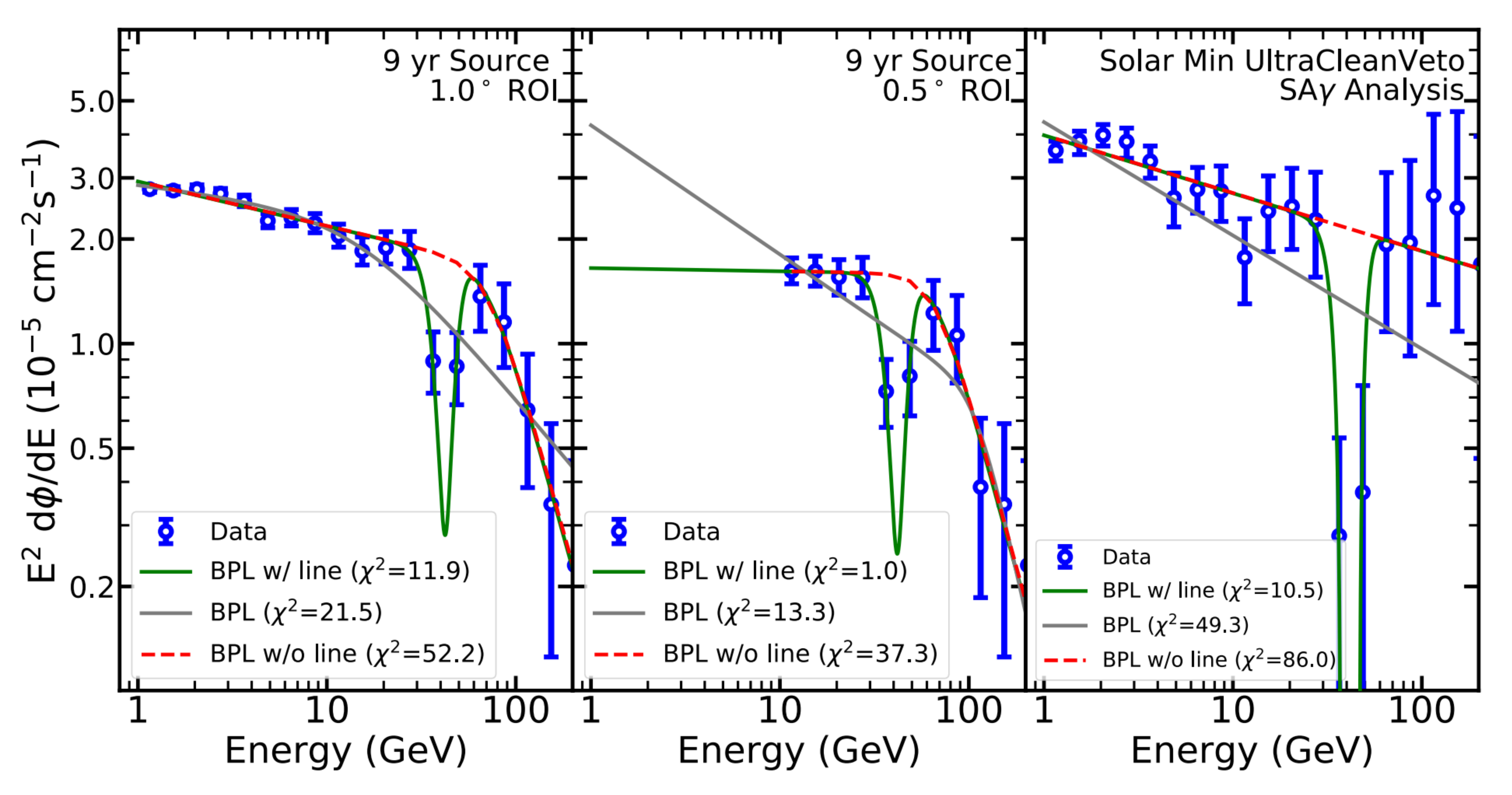
The Large Area Telescope (LAT) is designed for observations of celestial γ-ray sources from 20 MeV to >300 GeV.

Why is the AntiCoincidence Detector Necessary?

- The LAT instrument must identify cosmic γ rays in a background of charged cosmic rays 3-5 orders of magnitude more intense (mainly protons and electrons).
- ACD is the outermost LAT detector, surrounding the top and sides of the tracker.
- The majority of the rejection power against cosmic rays will be provided by the ACD.
- The required efficiency for charged particle detection for the ACD is 0.9997 averaged over the entire area.

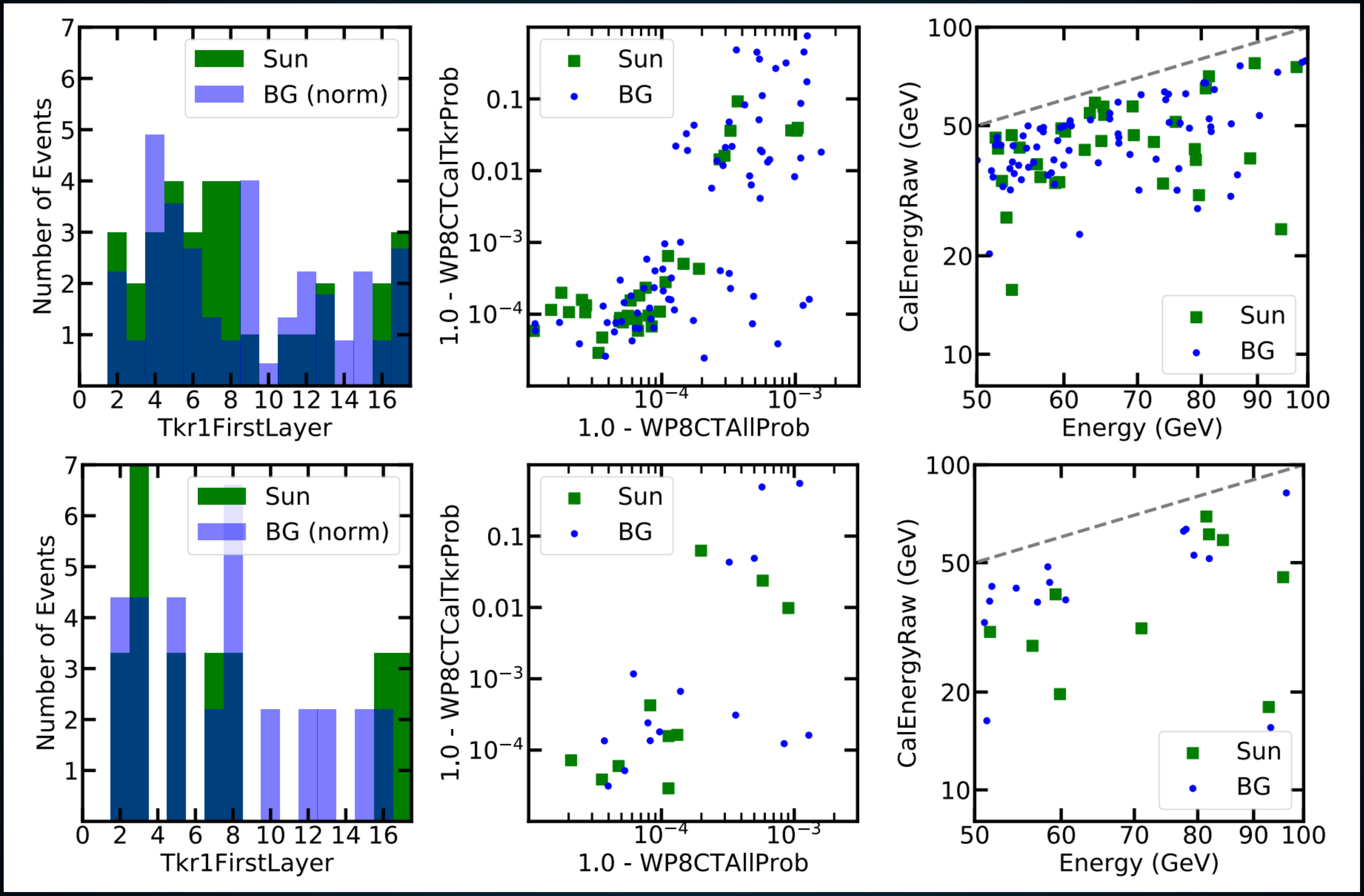
- **Neutrons from the Sun could be miscalibrated?**

AN INSTRUMENTAL WORKING HYPOTHESIS



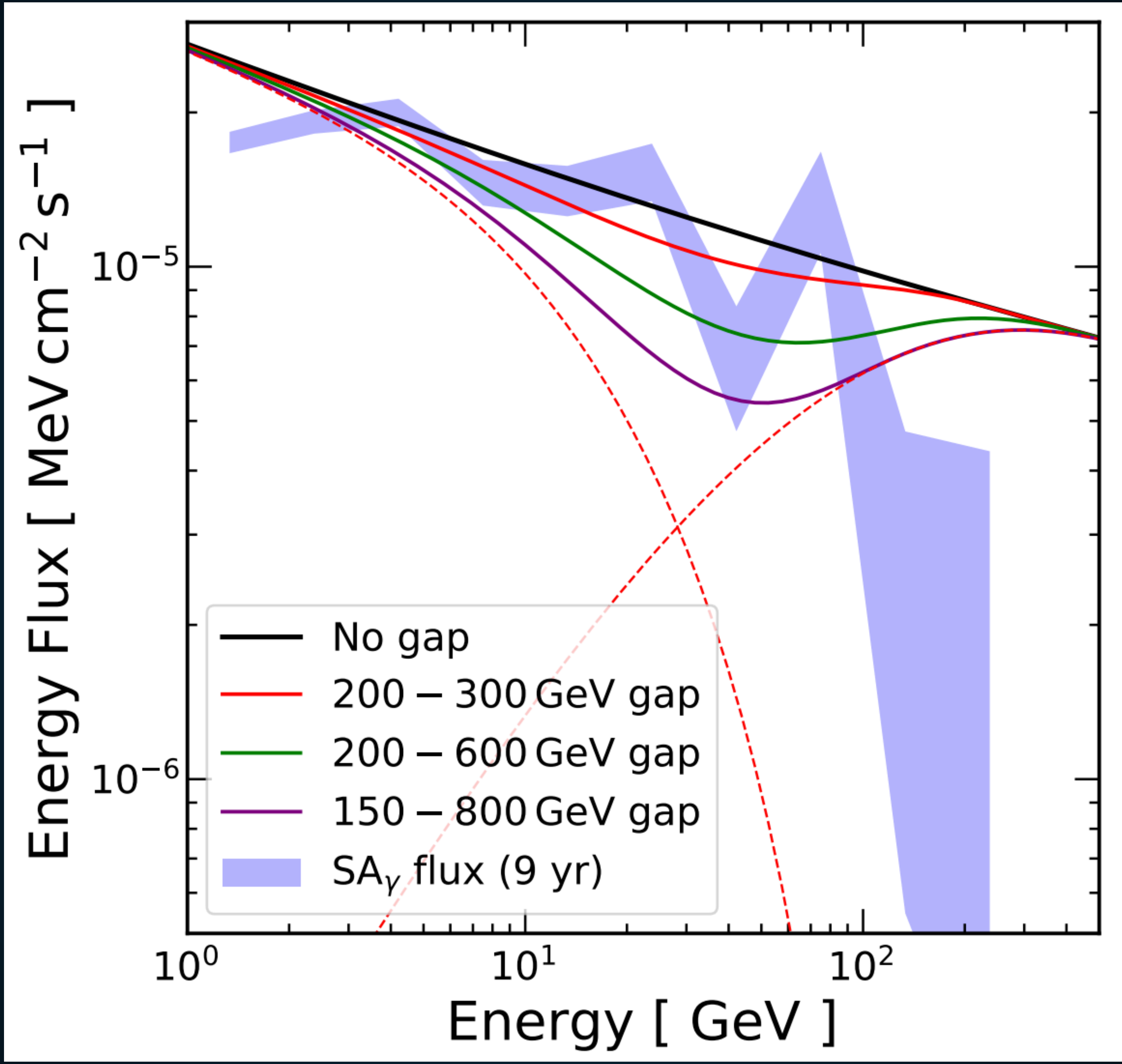
- **Neutrons from the Sun could be miscalibrated?**

AN INSTRUMENTAL WORKING HYPOTHESIS



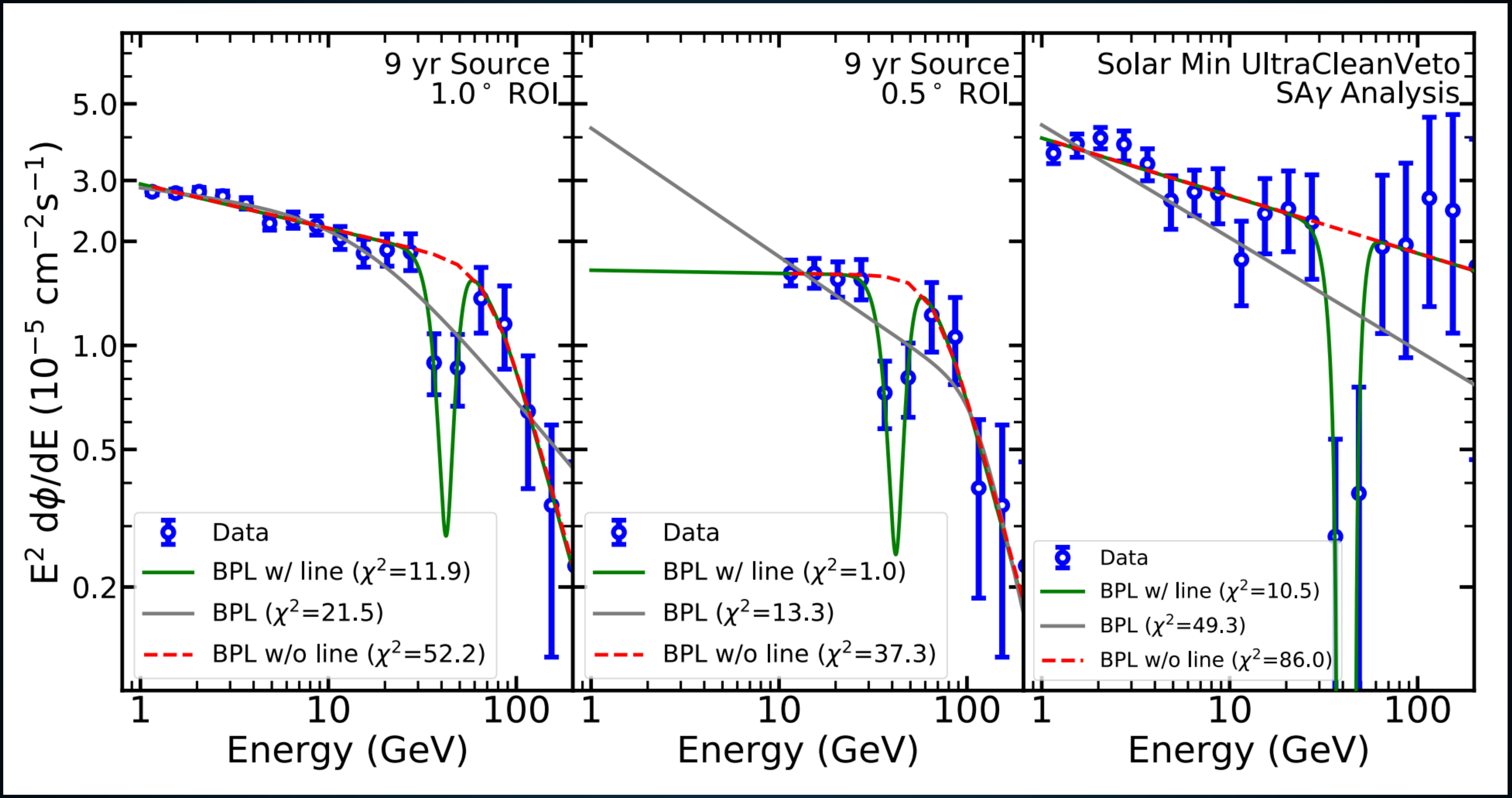
- **Neutrons from the Sun could be miscalibrated?**

AN INSTRUMENTAL WORKING HYPOTHESIS



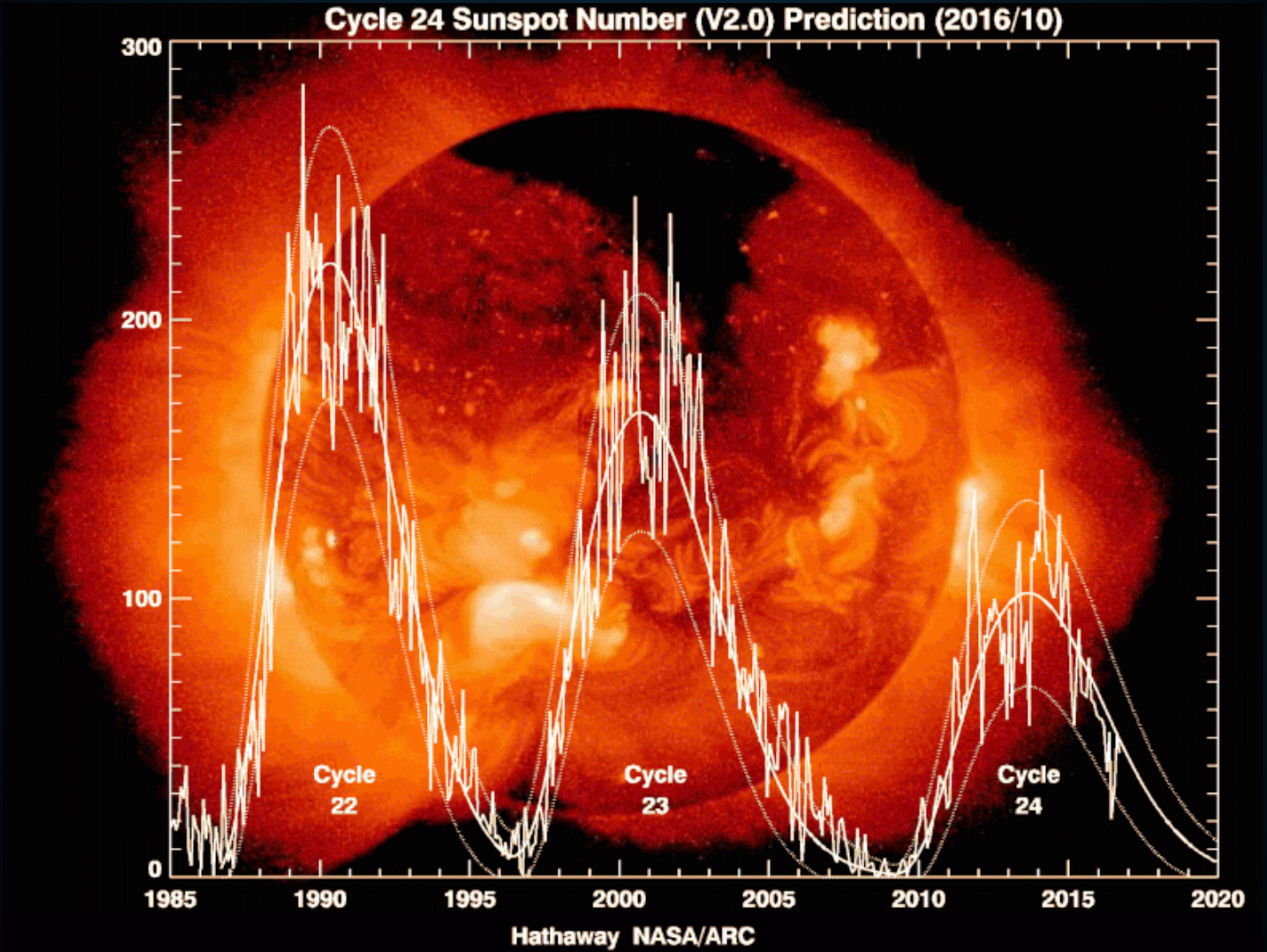
- **A combination of a real dip and low statistics?**

AN INSTRUMENTAL WORKING HYPOTHESIS



- **Or maybe new physics?**

HOW DO WE RESOLVE THESE ISSUES?

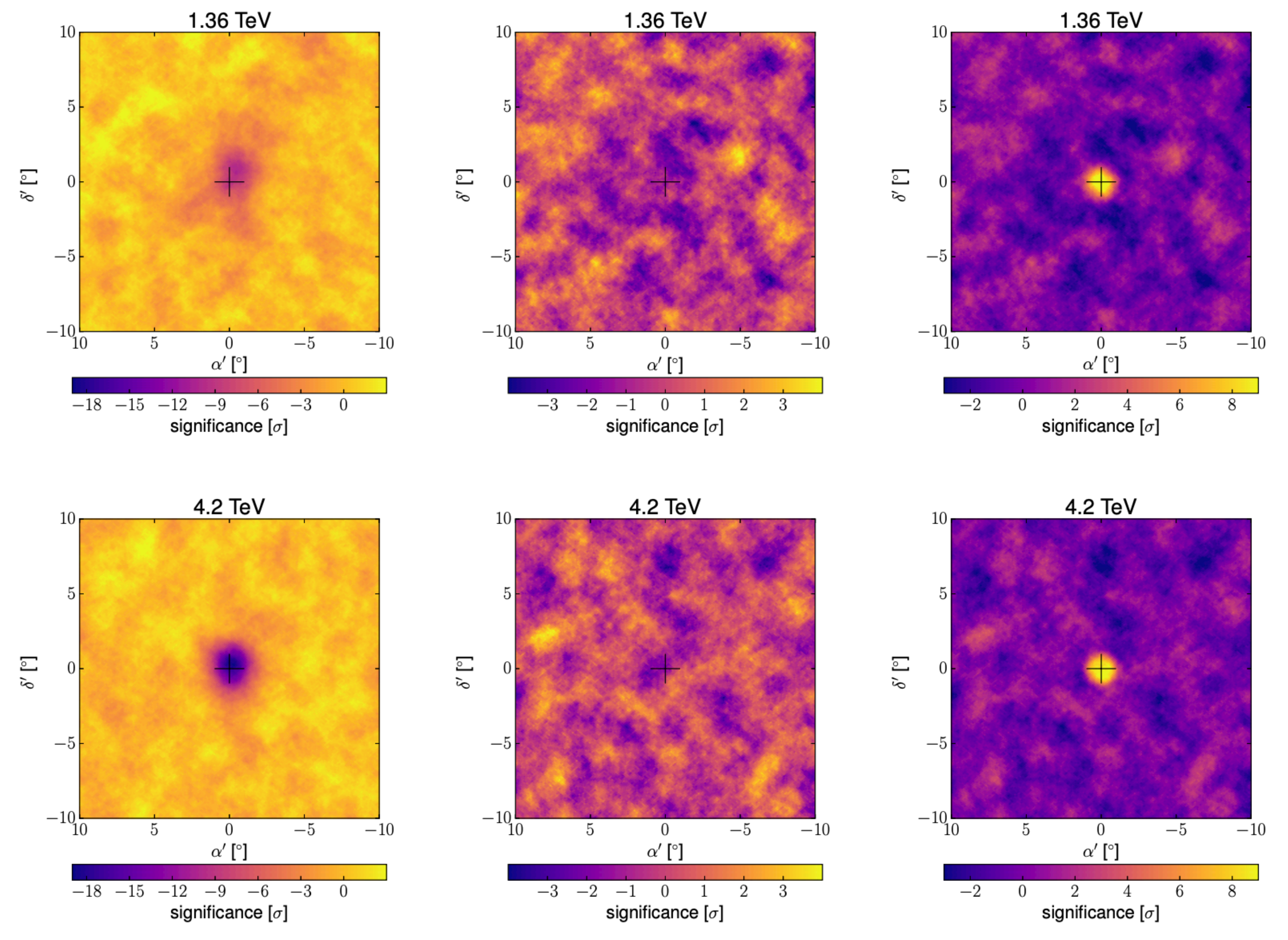


HOW DO WE RESOLVE THESE ISSUES?

TEV OBSERVATIONS OF THE SUN

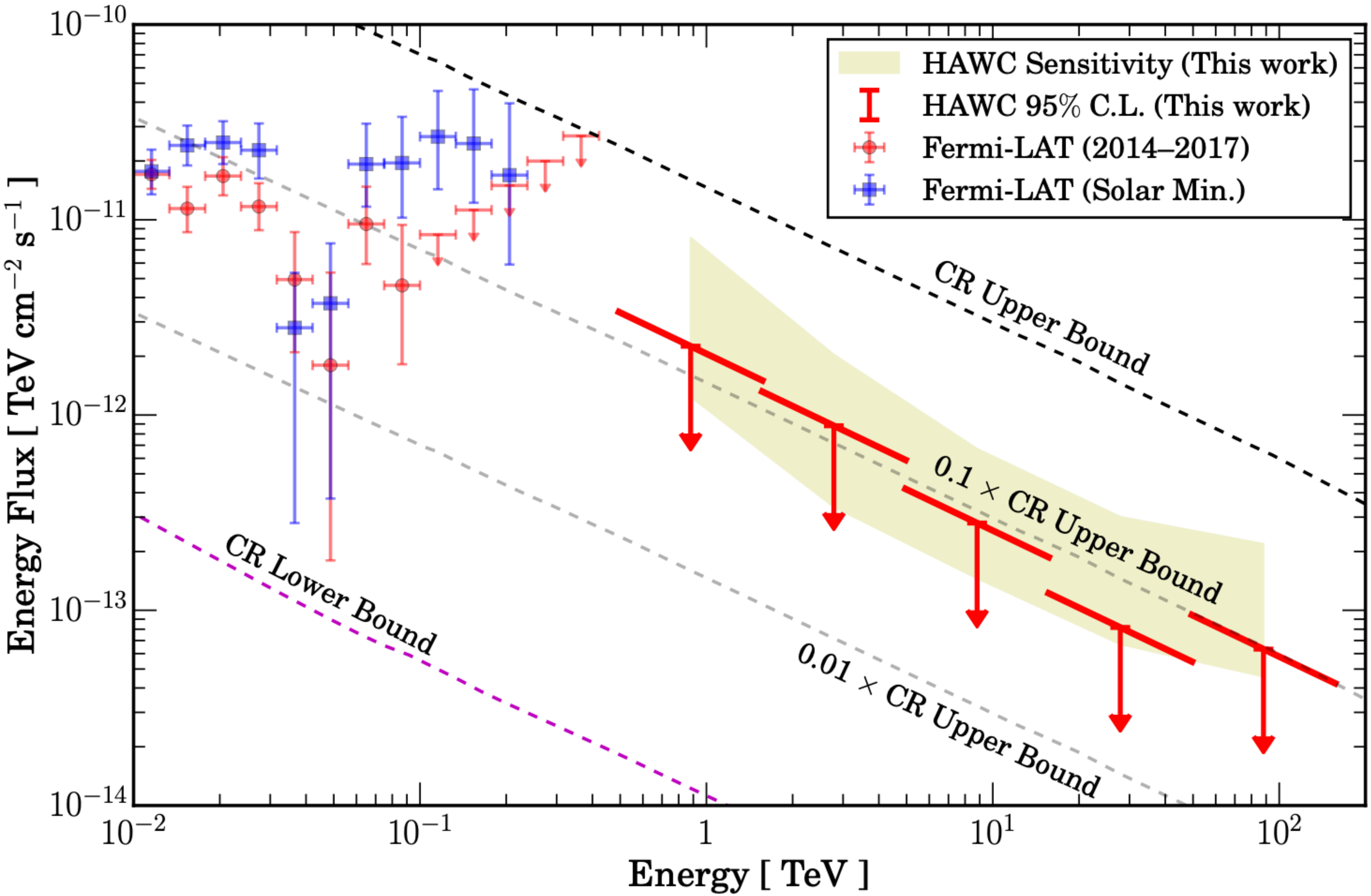
TEV OBSERVATIONS OF THE SUN

HAWC Collaboration (including TL) (2018; 1808.05620)



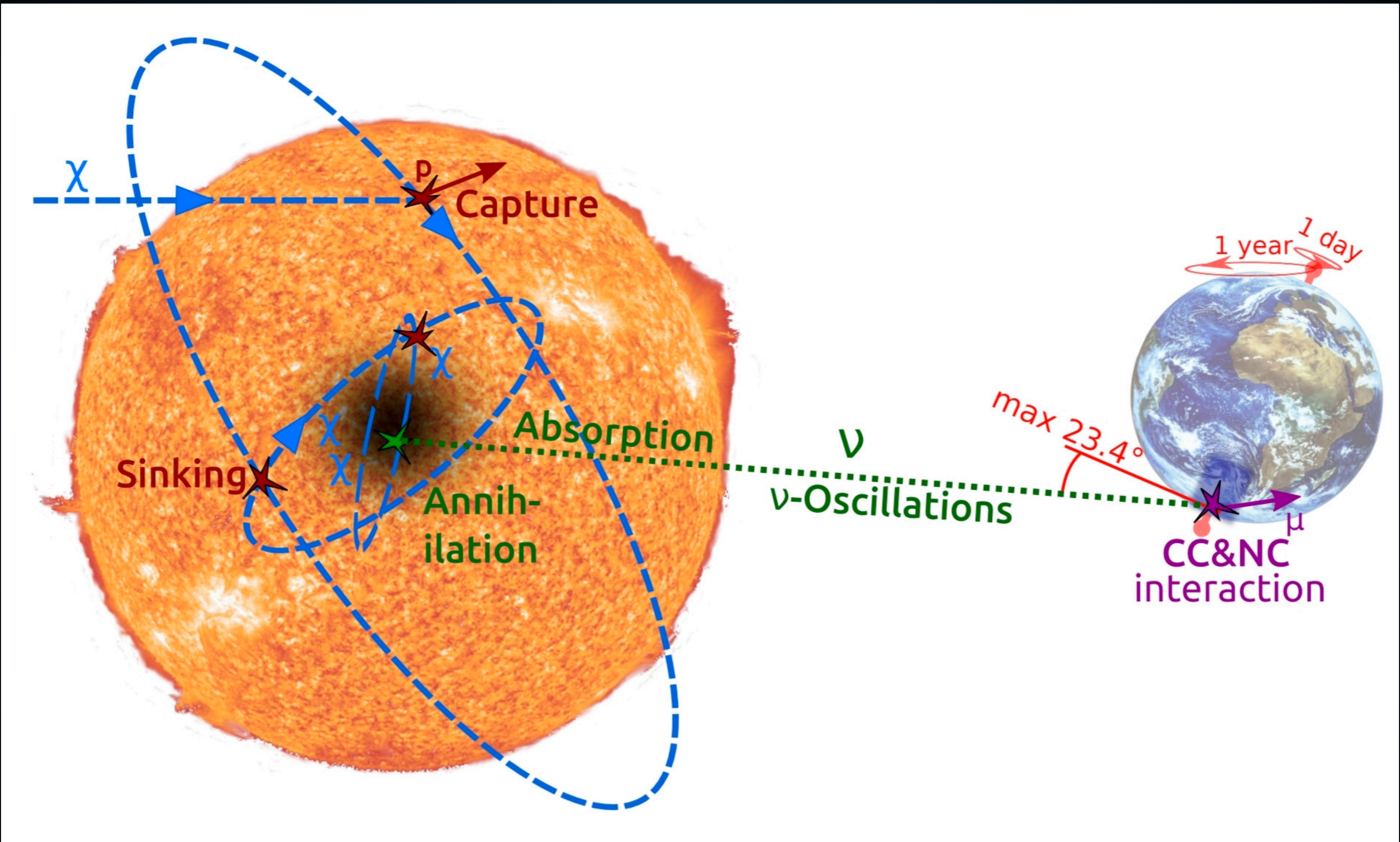
TEV OBSERVATIONS OF THE SUN

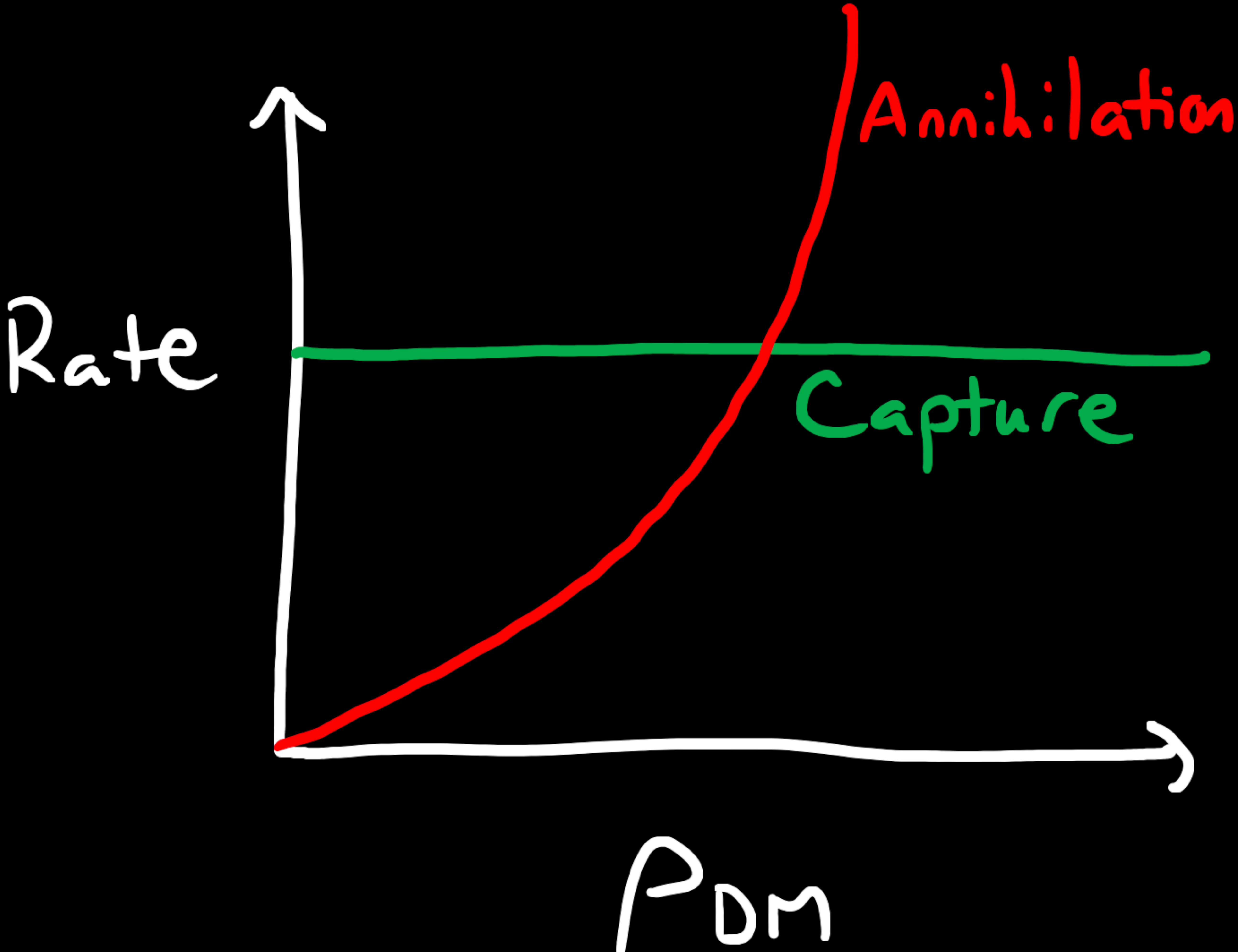
HAWC Collaboration (including TL) (2018; 1808.05620)



A DARK-MATTER CONNECTION

IceCube Collaboration (2016; 1612.05949)

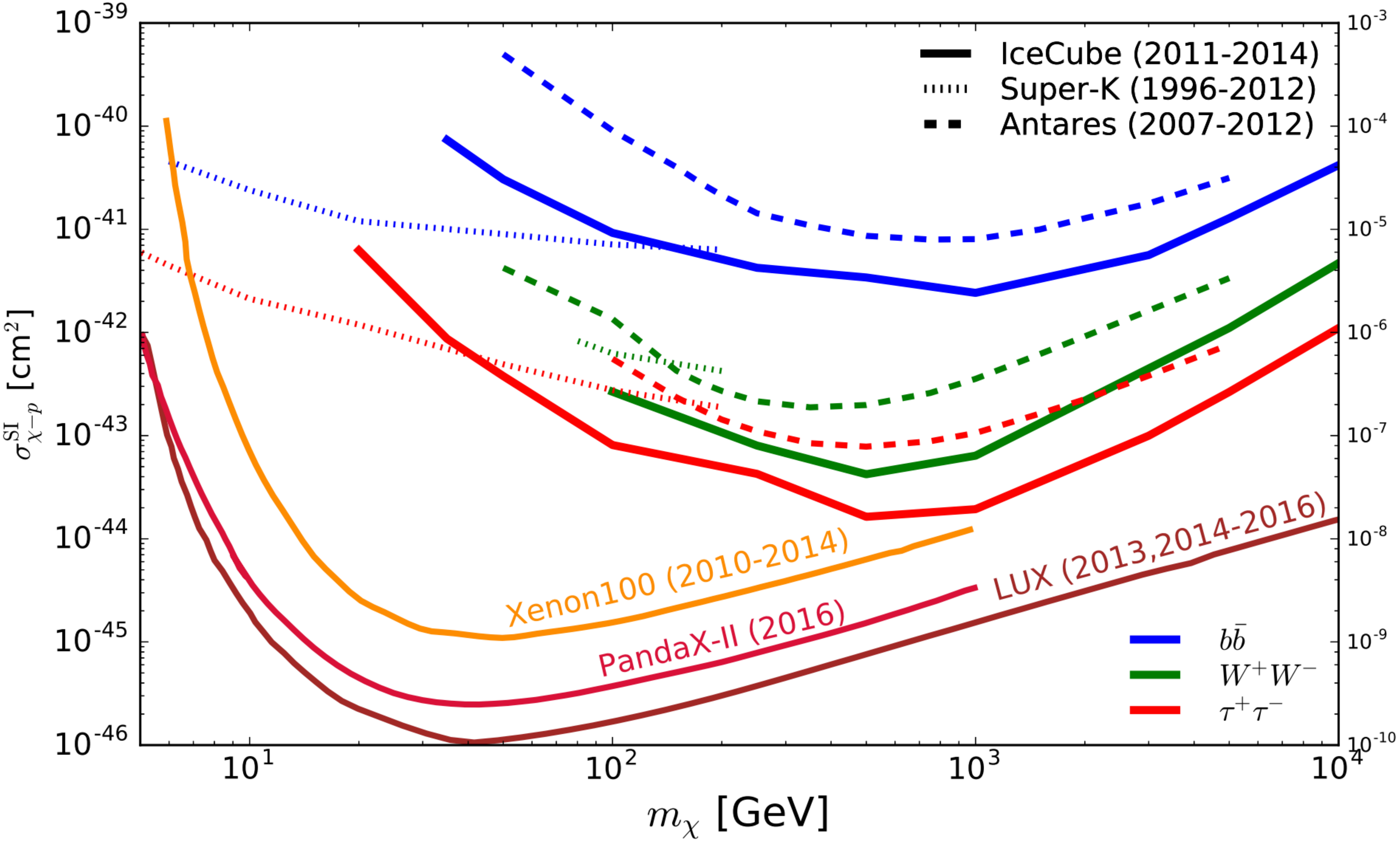




Rate
Annihilation
Capture
ρ_{DM}

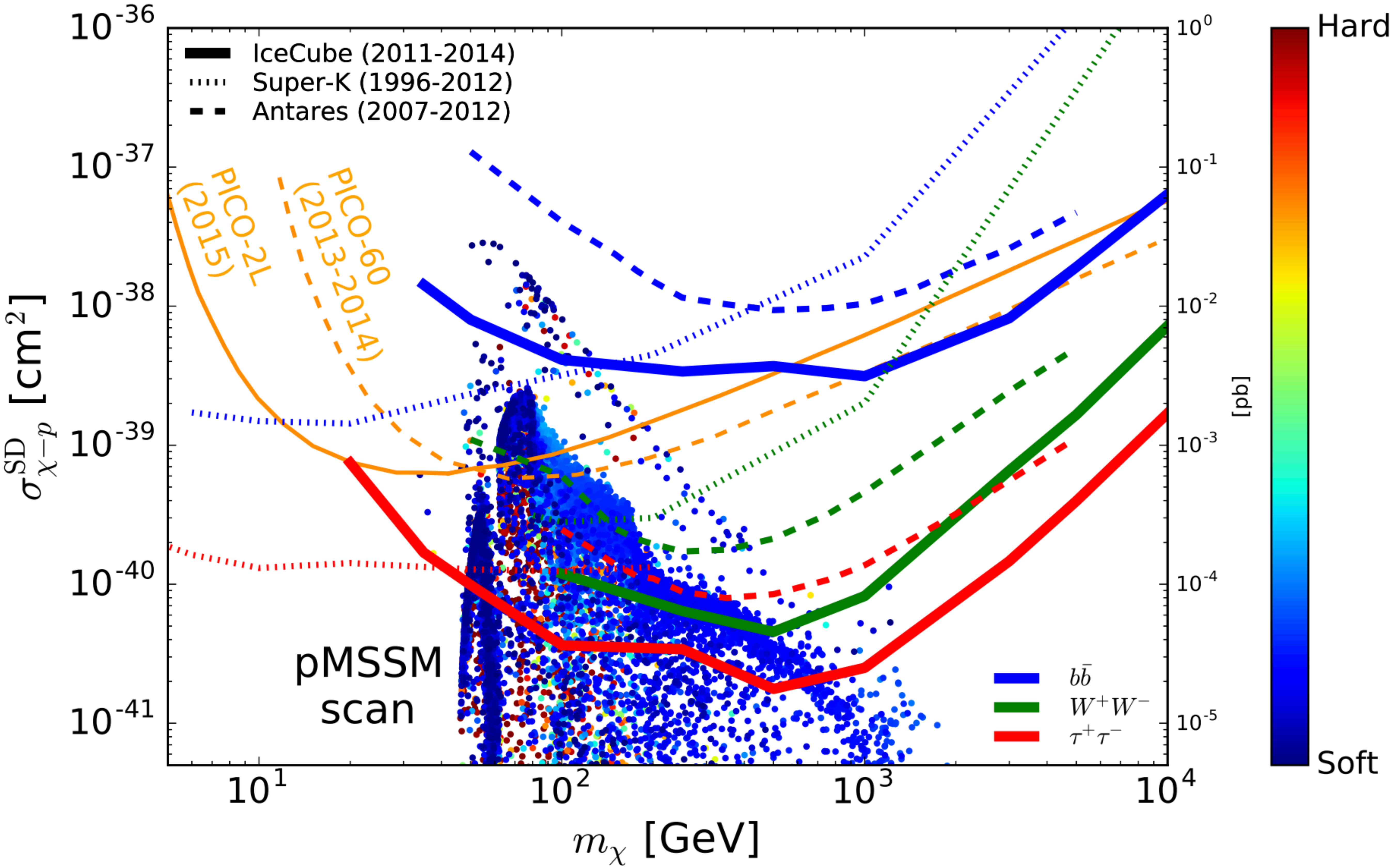
A DARK-MATTER CONNECTION

IceCube Collaboration (2016; 1612.05949)

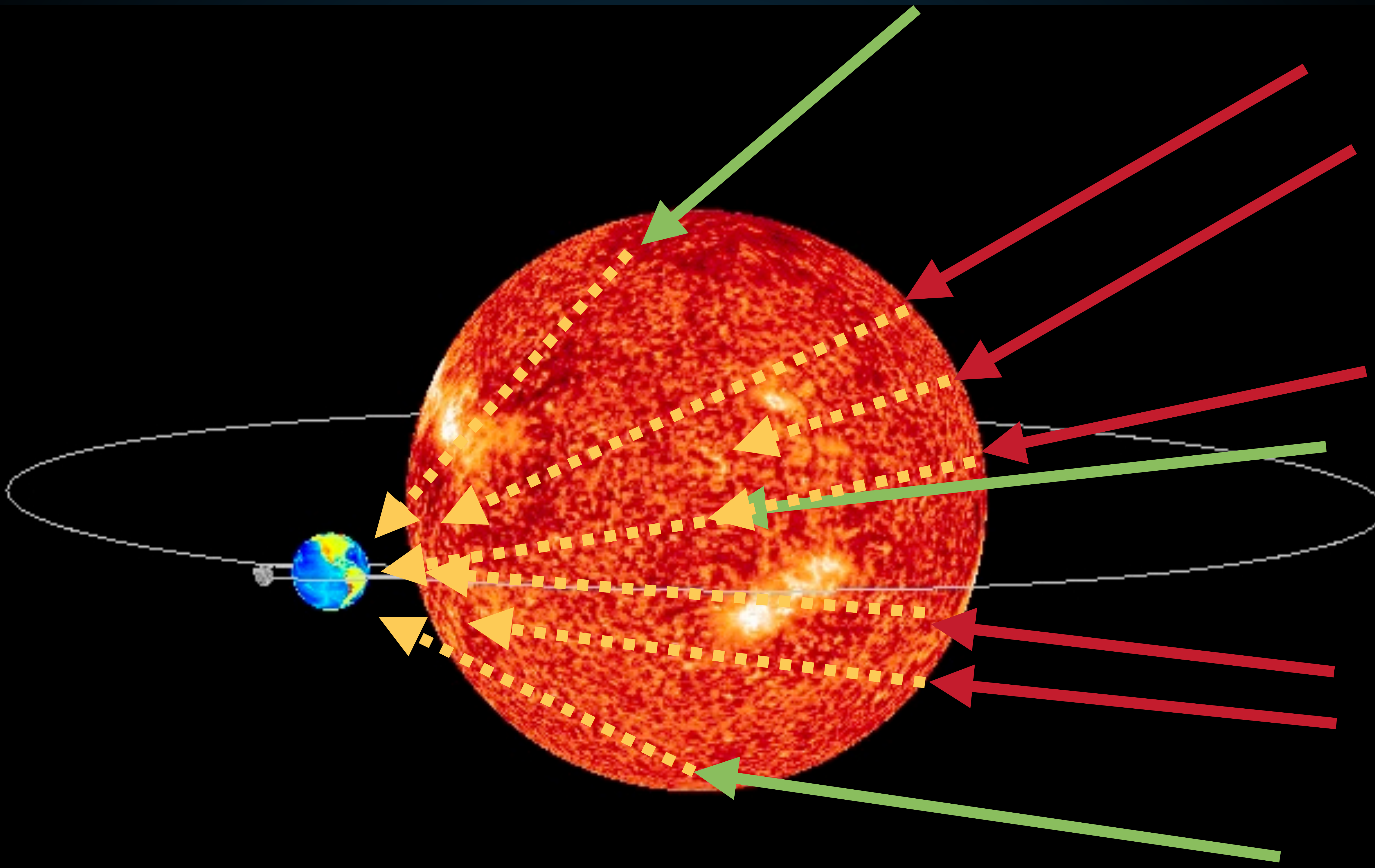


A DARK-MATTER CONNECTION

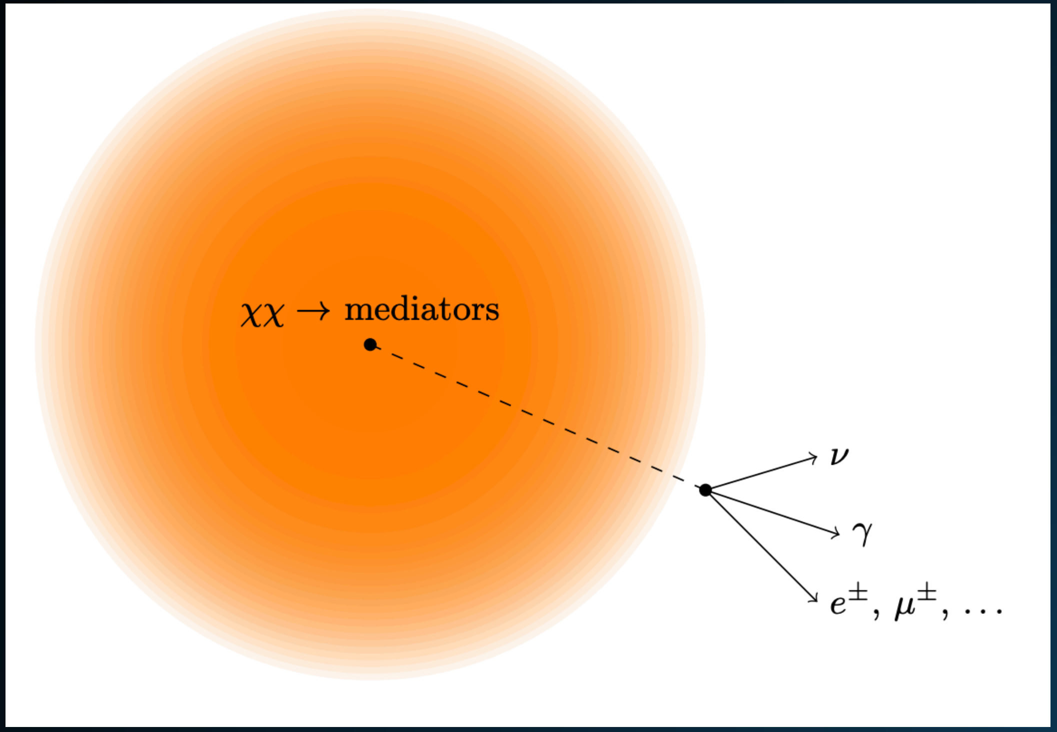
IceCube Collaboration (2016; 1612.05949)



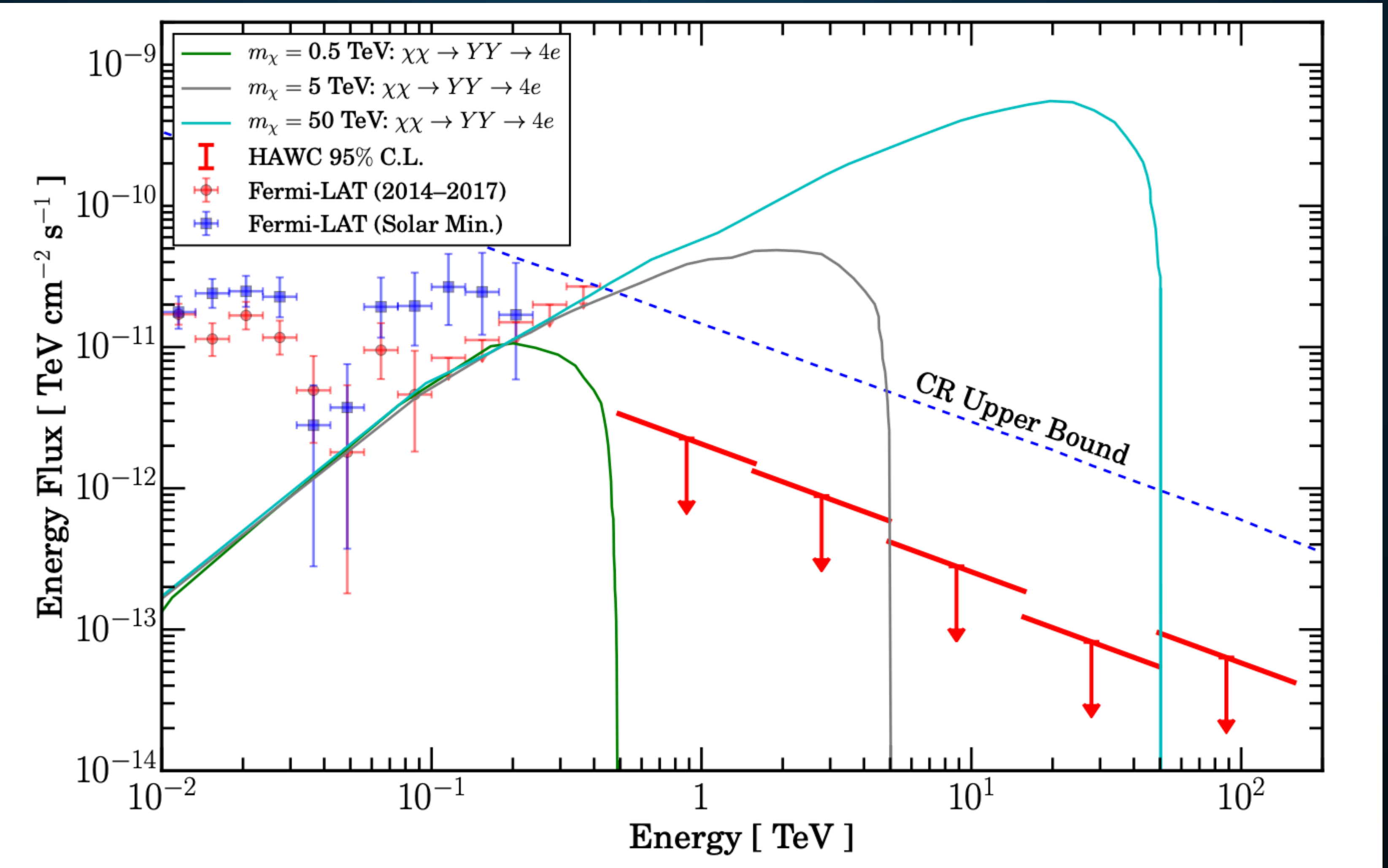
HADRONIC GAMMA-RAYS - HOW?



A DARK-MATTER CONNECTION

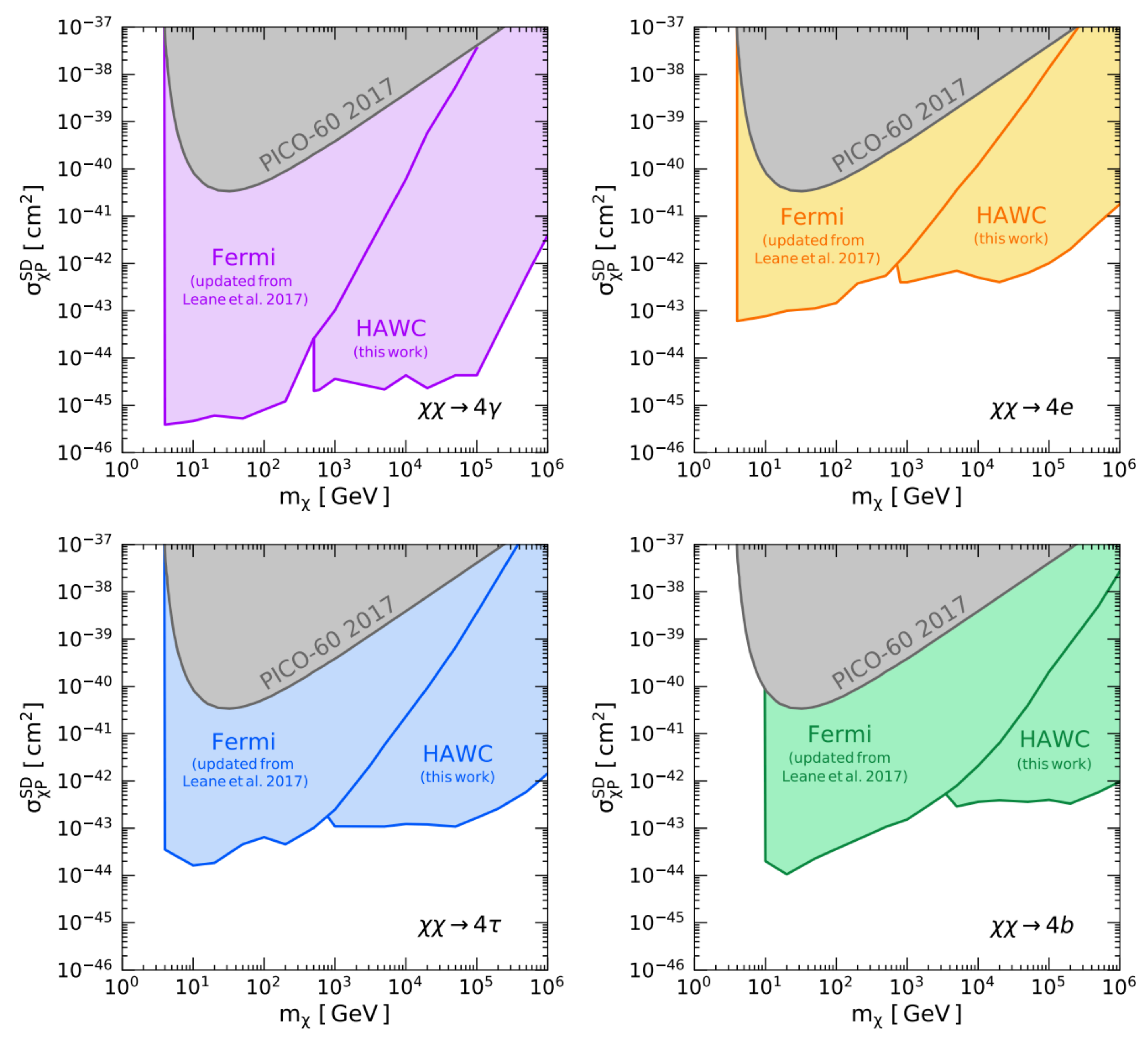


- **Can set limits on the gamma-ray signal, if annihilation goes to long-lived mediators.**



A DARK-MATTER CONNECTION

HAWC Collaboration (including TL) (2018; 1808.05624)



CONCLUSIONS

- We don't understand gamma-ray emission from the Sun.

- 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 dark matter annihilation.