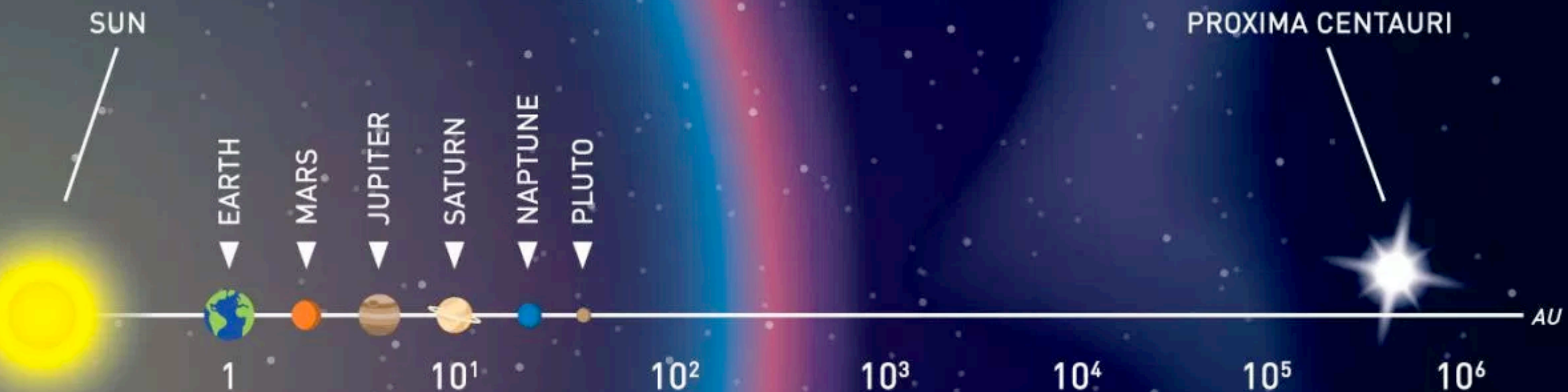


Physics and Astronomy Colloquium  
Clemson University  
January 24, 2019



**TIM LINDEN**  
**THE OHIO STATE UNIVERSITY**  
CENTER FOR COSMOLOGY AND  
ASTROPARTICLE PHYSICS

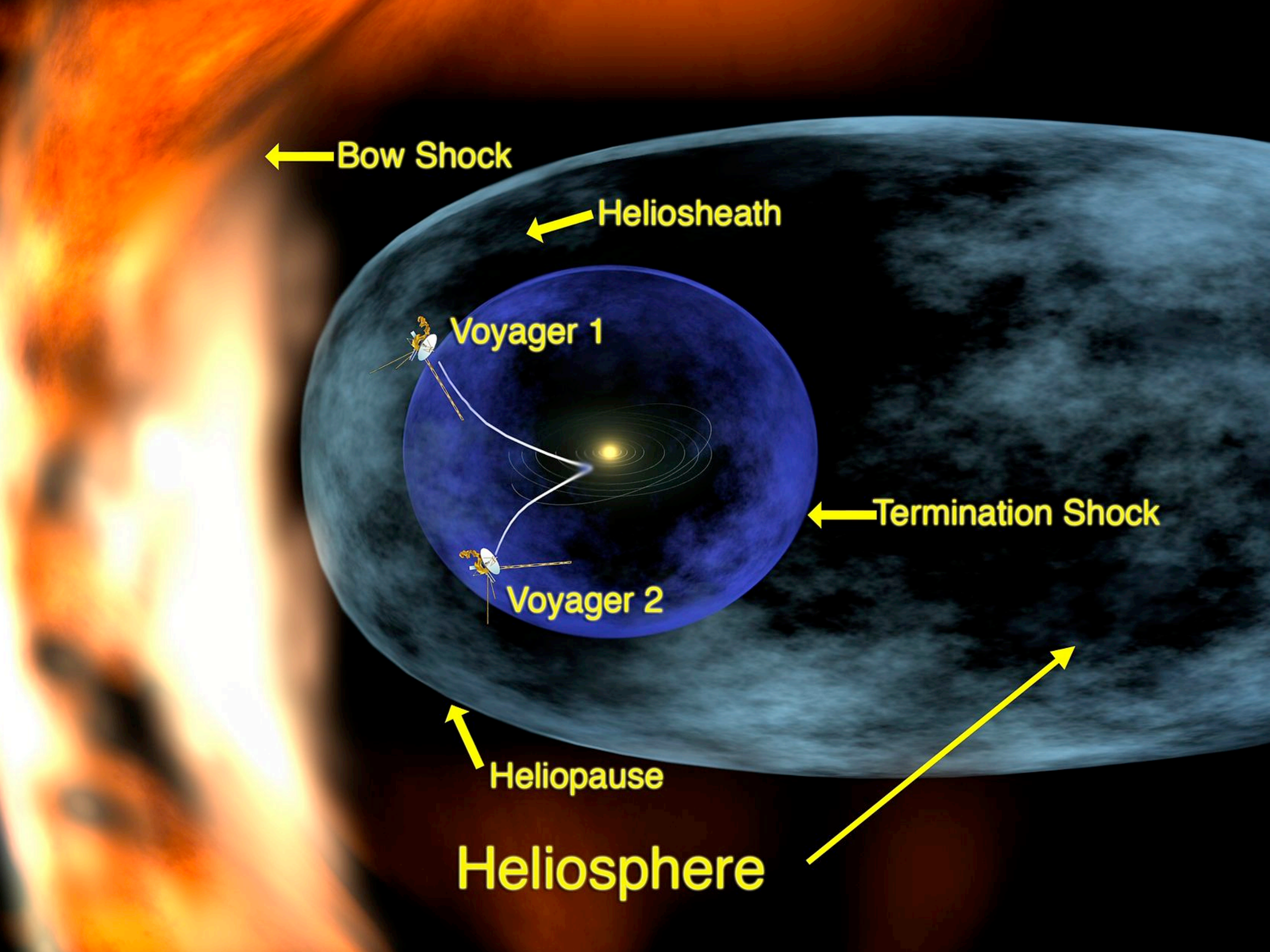


$$\left( \frac{d_{aCen}}{d_{\odot}} \right)^2 = 7 \times 10^{10}$$









← Bow Shock

← Heliosheath

Voyager 1

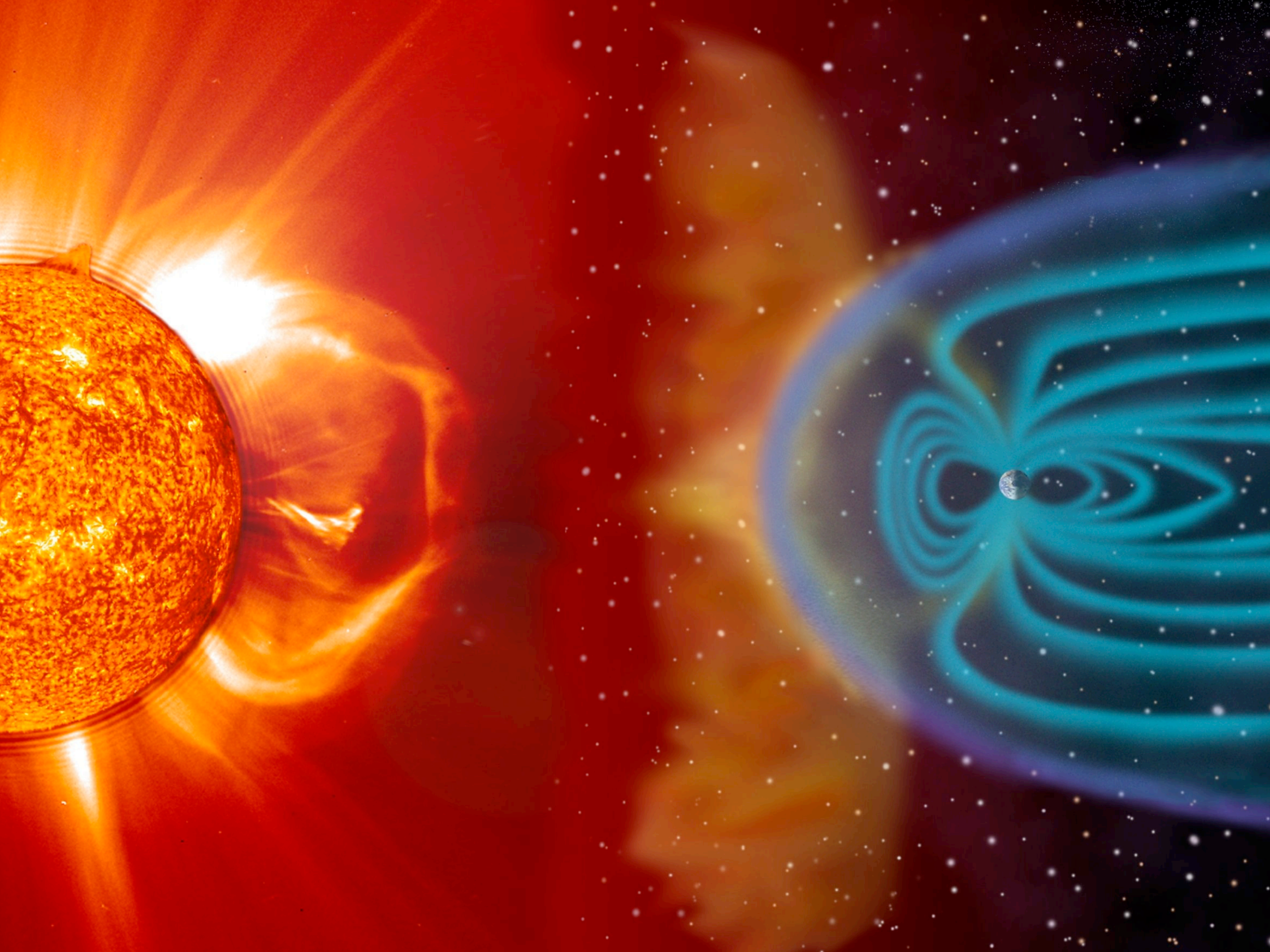
Voyager 2

← Termination Shock

← Heliopause

Heliosphere

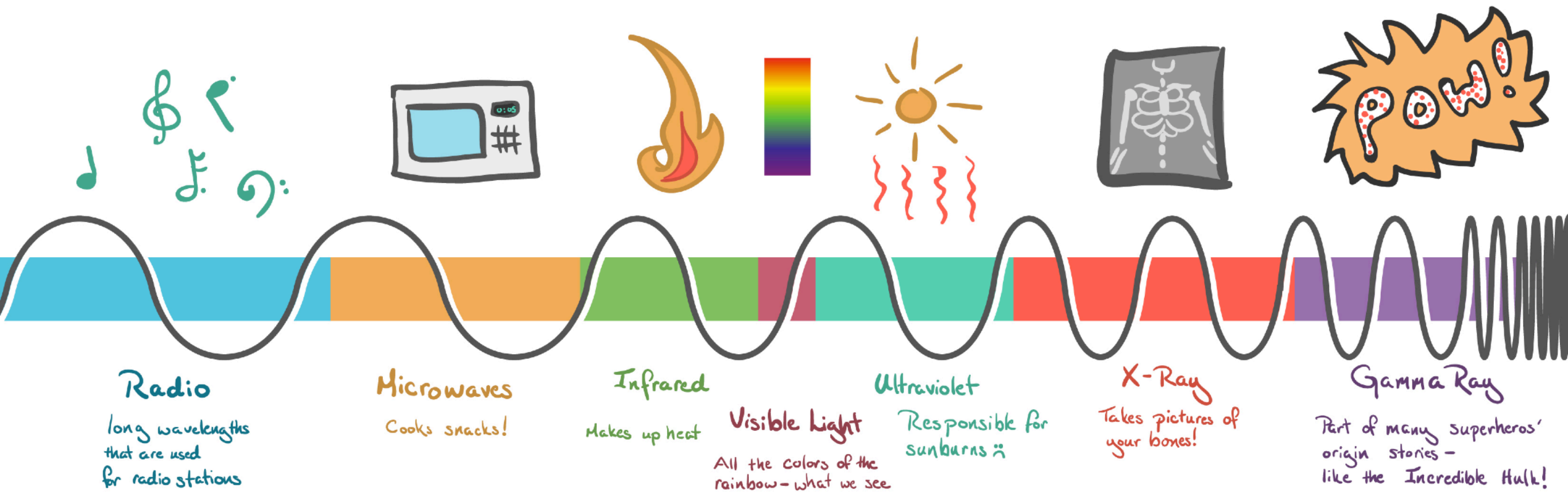




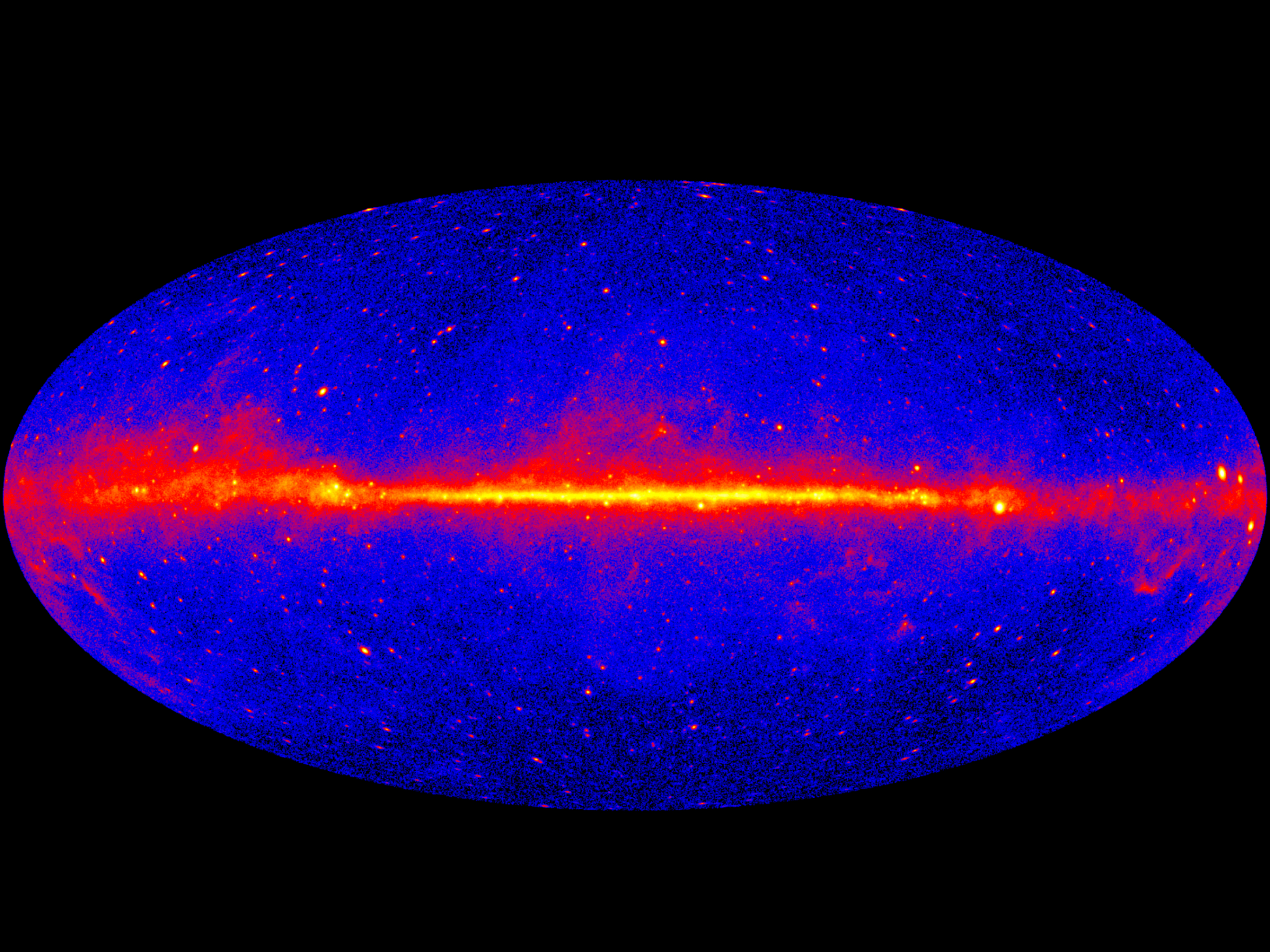


# WHAT IS THE ENERGY SCALE?

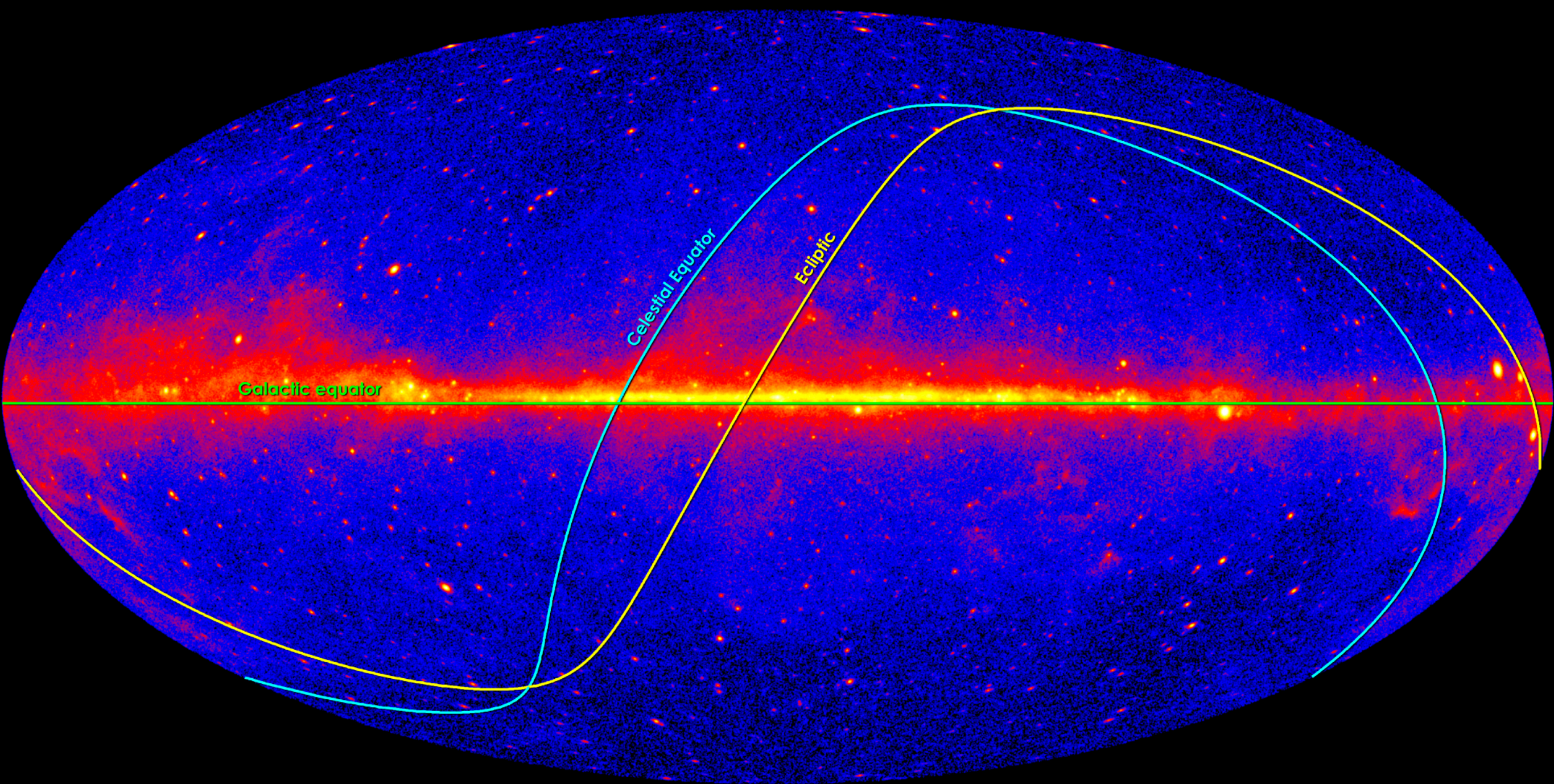
## The Electromagnetic Spectrum











Galactic equator

Celestial Equator

Ecliptic



# CRAZY FINE TUNING

- Solar gamma-ray flux is approximately:

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

- Solar disk gamma-ray flux:

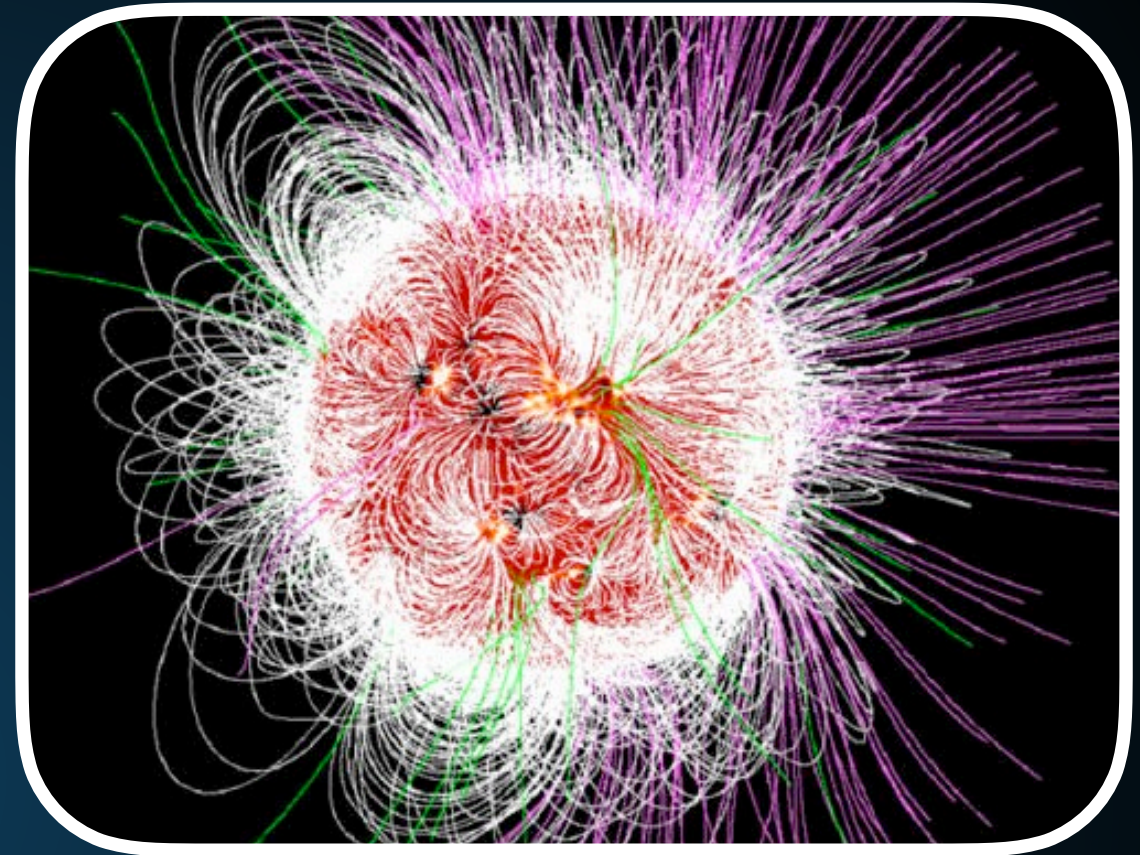
$$6 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$$

| <u>name</u><br>↓↑  | <u>assoc name 1</u><br>↓↑ | <u>energy flux</u><br>↓↑ [erg/cm^2/s] | <u>assoc name 2</u><br>↓↑ |
|--------------------|---------------------------|---------------------------------------|---------------------------|
| 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?

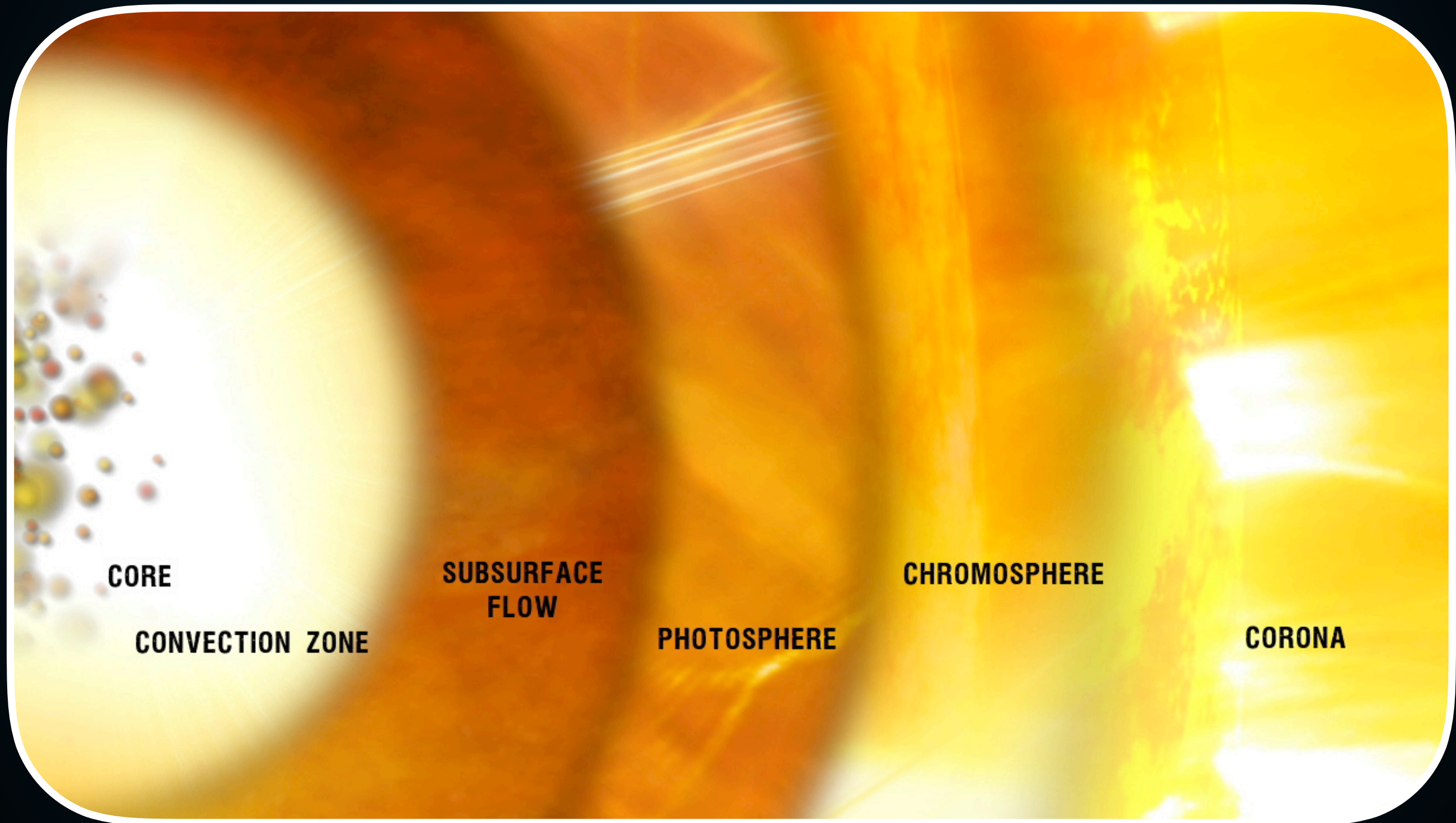
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# GAMMA-RAYS - WHY?

---





**How are these gamma rays produced?**



# GAMMA-RAYS - HOW?

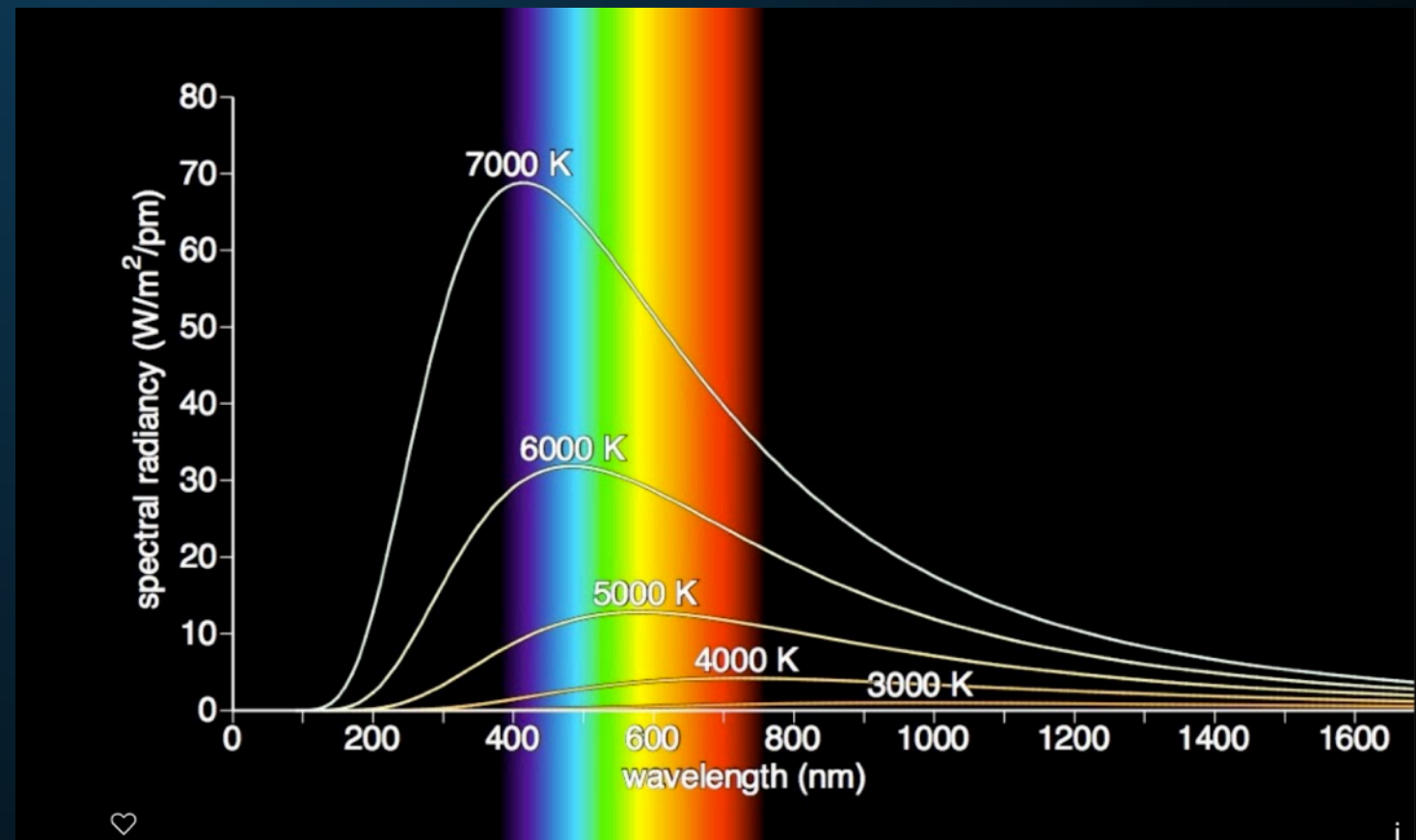
## THERMAL MECHANISMS

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

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



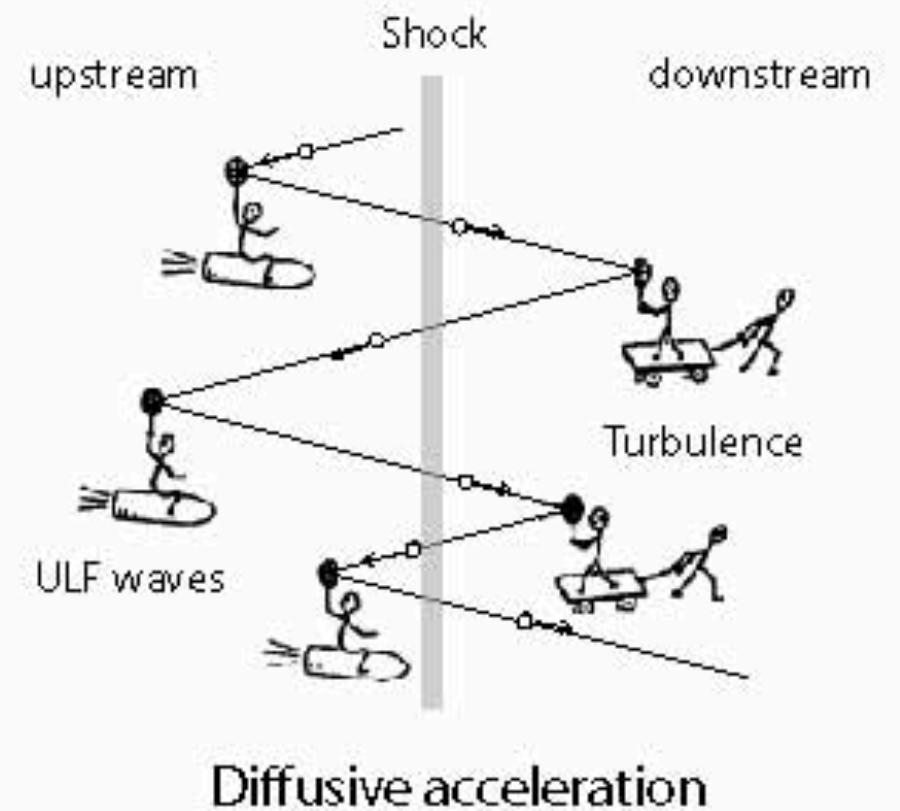
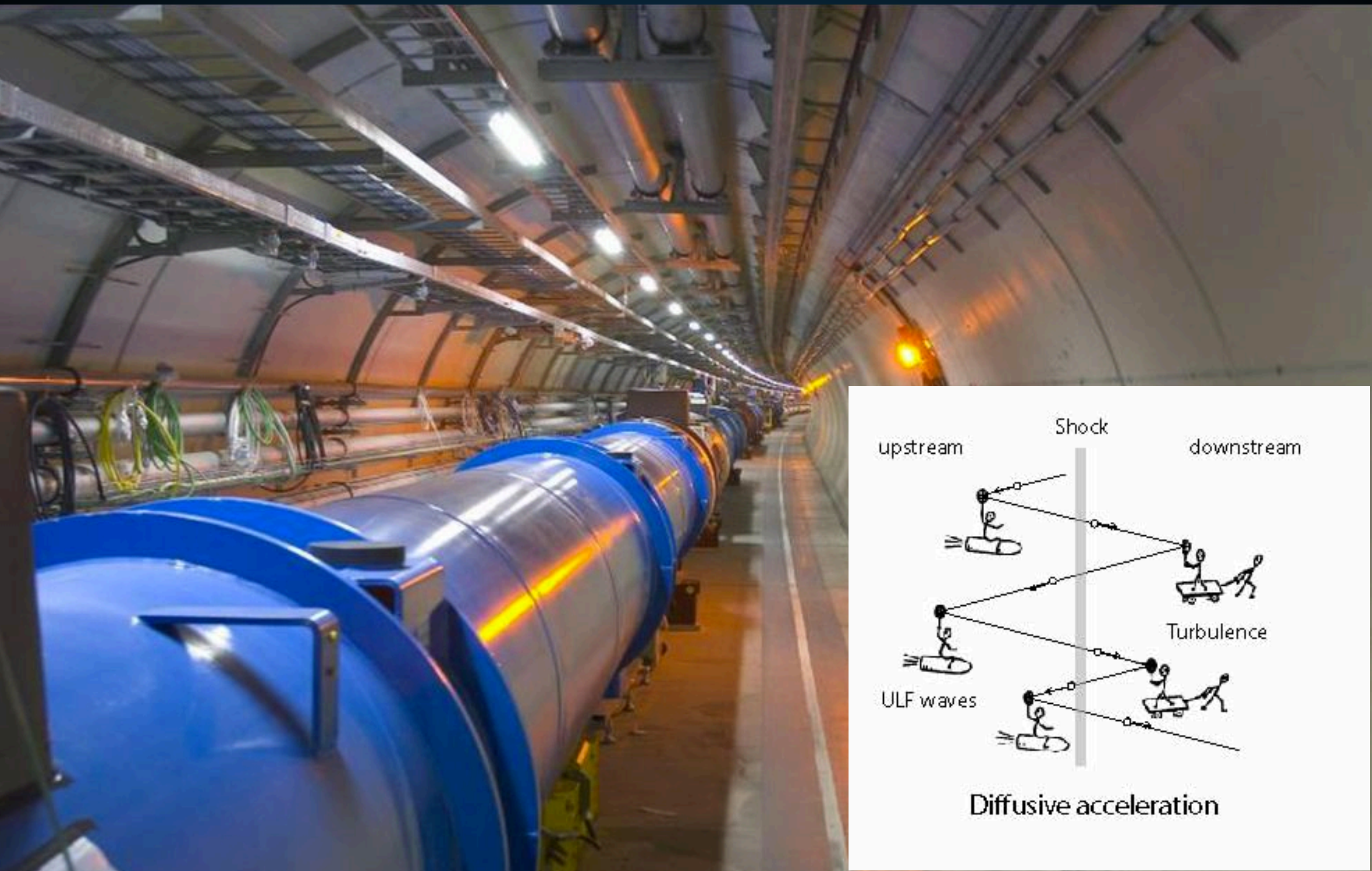
**Thermal production of  
gamma-rays is suppressed  
by  $\exp[-10^9] = 0$**





# GAMMA-RAYS - HOW?

## NON-THERMAL MECHANISMS



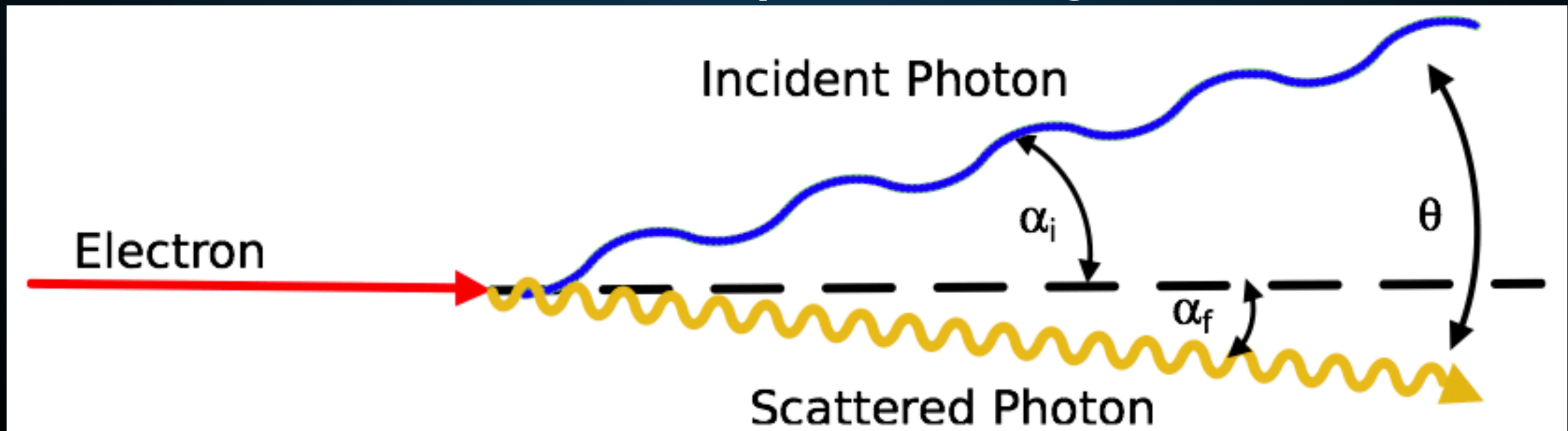


# WHAT IS THE ENERGY SCALE?

## Hadronic Interactions



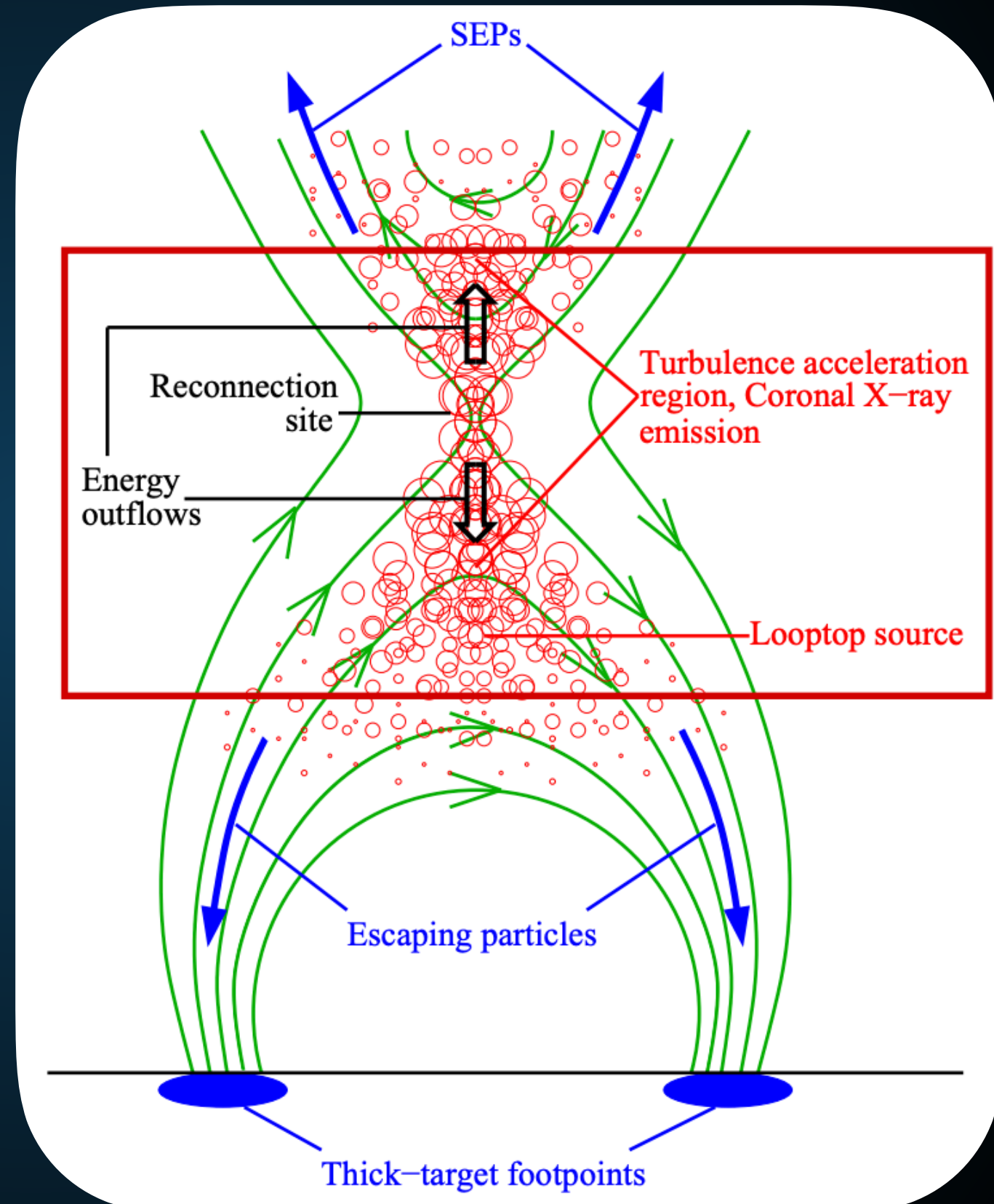
## inverse-Compton Scattering





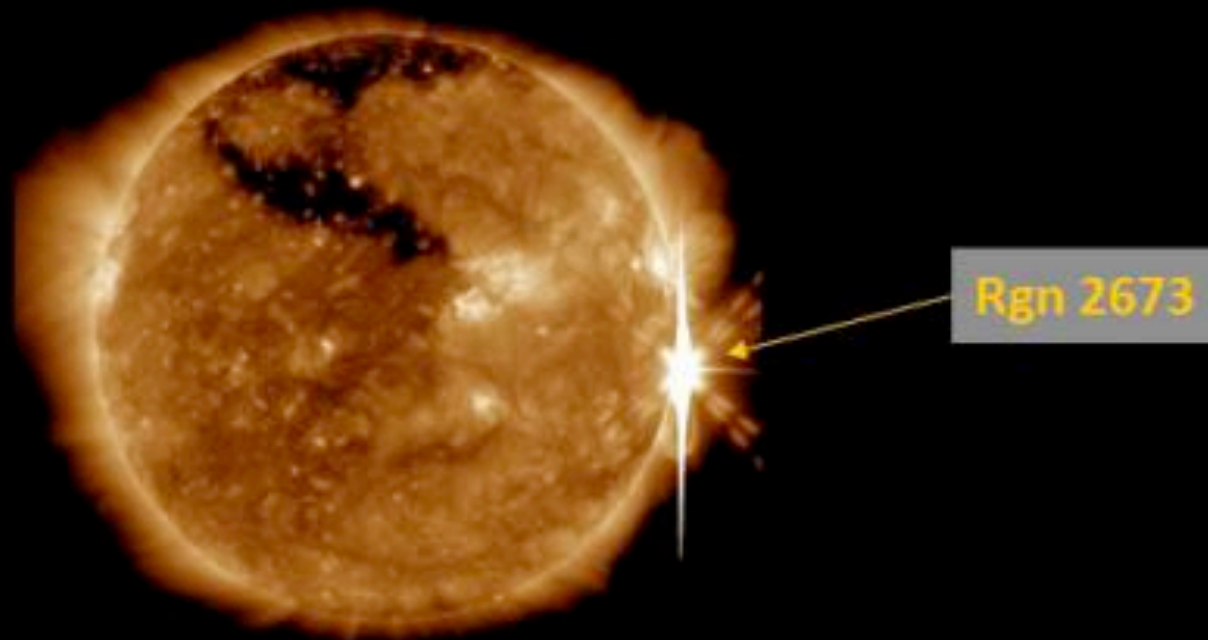
# GAMMA-RAYS - HOW?

- **Solar Flares and Reconnection events.**





## Strong Radio Blackout 10 Sep 17 at 1606 UTC



R3

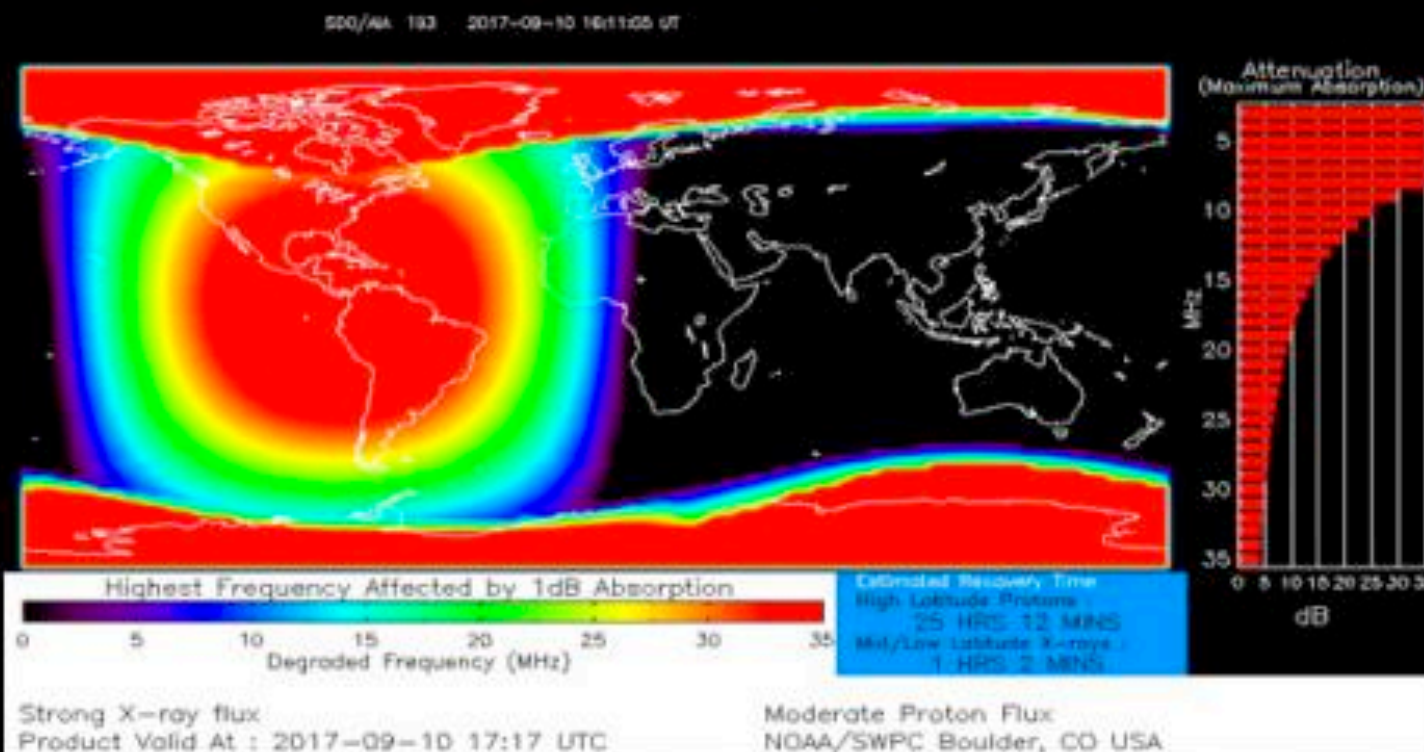
### PRIMARY AREA of IMPACTS

Large portions of sunlit side of Earth

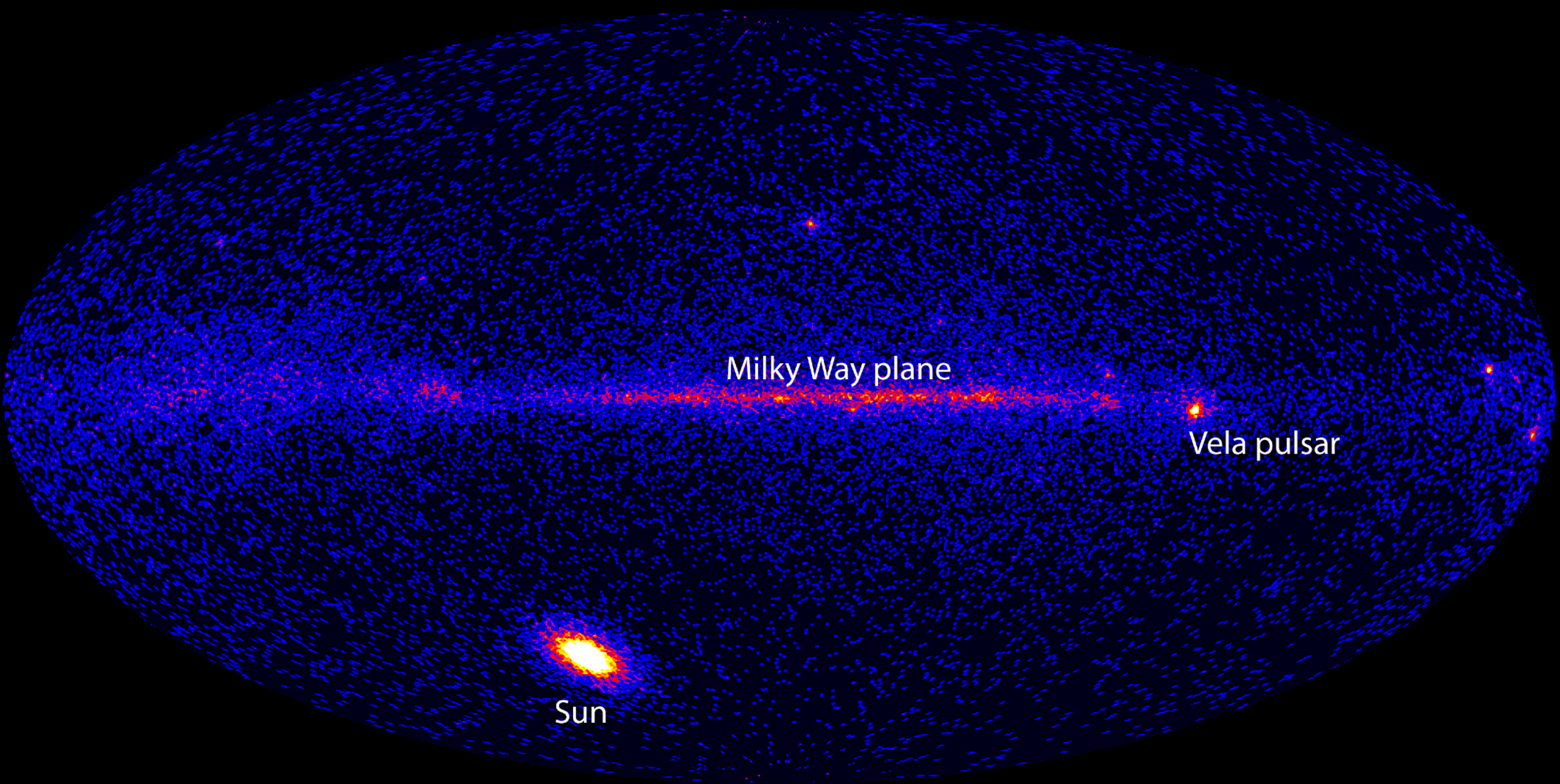
### POSSIBLE EFFECTS

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







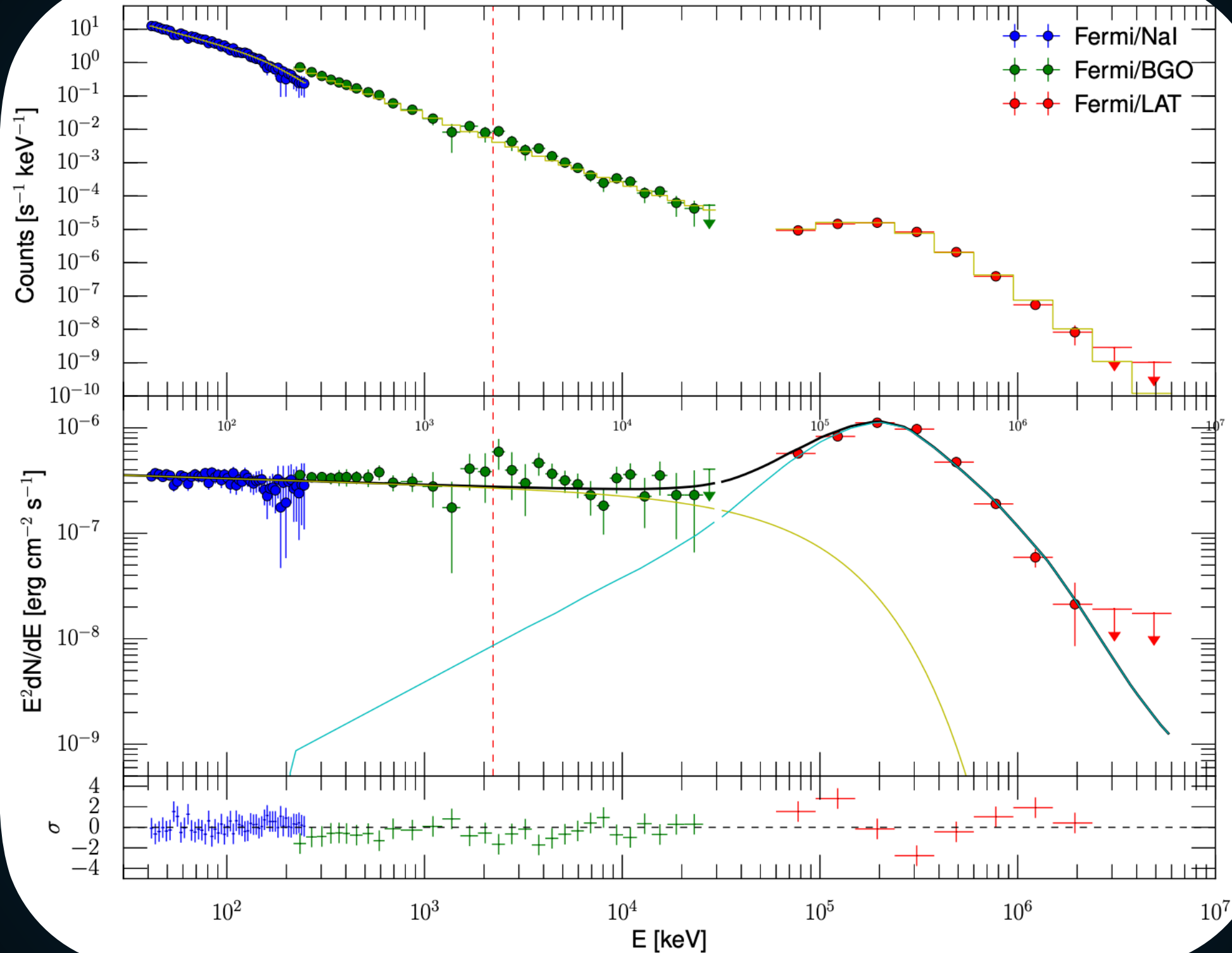
Milky Way plane

Vela pulsar

Sun



# GAMMA-RAYS - HOW?



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

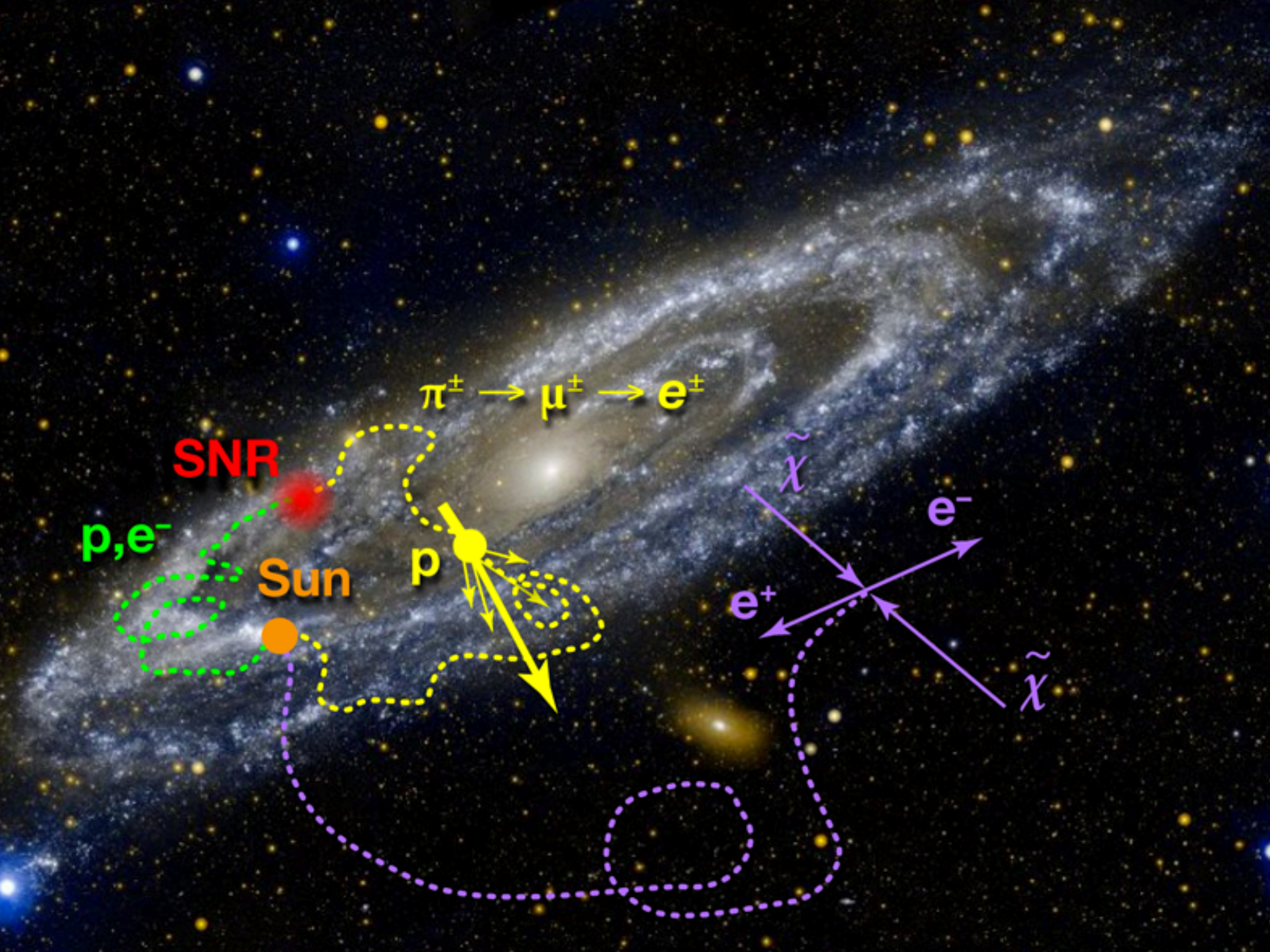


# **Exploiting the Energy of Galactic Cosmic-Rays**





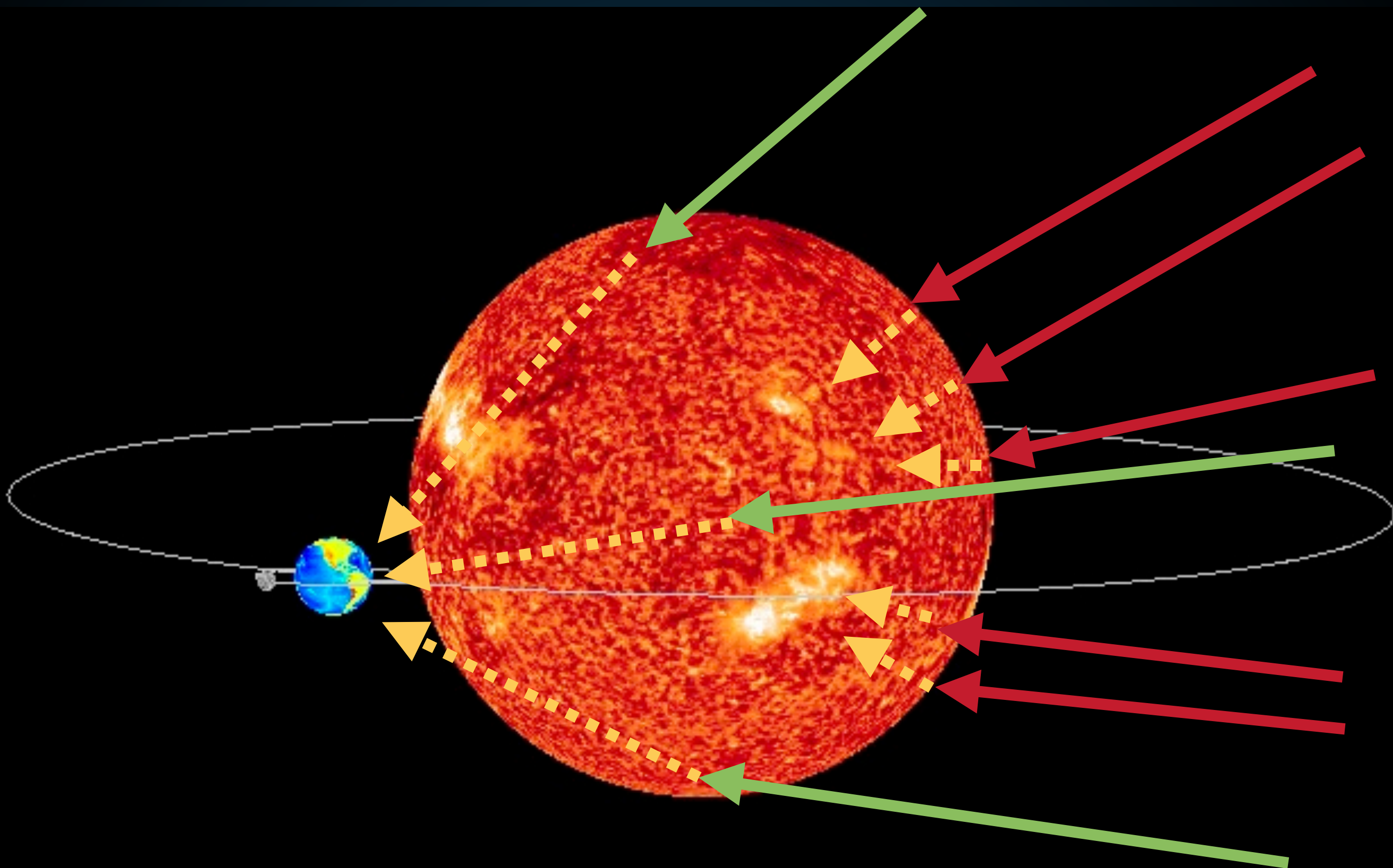






# HADRONIC GAMMA-RAYS - HOW?

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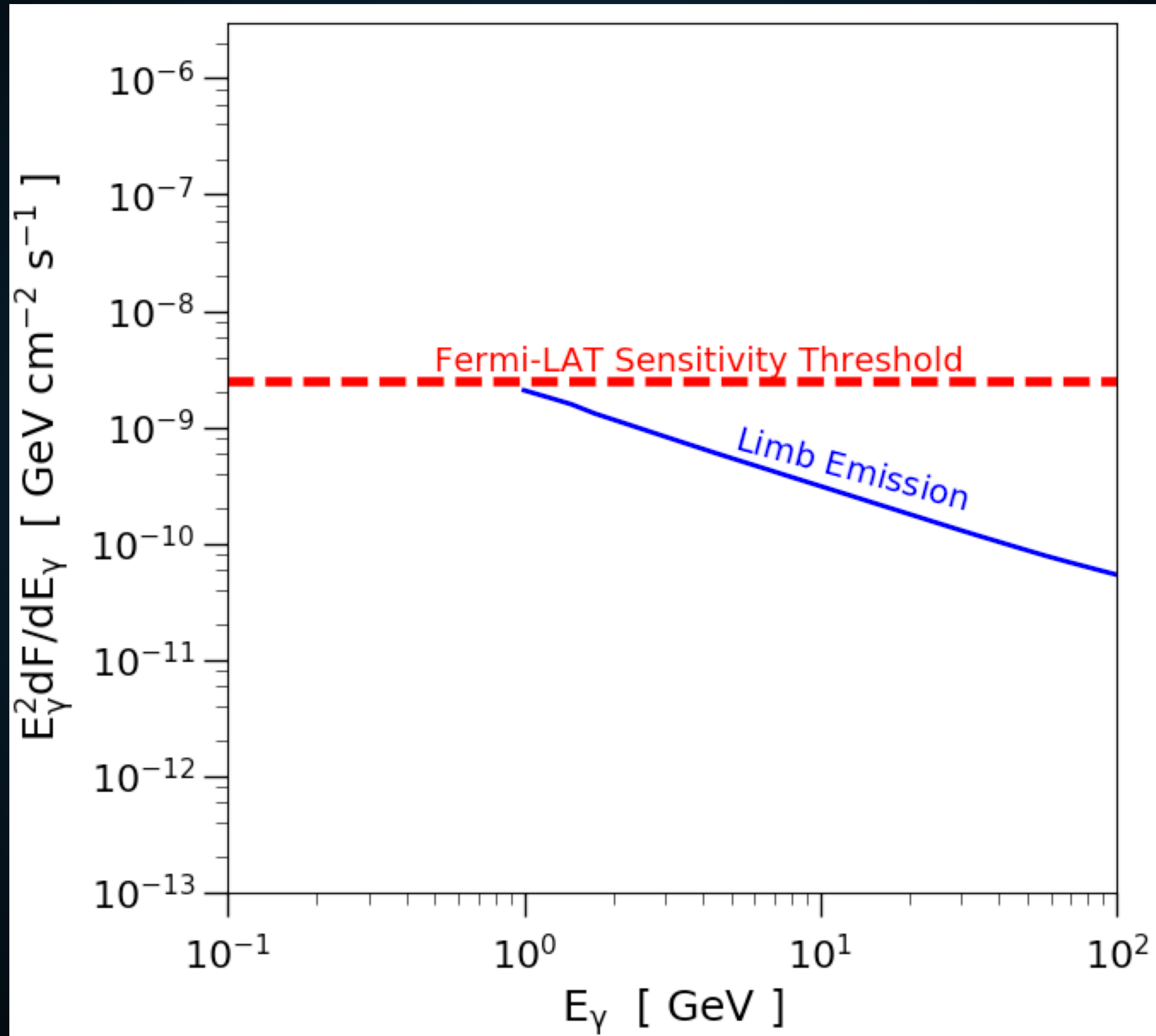
# HADRONIC GAMMA-RAYS - HOW?

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## HADRONIC GAMMA-RAYS - HOW?





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 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  $\gamma$ -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.

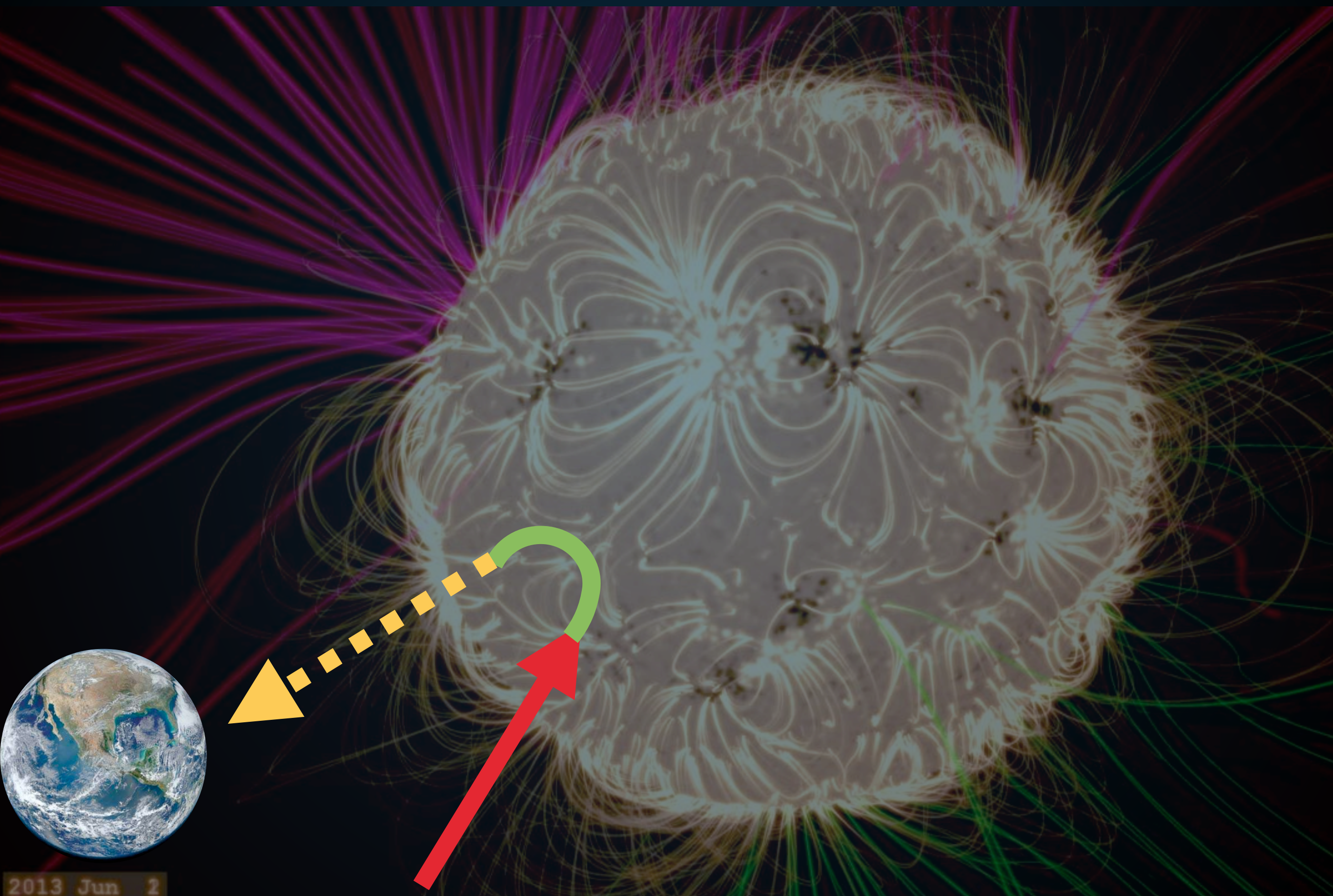
Third, to calculate fluxes from the Sun, one must take into account the details of the solar atmosphere. For example, typical cascades will take place in a less dense environment than for Earth, and that increases the yields of some by-products.

Despite these uncertainties, it is possible to make some quick



# HADRONIC GAMMA-RAYS - HOW?

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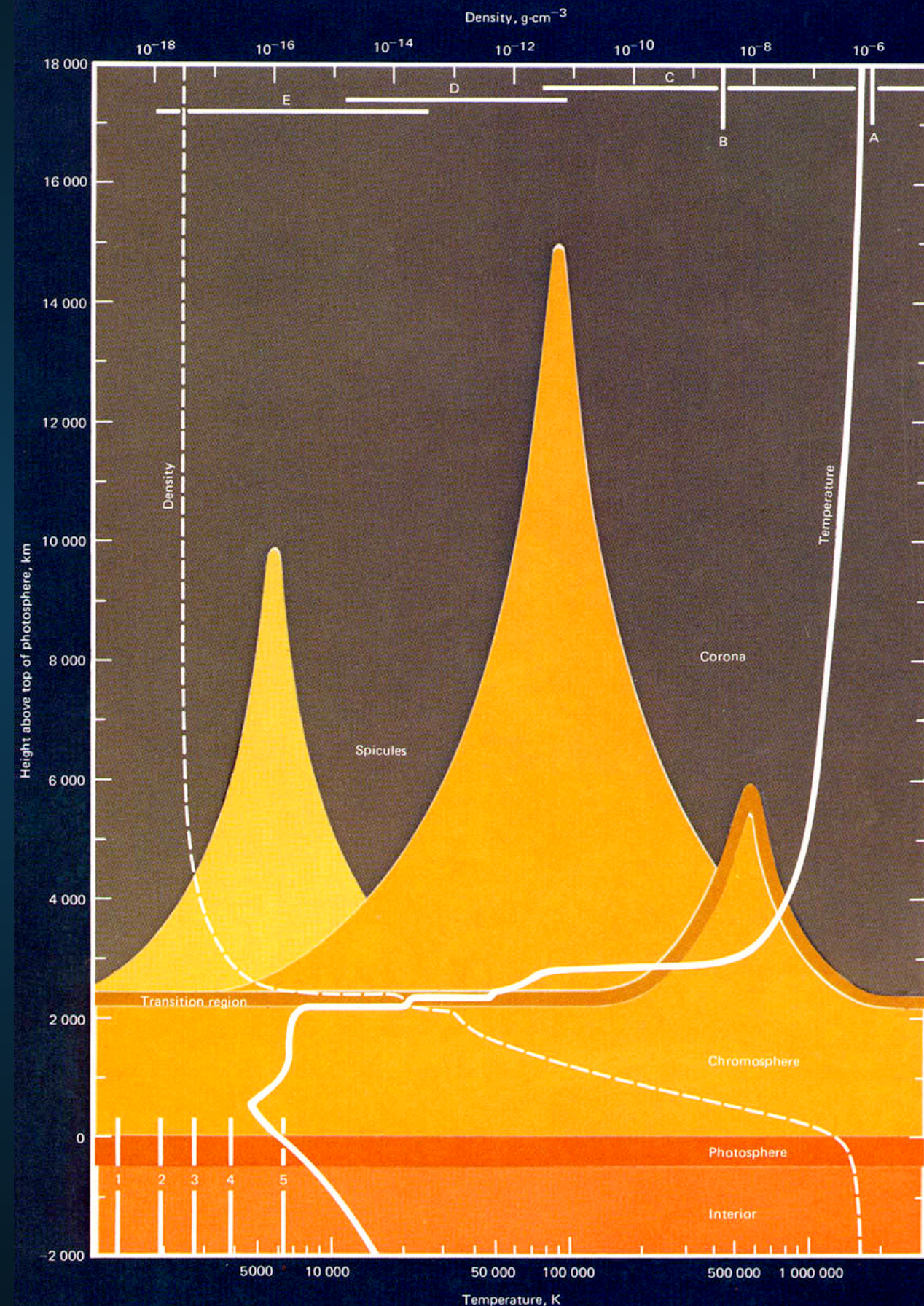
# HADRONIC GAMMA-RAYS - HOW?

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

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

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

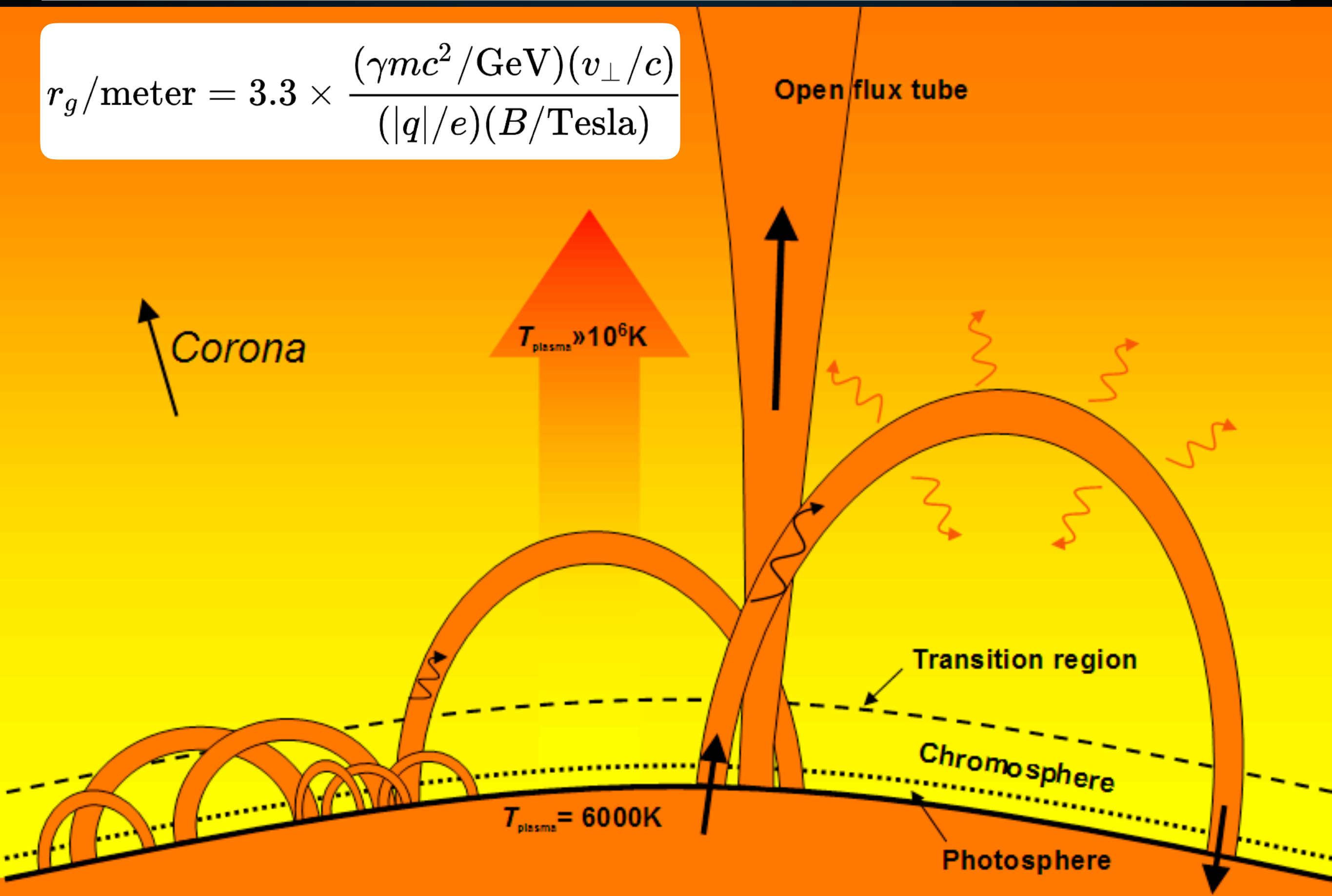
- **Cosmic rays encounter a grammage of 330 g cm<sup>-2</sup>**
- **Cosmic rays die before reflecting within the solar surface.**





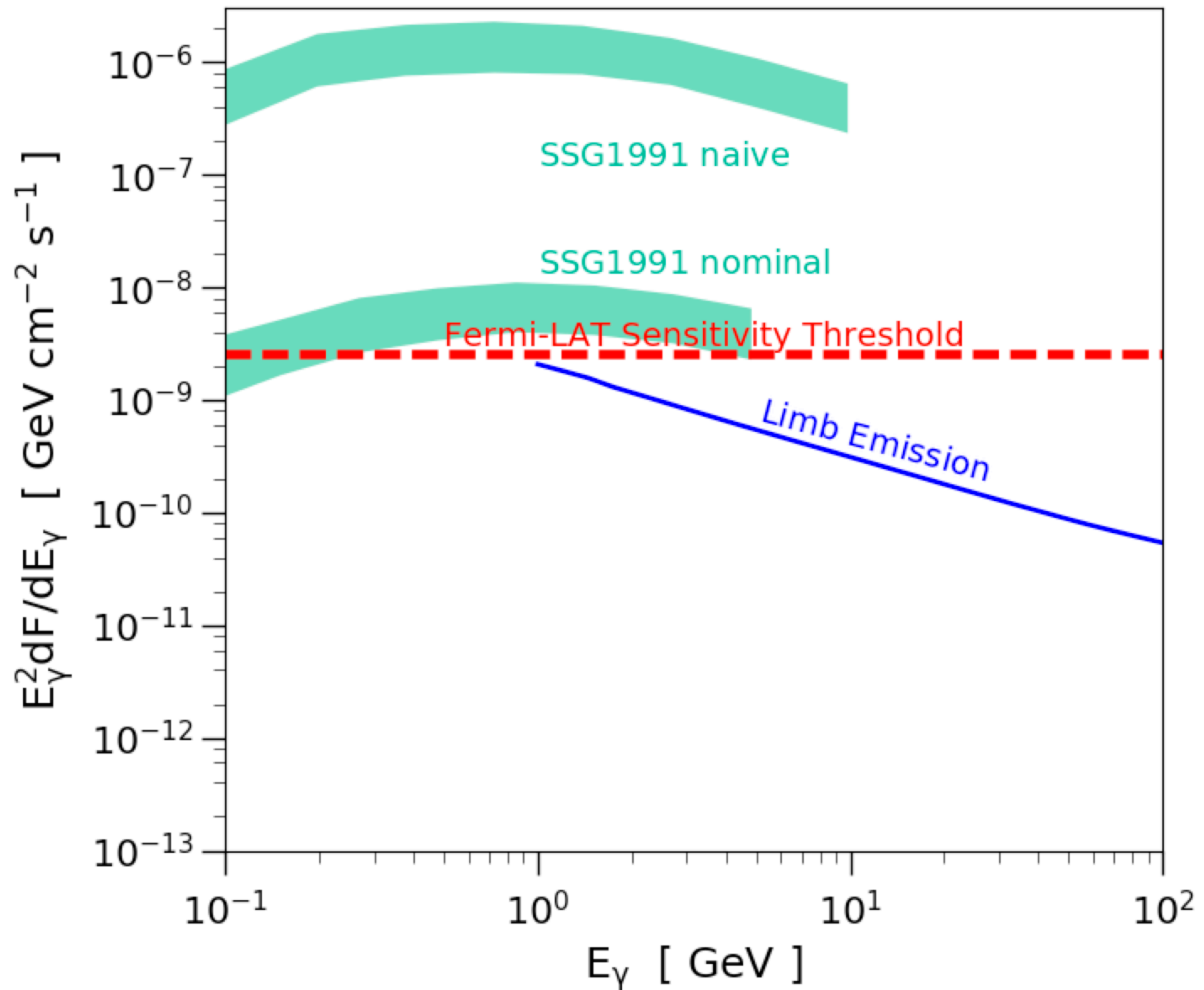
# HADRONIC GAMMA-RAYS - HOW?

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





# HADRONIC GAMMA-RAYS - HOW?





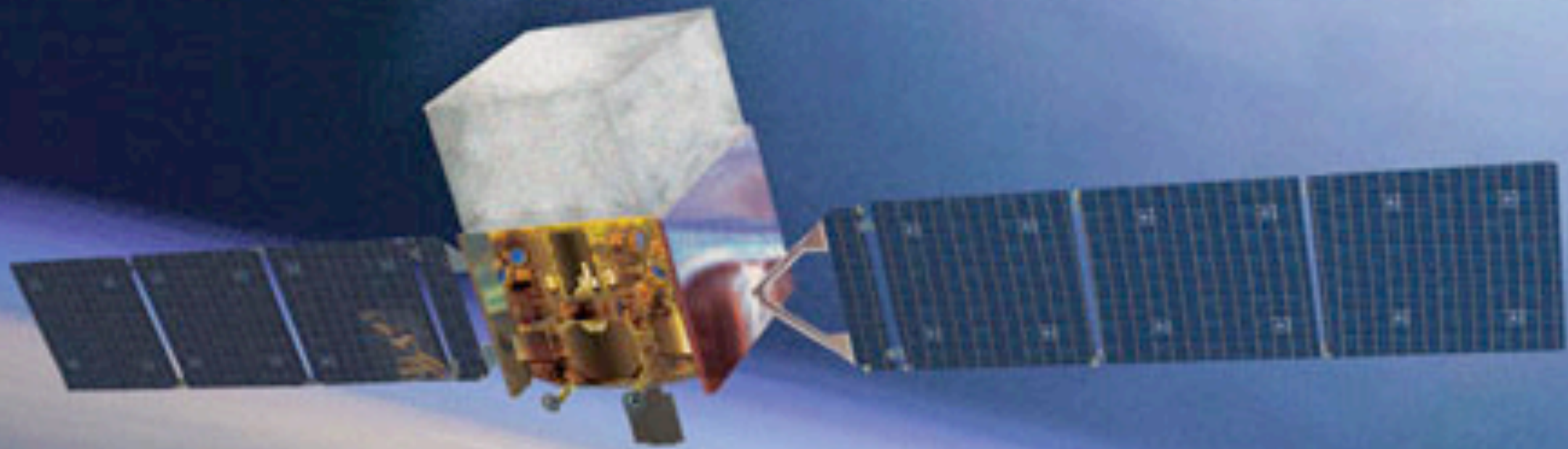
**Let the observations be your guide...**



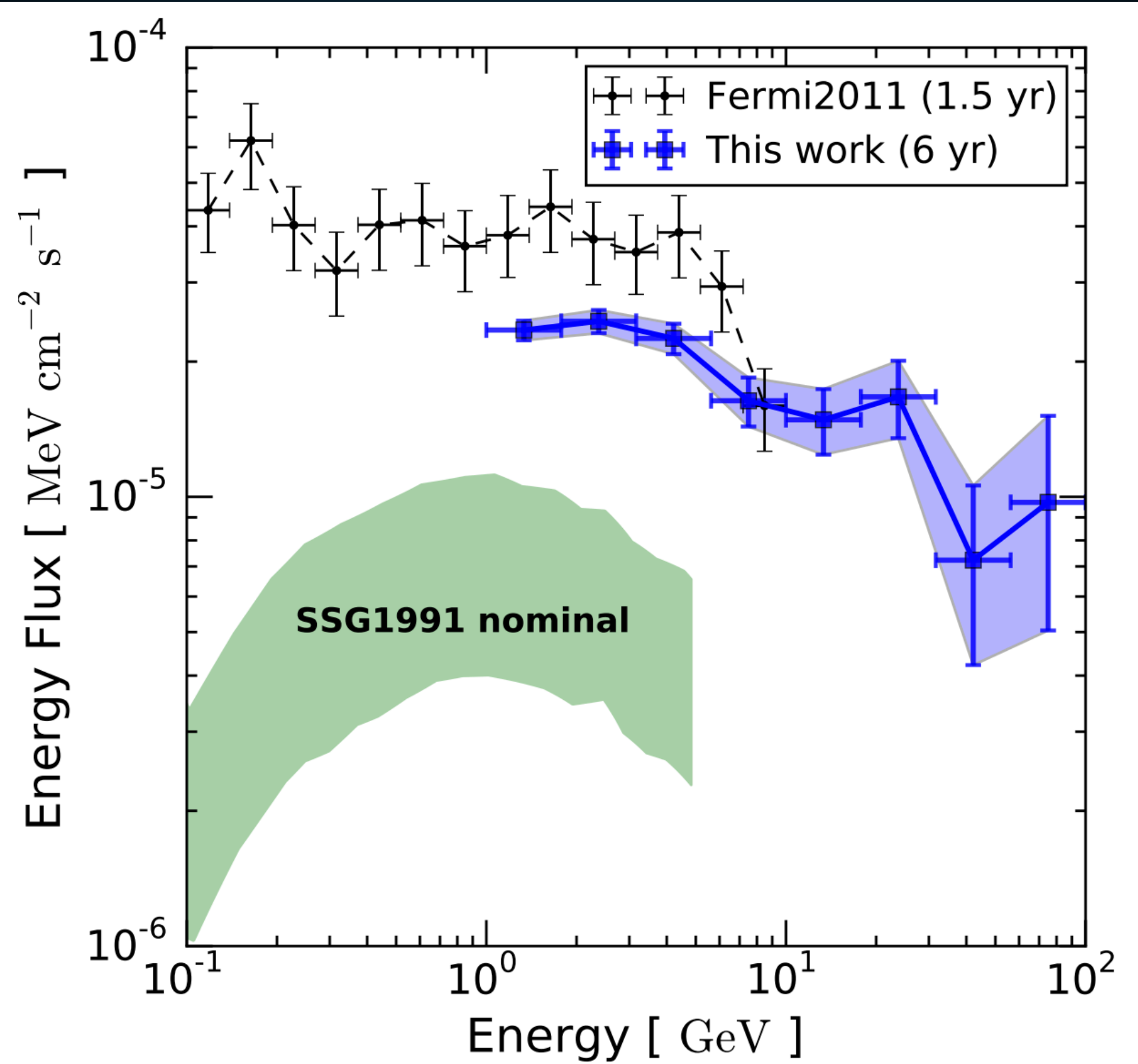


# GAMMA-RAYS - WHAT?

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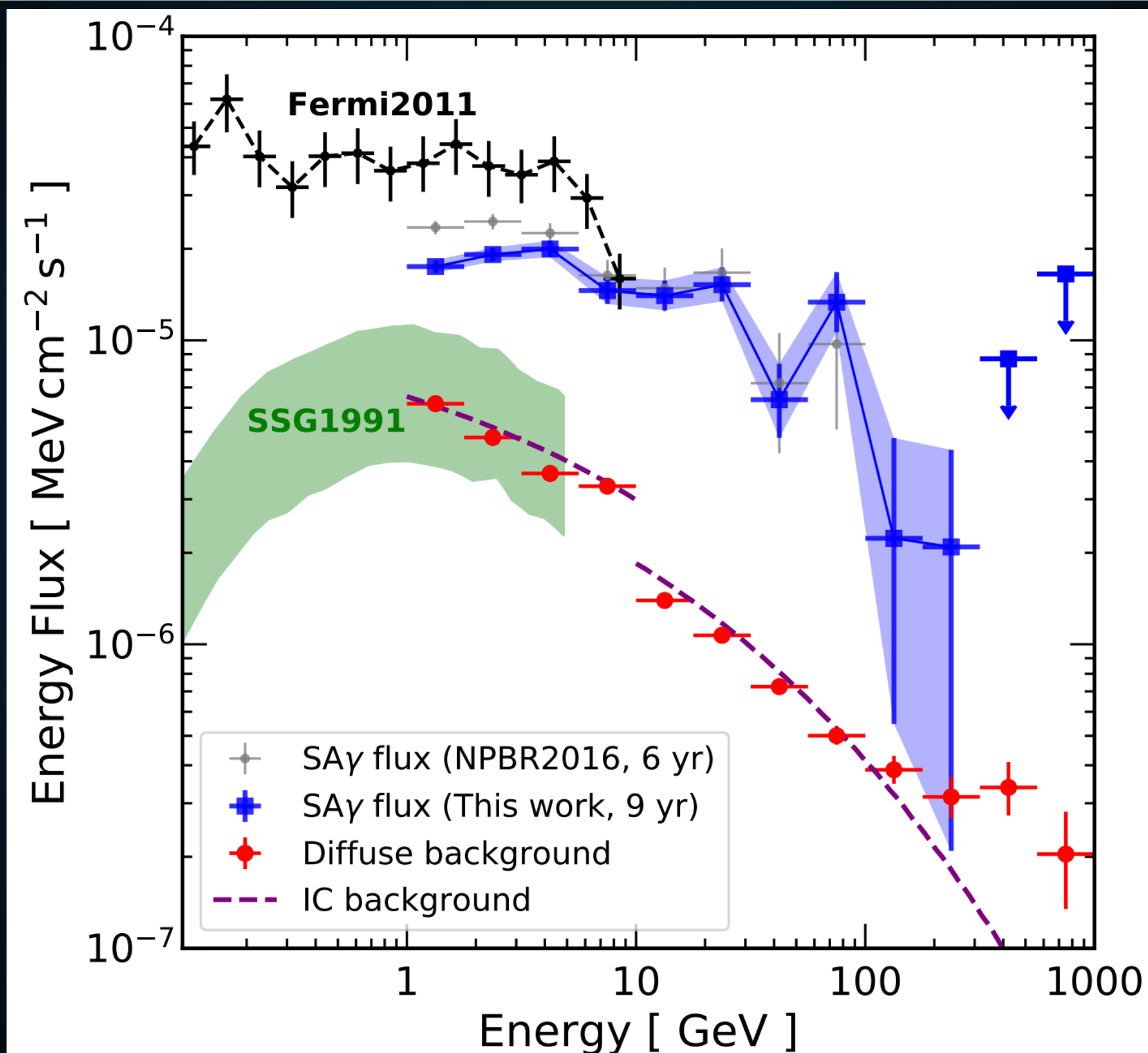
## GAMMA-RAYS - WHAT?

---

**Intensity**

**X**







## GAMMA-RAYS - WHAT?

---

**Intensity**

**X**

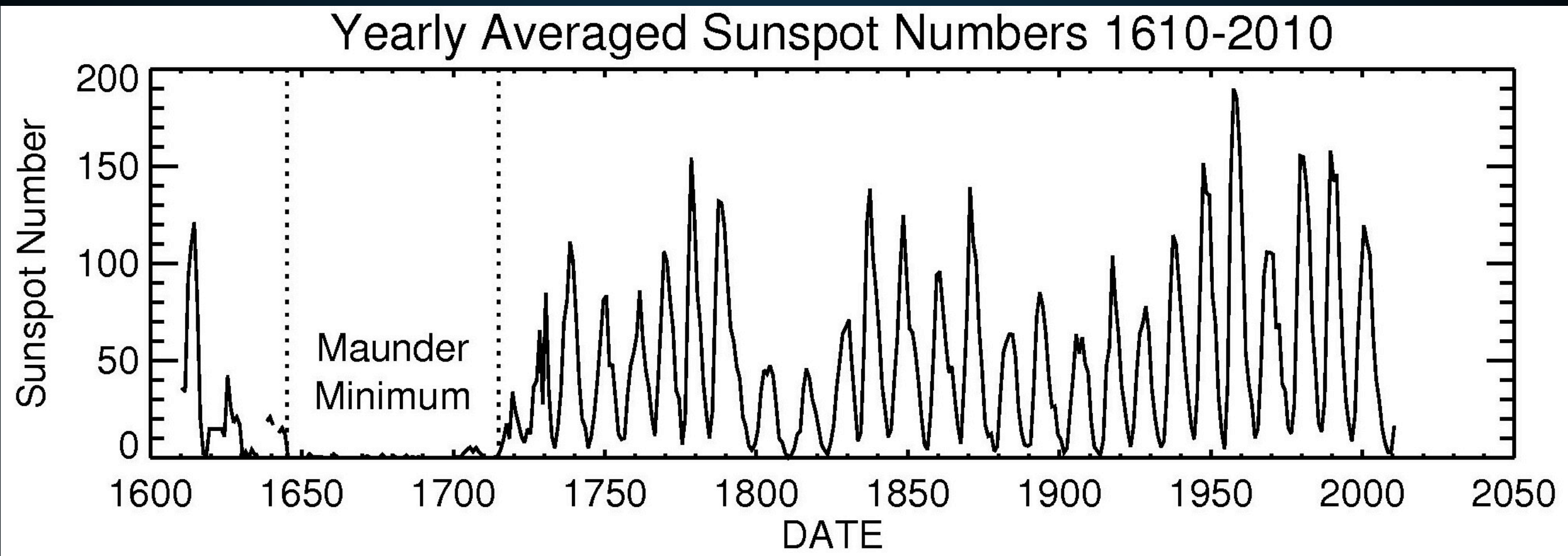
**Spectrum**

**X**



## OBSERVATIONS - TIME VARIABILITY

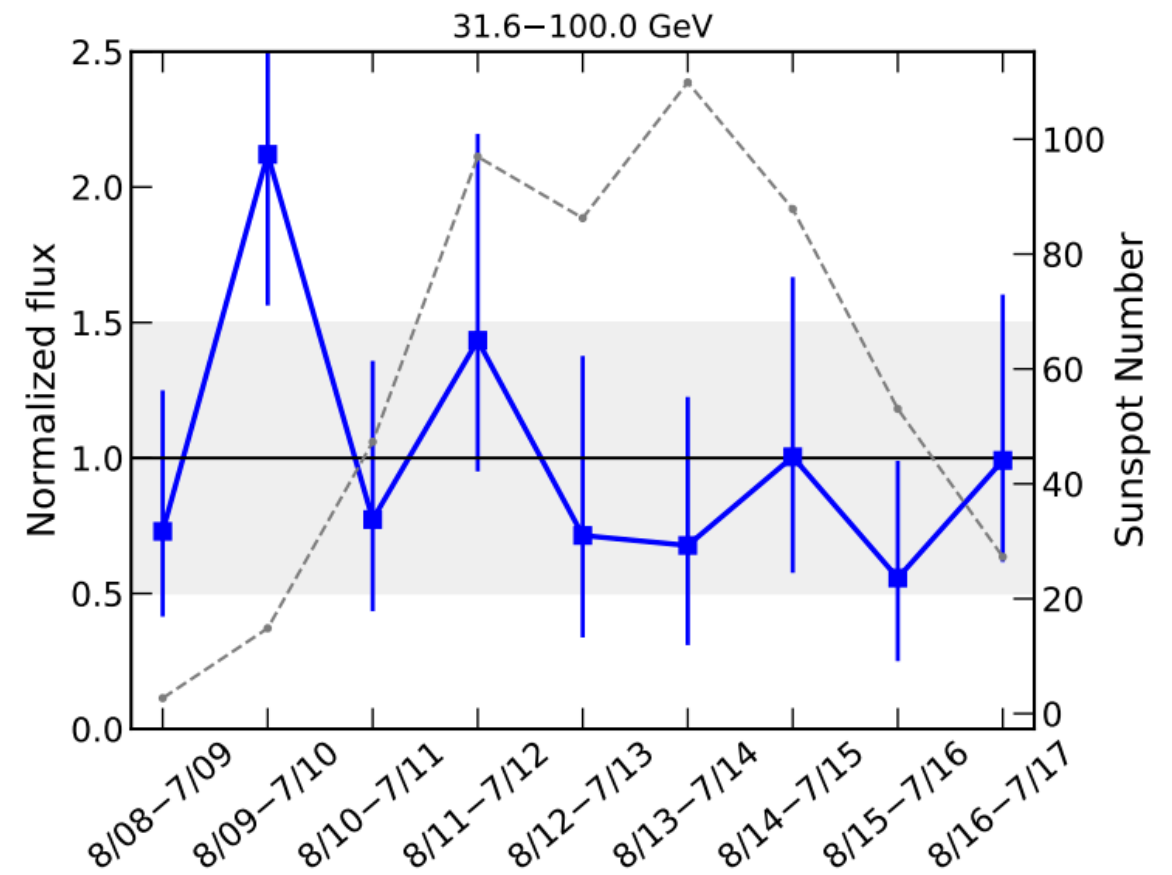
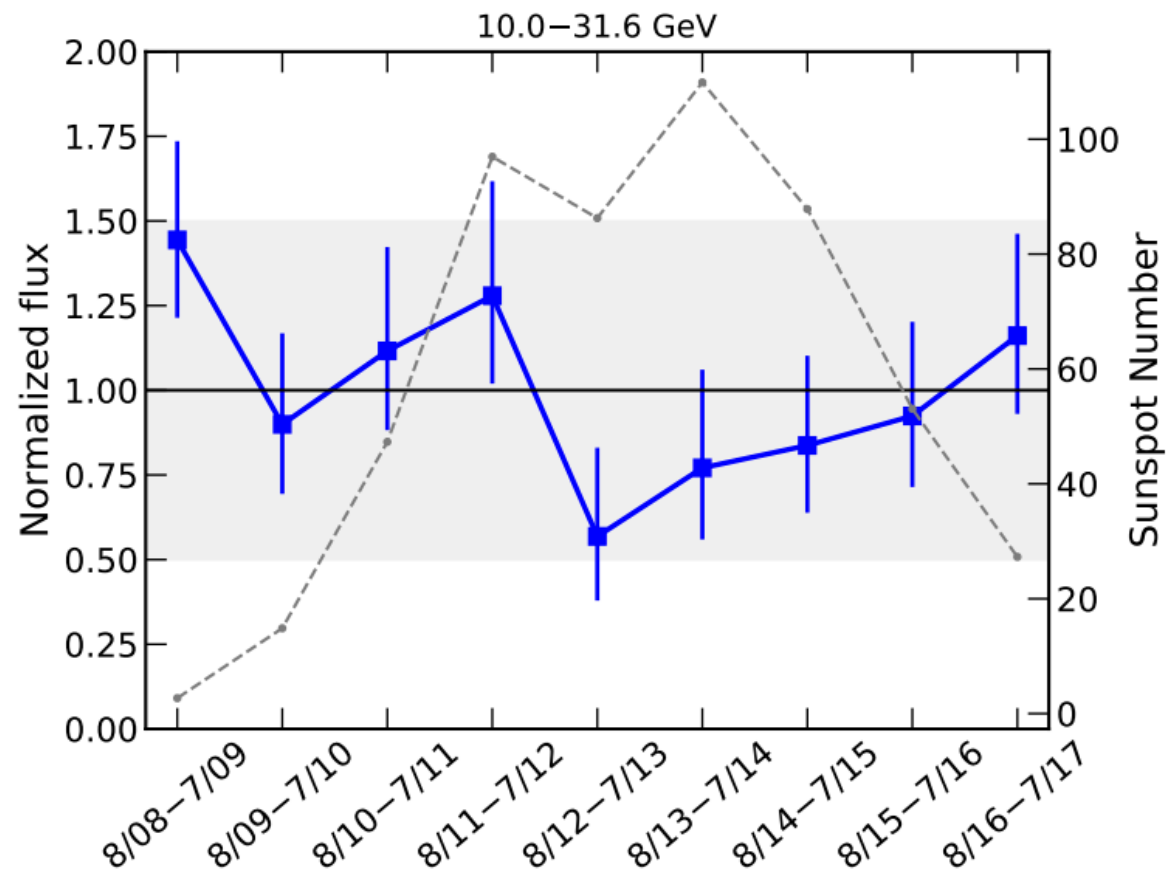
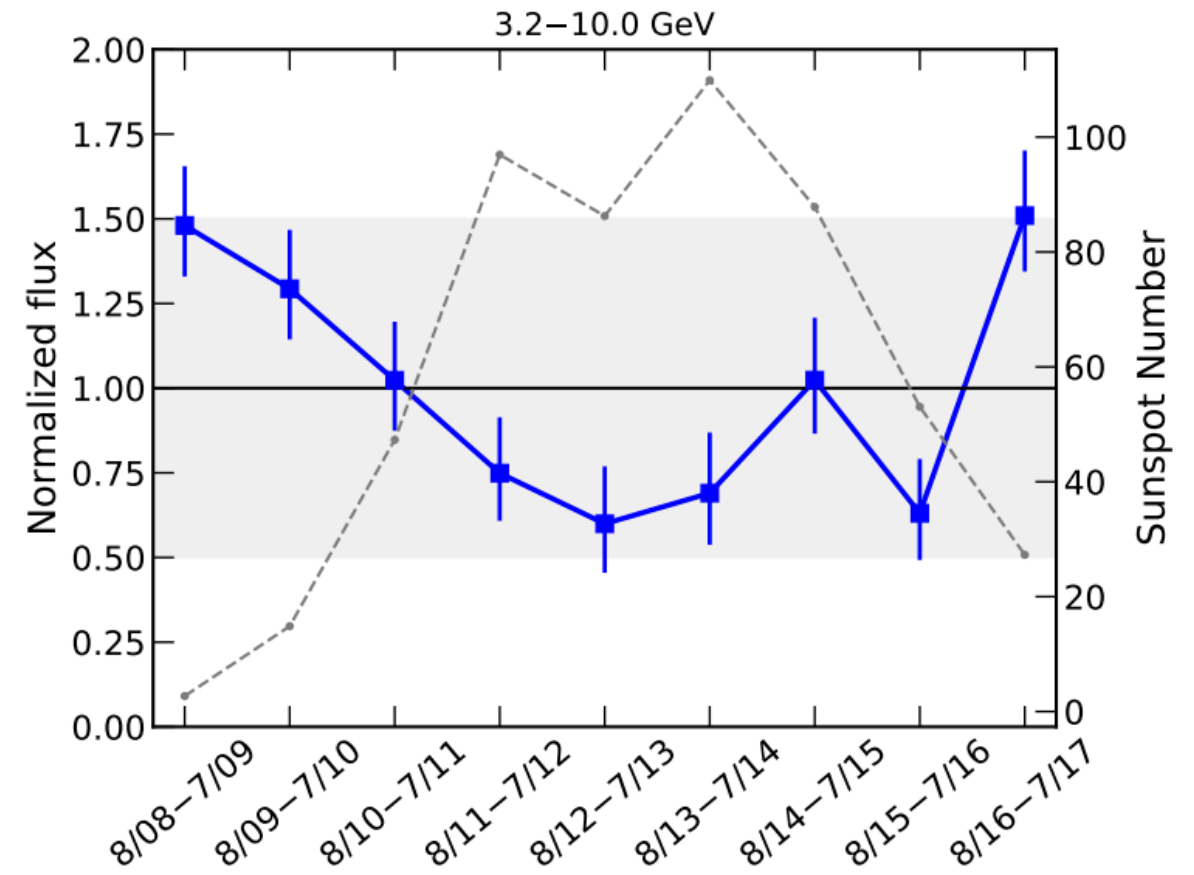
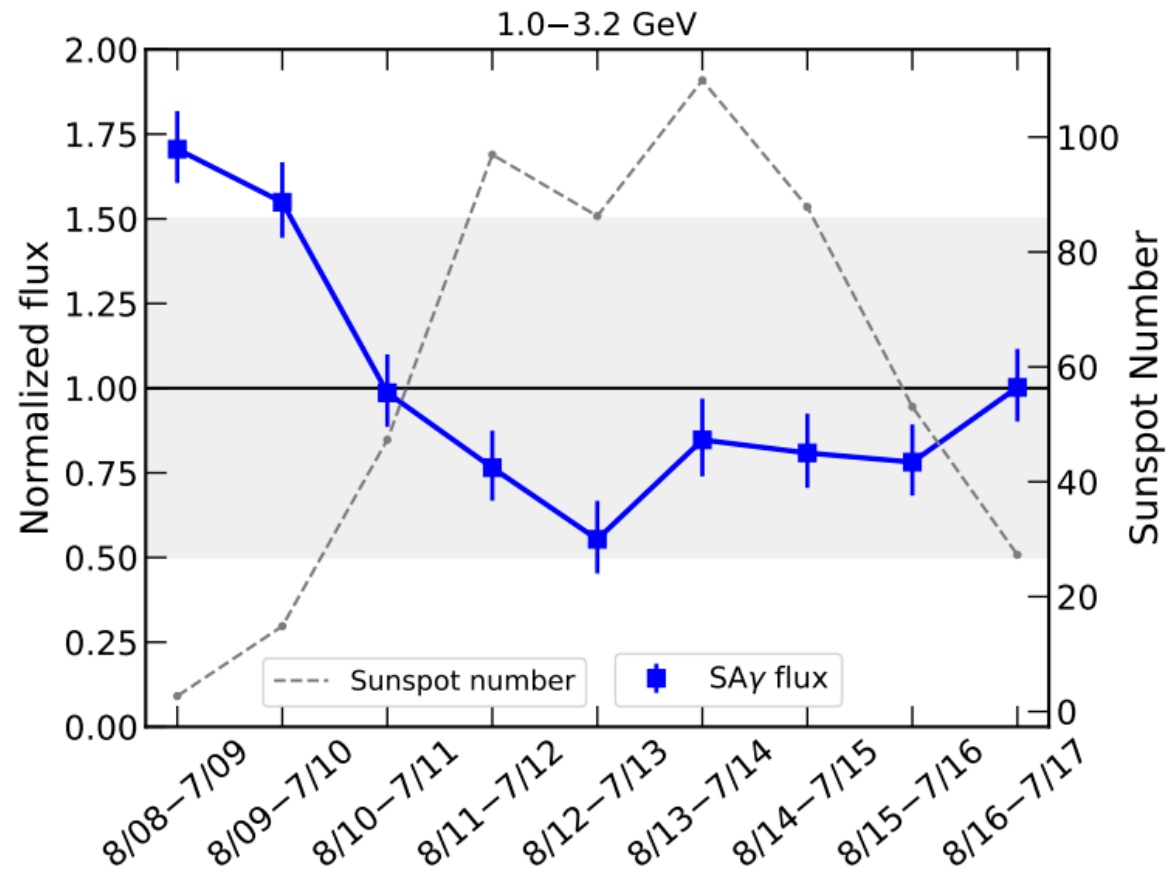
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# OBSERVATIONS - TIME VARIABILITY

Tang et al. 2018 (1804.06846)





## GAMMA-RAYS - WHAT?

---

**Intensity**

**X**

**Spectrum**

**X**

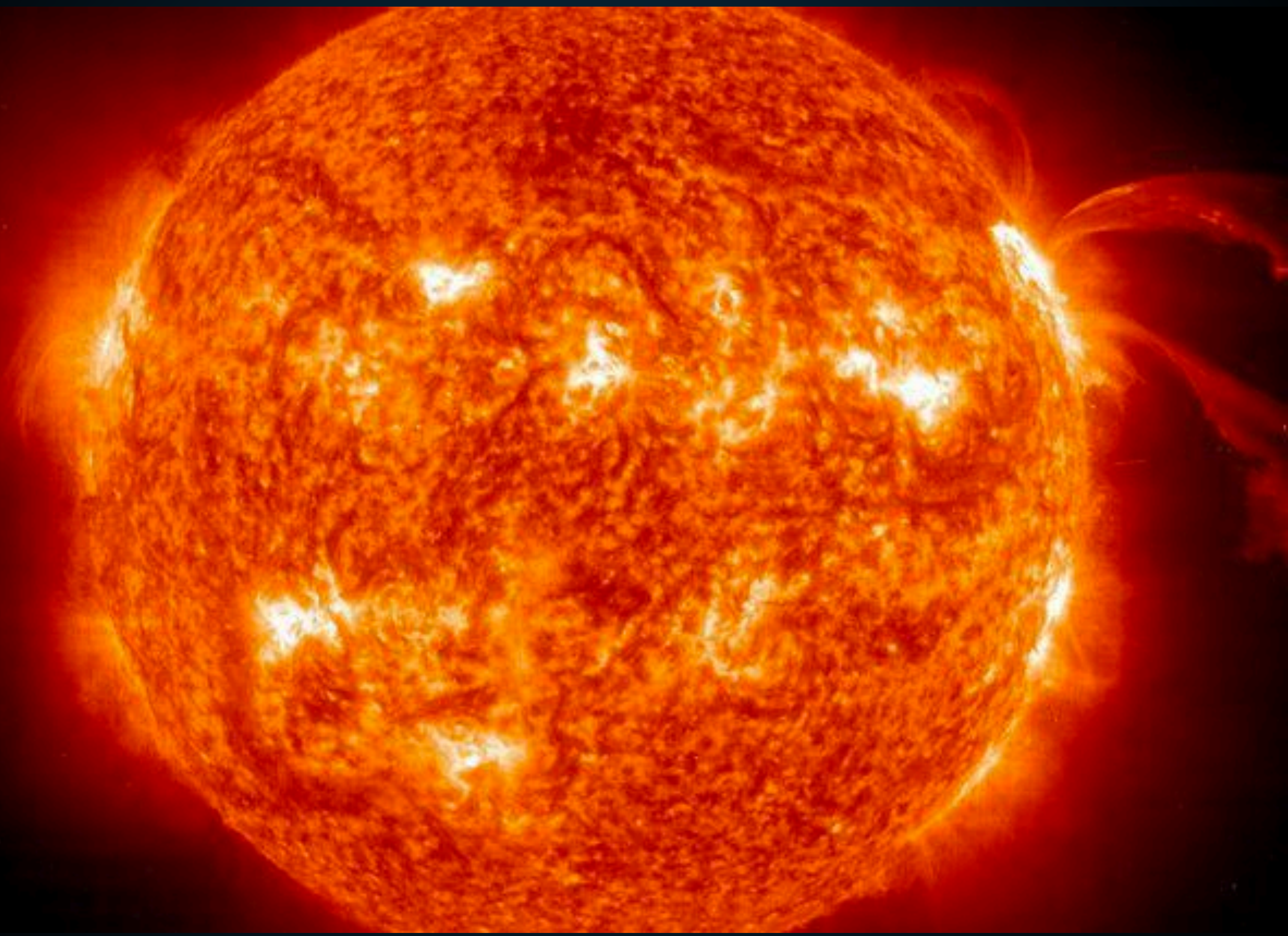
**Time Variability**

**X**

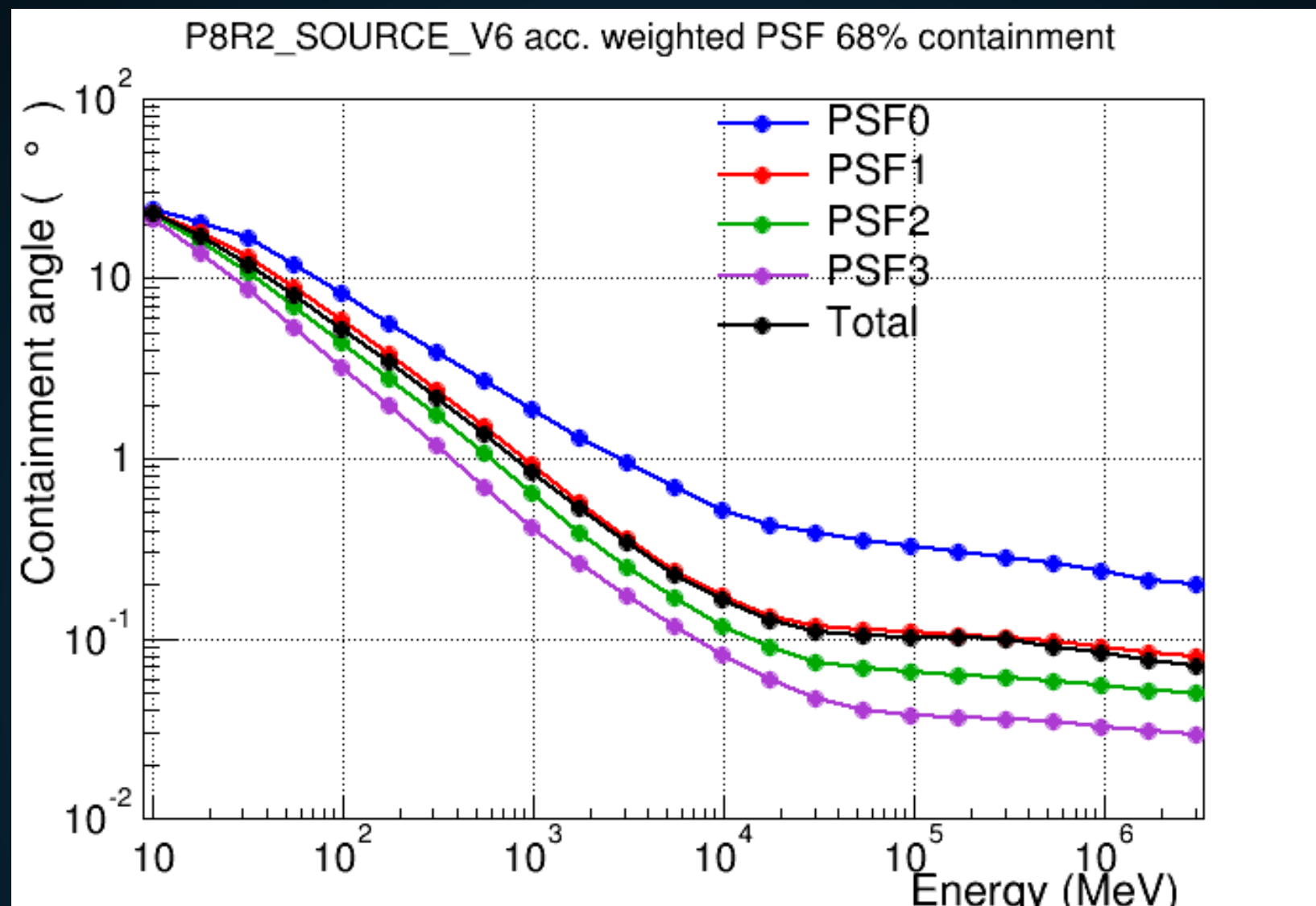


# A MORPHOLOGICAL STUDY

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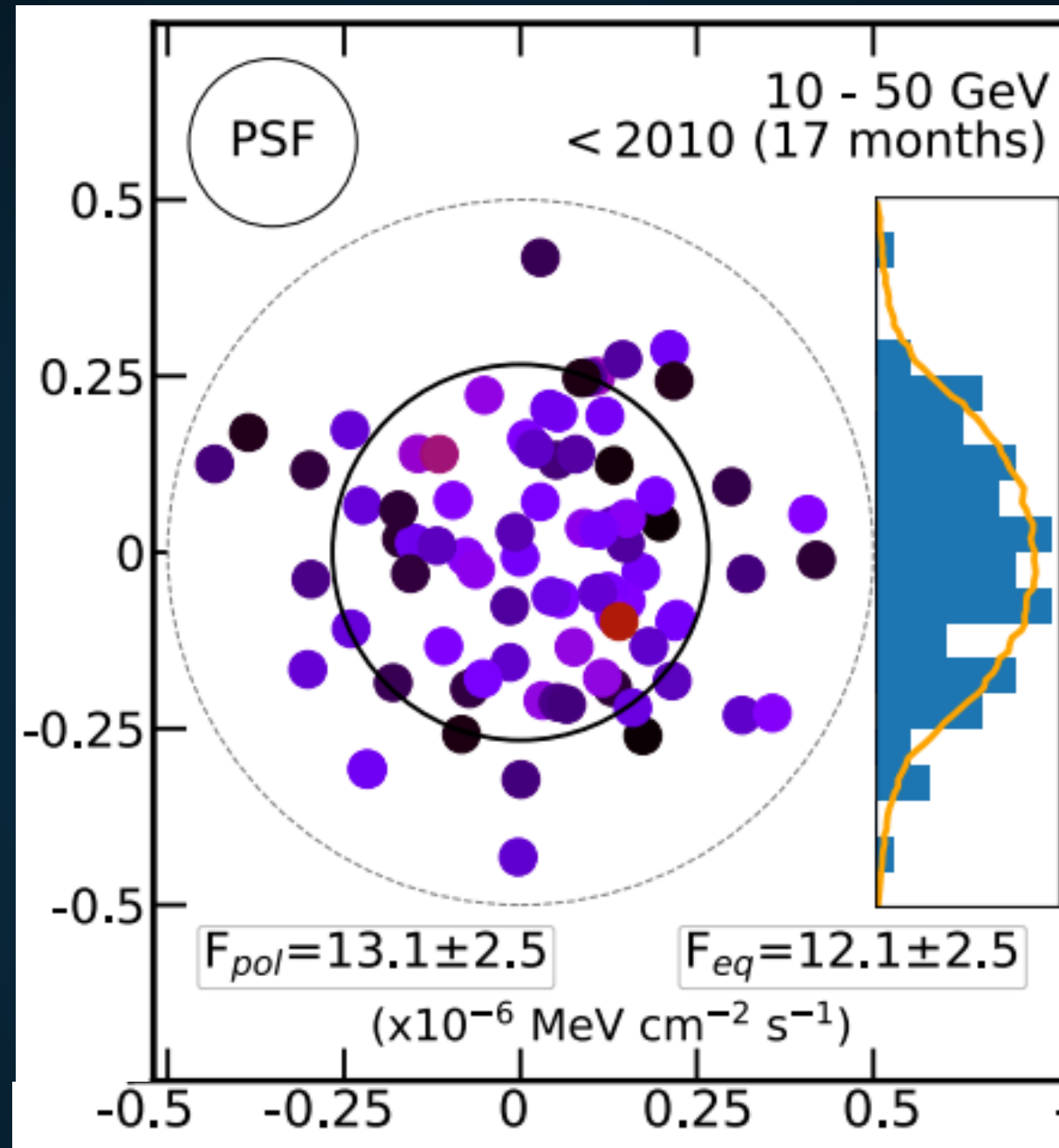
## A MORPHOLOGICAL STUDY



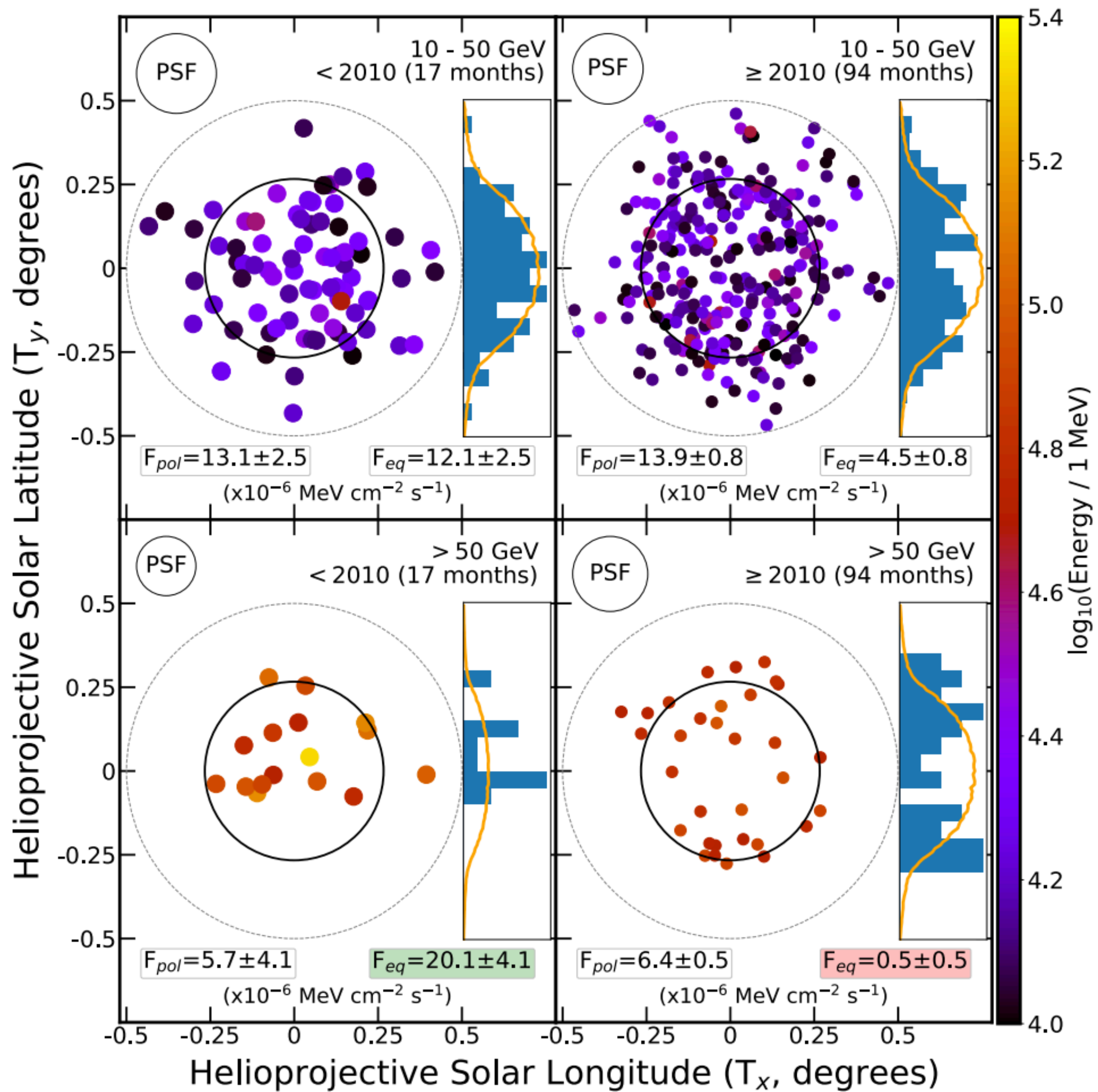
- Examine 9 years of gamma-ray data.
- Re-map each photon into Helioprojective Coordinates to conserve solar rotation and position.
- Examine events  $>10$  GeV, where  $\text{PSF} < \Theta_0$ .



## A MORPHOLOGICAL STUDY



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





## GAMMA-RAYS - WHAT?

---

**Intensity**

**X**

**Spectrum**

**X**

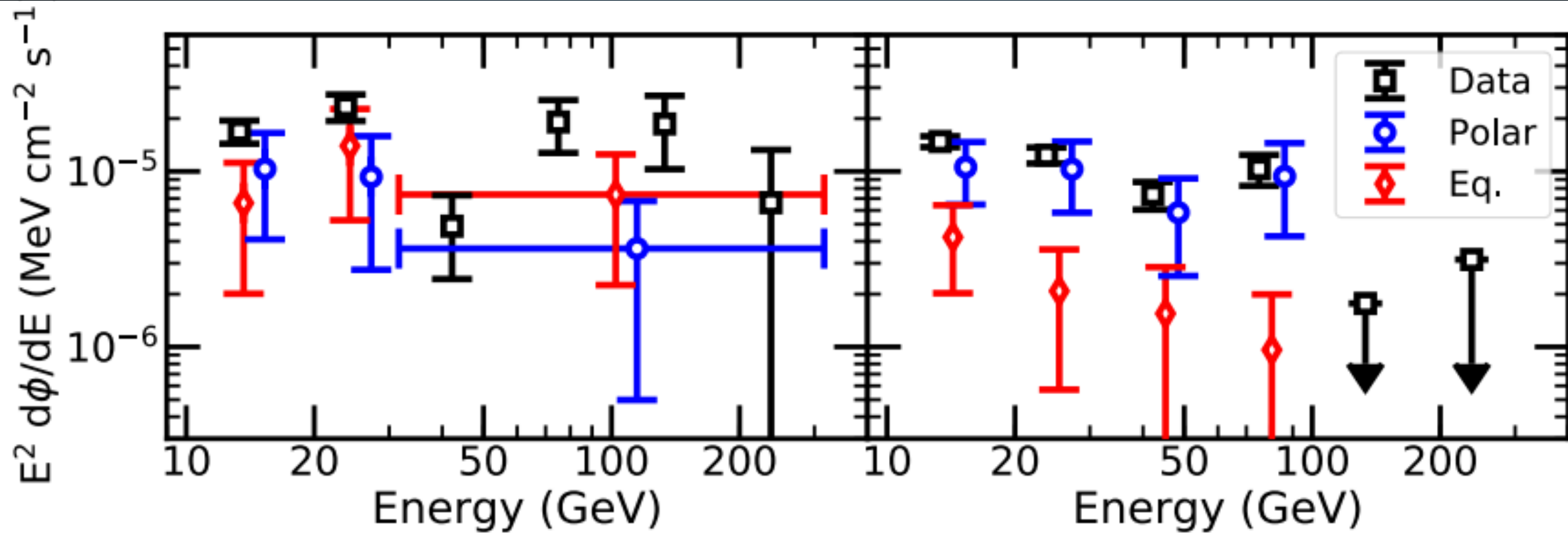
**Time Variability**

**X**

**Morphology**

**X**

## 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.



## 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.

*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  $0.36^\circ$  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  $0.5^\circ$  of the sun since 2009. The event may be connected to a Earth-bound CME observed on February 12, 2018.<sup>1</sup> Preliminary work indicates that this event increases the significance of the  $>100$  GeV time variability above  $5\sigma$ , 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**

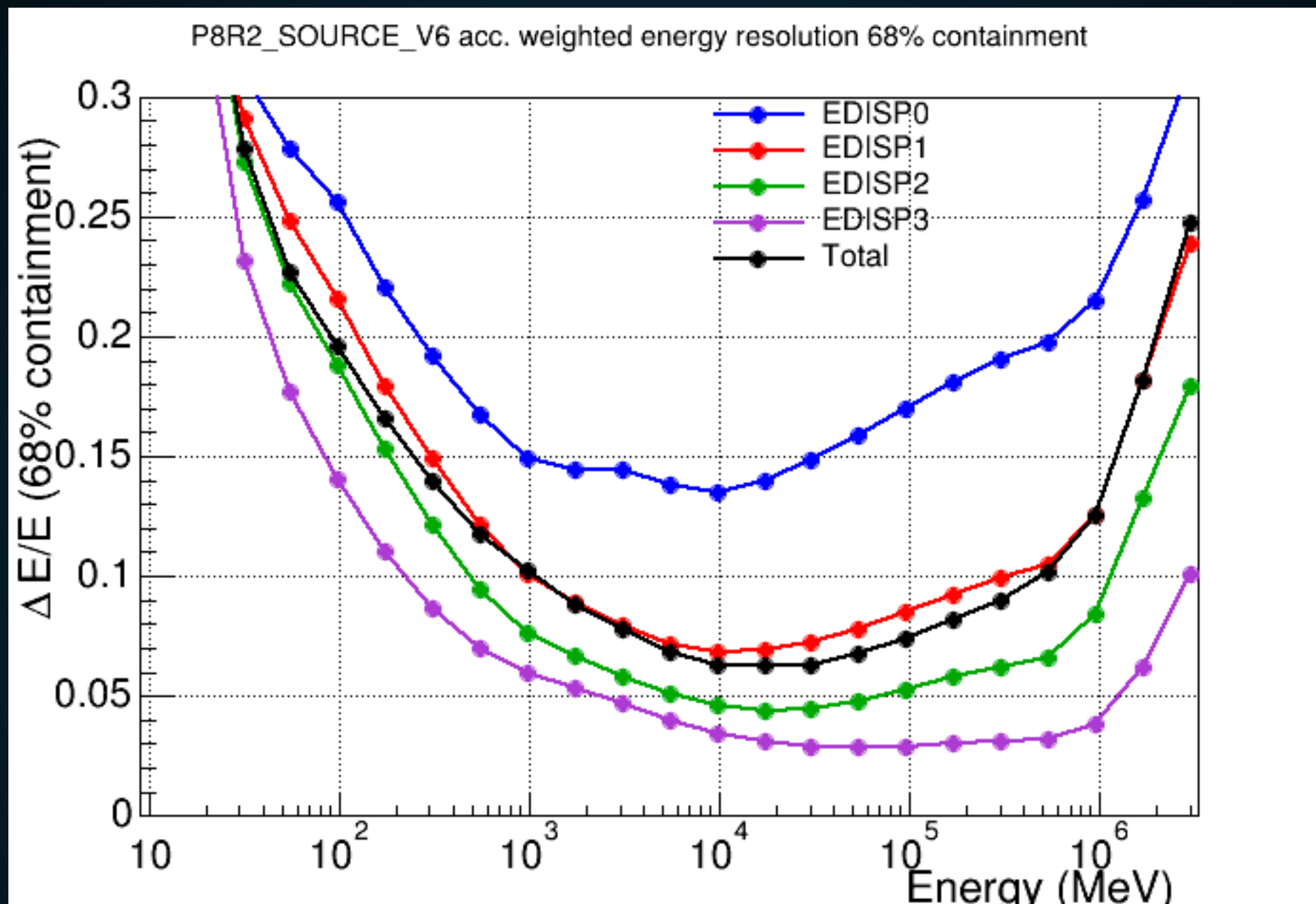
**Morphology**

**X**

**Spectral Variability**

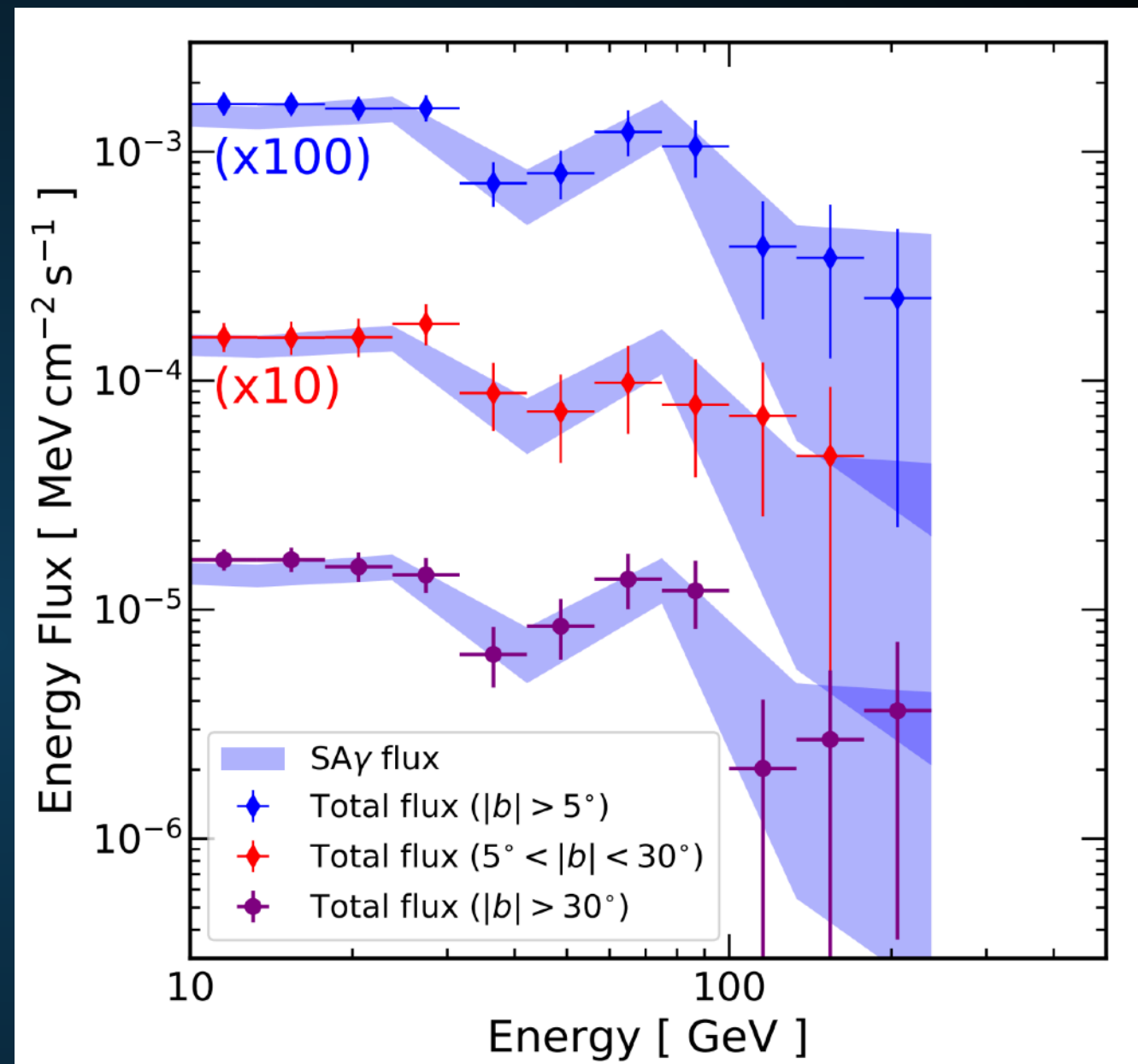
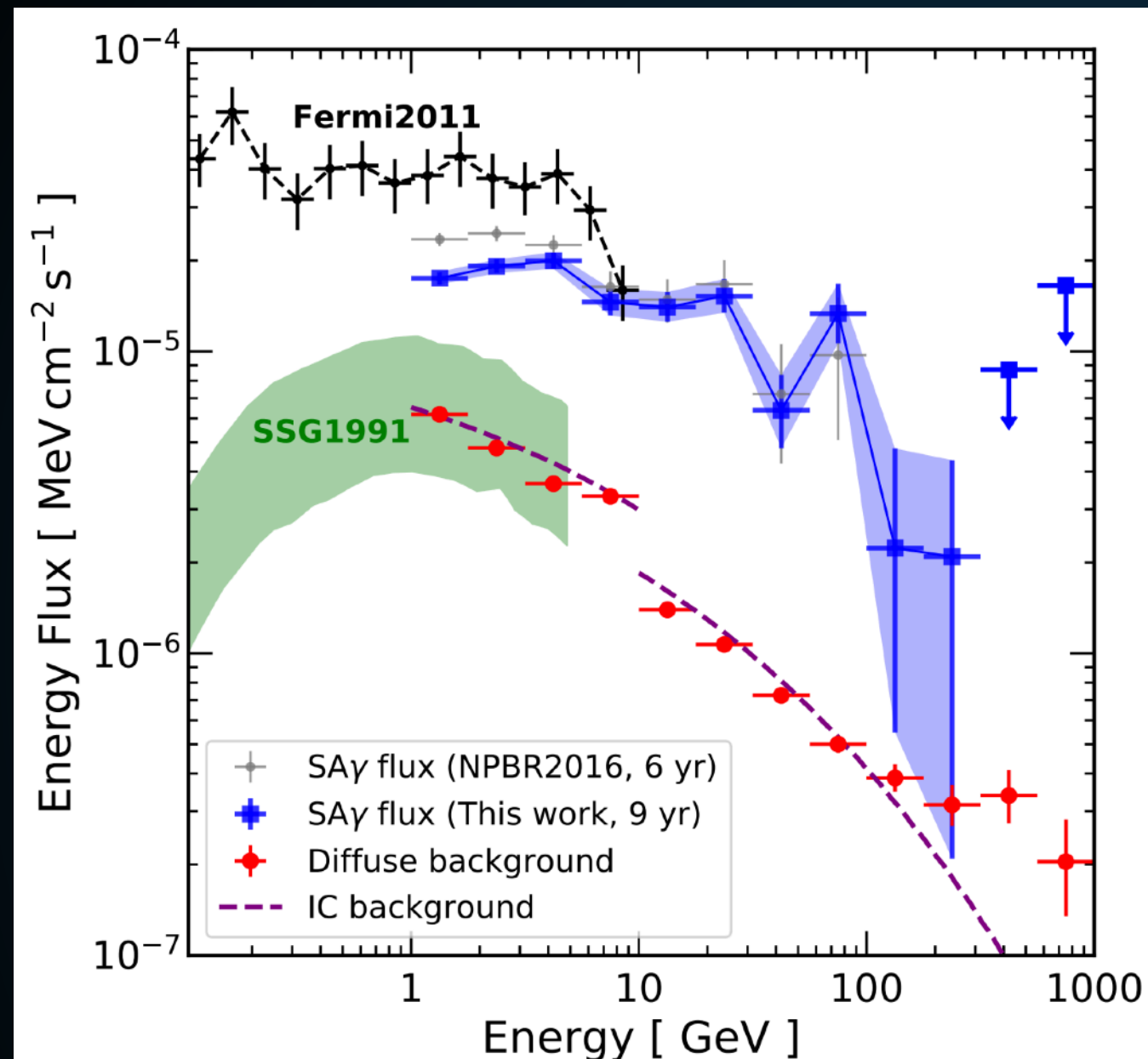
**X**

## A SPECTRAL STUDY

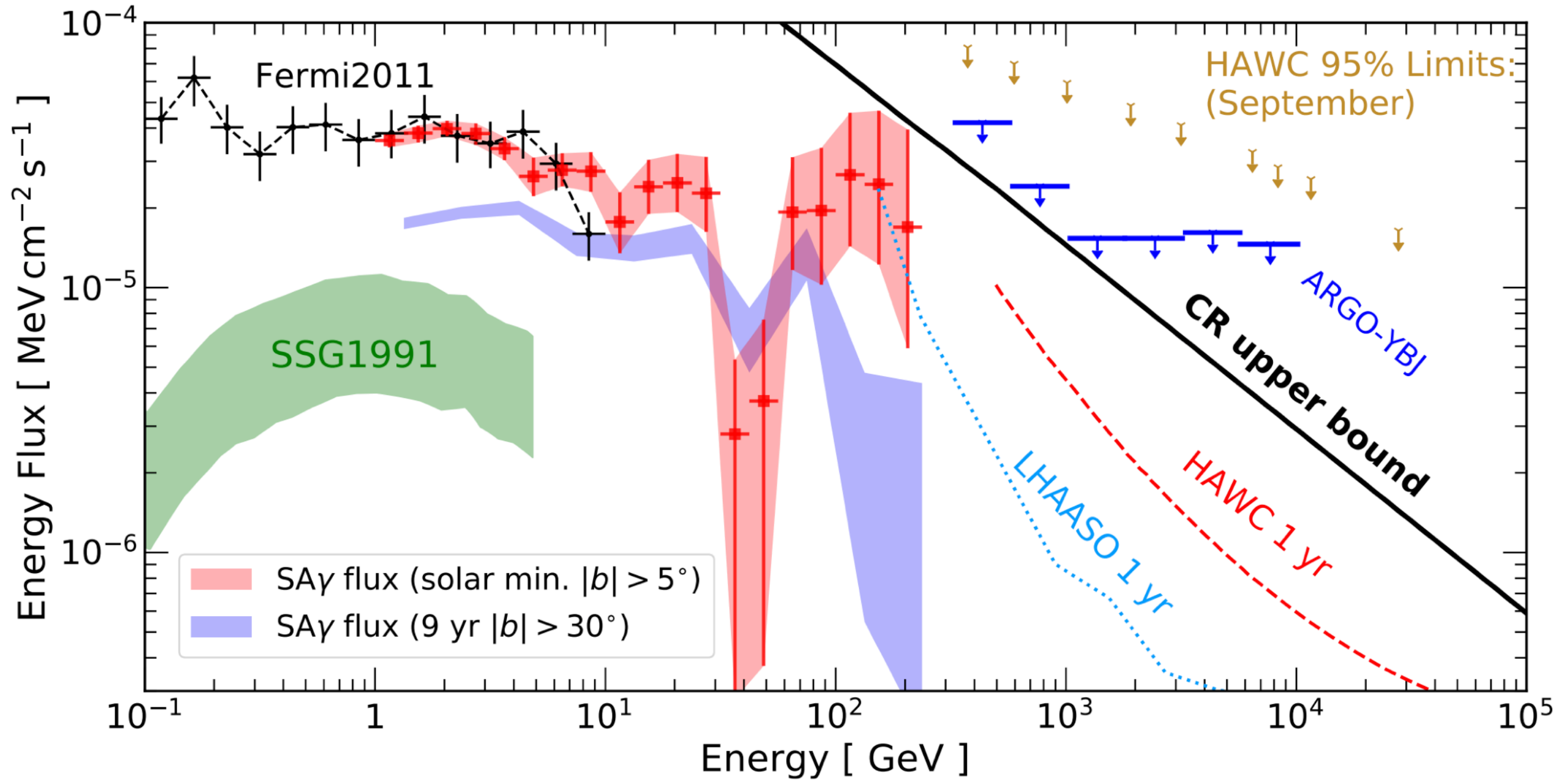


- Examine 9 years of gamma-ray data.
- Utilize all events more than 5° from the Galactic plane
- Convolve each event with a best-fit energy dispersion.





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





## GAMMA-RAYS - WHAT?

---

**Intensity**

**X**

**Spectrum**

**X**

**Time Variability**

**X**

**Morphology**

**X**

**Spectral Variability**

**X**

**Spectral Dip?**

**X**

## **GAMMA-RAYS - WHAT?**

---

**Oh wait... that's basically everything.**

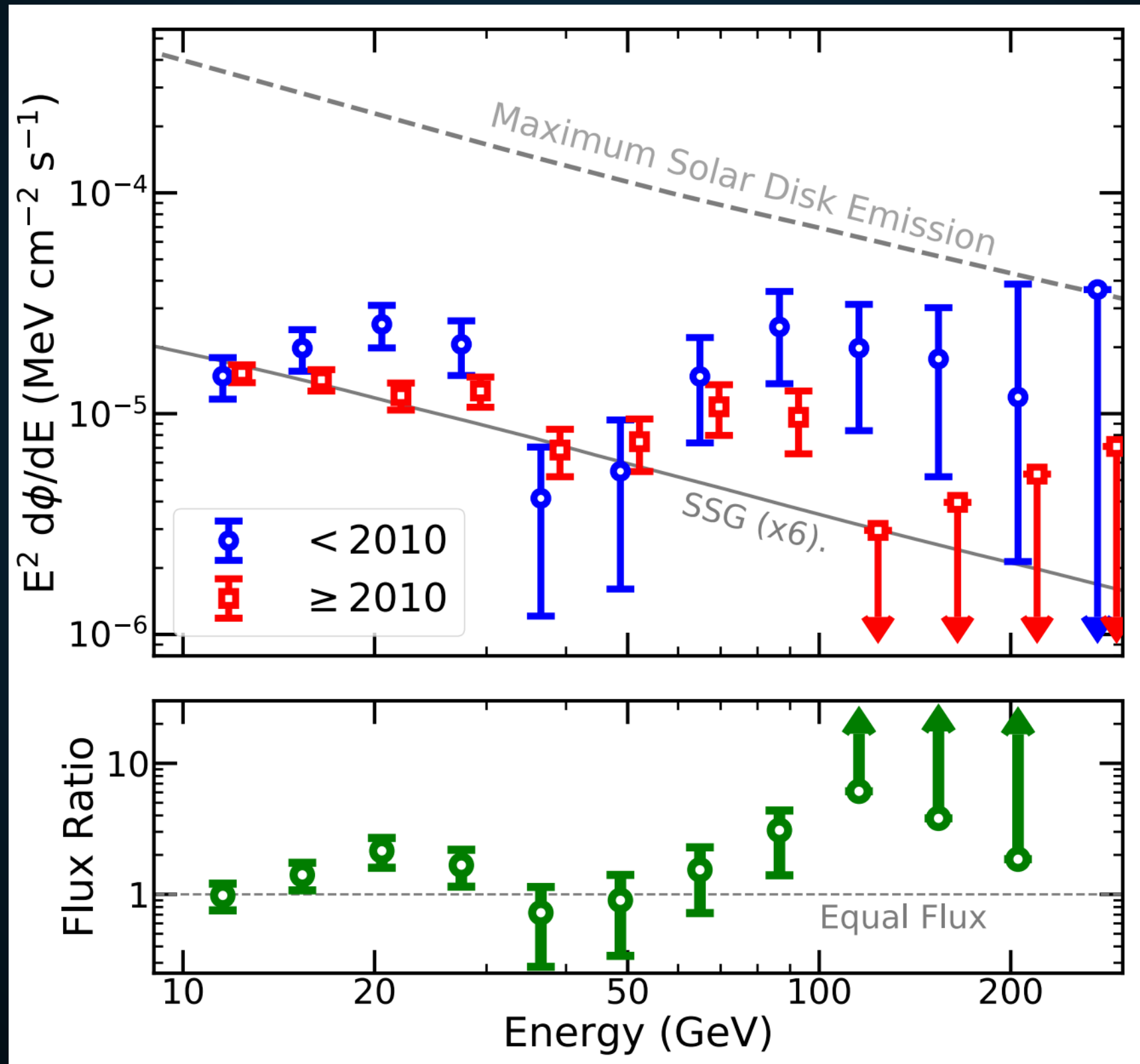


**Oh wait... that's basically everything.**

**How do we model this?**

## GAMMA-RAYS - HOW?

- Gamma-Ray Emission much brighter than expected

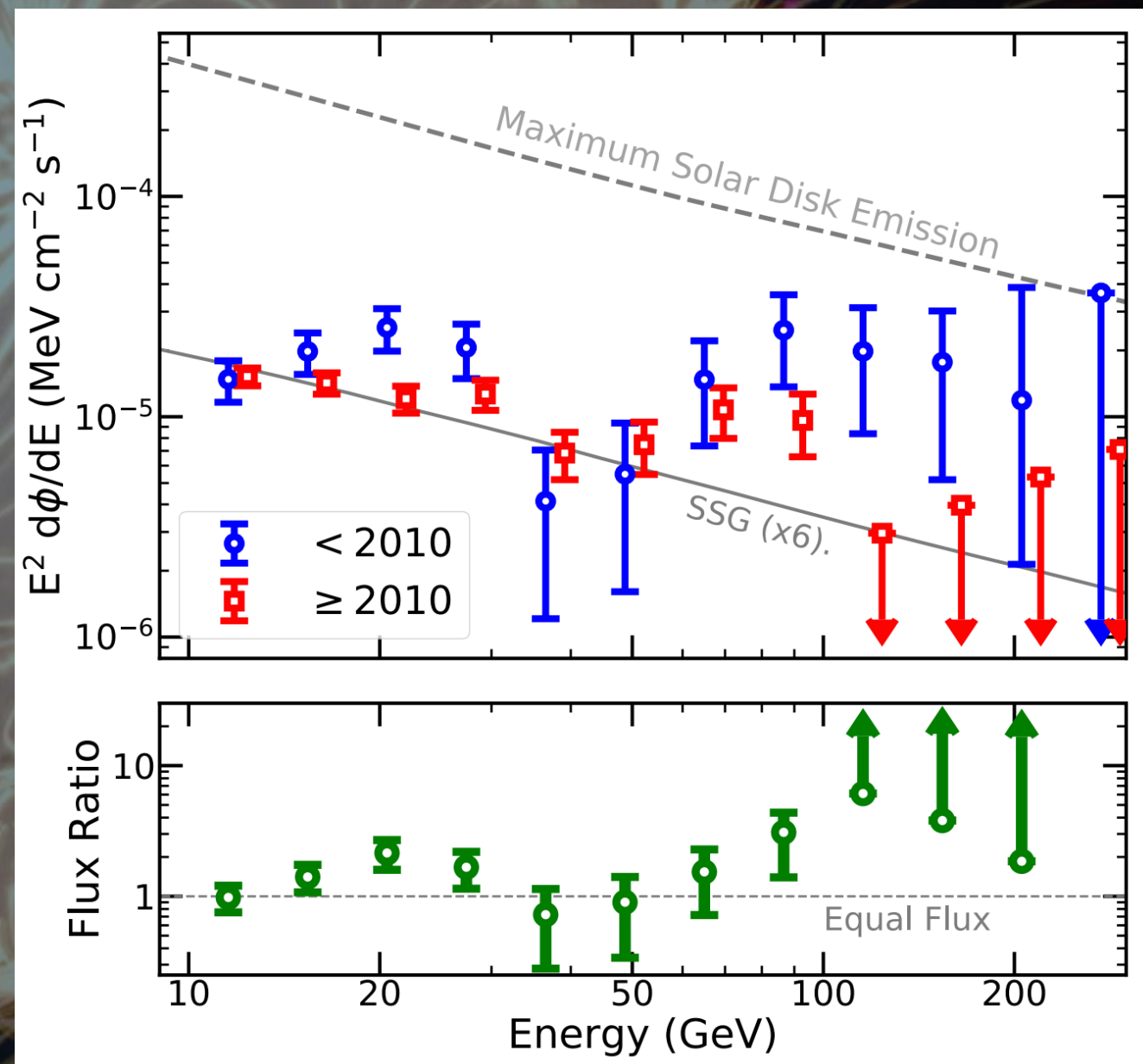
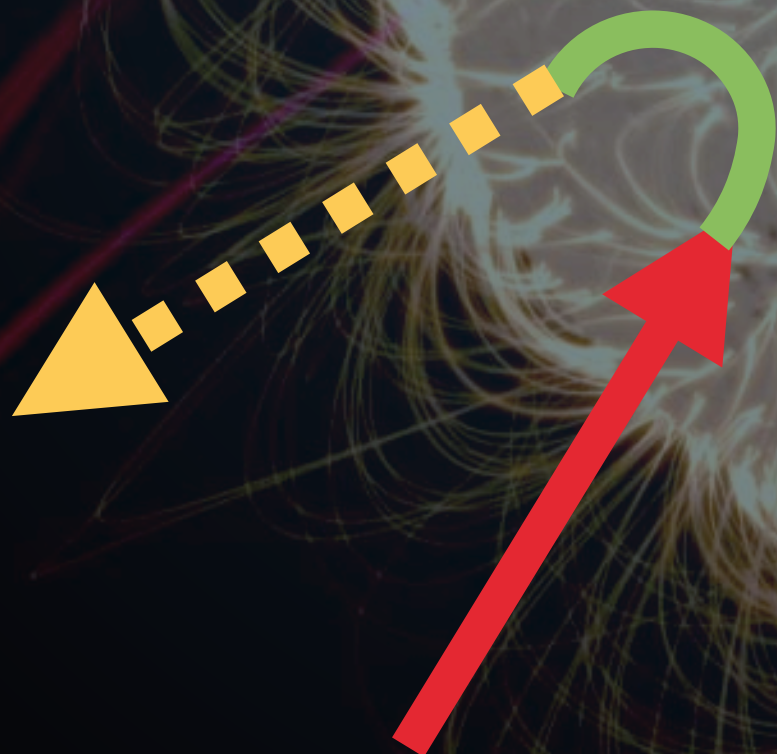




## GAMMA-RAYS - HOW?

- Gamma-Ray Emission much brighter than expected

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

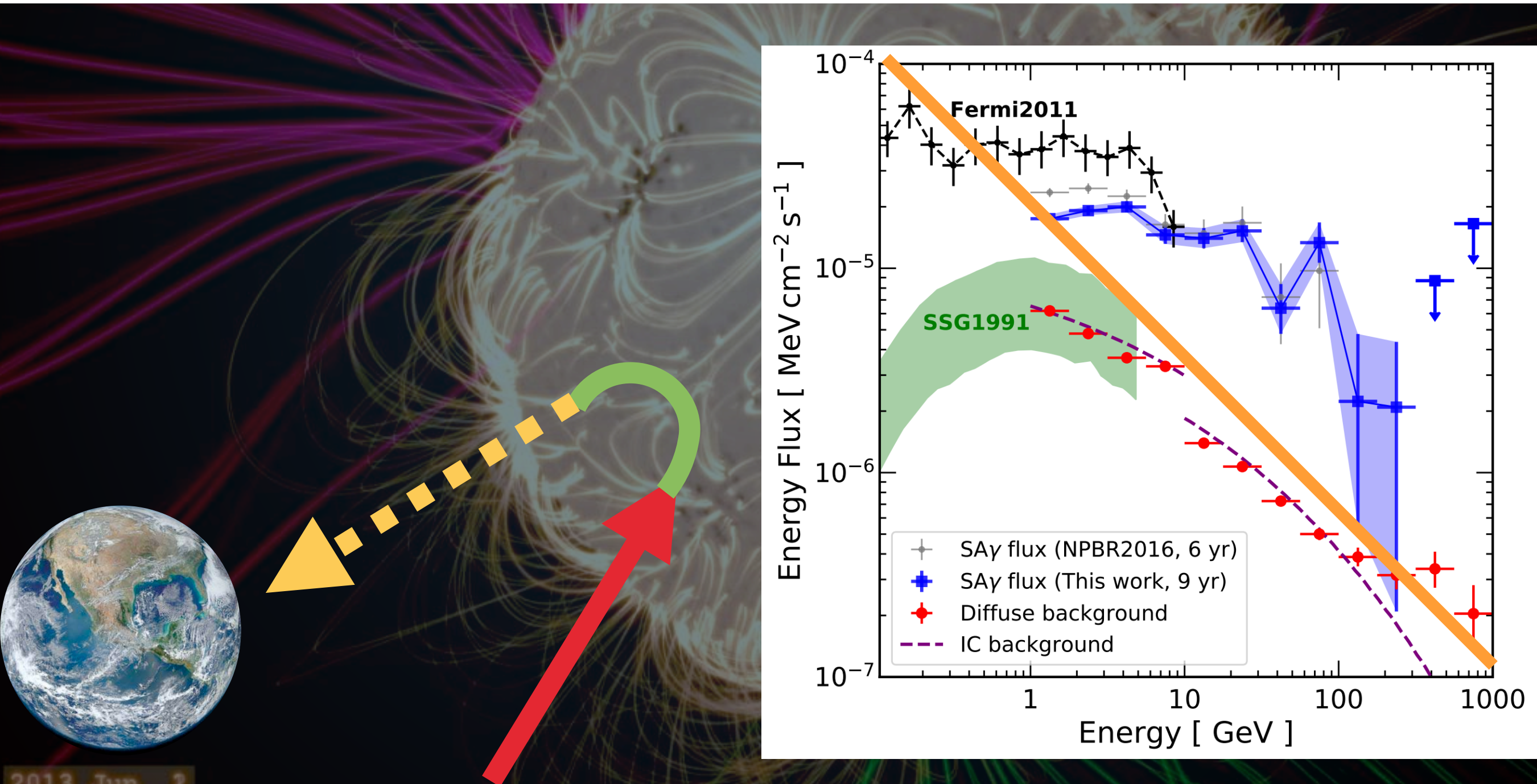




## GAMMA-RAYS - HOW?

- Gamma-Ray spectrum much harder than expected

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

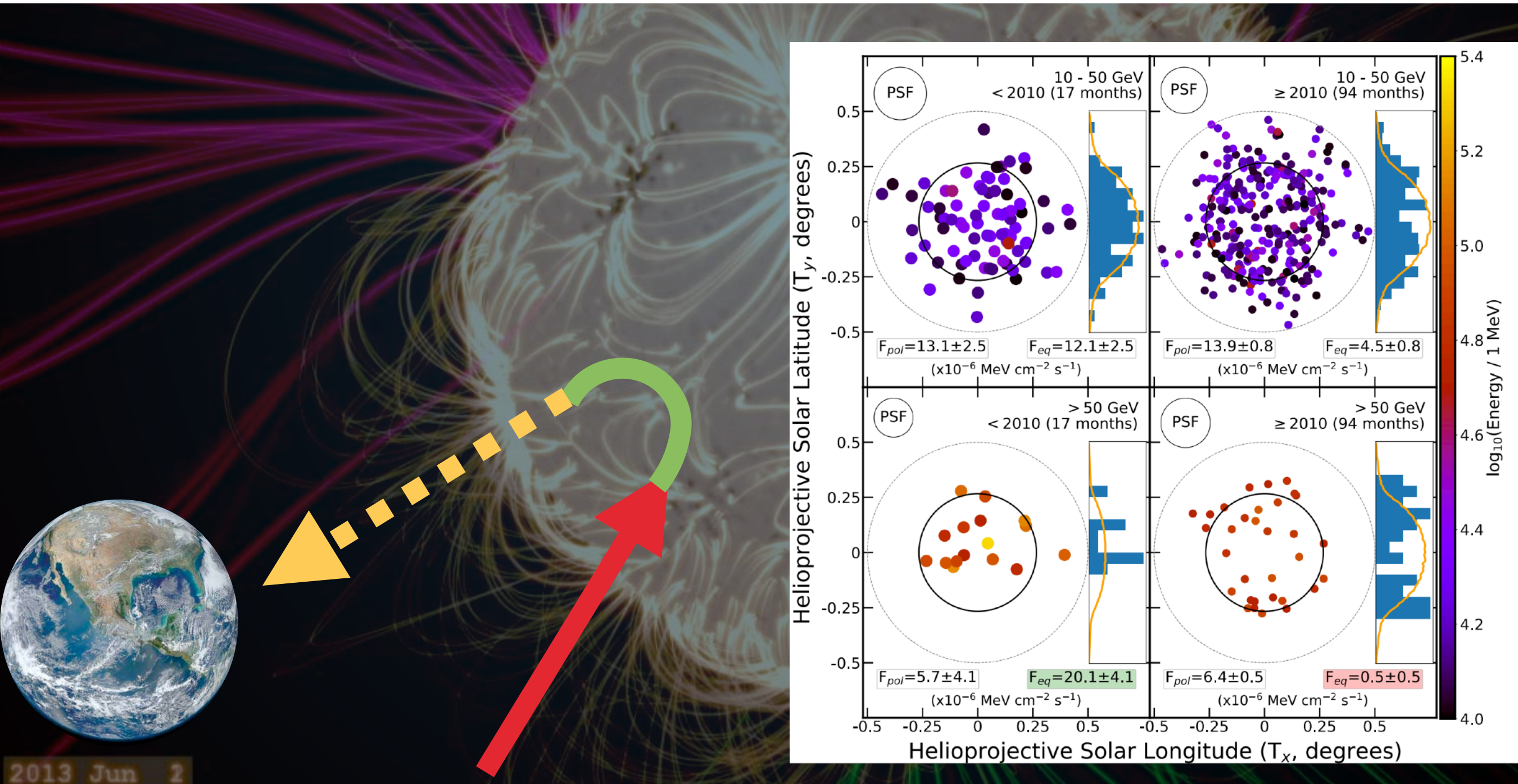




# GAMMA-RAYS - HOW?

- Gamma-Ray morphology not uniform

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

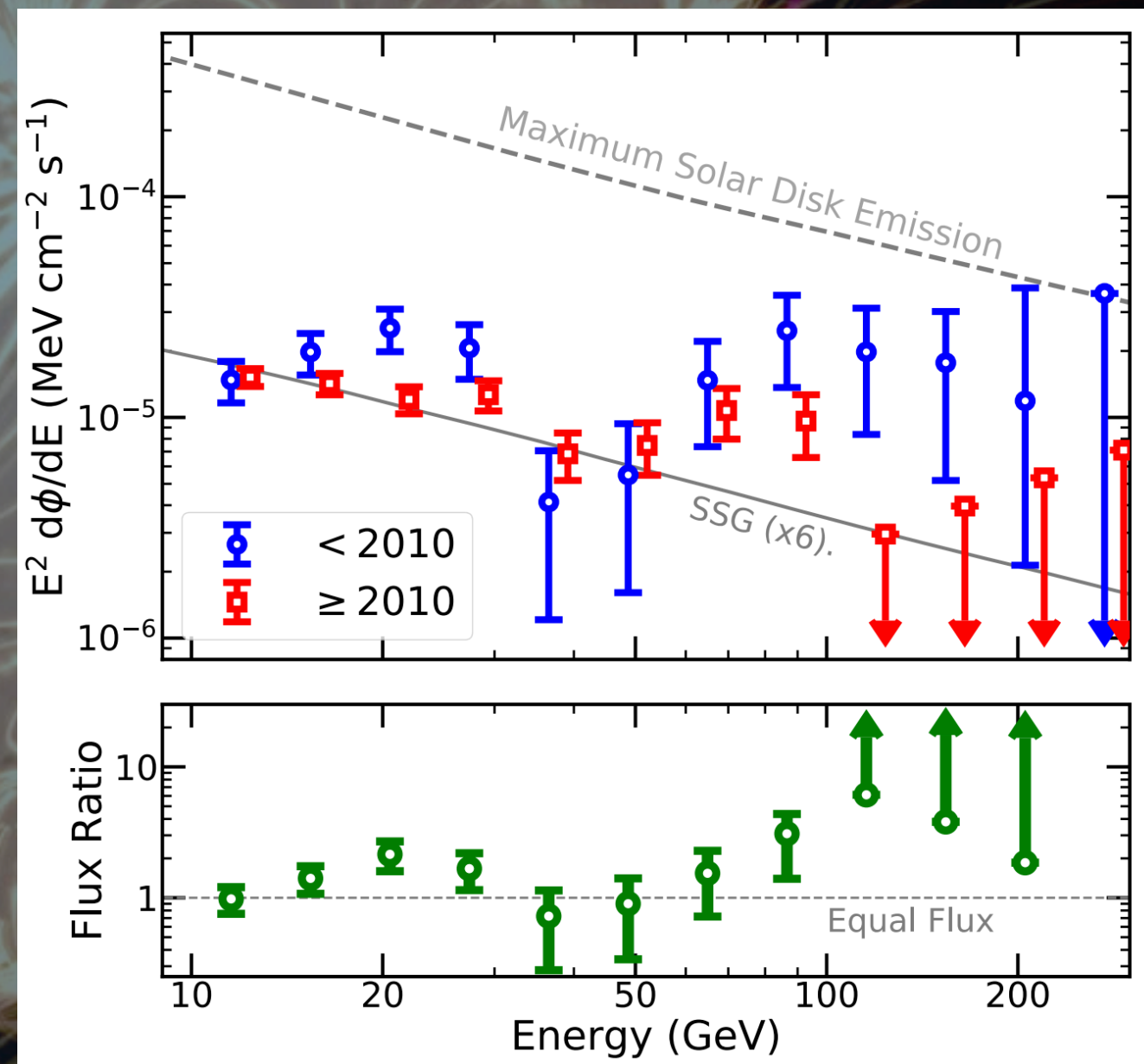
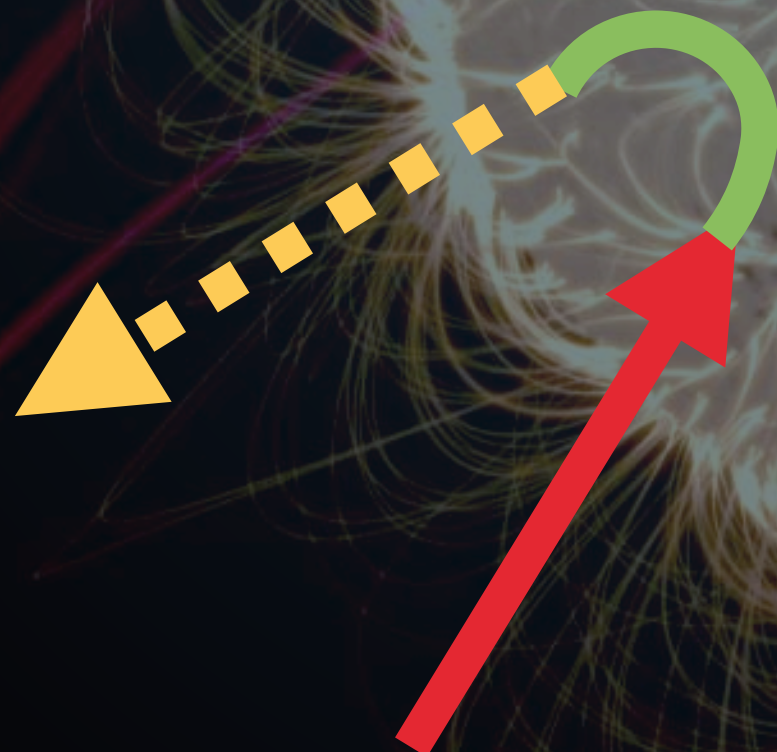




# GAMMA-RAYS - HOW?

- Evidence for two different emission mechanisms?

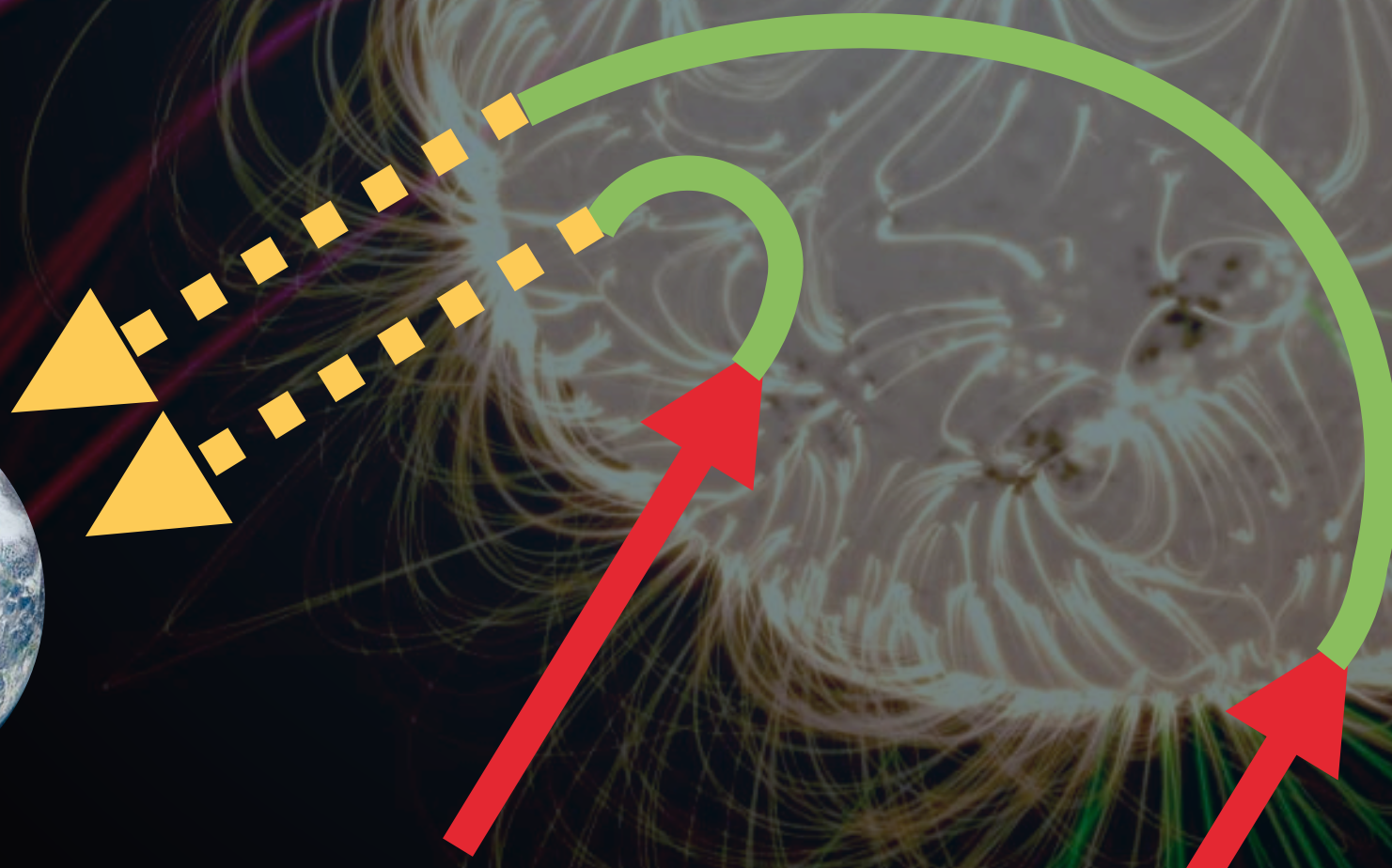
$$\Phi_{\odot}(E_{\gamma}) = \pi R_{\odot}^2 \Phi_{\text{CR}}(E_{\text{CR}}) C(E_{\gamma}, E_{\text{CR}}) f_{\text{sur}} f_{\text{turn}} f_{\text{int}}$$





# GAMMA-RAYS - HOW?

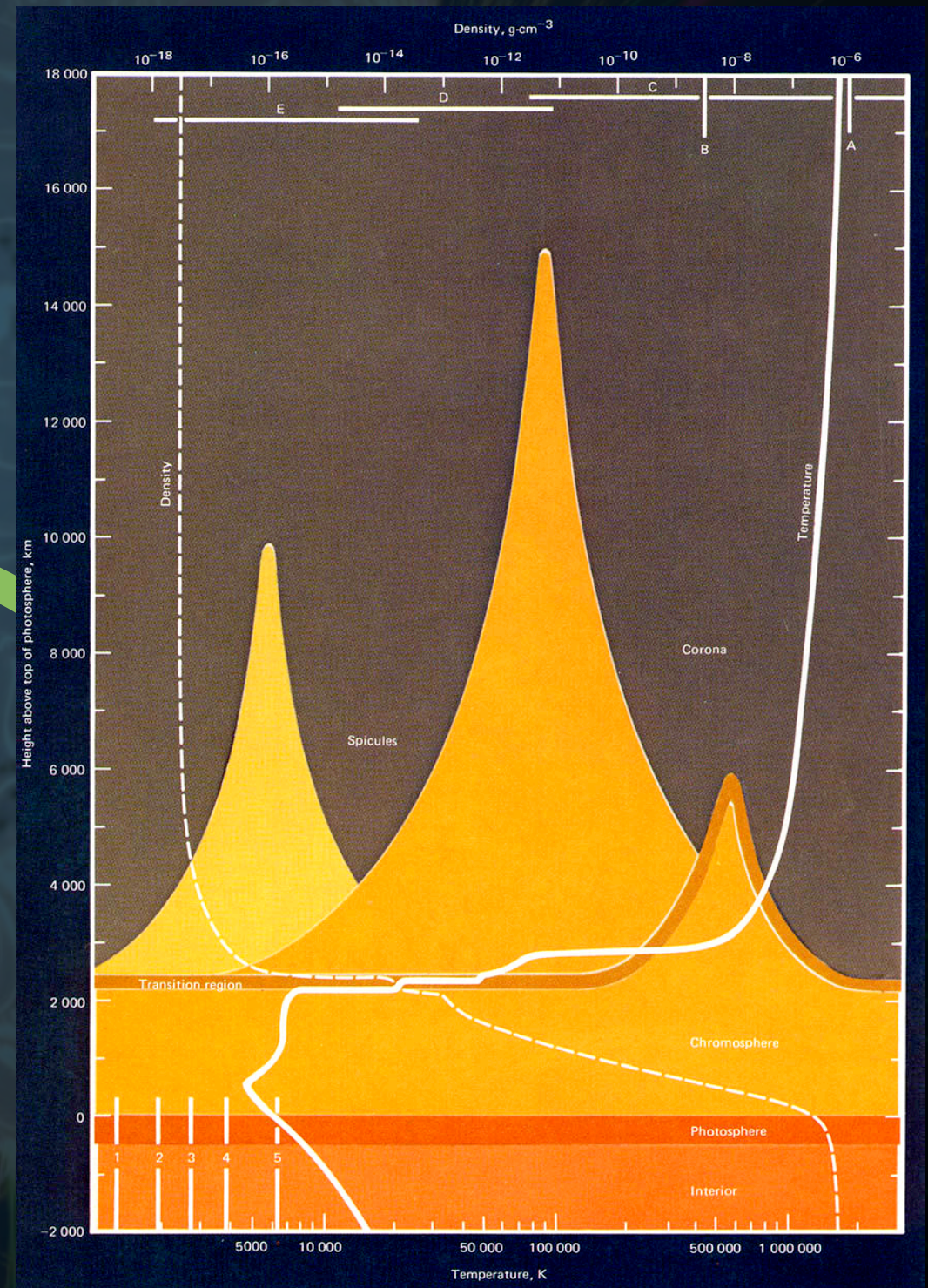
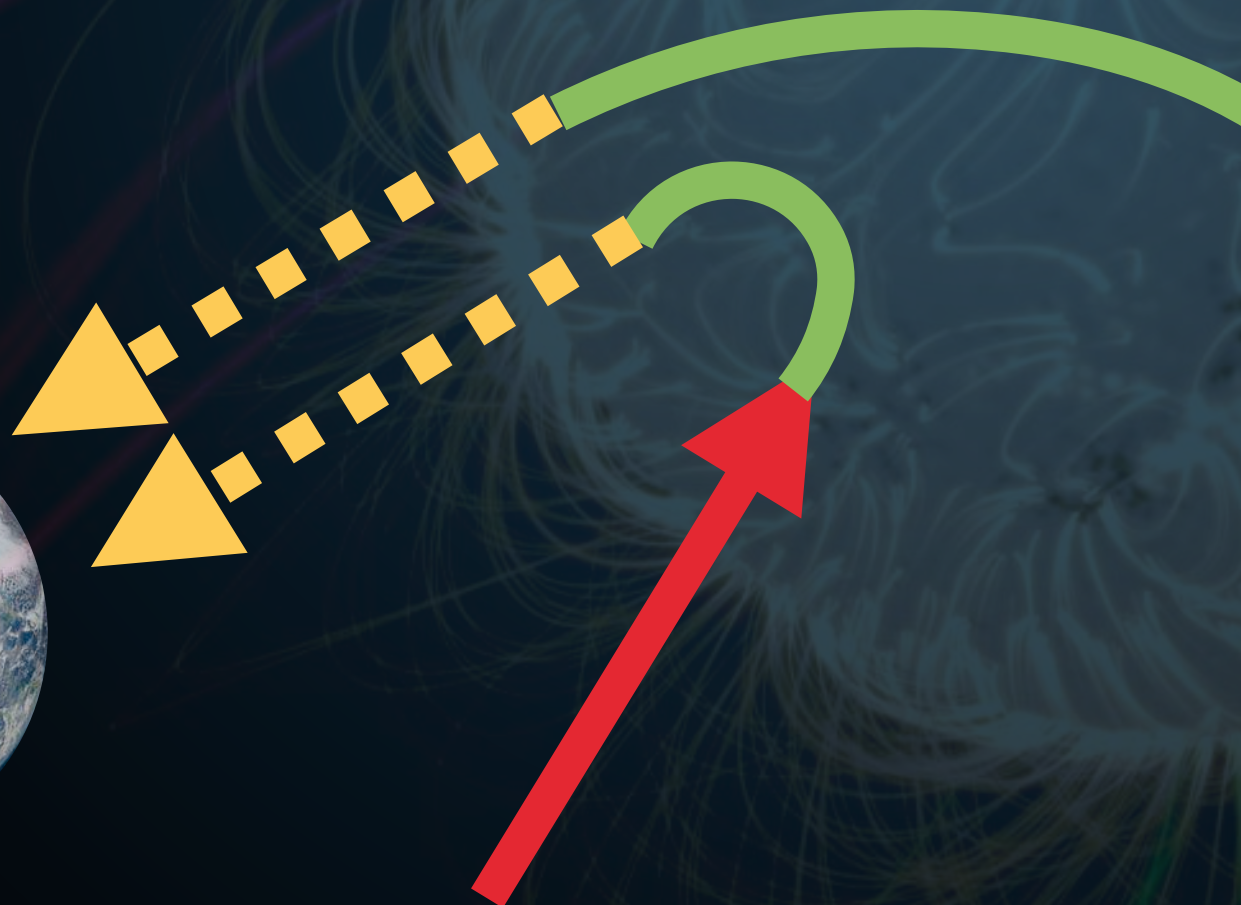
- Possibilities
  - Anisotropic gamma-ray emission





# GAMMA-RAYS - HOW?

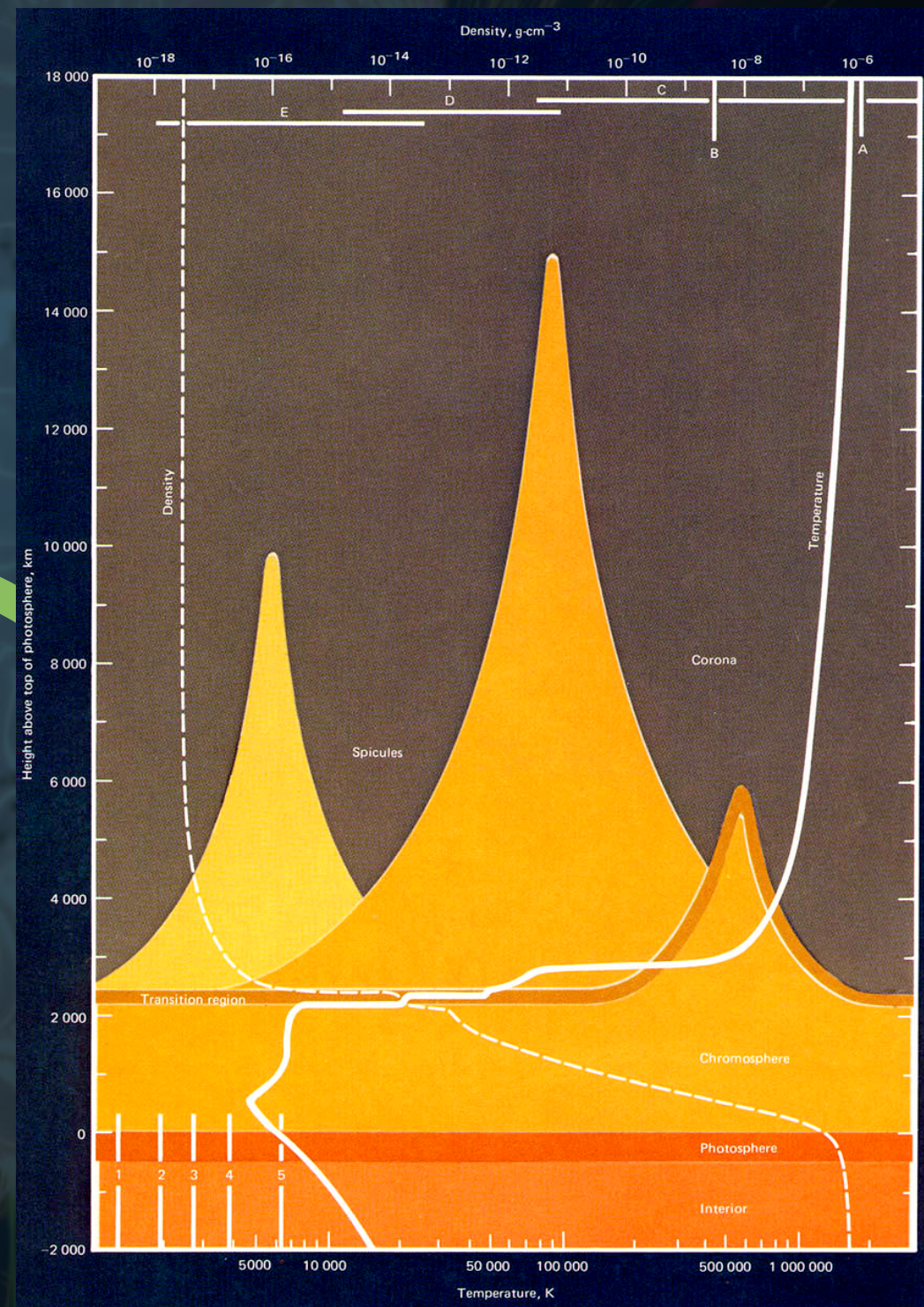
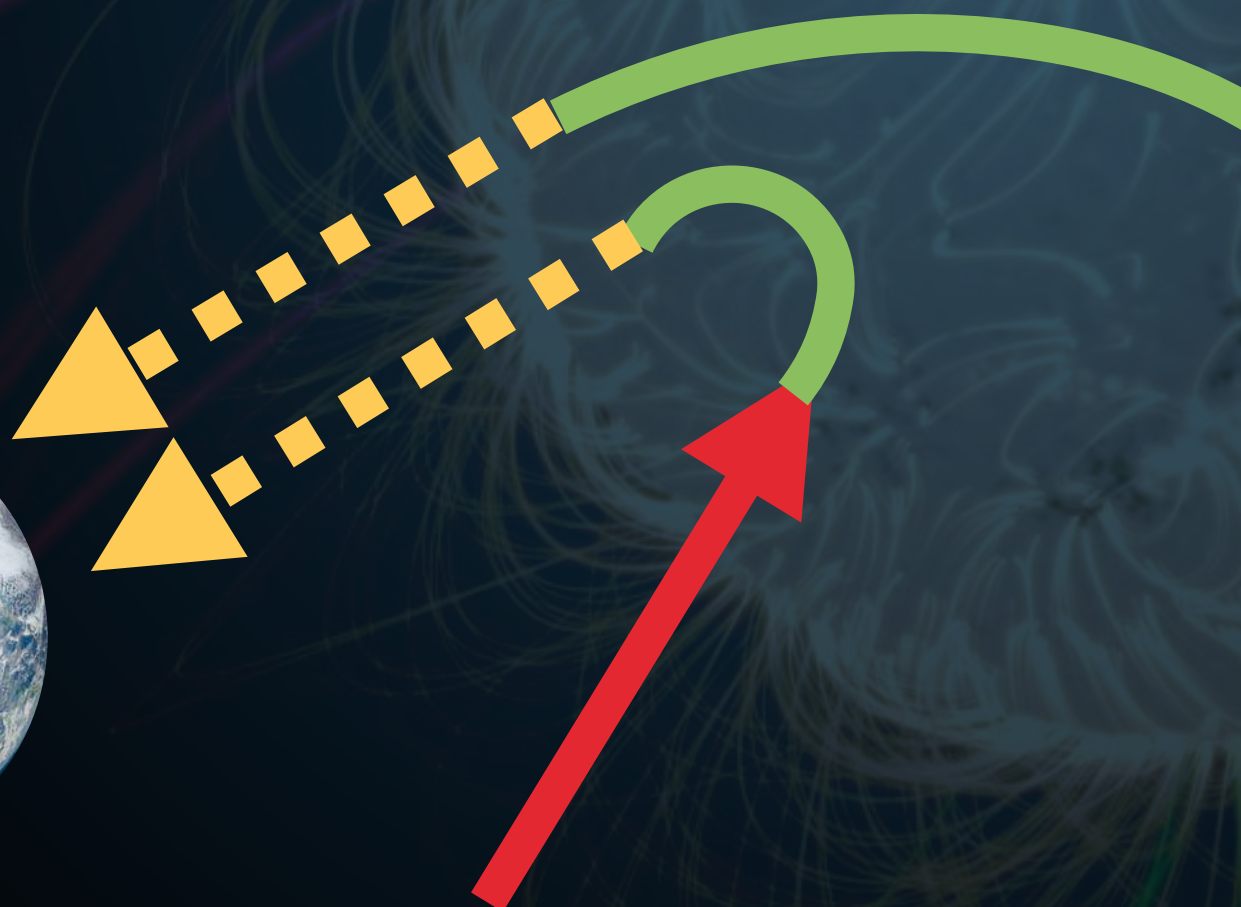
- Possibilities
  - Anisotropic gamma-ray emission





# GAMMA-RAYS - HOW?

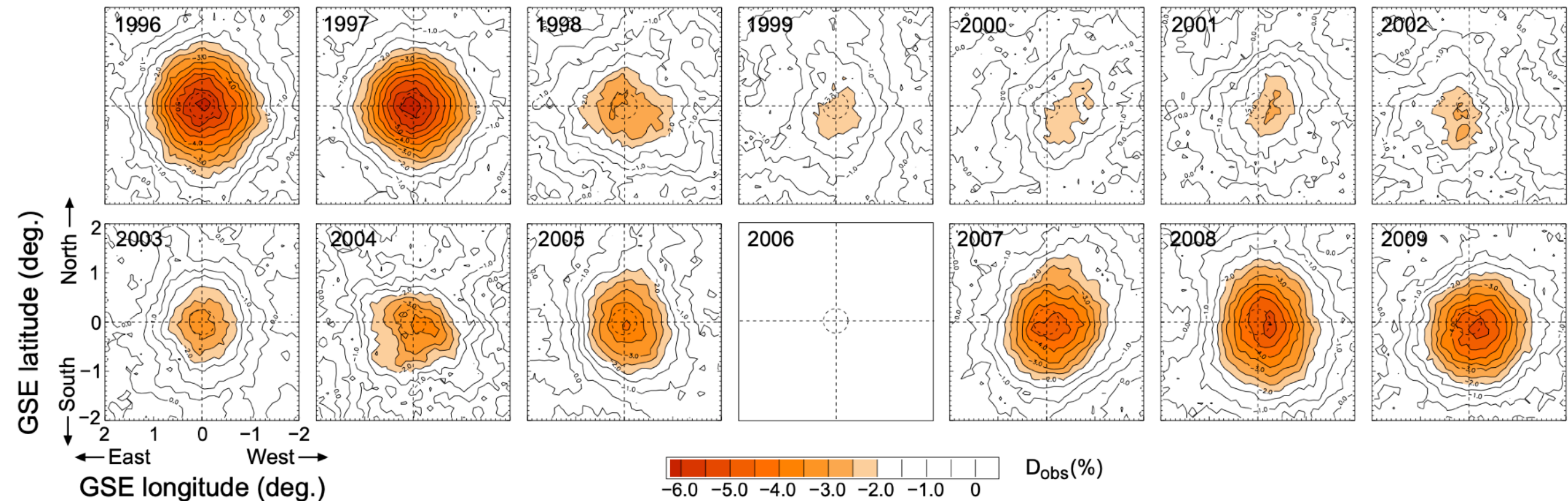
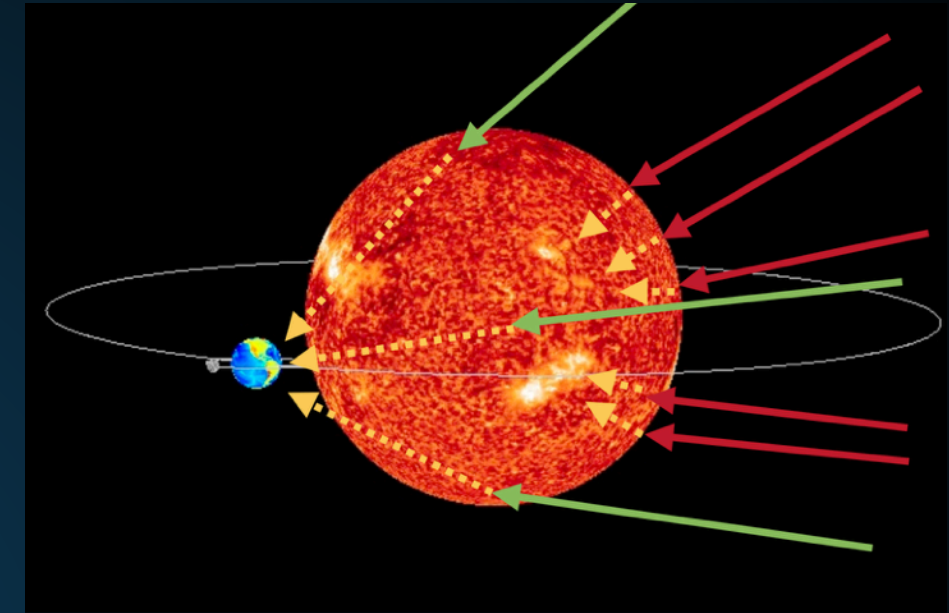
- Possibilities
  - Cosmic-Ray Storage





- Possibilities

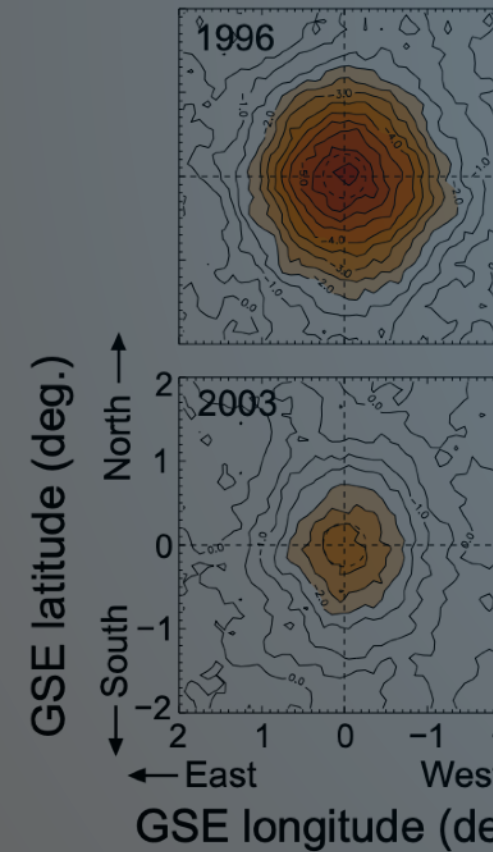
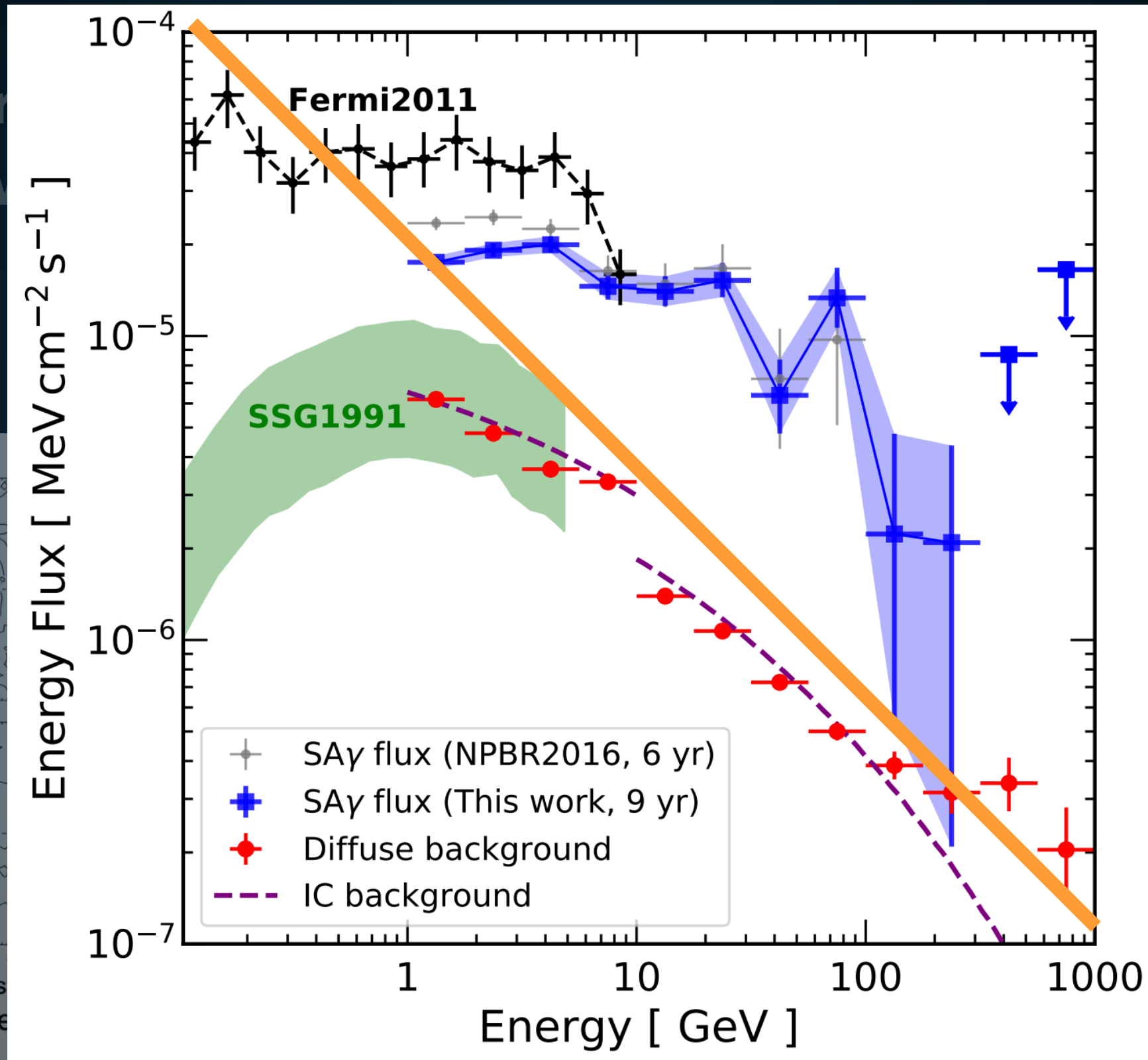
- Solar Magnetic Fields Draw in Cosmic-Rays





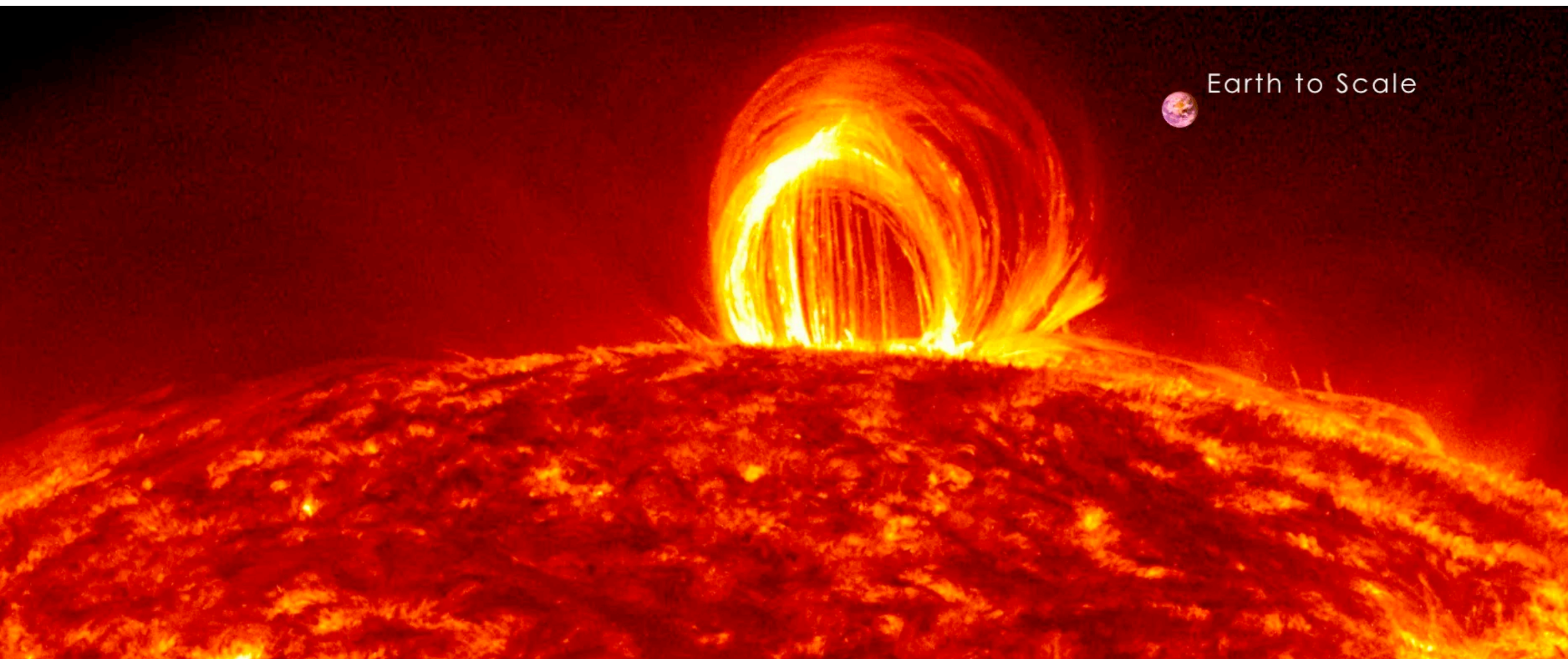
## • Possibilities

## • Solar Draw



# 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?**

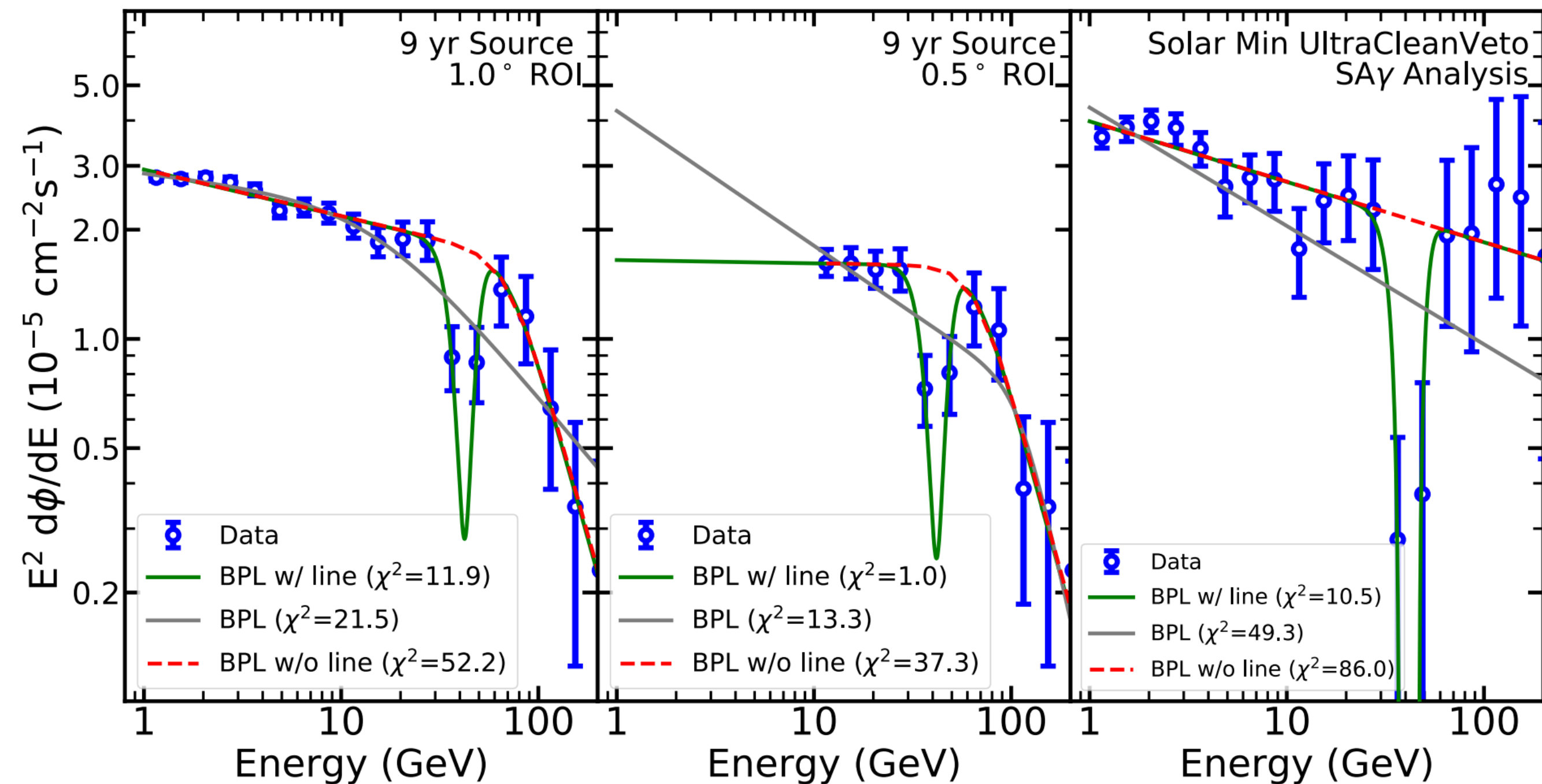
# GAMMA-RAYS - HOW?

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# THE SPECTRAL DIP?



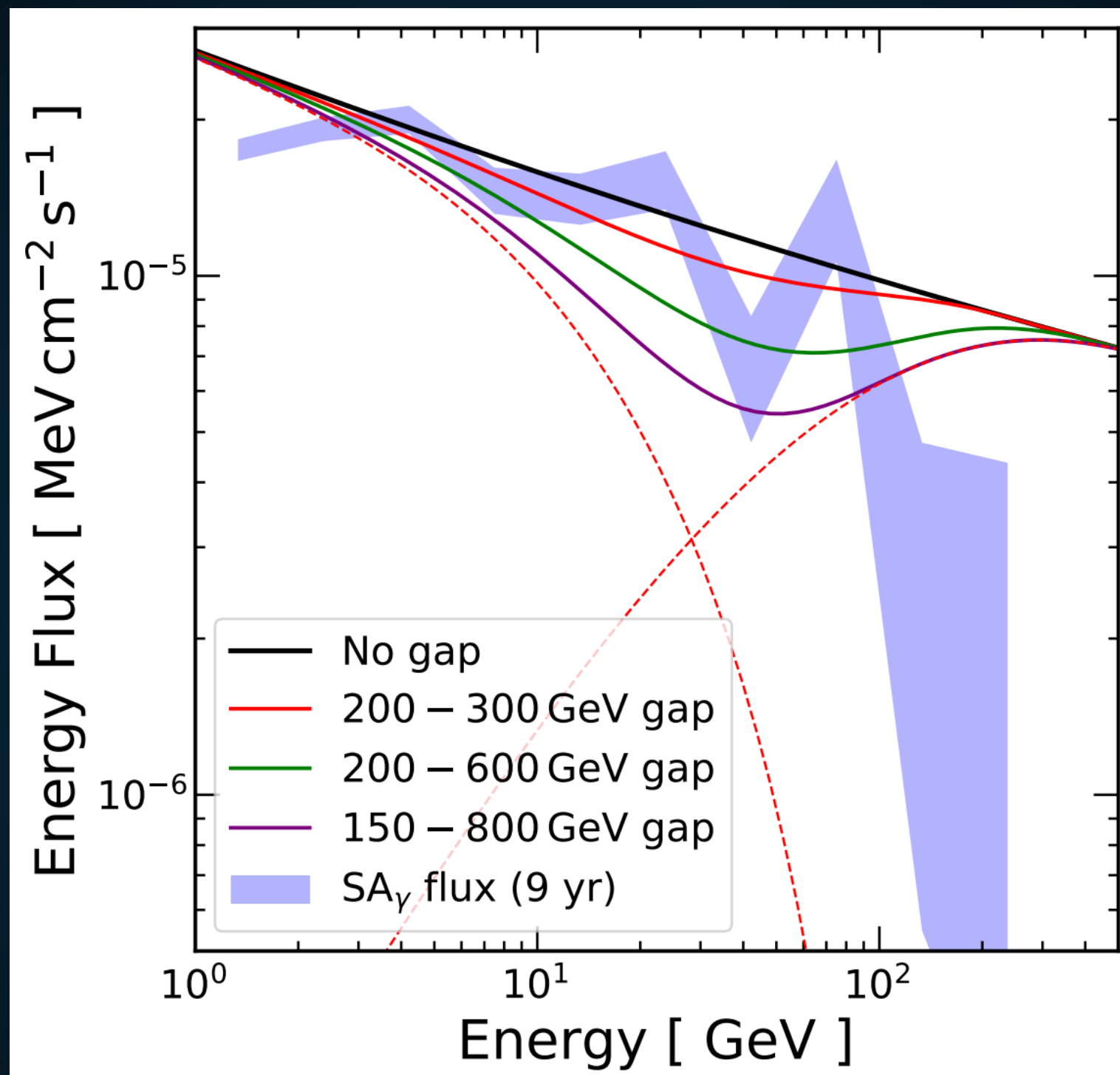
## THE SPECTRAL DIP?

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- **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.**

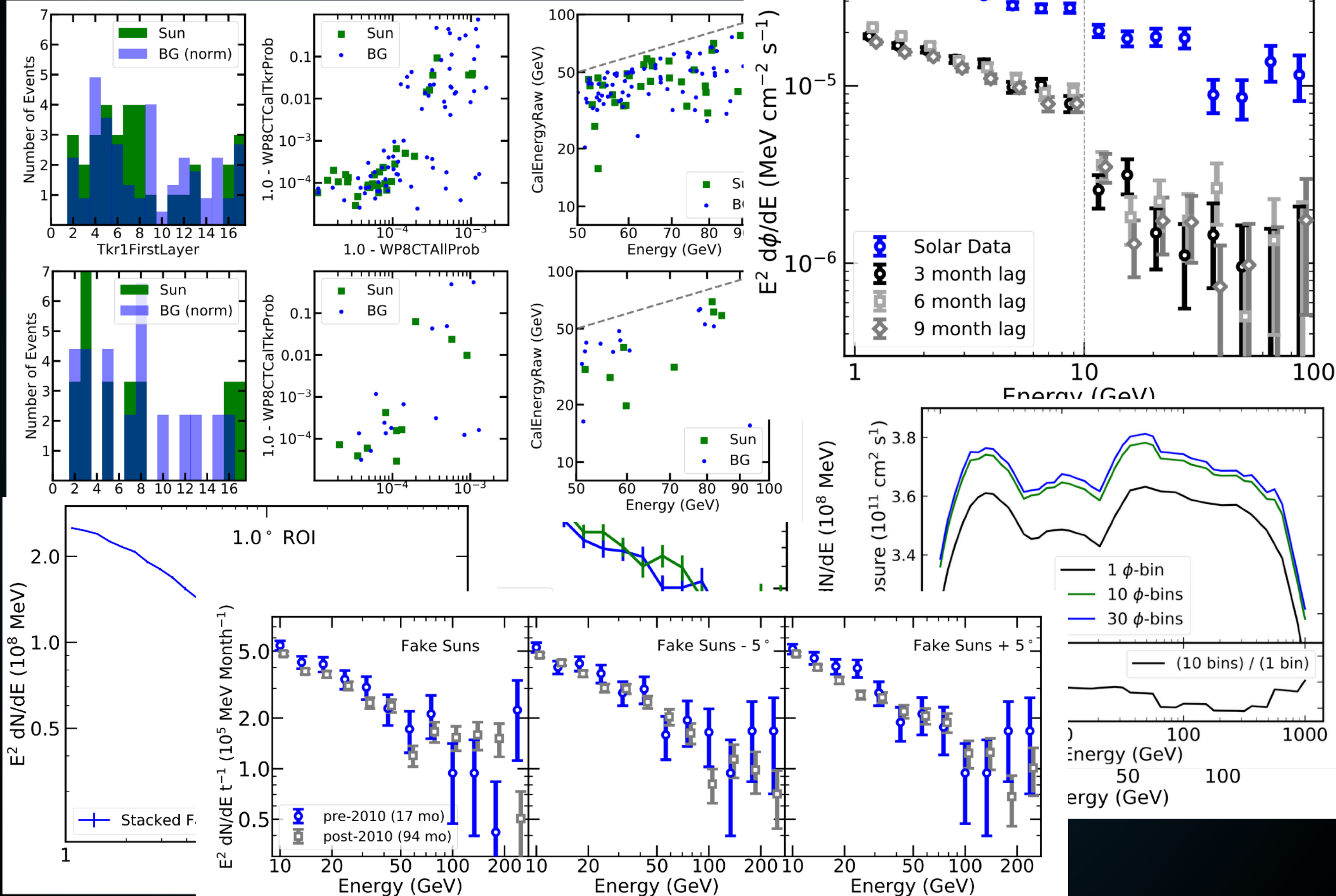
## THE SPECTRAL DIP?

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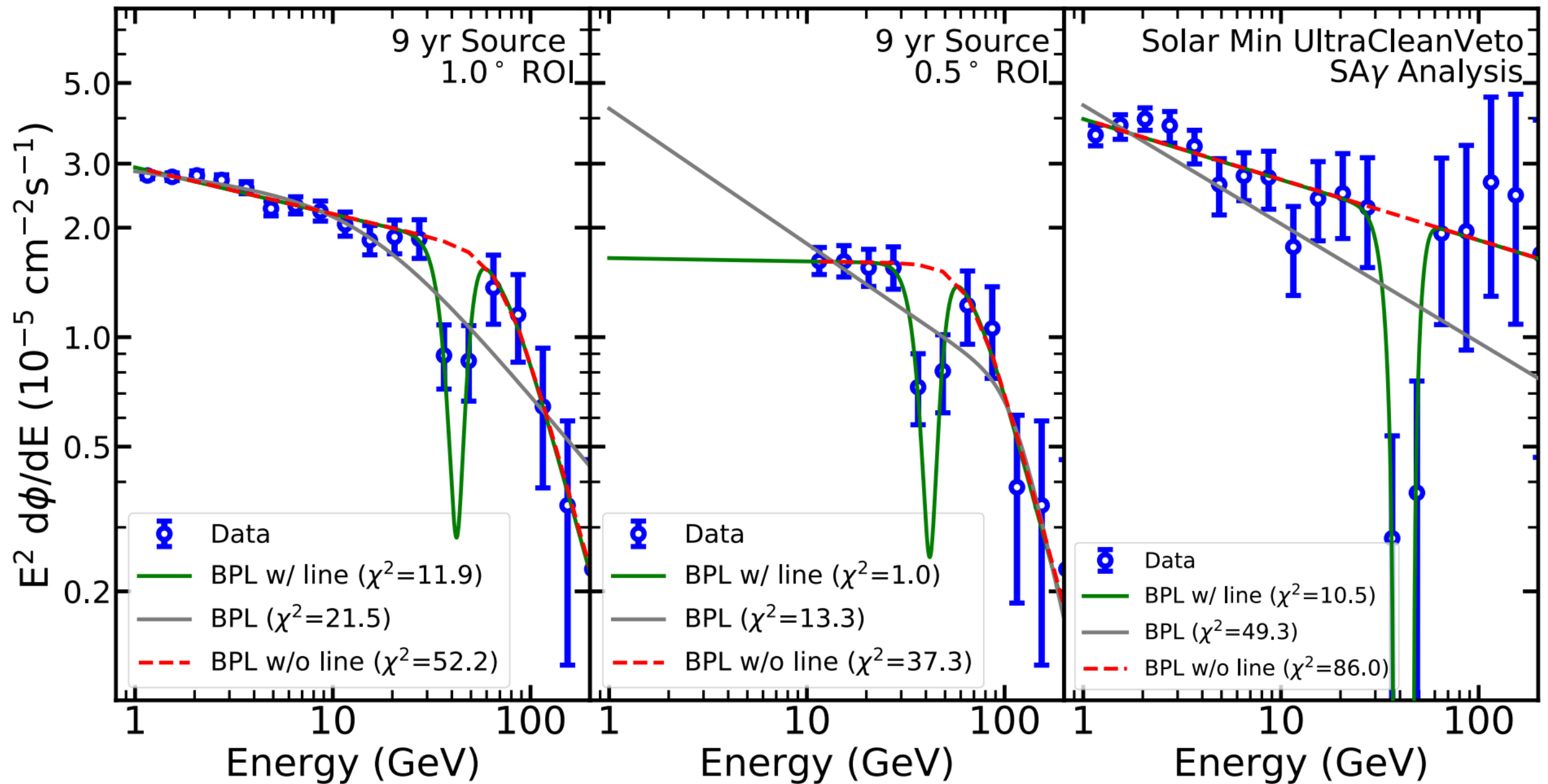
- **No clear mechanism for how energy-dependent photon absorption would work...**



# THE SPECTRAL DIP?



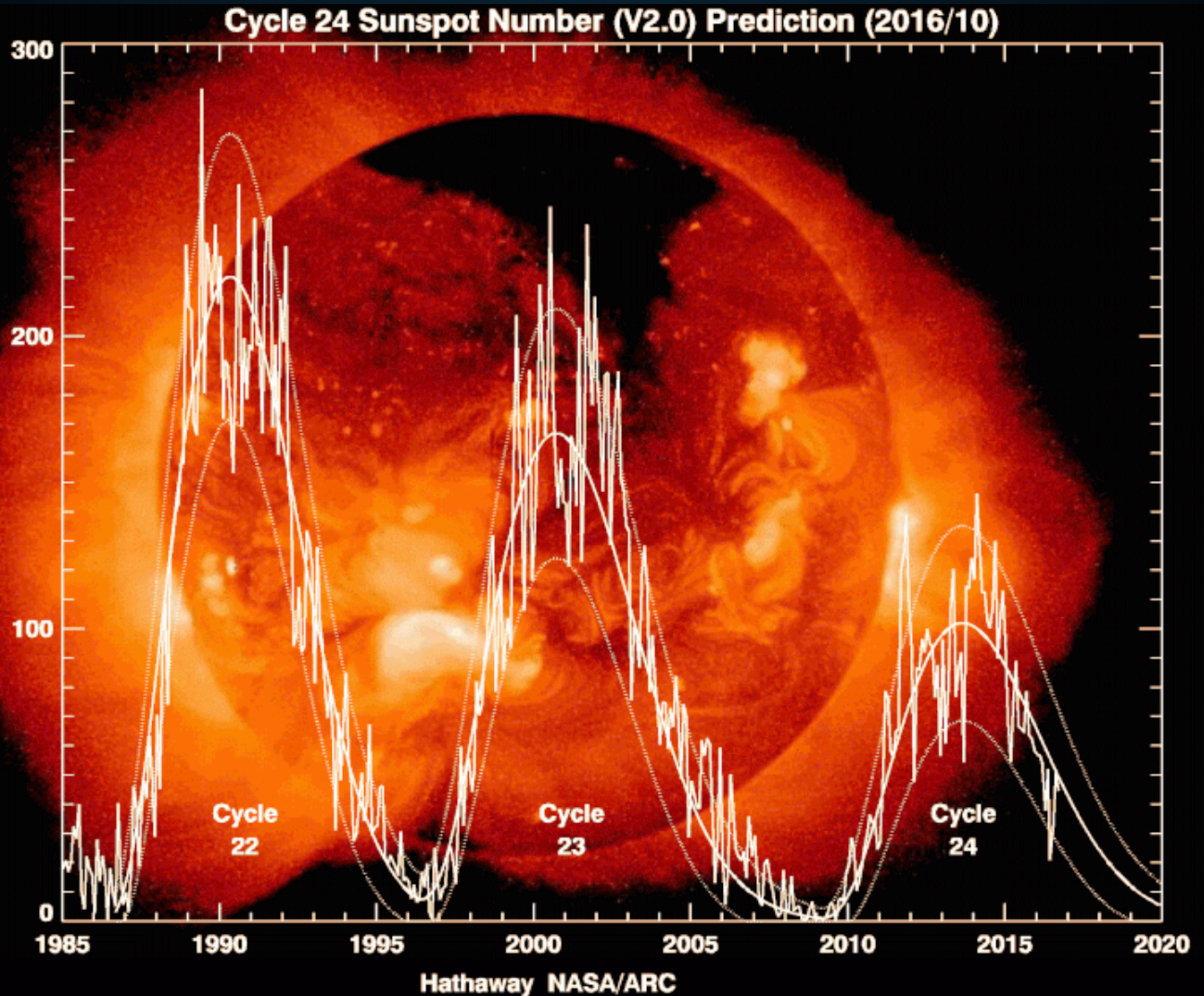
# AN INSTRUMENTAL WORKING HYPOTHESIS



- Or maybe new physics?



# HOW DO WE RESOLVE THESE ISSUES?





## HOW DO WE RESOLVE THESE ISSUES?

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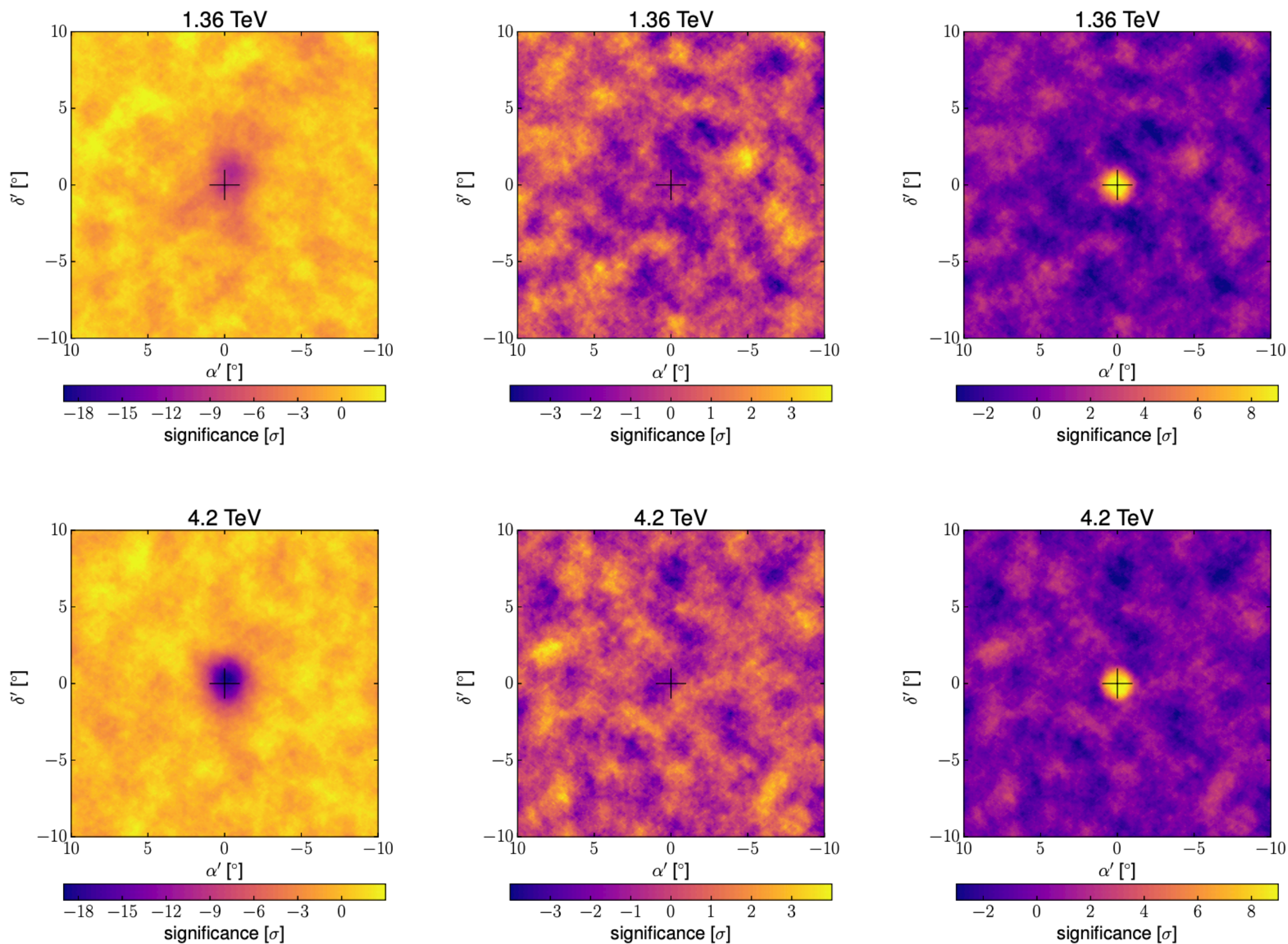


# TEV OBSERVATIONS OF THE SUN

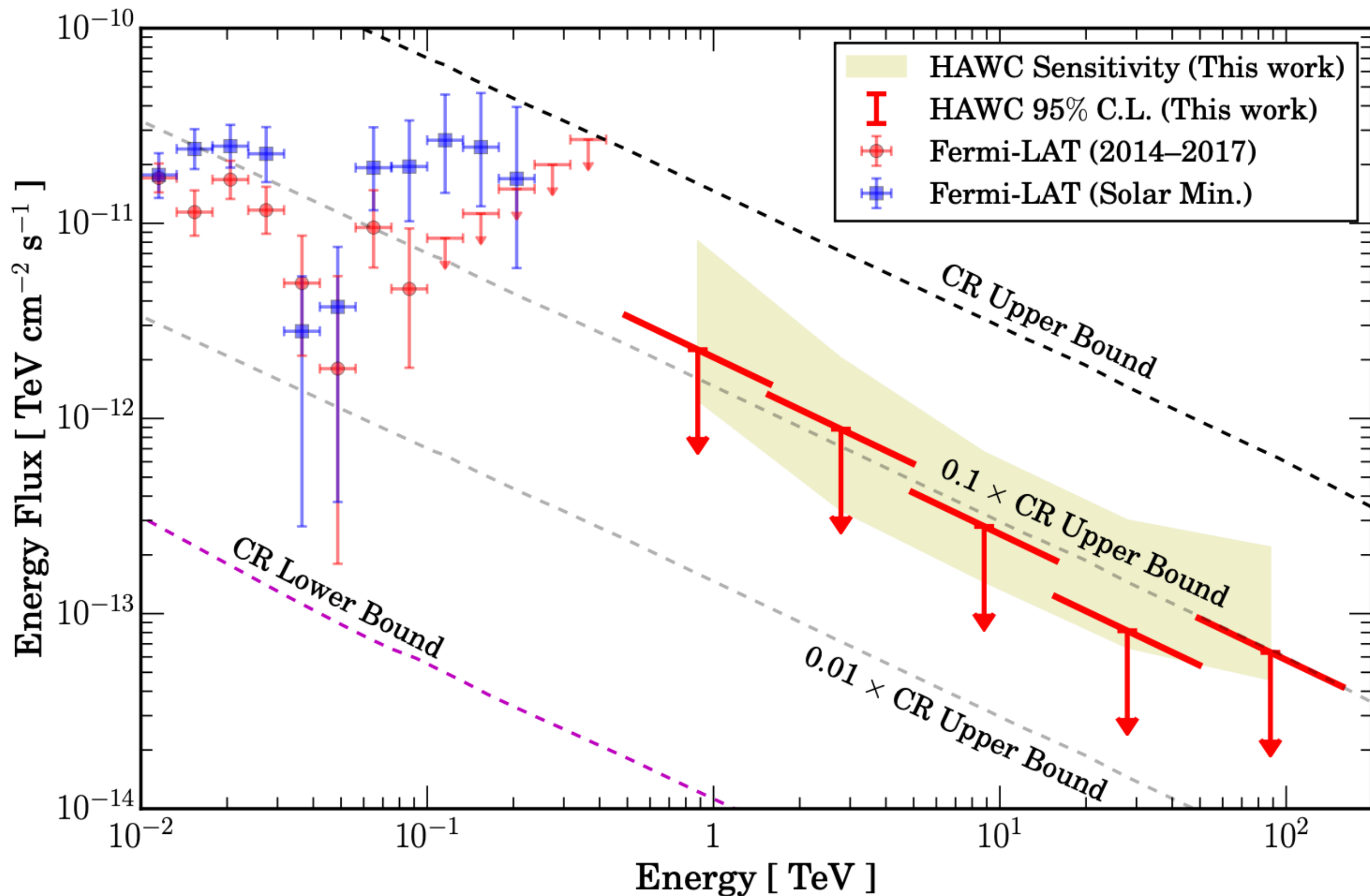
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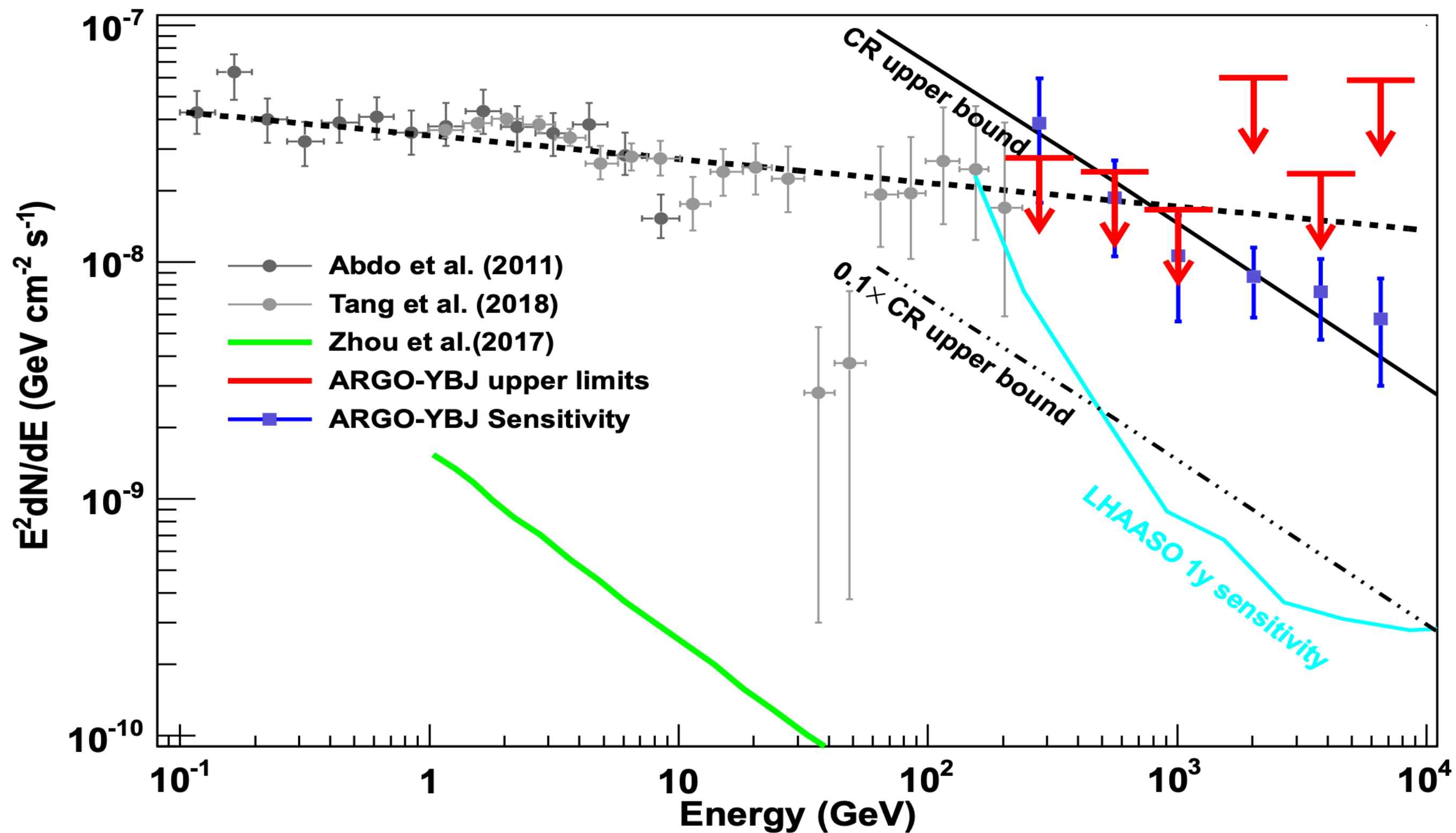














## CONCLUSIONS

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- **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 dark matter annihilation.**