

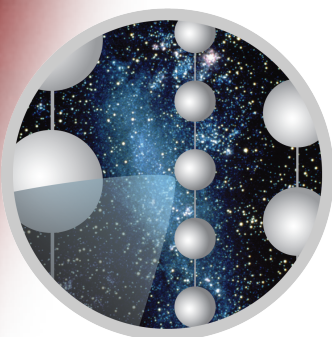
# THE SUN AS A TARGET FOR VERY-HIGH-ENERGY GAMMA-RAY OBSERVATIONS



Mehr Un Nisa  
*Michigan State University*



*AAS238 Virtual Meeting 06/07/21*



ICECUBE



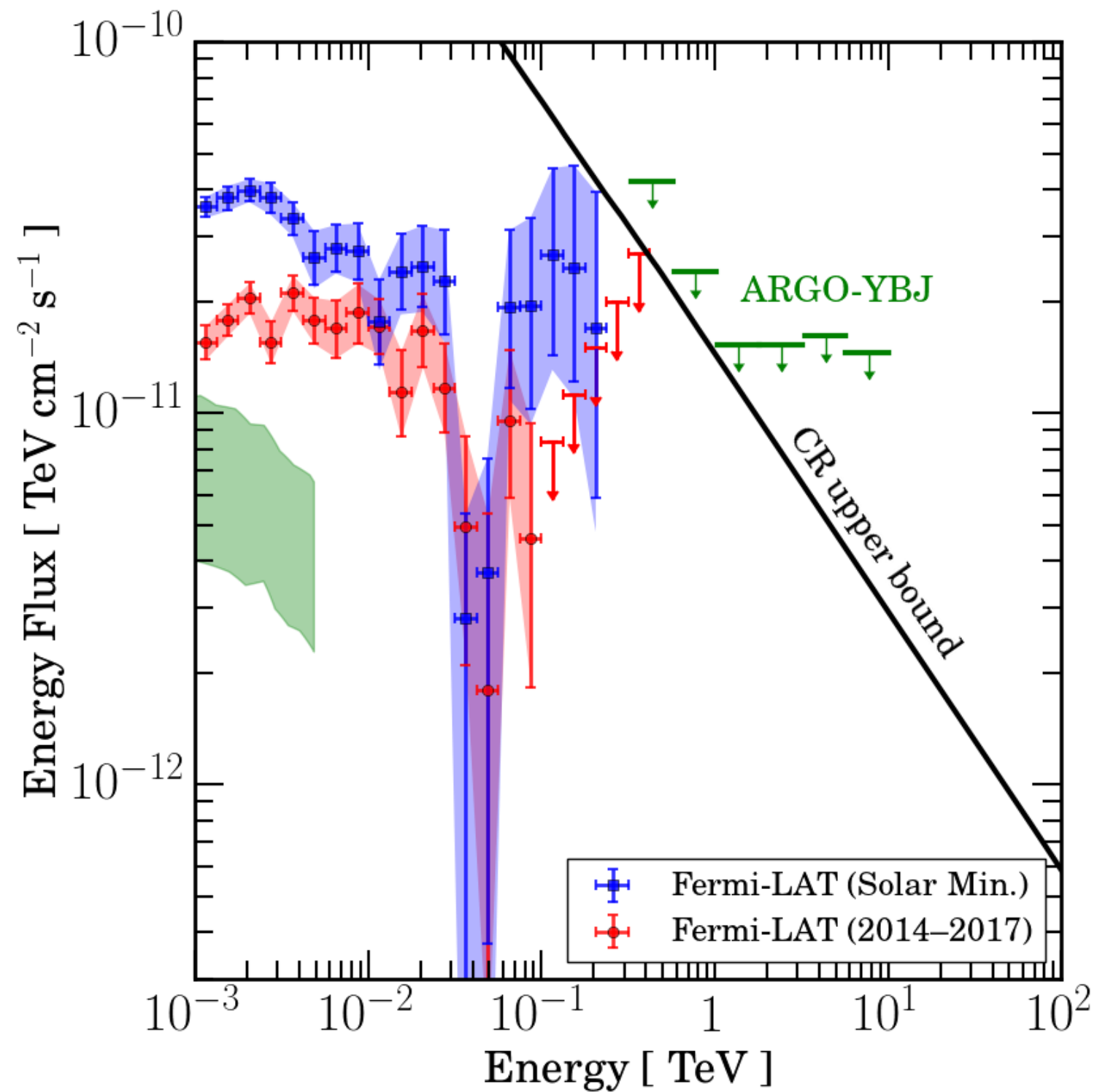
MICHIGAN STATE  
UNIVERSITY



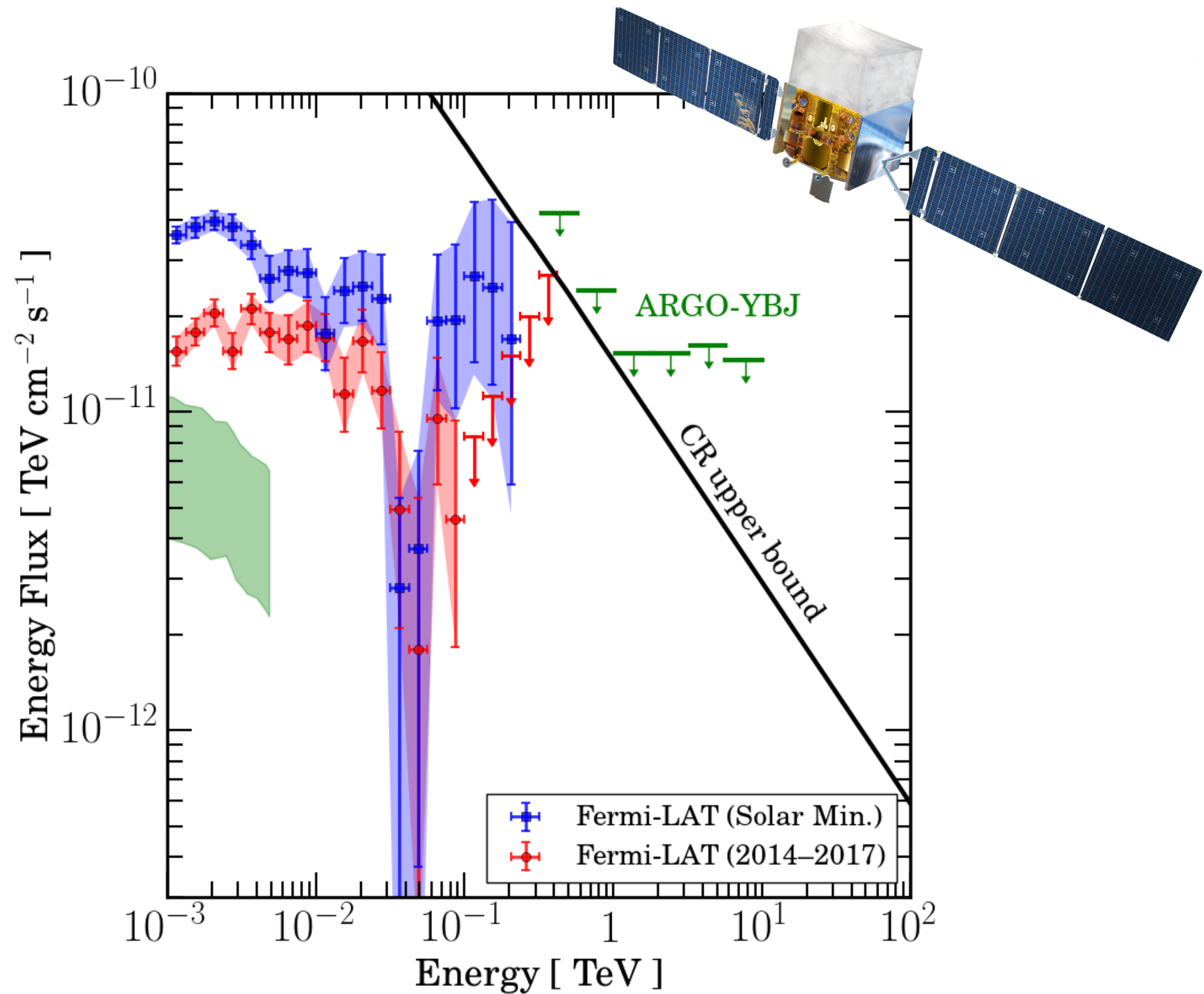
# OVERVIEW

- Why study the Sun above 100 GeV
- Observational Challenges
- Status, recent results and implications
- Synergies with neutrino astronomy
- Future Prospects

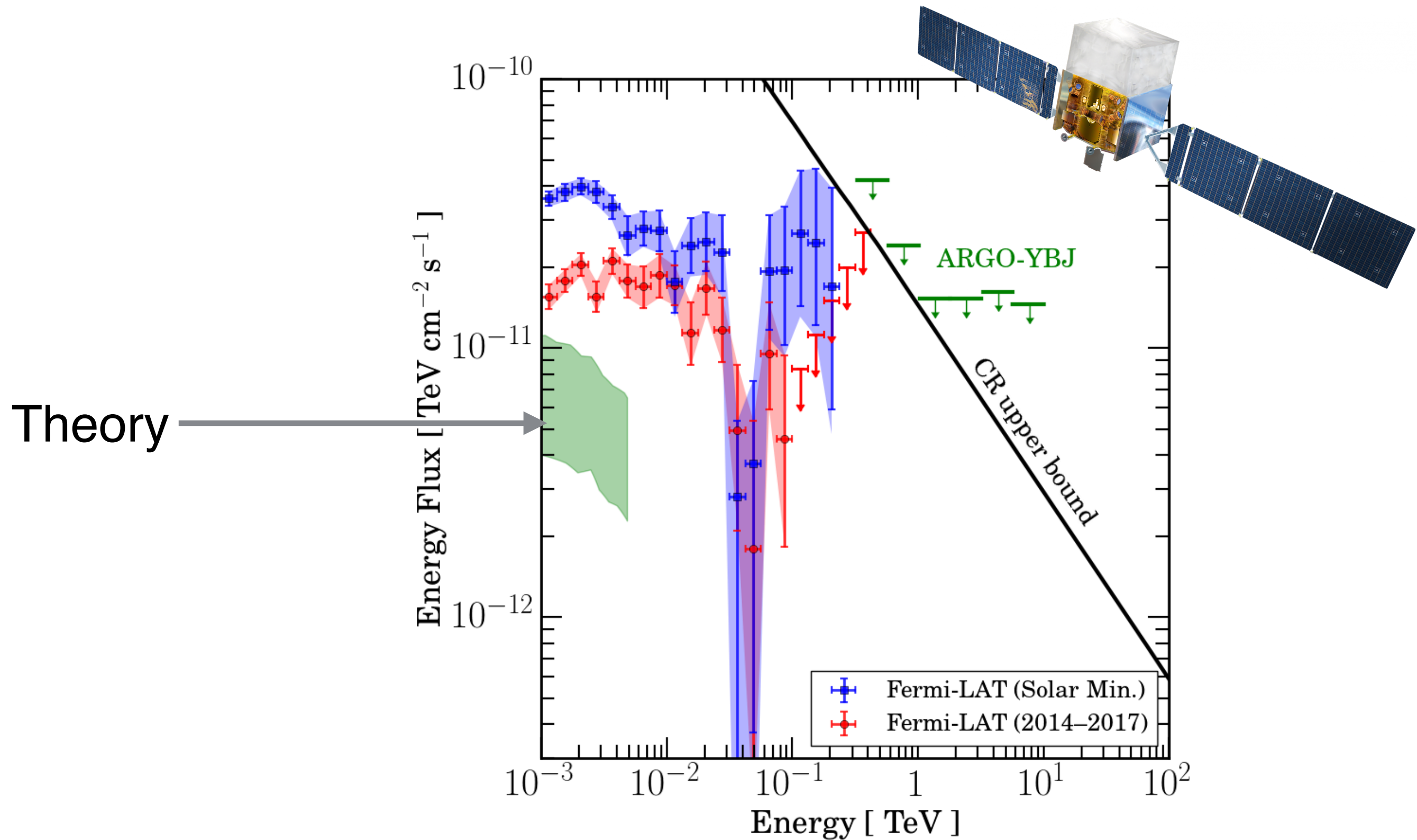
# Solar Disk at GeV: Brighter than expected!



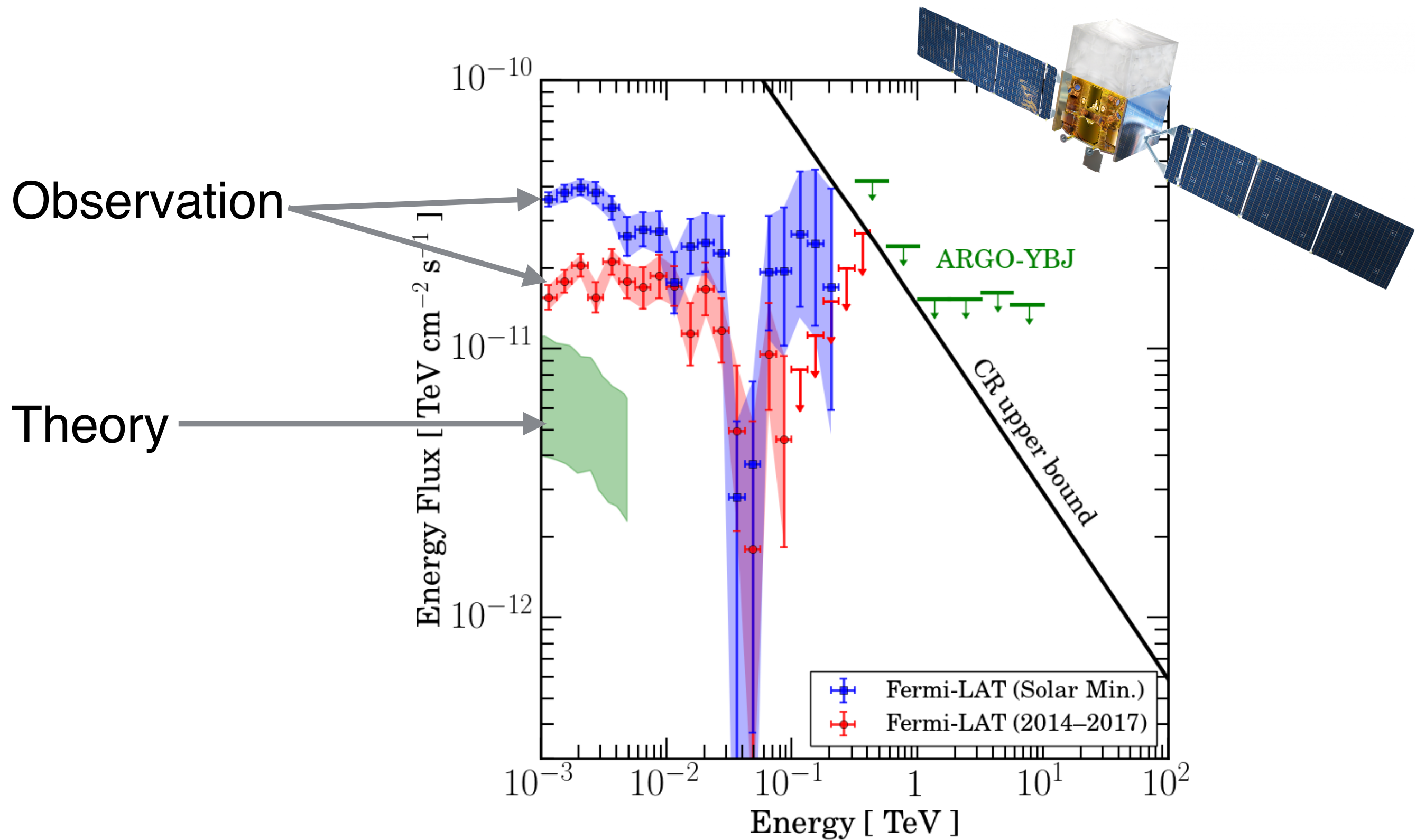
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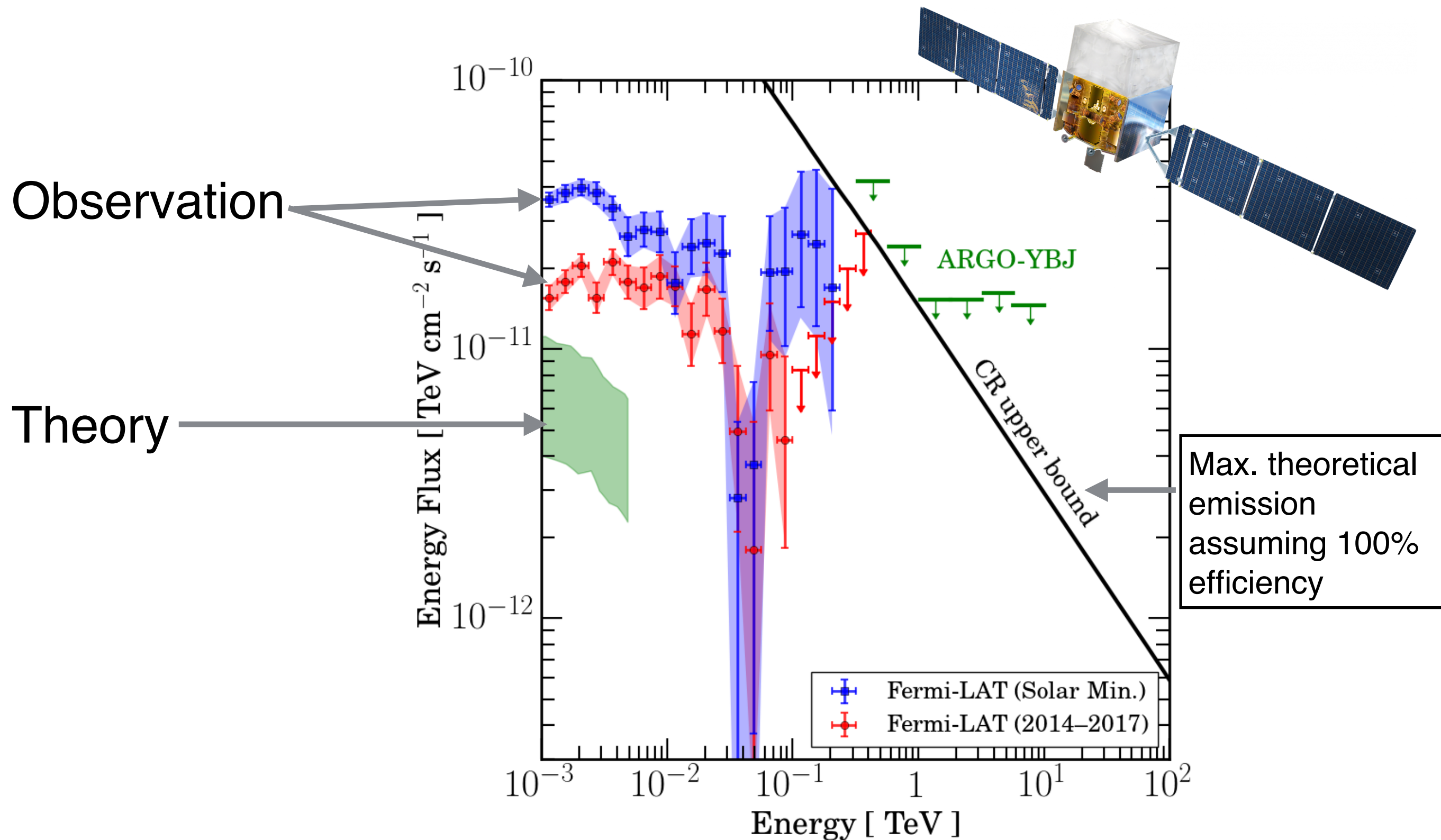
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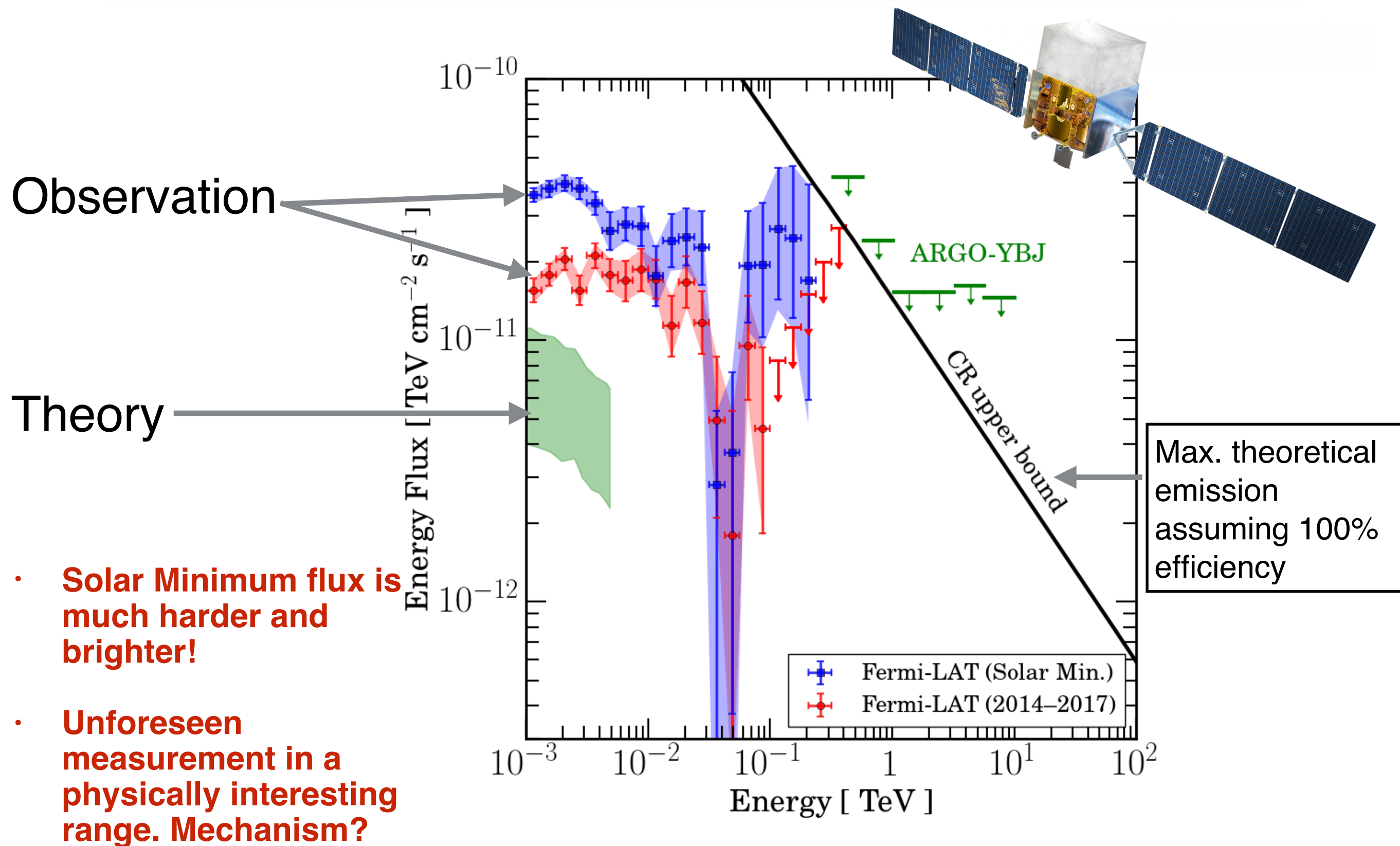
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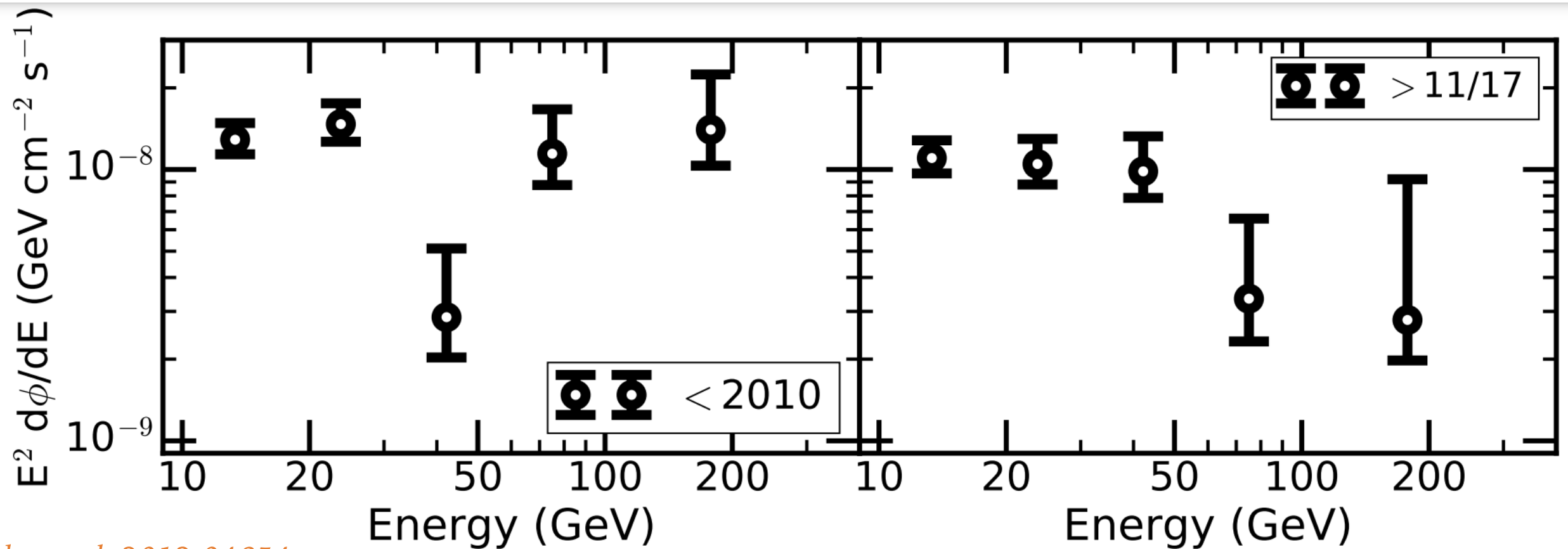


# Solar Disk at GeV: Brighter than expected!



# BEYOND 100 GEV WITH FERMI

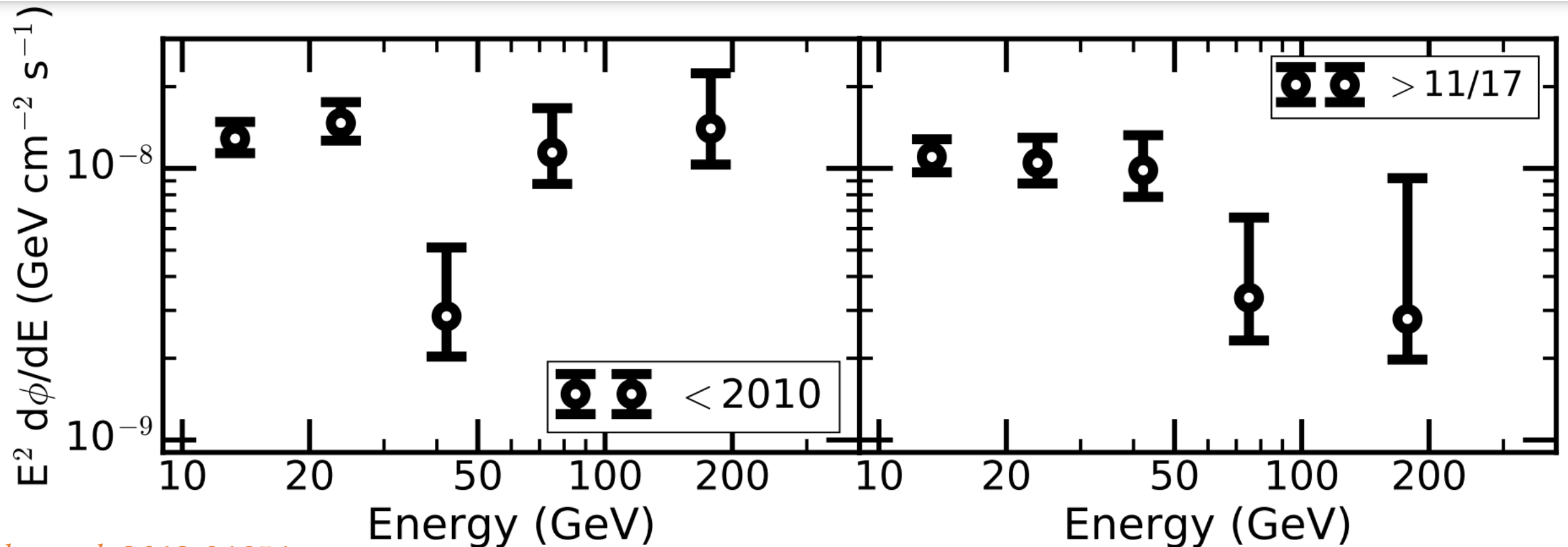
Last two solar minima



*Linden et al. 2012.04654*

# BEYOND 100 GEV WITH FERMI

Last two solar minima



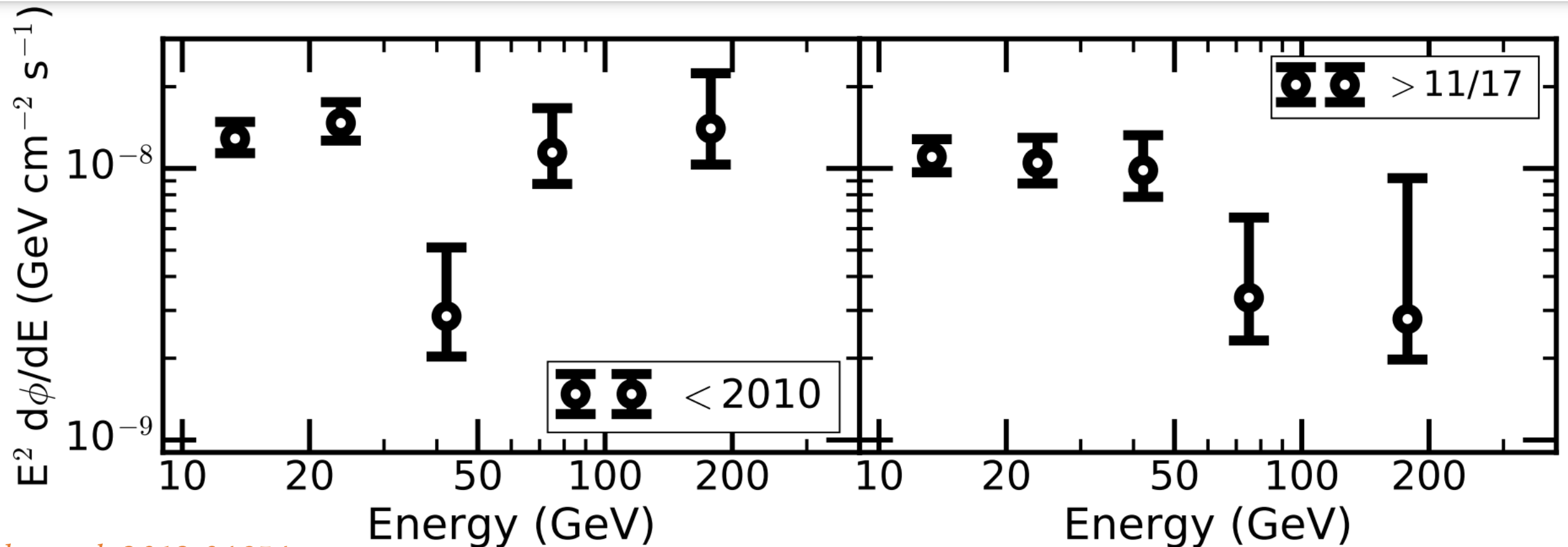
*Linden et al. 2012.04654*

Cycle 24

8 Photons

# BEYOND 100 GEV WITH FERMI

Last two solar minima



*Linden et al. 2012.04654*

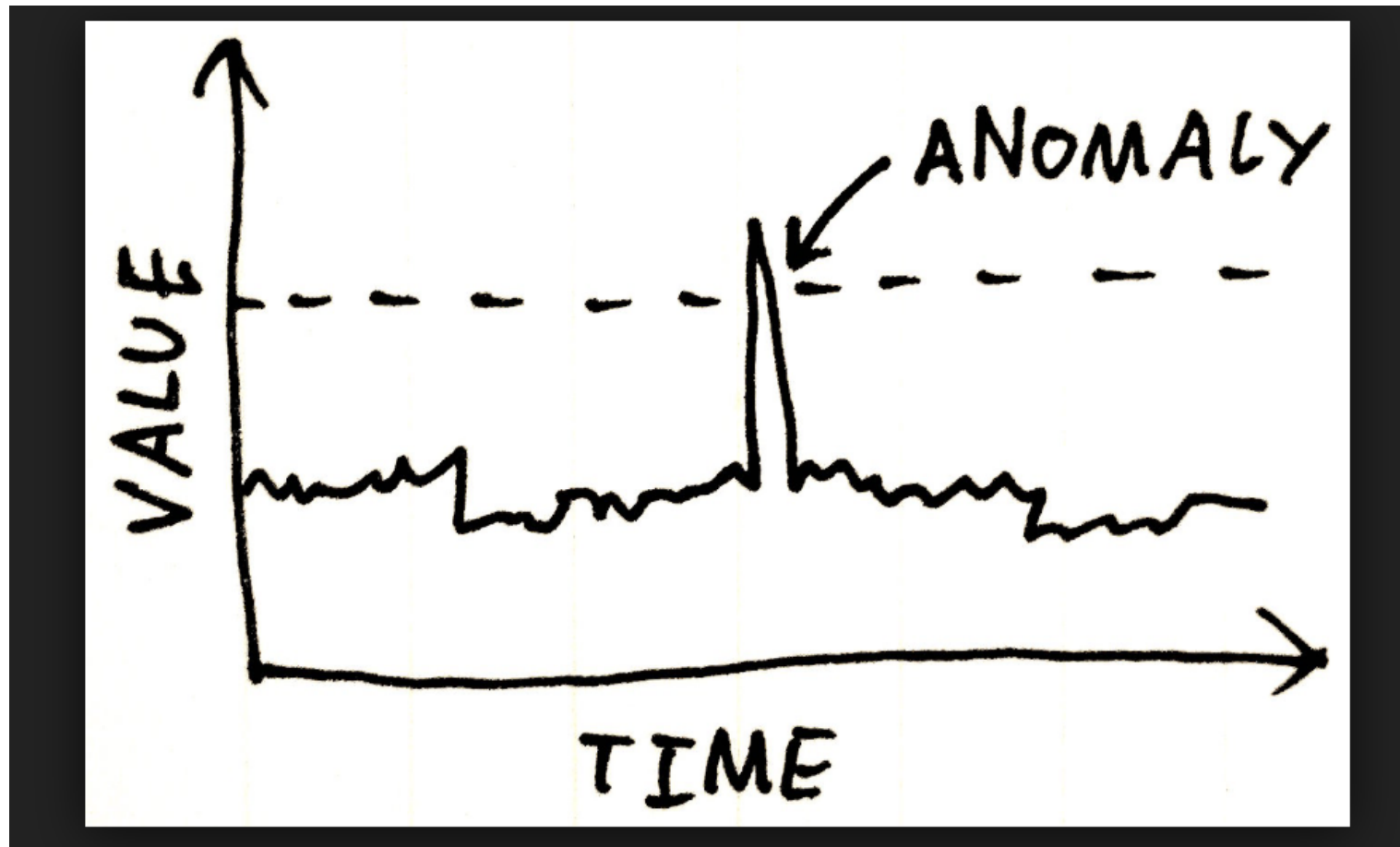
Cycle 24

8 Photons

Cycle 25

1 Photon

# THE GEV—TEV SUN FOR PHYSICS BEYOND THE STANDARD MODEL



© 2018 Stratus Innovations

- *Astrophysical anomalies >> Is it dark matter? 🤯*
- *The VHE Sun is an excellent target for indirect DM searches*

# TeV Observatories

Fermi



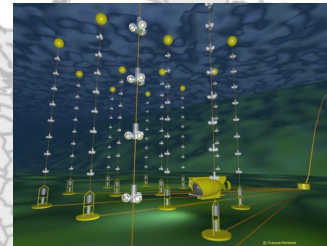
## TeV Gamma-Ray Telescopes



● VERITAS



● MAGIC



ANTARES



LHAASO



● HAWC



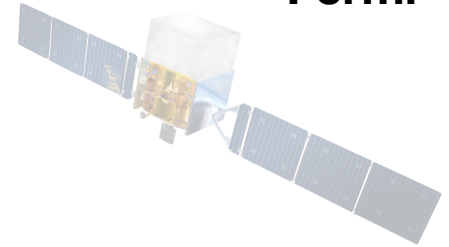
● HESS



IceCube

# TeV Observatories

Fermi



TeV Gamma-Ray Telescopes



● VERITAS

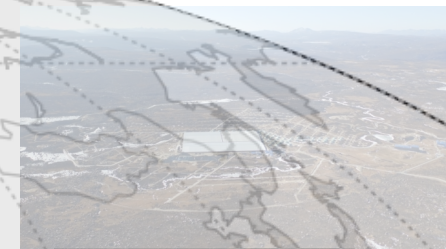


● MAGIC



● Crimea

ANTARES



LHAASO

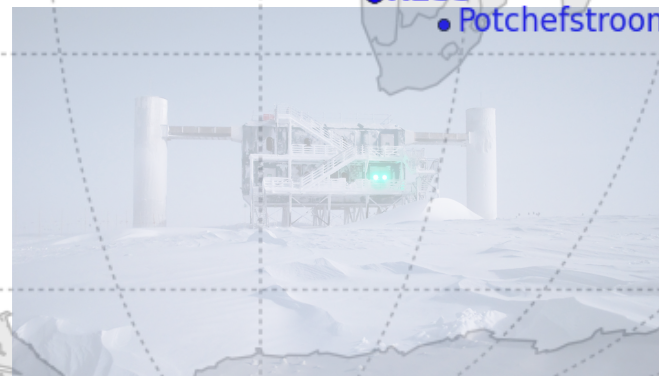


● HAWC



● HESS

● Potchefstroom



IceCube

IACs: Pointed  
Observations

Can't Observe  
the Sun :(

# TeV Observatories

Fermi



TeV Gamma-Ray Telescopes



• Milagro  
• VERITAS

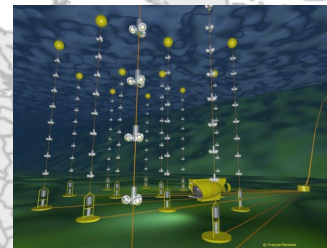
• HAWC



$\gamma$



• MAGIC

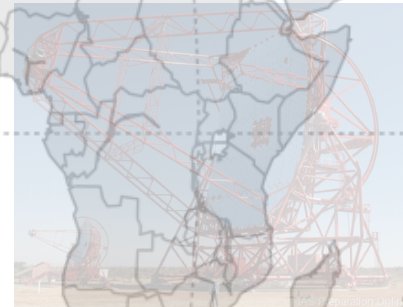


$\nu$  ANTARES



LHAASO

$\gamma$



• HESS

$\nu$



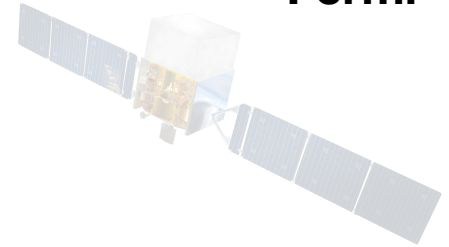
IceCube

Wide-Angle Surveys:

Surface/Volume Arrays  
Continuous monitoring,  
wide FOV  
100s of GeV to  $> 100$   
TeV

# TeV Observatories

Fermi



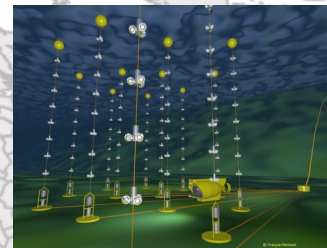
TeV Gamma-Ray Telescopes



• Milagro  
• VERITAS



• MAGIC



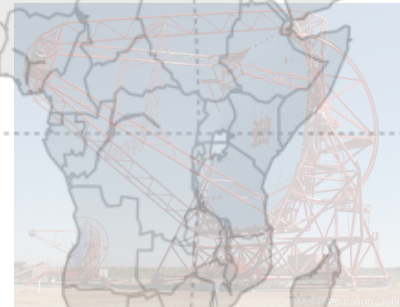
$\nu$  ANTARES



LHAASO  $\gamma$



• HAWC  $\gamma$



• HESS

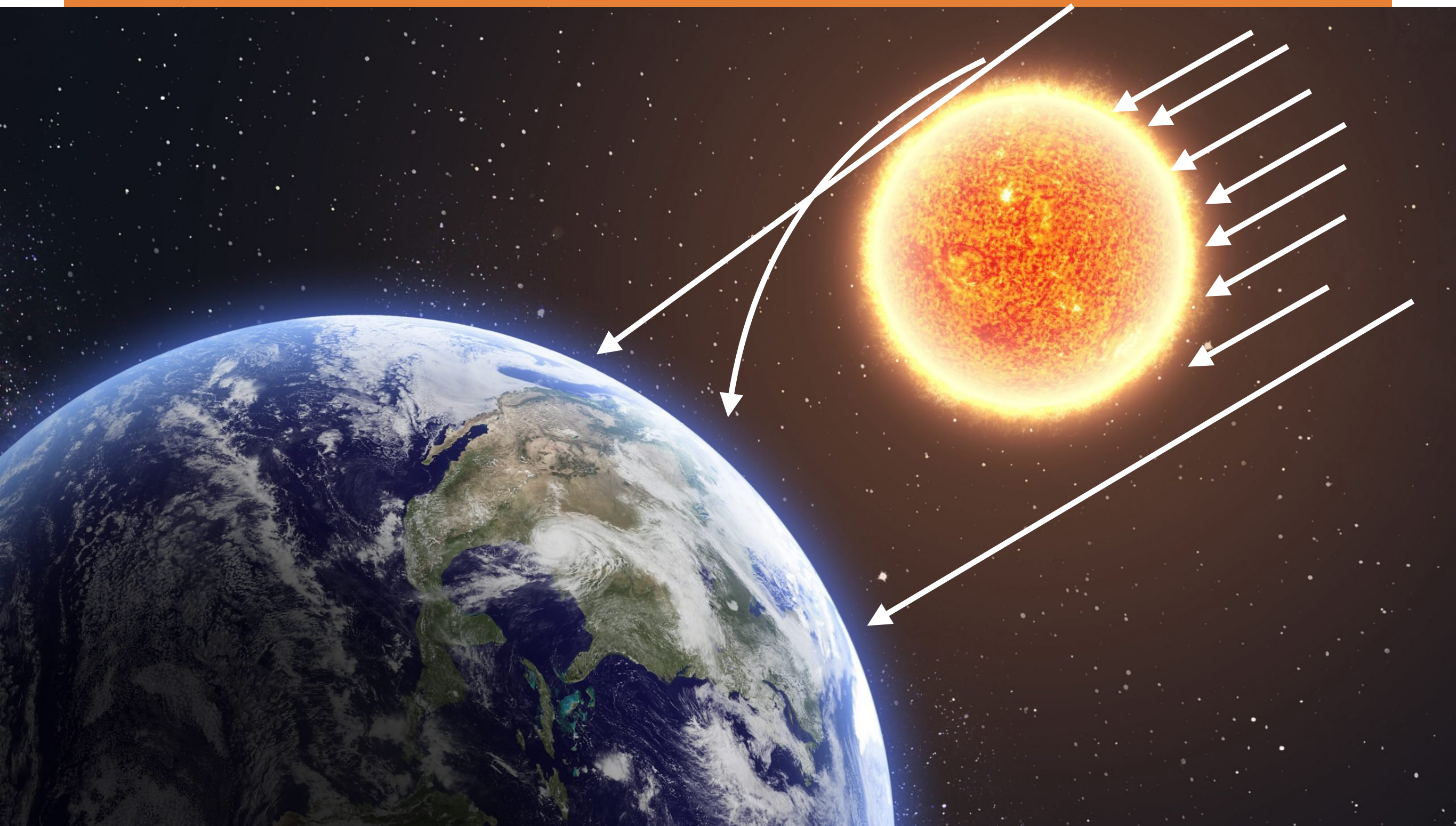


$\nu$  IceCube

Wide-Angle Surveys:

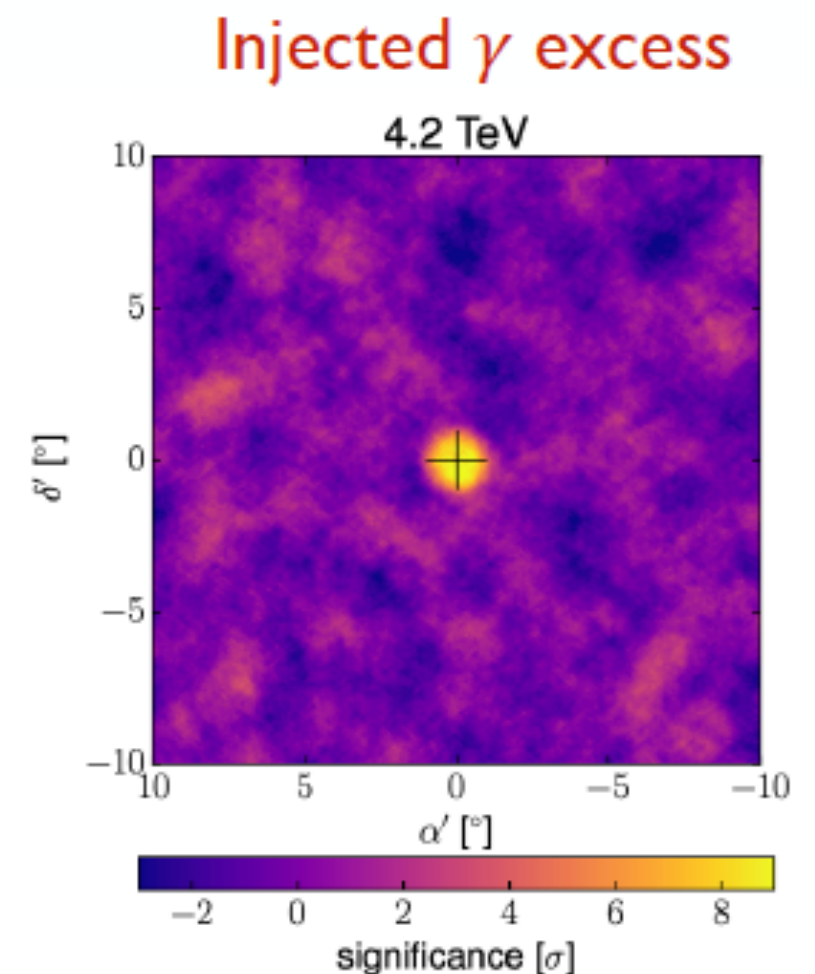
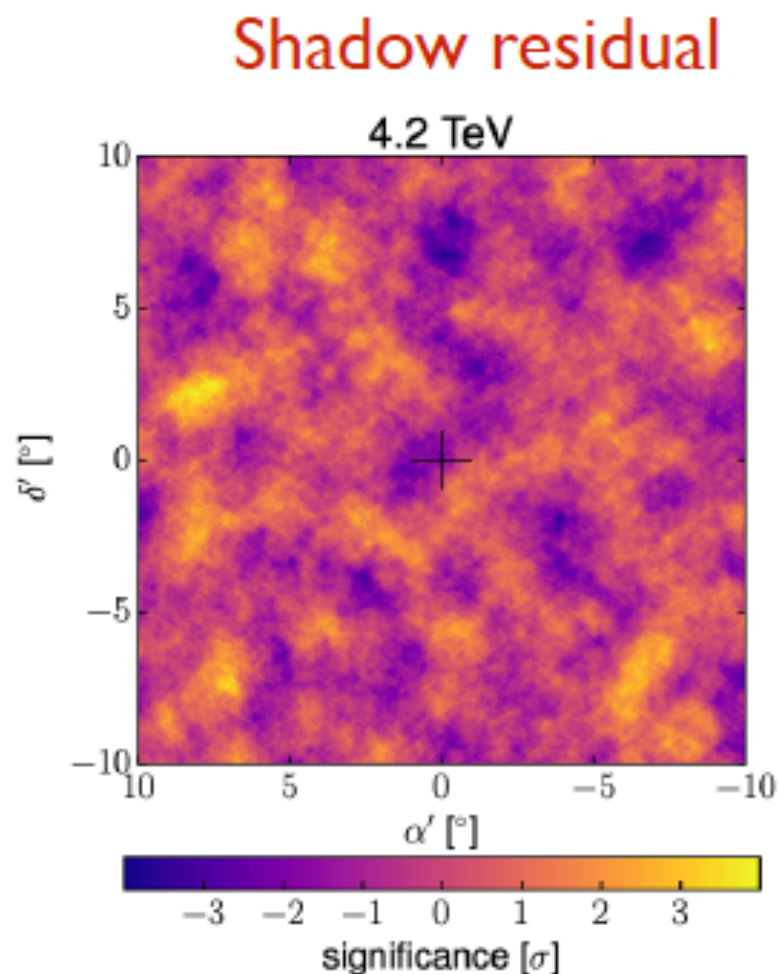
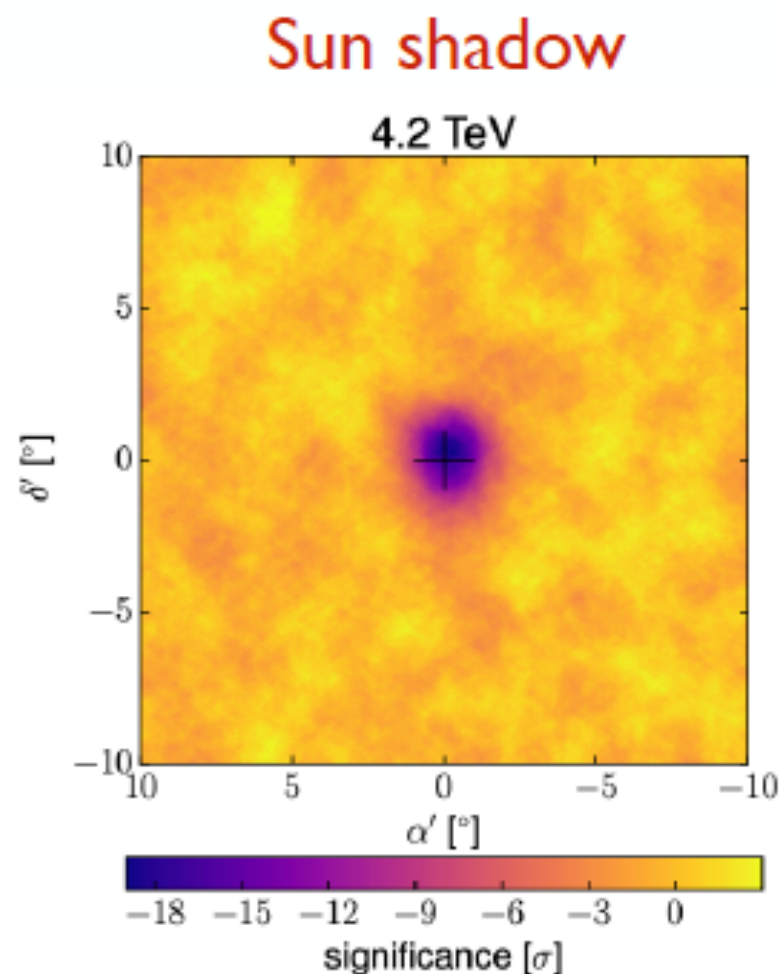
Surface/Volume Arrays  
Continuous monitoring,  
wide FOV  
100s of GeV to  $> 100$   
TeV

# THE SOLAR COSMIC RAY SHADOW

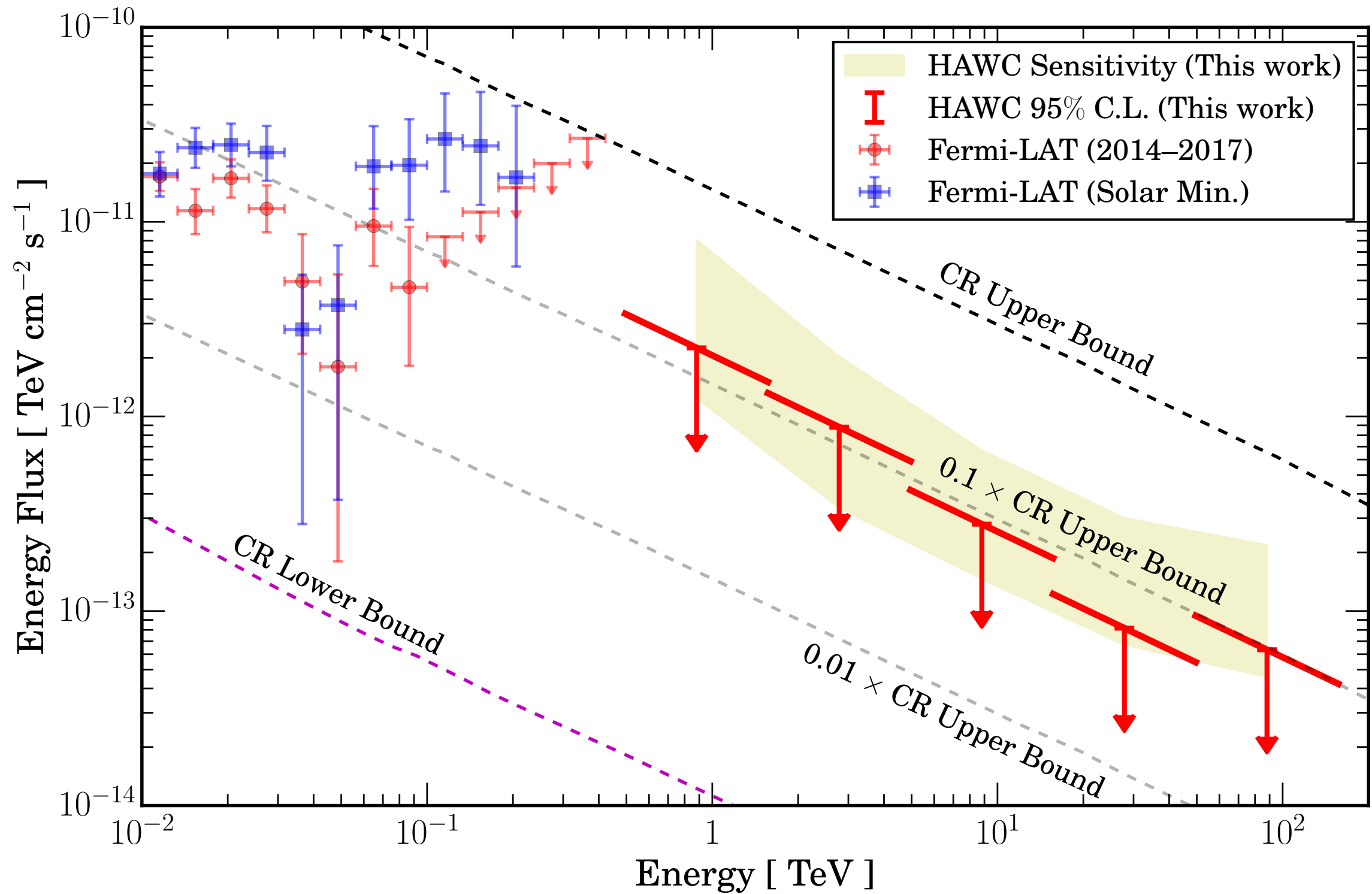


# WHAT WE DO IN THE SHADOWS

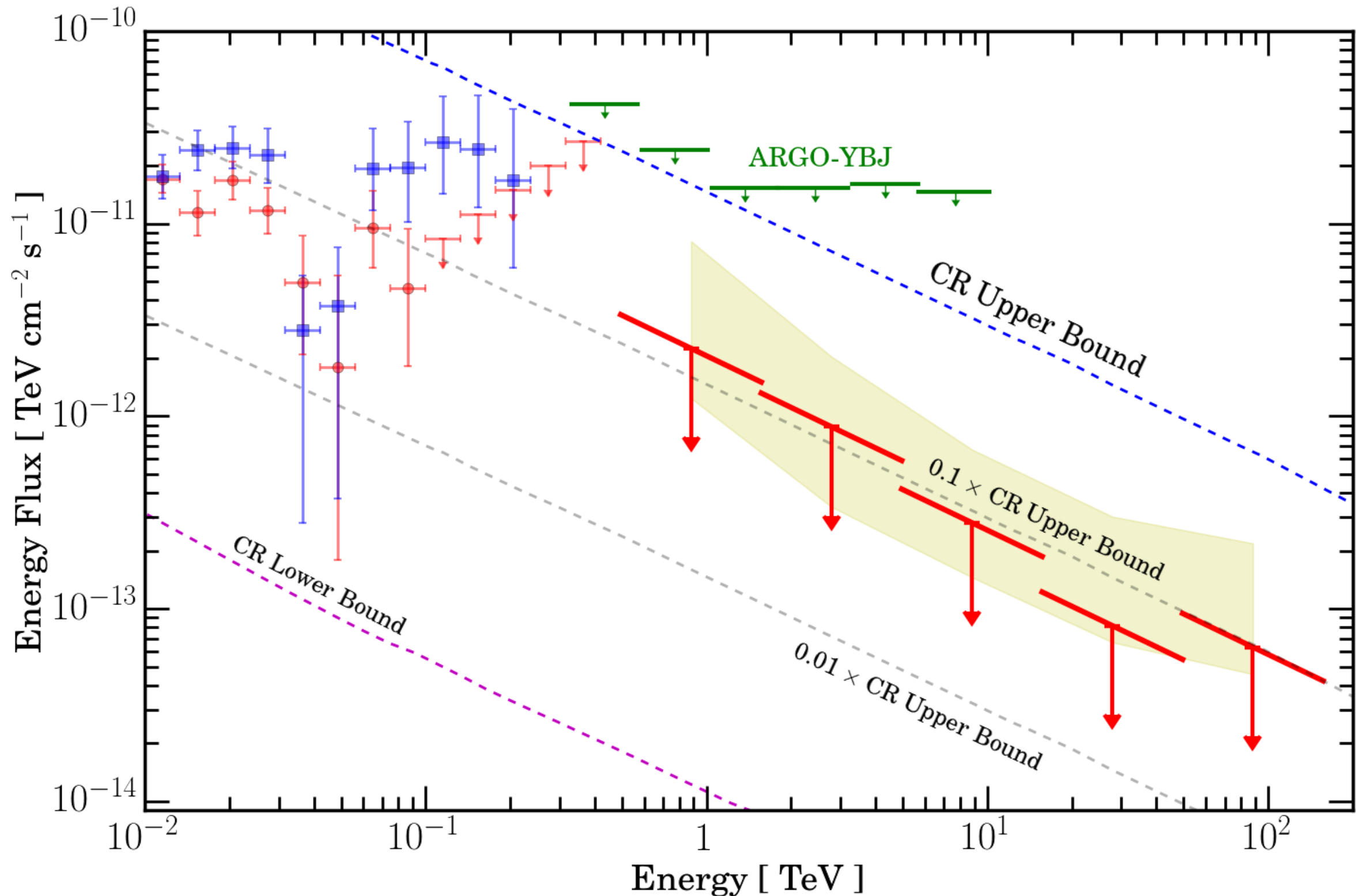
- ▶ Systematic: in HAWC detector, the Sun blocks Galactic cosmic rays and produces a deep “shadow” in the sky map.
- ▶ Fit & subtract the shadow, then look for  $\gamma$  ray excesses.



# First Results from HAWC



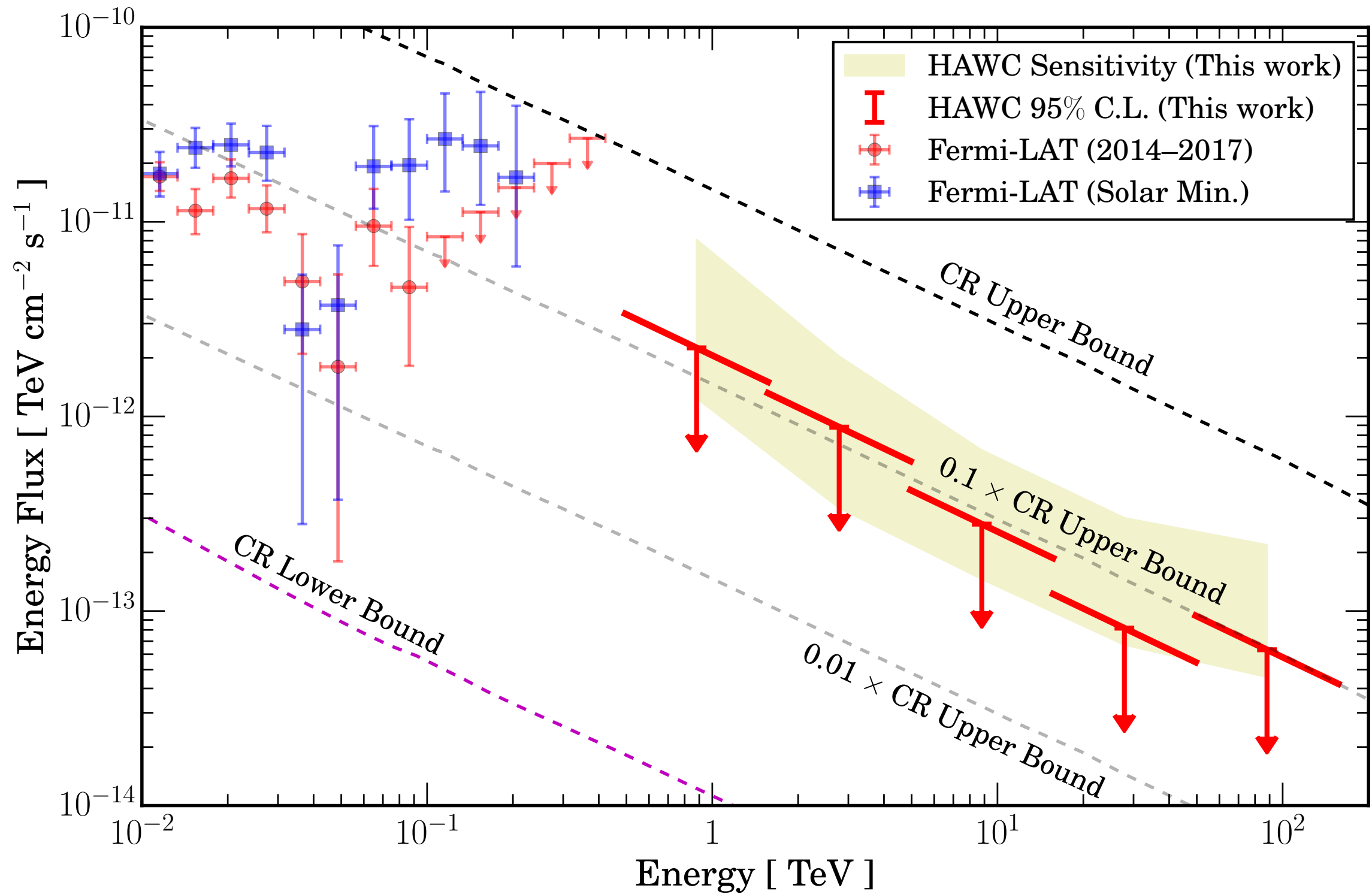
# First Results from HAWC



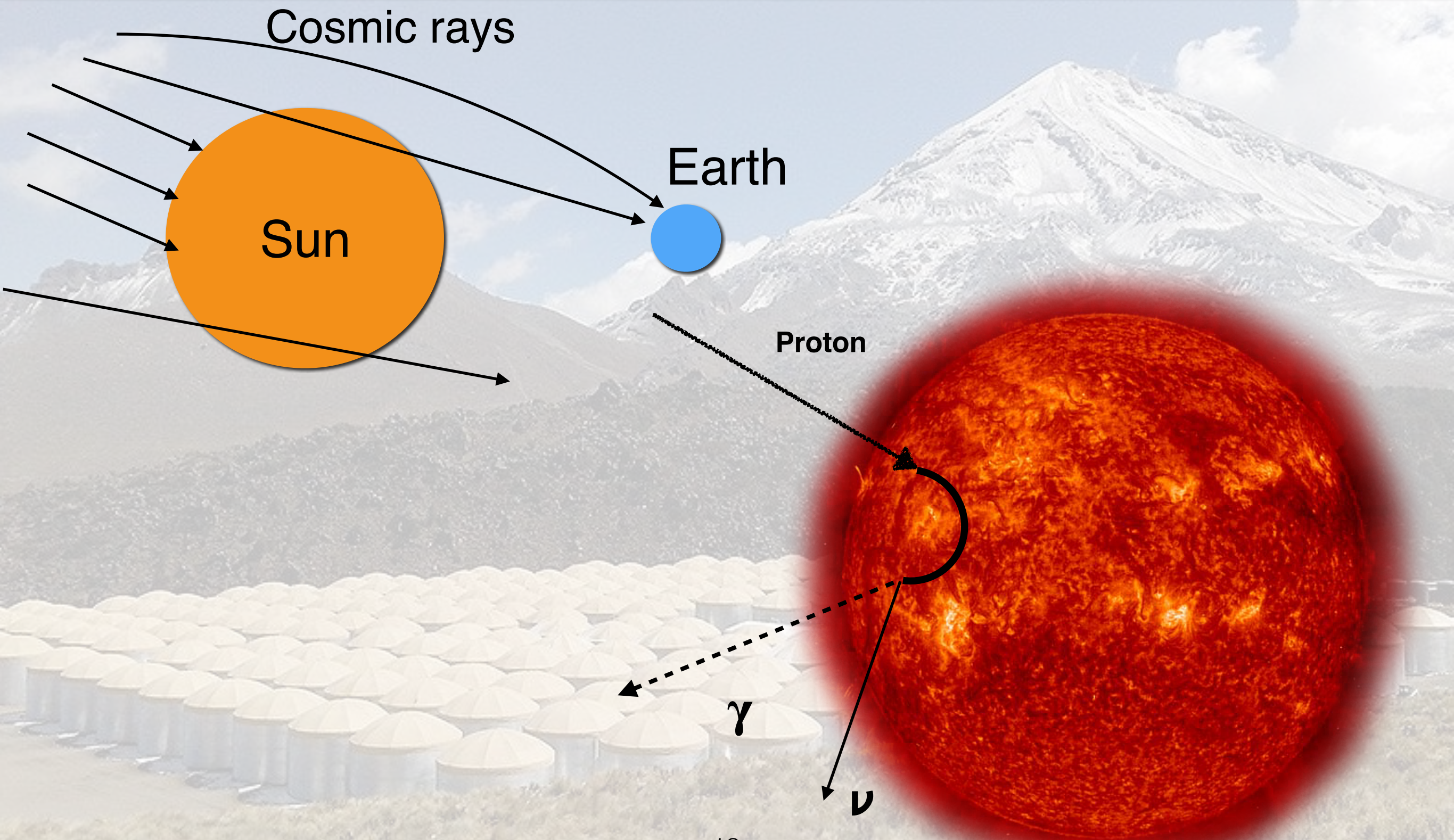
M.U. Nisa (for HAWC) + Beacom, Leane, Ng, Peter, Linden, Zhou.1808.05620

Phys. Rev D. 2018

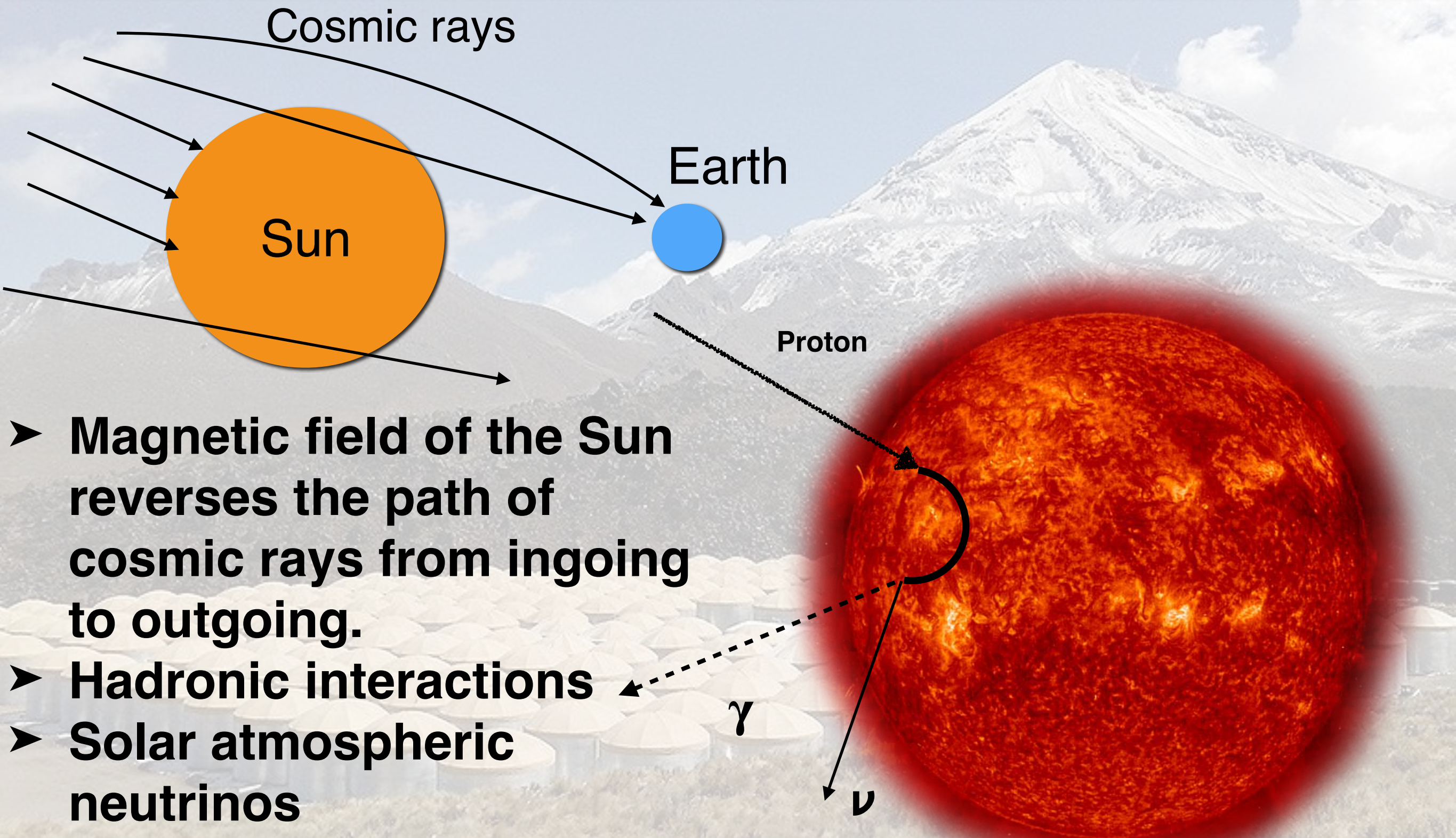
# First Results from HAWC



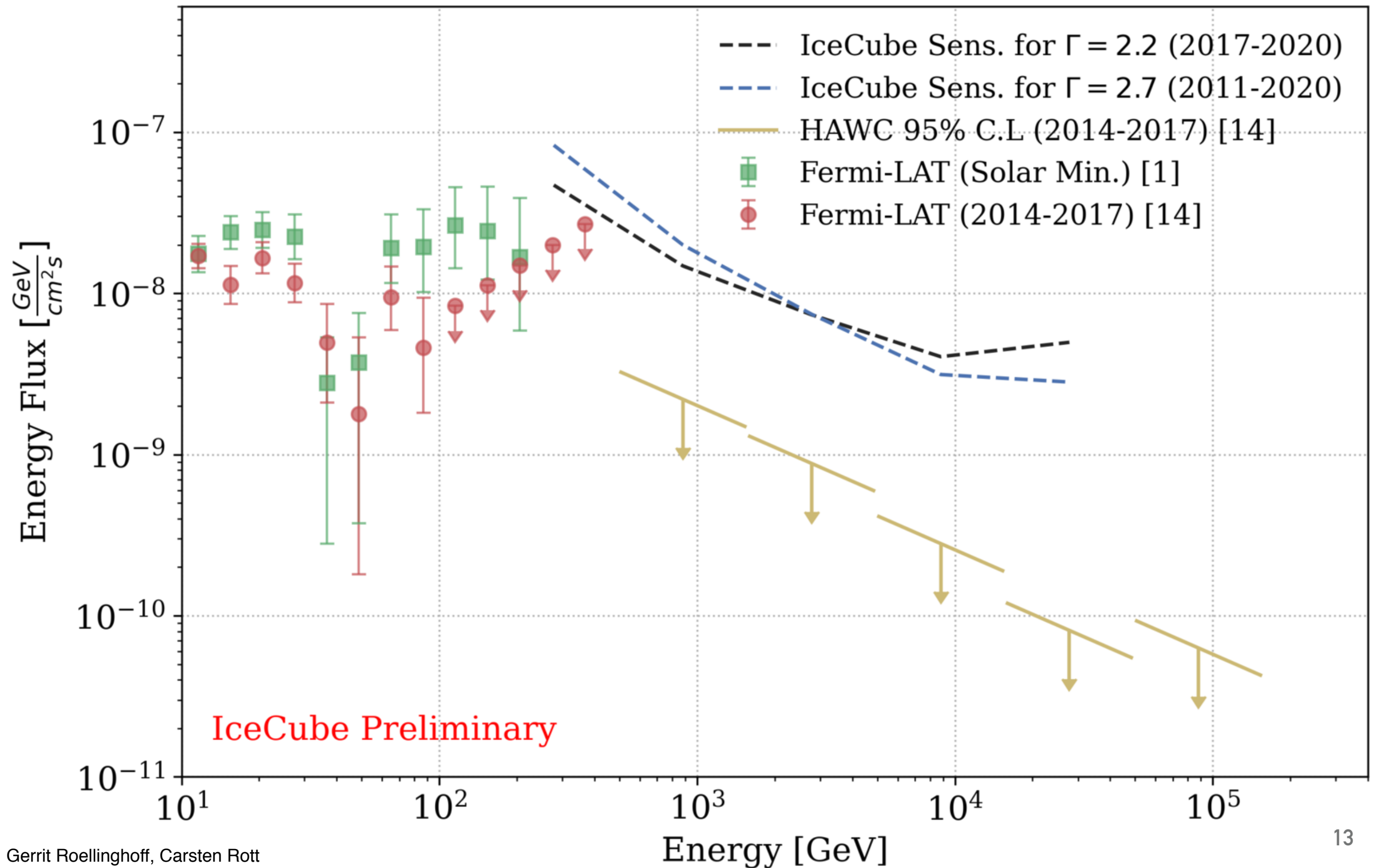
# Cosmic-ray interactions with the Sun's atmosphere produce $\gamma$ rays and neutrinos



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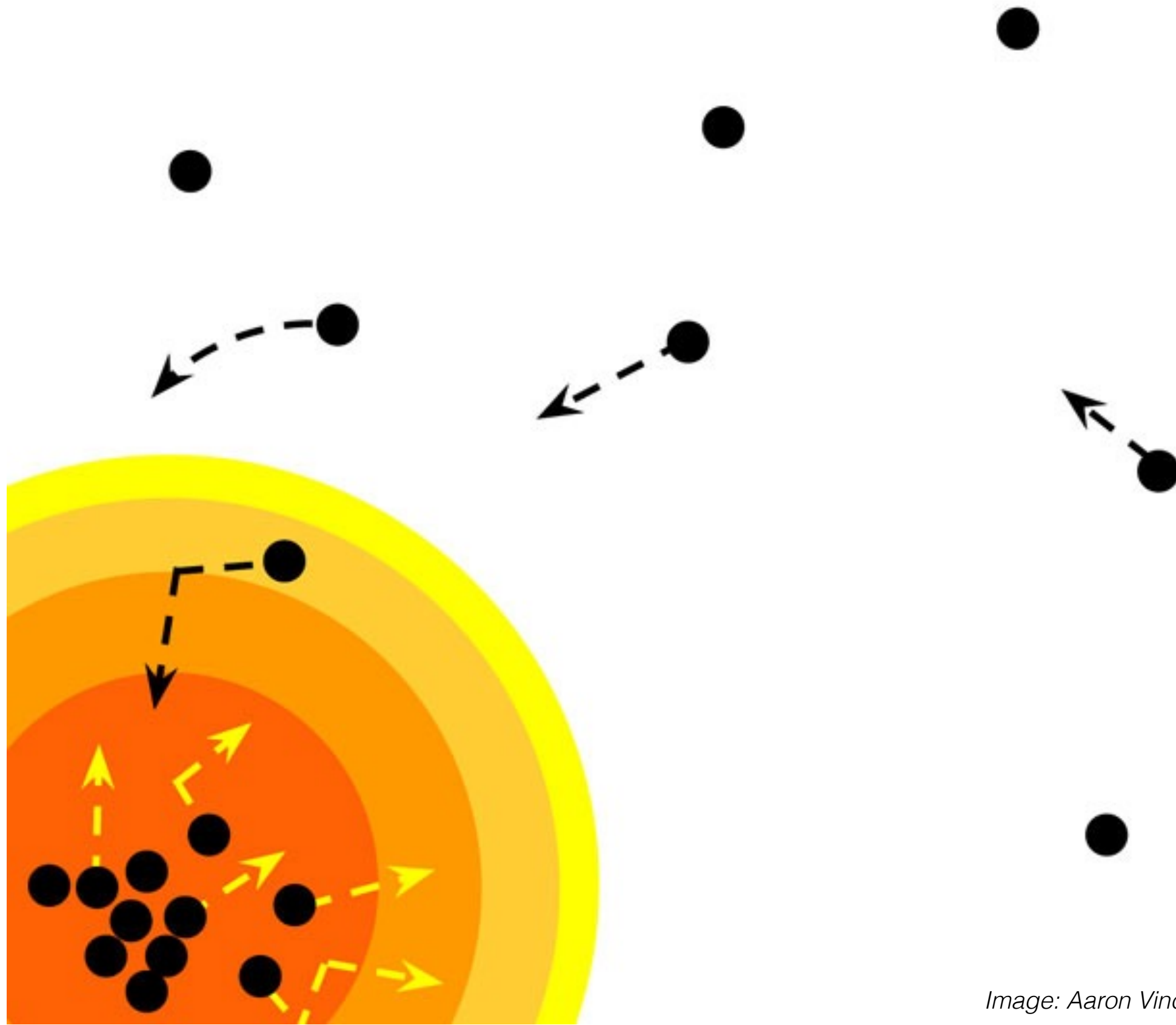


# COMPLEMENTARITY WITH NEUTRINOS

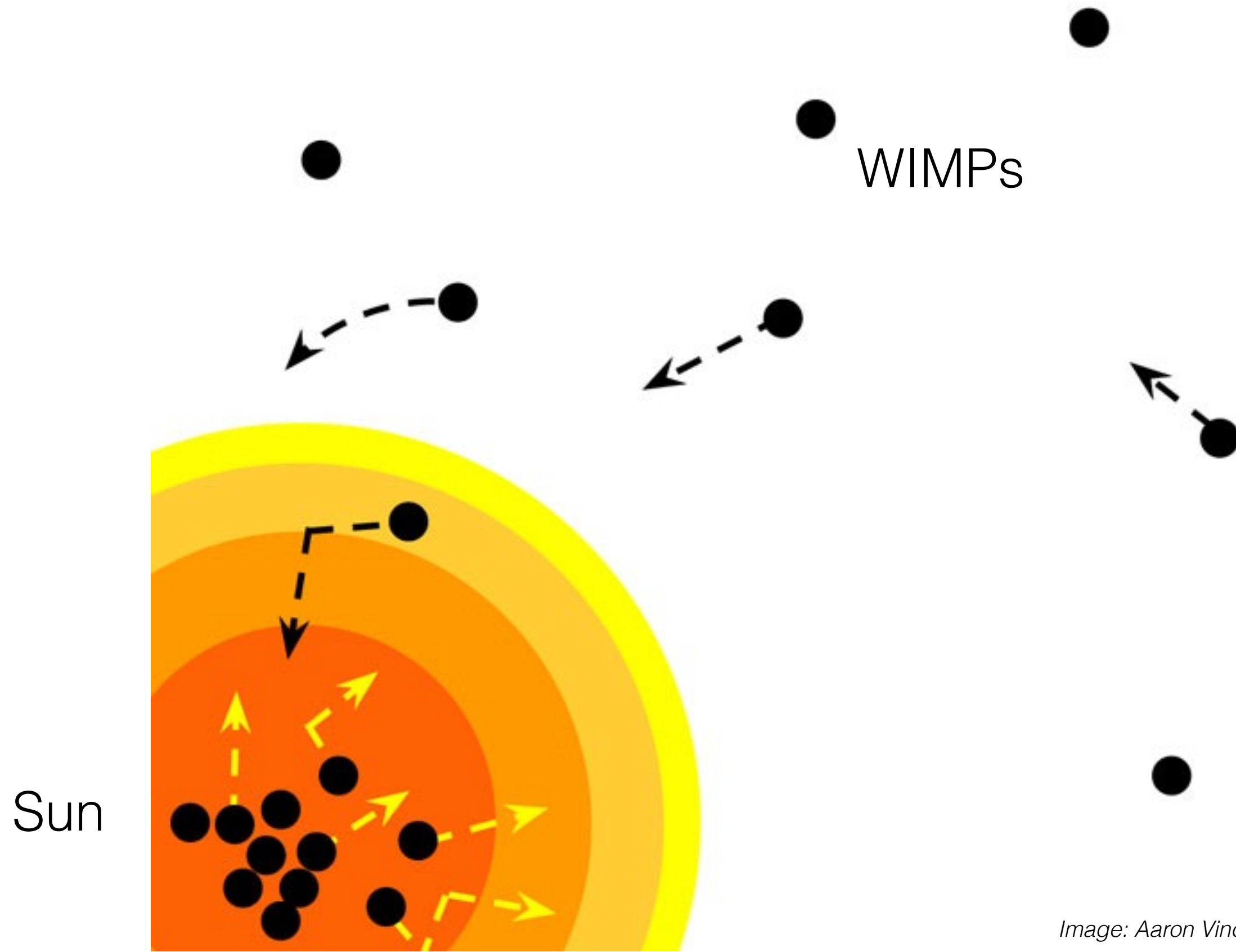


# Sun in the DM halo

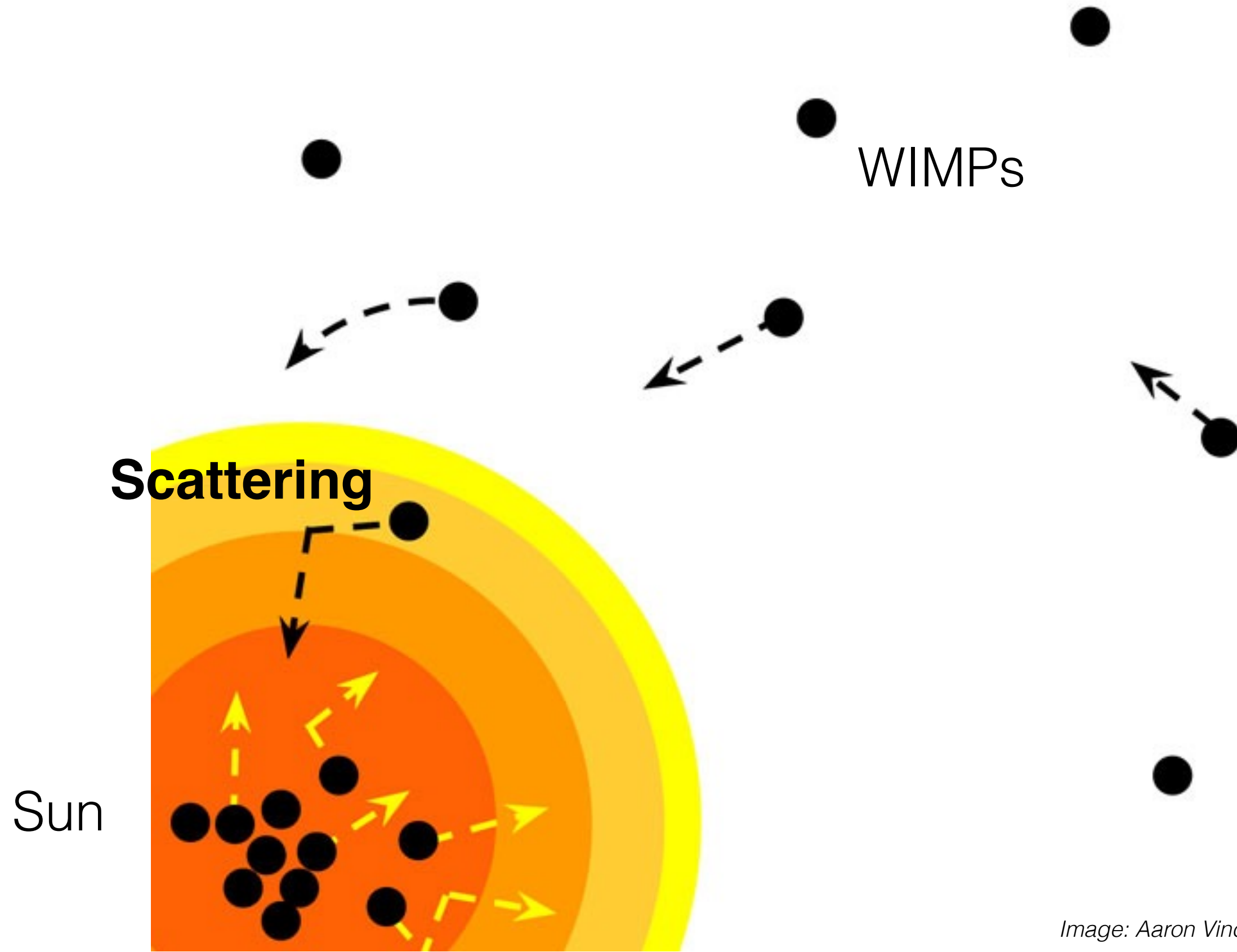
Sun



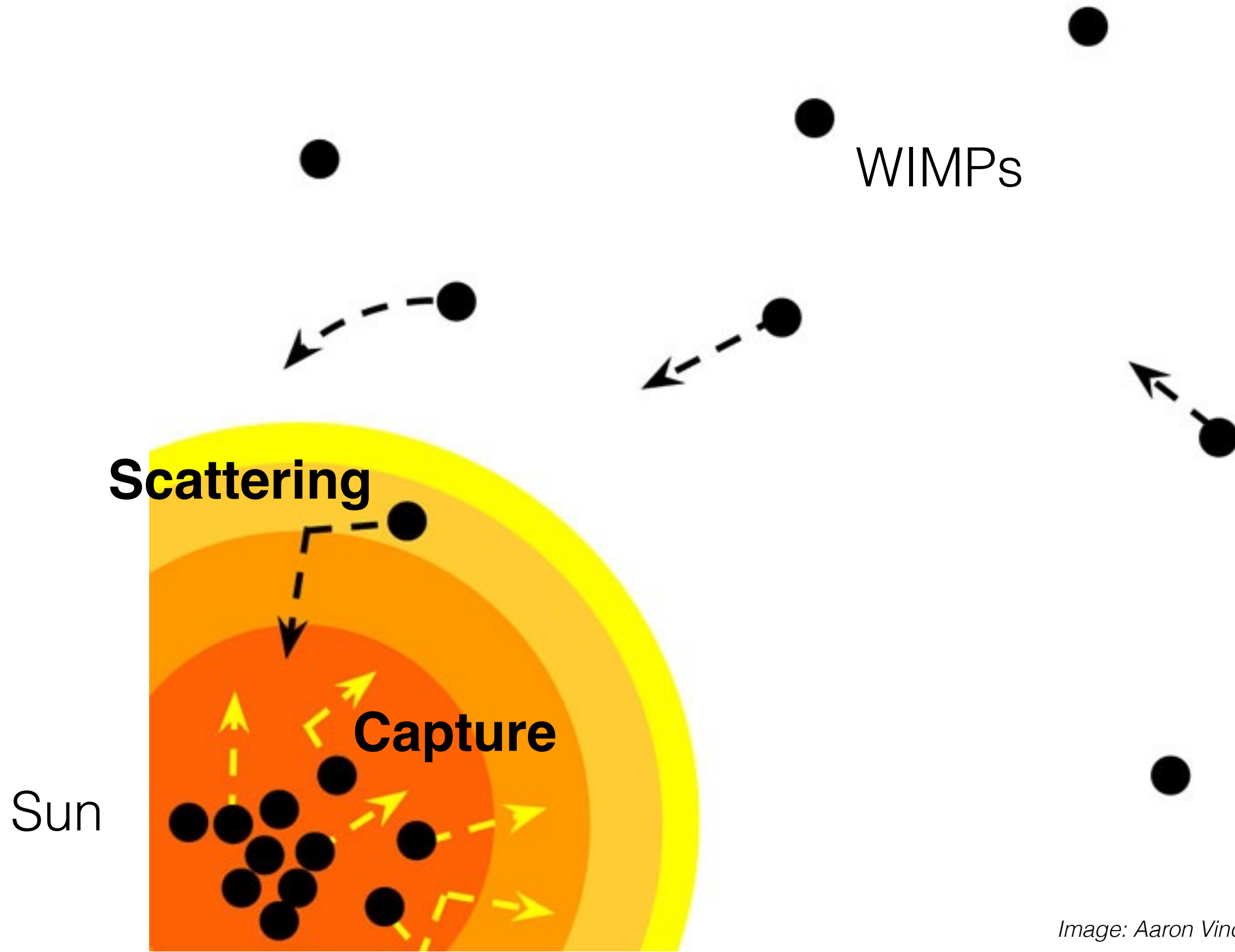
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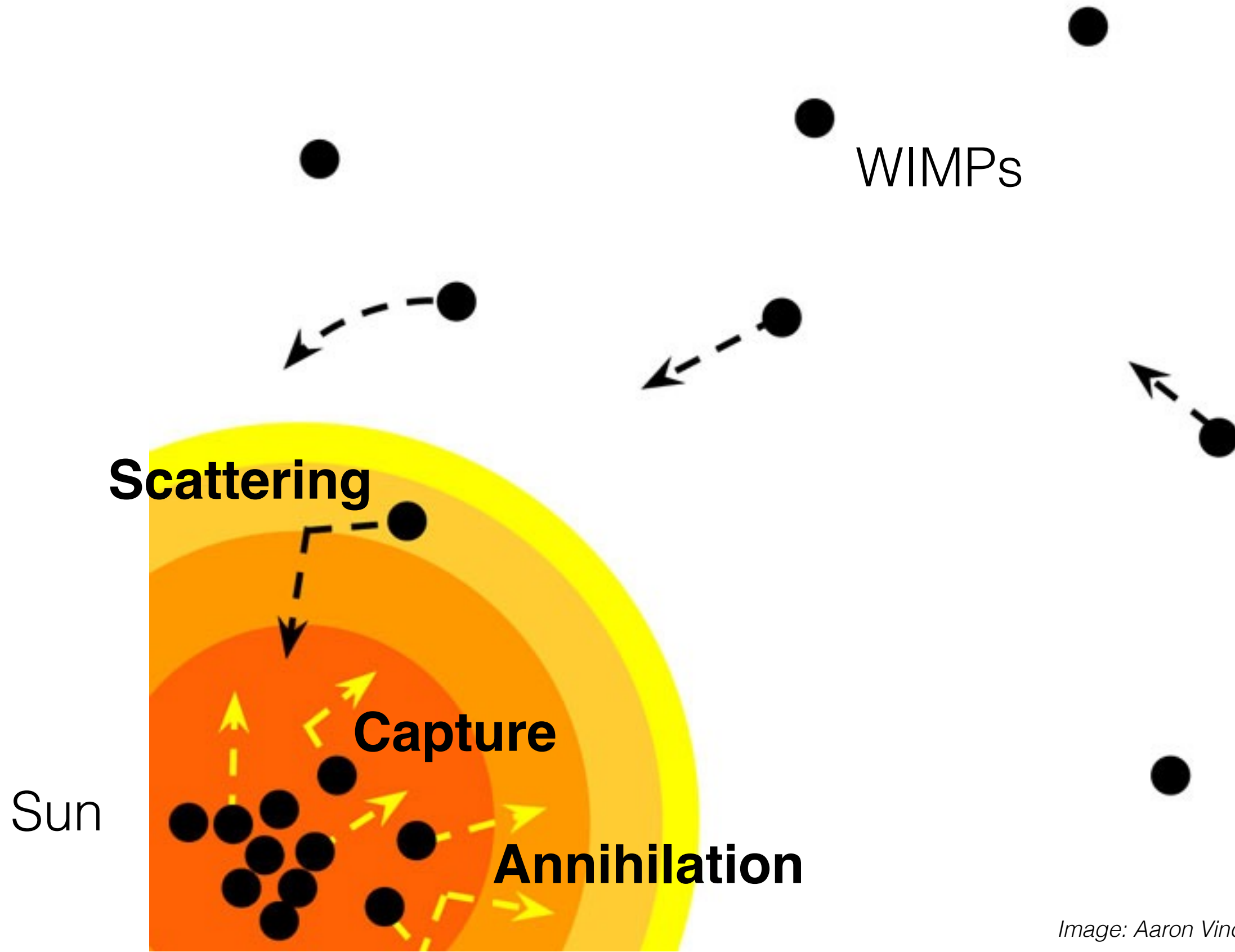
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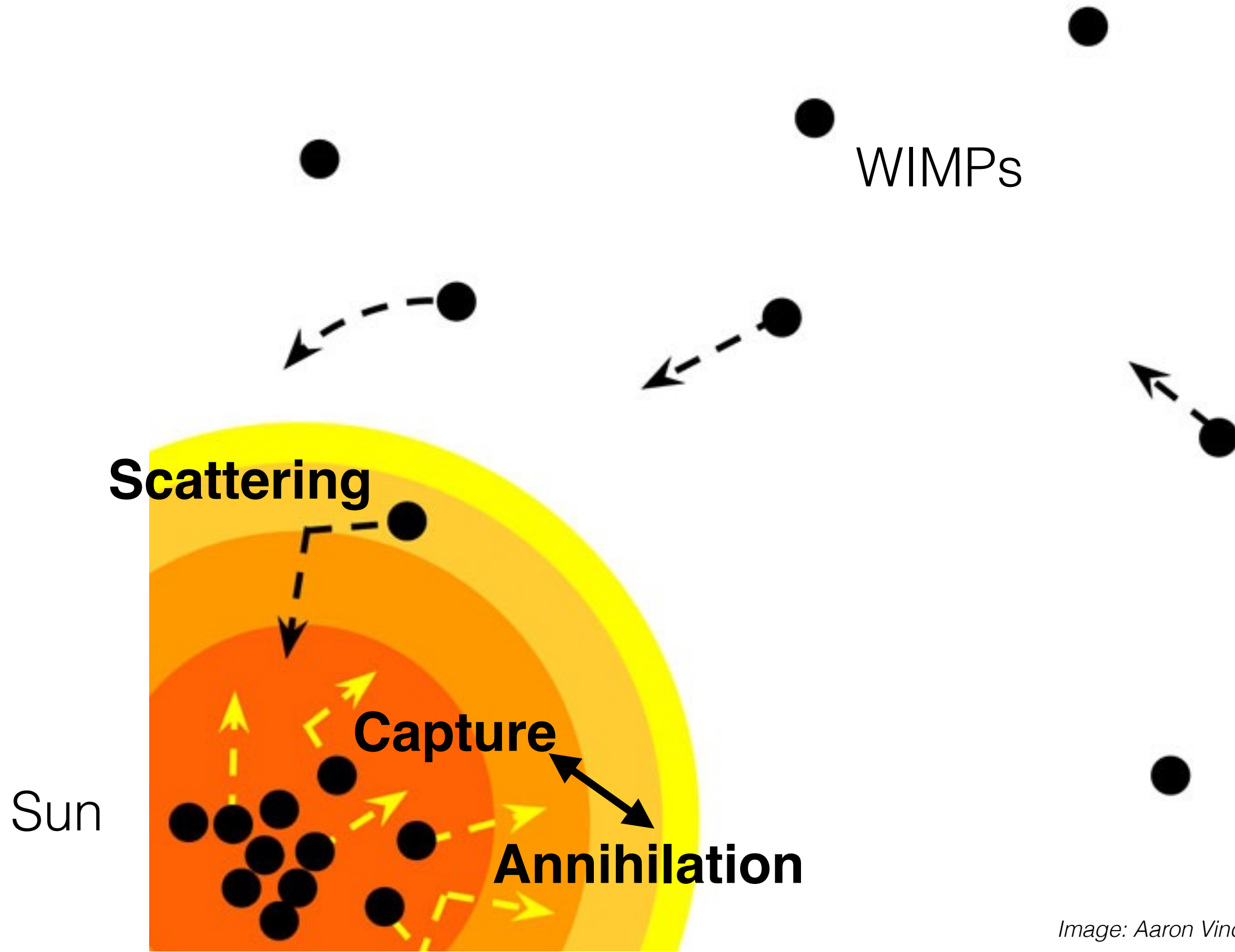
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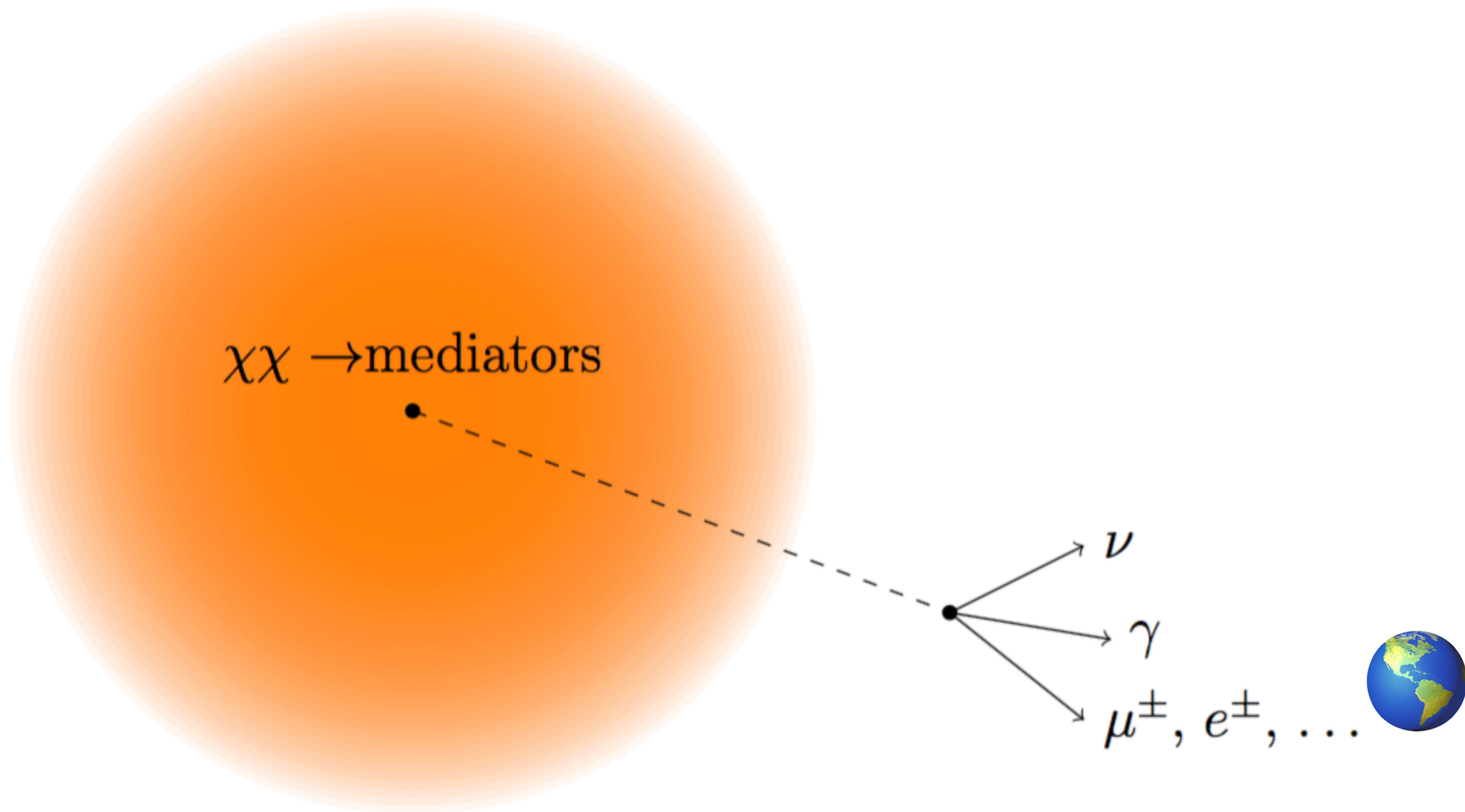


# Sun in the DM halo

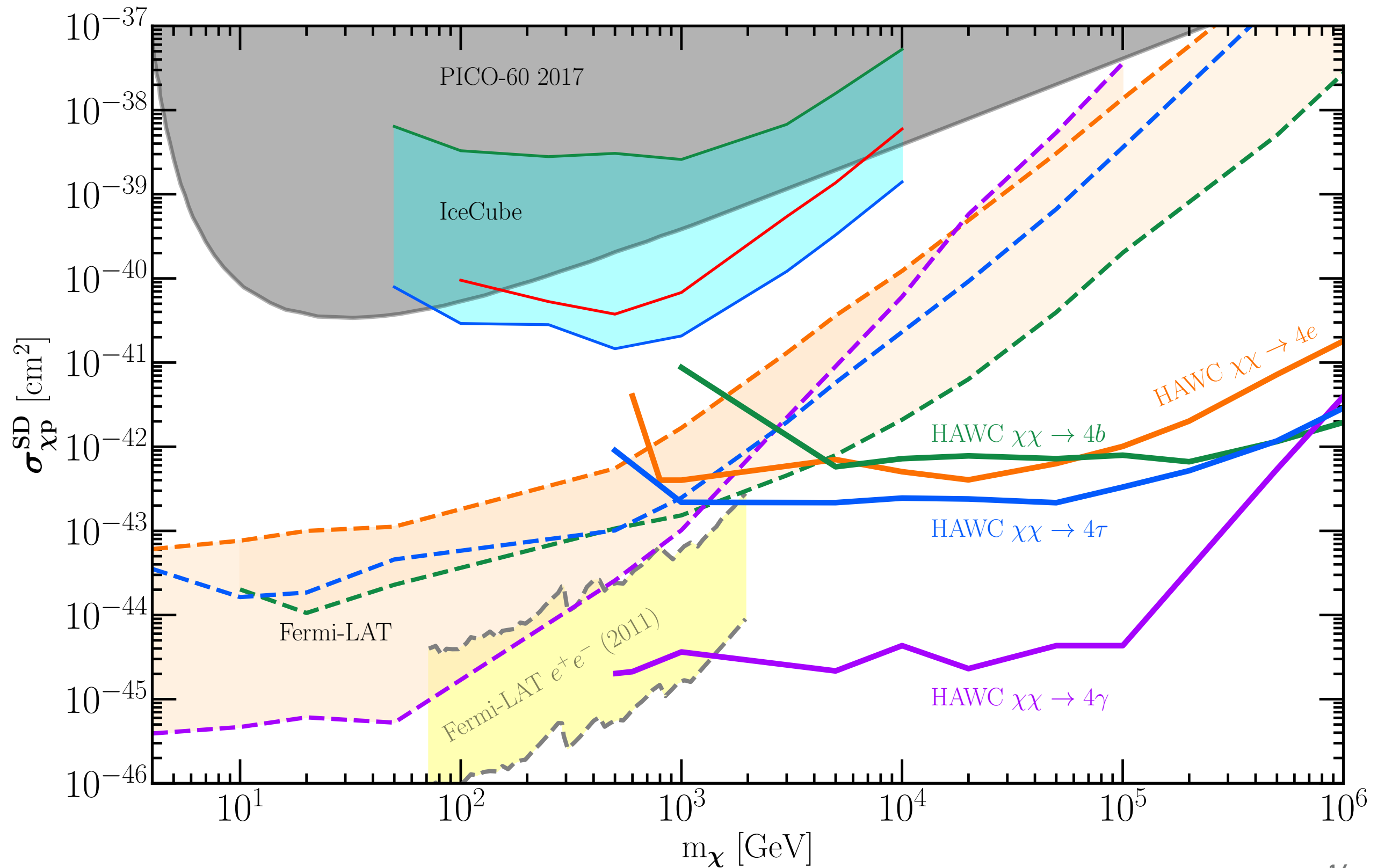


# Annihilation via Long-lived Mediator

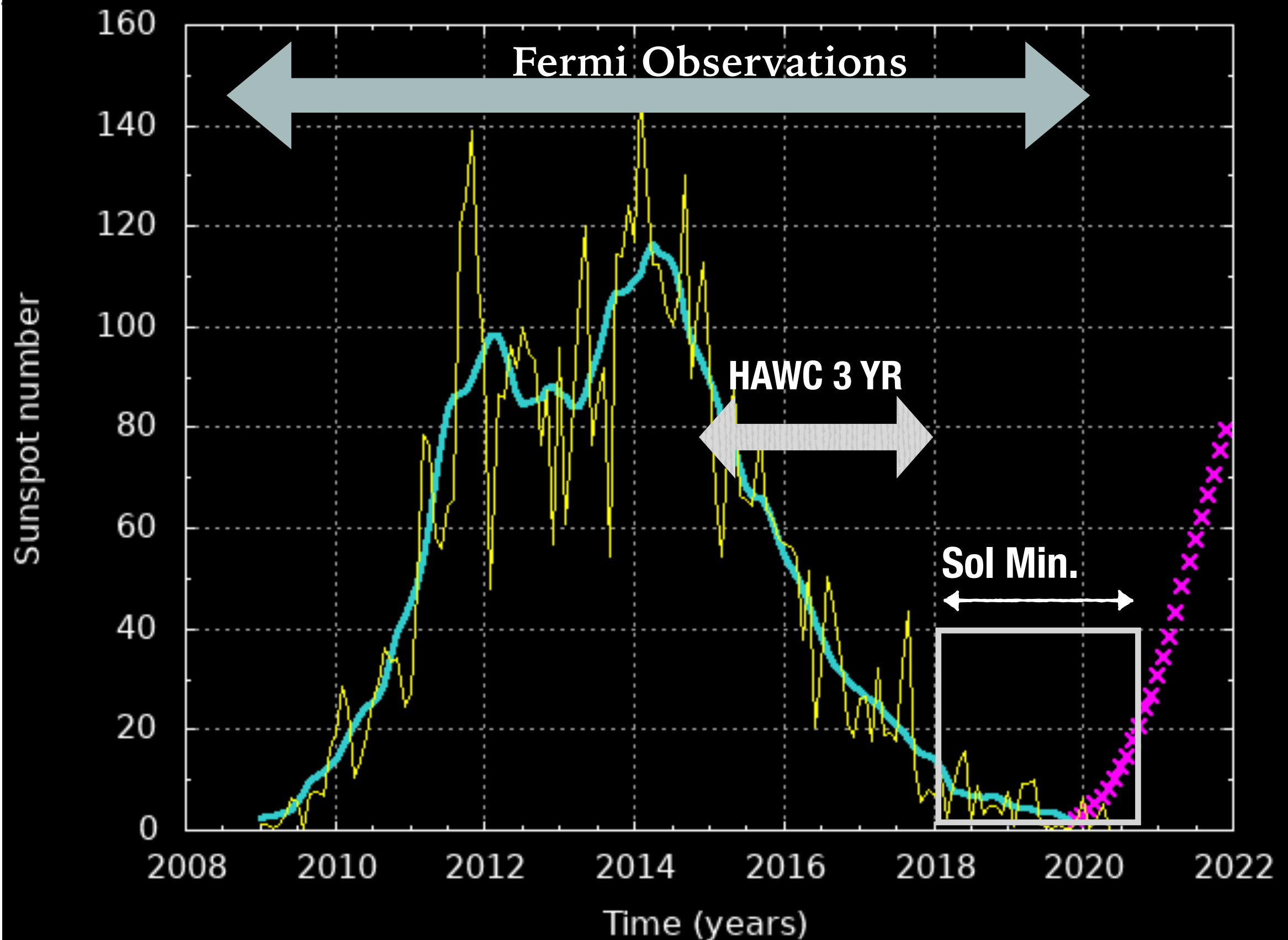
- **Mediator** could have sufficiently long lifetime to so that it **decays outside the Sun** and produces a detectable gamma-ray flux.



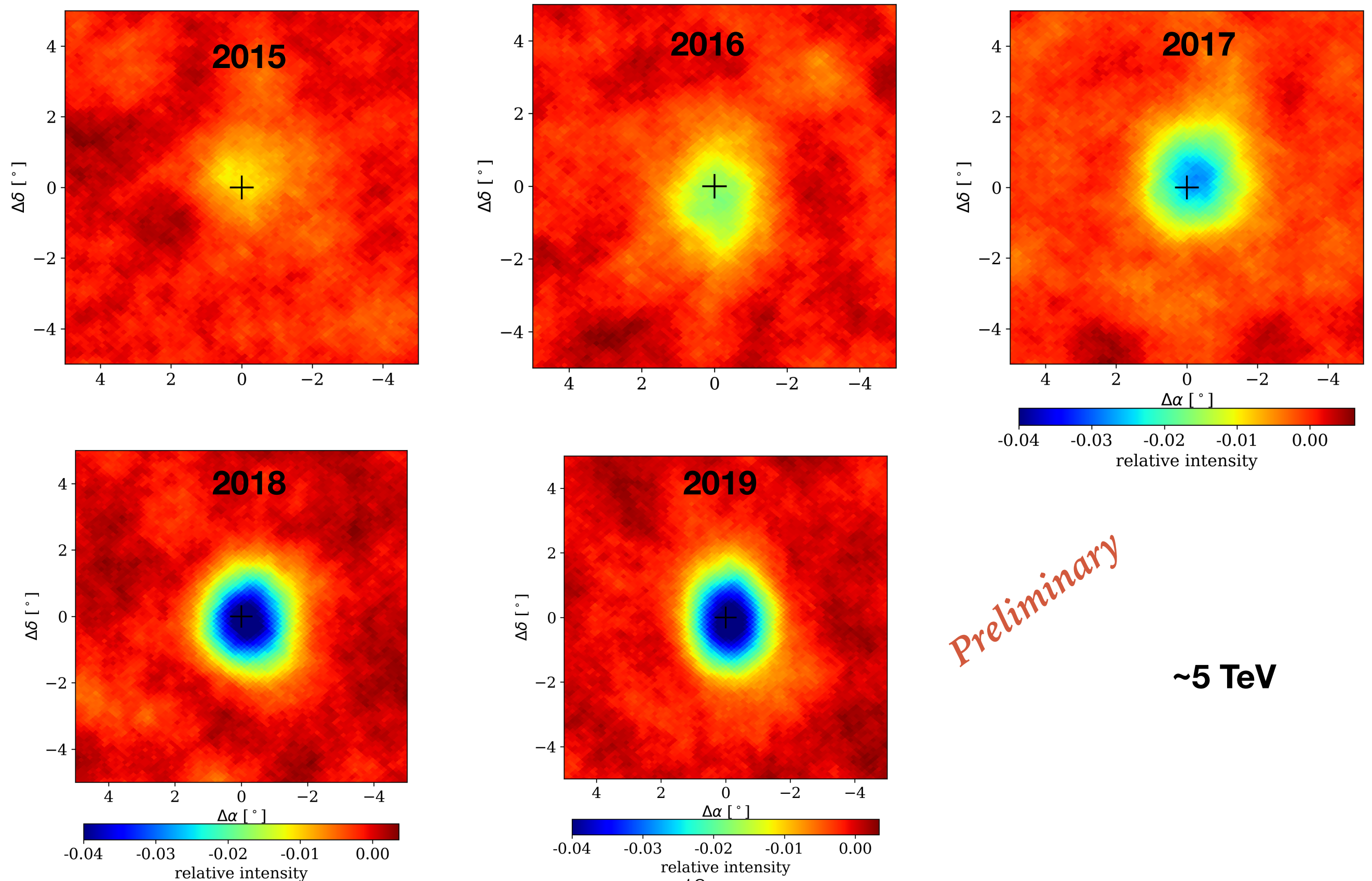
# DARK MATTER-PROTON SCATTERING LIMITS



# WHAT'S NEXT: SOLAR MINIMUM RESULTS FROM HAWC

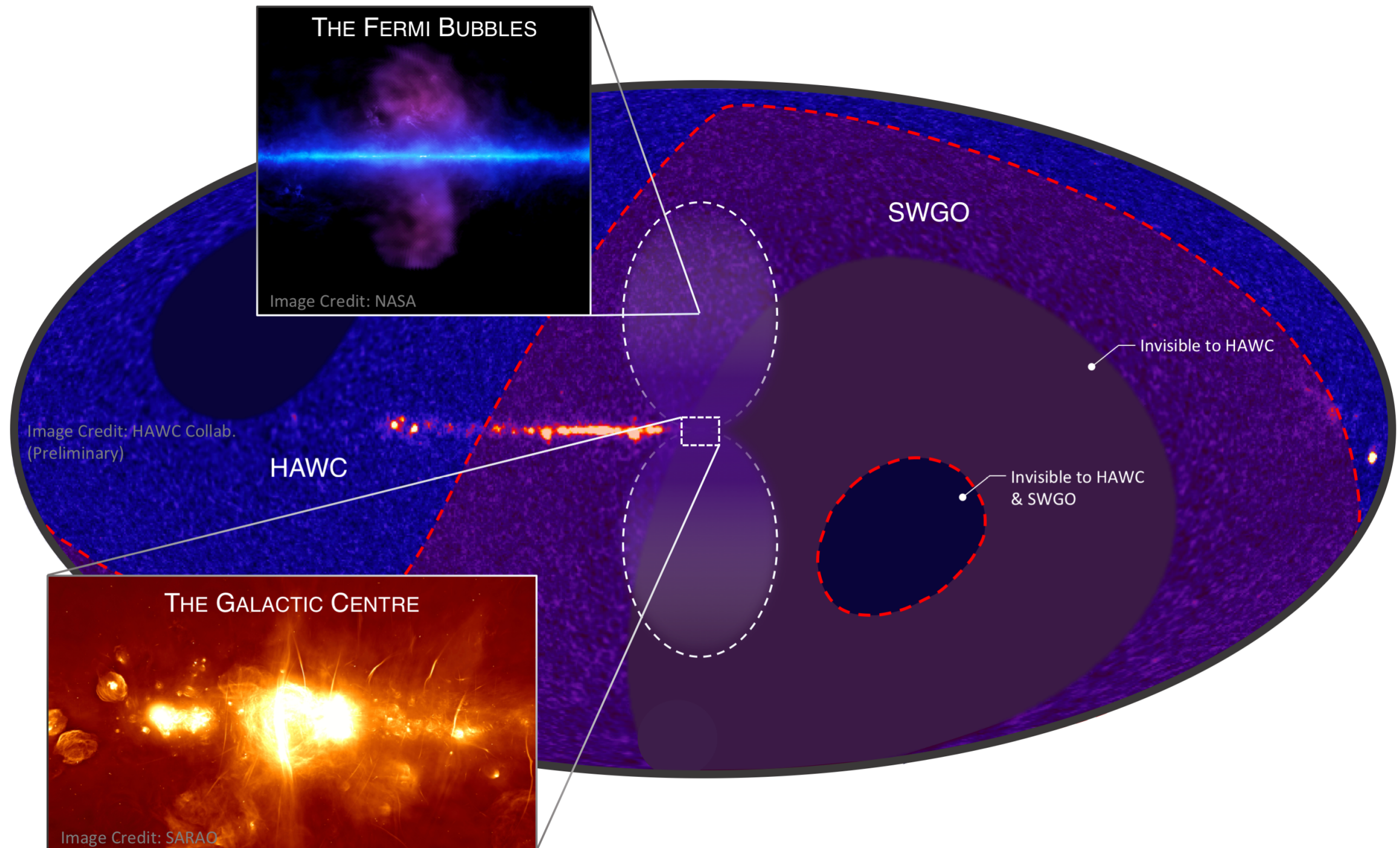


# Variation of the Sun shadow with Solar cycle

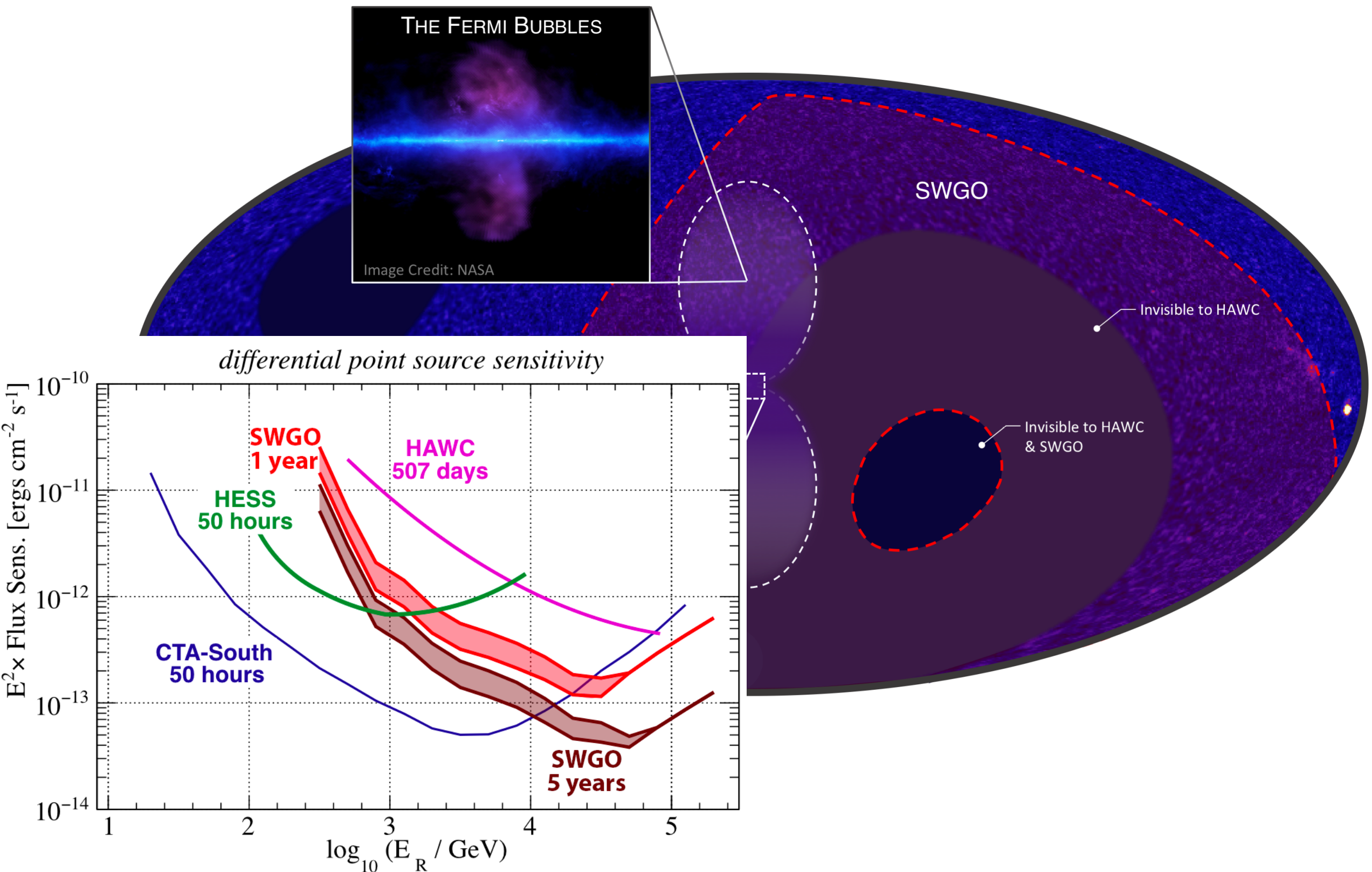


# **FUTURE GAMMA-RAY OBSERVATIONS OF THE SUN**

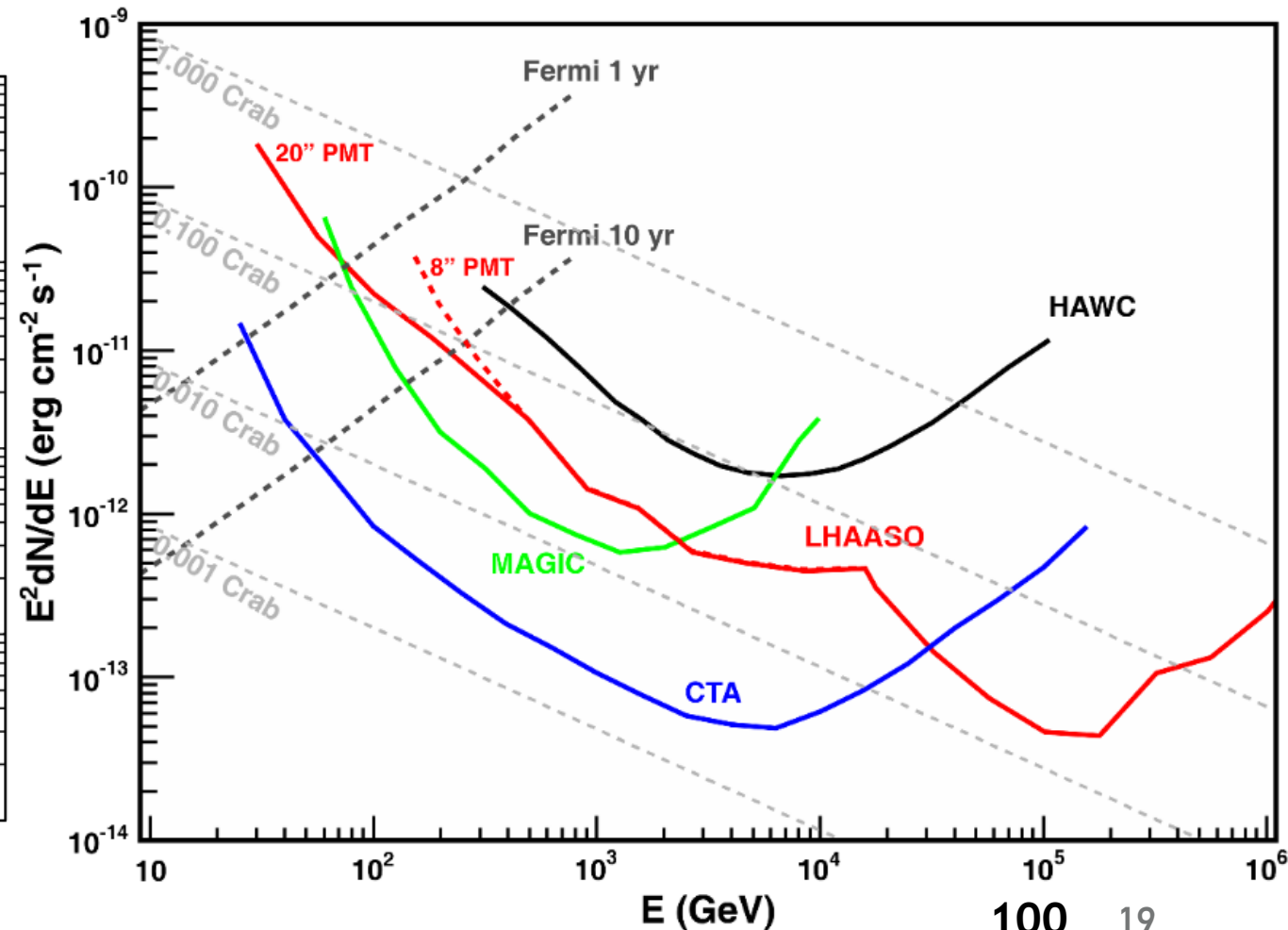
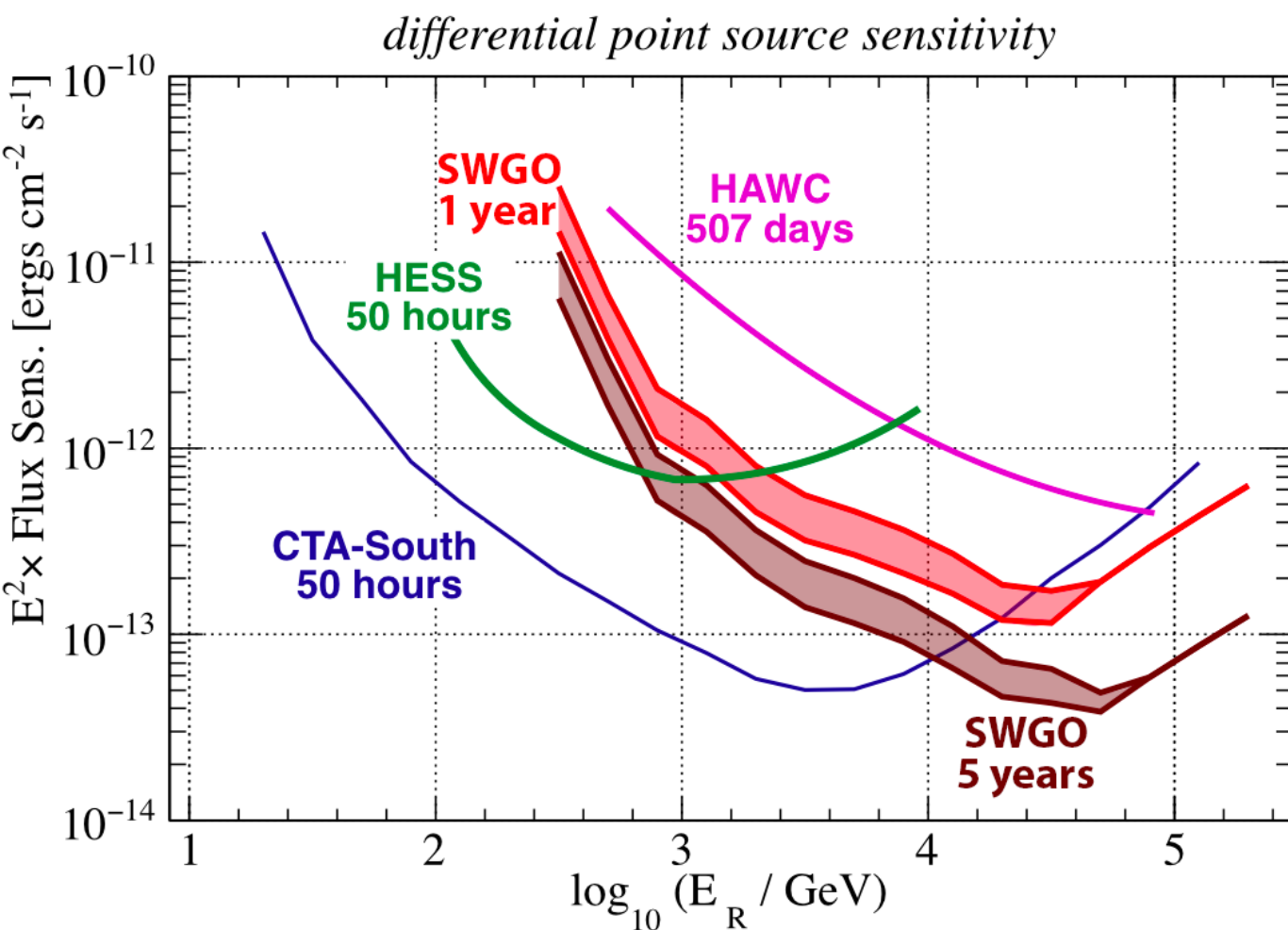
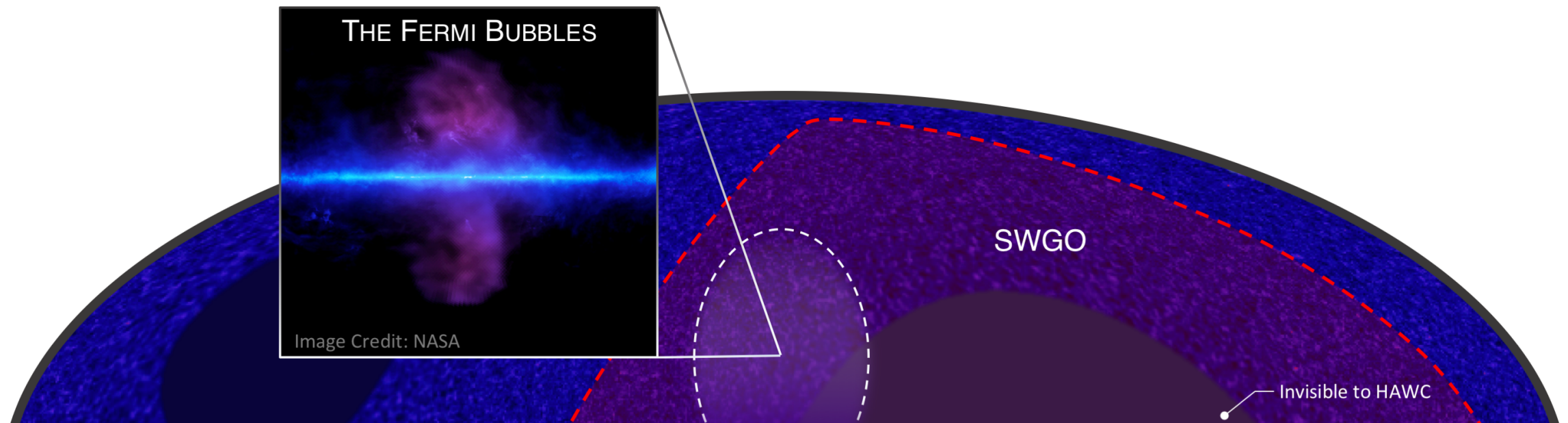
# FUTURE GAMMA-RAY OBSERVATIONS OF THE SUN



# FUTURE GAMMA-RAY OBSERVATIONS OF THE SUN



# FUTURE GAMMA-RAY OBSERVATIONS OF THE SUN



# TAKEAWAYS

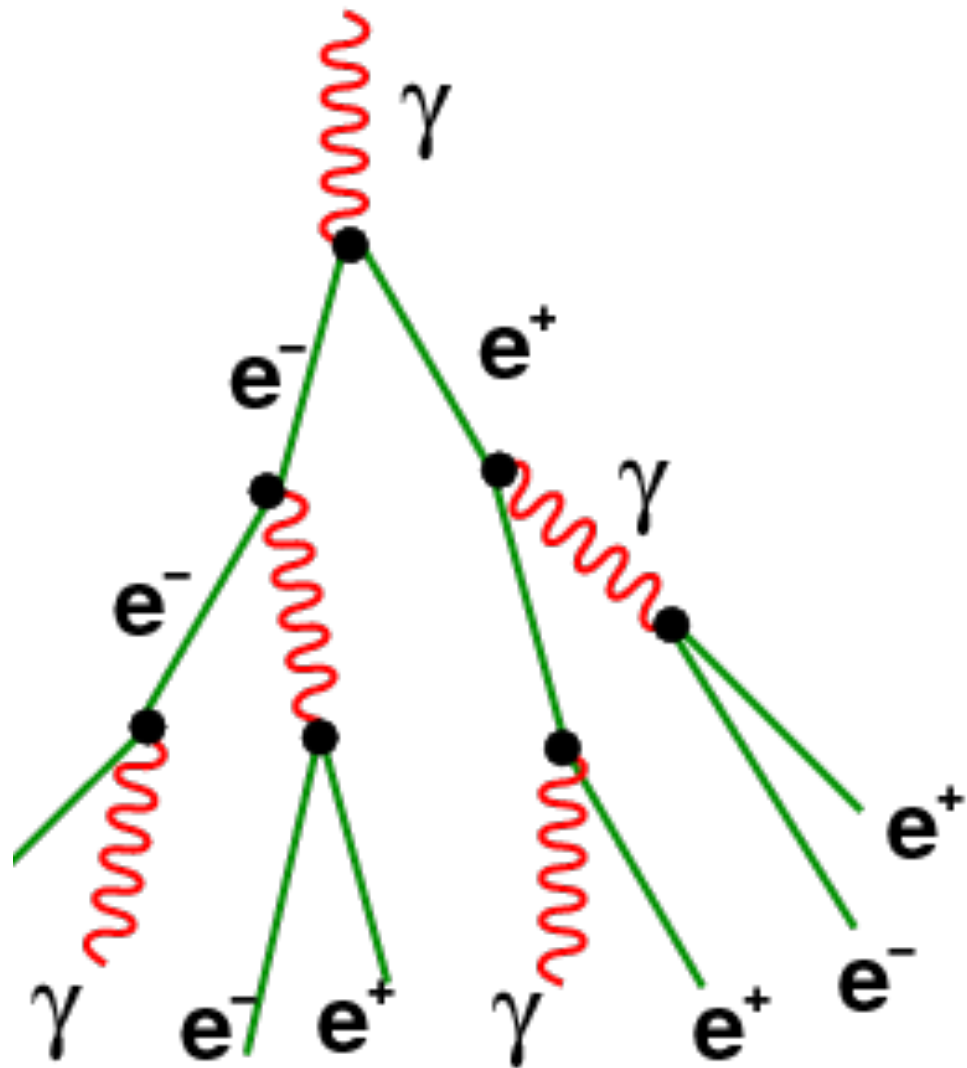
- There is a significant flux of likely hadronic gamma rays from the Sun upto at least 100 GeV.
- In tension with theoretical predictions: modulation, spectral hardness.
- Long-term monitoring of the Sun extending into the TeV energies along with efforts at the modeling front will hold the key in future.
- Six years of HAWC results contemporaneous with Fermi observations coming soon.
- Solar Physics 🤝 BSM Searches 🤝 Multi-messenger astronomy

# BACK UP



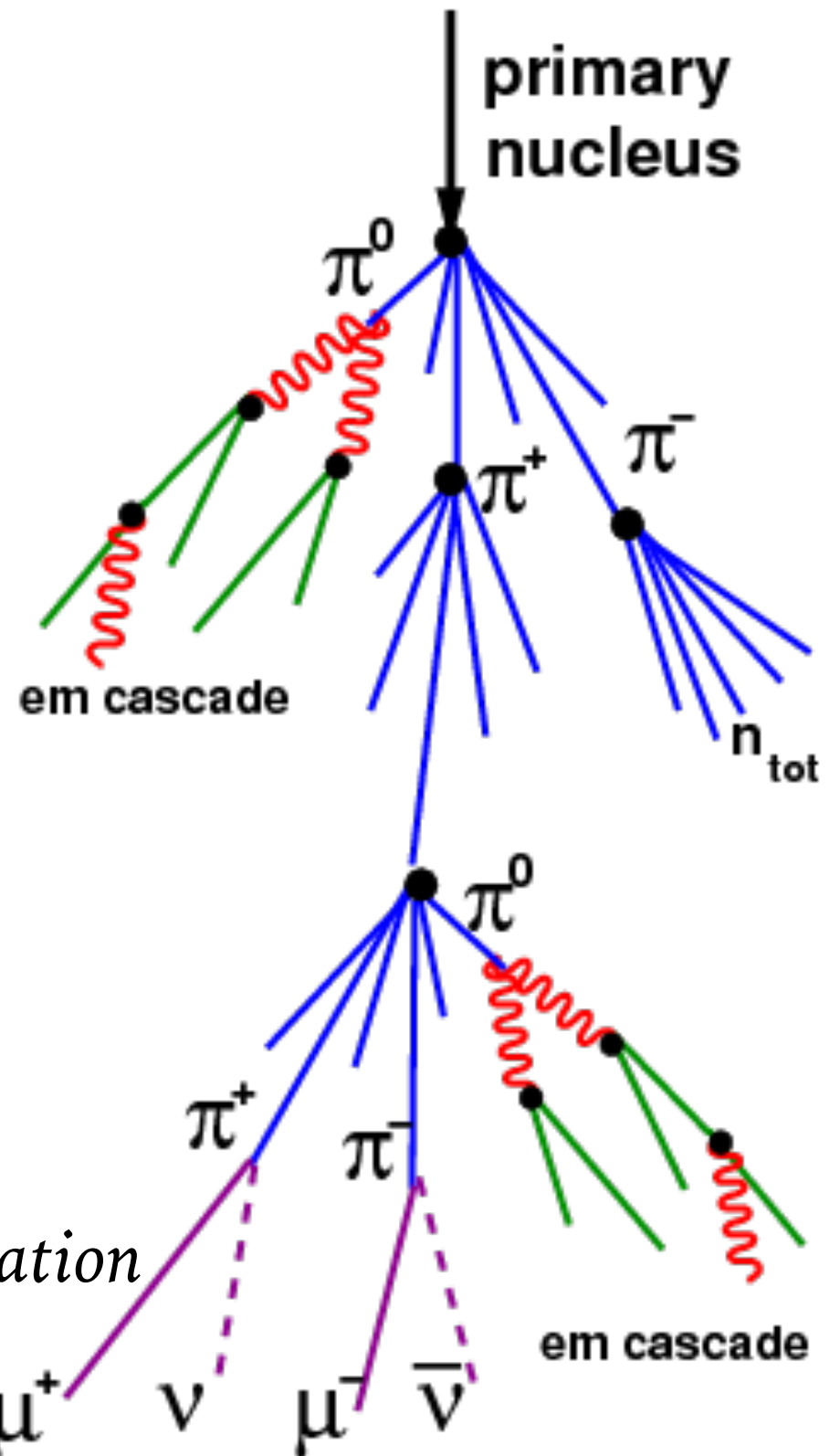
# LOOKING FOR TEV GAMMA RAYS

## em cascade

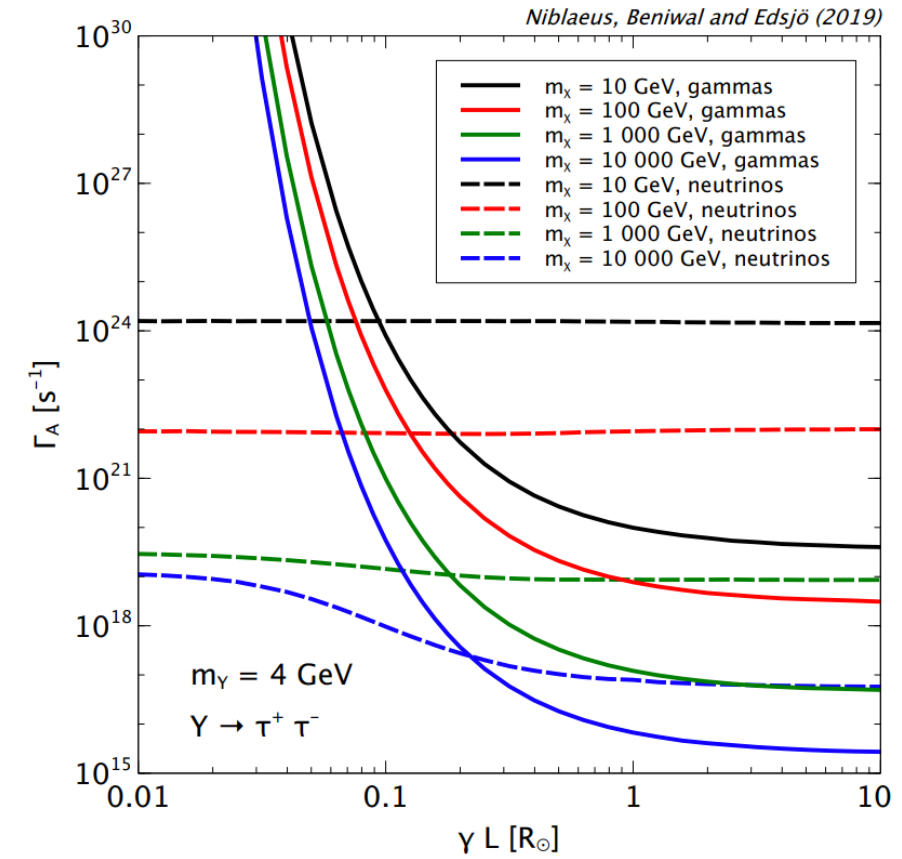
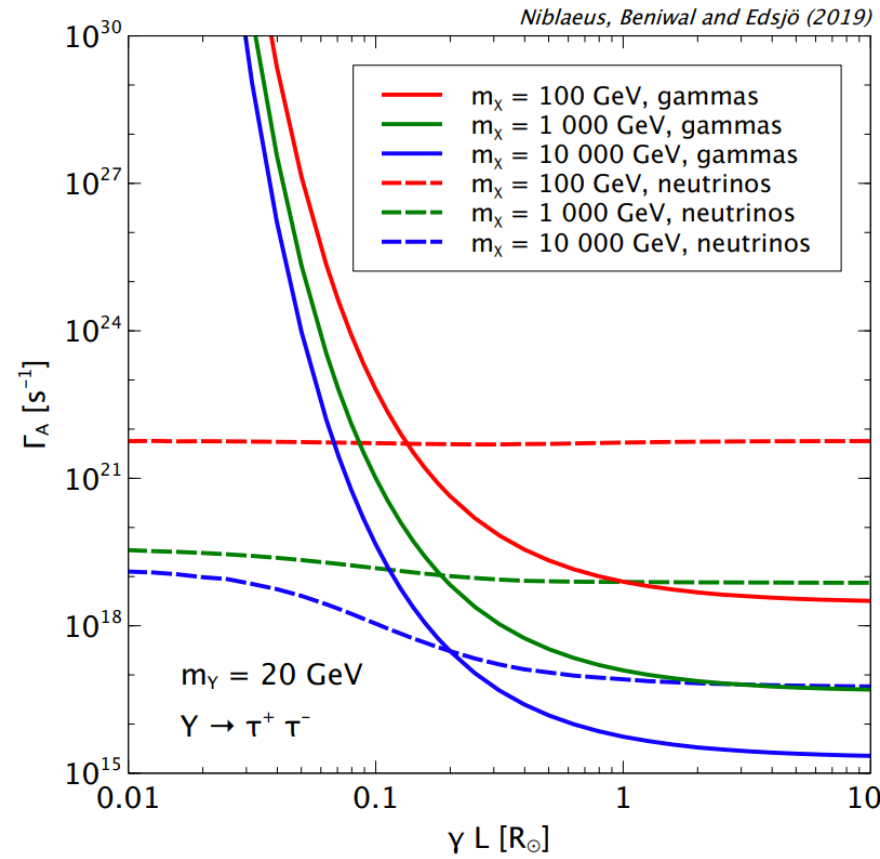
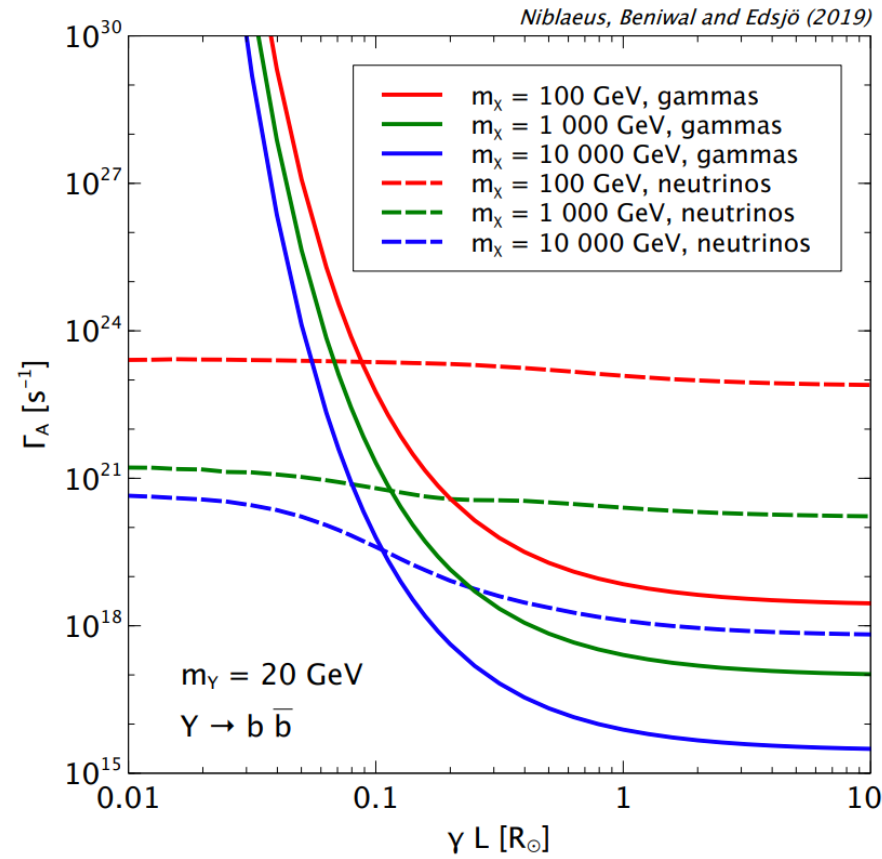


- *Ground-based gamma ray astronomy.*
- *Sample air showers by observing Cherenkov radiation*

## hadronic cascade

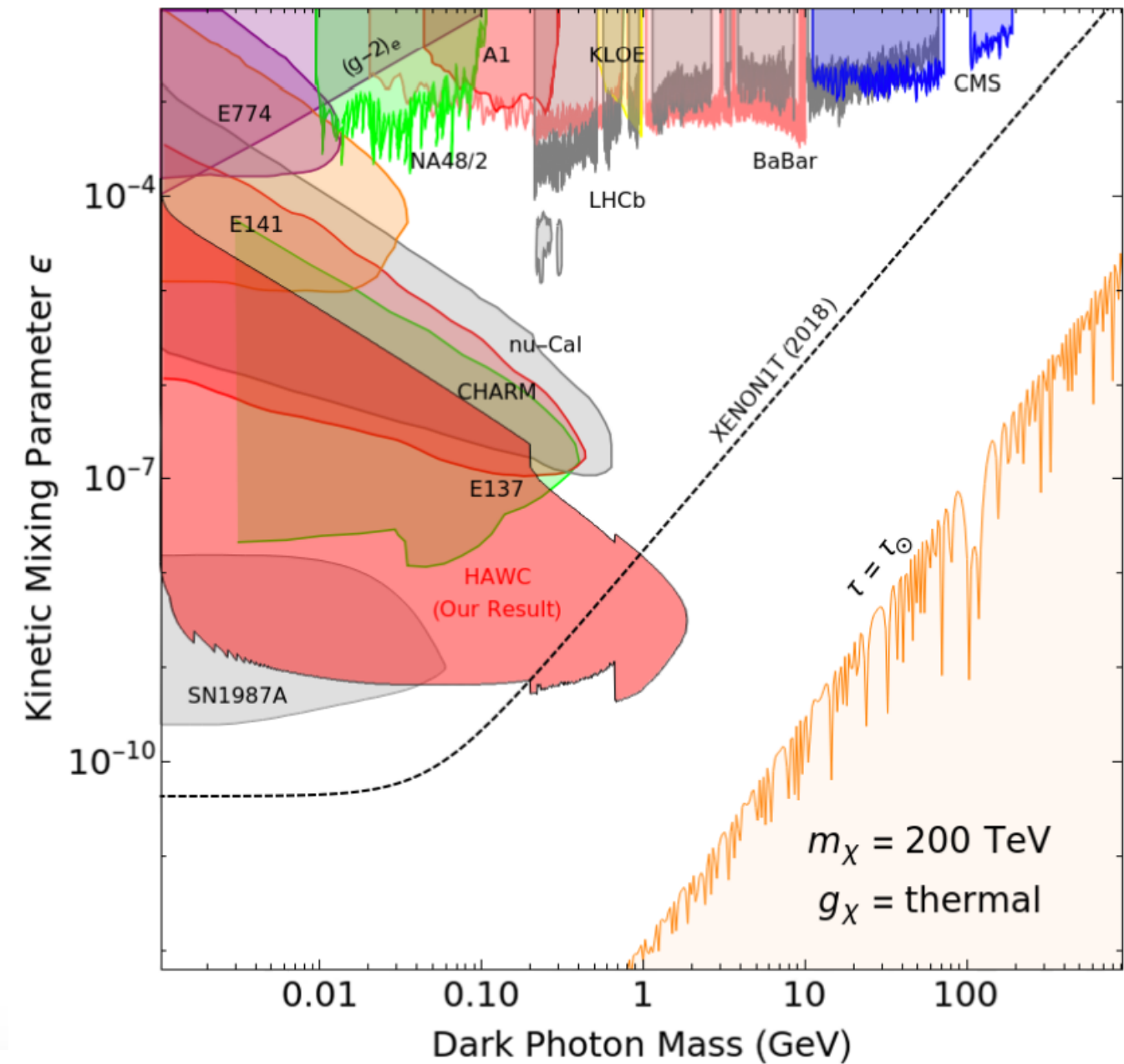
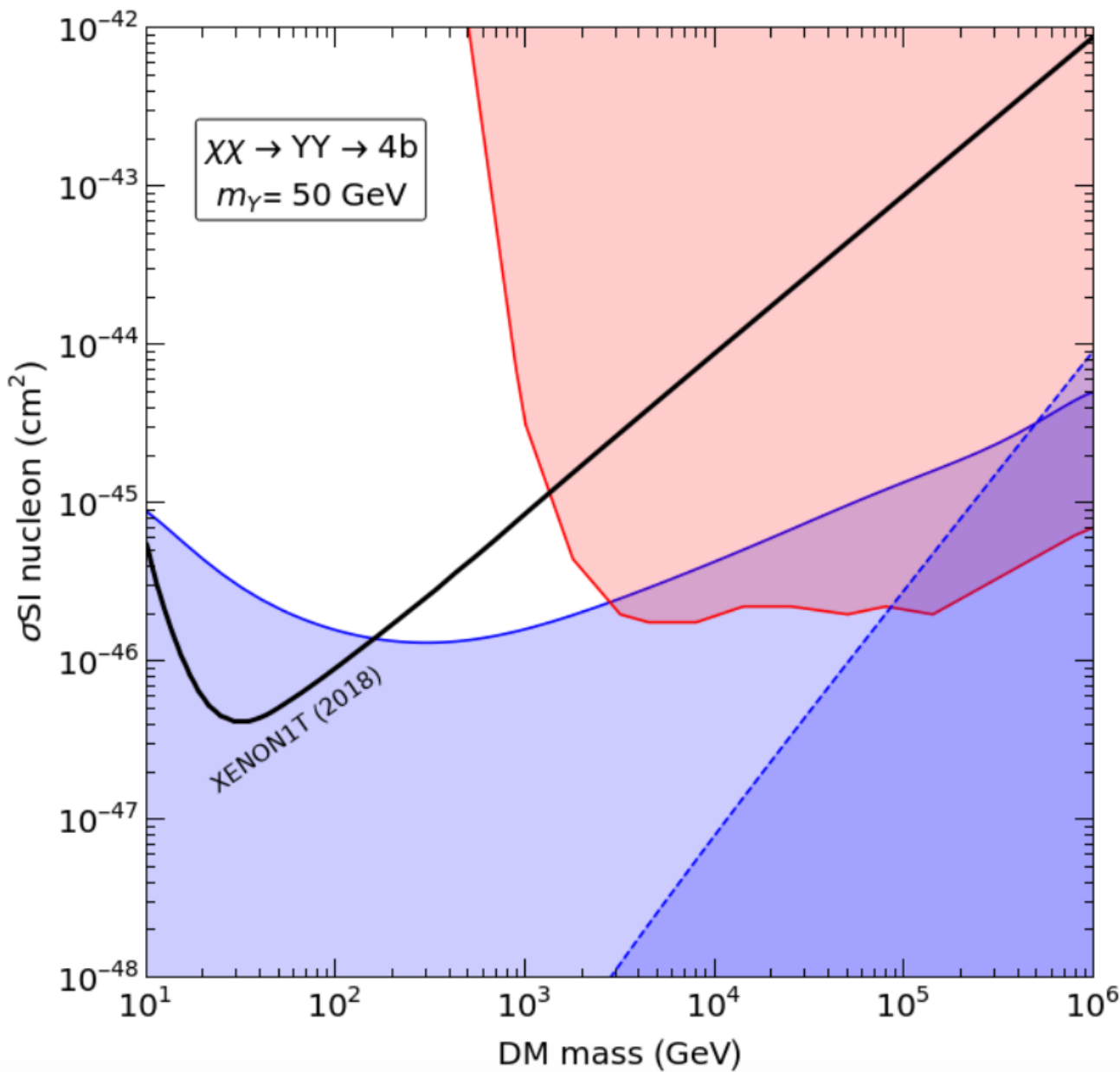


# COMPLEMENTARITY WITH NEUTRINOS



*Niblaeus et al. 1903.11363*

# DM CONSTRAINTS FROM THE VHE SUN



*Bell et al. 2103.16794*