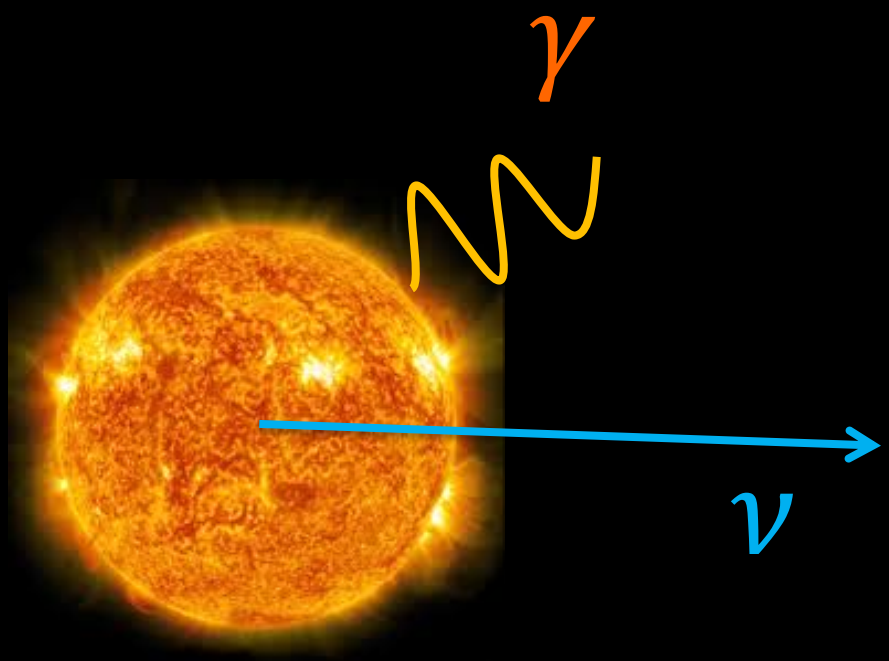
The Surprising Gamma Ray emission from the Sun



Kenny, Chun Yu Ng (吳震宇)
Weizmann Institute of Science

Soon:
GRAPPA, U of Amsterdam

Related works

- Gamma-ray analysis
  - **KCYN**, Beacom, Peter, Rott, 1508.06276 PRD
  - Linden, Zhou, Beacom, Peter, **KCYN**, Tang, 1803.05436 PRL
  - Tang, **KCYN**, Linden, Zhou, Beacom, Peter, 1804.06846 PRD
  - HAWC col. + **KCYN**, 1808.05620 PRD

- Dark Matter
  - Leane, **KCYN**, Beacom, 1703.04629 PRD
  - HAWC col. + **KCYN**, 1808.05624 PRD

- Solar atmospheric neutrinos
  - **KCYN**, Beacom, Peter, Rott, 1703.10280 PRD

- Solar gamma-ray estimations
  - Zhou, **KCYN**, Beacom, Peter 1612.02420 PRD

- *2020 Science White paper*
- *The Sun at GeV-TeV Energies: A New Laboratory for Astroparticle Physics*
  - Nisa, Beacom, BenZvi, Leane, Linden, **KCYN,** Peter, Zhou 1903.06349

Sun – Cosmic-Ray Beam Dump

CR electrons
Inverse-Compton

Moskalenko, Porter, Digel 2006
Orlando, Strong 2007

γ Continuous

γ Transient, soft

Seckel, Stanev, Gaisser (1991)
Zhou, ***KCYN***, Beacom, Peter
PRD 2017

CR protons
Hadronic

ν

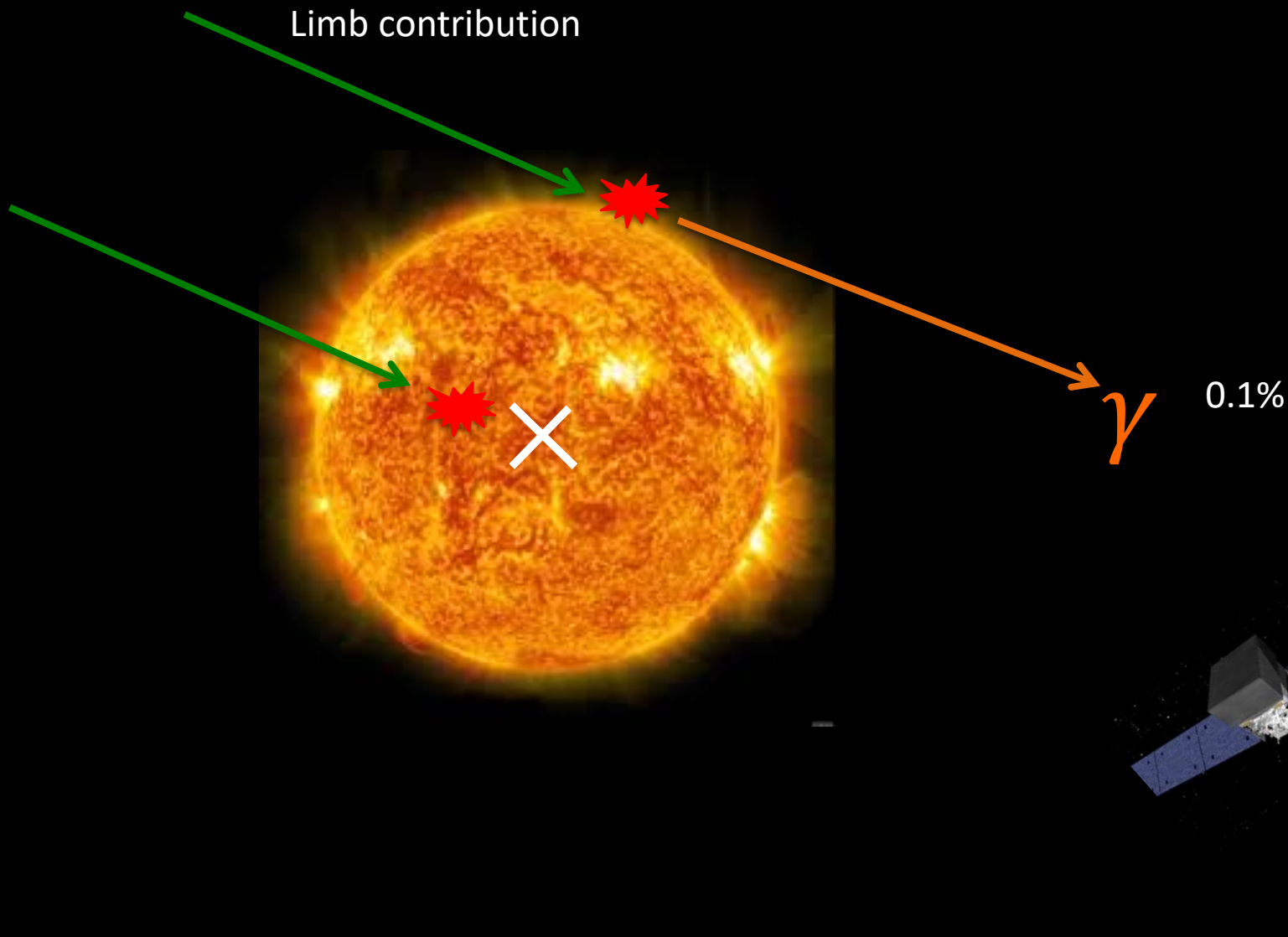
$e^{\pm}, \mu^{\pm}, \mathrm{n}$

γ Continuous

Kenny C.Y. NG, ICRC 2019

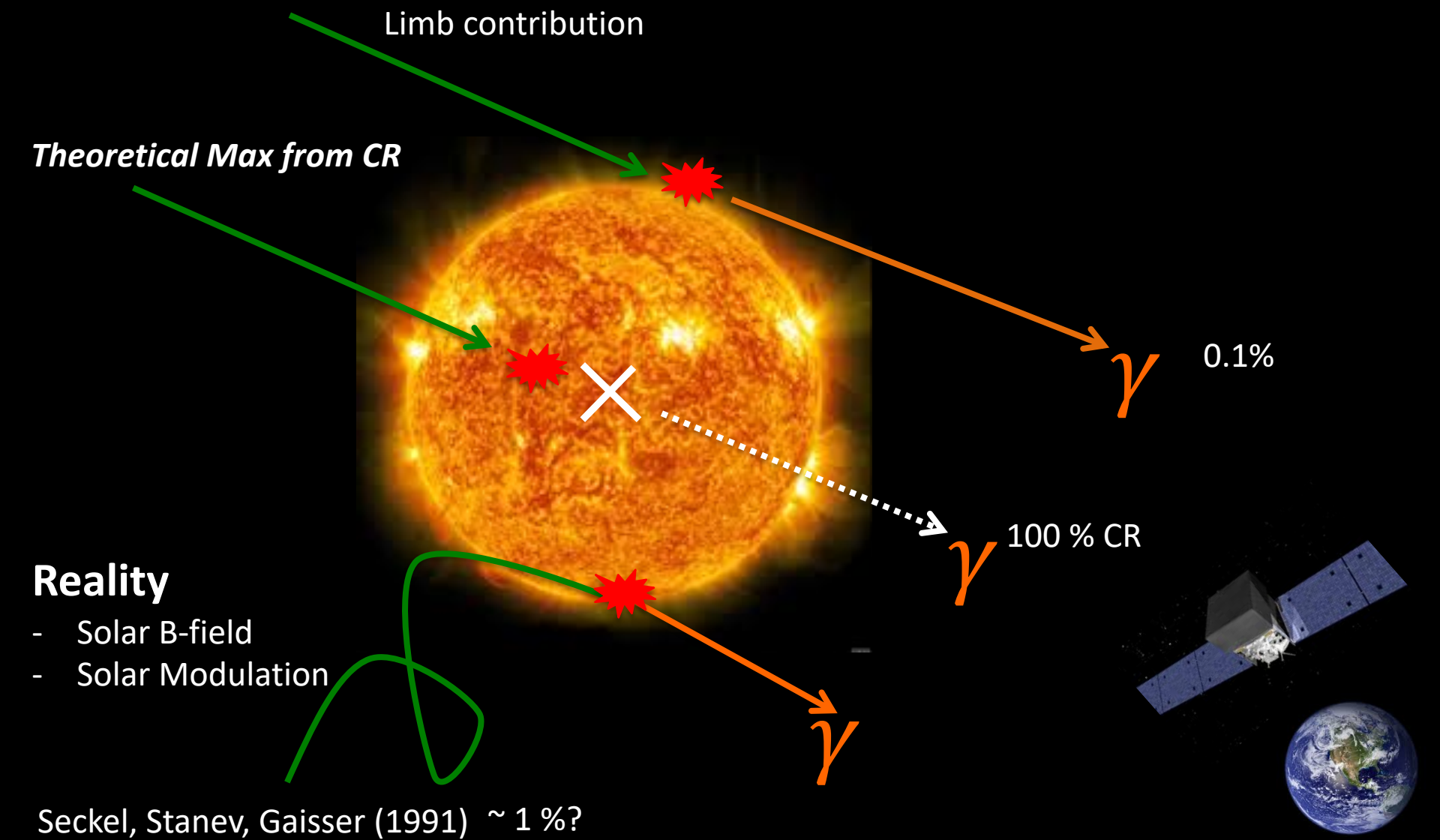
Solar atmospheric gamma rays

Zhou, ***KCYN***, Beacom, Peter PRD 2017

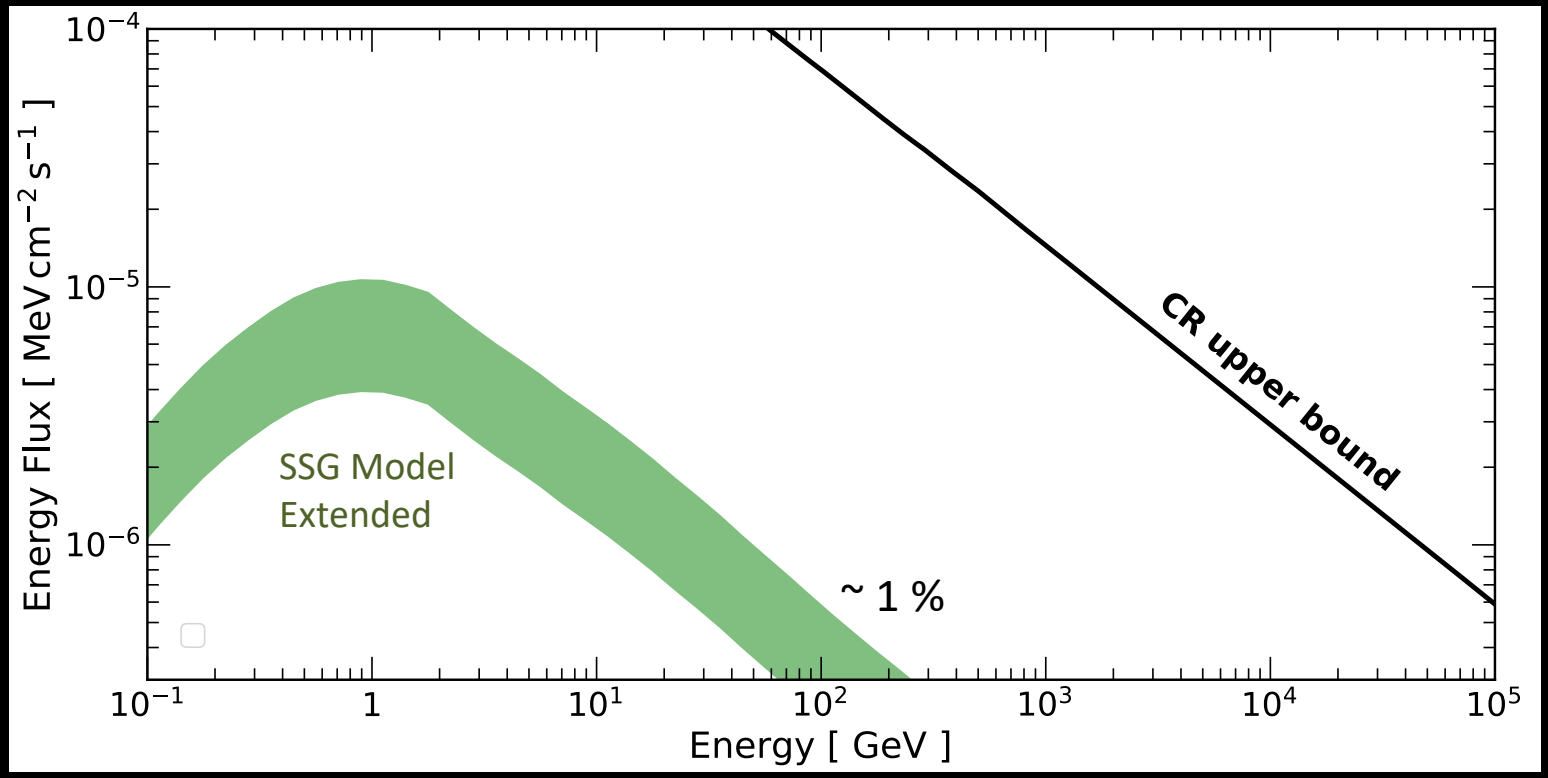


Solar atmospheric gamma rays

Zhou, ***KCYN***, Beacom, Peter PRD 2017

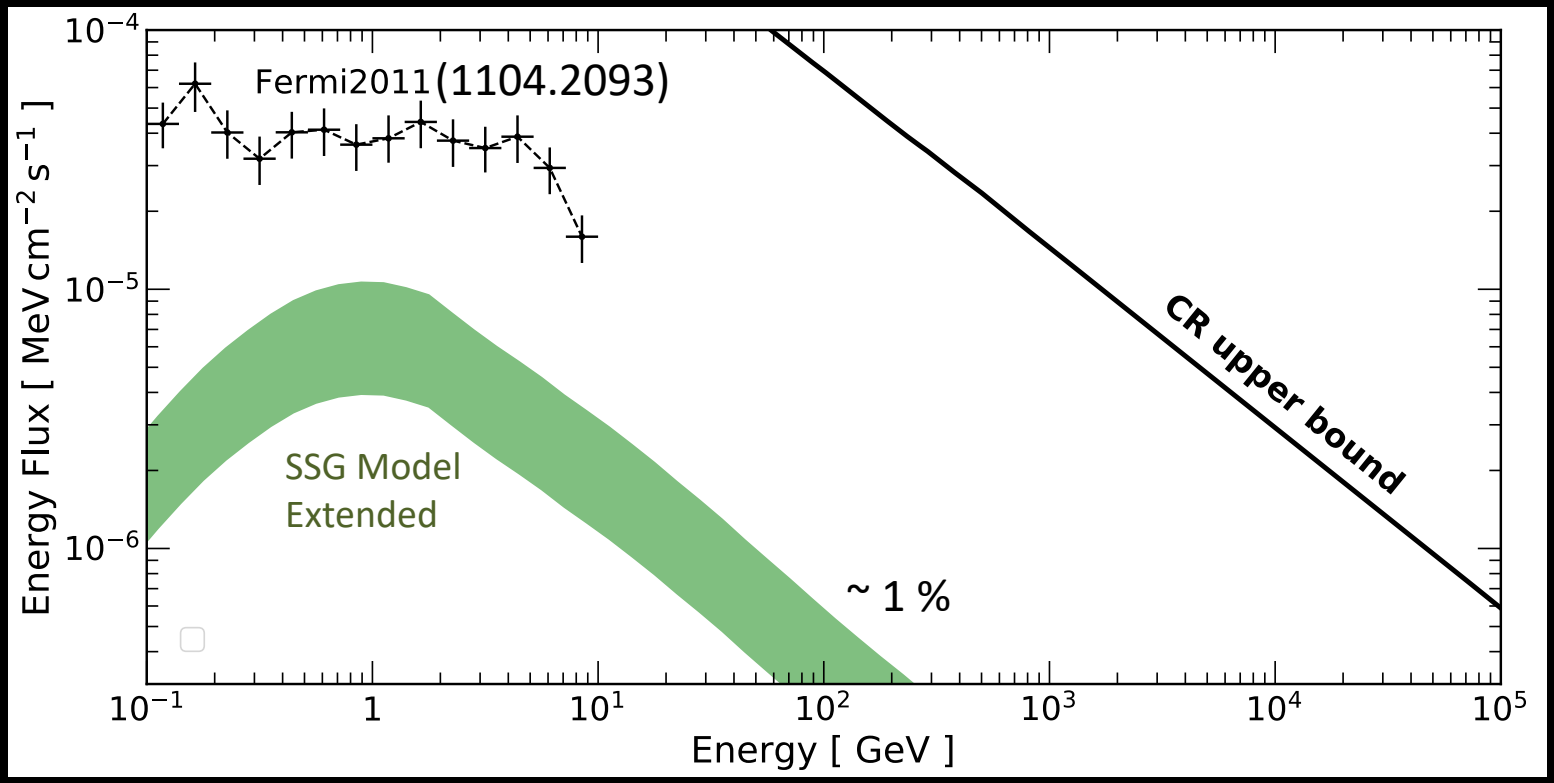


The overall picture



Fermi Detection (18 months)

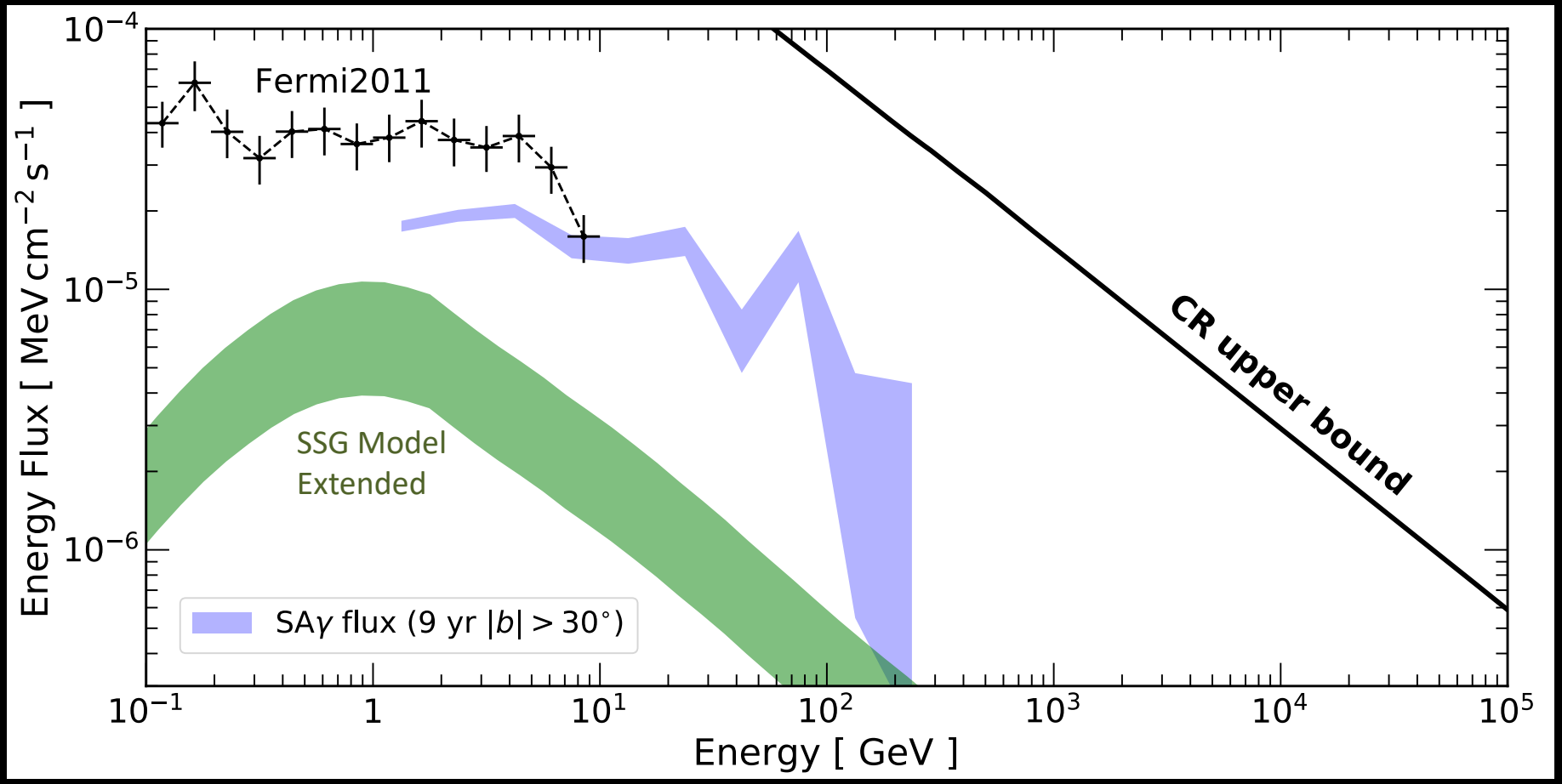
- First detection was EGRET (Orlando, Strong 2008)
- Model prediction too small
- Satisfy cosmic-ray bound ←→ CR model with large B-field enhancement



Observation: 9-year averaged spectrum

- 2008 – 2017 (9 years)

KCYN, Beacom, Peter, Rott PRD 2016
Tang, ***KCYN***, Linden, Zhou, Beacom, Peter PRD 2018



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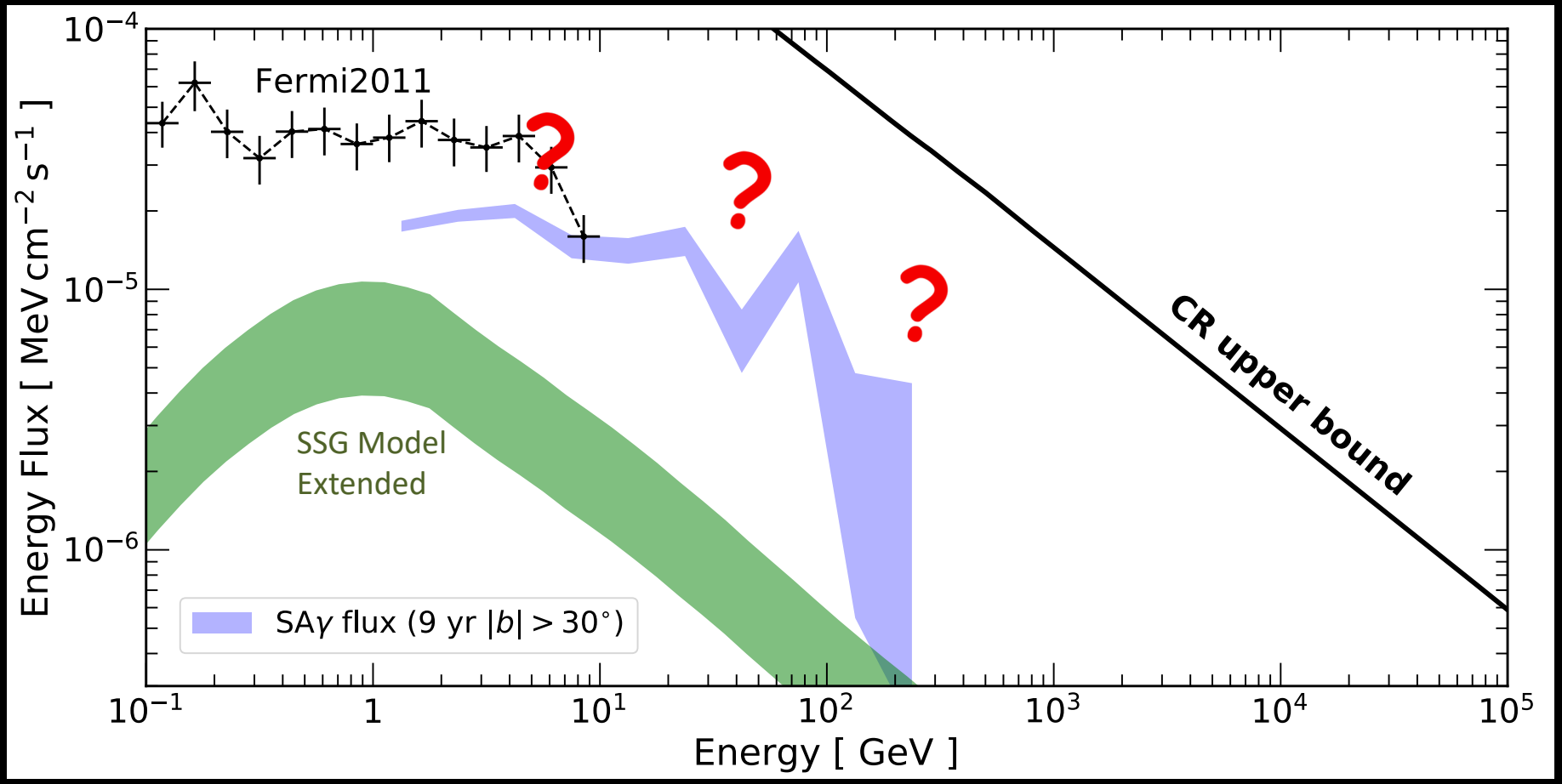
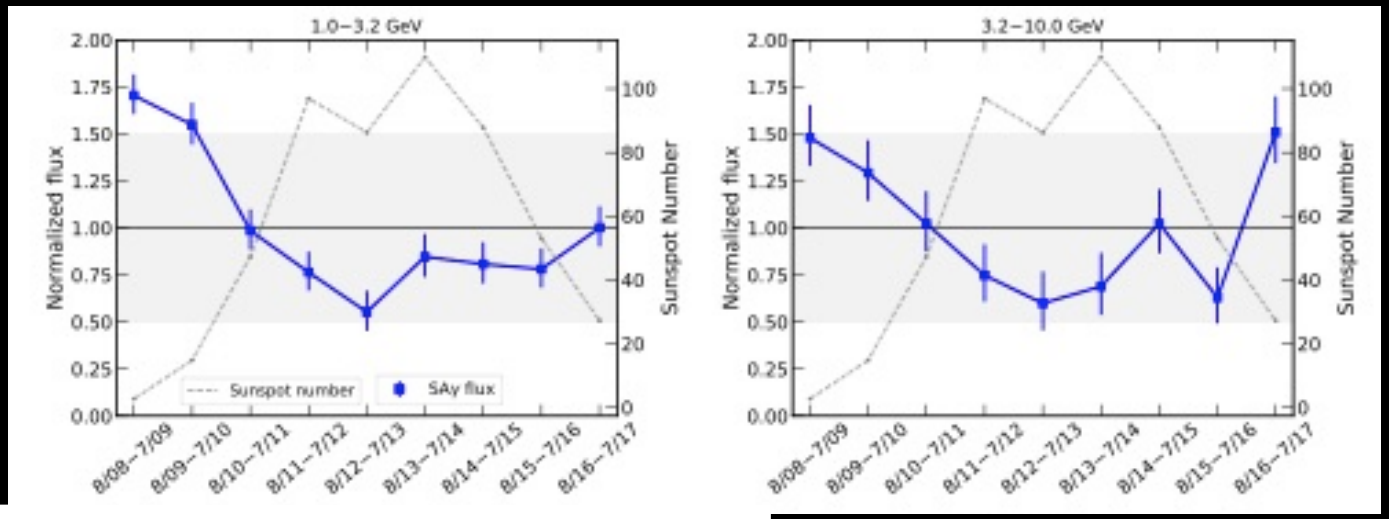
Tang, ***KCYN***, Linden, Zhou, Beacom, Peter PRD 2018

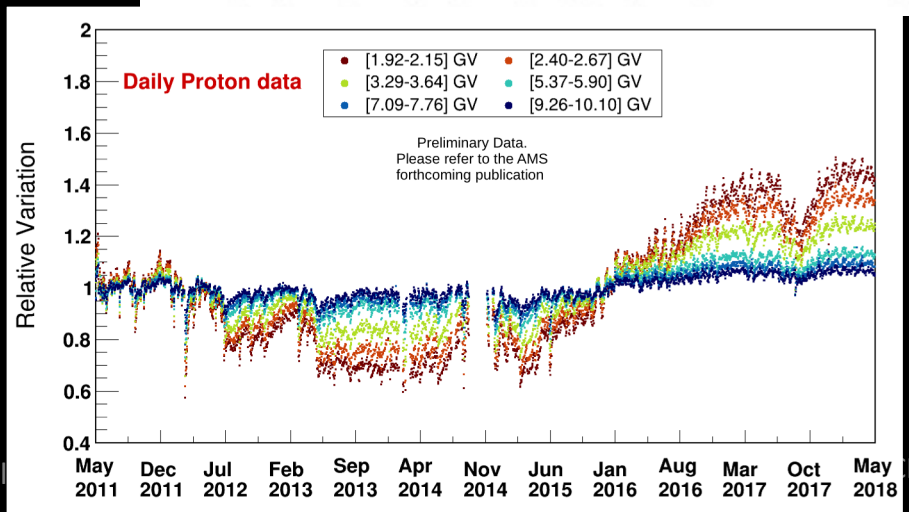


Time variation

KCYN, Beacom, Peter, Rott PRD 2016
Tang, ***KCYN***, Linden, Zhou, Beacom, Peter PRD 2018

- Clear anticorrelation with solar activity from 1-10 GeV
- Less clear in 10-100 GeV (less variation or insufficient statistics)



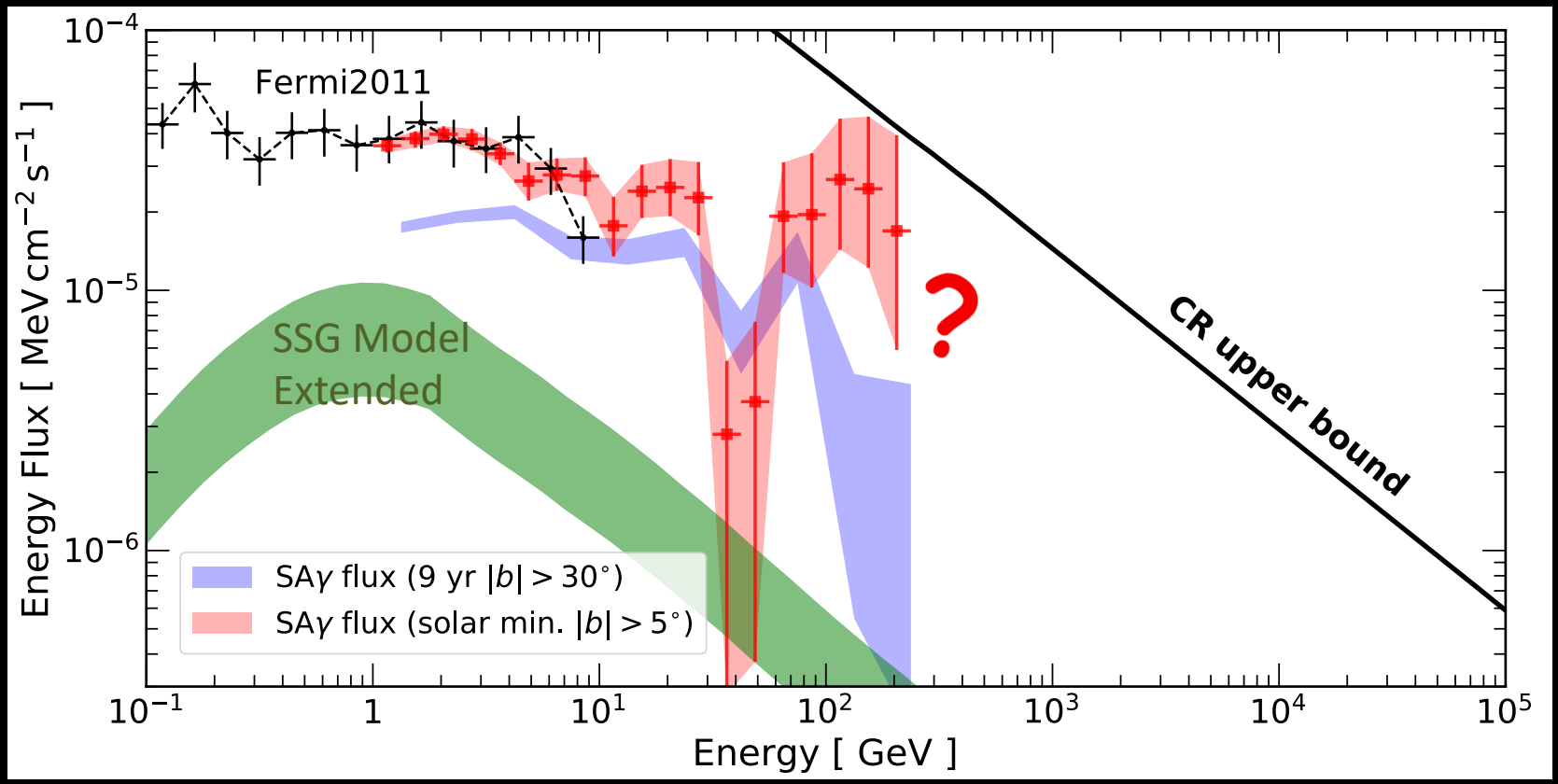


Small modulation amplitude
-> extra modulation needed near the Sun

C. Consolandi CRD8c

Observation: 9-year averaged spectrum

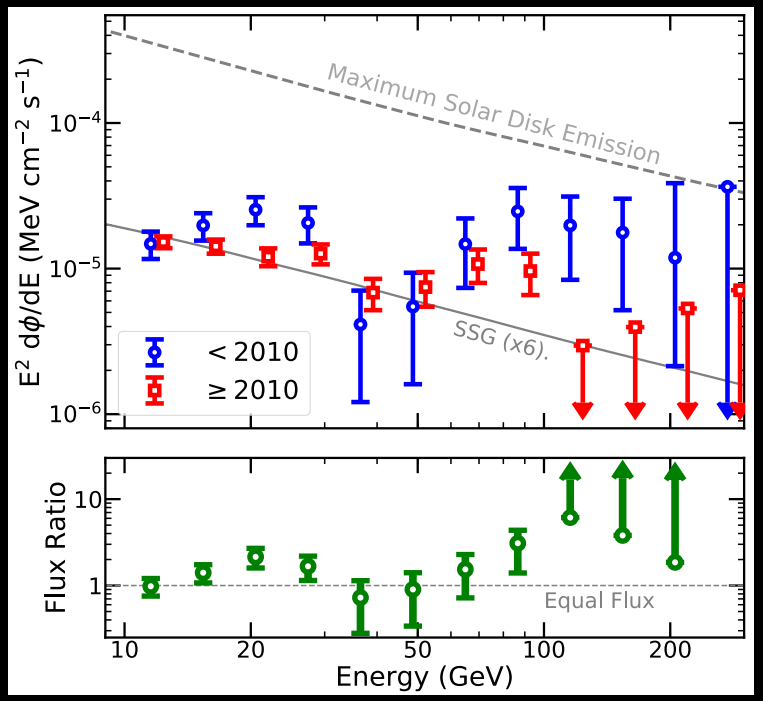
- Aug 2008 – Jan 2010 (solar min. 76 weeks)
- 2008 – 2017 (9 years)

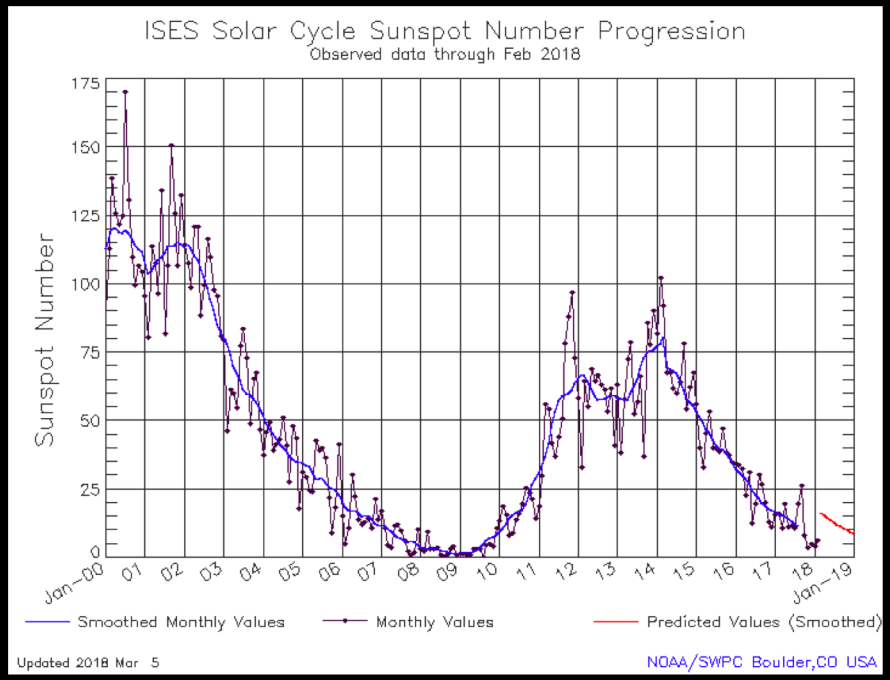


High energy photon/Time variation, *Surprise (1)*

- >100 GeV events
- 6 events from AUG 2008 to Jan 2010 (quiet Sun)
- 0 events for the next 7.8 years (active Sun) …….. +1 Feb 2018 !

Linden, Zhou, Beacom, Peter, KCYN, Tang PRL 2018

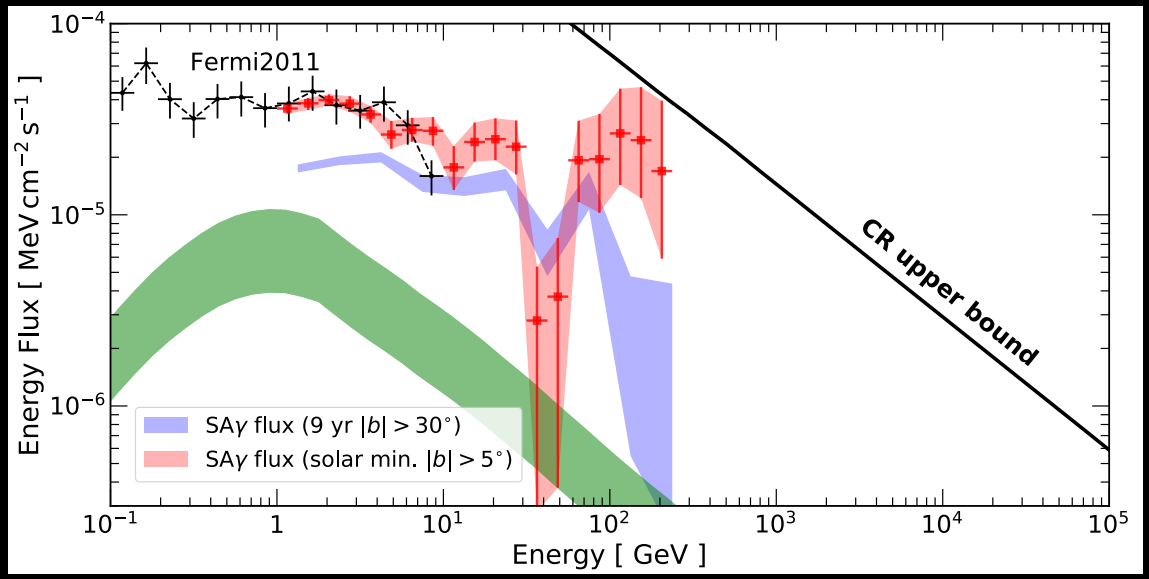




The high-energy photon production are very sensitive to the solar condition
Effect stronger than at lower energies!

Spectrum, *surprise (2)*

- Hard spectrum till ~100 GeV
  - Magnetic enhancement works for protons ~ TeV
  - Enhancement increasingly efficient! Close to upper bound at HE

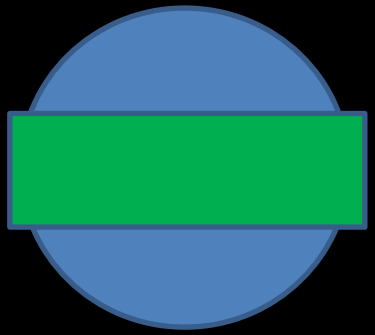


$$\text{FLUX(E)} \propto \sigma_{pp} \times \Phi_p(E) \times \epsilon\,(E)$$

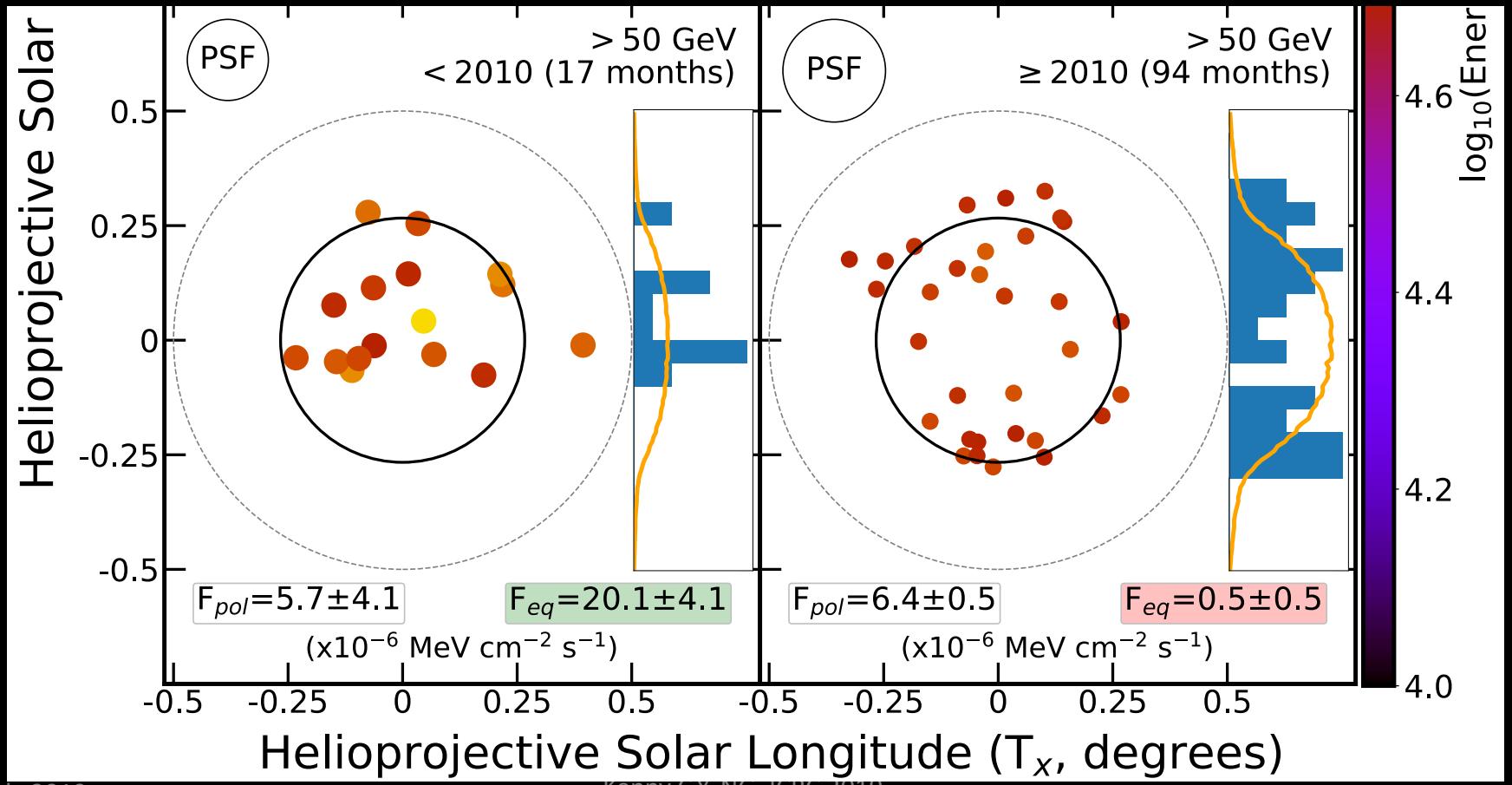
$$\sim E^{-2.2} \qquad \sim E^{-0} \qquad \sim E^{-2.7} \qquad \sim E^{+0.5}$$

Morphology, *surprise (3)*

- High Energy Bin
  - (> 50 GeV)

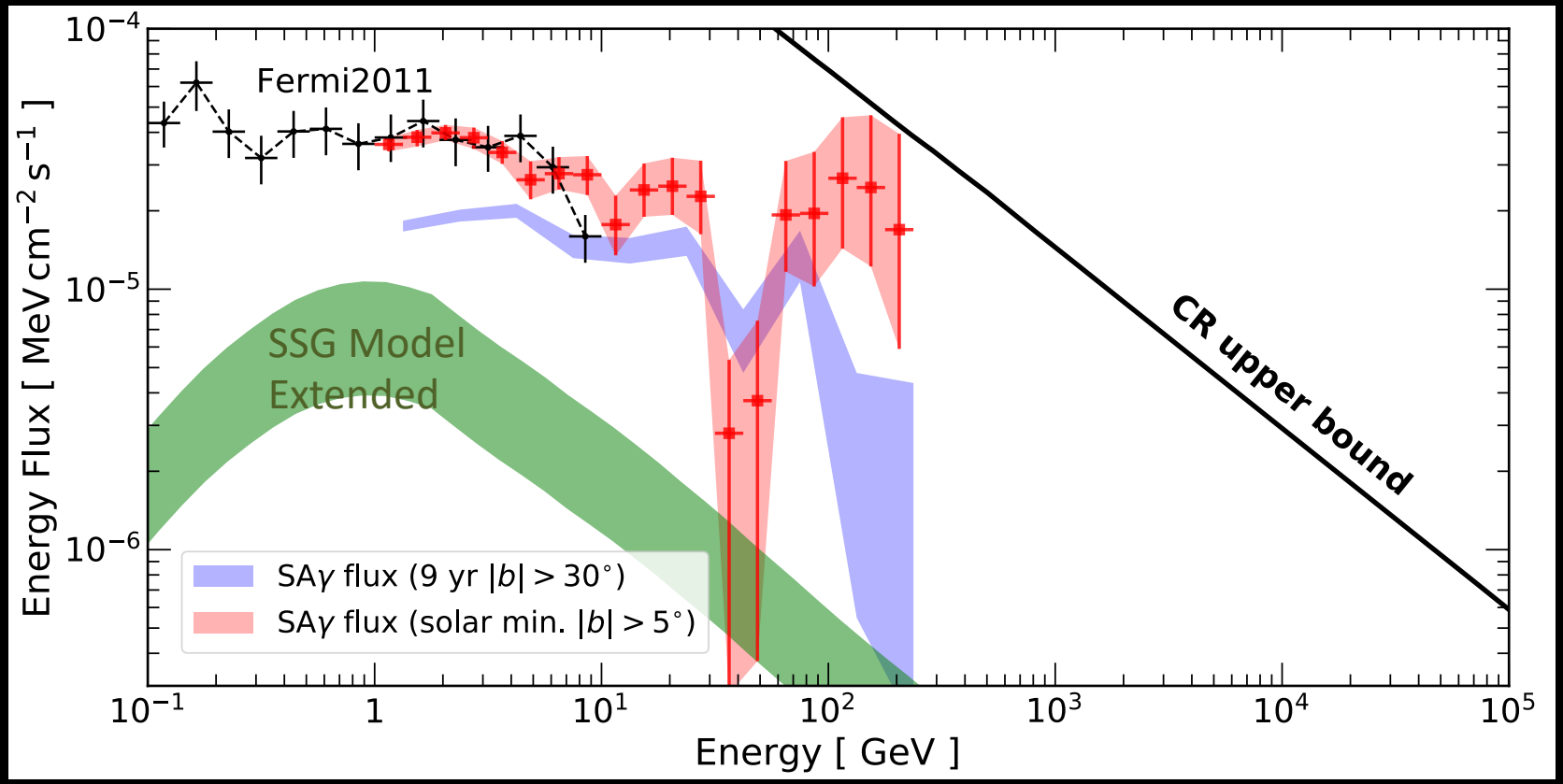


Linden, Zhou, Beacom, Peter, KCYN, Tang
PRL 2018



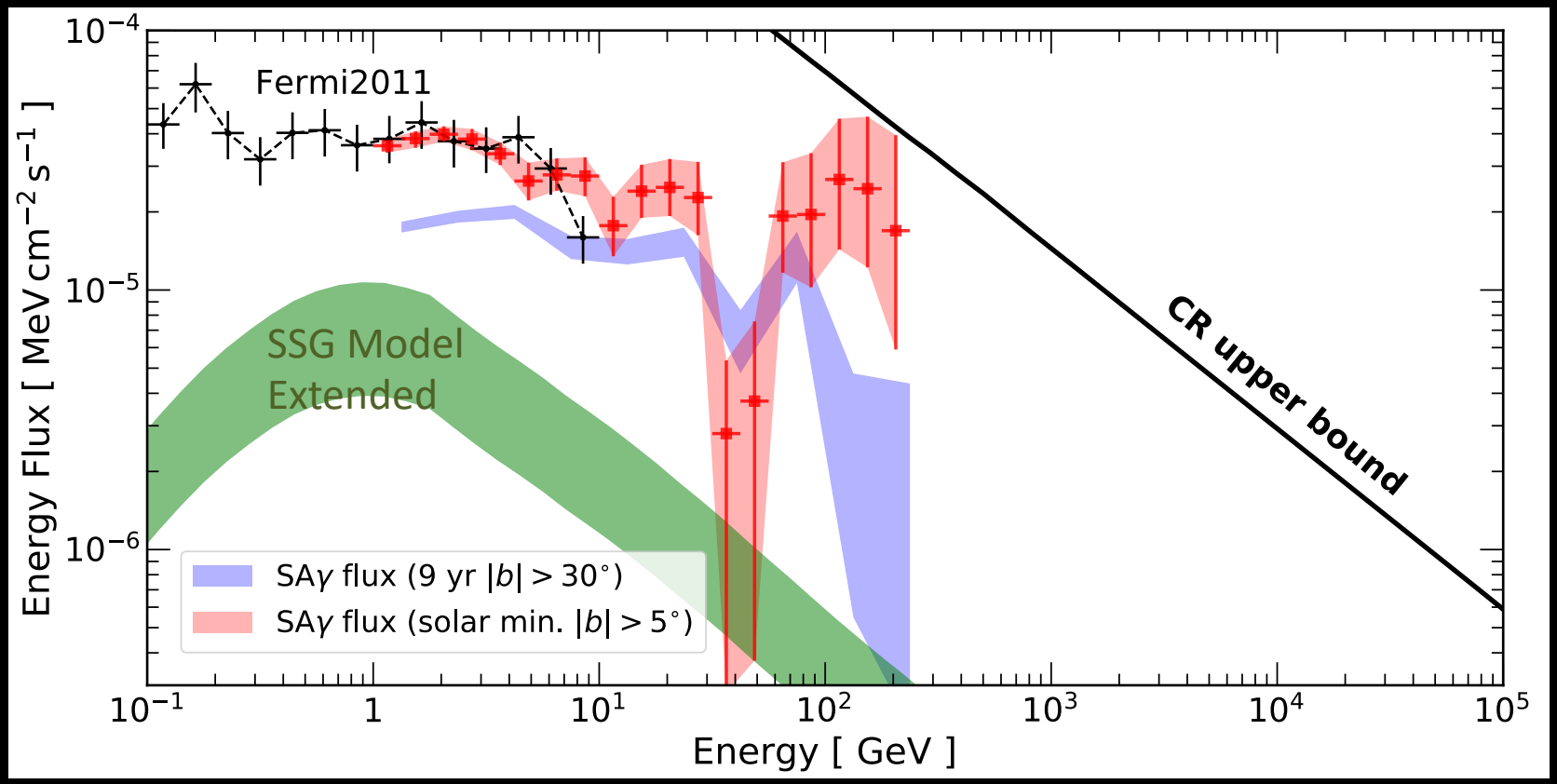
Spectrum, *surprise (4)*

- Strange “dip” between 30-50 GeV
  - Naively, two components, but not easy
  - No obvious instrumental explanation
  - Seems shallower outside solar minimum
  - Statistical fluke? Time-dependent feature/systematics? Will know soon

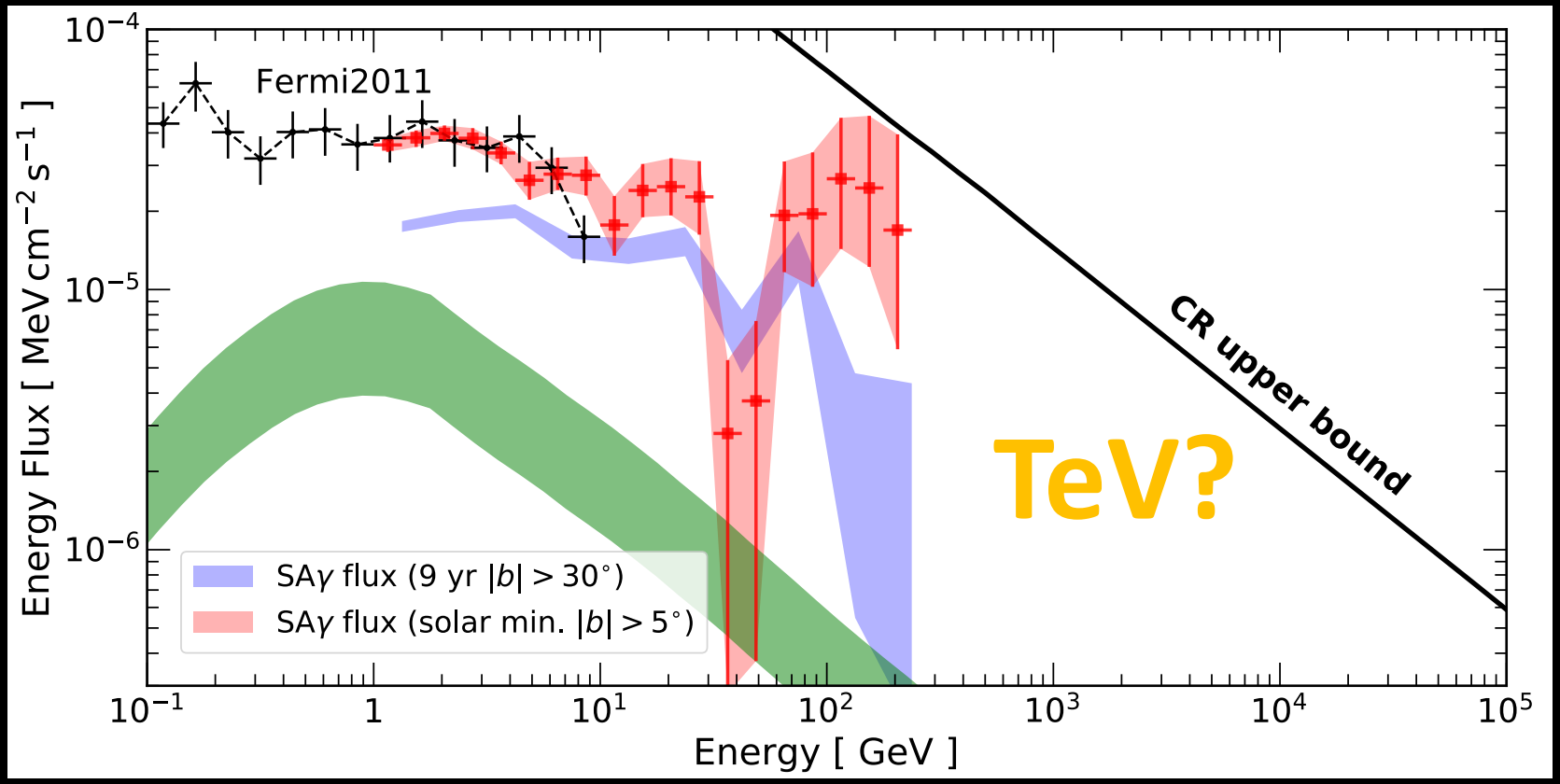


Spectrum, *surprise (4)*

- Observations of the Sun in GeV Gamma Rays by CALET on the ISS
- Nicholas Cannady, APS April Meeting 2019
  - 3 years
  - Consistent with hard spectrum
  - 3 photons above 10GeV, 1 at 30-50GeV ?!

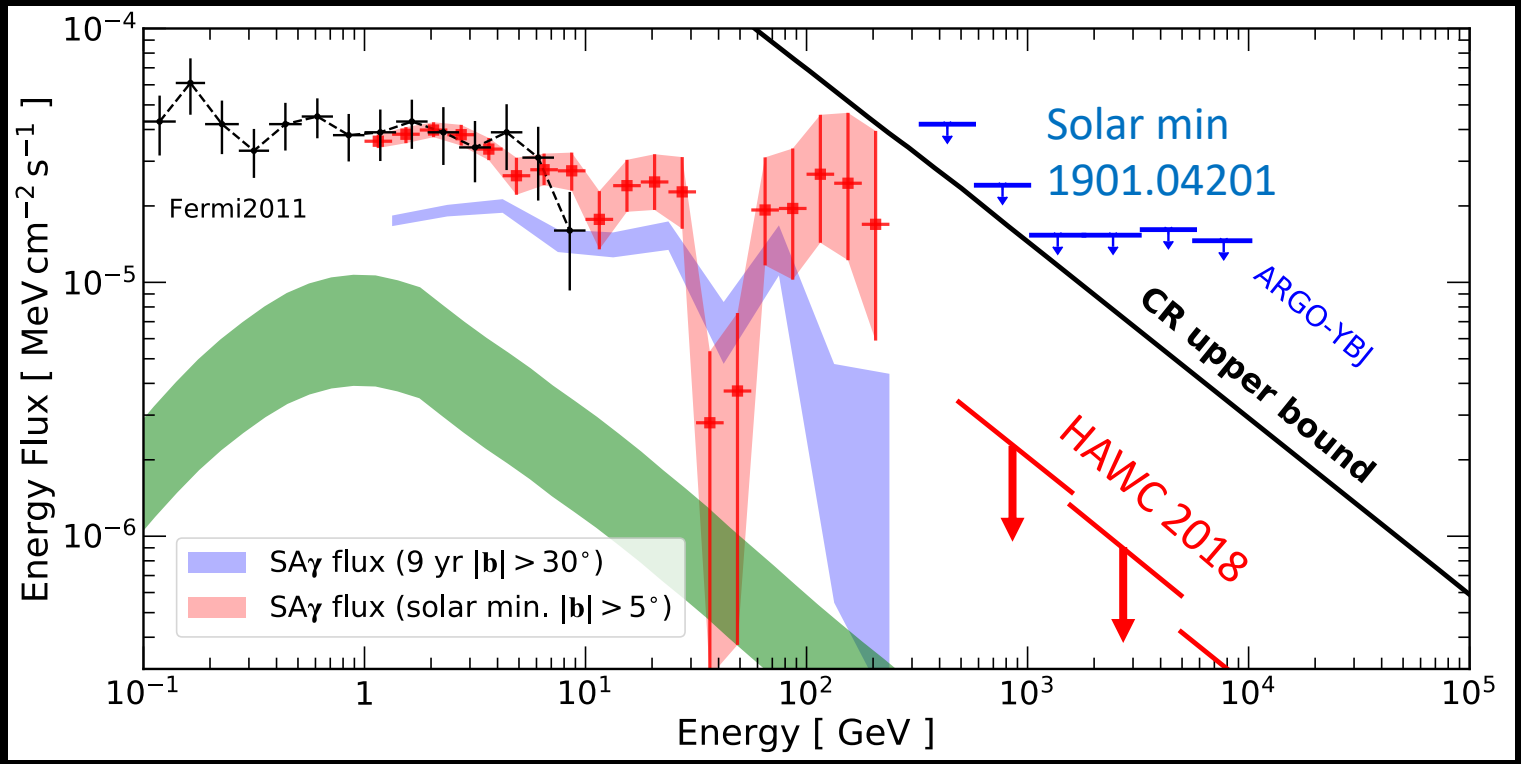


Solar Gamma Spectrum

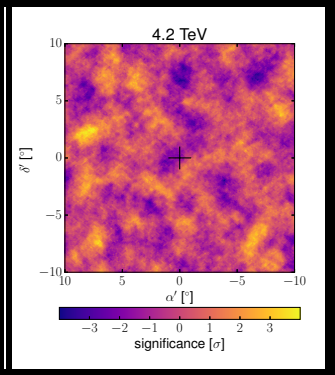


HAWC analysis of the Sun (2014-2017)

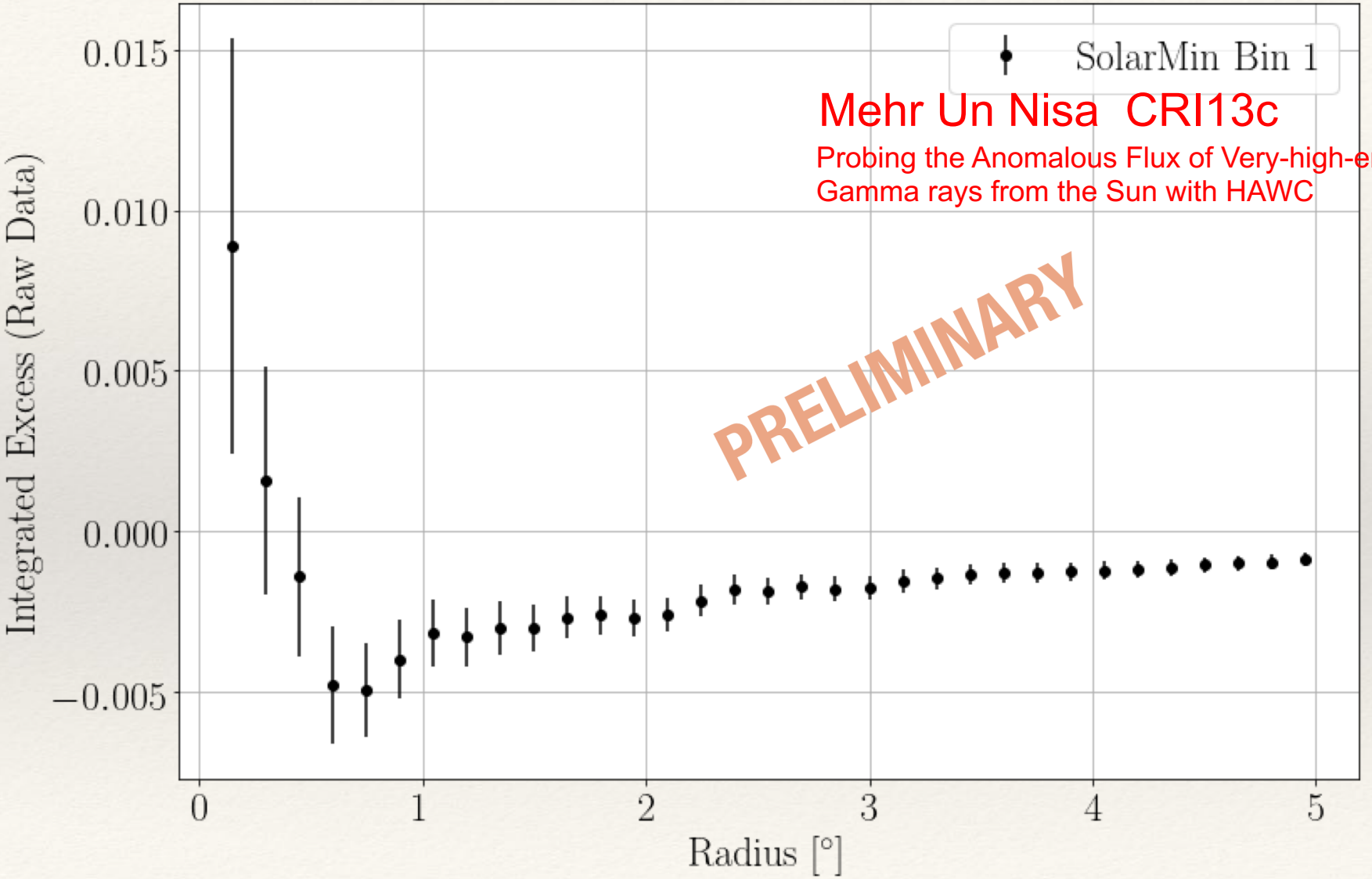
- Constrain ~10% of CR upper bound (active phase)
- Exciting prospect for current solar min (2018 -)



HAWC 1808.05620



2018 Data: Onwards to the Solar Minimum

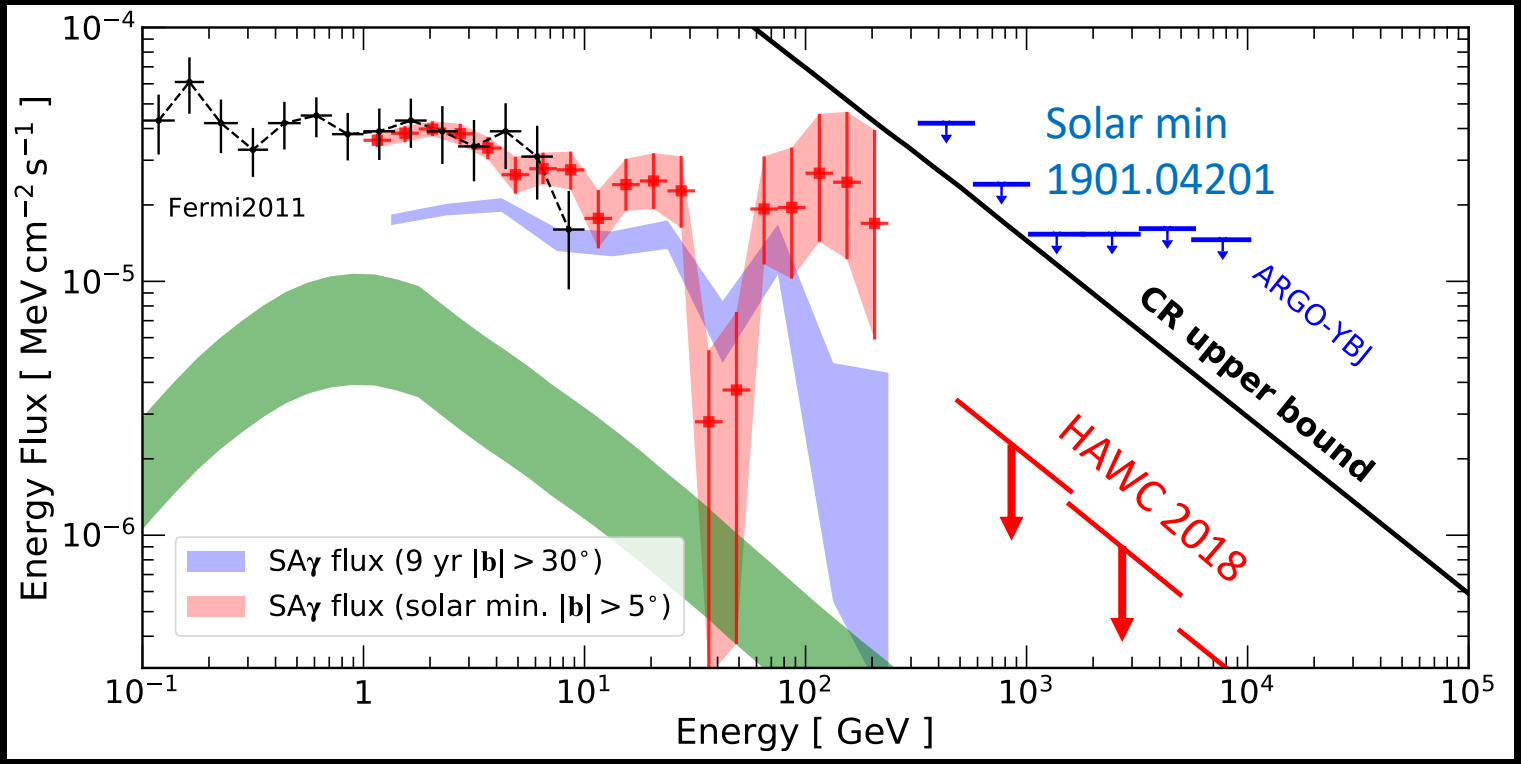


Mehr Un Nisa CRI13c

Probing the Anomalous Flux of Very-high-energy Gamma rays from the Sun with HAWC

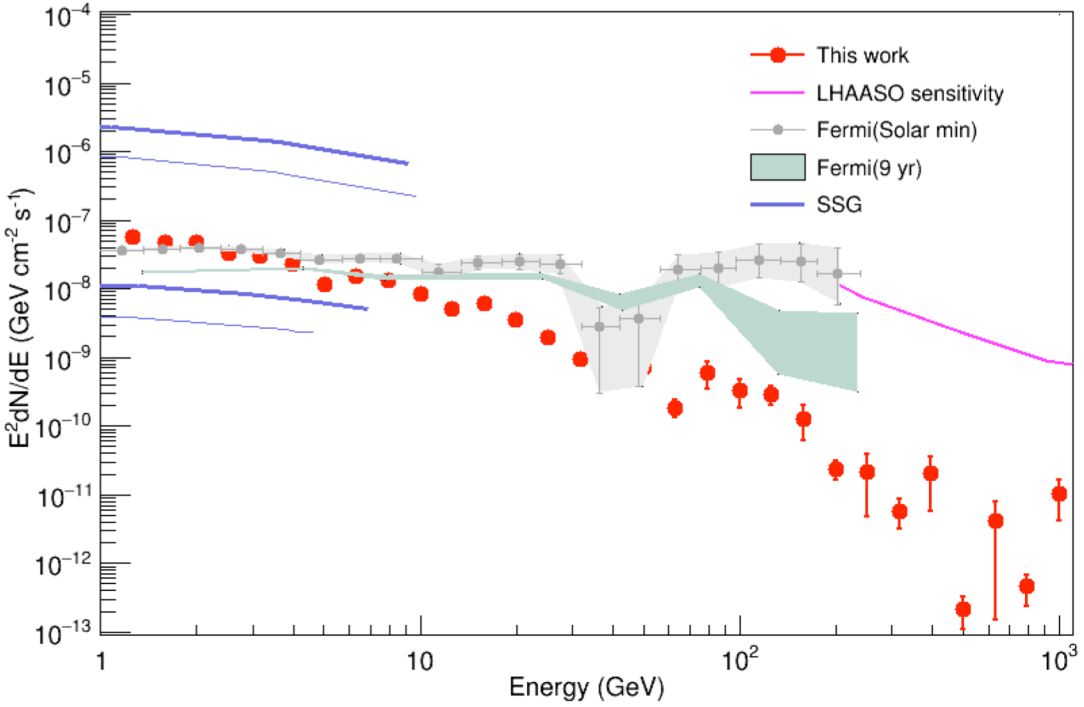
PRELIMINARY

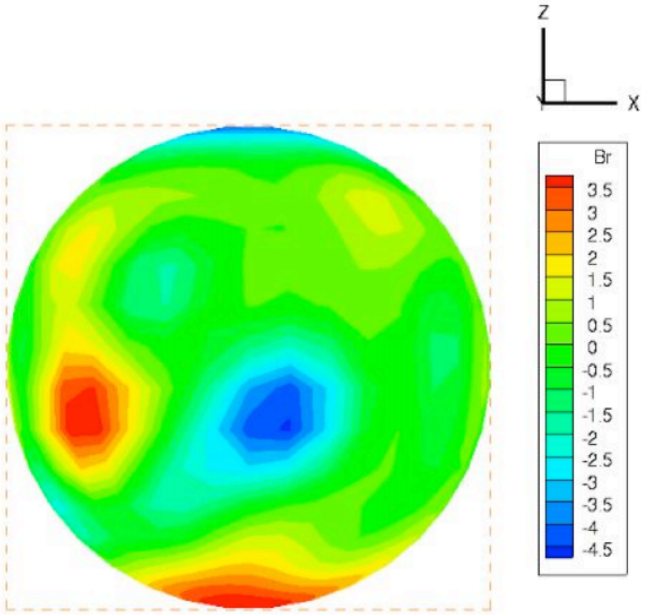
The Sun as a TeV source?!



First Solar gamma simulation w/ B-field

3. Solar disk simulation result



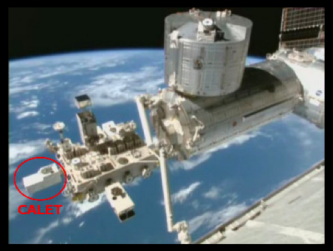


PFSS model for "quiet" Sun

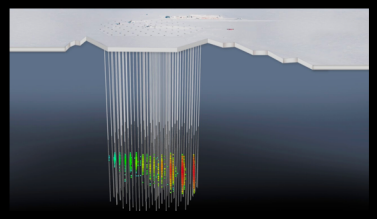
Zhe Li (IHEP)

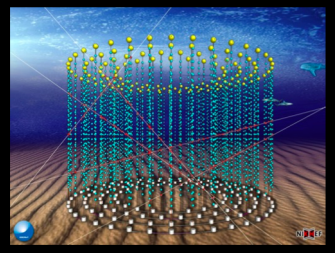
SH5e: Estimation of Solar Disk Gamma-ray Emission Based on Geant4

Summary



- Solar gamma rays
  - *Complicated -> solar physics*
  - *TeV* (HAWC-operating, LHAASO-soon)
  - CALET/ AMS?
  - *More time (solar minimum starting 2018)*



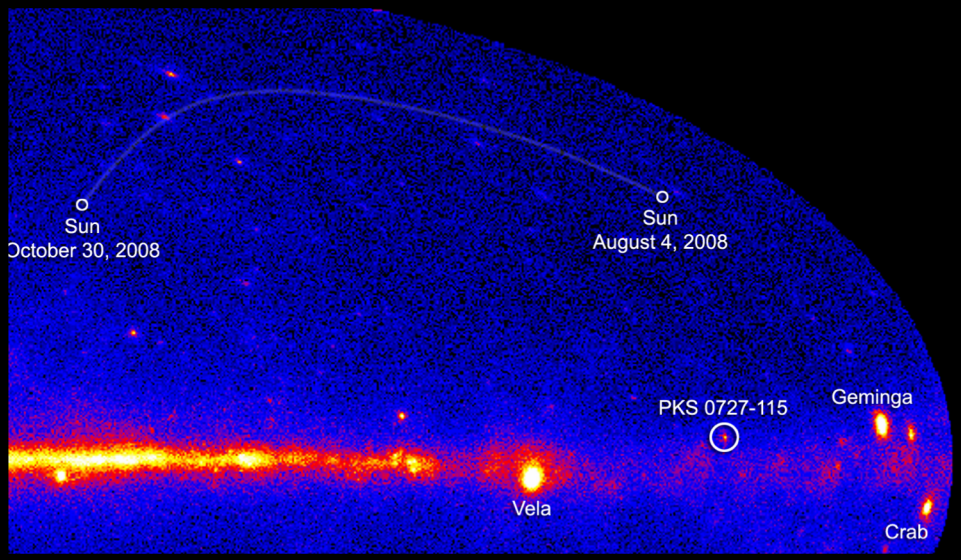


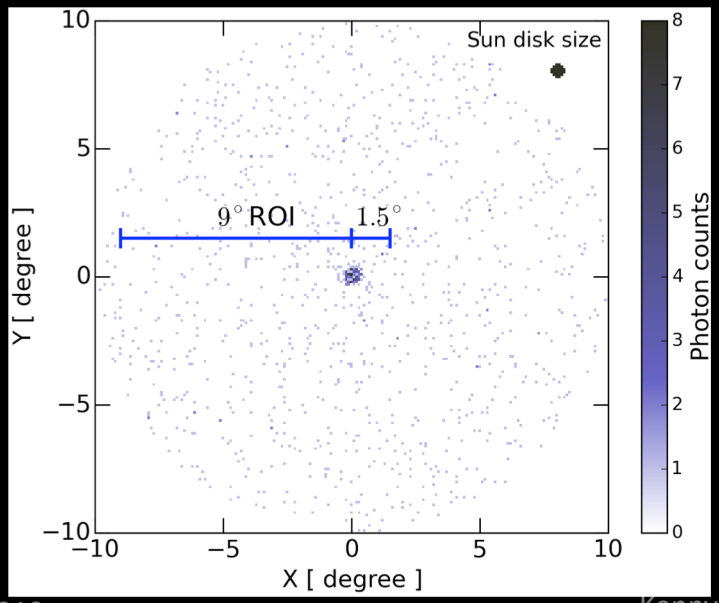
- *Solar atmospheric neutrinos*
  - *> TeV*
  - *IceCube, KM3NeT (future)*

- *Anomalous Signals from the Sun -> New Physics!*

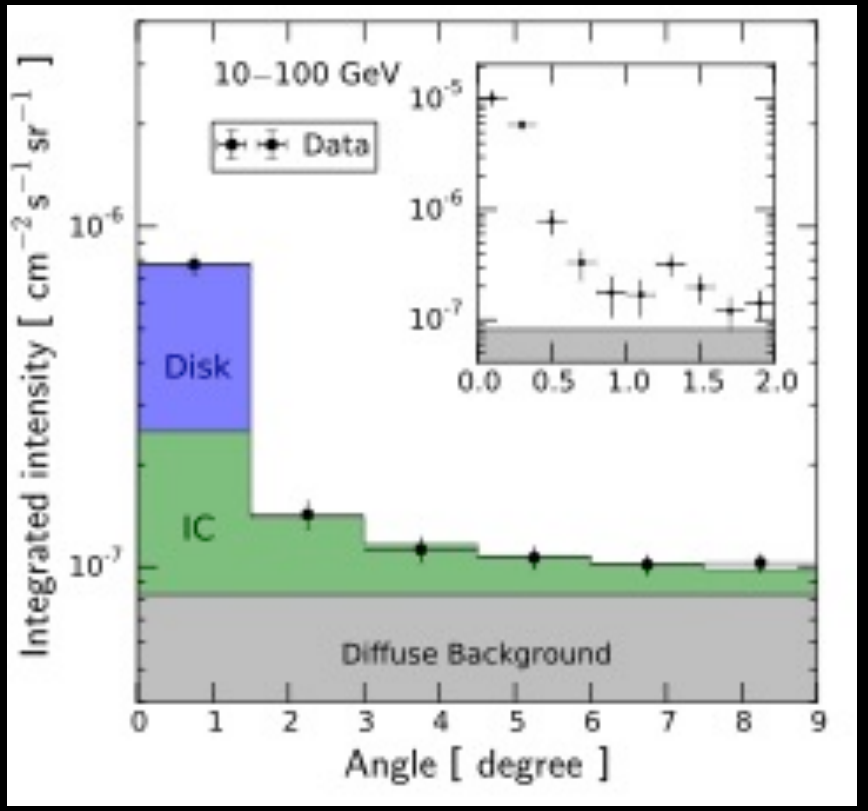
Thanks!

Finding the Sun with Fermi

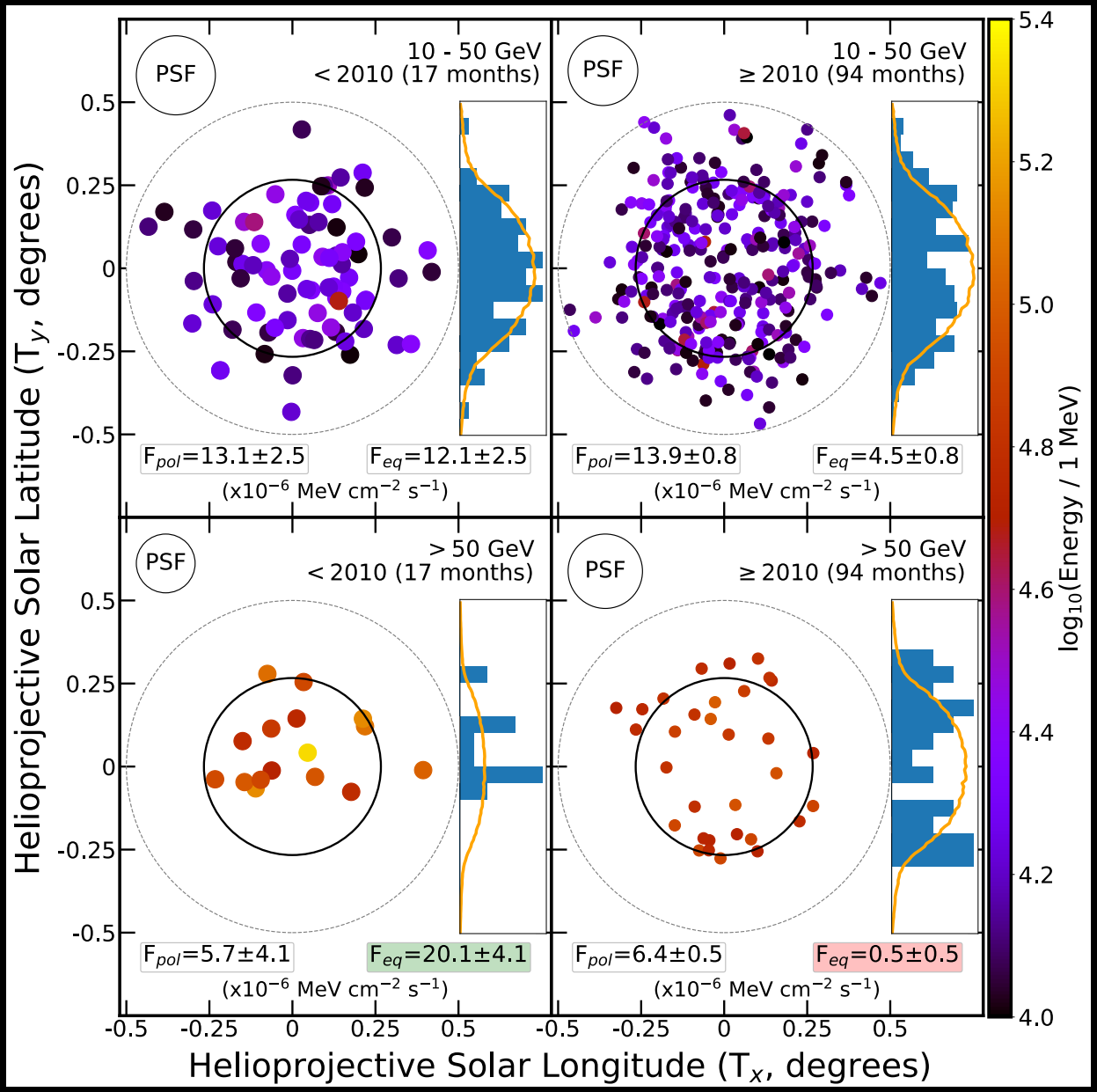




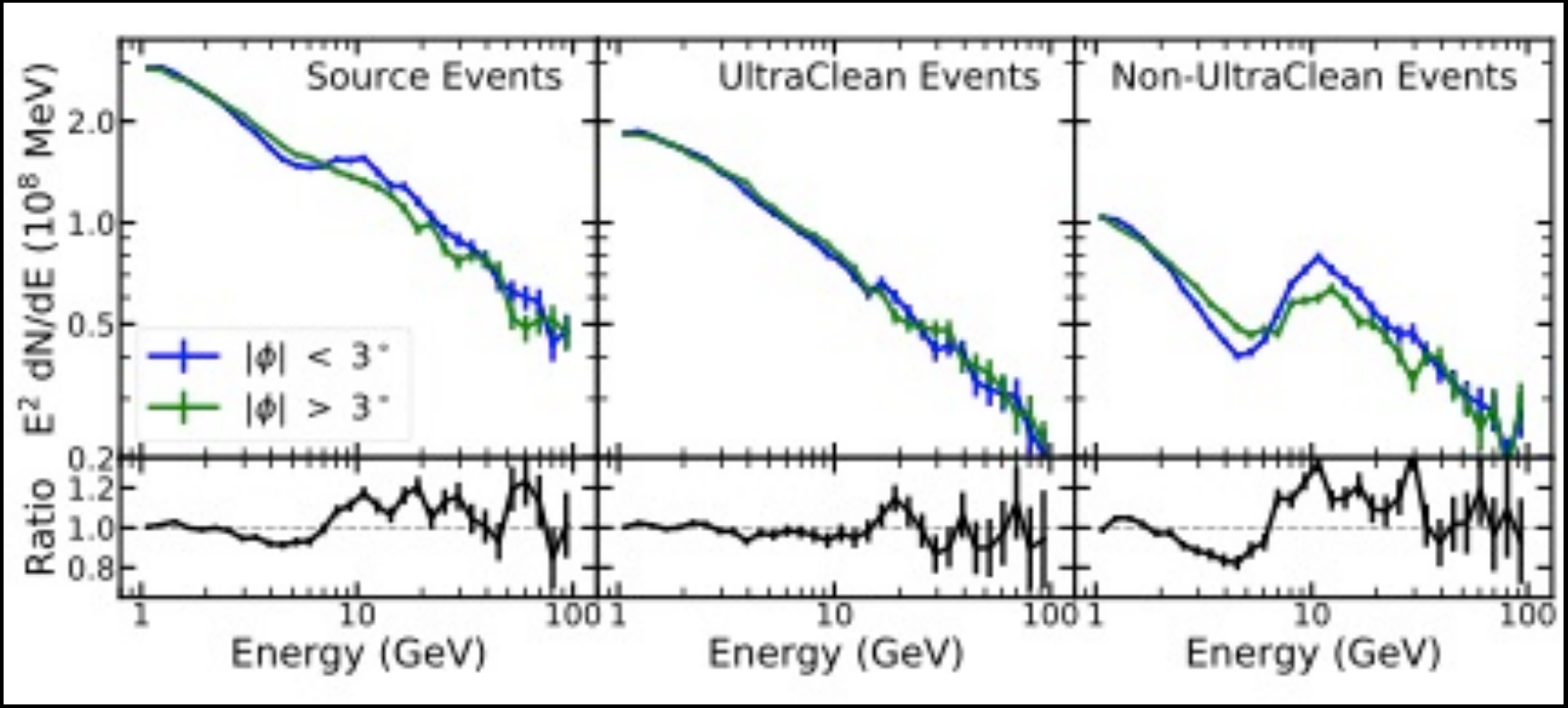
Angular distribution



KCYN+ 2015


PSF
10 - 50 GeV
< 2010 (17 months)
PSF
10 - 50 GeV
≥ 2010 (94 months)
PSF
> 50 GeV
< 2010 (17 months)
PSF
> 50 GeV
≥ 2010 (94 months)
F_pol=13.1±2.5
F_eq=12.1±2.5
(x10^-6 MeV cm^-2 s^-1)
F_pol=13.9±0.8
F_eq=4.5±0.8
(x10^-6 MeV cm^-2 s^-1)
F_pol=5.7±4.1
F_eq=20.1±4.1
(x10^-6 MeV cm^-2 s^-1)
F_pol=6.4±0.5
F_eq=0.5±0.5
(x10^-6 MeV cm^-2 s^-1)
Helioprojective Solar Latitude (T_y, degrees)
Helioprojective Solar Longitude (T_x, degrees)
log10(Energy / 1 MeV)
0.5
0.25
0
-0.25
-0.5
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4

- Background distribution
  - Test for energy features

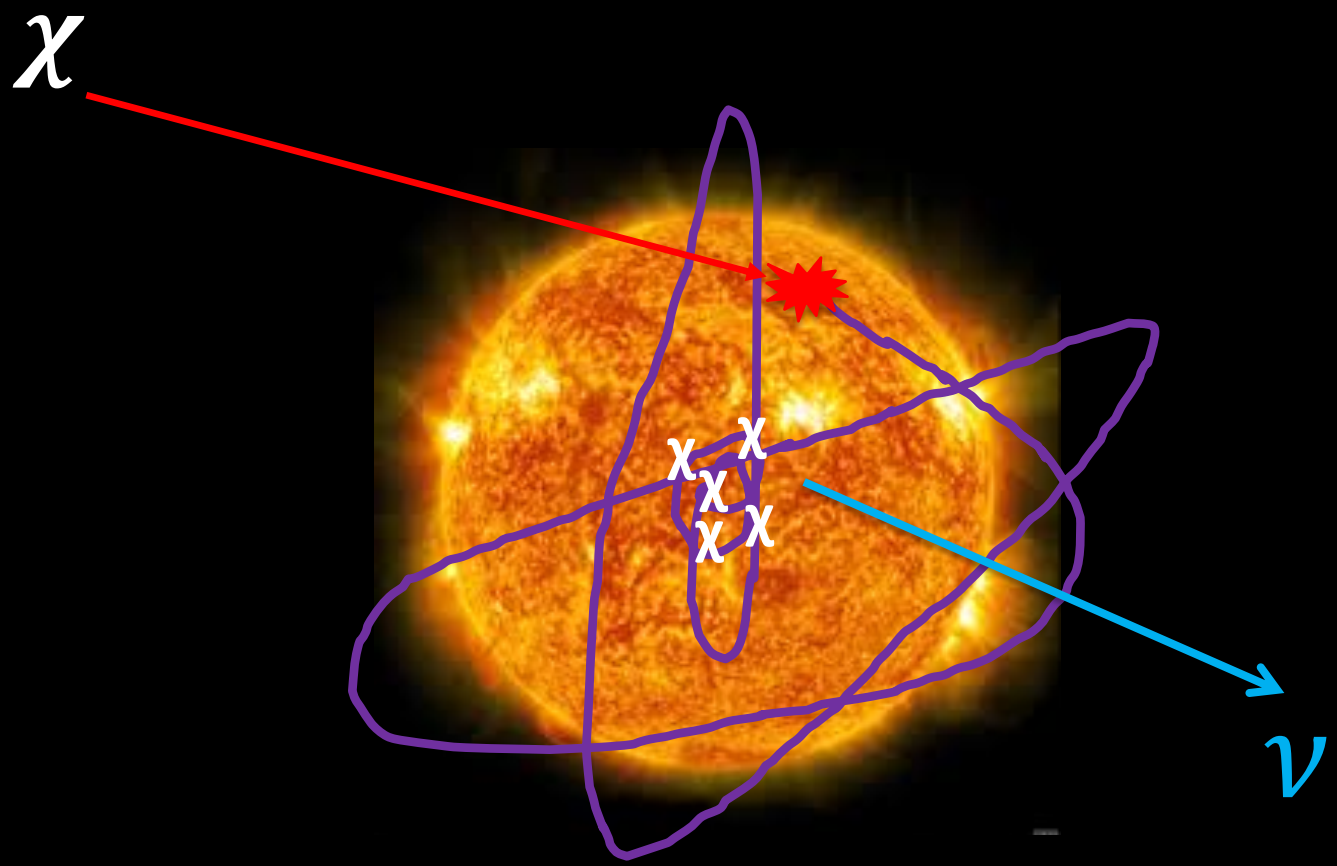


HE Solar Messengers

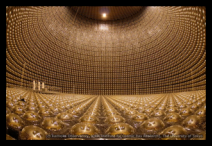
	Gamma Rays	Neutrinos (< TeV)	Neutrinos (> TeV)
Cosmic rays + Solar Atmosphere			
WIMP Dark Matter			
Dark Matter + Mediators			

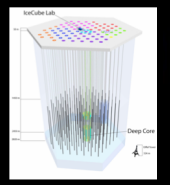
Maybe electrons/positrons or neutrons can also been seen from space?

Sun – Dark Matter detector



Press, Spergel (1985)
Krauss, Freese, Press, Spergel (1985)
Silk, Olive, Srednicki (1985)





Seckel Stanev Gaisser 1991

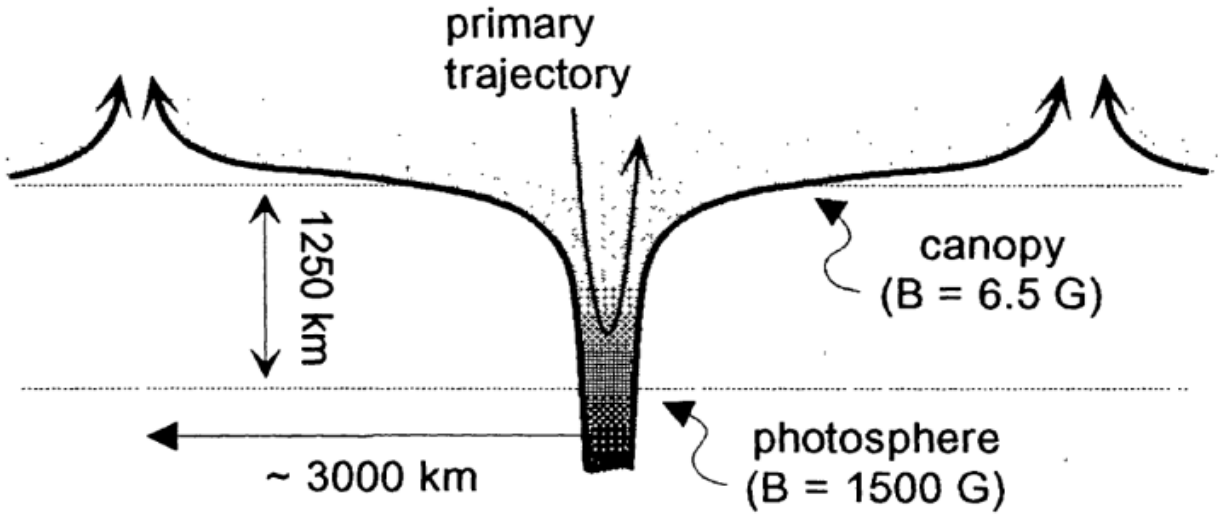


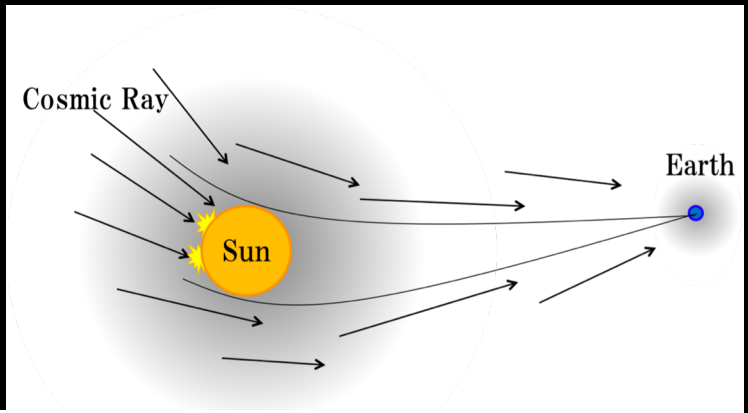
Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

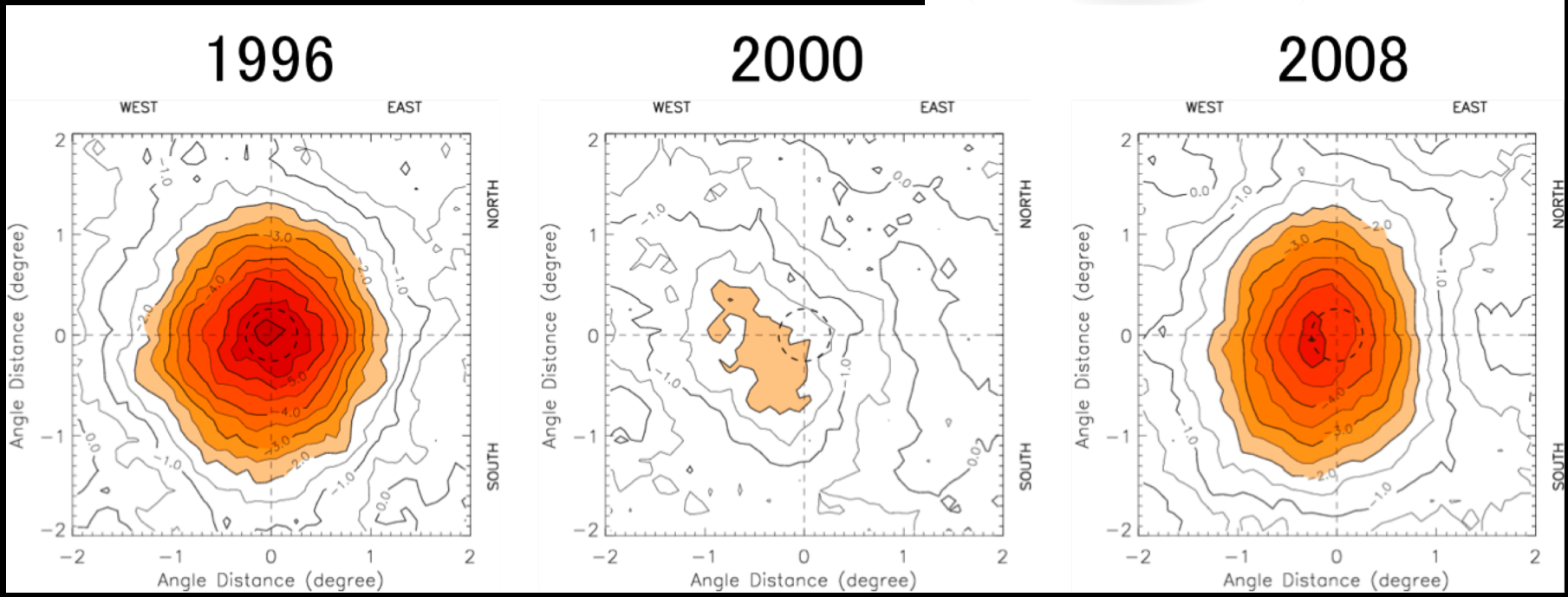
- Follow the field line
- Gas-B-field pressure equilibrium
- Magnetic field gradient -> mirroring
- Trajectory -> interaction probability -> ~ 1%

Boost gamma-ray production

Sun shadow observations

- **TeV** cosmic-ray Sun shadows (near Sun-trajectory)





ICRR, Tibet AS-gamma PRL 2013