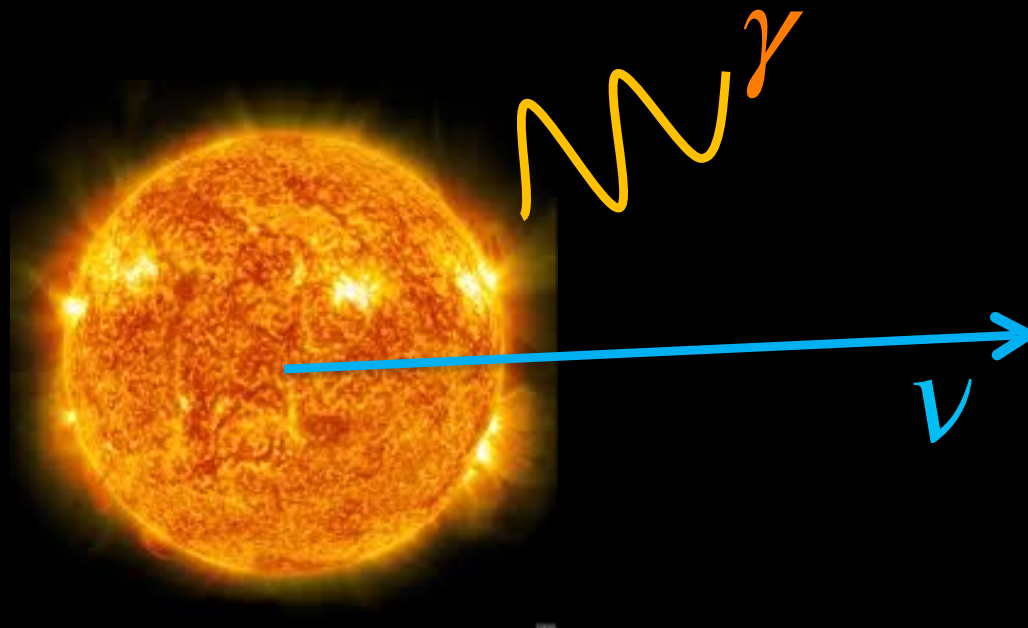


The Solar Gamma-ray Puzzle



Kenny, Chun Yu Ng (吳震宇)
The Chinese University of Hong Kong



My time in CCAPP

- PhD 2010 — 2016
 - Advisor: John Beacom



Kenny CY Ng



CCAPP 20th Anniversary 10-6-2026

----- Original Message -----

Subject:NASA NSPIRES - Proposal has been Submitted to NASA

Date:Mon, 24 Jun 2013 11:25:16 -0400 (EDT)

From:nspires@nasaprs.com

To:waling.1@osu.edu

CC:annika.peter@uci.edu

The following proposal has been submitted for consideration of an award by NASA:

Proposal Number: 12-FERMI12-0027

Proposal Title: CALCULATING GAMMA-RAY EMISSION FROM COSMIC-RAY INTERACTIONS IN THE SOLAR ATMOSPHERE

Submitting Organization: OHIO STATE UNIVERSITY THE

Authorized Organization Representative: Mike Waling

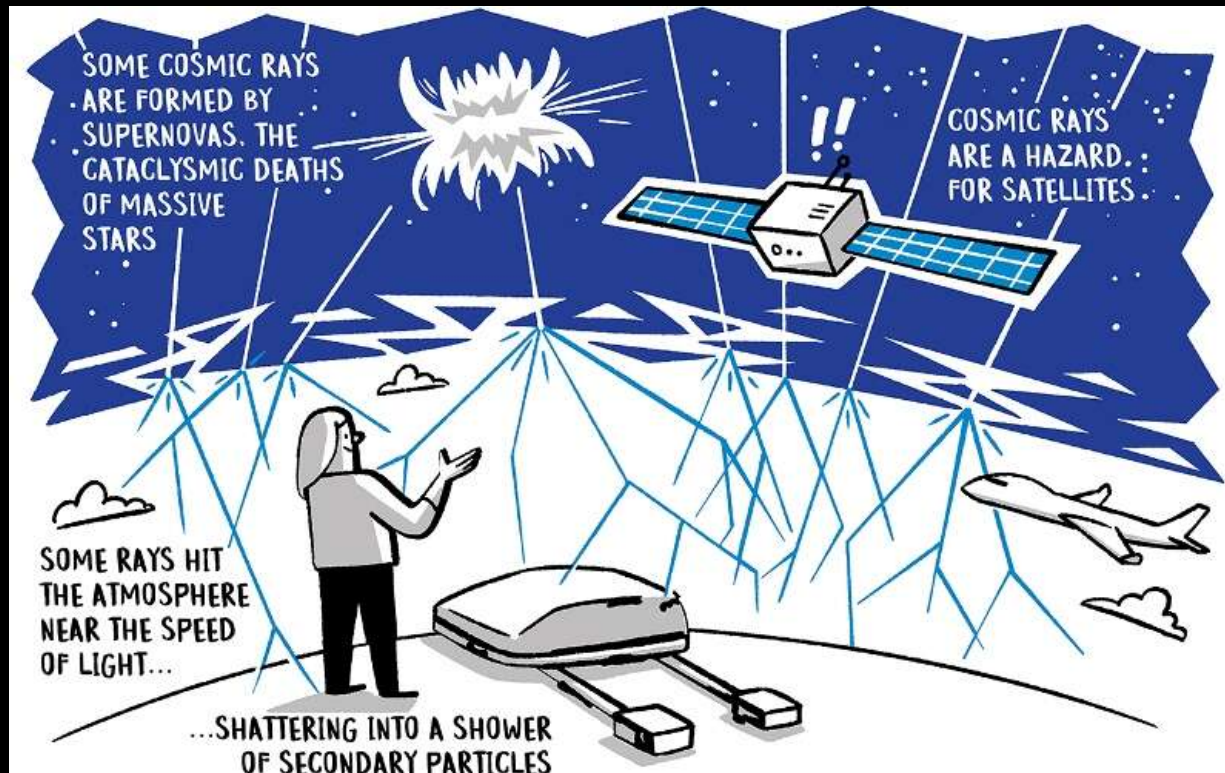
Principal Investigator: Annika Peter

Date submitted: 06/24/2013 11:25:16

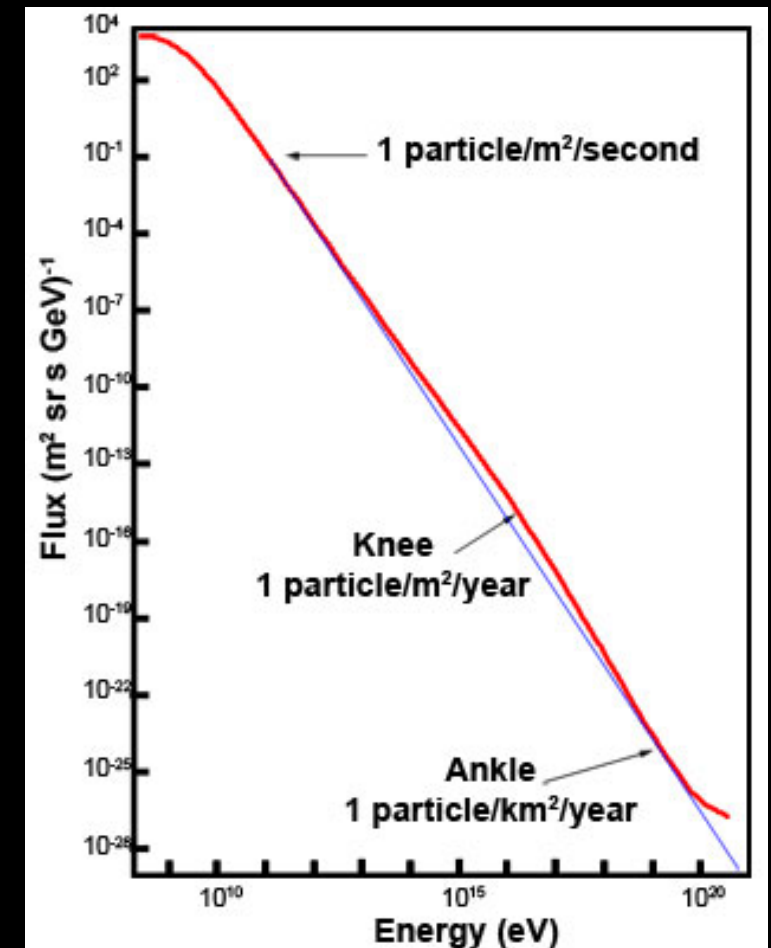


Cosmic rays

- Energetic particles in space
- Mostly proton/nuclei, some electrons



<https://www.iop.org/explore-physics/physics-around-you/understanding-surroundings/cosmic-rays>



Solar Atmospheric Gamma Rays

$$p + p \rightarrow \pi^0 / \pi^\pm + X$$

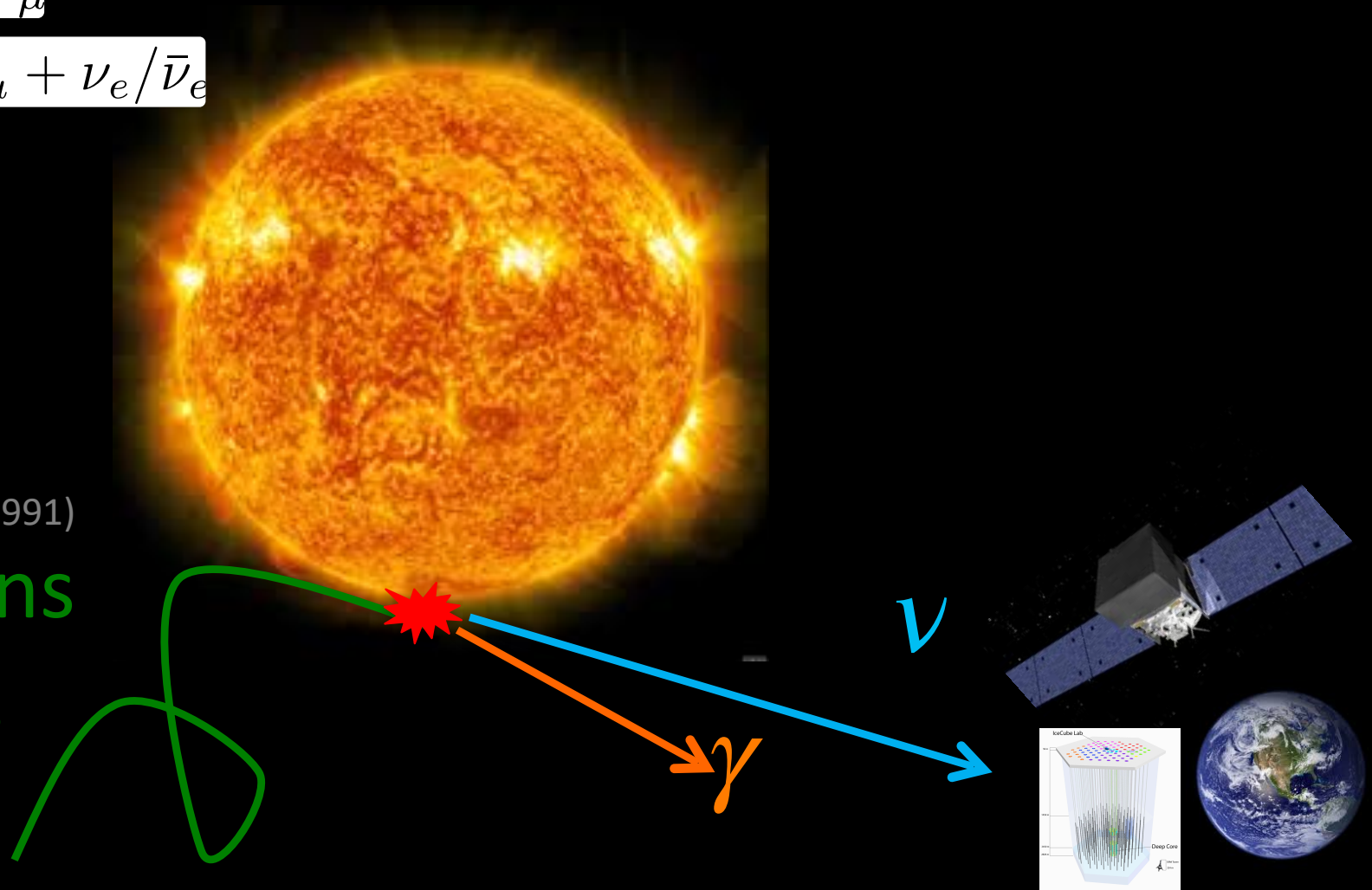
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu / \bar{\nu}_\mu$$

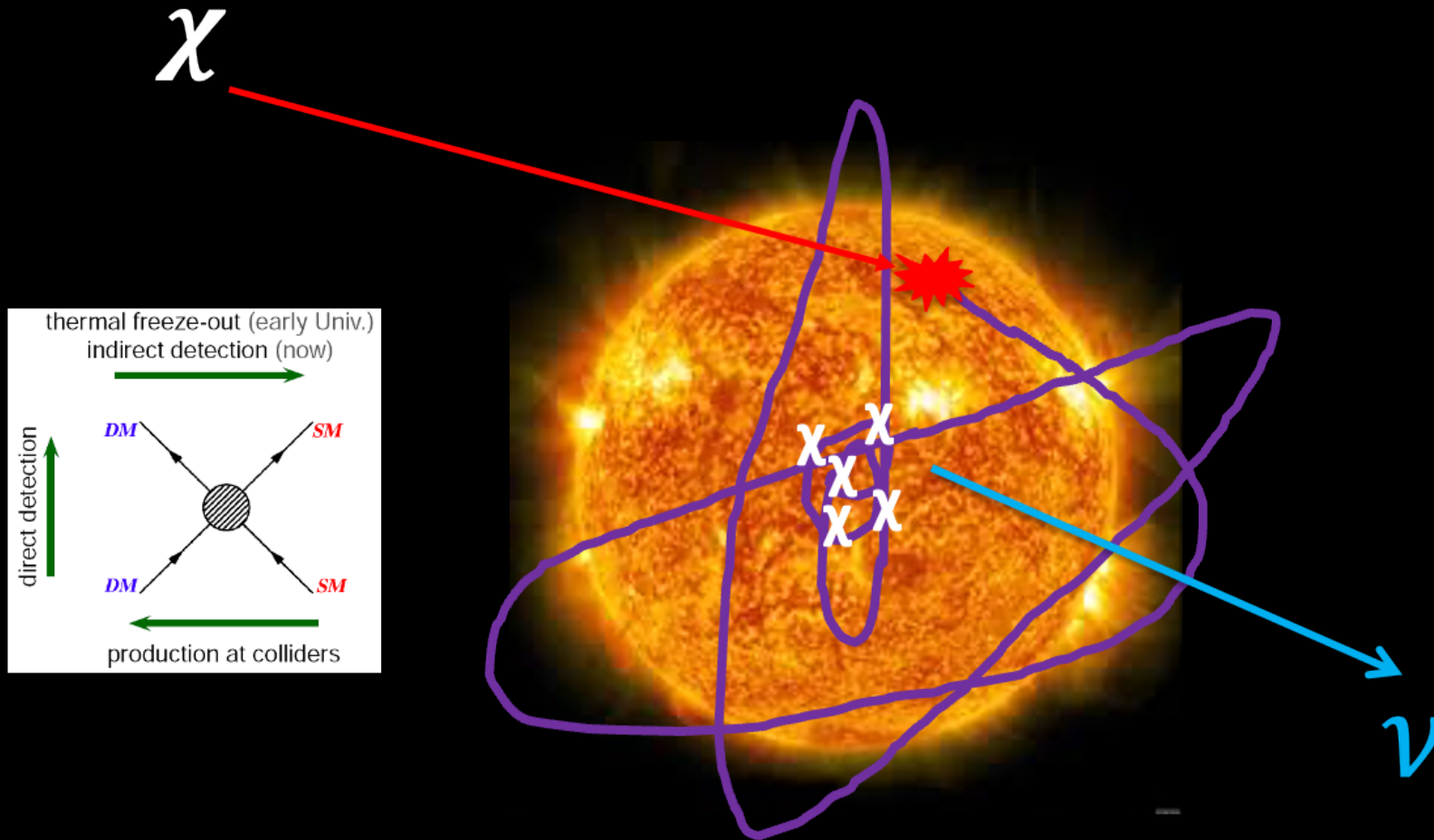
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu / \nu_\mu + \nu_e / \bar{\nu}_e$$

Seckel, Stanev, Gaisser (1991)

CR protons
Hadronic



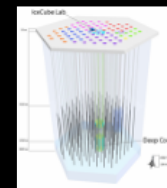
The Sun as a Dark Matter detector



Press, Spergel (1985)

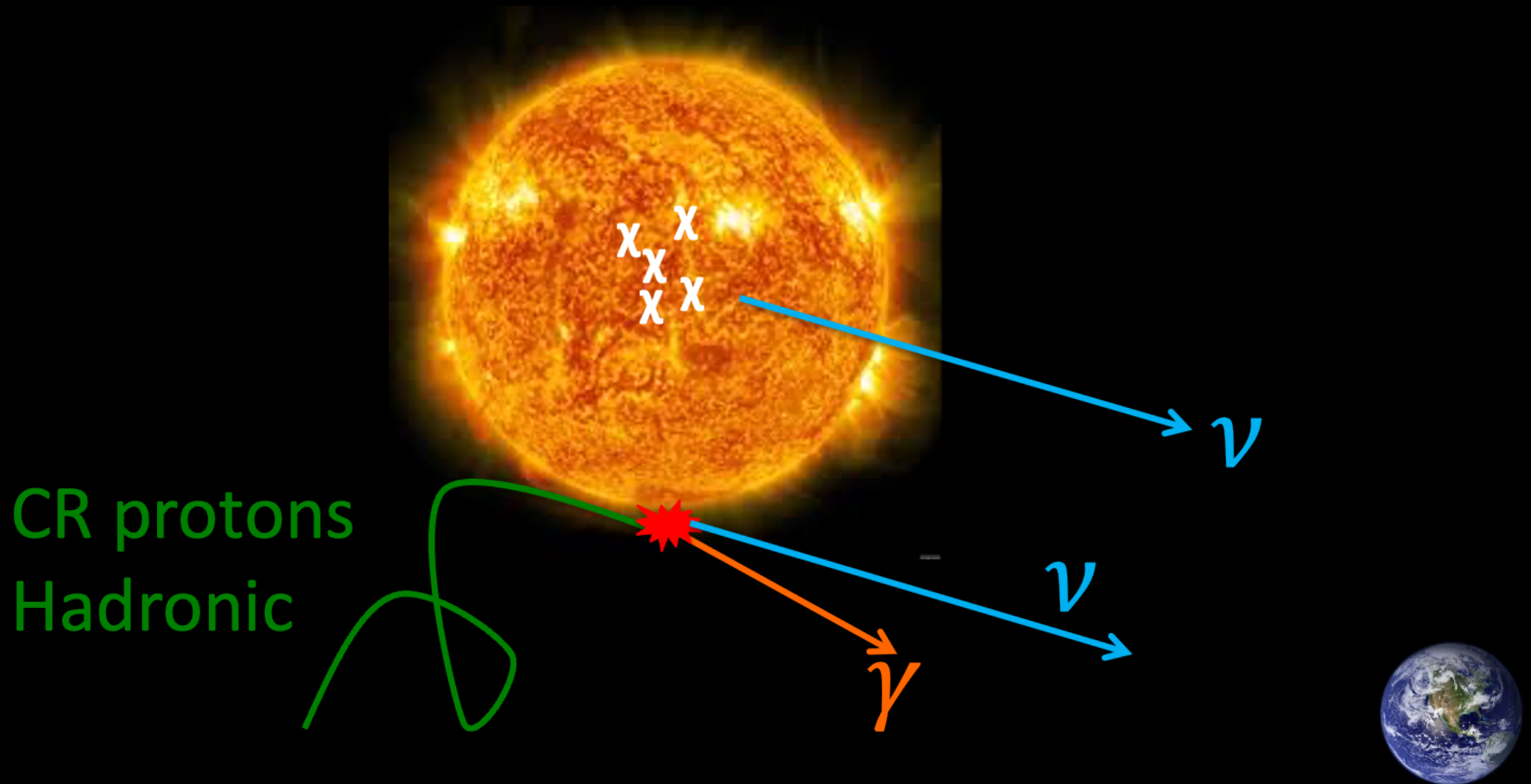
Krauss, Freese, Press, Spergel (1985)

Silk, Olive, Srednicki (1985)



The Sun as a Gamma and Neutrinos Source

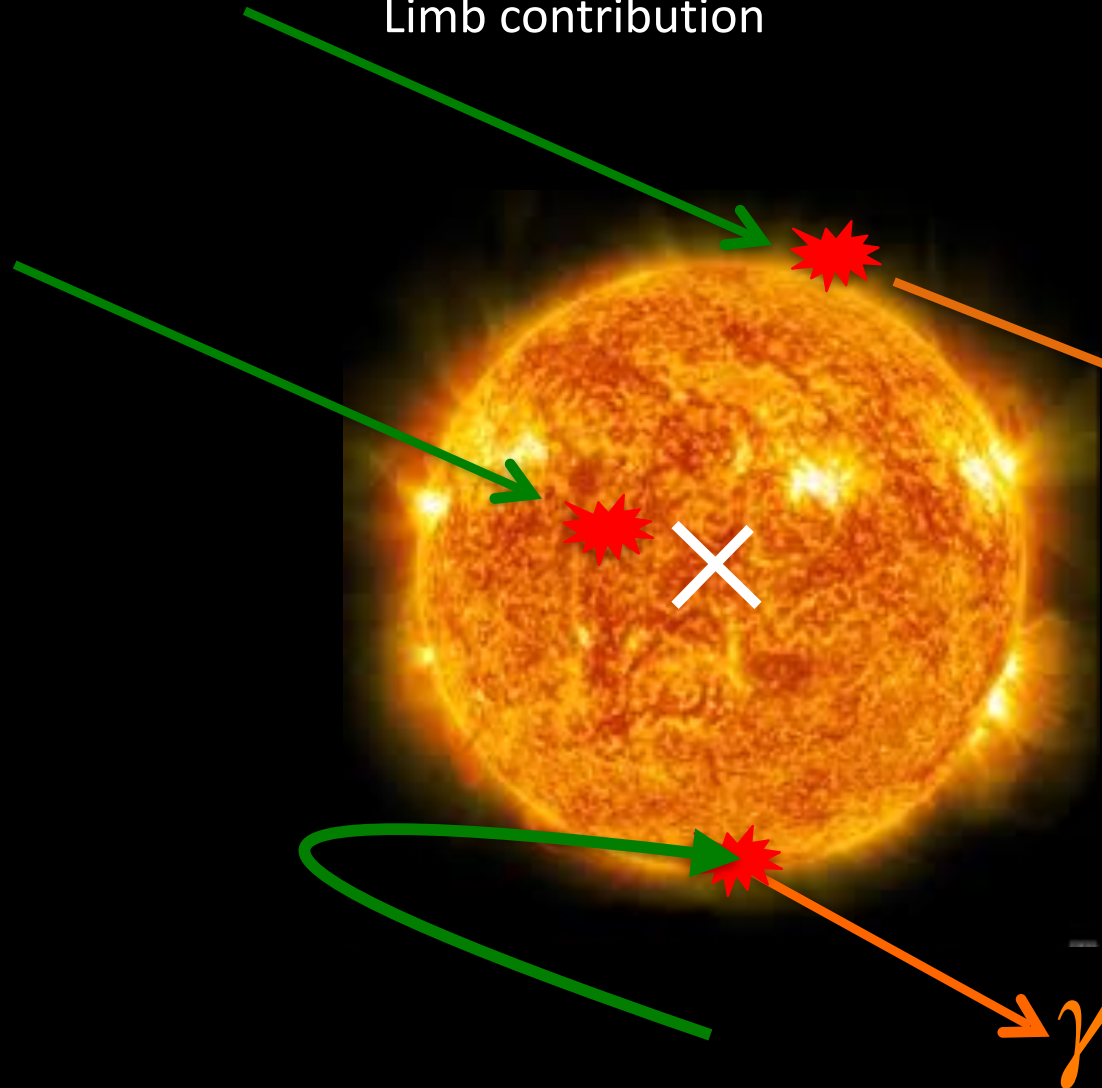
Dark Matter detector



Solar Atmospheric Gamma Rays

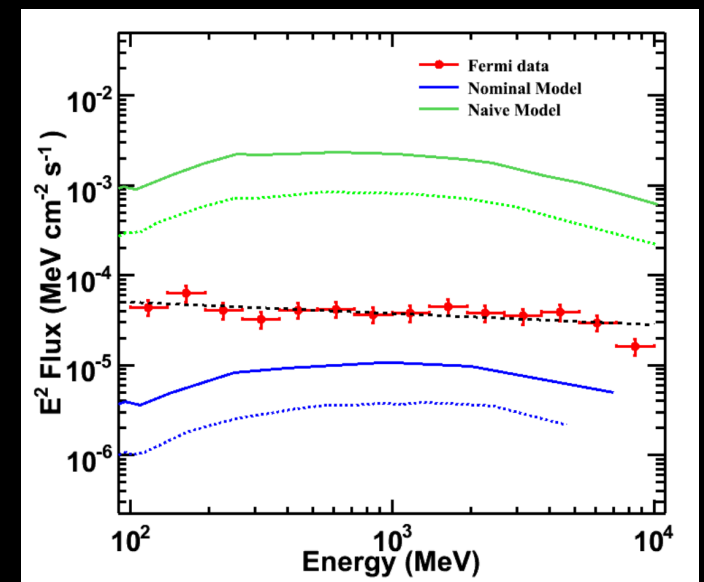
Zhou, *KCYN*, Beacom, Peter PRD 2017

Limb contribution



γ 0.1%

Abdo et al 2011

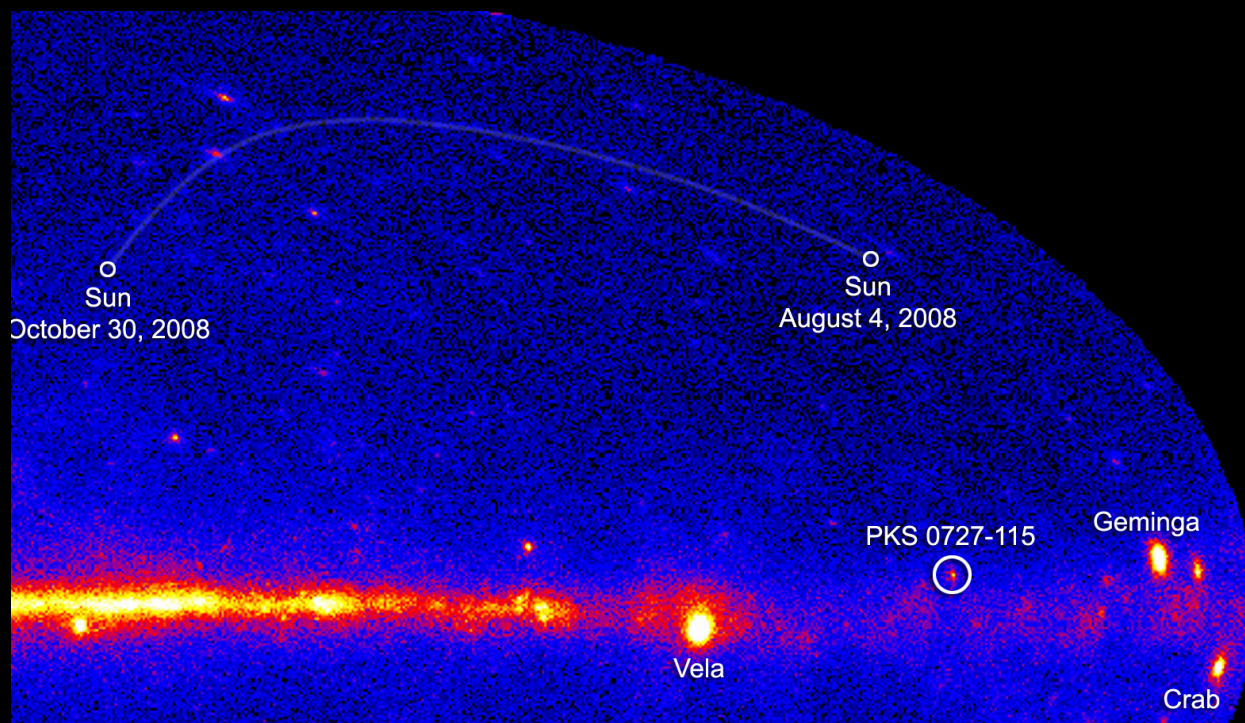


Seckel, Stanev, Gaisser (1991) $\sim 1\%$

Fermi data
 $\sim 5 - 10\%$

Solar gamma rays

- Before us, it was a nuisance to the Fermi team



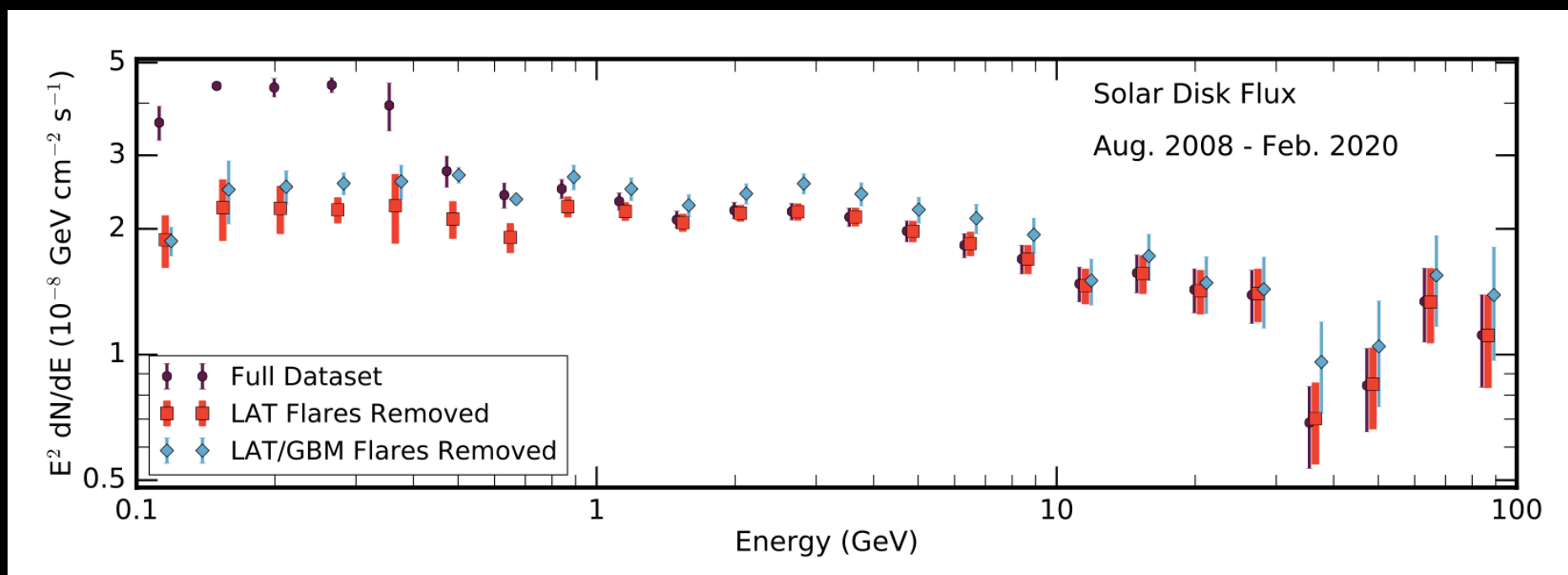
2008-2020 Averaged Spectrum

KCYN et al PRD 2016

Tang et al PRD 2018

Linden et al PRD 2022

- Linden et al 2022 PRD



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

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

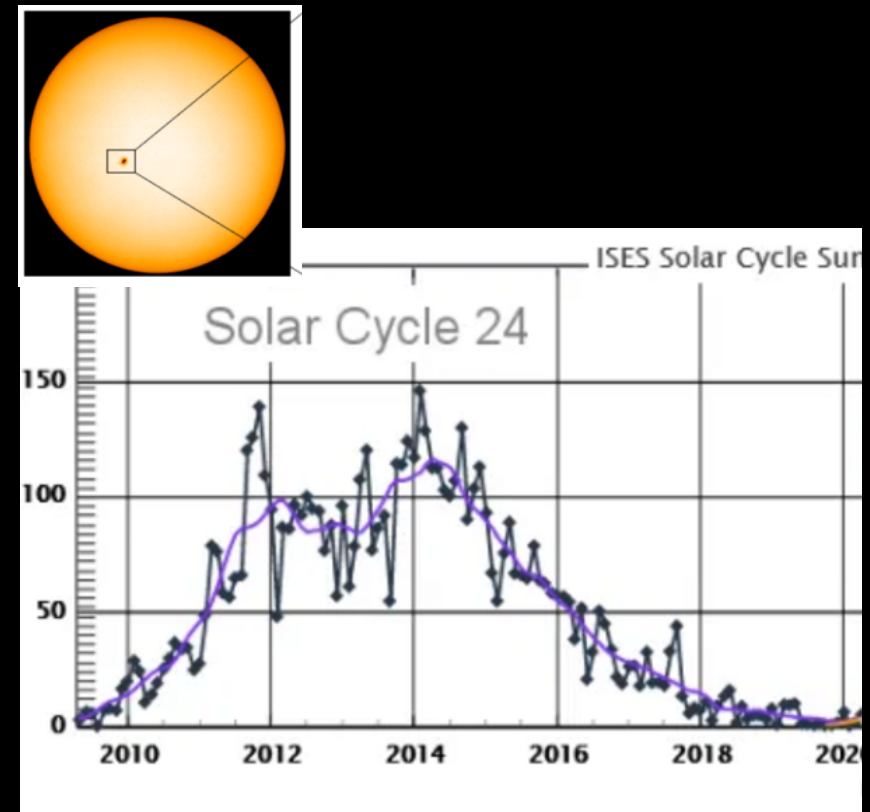
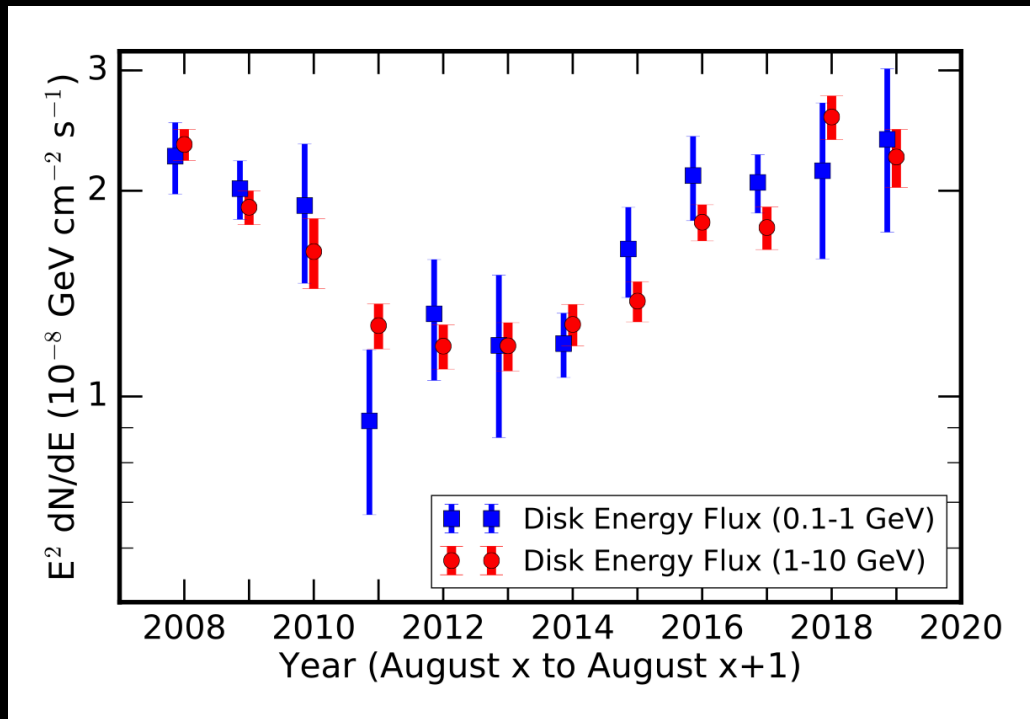
Magnetic
Efficiency factor

Time variation

KCYN et al PRD 2016
Tang et al PRD 2018
Linden et al PRD 2022

- Clear anticorrelation with solar activity from 0.1-10 GeV
- Less clear in 10-100 GeV (less variation or insufficient statistics)
- Can not be easily explained by solar modulation Li, Beacom, Peter APJ 2022

Linden et al PRD 2022

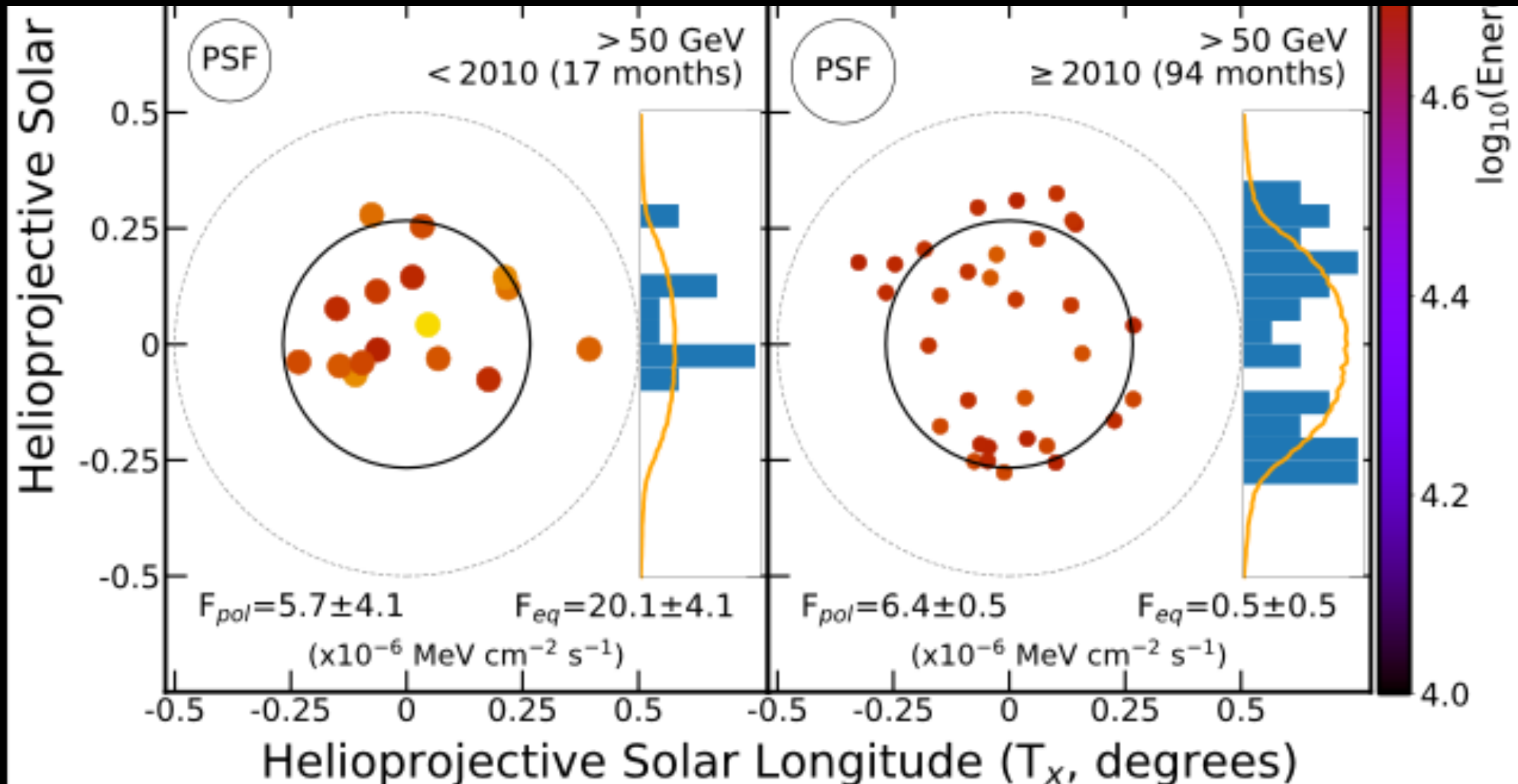


Not energy sensitive?

Morphology, *surprise!*

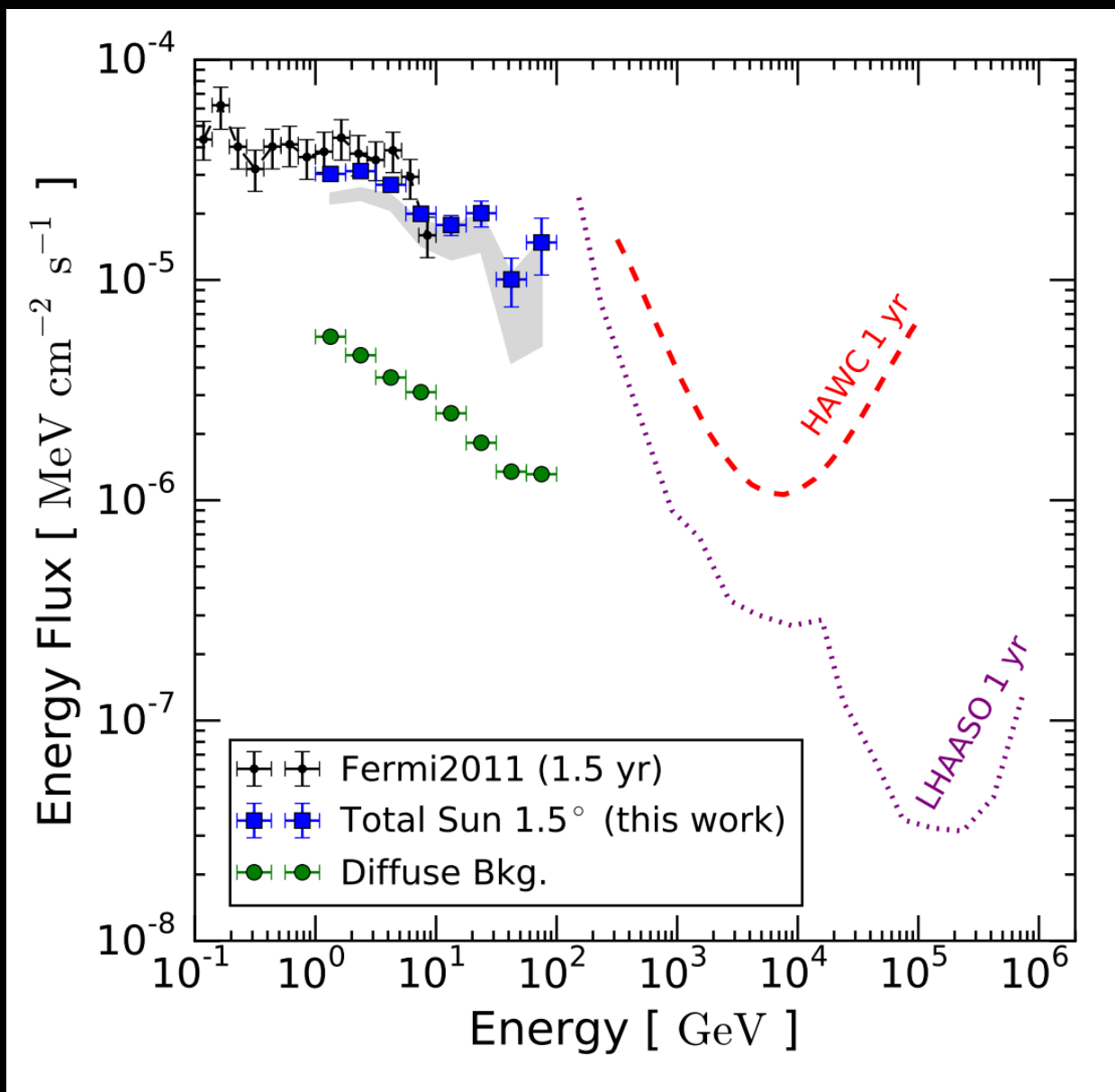
- High Energy Bin
 - (> 50 GeV)

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



TeV?

KCYN et al PRD 2016



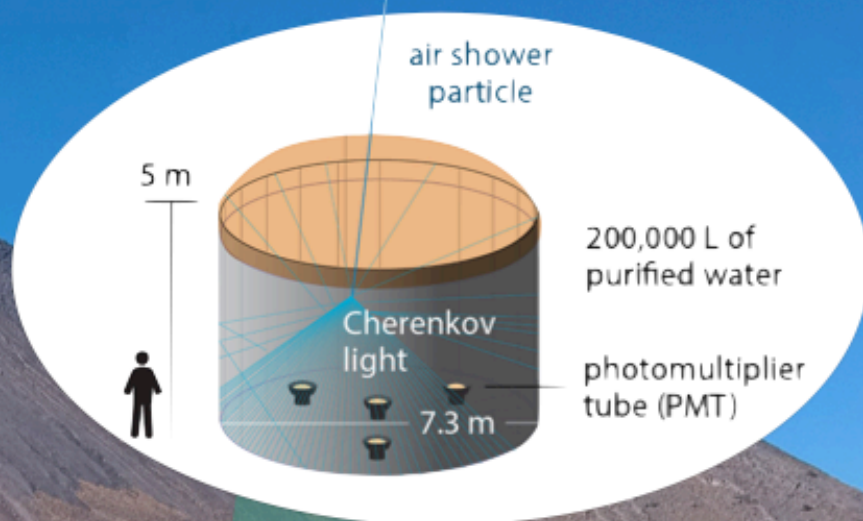


The HAWC Observatory

Hao Zhou TeVPA2018



- 300 Water Cherenkov Detectors
- 22,000 m² detector area
- Sub TeV - >100 TeV Sensitivity
- Wide field of view: ~2 sr
- High duty cycle: >95%

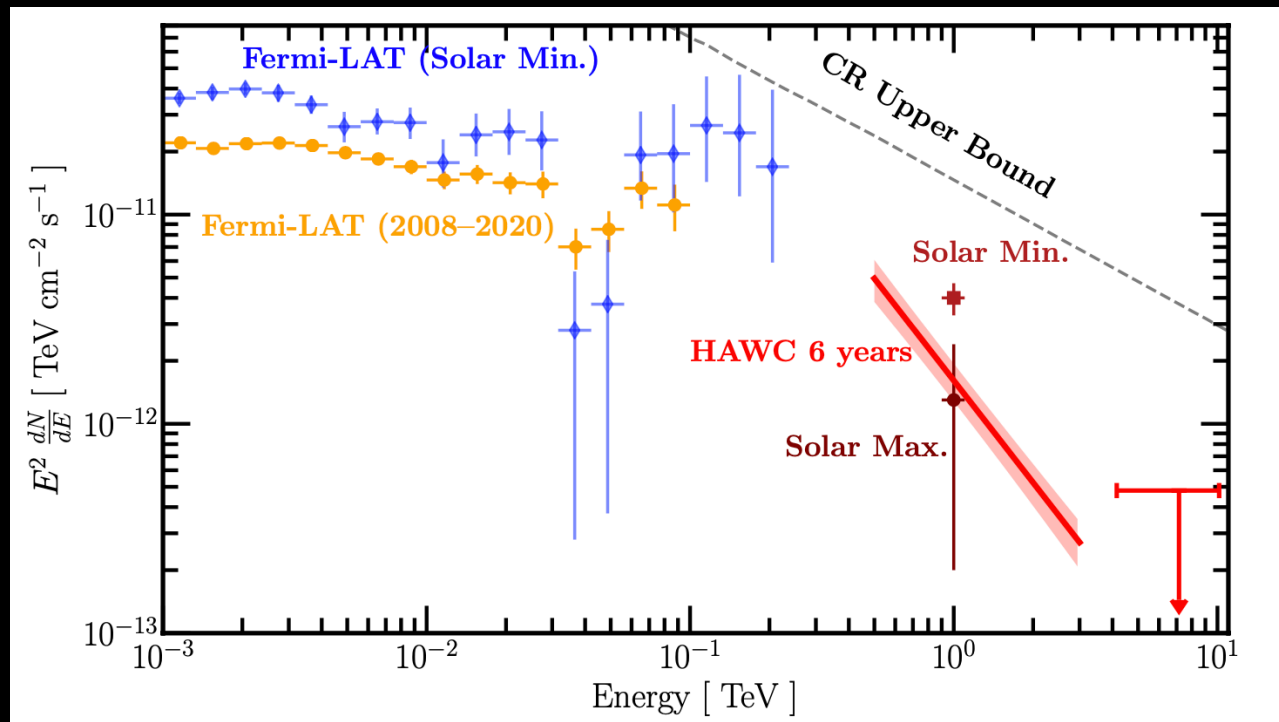


Excellent detector for extended sources

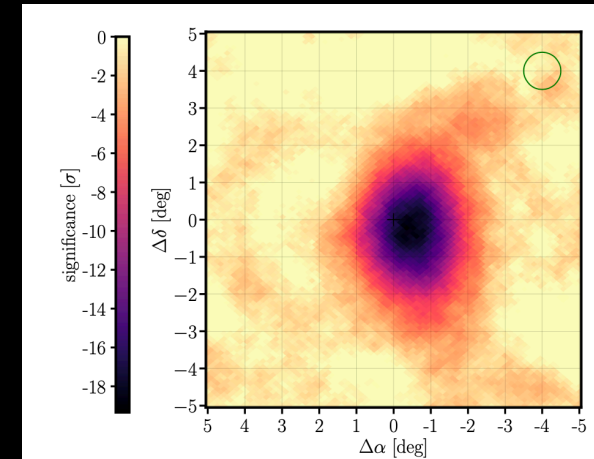
Main array inaugurated on March 20, 2015

The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC

Phys.Rev.Lett. 131 (2023) 5, 051201
HAWC col. + Beacom, Linden, Ng, Peter, Zhou

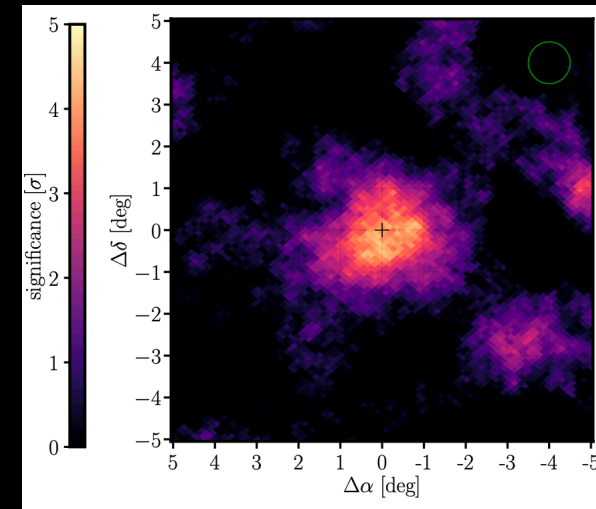


- Spectral index change!
- A sign that the magnetic field effect is decreasing?

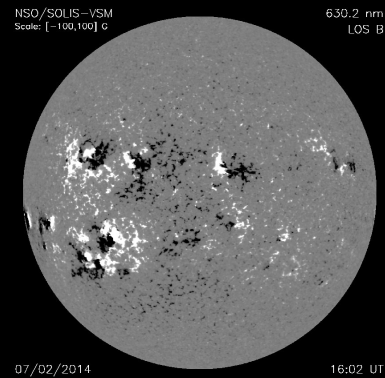


Raw data, Sun shadow!

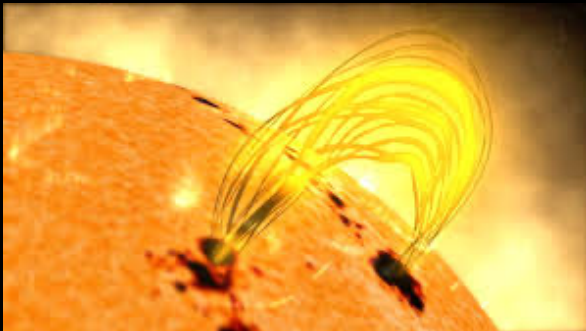
After hadron rejection and shadow subtraction



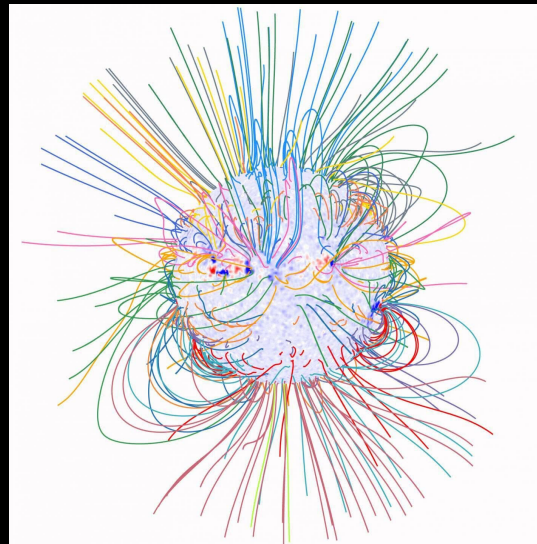
Theoretical developments



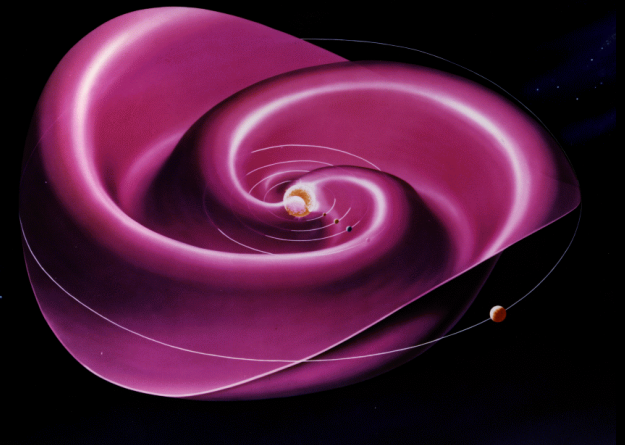
Best observational B-field data comes from
Optical data *at the photosphere*



Photosphere B-field
<1 R_{sun} to R_{sun}



Coronal B-field
R_{sun} to 10 R_{sun}



Interplanetary B-field
10 R_{sun} to interstellar Space

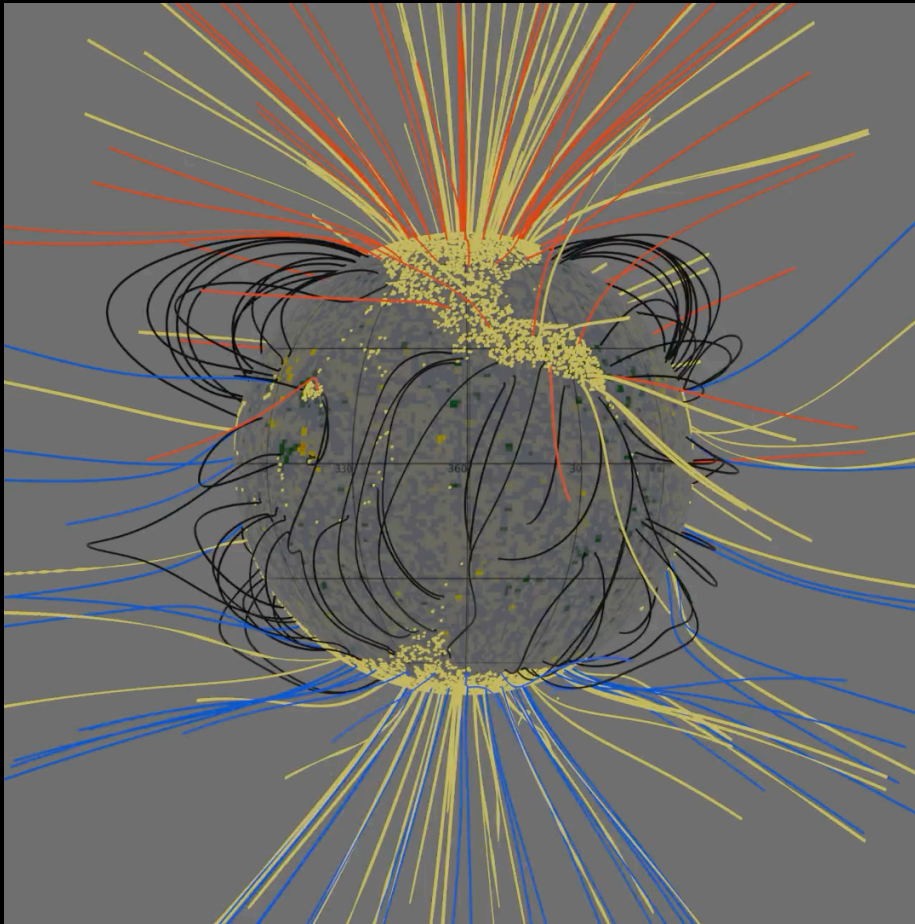
Simulating the Sun with Coronal fields

Li et al CPC 2024

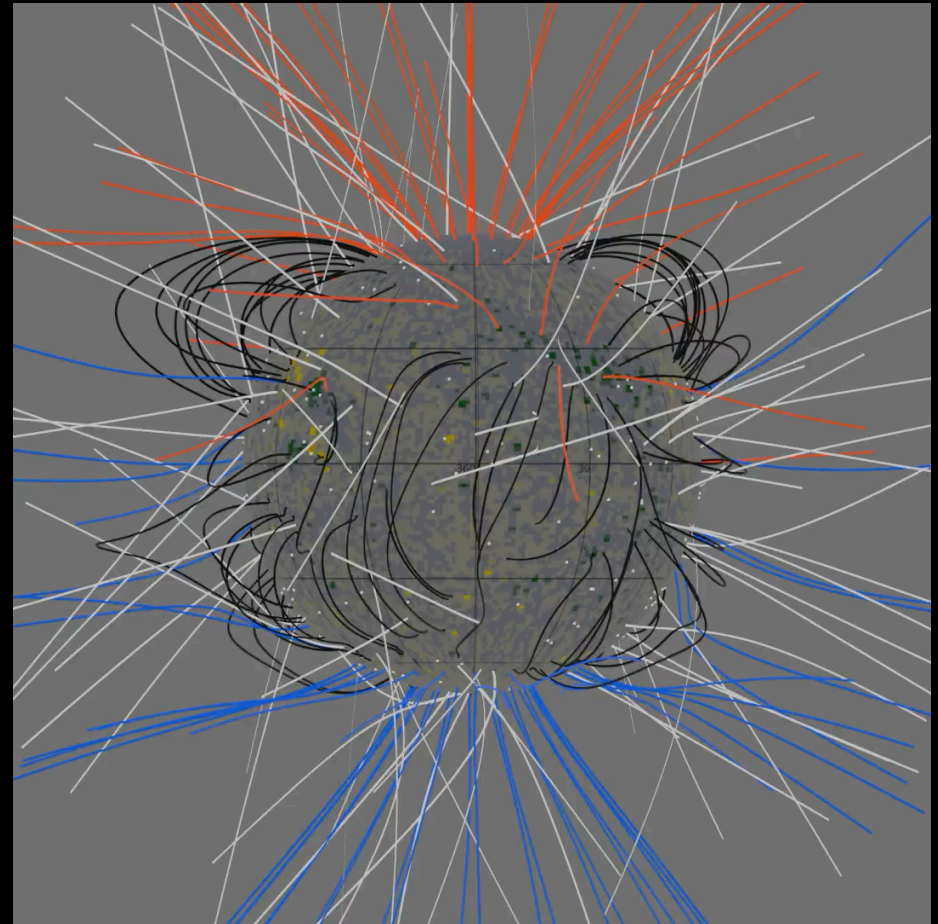
Mazziotta et al PRD 2020

Dorner et al APJ 2026

1-10 GeV protons

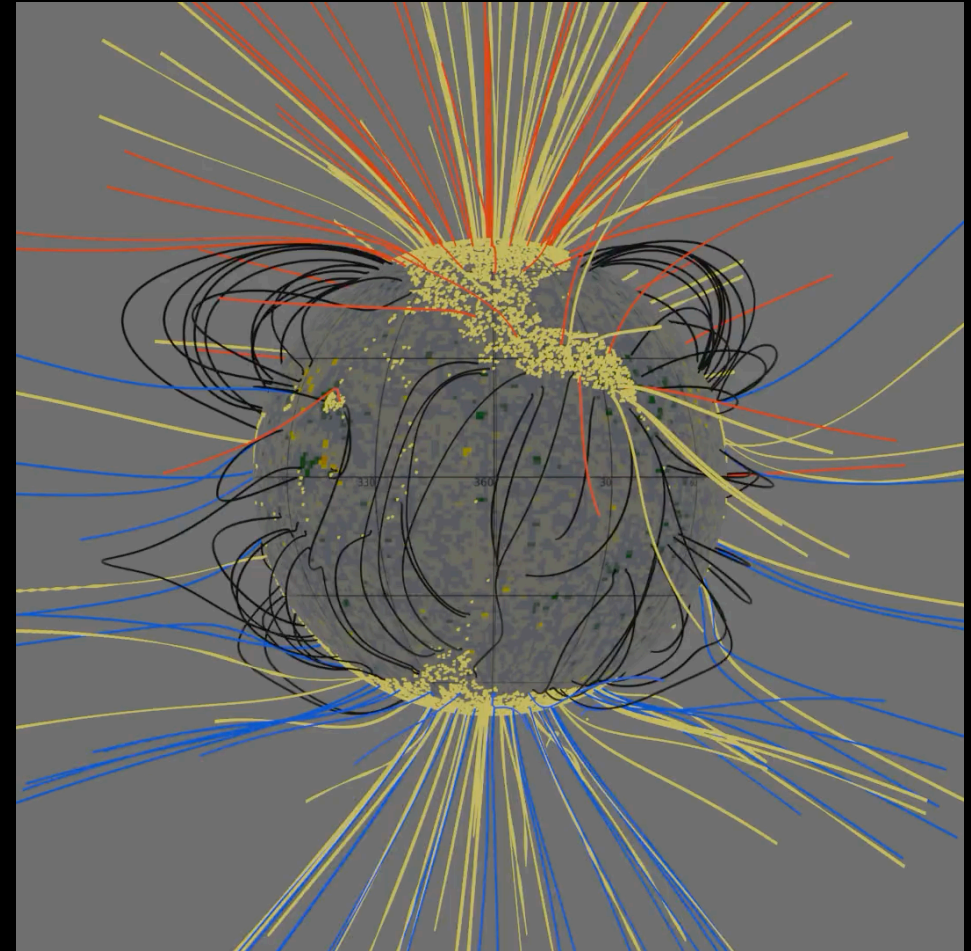
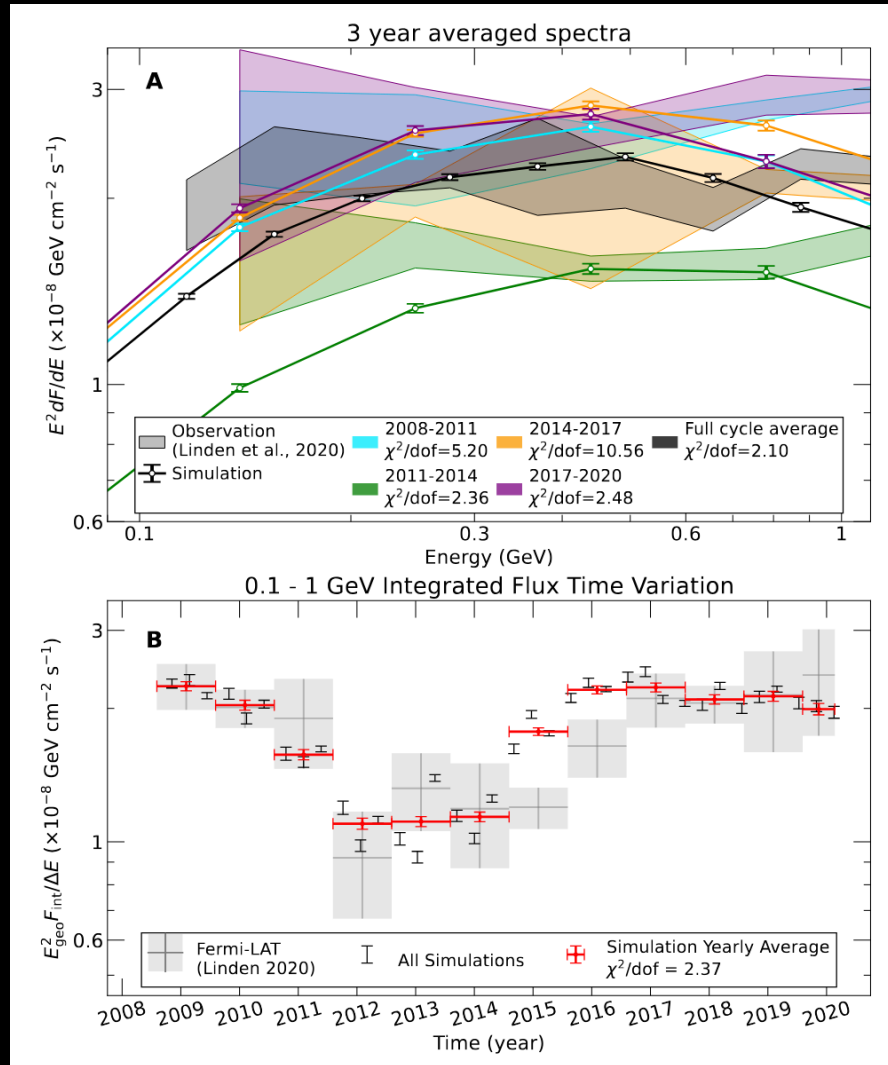


10-100 TeV protons



Fong, Li, KCYN, soon

GeV time variation can be explained by coronal fields



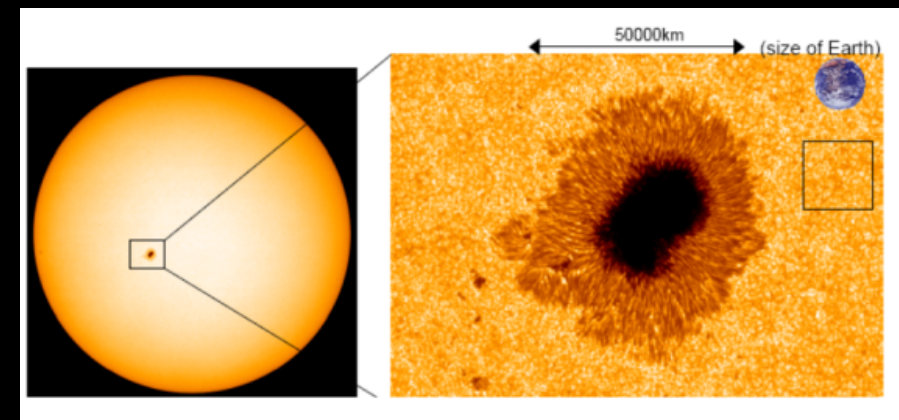
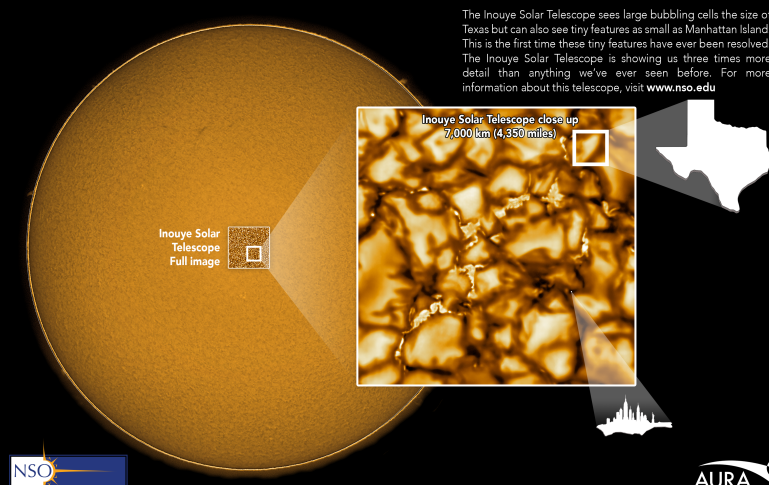
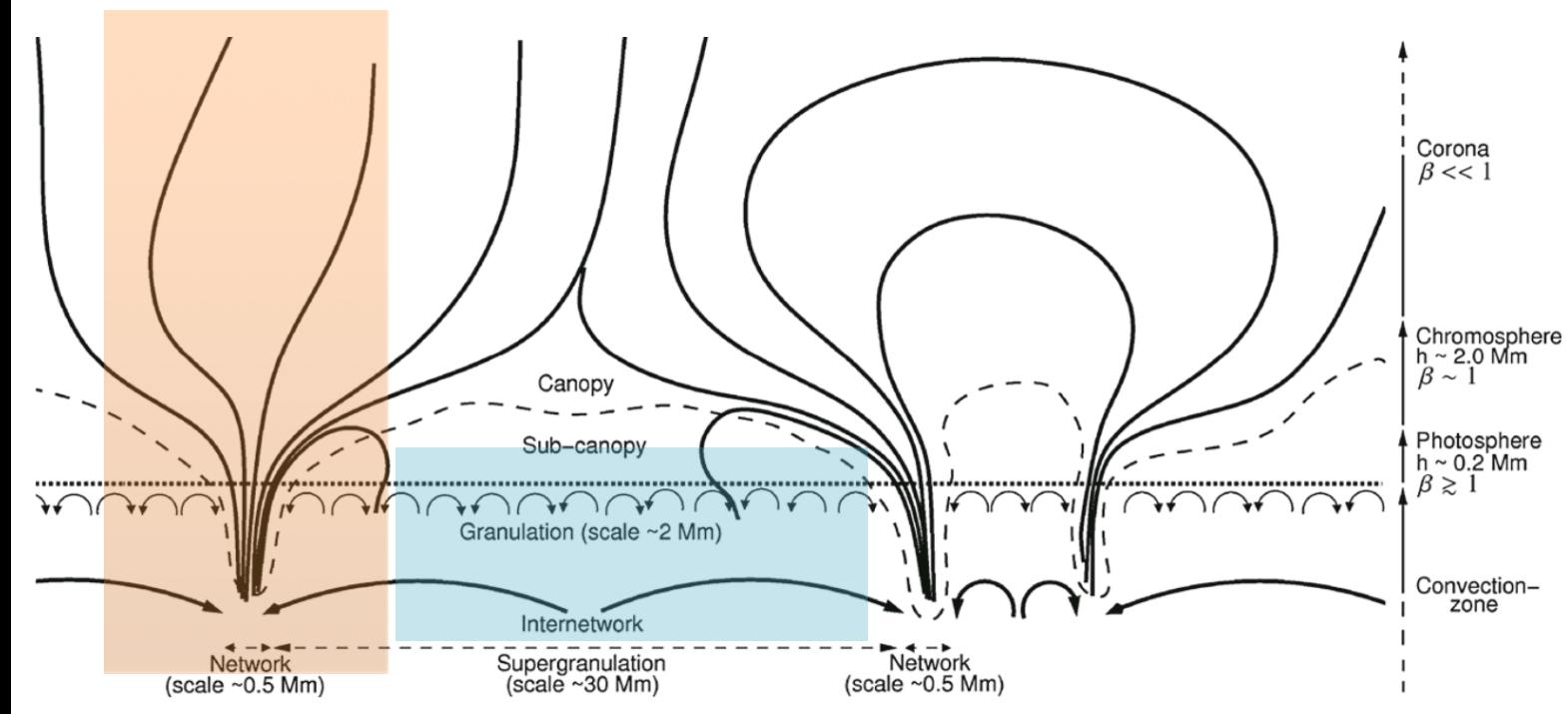
Fong, Li, KCYN, soon

Near the Solar surface

Cartoon

T. Wiegelmann et al.: The magnetic field in the solar atmosphere

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Basic considerations

- Larmor radius
 - Required to “reflect” proton

$$\frac{E}{20 \text{ TeV}} \simeq \frac{L}{R_{\odot}} \frac{B}{G} \simeq \frac{L}{10^3 \text{ km}} \frac{B}{\text{kG}}$$

- Interaction length for protons ~ 1 at
 - 600km below photosphere
 - At density $\sim 10^{-6} \text{ g/cm}^3$
- $\Rightarrow$ kG field $\sim 10^3$ km below photosphere could reflect protons and explain the HAWC TeV measurement

Whodunit



- Network flux tubes and lanes
- Plus turbulence

Li Beacom Griffith Peter APJ 2024

Li, Asgari-Targhi, Beacom, Peter APJ 2026

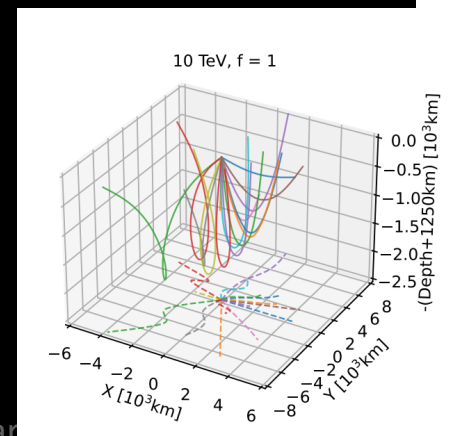
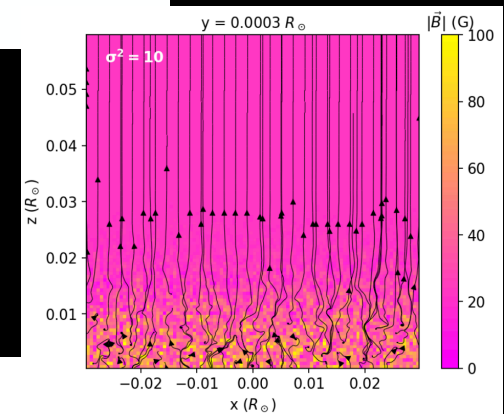
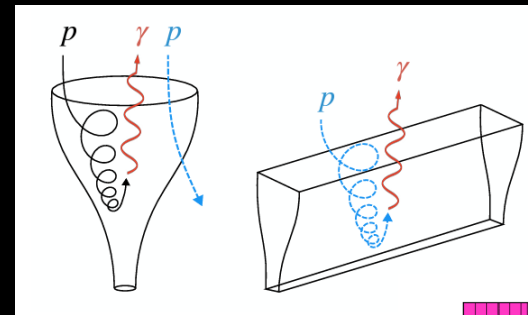
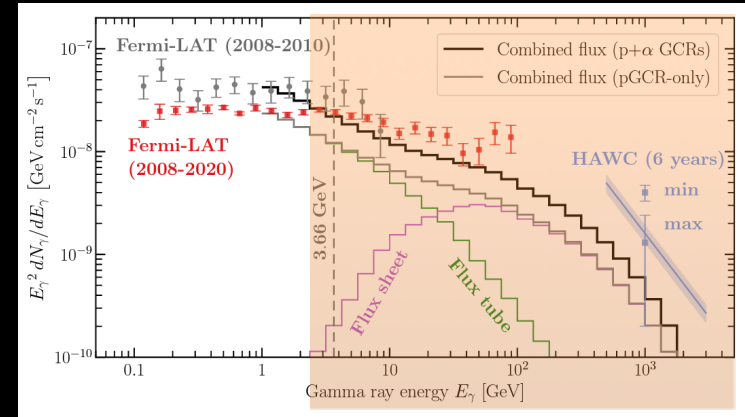
- Particle diffusion in turbulent fields

Puzzoni, Frascchetti, Kota, Giacalone APJ 2024

Puzzoni, Frascchetti, Kota, Giacalone APJL 2025

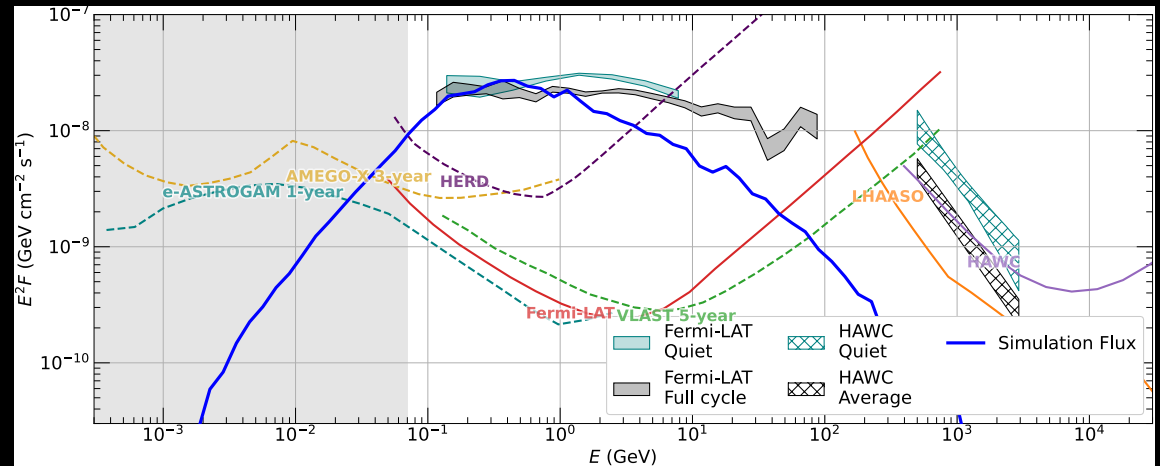
- Sub-surface horizontal fields?

- Ng, Hillier, Ando PRL 2025



What's next?

- MeV telescope
- Better TeV measurement
 - LHAASO/ SWGO
- Solar Inverse Compton Halo
- Neutrinos
- Sun shadow
- Dark matter implications
- More connection to other solar observables



What CCAPP was to me

- Great people
- Great atmosphere
- -> Interesting scientific adventures!

- | | | |
|----------------|---------------------|-------------------|
| • John Beacom | • Basudeb Dasgupta | • Ranjan Laha |
| • Annika Peter | • Shunsaku Horiuchi | • Eric Speckhard |
| | • Sheldon Campbell | • Bei Zhou |
| | • Jennifer Gaskins | • Chris Cappiello |
| | • Carsten Rott | |
| | • Tim Linden | |

CCAPP's 20th Anniversary Conference



THE COSMIC CONTINUUM

Celebrating Two Decades of Discovery in Cosmology and AstroParticle Physics

JUNE 10 - 12, 2026
THE OHIO STATE UNIVERSITY
COLUMBUS, OHIO

- Congratulations and happy anniversary!