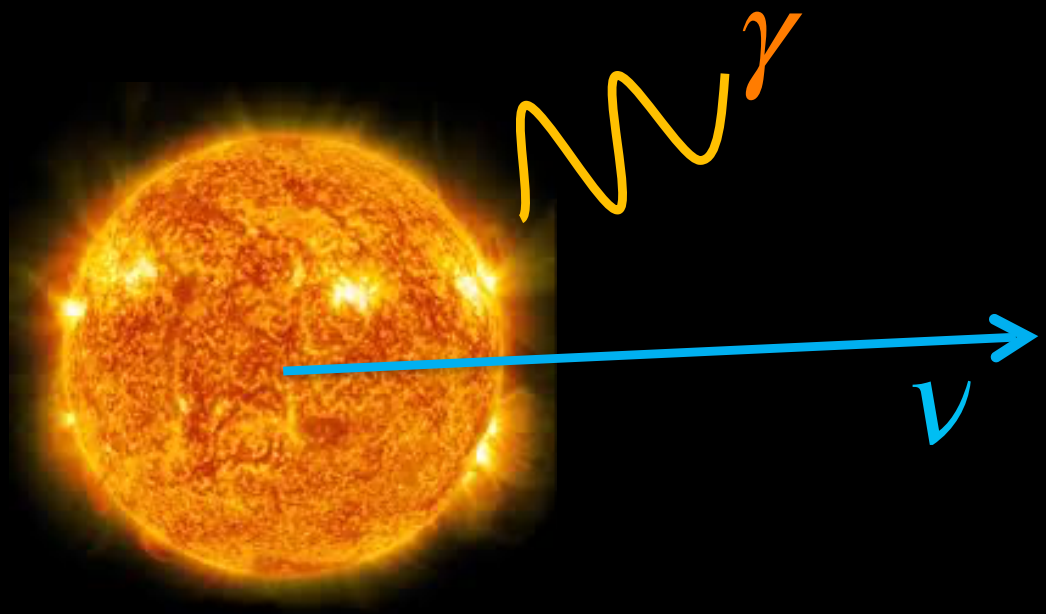
The High-Energy Astrophysics of the Sun

Multi-messenger



Kenny, Chun Yu Ng (吳震宇)

The Chinese University of Hong Kong

The Sun as a high-energy source

CR electrons

Inverse-Compton

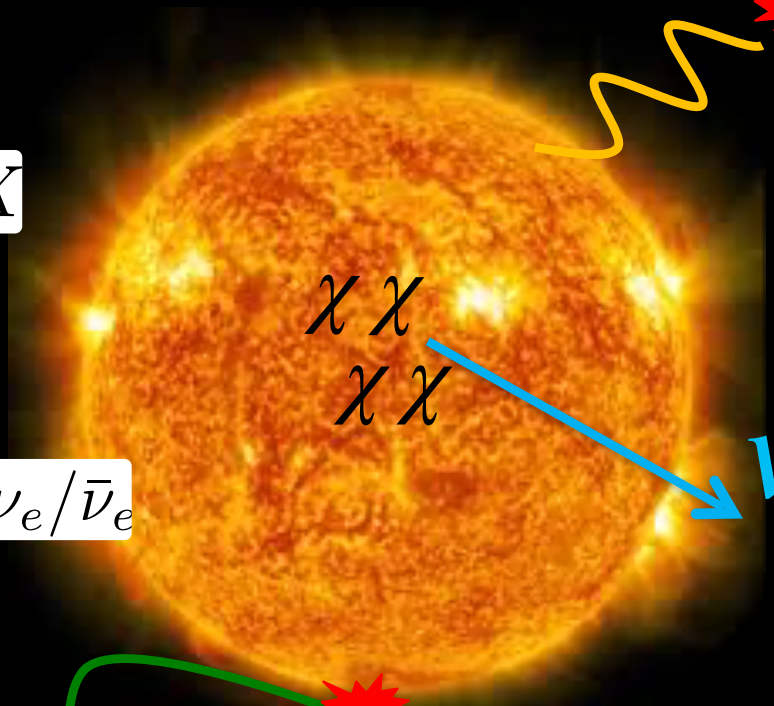
Moskalenko, Porter, Digel 2006
Orlando, Strong 2007
Zhou et al 2017
Yang et al 2023

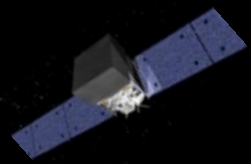
$$p + p \rightarrow \pi^0/\pi^\pm + X$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu/\nu_\mu + \nu_e/\bar{\nu}_e$$

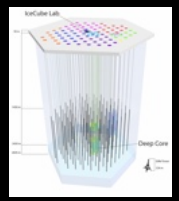
Seckel, Stanev, Gaisser (1991)

CR protons

Hadronic





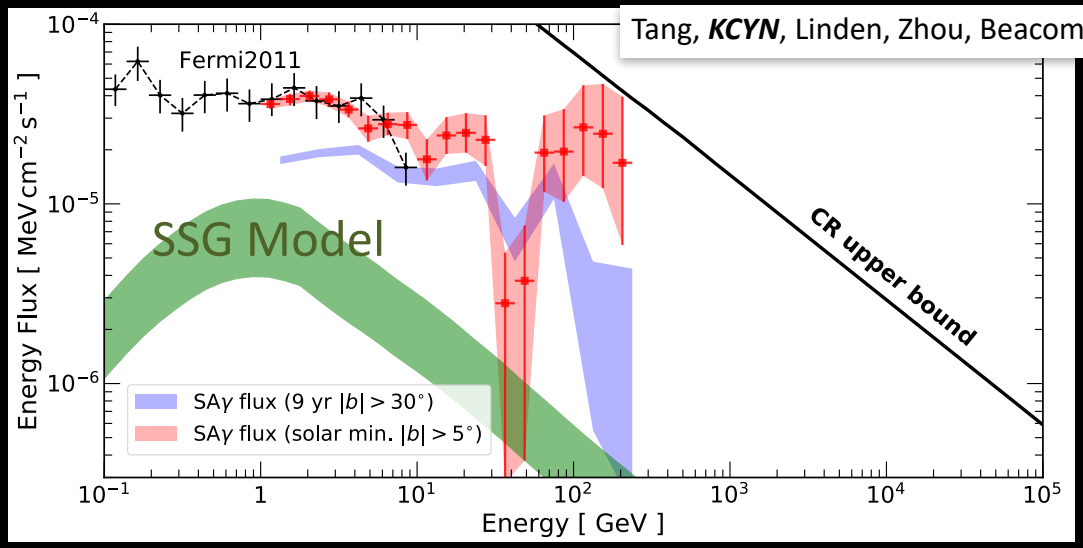


Observation: Energy Spectrum

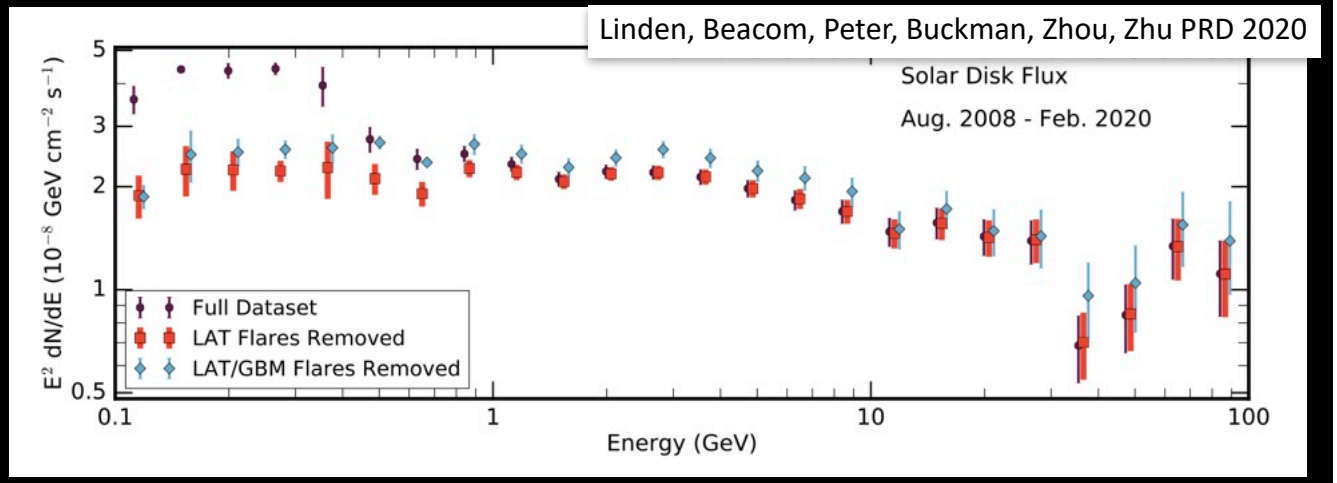
- Without magnetic fields, cosmic rays convert into gamma rays ~ 0.1% efficiency
  - Rest absorbed by Sun
- SSG (1991) ~ 1% CR
- Fermi Data about 5-50 %

Magnetic Effects are Crucial

- Hard spectrum up to 100 GeV
  - $\sim E^{-2.2}$



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



Linden, Beacom, Peter, Buckman, Zhou, Zhu PRD 2020

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

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

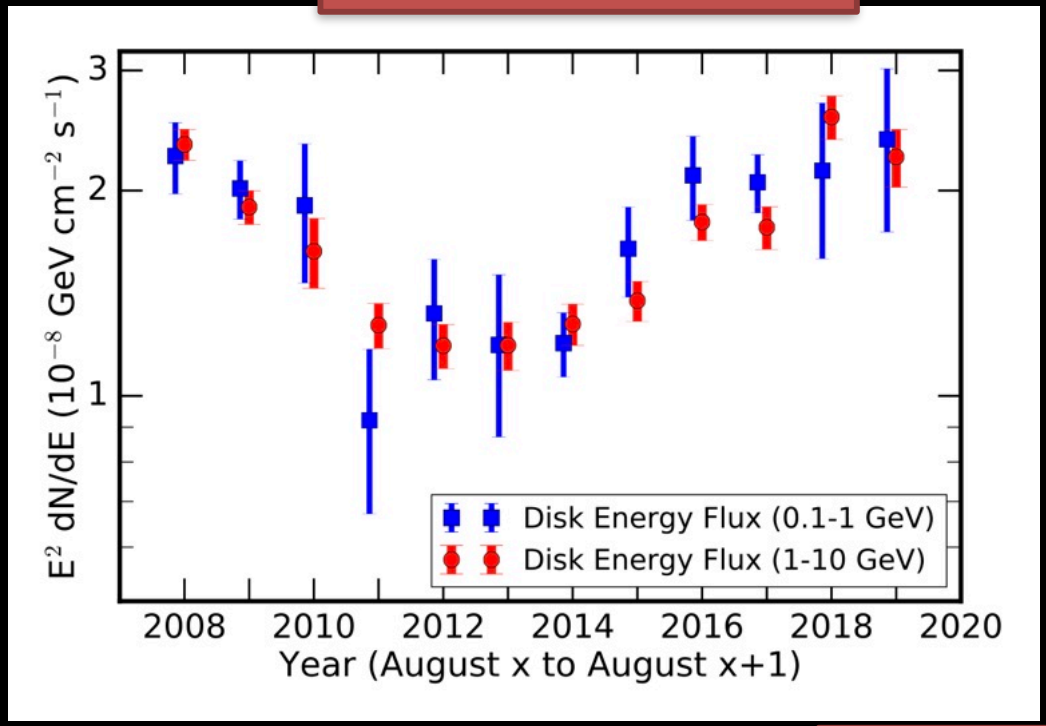
Magnetic Efficiency factor

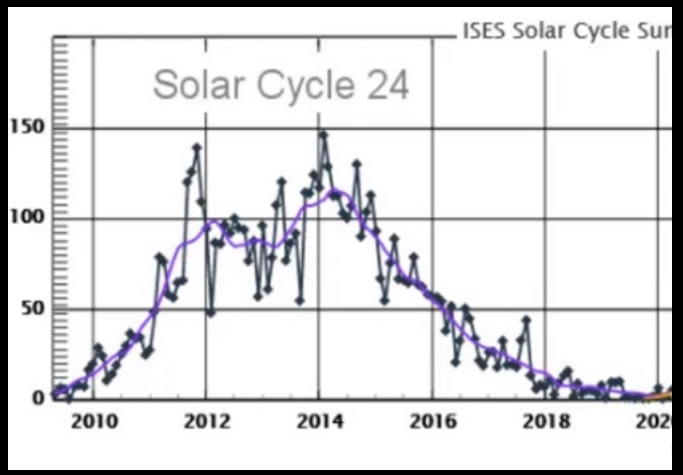
Time variation

KCYN et al PRD 2016
Tang et al PRD 2018
Linden et al PRD 2020

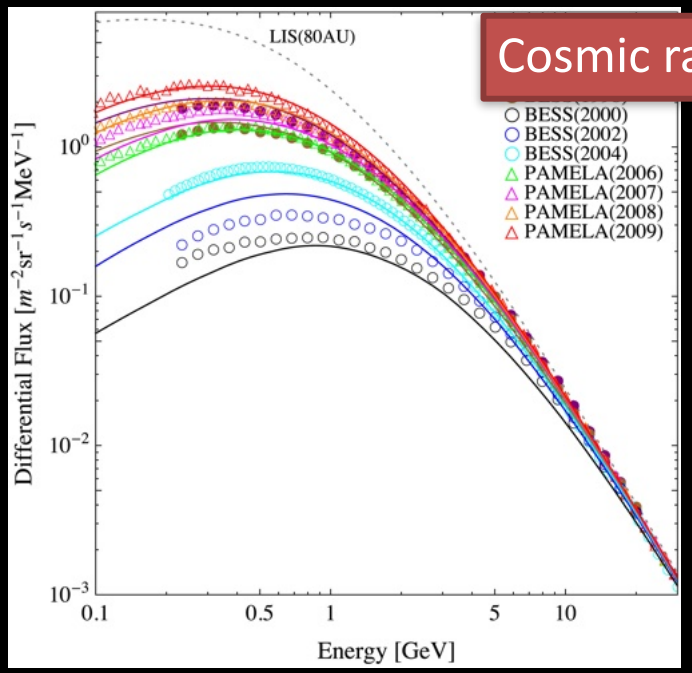
- Clear anticorrelation with solar activity from 0.1-1 GeV and 1-10 GeV
- Less clear in 10-100 GeV (less variation or insufficient statistics)

Gamma ray modulation





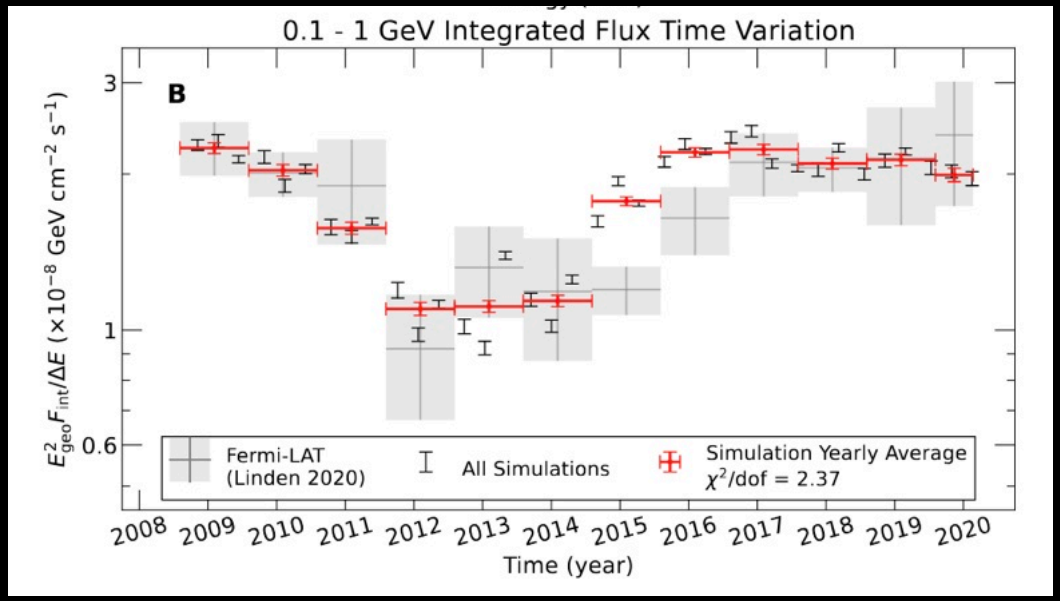
Cosmic ray data

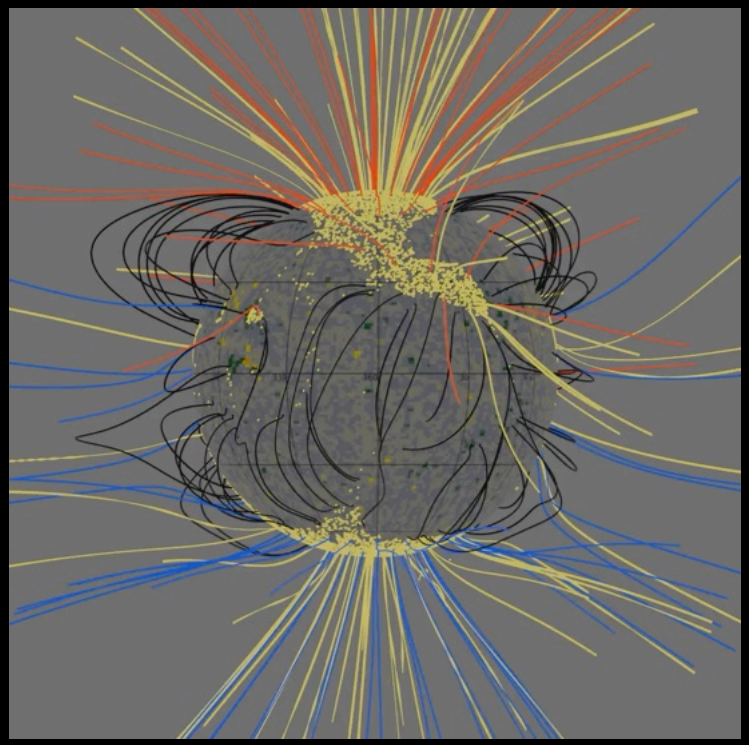


Not energy sensitive?

$E_\gamma \sim 0.1 E_p$

GeV time variation can be explained by coronal fields





- Solar modulation contributes to only ~ 1.3 in flux amplitude
- Adding coronal fields makes it a factor of ~ 2.5
  - Flux $\propto$ Open magnetic field area on the surface
- Both Flux Amplitude and Time-variation are explained at 0.1-1GeV
  - Coronal field too weak to affect E_γ > 1 GeV production

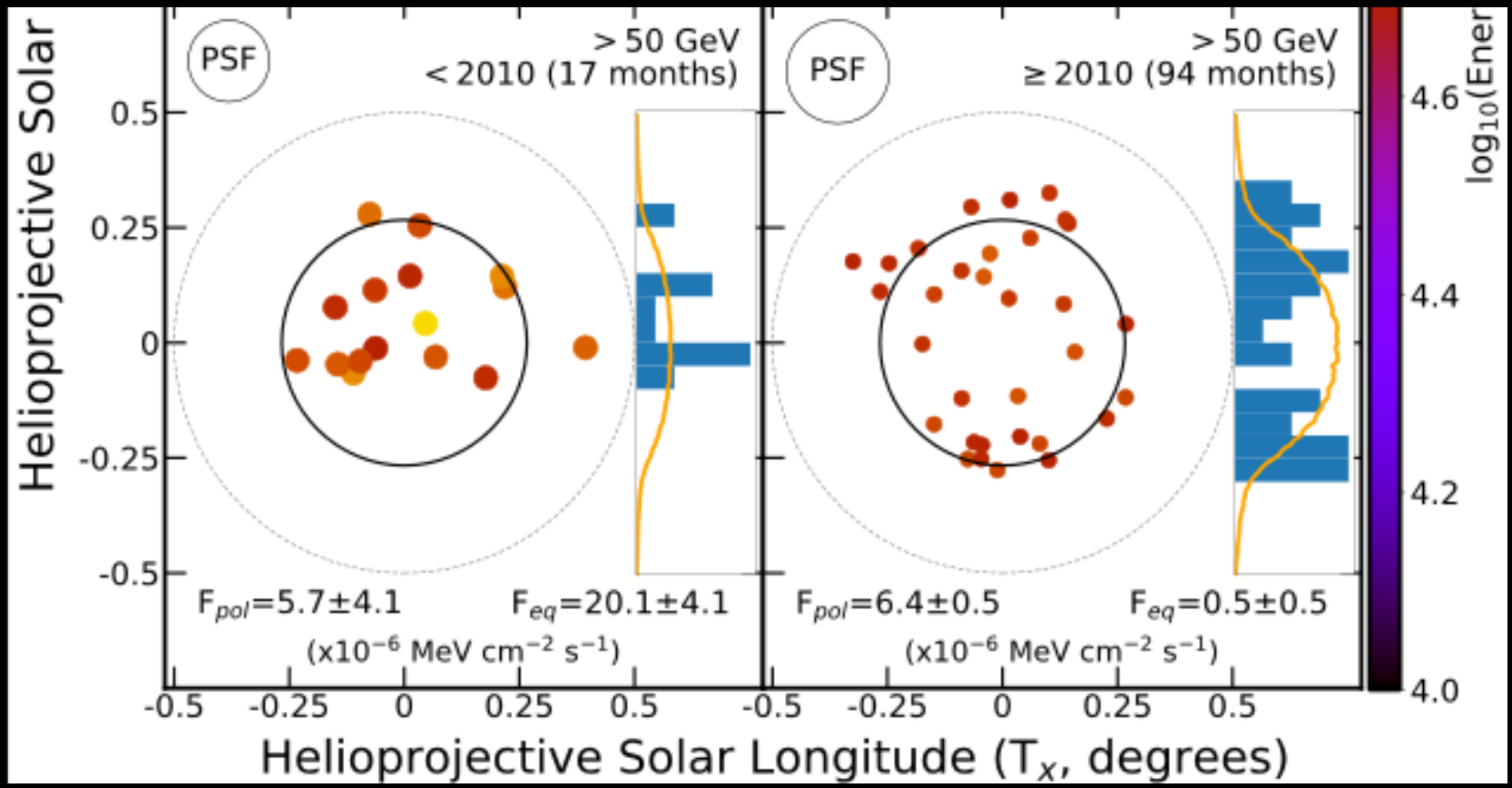
Coronal Magnetic Field Modulates GeV Solar Disk Gamma Rays
Fong, Li, KCYN, appear soon. WED CR5 Session

Chingam Fong

Morphology, *surprise!*

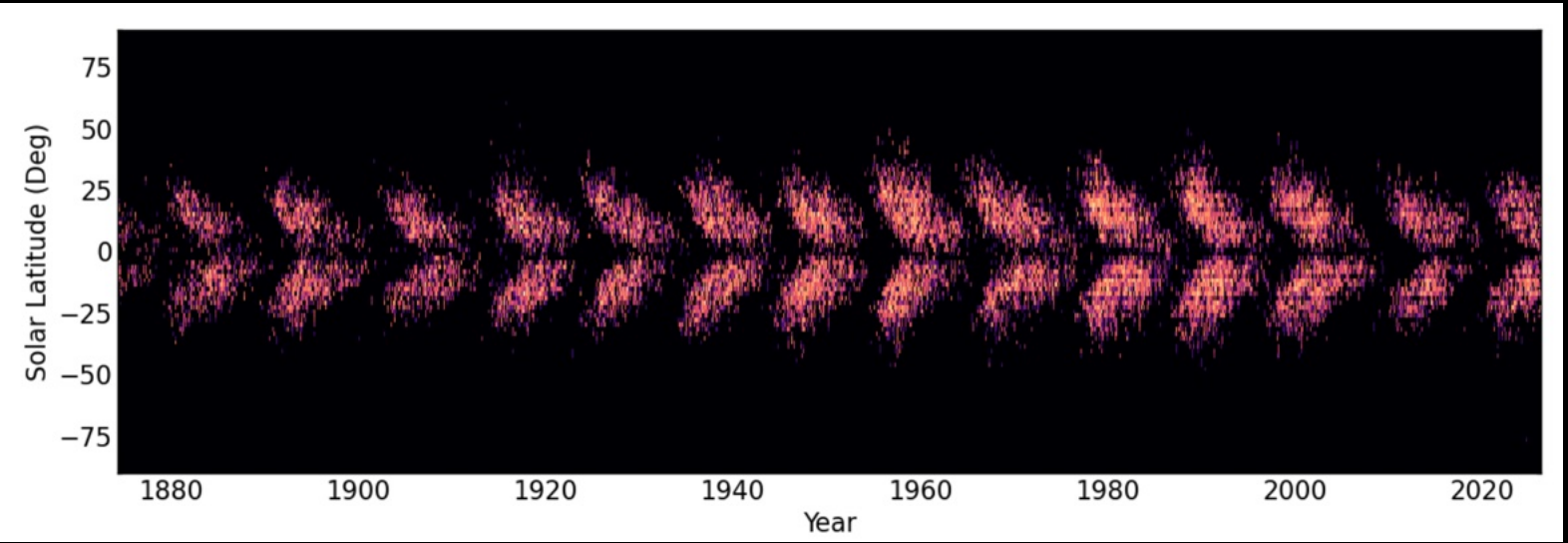
Linden, Zhou, Beacom, Peter, KCYN, Tang
PRL 2018

- High Energy Bin(> 50 GeV)
- Quiet phase: equatorial component dominant
- Active phase: polar component dominant



The Anti-Butterfly Effect?

- It is known that Sunspots moves from higher latitudes (quiet) towards equator (active)

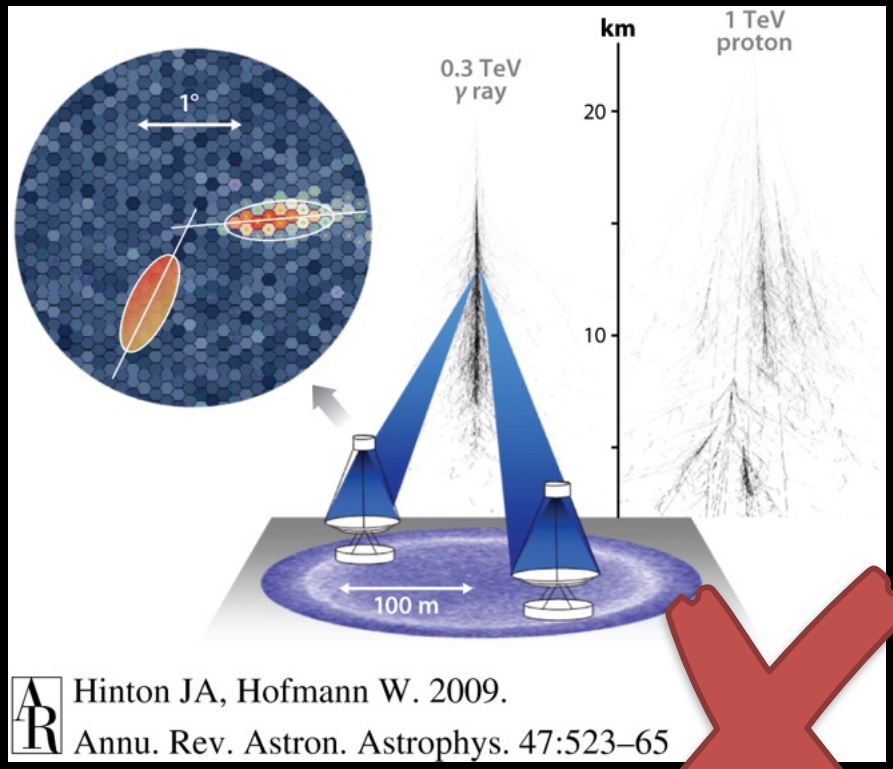


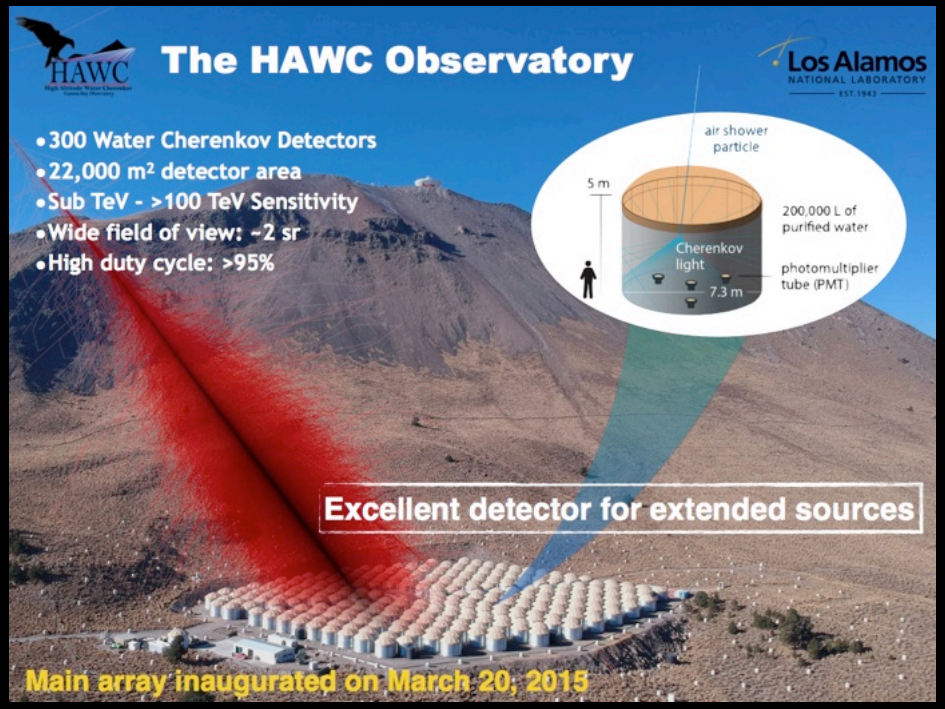
- The > 50 GeV photon distribution seems to Anti-correlate with the Sunspots

The Butterfly effect? Comparison of the morphology of high-energy Fermi-LAT events against sunspots
Kristy Fu, KCYN, soon. WED GR5 Session

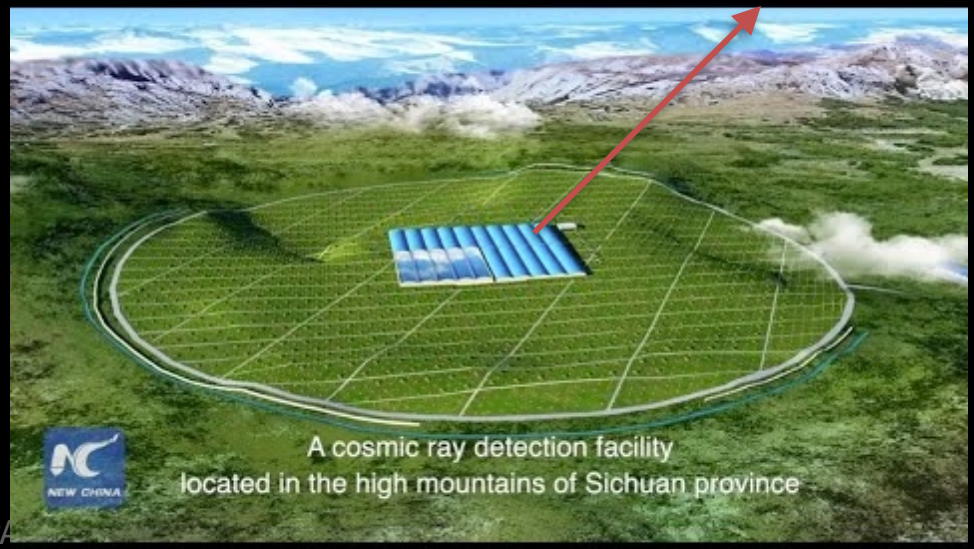
Kristy Fu

TeV observation of the Sun



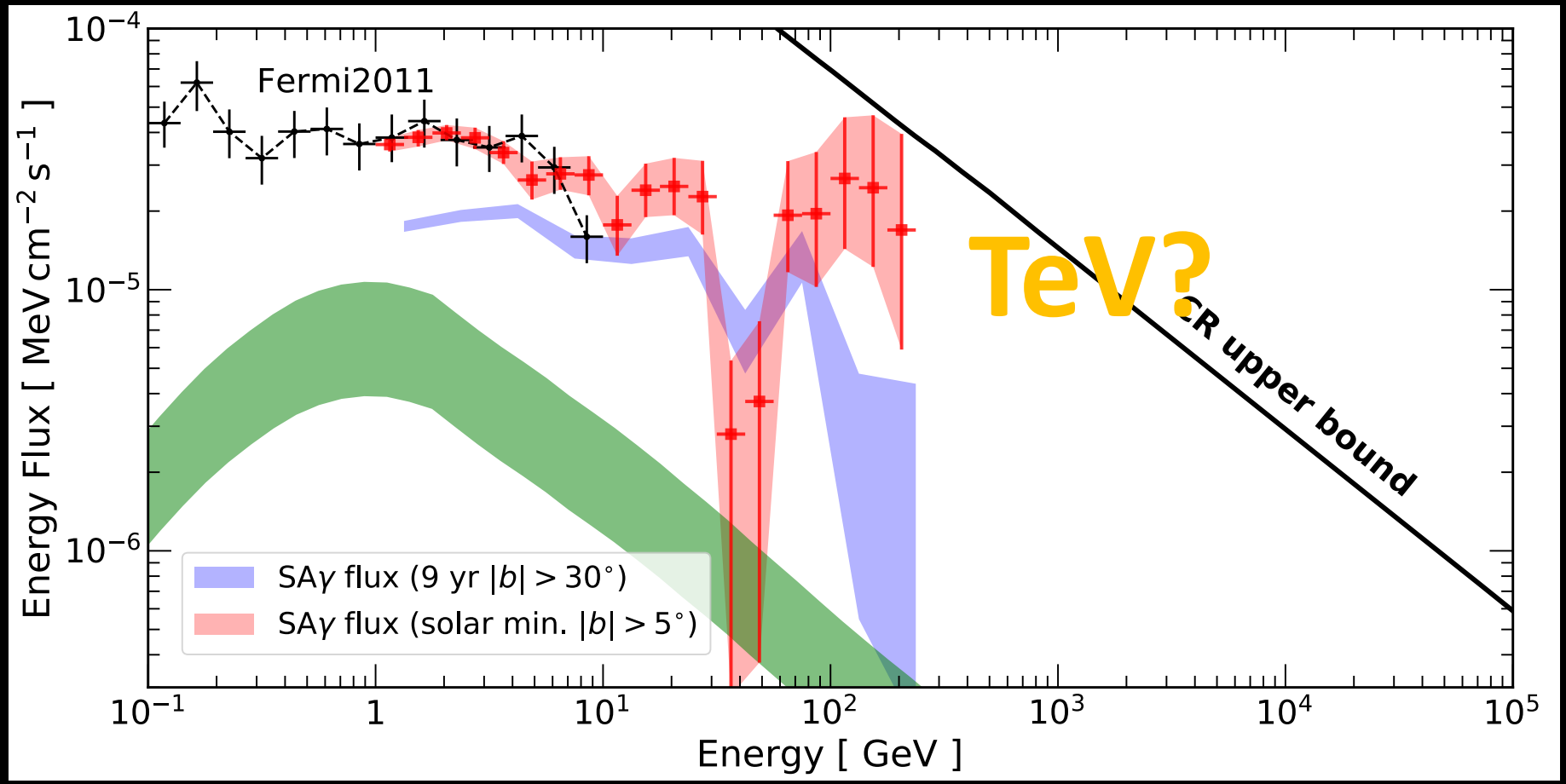


4X HAWC

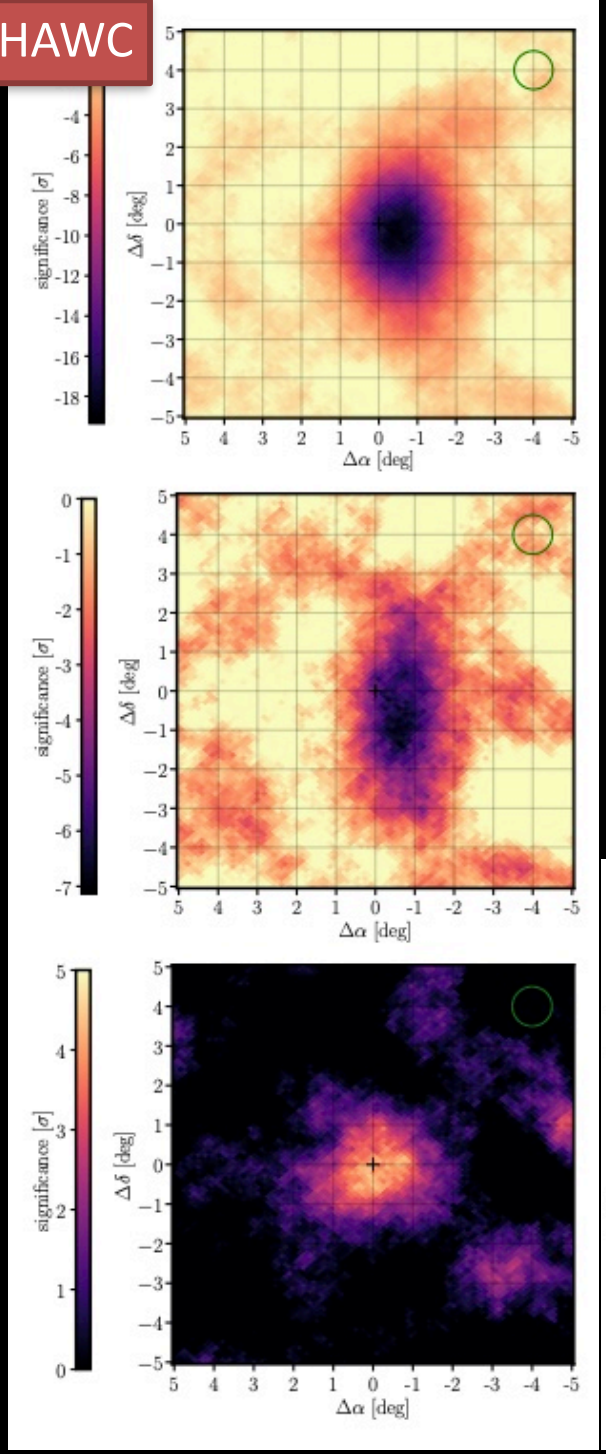


Air Shower Observatories (HAWC, LHAASO, SWGO) have the unique capability for observing the Sun

Solar Gamma Spectrum



HAWC



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

Phys.Rev.Lett. 131 (2023) 5, 051201
HAWC col. + KCYN

Data towards the Sun: Sun-shadow Deficit due to CR absorption by Sun

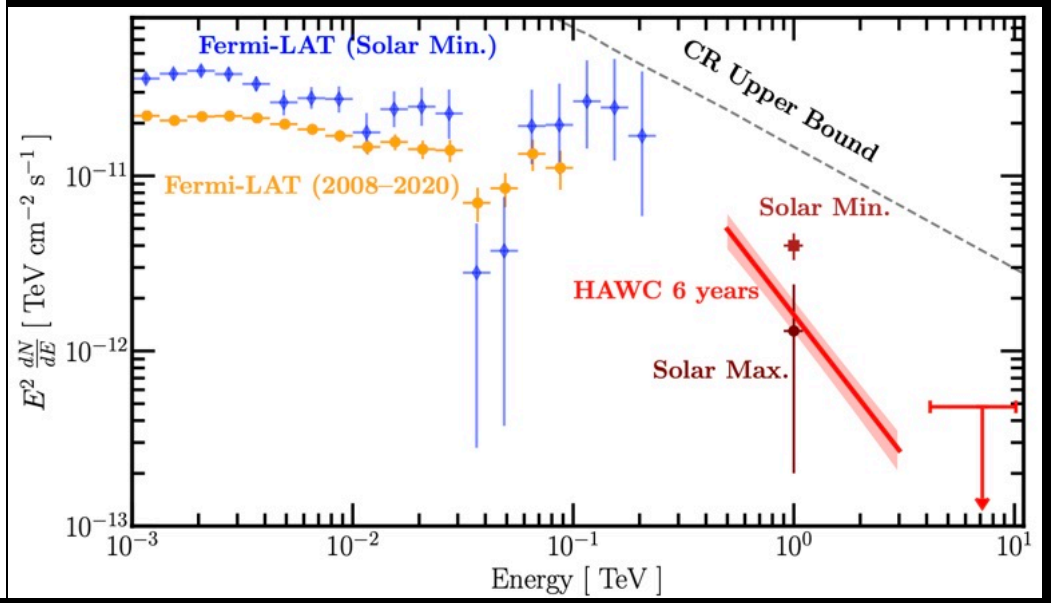
Apply γ-Hadron separation algorithm

A shadow remains

vs

Theoretical Shadow model after γ-Hadron separation

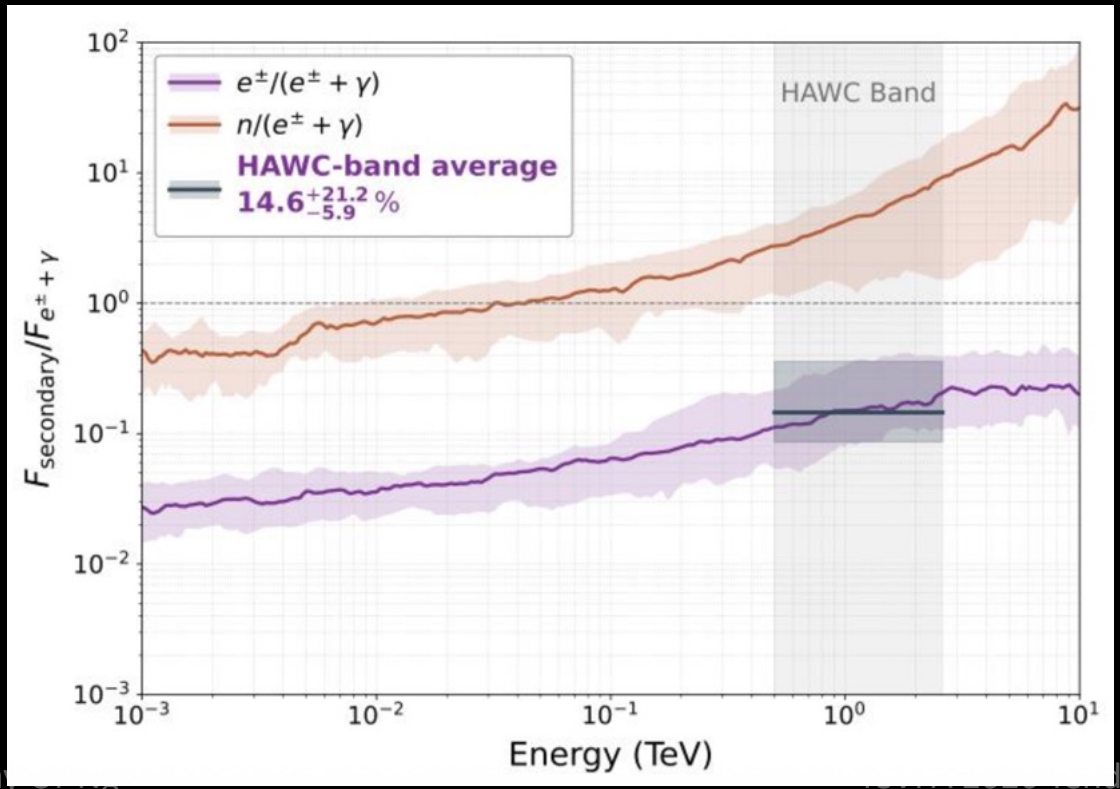
Hadron-only hypothesis



- 6.3σ detection
- Spectral change $\sim E^{-3.6}$

TeV contributions from electrons/positrons?

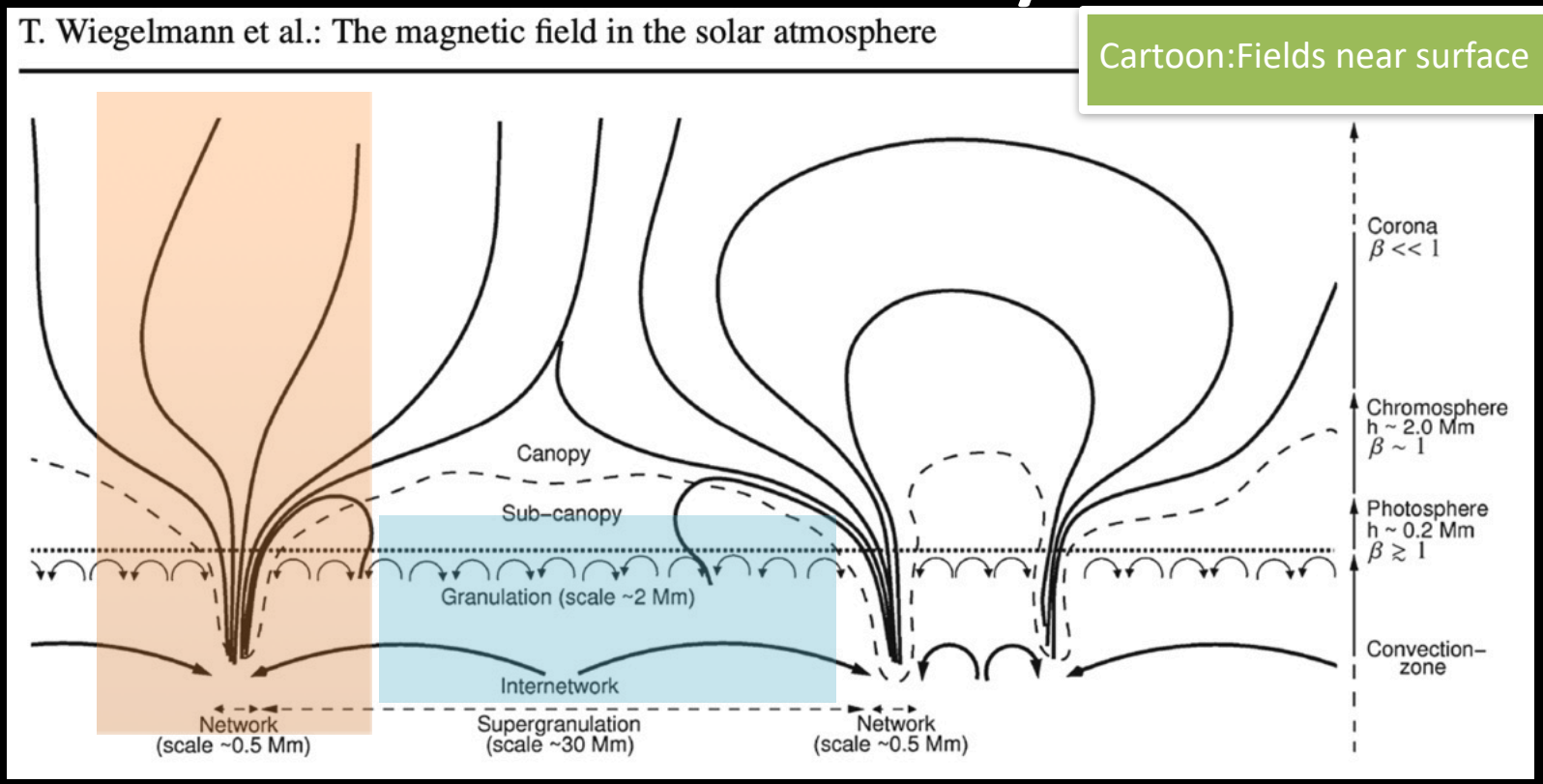
- It is very difficult to distinguish electrons/positrons for air shower arrays.
- HAWC results should have some contamination from $e^{\pm}$
- We estimated $\sim 15\,\%$
- But neutron flux can be even higher than the gamma flux!

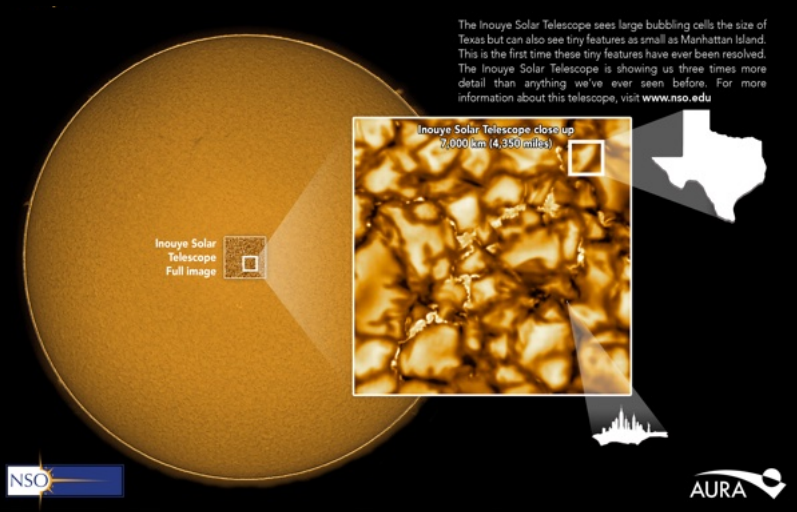


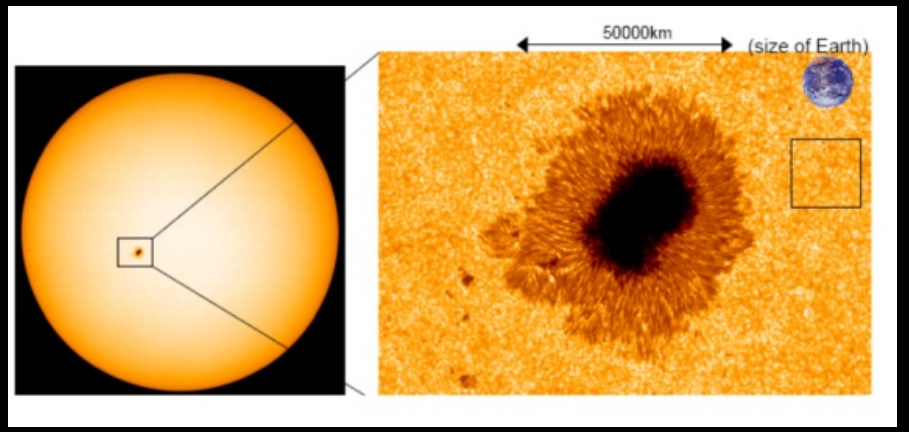
Secondary Electron-Positron Pairs as a Key Component of the Solar Disk TeV Emission
Cao, Fong, Li, KCYN, in prep
WED GR5 Session

Wenyu Cao

TeV: theory


T. Wiegelmann et al.: The magnetic field in the solar atmosphere
Cartoon:Fields near surface
Corona
$\beta << 1$
Chromosphere
h ~ 2.0 Mm
$\beta \sim 1$
Photosphere
h ~ 0.2 Mm
$\beta \gtrsim 1$
Convection–zone
Canopy
Sub–canopy
Granulation (scale ~2 Mm)
Internetwork
Network
(scale ~0.5 Mm)
Supergranulation
(scale ~30 Mm)
Network
(scale ~0.5 Mm)


The Inouye Solar Telescope sees large bubbling cells the size of Texas but can also see tiny features as small as Manhattan Island. This is the first time these tiny features have ever been resolved. The Inouye Solar Telescope is showing us three times more detail than anything we've ever seen before. For more information about this telescope, visit www.nso.edu
Inouye Solar Telescope close up
7,000 km (4,350 miles)
Inouye Solar Telescope Full image
NSO
AURA


50000km
(size of Earth)

Basic considerations

- Larmor radius
  - Required to “reflect” proton

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

- Interaction length for protons ~ 1 at
  - 600km below photosphere
  - At density ~ $10^{-6} g/cm^3$

- => kG field ~$10^3\,\mathrm{km}$ below photosphere could reflect protons and explain the HAWC TeV measurement

TeV: Whodunit

- Network flux tubes and lanes
  - Plus turbulence

  Li Beacom Griffith Peter APJ 2024

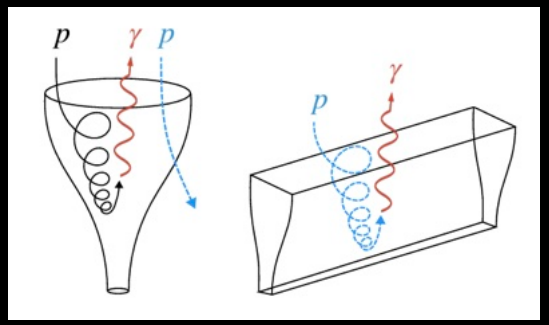
  Li, Asgari-Targhi, Beacom, Peter APJ
- Particle diffusion in turbulent fields

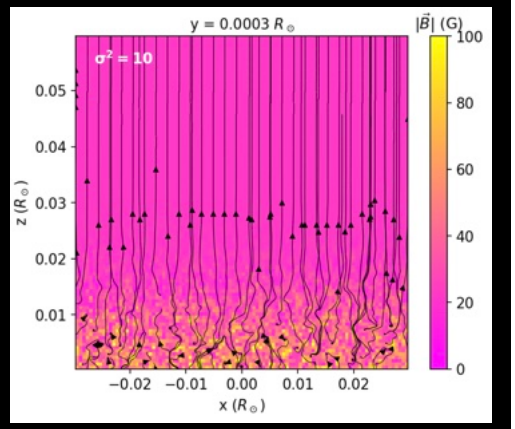
  Puzzoni, Fraschetti, Kota, Giacalone APJ 2024

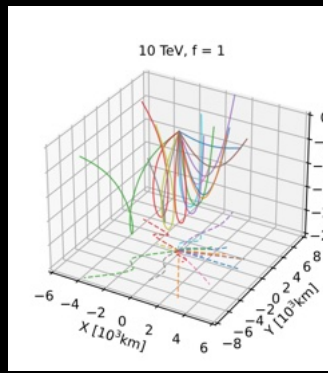
  Puzzoni, Fraschetti, Kota, Giacalone APJL 2025
- Sub-surface horizontal fields?
  - Horizontal fields are efficient in reflecting cosmic rays

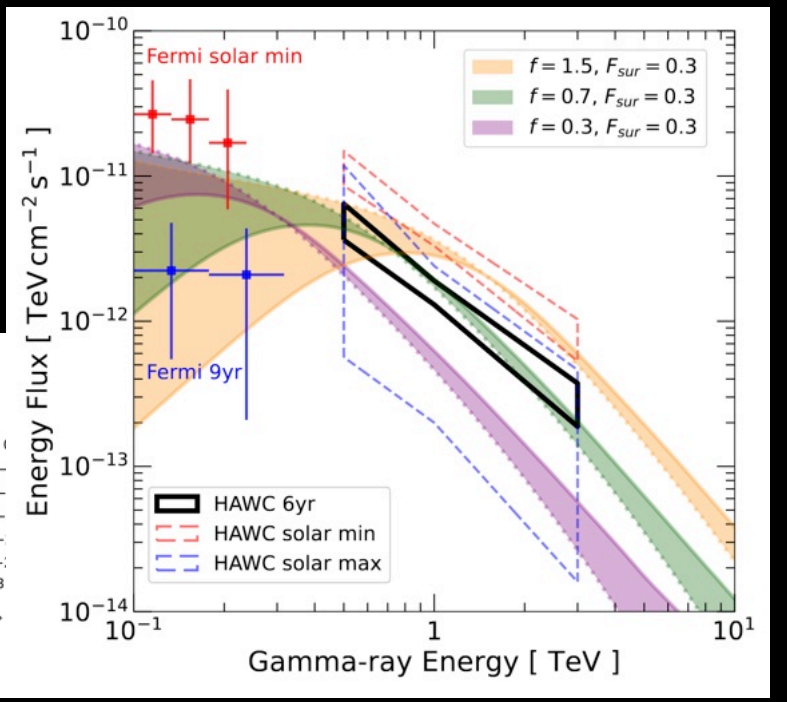
    Ng, Hillier, Ando PRL 2025
  - Horizontal B-fields dominates the quiet Sun?

    e.g.
    Lites et al 2008
    Campbell et al 2026

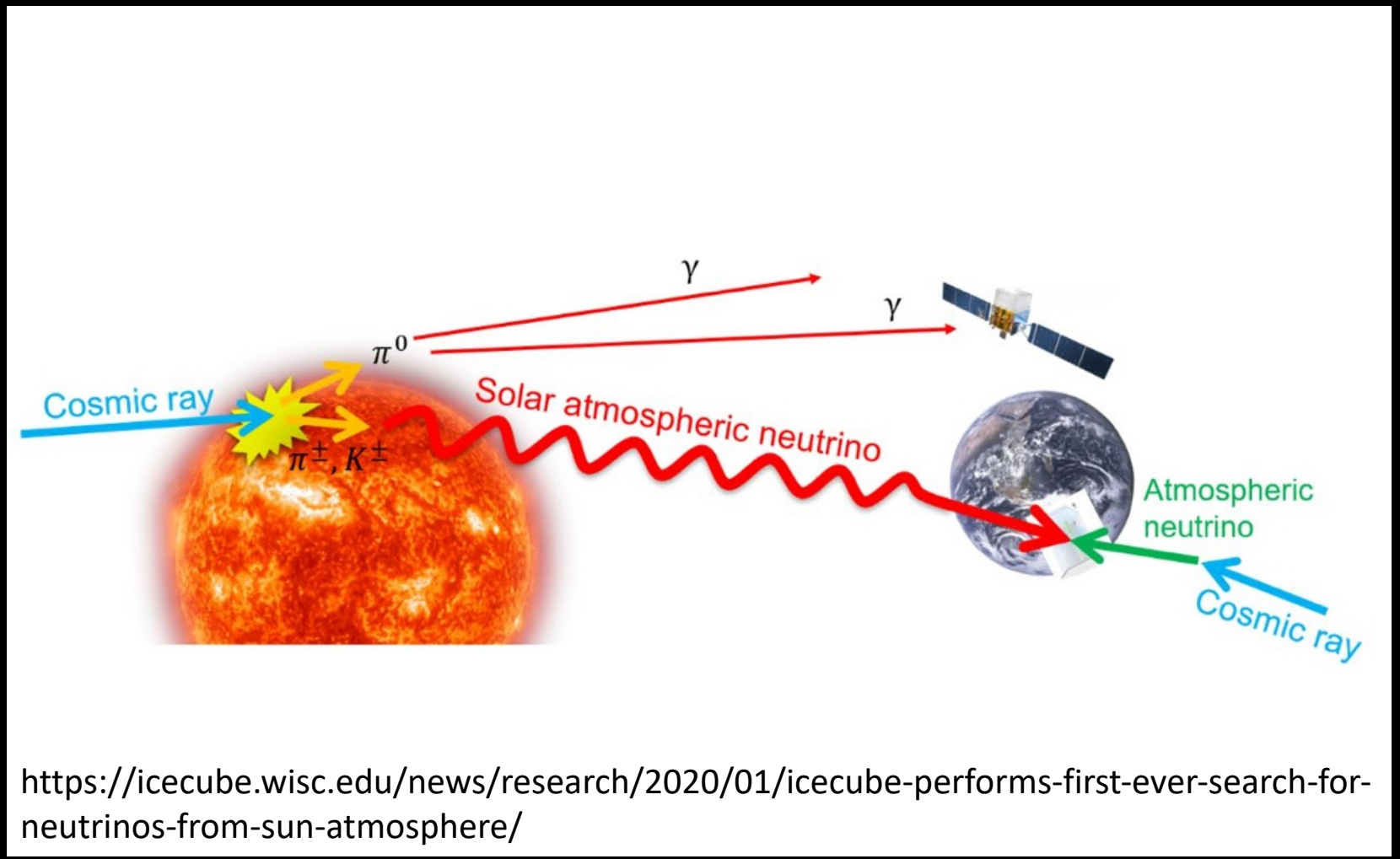






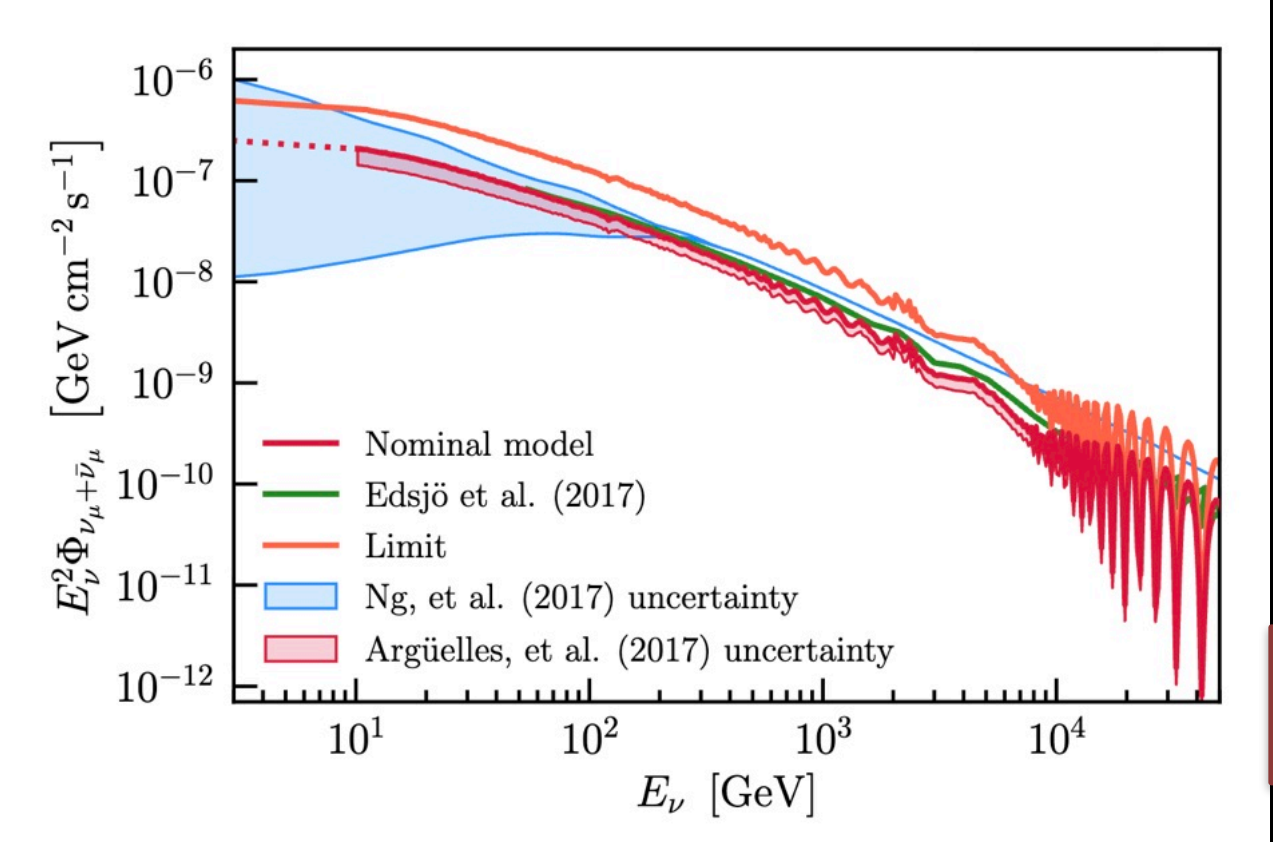


Solar Atmospheric Neutrinos



https://icecube.wisc.edu/news/research/2020/01/icecube-performs-first-ever-search-for-neutrinos-from-sun-atmosphere/

IceCube Search update(2507.08457)



Sun Shadow (of neutrinos) not taken into account!

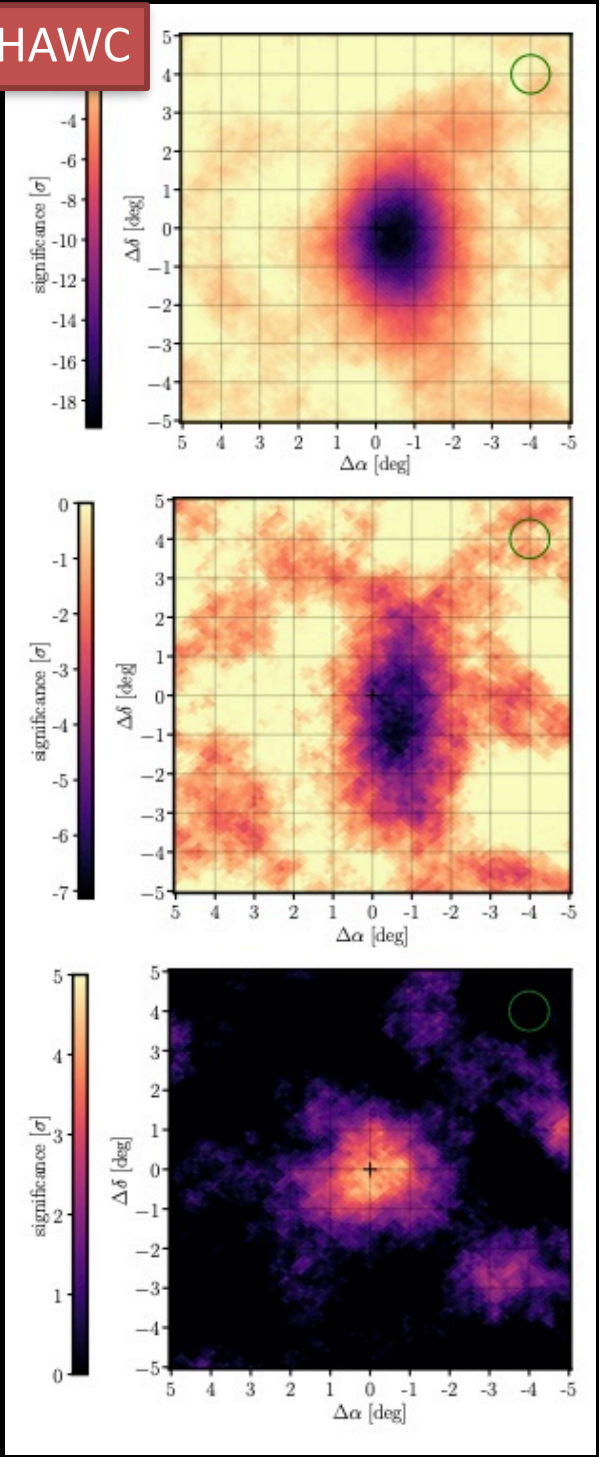
- Limit is about a factor of 2 from nominal flux
- Neutrino flux at TeV are robust wrt B-fields

Solar Atmospheric Neutrinos:
A Simulation-Based Flux Calculation with Solar Magnetic Field and Neutrino Propagation
Ma, KCYN, Fong, Li, in prep
WED NU4 session

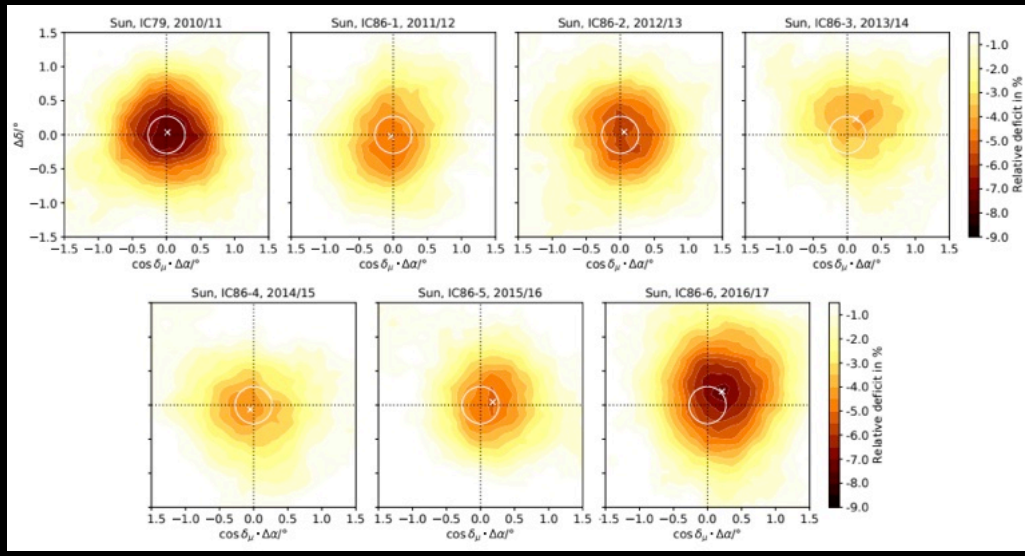
Jimmy Ma

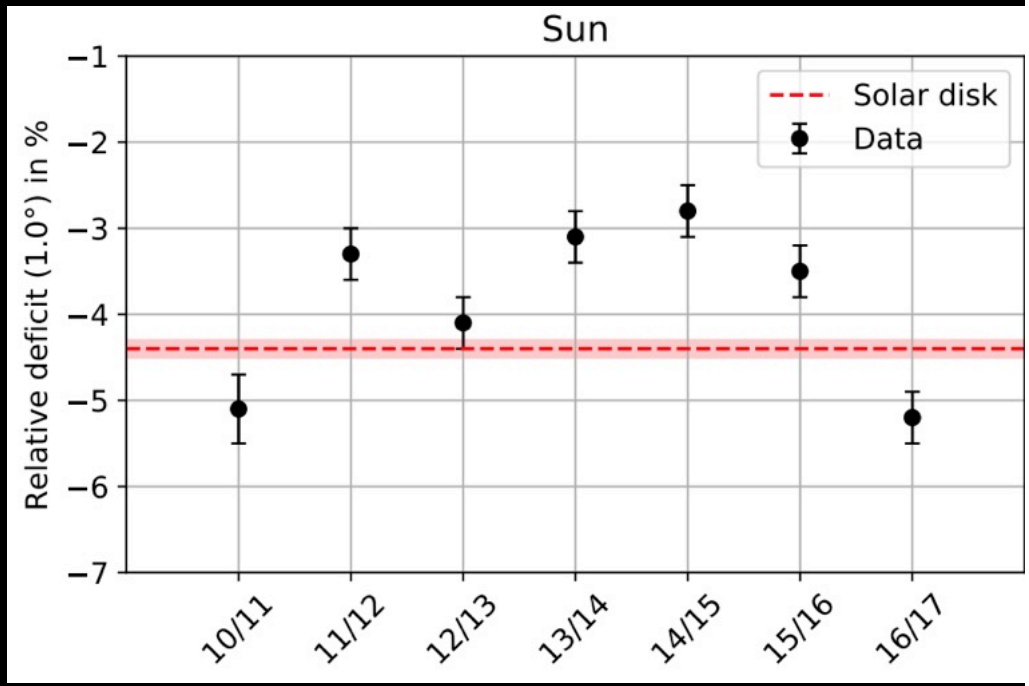
Atmospheric Muon Shadow

HAWC



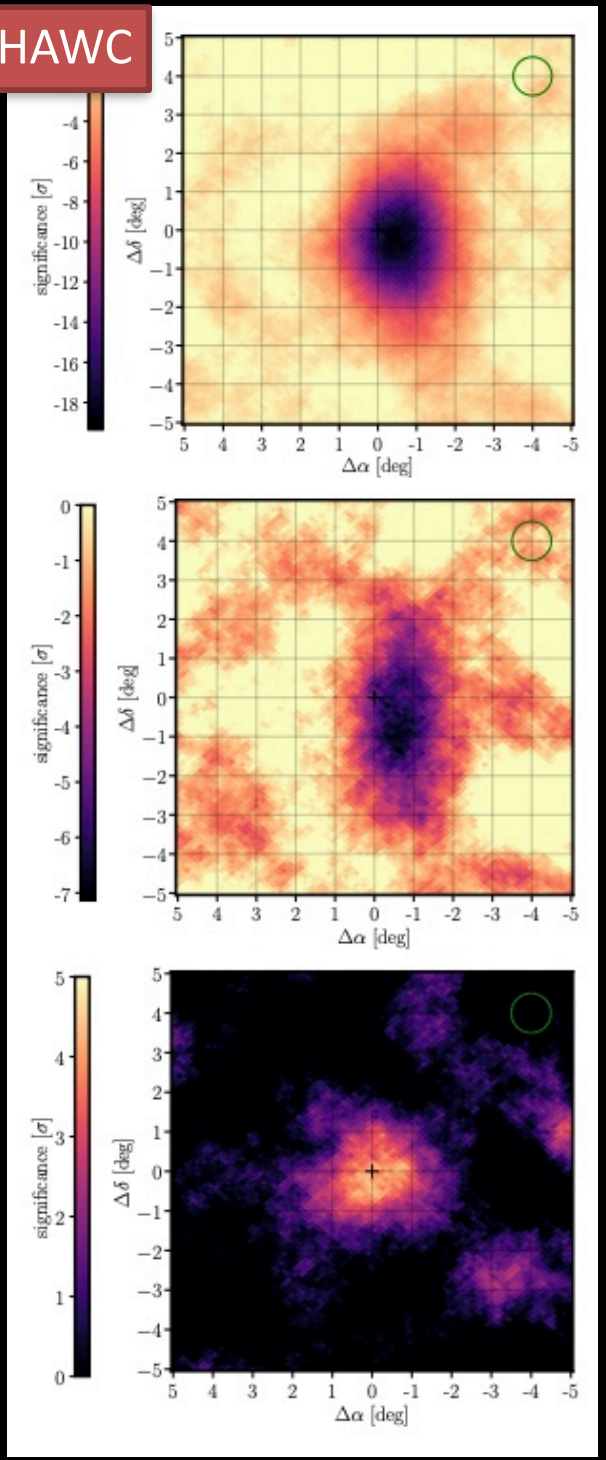
IceCube Phys. Rev. D **103**, 042005



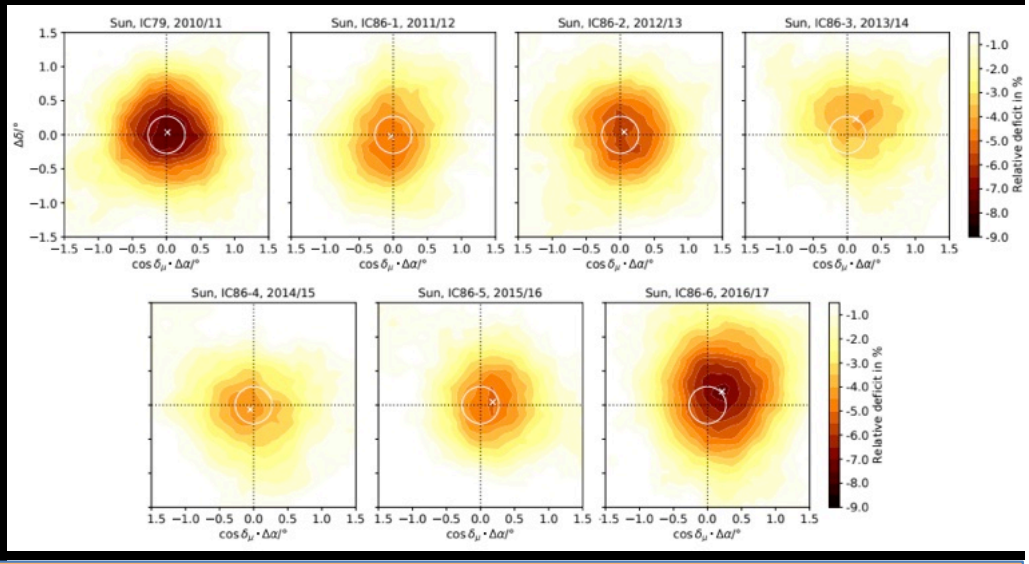


Atmospheric Muon Shadow

HAWC



IceCube Phys. Rev. D **103**, 042005



There must also a Atmospheric Neutrino shadow associated with the Muon shadow

- Earth ATM neutrino shadow not yet detected
  - Perhaps not yet searched?

- Just like HAWC/LHAASO analysis, signal/excess could be hiding in the shadow

Conclusion

- Multi-messenger astrophysics of the Sun (>100 MeV) is rich in physics and phenomenology
- GeV gamma rays are sensitive to large-scale B-fields
- TeV gamma rays could be unique probe to strong B-field regions that are optically obscured.

- TeV Neutrino detections maybe possible already?!

Thanks!

The works of the CUHK group are supported by Croucher foundation, RGC grants (24302721,14305822, 14308023), NSFC/ RGC joint research scheme(N CUHK456/22), NSFC grant 12322517, and various CUHK internal grants.