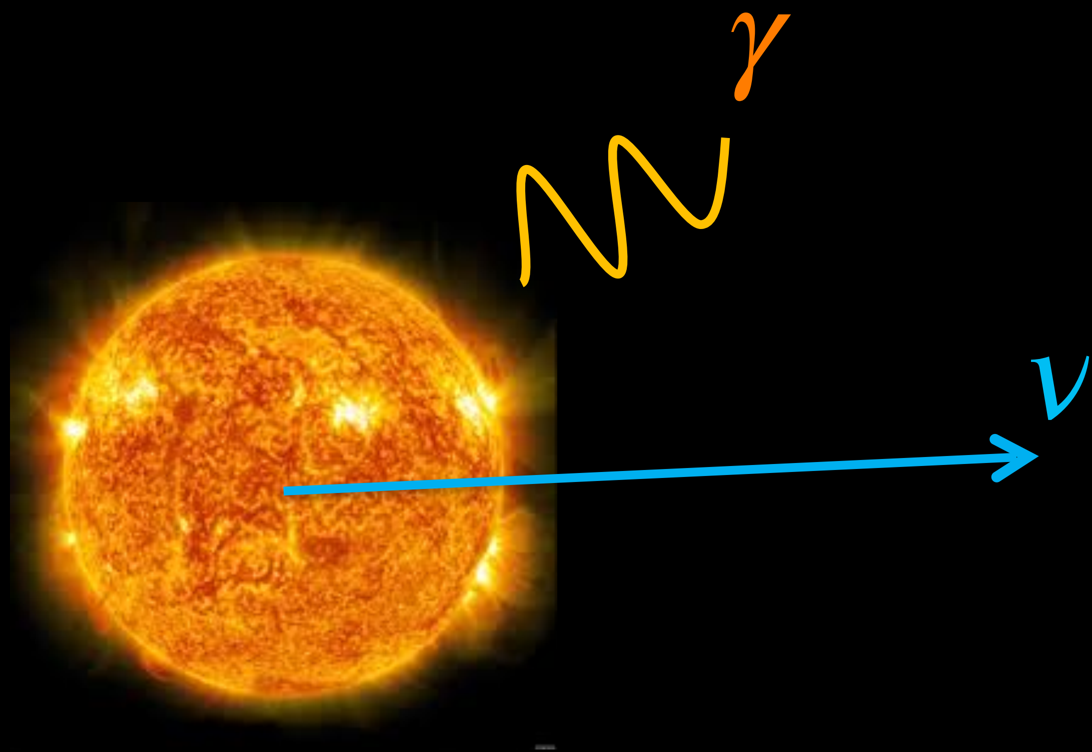
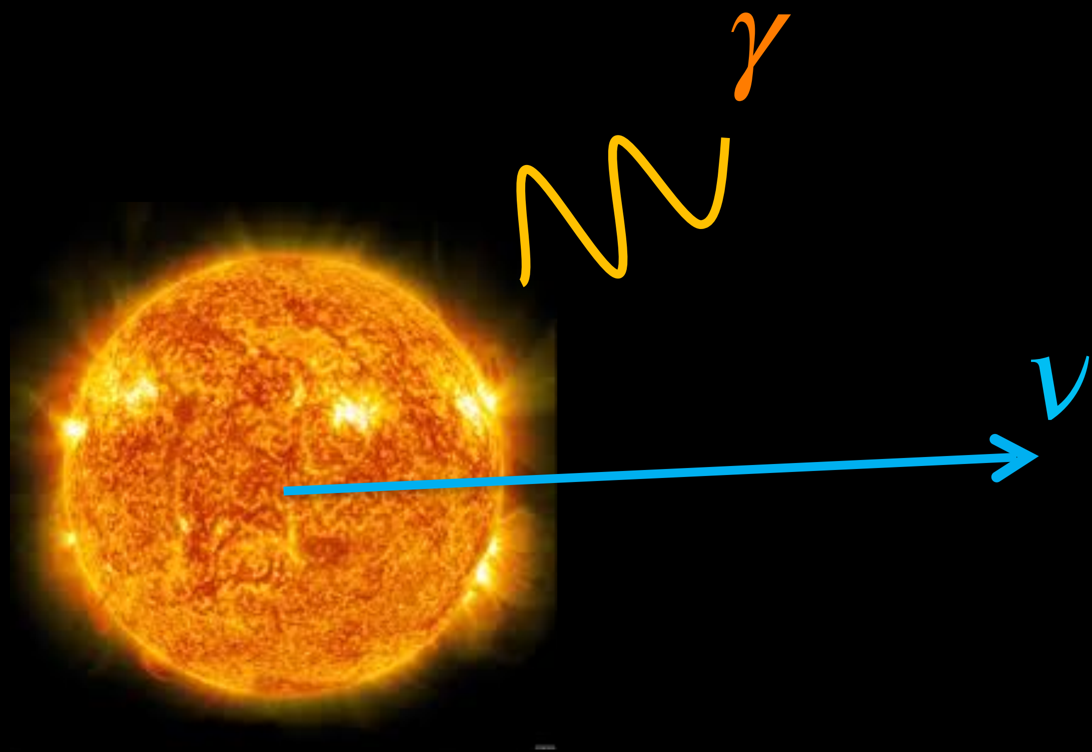
The TeV Astrophysics of the Sun



TAUP 2025
19TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS
XICHANG, SICHUAN, CHINA 2025.8.24 - 8.30

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

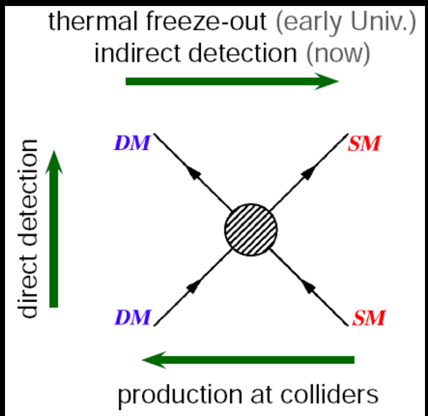
The Sun as a VHE neutrino source

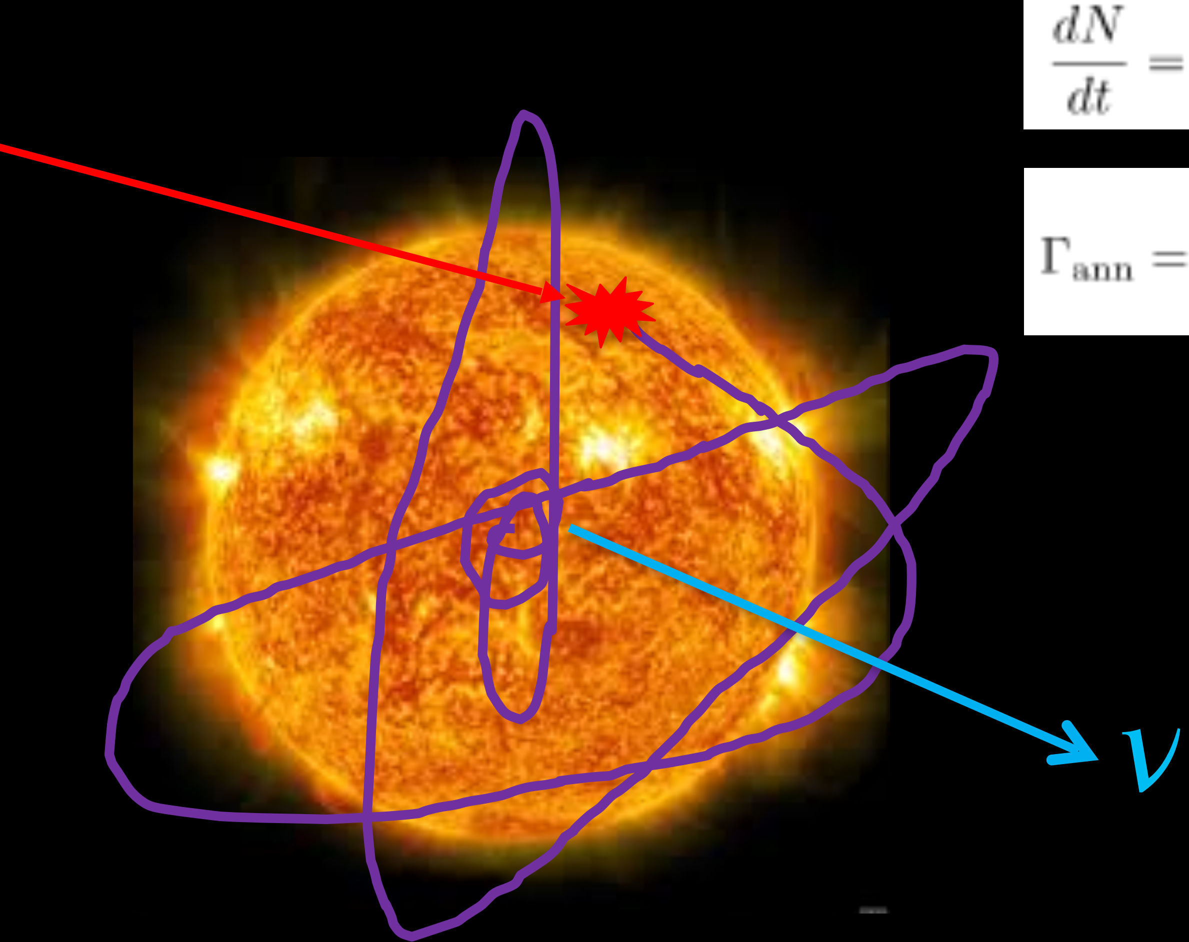


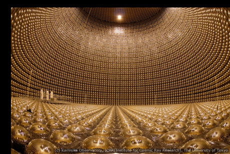
Sun – Dark Matter detector

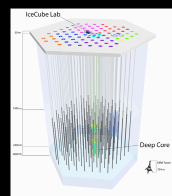
$$\frac{dN}{dt} = \Gamma_{\rm cap} - C_{\rm ann} N^2$$

$$\Gamma_{\rm ann} = \frac{1}{2} C_{\rm ann} N^2 = \frac{1}{2}\Gamma_{\rm cap}$$







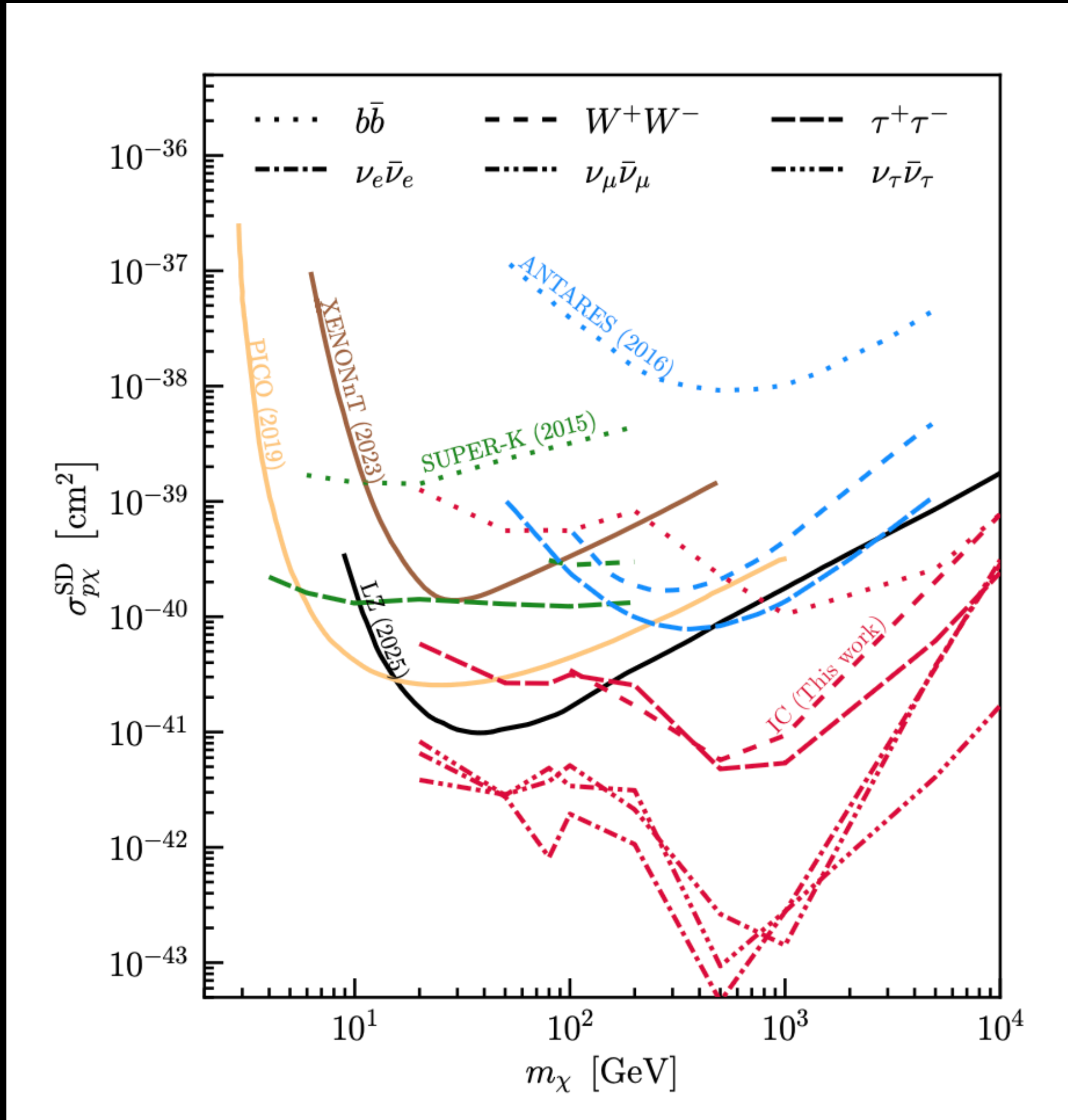


Solar WIMP Search

- Best limit on SD cross sections
  - Hard Channels

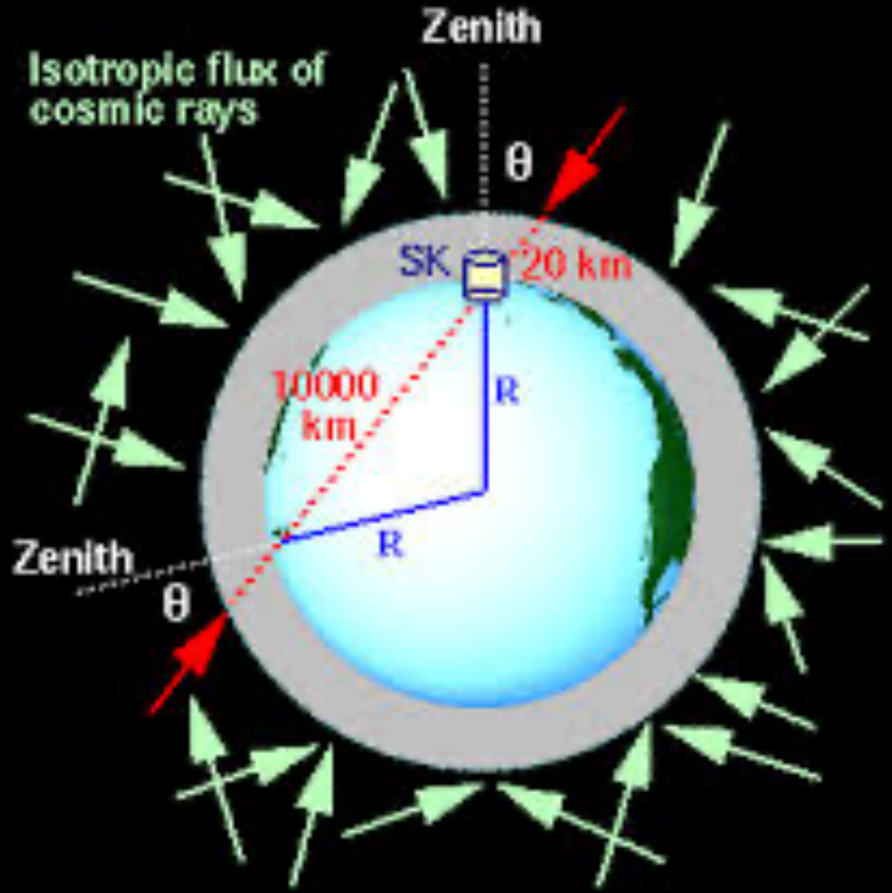
- Both scattering and Annihilation!

Also Qinrui Liu TAUP2025



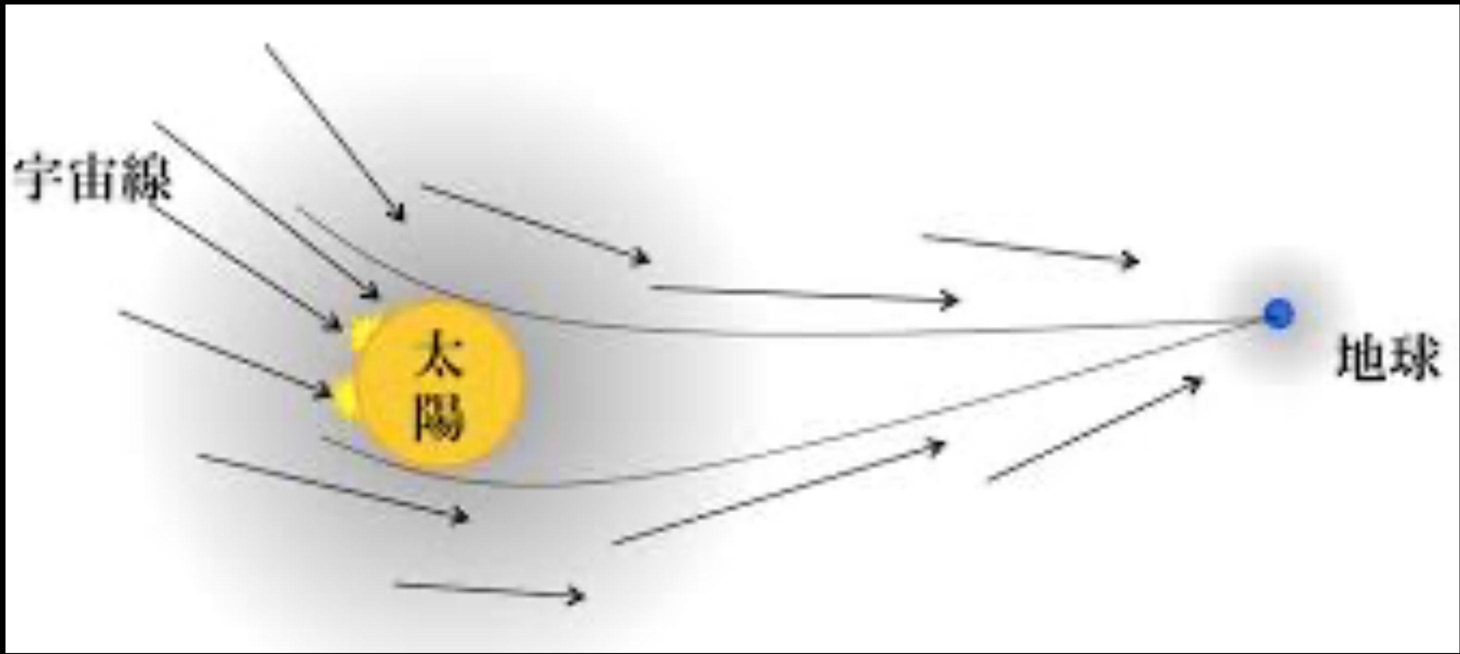
IceCube 2507.08457

Earth Atmospheric neutrinos



Sun absorbs cosmic rays

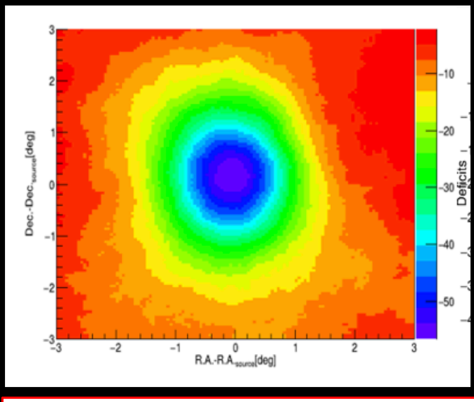
- We know that the Sun absorbs cosmic rays
- A shadow of cosmic rays towards the Sun



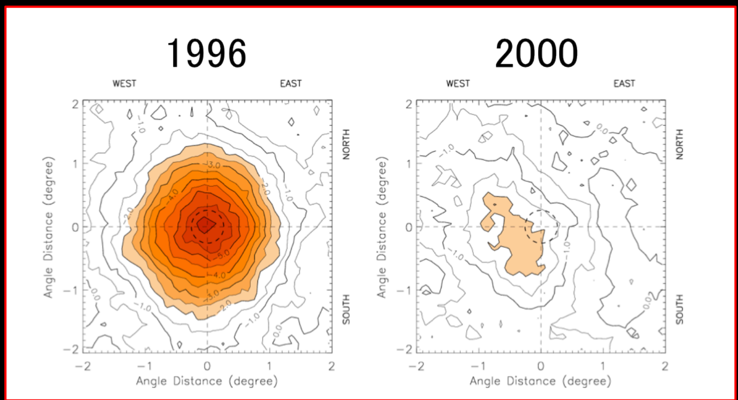
Sun absorbs cosmic rays

- We know that the Sun absorbs cosmic rays
- A shadow of "cosmic rays" towards the Sun

Cosmic Ray Shadow

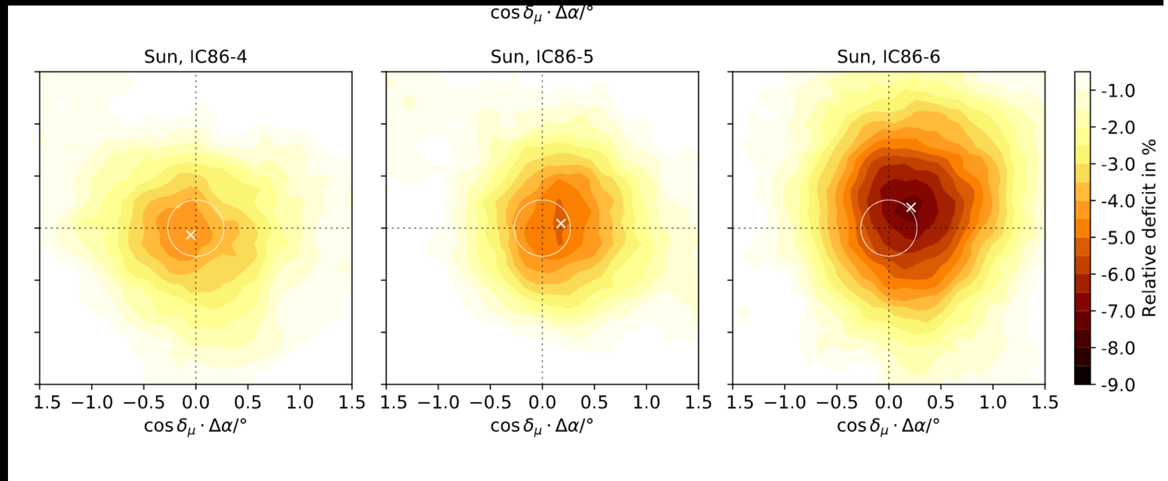


LHAASO WCDA
ICRC 2023



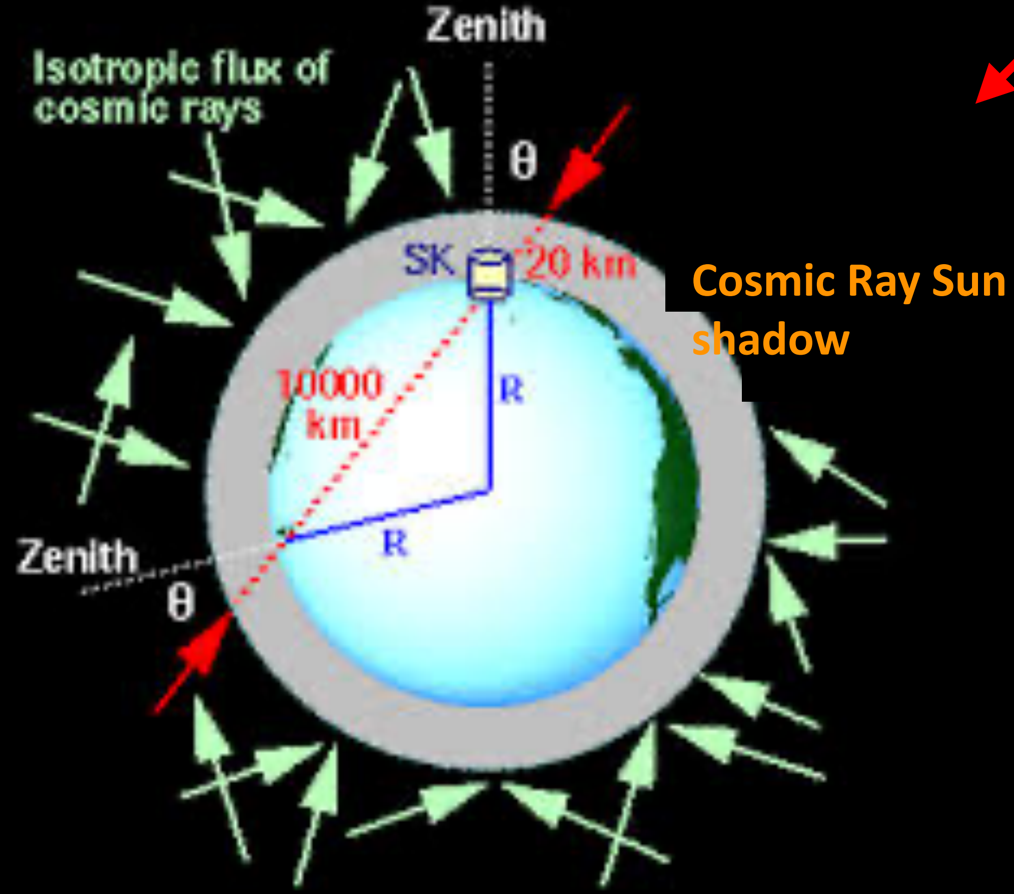
Tibet PRL 2013

Atmospheric Muon Shadow



IceCube PRD 2021

Solar Atmospheric Neutrinos



Solar ATM ν =

Earth ATM ν deficit?

No!

- Density of solar atmosphere << Earth atmospheric
- Meson decay >> Meson interaction
  => more Neutrinos!

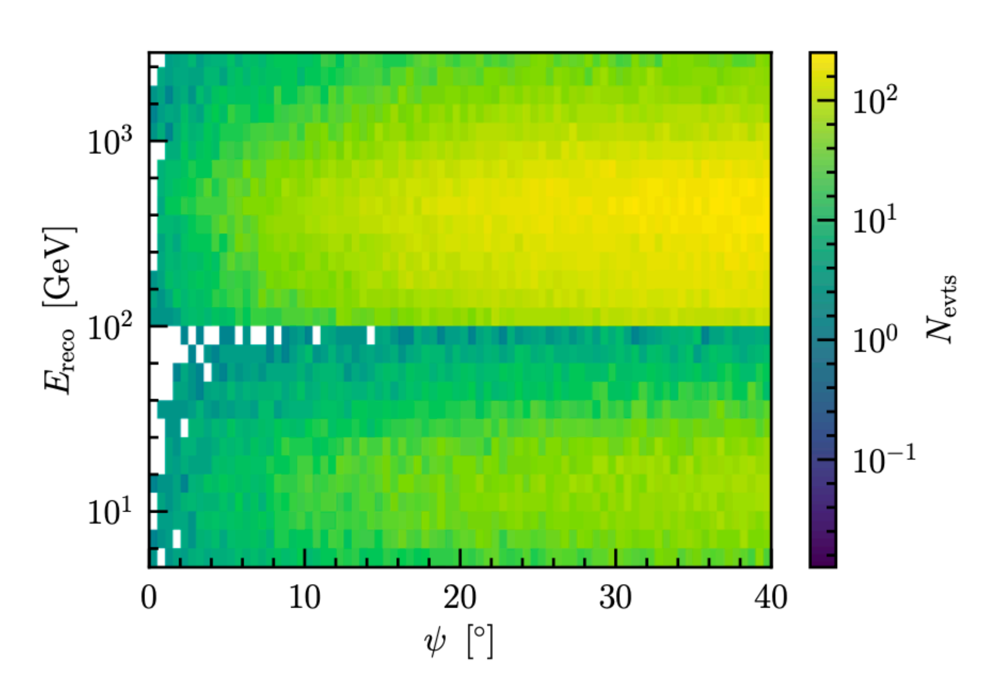
Ingelman and Thunmann 1999

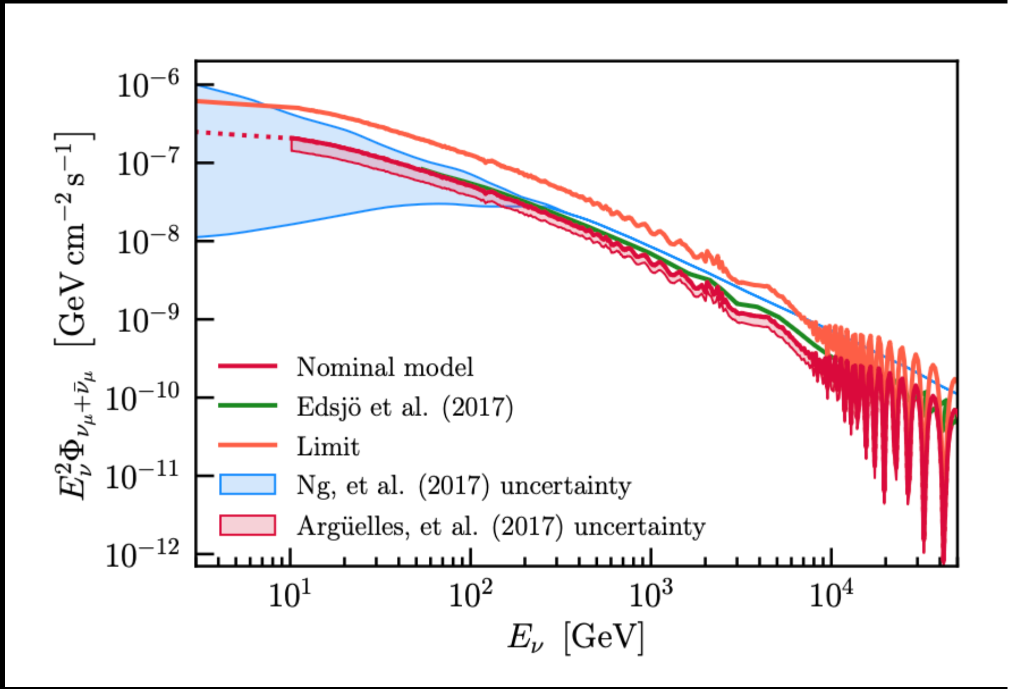
IceCube Solar ATM neutrino search

IceCube
1912.13135
2507.08457

Null observation

Limit sets at 2.48 times of the nominal model





- These models all have no magnetic fields
- Sun shadow not taken into account

Solar Atmospheric emission

The Sun is a cosmic-ray beam dump

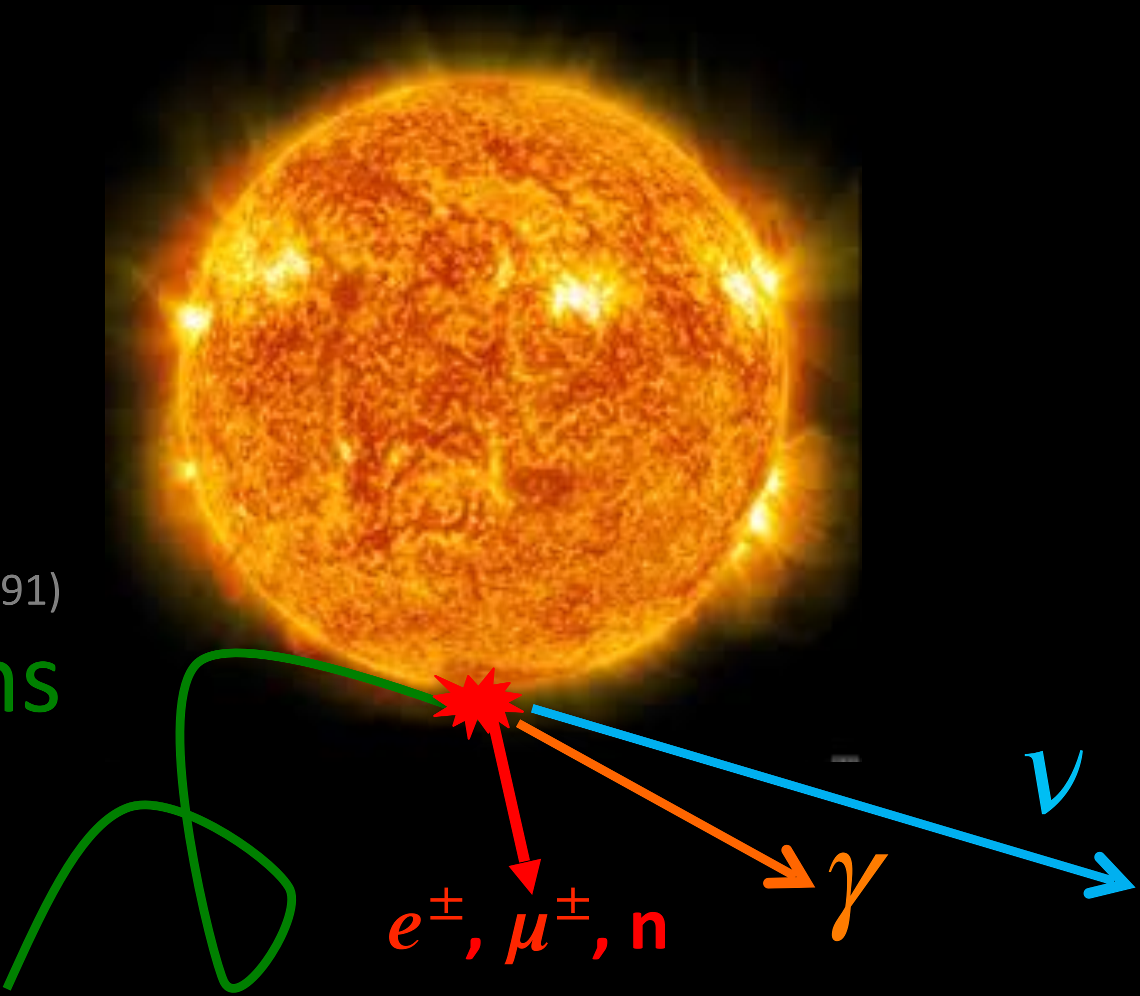
$$pp \to \pi^0/\pi^\pm + X$$

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

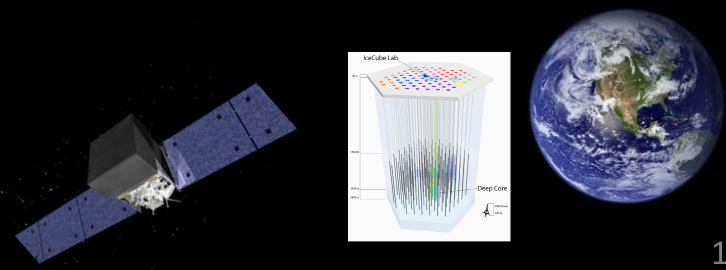
$$\pi^0 \to \gamma\gamma$$

Seckel, Stanev, Gaisser (1991)

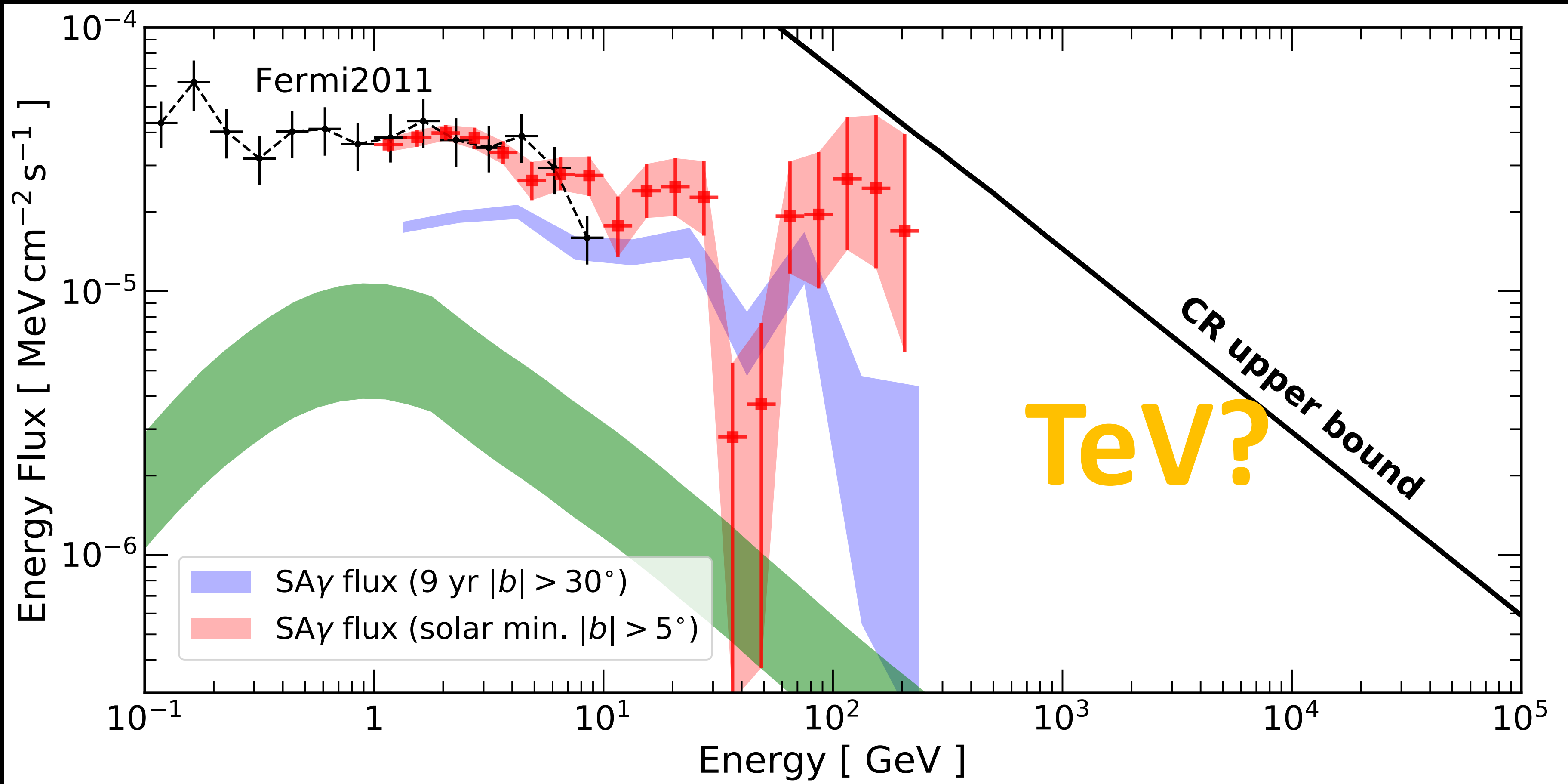
CR protons
Hadronic



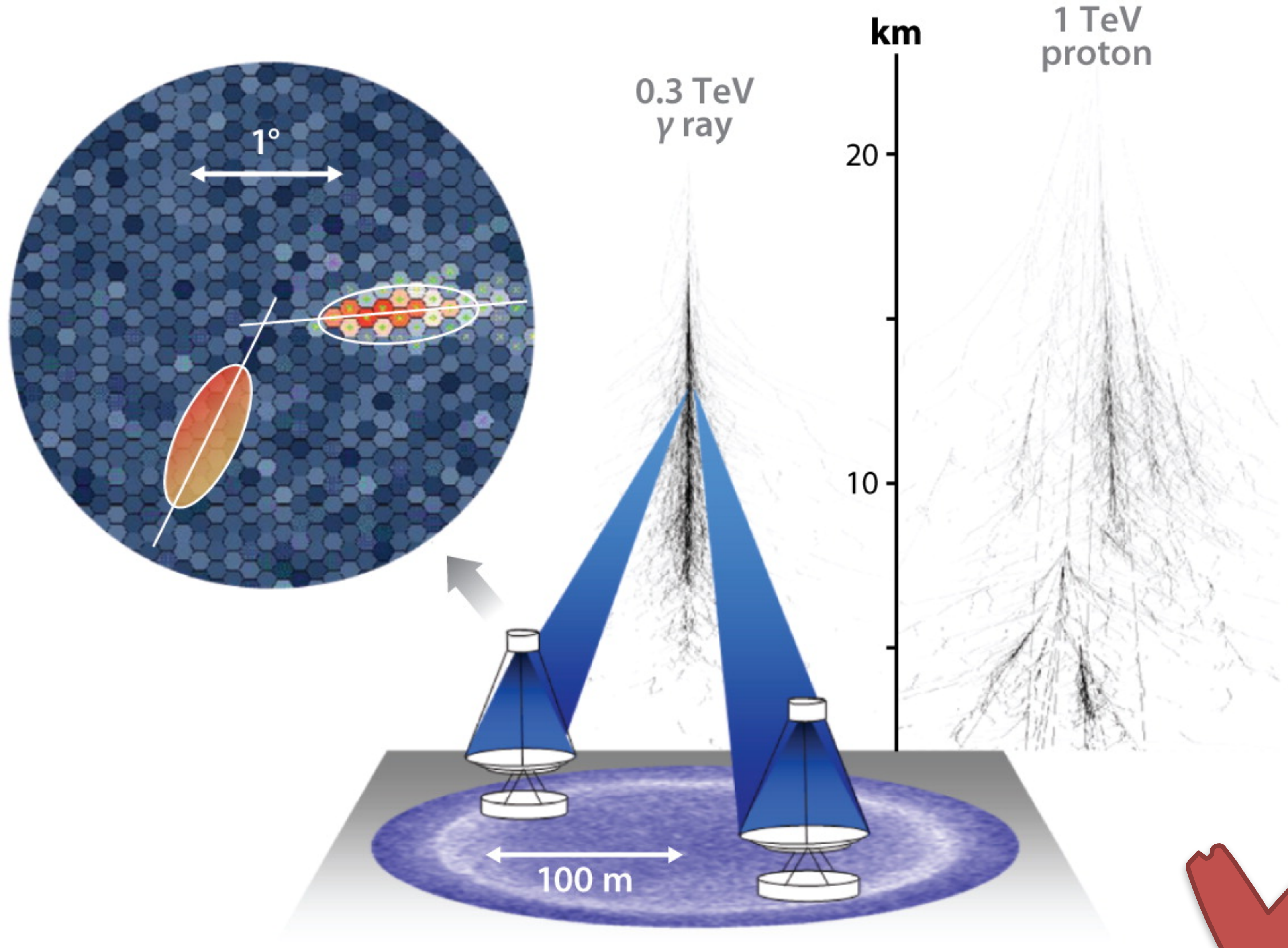
The effect of solar B-field is important!
(Lessons from gamma rays)



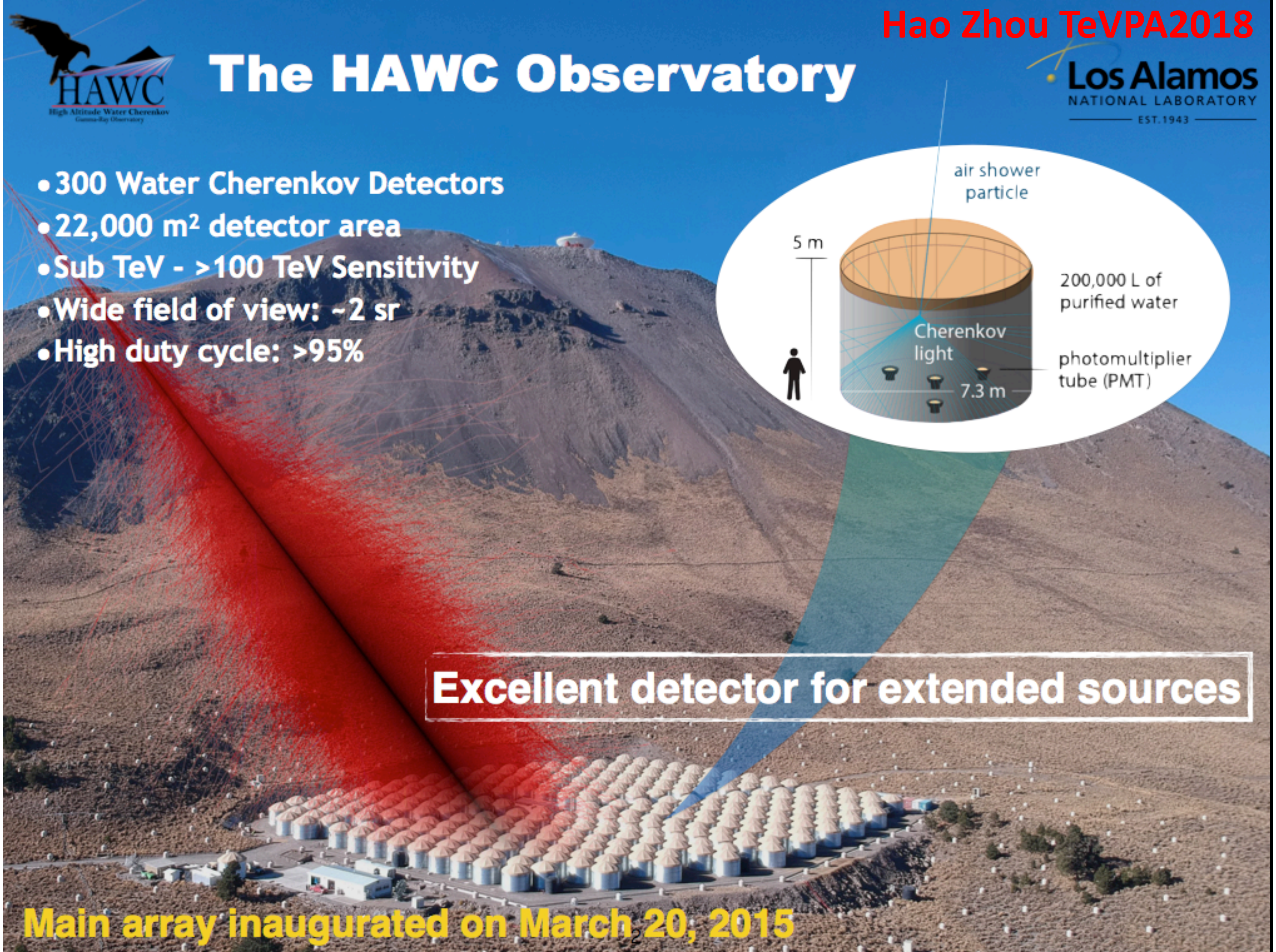
Solar Gamma Spectrum



Air Cherenkov Telescopes



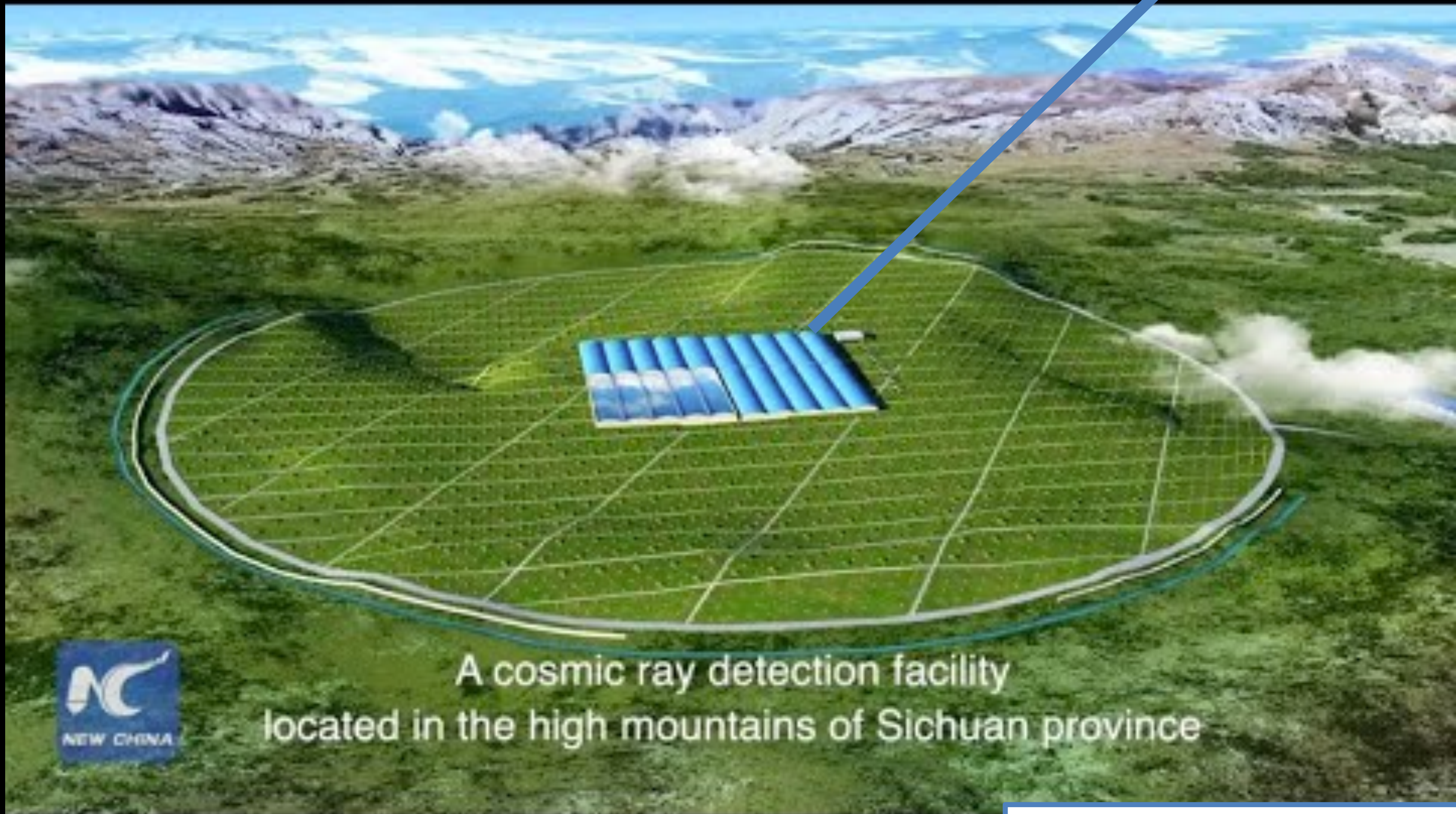
Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65


Hao Zhou TeVPA2018
HAWC
High Altitude Water Cherenkov
The HAWC Observatory
Los Alamos
NATIONAL LABORATORY
EST.1943
• 300 Water Cherenkov Detectors
• 22,000 m² detector area
• Sub TeV - >100 TeV Sensitivity
• Wide field of view: ~2 sr
• High duty cycle: >95%
air shower
particle
5 m
200,000 L of
purified water
Cherenkov
light
photomultiplier
tube (PMT)
7.3 m
Excellent detector for extended sources
Main array inaugurated on March 20, 2015

LHAASO-WCDA

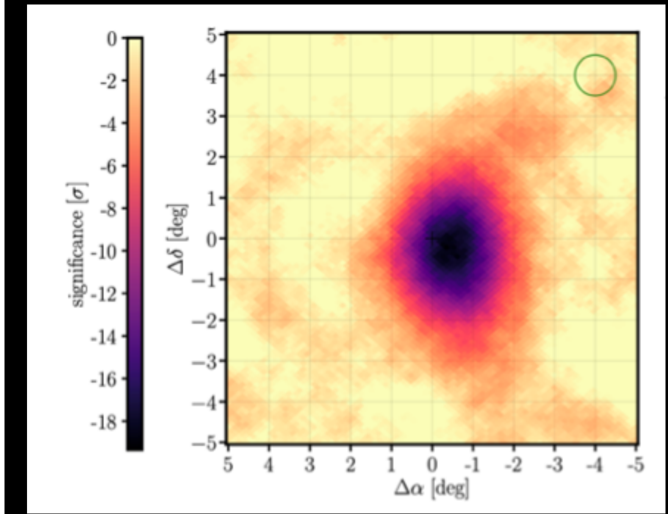
4X HAWC

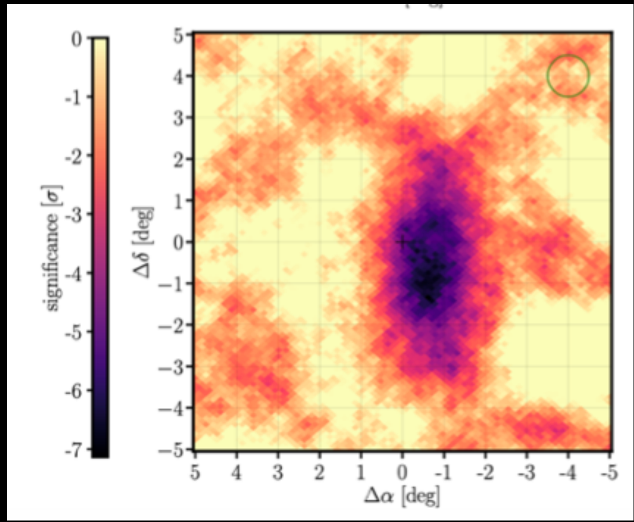
Unique VHE science case for air shower arrays!



~ 300km from Xichang!

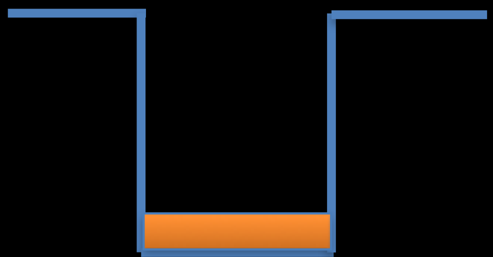
How to search for solar gamma rays with LHAASO/HAWC?





All data

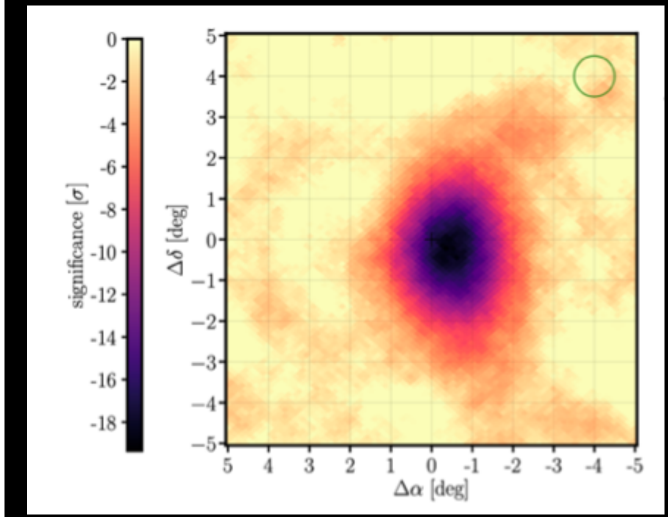
After Gamma/hadron separation



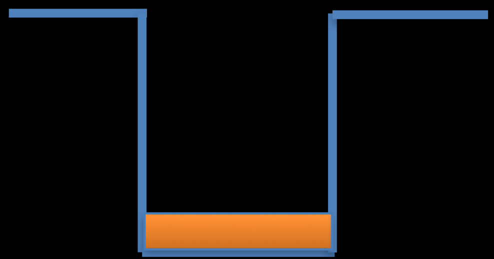
Cosmic ray shadow

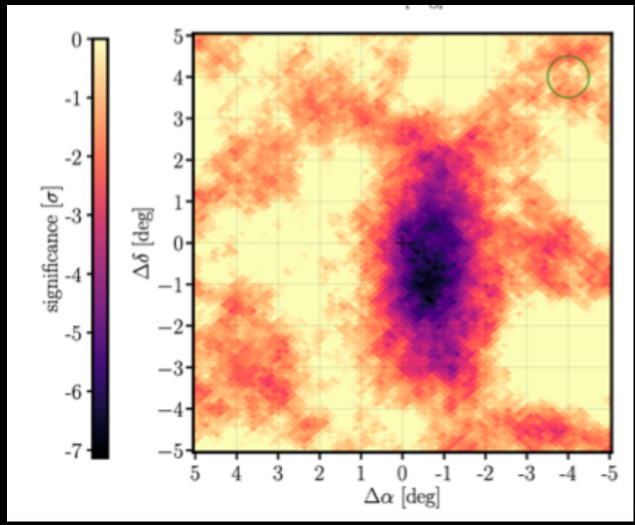
Deficit

How to search for solar gamma rays with LHAASO/HAWC?

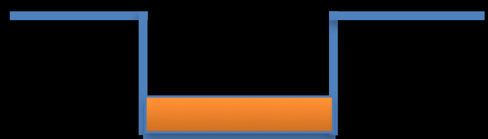


All data

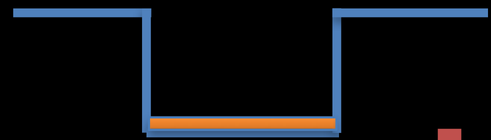


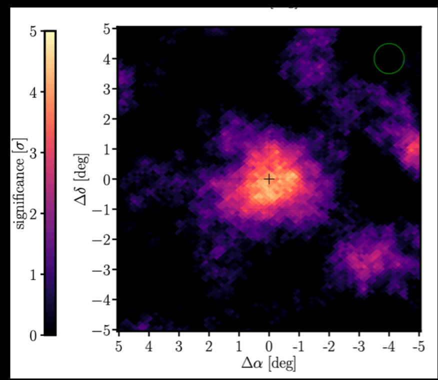


After Gamma/hadron separation



Expected shadow = All data x γ/hadron efficiency

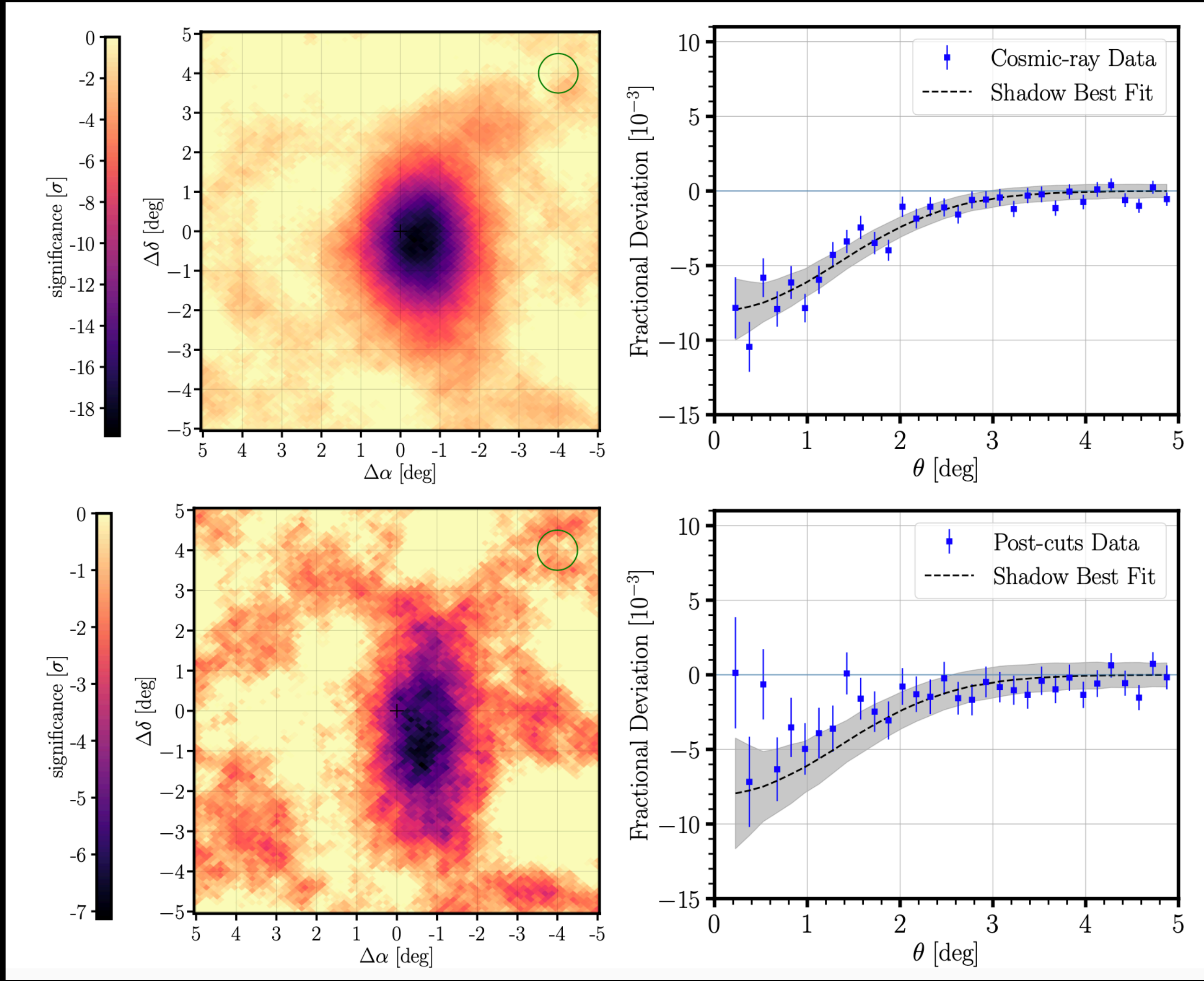




The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC

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

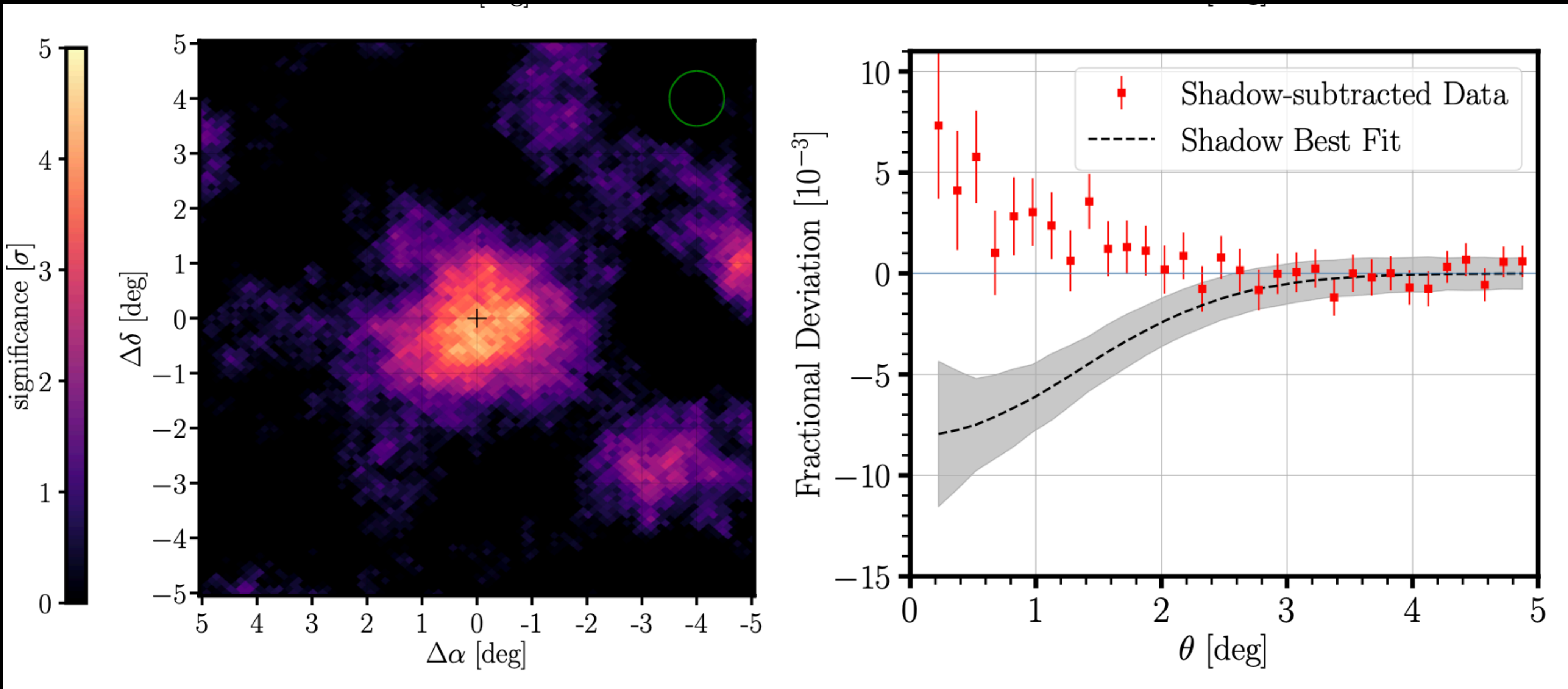
- 11/2014 - 1/2021
- Taking into account the Sun shadow
- Top: raw data, mostly cosmic rays
- Bottom panel: after gamma/ hadron separation



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

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

- Gamma/hadron separation map minus Expected shadow (data)
- 6.3 sigma detection



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

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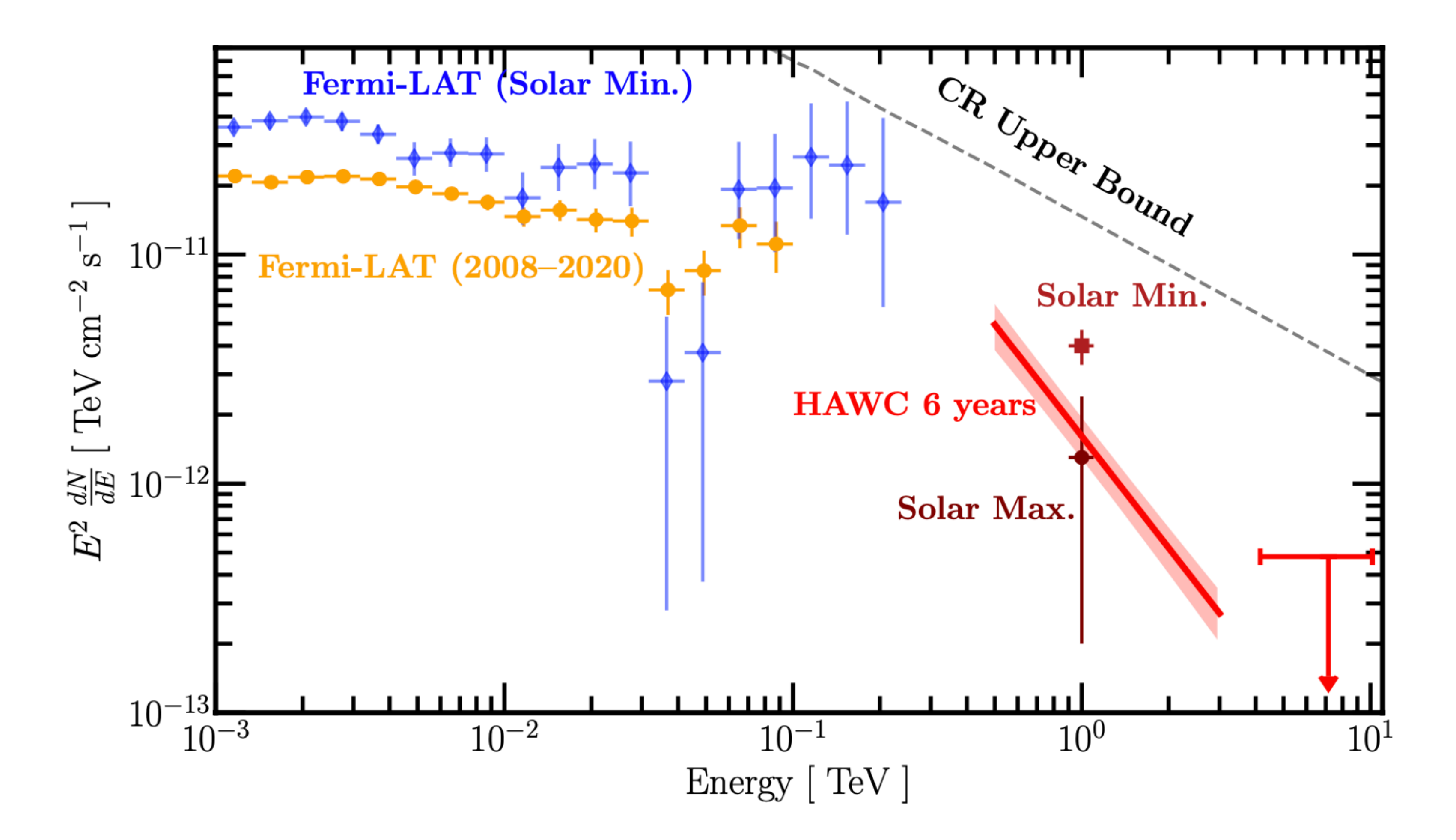
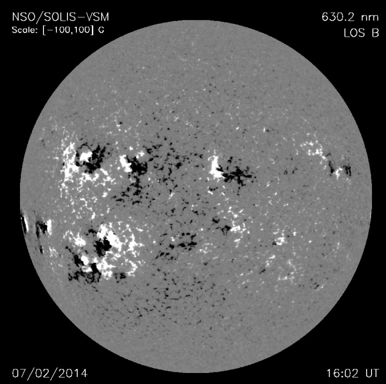


- If there are no magnetic field, Sun limb only ~ 0.1% of total cosmic ray energy
- Observation implies magnetic fields must be important

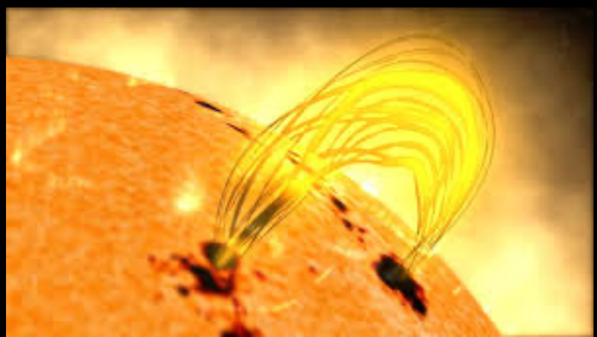
Theoretical developments

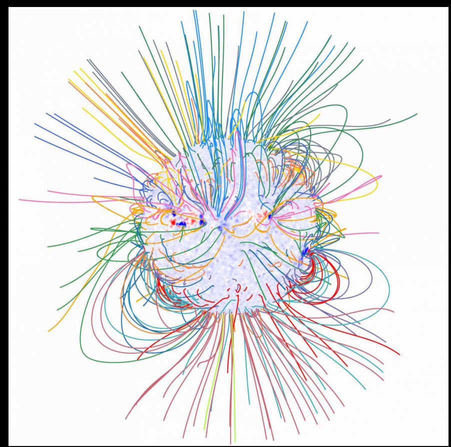


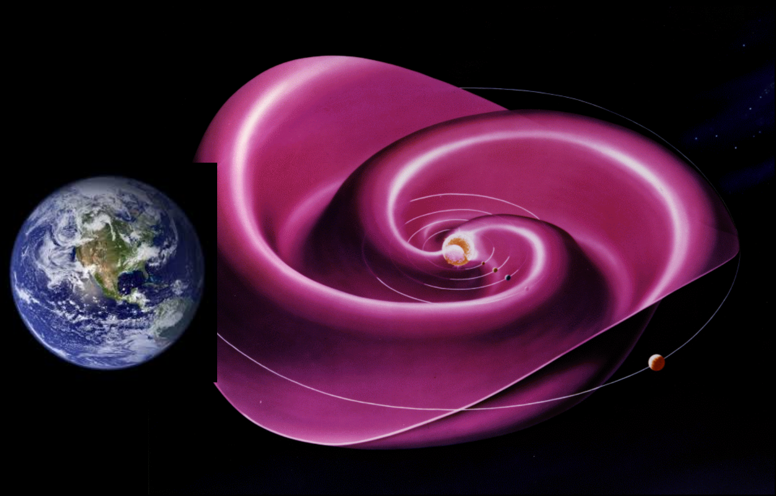
Best observational B-field data comes from Optical data ***at the photosphere***

Chingam Fong TAUP 2025

Lower energy solar gamma rays



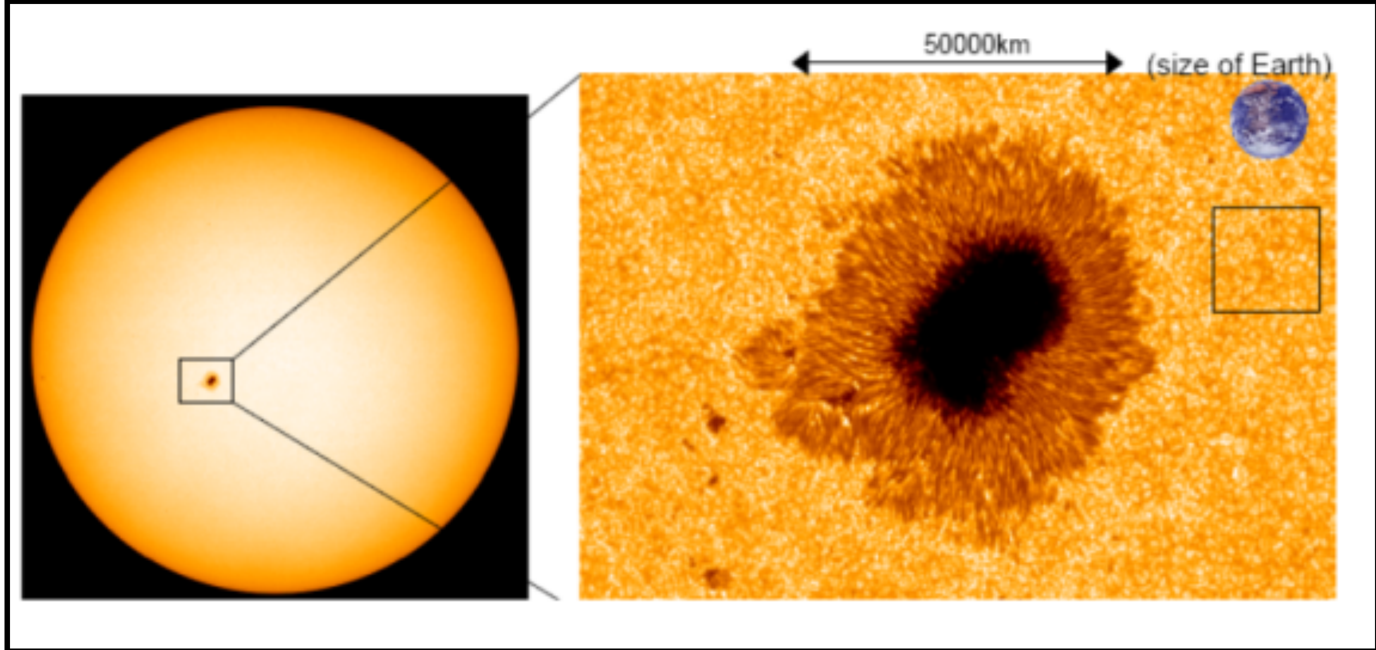




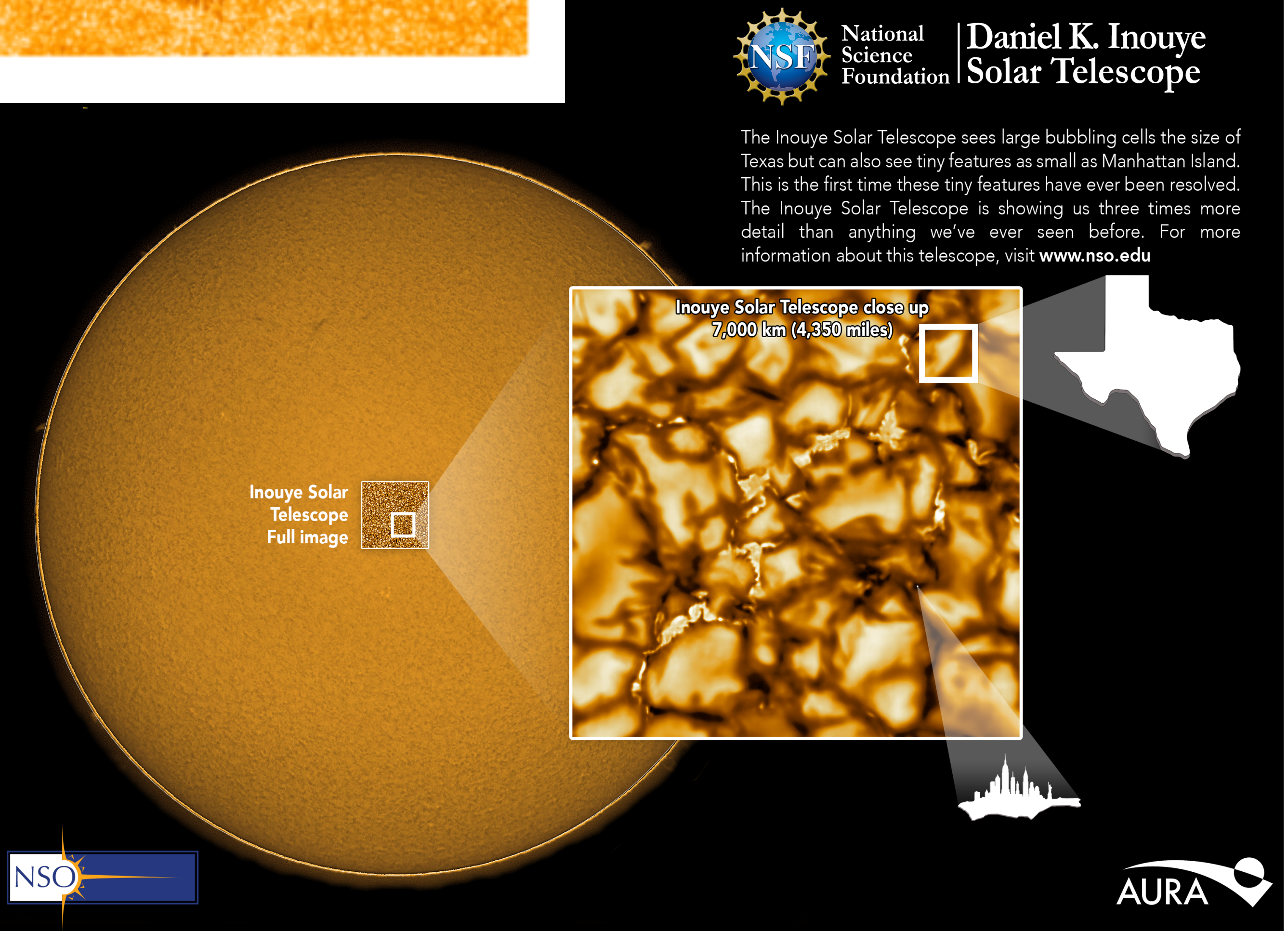
Photosphere B-field
<1 Rsun to Rsun

Coronal B-field
Rsun to 10 Rsun

Interplanetary B-field
10 Rsun to interstellar Space



Active regions

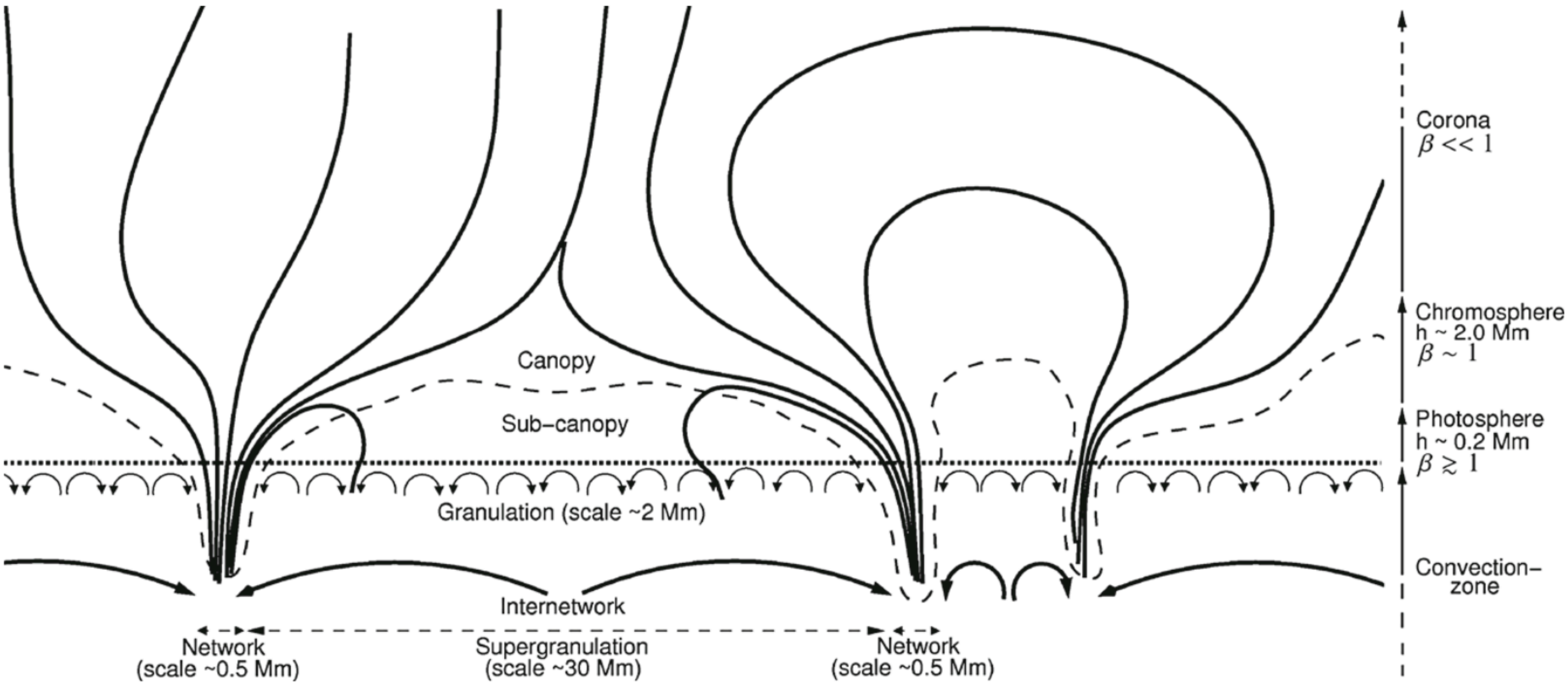


Quiet regions

Near the Solar surface

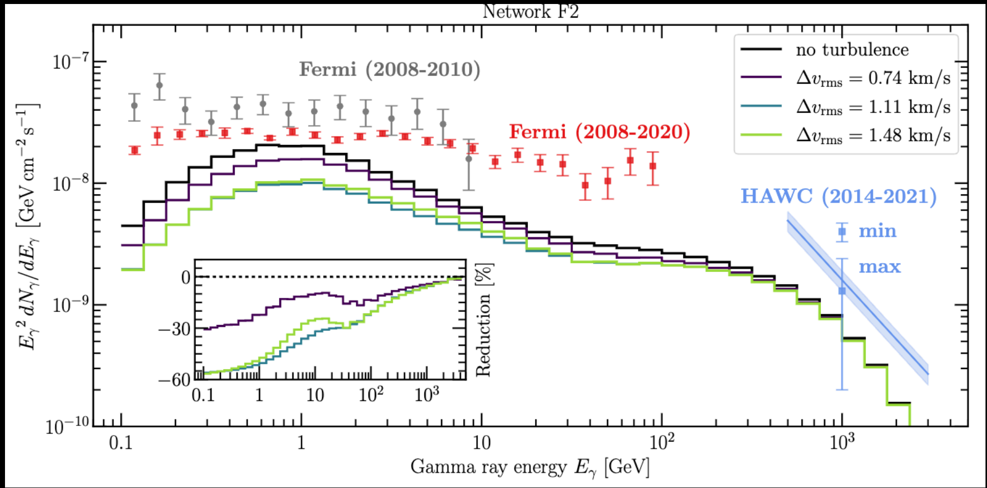
Cartoon

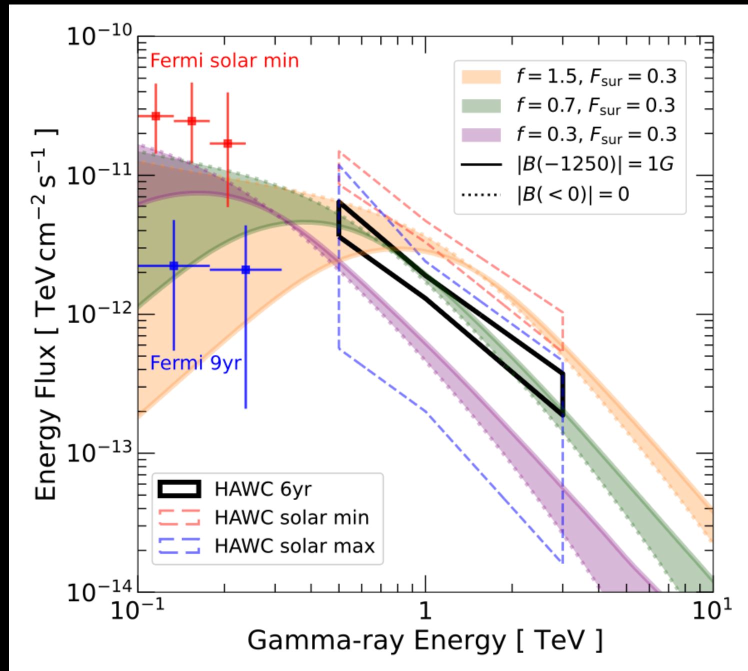
T. Wiegelmann et al.: The magnetic field in the solar atmosphere Page 17 of 106



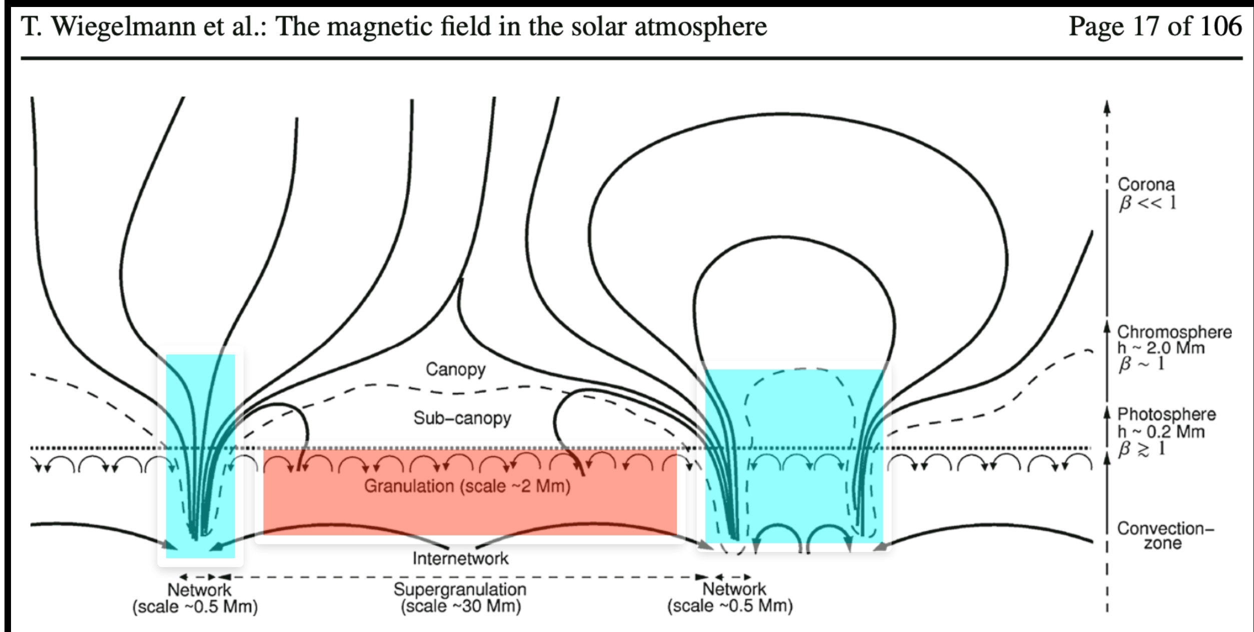
TeV Sun probes photospheric magnetic fields

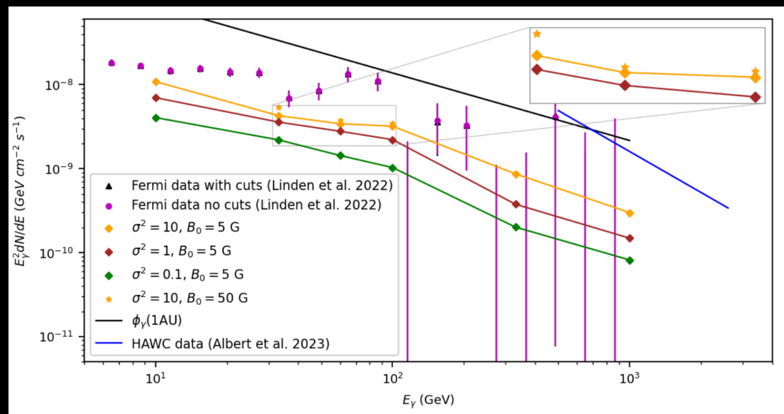
Flux tubes/sheets, + turbulence
Li, Beacom, Griffith, Peter, 2024
Li, Asgari-Targhi, Beacom, Peter, 2025





Horizontal Internetwork fields
KCYN, Hillier, Ando (Accepted PRL 2025)





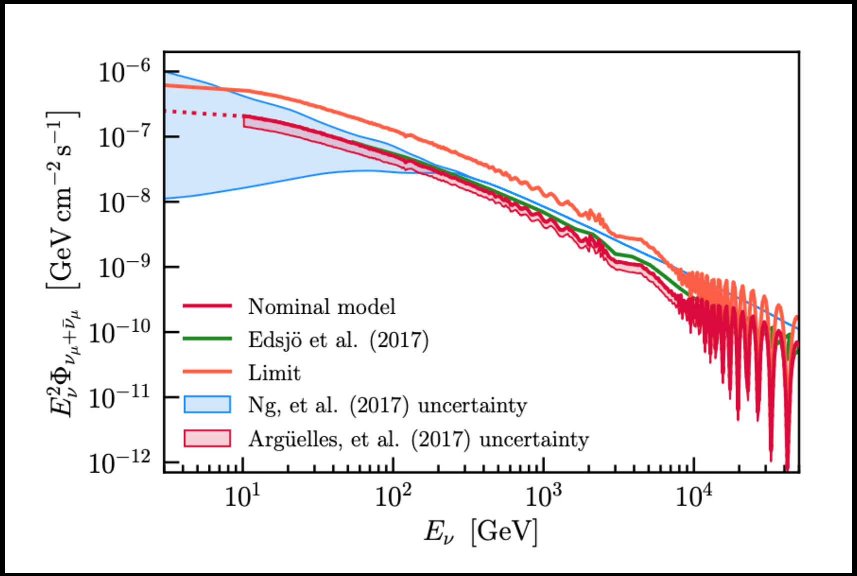
Turbulence+ open field line braiding
Puzzoni, Fraschetti, Kota, Giacalone
2024 and 2025

IceCube Solar ATM neutrino search

Null observation

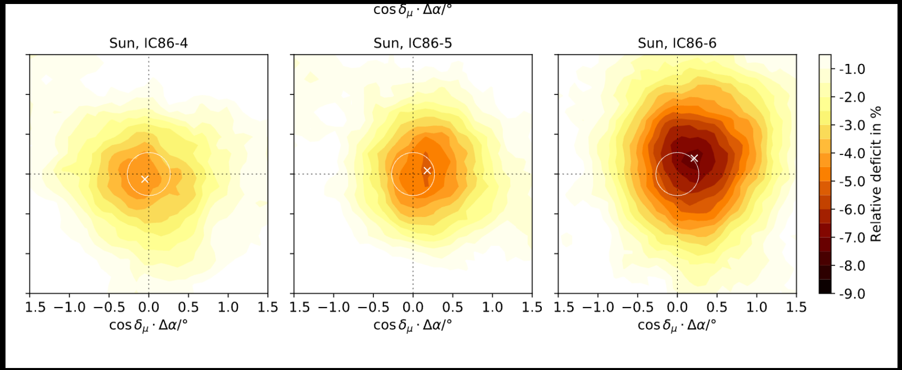
Limit sets at 2.48 times of the nominal model

IceCube 1912.13135, 2507.08457



- **These models all have no magnetic fields**
  - Effect of magnetic fields for TeV neutrinos still need to be investigated

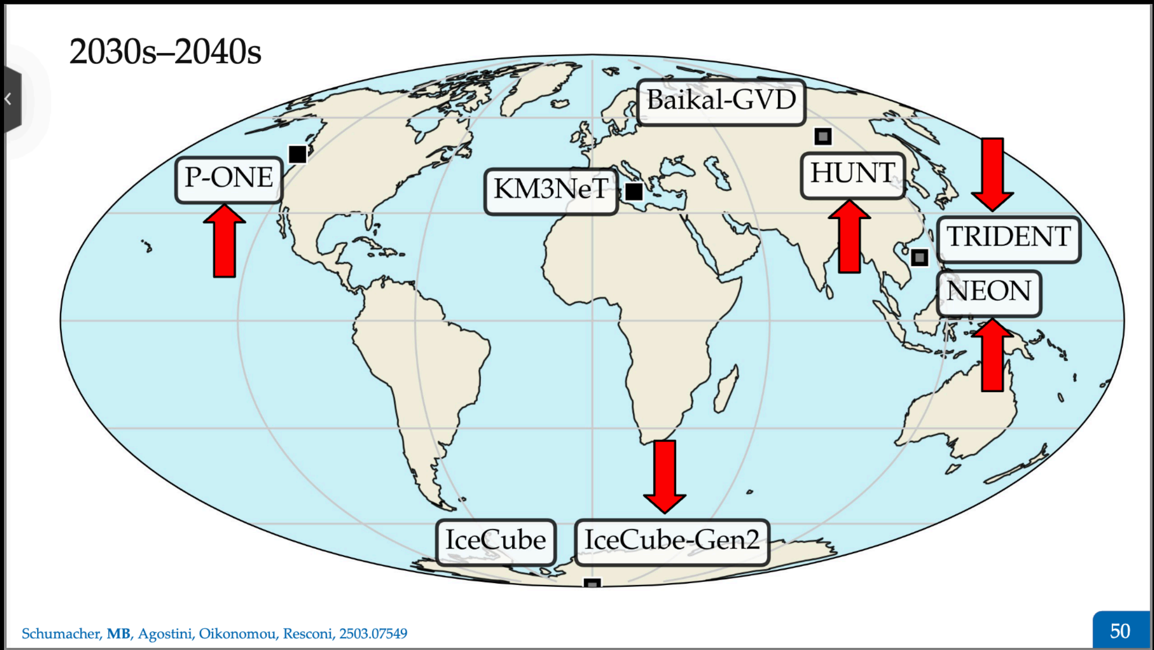
- **Sun shadow not taken into account**
  - ATM muon <=> ATM neutrino
  - There must be an ATM neutrino shadow (~ HAWC analysis)



Atmospheric Muon Shadow

Solar atmospheric neutrino

- Guaranteed "astrophysical" neutrinos source
- Important for dark matter search
- Unique probe for solar magnetic fields



TAUP 2025 Bustamante

- **Next-gen TeV telescopes**
- **Water**
  - **Better reconstruction**
- **NOT south pole**
  - **Less background from the Sun**