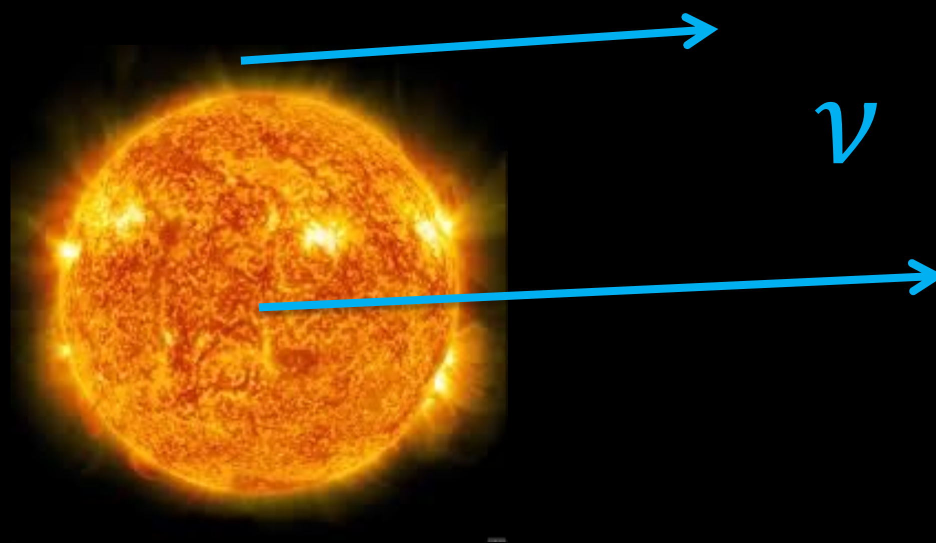
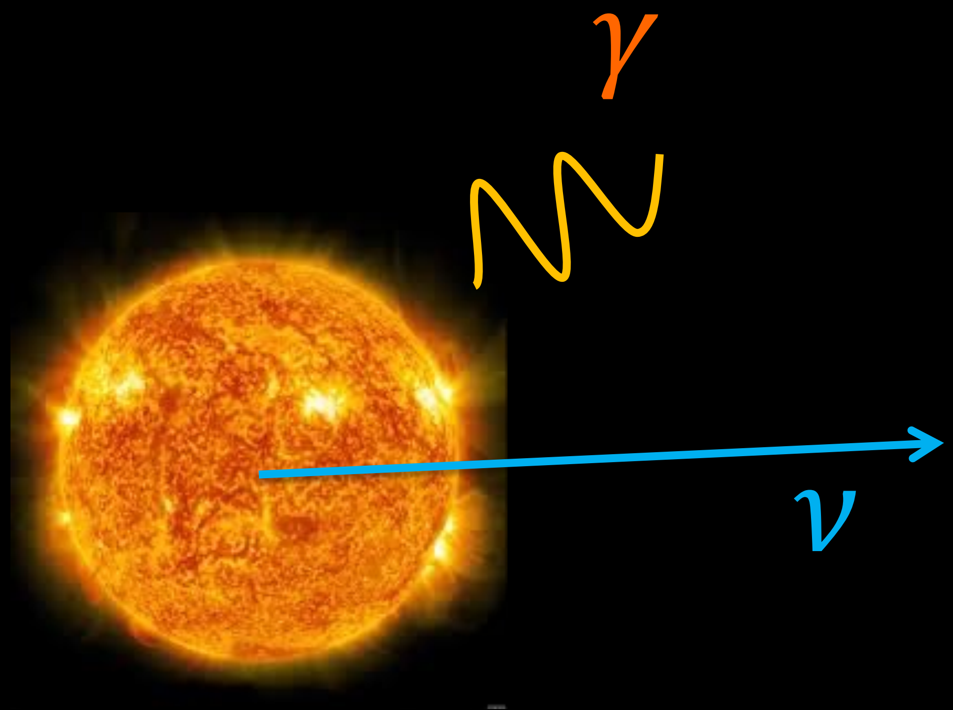
Solar Atmospheric Neutrinos



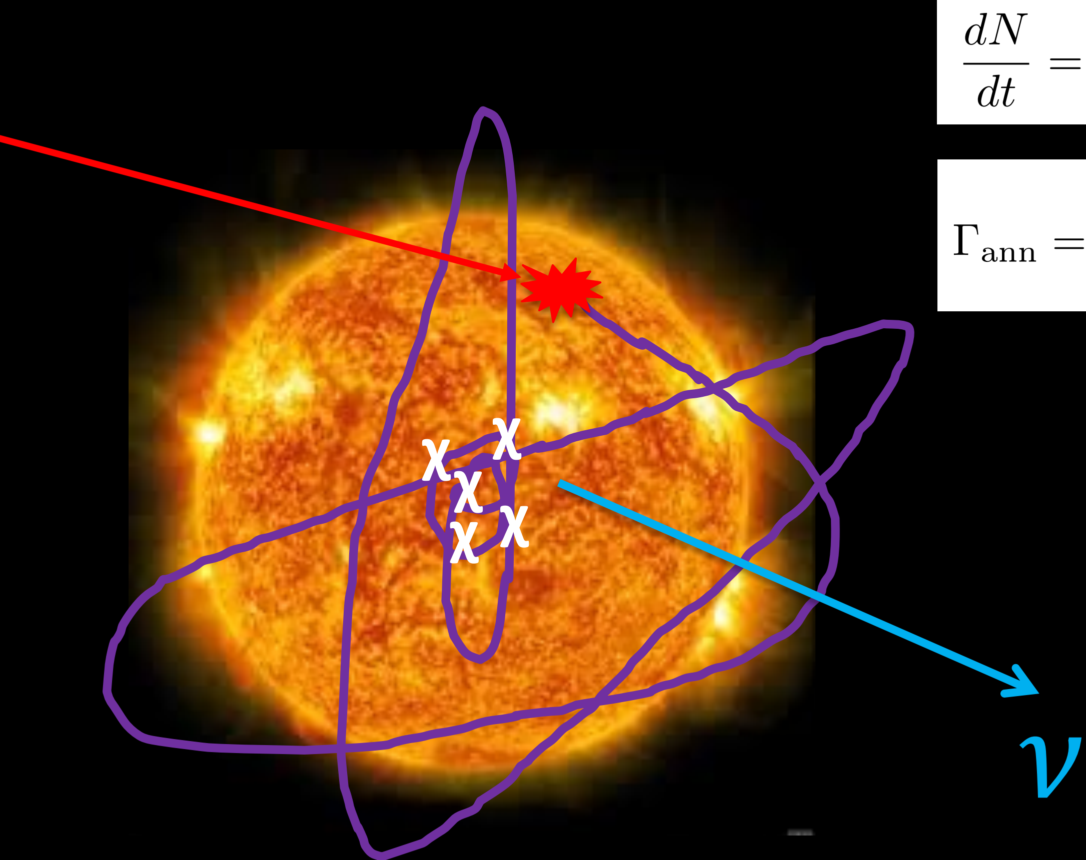
Kenny, Chun Yu Ng (吳震宇)
The Chinese University of Hong Kong

The Sun as a VHE source



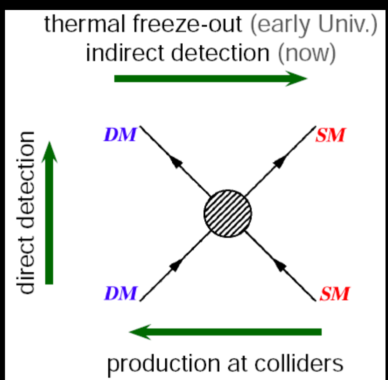
Kenny, Chun Yu Ng (吳震宇)
The Chinese University of Hong Kong

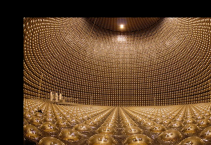
Sun – Dark Matter detector

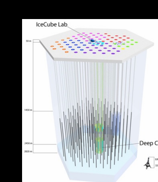


$$\frac{dN}{dt} = \Gamma_{\rm cap} - C_{\rm ann} N^2$$

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



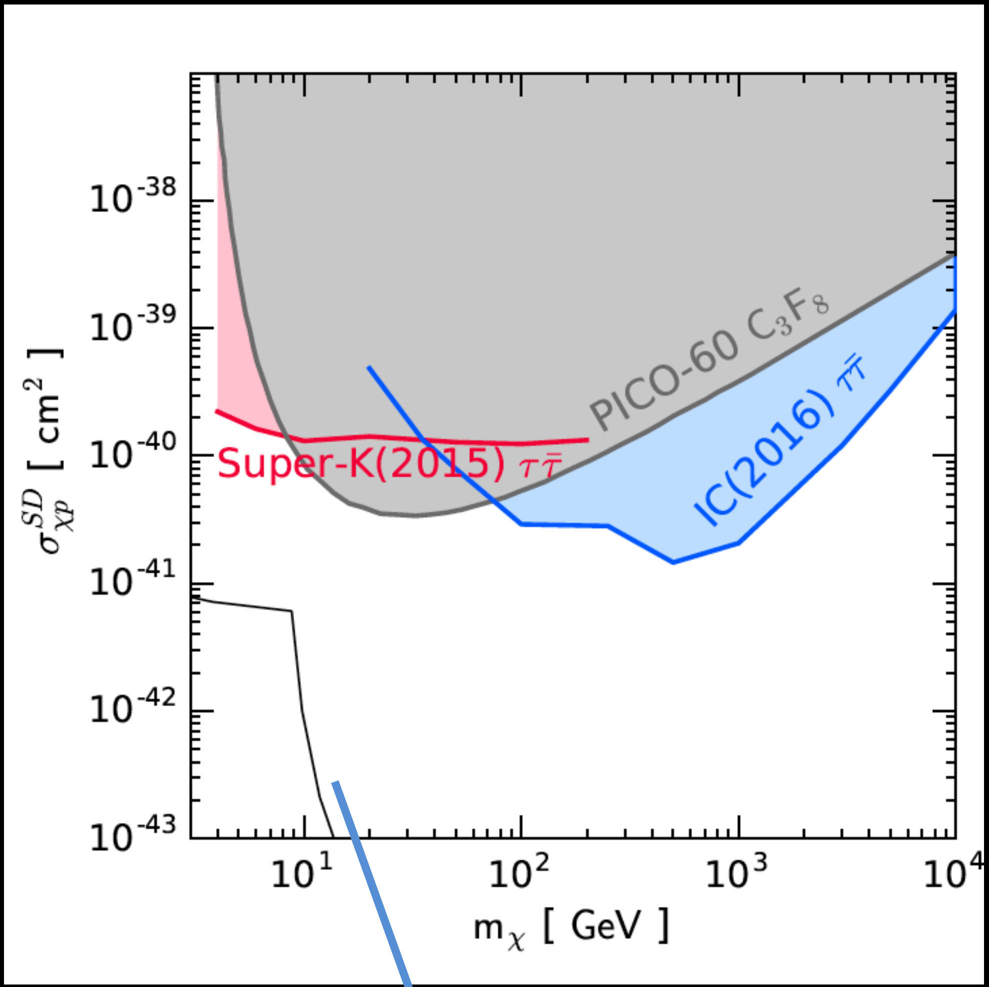




Press, Spergel (1985)
Krauss, Freese, Press, Spergel (1985)
Silk, Olive, Srednicki (1985)

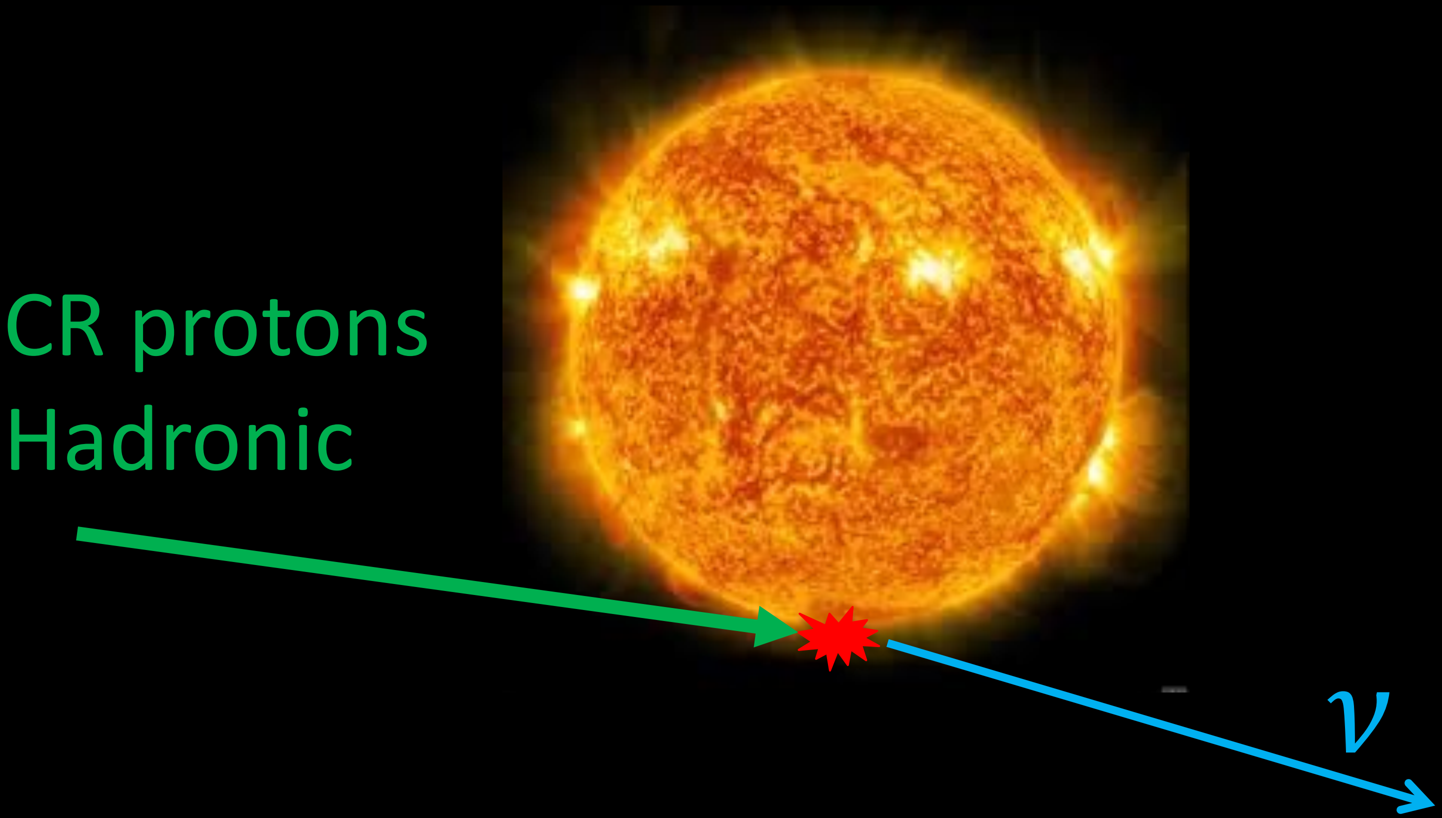
Solar WIMP Search

- Best limit on SD cross sections
  - Hard Channels
- Both scattering and Annihilation!
- How far can neutrino telescopes reach?



C_3F_8 Direct Detection Neutrino floor
Ruppin et al. 2014

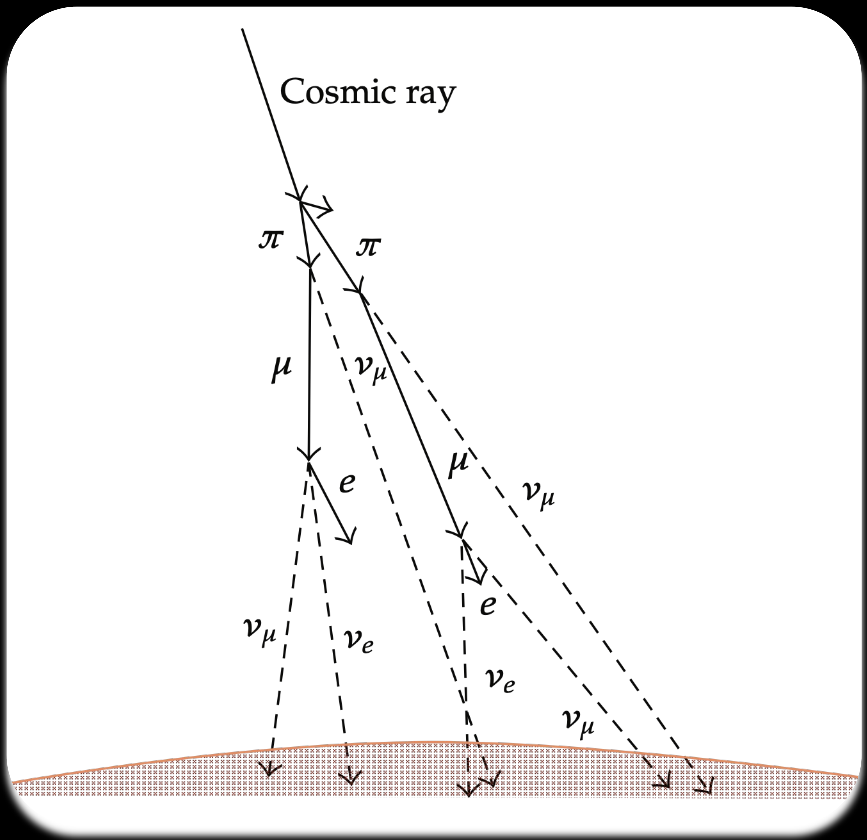
Sun – Cosmic-Ray Beam Dump

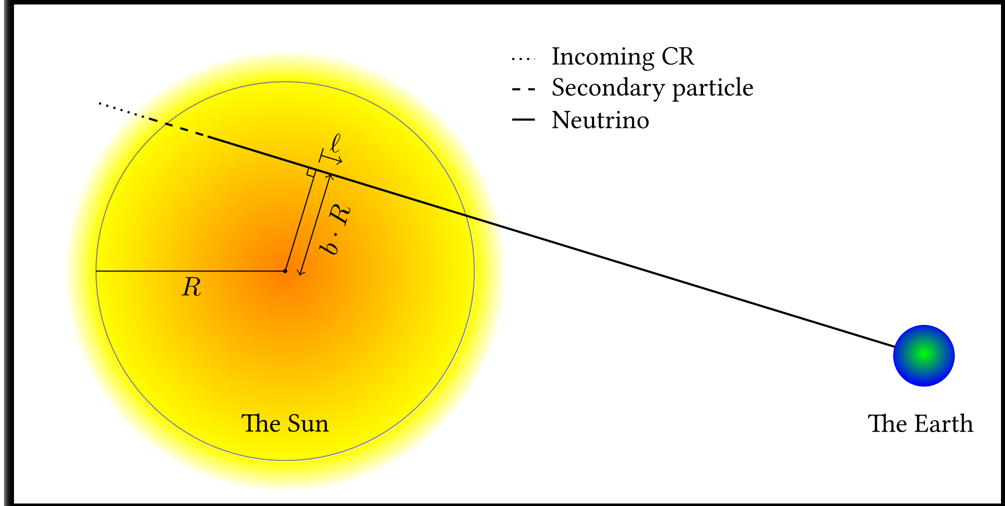


Solar atmospheric neutrinos

- Dark Matter Physics
  - Same direction as WIMP neutrinos
  - Different spectrum (poor energy resolution for ν_μ)
- Neutrino Physics
  - A guaranteed astrophysical neutrino source
- Cosmic-ray and Solar Physics
  - Cosmic ray in the inner solar system
  - Local environment of solar atmosphere

Solar Atmospheric Neutrinos





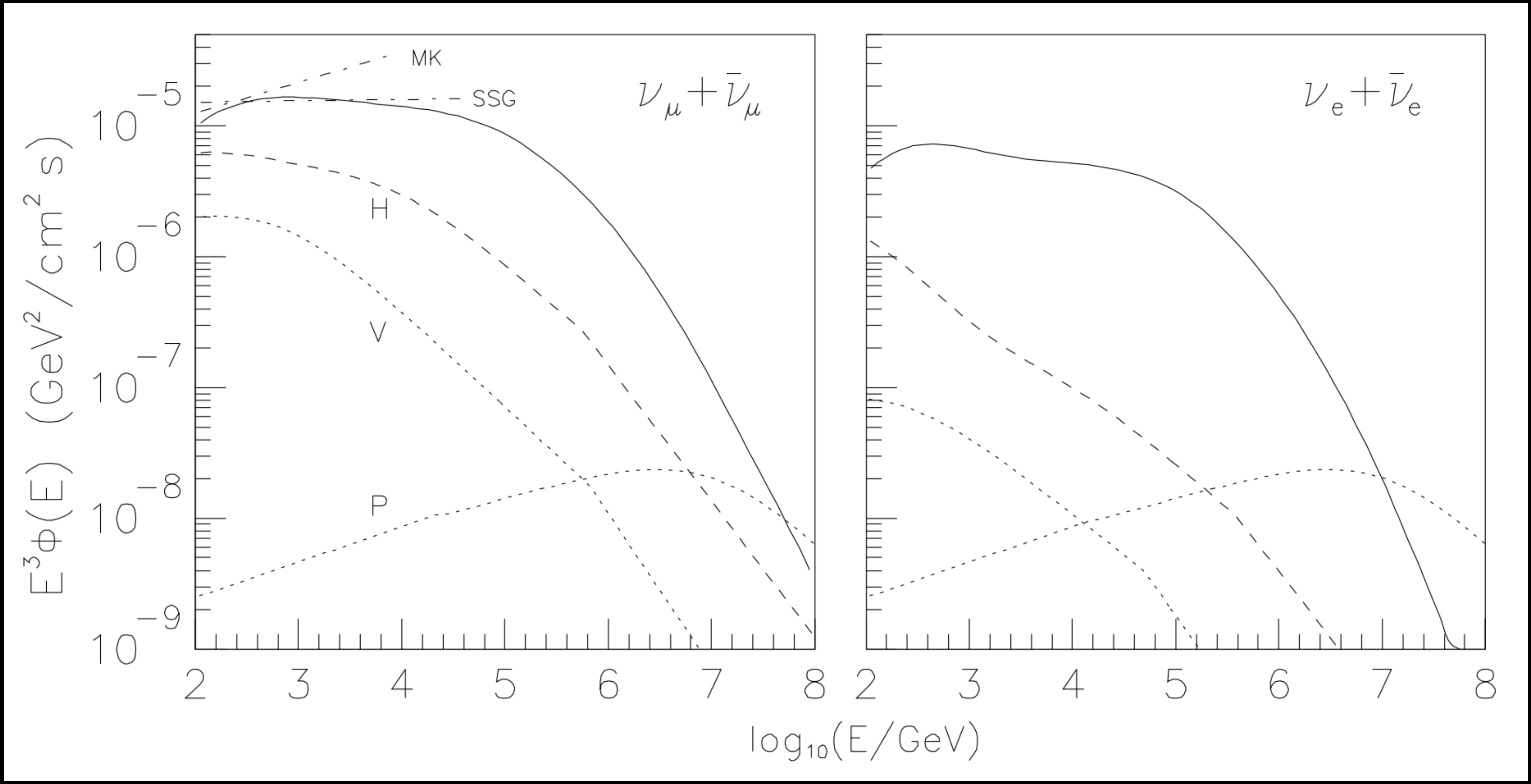
- Dilute atmosphere, larger neutrino flux

Seckel+ 1991, Moskalenko+, 1993, Ingelman+ 1996, Hettlage+ 2000, Fogli+ 2003

C.A. Argüelles+ 1703.07798
Joakim Edsjo+ 1704.02892
Mazziotta+ 2001.09933

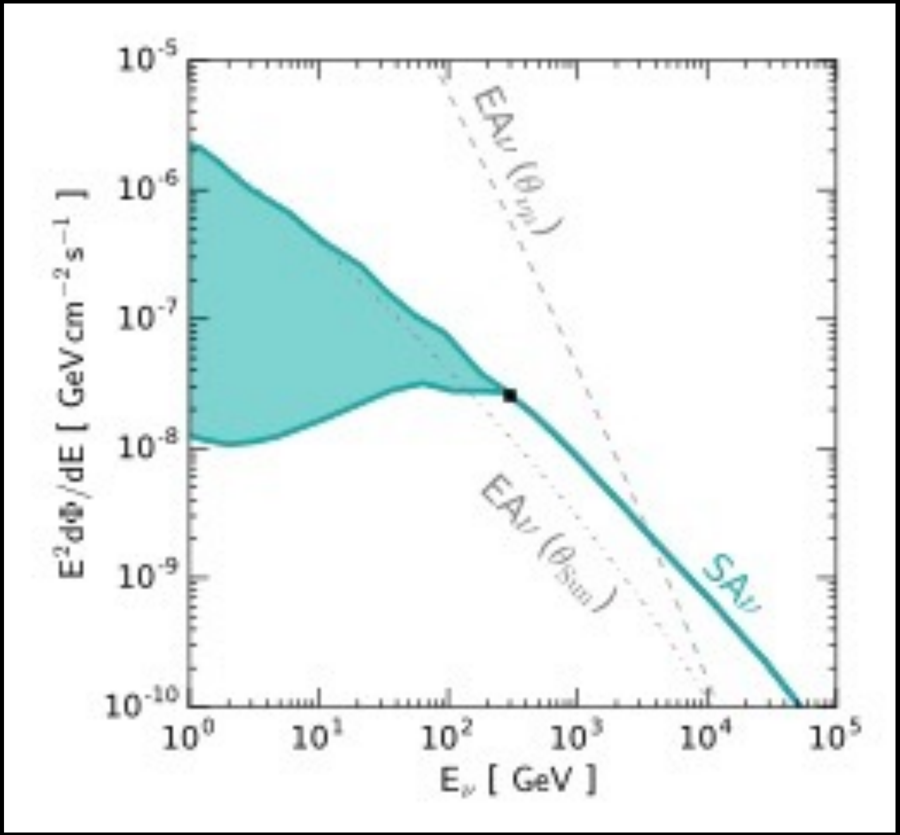
Meson decay in the Sun

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



Solar Atmospheric Neutrinos

KCYN, Beacom, Peter, Rott 2017



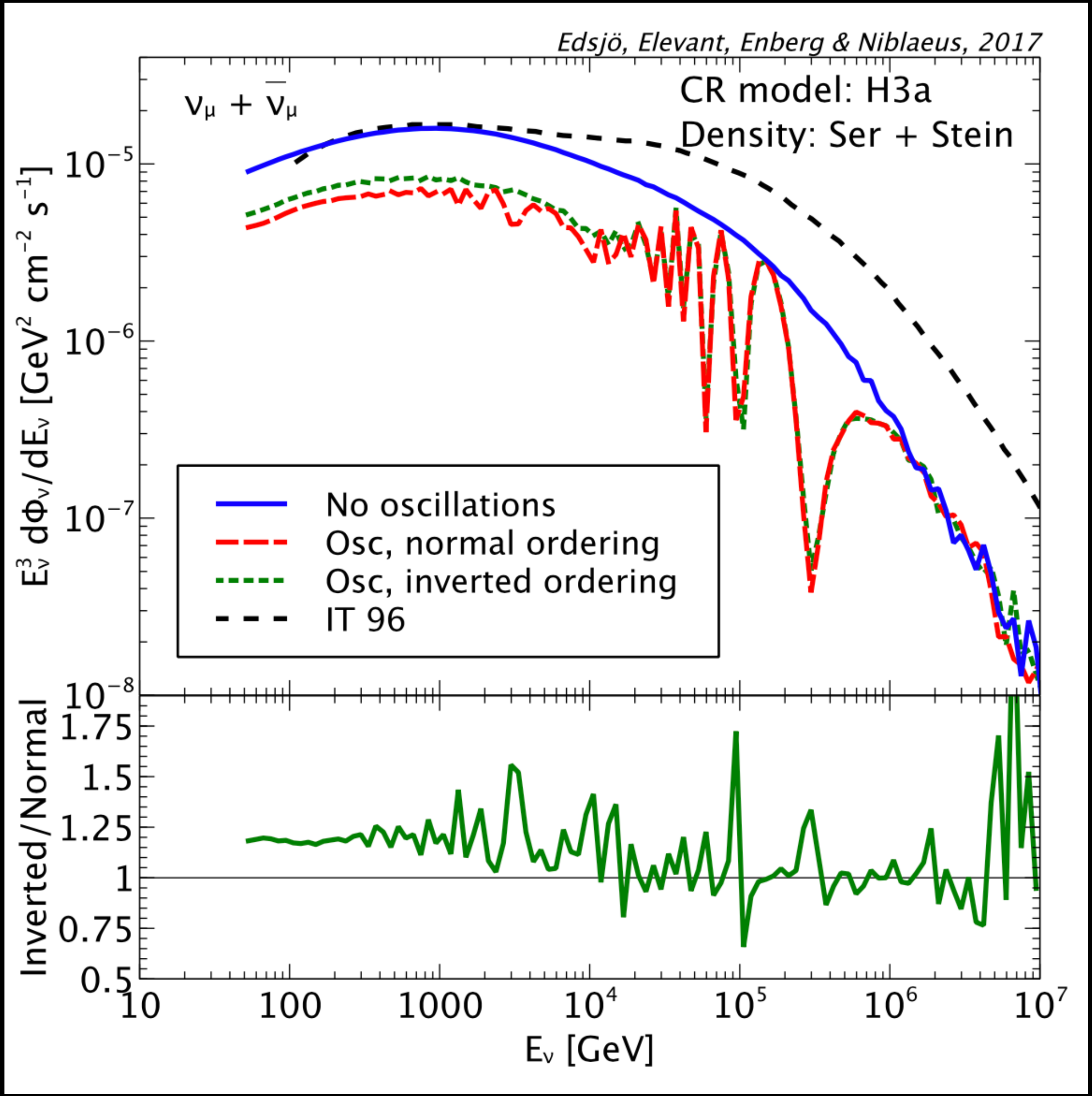
$$\theta_{\nu\mu} \simeq 1^\circ \sqrt{1\,\mathrm{TeV}/E_\nu}$$

- Dilute atmosphere, larger neutrino flux

Seckel+ 1991, Moskalenko+, 1993, Ingelman+ 1996, Hettlage+ 2000, Fogli+ 2003

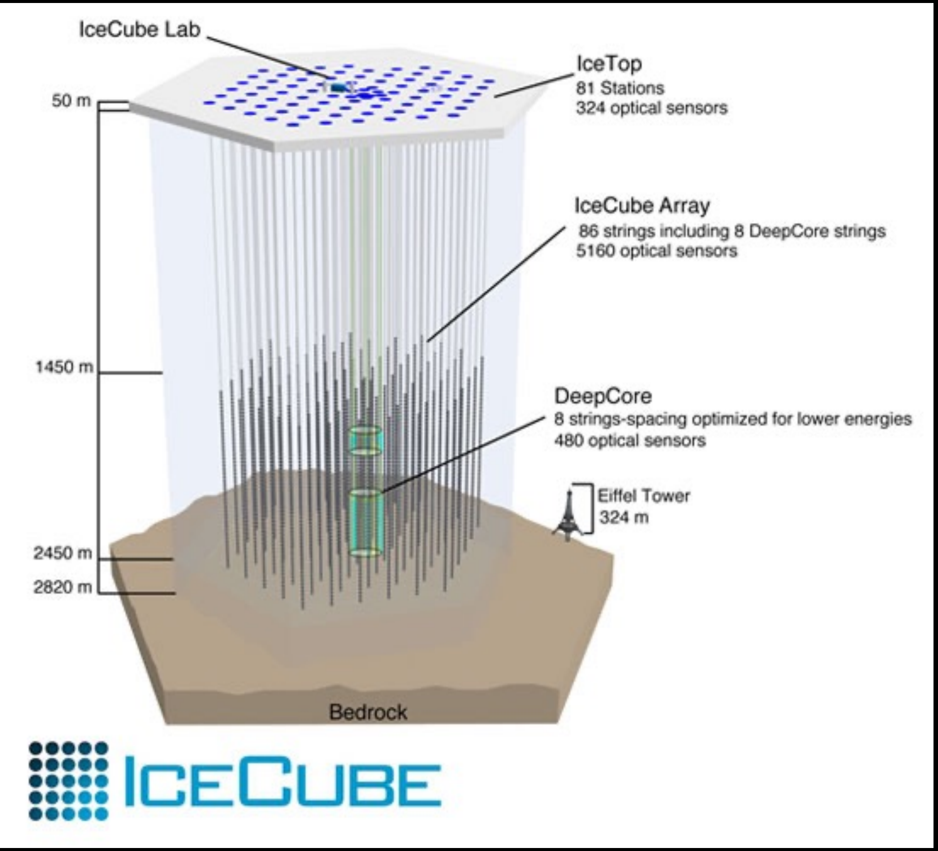
C.A. Argüelles+ 1703.07798
Joakim Edsjo+ 1704.02892

Solar Atmospheric Neutrinos

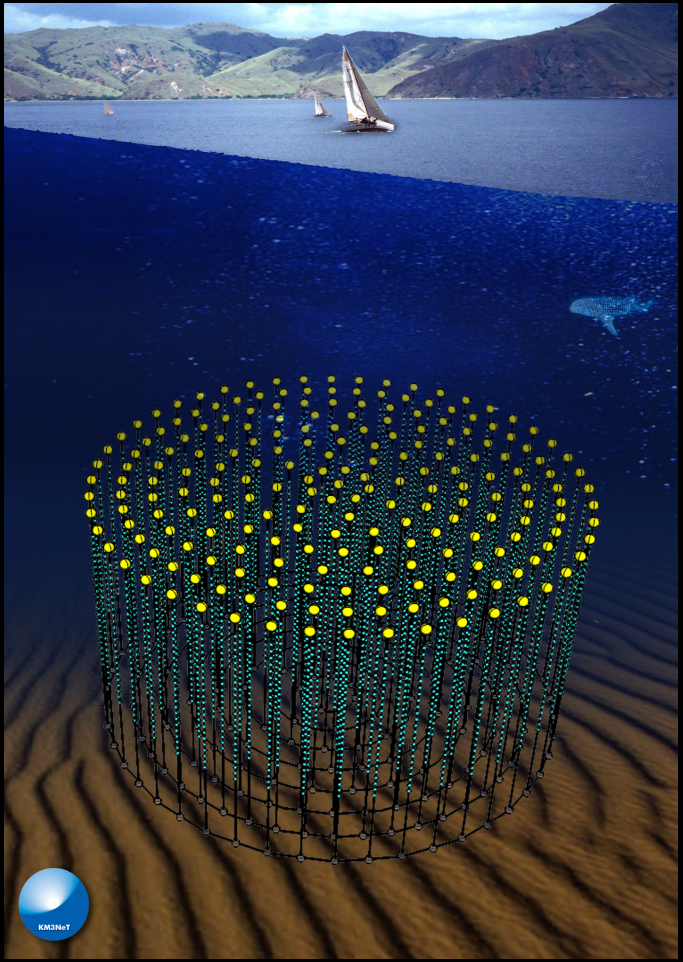


Gigaton Neutrino Detectors

IceCube 2013-
Southpole

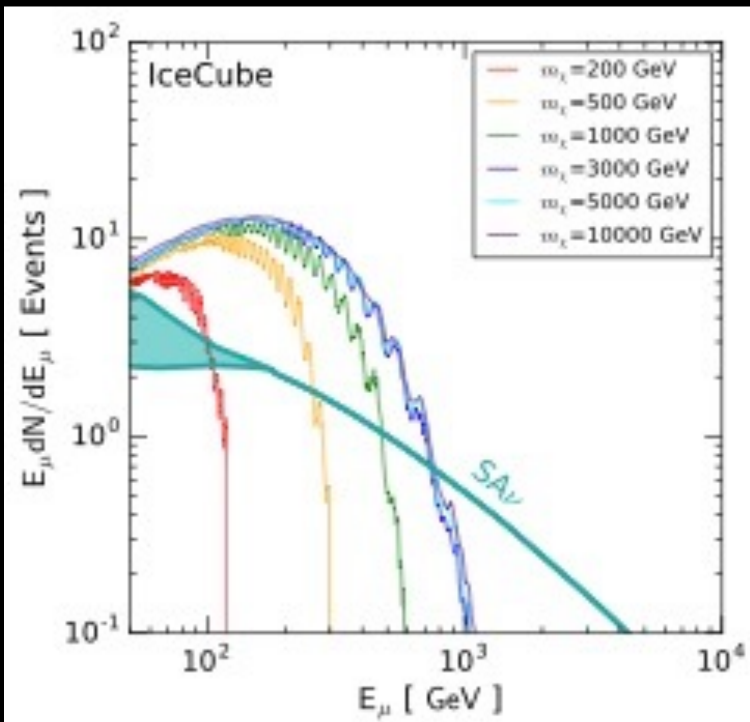


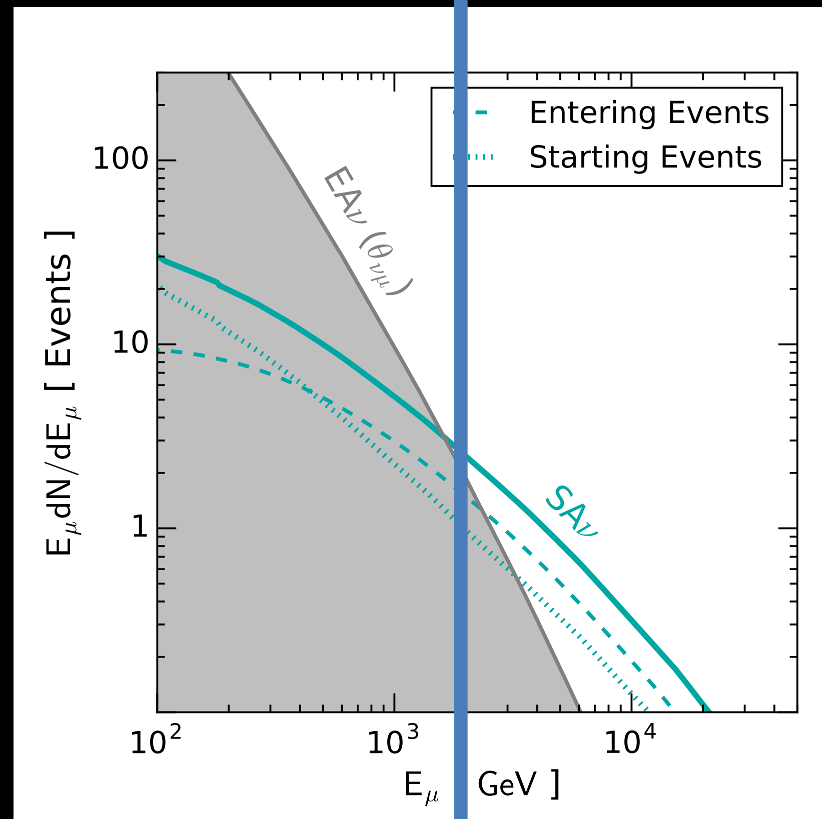
KM3NeT (building)
Mediterranean



Background or Signal? (Both!)

Theorist Expectation

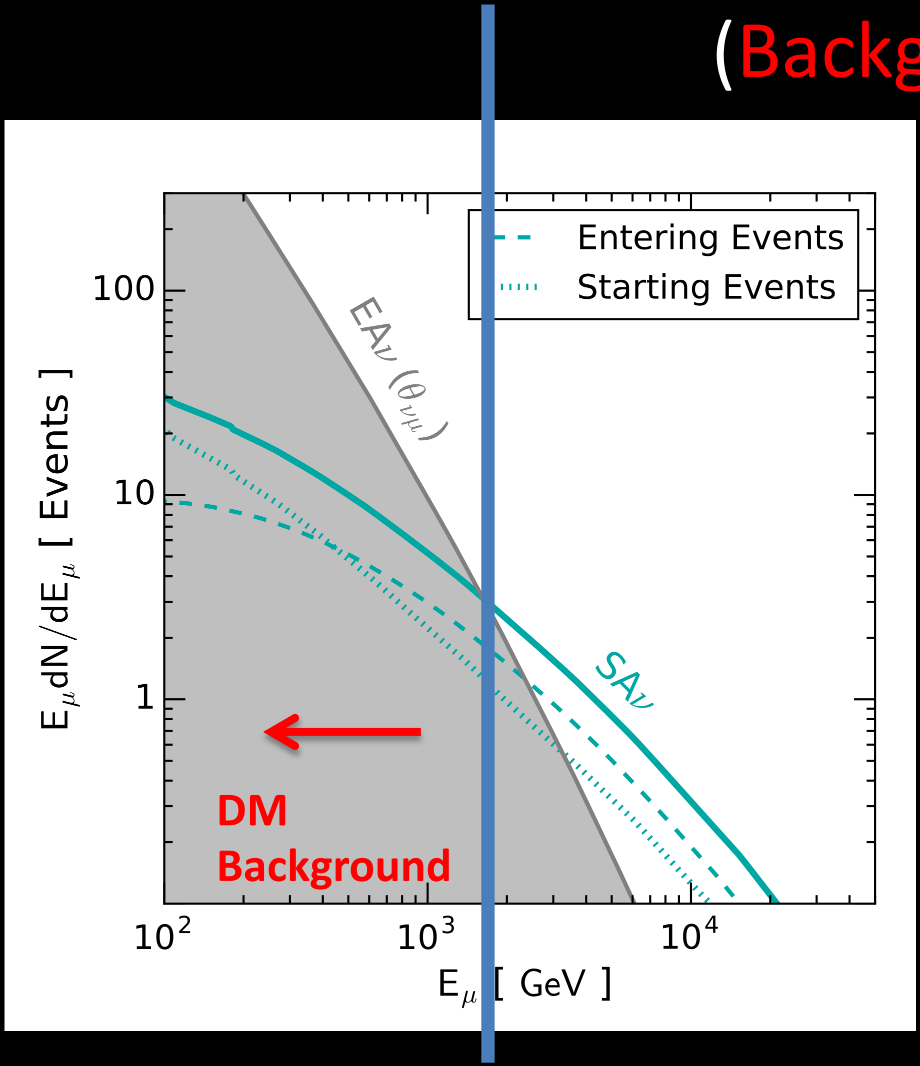


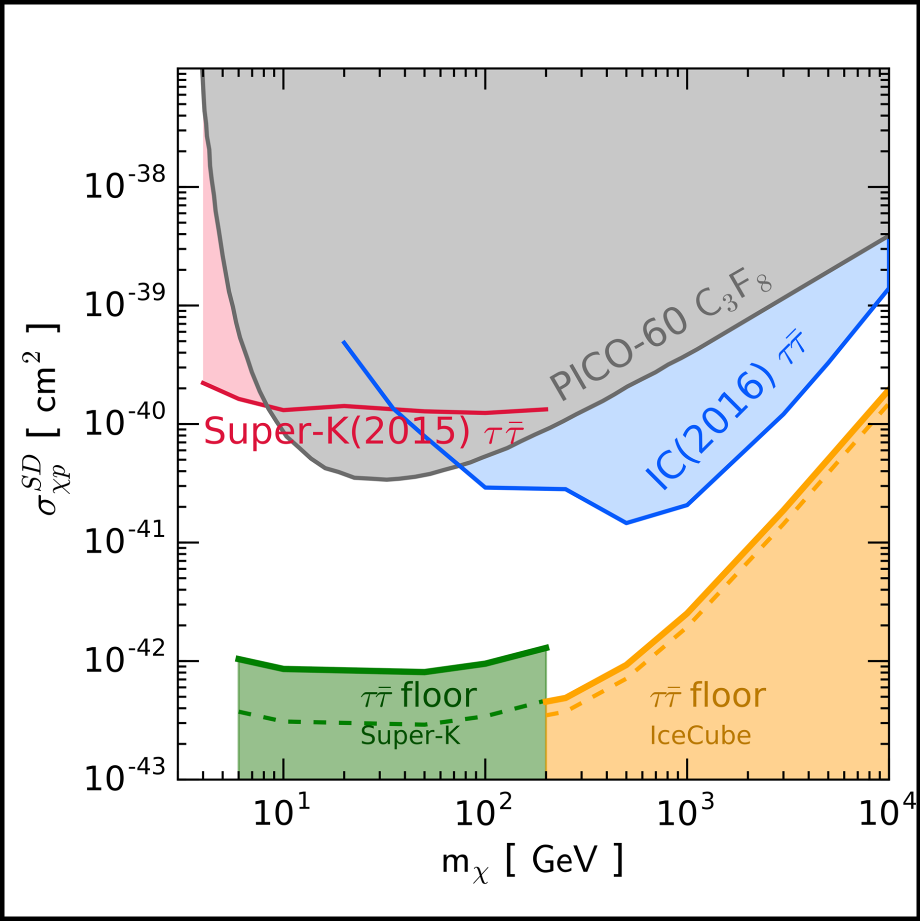


BAD energy-resolution
Difficult to distinguish from DM signal
Background!

Some energy-resolution
No DM signal*
Astrophysical signal!

Solar ATM neutrino – indirect detection Neutrino Floor (Background)





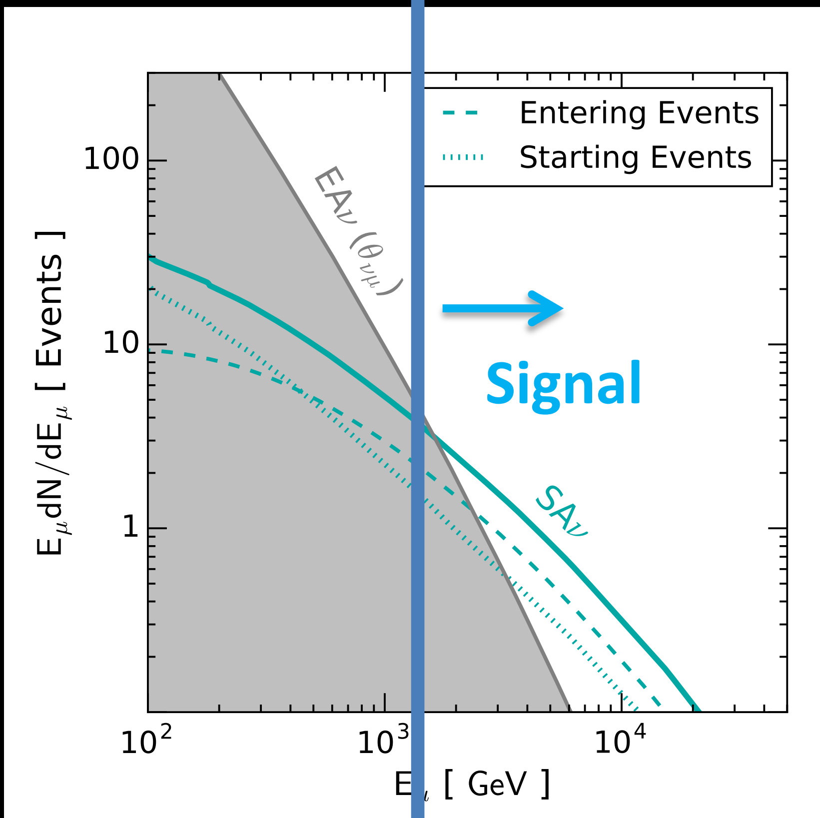
No B-field effect are considered

IceCube Search ongoing [S. In & C. Rott ICRC17 (965)]

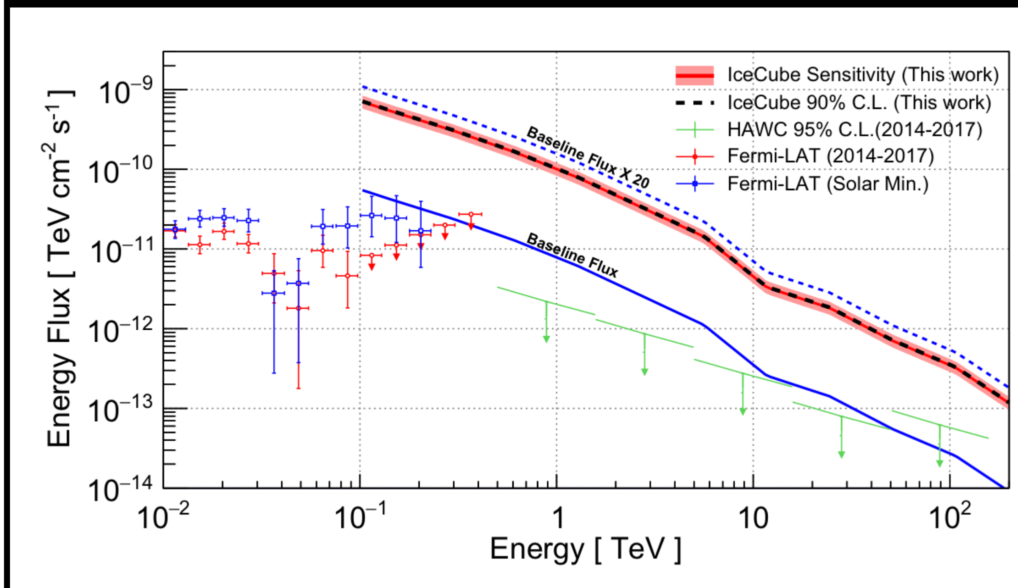
KCYN, Beacom, Peter, Rott, PRD 2017
See also
Arguelles+ 1703.07798
Edsjo+ 1704.02892

IceCube Search (Signal)

Theorist Expectation

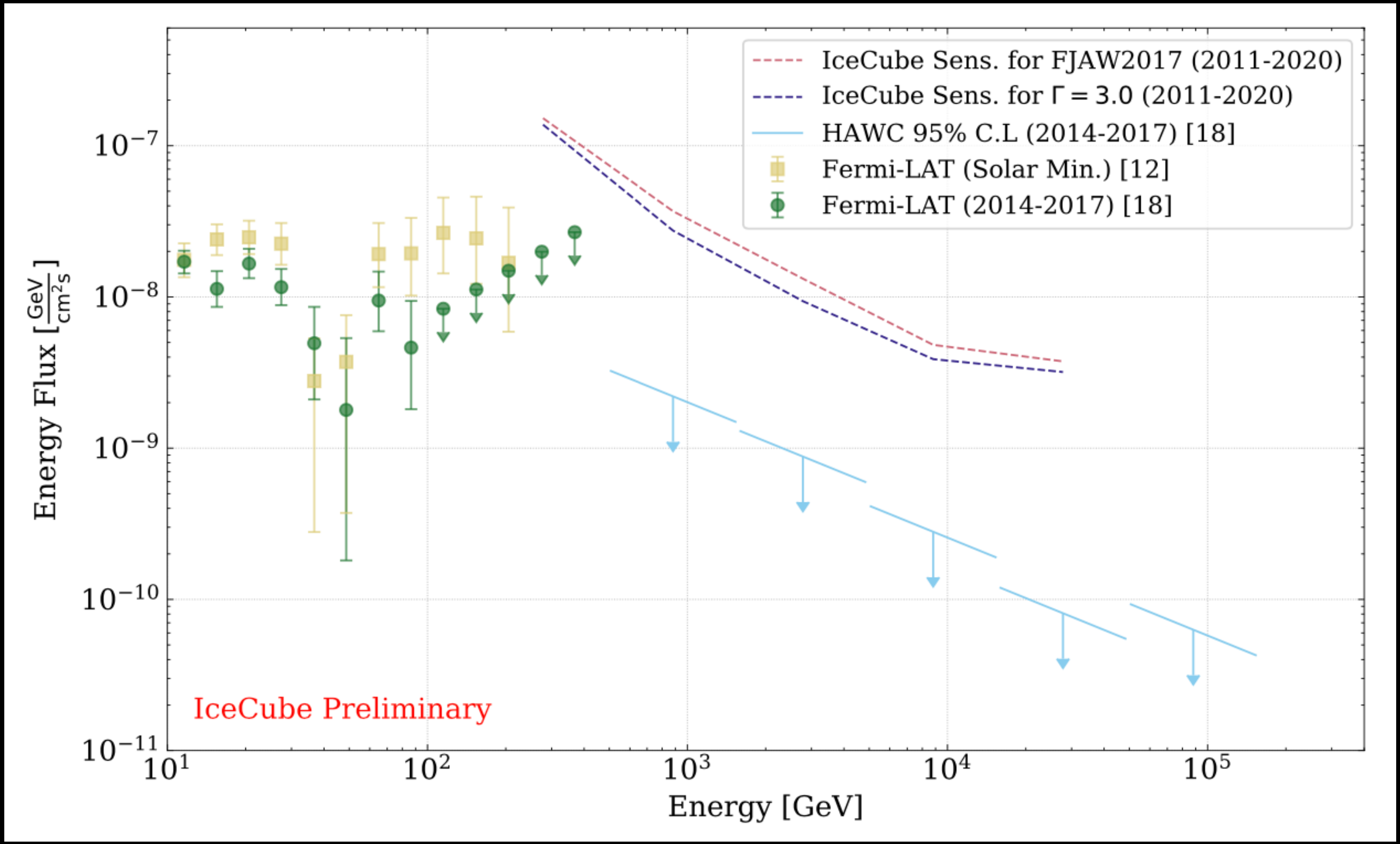


IceCube 2019
1912.13135
7 years of data



Seems difficult……
Improve analysis?

IceCube Search update(ICRC2021)



Only a factor of 2 away!

+ Sun shadow (analysis)?

+ Magnetic fields (theory)?

Solar Atmospheric Gamma Rays

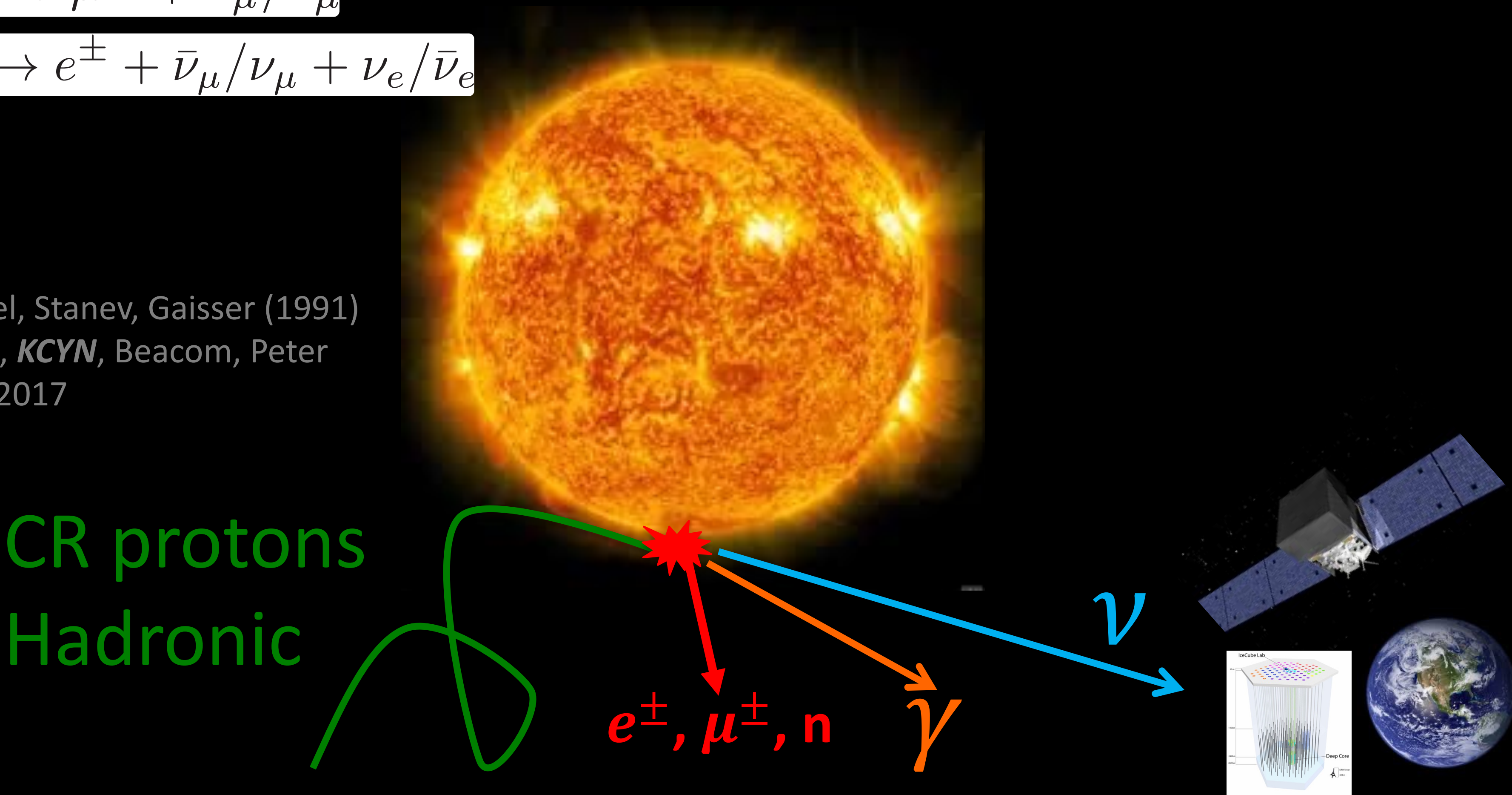
$$p + p \rightarrow \pi^0/\pi^\pm + X$$

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

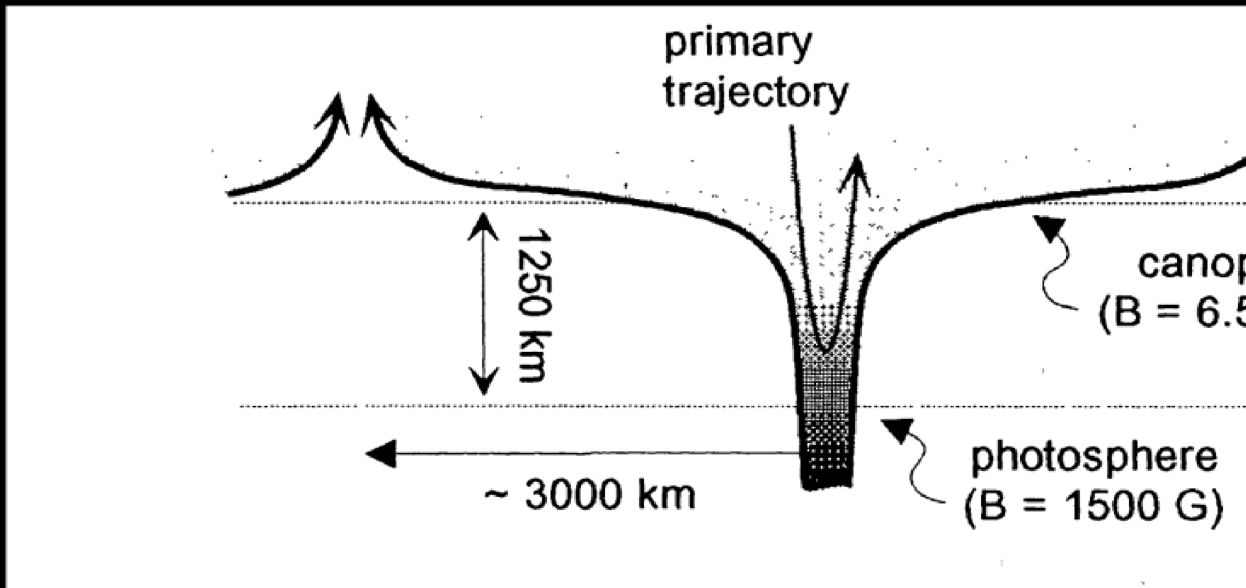
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$

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

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



Seckel Stanev Gaisser 1991



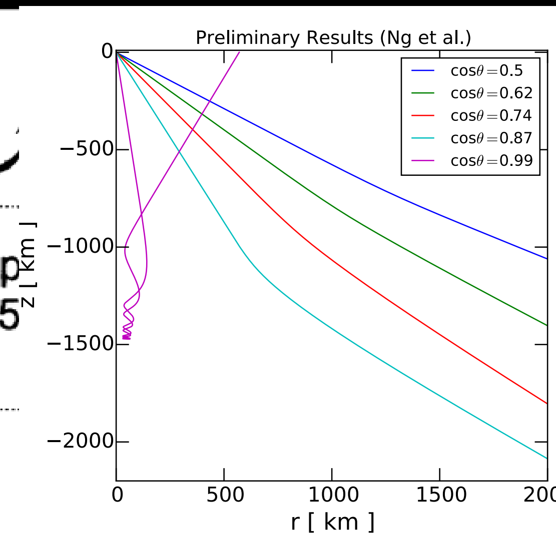


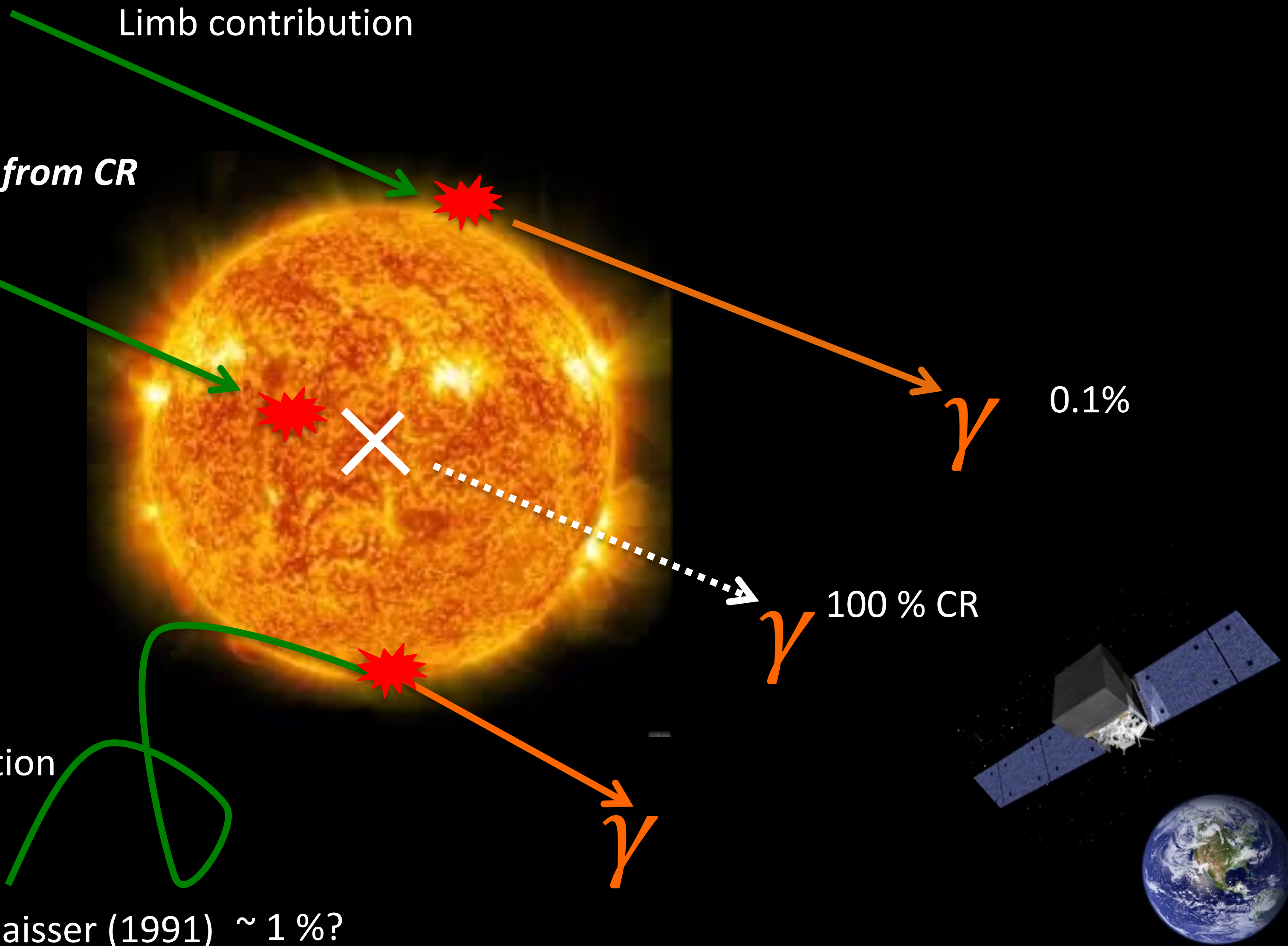
Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

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

Boost gamma-ray production

Solar atmospheric gamma rays

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

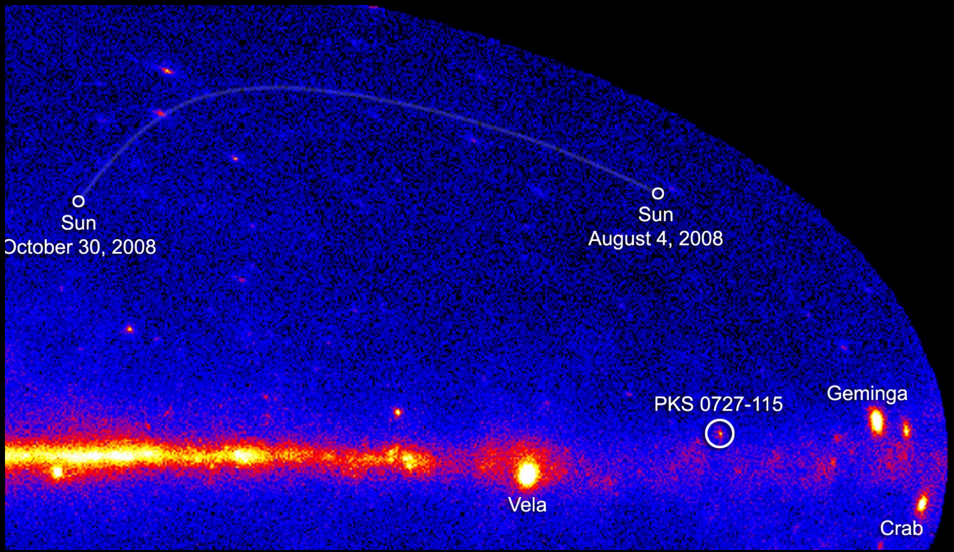


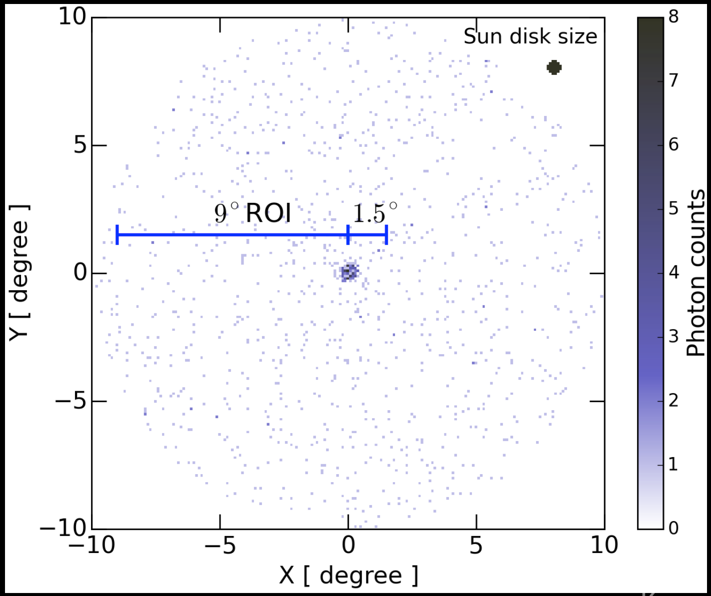
Reality

- Solar B-field
- Solar Modulation

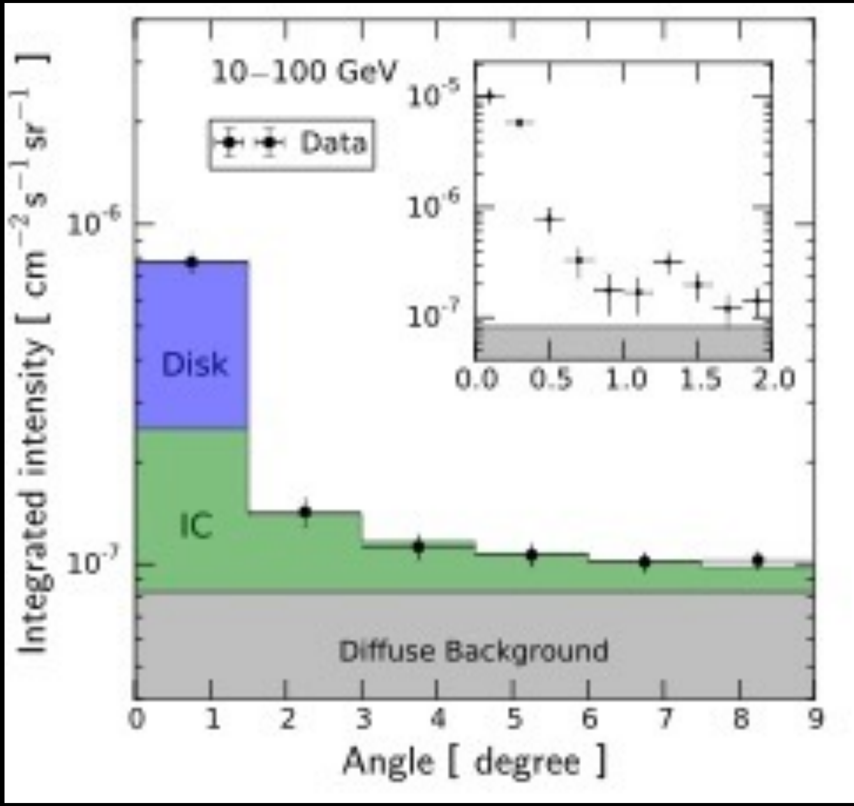
Seckel, Stanev, Gaisser (1991) ~ 1 %?

Finding the Sun with Fermi





Angular distribution

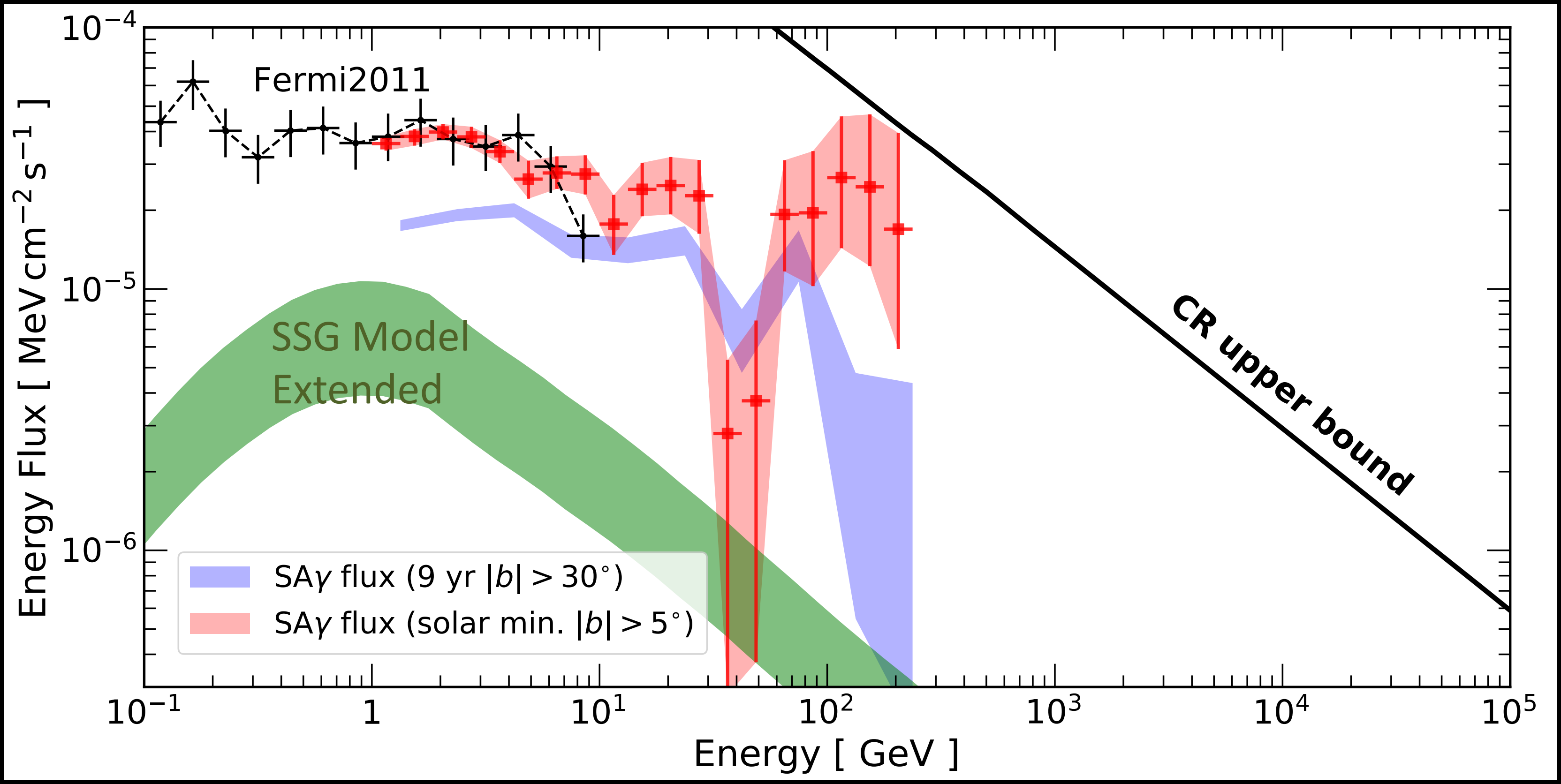


KCYN+ 2015

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

Observation: 9-year averaged spectrum

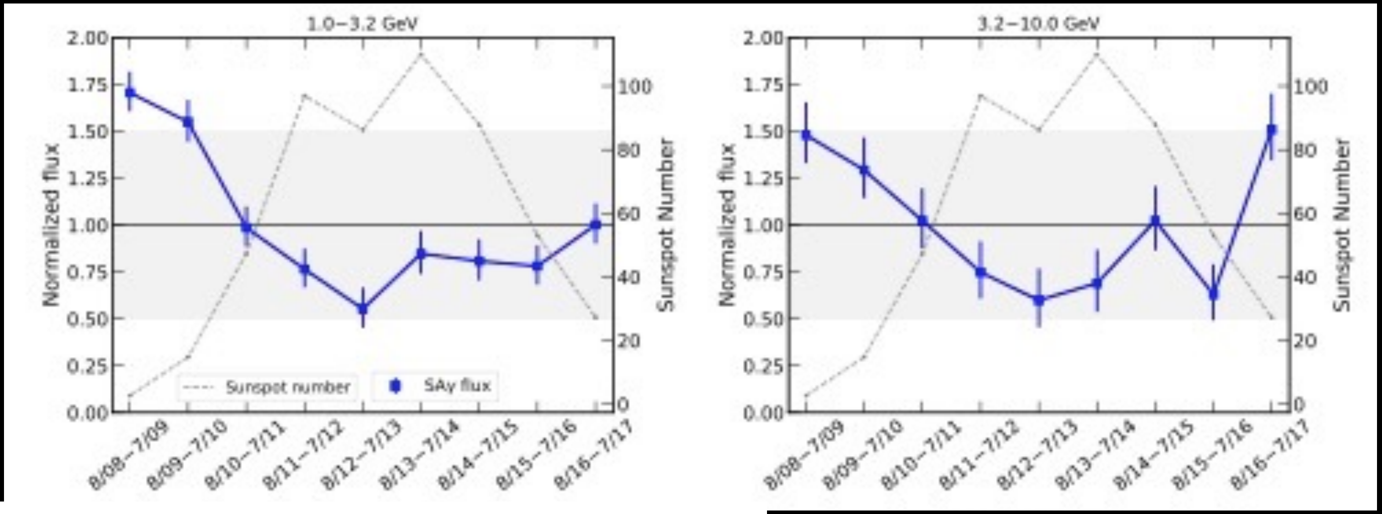
- Aug 2008 – Jan 2010 (solar min. 76 weeks)
- 2008 – 2017 (9 years)

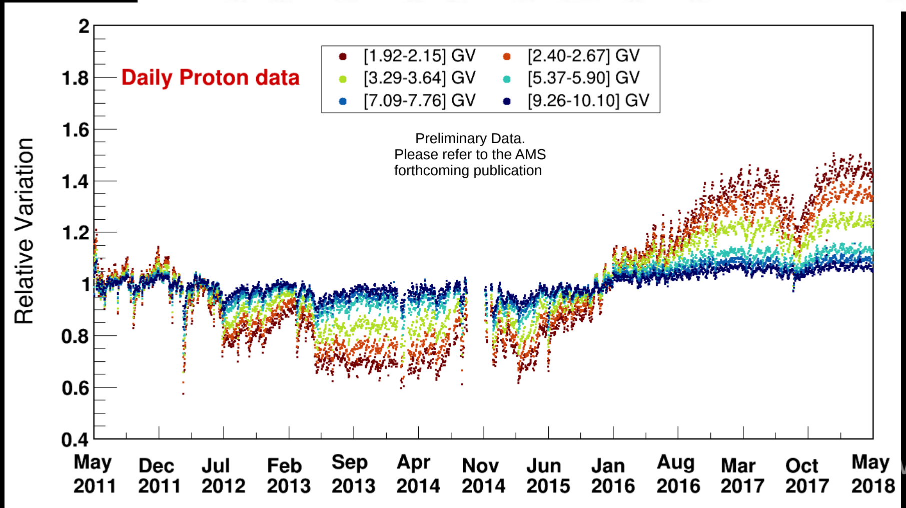


Time variation

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)



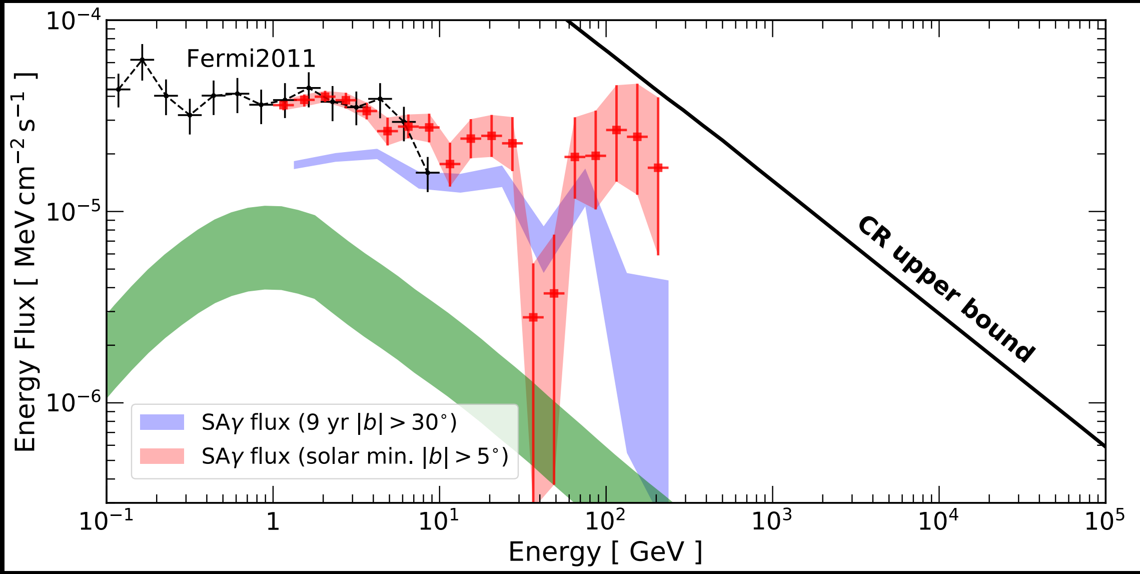


Small modulation amplitude
-> extra modulation needed near the Sun

C. Consolandi CRD8c

Spectrum, *surprise (2)*

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



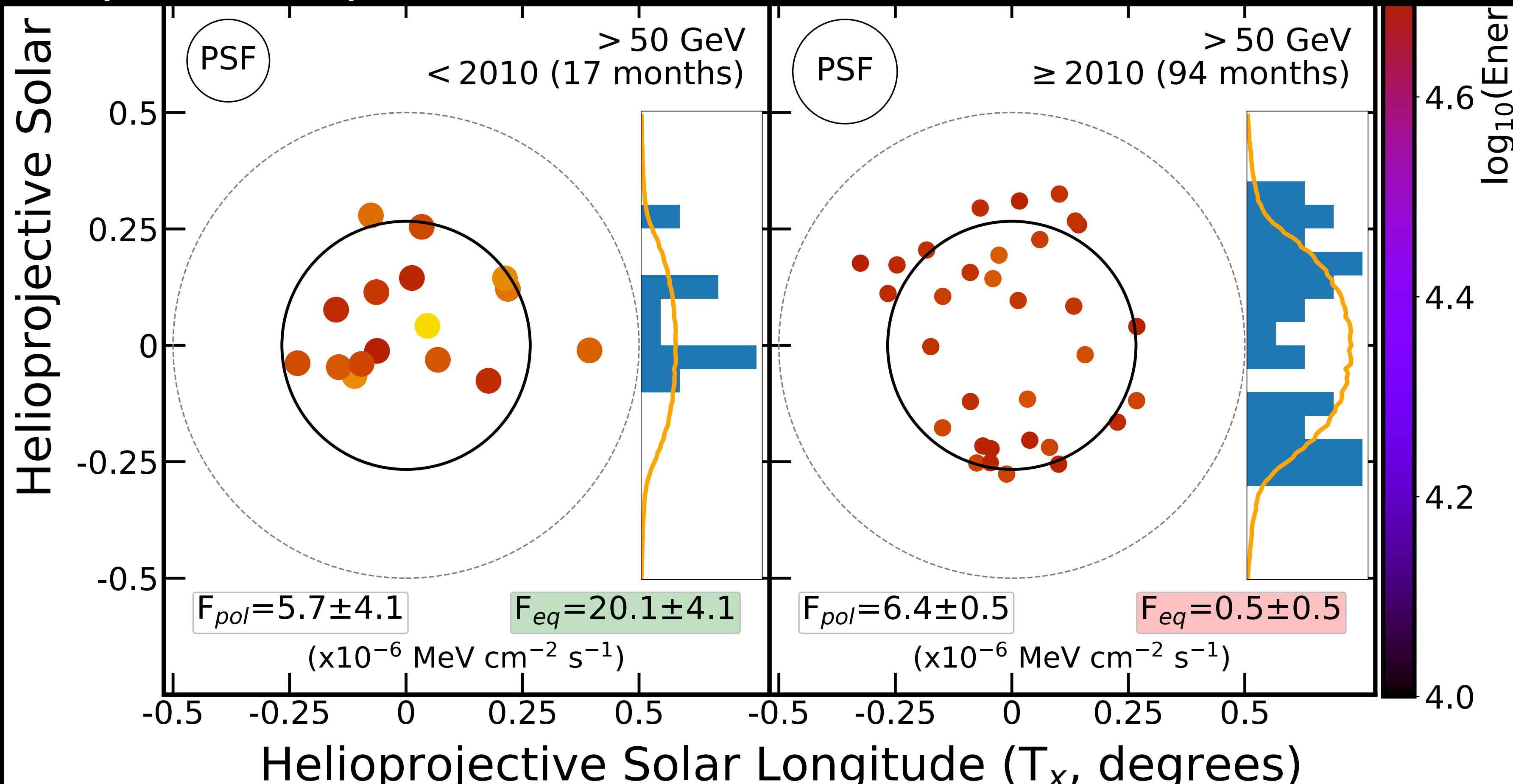
$$\text{FLUX(E)} \propto \sigma_{pp} \times \Phi_p(E) \times \epsilon(E)$$

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

Morphology, *surprise (4)*

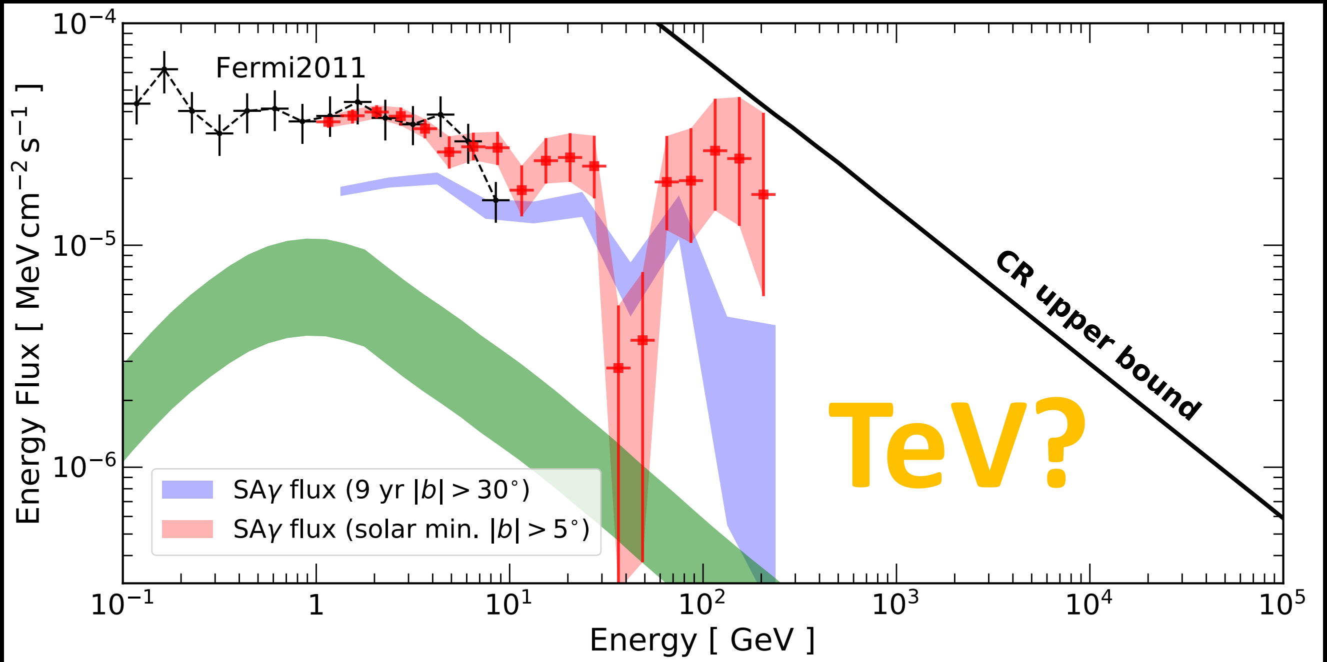
- High Energy Bin
  - (> 50 GeV)

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



Solar Gamma Spectrum

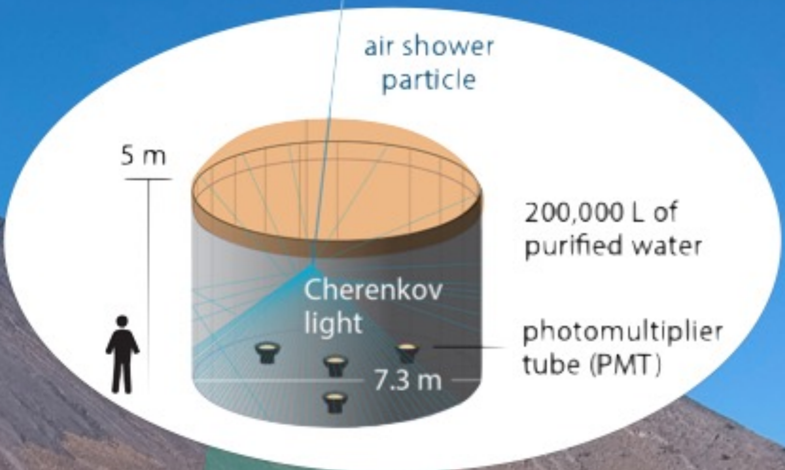
- Fermi data shows rich phenomenology
- The effect of magnetic fields is strong and not understood



Hao Zhou TeVPA2018

The HAWC Observatory

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



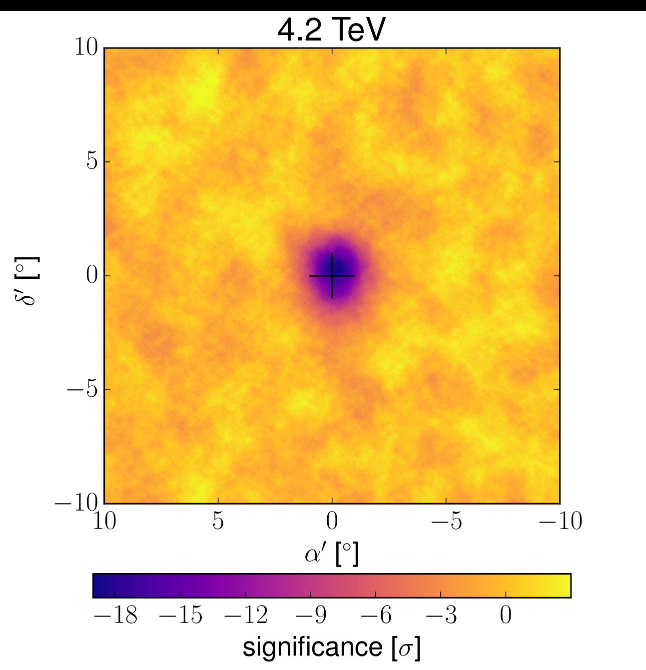
Excellent detector for extended sources

Main array inaugurated on March 20, 2015

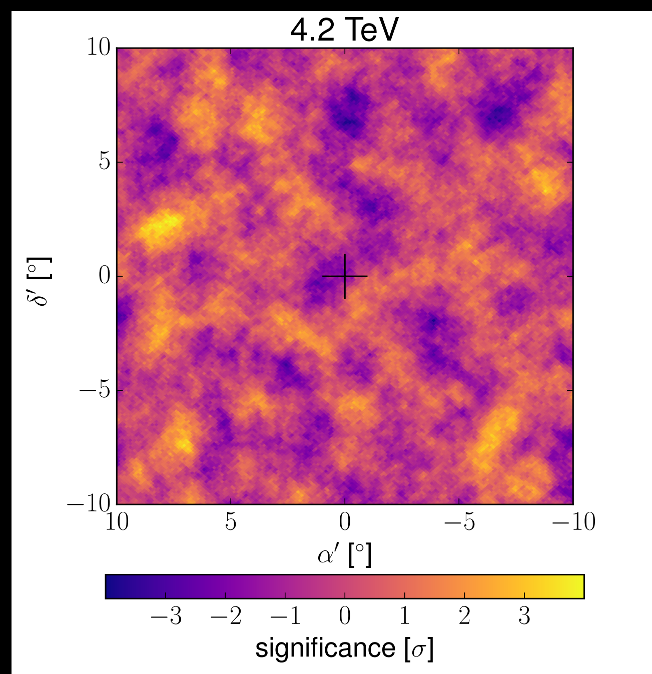
HAWC analysis

- Nov 2014 - December 2017 (829 days)
  - The sun was still active
- Significance map

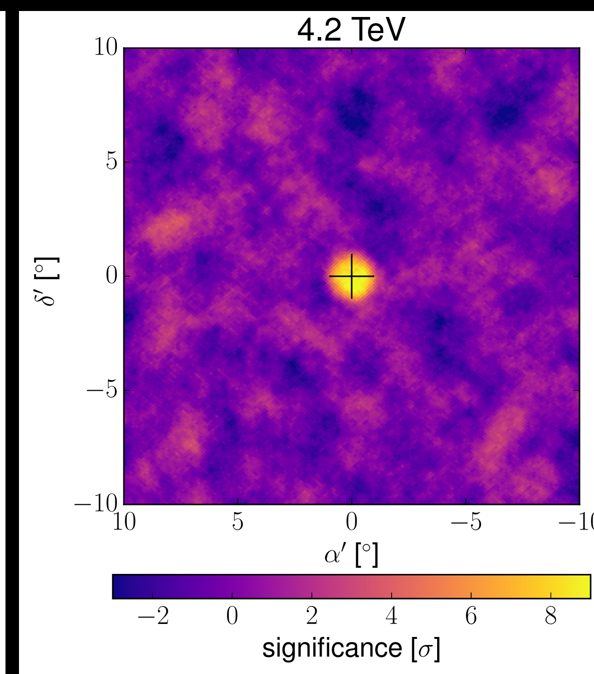
Sun Shadow (all data)



Gamma-hadron cut

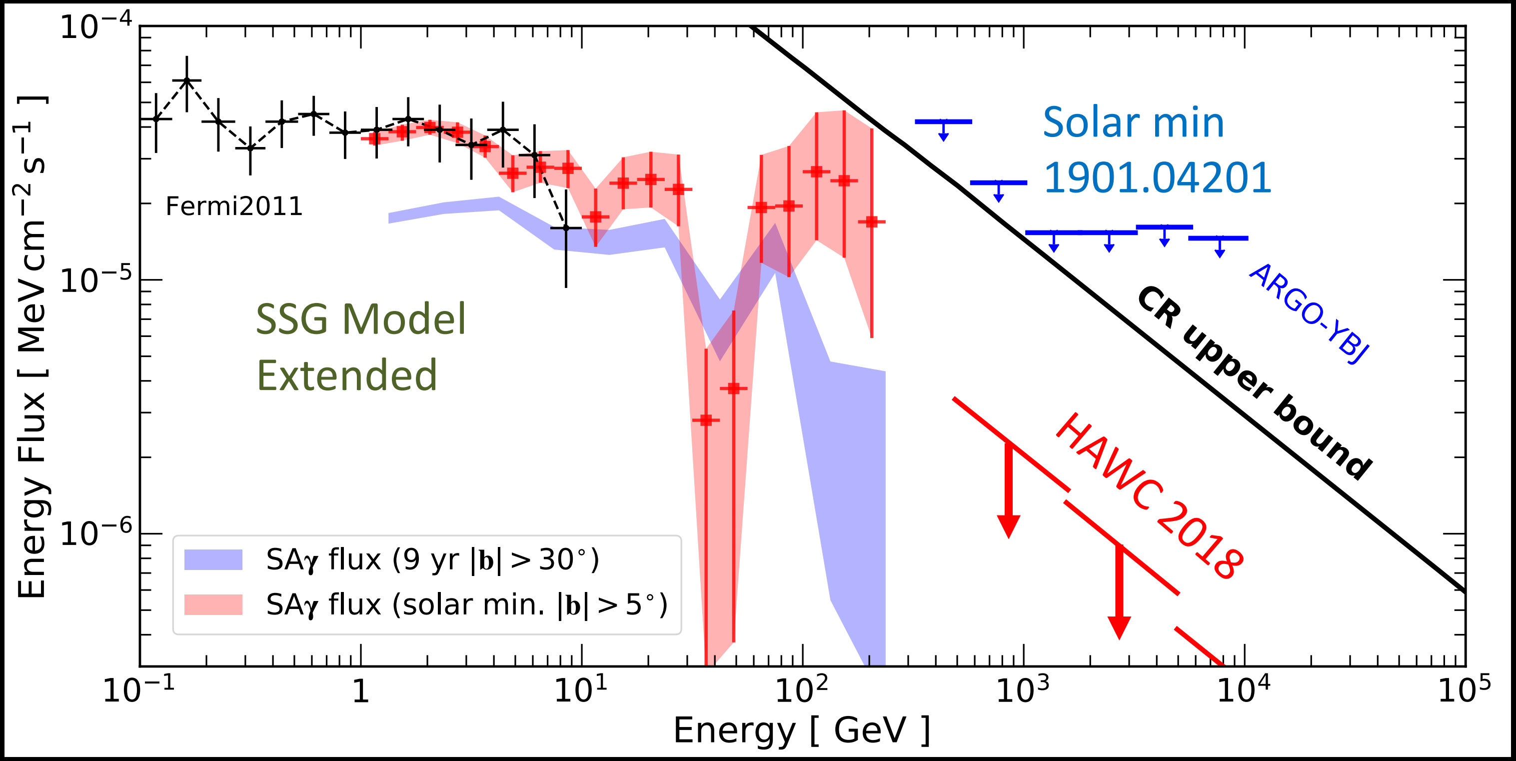


Expected (max. CR)

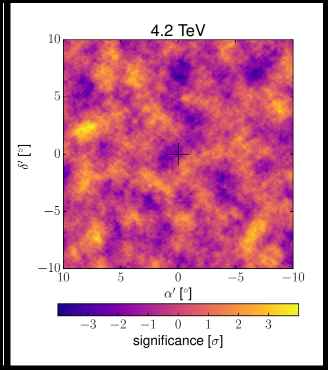


HAWC analysis of the Sun (2014-2017)

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



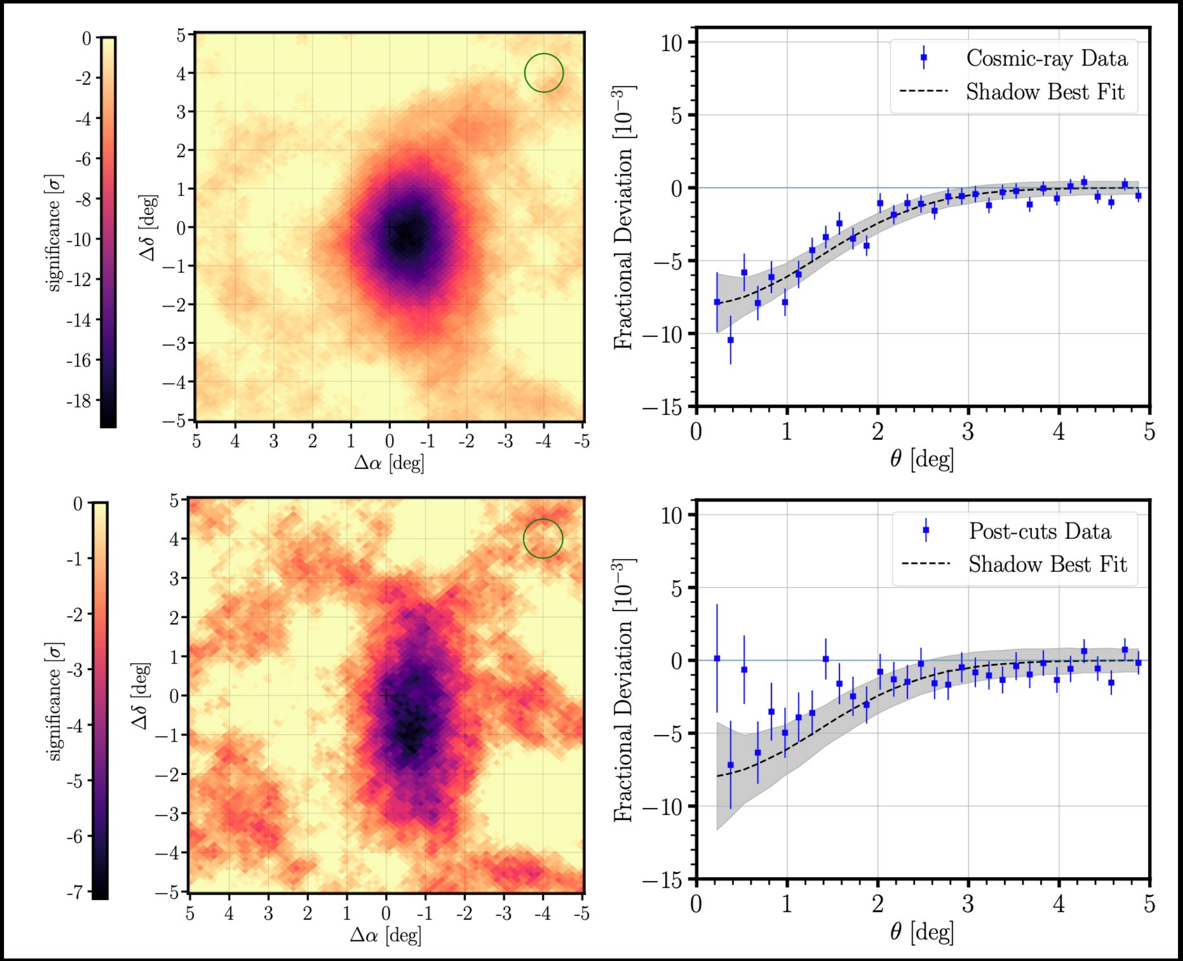
HAWC 1808.05620



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

2212.00815 [HAWC + Beacom, Linden *KCYN*, Peter, Zhou]

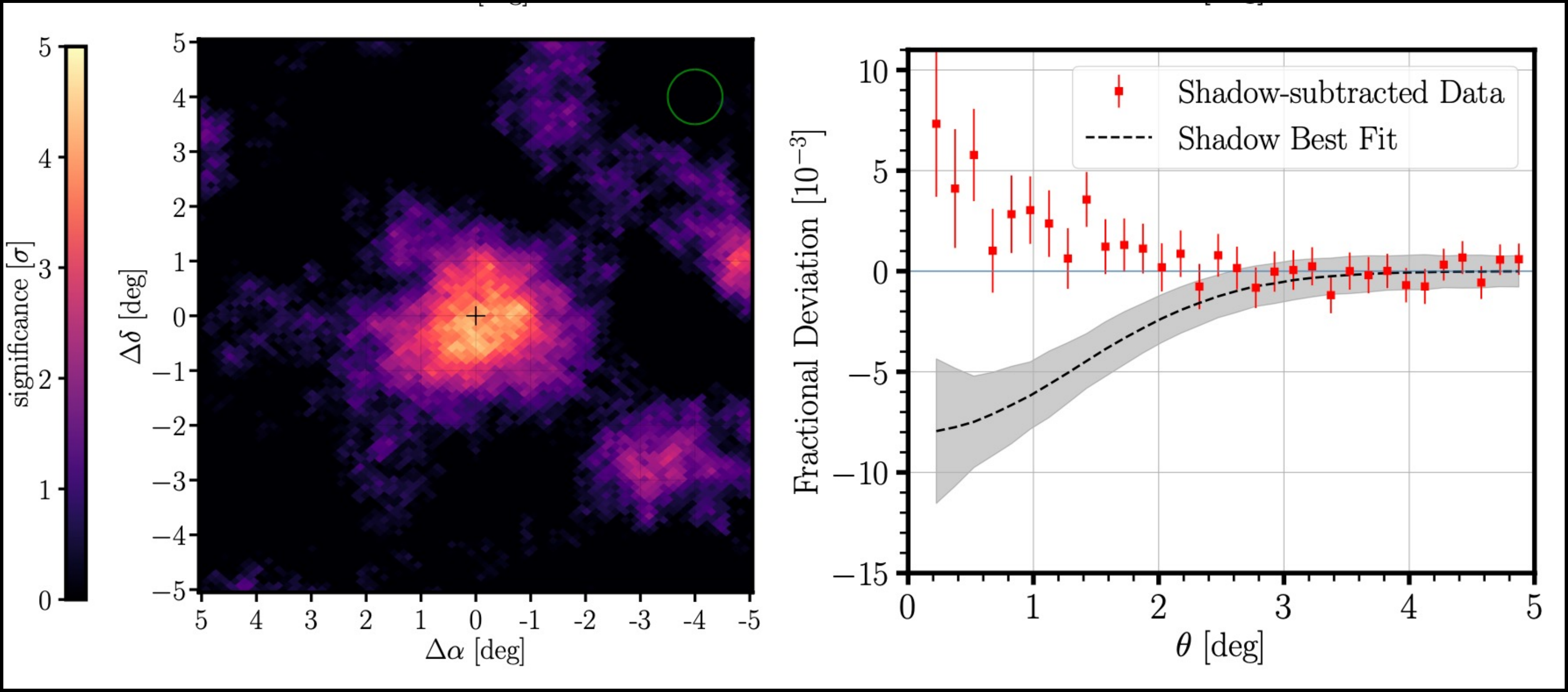
- Taking into account the Sun shadow
- Top: raw data, mostly cosmic rays
- Bottom panel: after gamma/hadron separation



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

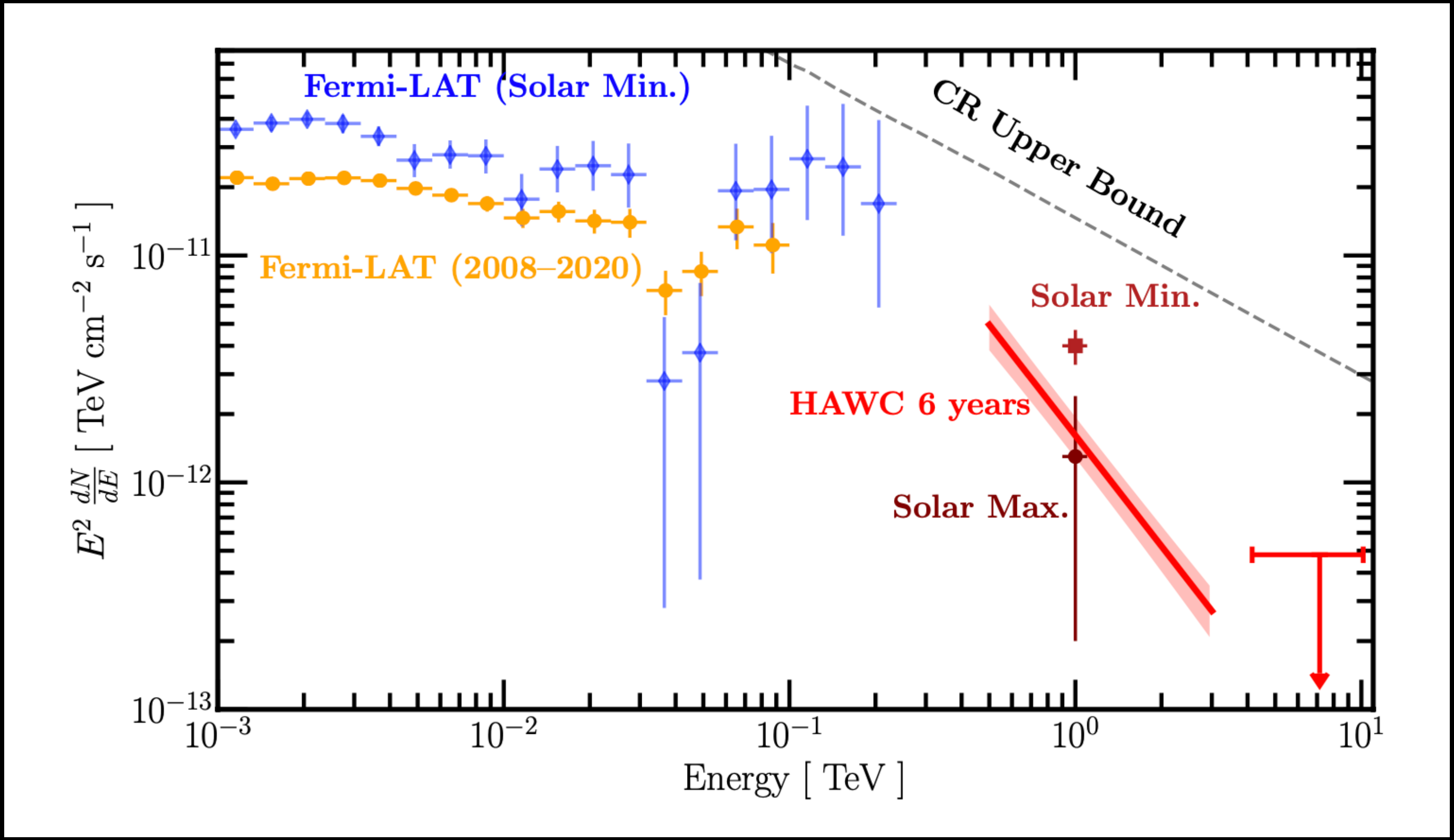
2212.00815 HAWC + Beacom, Linden *KCYN*, Peter, Zhou

- 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

2212.00815 HAWC + Beacom, Linden *KCYN*, Peter, Zhou

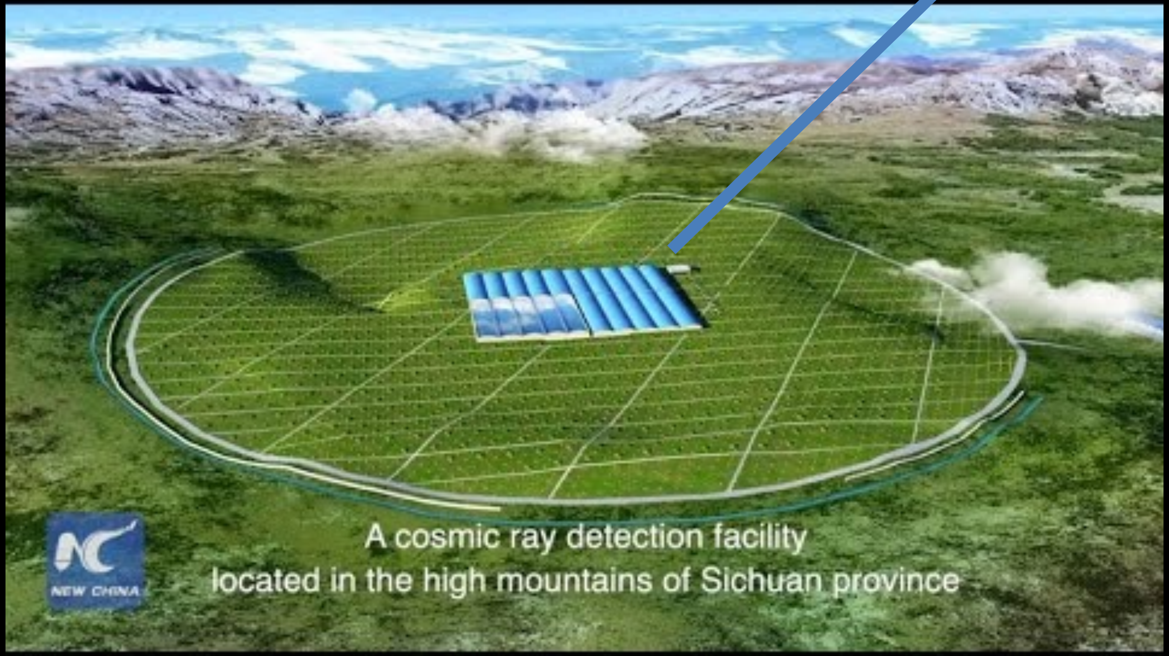


- Spectral index change!
- The Sun affects 10 TeV cosmic rays!

LHAASO

- South-western China

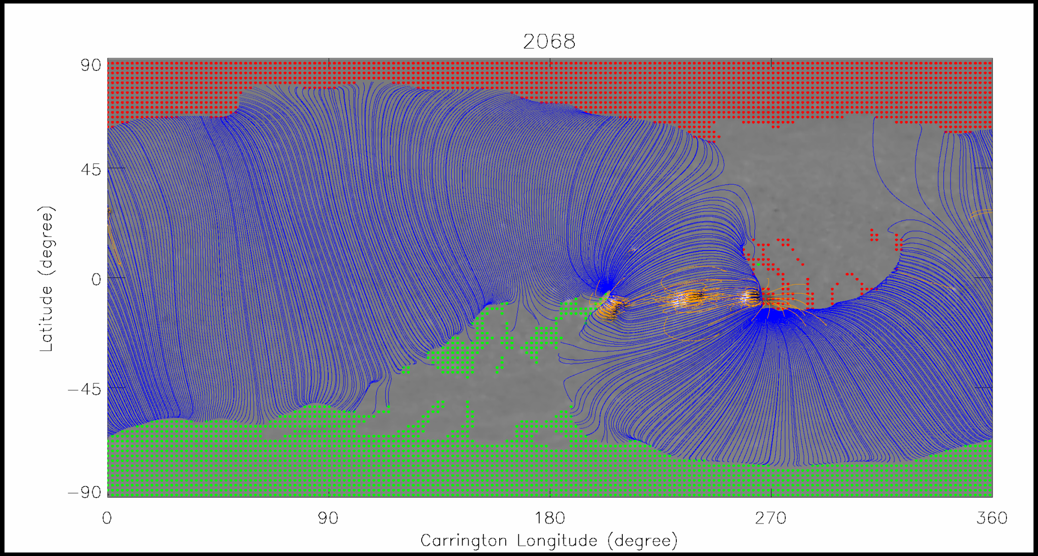
4X HAWC

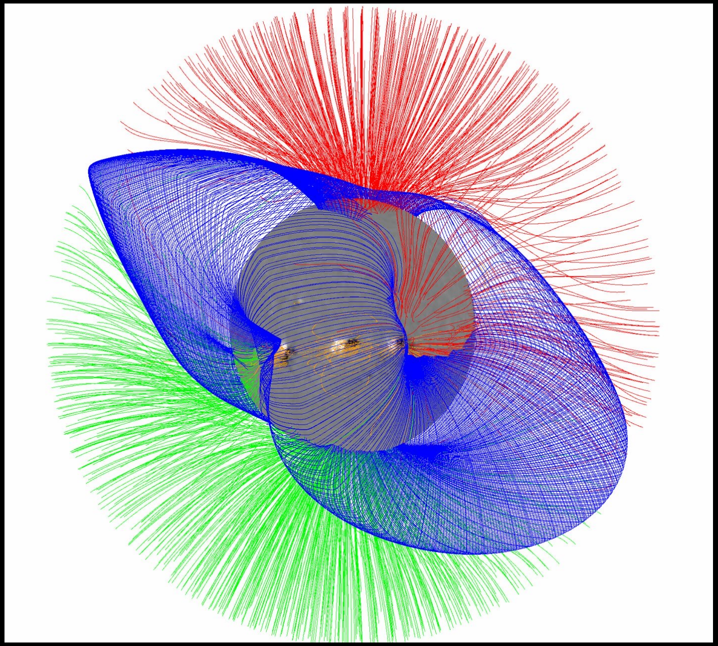


Simulating the Sun

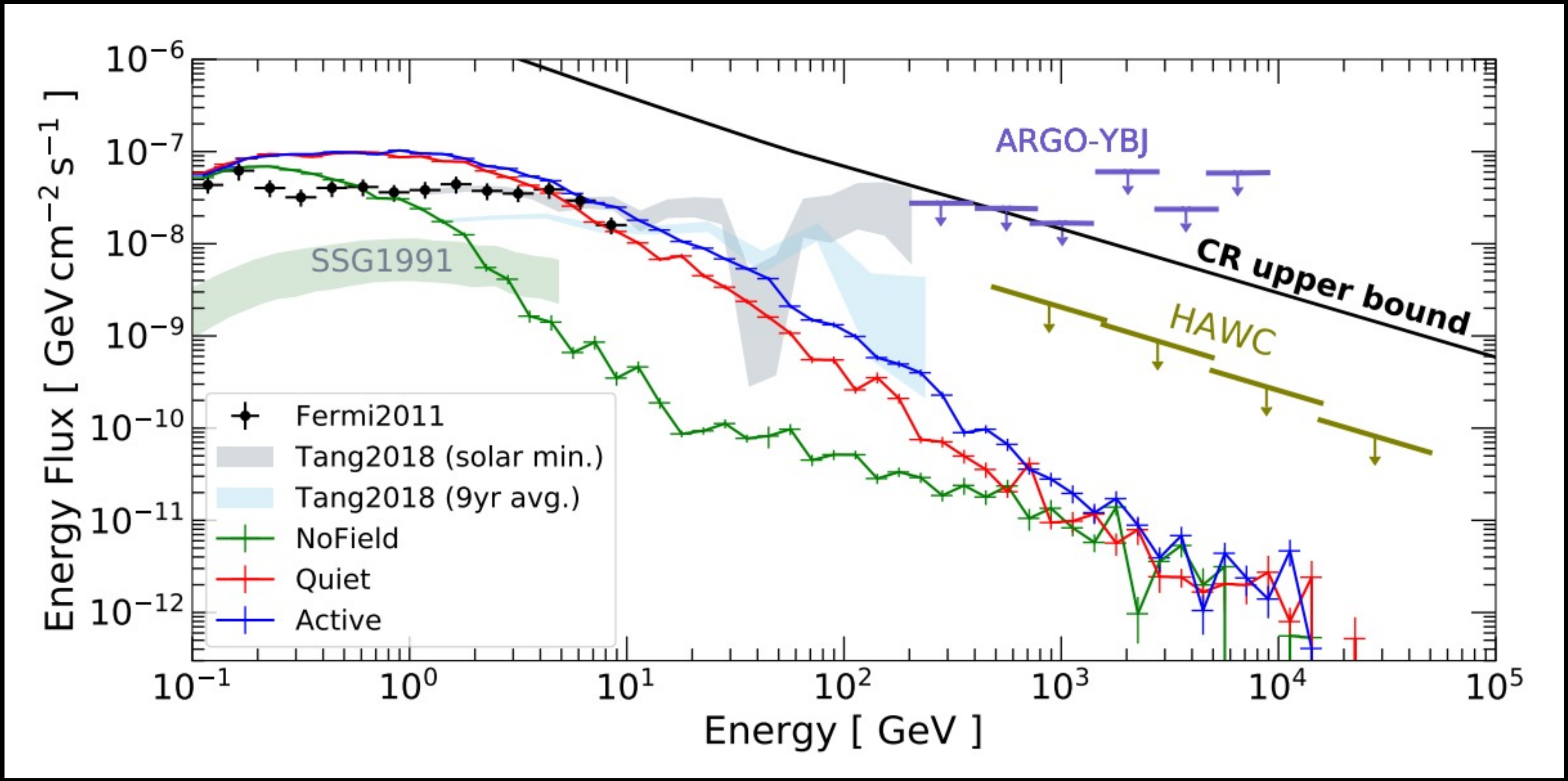
- Mazziotta et al 2001.09933 (FLUKA)
- Li et al (+KCYN) 2009.03888 (Geant4)

PFSS: Potential Field source surface Model





https://nso.edu/data/nisp-data/pfss/



- Corona B-field not enough to affect gamma-ray above 100 GeV arXiv.org > astro-ph > arXiv:2001.09933v3

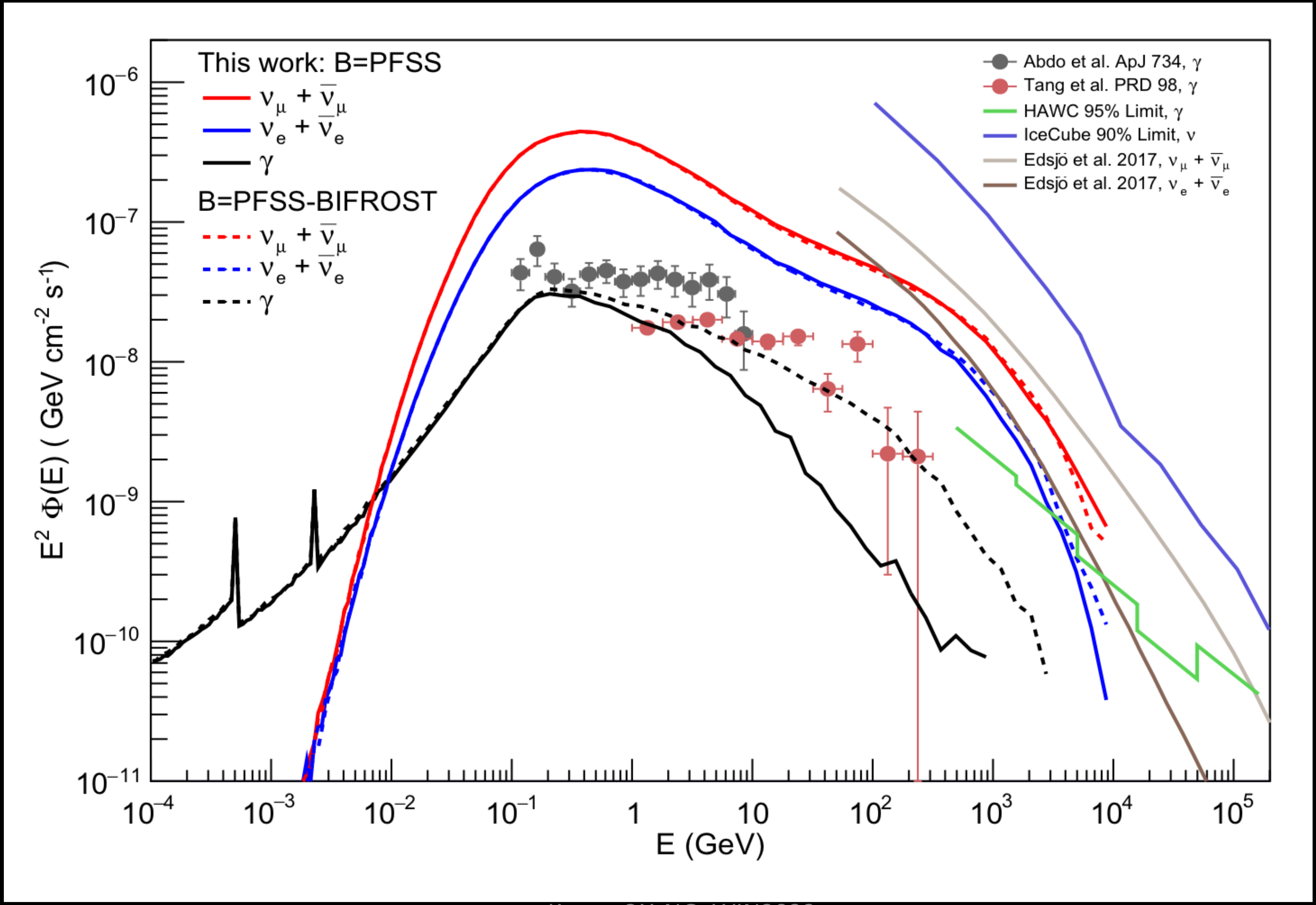
Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 27 Jan 2020 (v1), last revised 1 Oct 2020 (this version, v3)]

Neutrinos

Cosmic-ray interactions with the Sun using the FLUKA code

M. N. Mazziotta, P. De La Torre Luque, L. Di Venere, A. Fassò, A. Ferrari, F. Loparco, P. R. Sala, D.Serini



Summary

- *Solar atmospheric neutrinos*
  - *IceCube, KM3NeT (future)*
- *Gamma rays (Fermi + HAWC)*
  - *Not fully explained*
  - *Complete model necessary for accurate neutrino flux*
- *Anomalous Signals from the Sun -> New Physics!*

Thanks!

Thanks!

arXiv.org > astro-ph > arXiv:2001.09933v3

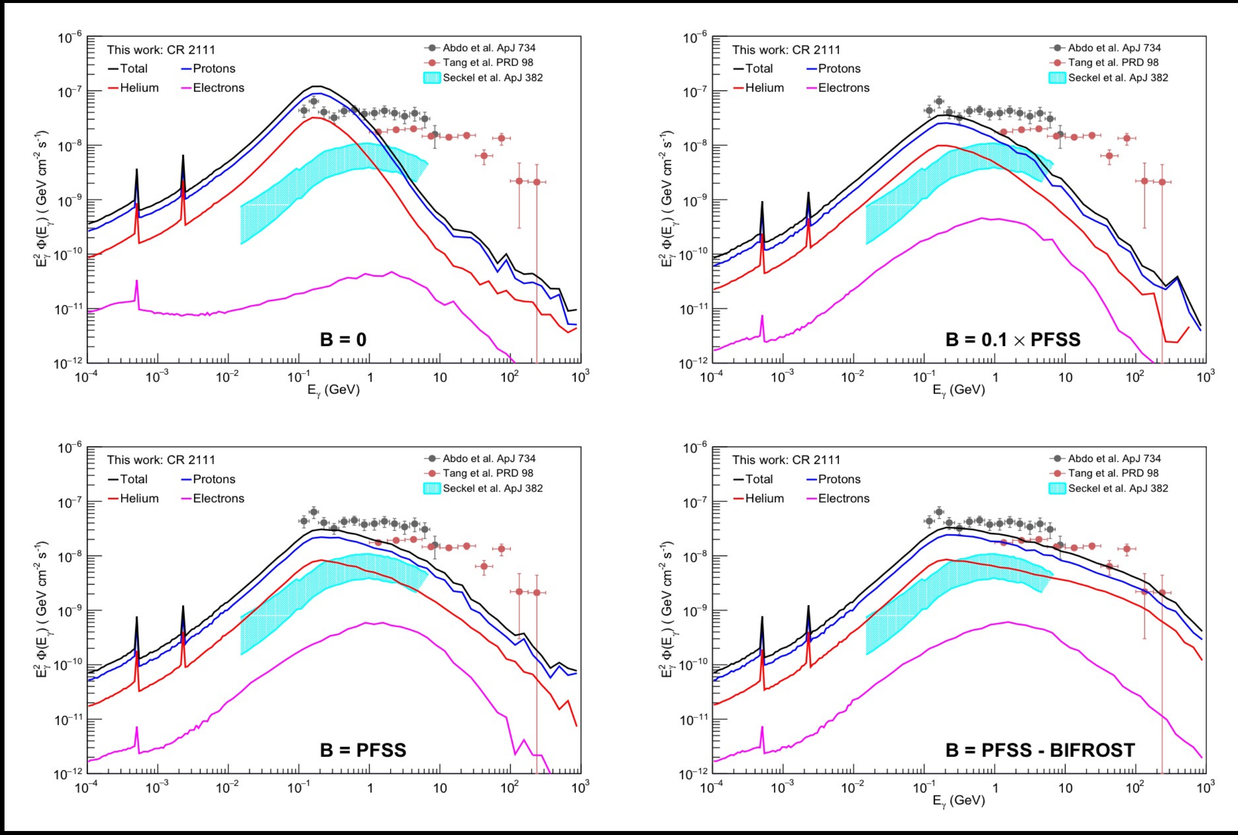
Astrophysics > High Energy Astrophysical Phenomena

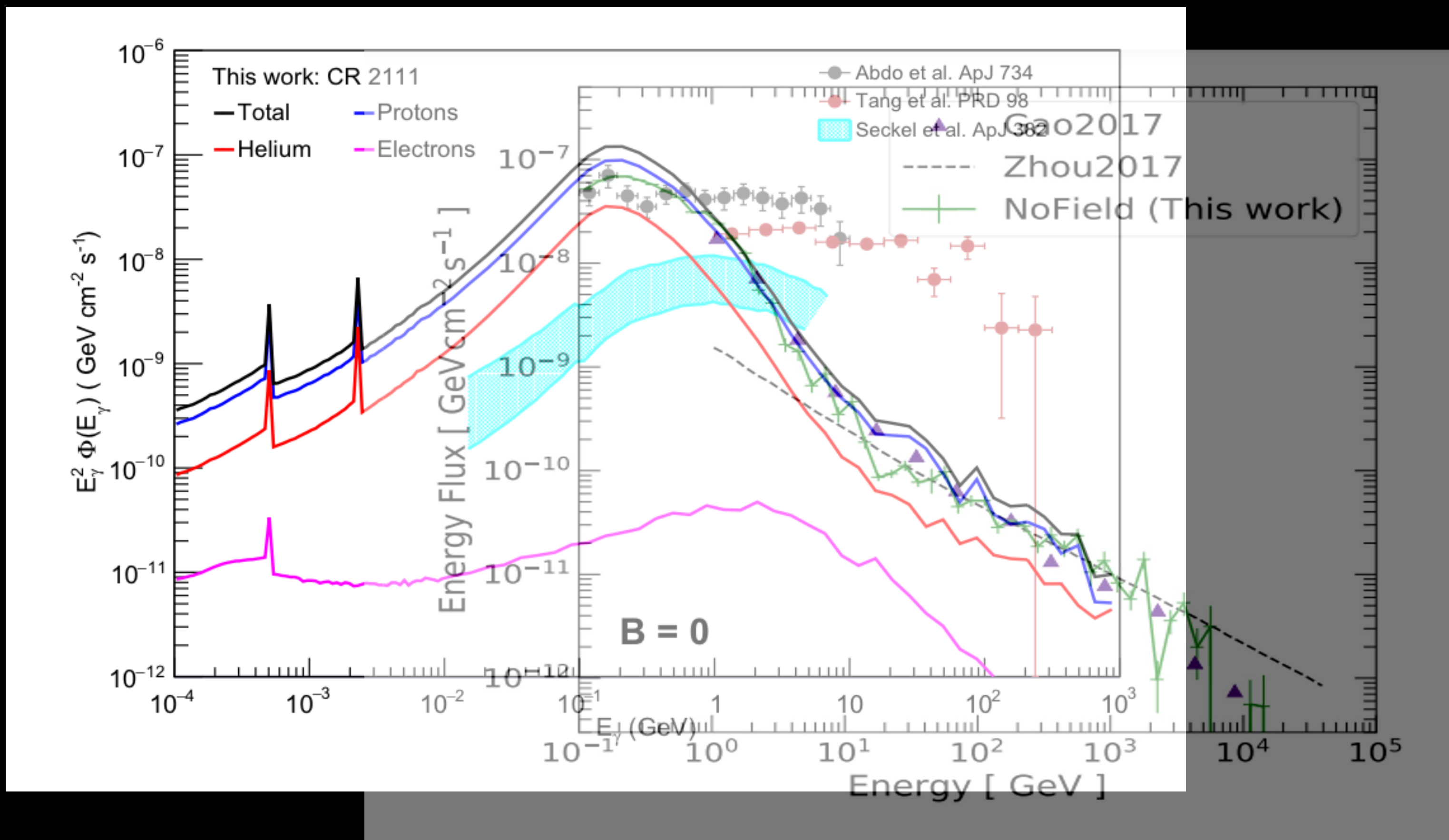
[Submitted on 27 Jan 2020 (v1), last revised 1 Oct 2020 (this version, v3)]

Cosmic-ray interactions with the Sun using the FLUKA code

M. N. Mazziotta, P. De La Torre Luque, L. Di Venere, A. Fassò, A. Ferrari, F. Loparco, P. R. Sala, D.Serini

- Cosmic ray propagation in the solar system
- PFSS magnetic fields
- BIFROST, enhancing B-field by 25 times below 1.01 Rsun
- 1. GeV flux enhanced without magnetic fields
- 2. B-field enhances high-energy flux




This work: CR 2111
Total
Protons
Helium
Electrons
Abdo et al. ApJ 734
Tang et al. PRD 98
Seckel et al. ApJ 382
Gao2017
Zhou2017
NoField (This work)
B = 0
Energy Flux [GeVcm⁻² s⁻¹]
Energy [GeV]
E_γ (GeV)

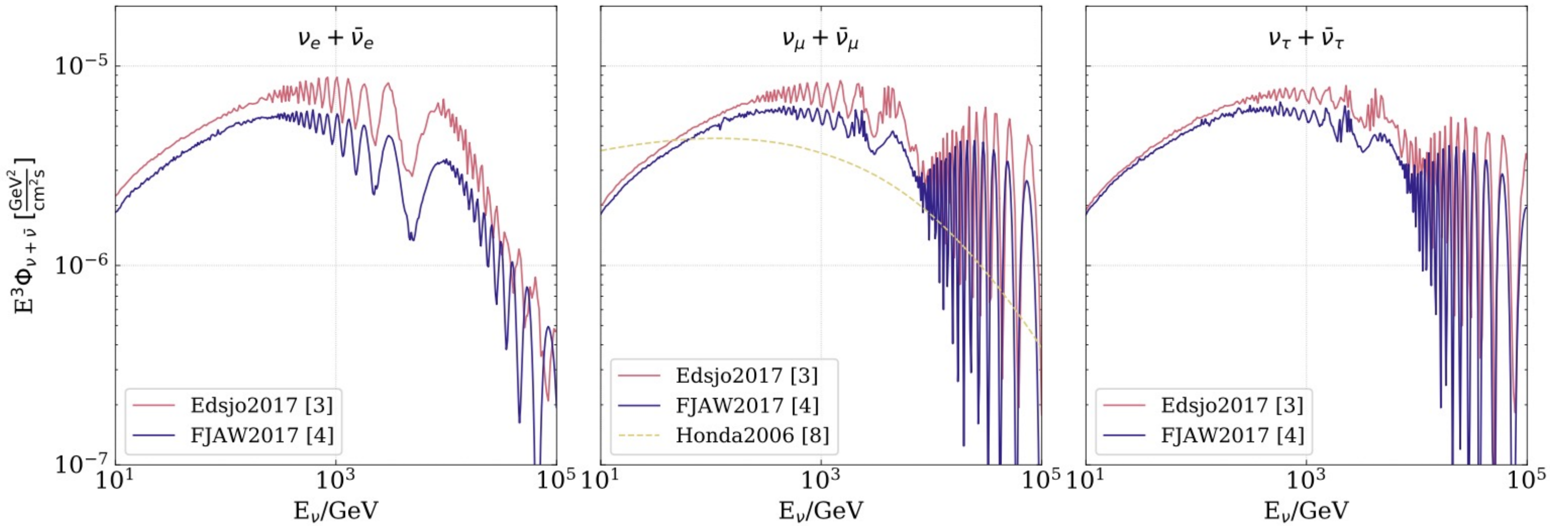
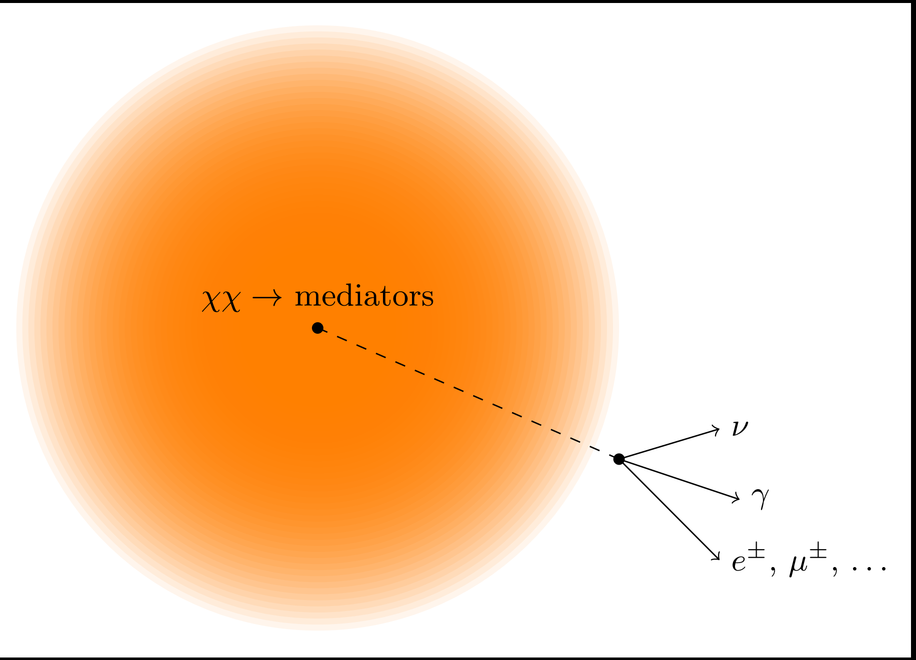


Figure 1: Neutrino flux after propagating 1 AU from the sun for our reference fluxes from [6] (Edsjo2017) and [7] (FJAW2017). For Edsjo2017, we pick the calculation based on Hillas-Gaisser H3a [8] as the Cosmic Ray model, Serenelli+Stein [9, 10] as the solar density model and normal neutrino mass ordering. For FJAW2017, we pick the calculation based on Hillas-Gaisser H4a [8] as the cosmic ray model and FJAW2017's custom sun model [7]. For μ-neutrinos, we also compare the fluxes to the expected flux for conventional atmospheric neutrinos from the direction of the solar disk using a flux prediction from [11].

Dark Matter with long-lived mediators

Leane, KCYN, Beacom 1703.04629



- Unlock
  - Gamma rays
  - Electrons, muon, etc
- Unsuppressed
  - Neutrinos!

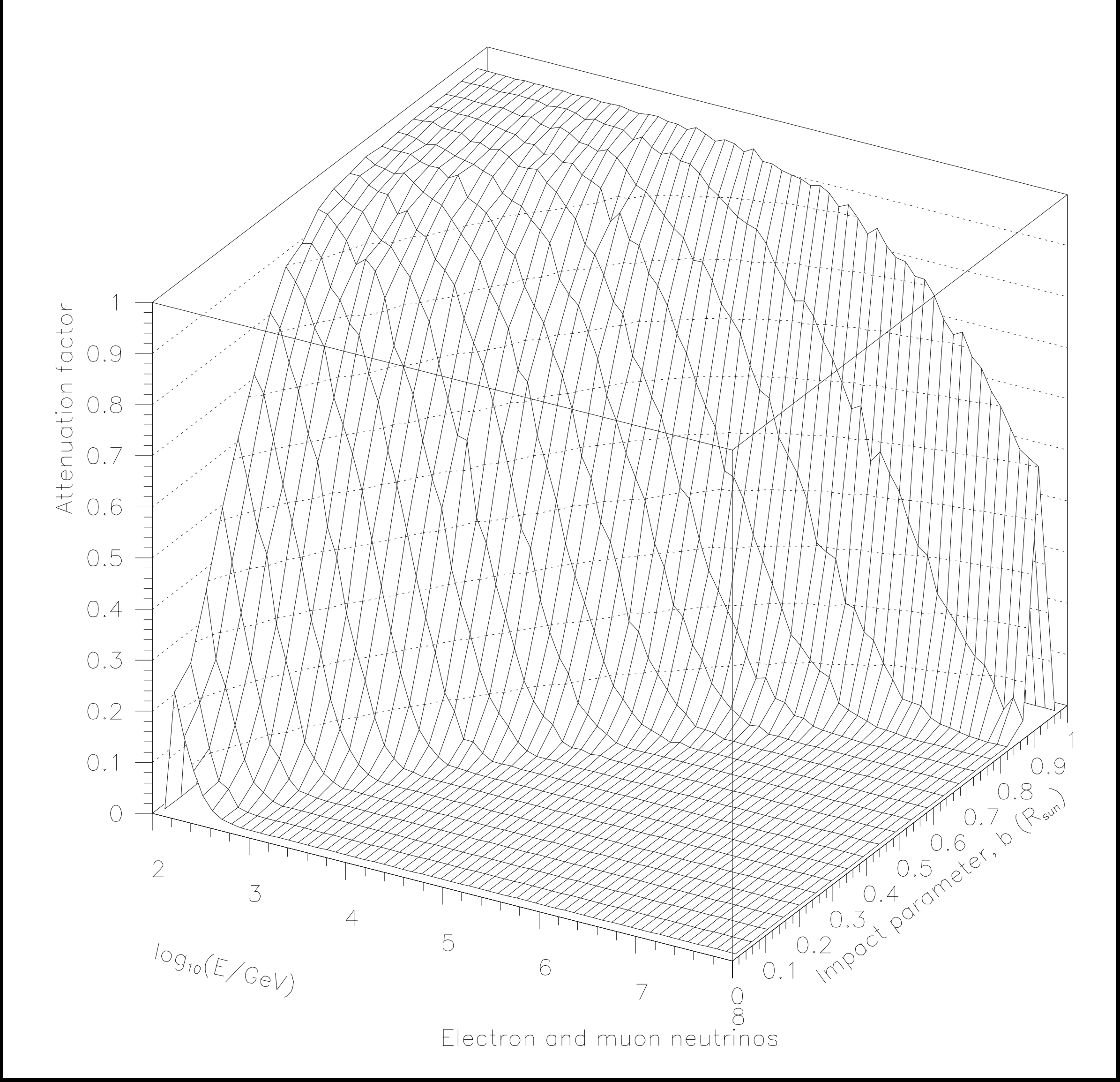
- Less absorption (ν)
- Lower density (ν)
- Decay tail (ν, γ)

Batell, Pospelov, Ritz, Shang, 0910.1567
Bell, Petraki, 1102.2958
Feng, Smolinsky, Tanedo, 1602.01465
Arina, Backovic, Heisig, Lucente, 1703.08087

Niblaeus, Beniwal, Edsjo, 1903.11363
etc

Flux without B/field

- Absorption through the sun
- Oscillation
  - Factor of 2 effect



Joakim Edsjo+ 1704.02892