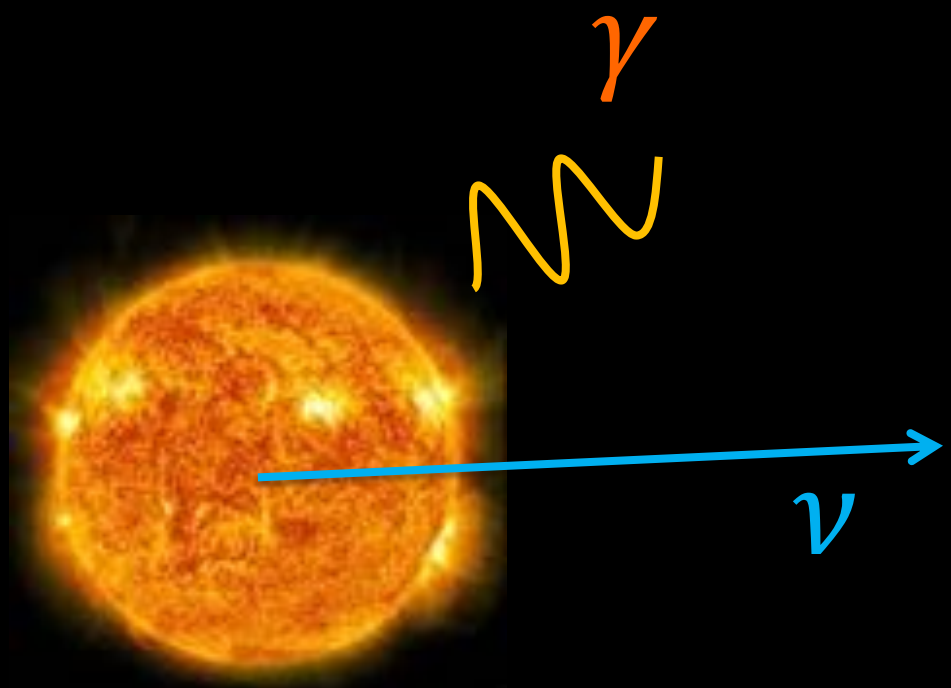
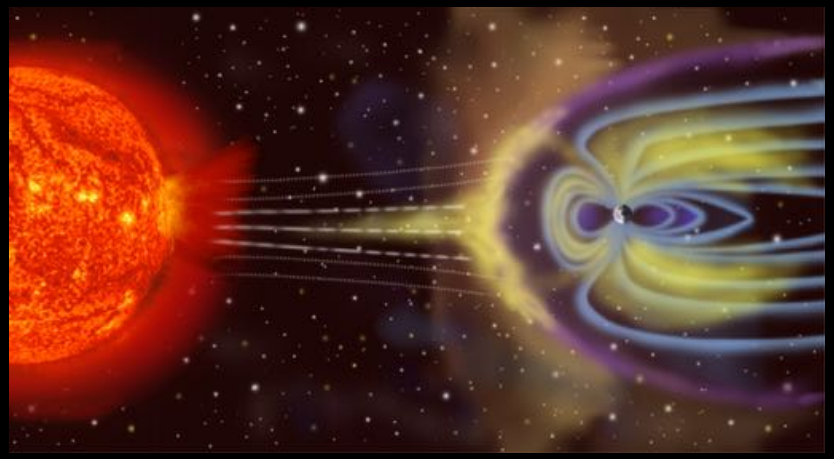
Astro-Particle Physics of the Sun



Kenny, Chun Yu Ng (吳震宇)
Weizmann Institute of Science
Soon:
GRAPPA, U of Amsterdam

The Sun-Earth Relationship

- Short term (11-yr activity)
  - E.g., 1989 geomagnetic storm
  - Power outage/ satellite drag/ communication/ magnetic guidance/ flight radiation

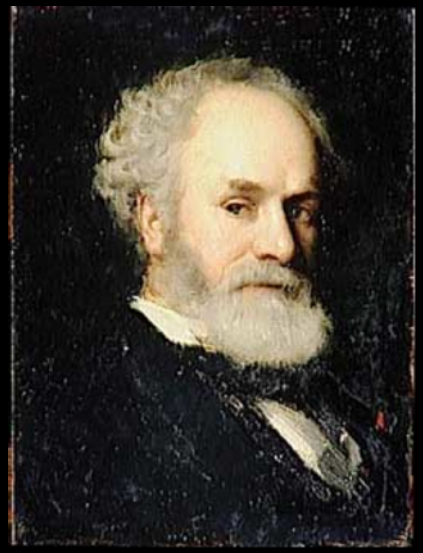


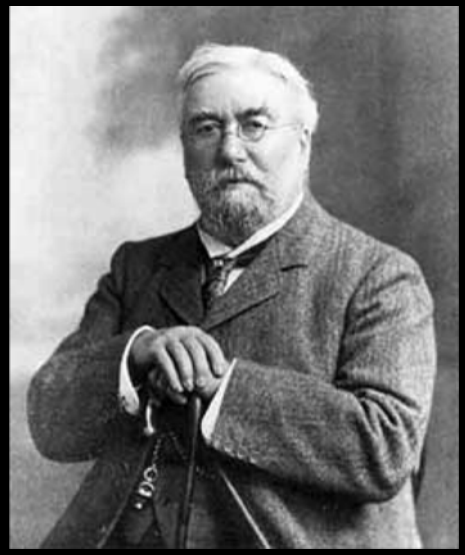
NASA

- Long term
  - Sun related climate effect

Bahcall +
Astronomy and Astrophysics Reports
National Academy Press, Washington DC 1991

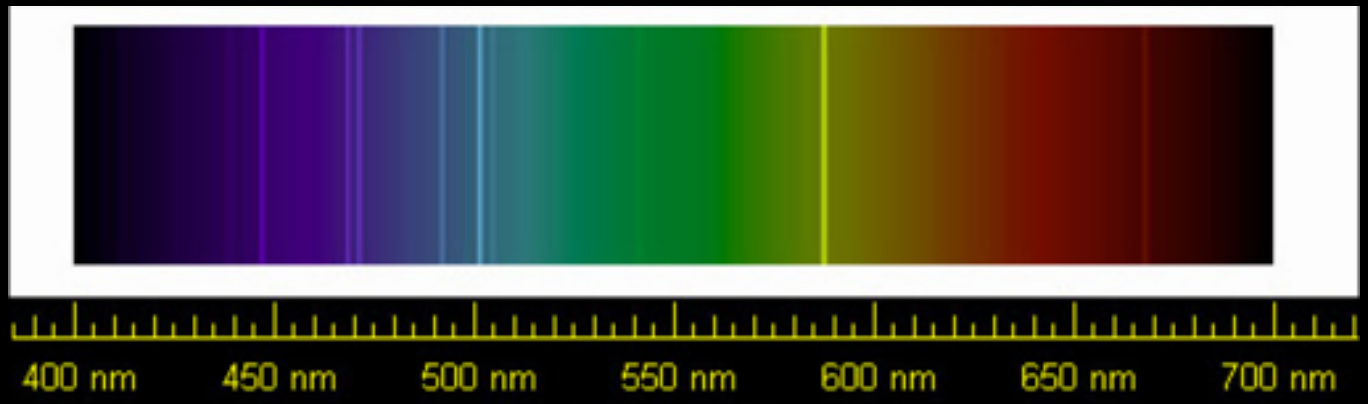
Discovery of Helium



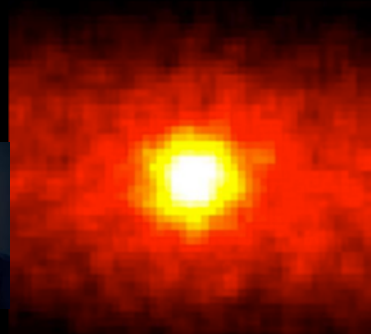


Photos by Wikipedia Commons
Pierre Janssen, Joseph Norman Lockyer

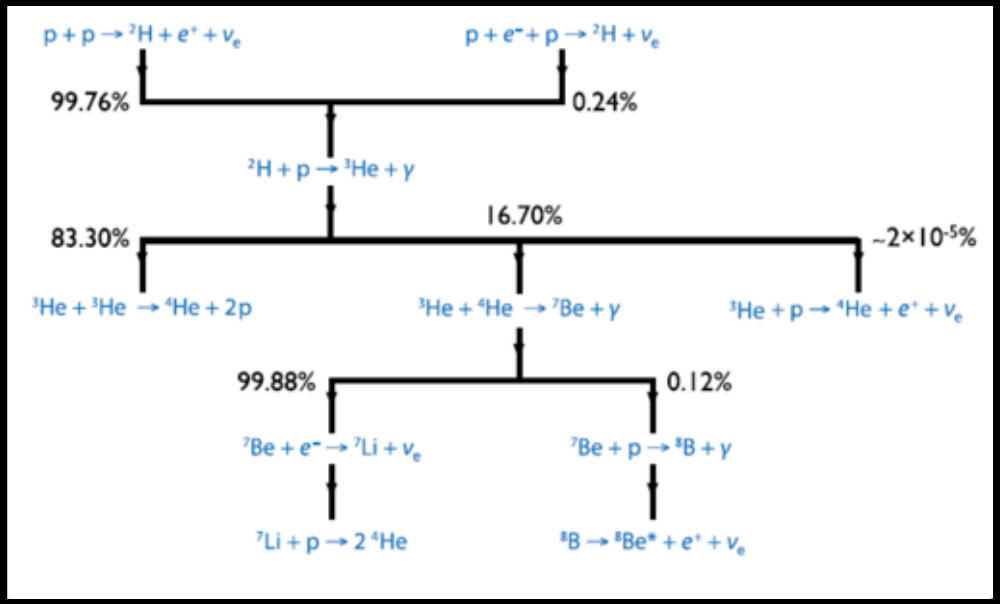
- 1868
- Helios -> Helium

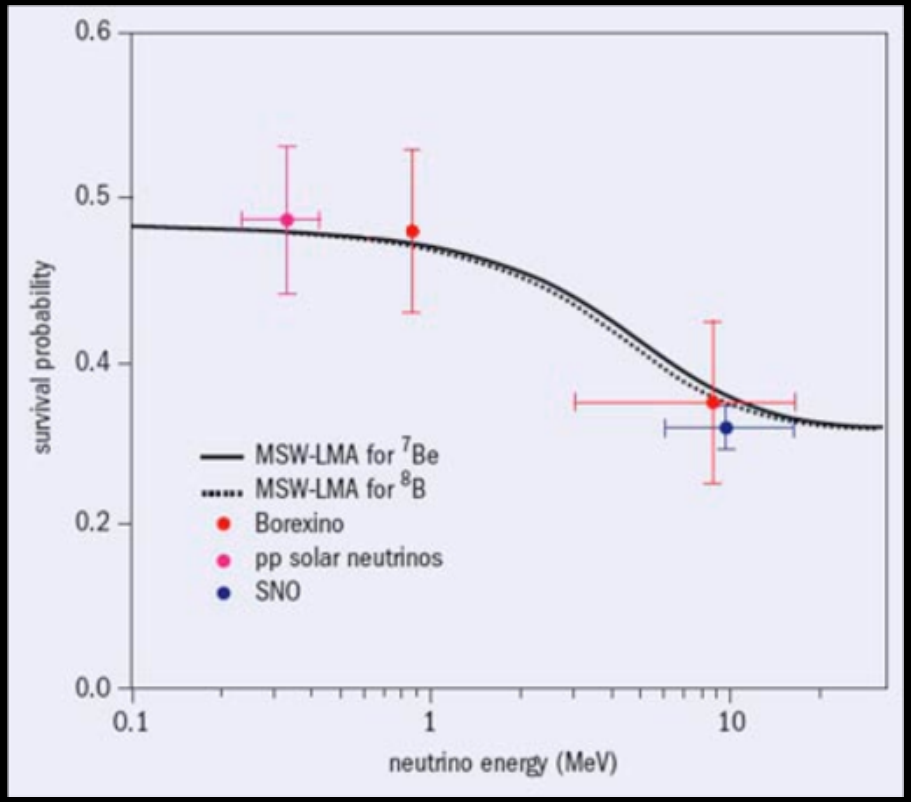


Solar Neutrinos



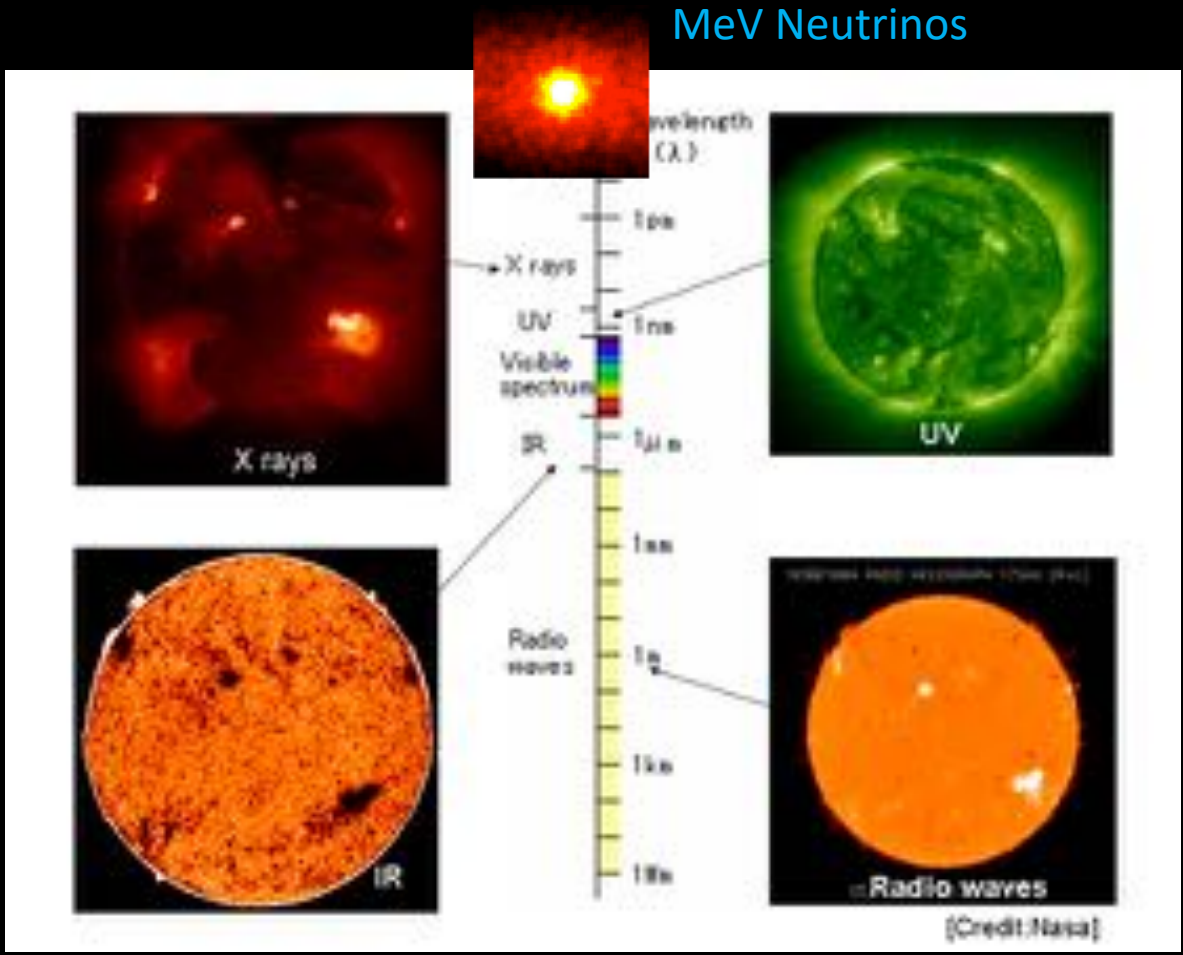
http://apod.nasa.gov/apod/ap980605.html



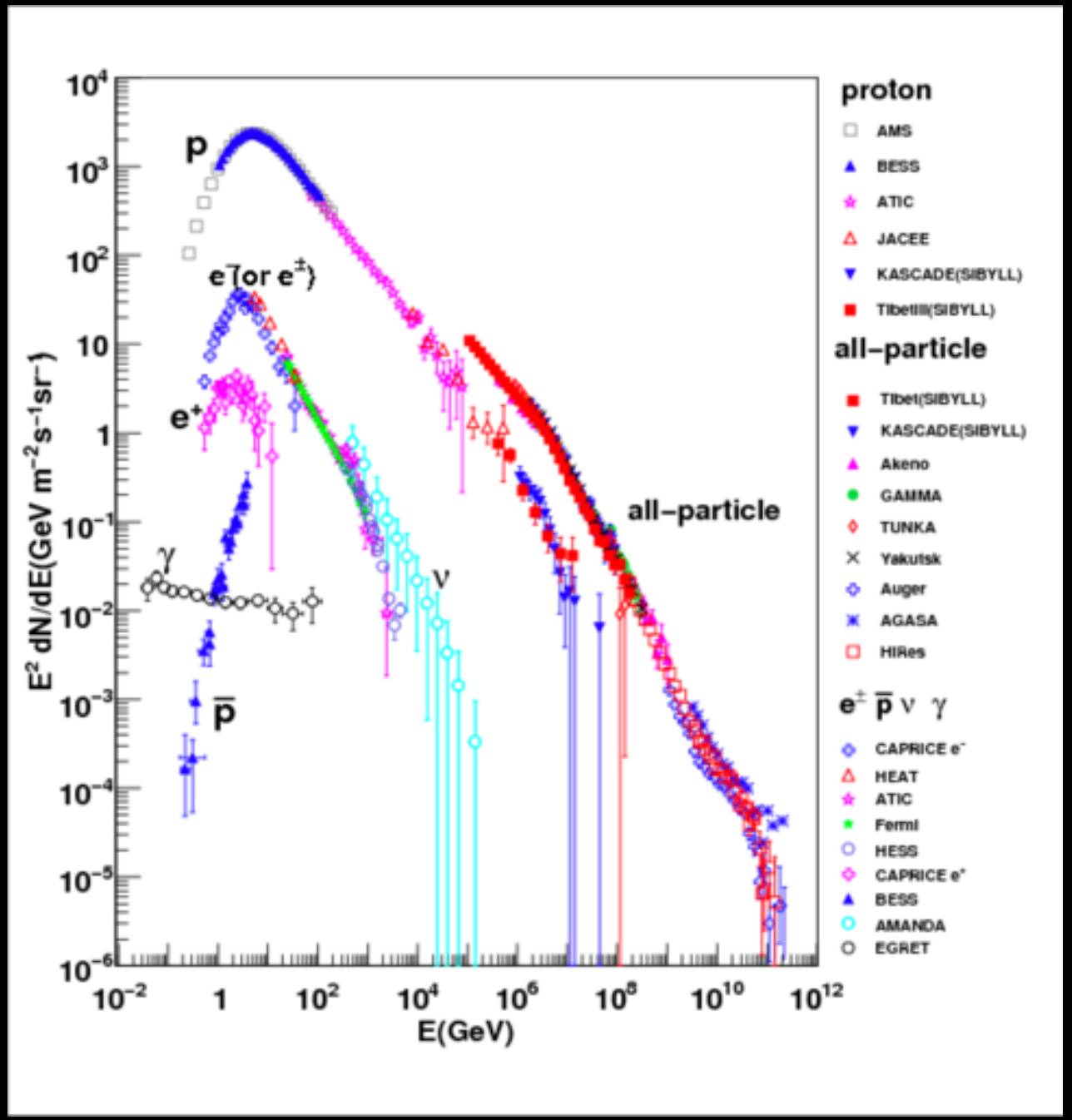


Observations of the Sun

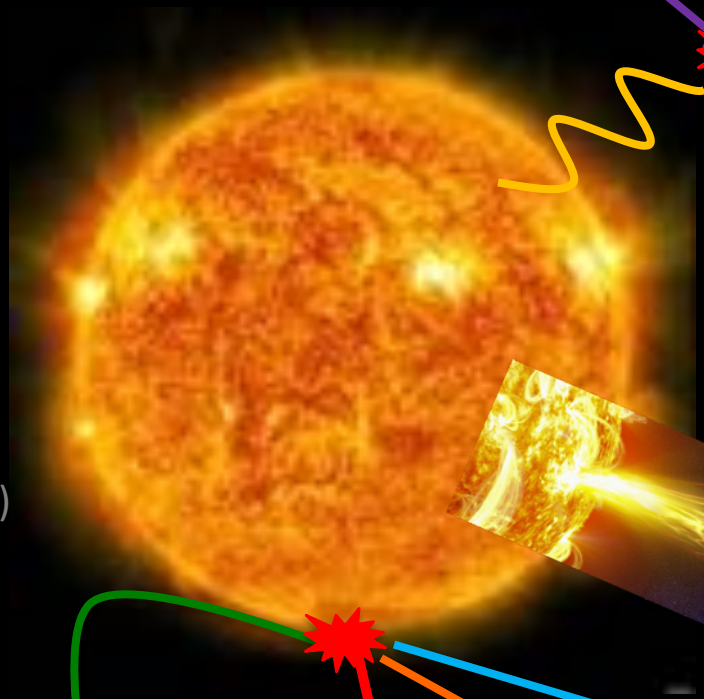
GeV ??? ⟶ The Sun is not hot enough!



Comsic rays


p
e⁻(or e±)
e⁺
γ
ν
p̄
all−particle
E² dN/dE(GeV m⁻²s⁻¹sr⁻¹)
E(GeV)
proton
AMS
BESS
ATIC
JACEE
KASCADE(SIBYLL)
Tibet III(SIBYLL)
all−particle
Tibet(SIBYLL)
KASCADE(SIBYLL)
Akeno
GAMMA
TUNKA
Yakutsk
Auger
AGASA
HiRes
e± p̄ ν γ
CAPRICE e⁻
HEAT
ATIC
Fermi
HESS
CAPRICE e⁺
BESS
AMANDA
EGRET

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

Solar Atmospheric Gamma Rays

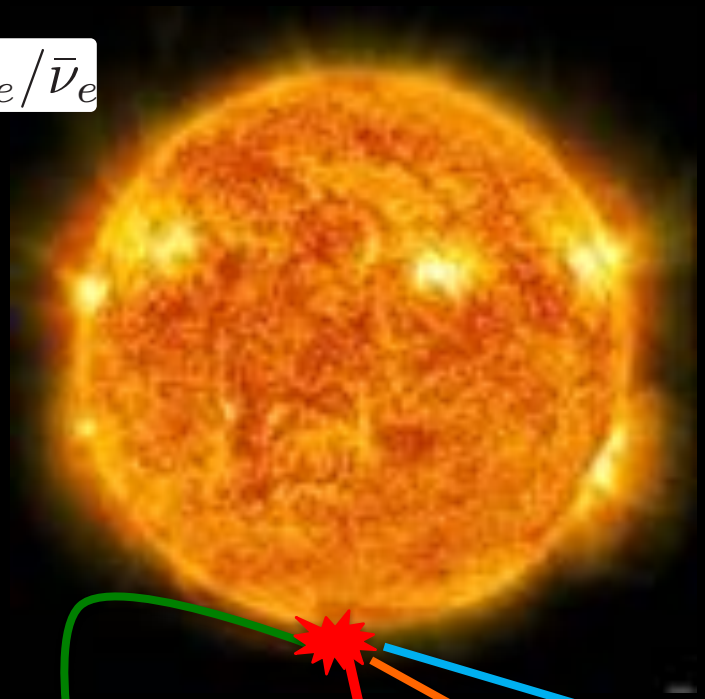
$$p + p \rightarrow \pi^0/\pi^\pm + X$$

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

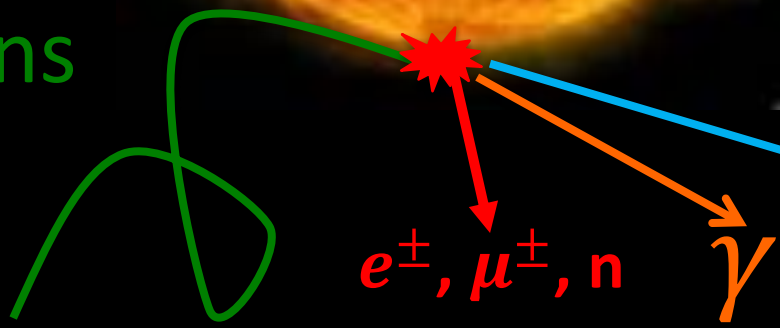
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$

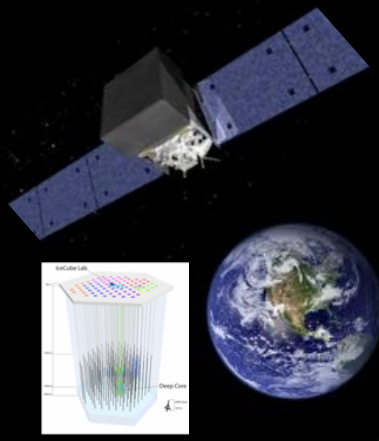
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu/\nu_\mu + \nu_e/\bar{\nu}_e$$

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



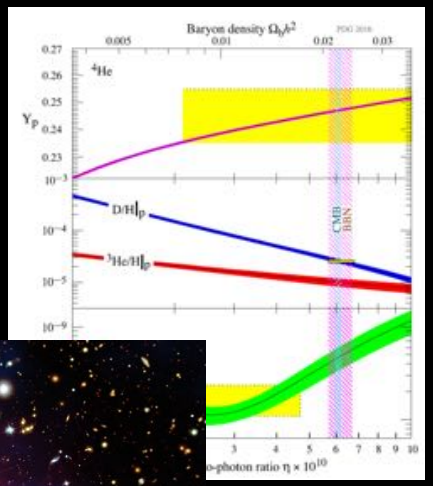
CR protons
Hadronic

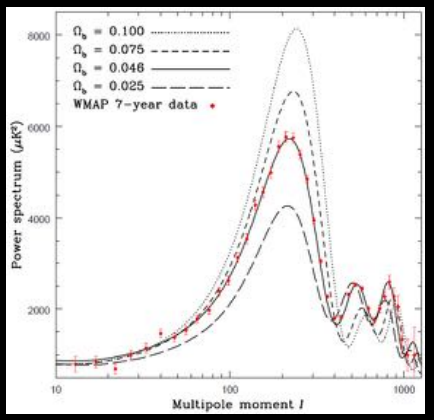




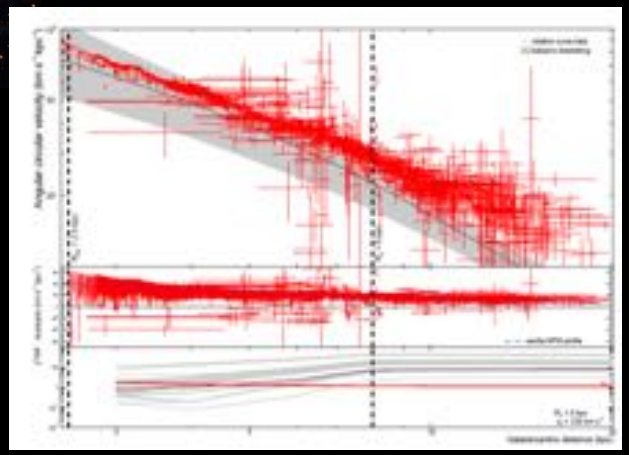
Dark Matter/Gravity problem

- Big Bang Nucleosynthesis \CMB





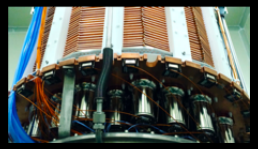
- Clusters



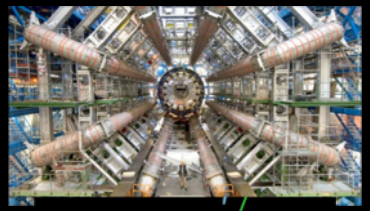
- Galaxies/Local

Weakly interacting massive particles

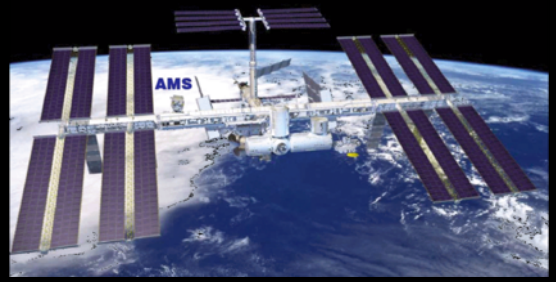
- Direct Detection

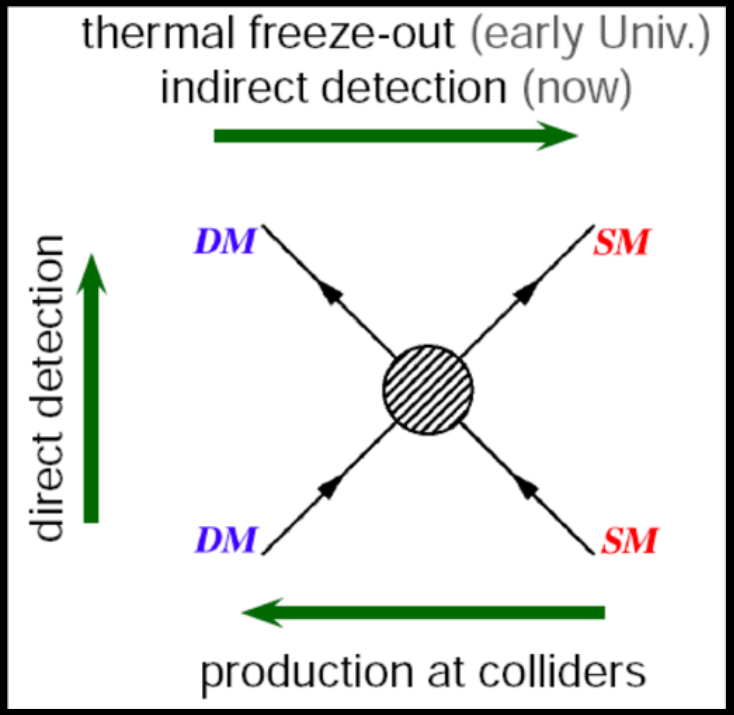


- Collider Search



- *Indirect Detection*



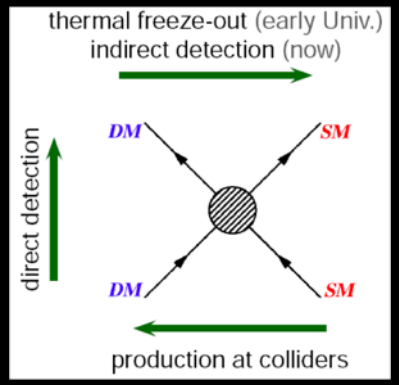


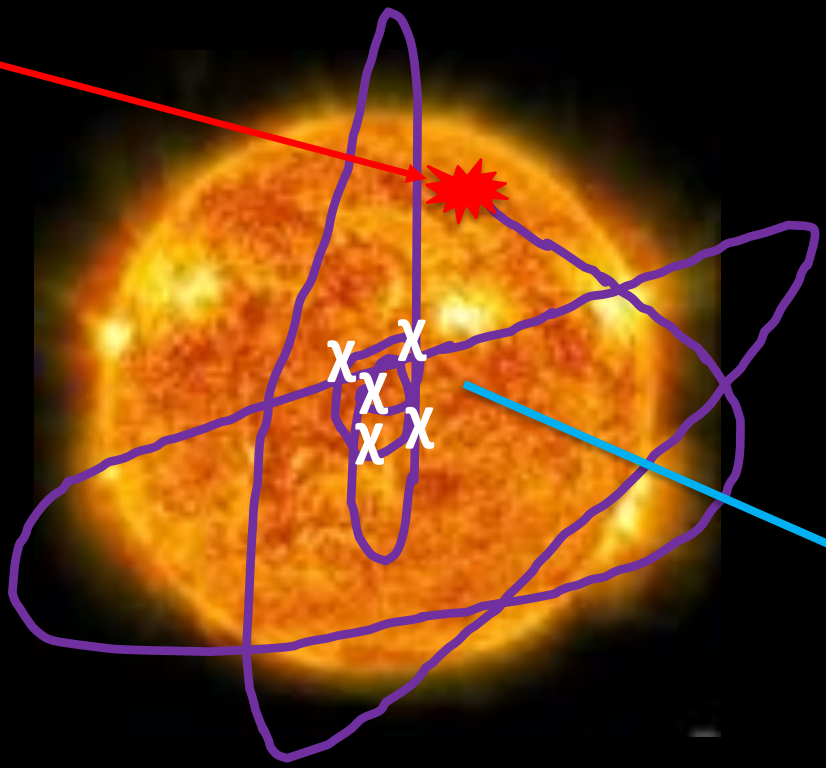
Sun – Dark Matter detector

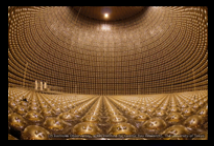
χ

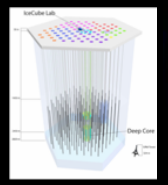
$$\frac{dN}{dt} = \Gamma_{\rm cap} - C_{\rm ann} N^2$$

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





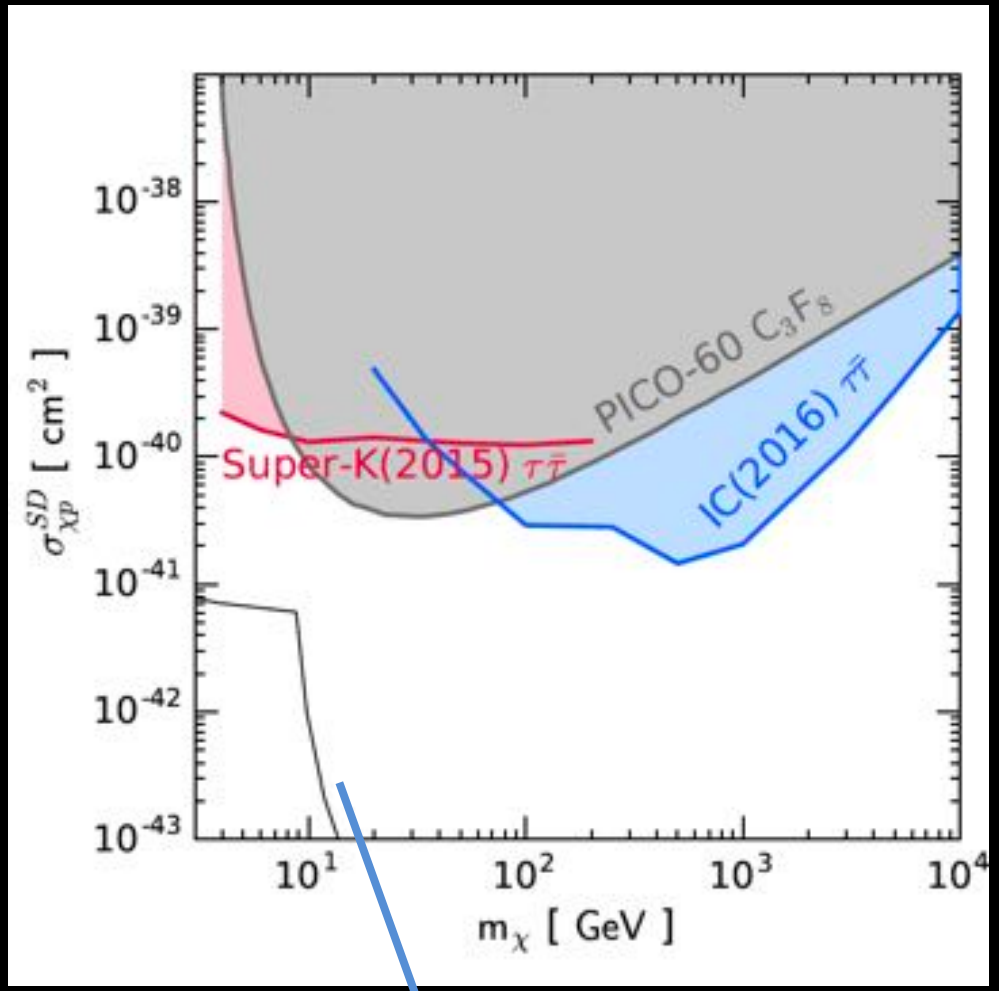




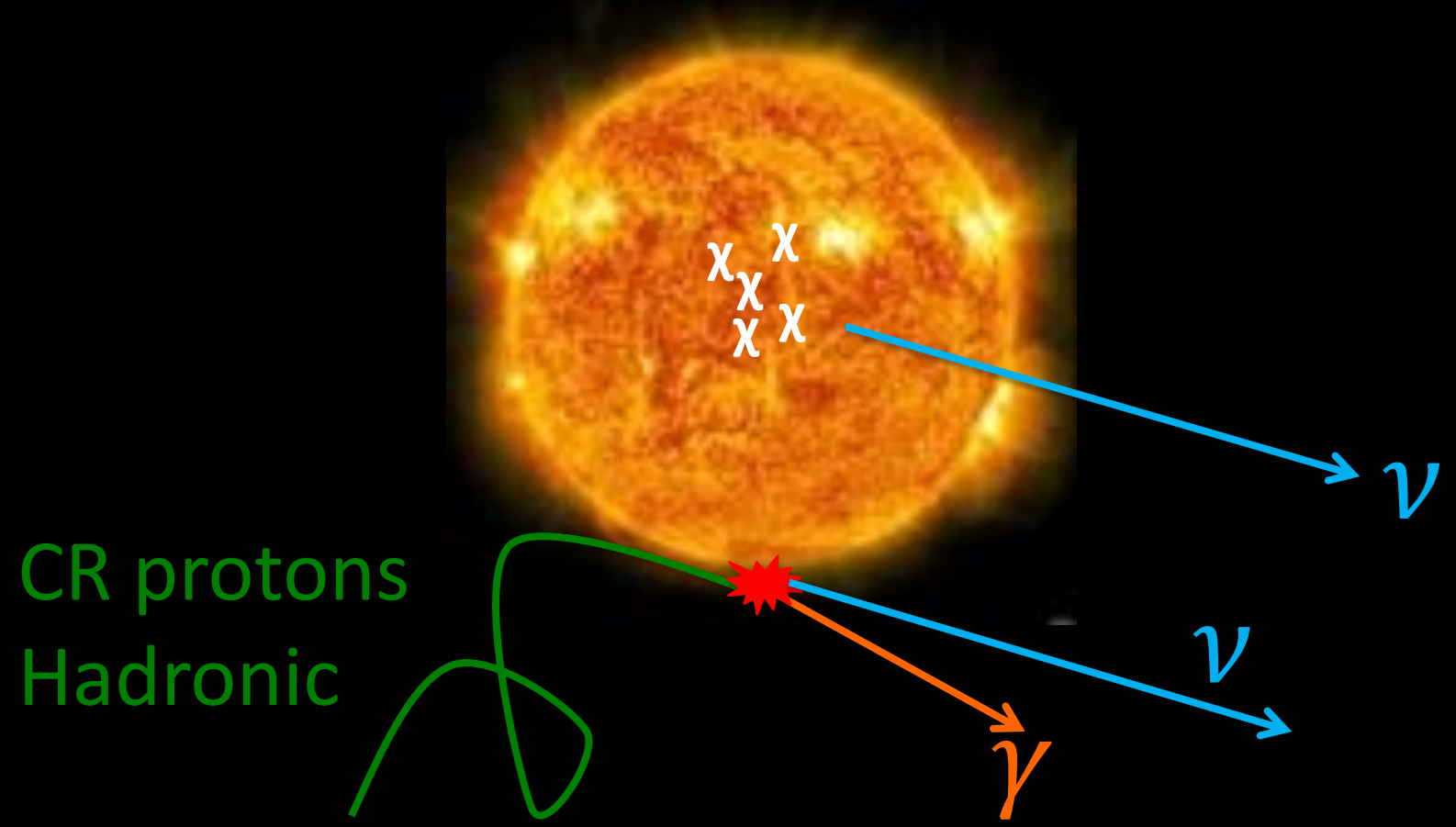
Press, Spergel (1985)
Krauss, Freese, Press, Spergel (1985)
Silk, Olive, Srednicki (1985)

Solar WIMP Search

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

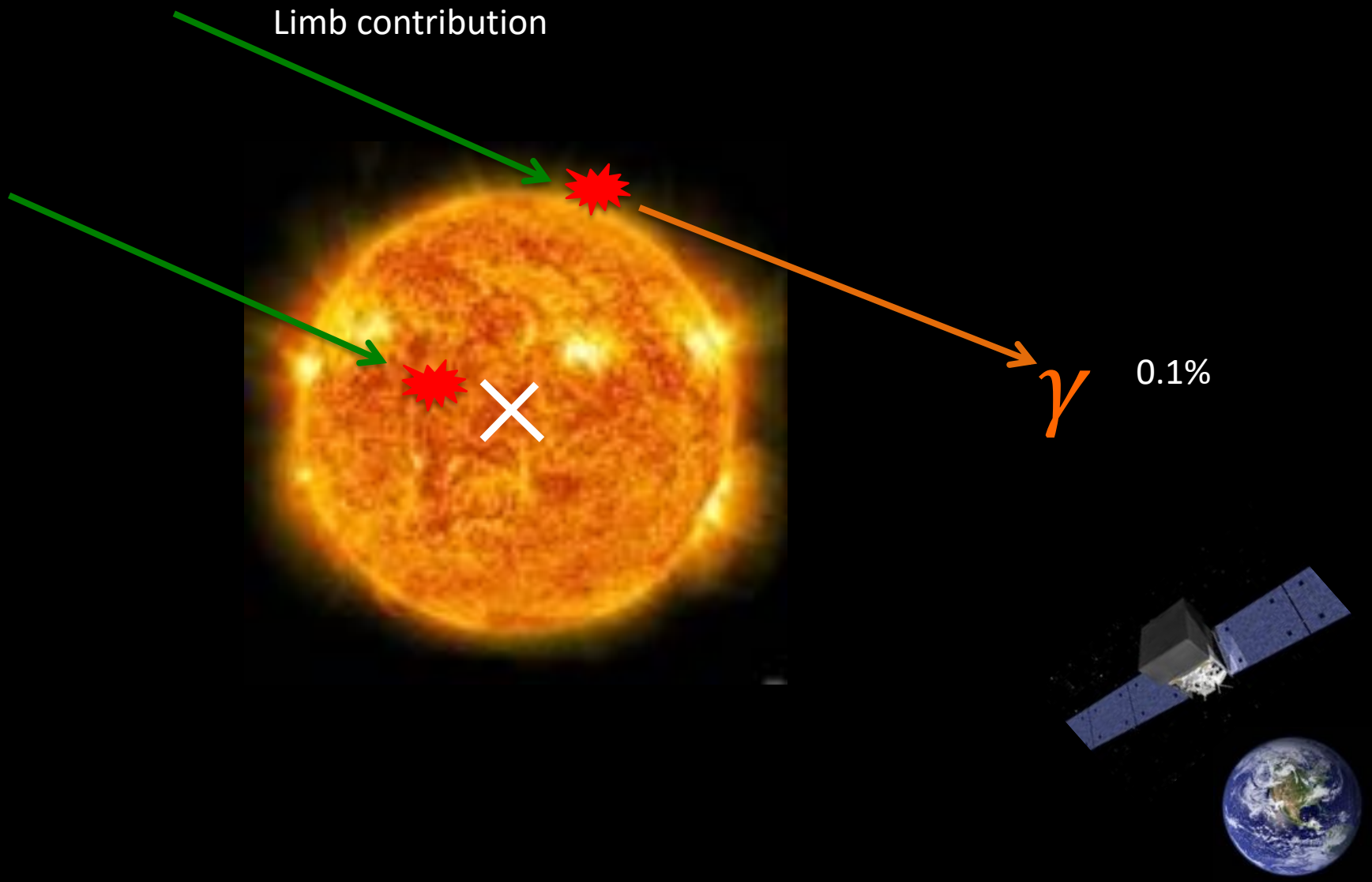


HE Gamma-ray Source
HE Neutrino Source
Dark Matter Detector



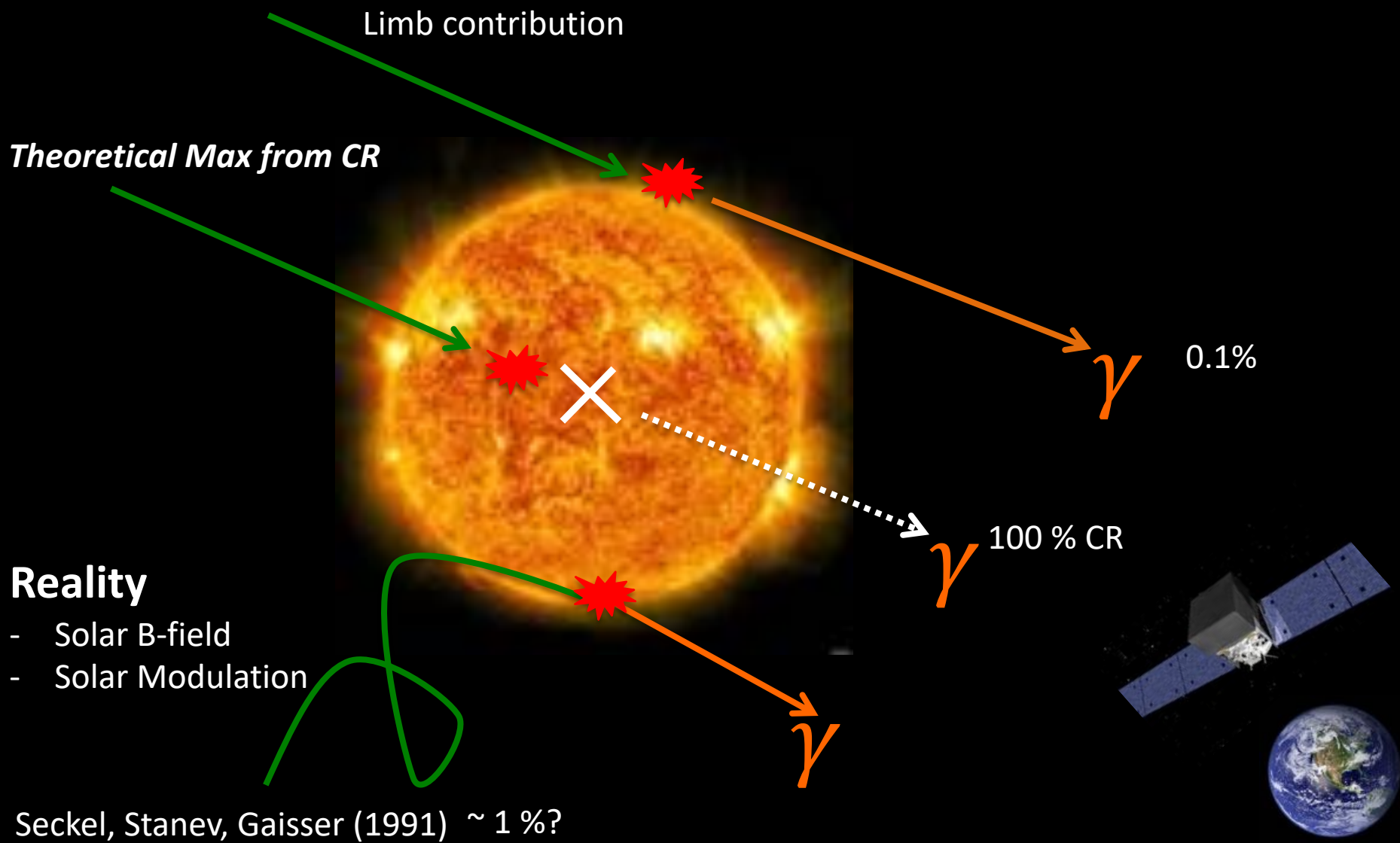
Solar atmospheric gamma rays

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

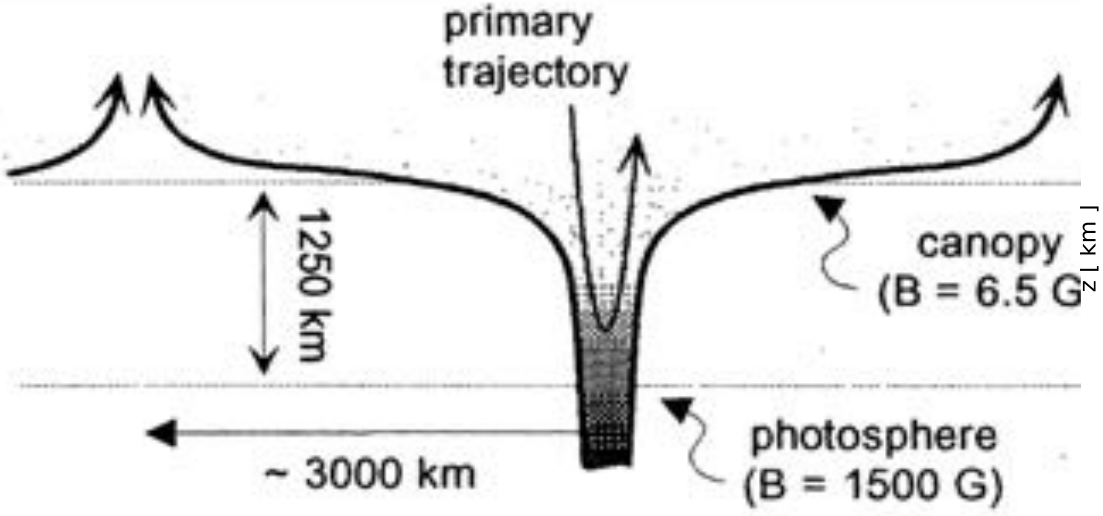


Solar atmospheric gamma rays

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



Seckel Stanev Gaisser 1991



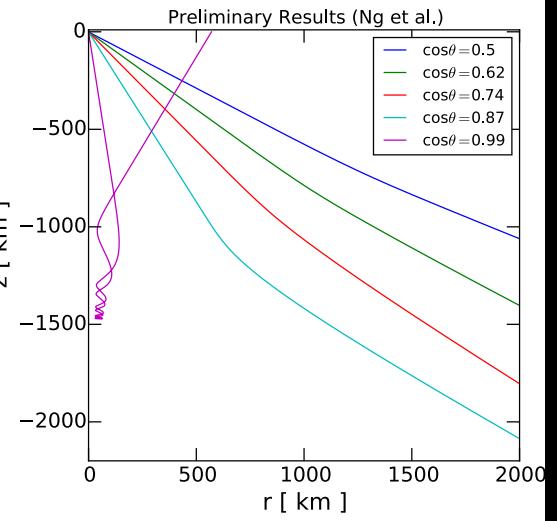
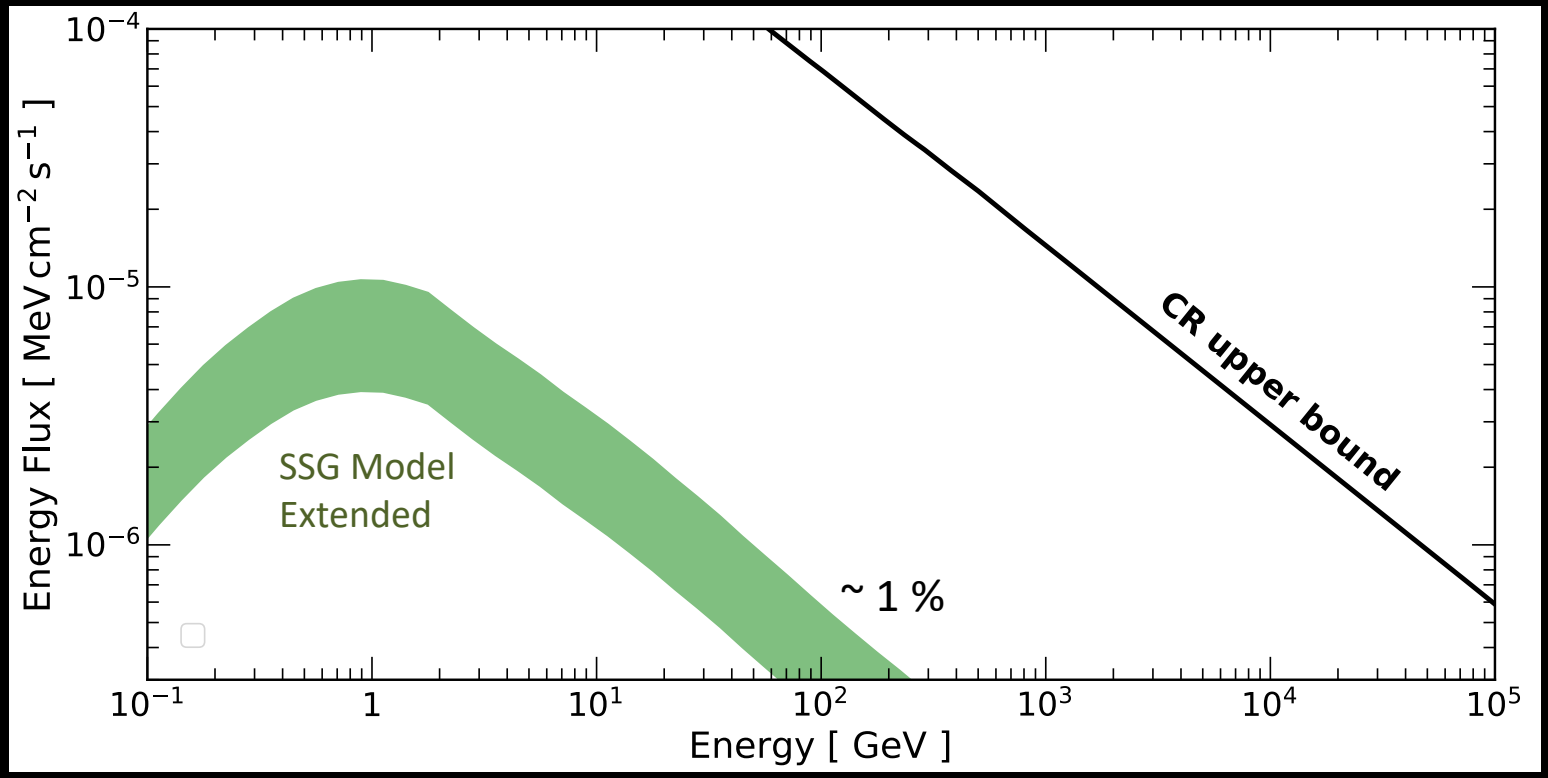


Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

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

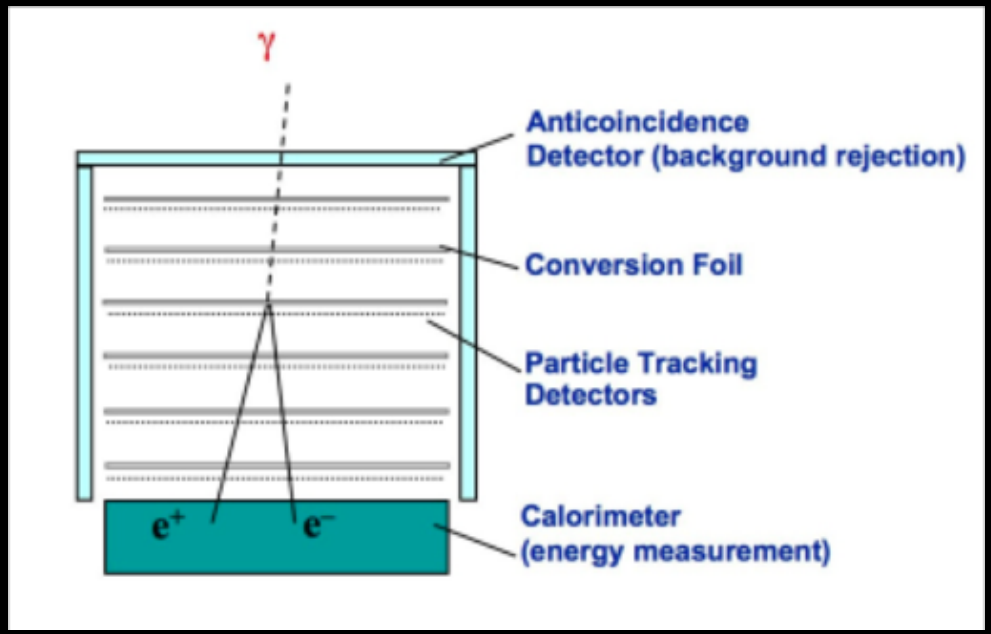
Boost gamma-ray production

The overall picture



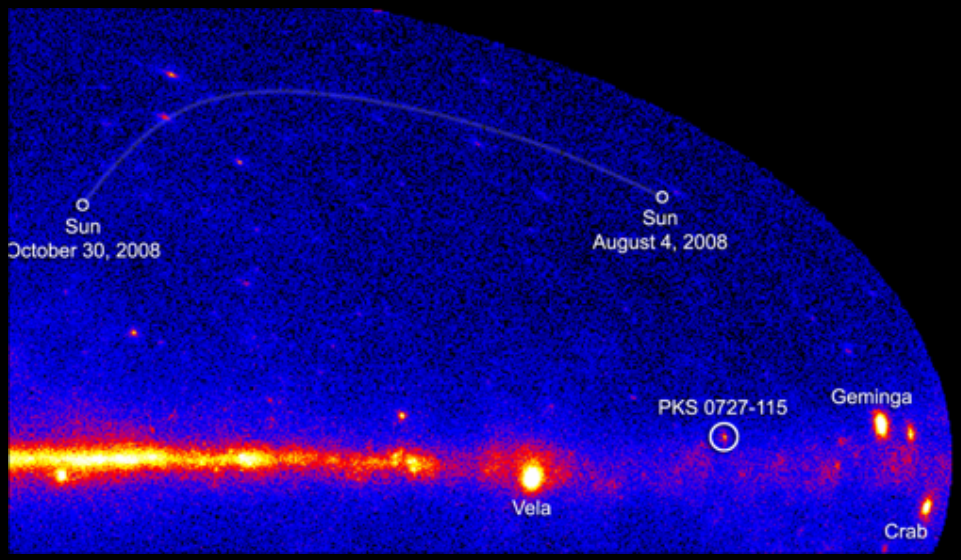
Fermi Gamma-ray Space Telescope

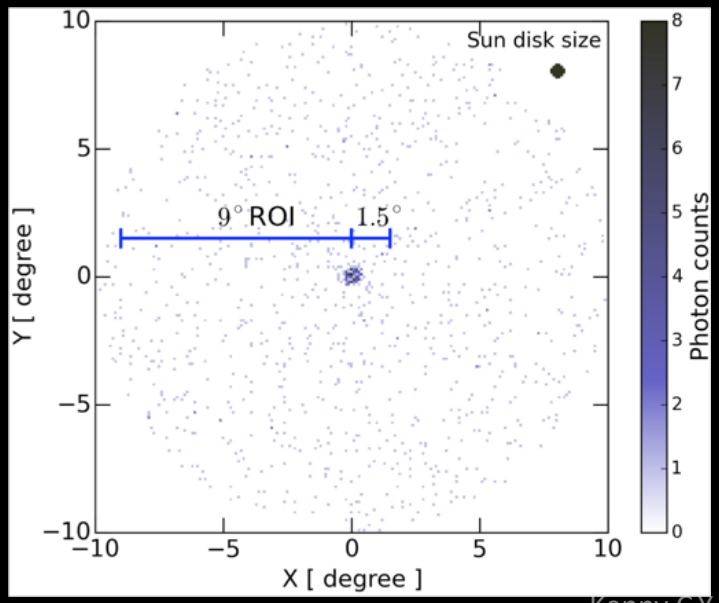
- LAT
  - Large area telescope



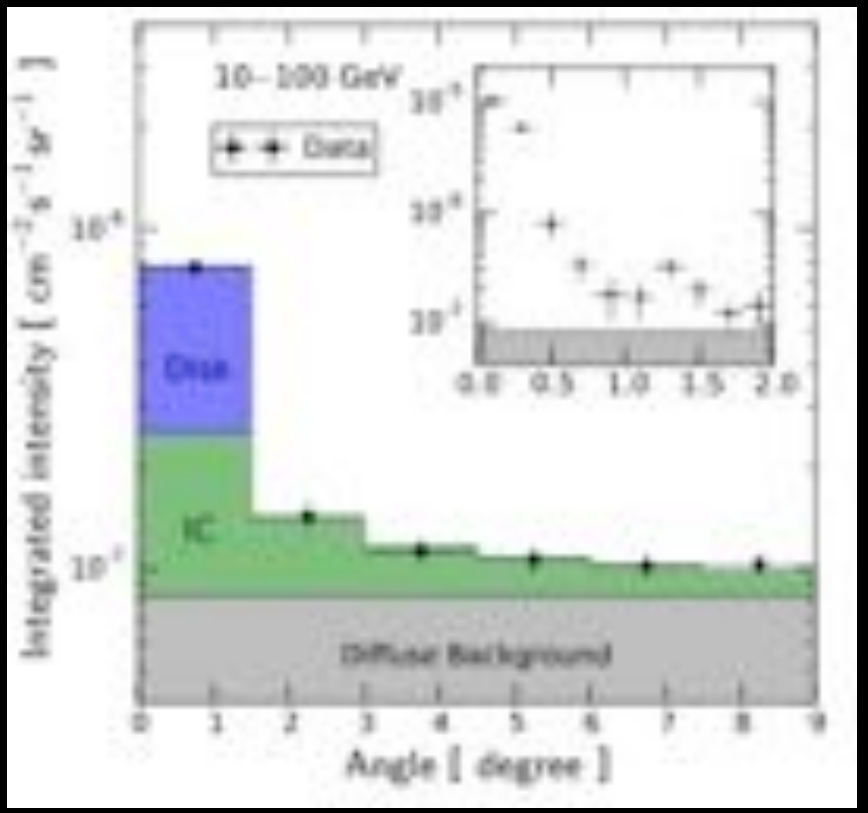
www-glast.stanford.edu

Finding the Sun with Fermi





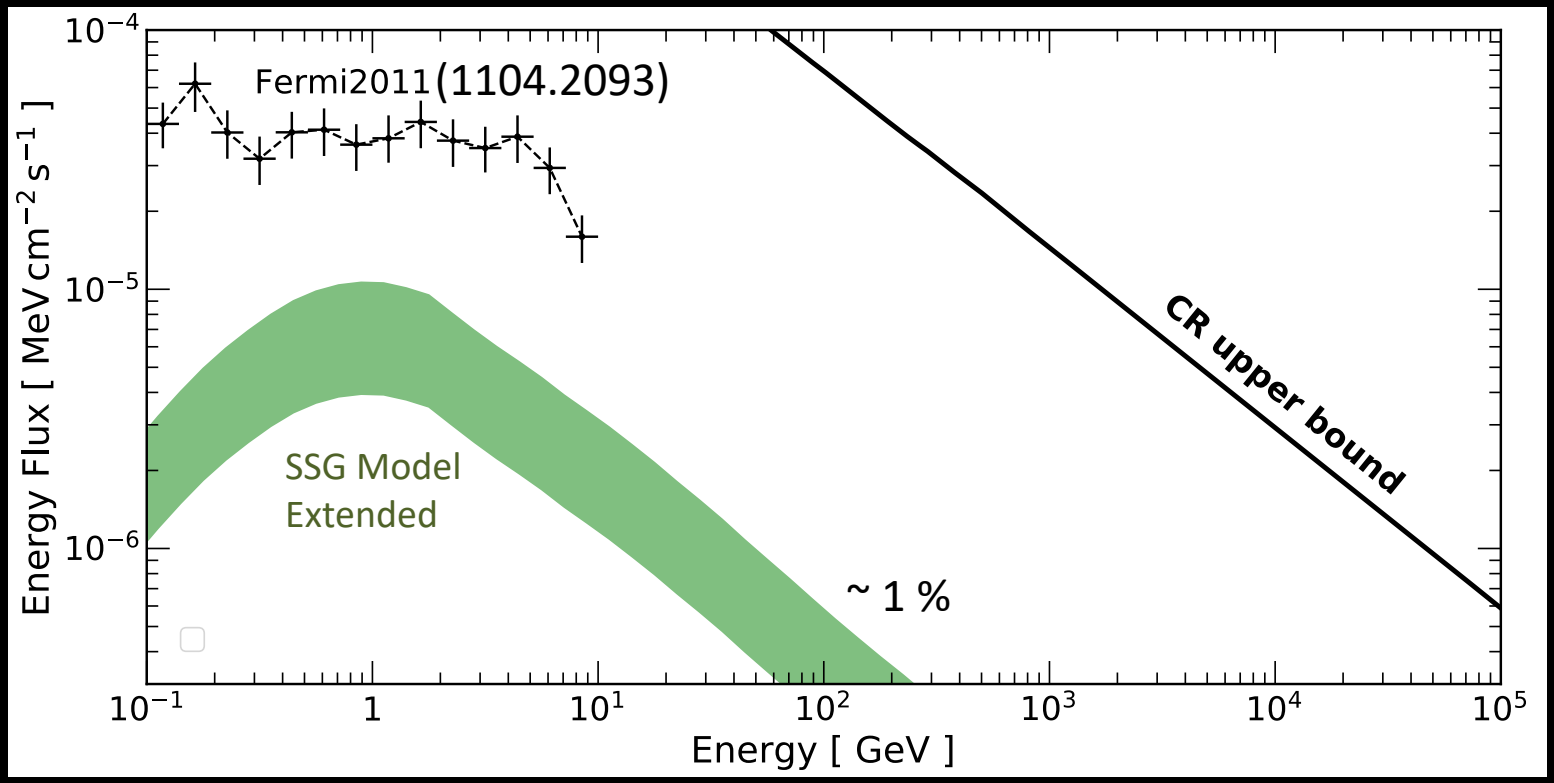
Angular distribution



KCYN+ 2015

Fermi Detection (18 months)

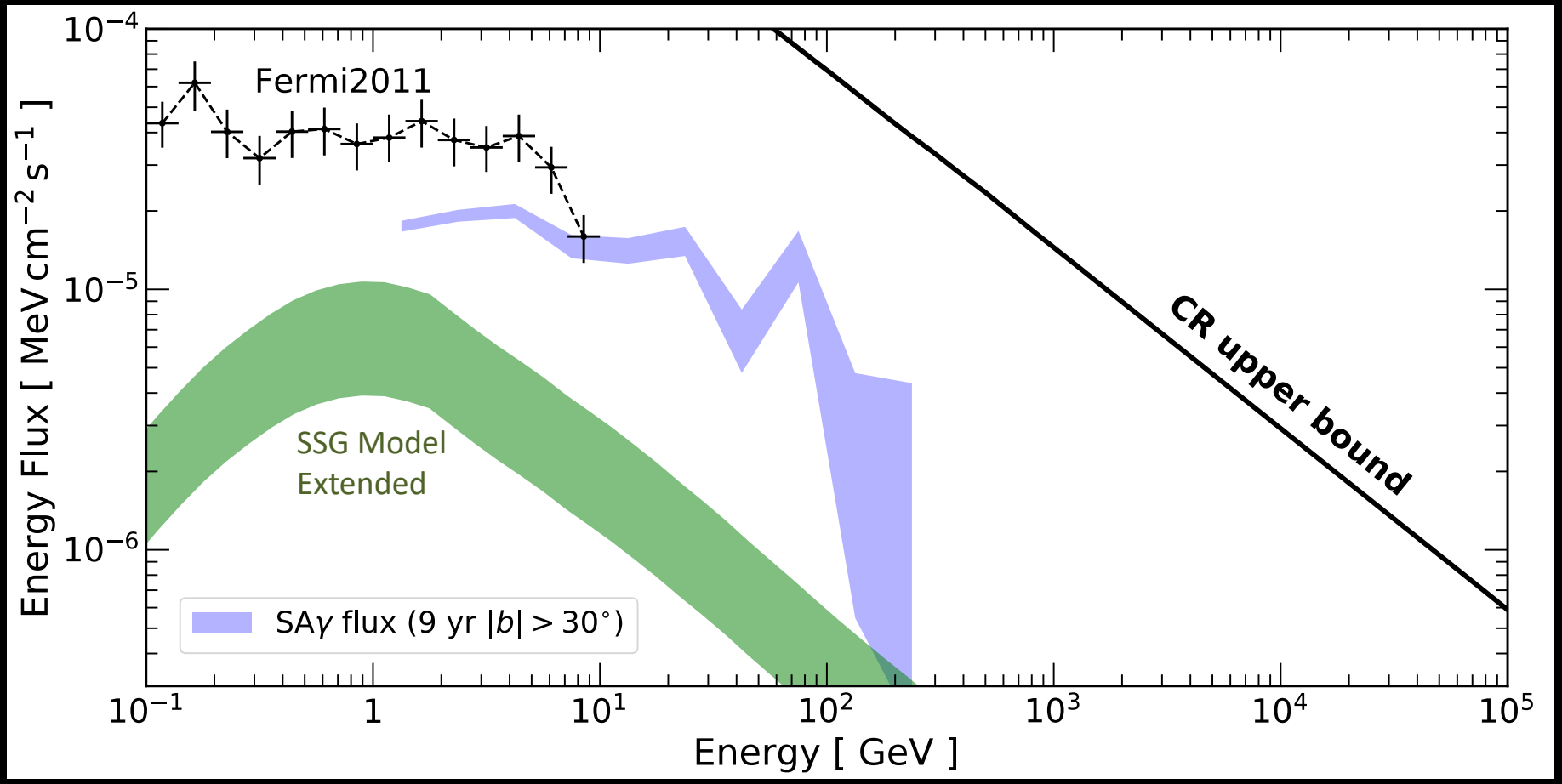
- First detection was EGRET (Orlando, Strong 2008)
- Model prediction too small
- Satisfy cosmic-ray bound ←→ CR model with large B-field enhancement



Observation: 9-year averaged spectrum

- 2008 – 2017 (9 years)

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



Observation: 9-year averaged spectrum

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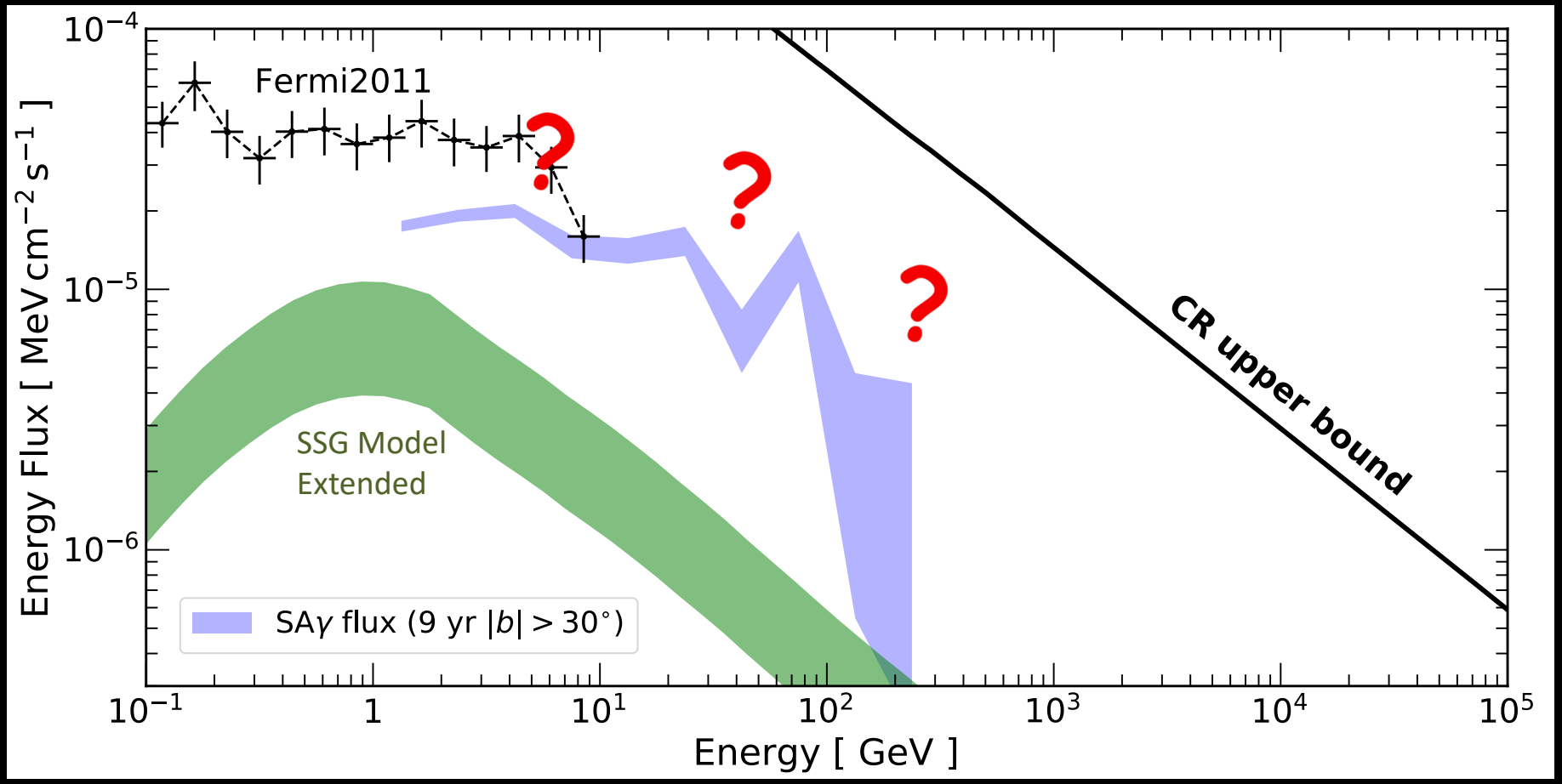
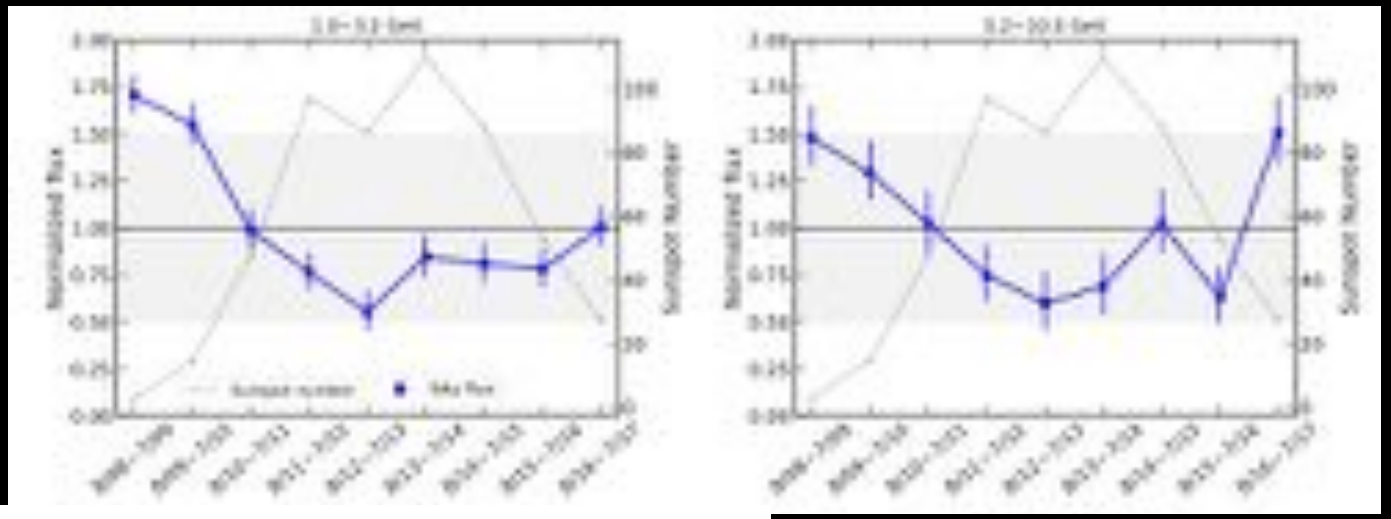
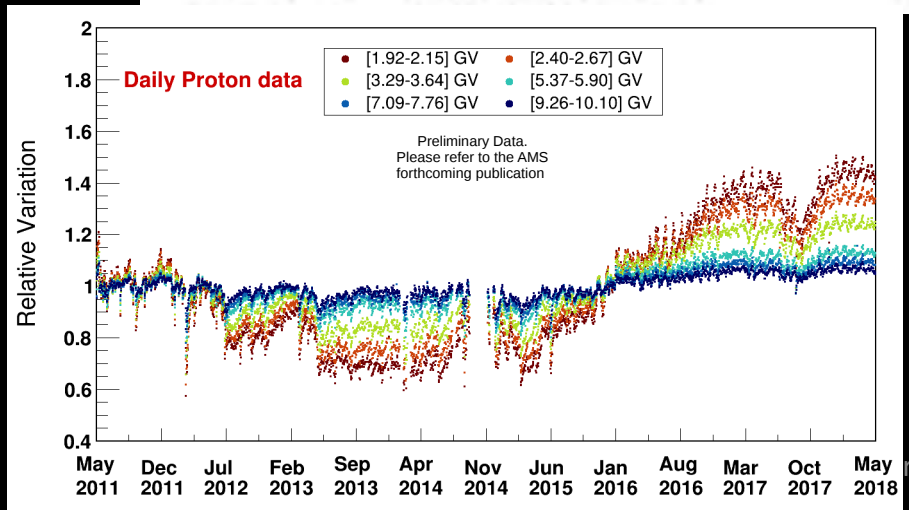


Time variation

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)



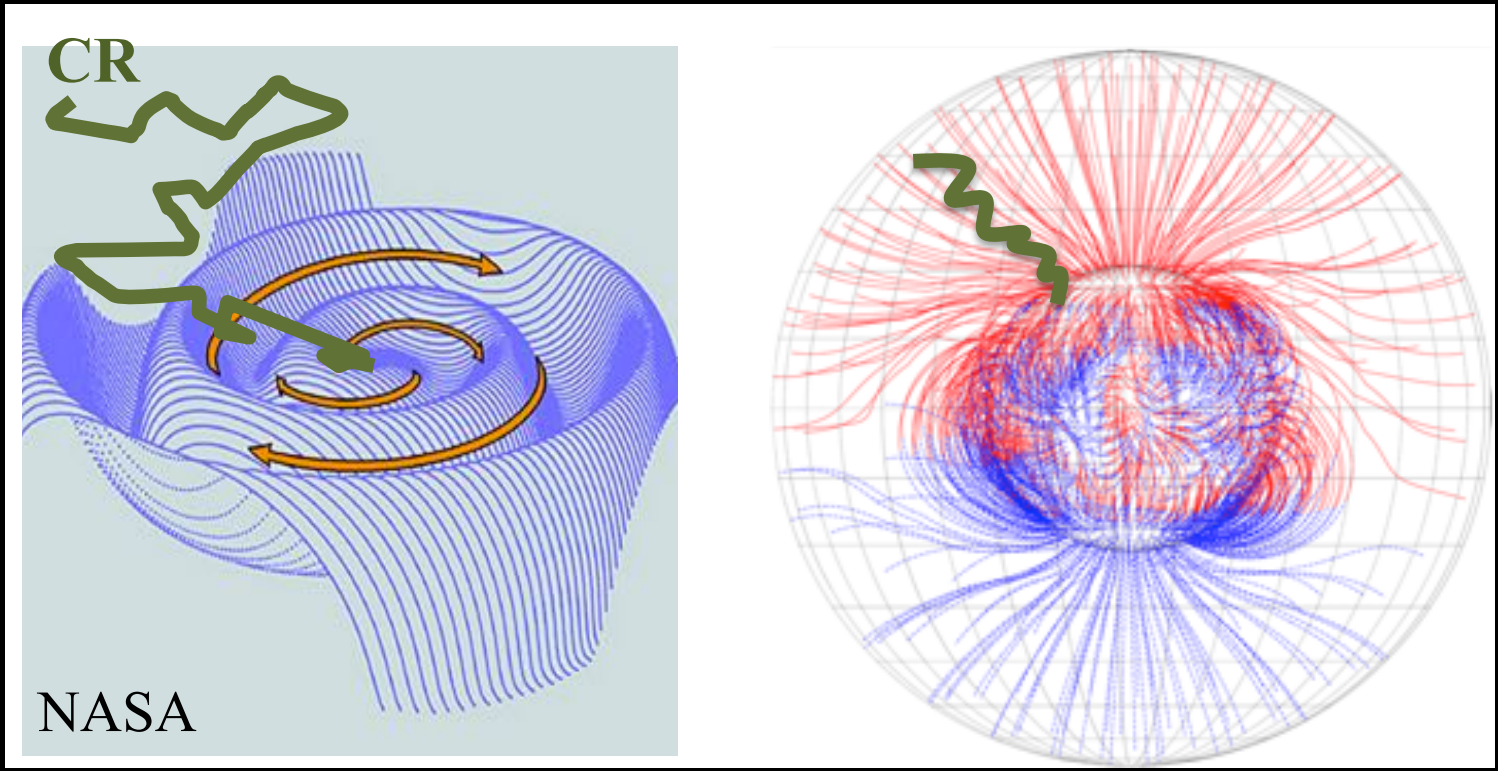


Small modulation amplitude
-> extra modulation needed near the Sun

C. Consolandi CRD8c

CR Solar Modulation / solar activity

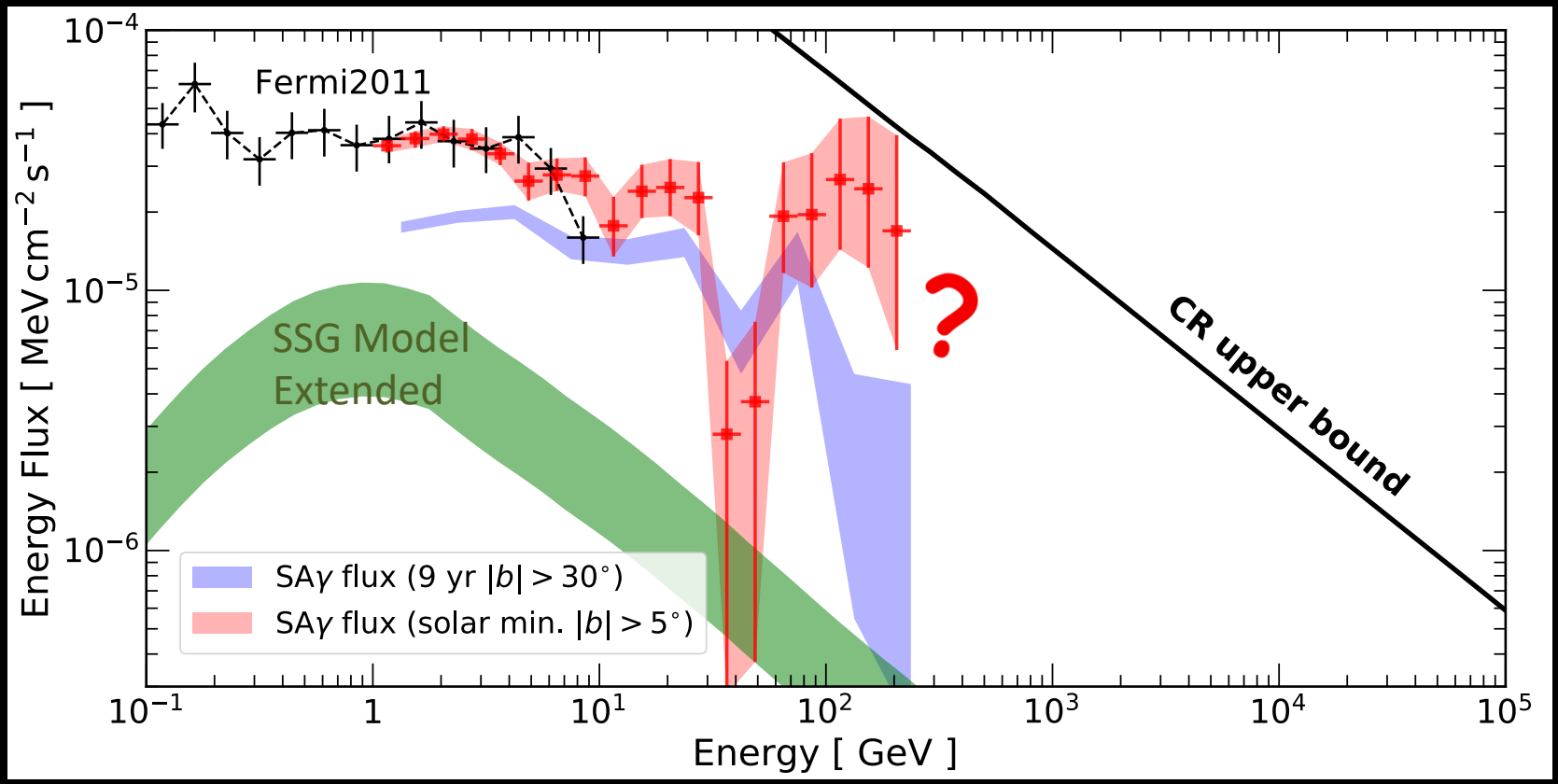
- 1. CR propagation in the solar system
- 2. CR propagation in the solar atmosphere



Adriani+ 2013

Observation: 9-year averaged spectrum

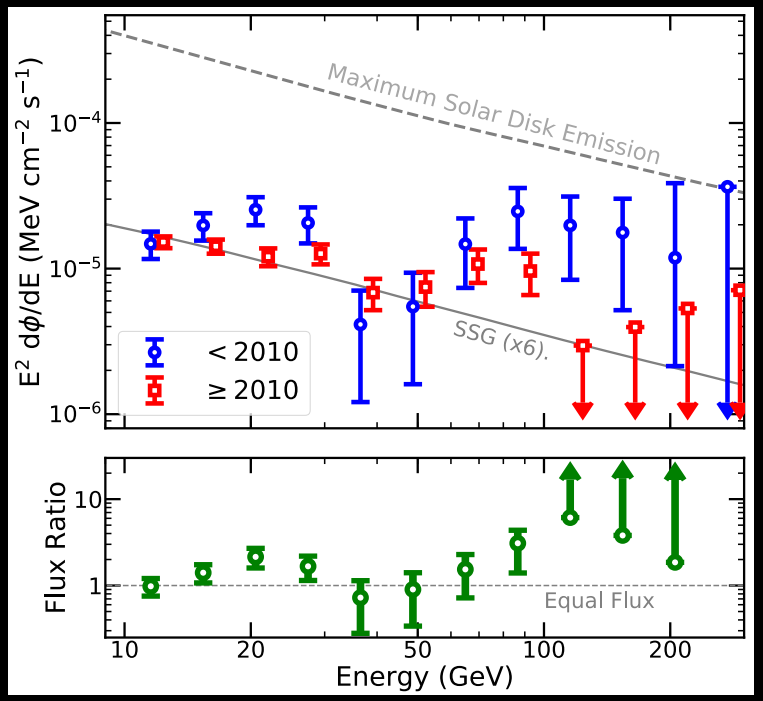
- Aug 2008 – Jan 2010 (solar min. 76 weeks)
- 2008 – 2017 (9 years)

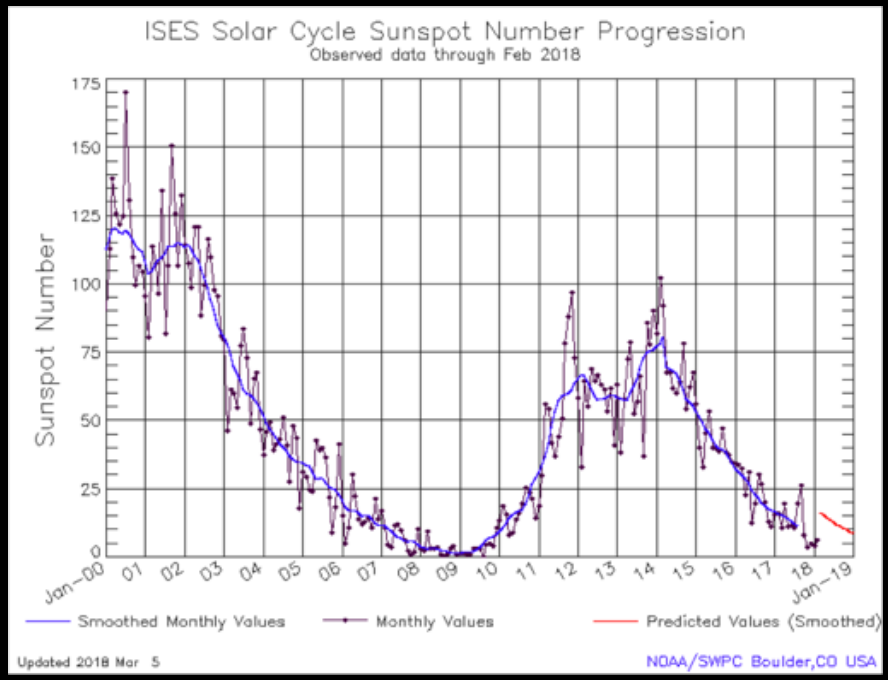


High energy photon/Time variation, *Surprise (1)!*

- >100 GeV events
- 6 events from AUG 2008 to Jan 2010 (quiet Sun)
- 0 events for the next 7.8 years (active Sun)

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

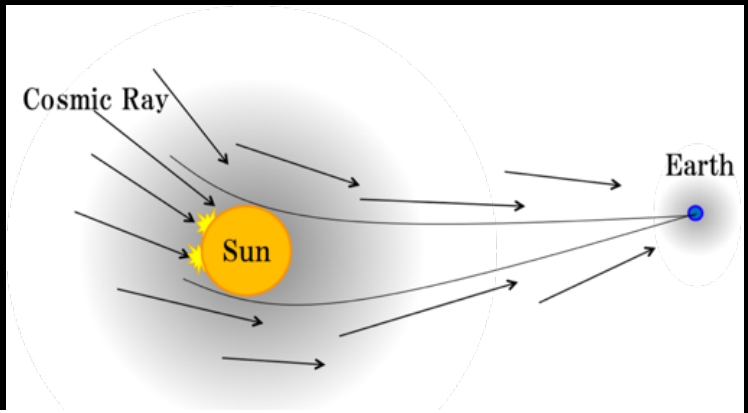


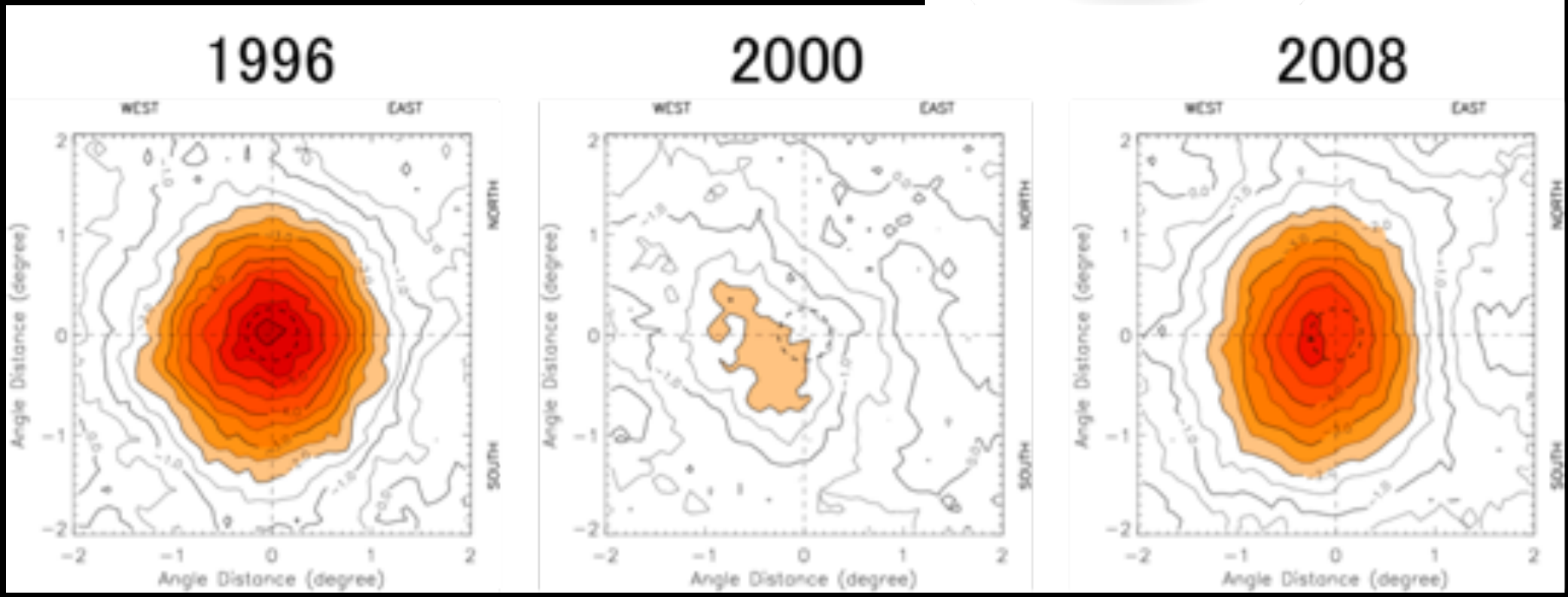


The high-energy photon production are very sensitive to the solar condition

Sun shadow observations

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

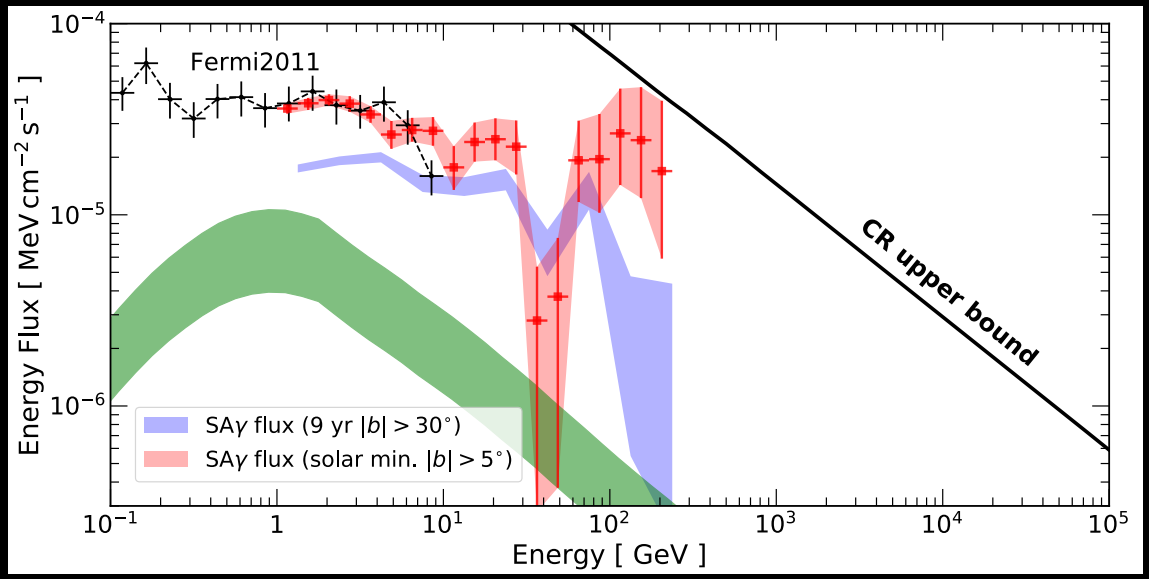




ICRR, Tibet AS-gamma PRL 2013

Spectrum, *surprise (2)*

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

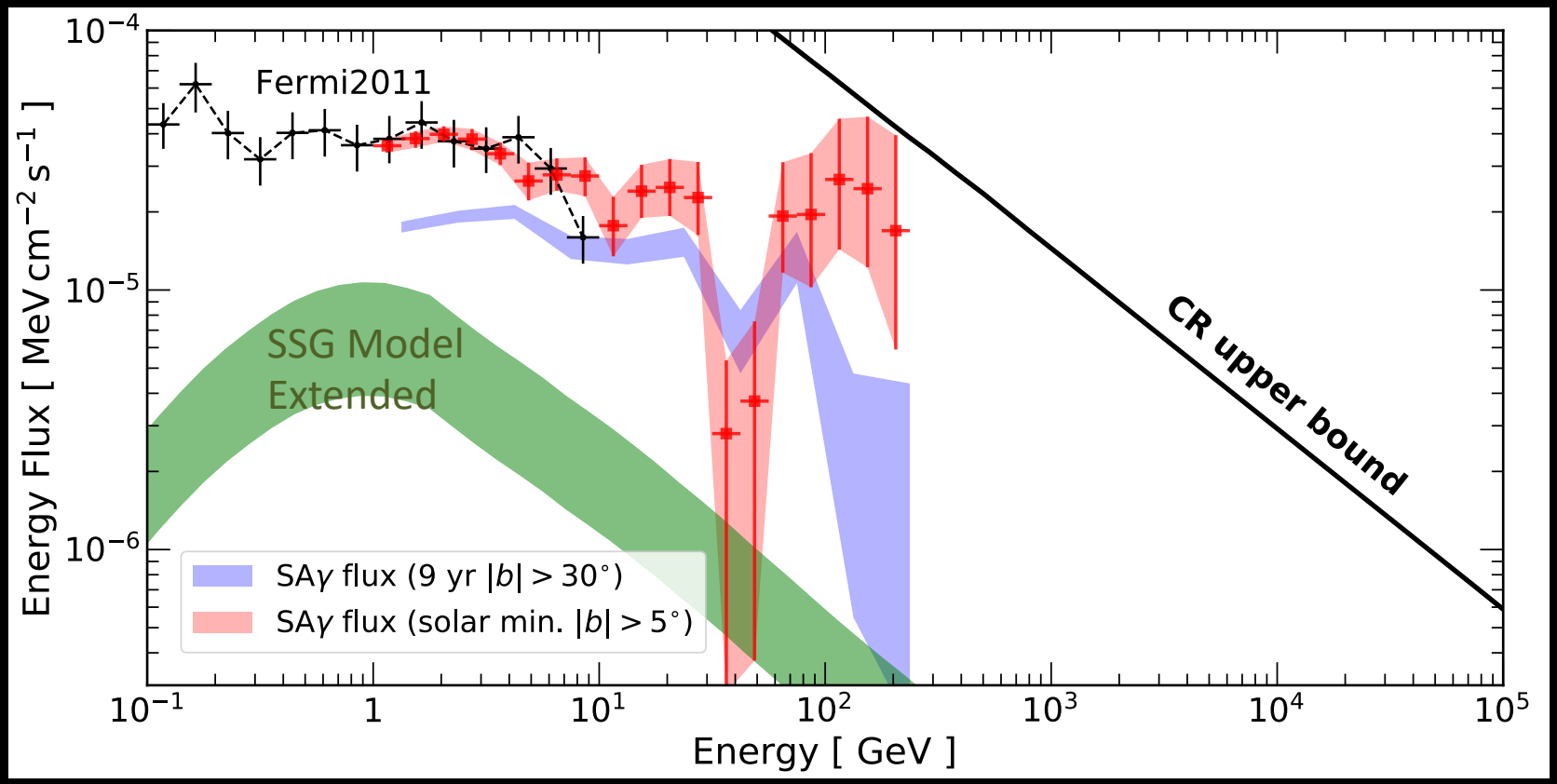


$$\text{FLUX(E)} \propto \sigma_{pp} \times \Phi_p(E) \times \epsilon\,(E)$$

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

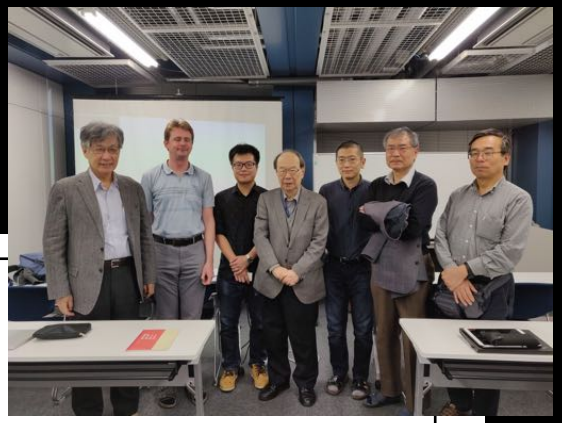
Spectrum, *surprise (3)*

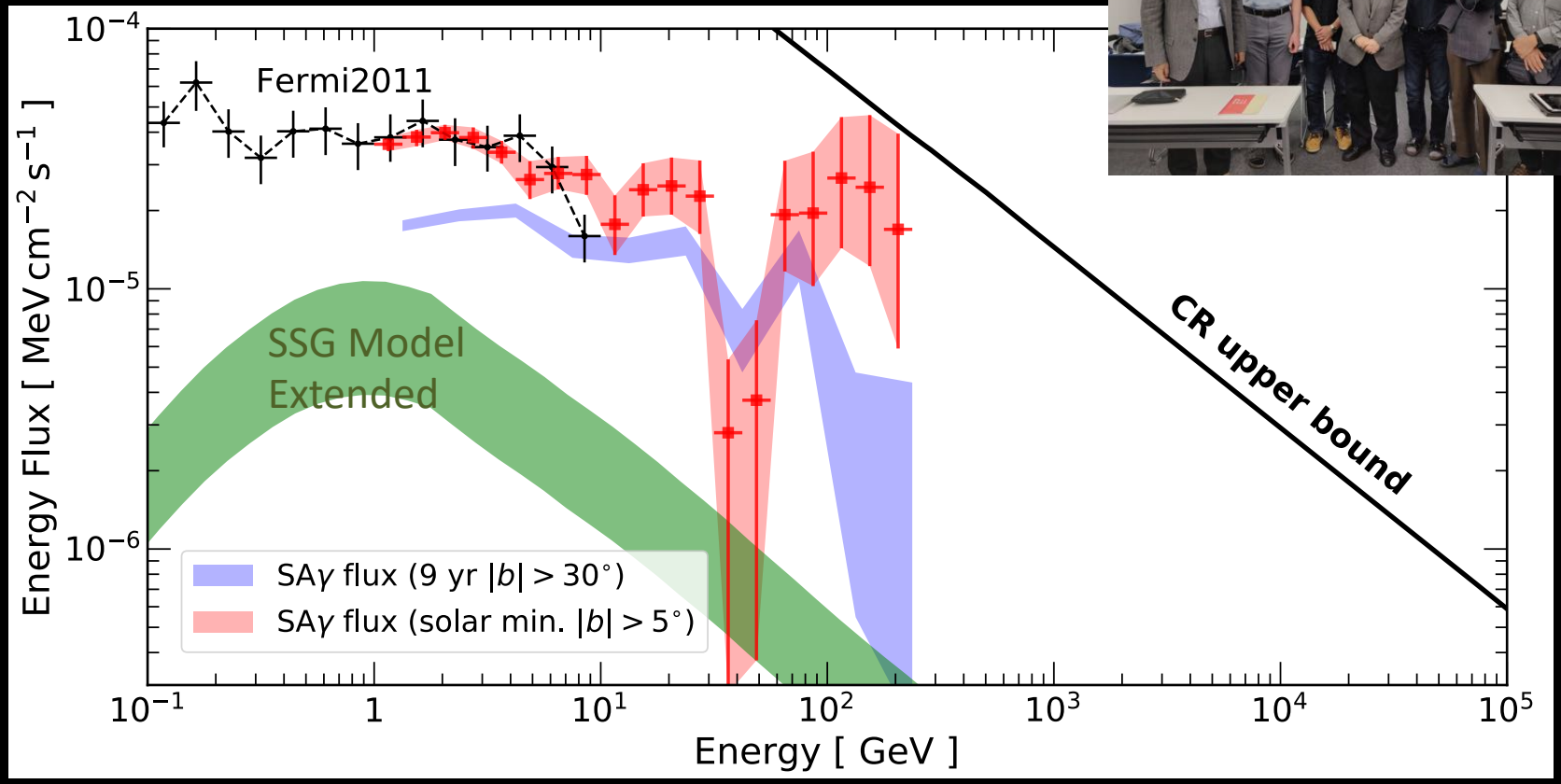
- Strange “dip” between 30-50 GeV
  - Naively, two components, but not easy
  - No obvious instrumental explanation
  - Seems shallower outside solar minimum
  - Statistical fluke? Time-dependent feature/systematics? Will know soon



Spectrum, *surprise (4)*

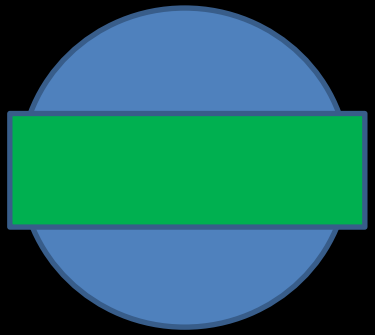
- Observations of the Sun in GeV Gamma Rays by CALET on the ISS
- Nicholas Cannady, APS April Meeting 2019
  - 3 years
  - Consistent with hard spectrum
  - 3 photons above 10GeV, 1 at 30-50GeV ?!



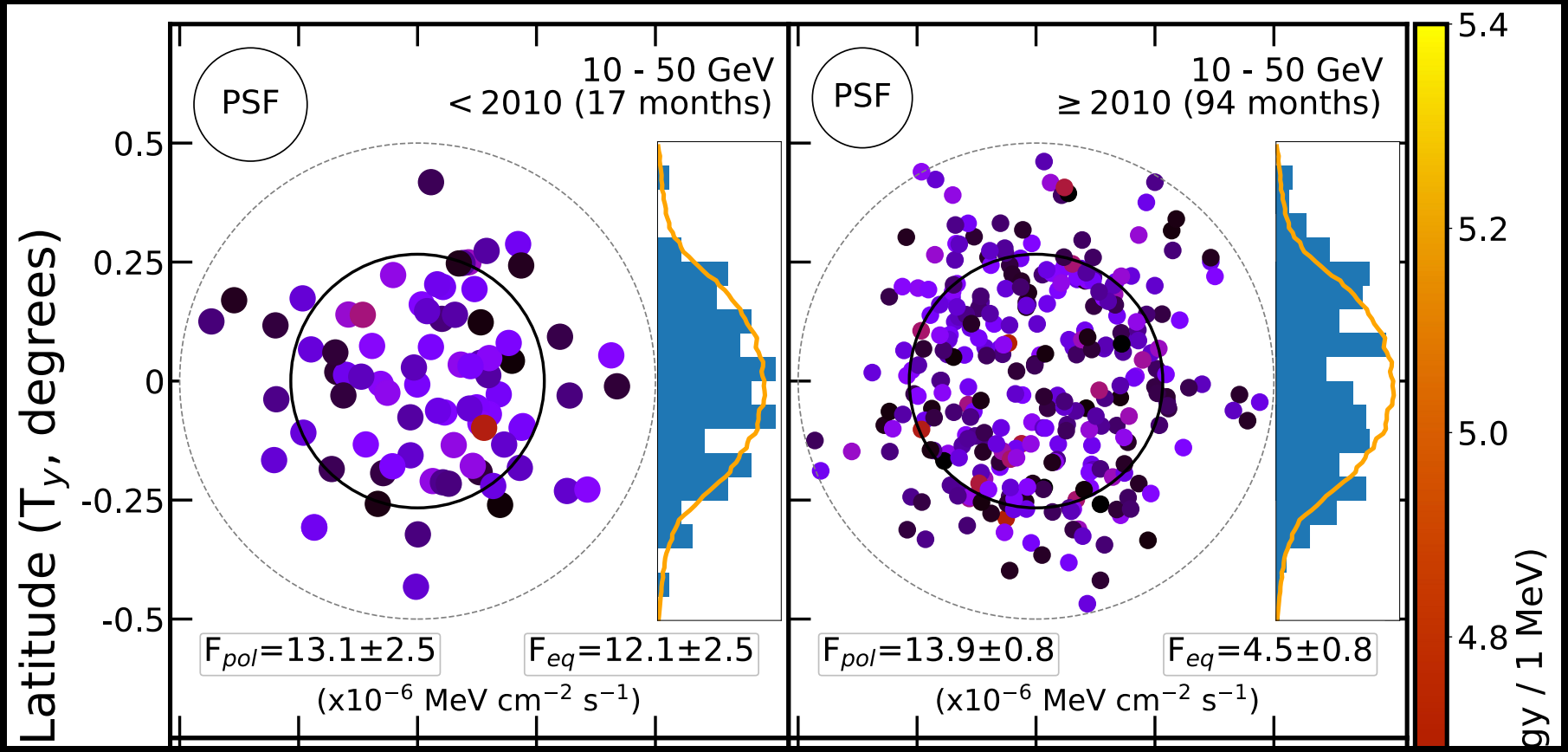


Morphology, *surprise (4)*

- Low Energy Bin
  - 10-50GeV



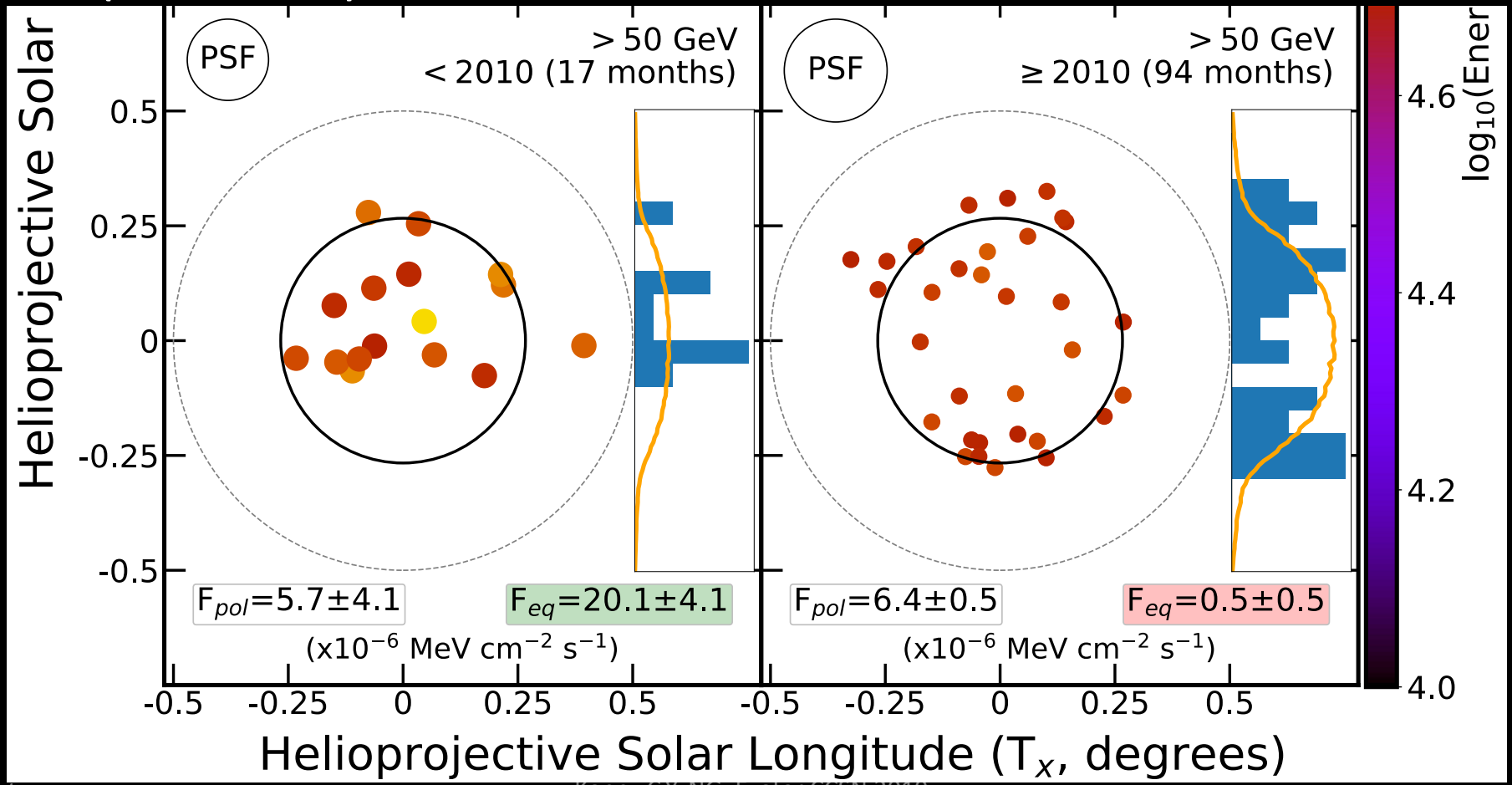
Linden, Zhou, Beacom, Peter, KCYN, Tang
PRL 2018



Morphology, *surprise (4)*

- High Energy Bin
  - (> 50 GeV)

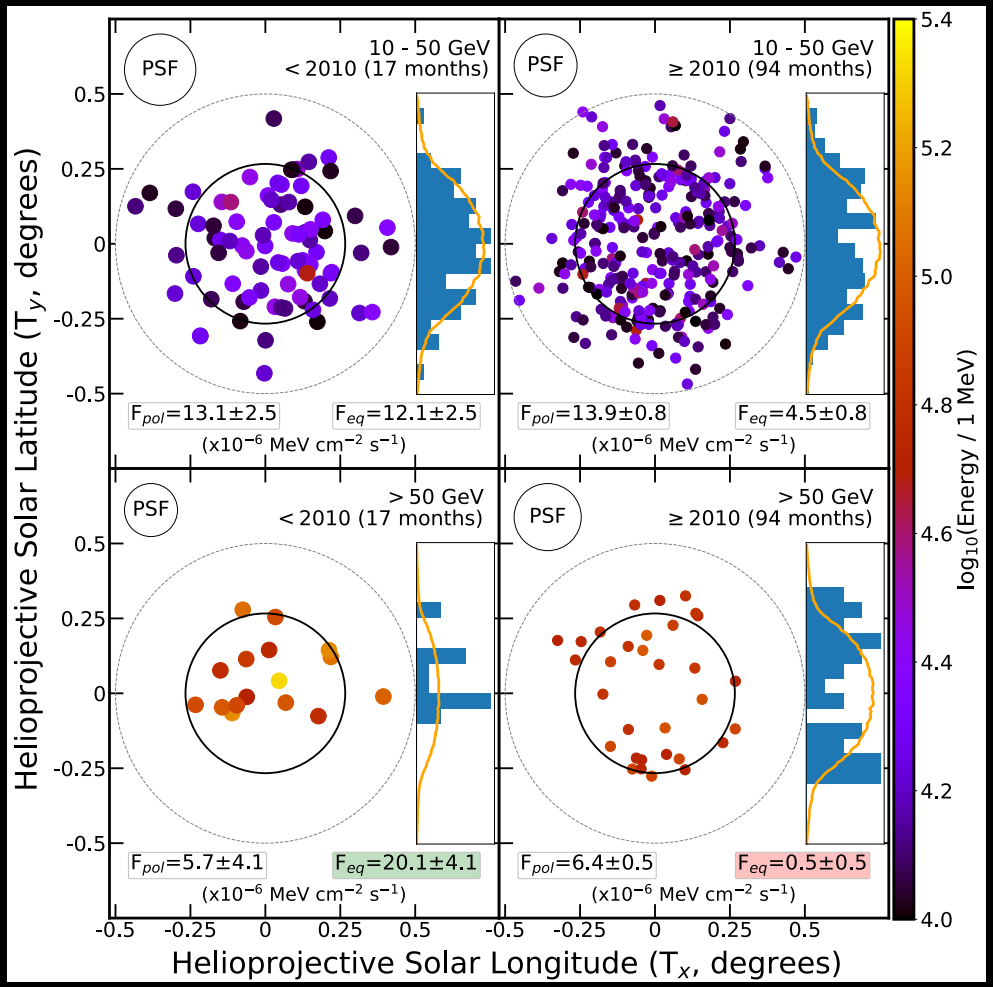
Linden, Zhou, Beacom, Peter, KCYN, Tang
PRL 2018



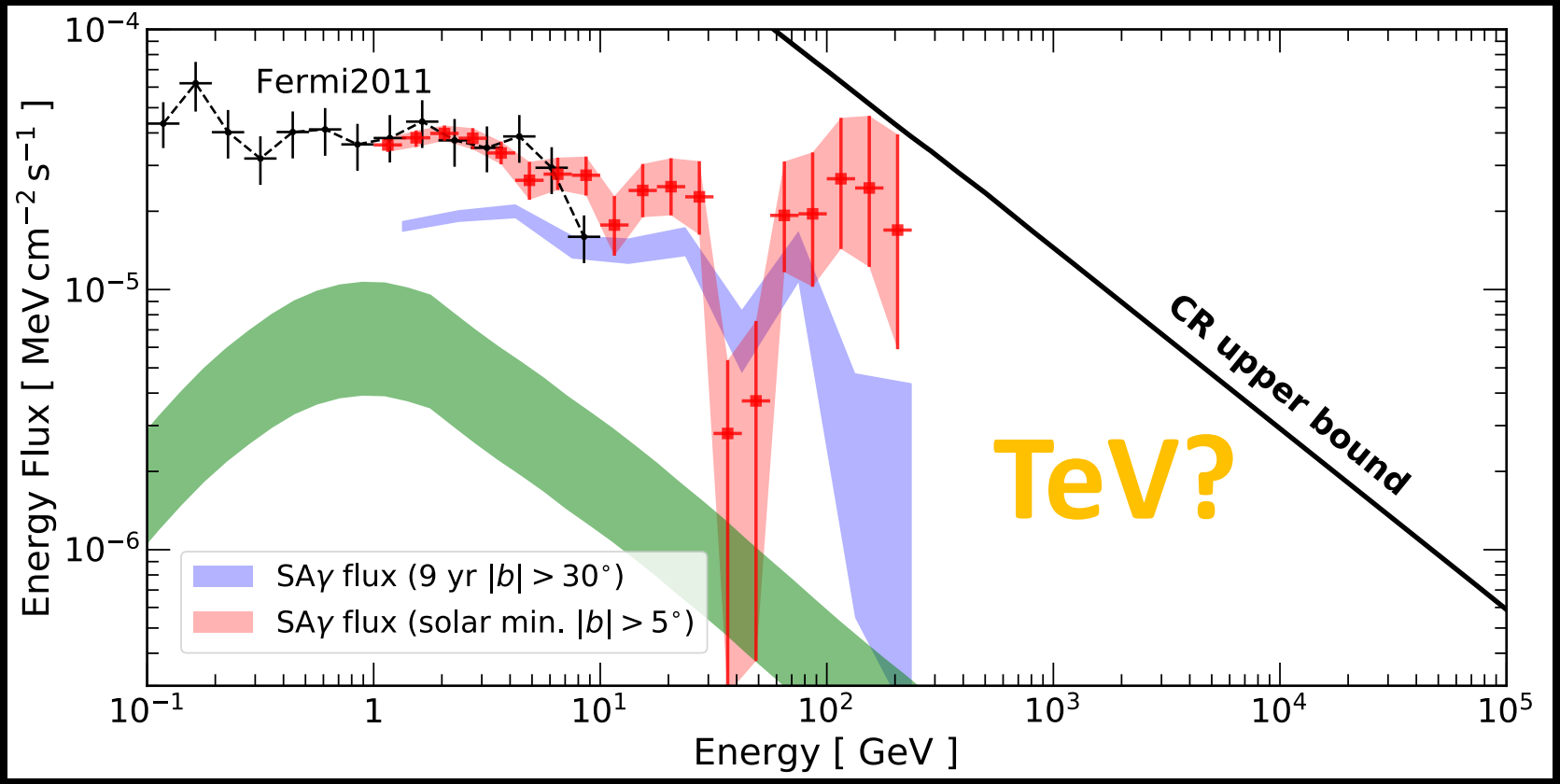
Morphology, *surprise(4)*

- Two spatial components
- Polar
  - Relatively stable vs time
- Equatorial
  - Extreme time variation

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



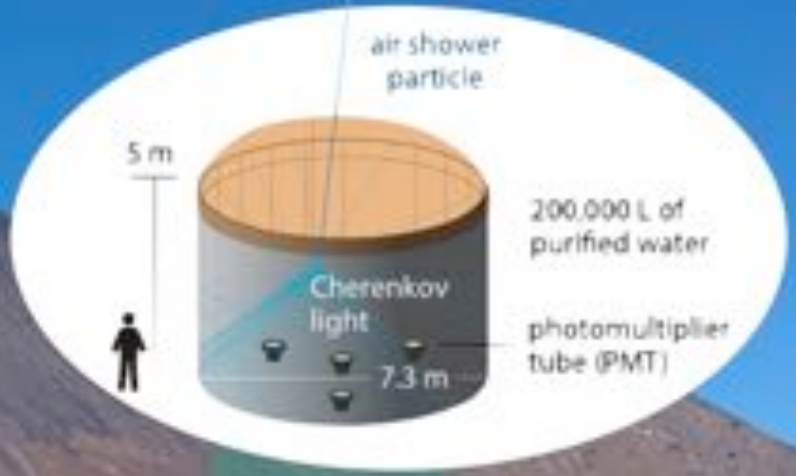
Solar Gamma Spectrum



The HAWC Observatory

Los Alamos NATIONAL LABORATORY

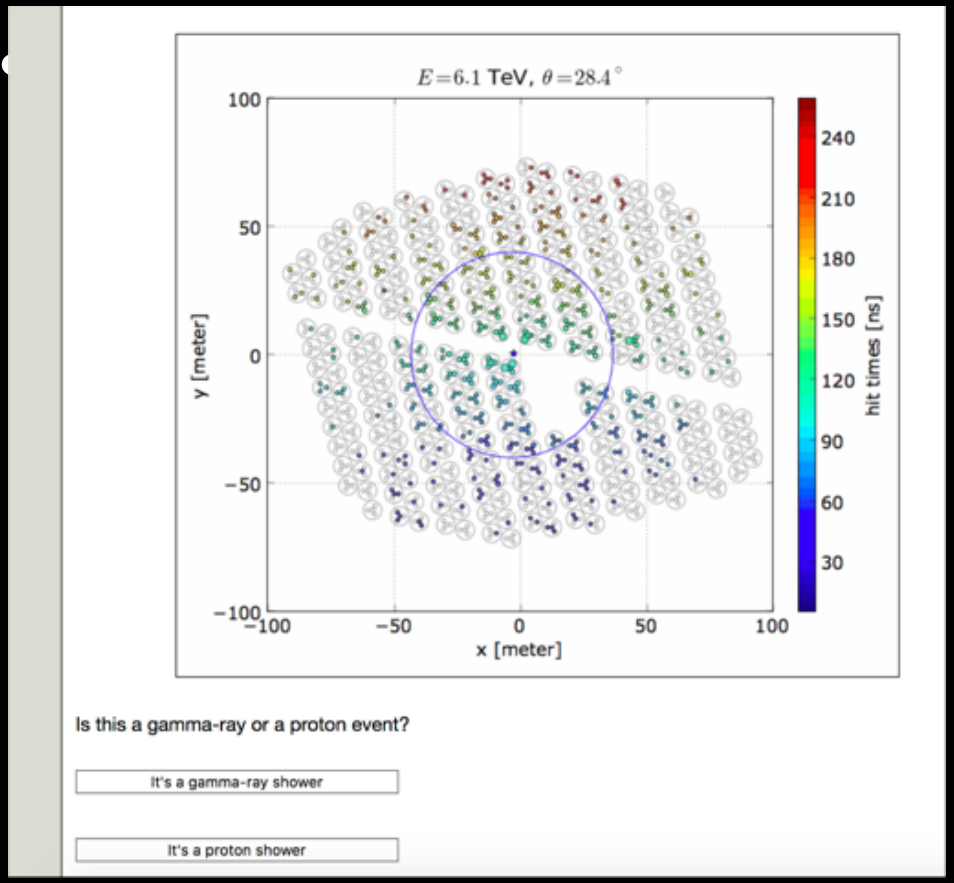
- 300 Water Cherenkov Detectors
- 22,000 m² detector area
- Sub TeV - >100 TeV Sensitivity
- Wide field of view: ~2 sr
- High duty cycle: >95%

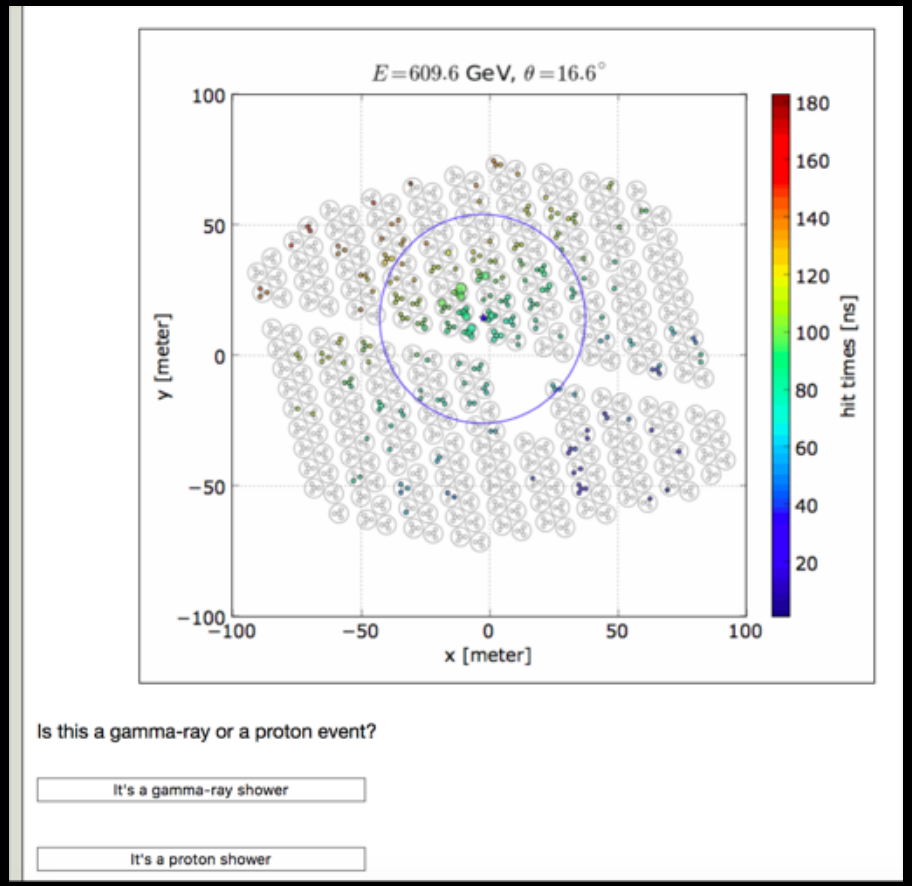


Excellent detector for extended sources

Main array inaugurated on March 20, 2015

Gamma Hadron Separation



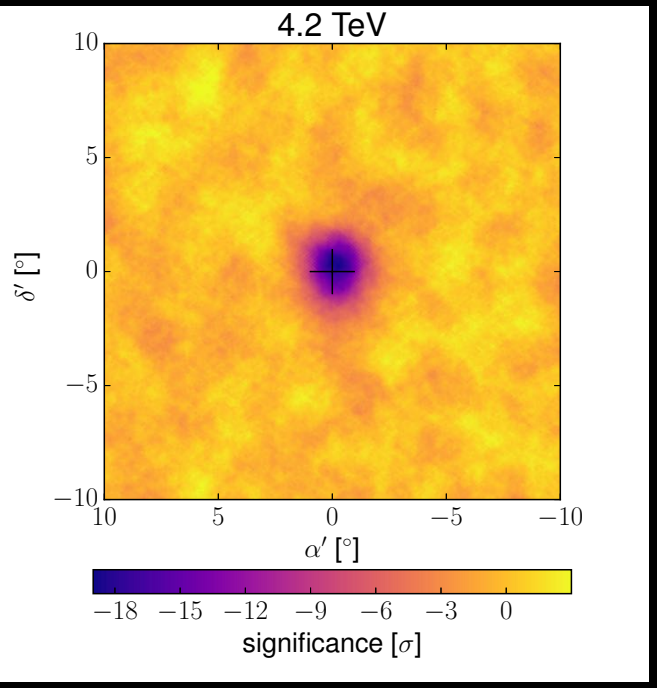


- Large FOV, all weather instrument

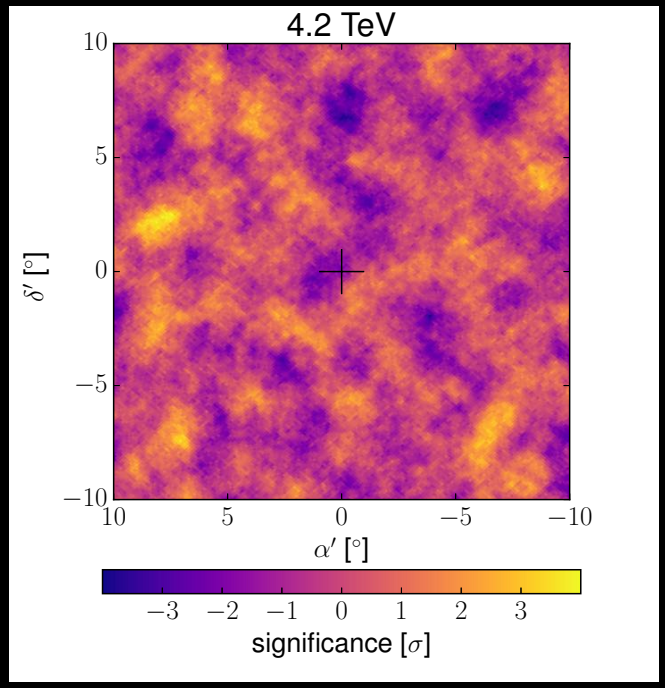
HAWC analysis

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

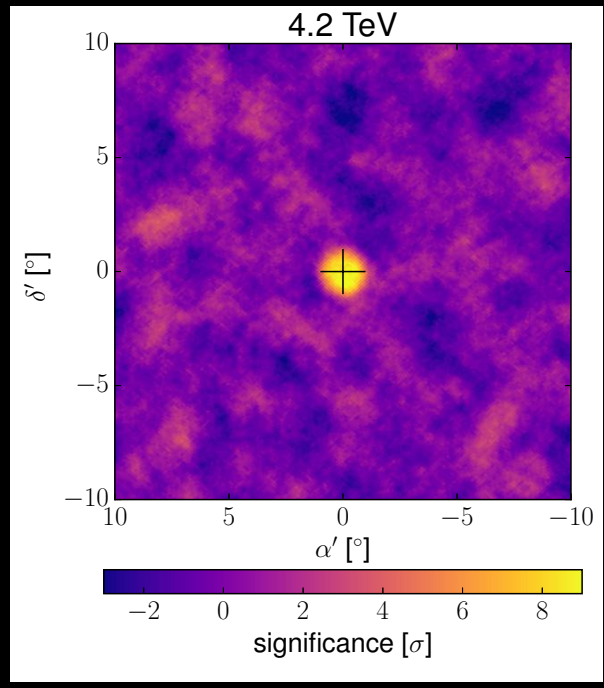
Sun Shadow (all data)



Gamma-hadron cut

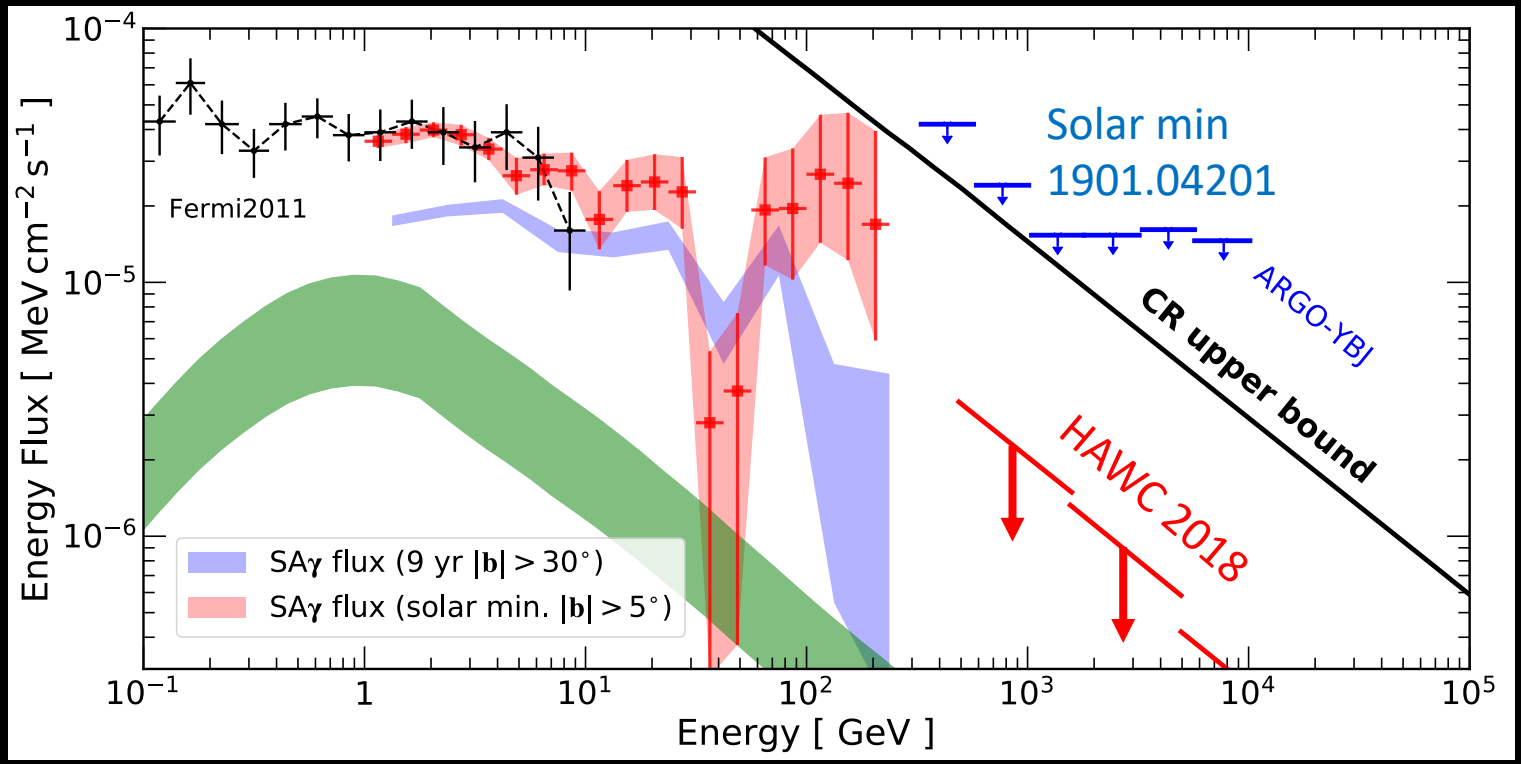


Expected (max. CR)

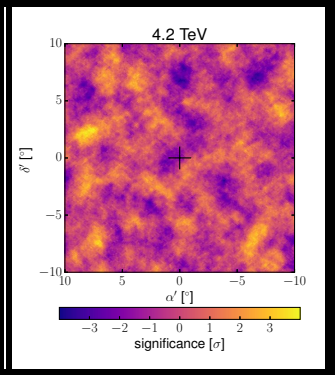


HAWC analysis of the Sun (2014-2017)

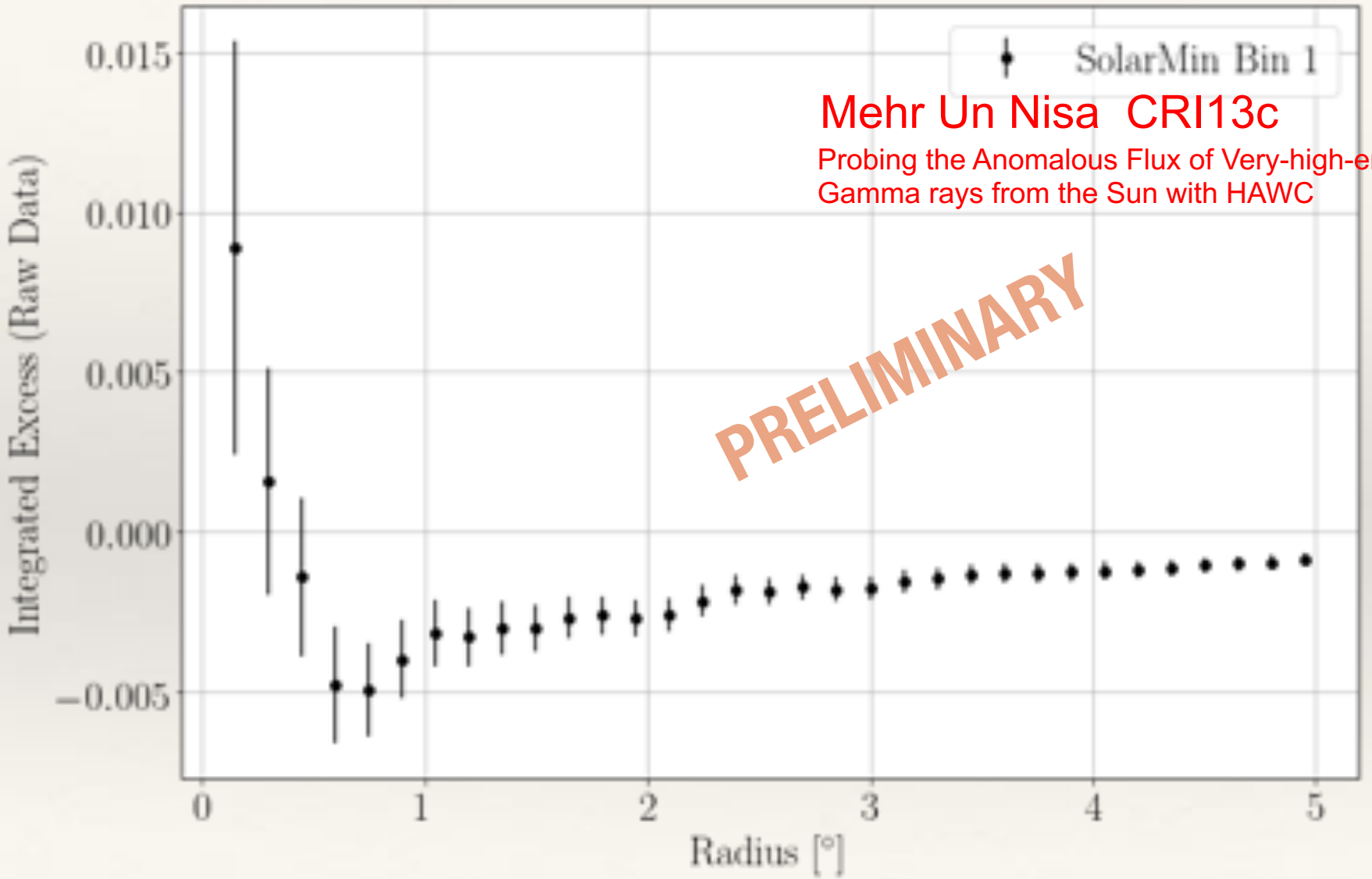
- Constrain ~10% of CR upper bound (active phase)
- Exciting prospect for current solar min (2018 -)



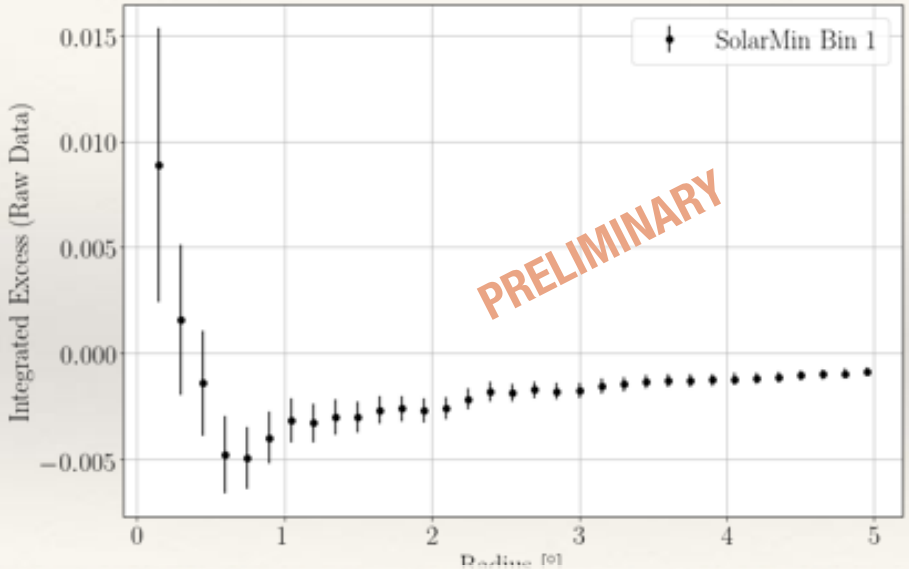
HAWC 1808.05620



2018 Data: Onwards to the Solar Minimum

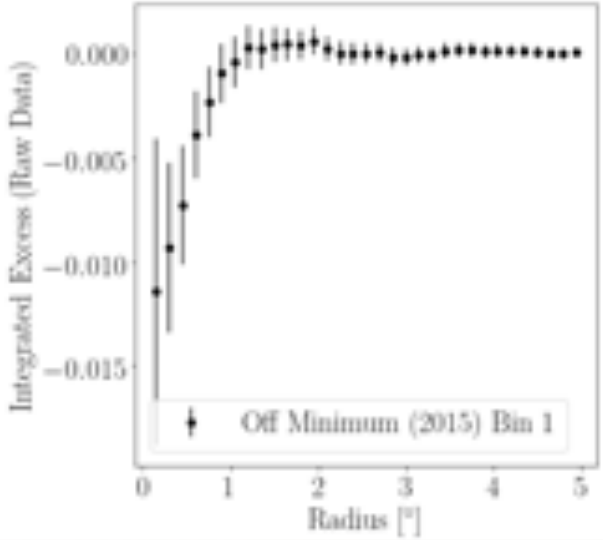


2018 Data: Onwards to the Solar Minimum

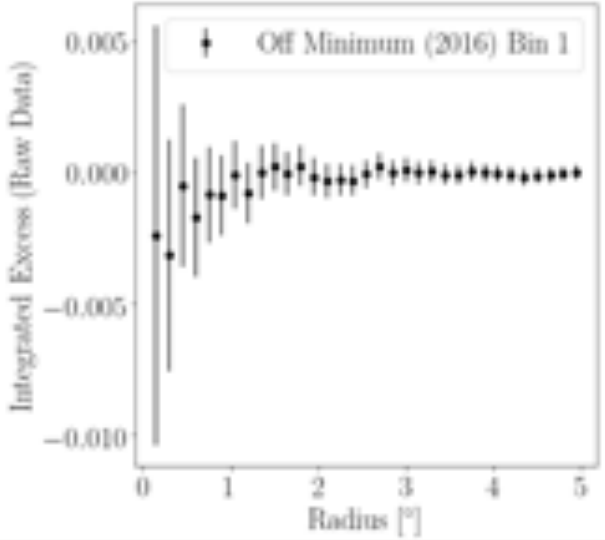


Mehr Un Nisa CRI13c

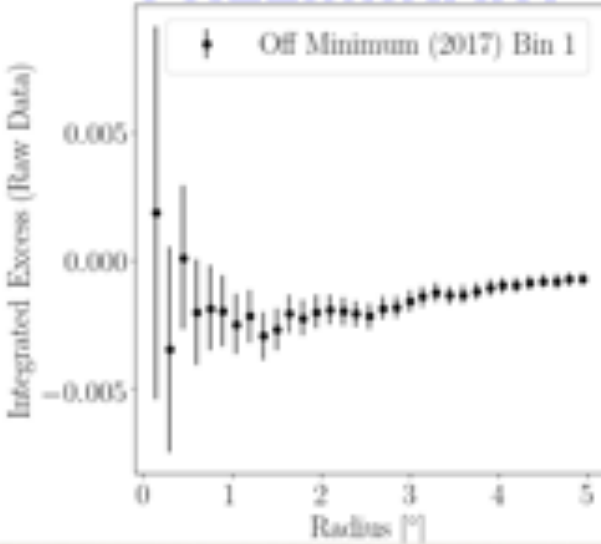
Probing the Anomalous Flux of Very-high-energy Gamma rays from the Sun with HAWC



2015

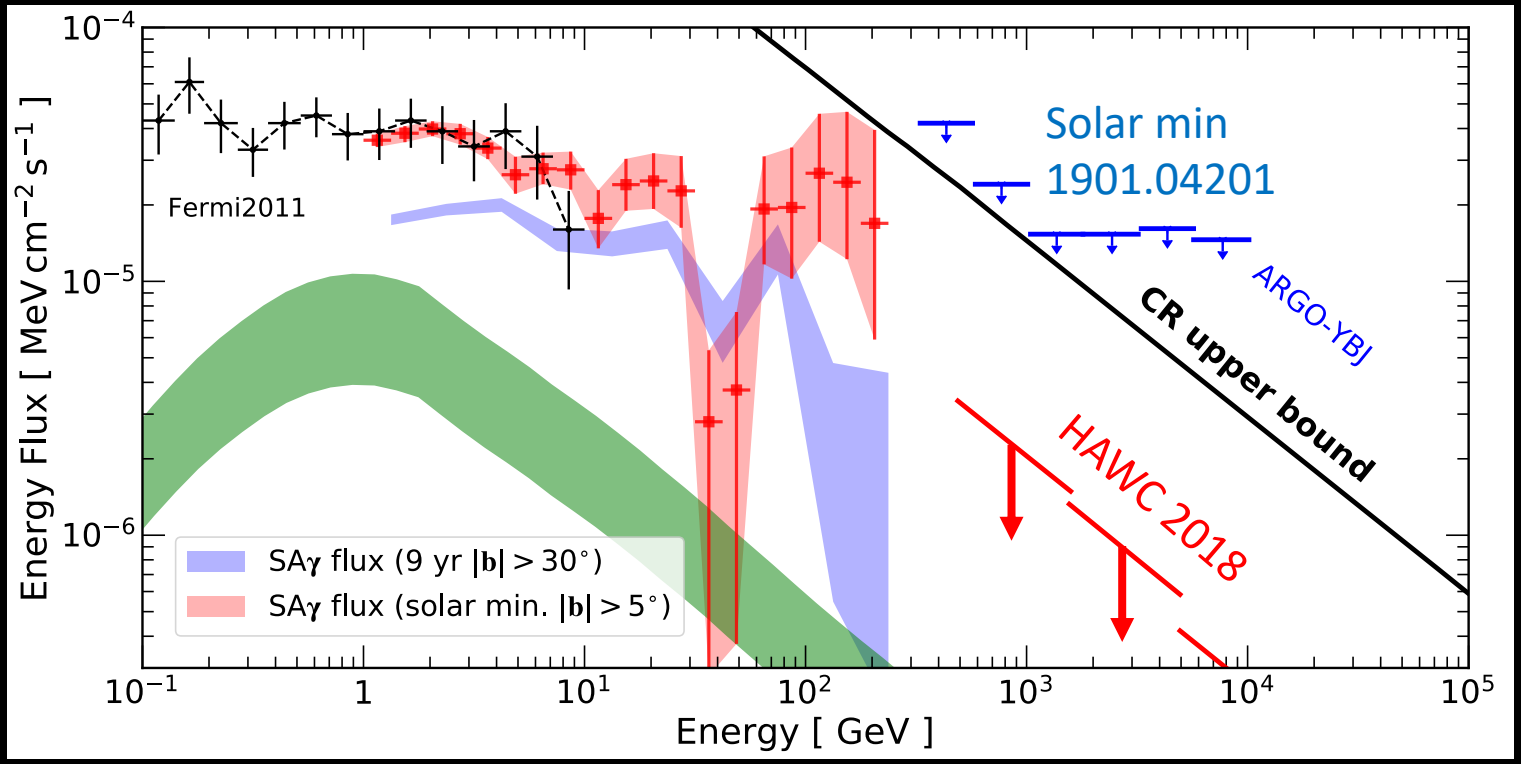


2016



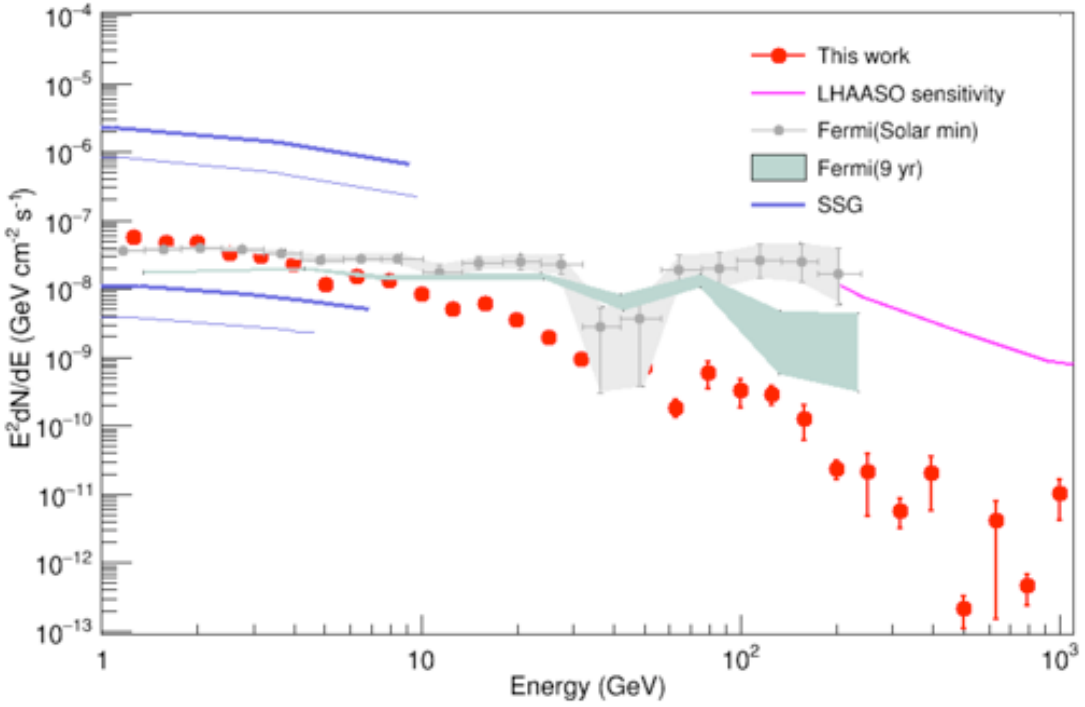
2017

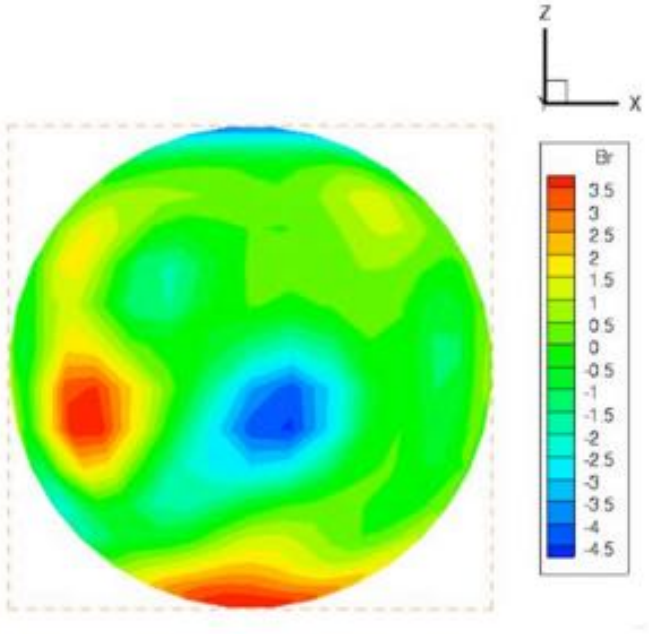
The Sun as a TeV source?!



First Solar gamma simulation w/ B-field

3. Solar disk simulation result





PFSS model for "quiet" Sun

Zhe Li (IHEP)

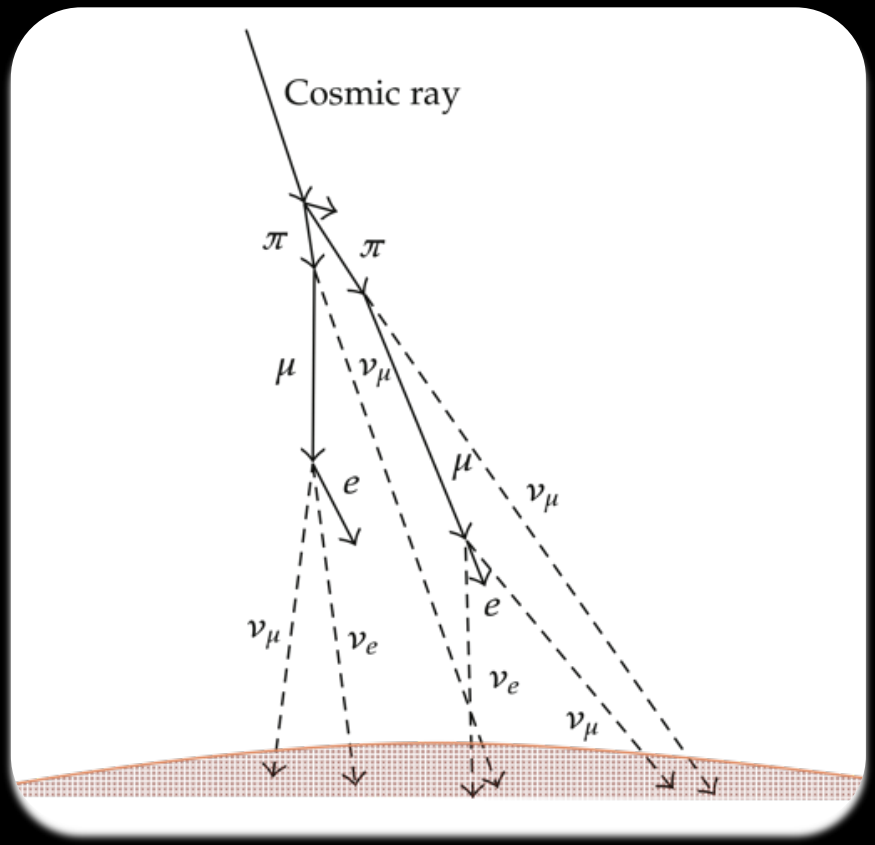
SH5e: Estimation of Solar Disk Gamma-ray Emission Based on Geant4

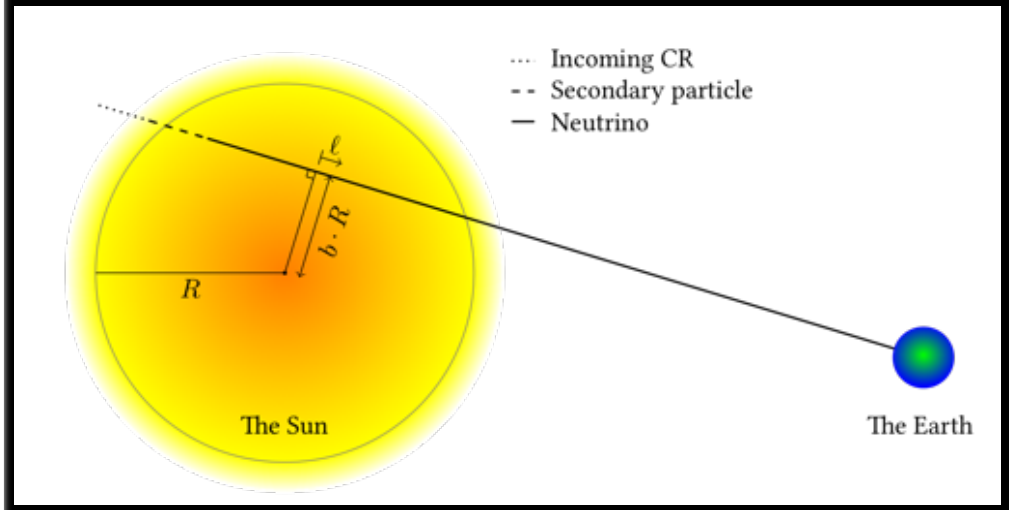
Solar Atmospheric Gamma rays

Complicated……

But could be a new probe for solar physics!

Solar Atmospheric Neutrinos





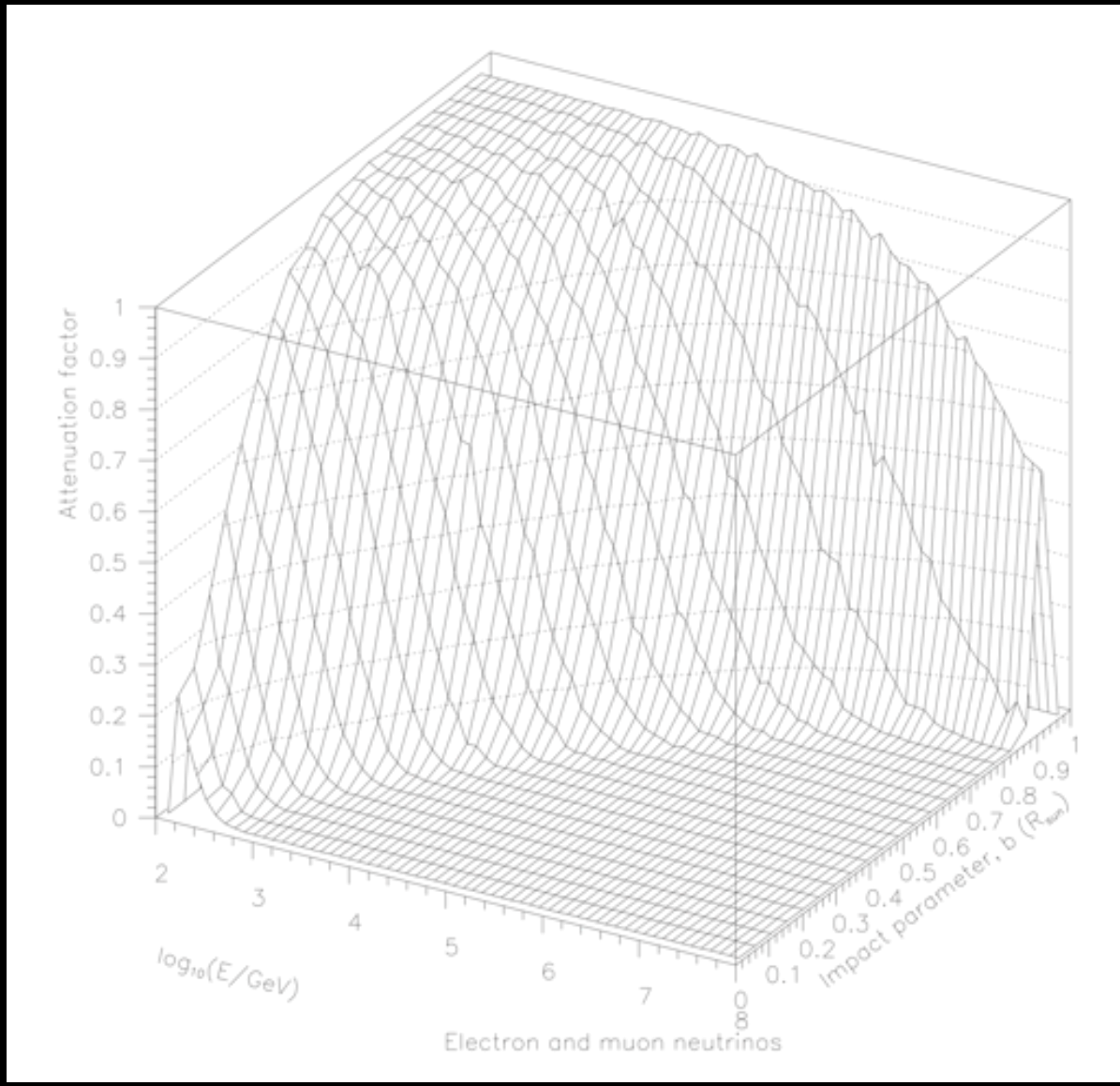
- Dilute atmosphere, larger neutrino flux

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

  C.A. Argüelles+ 1703.07798
  Joakim Edsjo+ 1704.02892

Flux without B/field

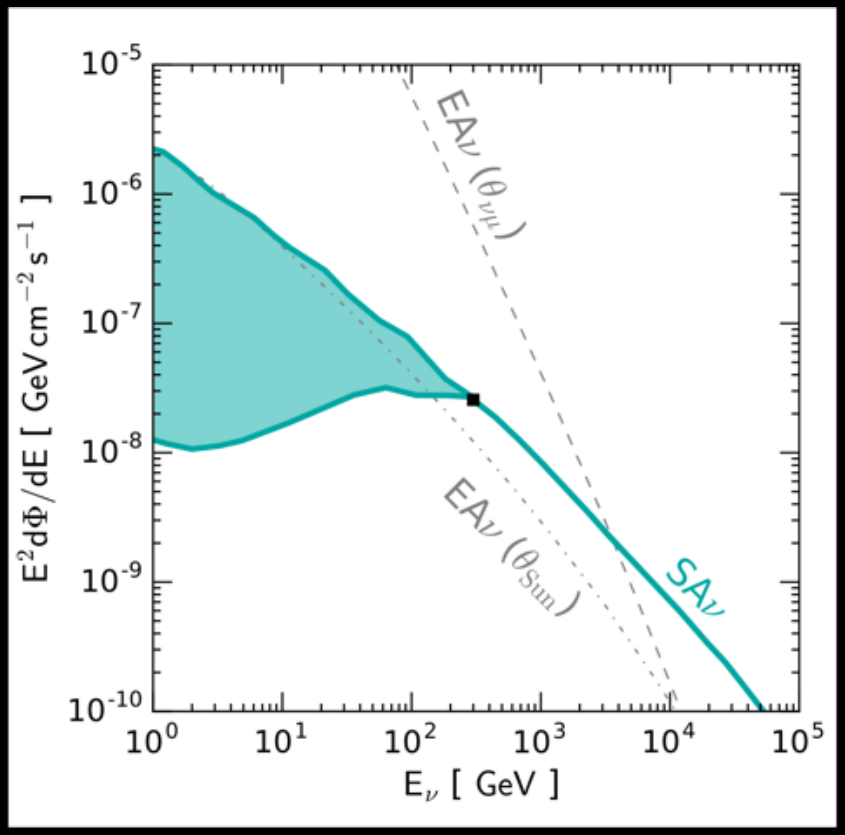
- Absorption
- Oscillation
  - Factor of 2 effect



Joakim Edsjo+ 1704.02892

Solar Atmospheric Neutrinos

KCYN, Beacom, Peter, Rott 2017



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

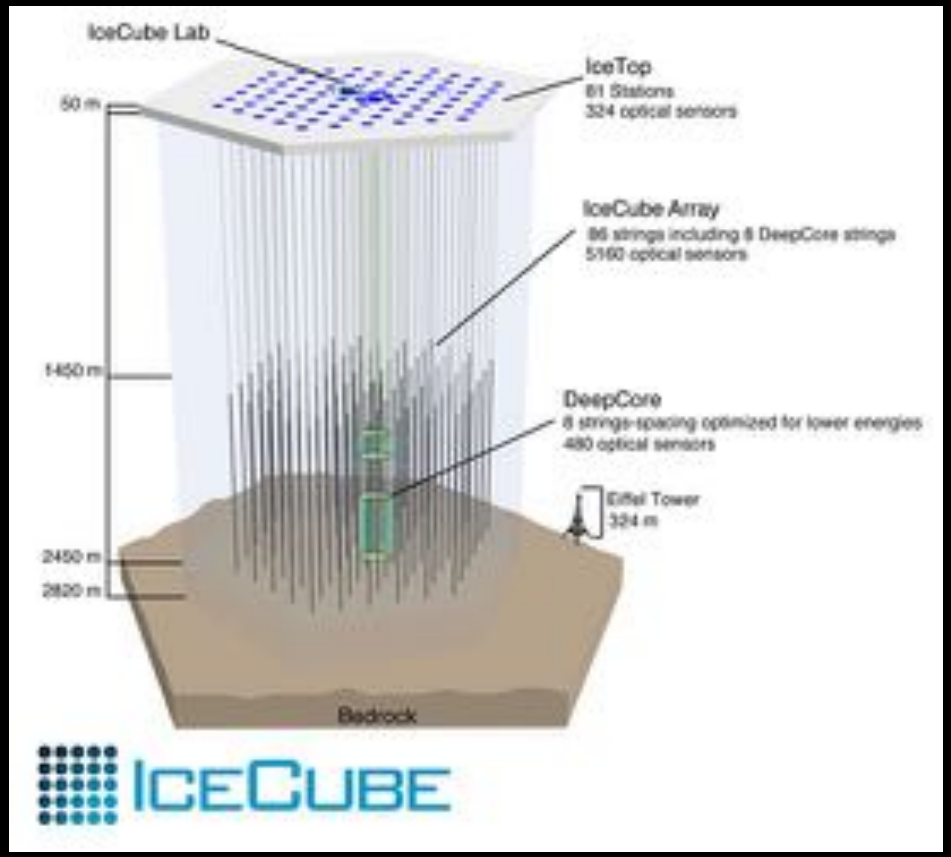
- Dilute atmosphere, larger neutrino flux

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

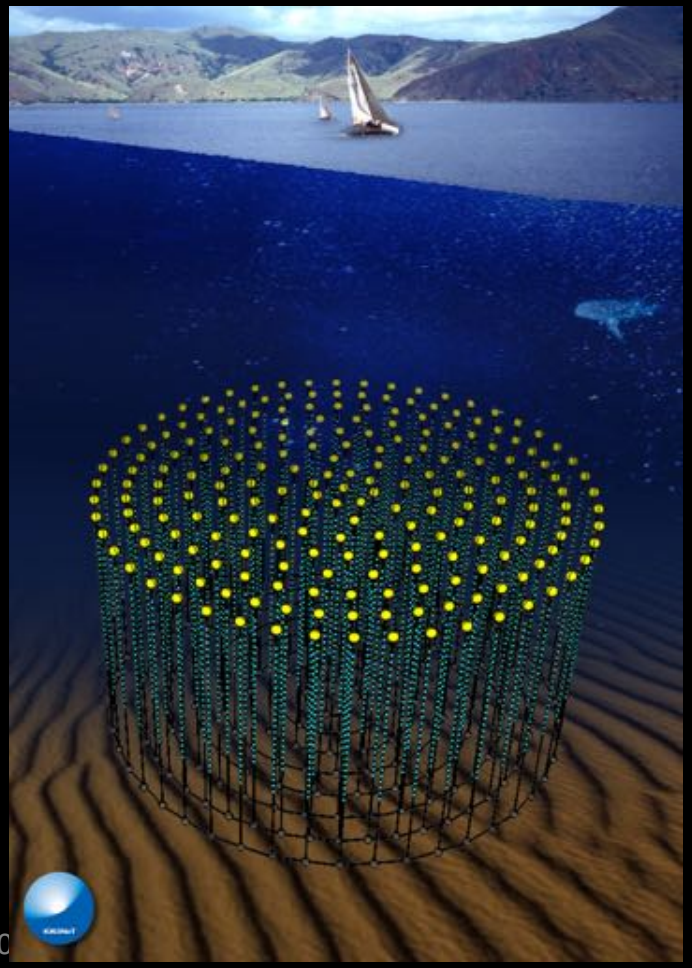
C.A. Argüelles+ 1703.07798
Joakim Edsjo+ 1704.02892

Gigaton Neutrino Detectors

IceCube 2013-
Southpole



KM3NeT (building)
Mediterranean



Neutrino point source detection

$\nu_\mu + N \rightarrow \mu + X$

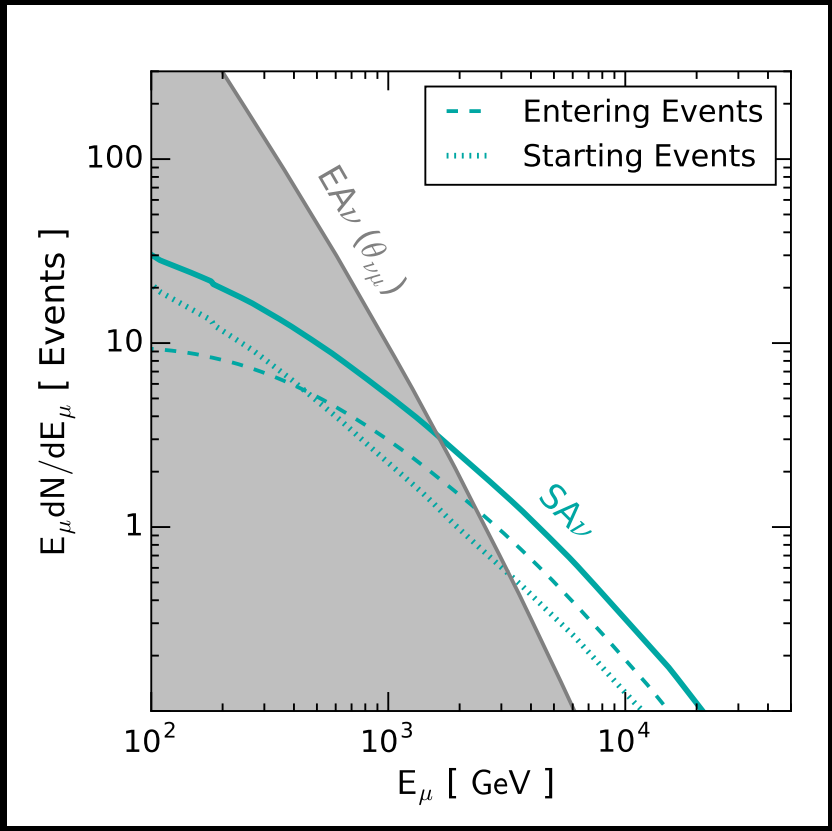
- ν_μ CC events
  - Starting events

$$\frac{dN^{\mathrm{sta}}}{dE_\mu} \simeq N_A \rho V T \frac{1}{1-y} \left[\frac{d\Phi}{dE_\nu}(E_\nu)\sigma(E_\nu) \right]_{E_\nu = \frac{E_\mu}{(1-y)}}$$

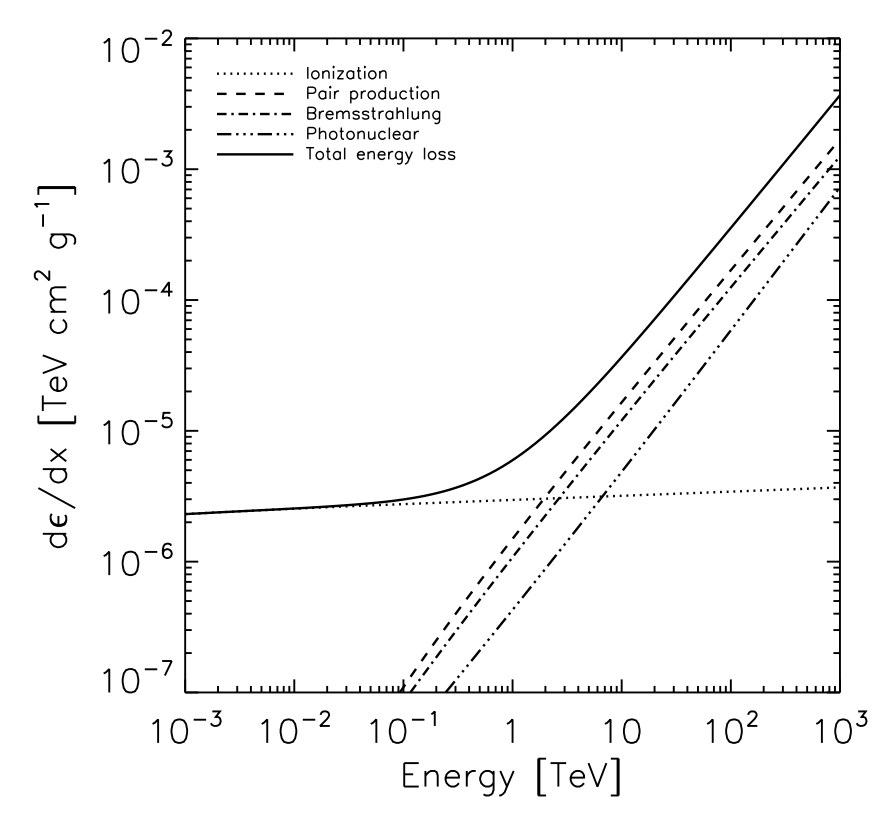
  - Entering events

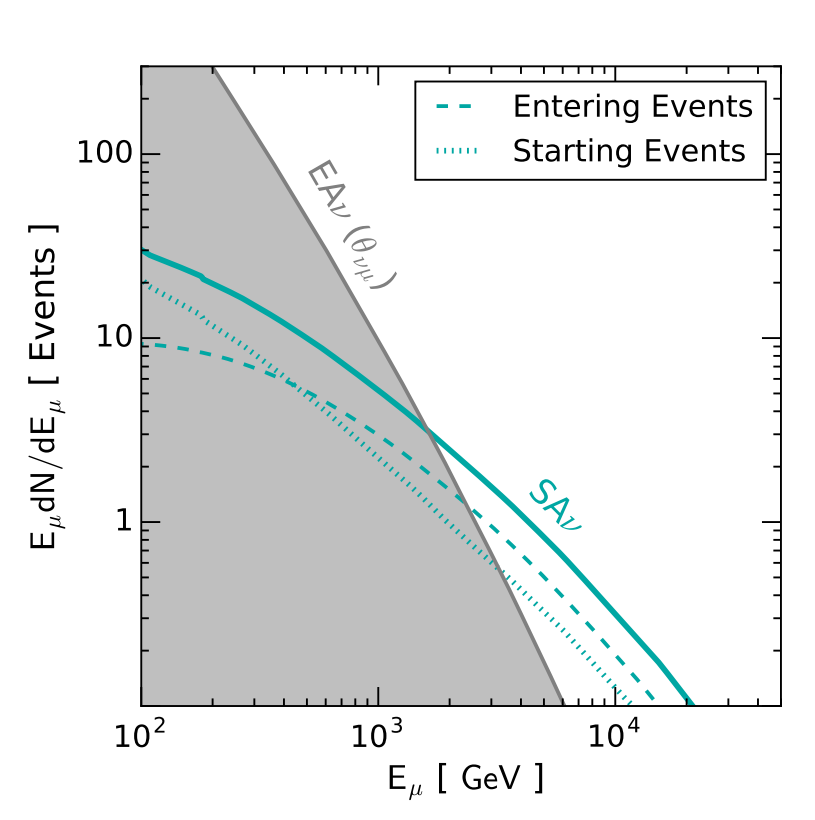
$$\frac{dN^{\mathrm{ent}}}{dE_\mu} \simeq \frac{N_A \rho A T}{\rho\,(\alpha + \beta E_\mu)} \int_{\frac{E_\mu}{1-y}}^{\infty} dE_\nu \frac{d\Phi}{dE_\nu}(E_\nu)\sigma(E_\nu)$$

Muon range



Energy information - Muon energy loss



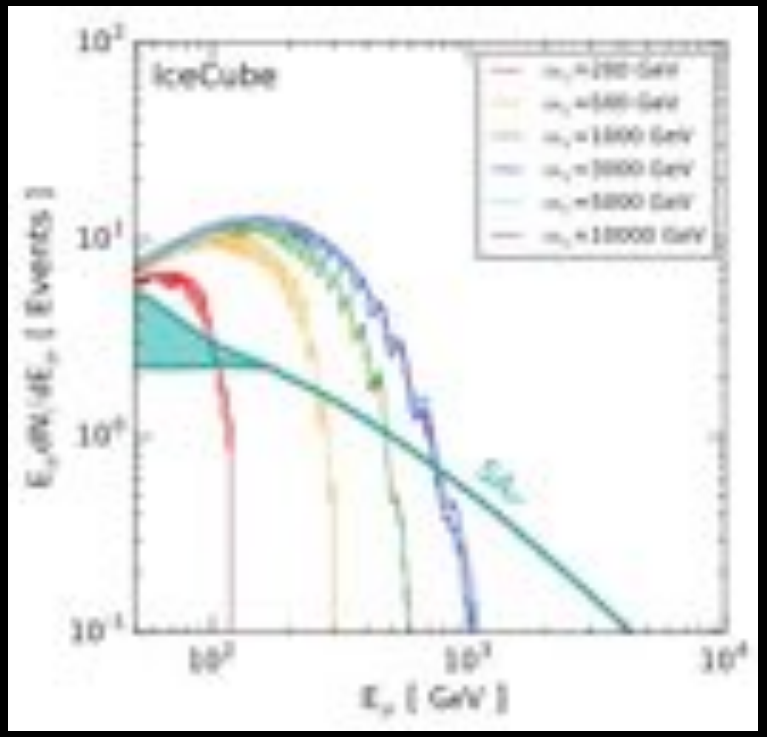


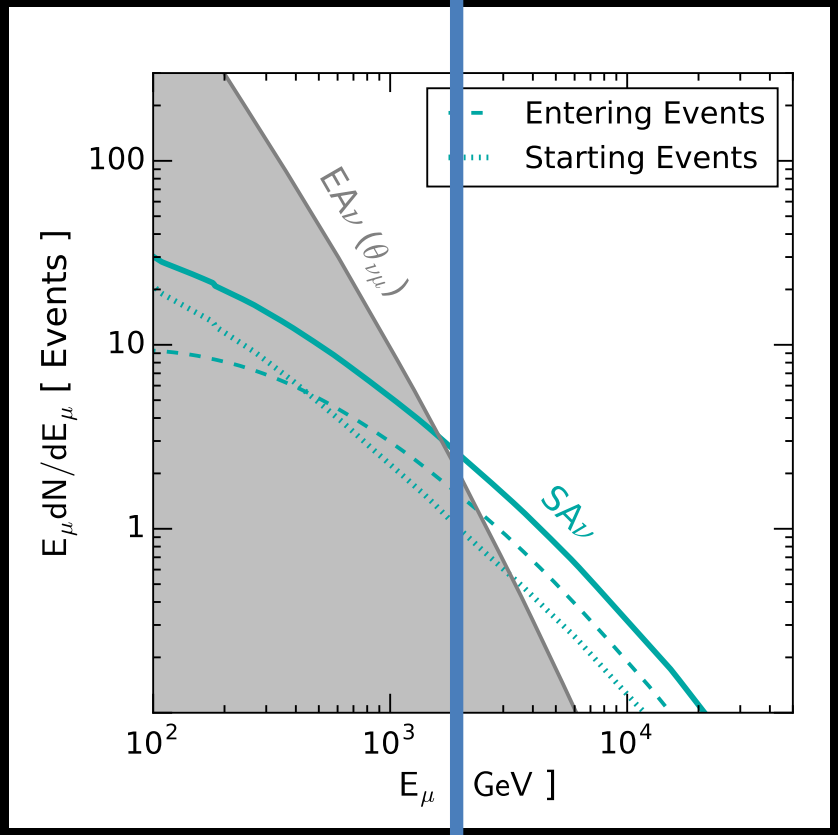
Astraatmadja 2011

- Energy resolution from muon radiative energy loss?

Background or Signal? (Both!)

Theorist Expectation

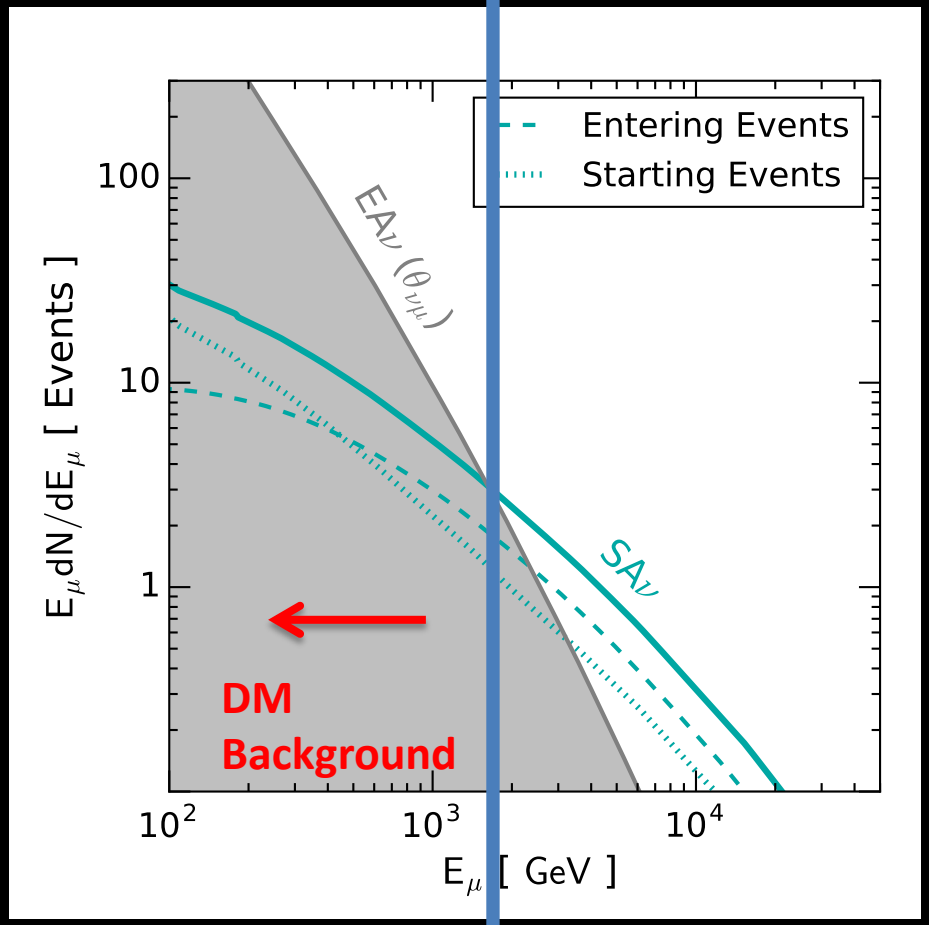


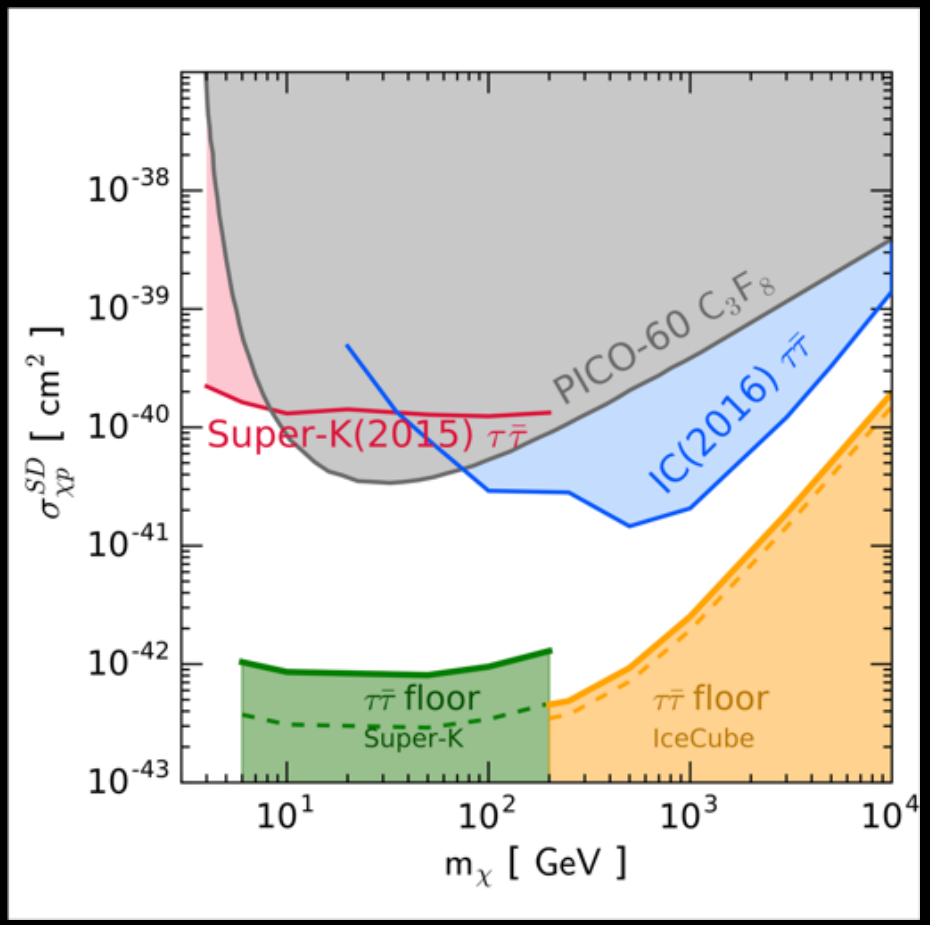


BAD energy-resolution
Difficult to distinguish from DM signal
Background!

Some energy-resolution
No DM signal*
Astrophysical signal!

Solar ATM neutrino – indirect detection Neutrino Floor





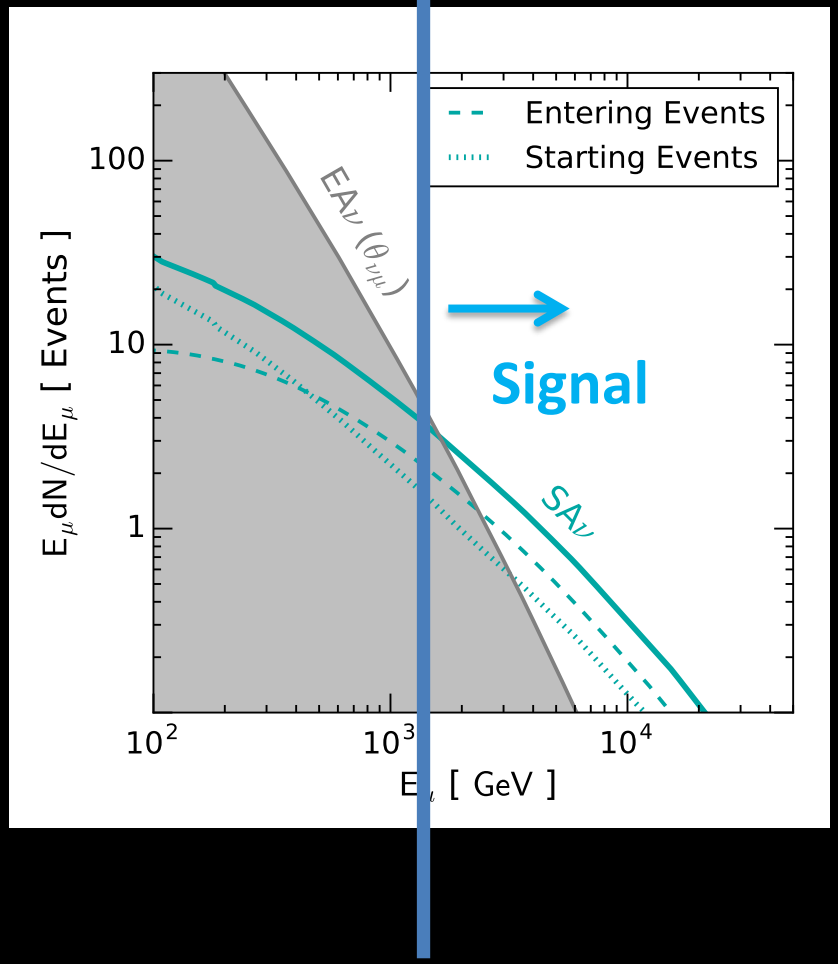
No B-field effect are considered

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

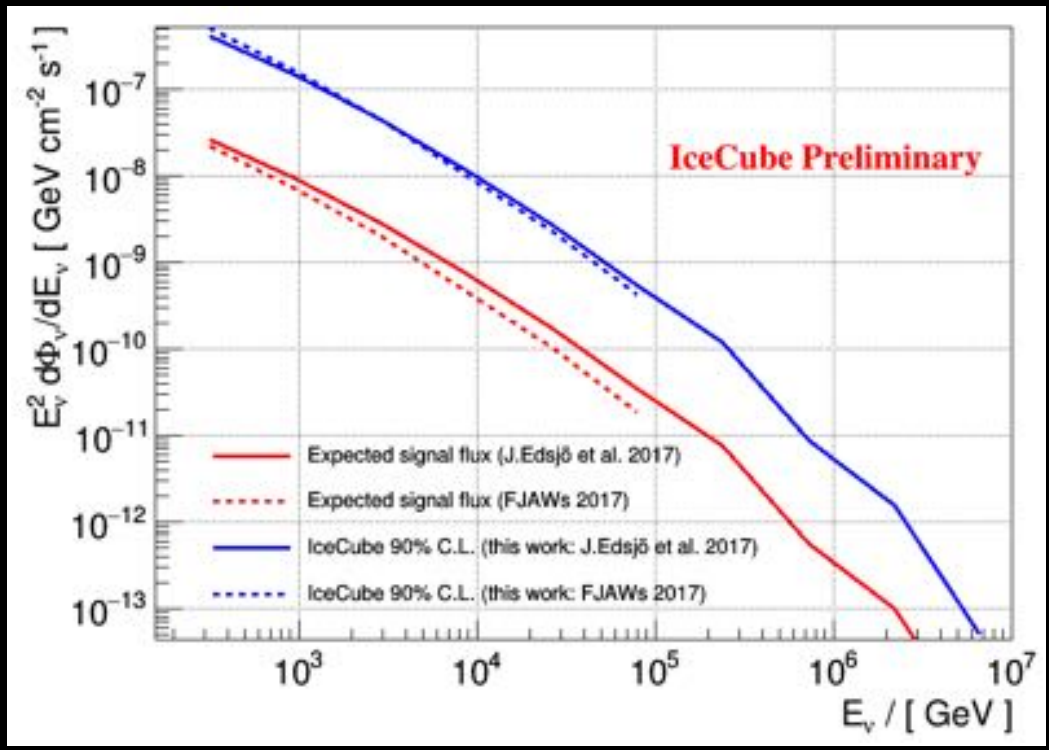
KCYN, Beacom, Peter, Rott, PRD 2017
See also
Arguelles+ 1703.07798
Edsjo+ 1704.02892

IceCube Search

Theorist Expectation

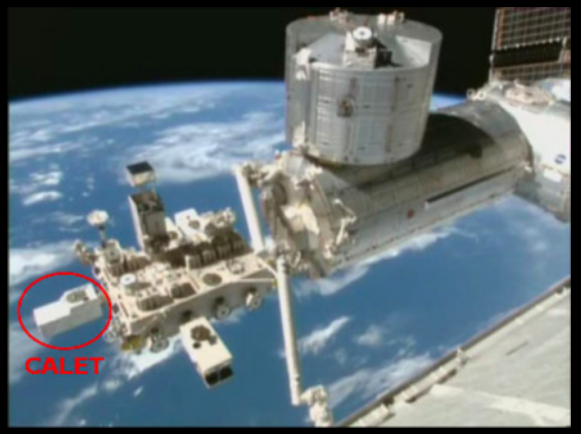


C. Rott, KIAS workshop 2018



Seems difficult……
Improve analysis?

Summary



- Solar gamma rays
  - *Complicated*
  - *TeV* (HAWC-operating, LHAASO-soon)
  - CALET/AMS2
  - *More time (solar minimum starting 2018)*

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

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

Thanks!