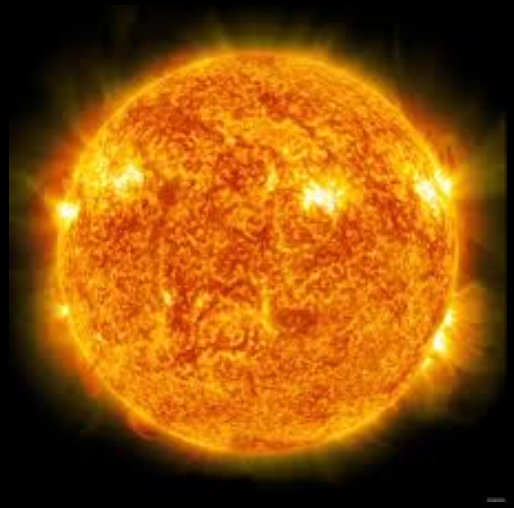
The Surprising Solar Gamma-ray Emission from Cosmic-Ray Interactions



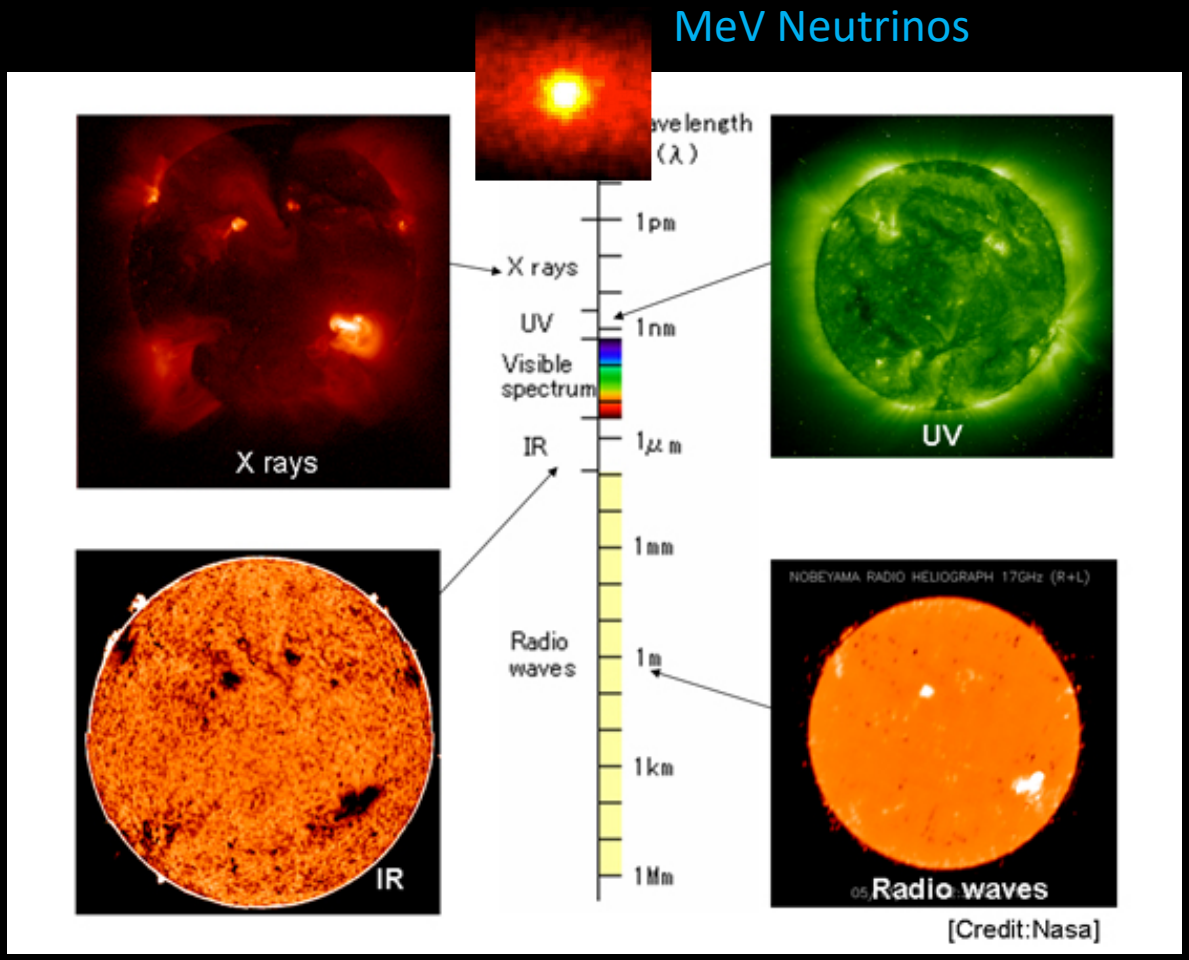
Kenny, Chun Yu Ng (吳震宇)
Weizmann Institute of Science

Observations of the Sun

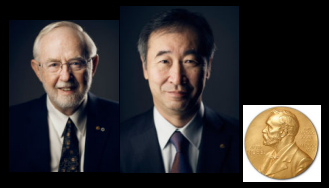
GeV ??? ⟶ The Sun is not hot enough!

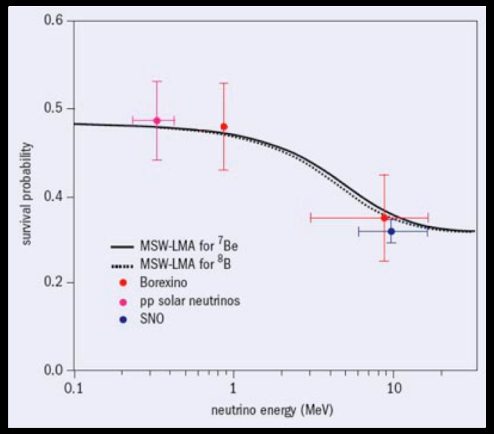
Fundamental Physics from the Sun

MeV Neutrinos

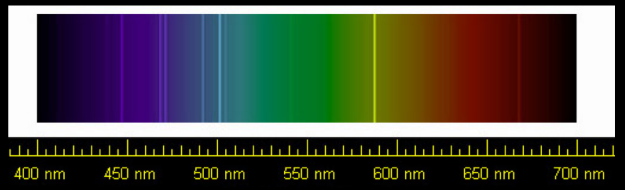


Neutrino Mass





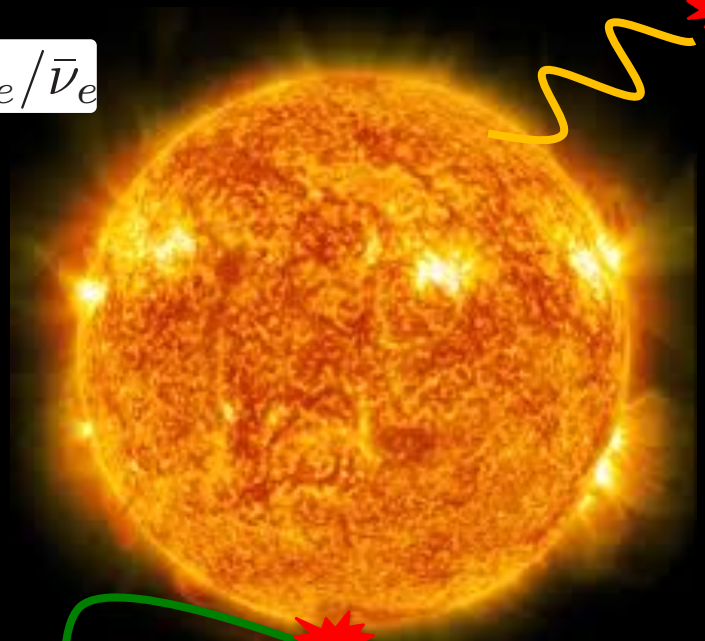
Helium Discovery



Sun – Cosmic-Ray Beam Dump

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

CR electrons
Inverse-Compton



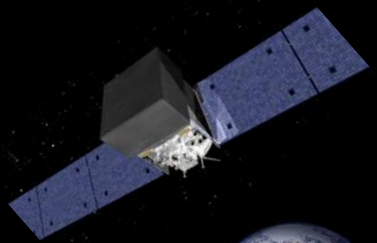
γ

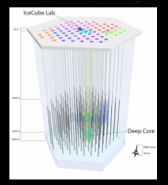
Seckel, Stanev, Gaisser (1991)
Zhou, KCYN, Beacom, Peter
[1612.06420]

CR protons
Hadronic

ν

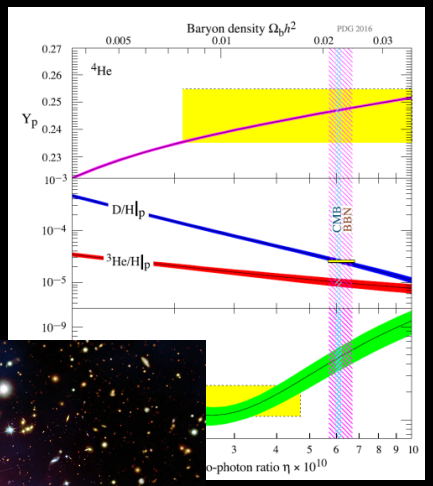
γ

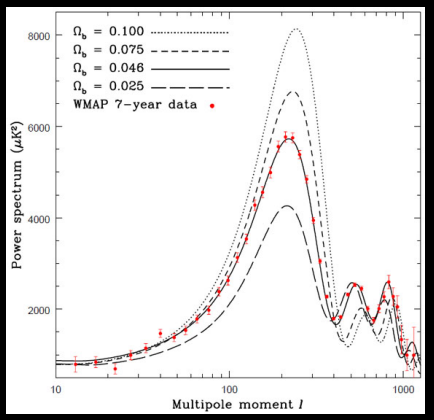


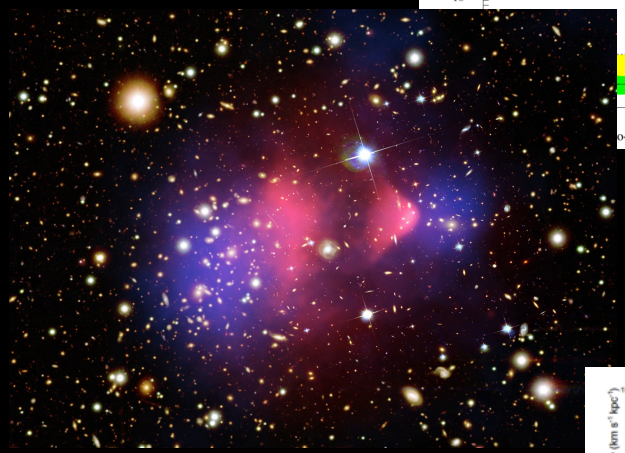


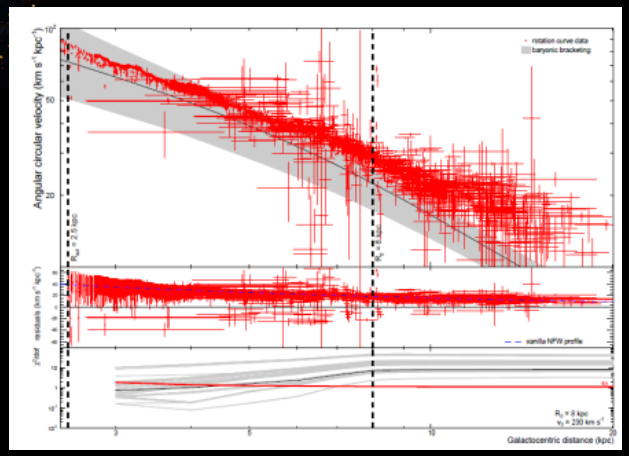
Dark Matter/Gravity problem

- Big Bang Nucleosynthesis \CMB
- Clusters
- Galaxies/Local



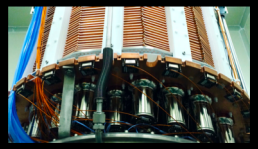




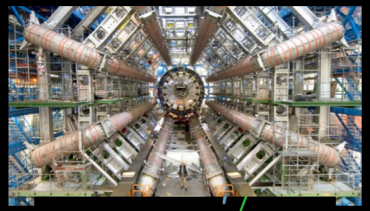


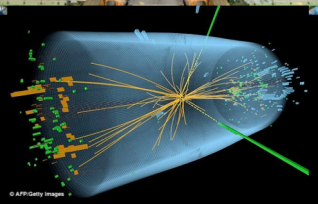
Weakly interacting massive particles

- Direct Detection

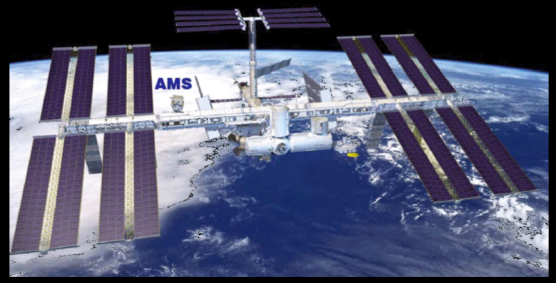


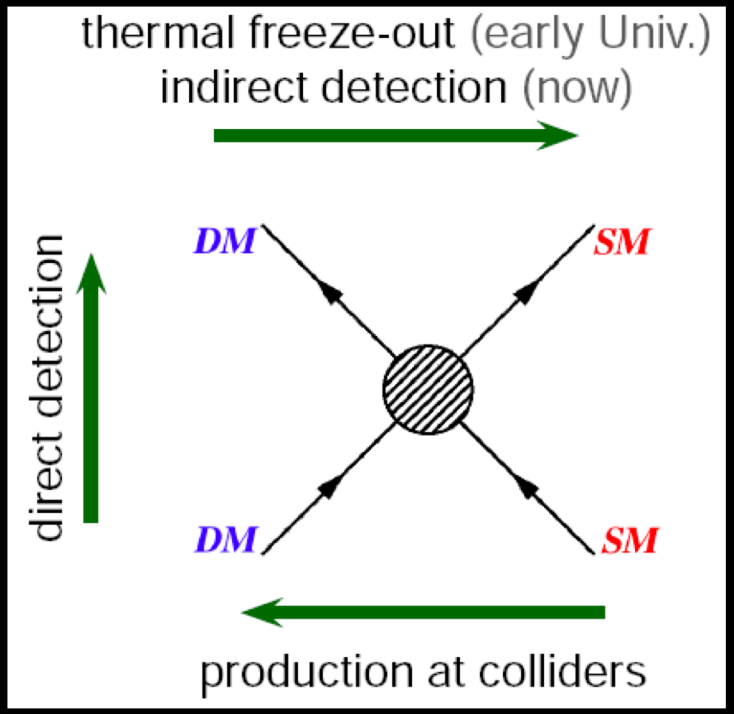
- Collider Search





- *Indirect Detection*



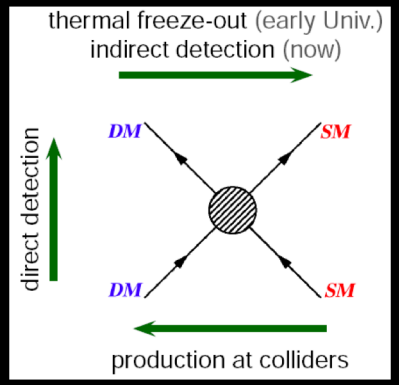


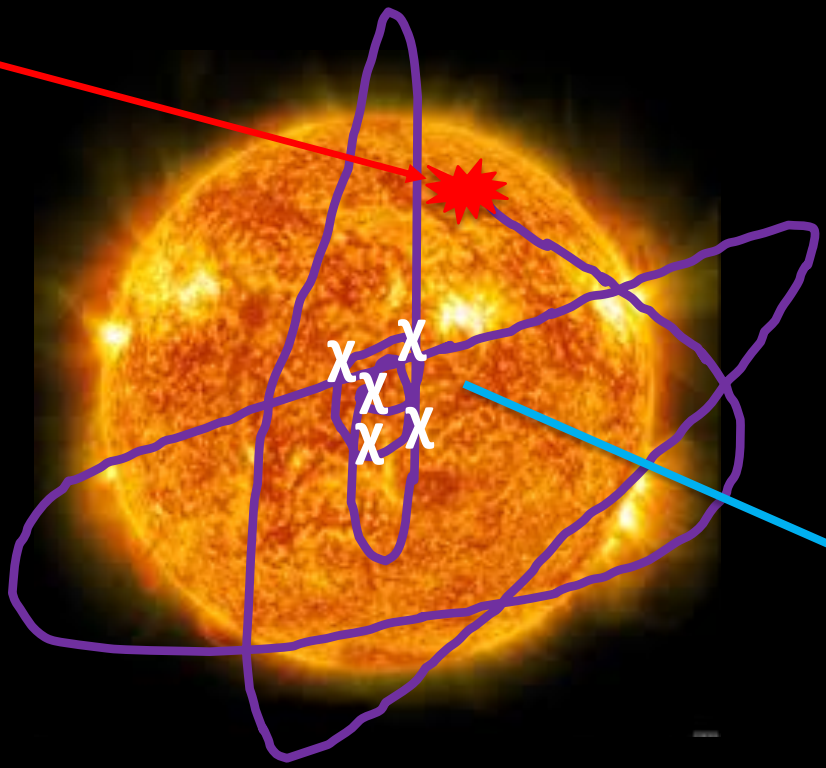
Sun – Dark Matter detector

χ

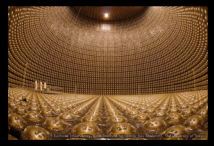
$$\frac{dN}{dt} = \Gamma_{\rm cap} - C_{\rm ann} N^2$$

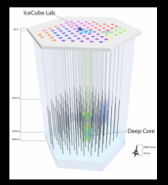
$$\Gamma_{\rm ann} = \frac{1}{2} C_{\rm ann} N^2 = \frac{1}{2} \Gamma_{\rm cap}$$





ν

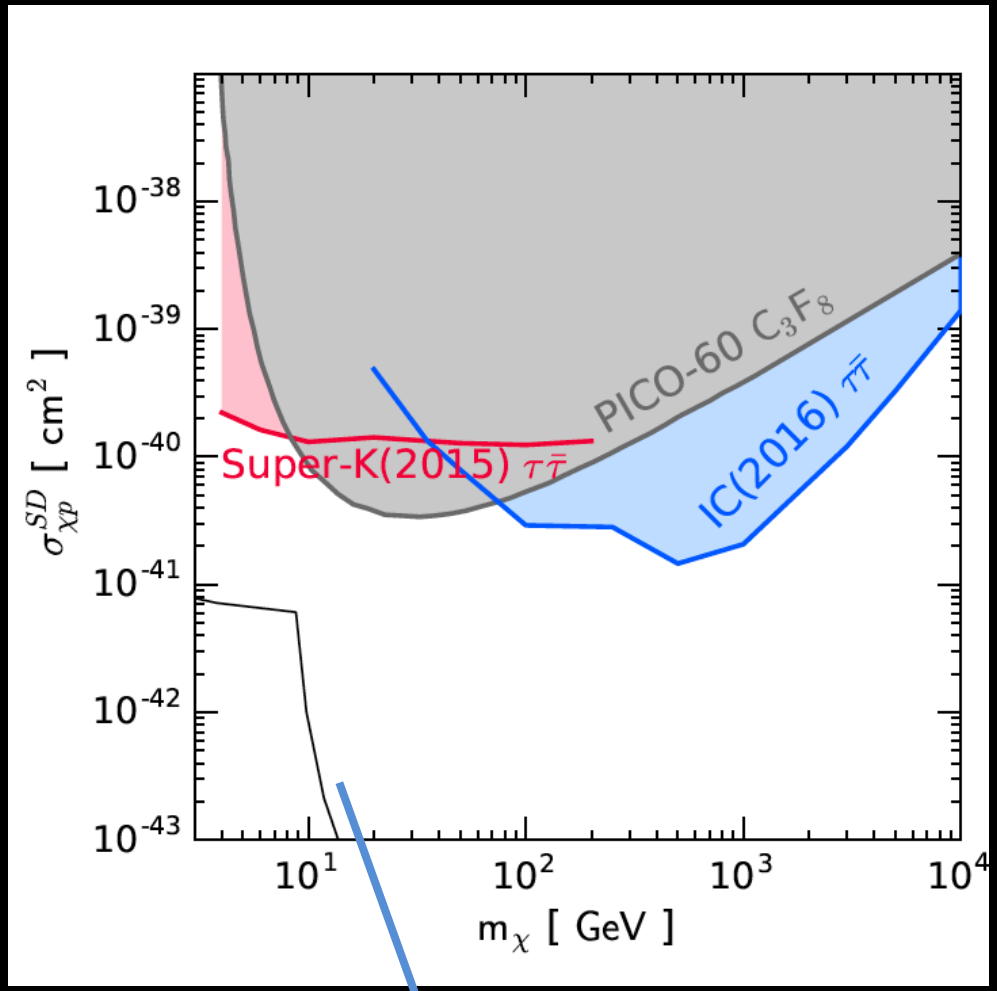




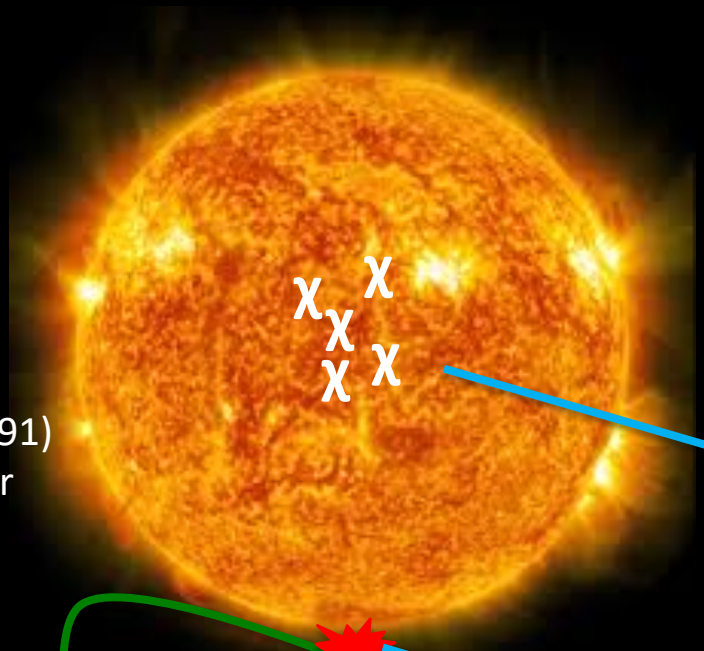
Press, Spergel (1985)
Krauss, Freese, Press, Spergel (1985)
Silk, Olive, Srednicki (1985)

Solar WIMP Search

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



Sun – Cosmic-Ray Beam Dump DM Detector



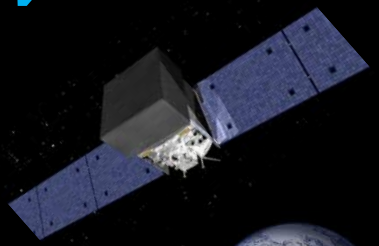
Seckel, Stanev, Gaisser (1991)
Zhou, KCYN, Beacom, Peter
[1612.06420]

CR protons
Hadronic

ν

ν

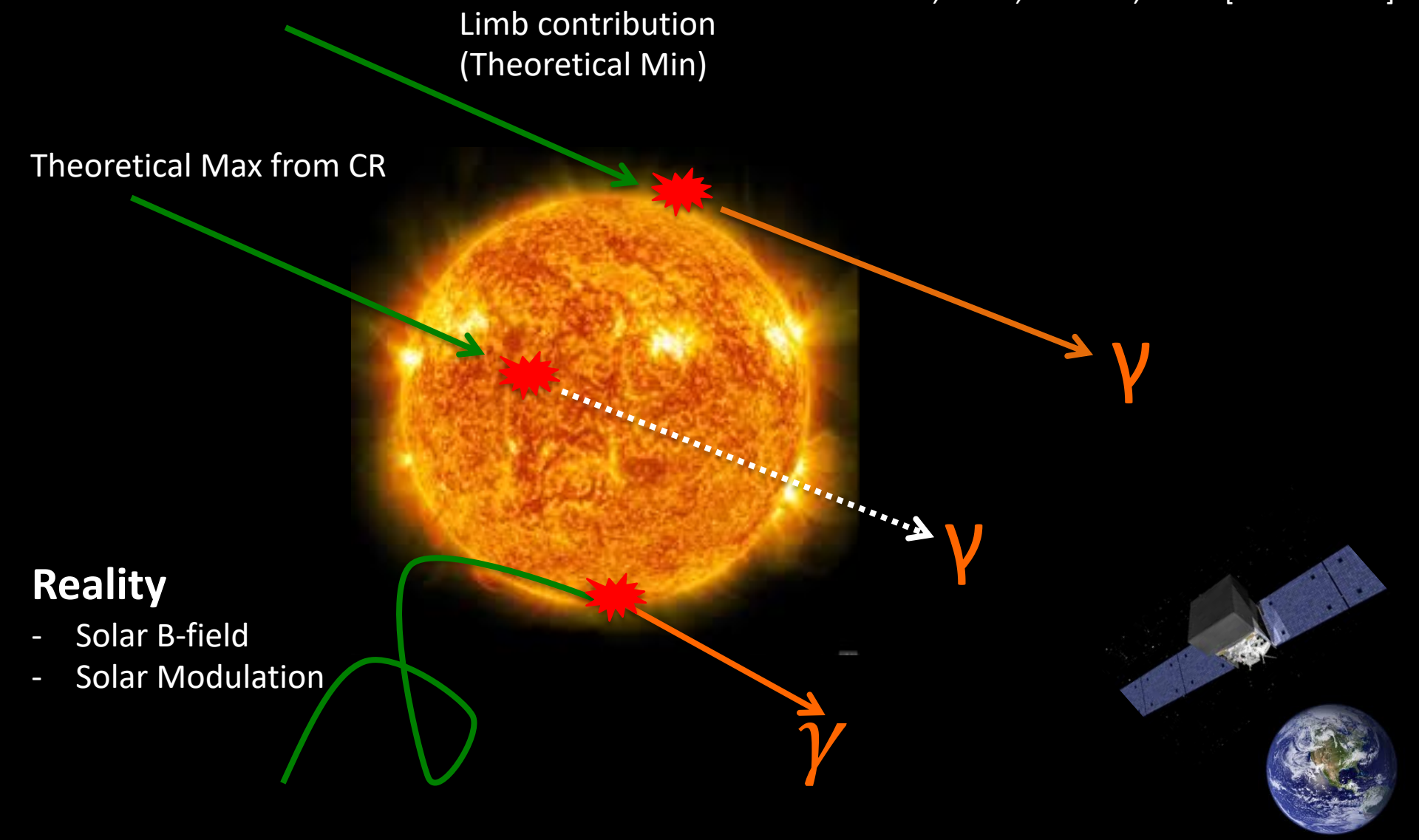
γ



γ

Solar atmospheric gamma rays

Zhou, KCYN, Beacom, Peter [1612.06420]



Solar ATM gamma-ray production

Limb contribution

Theoretical Max from CR

Boost gamma-ray production

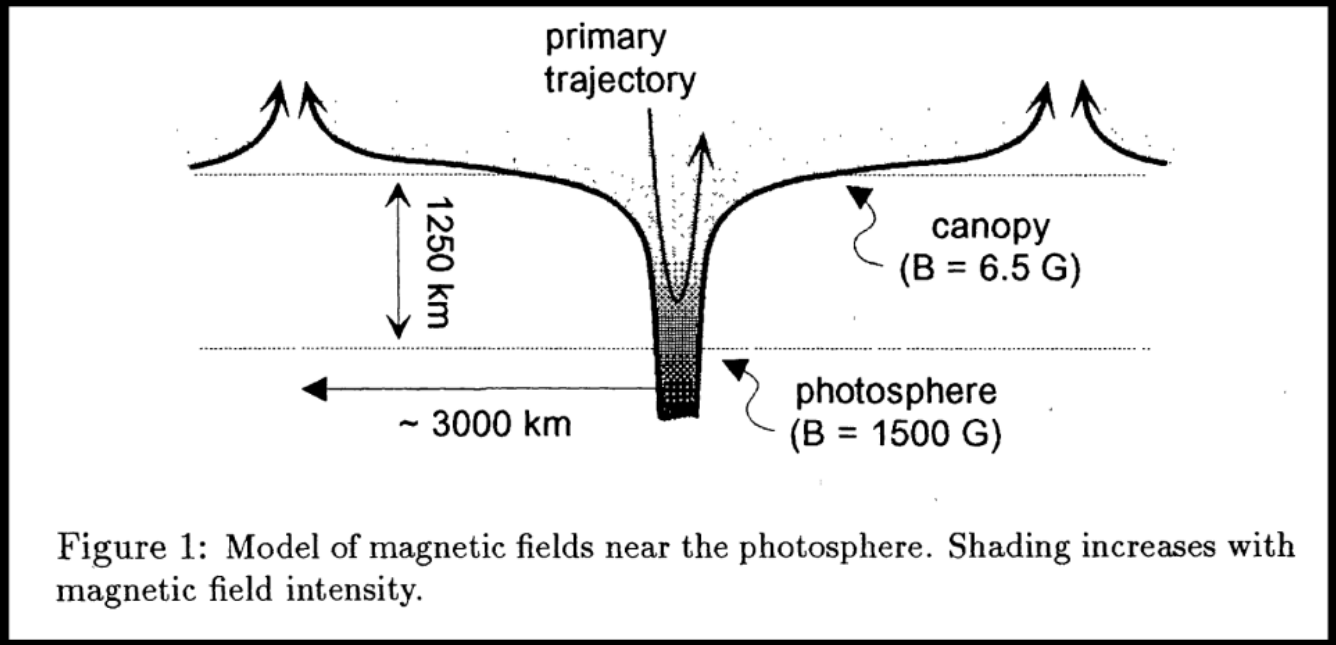
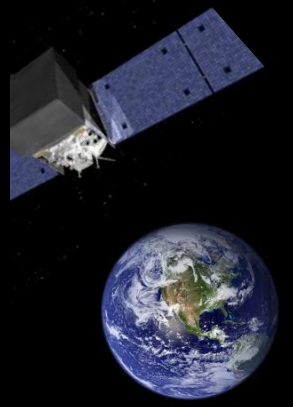


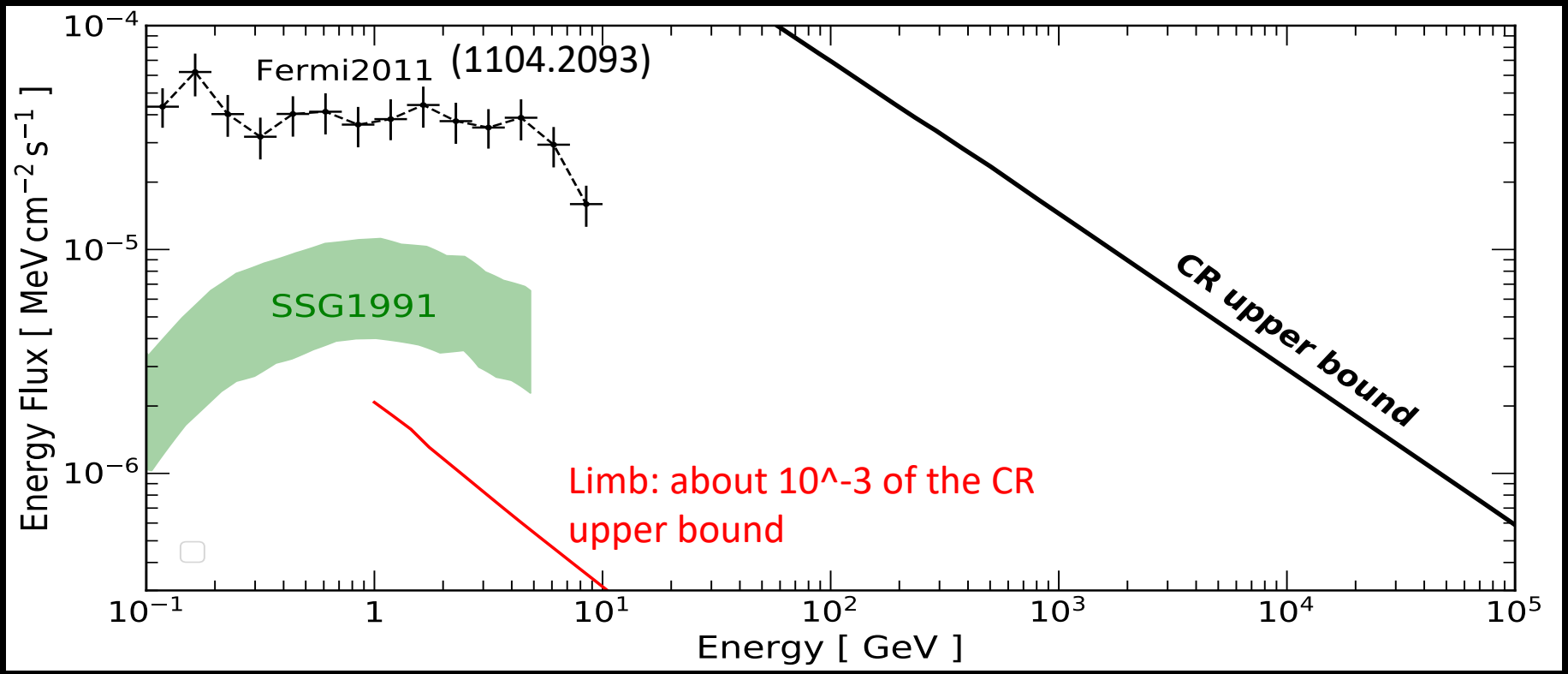
Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

Seckel, Stanev, Gaisser (1991)



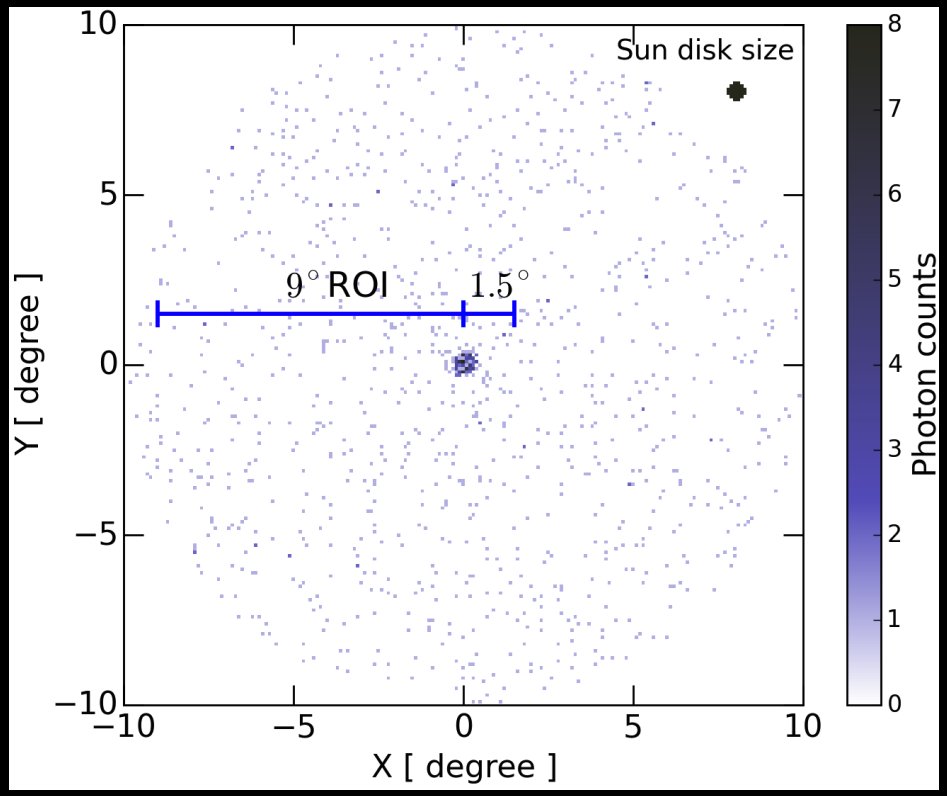
The overall picture 2011

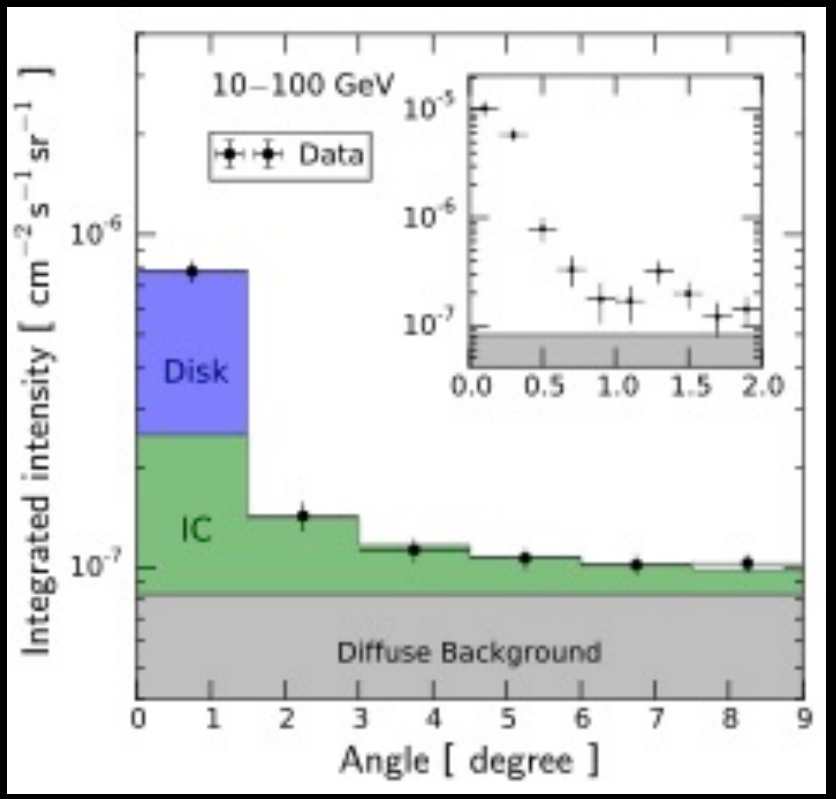
- Model prediction too small
- Limb too small
- Satisfy cosmic-ray bound → CR model with large B-field enhancement



Solar gamma analysis

- Fermi data (e.g., 6 years, 10-100 GeV)

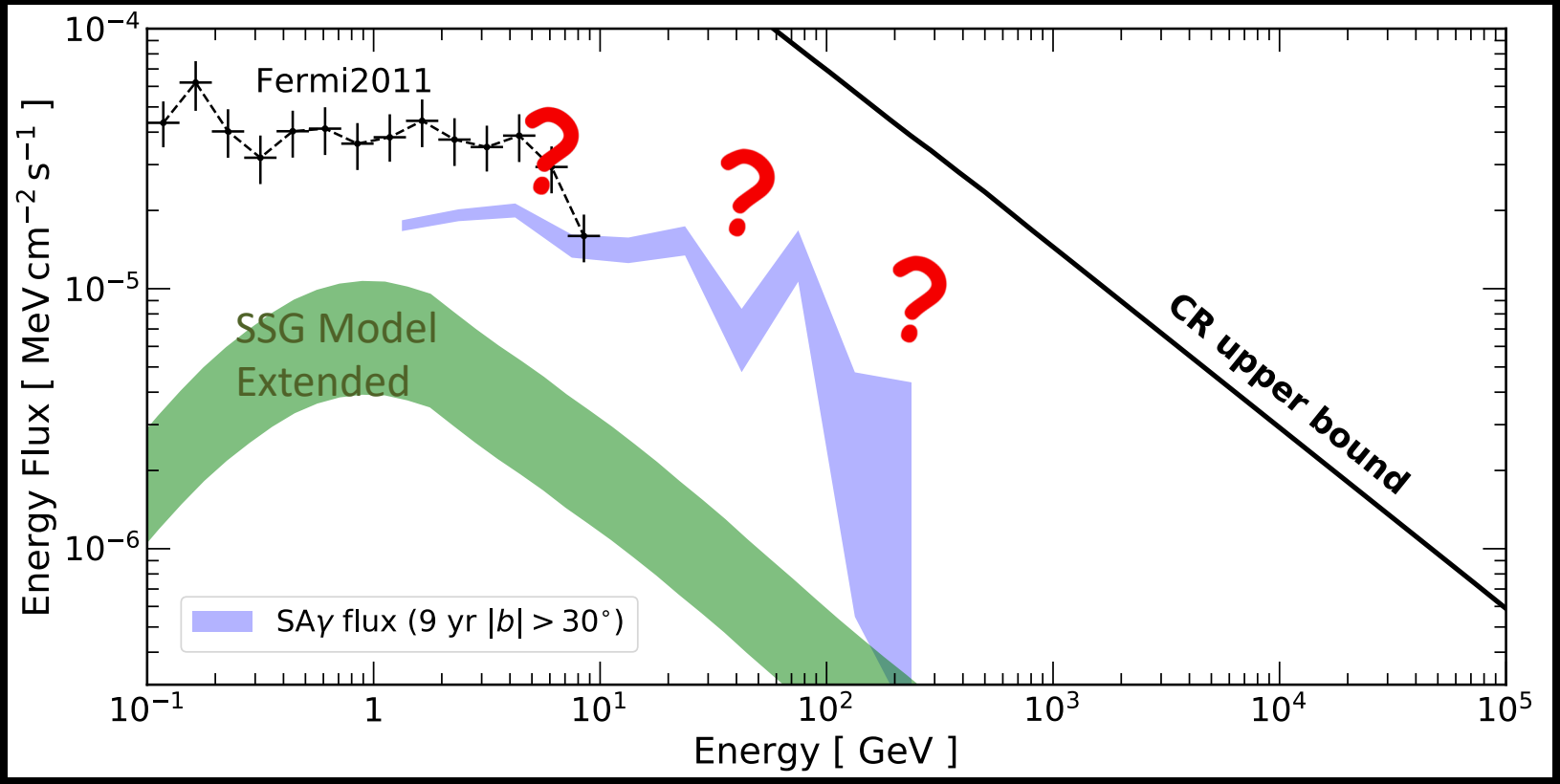




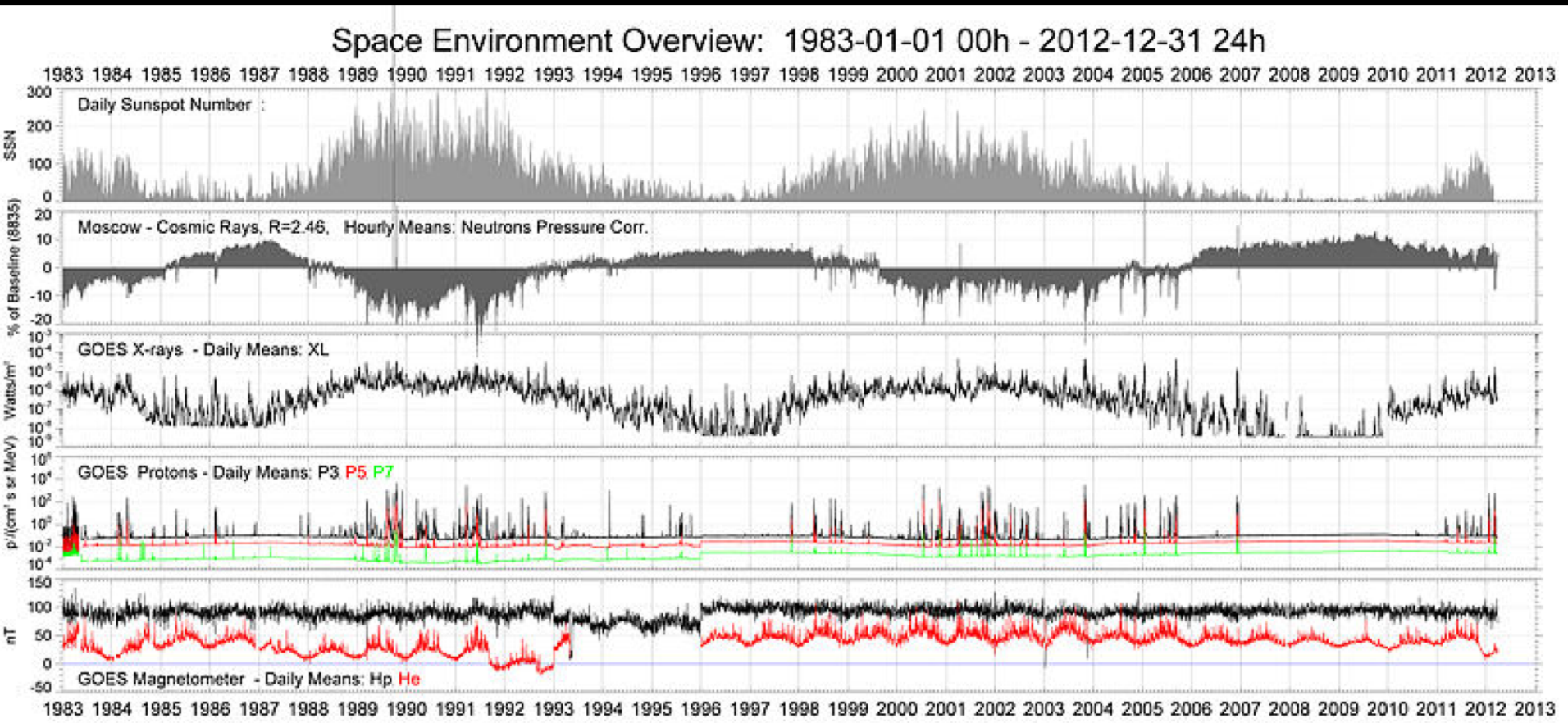
Observation: 9-year averaged spectrum

- 2008 - 2017

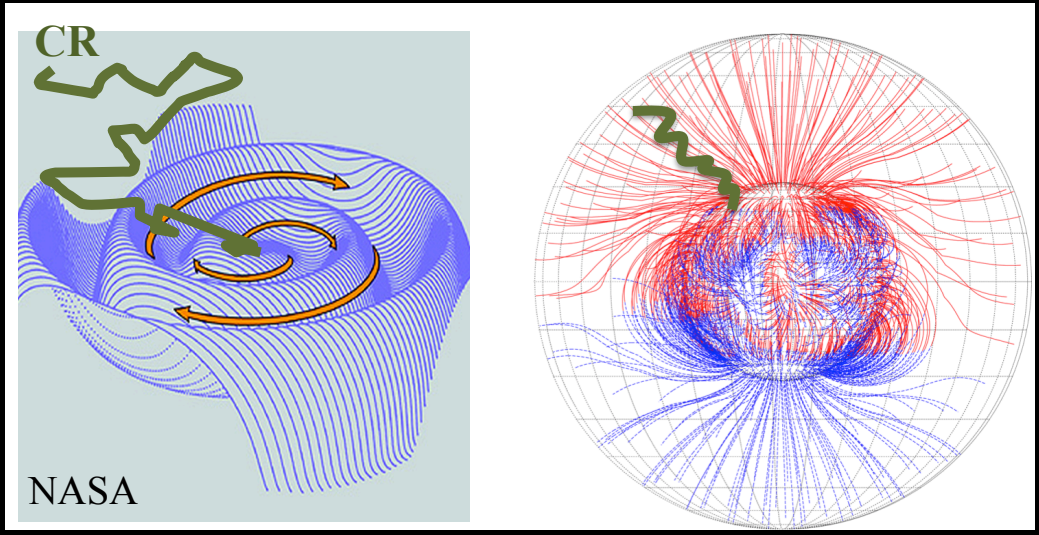
Tang + 1804.06846
PRD 98 no.6, 063019

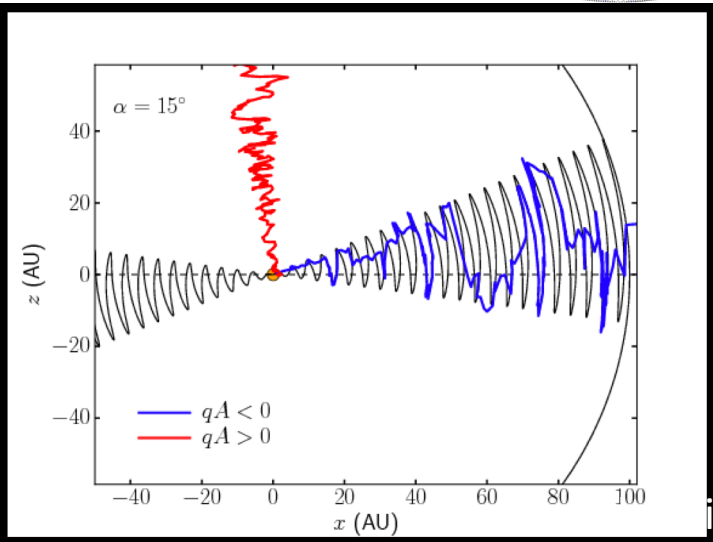


CR Solar Modulation / solar activity

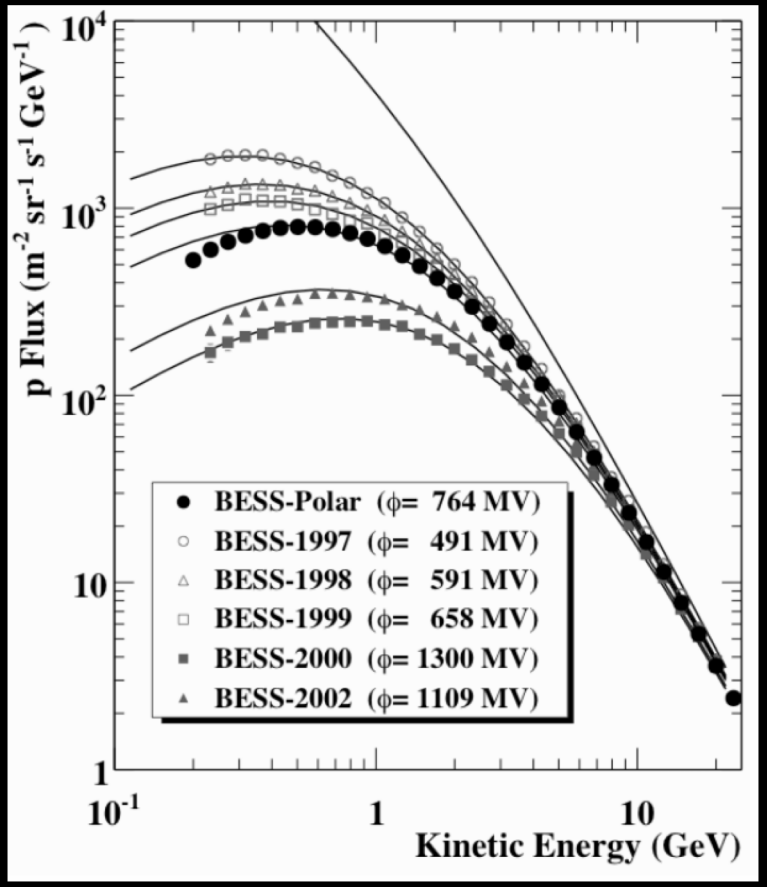


CR Solar Modulation / solar activity





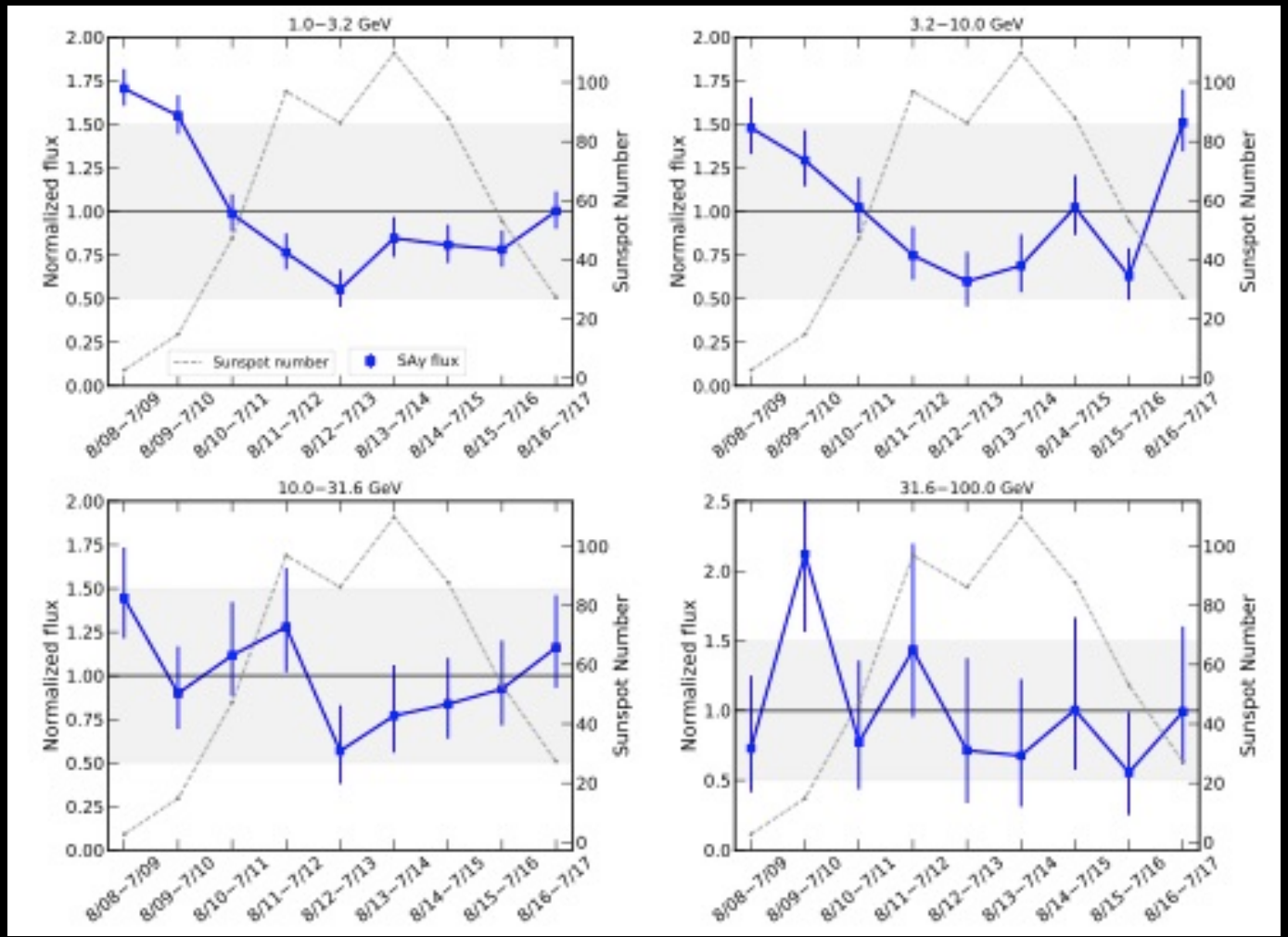
i+ 2013



Time variation

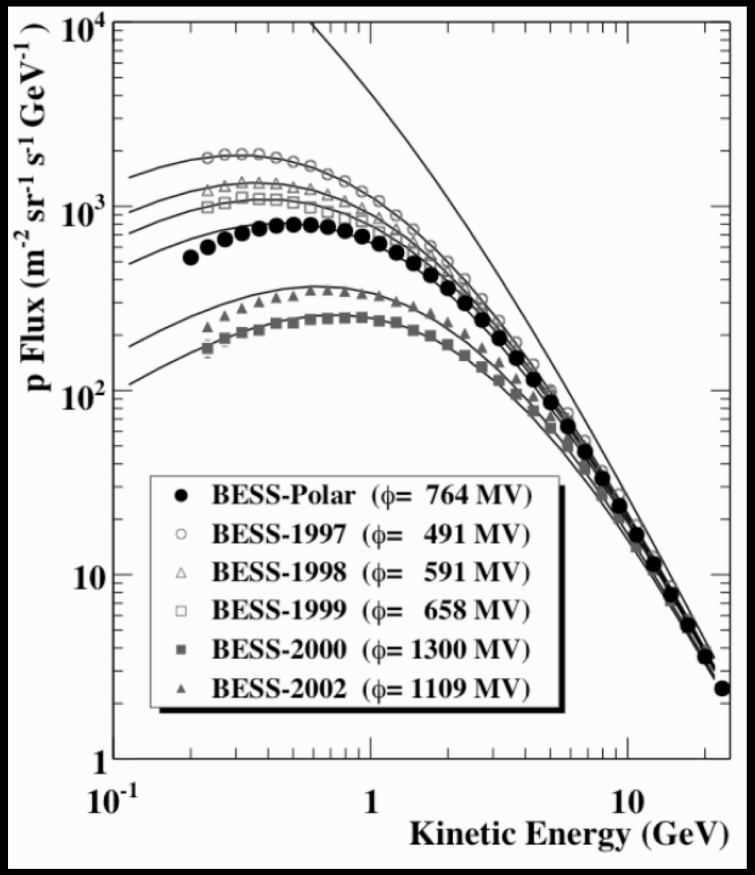
Tang + 1804.06846
PRD 98 no.6, 063019

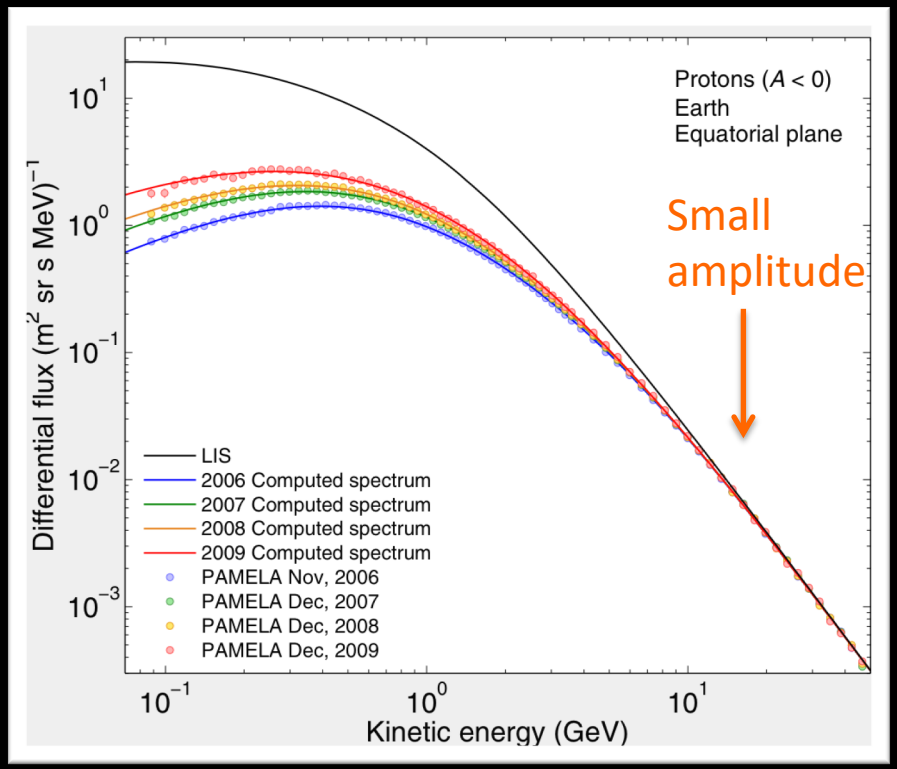
- Clear anticorrelation with solar activity from 1-10 GeV
- Less clear in 10-100 GeV (less variation or insufficient statistics)



Amplitude Problem

- 1 GeV gamma <-> 10GeV proton.
- Amplitude observed on Earth too small!



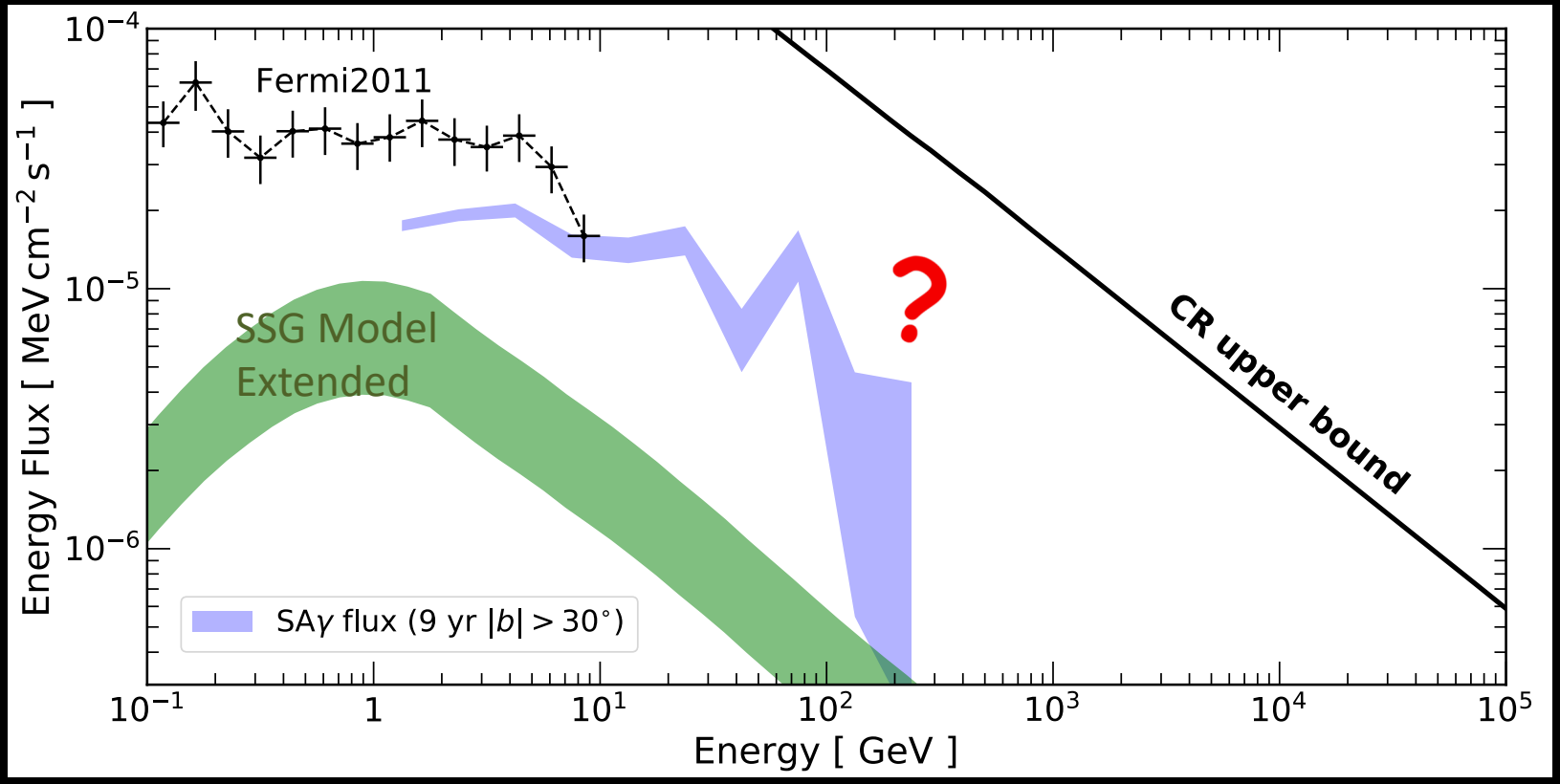


Additional modulation towards the Sun/ at the solar atmosphere!

Observation: 9-year averaged spectrum

- 2008 - 2017

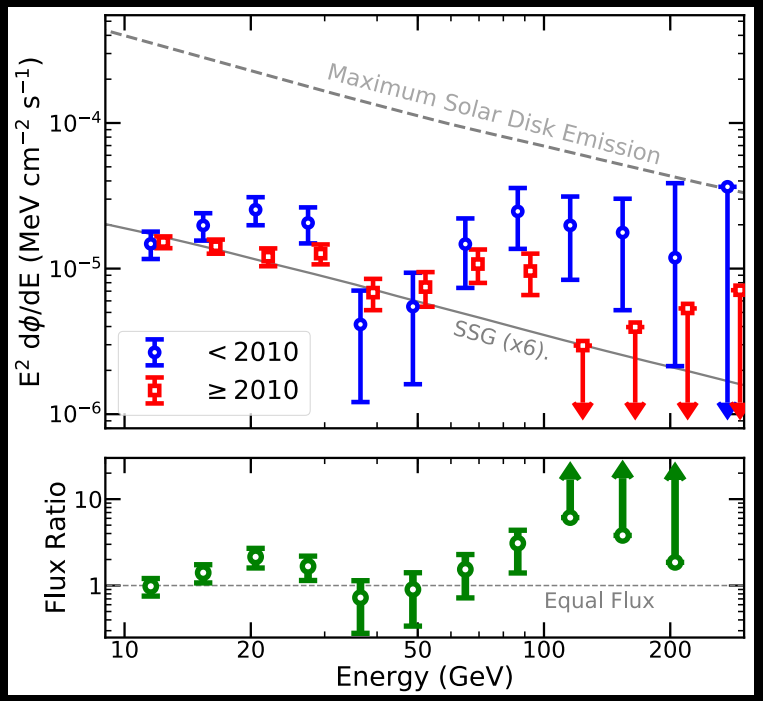
Tang + 1804.06846
PRD 98 no.6, 063019

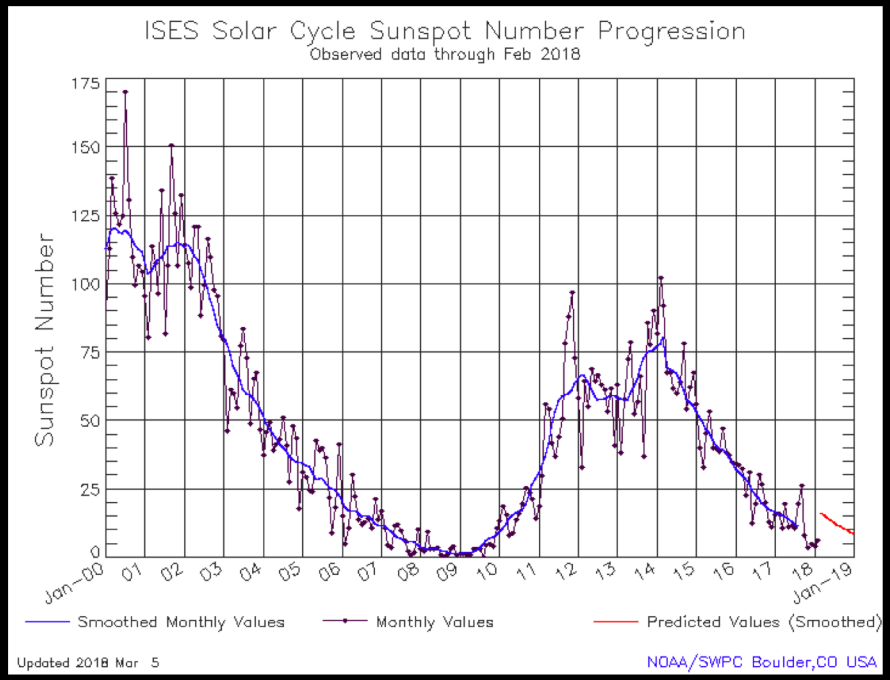


High energy photon/Time variation, *Surprise (1)!*

Linden + 1803.05436
PRL 121 no.13, 131103

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

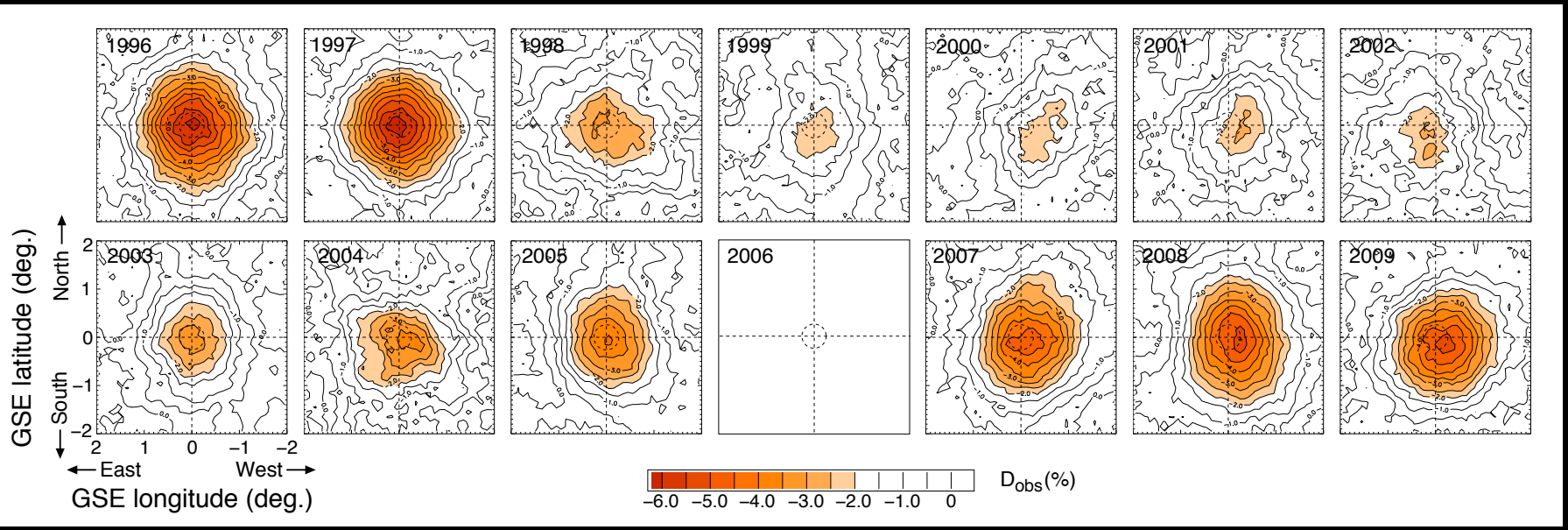




The high-energy photon production are very sensitive to the solar condition

Sun shadow observations

- Perhaps not too surprising actually.
- TeV cosmic-ray sun shadows (near Sun-trajectory)

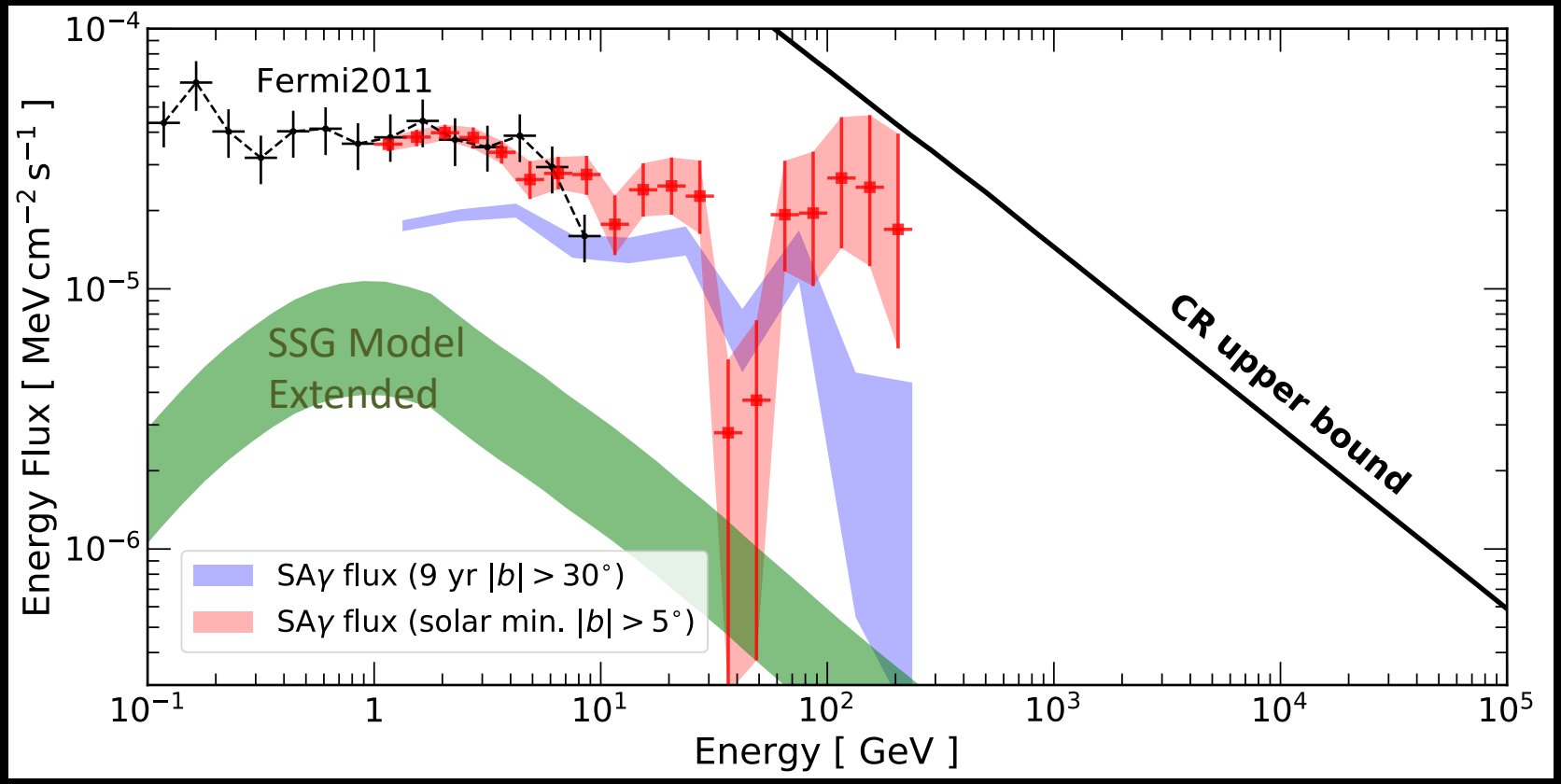


Tibet Asgamma
PRL 2013

Spectrum, *surprise (2)*

Tang + 1804.06846
PRD 98 no.6, 063019

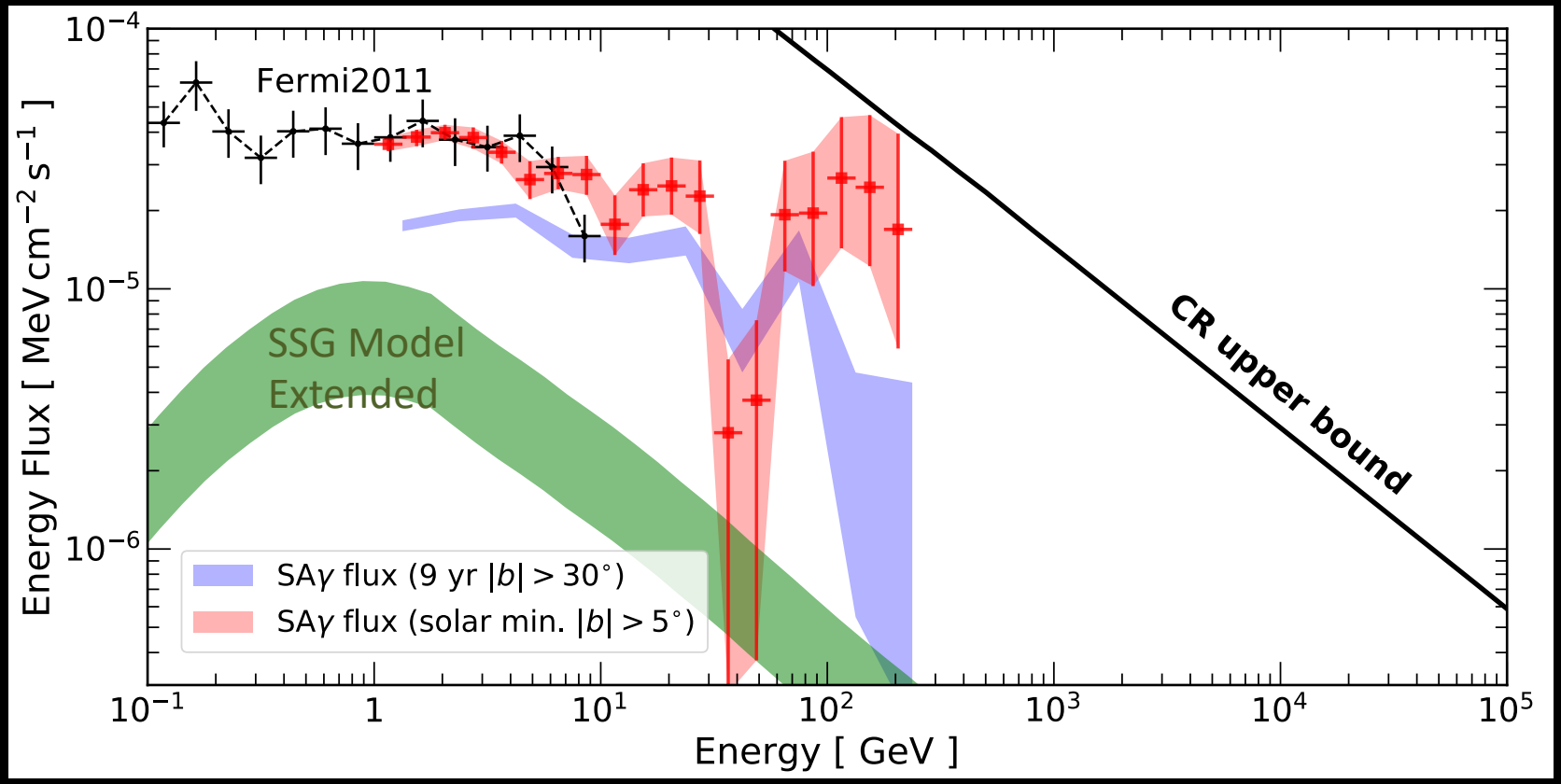
- Hard spectrum till ~100 GeV
  - Magnetic enhancement works for protons ~ TeV
  - Enhancement increasingly efficient! Close to upper bound at HE



Spectrum, *surprise (3)*

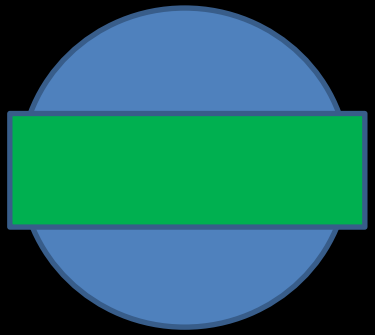
- Strange "dip" between 30-50 GeV
  - Naively, two components, but not easy
  - No obvious instrumental explanation
  - Seems shallower outside solar minimum
  - Statistical fluke? Time-dependent feature/systematics? Will know soon

Tang + 1804.06846
PRD 98 no.6, 063019

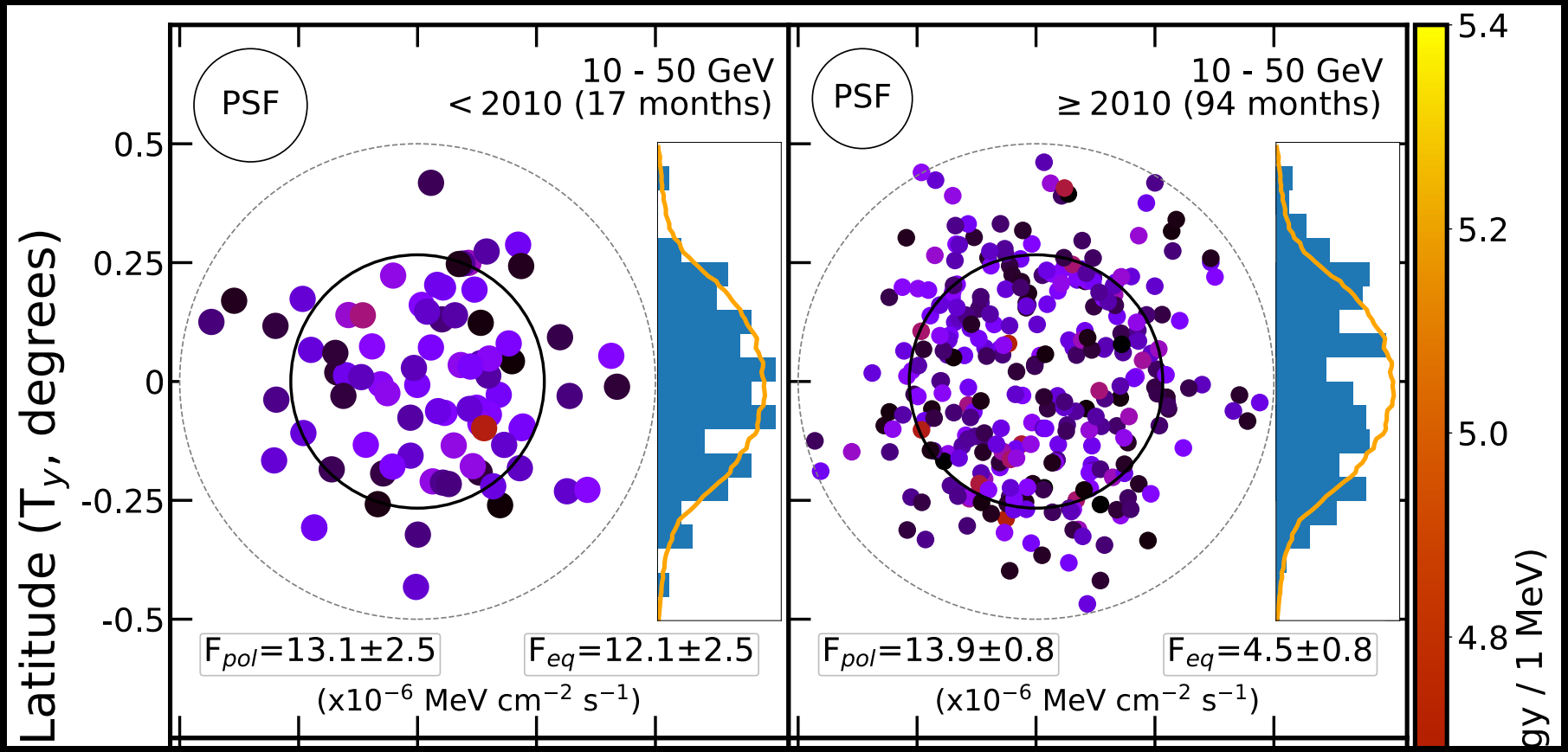


Morphology, *surprise(4)*

- Low Energy Bin
  - 10-50GeV



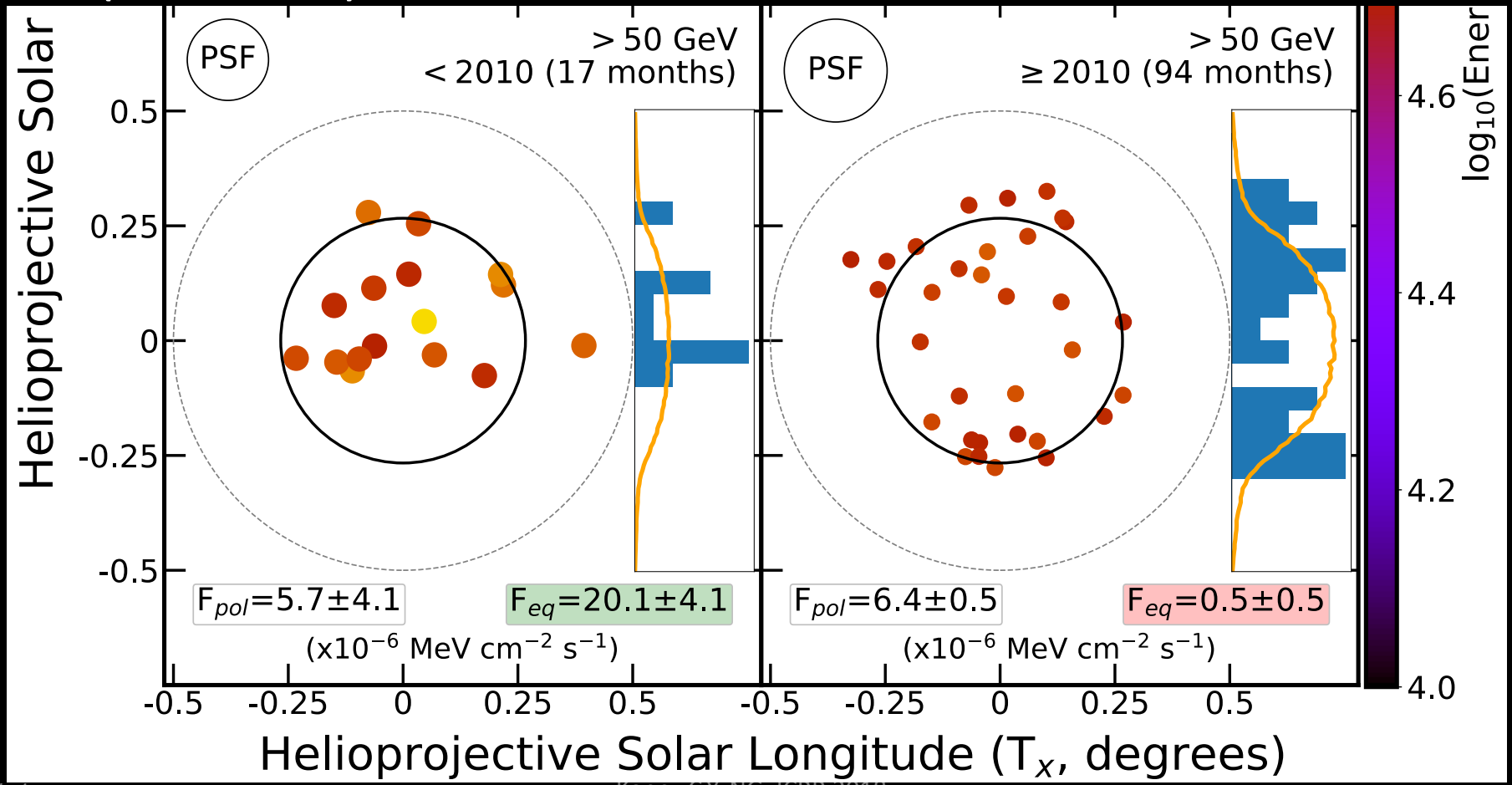
Linden + 1803.05436
PRL 121 no.13, 131103



Morphology, *surprise(4)*

- High Energy BIN
  - (> 50 GeV)

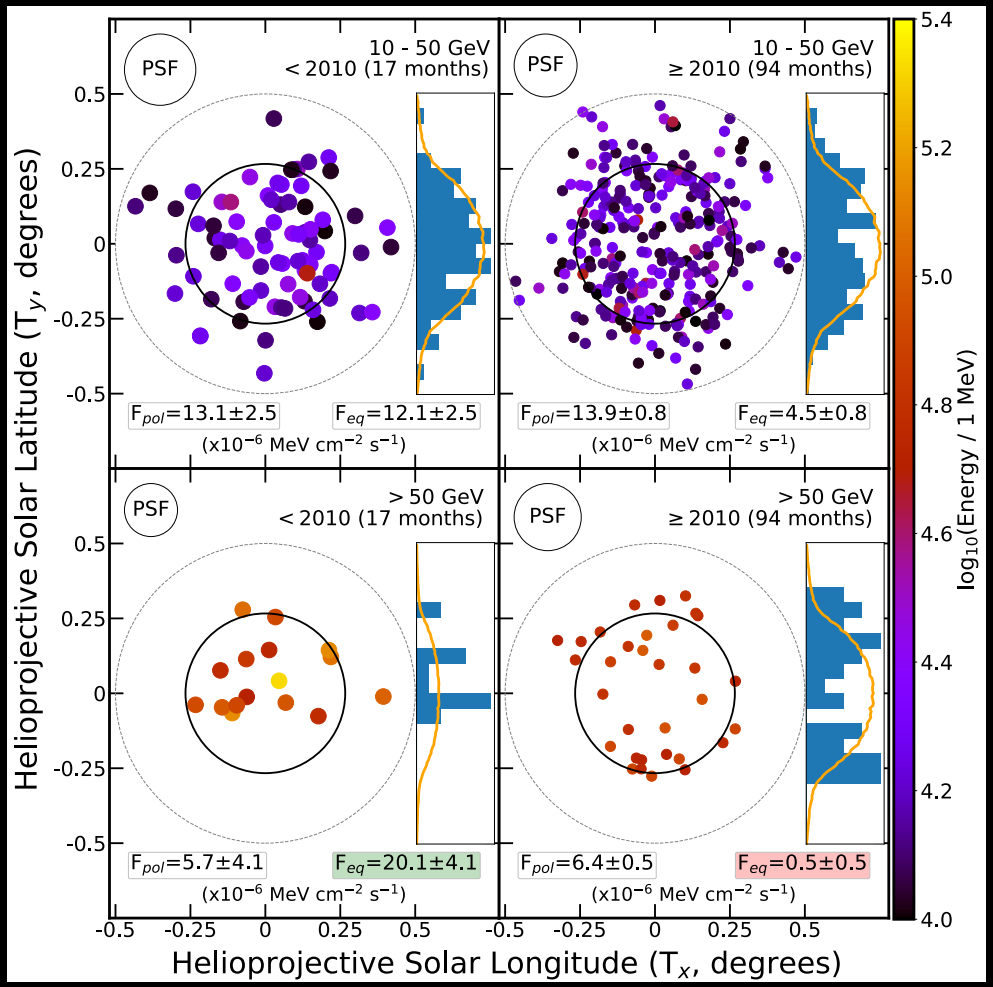
Linden + 1803.05436
PRL 121 no.13, 131103



Morphology, *surprise(4)*

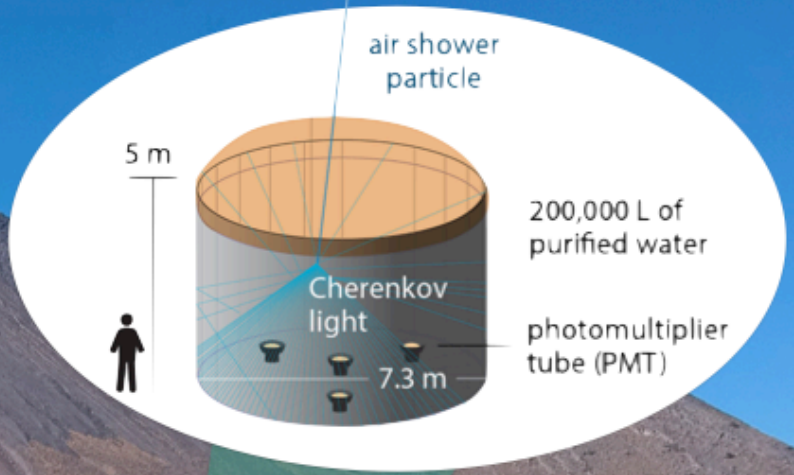
Linden + 1803.05436
PRL 121 no.13, 131103

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



The HAWC Observatory

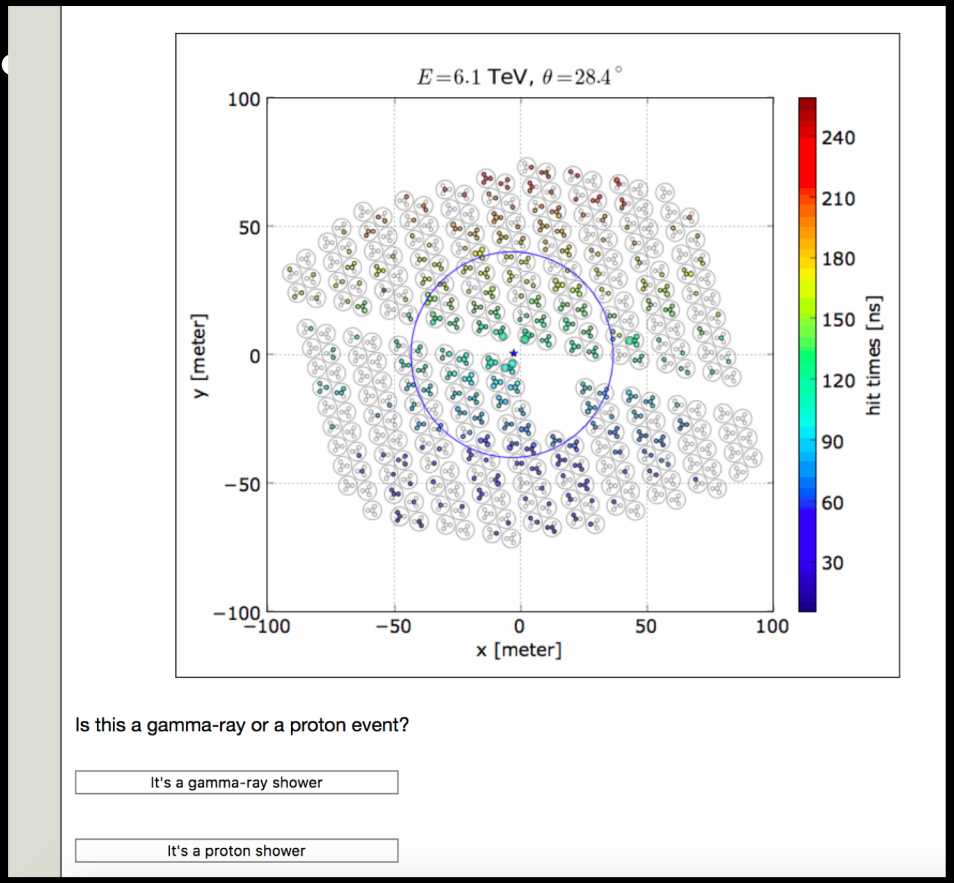
- 300 Water Cherenkov Detectors
- 22,000 m² detector area
- Sub TeV - >100 TeV Sensitivity
- Wide field of view: ~2 sr
- High duty cycle: >95%

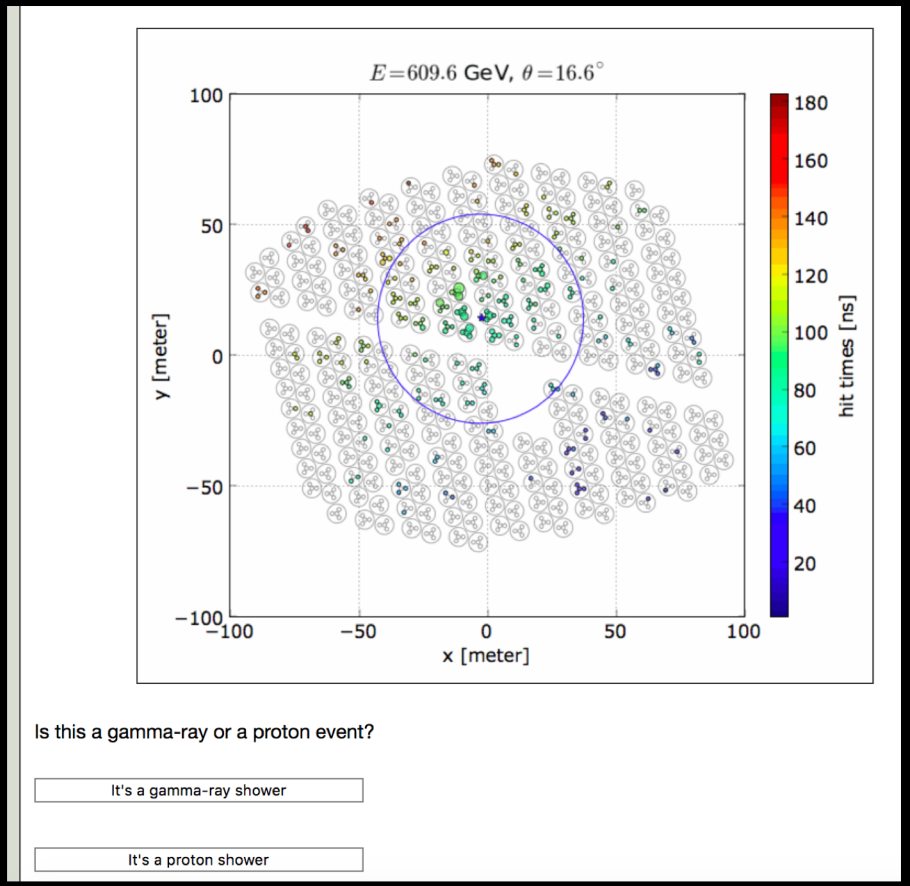


Excellent detector for extended sources

Main array inaugurated on March 20, 2015

Gamma Hadron Separation



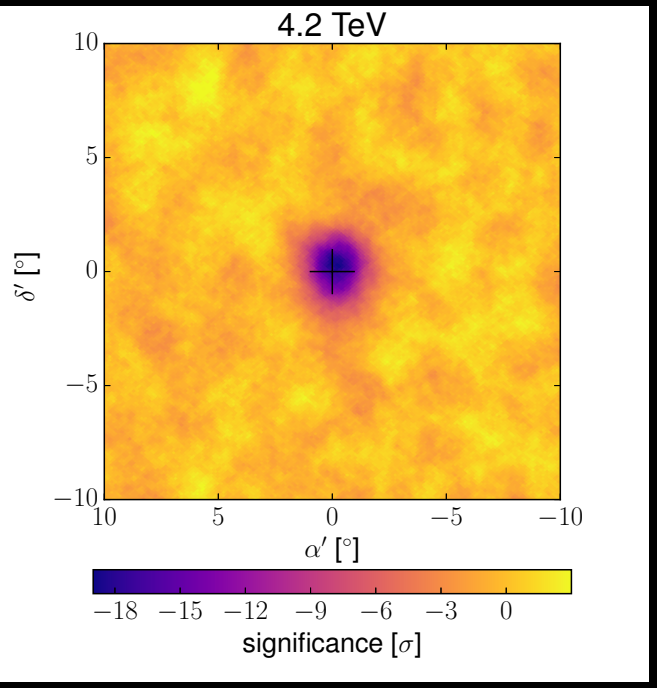


- Large FOV, all weather instrument

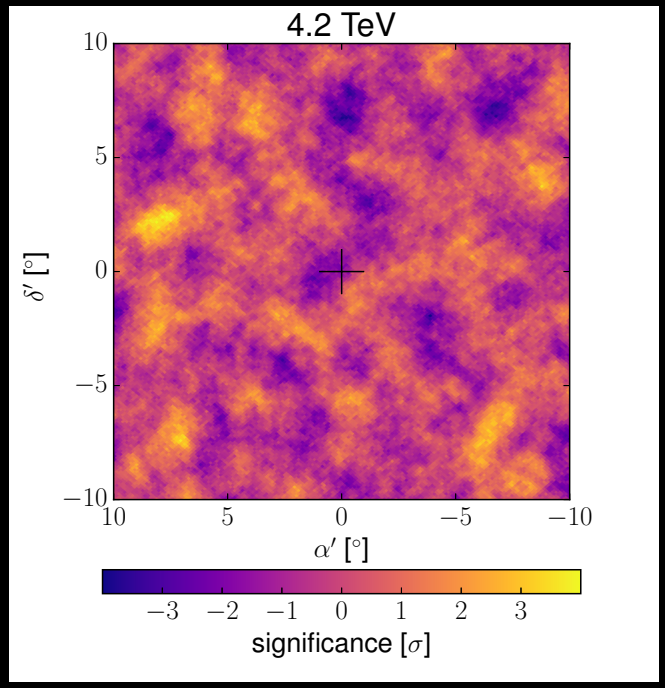
HAWC analysis

- Nov 2014 - December 2017 (829 days)
- Significance map

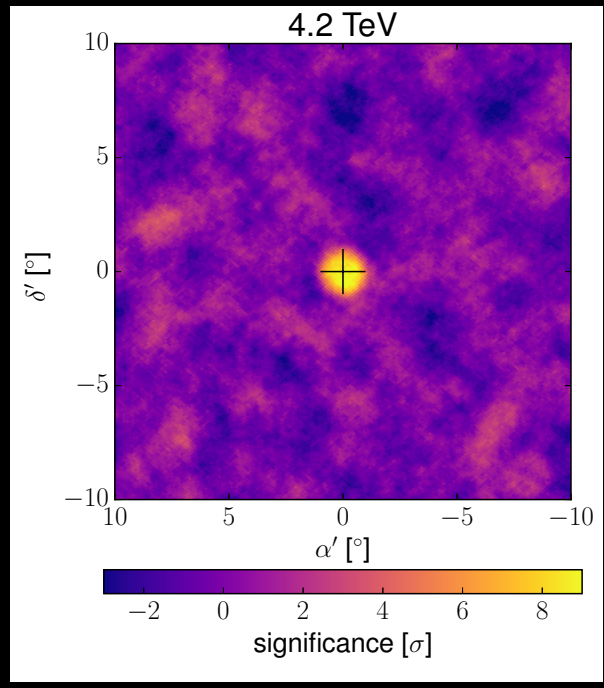
Sun Shadow (all data)



Gamma-hadron cut

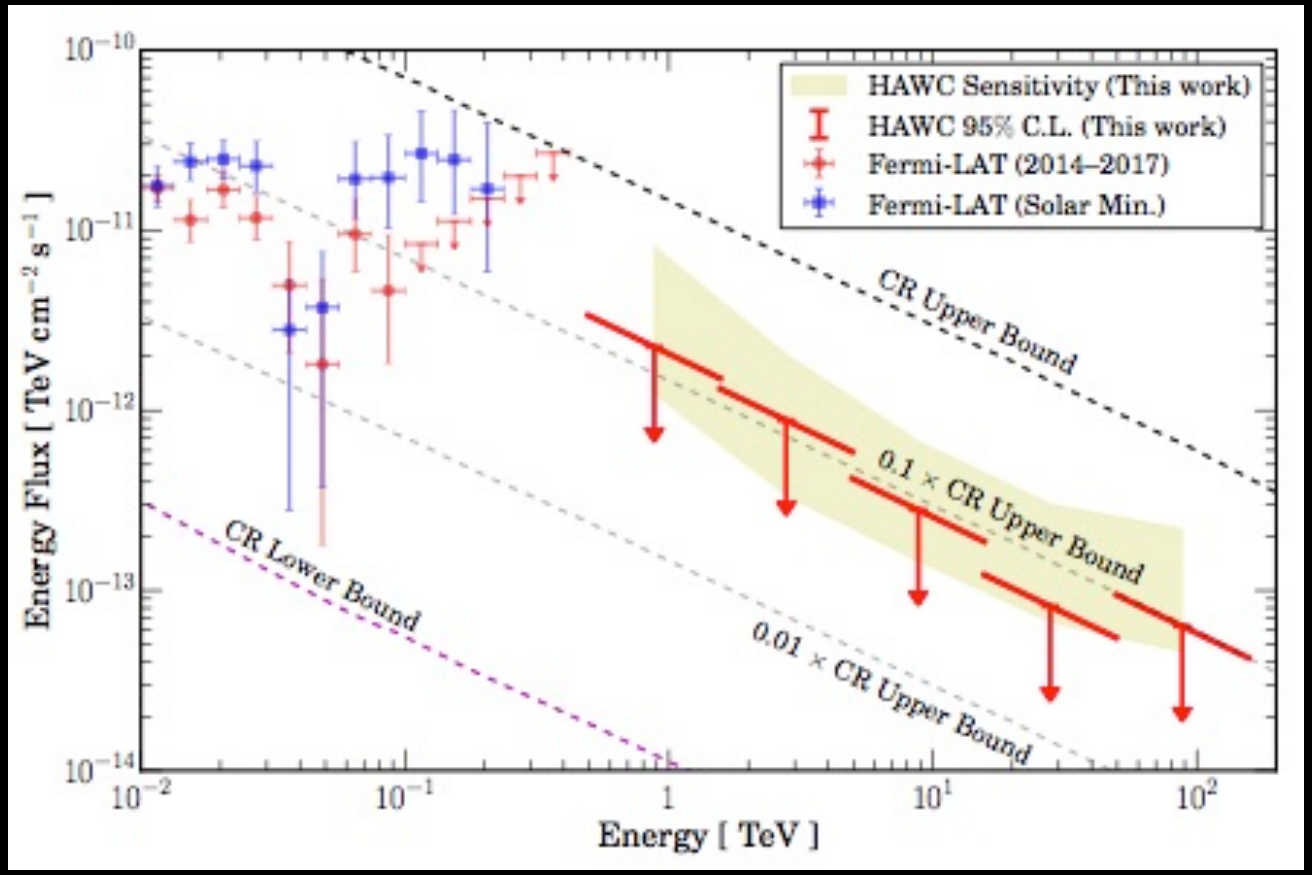


Expected (max. CR)

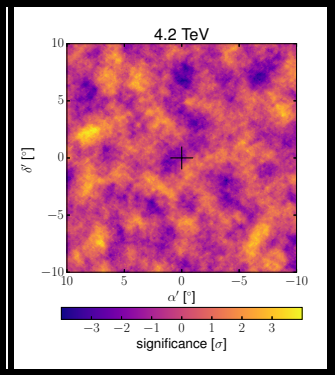


First HAWC analysis of the Sun (2014-2017)

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



HAWC 1808.05620
To PRD



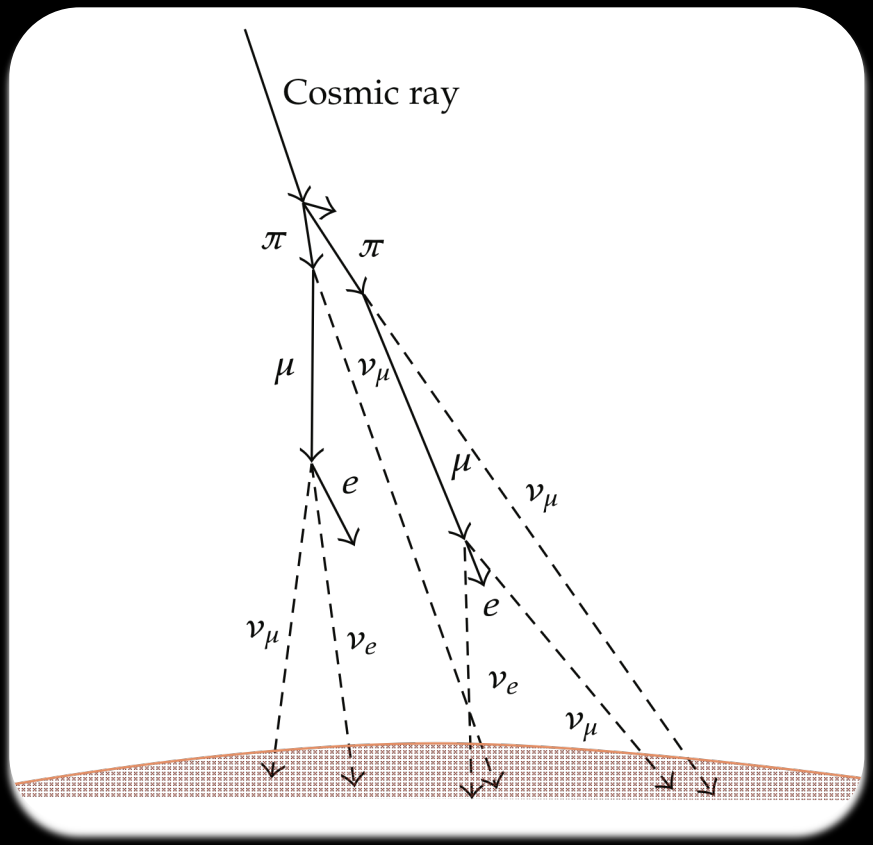
Solar Atmospheric Gamma rays

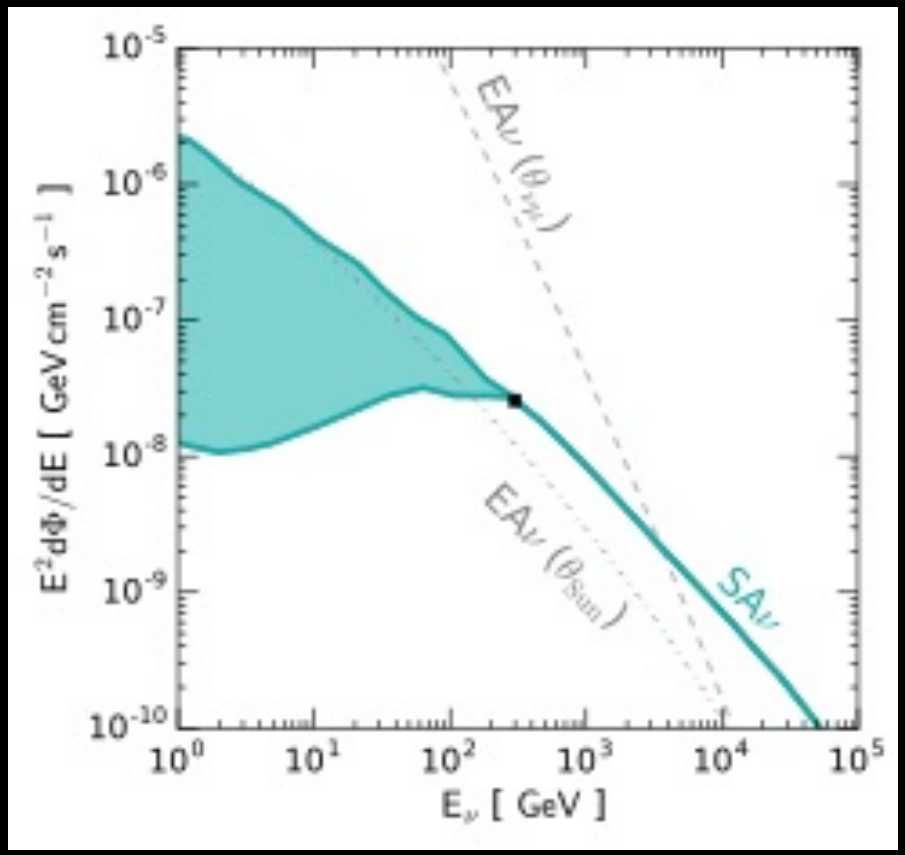
Complicated……

But could be a new probe for solar physics!

Solar Atmospheric Neutrinos

KCYN, Beacom, Peter, Rott 2017





- Dilute atmosphere, larger neutrino flux

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

  C.A. Argüelles+ 1703.07798

  Joakim Edsjo+ 1704.02892

Neutrino point source detection

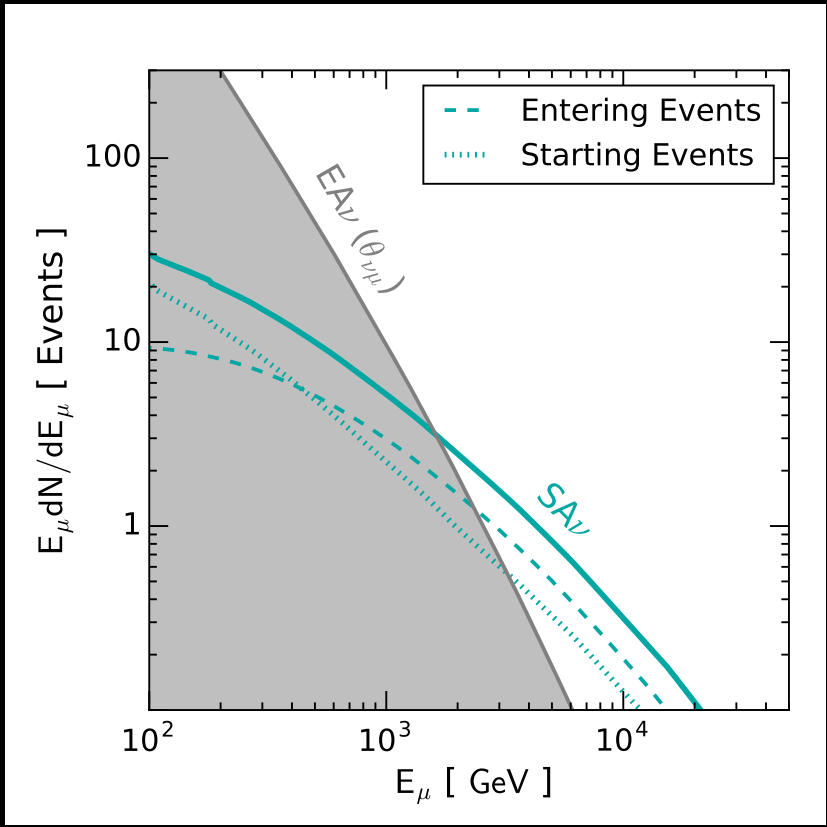
- Numu_CC events
  - Starting events

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

  - Entering events

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

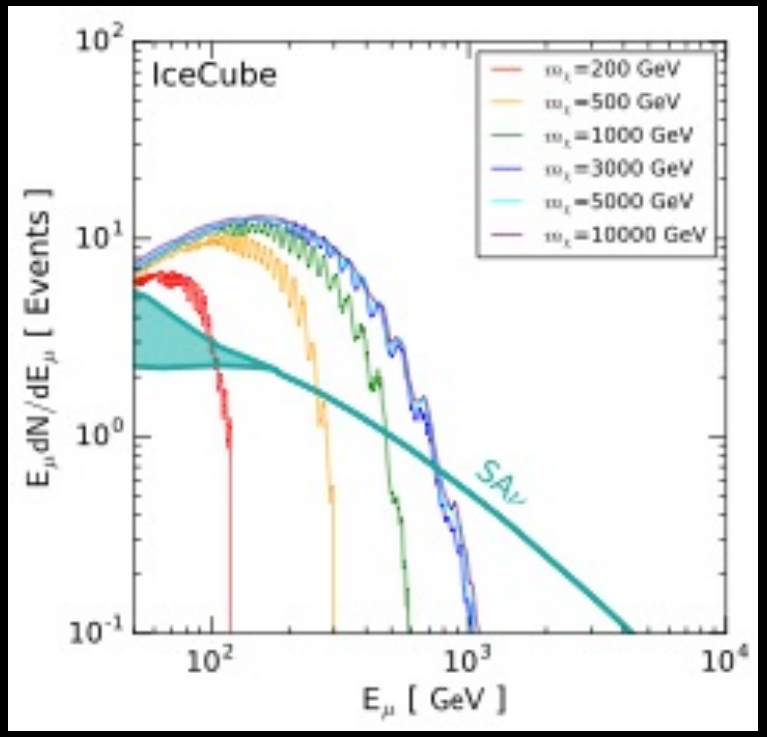
Muon range

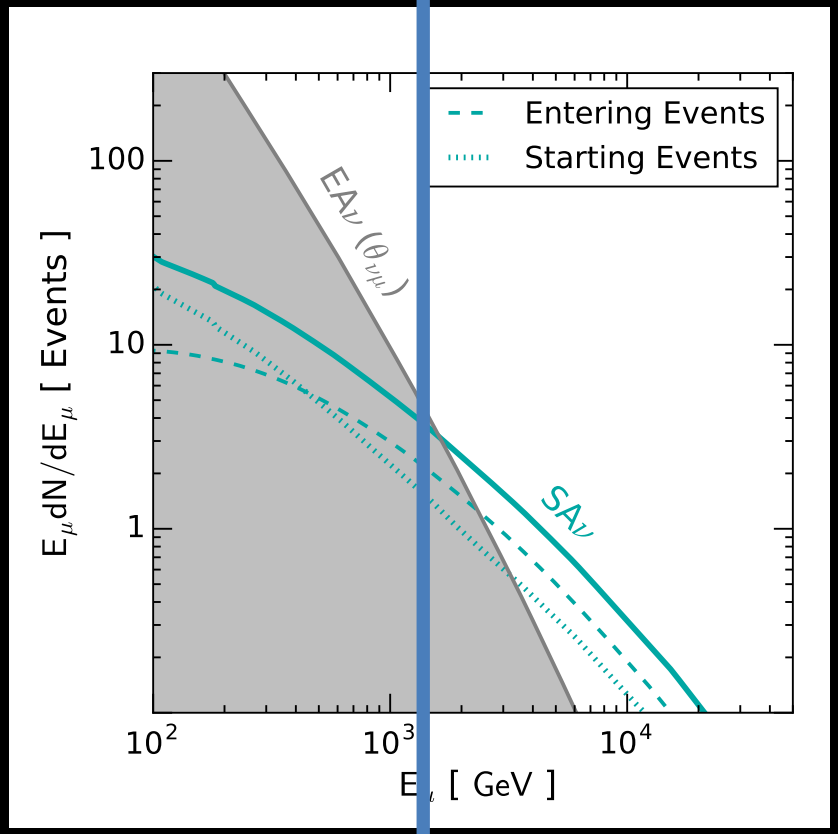


- Muon range limited by energy loss. Starting Events eventually wins (for Gen2 horizontal events?)

Background or Signal? (Both!)

Theorist Expectation



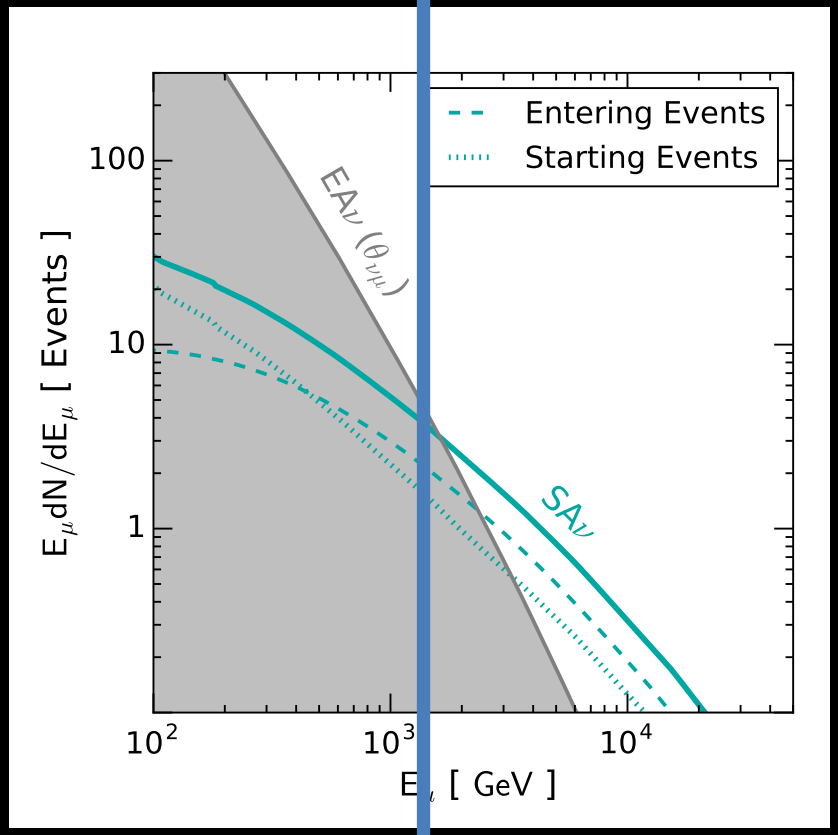


BAD energy-resolution
Difficult to distinguish from DM signal
Background!

Some energy-resolution
No DM signal*
Astrophysical signal!

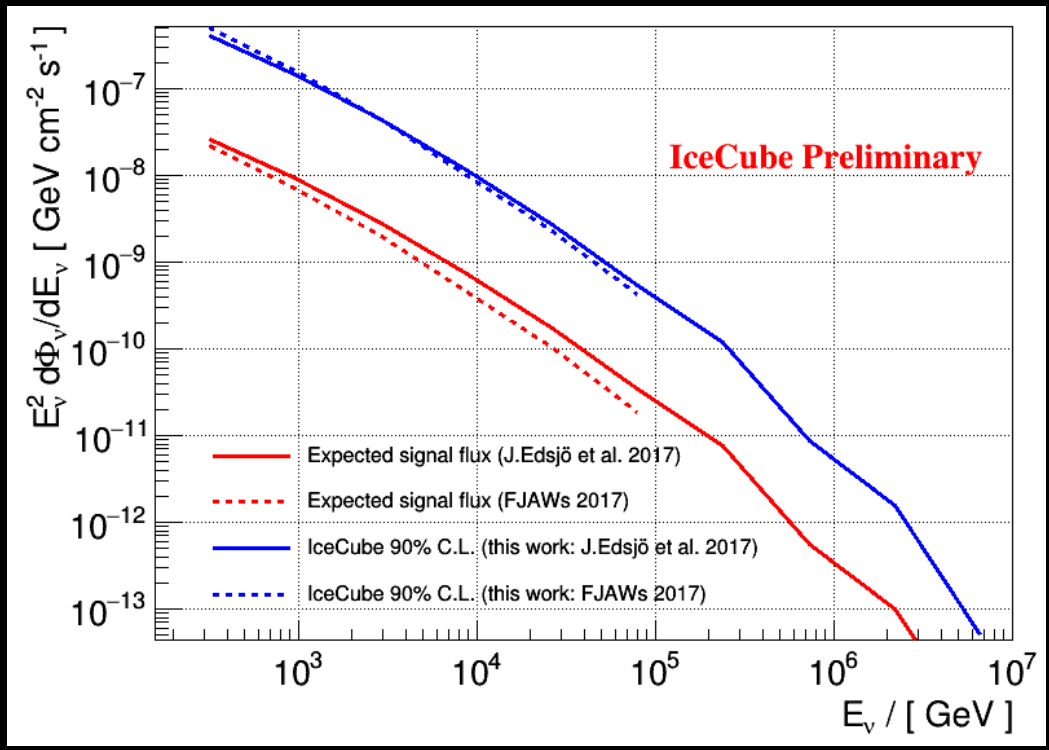
IceCube Search

Theorist Expectation



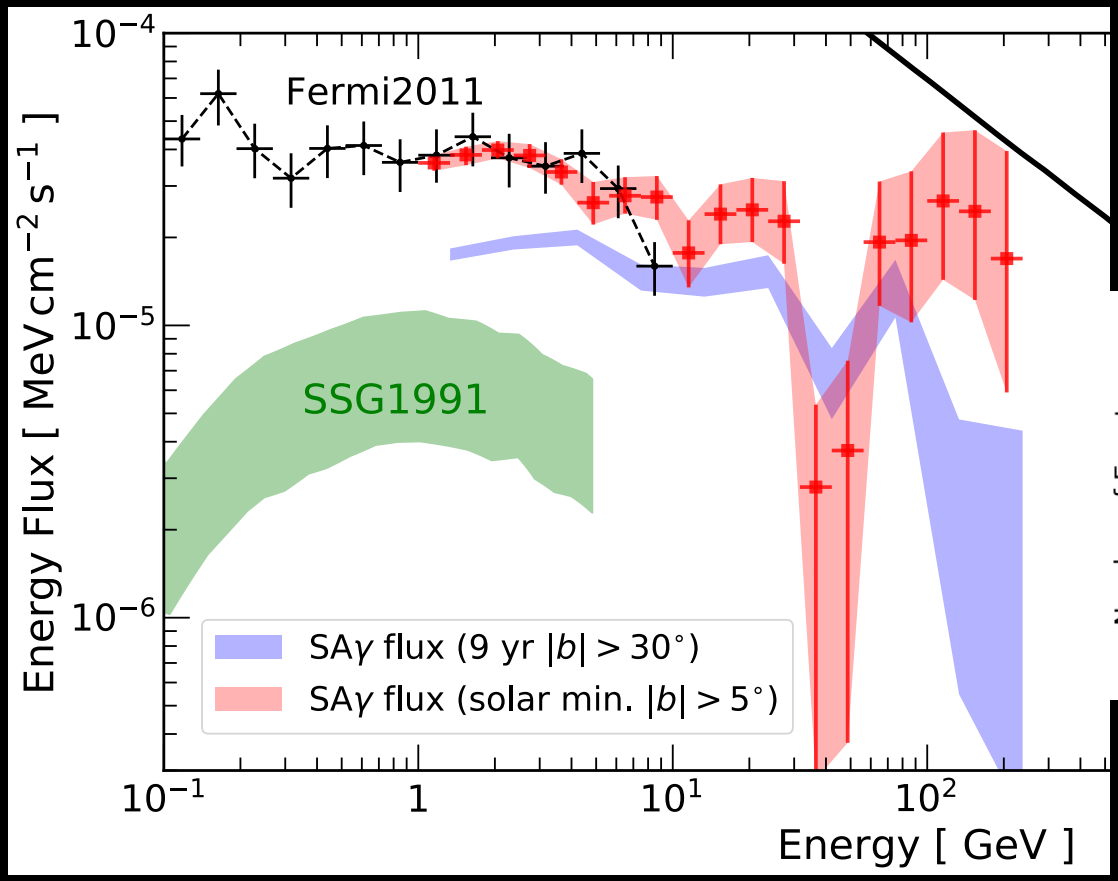
Signal

C. Rott, KIAS workshop 2018

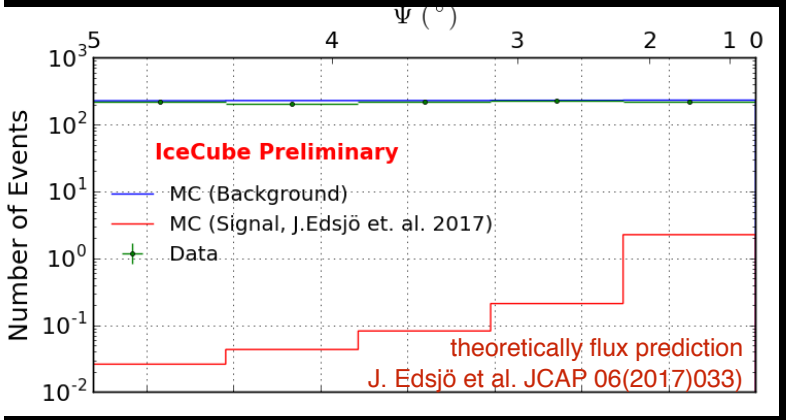


Seems difficult……

Gamma connection



200 total evts/7 years



C. Rott, KIAS workshop 2018

From gamma rays: mininum event rate is 1 event/ 1.5 years
Difficult…….

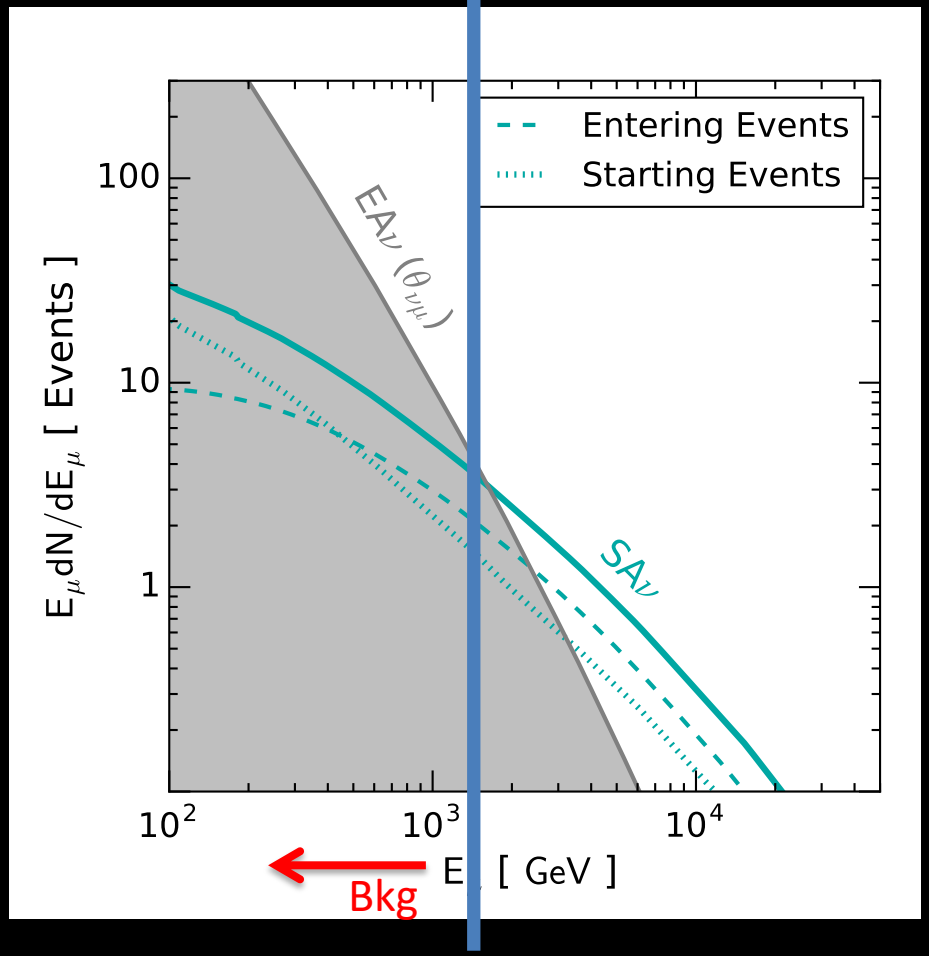
Are they (gamma) flares?

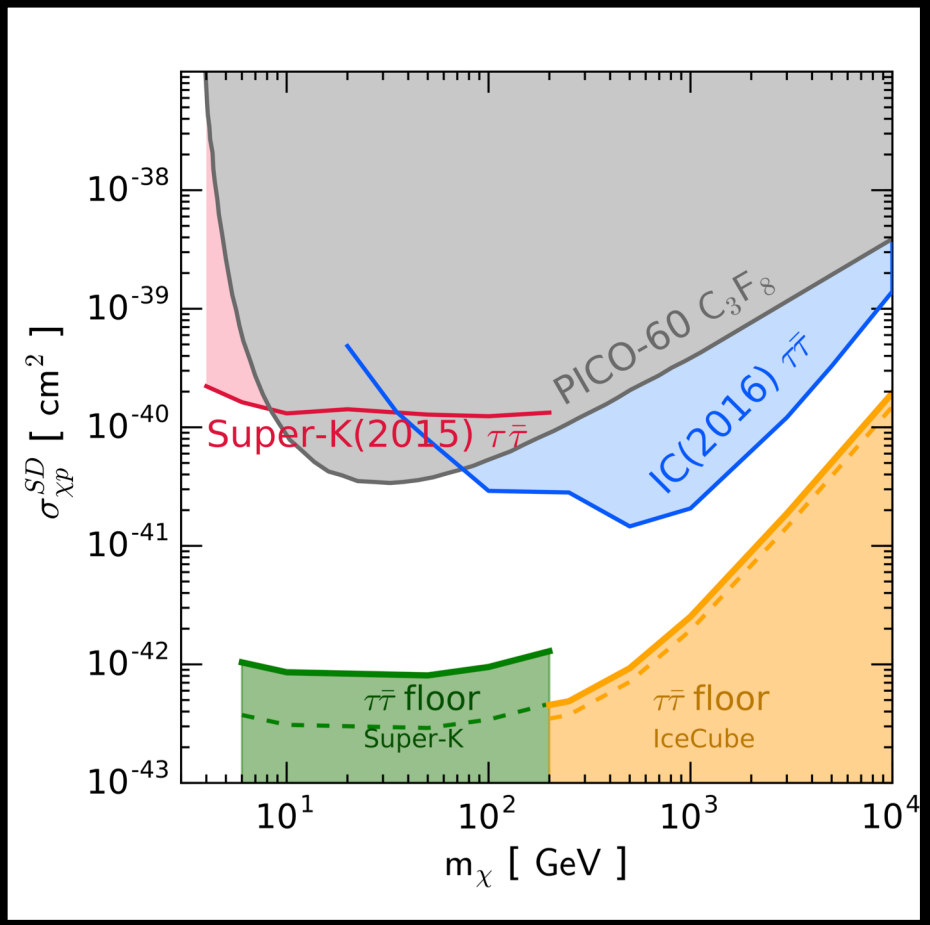
- Could have corresponding neutrinos flares
  - If the emission is associated with certain solar structures (coronal holes, etc)

Time (UTC)	Energy	R.A.	Dec	Solar Distance	Event Class	PSF Class	Edisp Class	P6	P7	BG Contribution
2008-11-09 03:47:51	212.8 GeV	224.497	-16.851	0.068°	UltraCleanVeto	PSF0	EDISP3	✓	✓	0.00050
2008-12-13 03:25:55	139.3 GeV	260.707	-23.243	0.126°	UltraCleanVeto	PSF2	EDISP1	X	X	0.00038
2008-12-13 07:04:07	103.3 GeV	260.346	-23.102	0.399°	UltraCleanVeto	PSF0	EDISP2	X	X	0.00052
2009-03-22 08:43:13	117.2 GeV	1.337	0.703	0.255°	UltraCleanVeto	PSF1	EDISP3	✓	✓	0.00027
2009-08-15 01:14:17	138.5 GeV	144.416	14.300	0.261°	UltraCleanVeto	PSF2	EDISP3	✓	✓	0.00021
2009-11-20 07:55:20	112.6 GeV	235.905	-19.473	0.288°	UltraCleanVeto	PSF1	EDISP1	X	X	0.00020
2008-12-24 05:41:53	226.9 GeV	272.899	-23.343	0.069°	UltraClean	PSF1	EDISP3	X	X	0.00128
2009-12-20 08:06:31	467.7 GeV	268.046	-23.177	0.338°	UltraCleanVeto	PSF1	EDISP0	X	X	0.00208

- Will continue monitor the incoming solar minimum
- Perhaps also correlate with HAWC search.

Solar ATM neutrino – indirect detection Neutrino Floor





No B-field effect are considered

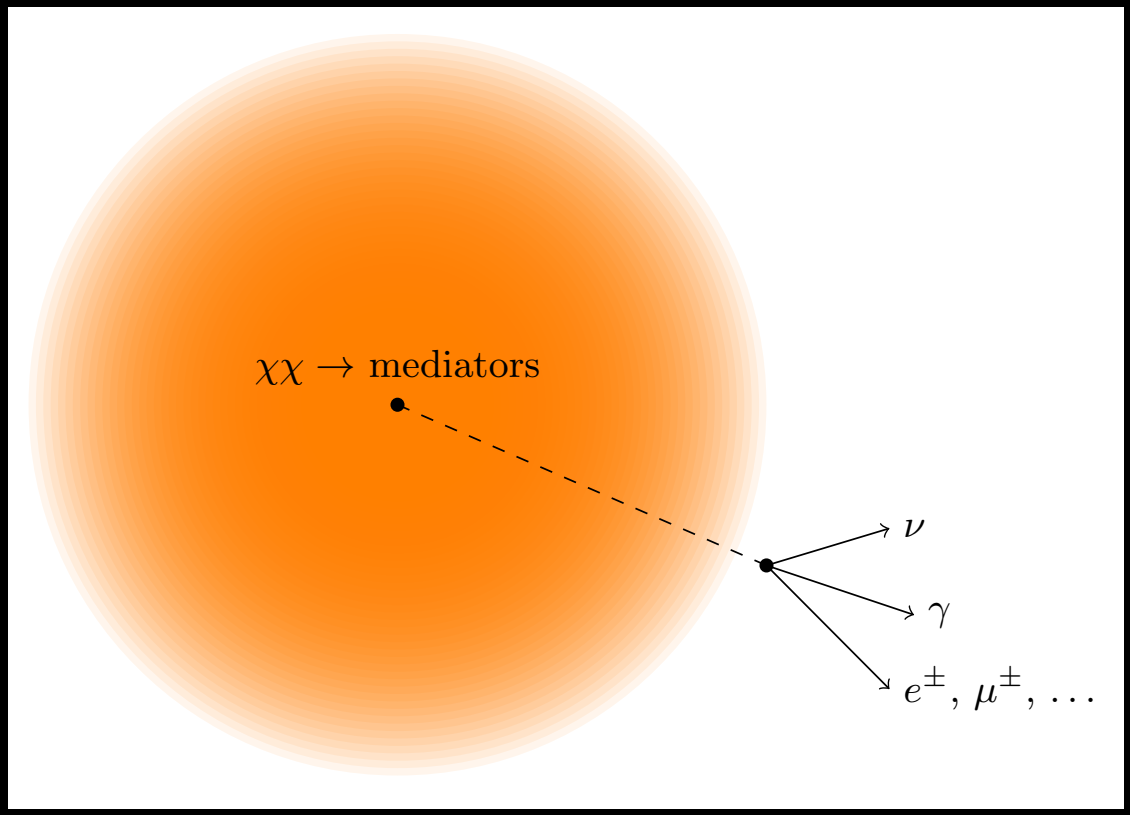
IceCube Search ongoing [S. In & C. Rott ICRC17 (965)]

KCYN, Beacom, Peter, Rott, 1703.10280
See also
Arguelles+ 1703.07798
Edsjo+ 1704.02892

Dark Matter with long-lived mediators

Leane, KCYN, Beacom 1703.04629

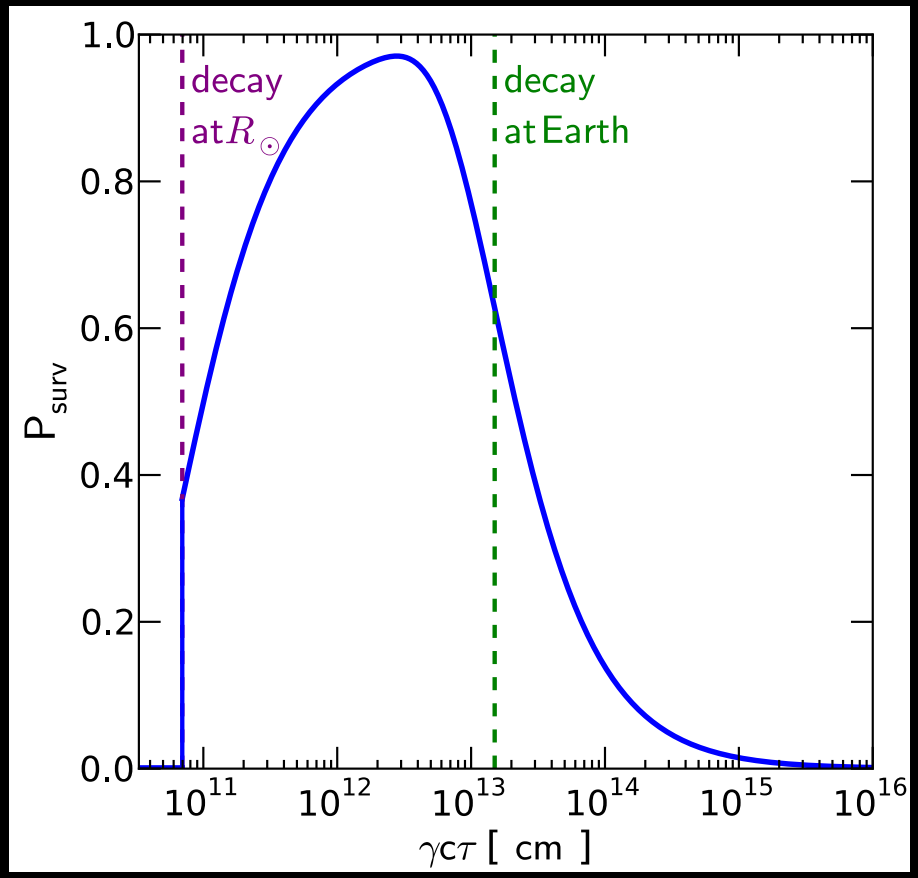
- Unlock
  - Gamma rays
  - Electrons, muon, etc
- Unsuppressed
  - Neutrinos!



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

Mediator Escape and Decay

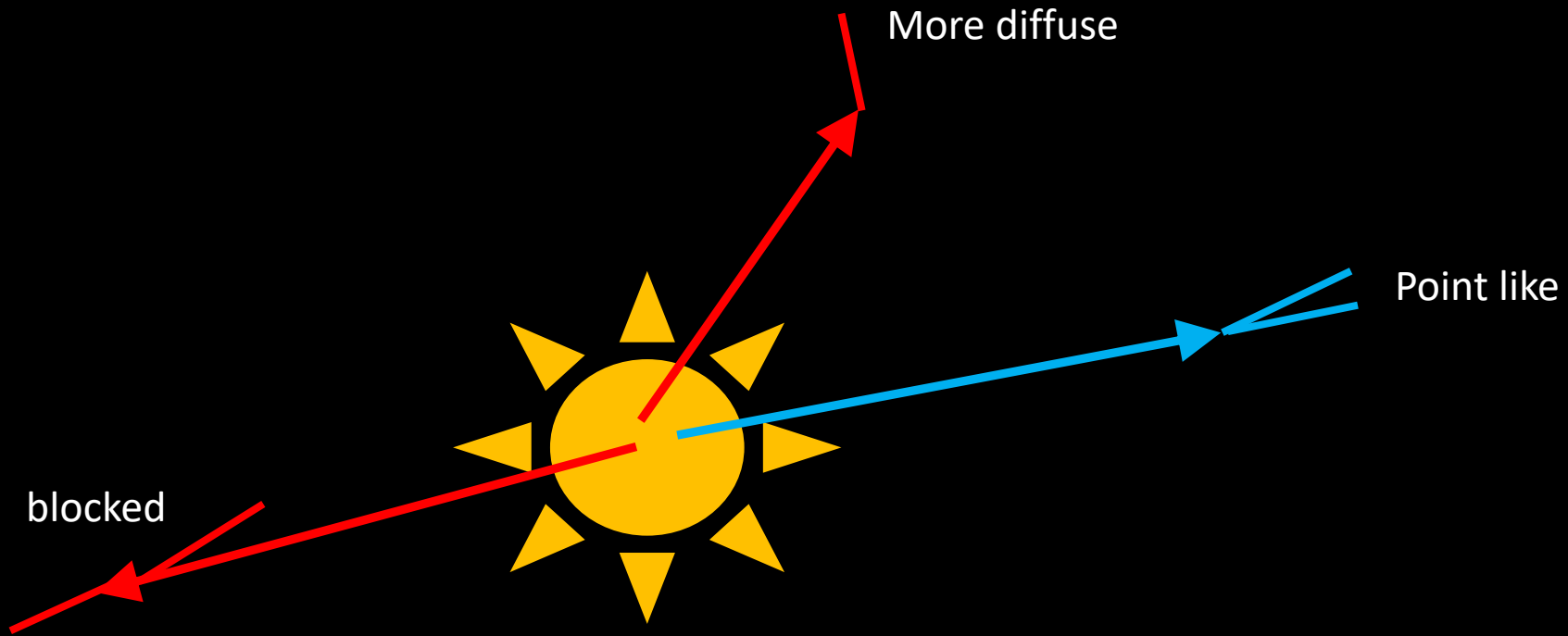
- Viable for a large range of lifetime, actually
- “Highly boosted”



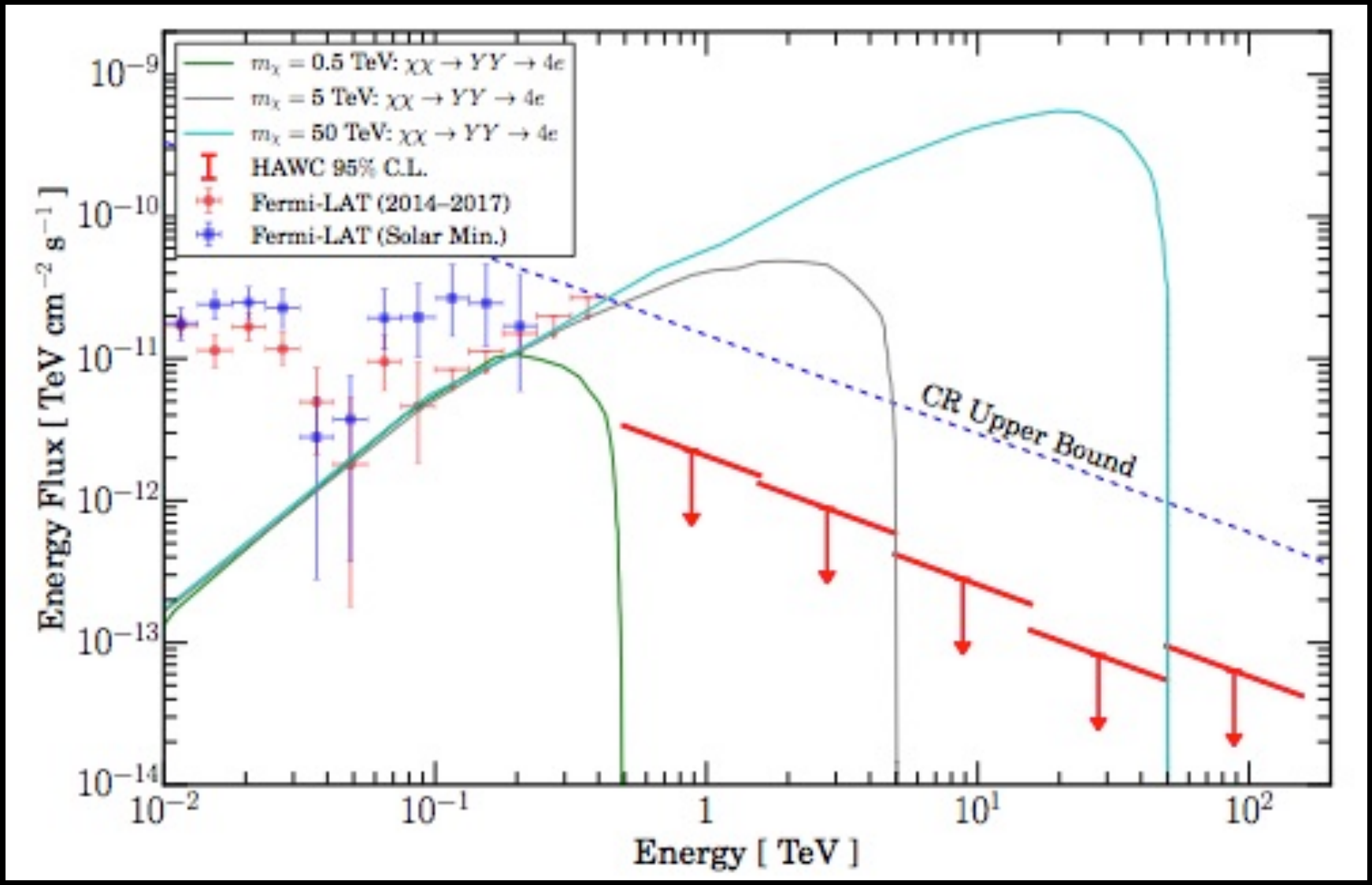
$$P_{\rm surv} = e^{-R_\odot/\gamma c\tau} - e^{-D_\oplus/\gamma c\tau}$$

Mediator Escape and Decay

- Viable for a large range of lifetime, actually
- “Highly boosted”
- Box spectrum cutoff at low E

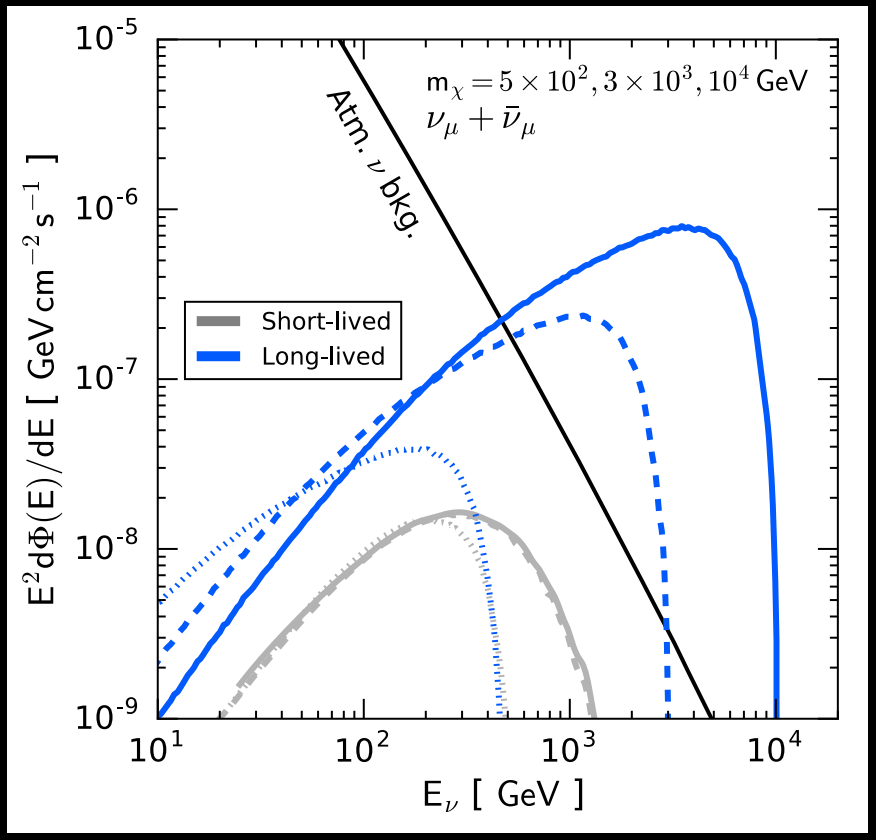


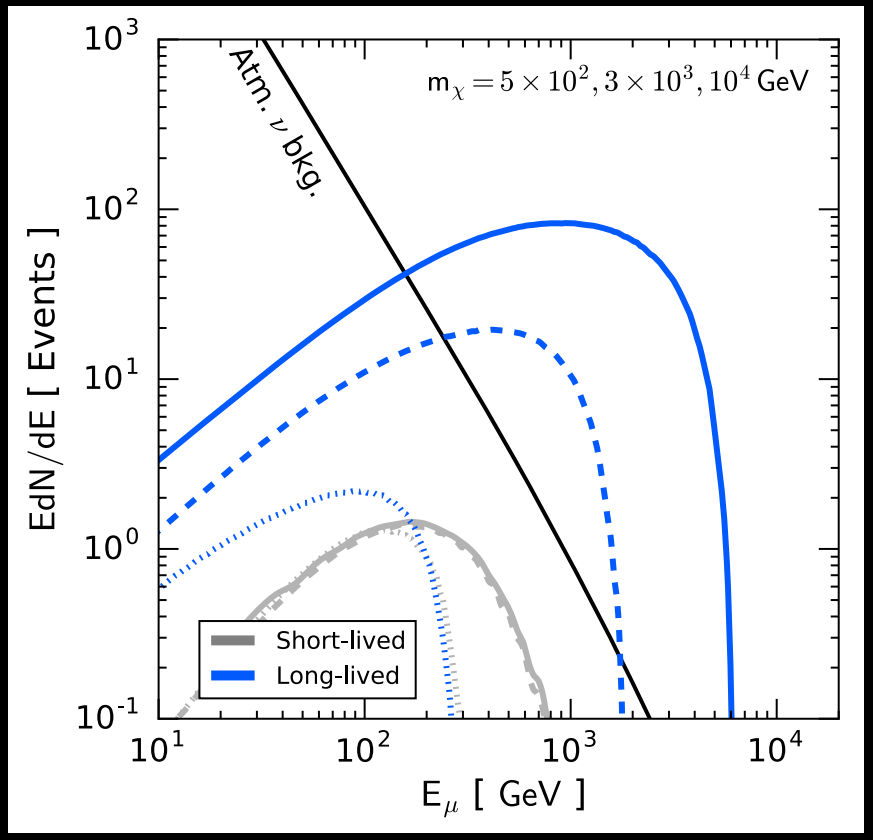
Secluded dark matter Gamma Rays



Secluded dark matter Neutrinos

- Expected Neutrinos and Muons
  - No Cooling and Absorption



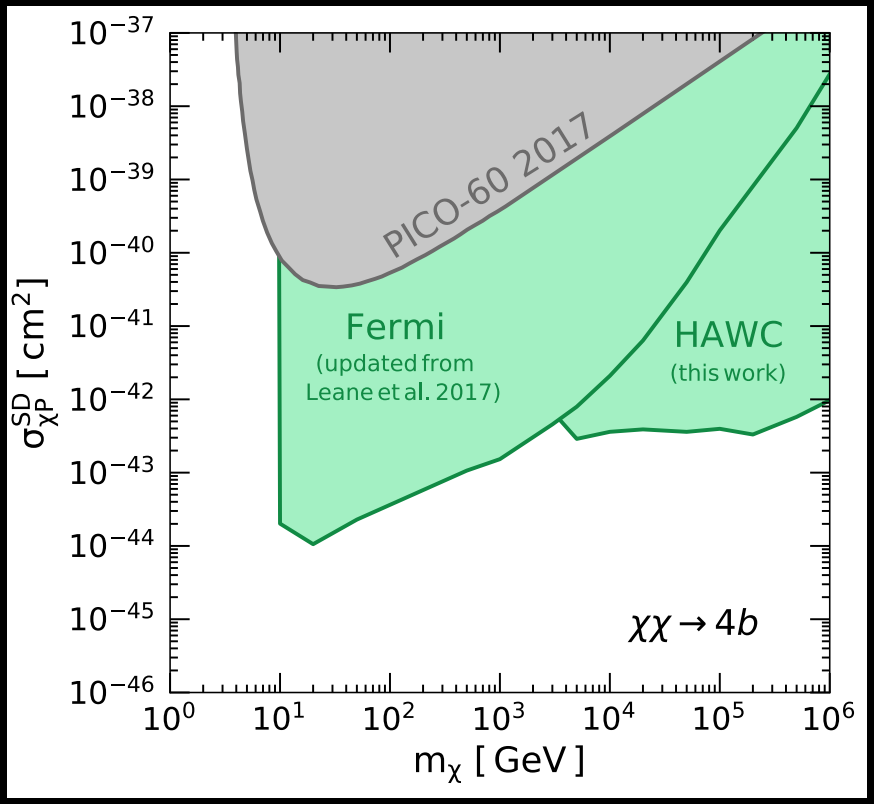


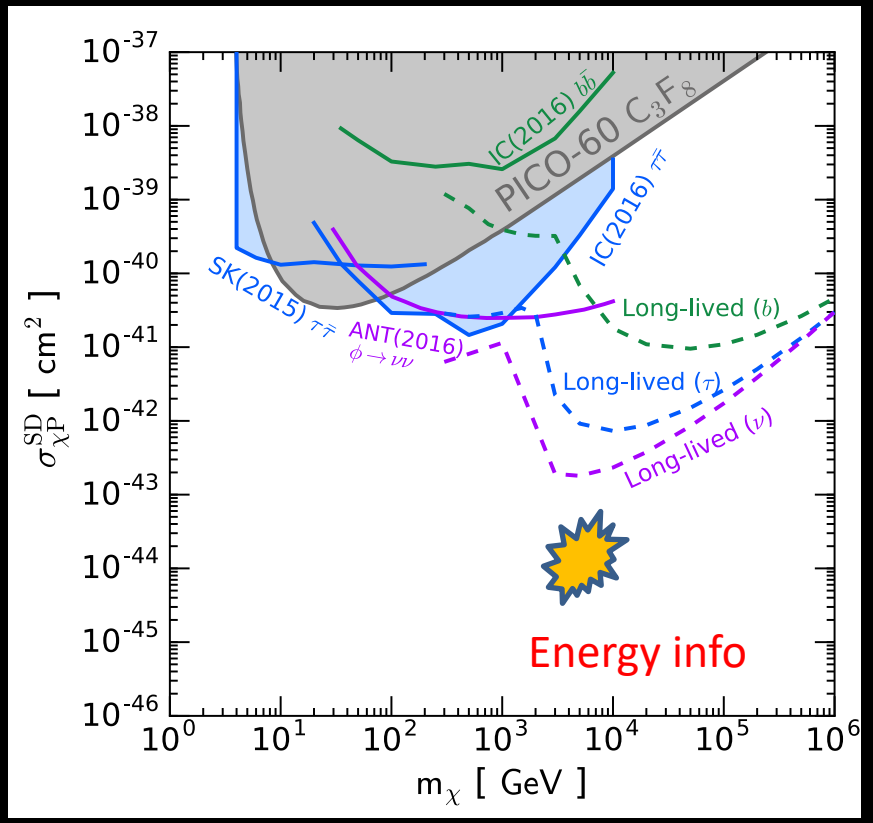
Dark Matter with long-lived mediators

HAWC 1808.05624

Also Leane, KCYN, Beacom 1703.04629

- Optimal mediator life time + capture equilibrium
- Complementary to direct detection (SD cross section)





HE Solar Messengers

	Gamma Rays	Neutrinos (< TeV)	Neutrinos (> TeV)
Cosmic rays + Solar Atmosphere			
WIMP Dark Matter			
Dark Matter + Mediators			

Maybe electrons/positrons or neutrons can also been seen from space?

Summary

- Solar gamma rays
  - *Complicated*
  - *TeV*
  - *More time (solar minimum starting this year)*
- *Solar atmospheric neutrinos*
  - *Not yet detected*
- *Looking for anomalous signal/new physics*

Thanks!

Backup slides