Sun as a New Laboratory:
cosmic rays, gamma rays, neutrinos, and dark matter

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Relevant work by our group:

Ng, Beacom, Peter, Rott, PRD, arXiv:1508.06276

***Zhou**, Ng, Beacom, Peter, arXiv:1612.02420*

Leane, Ng, Beacom, arXiv: arXiv:1703.04629

Ng, Beacom, Peter, Rott, arXiv:1703.10280

Zhou et al. in prep

Outline

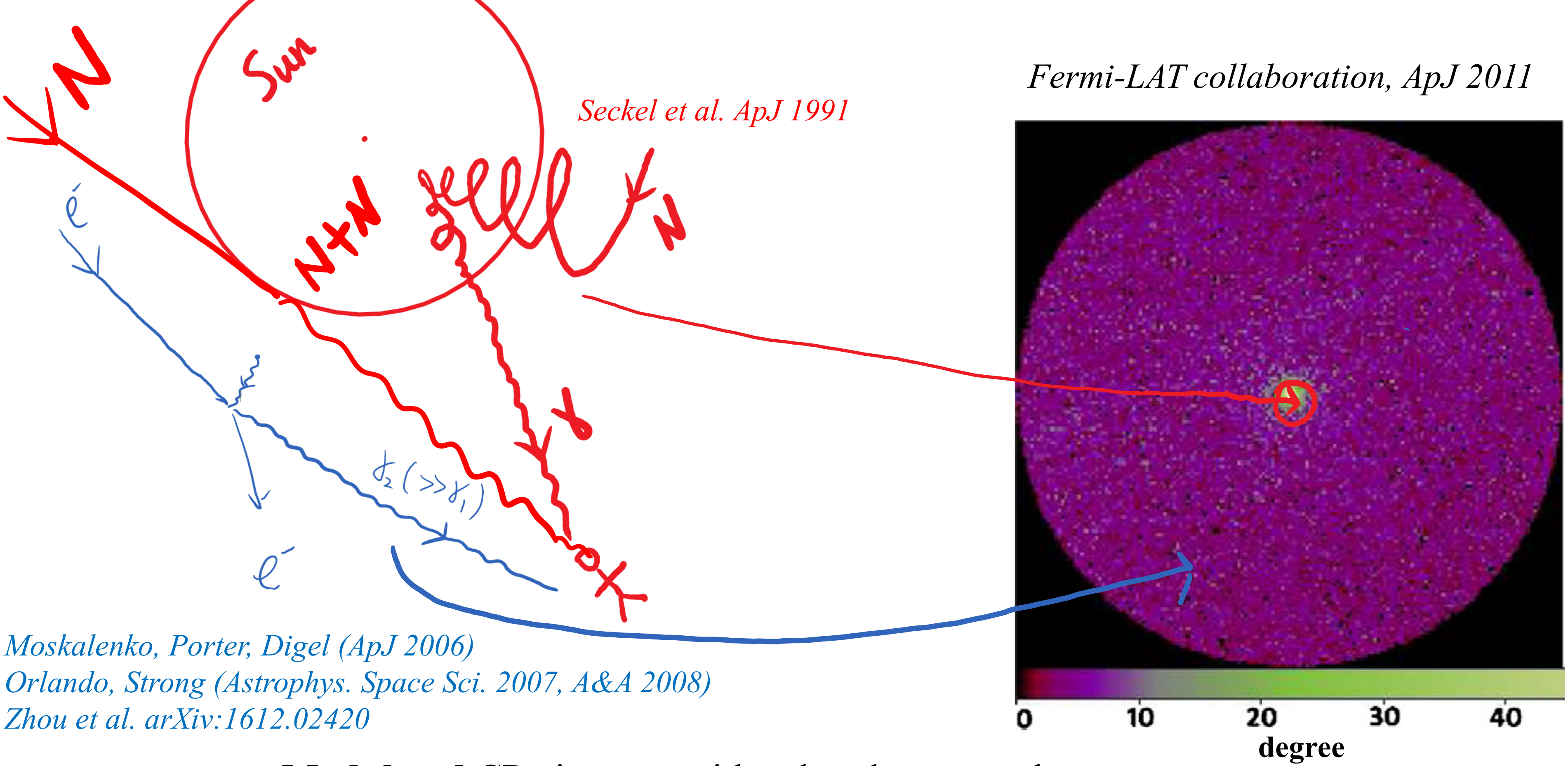
- Solar gamma rays from cosmic-ray interactions
- Solar atmospheric neutrinos from cosmic-ray interactions and a sensitivity floor for dark matter detection
- Gamma rays and neutrinos from the Sun as a powerful probe of dark matter with long-lived mediator

Cosmic-Ray Interactions Produce Gamma Rays

Zhou et al.
arXiv:1612.02420

Seckel et al. ApJ 1991

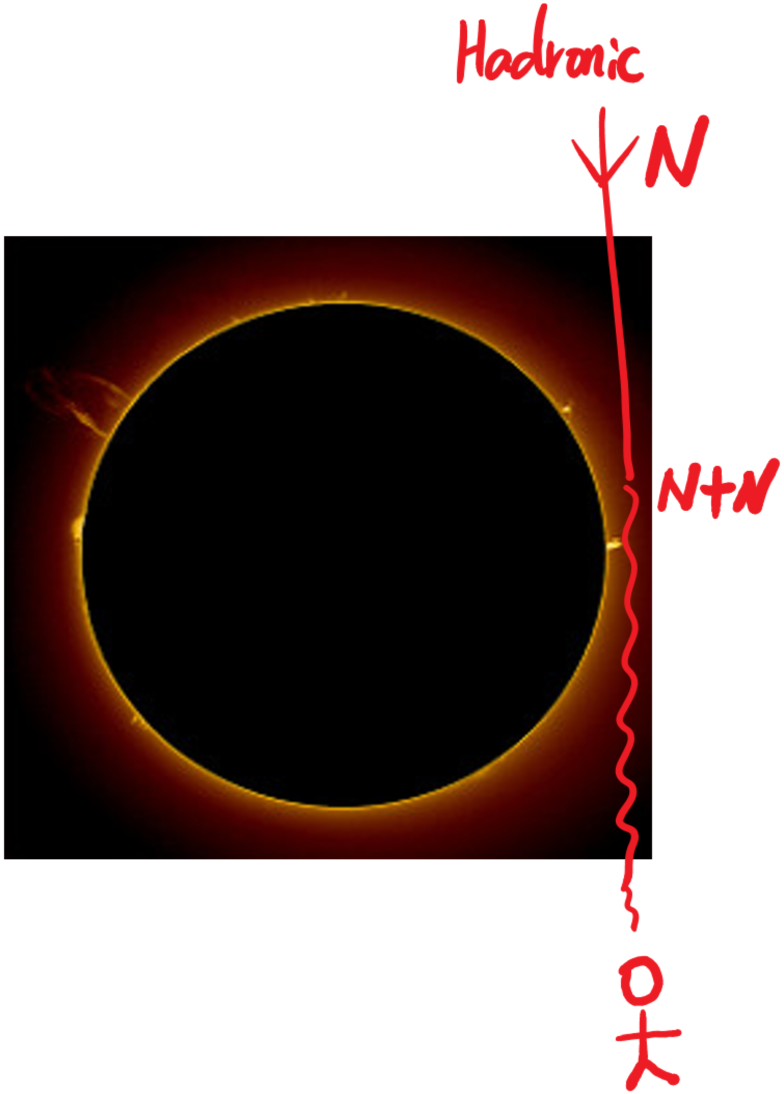
Fermi-LAT collaboration, ApJ 2011

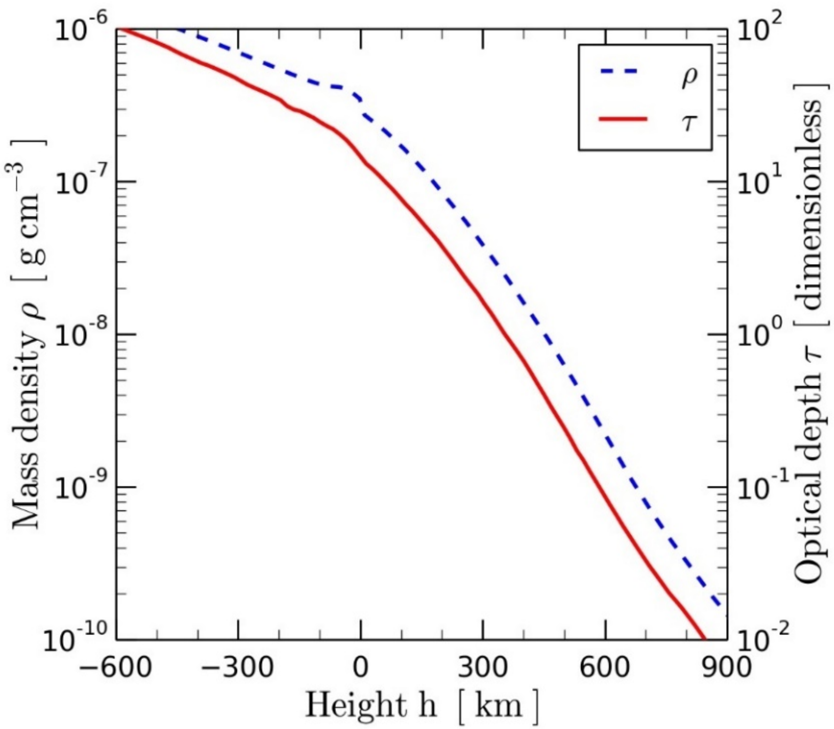


Moskalenko, Porter, Digel (ApJ 2006)
Orlando, Strong (Astrophys. Space Sci. 2007, A&A 2008)
Zhou et al. arXiv:1612.02420

Modulated CRs interact with solar photons and matter;
→ **top 20** brightest γ sources (> 10 GeV)
→ γ ray **probe CR** distance & energy dependently at < 1 AU

Disk flux: Contribution from Solar Limb

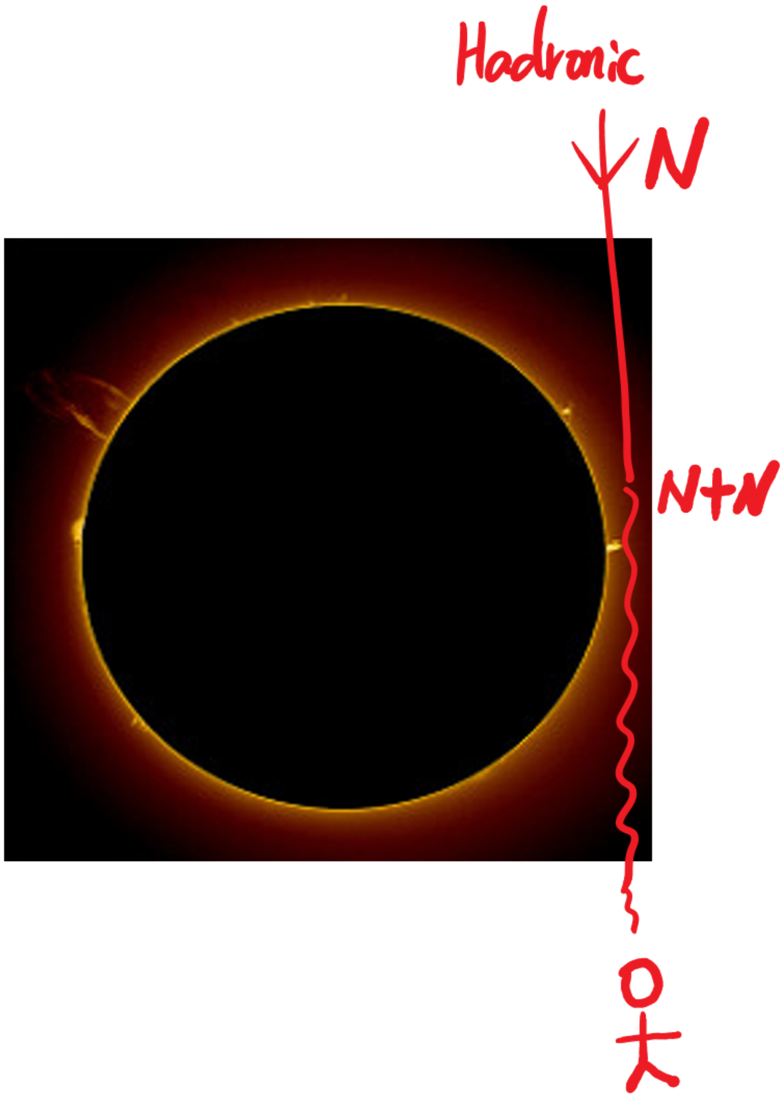




Zhou et al. arXiv:1612.02420

Limb emission: A very thin gamma ray ring, though with high intensity (surface brightness)

When Magnetic Effects Can Be Ignored?



$$E_c \sim 10^4\,\mathrm{GeV}\left(\frac{L}{R_\odot}\right)\left(\frac{B}{1\,\mathrm{G}}\right)$$

for CR proton

$$E_\gamma \sim 0.1 E_{c,proton} = 1\ \mathrm{TeV}$$

Disk flux: Contribution from Solar Limb

- Neglect magnetic effects.

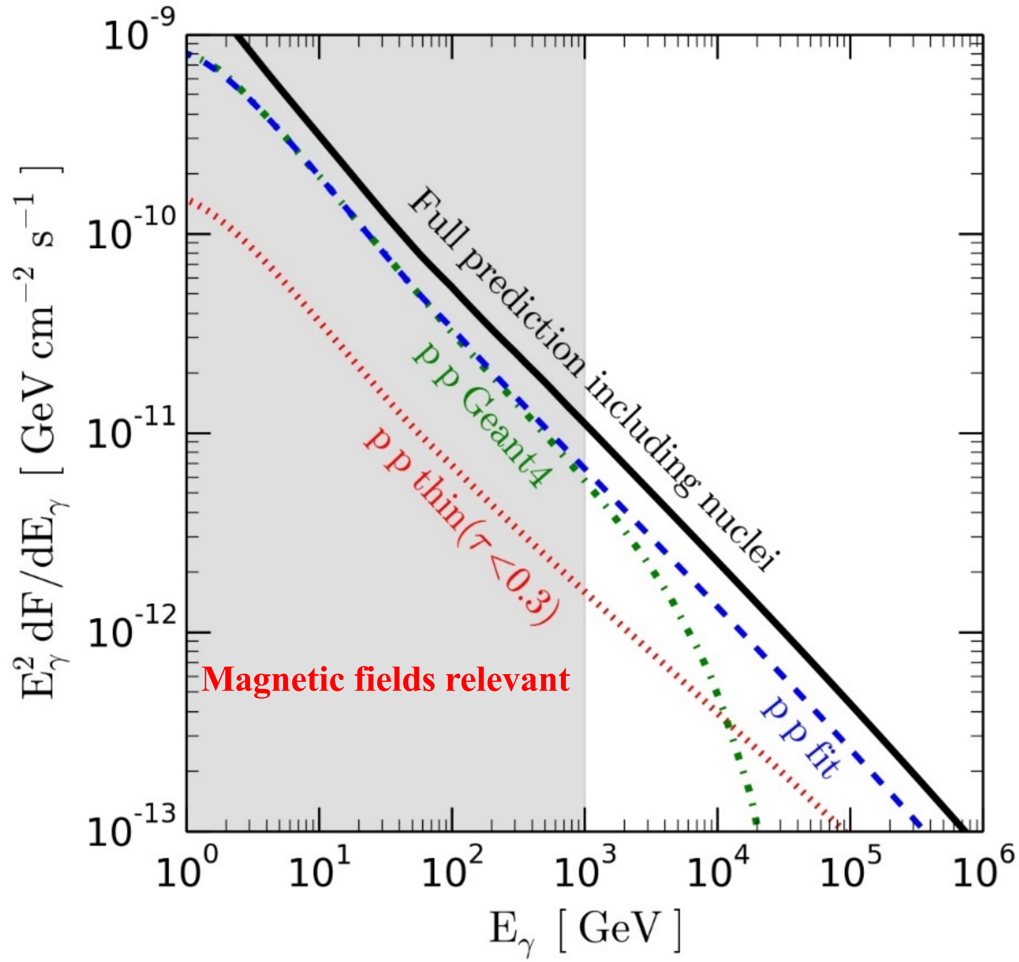
- **Red**: Thin region (tau = 0--0.3)

$$\frac{dF}{dE_\gamma}(E_\gamma) = \int d\Omega \int ds\, n_p(\vec{s}) \int dE_p \frac{dI}{dE_p}(E_p)\, \sigma_{\rm inel}(E_p) \frac{dN}{dE_\gamma}(E_p, E_\gamma)$$

- **Green** and **blue**: Thick region: Cascade & absorption are important. Use Geant4 simulation; regulation

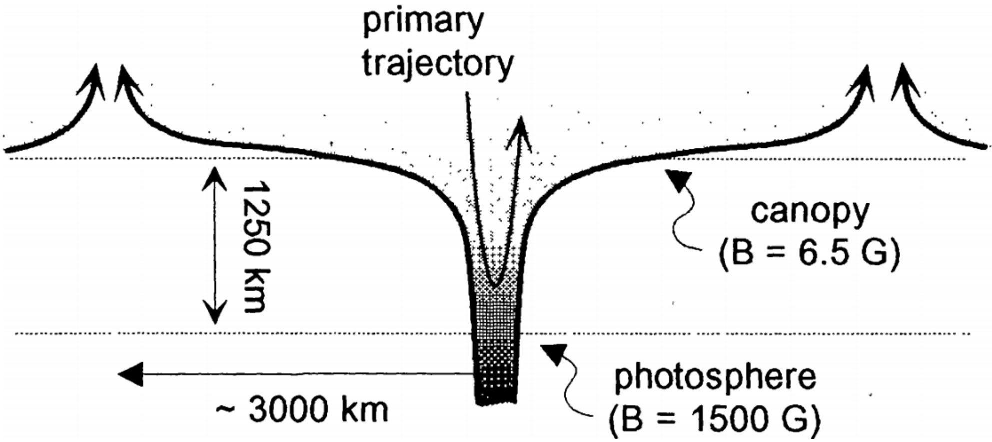
- **Black**: Enhancement by heavier nuclei → increase by a factor of ~2
- → Full limb prediction

- Calculation is robust > ~ TeV

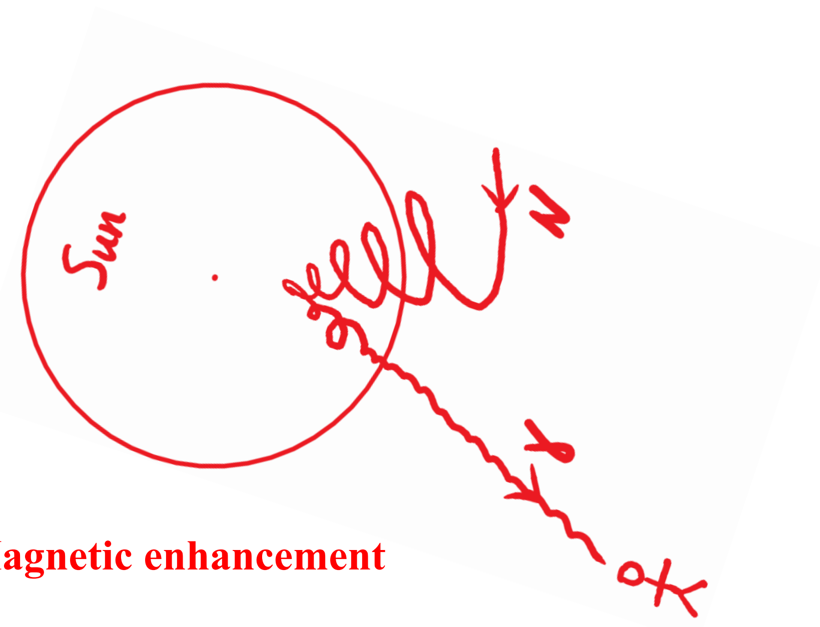


Zhou et al. arXiv:1612.02420

Disk Flux: Contribution from whole Sun

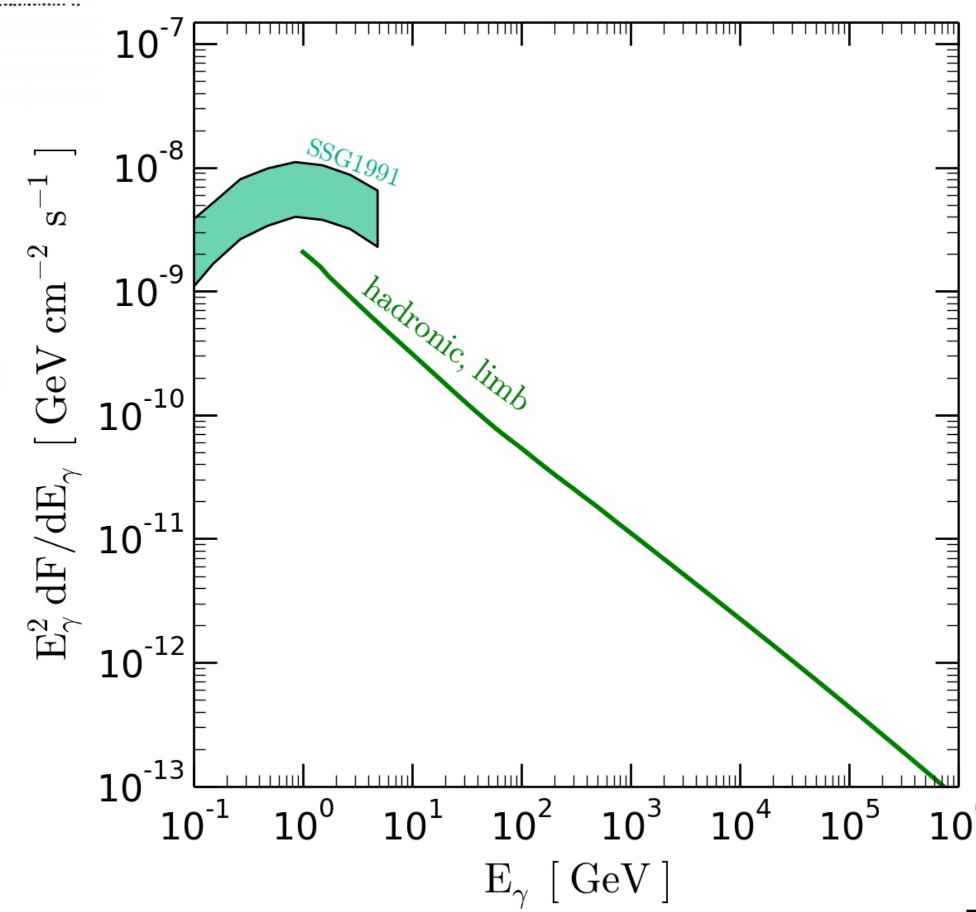


Whole scenario proposed by
Seckel, Stanev, and Gaisser, APJ 1991 (SSG1991)

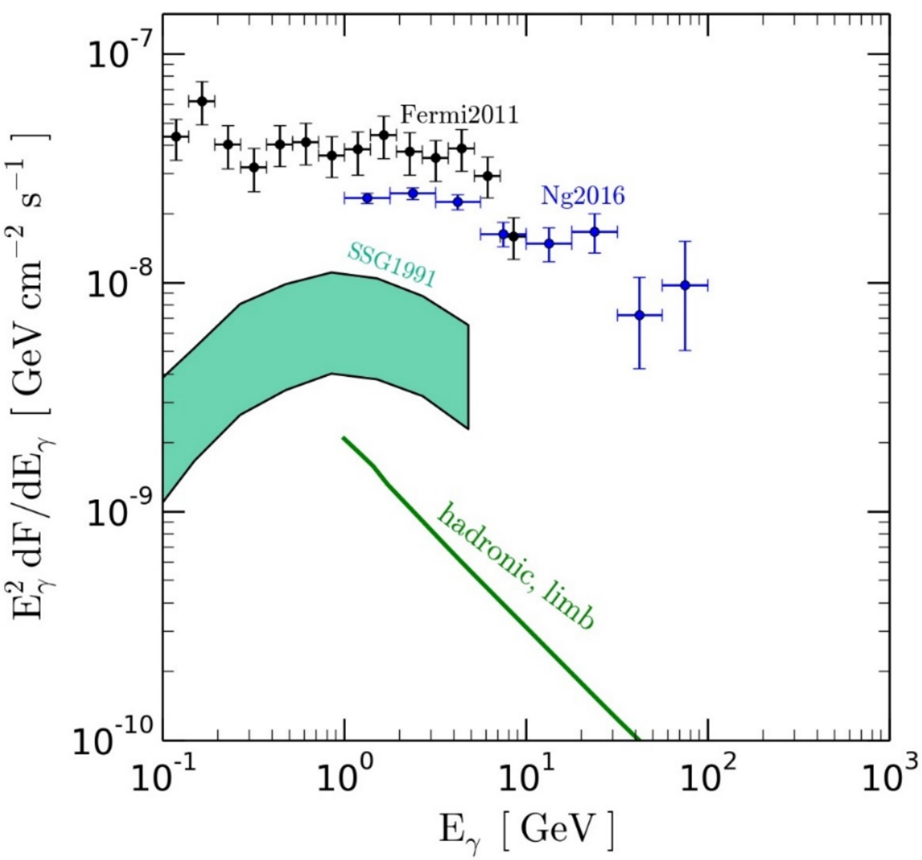


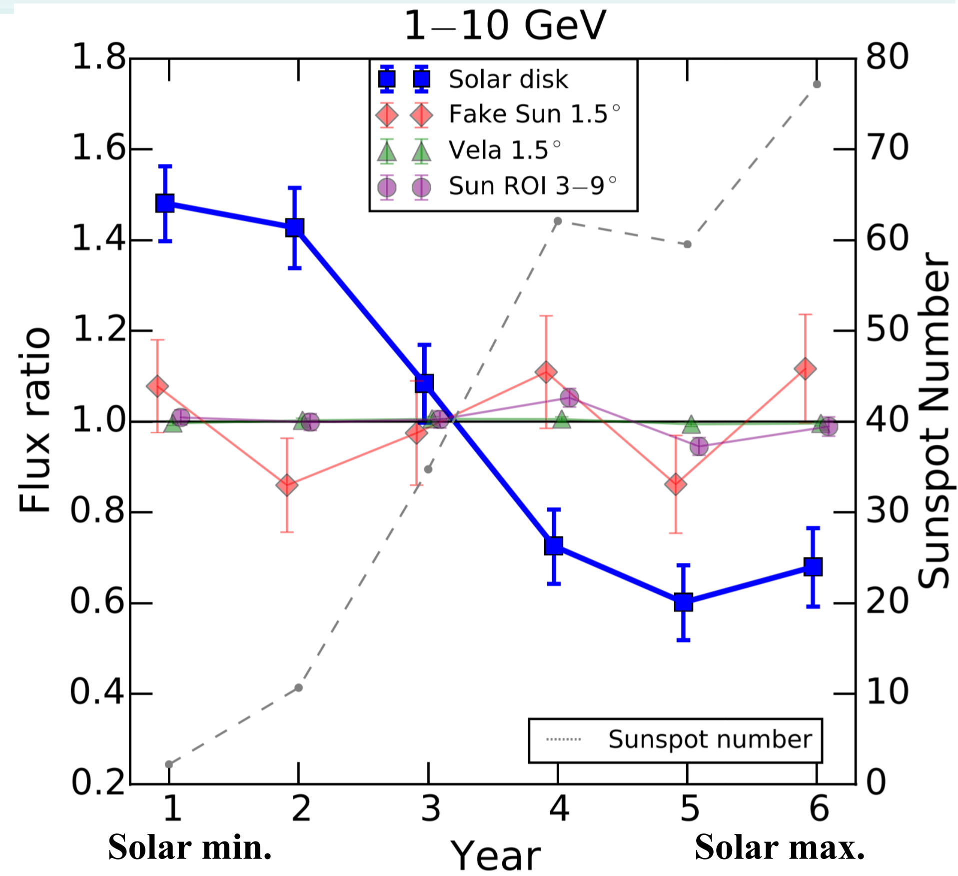
Magnetic enhancement

$$E_c \sim 10^4\,\mathrm{GeV}\left(\frac{L}{R_\odot}\right)\left(\frac{B}{1\,\mathrm{G}}\right)$$



Disk Flux: Observation from *Fermi*-LAT





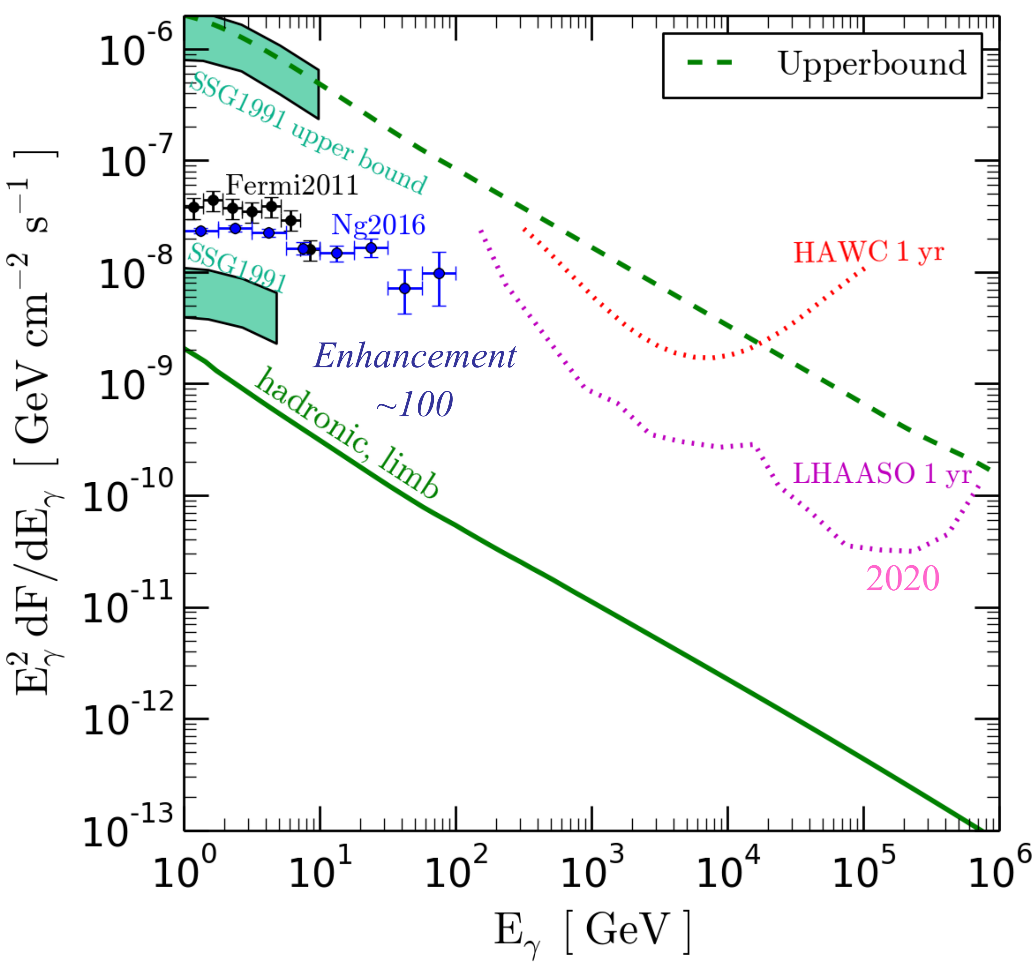
Ng, et al., PRD, arXiv:1508.06276

~ One order of magnitude higher than theory!

Magnetic enhancement is even stronger than SSG estimated.

Magnetic enhancement is even weaker as solar magnetic field get stronger??!!

Disk Flux: Up to Now



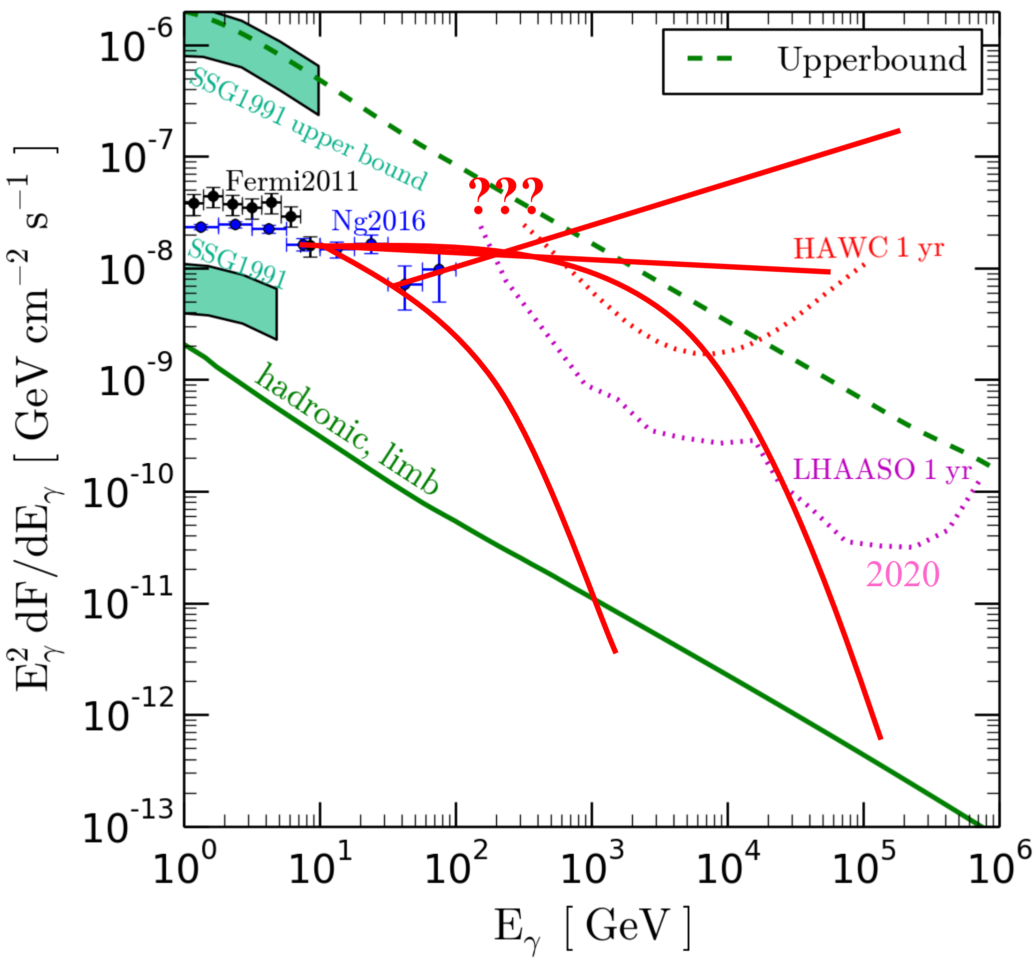
Zhou et al. arXiv:1612.02420

- Upper bound > sensitivities

Limb nominal:

- At high energies, total solar emission
- At lower energies, theoretical lower bound
- Obs./limb gives the an E-dep. enhancement factor of γ ray production due to solar magnetic field → future theoretical studies at GeV

Fermi & HAWC will Play a Vital Role



Zhou et al. arXiv:1612.02420

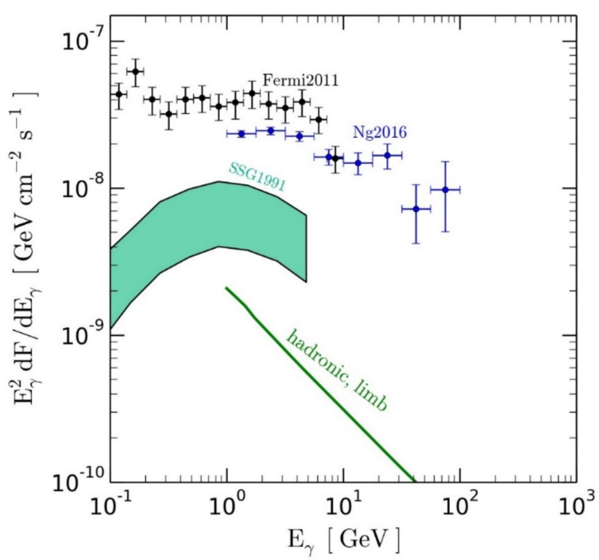
- Measure/Constrain the energy-dependent enhancement factor
- Measure/Constrain where transition happen.

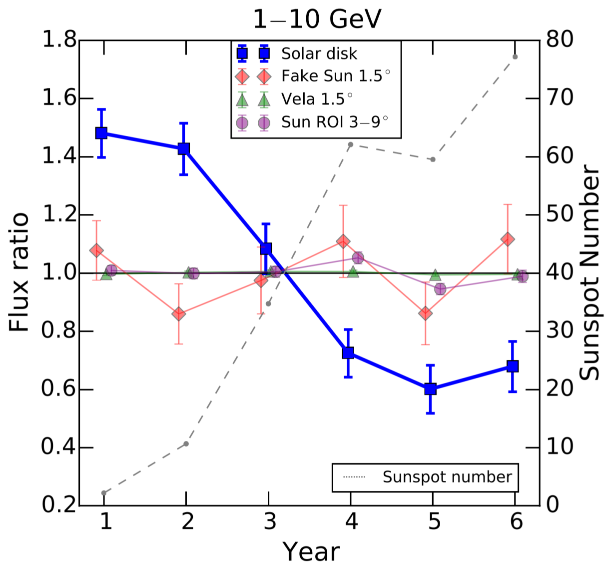
SSG gives: cutoff may be 30 GeV - ? TeV

Fix Disk Flux Model: Work in Prep.

- Interplanetary magnetic field modulation?
- Photosphere magnetic field?
- Coronal magnetic field ?

Zhou et al. in prep





Outline

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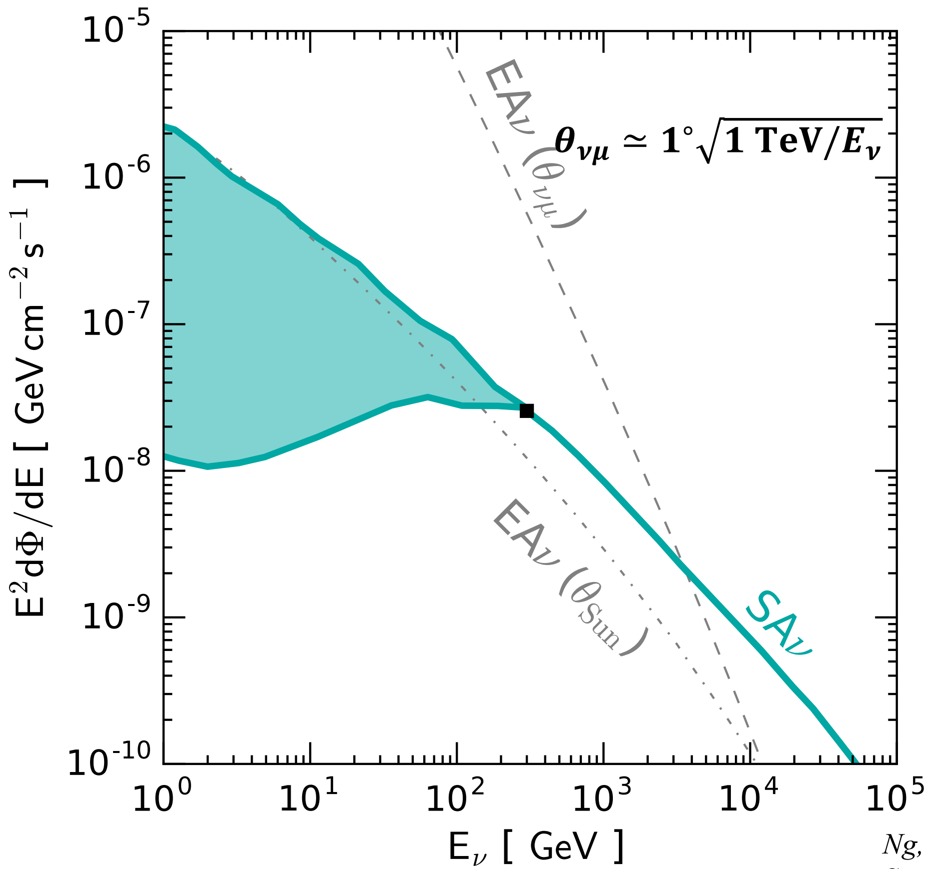
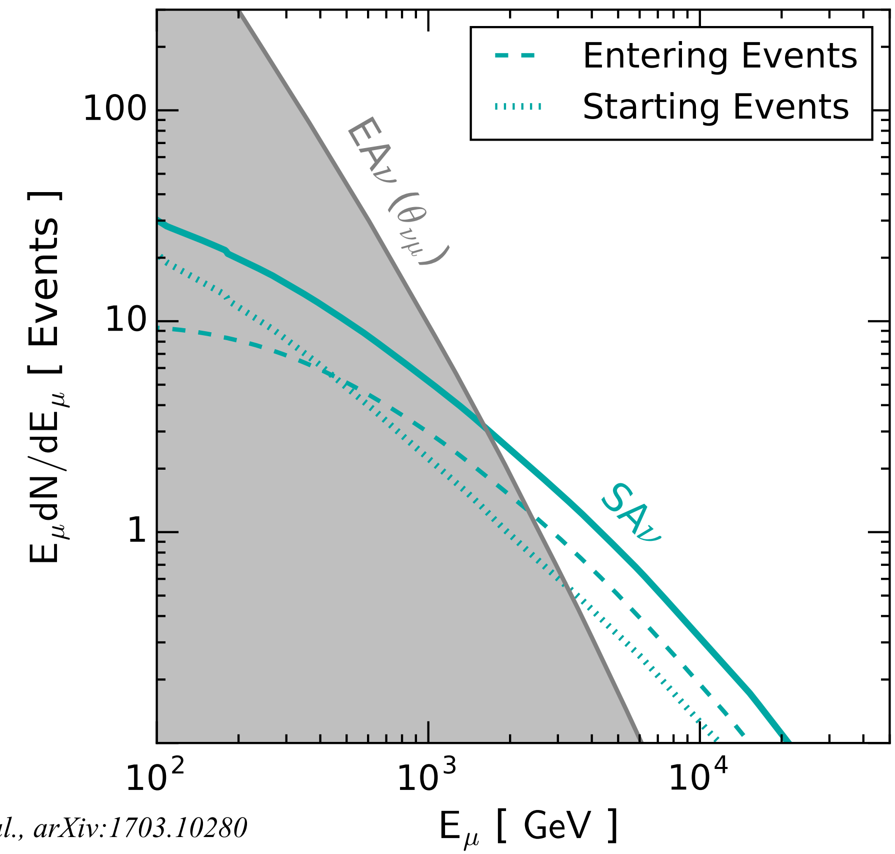
- Solar atmospheric neutrinos from cosmic-ray interactions and a sensitivity floor for dark matter detection
- Gamma rays and neutrinos from the Sun as a powerful probe of dark matter with long-lived mediator

Solar Atmospheric Neutrinos: As Signal





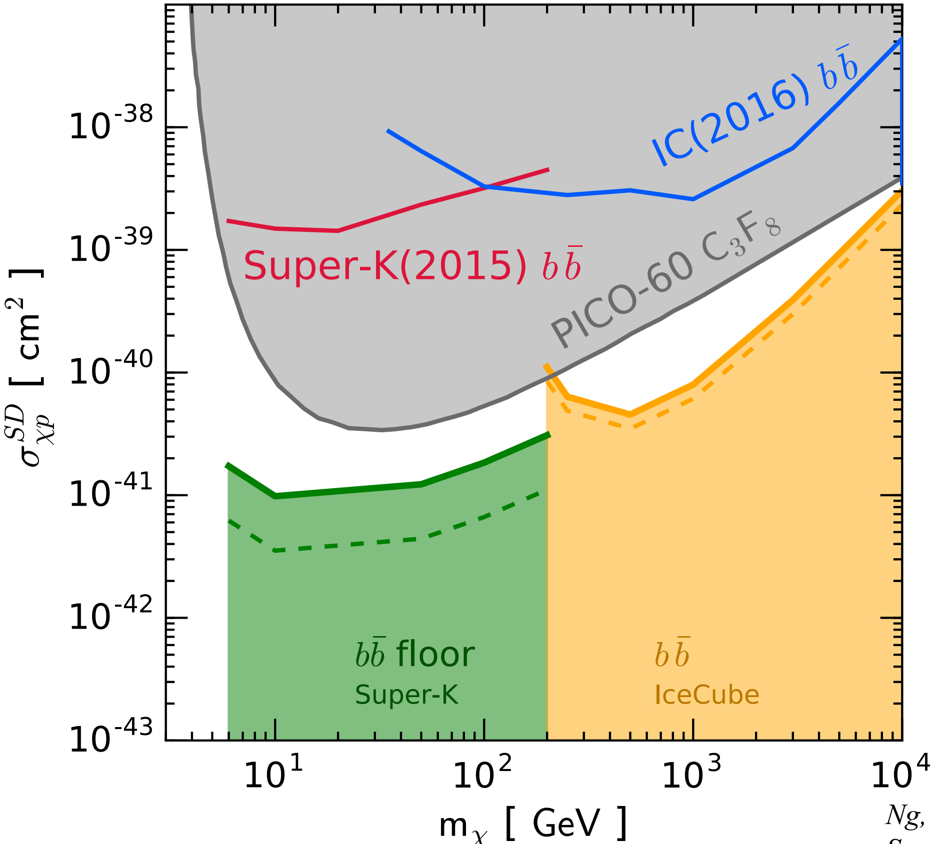
Ng, et al., arXiv:1703.10280
See also:
Arguelles, et al., arXiv:1703.07798
Edsjo et al., arXiv:1704.02892

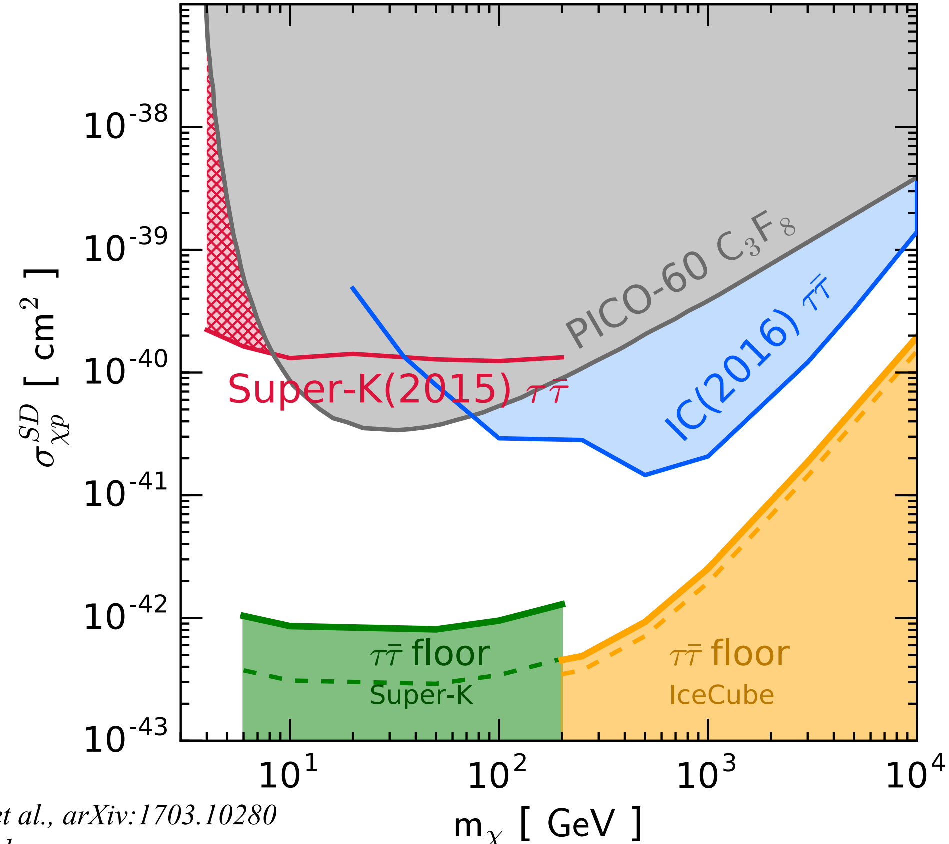
Solar atmospheric ***muon neutrino*** *(SAν) Flux:*
Below 300 GeV: *Seckel et al. APJ 1991*
Above 300 GeV: *Ingelman & Thunman, PRD 1996*

- Lower energy: magnetic effects uncertainty
- Higher energy: SAν flux is harder than EAν
- Realistic angular resolution worsen the situation
- > A few TeV, SAν > EAν

- **10 yrs., > 1 TeV, 4.5 events for SAν, 4.1 for EAν**
- **An important milestone for neutrino astronomy**
- Possible calibration source for **IceCube** & **KM3NeT**

Solar Atmospheric Neutrinos: As Background for IceCube and Super-K





Ng, et al., arXiv:1703.10280
See also:
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Left: $b\bar{b}$ channel, right: $\tau\bar{\tau}$ channel.
Solid to Dash line: rough magnetic effect uncertainty
SK will not touch the SAν floor.
IceCube could touch the SAν floor.

Outline

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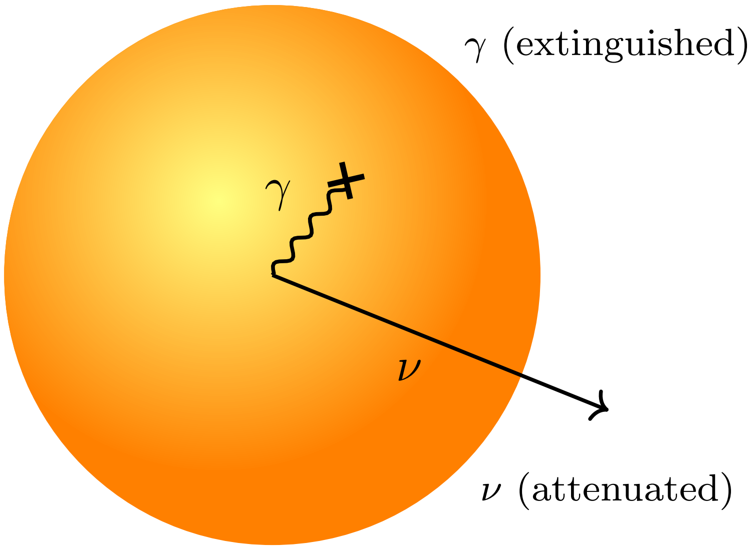
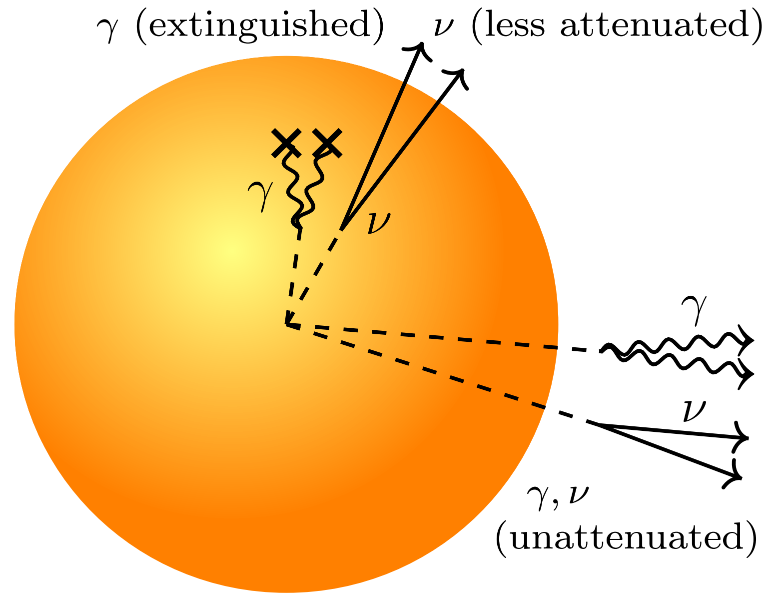
Gamma Rays from Dark Matter in the Sun



Short-lived mediators



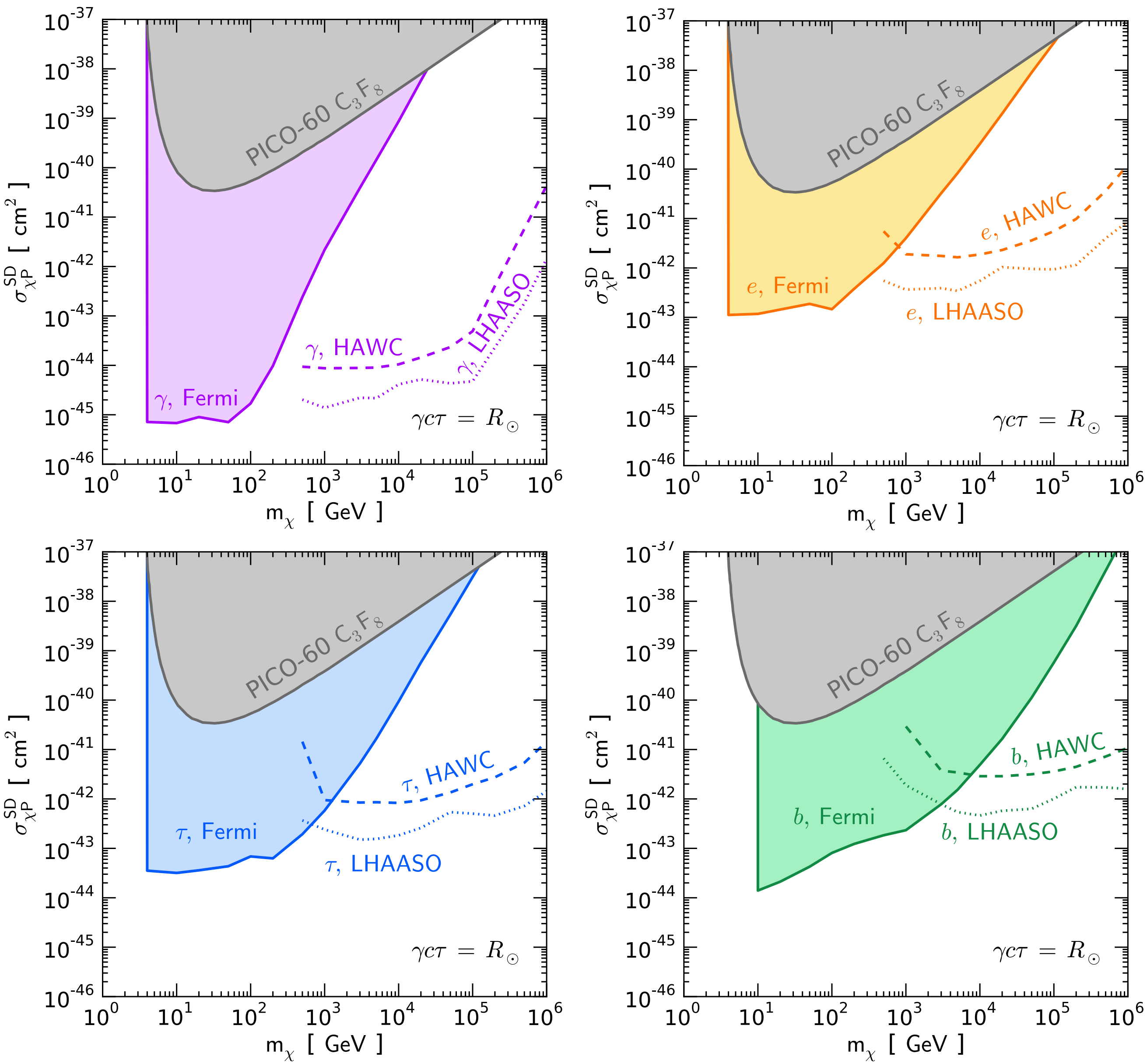
Long-lived mediators

Many new DM physics models:
annihilation: DM DM → Y Y
decay: Y → $\gamma\gamma$, e^+e^- , $\tau^+\tau^-$, or $b\bar{b}$, etc.

Model independent: $M_{DM} = \gamma M_Y$, $M_Y = 2E_{final\ state}$

Leane, et al., arXiv:1703.04629

Gamma Rays Constrain $\sigma_{\chi p}^{SD}$: Old v.s. New



Reasonable **assumptions**:
Optimal mediator scenario
Assum. $\boldsymbol{\gamma c \tau} \approx \boldsymbol{R_\odot}$, decay once escape the Sun.
Assum. $\boldsymbol{\gamma} \gg \mathbf{1}$, point source

Fermi+HAWC+LHAASO

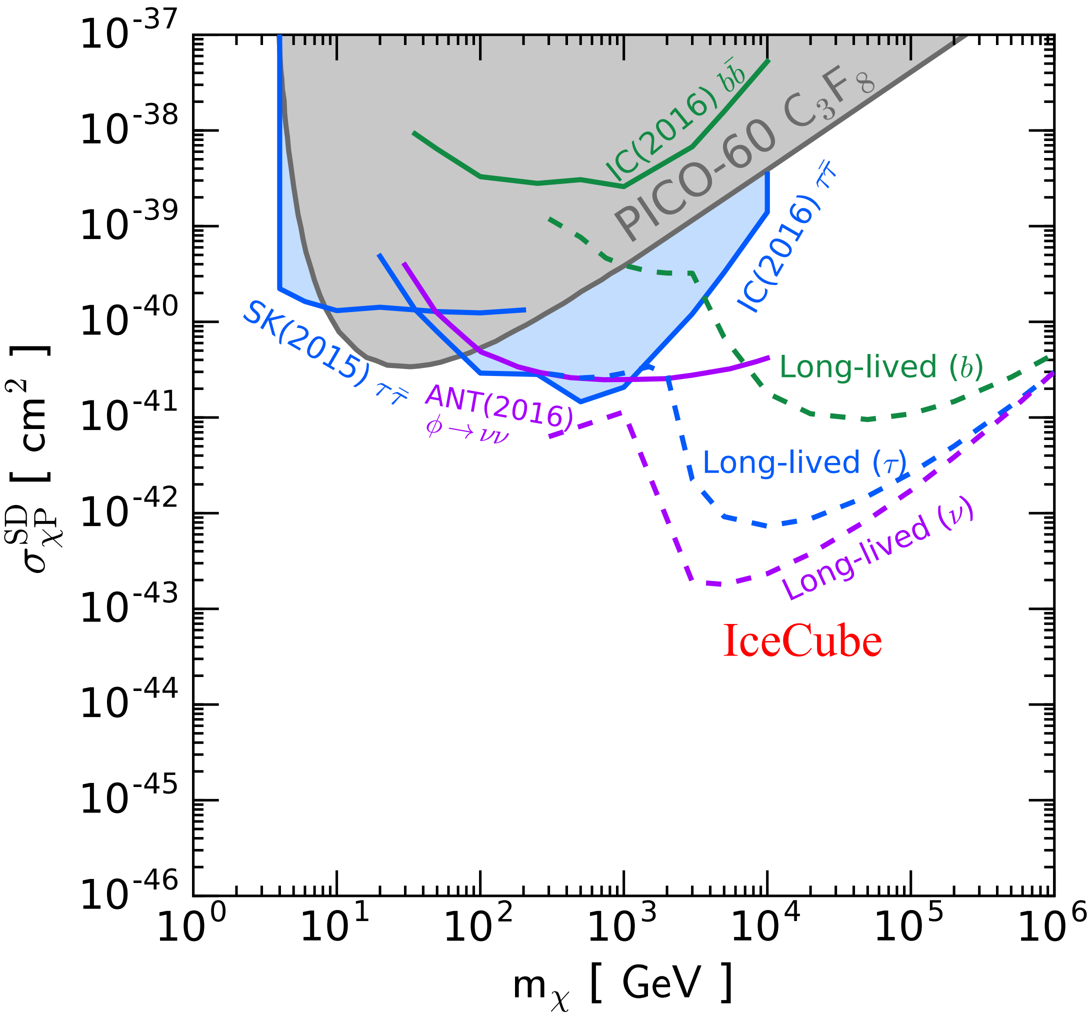
current best limit: $10^{-40}\ cm^2$

γ rays are **extremely powerful**,

Some channels even stronger than upcoming direct detection experiment **DARWIN** ($10^{-43} cm^2$)

Leane, et al., arXiv:1703.04629

Neutrinos Constrain $\sigma_{\chi p}^{SD}$: Old v.s. New



IceCube neutrino observation is as powerful as gamma ray observation

Leane, et al., arXiv:1703.04629

Conclusion & Goal

Gamma rays from Sun not well understood, but could be.

This will help exploit high-energy neutrinos from Sun.

Both will help test dark matter.

The Sun is still a "hotpot" of mysteries!

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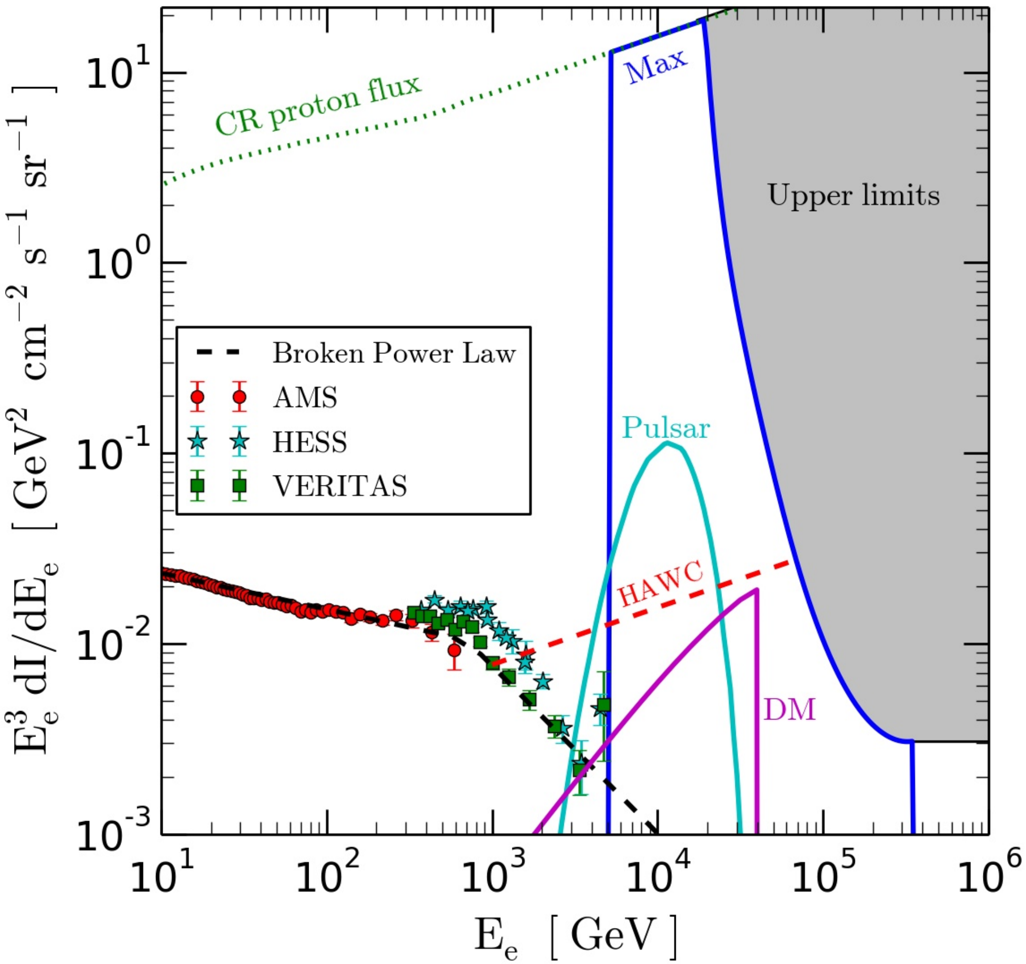
Thanks for your attention. Have a nice dinner!

~5-70 TeV CRe Obs. & Theo. Implications



Nothing between ~5-~70 TeV

Current detectors only goes to < 10 TeV

Hadron rejection rate: $\sim 10^{-3}$

HAWC can give a first look here.

→ Probe CRe 5-70 TeV

→ test pulsar & CR propagation models

→ constrain DM decay to ee

(100 TeV, 2*10^26 s lifetime, and NFW distribution)

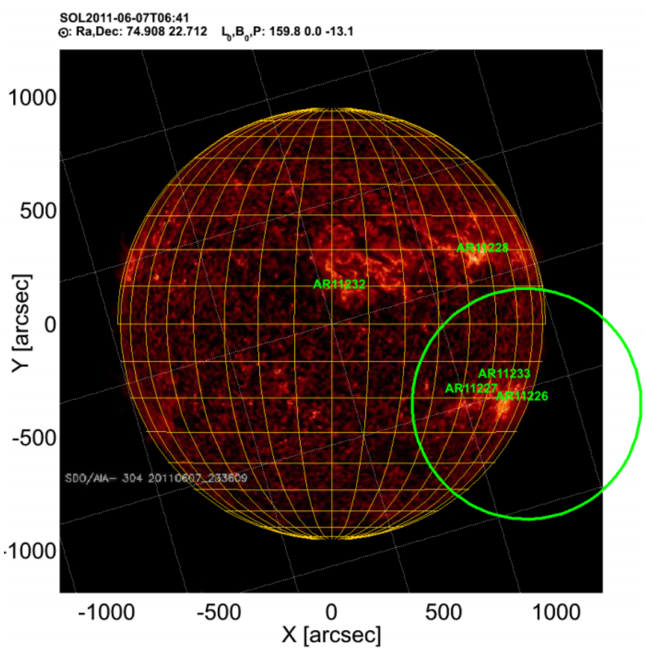
Therefore, it is strongly recommended HAWC to do an analysis of current CR electron-like data.

Zhou et al. arXiv:1612.02420

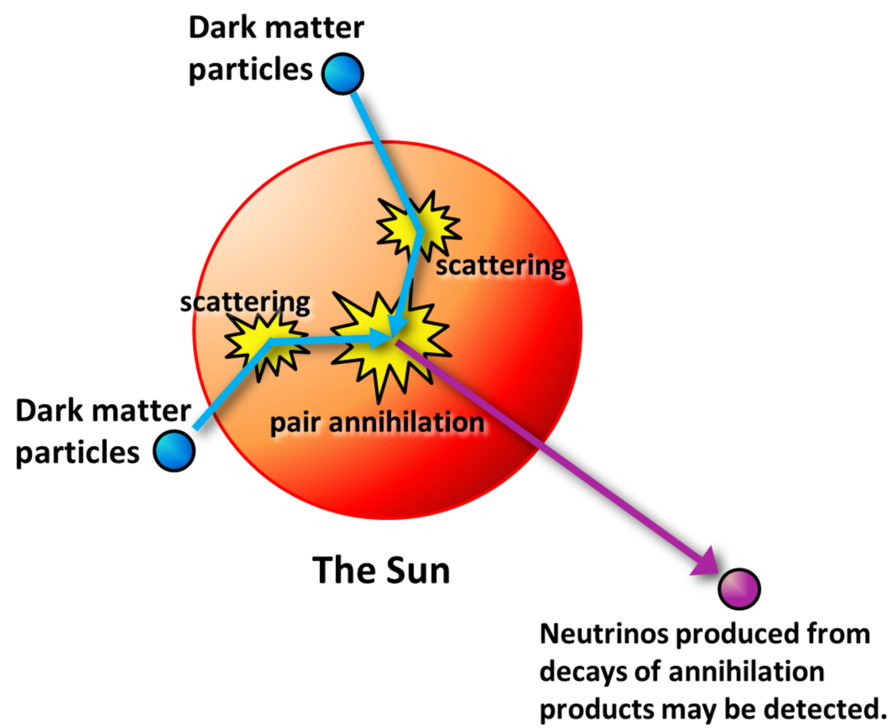
Sun: cosmic-ray generator

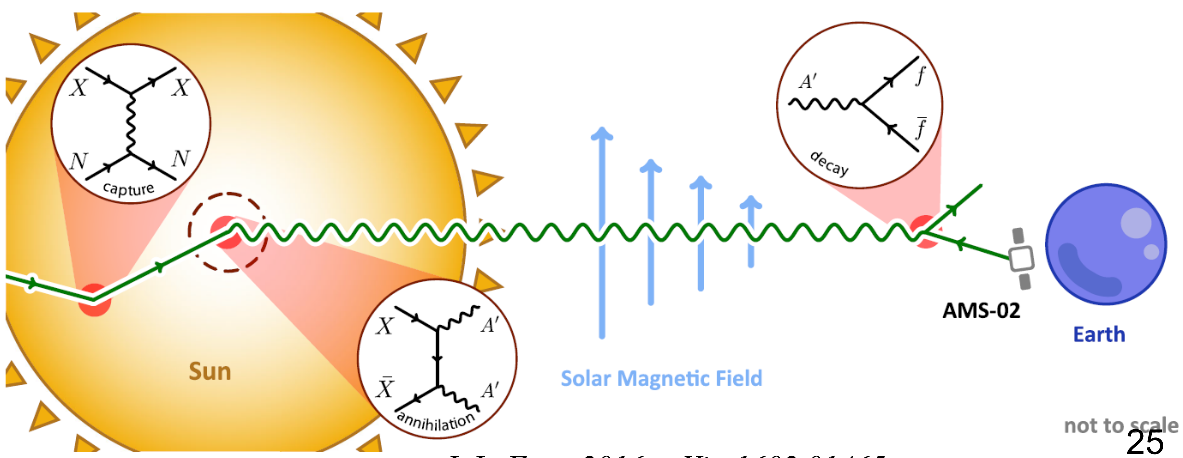
Solar flares (Hadronic or Bremsstrahlung)

< **4 GeV**



Fermi-LAT Collaboration, arXiv:1304.3749





L. Feng 2016 arXiv:1602.01465

Gamma-Ray Production Mechanisms

Leptonic

- Beam: CR electrons
- Target: Solar photons
- Typical interaction: Inverse-Compton scattering
  $e + \gamma_{low} \rightarrow e + \gamma_{high}$

Extended source (solar **halo**)

Situation: data, theory agree

Not focus of this section.

See references:

Moskalenko, Porter, Digel (APJ 2006)

Orlando, Strong (Astrophys. Space Sci. 2007, A&A 2008)

Fermi-LAT collaboration, APJ 2011

Zhou et al. arXiv:1602.02420

Hadronic

- Beam: CR nuclei
- Target: Solar matter
- Typical interaction:
  $pp \rightarrow pp\pi^0, \pi^0 \rightarrow \gamma\gamma, etc.$

Near-point source (solar **disk**)

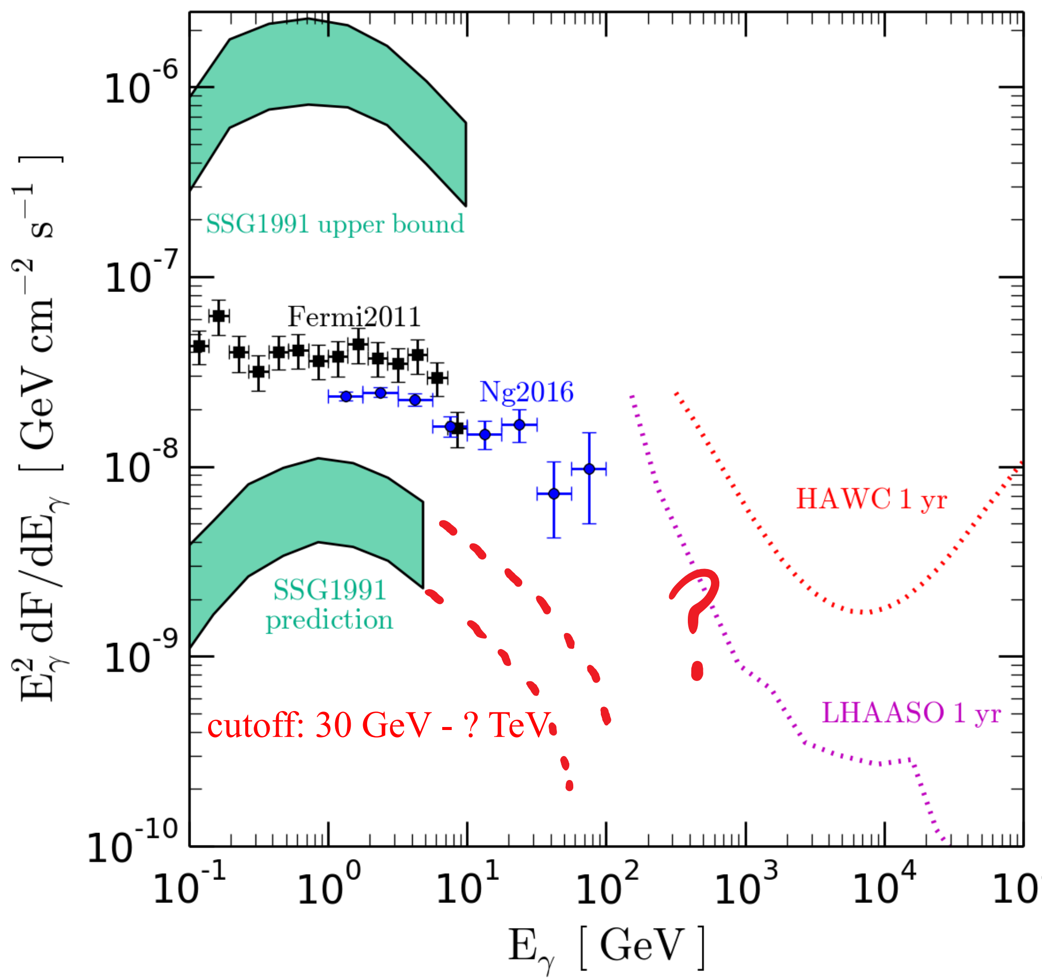
Situation: data, theory disagree

I focus on disk flux here

History is confusing, so tell story from smallest to largest flux

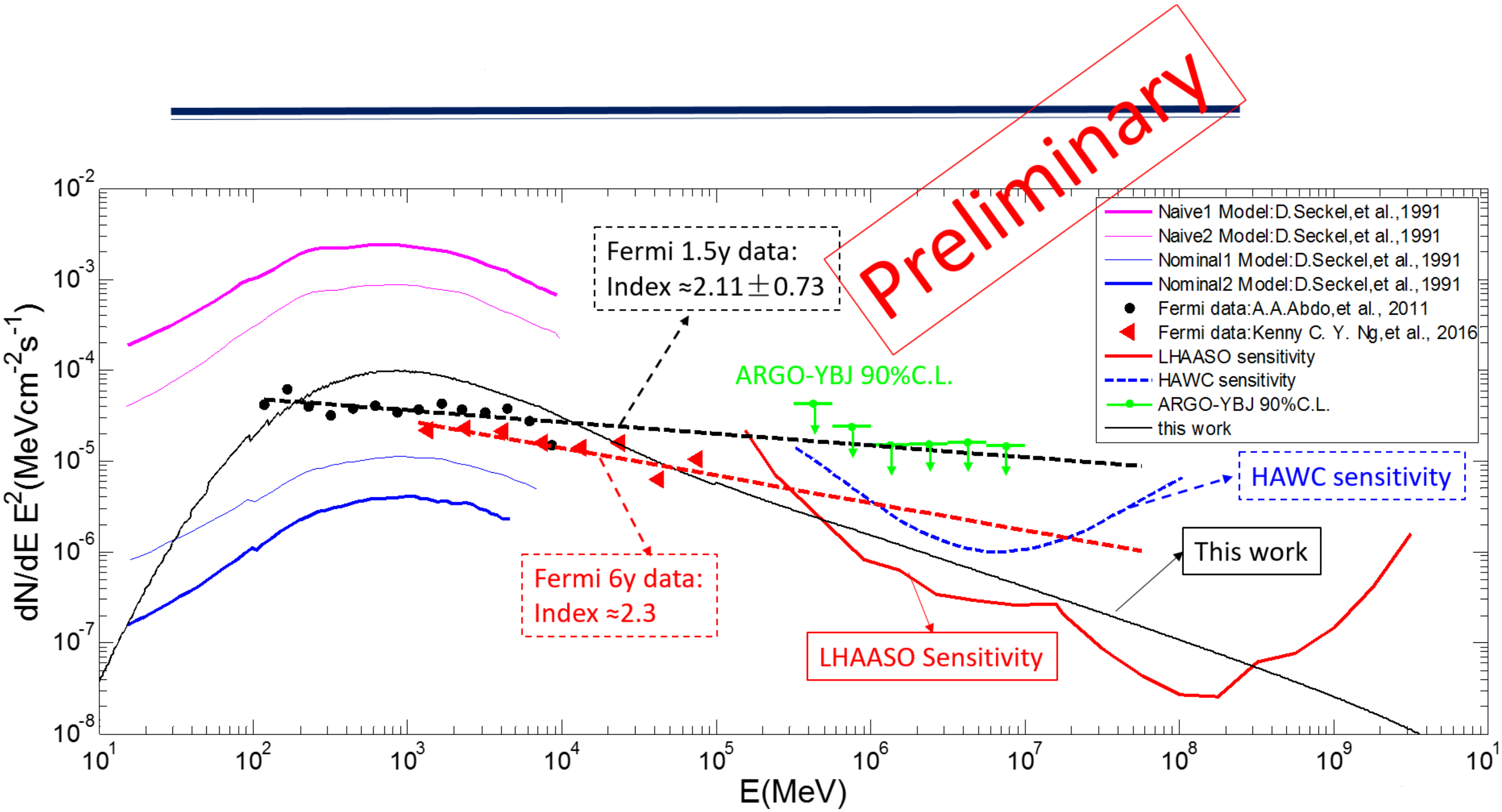
Hadronic Gamma Rays

- MeV-GeV: We have theories (mirror effect) and observations
- TeV ?: We have good telescopes. → time to study TeV
- The GeV theory can't go to TeV



$$E_c \sim 10^4\,\mathrm{GeV}\left(\frac{L}{R_\odot}\right)\left(\frac{B}{1\,\mathrm{G}}\right)$$

Coming Limit from ARGO-YBJ



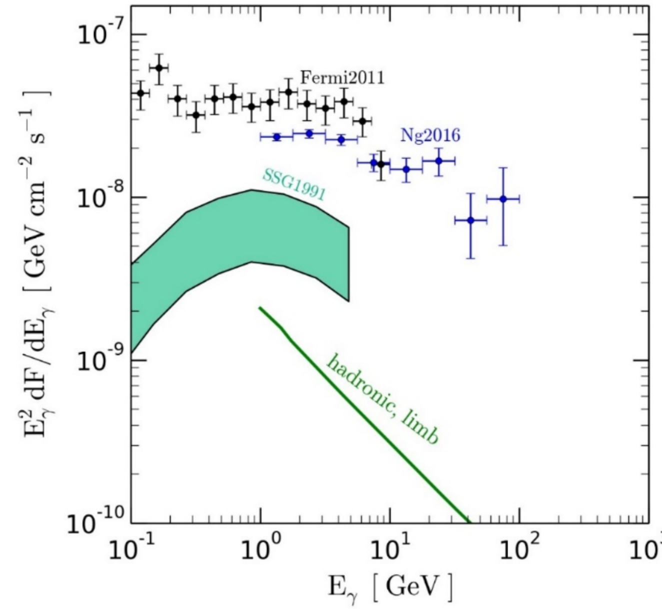
by Zhe Li, S. Z. Chen and H. H. He, for ARGO-YBJ collaboration, 2016

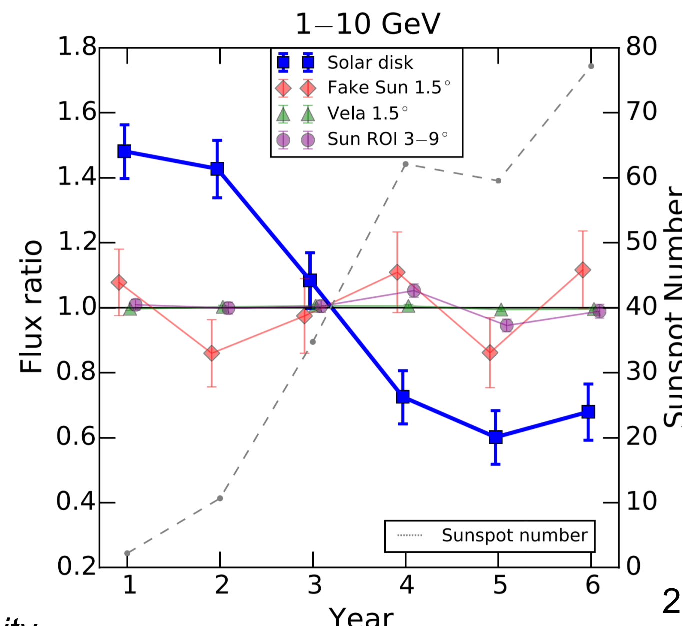
Fix SSG Model: Work in Prep.

- Interplanetary magnetic field modulation on cosmic rays?
  Can't fix norm.
  Too small to explain the anti-correlation

- Photosphere magnetic field?
  Easy for norm.
  Hard for time var.

- Coronal magnetic field (ignored by SSG)?
  So far still very poorly understood ($R_{\odot}$ to 0.3 AU)



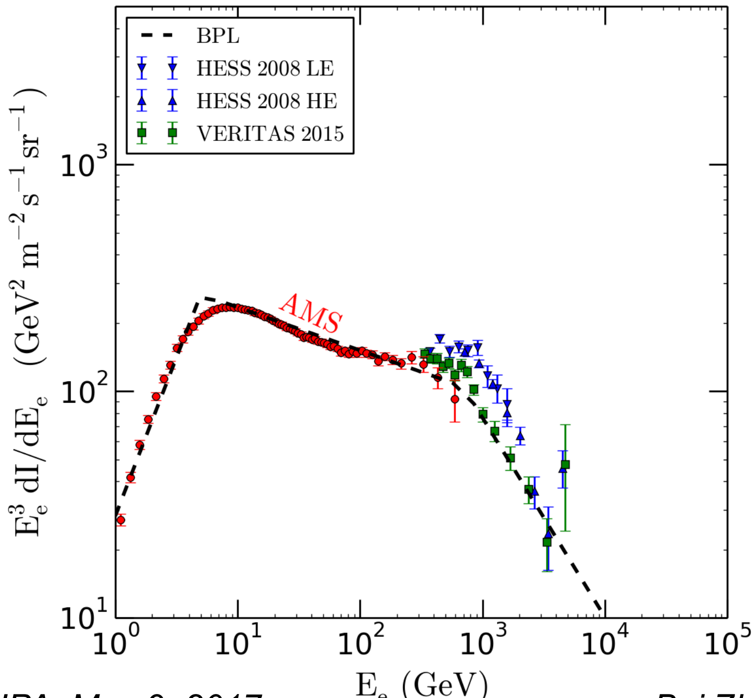


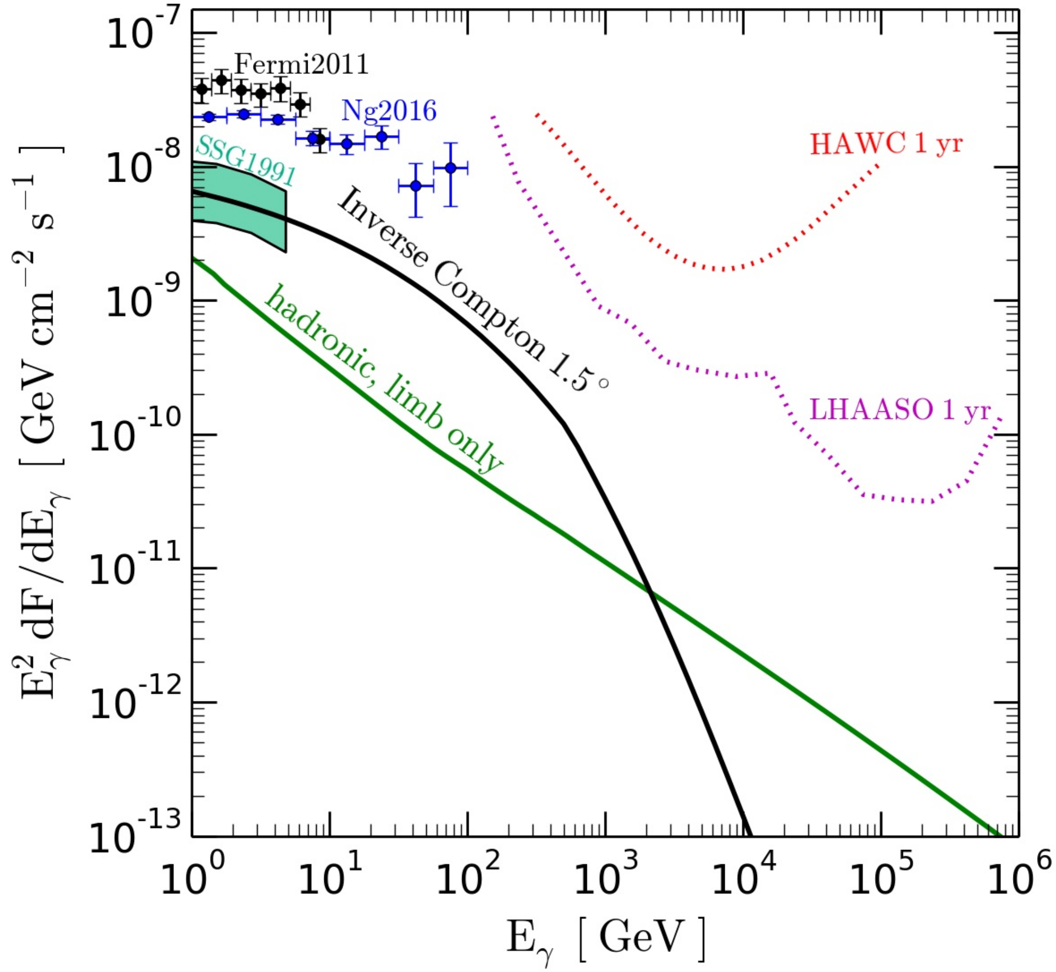
The Sun is a "hotpot" of mysteries!

Zhou et al. in prep

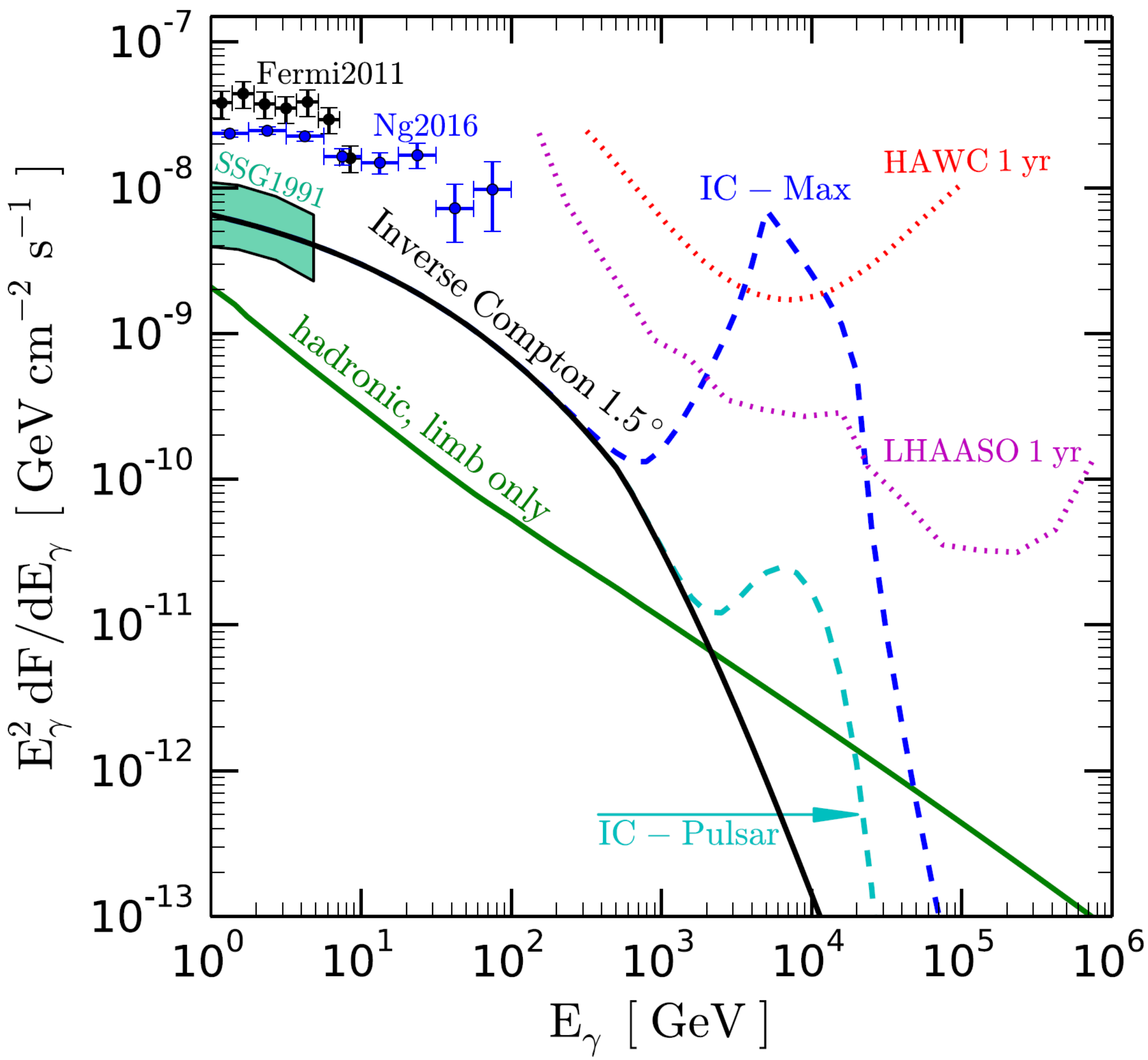
IC for HAWC

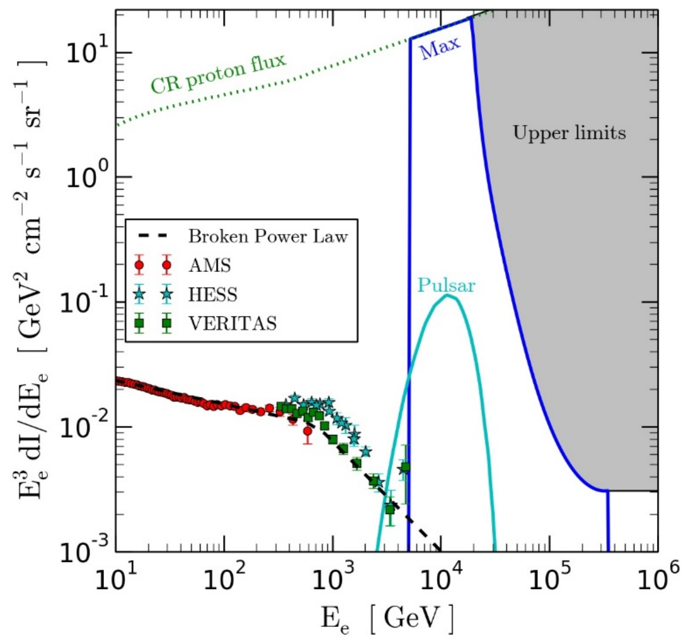
- Neglect magnetic effects
- Following
  Moskalenko, Porter, Digel (APJ 2006),and Orlando, Strong (Astrophys. Space Sci. 2007, A&A 2008),
  we first extend calc. above 1 TeV
- The flux drops fast due to Klein-Nishina suppression
  But this is a good thing





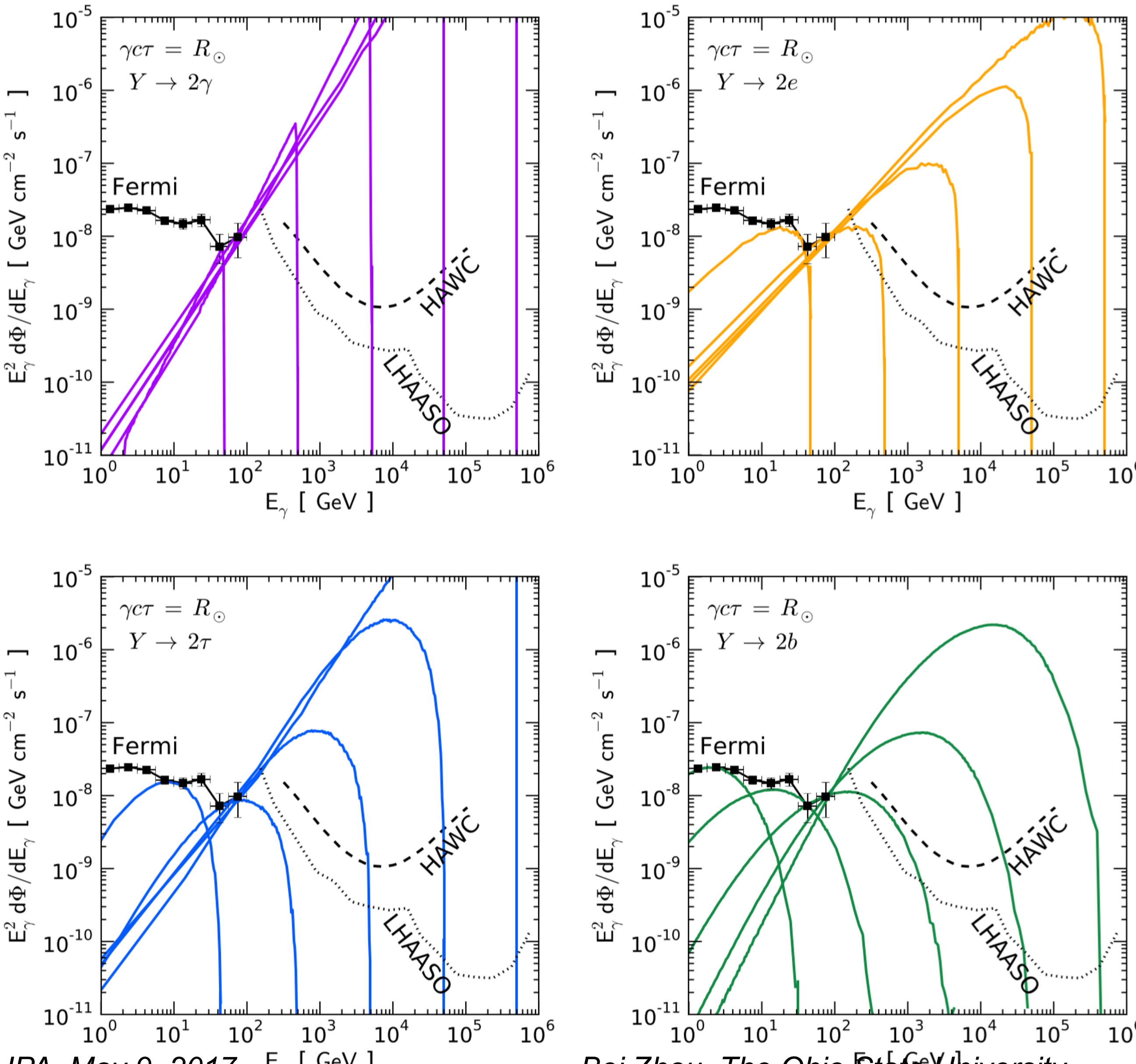
Electrons v.s. γ ray





Zhou et al. arXiv:1612.02420

Flux Sensitivity for Gamma Rays



Optimal mediator scenario
Assum. $\gamma c\tau \approx R_\odot$, decay once escape the Sun.
Assum. $\gamma \gg 1$, point source

GeV: limit from Fermi data

TeV: HAWC sensitivity;

And LHAASO in the future

Leane, Ng, and Beacom in prep.

Constraints on $\sigma_{\chi p}^{SD}$: Old v.s. New