Solar gamma rays from cosmic-ray interactions

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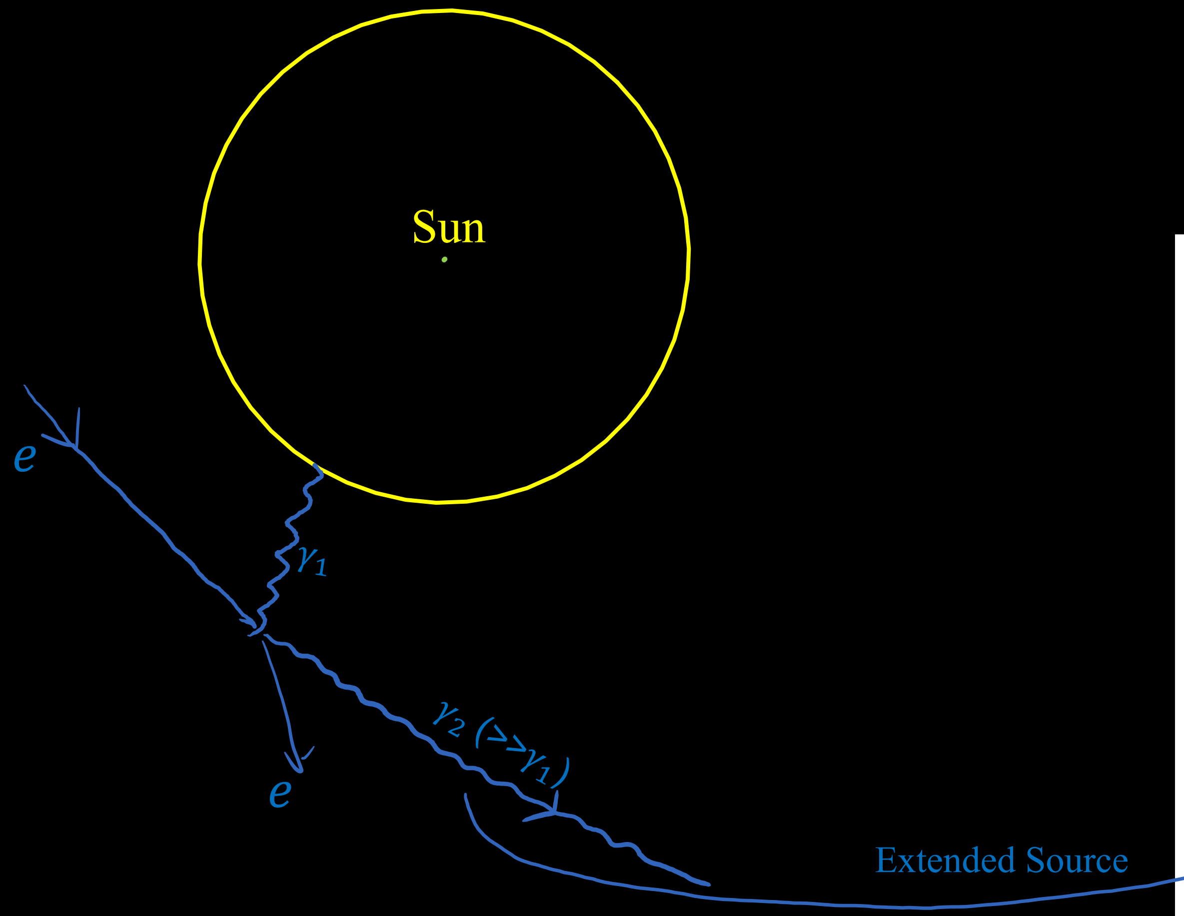
Relevant work by our group:

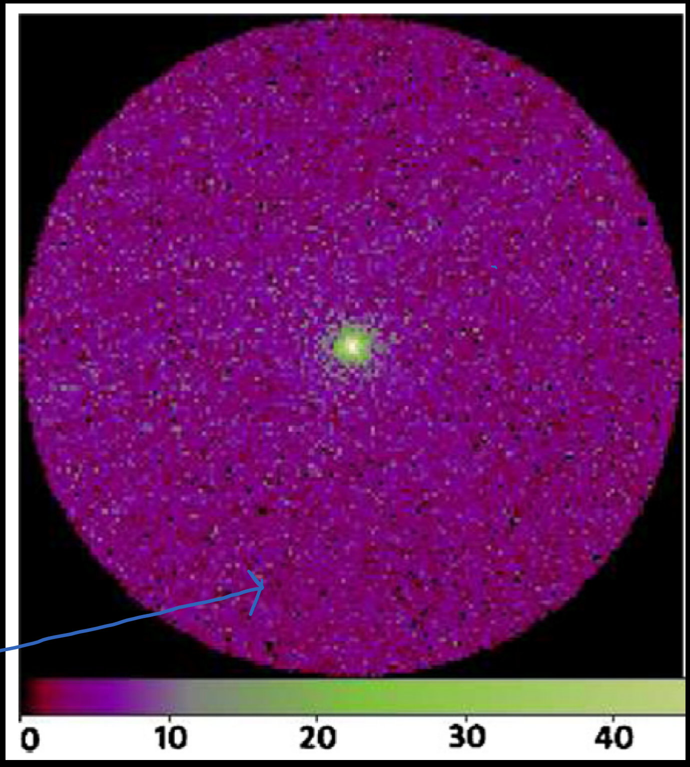
Ng, Beacom, Peter, Rott, PRD, arXiv:1508.06276

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

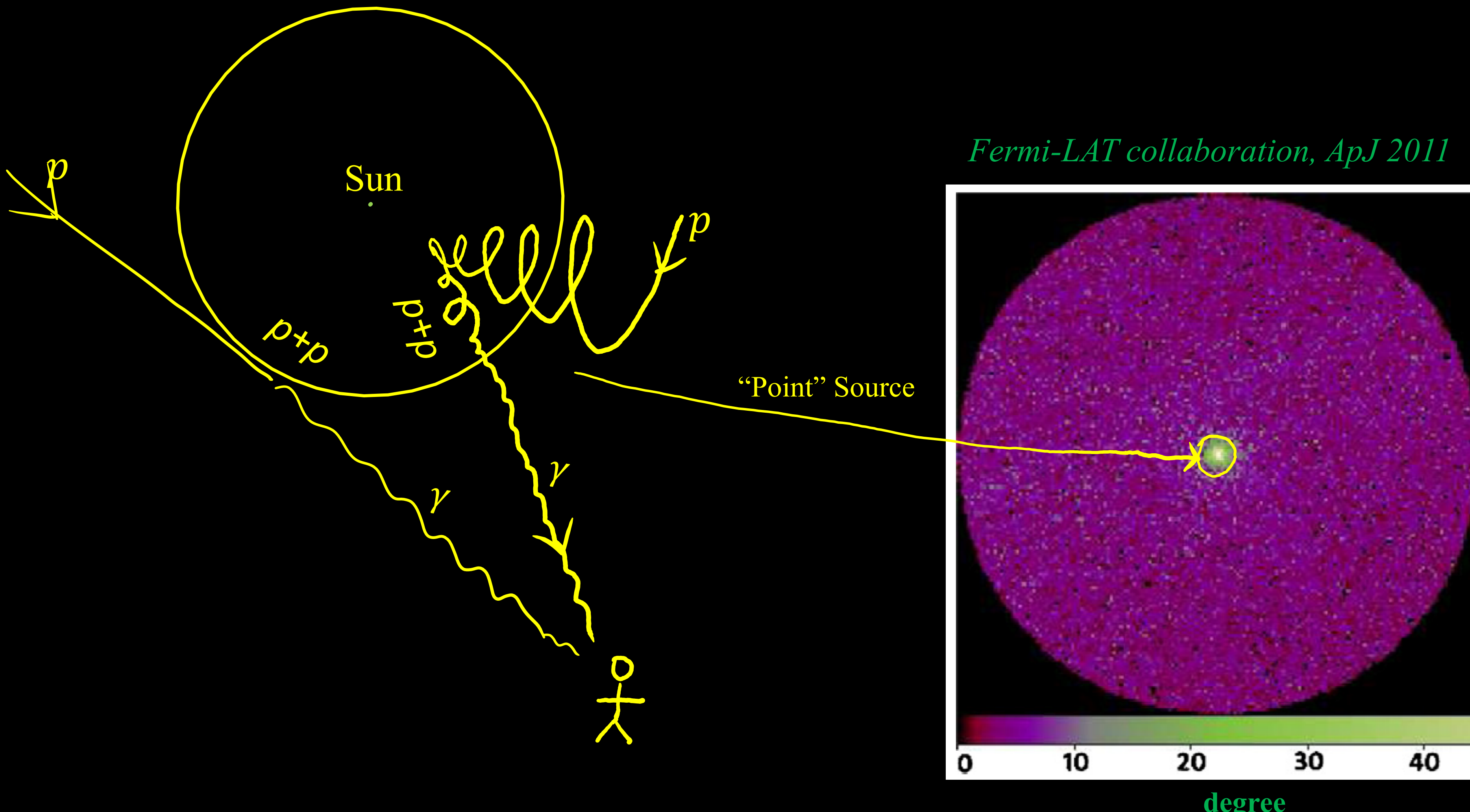
Leptonic solar gamma rays



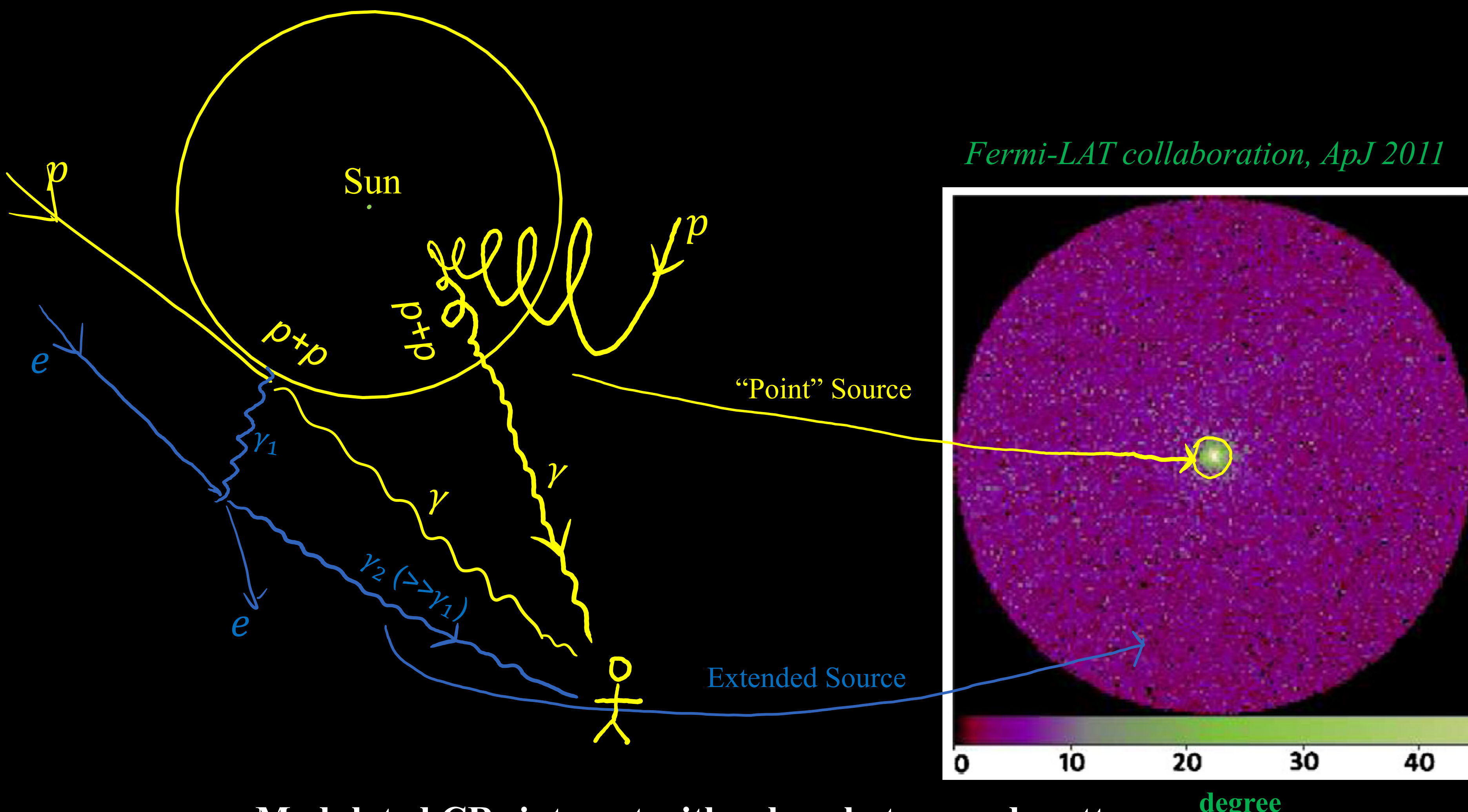
Fermi-LAT collaboration, ApJ 2011



Hadronic solar gamma rays



Cosmic-Ray Interactions Produce Gamma Rays



Modulated CRs interact with solar photons and matter;
→ top 20 brightest γ sources (> 10 GeV)

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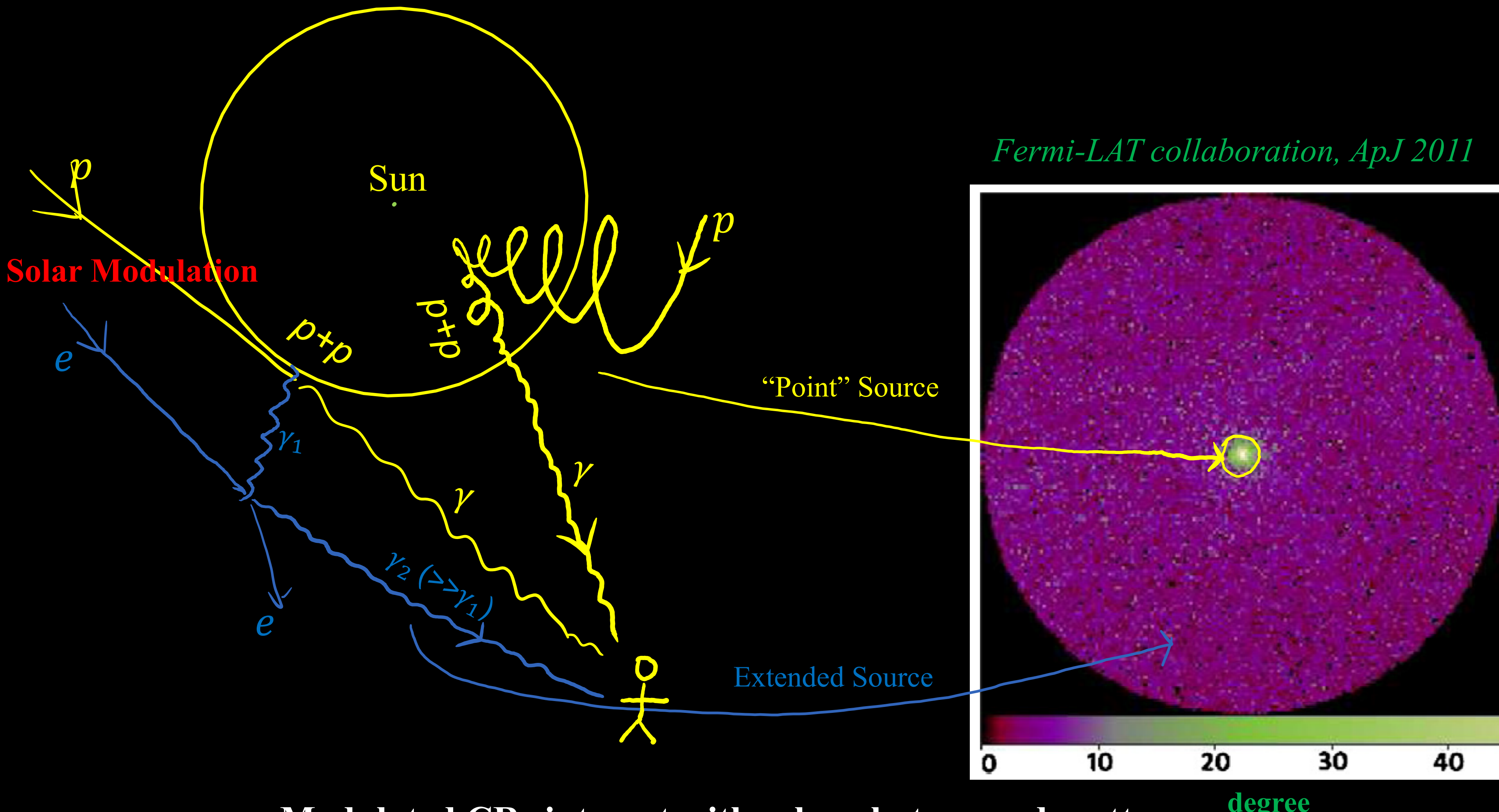

Modulated CRs interact with solar photons and matter;

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→ γ ray probe CR distance & energy dependently at < 1 AU

Disk flux: Contribution from Solar Limb

Limb emission

Small interaction region:
Solar limb, 0--600 km above solar surface,
→ thin gamma ray ring

High proton optical depth, $\tau \sim 1$
→ 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

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

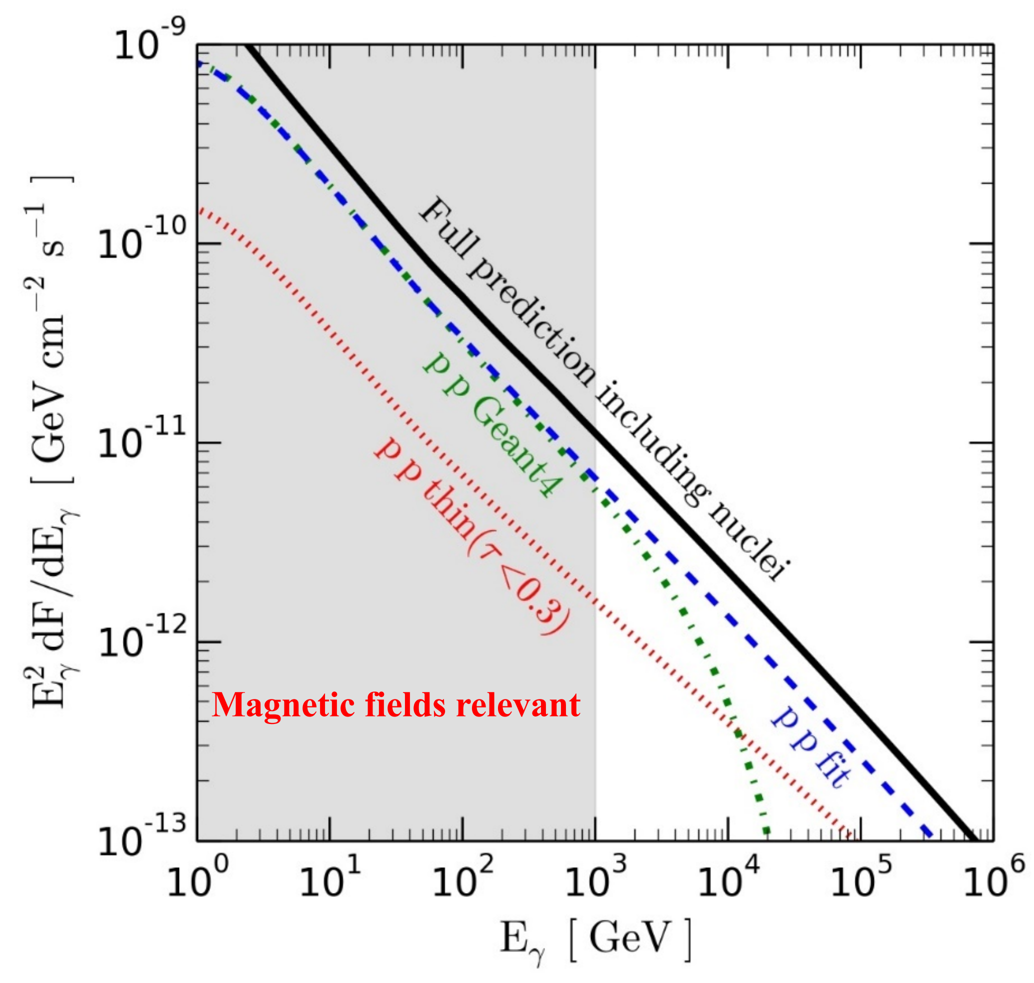
Disk flux: First Calculation of Contribution from Solar Limb

Zhou et al. arXiv:1612.02420, PRD 2017

- Neglect magnetic effects.
- **Red**: Thin region (tau = 0--0.3)

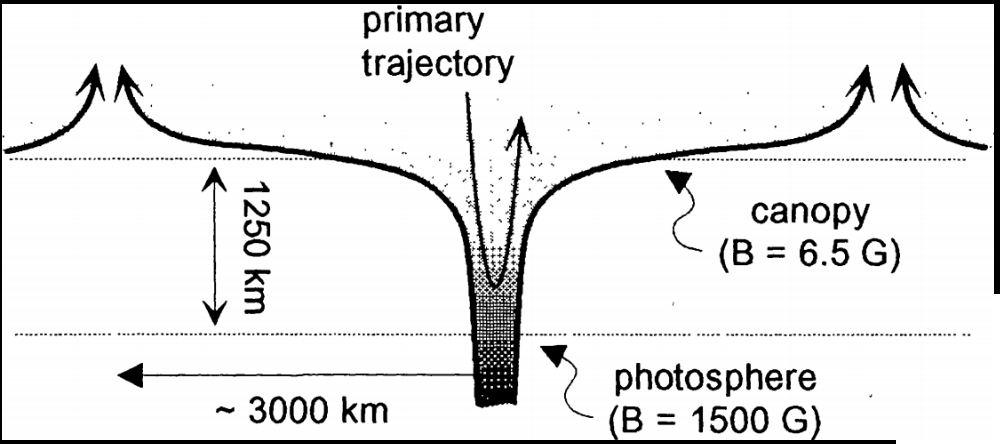
$$\frac{dF}{dE_\gamma}(E_\gamma) = \int d\Omega \int ds\, n_p(\vec{s}) \int dE_p \frac{dI}{dE_p}(E_p)\, \sigma_{\rm inel}(E_p) \frac{dN}{dE_\gamma}(E_p, E_\gamma)$$

- **Green** and **blue**: Thick region: Cascade & absorption are important. Use Geant4 simulation;
- **Black**: Contribution from heavy nuclei → increase by a factor of ~2
- → Full limb prediction
- Calculation is robust > ~ TeV

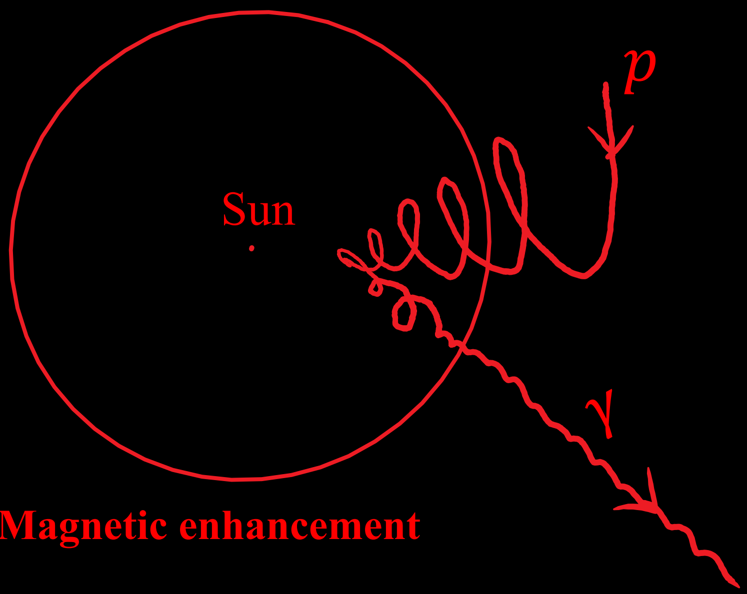


Zhou et al. arXiv:1612.02420, PRD 2017

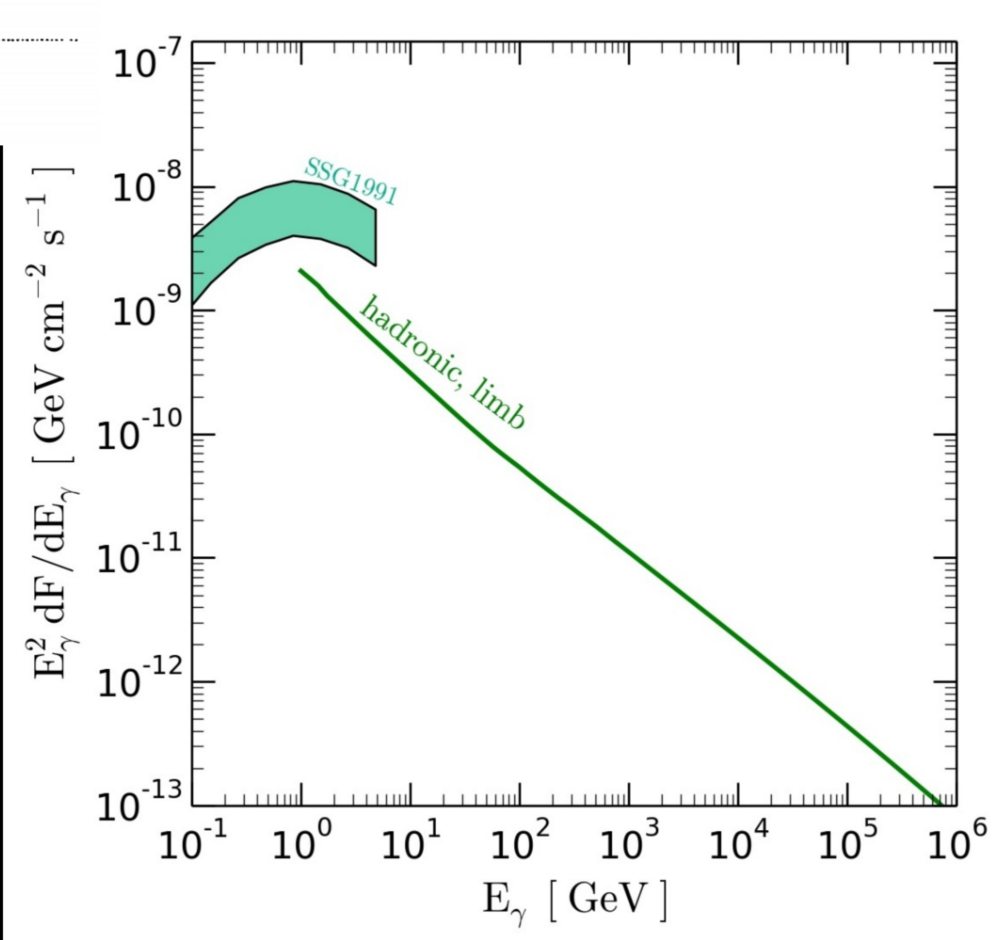
Disk Flux: Contribution from Magnetic Enhancement



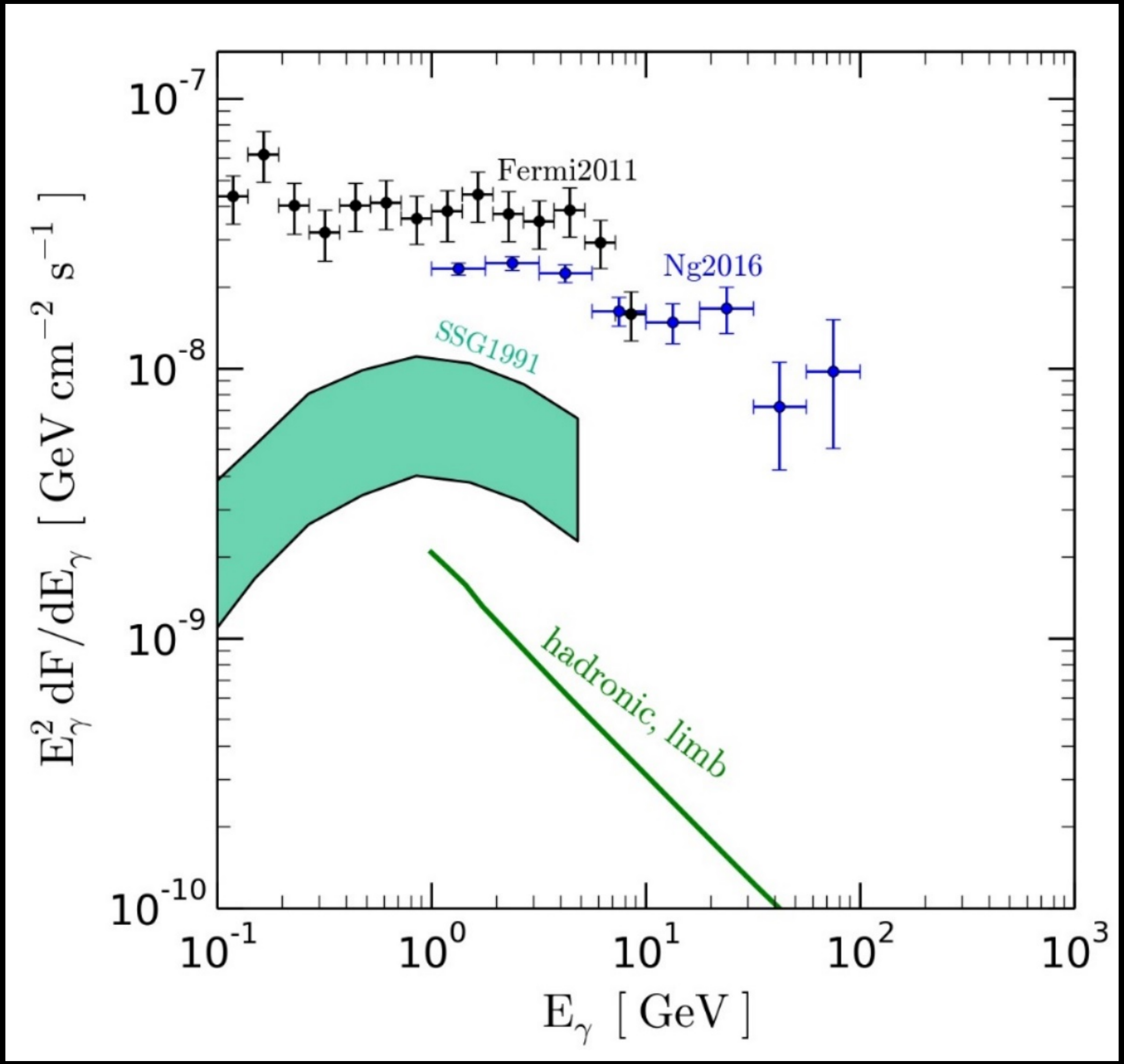
Seckel, Stanev, and Gaisser, APJ 1991 (SSG1991)



Magnetic enhancement



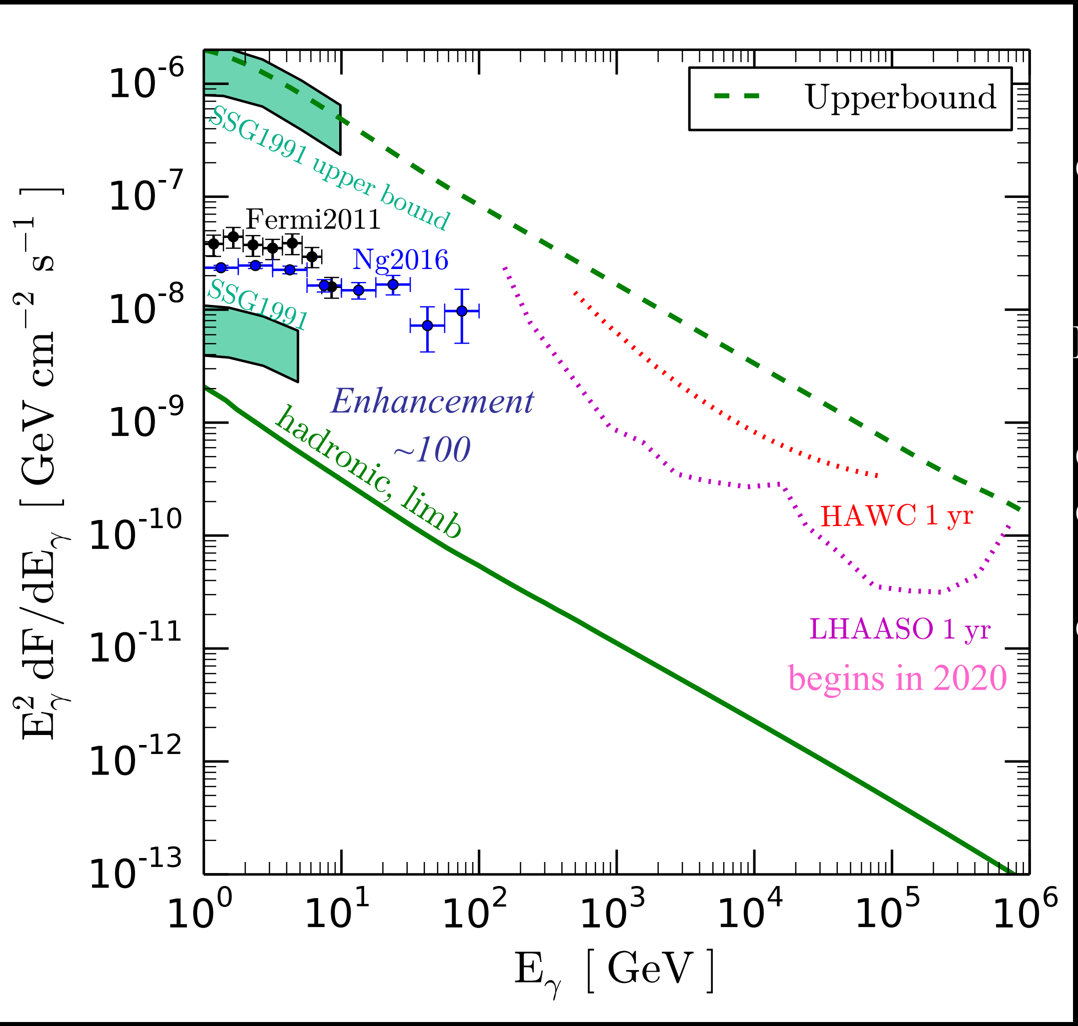
Disk Flux: Observation from *Fermi*-LAT



~ One order of magnitude higher than theory!

Magnetic enhancement is even stronger than SSG predicted!

Disk Flux: Up to Now



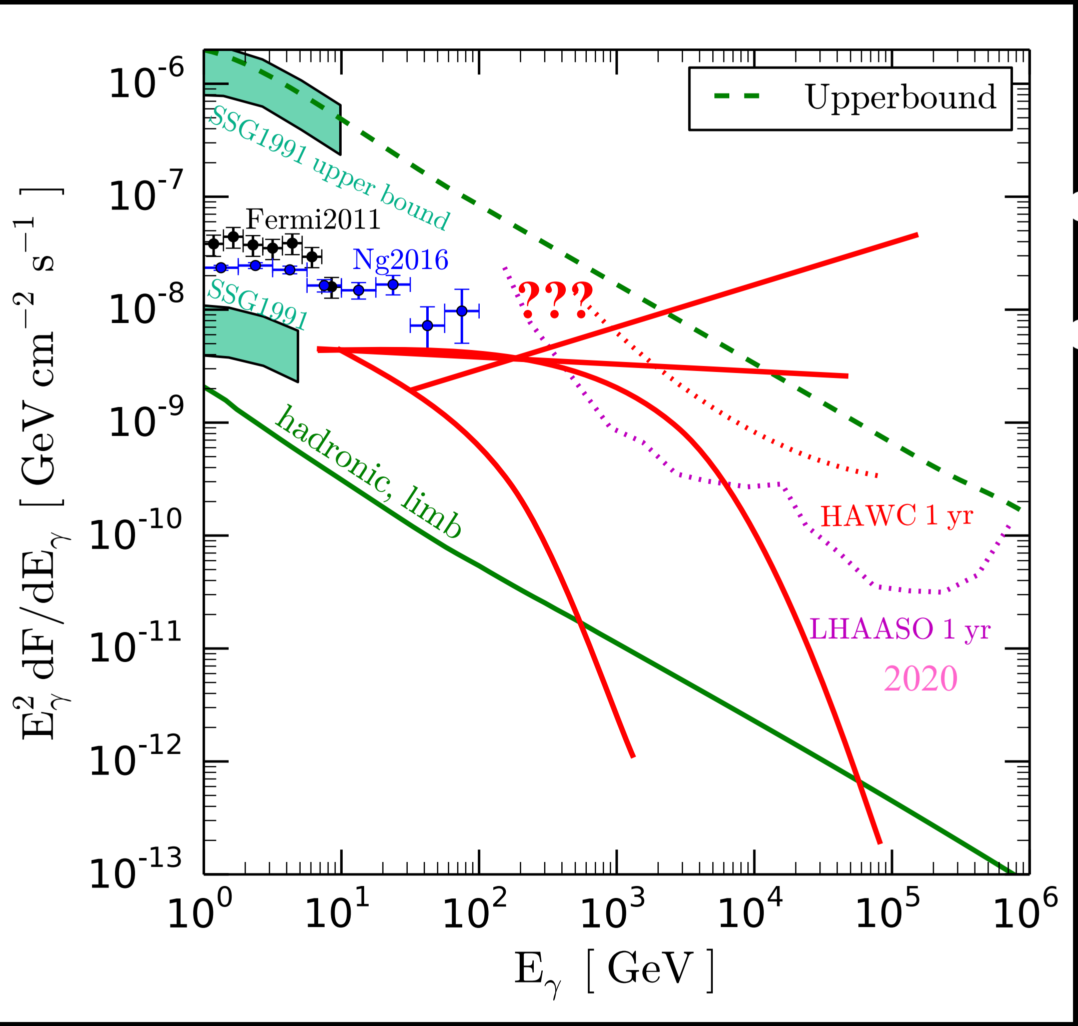
Zhou et al. arXiv:1612.02420, PRD 2017

- 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

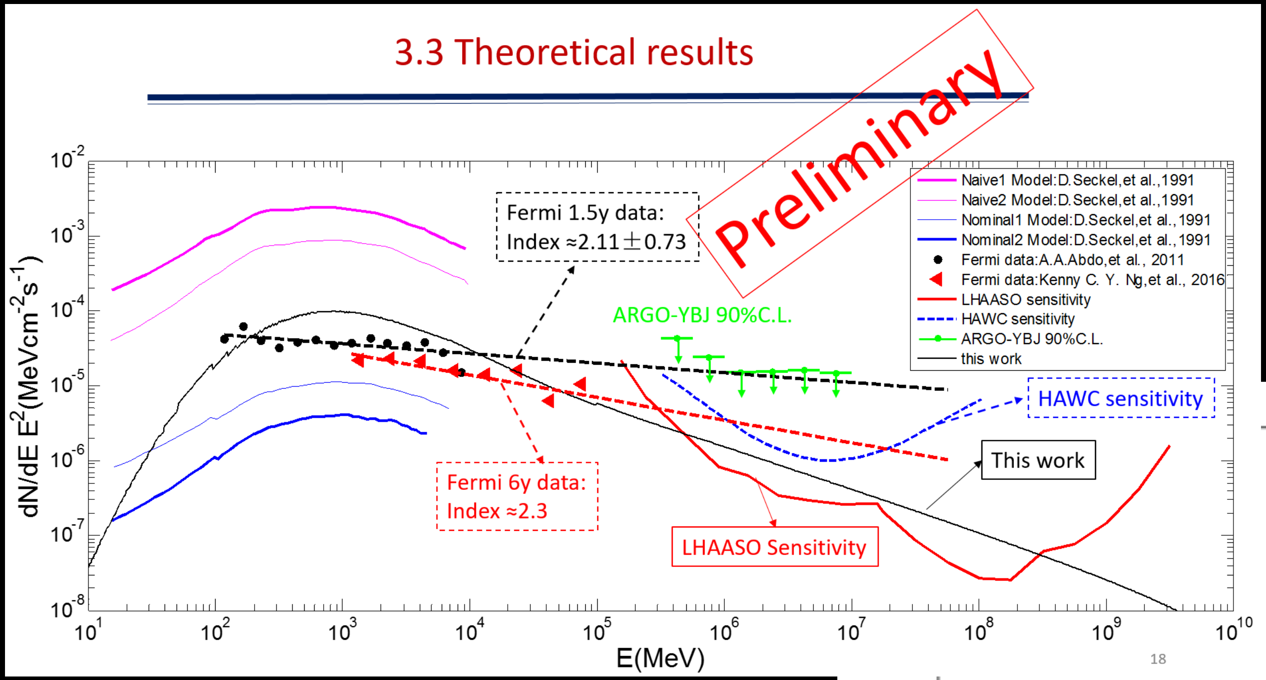


Zhou et al. arXiv:1612.02420, PRD 2017

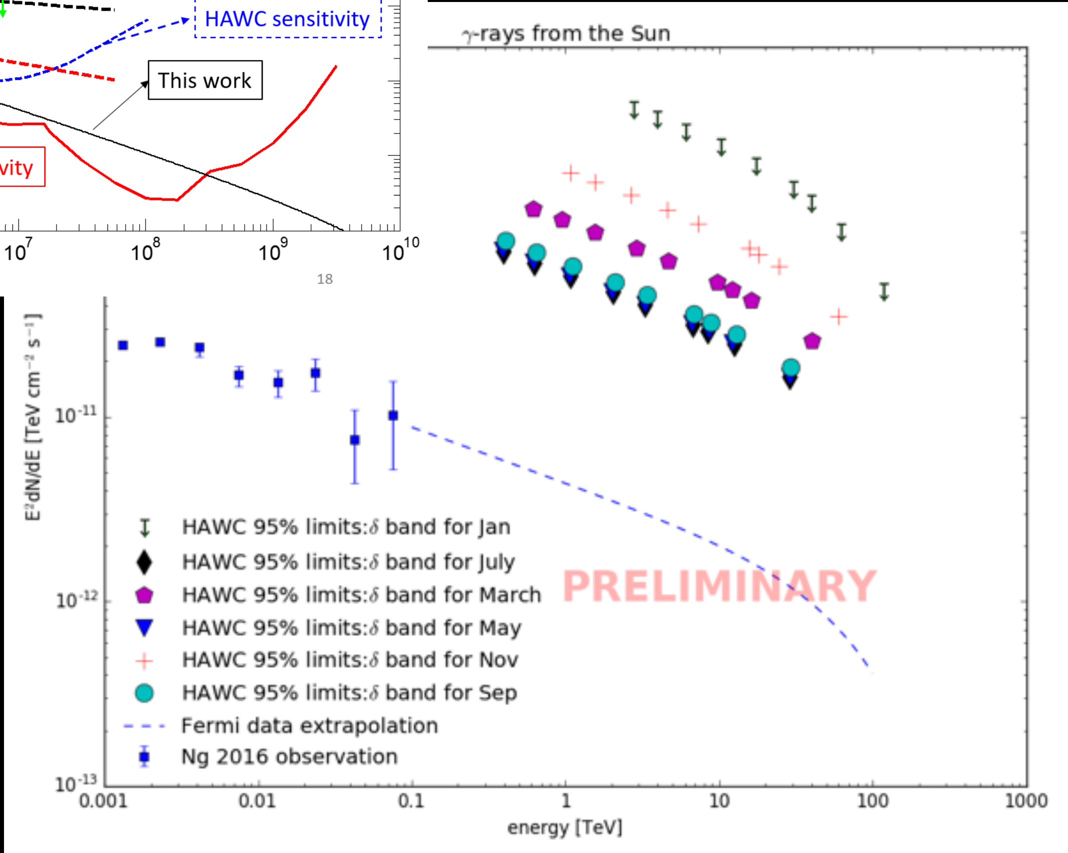
- Measure/Constrain the energy-dependent enhancement factor
- Measure/Constrain where transition happen.

SSG gives: cutoff may be 30 GeV - ? TeV

Current limit from ARGO-YBJ and HAWC



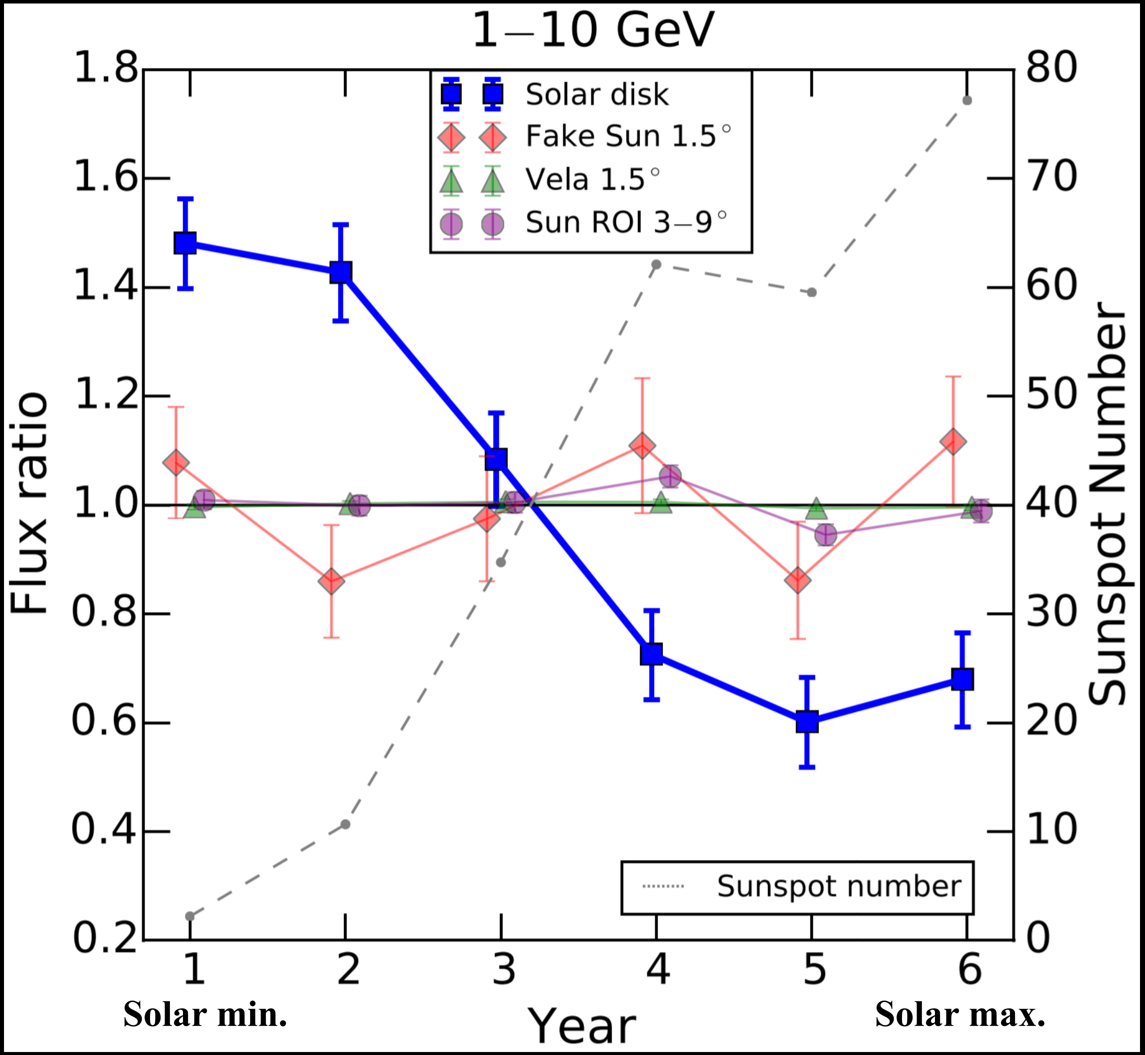
Credit: Zhe Li, S. Z. Chen and H. H. He, for ARGO-YBJ collaboration, 2016



Credit: Mehr Un Nisa, for HAWC collaboration, 2017

See Mehr Un Nisa's talk for more details.

Disk Flux: Found a time-variation!



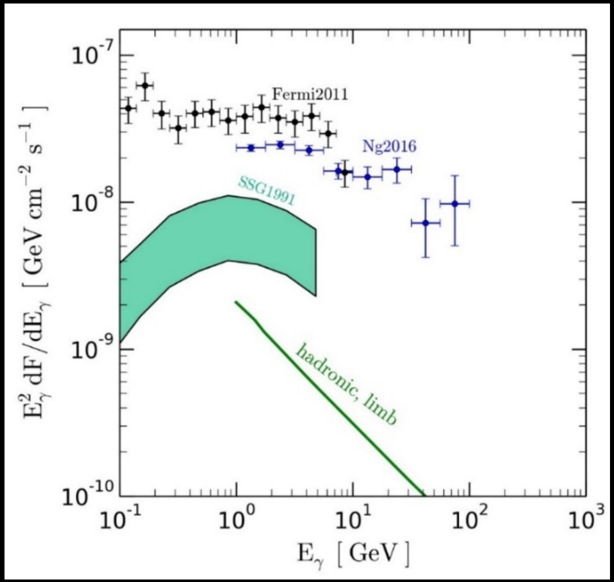
Magnetic enhancement is weaker as solar magnetic field get stronger?!

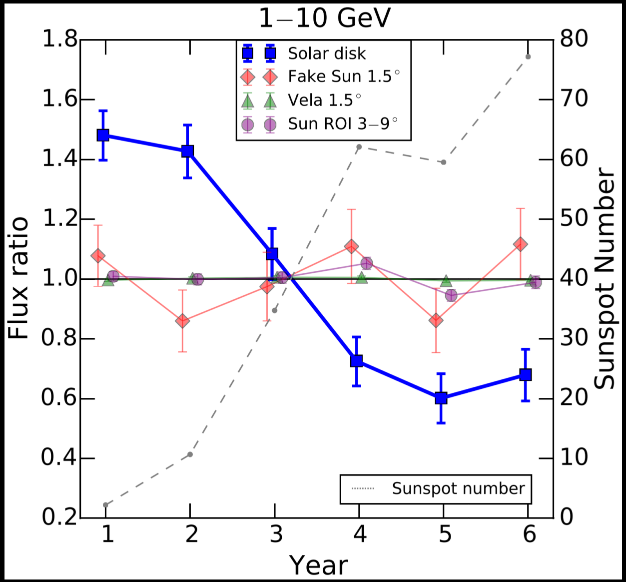
Ng et al. arXiv:1508.06276, PRD 2016

Fix Disk Flux Model: Work in Prep.

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

Zhou et al. in prep





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

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

This talk *(for Ng, Beacom, Peter, Rott, PRD, arXiv:1508.06276 & Zhou, Ng, Beacom, Peter, PRD, arXiv:1612.02420)*

This help understand high-energy neutrinos from the Sun.

(See Kenny Ng's talk *(for Ng, Beacom, Peter, Rott, arXiv:1703.10280)*
also see Carsten Rott's talk for observation by IceCube)

Both will help test dark matter.

(Also see Kenny Ng's talk; *Leane, et al., PRD 2017, arXiv:1703.04629*)

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This talk *(for Ng, Beacom, Peter, P…*
Zhou, Ng, Beacom, Pet…

The Sun is still a
“hotpot” of mysteries!!

This help… …m the Sun.
(See K… *…3.10280)*
also … …y IceCube)

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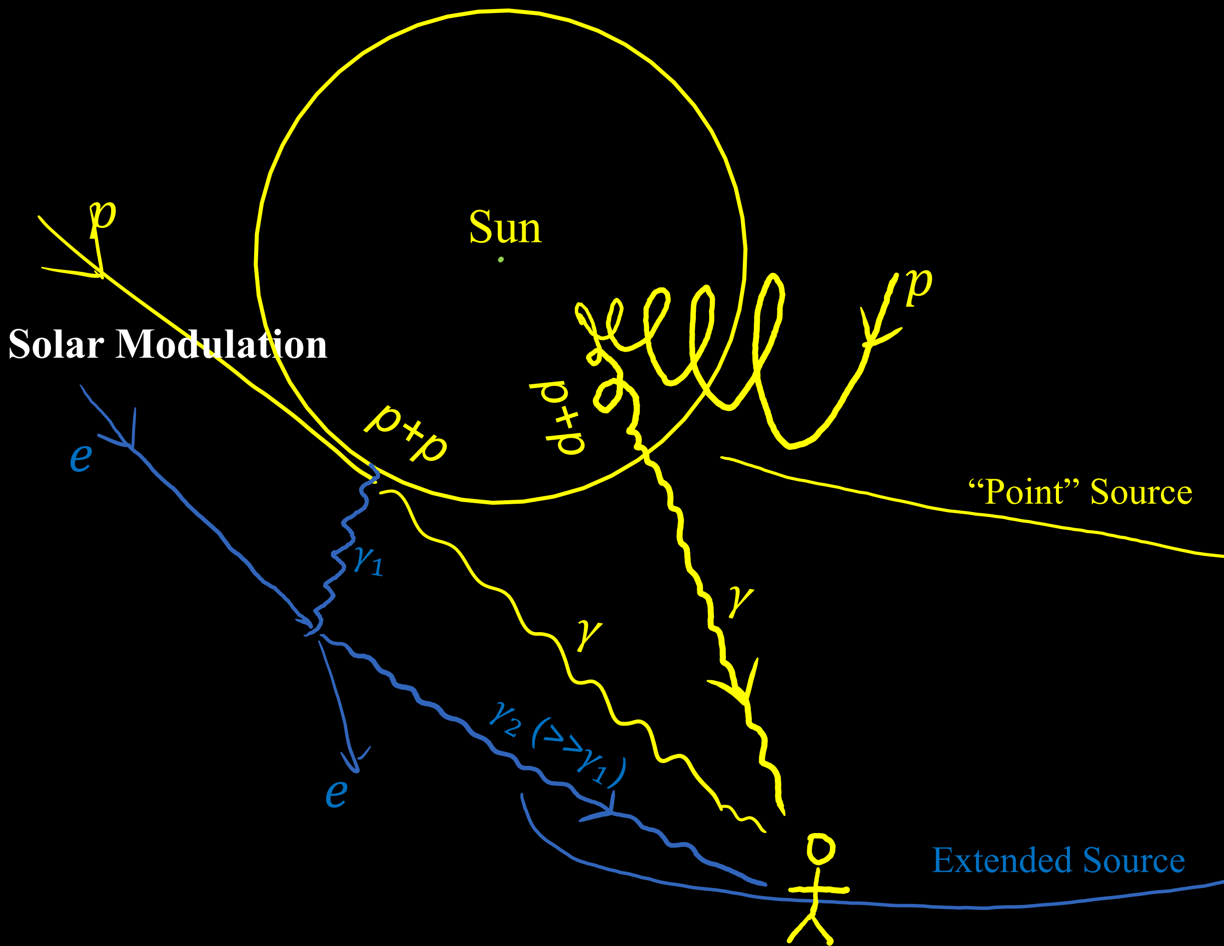
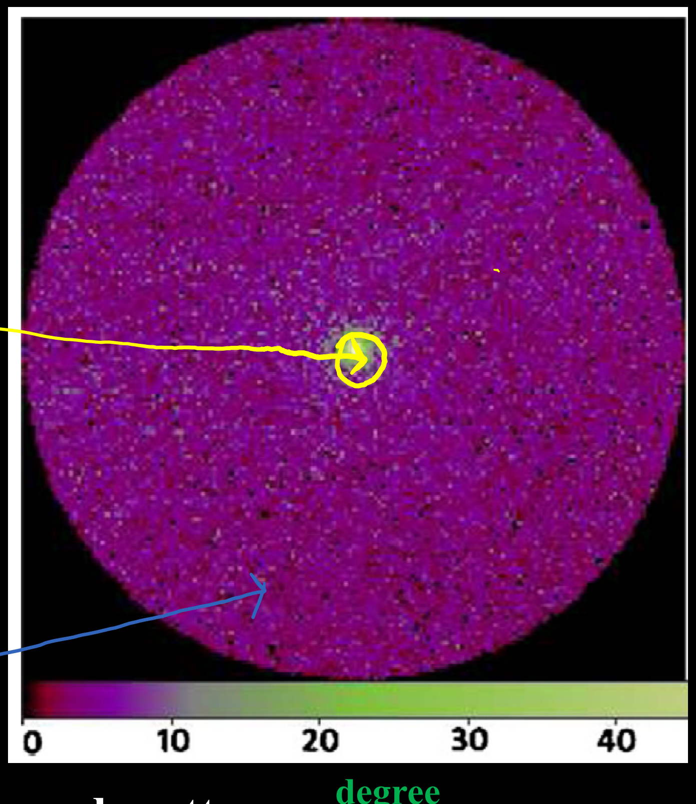


Fermi-LAT collaboration, ApJ 2011



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

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**)

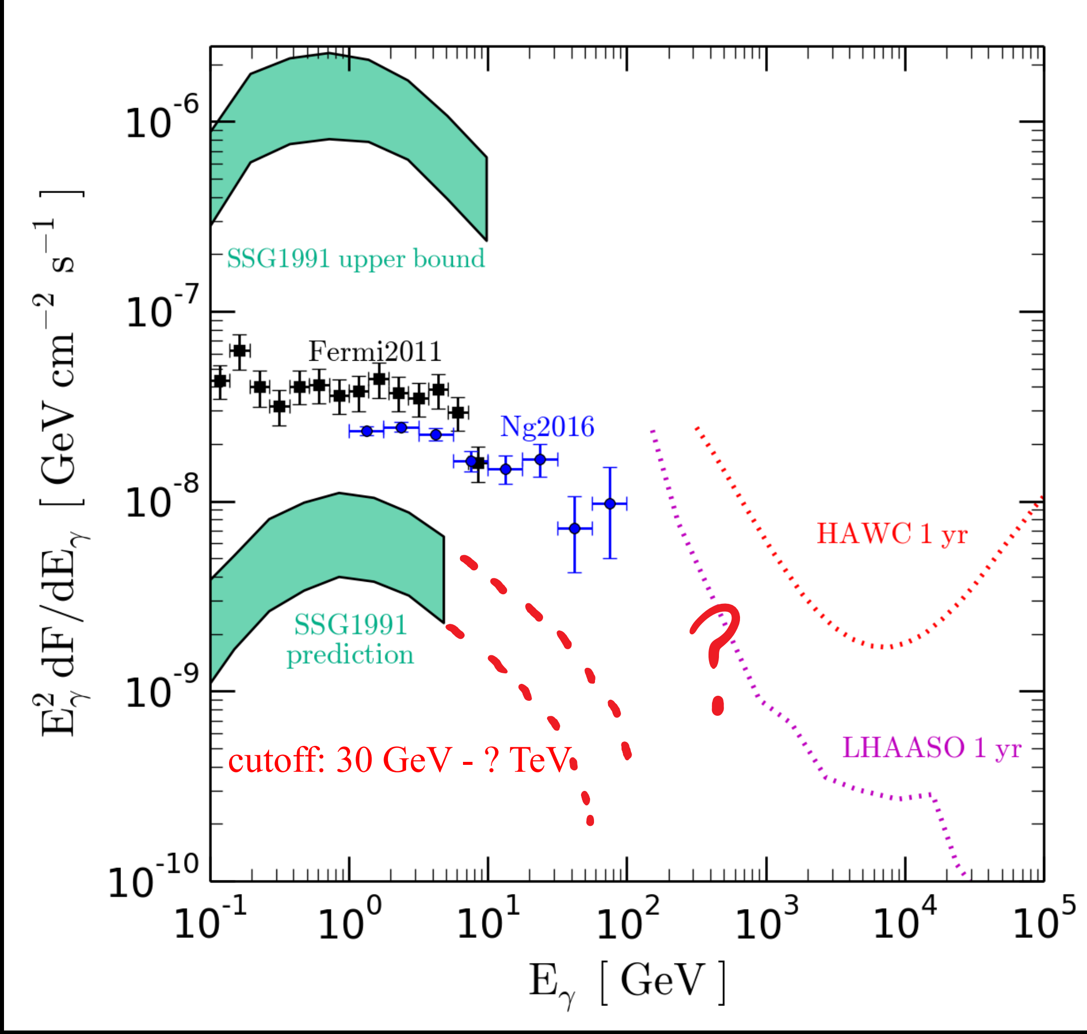
Situation: data, theory disagree

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



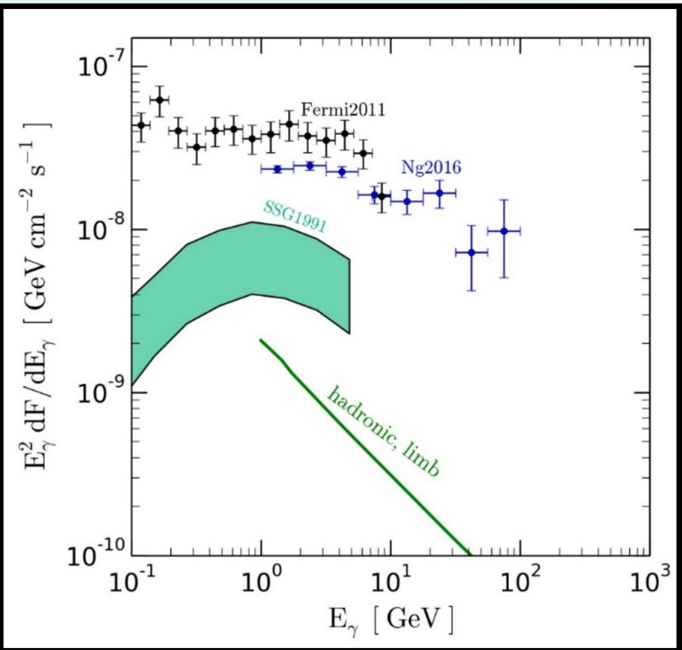
$$E_c \sim 10^4\,\mathrm{GeV}\left(\frac{L}{R_\odot}\right)\left(\frac{B}{1\,\mathrm{G}}\right)$$

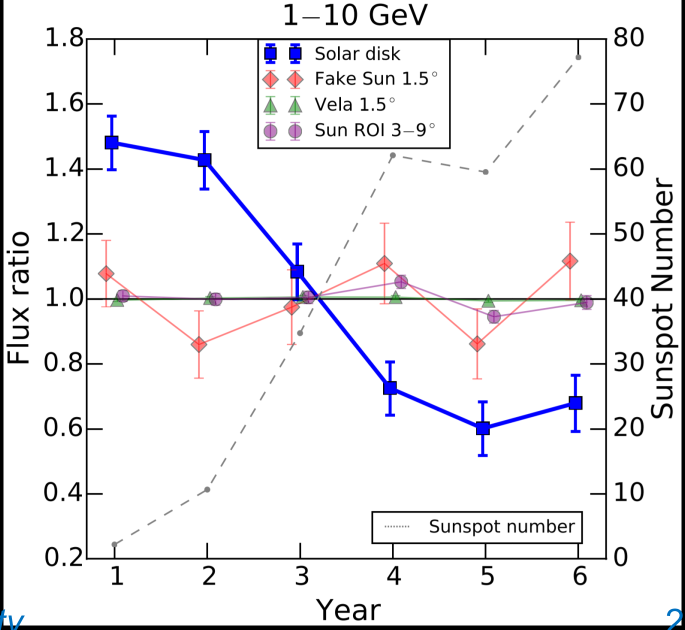
Fix SSG Model: Work in Prep.

- 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!

IC for HAWC

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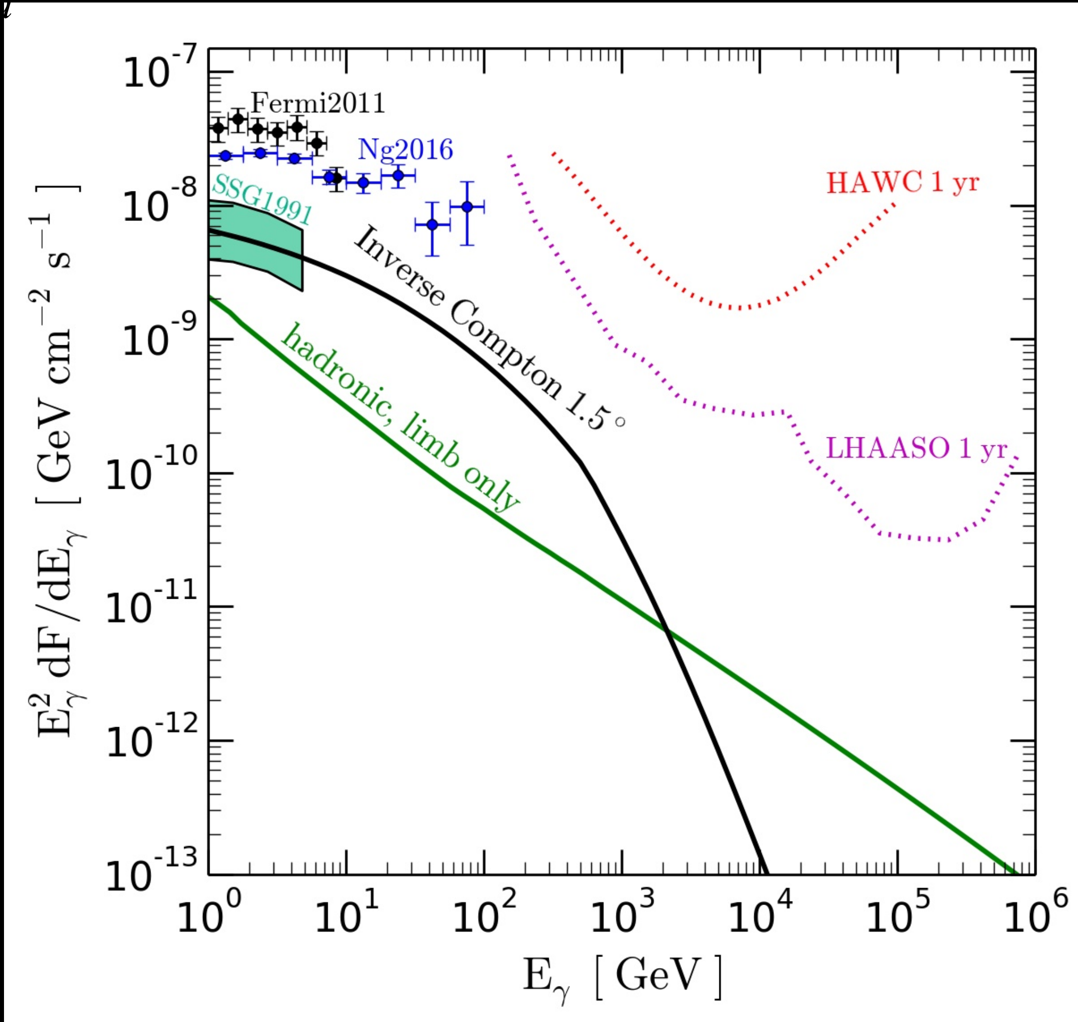

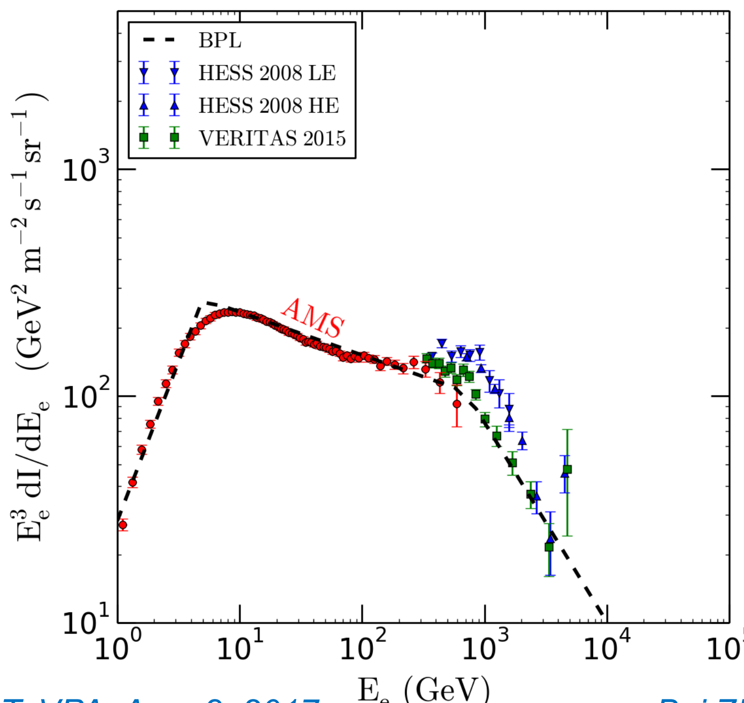

Electrons v.s. γ ray