BERKELEY LAB

Indirect detection of dark matter using gamma rays (specifically using Fermi telescope)

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Recap

- We know dark matter exists
  - Galaxy rotation curves, gravitational lensing, CMB, even universe simulations
- What is it? What is its mass, spin etc?
  - No idea!
  - Could be anything
- Where is it?
  - Apparently everywhere!
- Where do we look for it?
  - Everywhere
- How do we look for it?
  - Every way possible
  - From cosmos to colliders.

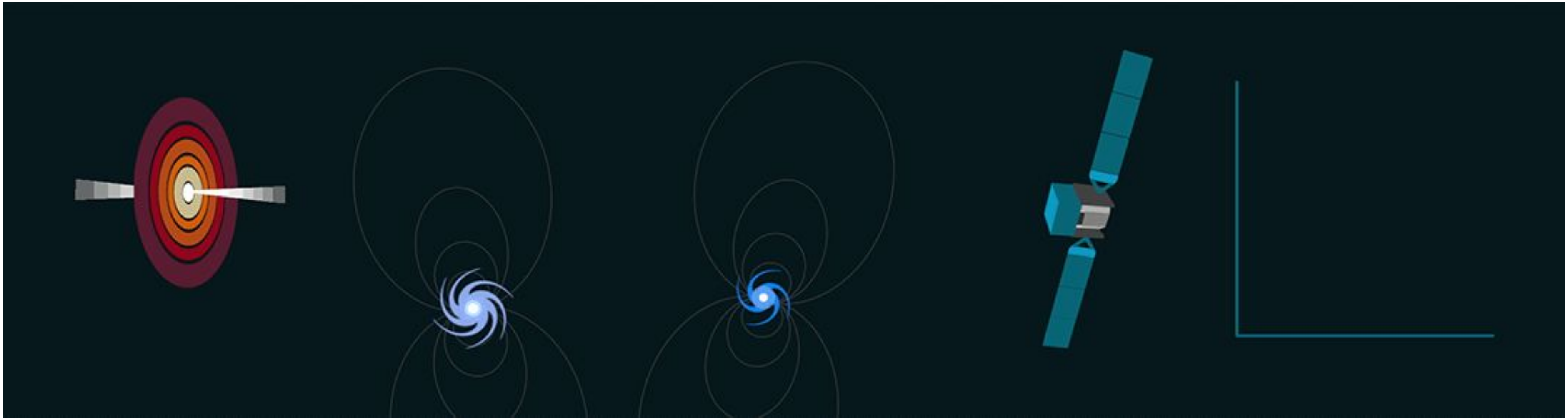
Today we will explore gamma rays!

Introduction

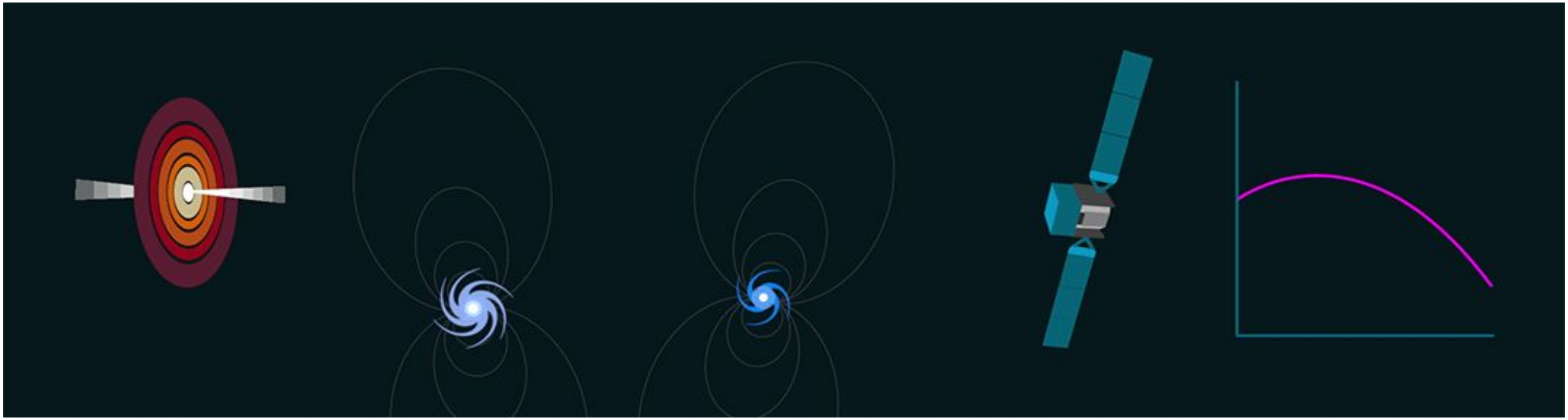
- How do gamma rays help in dark matter detection?
  - Weakly Interacting Massive Particles (WIMPs)
    - In dense regions of the universe, WIMPs might annihilate or decay into Standard Model particles like charged leptons, gamma rays and neutrinos
    - Gamma rays and neutrinos are excellent final states to look for as they can reach us almost unperturbed
  - Axion-like dark matter (ALPs)
    - If it couples to photons, then you might see their presence in gamma ray spectrum
    - Photons travelling from far away sources might convert into axions in the presence of strong electromagnetic fields

Introduction

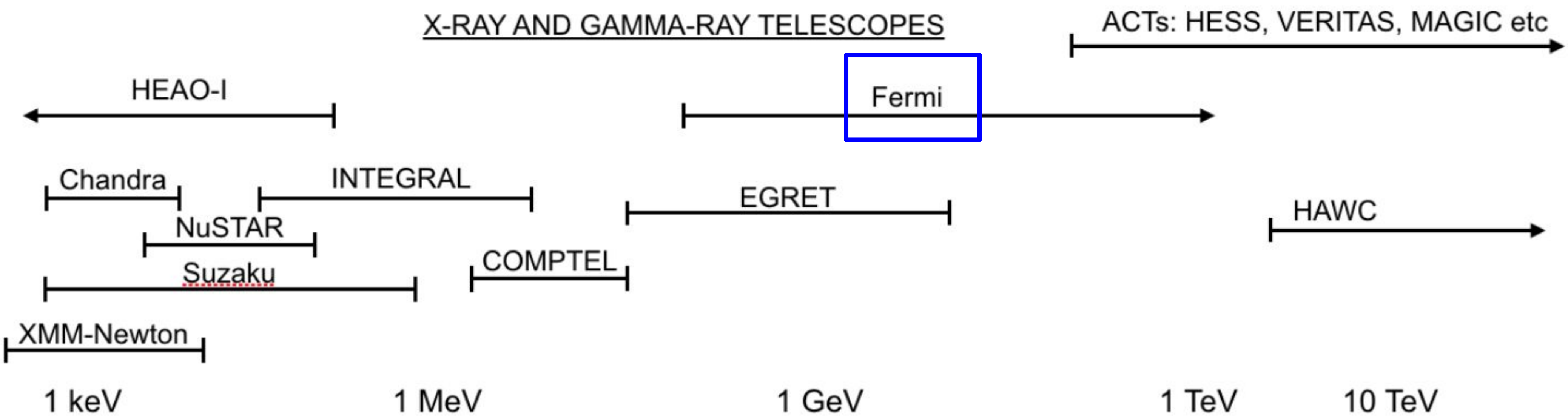
If photons do not convert into axion-like particles



If photons convert into axion-like particles



Different photon telescopes

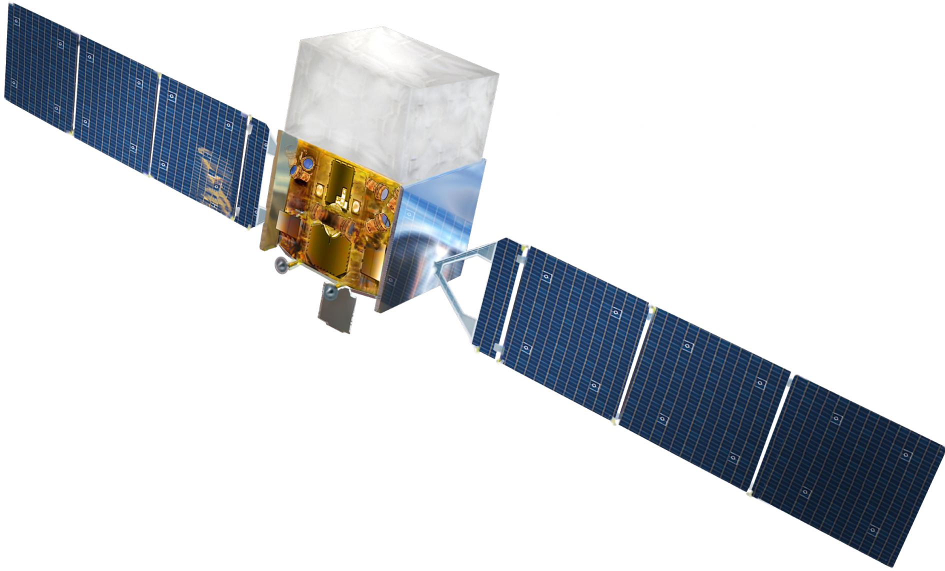


Dark matter masses probed →

Fermi Gamma-Ray Space Telescope

Source

- Space based telescope as earth’s atmosphere is opaque to gamma rays)
- In a low earth orbit with semi-major axis of 6000 km and period of 95 min
- Fermi includes two instruments
  - Large-Area telescope (LAT): A pair conversion instrument to detect gamma rays in energy range 20 MeV - 300 GeV. Covers 20% of the sky
  - Gamma-ray Burst Monitor (GBM): Can detect gamma ray bursts in energy range 8 KeV - 30 MeV at almost all angles



https://science.nasa.gov/toolkits/spacecraft-icons

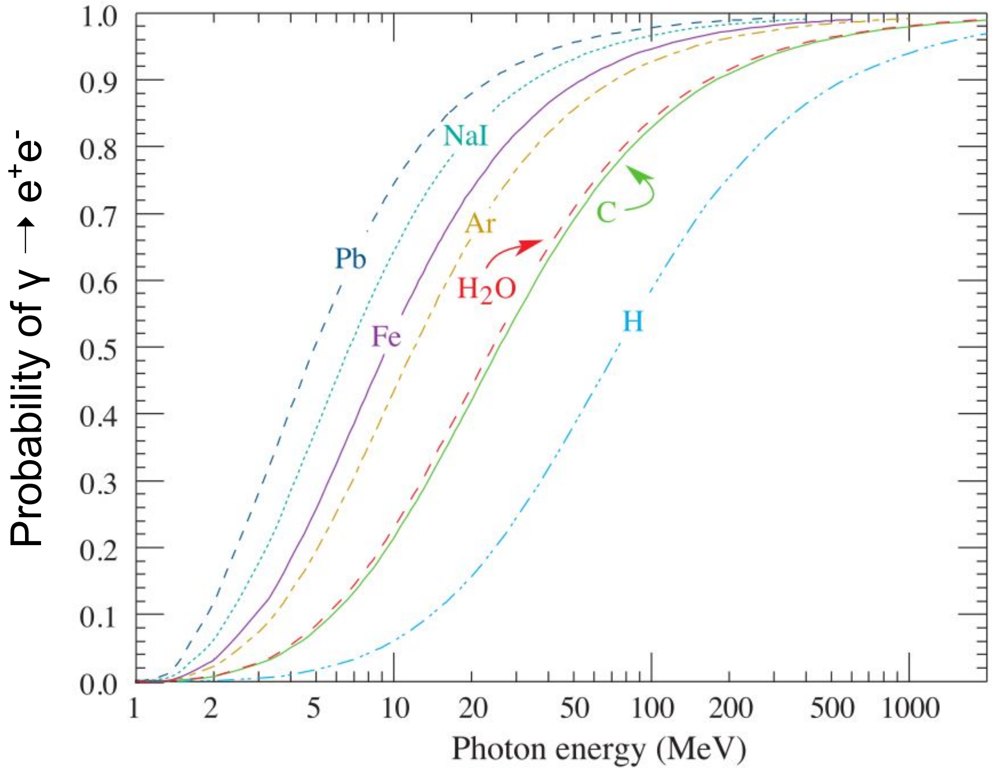
Fun facts about Fermi

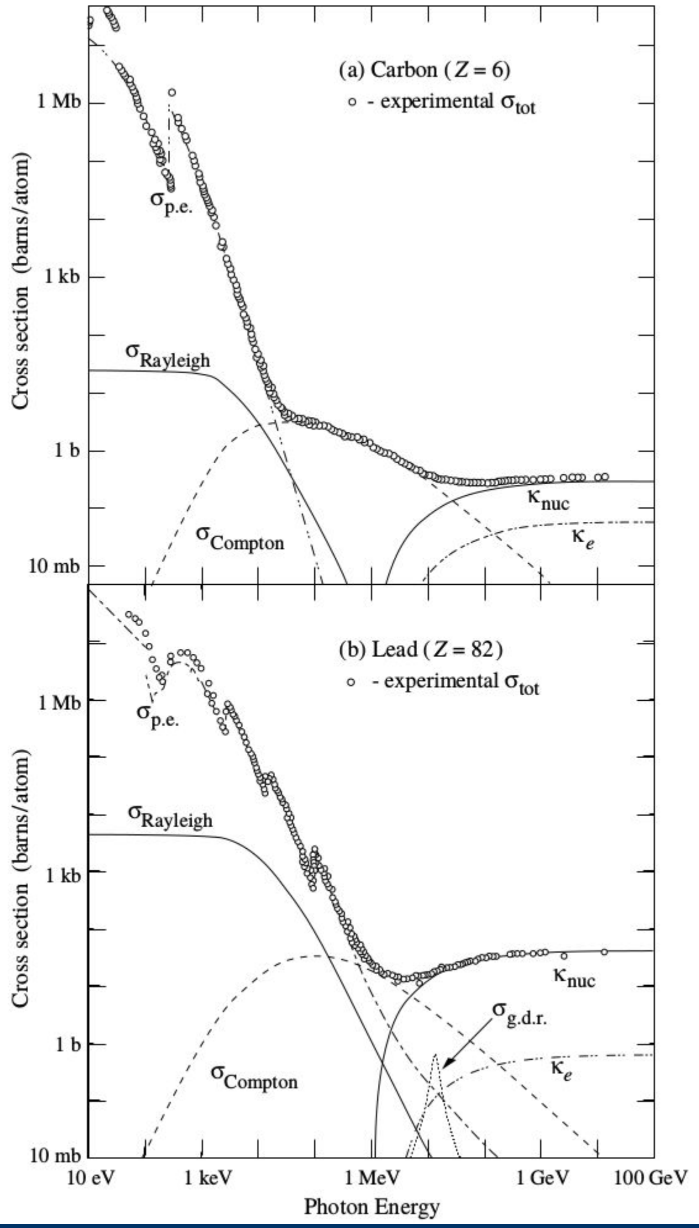
Source

- Launched in 2008 with a 5 year mission but still taking data
- In April 2012, it narrowly missed collision with another satellite
- In March 2018, the solar arrays stopped rotating and it was placed at fixed angle w.r.t its orbit to maximize solar power and eventually fixed after power cycling
- Successes:
  - Discovered a pulsar that only emits gamma-rays, first of its kind
  - Greatest Gamma Ray Burst ever recorded
  - In 2010, determined that supernova remnants act as enormous particle accelerators (fulfilling one of its missions)
  - Determined that active galactic nuclei only contribute to 30% of gamma rays detected on earth, origin of remaining unknown
  - Highest energy solar flare ever recorded

Large Area Telescope

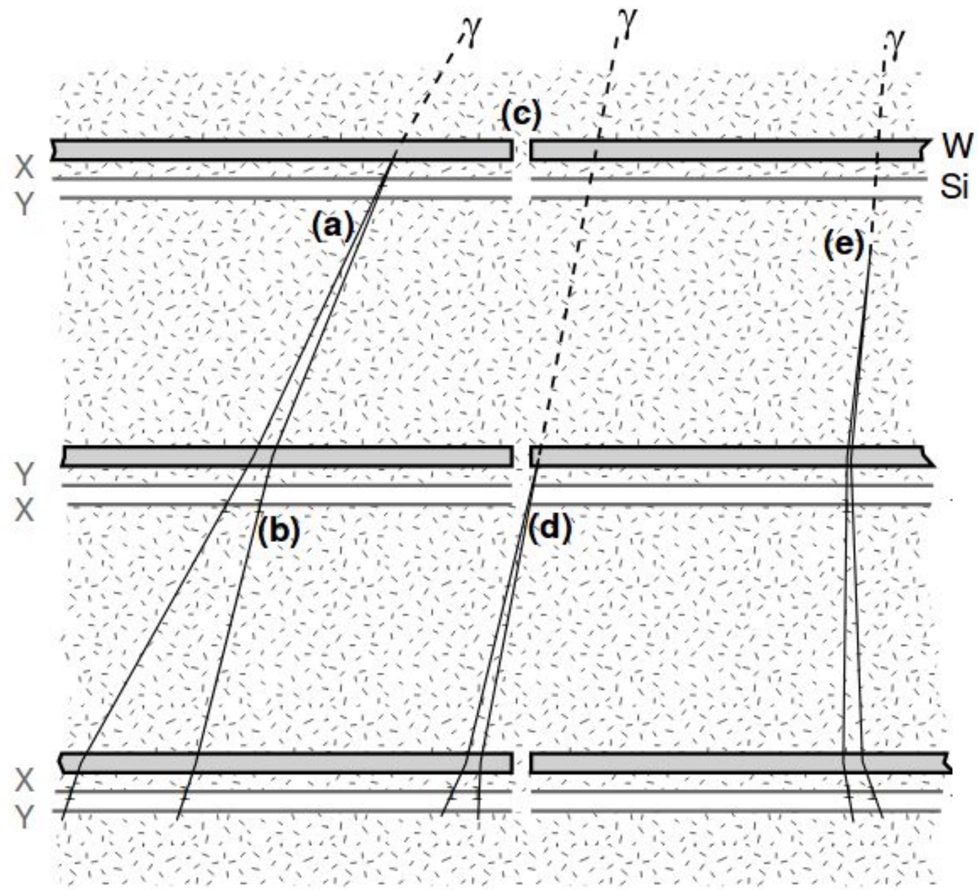
- Pair-conversion telescope. Why?
- When photons interact with matter, they loose energy via many different processes
  - For energies >20MeV, pair production dominates (source: PDG)





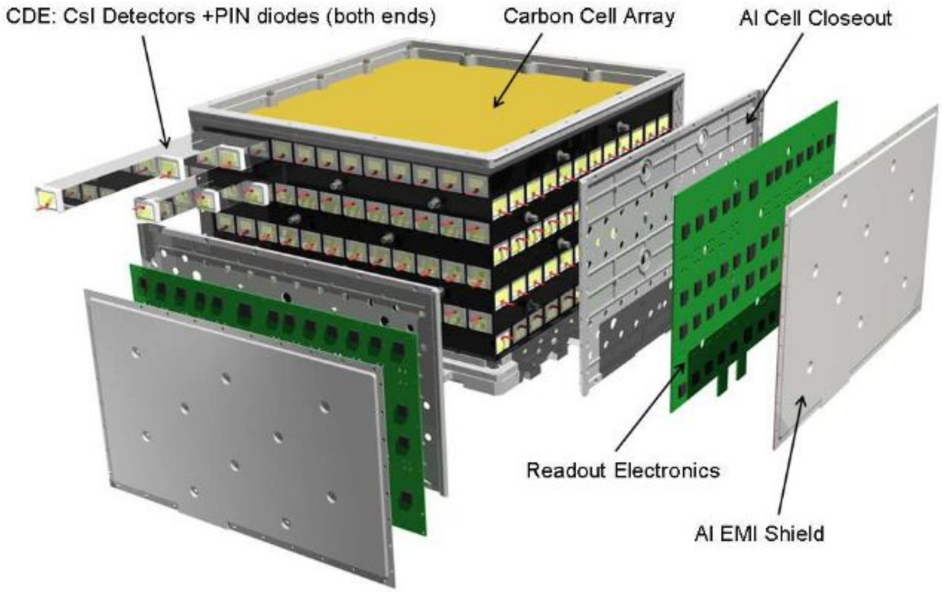
Tracker

- Tracker:
  - 16 layers of thin tungsten (for pair-production) interweaved with two single sided silicon strip detectors at 90° angle to facilitate e^-/e^+ reconstruction
  - The two silicon layers placed at 90° angle allow for position reconstruction
  - Use the two track signature to suppress charged cosmic ray background
  - Custom ASICs are used to in read-out electronics
  - Materials chosen based on high reliability for previous space experiments



Calorimeter

- Each calorimeter module has 96 CsI(Tl) crystals arranged in 8 layers alternating in orientation
- Photo diodes are used to detect energy deposited in each crystal on both sides
    - Use asymmetry on both sides to get position information of the shower along the crystal
- Although the calorimeter is only 8.6 radiation lengths, the longitudinal segmentation enables energy measurement upto a TeV



Anti-Coincidence Detector (ACD)

- Need to reject single charged particles entering LAT field of view
- Efficiency of ACD to detect single charged particles is 99.97%
- Use well segmented plastic scintillator tiles coupled with PMTs
  - It is most reliable, efficient, well-understood and inexpensive technology with previous successful use in space experiments
- For more details, please read the detailed instrumentation paper here
  - It is a great example for understanding design choices for a particle detector

LAT performance

Parameter	Value or Range
Energy range	20 MeV – 300 GeV
Effective area at normal incidence[a]	9,500 cm^2
Energy resolution (equivalent Gaussian 1σ):	
100 MeV – 1 GeV (on axis)	9%–15%
1 GeV – 10 GeV (on axis)	8%–9%
10 GeV – 300 GeV (on-axis)	8.5%–18%
>10 GeV (>60° incidence)	≤6%
Single photon angular resolution (space angle)	
on-axis, 68% containment radius:	
>10 GeV	≤0.15°
1 GeV	0.6°
100 MeV	3.5°
on-axis, 95% containment radius	$< 3 \times \theta_{68\%}$
off-axis containment radius at 55°	$< 1.7\times$ on-axis value
Field of View (FoV)	2.4 sr
Timing accuracy	$< 10\ \mu$sec
Event readout time (dead time)	26.5 μsec
GRB location accuracy on-board[b]	$< 10'$
GRB notification time to spacecraft[c]	<5 sec
Point source location determination[d]	$< 0.5'$
Point source sensitivity (>100 MeV)[e]	3×10^{-9} ph cm^{-2} s^{-1}

Known backgrounds

- Use previous experiments to figure out expected backgrounds

TABLE 5. DATA SOURCES FOR BACKGROUND MODEL

	Energy range $>$ local geomagnetic cutoff	150 MeV to geomagnetic cutoff	10 MeV – 150 MeV
Galactic Cosmic Rays			
protons + antiprotons	AMS		
electrons	AMS		
positrons	AMS		
He	AMS		
$Z > 2$ nuclei	HEAO–3		
Splash Albedo			
protons		AMS	Nina
electrons		AMS	Mariya
positrons		AMS	Mariya
Re-entrant Albedo			
protons		Nina	
electrons		Mariya	
positrons		Mariya	
Earth albedo γ-rays		10 MeV – 100 GeV, EGRET	
Neutrons		10 MeV – 1 TeV, various sources	

Dark matter signatures

- If WIMP DM exists, then they annihilate in high density DM regions creating energetic gamma rays which can be detected by Fermi LAT
- WIMP decays can result in two signatures at LAT
  - Continuous gamma ray excess: Can result due to pion decay from WIMP annihilations into SM particles
    - Generally has higher cross-section but difficult to separate from Galactic diffuse foreground
  - Mono-energetic gamma ray peaks: Arise when DM annihilates and creates two photons
    - Might have much lower cross-sections but has a clear distinguishable signature

Dark matter constraints from White dwarfs

Source

- Dwarf spheroidal galaxy (dSphs): Small, low-luminosity galaxy with older stellar population
- Kinematic data indicate that the dSphs accompanying Milky way have large DM density
- Expected signal flux in Fermi LAT due to DM density ρ_{DM}:

Annihilation cross-section

Differential gamma-ray yield per annihilation

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\min}}^{E_{\max}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\mathrm{l.o.s.}}\rho_{\mathrm{DM}}^2(\boldsymbol{r})\mathrm{d}l\mathrm{d}\Omega'}_{\text{J-factor}}$$

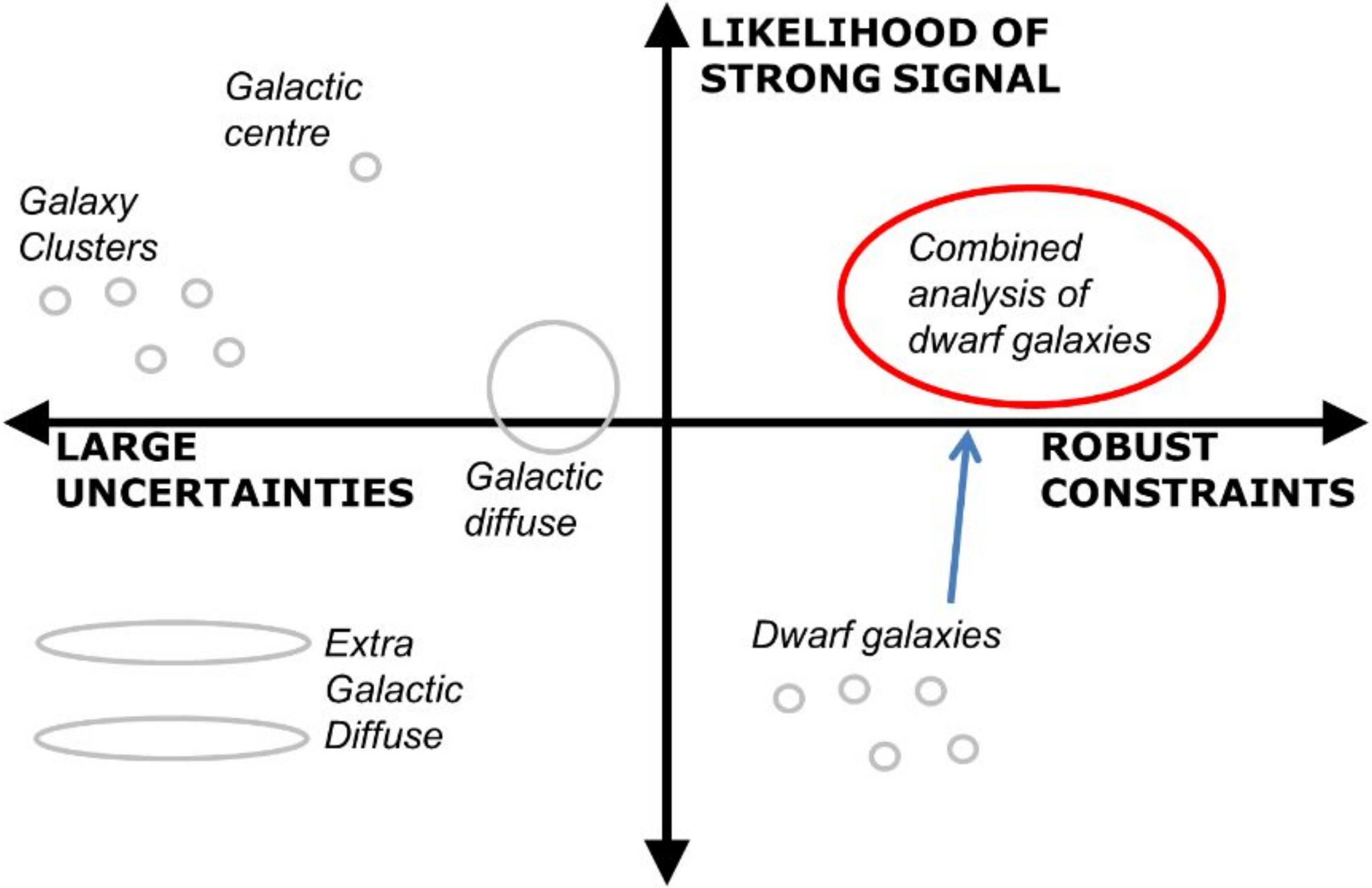
Signal flux (ph cm^{-1} s^{-1})

Line of sight integral through DM distribution over the solid angle

Why are white dwarfs good to probe DM?

- Milky way dSphs can result in J-factors of 10^{19} GeV^2 cm^{-5}
- They lack non-thermal astrophysical process
- Hence, the expected DM signal is clean with little background
- Gamma-ray studies from multiple dSphs result in most stringent limits on DM annihilation cross-sections
- In contrast, the DM signal expected from Galactic centers where the J factor is O(100) larger but the background is bright and structured

Why are white dwarfs good to probe DM?



https://arxiv.org/pdf/1411.1925.pdf

Analysis

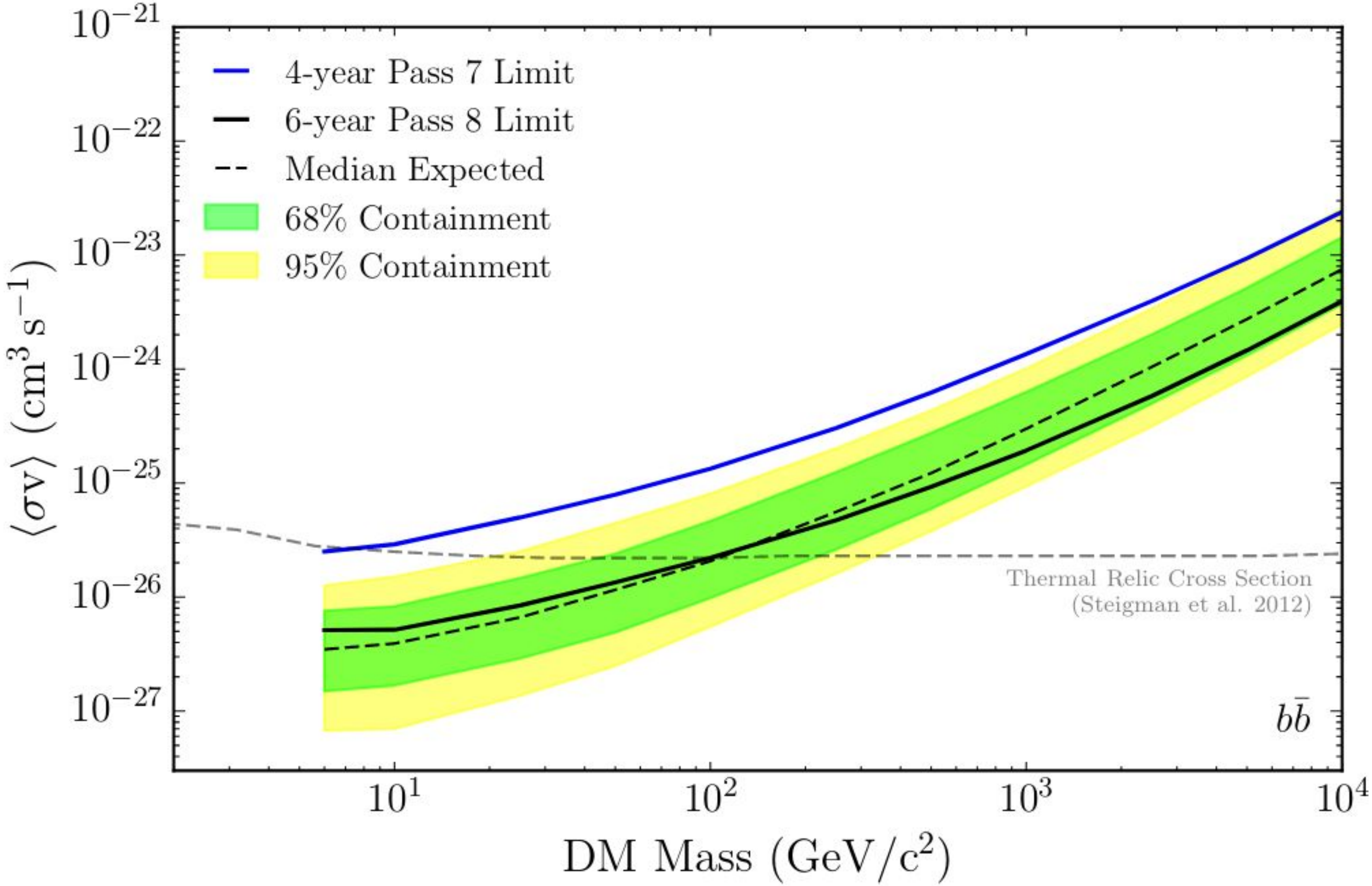
- Use 6 years of LAT data recording 15 Milky way dSphs
- Event selection:
  - Energy range 500 MeV - 500 GeV
  - To avoid terrestrial gamma rays, events with zenith angles larger than 100^o are rejected
  - Reject data during/around bright GRBs or solar flares
  - Extract Region of Interest, 10^o x 10^o square regions around each dSph
- Background:
  - Template modeled by data from another run in LAT which studies Galactic diffuse emission
  - The background is corrected for the dataset's intensity
- The data is divided into 24 bins of energy and 0.1^o angular bins
- Bin-by-bin likelihood analysis of gamma-ray emission coincident with each dSph is performed

Results

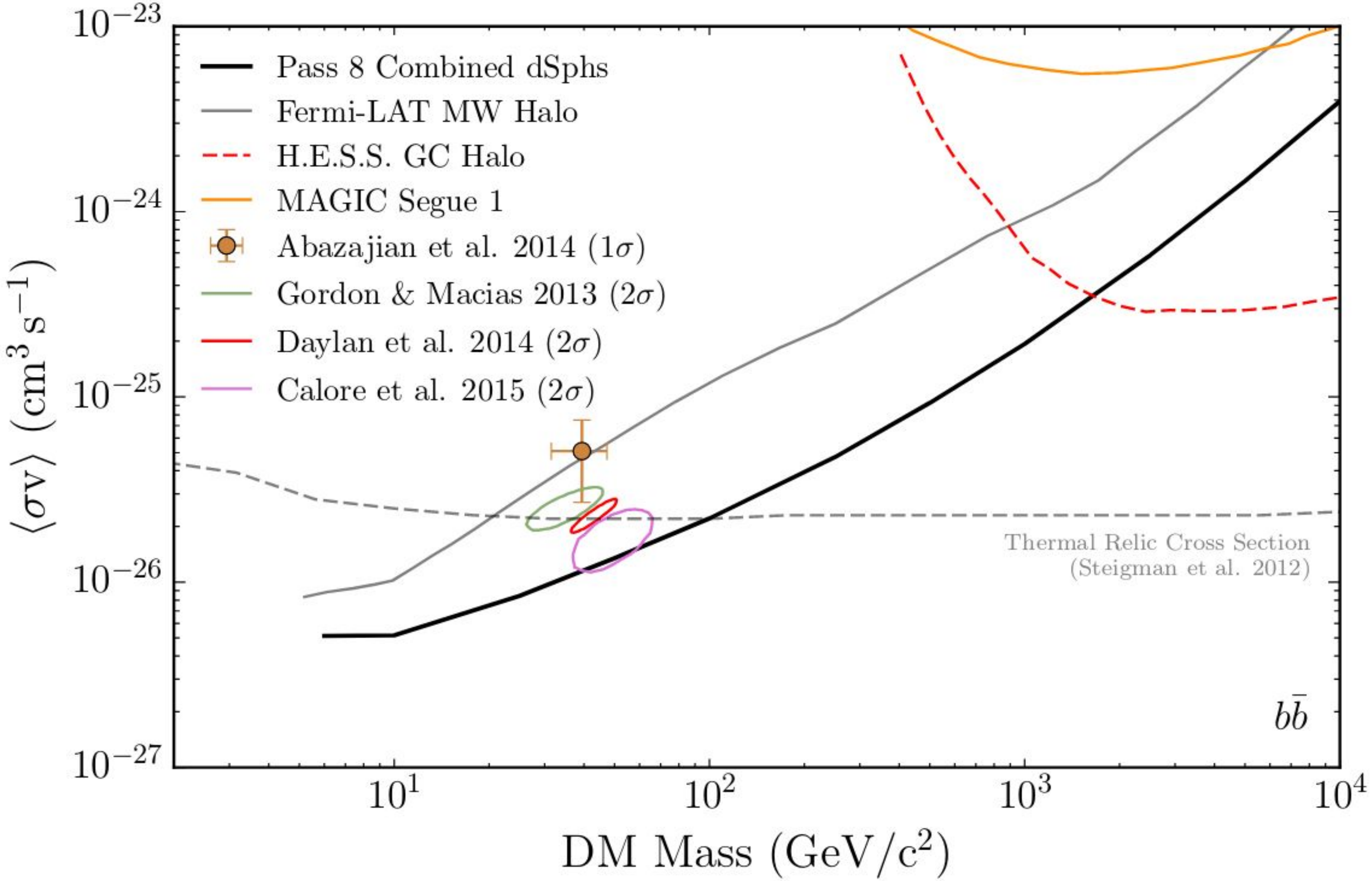
- No significant gamma-ray excess found
- Constraints are placed on dark matter annihilating into bbbar, and other SM particles

- Comment on systematics:
  - J-factor estimation gives highest contribution
  - Diffuse background modelling
  - Instrumentation related factors

Dark Matter constraints



Compared to other experiments



Summary

- Gamma-ray and other telescopes provide excellent test bed to look for dark matter indirectly
- This is complementary to direct searches like LZ and collider searches performed at ATLAS and CMS
- Fermi LAT telescope looks for DM using white dwarfs, galactic center and also for peaks in the gamma-ray spectrum
- The data has been interpreted by many theorists to come up with constraints on particular models
- Stay tuned for more results from Fermi and other telescopes