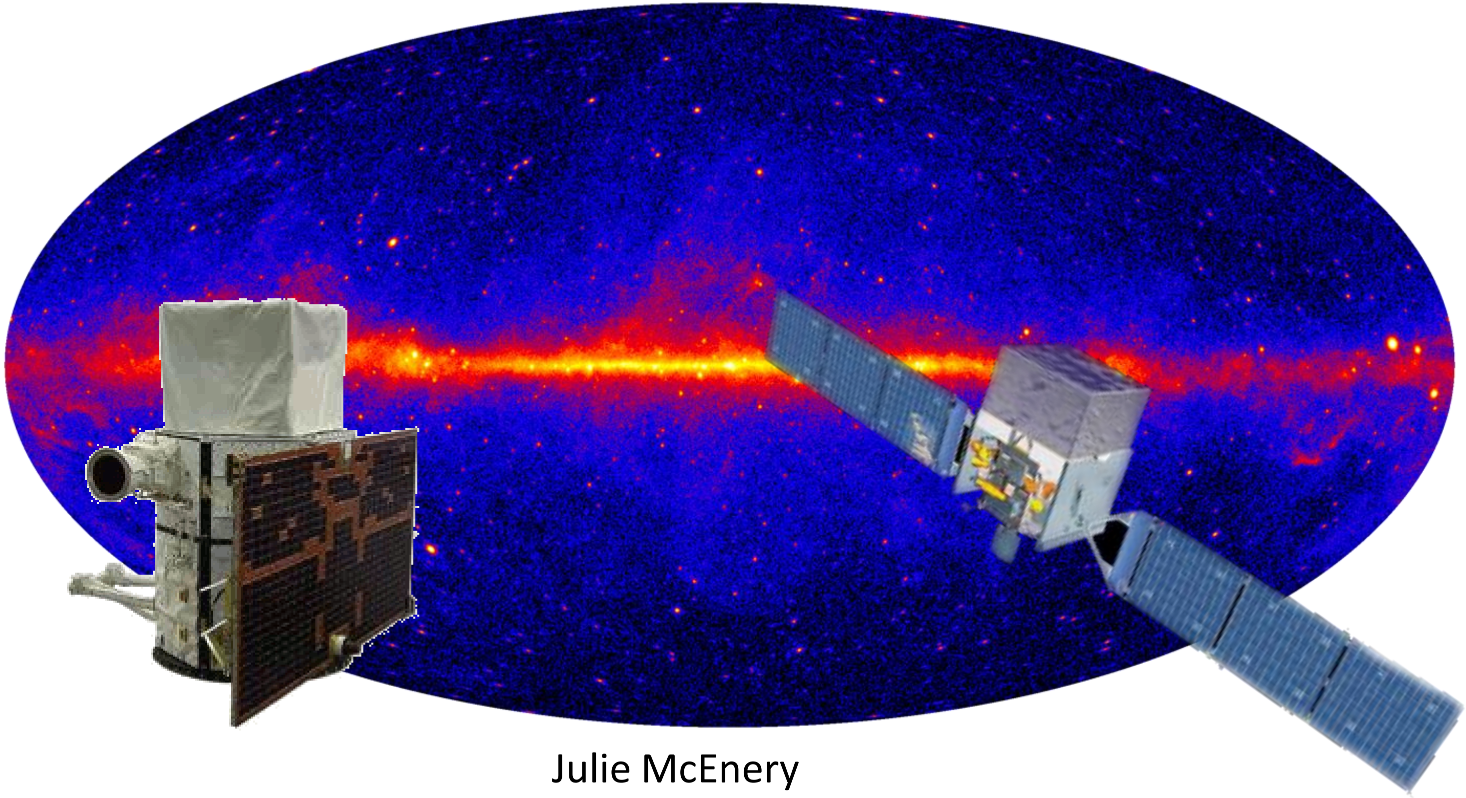
Space-based Gamma-ray observatories: Current Status, Future prospects and synergy with CTA



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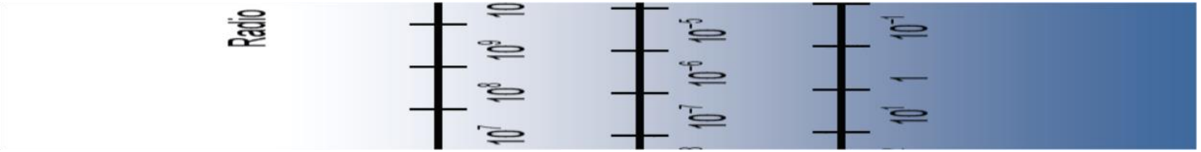
Gamma-ray Astrophysics

Gamma-ray

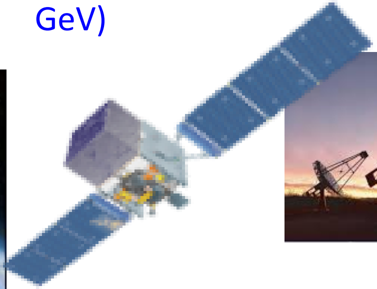
Freq (Hz)
Energy (ev)

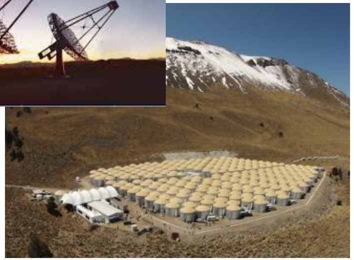


Medium Energy gamma-rays (aka MeV)

High Energy gamma-rays (aka GeV)

Very High Energy (VHE) gamma-rays (aka TeV)



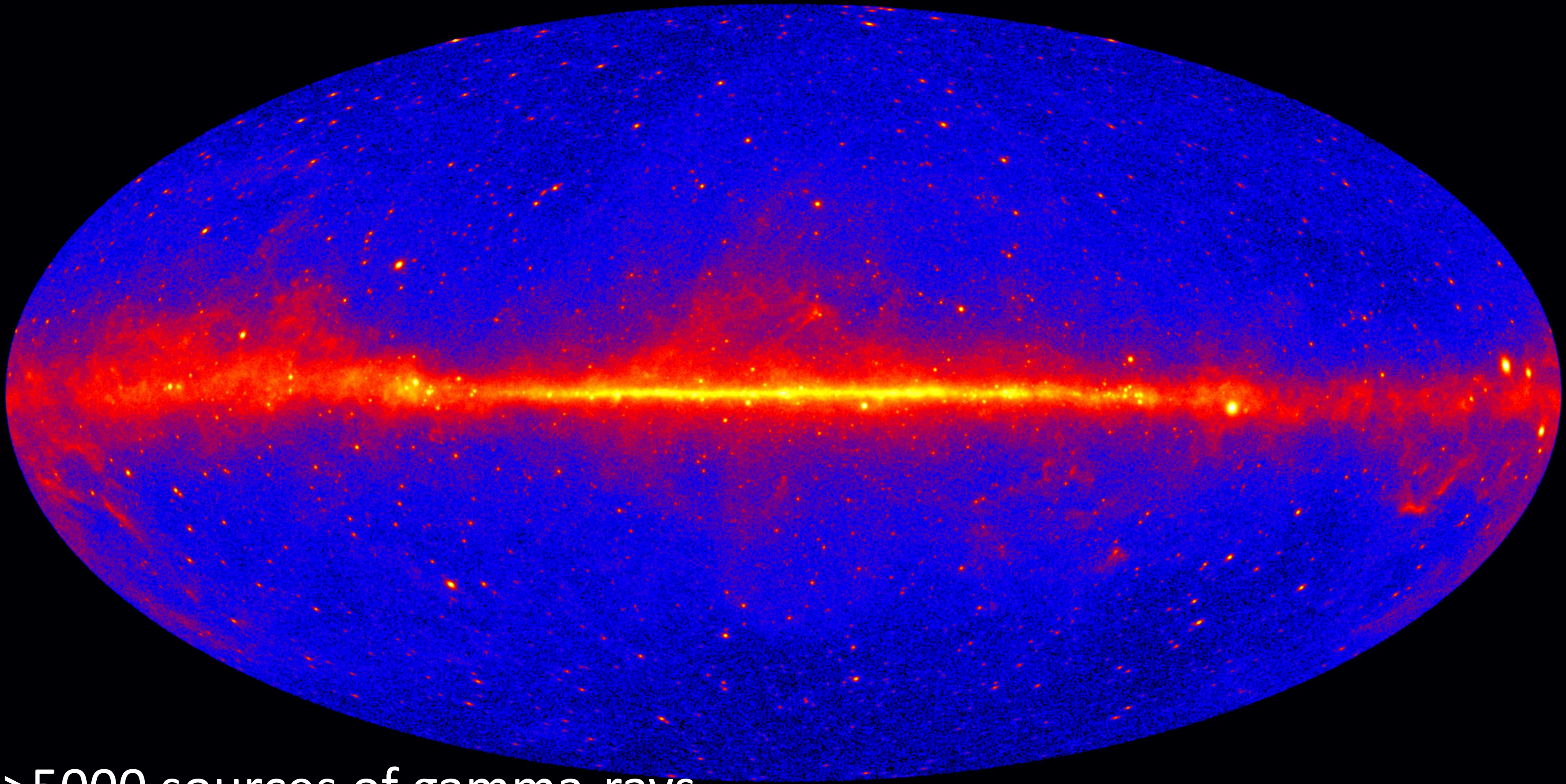


Current Space-Based Gamma-ray detectors

- AGILE
  - Gamma-ray imager (50 MeV-30 GeV)
  - Hard X-ray imager (18-60 keV)
  - Large FoV (1-2.5 sr)
  - Launch 2007

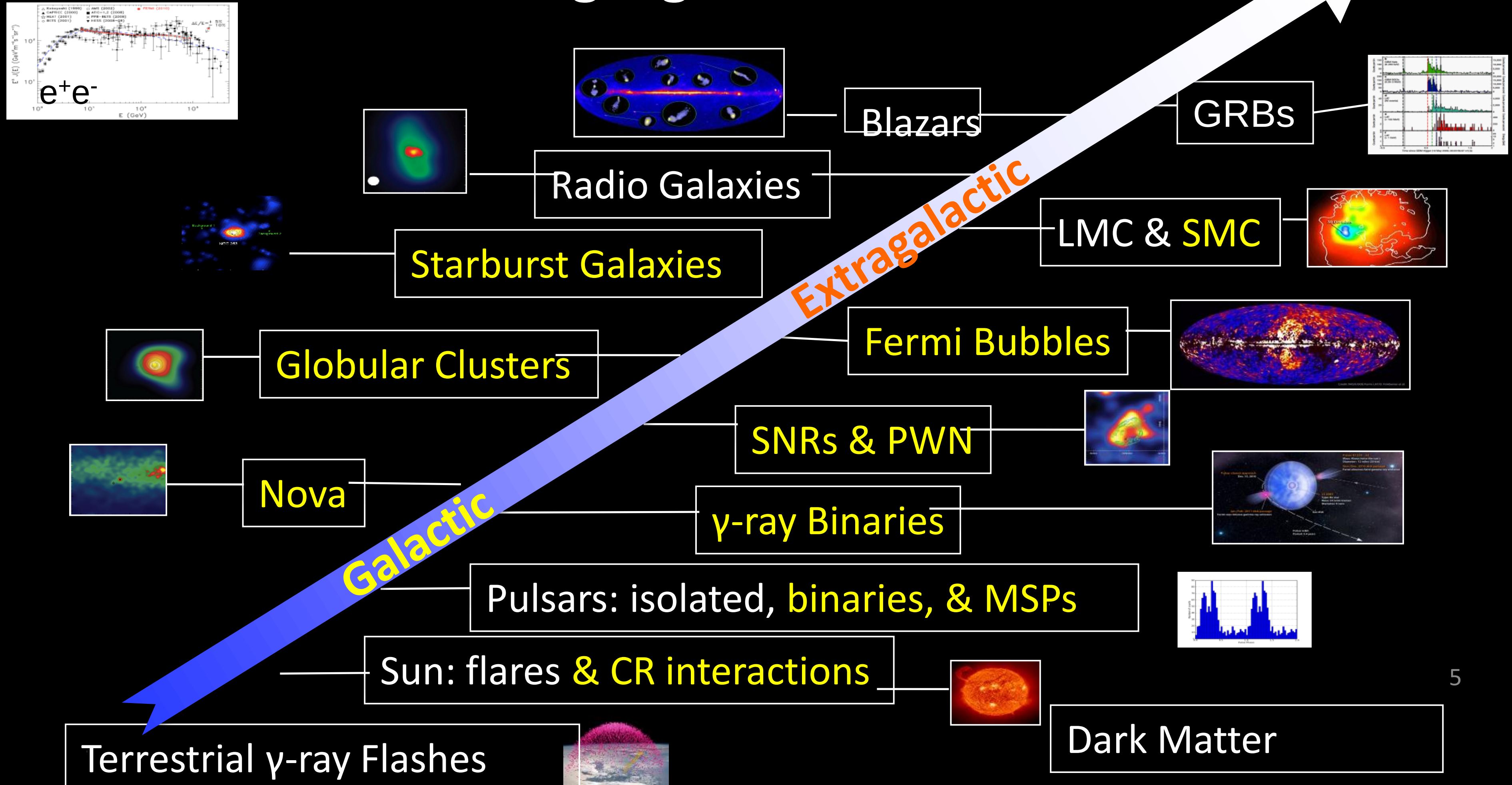
- Fermi
  - Large Area Telescope (20 MeV->300 GeV)
    - 2.5 sr FoV
  - Gamma-ray Burst Monitor (8 keV - 30 MeV)
    - 8.5 sr
  - Launch 2008

The Sky Above 1 GeV



- >5000 sources of gamma-rays

Fermi Highlights and Discoveries

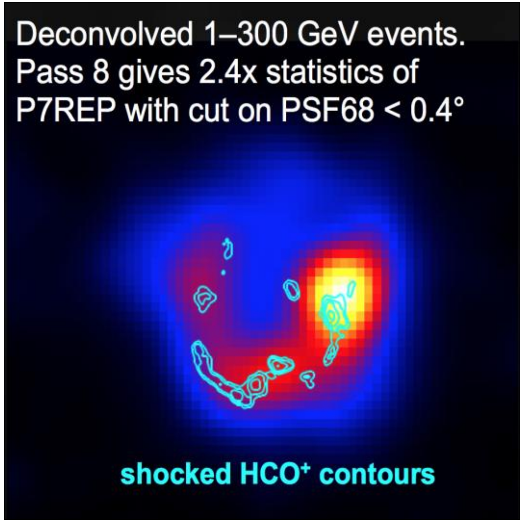


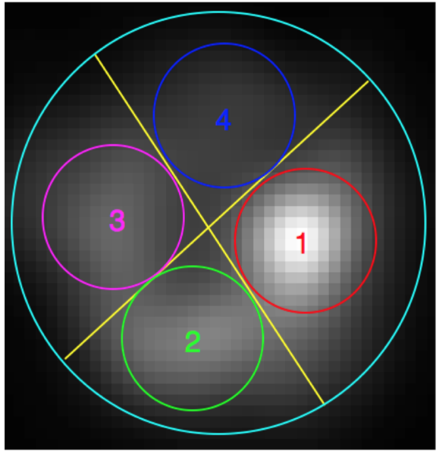
Ground and Space Working together

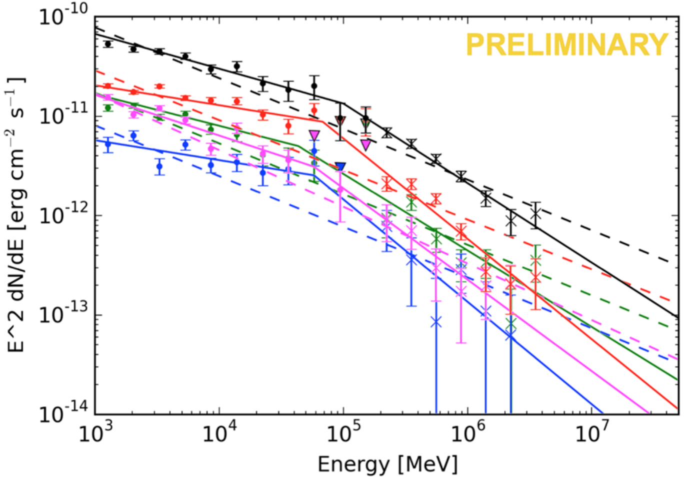
- Wide field (Fermi-LAT, AGILE, HAWC) can tell pointed (IACTs) instruments where and when to find interesting objects
- GeV (Fermi-LAT, AGILE) combined with TeV data (IACTs, ground arrays) provide large spectral lever arm
  - Hadronic versus leptonic scenarios in e.g. SNR
  - Maximum particle energy -> acceleration efficiency
  - Absorption features
    - Intrinsic to a source -> location of the emission region
    - Externally -> probe intergalactic radiation and magnetic fields
- Extended source spatial models from IACTs -> Fermi/AGILE
- Pulsar timing models from GeV -> TeV
  - For gamma-ray only pulsars, this is the only way to extend the observations to higher energy
- Sometimes the GeV and TeV detected emission are not directly related to one another!

Example: Resolving a Proton Accelerator

- Fermi data resolve the shell of IC 443 at physical scales of ~5 pc GeV/TeV gamma-rays match the distribution of shocked gas
- Dense molecular and diffuse atomic (fast shock) regions differ in flux by ~10x, but spectra are surprisingly consistent.

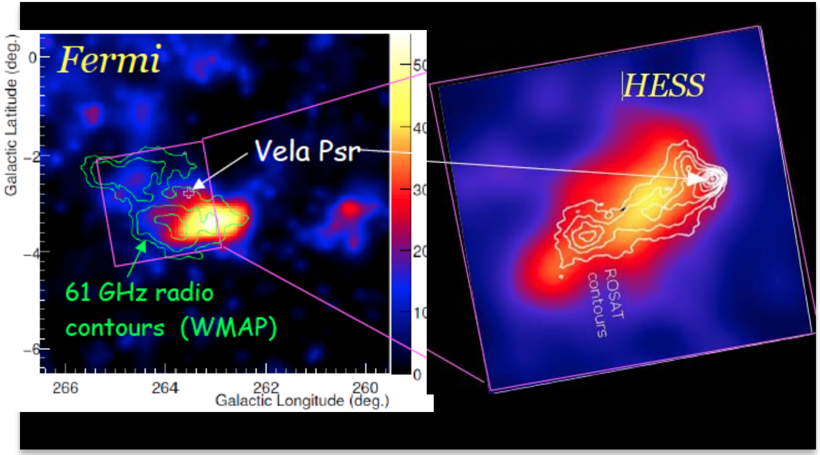


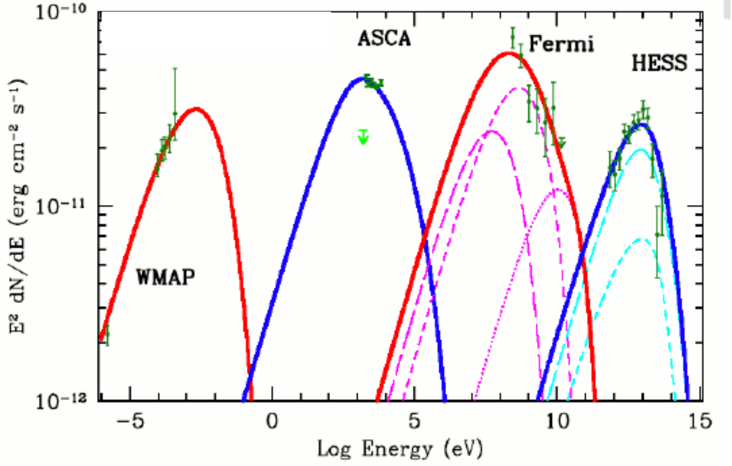




An Example Vela X – a pulsar wind nebula

- Morphology
  - Radio and HE gammas: Halo (old population)
  - X-rays & VHE: Cocoon (young population)

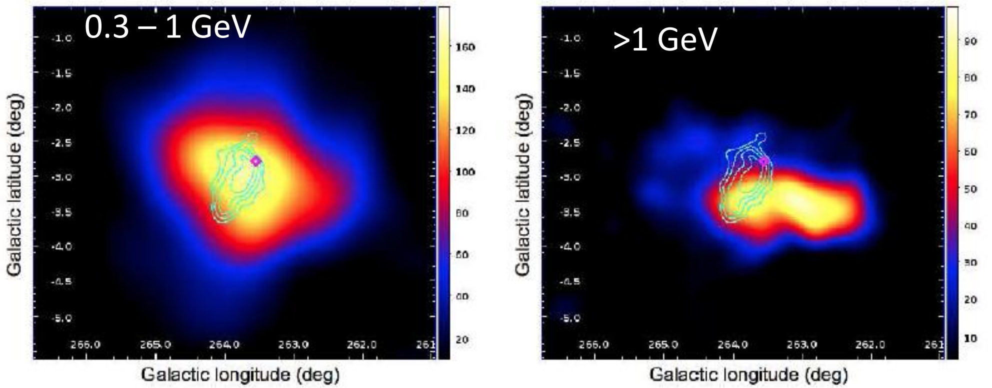




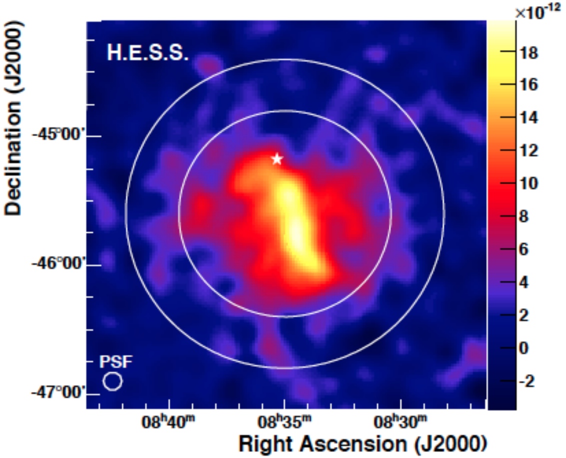
- Favors a two component model (deJager et al 2008): one young electron population for X-ray/VHE (cocoon) and a relic population for radio/GeV (halo)

The Puzzle Deepens with more observations…

- In the GeV range (Grondin et al 2013)
  - Unveils energy dependent morphology

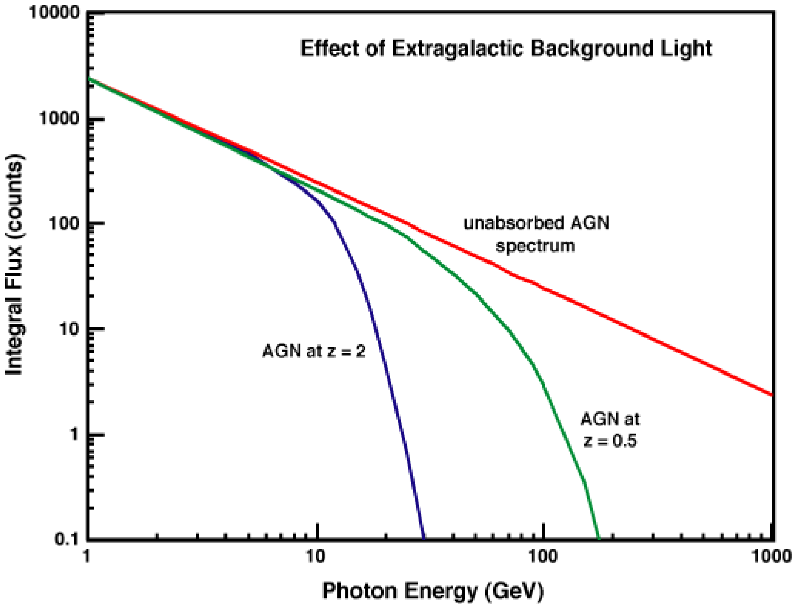


- In the TeV range (Abramowski et al 2012)
  - Bright TeV emission still correlates with X-rays
  - Fainter emission extends beyond X-ray cocoon
  - Uniform gamma-ray spectrum between the inner and outer regions



Gamma-ray absorption

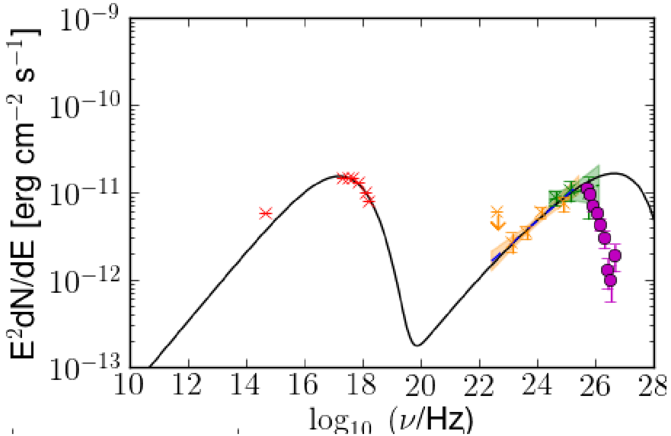
- The Universe is largely transparent to gamma-rays below ~10 GeV
- At higher energies gamma-rays are absorbed as they traverse intergalactic space by optical-UV photons.
  - Absorption depends on the distance to the gamma-ray source and on the density and spectrum of the optical-UV background radiation.

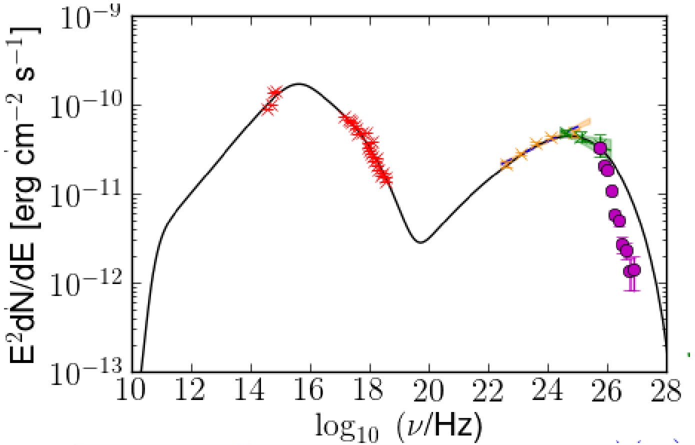


The distance to active galaxies can be determined from optical observations.

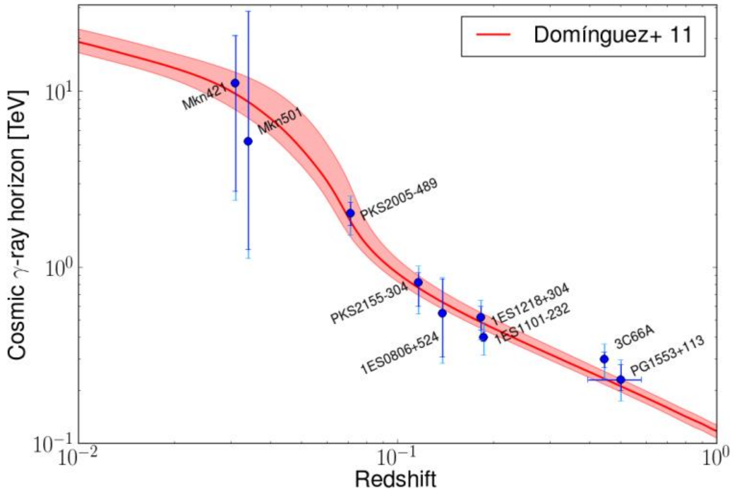
Measurement of gamma-ray cutoffs provides information on the optical-UV background -> galaxy and star formation as a function of time.

Extragalactic Background Light: combining GeV and TeV data



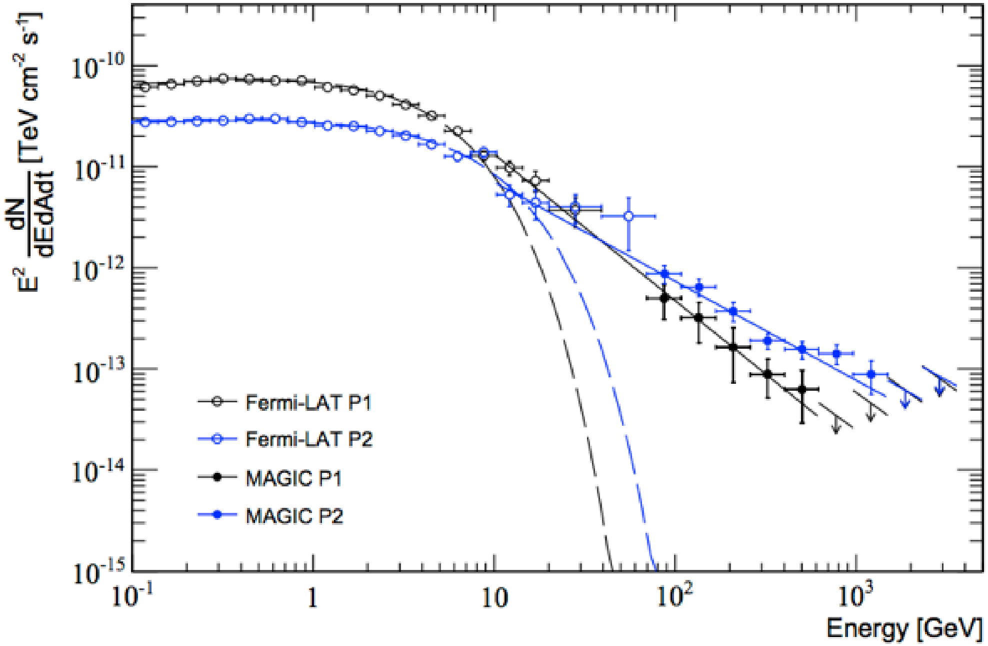


- Emission model is fit to the data excluding the TeV, and then extrapolated to the TeV regime - the intrinsic TeV spectrum
- Difference between the VHE data and the extrapolation allow a determination of the EBL attenuation vs redshift



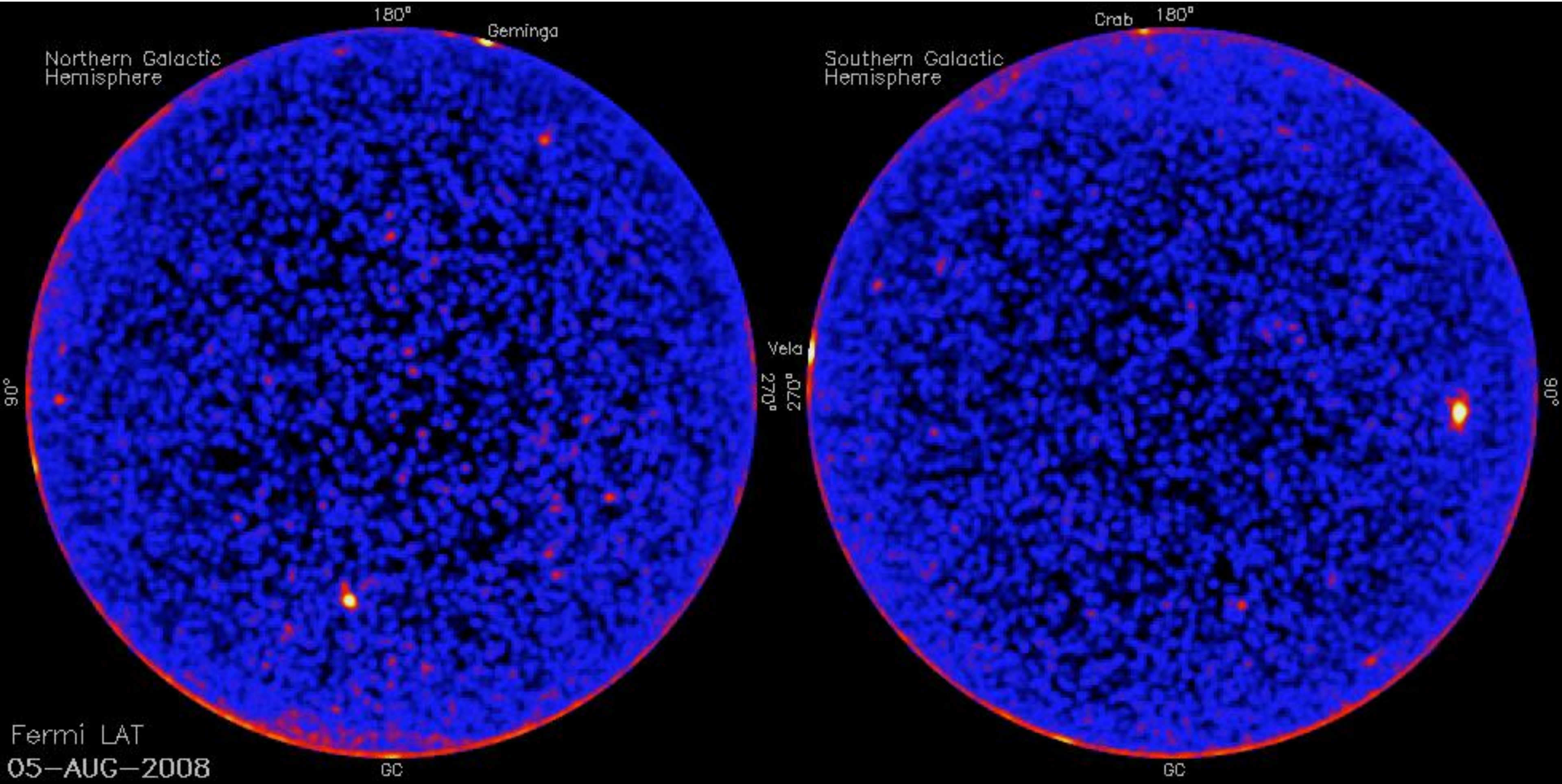
MAGIC/VERITAS and Fermi-LAT Observations of the Crab Pulsar

- Crab pulsar at >100 GeV!
- Above 100 GeV, peaks are narrower
- Cutoff of combined spectrum is not exponential
- Extension of Fermi-LAT spectrum or new component (e.g. inverse Compton)?

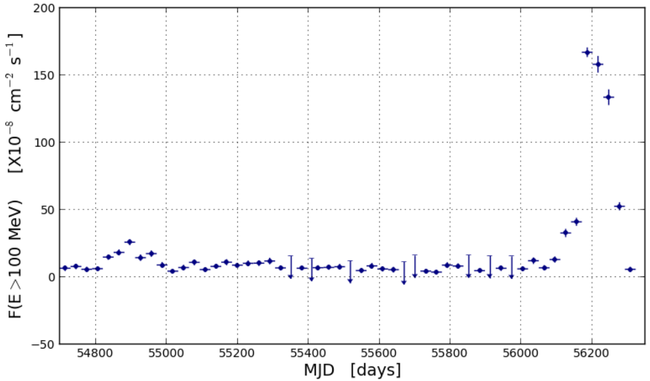


How many more will CTA find? - Timing information from GeV instruments important

The Variable Gamma-ray Sky

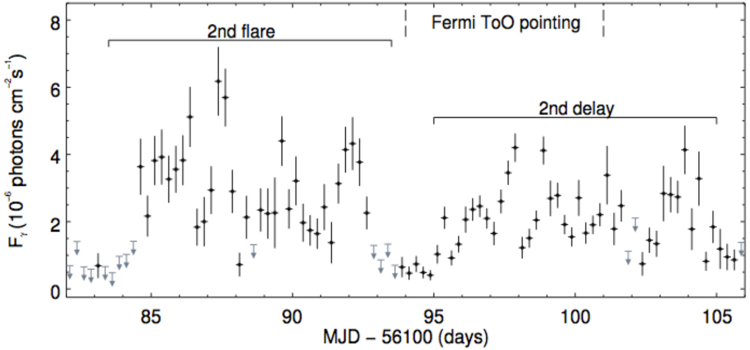


Gravitational Lensing in Gamma Rays
Blazar B0218+35

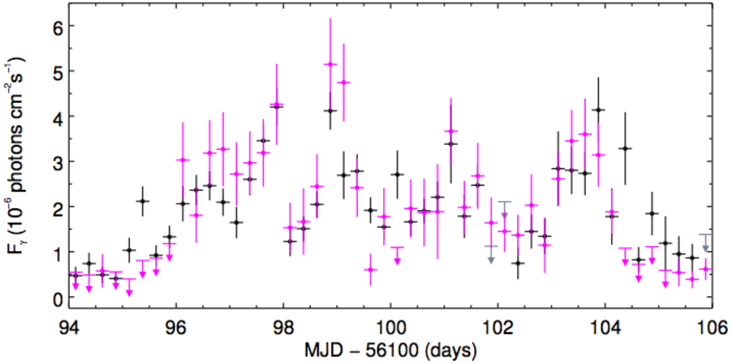


- Sometimes we have to wait a while…
  - The active galaxy S3 0218+35, quiescent for most of the Fermi mission, became active in September 2012
  - 4 distinct outbursts caused by 2 flares in the gravitationally lensed system

Gravitationally lensed system: flares come in pairs



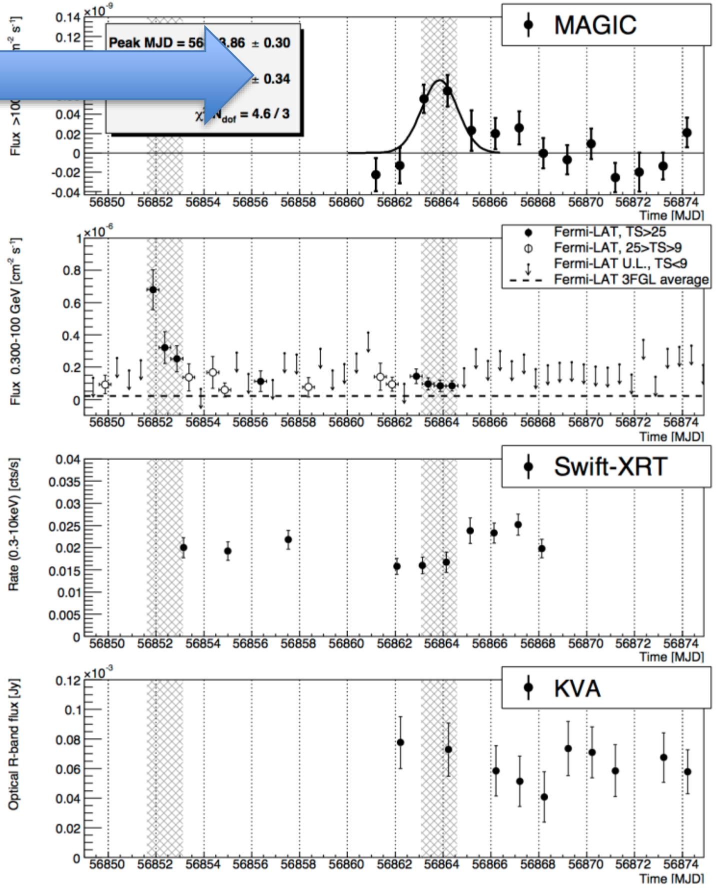
After shifting by 11.5 days and scaling by 1.16, the flares align beautifully



Gravitational lensing in gamma-rays – B0218+35

The MAGIC ground-based TeV telescopes detected the delayed flare 11 days later.

In July, 2014, Fermi LAT saw another flare. It was announced in an ATel.



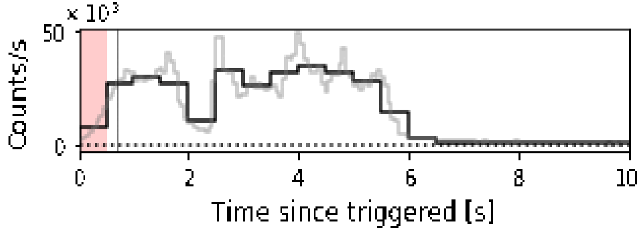
Ahnen, M. L. et al. 2016, A&A

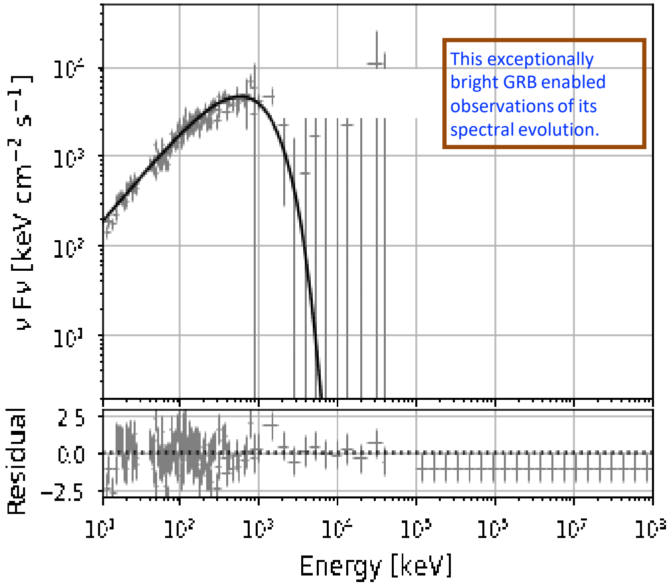
GRB 190114C: MAGIC detection of a gamma-ray burst

- First high significance detection of a gamma-ray burst by a VHE instrument

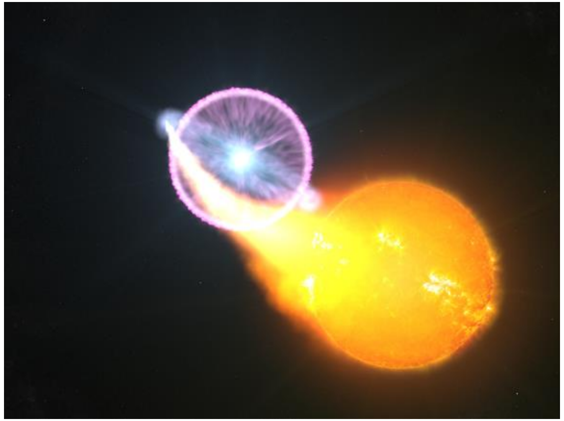
- Highest-energy photons ever seen from a GRB
- Spectacular time-resolved study of high-energy emission in a GRB's explosive phase

- GRB 190114C's very high energy, large distance and short timescale makes it an outstanding probe of intergalactic space, providing constraints on:
    - the density & spectrum of the IR-optical extragalactic background light
    - the intergalactic/primordial magnetic field



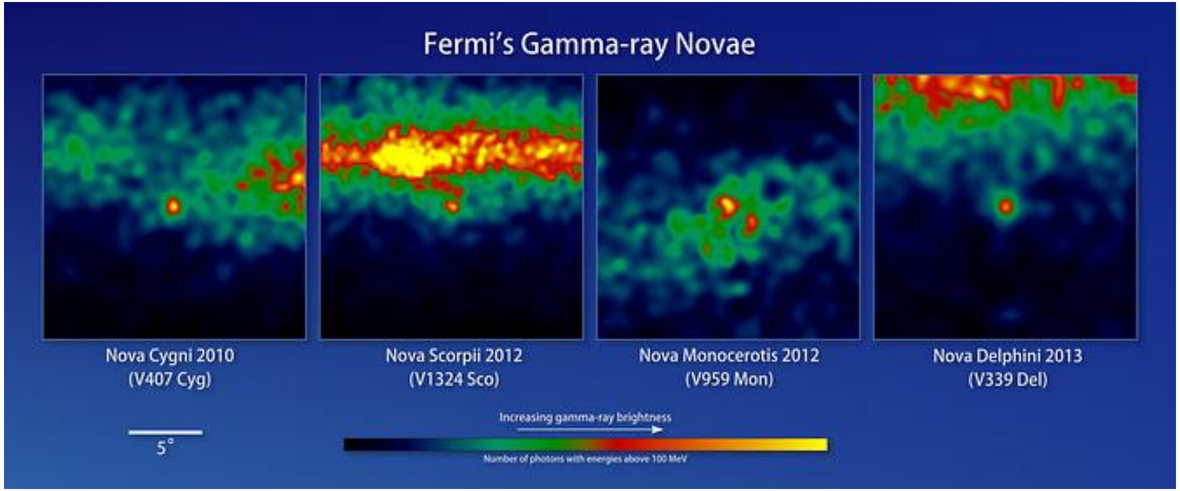


A new class of gamma-ray source – Stellar Novae



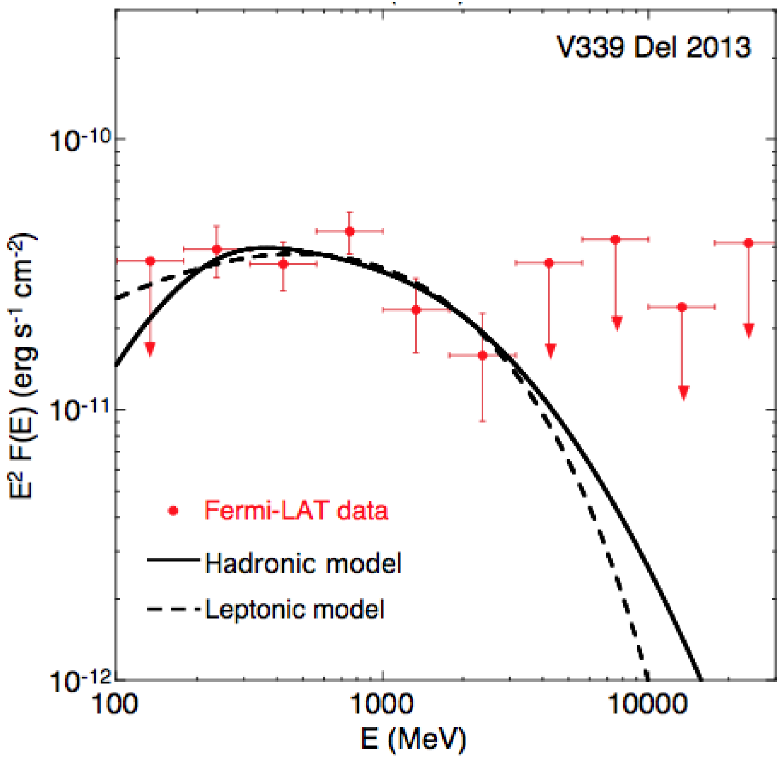
- Particles accelerated in multiple shock waves in the rapidly expanding debris shell
- An unexpected discovery – only possible because Fermi surveys the sky

Now have >10 detected Novae

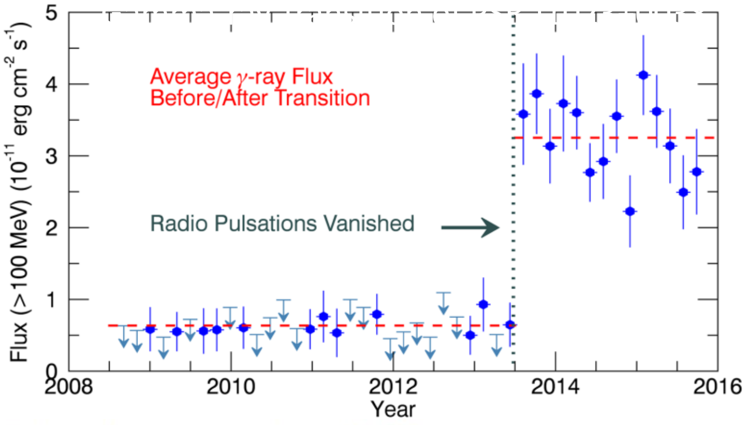


VHE Gamma-ray Observations of Novae

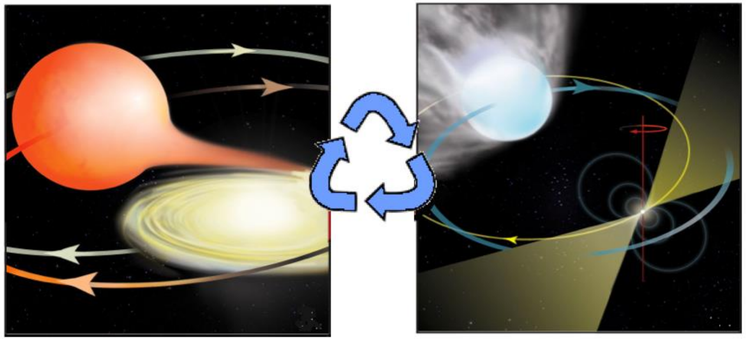
- Can't tell from the Fermi-LAT data alone if the gamma-rays are produced by electrons or protons
- Comparing VHE gamma-ray observations from MAGIC with predicted gamma-ray emission
  - Constraint on total luminosity of protons being less than around 15% of electrons



Transitional Millisecond Pulsars



Balance between gravity and field pressure



Transition between rotation powered and accretion powered state

More expected - LAT already detected two transitions between accreting and radio MSP states

γ-ray emission brighter in the accreting state – a mystery since accreting sources are *not* typical γ-ray emitters.

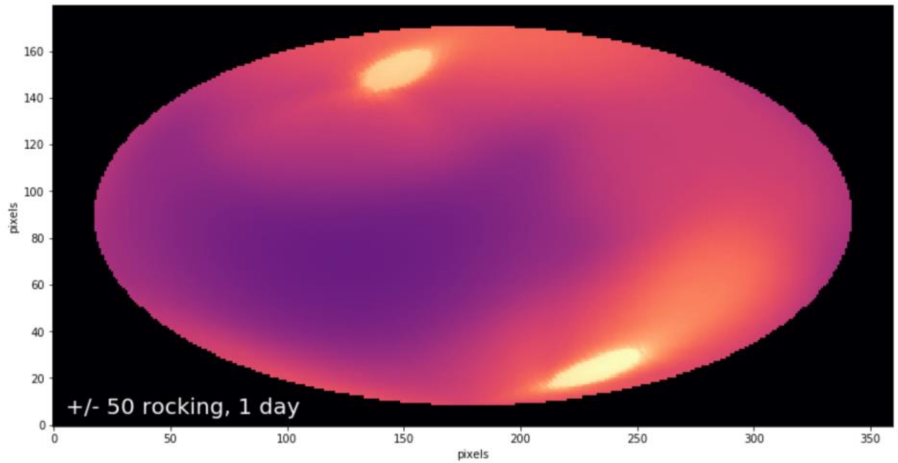
A new area of study for *Fermi* – will it become one for CTA too?

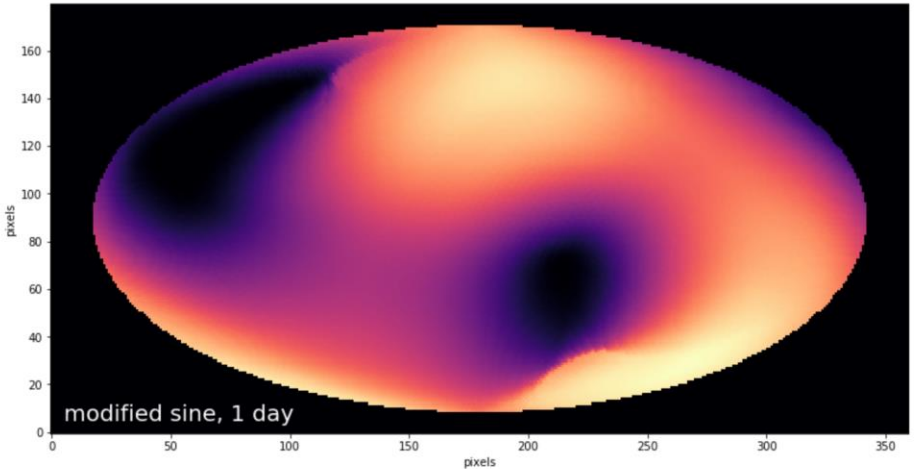
GeV and TeV: a quick summary

- ~90s (EGRET, Whipple, HEGRA, CAT etc):
  - Relatively small overlap between GeV and TeV source catalogs
  - Energy gap between ~10 GeV and ~200 GeV
- ~2000's (HESS, VERITAS MAGIC)
  - Explosion of TeV detections with the new generation of IACTs
  - Large increase in the classes of TeV sources, especially in the Galaxy
  - Energy gap between ~10 GeV and ~200 GeV
- ~2010's (Fermi, AGILE, HESS, VERITAS, MAGIC)
  - Explosion of GeV detections with AGILE and Fermi-LAT
  - Many correlated observations, joint GeV-TeV science comes of age
- 2020's
  - CTA!
  - No clear space-based successor to Fermi ☹

Fermi Status and Prospects

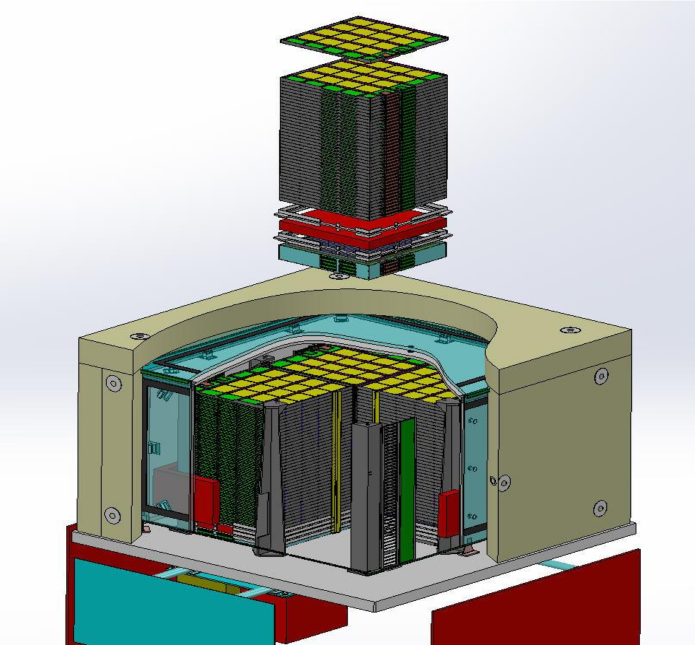
- Both instruments continue to operate with full scientific performance
- One of the solar array drives failed, mitigated by transitioning to a “modified” survey for ~1/3 of the time
- Anticipate that Fermi will operate into the CTA era

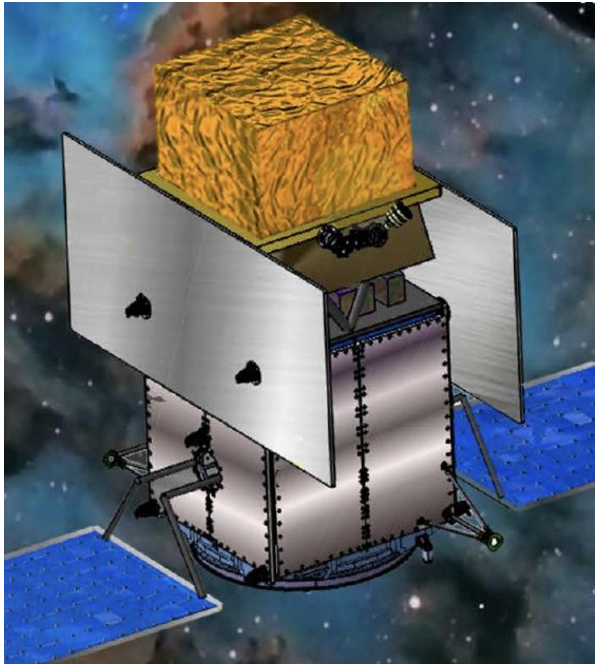




Future Gamma-ray Missions

- Greatest focus is on medium energy gamma-ray instruments
  - AMEGO (in US)
  - eAstrogam (in Europe)





Medium Energy Gamma-ray Astrophysics

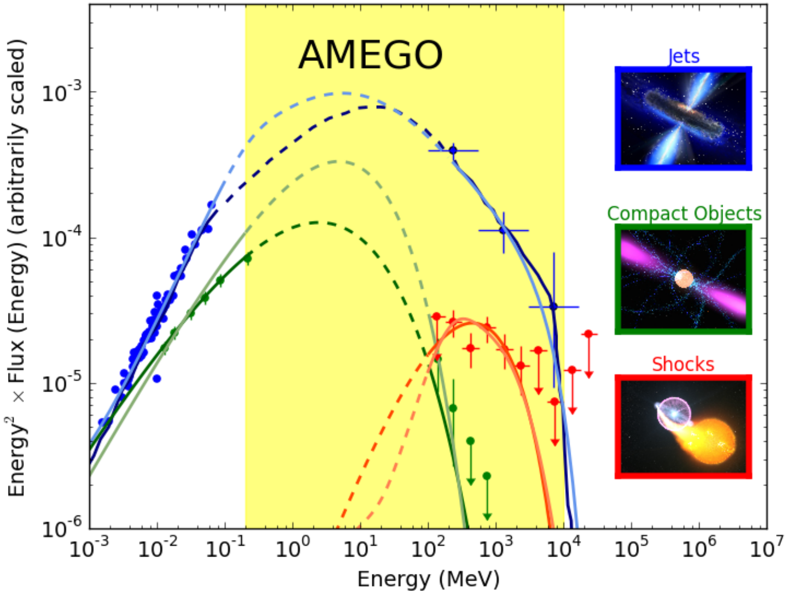
- Understanding how the Universe works requires observing astrophysical sources at the wavelength of **peak** power output **crucial for source energetics**
- Fermi, NuSTAR, and Swift BAT have uncovered source classes with peak energy output in the poorly explored MeV band

A critical energy band –
Transition between the thermal and non-thermal Universe

Only part of the EM spectrum where it is possible to directly observe nuclear processes (atomic nuclei de/excitations)

Covers positron annihilation line (511 keV)

Large population of known sources with peak power output in the MeV range

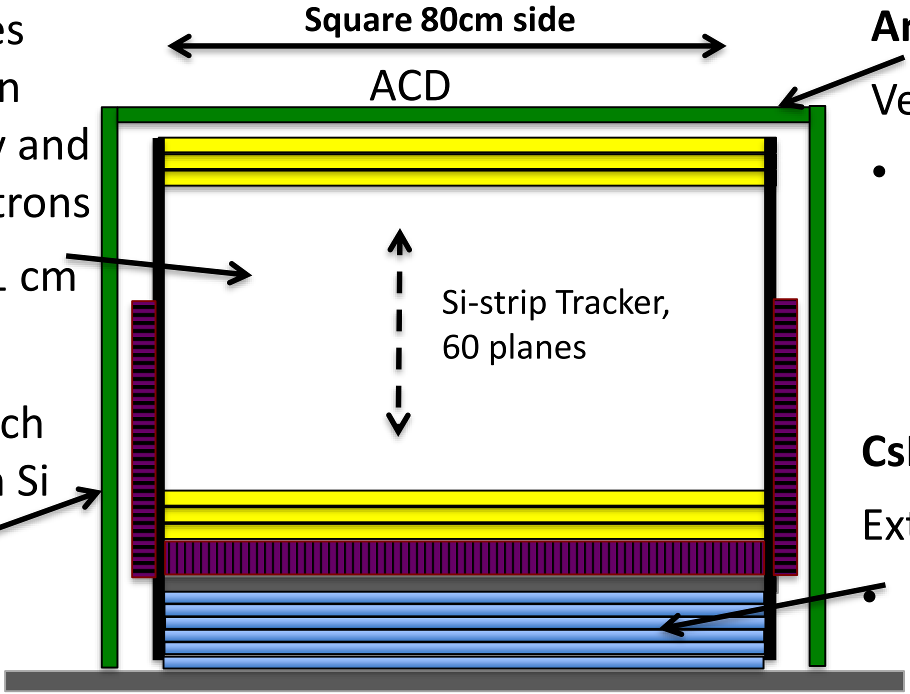


All-sky Medium Energy Gamma-ray Observatory

Tracker

Incoming photon undergoes pair production or Compton scattering. Measure energy and track of electrons and positrons

- 60 layer DSSD, spaced 1 cm
- Strip pitch 0.5mm
- Arranged in 4 towers each with 4x5 layers of 10 cm Si wafers



AntiCoincidence Detector

Veto charged background

- 5 tiles of plastic scintillator with SiPM readout

CsI Calorimeter

Extend high energy range

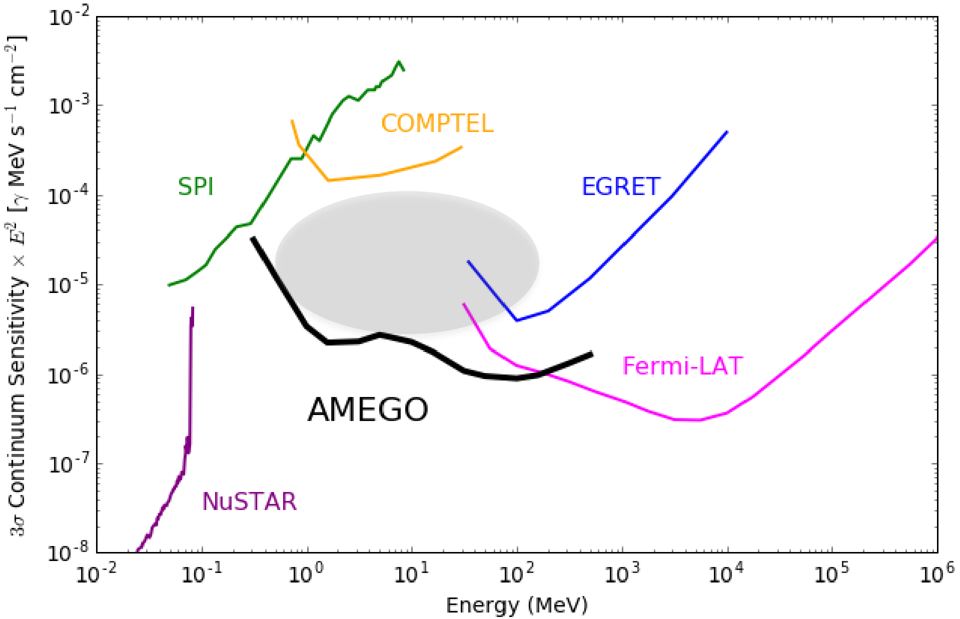
- 6 planes of 40cm x 1.5cm x 1.5 cm CsI (Tl) bars with SiPM readout

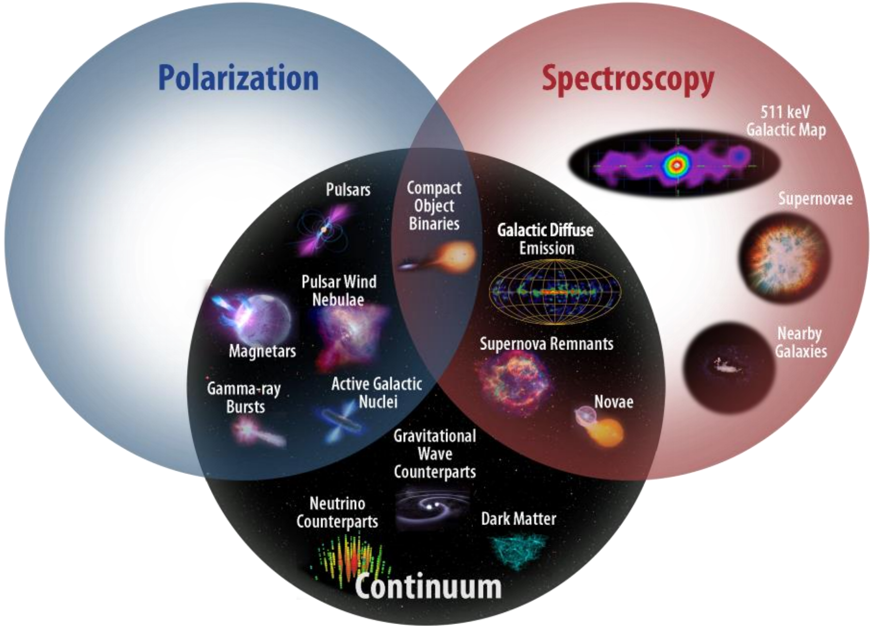
CZT Calorimeter

Measure location and energy of Compton scattered photons

- Layer of 0.8x0.8 x 4cm bar CZT (with 3D sub-pixel resolution)

AMEGO opens huge discovery space!

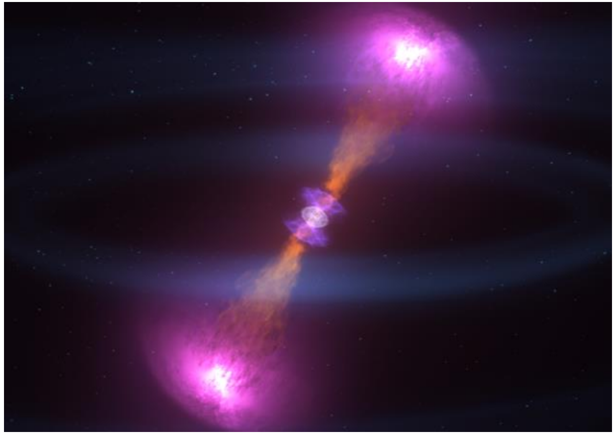




Huge field of view: 2.5 sr, survey full sky every 3 hours – explore time domain!
Broad Energy Range: 200 keV - >10 GeV
Polarization <1 MeV

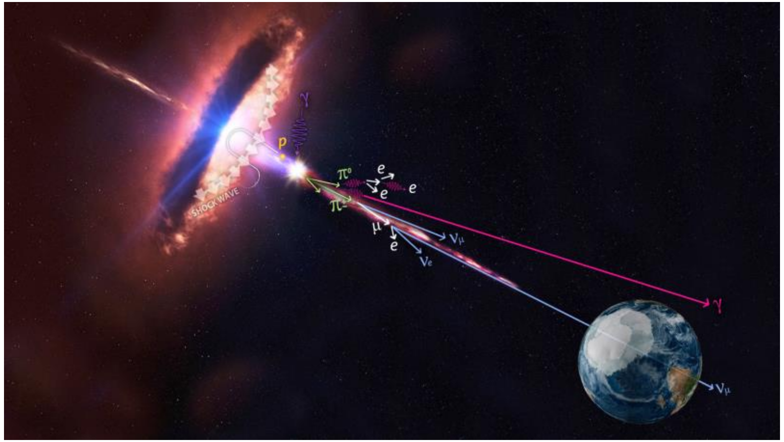
AMEGO is a Multimessenger Observatory

Extreme Explosions – GW counterparts



- High rate of well localized (~<1 deg) GRB
  - ~80 short GRB/year
  - ~450 long GRB/year
- Polarization probes GRB jets
- Direct observation of gamma-rays from nuclear processes in nearby kilonova

Extreme Accelerators – Neutrino counterparts



- Gamma-rays are generated in the same physical process that produces neutrinos
- Continuous monitoring of hundreds of the most luminous blazars
- MeV flux good proxy for neutrino flux
- Polarization observations probe jet composition

AMEGO Current Status

- Currently building prototype instrument
  - Beam test late 2019
  - Balloon flight 2021
- Preparing mission white paper for consideration by the 2020 decadal survey
- Large, international collaboration
  - Everyone is welcome to join the fun!

https://asd.gsfc.nasa.gov/amego/

Summary

- Ground and space based gamma-ray observatories have natural synergies
  - Complementary capabilities in time domain
  - Enables very broad spectral coverage
- Fermi dataset will be a valuable resource for CTA
- Fermi will likely continue into some of CTA operations
- Unlikely to have a next generation space-based gamma-ray observatory at the beginning of CTA operations, but hopefully will have something before the end

Intergalactic Magnetic Fields

Blazar $\xrightarrow{\text{TeV } \gamma}$ EBL $\xrightarrow{\text{e+e-}}$ CMB $\xrightarrow{\text{GeV } \gamma}$

- Intergalactic magnetic fields deviate the trajectories of the pairs
  - Pair halo (spatially extended source)
  - Time delay (longer path to observer)
  - Diluted GeV cascade flux
    - Fermi-LAT non-detection of TeV blazars sets lower bound on IGMF ($B \geq 3 \times 10^{-16}$) (Neronov and Vovk 2010)