# Overview of GeV and TeV Astrophysics

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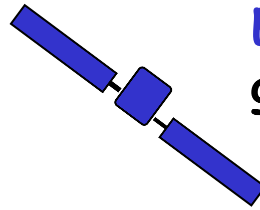
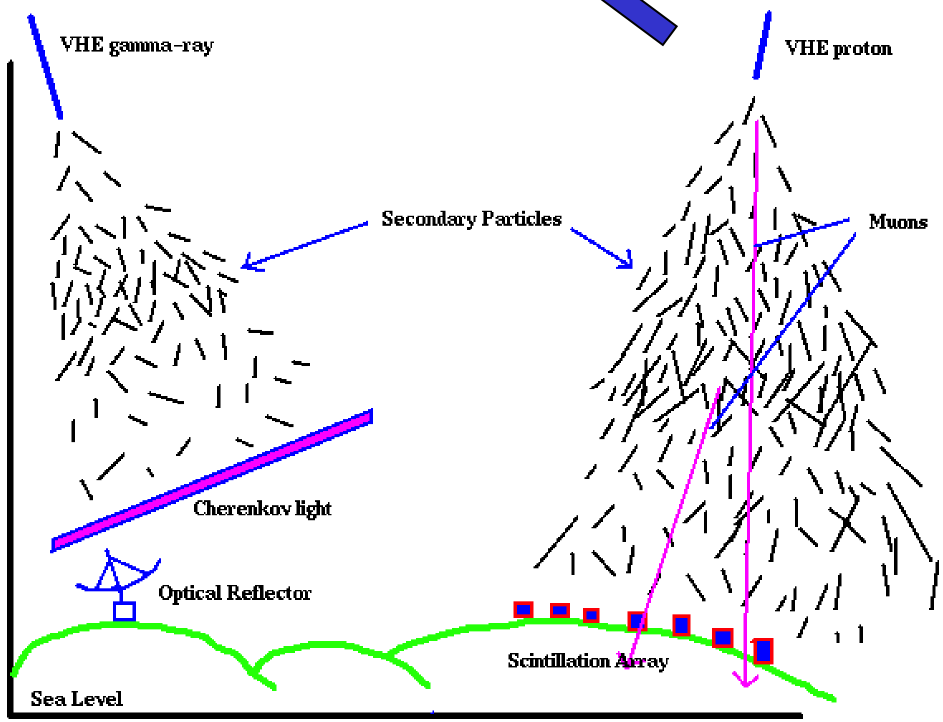
# Techniques for Gamma-ray Detection



Satellite (Fermi, AGILE, EGRET…) Detect the gamma-rays directly.

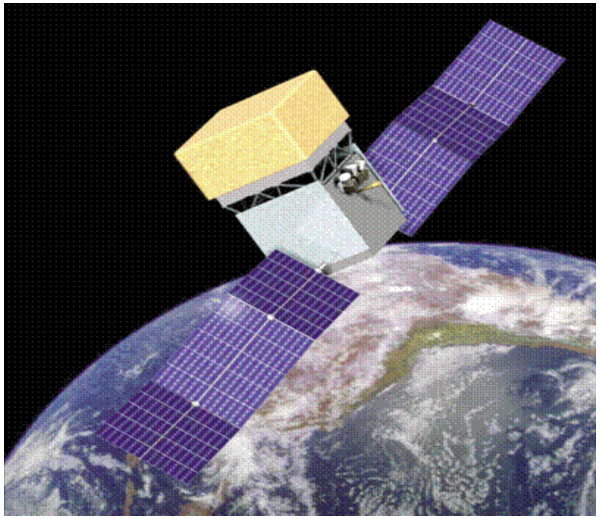



Atmospheric Cherenkov Telescope Array (HESS, MAGIC, VERITAS, CTA..) Detect Cherenkov light from air-shower particles as the traverse the atmosphere.

Ground Array (Milagro, Tibet, ARGO, HAWC…) Detect particles reaching ground level.

# Complementarity of Gamma-Ray Detectors

**Space-based**



**Imaging Air Cherenkov Telescopes**

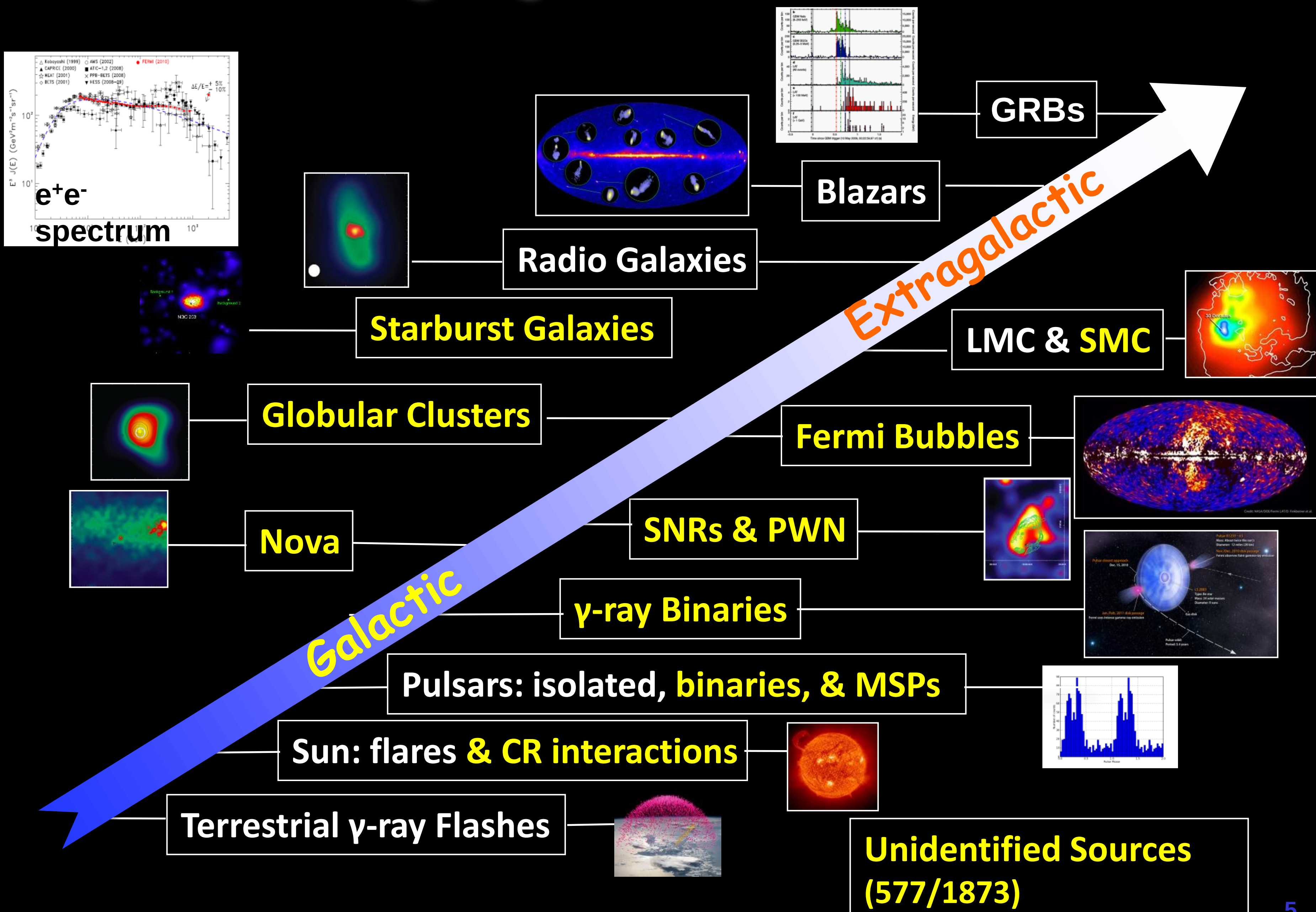
**Extensive Air Shower Arrays**

| | | | |
|---|---|---|---|
| Energy Range | 20-300 GeV | 0.05-50 TeV | 0.1-100 TeV |
| Area | small | Large | large |
| Background Rejection | Excellent | good | fair |
| Angular Resolution | good | excellent | good |
| Aperture | Large/all-sky every 3 hours | small | Large/~50% every day |
| Duty Cycle | 90% | 10% | 95% |

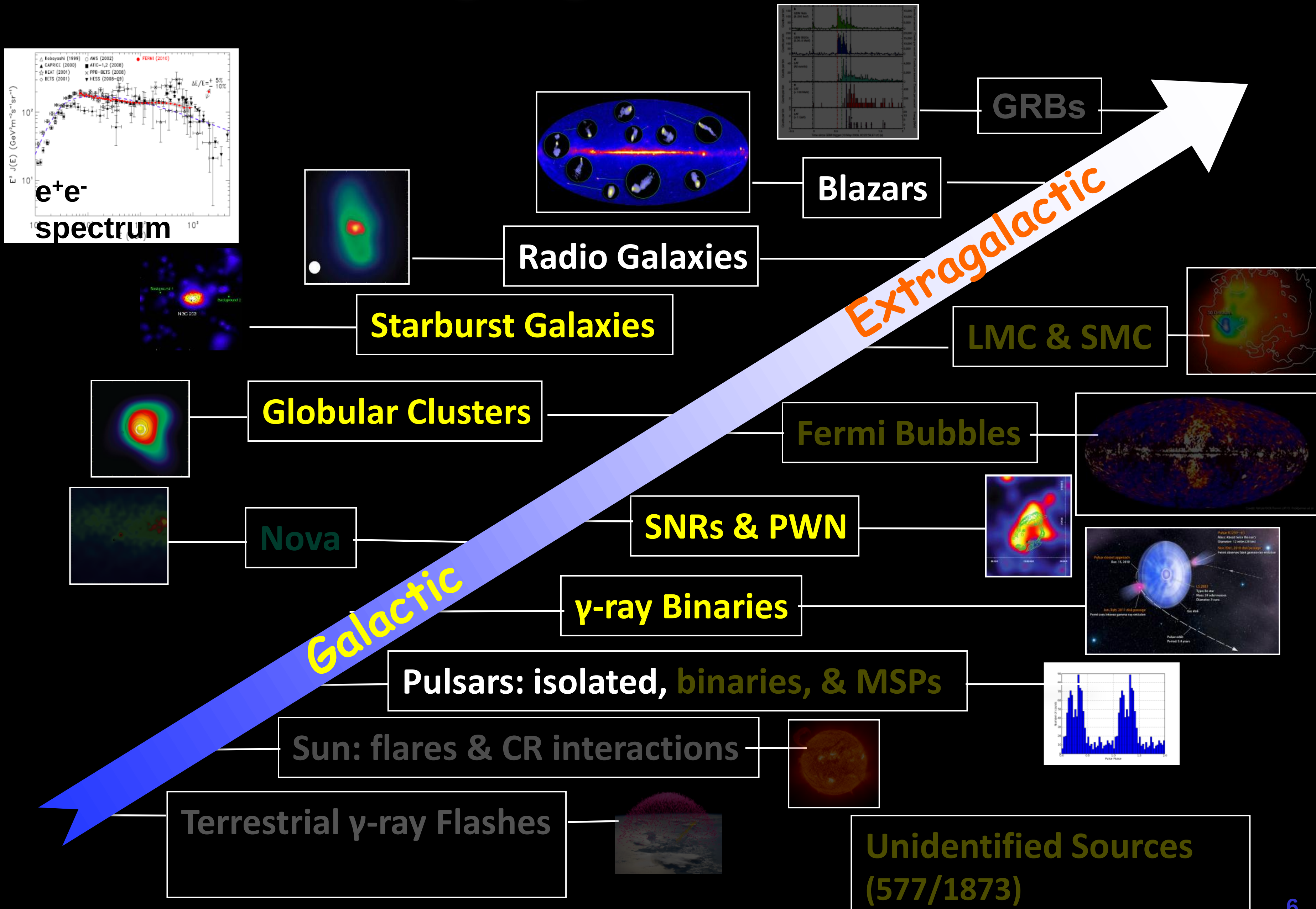
# GeV and TeV: a quick summary

- **~90s:**
  - **Relatively small overlap between GeV and TeV source catalogs**
  - **Energy gap between ~10 GeV and ~200 GeV**
- **~2000's**
  - **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**
- **~2100's**
  - **Explosion of GeV detections with AGILE and Fermi-LAT**
  - **Many correlated observations, joint GeV-TeV science comes of age**

# *Fermi* Highlights and Discoveries



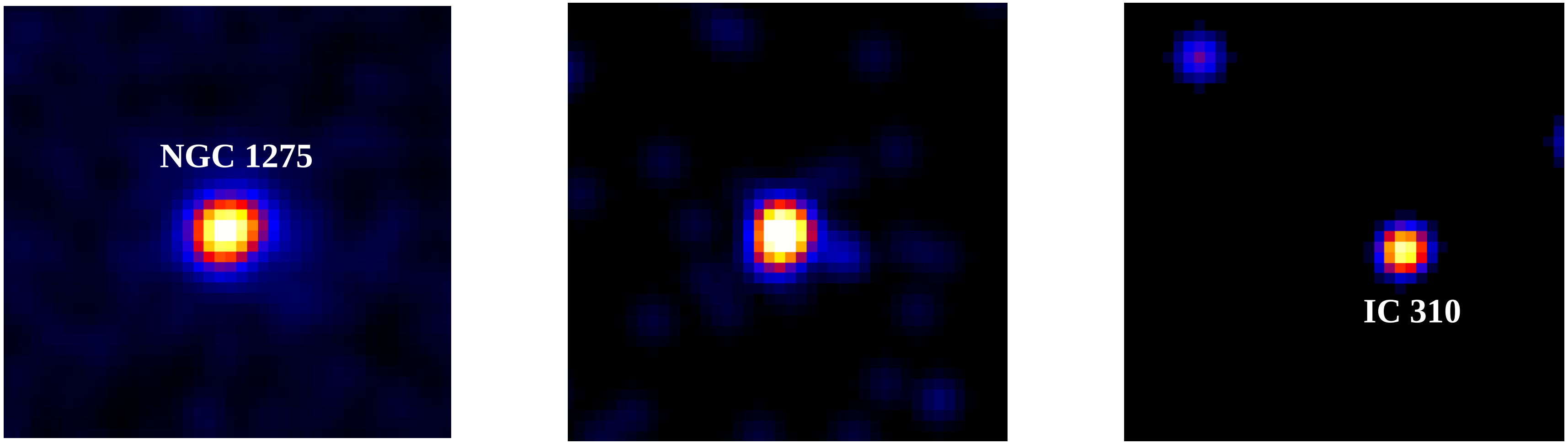
# GeV-TeV Highlights and Discoveries



# 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!

# Transition from GeV to TeV: An example

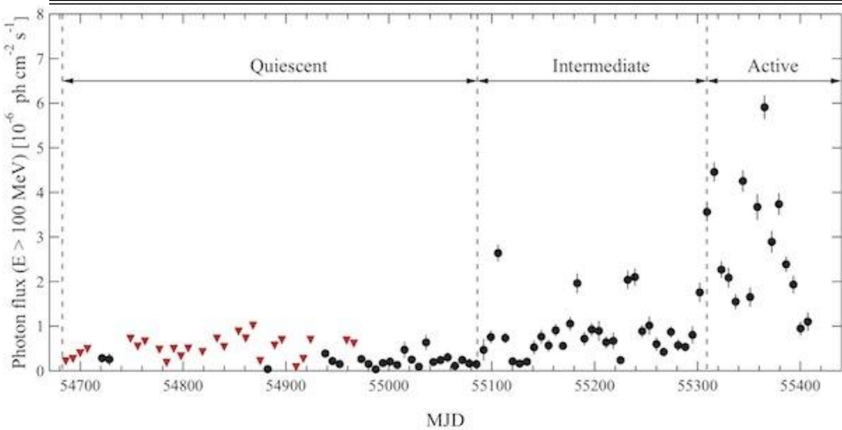



1-10 GeV 10-100 GeV >100 GeV

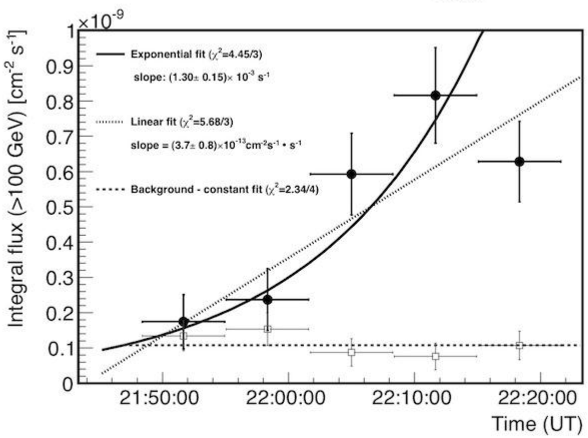
**At energies below 10 GeV, only the radio galaxy NGC 1275 (Perseus A) is visible, but above 10 GeV a second source (to the lower right) emerges. Above 100 GeV, only this source, the head-tail galaxy IC 310, remains. From Neronov et al (2010)**

**Observations by MAGIC revealed a TeV source**

# Ground and Space working together: 4C +21.35

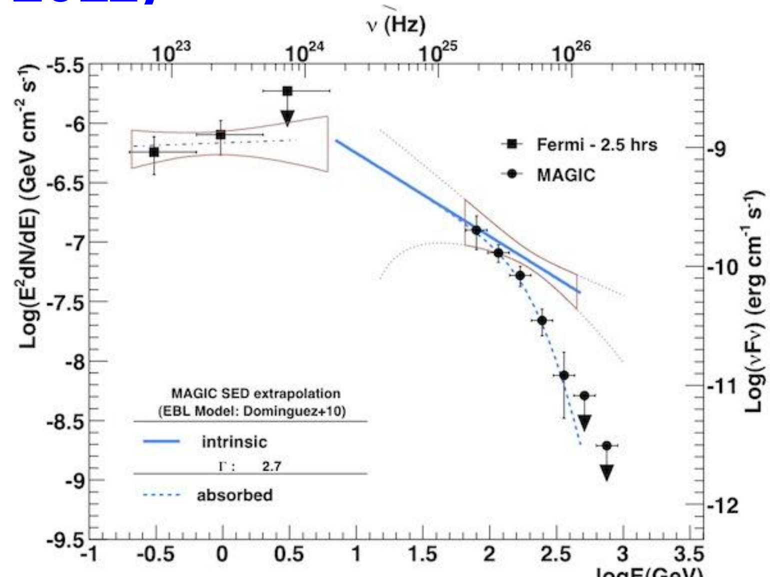



**After a long quiescent period, this blazar flared (Tanaka et al 2011). The Fermi-LAT and AGILE teams posted announcements**



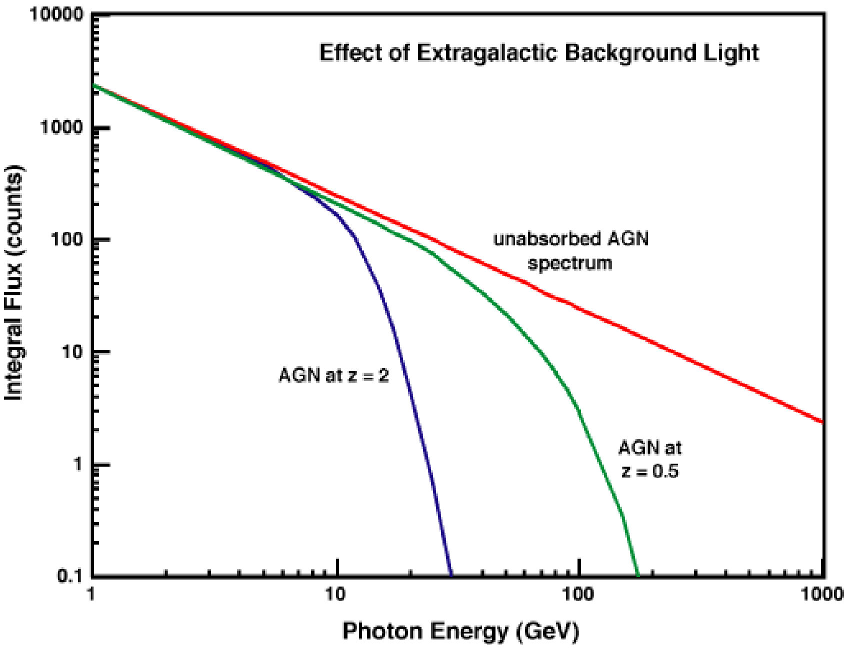

**MAGIC observed 4C +21.35 and found rapid variability on a scale of 10 minutes (Aleksić et al 2011)**

**Combining MAGIC and Fermi-LAT data produced this simultaneous Spectral Energy Distribution (Aleksić et al 2011)**



# Gamma-ray absorption

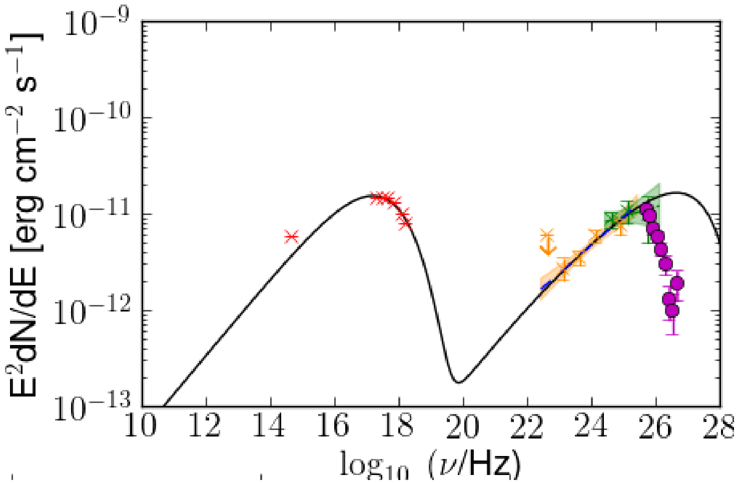
- **The Universe is largely transparent to gamma-rays below ~10 GeV - thus we can see to great distances in all directions.**
- **At higher energies gamma-rays are absorbed as they traverse intergalactic space by optical-UV photons.**
  - **Absorption depends on the distance to the gamma-ray source and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

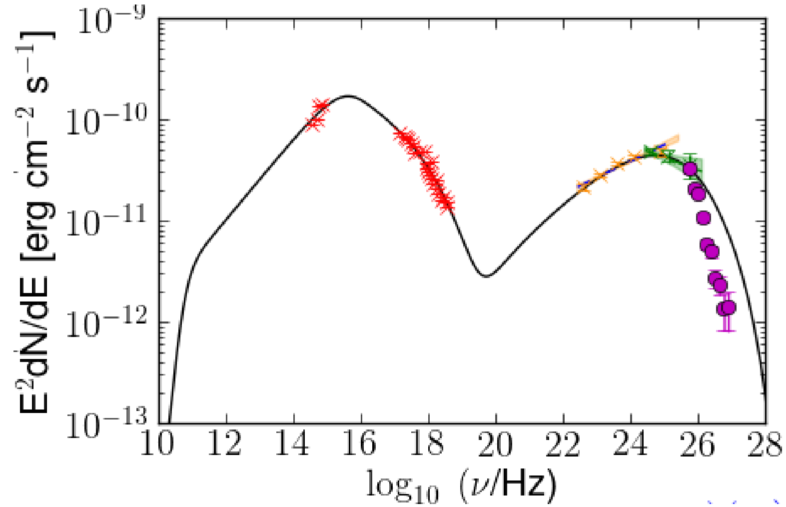



**The distance to active galaxies can be determined from optical observations.**

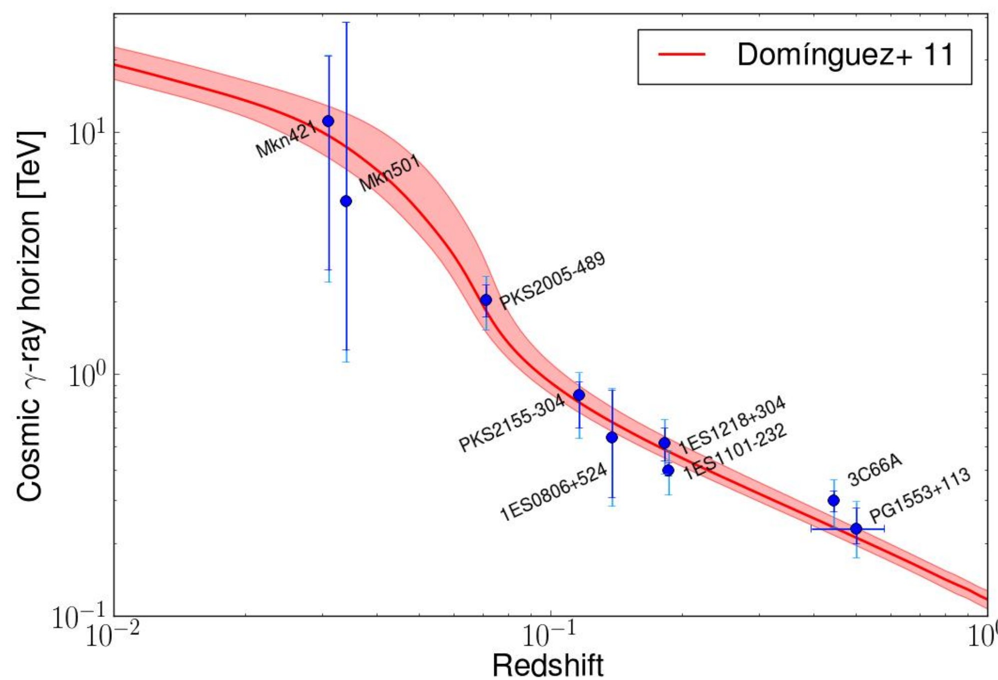
**Thus a measurement of gamma-ray cutoffs provides information on the optical-UV background -> galaxy and star formation as a function of time.**

# Extragalactic Background Light: combining GeV and TeV data



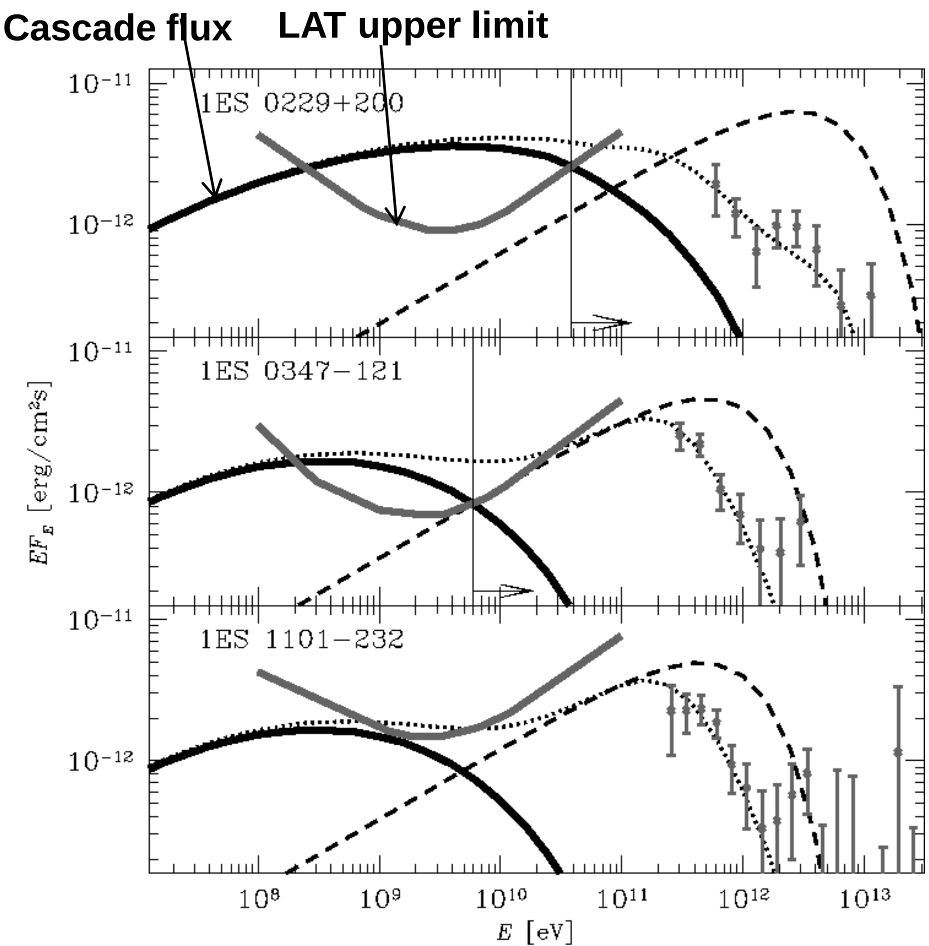

- **Emission model is fit to the data excluding the TeV, and then extrapolated to the TeV regime - the intrinsic TeV spectrum**
- **Difference between the VHE data and the extrapolation allow a determination of the EBL attenuation vs redshift**



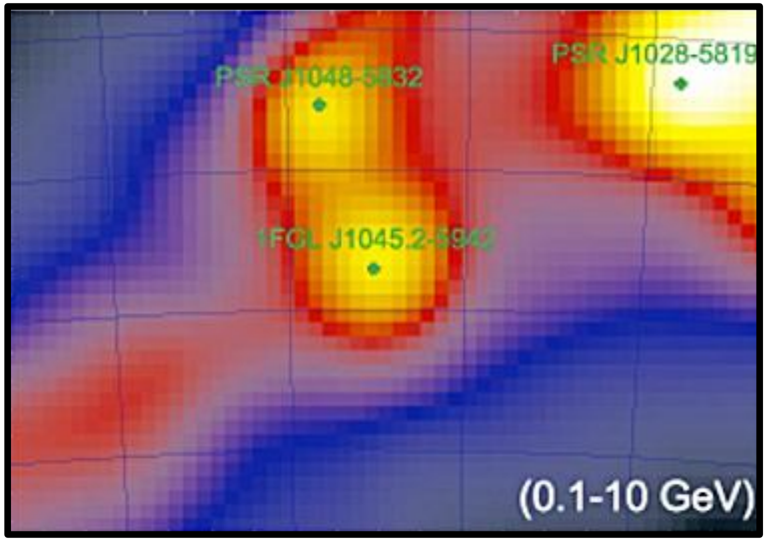
# Intergalactic Magnetic Fields

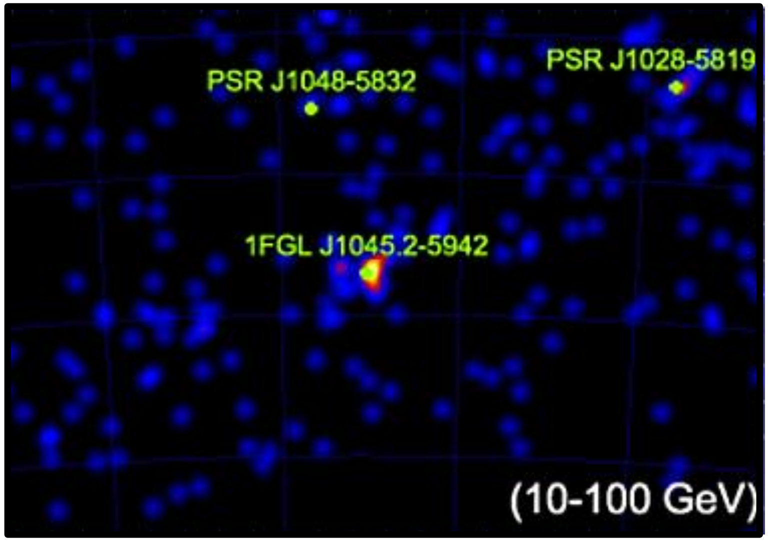
Blazar $\xrightarrow{\text{TeV } \gamma}$ EBL $\xrightarrow{e+e-}$ CMB $\xrightarrow{\text{GeV } \gamma}$

- **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)**

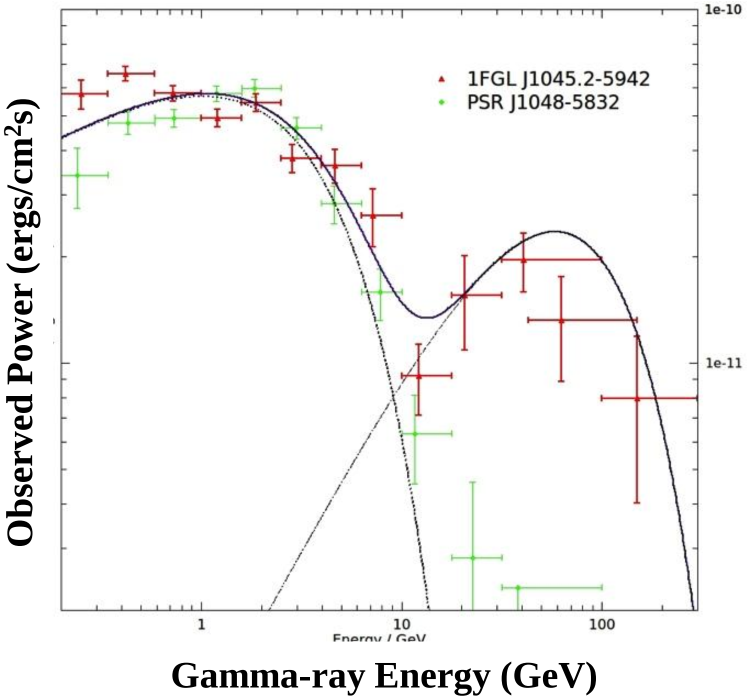


# Transition energy band: Galactic Sources



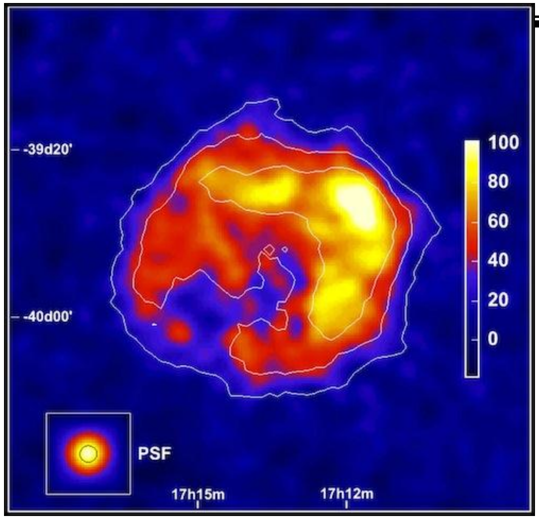




**The two bright pulsars seen below 10 GeV (top) fade above 10 GeV (bottom), while the third source (likely Eta Carinae) remains strong.**

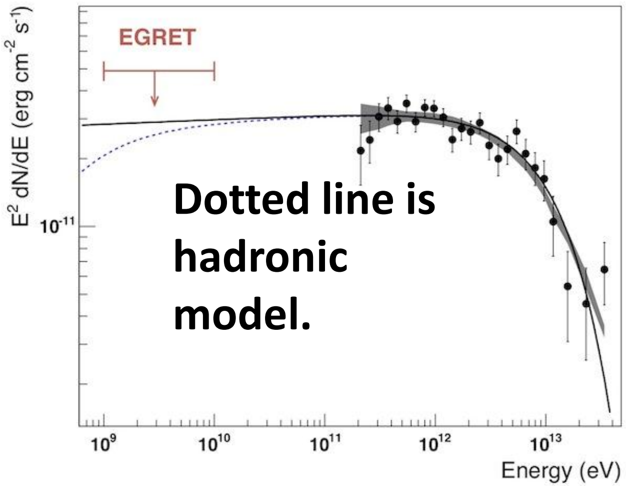


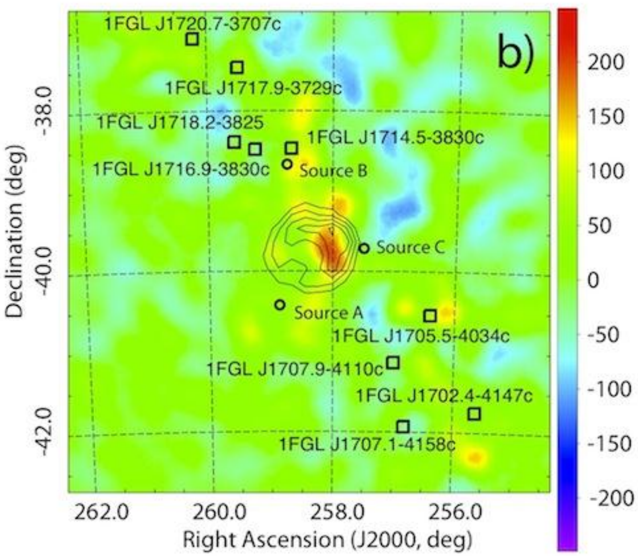

**The Eta Car source shows two components, one of which is only visible between 10 and 100 GeV.**

# Spatial and Spectral Studies

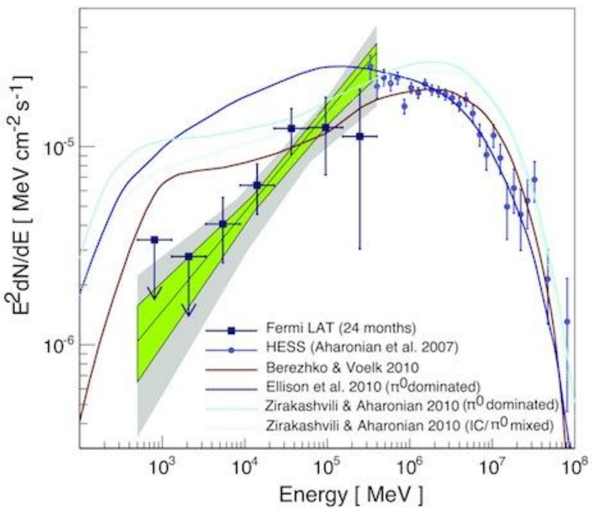



H.E.S.S. observations of supernova remnant RX J1713 provide a beautiful image, but the nature of the energy spectrum was uncertain (Aharonian et al. 2006).

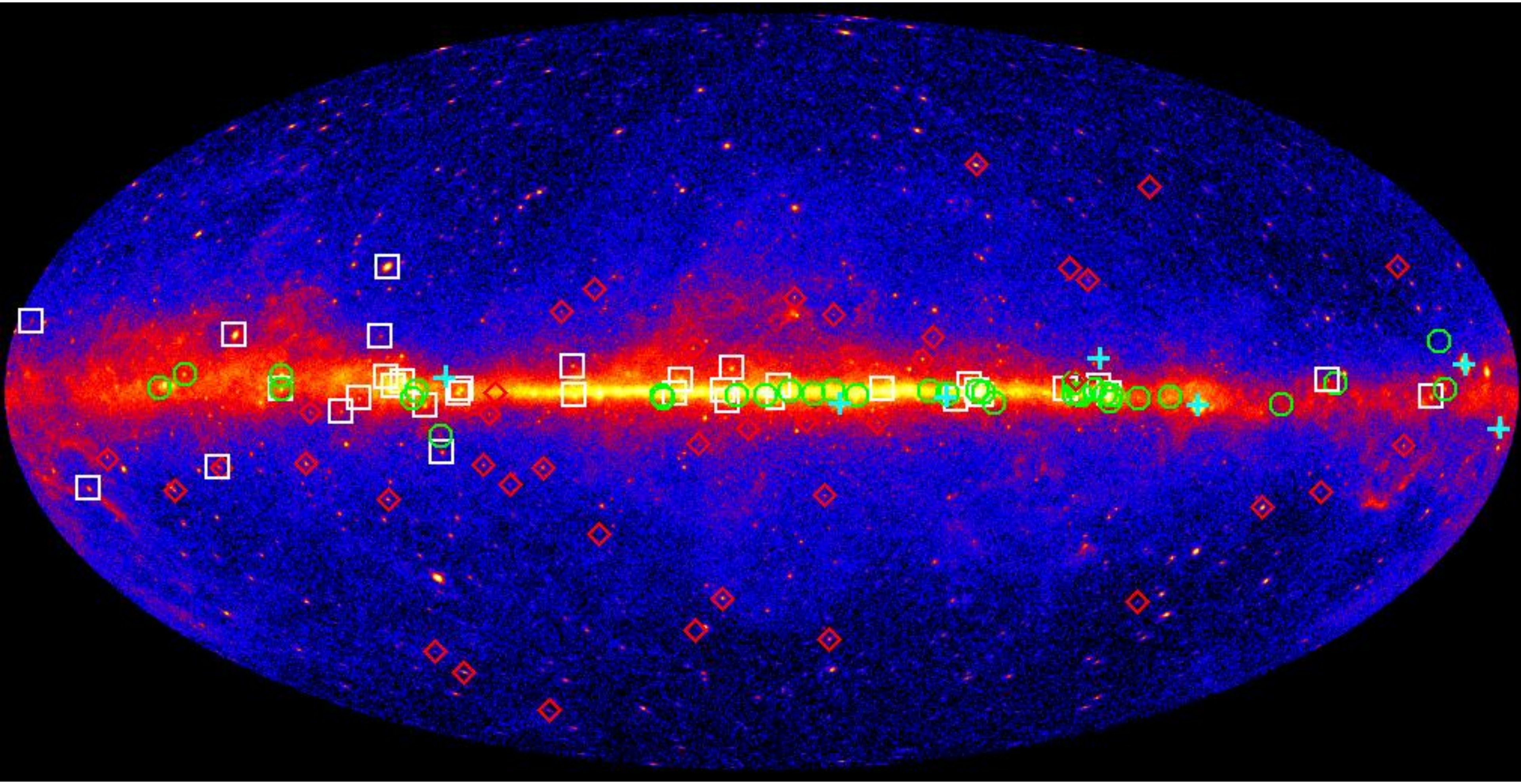



Fermi LAT image is not so clear, but the spectrum is dominated by a leptonic component.

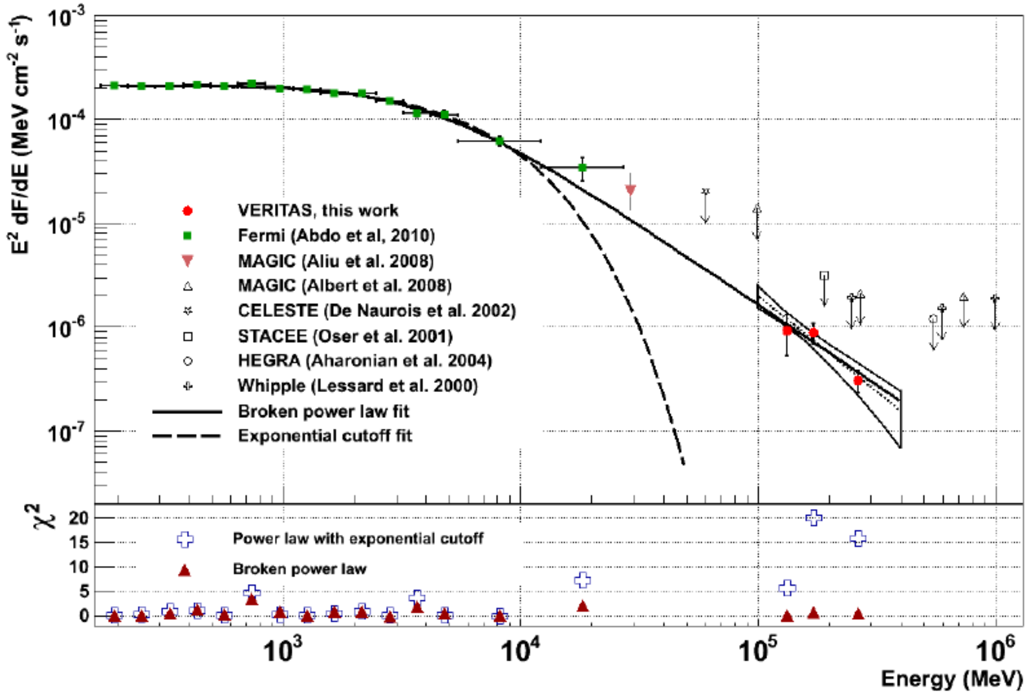


# 117 Gamma-ray pulsars



Shown above are the gamma-ray pulsars detected with the LAT superimposed on the 3 year, front-converting, ≥ 1 GeV sky map: CGRO PSRs(✚), young radio-selected (○), young gamma-selected(□), and MSPs(◇).

# Magic and VERITAS detection of the Crab Pulsar



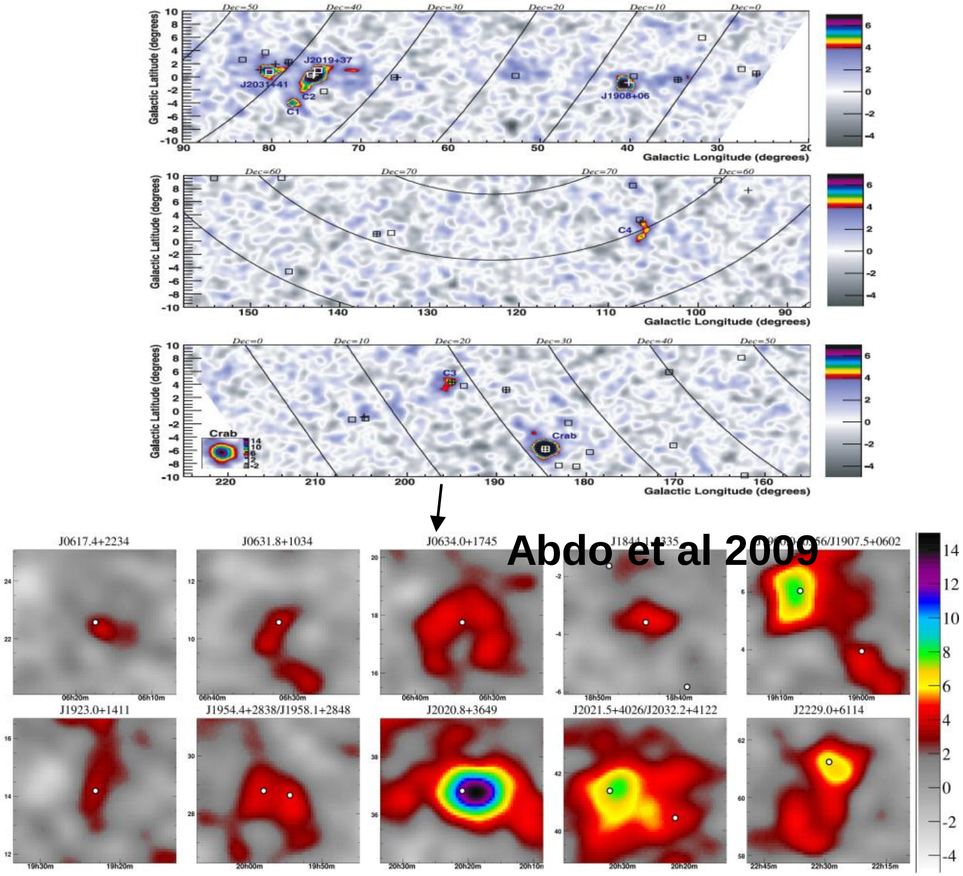

**Crab pulsar at 100 GeV? No theory predicted this!**

- **Above 100 GeV, peaks are narrower**
- **Cutoff of combined spectrum is not exponential (sub-exponential?)**
- **Extension of Fermi spectrum or separate component (inverse Compton)?**

- **Is the Crab unique or do other pulsars have > 100 GeV emission as well?**

# Pulsars and PWN

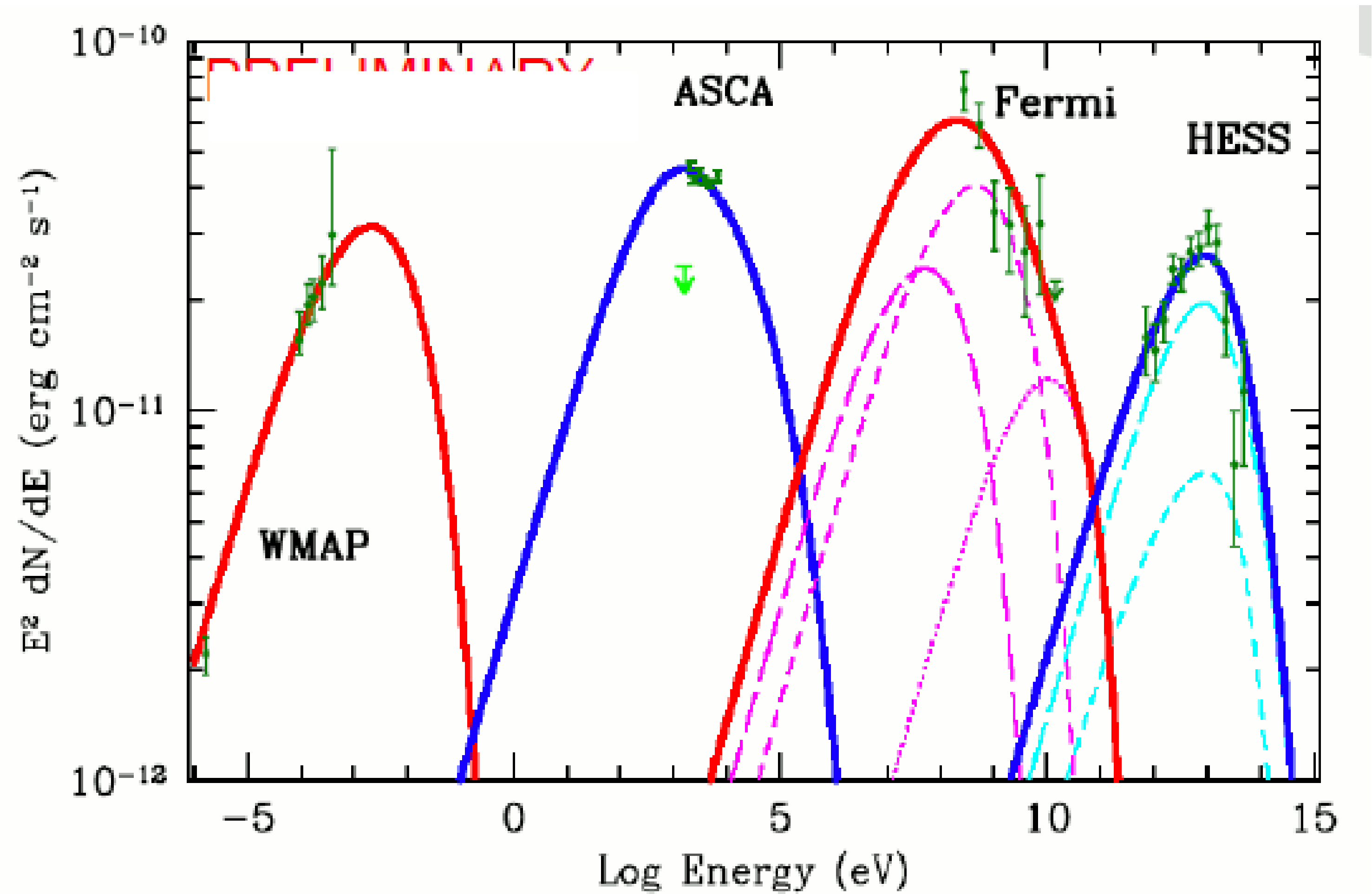
- Milagro observations (16/34 Galactic BSL sources with 3 sigma Milagro excess, 9 are pulsars)
- 7 of 8 previously known Milagro sources now associated with Fermi pulsars
- Fermi pulsars are likely powering the pulsar wind nebulae responsible for the TeV emission




Abdo et al 2009

Similarly, the Fermi-LAT detection of Terzan 5 globular cluster is likely due to MSPs, and the H.E.S.S. detection from accelerated pulsar wind particles

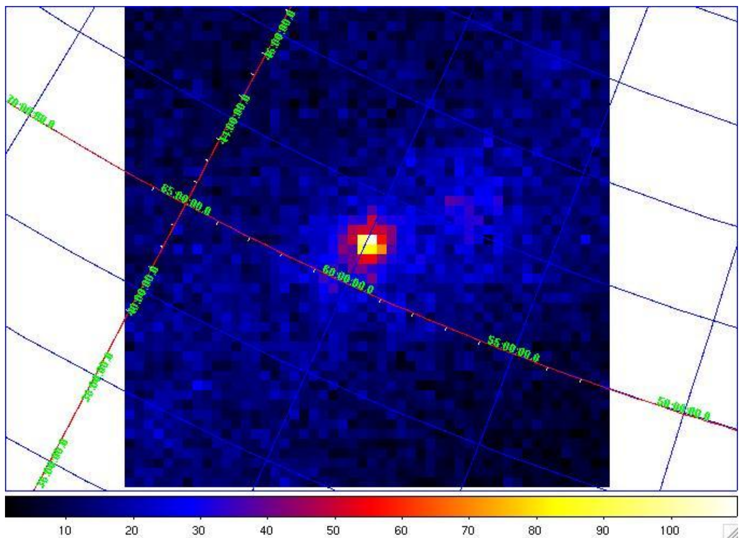
# Vela X – a pulsar wind nebula

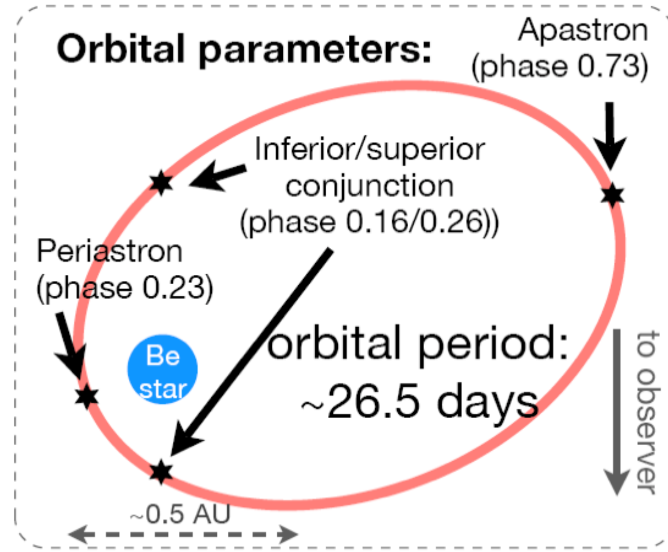



- **Strongly favors a two component model (suggested by deJager et al 2008): one young electron population for X-ray/VHE (cocoon) and a relic population for radio/GeV (halo)**

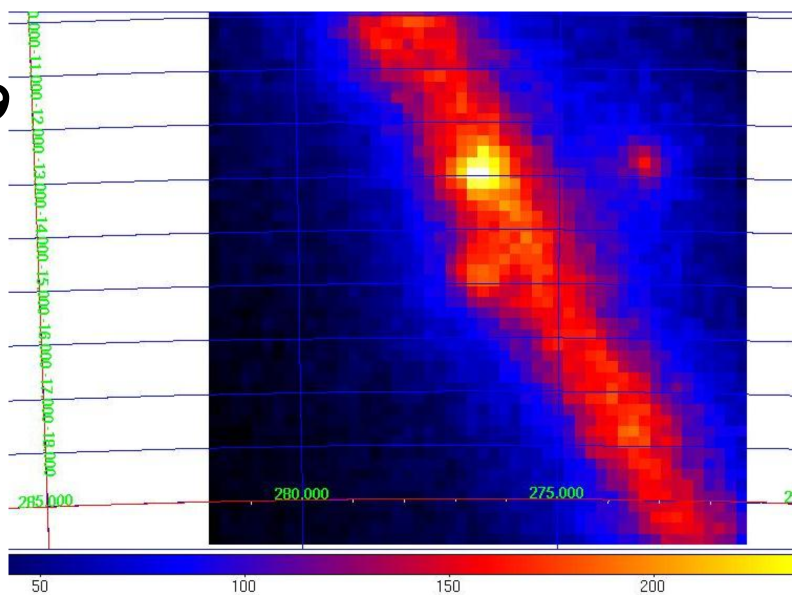
# Gamma-ray binaries – GeV and TeV at different phases!

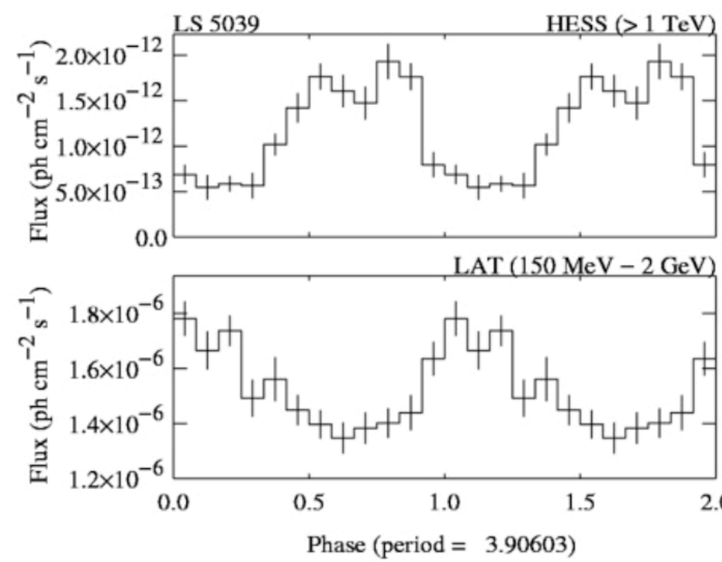
LSI +61 303 26.5 days





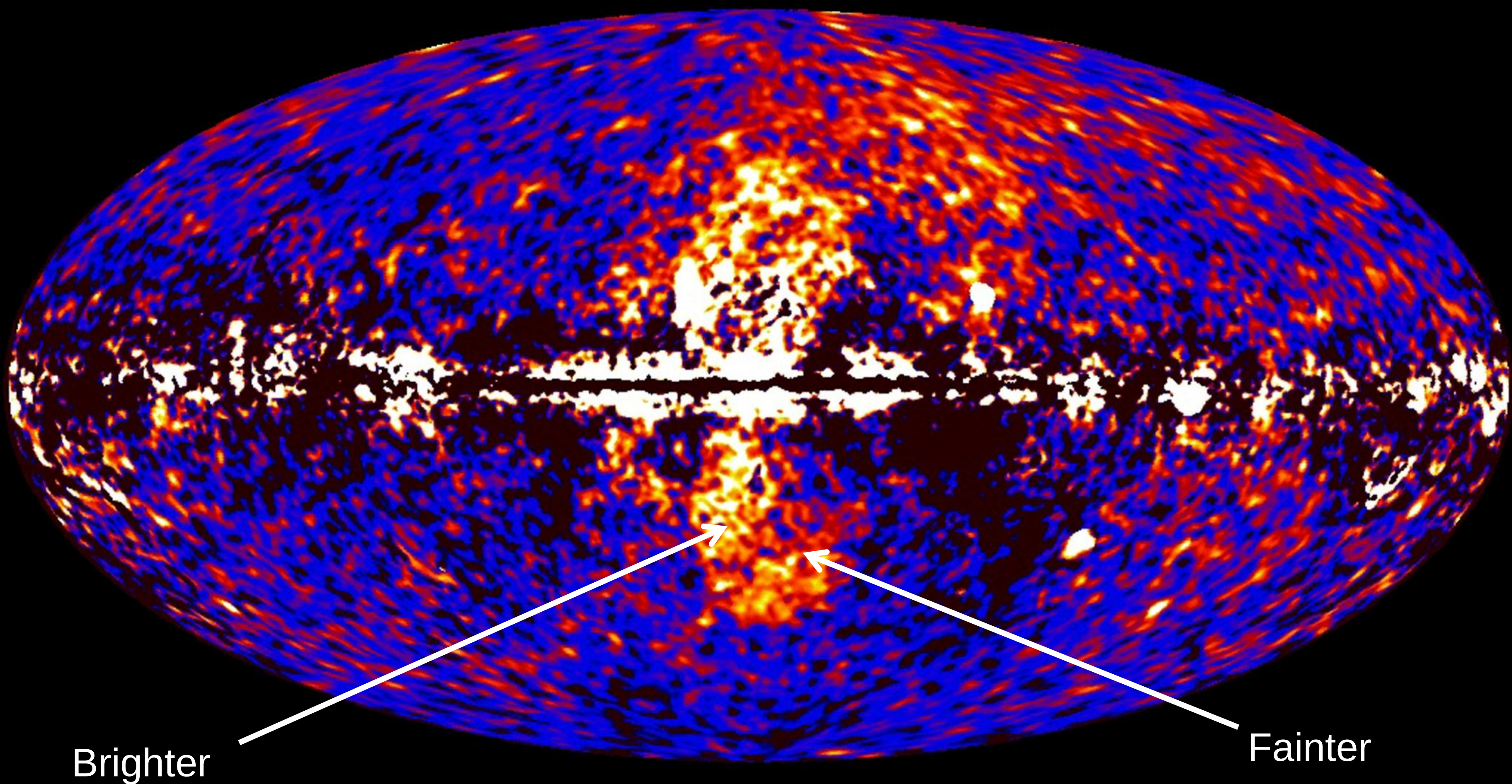

LS 5039 3.91 days





## Some things that we would like joint GeV-TeV detections, but haven't yet…

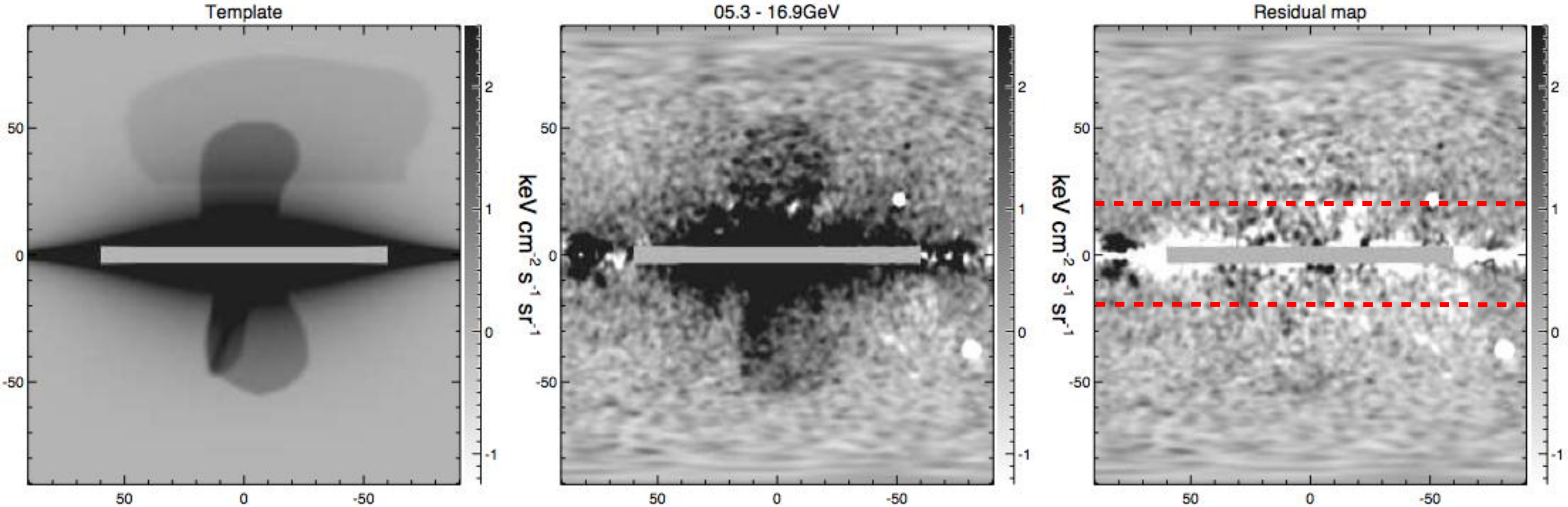
# Gamma-Ray Lobes




**The new structure consists of enormous bubbles extending about 50° north and south of the galactic center.**

Su, Slatyer and Finkbeiner, 2010

# Jets and Cocoon?




- Su and Finkbeiner (2012) suggested a gamma-ray cocoon and jet in the Fermi-LAT data
- Hard GeV spectrum (~$E^{-1.9}$)
  - Extrapolating the GeV spectrum to the VHE regime implies a VHE flux of ~0.01% Crab
  - Structure of the jet (knots etc) might be resolvable with CTA

# Indirect DM detection

## Satellites

Low background and good source id, but low statistics, astrophysical background

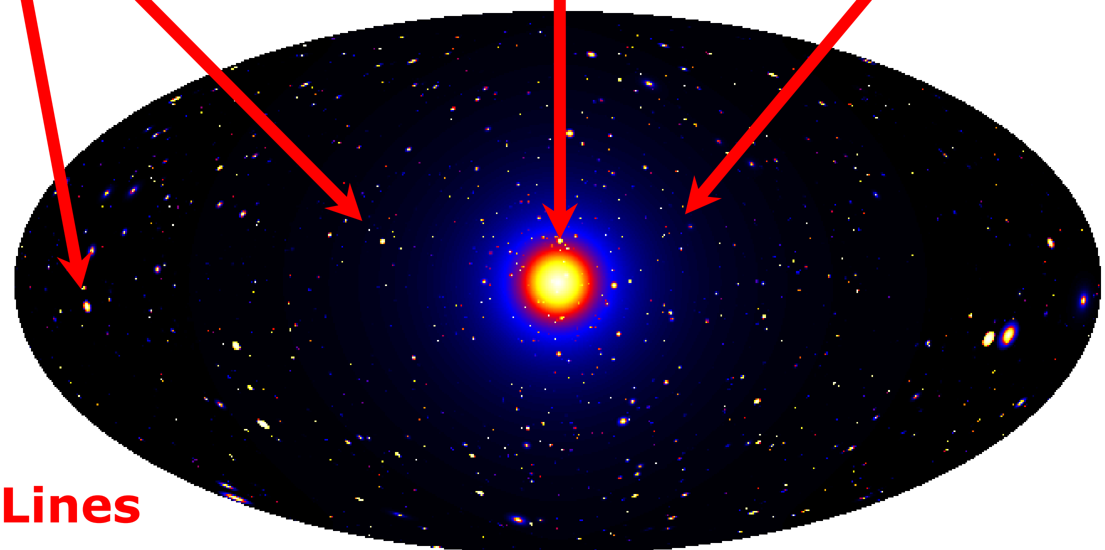
## Galactic Center

Good Statistics but source confusion/diffuse background

## Milky Way Halo

Large statistics but diffuse background

All-sky map of simulated gamma ray signal from DM annihilation (Pieri et al. arXiv:0908.0195)



## Spectral Lines

No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

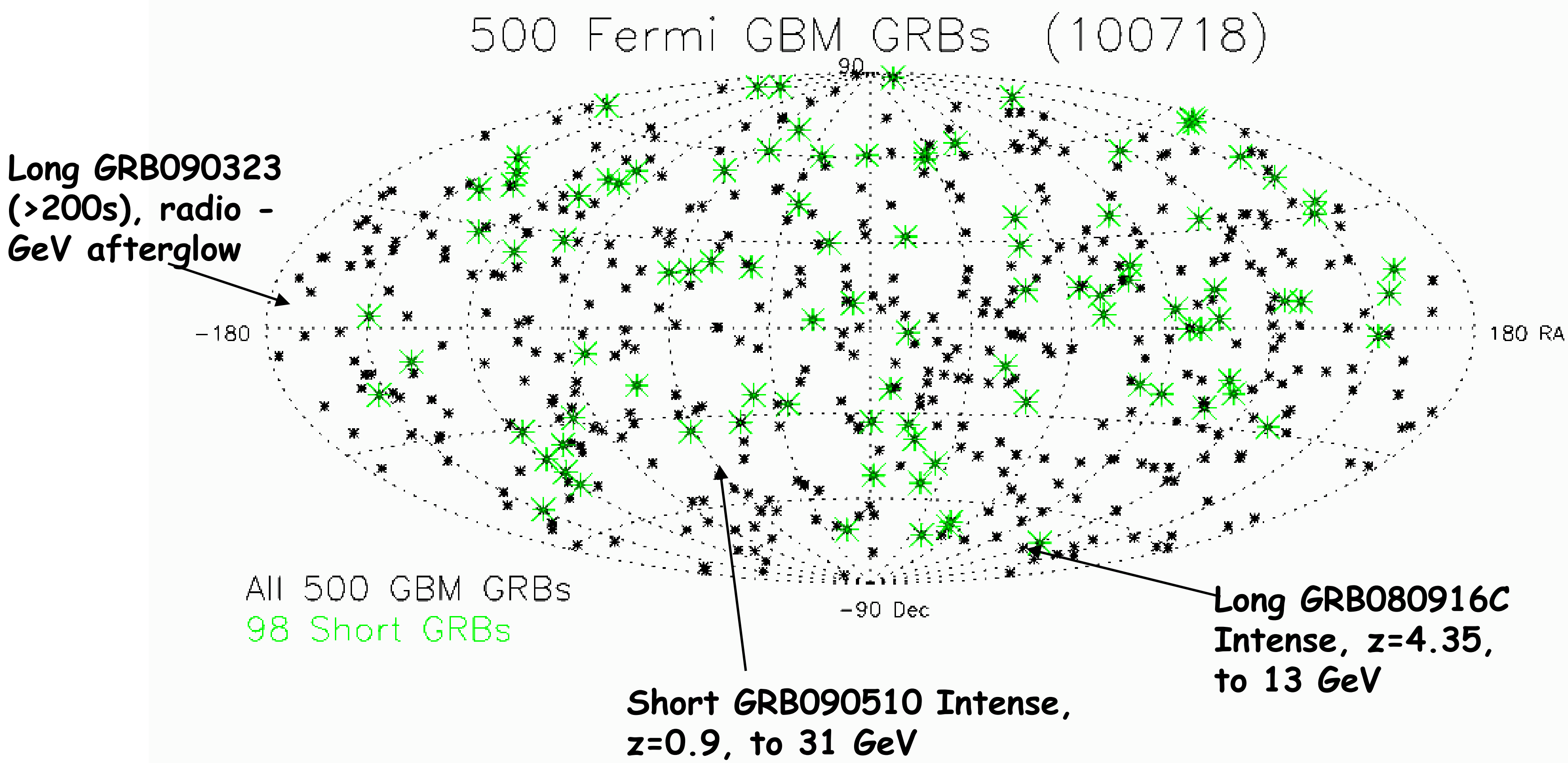
## Extra-galactic

Large statistics, but astrophysics, galactic diffuse background

Pre-launch estimates of sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

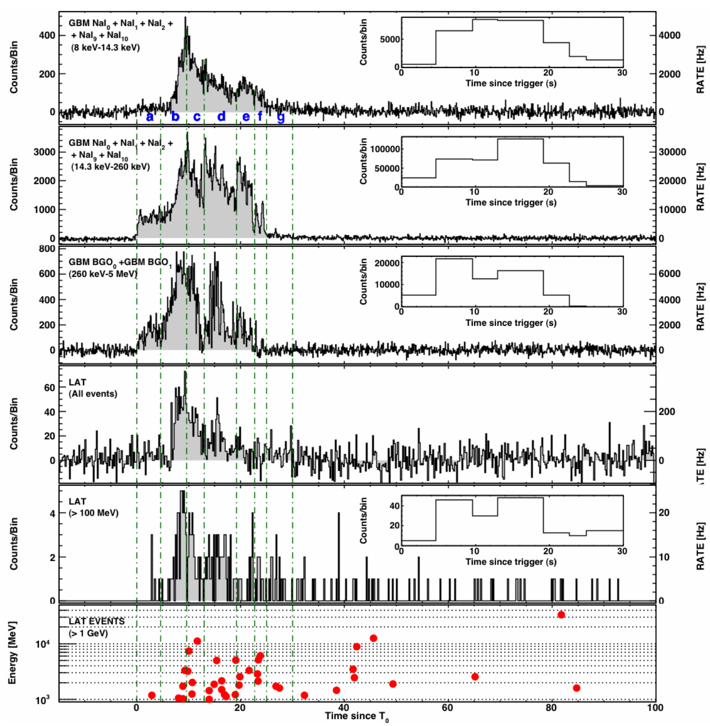
# Fermi Gamma-ray bursts

- **>1000 GRB detected by GBM**
- **18 long and 2 short bursts detected by LAT at GeV energies**

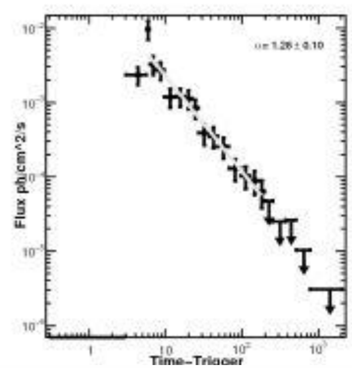


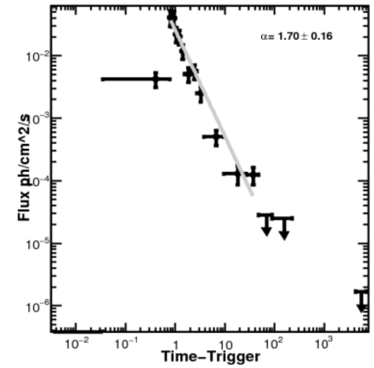
# GeV GRB Properties

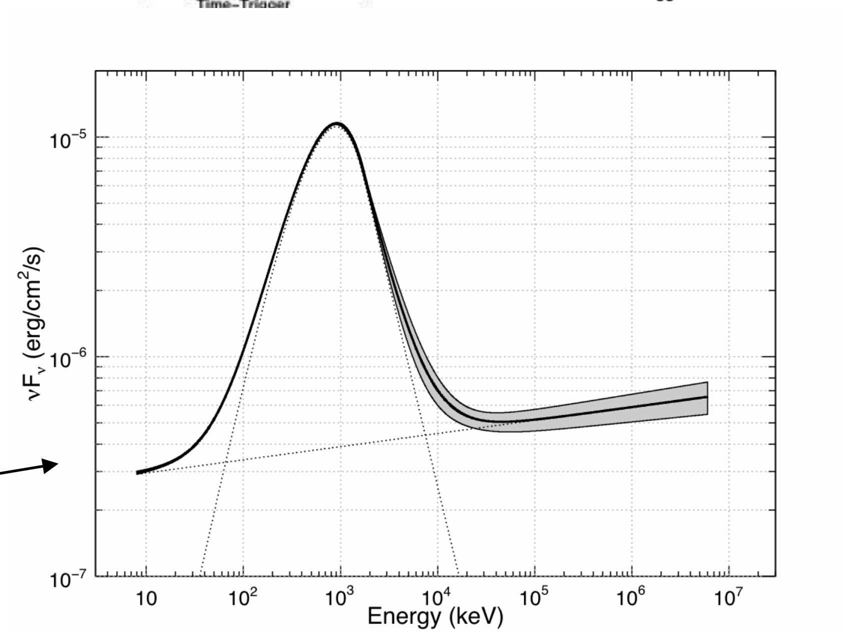
## Delayed onset of prompt emission




## GeV Afterglow with Powerlaw decay



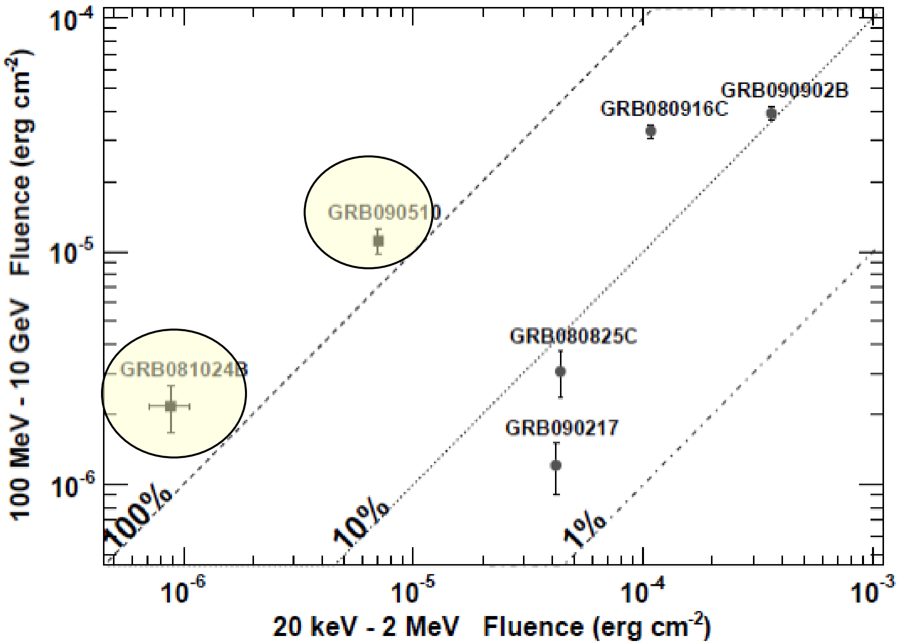




**Extra Spectral Component**

**Remarkably, these features are seen in most bright LAT-detected GRB!**

# Prospects for VHE detections




**Abdo, et al. 2010, ApJ, 712, 558**

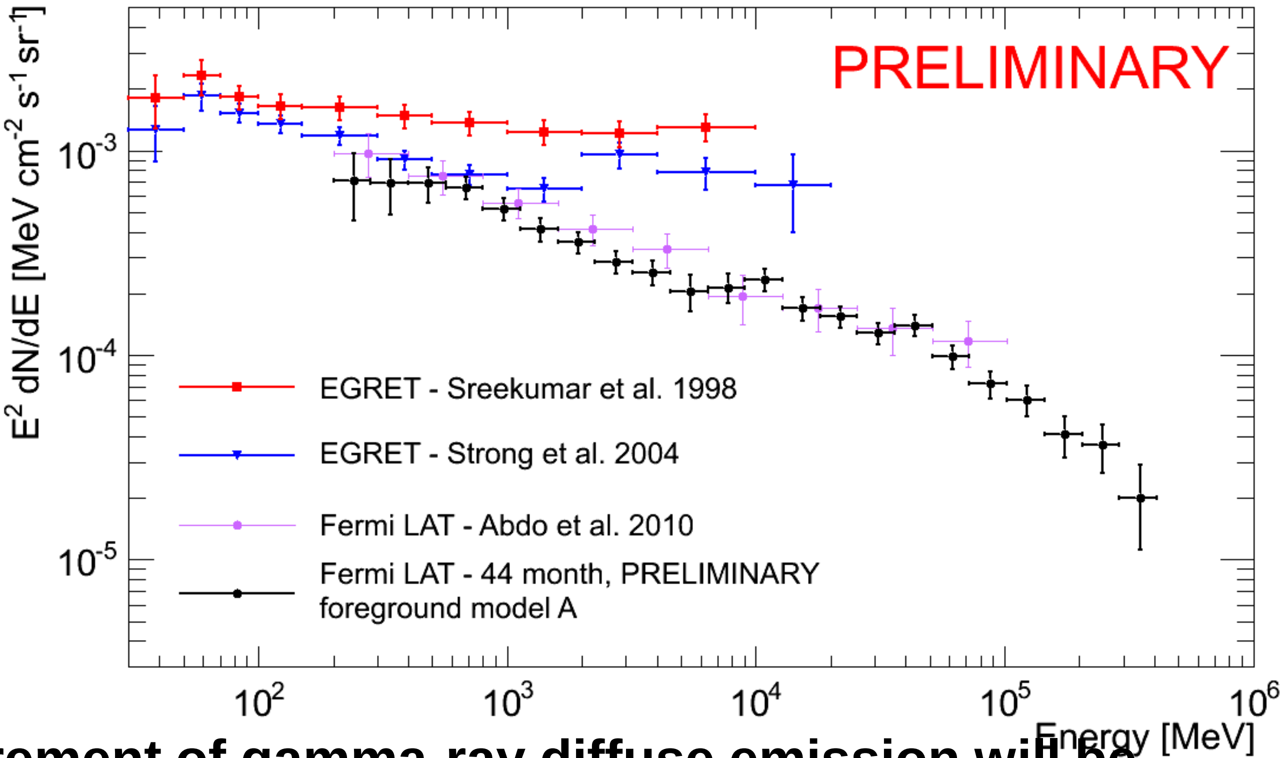
**Short GRBs appear to have systematically larger high-energy LAT/GBM fluence ratios**

**The Good news:**
*** Onset of high energy emission is delayed**
*** Hard spectrum component often seen**
*** HE emission extended in time (observations 30 mins after the burst still interesting)**

**The Bad News:**
*** Several bursts show high energy spectral cutoffs**
*** LAT detection rate relatively low**

**Great prospects for coordinated observations between CTA, HAWC and Fermi**

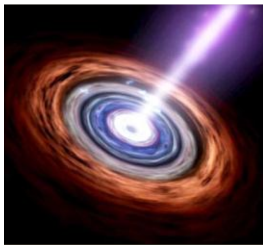
# Isotropic Gamma-ray Diffuse Emission




- **The measurement of gamma-ray diffuse emission will be extended to higher energies with**
  - **More data and improved event reconstruction**
- **Need a deep survey of point sources >100 GeV to determine the unresolved point source contribution to the background**
  - **Perfect for CTA!**

# The Origin of the Gamma-ray Background

## Undetected sources



Blazars

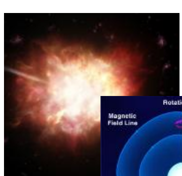
Dominant class of LAT extra-galactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%.

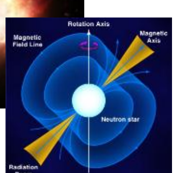
Non-blazar active galaxies

27 sources resolved in 2FGL
~ 25% contribution of radio galaxies to EGB expected. (e.g. Inoue 2011)

Star-forming galaxies

Several galaxies outside the local group resolved by LAT. Significant contribution to EGB expected. (e.g. Pavlidou & Fields, 2002, Ackermann et al. 2012)

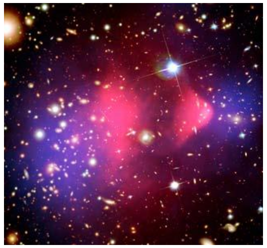





GRBs
High-latitude pulsars

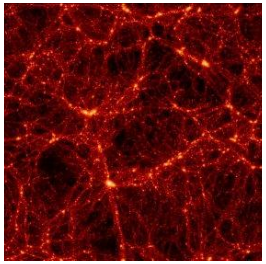
Small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

## Diffuse processes



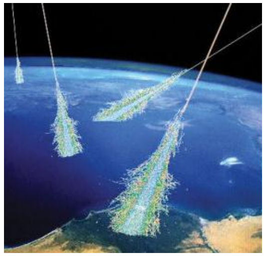
Intergalactic shocks

Widely varying predictions of EGB contribution ranging from 1% to 100% (e.g. Loeb & Waxman 2000, Gabici & Blasi 2003)



Dark matter annihilation

Potential signal dependent on nature of DM, cross-section and structure of DM distribution (e.g. Ullio et al. 2002)



Interactions of UHE cosmic rays with the EBL

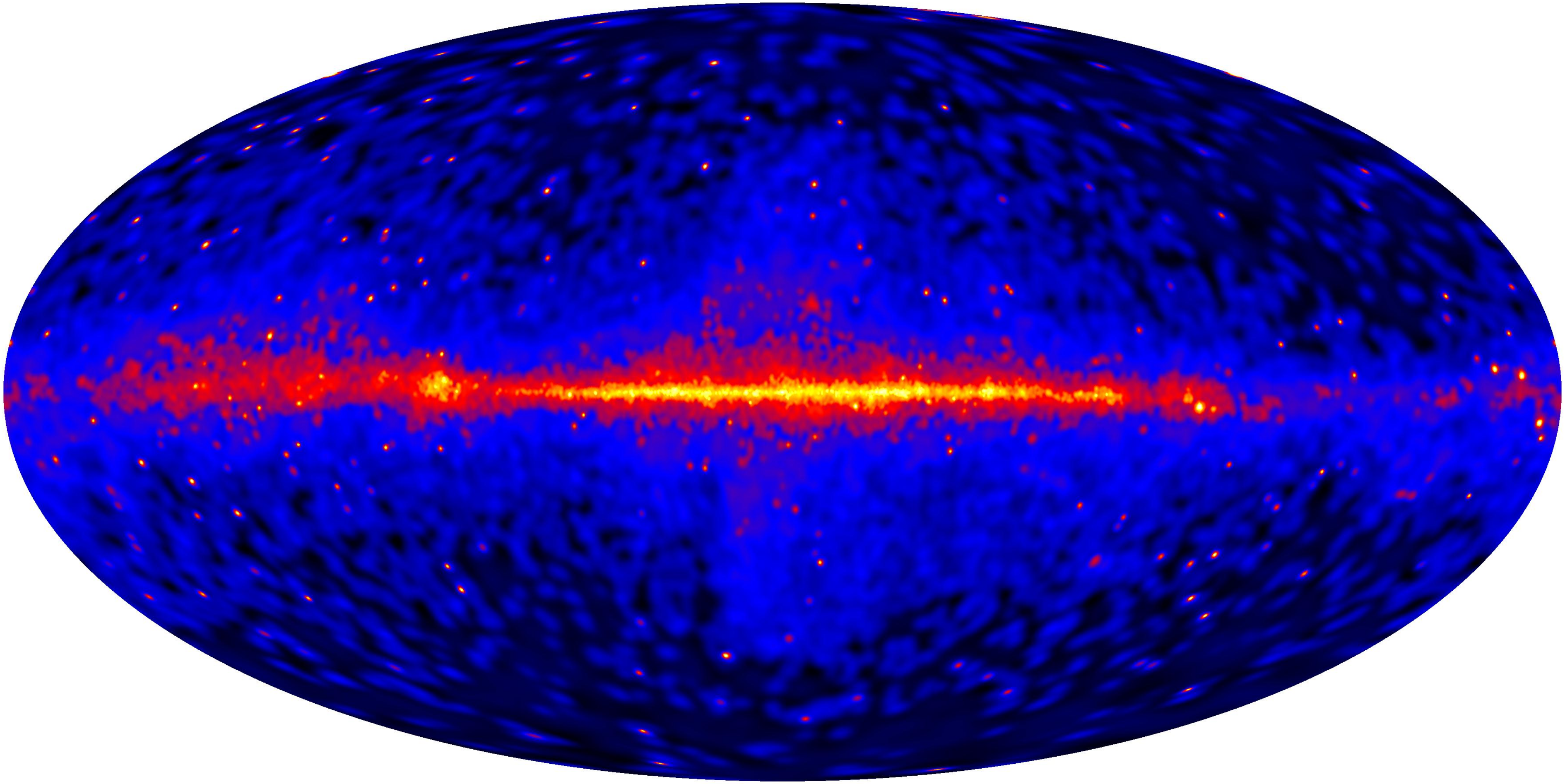
Dependent on evolution of CR sources, predictions varying from 1% to 100 % (e.g. Kalashev et al. 2009)

Extremely large Galactic electron halo (Keshet et al. 2004)

CR interaction in small solar system bodys (Moskalenko & Porter 2009)

# The Future

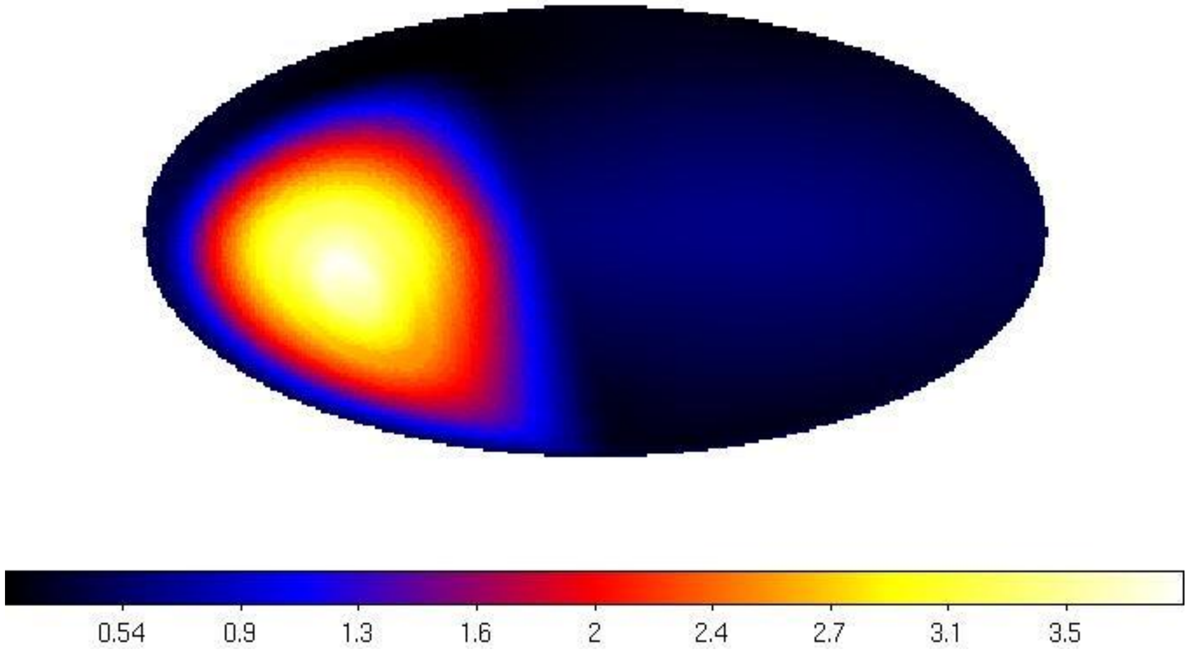
# Evolving sensitivity



- **Fermi-LAT sensitivity increases as sqrt(t) at low energies but linearly with time at high energies**
  - **Increase energy reach of Fermi**

# Observation Strategy: An opportunity

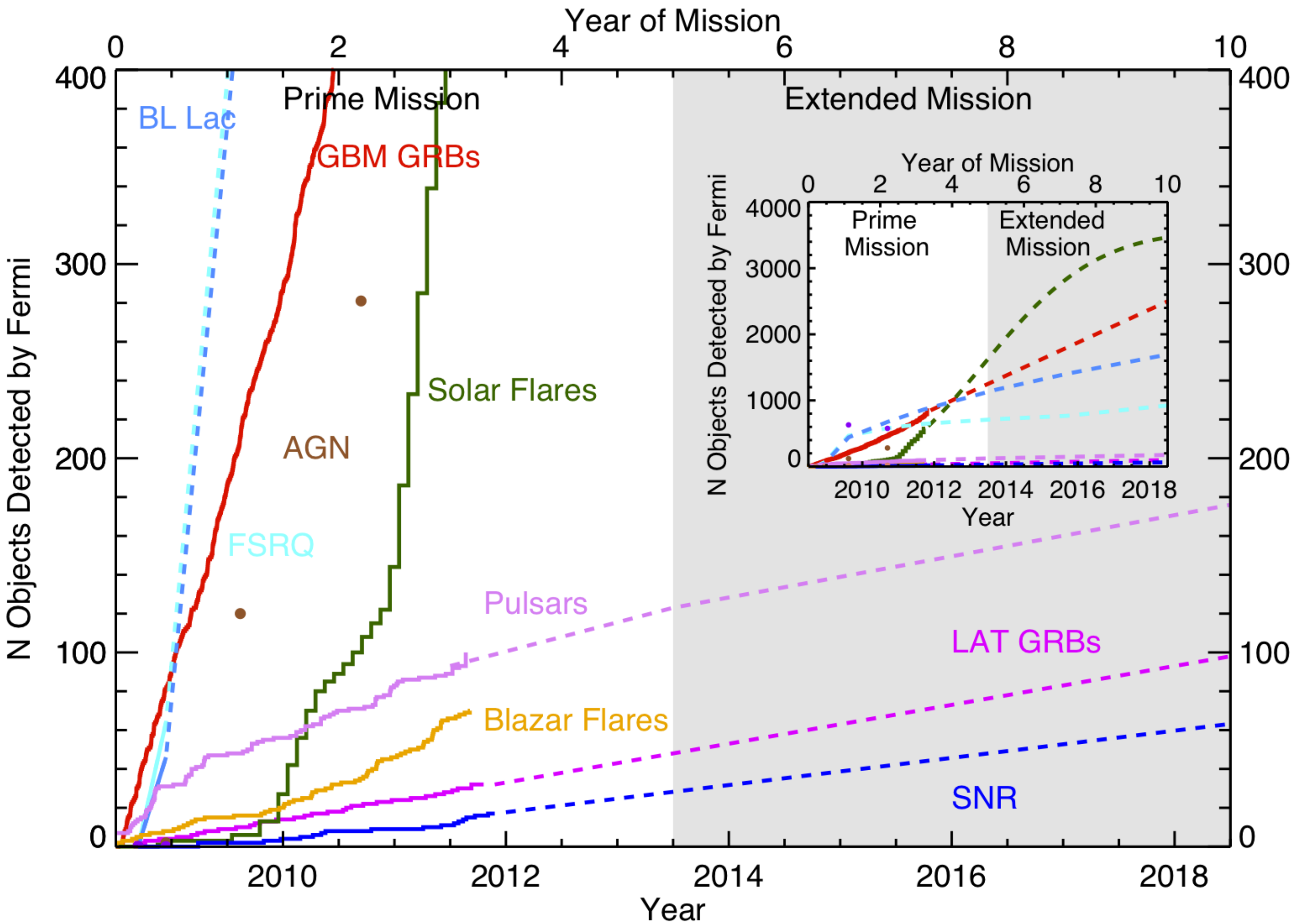
Ratio of exposure for a pointed observation at Galactic Center compared with survey mode




- **Pointed mode observations can increase exposure by factor of 2.5-3.5 (depending on declination) relative to all-sky survey mode**
- **Call for white papers describing desired observing strategies in Jan 2013, due by April/May 2013, review June/July 2013**

# More gamma-ray sources

- **Increasing flux sensitivity**
  - **More sources from known source classes - population studies!**



# Summary

- Joint GeV and TeV astrophysics has come of age!
  - Many compelling questions require the complementary capabilities of ground and space-based gamma-ray detectors
- We have only scratched the surface of what Fermi can do.
  - The gamma-ray sky is constantly changing, so there is always something new to see.
  - The energy range of Fermi increases - open new discovery space
  - Improved sensitivity allows the detection of new sources and the study of fainter details in existing objects
  - New observatories and experiments bring new meaning and relevance for Fermi data
  - The analysis and reconstruction are constantly being improved, so future capabilities are increasing faster than sqrt(t).
- Many enhancements at VHE range
  - Short term (HAWC, HESS2 etc)
  - Longer term – CTA
- Lots of new discoveries to come!

# Analysis Initiatives: LAT

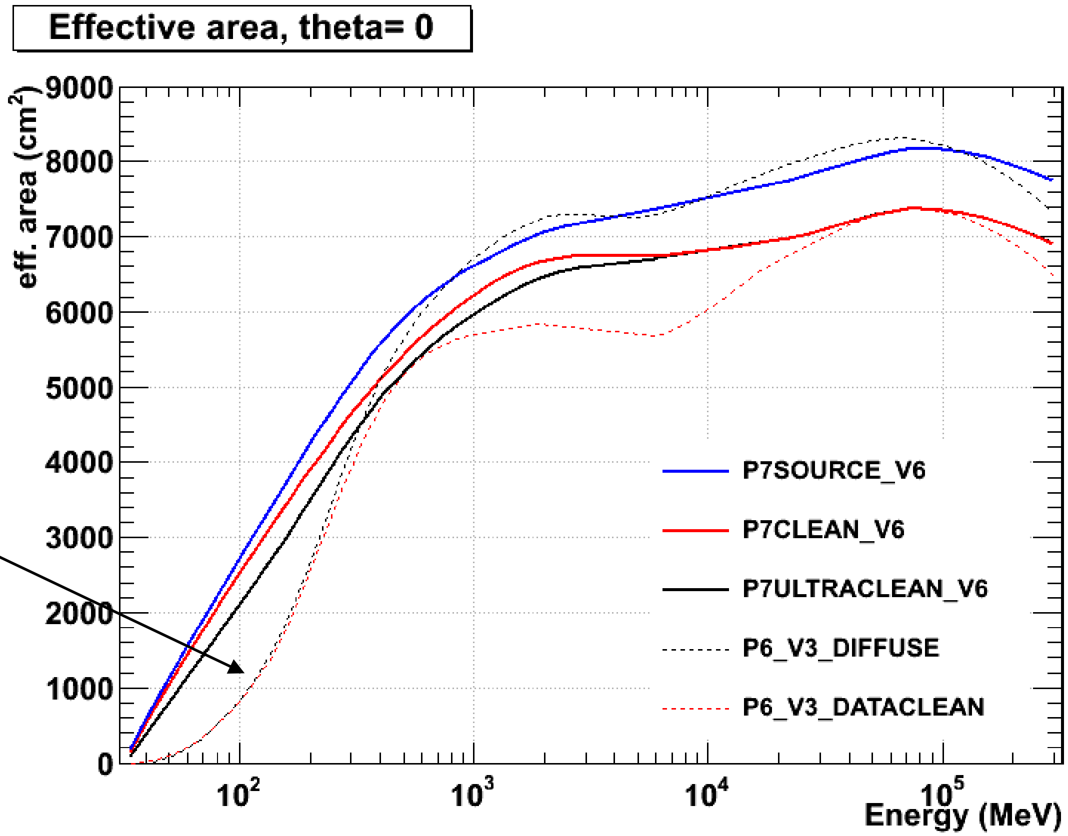
**The LAT collects a significant amount of information for each gamma-ray event - Extensive scope for analysis/configuration improvements tailored to specific science questions or scenarios**

- **Extensive rework of low-level algorithms is currently in progress**
  - **Improve PSF (especially at high energy)**
  - **25% increase in effective area**
  - **Expand energy range**
    - **Down to 20 MeV (increase effective area by factor of 3 below 100 MeV)**
    - **Up to 2 TeV (better handling of cal saturation)**
  - **Above 50 GeV use calorimeter only events to get additional 30% increase in effective area**

# What next for Fermi?

- We have only scratched the surface of what the Fermi Gamma-ray Space Telescope can do
- The gamma-ray sky is highly variable
  - Surprises - always something new to see
  - Long duration AGN lightcurves
  - Binary systems with long orbital periods
  - ….
- Increasing flux sensitivity (especially at high energies)
  - New classes of gamma-ray sources
  - More sources from known source classes - population studies!
  - Improved constraints on dark matter (or detection!)
- New observatories coming online
  - Unique opportunities for joint gravitational wave/photon detections of binary mergers with advanced LIGO and Fermi.
- Sun is waking up
  - Study the Sun as a GeV accelerator

# Analysis improvements




Pass 7 data released in August 2011

Note the large boost in Aeff at low energies

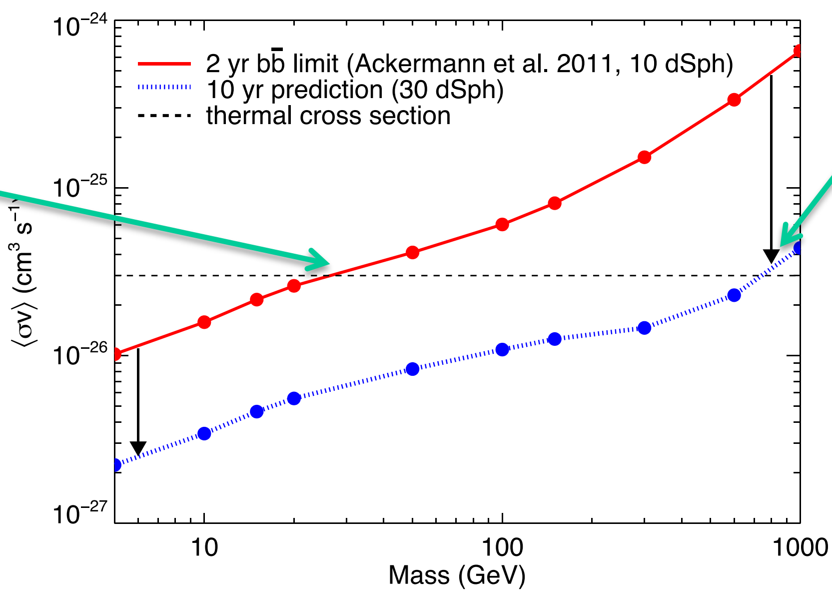
- The LAT is a complex instrument providing much scope for improvements in many areas including
  - Event selection (improve background rejection and gamma-ray retention)
  - Improving knowledge of instrument performance - this allows higher level analyses to be more finely tuned and reduces systematic uncertainties

# Increasing the Energy Reach

- **LAT sensitivity improves more quickly at high energies**
  - Opening a window into source populations above 50 GeV
  - Enabling measurement of expected spectral features in the extragalactic diffuse background above 300 GeV
  - Either revealing dark matter signatures or severely constraining popular WIMP models of dark matter

**Current limit excludes WIMP masses up to ~30 GeV**

**Dark Matter Limits from Dwarf Spheroidals**

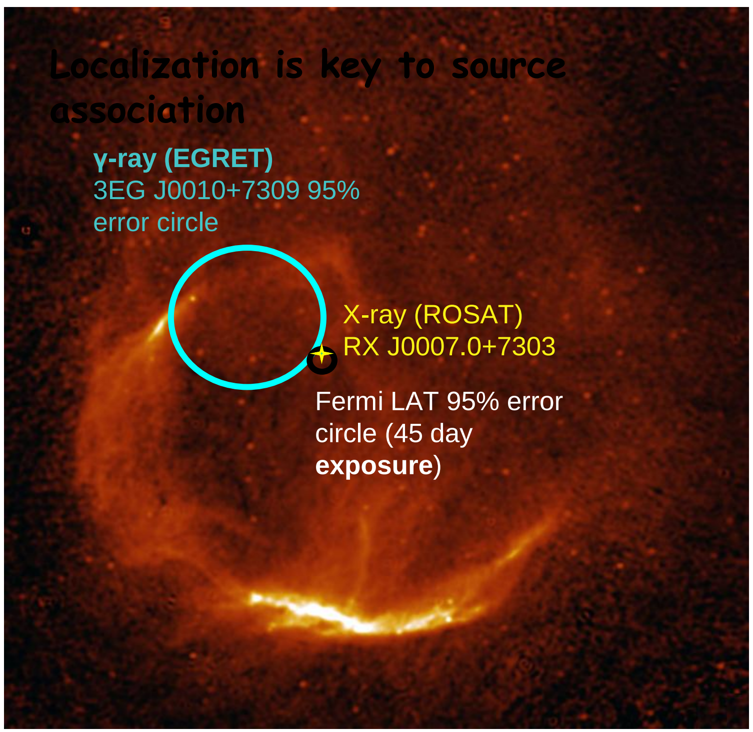



**After 10 years of data, the predicted Fermi limit will exclude WIMP masses up to 700 GeV**

**The leading candidate for particle dark matter, the WIMP, decays or annihilates ultimately producing Y-rays**

# Improved Localization

**~30% of *Fermi* catalog sources are not associated with a counterpart – some probably belong to new classes of gamma-ray emitters waiting for IDs!**




CTA 1: DRAO 1.4 GHz

- **Localization area**

**$\lesssim$ 1/(observation time) × flux**

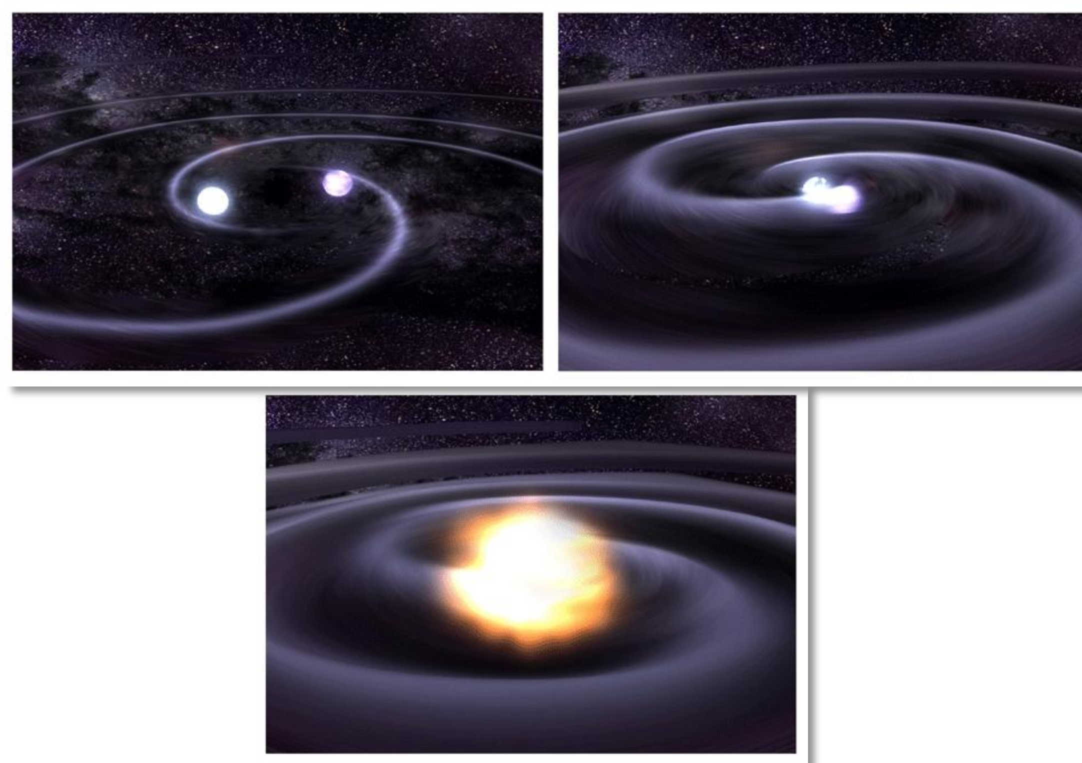
  - **Fainter sources need longer exposure**

# GRBs and Gravitational Waves

*Fermi*-GBM and Advanced LIGO (>2015) should see coincident Gravitational wave/Electromagnetic emission or rule out NS-BH mergers as the progenitors of short GRB

Large rate of short bursts in GBM is key to coincident detections

GBM Short GRBs in ALIGO horizon:
$N(z<0.11, \text{NS-NS}) \sim 2^{+4}_{-}\ \text{yr}^{-1}$
$N(z<0.22, \text{NS-BH}) \sim 8^{+6}_{-3}\ \text{yr}^{-1}$



- **Both observations bring complementary information: ALIGO → inspiral characteristics ; *Fermi* → jet properties & environment**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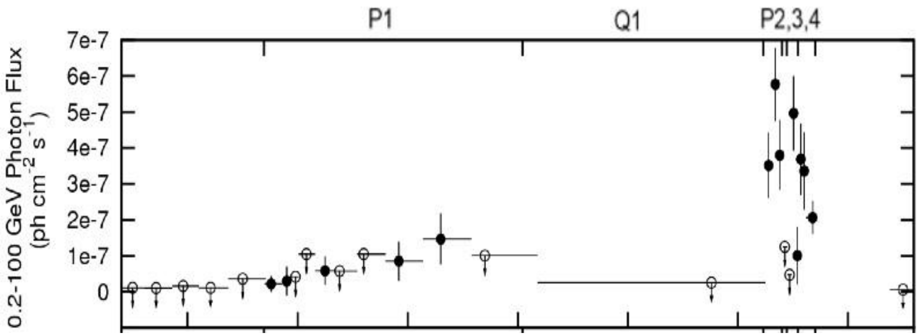
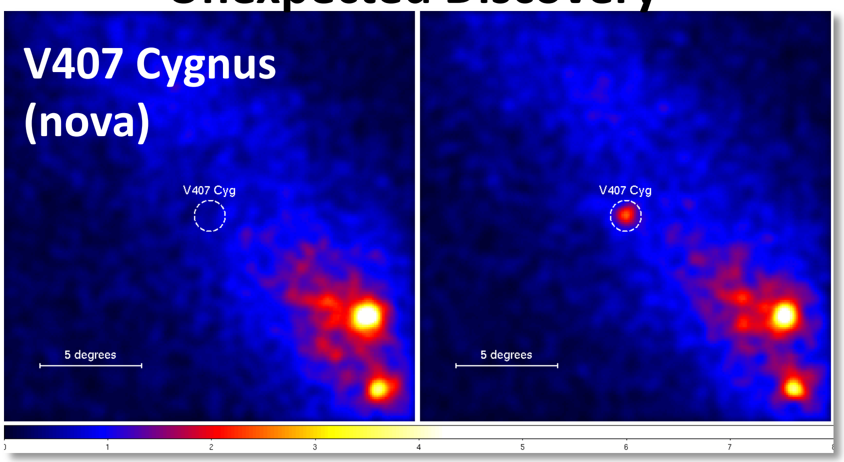
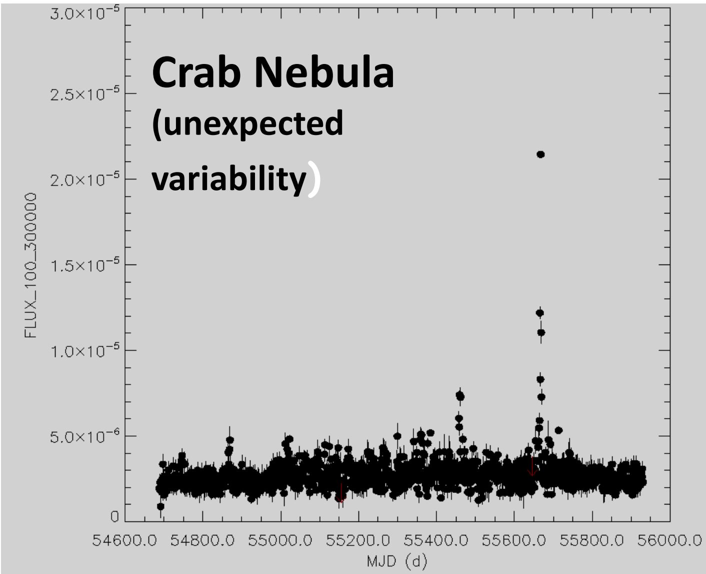
# The Surprising Sky

**Unexpected Behavior**




**Unexpected Discovery**



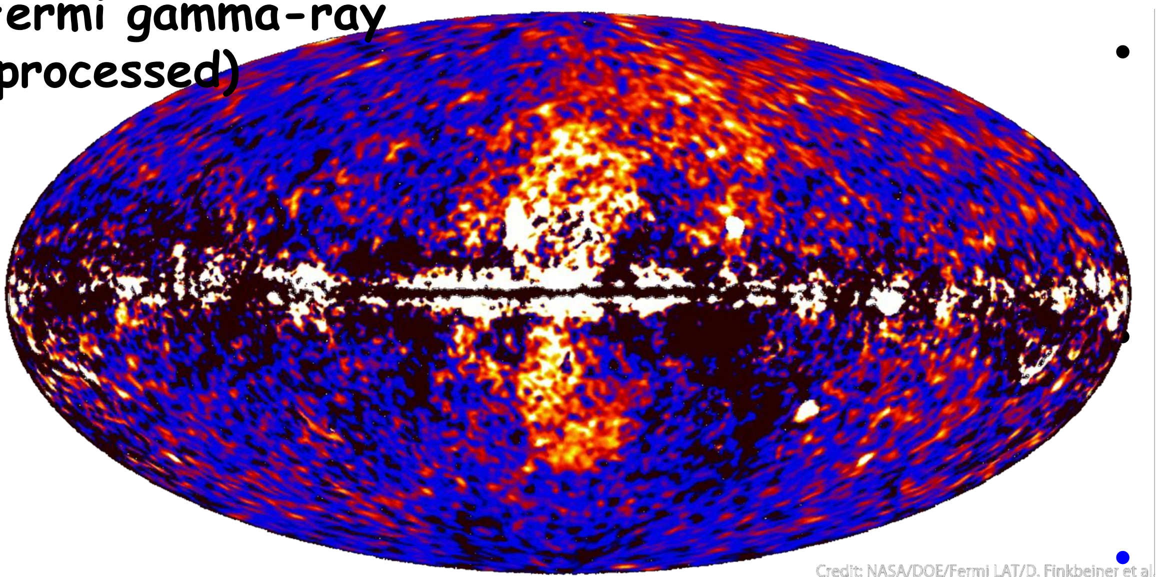




- **Gamma-ray astrophysics is relatively young – many "transformative" discoveries still being made**

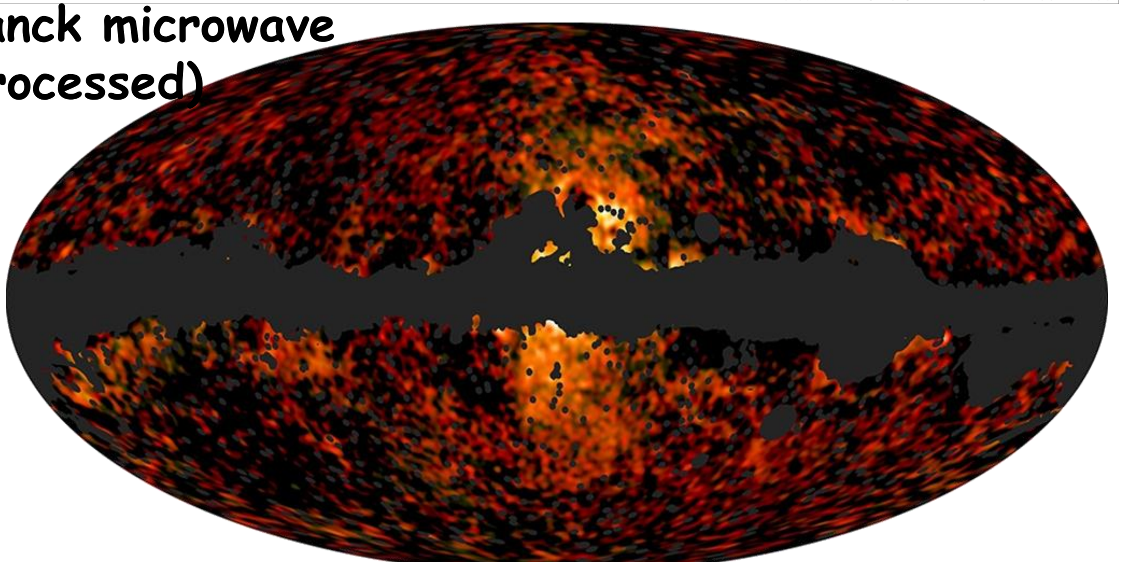
# Questions?

# *Fermi* Bubbles

Fermi gamma-ray (processed)




Planck microwave (processed)



- **Discovered huge lobes of high energy $\gamma$-rays above and below the galactic center**
- **In 2012, Planck maps confirm presence of lobes at lower energies**
- **Increased statistics at high energy will allow study of spectral and spatial properties of the lobes to understand their origin**

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