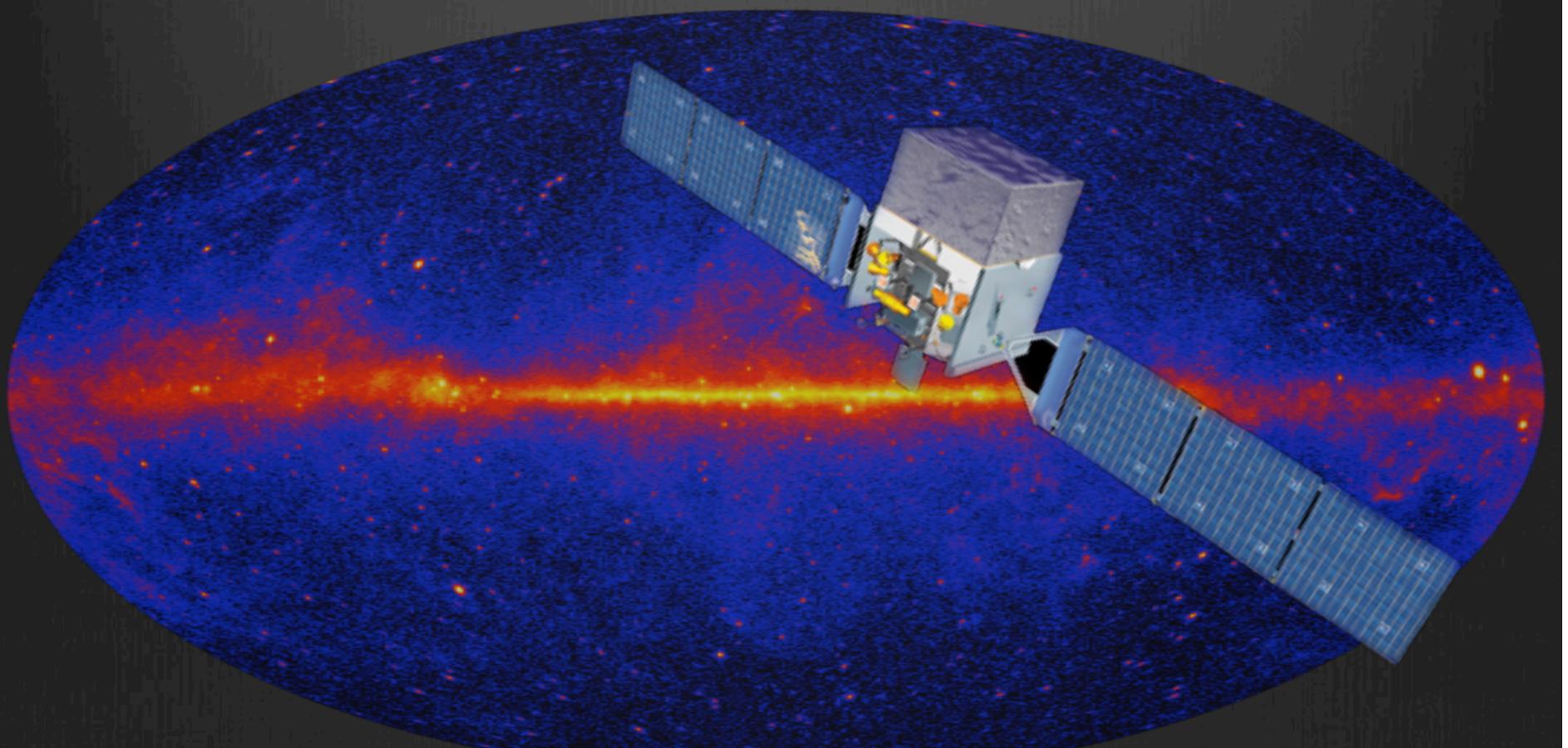


# Fermi Science Highlights

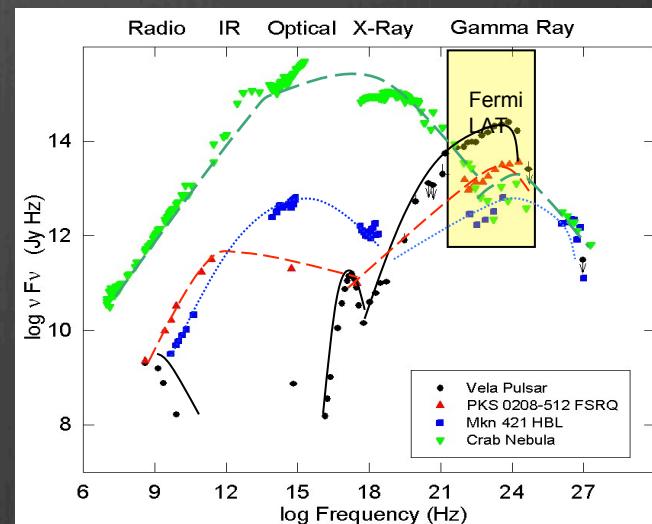
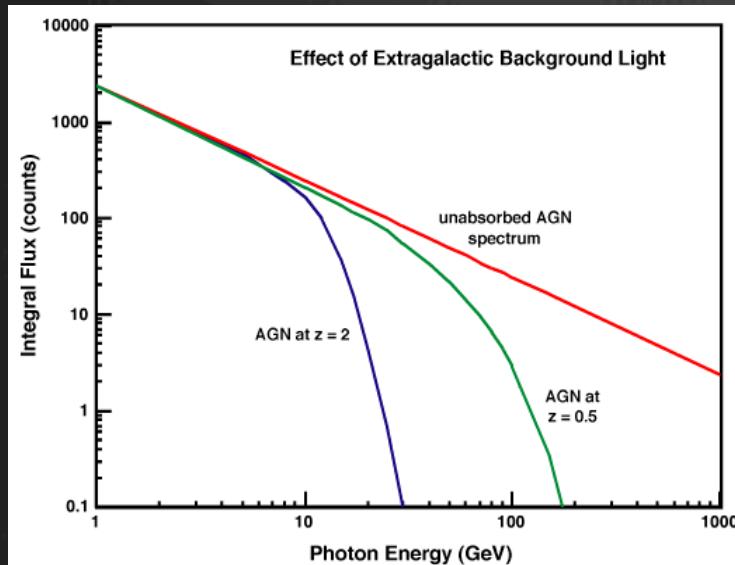
Approaching a decade of discovery in high energy gamma-ray  
Astrophysics



# Why High Energy Gamma-Rays?

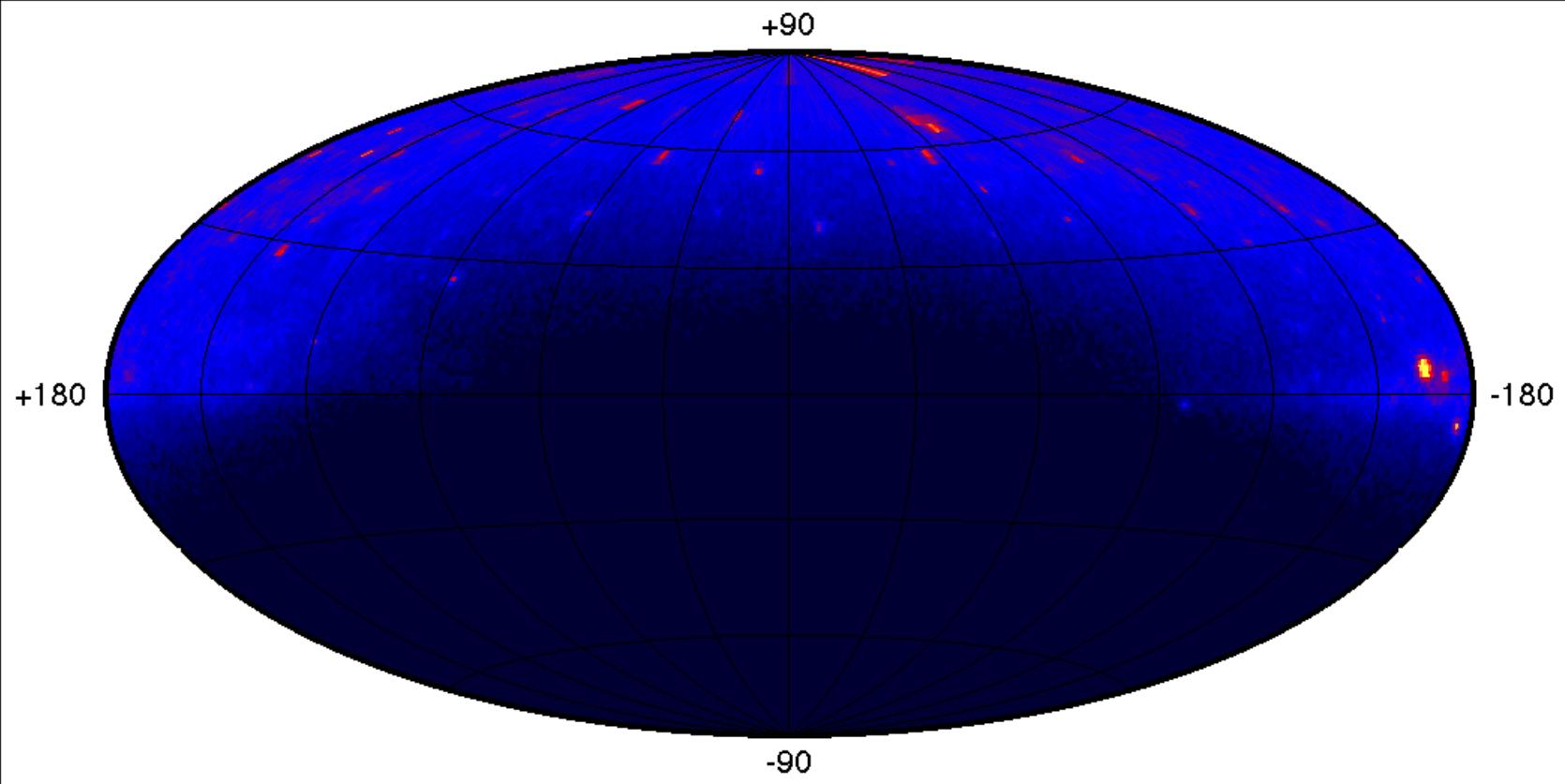
- High energy gamma-rays explore nature's accelerators - “Where the energetic things are”
  - natural connections to UHE cosmic-ray and neutrino astrophysics

High energy photons often produced in a different physical process to the lower energy emission -> Independent handle on the physical conditions.

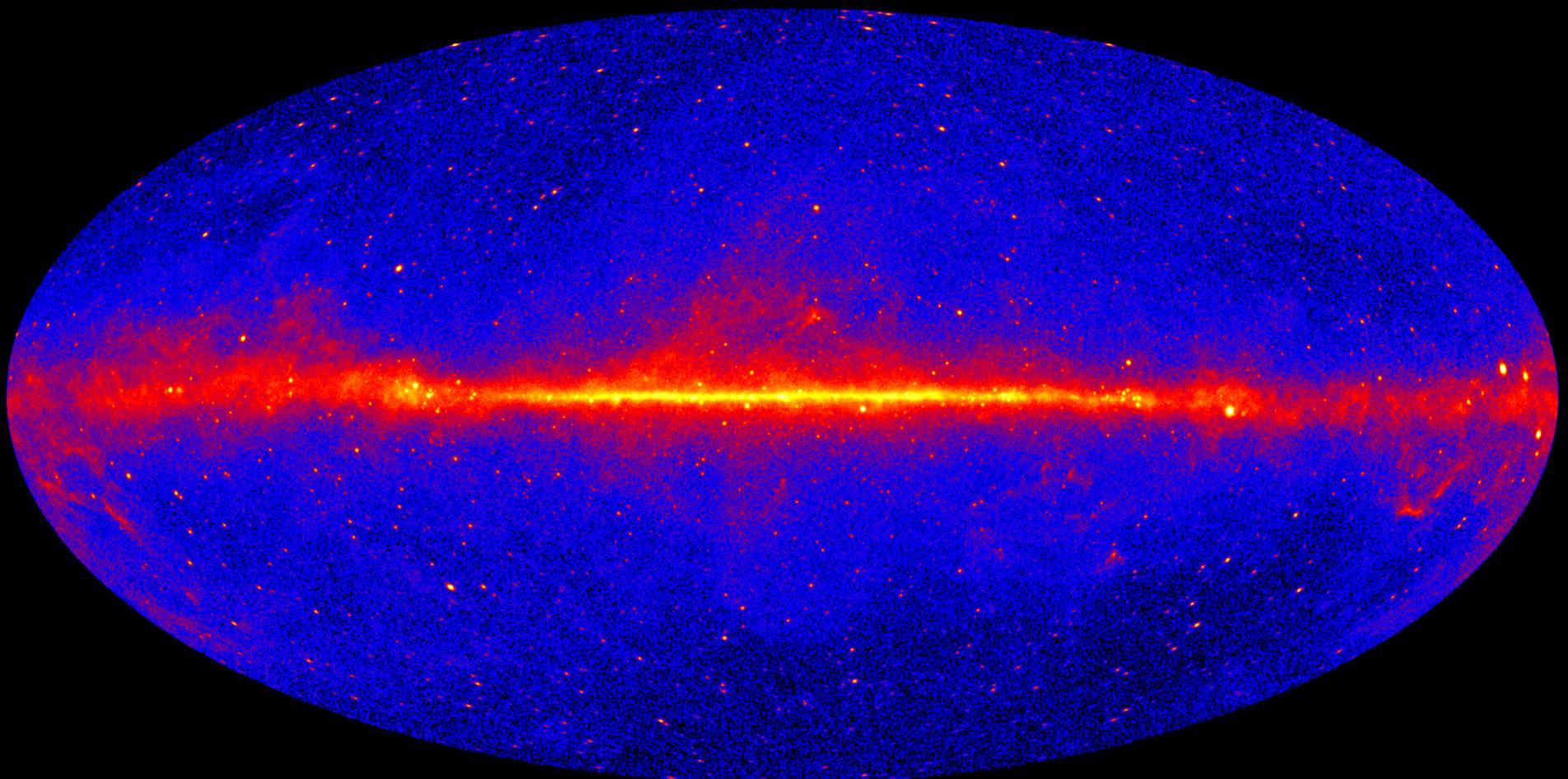


High energy gamma-rays can be attenuated by pair-production with lower energy photons

- Probe conditions in emission regions (gammas need to get out)
- Explore the optical/UV diffuse background

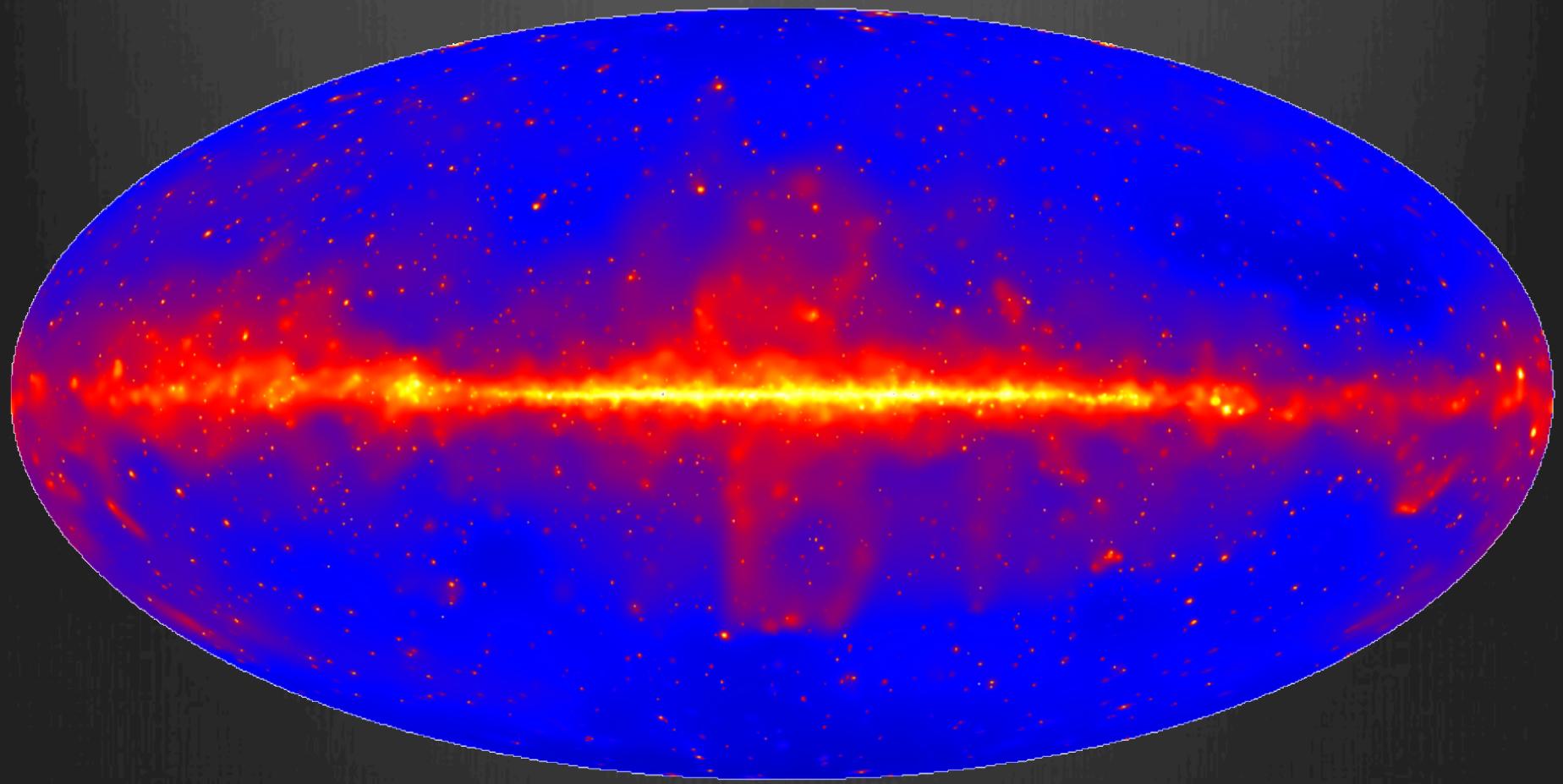


# The Fermi Sky above 1 GeV



>3000 sources above 100 MeV (c.f. ~300 known 10 years ago)

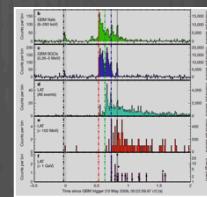
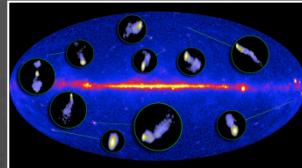
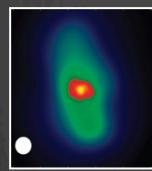
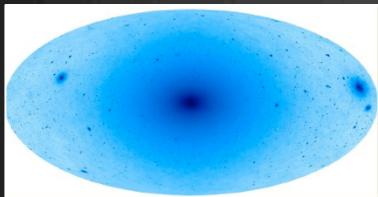
# The Fermi Sky above 10 GeV



>1500 sources above 10 GeV

# Fermi Highlights and Discoveries

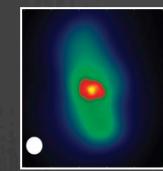
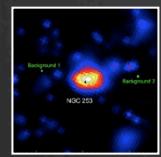
Dark Matter searches



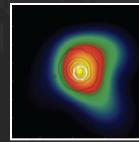
GRBs

Blazars

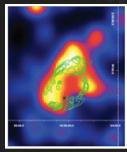
Radio Galaxies



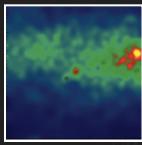
Starburst Galaxies



Globular Clusters



SNRs & PWN

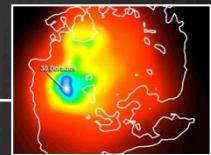


Novae

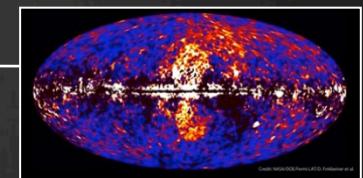
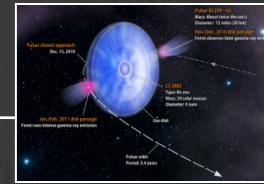
Galactic

$\gamma$ -ray Binaries

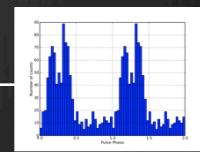
LMC & SMC



Fermi Bubbles



Pulsars: isolated, binaries, & MSPs



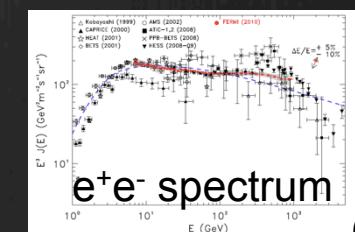
Sun: flares & CR interactions



Terrestrial  $\gamma$ -ray Flashes

Unidentified Sources

Extragalactic

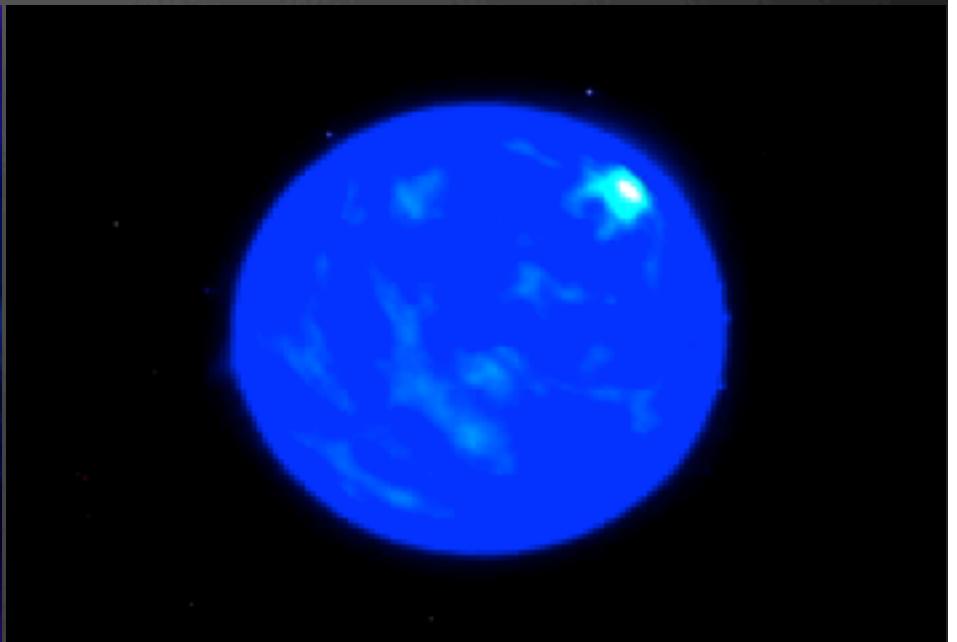


# Gamma-ray bursts

Huge flux of gamma-rays lasting from 0.1-1000's seconds



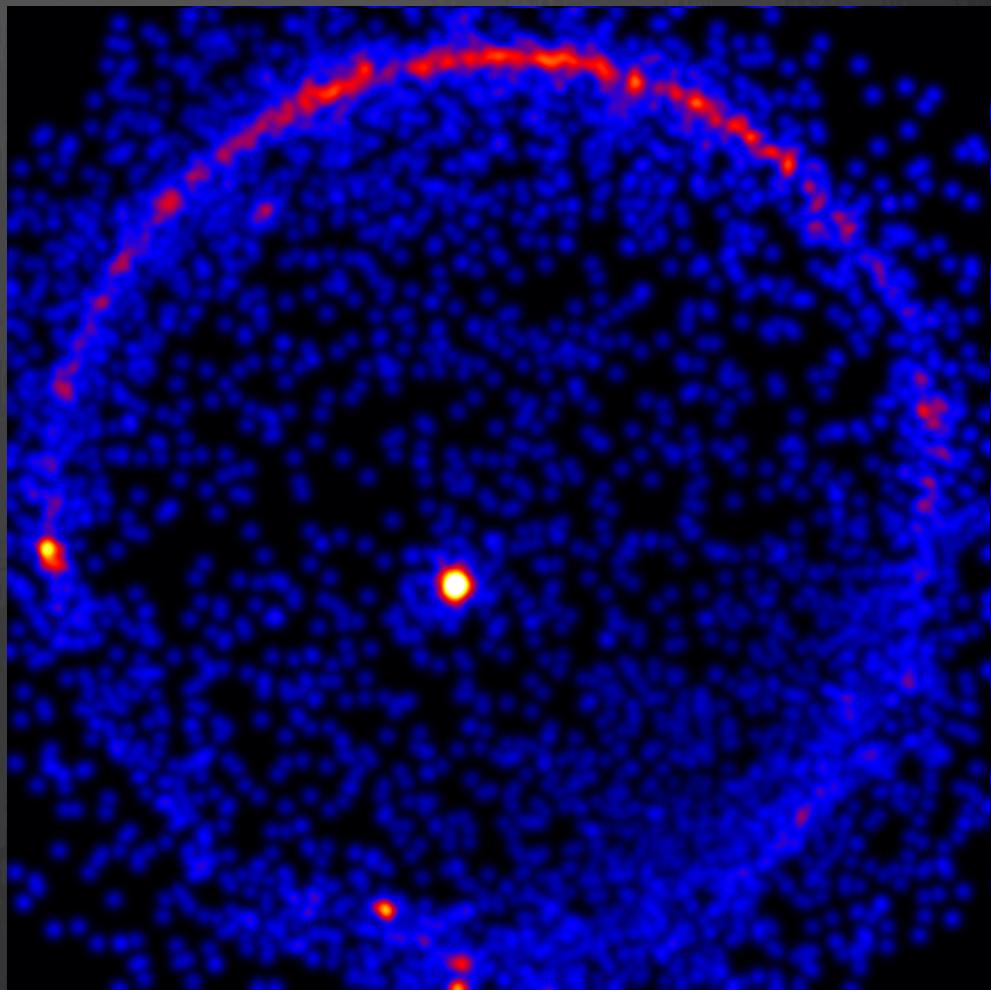
Compact Mergers: Two neutron stars, or a neutron star and a black hole, collide and merge, producing a jet.



Collapsars: A rapidly spinning stellar core collapses and produces a supernova, along with jets.

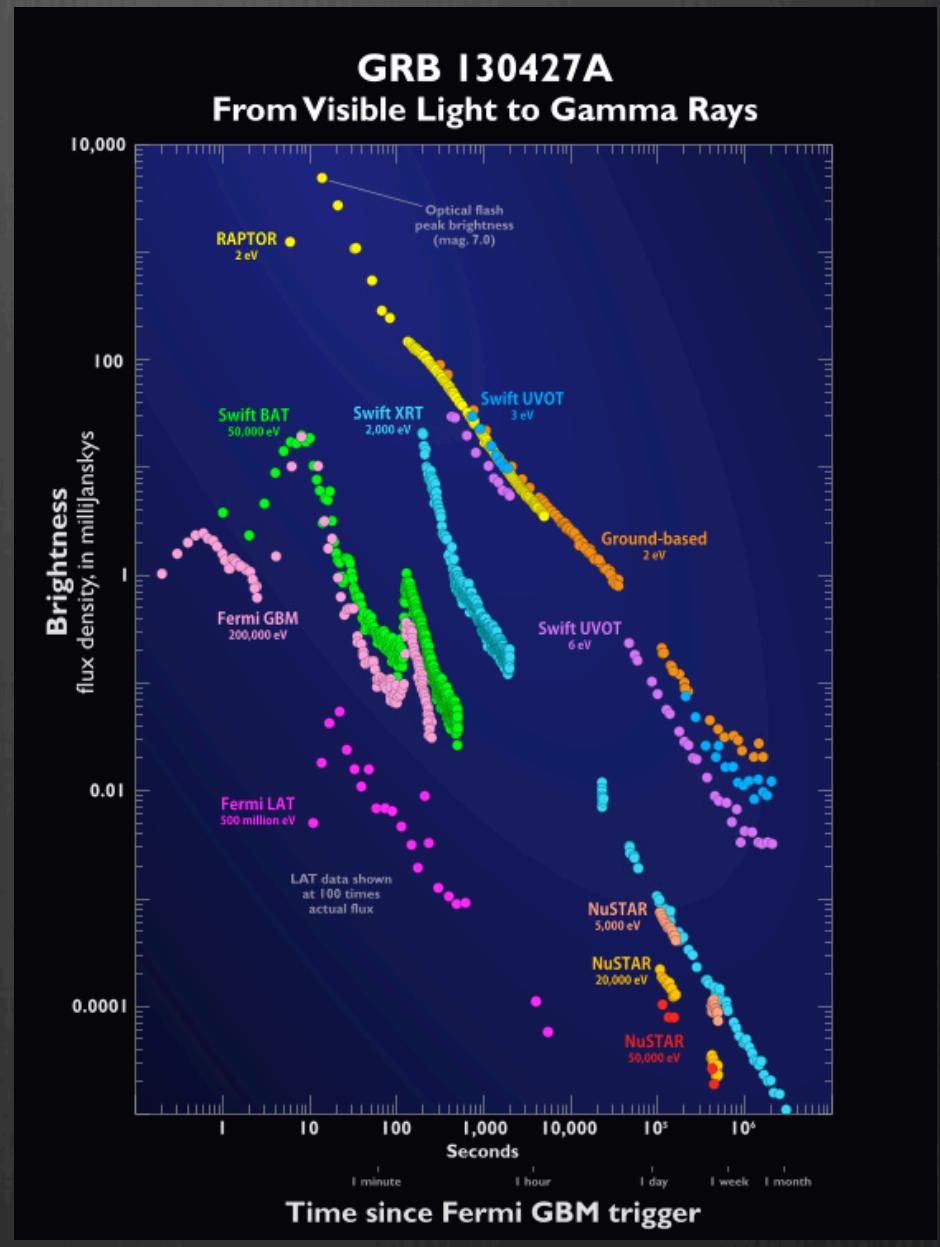
# GRB130427A – A nearby ordinary monster

- Redshift = 0.34
- One of the brightest GRBs in gamma-rays ever detected
- Highest energy photon (95 GeV)
- Longest lasting GeV emission – LAT detected emission for over 20 hours



# GRB139427A Long lived GeV Emission

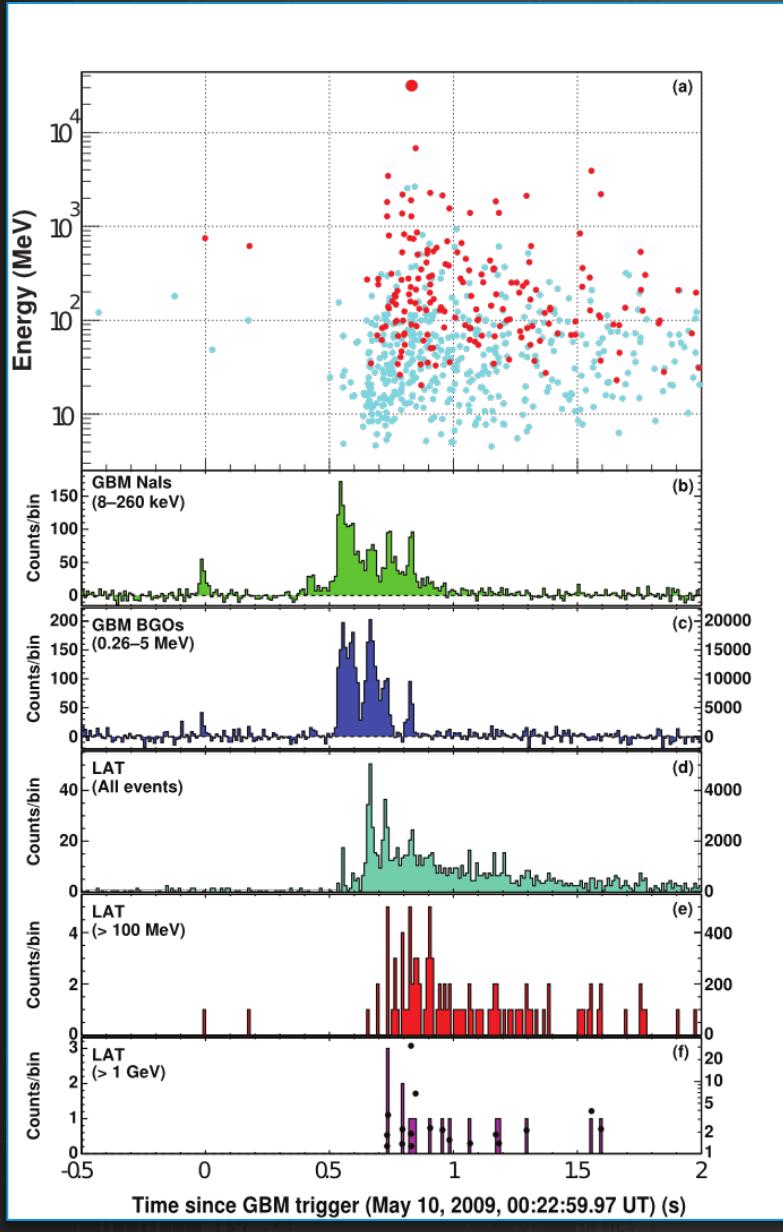
- The very high energy photons at late times are inconsistent with the standard model that the afterglow emission is produced by synchrotron emission from electrons accelerated in the forward shock of the ejecta
- Fermi observations challenge standard models of particle acceleration



# Lorentz Invariance Violation

- Several quantum-gravity theories predict a break of Lorentz symmetry when approaching the Planck mass scale
  - Consider simple phenomenological form:
    - $c^2 p^2 = E_\gamma^2 [1 + (E_\gamma / \xi M_{pl} c^2)^n]$
    - $v_\gamma = dE_\gamma / dP_\gamma \sim c[1 - (1+n)/2 * (E_\gamma / \xi M_{pl} c^2)^n]$
    - $M_{pl} = \text{Planck mass} = 1.22 \times 10^{19} \text{ GeV}/c^2$
  - Models with LIV
    - Loop quantum gravity
    - String theory
    - Doubly special relativity
- To measure this we need:
    - High energy photons
    - Large distances
    - Well defined start time
  - **A Gamma-ray Burst is perfect!**

# GRB090510

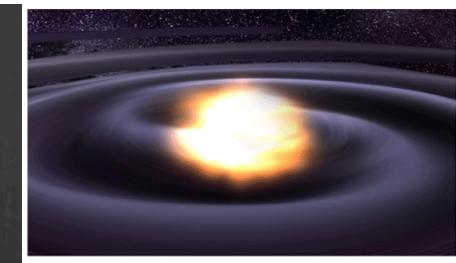
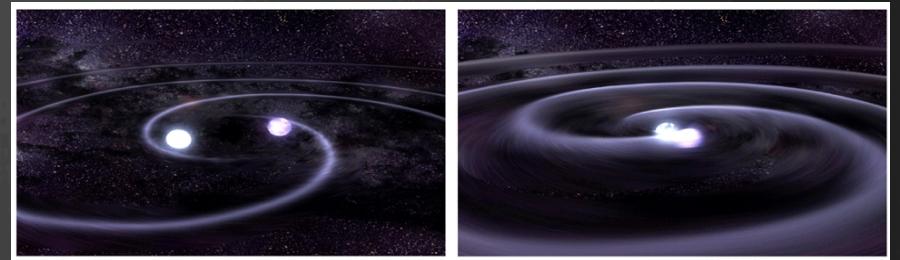
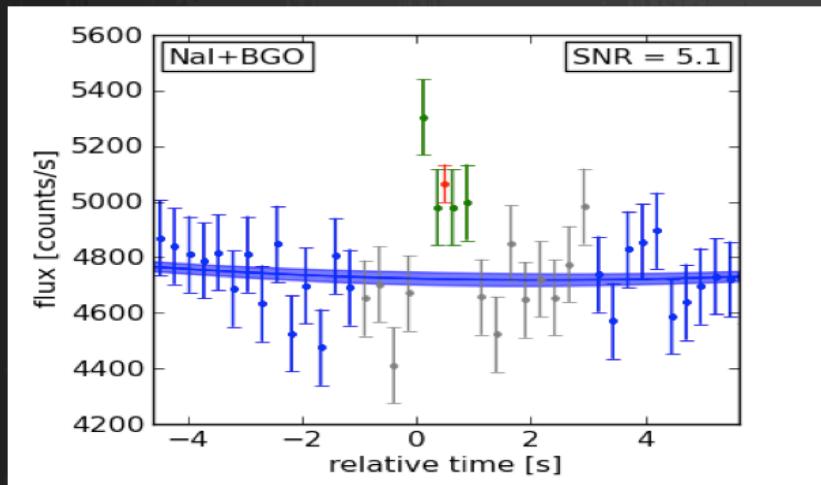


- 31 GeV photon was emitted 859 ms after the start of the GRB
- $\Delta t < 859$  ms;  $M_{QG} > 1.19 M_{pl}$
- This was the first time that observations found a limit on  $M_{QG}$  that exceeded the Planck scale
  - Exclude quantum gravity models that predicted this
- Results support Lorentz invariance and disfavor models in which the quantum nature of space time alters the speed of light

# GRBs and Gravitational Waves

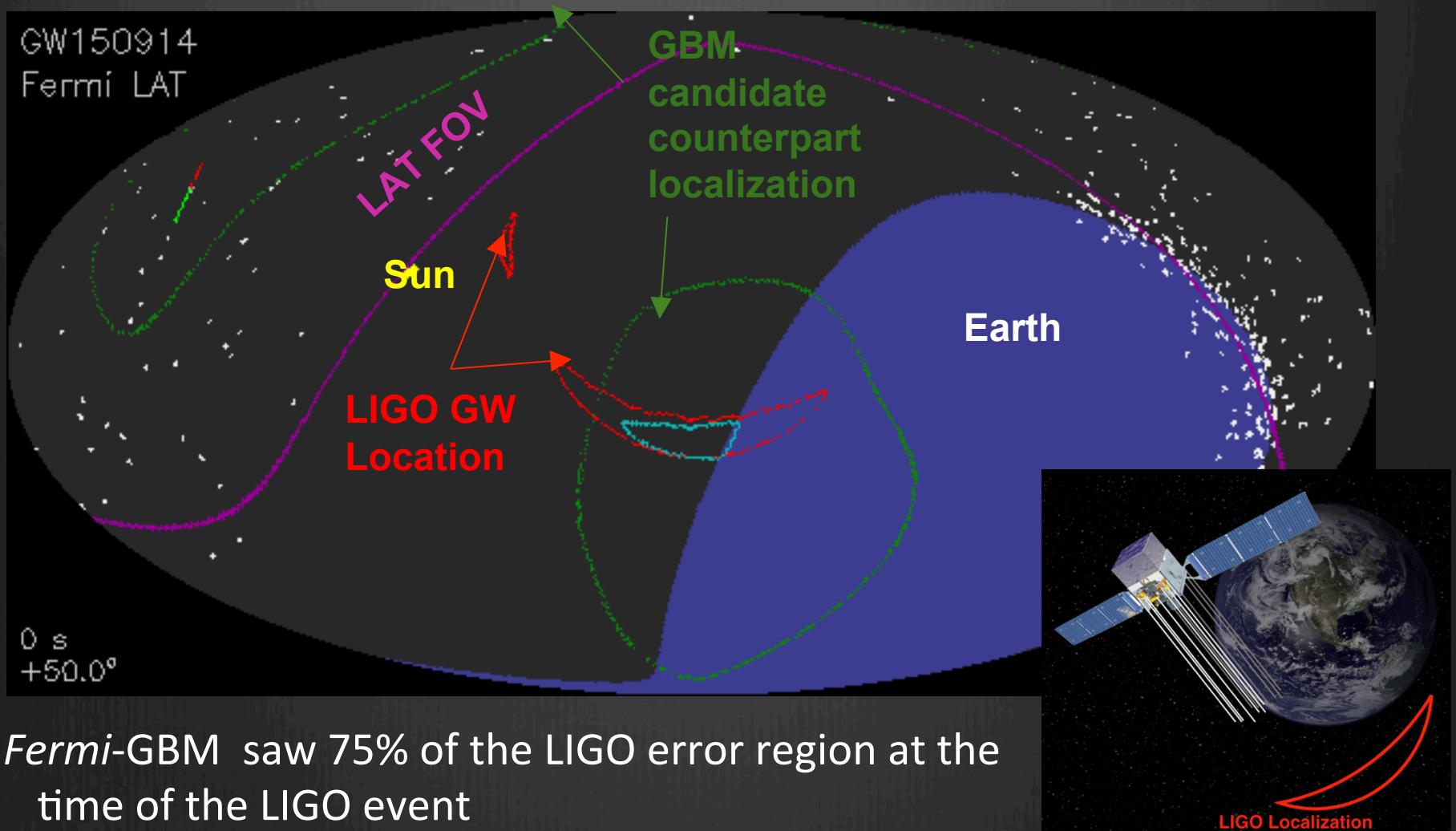
- LIGO is sensitive to gravitational waves produced in merger of compact objects (NS-NS, NS-BH and BH-BH)
- Compact mergers are also presumed progenitors for short GRBs
  - Searches for counterparts to LIGO GW events have focused on short GRBs – Fermi is the most prolific detector of short GRBs!

Fermi-GBM detected small excess 0.4 secs after the LIGO event GW150914 with a duration  $\sim 1$  sec, consistent with short GRB



LIGO localizations cover a large area. Fermi's wide-field is excellent for follow-up of future LIGO detections

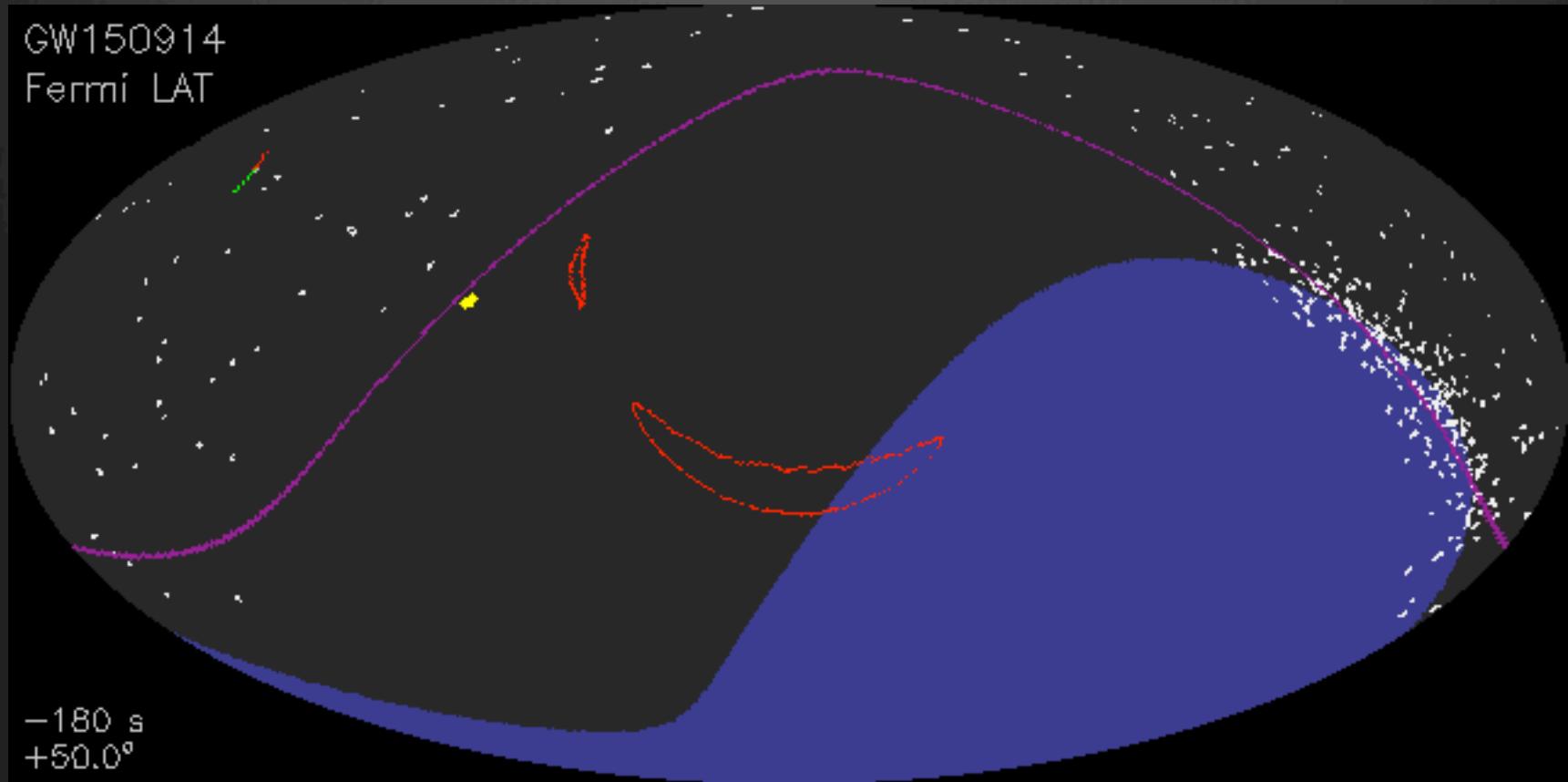
# Fermi Observations of GW150914



*Fermi*-GBM saw 75% of the LIGO error region at the time of the LIGO event

Joint GBM-LIGO data reduced error region by 66%

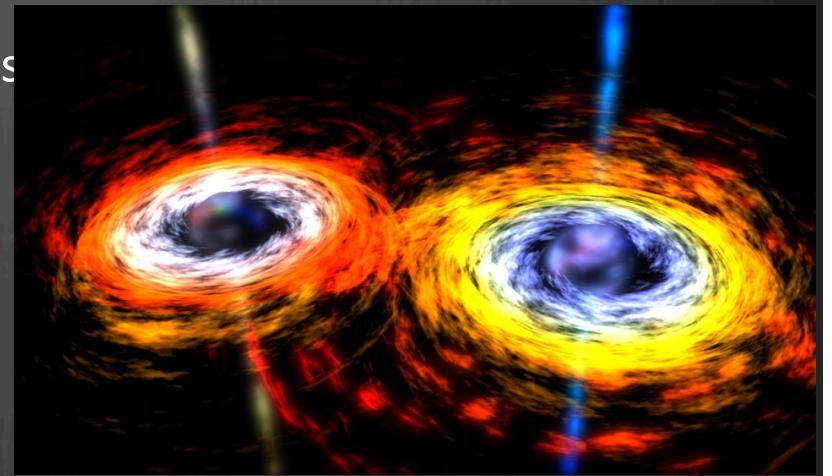
# *Fermi* Observations of GW150914



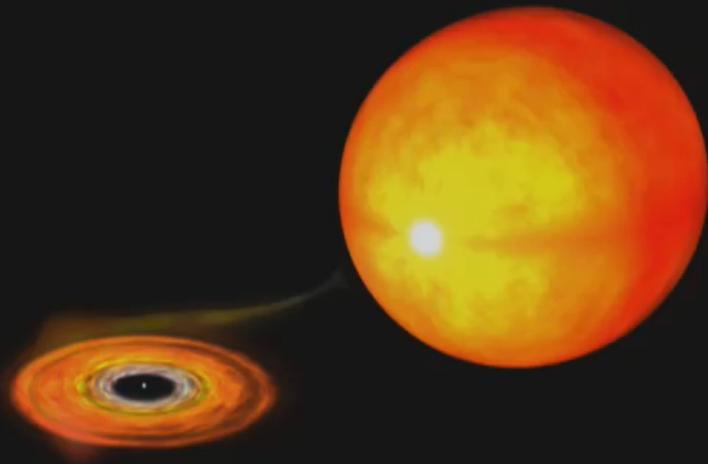
Both instruments see the entire LIGO localization region within ~2 hours of the LIGO trigger; nearly worst case in terms of LAT latency

# What might it mean?

- Gamma-rays (or any photons) were not expected in a merger between two black holes
- If the short GRB detected by GBM is associated with the LIGO event some ideas include:
  - Two black holes inside a single large star, the matter from the star produces an accretion disk and relativistic jet (Loeb 2016)
  - **Mini-disk of matter surrounding the black holes (Murase, 2016)**
  - **One or both of the black holes has an electric charge, then the system will behave like a giant pulsar and power the gamma-ray burst seen by Fermi (Zhang, 2016)**
  - ...
- **LIGO localizations cover a large area of the sky -> wide-field survey instruments are essential for EM-follow up**
  - ***Fermi* is excellent for this**
  - **Looking forward to confirming with another detection!**



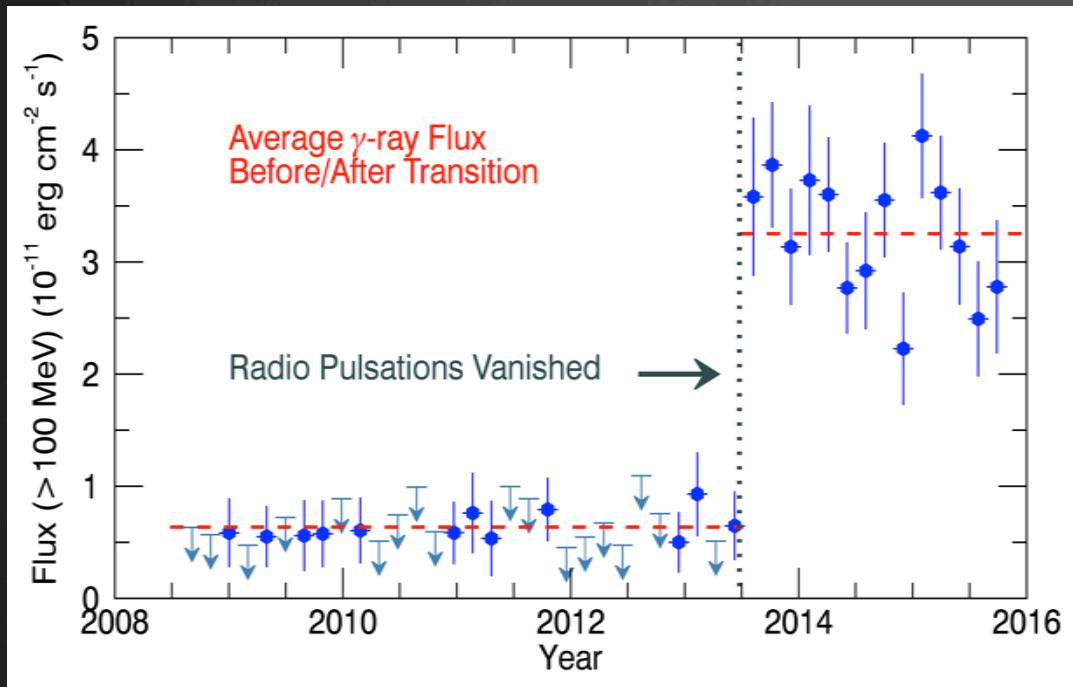
# Millisecond Pulsars



- Very rapidly spinning neutron stars, Fermi is very good at finding these - <http://www.einsteinathome.org/>

# Transitional Millisecond Pulsars

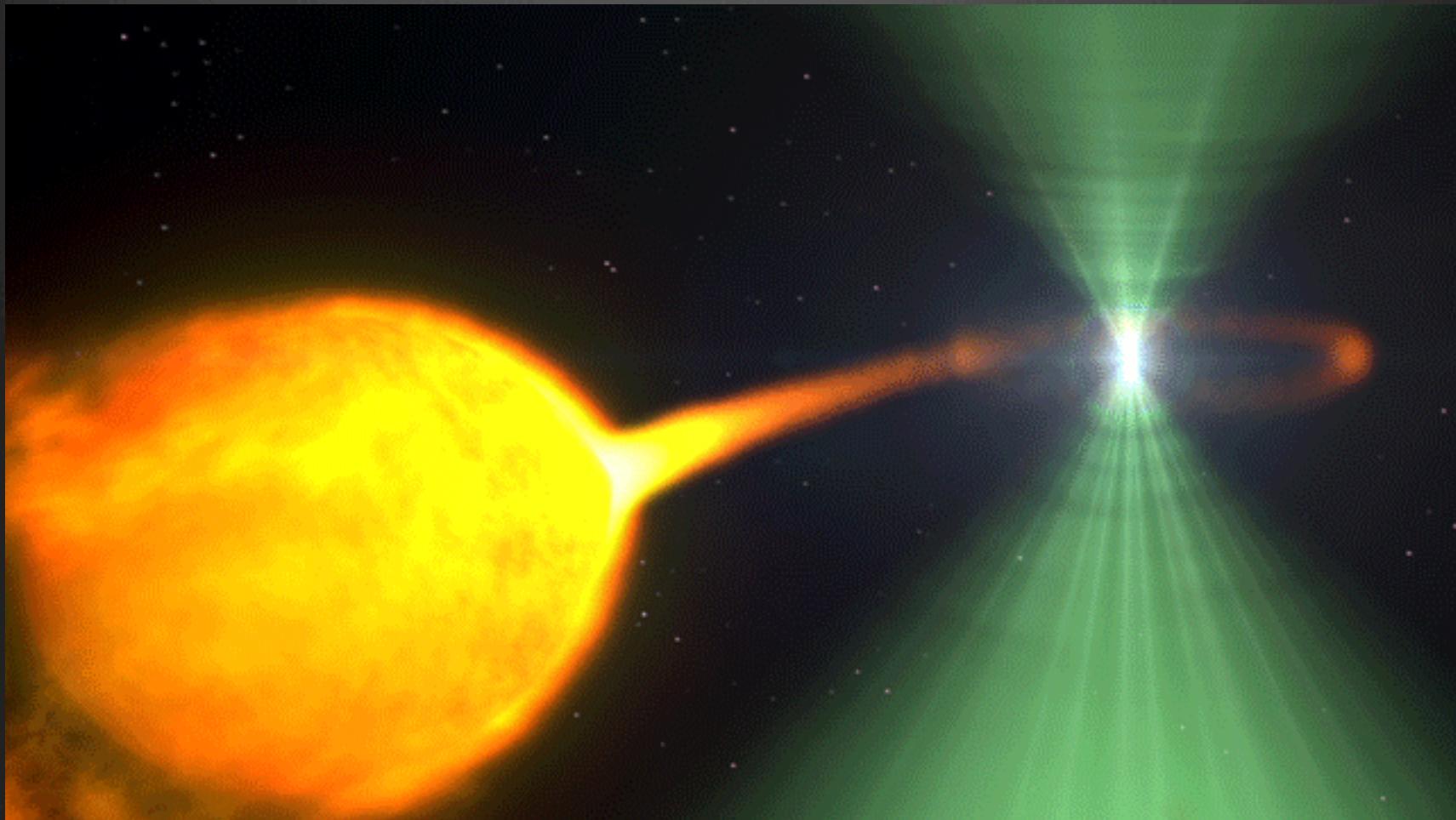
Gamma-ray Transition of PSR J1023+0038



- 40% of MSPs discovered in searches of LAT sources are interacting binaries
  - i.e. systems in, or close to, transition
- $\gamma$ -ray emission brighter in the accreting state – a surprise since accreting sources are *not* typical  $\gamma$ -ray emitters.

Fermi Studies Pulsars in Transition!

# Battle between pulsar wind and accretion



# Fermi and Pulsar Timing Arrays

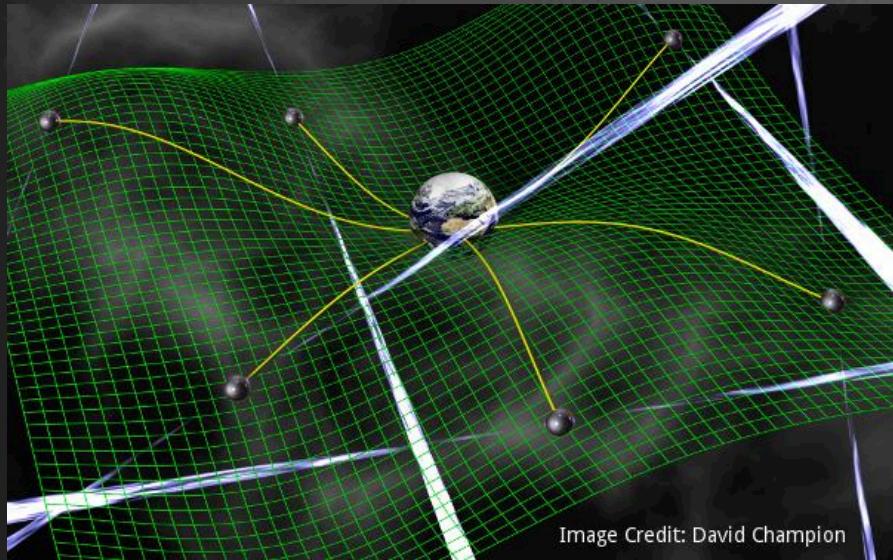
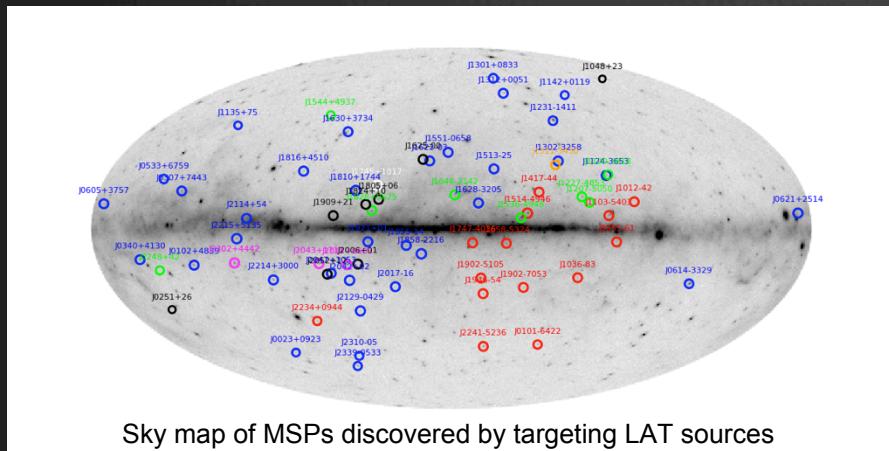


Image Credit: David Champion

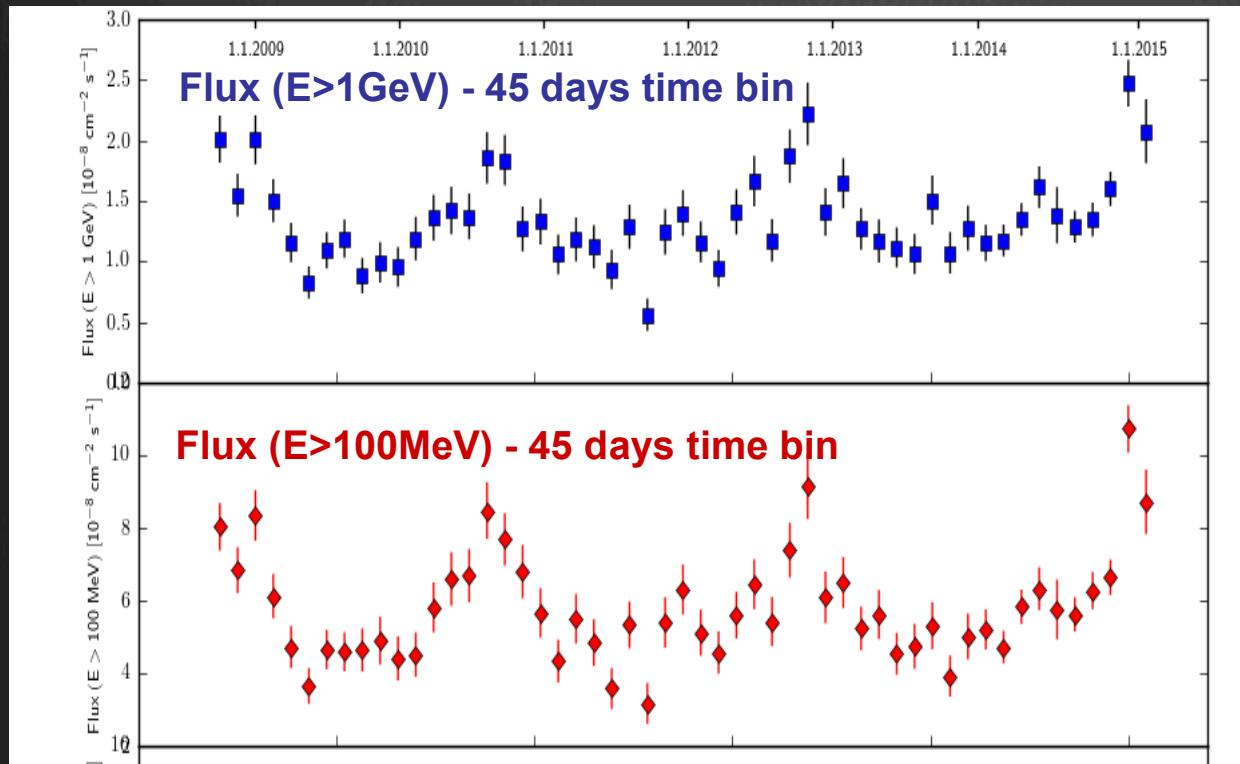


Sky map of MSPs discovered by targeting LAT sources

- Pulsar Timing Array (PTA) projects, like NANOGrav, are poised to open the next gravitational wave band (5–500 nHz, as compared to 30–1000 Hz for LIGO)
- The *Fermi* Pulsar Search Consortium has discovered 70 MSPs in searches of LAT unassociated sources (40% of the MSP discoveries since 2008 and about  $\frac{1}{3}$  of all known Galactic MSPs!)
  - More expected from new Pass 8 catalog analysis
- >12 new MSPs have been added to PTA projects, and more are being evaluated

# Active Galaxies

- The “bread and butter” science from Fermi observations of AGN variability is to explore physical conditions in the gamma-ray emission regions in the AGN jet
- Sometimes we find things that we didn’t expect....

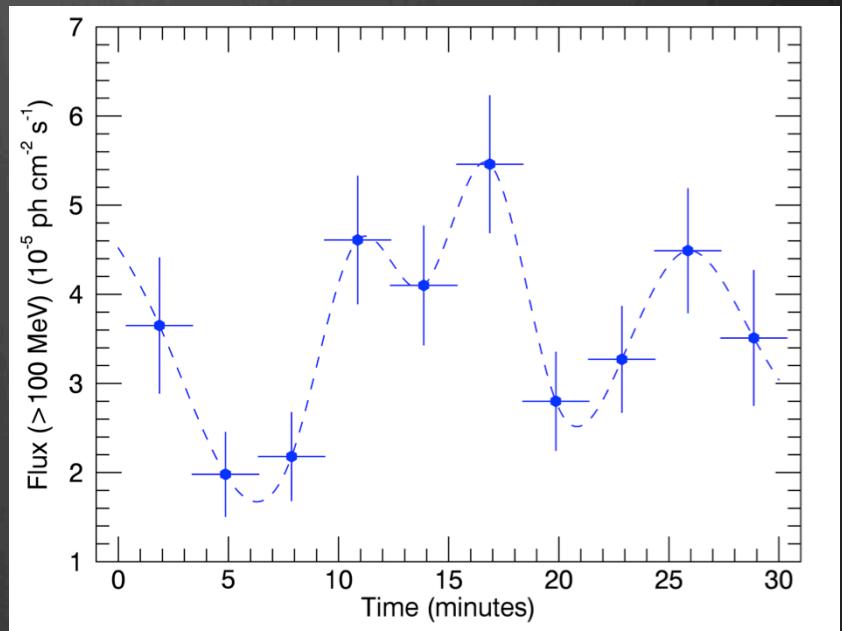


Year-scale periodicity in an AGN  $\rightarrow$  suggests a supermassive black hole binary

# Challenges for Acceleration Models

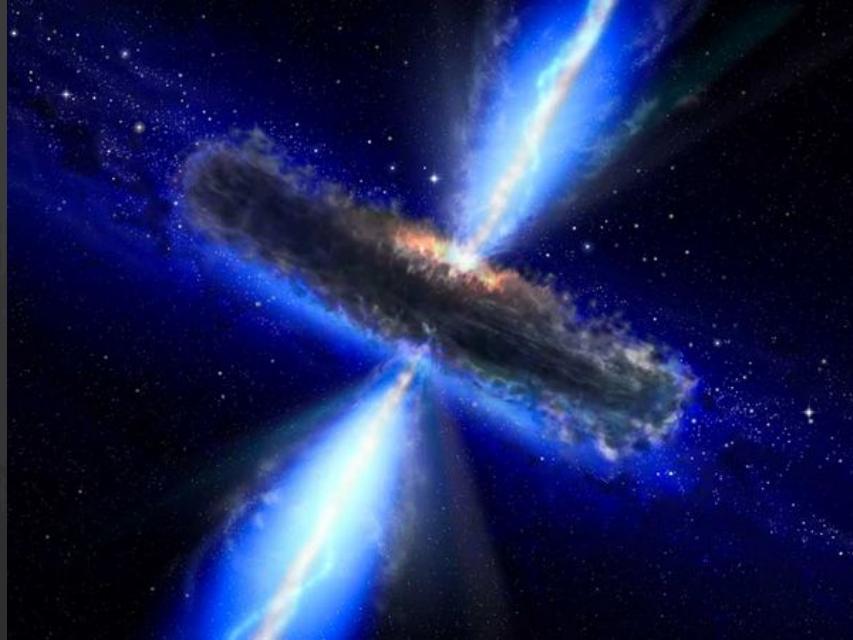
- Minute-scale variability observed in a TOO targeting the blazar 3C 279
  - Severely challenges particle acceleration and interaction models in jets
  - Magnetic reconnection can provide variability on time scales smaller than the light crossing time for a supermassive black hole (Cerutti et al. 2012)

Intense Flare of 3C 279 in June 2015



- Fermi observations test and challenge particle acceleration models at physical extremes

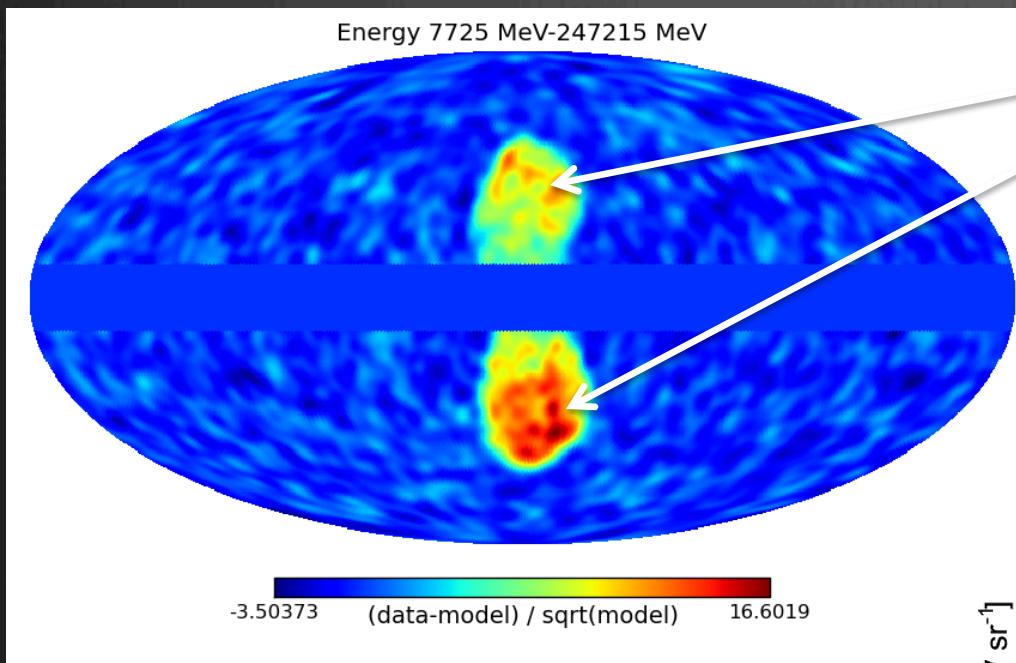
# Measuring extragalactic magnetic fields



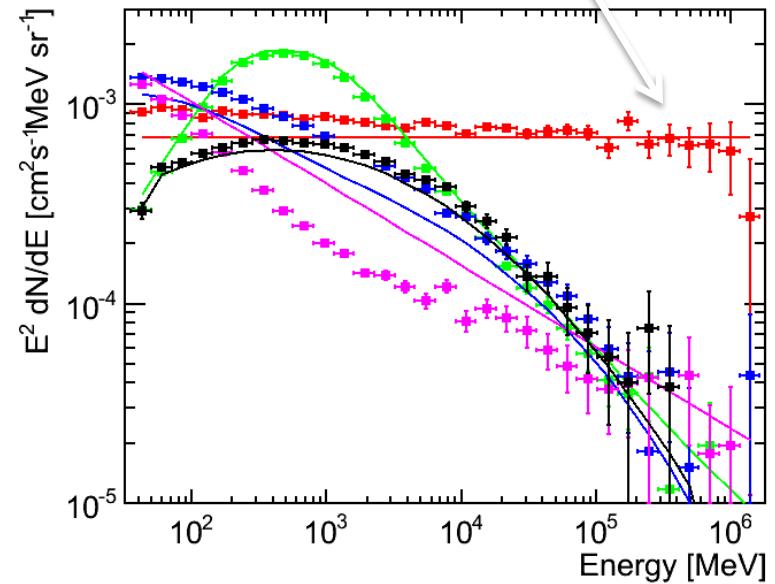
Neronov and Vovk (Science Magazine 2010)

- Active galaxies detected at TeV energies (factor of 1000 higher than Fermi), but not seen by Fermi can be used to constrain primordial magnetic fields
- Electrons/positrons produced as the TeV photons interact in intergalactic space should, in turn, interact with the CMB to produce GeV photons.
  - We don't see this flux, and infer the electrons must be bent by a magnetic field in intergalactic space, so that the GeV gammas are no longer directed towards us.

# Fermi Bubbles



- In 2010, discovered huge lobes of high energy  $\gamma$ -rays above and below the galactic center
- Very hard spectrum

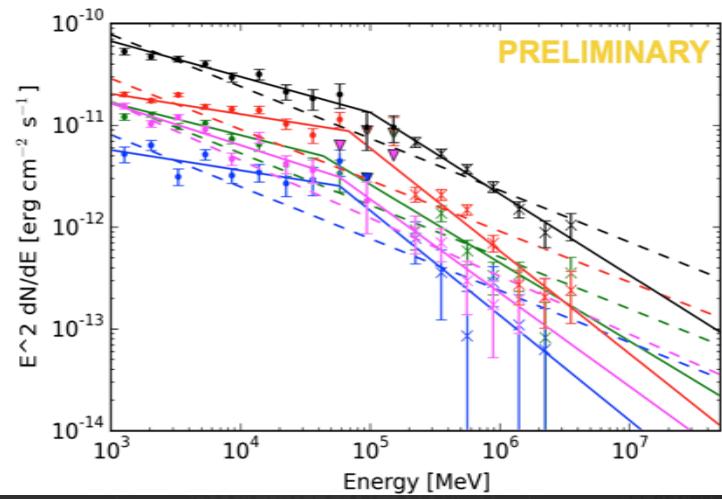
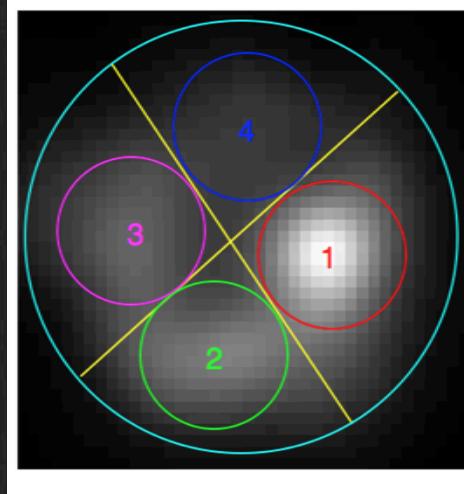
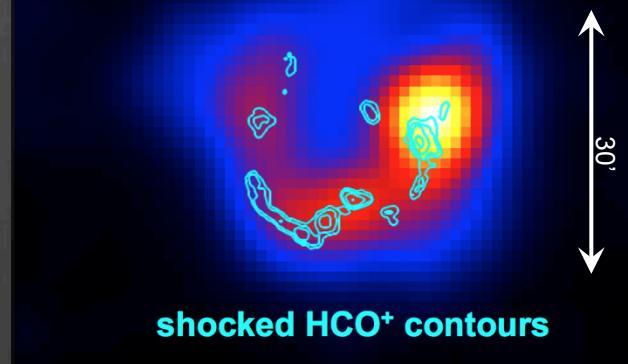


- Indicates that the center of our galaxy had some kind of activity several million years ago
  - Perhaps an outburst from the supermassive black hole

# Resolving a Proton Accelerator

- Fermi data resolve the shell of supernova remnant IC 443 at physical scales of  $\sim 5$  pc
- GeV/TeV  $\gamma$ -rays match the distribution of shocked gas ( $\text{HCO}^+$ )
- Dense molecular and diffuse atomic (fast shock) regions differ in brightness by  $\sim 10x$ , but spectra are surprisingly consistent

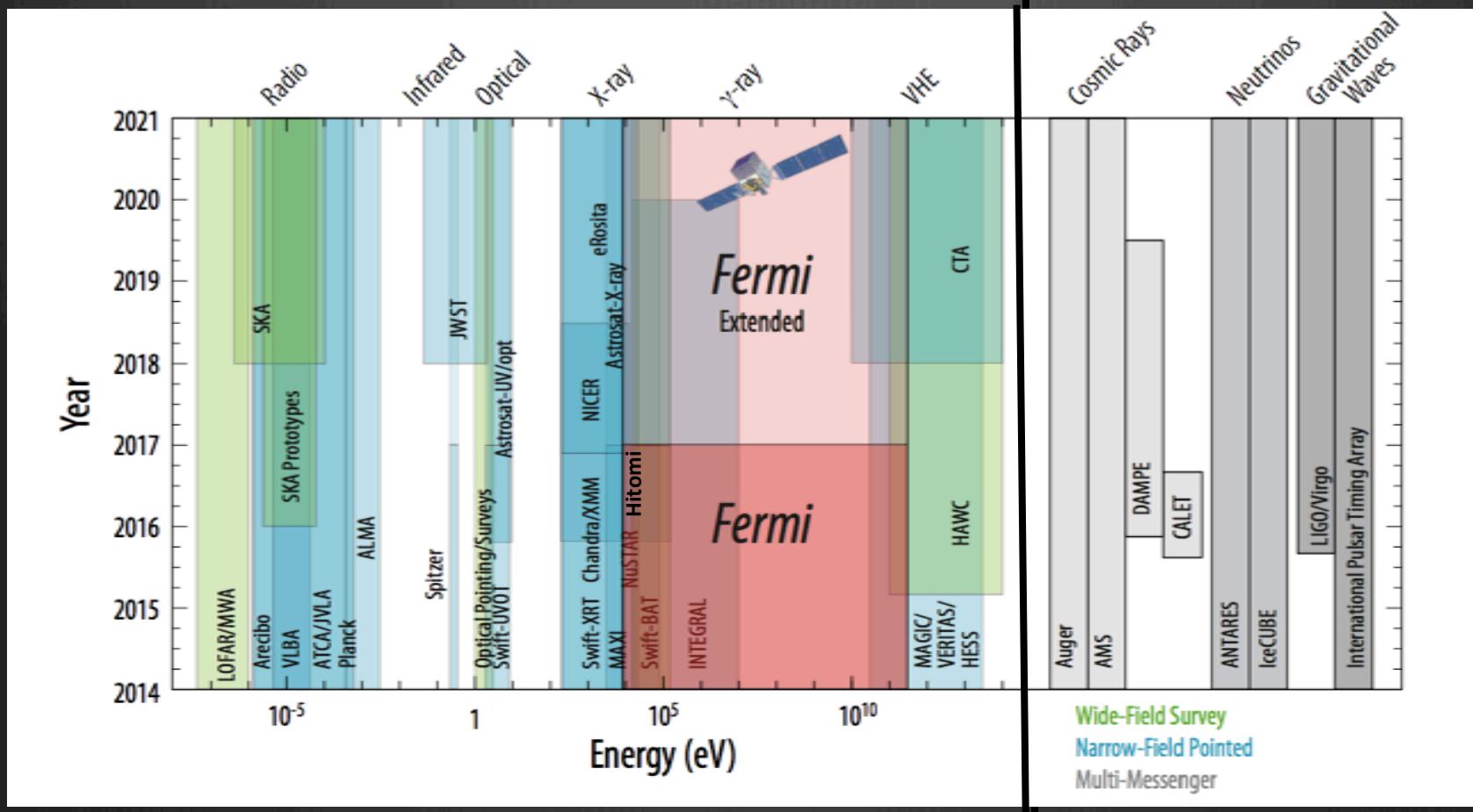
Deconvolved 1–300 GeV events.  
Pass 8 gives 2.4x statistics of  
P7REP with cut on PSF68 < 0.4°



*Fermi*-LAT paper in  
preparation with  
VERITAS

A new capability enabled by Pass 8

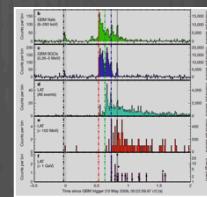
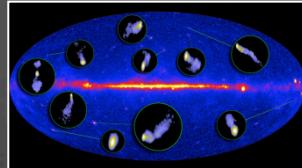
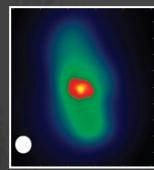
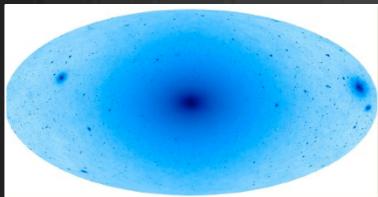
# Fermi in Context



- *Fermi* is the only mission in its waveband for the foreseeable future!
- New multiwavelength-multimessenger opportunities have opened up

# Fermi Highlights and Discoveries

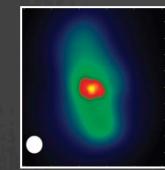
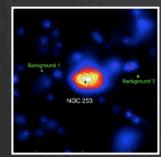
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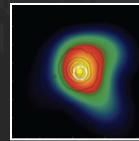
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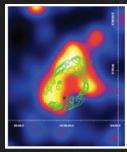
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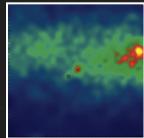
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Globular Clusters



SNRs & PWN



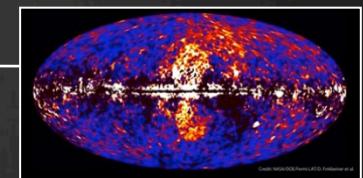
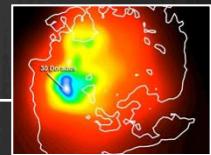
Novae

Galactic

$\gamma$ -ray Binaries

Extragalactic

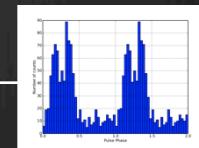
LMC & SMC



Fermi Bubbles



Pulsars: isolated, binaries, & MSPs

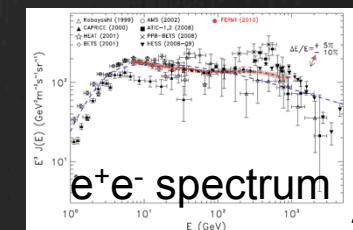


Sun: flares & CR interactions



Terrestrial  $\gamma$ -ray Flashes

Unidentified Sources



$e^+e^-$  spectrum

# The End



- Elliott and the flight simulator in the Air and Space Museum
  - Discovery that it is important to be fully tied in....