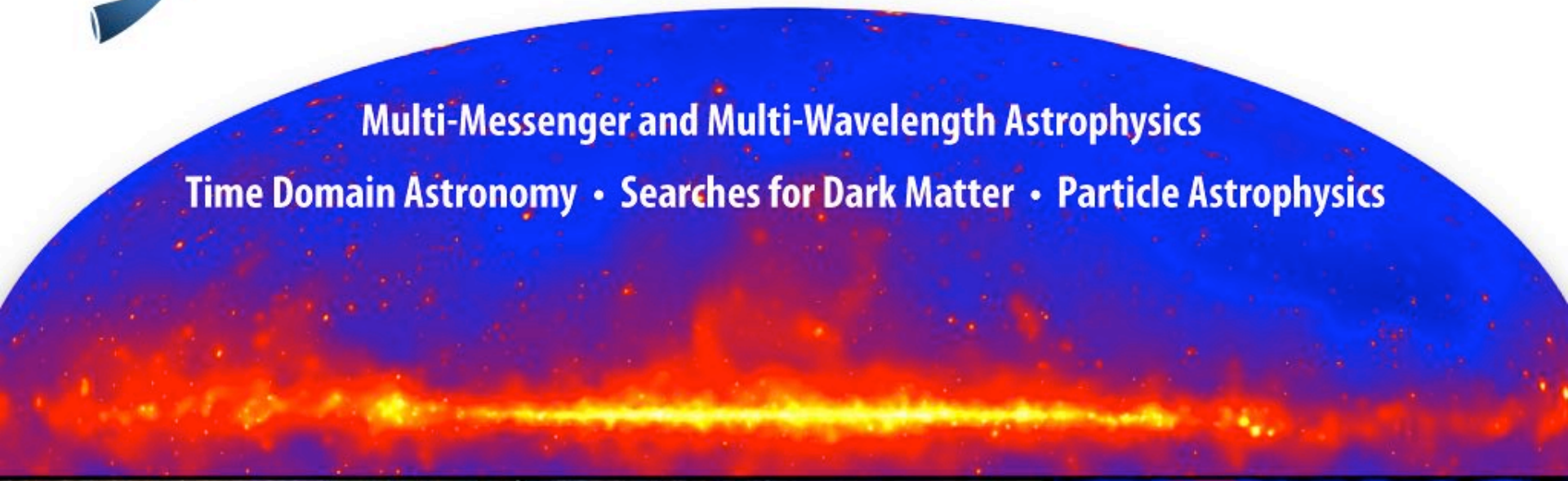
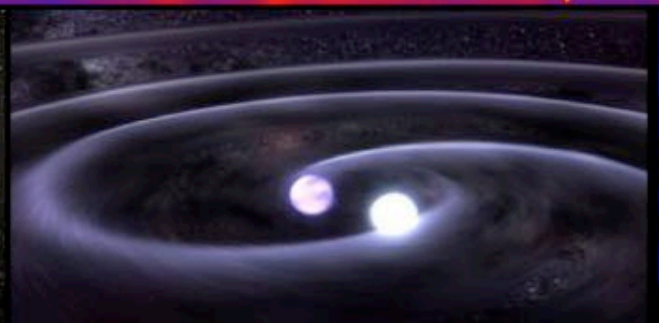
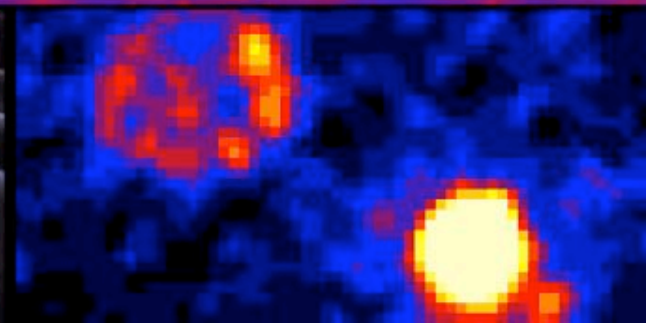
Fermi Gamma-Ray Space Telescope



Multi-Messenger and Multi-Wavelength Astrophysics

Time Domain Astronomy • Searches for Dark Matter • Particle Astrophysics





The *Fermi* Observatory

Probe class mission to study the extreme high-energy Universe

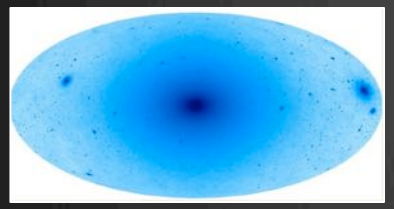
Large Area Telescope (LAT): 20 MeV to more than 300 GeV
observes 20% of the sky at any instant, entire sky every 3 hrs

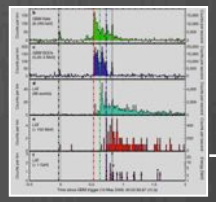
International and interagency collaboration between NASA and DOE in the US and agencies in France, Germany, Italy, Japan and Sweden

Gamma-ray Burst Monitor (GBM):
8 keV to 40 MeV
observes entire unocculted sky

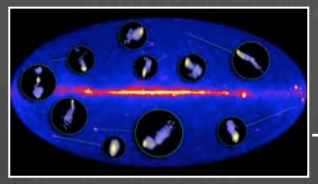
Fermi Highlights and Discoveries

Dark Matter searches

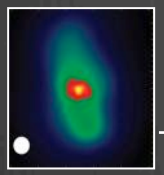




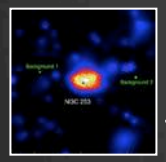
GRBs



Blazars

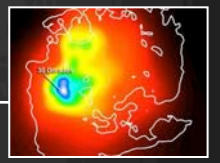


Radio Galaxies

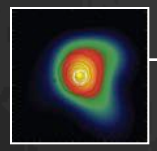


Starburst Galaxies

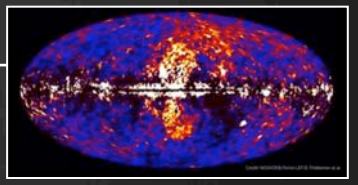
Extragalactic



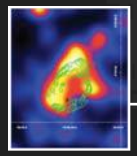
LMC & SMC



Globular Clusters

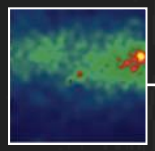


Fermi Bubbles



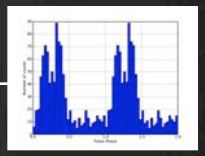
SNRs & PWN

γ-ray Binaries

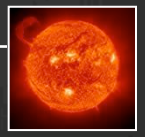


Novae

Galactic



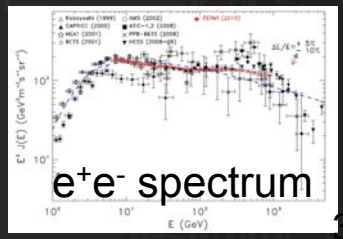
Pulsars: isolated, binaries, & MSPs



Sun: flares & CR interactions

Terrestrial γ-ray Flashes

Unidentified Sources



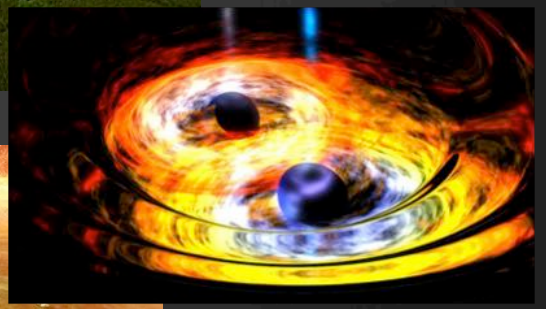
Fermi and Multimessenger Astrophysics

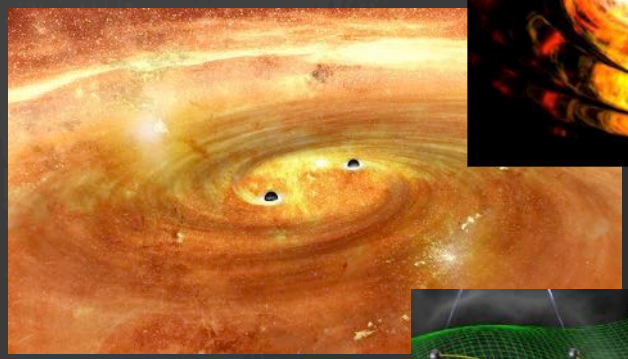
Suddenly more prominent than it was...

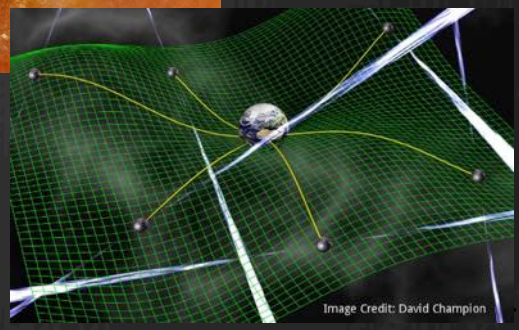
Fermi synergies with LIGO/ Virgo – already extensively discussed

Longer wavelength gravitational waves - *Fermi* and pulsar timing arrays

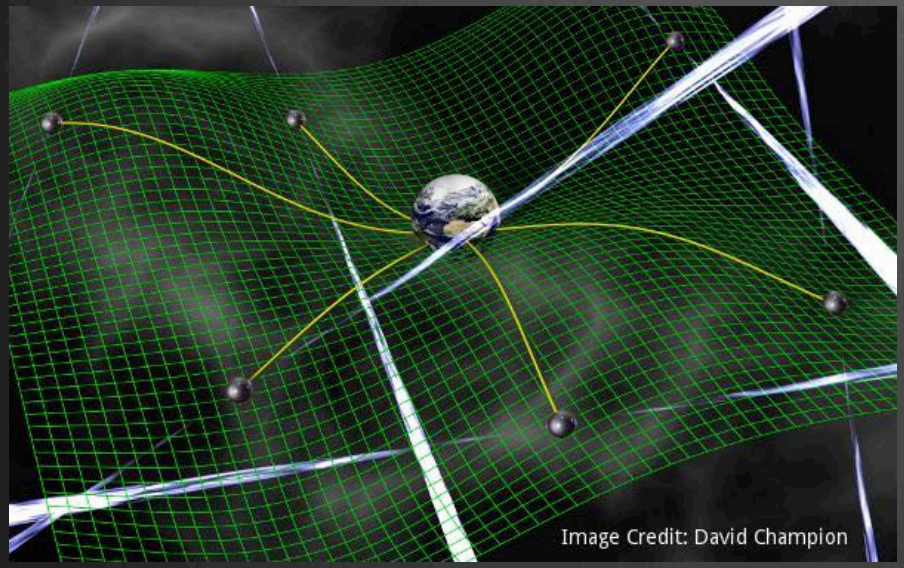
Neutrino Counterpart searches

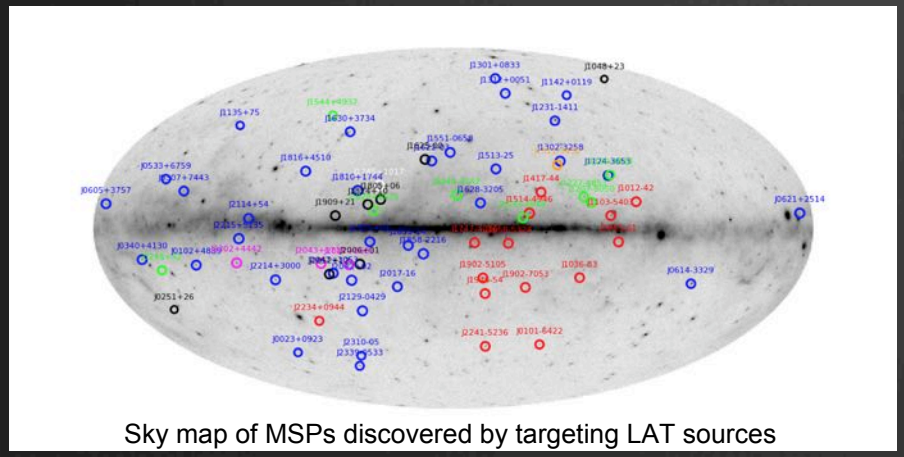






Fermi and Pulsar Timing Arrays

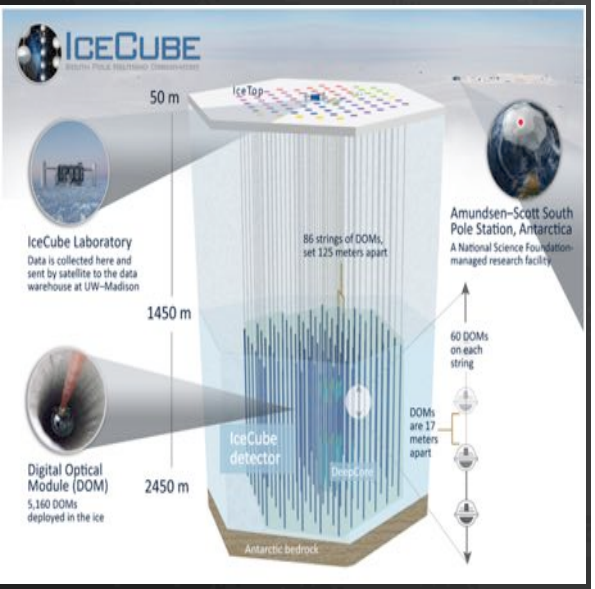


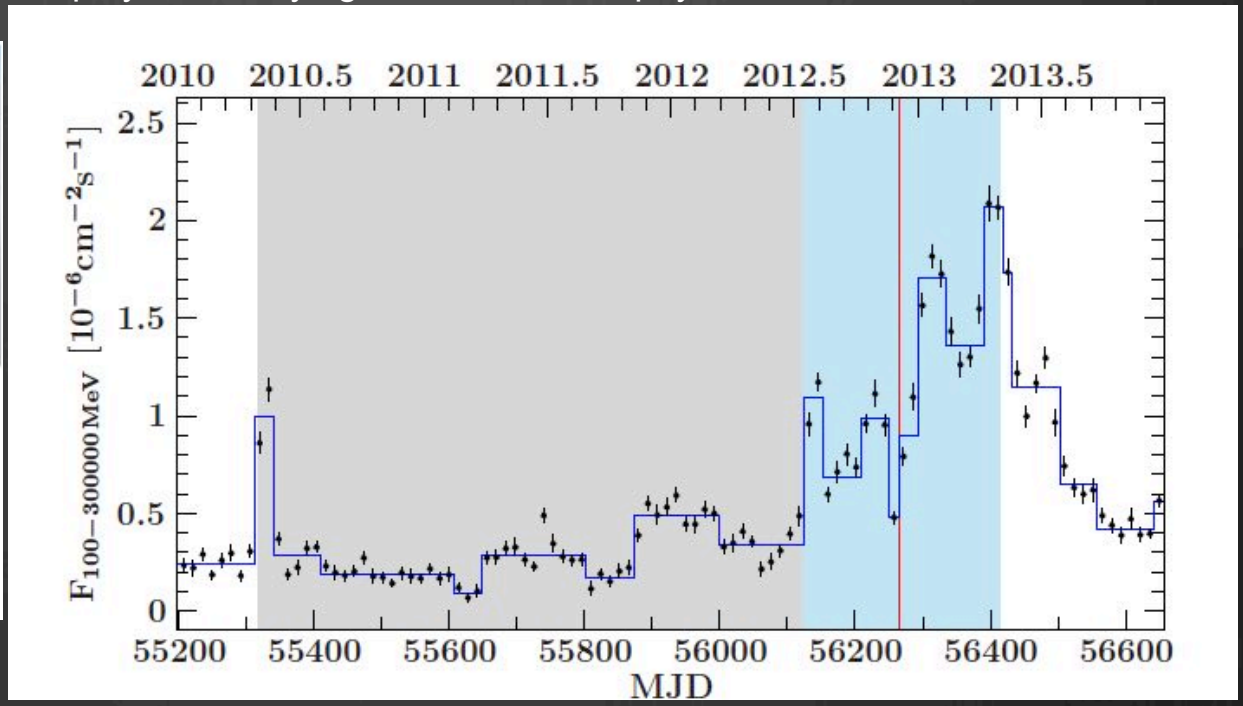

Sky map of MSPs discovered by targeting LAT sources

- 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 ⅓ of all known Galactic MSPs!)
  - More expected from Pass 8 catalog analysis
- >12 new MSPs have been added to PTA projects, and more are being evaluated

Multi-messenger astronomy: Possible link between a high-energy cosmic neutrino and a distant galaxy

The physical process that produces high energy neutrinos also produces high energy gamma-rays, thus Fermi has a unique role to play in identifying sources of astrophysical neutrinos

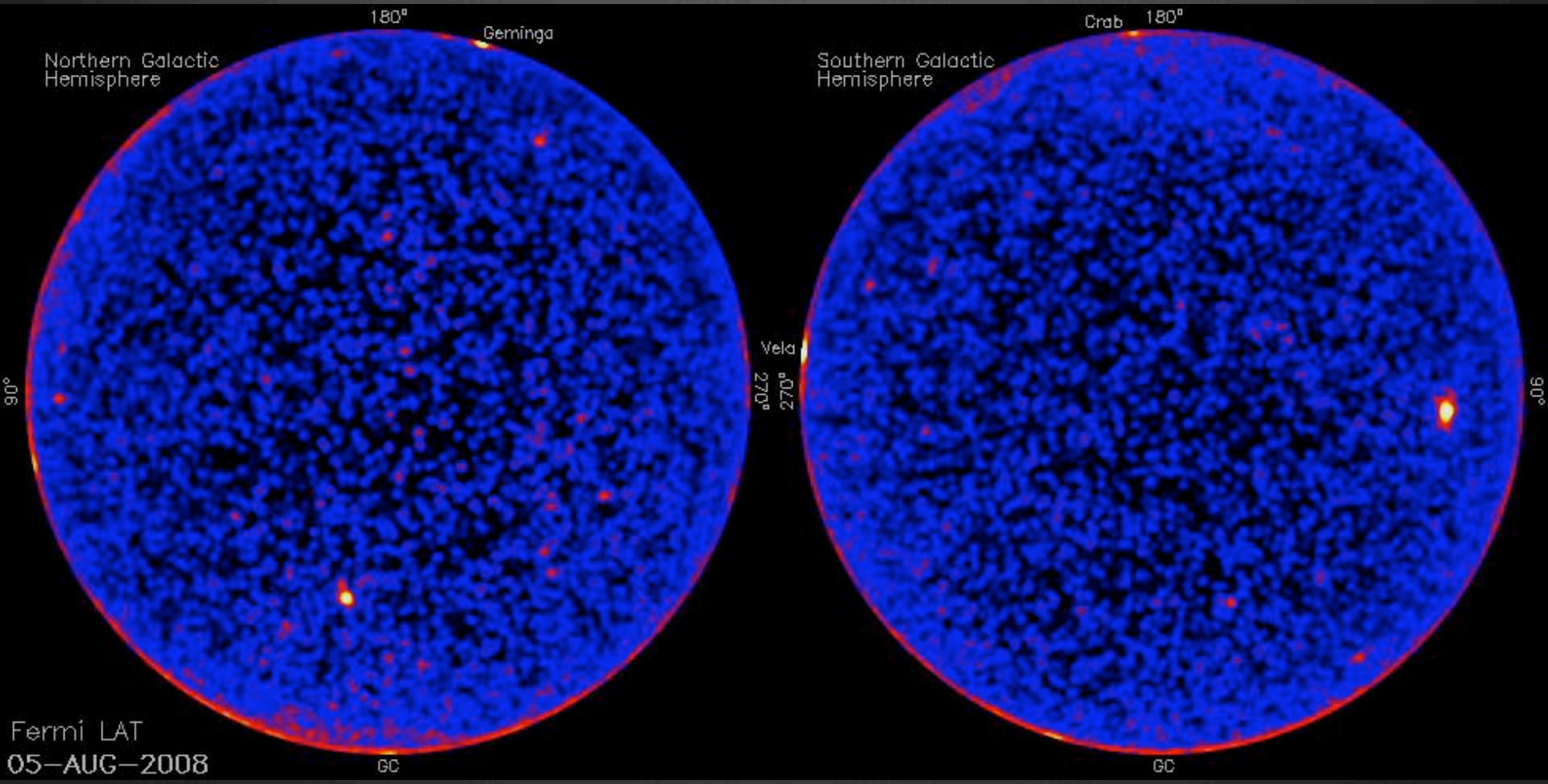




Gamma-ray lightcurve (data points) for PKS 1424-418 showing a large outburst positionally and temporally consistent with the third PeV neutrino seen by IceCube (red line)

The IceCube Neutrino Observatory at the South Pole has detected astrophysical high-energy neutrinos. Using Fermi, we have found the first plausible association between the highest energy neutrino observed and a dramatic gamma-ray flare of the active galaxy PKS 1424-418. This is a major step towards understanding fundamental physics of neutrinos.

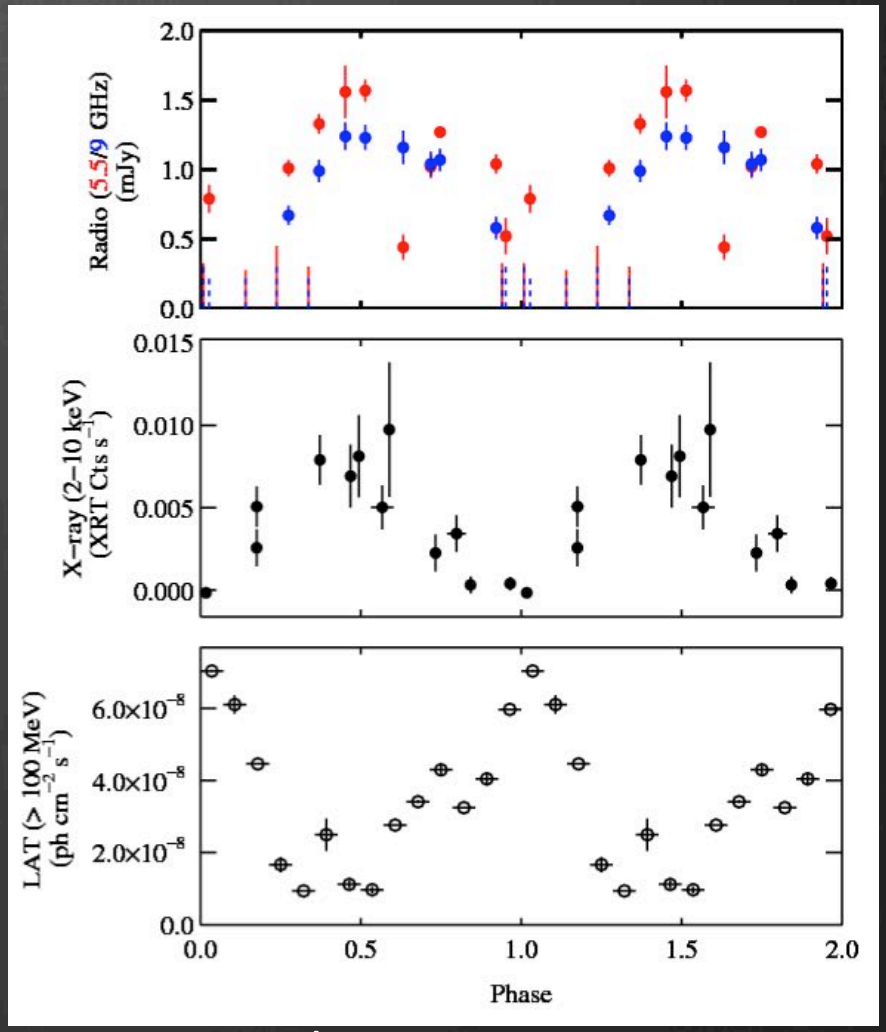
Time Domain Astronomy



Fermi explores the high energy γ-ray sky on timescales from milliseconds to years with a wide field-of-view and survey-mode observations

A Luminous LMC γ-ray Binary

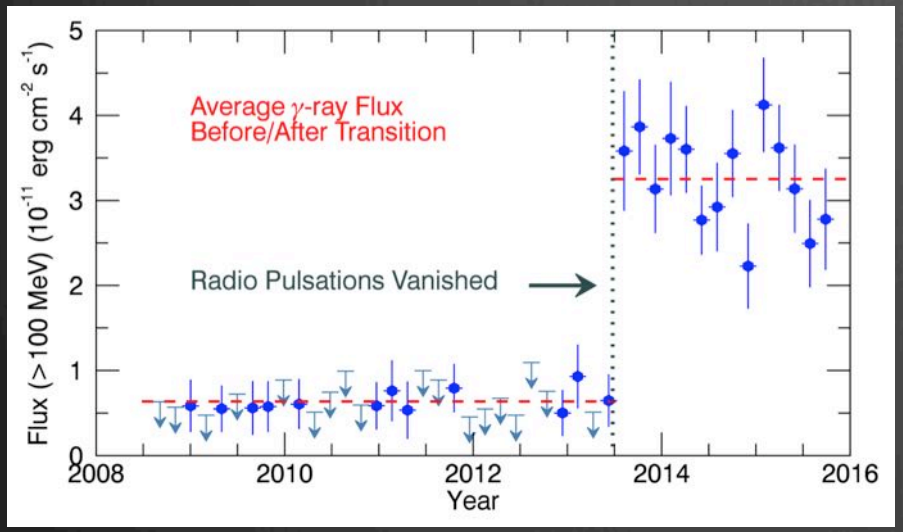
- New γ-ray binary discovered in the LMC from a periodic modulation search of 3FGL sources
- O-giant counterpart in a supernova remnant may have a neutron star or black hole companion (DEM L241)
- Follow-up X-ray and radio observations confirmed 10.3 day period
- > 10x more luminous at all wavebands than Galactic γ-ray binaries and may be a new class of γ-ray source



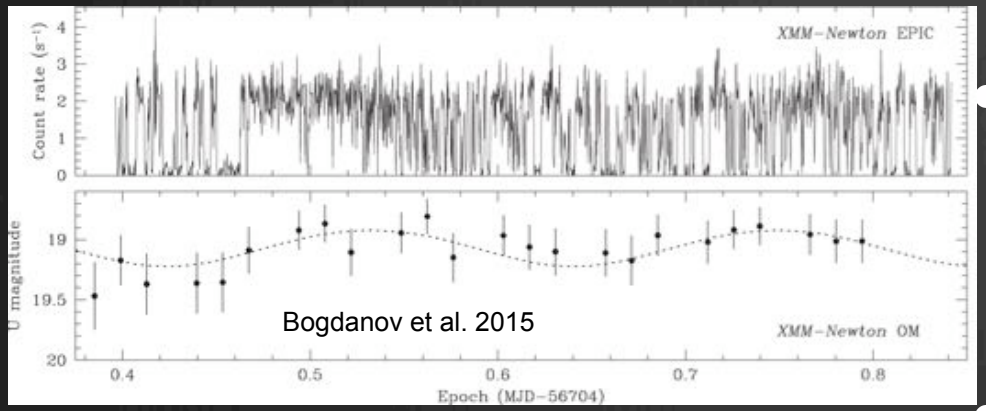
Corbet+ 2016, in-prep

Transitional Millisecond Pulsars

Gamma-ray Transition of PSR J1023+0038



X-ray and U Band Light Curves of 3FGL J1544.6-1125

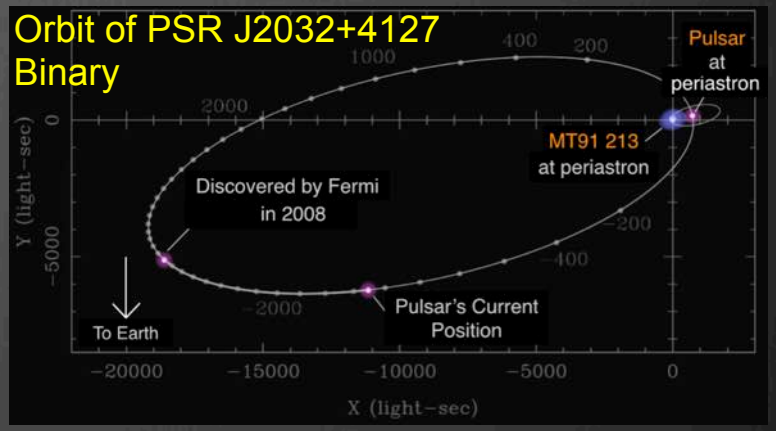


- 40% of MSPs discovered in searches of LAT sources are interacting binaries (`black widows' and `redbacks')
- Prior to *Fermi* only 1 redback and ~6 black widows were known outside of globular clusters (now ~12 and 24)
- More expected - LAT already detected two transitions between accreting and radio MSP states
- γ-ray emission brighter in the accreting state – a mystery since accreting sources are *not* typical γ-ray emitters. What is the mechanism?
- Optical searches of LAT sources have revealed new candidates

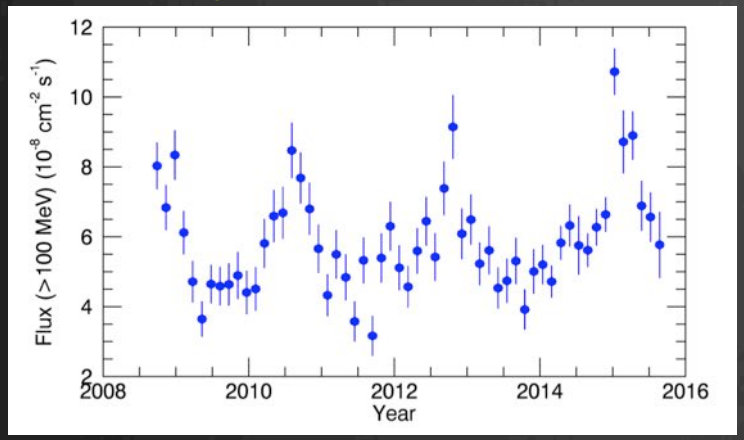
A new area of study for *Fermi*

Much more to come in TDA

Things we expect: e.g., the periastron passage for the ~25 yr period binary system



LAT Light Curve of PG 1553+113



Discovery space with long temporal baselines: e.g.,(quasi-)periodicities in supermassive black hole systems PG 1553+113, OJ 287

Observe rare extreme events such as a giant magnetar flare

?

Things that we don't expect, a prime area of discovery space showing no signs of slowing down

Fermi Transient Searches

Transients Timescale Pipelines

LAT Transient Factory (LTF)

Fermi All-sky Variability Analysis (FAVA)

LAT Burst Advocate Tool

LAT Automated Science Processing (ASP) + Flare Advocates

GBM Untriggered Search

GBM Onboard Triggers

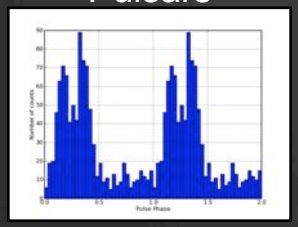
LAT Catalogs

μs ms s minutes hours days months years

Photon Timing

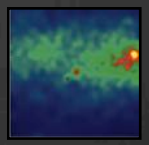
All Sky Cadence

Pulsars

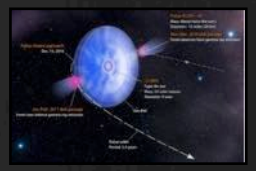


Solar Flares

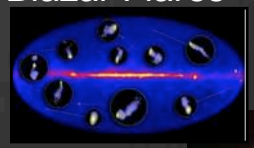
Novae



γ-ray Binaries

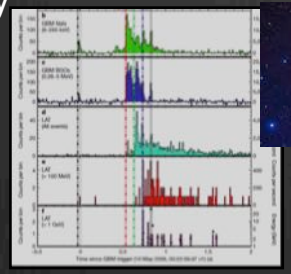


Blazar Flares



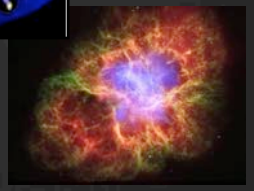
Terrestrial γ-ray Flashes

GRBs



Magnetar Flares

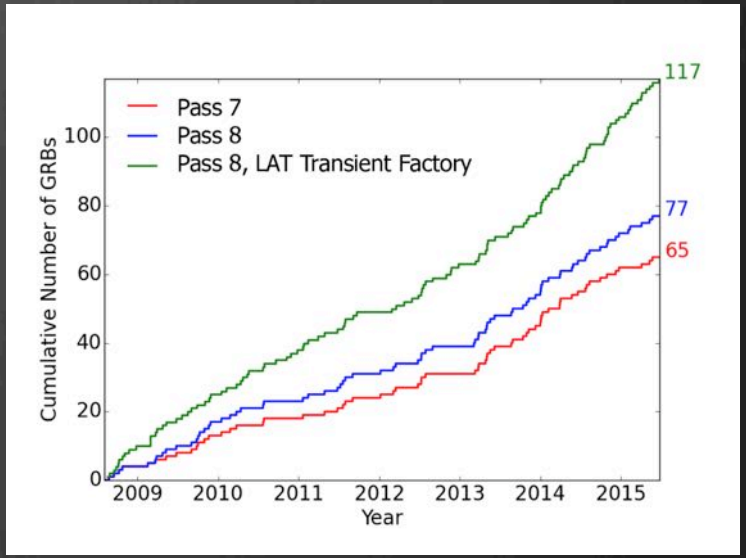
Crab Flares



Not to scale

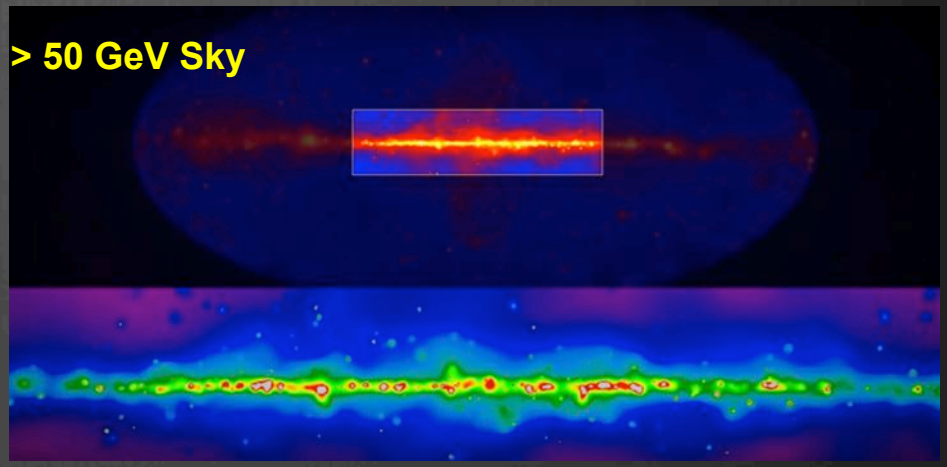
Initiatives: Enhancing Observations of Transients

- Pass 8 improves localizations
  - More photons
  - Narrower PSF
- Reduce data latency by ~30–40%
  - Already increasing frequency of short downlink passes
  - Plans to parallelize ground data transfer
- New automated pipelines searching for transients
  - *Fermi* All-Sky Variability Analysis (FAVA) - 1 week aperture photometry
  - LAT Transient Factory (LTF) - improvements in pipeline that searches for LAT counterparts to GBM GRBs
- *Will lead to faster notifications of transients to community (via ATel, GCN, VOEvent, email lists), and potentially more LAT TOOs and TOO requests for follow-up facilities (e.g., Swift)*



Maximizing the Science Return from Pass 8

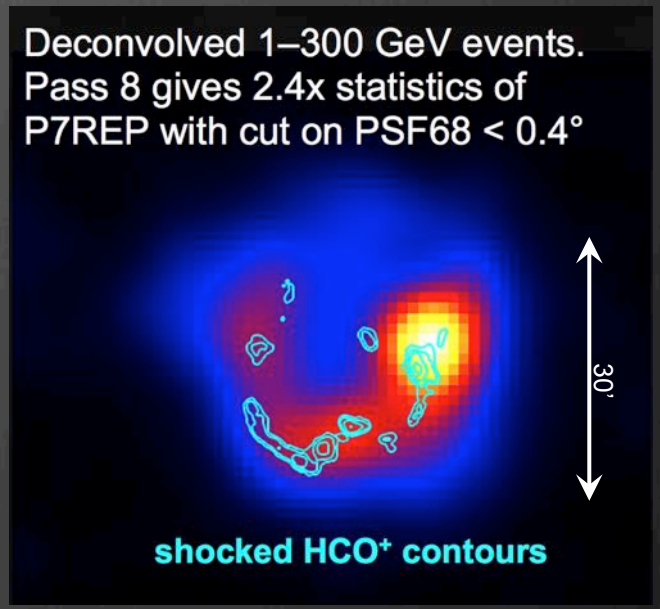
- High Energies (>10 GeV)
  - Pass 8 increases acceptance by >30%
  - New diffuse models needed in energy range requiring extrapolating template fits plus non-template components, e.g. the Fermi bubbles

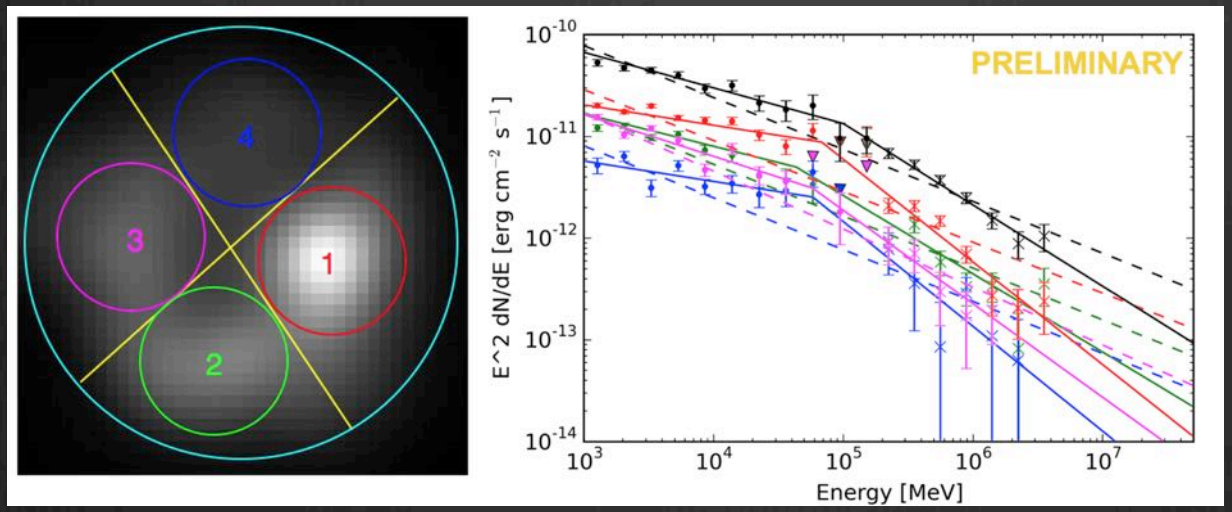


- Low Energies (< 100 MeV)
  - Pass 8 increases acceptance >60% at low energies
  - Earth Limb contamination more difficult to account for at low energies with wide PSF
  - New Diffuse Models and instrument response functions needed
- Longer Baseline with an extended mission
  - New Diffuse models and updated source catalogs needed for any long-term analysis

Resolving a Proton Accelerator

- Pass 8 data resolve the shell of supernova remnant IC 443 at physical scales of ~5 pc
- GeV/TeV γ-rays match the distribution of shocked gas (HCO+)
- Dense molecular and diffuse atomic (fast shock) regions differ in brightness by ~10x, but spectra are surprisingly consistent



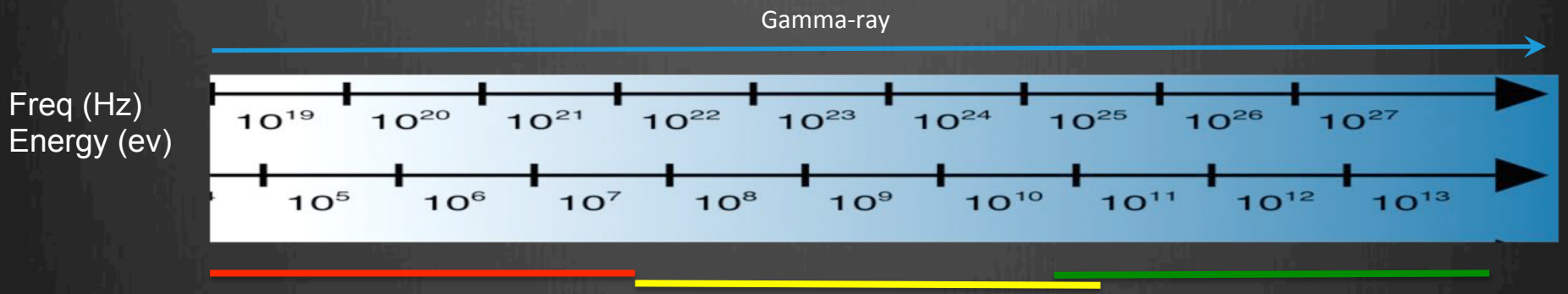


Fermi-LAT paper in preparation with VERITAS

A new capability with Pass 8

Gamma-ray Astrophysics after Fermi?

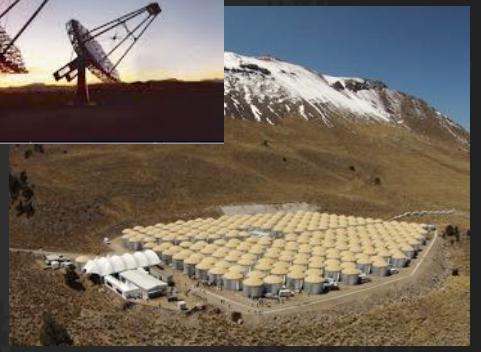
Gamma-ray Astrophysics



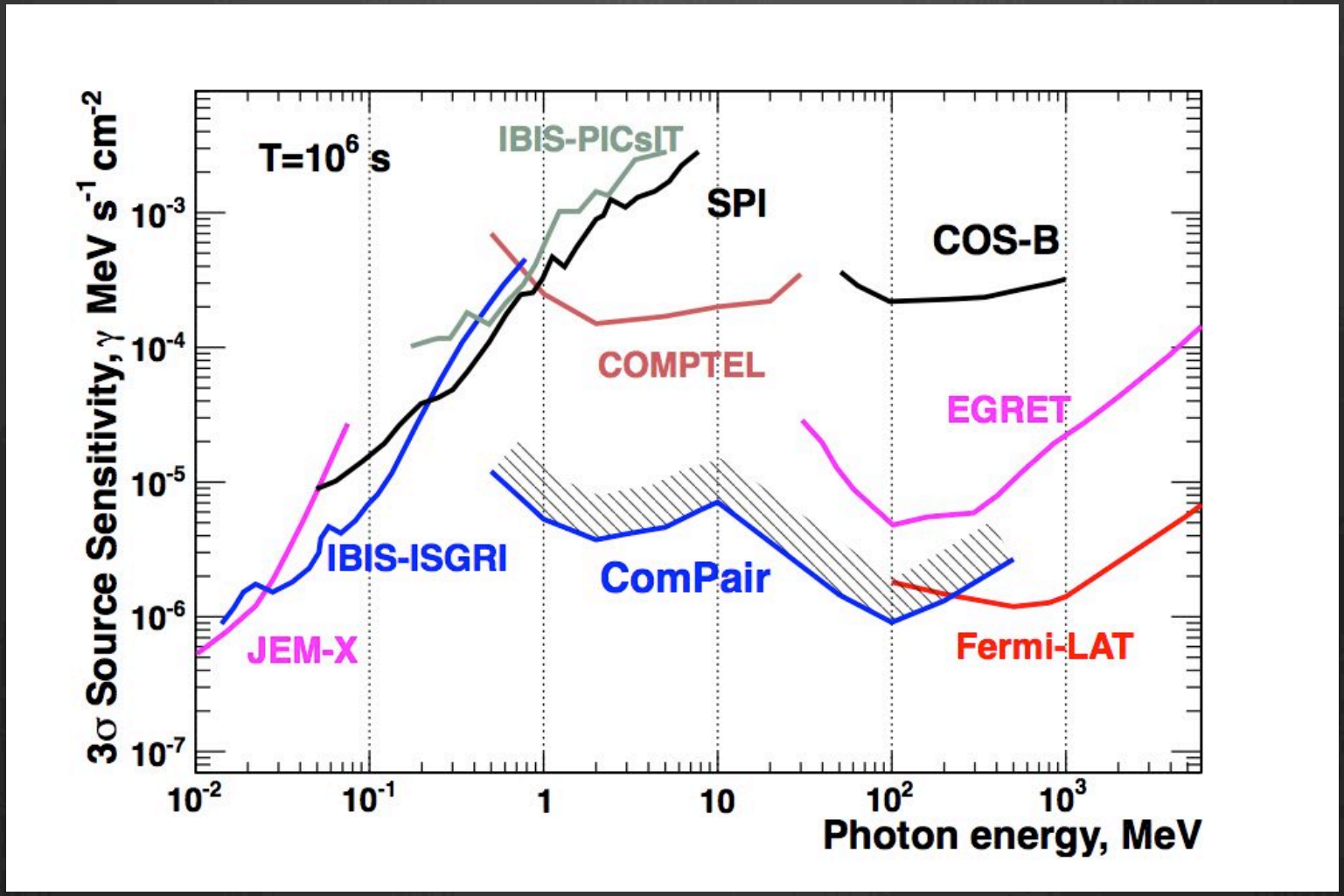
Medium Energy gamma-rays (aka MeV)

High Energy gamma-rays (aka GeV)

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



An Underexplored Energy Band

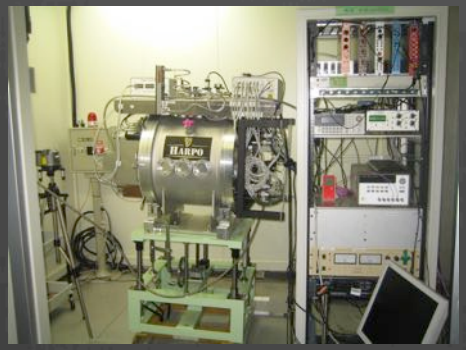


- No significant progress in the MeV band over the past 20 years

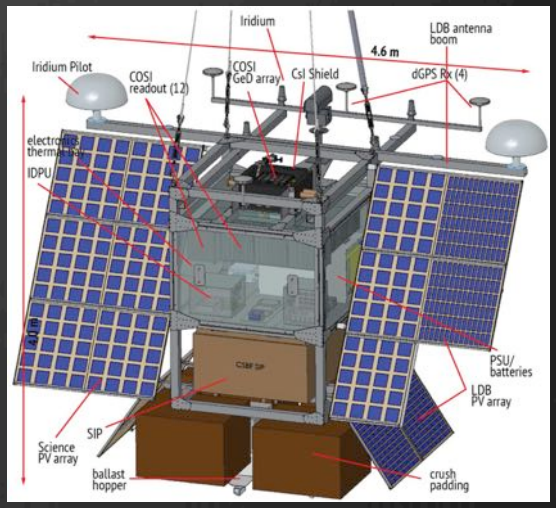
MeV Gamma-ray Instrument Landscape

Understanding the MeV universe requires a *multi-instrument, multi-technique* approach.

Time Projection Chambers: (AdEPT, HARPO, LArGO) high angular resolution, good polarization capability

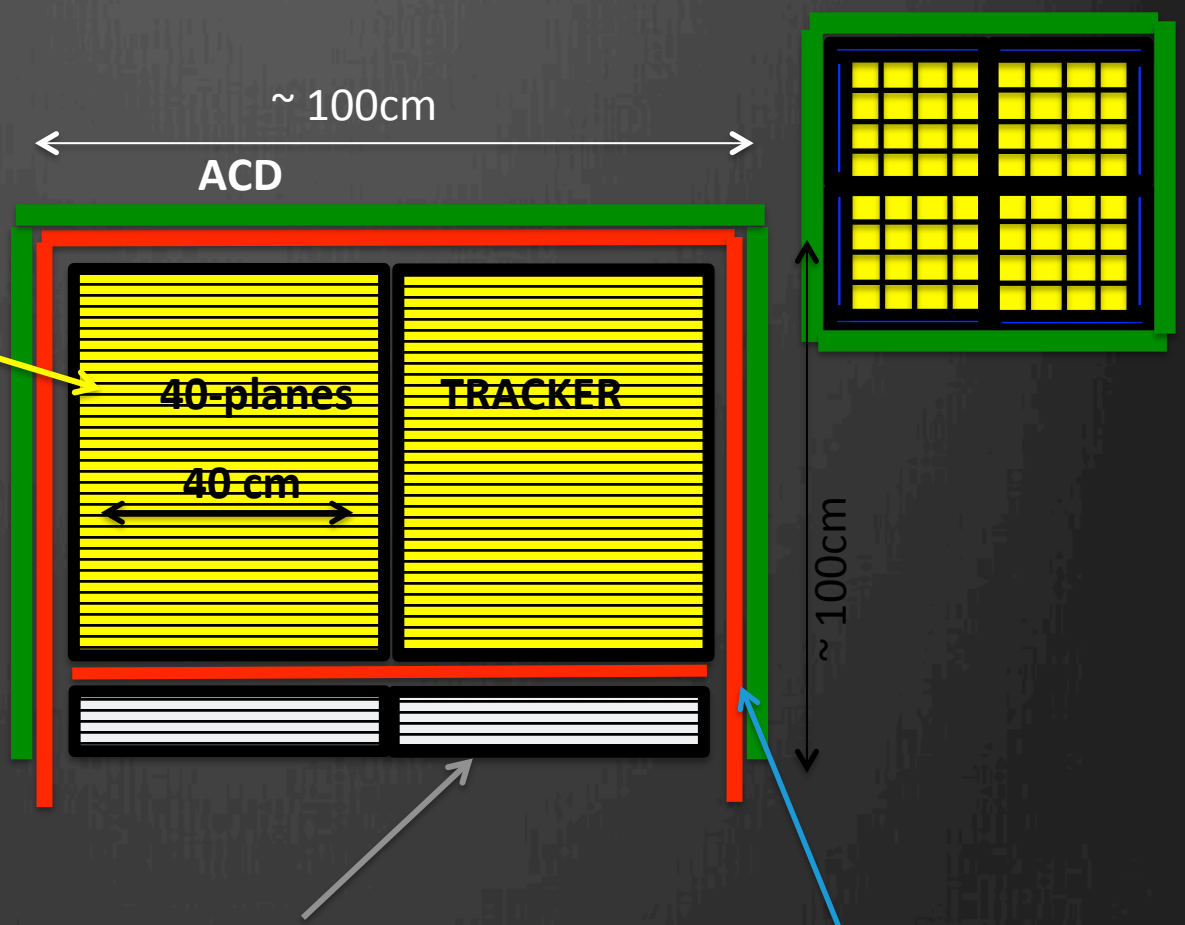


Spectrometers / mappers: (COSI, GRX) high resolution spectroscopy, wide field of view, some polarization capability



Continuum / survey mappers: (ComPair, MEGA, AstroGAM) high flux sensitivity, wide field of view, broad energy coverage, some polarization capability

ComPair Instrument



Tracker

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

- 40 layers DSSD, spaced by 1.5 cm
- Strip pitch 0.5mm

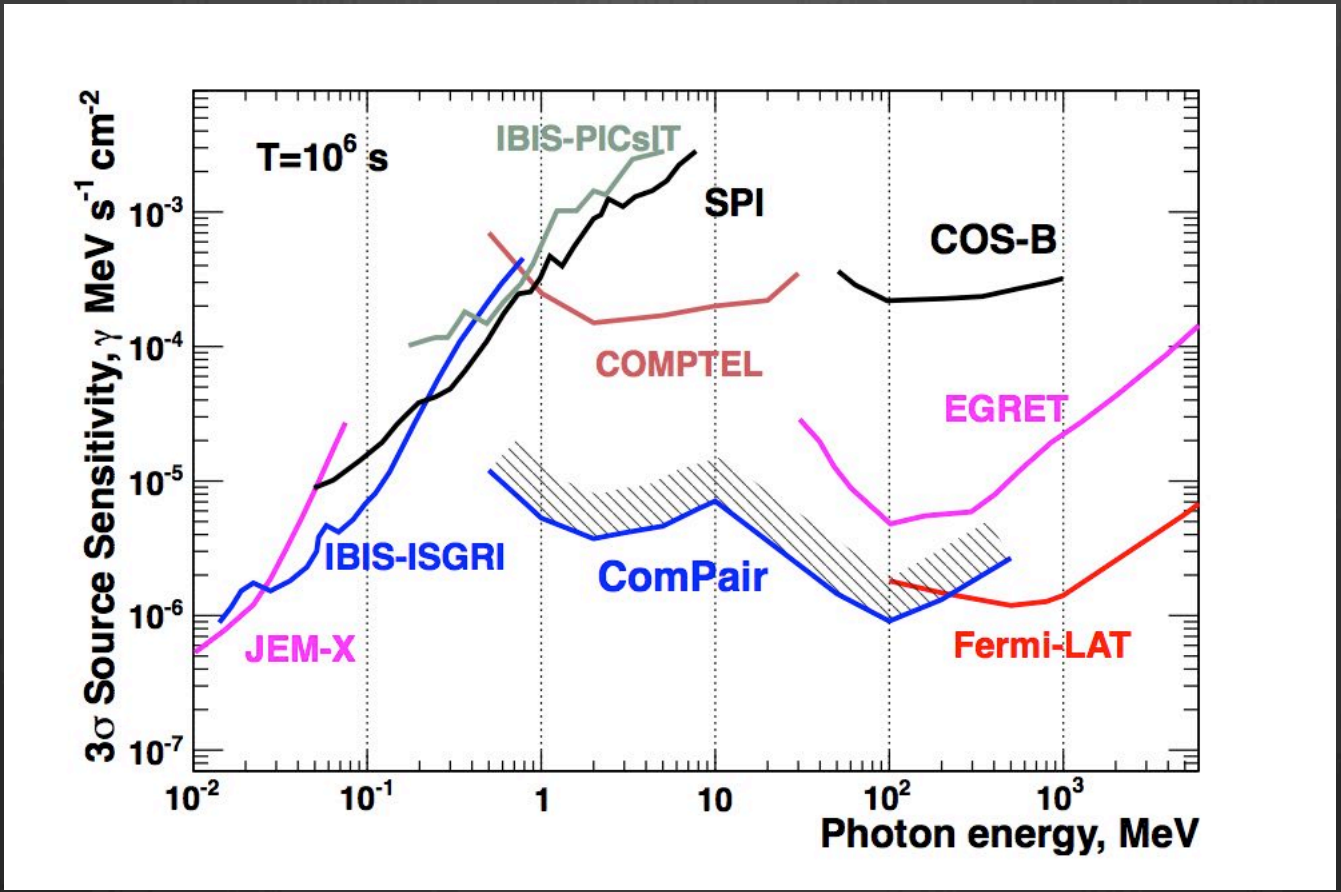
CsI Calorimeter

Measure energy and position of scattered Compton gamma-rays, and particles from Pair events

- 4 layers of CsI logs, each log is 1.5cm x 1.5 cm x 38 cm
- 4 segments per layer, 26 logs per segment

ACD vetos charged particle background

ComPair: *A wide aperture discovery mission for the MeV band*



- Energy range: 500 keV – 500 MeV
- Angular resolution: 3° (1 MeV), 10° (10 MeV), 1.5° (100 MeV)
- Field of View: ~2.5 sr
- Operate in survey mode, view 80% of the sky in one orbit
- Some sensitivity to polarization and nuclear lines

ComPair Science

Understanding Extreme Environments

Astrophysical Jets

Enormous power from small regions

Compact Objects

Laboratories for extreme gravity & magnetism

Unidentified GeV Sources

Guaranteed discovery space in determining the origin of these sources

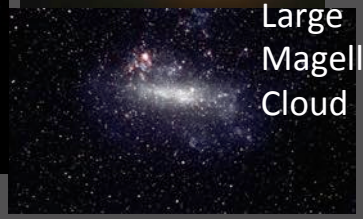
Diffuse galactic lines

Pulsars

Gamma-ray Bursts

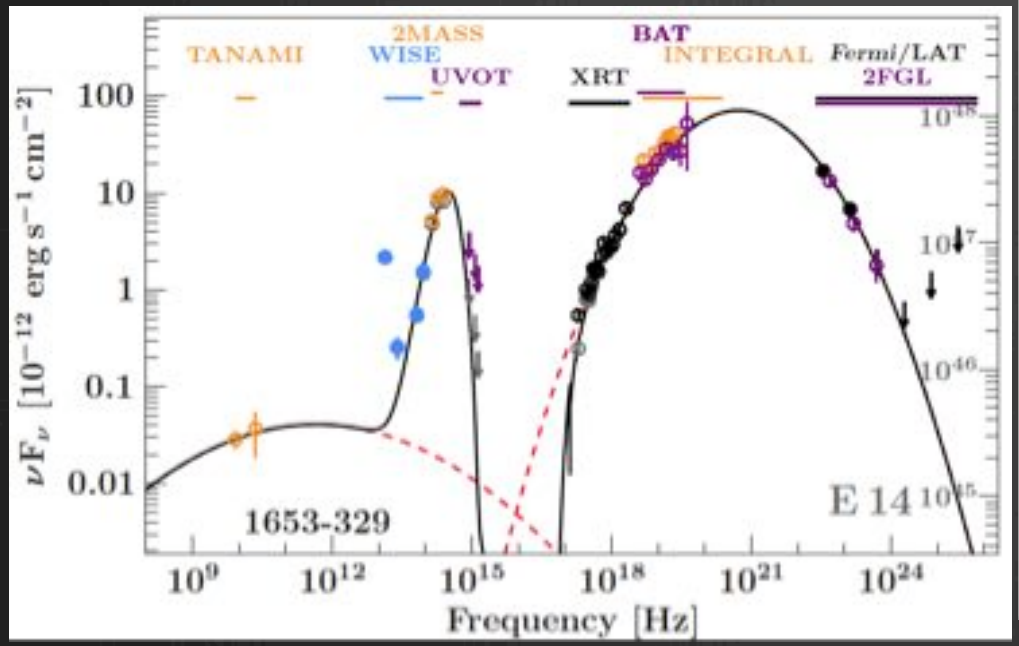
Sun

Dark Matter



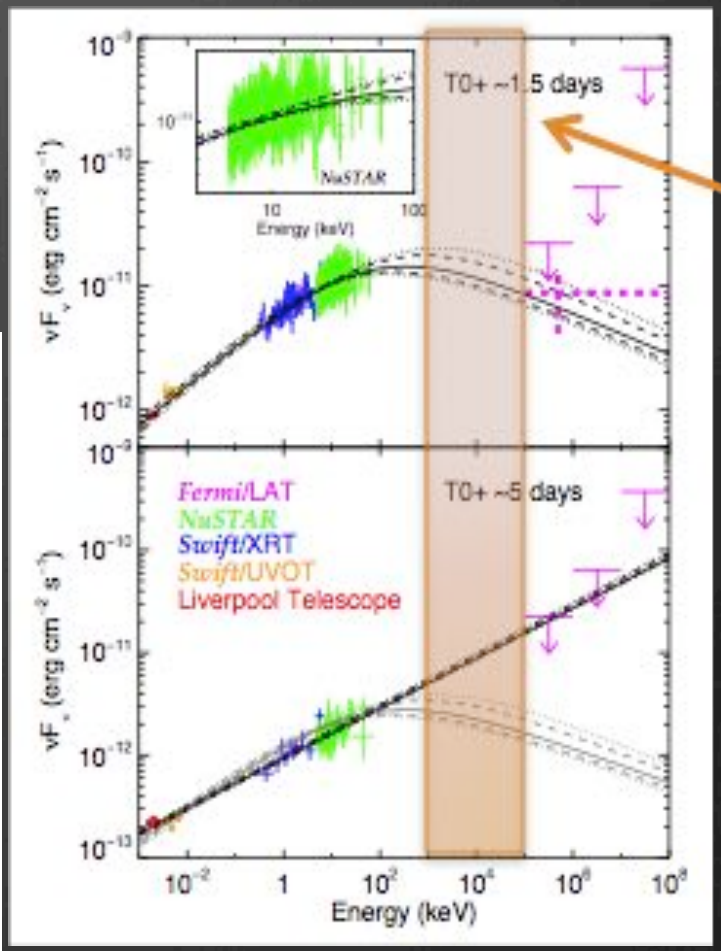
Ubiquity of Jets

- Jets are powerful accelerators, but we do not yet understand their emission mechanisms
- Measurement of their SEDs is vital for physical models of their radiation processes



J1653-329 a candidate PeV neutrino emitter (Krauss et al 2014)

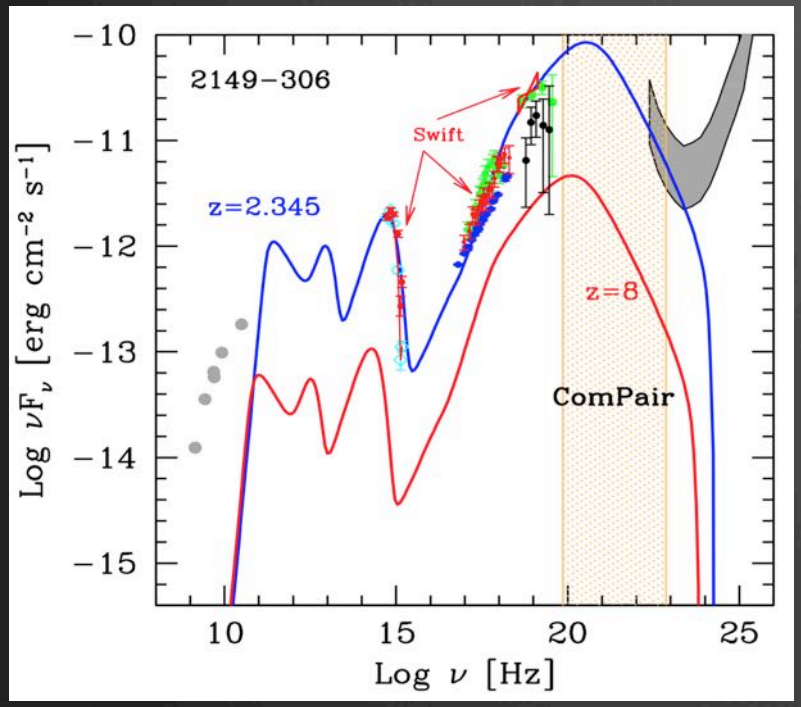
GRB 130427A



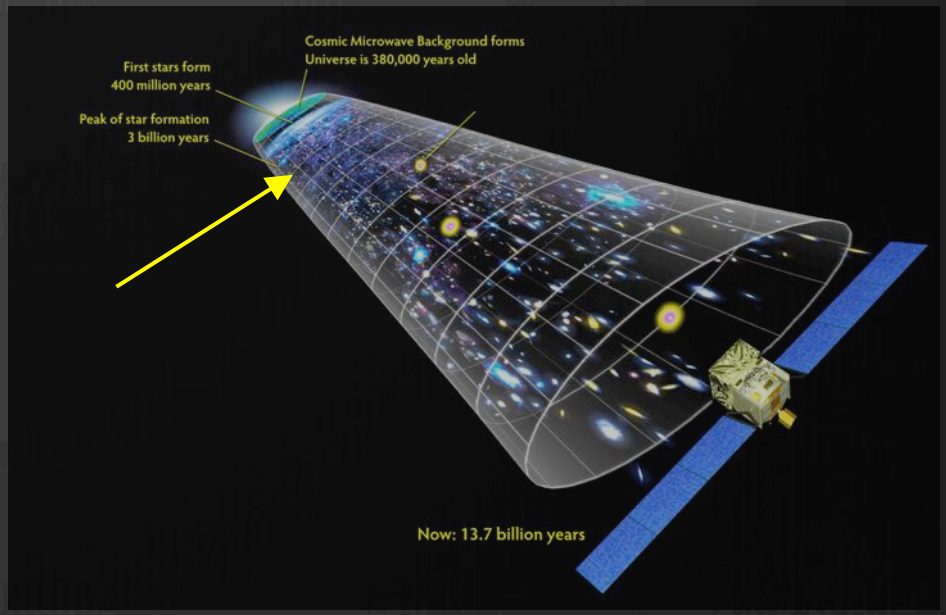
1-100 MeV

Kouveliotou et al. 2013

MeV Blazars: The Heaviest Black Holes



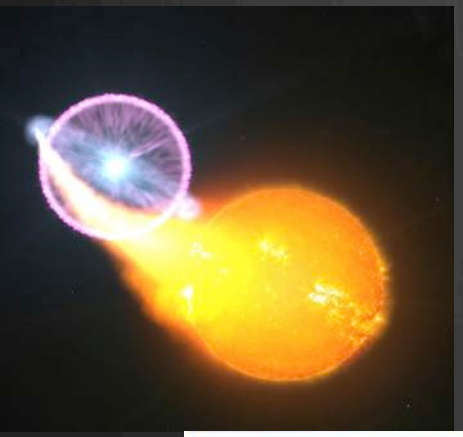
- Blazars whose power output peaks at ~1 MeV
  - are more luminous and have faster jets than all other active galactic nuclei
  - are known to harbor the heaviest black holes ($M_{\odot}>10^{9}$)
  - are the most distant persistent gamma-ray sources



ComPair will detect >500 blazars out to z~6-8

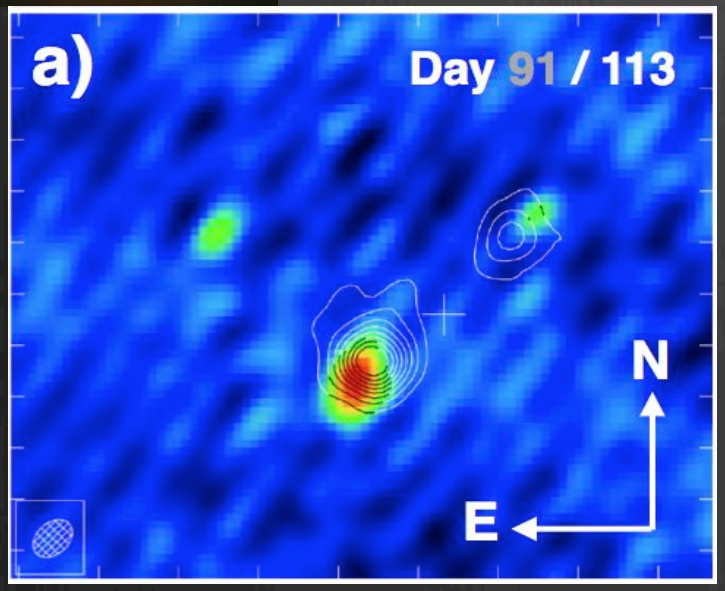
- Discovery of MeV blazars at high redshift will show that massive black holes can grow via processes other than accretion

Novae: A New Player

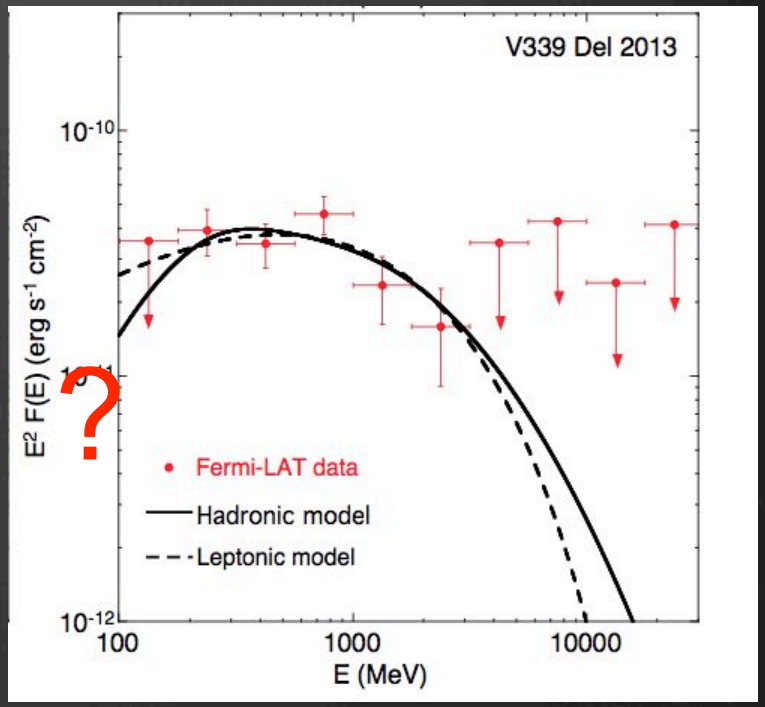


How do close binary star systems like classical novae eject mass during outbursts?

Shocks in the expanding nova envelope produce gamma rays. ComPair will measure the energy spectrum below 100 MeV to determine the shock properties and identify novae missed by optical observations.



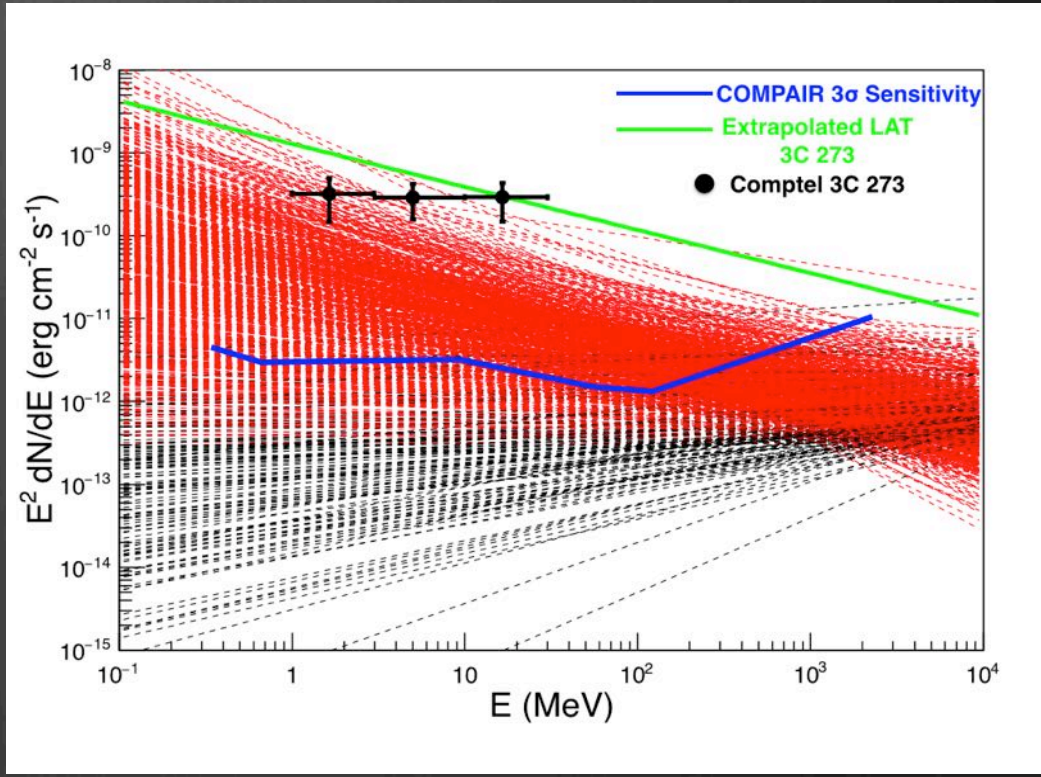
Synergy with radio observations that reveal shock sites - V959 Mon gamma-ray nova example.



Fermi LAT - energy spectrum below 100 MeV is undetermined

Discovery Space

- Previous instruments covering the 1-100 MeV range were COMPTEL/OSSE on CGRO and Integral SPI
- ~⅓ of Fermi-LAT sources remain unidentified
  - ComPair will provide a bridge between high- energy gamma-ray and X-ray regimes, helping to identify and understand these objects
- Below 200 MeV, ComPair will dramatically improve sensitivity will open a new window in the EM spectrum leading to the discovery of many new sources and source classes



>50% of Fermi-LAT catalog sources have a peak below the Fermi-LAT band.

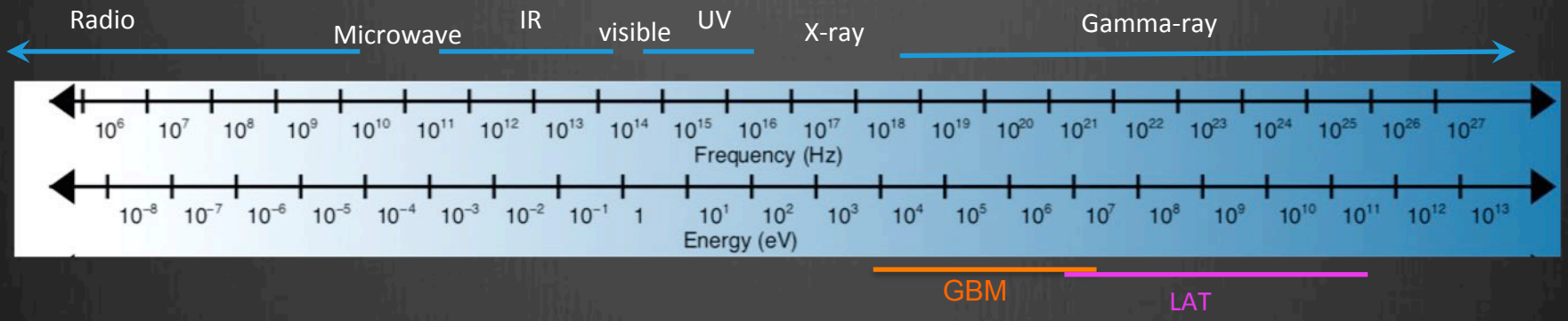
Summary

- The MeV gamma-ray band has enormous scientific potential
- ComPair, optimized for high flux sensitivity, broad energy range and a wide field of view will focus on astrophysical extremes
  - High matter densities
  - Strong magnetic fields
  - Powerful jets

And will be sensitive to spectral features such as breaks, turnovers, cutoffs, and temporal behavior, which are critical to discriminate between competing physical models, occur within the MeV energy range.

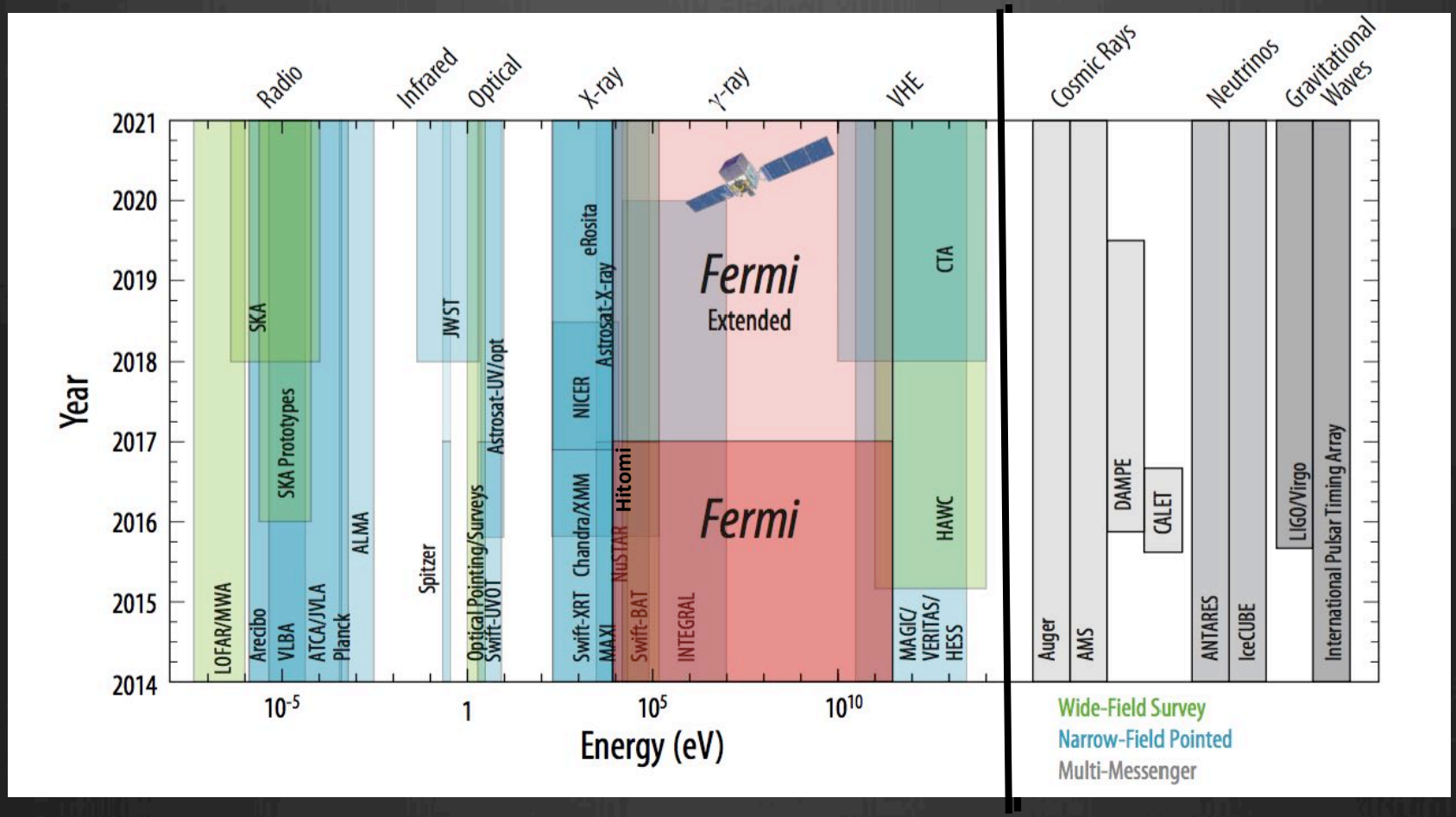
Lots of cool science that I have not mentioned…

Gamma-ray Astrophysics



- Gamma-rays cover a huge swath of the electromagnetic spectrum
- The gamma-ray sky is still very new
- High-energy gamma-rays probe the non-thermal universe
  - Explore extreme environments hosting powerful particle accelerators

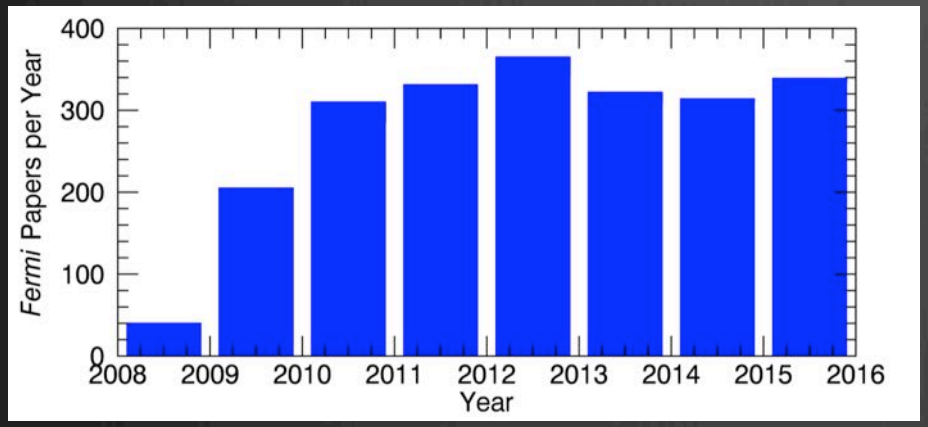
Fermi in Context



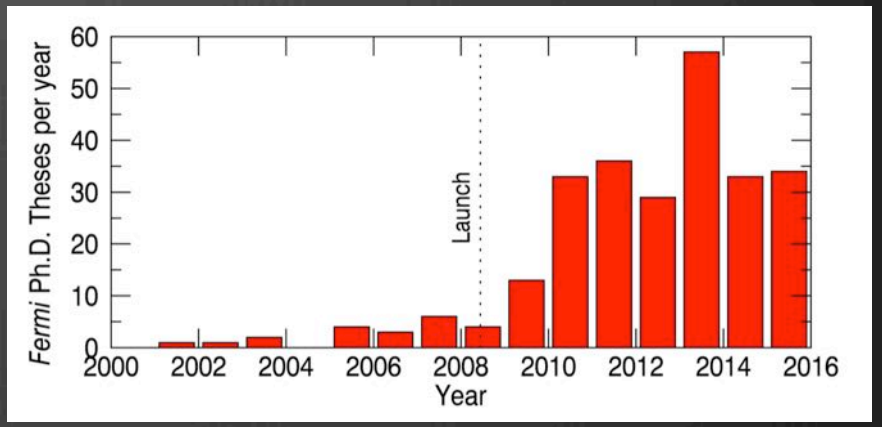
- *Fermi* is the only mission in its waveband for the foreseeable future!
- New multiwavelength-multimessenger opportunities have opened up

Science Return: Papers and Theses

***Fermi*-Related Papers**

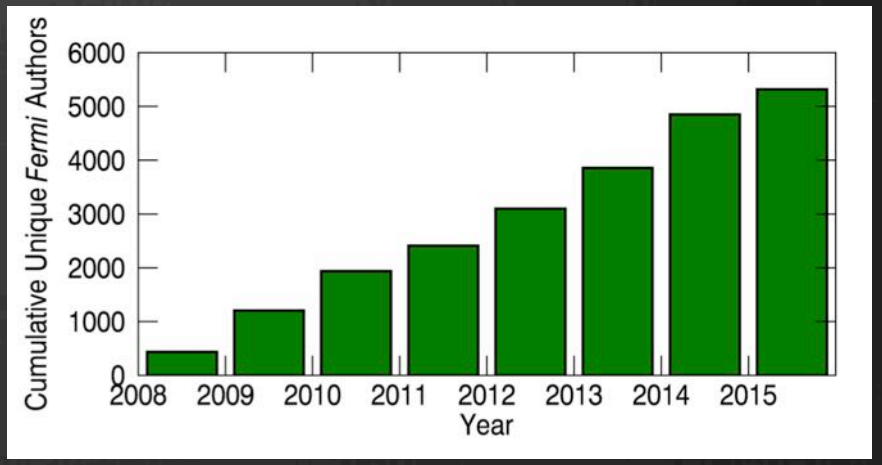


***Fermi*-Related Ph.D. Theses**



- Rates of refereed publications and student theses remain high
- Community of *Fermi* users is growing!

***Fermi* Paper Authors**



3 *Fermi* papers in top 10 most cited papers in all of astrophysics published in 2015

#3 *Fermi Large Area Telescope Third Source Catalog*, Acero, F. et al., ApJS 218, 23, 2015

Source catalog is essential for analysis of all *Fermi*-LAT sources, population studies, and is mined for unassociated sources

#9 *Background model systematics for the Fermi GeV excess*, Calore, F. et al., JCAP 03, 038, 2015

Exploring a possible dark matter signal in *Fermi* data in excess GeV emission from GC

#10 *Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data,* Ackermann, M. et al., PRL 115, 1301, 2015

Limits on dark matter signal in *Fermi* data, the most stringent to date

#12 & 13 also *Fermi* papers (recently bumped by Advanced LIGO & Virgo Instrument Papers)