Fermi
Gamma-ray
Space Telescope

Fermi Sky I: (Mostly) non-variable sources

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Lewes, Delaware

Outline

Non-variable

- Gamma-ray astronomy and Fermi
- Galactic Diffuse Emission
- Isotropic Diffuse Emission
- External ‘Normal’ galaxies
- Sources in the Milky Way
  - Pulsars
  - Pulsar Wind Nebulas
  - Globular Clusters
  - Supernova Remnants
  - Eta Carinae (not classified)
  - Sun & Moon
- Unassociated sources

Why is there gamma-ray astronomy?

- Nature has a remarkable number of ways to make cosmic rays (CRs, particles with extremely nonthermal energies)
  - Acceleration in shocks – on scales from solar flares to supernova remnants to colliding clusters
  - Intense, moving magnetic fields – rotating (pulsars)
  - Annihilation or decay of hypothetical dark matter particles
- Cosmic rays are not well suited for astronomy but gamma rays from CR interactions have
  - No optical depth (once they escape their emitting regions)
  - No trajectory scrambling by magnetic fields
- They are difficult to detect – but the fluxes are great enough and the technologies have advanced enough for astronomy to be possible
- There's a lot to learn from gamma rays – both uniquely and from multiwavelength studies

Why is there gamma-ray astronomy? (2)

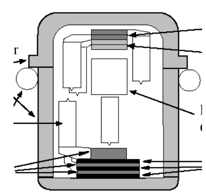
- **1948-1952, relevant cosmic production mechanisms of gamma rays were understood (Feenberg & Primakoff, Hutchinson, Hayakawa)**
- **1951, 21-cm line of H I (Ewen & Purcell, Muller & Oort)**
- **1949-1960s, upper limits on cosmic fluxes from balloon and suborbital experiments**
- **1960s-1970s, theoretical development from advances in particle physics (Stecker, Ginsburg,...)**

Brief History of Detectors* for GeV Gamma-ray Astronomy

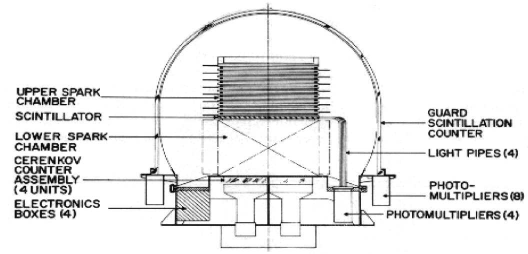
* in space

- 1967-1968, OSO-3 detected Milky Way as an extended γ-ray source, 621 γ-rays
- 1972-1973, SAS-2, ~8,000 celestial γ-rays
- 1975-1982, COS-B, orbit resulted in a large and variable background of charged particles, ~200,000 γ-rays
- 1991-2000, EGRET, large effective area, good PSF, long mission life, excellent background rejection, and >1.4 × 10^6 γ-rays
- 2007-, AGILE, like 1/16-th LAT, with small calorimeter, sensitivity ~EGRET

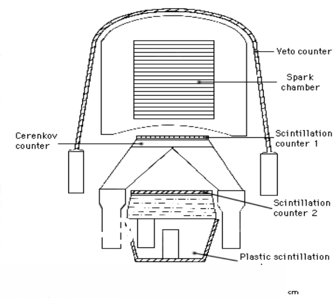
OSO-3



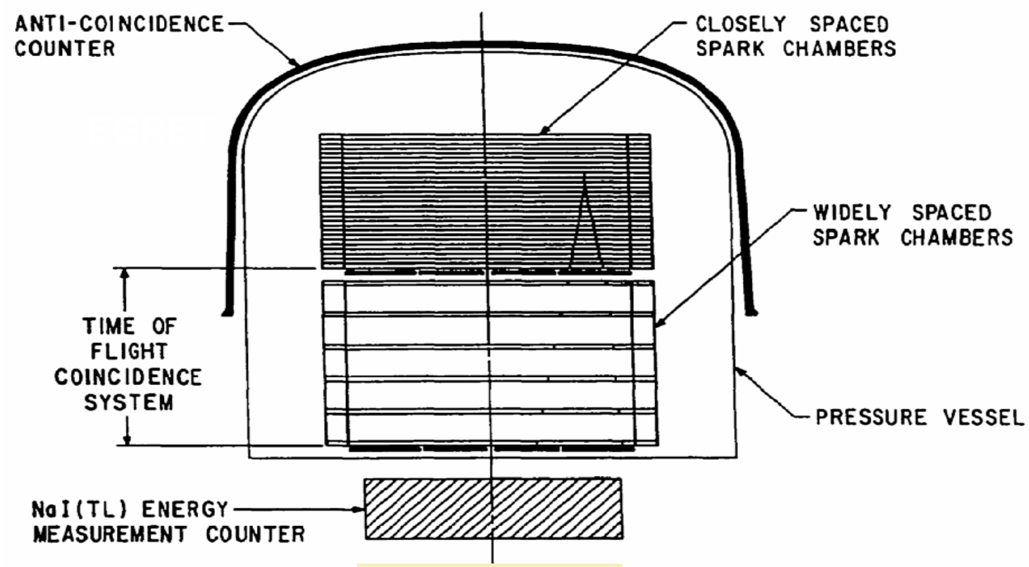
SAS-2



COS-B

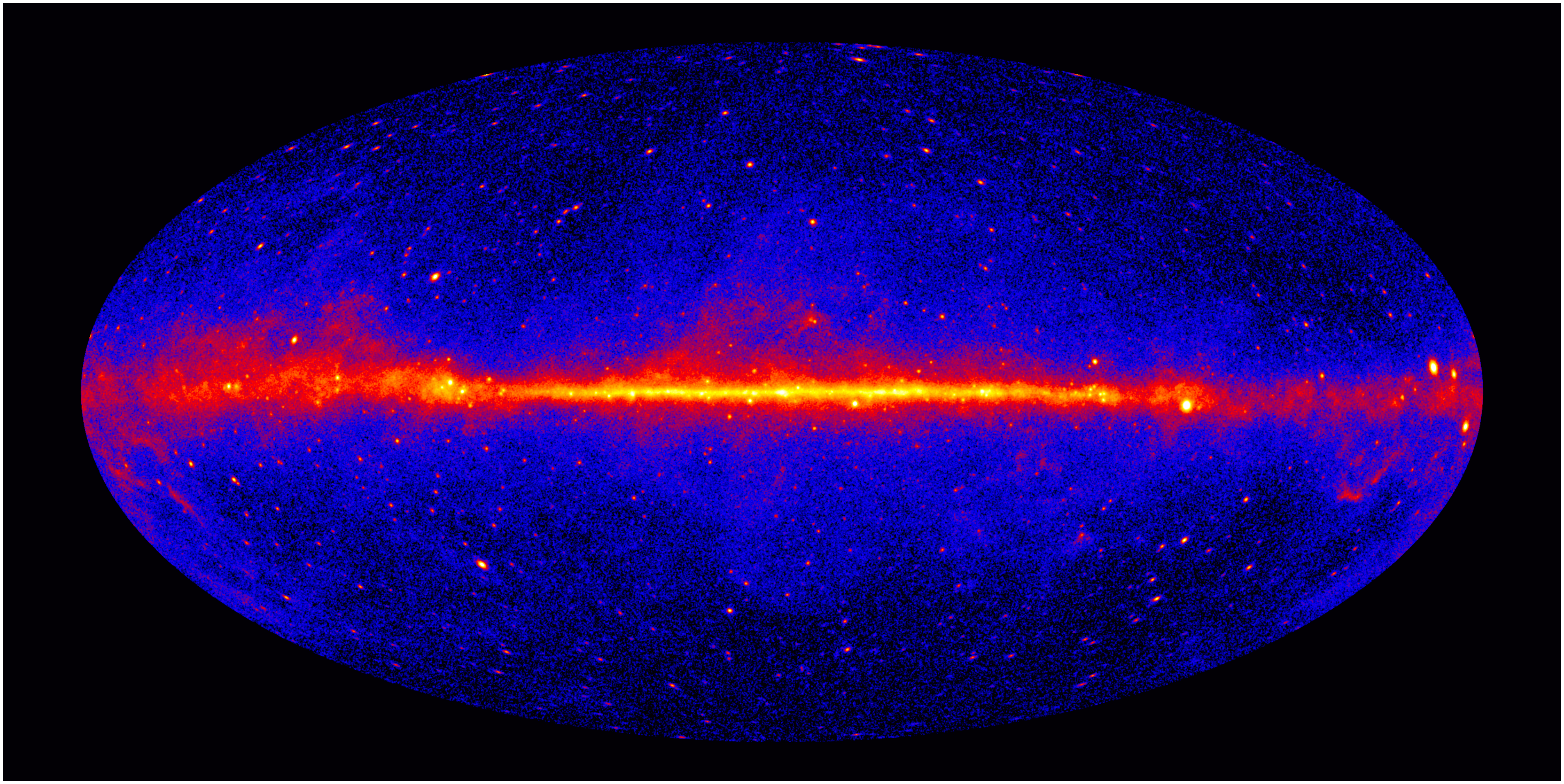


EGRET



AGILE

Reminder: The LAT Sky



>1 GeV for three years

The LAT Sky (asides)

- Few thousand gamma-ray sources
- For these we have measured source locations, spectra, light curves, and (for some) angular extent

- Absolutely identifying sources with counterparts at other wavelengths is often not possible
  - But of course it is what we would like to do
  - Identification requires correlated variability or angular extent
- That said, a positional association can be quite confident
  - Within a source class that confidence can often be quantified
- It is worth being careful about the distinction between identification and association

Galactic Diffuse Emission

- Galactic = from the Milky Way
- Diffuse = not from point sources

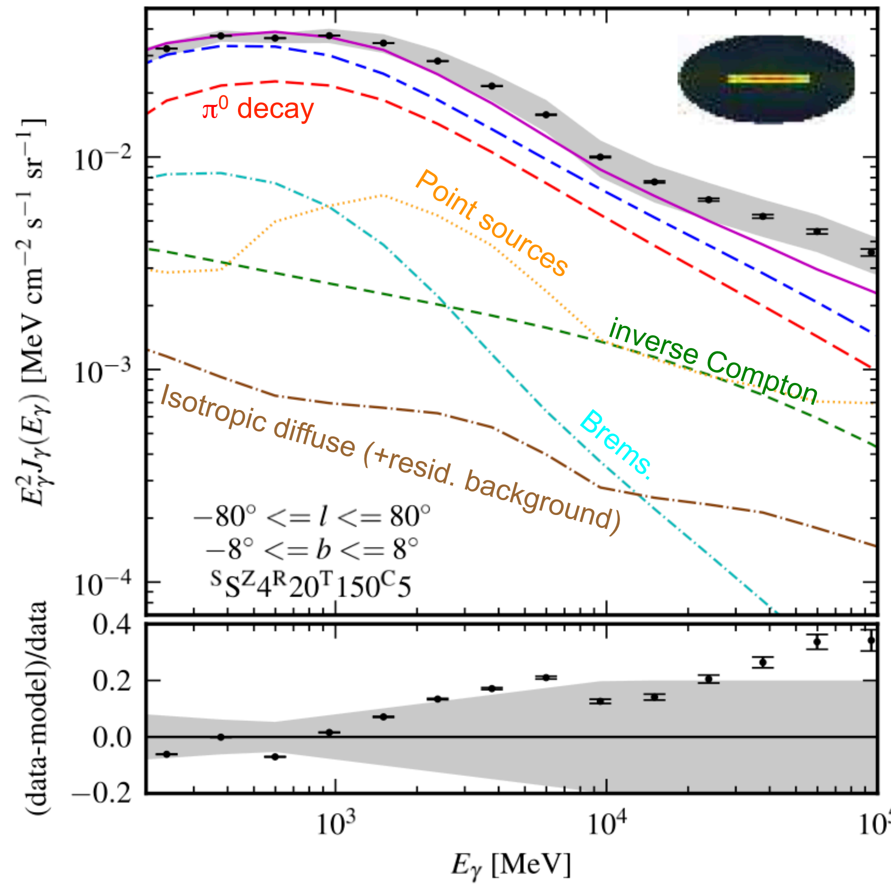
- Cosmic rays – high-energy particles propagating in the Milky Way
  - More on this from Pasquale Blasi later this morning and over the coming days
- Cosmic rays occasionally interact with interstellar nucleons and interstellar photons
- Interstellar nucleons are in the gas and dust between the stars
  - The mass of the interstellar medium is ~10% of the mass of the stars in the Milky Way, but for Galactic diffuse emission the stars essentially do not matter
  - Point later about the gamma-ray emission from the Sun
- Interstellar photons are starlight, and starlight reprocessed by interstellar dust, and the cosmic microwave background

Galactic Diffuse Emission (3)

- **In the GeV energy range the Galactic diffuse emission is relatively bright**
- **~65% of the celestial gamma rays detected by the LAT are Galactic diffuse**

- **The Galactic diffuse emission traces the distribution of interstellar gas and also relates to the (generally more smooth) distribution of cosmic rays**

Spectrum of the Inner Milky Way with Model Components



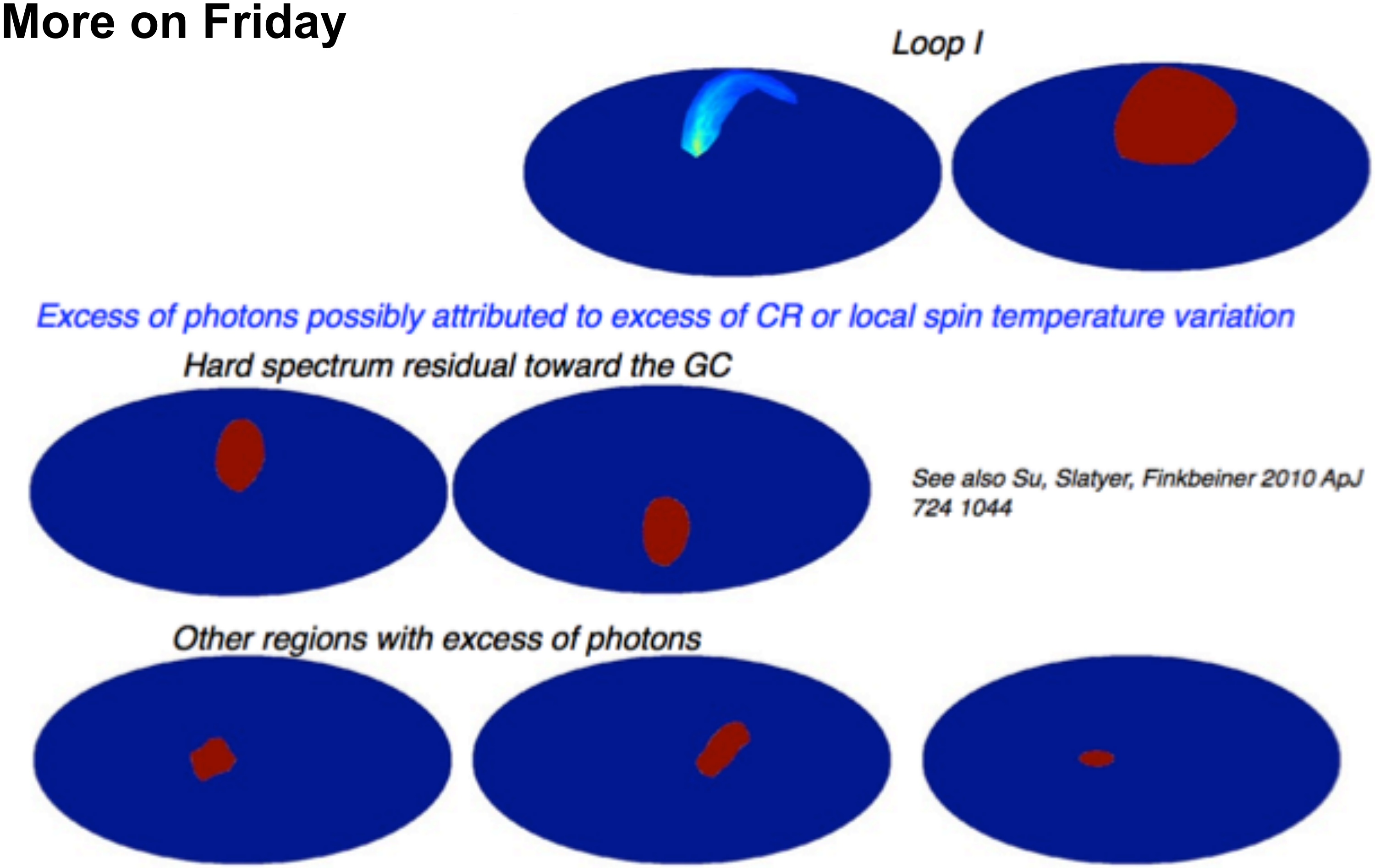
Ackermann et al. (2012)

Galactic Diffuse Emission (2)

- An approximation that worked well until Fermi was to consider the Galactic diffuse emission to be a simple combination of model for the interstellar gas with a smooth distribution of cosmic rays (plus a model for inverse Compton emission which is even smoother)
- This is no longer the case, and the reasons for the residuals are various and still being debated

Galactic Diffuse Emission (3)

- **For example, here are the additional components required in the model used for the analysis for the 2FGL catalog**
- **More on Friday**



Casandjian on behalf of the LAT Collaboration (Fermi Symposium 2011)

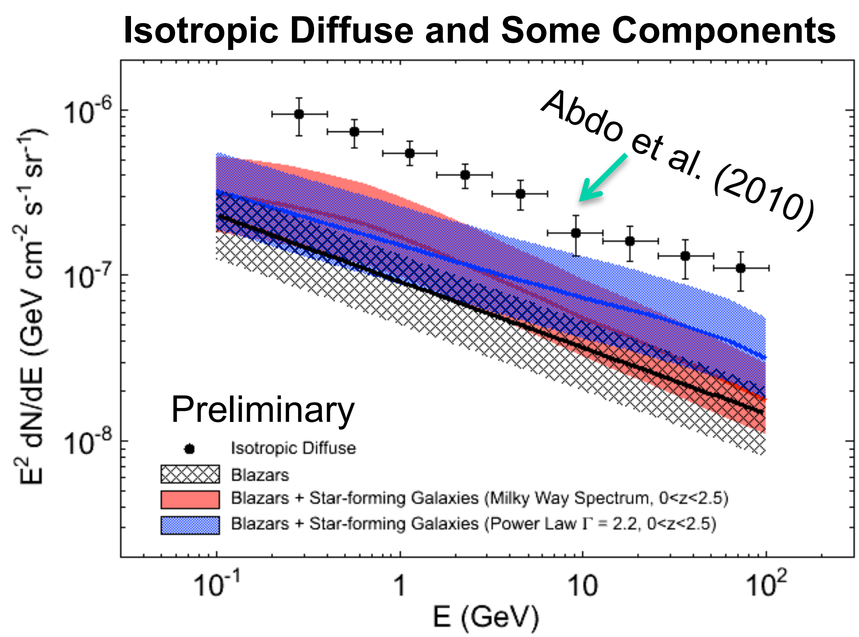
Isotropic Diffuse Emission

- Do we need it? Apparently yes
  - Isotropic diffuse emission was first detected by SAS-2 (Fichtel et al. 1977) and confirmed by EGRET (Sreekumar et al. 1997, Strong, Moskalenko, & Reimer 2004) and by Fermi
  - You should be reasonably concerned that it might be residual cosmic rays
  - But it is not
- That said, it obviously depends on what is attributed to Galactic diffuse emission
  - At high Galactic latitudes, the level of the Galactic diffuse emission depends on the (large) scale heights of cosmic-ray electrons and of the interstellar radiation, both of which are not tightly constrained
- And it depends on the sensitivity and resolving power of your gamma-ray telescope
  - At least some component of it is unresolved point sources

Isotropic Diffuse Emission (2)

- Decomposition into components is irresistible
- Evaluating contributions from blazars (BL Lac and FSRQ) and normal galaxies depends on measuring their luminosity functions
- Potential Dark Matter annihilation signal…

- At the highest energies, absorption from pair production on the extragalactic background light should become important

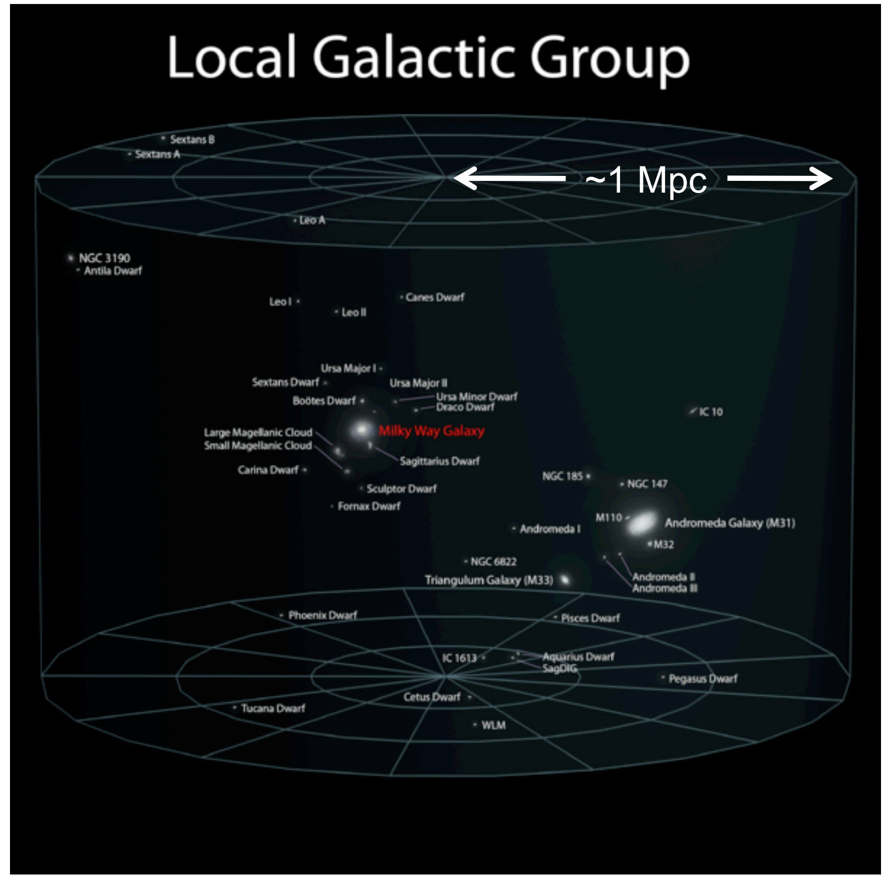


LAT collab. in prep.*

* Just an example; you can find many other decompositions in the literature

External Normal Galaxies

- **Normal means gamma-ray emission from cosmic-ray interactions with the interstellar medium and photons**
- **This emission is not beamed and the luminosities are low enough that the Local Group is the best hunting ground**
  - **Detections so far: Large Magellanic Cloud, Small Magellanic Cloud, Andromeda (M31)**
- **Some starburst galaxies are not too far to be detected as well (within ~few Mpc)**

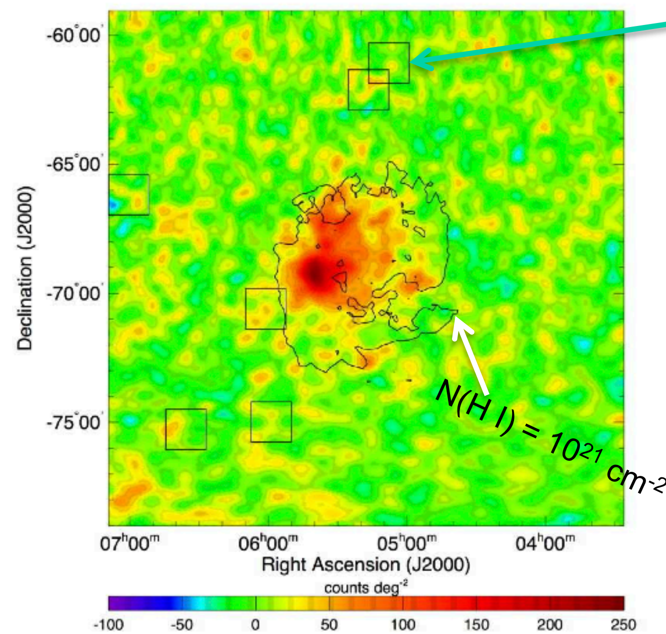


Wikipedia

Large Magellanic Cloud

- **This is the largest in angular size and has the greatest flux (~65 kpc distant)**
- **The analysis is complicated by the large angular size – several background blazars are present**
- **It has a fairly large inclination to the line of sight and is classified as an irregular galaxy but studying it from an external perspective has advantages relative to the Milky Way**
  - **Murphy et al. (2012) quantitative investigation of CR propagation**

LAT image after background model subtraction



Boxes indicate positions of blazars included in the background model

>100 MeV

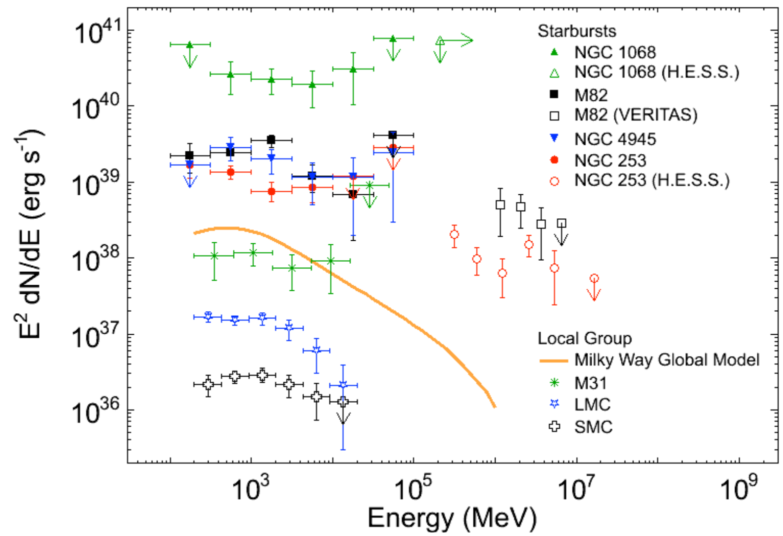
Abdo et al. (2010)

Starburst Galaxies

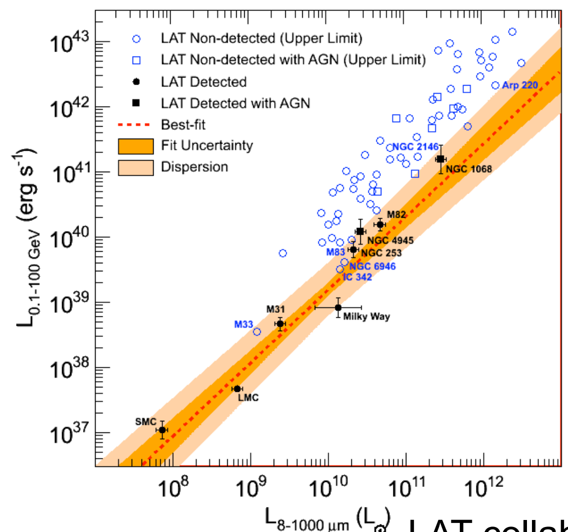
- The exceptionally large densities of gas and of massive star formation (= lots of SNRs) is responsible for the relatively large gamma-ray luminosities of these galaxies

- The gamma-ray and infrared luminosities of 'normal' galaxies seem to be well correlated…

Spectral Energy Distributions of Starburst and Local Group Galaxies



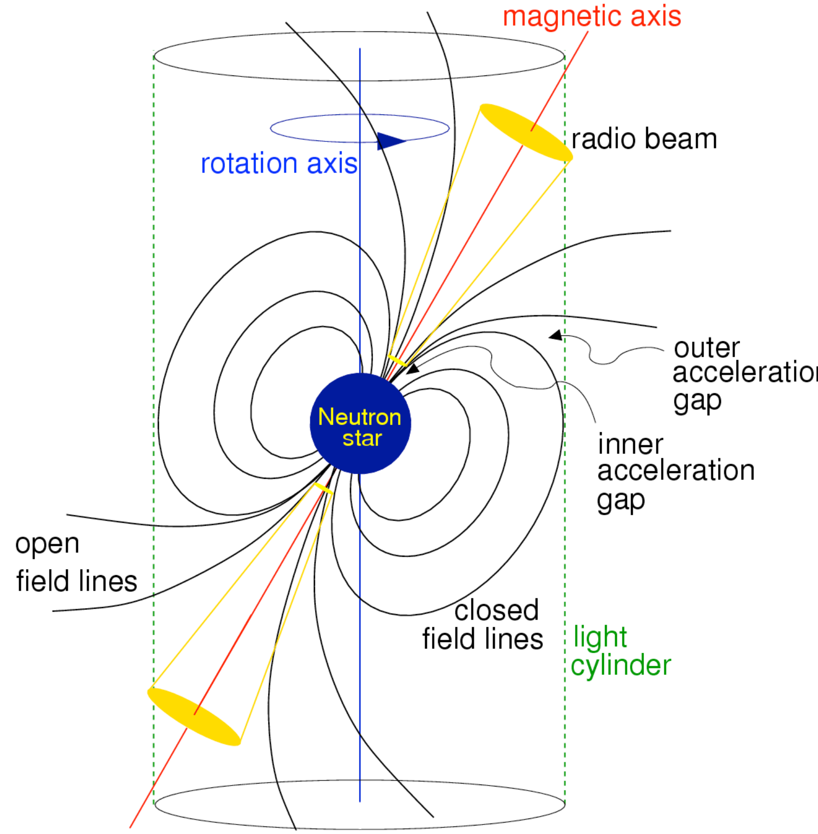
Luminosity-Luminosity Correlation



LAT collab. in prep.

Sources in the Milky Way: Pulsars

- **Rotating magnetized neutron star:**
  - **Intense magnetic field**
  - **Rotating fast**
  - **And the magnetic dipole moment is not aligned with the spin axis**
- **The gamma-ray beam tends to be broader than in the radio and is associated with particle acceleration in the outer gap**
- **The spectral energy distribution can peak in gamma rays (in the gamma-ray beam)**
  - **A number of pulsars are now known to be gamma-ray only**



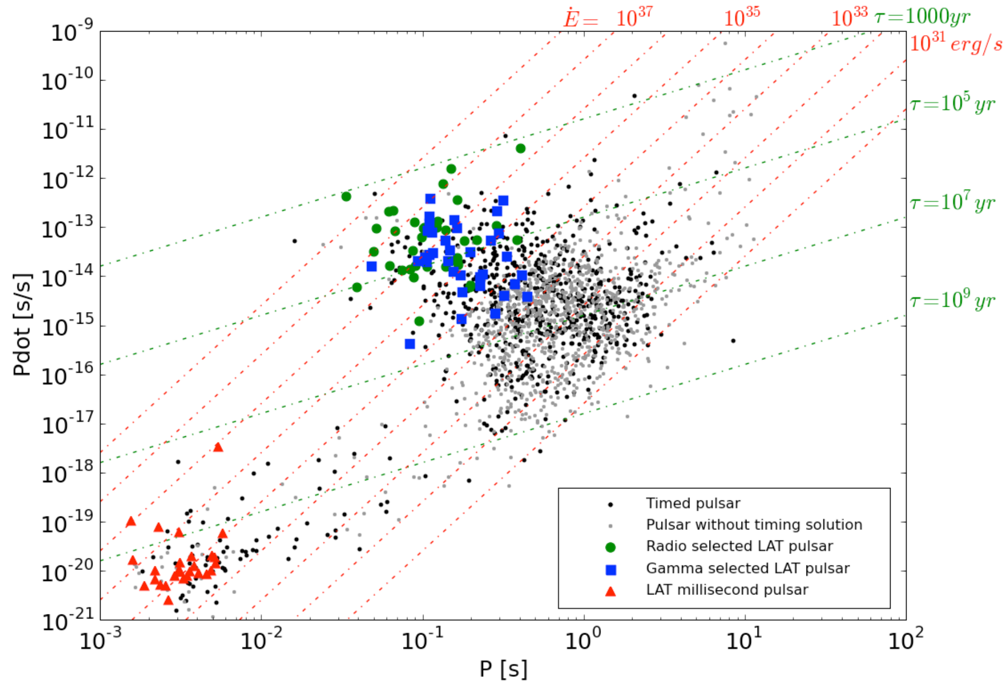
http://www.cv.nrao.edu/course/astr534/Pulsars.html

Pulsars (2)

- **The brightest persistent LAT sources are gamma-ray pulsars**
- **With the LAT the number of known gamma-ray pulsars has increased from 7 pre-Fermi to 101 publicly announced**

Type	#
Young, radio selected	36
Young, gamma selected	35
Young, X-ray selected	3
Millisecond, radio selected	27

Period-Period derivative



Gamma-ray luminosities range from ~10^{32}-10^{37} erg s^{-1}

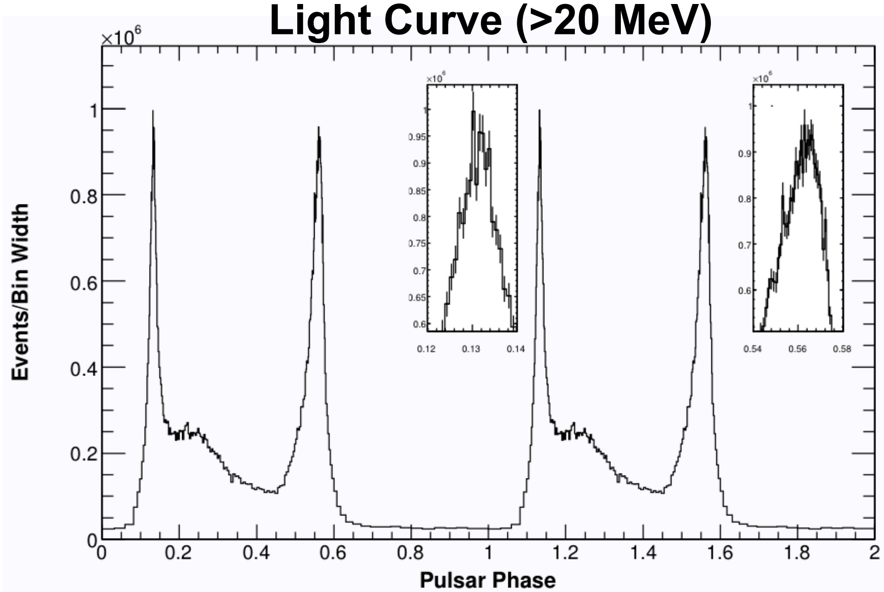
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

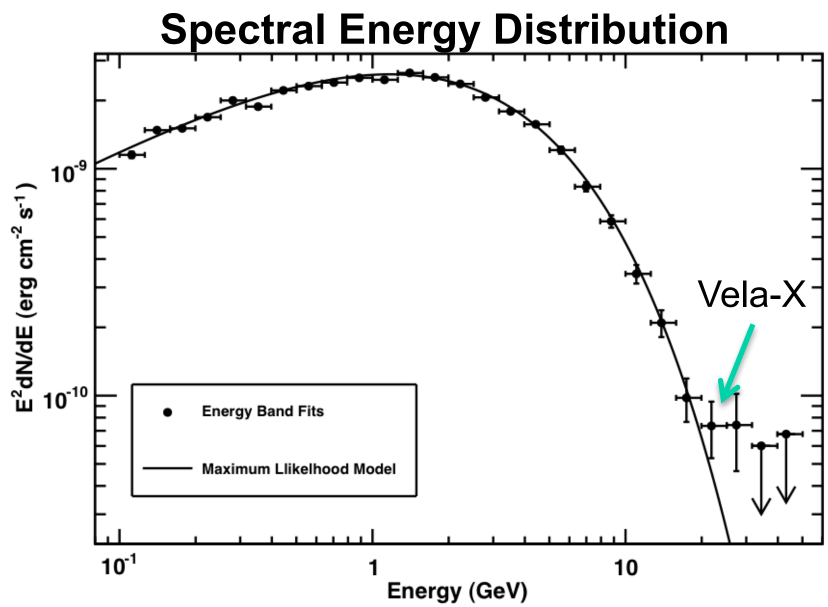
Pulsars (3)

- Part of the increase is due to powerful new ways to find periodicity in the gamma-ray data
  - Not a simple problem: Pulsars are slowing down, their positions on the sky are not perfectly known, they sometimes glitch, and for even a bright pulsar the LAT might detect only one gamma ray per 100,000 revolutions
  - Some gamma selected pulsars have since been detected in very deep radio observations
- In some cases LAT pulsar detections have followed from radio pulsations detected in unassociated LAT sources
  - Contemporary ephemerides are essential for phase assignment
  - Many of these are millisecond pulsars, the fastest-spinning and oldest
  - Their magnetic fields are relatively weak but they are spinning rapidly enough to be gamma-ray sources

Pulsars (4)

- **Some LAT measurements for Vela (N.B. Not a typical example)**





Abdo et al. (2010)

- **More on pulsar observations and physics from Paul Ray and Pasquale Blasi next Monday**

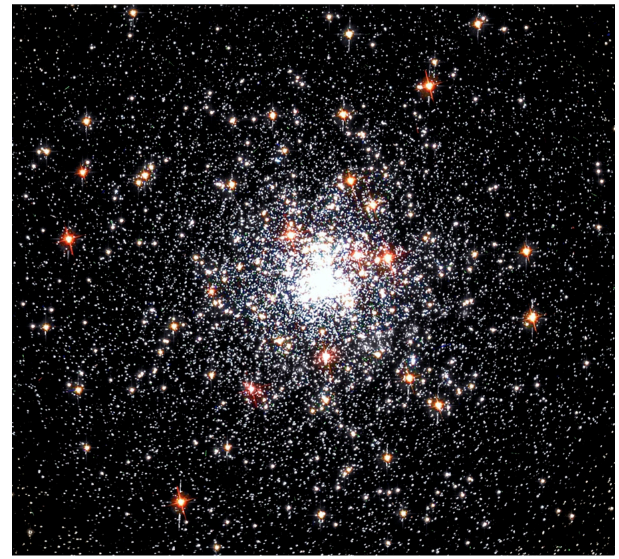
Pulsar Wind Nebulas

- The particles accelerated by pulsars can power nebulas surrounding pulsars
  - The termination shock (where the wind is decelerated by sweeping up ejecta from the SN explosion) can accelerate particles
- PWNs are not angularly resolved by the LAT but can be spectrally resolved (and phase selected to cancel the pulsar) in LAT data – see Vela-X component in the spectrum of Vela
  - The electrons lose energy quickly and the angular size of a PWN decreases with increasing energy
- ~4 PWNs are known in the LAT data and some more at TeV energies
  - They tend to be associated with very energetic pulsars
- More from Pasquale Blasi next Monday
- Also Martin Weisskopf tomorrow and Trevor Weekes next Tuesday about the Crab nebula

Globular Clusters

- Likely not an independent class
- Globular clusters are large clusters of very old stars in the halo of the Milky Way
  - Because of the stellar densities and ages they are good hunting places for millisecond pulsars
- A number of globular clusters are positionally associated with LAT sources (11 in the 2FGL catalog)
- The suspicion long was that they are shining in the light of millisecond pulsars
- Strong evidence for this hypothesis: a detection of a millisecond pulsar

NGC 6624



~3' across

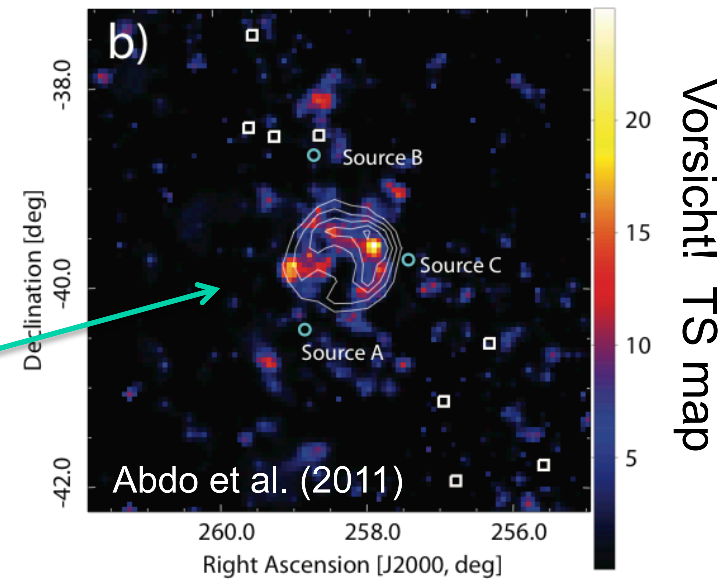
NASA/ESA/I. King, UC Berkeley/ Wikisky.org

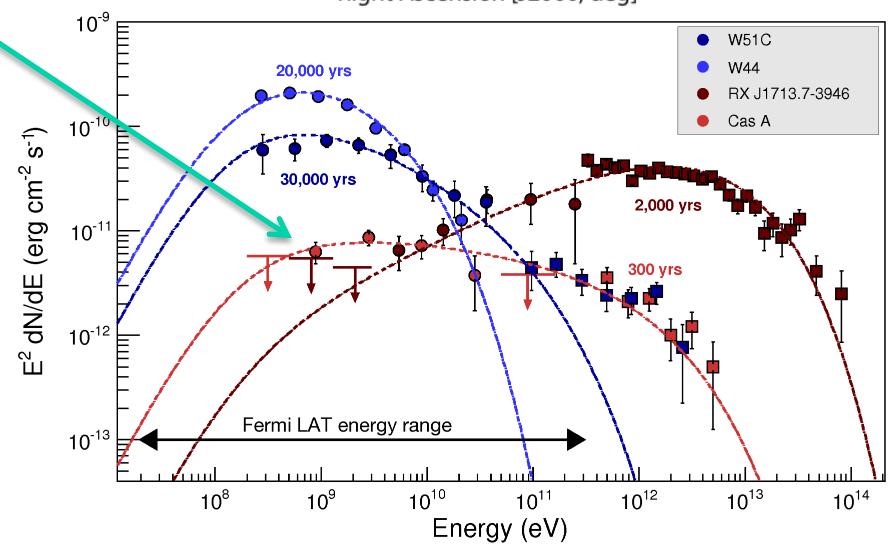
- A millisecond gamma-ray pulsar J1823-3021A was detected in globular cluster NGC 6624 (Freire et al. 2011)

Supernova Remnants

- These accelerate CRs and can be sources of gamma rays, e.g., from interactions of 'fresh' CRs with a nearby interstellar cloud
- Some are extended sources for the LAT
- The character of the emission depends on the age (state of evolution) of the SNR
- Particle acceleration models – search for evidence of proton acceleration
  - No 'smoking gun' yet
- More on SNRs from Jack Hewitt on Thursday

LAT RX J1713-3946





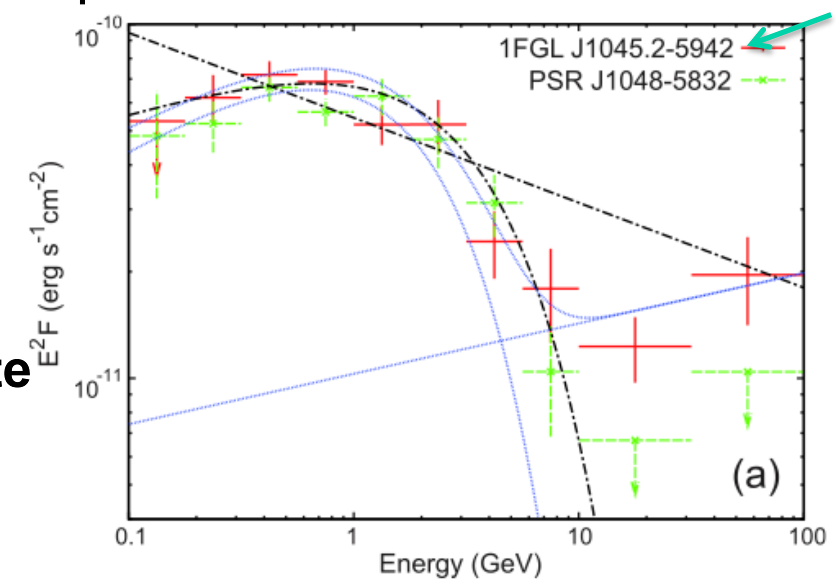
Eta Carinae

- Maybe a LAT source anyway
- Eta Carina is a binary star system with a >100 solar mass star
- A bright gamma-ray source is positionally coincident, but does not appear to vary in coincidence with the X-ray variability
- In the 2FGL catalog it is listed as an association but without a classification
- The gamma-ray source is quite interesting, e.g., with a hard high-energy spectrum

Homunculus Nebula around Eta Car

Hubble Space Telescope

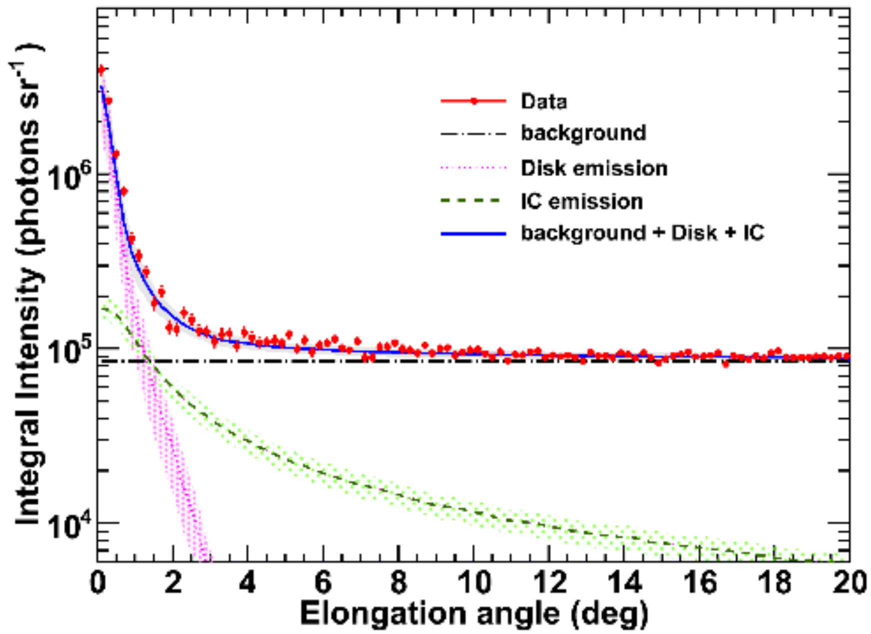
Spectrum of LAT source coincident with Eta Car



Abdo et al. (2010)

'Quiescent Sun'

- It is a gamma-ray source from CR interactions in the outer atmosphere and inverse Compton scattering of CR electrons in the radiation field
  - The former is essentially only from the rim of the Sun*
  - The latter makes the Sun a sort of all-sky source



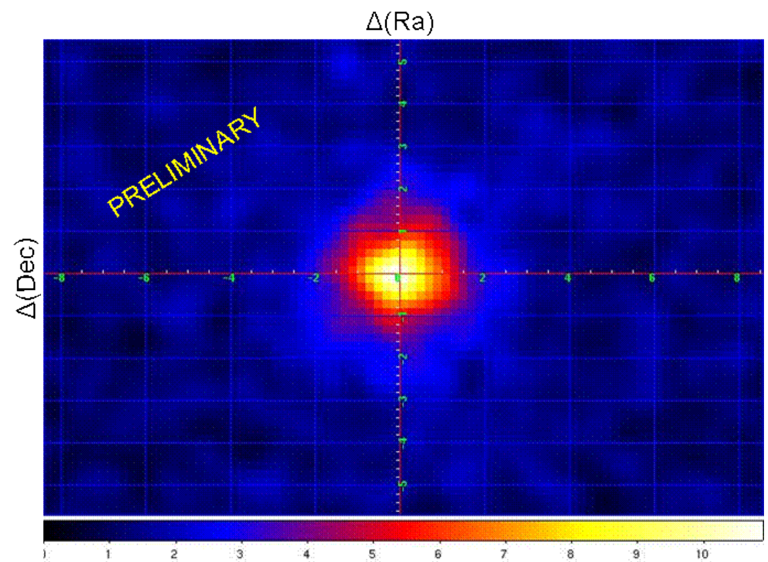
>500 MeV, Abdo et al. (2011)

- The flux of the Sun depends on the phase of the solar cycle
  - CRs that cannot overcome 'solar modulation' cannot interact with the solar atmosphere
- N.B. The Sun also moves
  - The 2FGL catalog flags several sources at low ecliptic latitude that brightened only when the Sun was nearby

* If the Sun were transparent to gamma rays its flux would be ~10^{14}x greater

Moon

- It shines in gamma rays only from cosmic rays interacting with the rocks
- The favorable direction is forward scattering from cosmic rays just skimming the edge of the Moon (Moskalenko & Porter 2007)
  - The interaction depth is ~20 cm
  - At high energies the center of the disk of the Moon should be very dark (most gamma rays produced are absorbed)
- The gamma-ray brightness of the Moon should vary with the solar cycle



>100 MeV early LAT image

- N.B. The Moon also moves, but it moves much faster than the Sun (~13°/day) and has appreciable orbital parallax for the LAT (~±1°) and so is much less of a contaminator of sources it passes near

Unassociated LAT Sources

- [Not all belong in the 'non-variable' category as a class]
- Already mentioned as profitable targets for searches for millisecond pulsars
- In general the unassociated sources are what one would study for evidence of a new population (new class) of gamma-ray sources
- Broadly speaking, classification schemes based on measured properties of sources can made educated guesses regarding whether each unassociated source is a pulsar or a blazar*
- The bottom line is that there's not much left over

* e.g., Ackermann et al. (2012, in press)

Apparently-missing Source Classes

- **What has the LAT not detected that we had expected to?**
  - **Clusters of galaxies**
  - **Supernova/OB associations (SNOBs)**
  - **Colliding Wind Binaries?**
  - **N.B. Unassociated LAT sources have been studied as potential DM signals – but no detections**

Summary

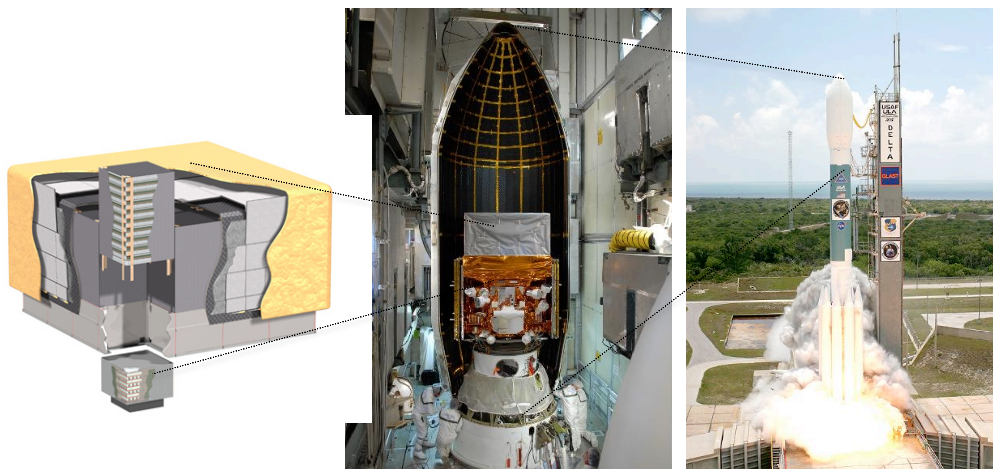
- The steady LAT sources are responsible for >90% of the celestial gamma rays
- The sensitivity, resolution, and energy range of LAT observations, are providing discoveries and forcing new understanding of Galactic diffuse emission
- More than 100 gamma-ray pulsars are now known, enough for population studies of sub-classes such as millisecond pulsars
- PWNs and Globular clusters are in a sense pulsar-derived
- Supernova remnants of a variety of ages have been detected, allowing study of the gamma-ray evolution of SNRs
- Unassociated sources and Eta Carinae – searches for additional new source populations and dark matter signals are ongoing

Next: The Dynamic Fermi Sky

Backup slides

Fermi and the LAT

- Large Area Telescope was launched in June 2008 on the NASA mission now called Fermi



- Major contributions from France, Italy, Japan, Sweden, & U.S.
- LAT collaboration has ~400 members

Fermi and the LAT

- LAT energy range is 20 MeV - >300 GeV (>4 orders of magnitude)
- Peak collecting area is about 8000 cm^2 (moderate)
- Field of view is 2.4 sr (huge)

- High-energy gamma-ray astronomy is a relatively young field, partly because at GeV energies it must be done from space

- LAT is by far the most sensitive instrument ever in this energy range
  - Celestial gamma-ray rate is ~2 Hz for the LAT
  - Within the first few weeks of the mission, LAT had collected as many gamma rays than had been detected by all previous missions combined, and measured them with better precision
  - Huge 'discovery potential'