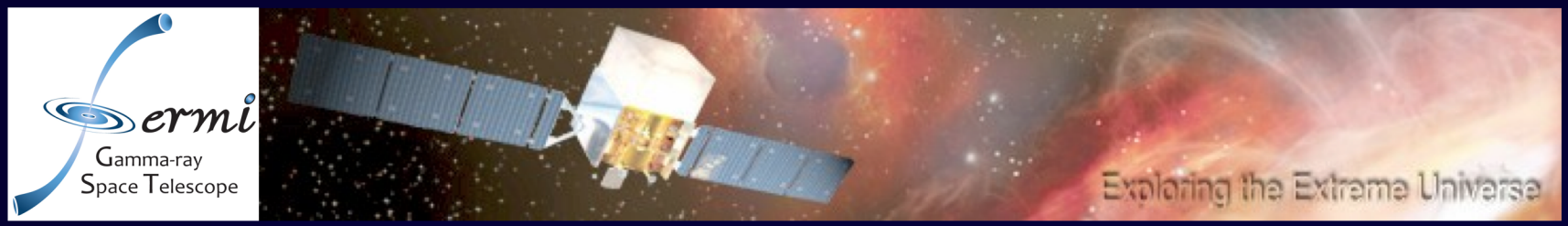
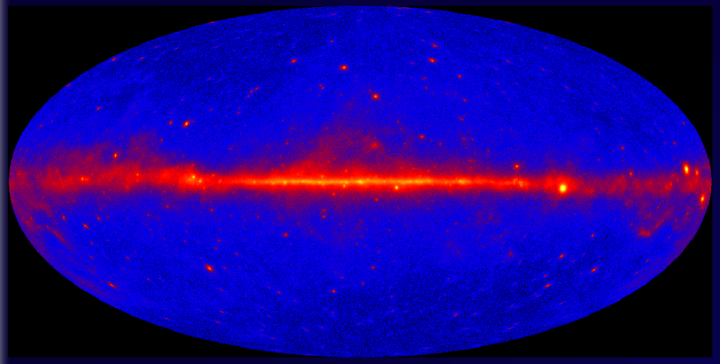




GeV Flares and Particle Acceleration in the Galaxy

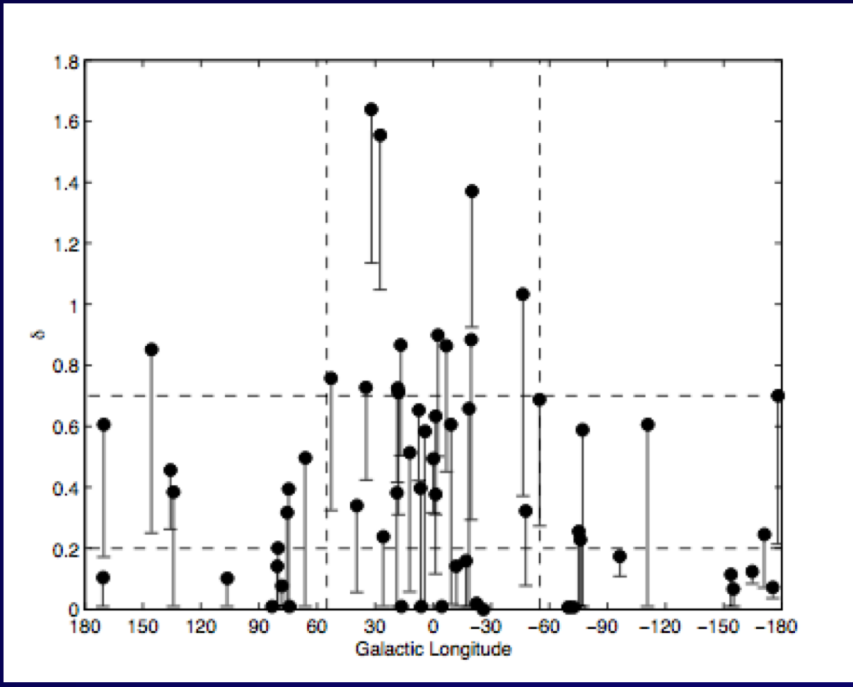
Elizabeth Hays
(NASA/GSFC)
on behalf of the Fermi-LAT Collaboration

GeV Galactic Transients

- Expectations for Fermi
  - Binary Systems
    - High-mass X-ray binaries
    - Microquasars?
  - Colliding wind systems ?
    - Massive stars with strong outflows and companions
  - What else?
    - EGRET searches for variability in pulsar wind systems, X-ray novae

Some History

- Early gamma-ray detections
- Variable source population along the Galactic plane in EGRET

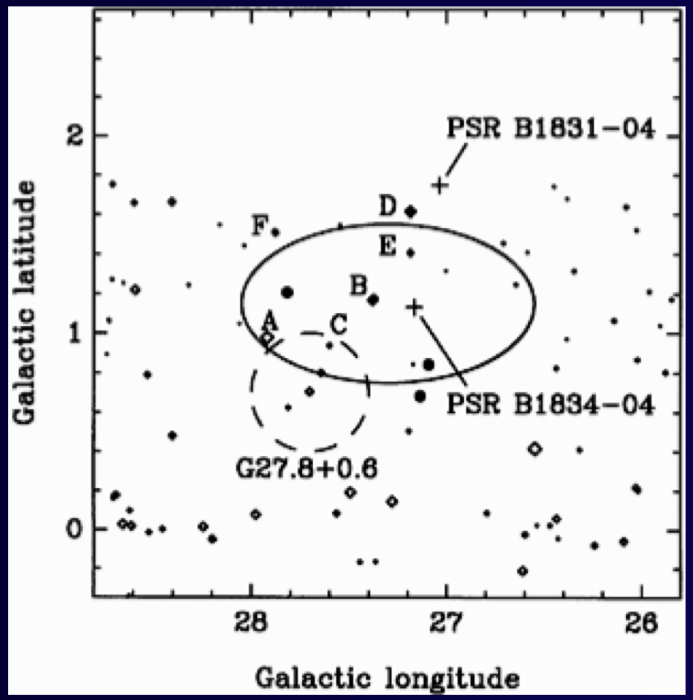


Nolan et al. 2003, ApJ 597

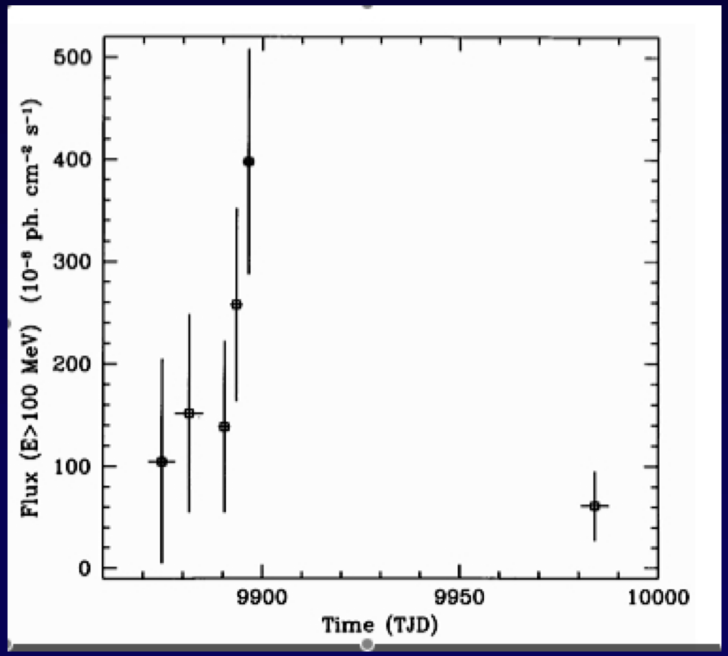
A Galactic transient candidate from EGRET

GRO J1838-04

EGRET observed 3.5 day flare near the Galactic Plane in June 1995



No blazar candidates found



Tavani et al. 1997, ApJ, 479, L109

LAT as an all-sky monitor

- What the LAT covers
- How the sky is monitored
- Flare monitoring next steps: refinement and follow-up
- What has been found in the Galaxy?

LAT Sensitivity with Time

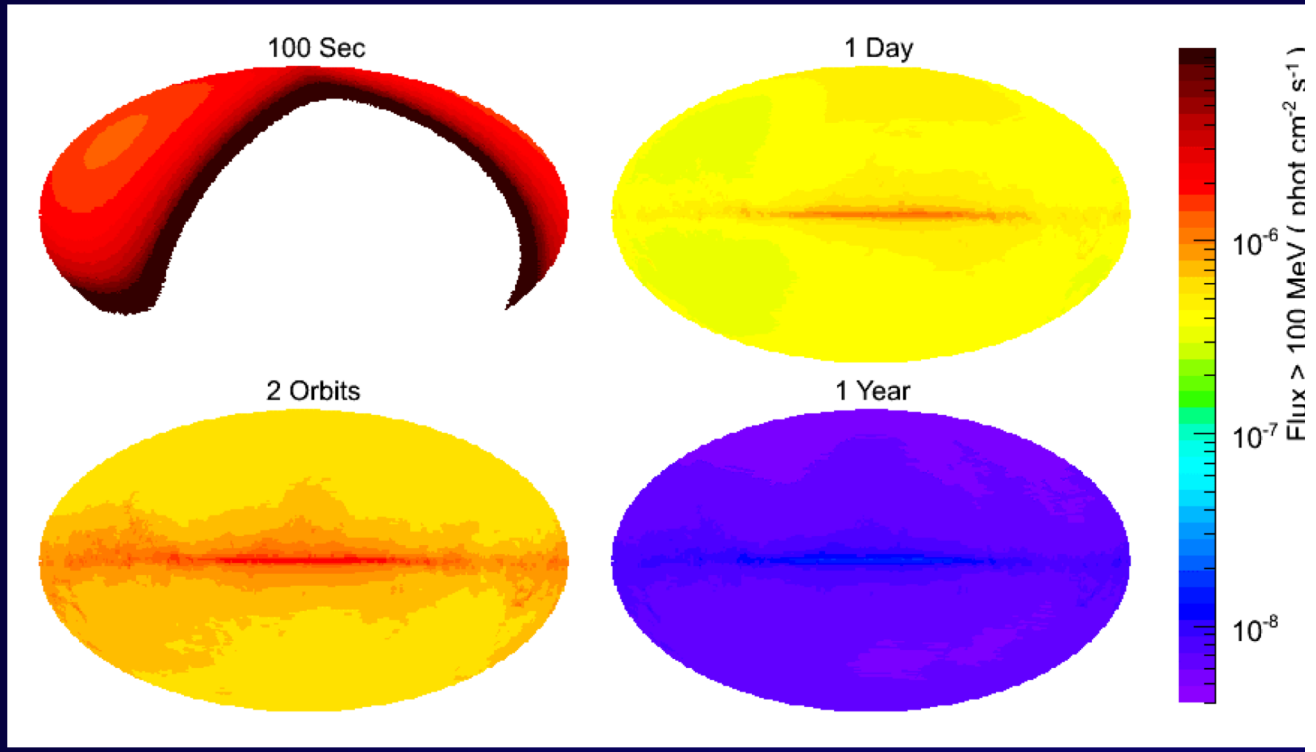
Transient Science: Flares, bursts, multiwavelength campaigns, unidentified transients

Accumulated Science: New source types, populations, long-term monitoring, spatially extended and diffuse studies

Deepest and most uniform survey of the sky at these energies

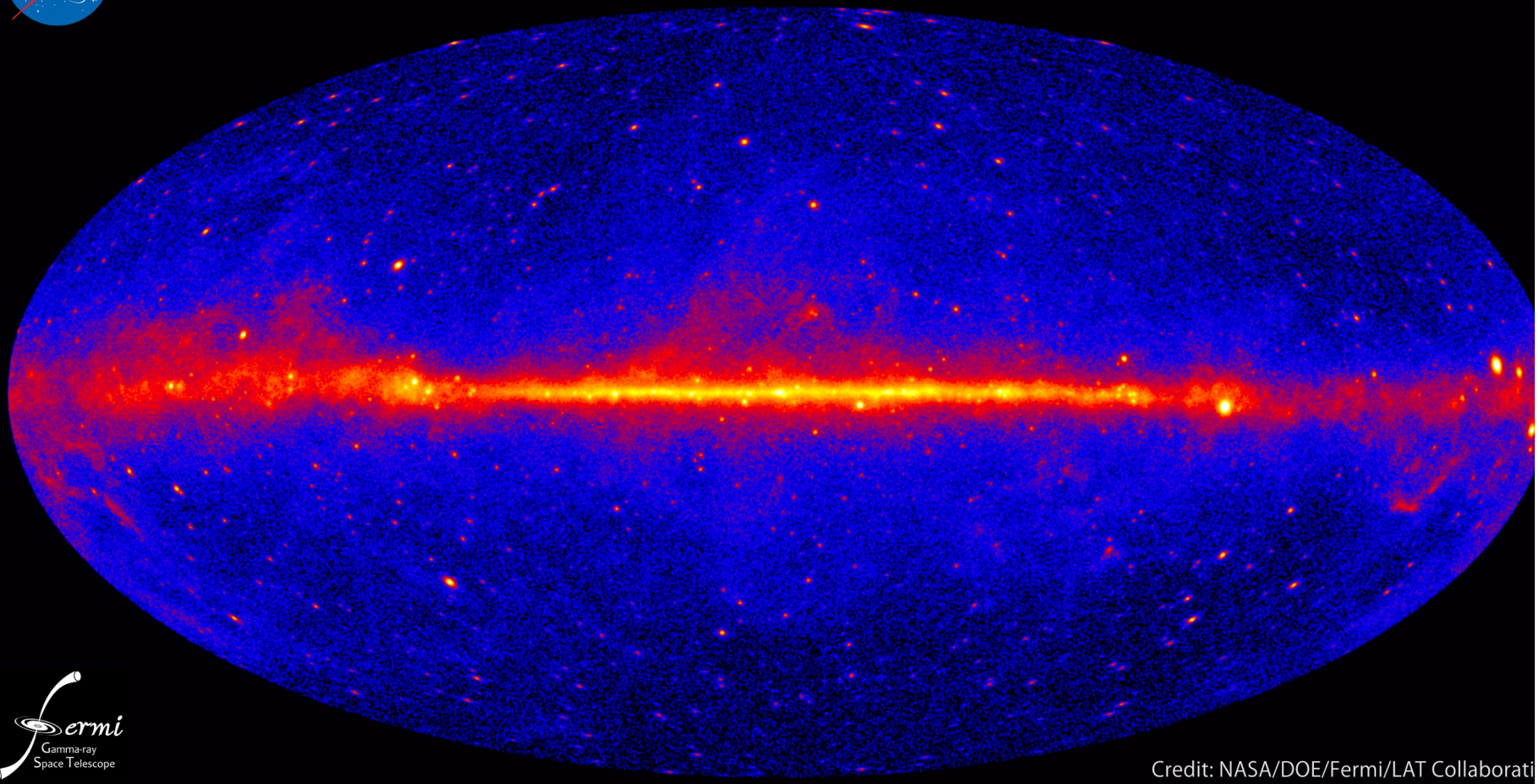
All-sky in ~3 hrs (2 orbits)

Minor asymmetry due to passages through South Atlantic Anomaly



The Steady Sky at 2 Years

Fermi two-year all-sky map



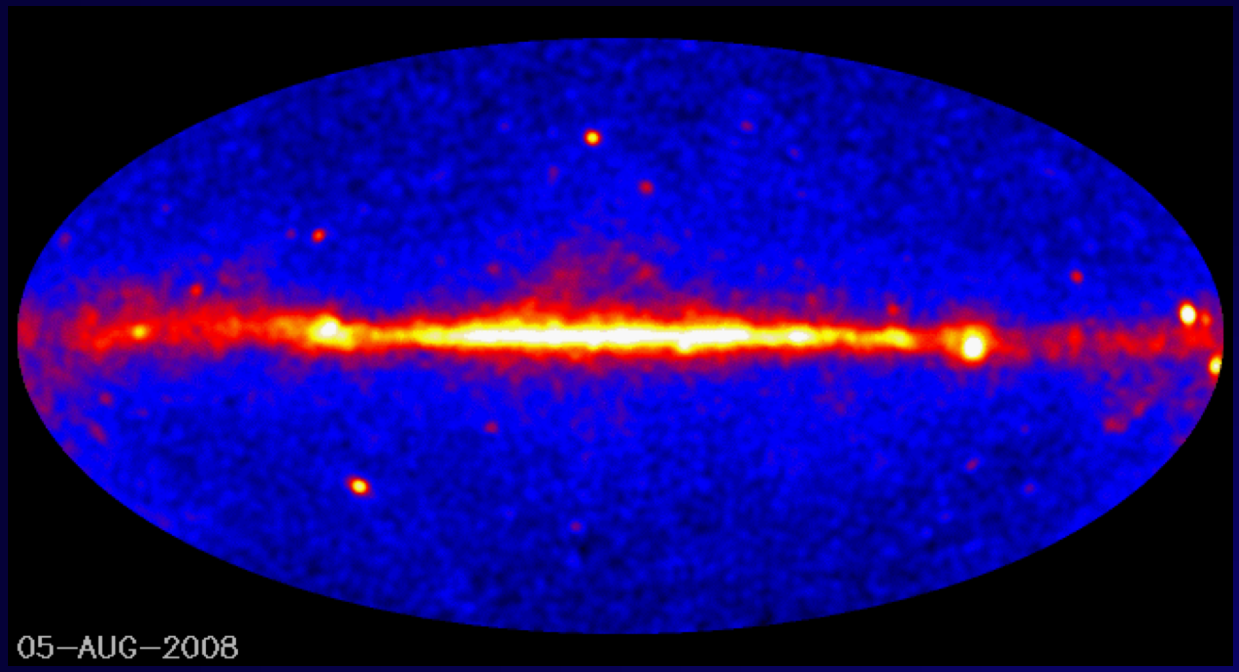
Credit: NASA/DOE/Fermi/LAT Collaborati

>1 GeV

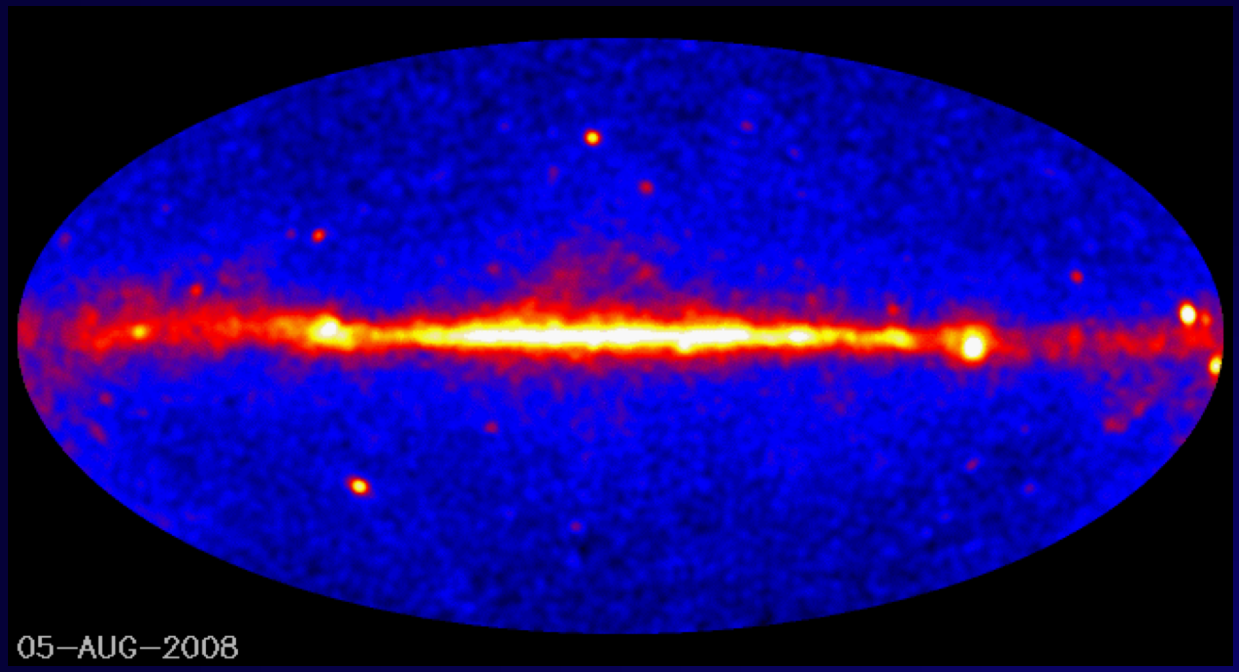
June 9, 2011

E. Hays

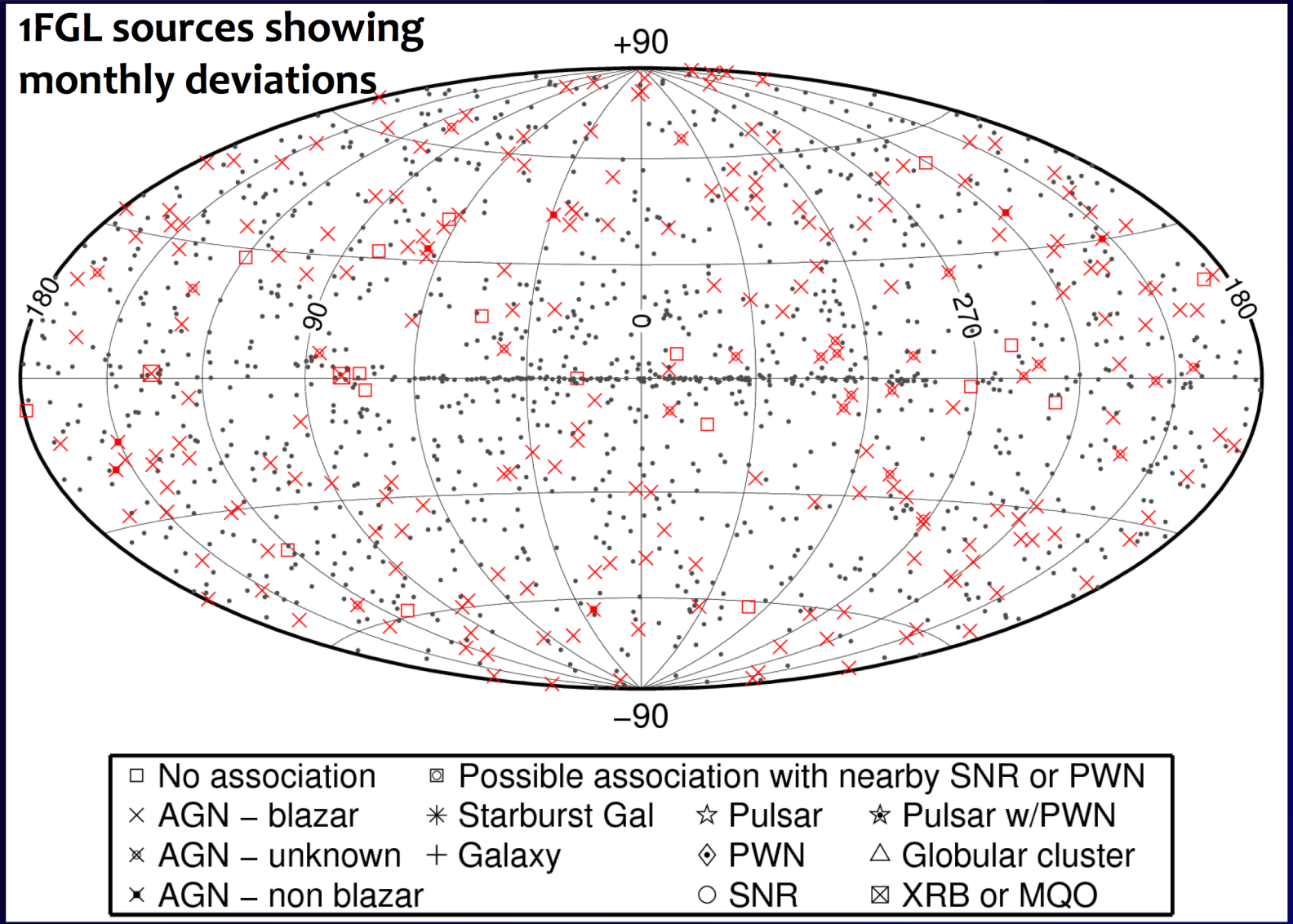
The variable sky



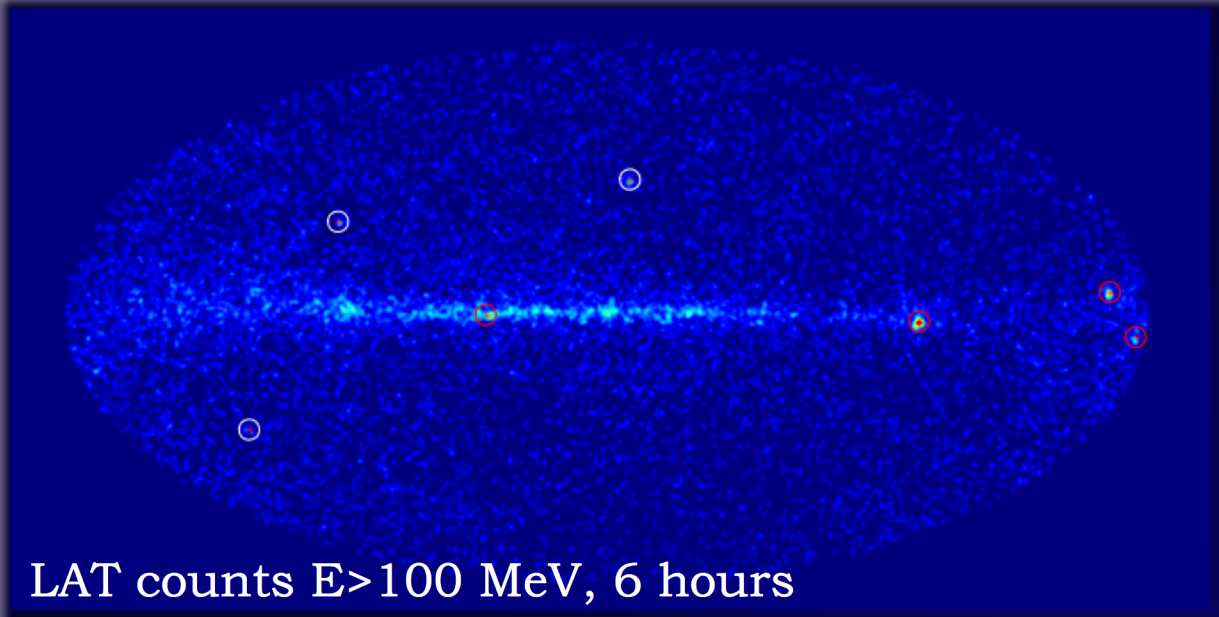
The variable sky



The Variable Sky



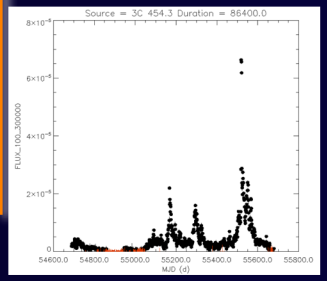
LAT Automated Science Processing



LAT counts E>100 MeV, 6 hours

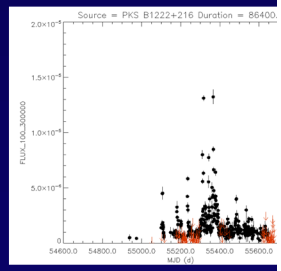
All-sky search
runs every
6 hours
1 day
1 week

>100 Fermi LAT
ATels



LAT Flare advocates monitor the sky daily

- Check for flaring and new sources
- Coordinate multiwavelength follow-up
- Post reports **http://fermisky.blogspot.com**



Lightcurves for >70 flaring sources hosted by FSSC
http://fermi.gsfc.nasa.gov/ssc

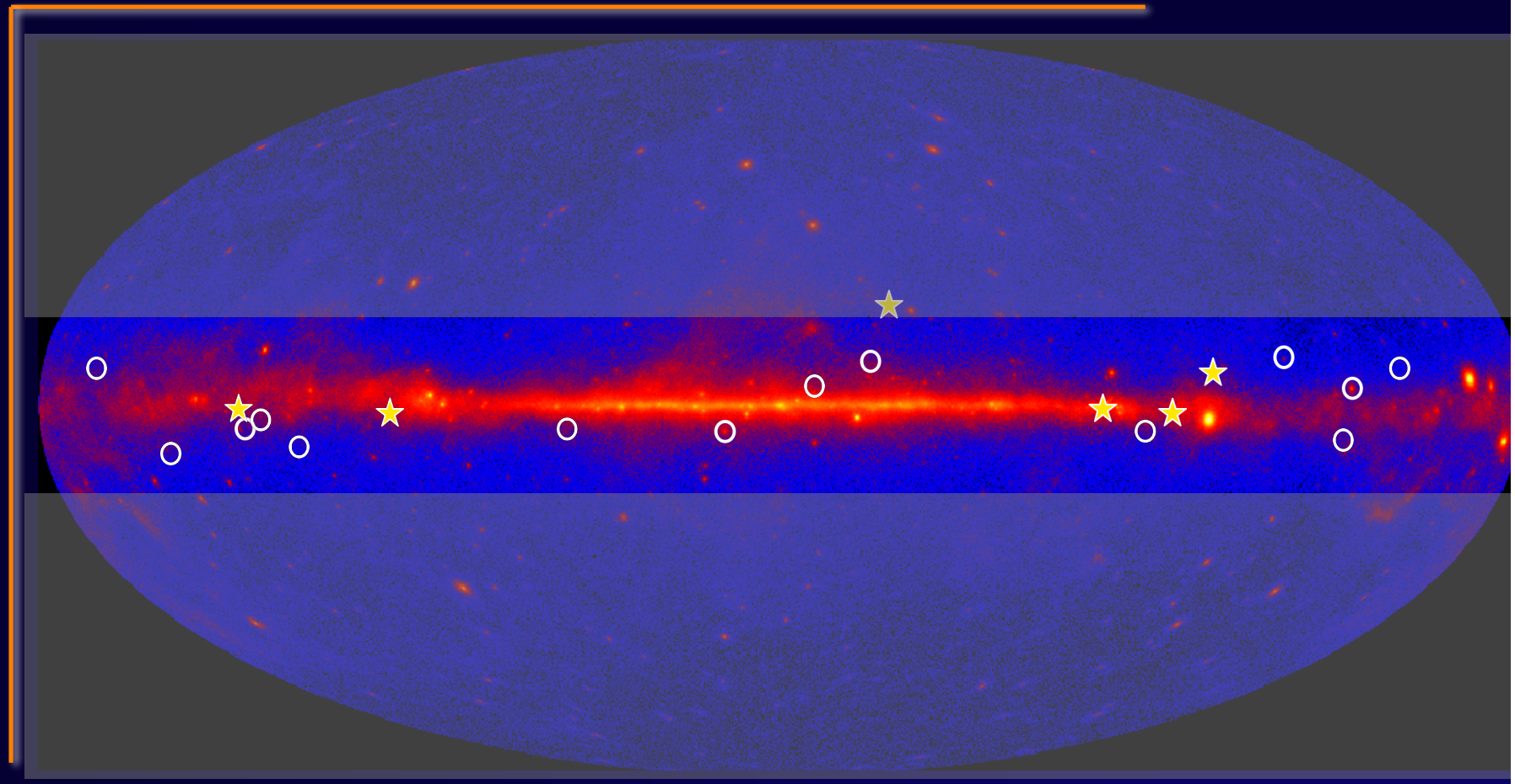
June 9, 2011

E. Hays

Methods for source detection in counting detectors

- Wavelet-based
  - Wavelet transforms - Damiani et al. (1997), Ciprini et al. (2007)
  - Multi-resolution filtering - Starck and Pierre (1998)
- Count-based
  - Likelihood test, e.g. pointfind in 1FGL - Abdo et al. (2010)
  - Clustering, e.g. Minimal Spanning Tree - Campana et al. (2008)

LAT Transients at Low Galactic Latitude



★ Originally **unassociated** transients from daily search

○ Low latitude blazars from First LAT Catalog

June 9, 2011

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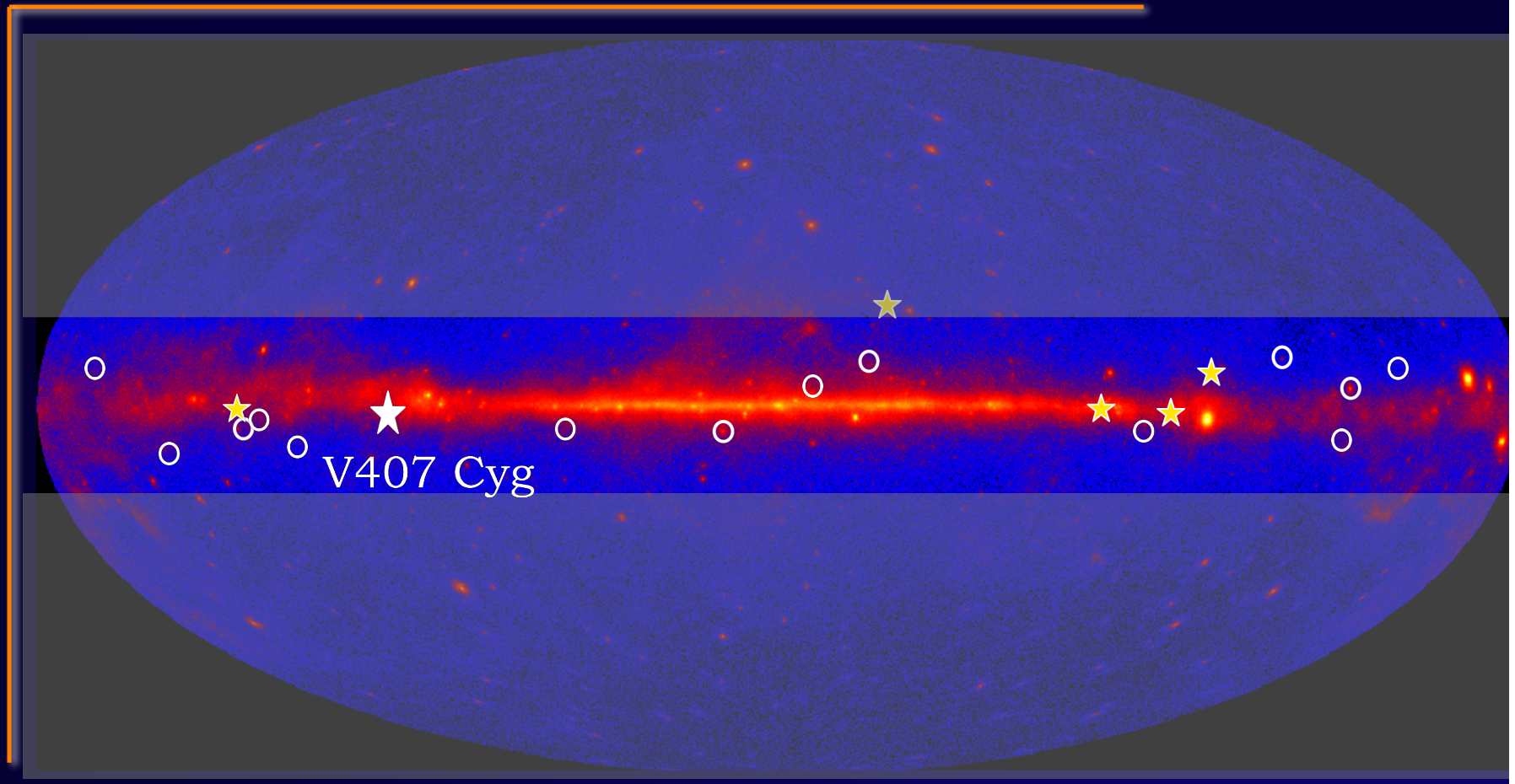
LAT Transients at Low Galactic Latitude



★ Originally **unassociated** transients from daily search

○ Low latitude blazars from First LAT Catalog

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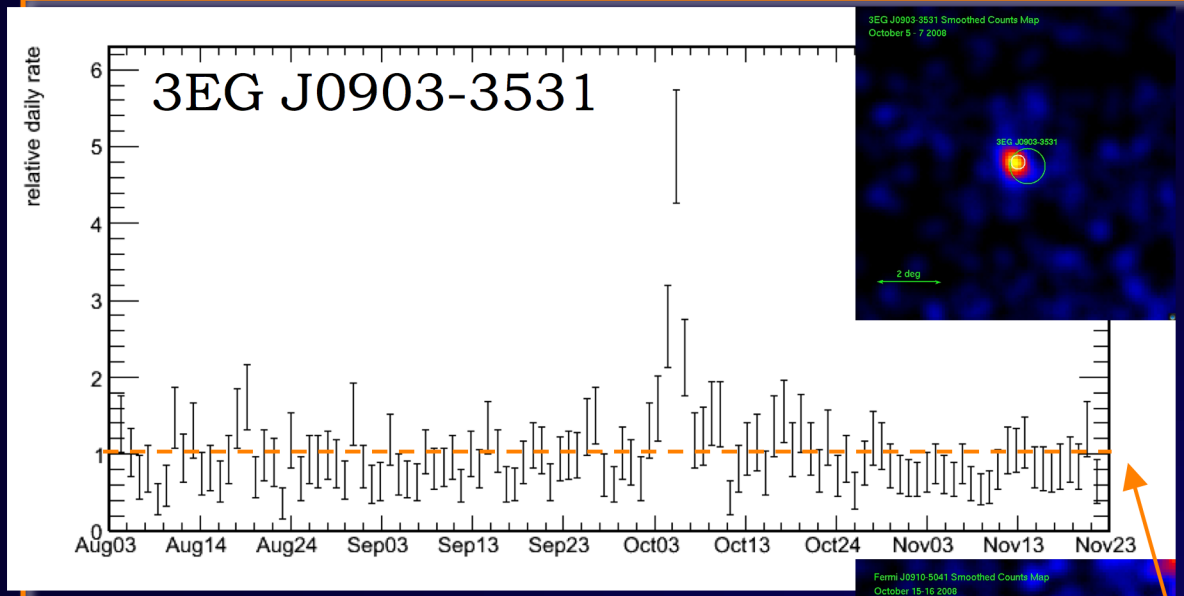
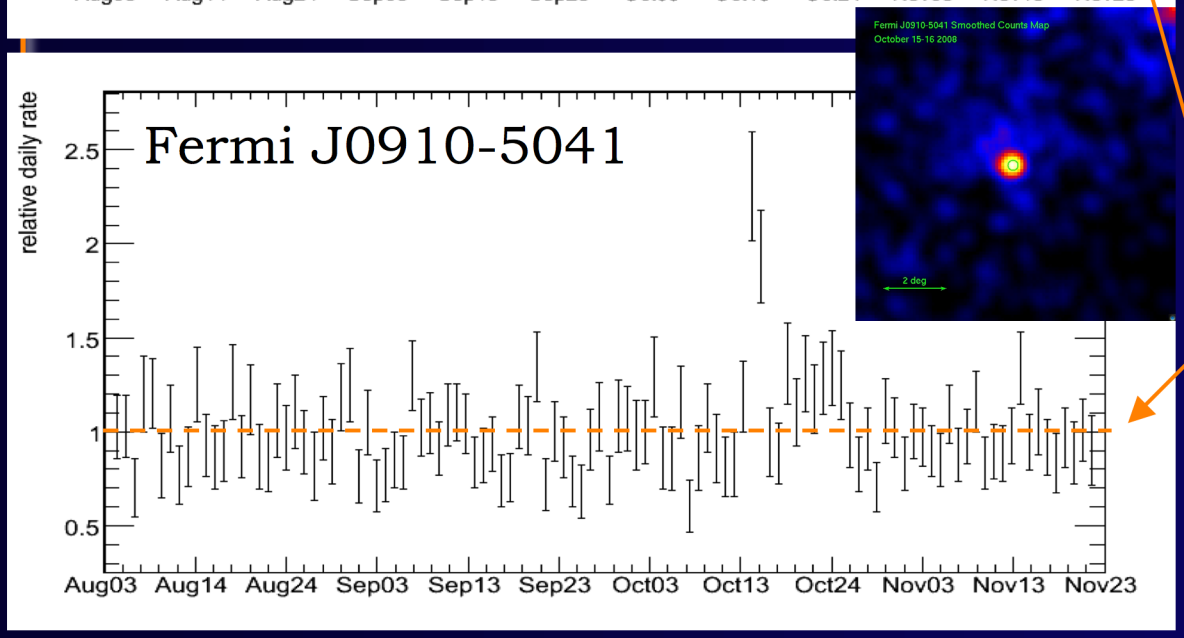
Two Early Unassociated Transients





High confidence
>10 sigma

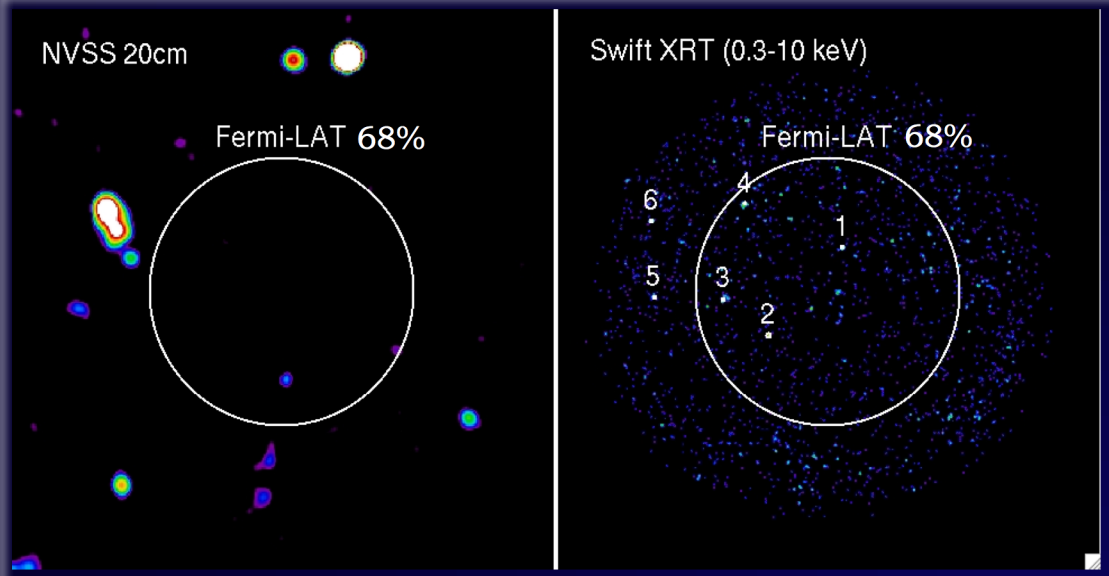
Counts per day
(E>200 MeV)

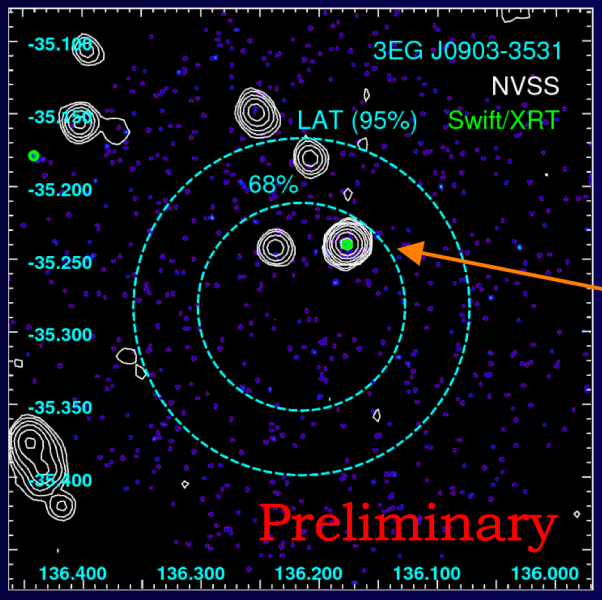
- 2 deg radius
- exposure corrected
- scaled to average background rate

Average background rate

E. Hays

Counterpart Search - 3EG J0903-3531



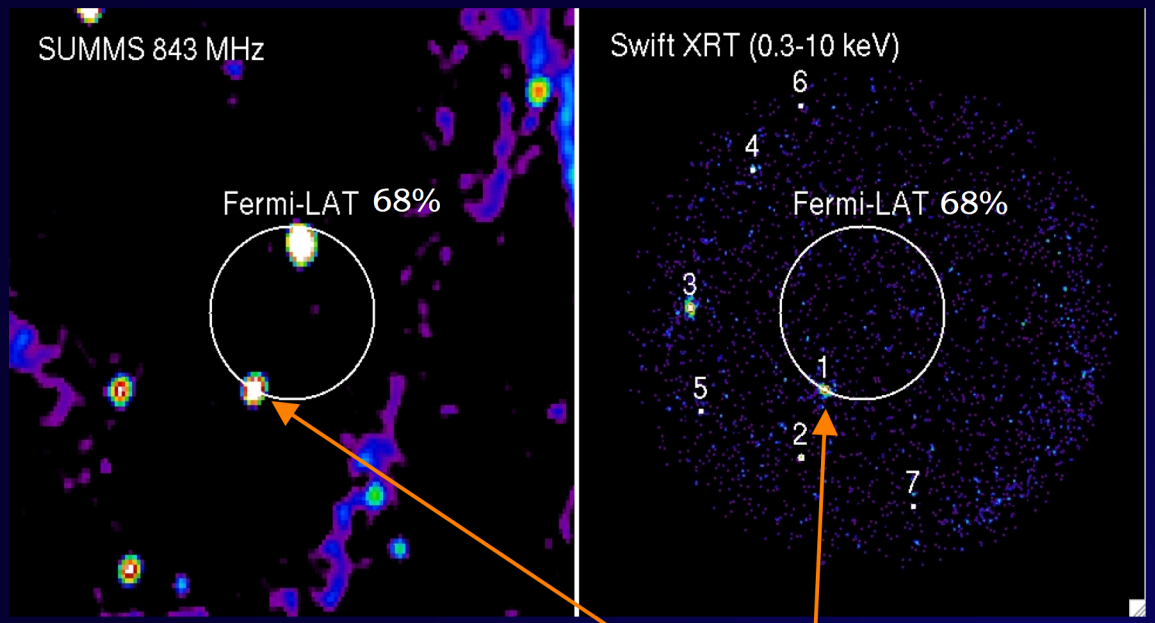


3EG J0903-3531
(ATEL #1771)

- October 5, 2008, gamma-ray increase over 3 days
- 5x above 3EG flux
- 15x above average gamma-ray flux
- Swift XRT TOO within 2 days

Updated LAT 95% error circle (8 months) contains a flat-spectrum radio source and Swift/XRT source

Counterpart Search - Fermi J0910-5041

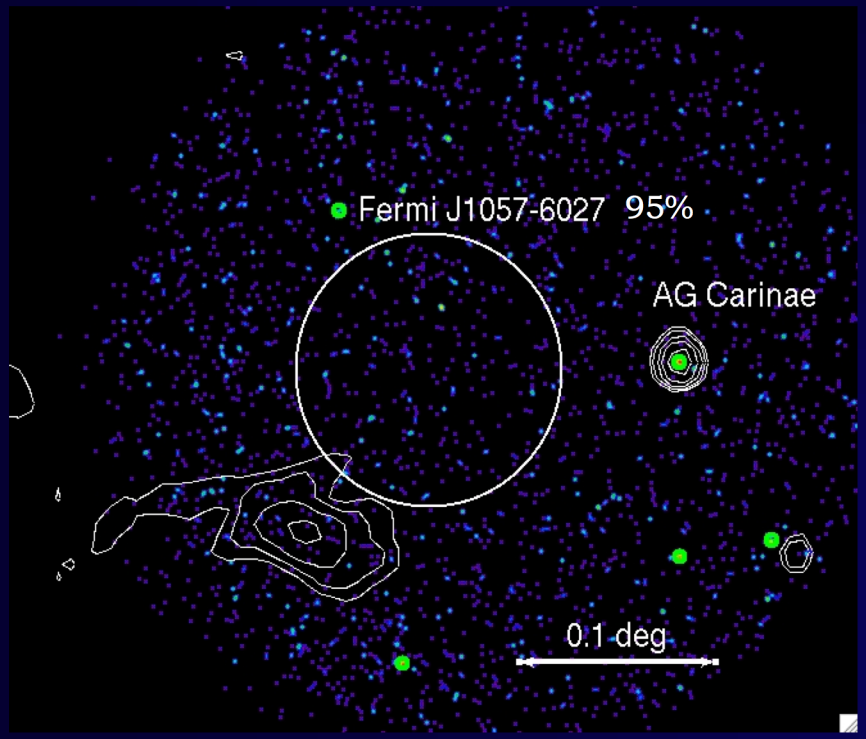


Fermi J0910-5041
(ATEL #1788)

- October 15, 2008
- ~10x above average gamma-ray flux for 2 days
- Swift XRT ToO within 1 day
-1 of 2 high confidence LAT transients without a firm counterpart

LAT 95% error circle contains Swift XRT source (Landi et al. ATEL #1822) coincident with flat-spectrum radio source from SUMMS and AT20G (Sadler ATEL #1843)

LAT Transient - J1057-6027



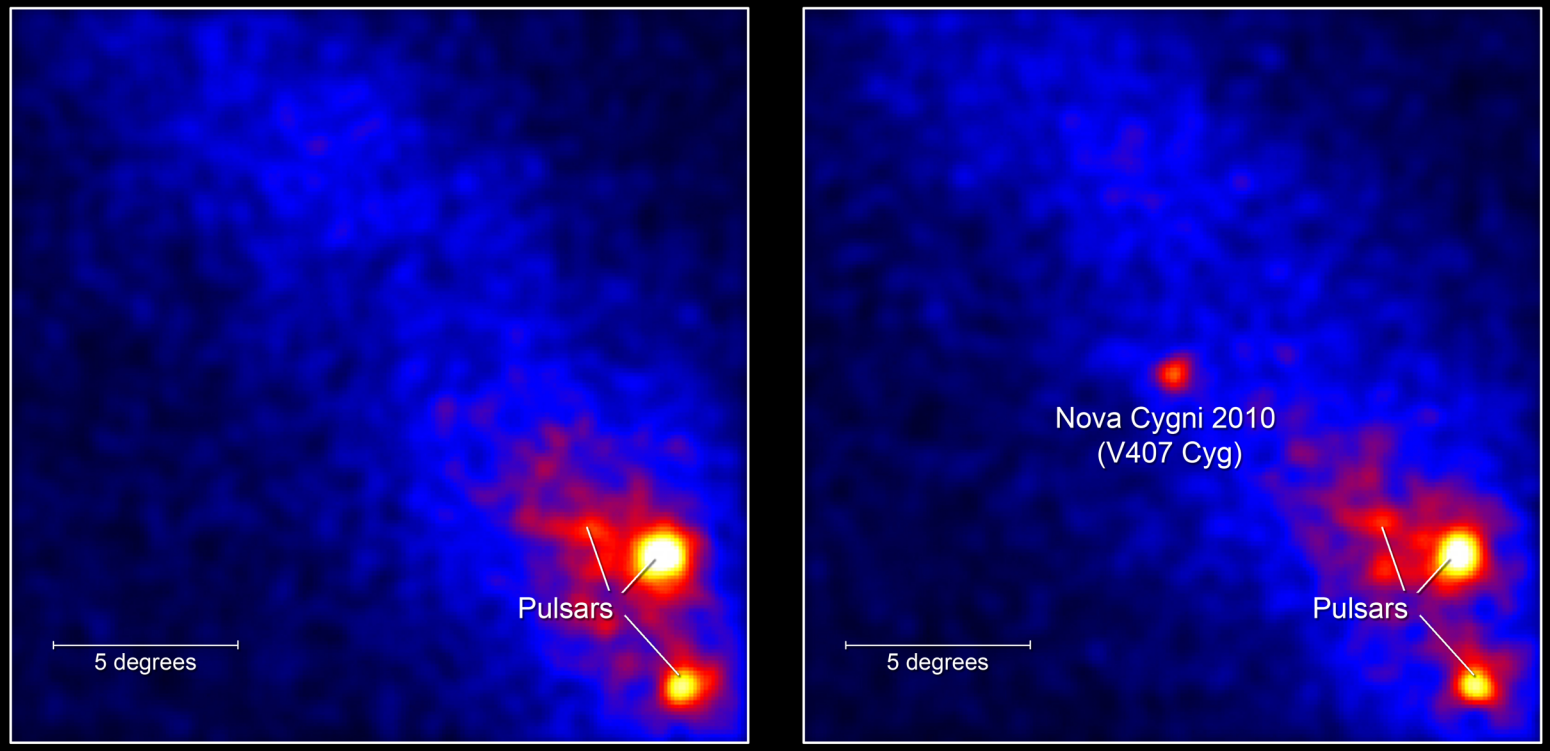
X-ray map: Swift XRT (0.3-10 keV)
Radio contours: MGPS

Fermi J1057-6027

- June 11, 2009, gamma-ray increase over 1 day
- Coincident with a known LAT source
  - 95% confidence radius 0.07 deg
- 10x above average gamma-ray flux
- Swift XRT TOO within 1 day (ATELS #2082, #2083)
  - AG Carinae, luminous blue variable (LBV) star with X-ray and radio emission, 7.7' away

LAT Before and After

Fermi Detects Gamma Rays from Nova Cygni 2010



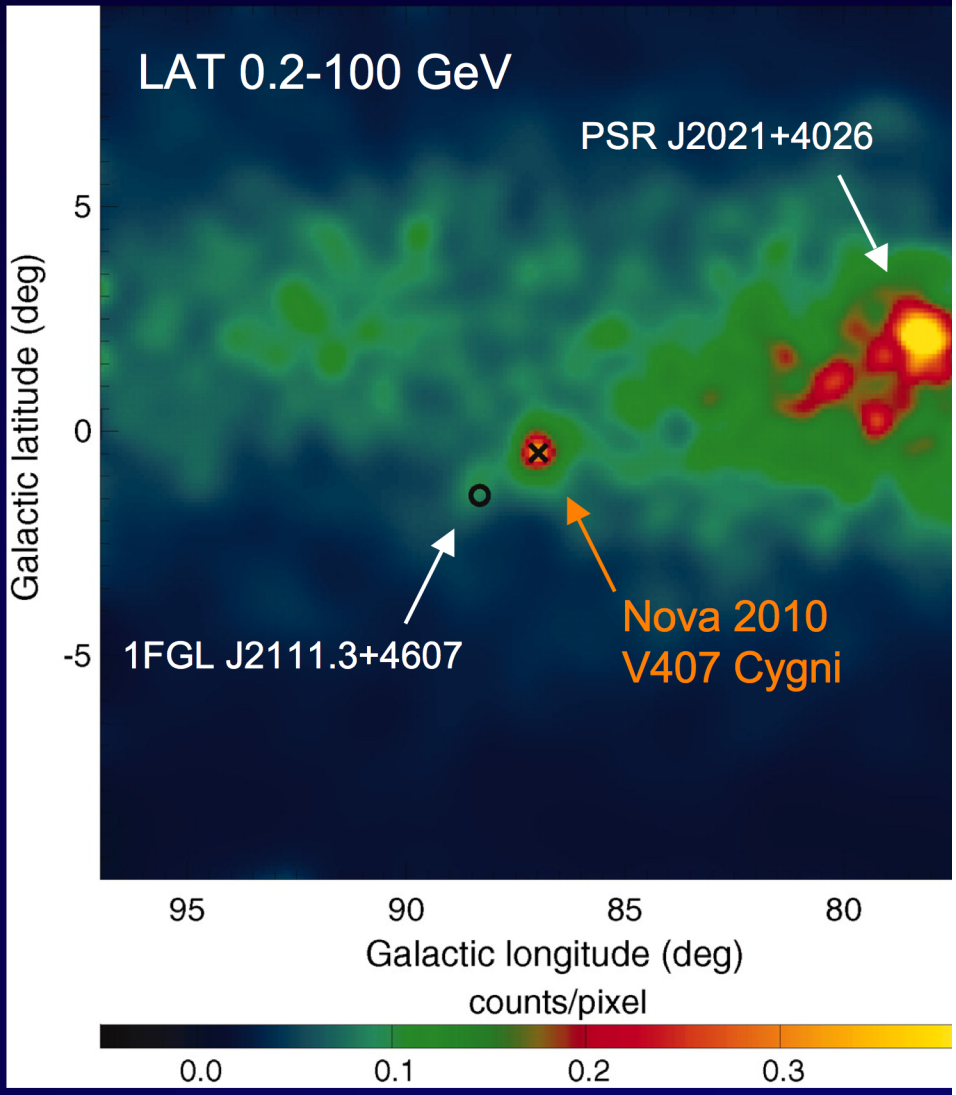
Feb. 19 to March 9, 2010

March 10 to 29, 2010

LAT >100 MeV counts maps

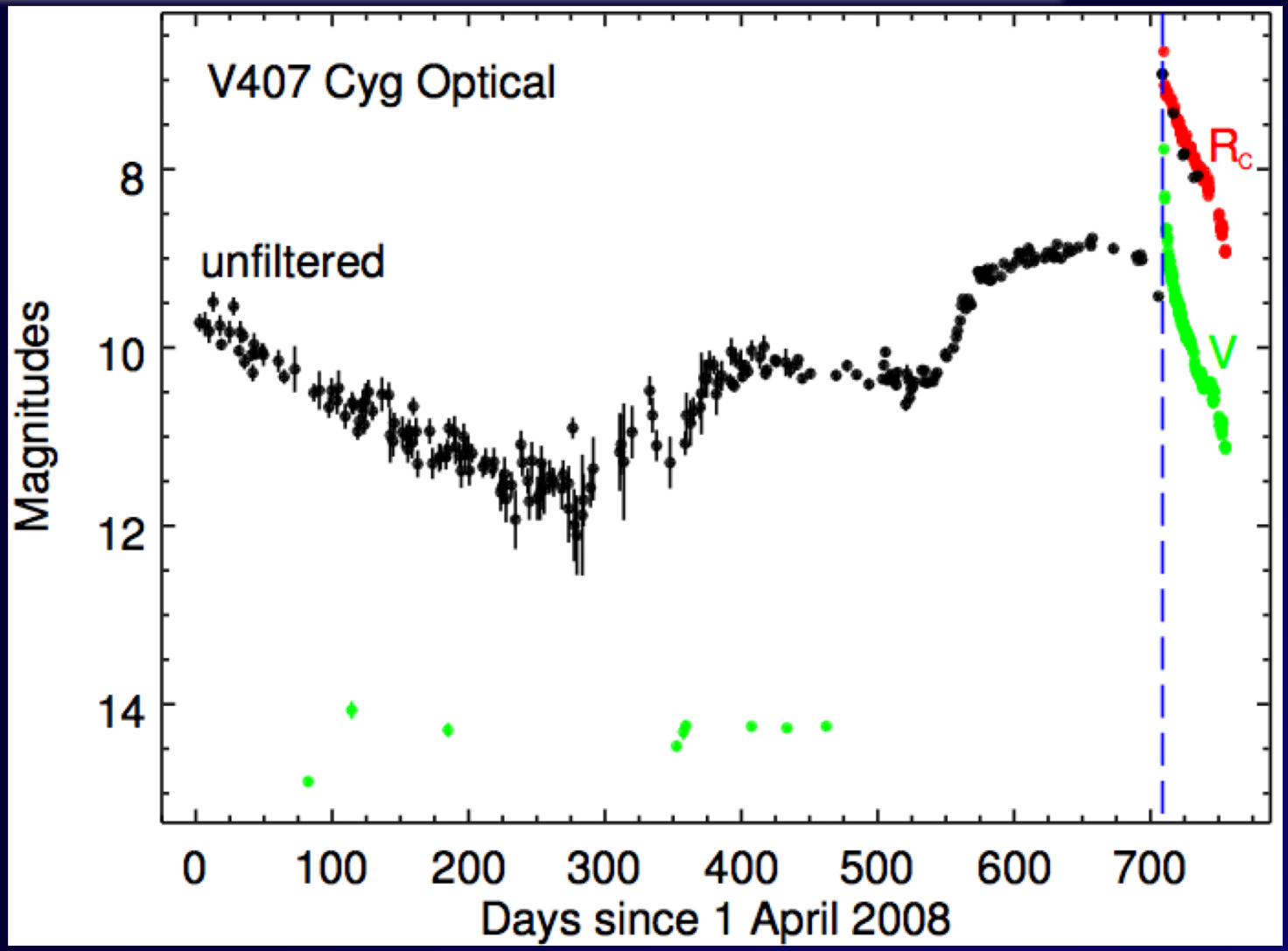
Gamma Rays Concurrent with a Nova

- Fermi J2102+4542: First detection of a nova in gamma rays
- 6-8σ in automated processing on 2010 March 13, 14 (Cheung et al. ATEL #2487)
- LAT position within 3.7' of V407 Cygni (white dwarf, red giant binary)
- Further analysis shows gamma rays close in time to nova discovery on March 10 by Nishiyama and Kabashima

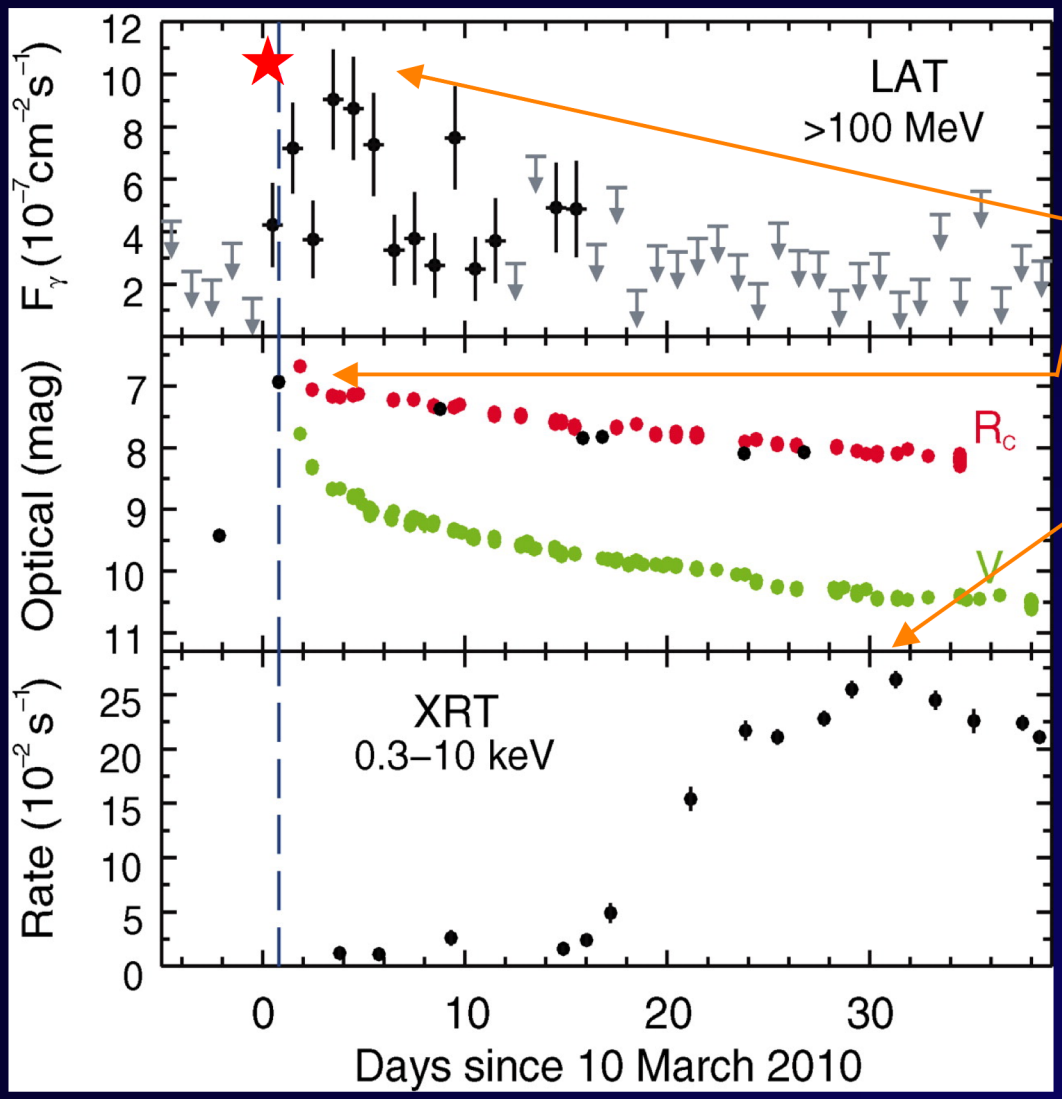


Science 329, 817 (2010)

Historical Optical Lightcurve



Nova Lightcurves



1) Optical peaks first

2) Gamma rays peak at 3-4 days and last ~2 weeks

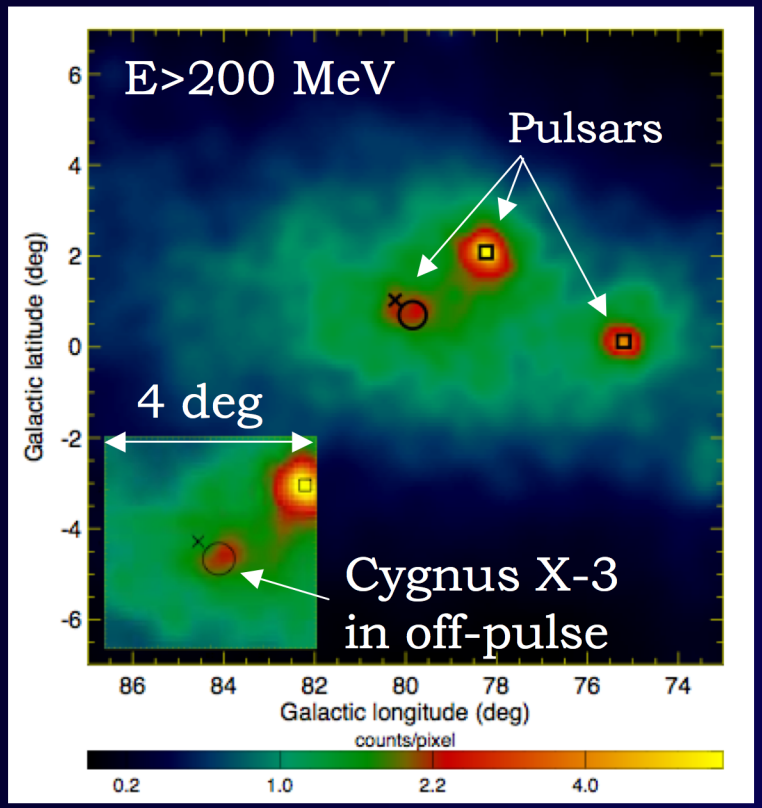
3) X-rays peak at ~30 days, last and longest

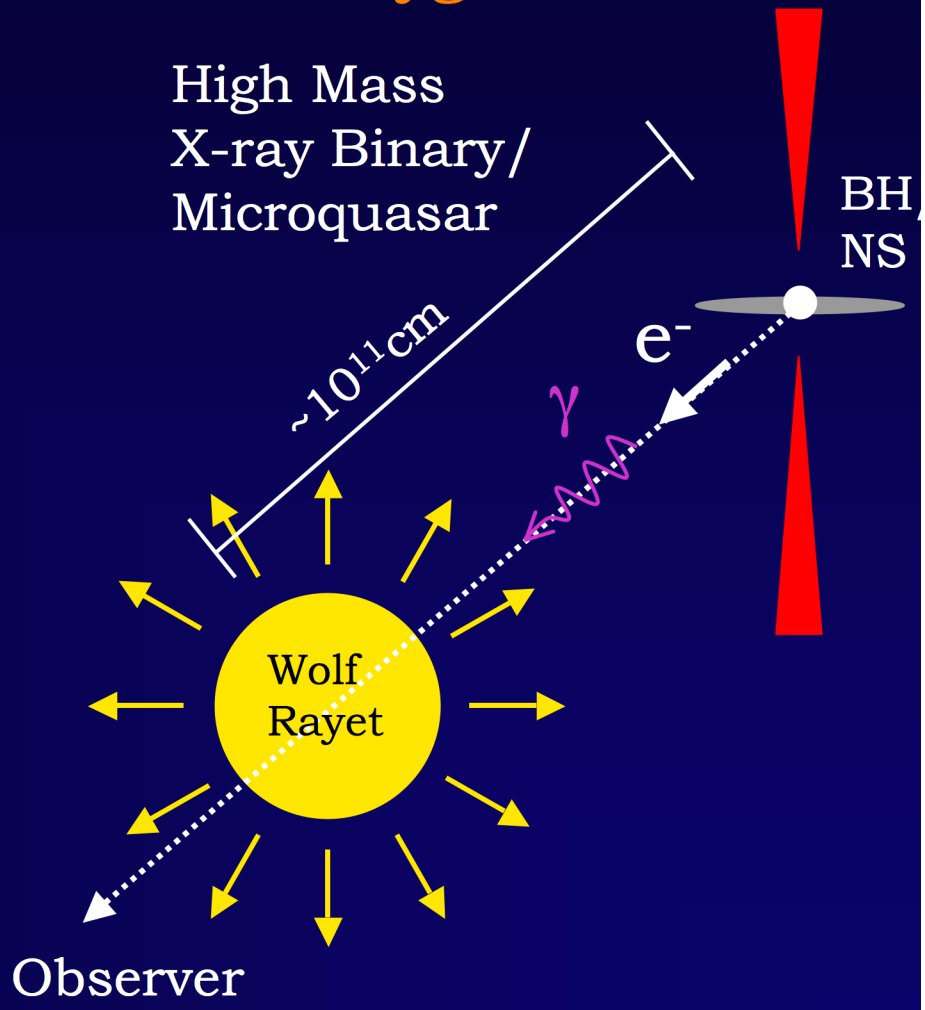
Relative timing can be understood from the system geometry

Cygnus X-3

First secure gamma-ray detection of Cygnus X-3

- high significance source and binary modulation





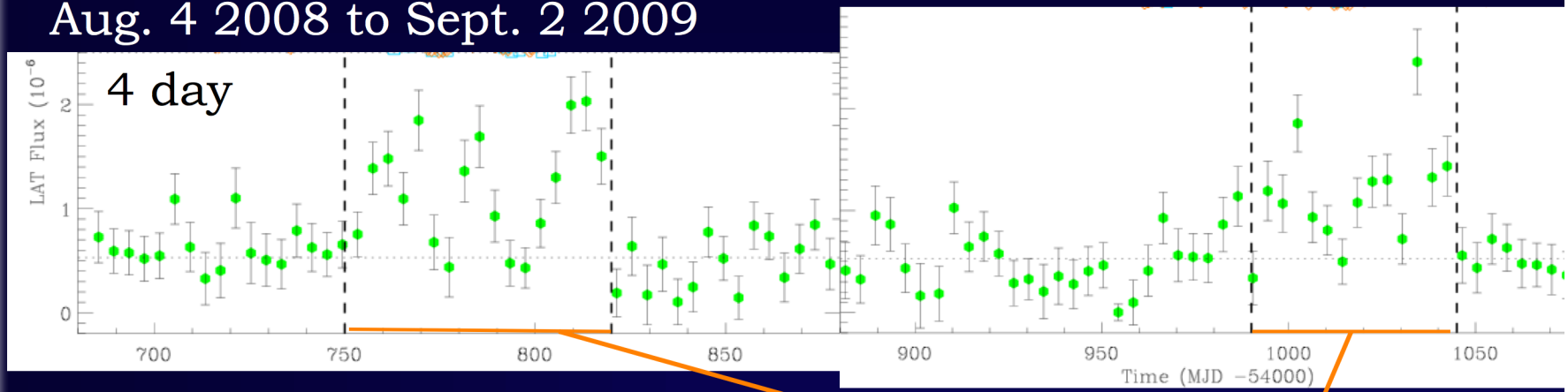
Science 326, 1512 (2009)

June 9, 2011

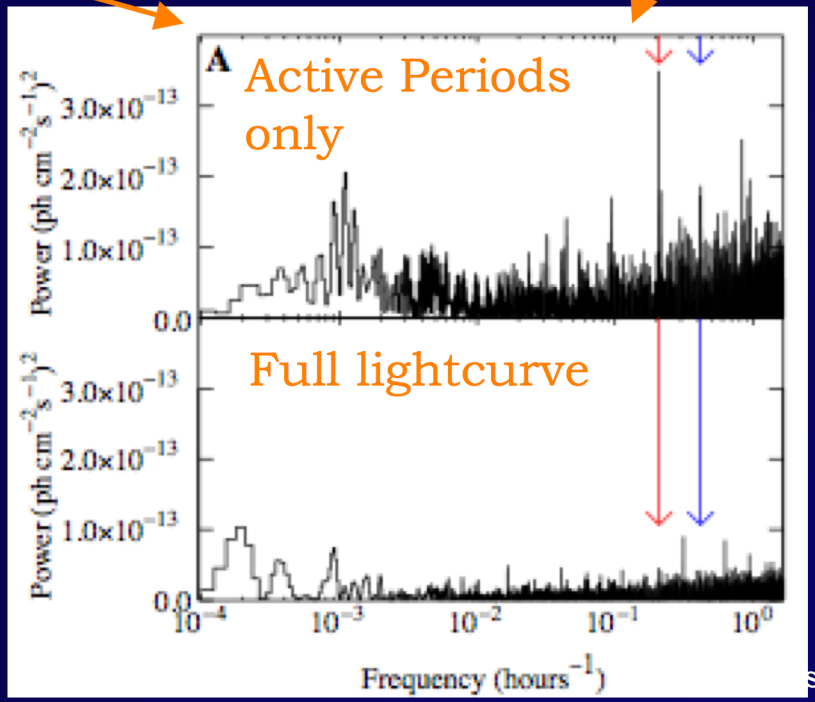
E. Hays

Gamma-ray Flares and Modulation

Aug. 4 2008 to Sept. 2 2009



- LAT active periods correspond to soft X-ray state
- Gamma rays modulated at 4.8 hour binary period
- Additional GeV activity during May 2010 (Corbel et al. ATEL #2646)



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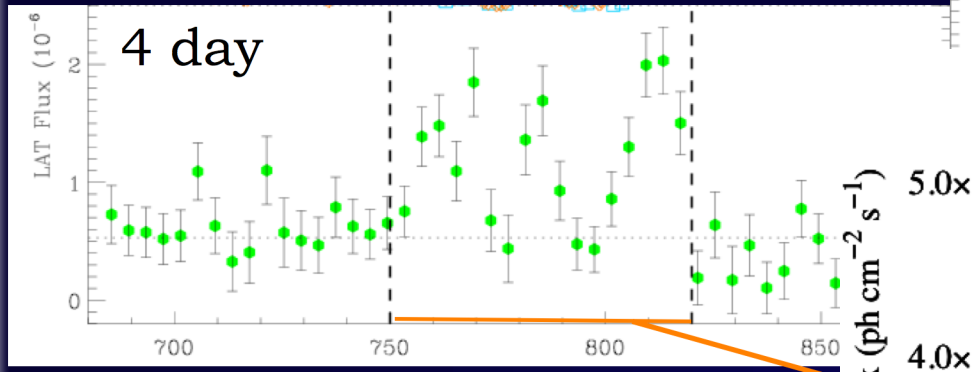

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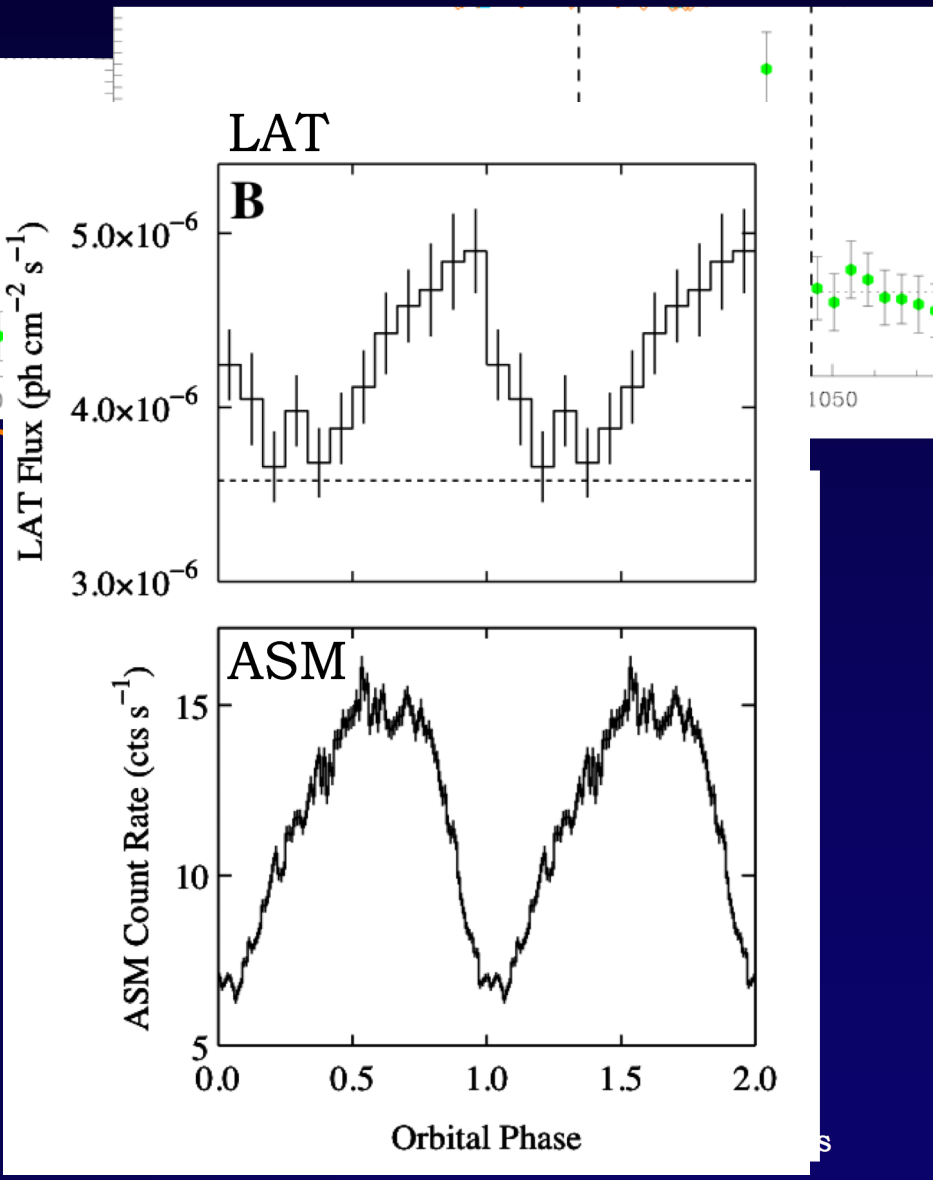
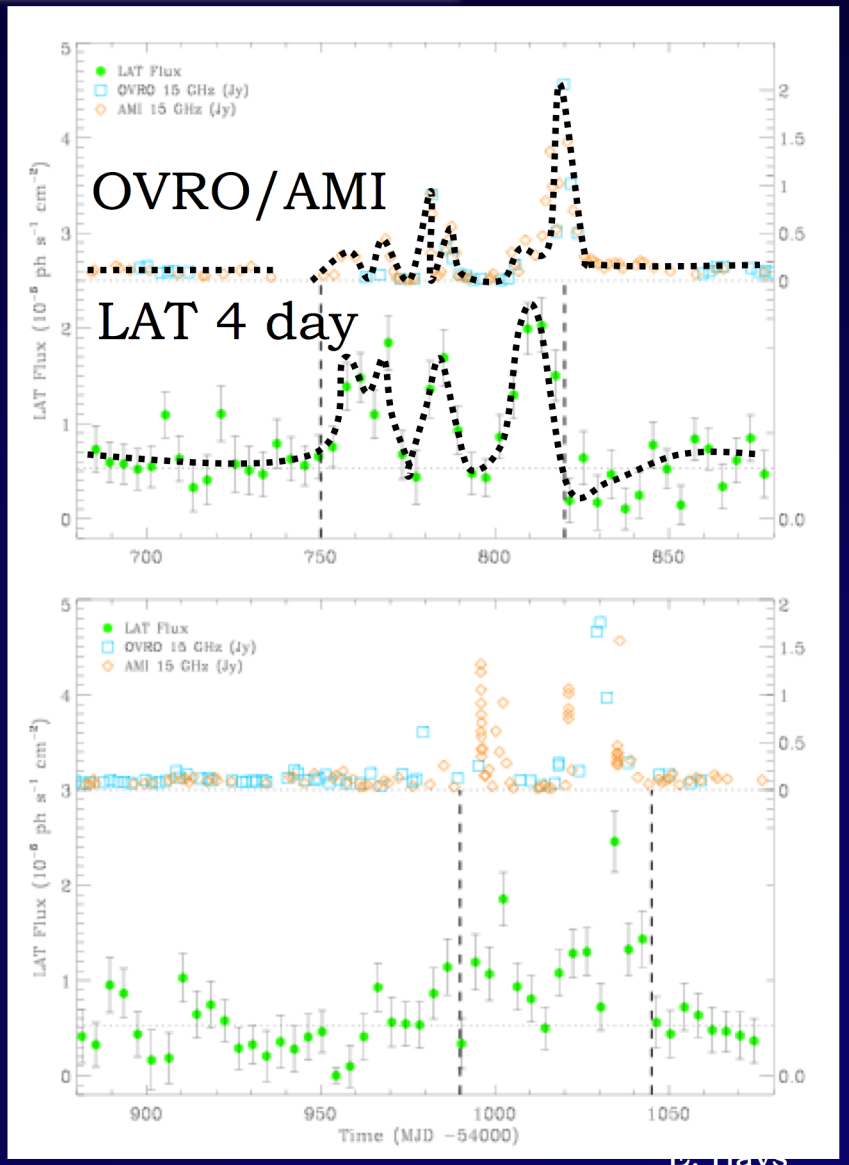
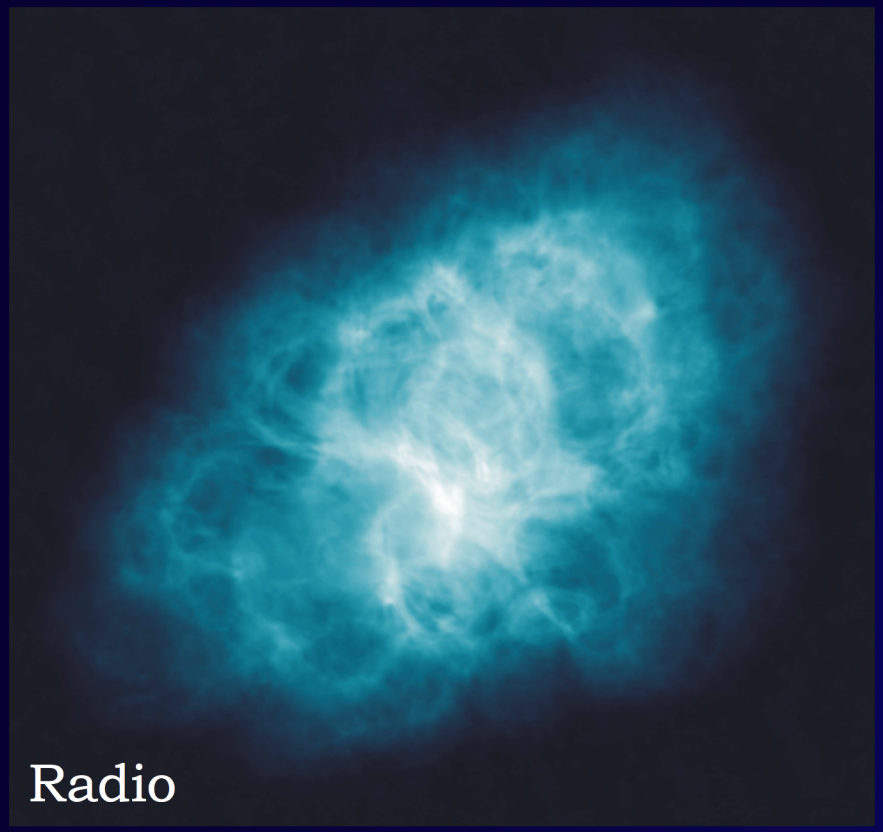


Connection to Jet Activity

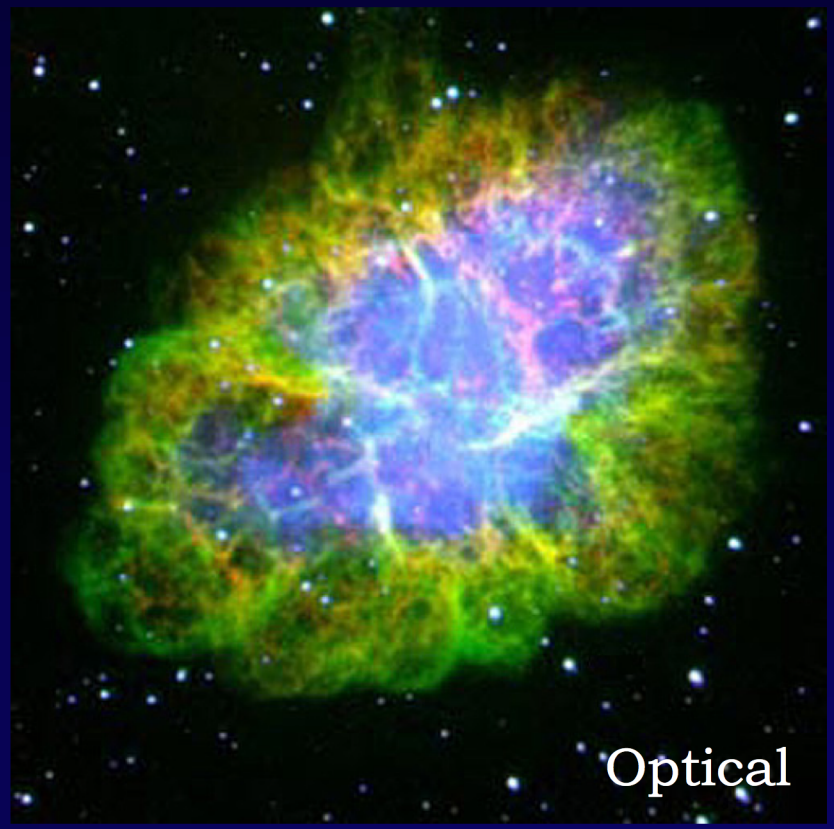
- LAT active periods correspond to radio flares
  - Possible radio lag is not well constrained by correlation analysis
- Expect high energy electrons somewhere along the jet to scatter the stellar radiation field (UV) via inverse Compton
  - Superior conjunction favored for gamma-ray production



The Crab Nebula



NRAO/AUI and M. Bietenholz

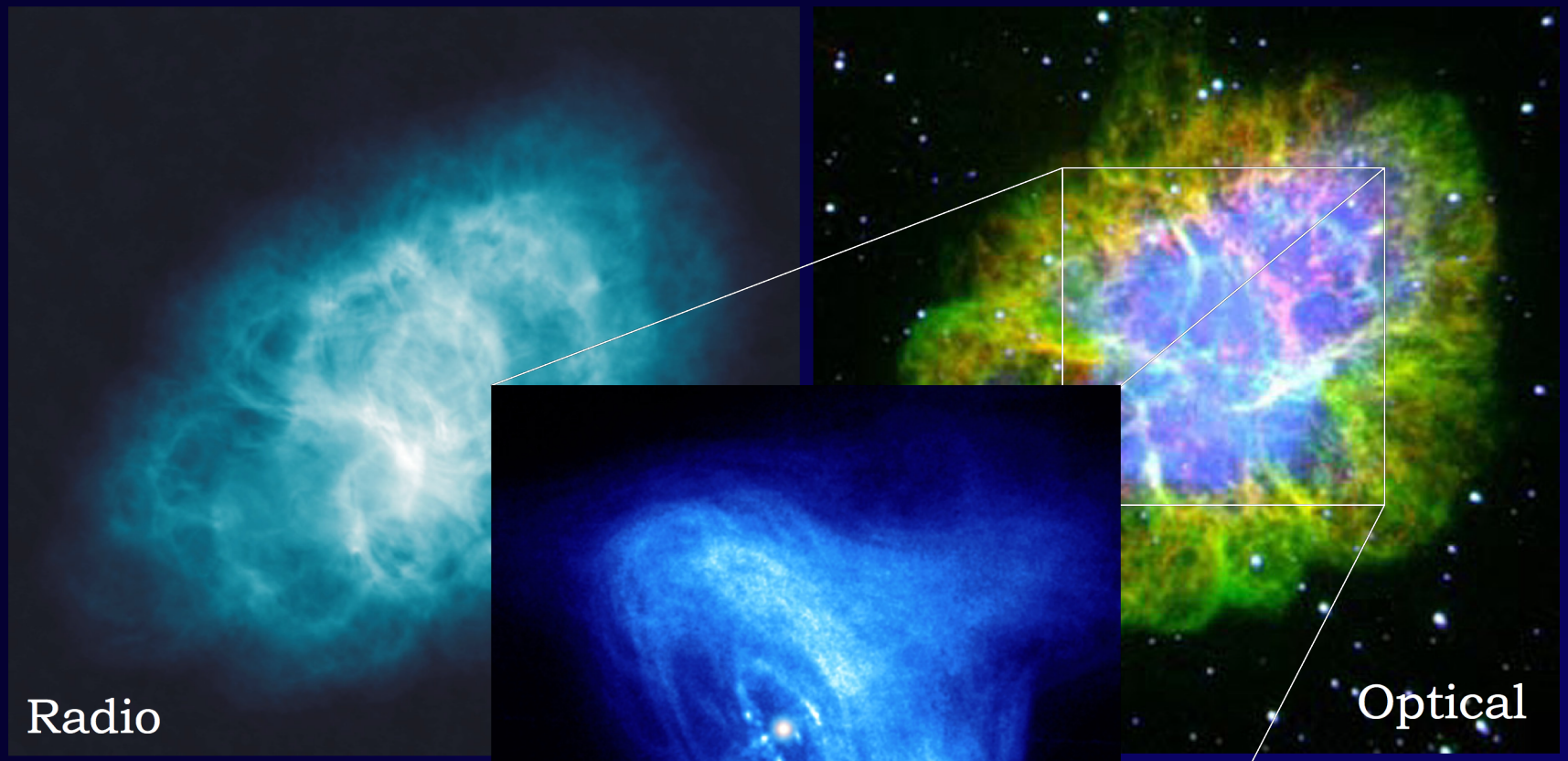


NASA/ESA/ASU/J.Hester & A.Loll)

See review
Hester, J. J., 2008,
ARA&A, 46, 127

X-ray

The Crab Nebula



NRAO/AUI and M. Bietenholz

SU/J.Hester & A.Loll)

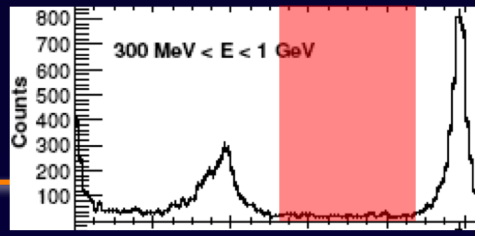
NASA/CXC/ASU/J.Hester et al.

See review
Hester, J. J., 2008,
ARA&A, 46, 127

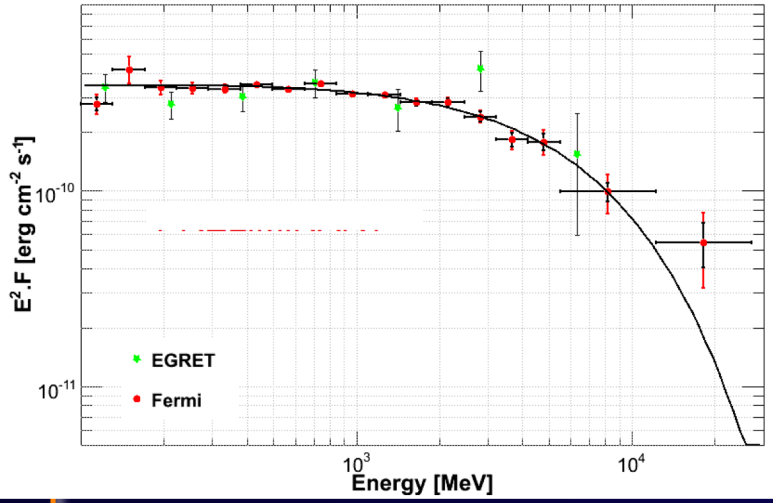
June 9, 2011

E. Hays

The Crab in LAT



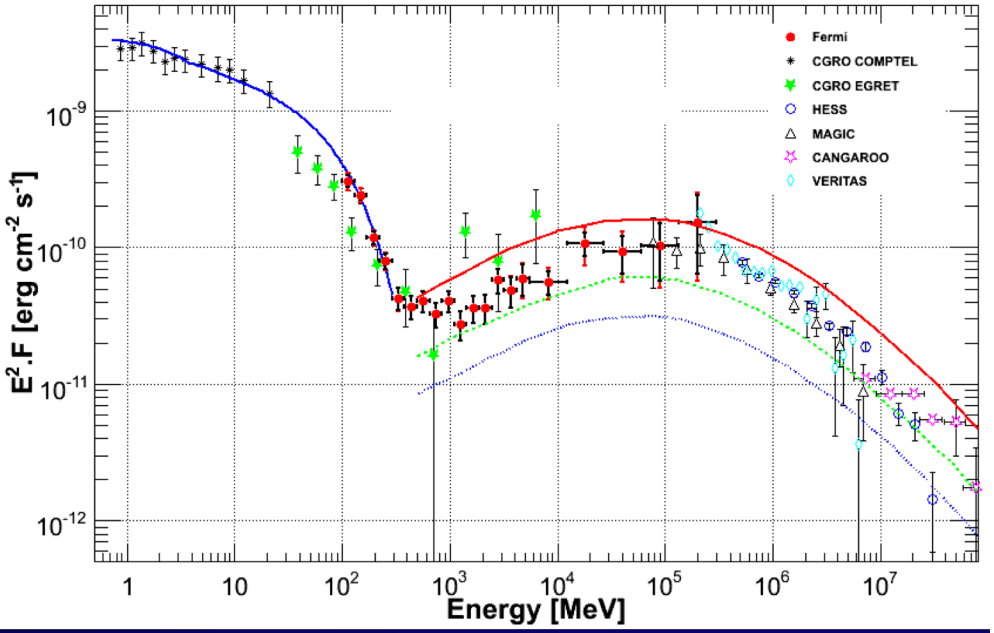
Pulsar 100 MeV to 20 GeV



Hyper-exponential cutoff excluded at ~5 sigma

Consistent with emission well above the neutron star surface

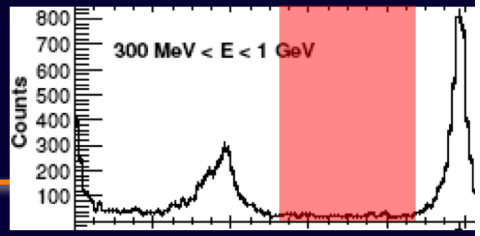
Nebula from MeV to TeV



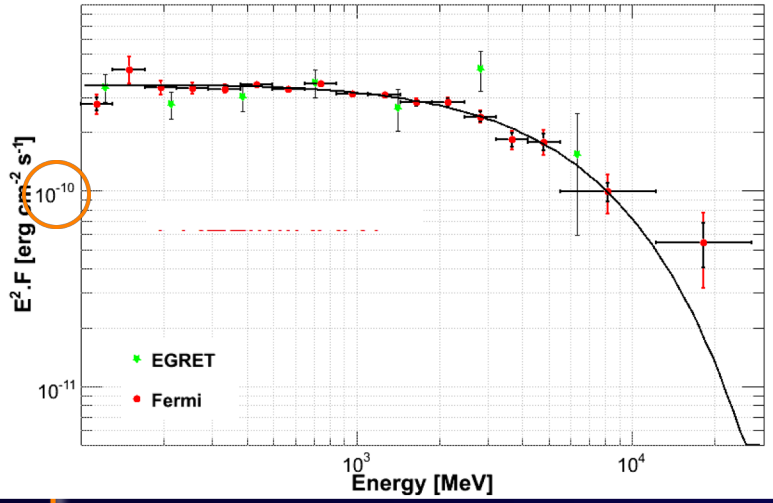
Two components: Synchrotron + Inverse Compton extending to TeV. Mean nebula B field of 100 to 200 μG

Abdo et al. 2010, ApJ, 708, 1254

The Crab in LAT



Pulsar 100 MeV to 20 GeV



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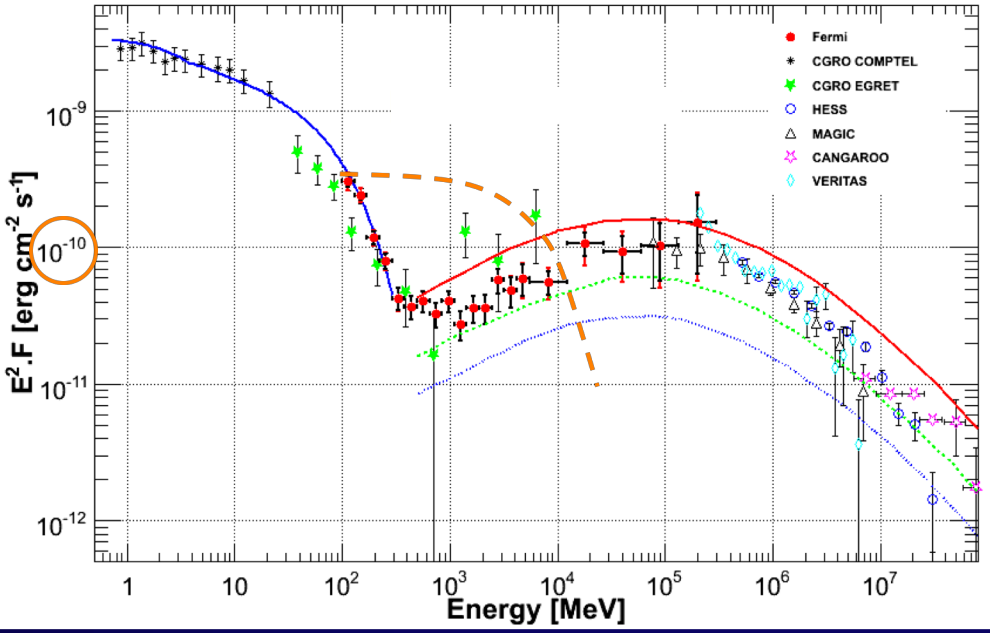


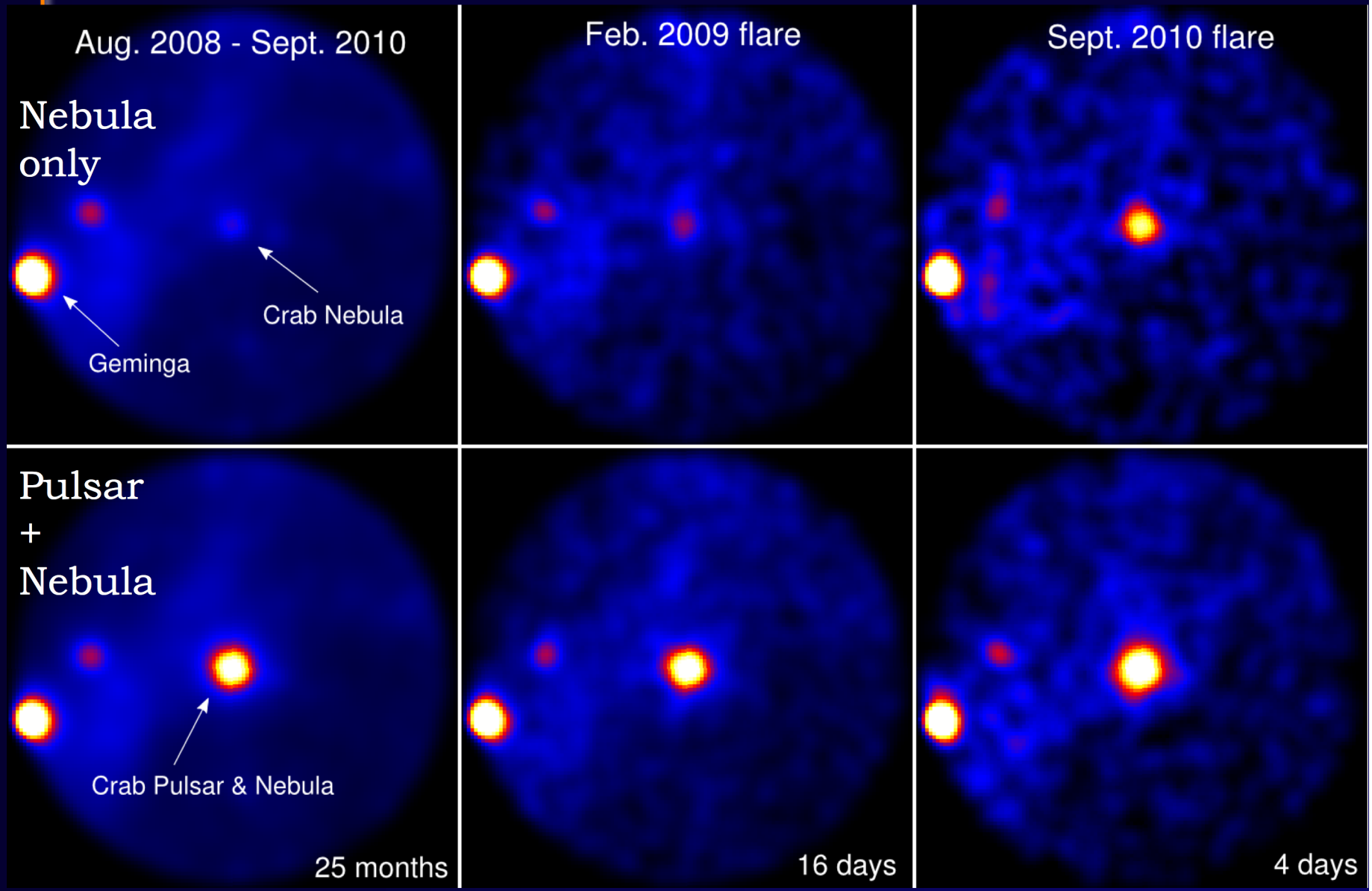
Two components: Synchrotron + Inverse Compton extending to TeV. Mean nebula B field of 100 to 200 μG

Abdo et al. 2010, ApJ, 708, 1254

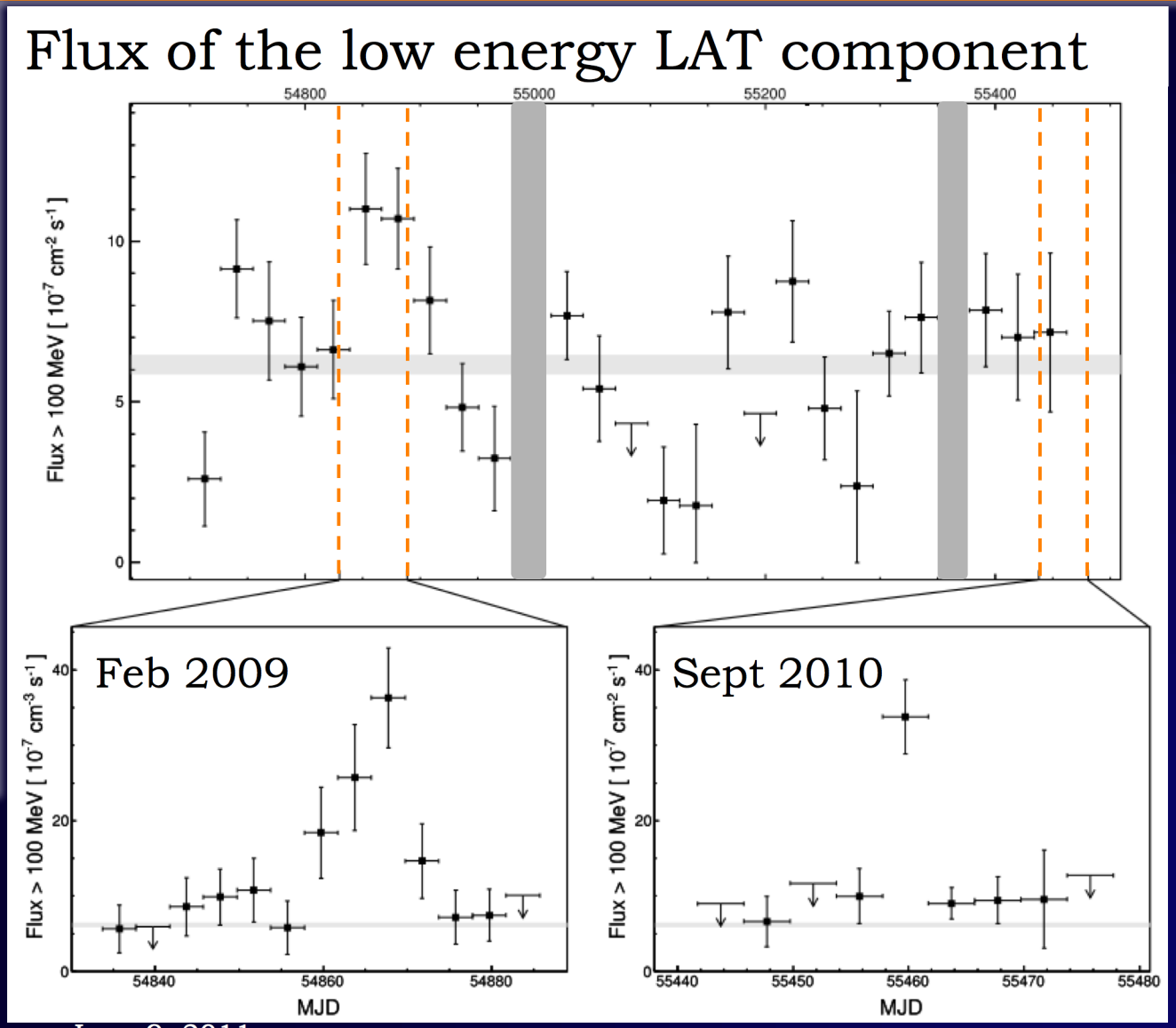
Our candle is not so standard

- Crab flickers in hard X-ray
  - Fermi GBM reports hard X-ray variability, ~3.5% decline per year since launch. Confirmed by multiple instruments (C. A. Wilson-Hodge et al. arXiv:1010.2679v1)
- Crab flares at high energy (>100 MeV)
  - AGILE reports enhanced Crab flux over a few days, Sept. 19-21 (M. Tavani et al. ATEL #2855)
  - Fermi LAT confirms flare and triggers LAT ToO (R. Buehler et al. ATEL #2681)
    - Earlier flare found using new offline all-sky variability search developed by R. Buehler
  - Fermi LAT reports end of flare. Variability present in off-pulse phase of pulsar (E. Hays et al. ATEL #2893)

Exposing the Nebula Flare



Two Short Flares from the Nebula



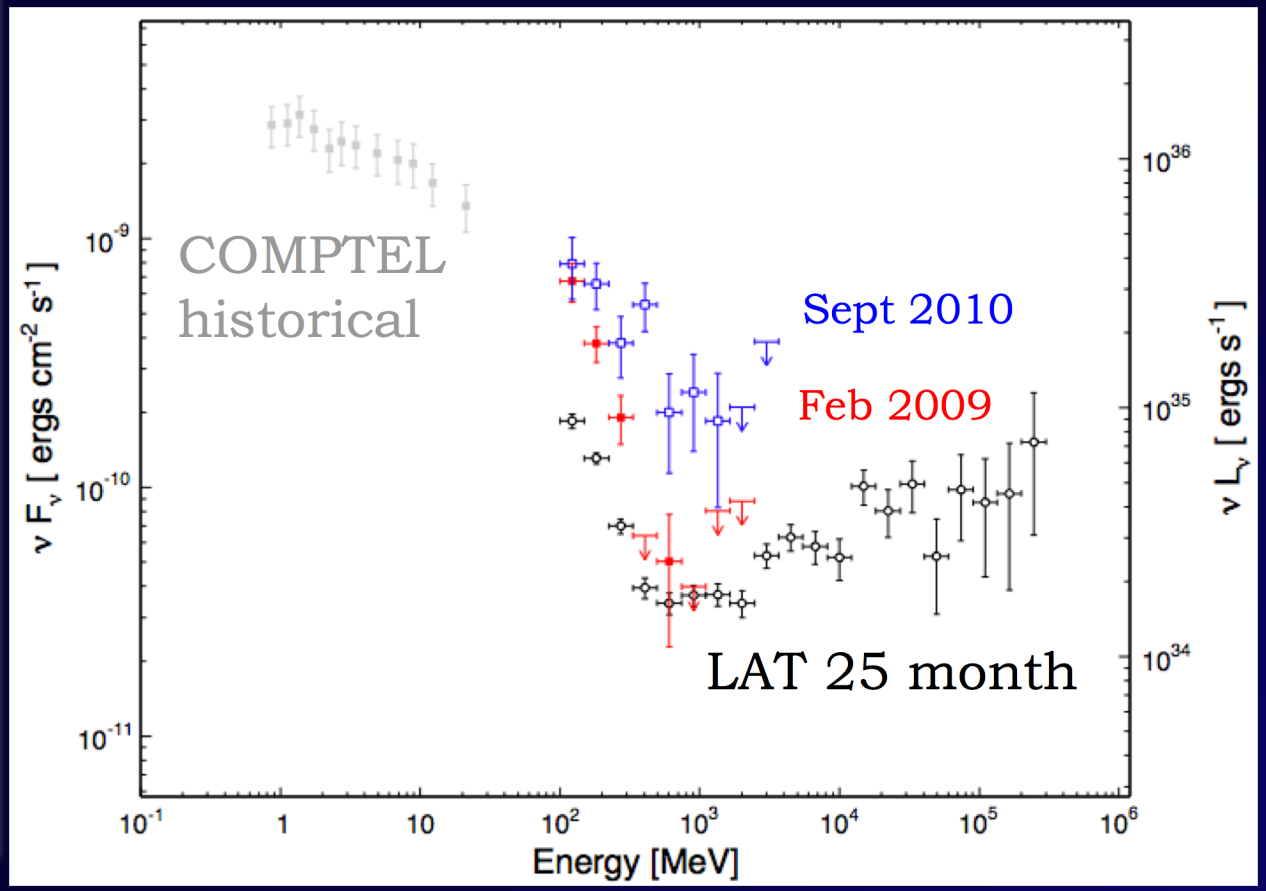
No variability found in pulsar or high energy LAT component

4 week intervals
Sun passages excluded

4 day intervals covering flare periods

Abdo et al. 2011, Science, 331, 739

Crab Flare Spectra



Low energy LAT component shows spectral variability

25 month index: 3.69 ± 0.11

Feb 2009 index: 4.3 ± 0.3

Sept 2010 index: 2.7 ± 0.2

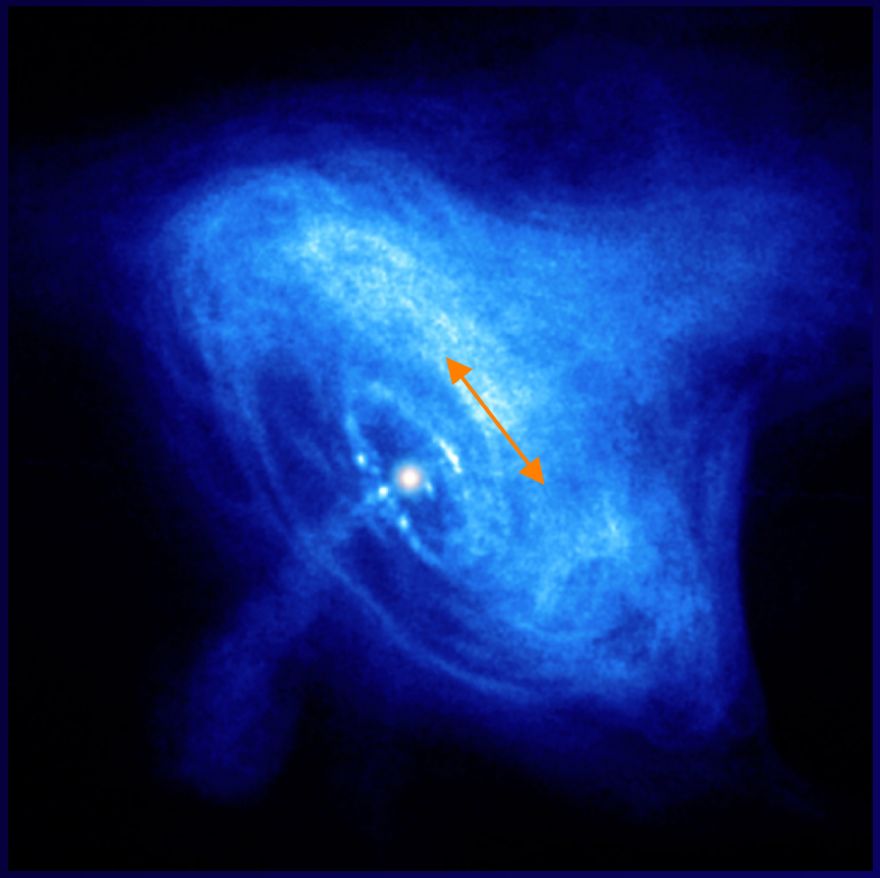
Abdo et al. 2011, Science, 331, 739

Origin of the Gamma-ray Flares?

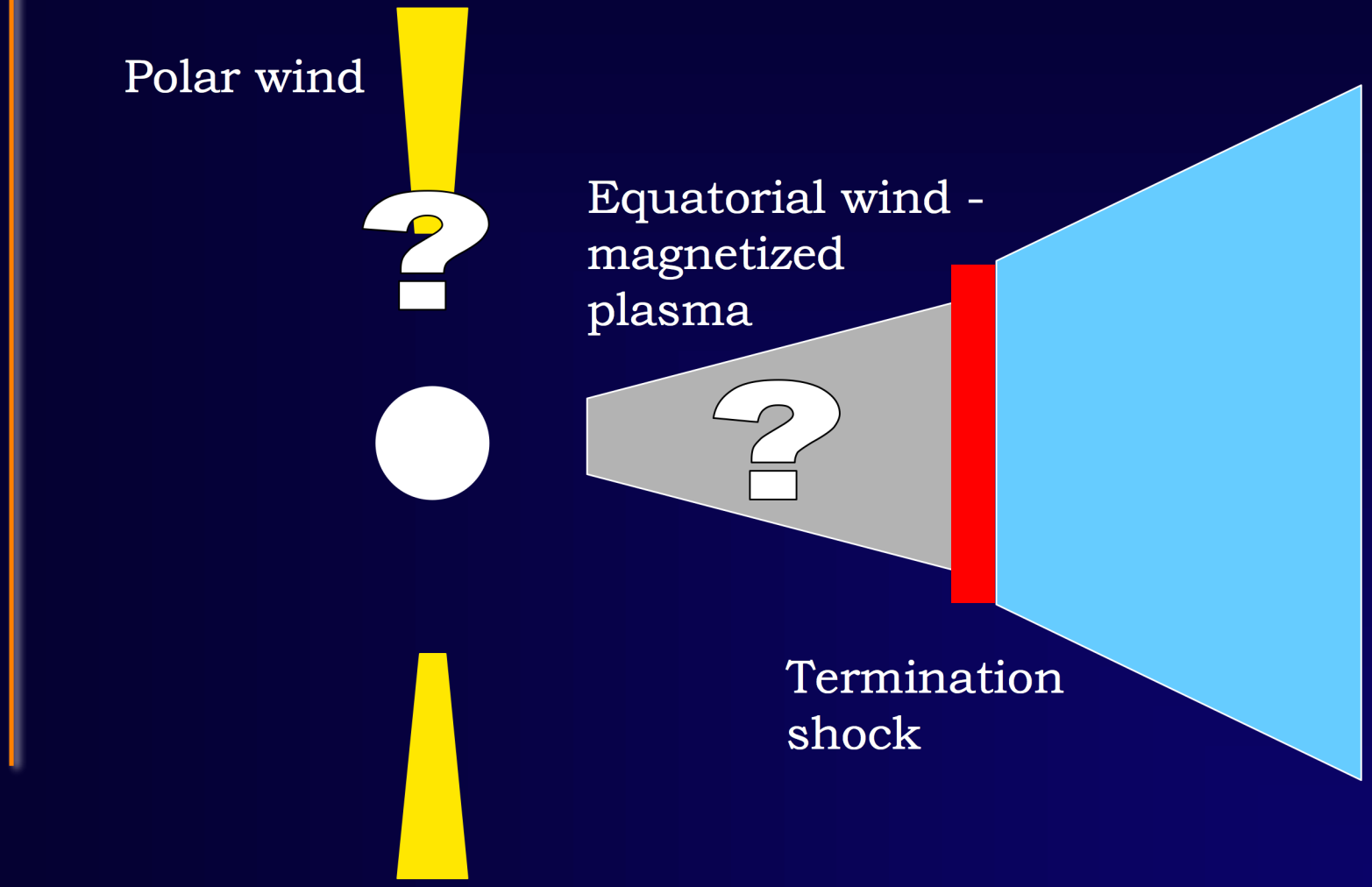
- Gamma-ray luminosity is a small fraction of the pulsar power
  - 10^{35} erg/s in the flare -> ~10^{-3} L_{rot} of the pulsar
  - About 10^{28} Watts or ~100x Solar luminosity
- The Crab Pulsar is an immensely powerful dynamo
  - Voltage drop ~50 PV

Origin of the Gamma-ray Flares?

- Gamma-ray luminosity is a small fraction of the pulsar power (10^{35} erg/s -> ~10^{-3} L_{rot})
- 4 day duration implies small region size, diameter < 1.4 x 10^{-2} pc (~1.5 arcsec) (3×10^{16} cm)



Crash Course in Nebula Structure



Basics from Rees and Gunn 1974

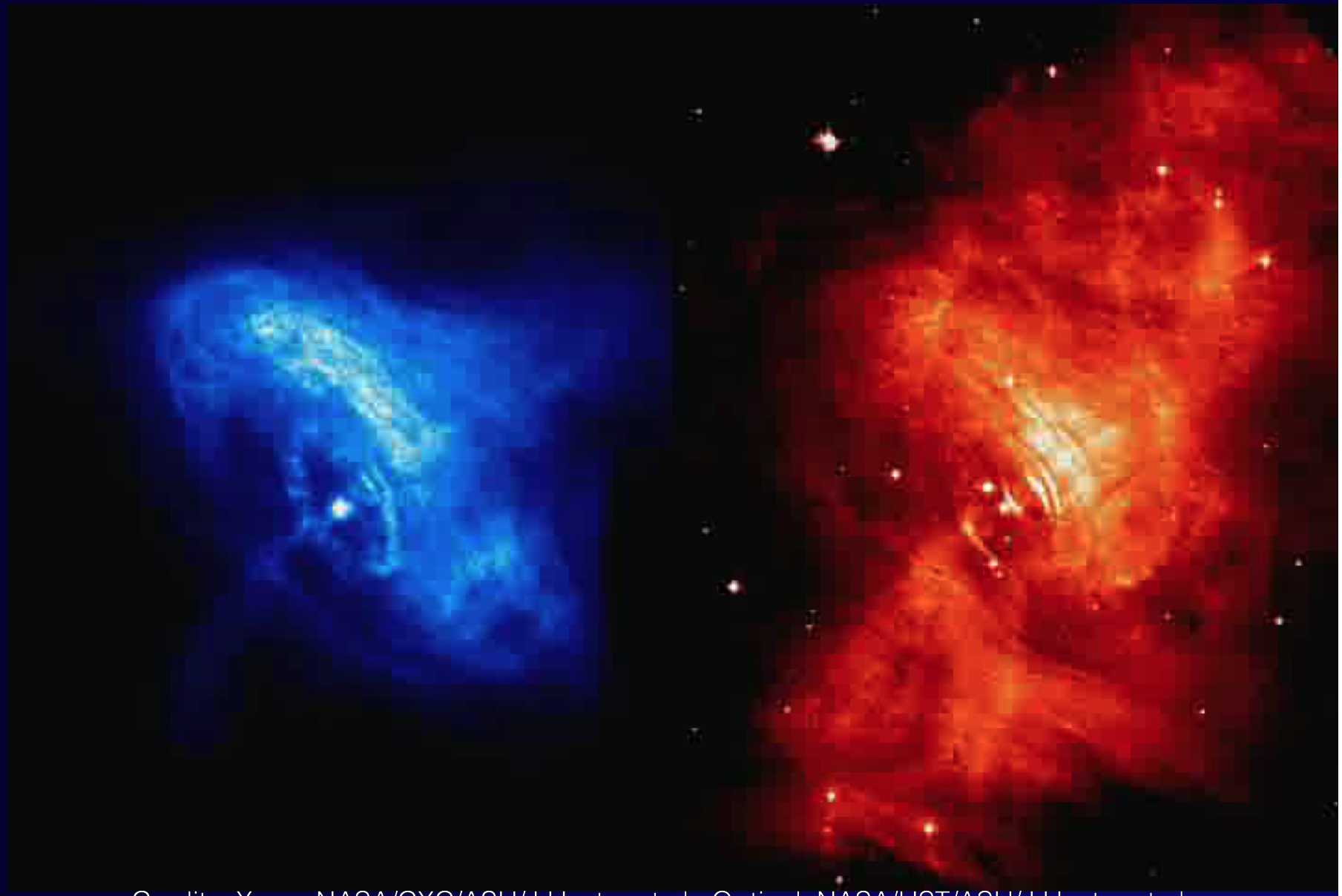
Origin of the Gamma-ray Flares?

- Items
  - Gamma-ray luminosity is a small fraction of the pulsar power (10^{35} erg/s -> ~10^{-3} L_{rot})
  - 4-day duration implies small region size, diameter < 1.4 x 10^{-2} pc (~1.5 arcsec)
  - Electron synchrotron cooling time in 200 uG <~15 days
  - Competing processes (brehmsstrahlung, inverse Compton) require >~ Myr
- Conclude
  - LAT low energy spectral form + short timescale variability support a synchrotron interpretation
  - Implies electrons accelerated to >PeV in structures somewhere in the inner region of the nebula near the termination shock or base of the jet

Searching for the Emission Region

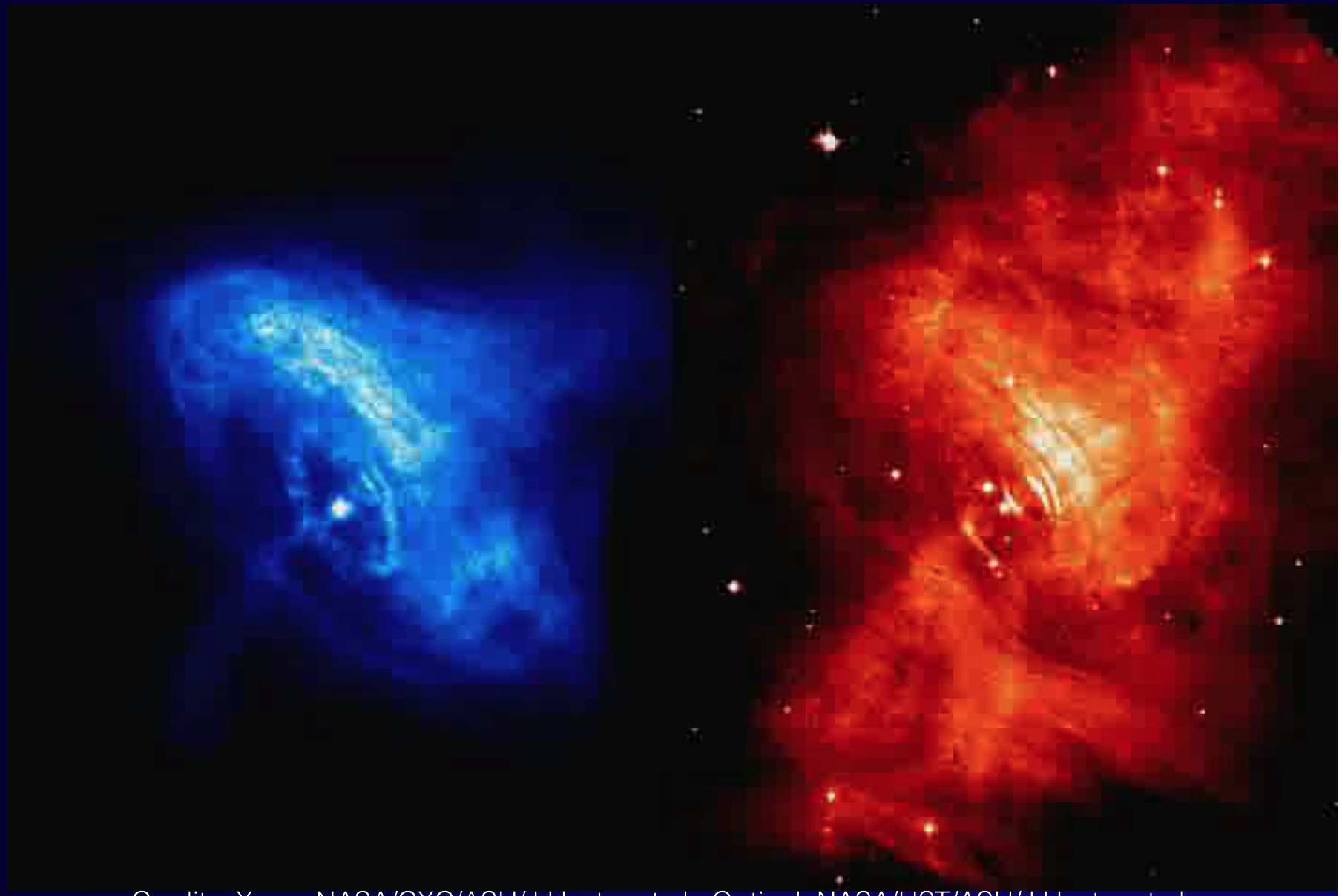
No corresponding variability found in radio, optical, infrared, soft and hard X-rays around time of flare

Inner Nebula Dynamics



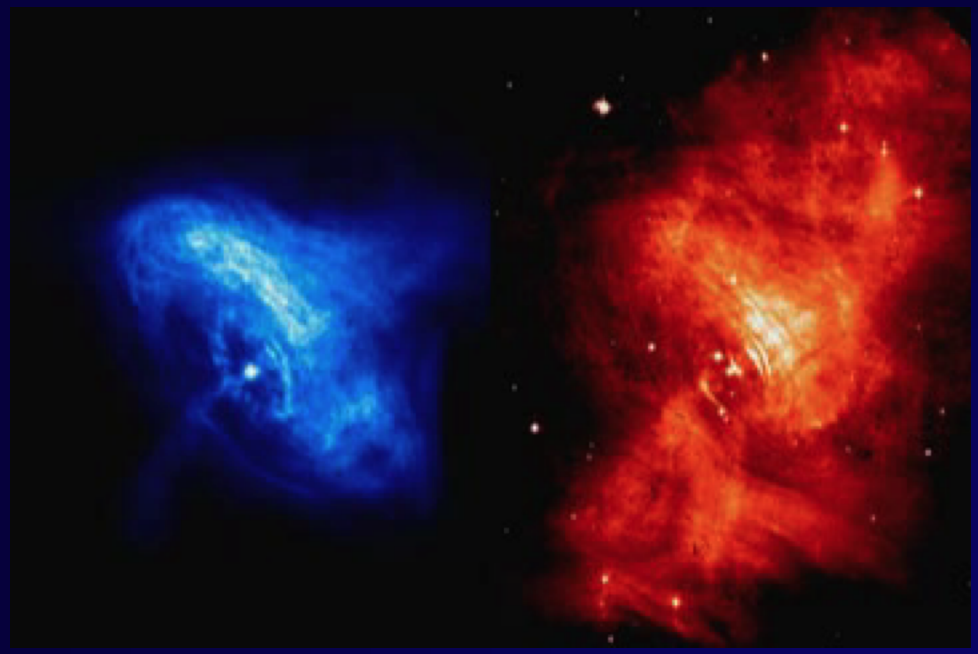
Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

Inner Nebula Dynamics



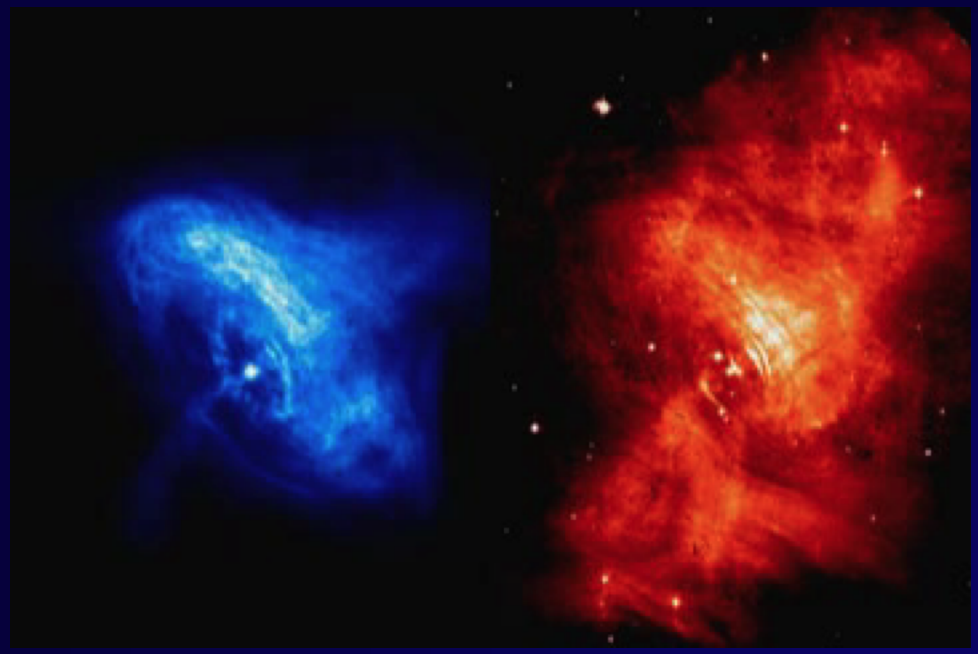
Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

Inner Nebula Dynamics (low res)



Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

Inner Nebula Dynamics (low res)



Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

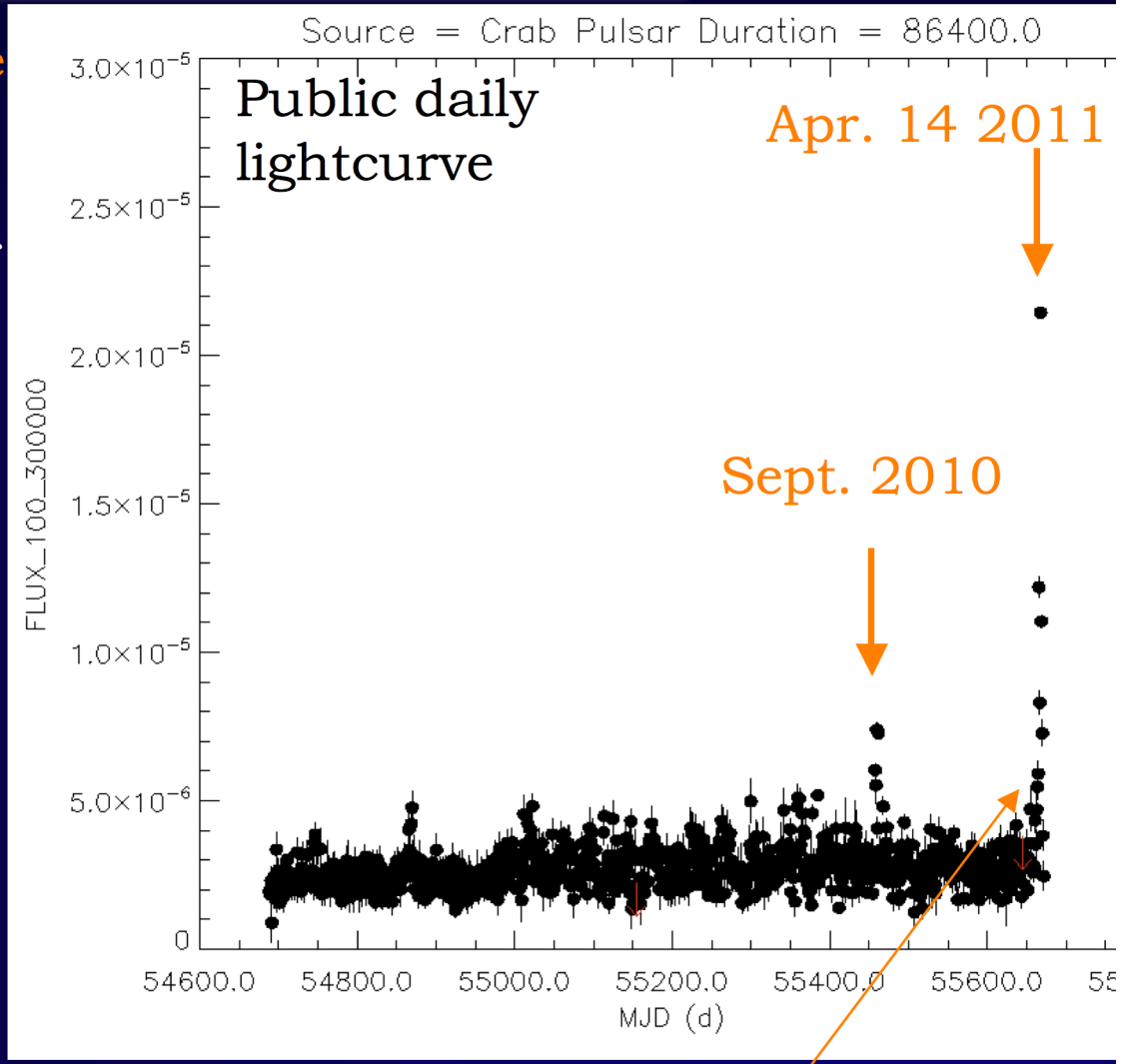
And then…

New, extremely bright flare in April 2011! (Buehler et al. ATel #3276)

LAT TOO captured peak of the flare (Hays et al. ATel #3284)

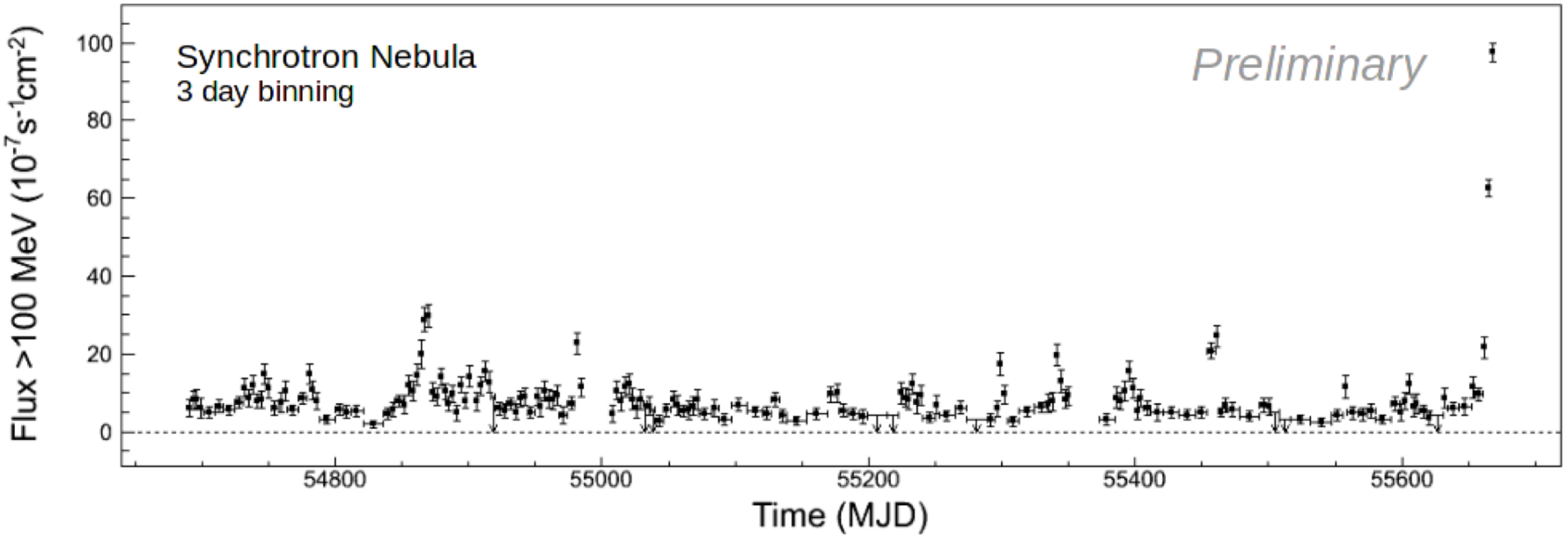
Quick identification enabled sequence of Chandra observations

Rapid variability of PeV electrons poses severe challenges for acceleration mechanisms



http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

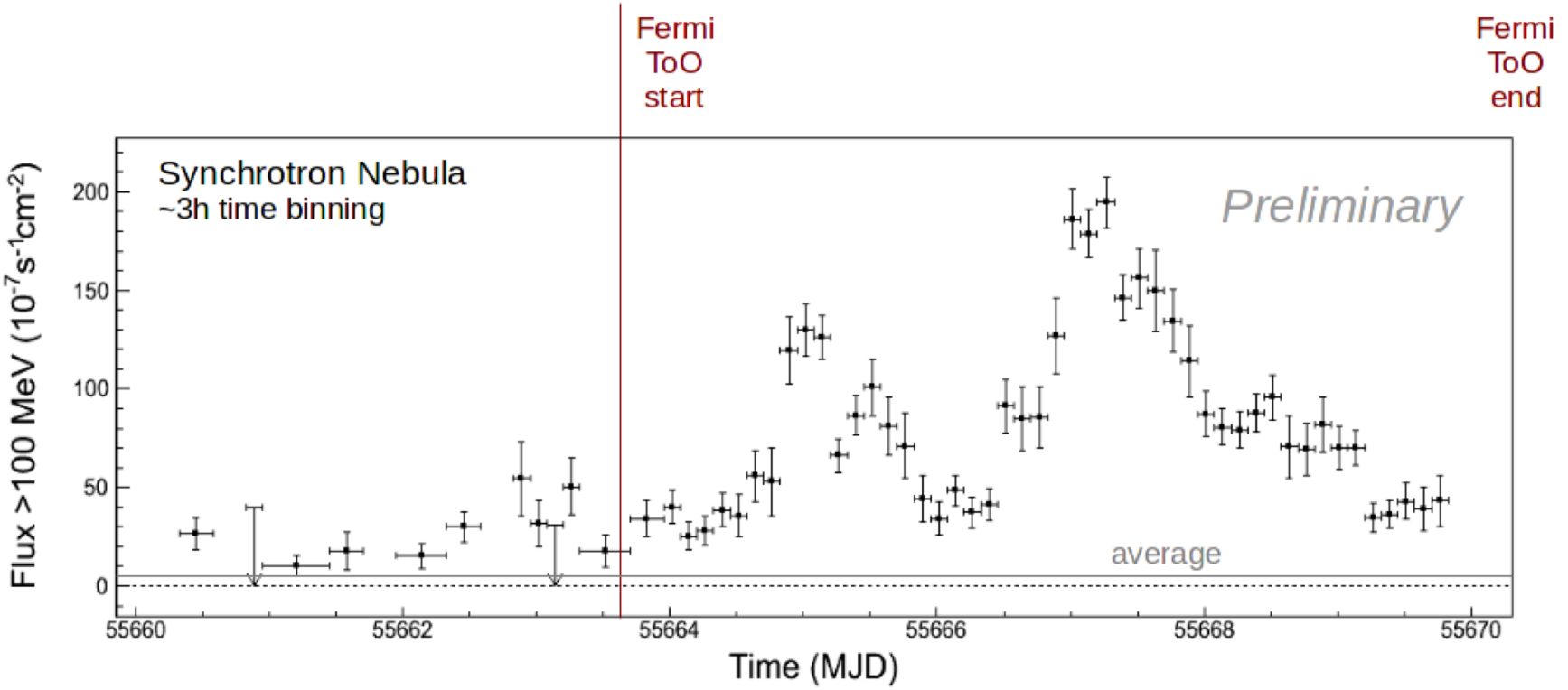
Three day Crab synch. 32 month light curve



Average ~6 10^{-7} ph/cm^2/s and persistently variable

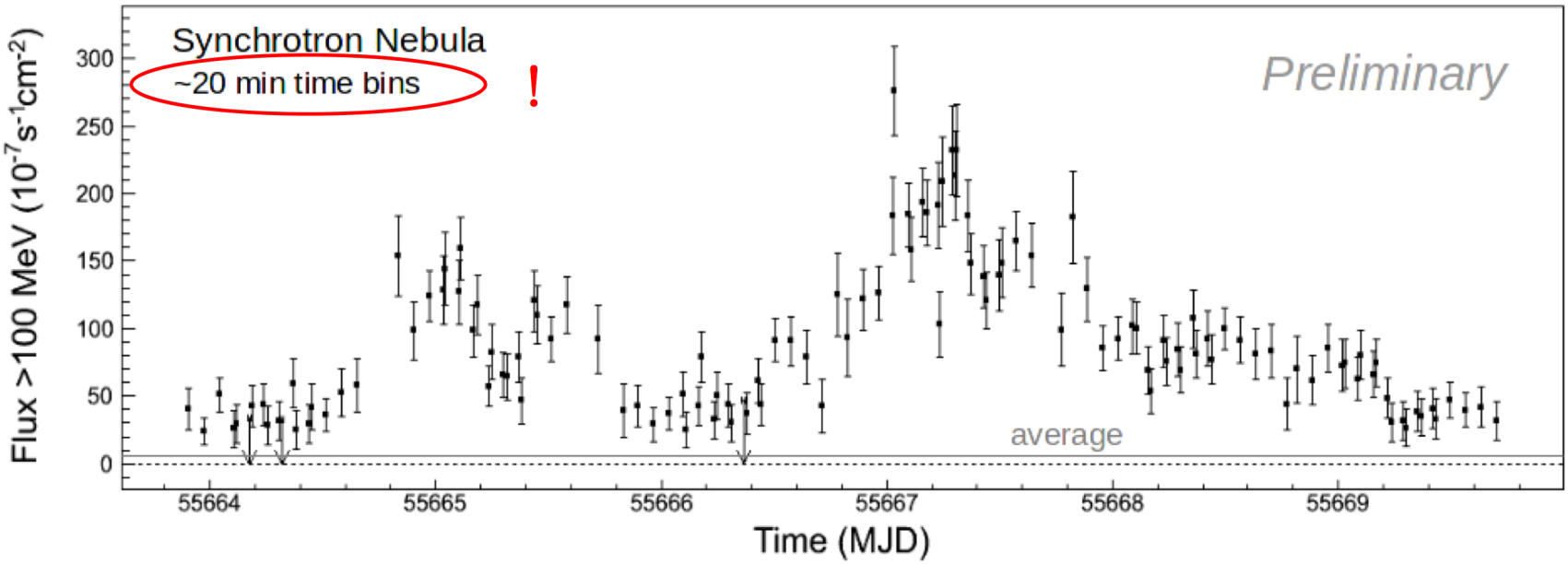
Slides from R. Buehler

Flare light curve and ToO



Synchrotron nebula increased by factor ~30
Very good Chandra coverage

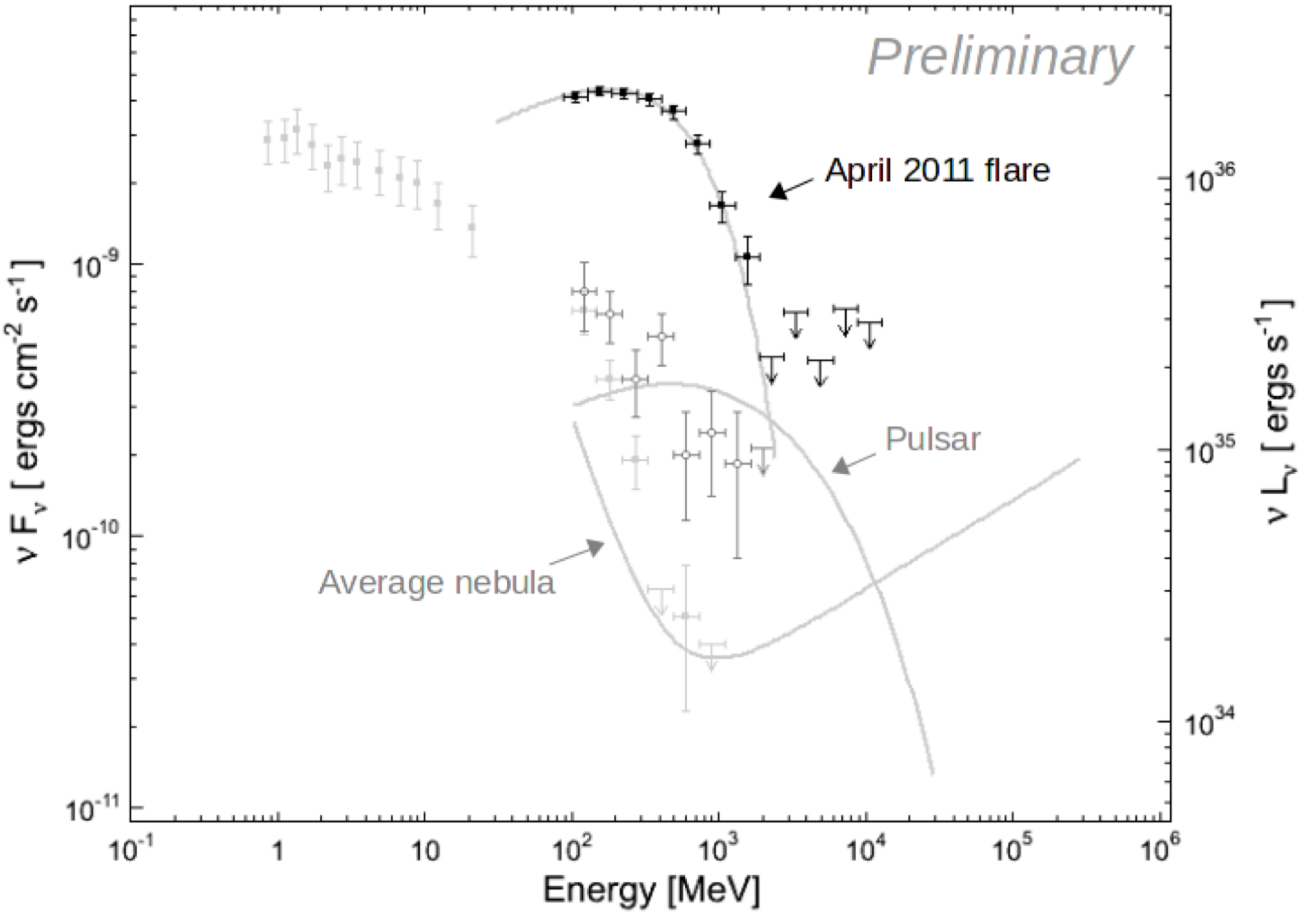
20 min flare light curve



Fast variability (<1h)

Homework! Run Chuck's variability time prescription…
t<1hr => r < 4×10^{14} cm (assume δ_D<4.4 and region moving toward us)

Nebula Flare spectrum



Flare spectrum well described by power law of index 1.6 with exponential cutoff at 580 MeV

No sign of pulsation in flare photons found yet

Open Questions

- What is the flare emission mechanism?
- Where do the flares originate in the nebula?
- Is there (can there be) variability in the VHE energies? (See, for example, Bednarek 2011, MNRAS, 551)

Summary

- LAT is revealing sites and mechanisms of particle acceleration in the Galaxy
  - Small, but interesting number of variable/transient sources in the Galaxy
    - Result of a variety of monitoring methods
  - Variability is an important tool! *(See Chuck's lectures)*
  - Fast, high-energy gamma-ray flares from the Crab
    - Indirectly 'seeing' the highest energy astrophysical electrons we can pinpoint…but where are they?

http://fermi.gsfc.nasa.gov