

GALACTIC SOURCES AT GEV ENERGIES

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NASA / Goddard
Greenbelt, MD

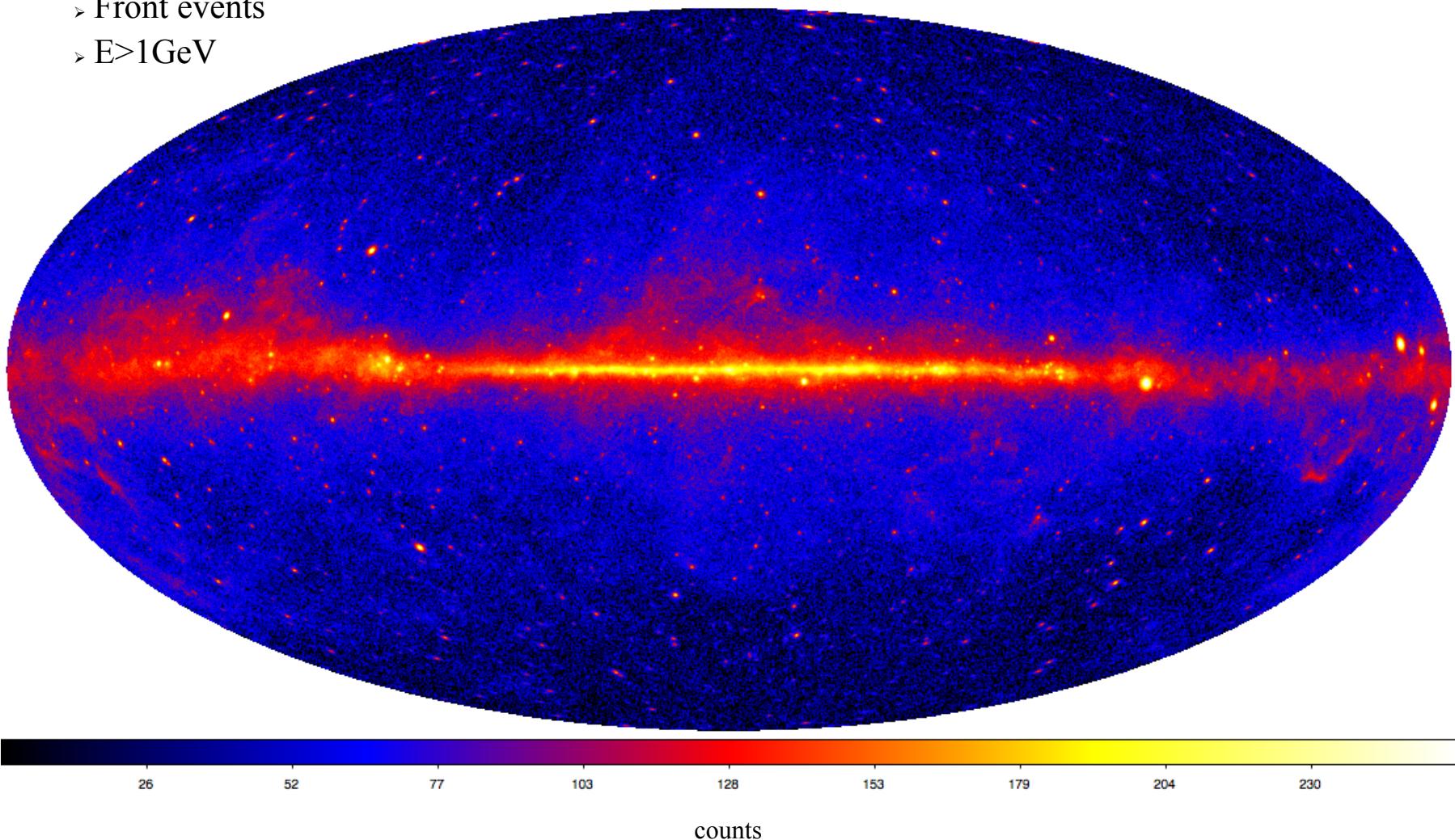
TeVPA
30 Aug 2013
Irvine, CA



Fermi-Detected γ -ray Emission

Data:

- › 4yrs' exposure
- › P7v6
- › Front events
- › $E > 1\text{GeV}$



Galactic GeV Sources

Come in a wide and sometimes surprising variety!

- › Pulsars: 83+25 (2FGL) → 117 identified! (2PC)
- › PWNe: 3 (2FGL) → 3+13 (TeV PWNe Search) (5-7?)
- › SNRs: 6 + 4 + 58 (2FGL) → > 13 identified! (SNR Cat)
- › Binaries: 4
- › Novae! 1(2FGL) → 4 (Symbiotic + Classical!)

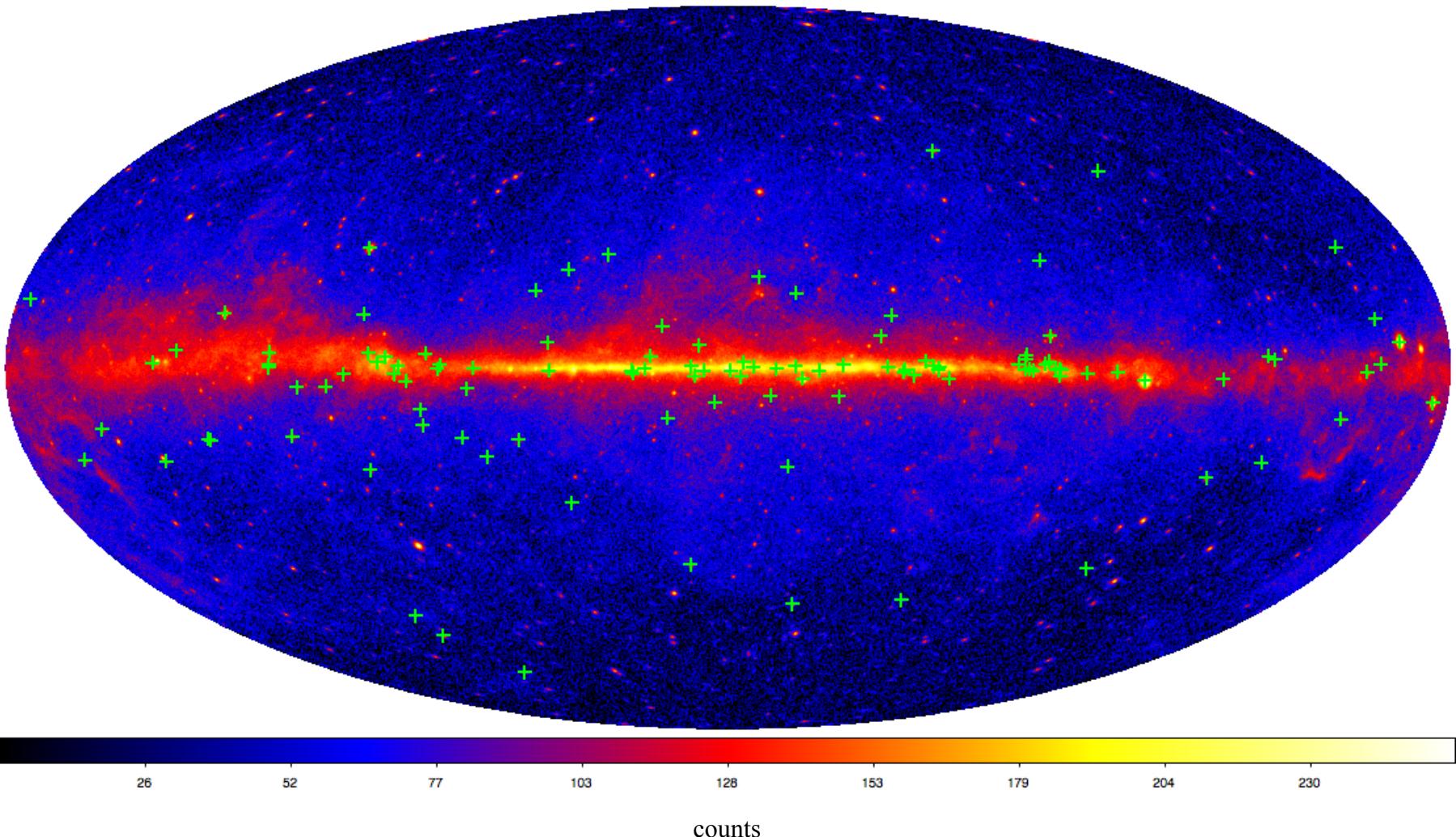
2FGL: 1873 Sources

- › 195 Identified or Associated Galactic sources (~10%)
- › 575 Unassociated → <100

Pulsars

2nd Fermi-LAT Pulsar Catalog (2PC):

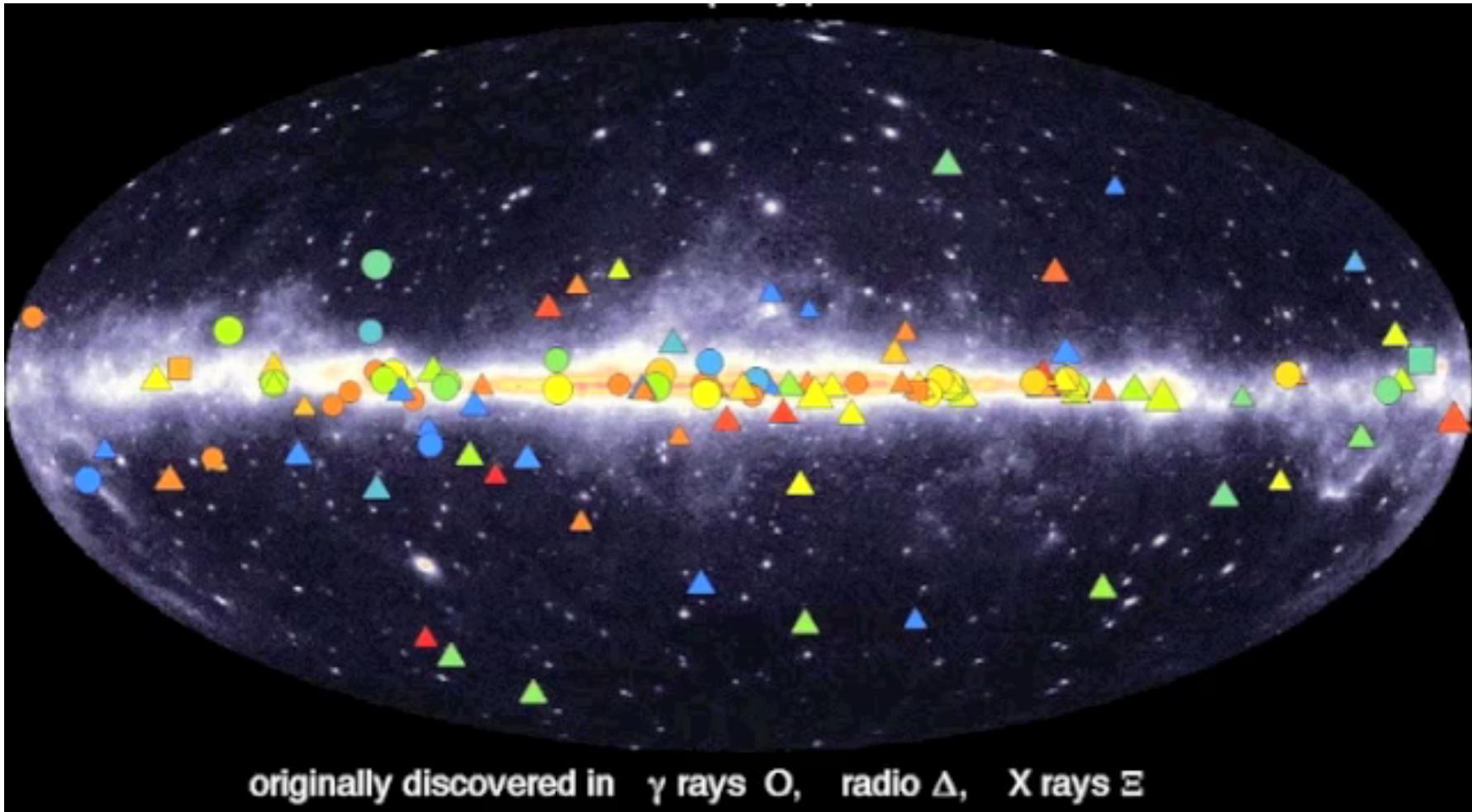
- › Young, radio selected: 38
- › Young, g-ray selected: 36
- › Young, X-ray selected: 3
- › MSP, radio selected: 40
- › MSP, g-ray selected: 0
- › Black Widows: 8
- › Found in radio searches of LAT sources: 21
- › EGRET/COMPTEL pulsars: 7



Pulsars

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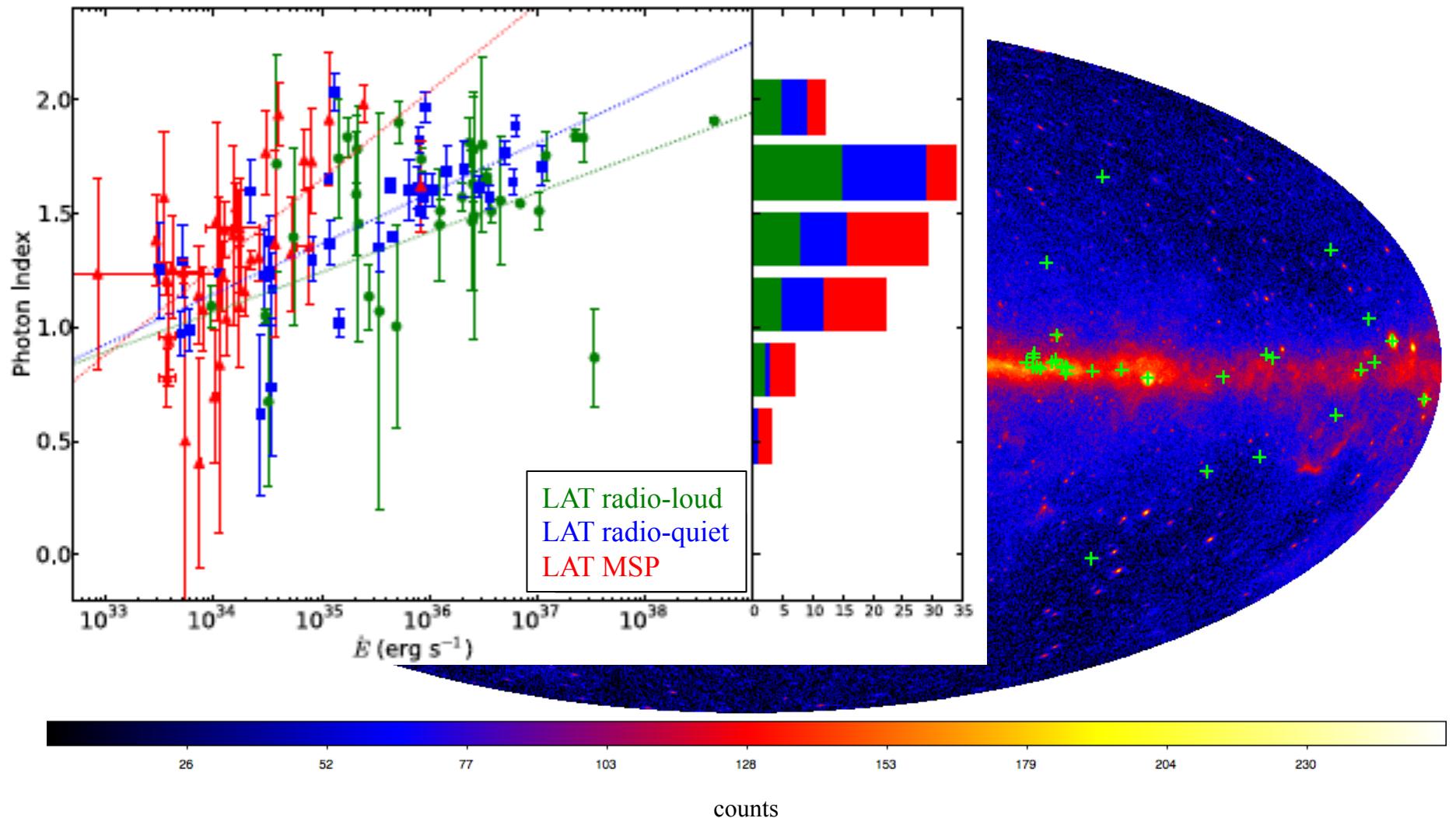
- › Symbol size: scales as $F(100\text{MeV})$
- › MSP: Period $\times \sim 30$
- › Symbol color: red → blue: inc. spectral index
- › Other pulsars: Period $\times \sim 12$



Pulsars

2nd Fermi-LAT Pulsar Catalog (2PC):

- › Majority of PSRs follow cutoff power law with $1 \leq E_{\text{cut}} \leq 7 \text{ GeV}$
- › Index related to spindown power: $\Gamma = A \log(\dot{E}) + B$

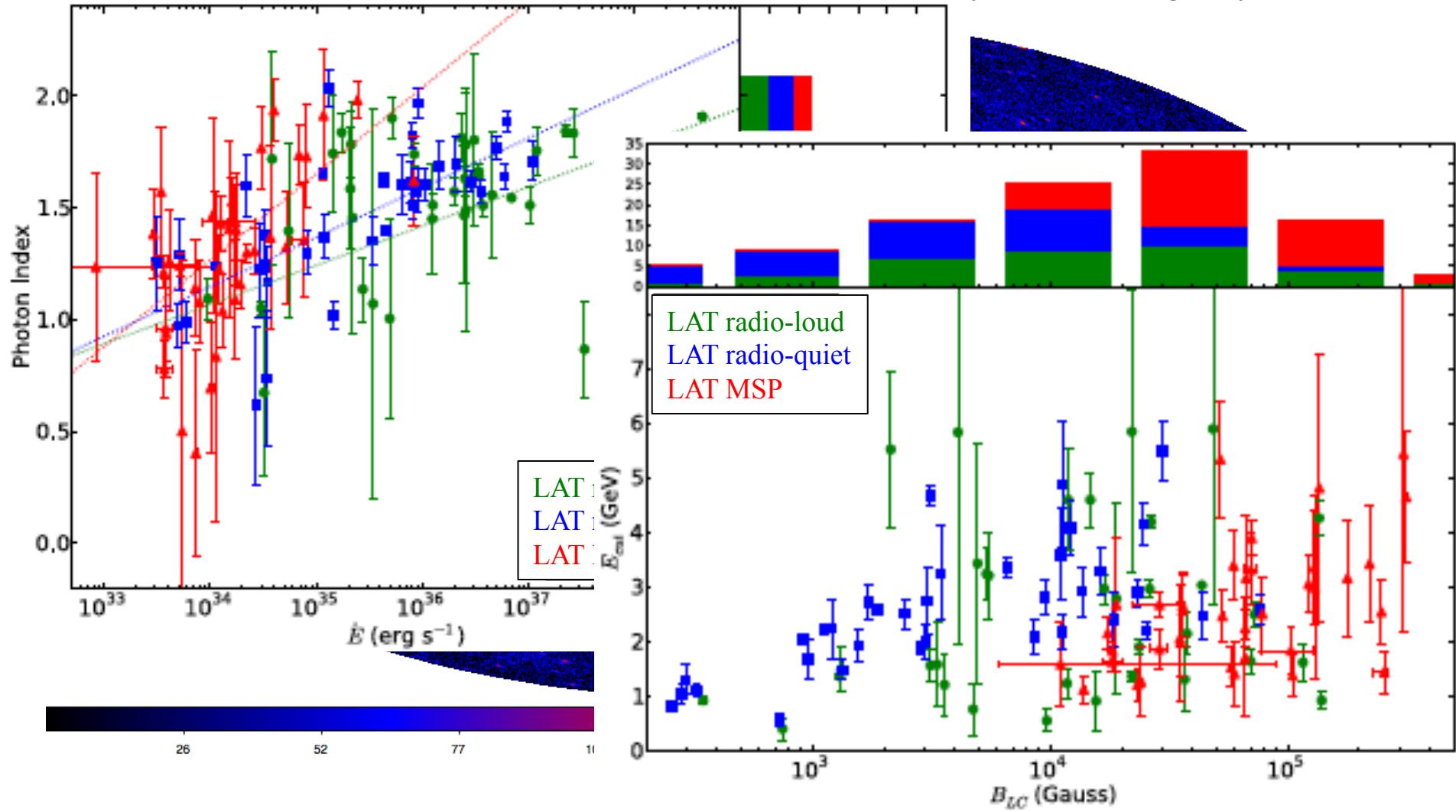


Pulsars

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› Cutoff energy related to light cylinder B-field

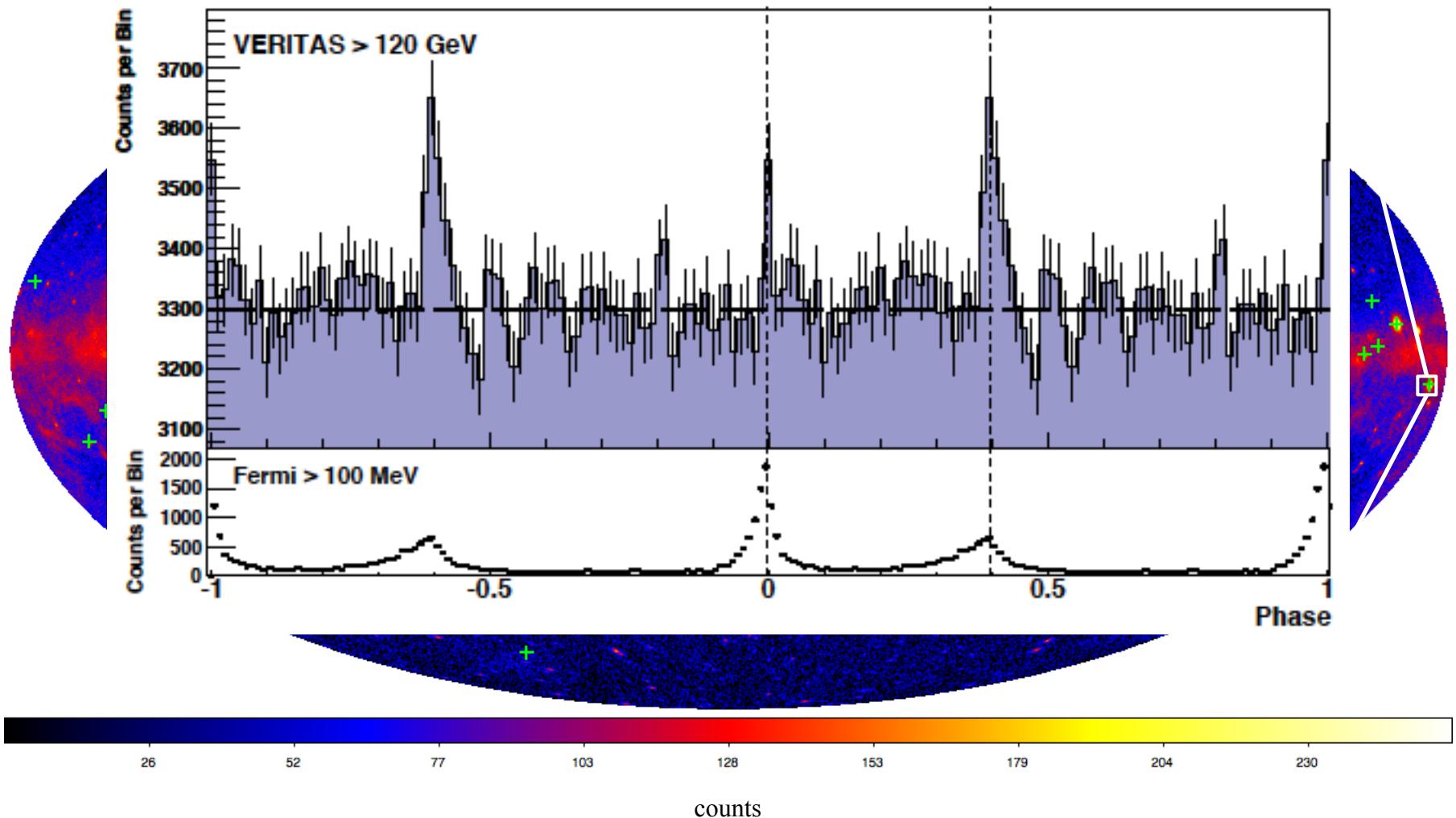


Pulsars

The Canonical Crab:

- First pulsar detected > 100 GeV

Otte+11

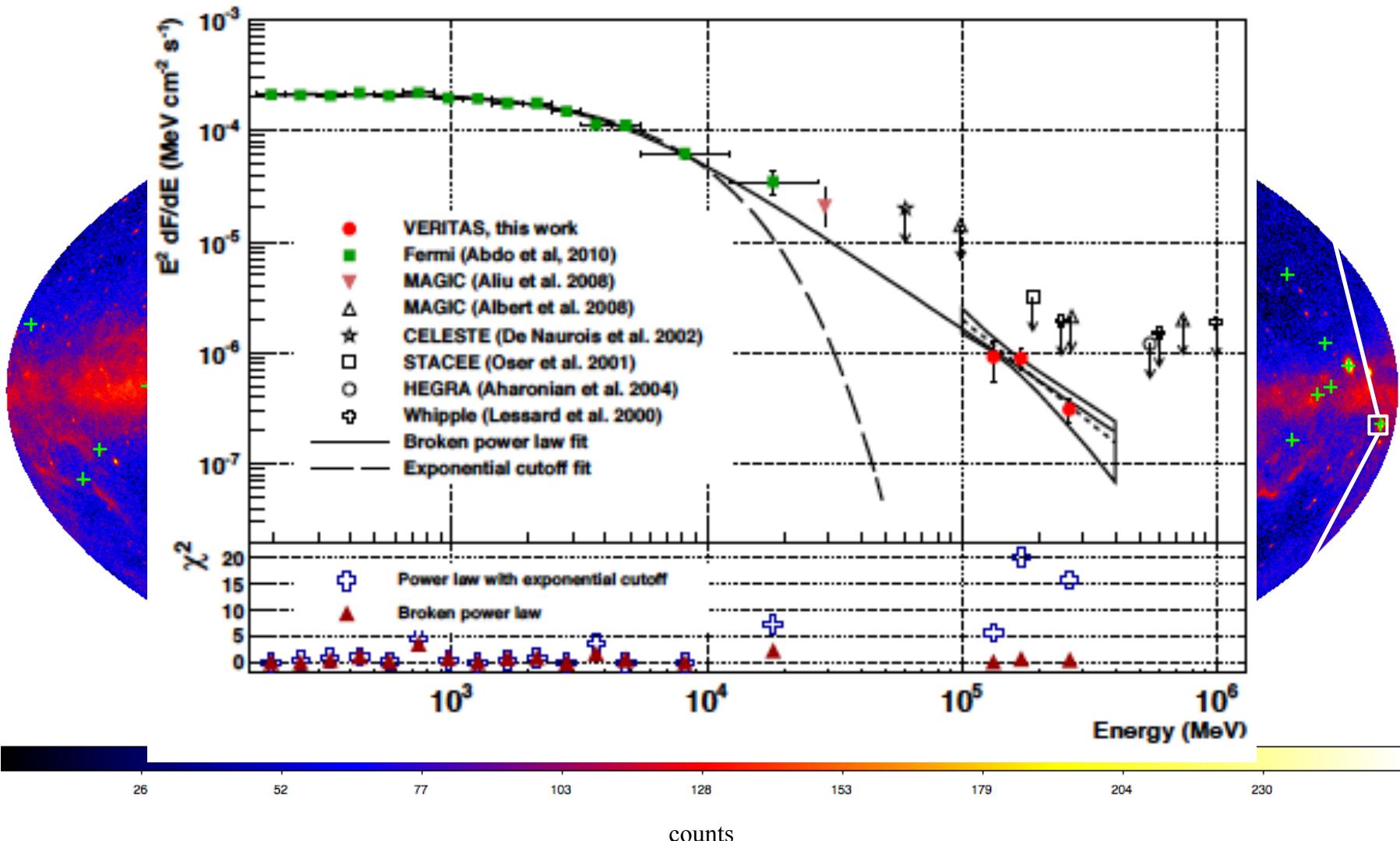


Pulsars

The Canonical Crab:

Otte+11

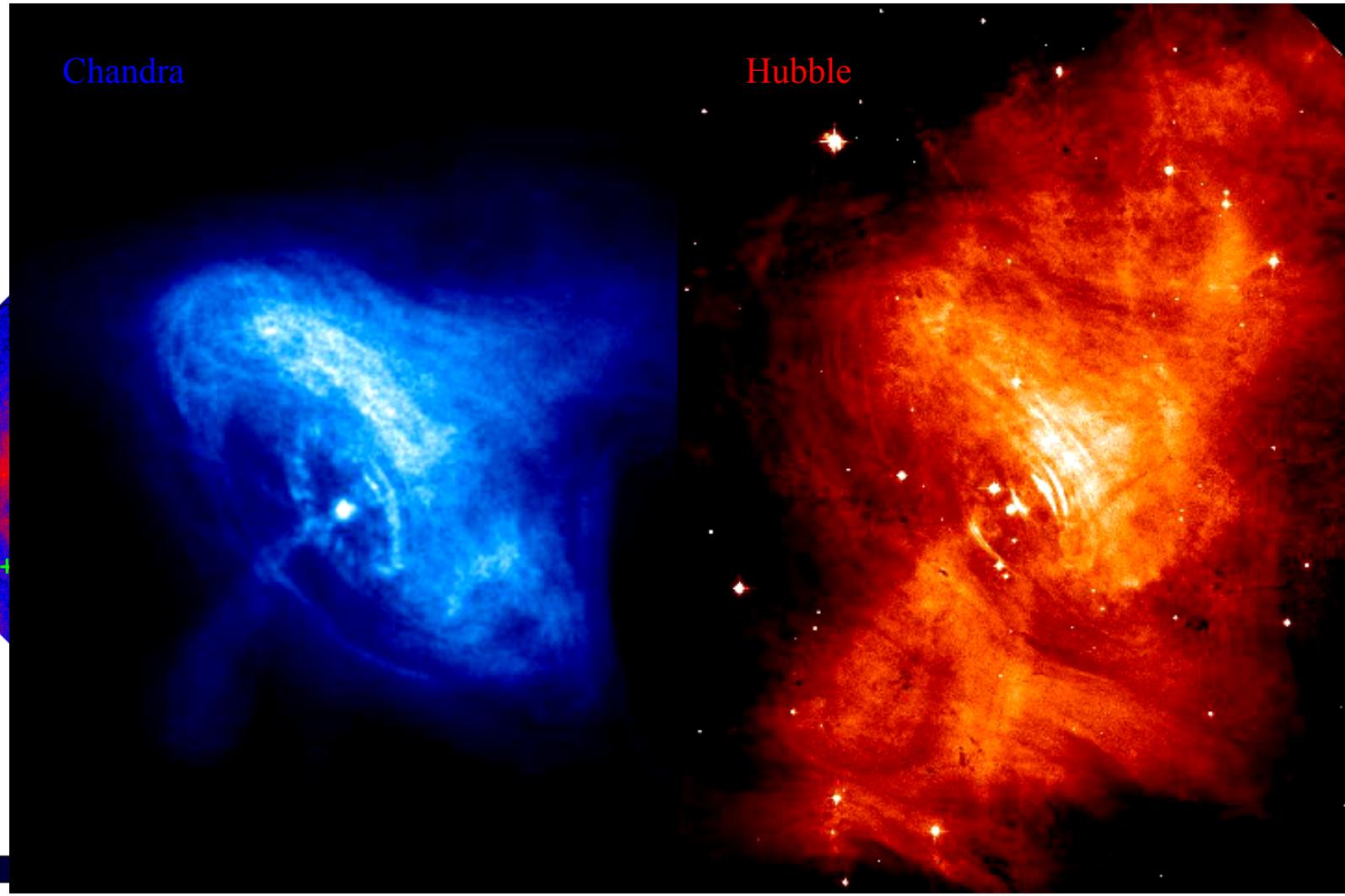
- › First pulsar detected > 100 GeV
- › GeV+TeV spectrum preferentially follows a broken power law:



Pulsars

The Canonical Crab, pulsing within its nebula:

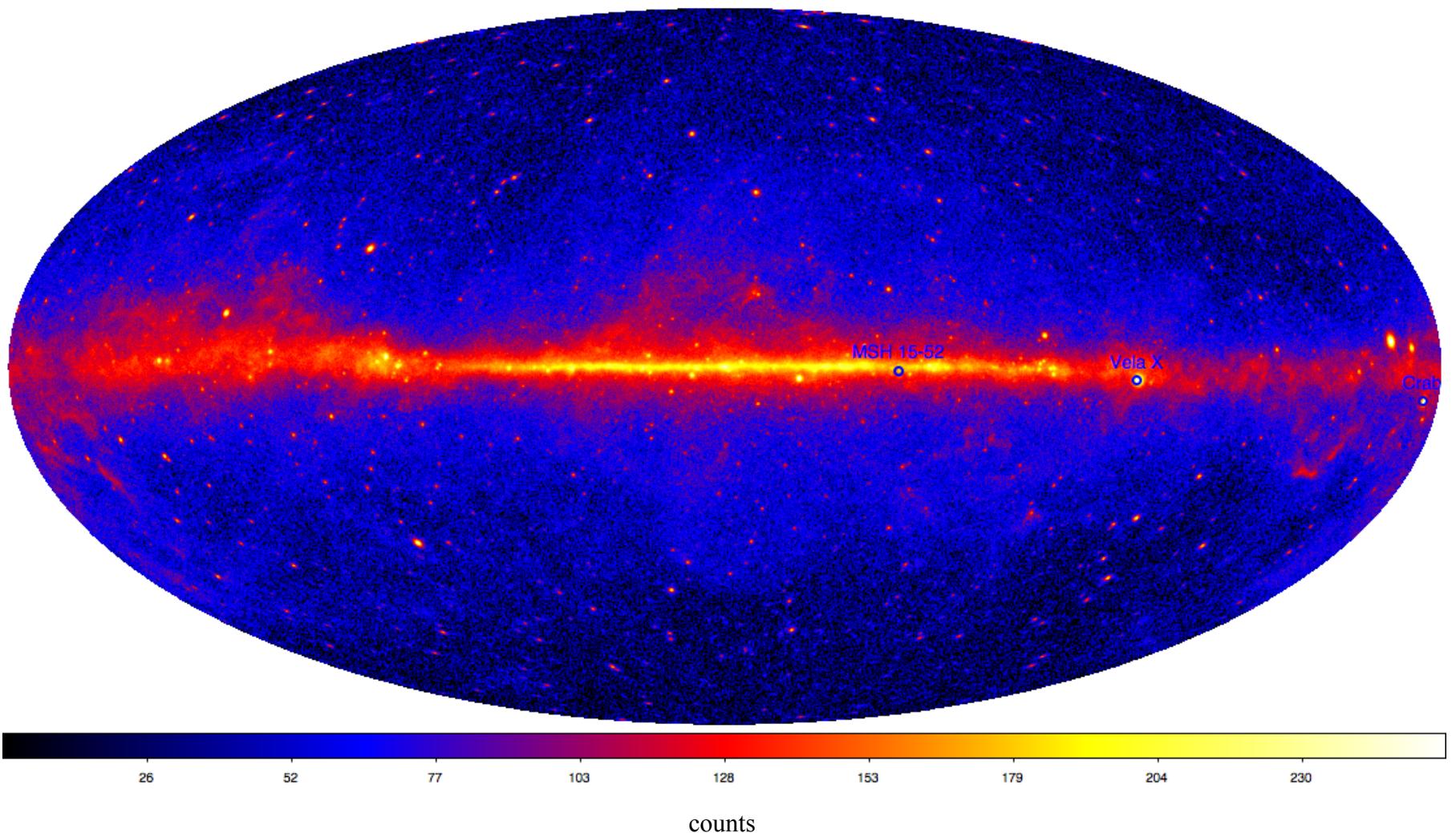
- › 7 images from Nov 2000 – Apr 2001



Pulsar Wind Nebulae (PWNe)

Fermi PWNe:

- 3 initial detections:

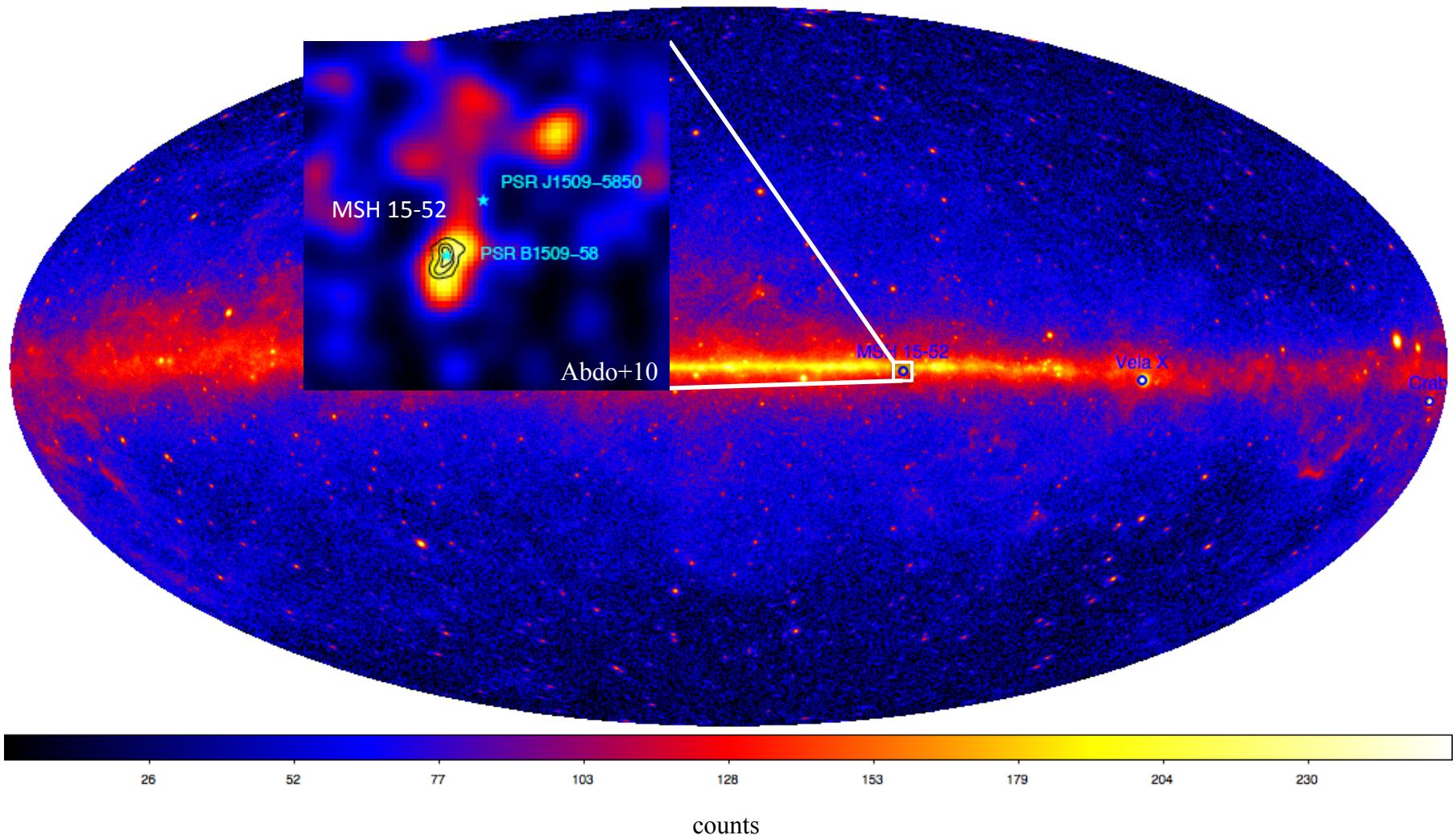


PWNe

Fermi PWNe:

› 3 initial detections:

› MSH 15-52: extended ($r \approx 0.25^\circ$), GeV+TeV suggests IC emission

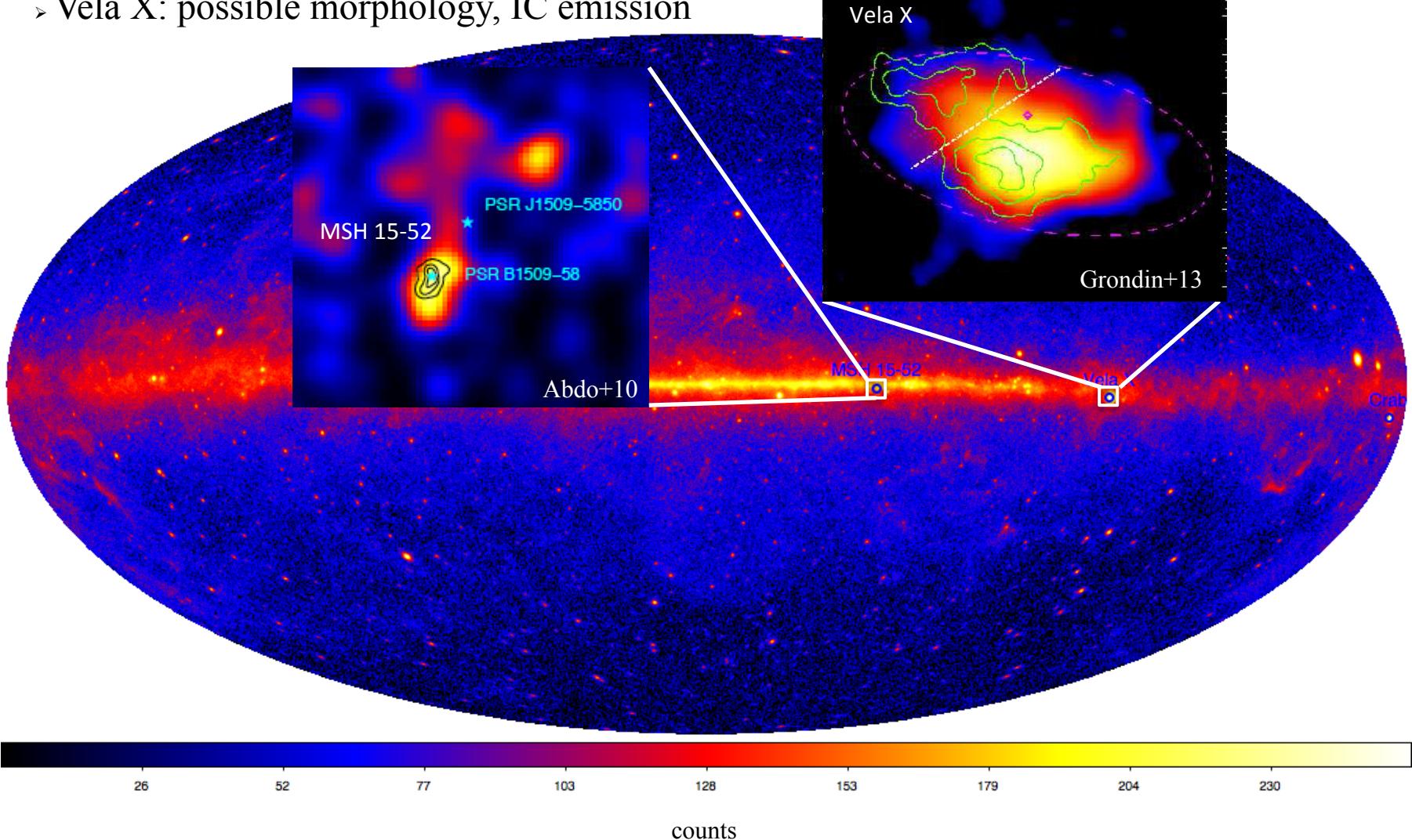


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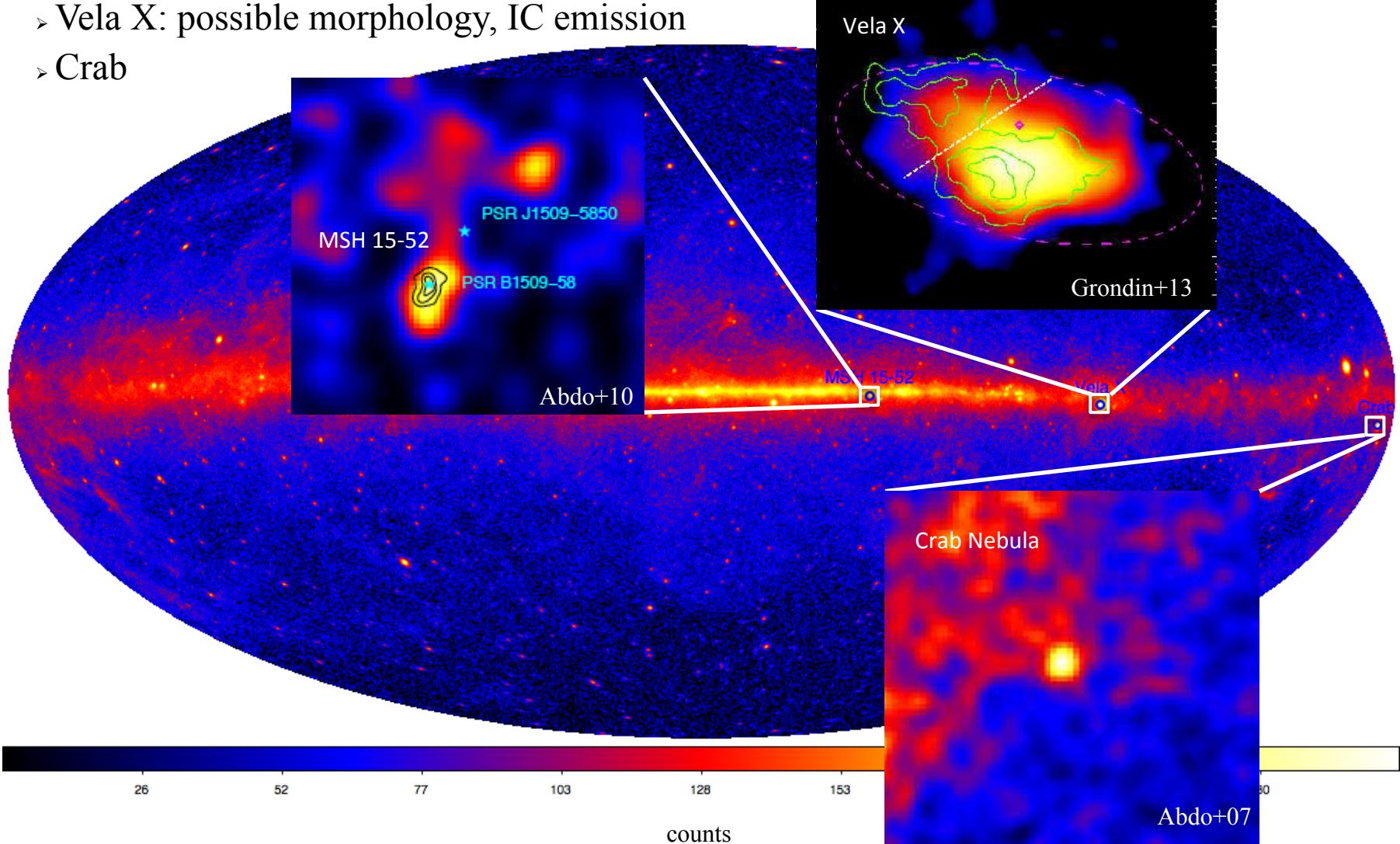


PWNe

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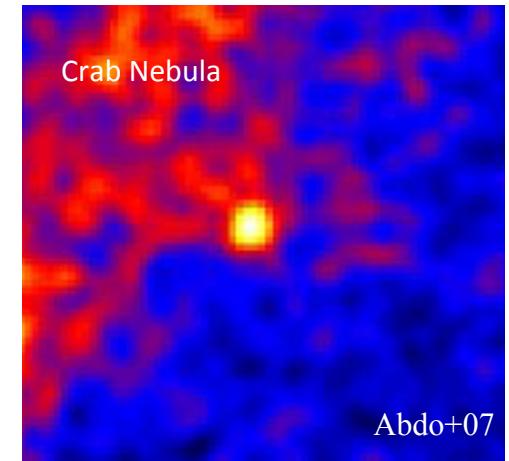
- › MSH 15-52: extended ($r \approx 0.25^\circ$), GeV+TeV suggests IC emission
- › Vela X: possible morphology, IC emission
- › Crab



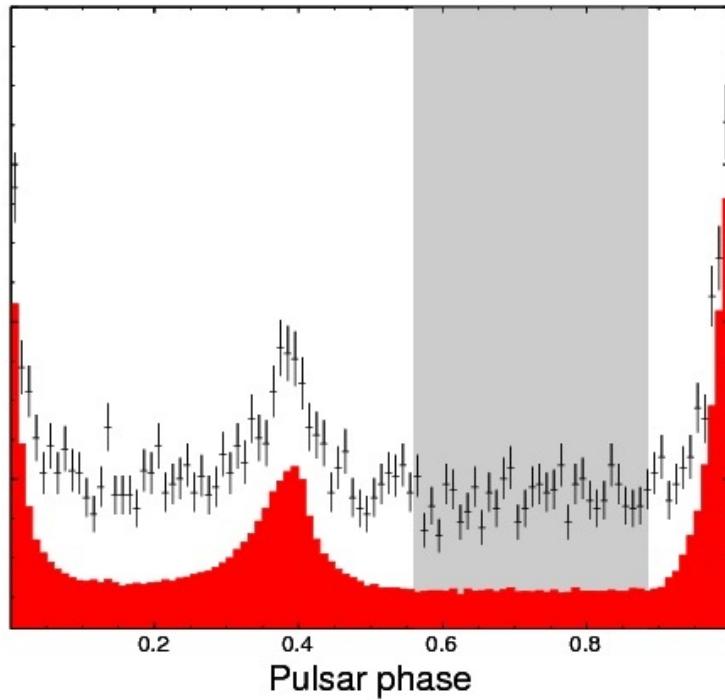
The Crab

Separate nebular from pulsar emission:

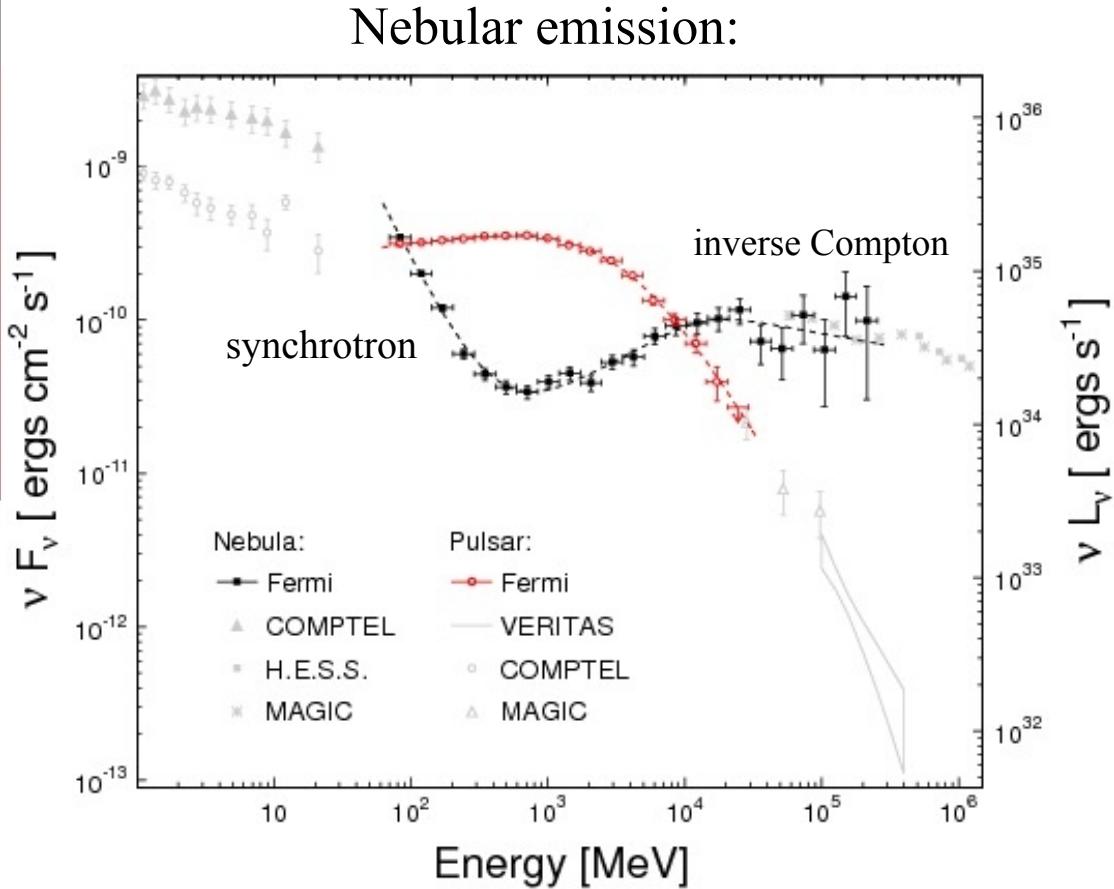
- › High energy or
- › Off pulse



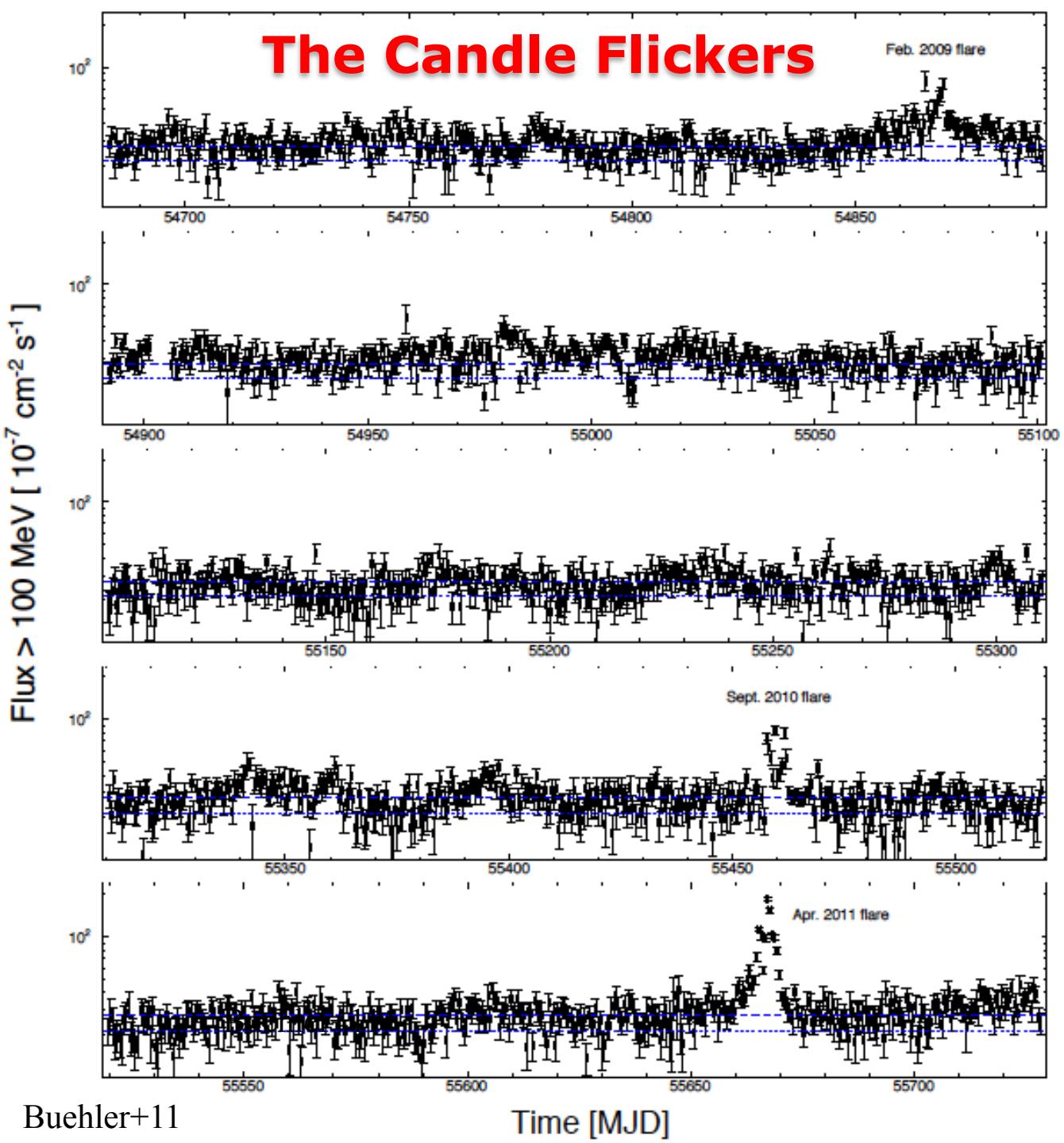
Counts in arbitrary units



Buehler+11



The Candle Flickers



Integral flux for 35mos:

› 12hr bins

— avg sync+pulsar

... avg IC+pulsar

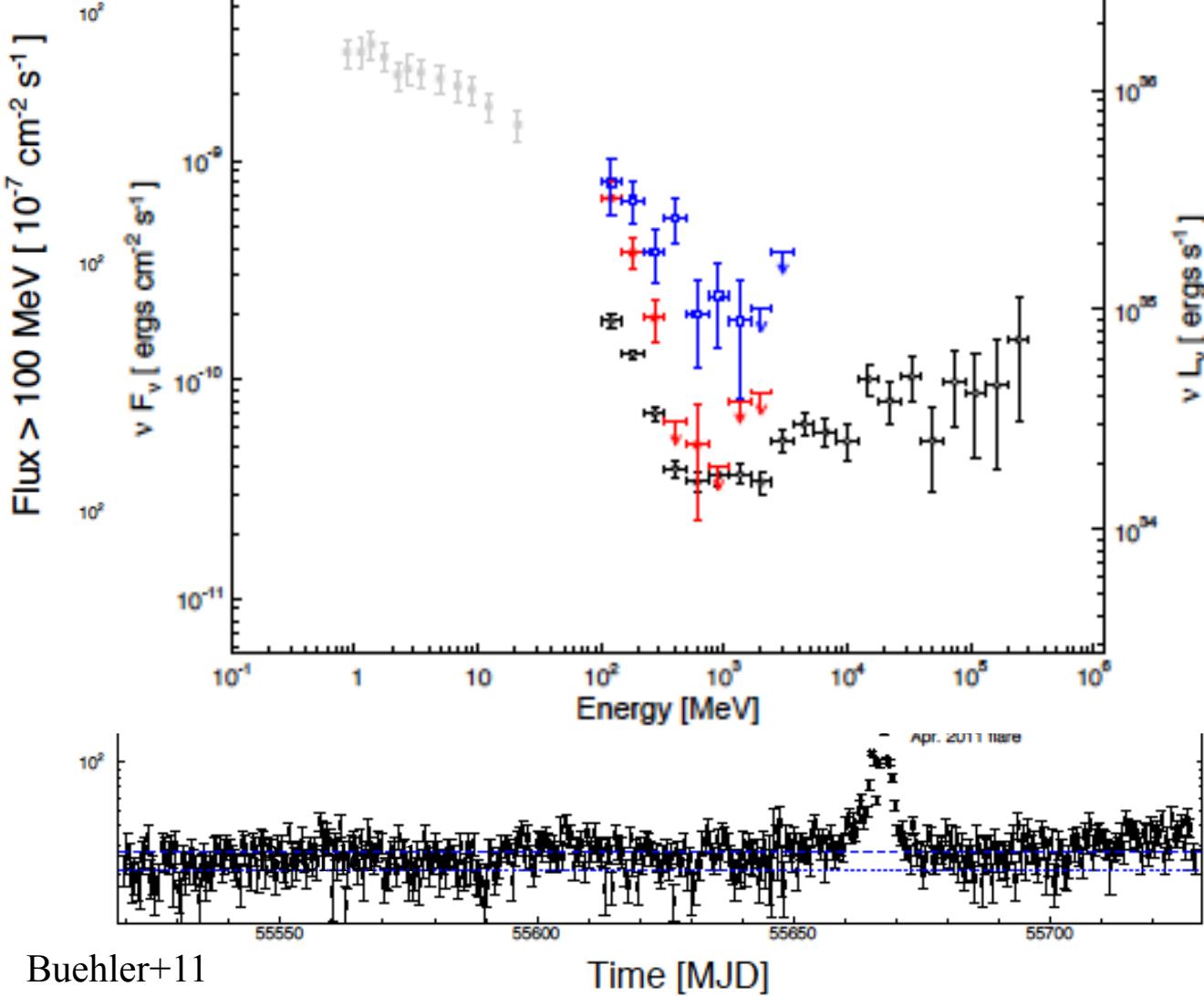
and Flares!

- › Oct 2007 (AGILE)
- › Feb 2009
- › Sept 2010
- › Apr 2011
- › Mar 2013

5 flares and counting...

The Candle Flickers

Feb. 2009 flare



Integral flux for 35mos:

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and Flares!

› Oct 2007 (AGILE)

› Feb 2009

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› Mar 2013

5 flares and counting...

Rapidly varying
synchrotron component.

Abdo+11

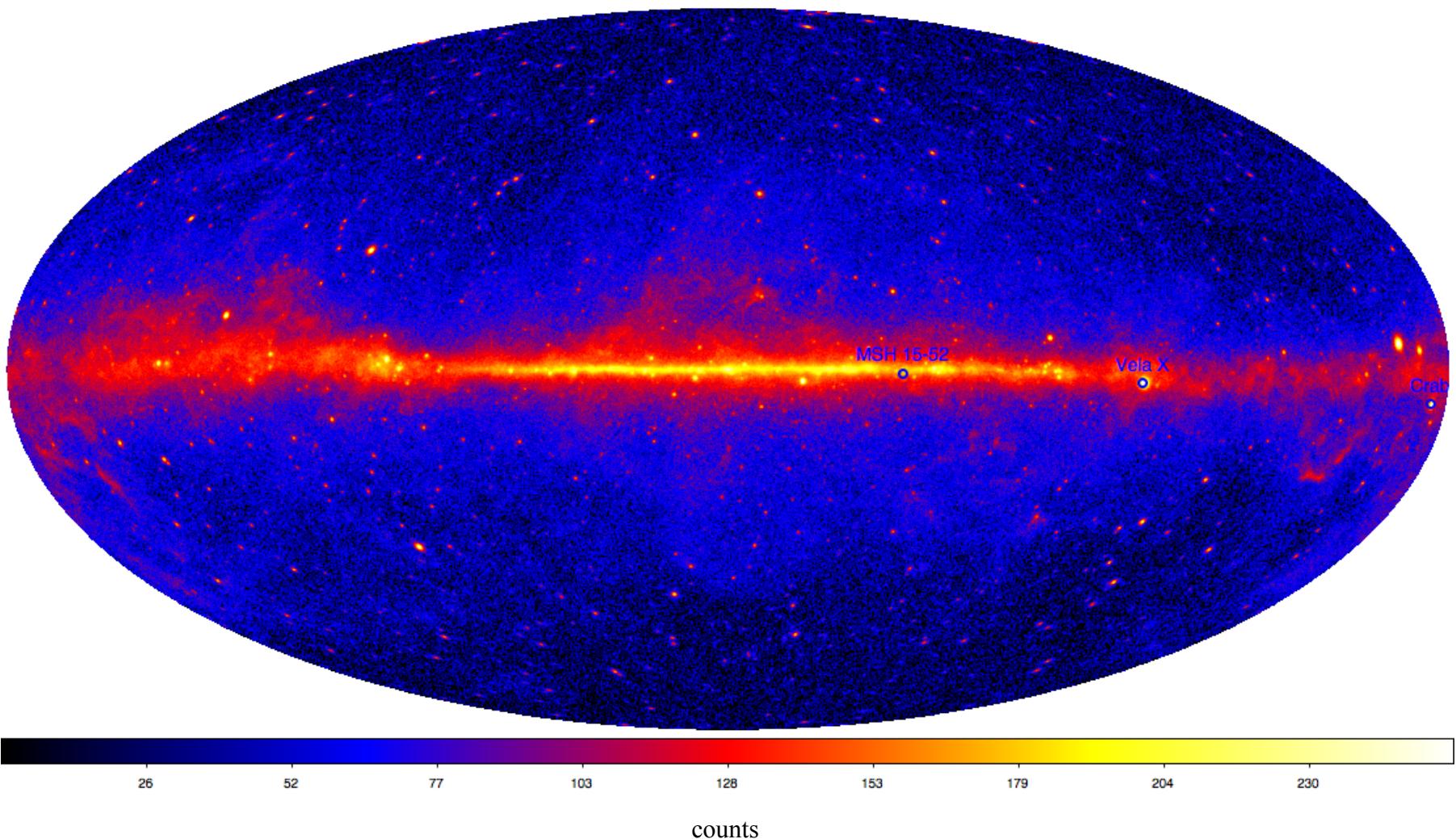
Magnetic reconnection?

PWNe

Acero+13

Fermi TeV PWNe Search:

- › 45mo data, $E > 10$ GeV
- › 58 TeV PWNe and unidentified objects:



PWNe

Acero+13

Fermi TeV PWNe Search:

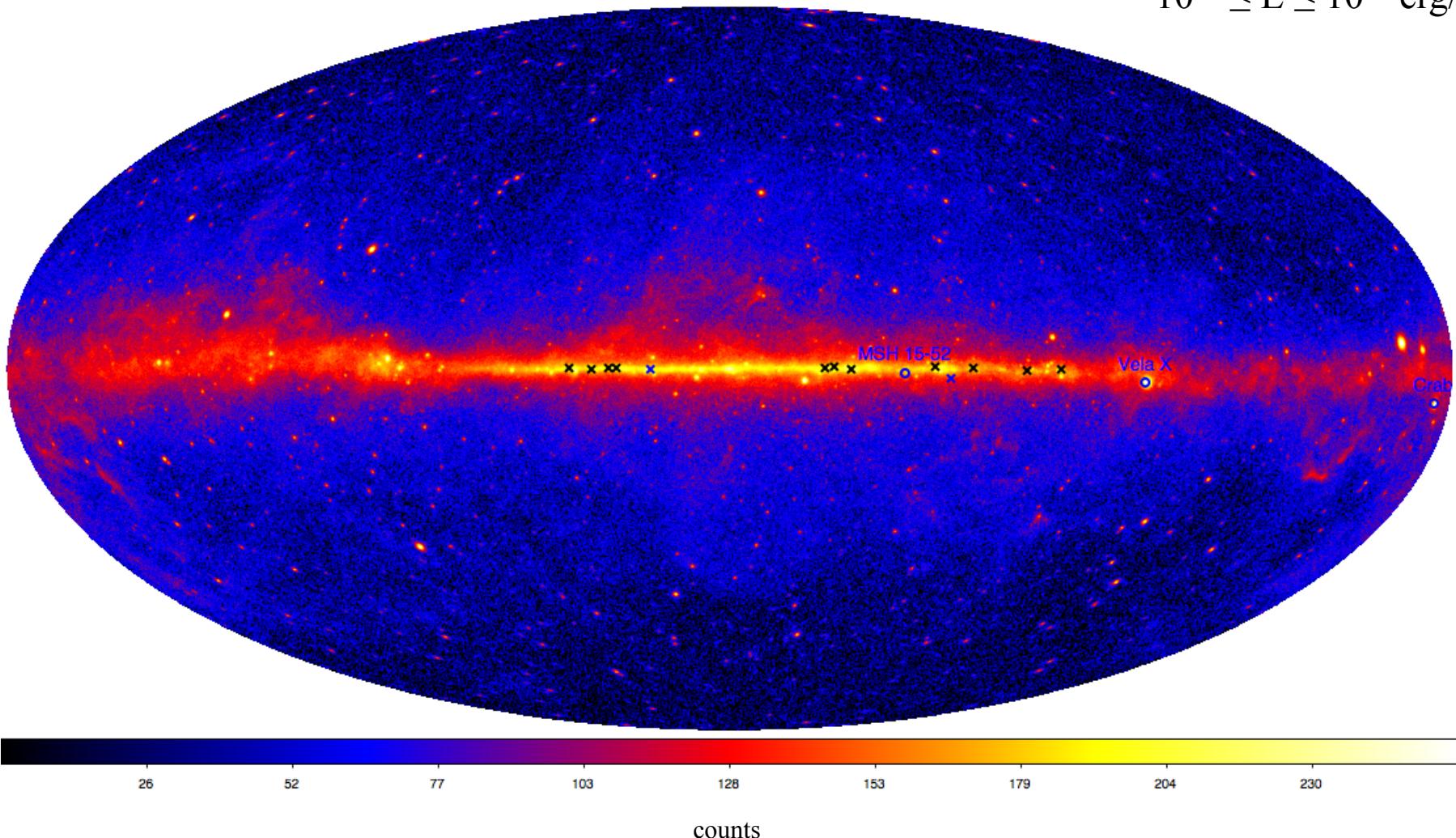
- › 45mo data, $E > 10$ GeV
- › 58 TeV PWNe and unidentified objects:

› 30 detections!

› 5 PWNe

› 11 PWNe Candidates

› Associated w young, powerful pulsars w $10^{36} \leq \dot{E} \leq 10^{39}$ erg/s



PWNe

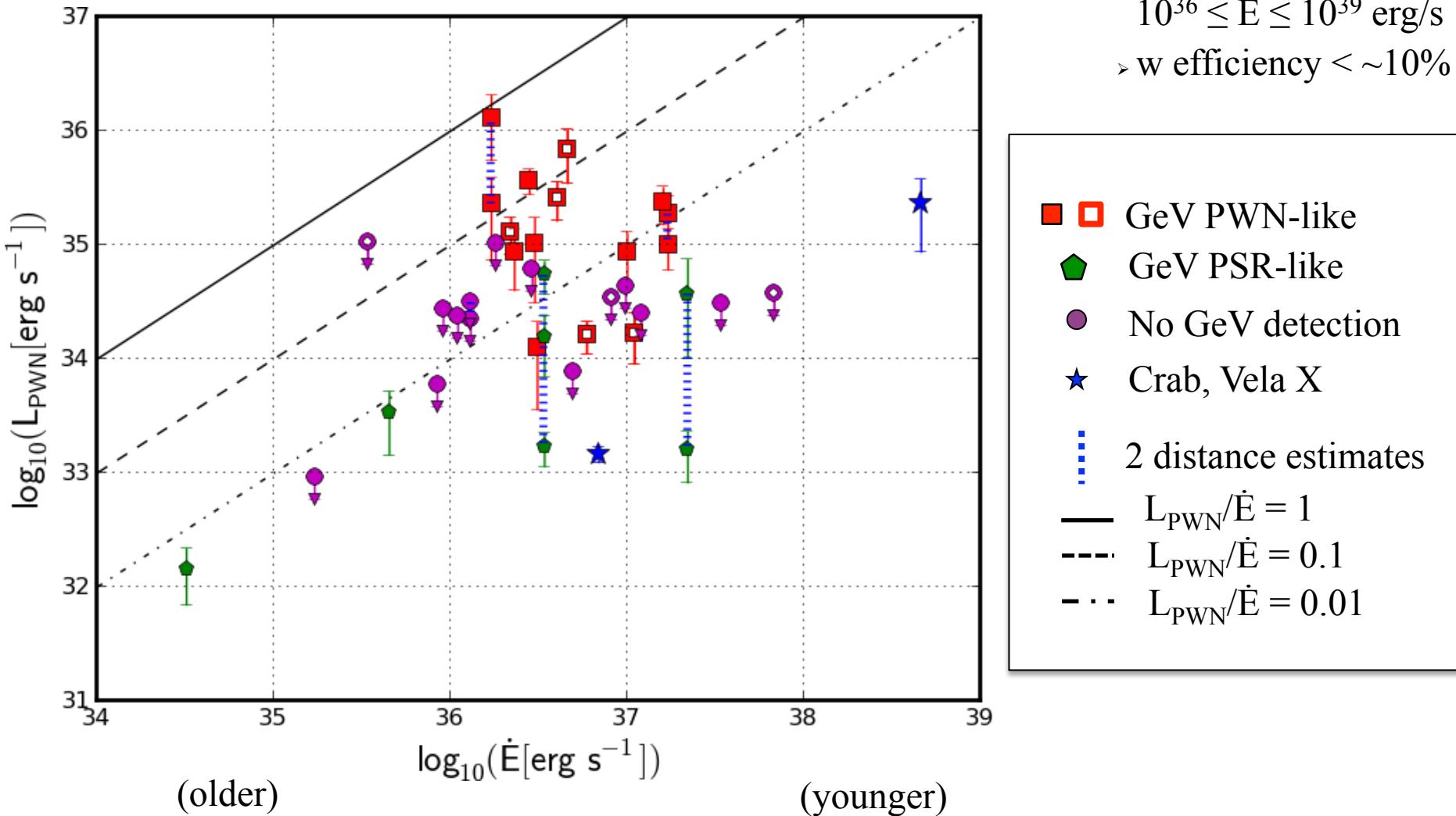
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Fermi TeV PWNe Search:

- › 45mo data, $E > 10$ GeV
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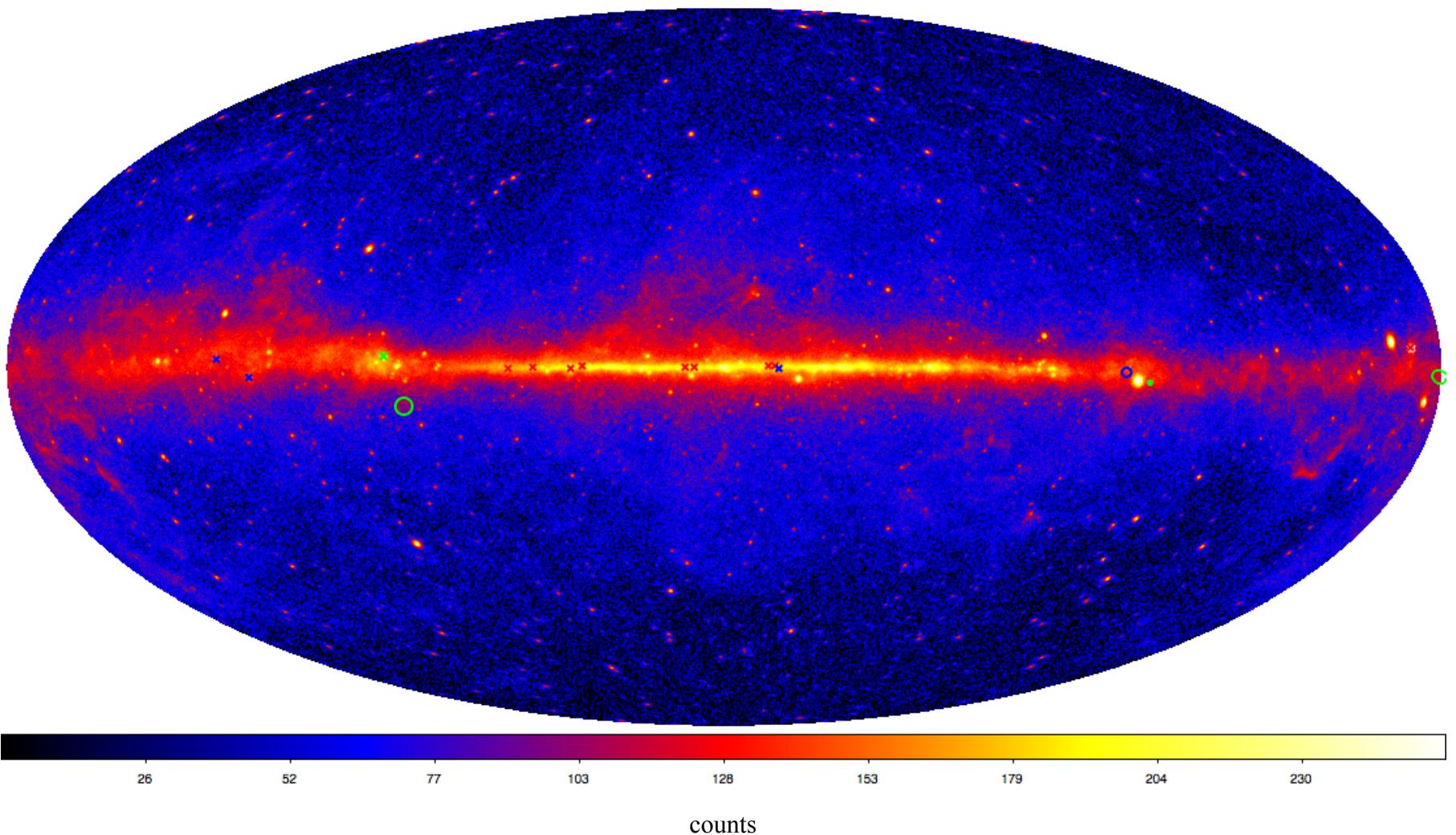
- Associated w young, powerful pulsars w $10^{36} \leq \dot{E} \leq 10^{39}$ erg/s
 - w efficiency < $\sim 10\%$



Fermi-Detected SNRs

13 identified SNRs, including

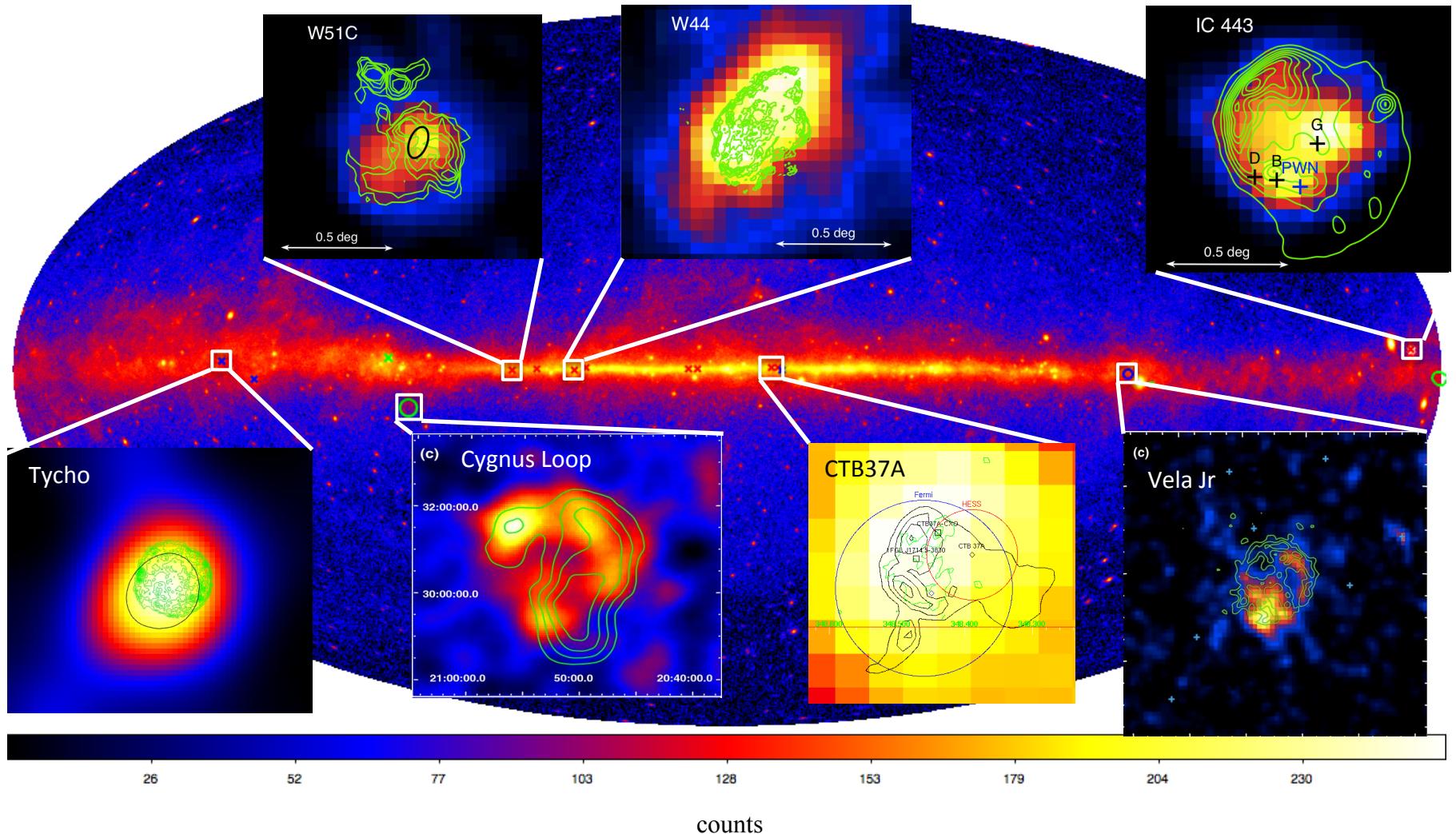
- 9 interacting
- 4 young SNRs



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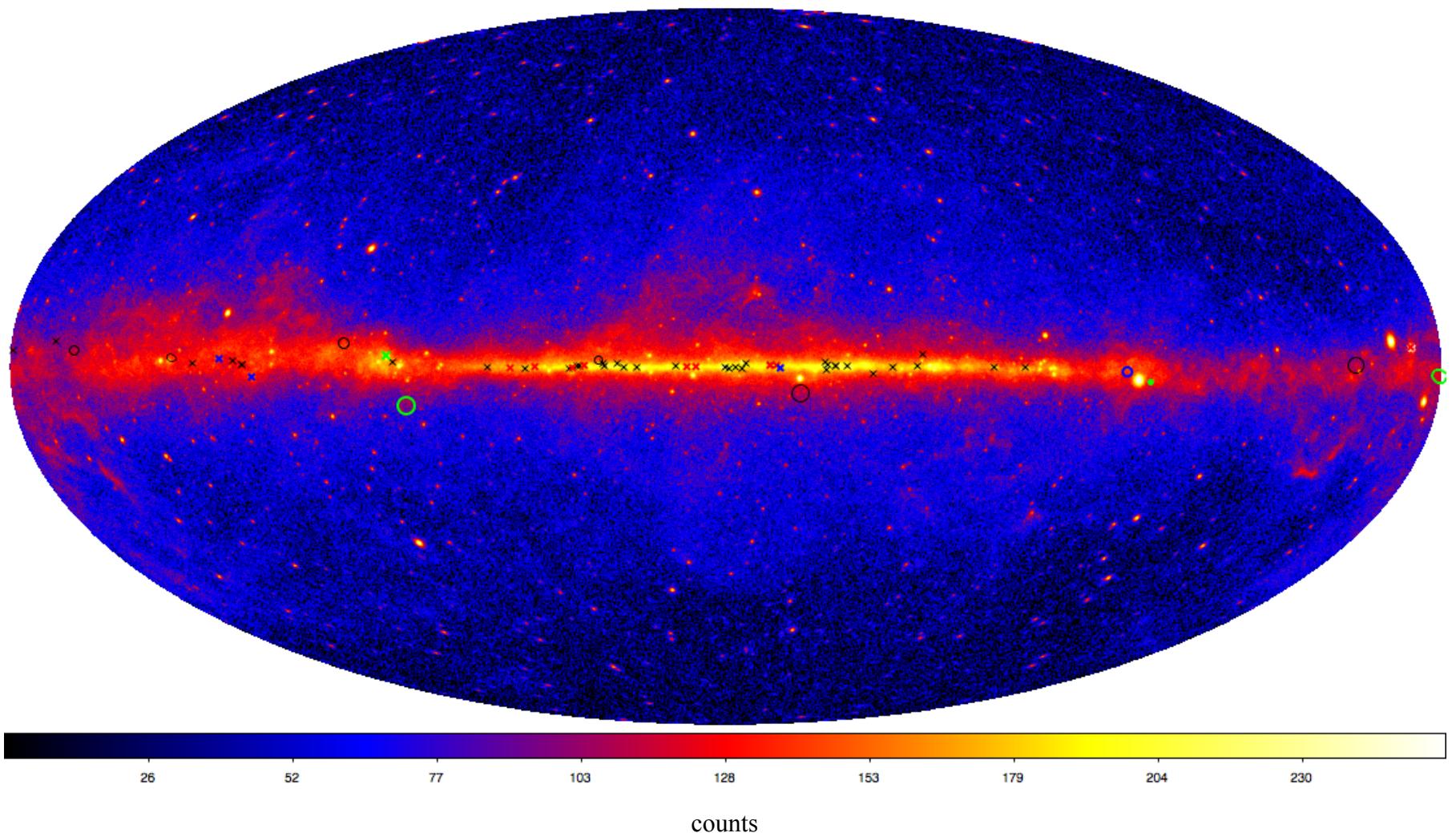


Fermi-Detected SNRs

13 identified SNRs, including

- 9 interacting
- 4 young SNRs

+ 43 2FGL candidates,
excluding identified PSRs, PWN, AGN



SNR Catalog:

To better understand SNRs in a statistically significant manner within a MW context.

- › Characterize GeV emission in regions containing SNRs
- › Examine multi-wavelength (MW) correlation, including spectrum
+ morphology for radio, X-ray, and TeV and CO, maser, IR, ...
- › Determine statistically significant SNR classification(s) and
perform spectral modeling

With particular efforts from:

- F. Acero, J. W. Hewitt (NASA/Goddard)
- F. de Palma, F. Giordano (INFN/Bari)

CTB 37a: an Example

Detection: Fermi-LAT data shows non-variable emission from a region coincident with the MW SNR.

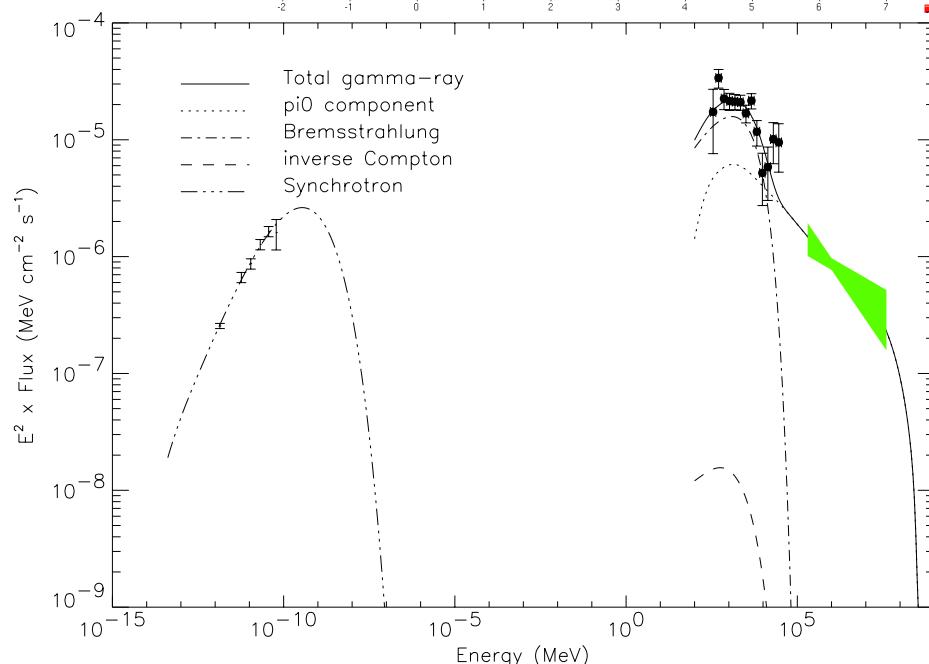
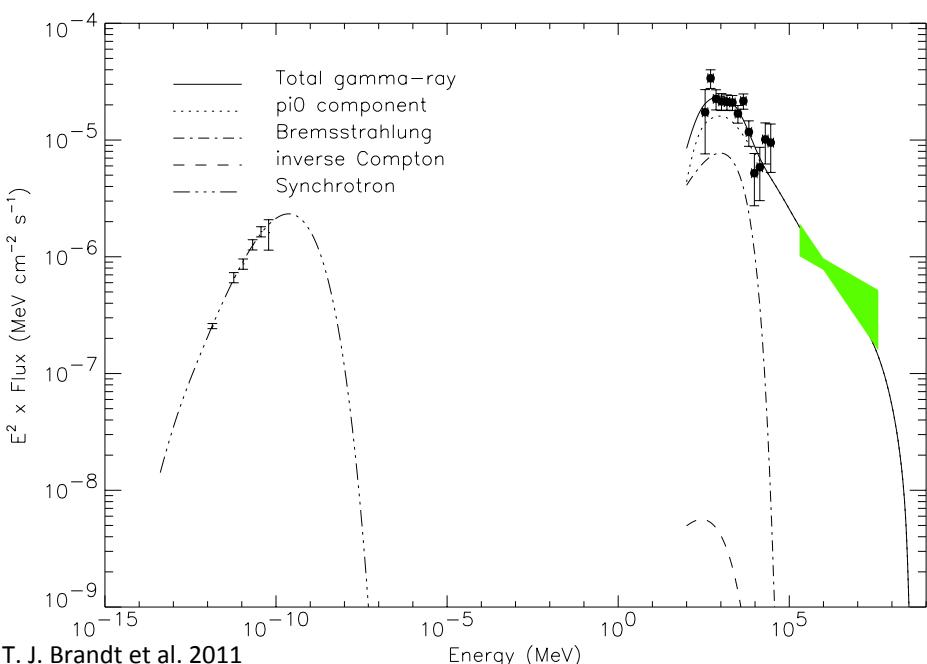
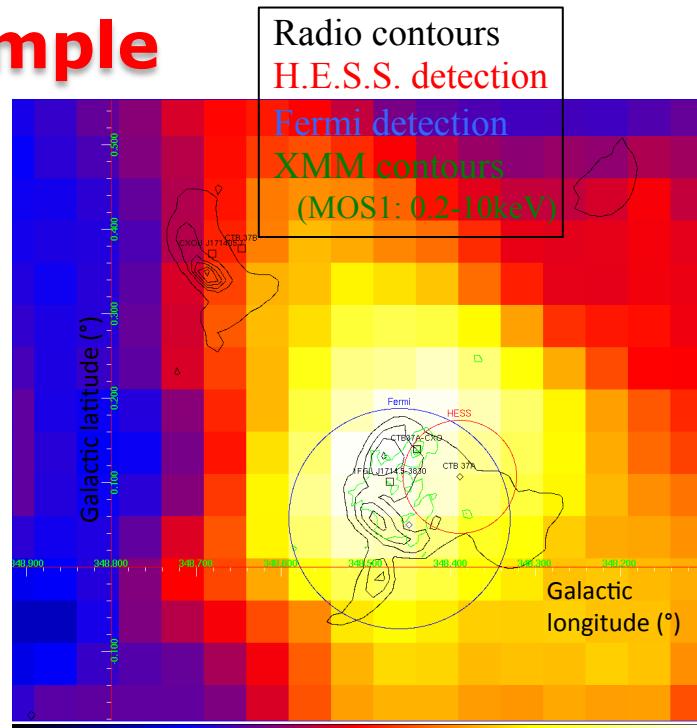
Spectral study: MW model fitting shows emission is best-fit with π^0 -decay + bremsstrahlung.

Energetics: ~5% of the energy goes into (hadronic) CRs.

Particle populations' and environment constraints:

Particle power laws: flux, index, (lepton) cutoff E

B-field: first lower limit, constraining UL



Data Set:

- › 3 years of P7SOURCE_V6 LAT data
- › E: 1-100 GeV
- › Region Of Interest: 10° around each SNR

Charaterize GeV Emission: Analysis Procedure

Green's Catalog: (2009)

- › 278 SNRs

Starting Model:

- › 2FGL

Overlapping sources?

- › = None: Add a new extended source
- › = 1 source (not PSR): Replace w extended source
- › > 1 source: Replace (non-PSR) source closest to radio centroid w extended source. Delete all other (non-PSR) sources.

Localize source, fit extension

- › Disk extension seed = radio size
- › Spectral model: power law
- › Normalization of Galactic diffuse and all sources w/in 5° of candidate are free during minimization procedure.

Output:

- › Position, extension, significance
- › Spectral energy distribution
- › Region and residual maps
- › Diagnostics

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Effect of starting model

Characterizing systematic error from the interstellar emission model.

Localize source, fit extension

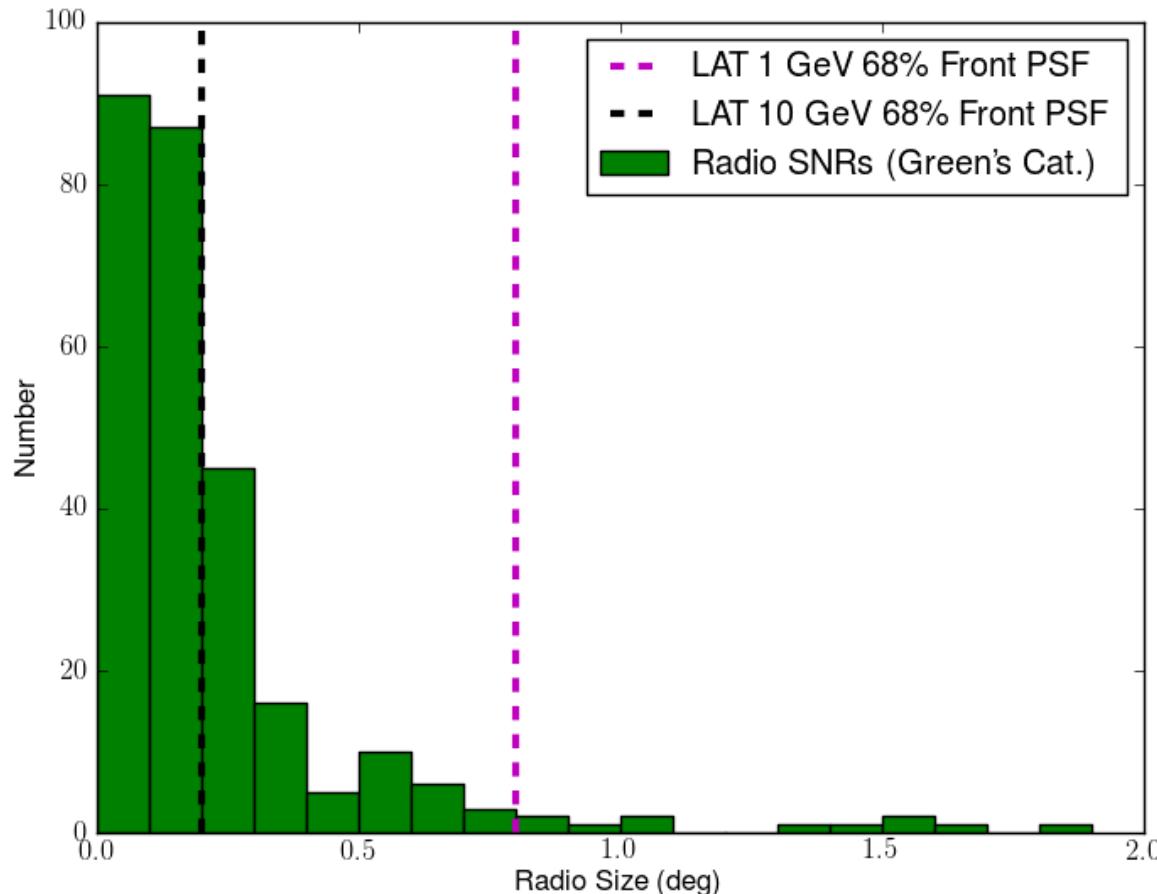
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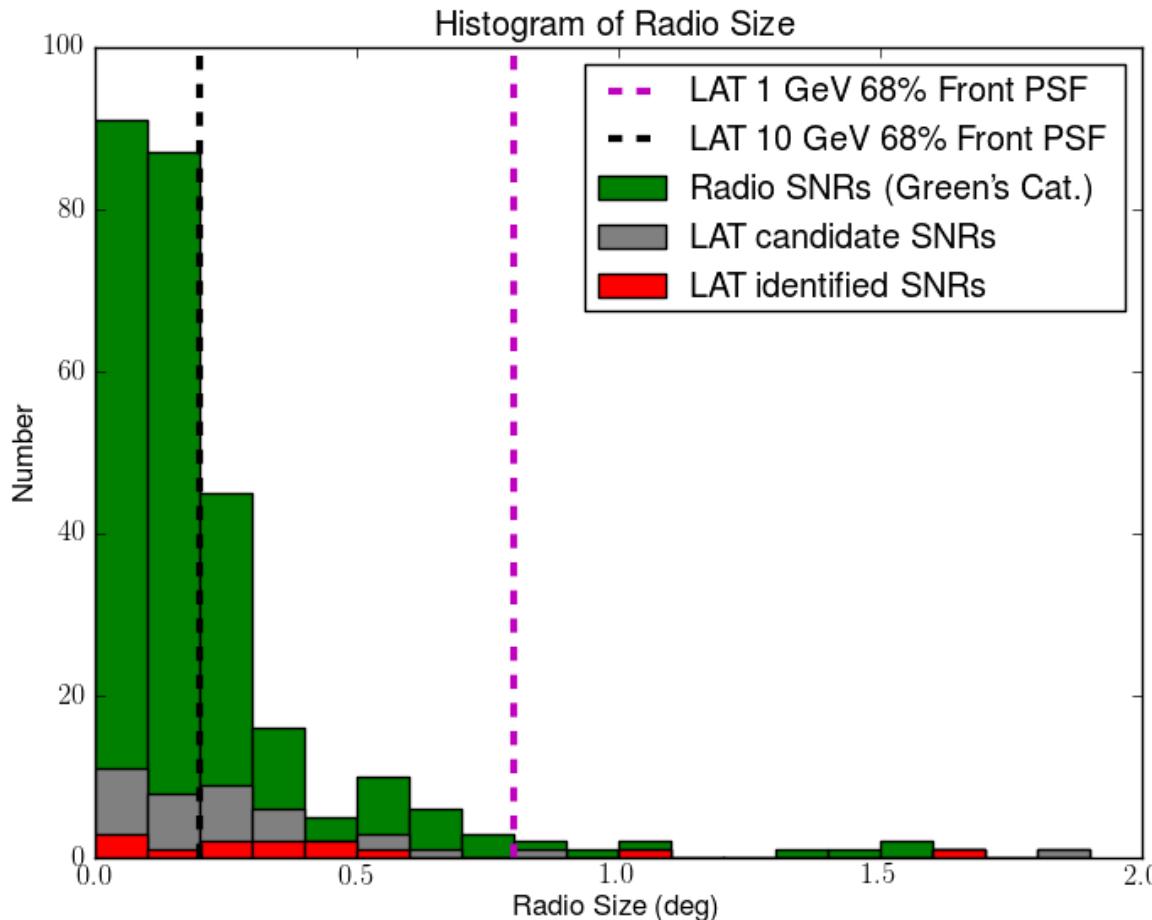
SNR Catalog:

- › Fermi-LAT has the ability to spatially resolve a large number of the 278 known SNRs.



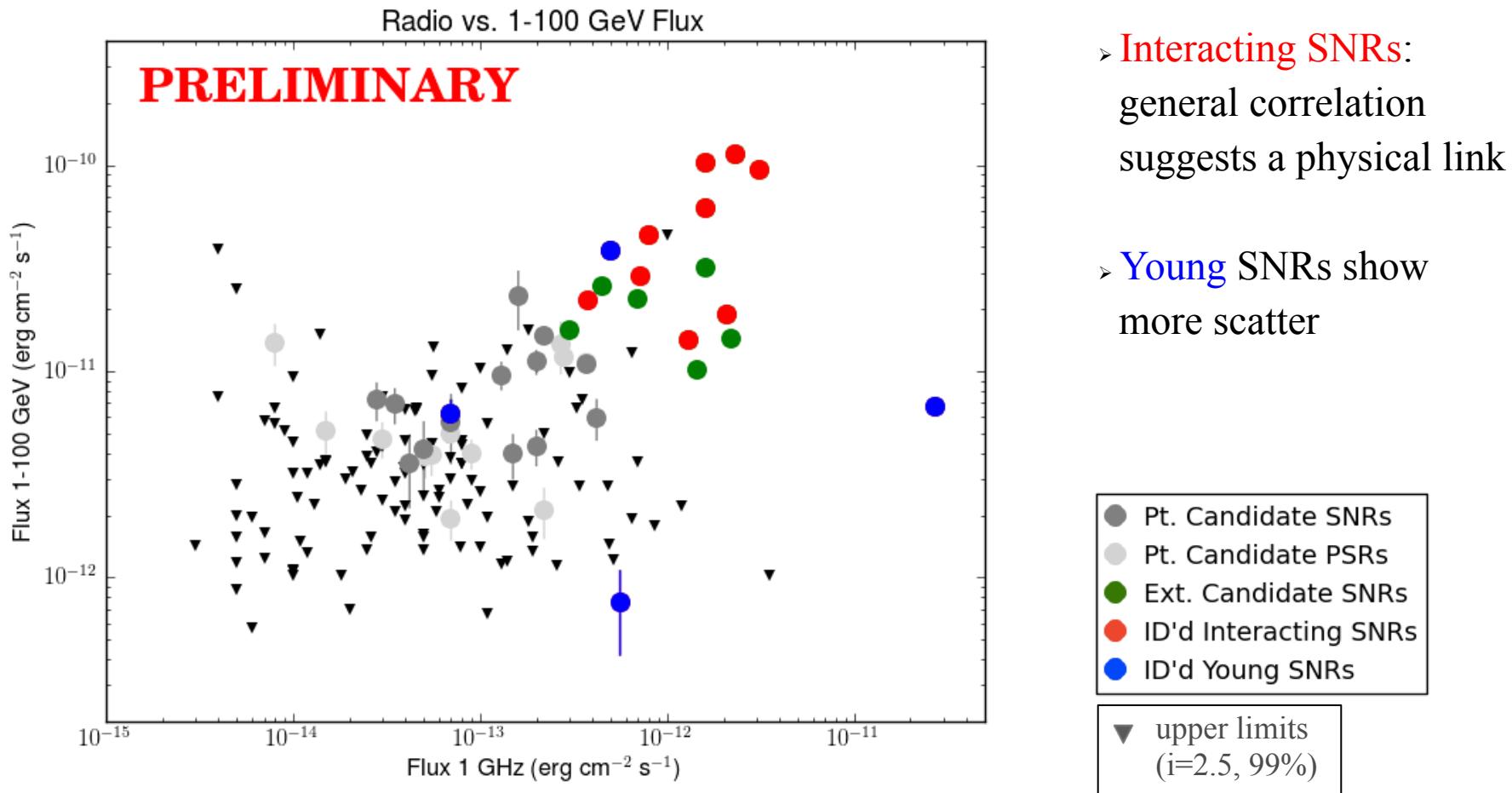
SNR Catalog:

- › Fermi-LAT has the ability to spatially resolve a large number of the 278 known SNRs.
- › Spatial extension measured for 15 SNRs, including **6 new** candidates, permitting clear identification.



Radio-GeV Correlation?

Radio synchrotron emission indicates the presence of relativistic leptons.
LAT-detected SNRs tend to be radio-bright:

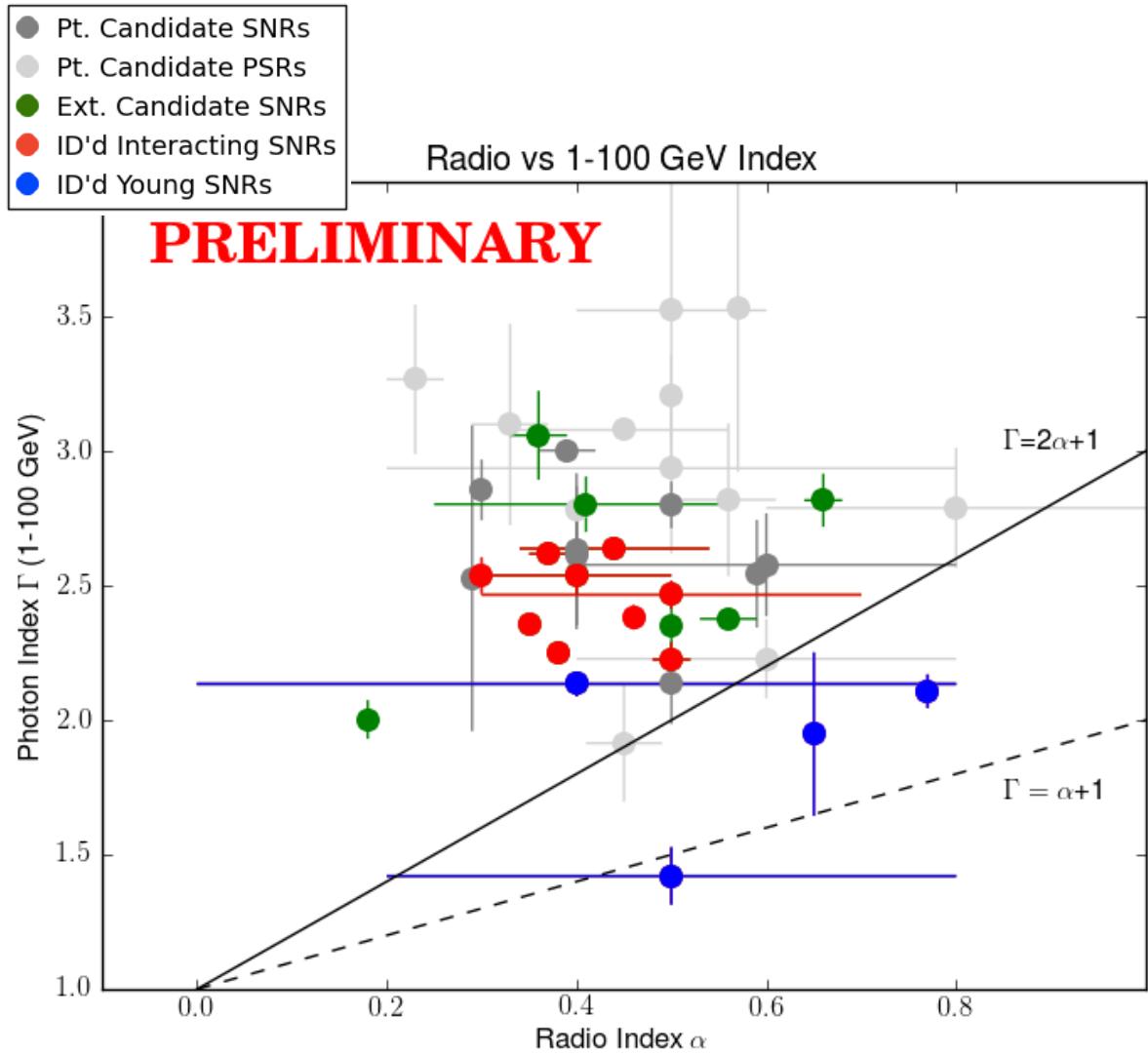


➤ **Interacting SNRs:**
general correlation
suggests a physical link

➤ **Young SNRs show**
more scatter

Radio-GeV Index

If radio and GeV emission arise from the same particle population(s), under simple assumptions, the GeV and radio indices should be correlated:



- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected

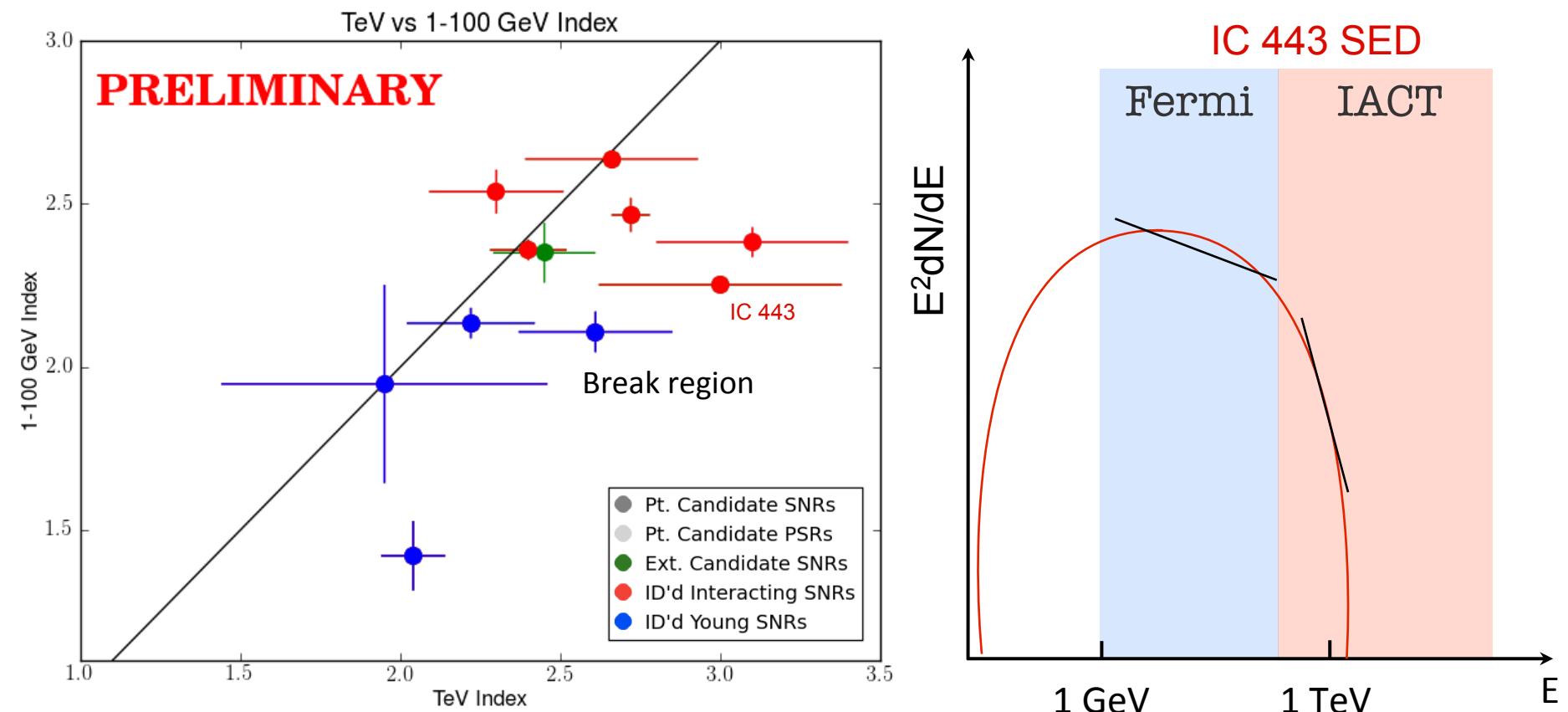
GeV-Radio slope correlation for:

- π^0 decay or $e^{+/-}$ bremsstrahlung
- inverse Compton

Data now challenge model assumptions!

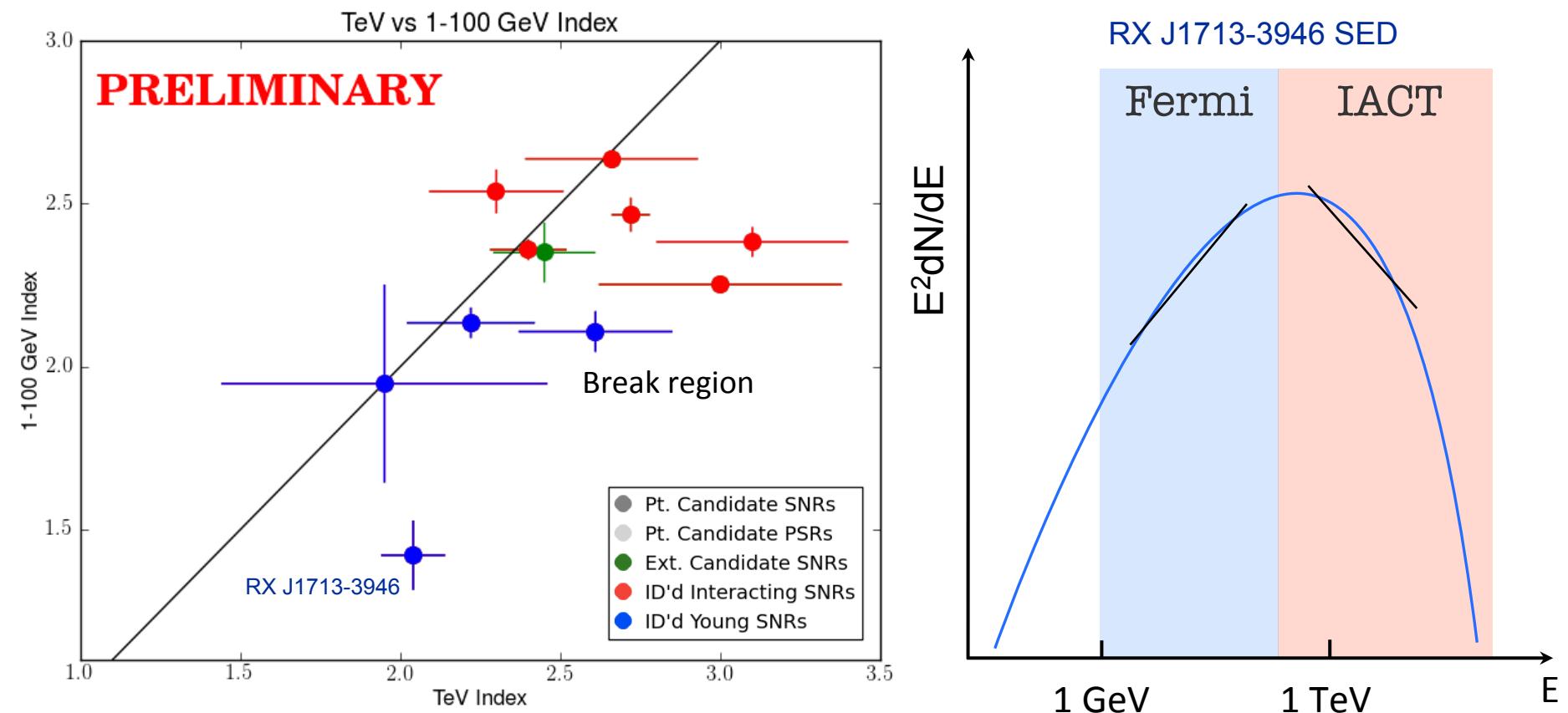
- Underlying particle populations may have different indices.
- Emitting particle populations may not follow a power law; breaks?
- Multiple emission zones?

GeV-TeV Index



- › Indication of break at TeV energies
- › Caveat: TeV sources are not uniformly surveyed.

GeV-TeV Index



- › Indication of break between GeV and TeV
- › Caveat: TeV sources are not uniformly surveyed.

Environment?

Interacting SNRs tend to be more luminous than young SNRs.

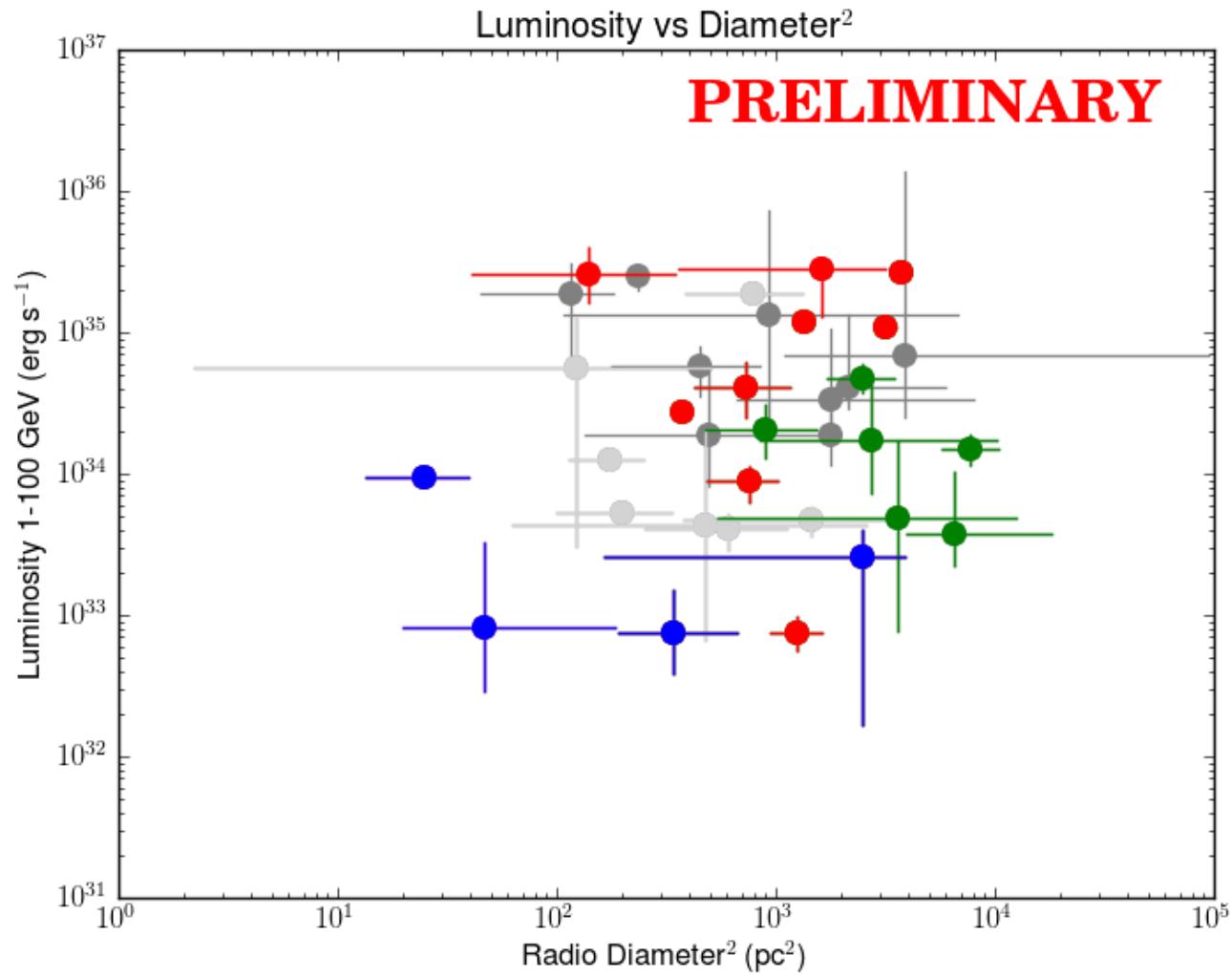
Young SNRs:

- › Low $L_\gamma \Rightarrow$ evolving into low density medium?

Interacting SNRs:

- › Higher $L_\gamma \Rightarrow$ encountering higher densities?

- Ext. Candidate SNRs
- Pt. Candidate PSRs
- Pt. Candidate SNRs
- ID'd Interacting SNRs
- ID'd Young SNRs



... or Evolution?

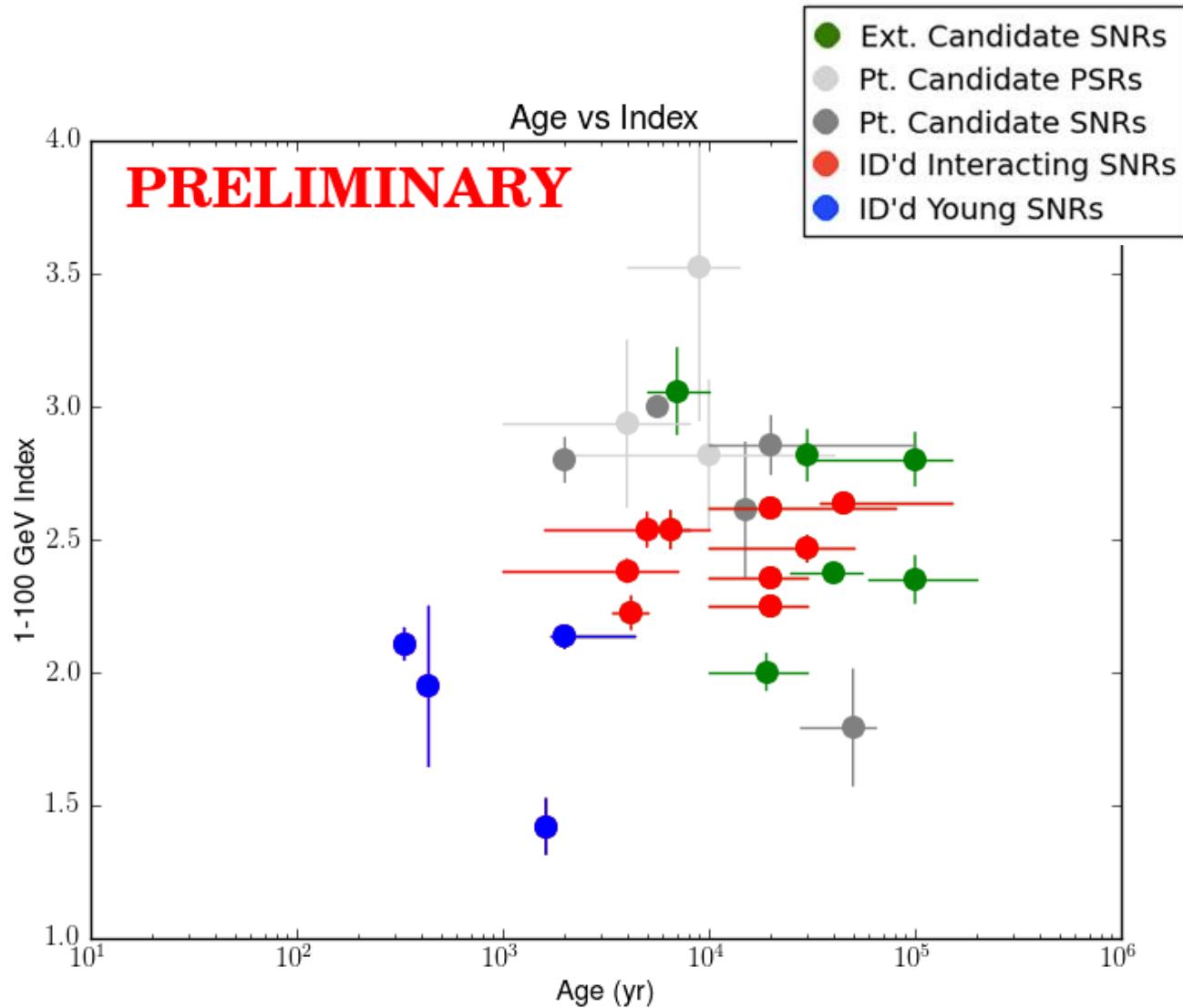
Young SNRs tend to be harder than older, interacting SNRs.

GeV index evolves w time:

- › increases for older remnants

Due to a combination of:

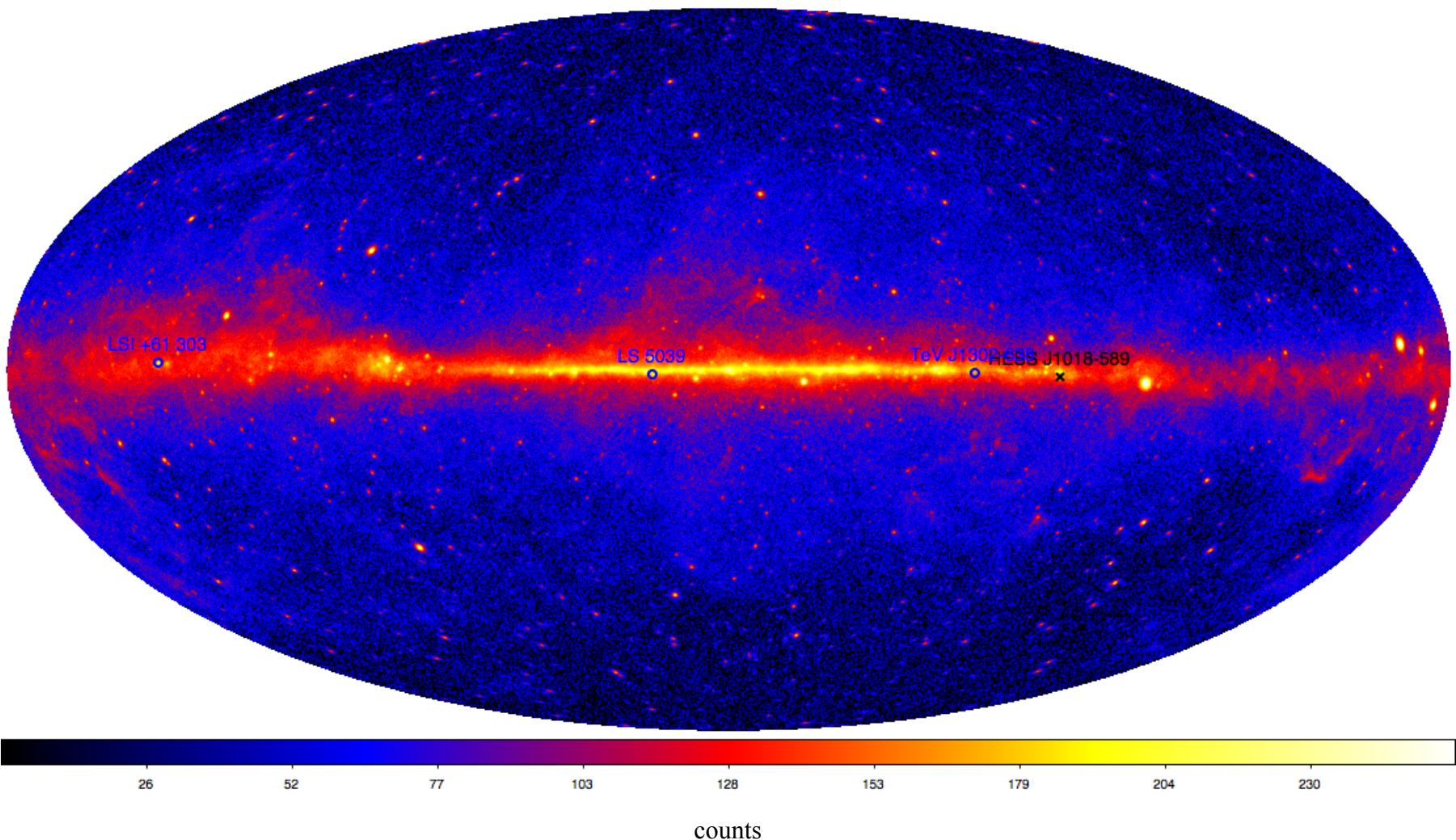
- › decreasing shock speed allowing greater particle escape?
- › decreasing maximum acceleration energy as SNRs age?



Binaries

GeV detected binaries:

- › Fewer than anticipated pre-launch
- › Currently: 4 w GeV emission

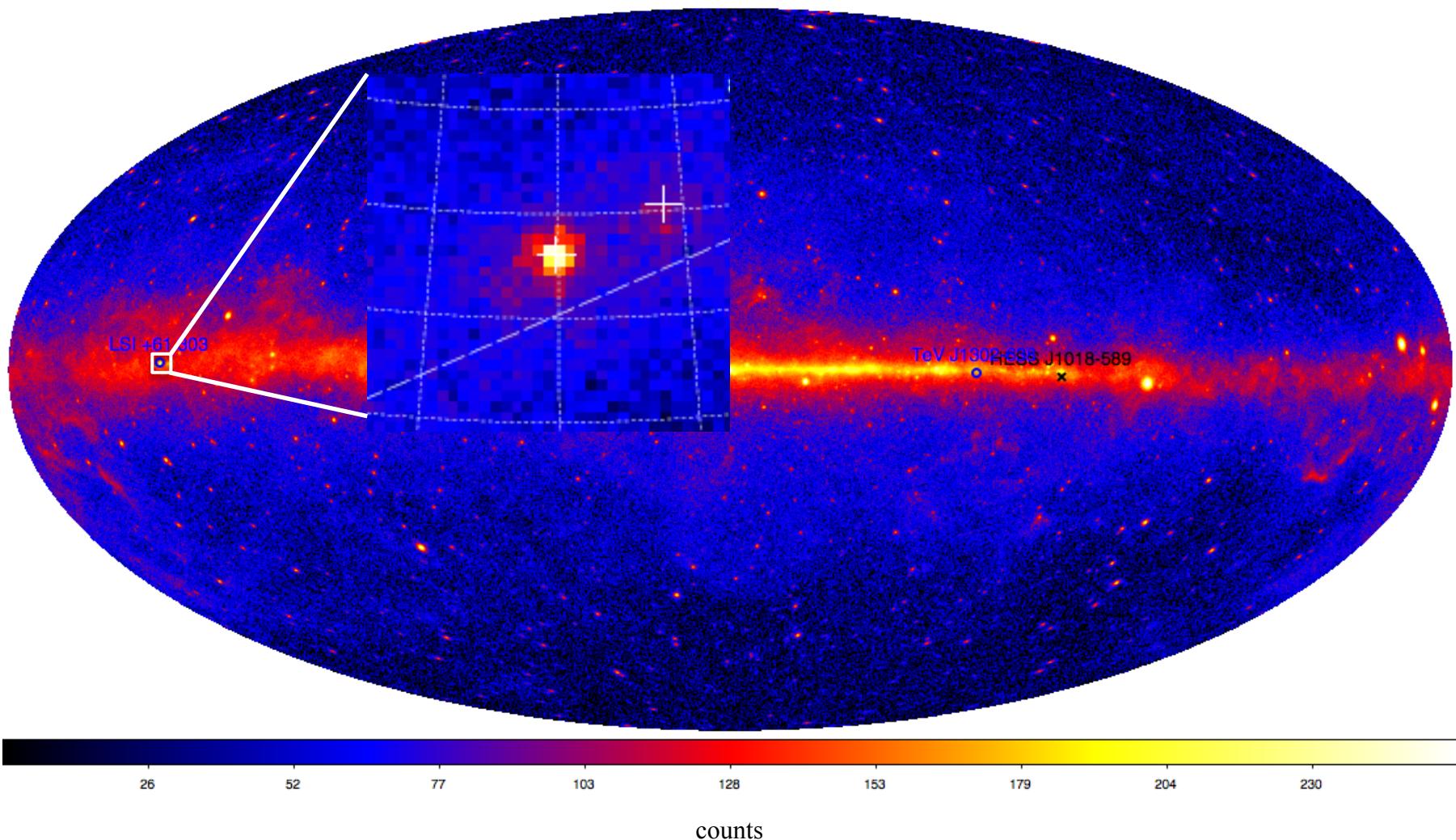


Binaries

GeV detected binaries:

- › LSI +61 303:
- › Be X-ray system
- › w superorbital period detected at GeV!

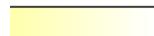
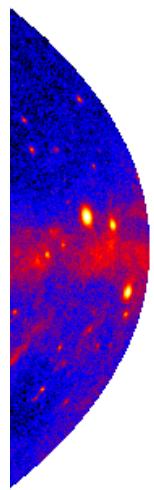
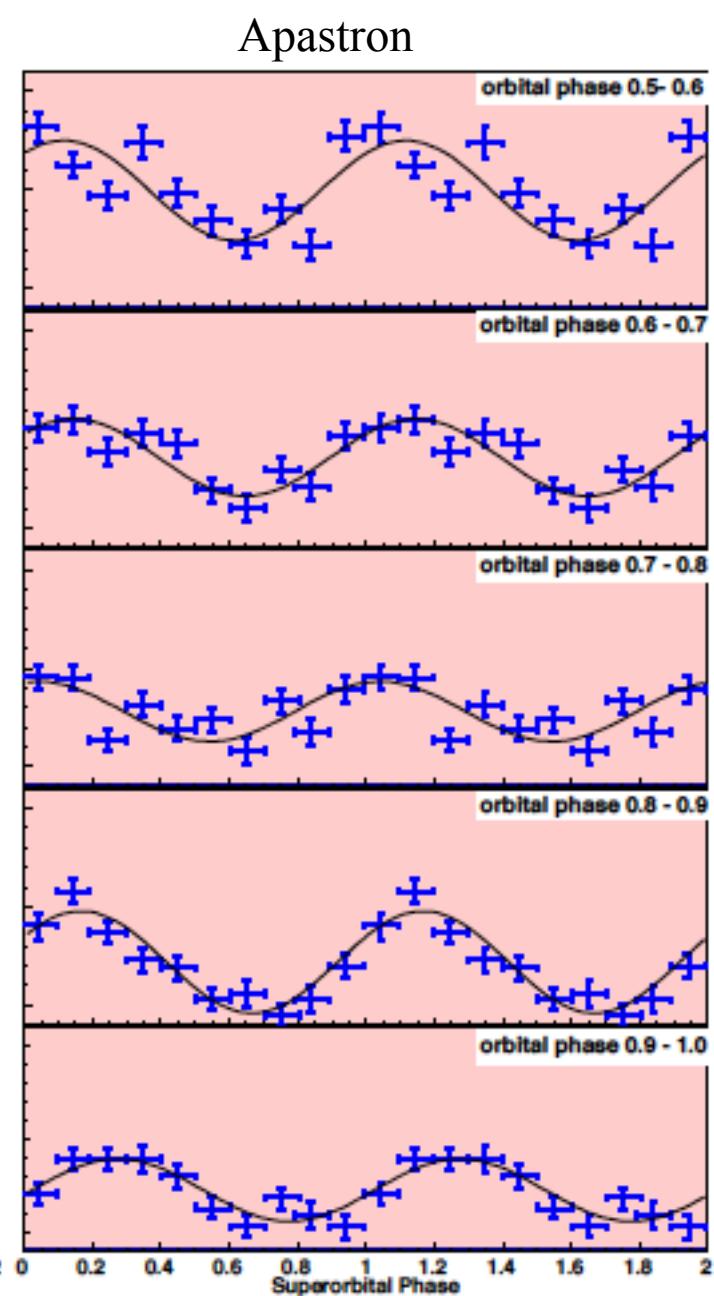
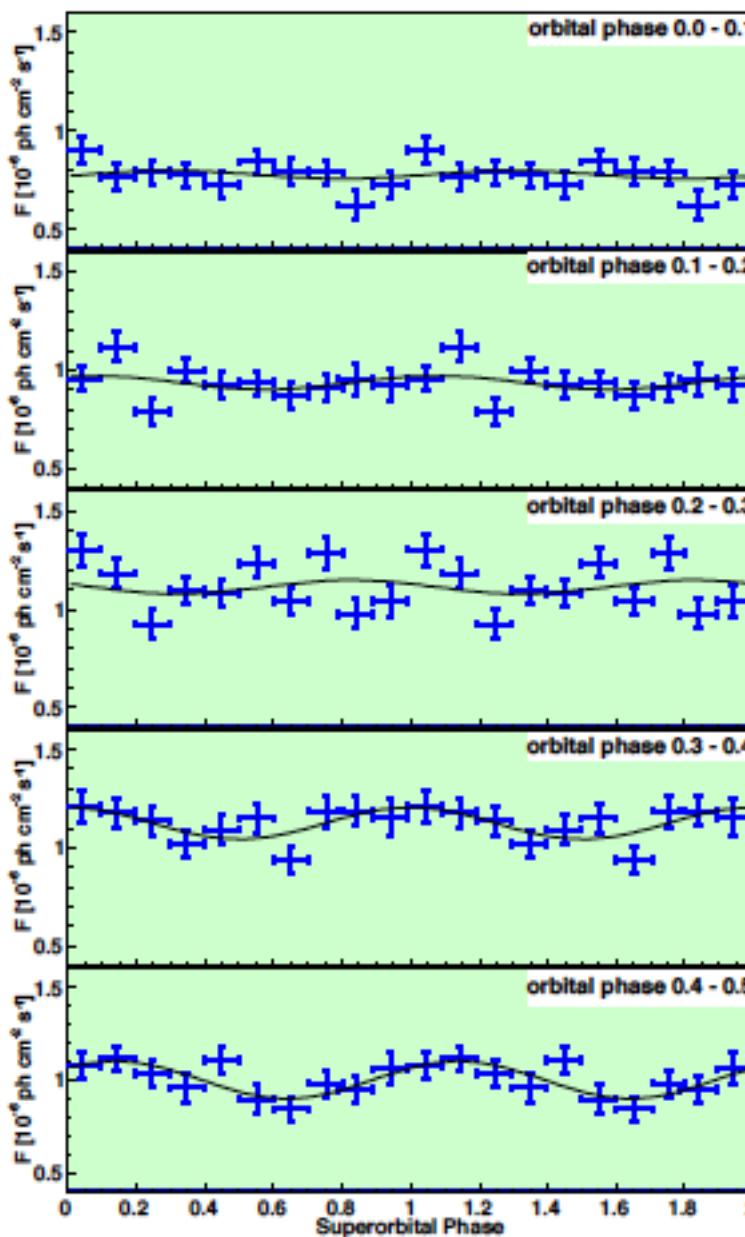
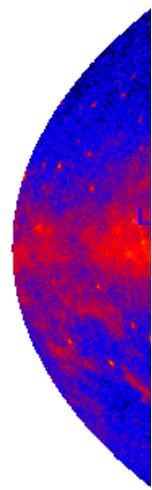
- › Size of Be disk may correlate w H α emission line equivalent width



Binaries

GeV detected binaries

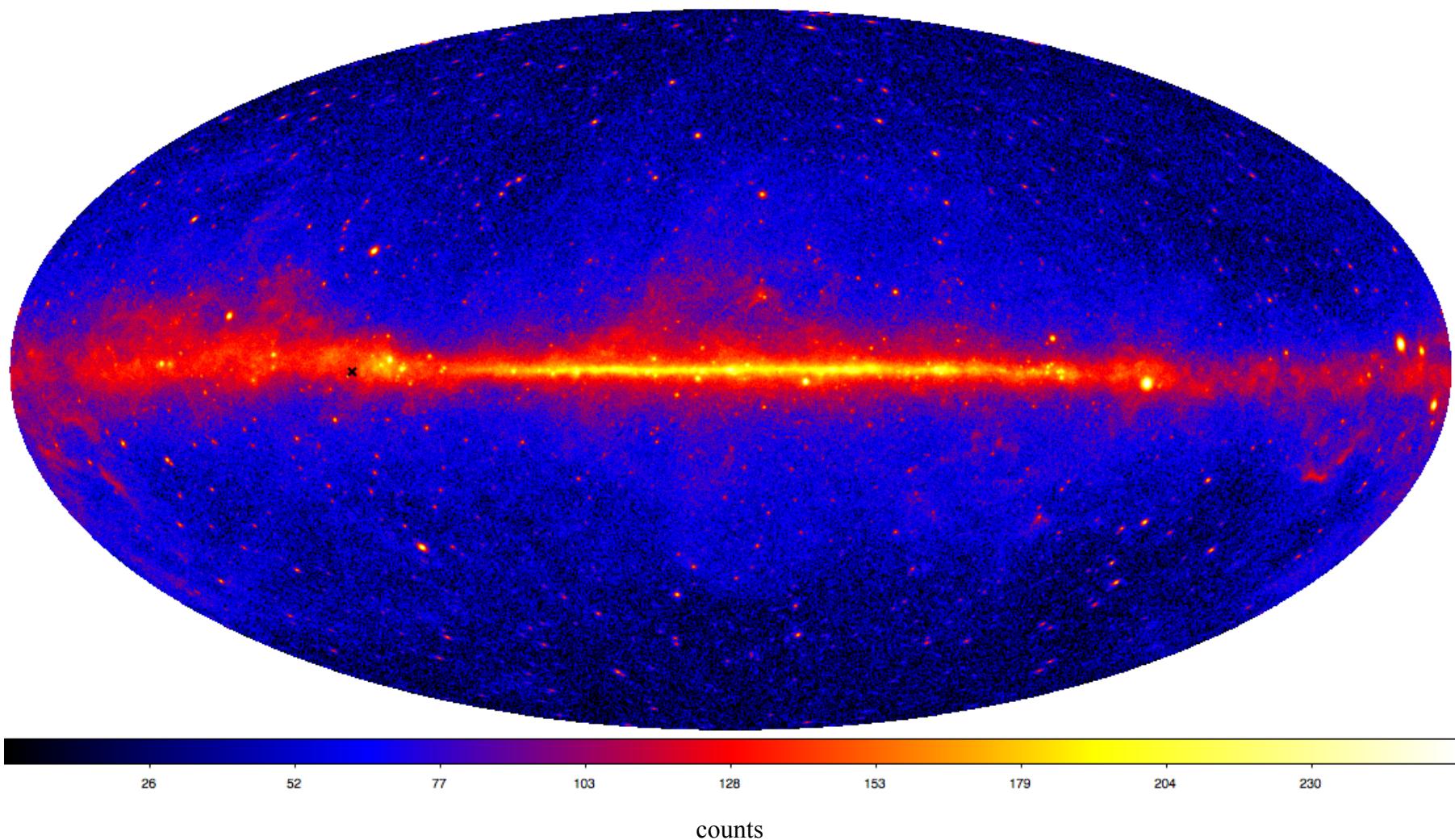
- > Fewer
- > Current
- > LSI +6



Novae!

V407 Cyg: an unexpected g-ray detection

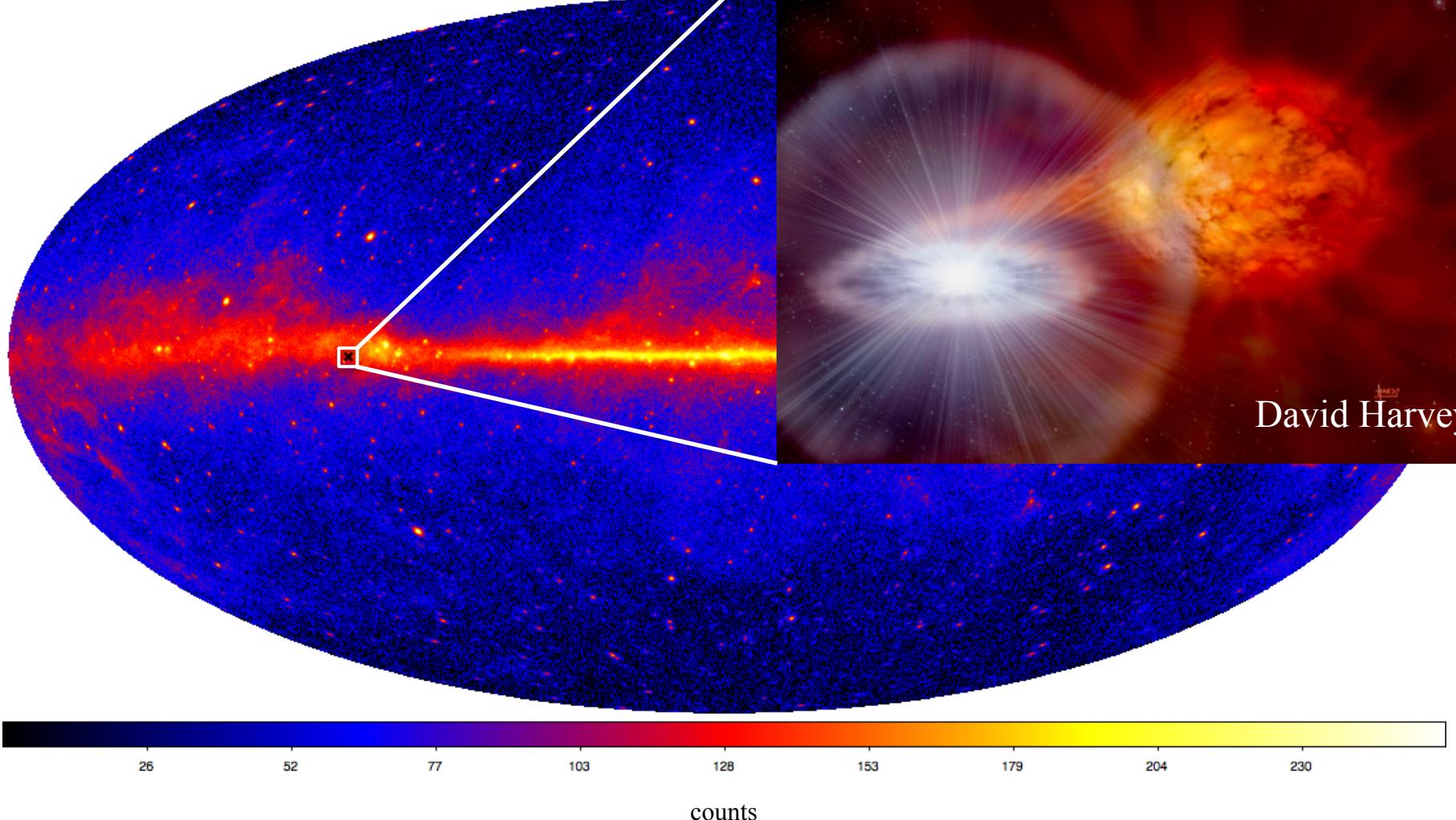
Abdo+2010



Novae!

V407 Cyg: an unexpected g-ray detection

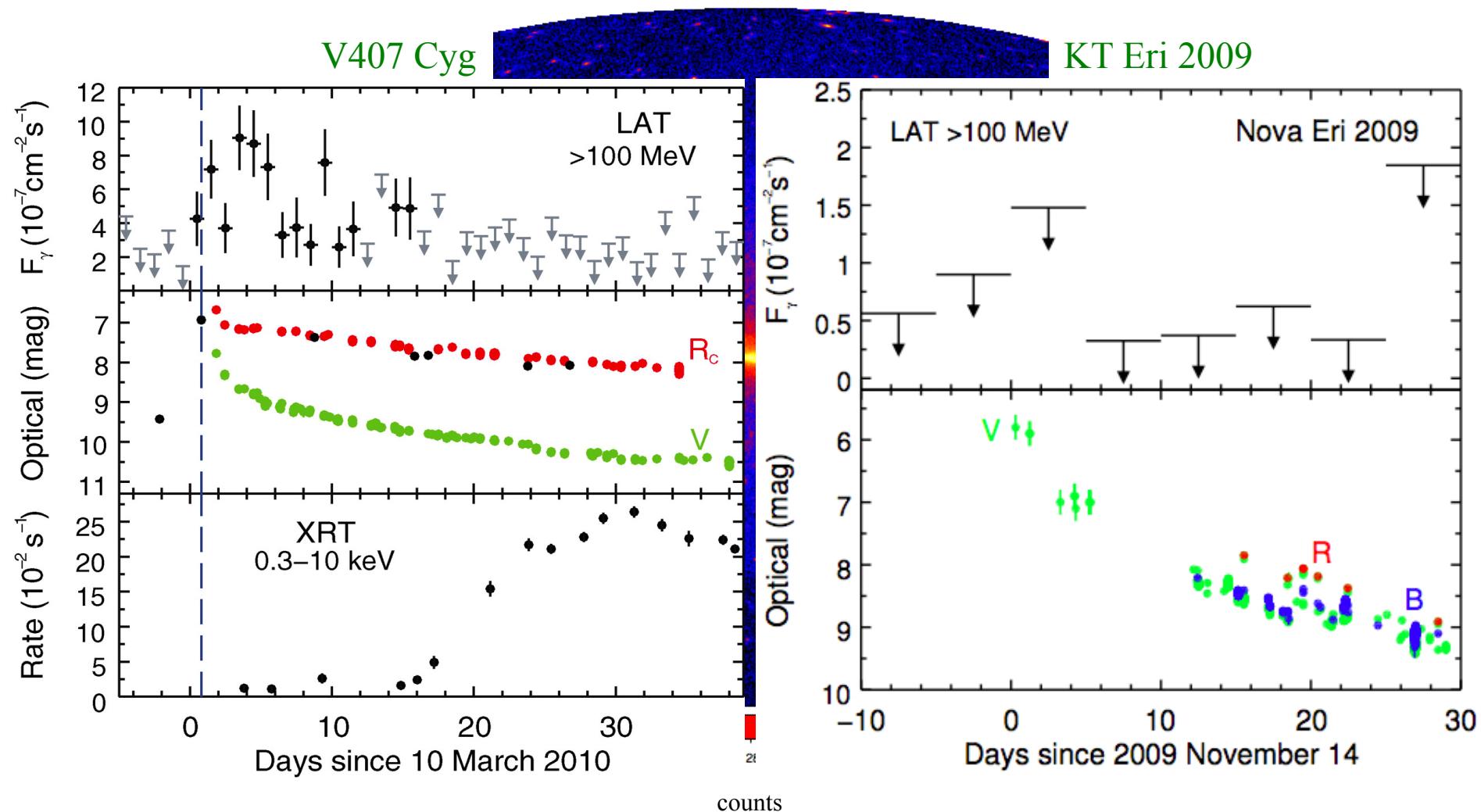
- › Symbiotic binary
- › Particle acceleration at a shock front
- › Massive white dwarf accreting from red giant w wind



Novae!

KT Eri 2009?

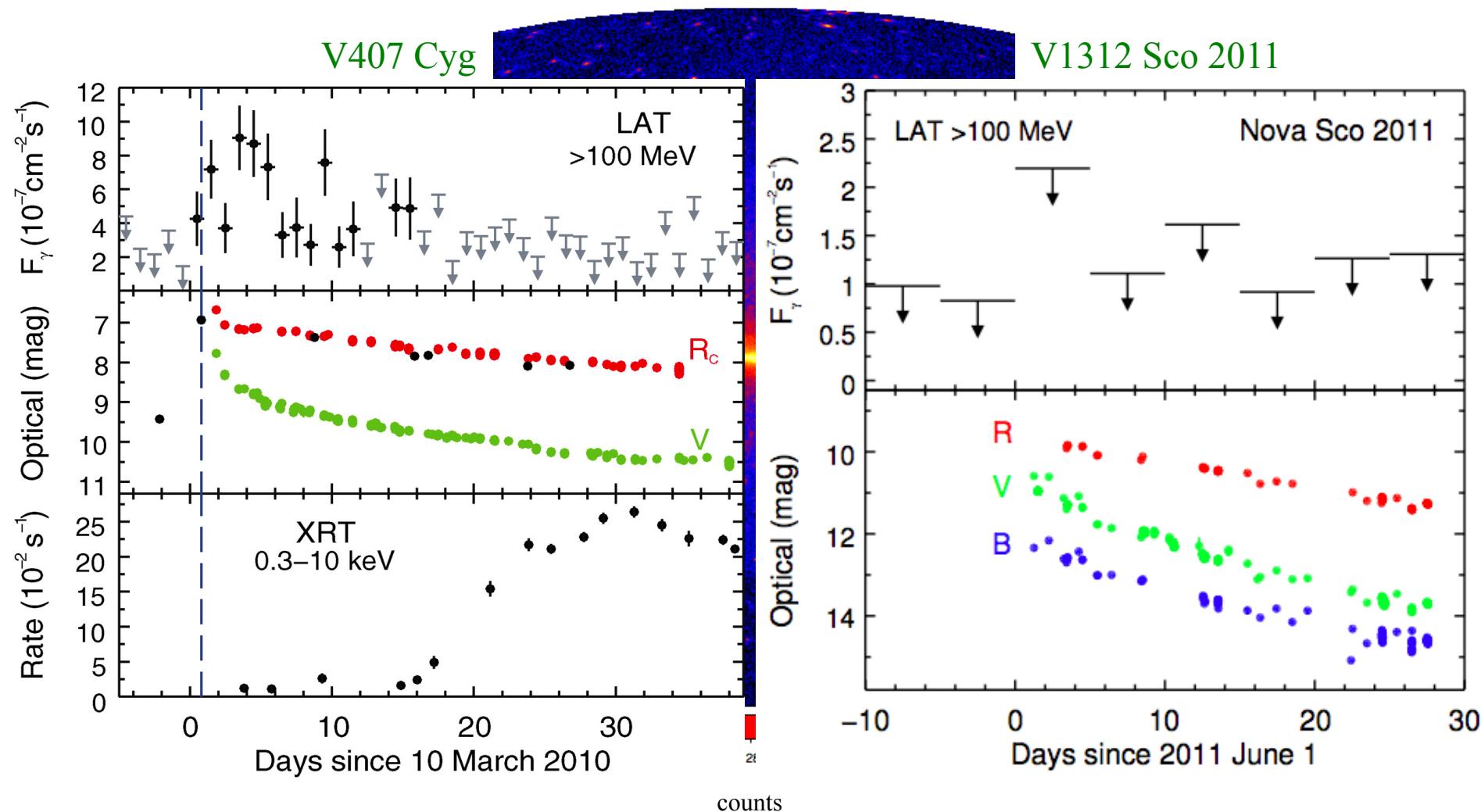
- › Classical Novae
- › Particle acceleration at a shock front?



Novae!

V1312 Sco 2011?

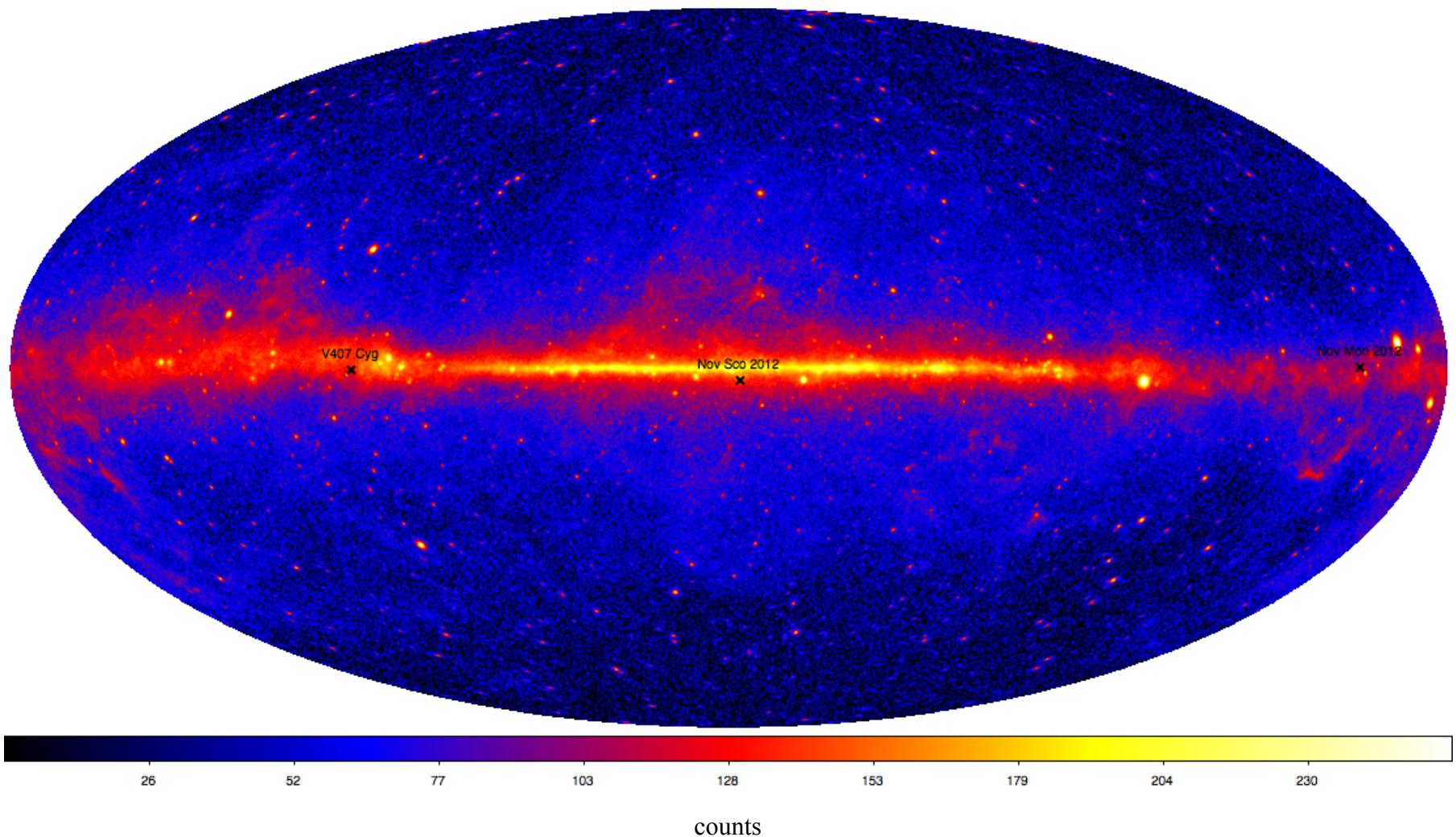
- › Classical Novae
- › Particle acceleration at a shock front?



Novae!

June 2012: Two *classical* novae, 4 days apart

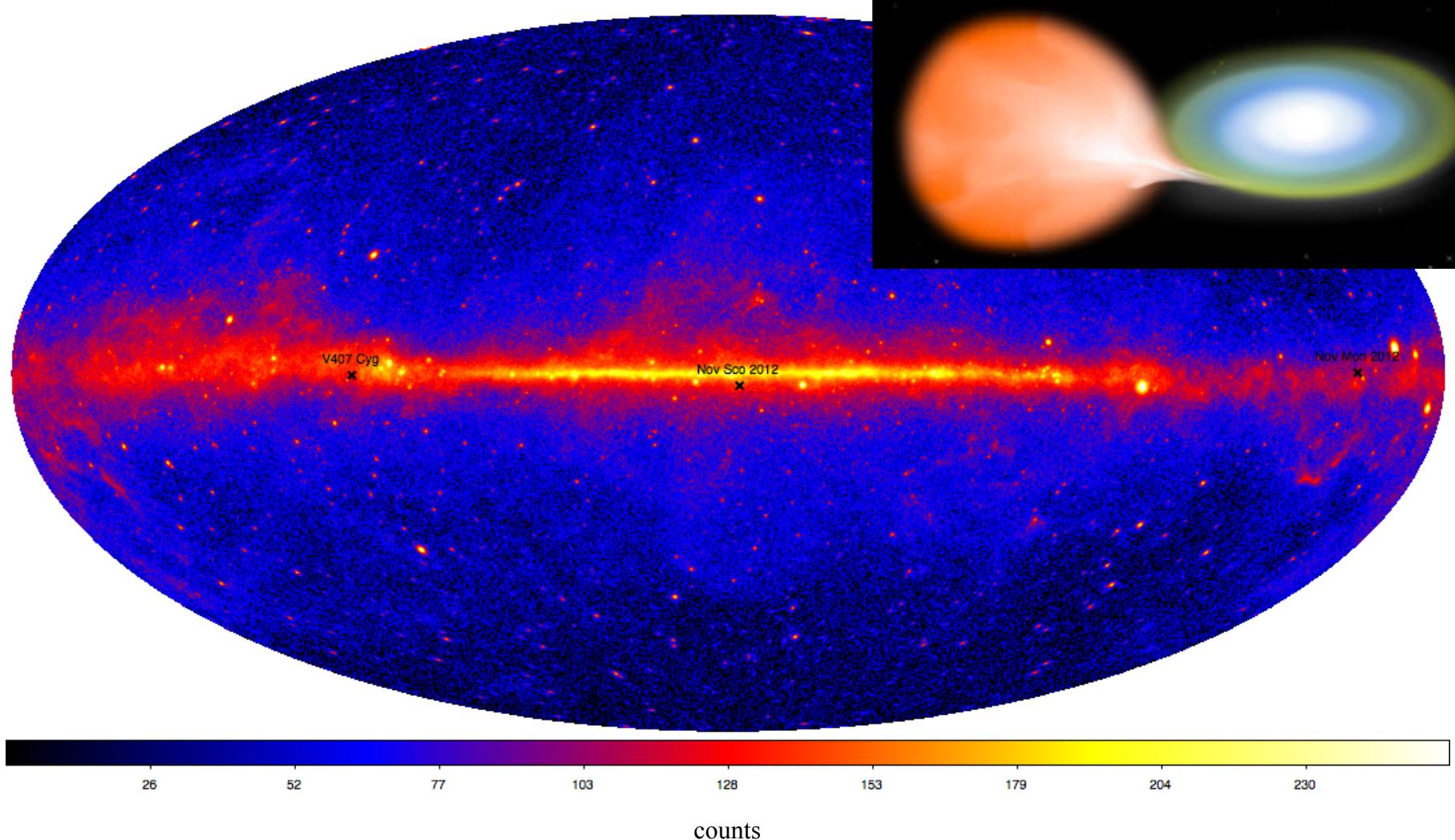
› Nov Sco (FAVA detection) and Nov Mon (ONe type, Fermi discovery!)



Novae!

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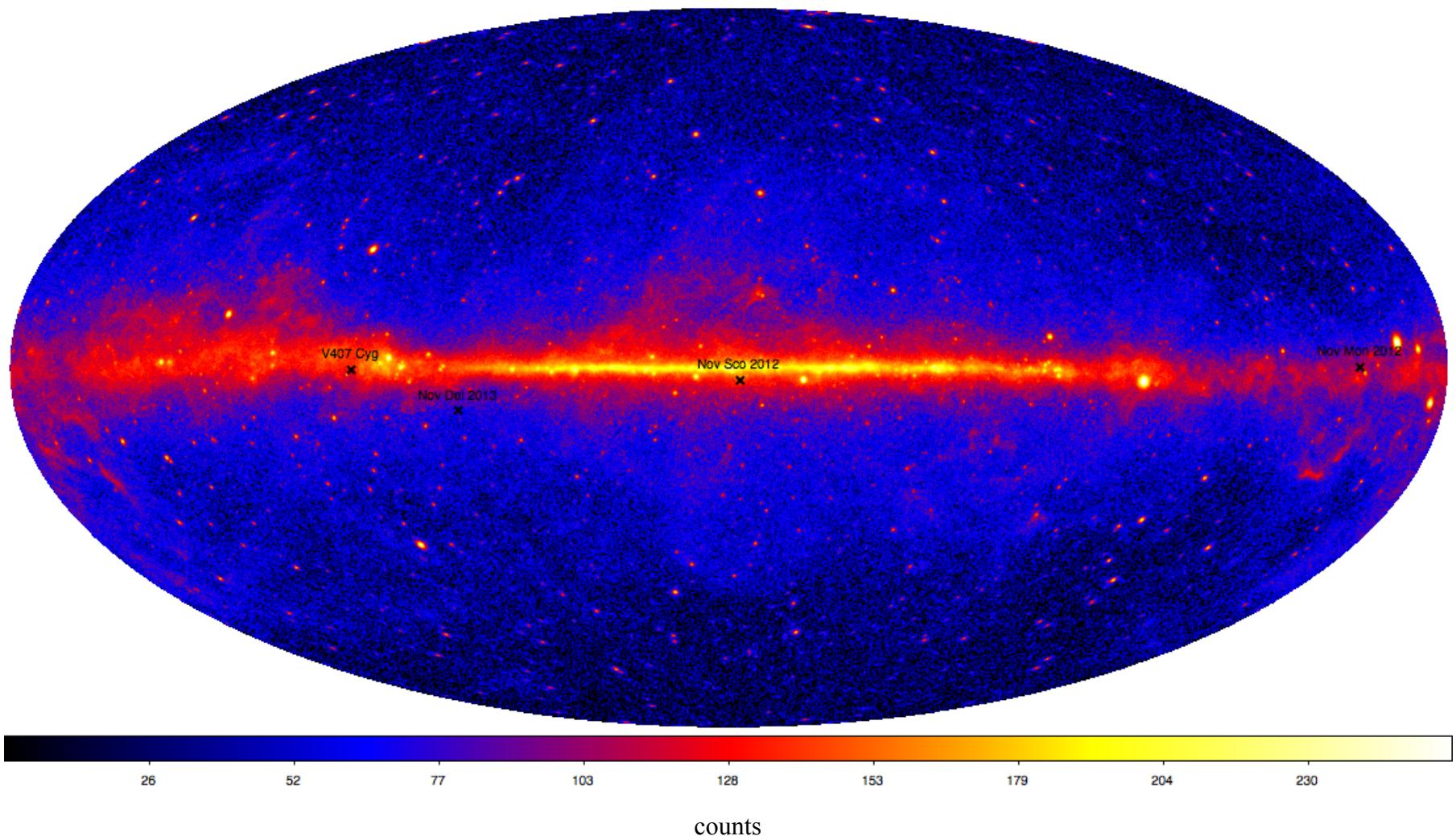
- › Nov Sco (FAVA detection) and Nov Mon (ONe type, Fermi discovery!)
- › White dwarf accreting from main sequence star, Roche lobe overflow
- › Particle acceleration at a shock front?



Novae!

15 Aug 2013: Nova Del

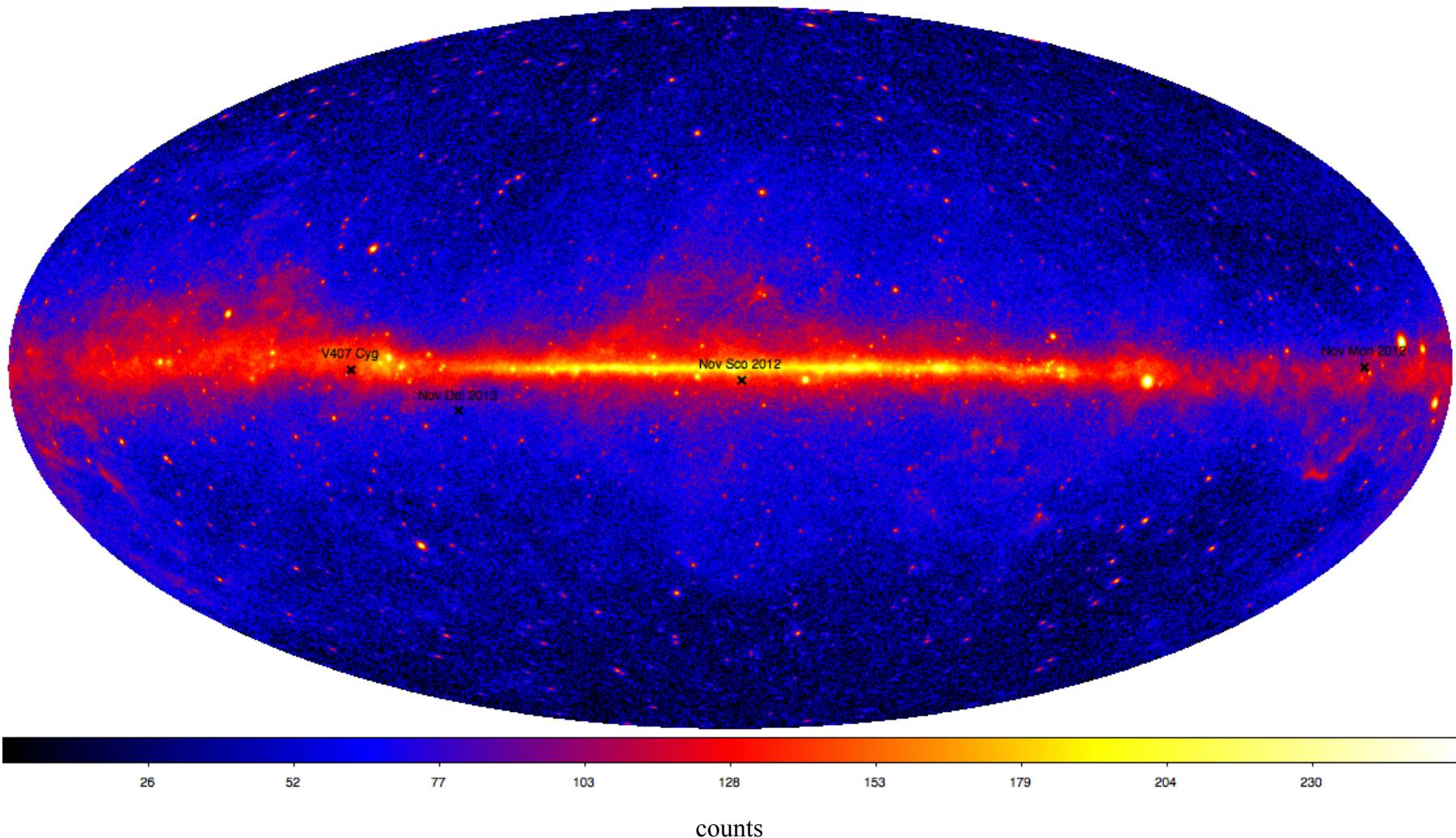
- › ~ once per decade naked eye event
- › Classical CO type Nova



Novae!

15 Aug 2013: Nova Del

- › Origin and site of gamma-ray emission remains unclear
- › Necessary: massive WD & fast, massive ejecta
- › Companion and environment matter
- › LAT as nova finder?! (w/in 4-6kpc)



Conclusions

- We have measured a wide variety of Galactic sources at GeV energies:
 - Pulsars
 - Pulsar Wind Nebulae
 - Super Novae
 - Binaries
 - Novae!
 - Unidentified sources remain...
- Combining our GeV with multiwavelength and multimessenger observations
 - will give us significantly greater insight into the acceleration mechanisms and environments of all sources
 - including evidence for CR origin and acceleration

