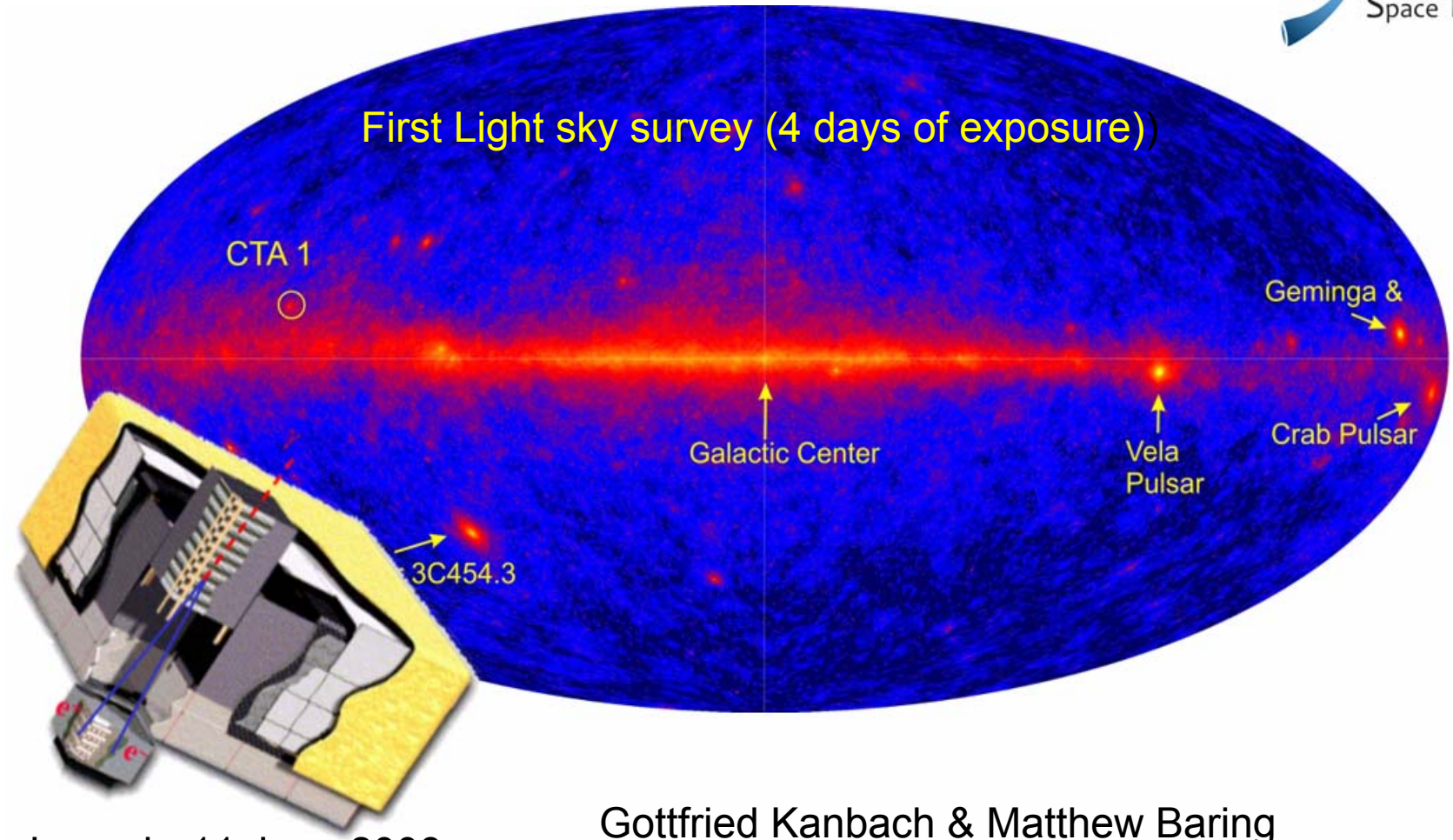
Pulsar Observations with the Fermi Large Area Telescope



Launch: 11 June 2008

Gottfried Kanbach & Matthew Baring
for the Fermi-LAT Collaboration

The high-energy pulsar world we knew 6 months ago…

- 6 pulsars detected with high confidence by *CGRO/COS-B/SAS-2:*

  5 radio-loud young pulsars with top ranked $\dot{E}_{rot}/d^2$ values
  1 radio-faint (or -quiet) pulsar (Geminga)
- ~ half a dozen lower confidence candidates, including a ms pulsar

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Layout of our presentation:

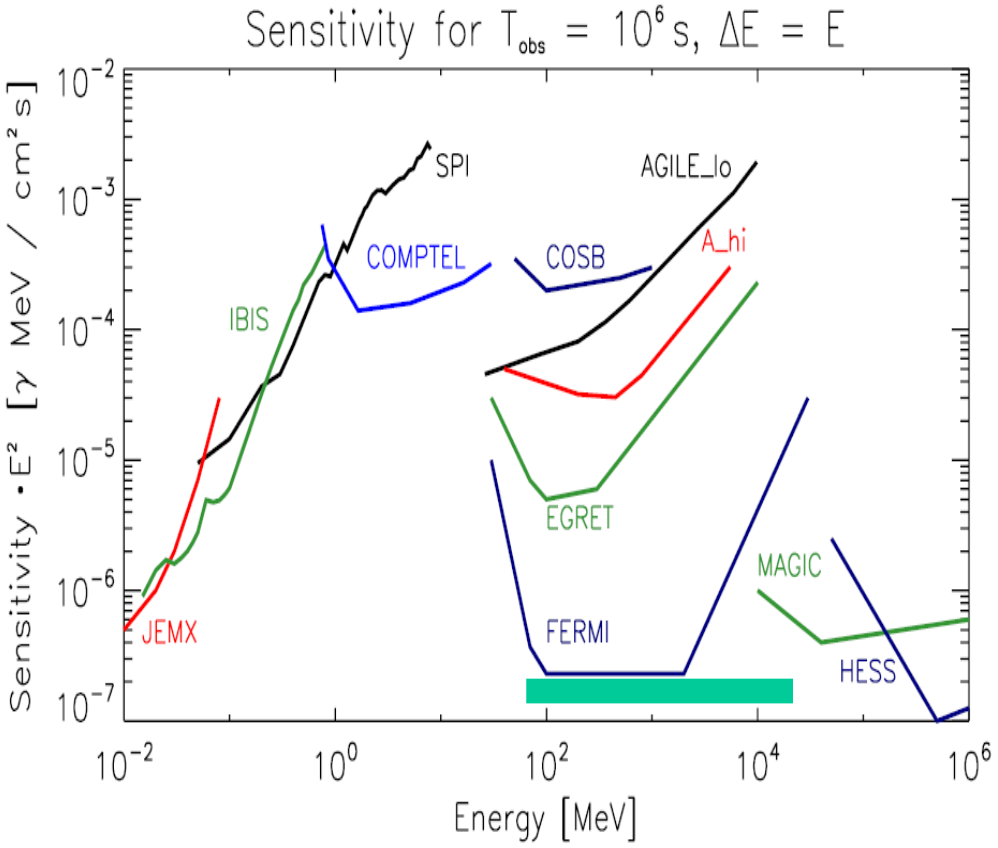
G.K.:

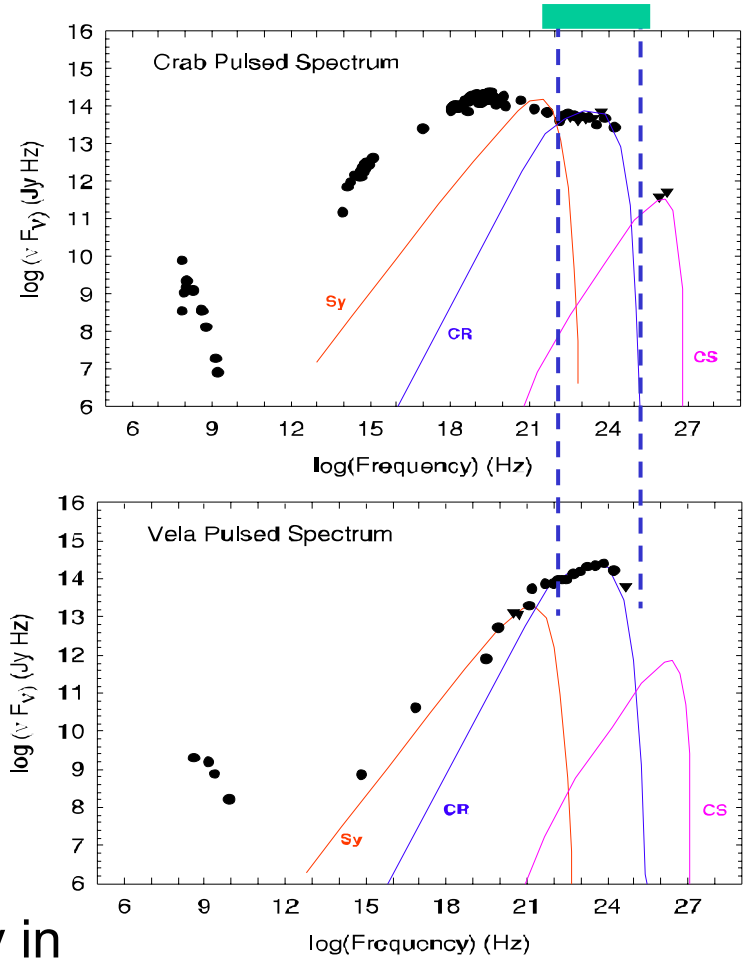
- the Fermi LAT in the context of multi-wavelength astronomy
- pre-flight preparations of timing tools for radio- or γ-ray-only pulsars
- Pulsar observations during initial on-orbit operations & first results
  - the ‚classical' Vela pulsar
  - the first ‚blind-search' γ-ray only pulsar in the SNR CTA-1

M. B.:

- the Fermi LAT pulsar legacy burgeons:
  the pulsar catalogue after 5 months of operations
- lightcurves and spectra of selected radio pulsars
- insights into γ-radiation processes and magnetospheric models
- the new GeV ms pulsar population

Fermi LAT (~ 100 MeV to 100 GeV) and the observation of Pulsars





The LAT sensitivity is a good match for the SEDs expected from young high-energy pulsars – especially in the region of GeV spectral cut-offs

Preparation of timing tools for radio- or γ-ray-only pulsars

Typical pulsar fluxes of 10^{-6} to 10^{-8} γ(>100 MeV) cm^{-2} s^{-1}
lead to LAT detection rates of 1 γ/several minutes to 1γ/several hours
→ requires long observation times and high precision ephemerides

Radio pulsar timing database:

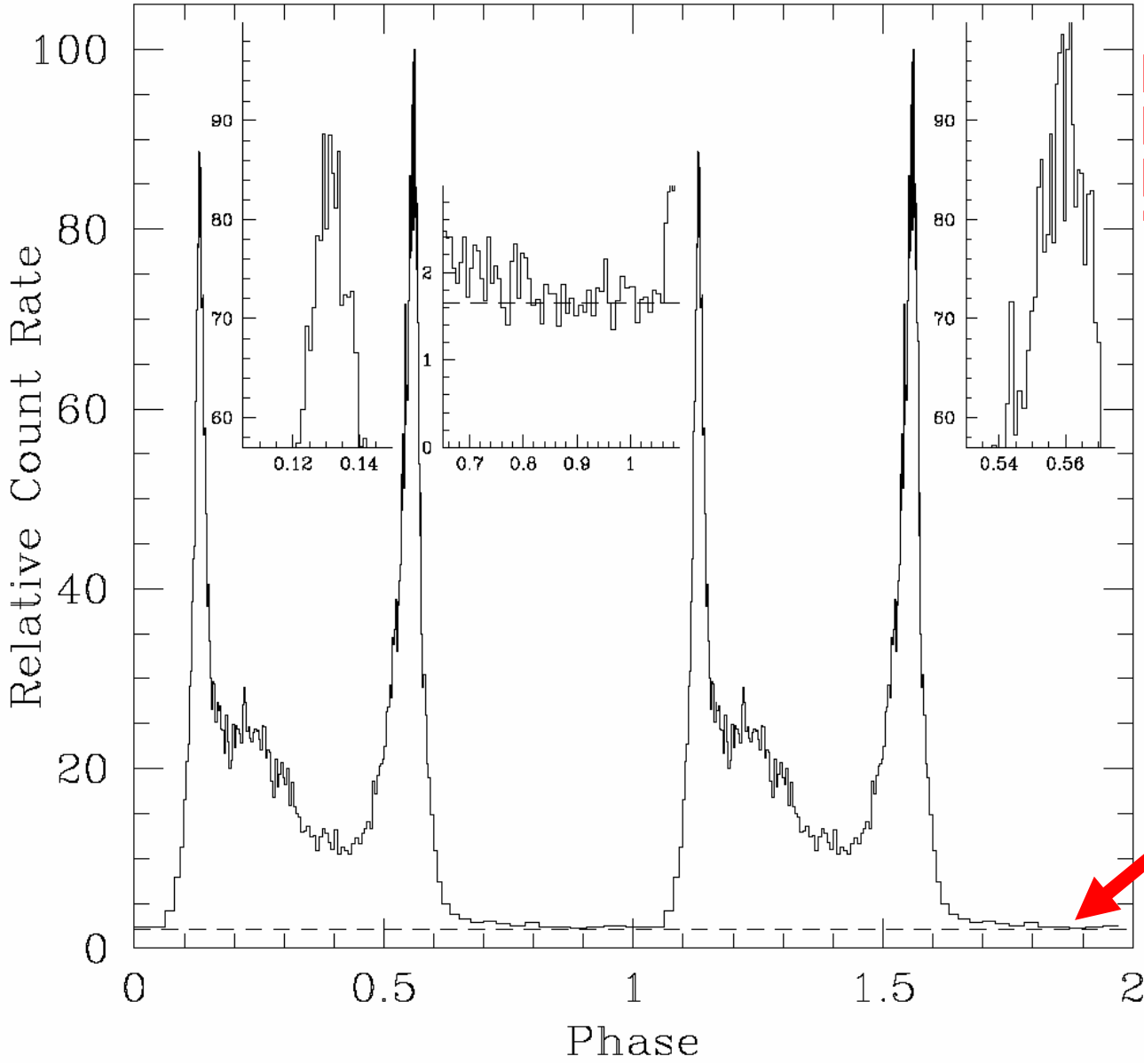
Monitoring of radio ephemerides for over 200 pulsars
with large spin-down powers by an international consortium
of radio telescopes
(Smith et al., 2008, http://xxx.lanl.gov/abs/0810.1637v1)

Searching periodicity directly in the γ-ray data (‚blind-search pulsars'):

Time differencing technique: Atwood et al., ApJ, **652**, L49, 2006

Follow up refined analysis for P, $\dot{P}$ using FFT & folding techniques

The Vela pulsar taken to a new level of statistical detail with *Fermi LAT*



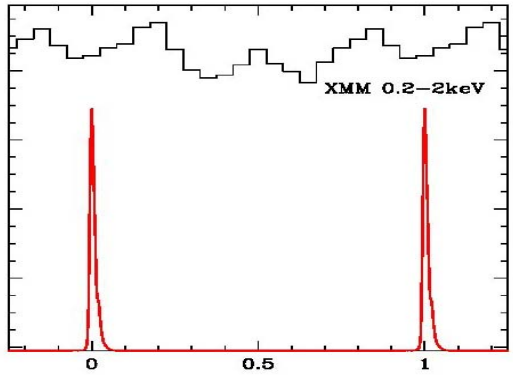
100 MeV < E < 10 GeV

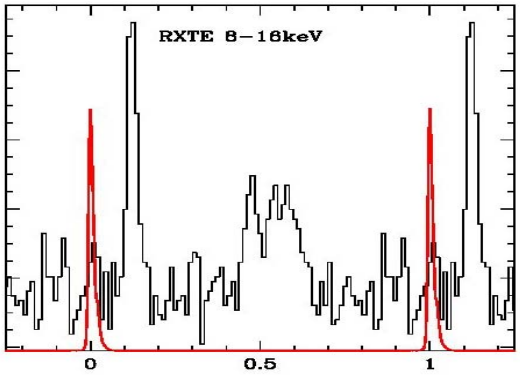
~50000 photons !

Remarkably sharp peaks; features to ~0.3 ms

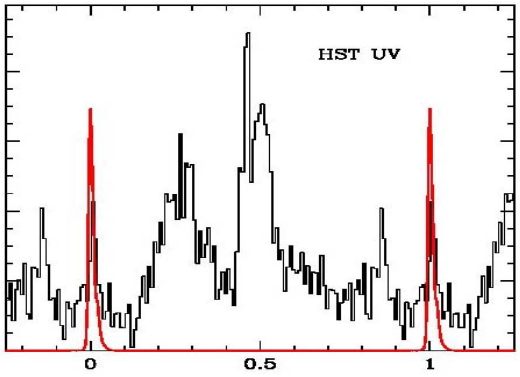
Turns almost completely off between the double pulses

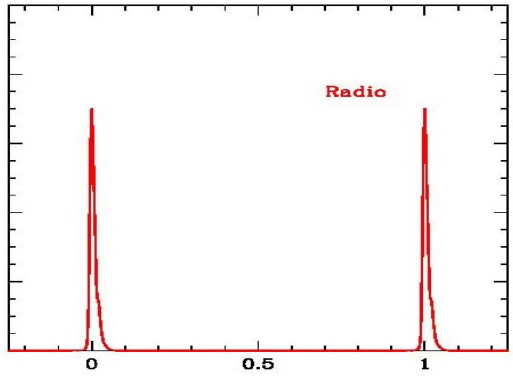
Vela Lightcurves across the e-m spectrum





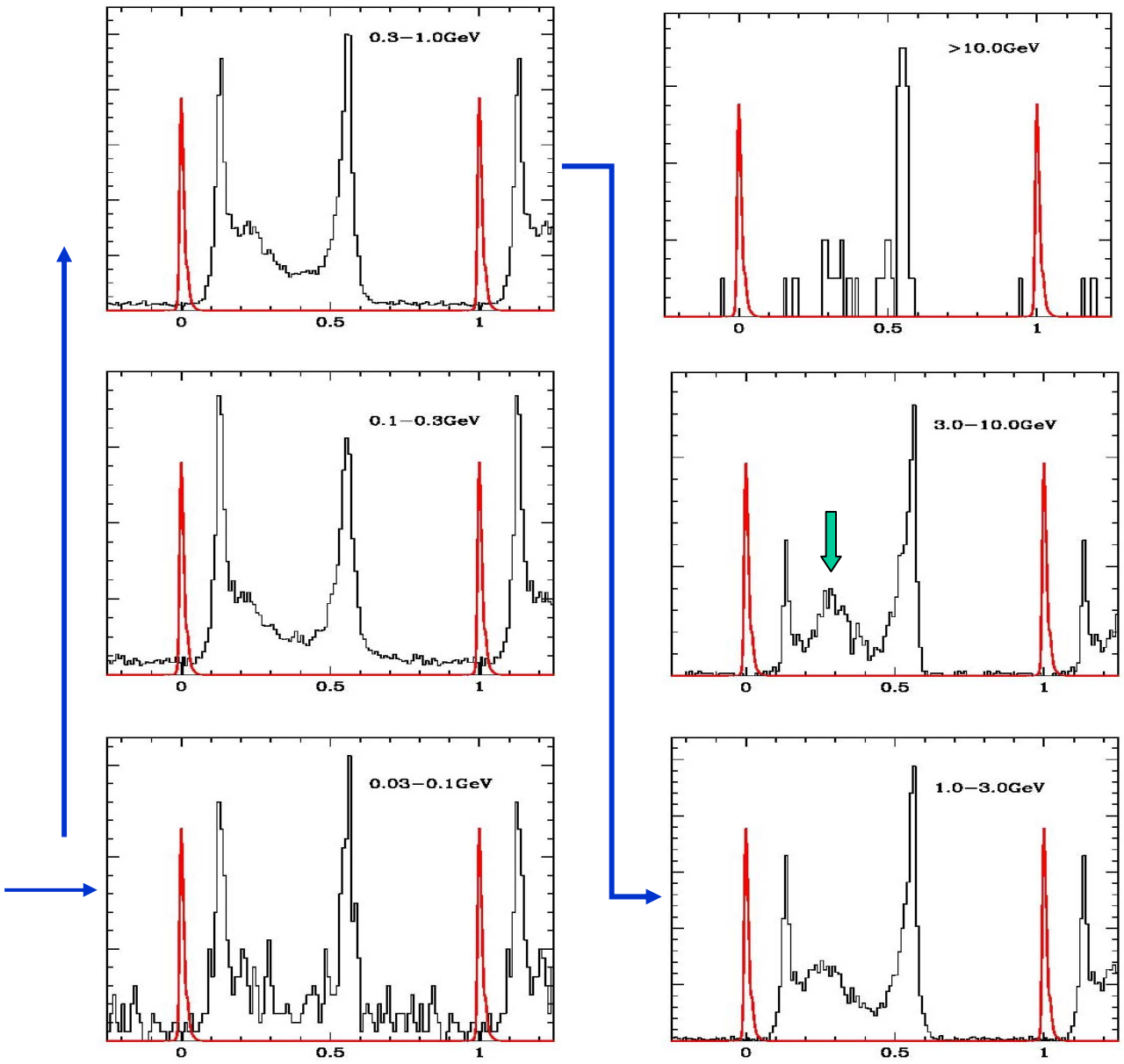
γ





From Radio
to hard X-rays

Fermi LAT lightcurves from 30 MeV to >10 GeV

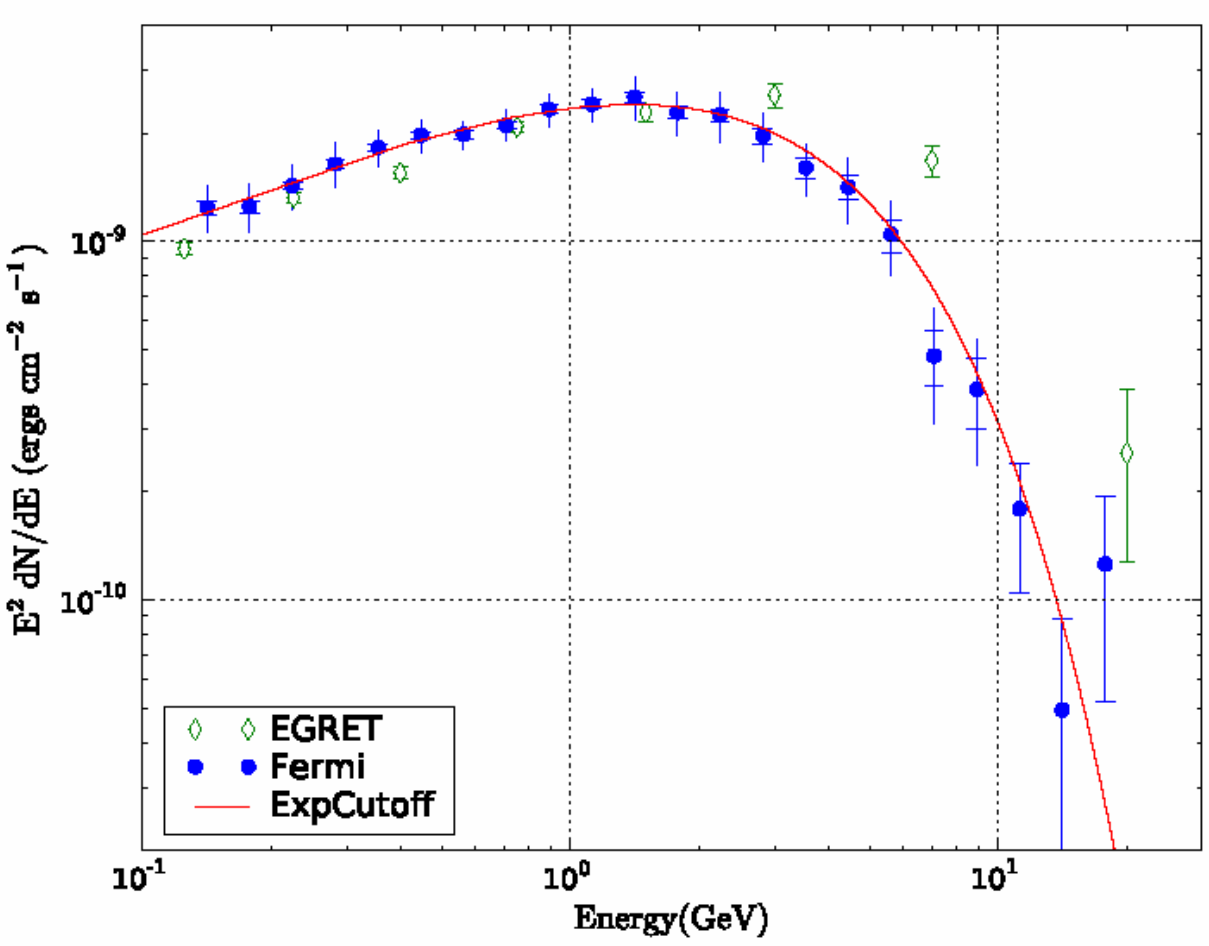


NB: the first pulse has disappeared

NB: the ‚bridge' emission separates into a broad pulse

Vela Phase-averaged spectrum

$$N(E) = N_0 E^{-\Gamma} e^{-(E/E_c)^b}$$



Consistent with b=1 (simple exponential)

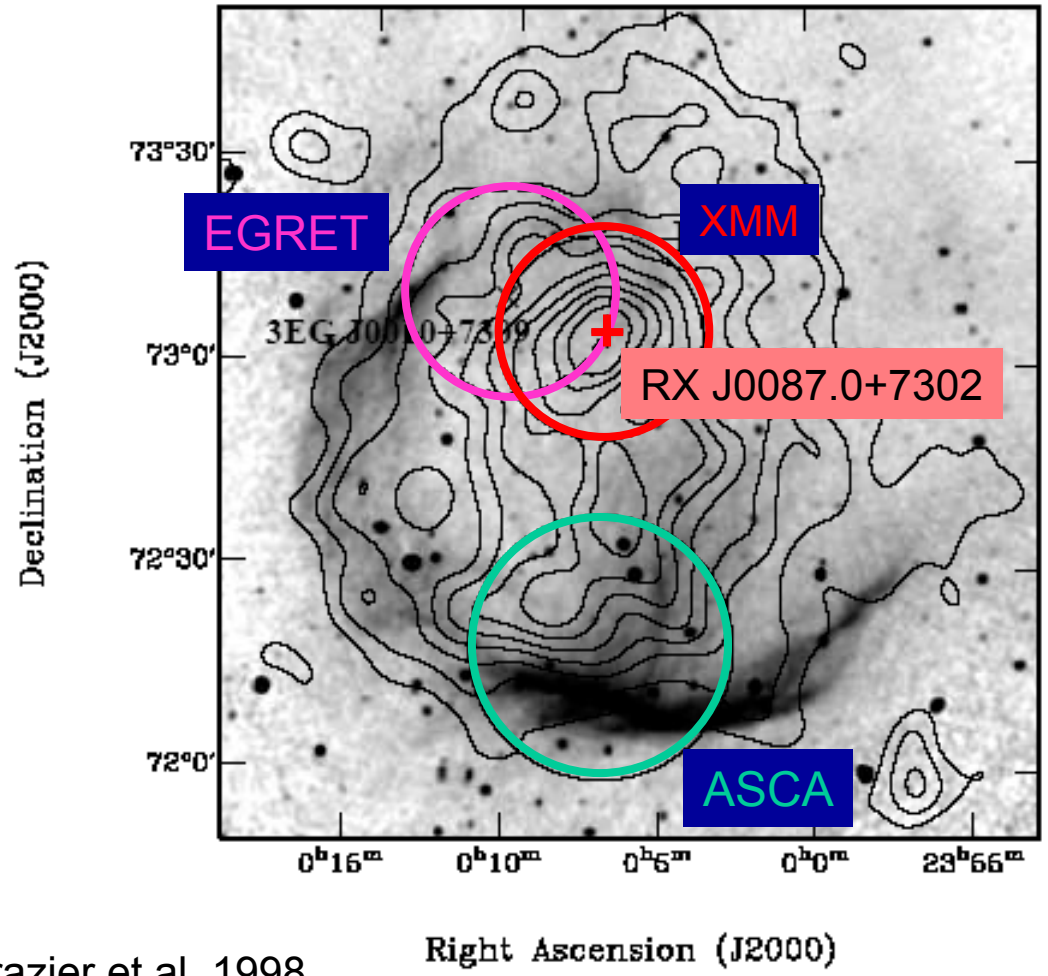
$$\Gamma = 1.51^{+0.04}_{-0.05}$$

$$E_c = 2.9 \pm 0.1 \text{ GeV}$$

b=2 (super-exponential) rejected at 16.5σ

Interpretation
→ Matthew Baring's part

Pulsar search in an unidentified 3EG source: SNR CTA1 in radio, X, and γ-rays



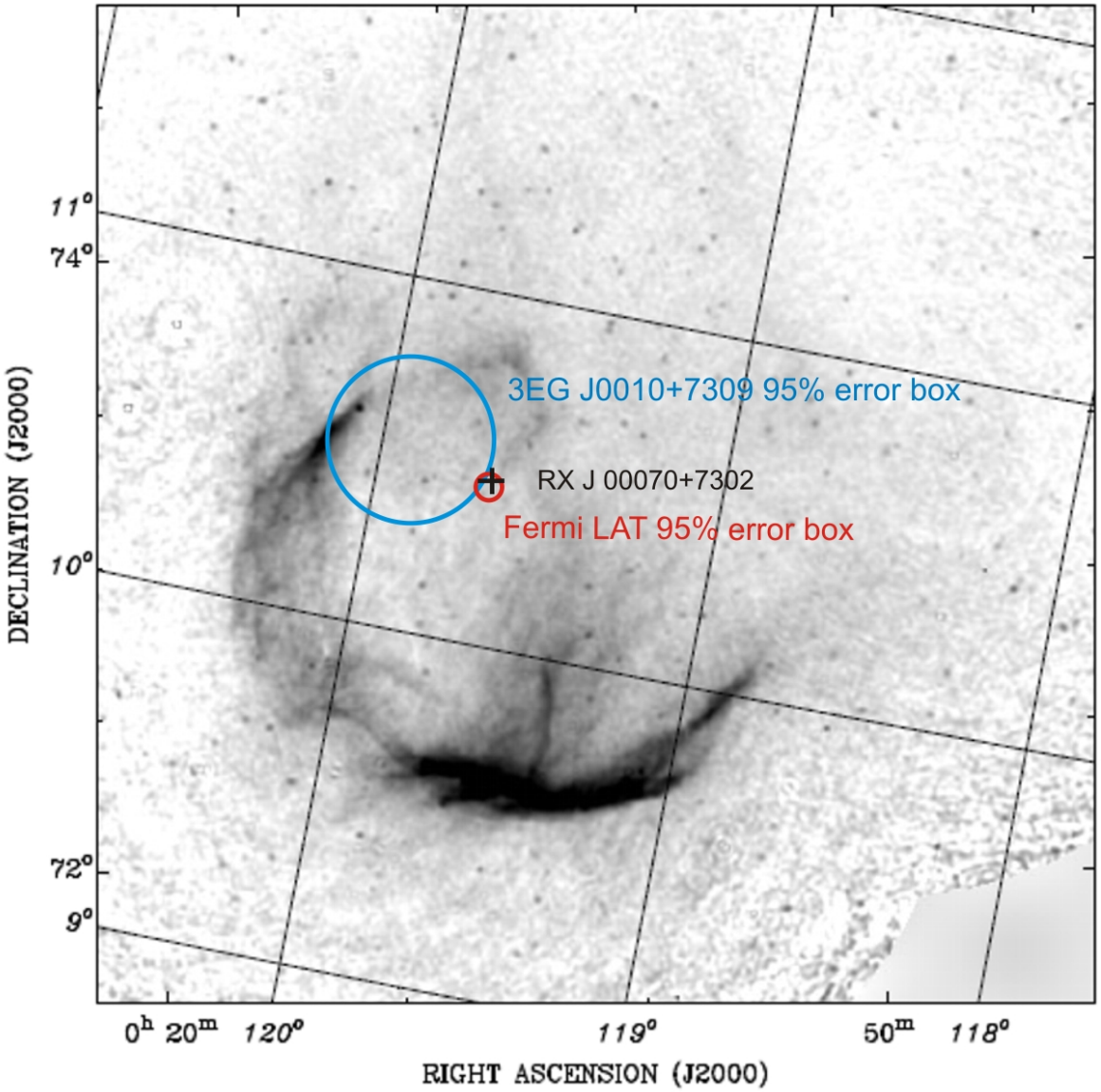
Brazier et al, 1998
Hartman et al., 1999 (3EG)
Slane et al., 2004
Halpern et al., 2004

SNR discovered in 1960 at 960 MHz
Age ~(0.5 – 1)x10^4 years
Distance ~ 1.4 kpc
Diameter ~ 1.5°

- ROSAT image of SNR with pointsource
- XMM & Chandra show a PWN around the source (L_{PWN} ~10^{35} – 10^{36} erg/s)
- X-ray spectrum consistent with a NS
- unid EGRET source γ-ray energetics agree with PSR interpretation
- no radio (< 20 μJy kpc^2) or optical (R>25) counterpart yet!

now … FERMI-LAT!

10 days L&EO commissioning
+10 days survey obs. (<Aug 22, 2008)

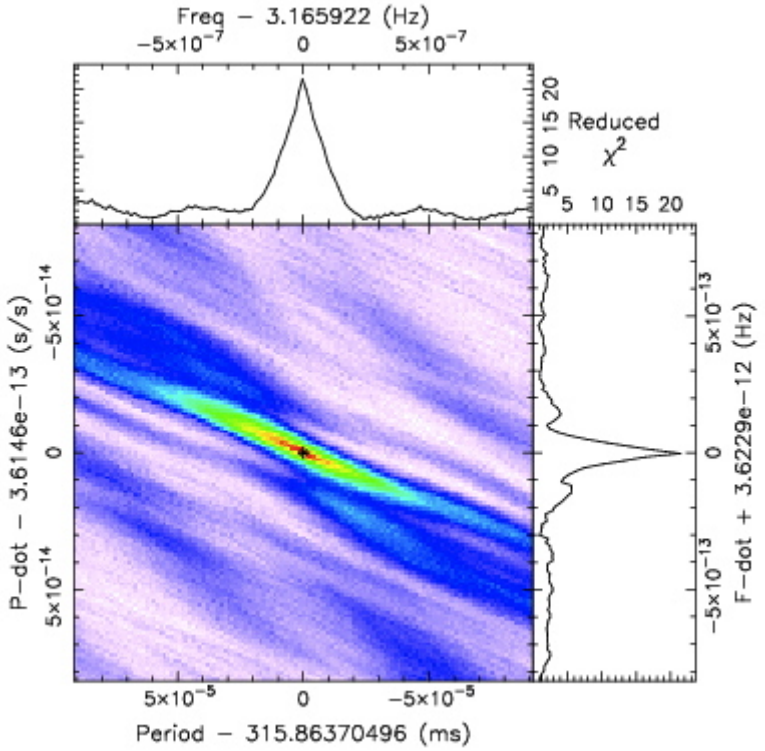


~900 γ's (>100 MeV)

location of high-energy source agrees with Rosat X-ray position

application of LAT ‚blind-search' techniques → discovery of pulsations on July 10/11, 2008

P-$\dot{P}$ map of significances (χ^2) around strongest detection in `time differencing`search (Atwood et al., ApJ. 652, L49, 2006)



Detection in 3 independent subsets of the data

Fit of ephemeris with Tempo2 and PRESTO

ν = 3.165922467(9) Hz P = 315.8637050(9) ms

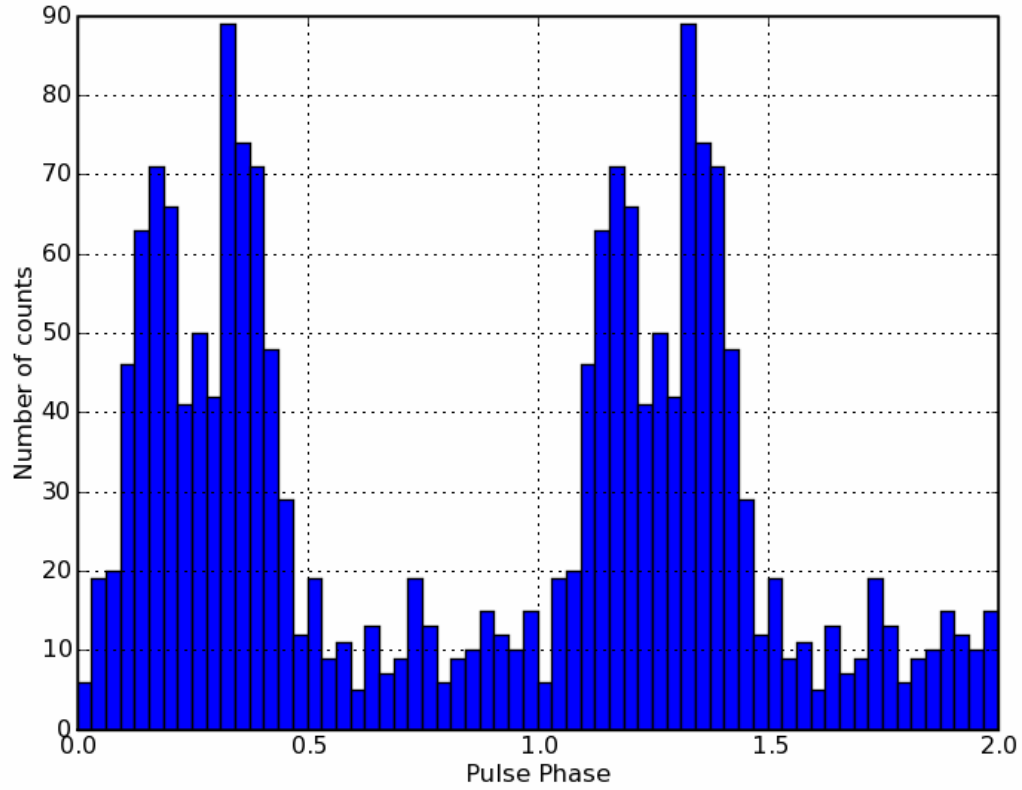
$\dot{\nu}$ = -3.623(4) $\times 10^{-12}$ s^{-2} $\dot{P}$ = 3.615(4) $\times 10^{-13}$ s s^{-1}

T_o = 54647.440 938 MJD(TDB)

Derived Parameters:

τ_{rot} = 1.4 x10^4 years, $\dot{E}_{rot}$ = 4.5 x 10^{35} erg s^{-1}, B_{surf} = 1.1 x 10^{13} G

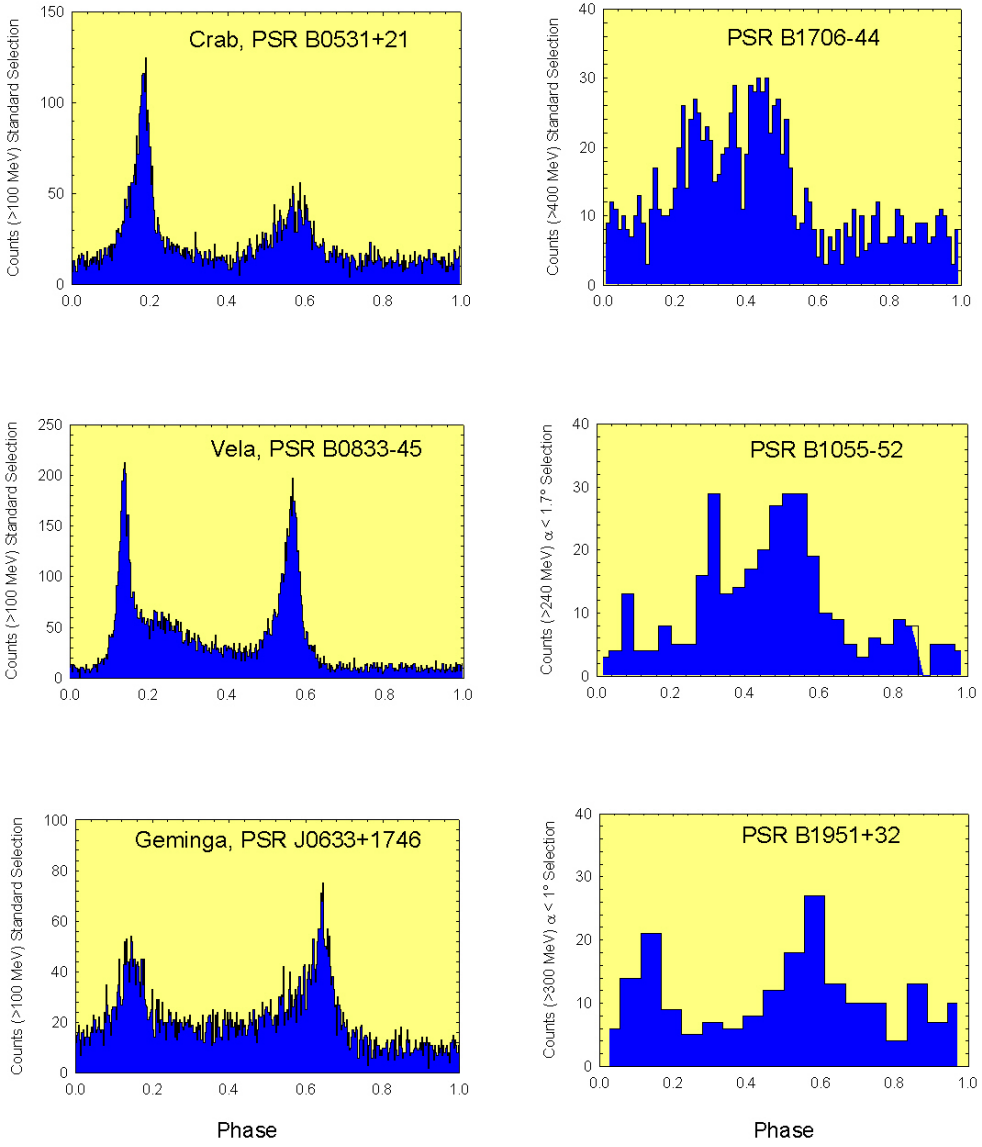
Gamma-Ray Lightcurve (>100 MeV)
Pulsed emission visible to > 5 GeV



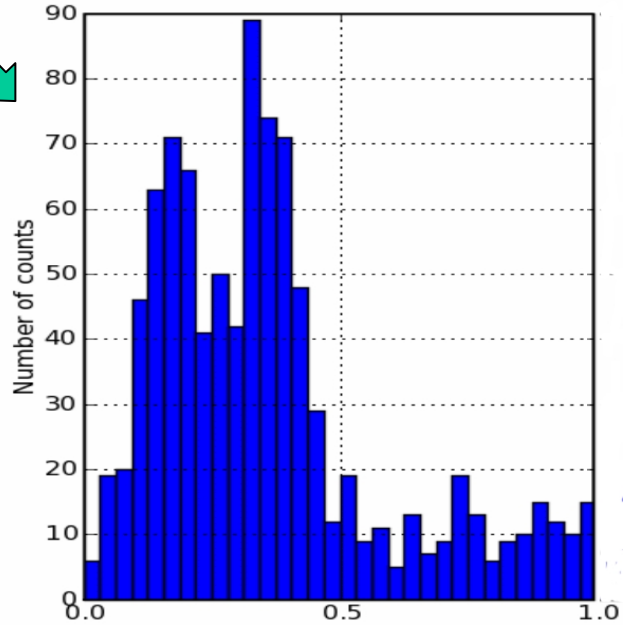
N.B.: two rotations displayed

The γ flux from the CTA 1 pulsar corresponds to about 1-10% of $\dot{E}_{rot}$ (depending on beam geometry)

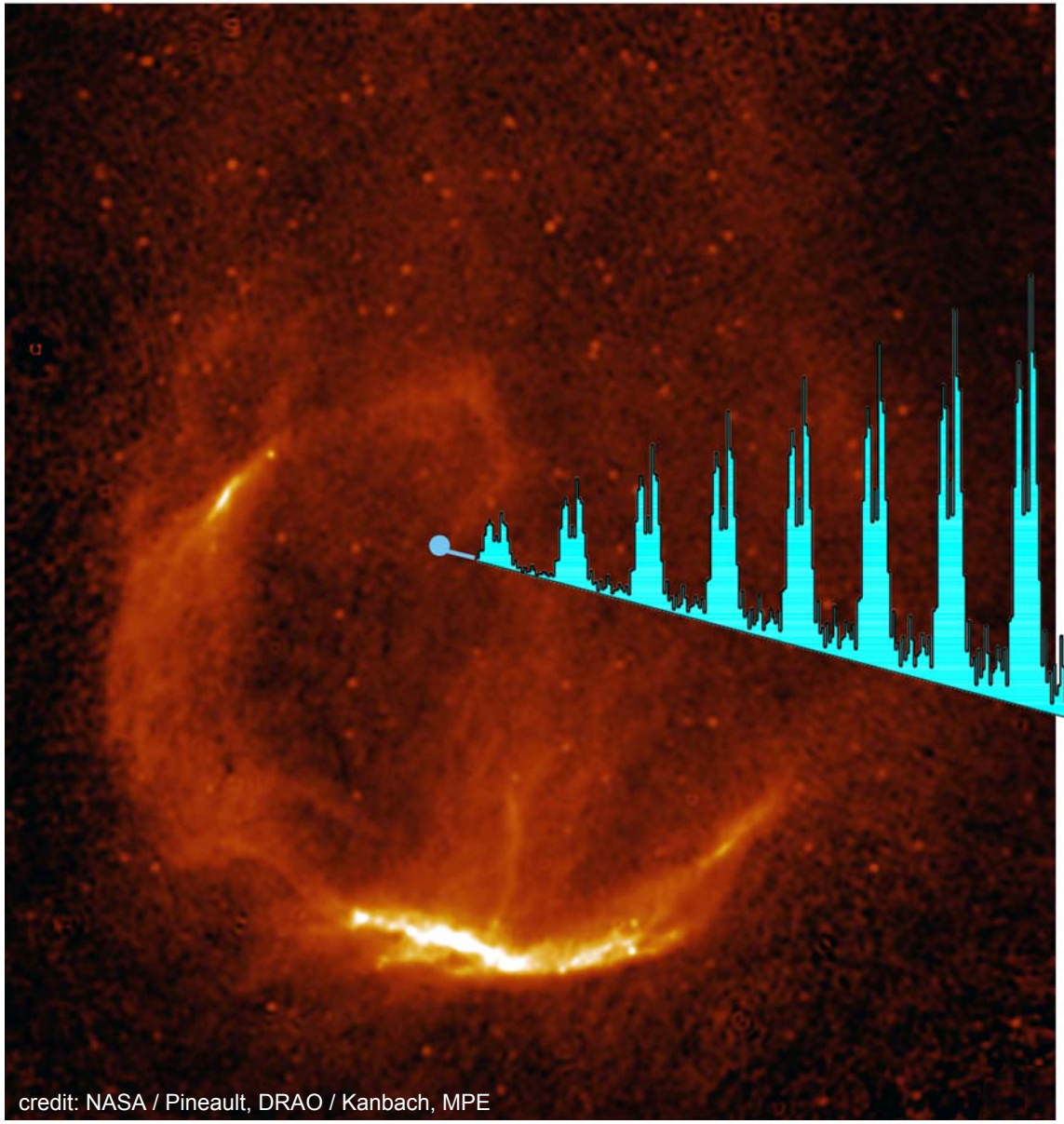
the classic EGRET 6



CTA 1



CTA 1 and the Gamma-Ray Pulsar discovered with Fermi-LAT



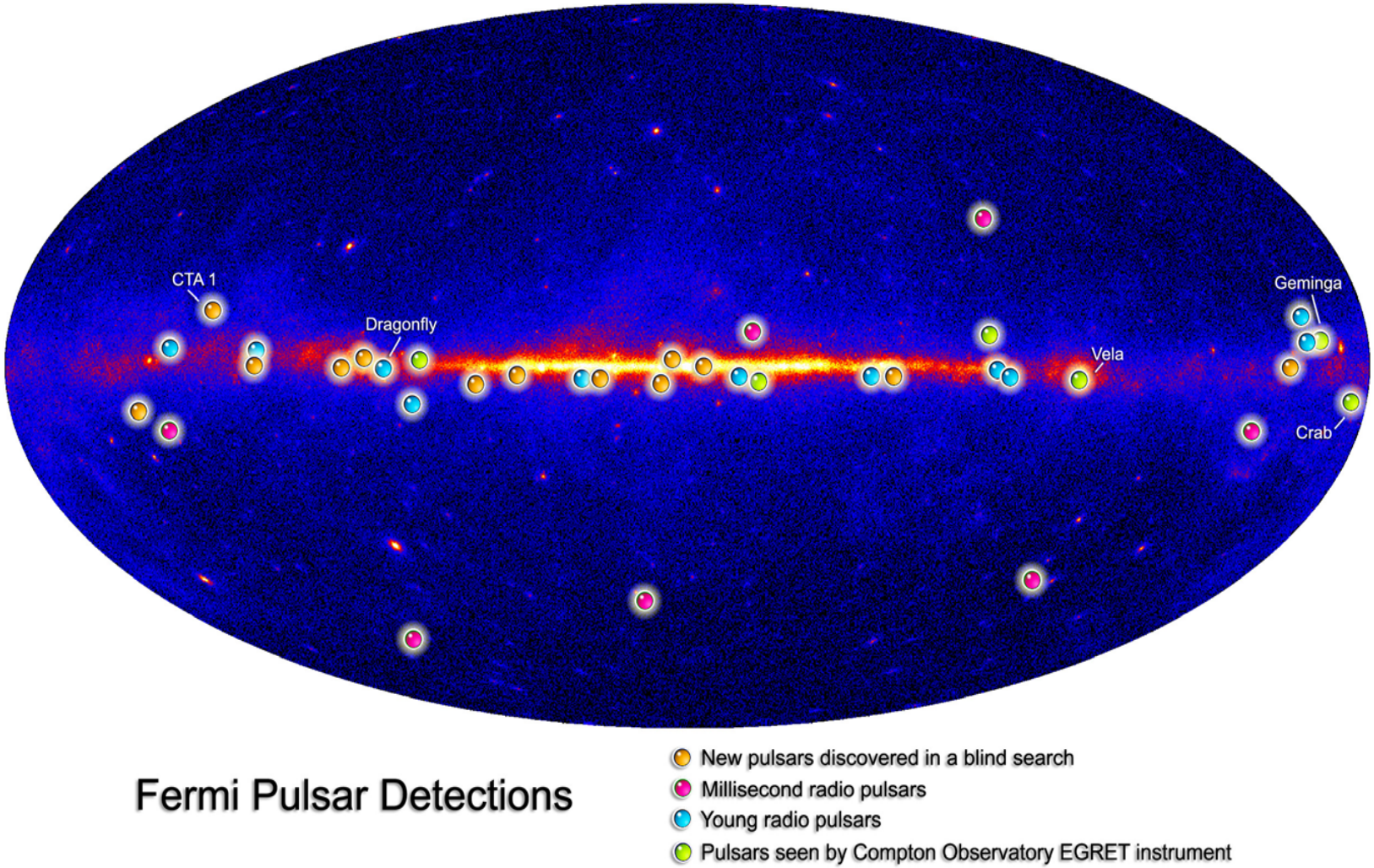
$P = 316.86$ ms

$\dot{P} = 3.614\ 10^{-13}$ s s^{-1}

Abdo, et al., Science, **322**, 1218, 2008

The Fermi-LAT Pulsar Legacy Burgeons

Matthew G. Baring on behalf of the Fermi LAT Collaboration

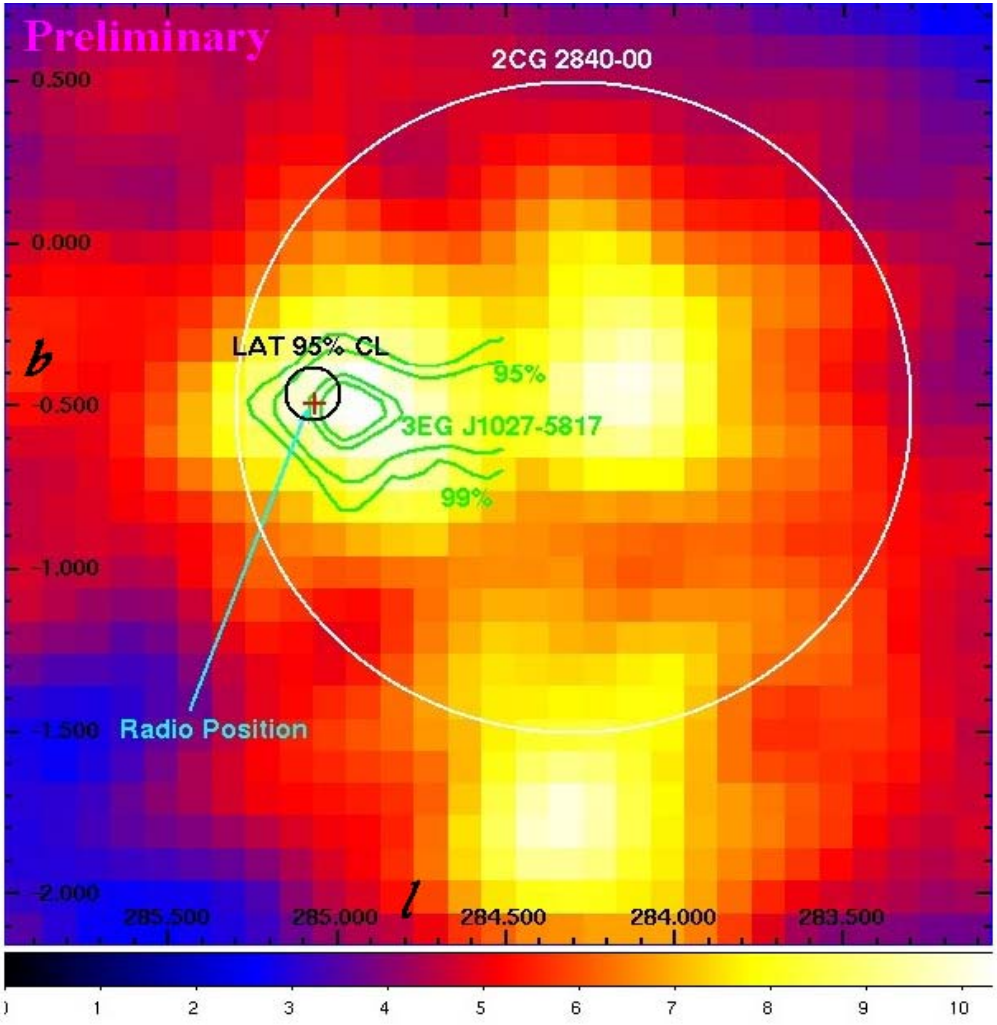


Fermi LAT Pulsar Discoveries

- AAS Press Conference (January 6, 2009) - announcement of the Fermi-LAT discovery of
  - (a) 12 ***new*** pulsars found directly in the gamma-rays, and
  - (b) 17 additional pulsars seen for the first time as gamma-ray emitters.

- In the first 4 months of the mission, over 3 dozen pulsars detected!
  - confirmed 6 known EGRET pulsars (and several EGRET candidates);
  - Found 12 new young radio pulsars;
  - Found 13 young pulsars pulsing in Gamma-rays alone;
  - Found 7 'Millisecond' Gamma-ray pulsars.
- This harvest tells us many things:
  - A unique probe into the heart of the pulsar machine;
  - A new, less biased look at the fate of massive stars.

Fermi-LAT Disentangles Crowded Fields: PSR J1028-5819



Counts map above 100MeV, gaussian smoothing applied with kernel radius of 3.

COS-B flux 2.7×10^{-6} ph/cm2/s
- Multiple source contributions

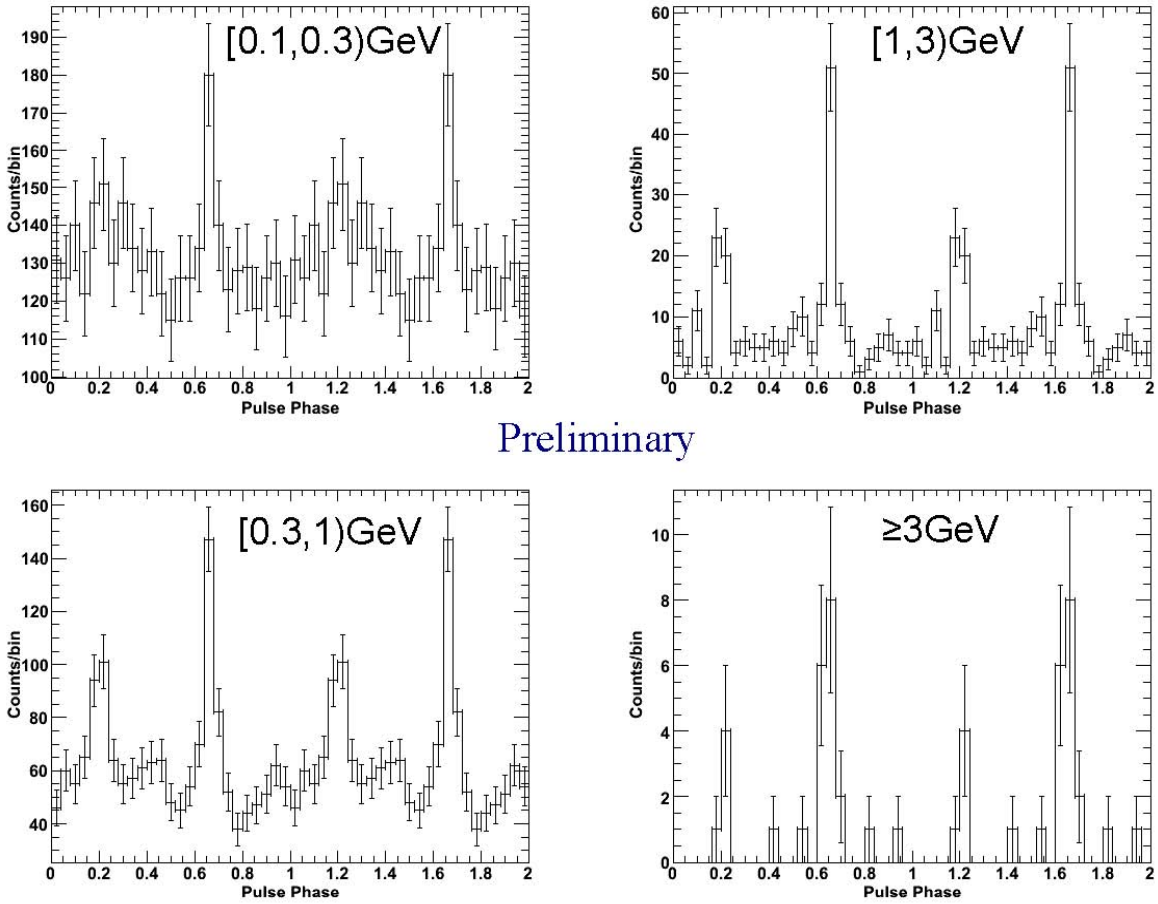
EGRET 3EG flux $(6.6 \pm 0.7) \times 10^{-7}$ ph/cm2/s
- Likely low energy contribution from nearby sources

LAT point source: integrated 0.1-30GeV flux:
- $(1.62 \pm 0.27 \pm 0.32) \times 10^{-7}$ ph/cm2/s

Shortly before launch of *Fermi*, PSR J1028-5819 discovered in radio search of EGRET error boxes *(Keith et al. 2008).*
- *P = 91.4 ms*
- *dP/dt = 1.61×10^{-14} sec/sec*
- *Characteristic age 9.21×10^{4} yr*
- *Spin-down power 8.43×10^{35} erg/s*

LAT point source is consistent with pulsar position. Pulsation detected with *6×10^{-28} chance probability*.

PSR J1028-5819: Energy-Dependent Pulse Profiles



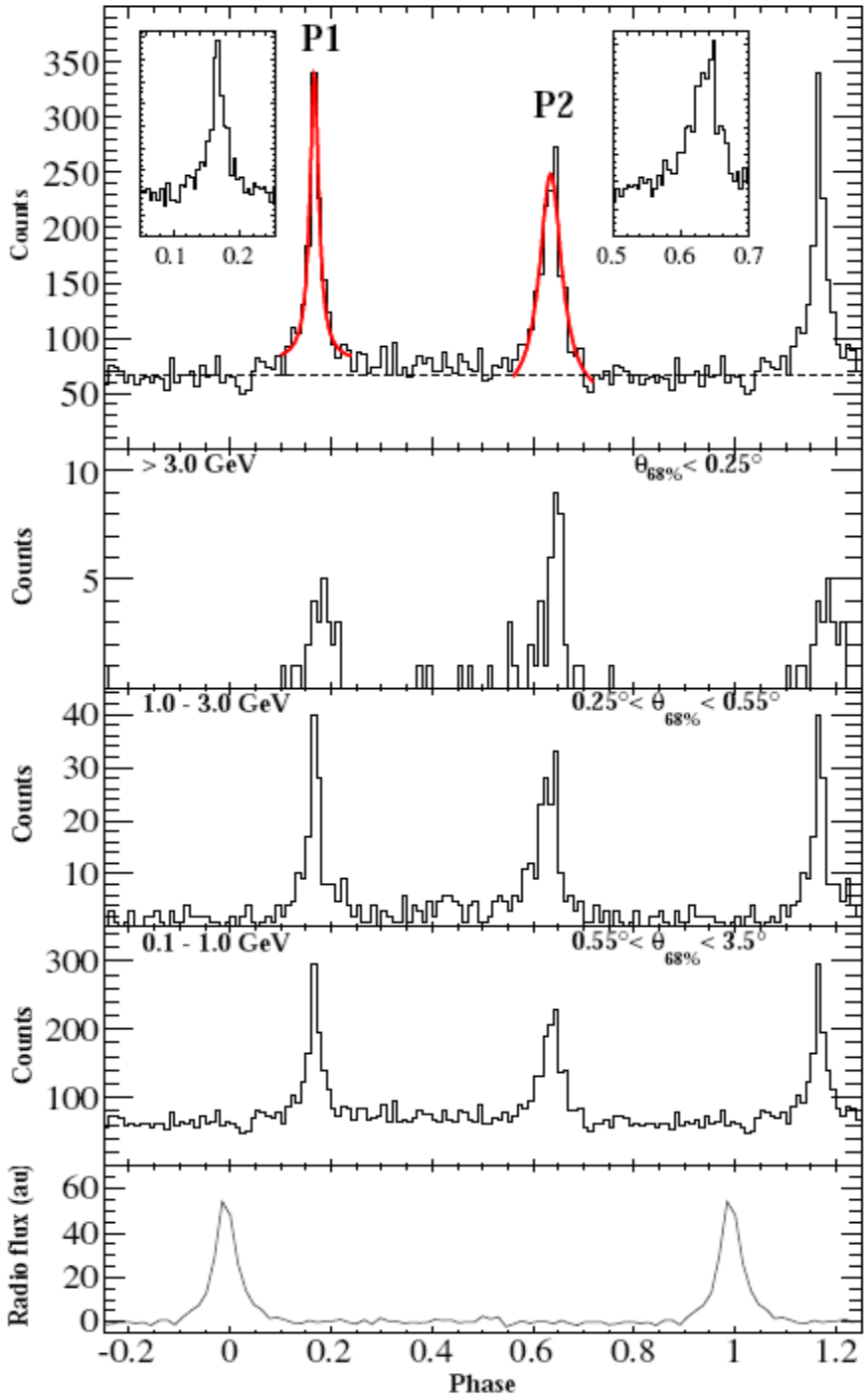
Light curve of PSR J1028-5819 in four energy bands as labeled, 25bins/rotation.

Two *narrow peaks*, separated by phase 0.460±0.004, with P1 offset from radio peak by phase 0.200±0.003.

P2 persists more strongly than P1 up to several GeV.

Evidence for pulsed emission up to ~4 GeV; rules out emission very near the neutron star surface.

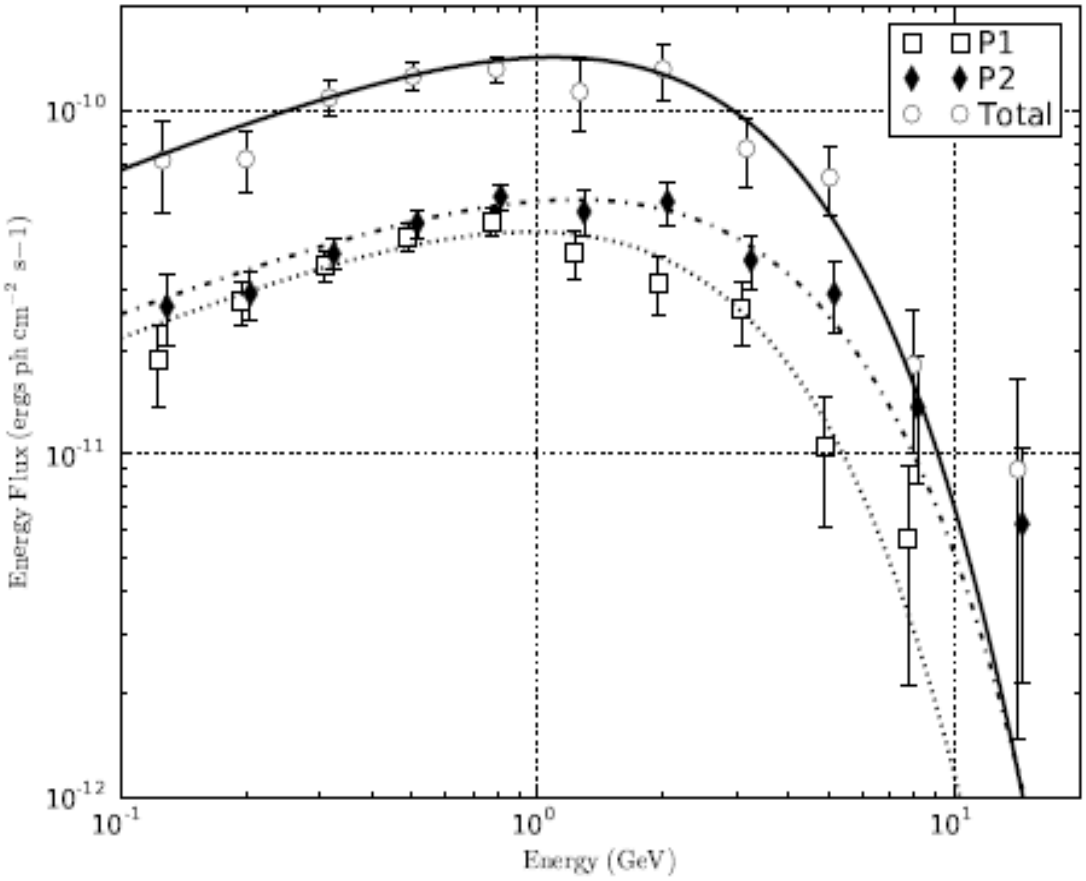
Peak separation and widths constrain the angles of magnetic inclination (α) and viewing (ζ) to large values (>60º-70º) in *slot-gap* or *outer gap* models.



PSR J2021+3651: a Vela-like Pulsar

- 3EG J2021+3716 catalogued as a very bright EGRET source;
- Subsequent radio search revealed a Vela-like pulsar (Roberts et al. 2002):
  - *Period = 103.7 ms*
  - *Spin down power $\dot{E}$ = 3.38 × 10^{36} ergs s^{-1}*
  - *Characteristic age = 17 kyr*
  - *Large distance d=12 kpc due to dispersion measure: DM = 369.3 ± 0.3 pc cm^{-3}.*
- AGILE (Halpern et al. 2008) and the *Fermi*-LAT (Abdo et al. 2009) discovered gamma-ray pulsar independently.
- Two *narrow peaks*, separated by phase 0.468±0.002, with P1 offset from radio peak by phase 0.182±0.004.
- **Pulse asymmetry like Vela**: P1/P2 ratio decreases at higher energy.

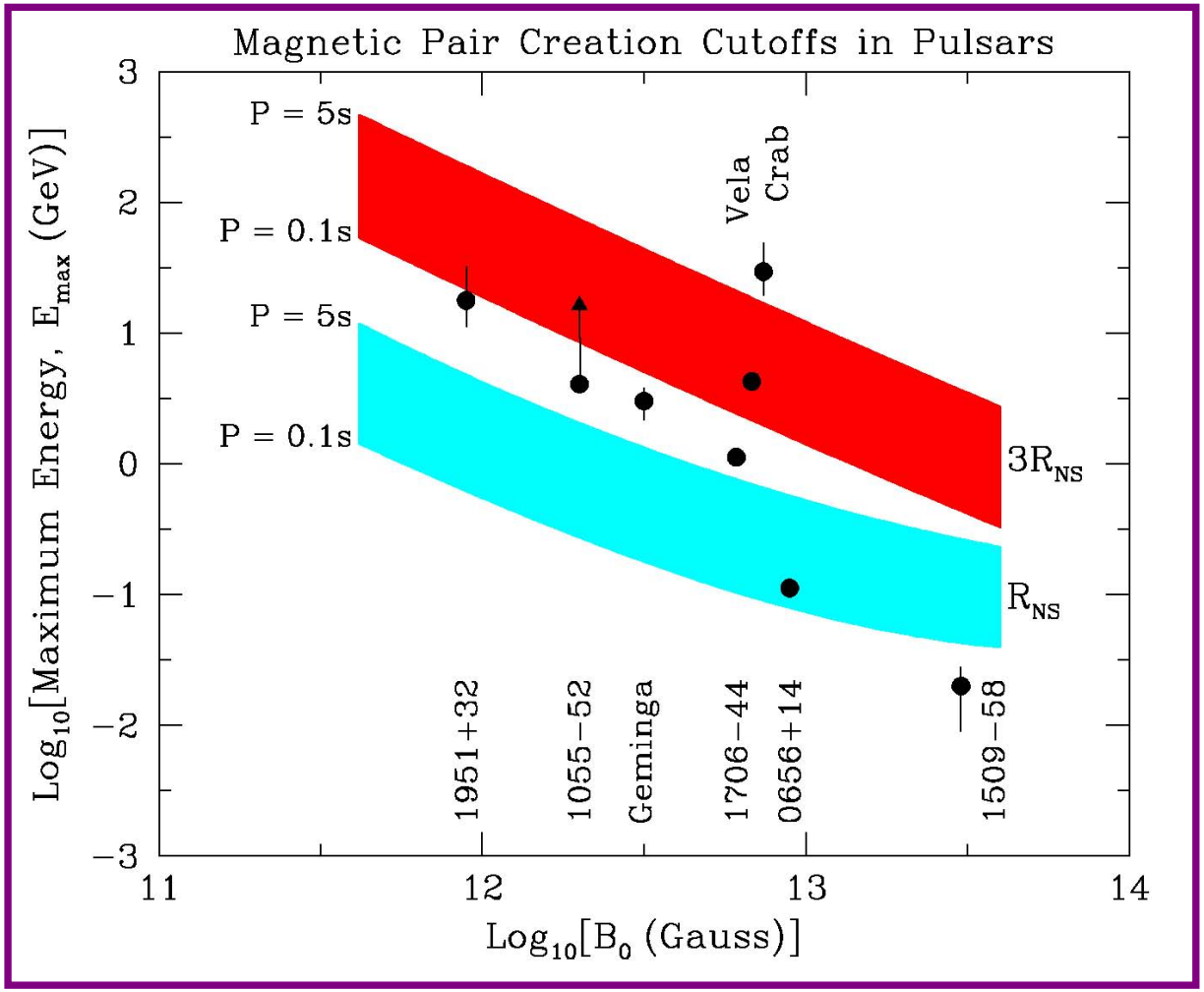
PSR 2021+3651: Spectral Turnovers below 5 GeV are Exponential



$$\frac{dF}{dE} = kE^{-\Gamma}e^{(-E/E_c)^b}$$

- Integral energy flux 4.6 ± 0.7 x 10^{-10} ergs cm^{-2} s^{-1}.
- Γ=1.5 ± 0.1 is power-law index, and E_c = 2.4 ± 0.3 ± 0.5 GeV is the cutoff energy.
- Super-exponential turnovers are excluded (b>1):
  - => **majority of emission very near the stellar** surface that is attenuated by magnetic pair creation **is not possible.**
  - This conclusion is true for both P1 and P2 peaks.
- Transparency to magnetic pair creation at and below 2 GeV also suggests moderate to high altitudes of emission.

Polar Cap Pair Creation Turnover Trends



(from Baring 2008)

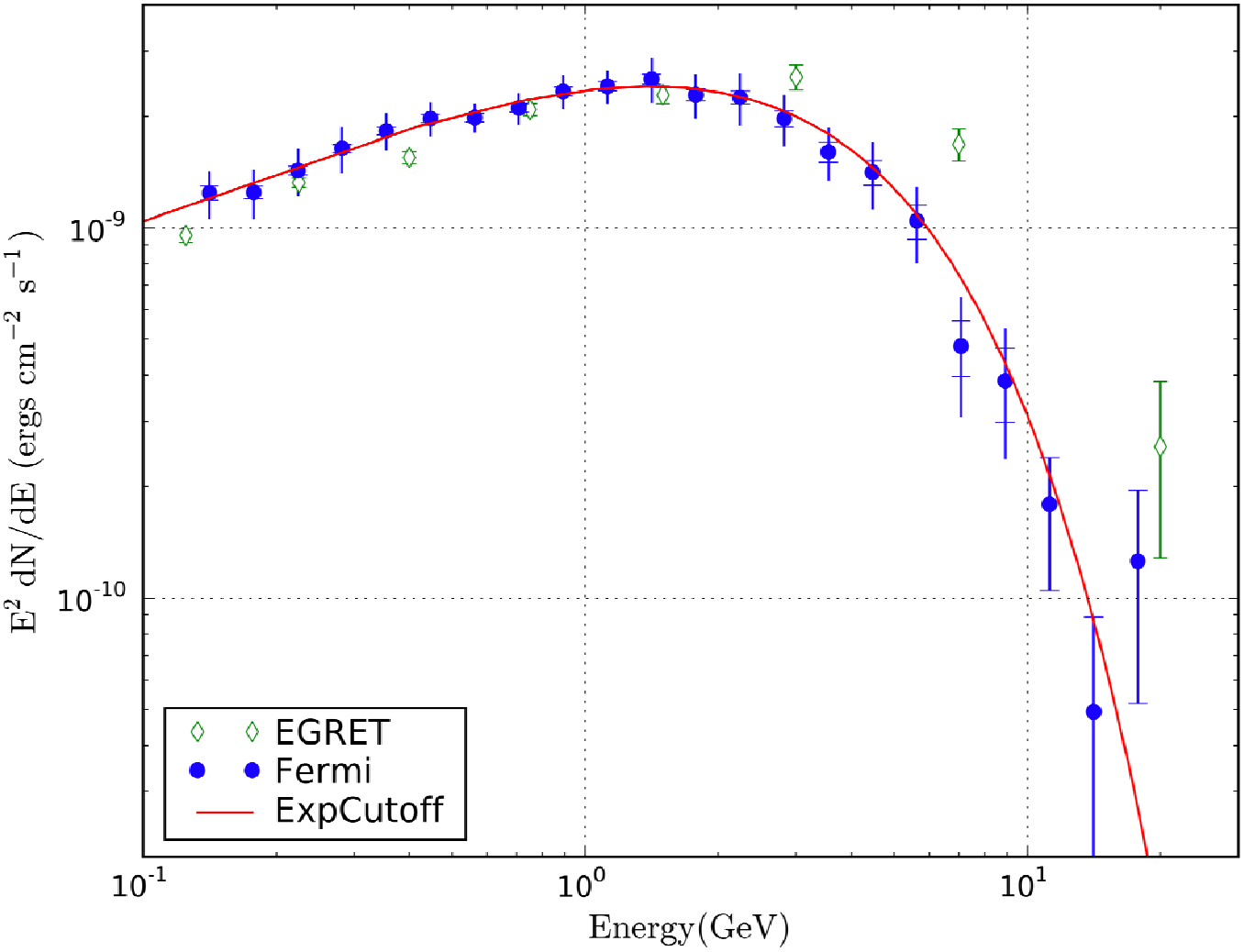
Polar cap $\gamma \rightarrow e^+e^-$ physics dictates that E_{max} declines monotonically with surface polar field strength B_0

(Baring & Harding 2001; Harding 2001; Baring 2002, and later papers)

$$\varepsilon_{MAX} \approx 0.4\sqrt{P}\left(\frac{r}{R_0}\right)^{1/2} \max\left\{1,\ \frac{0.1\,B_{cr}}{B_0}\left(\frac{r}{R_0}\right)^3\right\}\ \mathrm{GeV}$$

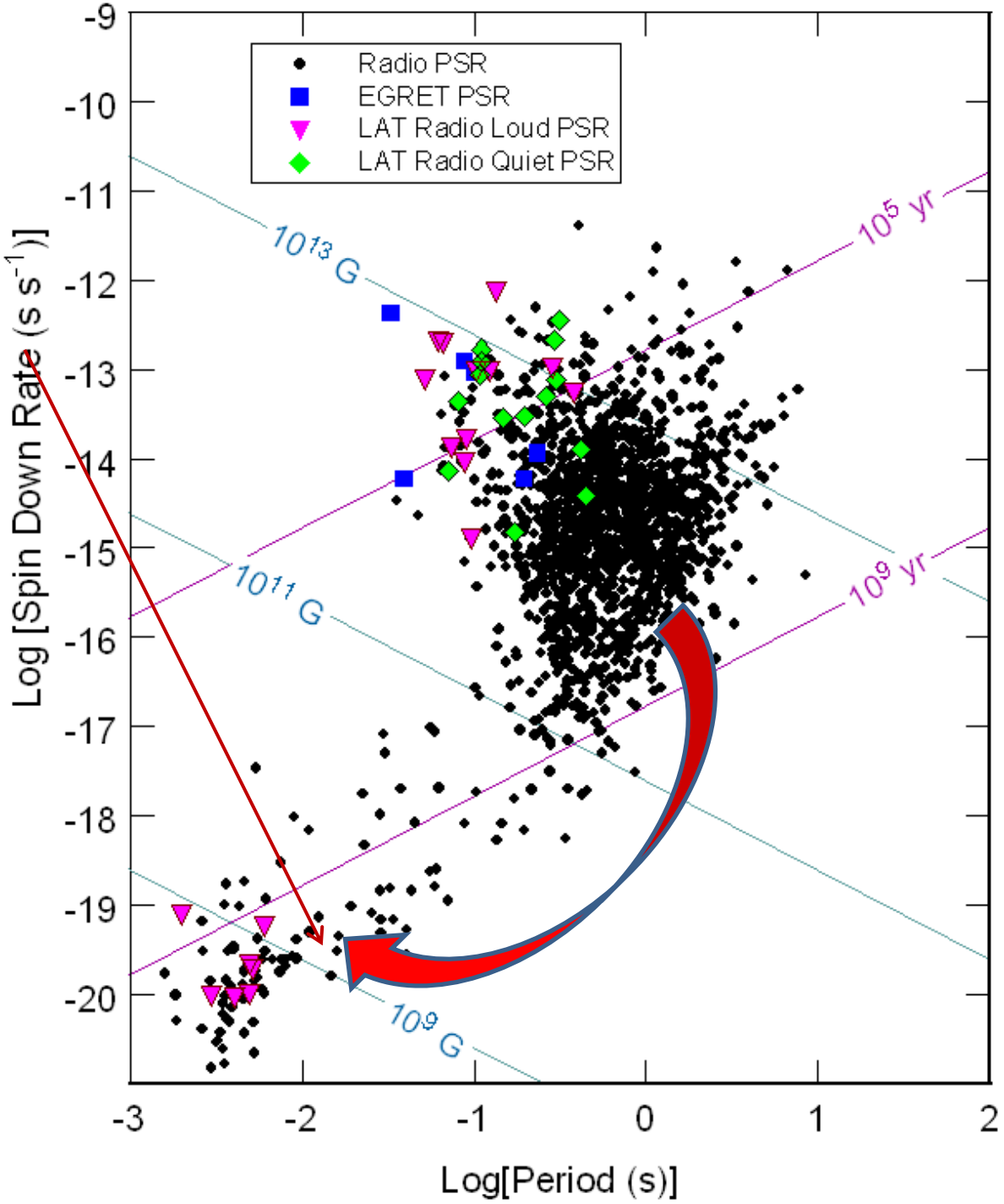
Phase-Averaged LAT Spectrum for the Vela Pulsar

Abdo et al. (2009, in press)



7 *Fermi*-LAT (6 new) ms gamma-ray pulsars

- Very different characteristics from the normal gamma-ray pulsars:
  - Spinning 100 times faster
  - Magnetic fields ~10,000 times *lower*
  - ~10,000 times *older*
- "Recycled" pulsars spun-up by binary companion stars



First *Fermi* millisecond pulsar

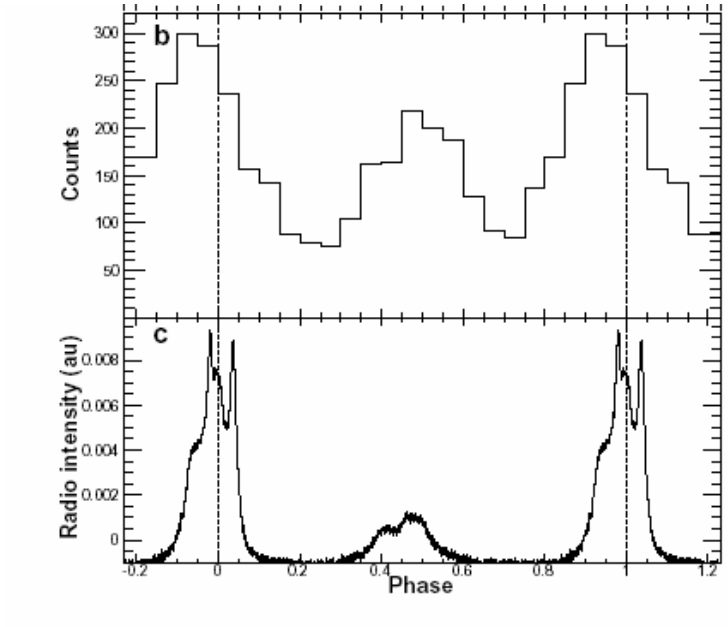
PRELIMINARY

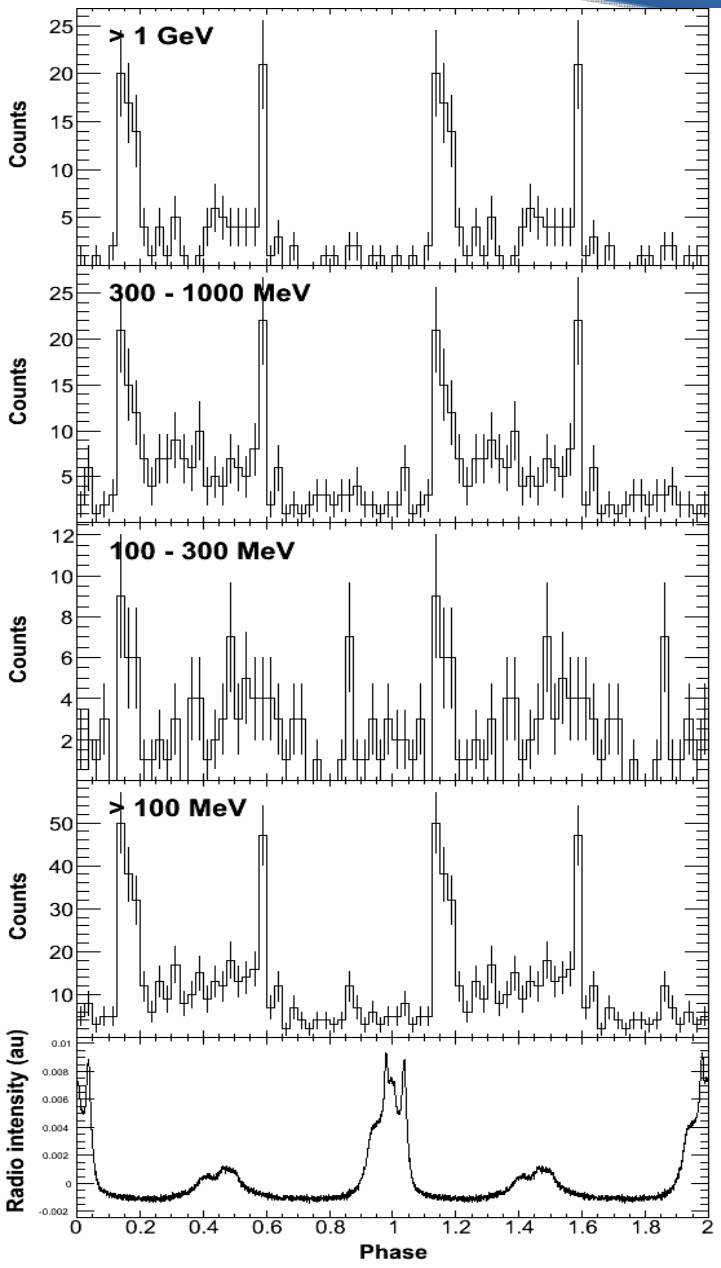
PSR J0030+0451

- P = 4.56 ms
- Nearby: d = 317 pc
- Low spin-down power

$$\dot{E}_{sd} = 3.3 \times 10^{33}\,\mathrm{erg/s}$$

- γ-ray and radio are not aligned
- X-ray and radio pulses nearly aligned
- (Abdo et al. 2009, ApJ submitted)





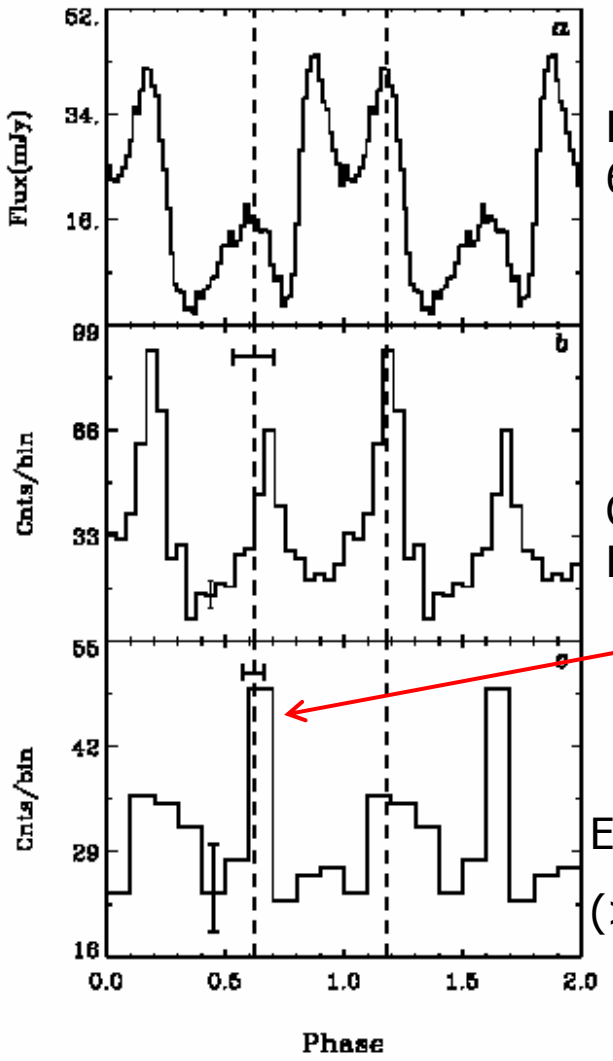
Confirmation of gamma-rays from PSR J0218+4232

Fermi

Gamma-ray Space Telescope

PRELIMINARY

Kuiper et al. (2000, 2002)



Radio 610 MHz

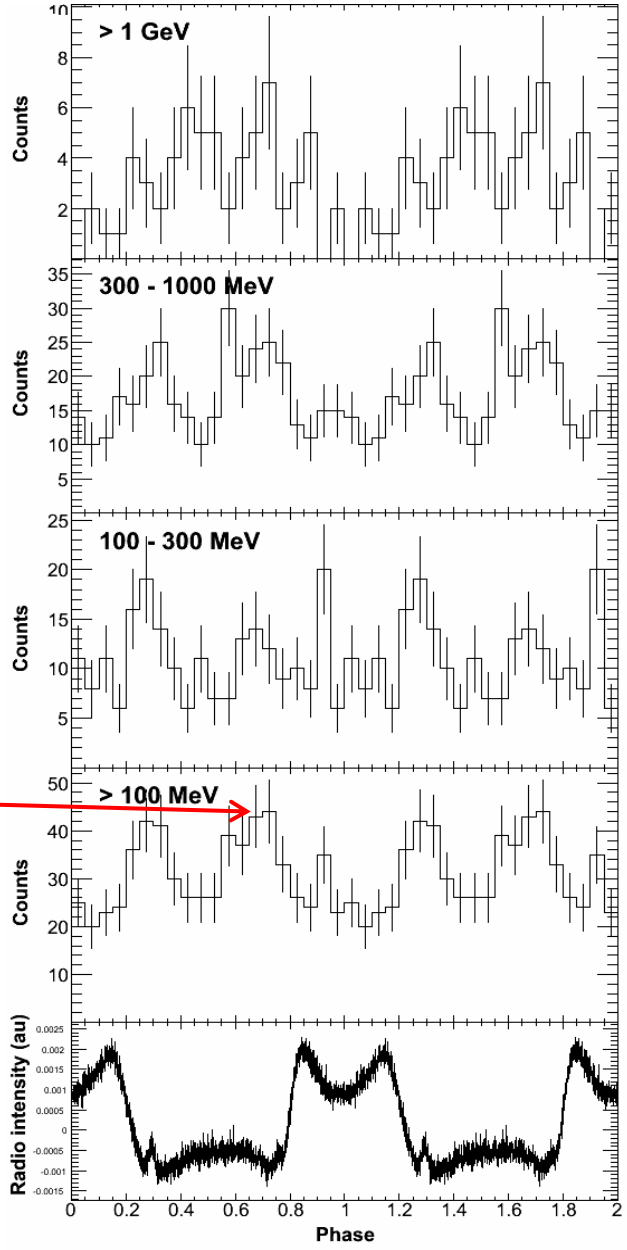
Chandra HRC

EGRET (> 100 MeV)

Near bright blazar 3C 66A

Re-analysis of EGRET data finds second peak at 0.7, in agreement with Fermi

Radio Nancay



The Incipient *Fermi* Pulsar Legacy

- What the *Fermi*-LAT can do:
  - Find gamma-ray counterparts to known radio pulsars and discover previously unknown pulsars through blind searches;
  - Resolve crowded fields and provide much more sensitive phase-resolved spectroscopy;
- What *Fermi*-LAT has told us so far about pulsars:
  - Many young gamma-ray PSRs are radio-quiet or radio-weak;
  - Peak phase separation is large, and exponential spectral turnovers in ~2-10 GeV range abound;
  - Young pulsars do not emit predominantly very near the stellar surface => slot-gap or outer gap scenarios;
  - Higher spin-down power millisecond PSRs commonly emit gamma-rays, probably in 47 Tuc too.