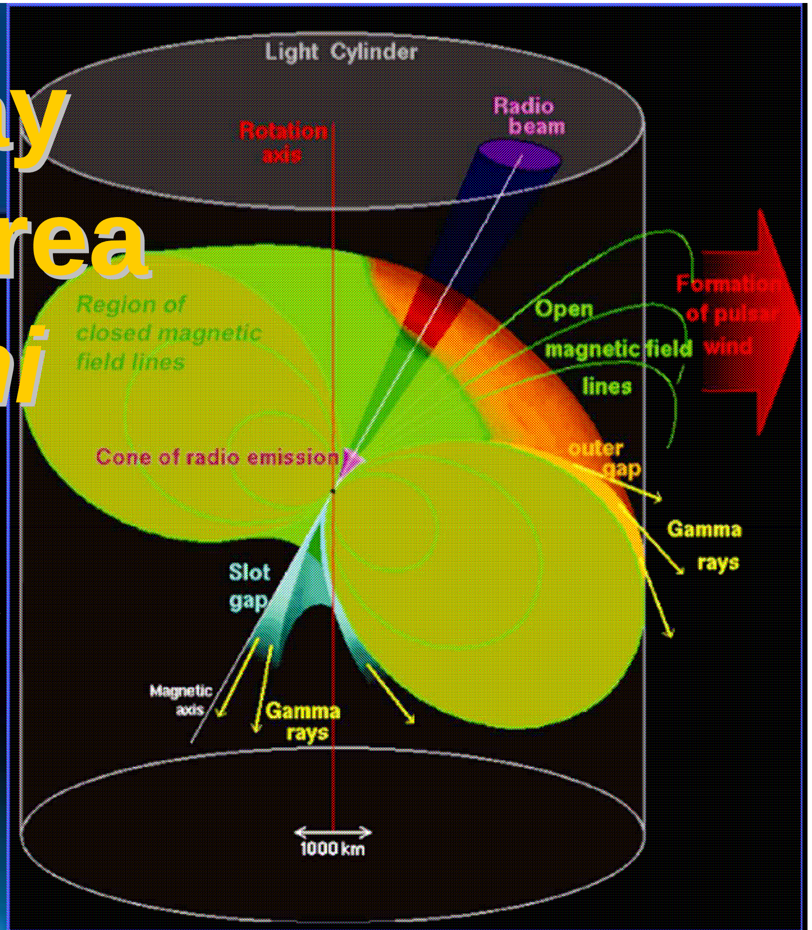
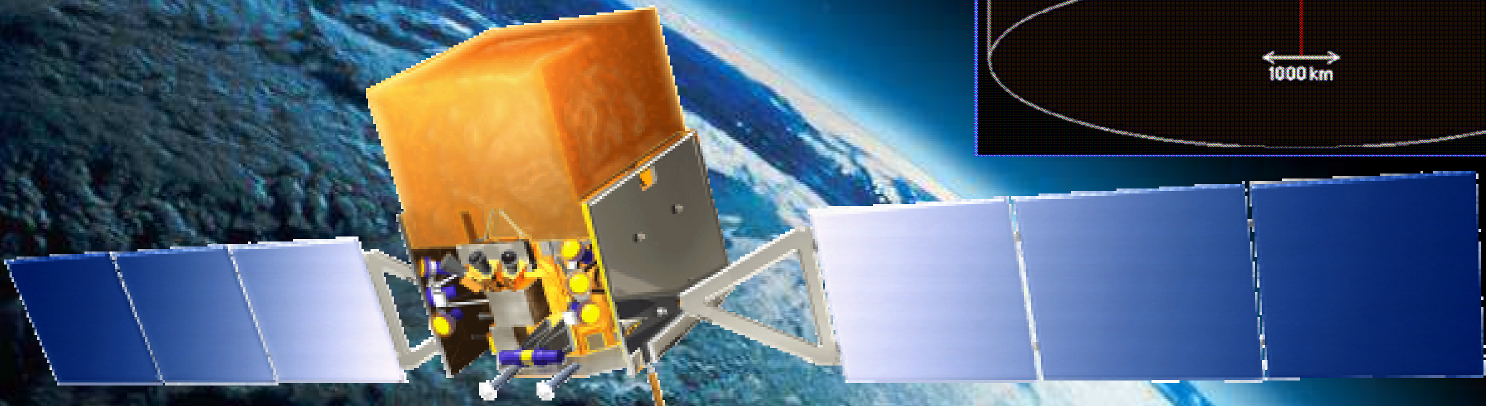
The GeV Gamma-ray Sky with the Large Area Telescope on *Fermi*

(formerly GLAST)

with an accent on pulsars

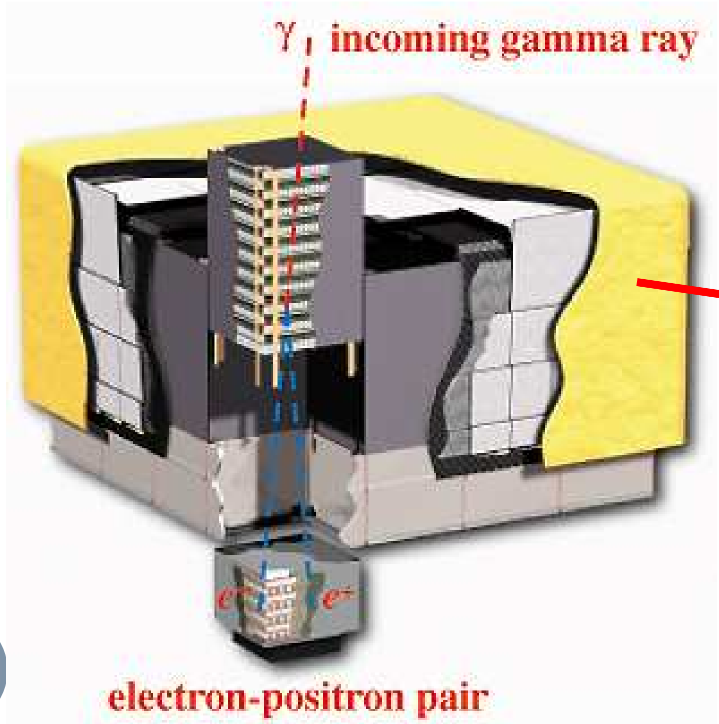




David A. Smith, for the *Fermi* LAT collaboration
Centre d'Études Nucléaires de Bordeaux-Gradignan
(CENBG / IN2P3 / CNRS)
smith@cenbg.in2p3.fr

TANGO in Paris
IAP, 4-6 May 2009

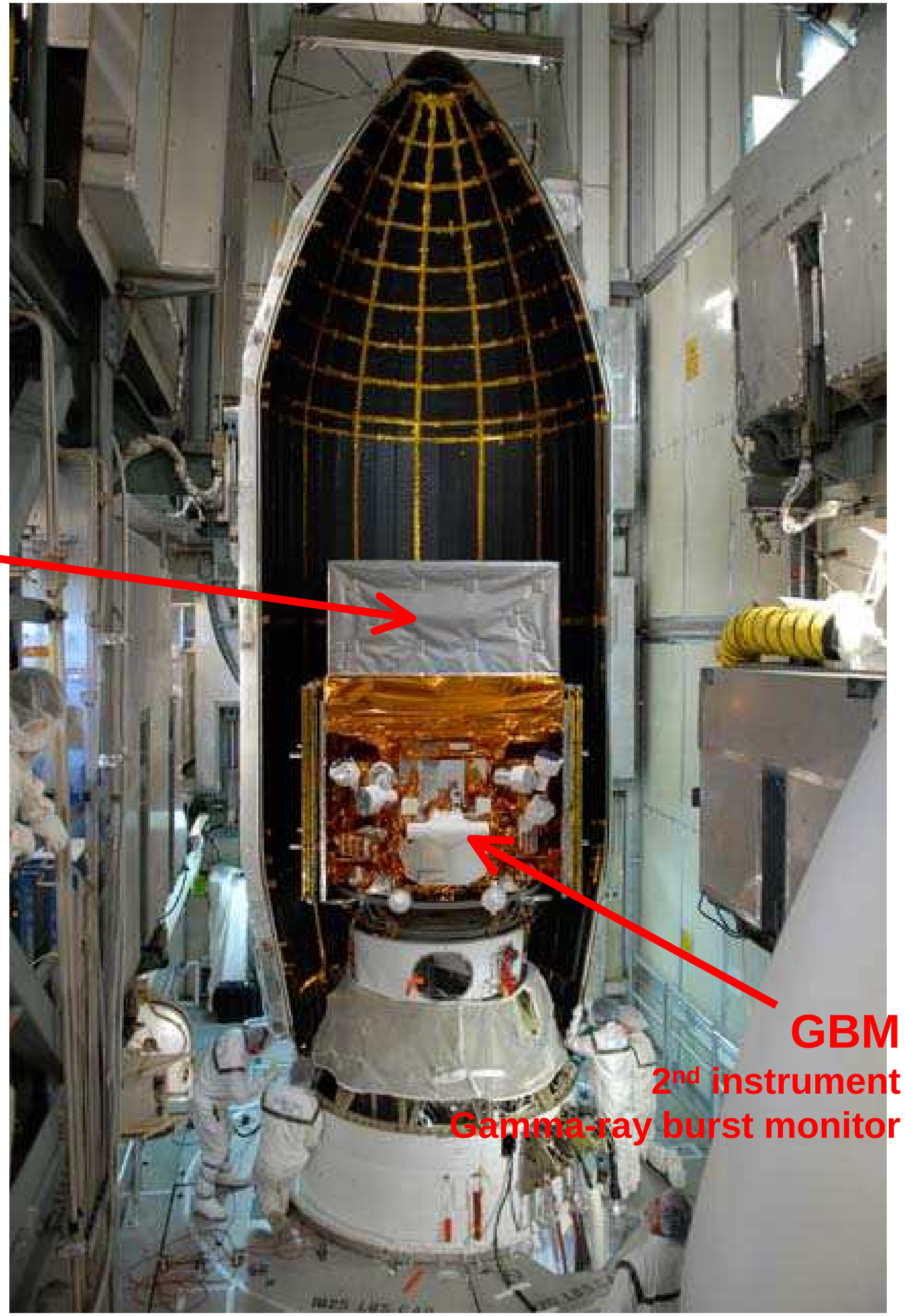
The Large Area Telescope (LAT)



<u>The whole sky, 8 times per day</u>:

• Record the expected, as well as the unexpected.

• Including variable objects.



Fermi LAT science objectives

> 2000 AGNs
blazars and radiogal = f(θ,z)
evolution z < 5
Sag A*

10-50 γ-ray bursts/year
GeV afterglow
spectra to high energy

γ-ray binaries
Pulsar winds
μ-quasar jets

Possibilities
starburst galaxies
galaxy clusters
measure EBL*
Un-IDs

*Extragalactic Background Light. Probed via $\gamma\gamma \rightarrow e^+e^-$.

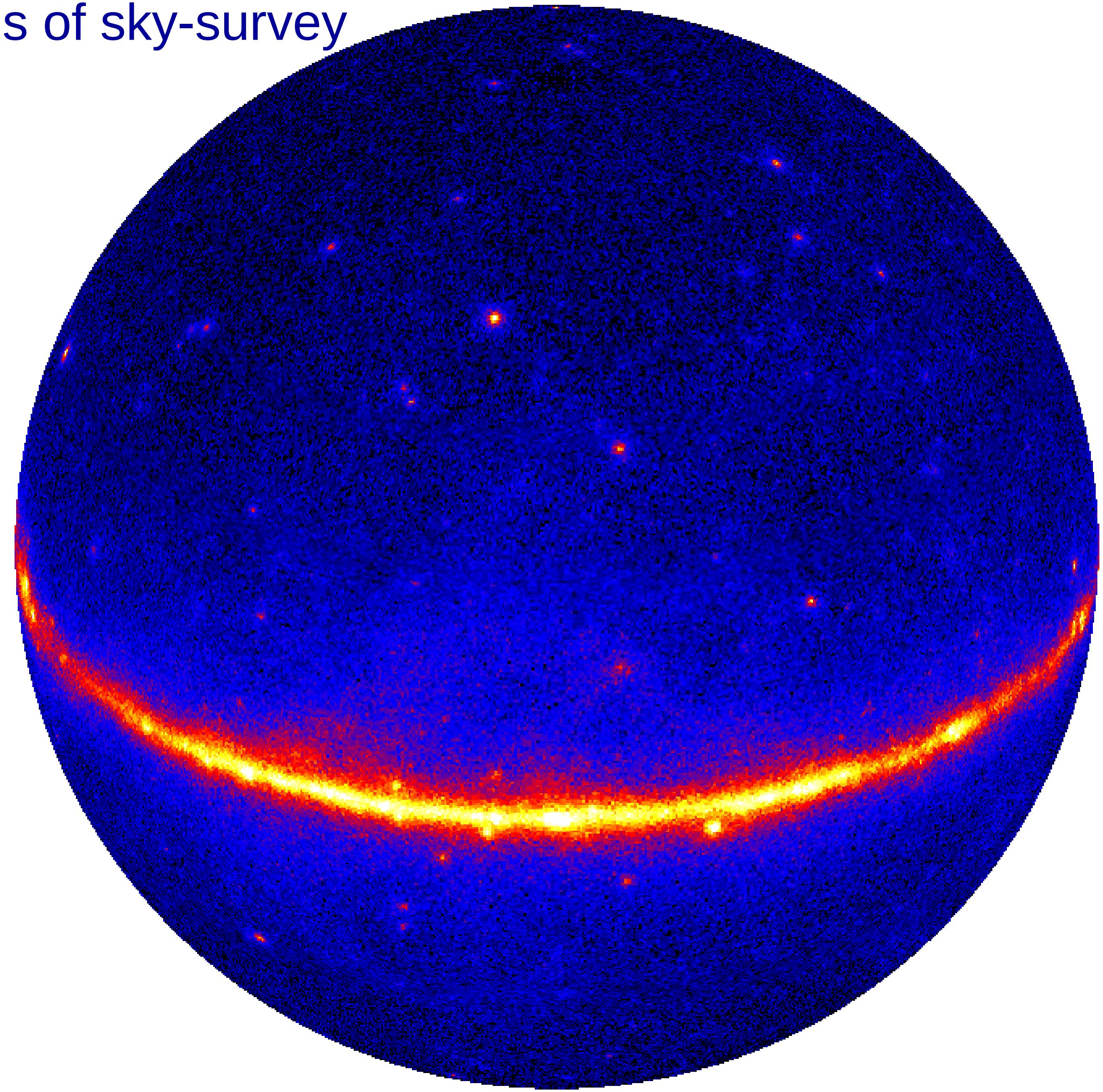
Dark Matter
neutralino lines
sub-halo clumps

Cosmic rays and clouds
acceleration in Supernova remnants
OB associations
propagation (Milky Way, M31, LMC, SMC)
Interstellar mass tracers in galaxies

Pulsars
gammas from radio and X-ray pulsars
blind searches for new Gemingas*
pulsar wind nebulae

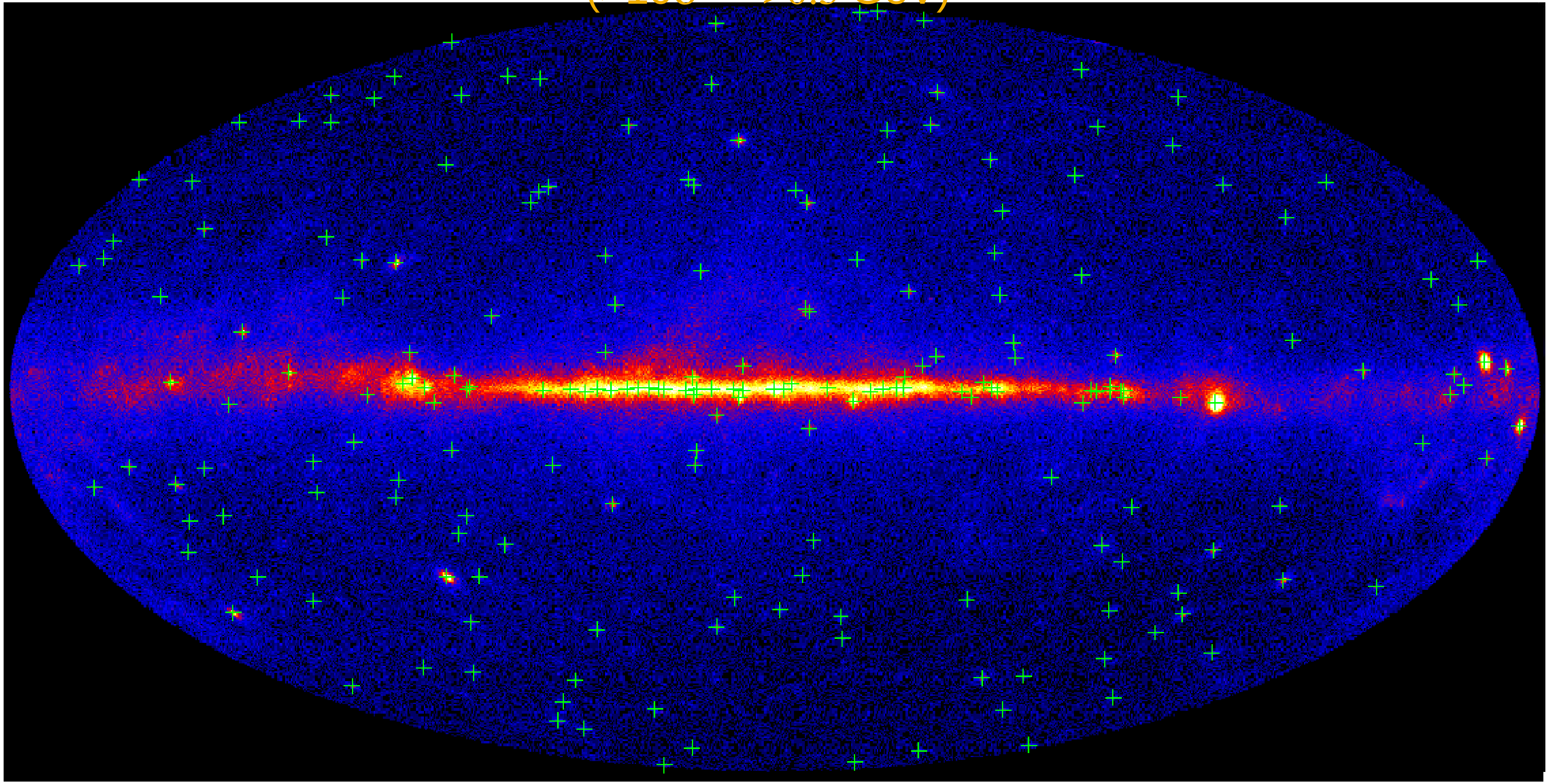
* Name of the only radio-quiet gamma-ray pulsar known before launch

3 months of sky-survey



3 months: 205 LAT Bright Sources

(>10σ   >0.3 GeV)



Fermi Large Area Telescope Bright Gamma-ray Source List

Abdo, A. A. et al. 2009, Ap J Suppl *submitted*, arXiv: 0902.1340

Bright AGN Source List from the First Three Months of the Fermi Large Area Telescope Sky Survey

Abdo, A. A. et al. 2009, Ap J *submitted*, arXiv: 0902.1559

Fermi LAT Publications: http://www-glast.stanford.edu/cgi-bin/pubpub

Discovery of Pulsed Gamma Rays from the Young Radio Pulsar PSR J1028-5819 with the Fermi Large Area Telescope
Abdo et al. 2009, ApJL, 695, L72 arXiv: 0903.1602

Fermi observations of high-energy gamma-ray emission from GRB 080916C
Abdo, A. A. et al. 2009, Science, 323, 1688

The Fermi Large Area Telescope discovers the pulsar in the young galactic supernova remnant CTA 1
Abdo, A. A. et al. 2008, Science, 322, 1218 arXiv: 0810.3562

Fermi/LAT discovery of gamma-ray emission from a relativistic jet in the Narrow-Line Quasar PMN J0948+0022
Abdo, A. A. et al. 2009, ApJ

Measurement of the cosmic ray e+ + e- spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope
Abdo, A. A. 2009, Phys. Rev. Lett.

Fermi LAT Observations of the Vela Pulsar
Abdo, A. A. et al. 2009, ApJ, arXiv: 0812.2960

Fermi/LAT discovery of gamma-ray emission from the flat-spectrum radio quasar PKS 1454-354
Abdo, A. A. et al. 2009, ApJ, arXiv: 0903.1713

~10 more papers submitted, or very close.

Fermi Discovery of gamma-ray emission from NGC1275
Abdo, A. A. et al. 2009, ApJ, 699, arXiv: 0904.1904

Pulsed Gamma-rays from the millisecond pulsar J0030+0451 with Fermi
Abdo, A. A. et al. 2009, ApJ, arXiv: 0904.4377

Early Fermi Gamma-ray Space Telescope Observations of the Quasar 3C 454.3
Abdo, A. A. et al. 2009, ApJ,arXiv: 0904.4280

Simultaneous observations of PKS 2155-304 with H.E.S.S., Fermi, RXTE and ATOM…
Abdo, A. A. et al. 2009, ApJL, arXiv: 0903.2924

This talk:

- Focus on pulsars
  - We have already seen many
  - Why more may be coming

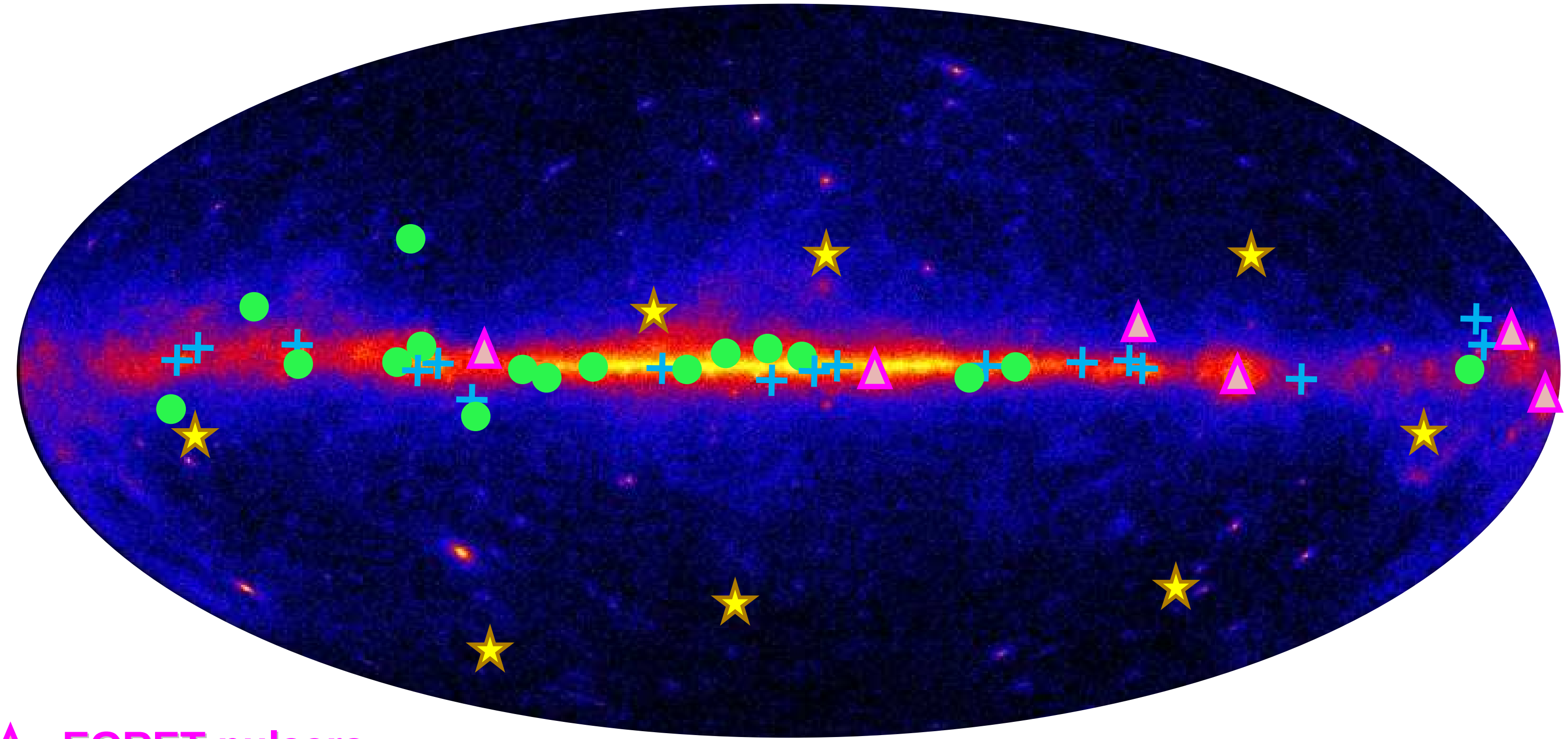
- Very few words about other Galactic sources

- No words about other source types (GRBs, blazars… sorry – time constraint)

Fermi pulsars

29 gamma-ray and radio pulsars (includes 8 millisecond pulsars)

16 gamma-ray only pulsars



EGRET pulsars

young pulsars discovered using radio ephemeris

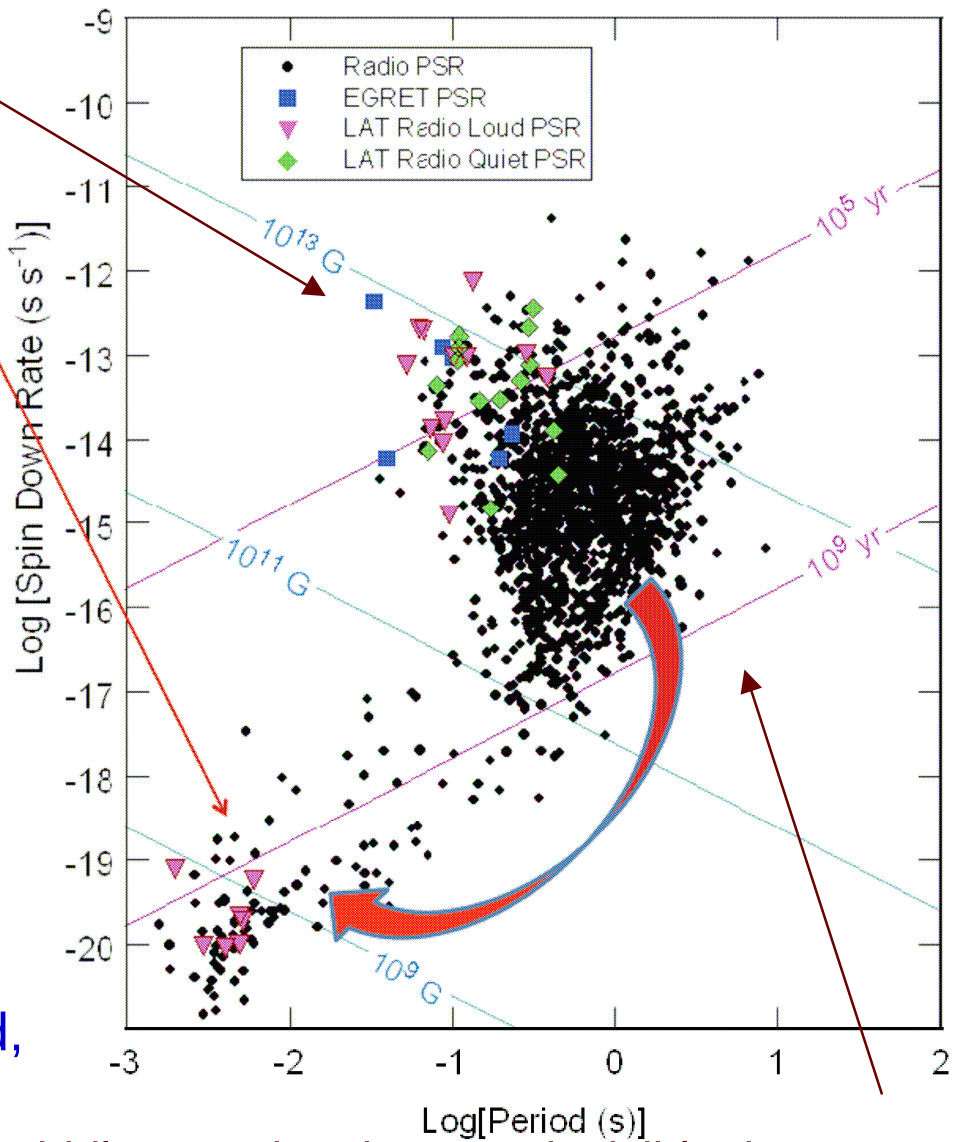
pulsars discovered in blind search

millisecond pulsars discovered using radio ephemerides

Spin-down power Edot = 4π²Pdot/P³.

newborn pulsars
(The EGRET pulsars are here)

"Recycled", or millisecond pulsars



>1800 known radio pulsars

(perhaps millions in Galaxy)

~ 50 in X-rays, 6 in optical, and, before *Fermi*, 6 in γ-rays.

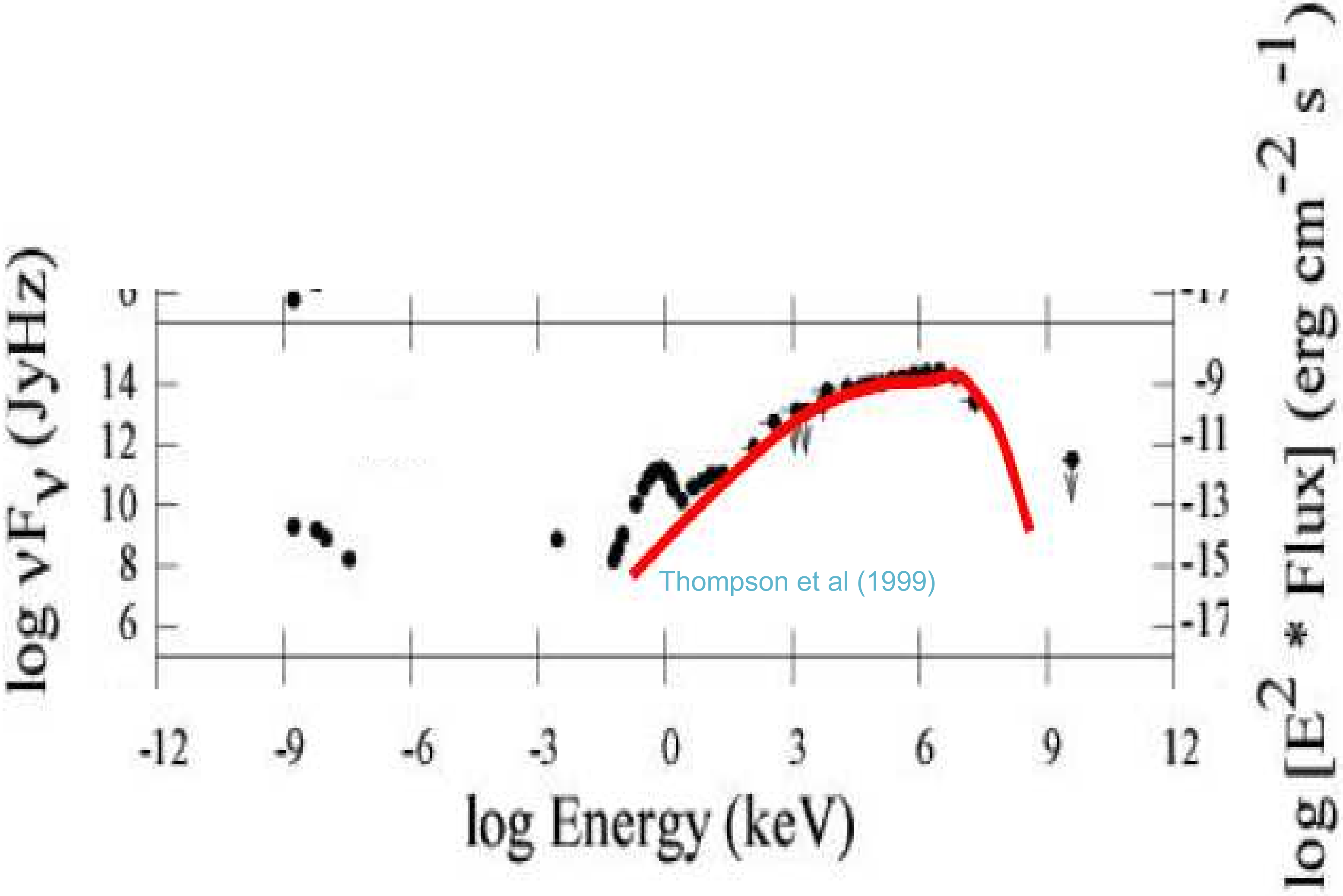
In middle age, they become invisible, but can accrete a binary companion's spin, to live again.

Most photon power in gammas (for known γ psr's) .

➔A fraction to tens of % of Edot.

Even bigger fraction of Edot in the electron wind.

Power



Pulsar categories:

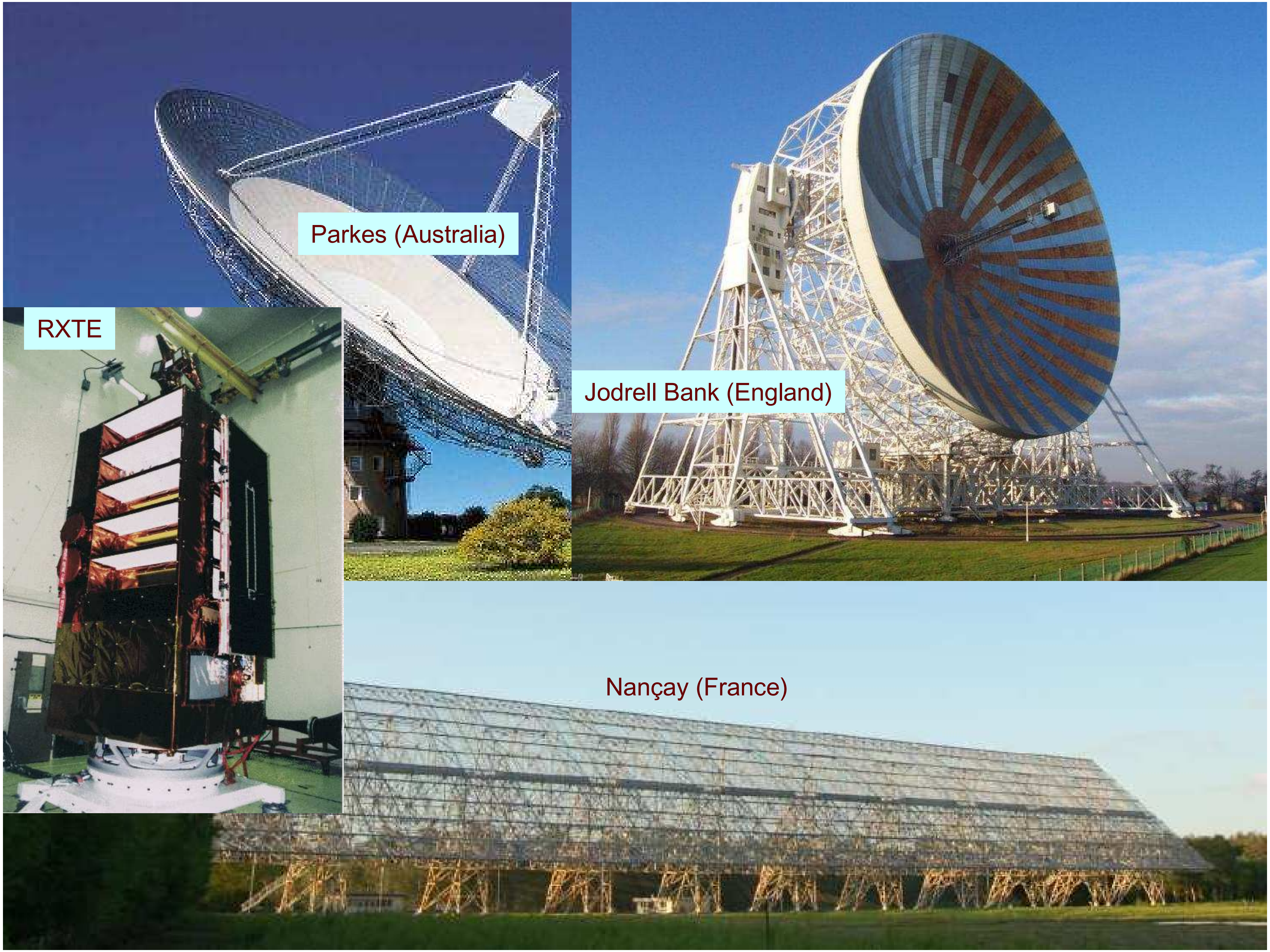
- EGRET-like. Young radio pulsars with large Edot, but "timing noise"
  - ➢ Substantial pre- to post-launch radio and X-ray timing campaign
  - ➢ 224 target pulsars with Edot > 1E34 erg/s

- Geminga-like. If the gamma-ray beam is wider than the radio beam, or oriented differently, both may not sweep the Earth. *("outer magnetosphere models")*
  - ➢ High-performance "blind rotation period search" algorithms.
  - ➢ Clever choices of candidate locations (e.g. X-ray neutron star candidates)

- Millisecond pulsars. Lower B-field, higher spin, similar gamma-ray emission.

- None-of-the-above. Sky-survey ensures that all bright emitters are recorded. Our analysis infrastructure accepts broadening search categories.
  - ➢ Rotation ephemerides for ~800 pulsars of all types, from Nançay and Jodrell Bank.

- Radio follow-up of gamma-ray point sources.
  - ➢ Radio sky surveys are *far* from complete.
  - ➢ For low gamma-ray counts, or for binary systems, radio searches better.


Parkes (Australia)
RXTE
Jodrell Bank (England)
Nançay (France)

Campaign to time 224 high Edot "Egret-like" pulsars

Excellent working relation with the radio and X-ray pulsar experts.

Pulsar Timing for the *Fermi* Gamma-ray Space Telescope

D. A. Smith[1,2], L. Guillemot[1,2], F. Camilo[3], I. Cognard[4,5], D. Dumora[1,2], C. Espinoza[6], P. C. C. Freire[7], E. V. Gotthelf[3], A. K. Harding[8], G. B. Hobbs[9], S. Johnston[9], V. M. Kaspi[10], M. Kramer[6], M. A. Livingstone[10], A. G. Lyne[6], R. N. Manchester[9], F. E. Marshall[8], M. A. McLaughlin[9], A. Noutsos[6], S. M. Ransom[10], M. S. E. Roberts[13], R. W. Romani[14], B. W. Stappers[6], G. Theureau[4,5], D. J. Thompson[8], S. E. Thorsett[15], N. Wang[16], and P. Weltevrede[9]

[1] Université de Bordeaux, Centre d'études nucléaires de Bordeaux Gradignan, UMR 5797, Gradignan, 33175, France
[2] CNRS/IN2P3, Centre d'études nucléaires de Bordeaux Gradignan, UMR 5797, Gradignan, 33175, France
[3] Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[4] Laboratoire de Physique et Chimie de l'Environnement, LPCE UMR 6115 CNRS/INSU, Orléans, 45071, France
[5] Station de radioastronomie de Nançay, Observatoire de Paris, Nançay, 18330, France
[6] University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, UK
[7] Arecibo Observatory, HC 3 Box 53995, Arecibo, Puerto Rico 00612, USA
[8] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[9] Australia Telescope National Facility, CSIRO, PO Box 76, Epping NSW 1710, Australia
[10] McGill University, Montreal, Quebec, Canada
[11] West Virginia University, Department of Physics, PO Box 6315, Morgantown, WV 26506, USA
[12] National Radio Astronomy Observatory, Charlottesville, VA 22903, USA
[13] Eureka Scientific, Inc., 2452 Delmer Street Suite 100, Oakland, CA 94602-3017, USA
[14] Department of Physics, Stanford University, California, USA
[15] Department of Astronomy & Astrophysics, University of California, Santa Cruz, CA 95064, USA
[16] National Astronomical Observatories-CAS, 40-5 South Beijing Road, Urumqi 830011, China

Preprint online version: September 4, 2008

ABSTRACT

We describe a comprehensive pulsar monitoring campaign for the Large Area Telescope (LAT) on the *Fermi Gamma-ray Space Telescope* (formerly GLAST). The detection and study of pulsars in gamma rays give insights into the populations of neutron stars and supernova rates in the Galaxy, into particle acceleration mechanisms in neutron star magnetospheres, and into the "engines" driving pulsar wind nebulae. LAT's unprecedented sensitivity between 20 MeV and 300 GeV together with its 2.4 sr field-of-view makes detection of many gamma-ray pulsars likely, justifying the monitoring of over two hundred pulsars with large spin-down powers. To search for gamma-ray pulsations from most of these pulsars requires a set of phase-connected timing solutions spanning a year or more to properly align the sparse photon arrival times. We describe the choice of pulsars and the instruments involved in the campaign. Attention is paid to verifications of the LAT pulsar software, using for example giant radio pulses from the Crab and from PSR B1937+21 recorded at Nançay, and using X-ray data on PSR J0218+4232 from XMM-Newton. We demonstrate accuracy of the pulsar phase calculations at the microsecond level.

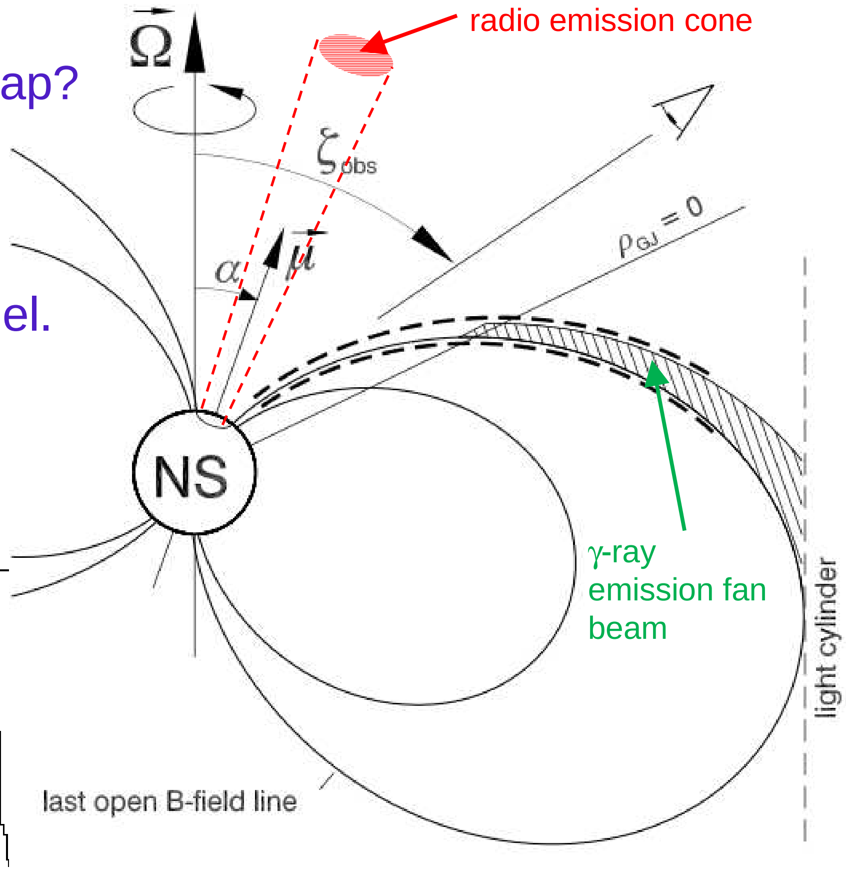
A&A 492, 293 (2008)

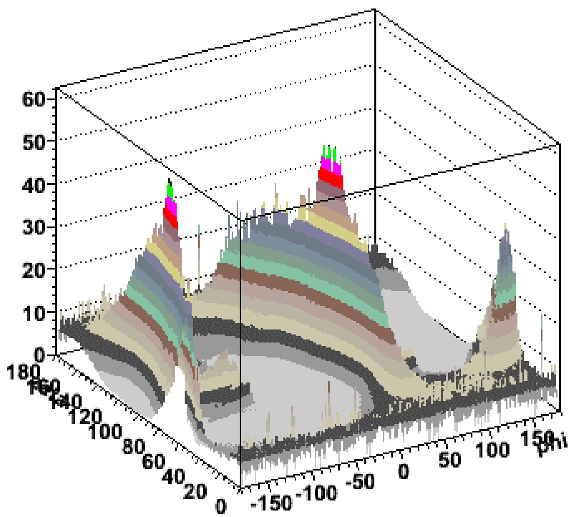
Key words. pulsars:general – Gamma-rays:observations – Ephemerides

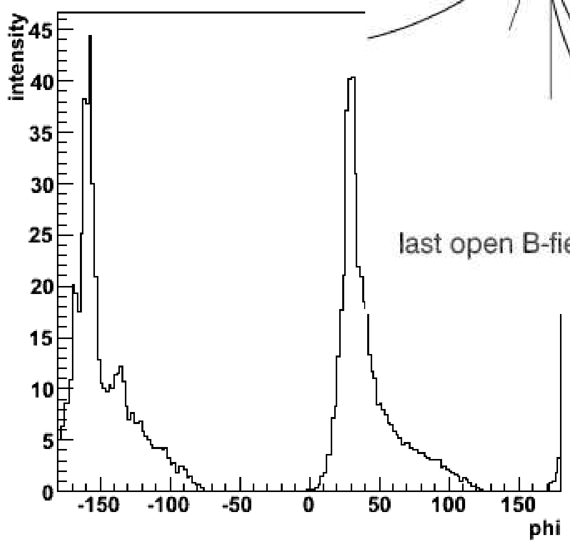
~~Radio-quiet, Geminga-like~~ "Gamma-ray selected" pulsars

- Geminga : no radio pulsations even with very deep searches.
- Deep radio searches of LAT discovered pulsars ongoing.
- Cone-like radio beam from polar cap?
- Fan-like gamma beam from "outer" or "slot" gap?
- Relative radio/gamma pulse profiles
  - ➔ Powerful model discriminant

- Below left: ζ vs phase φ for a "slot gap" model.
- Below right: Cut across some line-of-sight ζ.





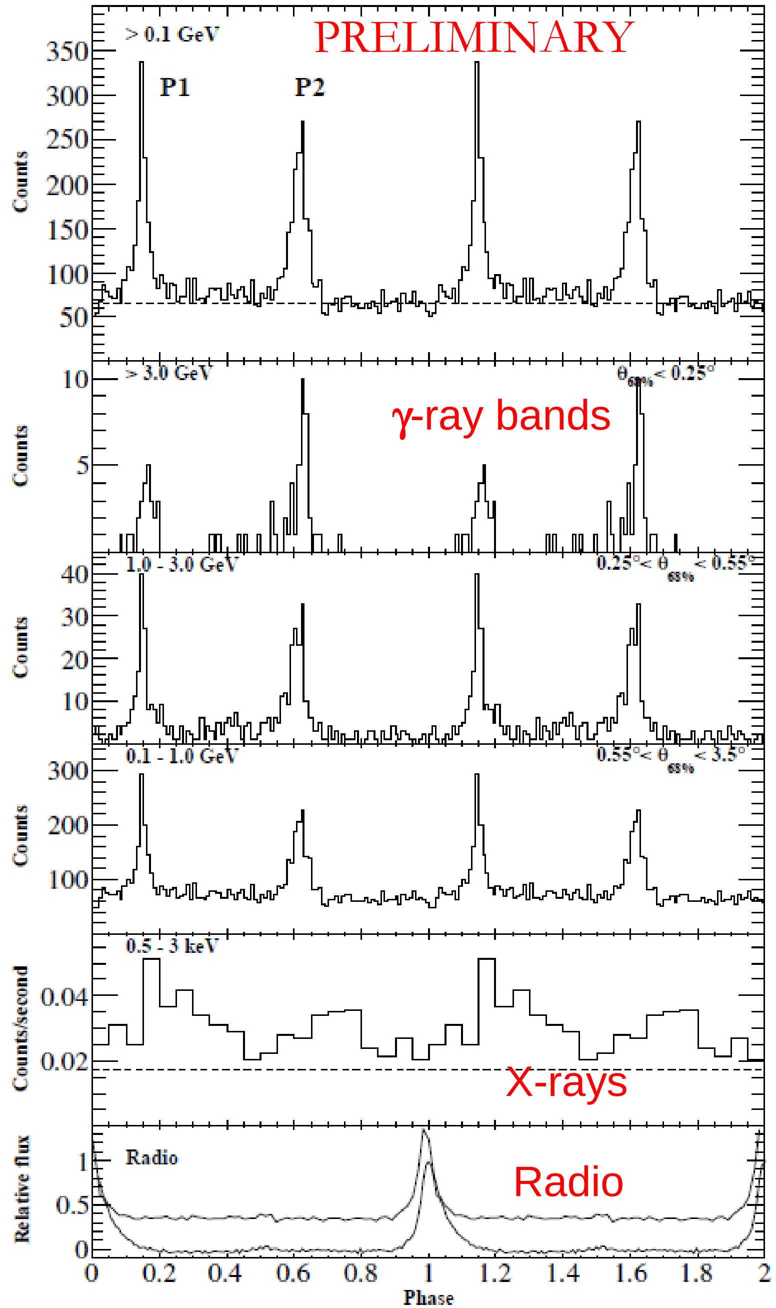


PSR J2021+3651

first new pulsar seen with the LAT

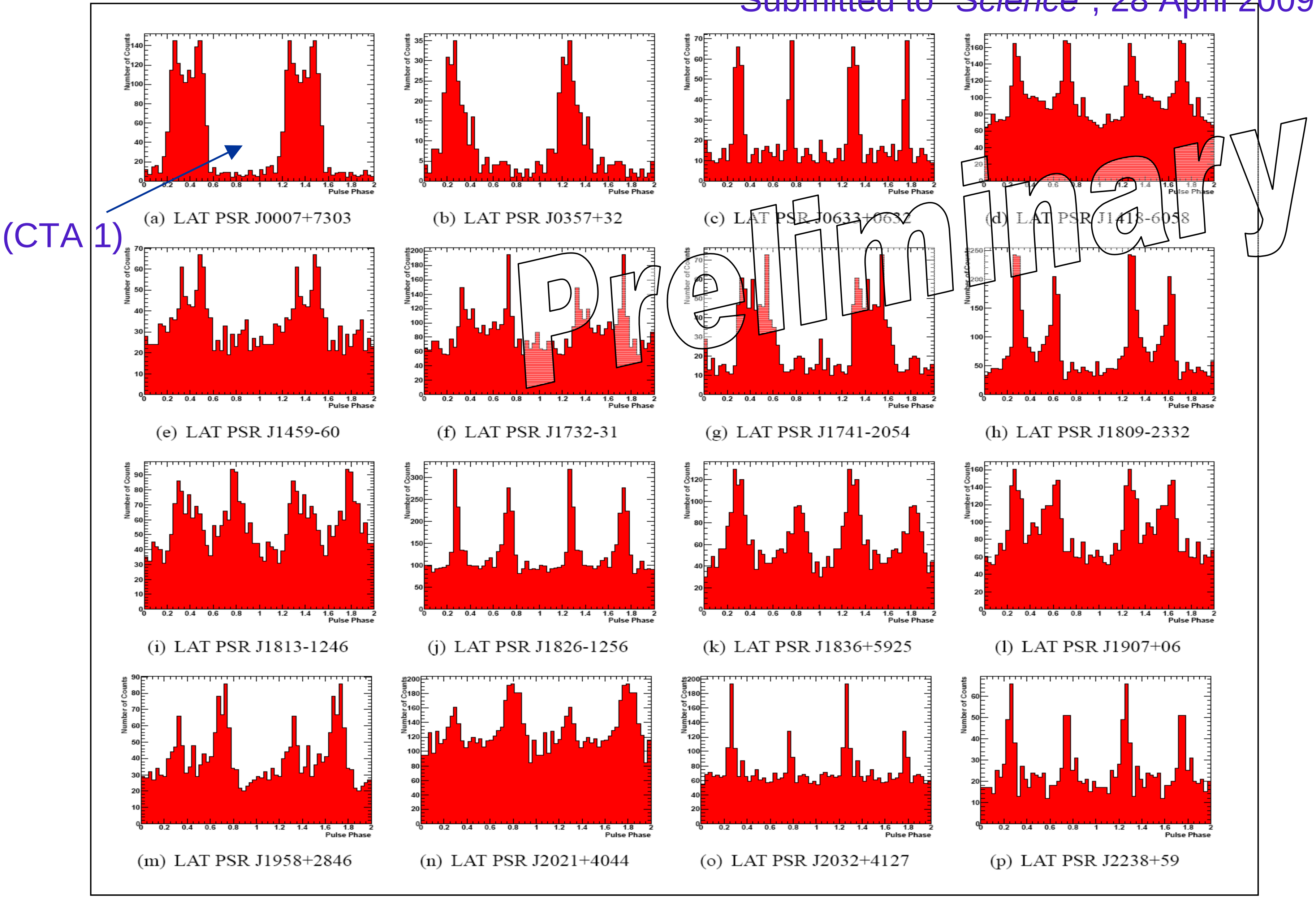
Multi-wavelength Pulsations

- P2/P1 ratio grows with energy.
- No significant change in gamma peak location or shape with energy
- Chandra X-ray light curve (Hessels et al. 2004, re-analzyed by Andrea De Luca):
  - pulsed at the 4-sigma level
  - appears roughly aligned with gamma peaks (interpretation in OM model)
- Radio polarization data provides "tilt" of the magnetic dipole axis ("RVM" = Rotating Vector Model)
- One of many examples of very high quality radio/gamma synergy.



Blind search γ-ray pulsar light curves

Submitted to "*Science*", 28 April 2009



(a) LAT PSR J0007+7303
(b) LAT PSR J0357+32
(c) LAT PSR J0633+0632
(d) LAT PSR J1418-6058
(e) LAT PSR J1459-60
(f) LAT PSR J1732-31
(g) LAT PSR J1741-2054
(h) LAT PSR J1809-2332
(i) LAT PSR J1813-1246
(j) LAT PSR J1826-1256
(k) LAT PSR J1836+5925
(l) LAT PSR J1907+06
(m) LAT PSR J1958+2846
(n) LAT PSR J2021+4044
(o) LAT PSR J2032+4127
(p) LAT PSR J2238+59

Millisecond ("recycled") pulsars

Pre-launch opinions about γ detectability were divided.

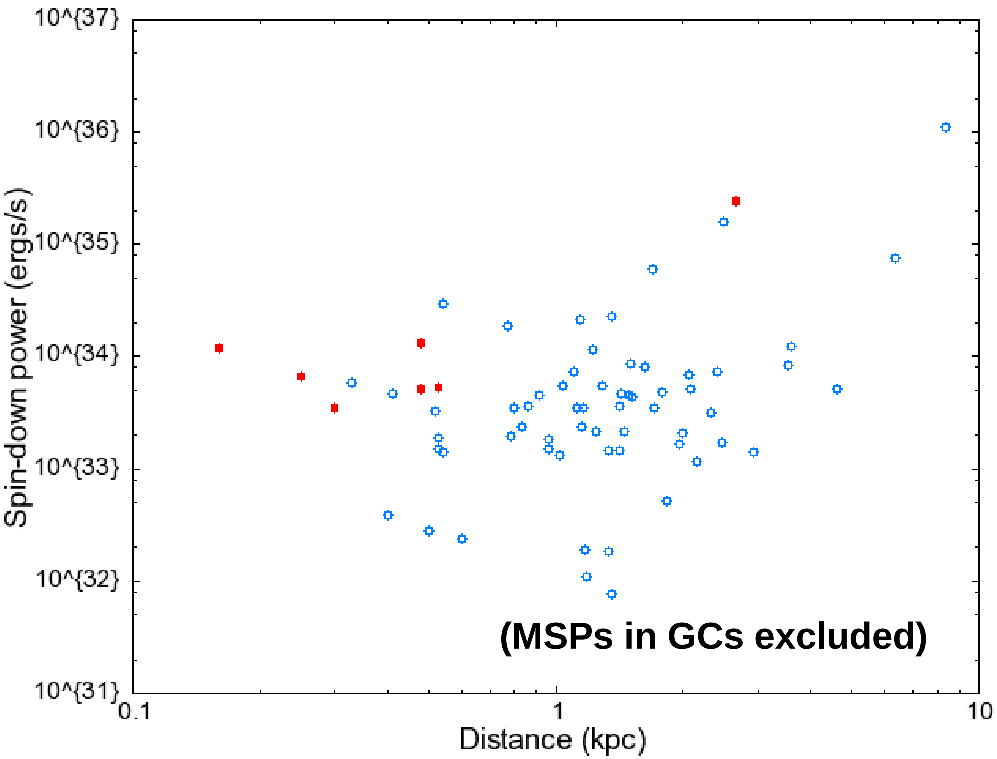
The far, high Edot, and the close, intermediate Edot MSPs are detected.

=> high spin-down flux MSPs (Edot / d^2)

Many intermediate distance MSPs should be detected with time.
Gamma-ray emission from MSPs: a general rule ? Is there a threshold ?

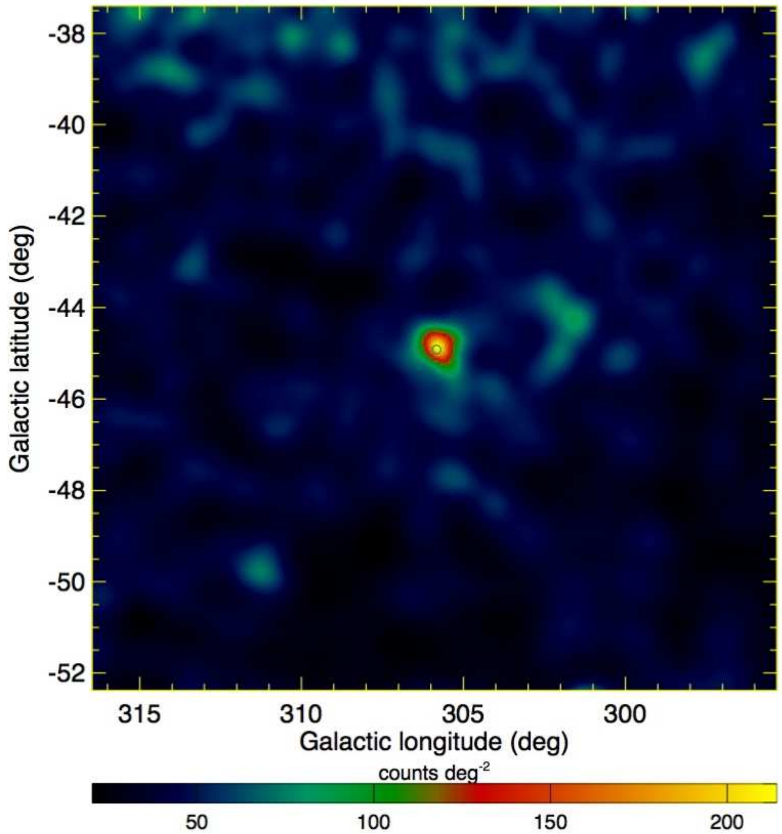
Name	P0 (s)	Edot (ergs/s)	Dist (pc)
J0030+0451	0,004865	3,48E+033	300
J0218+4232	0,002323	2,44E+035	2670
J0437-4715	0,005757	1,19E+034	156
J0613-0200	0,003062	1,32E+034	480
J1024-0719	0,005162	5,32E+033	530
J1744-1134	0,004075	5,21E+033	480
J2124-3358	0,004931	6,78E+33	250

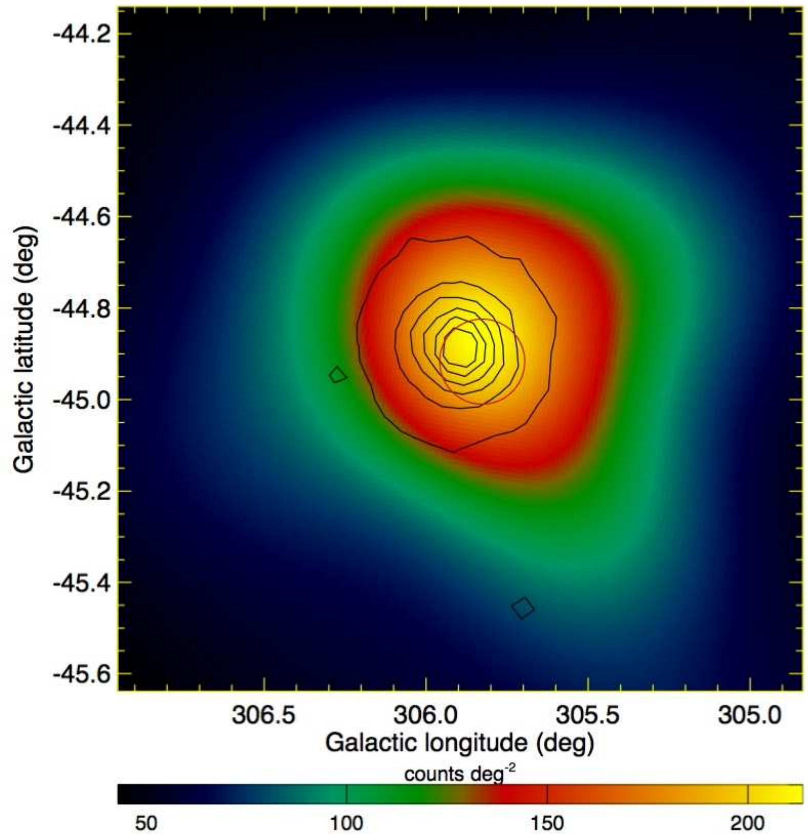
Soon to be submitted to "*Science*".



23 radio millisecond pulsars in the globular cluster 47 Tucanae. Detected as a (steady) GeV gamma-ray source.

Adaptively smoothed counts maps (200 MeV - 10 GeV, s.n.r = 5)





Large area

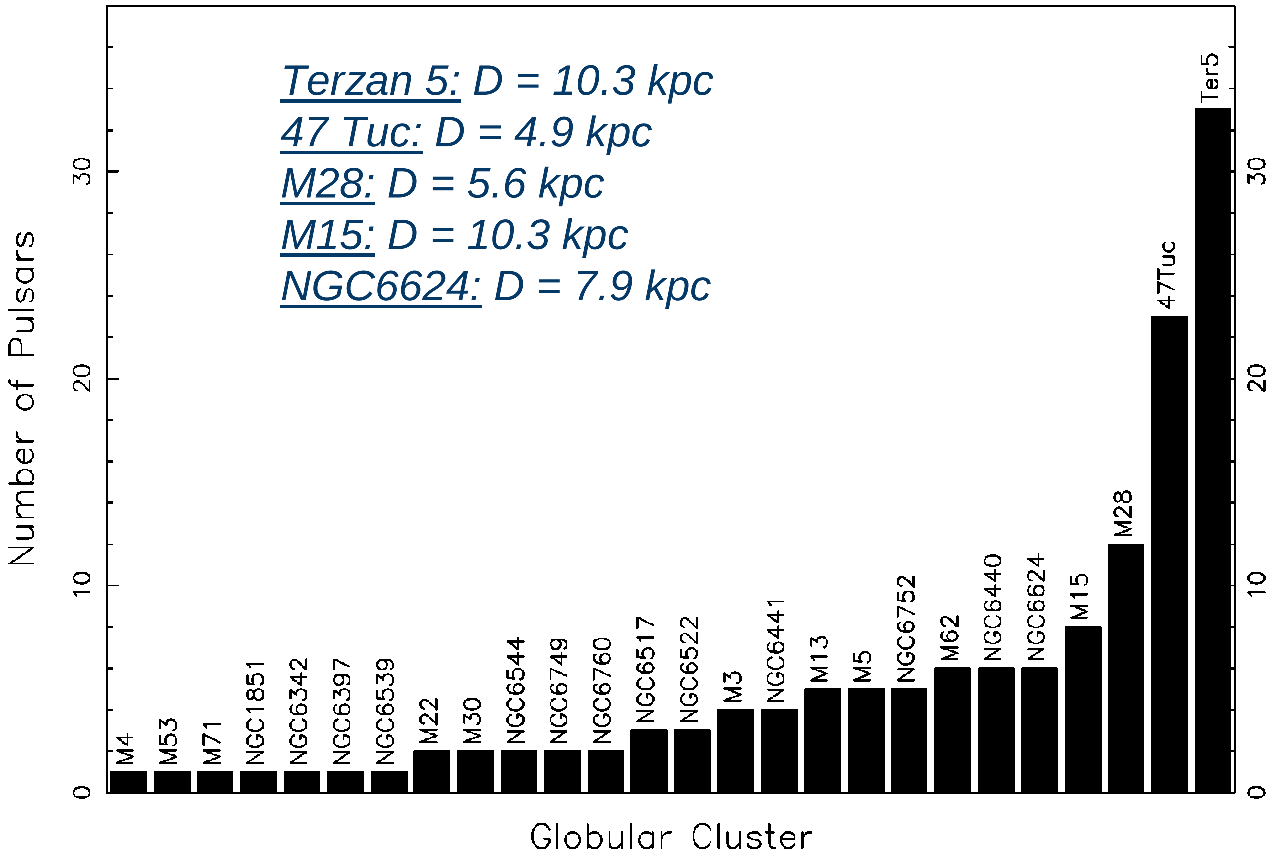
The source lies in an isolated sky region

Publication in preparation (J. Knodsleder, CESR Toulouse).

Zoom

Location of LAT source relative to 47 Tuc
red circle: LAT 95% error radius
contours: DSS2 stellar distribution (arbitrary units)

Other Globular Clusters ?



There are ~ 100 MSPs in 26 GCs.

Promising sources of collective emission. Some individuals might be detectable.
Search for pulsations ongoing.

Many galactic EGRET unidentified sources are pulsars

- Example 1:

3EG J2033+4118 coincides with the TeV source near Cyg OB2.

> ➢ Shocks between the winds of massive stars? T. Montmerle, ApJ 231, 95-110 (1979)
> M. Cassé & J. Paul, ApJ 237, 236-243 (1980)
> R. Mukherjee et al, ApJ 589, 487-494 (2003)

> ➢ No! LAT PSR J2032+4127

- Example 2:

3EG J2021+3716 coincides with the open cluster Berkeley 87.

> ➢ A hadron accelerator driven by shocks from winds from WR star(s) ?
> W. Bednarek MNRAS 382, 367 (2007) and references therein

> ➢ No! radio PSR J2021+3651 in the "Dragonfly" PWN.

- Example 3:

3EG J2020+4017 associated with SNR γ Cygni. Shock acceleration?

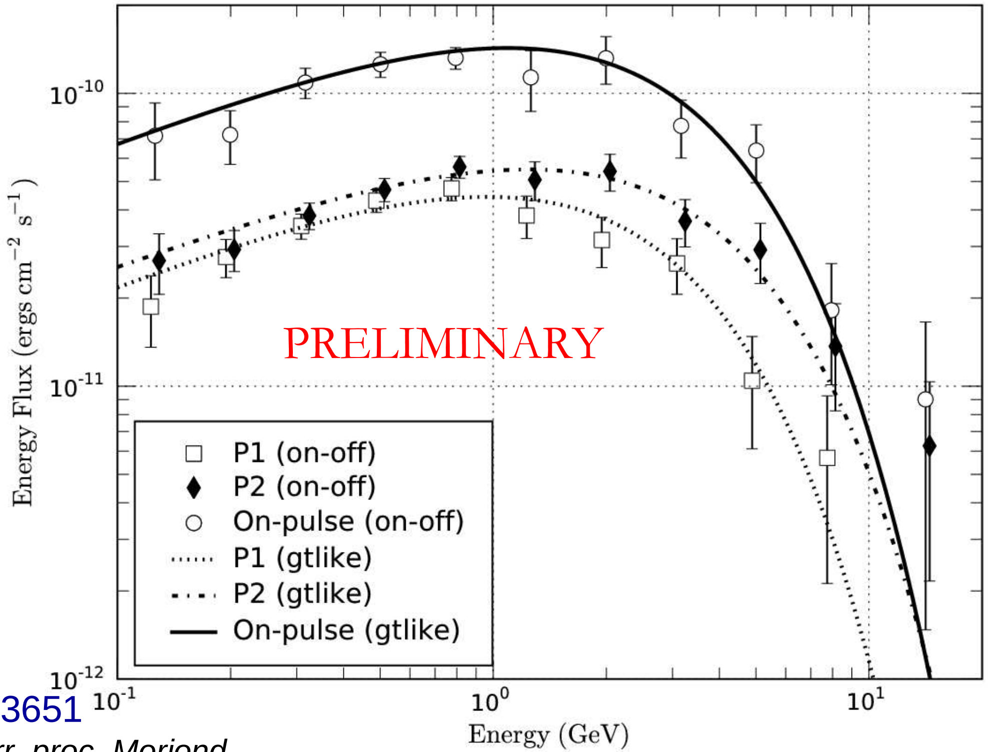
> ➢ No! LAT PSR J2021+4044

Yet another example: 3EG J1028-5819 is indeed the recently discovered radio pulsar PSR J1028-5819, see
Abdo et al. 2009, ApJL, 695, L72 arXiv: 0903.1602

All within 10° in Cygnus… *The point is*: of the large variety of proposed accelerators, the correct answer is "*pulsar*" in a majority of cases so far.

About the LAT pulsars

- Generally (but not always), two peaks separated by ½ rotations.
- Generally (but not always), gamma peak offset from radio.
- Exponential cut-offs at ~1 to ~3 GeV.
- Favors outer magnetospheric emission.
- MSPs resemble young pulsars.



LAT spectra for PSR J2021+3651

Ap J submitted, January 2009. Here: M. Kerr, proc. Moriond

Plenty of nearby, energetic pulsars

Geminga & Monogem – over-emphasis in cosmic ray $e^{\pm}$ discussion?

ATNF pulsar database (http://www.atnf.csiro.au/research/pulsar/psrcat) :

- 115 have DIST1<1000pc and are older than 50,000 years
  (so the nebula has dissipated and the electron wind can escape).

- 547 have DIST1<3000 pc and are older than 50,000 years.
- Of these, 174 have Edot > 1E33 and 45 have Edot > 1E34.

- exclude MSPs (P0>0.03): 34 pulsars with d<3 kpc, Edot>1E34.

Radio pulsar searches *NOT* complete

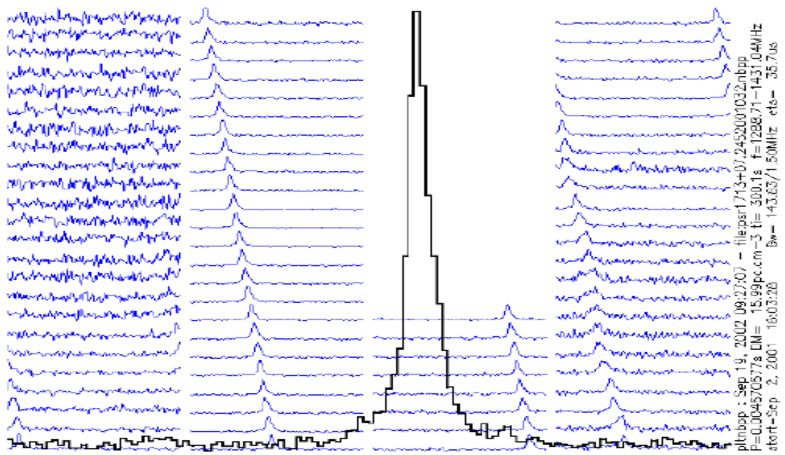
• Trend to higher radio frequencies (>10 GHz) to search for distant pulsars in highly dispersed directions (e.g. galactic plane).

➢ Biased against nearby pulsars! *Have* to see dispersion to distinguish from earthly interference.

• Surveys favor the plane: more pulsars per square degree.

➢ Biased against nearby pulsars! They're off the plane…

Fermi catalogs seeding new radio pulsar searches.



Example of radio frequency dependence of pulse arrival time, due to interstellar electron plasma.
Courtesy I. Cognard, Nançay radiotelescope

Population synthesis

- LAT all-sky survey yielding
  - ➢ better neutron star tallies
  - ➢ better emission models (e.g. beam sizes, Lγ vs Edot)
- Better population syntheses ➔ contribution to diffuse gamma and electron fluxes.

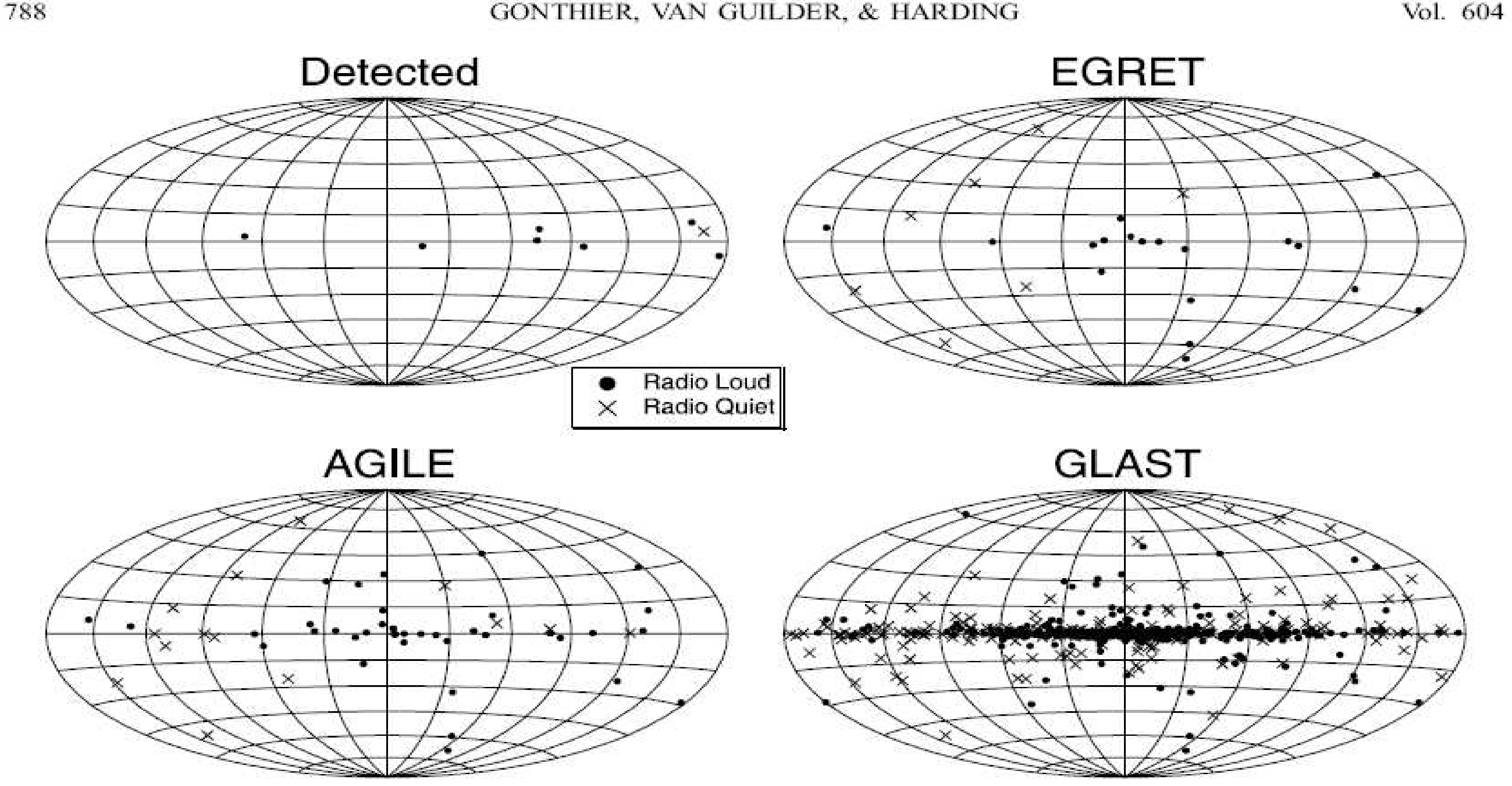


FIG. 12.—Aitoff plots of radio-quiet (*crosses*) and radio-loud (*dots*) γ-ray pulsars detected by EGRET (*top left*) and simulated for EGRET (*top right*), *AGILE* (*bottom left*), and *GLAST* (*bottom right*), assuming a field decay constant of 2.8 Myr.

Figure: ApJ 604:775-790 (2004) "Role of Beam Geometry in Population Statistics and Pulse Profiles of Radio and Gamma-Ray Pulsars", Gonthier, Van Guilder, & Harding

This talk:

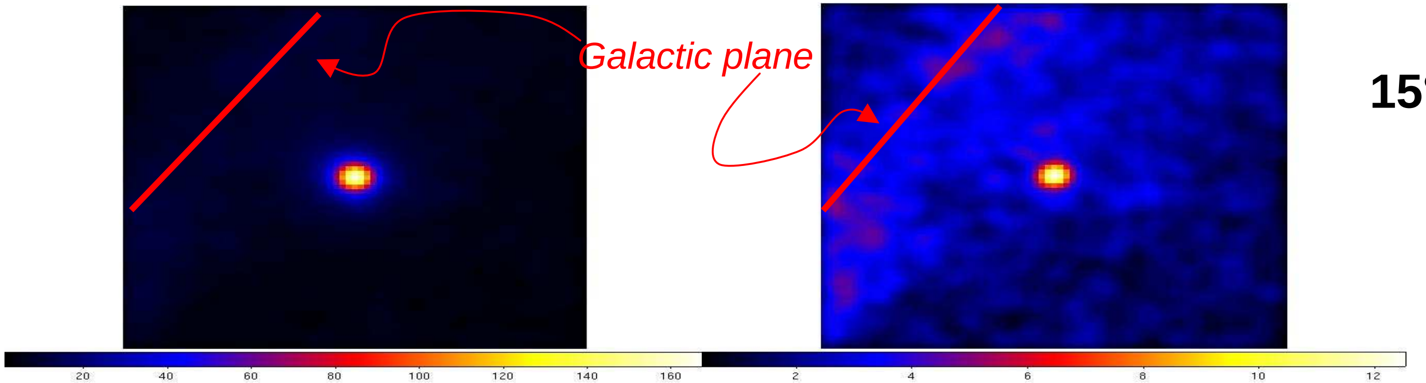
- Focus on pulsars
  - We have already seen many
  - Why more may be coming

- Very few words about other Galactic sources

- No words about other source types (GRBs, blazars… sorry – time constraint)

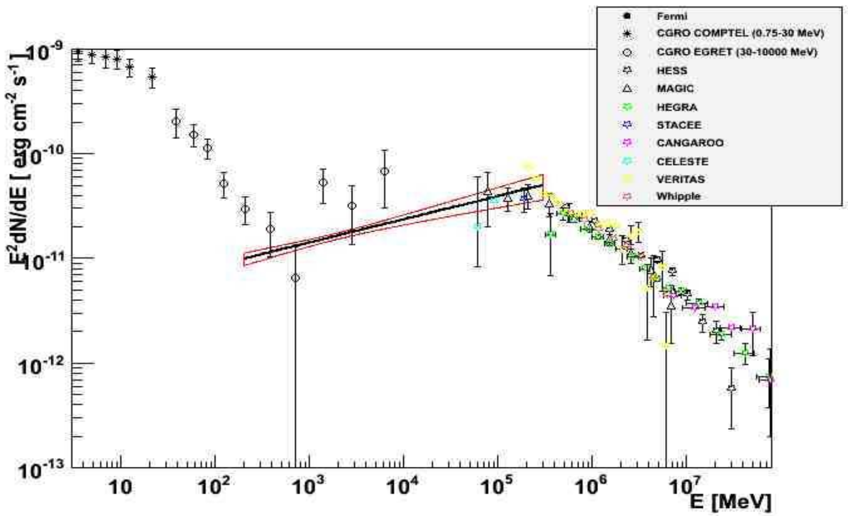
Pulsar Wind Nebulae (PWNs)
& Supernova Remnants (SNRs)

- Clear detection of the Crab nebula
  - ➢ Source detection in pulsar "off-pulse" phase
  - ➢ Spectrum joins neatly with that of TeV (Cherenkov)



15°x 15°

All pulsar phases **Off-pulse only**

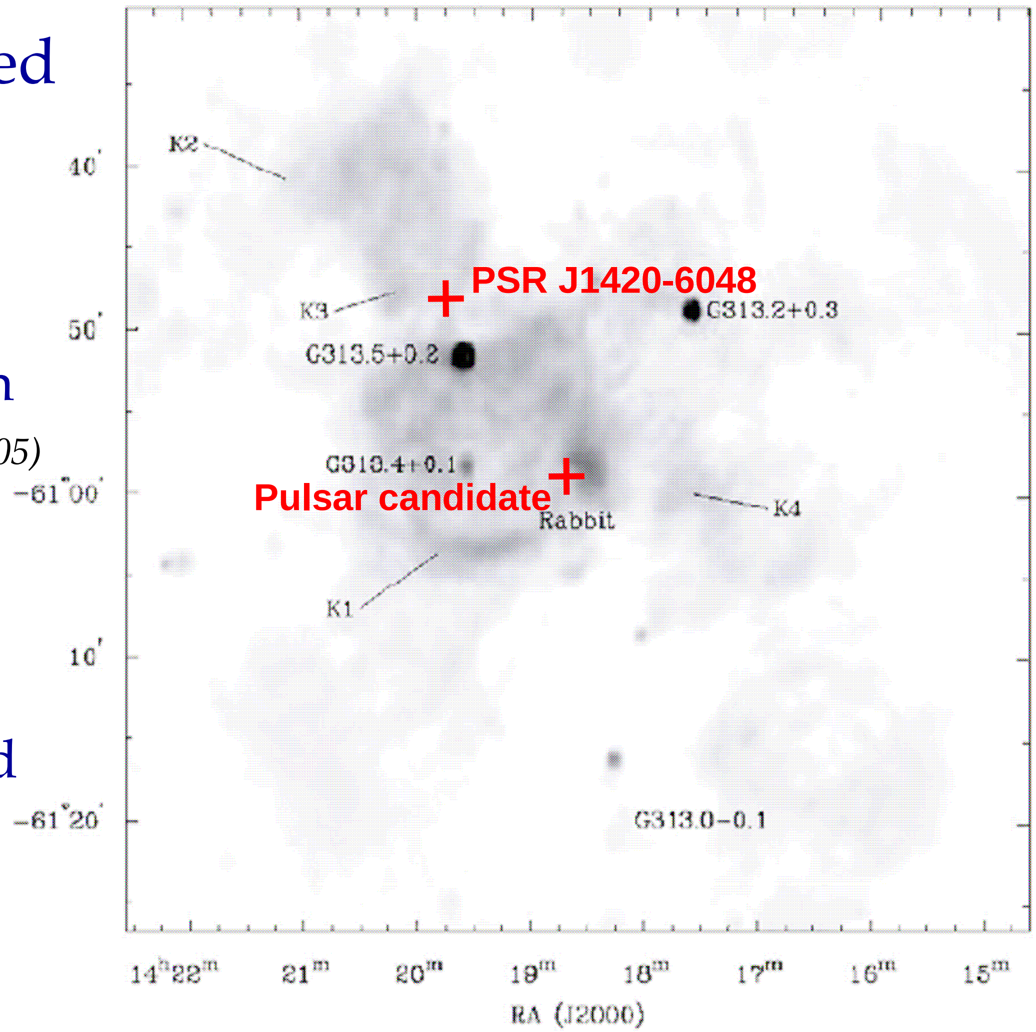


M-H Grondin & M. Lemoine-Goumard
in proc. Moriond

The Kookaburra complex

- Complex region with varied non-thermal sources :
  - K3/Kookaburra, PWN G 313.6+0.3
  - Rabbit, PWN G313.1+0.1
  - A 108ms pulsar candidate in the Rabbit *(Ng et al, ApJ 627:904, 2005)*
- Kookaburra was assumed to be powered by one of the most energetic pulsars :
  - PSR J1420-6048, 68ms period
  - dE/dt = 1e37 erg/s
  - distance = 5.6 kpc
  - age = 13000 yrs

EGRET source. *Two* HESS sources.



Radio observation of the Kookaburra region (Roberts et al, ApJ 515:712, 1999)

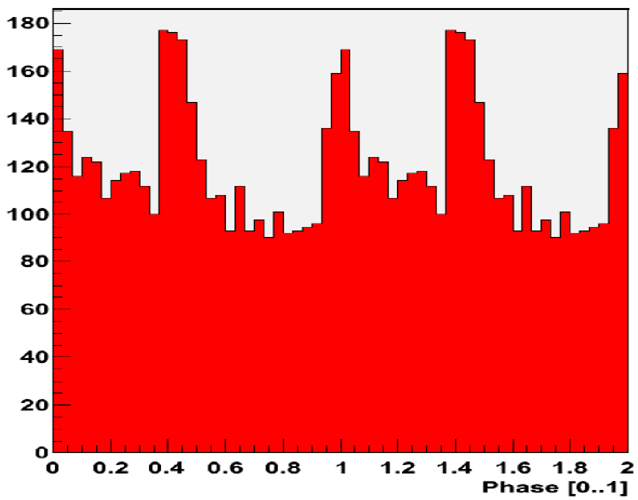
Fermi LAT work-in-progress

** P~110 ms pulsar discovered in the Rabbit nebula ("blind period search").

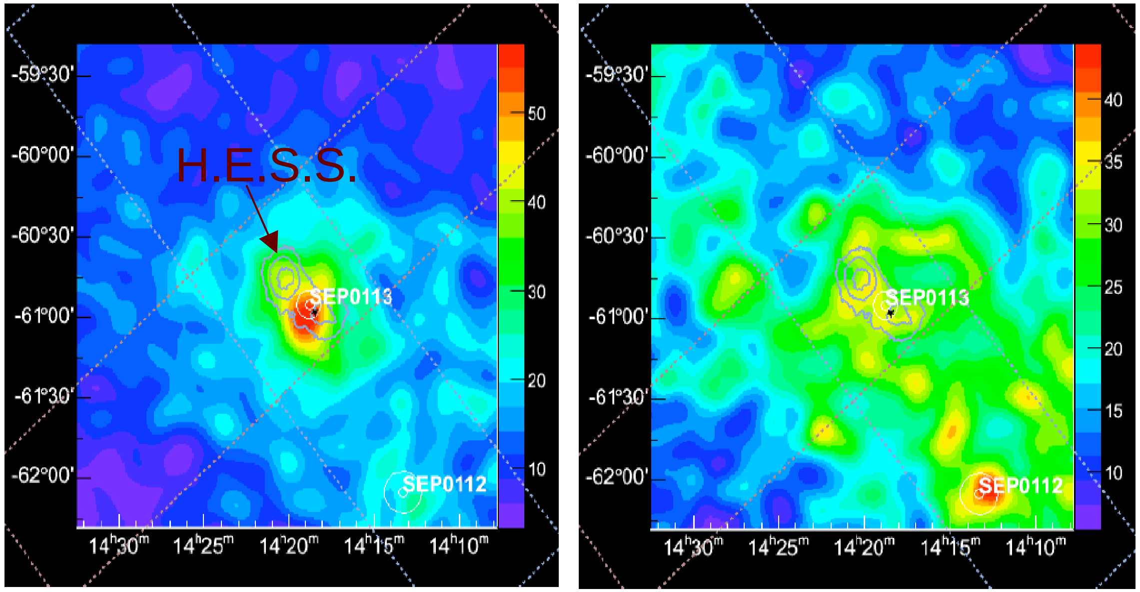
** Radio quiet?

** Seems to be off-pulse emission *(extended?)*

** Very good case for multi-wavelength studies (especially GeV-TeV)



Detection of pulsed emission in the Rabbit Nebula (2 cycles are shown)



On- (left) and off-pulse (right) emission

preliminary

Pulsars as a bright foreground

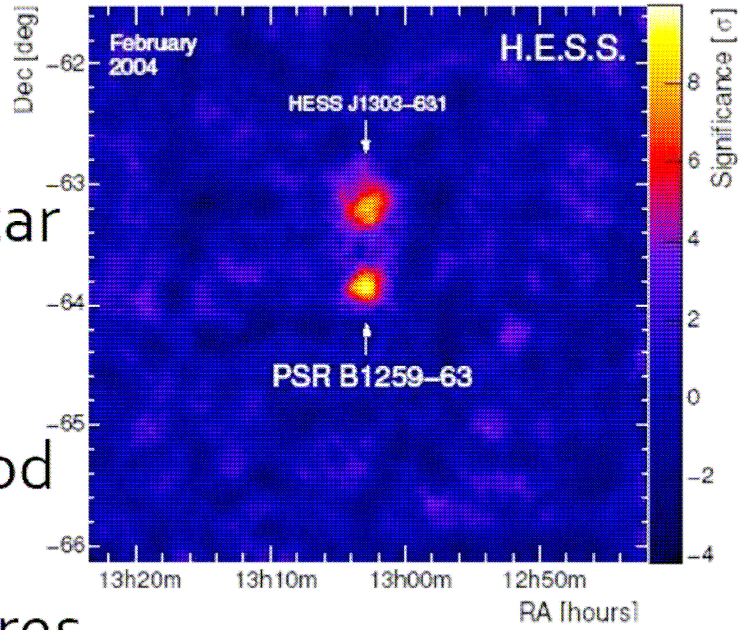
- The PWN story illustrates that to study faint, subtle signals
  - ➢ must subtract nearby pulsars
  - ➢ Off-pulse is a good handle
  - ➢(but are you *sure* the neutron star doesn't emit at all rotation phases?)
  - ➢ must wait a little longer for statistics, and
  - ➢ for better diffuse modeling & instrument knowledge, etc
  - ➢ I.e….. more care about systematics (duh).

- *Unless a Dark Matter signal is surprisingly strong, great care for classical astrophysics has to come first.*

High-mass X-ray binaries (often called μQuasars)

A number of X-ray binaries have been detected at > 1 TeV:

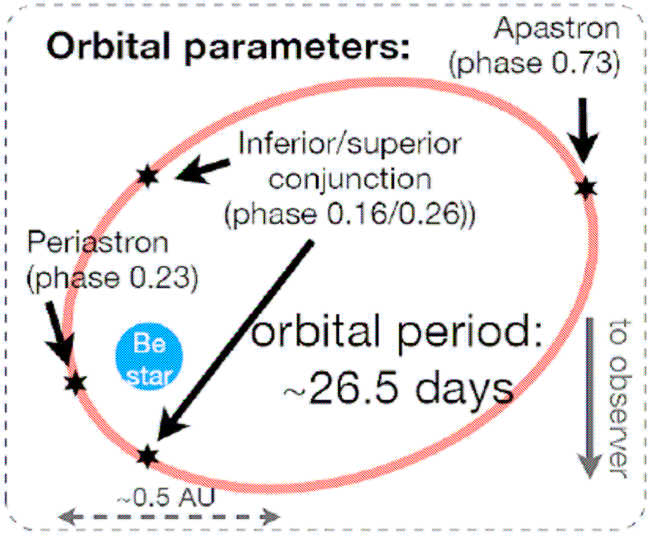
- PSR B1259-63
  - Radio pulsar in 3.5 yr orbit of Be star
  - HESS detection at periastron
- LS 5039
  - HESS detects 3.9 day orbital period
- LS I +61°303
  - Be HMXB shows periodic radio flares
  - MAGIC & VERITAS see VHE emission modulated on 26 day orbital period



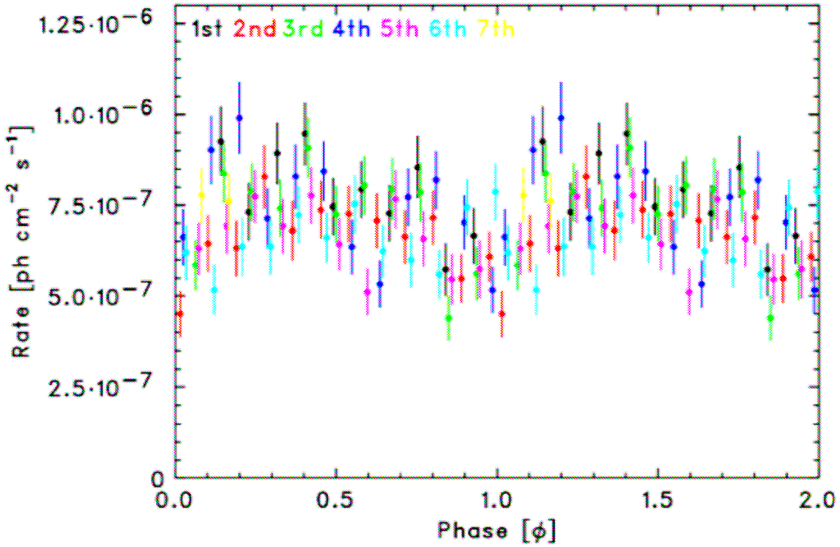
Fermi LAT detection of LS I +61°303

A. Hill & G. Dubus, Grenoble. R. Dubois, SLAC
Here: proc. Moriond
Ap J submitted

- Investigating signs of orbit to orbit variability
- As more orbits are observed evidence will become clearer



J.Casares et al (2005)



X-ray binaries (a.k.a. "μQuasars")

The following question is intriguing:

A&A 456, 801–817 (2006)
DOI: 10.1051/0004-6361:20054779

Astronomy & Astrophysics

Gamma-ray binaries: pulsars in disguise?

G. Dubus[1,2]

[1] Laboratoire Leprince-Ringuet, UMR 7638 CNRS, École Polytechnique, 91128 Palaiseau, France
e-mail: dubus@in2p3.fr
[2] Institut d'Astrophysique de Paris, UMR 7095 CNRS, Université Pierre & Marie Curie, Paris 6, 98bis Bd. Arago, 75014 Paris, France

Received 27 December 2005 / Accepted 6 May 2006

ABSTRACT

Context. LS 5039 and LS I+61°303 are unique amongst high-mass X-ray binaries (HMXB) for their spatially-resolved radio emission and their counterpart at >GeV gamma-ray energies, canonically attributed to non-thermal particles in an accretion-powered relativistic jet. The only other HMXB known to emit very high-energy (VHE) gamma-rays, PSR B1259-63, harbours a non-accreting millisecond pulsar

Not the case for LS +61°303.

But those pesky pulsars can be in the darndest places.

Conclusions

- *Fermi* LAT is working marvelously.
  - ➢ Excellent localization even in the confused Galactic plane.

- *Fermi* pulsar searches are working marvelously.
  - ➢ μS GPS clock accuracy – rare that a satellite gets it so right!
  - ➢ Radio ephemerides ➔ γ-ray phase folding: a smooth pipeline
  - ➢ Efficient blind rotation-period search

- Pulsars appear to be the main source of (non-diffuse) Galactic gamma-rays.

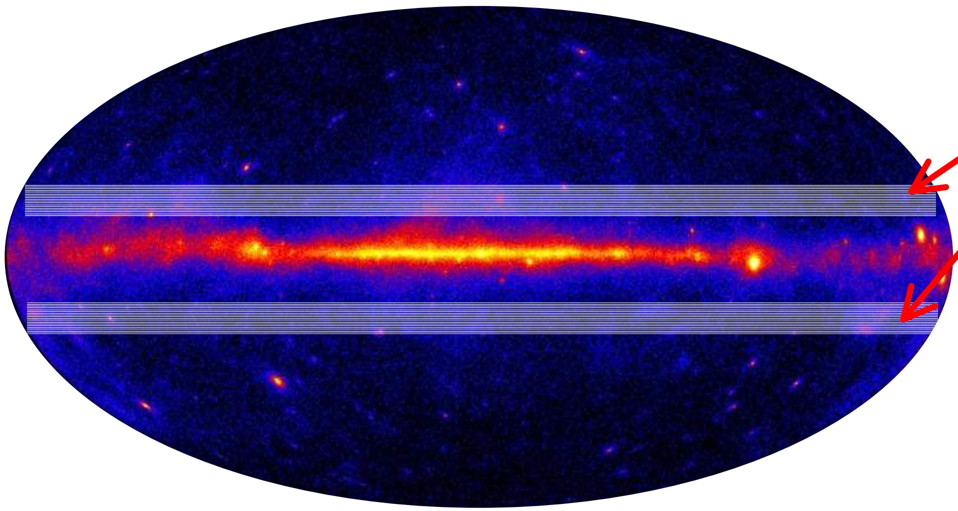
- Gamma-triggered radio pulsar searches underway

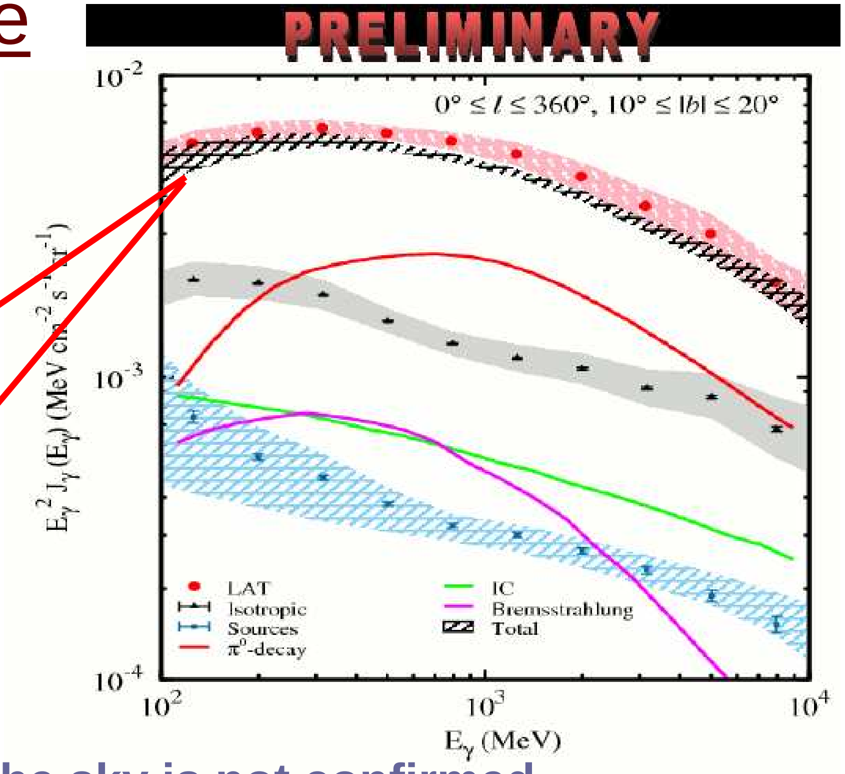
- Improved pulsar modeling driven by observations

- Even if you don't much care about rotating neutron stars, they are ubiquitous and must be treated carefully.

Back-up slides

Diffuse γ-ray emission: *no* GeV excess at mid-latitude





- **Spectra shown for mid-latitude range**
  ➔EGRET GeV excess in this region of the sky is <u>not</u> confirmed
- **Sources are a minor component**
- **LAT errors are systematics dominated and estimated ~10%.**
- **Ongoing: diffuse emission over the entire sky and broader energy range.**
- **If TANGO want details a) I have Troy Porter's slides b) Andy Strong is here.**

ApJ submission this month.