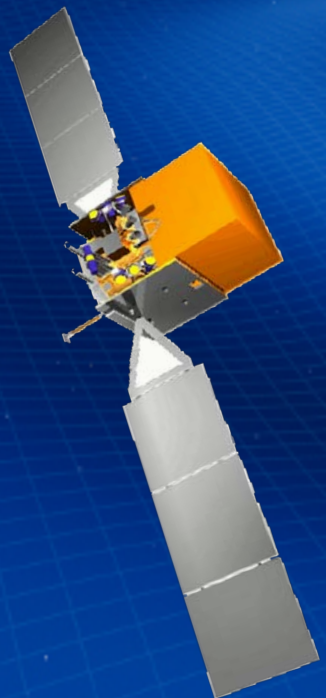
High-energy pulsars

from gamma rays to gravitational waves

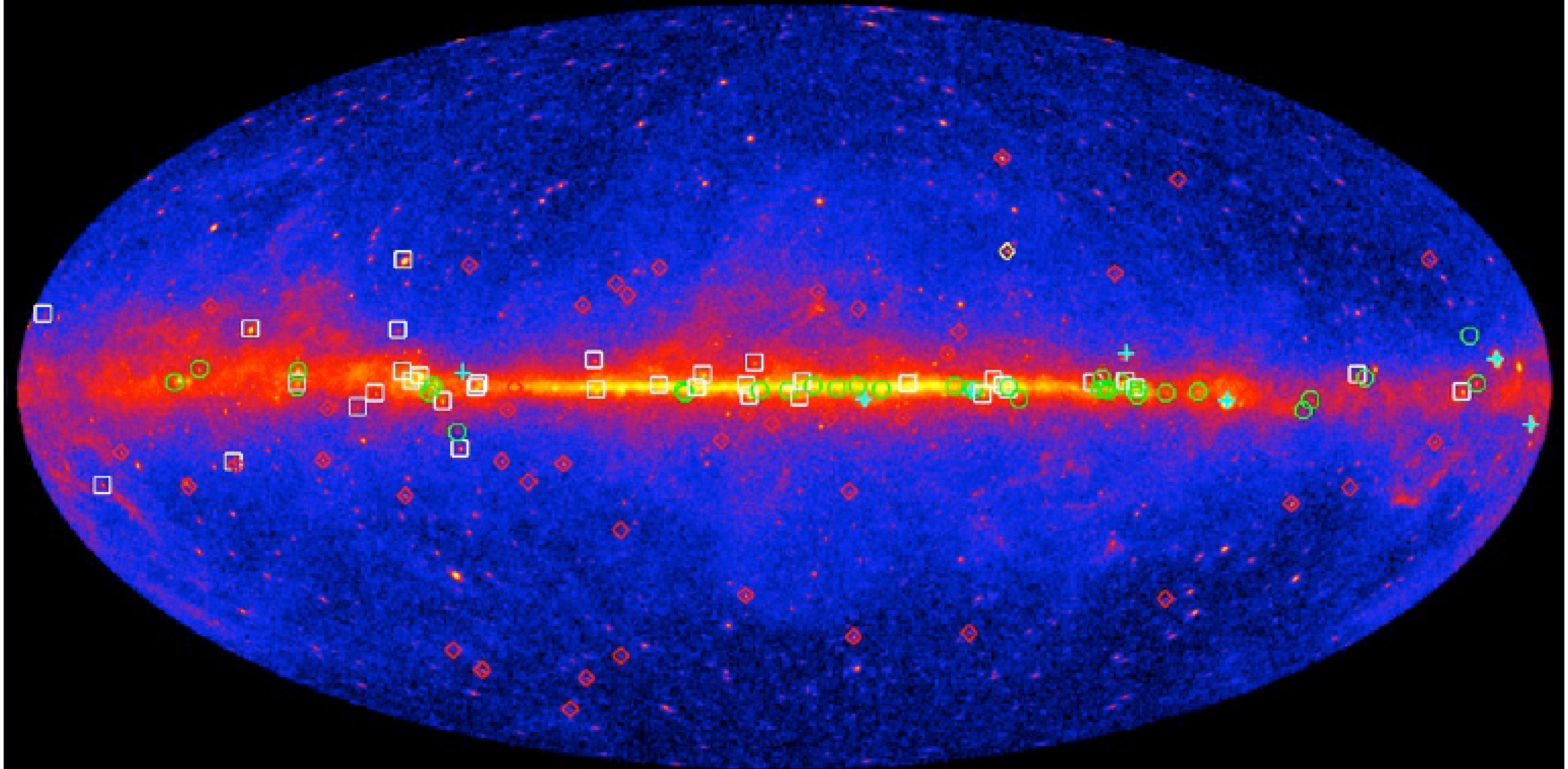
Massimiliano Razzano
(Università di Pisa & INFN)

On behalf of the Fermi-LAT collaboration



10th Workshop SciNeGHE
Lisbon, 4-6 June 2014

~6 years of gamma-ray observations = 147 pulsars



42 young radio- and X-ray-selected (green circles, cyan crosses)
36 young γ-ray-selected (white squares)
46 radio-selected MSPs (red diamonds) + 1 γ-ray-selected MSP (yellow diamond)
(+20 to be published!)

Public gamma-ray pulsars list
http://tinyurl.com/fermipulsars

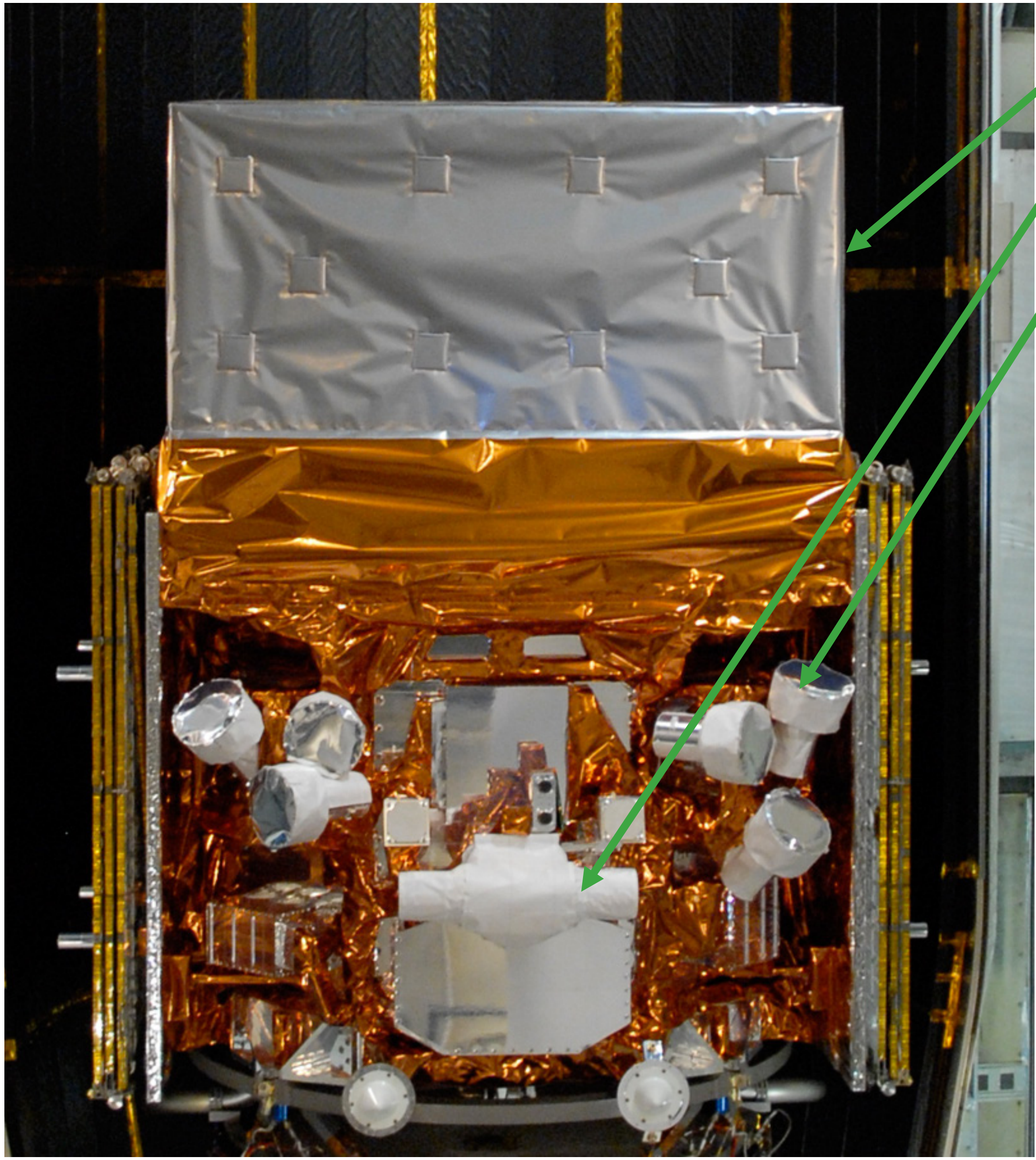
Why gamma rays?

- Efficiency
  - Radio emission is a negligible fraction of the energy budget
  - Gamma ray efficiency can be as high as 10%
  - →Probes of primary acceleration processes in the magnetosphere

- "Magnetic" science
  - Gamma rays are beamed along B field lines with small pitch angles
  - →Can track magnetic field structure

- Beam structure
  - Very different from radio
  - →Gamma rays can track different pulsar populations

The Fermi Observatory



Large Area Telescope (LAT)
20 MeV - >300 GeV

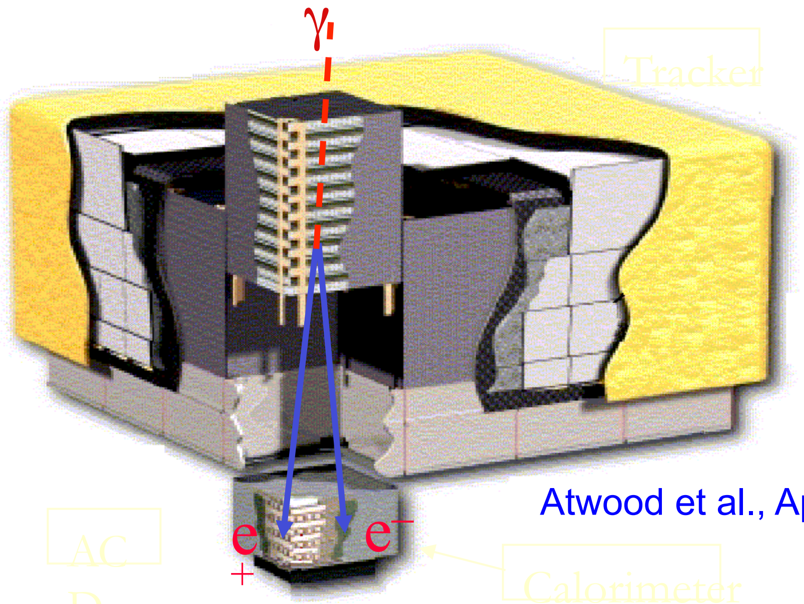
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

KEY FEATURES

- **Huge field of view**
  - **–LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.**
- **Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!**
- **Large effective area**
- **Large leap in all key capabilities. Great discovery potential.**

The Large Area Telescope (LAT)

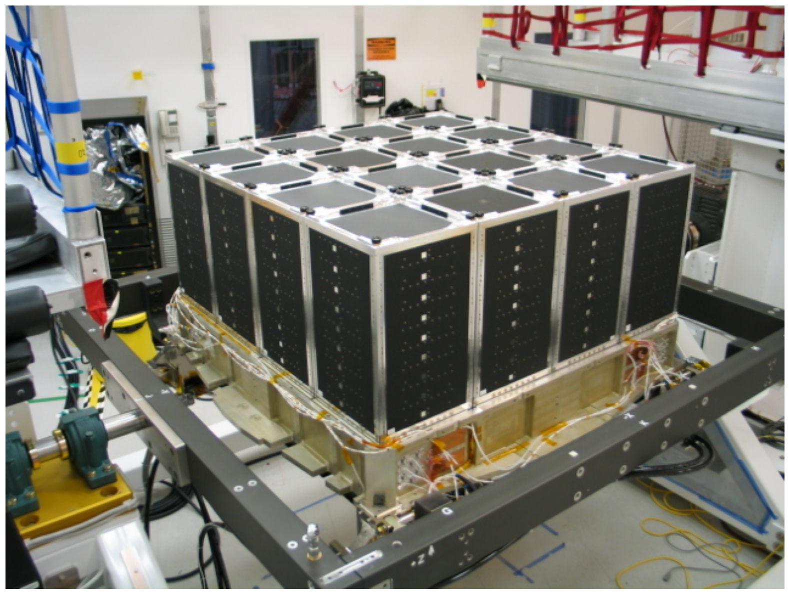
- International collaboration: USA, Italy, France, Germany, Sweden, Japan
- PI: Peter Michelson (Stanford University)
- Italy involvement through ASI, INFN, INAF and many Universities



Atwood et al., ApJ, 2009

- Electron-positron pair conversion
- 4x4 modularity
- Redundancy
- Weight 3000 kg, Power 650 W

- Main LAT subsystems
  - Silicon microstrip tracker
  - CsI hodoscopic calorimeter
  - Anticoincidence detector

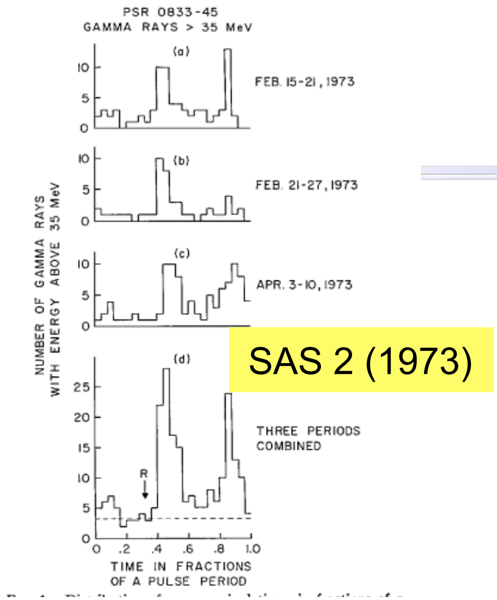


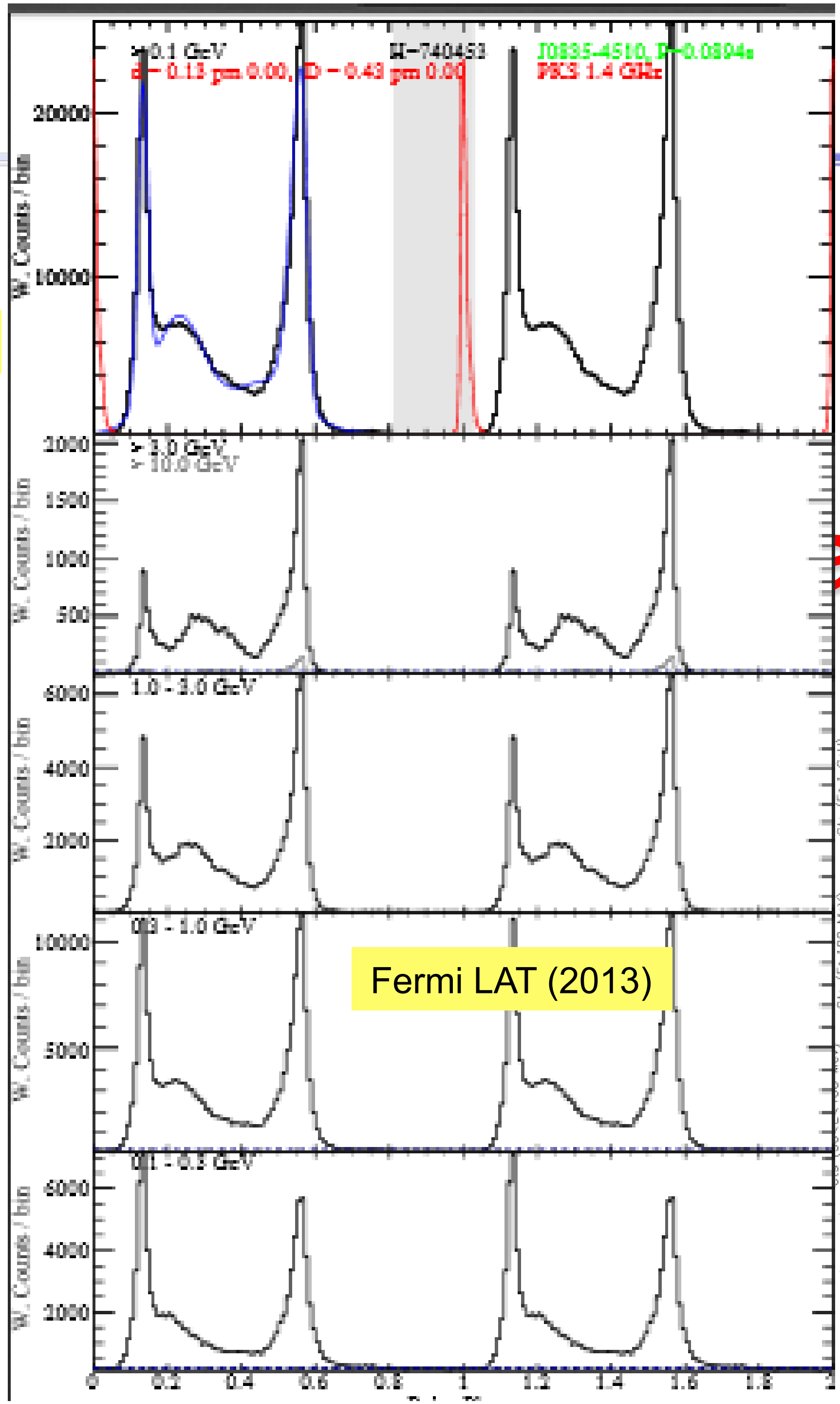
Fermi LAT & pulsars

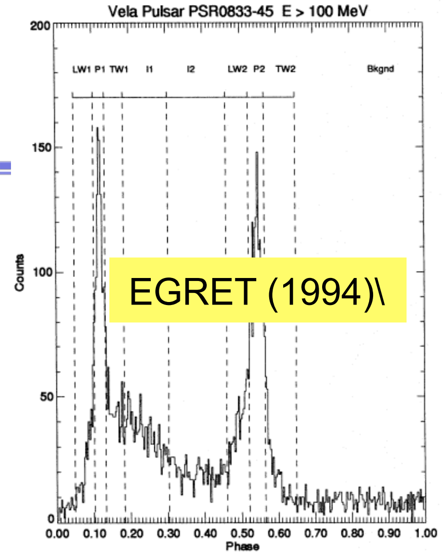
Many improvements w.r.t. EGRET !

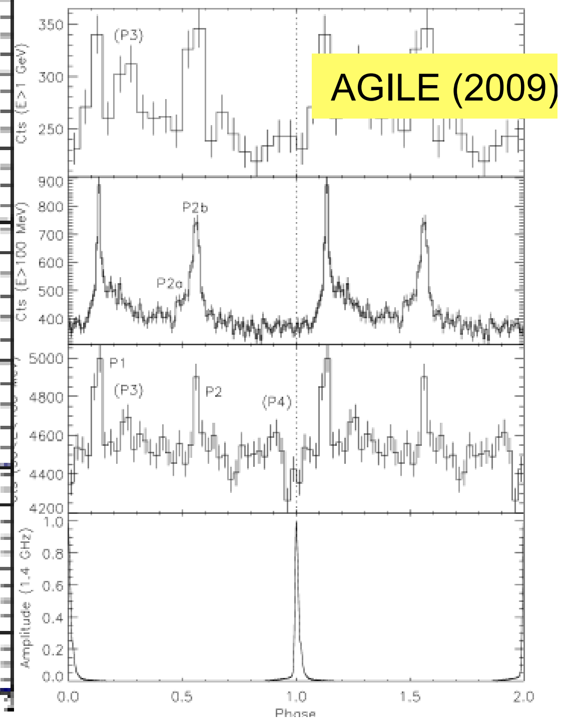
- Detector
  - Large Field of View (~2.4 sr)
  - Excellent absolute timing (<1 μs)
  - Sharp PSF (~0.6° $R_{68\%}$ at 1 GeV on axis)
  - Large effective area (~8000 cm^2 on-axis)
  - Great sensitivity at GeV energies

- Observations
  - Survey mode (uniform coverage every ~3 hr)
  - Timing campaign for radio & X pulsars (contemporaneous ephemerides)
  - Deep radio searches and multi-λ campaigns on LAT UNID. sources
  - New blind search algorithms – UCSC & Hannover team (Atwood +2008)


PSR 0833-45
GAMMA RAYS > 35 MeV
FEB. 15-21, 1973
FEB. 21-27, 1973
APR. 3-10, 1973
THREE PERIODS COMBINED
NUMBER OF GAMMA RAYS WITH ENERGY ABOVE 35 MeV
TIME IN FRACTIONS OF A PULSE PERIOD
SAS 2 (1973)


> 0.1 GeV
PKS 1.4 GHz
> 1.0 GeV
> 10.0 GeV
1.0 - 3.0 GeV
0.3 - 1.0 GeV
0.1 - 0.3 GeV
W. Counts / bin
Fermi LAT (2013)


Vela Pulsar PSR0833-45 E > 100 MeV
LW1 P1 TW1
I1
I2
LW2 P2 TW2
Bkgnd
Counts
Phase
EGRET (1994)\


(P3)
P2b
P2a
P1
P2
(P4)
Cts (E>1 GeV)
Cts (E>100 MeV)
Amplitude (1.4 GHz)
Phase
AGILE (2009)

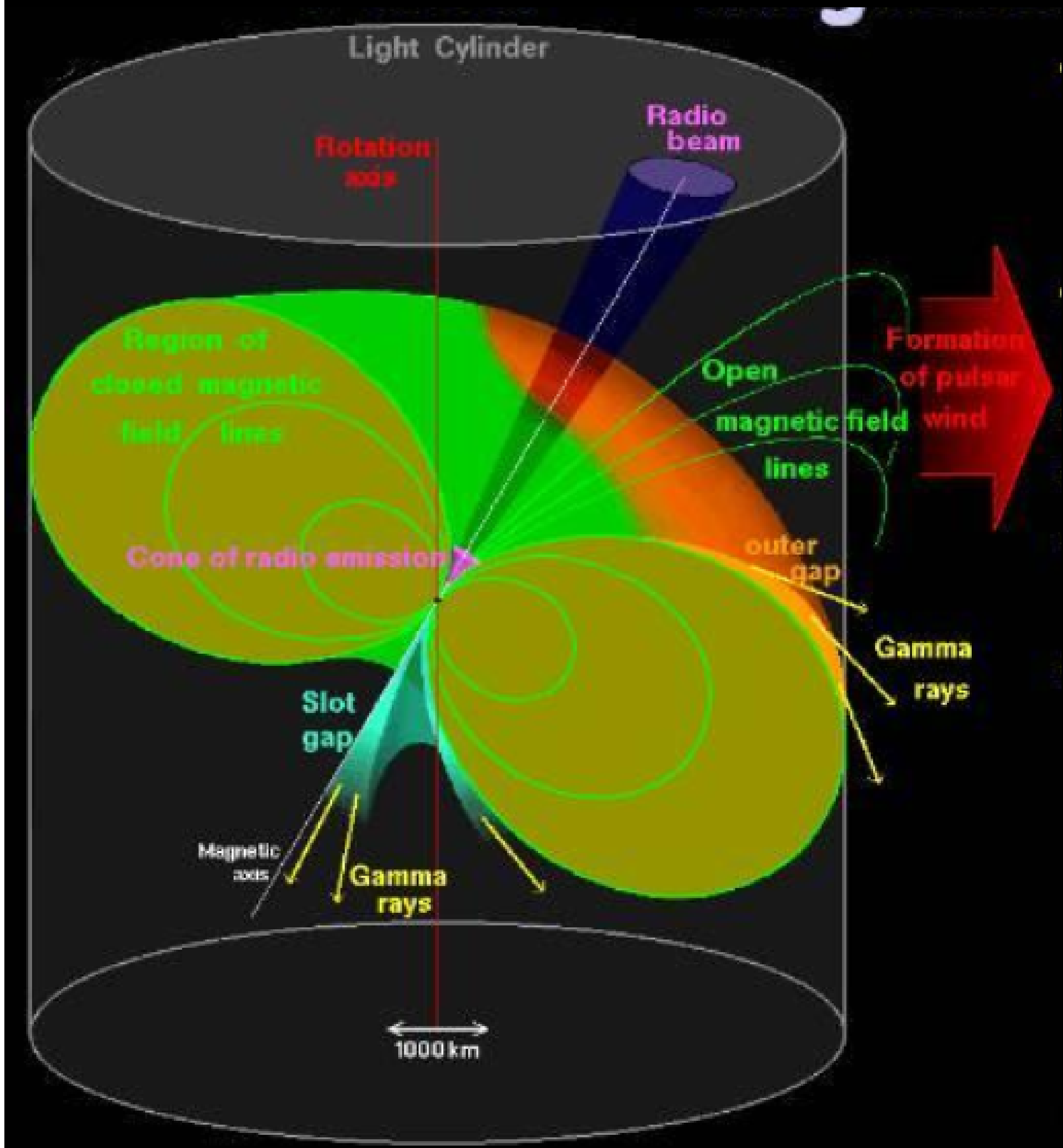
How to find new gamma-ray pulsars ?

- Gamma-ray telescopes have poor angular resolution (<< X-ray/optical/ radio).
  - LAT is good (0.1°@ 10 GeV) , but not enough…
  - A pure spatial-based identification is very difficult….

But there is something that we can do….

- Radio/X-ray loud pulsars
  - Fold to known frequencies
- Blind searches
  - Custom search algorithms
- Multi-λ campaigns
  - Deep searches in LAT UNID. sources

The “basic” picture



High-E particles + B-fields
→ gamma rays

Where is the acceleration zone?

Polar Cap models:
above the magnetic poles;

Outer Gap models:
between the last closed lines and the null surface (i.e. $\Omega \cdot B = 0$)

Slot Gap models:
along the last closed field lines

Wind models:
external regions

Gamma rays from known pulsars

1. Timing monitoring campaign (Pulsar Timing Consortium, Smith+2008)
2. Provide rotational ephemerides
3. Check if gamma rays are modulated as radio/X rays

Jodrell Bank (England)

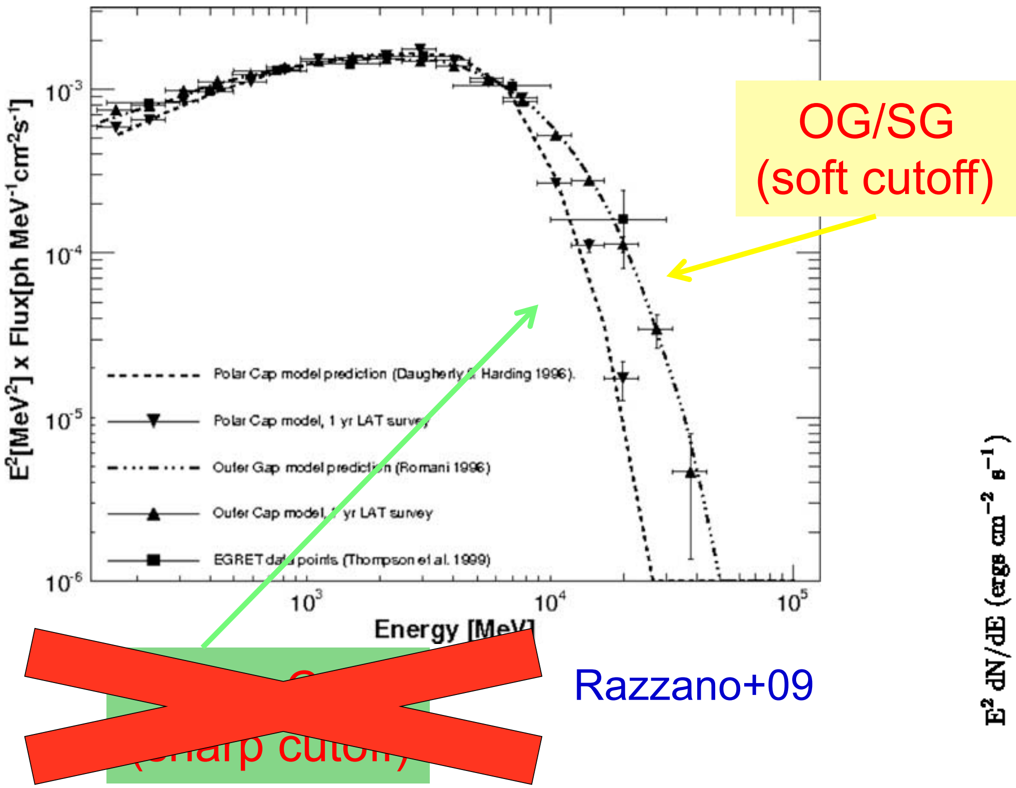
Parkes (Australia)

GBT (US)

Arecibo (Puerto rico)

And many others !

Constraining models

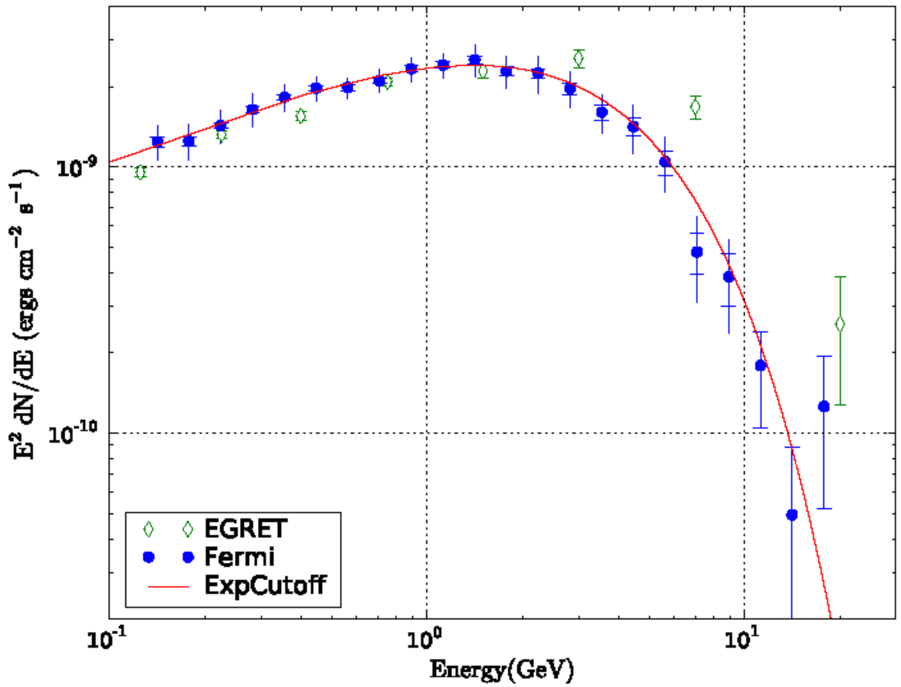


Razzano+09

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

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

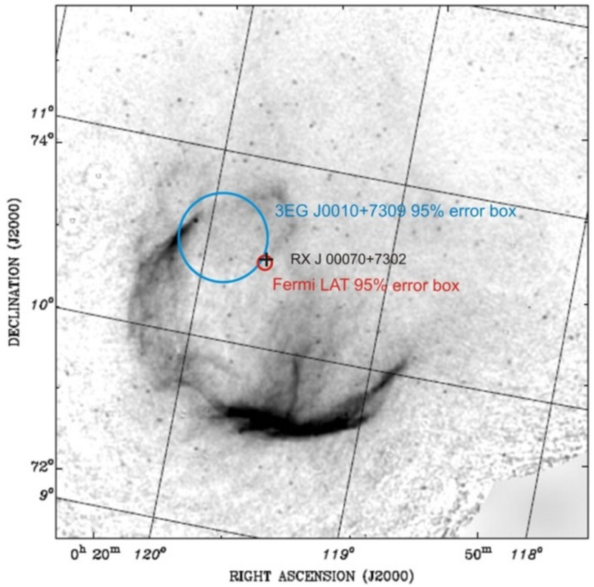
$$E_c = 2.9 \pm 0.1 \text{ GeV}$$

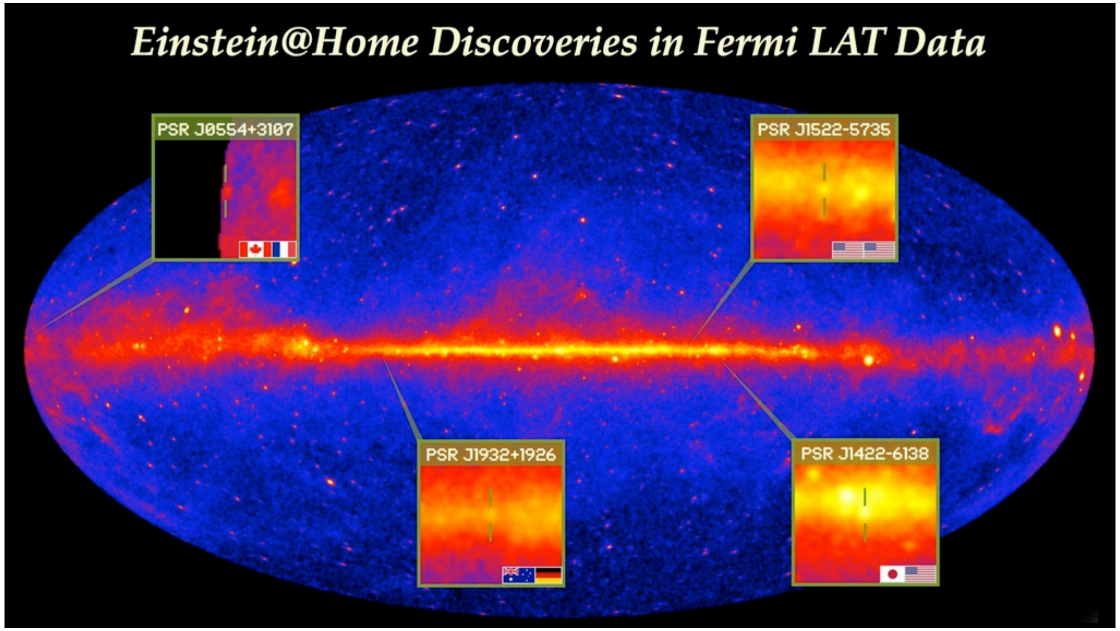


Abdo+08,09

Pulsar blind searches

- Why "blind"
  - We don't know frequency, etc..
  - We don't know position
  - Is it binary?
- Search is difficult
  - Gamma rays are sparse (1 ph/100 periods)
  - N_{trials} huge (>>10^{10})
  - CPU intensive
- So?
  - Time-differencing technique
  - (Atwood+06, Ziegler+08)



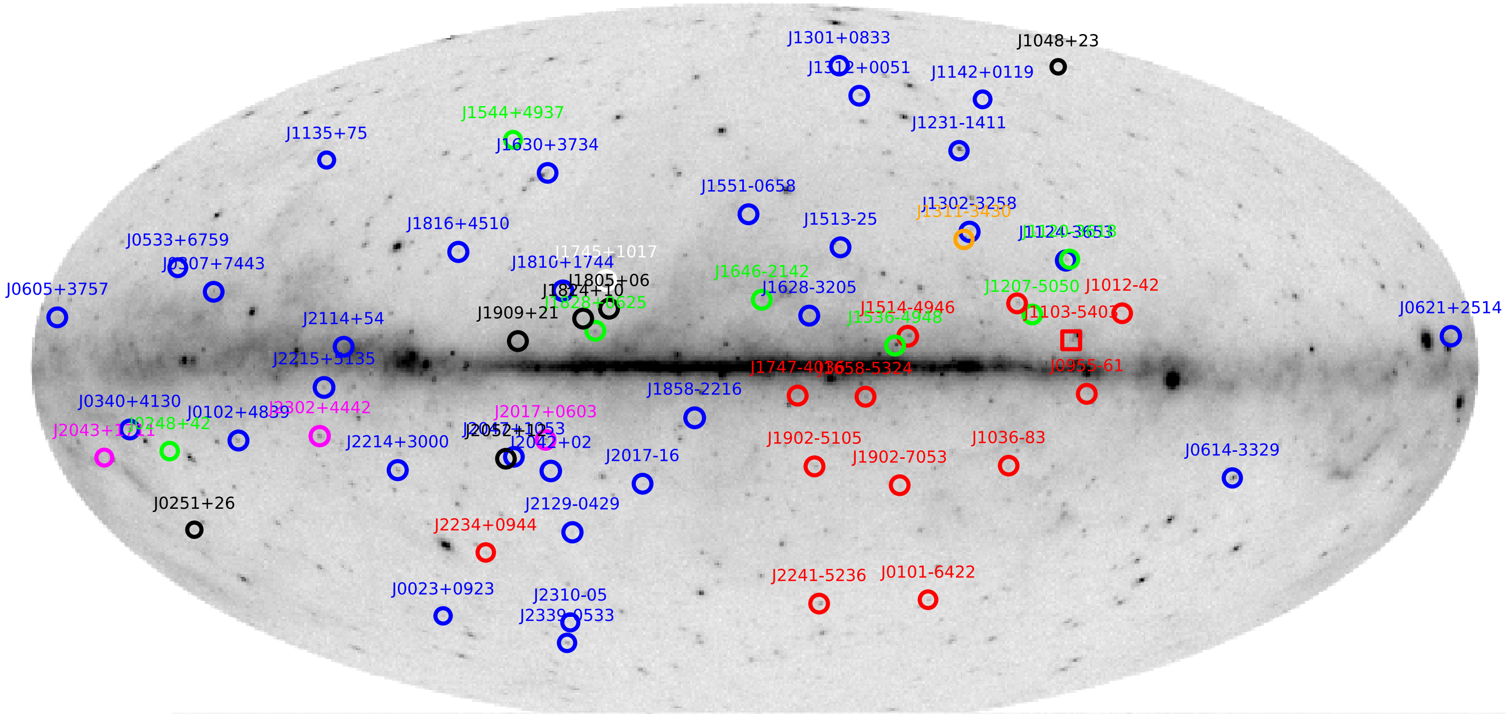


EINSTEIN@HOME
Catch a Wave From Space

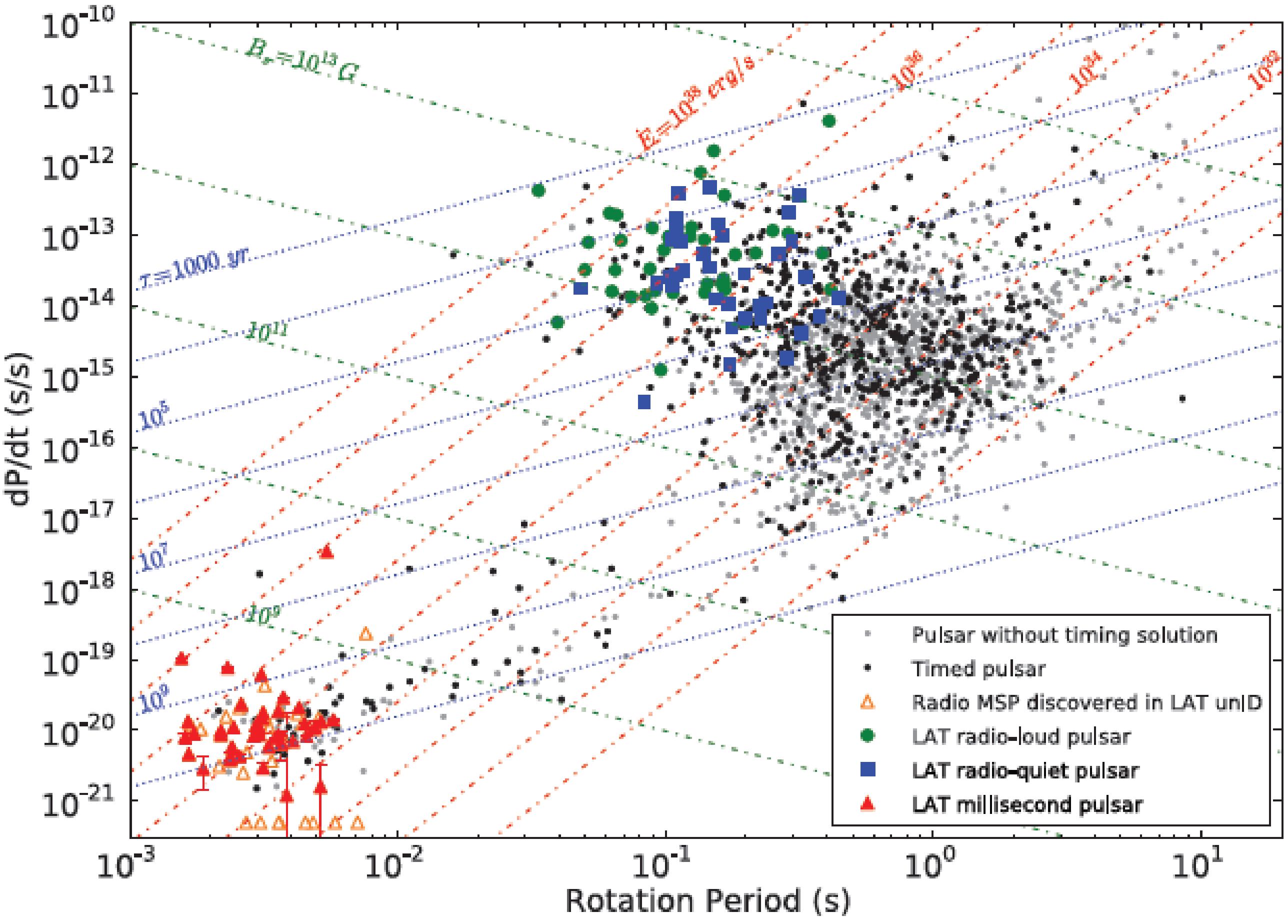
http://einstein.phys.uwm.edu/

Gamma-ray millisecond pulsars !

- New population
- Phase-folding
- Radio searches in UNID. LAT sources
- Now 62
- Including the interesting «black widows»



Family portrait



From the Second LAT Pulsar Catalog (2PC)

Ackermann+13, ApJS

Current Stats :
Total pulsars: 147

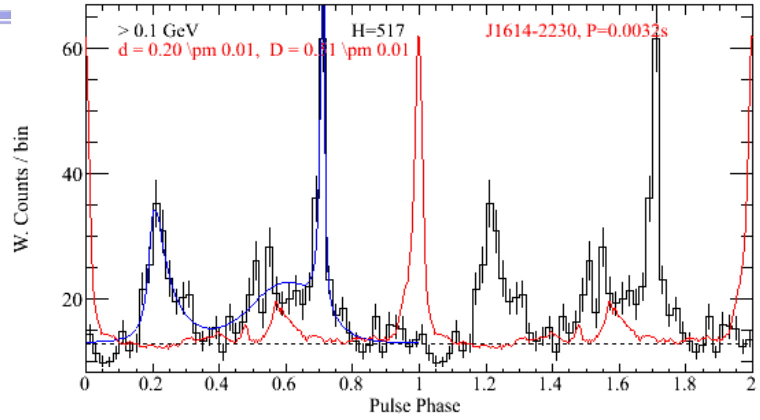
- Young, radio selected: 42
- Young, gamma selected: 40
- Young, X-ray selected: 3
- MSP, radio selected : 61
- MSP, gamma selected : 1
- Found in radio searches of LAT sources : 35
- EGRET/COMPTEL pulsars: 7

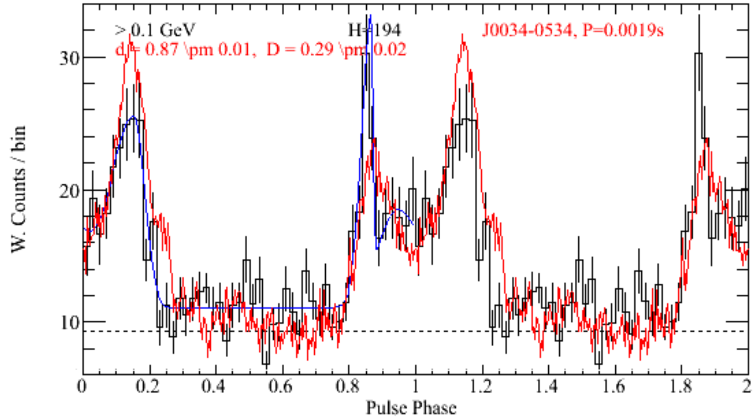
Light curves

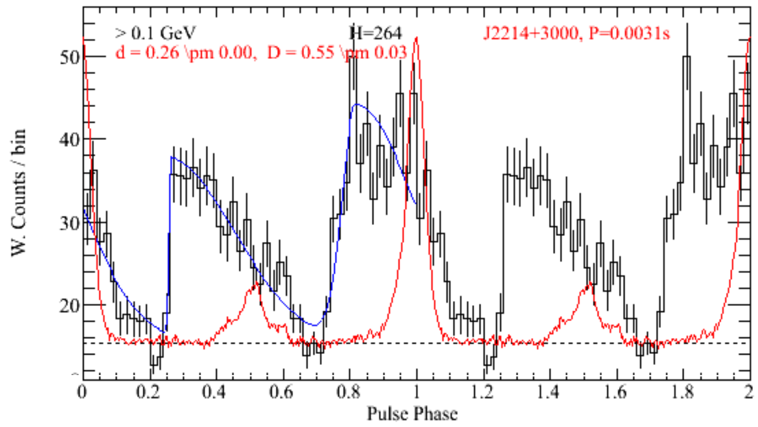
1. γ-ray peak(s) *lag* main radio peak
   – Young pulsars & MSPs

2. γ-ray peaks *aligned* with radio peaks
   – *Nearly* exclusive to MSPs

3. γ-ray peak(s) *lead* main radio peak(s)
   – Exclusive to MSPs



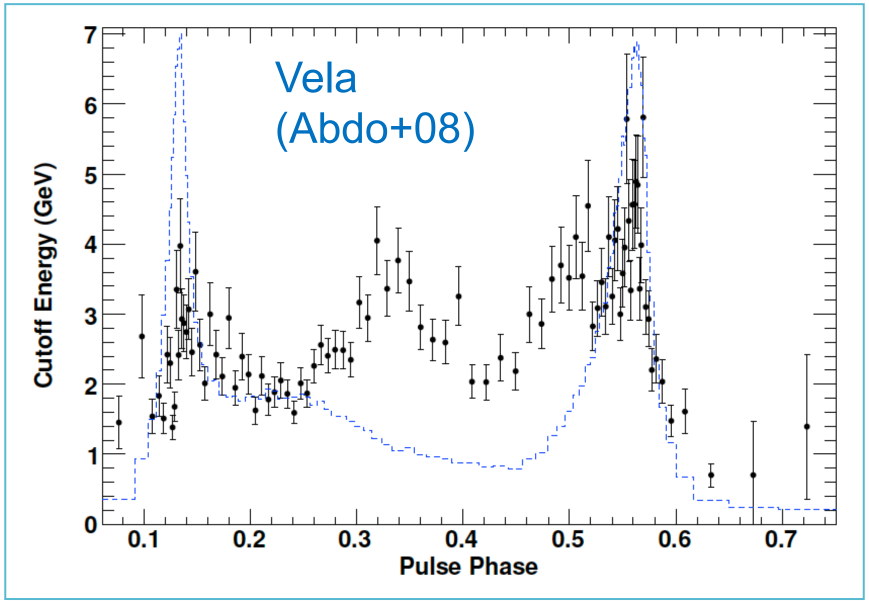


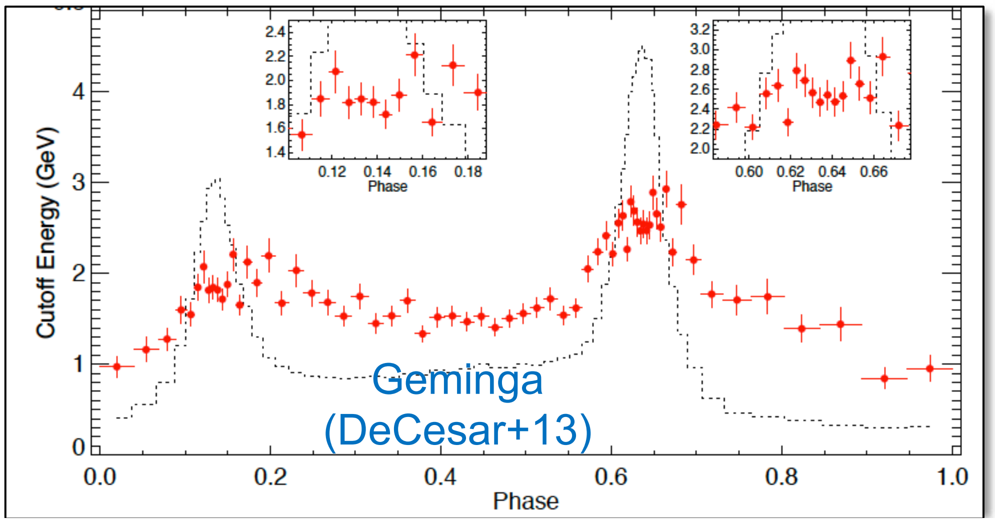


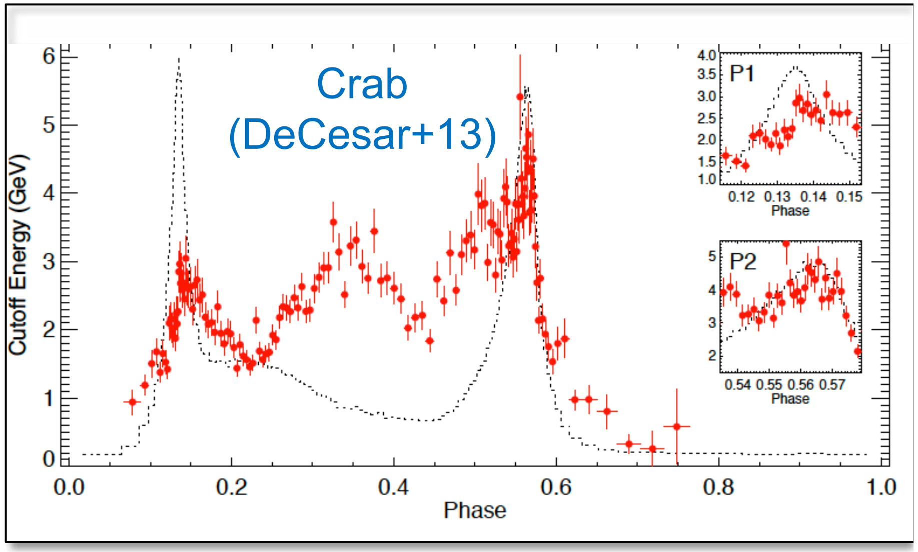
Credits A. Harding

Phase-resolved spectra

- Vela & Crab vs Geminga
- P2 harder than P1
- Bridge softer than peaks in Vela & Crab
- Track B, E_{par}, ρ_c



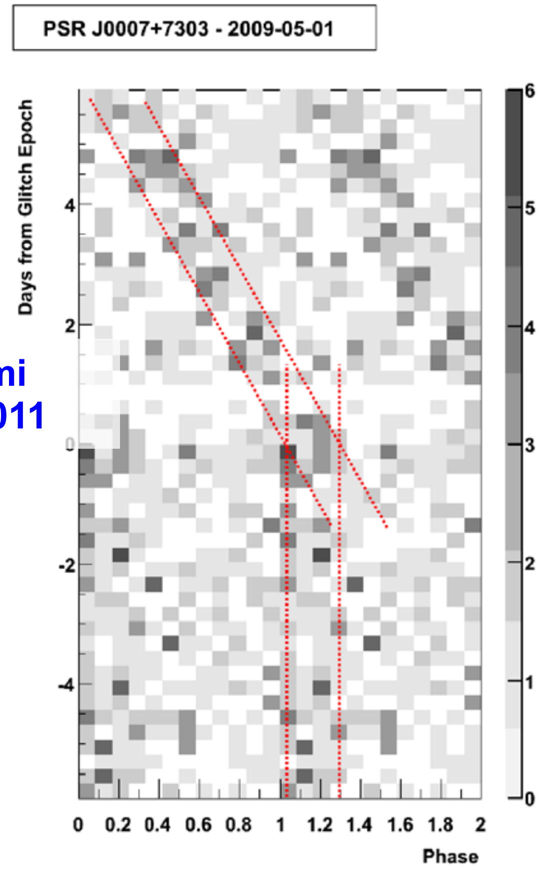




Credits A. Harding

Surprises: glitches

- **Continuous monitoring**
  - **Catching glicthes "on the fly"**
  - **Characterize them**
- **Unique instrument for radio-quiet pulsars**



Belfiore, Fermi Symposium 2011

PULSAR	Distance (kpc)	f (hz)	$\dot{f}$ (hz/s)	$\frac{\Delta f}{f}$	Glitch Time (MJD)	Radio?
J0007+7303	$1.4 \pm .3$	3.1658268380	-3.58×10^{-12}	5.54×10^{-7}	54954	Quiet
J0007+7303	$1.4 \pm .3$	3.1658268380	-3.58×10^{-12}	1.26×10^{-6}	55466	Quiet
J0205+6449	$2.6 - 3.2$	15.2143754050	-4.48×10^{-11}	1.74×10^{-6}	54795	Loud
J0835-4510	$.287^{+.019}_{-.017}$	11.189512263	-1.56×10^{-11}	1.92×10^{-6}	55408	Loud
J1023-5746	$2.4*$	8.9703354320	-3.08×10^{-11}	3.56×10^{-6}	55041	Quiet
J1124-5916	$4.8^{+.7}_{-1.2}$	7.379534279	-4.1×10^{-11}	3.06×10^{-8}	55191	Faint
J1413-6205	$1.4*$	9.1123866570	-2.29×10^{-12}	1.73×10^{-6}	54735	Quiet
J1420-6048	5.6 ± 1.7	14.66123111	-1.78173×10^{-11}	1.35×10^{-6}	55435	Loud
J1709-4429	$1.4 - 3.6$	9.7564601870	-9.03×10^{-12}	2.75×10^{-6}	54693	Loud
J1813-1246	$3.19 \pm .69$	20.80188547	-7.61×10^{-12}	1.16×10^{-6}	55094	Quiet
J1838-0537	1.49—3.93	6.863	2.1896×10^{-11}	5.5×10^{-6}	55100	Quiet
J1907+0602	$3.2 \pm .6$	9.377661105	-7.631×10^{-12}	4.66×10^{-6}	55422	Faint
J1952+3252	$2.0 \pm .5$	25.29471117	-3.727×10^{-12}	1.5×10^{-6}	55325	Loud
J2021+3651	$2.1^{+2.1}_{-1.0}$	9.6390889420	-8.87×10^{-12}	2.23×10^{-6}	55109	Loud
J2229+6114	$.8 - 6.5$	19.361874486	-2.91834×10^{-11}	2.05×10^{-7}	55130	Loud
J2229+6114	$.8 - 6.5$	19.361874486	-2.91834×10^{-11}	1.231×10^{-6}	55599	Loud

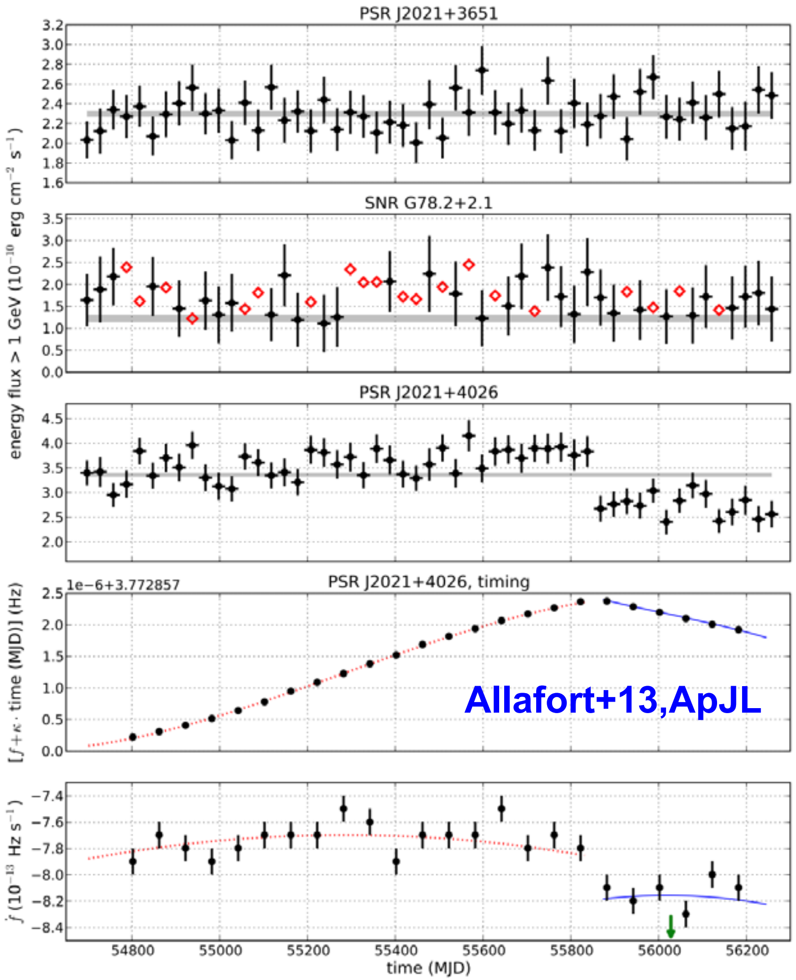
Stopnitzky & Profumo +13,ApJ

Surprises: pulsar variability

PSR J2021+4026

aka Gamma Cyg PSR

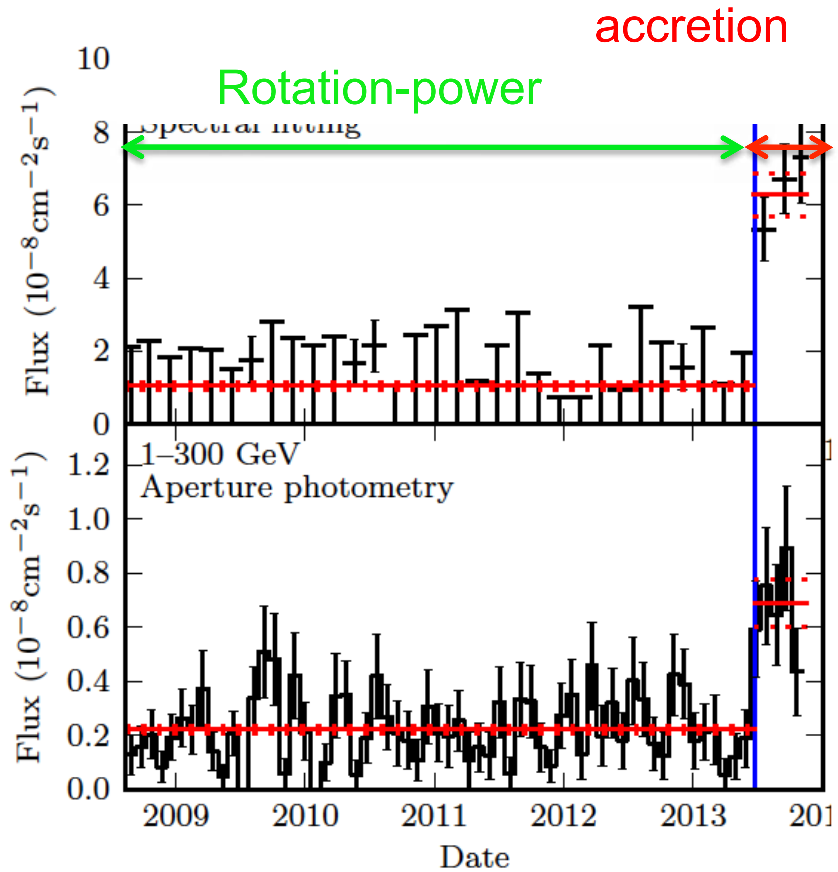
Mode changes



PSR J1023+0038

aka “the missing link” PSR

State changes

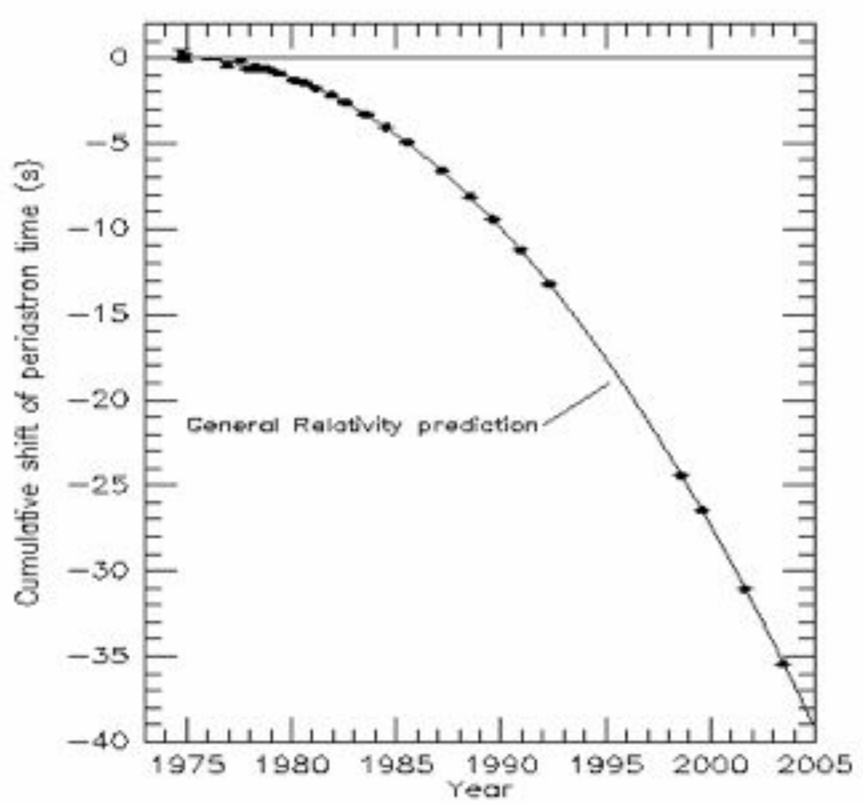


Stappers+13

A long-standing relationship…

…between pulsars and gravitational waves

- PSR B1913+16 (1974)
- Discovered by Russel Hulse and Joseph Taylor
- Binary ! 59-ms pulsar + neutron star, orbit of 77 hrs
- Orbital decay consistent with GW emission
- $L_{GW} = 7x10^{24}$ W (1.4% L_{sun})
- (Nobel prize in 1993)



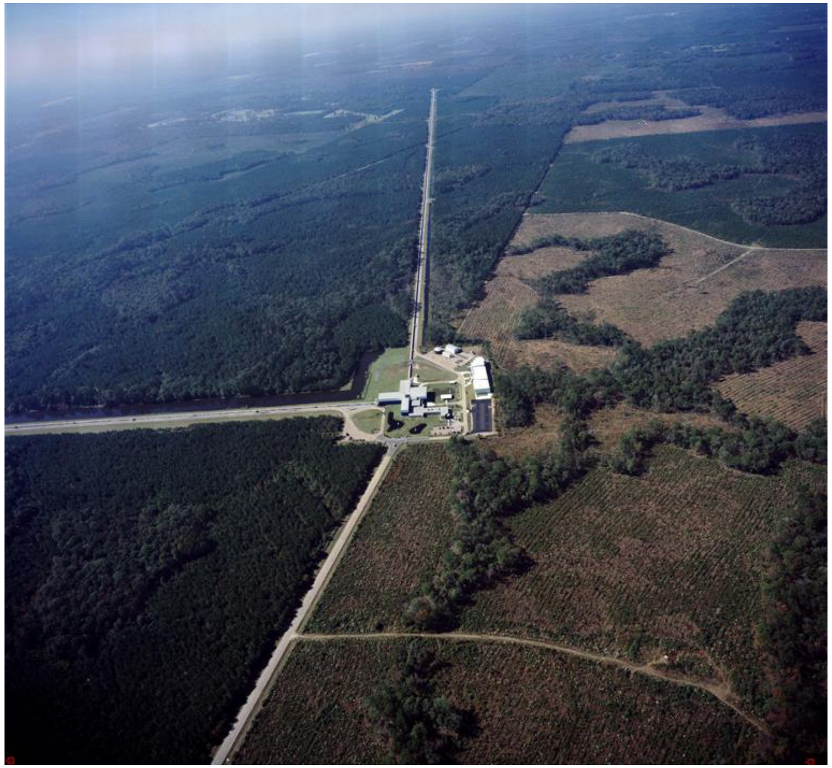
However, this was an indirect observation of GWs…

The multi-messenger connection

- Advanced gravitational interferometers coming online in the next years (Virgo/LIGO)
- Mergers are the most promising GW sources, but also continuous signal from pulsars
- Gravitational-electromagnetic synergy is crucial

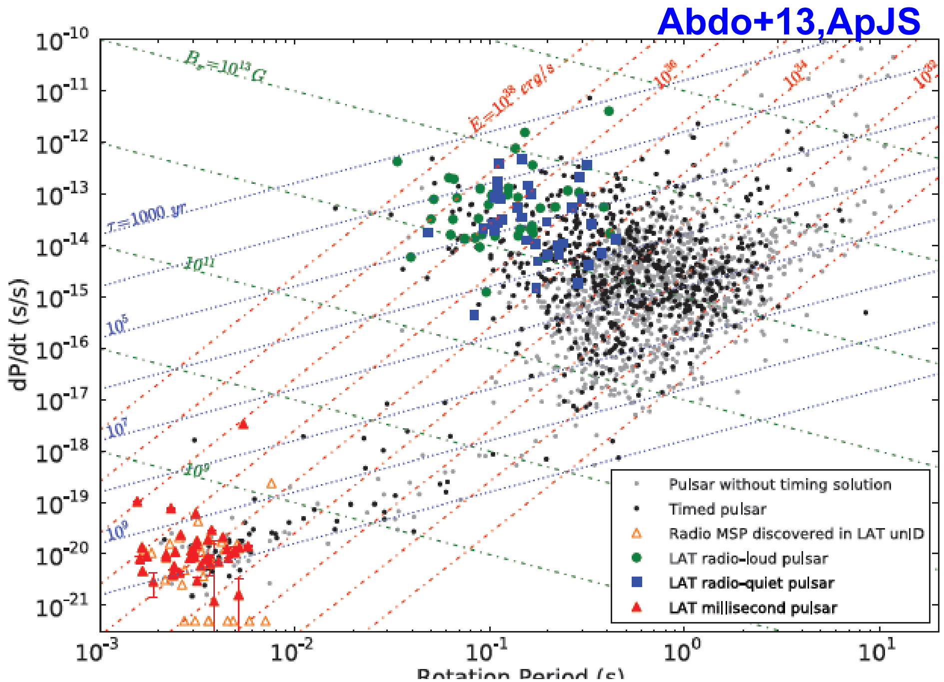
Virgo
1 x 3km (Cascina, Pisa, Italy)
www.virgo.infn.it

LIGO
2 x 4 km (Richland, WA + Livingston, LA)
www.ligo.caltech.edu

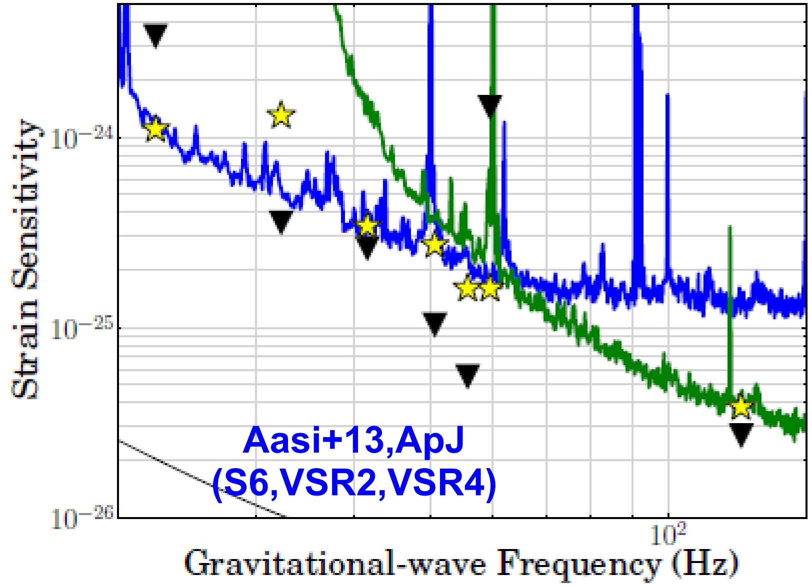


The pulsar connection

- **Quadrupole momentum from oblate neutron stars**
- **Periodic continuous GW signal**
- **Complementary information**
  - GWs from neutron star
  - Gamma rays from magnetosphere



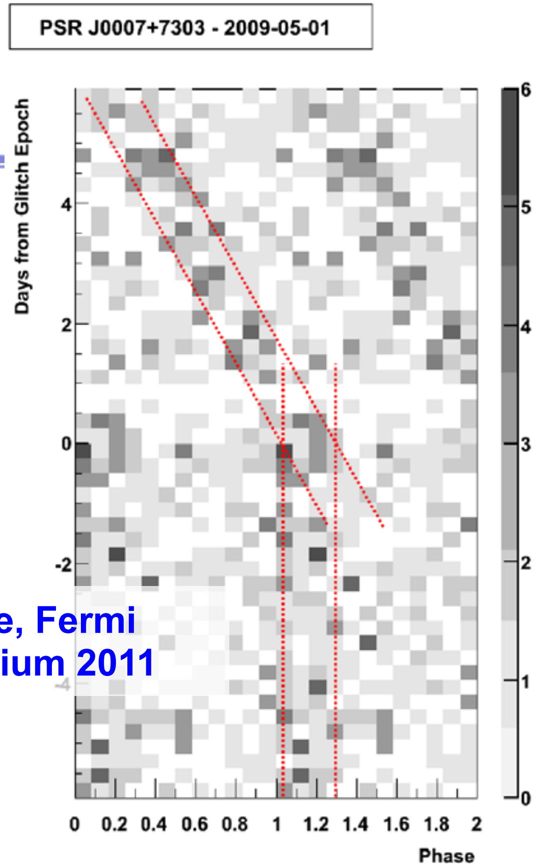
- **EM →GW**
  - Many Fermi pulsars are young, energetic, and relatively nearby, i.e. good GW candidates
  - Fermi continuously monitors pulsars, providing timing solutions
  - Fermi is the only instrument capable of timing most radio-quiet pulsars



GWs & pulsar glitches

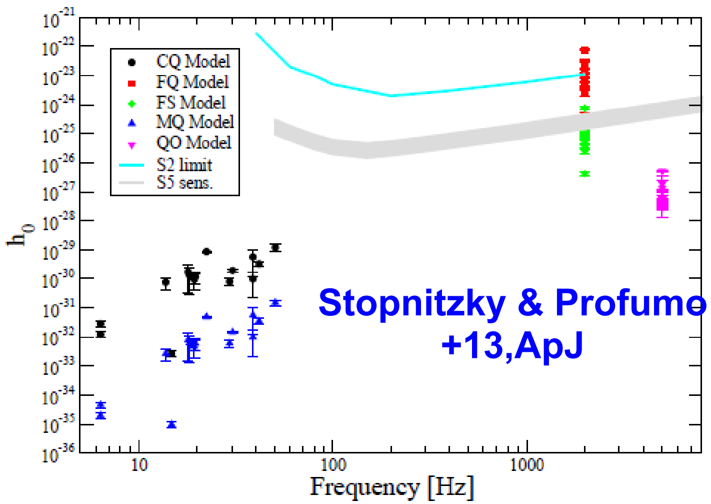
- **Burst-like signal from pulsar glitches**
- **Loss of coherence**
- **GW Upper limits for some pulsars (e.g. Vela)**

- **Complementary information**
  - GWs from neutron star
  - Gamma rays from magnetosphere



Belfiore, Fermi Symposium 2011

- **EM →GW**
  - Fermi continuously monitors the sky, detects glitches “on the fly”
  - Extract glitch parameters from gamma-ray data, crucial for addressing GW searches
  - Unique instrument for radio-quiet pulsars



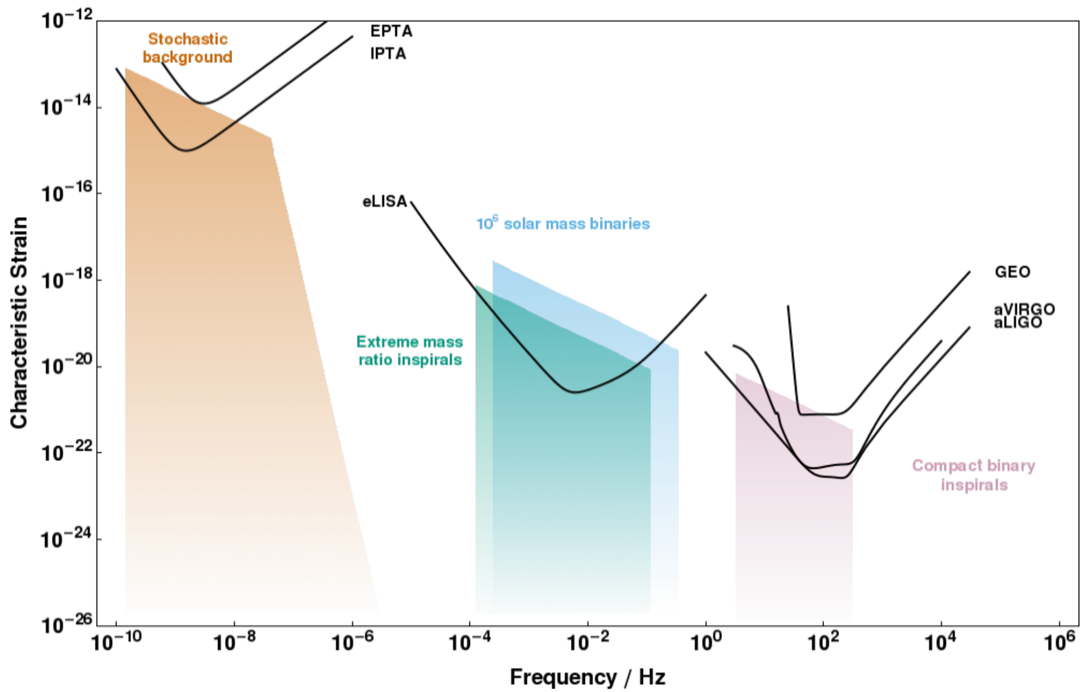
Stopnitzky & Profumo +13,ApJ

A Galactic GPS

- GWs affect times of arrival of pulses
- Frequency 10^{-6} 10^{-9} Hz (stochastic background)
- Requires very stable clocks, i.e. MSPs !
- Long observation times
- MSPs discovered with Fermi-LAT are used and will be used in these projects

- Main projects
    - Pulsar Timing Array (PTA)
    - European Pulsar Timing Array (EPTA)
    - North American Nanoherz Observatory for gravitational waves (NANOGrav)

International Pulsar Timing Array (IPTA)



Credits C. Moore et al.
(Univ Cambridge)

Exciting times for pulsars (and for us!)

- Natural laboratories to probe fundamental physics
- Major contributors to the gamma-ray Galactic population
- Gamma rays are crucial to understand emission processes

- A huge variety of pulsars out there!
  - New populations
  - Constrain models
  - Relation with PWNe
  - Continuous monitoring

- Possible candidates for advanced gravitational interferometers
- MSPs also useful tools for pulsar timing arrays

A new multimessenger era is coming !


Thanks for your attention !