Discovery of gamma-ray pulsars in *Fermi*-LAT data

with new methods inspired from gravitational-wave astronomy

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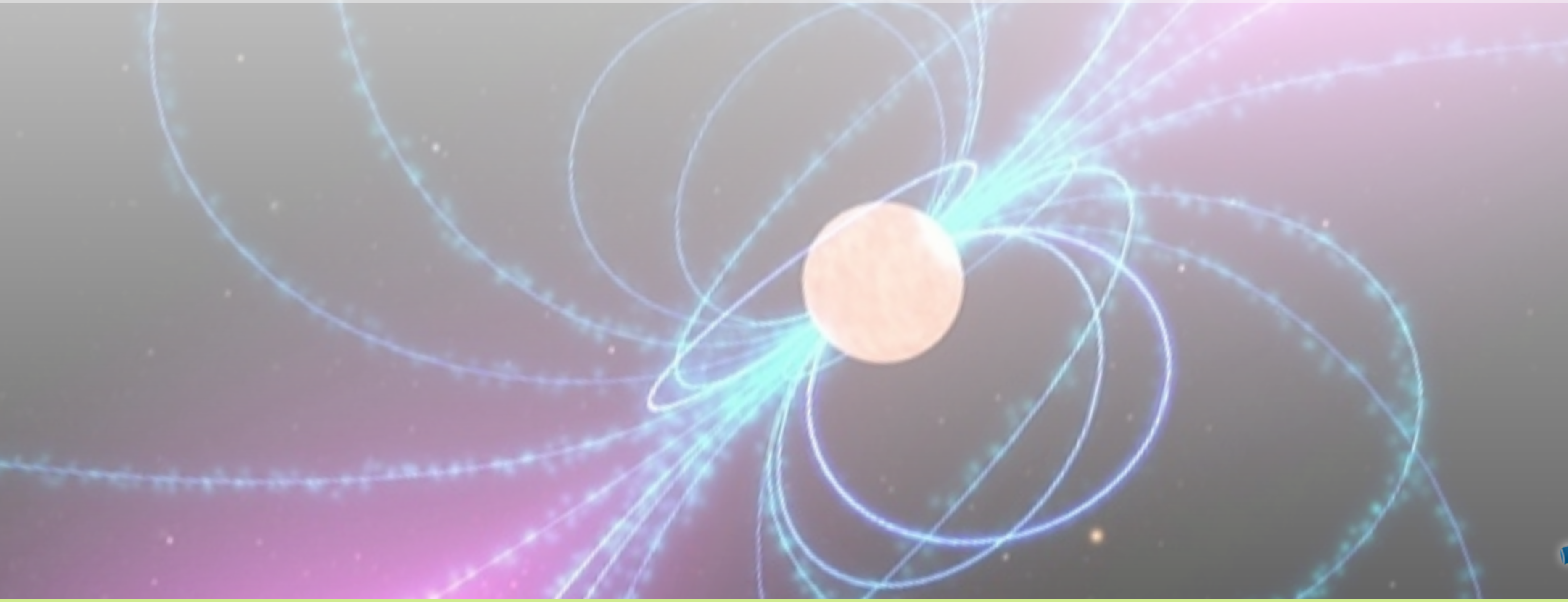
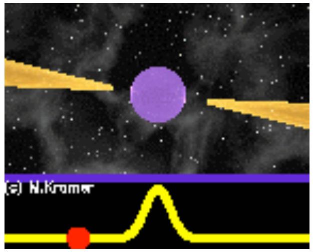


Executive summary

"Electromagnetic pulsars":

- Rapidly spinning & highly magnetized neutron stars.
- Lighthouse effect, beams of EM radiation



➜ Pulsations observable in **radio, optical, X-rays, and gamma-rays**.

"Gravitational-wave pulsars":

Fast spinning neutron star, e.g. with a tiny mountain.

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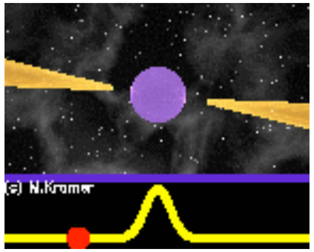

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Blind searches for gamma-ray pulsars

~~Multi-messenger~~

- No prior knowledge of pulsar parameters.

BUT:

- Same parameter space as GW pulsar searches.
- Similar data time span of *Fermi*-LAT and LIGO/Virgo.
- In both cases: signals are extremely weak.

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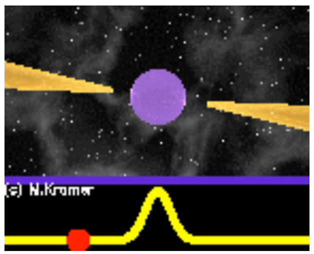

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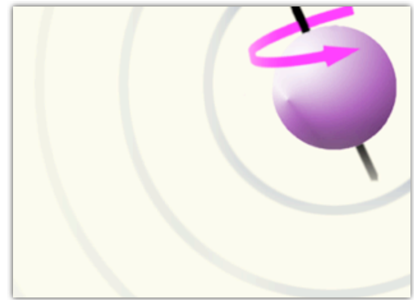

Fast spinning neutron star, e.g. with a tiny mountain.

Apply GW data-analysis "technology" to EM data

- to enhance search sensitivity
- to increase detections

➜ Discovery of several new pulsars

➜ Significant population increase (~30%)

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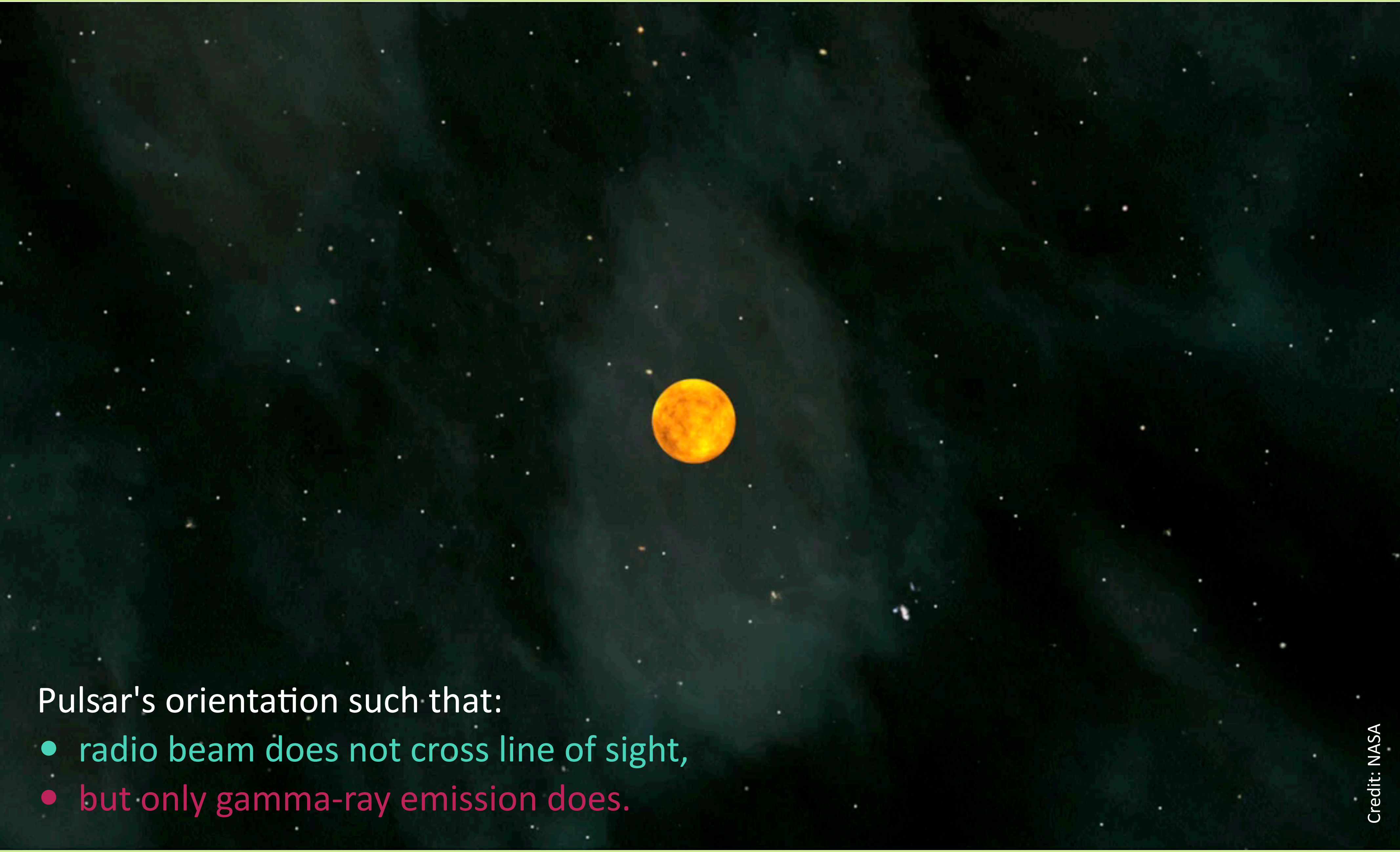
A radio-quiet gamma-ray pulsar



Pulsar's orientation such that:

- radio beam does not cross line of sight,
- but only gamma-ray emission does.

Credit: NASA

The *Fermi* Gamma-ray Space Telescope

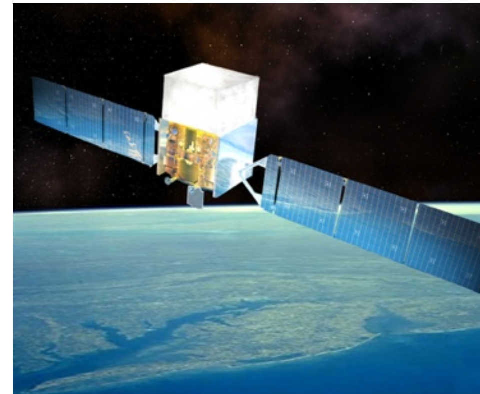
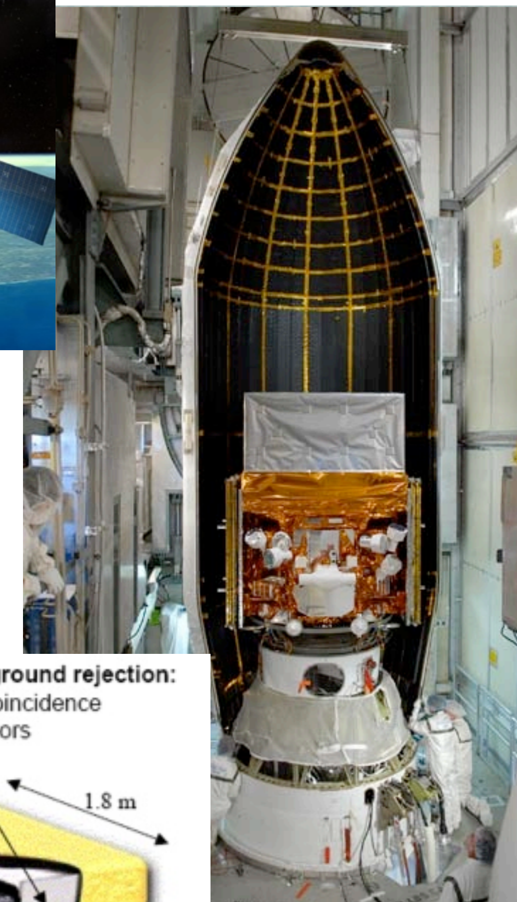


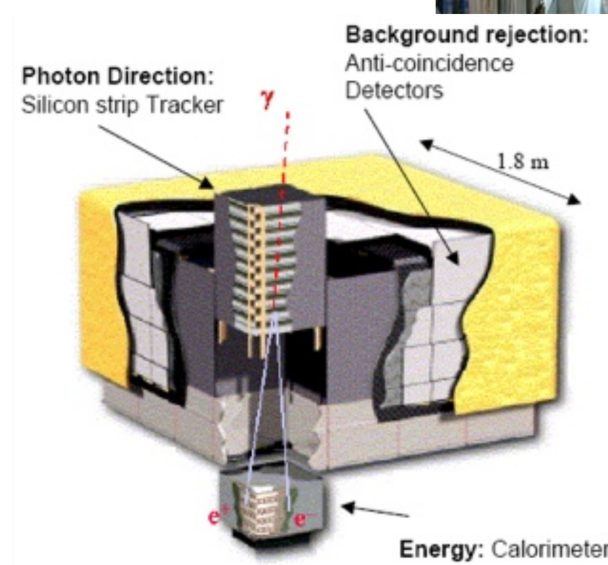
Image Credit: NASA



- ***Fermi*** launched June 11, 2008.
  Expected lifetime: 10 years.

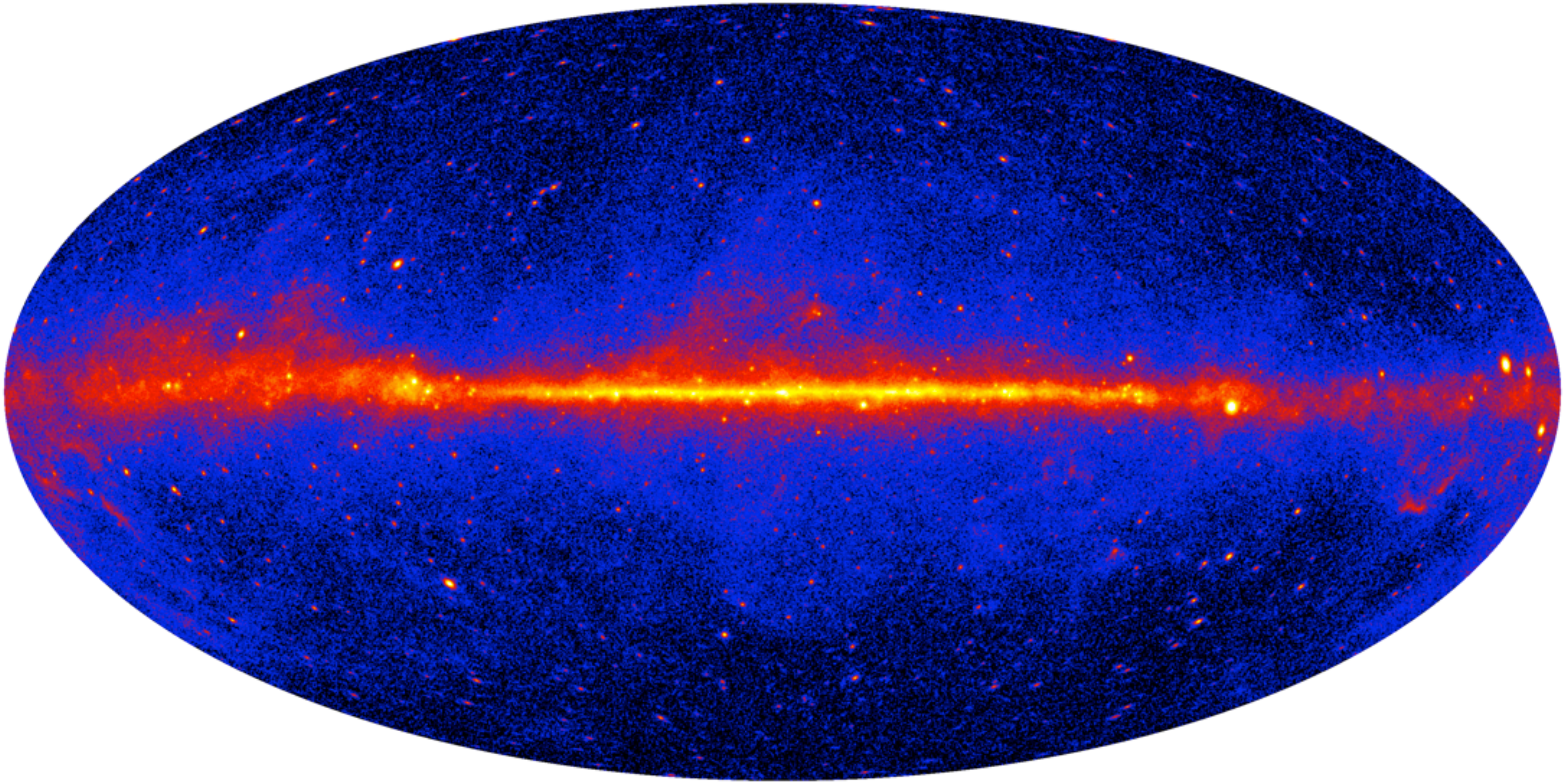
- The **Large Area Telescope (LAT)**
  on board *Fermi*:

  - Pair production telescope with silicon tracker, calorimeter, and segmented anti-coincidence detector.
  - Energy range: 20 MeV to > 300 GeV.
  - Continuous sky survey mode of operation, entire sky captured every 3 hrs, survey started August 8, 2008.
  - Big improvements in area, FOV, directional precision, background reduction, compared to precursor EGRET.



Atwood et al., ApJ, 2009

LAT all-sky map



Fermi-LAT Second Source Catalog (2FGL) based on two years: 1873 sources.

Among these **576** unidentified, not associated with counterparts at other wavelengths.

➜ Contain unknown gamma-ray pulsars?

Detecting pulsars with *Fermi*

BTW, **before** *Fermi*: < 10 gamma-ray pulsars

Now: > **100** pulsars identified with the *Fermi* LAT
in **3 different ways** (so far with about equal success rate):

Indirect ways (radio-loud pulsars):

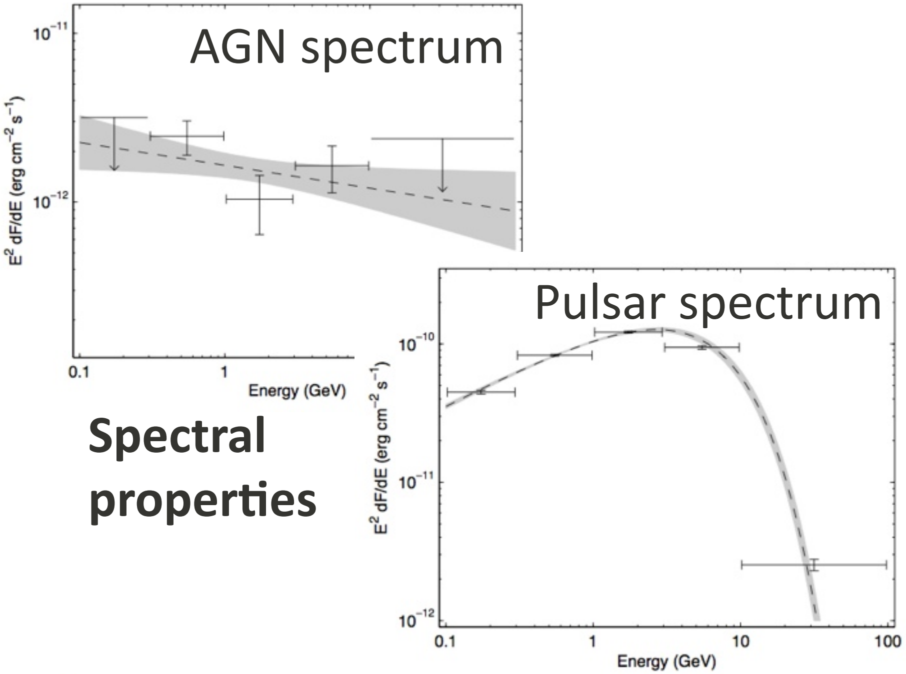
1) **Using ephemeris of pulsars known from radio or X-ray**
   - Assigning phases to gamma-ray photons based on known timing model

2) **Radio pulsar searches at sky positions of LAT unidentified sources**
   - From radio pulsar finding assign again phases to gamma-ray photons

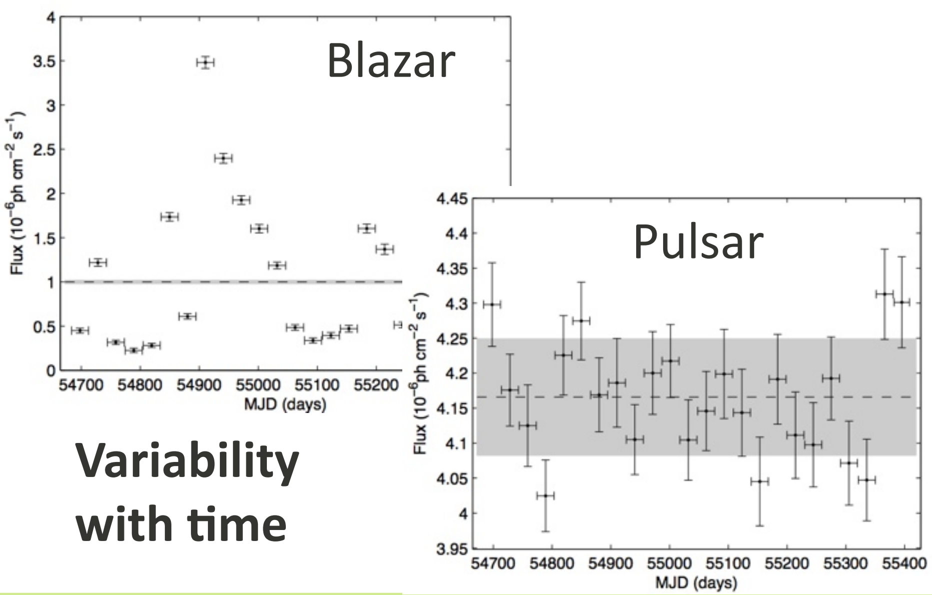
Direct way (the only way for radio-quiet systems):

3) **Blind searches for pulsars directly in LAT data**
   - *Fermi* is the first instrument to enable us blind-search discoveries
   - Very successful in finding young pulsars, no millisecond pulsar yet

"Pulsar-like" catalog sources



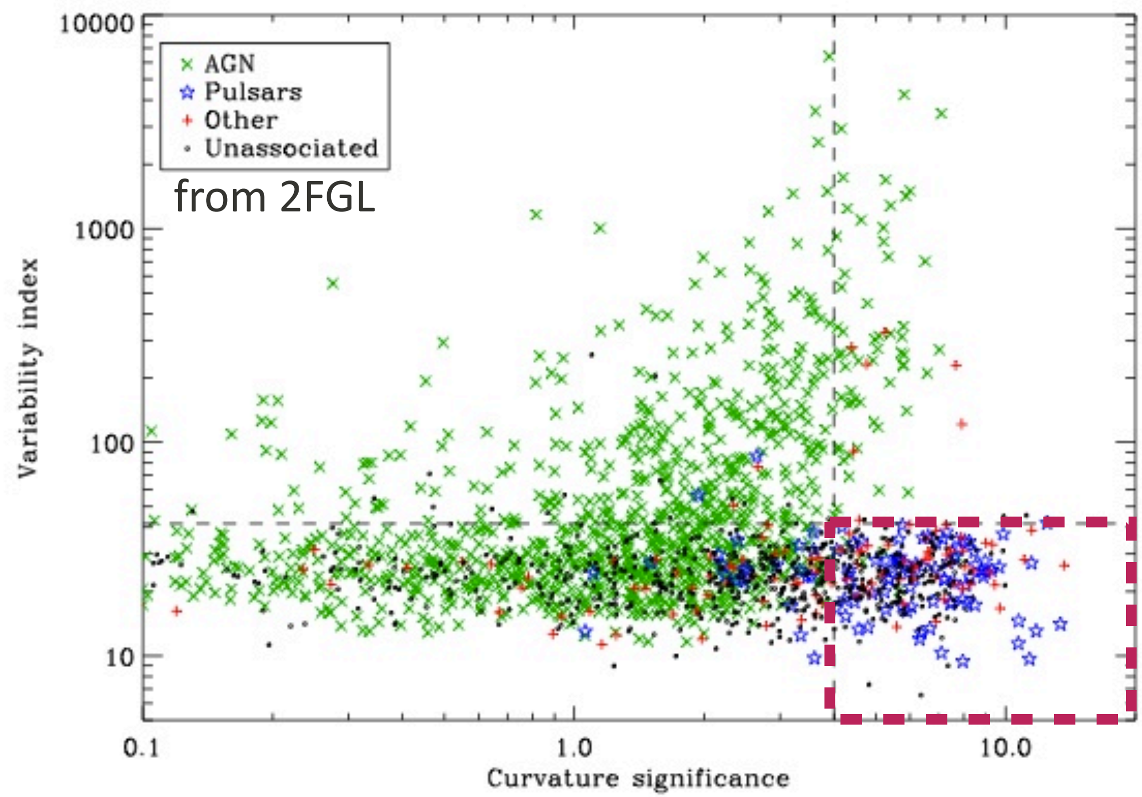
Spectral properties



Variability with time

Selecting "pulsar-like" 2FGL-catalog sources:

- Curvature significance ≥ 4σ,
- Variability index < 41.6,

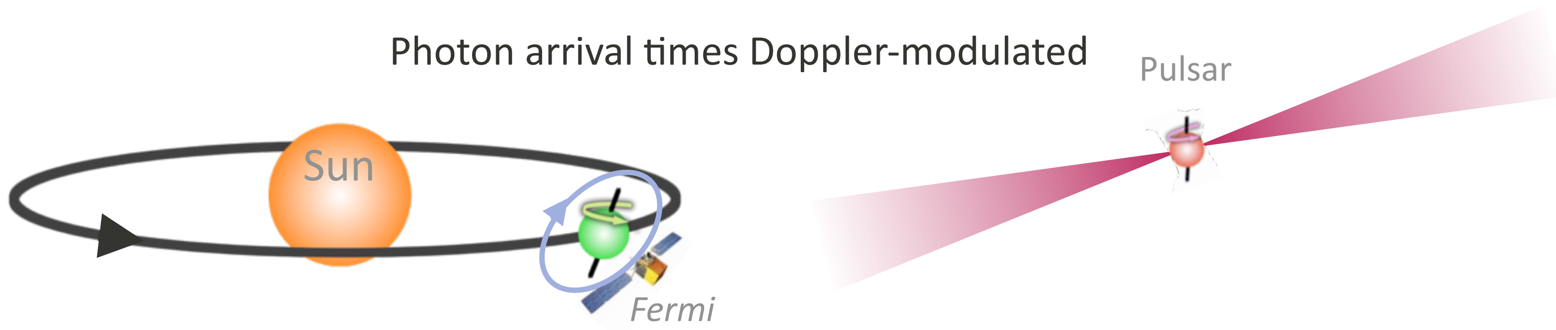


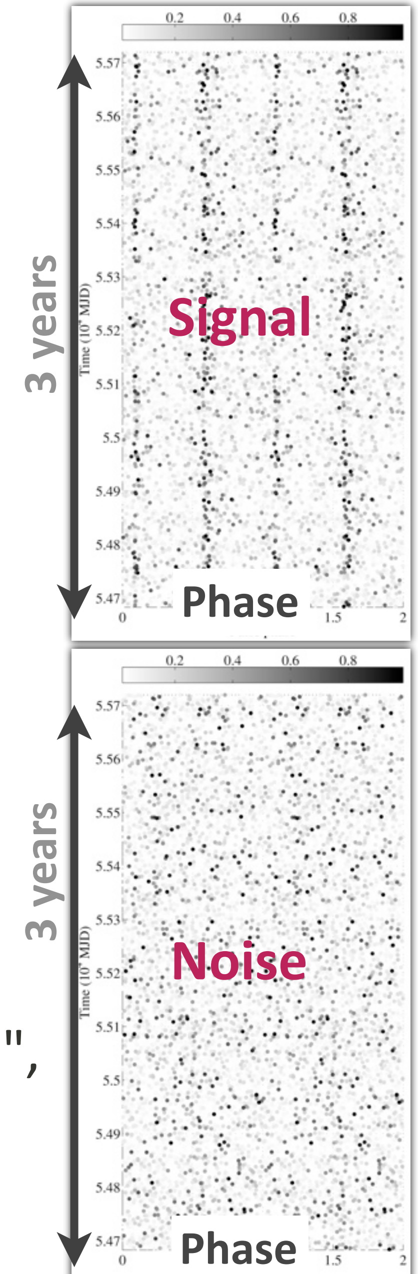
➜ **List of about 100 pulsar-like 2FGL sources with no known associations.**

The blind-search problem

- **In one year:** - LAT detects ~1000 photons from a typical pulsar
  - pulsar rotates at least 10^8 times around its axis

- For **isolated** systems:
  Need to find **rotational phase model** $\Phi(t) = 2\pi(ft + \dot{f}t^2/2)$
  with **spin frequency** f and **frequency derivative** $\dot{f}$,
  plus a **sky position** to match SSB arrival times t of the photons.





- **Signal hypothesis:** Arrival times "cluster" near specific "orientations", i.e. $\Phi(t) \mod 2\pi$ deviates from uniformity on interval $[0, 2\pi]$.

- **Null hypothesis:** photon arrival times are a random process.

Computational constraint

Ideal world: **infinite computing power**

➜ Fully coherent Fourier analysis on a dense 4D template grid

Reality: **finite computing resources limit search sensitivity**

➜ Enormously wide parameter space: fully coherent approach impractical

➜ Need: a) **more efficient search methods**

b) more computing power

➜ Goal: Maximize sensitivity at fixed computing cost

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Problem analogous to searches for GW pulsars

➜ **Solution:** use latest *GW-pulsar data-analysis* "technology"

- **Hierarchical search strategies**

Schutz & Papa (2000), Papa et al. (2000), Brady & Creighton (2000), Krishnan et al. (2005), Cutler et al. (2005), HJP & Allen (2009), HJP (2011), Cutler (2011), Prix, Shaltev (2012)

- **Parameter-space metric to construct efficient search grid**

Balasubramanian et al. (1995), Owen (1996), Brady et al. (1998), Jones et al. (2005), Prix (2007), HJP & Allen (2009), HJP (2010)

Search strategy aspects

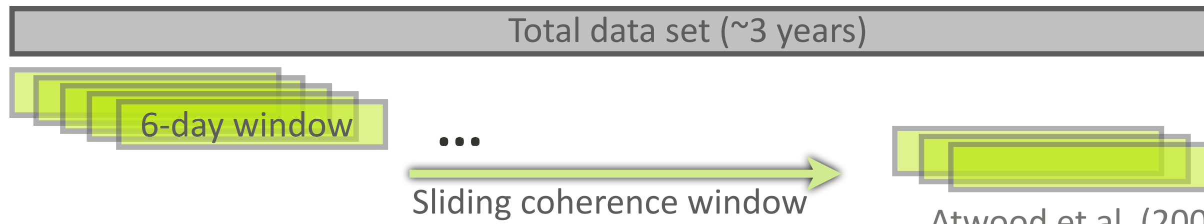
Hierarchical, 3-staged search scheme:

Discarding unpromising regions in parameter space as early as possible

"zooming in"

1. Semi-coherent:

- 6-day coherence window slid over 3 years while incoherently combining results.



Atwood et al. (2006)
HJP (2011)

2. Coherent follow-up:

- For every **semi-coherent candidate** compute fully coherent Fourier power over entire data set on significantly refined grid.

3. Including higher signal harmonics:

- Typically pulse profile non-sinusoidal, also Fourier power at harmonics of spin frequency.
- For every **coherent candidate** sum fully coherent power over entire data set from harmonically related frequencies using a further refined grid.

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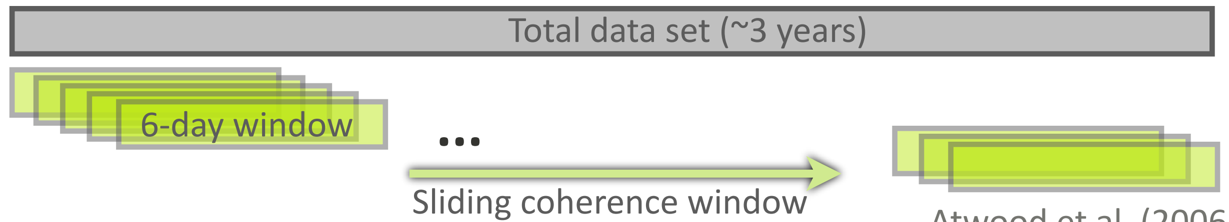

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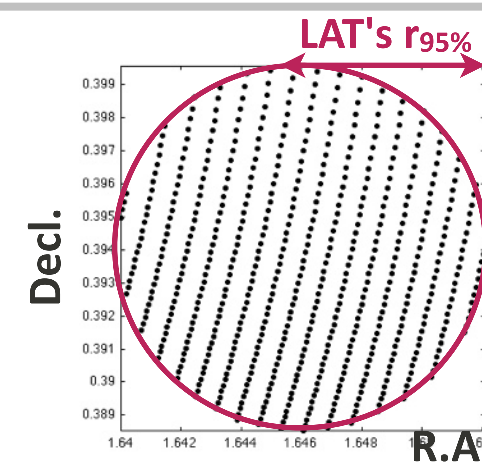
Parameter-space metric to guide grid construction of each stage:

- Geometric tool: measure fractional loss in expected detection statistic for a given signal at a nearby grid point (4D); no sky gridding in previous searches.

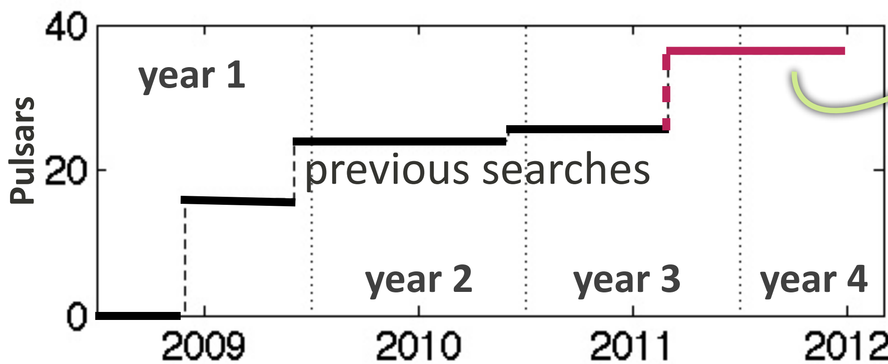
- Fully analytic semi-coherent pulsar metric; Ansatz by Brady & Creighton (2000) of "averaging coherent metrics"; using recent solution from HJP & Allen (2009).



Discoveries

Blind-search pulsars discovered during the *Fermi* mission:

No new discoveries with previous search methods since 2nd mission year.



New method discovered 9 pulsars: 1/3 of the known population!

THE ASTROPHYSICAL JOURNAL, 744:105 (20pp), 2012 January 10 doi:10.1088/0004-637X/744/2/105

DISCOVERY OF NINE GAMMA-RAY PULSARS IN *FERMI* LARGE AREA TELESCOPE DATA USING A NEW BLIND SEARCH METHOD

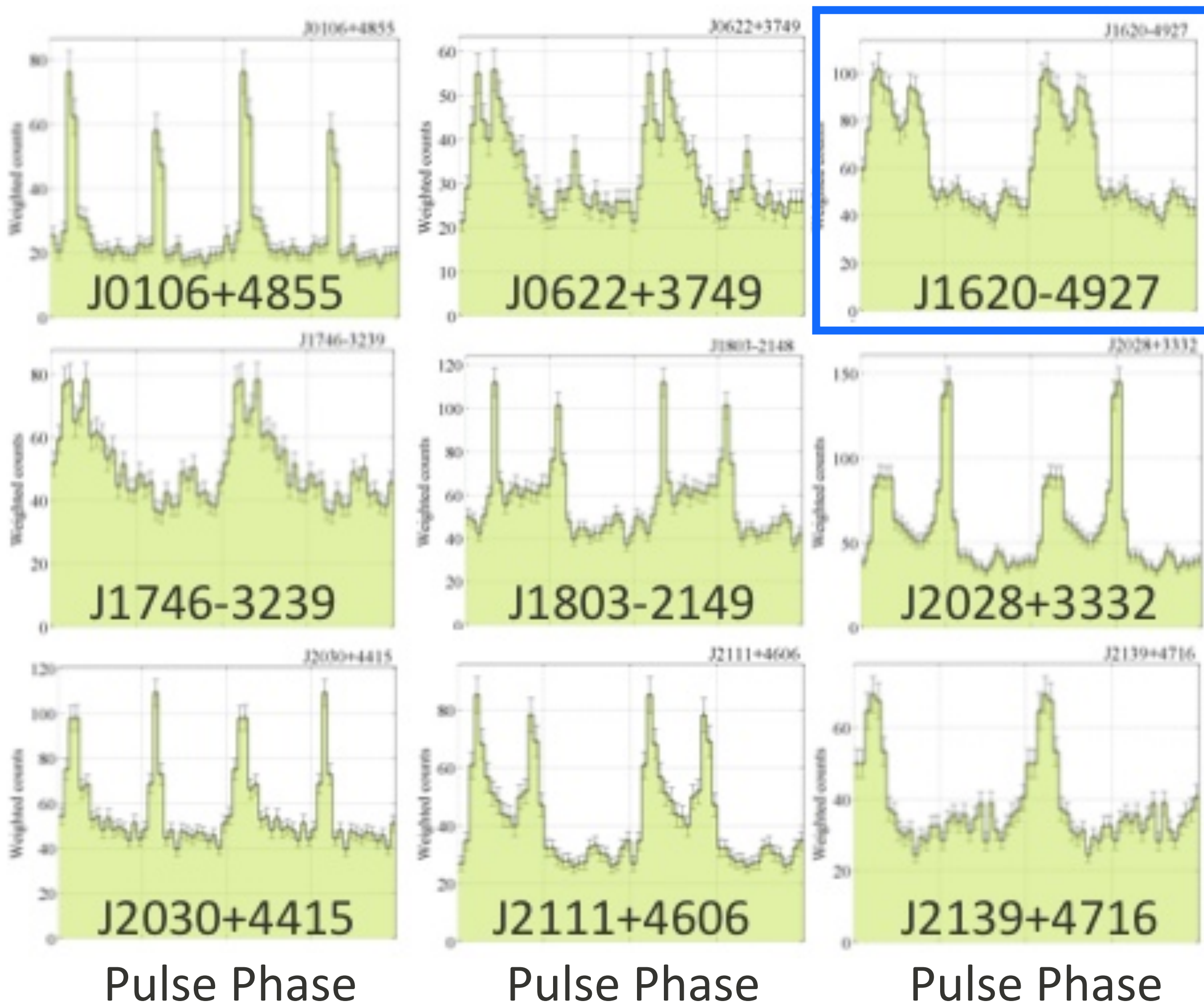
H. J. PLETSCH[1,3], L. GUILLEMOT[4], B. ALLEN[1,2,3], M. KRAMER[4,5], C. AULBERT[1,3], H. FEHRMANN[1,3], P. S. RAY[6], E. D. BARR[4], A. BELFIORE[7,8,9], F. CAMILO[10], P. A. CARAVEO[9], Ö. ÇELIK[11,12,13], D. J. CHAMPION[4], M. DORMODY[7], R. P. EATOUGH[4], E. C. FERRARA[11], P. C. C. FREIRE[4], J. W. T. HESSELS[14,15], M. KEITH[16], M. KERR[17], A. DE LUCA[9,18], A. G. LYNE[5], M. MARELLI[9], M. A. MCLAUGHLIN[19], D. PARENT[20,23], S. M. RANSOM[21], M. RAZZANO[7,22], W. REICH[4], P. M. SAZ PARKINSON[7], B. W. STAPPERS[5], AND M. T. WOLFF[6]

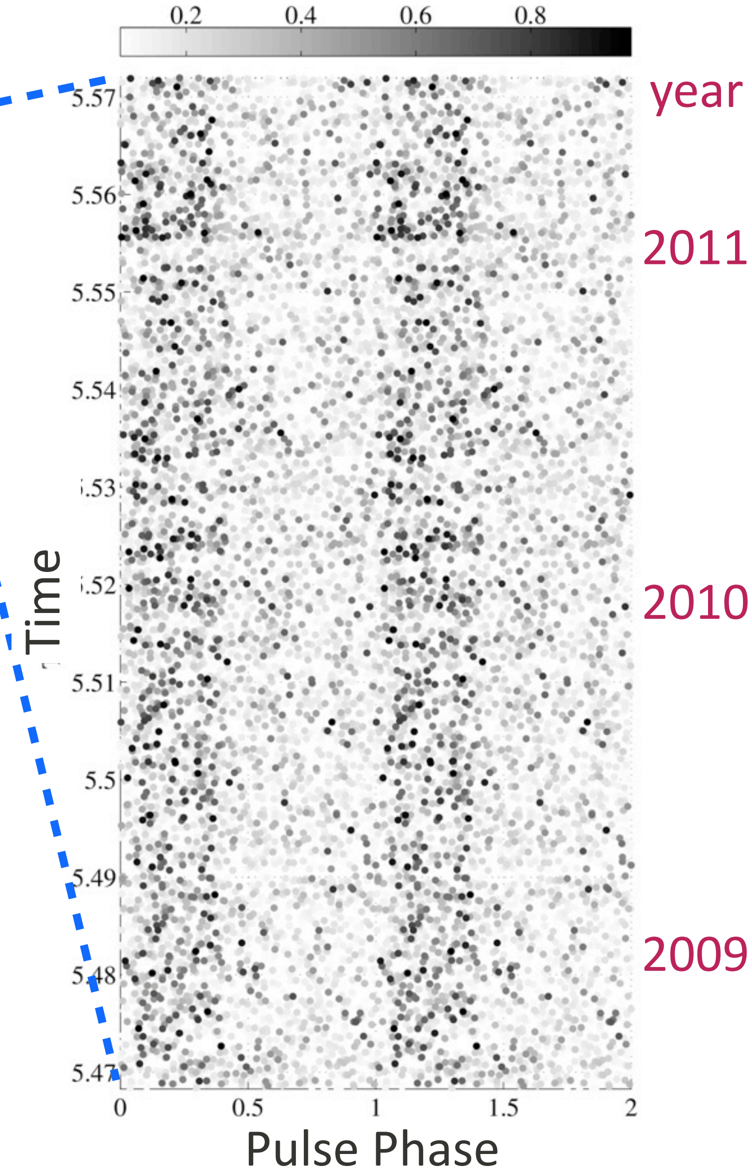
Found in first blind survey using ATLAS computing facility at AEI Hannover.

The 1st batch of discoveries

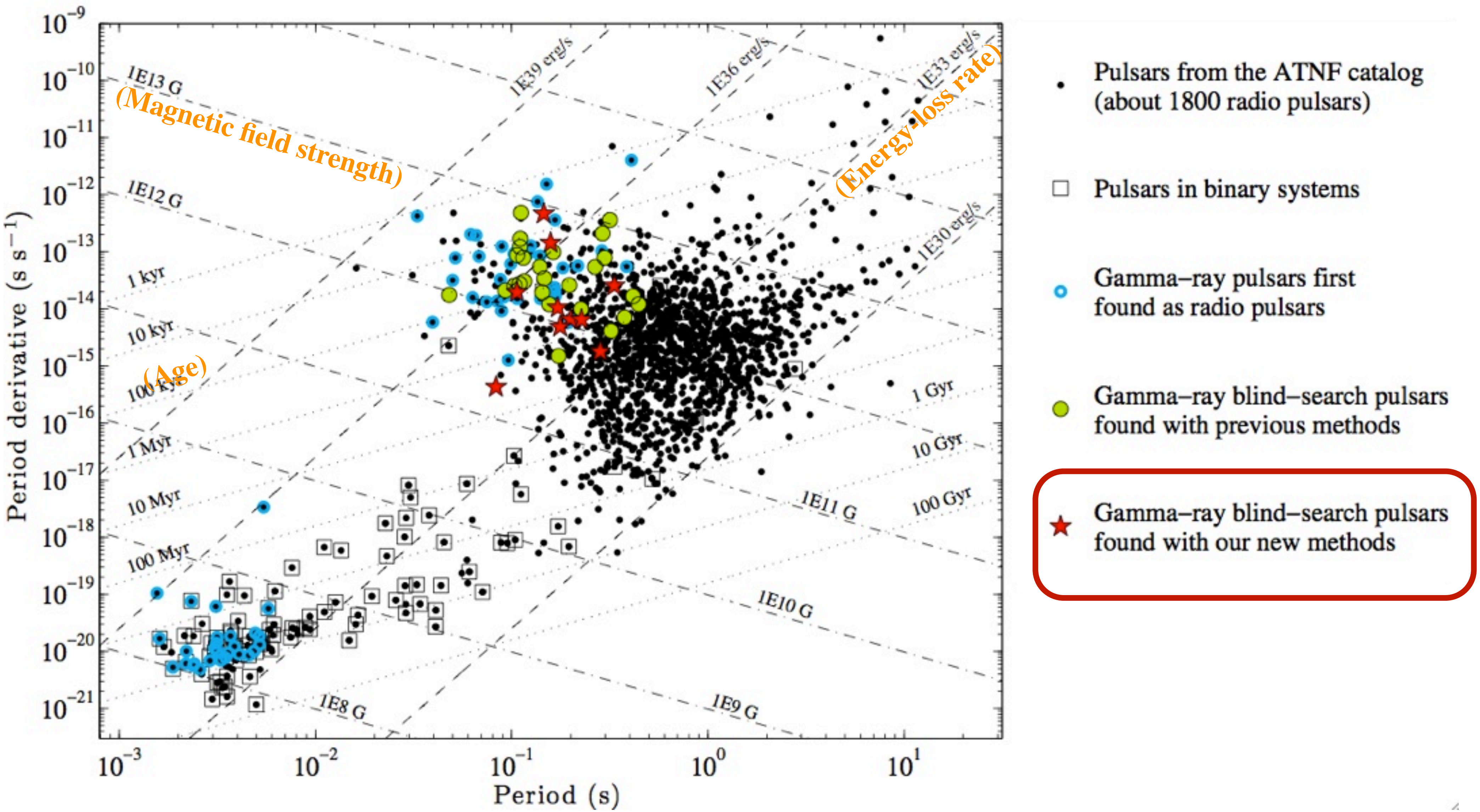
Pulse profiles of the 9 new gamma-ray pulsars:

(Two rotations shown for clarity)





Comparison to known population



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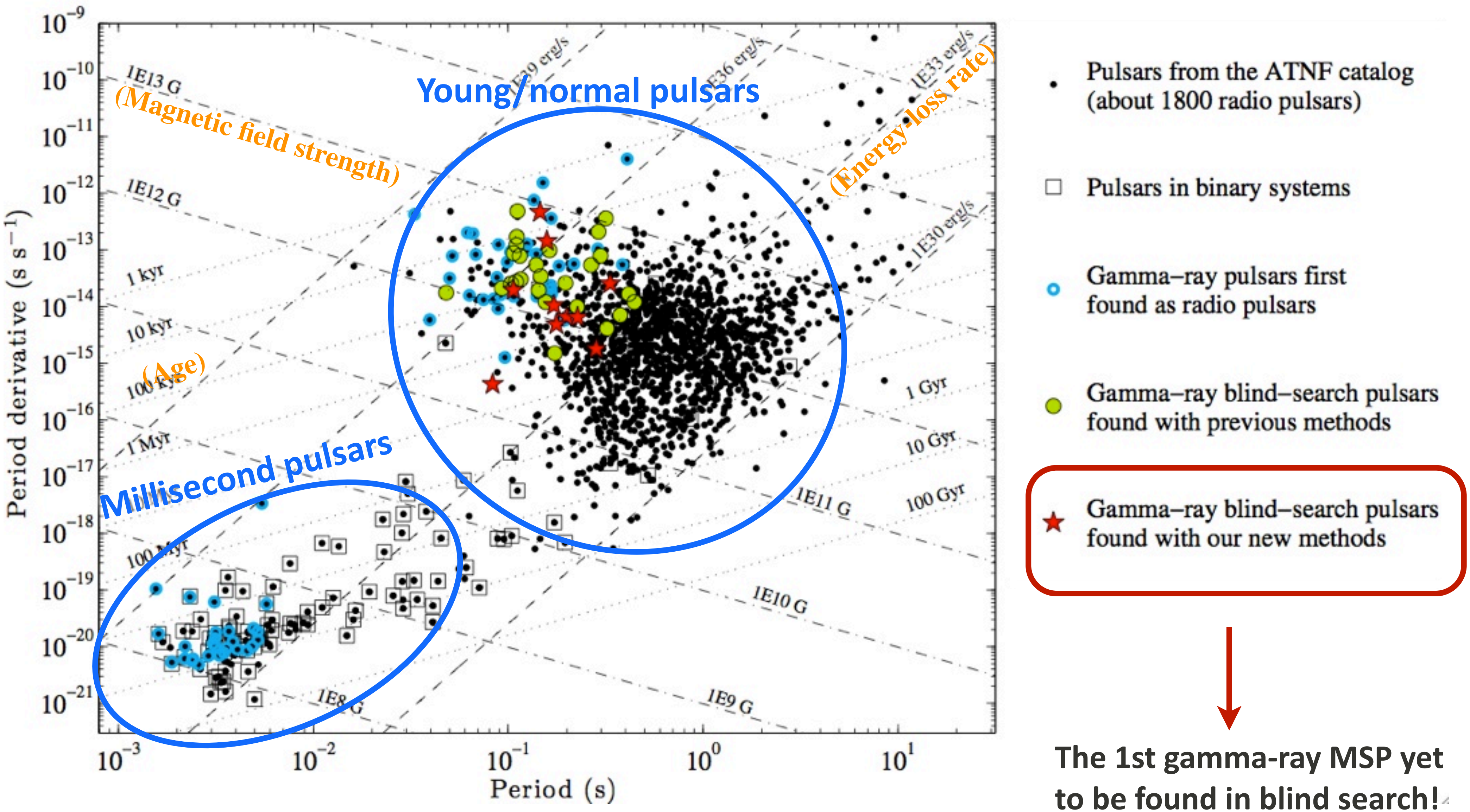


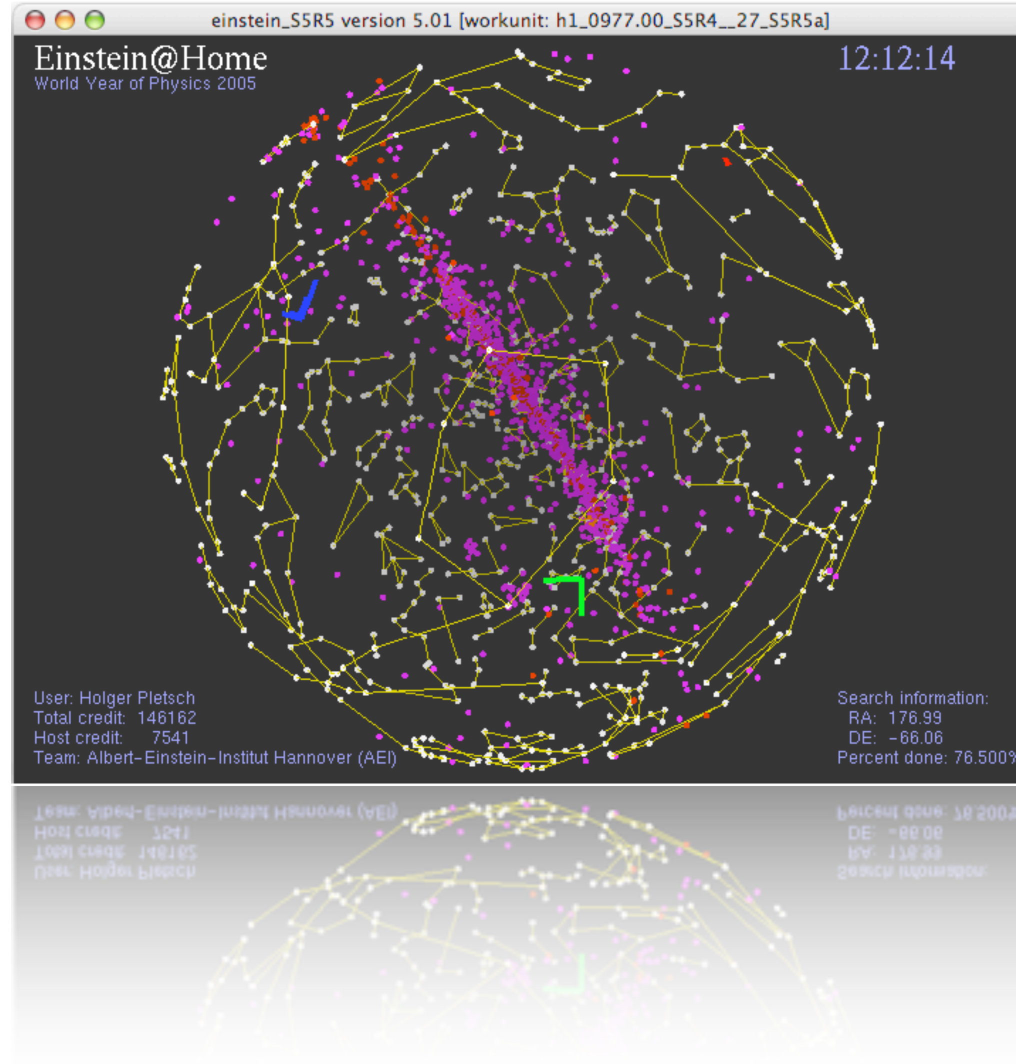
The 1st gamma-ray MSP yet to be found in blind search!

➜ Einstein@Home

Einstein@Home: volunteer supercomputing

- **Numbers:**
  - About 300 000 volunteers worldwide
  - About 50 000 active computers
  - About 500 TFlop/s sustained computing power

- **Infrastructure:**
  - Built upon *BOINC*
  - Servers in Milwaukee (USA) and Hannover (Germany)



Three distinct searches for neutron stars:

1. Gravitational-wave pulsar search,
   Data from LIGO, Virgo, GEO600 (since 2005)
2. Radio pulsar search,
   Data from Arecibo, Parkes (since 2009)
3. Gamma-ray pulsar search,
   Data from *Fermi* LAT (since 2011)

Conclusion

- GW astronomy: signal absence, but **efficient data-analysis methods**
  ⇒ Useful in related fields: signal-rich EM astronomy.

- **Finding radio-quiet gamma-ray pulsars** in *Fermi*-LAT data:
  Search sensitivity computationally bound: analog to blind GW pulsar searches
  ⇒ Apply GW pulsar search methods

- **Pulsar discoveries** in *Fermi*-LAT data:
  - Traditional methods successful during early mission
    (24 within 1 year, but detection rate stagnated since)
  - **New search method** using 3 years of LAT data: **9+** ⇒ **Increased population by ~30%!**

- Computational load of survey now moved to **Einstein@Home**:
  Hope to find the *first radio-quiet millisecond gamma-ray pulsar*.
  ⇒ Potential important advance in understanding of pulsars.