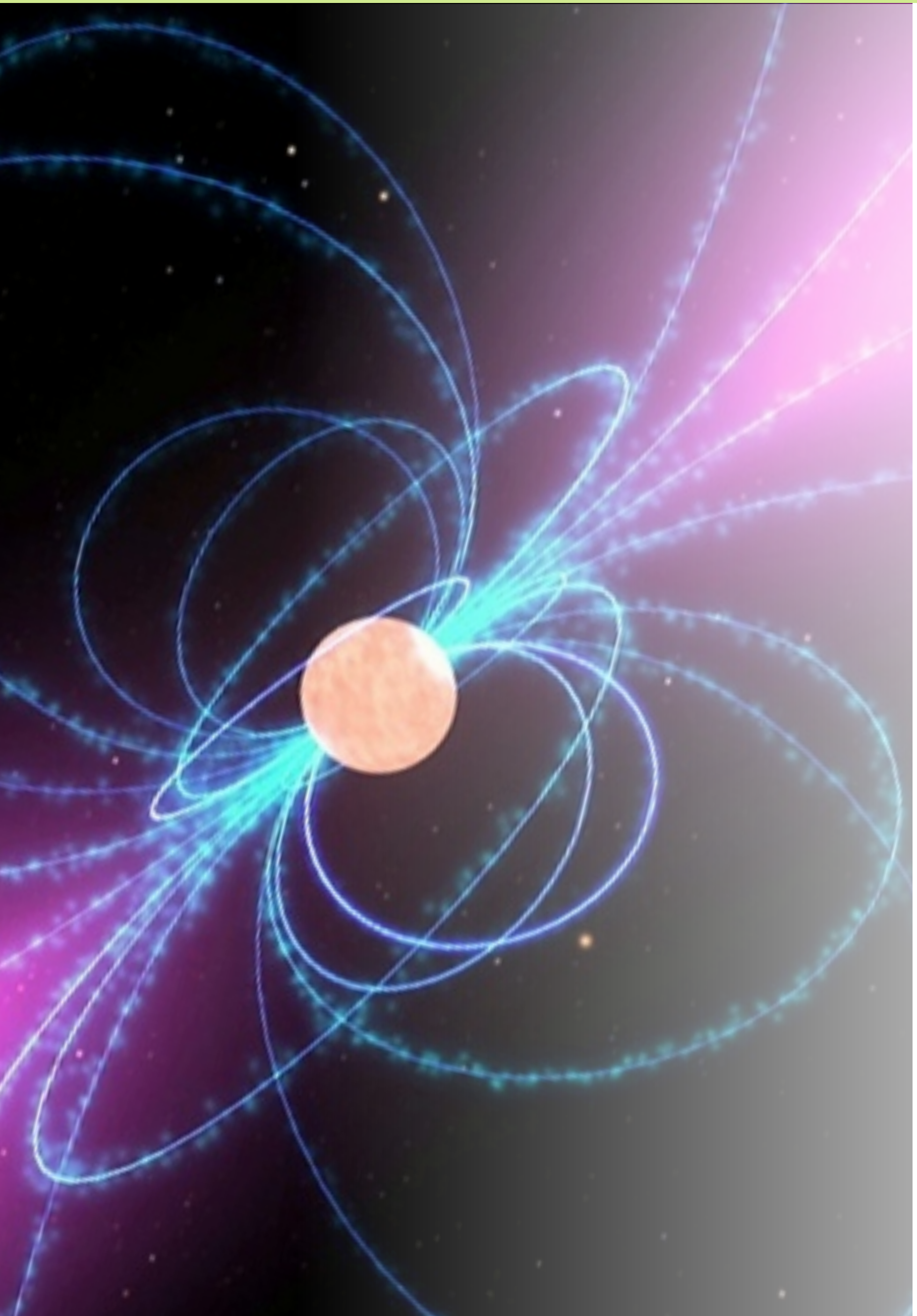

Searches for Gamma-ray Pulsars in *Fermi*-LAT data with methods inspired from GW astronomy

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VESF School, 17 Apr 2013

VESF Virgo EGO Scientific Forum

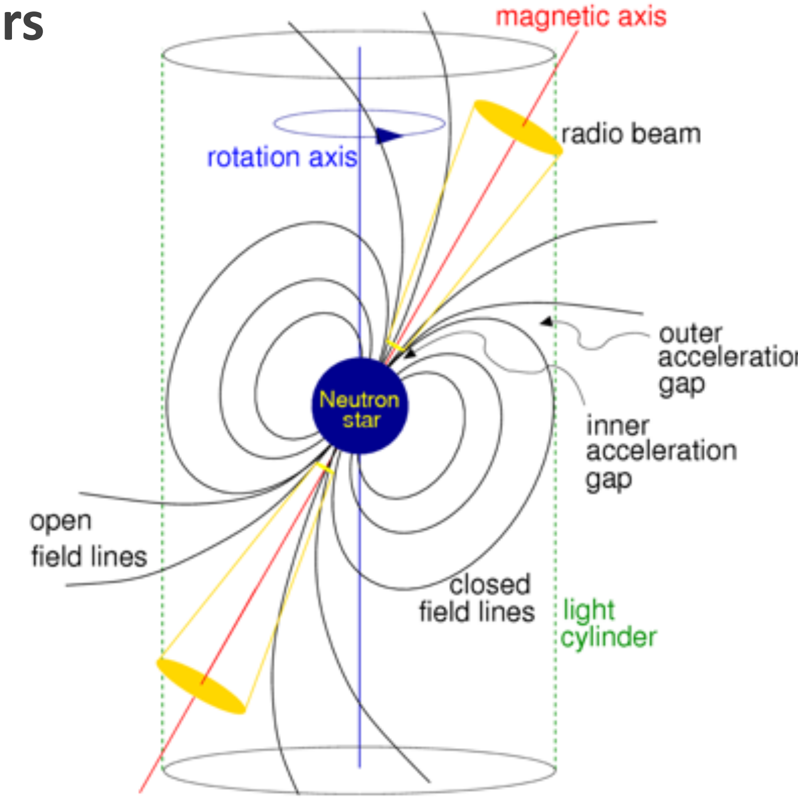
Outline

- Pulsars (in a nutshell)
- The *Fermi* Large Area Telescope (LAT)
- Blind searches for new gamma-ray pulsars
  - **Data analysis methods**
  - Recent discoveries
- Concluding summary

Pulsars

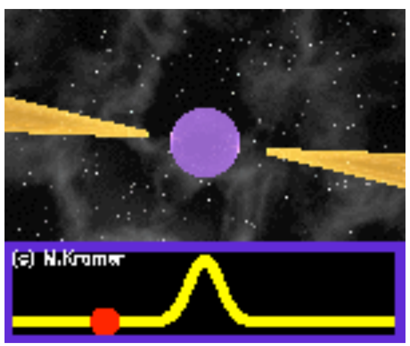
Pulsars: fast spinning, highly magnetized **neutron stars**

- Born in supernova explosions of massive stars.
- Spin periods: a) normal/young pulsars (~1s)
  b) millisecond pulsars (down to 1.4ms)
- ***Observable in every astronomical window!***



Magnetosphere extends to the light cylinder, traditionally approximated by dipole field.

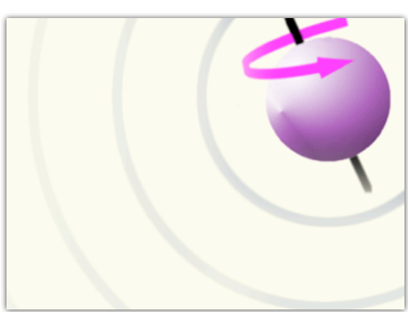
- **"Electromagnetic pulsars"**



Lighthouse effect: Charged particles accelerated in magnetic field produce beams of EM radiation. Misalignment of magnetic and spin axes makes beams sweep around.

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

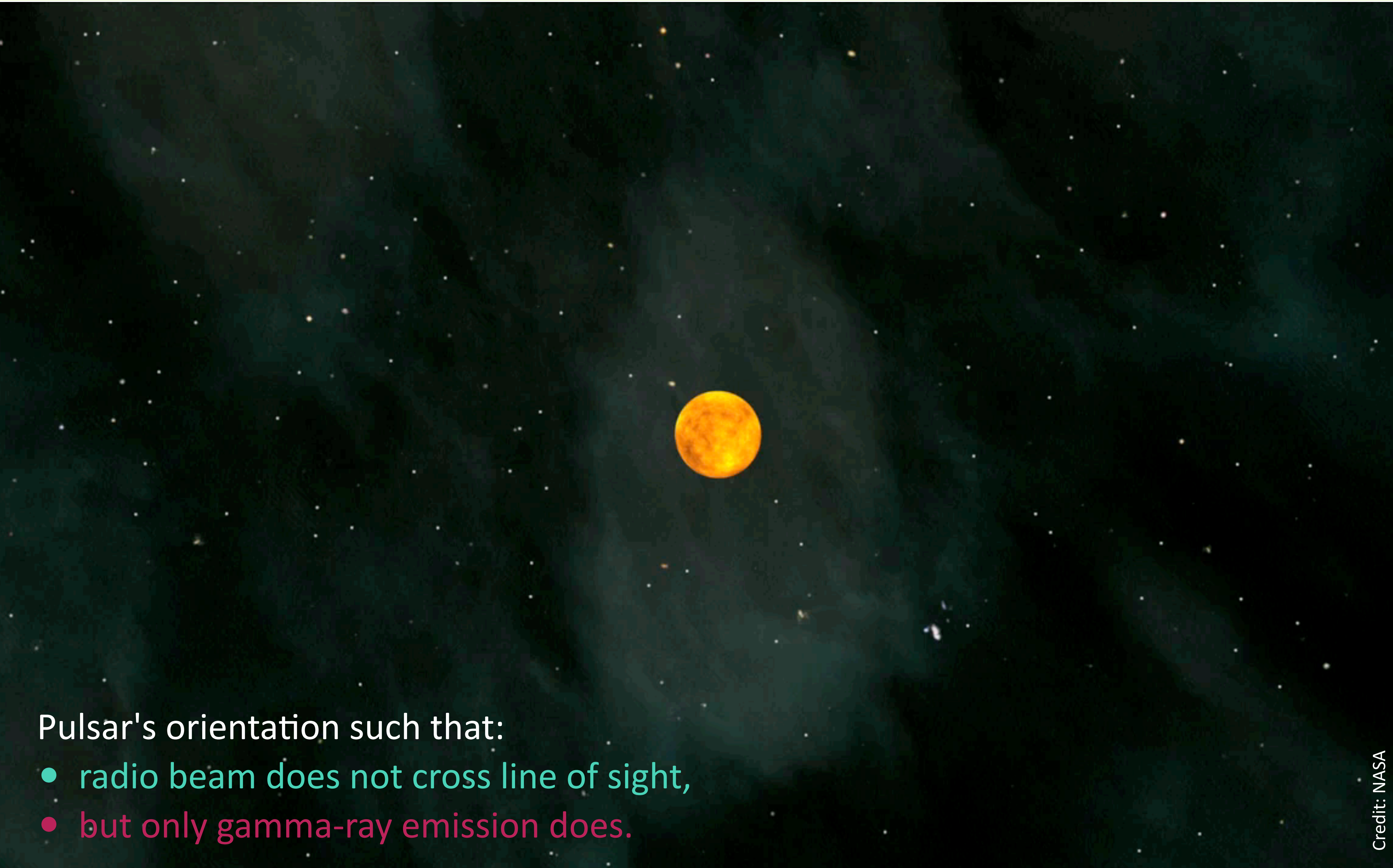
- **"Gravitational-wave pulsars"**



Spinning neutron stars with a deviation from symmetry, e.g. a *tiny* mountain.

➜ Emit **continuous gravitational waves**

A *Radio-quiet* Gamma-ray Pulsar



Credit: NASA

Pulsar's orientation such that:

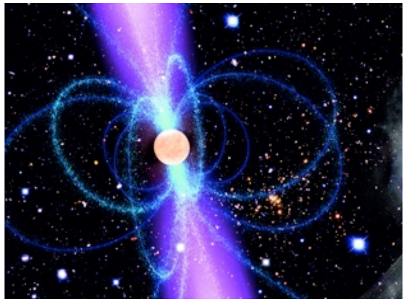
- radio beam does not cross line of sight,
- but only gamma-ray emission does.

Executive Summary

Blind searches for previously unknown pulsars

➜ No prior knowledge of exact pulsar parameters!

Gamma-ray pulsars



Gravitational-wave pulsars

BUT:

- Same parameter space to search.
- Similar data time span of *Fermi*-LAT and LIGO/Virgo.
- In both cases: periodic signals that are extremely weak.

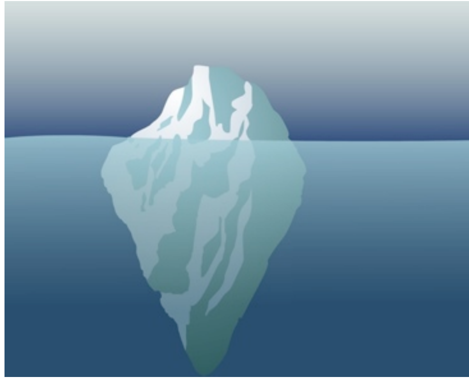
Cross-field application of search methodologies:

Apply GW data-analysis "technology" to EM data

- Enhancing search sensitivity and increase detections

➜ Led to discovery of several new pulsars

➜ Significant population increase; beyond "tip of iceberg"



Gamma-ray Pulsars before *Fermi*

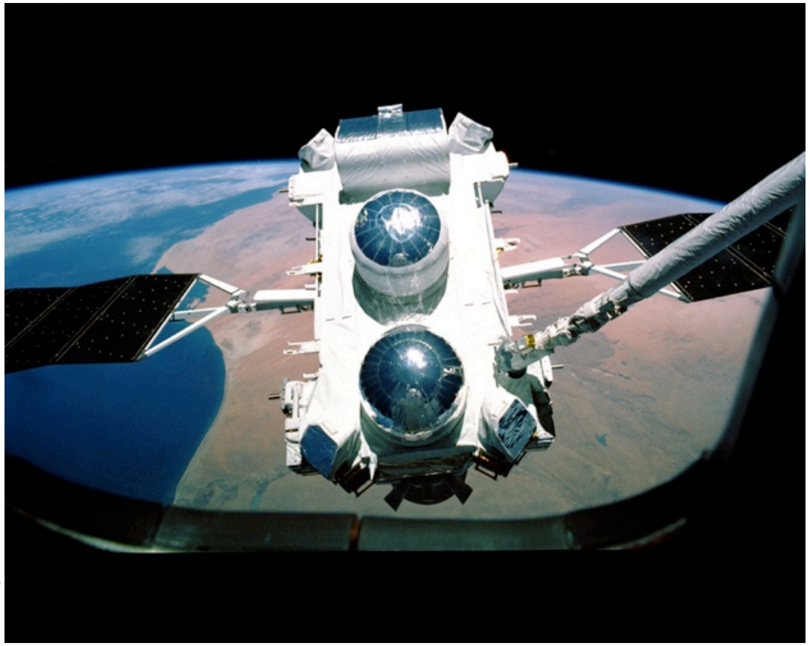


Image Credit: NASA

CGRO (1991-2000): BATSE, OSSE, COMPTEL, EGRET

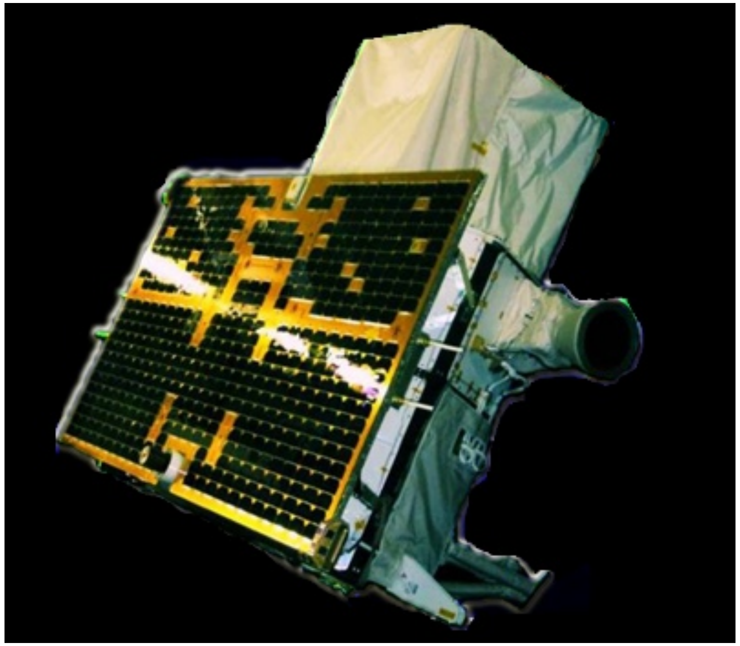


Image Credit: ASI

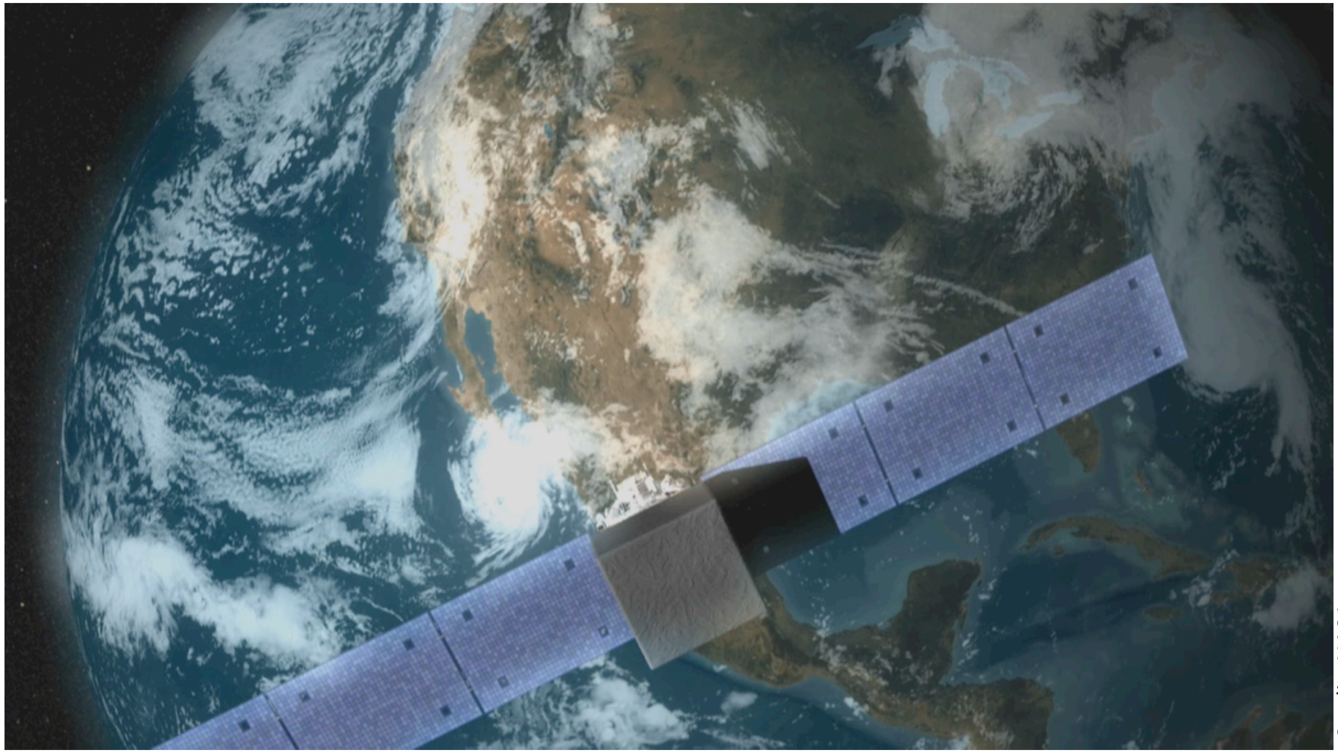
AGILE (2007 -)

CGRO: 7 detected pulsars (1 COMPTEL and 6 EGRET), where 1 radio-quiet

AGILE: 2 detected pulsars

➜ **Before *Fermi* mission: < 10 gamma-ray pulsars known!**

The *Fermi* Gamma-ray Space Telescope

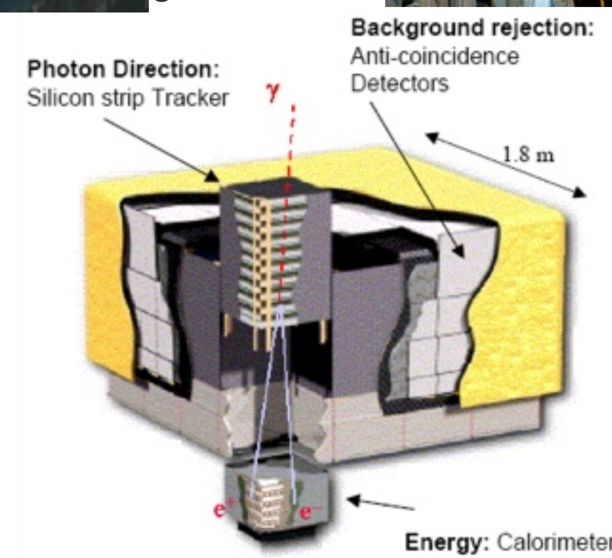


Credit: NASA

Fermi launched June 2008.

The **Large Area Telescope (LAT)** aboard ***Fermi***:

- Pair-conversion 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.
- Big improvements in area, field of view, directional precision, background reduction.



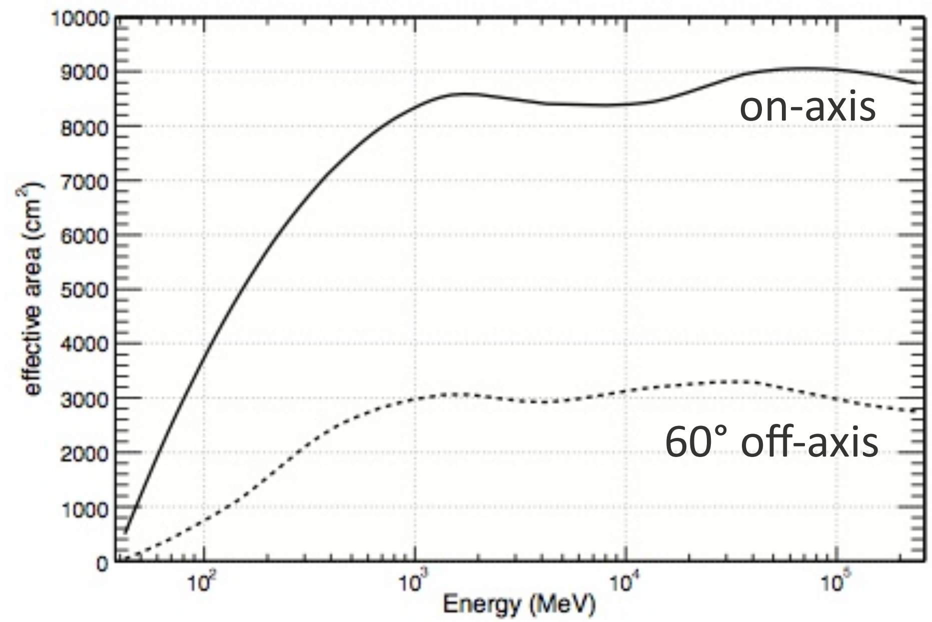
Atwood et al., ApJ, 2009

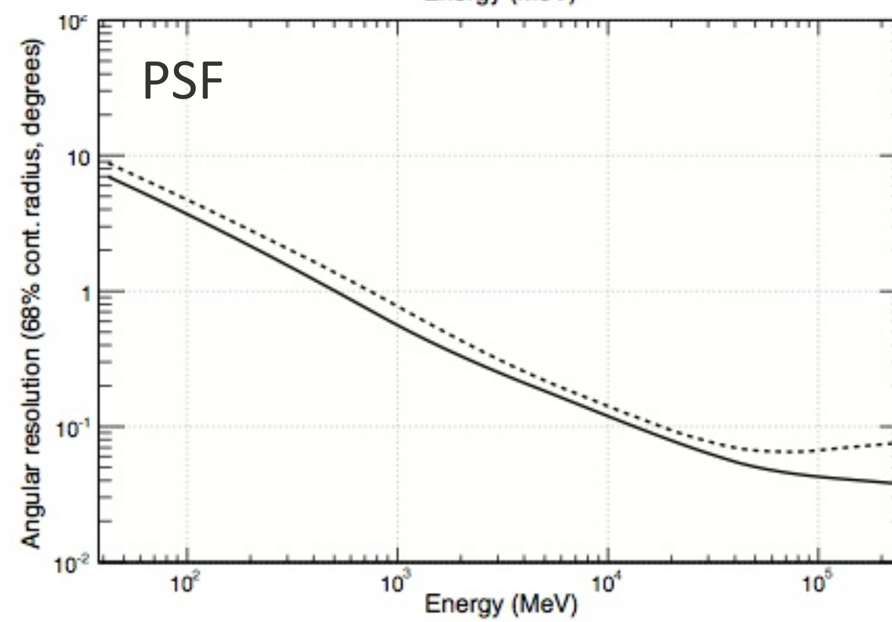
Performance of the LAT

Effective area depends on energy, about 0.8 m^2 at 1 GeV (on-axis).

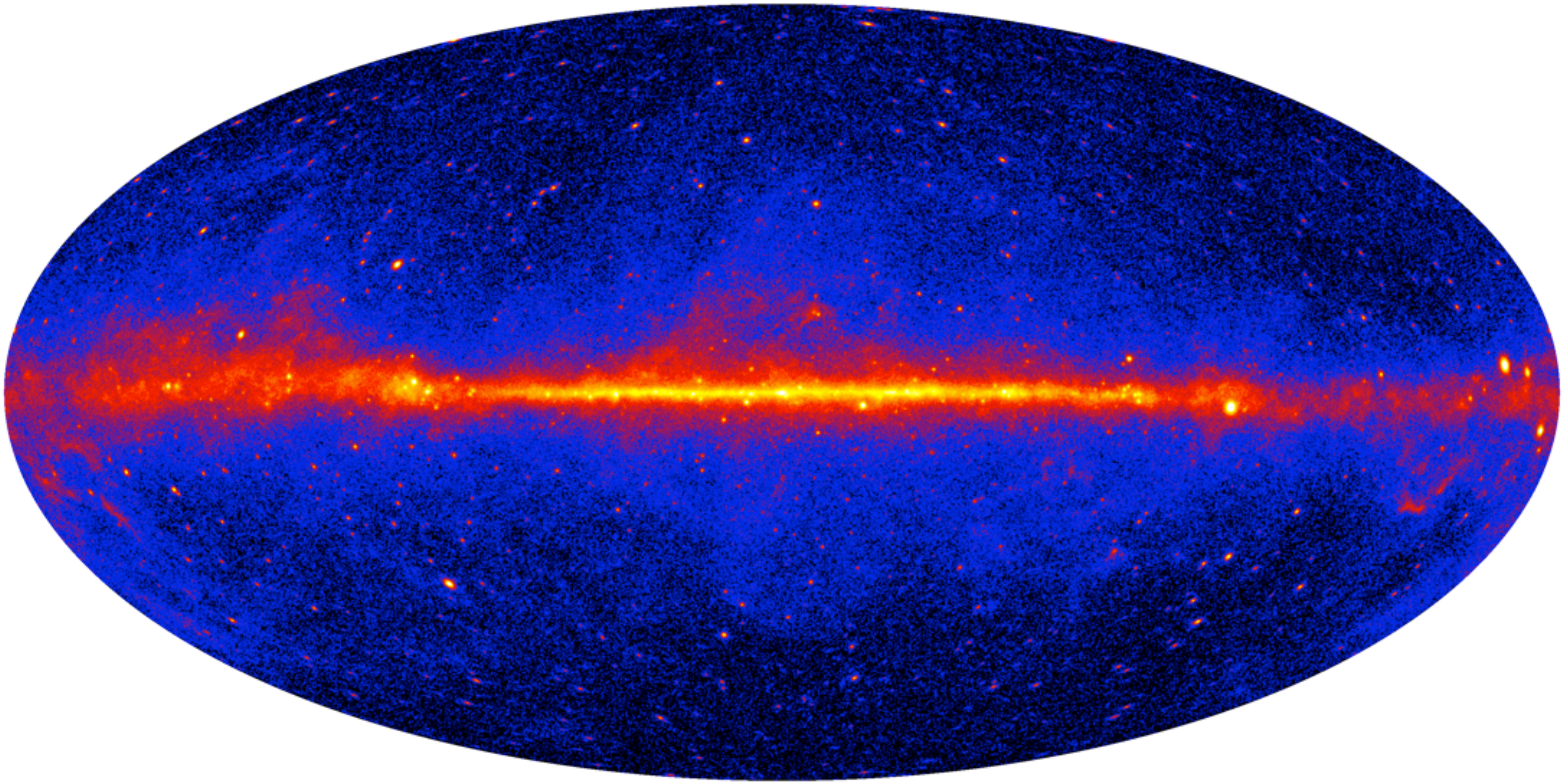
Post-processing assigns each gamma-ray photon: **Arrival time**, **Energy** and **direction**.

- Timing accuracy better than 1μs.
- Energies accurate to better than 15% between 0.1 and 10 GeV.
- Directional precision:
  - Point spread function (PSF) energy dependent, larger at lower energies.
  - 68% of photons have angular offsets less than $\sim 0.^\circ 8 \times (E/\mathrm{GeV})^{-0.8}$ from true direction.





The LAT Gamma-ray Sky



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?

Observing Pulsars with *Fermi*

Detecting pulsars with the *Fermi* LAT

Three different ways to discovery:

indirect

1) **Using ephemeris of pulsars known from radio or X-ray**
   - Assigning phases to gamma-ray photons based on known timing model
   - All 6 EGRET pulsars detected this way

indirect

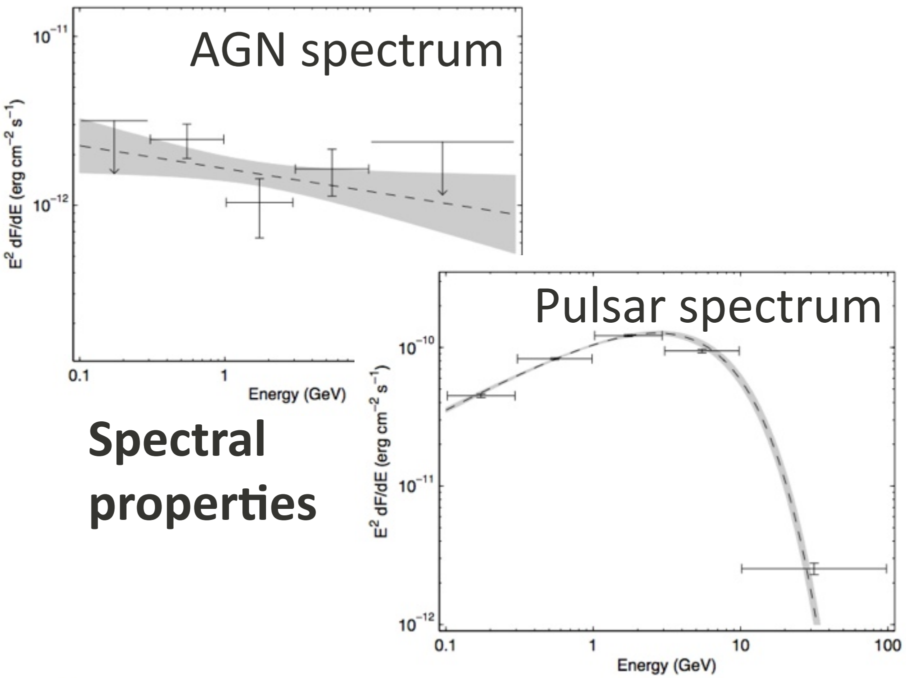
2) **Radio pulsar searches at positions of LAT unidentified sources**
   - Revealed many ms pulsars, also in binary systems

direct

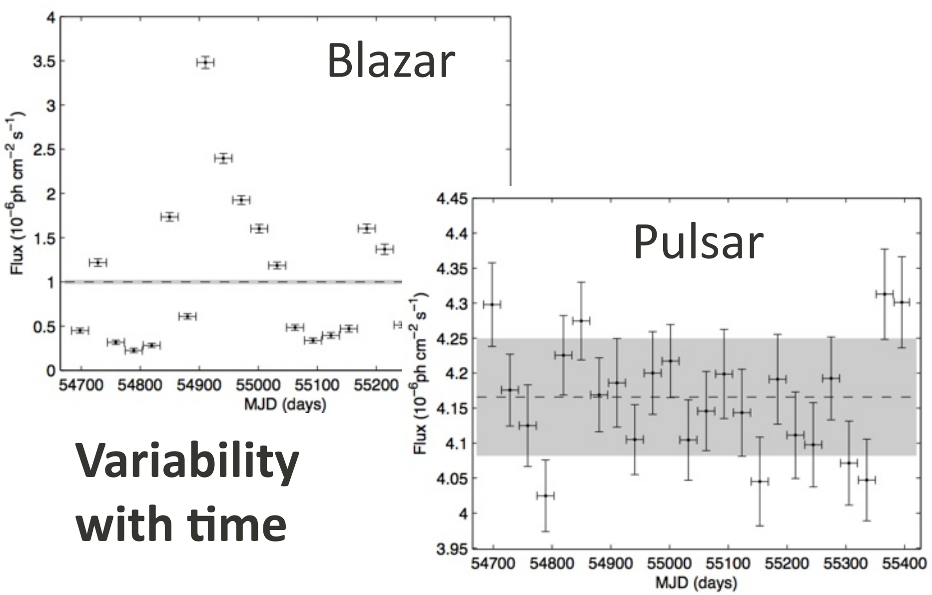
3) **<u>Blind pulsar searches</u> for periodicity directly in LAT data**
   - No prior knowledge of exact pulsar parameters
   - *Fermi*: first instrument to enable successful blind searches

   ⇒ New window on Galactic neutron star population

Selecting Promising Catalog Sources



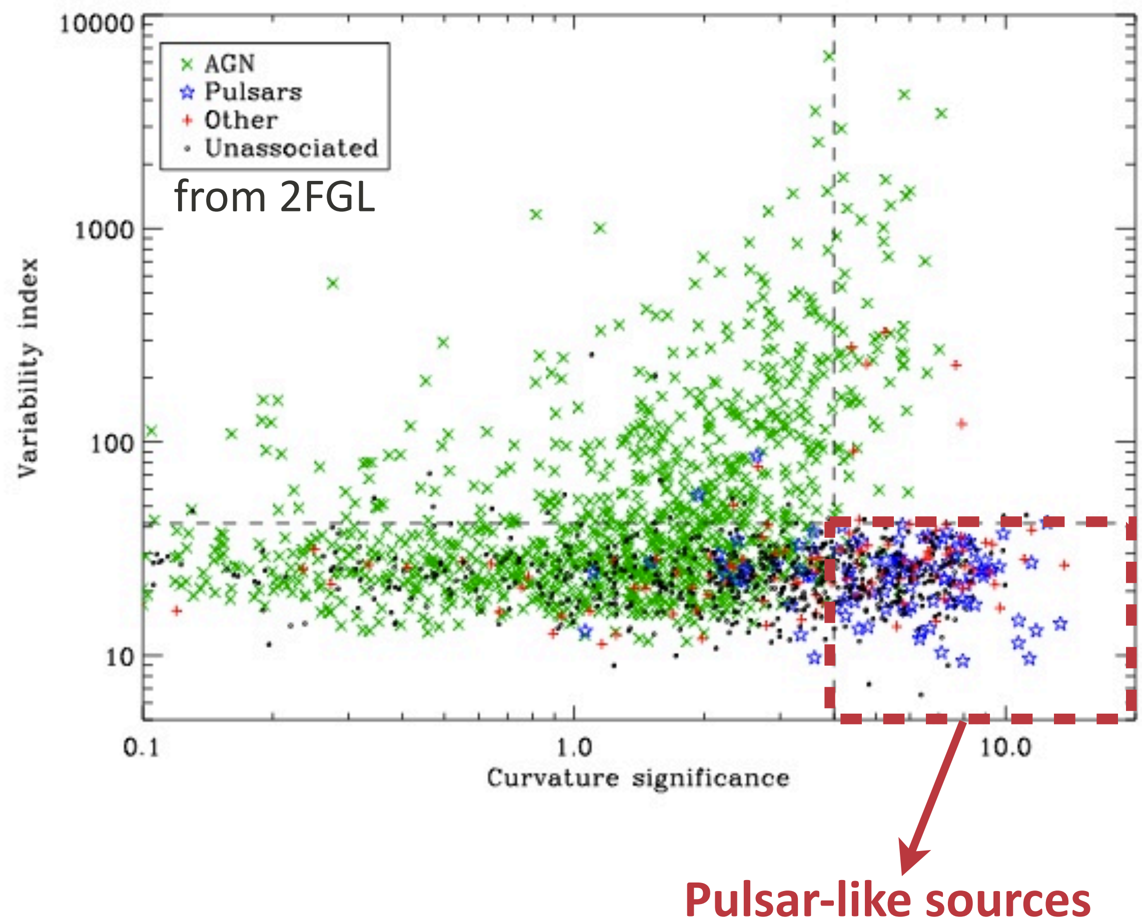
Spectral properties



Variability with time

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

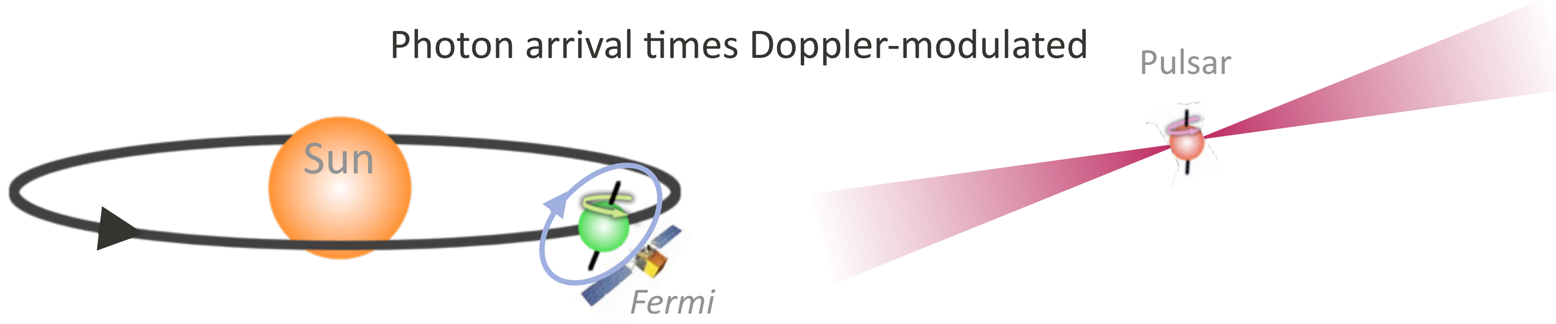
- Curvature significance ≥ 4σ,
- Variability index < 41.6,

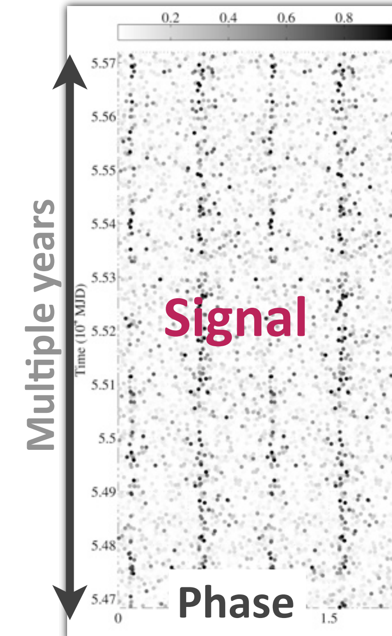


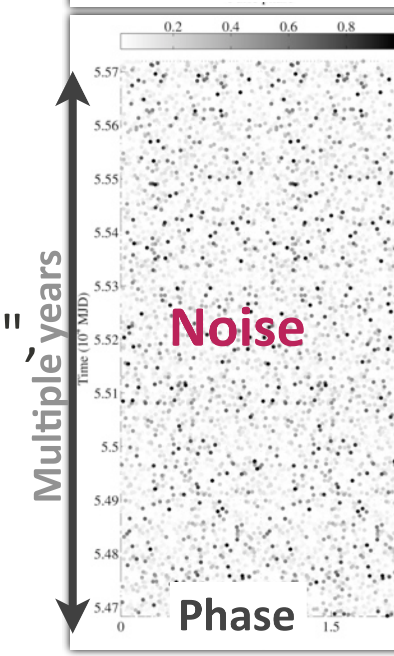
The Blind-Search Problem

- **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** $\Phi(t) = 2\pi(f t + \dot{f} t^2/2)$
  with **frequency** f and **spin-down rate** $\dot{f}$,
  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.

The Blind-Search Problem

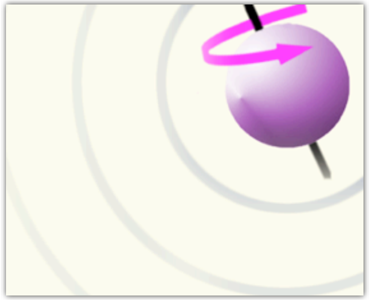
Credit: AEI / NASA's Goddard Space Flight Center

Computational Constraints

- Ideal world: Infinite computing power
  ➜ Do fully coherent analysis on a dense 4D template grid

- Reality: Finite computing resources severely limit sensitivity
  ➜ Fully coherent approach impossible for blind search

- **Problem analog to blind searches for GW pulsars**



➜ Use concepts from GW astronomy:

- **Hierarchical & semi-coherent strategies** (to enhance efficiency)

  Schutz & Papa (2000); Papa et al. (2000); Brady & Creighton, PRD (2000);
  Krishnan et al., PRD (2005); Cutler et al., PRD (2005); HJP & Allen, PRL (2009);
  HJP, PRD (2011); Cutler, PRD (2011)

- **Parameter-space metric** (to construct optimal grid)

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

➜ Goal: **Maximize sensitivity at fixed computing cost**

Some recent studies: Cutler et al., PRD (2005), Prix & Shaltev, PRD (2012)

Concept 1: Hierarchical Strategy

Hierarchical search strategy

- First stage: Use most efficient method to explore **wide** parameter space
- Last stage: Use most sensitive method to search **small** parameter space (around candidates)

Simplified Example

Divides data into $N_{\rm seg}$ segments & sums coherent Fourier powers from each segment (incoherent=phase information lost between segments)

- Semicoherent search: $T_{\rm seg}$ | $T_{\rm seg}$ | $\cdots$

- Fully coherent search: $\longleftarrow T_{\rm coh} \longrightarrow$

1) Computing cost scalings

(from number of required grid points to scan for *solitary* pulsars)

$$C_{\rm semicoh} \propto T_{\rm seg}^3 N_{\rm seg}$$

$$C_{\rm coh} \propto T_{\rm coh}^3$$

At same computing cost:

$$C_{\rm semicoh} = C_{\rm coh} \Rightarrow T_{\rm coh} = T_{\rm seg} N_{\rm seg}^{1/3}$$

2) Sensitivity scalings

Approximate minimum detectable pulsed flux:

$$\theta_{\rm semicoh} \propto \frac{1}{\sqrt{T_{\rm seg}}\, N_{\rm seg}^{1/4}}$$

$$\theta_{\rm coh} \propto \frac{1}{\sqrt{T_{\rm coh}}}$$

$$\frac{\theta_{\rm semicoh}}{\theta_{\rm coh}} = N^{-1/12} \leqslant 1 \quad \Rightarrow \quad \theta_{\rm semicoh} \leqslant \theta_{\rm coh}$$

At fixed computing cost and for large search parameter spaces, the semicoherent approach is in most cases much **more efficient**!

3-Staged Search Scheme

Hierarchical gamma-ray pulsar blind search using 3 stages:

Goal: Discard unpromising regions in parameter space as early as possible.

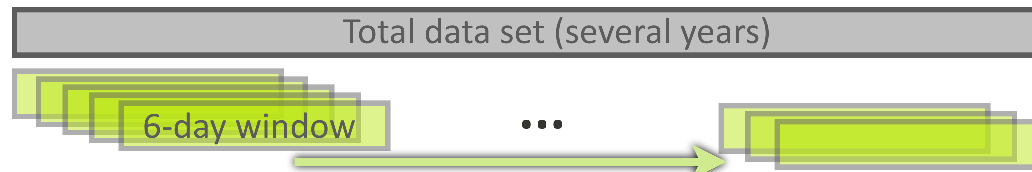
HJP et al. ApJ & ApJL 2012

Dr. Timo Mappes, www.musoptin.com.

Zooming in

Most **compute cycles** spent at this stage.

1. Semi-coherent stage:



extending Atwood et al., ApJL 2006; HJP, PRD 2011

- **Sliding coherence window,** summing coherent Fourier power;
- Coarse graining: Less sensitive, but most efficient to ***scan entire search space***
- Uses heterodyning to process f range in bands and the FFT is used.

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 (*H*-test):

de Jager et al. 1989

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

Concept 2: Metric

Problem: How dense should search grid points be placed?

- Too wide ⇒ miss signals
- Too close ⇒ inefficient, nearby signals are correlated

Goal: Want analytic control of fractional loss due to gridding!

Solution: Define **metric on search parameter space**.

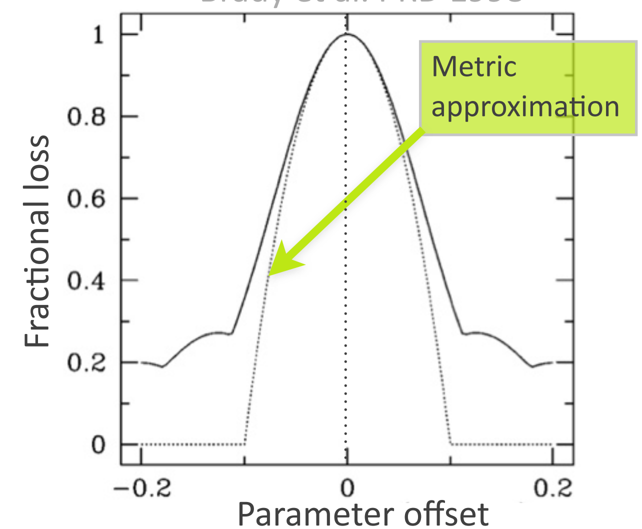
Key quantity: Fractional loss in expected detection statistic for a given signal at $\mathbf{p} = (\mathbf{f}, \dot{\mathbf{f}}, \boldsymbol{\alpha}, \boldsymbol{\delta})$ and a nearby grid point $\mathbf{p}'$ defines the **mismatch** $\mathcal{M} = 1 - \frac{P(\Delta\mathbf{p})}{P(0)}$ where $\Delta\mathbf{p} = \mathbf{p} - \mathbf{p}'$.

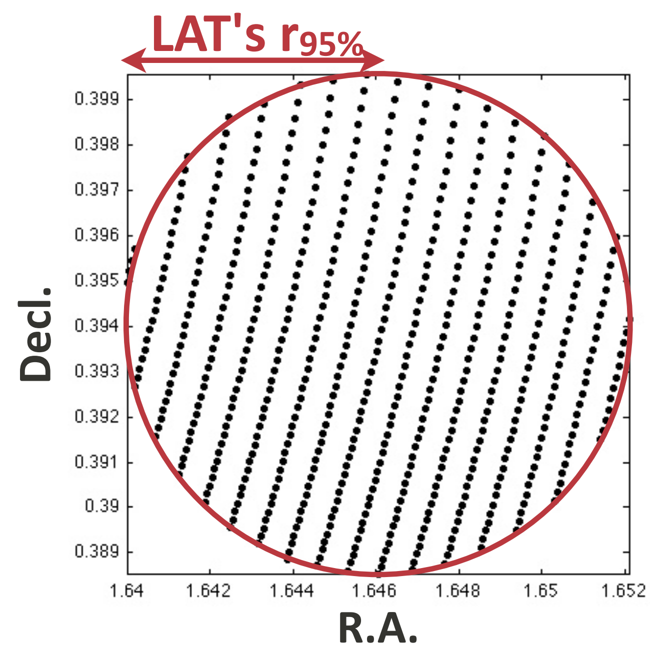
Taylor-expanding mismatch in offsets $\Delta\mathbf{p}$ to quadratic order gives the **metric**: $\mathcal{M} \approx \sum_{k,\ell} g_{k\ell}\, \Delta p^k\, \Delta p^\ell$

Analytic metric allows to construct optimized grid at given $\mathcal{M}$

- Metric for **semicoherent** search obtained from "**averaging** coherent metrics" [Brady & Creighton, PRD, 2000], first fully analytic solution in HJP & Allen, PRL, 2009; incl. spindown refinement factor.
- **Sky-grid** separations relate to equal Doppler shifts from Earth's (more precisely *Fermi*'s) motion around the Sun.

Brady et al. PRD 1998



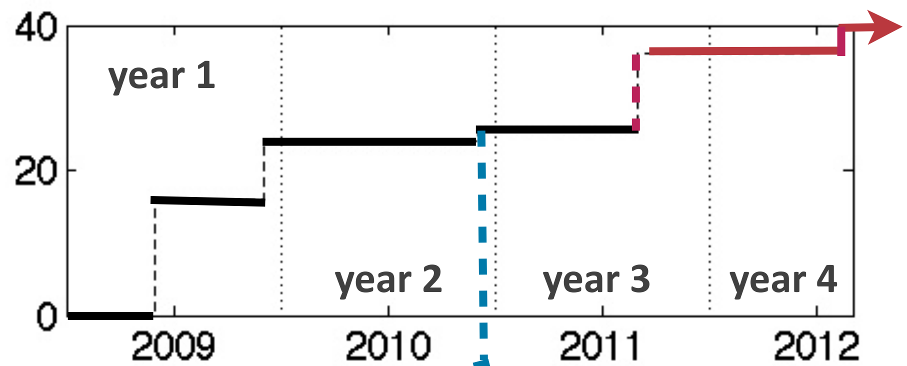


Sky gridding necessary, not done previously!

Sky points increase with f^2

Blind Pulsar Searches with *Fermi*

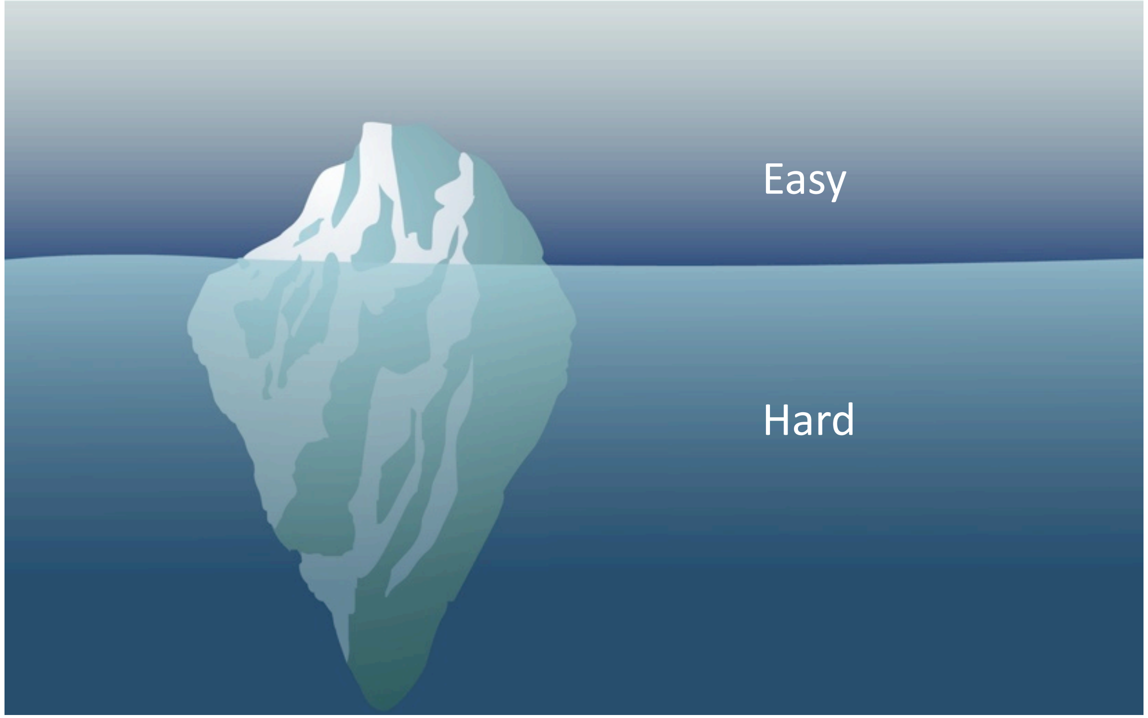
Blind-search pulsar discoveries during the *Fermi* mission



Improved search methods (3-staged hierarchical & metric-based approach):

HJP et al., ApJ & ApJL , 2012;
HJP et al., Science, 2012

Previous search efforts successful during early mission, but NO new discoveries since 2nd mission year.
[Abdo et al., Science, 2009; Saz Parkinson et al. ApJ, 2010]



Recent Discoveries with new methods:

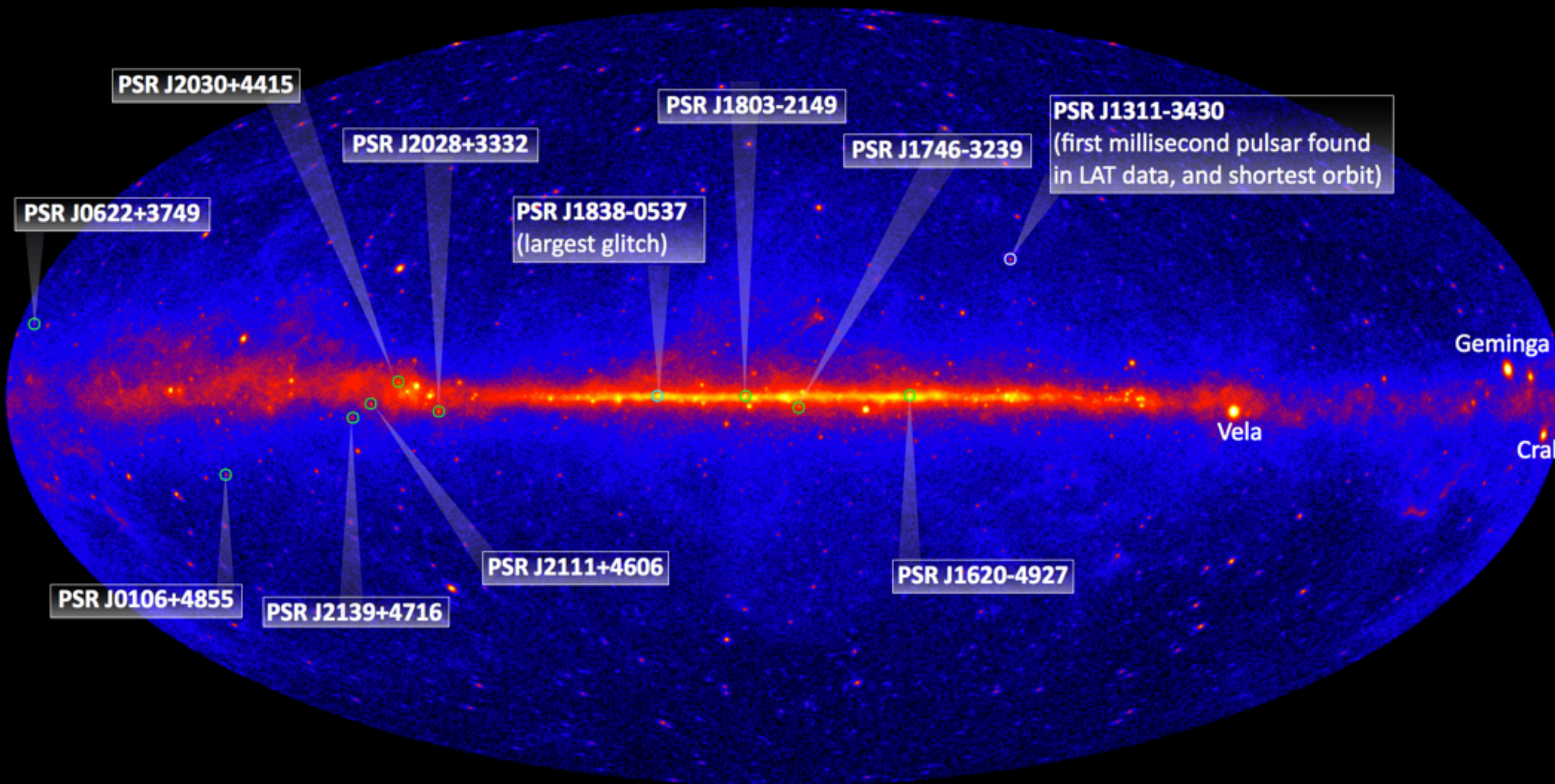
- About *10* new isolated gamma-ray pulsars previously hidden

  ⇒ 30% population increase!

- Found the *first millisecond pulsar* in a blind search of gamma-ray data

  ⇒ Pulsar is in a compact binary; required extension to include searching over orbital parameters

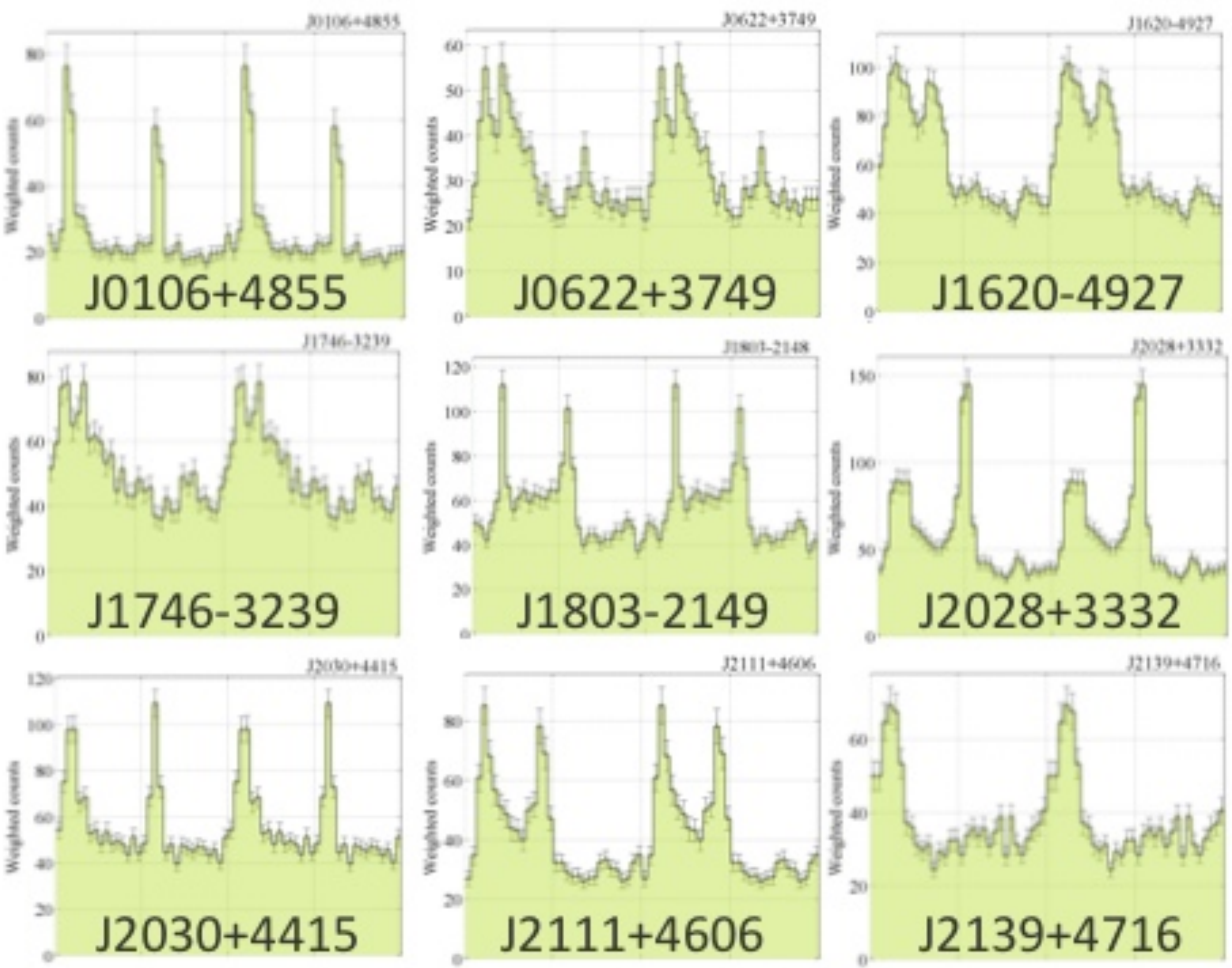
Recent Pulsar Discoveries



⇒ Resolve mysteries behind brightest formerly unidentified gamma-ray sources (some of which have been known since decades but their nature remained enigmatic).

Recent Pulsar Discoveries (2)

Pulse profiles



Each plot shows two pulsar rotations for clarity.

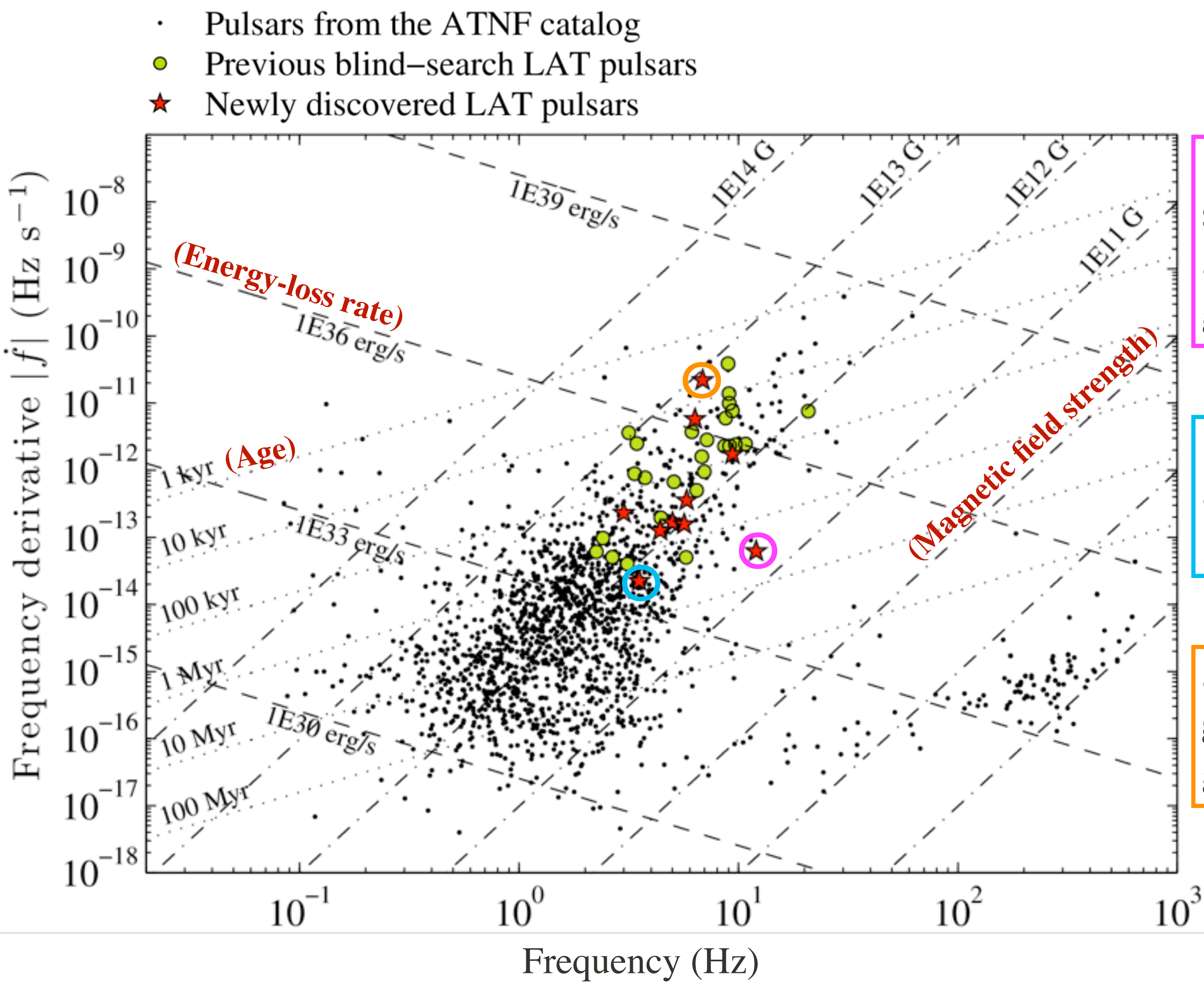
HJP et al., ApJ, 2012

Pulse shapes:

- **Wide beams**
  ➜ Enable more unbiased survey of Galactic supernovae

- **Mostly 2 peaks**
  ➜ Actual spin frequency tricky to identify when two peaks nearly half rotation apart.
  ➜ Tests with resulting two peaks:
  - Have phase separation measurably from 0.5?
  - Integrated counts under each peak differ?
  - Have different energy evolution?

Comparison to Known Population



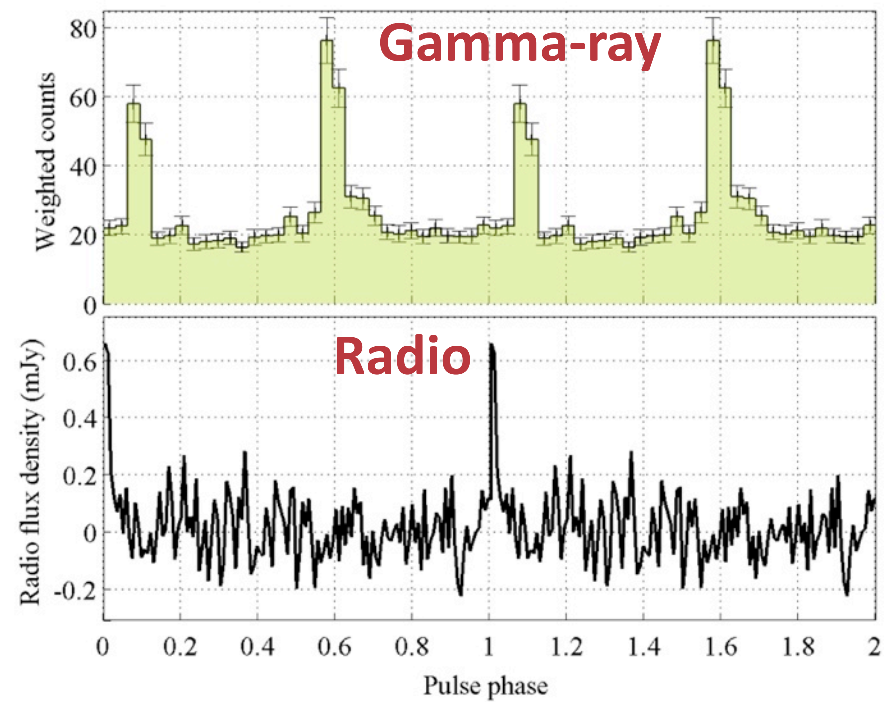
Largest age and **smallest surface magnetic field** among all blind-search gamma-ray pulsars!

Lowest spin-down power among ***all*** gamma-ray pulsars!

2nd youngest, largest glitch among ***all*** gamma-ray pulsars!

Multi-Messenger Follow-Ups

PSR J0106+4855

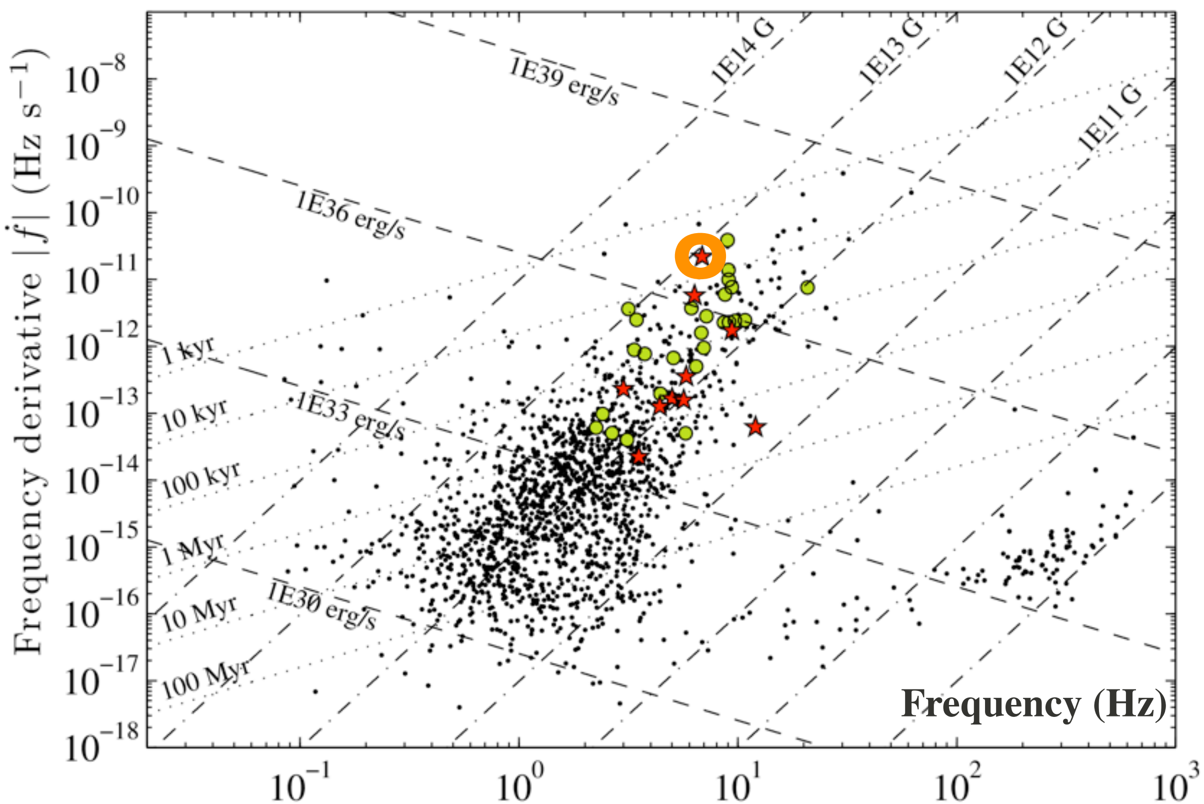


- **Targeted deep radio observations:**
  - Including GBT, Effelsberg, Jodrell, Parkes.
  - Successful for one pulsar:
    - ⇒ Radio pulsations detected with GBT.
  - Others are *radio-quiet*.

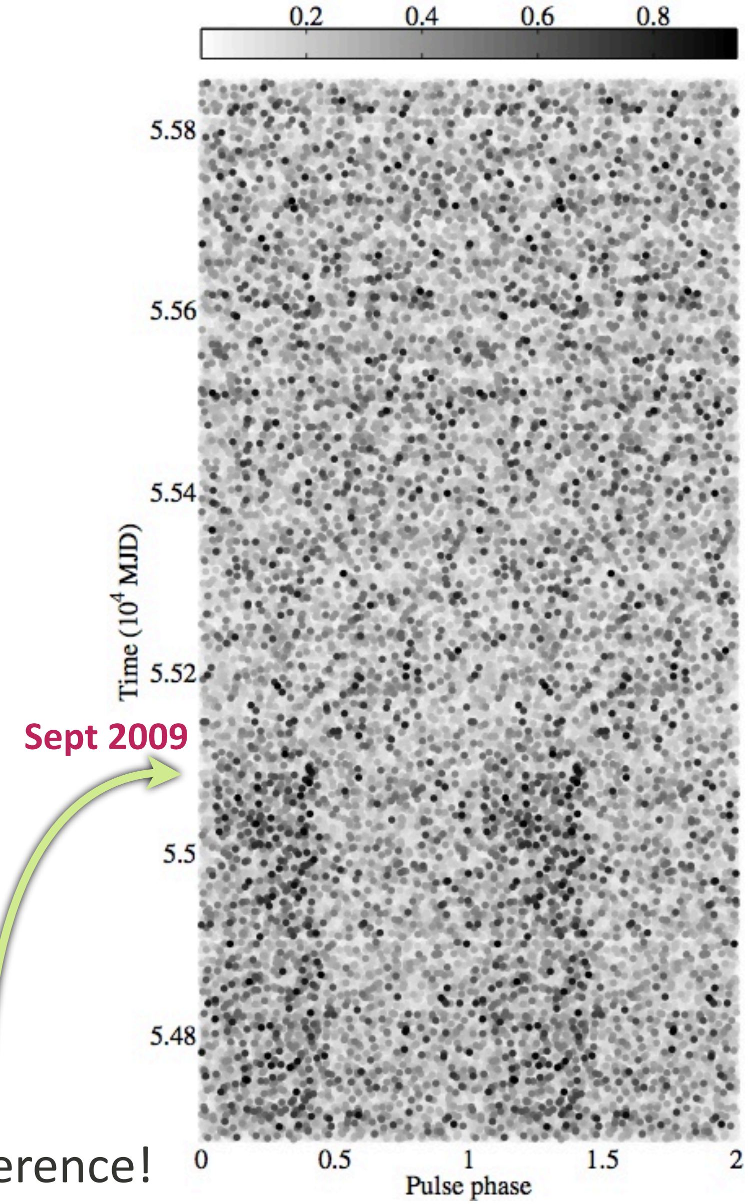
- **Targeted GW observations:**
  - This same radio-loud gamma-ray pulsar has been added to the list of targeted GW search objects with LIGO/Virgo.

Gravitational Waves?

A Special Case: PSR J1838-0537



Discovery plot



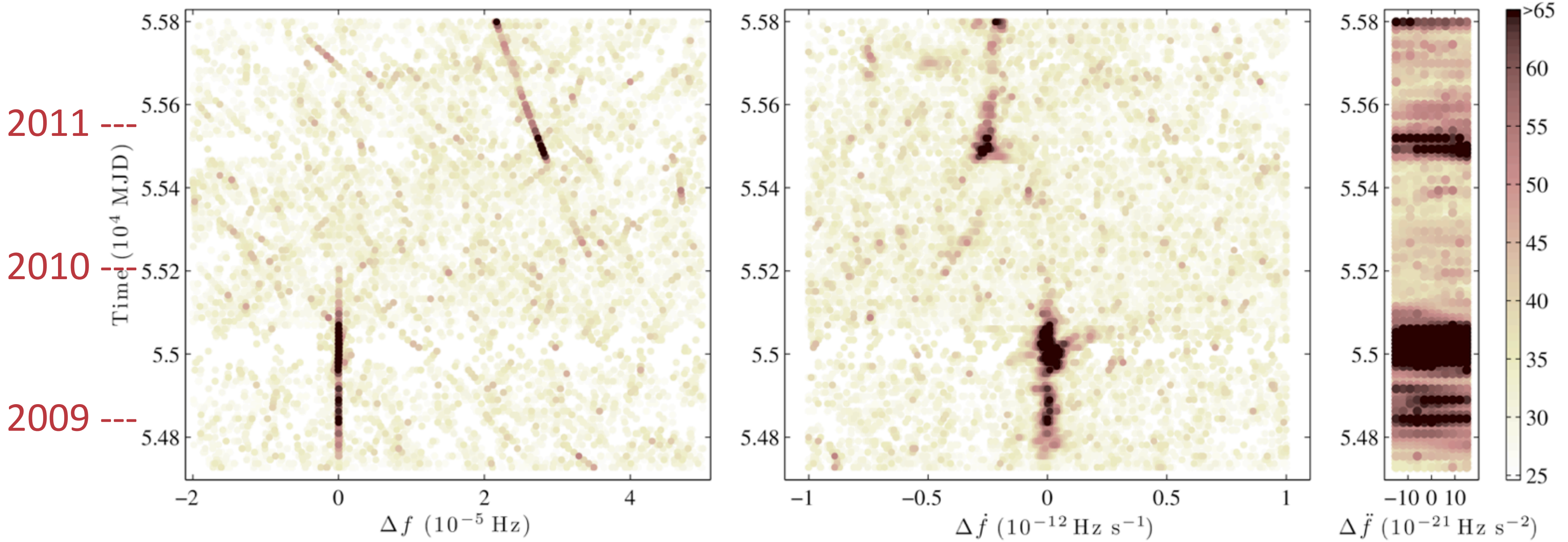
Young pulsars typically show irregularities in their spin-frequency evolution of 2 kinds:

1) Timing noise:
Slowly varying, non-deterministic fluctuations

2) Glitch:
Abrupt change in frequency -> loss of signal phase coherence!

A Massive Glitch

Pulsar glitch analysis:

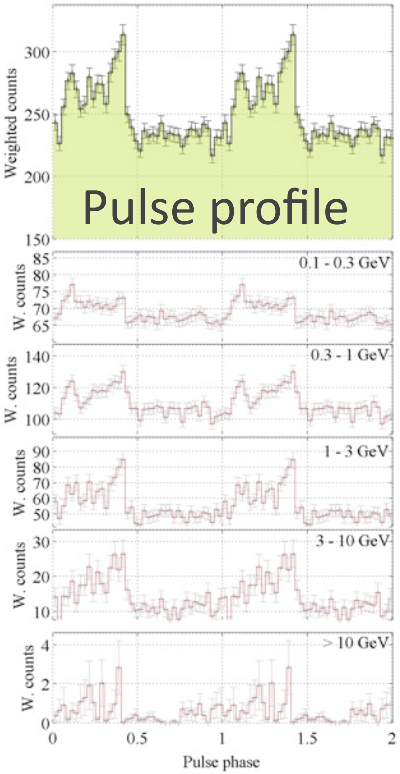


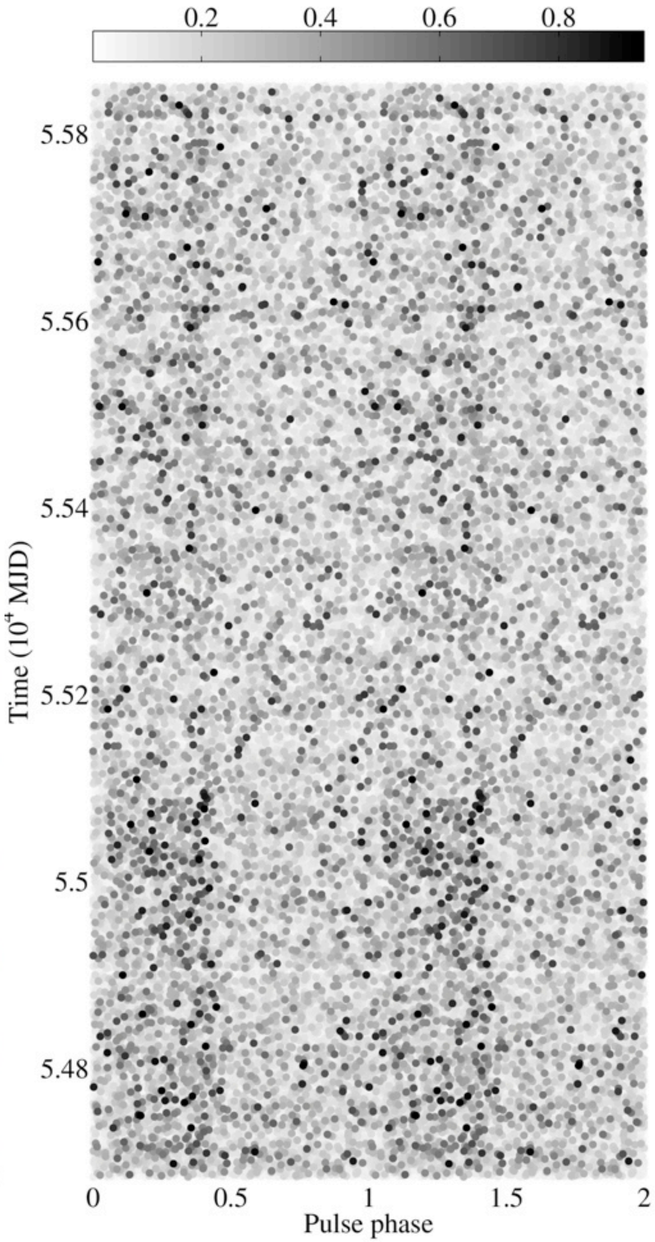
Offset in spin frequency *f* Offset in *df/dt* Offset in *d²f/dt²*

- **Slide a 90-day window over the entire ~3 years of data and analyze coherent power (incl. harmonics) for photons in each window.**
  - ➜ Significant glitch (abrupt change in frequency) becomes apparent!
  - ➜ Largest seen so far in any gamma-ray-only pulsar, among top 5% of *all* pulsars.

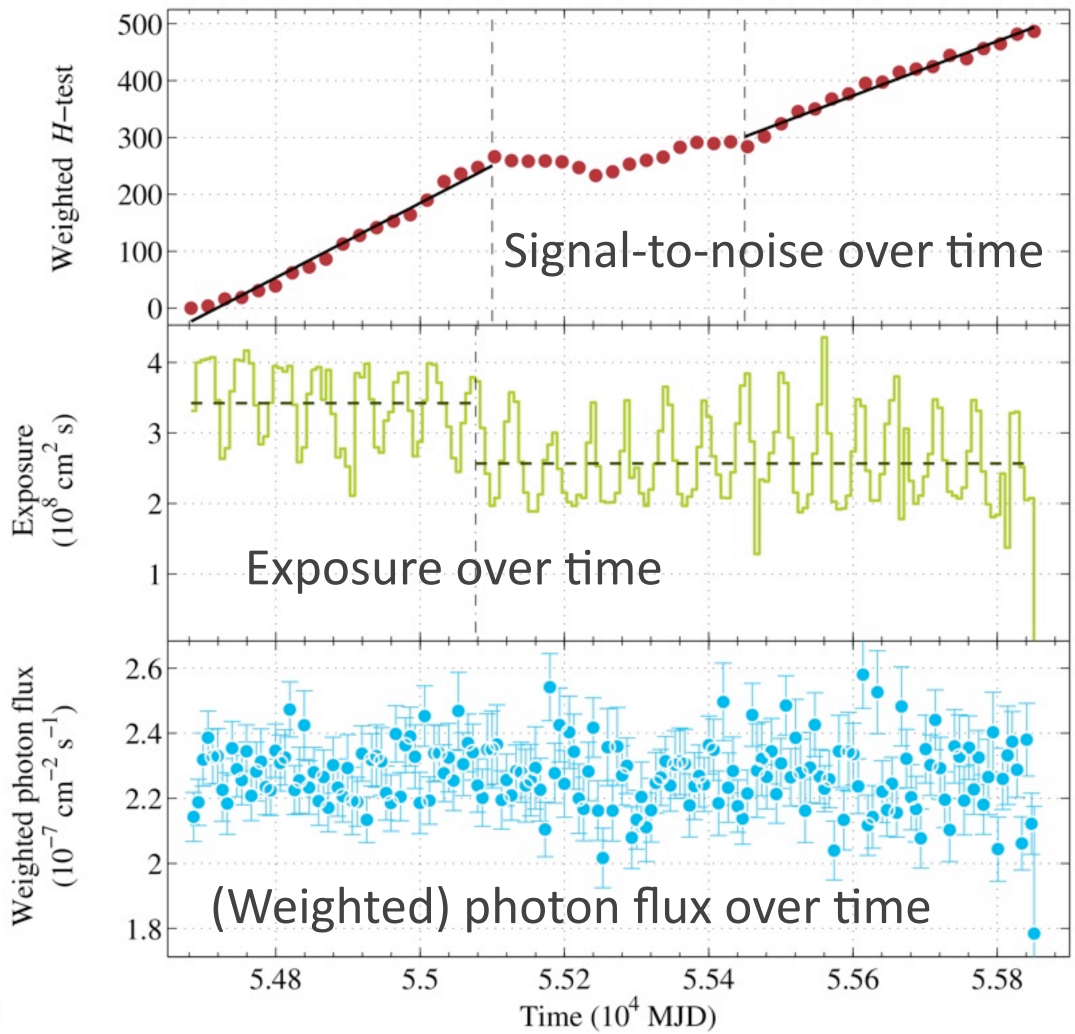
Puzzle Solved

Including the parameter changes due to the glitch:



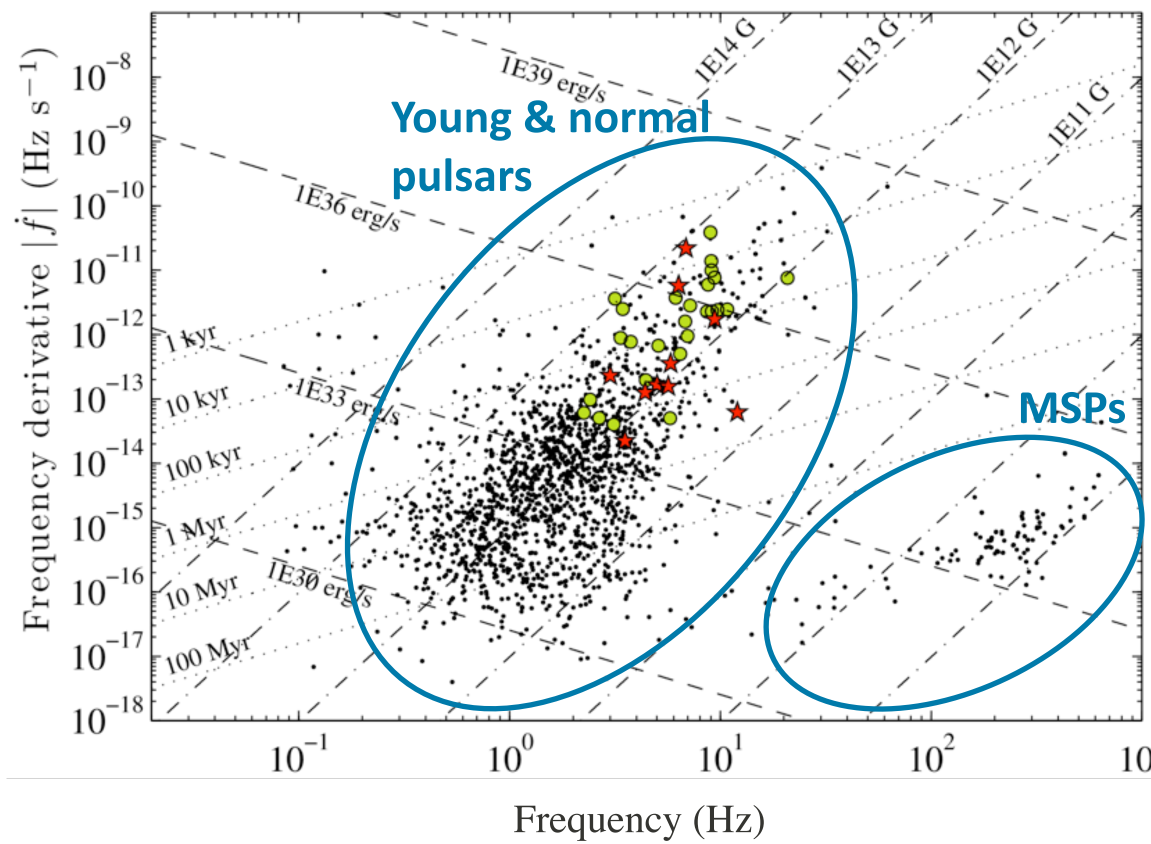


Signal-to-noise variation with time



Gamma-ray Millisecond Pulsars

- **Millisecond pulsars** (MSPs):
  - Old neutron stars, **spun up** by accreting matter from companion star.
  - Reach high rotation rates of several hundreds of Hertz (fastest: 716Hz).
  - 30 years ago: First MSP detected in radio observations. Backer et al., Nature 1982

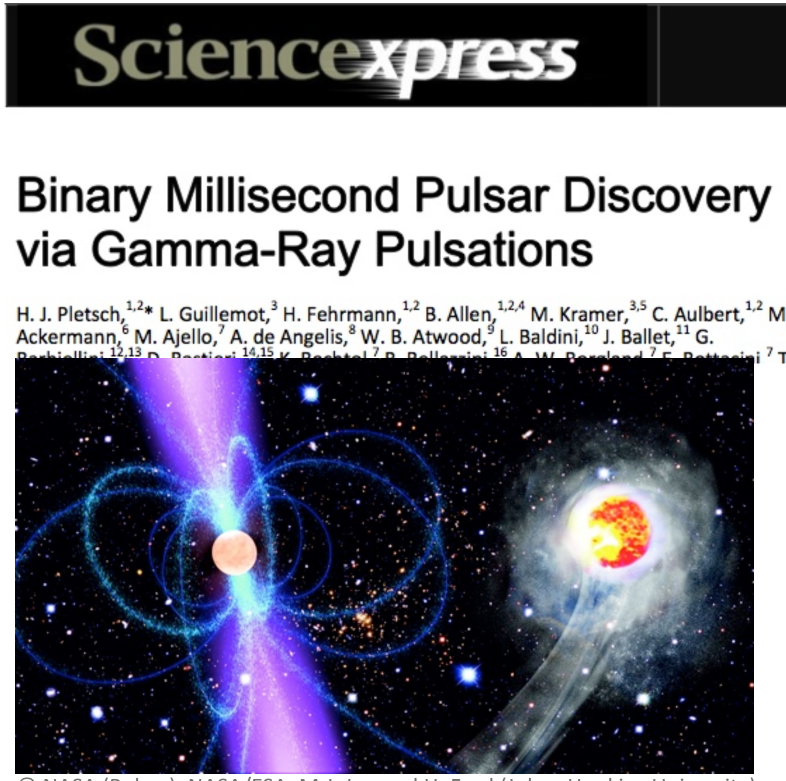


- Until recently: **ALL** such MSPs discovered only by spin-modulated **radio** emission.
  - *Fermi* LAT confirmed that many radio-detected MSPs also pulsate in gamma-rays:
    - ⟶ Gamma-ray pulsations revealed only by rotation parameters obtained from radio telescopes. Smith et al., A&A 2008; Abdo et al., Science 2009
  - **No MSP previously found in blind search of gamma-ray data.**

First MSP Discovery in Blind Search

- Blind searches for **MSPs** vastly more difficult than for slower pulsars
  - Must scan up to **higher spin frequencies** [to and beyond 716Hz]
  - Plus, most MSPs are in binaries:
    - → Additionally unknown **orbital** parameters
    - → Increases computational complexity by orders of magnitude
  - Blind binary-MSP searches were hitherto virtually unfeasible

- **First MSP discovered in blind search**
  - Computing-intensive blind search in *Fermi*-LAT data **using advanced methods** and with partial constraints from optical data ⇒ Discovery of PSR J1311-3430
  - First **MSP** found via **gamma-ray** pulsations!
  - Extremely **compact** binary: Shortest orbital period of all pulsar binaries!
  - Clarifies nature of decade-long enigma!


Sciencexpress

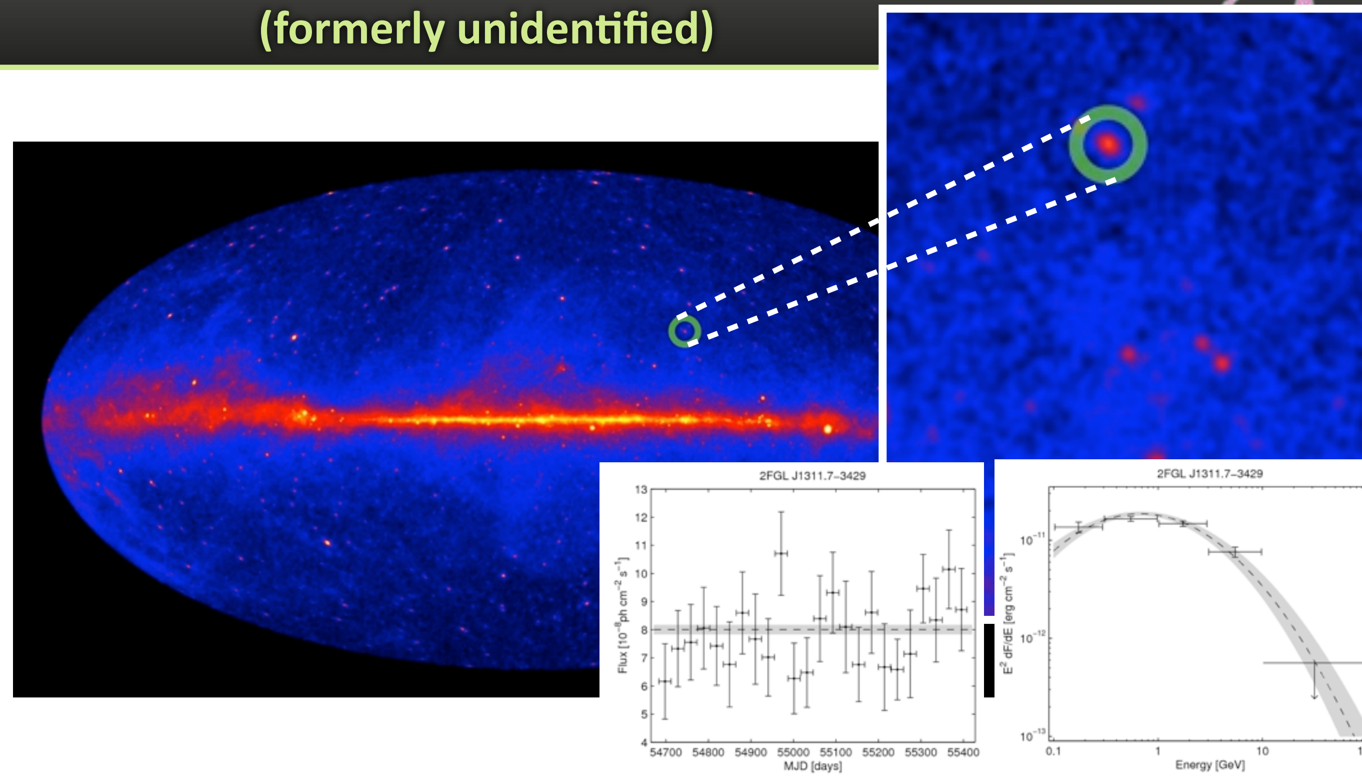
Binary Millisecond Pulsar Discovery via Gamma-Ray Pulsations

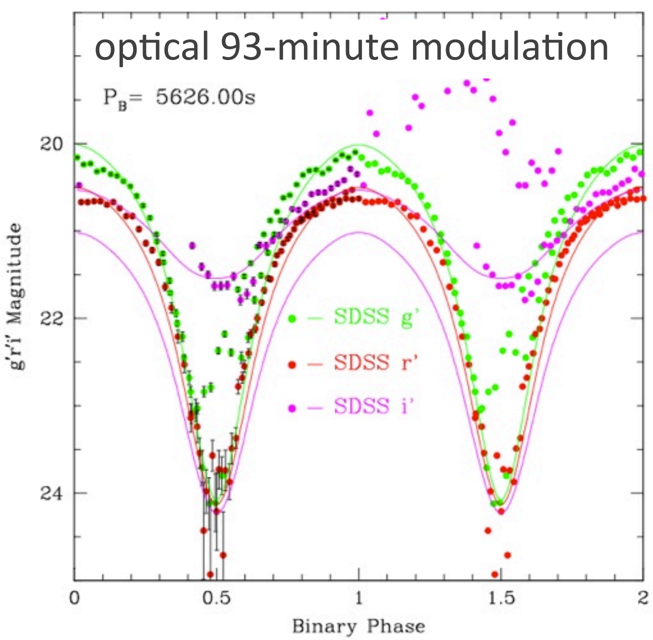
H. J. Pletsch,[1,2]* L. Guillemot,[3] H. Fehrmann,[1,2] B. Allen,[1,2,4] M. Kramer,[3,5] C. Aulbert,[1,2] M
Ackermann,[6] M. Ajello,[7] A. de Angelis,[8] W. B. Atwood,[9] L. Baldini,[10] J. Ballet,[11] G.

Target Source: 2FGL J1311.7-3429

(formerly unidentified)

- First seen by **EGRET.**
- Most significant (43σ) unidentified **LAT** source in 2FGL.
- Good pulsar candidate:
  - low flux variability
  - very curved spectrum





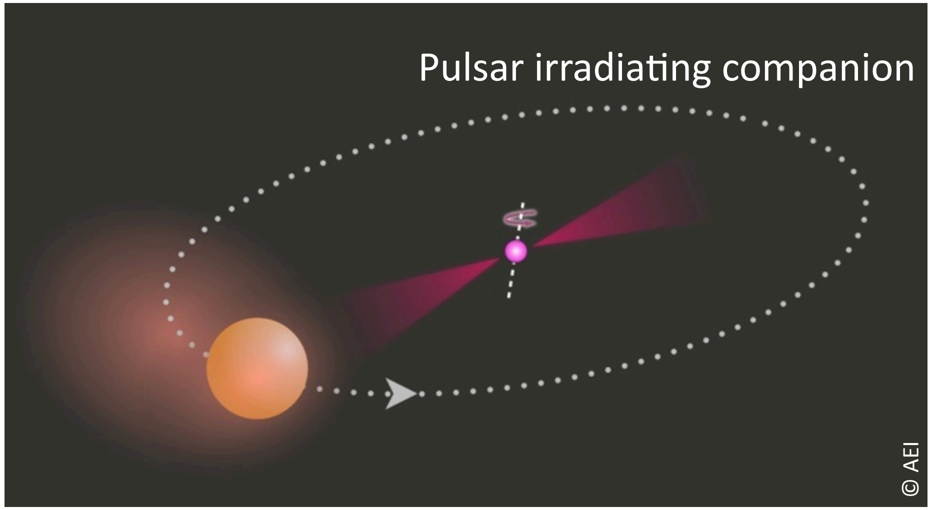
- Crucial: In search for **optical counterparts**, Romani (2012, ApJL) identified quasi-sinusoidal optical flux modulation. (Romani ApJL,2012; Kataoka et al. ApJ,2012)

  → <u>Conjecture:</u> **"black widow" pulsar binary**
  - MSP irradiates companion star
  - Heating one side of companion, explains optical brightness variation

The Search Space

- **"Black widow" pulsar interpretation:**
  - Optical variation associated with period of circular orbit.
  - Confines sky position.

  → These constraints made **blind binary-MSP search feasible.**
  BUT: still enormous computational challenge, because uncertainties on orbital parameters by far larger than required for pulsar detection (and f, $\dot{f}$ unknown)



→ **Pulsar search parameter space left 5-dimensional:**

1. Spin frequency: $0 < f < 1400$ Hz
2. Its rate of change: -5×10^{-13} Hz/s $< \dot{f} < 0$
3. Orbital period: $P_{orb} = 5626.0 \pm 0.1$ s
4. Time of ascending: $T_{asc} = 56009.131 \pm 0.012$ MJD
5. Projected semi-major axis: $0 < x < 0.1$ lt-s

Stochastic Metric-based Search Grids

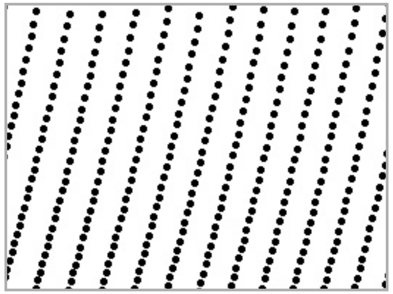
Concept #3 -- inspired from GW searches: **Stochastic grid construction**

Messenger et al., PRD 2009; Harry et al., PRD, 2009; Fehrmann & HJP, in prep

Problem: Metric **orbital** components (in P_{orb}, T_{asc}, x) explicitly depend on parameters (unlike in f and $\dot{f}$)

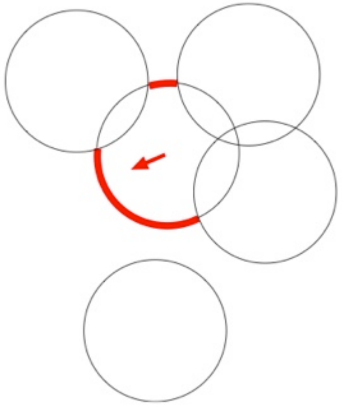
→ To achieve constant mismatch the required grid-point density changes across orbital parameter space.

→ Simple lattice would either vastly over- or undercover.



Solution: New grid construction algorithm to utilize metric

- First place orbital grid points **at random**.
  (fast MC integration using metric provides total number of grid points required to achieve predefined mismatch)
- Then move those that are too close or too far apart by **barycentric shifts** towards optimal coverage.
- In this search: Designed to never lose > 30% in S/N for any given signal.

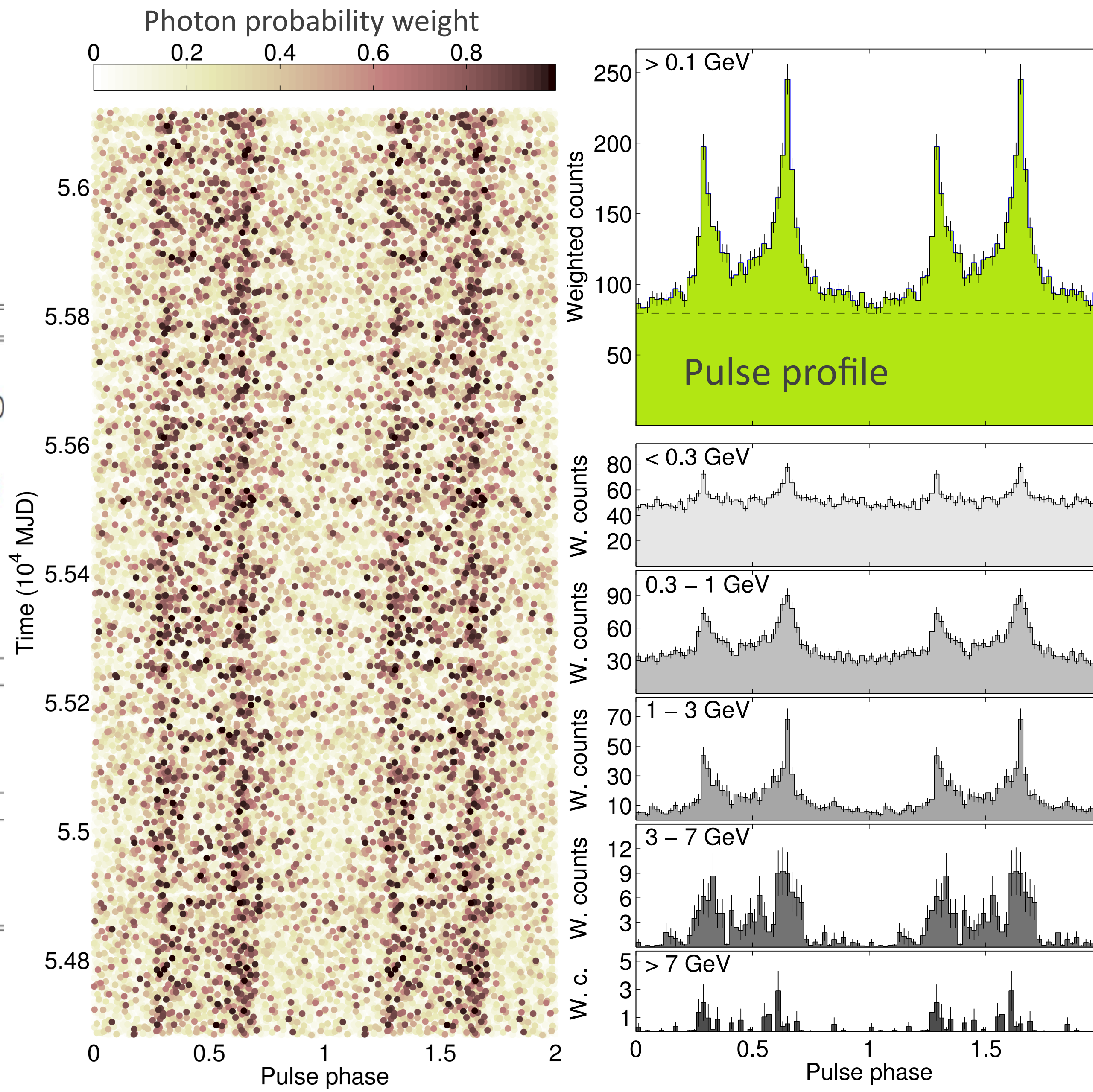


The PSR J1311-3430 System

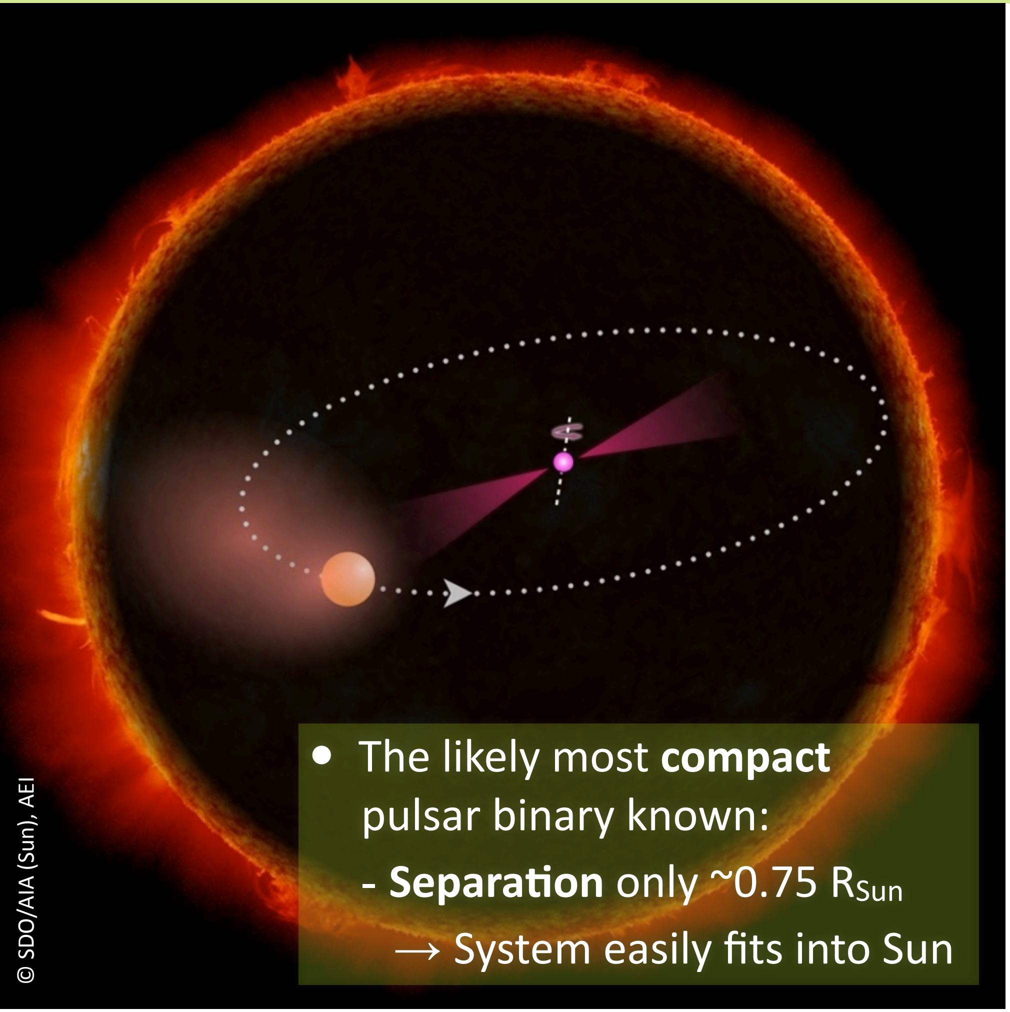
Following the discovery:

→ pulsar timing to precisely measure the system parameters ( )

Parameter	Value
Right ascension (J2000.0) (hh:mm:ss)	13:11:45.7242(2)
Declination (J2000.0) (dd:mm:ss)	−34:30:30.350(4)
Spin frequency, f (Hz)	390.56839326407(4)
Frequency derivative, $\dot{f}$ (Hz s^{-1})	$-3.198(2) \times 10^{-15}$
Reference time scale	TDB
Reference time (MJD)	55266.90789575858
Orbital period $P_{\rm orb}$ (d)	0.0651157335(7)
Projected pulsar semi-major axis x (lt-s)	0.010581(4)
Time of ascending node $T_{\rm asc}$ (MJD)	56009.129454(7)
Eccentricity e	< 0.001
Data span (MJD)	54682 - 56119
Weighted RMS residual (μs)	17
Derived Quantities	
Companion mass m_c (M$_\odot$)	> 0.0082
Spin-down luminosity $\dot{E}$ (erg s^{-1})	4.9×10^{34}
Characteristic age τ_c (yr)	1.9×10^{9}
Surface magnetic field B_S (G)	2.3×10^{8}
Gamma-Ray Spectral Parameters	
Photon index, Γ	1.8 ± 0.1
Cutoff energy, E_c (GeV)	3.2 ± 0.4
Photon flux above 0.1 GeV, F (10^{-8} photons cm^{-2} s^{-1})	9.2 ± 0.5
Energy flux above 0.1 GeV, G (10^{-11} erg cm^{-2} s^{-1})	6.2 ± 0.2



An Extreme Pulsar Binary



Rotational ephemeris also constrains companion mass: $m_c > 0.0083\, M_{Sun}$ (~8 $M_{Jupiter}$)

[for m_p = 1.35 M_{Sun}, i=90°]

- Companion Roche lobe radius: ~0.63 $R_{Jupiter}$
- Mean density: ~45 g cm^{-3}

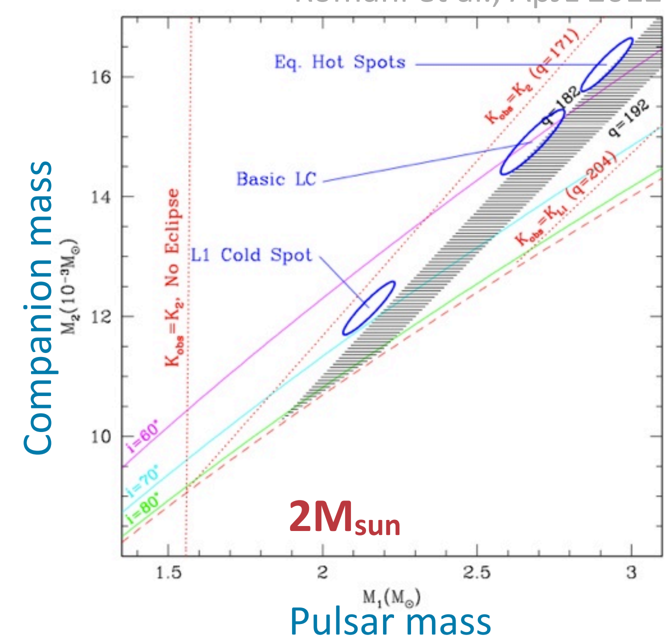
  → 30 times higher than Jupiter

Further optical observation results:

- Radial velocity measurements of companion.
- Neutron star likely to have **very large mass!**

  → **EOS**

Romani et al., ApJL 2012



Radio follow-up observations: Ray et al., ApJL 2013

- In several attempts, only one weak, intermittent radio detection → Radio eclipsing/absorption by companion/wind.
- Would not have been found in typical radio search.

Computing Resources

ATLAS cluster at AEI Hannover

- 1680 nodes, 6720 CPU-cores, 8 GB random-access memory each
- Largest cluster in the field

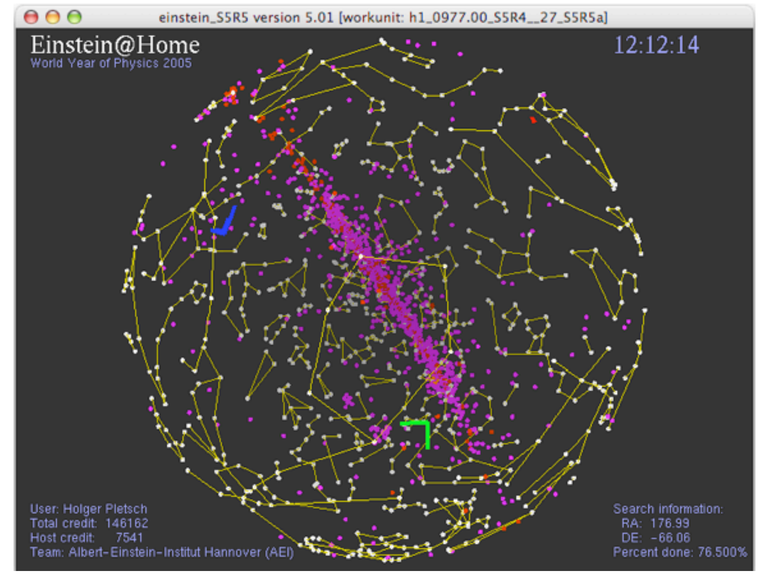
Volunteer Computing: Einstein@Home

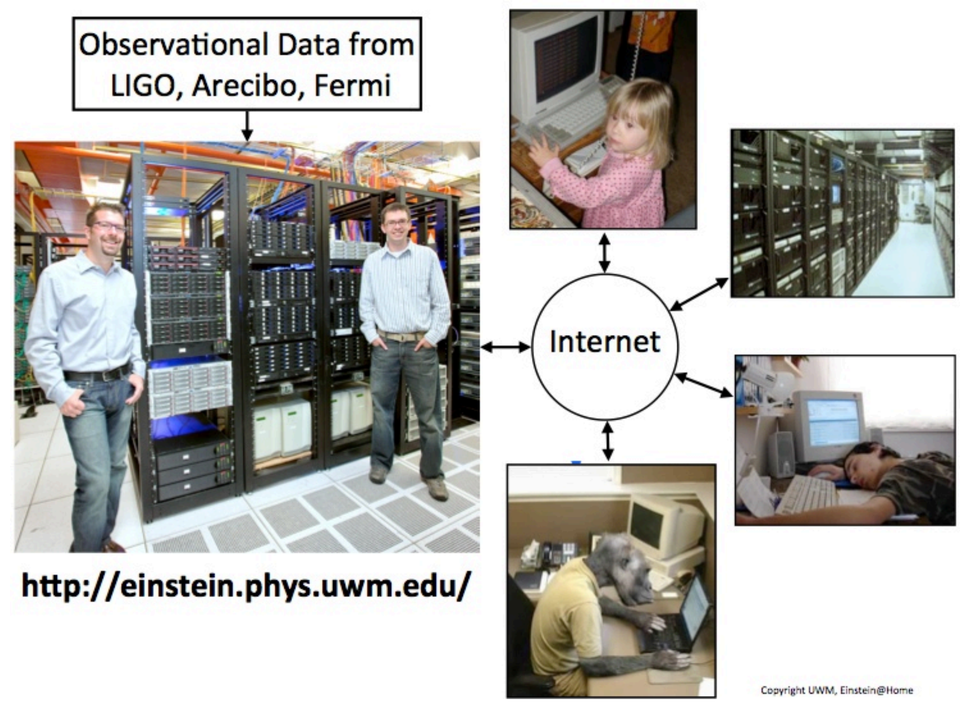
- **A volunteer supercomputer**
  - Screensaver downloads astronomical data in background
  - Analyses data for pulsars when computer is idle
  - Reports back results

- **Numbers**
  - About 340 000 volunteers
  - About 50 000 active computers
  - About 1 PFlop/s sustained computing power
  - Servers in Milwaukee (USA) and Hannover (Germany)
  - Built upon *BOINC* infrastructure

- **3 distinct search efforts for neutron stars**
  - Gravitational-wave data (since 2005)
  - Radio data (since 2009)
  - Gamma-ray data (since 2011)

Screensaver





Quintessence

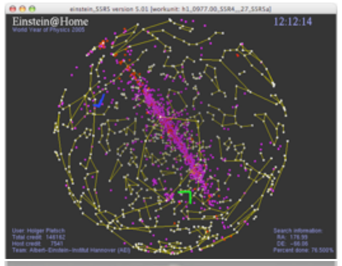
- GW astronomy: signal absence, but **advanced data analysis methods** also useful in related fields: signal-rich EM astronomy.

- Data analysis concepts (from GW to EM)
  - Hierarchical strategy for highest efficiency of blind searches
  - Metric on parameter space for optimized grid construction
  - Stochastic metric-based grids for "non-flat" parameter spaces

- Enabled recent discoveries
  - Significant fraction of the young pulsar population revealed
  - First MSP in gamma-ray blind search, shortest orbital-period pulsar binary known

- *Fermi* pulsar revolution still ongoing
  - Still hundreds of pulsar-like sources unidentified
  - Data analysis will be crucial to unlock the secrets behind

http://einstein.phys.uwm.edu



The End

Backup Slides Follow

Source Confusion: Use Photon Weights

To **enhance search sensitivity** a **weight** w_j is assigned to each selected photon j within a few degrees around target source position:

- Weight represents the **probability** that the photon originates from the putative pulsar.

- Computed from full spectral model of region around target source and instrument response functions.

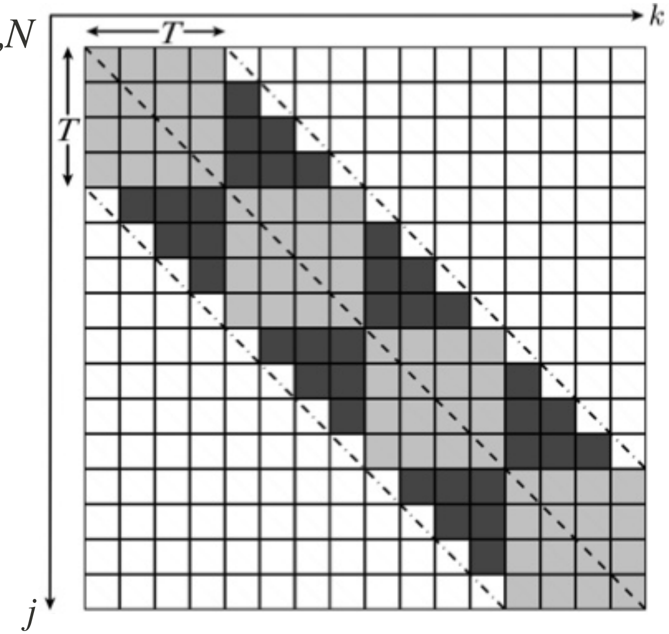
- Shown to improve sensitivity in periodicity searching:
  ➜ Superior **background rejection** than simple angular cuts.
  ➜ Found particularly great improvements in crowded regions of the gamma-ray sky (e.g. near Galactic plane).

Kerr, ApJ (2011)

3-Staged Search Scheme

1. Semi-coherent detection statistic

Photons: $j,k=1,\ldots,N$



Sliding window: photon pairs (j,k) combined coherently if $0 < |\Delta t_{jk}| \leq T$, otherwise incoherently; $\Delta t_{jk} = t_j - t_k$.

$$S = \sum_{j,k=1}^{N} Q(|\Delta t_{jk}|/T)\, w_j w_k\, e^{-2\pi i f \Delta t_{jk} - i\pi \dot{f}\,(t_j^2 - t_k^2)}$$

with rectangular function $Q(x)$ is unity if $0 < x \leq 1$, zero otherwise.

➜ S can be evaluated efficiently with **FFT**.

2. Fully coherent detection statistic

$$P = \frac{1}{\kappa^2}\left|\sum_{j=1}^{N} w_j\, e^{-i\Phi(t_j)}\right|^2 \quad \text{with normalization:} \quad \kappa^2 = \frac{1}{2}\sum_{j=1}^{N} w_j^2$$

- For every semi-coherent candidate, P computed on refined grid (where $\gamma=1$ and $T \to T_{\text{data}}$).
- Narrow parameter-space region plus sparsity of photon data allow direct computation of P (no FFTs used).
- If P of candidate statistically significant, then further refinement in 3. stage.

3. Fully coherent detection statistic using higher harmonics

De Jager et al., ApJ (1989)

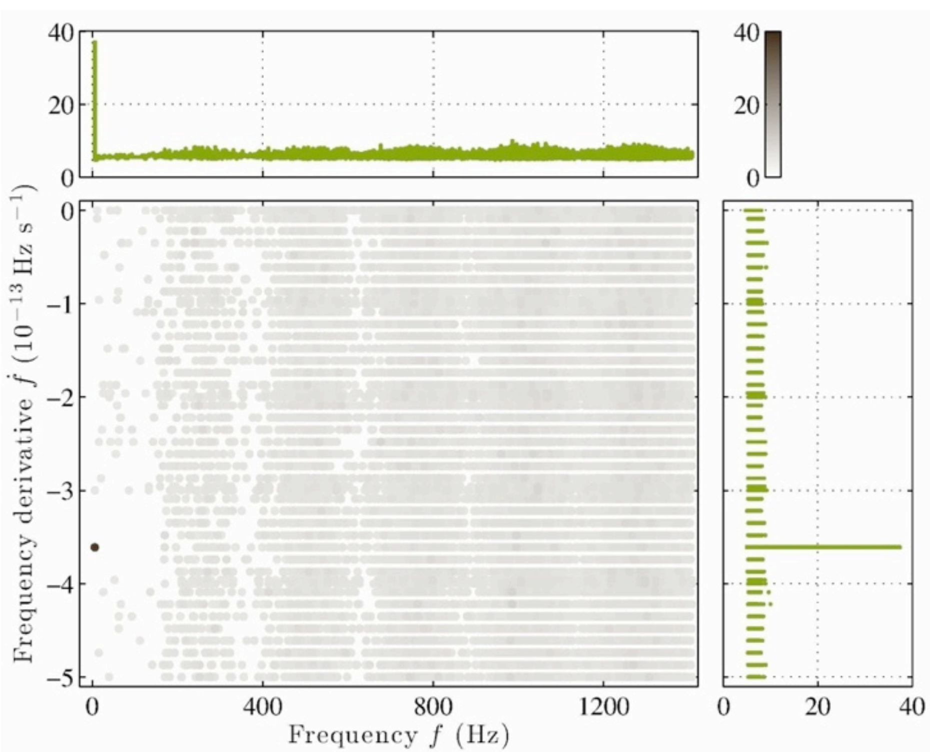
$$H = \max_{1 \leq L \leq 20}\left[\sum_{\ell=1}^{L} |\alpha_\ell|^2 - 4(L-1)\right] \quad \text{with Fourier coefficients } (P = |\alpha_1|^2)\text{:} \quad \alpha_\ell = \frac{1}{\kappa}\sum_{j=1}^{N} w_j\, \mathrm{e}^{-2\pi i\, \ell\, \Phi(t_j)}$$

- Exact pulse profile unknown, so maximize over different number of harmonics ℓ; refinement by about ℓ per dim'.

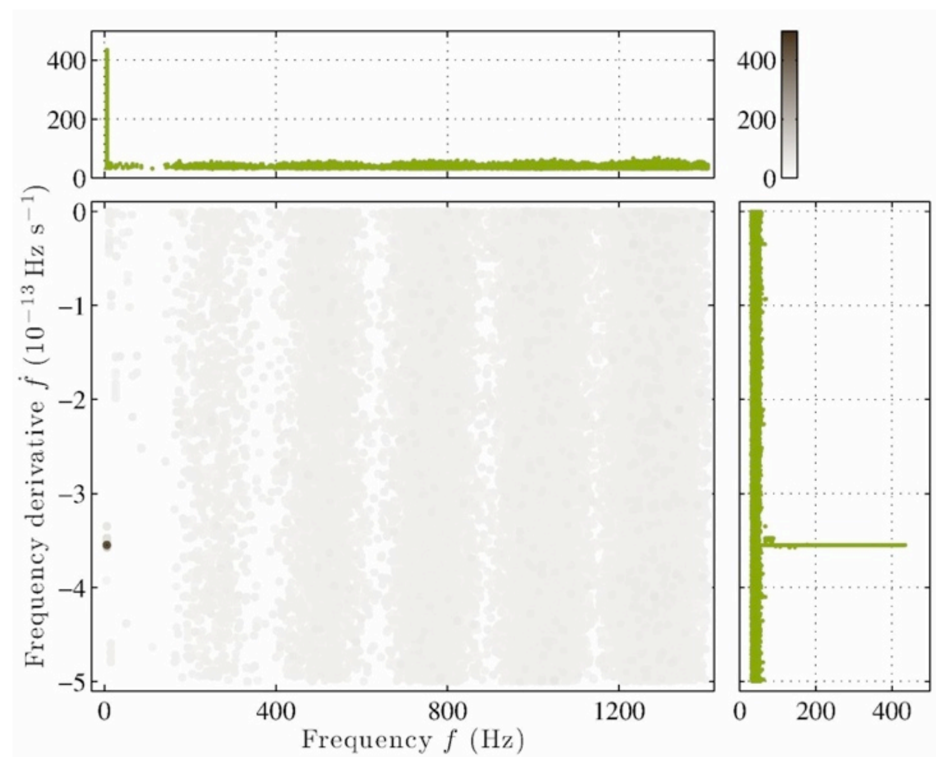
Example: PSR J1620-4927

Illustrating complete search scheme with detailed example: our first discovery

1. **Semi-coherent search** using sliding coherence window technique (coherence window size ≈6 days):

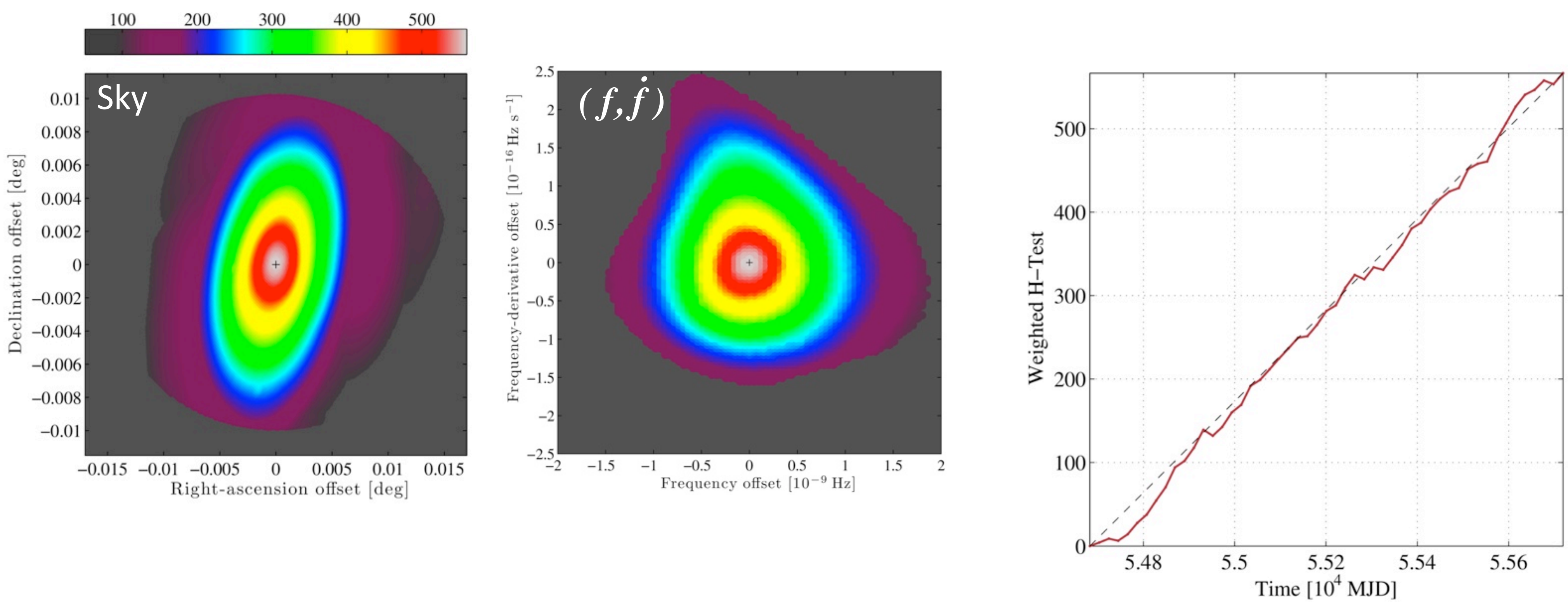


2. **Coherent follow-up** of significant candidates, fully-coherently integrating over the entire dataset (≈975 days):



Example: PSR J1620-4927

3. **Maximizing weighted H-test** over 4D search parameter space:



Maximum weighted H-test value accumulates linearly with time.

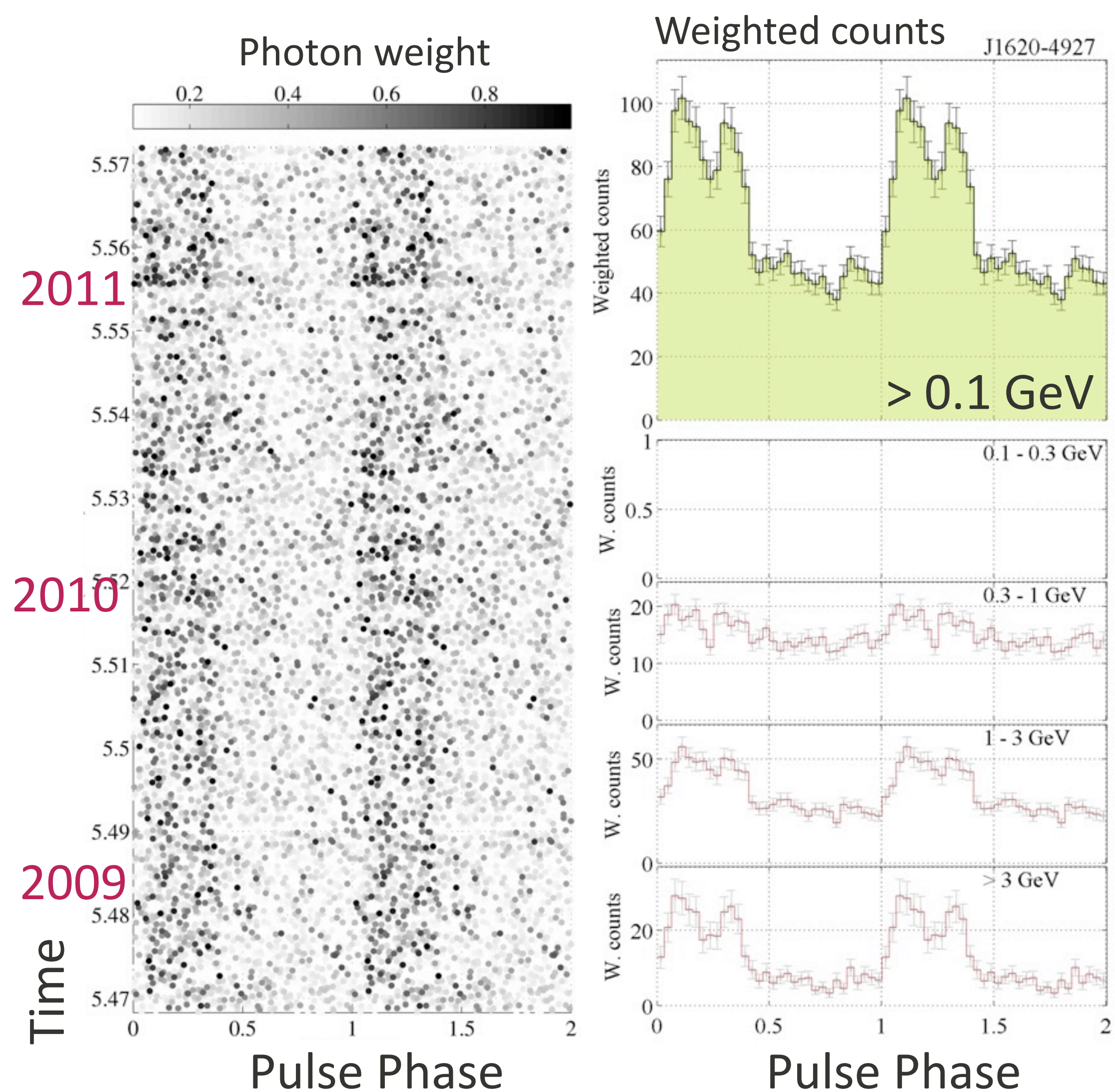
After $\approx 10^3$ days: H=566 ⇒ single-trial false alarm probability $\approx 10^{-98}$

⇒ Pulsar signal is real!

Example: PSR J1620-4927

4. Final **timing** solution using methods described in Ray et al., 2011:

- Divide data into a few segments.
- Fold photon arrival times with preliminary ephemeris to get set of pulse profiles.
- **Getting TOAs:** Cross-correlate each pulse profile with multi-Gaussian template derived from all data.
- Use ***TEMPO2*** to fit TOAs to a timing model.



Conclusion

- GW astronomy: signal absence, **advanced data-analysis methods**, also useful in related fields: signal-rich EM astronomy.

- **New gamma-ray pulsars discovered in blind searches of *Fermi*-LAT data**
  - Traditional methods:
    With 1 year of LAT data: 24
    with 2 years: 2
    with 3 years: 0

  ⇒ New search methods using ~3 years of LAT data: **9 + 1 + ...**

- So far: only one of the 10 pulsars also seen in radio.
  ⇒ **Rest: radio-quiet gamma-ray pulsars**
  (would not have been found without blind search!)

- **Increased population of known radio-quiet pulsars by ~30%!**
  ⇒ A larger sample is important to improve the understanding of geometry/emission
- To find the **first radio-quiet millisecond gamma-ray pulsar**, search now underway with volunteer computing on **Einstein@Home**.
  ⇒ Would be important advance in understanding of pulsars.

Fermi Gamma-ray Space Telescope

- ***Fermi*** launched June 11, 2008.
  Expected lifetime: 5-10 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.

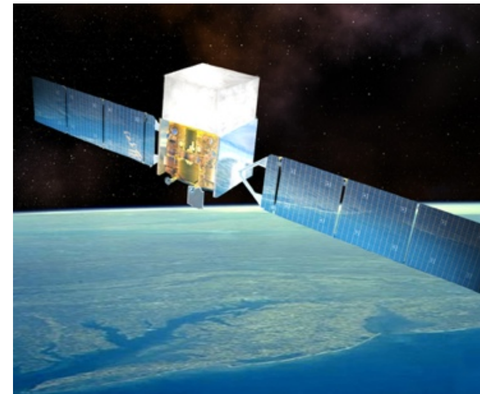
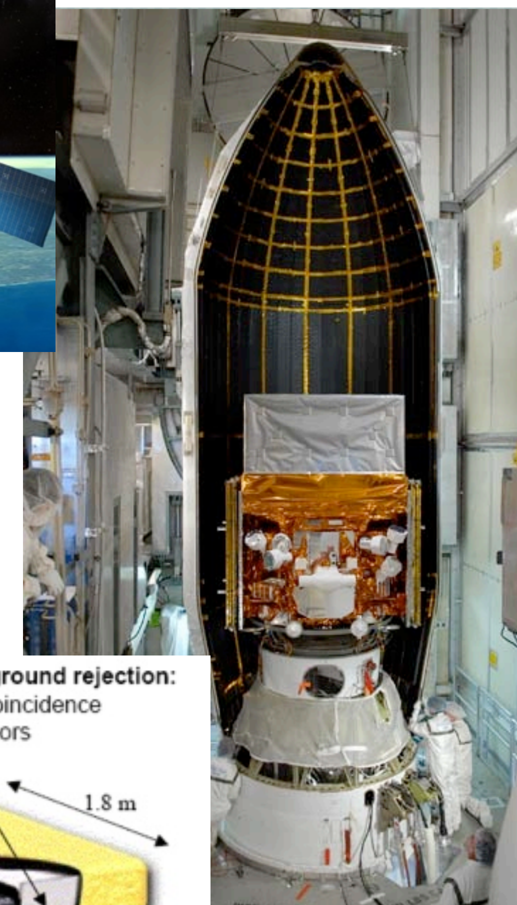
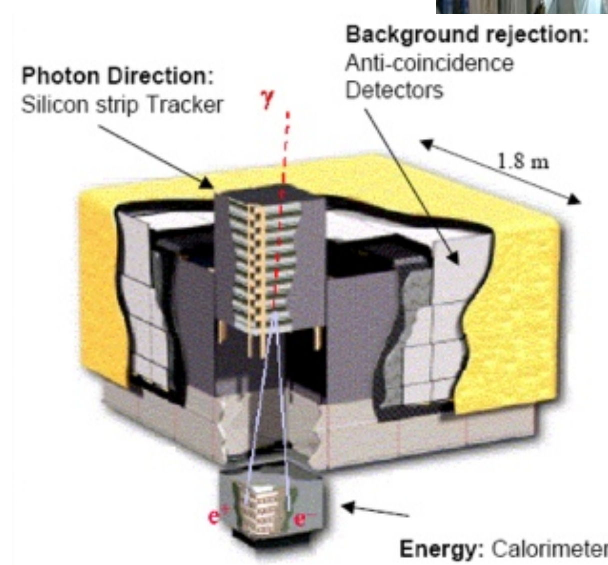


Image Credit: NASA



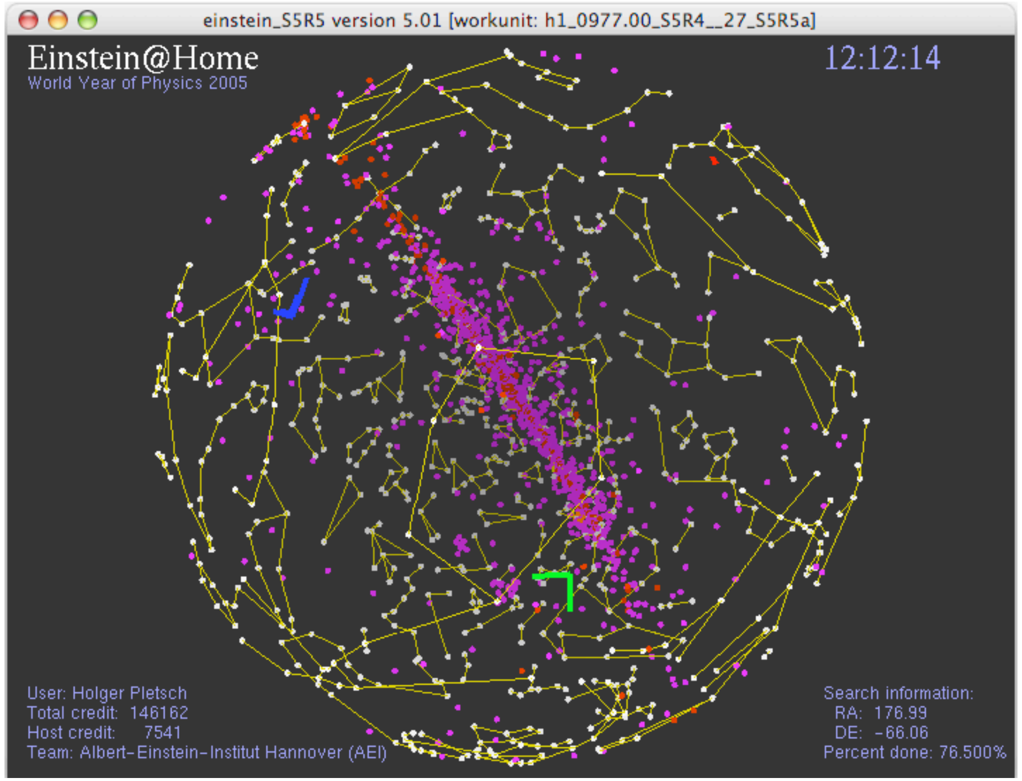


Atwood et al., ApJ, 2009

Volunteer computing: Einstein@Home

- **Numbers:**
  - About 300 000 volunteers
  - About 50 000 active computers
  - About 200 TFlop/s sustained computing power

  - Servers in Milwaukee (USA) and Hannover (Germany)
  - Built upon BOINC infrastructure



- **Now: 3 distinct searches for neutron stars**
  - Gravitational-wave data (since 2005)
  - Radio data (since 2009)
  - Gamma-ray data (since 2011)

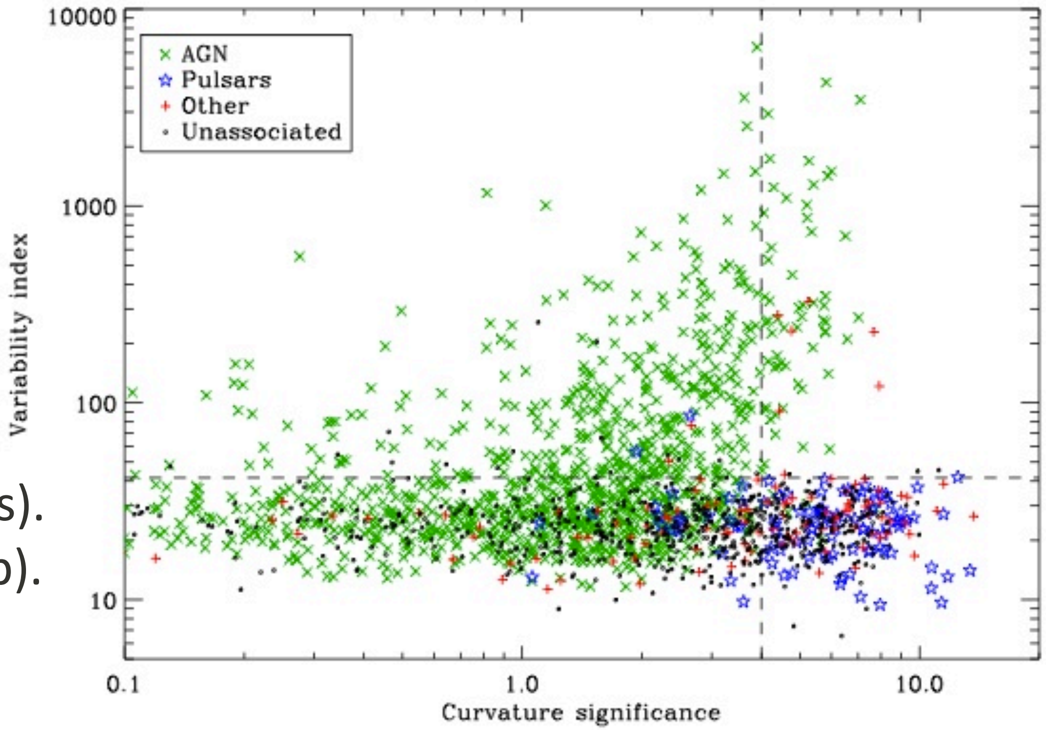
E@H search in *Fermi*-LAT data

- Searching **all** 100 selected sources up to **1 kHz (incl. millisecond-pulsar frequencies)**:
  ➜ **Using fraction of E@H**, next to searches for gravitational-wave and radio pulsars.
  ➜ Small input data size perfectly fits infrastructure!

- E@H computing power used this way is about 3 times ATLAS (based on processing rate, including 2x redundancy for validation).

- **Expect further pulsar discoveries!**

- Plans:
  - search ***all*** remaining unassociated 2FGL sources for young pulsars (~500 targets).
  - search new catalog sources (3FGL coming up).
  - search for pulsars in binary systems.



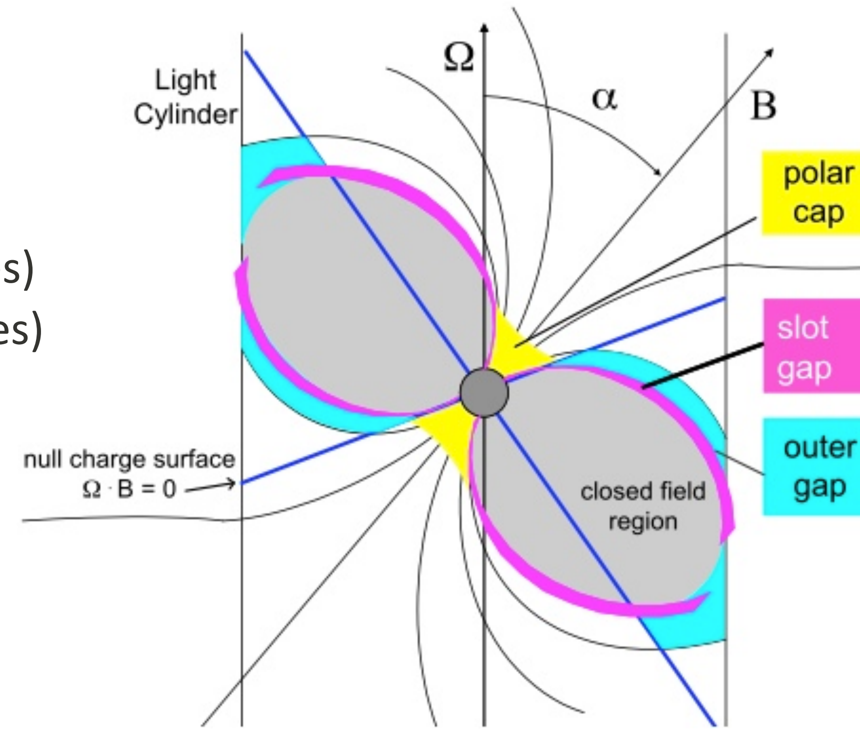
Gamma-ray emission region & geometry

Radio pulsars: emission from modest altitudes (few to tens of R_{NS}) above polar cap.

Gamma-ray pulsars: theoretical modeling of magnetosphere, based on observed pulse shapes (also combined radio/gamma-ray/X-ray).

➜ **Different models expect different pulse patterns.**

- **Three models** with locations of lower charge density "gap" zones causing particle acceleration and radiation:
  - **polar cap** (lower altitudes)
  - **outer gap**, above null charge surface to LC (higher altitudes)
  - **slot gap**, at rims of polar caps extend to LC (higher altitudes)



- Enlarged gamma-ray pulsar population helps to improve understanding of emission geometry and physics.
  ➜ **Outer magnetosphere models favored** based on observed energy spectra of LAT pulsars.

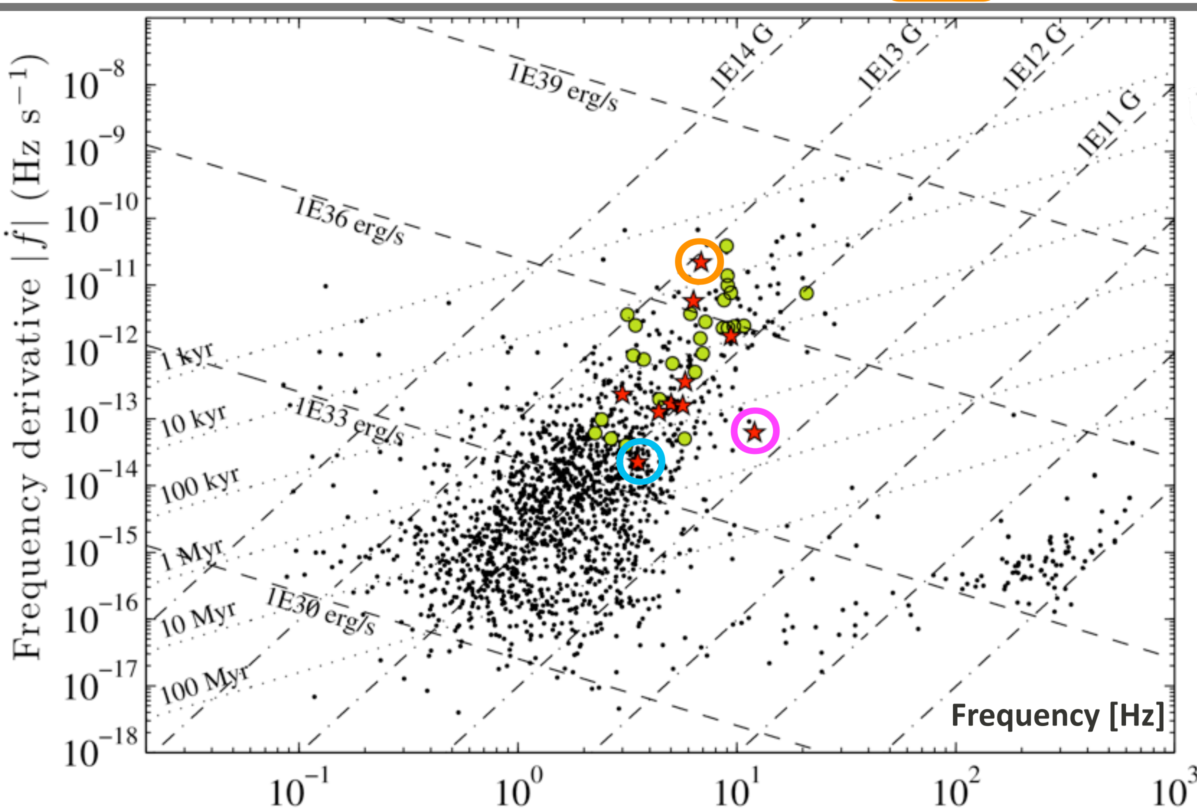
Comparison to known population

Pulsar Name	f (Hz)	$\dot{f}$ (-10^{-13} Hz s^{-1})	τ (kyr)	$\dot{E}$ (10^{34} erg s^{-1})
J0106+4855	12.02540173638(8)	0.61881(7)	3081.1	2.9
J0622+3749	3.00112633651(5)	2.28985(4)	207.8	2.7
J1620–4927	5.81616320951(5)	3.54782(4)	259.9	8.1
J1746–3239	5.01149235750(3)	1.64778(3)	482.2	3.3
J1803–2149	9.4044983174(2)	17.25894(6)	86.4	64.1
J2028+3332	5.65907208453(2)	1.55563(2)	576.8	3.5
J2030+4415	4.4039248637(5)	1.2576(2)	555.2	2.2
J2111+4606	6.3359340865(4)	57.4218(3)	17.5	143.6
J2139+4716	3.5354509962(2)	0.2232(2)	2511.5	0.3
J1838-0537	6.863015715(4)	218.964(6)	4.97	590.0

Older, less energetic pulsars

Young, energetic, Galactic-plane pulsars

Very young, very energetic



★ Newly discovered pulsars

Largest age and **smallest surface magnetic field** among all blind-search gamma-ray pulsars!

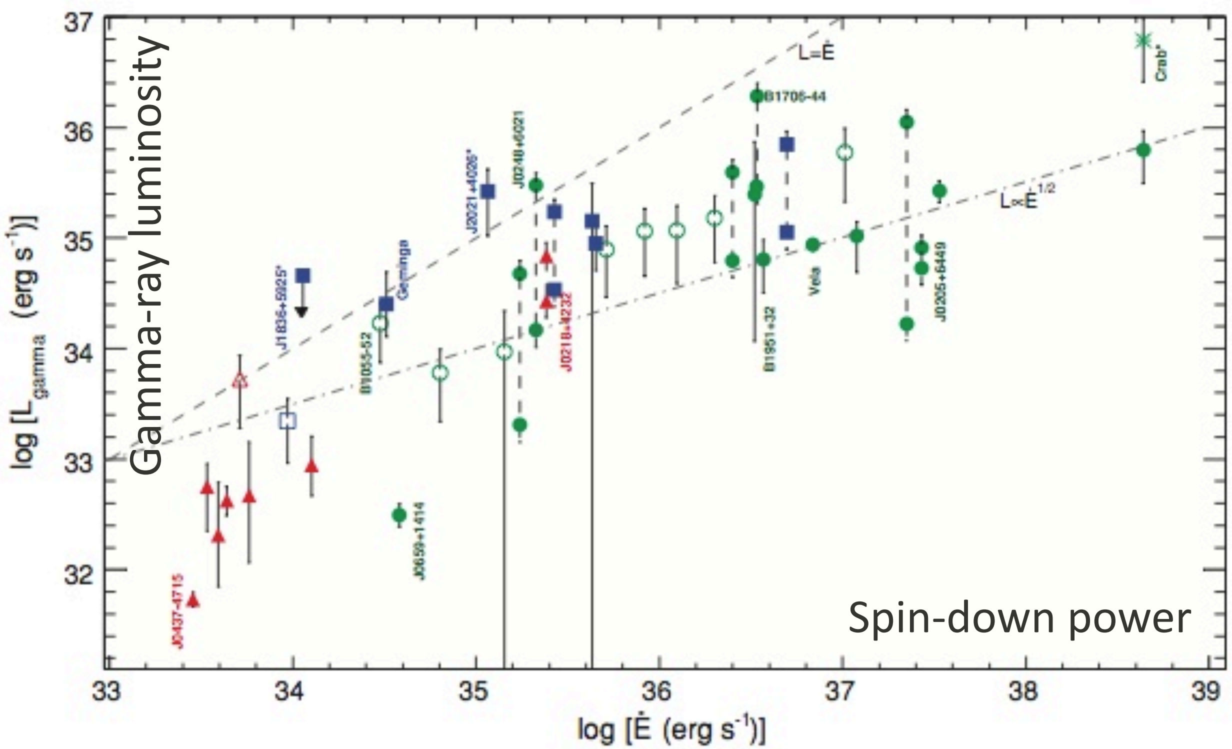
Lowest spin-down power among ***all*** gamma-ray pulsars!

2nd youngest, largest glitch among ***all*** gamma-ray pulsars!

Distance-estimate attempts

- **Observed correlation** gives rise to **"pseudo" gamma-ray luminosities**:

$$L_{ps} \sim 3.2 \times 10^{33} (\dot{E}/10^{34}\,\mathrm{erg\ s^{-1}})^{1/2}\,\mathrm{erg\ s^{-1}}$$



Abdo et al., ApJS 187, 2010

- Given **energy flux** G_{100}, assume pseudo gamma-ray luminosity, estimate **distance** d from

$$L_\gamma = 4\pi f_\Omega G_{100} d^2$$

with geometrical factor set to 1.

➜ **"Pseudo distances" :**

Pulsar Name	d_{ps} (kpc)
J0106+4855	1.4[c]
J0622+3749	1.6
J1620–4927	0.7
J1746–3239	0.8
J1803–2149	1.3
J2028+3332	0.9
J2030+4415	0.7
J2111+4606	2.7
J2139+4716	0.8

Actual distance is 3 kpc from radio detection!

ATLAS computing facility

- May 2011: Started search on **ATLAS** cluster at AEI Hannover.
- 1680 nodes, 6720 CPU-cores, 8 GB random-access memory, allowed 256-Hz heterodyning frequency bandwidth.
- Most computing power really only needed to cover **ms** spin frequencies (up to 1kHz).

  If searched only up to 64 Hz (as previously): first pulsar discovery within 1.4 CPU days on a single core!
- With ATLAS: scanned most sources up to about 400 Hz within a few months.

Stage 2: Coherent Follow-up

- **Fully coherent detection statistic:**

$$P = \frac{1}{\kappa^2} \left| \sum_{j=1}^{N} w_j \, e^{-i\Phi(t_j)} \right|^2$$

with normalization: $$\kappa^2 = \frac{1}{2} \sum_{j=1}^{N} w_j^2$$

- For every semi-coherent candidate, $\boldsymbol{P}$ computed on refined grid (where γ=1 and $\boldsymbol{T} \rightarrow \boldsymbol{T}_{\text{data}}$) covering 4 grid intervals of the original semi-coherent grid.

- Narrow parameter-space region plus sparsity of photon data allow direct computation of $\boldsymbol{P}$ (no FFTs used).

- If $\boldsymbol{P}$ of candidate statistically significant, then further refinement in 3. stage.

Stage 3: Including Higher Harmonics

- Measure statistical significance of energy in first 20 (non-DC) **Fourier components** (harmonics) of pulse profile as function of phase.
  ➜ Exact profile unknown, so maximize over different # of harmonics.

- Adapted the so-called ***H*-test** (a version including photon weights):

De Jager et al. (1989), Kerr (2011)

$$H = \max_{1 \le L \le 20} \left[\sum_{\ell=1}^{L} |\alpha_\ell|^2 - 4(L-1) \right]$$

with Fourier coefficients ($P = |\alpha_1|^2$): $\alpha_\ell = \frac{1}{\kappa} \sum_{j=1}^{N} w_j \, \mathrm{e}^{-2\pi \mathrm{i} \ell \mathrm{x_j}}$

and phase (between 0 and 1): $x_j = \left[\Phi(t_j) \mod 2\pi \right] / 2\pi$.

- **Further grid refinement** in each dimension (roughly by number of max. harmonics).

Einstein@Home searches

- **Blind searches for gravitational-wave pulsars:**
  - 2 publications of all-sky upper limits using LIGO S4 and S5 data
  - Frequency band 50Hz-1500Hz
  - Full S5 & S6 search ongoing

- **Blind searches for binary radio pulsars:**
  - 2 publications of radio pulsar discoveries with Arecibo.
  - Both are somewhat unusual, one DRP, one IMBP.
  - Meanwhile: 18 more radio pulsars found in Parkes and Arecibo data

PHYSICAL REVIEW D **79**, 022001 (2009)

Einstein@Home search for periodic gravitational waves in LIGO S4 data

B. Abbott,[16] R. Abbott,[16] R. Adhikari,[16] P. Ajith,[2] B. Allen,[2,55] G. Allen,[32] R. Amin,[20] D. P. Anderson,[41] S. B. Anderson,[16] W. G. Anderson,[55] M. A. Arain,[42] M. Araya,[16] H. Armandula,[16] P. Armor,[55] Y. Aso,[10] S. Aston,[40] P. Aufmuth,[15] C. Aulbert,[2] S. Babak,[1] S. Ballmer,[16] H. Bantilan,[8] B. C. Barish,[16] C. Barker,[18] D. Barker,[18] B. Barr,[43] P. Barriga,[54] M. A. Barton,[43] M. Bastarrika,[43] K. Bayer,[17] J. Betzwieser,[16] P. T. Beyersdorf,[28] I. A. Bilenko,[23] G. Billingsley,[16]

PHYSICAL REVIEW D **80**, 042003 (2009)

Einstein@Home search for periodic gravitational waves in early S5 LIGO data

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Pulsar Discovery by Global Volunteer Computing

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The Astrophysical Journal Letters, 732:L1 (5pp), 2011 May 1 doi:10.1088/2041-8205/732/1/L1

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