Blind searches for gamma-ray pulsars in Fermi-LAT data with methods from gravitational-wave astronomy and Einstein@Home

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• Pulsars (in a nutshell) and the *Fermi* Large Area Telescope (LAT)

• The data analysis problem: Searching for gamma-ray pulsars

• The improved data analysis method

• The discoveries made owing to new method

• Future prospects and *Einstein@Home*
Pulsars

- Rapidly spinning and highly magnetized neutron stars
- Born in supernova explosions of massive stars
- 1-2 solar masses, 10 km radius
- Spin periods: a) normal/young pulsars (~1s)
  b) millisecond pulsars (down to 1.4ms)

- Lighthouse effect:
  ➜ Pulsations detected in radio, optical, X-rays, gamma-rays

- Gravitational-wave pulsar:
  Spinning neutron star with a deviation from symmetry

→ Neutron stars are observable in every astronomical window!
What's 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

- **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*
**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

Before Fermi: < 10 gamma-ray pulsars known!

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

Indirect ways:
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:
3) Blind searches for pulsars directly in LAT data
   - No prior knowledge of pulsar parameters
   - Very successful in finding young pulsars during early mission
   - No millisecond pulsar yet

Abdo et al., 2009
Saz Parkinson et al., 2010
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 *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.
Bottleneck: computing power

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 impossible
   ➔ Need:  a) more efficient search methods
            b) more computing power
   ➔ Goal: Maximize sensitivity at fixed computing cost

Problem analogous to searches for gravitational-wave pulsars
   ➔ Solution: use gravitational-wave data-analysis "technology"

- Hierarchical, semi-coherent 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)

- Parameter-space metric to construct optimal grid
  Balasubramanian et al. (1995), Owen (1996), Brady et al. (1998), Jones et al. (2005),
Hierarchical, 3-staged search scheme:
Discard unpromising regions in parameter space as early as possible

1. Semi-coherent:
   - 6-day coherence window slide over 3 years while incoherently combining results.
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.

Parameter-space metric to guide grid construction
- Geometric tool: measure fractional loss in expected detection statistic for a given signal at a nearby grid point, 
  \[ M = \sum_{a,b} g_{ab} \Delta p^a \Delta p^b + \mathcal{O}(\Delta p)^3 \]
- Recently: first analytic semi-coherent pulsar metric in HJP & Allen, PRL (2009) \( \rightarrow \) significant efficiency improvement
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!

Pulse profiles of the 9 new gamma-ray pulsars:

(Two rotations shown for clarity)

Comparison to known population

- Pulsars from the ATNF catalog (~2000 radio pulsars)
- Previous blind-search LAT pulsars
- Newly discovered LAT pulsars
Einstein@Home: a volunteer supercomputer

- **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)
  - Extremely cost-effective

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)
Summary

• Gravitational-wave astronomy: signal absence, but **efficient data-analysis methods**
  ⇒ Useful in related fields: signal-rich electromagnetic astronomy.

• **Finding radio-quiet gamma-ray pulsars** in *Fermi*-LAT data:
  Search sensitivity computationally bound
  ⇒ Efficient search methods & massive computing power required

• **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%!

• New paradigm: **volunteer computing**
  Computational load of survey now moved to *Einstein@Home*
  to find the *first radio-quiet millisecond gamma-ray pulsar.*
  ⇒ Would be important advance in understanding of pulsars.

http://einstein.phys.uwm.edu