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# The *Einstein@Home* Survey for Gamma-ray Pulsars

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**Abstract.** Since the launch of the *Fermi Gamma-ray Space Telescope* in 2008, the onboard Large Area Telescope (LAT) has detected gamma-ray pulsations from more than 200 pulsars. A large fraction of these remain undetected in radio observations, and could only be found by directly searching the LAT data for pulsations. However, the sensitivity of such "blind" searches is limited by the sparse photon data and vast computational requirements. In this contribution we present the latest large-scale blind-search survey for gamma-ray pulsars, which ran on the distributed volunteer computing system, *Einstein@Home*, and discovered 19 new gamma-ray pulsars. We explain how recent improvements to search techniques and LAT data reconstruction have boosted the sensitivity of blind searches, and present highlights from the survey's discoveries. These include: two glitching pulsars; the youngest known radio-quiet gamma-ray pulsar; and two isolated millisecond pulsars (MSPs), one of which is the only known radio-quiet rotationally powered MSP.

**Keywords.** pulsars: general, gamma rays: observations

## 1. Introduction

Seven years after Jocelyn Bell Burnell's historic discovery (Hewish *et al.* 1968), the SAS-2 satellite made the first significant detections of pulsations in the arrival times of gamma-ray photons from the Crab and Vela pulsars (Kniffen *et al.* 1974; Thompson *et al.* 1975). However, the third brightest gamma-ray source, "Geminga", would remain unexplained for almost another twenty years, until the eventual discovery of its X-ray pulsations (Halpern & Holt 1992), and subsequent gamma-ray pulsation detection (Bertsch *et al.* 1992), identified it as the first *radio-quiet* gamma-ray pulsar.

Due to the sparsity of gamma-ray count data, and the extreme computational demands of "blindly" searching for pulsations within it (Chandler *et al.* 2001), it would take another sixteen years for the next radio-quiet gamma-ray pulsar to be discovered. Using an efficient "time differencing" search technique (Atwood *et al.* 2006) to search within just one month of early commissioning data from the Large Area Telescope (LAT) on board the *Fermi Gamma-ray Space Telescope*, Abdo *et al.* (2008) discovered the first blind-search gamma-ray pulsar, PSR J0007−7303, within the CTA1 supernova remnant. This opened the floodgates: a total of twenty-six young pulsars were discovered by blind gamma-ray pulsation searches within the first two years of LAT data (Abdo *et al.* 2009; Saz Parkinson *et al.* 2010). Two years later, further methodological improvements brought another wave of pulsar discoveries (Pletsch *et al.* 2012a,c), including the first (and so far only) blind-search binary millisecond pulsar (MSP), the black widow PSR J1311−3430 (Pletsch *et al.* 2012b).

However, as the time interval spanned by the continuing LAT observations grows, so does the computational cost of performing a blind pulsation search. To meet the growing demands, blind searches are now performed on the *Einstein@Home* distributed volunteer computing system†. In these proceedings, we give a summary of the latest blind searches which have been running on *Einstein@Home* since late 2014.

## 2. The Latest *Einstein@Home* Survey

The first set of gamma-ray pulsar searches performed by *Einstein@Home* discovered four new gamma-ray pulsars (Pletsch *et al.* 2013). Following this success, we performed an in-depth investigation of blind-search techniques to improve their sensitivity to weak pulsations (Pletsch & Clark 2014). Armed with these new methods, and the newly-improved "Pass 8" LAT data (Atwood *et al.* 2012) which offered $\sim 25\%$ increases in detected photon counts, we searched for pulsations from 152 unidentified pulsar-like gamma-ray sources from the *Fermi*-LAT Third Source Catalog (3FGL) (Acero *et al.* 2015).

The first new pulsar came shortly after the start of this survey, with the discovery of the young pulsar, PSR J1906+0722, within a previously puzzling unidentified pulsar-like gamma-ray source (Clark *et al.* 2015). Subsequent timing analyses revealed that the pulsar exhibited strong timing noise (not accounted for by our blind searches) and underwent a large glitch ($\Delta f/f \sim 4.5 \times 10^{-6}$) one year into the LAT observations. Furthermore, the pulsar was not where we thought it was! Its timing position lay outside the 99% confidence localisation region of the targeted gamma-ray source. Analysis of the off-pulse emission from a region around the pulsar, using the refined timing solution over 6 years of data, revealed the gamma-ray source to be a combination of the pulsar's flux and a second source of gamma-ray emission, coincident with the location of a nearby, but unrelated, supernova remnant. The discovery of PSR J1906+0722 despite this source confusion (a common problem within the Galactic plane) and adverse timing behaviour left us optimistic for further discoveries.

Sure enough, another 16 young gamma-ray pulsars were found, including one more glitching pulsar; their detections and subsequent multiwavelength analyses are described in Clark *et al.* (2017), Wu *et al.* (2017), *ApJ*, submitted, and Clark (2017). Similarly to the early blind-search discoveries, only two of these were subsequently detected in dedicated radio follow-up searches; the rest appear to be radio-quiet.

Perhaps the most exciting young pulsar discovery made during the *Einstein@Home* survey was that of PSR J1208−6238 (Clark *et al.* 2016). This is the youngest known radio-quiet gamma-ray pulsar, with a characteristic age of just 2,700 yr. It is also extremely highly magnetized, with an inferred surface magnetic field strength of $3.8 \times 10^{13}$ G, the third highest seen in any gamma-ray pulsar, surpassed only by the magnetar-like rotationally-powered pulsars PSR J1119−6127 (Parent *et al.* 2011) and PSR J1846−0258 (Kuiper *et al.* 2017). PSR J1208−6238 is young enough that its long-term braking

† `https://www.einsteinathome.org`

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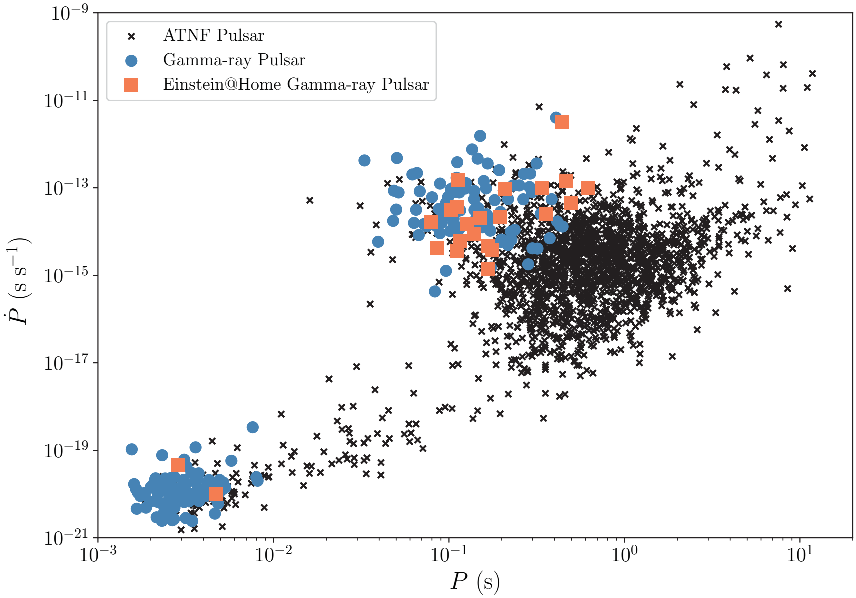


**Figure 1.** $P$-$\dot{P}$ diagram, showing all pulsars within the ATNF Pulsar Catalogue (Manchester *et al.* 2005) (crosses), all known gamma-ray pulsars (circles), and those discovered by *Einstein@Home* in blind gamma-ray pulsation searches (squares).

behaviour appears to be dominant over timing noise, with a braking index value of $n \approx 2.6 \pm 0.1$ measurable within 7.5 years of LAT data. As with all but one of the nine other pulsars with measurable braking indices (Archibald *et al.* 2016), this value is significantly below the $n = 3$ predicted by a simple dipole braking model.

Finally, our *Einstein@Home* survey has discovered two isolated gamma-ray MSPs, the first to be discovered in completely blind gamma-ray searches without relying on positional information from multiwavelength observations (Clark *et al.* 2017, *Science Advances*, submitted). One of these MSPs has remained undetected in dedicated radio follow-up searches, making it the first known rotationally-powered MSP without detected radio pulsations.

## 3. Summary & Outlook

*Einstein@Home* has now discovered 23 gamma-ray pulsars (see Figure 1) bringing the total number of gamma-ray selected pulsars discovered in *Fermi*-LAT data to 60, more than a quarter of all known gamma-ray pulsars†. Of these, 54 remain radio-quiet, and would therefore likely remain unknown without these searches. *Einstein@Home* continues to perform blind gamma-ray pulsar searches; we are currently searching for pulsations from unidentified gamma-ray sources in the inner Galaxy (Fermi-LAT Collaboration 2017), while GPU-accelerated searches for binary MSPs are currently being performed in an attempt to finally identify high-confidence "spider" MSP candidates (see contribution by L. Nieder to these proceedings). Finally, an upcoming 4th *Fermi*-LAT source catalogue based on twice as much data as the 3FGL catalogue is expected soon, and will provide a large number of new unidentified gamma-ray sources. We therefore remain optimistic for further exciting gamma-ray pulsar discoveries with *Einstein@Home*.

† `http://tinyurl.com/fermipulsars`

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