First Einstein@Home Radio Pulsar Discoveries

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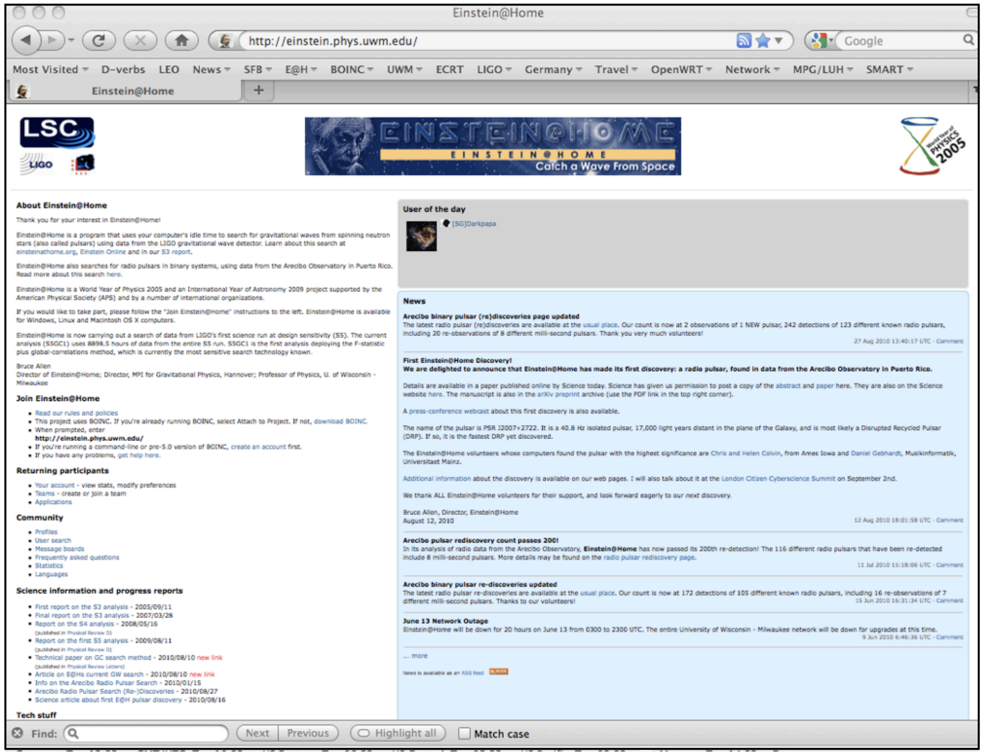
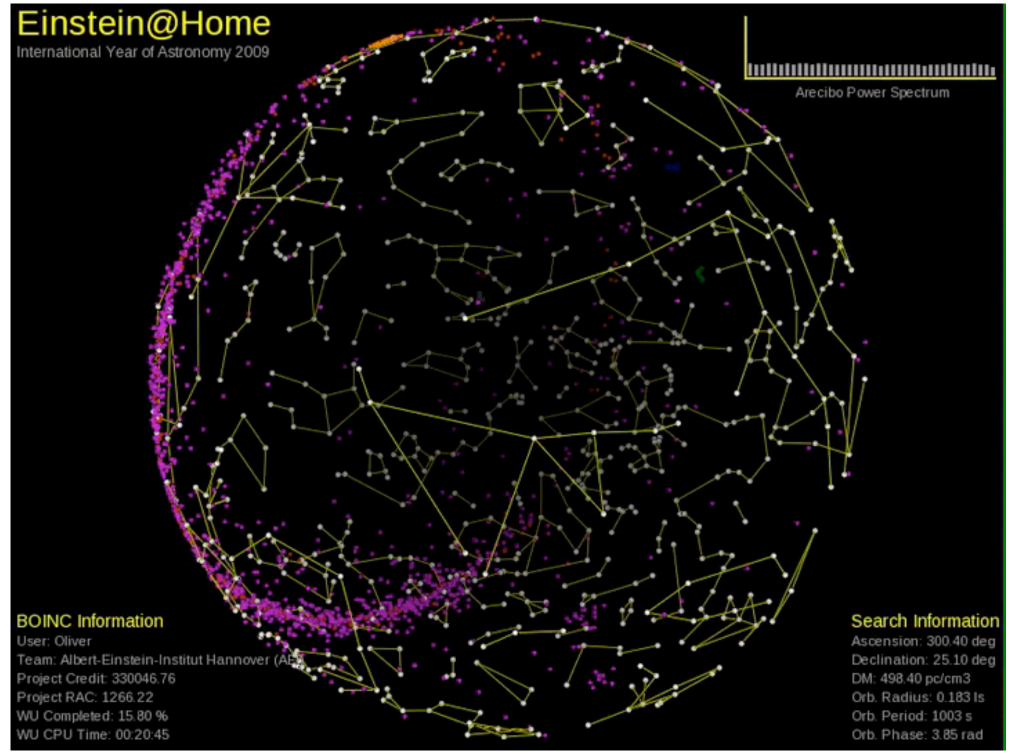
Einstein@Home
Volunteer Distributed Computing Project





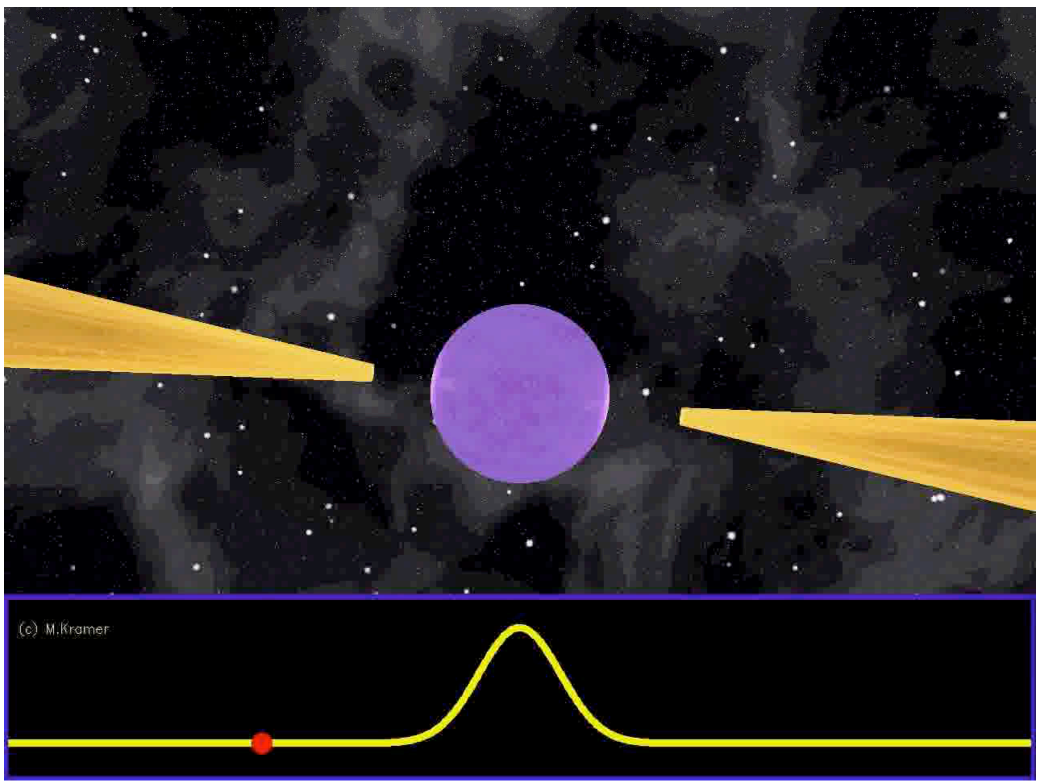
- Launched 2005; more than 250k volunteers
- Most development and operation: UWM and AEI
- Currently 312 TFlop/s. More than 100k computers contact Einstein@Home servers each week.

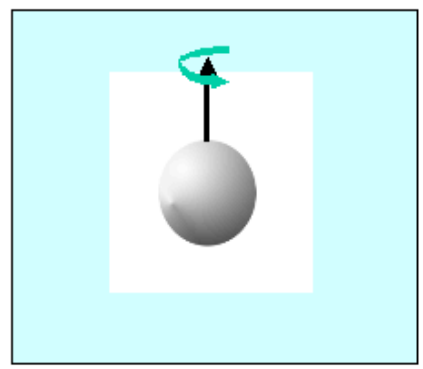
LSC work

- *The Einstein@Home search for periodic gravitational waves in LIGO S4 data*, **Phys. Rev. D 79 (2009) 022001**
- *Einstein@Home search for periodic gravitational waves in early S5 LIGO data*, **Phys. Rev. D 80 (2009) 042003**
- Einstein@Home Hough-method search on full S5 data: **paper in preparation** (Papa & Leaci, plenary talk)
- **Now running**: Einstein@Home search (full S5 data set) with method from Pletsch and Allen, *Exploiting Large-Scale Correlations to Detect Continuous Gravitational Waves*, Phys. Rev. Lett. 103, 181102 (2009)

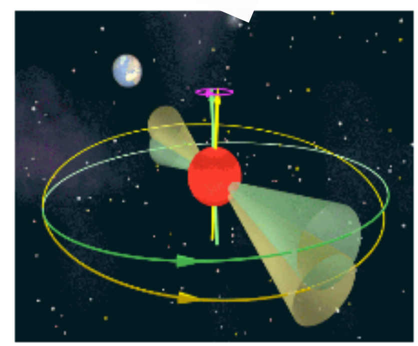
Main E@H Target: Neutron Stars

- Discovered 1967
- 10 km radius stellar-mass objects
- About 1,900 have been found electromagnetically; rotation frequencies 0.1 Hz to 716 Hz
- Galaxy contains ~ 100 million NS





Mountain on a star



Wobbling star

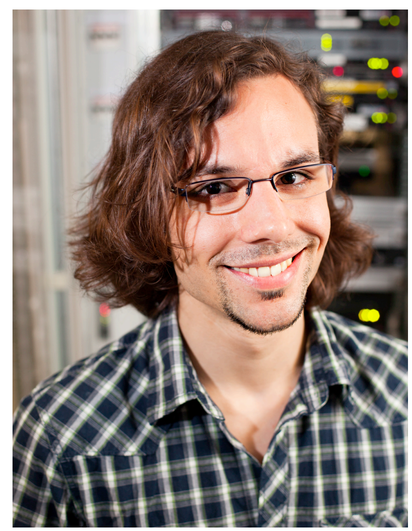
Einstein@Home Radio Pulsar Search

WHAT

- Since 2009, using about one-third of Einstein@Home CPU cycles searching radio data from Arecibo Observatory.
- Search new part of parameter space: binary orbits with periods > 11 minutes
- PALFA collaboration (Jim Cordes, Cornell), not LSC.
- Author list is E@H and PALFA people who have made significant contributions to the work.
- So far 242 re-detections of 123 known pulsars.

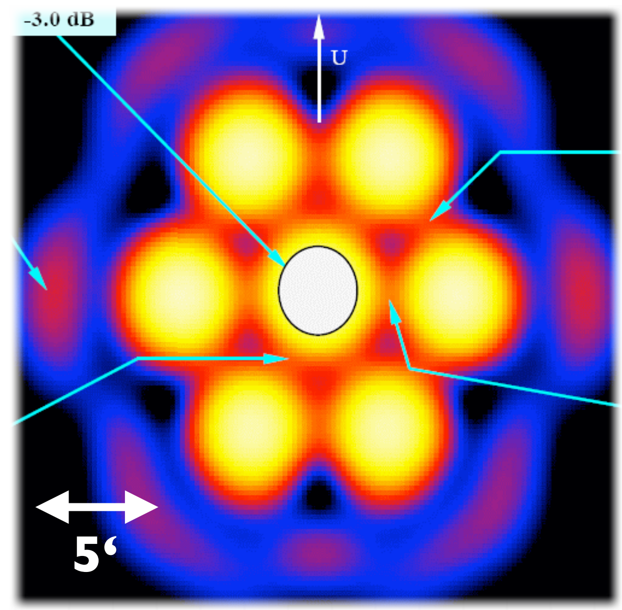
WHY

- Motivate volunteers, increase their confidence in the project, get publicity for Einstein@Home.
- Forge stronger working links with radio astronomers.
- Gain experience in developing and deploying GPU code
- Apply methods developed for the GW search, such as stochastic template placement.

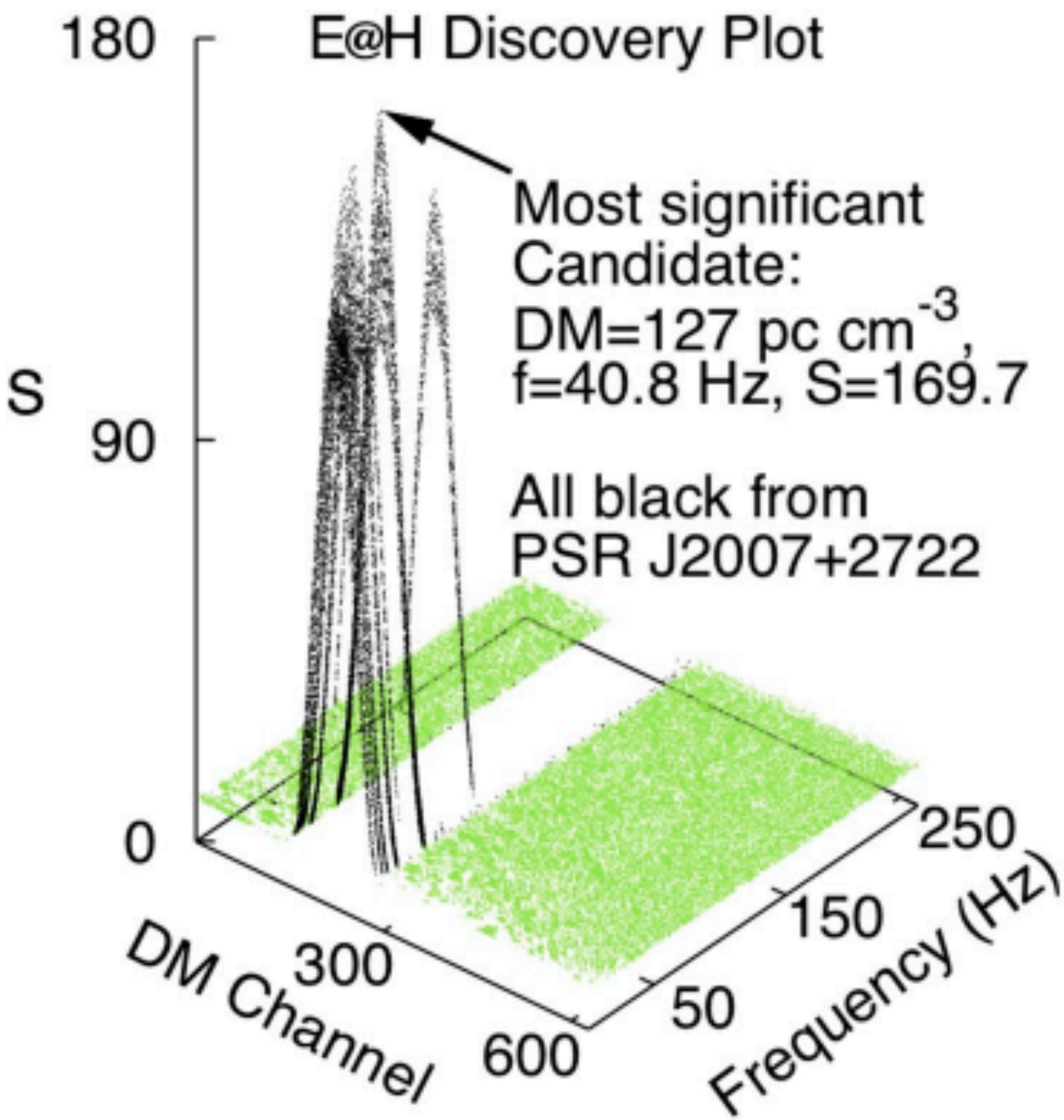


Pulsar Arecibo L-band Feed Array (PALFA) Survey

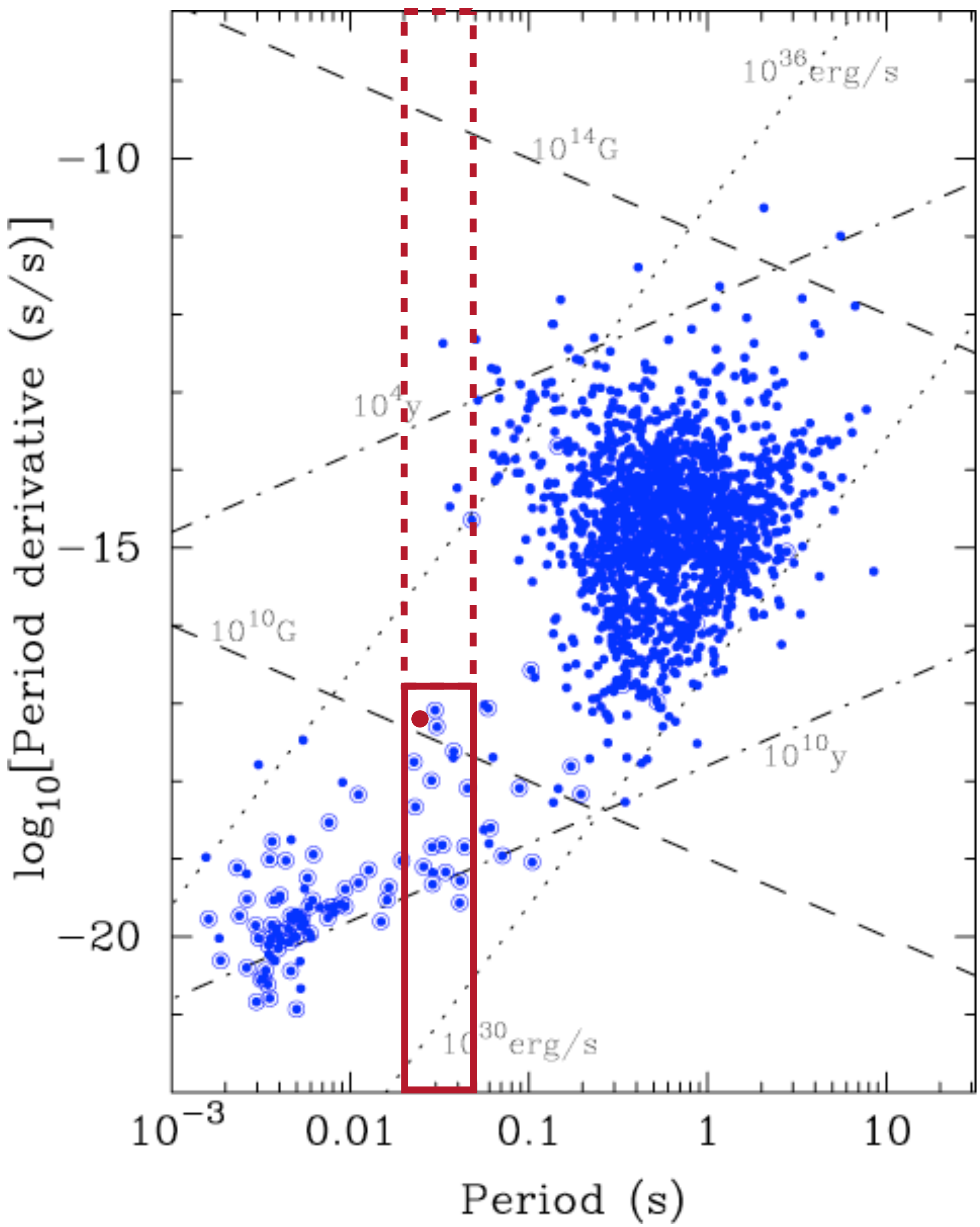
- 1225-1525 Mhz, cryogenic, 7 feeds, 2 polarizations per feed. Seven-pixel radio camera.
- Survey began in 2005. About 70,000 beams (10k pointings) typically five minutes each. Average is about 7 pointings/day. About 150 TB of data..
- “Old” back-end (WAPP): 100 Mhz power spectrum. 256 frequency bins every 64 us.
- New back-end (Mock): 300 Mhz power spectrum. 1024 frequency bins every 64 us.



First Einstein@Home Discovery



- Found in postprocessed Einstein@Home output on July 11th, in Arecibo data from February 2007.
- NOT a boring 1 Hz dying pulsar.
- PSR J2007+2722 is a 40.8 Hz **isolated** pulsar with **very small spindown**
- $|df/dt| < 3 \times 10^{-14}/s^2$ implies age > 21 My
- Located in the Galactic plane. The dispersion measure 127 pc/cm^3 implies distance of 5.6 kpc.
- **Unusually wide** beam profile
- Too far away to be a promising GW target.



Most pulsars with similar frequencies and spin-down rates are in binary systems.

Interpretation

- To be spinning at 40.8 Hz, but spinning down slowly, pulsar must have been recycled to bury the magnetic field.
- Not fully recycled, hence it lost its companion, hence not WD companion.
- Probably was disrupted when the companion exploded in a SN
- In this case, the fastest known Disrupted Recycled Pulsar (DRP)

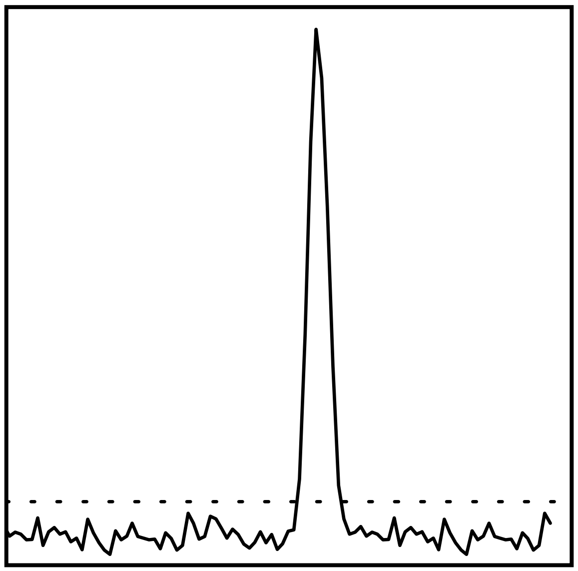
DRPs ($B < 3.0 \times 10^{10}$ G)[2]

J0609+2130	55.7	9.6	9.6	1.8	30	9
J1038+0032	28.9	9.8	9.1	2.4	1800	10
J1320−3512	458.5	9.6	10.5	0.9	430	11
J1333−4449	345.6	10.0	10.1	2.3	690	12
J1339−4712	137.1	9.6	9.9	1.8	450	12
J1355−6206	276.6	9.1	10.5	8.0	20	13
J1548−4821	145.7	9.5	10.0	3.8	310	13
J1611−5847	354.6	9.4	10.4	2.4	230	14
J1753−1914	63.0	8.7	10.1	2.7	160	14
J1816−5643	217.9	9.2	10.3	3.1	940	12
B1952+29	426.7	9.6	10.4	0.4	10	15
J2235+1506	59.8	9.8	9.5	1.2	680	16

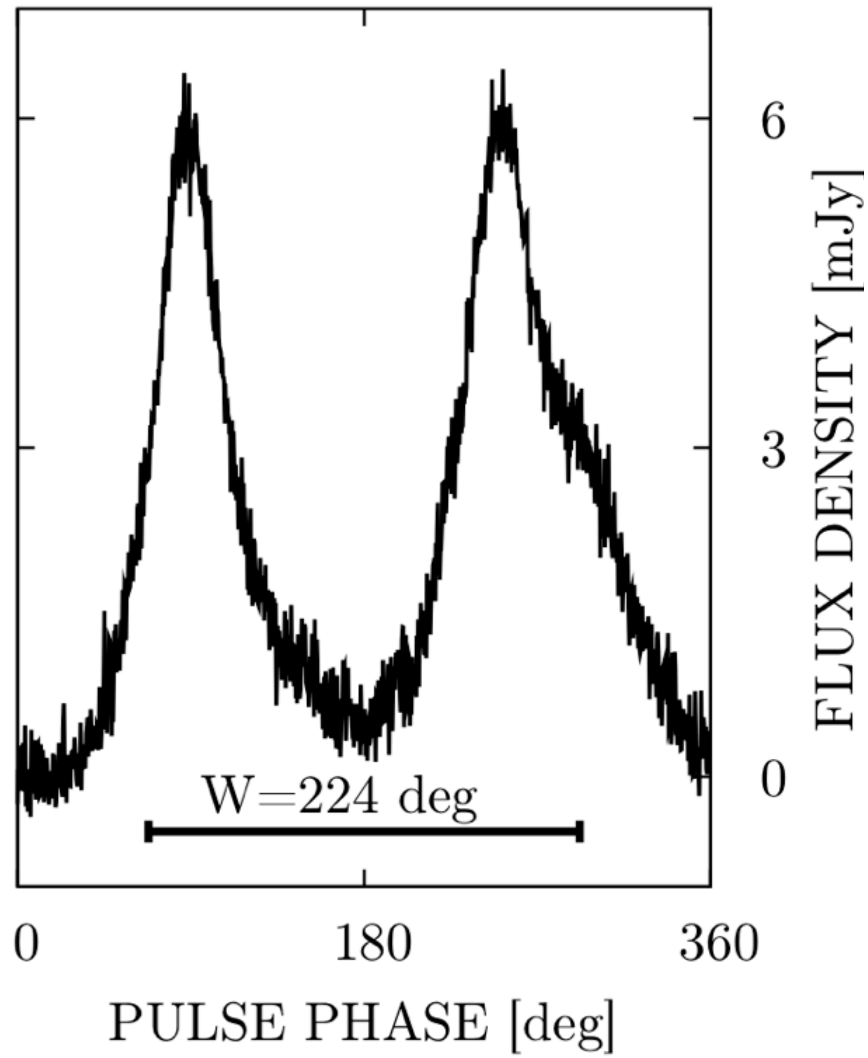
Table 1 from Belczynski, K. *et al.*, *Double and single recycled pulsars: an evolutionary puzzle?, MNRAS* **407**, p. 1245–1254 (2010).

Very wide beam profile

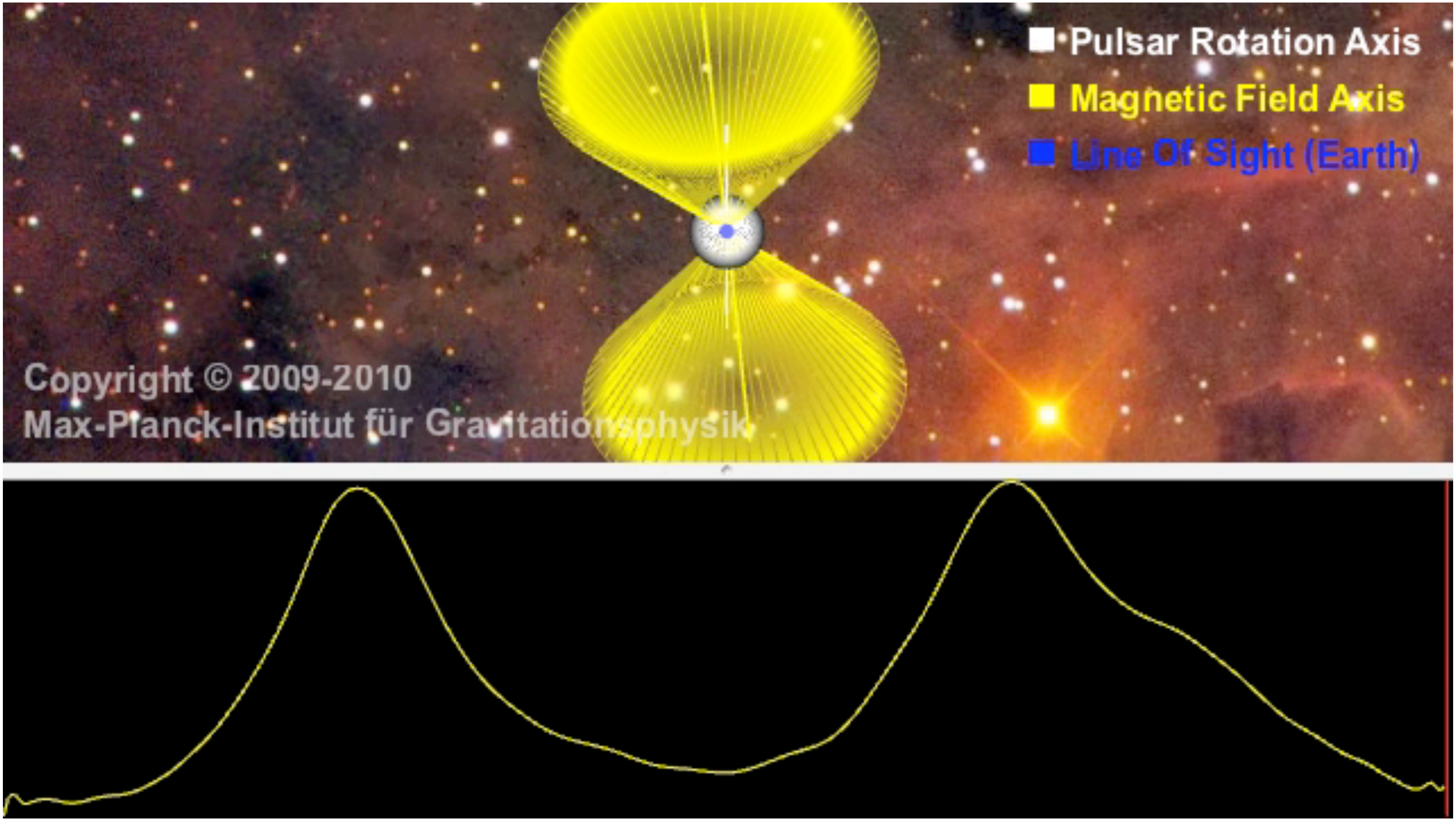
Typical Pulsar Pulse Profile



J2007+2722 Pulse Profile



J2007+2722



Pulsar Rotation Axis
Magnetic Field Axis
Line Of Sight (Earth)
Copyright © 2009-2010
Max-Planck-Institut für Gravitationsphysik

“Winning” Volunteers

Helen and Chris Colvin

Daniel Gebhardt

Pulsar Discovery by Global Volunteer Computing

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Einstein@Home (*1*) (E@H) is a volunteer distributed computing project (*2*). Members of the public sign up their home or office computers (hosts), which automatically download work units from the servers, carry out analyses when idle, and return results. These are automatically validated by comparison with results for the same work unit produced by a different volunteer's host. More than 250,000 individuals from 192 countries have contributed; each week about 100,000 different computers download work. The aggregate computational power (0.25 Pflop/s) is on par with the largest supercomputers. E@H's primary goal is to detect gravitational waves from rapidly spinning neutron stars in data from Laser Interferometer Gravitational-Wave Observatory (LIGO) and VIRGO (*1*).

Since 2009, about 35% of E@H compute cycles have also been used to search for pulsars in radio data from the Pulsar ALFA (PALFA) project [supporting online material (SOM)] at the 305-m Arecibo Telescope (Puerto Rico). Data disks are sent to Cornell University's Center for Advanced Computing (United States), where data are archived. For E@H, data are transferred to Liebniz Universität (Hannover, Germany), dedispersed for 628 different dispersion measures (DM $\in$ [0, 1002.4] pc cm^{-3}), and resampled at 128 µs. Hosts receive work units containing time series for four DM values for one beam. Each is 2 MB in size, covering 268.435456 s. A host demodulates each time series (in the time domain) for 6661 different circular orbital templates with periods greater than 11 min (our Galaxy has even shorter period binaries). The grid of templates is spaced so that, for pulsar spin frequencies below 400 Hz, less than 20% of signal-to-noise ratio is lost. Fourier algorithms sum up to 16 harmonics. A total of 1.85% of the power spectrum is removed to eliminate well-known sources of radio frequency interference. A significance ($S = -\log_{10} p$, with p the false-alarm probability in Gaussian noise) is calculated at each grid point. After ~2 central processing unit hours, the host uploads the 100 most significant candidates to the server.

When all work units for a given beam are complete, the results are postprocessed on servers at Hannover. Candidates with $S > 15$ are identified by eye, then optimized with PRESTO (www.cv.nrao.edu/~sransom/presto/) (SOM). To date E@H has searched 27,000 of 68,000 observed beams. It has redetected 120 pulsars, most in the past 4 months, because code and algorithm optimizations sped up the search by a factor of ~7.

On 11 July, the 24-ms PSR J2007+2722 was discovered with a significance of $S = 169.7$ (Fig. 1) in survey data from February 2007. It was later re-detected in another PALFA survey observation. Follow-up observations were done by the Green Bank Telescope (GBT, United States), the Lovell Telescope at Jodrell Bank Observatory (United Kingdom), the radio telescope at Effelsberg (Germany), the Westerbork Synthesis Radio Telescope (WSRT, Netherlands), and Arecibo. The period-averaged flux density is 2.1 mJy (1 Jy = 10^{-26} W m^{-2} Hz^{-1}) at 1.5 GHz. Gridding observations using Arecibo and WSRT unambiguously associate the pulsar with a source in an archival Very Large Array (VLA) C-array observation, having 1.2 mJy flux density at 4.86 GHz, at right ascension (RA) $20^h07^m15^s.77$ and declination (Dec) 27°22′47″.7 (J2000) with uncertainty $\lesssim 1''$. The pulsar is not in a supernova remnant or globular cluster and has no counterpart in x-ray or gamma-ray point-source catalogs. The DM of 127 pc cm^{-3} implies a distance of 5.3 kpc (*3*). The full pulse width between the outer half-maxima is $W \approx 224°$. The wide pulse and initial polarization observations indicate that the pulsar likely has nearly aligned magnetic and spin axes.

The pulsar's barycentric spin frequency (*4*) is 40.820677620(6) Hz at MJD 55399.0. With the VLA position, the 2010 data give limits $|\dot{f}| < 3 \times 10^{-14}$ s^{-2}, magnetic field $B < 2.1 \times 10^{10}$ G, and spin-down age $> 21 \times 10^6$ years. These limits and lack of a companion mean that J2007+2722 is likely the fastest-spinning disrupted recycled pulsar yet found (*5*). However we cannot rule out it having been born with low B (*6*). Either way, PSR J2007+2722 is a rare, isolated low-B pulsar, which contributes to our understanding of pulsar evolution.

This result demonstrates the capability of "consumer" computational power for realizing discoveries in astronomy and other data-driven science.

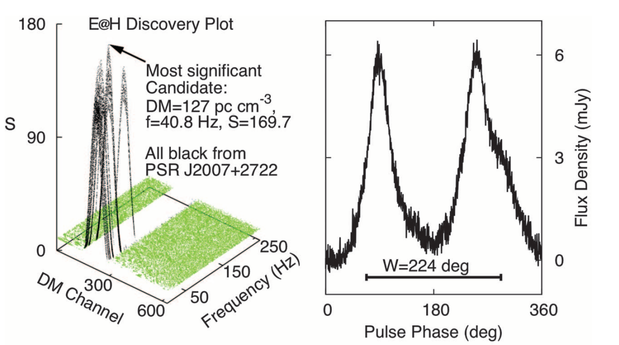

Fig. 1. (**Left**) Significance S as a function of DM and spin frequency (all E@H results for the discovery beam). (**Right**) The pulse profile at 1.5 GHz (GBT). The bar illustrates the extent of the pulse.

References and Notes

1. B. P. Abbott *et al.*, *Phys. Rev. D* **80**, 042003 (2009).
2. D. P. Anderson *et al.*, in *Proceedings of the 2006 ACM/IEEE Conference on Supercomputing*, Tampa, FL, 11 to 17 November 2006 (Association for Computing Machinery, New York, 2006), p. 126.
3. J. M. Cordes, T. J. W. Lazio, "NE2001. I. A new model for the Galactic distribution of free electrons and its fluctuations," http://arxiv.org/abs/astro-ph/0207156v3.
4. Results were obtained by using the Tempo software package (http://tempo.sourceforge.net/) and the Jet Propulsion Laboratory DE405 ephemeris.
5. K. Belczynski *et al.*, *Mon. Not. R. Astron. Soc.*, in press; available online at http://arxiv.org/abs/0907.3486v3.
6. J. P. Halpern, E. V. Gotthelf, *Astrophys. J.* **709**, 436 (2010).
7. We thank Einstein@Home volunteers, who made this discovery possible. The computers of C. and H. Colvin (Ames, Iowa, USA) and D. Gebhardt (Universität Mainz, Musikinformatik,Germany) identified J2007+2722 with the highest significance. This work was supported by Canada Foundation for Innovation, Canadian Institute for Advanced Research, fonds québécois de la recherche sur la nature et les technologies, Max Planck Gesellschaft, National Astronomy and Ionosphere Center, National Radio Astronomy Observatory, Natural Sciences and Engineering Research Council (of Canada), NSF, and Netherlands Organization for Scientific Research, Science and Technology Facilities Council; see the SOM for details.

*Affiliations are listed in the SOM.

Supporting Online Material

www.sciencemag.org/cgi/content/full/science.1195253/DC1
Materials and Methods
SOM Text
References

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10.1126/science.1195253
Include this information when citing this paper.

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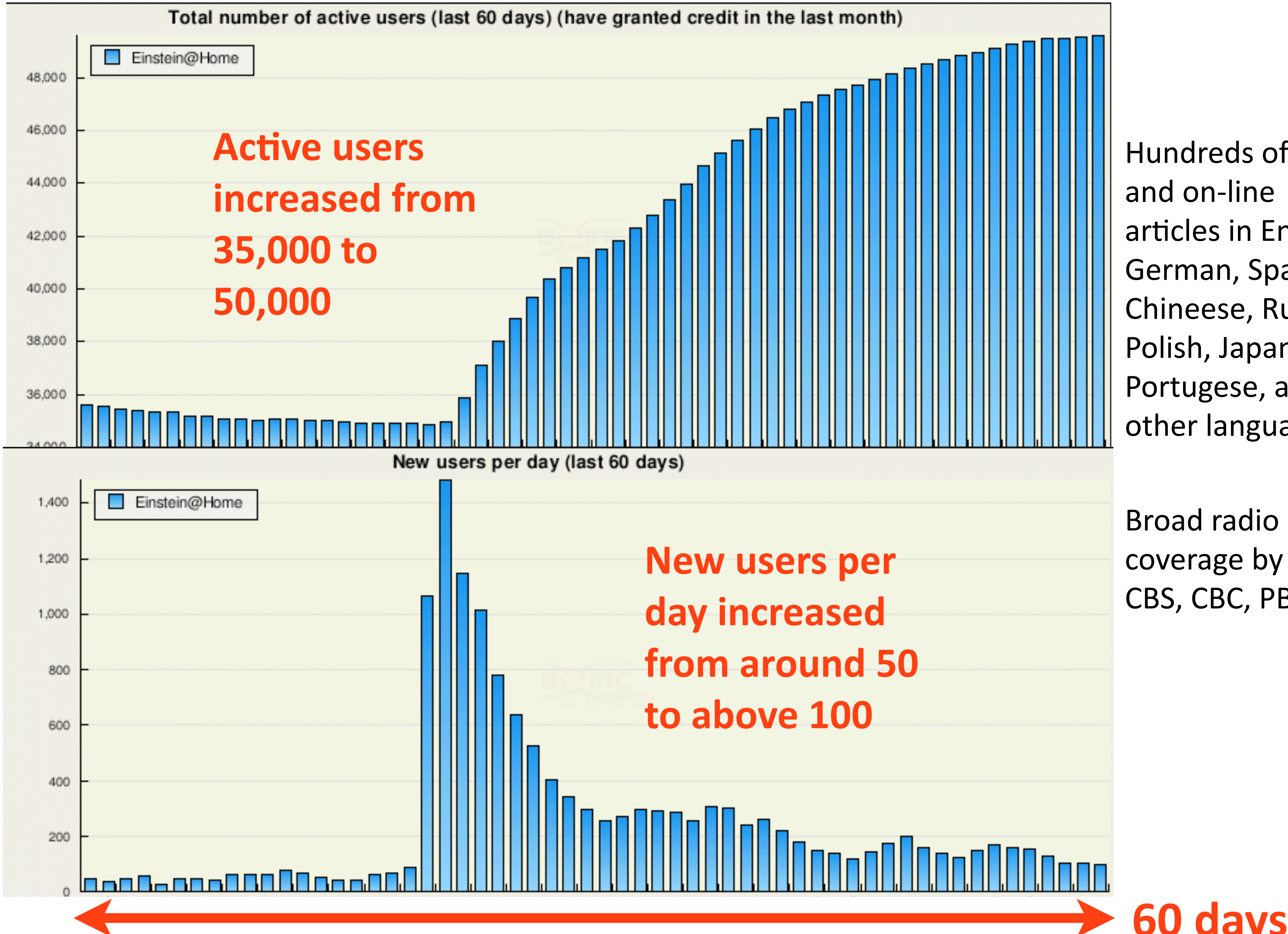
Time line
41 authors from 21 Institutions

- July 11th, Benjamin Knispel saw beamplot, emailed me and Cordes.
- **July 12/13th**, J2007+2722 reconfirmed by Green Bank Telescope observations
- July 12-15th, reobservations by Arecibo, GBT, Jodrell Bank, Effelsberg
- July 16th, first draft submitted to Science
- July 23rd, manuscript submitted for formal refereeing
- August 3rd, referee reports received
- August 4th, revised paper submitted
- August 5th, paper formally accepted for publication
- **August 12th**, online publication of the paper

Positive Effects of Publicity



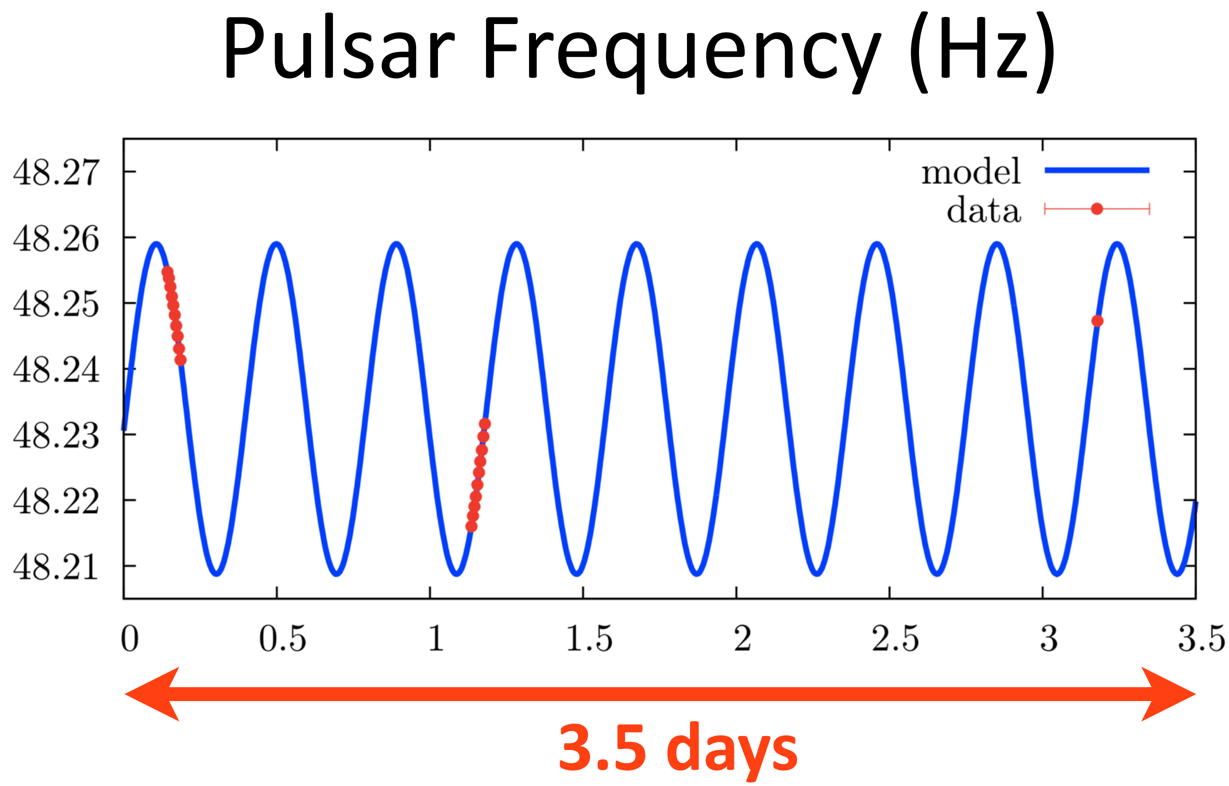
Hundreds of print and on-line articles in English, German, Spanish, Chineese, Russian, Polish, Japanese, Portugese, and other languages.

Broad radio coverage by BBC, CBS, CBC, PBS.

Second Einstein@Home Discovery

- Volunteers from UK and Russia
- PALFA data from before 2007

  Frequency: 48 Hz
  Circular orbit, 9.4 hour period
  Companion mass > 0.93 M_{solar}
  a sin(i) = 2.8 sec
- Lack of eccentricity and minimum companion mass suggests that the companion is a white dwarf. But a neutron star is not ruled out.
- System also interesting: virtually all WD/pulsar systems have masses below this one
- For now, PALFA collaboration is keeping details (sky location) and dispersion measure a secret
- Future measurements of the Shapiro delay might enable companion mass determination.



Future Prospects

- During the next months Einstein@Home will finish working through the PALFA data backlog
- Afterwards, E@H will continue search new PALFA data. The plan is to use up to 50% of compute cycles searching this and other radio data, including data from the upcoming Effelsberg survey.
- Einstein@Home should find more radio pulsars

Search progress	
Beams processed	43230
Fraction of beams completed	63.5 %
Progress rate today	243 beams/day
Percentage of data taking rate	496 %