Einstein@Home

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Abstract

Einstein@Home [1] is one of the largest public distributed computing projects in the world, harnessing the idle cycles of participants' computers by distributing the workload via the internet. E@H was developed to perform searches for continuous gravitational waves (GWs), as would be emitted from spinning neutron stars (NSs) with non-axisymmetric deformations. The sensitivity of such searches for unknown NSs is largely limited by the available computing power. With the new Hierarchical search on LIGO S5 data, E@H promises to achieve the best sensitivity for continuous GWs to date.

Gravitational waves from Spinning Neutron Stars

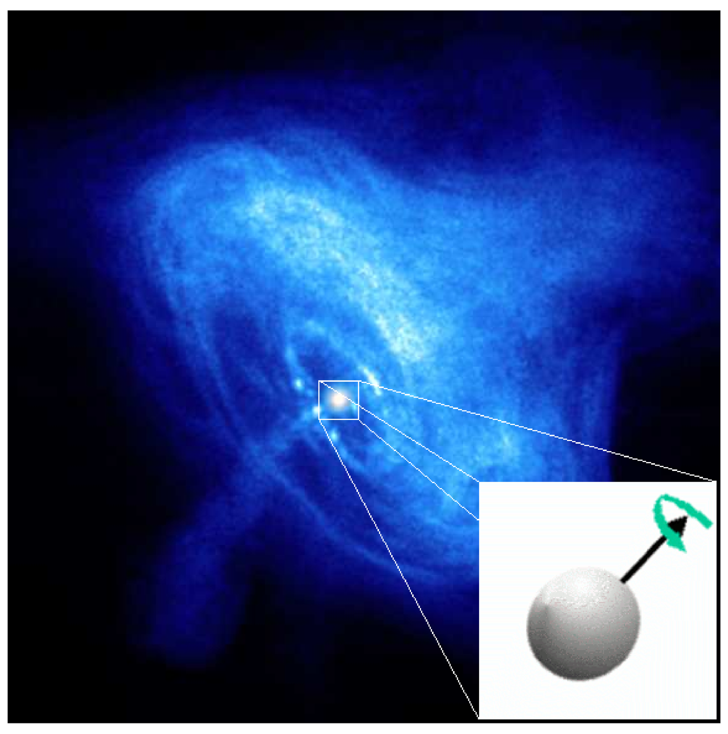

Figure 1: *Spinning non-axisymmetric NSs emit GWs of frequency $f = 2\nu$, where ν is the rotation rate of the NS.*

Spinning neutron stars with rotation rate $\nu\hat{z}$, equatorial non-axisymmetry $\epsilon = (I_{xx} - I_{yy})/I_{zz}$ (where I_{ij} are the moments of inertia), emit GWs with frequency $f = 2\nu$. The measured strain-amplitude h_0 on Earth would be:

$$h_0 = 4\times10^{-25}\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right)\left(\frac{\nu}{100\,\mathrm{Hz}}\right)^2\left(\frac{100\,\mathrm{pc}}{d}\right),$$

where d is the distance to the source.

Data-analysis challenge: These signals are extremely weak, and their waveform depends on the sky-position $\{\alpha, \delta\}$ and frequency-evolution $\{f, \dot{f}, \ldots\}$ of the source. When searching for unknown sources, we need to compute a detection statistic for a huge number N_p of waveform *templates* covering the search space. N_p grows at least as $N_p \propto T_{\mathrm{stack}}^5$ with coherent integration time T_{stack}, while the sensitivity (minimum h_0 detectable) improves only as $\sqrt{T_{\mathrm{stack}}\,N_{\mathrm{det}}}$ (where N_{det} is the number of detectors).

Hierarchical Search: One can further increase the sensitivity by incoherently combining the statistics of several coherent "stacks", at moderate additional computing cost. This hierarchical approach gains sensitivity as $N_{\mathrm{stack}}^{1/4}$, where N_{stack} is the number of stacks. An estimate of the sensitivity of such a hierarchical scheme is given by Eq. (1). This search uses the "$\mathcal{F}$-statistic" [4] for the coherent stacks, and the "Hough transform" [5] to combine the different stacks.

Interferometric GW detectors

The two most sensitive GW detectors currently operating are the LIGO detectors at Hanford (H1) and Livingston (L1), which are interferometers with 4 km arm length (Fig. 2). The Virgo detector has recently started to take science data, but has not yet reached a competitive sensitivity, which is why Einstein@Home currently analyzes data from H1 and L1.

Figure 2: *E@H uses data from the currently most sensitive GW detectors: LIGO Hanford (H1) and Livingston (L1).*

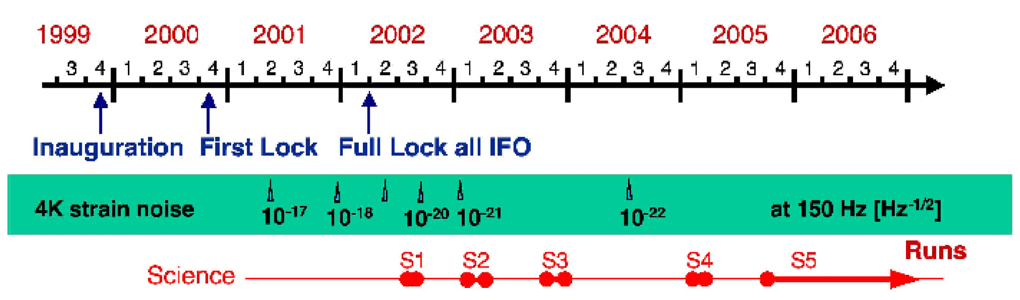

Figure 3: *LIGO time line: five science-runs (S1 - S5) have been performed so far, with improving sensitivities (Fig. 4).*

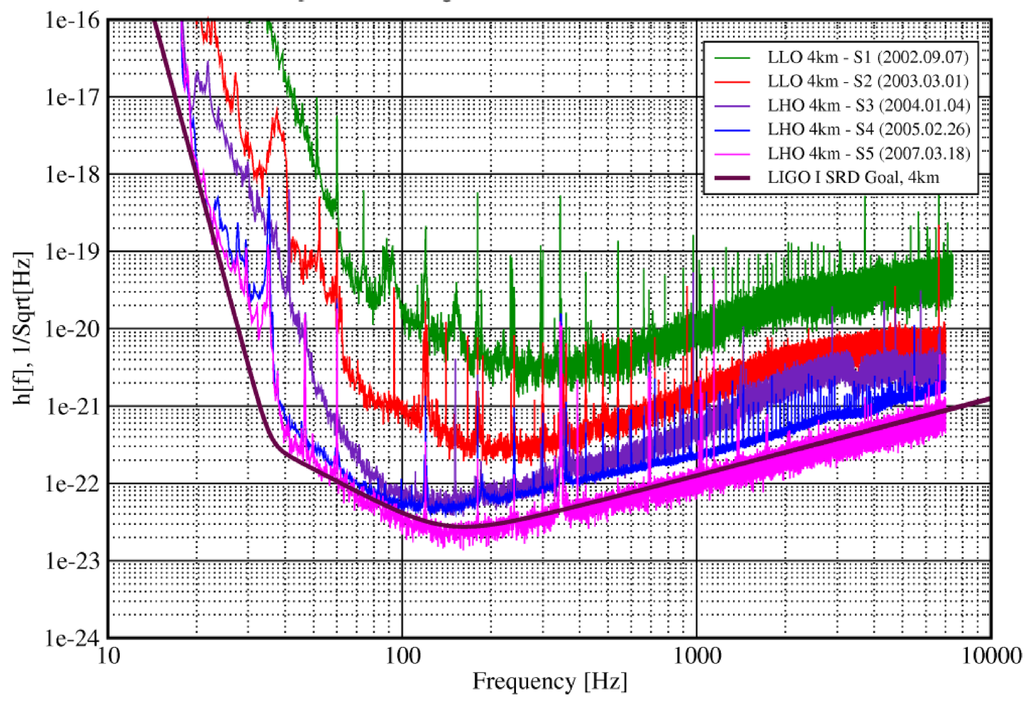

Figure 4: *Noise power spectrum $S_n^{1/2}(f)$ of the LIGO science runs S1 to S5. With the S5 run, LIGO has reached its design goal (SRD) in most of the frequency band.*

The Einstein@Home Project

Einstein@Home is built on the BOINC infrastructure [3], initially developed by SETI@home, and uses idle compute cycles of participants' computers to perform a massively distributed search for continuous GWs.

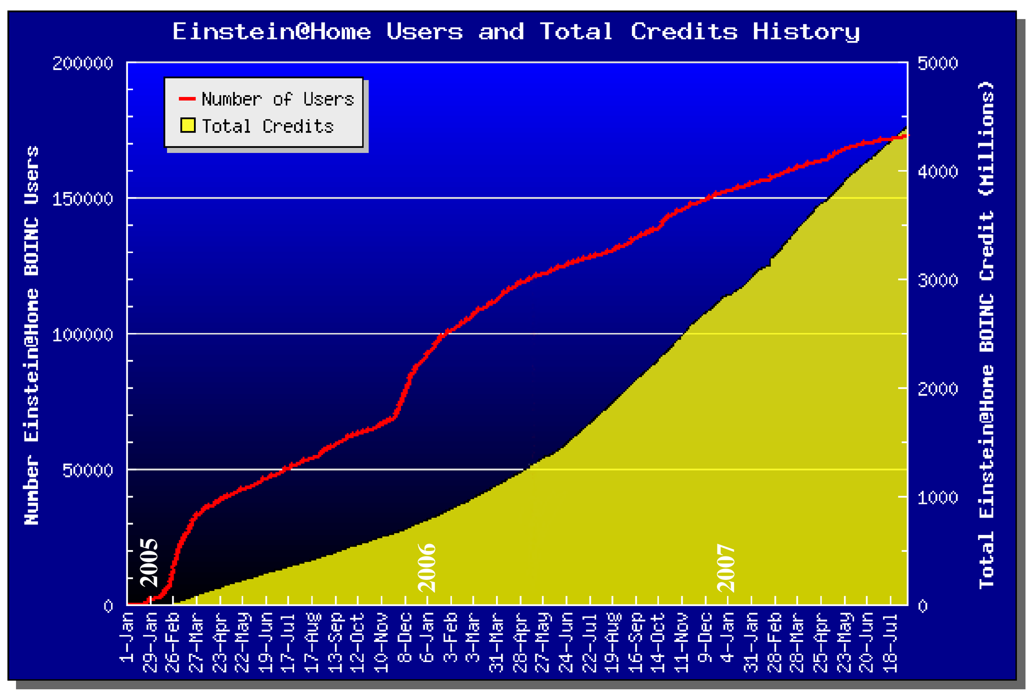

Figure 5: *Time line of Einstein@Home in terms of number of users and work completed (reflected by the total 'credit' attributed to users).*

Einstein@Home was launched in Feb 2005, as part of the APS "World Year of physics 2005" initiative. It has been growing steadily since its launch (Fig. 5), and currently delivers a continuous computing power of ~ 70 Tflops (Fig. 6).

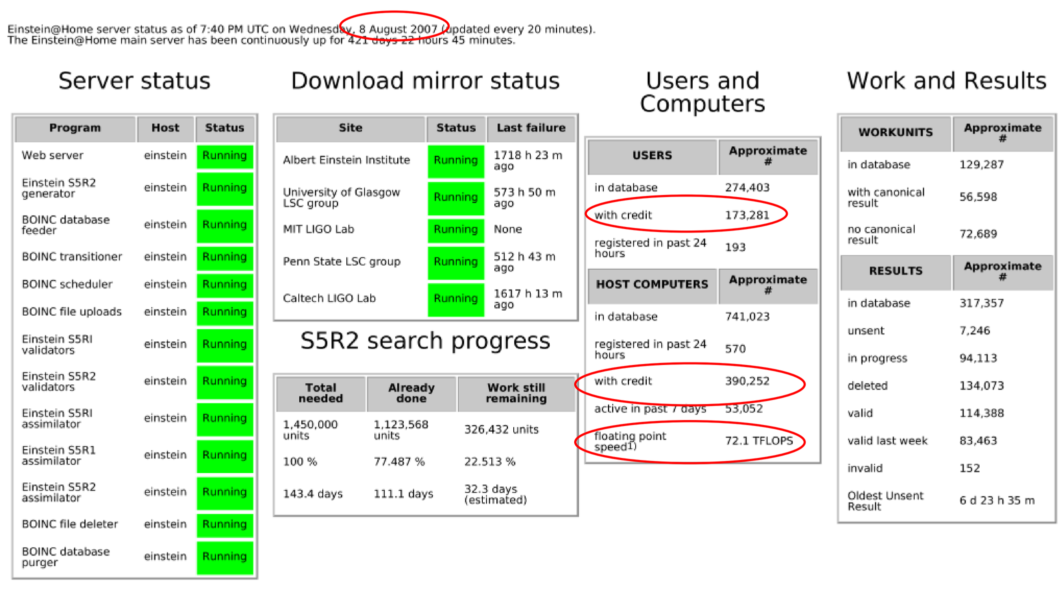

Figure 6: *Current status of the Einstein@Home project.*

Previous Searches: E@H has completed a search (S3 R2) on S3 data, and the results are published online [2]. This search consisted of $N_{\mathrm{stack}} = 60$ "stacks" of coherent integration $T_{\mathrm{stack}} = 10\,$h. The $\mathcal{F}$-statistic on stacks was returned to the server for a coincidence analysis. The result is summarized in Fig. 7, no credible GW sources were found. Similar searches have been performed on S4 and S5 data (Table 1), the results are currently under internal review.

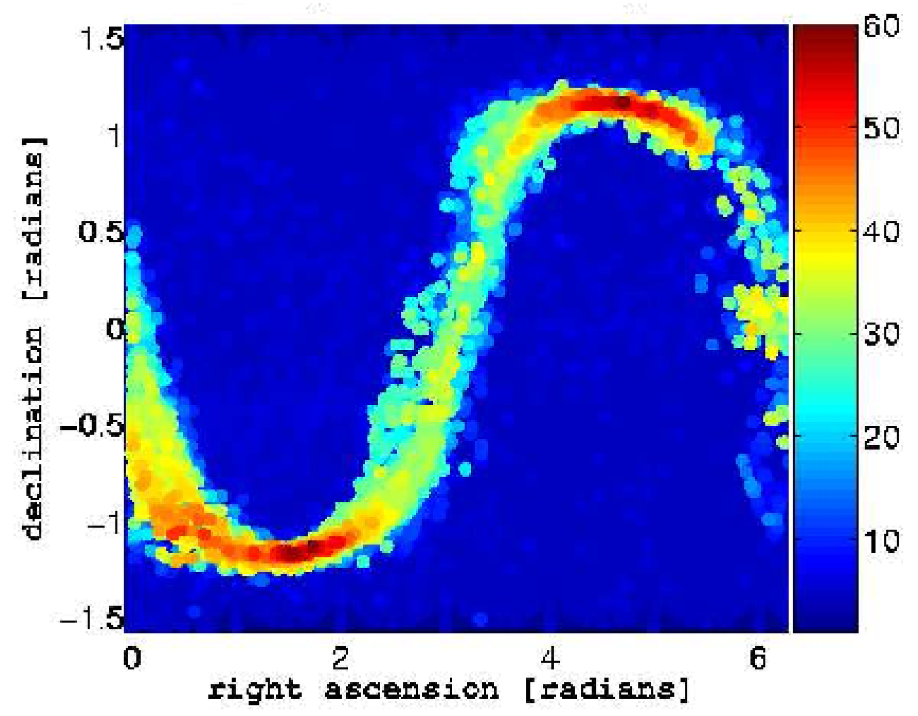

Figure 7: *Sky map of coincidence number counts over all frequencies $f \in [50, 1500]$ Hz of the S3 R2 search, after removal of injected signals. The remaining "candidates" lie on a band consistent with instrumental disturbances.*

The new Hierarchical search [S5 R3]

Einstein@Home is about to launch a new Hierarchical search on S5 data (codename S5 R3, the current test phase is labelled S5 R2). The key improvement of this search is to combine the N_{stack} coherent stacks *on the hosts* before returning the results. This allows using the optimal threshold of $2\mathcal{F}_{\mathrm{th}} = 5.2$ for the coherent stacks, which previously had to be chosen as high as $2\mathcal{F}_{\mathrm{th}} \sim 25$ in order to limit the data-volume returned to the E@H server. The lower threshold (combined with a larger amount of data) results in a substantial improvement of sensitivity, as illustrated in Table 1 and Fig. 8.

Sensitivity estimate: [5] smallest GW amplitude h_0 detectable on average with false-alarm $f_A = 3\times10^{-13}$, false-dismissal $f_D = 10\,\%$, and template mismatch $\mathrm{MM} = 0.5$:

$$\langle h_0 \rangle_{f_A}^{f_D} \sim \frac{5/2}{\sqrt{\mathrm{MM}}}\,\frac{\mathrm{SNR}_1(f_A, f_D, \mathcal{F}_{\mathrm{th}})}{N_{\mathrm{stack}}^{1/4}\,\sqrt{N_{\mathrm{det}}\,T_{\mathrm{stack}}}}\sqrt{S_n} \equiv \frac{\sqrt{S_n\cdot\mathrm{Hz}}}{\mathrm{sens}} \quad (1)$$

Table 1: *Key parameters and estimated sensitivities (1) of different E@H searches. The lower threshold $2\mathcal{F}_{\mathrm{th}}$ achieved in S5 R3 yields a large sensitivity improvement.*

RUN	N_{stack}	T_{stack}	N_{det}	$2\mathcal{F}_{\mathrm{th}}$	sens	$\langle h_0\rangle_{\mathrm{best}}$
S3 R2	60	10 h	1	25	7.3	8×10^{-24}
S4 R2	17	30 h	1	26*	8.4	6×10^{-24}
S5 R1	28	30 h	1	26*	9.6	3×10^{-24}
S5 R3	84	25 h	2	**5.2**	63	4.5×10^{-25}

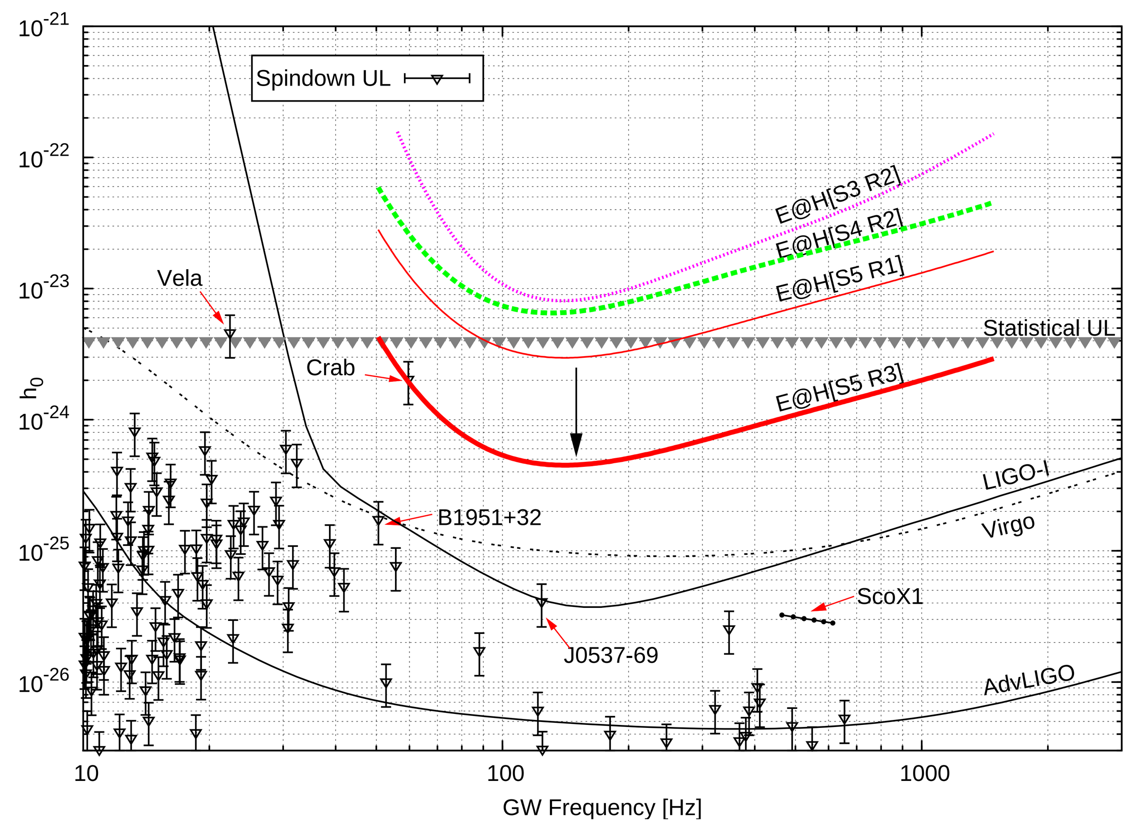

Figure 8: *Estimated sensitivities (Eq. (1), Table 1) of successive E@H runs. The curves 'LIGO-I', 'Virgo' and 'AdvLIGO' refer to a one-year targeted search for known pulsars at design sensitivity. The 'spindown UL' indicate the maximal GW amplitude from pulsars with known distance and spindown $\dot{f}$. The 'Statistical UL' is the statistically strongest expected amplitude [6] from a galactic population of unknown NSs spinning down due to GWs.*

Summary and future Plans

- The upcoming Hierarchical Search [S5 R3] promises to be the most sensitive search for GWs from spinning NSs.
- Hope to provide some of E@H's computing power to search for pulsars in radio/X-ray data. Would focus on most promising sources of GWs (i.e. large f, $\dot{f}$).

References

[1] Einstein@Home: http://einstein.phys.uwm.edu

[2] http://einstein.phys.uwm.edu/FinalS3Results

[3] BOINC: http://boinc.berkeley.edu

[4] Jaranowski, Królak, Schutz, *PRD* **58**, 063001 (1998)

[5] B. Krishnan et al., *PRD* **70**, 082001 (2004)

[6] LIGO Scientific Collaboration, 2007, gr-qc/0605028