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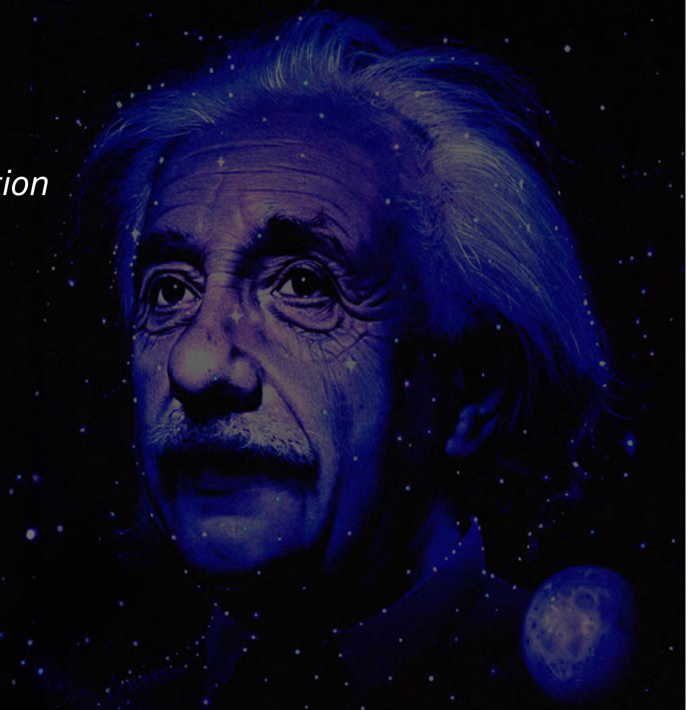
on behalf of the LIGO Scientific
Collaboration and the Virgo Collaboration



Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data

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OUTLINE

- LIGO and the search for Continuous Waves
- The coherent technique and the need of hierarchical methods
- The Hough-transform
- Einstein@Home
- The recent *Einstein@Home all-sky search* (Upcoming paper)
- **The post-processing pipeline**
- **Upper limit results**
- **Astrophysical reach of the search**
- Summary

LIGO and the search for Continuous Waves

- We focus on a recent set of searches that used data from the fifth science run (S5) of the Hanford (H1) and Livingston (L1) LIGO detectors, collected between the GPS times of 815 155 213 s (Nov. 4, 2005) and 875 145 614 s (Sept. 30, 2007) to look for continuous gravitational wave signals (CWs).

- Spinning neutron stars (NSs) with rotation rate f_r, equatorial non-axisymmetry $\varepsilon = (I_{xx}-I_{yy})/I_{zz}$ (with I_{ab} moments of inertia) are expected to emit CWs with frequency $f = 2\, f_r$.

- The measured strain amplitude h_0 on Earth is given by

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

with d distance to the source. These weak signals are received at Earth-based detectors with a Doppler modulation due to the relative motion between the source and the detector. Consequently the observed phase evolution depends on the intrinsic frequency-evolution of the source (f, $\dot{f}$,…) and sky-position (α, δ).

The coherent technique and the need of hierarchical methods

- The coherent strategy (so-called *F*-statistic) used to extract the faint CW signals from the noisy data is given by the the standard coherent matched filtering method, that is based on the *maximum-likelihood detection* (PRD 58, 063001, 1998).

- Fully coherent methods become computationally undoable when very long data stretches (~ months or years) are used and a wide fraction of the parameter space is searched over, because of the increasing number of waveform templates.

- Hence, hierarchical approaches have been proposed, such as the *Hough-transform* (PRD 70, 082001, 2004).

The Hough-transform

➢ The *Hough-transform* method has been used in the search presented here and is sketched in the following:

- The input data set is partitioned in N (=121) data segments, each spanning no more than 25 hours and with at least 40 hours of data (including data from both detectors).
- The multi-detector F-statistic ($2F$) is computed for each segment at each point of the search parameter space $\xi = (\alpha, \delta, f, \dot{f})$.
- For each point ξ a value $n_i = 1$ or 0 is assigned in the i-th segment depending on whether the corresponding $2F$ is above a certain threshold (=5.2) or not.
- The values n_i are the input to the Hough-transform.

➢ The final statistic used by the Hough search is the *Hough number count*:

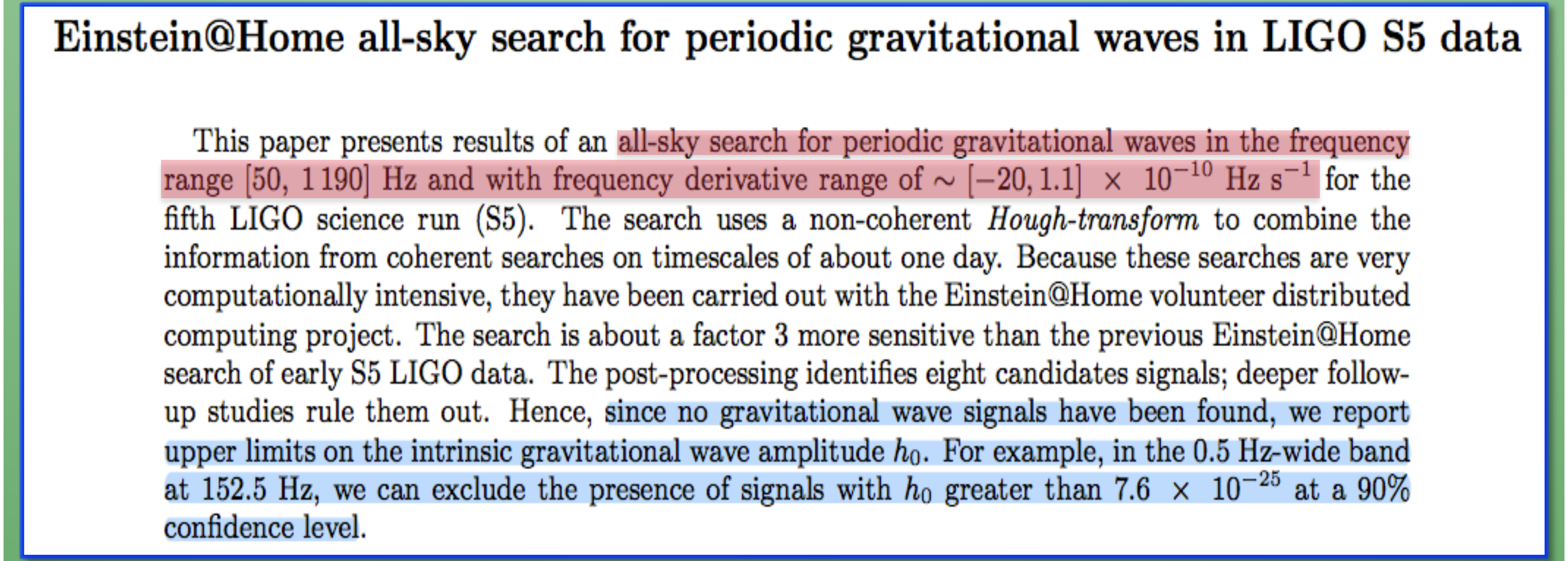
$$\boxed{n_c = \sum_{i=1}^{N} w_i \, n_i}$$

w_i -> Hough-weights, depending on the single-sided power spectral density of the detector noise and the detector antenna pattern (PRD 77, 022001, 2008).

Einstein@Home (in a nutshell)

- A powerful method that allows us to use the longest possible coherent integration time, and thus improve the search sensitivity, is represented by distributing the computation through the volunteer computing project Einstein@Home (http://einstein.phys.uwm.edu/):
  - a program that uses the idle time on volunteer computers to solve scientific problems that require large amounts of computer power, such as to process data from gravitational wave detectors, performing all-sky searches for CW signals;
  - *about 66 000 active users contribute about 450 teraFLOPS of computational power, which would rank Einstein@Home among the top 20 on the top-500 list of supercomputers.*
- The computational work of a search is partitioned in independent Work-Units (WUs), analyzed by machines owned by volunteers.
- In the all-sky search presented here ~10^7 WUs were used. Each WU analyzed :
  - a fixed frequency bandwidth of ~ 20 mHz;
  - the entire $\dot{f}$-range, i.e. ~ $[-20, 1.1] \times 10^{-10}$ Hz s^{-1};
  - a limited area of the sky (~ 10^2 sky-points).

Abstract – (preliminary results)



Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data

This paper presents results of an all-sky search for periodic gravitational waves in the frequency range [50, 1 190] Hz and with frequency derivative range of $\sim [-20, 1.1] \times 10^{-10}$ Hz s^{-1} for the fifth LIGO science run (S5). The search uses a non-coherent *Hough-transform* to combine the information from coherent searches on timescales of about one day. Because these searches are very computationally intensive, they have been carried out with the Einstein@Home volunteer distributed computing project. The search is about a factor 3 more sensitive than the previous Einstein@Home search of early S5 LIGO data. The post-processing identifies eight candidates signals; deeper follow-up studies rule them out. Hence, since no gravitational wave signals have been found, we report upper limits on the intrinsic gravitational wave amplitude h_0. For example, in the 0.5 Hz-wide band at 152.5 Hz, we can exclude the presence of signals with h_0 greater than 7.6×10^{-25} at a 90% confidence level.

The post-processing pipeline

- The total search frequency and frequency-derivative ranges investigated here are [50, 1 190] Hz and ~ [-20, 1.1] x 10^{-10} Hz s^{-1} with resolution of ~7 μHz and ~0.12 *n*Hz s^{-1}, respectively.

- All in all, of the order of 10^{11} (~2.3 TB of data) candidates were returned to the Einstein@Home server and post-processed as follows:

  - Selection of most significant 100 candidates in each 0.5 Hz band (=> 228 000 candidates).

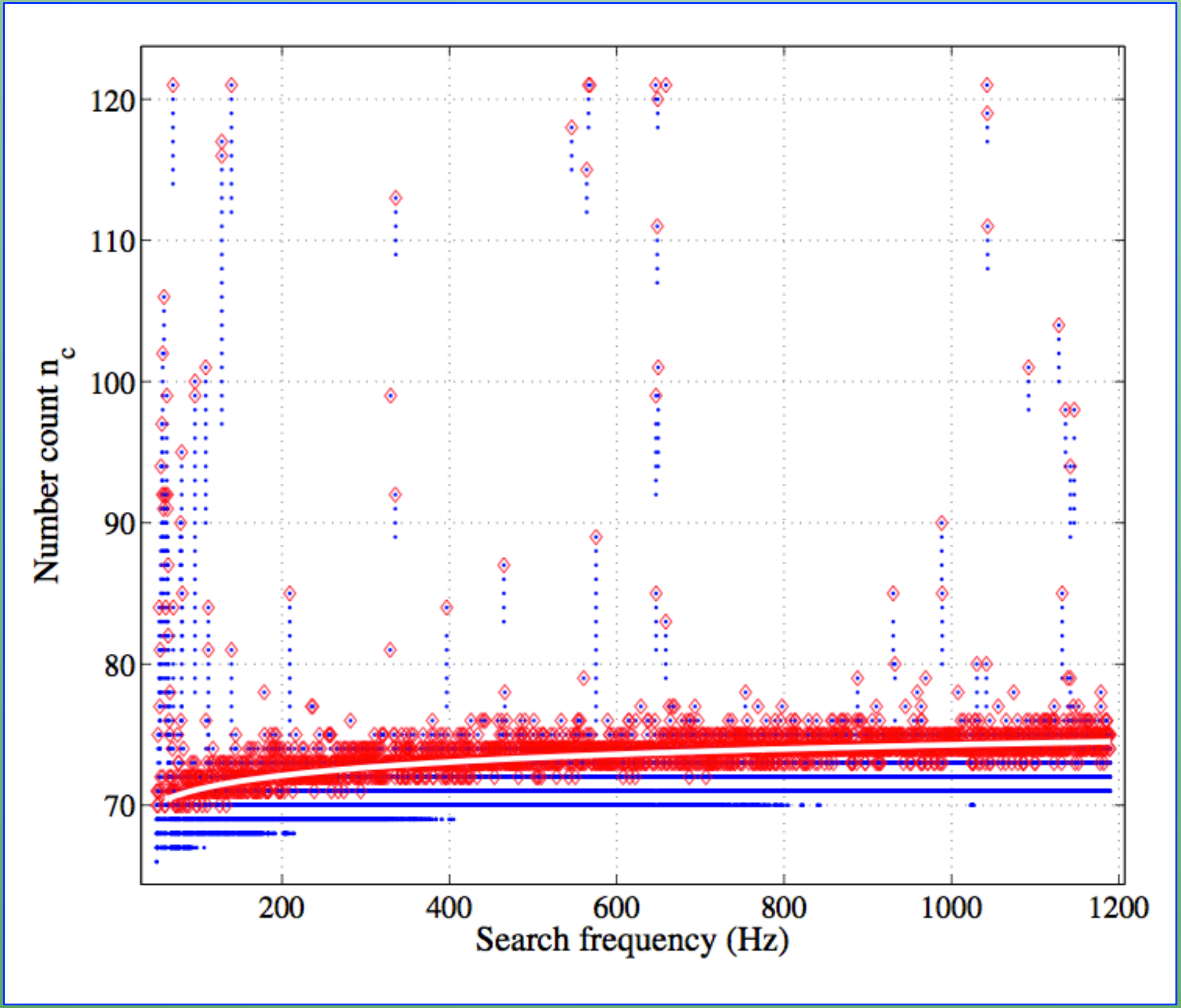
  - Discard candidates (~ 25%) that could have been affected by known spectral disturbances or by the artificial noise control-bands.

  - Multi-IFO/single-IFO average *F*-statistic consistency veto (~4% of candidates at this stage are eliminated).

  - Threshold on average multi-IFO *F*-statistic over the segments (**184 remaining candidates**).

  - Follow-up of loudest surviving candidates.

The post-processing pipeline: top 100 candidates in each 0.5 Hz band

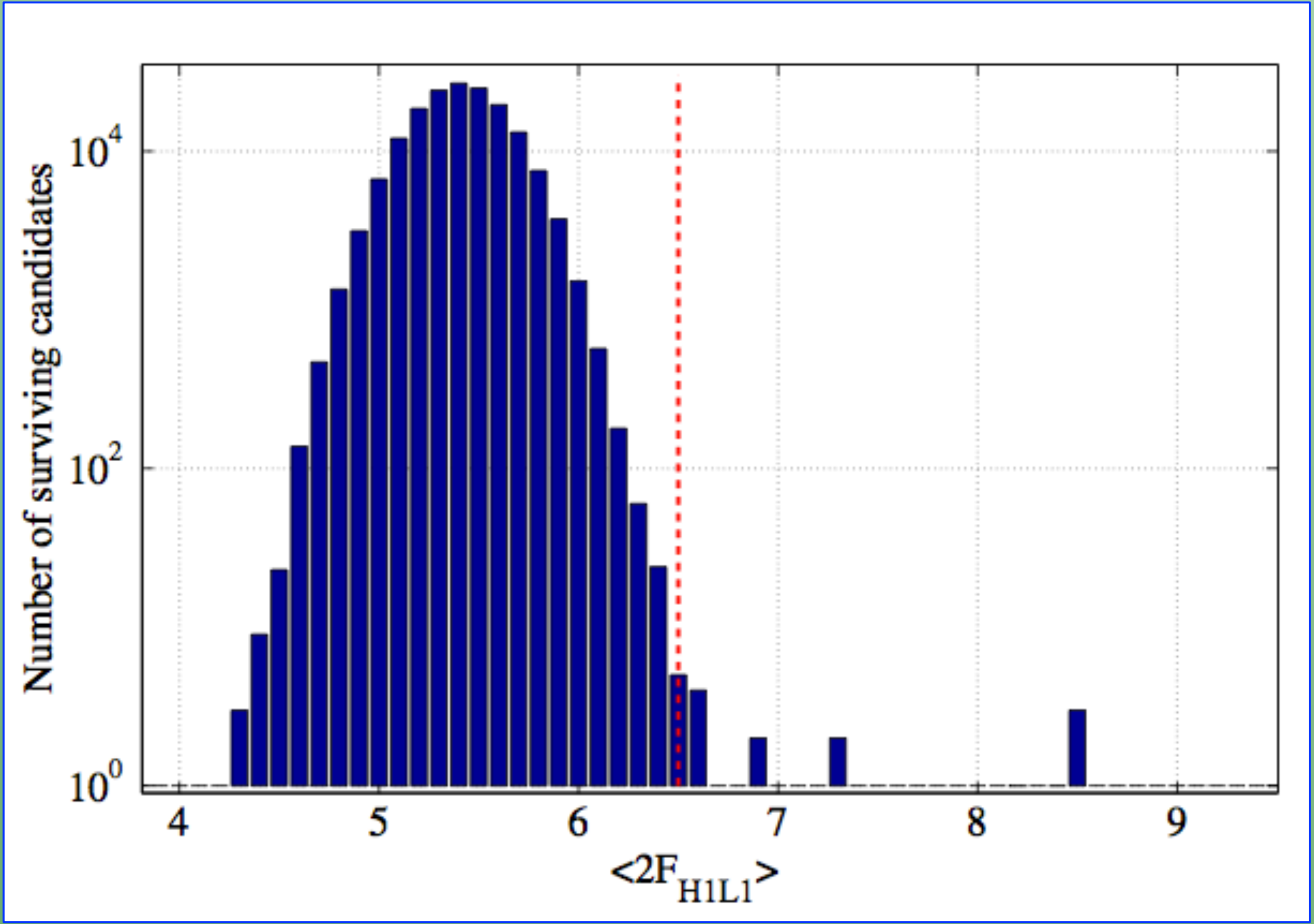


- Top 100 candidates in each 0.5 Hz

◇ Most significant candidate in every 0.5 Hz

— Expected values of the loudest candidates

The post-processing pipeline: after the multi-IFO/single-IFO average *F*-statistic consistency veto

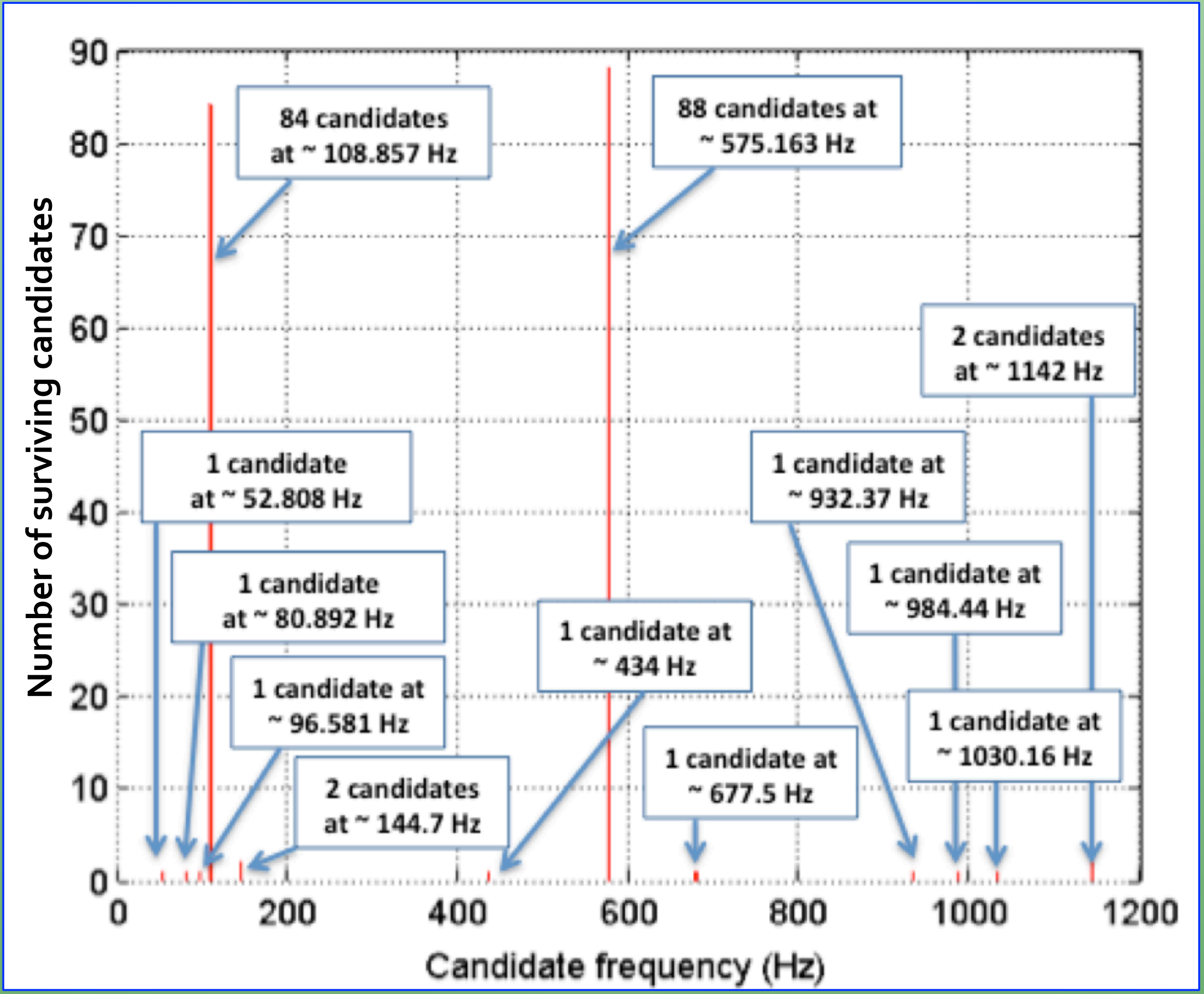


184 remaining candidates, for which $\langle 2F_{H1L1} \rangle > 6.5$ [not all shown in the adjacent plot]

Histogram of average multi-detector 2F-values for 164 971 surviving candidates.

The red dotted line draws the boundaries of the bulk of candidates, and corresponds to the threshold $\langle 2F_{H1L1} \rangle = 6.5$.

The post-processing pipeline: 184 remaining candidates after the cut at <$2F_{H1L1}$> =6.5; they are clustered at 12 frequencies



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The post-processing pipeline: follow-up with “1st year of S5” data; only the candidate at ~ 80.9 Hz was discarded!

	f (Hz)	n_c^B	$E[n_c^A]$	n_c^A
1.	52.808297682	70	49	37
2.	80.891816186	82	57	34
3.	96.581099597	72	50	37
4.	108.85716501	101	70	55
5.	144.74321811	71	49	42
6.	434.09886421	70	49	46
7.	575.16357663	89	62	53
8.	677.47882796	71	50	46
9.	932.36948703	74	51	46
10.	984.44286823	73	50	47
11.	1030.1650892	77	55	53
12.	1141.9926498	78	54	48

Candidates for which the measured value n_c^A was more than 3 σ less significant than the expected $E[n_c^A]$ were discarded as not being consistent with a CW signal; $\sigma \sim 4.8$

n_c^B -> number count before the follow-up;

n_c^A -> number count after the follow-up with the 1st year of S5 data (collected between Dec. 2005 and Jan. 2007) set;

$E[n_c^A]$ *-> expected number count from the follow-up with the 1st year of S5 data, having assumed that n_c^B is the expected number count due to a signal.*

The post-processing pipeline: 11 “surviving” candidates, none of which constitutes a defensible CW candidate

PRELIMINARY

- ~ 52.8 Hz
- ~ 108.9 Hz
- ~ 575.2 Hz

They correspond to 3 simulated signals injected in the data stream!

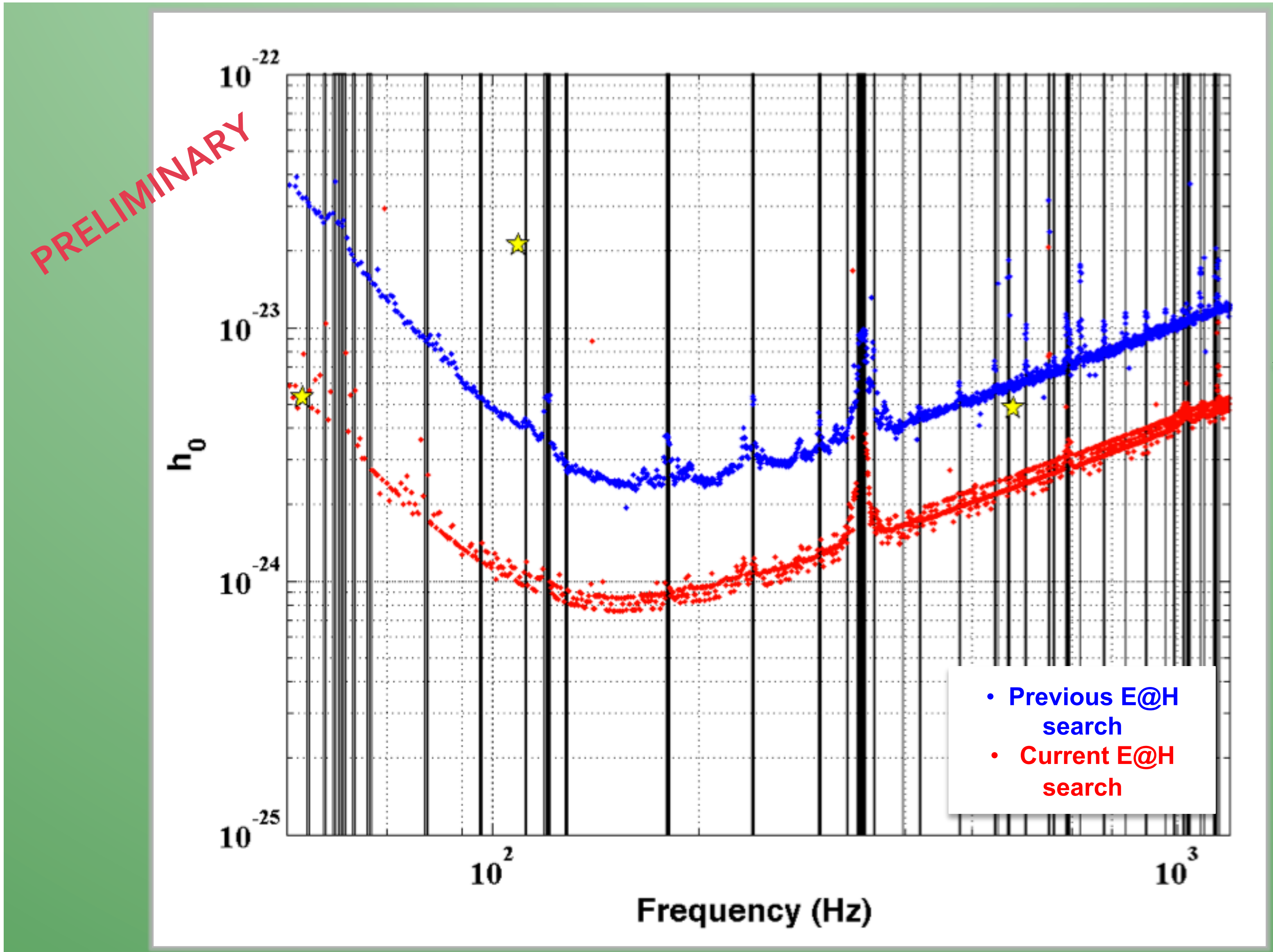
- ~ 96.6 Hz
- ~ 144.7 Hz
- ~ 932.4 Hz
- ~ 1030.2 Hz
- ~ 1142 Hz

- They fail the *F*-statistic consistency veto after a search utilizing the same data set as our “2nd year of S5” search but a finer grid in parameter space!
- Line artifacts appear in S5 H1 data at ~ 932.4 Hz, ~ 1030.2 Hz and at ~ 1142 Hz.

- ~ 434.1 Hz
- ~ 677.5 Hz
- ~ 984.4Hz

- They survive the F-statistic consistency veto on the finer grid and are followed-up with a coherent search that spans the entire duration of the “2nd year of S5” data set. The search is performed in a large enough parameter space box around the estimated putative signal values to include the actual signal parameters.
- **The measured values of the maximum of the detection statistic** over the parameter space searched **for each of the candidates are consistent with** the expectations even in **Gaussian noise!** **[See M. Shaltev’s talk]**

Upper limits: loudest event 90% confidence upper limits on h_0 in 0.5 Hz bands

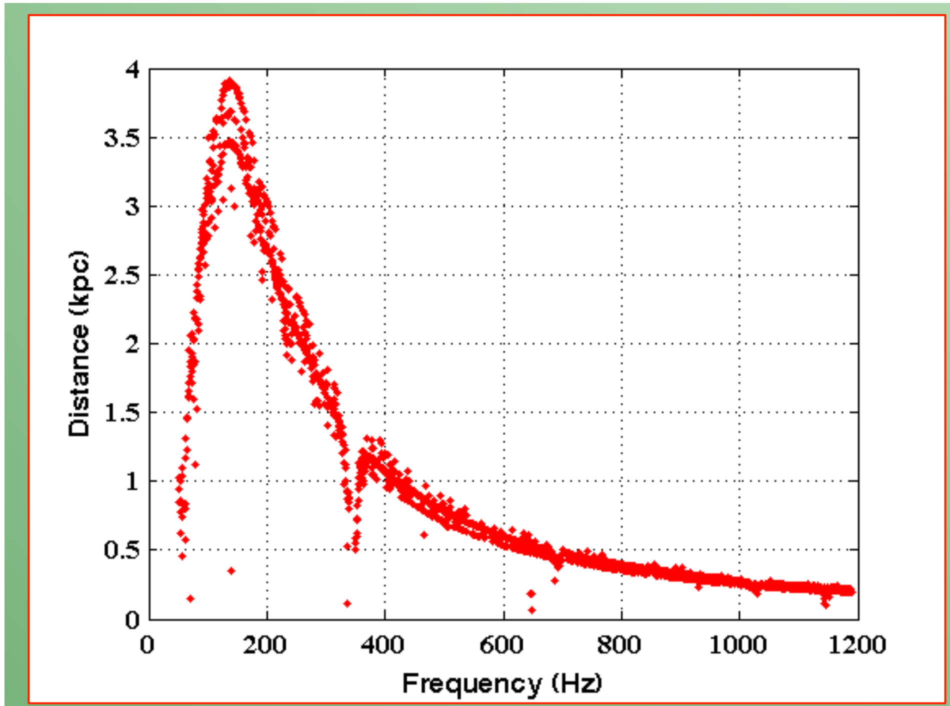


☆ ➡ Simulated signals injected in the data stream.

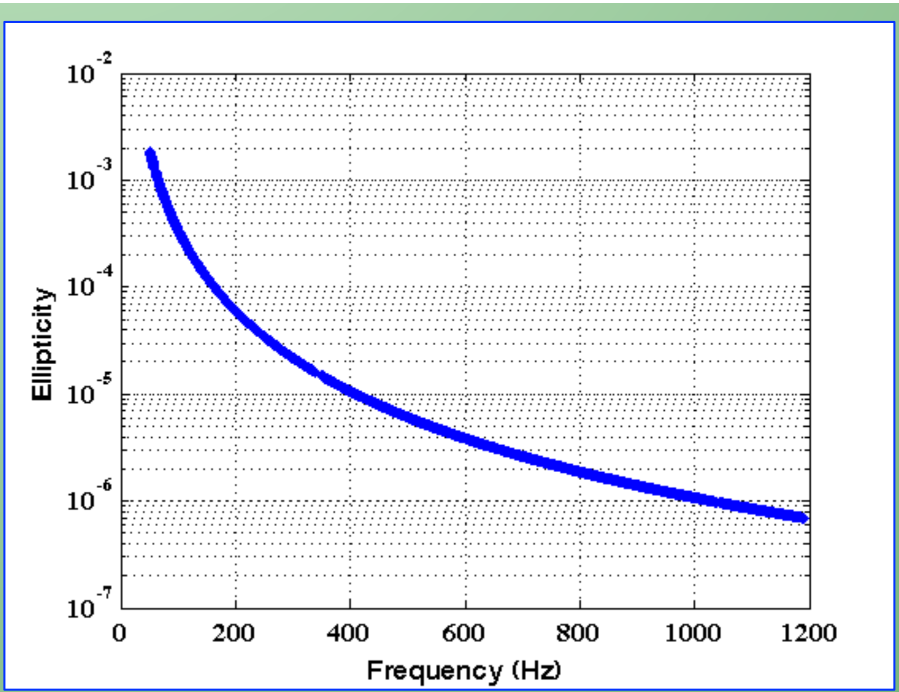
Source strain amplitude h_0 at which 90% of simulated signals would have been confidently detected.

The vertical stripes represent 156 half-Hz frequency bands contaminated by instrumental disturbances or simulated noise and for which no upper limits are provided.

Astrophysical reach of the search – PRELIMINARY



The maximum distance of a source emitting a CW signal with a strain that we could have detected. The source is assumed to be spinning down at the maximum spindown rate of the search (~ 2 x 10⁻⁹ Hz/s), and emitting all the lost angular energy in gravitational waves.



Plot that shows what ellipticity values, as a function of the frequency, the sources of the adjacent plot would need in order to emit in gravitational waves all the energy lost while spinning down at a rate of ~ - 2 x 10⁻⁹ Hz/s.

- At ~ **152.5 Hz**, the frequency of highest sensitivity, we are sensitive to objects as far as **3.8 kpc** and with an ellipticity $\varepsilon \sim 10^{-4}$.
- More plausible values of $\varepsilon \sim 3.5 \times 10^{-6}$ could be detectable by a search like this if the object were emitting at **625 Hz**, corresponding to distances no further than **500 pc**.

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Summary & Future Plans

- **The results presented here are about a factor of 3 more sensitive than the previous Einstein@Home search in early S5 data *(PRD 80, 042003, 2009)*.**

- **This is the most sensitive wide-frequency-range, all-sky search for CW signals performed to date. The upper limit values are comparable to those obtained recently using the *PowerFlux* method *(PRD 85, 022001, 2012)* on the entire S5 data set.**

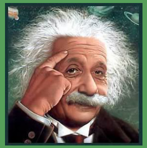
- **In** an Einstein@Home processing run, that began in March 2012, some of the post-processing techniques developed for this analysis have been "moved upstream" to the hosts. Moreover, a simpler optimal semi-coherent method, based on a detailed analysis of correlations in parameter space, which allows us to use longer coherent time baselines, is also employed *(PRD 78, 102005,2008; PRL 103, 181102, 2009)*.

- **LIGO and Virgo detectors are now being upgraded for their Advanced stage, expected by 2015.**

- **We are looking forward to the advanced detector era! STAY TUNED!**

THANKS for listening!

If you are interested to join



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please visit

http://einstein.phys.uwm.edu/