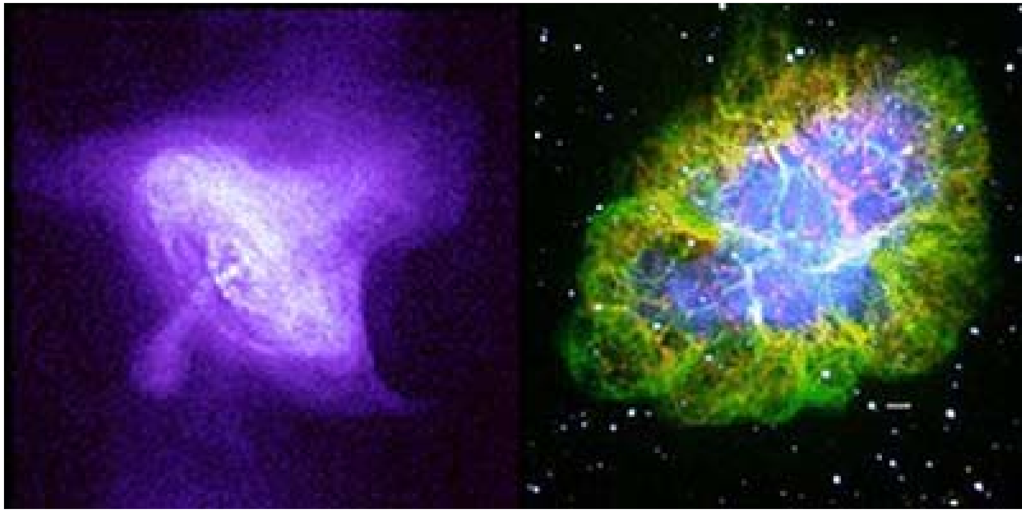
Current searches for continuous gravitational waves

Alicia M. Sintes
Universitat de les Illes Balears
Paris,17 November 2006



LIGO-G060682-00-Z

Content

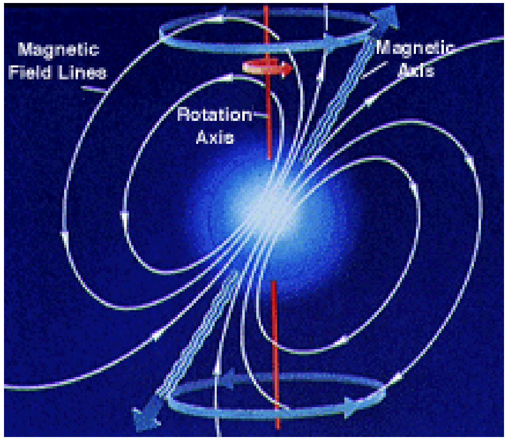
- Basics about CW searches from the GW data-analysis point of view.
  - Emission mechanisms
  - Signal model
- Brief overview of our searches including recent (released) results:
  - Directed pulsar search
  - All Sky search
    - Coherent methods
    - Einstein@Home
    - Hierarchical strategies
    - Semi-coherent methods
- Summary of results and perspectives

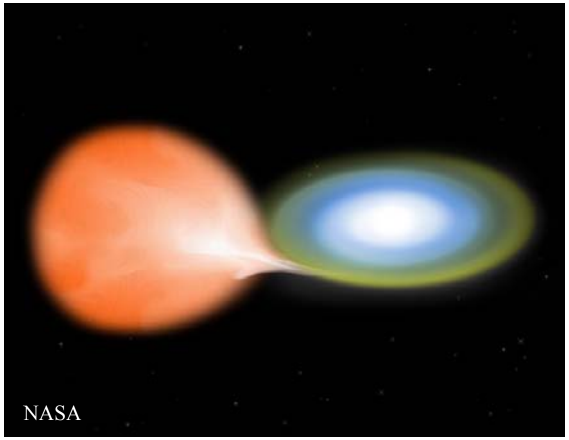
Rotating neutron stars

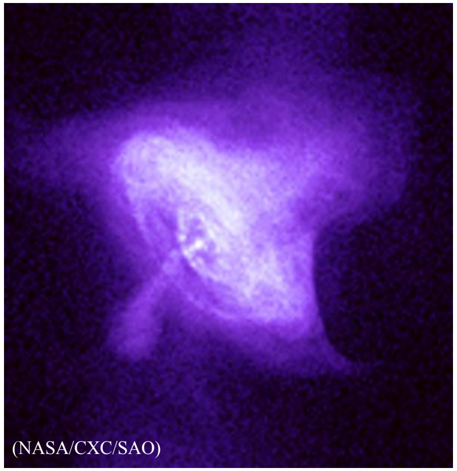
- Neutron stars can form from the remnant of stellar collapse
- Typical size of 10km, and are about 1.4 solar masses
- Some of these stars are observed as pulsars
- Gravitational waves from neutron stars could tell us about the equation of state of dense nuclear matter

Pulsars in our galaxy: *“periodic”*

- Our galaxy might contain ~10^9 NS, of which ~10^3 have been identified
    - search for observed neutron stars
    - all sky search (computing challenge)



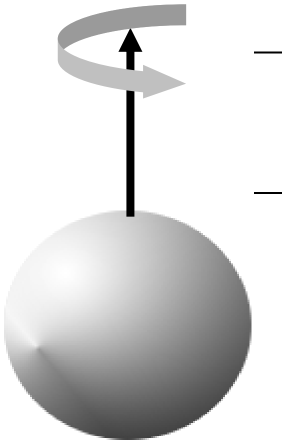

NASA


(NASA/CXC/SAO)

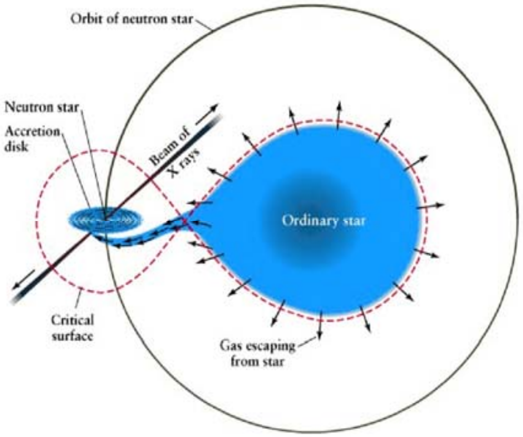
Gravitational waves from pulsars:

brief overview of emission circumstances

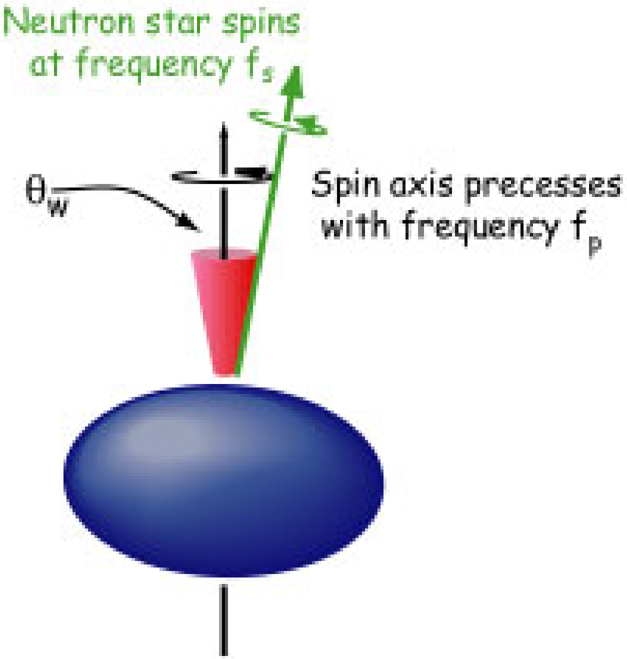
- Pulsars (spinning neutron stars) are known to exist!
- Emit gravitational waves if they are non-axisymmetric:



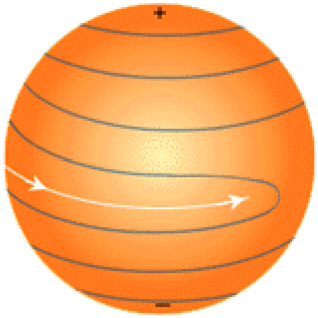
Bumpy Neutron Star



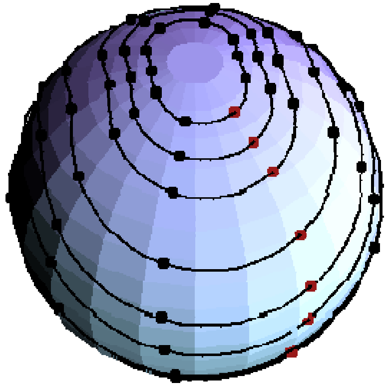
Low Mass X-Ray Binaries



Wobbling Neutron Star



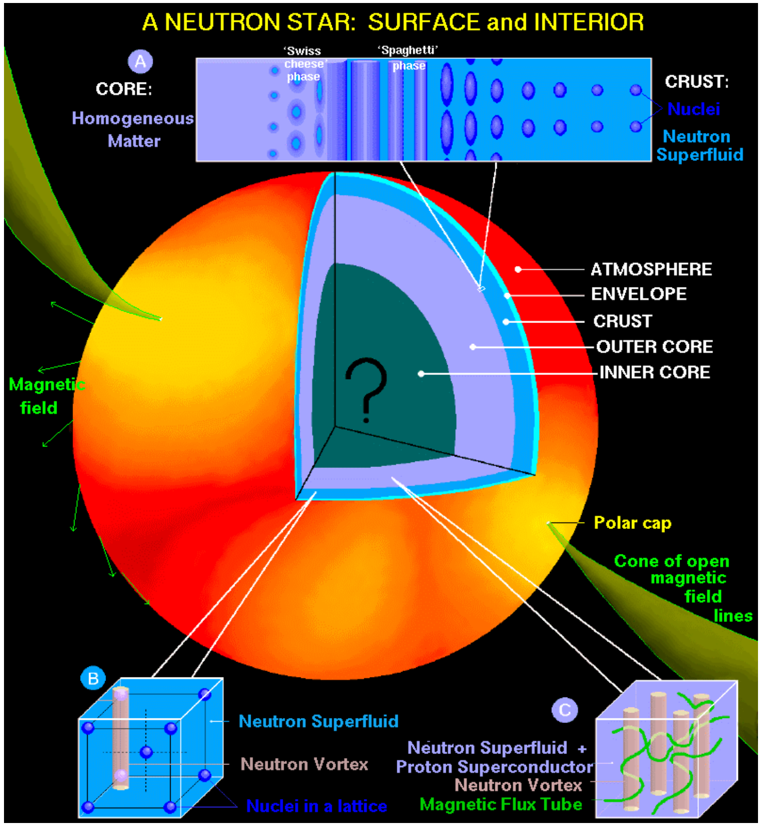
Magnetic mountains



R-modes in accreting stars

Neutron Stars Sources

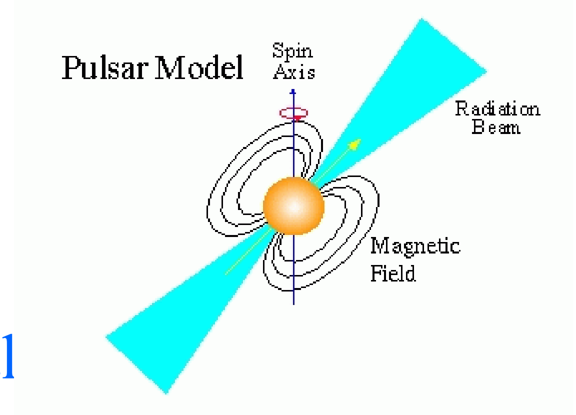
- Great interest in detecting radiation: physics of such stars is poorly understood.
  - After 40 years we still don’t know what makes pulsars pulse.
  - Interior properties not understood: equation of state, superfluidity, superconductivity, solid core, source of magnetic field.
  - May not even be neutron stars: could be made of strange matter!



The signal from a NS

- The GW signal from a neutron star:

$$h(t) = h_0\, A(t) e^{\Phi(t)}$$



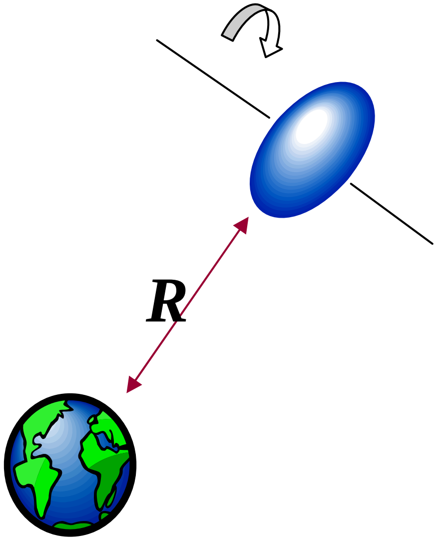
- Nearly-monochromatic continuous signal
  - spin precession at $\sim f_{rot}$
  - excited oscillatory modes such as the r-mode at $4/3^* f_{rot}$
  - non-axisymmetric distortion of crystalline structure, at $2f_{rot}$

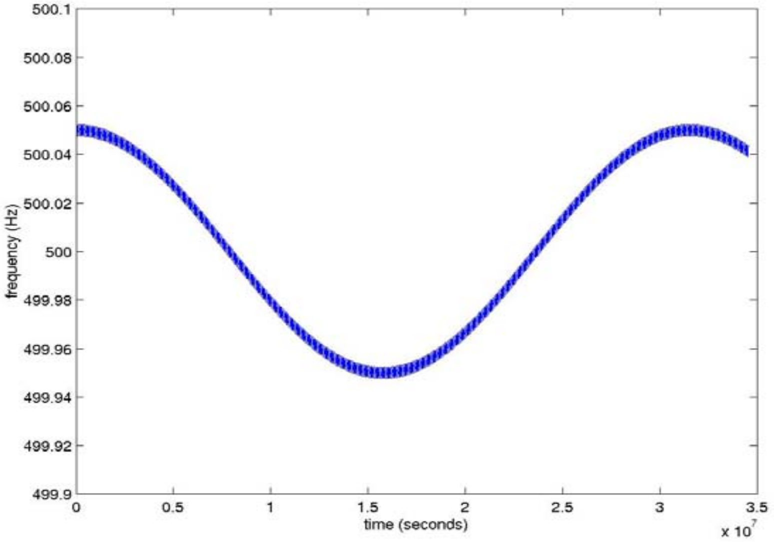
- (Signal-to-noise)^2 ~ $\displaystyle\int_0^T \frac{h^2(t)}{S_h(f_{gw})} dt$

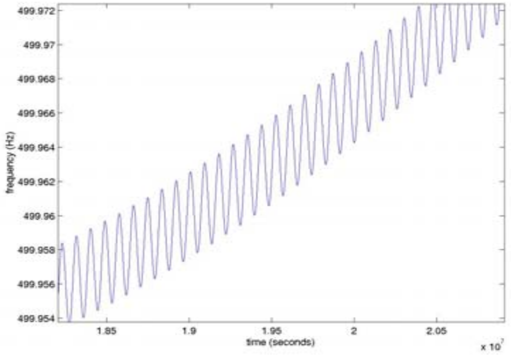
The expected signal at the detector

A gravitational wave signal we detect from a NS will be:

- Frequency modulated by relative motion of detector and source
- Amplitude modulated by the motion of the non-uniform antenna sensitivity pattern of the detector







Signal received from *an isolated* NS

$$\boxed{h(t) = F_+(t;\psi)\,h_+(t) + F_\times(t;\psi)\,h_\times(t)}$$

$$\boxed{\begin{aligned} h_+ &= A_+\cos\Phi(t) \\ h_\times &= A_\times \sin\Phi(t) \end{aligned}}$$

$$\left.\begin{matrix} F_+(t,\psi) \\ F_\times(t,\psi) \end{matrix}\right\}$$

strain antenna patterns. They depend on the orientation of the detector and source and on the polarization of the waves.

$$\boxed{\Phi(t)=\phi_0+2\pi\sum_{n=0}^{\infty}\frac{f_{(n)}}{(n+1)!}(T(t)-T(t_0))^{n+1}}$$

the phase of the received signal depends on the initial phase, the frequency evolution of the signal and on the instantaneous relative velocity between source and detector. *T(t)* is the time of arrival of a signal at the solar system barycenter, *t* the time at the detector.

In the case of an isolated tri-axial neutron star emitting at twice its rotational frequency

$$\boxed{\begin{aligned} A_+ &= \frac{1}{2}h_0(1+\cos^2\iota) \\ A_\times &= h_0\cos\iota \\ h_0 &= \frac{4\pi^2 G}{c^4}\frac{I_{zz}\varepsilon f_{gw}^{\;2}}{d} \end{aligned}}$$

h_0 - amplitude of the gravitational wave signal

ι - angle between the pulsar spin axis and line of sight

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$ - equatorial ellipticity

The searches

- Signal parameters: position (may be known), inclination angle, [orbital parameters in case of a NS in a binary system], polarization, amplitude, frequency (may be known), frequency derivative(s) (may be known), initial phase.

- Most sensitive method: coherently correlate the data with the expected signal (template) and inverse weights with the noise. If the signal were monochromatic this would be equivalent to a FT.
  - Templates: we assume various sets of unknown parameters and correlate the data against these different wave-forms.
  - Good news: we do not have to search explicitly over polarization, inclination, initial phase and amplitude.
- Because of the antenna pattern, we are sensitive to all the sky. Our data stream has signals from all over the sky all at once. However: low signal-to-noise is expected. Hence confusion from many sources overlapping on each other is not a concern.

- Input data to our analyses:
  - A calibrated data stream which with a better than 10% accuracy, is a measure of the GW excitation of the detector. Sampling rate 16kHz, but since the high sensitivity range is 40-1500 Hz we can downsample at3 kHz.

Four neutron star populations and searches

- Known pulsars
    - Position & frequency evolution known (including derivatives, timing noise, glitches, orbit)
- Unknown neutron stars
    - Nothing known, search over position, frequency & its derivatives
- Accreting neutron stars in low-mass x-ray binaries
    - Position known, sometimes orbit & frequency
- Known, isolated, non-pulsing neutron stars
    - Position known, search over frequency & derivatives

- What searches?
    - Targeted searches for signals from known pulsars
    - Blind searches of previously unknown objects

    - Coherent methods (require accurate prediction of the phase evolution of the signal)
    - Semi-coherent methods (require prediction of the frequency evolution of the signal)

What drives the choice? The computational expense of the search

Coherent detection methods

There are essentially two types of coherent searches that are performed

Frequency domain

Conceived as a module in a hierarchical search

- **Matched filtering techniques. Aimed at computing a detection statistic.**
  These methods have been implemented in the frequency domain (although this is not necessary) and are very computationally efficient.
- **Best suited for large parameter space searches**
  (when signal characteristics are uncertain)
- **Frequentist approach** used to cast upper limits.

Time domain

process signal to remove frequency variations due to Earth's motion around Sun and spindown

- **Standard Bayesian analysis,** as fast numerically but provides natural parameter estimation
- **Best suited to target known objects, even if phase evolution is complicated**
- Efficiently handless missing data
- Upper limits interpretation: **Bayesian approach**

Calibrated output: LIGO noise history

Integration times

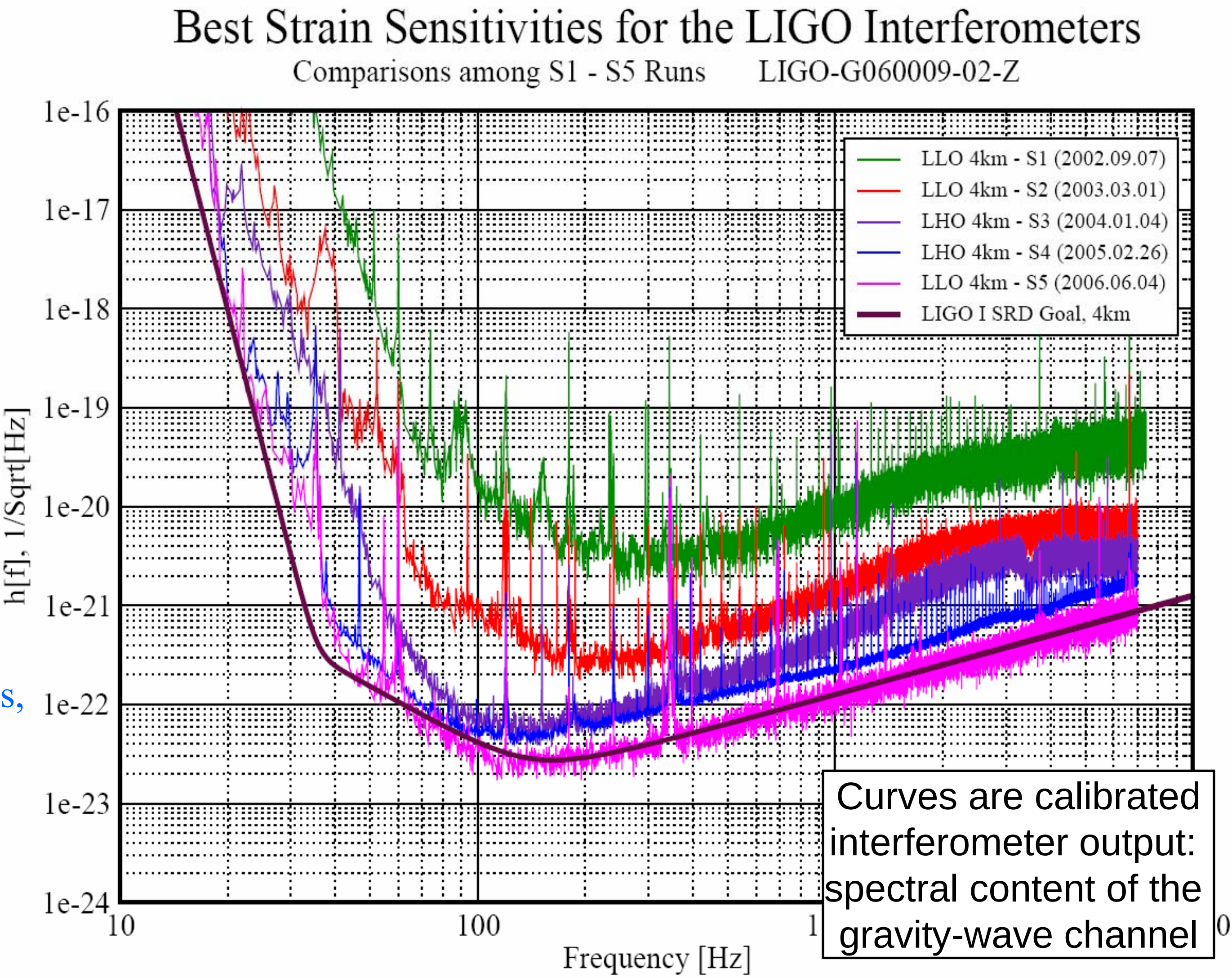
S1 - L1 5.7 days, H1 8.7 days, H2 8.9 days

S2 - L1 14.3 days, H1 37.9 days, H2 28.8 days

S3 - L1 13.4 days, H1 45.5 days, H2 42.1 days

S4 - L1 17.1 days, H1 19.4 days, H2 22.5 days

S5 (so far...) - L1 180.6 days, H1 223.5 days, H2 255.8 days



Curves are calibrated interferometer output: spectral content of the gravity-wave channel

Calibrated output: GEO noise history

Summary of directed pulsar searches

- S1 (LIGO and GEO: separate analyses)
  - Upper limit set for GWs from J1939+2134 ($h_0 < 1.4 \times 10^{-22}$)
  - Phys. Rev. D **69**, 082004 (2004)

- S2 science run (LIGO: 3 interferometers coherently, TDS)
  - End-to-end validation with 2 hardware injections
  - Upper limits set for GWs from 28 known isolated pulsars
  - Phys. Rev. Lett. **94**, 181103 (2005)

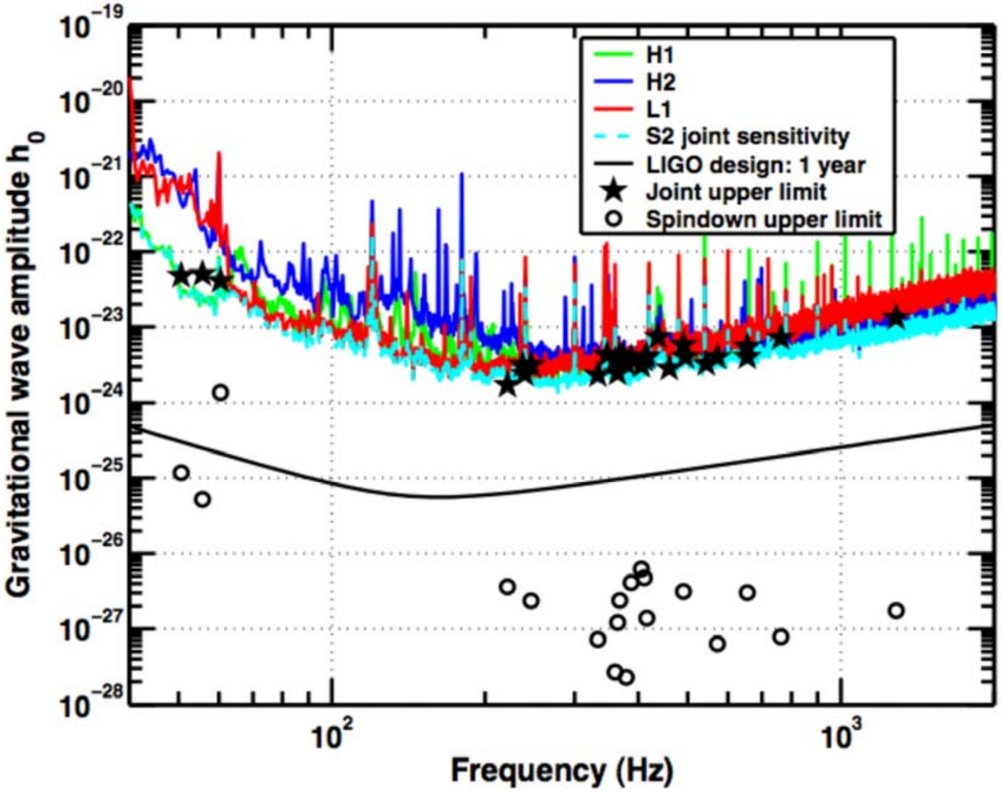
- S3 & S4 science runs (LIGO and GEO: up to 4 interferometers coherently, TDS)
  - Additional hardware injections in both GEO and LIGO
  - Add known binary pulsars to targeted search
  - Full results with total of 93 (33 isolated, 60 binary) pulsars

- S5 science run (ongoing, TDS)
  - 32 known isolated, 41 in binaries, 29 in globular clusters

S2 Search for known pulsars

S2 Results reported in

Physical Review Letters ***94*** *181103 (2005)*



Pulsars for which the ephemeris is known from EM observations

In S2

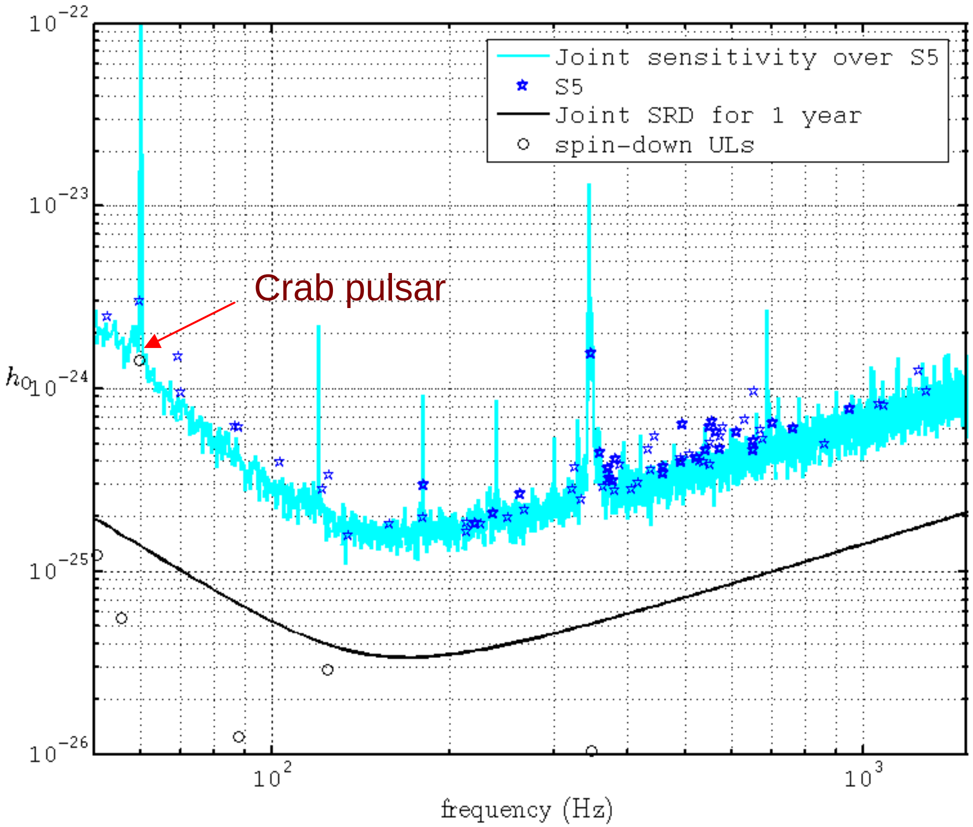
- 28 known isolated pulsars targeted

Spindown limit

- assumes all loss of angular momentum radiated to GW

Early S5 run

- Used parameters provided by Pulsar Group, Jodrell Bank Observatory for S3 – checked fo validity over the period of S5
- Analysed from 4 Nov - 31 Dec 2005 using data from the three LIGO observatories - Hanford 4 and 2k (H1, H2) and Livingston 4k (L1)
- 32 known isolated, 41 in binaries 29 in globular clusters



Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6Hz, r = 0.25kpc)
ellipticity = 4.0×10^{-7}

Universitat de les
Illes Balears

Early S5 Results, 95% upper limits

h_0	Pulsars
$1\times10^{-25} < h_0 < 5\times10^{-25}$	44
$5\times10^{-25} < h_0 < 1\times10^{-24}$	24
$h_0 > 1\times10^{-24}$	5

Lowest h_0 upper limit:

PSR J1603-7202 (f_{gw} = 134.8 Hz, r = 1.6kpc) $h_0 = 1.6\times10^{-25}$

Lowest ellipticity upper limit:

PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0\times10^{-7}$

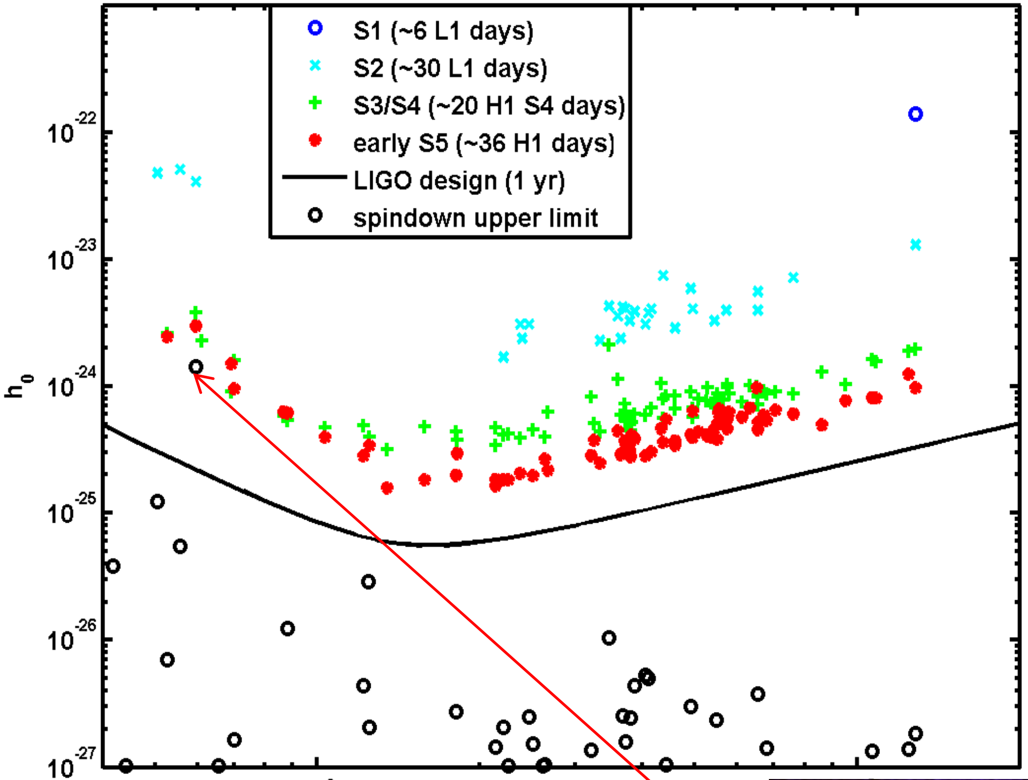
Ellipticity	Pulsars
$\varepsilon < 1\times10^{-6}$	6
$1\times10^{-6} < \varepsilon < 5\times10^{-6}$	28
$5\times10^{-6} < \varepsilon < 1\times10^{-5}$	13
$\varepsilon > 1\times10^{-5}$	26

All values assume I = 10^{38} kgm^2 and no error on distance

$$\varepsilon = 0.237 \frac{h_0}{10^{-24}} \frac{r}{1\mathrm{kpc}} \frac{1\mathrm{Hz}^2}{\nu^2} \frac{10^{38}\,\mathrm{kgm}^2}{I_{zz}}$$

Progression of targeted pulsars upper limits

- Results for first two months of S5 only.
- How will the rest of the run progress?
- Will have more up-to-date pulsar timings for current pulsars and possibly more objects.
- Amplitudes of < 10^{-25} and ellipticities <10^{-6} for many objects
- Our most stringent ellipticities ($4.0\text{x}10^{-7}$) are starting to reach into the range of neutron star structures for some neutron-proton-electron models (B. Owen, **PRL**, 2005).
- Crab pulsar is nearing the spin-down upper limit



Crab pulsar

New results to be realised at GWDAW11

Blind searches and coherent detection methods

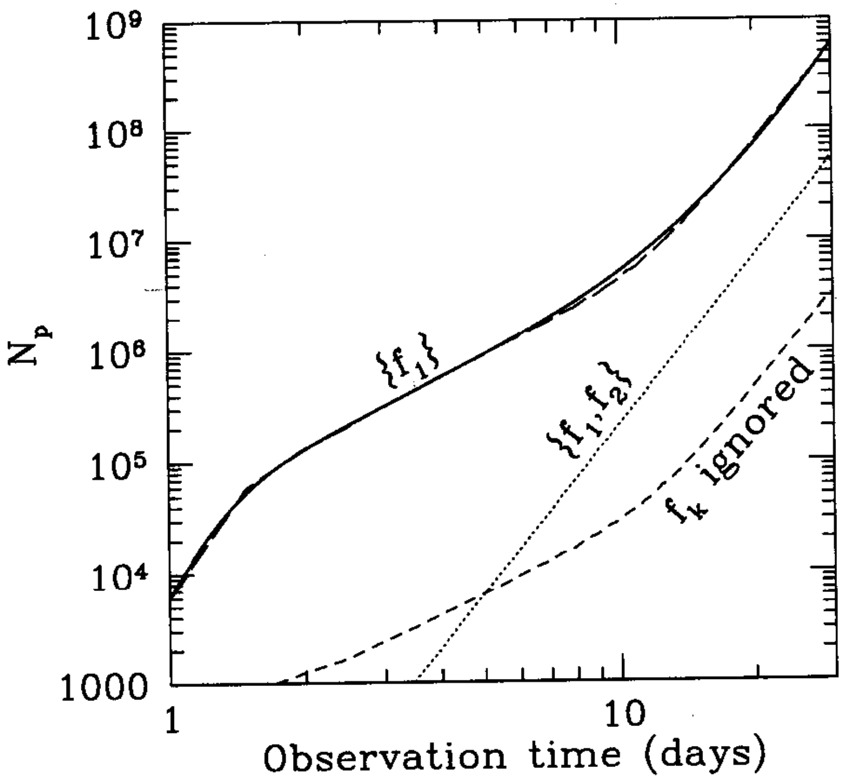
- Coherent methods are the most sensitive methods (amplitude SNR increases with sqrt of observation time) but they are the most computationally expensive,

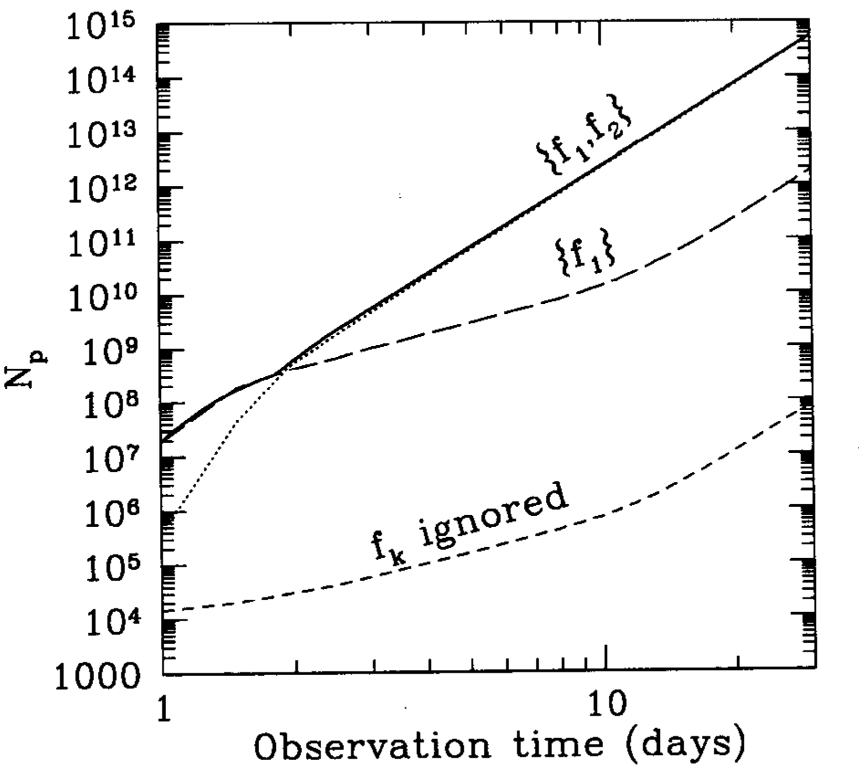
  why?

  - Our templates are constructed based on different values of the signal parameters (e.g. position, frequency and spindown)
  - The parameter resolution increases with longer observations
  - Sensitivity also increases with longer observations
  - As one increases the sensitivity of the search, one also increases the number of templates one needs to use.

Number of templates

The number of templates grows dramatically with the coherent integration time baseline and the computational requirements become prohibitive





[*Brady et al., Phys.Rev.D57 (1998)2101*]

S2 run: Coherent search for unknown isolated sources and Sco-X1

- Entire sky search
- Fully coherent matched filtering
- 160 to 728.8 Hz
- df/dt < 4 x 10^{-10} Hz/s
- 10 hours of S2 data; computationally intensive
- 95% confidence upper limit on the GW strain amplitude range from 6.6x10^{-23} to 1.0x10^{-21} across the frequency band

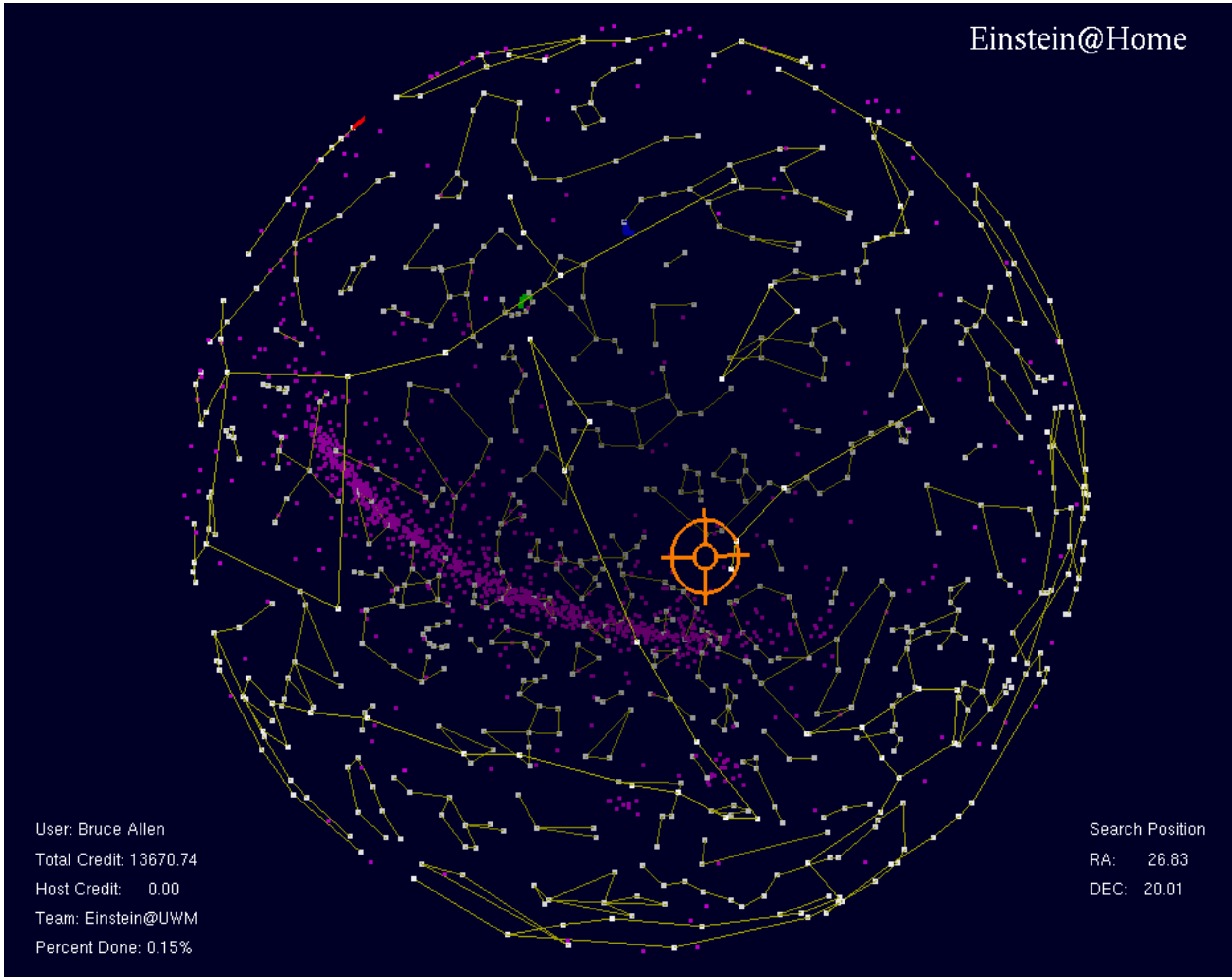
- Scorpius X-1
- Fully coherent matched filtering
- 464 to 484 Hz, 604 to 624 Hz
- df/dt < 1 x 10^{-9} Hz/s
- 6 hours of S2 data
- 95% confidence upper limit on the GW strain amplitude range from 1.7x10^{-22} to 1.3x10^{-21} across the two 20 Hz wide frequency bands

- See gr-qc/0605028

Einstein@home

- Like SETI@home, but for LIGO/GEO data
- American Physical Society (APS) publicized as part of World Year of Physics (WYP) 2005 activities
- Use infrastructure/help from SETI@home developers for the distributed computing parts (BOINC)
- Goal: pulsar searches using ~1 million clients. Support for Windows, Mac OSX, Linux clients
- From our own clusters we can get ~ thousands of CPUs. From Einstein@home hope to get order(s) of magnitude more at low cost
- Currently : ~140,000 active users corresponding to about 80Tflops

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



User: Bruce Allen
Total Credit: 13670.74
Host Credit: 0.00
Team: Einstein@UWM
Percent Done: 0.15%

Search Position
RA: 26.83
DEC: 20.01

Einstein@home

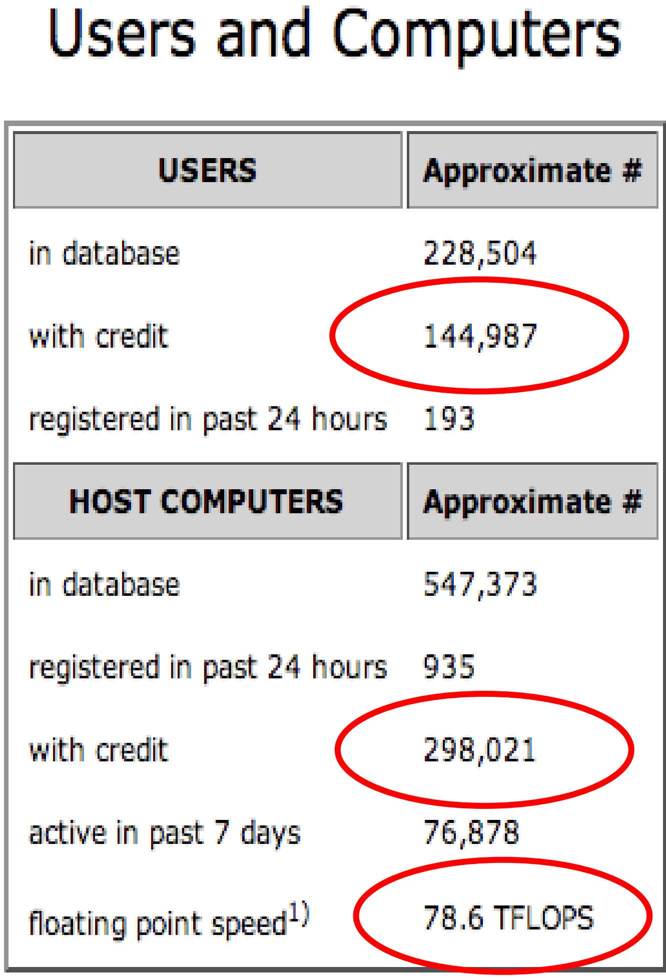
- Public distributed computing project to look for isolated pulsars in LIGO/GEO data ~ 80 TFlops 24/7

- Makes use of coherent F-statistic method

S3 - no spindown
- No evidence of strong pulsar signals
- Outliers are consistent with instrumental artifacts or bad bands. None of the low significance remaining candidates showed up in follow-up on S4 data.

S4 - one spindown parameter, up to f/fdot ~ 10,000 yr
- Using segment lengths of 30 hours
- Analysis took ~ 6 months
- Currently in post-processing stage

S5 - just started
- Faster more efficient application
- Estimated 6-12 months

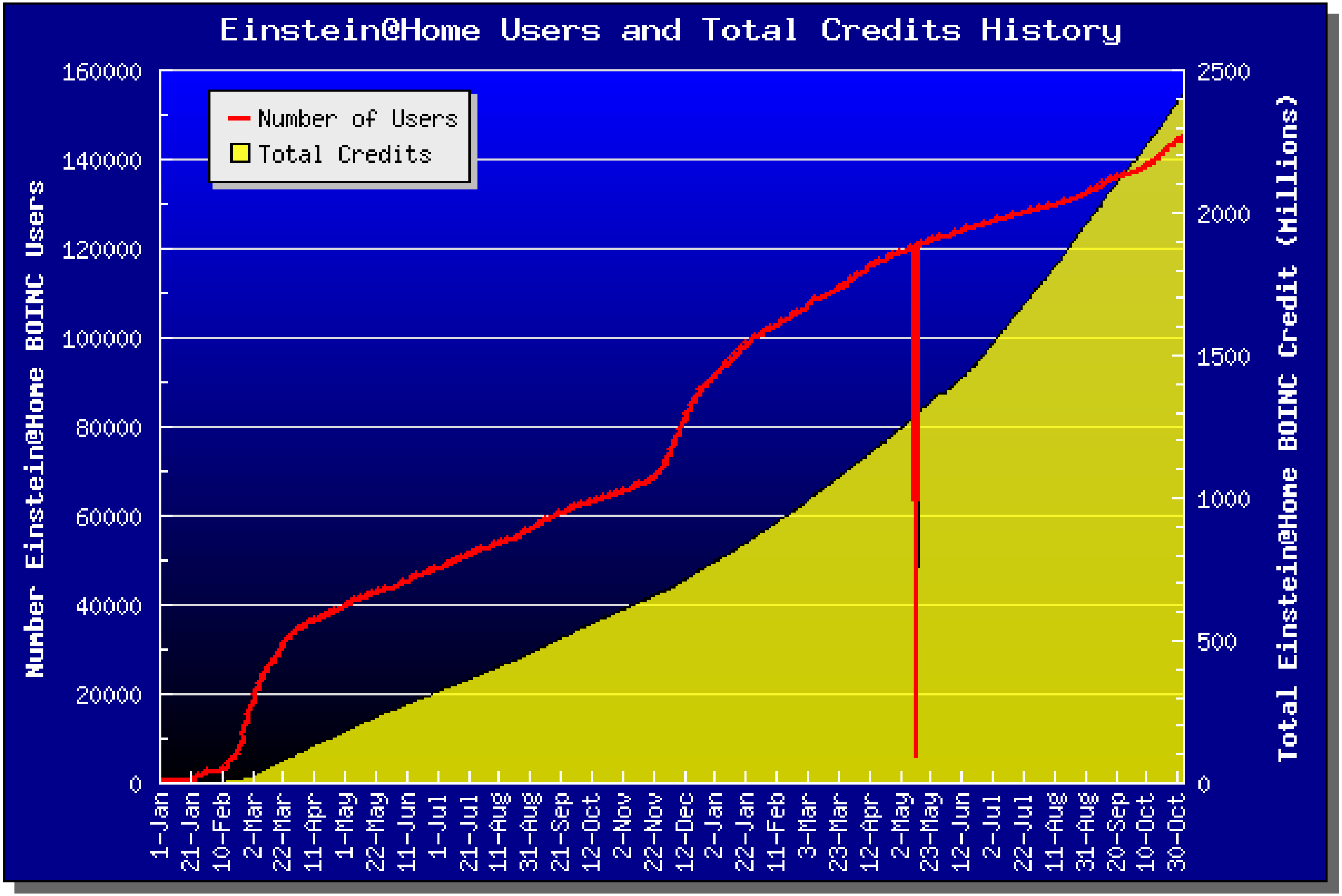


Users and Computers

USERS	Approximate #
in database	228,504
with credit	144,987
registered in past 24 hours	193
HOST COMPUTERS	**Approximate #**
in database	547,373
registered in past 24 hours	935
with credit	298,021
active in past 7 days	76,878
floating point speed[1)]	78.6 TFLOPS

Universitat de les
Illes Balears

User/Credit History



http://www.boincsynergy.com/stats/

Current performance

http://www.boincstats.com/

Projects	Users	last day	Hosts	last day	Teams	last day	Countries	last day	Total credit	last day
BOINC combined	842,945	+1,149	1,457,980	+2,946	54,093	+53	237	0	18,046,567,207	+54,224,702
SETI@Home	546,374	+823	1,182,099	+1,967	44,064	+43	228	0	10,316,965,770	+28,264,616
Einstein@Home	144,762	+193	297,744	+456	6,082	+13	194	0	2,418,766,901	+8,432,501
Climate Prediction	99,498	+71	185,147	+161	4,066	+2	183	0	2,120,418,976	+3,279,191
BBC Climate Change	117,431	+195	131,697	+264	1,087	+2	96	0	1,041,755,072	+7,014,464
Rosetta@Home	94,037	+184	212,958	+667	3,898	+11	184	0	965,064,540	+3,701,039
Predictor@Home	54,793	0	132,193	-5	2,960	0	166	0	420,727,364	0
World Community Grid	23,492	+60	58,584	+171	3,125	+8	137	+1	294,197,984	+1,902,848
LHC@Home	33,245	0	72,359	0	1,992	0	139	0	111,339,176	0
SIMAP	13,194	+8	31,645	+283	976	+1	124	0	92,177,896	+14,496
QMC@Home	9,684	+46	17,517	+103	722	+2	110	0	62,511,192	+531,576
Seasonal Attribution	3,912	+13	5,287	+13	328	+2	79	0	26,136,852	+144,432
Malaria Control	2,179	+1	6,163	+22	313	0	86	0	25,127,572	+135,696

Einstein@Home is currently getting 84 Tflops

All-Sky surveys for unknown gravity-wave emitting pulsars

It is necessary to search for every signal template distinguishable in parameter space. Number of parameter points required for a coherent T=10^7s search

[*Brady et al., Phys.Rev.D57 (1998)2101*]:

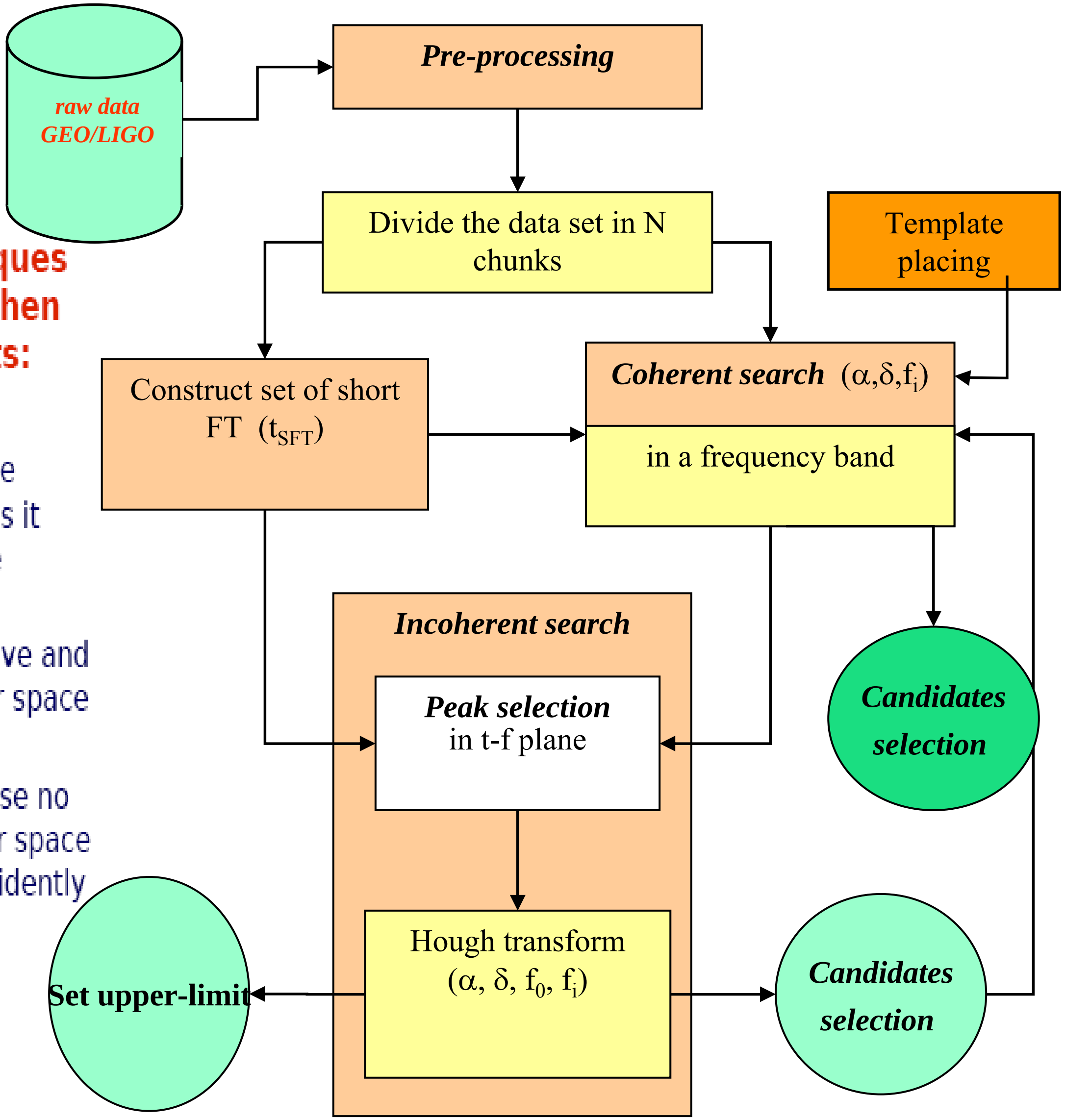
Class	**f (Hz)**	**τ (Yrs)**	**N_s**	**Directed**	**All-sky**
Slow-old	<200	$>10^3$	1	**$3.7\text{x}10^6$**	**$1.1\text{x}10^{10}$**
Fast-old	$<10^3$	$>10^3$	1	**$1.2\text{x}10^8$**	**$1.3\text{x}10^{16}$**
Slow-young	<200	>40	3	**$8.5\text{x}10^{12}$**	**$1.7\text{x}10^{18}$**
Fast-young	$<10^3$	>40	3	**$1.4\text{x}10^{15}$**	**$8\text{x}10^{21}$**

Number of templates grows dramatically with the integration time. To search this many parameter space coherently, with the optimum sensitivity that can be achieved by matched filtering, is computationally prohibitive.

Hierarchical strategies

Hierarchical searches are the best techniques when the parameter space is large and when there exist computing power constraints:

- The smallest signal detectable with a given confidence becomes larger as the parameter space increases. Thus it makes no sense to use techniques that ``dig out of the noise'' signals that are too small to be significant.
- We use methods that are less computationally intensive and not as sensitive in order to narrow down the parameter space to the final sensitivity level.
- This is a better use of computational resources because no calculations are lost to search regions of the parameter space where, if present, a signal would be to small to be confidently detected.
- Hierarchy of coherent and non-coherent searches



raw data GEO/LIGO

Pre-processing

Divide the data set in N chunks

Template placing

Construct set of short FT (t_{SFT})

Coherent search (α,δ,f_i)

in a frequency band

Candidates selection

Incoherent search

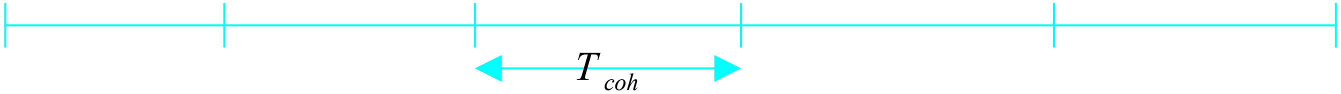
Peak selection in t-f plane

Hough transform $(\alpha, \delta, f_0, f_i)$

Set upper-limit

Candidates selection

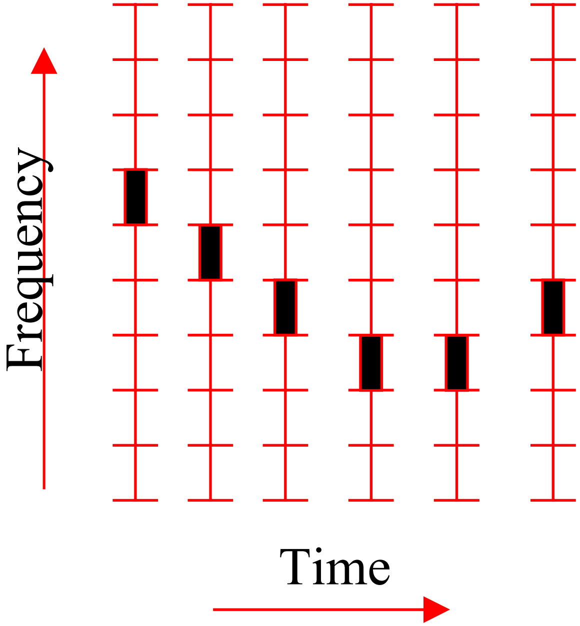
Incoherent power-sum methods



- The idea is to perform a search over the total observation time using an *incoherent* (sub-optimal) method:

- Three methods have been developed to search for cumulative excess power from a hypothetical periodic gravitational wave signal by examining successive spectral estimates:
  - Stack-slide (Radon transform)
  - Hough transform
  - Power-flux method

They are all based on breaking up the data into segments, FFT each, producing Short (30 min) Fourier Transforms (SFTs) from h(t), as a coherent step (although other coherent integrations can be used if one increasing the length of the segments), and then track the frequency drifts due to Doppler modulations and df/dt as the incoherent step.



Differences among the incoherent methods

What is exactly summed?

- StackSlide – Normalized power (power divided by estimated noise)
  → Averaging gives expectation of 1.0 in absence of signal

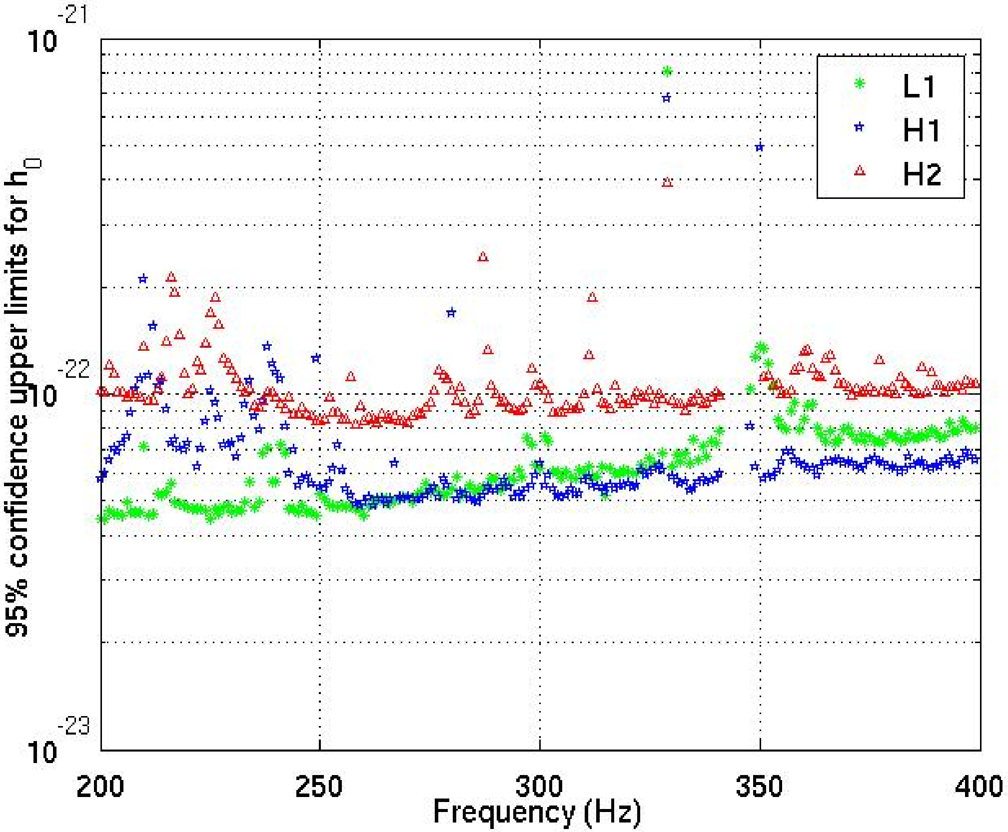
- Hough – Weighted binary counts (0/1 = normalized power below/above SNR), with weighting based on antenna pattern and detector noise

- PowerFlux – Average strain power with weighting based on antenna pattern and detector noise
  → Signal estimator is direct excess strain noise
  (circular polarization and 4 linear polarization projections)

Hough S2: UL Summary

Feb.14-Apr.14,2003

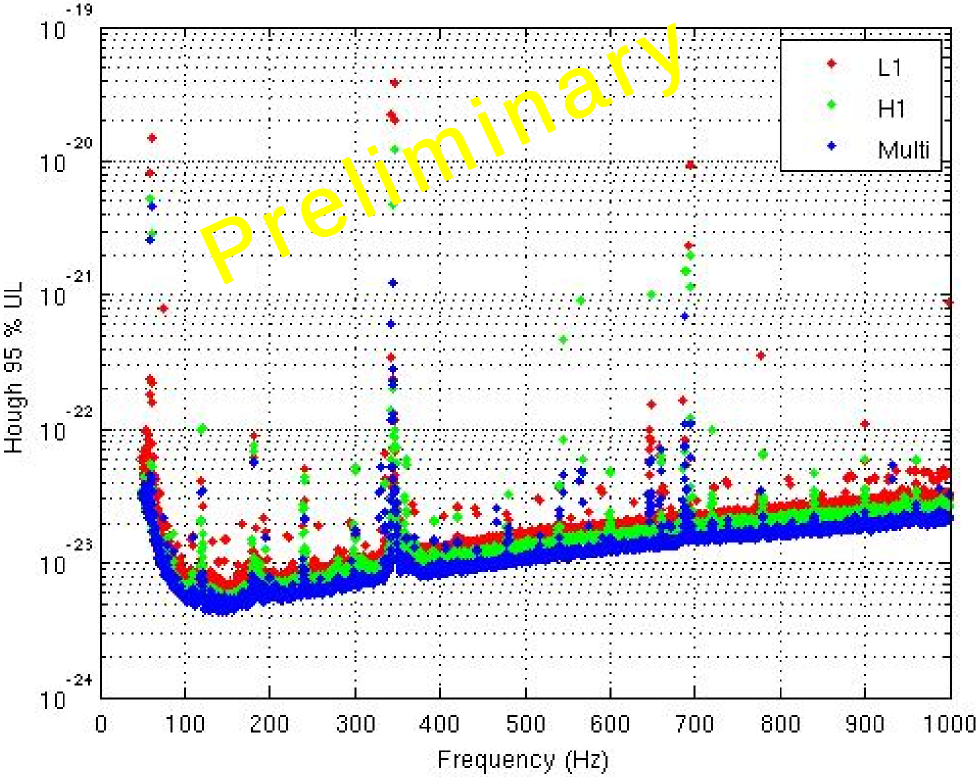
- S2 analysis covered 200-400Hz, over the whole sky, and 11 values of the first spindown ($\Delta f = 5.55\times10^{-4}$ Hz, $\Delta f_1 = -1.1\times10^{-10}$ Hz s^{-1})
- Templates: Number of sky point templates scales like (frequency)^2
  - 1.5×10^5 sky locations @ 300 Hz
  - 1.9×10^9 @ 200-201 Hz
  - 7.5×10^9 @ 399-400 Hz
- Three IFOs analyzed separately
- No signal detected
- Upper limits obtained for each 1 Hz band by signal injections: Population-based frequentist limits on h_0 averaging over sky location and pulsar orientation



Detector	L1	H1	H2
Frequency (Hz)	200-201	259-260	258-259
$h_0^{95\%}$	4.43×10^{-23}	4.88×10^{-23}	8.32×10^{-23}

The S4 Hough search

- As before, input data is a set of *N* 1800s SFTs (no demodulations)
- Weights allow us to use SFTs from all three IFOs together:
  1004 SFTS from H1, 1063 from H2 and 899 from L1
- Search frequency band 50-1000Hz
- 1 spin-down parameter. Spindown range $[-2.2,0]\times10^{-9}$ Hz/s with a resolution of 2.2×10^{-10} Hz/s
- All sky search
- All-sky upper limits set in 0.25 Hz bands
- Multi-IFO and single IFOs have been analyzed

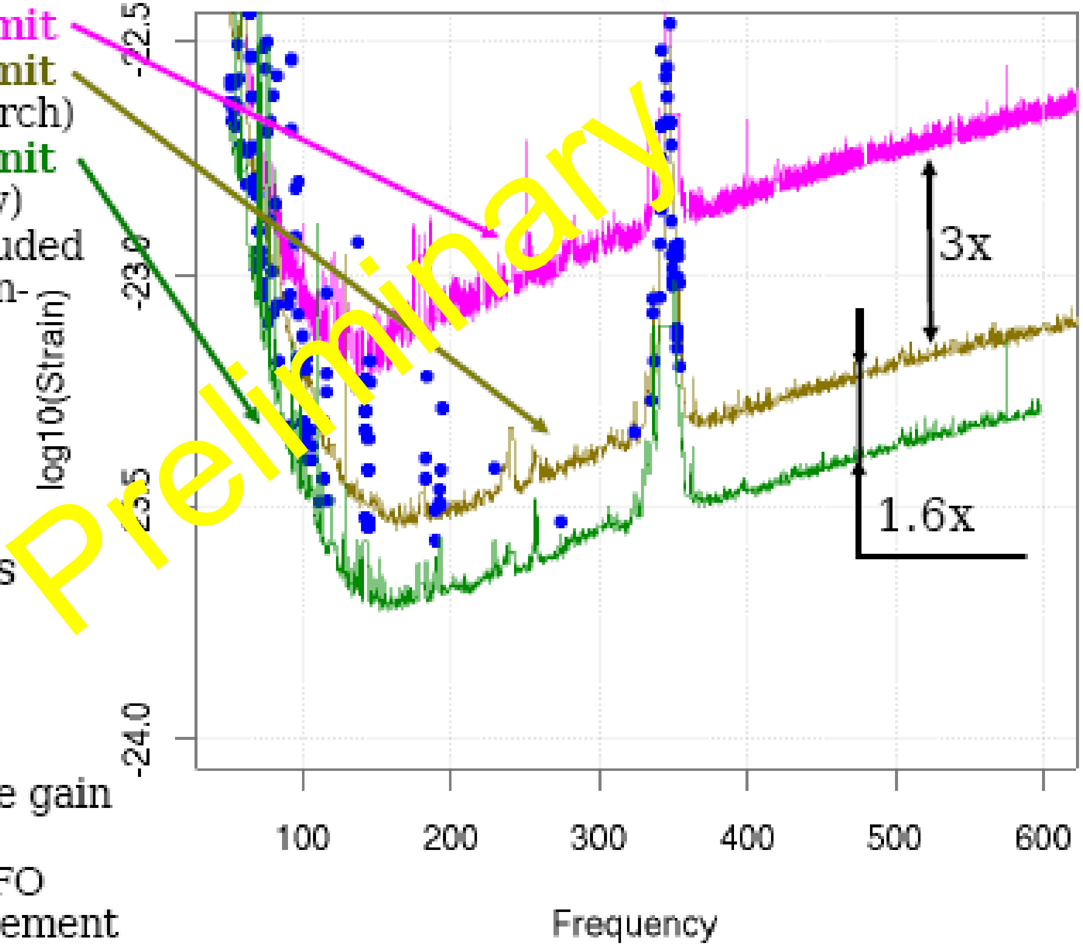


Best UL

for L1: 5.9×10^{-24}
for H1: 5.0×10^{-24}
for Multi H1-H2-L1: 4.3×10^{-24}

S5 incoherent searches
preliminary PowerFlux results

S5 spindown-0 run



- **S4 L1 upper limit**
- **S5 L1 upper limit** (data through March)
- **S5 L1 upper limit** (data through July)
- 60 Hz lines excluded
- Blue points – non-gaussian noise in July run

July L1 SFTs=
3x March SFTs

Maximum possible gain
3^0.25=1.32
Extra gain from IFO sensitivity improvement

Next S5 E@H Search

- The CW group is planning to start running the **first true** Einstein@Home **hierarchical search** in about 3 months!
- All-sky, TBD: f < ~900 Hz, spindown ages > 10000 years
- A new search code (union of multi-detector Fstat and Hough). A stack-slide incoherent option is also "in the works".
- This will use approximately 96 x 20 hours of coincident H1/L1 data
- Combines coherent Fstat method with incoherent Hough method
- Should permit a search that extends hundreds of pc into the Galaxy
- This should become the most sensitive blind CW search possible with current knowledge and technology

LSC CW publications

Summary of LIGO publications for periodic GWs:

1. Setting Upper Limits on the Strength of Periodic GW from PSR J1939+2134 Using the First Science Data from the GEO600 and LIGO Detectors, PRD 69, 082004 (2004) .
2. Limits on Gravitational-Wave Emission from Selected Pulsars Using LIGO Data,
PRL 94, 181103 (2005).
3. First All-sky Upper Limits from LIGO on the Strength of Periodic Gravitational Waves Using the Hough Transform, PRD 72, 102004 (2005).
4. Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run, gr-qc/0605028, submitted to PRD
5. Einstein@home online report for S3 search: http://einstein.phys.uwm.edu/PartialS3Results
6. Upper limits on gravitational wave emission from 76 radio pulsars,
Still in internal review process
7. All-sky LIGO (incoherent) search for periodic gravitational waves in the S4 data run,
Still in internal review process

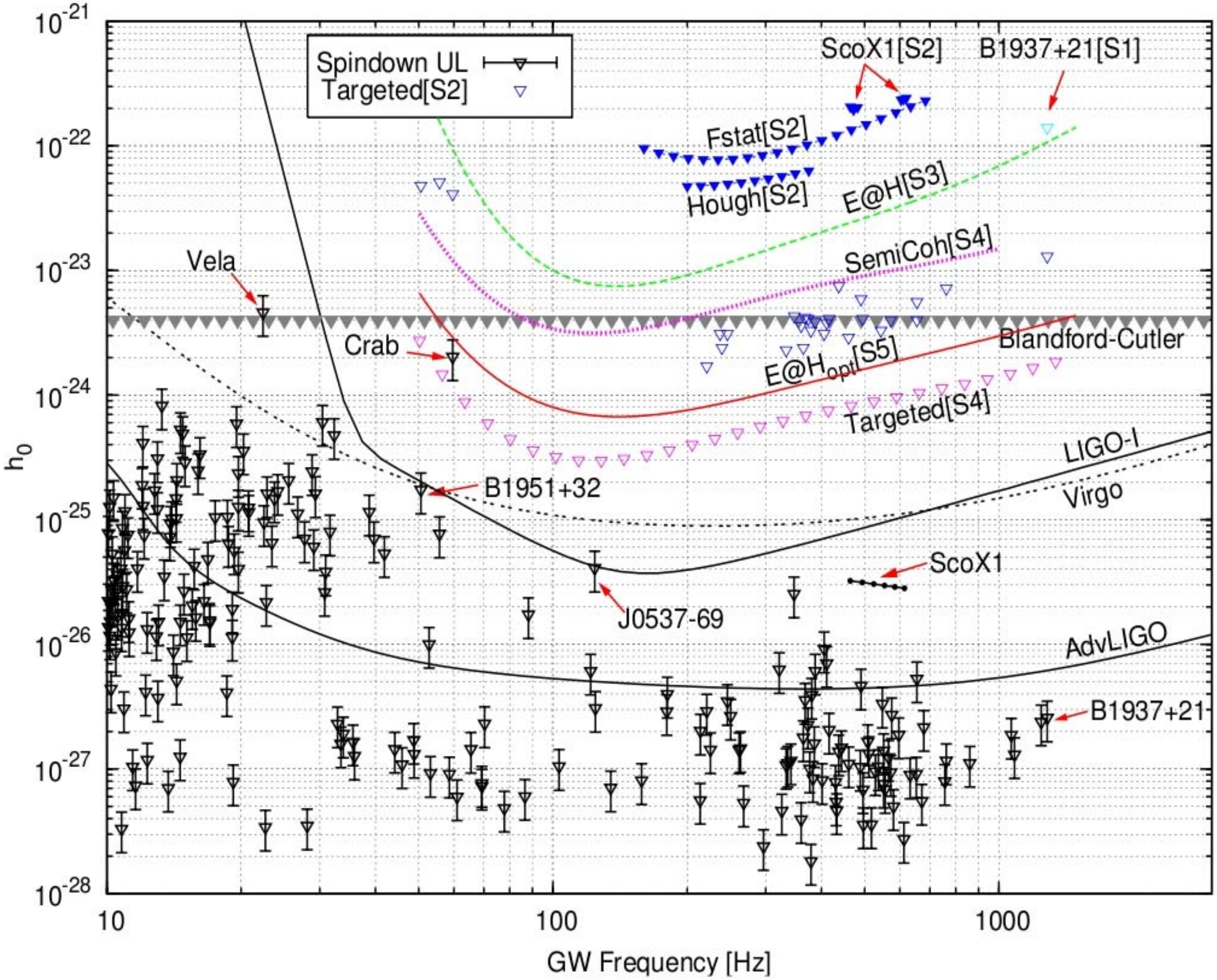
S1

S2

S3

S4

Searches for Continuous Waves,
present, past and future



Conclusions

- Analysis of LIGO data is in full swing, and results from LIGO searches from science runs 4, 5 are now appearing.
  - Significant improvements in interferometer sensitivity since S3.
  - In the process of accumulating 1 year of data (S5).
  - Known pulsar searches are beginning to place interesting upper limits in S5
  - All sky searches are under way and exploring large area of parameter space