Searches for periodic gravitational waves

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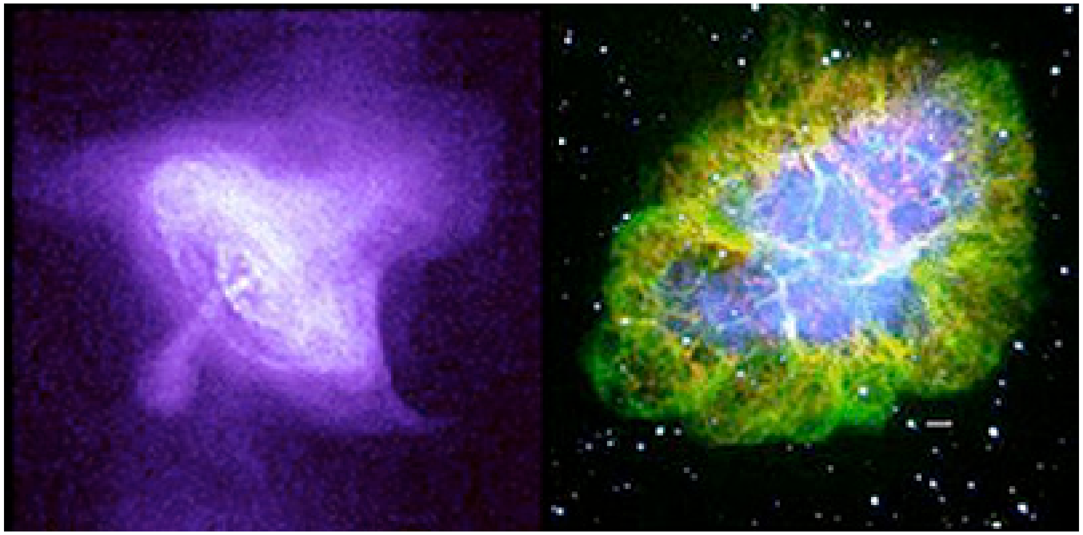
on behalf of the LSC
http://www.ligo.org



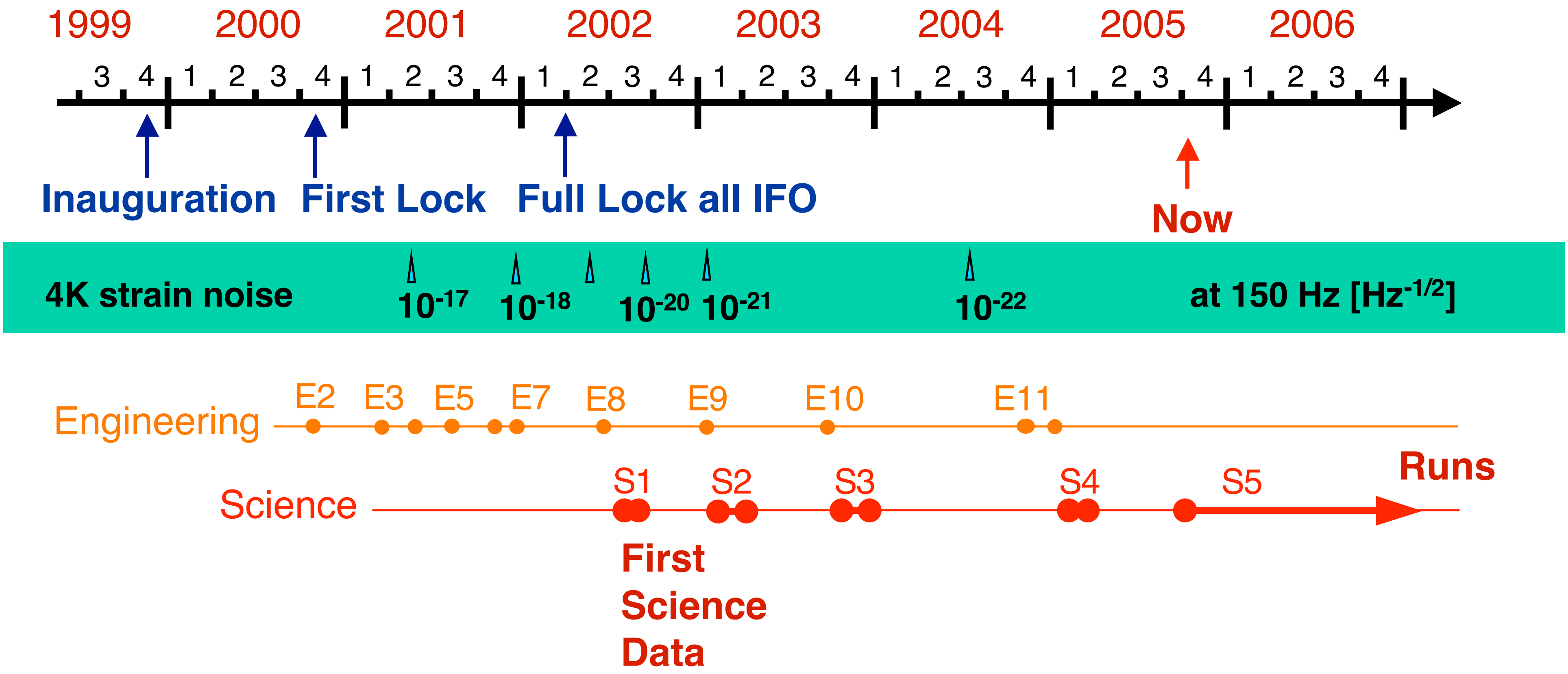
CaJAGWR Seminar
20 December 2005

LIGO-G050657-00-Z

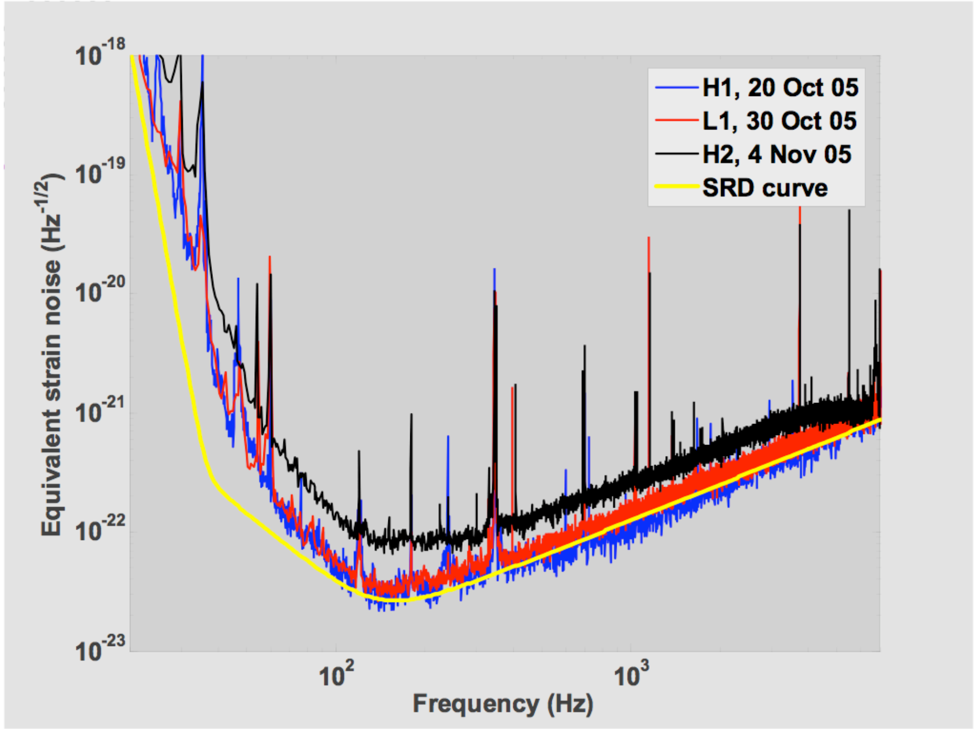
Outline of talk

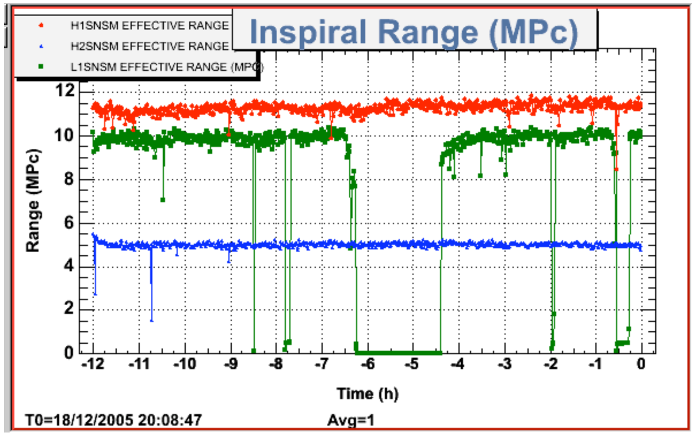
1. LIGO status
2. Overview of LSC periodic search methods
3. Nature of periodic gravitational wave signals
4. Targeted time-domain Bayesian search
    - Description of method
    - Application to LIGO and GEO data (S1-S5)
5. Large parameter space periodic searches
6. Future plans

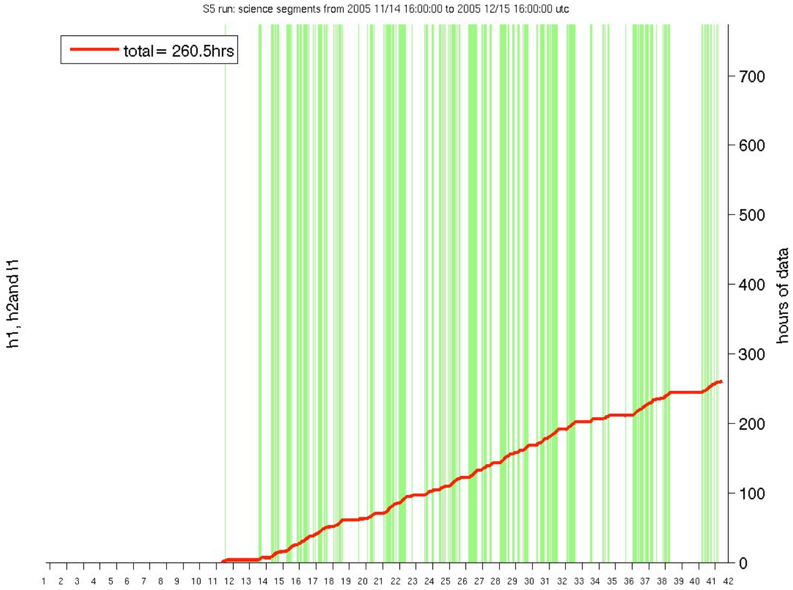
LIGO timeline



LIGO status


H1, 20 Oct 05
L1, 30 Oct 05
H2, 4 Nov 05
SRD curve
Equivalent strain noise (Hz$^{-1/2}$)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{2}
10^{3}
Frequency (Hz)


H1SNSM EFFECTIVE RANGE
H2SNSM EFFECTIVE RANGE
L1SNSM EFFECTIVE RANGE (MPC)
Inspiral Range (MPc)
Range (MPc)
12
10
8
6
4
2
0
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Time (h)
T0=18/12/2005 20:08:47
Avg=1


S5 run: science segments from 2005 11/14 16:00:00 to 2005 12/15 16:00:00 utc
total = 260.5hrs
h1, h2and l1
hours of data
0
100
200
300
400
500
600
700
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42

LSC periodic search methods

Coherent searches:

- Bayesian time-domain (TDS)
  - Isolated and binary pulsars
  - Markov chain Monte Carlo

} Finely tuned searches over a narrow parameter space

- F-statistic frequency domain
  - Isolated all-sky over wide frequency range
  - Einstein@home
  - Binary x-ray with some unknown orbital parameters

} Deep searches over a broad parameter space

Incoherent searches:

- Hough transform
- Stack-slide
- Powerflux

} Efficient, robust, wide-parameter searches

LSC pulsar group

http://www.lsc-group.phys.uwm.edu/pulgroup/

Summary of published searches for periodic GWs with LIGO:

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,
   B. Abbott et al. (LSC), Phys. Rev. D 69, 082004 (2004) .

2. Limits on Gravitational-Wave Emission from Selected Pulsars Using LIGO Data,
   B. Abbott et al. (LSC), Phys. Rev. Lett. 94, 181103 (2005).

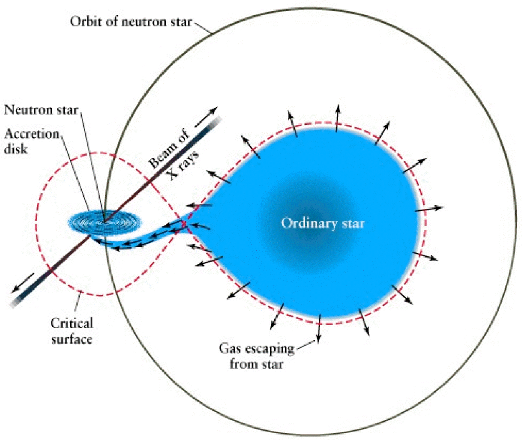
3. First All-sky Upper Limits from LIGO on the Strength of Periodic Gravitational Waves Using the Hough Transform,
   B. Abbott et al. (LSC), Phys. Rev. D 72, 102004 (2005).

4. Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run,
   Final phases of internal review, to be submitted asap.

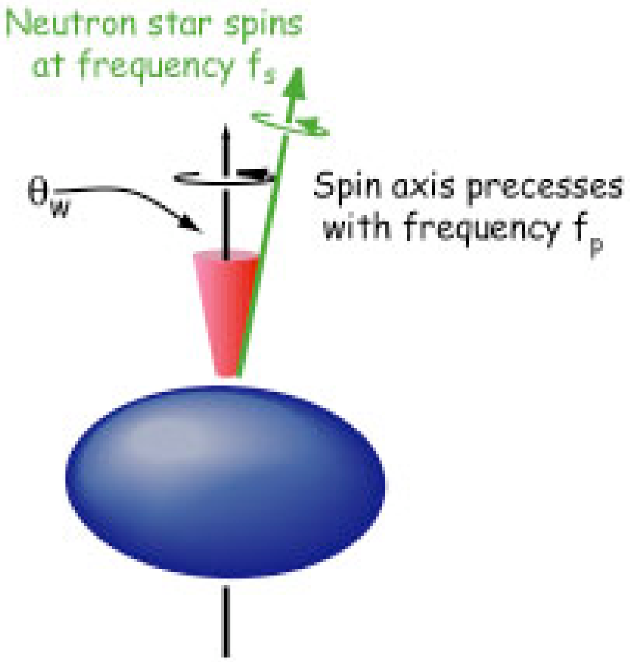
5. Einstein@home online report for S3 search:
   http://einstein.phys.uwm.edu/PartialS3Results/

Gravitational waves from pulsars

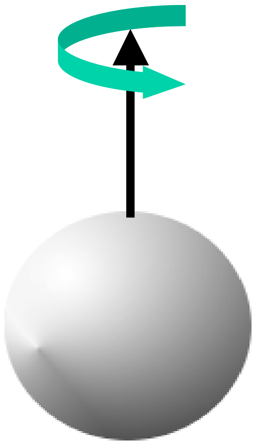
- Neutron stars are good potential sources are GWs since they are known to exist (!) and in some cases are observed electromagnetically which can reduce the parameter space to be explored considerably.



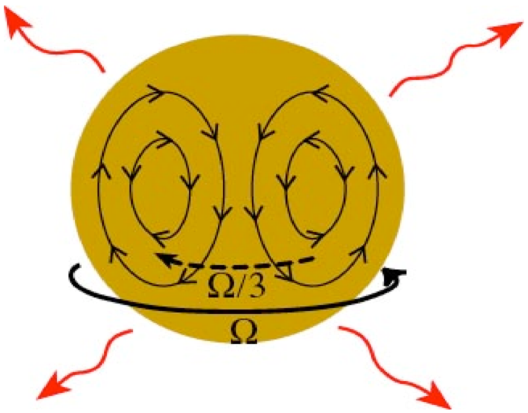
Low Mass X-Ray Binaries



Wobbling Neutron Stars



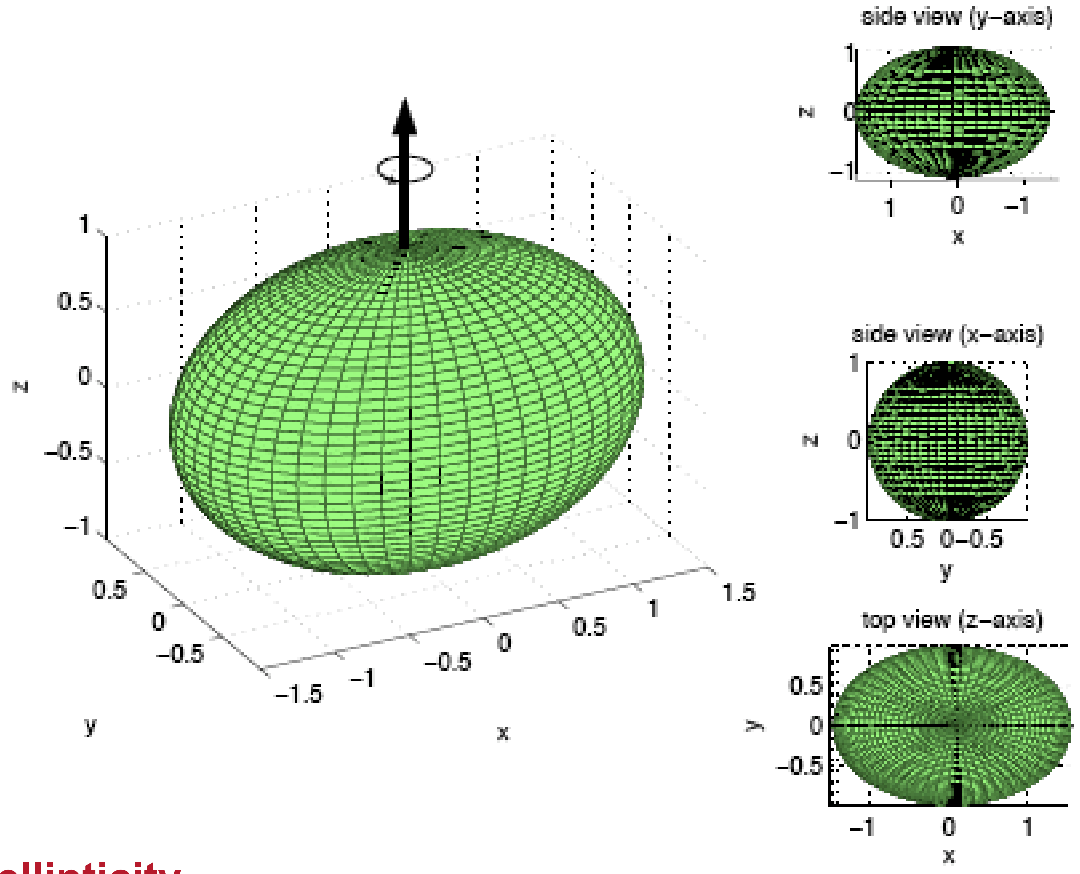
Bumpy Neutron Stars



Young Neutron Stars

GWs from triaxial pulsar

- Spherically symmetric neutron stars will not emit gravitational waves
- Ellipticity, ε, measures asymmetry in triaxially shaped pulsar



$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz} f_0^2}{R}\varepsilon$$

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

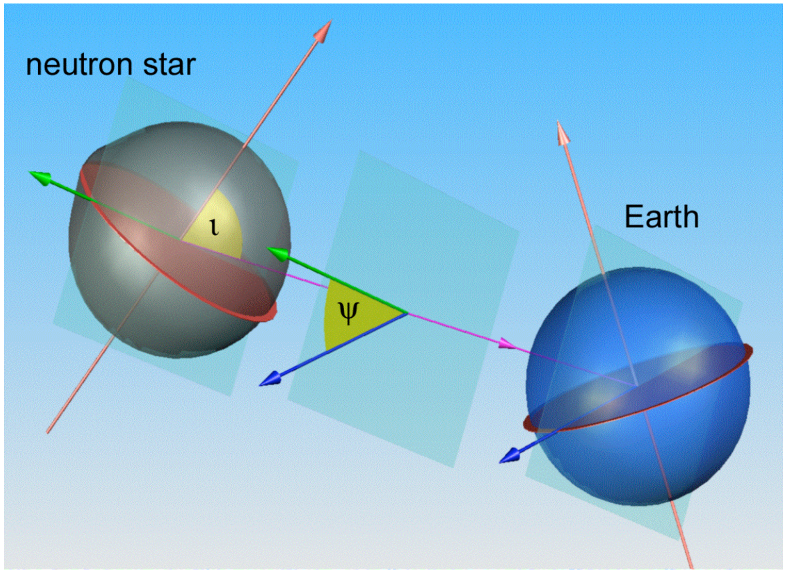
equatorial ellipticity

Nature of gravitational wave signal

- The GW signal from a triaxial pulsar can be modelled as

$$h(t) = \frac{1}{2}F_+(t;\psi)h_0(1+\cos^2\iota)\cos 2\Psi(t) + F_\times(t;\psi)h_0\cos\iota\sin 2\Psi(t)$$

- The unknown parameters are
  - h_0 - amplitude of the gravitational wave signal
  - ψ - polarization angle of signal; embedded in $F_{x,+}$
  - ι - inclination angle of the pulsar
  - ϕ_0 - initial phase of pulsar $\Phi(0)$



- In the targeted searches we only look for signals at twice the rotation frequency of the pulsars

- For blind searches the location in the sky and the source's frequency evolution are also unknown.

Pulsar timing

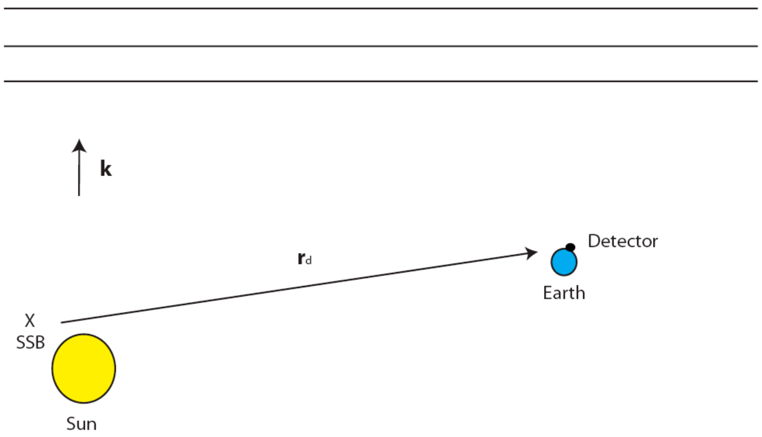
For known pulsars the phase can be predicted from radio observations:

$$\Psi(T) = \phi_0 + 2\pi \left[f_0(T - T_0) + \frac{1}{2}\dot{f}_0(T - T_0)^2 + \frac{1}{6}\ddot{f}_0(T - T_0)^3 + \mathcal{O}(T^4) \right]$$

$$T = t + \delta t = t + \Delta_{\text{Roemer}} + \Delta_{\text{Shapiro}} + \Delta_{\text{Einstein}} + \Delta_{\text{Binary}}$$

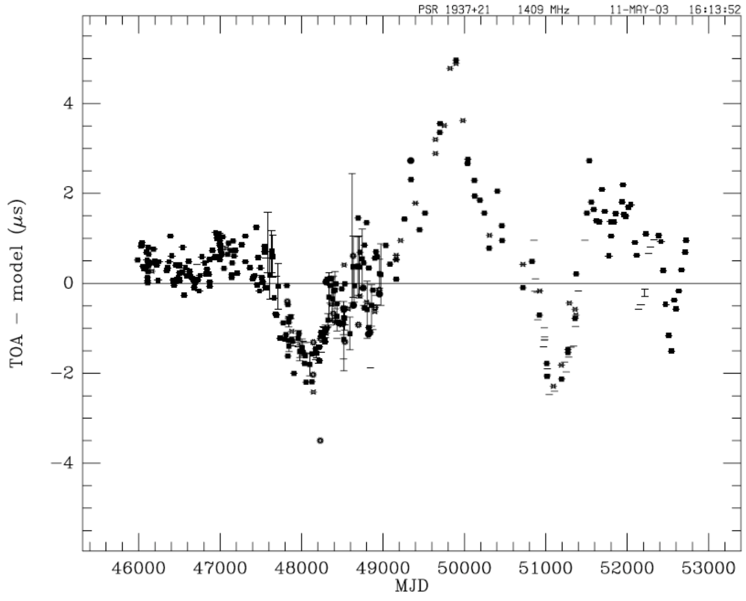
The largest component in the transformation to time at the Solar System Barycenter T is the Roemer delay which can be as large as 8.5 minutes.

$$\Delta_{\text{Roemer}} = \frac{\mathbf{r}_\text{d} \cdot \mathbf{k}}{c} + \frac{(\mathbf{r}_\text{d} \cdot \mathbf{k})^2 - |\mathbf{r}_\text{d}|}{2cd}$$



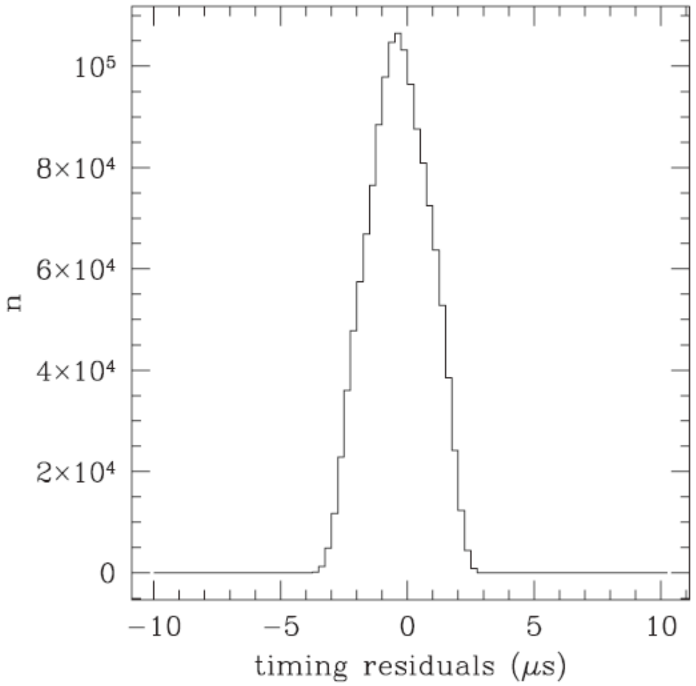
Pulsar Timing

- Timing noise might be indicative of irregularities in pulsar rotation; its physical origin remains unclear.



Lommen & Backer

- GW timing software agrees with radio astronomy software.



- For the Crab pulsar the timing noise is taken into account using monthly the ephemeris provide by JBO.

Complex heterodyning

By heterodyning the detector s(t) at the known frequency of the pulsar we can `unwind' its phase evolution so that the remaining signal is the antenna response of the detector.

$$s(t) = h(t) + n(t)$$

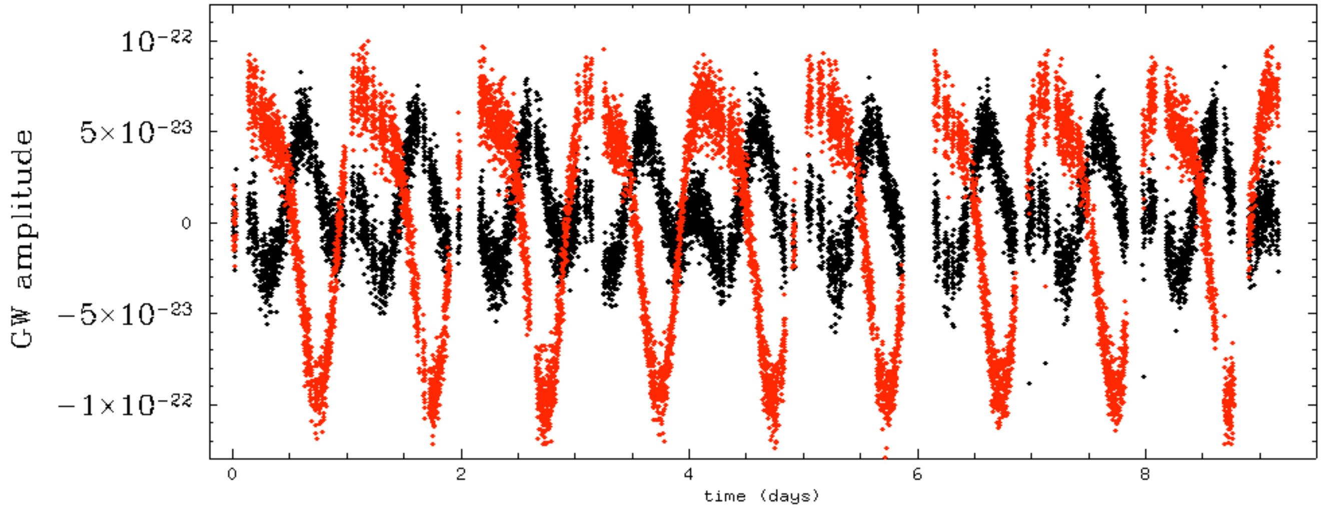
Multiplied by

$$e^{-i\phi(t)}$$

(+ low-pass filter)

gives

$$\begin{aligned} B_k =& \frac{1}{4} F_{+}(t_k;\psi) h_0 (1+\cos^2 \iota) e^{i\phi_0} \\ & - \frac{i}{2} F_{\times}(t_k;\psi) h_0 \cos\iota \, e^{i\phi_0} + n(t_k)' \end{aligned}$$



This is a plot of Bk's for a fake pulsar signal injected into 9 days recent H1 data with an amplitude of $h_0 \sim 10^{-22}$.

Bayesian formalism

- A Bayesian approach is used to determine the joint posterior distribution of the probability of the unknown parameters, **a**.
- Uniform prior for cosι, ϕ_0, ψ and h_0 (>0).

prior

likelihood

$$p(\mathbf{a}|\{B_k\},I) = \frac{p(\mathbf{a}|I)p(\{B_k\}|\mathbf{a},I)}{p(\{B_k\}|I)}$$

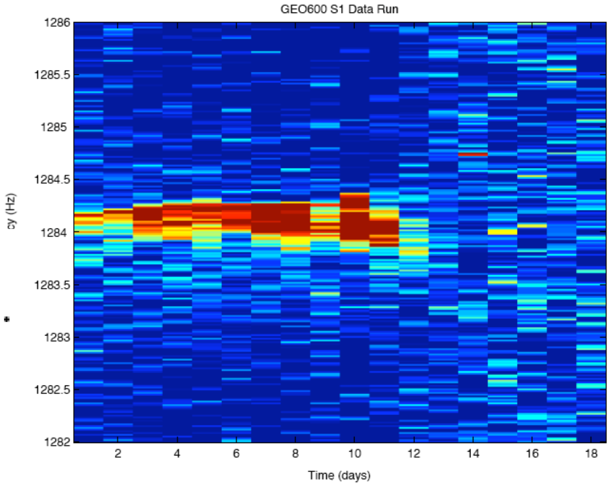
normalization

posterior

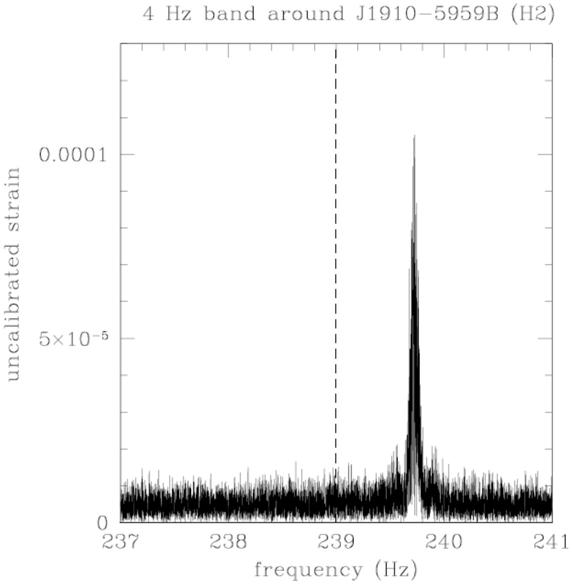
Likelihood function

We used a bivariate normal distribution for the likelihood function in the S1 analysis.

$$p(\{B_k\}|\mathbf{a},\{\sigma_k\}) = (\sqrt{2\pi}\sigma_k)^{-2n} \exp\left(-\sum_{k=1}^{n} \frac{|B_k - y_k|^2}{2\sigma_k^2}\right).$$



We marginalized over the noise level for post-S1 analysis (thanks to improvements in the stationarity of the data) to deal with spectral lines contaminating our estimates of the noise.



$$p(\{B_k\}|\mathbf{a}) \propto \prod_{j}^{M} \left(\sum_{k=k_{1(j)}}^{k_{2(j)}} |B_k - y_k|^2\right)^{-m_j}$$

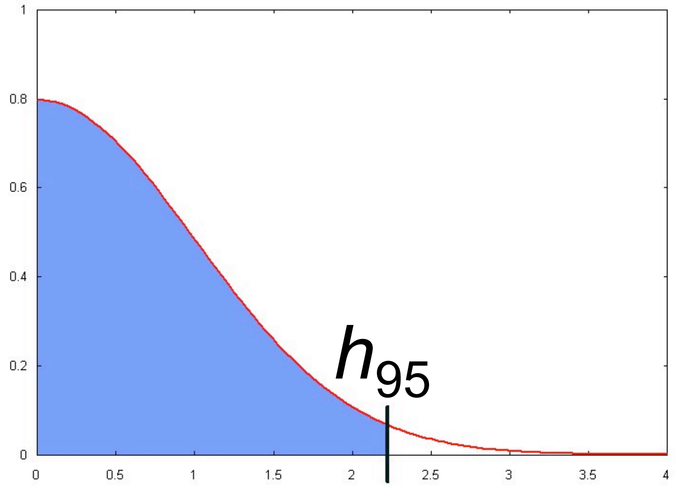
Setting upper limits

- Marginalize over the nuisance parameters ($\cos\iota$, φ_0, ψ) to get the posterior distribution for the probability of h_0

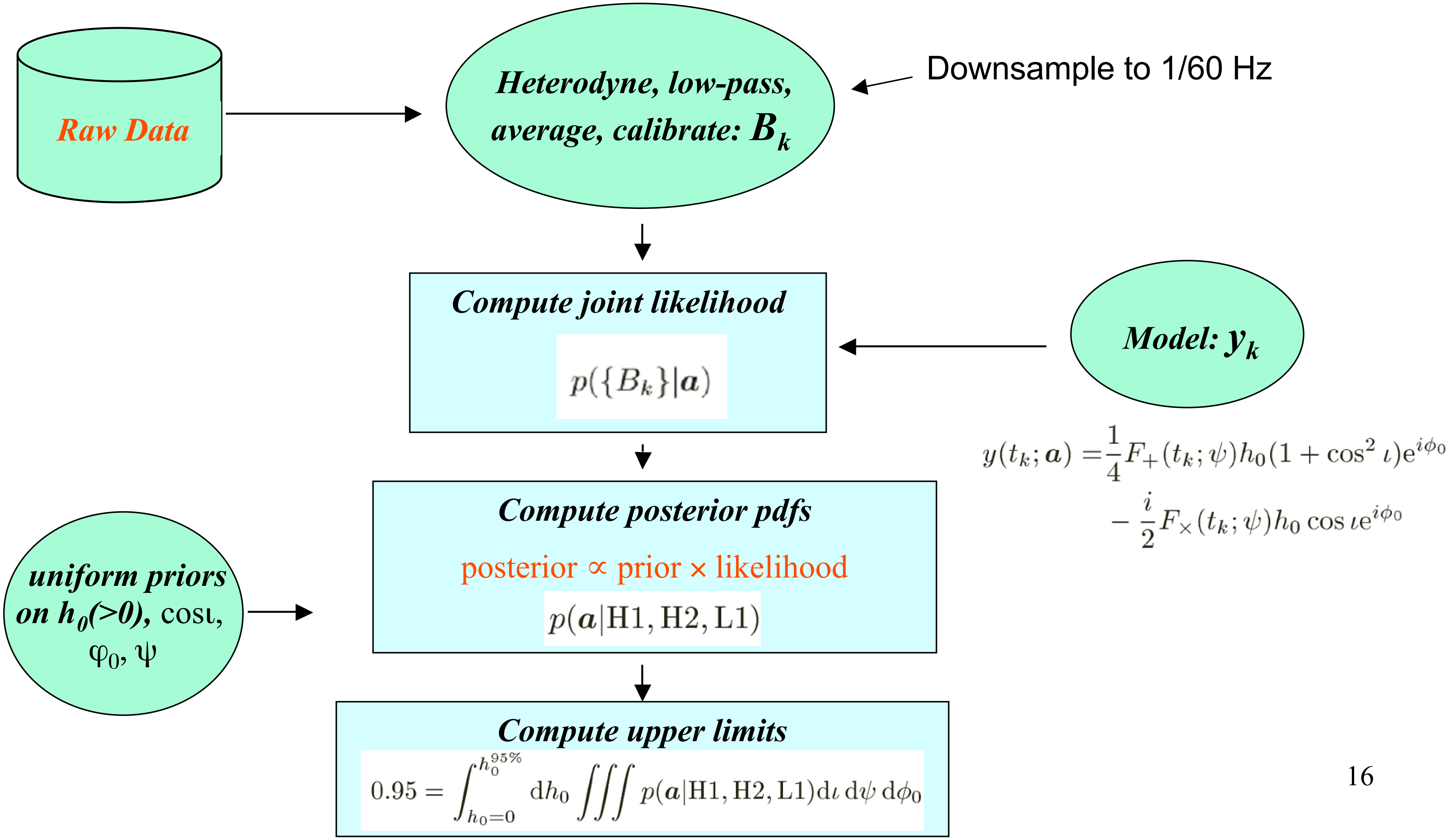
$$p(h_0|\{B_k\}) \propto \iiint p(\{B_k\}|\mathbf{a})p(\mathbf{a})\,\mathrm{d}\phi_0\,\mathrm{d}\psi\,\mathrm{d}\cos\iota$$

- We define h_{95} by value of h_0 that bounds 95% of the cumulative probability (from h_0=0)

$$0.95 = \int_{h_0=0}^{h_{95}} p(h_0|\{B_k\})\mathrm{d}h_0$$



TDS method



Raw Data

Heterodyne, low-pass, average, calibrate: B_k

Downsample to 1/60 Hz

Compute joint likelihood

$$p(\{B_k\}|\boldsymbol{a})$$

Model: y_k

$$y(t_k;\boldsymbol{a}) = \frac{1}{4}F_+(t_k;\psi)h_0(1+\cos^2\iota)e^{i\phi_0} - \frac{i}{2}F_\times(t_k;\psi)h_0\cos\iota e^{i\phi_0}$$

uniform priors on $h_0(>0)$, $\cos\iota$, φ_0, ψ

Compute posterior pdfs

posterior ∝ prior × likelihood

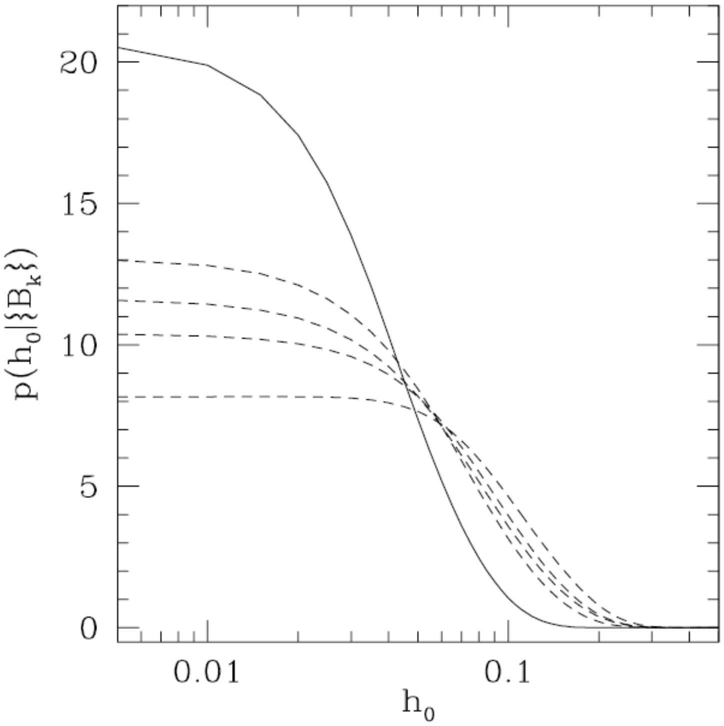
$$p(\boldsymbol{a}|\mathrm{H1},\mathrm{H2},\mathrm{L1})$$

Compute upper limits

$$0.95 = \int_{h_0=0}^{h_0^{95\%}} \mathrm{d}h_0 \iiint p(\boldsymbol{a}|\mathrm{H1},\mathrm{H2},\mathrm{L1})\,\mathrm{d}\iota\,\mathrm{d}\psi\,\mathrm{d}\phi_0$$

Network analysis

The combined posterior distribution from all the available interferometers comes naturally out of a Bayesian analysis, and for independent observations is simply the product of the contributing probability distributions:

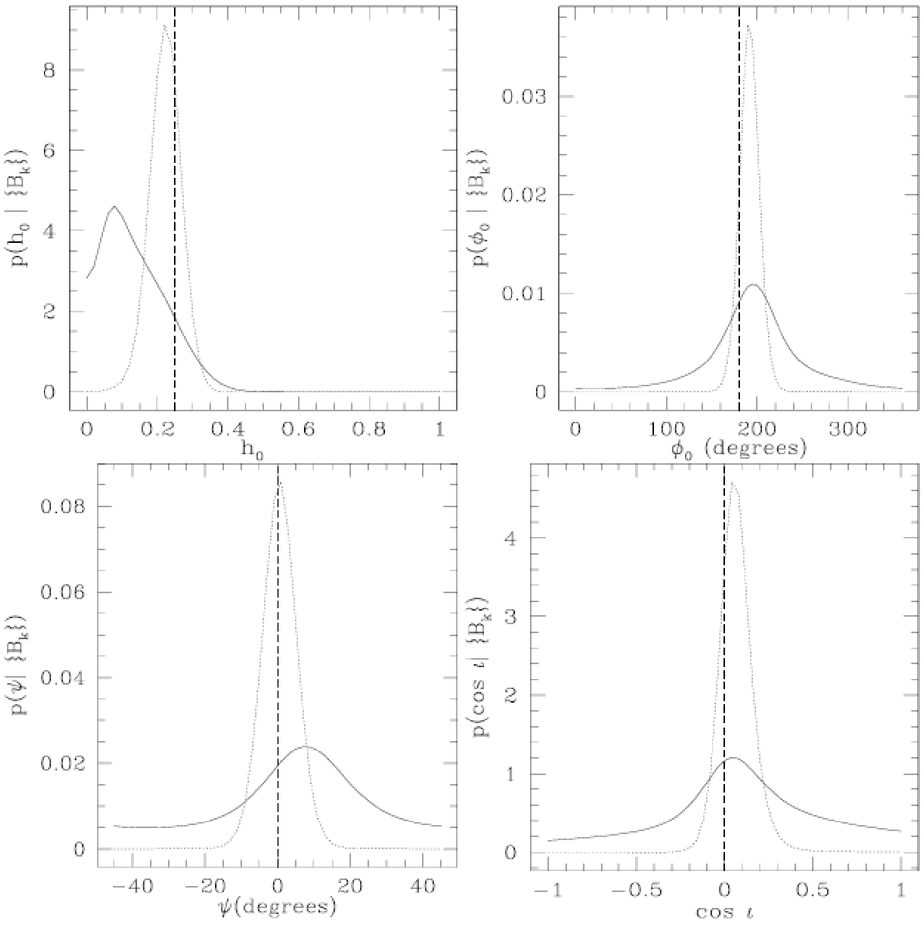


$$p(\{B_k\}_{\rm Joint}|\mathbf{a}) = \prod_{i=1}^{4} p(\{B_k\}_i|\mathbf{a}, i)$$

$$p(\boldsymbol{a}|\mathrm{H1}, \mathrm{H2}, \mathrm{L1}) \propto p(\boldsymbol{a})p(\mathrm{H1}|\boldsymbol{a})p(\mathrm{H2}|\boldsymbol{a})p(\mathrm{L1}|\boldsymbol{a})$$

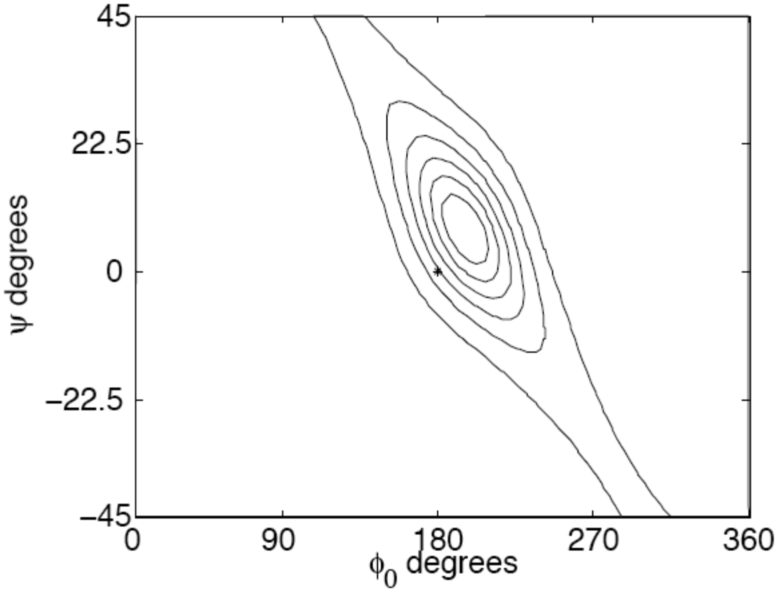
Network analysis

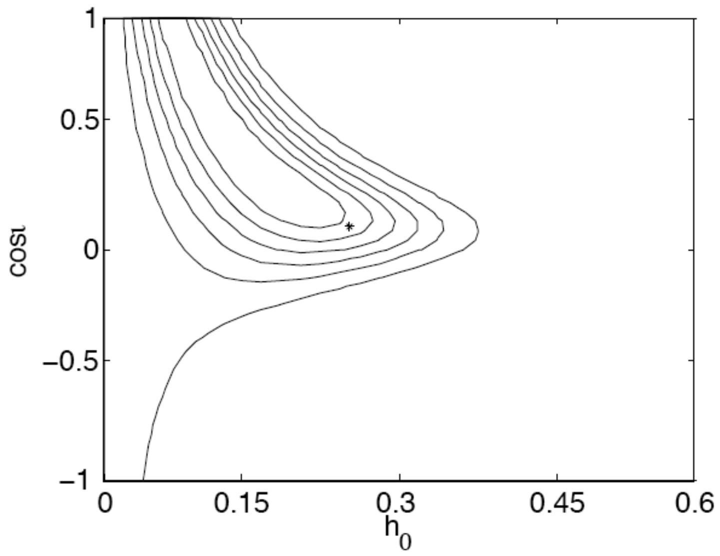
This is an example of a weak signal injected in simulated data. The solid lines shows the marginalized pdfs utilizing only the data from one detector while the dotted line shows the same signal analyzed using data from four detectors coherently.



Covariance between parameters

- When $\cos\iota \neq 0$ then $\cos\iota$ and h_0, as well as ϕ_0 and φ, are strongly anti-correlated.
- The width of the marginal posteriors depends on both the level of the noise and the covariance of the parameters.
- Even under conditions of high signal-to-noise the posterior pdf for h_0 will be widened due to this covariance.

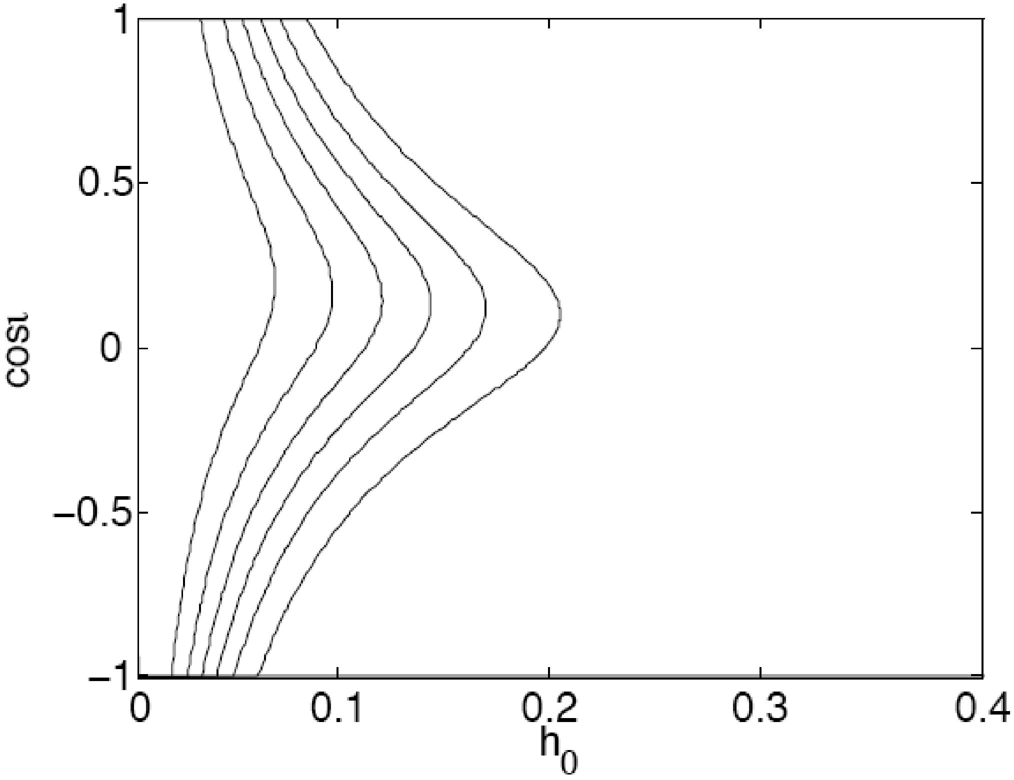




$h_0 = 0.25$, $\cos\iota = 0.1$, $\phi_0 = 180°$, $\psi = 0°$

Covariance between parameters (no signal)

- The flat prior we use for h_0 and the covariance between cosι and h_0 causes the posterior for cosι to peak near zero when no signal is present ($h_{0=}0$).
- No signal is interpreted as the pulsar having an unfavorable orientation.



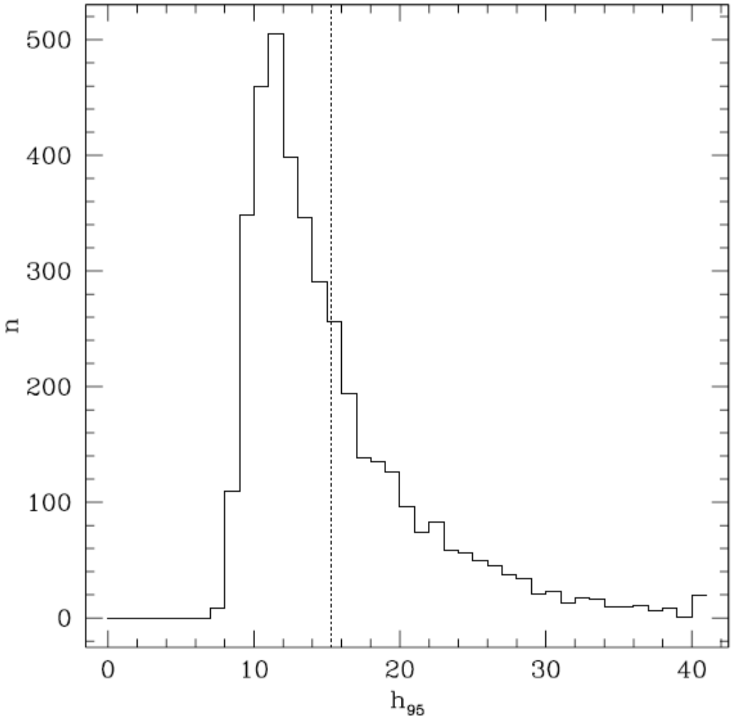
Expected sensitivity

Using simulations we can calculate the average 95% upper limits on h_0 expected from sources randomly located in the sky.

$$\langle h_{95} \rangle = (10.8 \pm 0.2)\sqrt{S_n(f)/T}$$

Where $S_n(f)$ is the single-sided power spectral density and T is the observation time.

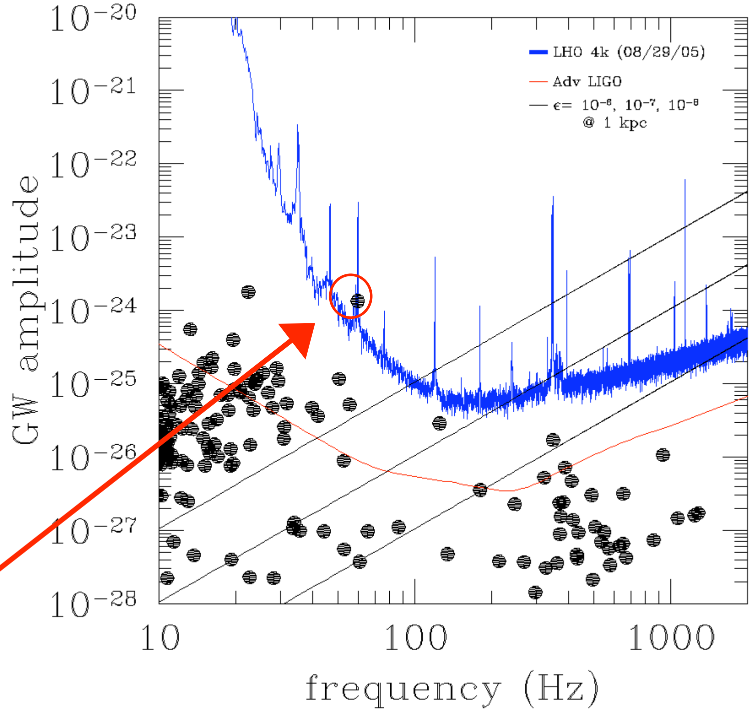
Note that width of distribution is fairly wide so can expect upper limits to vary by factor of two on data of same sensitivity.

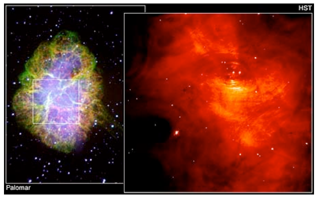


Spindown limits

- Blue line represent average average 95% Bayesian upper limit using 1-year of data at sensitivity post-S4 (LHO 4k).
- Red line for Advanced LIGO.
- Note that spindown limit for the Crab is above current LIGO sensitivity with 1-year observation.
- Several globular cluster pulsars not included since they are seen spinning up (due to pulsar motion).

Black dots show GW amplitude if all rotational energy loss of known pulsars goes to gravitational waves.





Summary of TDS results

- S1 science run
  - Upper limit set for GWs from B1937+21 using both LIGO and GEO data:
    - $h_0 < 1.4 \times 10^{-22}$
- S2 science run
  - First end-to-end validation of analysis method completed via hardware injections
  - Preliminary upper limits set for GWs from 28 known isolated pulsars
  - Special treatment for Crab pulsar to take into account timing noise
- S3 & S4 science runs
  - Additional hardware injections in both GEO and LIGO
  - Added known binary pulsars to targeted search
  - First coherent analysis using LIGO and GEO data
  - Within order-of-magnitude from spindown limit for the Crab
- S5 science run
  - Preliminary study of hardware injections promising
  - Expand number of pulsars in analysis to include new discoveries and old pulsars for which we did not have sufficiently accurate timing information in previous runs.
  - Expand analysis to also consider signals at other frequencies
  - Increase efficiency of code

TDS: S2 analysis

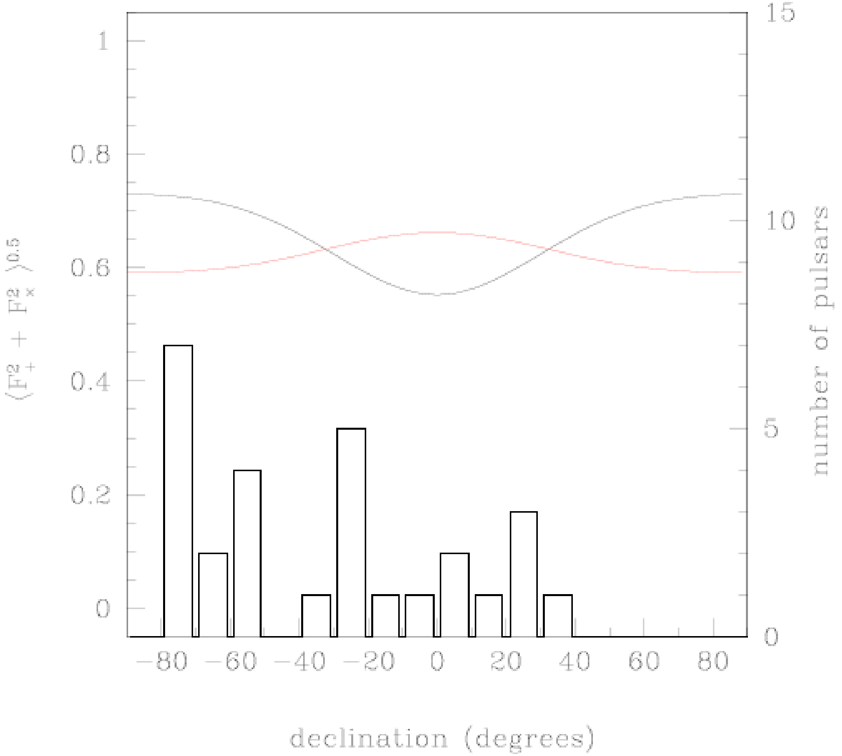
- Analyzed 28 known isolated pulsars with $2f_{rot} > 40$ Hz
  - –Timing information has been provided using radio observations collected over S2 for 18 of the pulsars (Jodrell Bank Pulsar Group)
  - –Timing information from the Australia Telescope National Facility catalogue used for 10 pulsars
- An additional 10 isolated pulsars were known with $2f_{rot} > 40$ Hz but the uncertainty in their spin parameters was such that a search over frequency was warranted
- Analysis limited to continuous 30 minute segments of data, which covers 88% of S2 data.
- Crab pulsar heterodyned to take timing noise into account.
- Observation times:
  - **H1(4 km):** 910 hours (64%)
  - **H2(2 km):** 691 hours (49%)
  - **L1(4 km):** 342 hours (24%)
- First direct GW upper limits for 26 of the 28 pulsars.

S2: sensitivity to sky location

Average antenna pattern of LLO (red) and LHO (black)
over the length of the S2 run.

The bars indicate the location of the pulsars in the sky
in intervals of declination.

There are no highly preferential directions in the sky for this analysis.



S2 hardware injections

- Increase confidence in software and timing stability between sites

P1: Constant Intrinsic Frequency

Sky position: **0.3766960246** latitude (radians)

5.1471621319 longitude (radians)

Signal parameters are defined at SSB GPS time **733967667.026112310** which corresponds to a wavefront passing:

LHO at GPS time **733967713.000000000**

LLO at GPS time **733967713.007730720**

In the SSB the signal is defined by

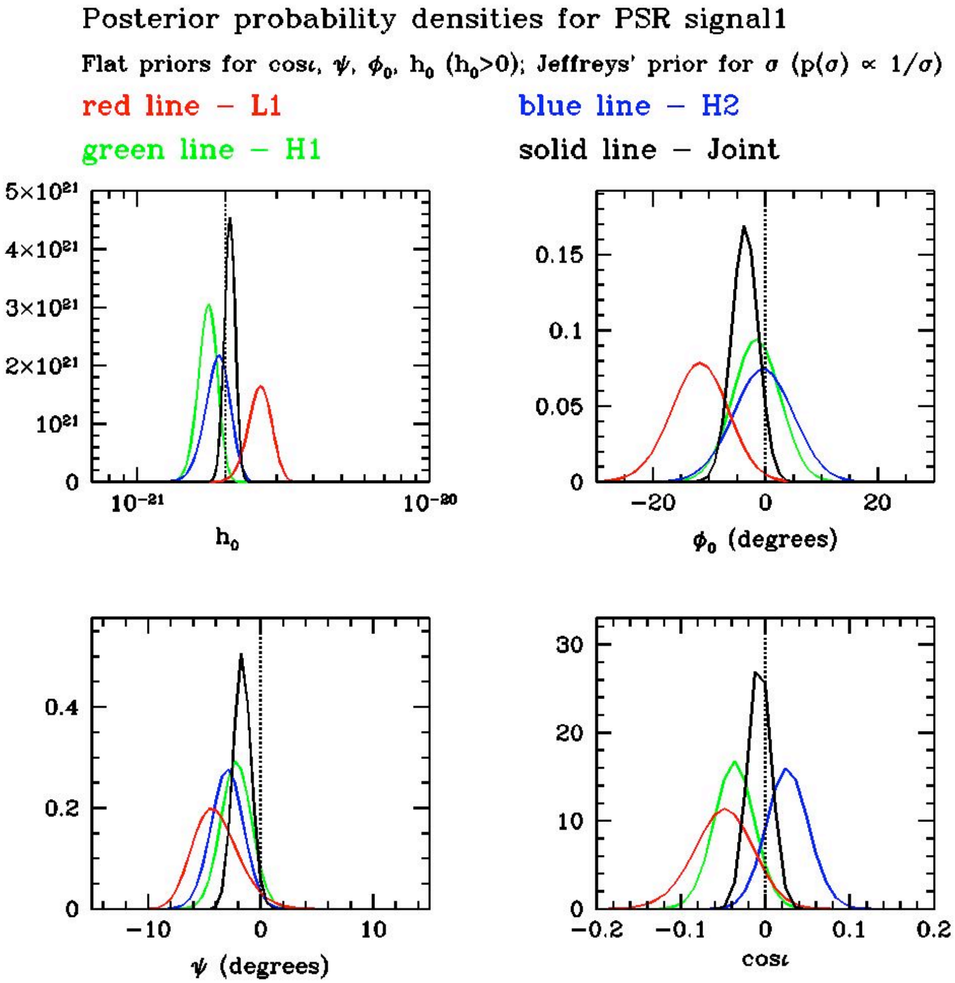
f = 1279.123456789012 Hz

fdot = 0

phi = 0

A+ = 1.0 x 10^{-21}

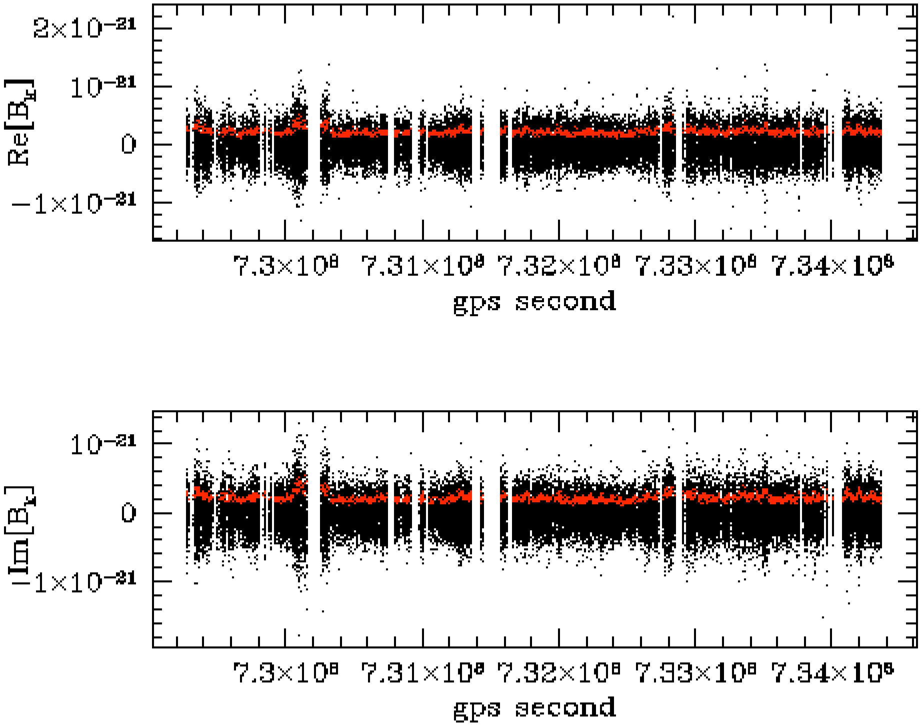
Ax = 0 [equivalent to iota=pi/2]



Stationarity of the S2 data

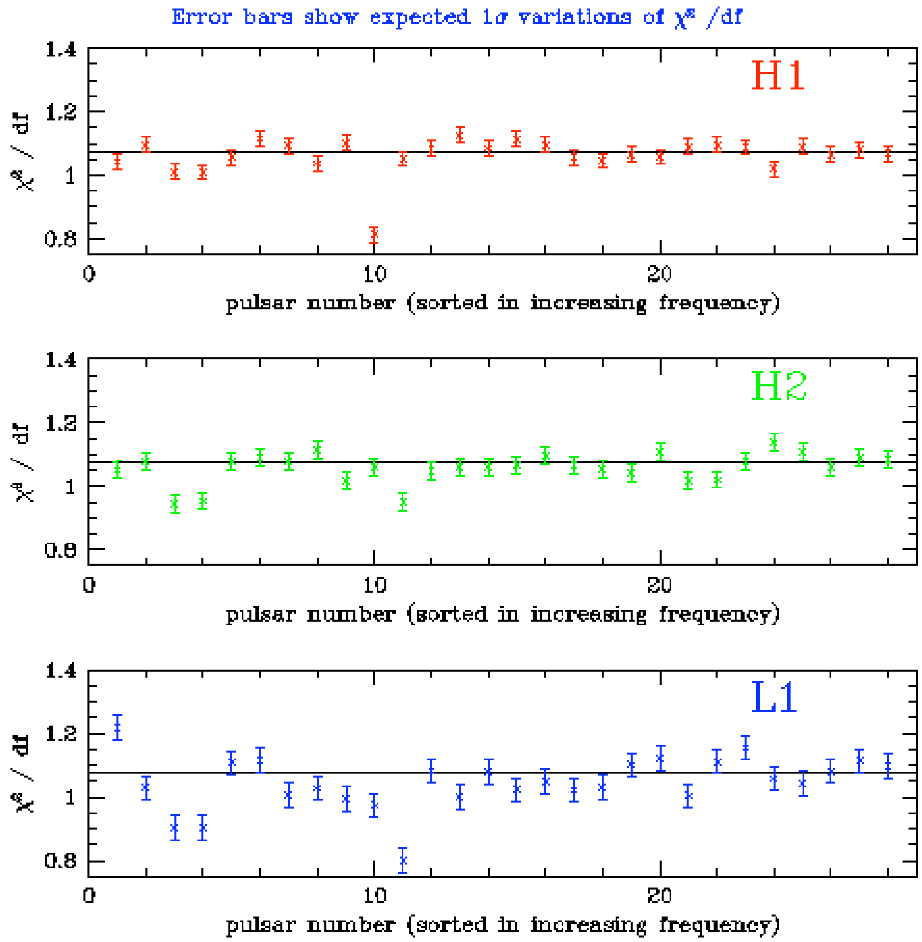
- Bk’s for B1937+21 over 59 days of S2 run
- 1/60 Hz band around Doppler modulated pulsar frequency around 1284 Hz
- Data fairly stationary over 30 min time scale

Time series of B_k’s for PSR B1937+21 for H1
S2 run (Feb 14 – Apr 14, 2003)
The black dots are the Bk's and the red dots
are the sample stdev of segments of 30 Bk's



Characterization of S2 data

The data, the Bk's, are generally consistent with coming from a normal distribution.



$$\chi^2_R = \frac{1}{N}\sum_k \left[\Re(\bar{B}_k)^2/\sigma^2_{\Re\{B_k\}} + \Im(\bar{B}_k)^2/\sigma^2_{\Im\{B_k\}}\right].$$

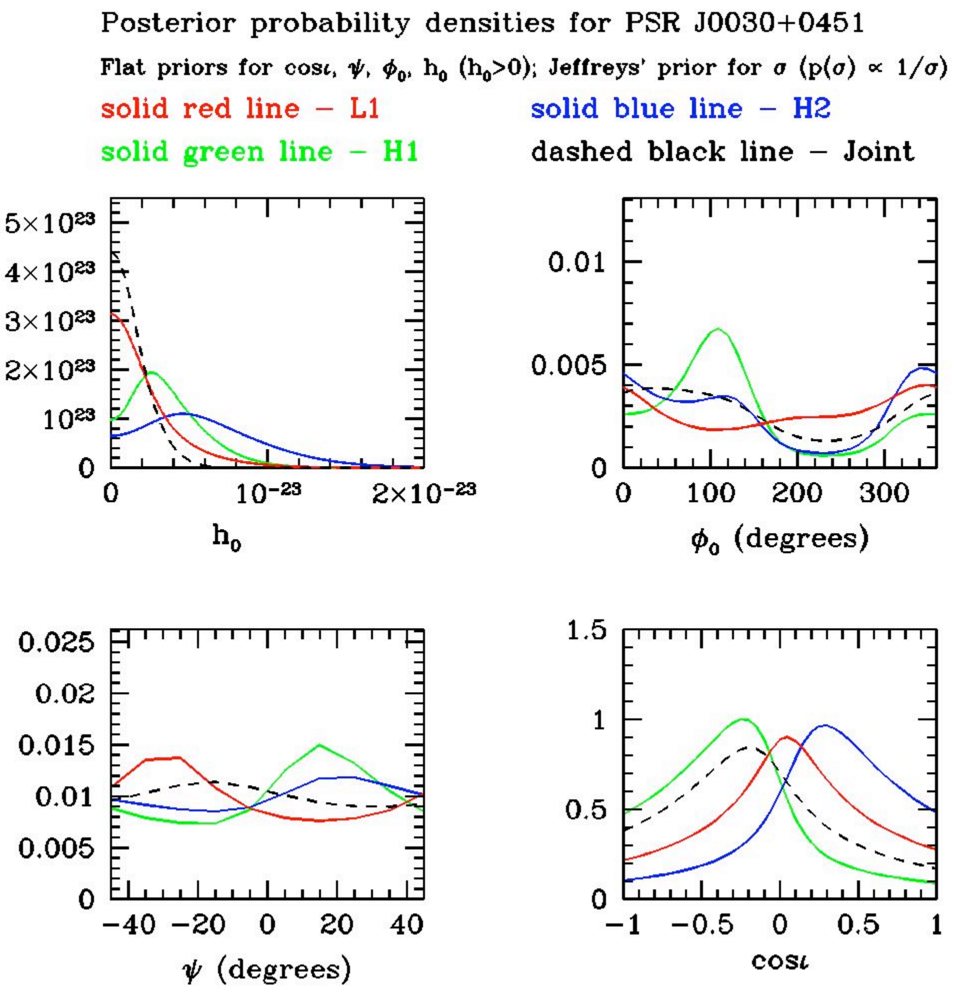
$$\langle\chi^2_R\rangle = \frac{1}{N}\sum_{i=1}^{N} E(t^2) = \frac{r}{r-2}$$

$$\langle\chi^2_R\rangle = \frac{29}{29-2} \simeq 1.074$$

$$\mathrm{var}(\chi^2_R) = \frac{1}{N}\left[\frac{3r^2}{(r-2)(r-4)} - \left(\frac{r}{r-2}\right)^2\right]$$

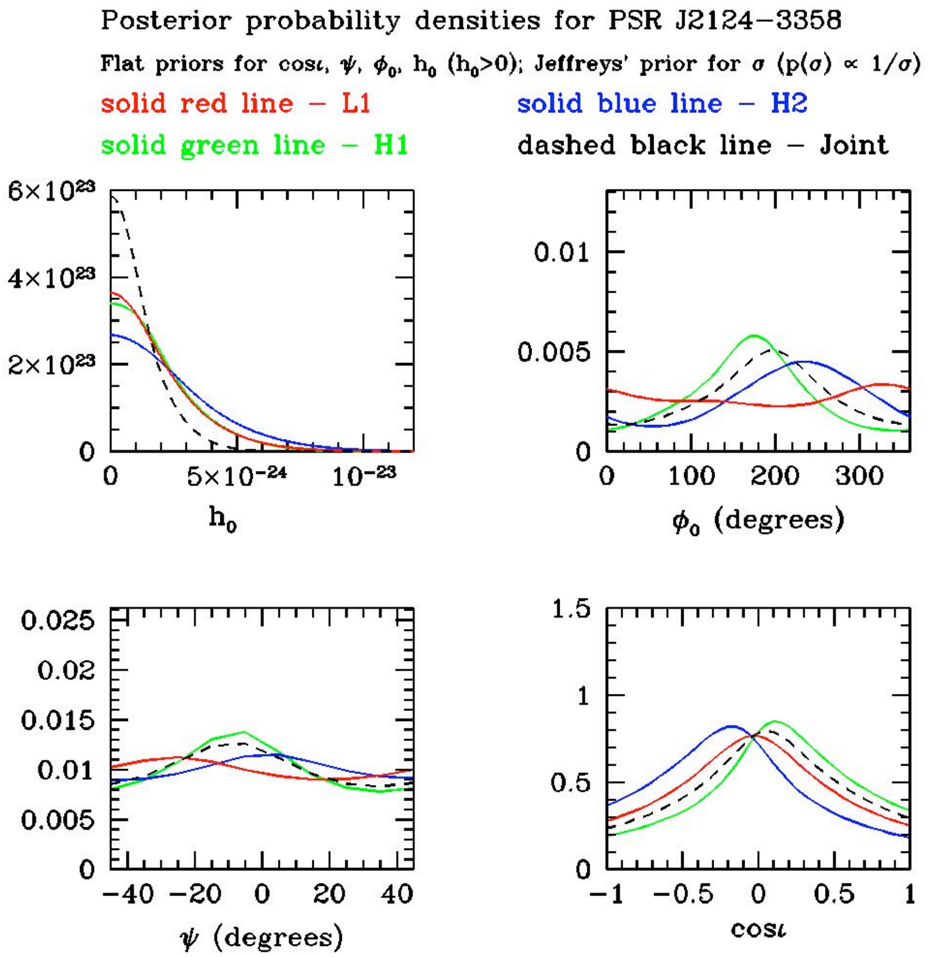
S2: PSR J0030+0451

- This is the closest pulsar in our S2 set at a distance of 230 pc.
- $f_{GW} \approx 411$ Hz
- 95% upper limits were
  - L1: $h_0 < 6.9 \times 10^{-24}$
  - H1: $h_0 < 7.9 \times 10^{-24}$
  - H2: $h_0 < 1.3 \times 10^{-23}$
  - Joint: $h_0 < 3.8 \times 10^{-24}$
  - $\varepsilon < 4.8 \times 10^{-6}$



S2: PSR J2124-3358

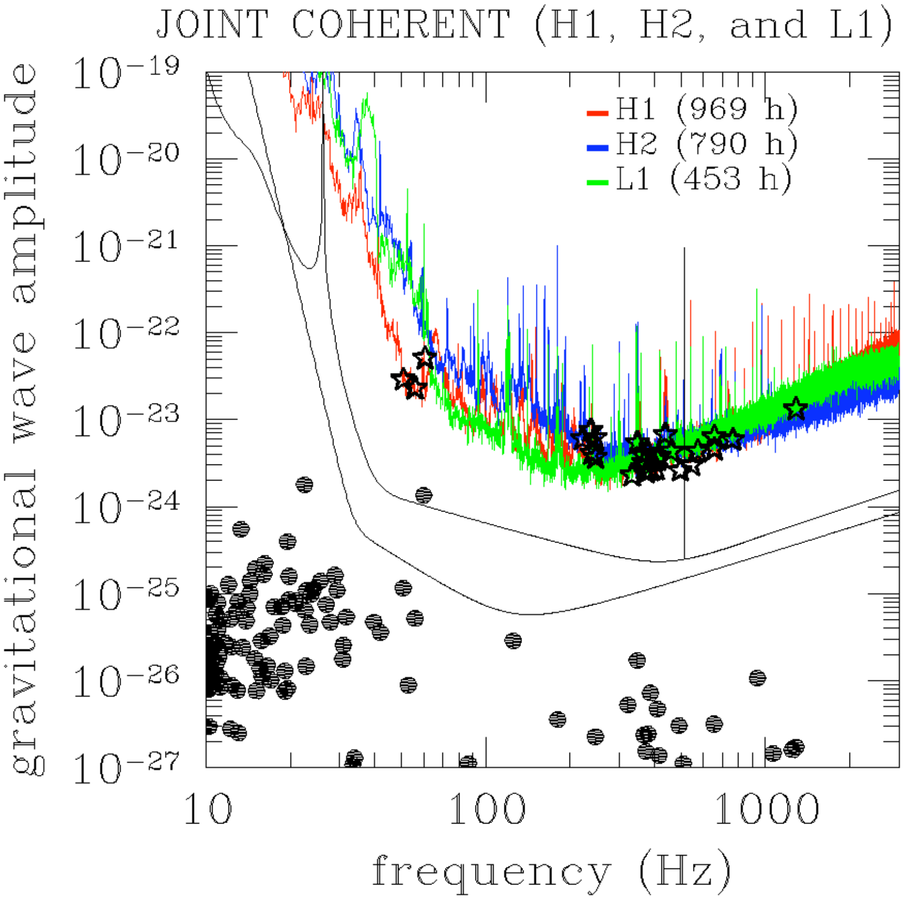
- $f_{GW} \approx 405$ Hz
- distance ≈ 250 pc
- $h_0 < 3.1 \times 10^{-24}$
- Most sensitive ellipticity limit
- $\varepsilon < 4.5 \times 10^{-6}$



While still above maximum expected from conventional models, a solid strange quark stars could sustain such strains (B. Owen, 2005).

S2 upper limits

☆ 95% upper limits



- Performed joint coherent analysis for 28 pulsars using data from all IFOs.
- Most stringent UL was for pulsar J1910-5959D (~221 Hz) where 95% confident that $h_0 < 1.7\times10^{-24}$.
- 95% upper limit for Crab pulsar (~ 60 Hz) was $h_0 < 4.1 \times 10^{-23}$.
- 95% upper limit for J1939+2134 (~ 1284 Hz) was $h_0 < 1.3 \times 10^{-23}$.

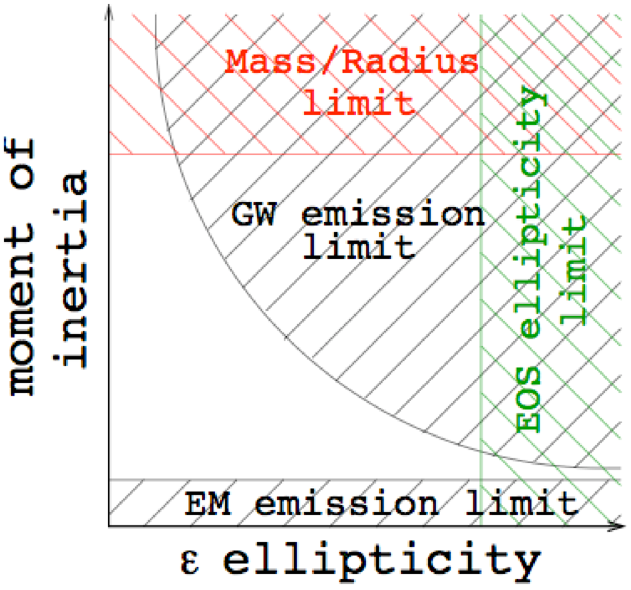
S2 ellipticity limits

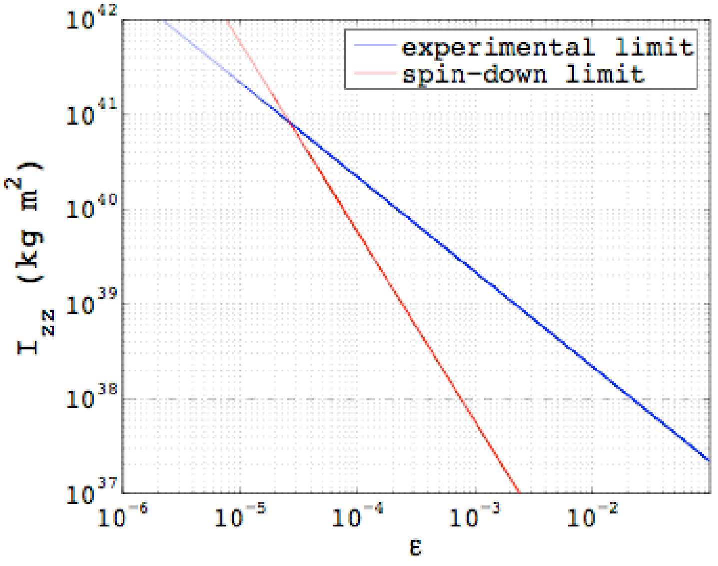
ε UL range	Pulsar
10^{-2}-10^{-1}	B1951+32, J1913+1011, B0531+21
10^{-3}-10^{-2}	-
10^{-4}-10^{-3}	B0021-72D, B1516+02A, J1748-2446C, B1820-30A
10^{-5}-10^{-4}	B1821-24, J1910-5959D, J1910-5959B, J1939+2134, B0021-72C, B0021-72F, B0021-72L, B0021-72G, B0021-72M, B0021-72N, J0711-6830, J1730-2304, J1721-2457, J1629-6902, J1910-5959E, J1910-5959C, J2322+2057
10^{-6}-10^{-5}	J1024-0719, J2124-3358, J0030+0451, J1744-1134

Dark blue: timing checked by Jodrell Bank

Red: ATNF catalogue

S2: Crab I-ε plane limits





Pulsar population statistics

- Can study properties of pulsar population using current pulsar upper limits on strains

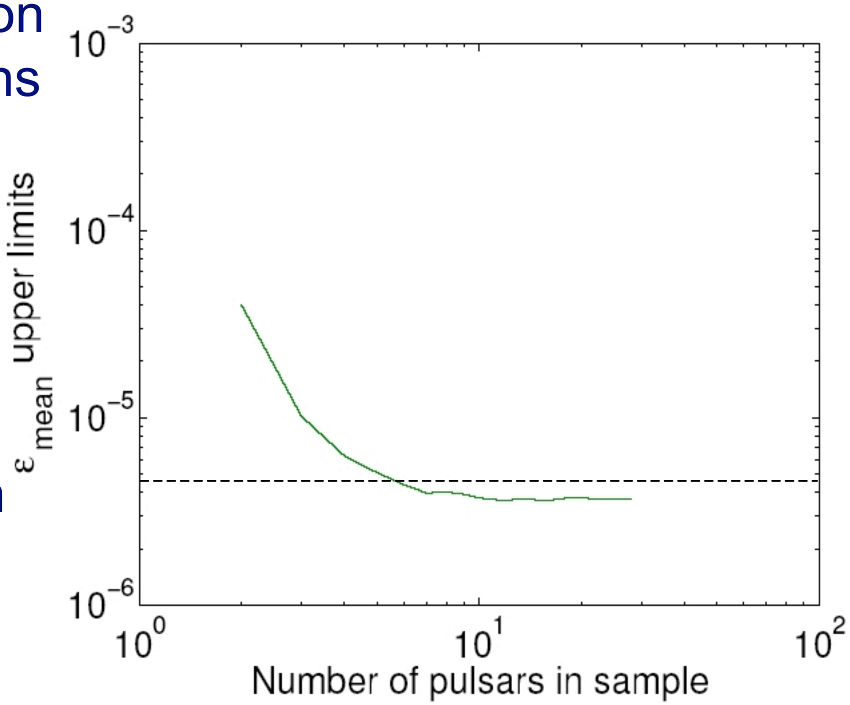
$$p(\bar{\epsilon}|\{P_i\}) \propto \prod_i \int_0^{+\infty} p(P_i|\epsilon)\ \ p(\epsilon|\bar{\epsilon}) d\epsilon$$

$$p(P_i|\epsilon) \propto p(h_0|P_i)$$

- Use least informative prior distribution for average ellipticity of pulsar population (maximum entropy)

$$p(e|\bar{\epsilon}) = \frac{1}{\bar{\epsilon}} e^{-\epsilon/\bar{\epsilon}}$$

- Upper limit on <ε> about 50% lower than limit on ε for any individual pulsar. For Adv. LIGO most nearby pulsars, UL ~10^{-9}.



This plot shows how 95% upper limit on <ε> improves as less sensitive pulsars are added to the sample used to infer <ε> using LIGO S2 data. The dashed lined represents the best individual upper limit on ε in S2.

SURF student: Milivoje Lukic

TDS: S3/S4 analysis

- There are ~150 known pulsars with f_0 > 25 Hz, many of them in binary systems which were not included in the S2 analysis

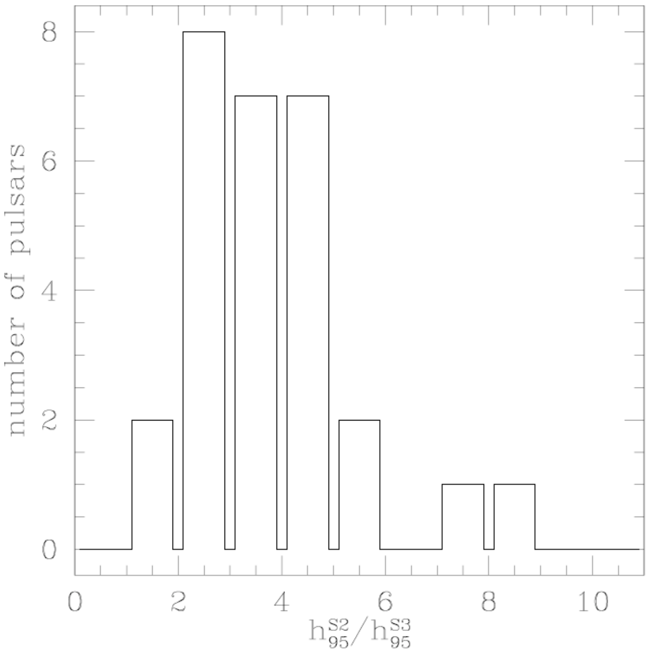
- Need extra terms in the timing to account for motion in the binary.

- We have sufficiently accurate timing information for ~80 of these pulsars provided to us by the Pulsar Group at JBO.

- We injected 10 isolated pulsar signals in the LIGO IFO's during S3 and S4.

- An extra 2 pulsars with Doppler shifts consistent with having a binary companion were injected in the last few days of S4 to check the binary demodulation code.

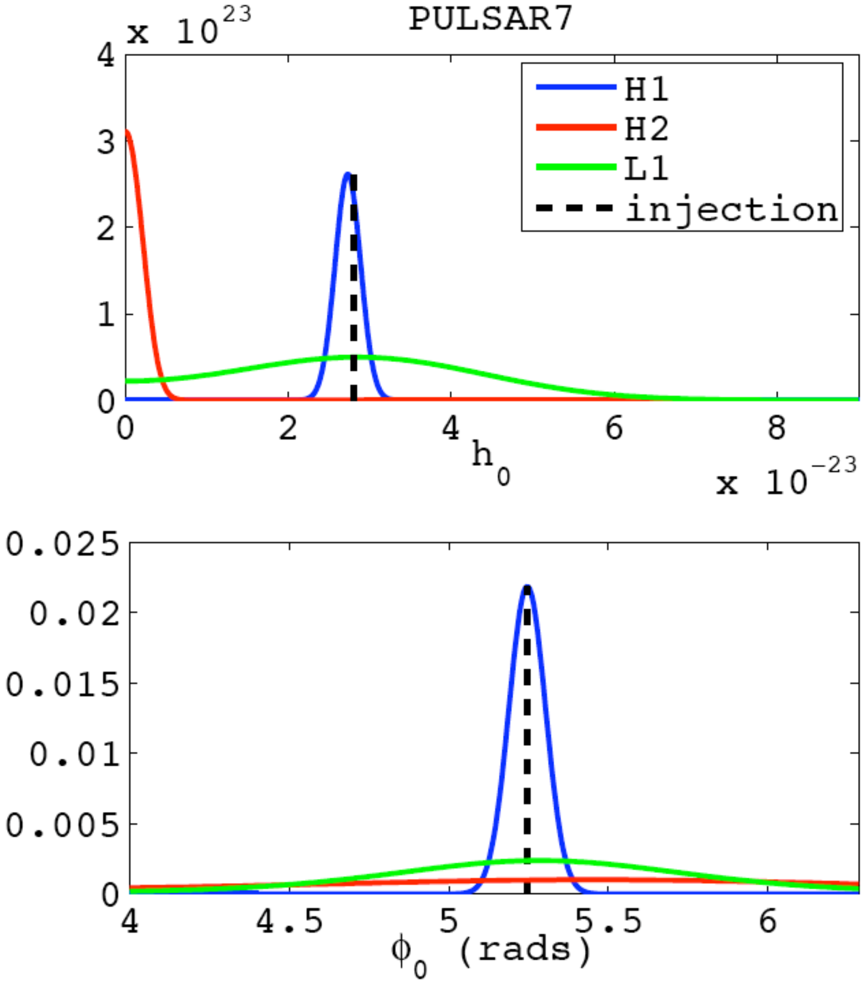
Significant improvements with S3 data in upper limits on 28 pulsars analyzed during S2.



S3/S4 hardware injections

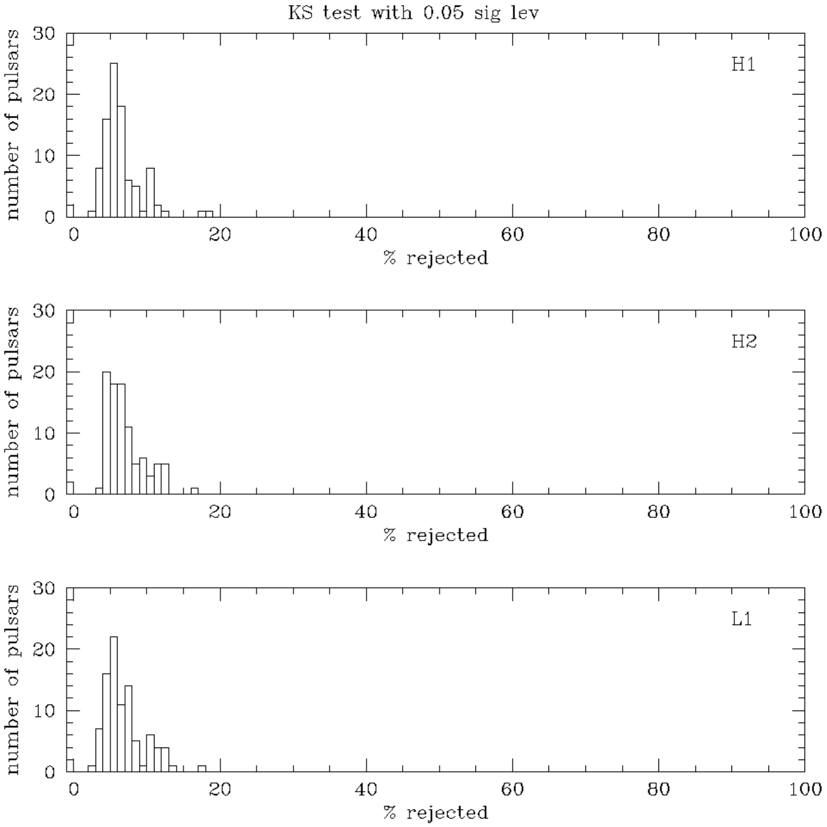
10 signals imitating isolated pulsars were injected in the IFO’s during part of the S3 and S4 runs. An additional 2 binary pulsar signals were injected in the last days of S4.

Generally well understood with a few ‘minor’ problems. For example, one of the pulsars in H2 was accidentally injected with an amplitude 1/60th of intended value.

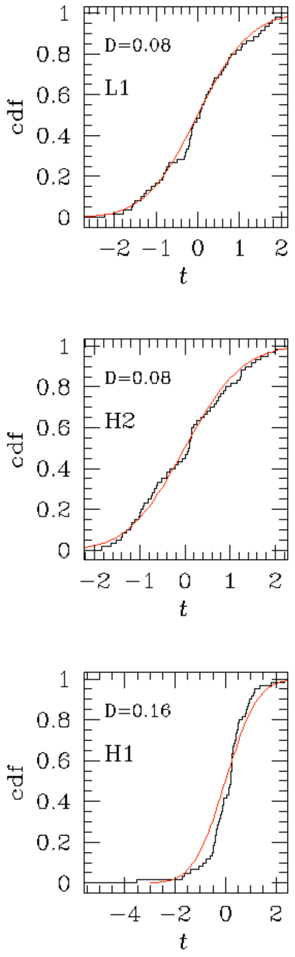


S4 noise - KS test sanity check

Generally narrow-banded heterodyned data is well described by Gaussian distribution for all pulsars.



e.g. 30 min in Crab band



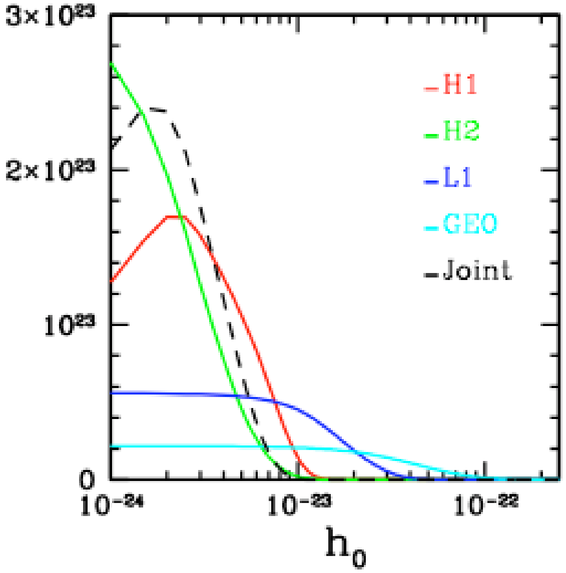
First coherent LIGO-GEO analysis

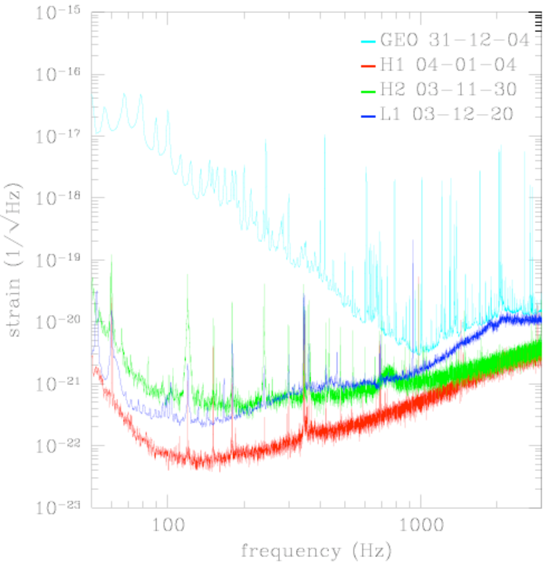
- Successfully injected pulsar signals simultaneously in GEO and LIGO

- Increased confidence in timing between sites.

- For B1937+21 we have a preliminary joint multi-detector upper limit using only S3 data of $h_0 < \sim 5 \times 10^{-24}$.

- When we include S4 data upper limit reduces by about a factor of two giving preliminary limit of $\varepsilon < \sim 4 \times 10^{-6}$.





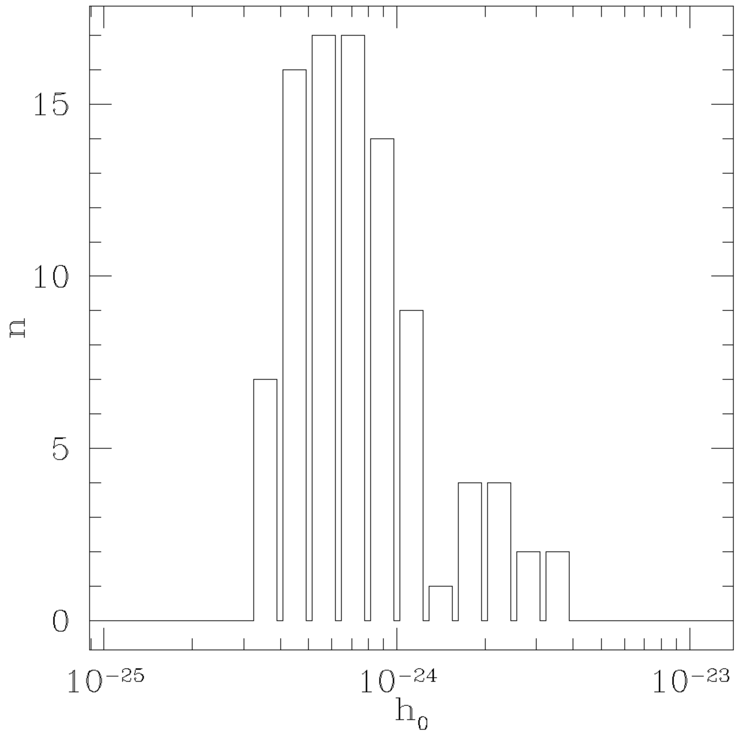
S3/S4 preliminary results

- Best upper limits are for pulsars with f_{GW} in the LIGO ‘sweet spot’ between 100-200 Hz.
- For majority of pulsars $h_0 < 10^{-24}$

E.g., J0737-3039A

binary pulsar system
distance: 560 pc
f_{GW}= 88.1 Hz
$h_0 < \sim 5 \times 10^{-25}$
spindown ratio ~40

Final version of S4 calibration (with ~10% changes) was released on Sunday so the analyses will have to be re-run and the exact distribution of these upper limits may change.



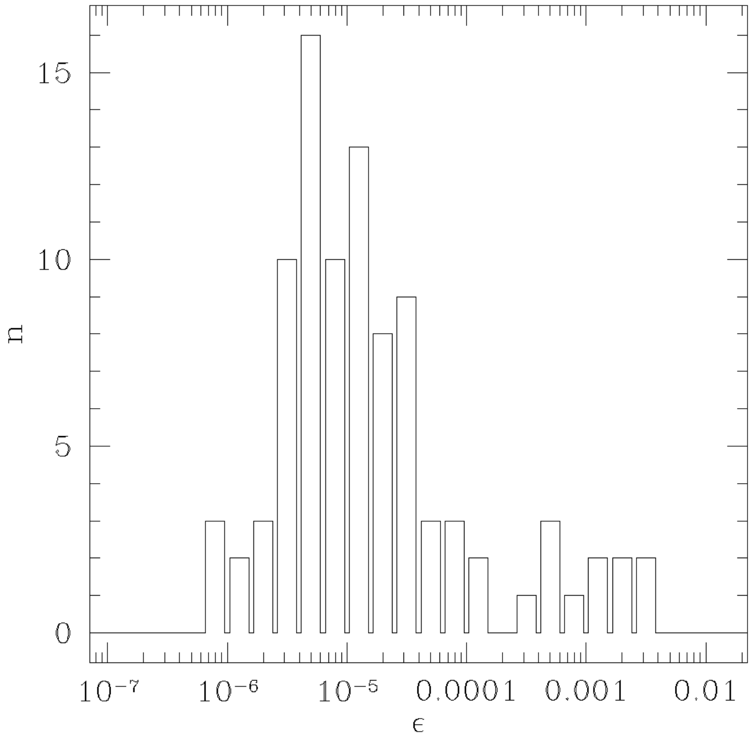
* 13 of the pulsars may have to be excluded from the analysis due to uncertainty in source parameters.

S3/S4 preliminary results

Three best limits on ellipticity are for nearby pulsars

- J2124-3358; 250 pc, 406 Hz
- J1744-1134; 360 pc, 491 Hz
- J0030+0451*****; 230 pc, 411 Hz

where ε is less than ~10^{-6}.



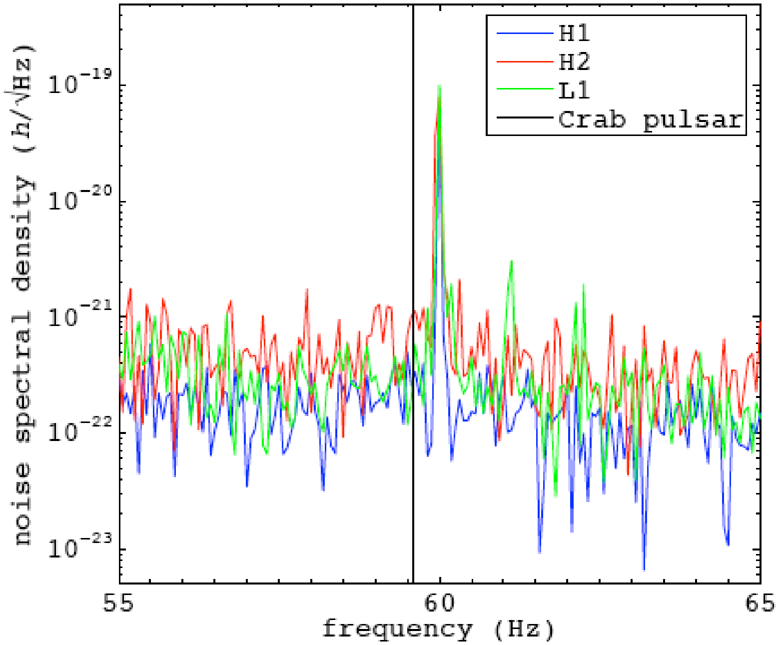
- For about half of pulsars ε < ~10^{-5}

* 13 of the pulsars, including J0030+0451, may have to be excluded from the analysis due to uncertainty in source parameters.

S3/S4 preliminary results: Crab

We are very close to the spindown upper limit for the Crab pulsar in the S3/S4 analysis.

With f_{GW} ~ 59.6 Hz the signal seems to be far enough from the 60 Hz power line not to interfere.



TDS: S5 analysis

- Plan to continue with pulsar hardware injections during the run
    - 10 isolated pulsars and maybe 2 extra later in run
    - The injections will be ‘2 weeks on weeks off’ to ensure we don’t accidentally contaminate all the data

- Might beat spindown limit for the Crab

- Expand list of pulsars to include recently discovered systems

- Provide monthly status report for several pulsars and the injections to notice any specific spectral lines causing problems early

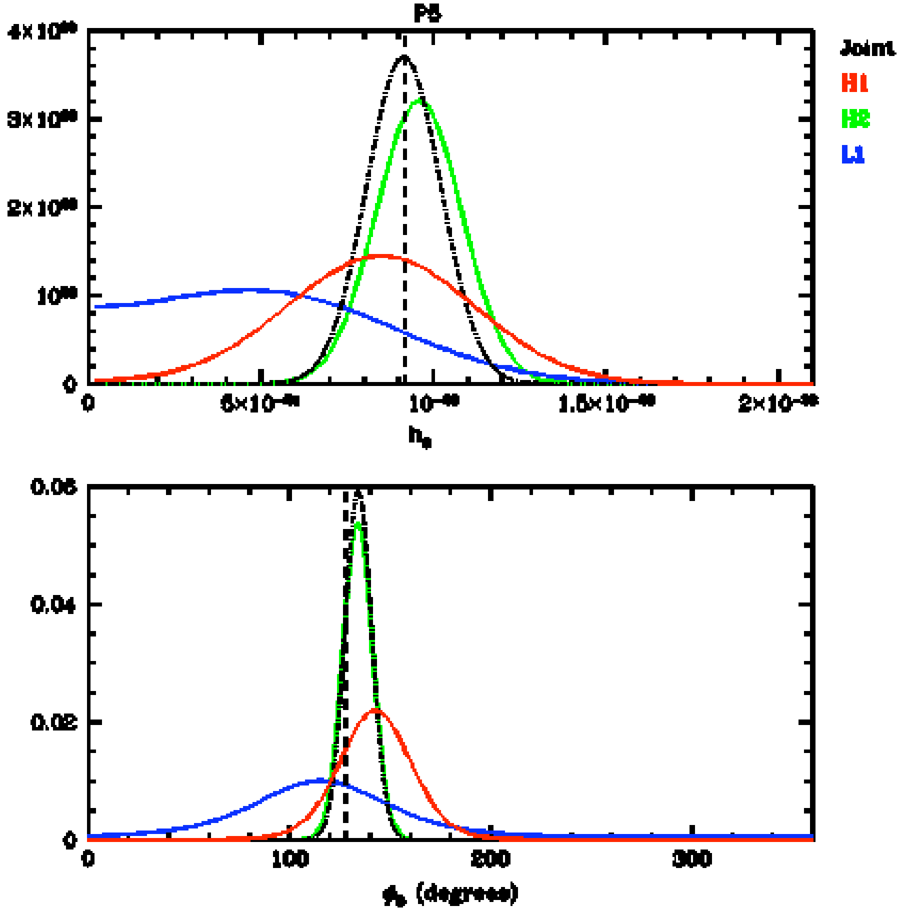
S5 hardware injections: P5

23 Nov - 6 Dec, 2005

$h_0 = 9.2 \times 10^{-24}$
$\phi_0 = 128°$
$\psi = -21°$
$\cos\iota = 0.46$

$f_{GW} = 52.8$ Hz

$\alpha = 5.28$ rads
$\delta = -1.46$ rads



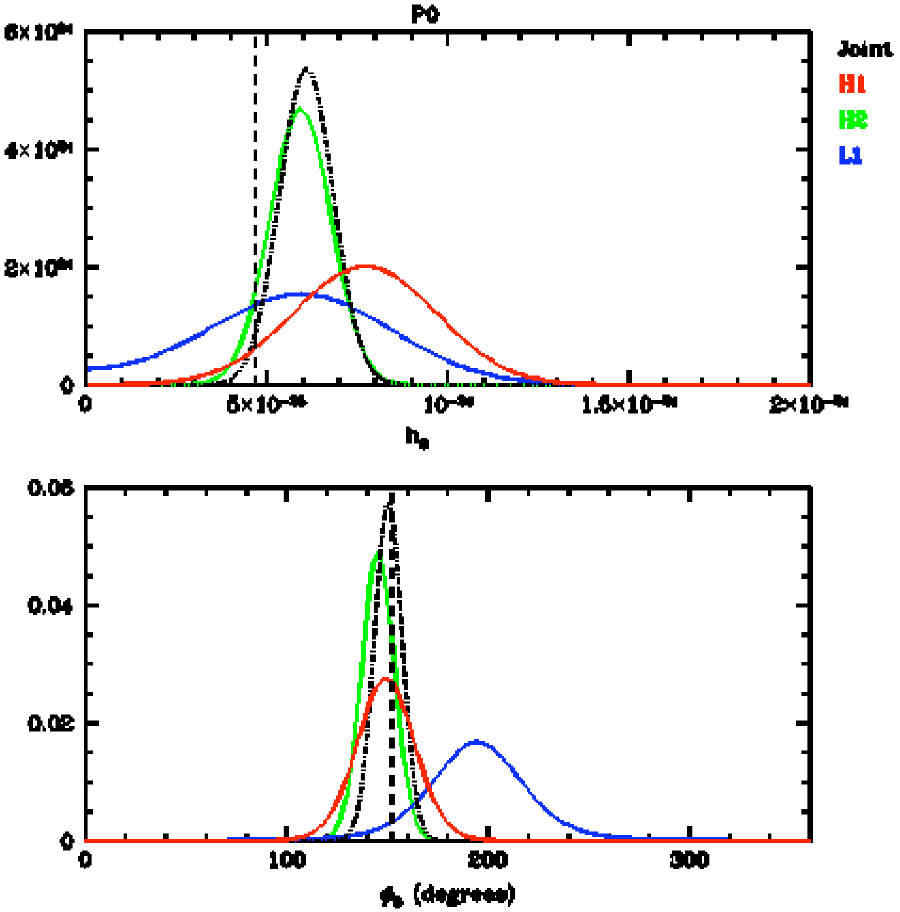
S5 hardware injections: P0

23 Nov - 6 Dec, 2005

$h_0 = 4.7 \times 10^{-25}$
$\phi_0 = 152°$
$\psi = 44°$
$\cos\iota = 0.79$

$f_{GW} = 265.6$ Hz
$d\, f_{GW}/dt = -4.15 \times 10^{-12}$ Hz/s

$\alpha = 1.25$ rads
$\delta = -0.98$ rads



S2: Large parameter space periodic searches

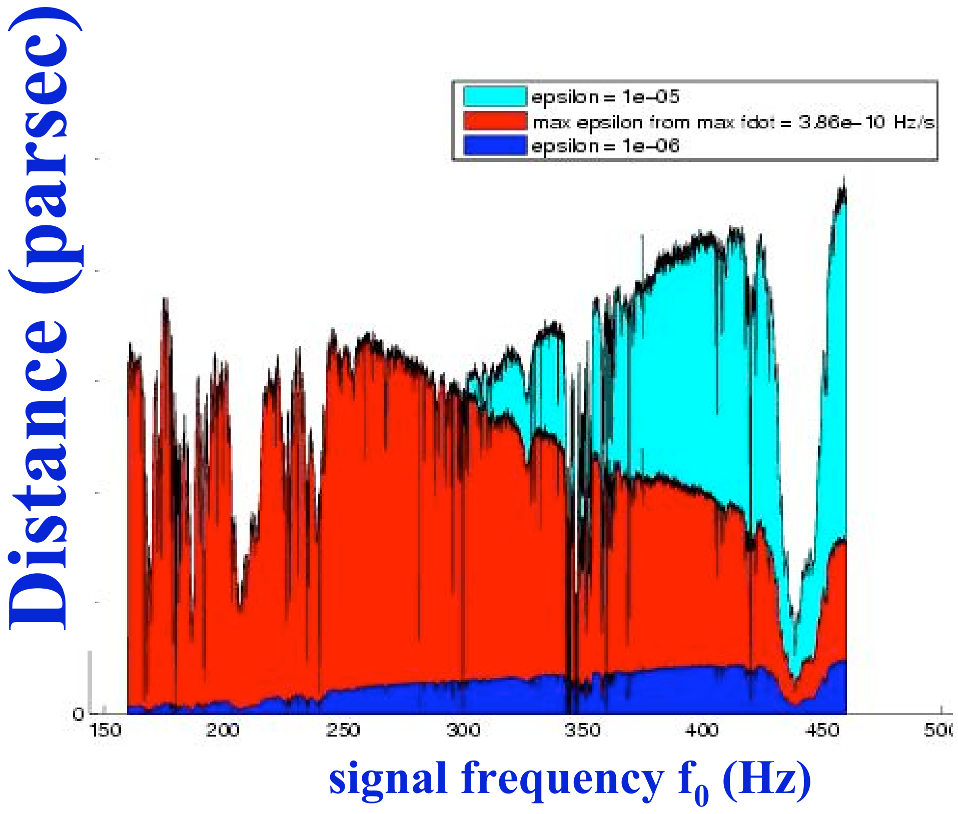
Coherent (F-statistic):

Isolated neutron stars search :

- all sky, no spindown,160 -728.8 Hz
- 10 hours of S2 data, 5 x 10^{12} templates
- preliminary ULs ~6.6 x 10^{-23} (up to ~10^{-21}).
- Range of about 30 pc (looking for unknown in our backyard)

Sco X-1 LMXB search

- orbital parameters
- 464 - 484 HZ & 604 - 624 Hz
- 6 hours of S2 data, 3 x 10^{10} templates
- preliminary ULs
  $h_0^{95\%} \sim 2 \times 10^{-22}$ and $\varepsilon^{95\%} \sim 5 \times 10^{-4}$



Incoherent:

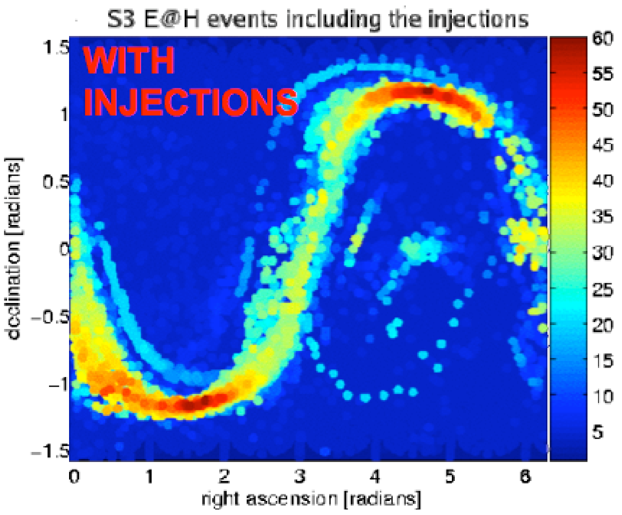
Hough transform:

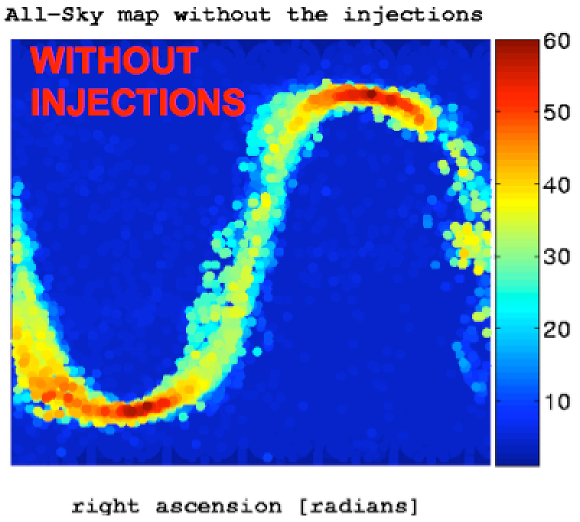
- all-sky, 1 spindown, 200-400 Hz, full S2 data set
- efficient, robust, ULs 4.4 x 10^{-23} (up to ~10^{-21})

(References on page 5)

Einstein@home

- Public distributed computing project to look for isolated pulsars in LIGO/GEO data
- Makes use of coherent F-statistic method
- Currently have 142 000 users and 240 000 computers from 167 countries delivering ~70 Tflops of CPU, 24x7
- Computational workhorse for future LSC pulsar searches
- S3 results show no evidence of strong pulsar signals
- Outliers are consistent with instrumental artifacts



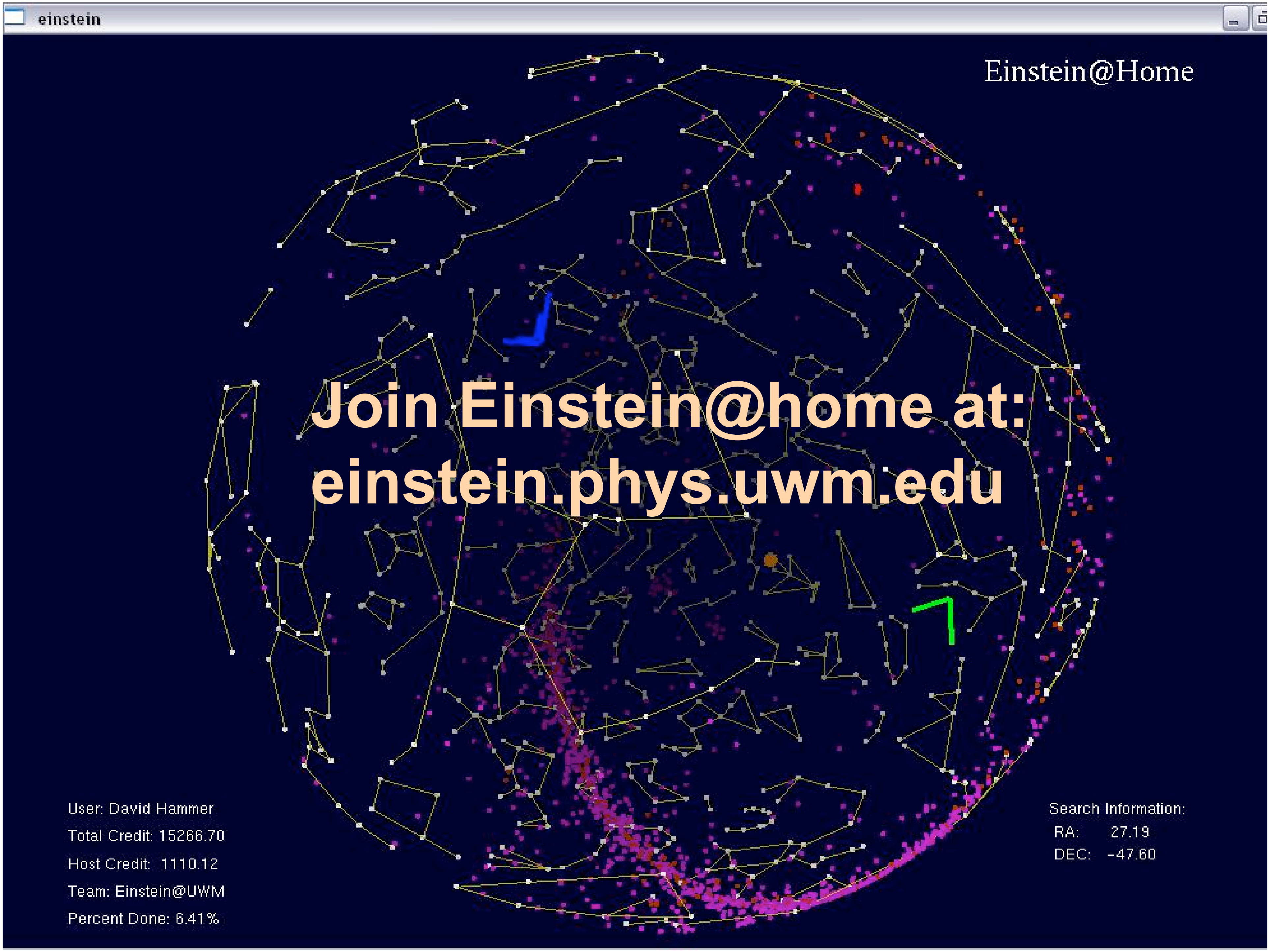


Future plans

- Time domain search
  - Search for signals in S5 data with expanded list of pulsars
- F-statistic coherent search
  - Einstein @ home
    - S3 data: analysis complete. S4 analysis underway
  - Search for signals from Sco-X1 and other LMXBs

- Power-flux, Stack-slide & Hough search
  - S4 data, all-sky, wide band search for isolated pulsars

- Goal is to employ hierarchical schemes which make use of coherent and semi-coherent techniques



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