Results from the LSC
Periodic Sources Working Group

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On behalf of the LIGO Scientific Collaboration

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Recontres de Moriond

Gravitational Waves and Experimental Gravity

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Periodic Sources Working Group

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The group is working on methods to search for continuous gravitational waves from rotating neutron stars:

- We have exercised different analysis pipelines,
- established methods for setting upper limits on the strain amplitude of continuous gravitational waves from known pulsars,
- analyzed data collected during the first science run (S1) of GEO and LIGO,
- set upper limits on waves emitted by pulsar J1939+2134

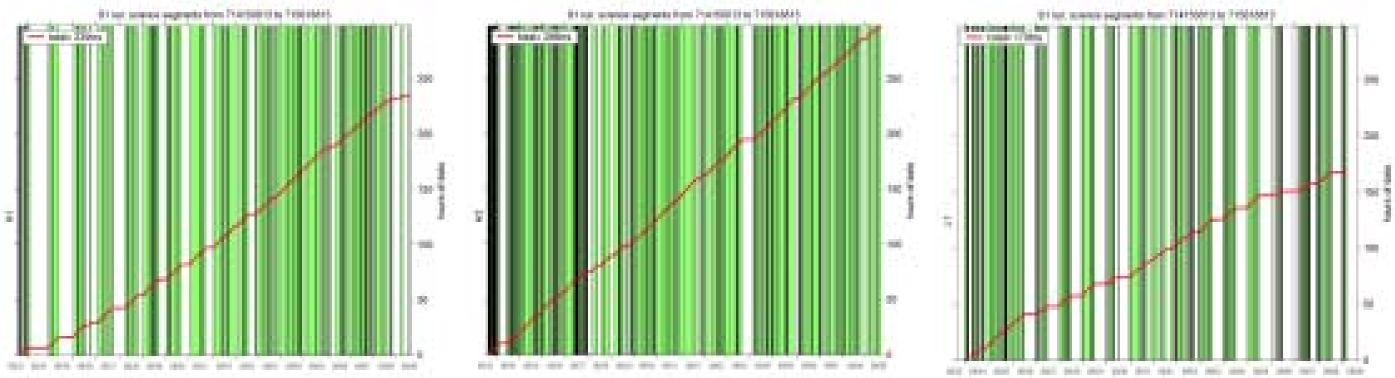
Content

- GEO600 and LIGO first science run (S1)
- Two complementary analysis approaches:
  - time domain method
  - frequency domain method
- Future plans

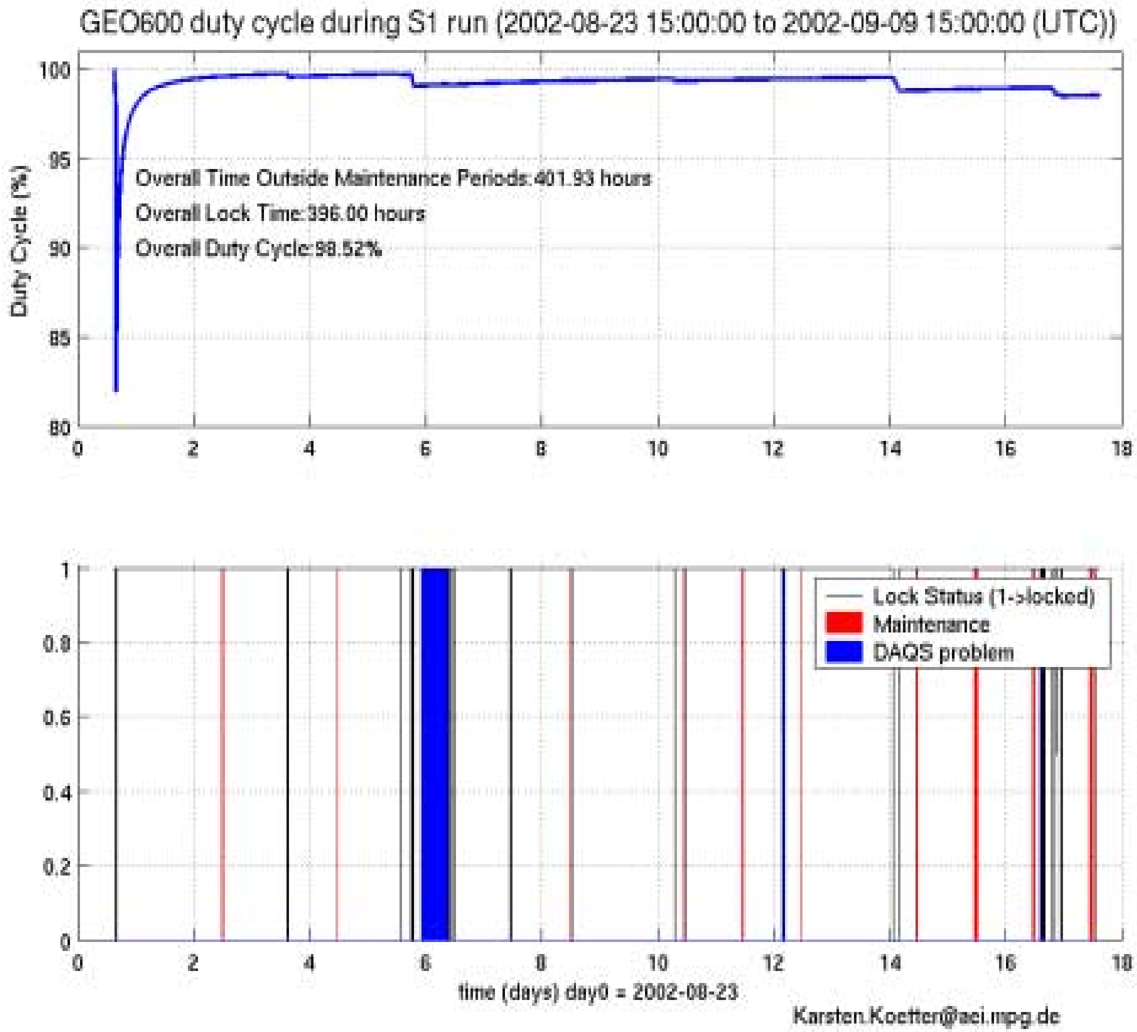
In-Lock Data Summary from LIGO S1

Red lines: integrated up time   Green bands (w/ black borders): epochs of lock

H1: 235 hrs   H2: 298 hrs   L1: 170 hrs



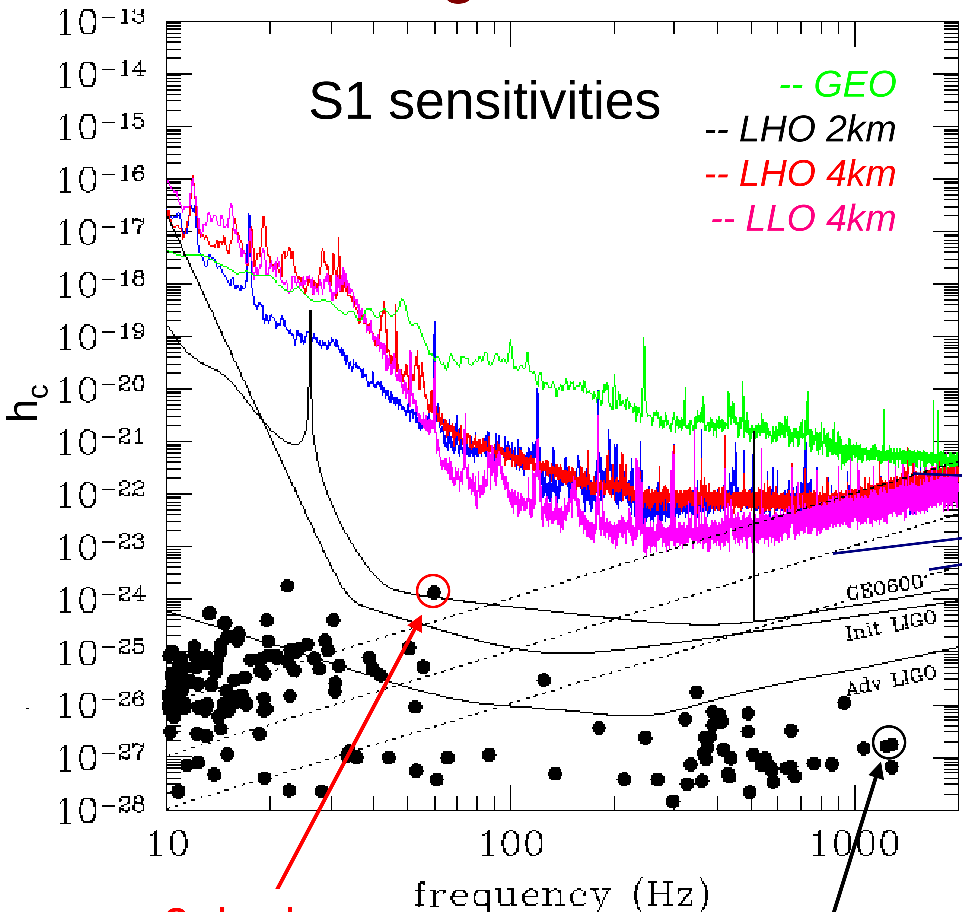
- **August 23 – September 9, 2002: 408 hrs (17 days).**
  - **H1 (4km): duty cycle 57.6% ; Total Locked time: 235 hrs**
  - **H2 (2km): duty cycle 73.1% ; Total Locked time: 298 hrs**
  - **L1 (4km): duty cycle 41.7% ; Total Locked time: 170 hrs**
- **Double coincidences:**
  - **L1 && H1 : duty cycle 28.4%; Total coincident time: 116 hrs**
  - **L1 && H2 : duty cycle 32.1%; Total coincident time: 131 hrs**
  - **H1 && H2 : duty cycle 46.1%; Total coincident time: 188 hrs**
- **Triple Coincidence: L1, H1, and H2 : duty cycle 23.4% ; 95.7 hrs**



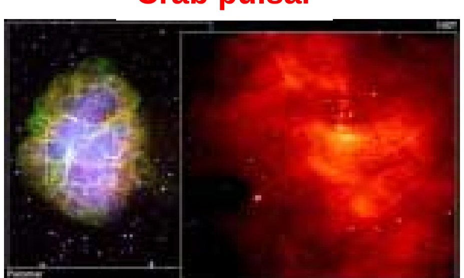
In-Lock Data Summary from GEO S1

- First lock lasted over ~5 days
- Total Locked time: 396 hrs
- Duty cycle: 98.5%
- Including maintenance periods: 453 hrs

Limits on gravitational waves radiated by periodic sources



Crab pulsar



h_c: Amplitude detectable with 99% confidence during observation time T:

$$h_c = 4.2\,[S_h(f)/T]^{1/2}$$

Limit of detectability for rotating NS with equatorial ellipticity, $\varepsilon = \delta I/I_{zz}$:

10^{-3} , 10^{-4} , 10^{-5} @ 10 kpc

***Known** EM pulsars*

Values of h_c derived from measured spin-down

- *IF spin-down were entirely attributable to GW emissions*
- *Rigorous astrophysical upper limit from energy conservation arguments*

PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0519 10^{-19} s/s
D = 3.6 kpc

The signal – a reminder

We use the standard model for the detected strain signal from a non-precessing neutron star:

$$h(t) = \tfrac{1}{2} h_0 F_+(t,\psi)(1+\cos^2\iota)\cos(\omega t + \phi_0) + h_0 F_\times(t,\psi)\cos\iota\sin(\omega t + \phi_0)$$

$F_+, F_\times$	polarisation beam patterns
ψ	polarisation angle
ι	inclination angle
h_0	strain amplitude
ω	signal's (instantaneous) angular frequency
ϕ_0	phase offset

The GW signal from a pulsar will be frequency modulated by the motion and rotation of the Earth, and amplitude modulated due to the varying sensitivity of the detector with respect to a fixed source.

Accurate timing routines (~2μs) have been developed to convert between GPS and SSB time. Maximum phase mismatch ~10^{-2} radians for a few months.

Two signal generation codes.

Two different analysis methods

- Time domain search – process signal to remove frequency variations due to Earth's motion around Sun
    - Best suited for targeted searches
    - Efficiently handless missing data
    - Adaptable to complicated phase evolutions
    - Upper limits interpretation straightforward: Bayesian approach
- Frequency domain search – conceived as a module in a hierarchical search
    - Efficient method for wide parameter searches -when signal characteristics are uncertain
    - Straightforward implementation of standard matched filtering technique (maximum likelihood detection method):
        - Cross-correlation of the signal with the template and inverse weights with the noise
    - Frequentist approach used to cast upper limits.

Time domain target search

Data are successively *heterodyned* to reduce the sample rate and take account of pulsar slowdown and Doppler shift, reducing the data rate to 1 sample per minute B_k

Noise level is estimated from the variance of the data over each minute σ_k

Fit a model to this signal model.

$$y(t;\mathbf{a}) = \tfrac{1}{4} h_0 F_+(t,\psi)(1+\cos^2\iota)e^{2i\phi_0} - \tfrac{1}{2} i h_0 F_\times(t,\psi)\cos\iota\, e^{2i\phi_0}$$

We take a Bayesian approach, and determine the joint posterior distribution of the probability of our unknown parameters, using uniform priors on $h_0, \cos\iota, \psi$ and ϕ_0 over their accessible values, i.e.

$$p(\mathbf{a}\,|\,\{B_k\}) \propto p(\mathbf{a}) \cdot p(\{B_k\}\,|\,\mathbf{a})$$

posterior — prior — likelihood

The *likelihood* is proportional to exp(-χ^2 /2), where

$$\chi^2(\mathbf{a}) = \sum_k \left| \frac{B_k - y(t;\mathbf{a})}{\sigma_k} \right|^2$$

***Marginalize* over the uninteresting parameters to leave the posterior distribution for the probability of h_0:**

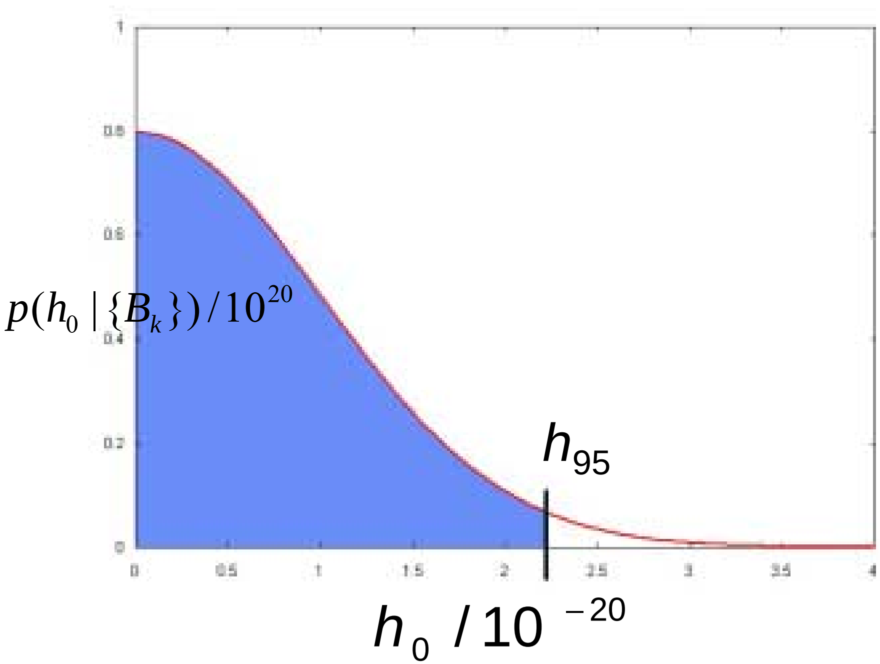
$$p(h_0\,|\,\{B_k\}) \propto \iiint e^{-\chi^2/2}\, \mathrm{d}\phi_0\, \mathrm{d}\psi\, \mathrm{d}\cos\iota$$

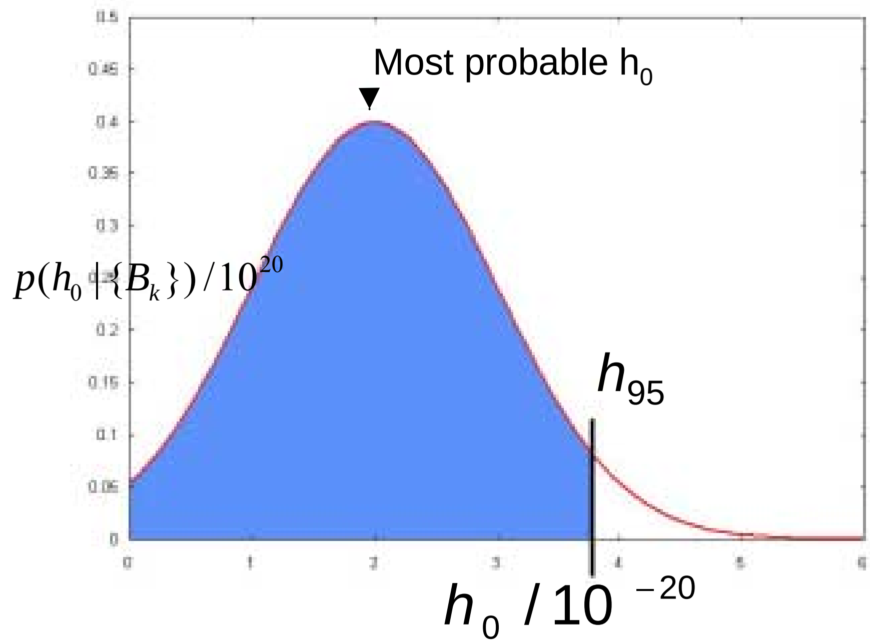
Upper limit definition & detection

The 95% confidence upper limit is set by the value h_{95} satisfying

$$0.95 = \int_0^{h_{95}} p(h_0 \mid \{B_k\})\mathrm{d}h_0$$

A detection would appear as a maximum significantly offset from zero

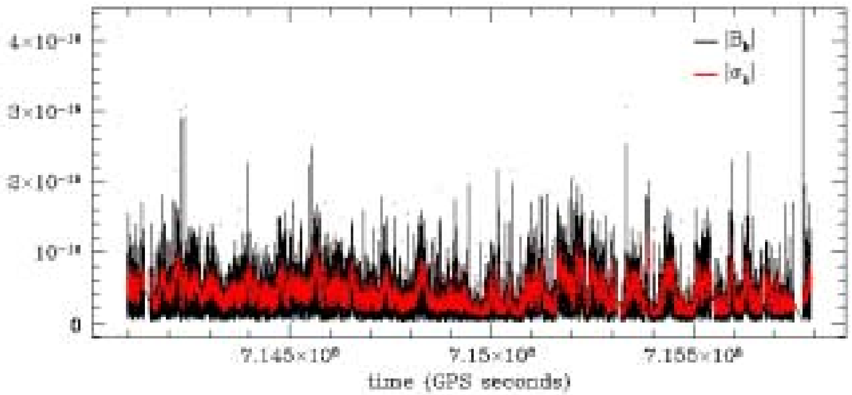


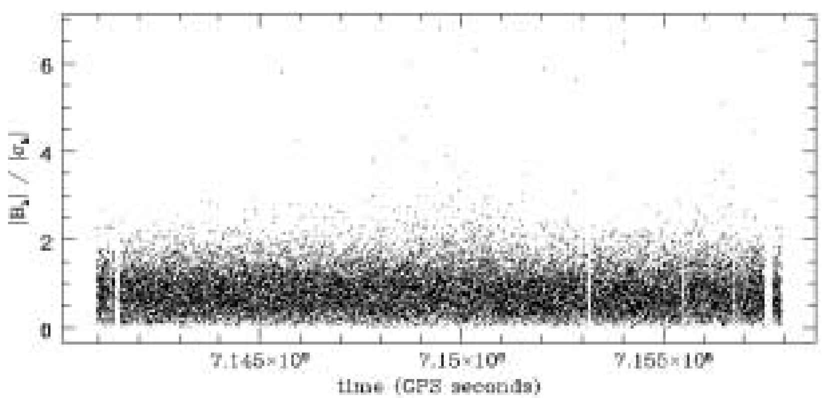


Time domain S1 analysis

- We looked for the expected signal from PSR J1939+2134 at f=1283.86 Hz, with the entire accessible datasets from LHO 2km, LHO 4km, LLO 4km, and GEO.
- Set upper limits from all four interferometers and a joint upper limit.
- Analysis can easily be expanded to other pulsars. PSR1939+2134 is our 'generic pulsar'.

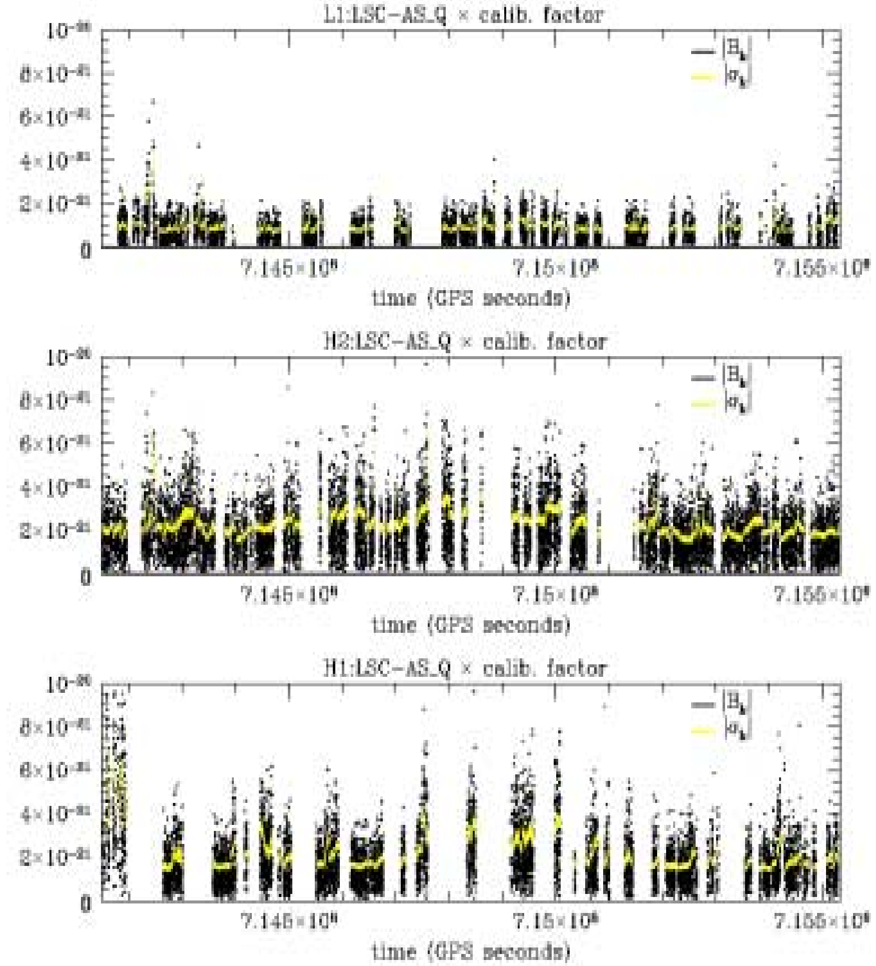
Time series for the GEO S1 data (~20 days). Black line is the heterodyned data, the red dots our estimate of the corresponding noise level.



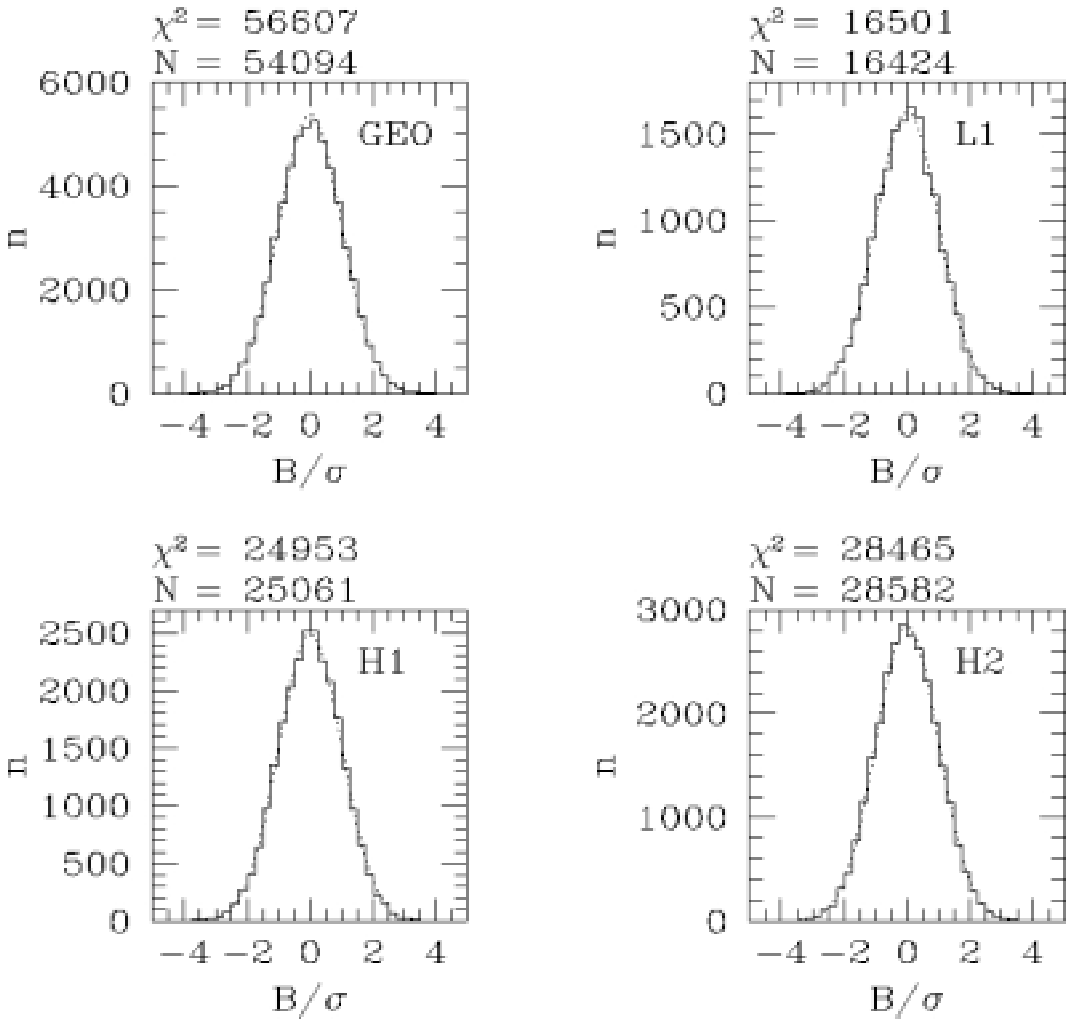


Ratio of |data| / |noise| over the same period. The distribution is close to Gaussian, with the exception of a few outliers.

Data (black) and noise estimates (yellow) for the LIGO S1 datasets.



Gaussianity of B_k data

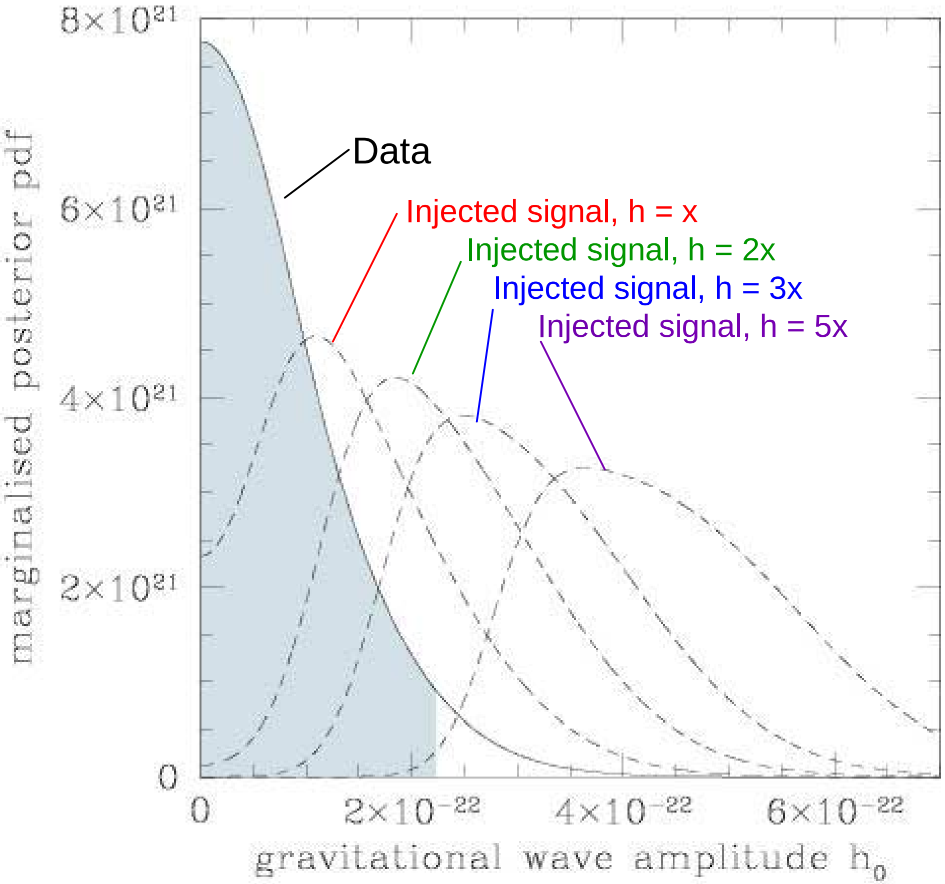


<u>if the data is Gaussian</u>: the histogram should be Gaussian with $\mu=0$ $\sigma=1$. The dots in the figures are the expected distribution.

$$\chi^2 = \sum_{k}^{N/2} \frac{\left|B_k - y(t_k;\vec{a})\right|^2}{\sigma_k^2}$$

N: number of degrees of freedom = 2*number of B_ks

"Results" (EM pulsar) PSR J1939+2134



Time domain analysis:
No evidence of signal from PSR J1939 at f = 1283.86 Hz

Ref. -- $h_{max} < 3 \times 10^{-20}$ *for PSR J1939 -- Hough, J. et al., Nature,* ***303*** *(1983) 216*

$h_{max} < 3 \times 10^{-24}$ *at f =921.35 (+/- 0.03) Hz - Astone, Phys.Rev. D65 (2002) 022001 (untargeted search)*

Frequency domain search

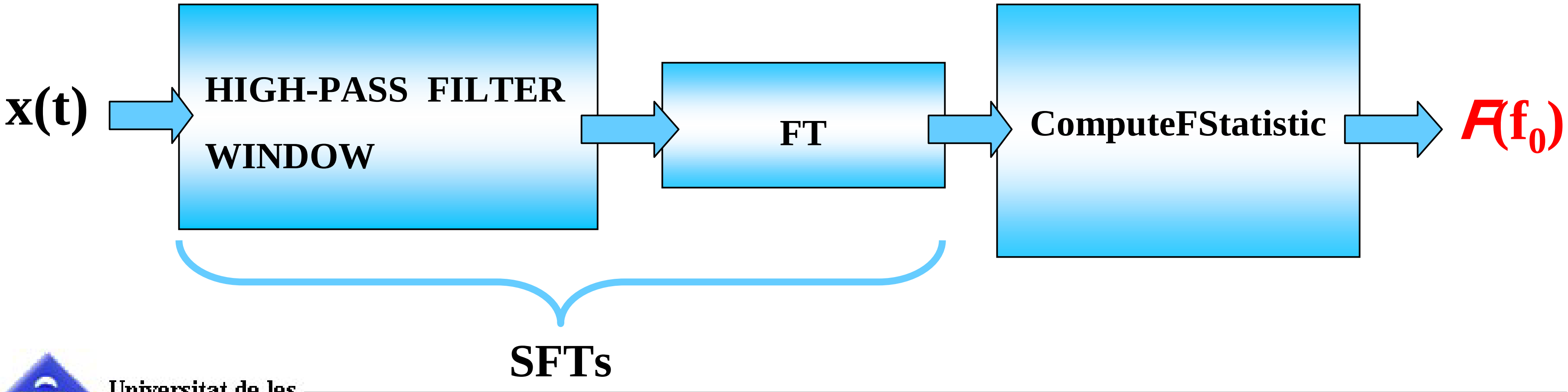
The input data are a set of SFTs of the time domain data, ***with a time baseline such that the instantaneous frequency of a putative signal does not move by more than half a frequency bin*** **(60s for S1 to ensure stationarity)**

Data are studied in a narrow frequency band (0.5 Hz) and $S_h(f)$ is estimated for each SFT.

Detection statistic used is described in *[Jaranoski, Krolak, Schutz, Phys. Rev. D58(1998)063001]*

$h_0, \cos\iota, \psi$ and ϕ_0

The *F* detection statistic provides the maximum value of the likelihood ratio with respect to the unknown parameters, $f_{0min} < f_0 < f_{0max}$ **data and the template parameters that are known**



F statistic & frequentist upper limit

- The outcome of a target search is a number *F** that represents the optimal detection statistic for this search.
- 2*F** is a random variable, for *Gaussian stationary noise*, follows a χ^2 distribution with 4 degrees of freedom. If the *data contains the signal*, 2*F** follows a χ^2 dist. with 4 degrees of freedom and non-centrality parameter λ, $p(2F|\lambda)$. $\lambda \propto (h|h)$
- Fixing ι, ψ and ϕ_0, for every value of h_0, we can obtain a pdf curve: $p(2F \mid h_0)$
- The frequentist approach says the data will contain a signal with amplitude $\geq h_0$, with confidence C, if in repeated experiments, some fraction of trials C would yield a value of the detection statistics $\geq F^*$

$$C(h_0) = \int_{2F^*}^{\infty} p(2F \mid h_0) \mathrm{d}(2F)$$

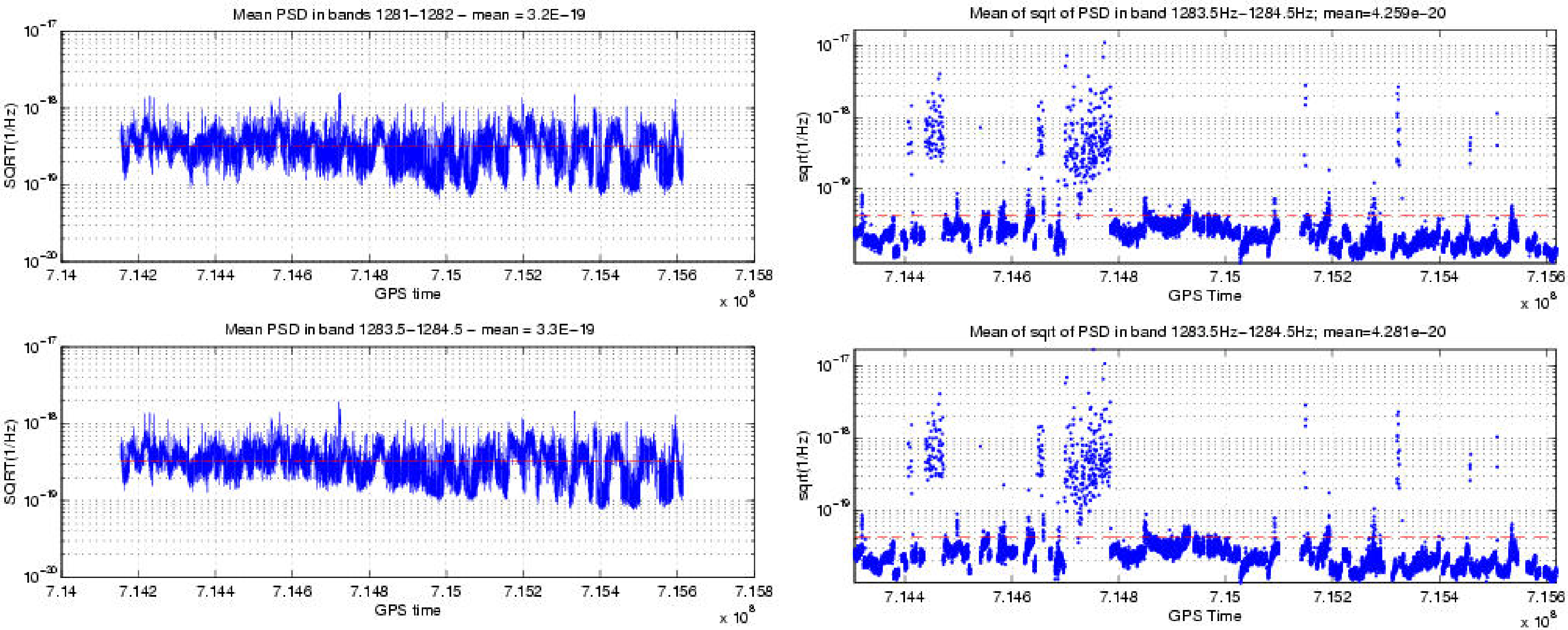
- $h_0(C)$ is the functional inverse of $C(h_0)$
- $p(2F \mid h_0)$ is estimated by means of Monte Carlo simulations, *injecting fake signals with fixed amplitude (for many different h_0), using the worse case for* $\cos\iota, \psi$ and ϕ_0

S1 analysis for PSR J1939+2134

Noise studies

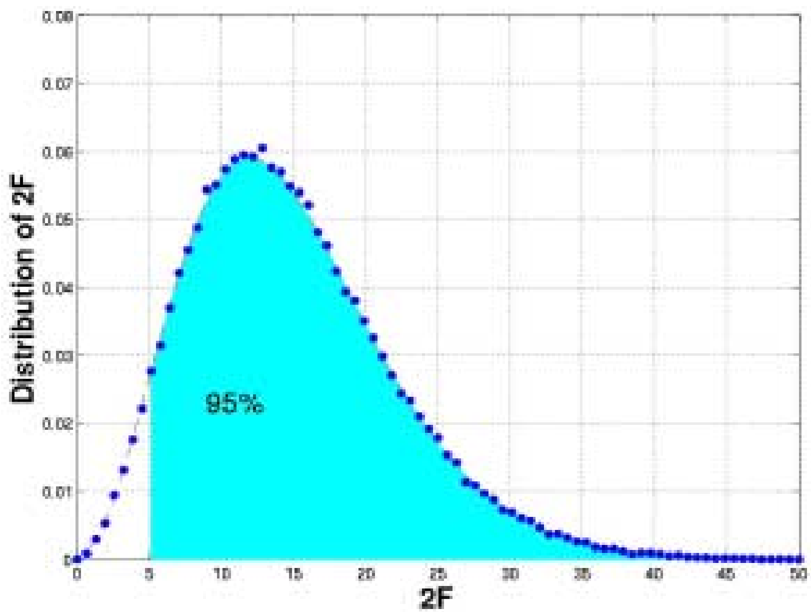
Value of $\langle\sqrt{S_h}\rangle$ over a band of 1Hz over the entire S1 data.

Bands 1281-1282 Hz and 1283.5-1284.5 Hz



GEO **LHO 2km**

Results for PSR J1939+2134 at f=1283.86 Hz



Measured pdf for the *F* statistic

Injected signals at **h_0= ?**

Dots: Monte Carlo simulations

Line: χ^2 distribution (4 dof, λ=?)

Area: integral pdf between 2*F** and ∞

Frequency domain search

The 95% confidence upper limit values of h_0

IFO	*F* *	$h_0(95\%)$	λ_{fit}	λ_{theory}
GEO	0.75	?	?	?
LLO 4km	1.95			
LHO 4km	2.51			
LHO 2km	2.56			

Future plans

- Expand analysis to all known isolated pulsars whose emission frequency lies in the sensitivity band of the detectors
- Extend the targeted searches to pulsars in binary systems (work in progress for LMXRBs, e.g. Sco X-1)
- With time domain method, track systems with complex phase evolutions, e.g. Crab pulsar
- Extend searches to unknown sources using the frequency domain method
- Use incoherent methods (under development) to perform extensive parameter space surveys (e.g. unbias search, Hough transform)