# Setting upper limits on the strength of periodic GWs using the first science data from the LIGO and GEO detectors


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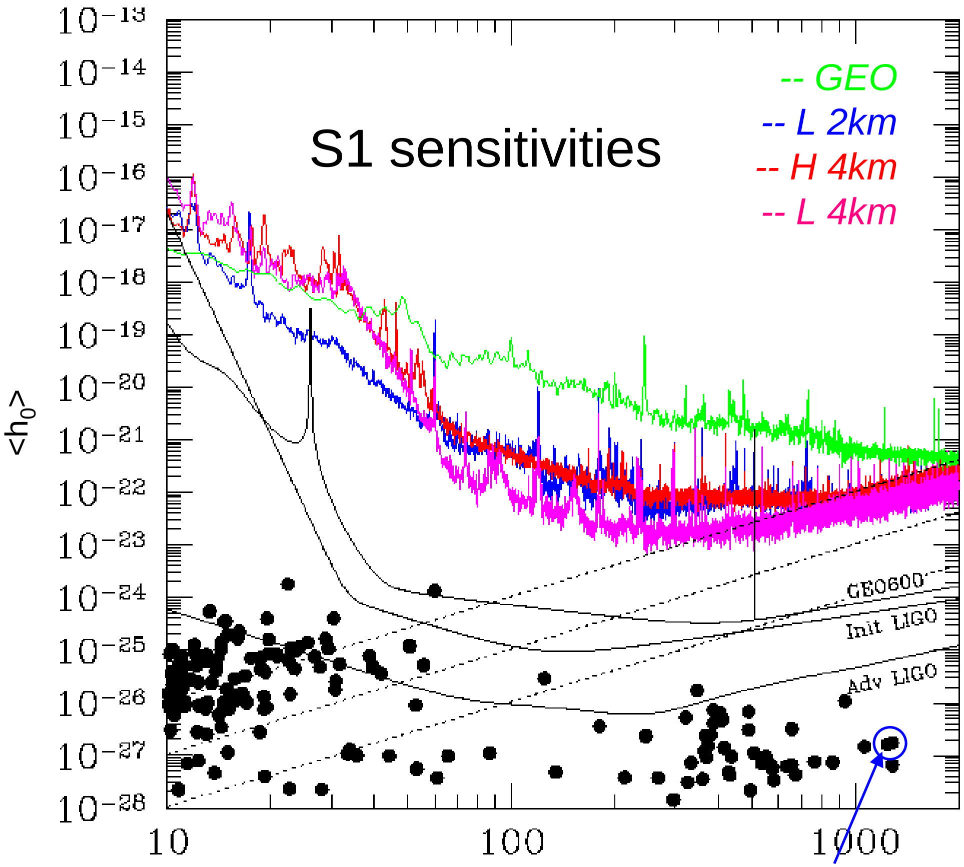
Amaldi Meeting, 9 July 2003

# CW/Pulsars Working Group

- Co-Chairs:
  **Maria Alessandra Papa** (AEI, GEO)
  **Mike Landry** (LHO Hanford, LIGO)
- Search code development work has been underway since mid-to-late 1990s
- For S1: set upper limit on a single known pulsar using two independent methods:
  - » Frequency domain (optimal for large parameter space searches)
  - » Time domain (optimal for targeted searches)
- For S2: set upper limits on all known pulsars and do some wide-area and targeted searches (last slide)

# Expectations for Sensitivity to Continuous Waves from Pulsars




**PSR J1939+2134**
**P = 0.00155781 s**
**$f_{GW}$ = *1283.86 Hz***
**dP/dt = -1.0511 $10^{-19}$ s/s**
**D = 3.6 kpc**

- Colored curves: S1 sensitivity for actual observation time @1% false alarm, 10% false dismissal:

$$\langle h_0 \rangle = 11.4 \sqrt{S_h(f) / T_{obs}}$$

- Solid curves : Expected instrumental sensitivites for **One Year of Data**
- Dotted curves: NS @ 8500 pc with equatorial ellipticities of: $\varepsilon = \delta I / I_{zz} = 10^{-3}, 10^{-4}$, and $10^{-5}$
- Dots: Upper limits on $h_0$ if observed spindown all due to GW emission

**S1: NO DETECTION EXPECTED**

# Known/Unknown Parameters

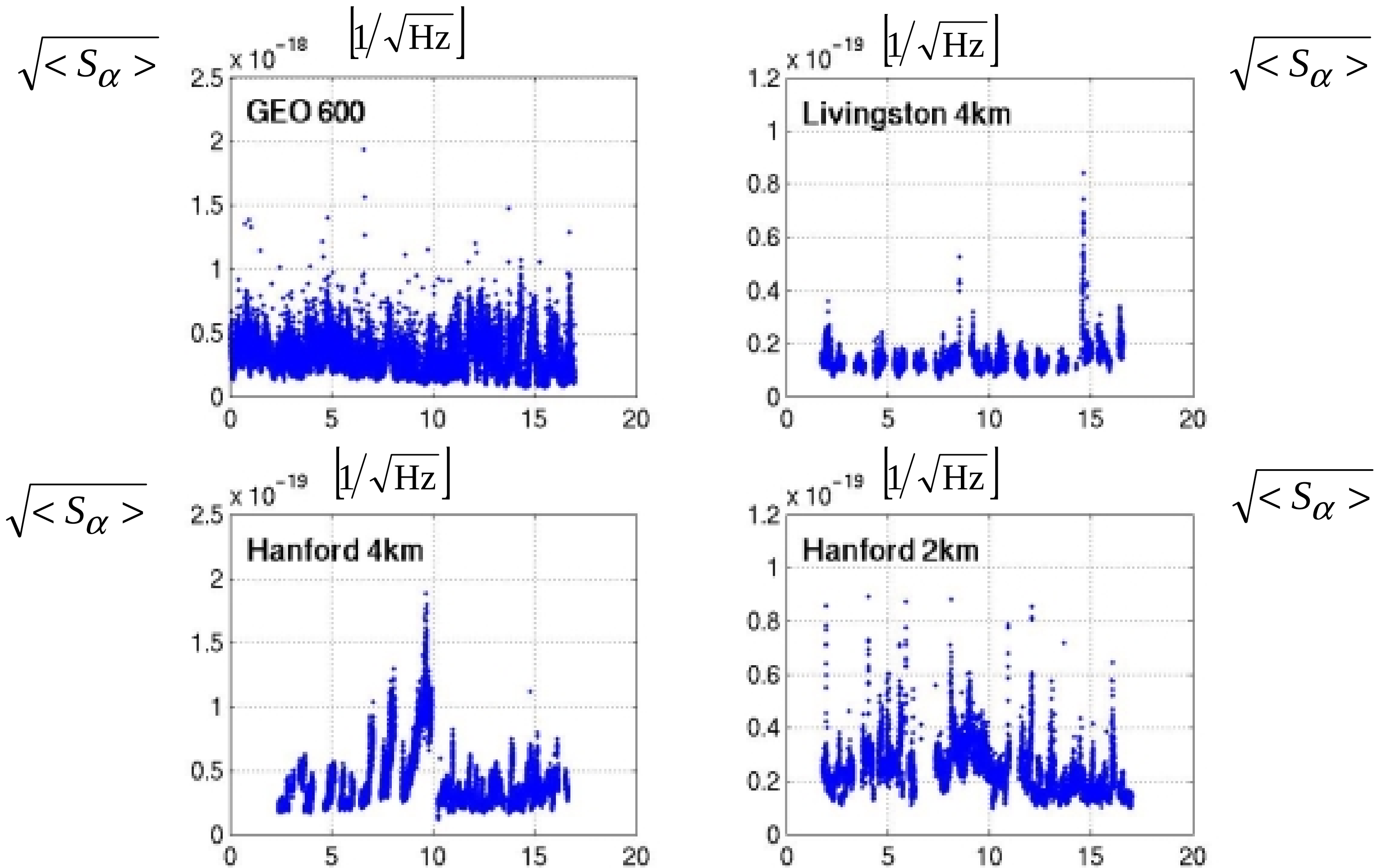
## Parameters needed for search:

- **Frequency f** of source in Solar System Barycenter (SSB)
- **Rate of change of frequency df/dt** in SSB
- **Sky coordinates ($\alpha$, $\delta$)** of source
- **Strain amplitude $h_0$**
- **Spin-axis inclination $\iota$**
- **Phase, Polarization $\varphi$, $\psi$**

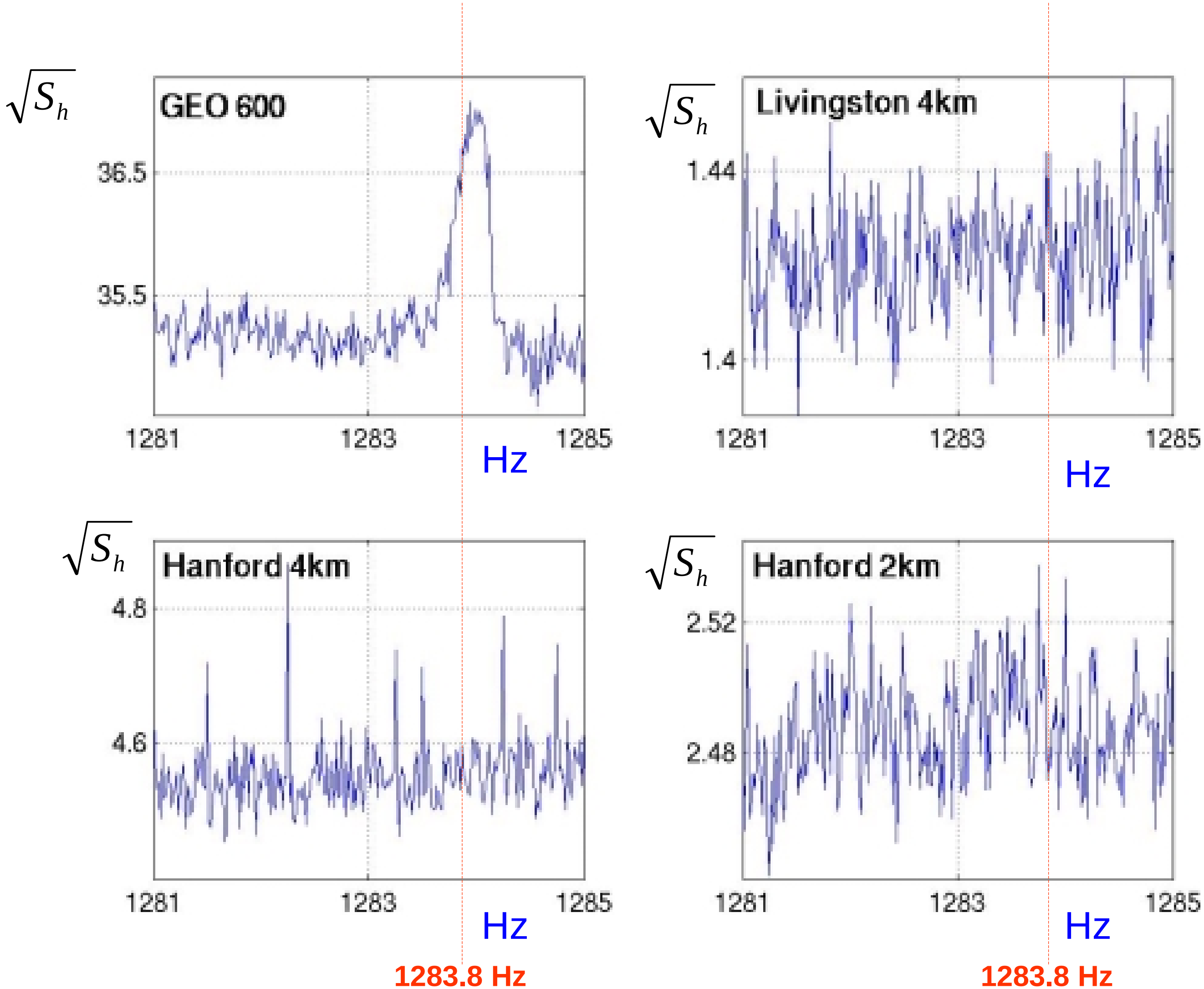
# Frequency domain method

- Input data: Short Fourier Transforms (SFT) of time series
  - » Time baseline: 60 sec
  - » High-pass filtered at 100 Hz
  - » Tukey windowed
  - » Calibrated once per minute
- Dirichlet Kernel used to combine data from different SFTs (efficiently implements matched filtering)
- Detection statistic: **F =** likelihood ratio maximized over the three unknown parameters: **Orientation $\iota$, Phase $\varphi$, Polarization $\psi$.**
- Use signal injection Monte Carlos to measure Probability Distribution Function (PDF) of F
- Use frequentist approach to derive upper limit (extensive simulations to determine detection efficiency)

# The data: time behaviour
## (4 Hz band around 1283 Hz)

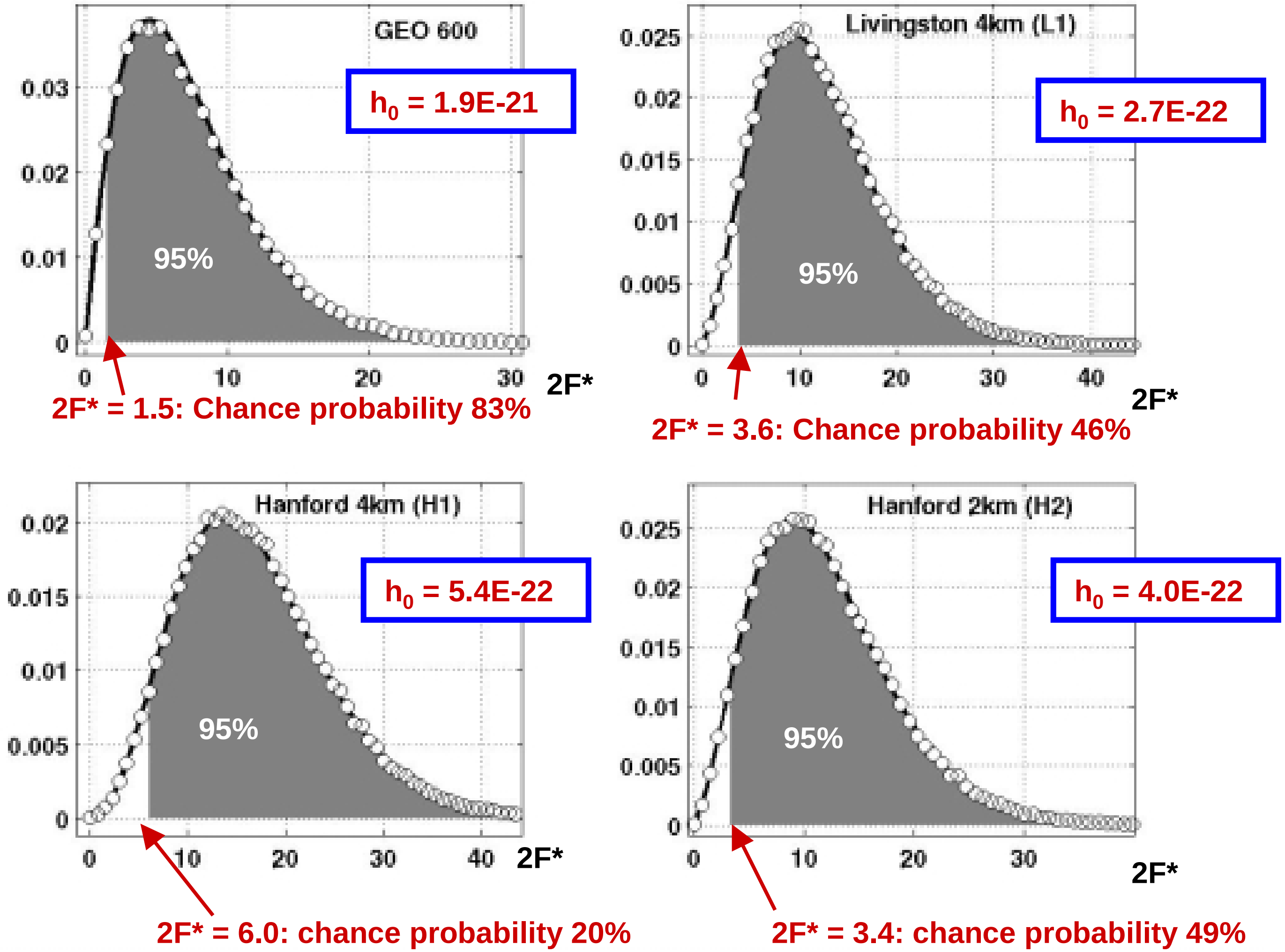


# The data in frequency



# CW: Measured PDFs for the F statistic with fake injected *worst-case* signals at nearby frequencies

Note: **hundreds of thousands** of injections were needed to get such nice clean statistics!



# Computational Engine

Searches run offline at:

- Medusa cluster (UWM)
  - » 296 single-CPU nodes (1GHz PIII + 512 Mb memory)
  - » 58 TB disk space
- Merlin cluster (AEI)
  - » 180 dual-CPU nodes (1.6 GHz Athlons + 1 GB memory)
  - » 36 TB disk space
- CPUs needed for extensive Monte-Carlo work

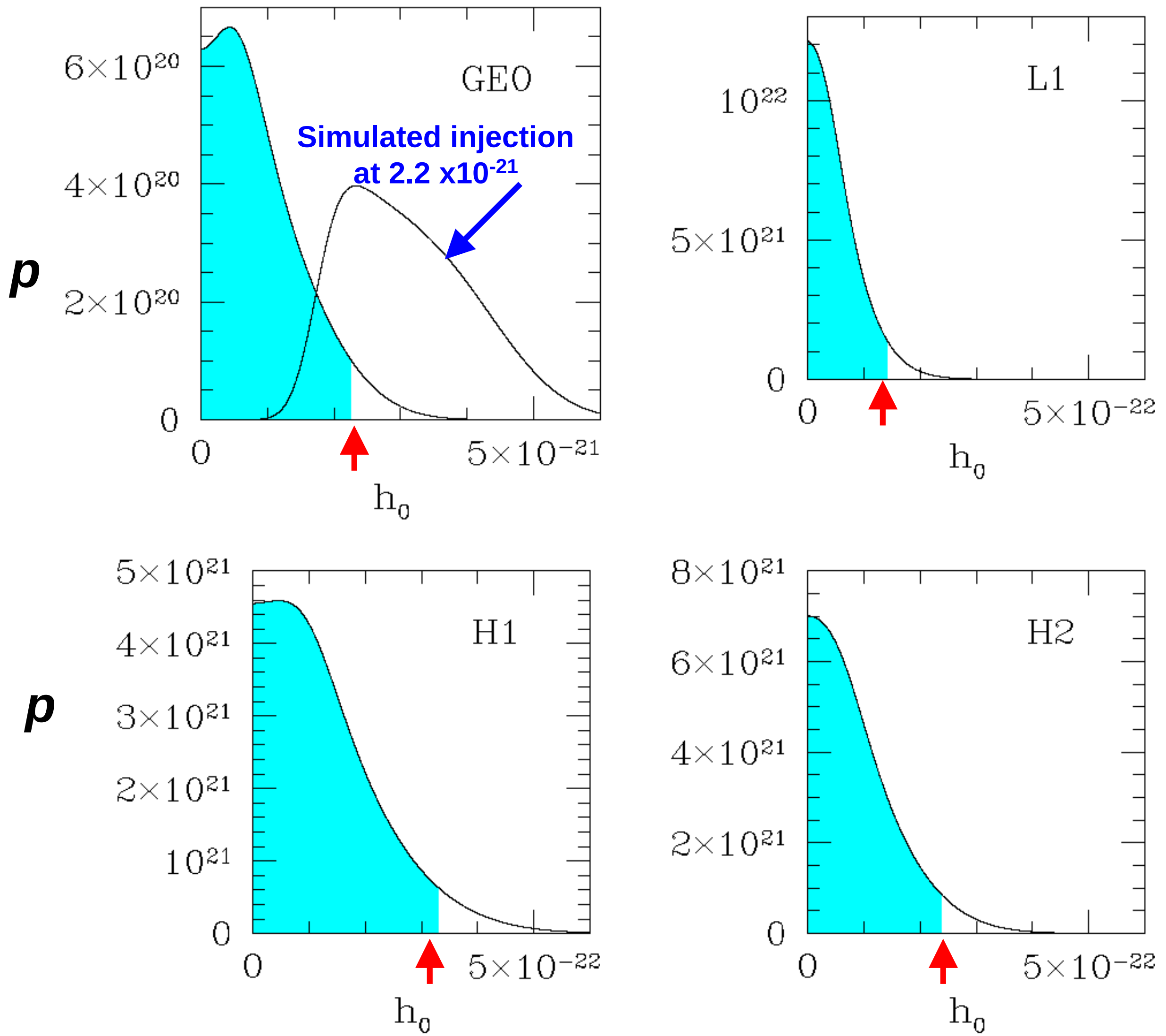
# Time domain method

- Method developed to handle NS with ~ known complex phase evolution. Computationally cheap.
- Two stages of heterodyning to reduce and filter data:
  - » Coarse stage (fixed frequency) 16384 $\Rightarrow$ 4 samples/sec
  - » Fine stage (Doppler & spin-down correction) 240 $\Rightarrow$ 1 samples/min
- Noise variance estimated every minute to account for non-stationarity.
- Standard Bayesian parameter fitting problem, using time-domain model for signal -- a function of the unknown source parameters $h_0$, $\iota$, $\varphi$, $\psi$.

# Time domain: Bayesian approach

- Uniform priors on $\varphi$ [0,2π], $\psi$ [-π/4,π/4], $\cos \iota$ [-1,1] and $h_0$ [0,∞]. Gaussian likelihood for the data using noise variance estimated from the data.
- Results are expressed in terms of the posterior PDF for $h_0$, marginalizing with respect to the nuisance parameters $\iota$, $\varphi$, $\psi$ (which could be determined if necessary).
- Upper credible limit determined from cumulative probability for $h_0$.

# Posterior PDFs for CW time-domain analyses




**shaded area = 95% of total area**

# Results from the continuous wave search

**No evidence** of continuous wave emission from PSR J1939+2134.

- Summary of **95% upper limits for** $h_o$:

| IFO | Frequentist FDS | Bayesian TDS |
|---|---|---|
| GEO | $(1.9\pm0.1) \times 10^{-21}$ | $(2.2\pm0.1) \times 10^{-21}$ |
| LLO | $(2.7\pm0.3) \times 10^{-22}$ | $(1.4\pm0.1) \times 10^{-22}$ |
| LHO-2K | $(5.4\pm0.6) \times 10^{-22}$ | $(3.3\pm0.3) \times 10^{-22}$ |
| LHO-4K | $(4.0\pm0.5) \times 10^{-22}$ | $(2.4\pm0.2) \times 10^{-22}$ |

- $h_o<1.4\times10^{-22}$ constrains **ellipticity < $2.7 \times 10^{-4}$** ($M=1.4\ M_{sun}$, $r=10$ km, $R=3.6$ kpc)
- Previous results for this pulsar: $\mathbf{h_o < 10^{-20}}$ (Glasgow, Hough et al., 1983), $\mathbf{h_o < 1.5 \times 10^{-17}}$ (Caltech, Hereld, 1983).

# Pulsar/CW Plan for S2

- Pulsar Time domain method:
  - » Upper limits on all known pulsars > 50 Hz
  - » Search for Crab
  - » Develop specialized statistical methods (Monte-Carlo Markov Chain) to characterize PDF in parameter space
- Pulsar Frequency domain method
  - » Search parameter space (nearby all-sky broadband + deeper small-area)
  - » Specialized search for SCO-X1 (pulsar in binary)
  - » Incoherent searches: Hough, unbiased, stack-slide

# LIGO/GEO Summary

- **Burst**
  - » For 1ms Gaussian pulses:1.6 events/day rising up as the detection efficiency reduces (50% efficiency point is at $h_{rss}$~$3x10^{-17}$).
- **Stochastic**
  - » H1-H2 cross-correlation contaminated by environmental noise (anticorrelation corresponds to $-9.9 < h^2_{100}\ \Omega_{GW} < -6.8$)
  - » Limit from H2-L1 (with 90% confidence): $h^2_{100}\Omega_{GW}$ (40Hz - 314 Hz) < 23±4.6
- **Inspiral**
  - » No event candidates found in L1-H1 coincidence
  - » 90% confidence upper limit: inspiral rate < 170/year per Milky-way equivalent galaxy, in the (m1, m2) range of 1 to 3 solar masses.
- **Pulsar** (two methods used)
  - » $h_o<1.4x10^{-22}$ (from L1). Constrains ellipticity < $2.7x10^{-4}$
  - » Beautiful agreement between theoretical and actual noise statistics!