ALL-SKY LIGO SEARCH FOR PERIODIC GRAVITATIONAL WAVES IN THE S4 DATA

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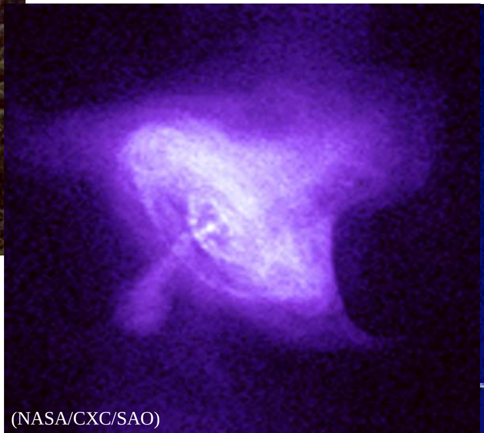
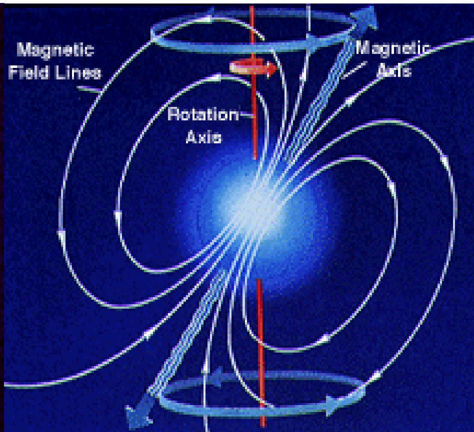


(NASA/CXC/SAO)



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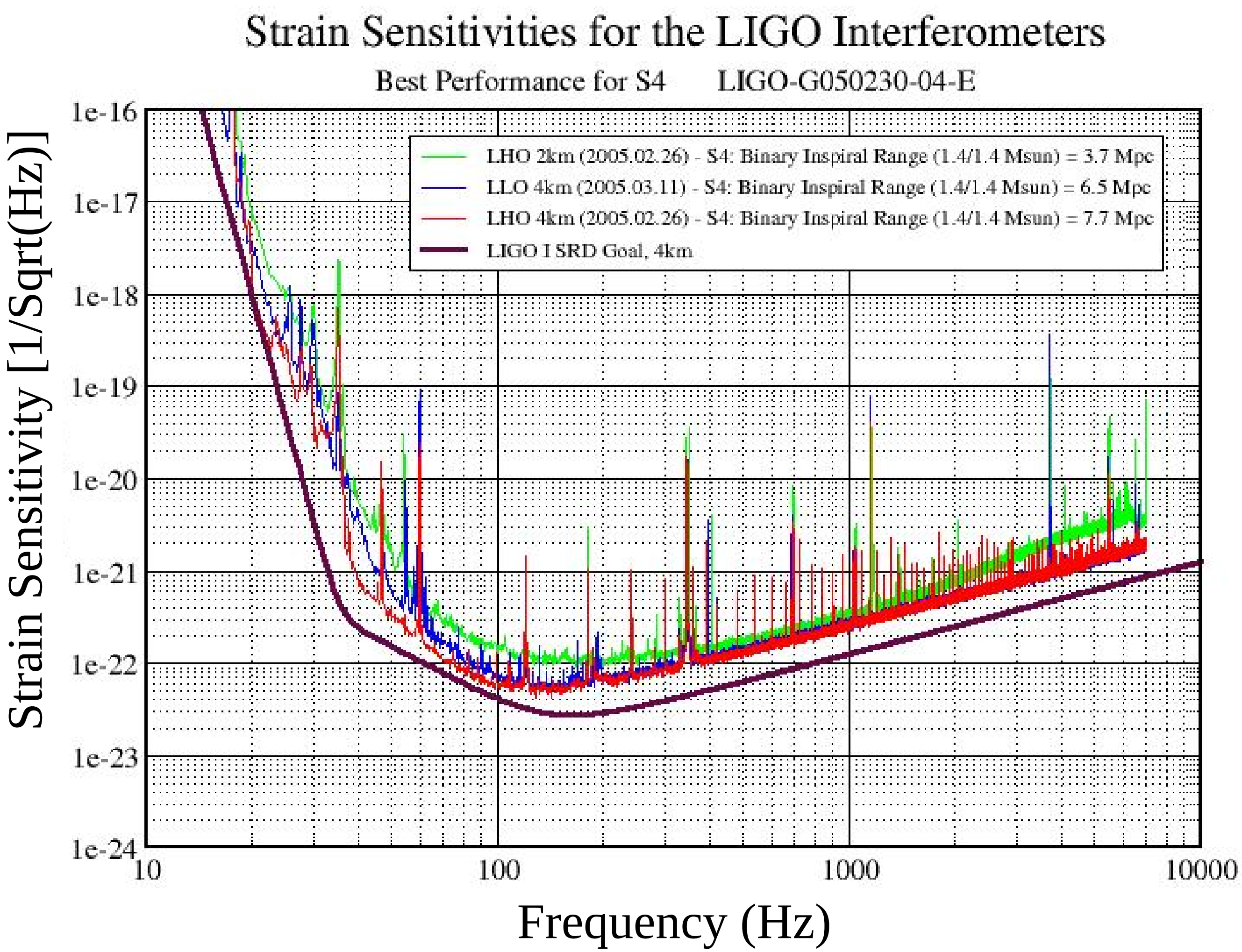
Content

- Brief overview of the target sources and S4 run
- Semi-coherent methods:
  PowerFlux, StackSlide, Hough
  - Similarities and differences
  - Comparison of the searches carried out
  - Hardware injections validation
  - S4 Astrophysical reach
- Summary of results and perspectives

Fourth Science Run (S4) Sensitivity

(February 22, 2005 – March 23, 2005)



S5 is currently running at design sensitivity!

Signal received from *an isolated* NS

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

F_+ and $F_\times$ are the strain antenna patterns. They depend on the orientation of the detector and source and on the polarization of the waves.

- Expected waveform from an isolated spinning NS is sinusoidal with small spin-down:
- Doppler frequency modulation due to motion of Earth and amplitude modulation due to detector antenna pattern.

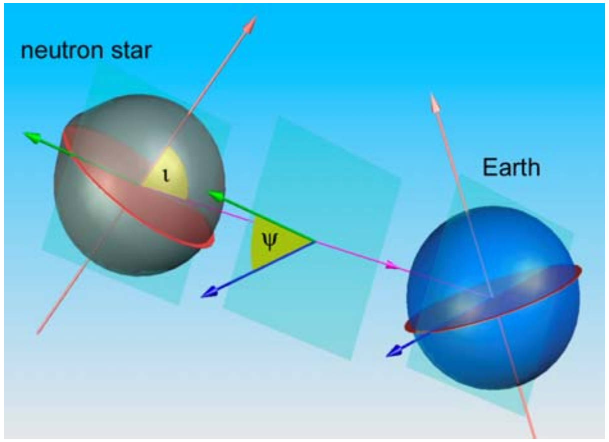
$$h_+ = A_+ \cos\Phi(t)$$
$$h_\times = A_\times \sin\Phi(t)$$

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

T(t) is the time of arrival of a signal at the solar system barycenter, *t* the time at the detector.

Signal model: *isolated non-precessing NS*

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



$$A_+ = \frac{1}{2} h_0 (1+\cos^2 \iota)$$

$$A_\times = h_0 \cos \iota$$

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \varepsilon f_{gw}^{\ 2}}{d}$$

h_0 - amplitude of the gravitational wave signal

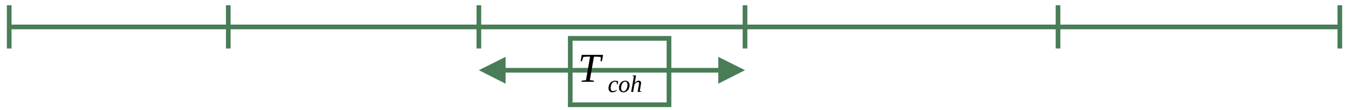
ι - angle between the pulsar spin axis and line of sight

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

Coherent wide-parameter searches

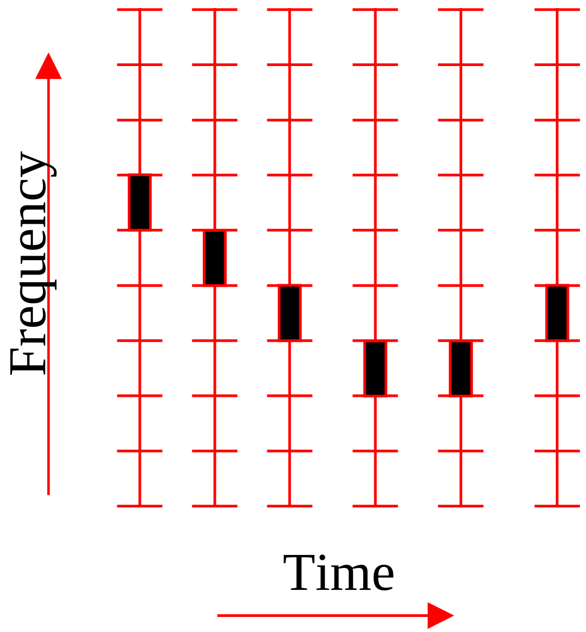
- Coherent methods are the most sensitive methods (amplitude SNR increases with $\sqrt{T_{obs}}$) but they are the most computationally expensive, why?
  - Our templates are constructed based on different values of the signal parameters (e.g. position, frequency and spindown)
  - The parameter resolution increases with longer observations
  - Sensitivity also increases with longer observations
  - As one increases the sensitivity of the search, one also increases dramatically the number of templates one needs to use.
- The second effect of the large number of templates N_p is to reduce the sensitivity compared to a targeted search with the same observation time: increasing the number of templates increases the number of expected false-alarm candidates at fixed detection threshold. Therefore the detection-threshold needs to be raised to maintain the same false-alarm rate, thereby decreasing the sensitivity.
  - Note that increasing the number of equal-sensitivity detectors N improves the SNR in the same way as increasing the integration time T_{obs}. However, increasing the number of detectors N does — contrary to the observation time T_{obs} — not increase the required number of templates N_p, which makes this the computationally cheapest way to improve the SNR of coherent wide-parameter searches.
- Different search strategies need to be pursued.

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 three 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)

Comparing the Methods (cont.)

What kind of limits are set?

StackSlide & Hough

Population-based frequentist limits on h_0

Averaged over sky location and pulsar orientation

PowerFlux

Strict frequentist limits on circular and linear polarization amplitudes h_0^{CIRC} and h_0^{LIN}

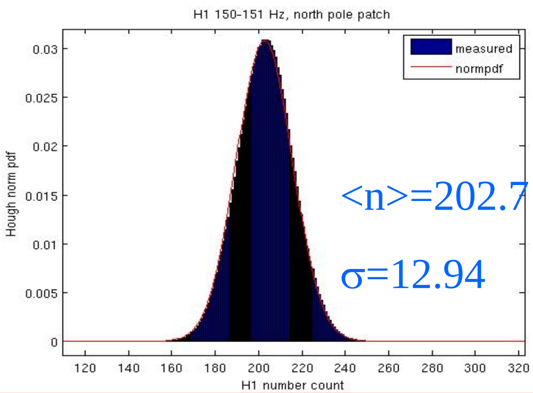
Results interpreted as limits on best-case and worst-case pulsar amplitudes h_0

→ Limits placed separately on tiny sky patches

→ Worst limit over fiducial sky is quoted

Hough analysis

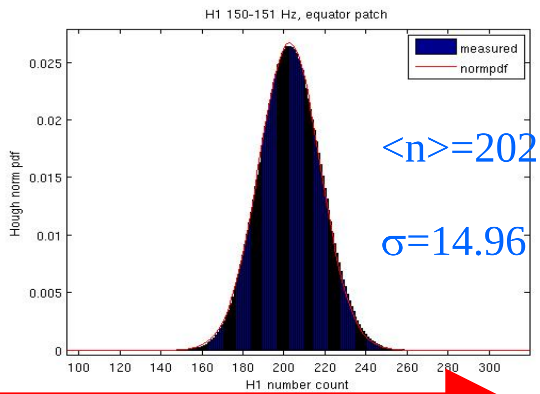
(North Pole)



$<n>=202.7$

$\sigma=12.94$

(Equator)



$<n>=202.7$

$\sigma=14.96$

Histograms of the Hough number count for the H1 detector in the frequency band 150-151 Hz. Number of templates analyzed in each sky patch ~11×10^6

(2 of 92 sky patches shown)

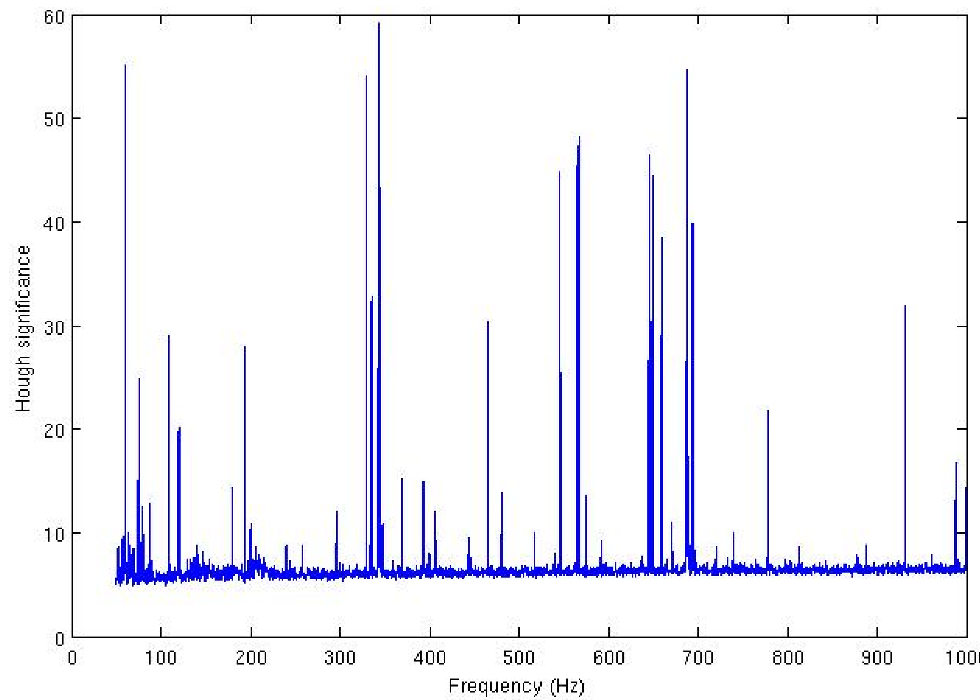
Hough count

All-sky loudest events for every 0.25 Hz, Multi-interferometer case

Significance defined as

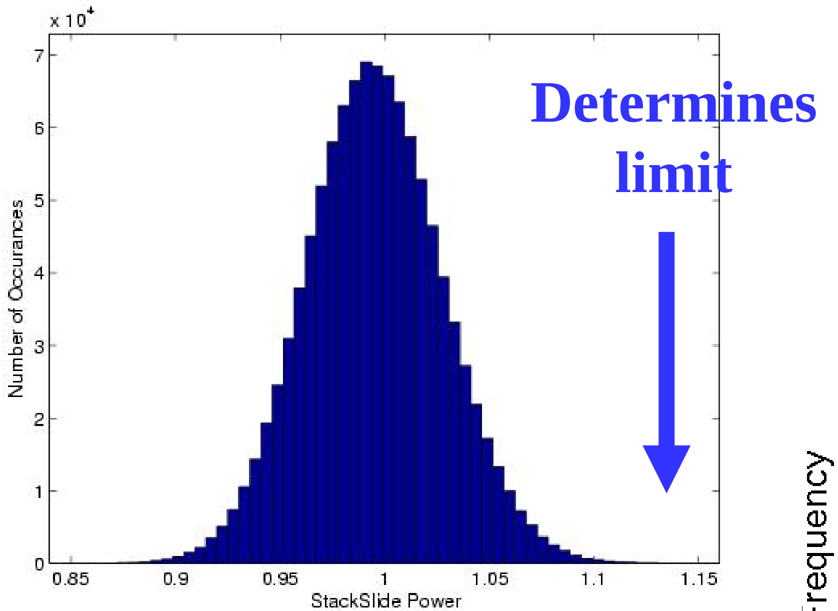
$$s=(n_{max}-<n>)/\sigma$$

Determines limit



Setting Upper Limits

StackSlide

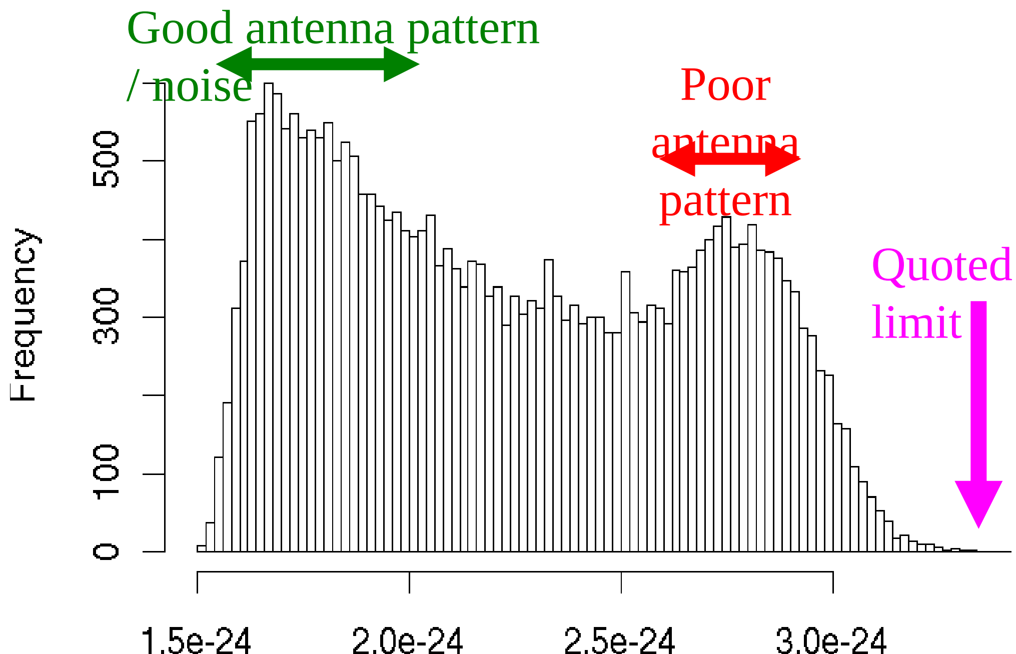


StackSlide power

PowerFlux

Sample of 95% CL Upper Limits on h_{linear}

(0.25-Hz band near 149 Hz)



Strain limit 95% UL

Comparing the Methods

How are instrumental lines handled?

StackSlide & Hough

Direct removal of known lines from spectrum (replaced with random noise)

Allows entire sky to be searched (population-based limits)

PowerFlux

Spectral lines flagged on the fly and bins marked for avoidance

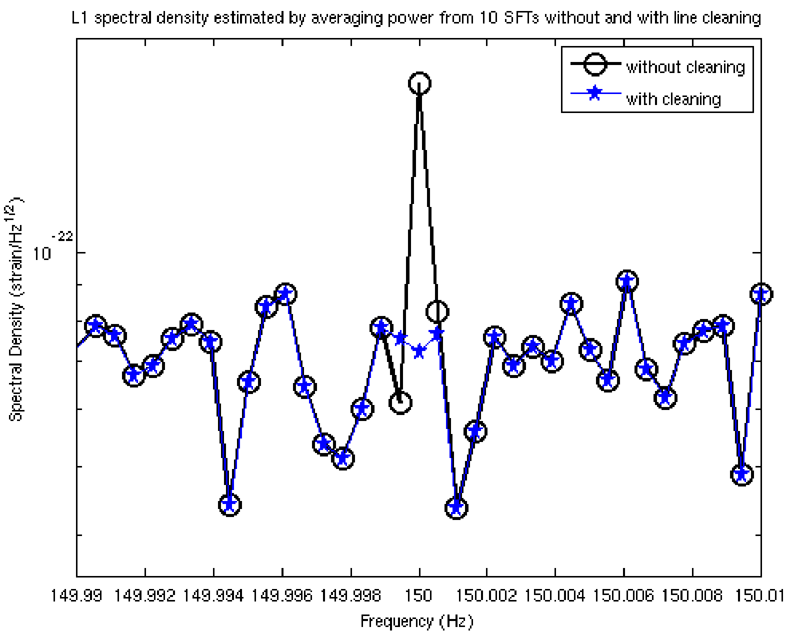
Source occupancy tracked – no limits placed if source would be lost

Leads to exclusion of Doppler-stationary skybands (dependent on frequency and spindown)

Handling instrumental lines

StackSlide & Hough Line Removal:

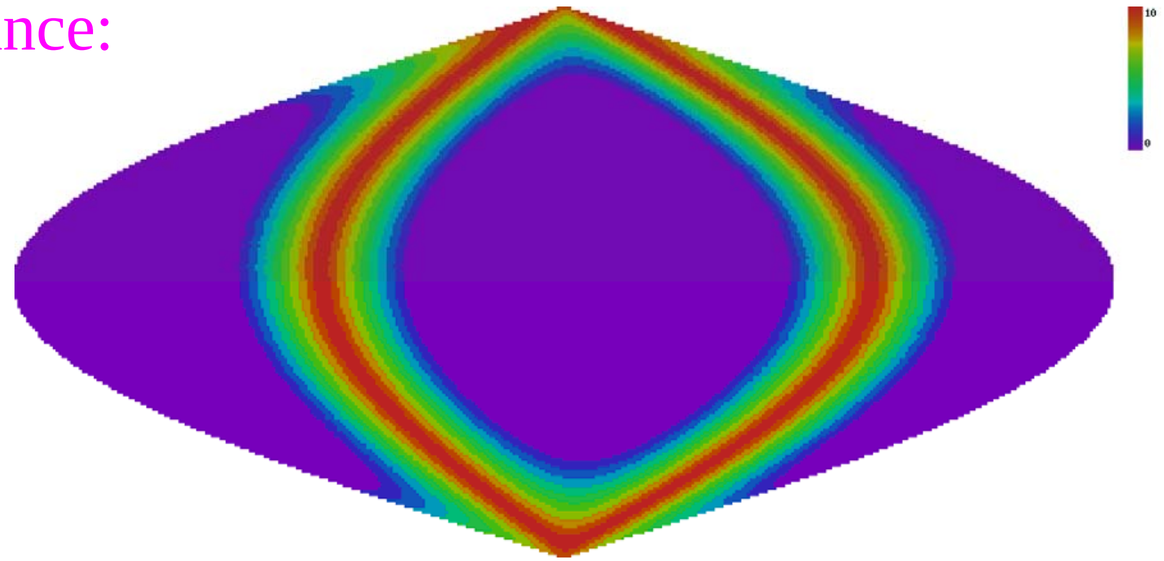
Known lines replaced by random noise
(Effects included in Monte Carlo simulation)



PowerFlux Line Avoidance:

Regions of Doppler stationarity excluded from quoted limits

(frequency & spindown dependent)



Doppler skybands defined by "S parameter"

$$f(t) \cong \left(1 + \frac{\vec{v}(t)}{c} \cdot \hat{n}\right)\left[f_0 + f_1(t - t_0) + \ldots\right]$$

$$\dot{f}(t) \cong \left(\frac{\vec{a}(t)}{c} \cdot \hat{n}\right)\left[f_0 + f_1(t - t_0)\right] + \left(1 + \frac{\vec{v}(t)}{c} \cdot \hat{n}\right) f_1 + \ldots$$

$$S = \left(\frac{\vec{a}_{orb}(t)}{c} \cdot \hat{n}\right) f_0 + f_1$$

Measures combined effect of source spindown and frequency drift due to average acceleration of the Earth w.r.t the source

For analysis < 1 yr sky points with small S have small Doppler variation; harder to distinguish GWs from Instrument lines at these points.

Thresholds chosen for fiducial skybands:

H1: $S_{Large} = 1.85 \times 10^{-9}$ Hz/s

L1: $S_{Large} = 3.08 \times 10^{-9}$ Hz/s

→ Driven by prominent 1 Hz lines in L1

S4 Analysis

What frequency & spindown ranges are covered? [50-1000 Hz for all]

StackSlide & PowerFlux:

-1.0×10^{-8} Hz/s < df/dt < 0

Hough:

-2.2×10^{-9} Hz/s < df/dt < 0

What interferometer data is analyzed?

StackSlide & PowerFlux – H1 and L1 individually

(coincidence checks for high-SNR candidates)

Hough – H1, H2, and L1 combined powers

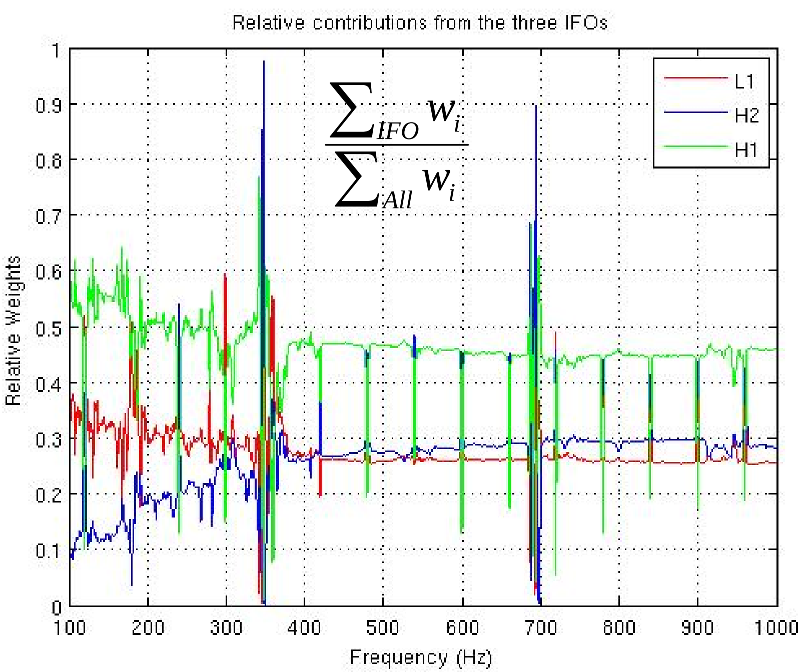
(coincidence check for high-SNR candidates;
also: sample single-IFO limits produced for comparison)

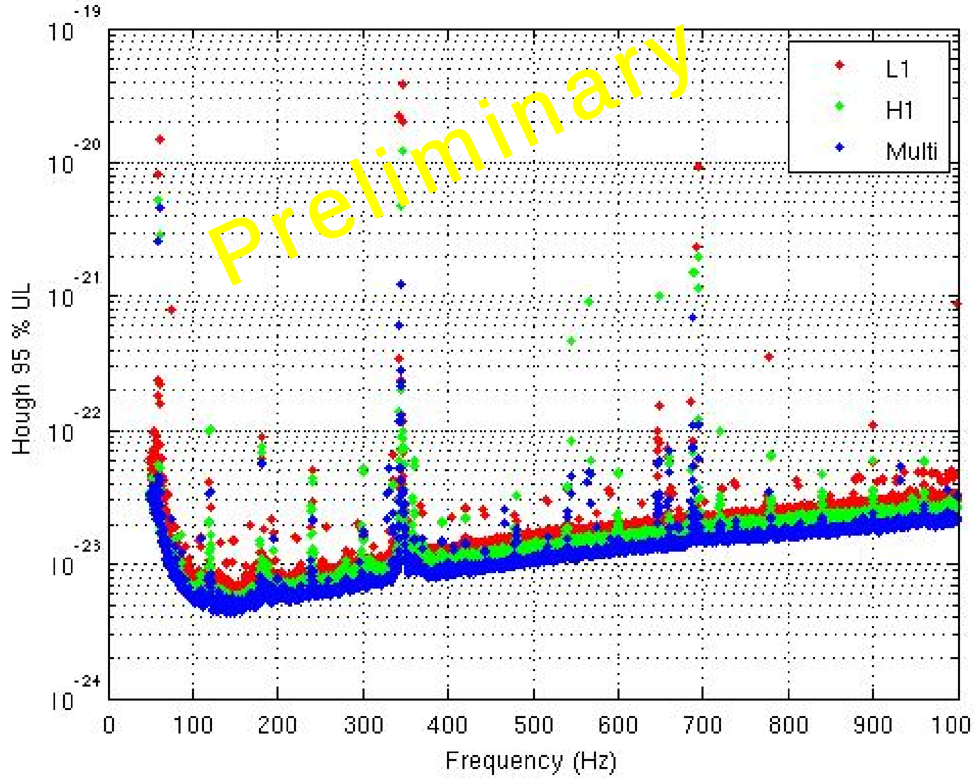
StackSlide/Hough/PowerFlux differences

	StackSlide	Hough	PowerFlux
Windowing	Tukey	Tukey	Hann
Noise estimation	Median-based floor tracking	Median-based floor tracking	Time/frequency decomposition
Line handling	Cleaning	Cleaning	Skyband exclusion
Antenna pattern weighting	No	Yes	Yes
Noise weighting	No	Yes	Yes
Spindown step size	2×10^{-10} Hz/s	2×10^{-10} Hz/s	Freq dependent
Limit at every skypoint	No	No	Yes
Upper limit type	Population-based	Population-based	Strict frequentist

The S4 Hough search

- Weights allow us to use SFTs from all three IFOs together: 1004 SFTS from H1, 1063 from H2 and 899 from L1

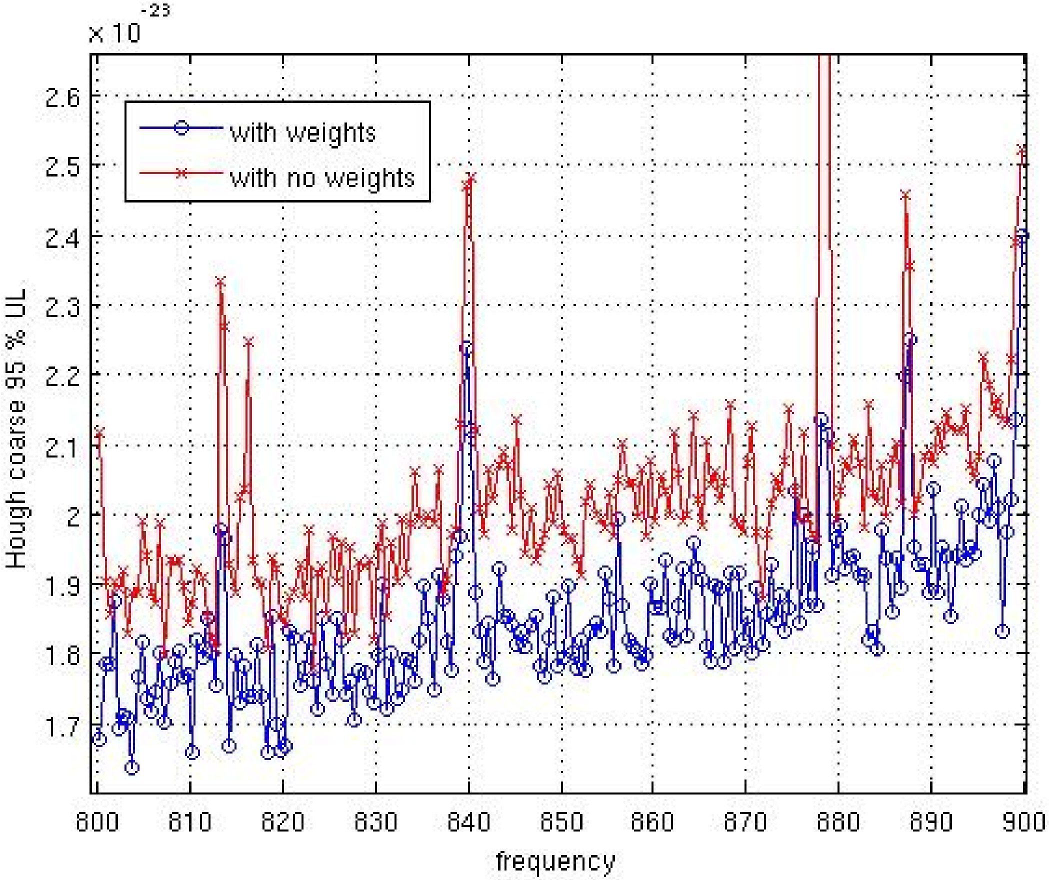




Best UL

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

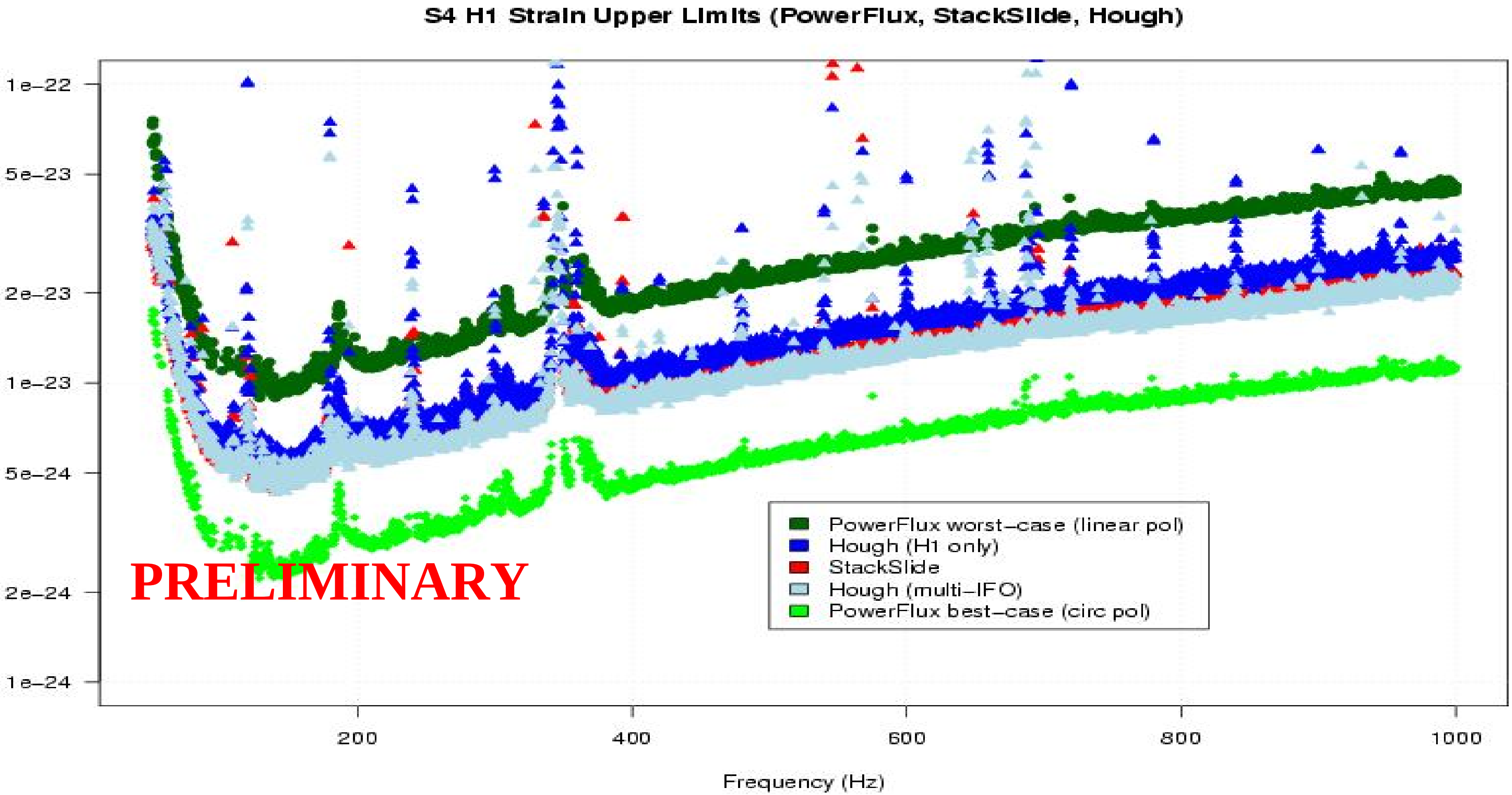
Improvements due to the weights



Comparison of the All-sky 95% upper limits obtained by Monte-Carlo injections for the multi-IFO case.

The average improvement by using weights in this band is 9.25% for the multi-IFO case, but only ~6% for the single IFO

H1 (Hanford 4-km) and Multi-IFO Results

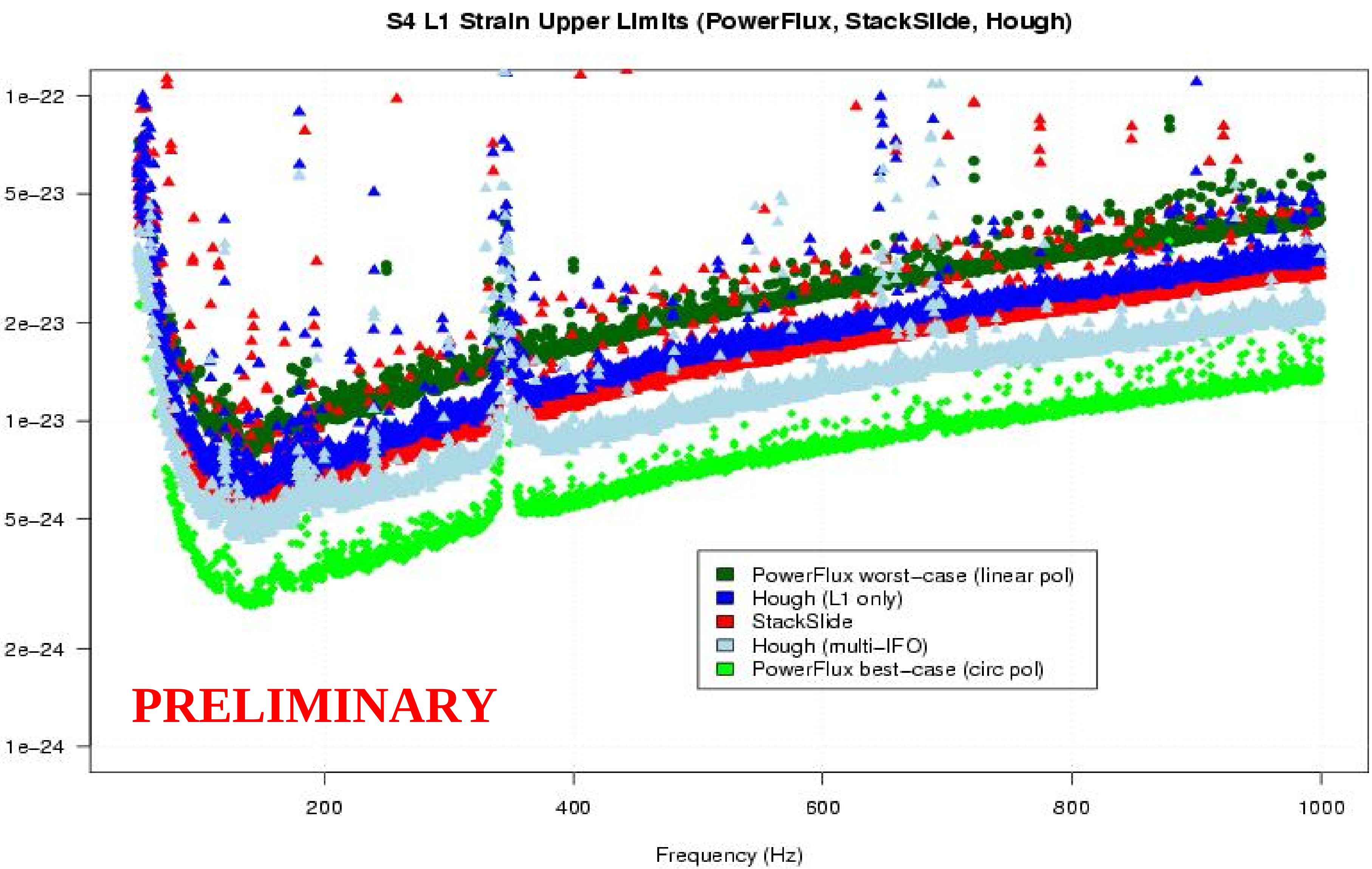


PowerFlux: Comparing linear to circular polarization limits

Linear amplitude = $0.5 \times h_0^{\text{worst-pulsar}}$ Circular amplitude = $h_0^{\text{best-pulsar}}$

Typical: $h_0^{\text{worst-pulsar}} \sim (3\text{-}4) \times h_0^{\text{best-pulsar}}$

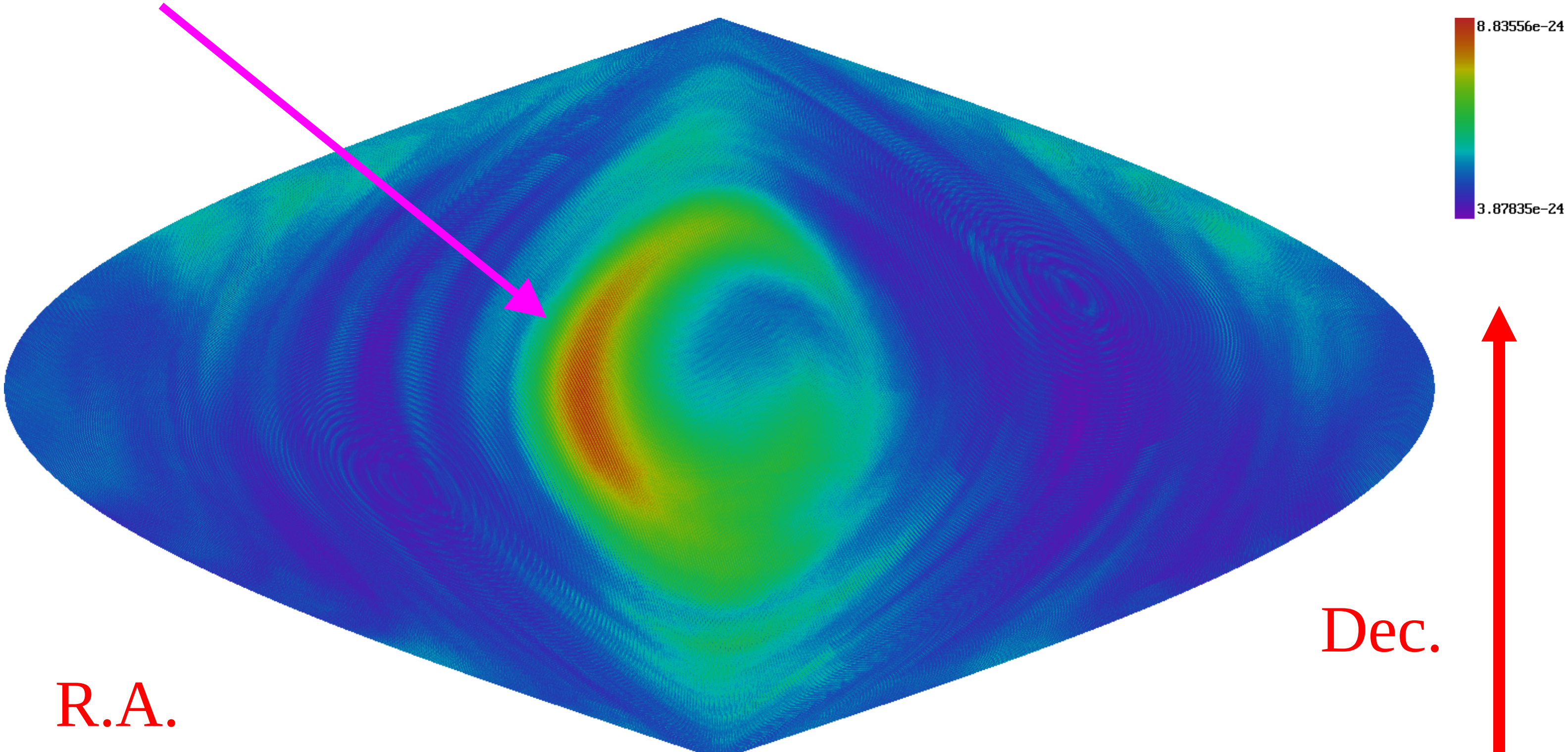
L1 (Livingston 4-km) and Multi-IFO Results



Hardware injections. Validation

Sample skymap of Feldman Cousins upper limits on circularly polarized strain for H1 in 575.00-575.25 Hz band using PowerFlux

Hardware injected Pulsar2 ($A_+ = A_- = 8.4 \times 10^{-24}$)



Dec.

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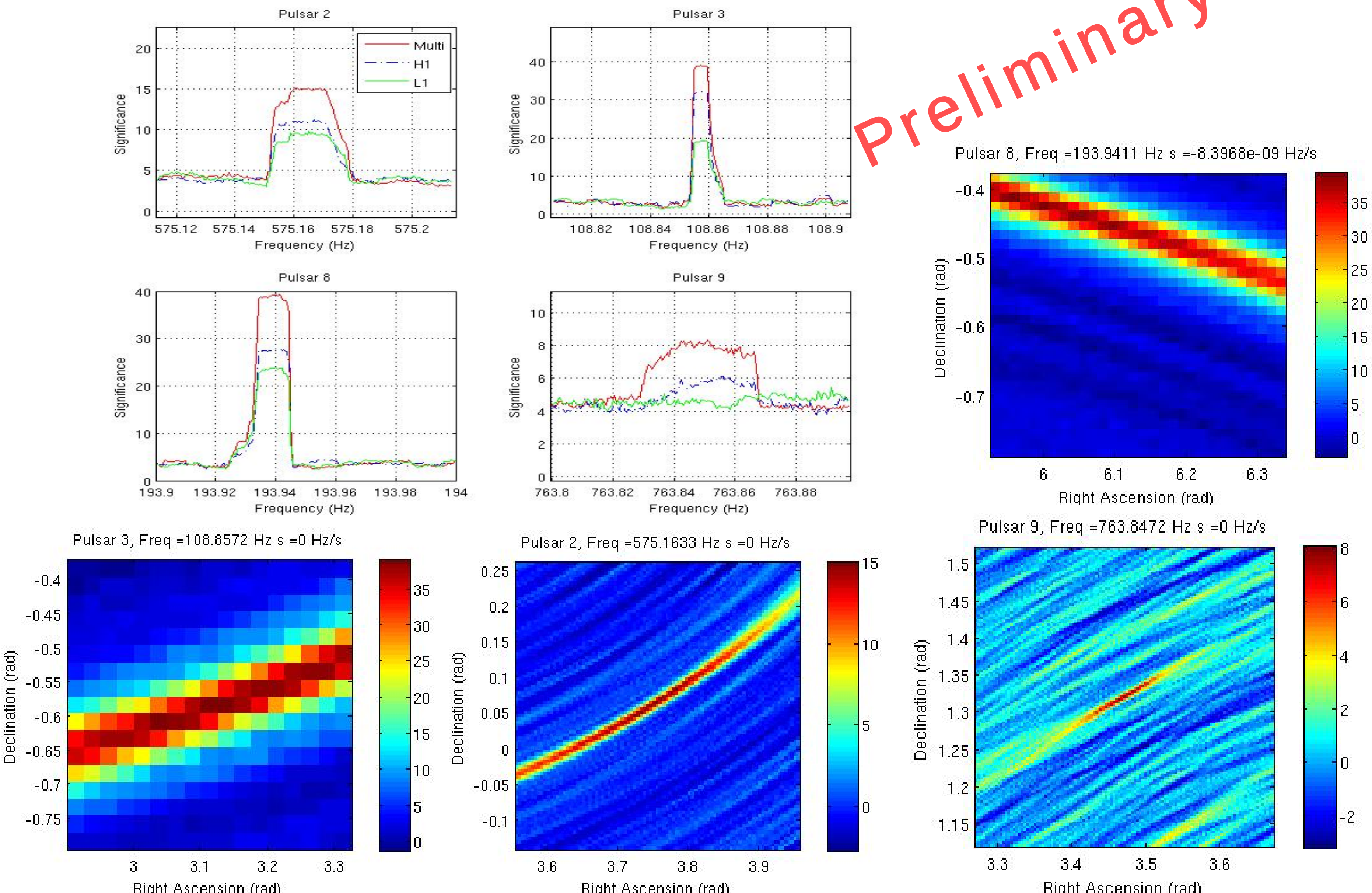
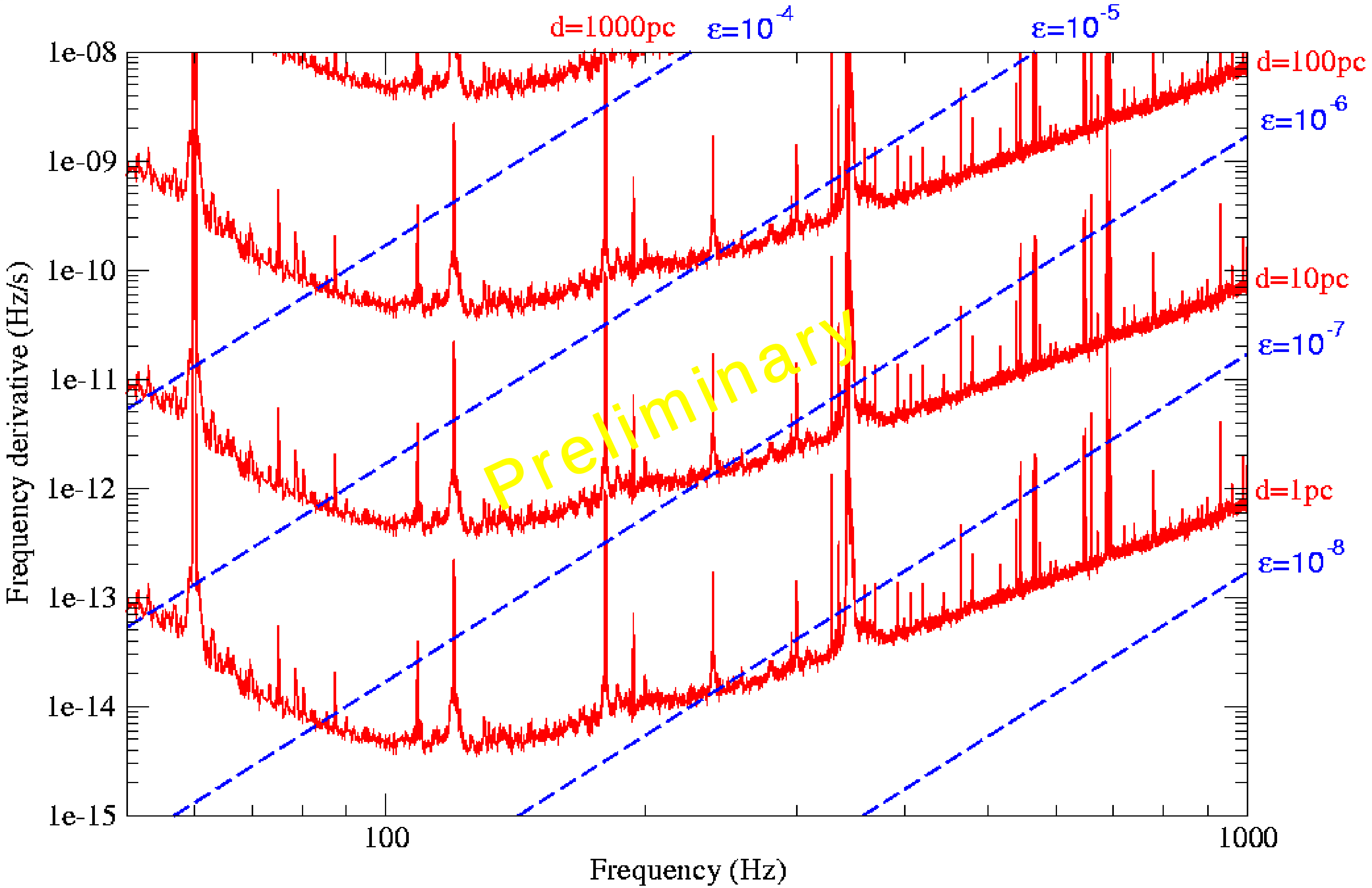
PRELIMINARY

Hardware Injections
Hough results

Preliminary



S4 Semicoherent Search
Astrophysical Reach



Results & Prospects

Three different methods have been used to search for periodic GWs in the S4 data:
PowerFlux, StackSlide and Hough.

- Hough is computationally faster and more robust against large transients but less sensitive than StackSlide for stationary data. Hough also allows multi-interferometer search
- PowerFlux has better performance in most frequency ranges, except when there are non-stationary artifacts.
- Hough and StackSlide can be made more sensitive by starting F-statistics rather then SFT power input data.

Parameter space covered: All-sky, frequency range 50-1000 Hz, Spindown range -1.0×10^{-8}-0 Hz/s

Carried out follow-up coincidence (frequency, spindown, sky location) studies on outliers from individual interferometers

- No plausible candidates found

The best populated based Upper limit for isolated rotating neutron stars is 4.28×10^{-24}.
UL were also obtained for small patches on the sky for best-case and worst-case orientations.

Now carrying out analysis of data from ongoing S5 data run with PowerFlux as "first look" algorithm

StackSlide & Hough incorporated into distributed-computing project called Einstein@Home, using longer coherence times and a hierarchical search algorithm

Upper limits improving and now probing interesting astrophysical territory ($h < 10^{-24}$) → Stay tuned…