Recent results from the LIGO pulsar searches

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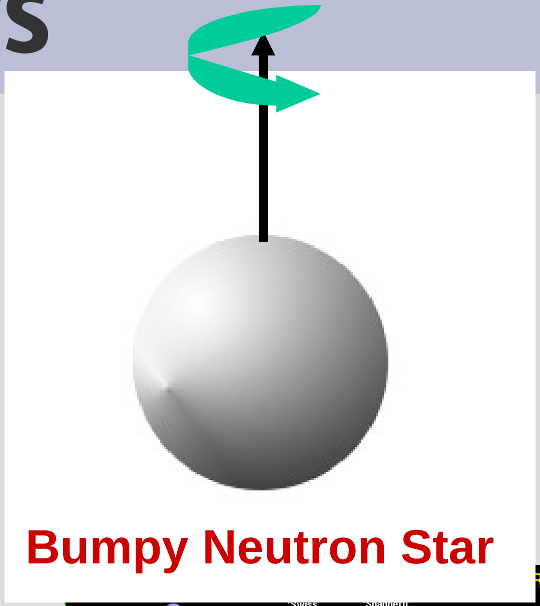
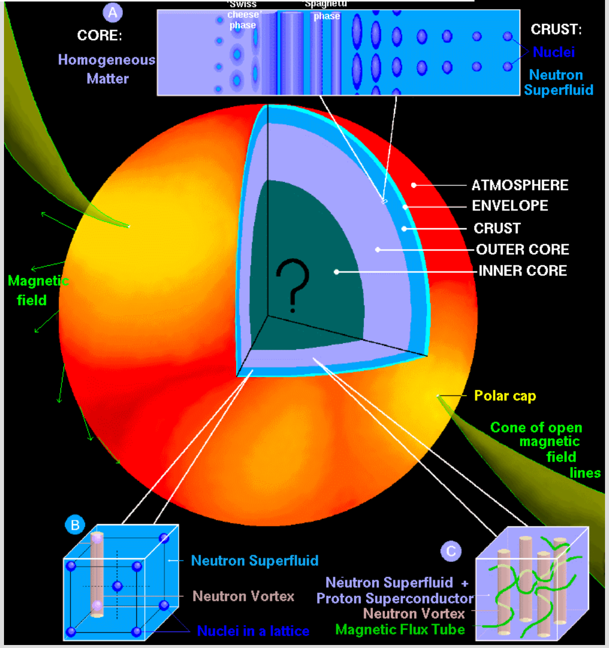
Gravitational waves from neutron stars

- Rapidly spinning neutron stars provide a potential source of continuous gravitational waves
- To emit gravitational waves they must have some degree of non-axisymmetry
  - Triaxial deformation due to elastic stresses or magnetic fields
  - Free precession about axis
  - Fluid modes e.g. r-modes

- Size of distortions can reveal information about the neutron star equation of state


Bumpy Neutron Star



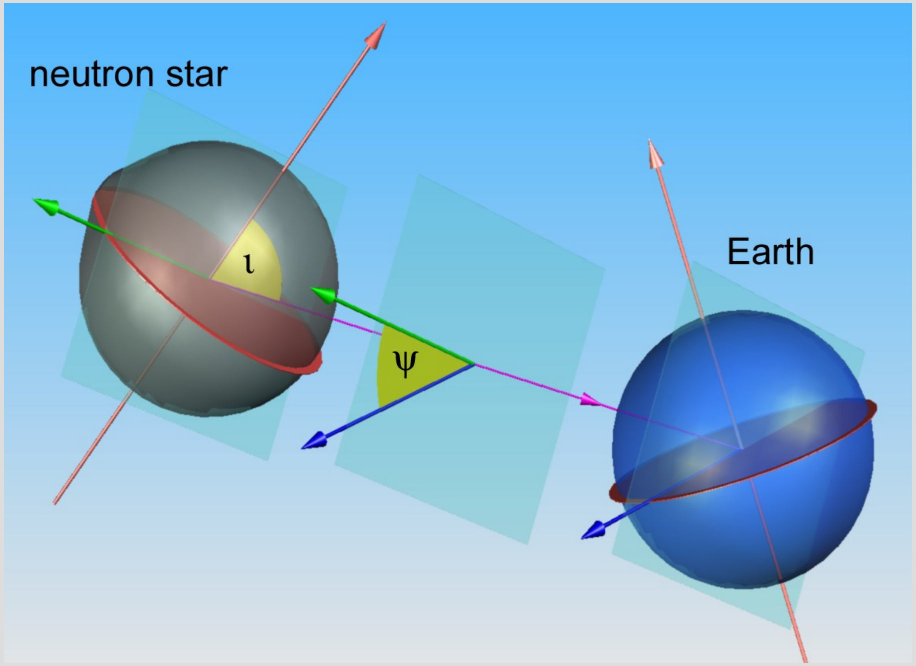
www.astroscu.unam.mx/neutrones/NS-Picture/NStar/NStar_1S.gif

The signal

- The signal at Earth from a triaxial star will be

$$h(t)=F_{+}(t,\psi)h_0\frac{1+\cos^2\iota}{2}\cos\Phi(t)+F_{¿}(t,\psi)h_0\cos\iota\sin\Phi(t)$$

- where: h_0 is the gravitational wave amplitude, ι is the pulsar orientation, Φ is the gravitational wave phase, and ψ is the polarisation angle



$$\Phi(t)=2\pi(\varphi_0+2\nu_r[t+\delta t]+\ldots)$$

I = moment of inertia

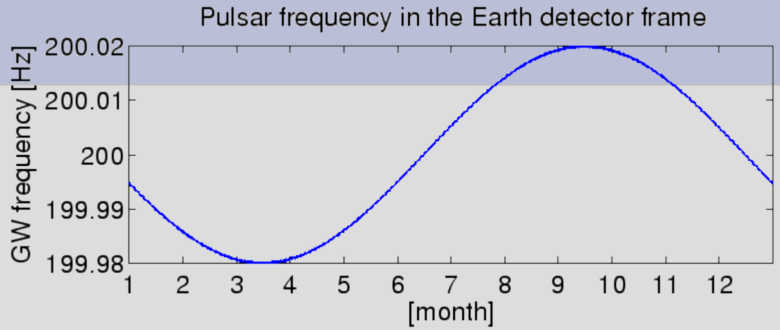
ε = equatorial ellipticity

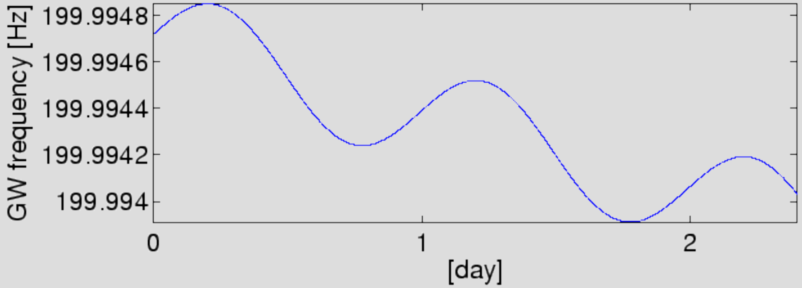
ν_r = rotational frequency

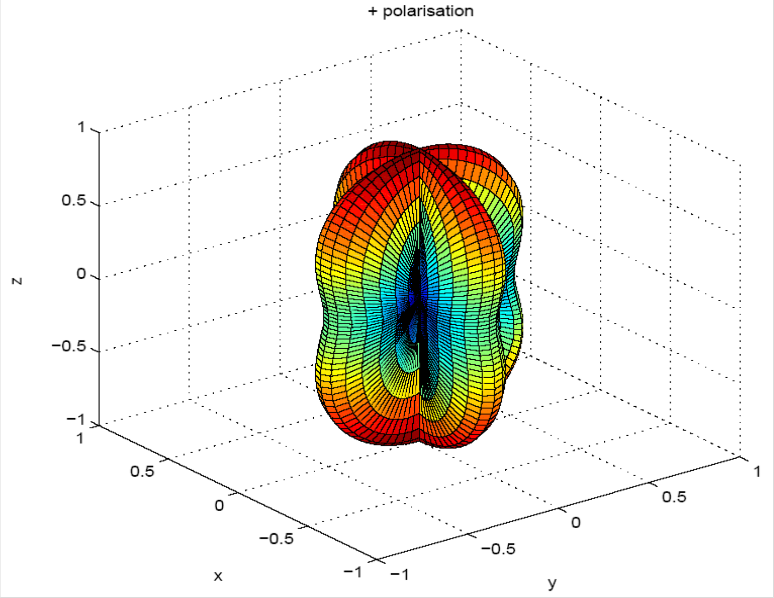
$$h_0=\frac{16\pi^2 G}{c^4}\frac{I\varepsilon\nu_r^2}{d}$$

The signal

- The signal will be Doppler modulated
  - Earth’s motion about the Sun
  - Binary system orbital motion
  - Relativistic delays
- Depends on the source’s sky position
  - High ecliptic latitude – small modulation
  - Low ecliptic latitude – large modulation
- The signal will be amplitude modulated
  - Beam pattern of detector depends on source position and wave polarisation angle
  - Daily variation

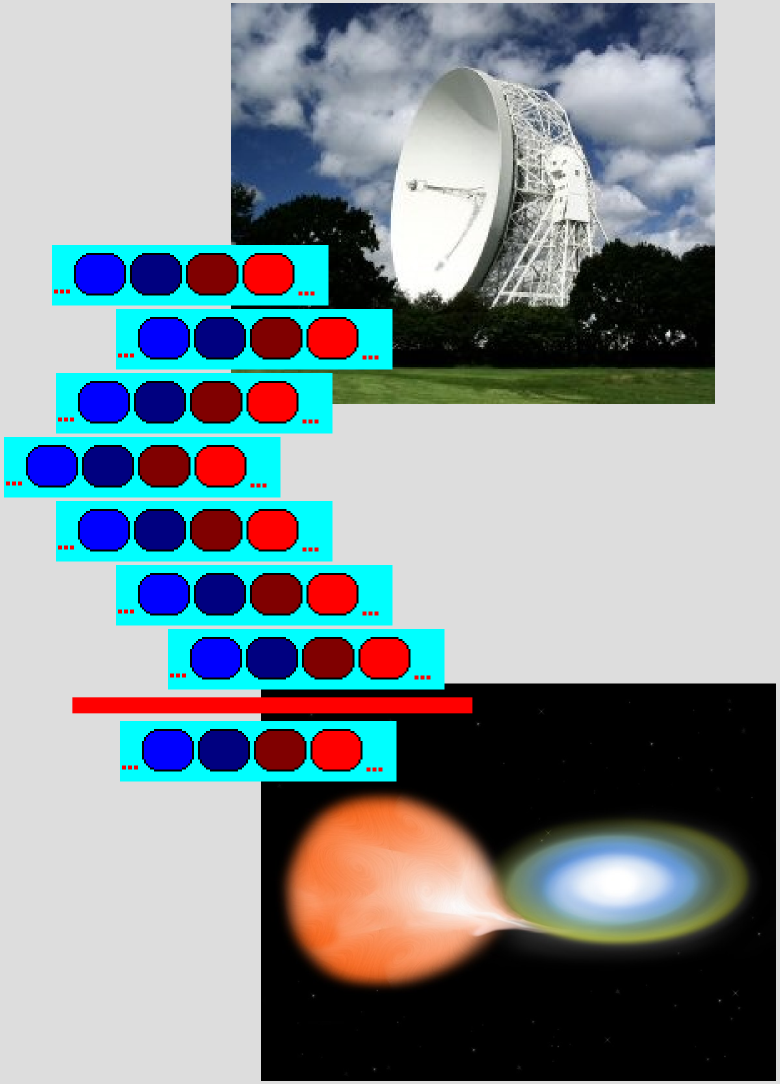

Pulsar frequency in the Earth detector frame




+ polarisation

The searches

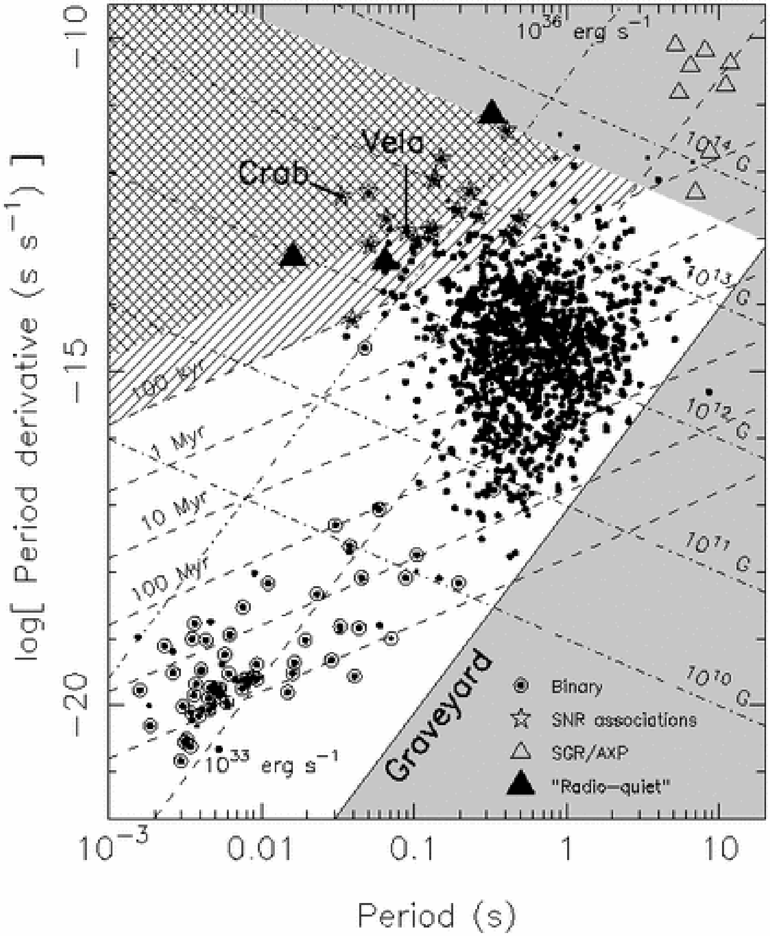
- Current searches for periodic gravitational waves include:
  - Known pulsar searches
    - Targeting all pulsars within the frequency band (ν_{gw} >50Hz) including pulsars in binary systems using radio inferred phase evolution
  - Semi-coherent searches for excess monochromatic power
    - Hough
    - Stack-slide
    - Power flux
  - Coherent searches over large parameter spaces
    - All sky broadband search and targeted LMXB searches
    - Einstein@home



Targeted pulsar search – Why?

- Many millisecond and fast young pulsars have very well determined parameters and are generally very stable - excellent candidates for a targeted search using gravitational detectors!
- The greatly reduced unknown parameter space allows deep, relatively computational inexpensive searches using long time spans of data

- Within the LIGO sensitive band (ν_{gw} > 50 Hz) there are currently 163 known pulsars (from the ATNF pulsar catalogue) - with 98 in binary systems and 91 within globular clusters

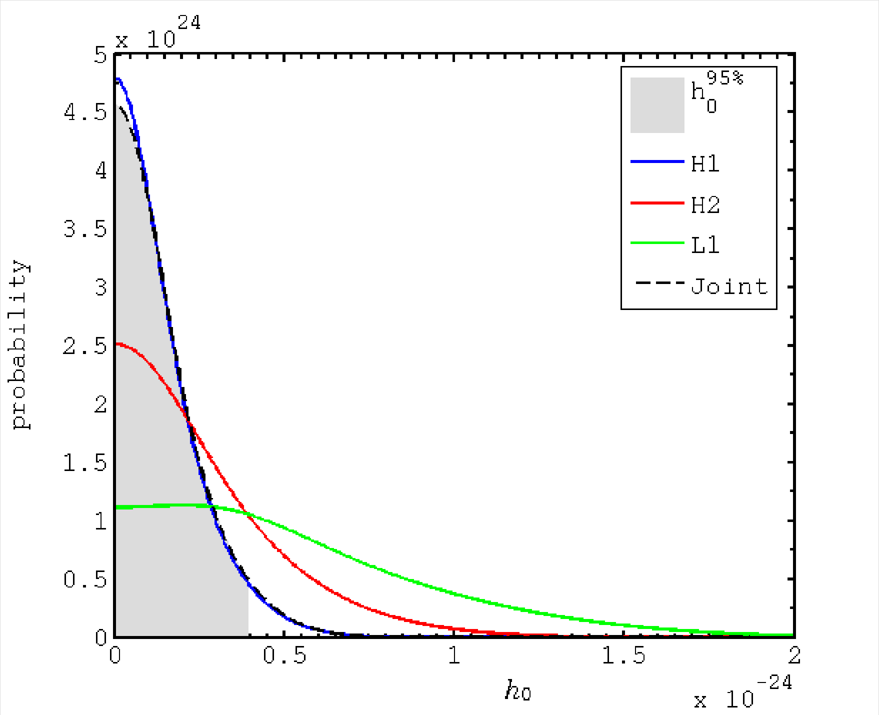


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Targeted search - method

- Heterodyne time domain data using the known phase evolution of the pulsar
  - Bayesian parameter estimation of unknown pulsar parameters using data from all interferometers
  - produce probability distribution functions for unknown parameters and marginalise over angles to set 95% upper limit on h_0

$$0.95=\int_{h_0=0}^{h_0^{95}} dh_0 \iiint p(a \,|\, \text{all data})\, d\varphi_0\, d\psi\, d\cos\iota$$



Probability distribution functions for the 3 LIGO interferometers for h0 for PSR J0024-7204C over S5

- Set limits on the pulsar ellipticity and compare with limits from spin-down arguments i.e. assuming all energy lost as the pulsar spins-down is dissipated via gravitational waves

$$\varepsilon=0.237\frac{h_0}{10^{-24}}\frac{d}{1\,\text{kpc}}\frac{1\,\text{Hz}^2}{\nu_r^2}\frac{10^{38}\,\text{kgm}^2}{I}$$

Preliminary S5 search results

- Obtain pulsar parameter information from pulsar group at Jodrell Bank and the ATNF pulsar catalogue
- Have *preliminary* results – joint 95% h_0 upper limits using timings for 97 pulsars using H1, H2 and L1 data from first 10 months of S5 data – 1st Nov 05 – 17th Sep 06
  - many will require to timing over the period of the run to be sure of phase coherence

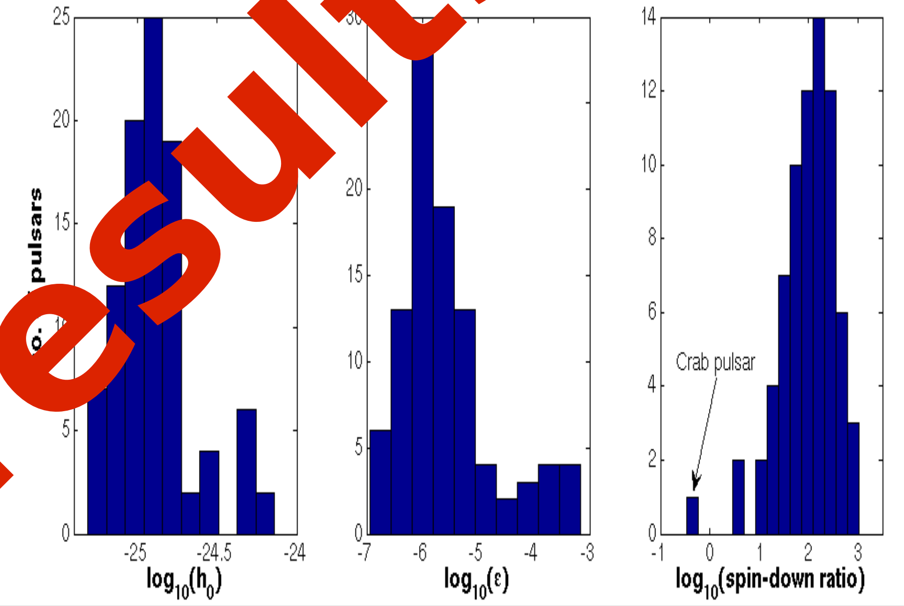
$$h_{0\,\text{spin-down}} = \left(\frac{5}{2} \frac{G I \dot{\nu}}{c^3 d^2 \nu_r} \right)^{\frac{1}{2}}$$

Lowest h_0 upper limit:

PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 3.8 kpc) $h_0 = 4.8\text{x}10^{-26}$

Lowest ellipticity upper limit:

PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 1.1\text{x}10^{-7}$

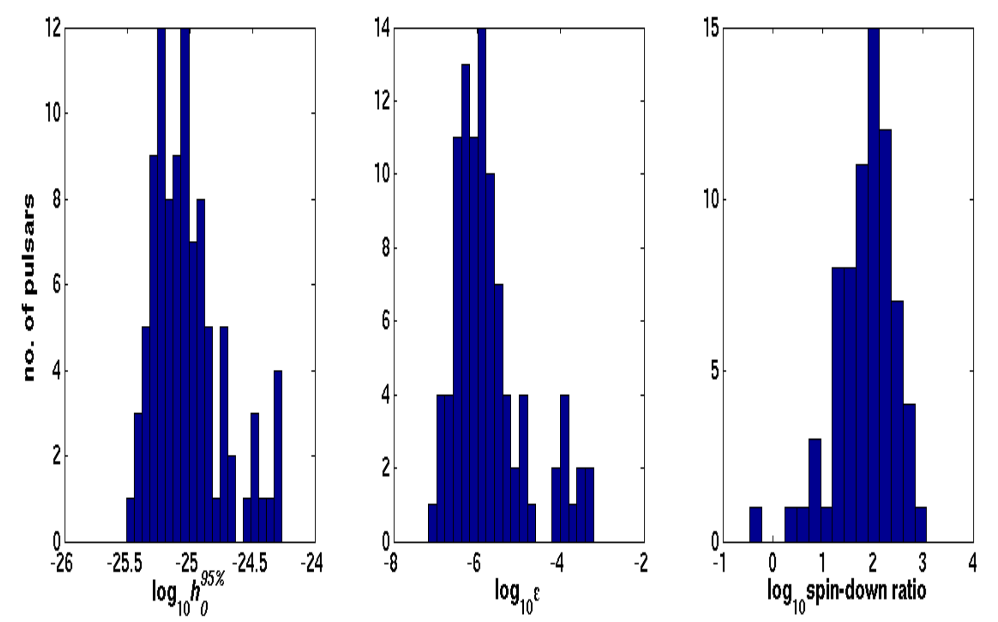


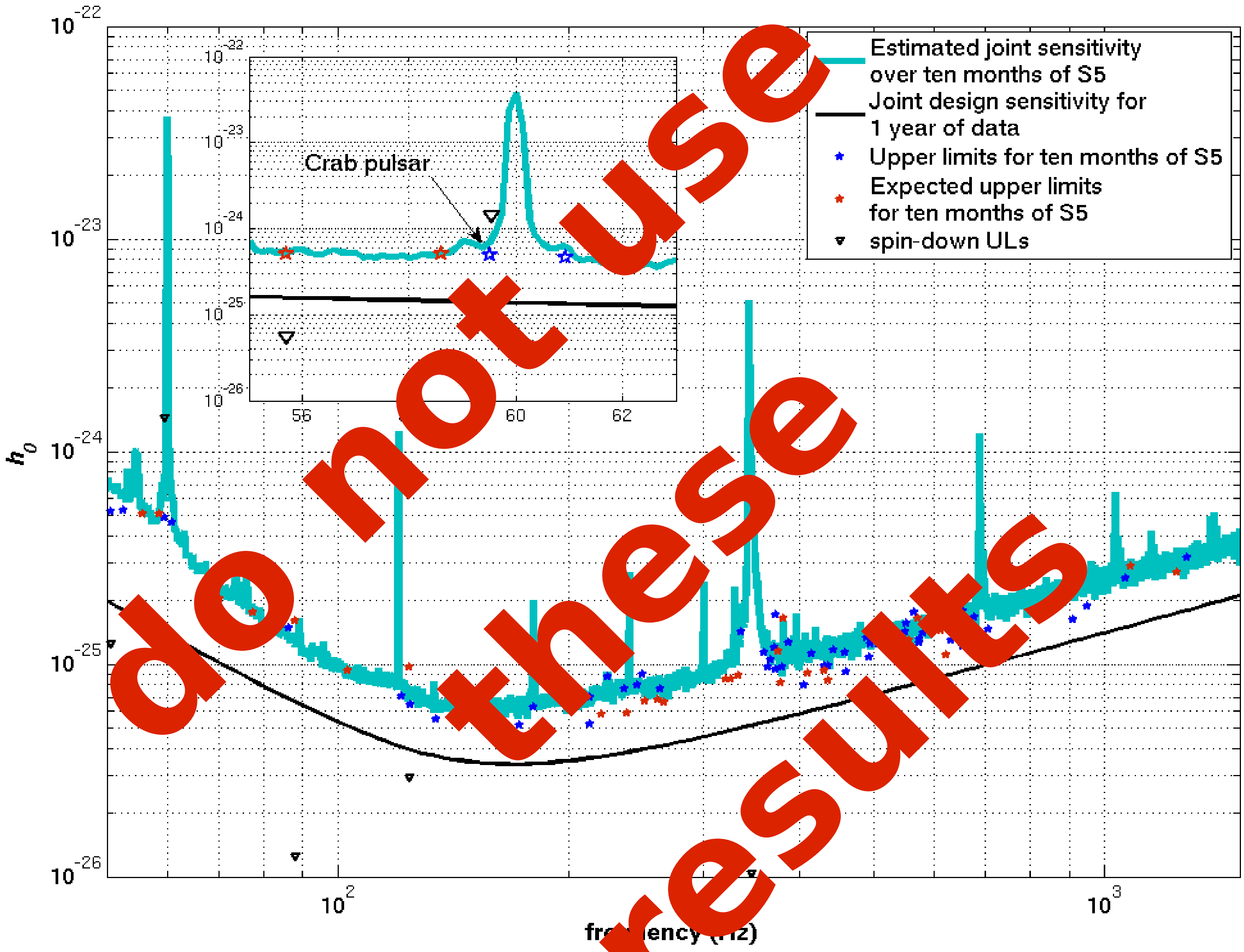
Preliminary S5 search results

- Obtain pulsar parameter information from pulsar group at Jodrell Bank and the ATNF pulsar catalogue
- Have *preliminary* results – joint 95% h_0 upper limits - using timings for 97 pulsars using H1, H2 and L1 data from first 13 months of S5 data – 1st Nov 05 – 17th Dec 06
  - many will require to timing over the period of the run to be sure of phase coherence

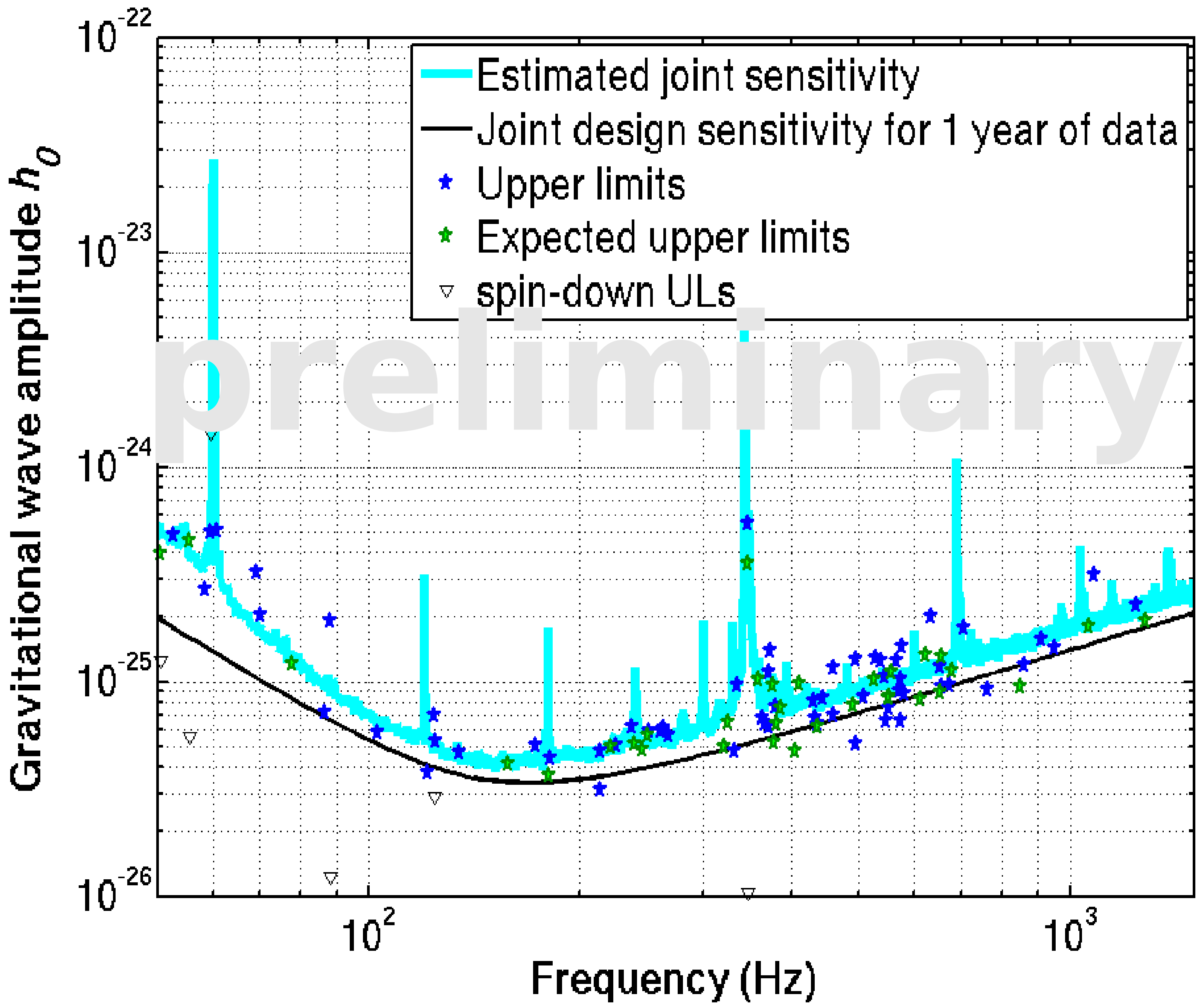
$$h_{0\,\text{spin-down}} = \left(\frac{5}{2}\frac{GI\dot{\nu}}{c^{3}d^{2}\nu_{r}}\right)^{\frac{1}{2}}$$

Lowest h_0 upper limit:
PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 3.8 kpc) $h_0 = 3.4\text{x}10^{-26}$
Lowest ellipticity upper limit:
PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 7.3\text{x}10^{-8}$





do not use these results



- **Black** curve represents one full year of data for all three interferometers running at design sensitivity
- **Blue** stars represent pulsars for which we are reasonably confident of having phase coherence with the signal model
- **Green** stars represent pulsars for which there is uncertainty about phase coherence

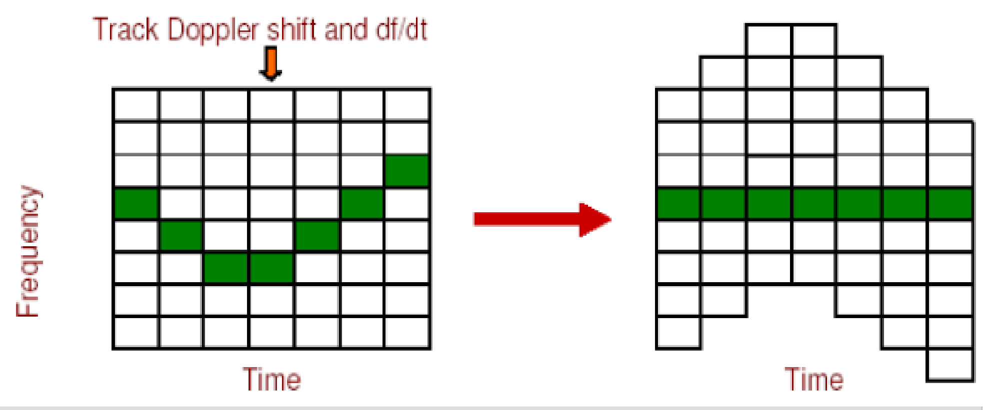
Crab pulsar

- Crab pulsar result uses data up to the time of a significant glitch – 23rd Aug 2006

- We have beaten the spin-down limit for the Crab pulsar, but what does this mean?
- We can start to constrain the rather uncertain energy budget of the pulsar
  - large uncertainties on the nebula mass give rather poor constraints onto the amount of energy from the pulsar required to power its expansion
  - we can give limits on the amount on energy emitted solely by gravitational radiation
  - upper limit could vary due to ~ factor of 3 uncertainty in the pulsar’s moment of inertia

Semi-coherent search - method

- There are three semi-coherent methods of searching for unknown continuous wave sources
  - Hough, StackSlide, PowerFlux
  - More computationally efficient than a fully coherent search, but with loss of sensitivity
- The data is divided up into short Fourier transformed segments (SFTs) and combined in a way as to compensate for Doppler modulation and spin-down for a particular source location
- Sum power (StackSlide, PowerFlux) or binary number counts (Hough)
- Create a sky map of power, or Hough number counts



$$\rho = \sum_{i=1}^{N} |\tilde{x}_{k(i)}|^2$$

$$\rho = \sum_{i=1}^{N} w_i |\tilde{x}_{k(i)}|^2$$

$$n = \sum_{i=1}^{N} n_{k(i)}$$

Stackslide

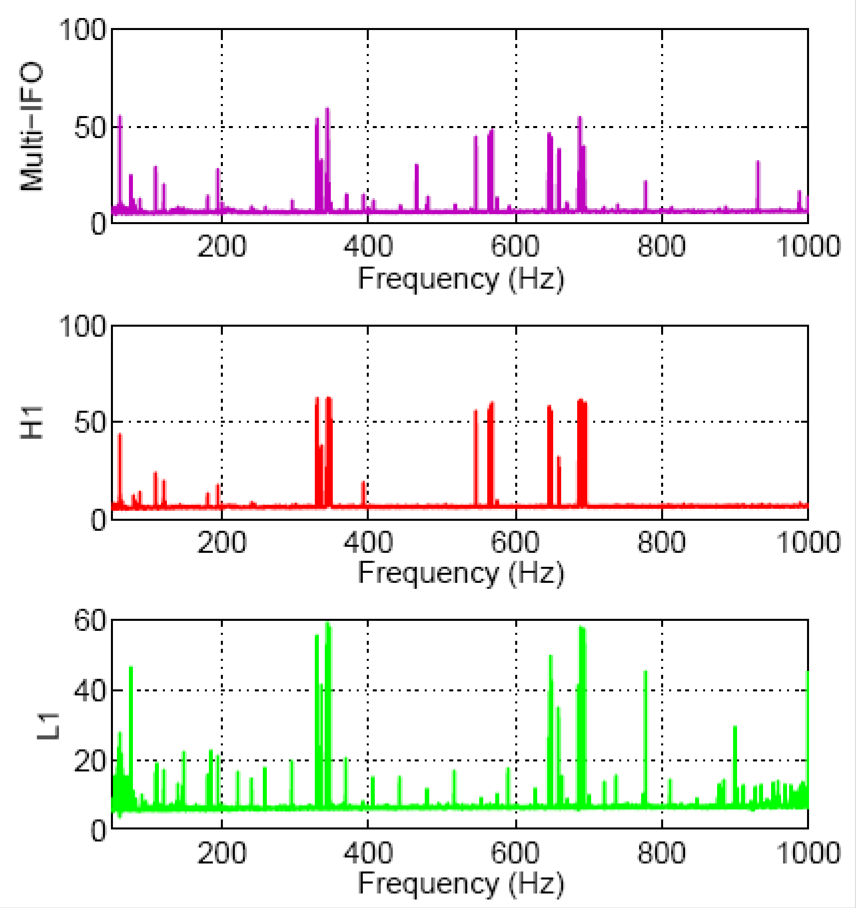
PowerFlux

$$n_{k(i)} = \begin{cases} 1 & \text{if} \quad |\tilde{x}_{k(i)}|^2 \geq \rho_0 \\ 0 & \text{if} \quad |\tilde{x}_{k(i)}|^2 < \rho_0 \end{cases}$$

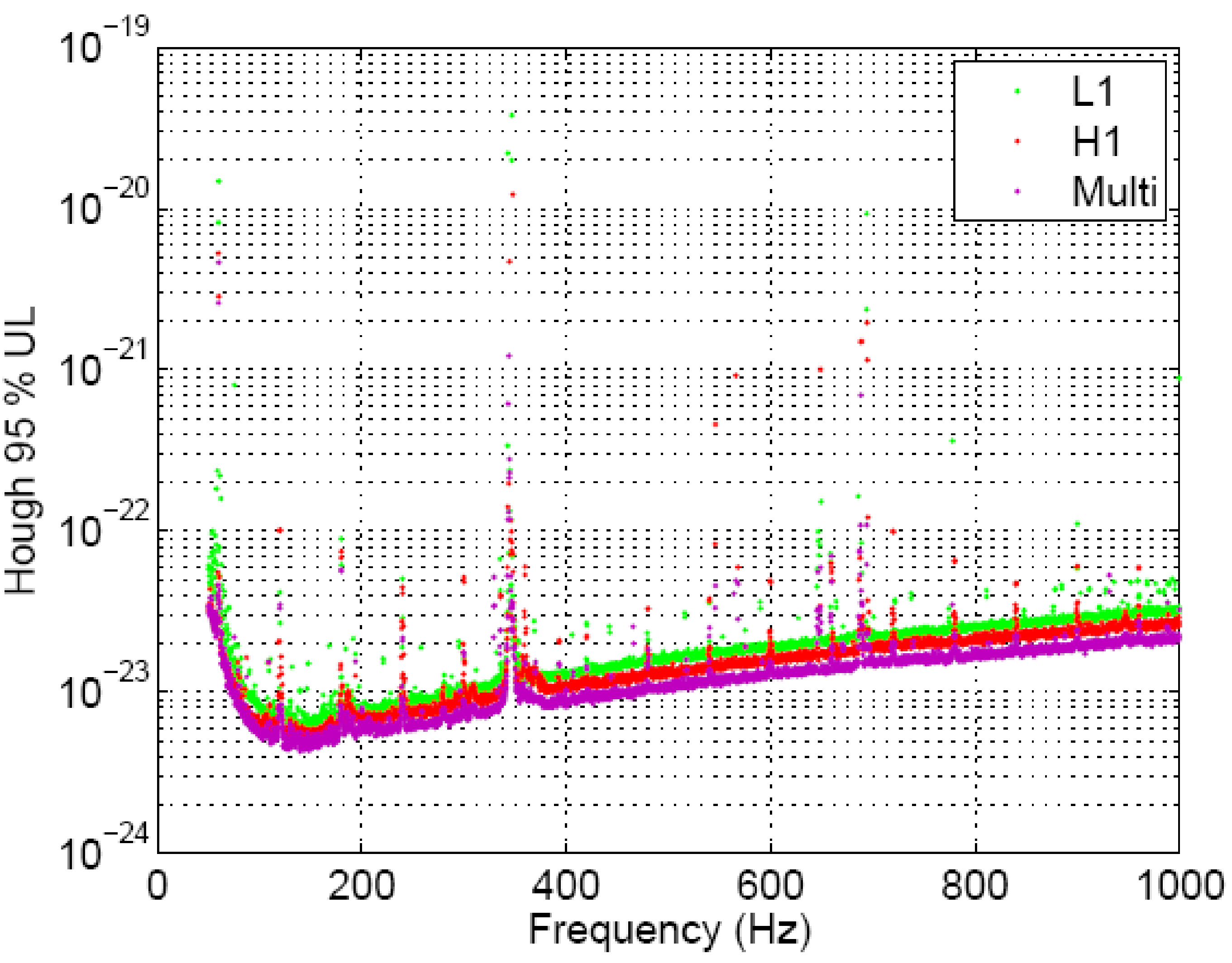
Hough search

Hough search – Preliminary S4 results

- Weighting allows coincident comparison of data from all interferometers
- All-sky search performed over the frequency range of 50-1000 Hz
- Sky is divided into 92 patches ~ 0.4 rads wide
- 10 spin-down parameters used with resolution $\delta f = (T_{obs} T_{SFT})^{-1} \sim 2.2\times10^{-10}$ Hz
- Upper limits set based loudest events in 0.25 Hz bands
  - Set threshold of 7 for multi-detector results and look for coincident candidate with threshold > 6.6 in H1 and L1
- **No** unexplained candidates seen



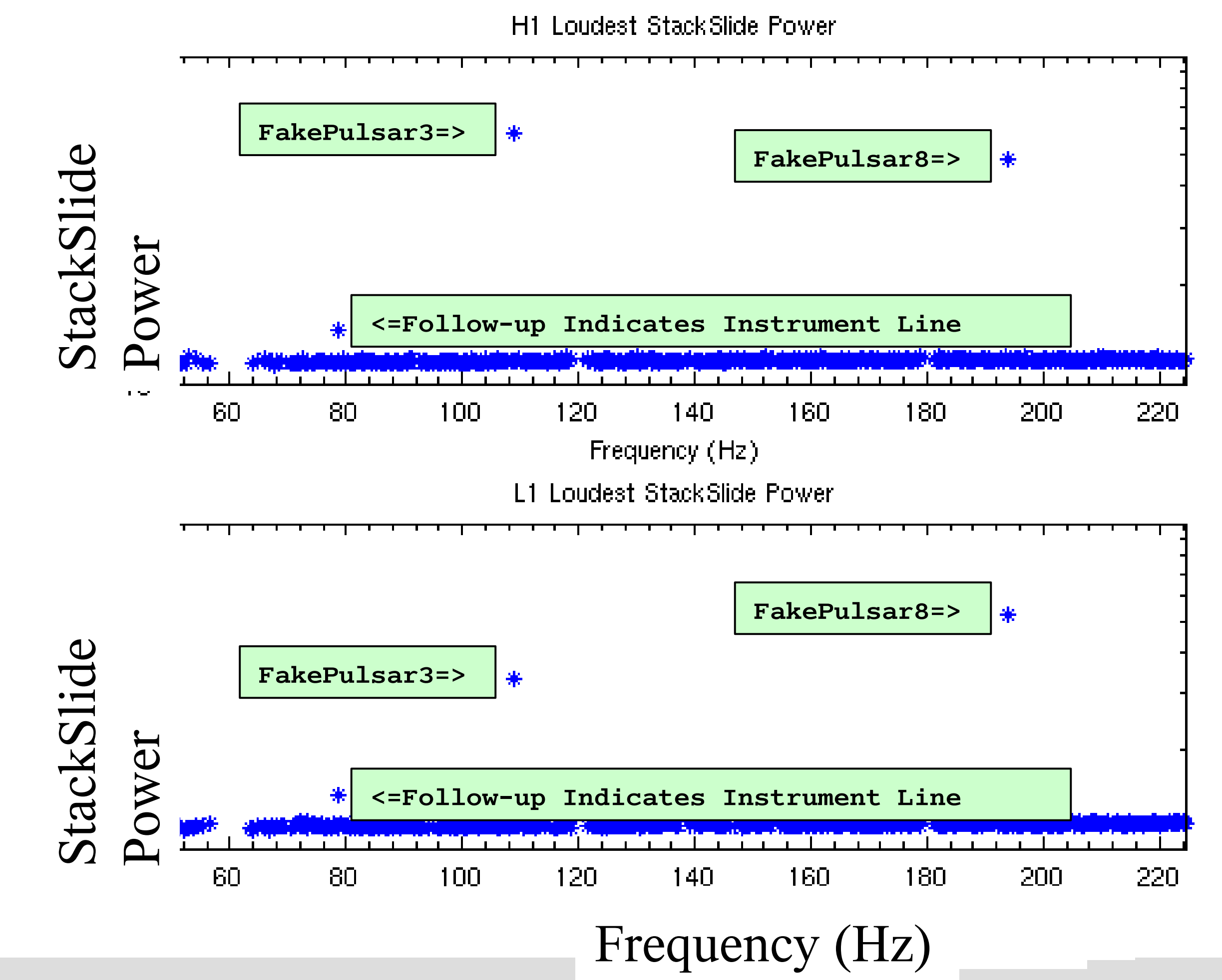
Hough results – upper limits



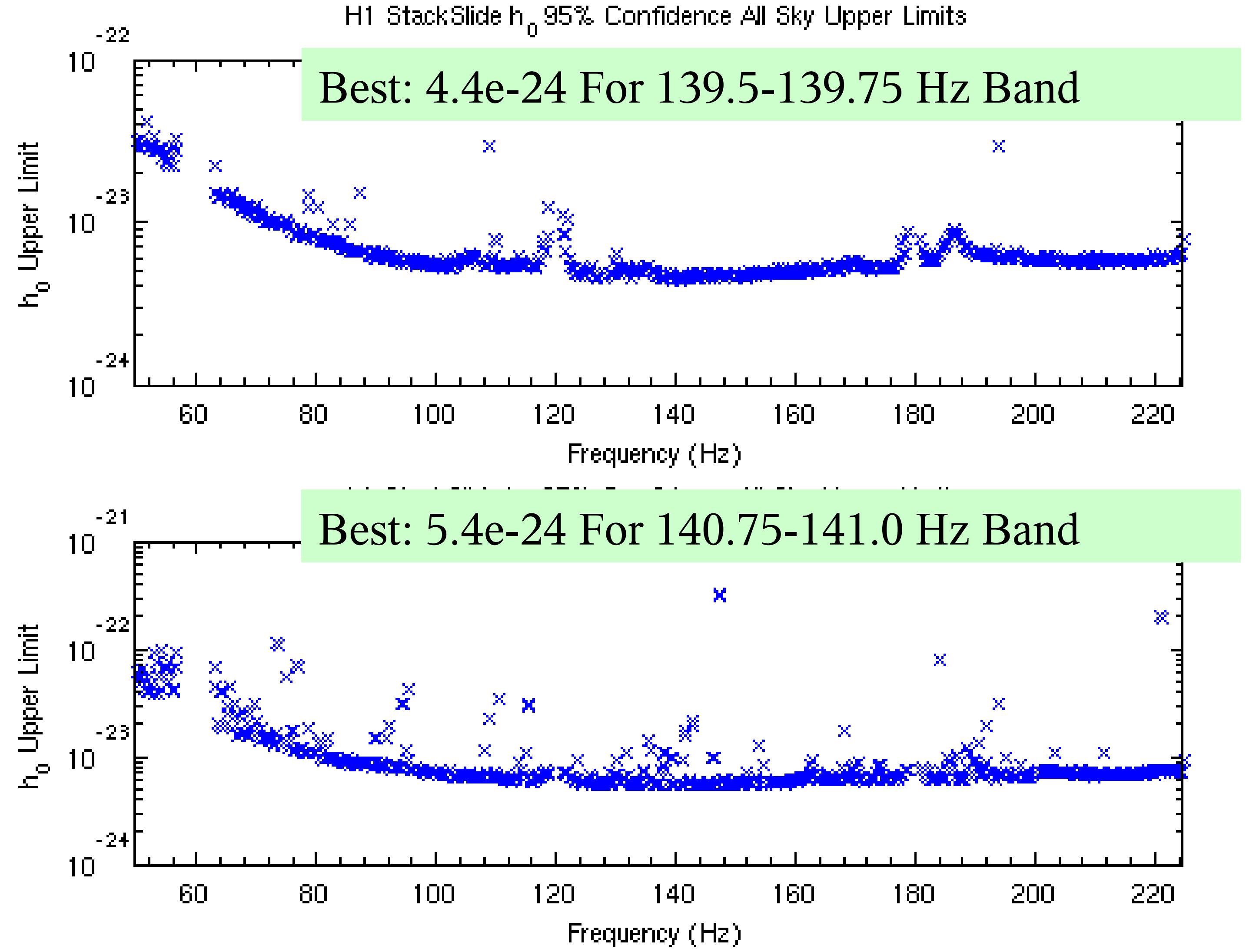
best h_0 upper limit = 4.3×10^{-24} (140.25-140.50 Hz)

StackSlide – preliminary S4 results

- Searched 450 frequencies per 0.25 Hz band, 51 values of d*f*/d*t*, between 0 and -1×10^{-8} Hz/s, up to 82120 sky positions (up to 2×10^{9} templates). The expected loudest StackSlide Power was ~ 1.22 (SNR ~ 7)
- Veto bands affected by harmonics of 60 Hz
- Simple cut: if SNR > 7 in only one IFO veto; if in both IFOs, veto if $\mathrm{abs}(f_{H1}-f_{L1}) > 1.1\times10^{-4} f_0$



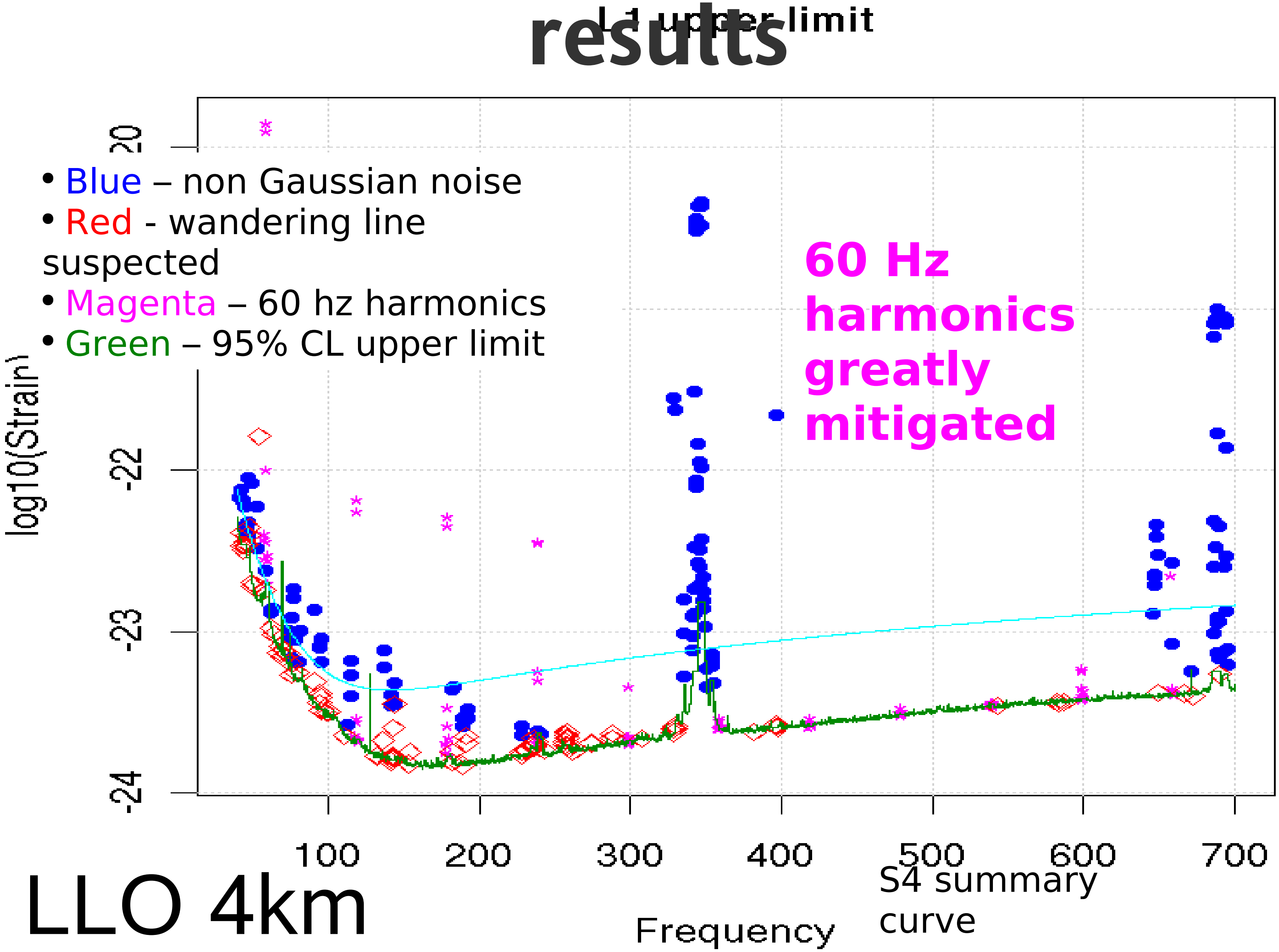
Stackslide 95% all-sky upper limits



Best: 4.4e-24 For 139.5-139.75 Hz Band

Best: 5.4e-24 For 140.75-141.0 Hz Band

PowerFlux – preliminary early S5 results



- Blue – non Gaussian noise
- Red - wandering line suspected
- Magenta – 60 hz harmonics
- Green – 95% CL upper limit

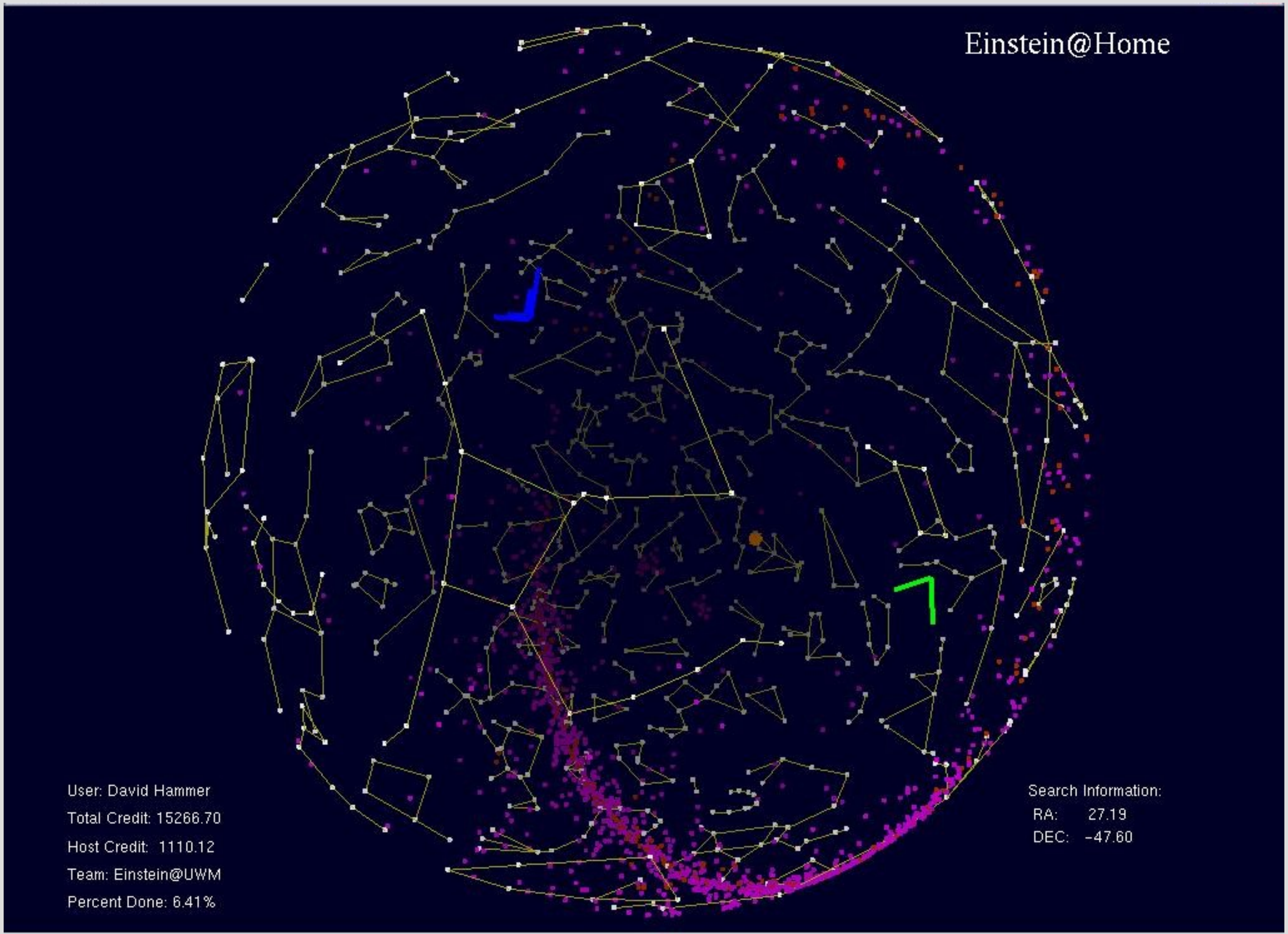
60 Hz harmonics greatly mitigated

LLO 4km

S4 summary curve

Einstein@home – final S3 results

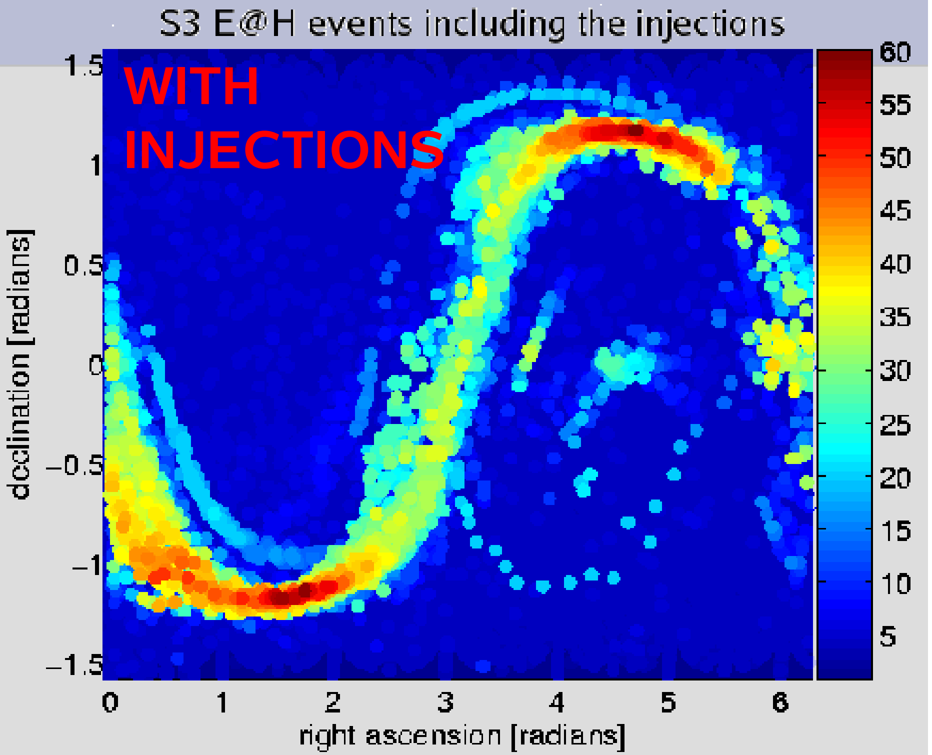
- Fully coherent all-sky search

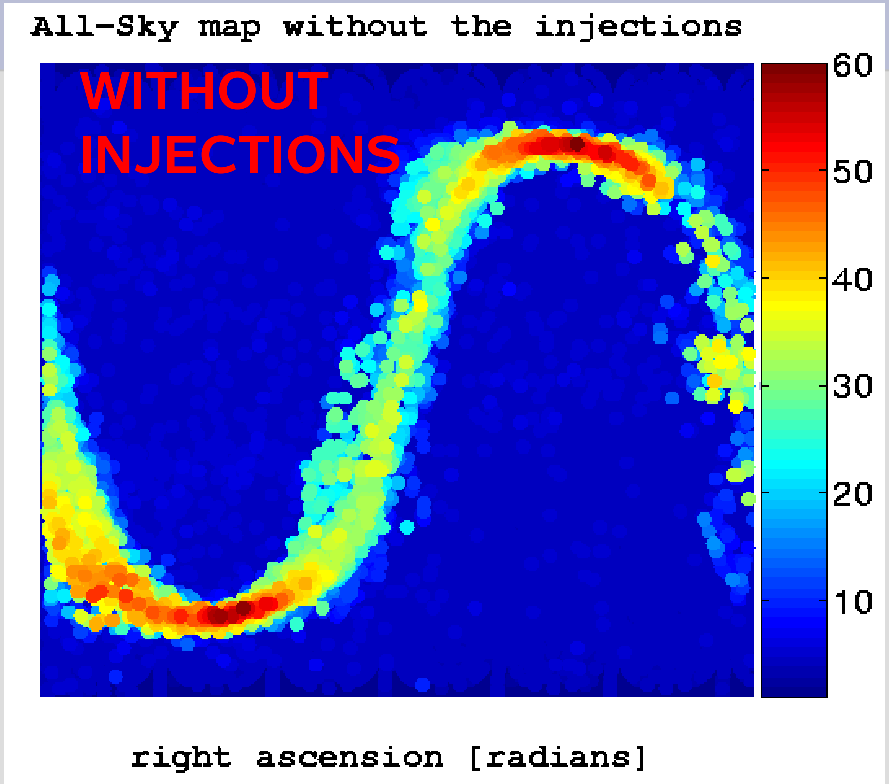


User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

Search Information:
RA: 27.19
DEC: -47.60

Einstein@home – S3 final results

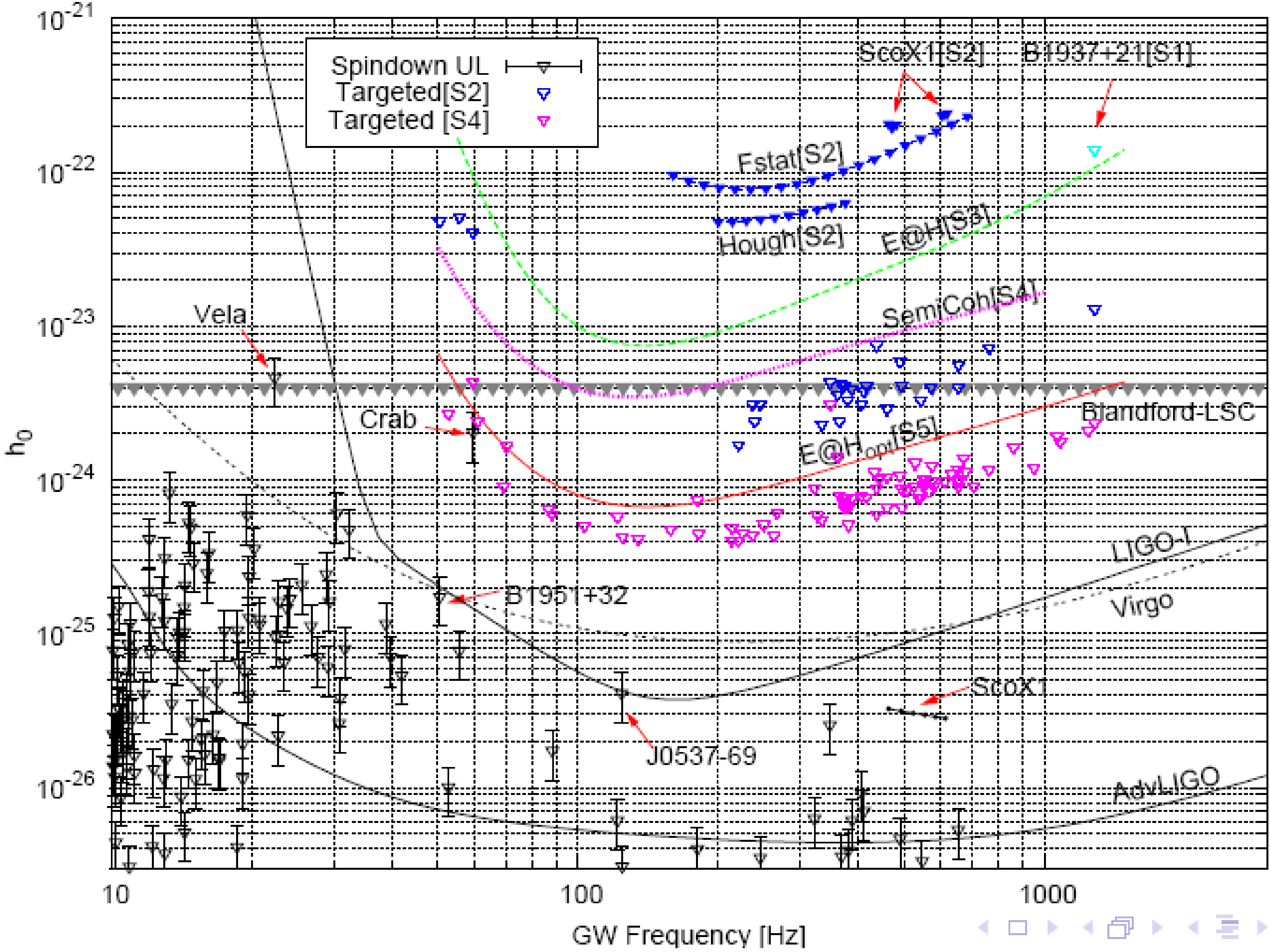

S3 E@H events including the injections


All-Sky map without the injections

- 50-1500 Hz band shows no evidence of strong pulsar signals in sensitive part of the sky, apart from the hardware and software injections. There is nothing “in our backyard”.
- Outliers are consistent with instrumental lines. All significant artifacts away from r.n=0 are ruled out by follow-up studies.

Future

- Known pulsar search will continue to add more S5 data and more pulsars
  - Sensitivity increase by $\sim 2^{1/2}$
  - possibly approach two more spin-down upper limits with more data
- Fully coherent all-sky search on S5 data with Einstein@home currently underway
  - Hough search as part of Einstein@home S5 data as part of hierarchical search
  - follow up Hough candidates with fully coherent search
- PowerFlux analysis continuing on S5 data
- MCMC targeted searches over small frequency/position space e.g. SN1987A


10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
h_0
10
100
1000
GW Frequency [Hz]
Spindown UL
Targeted[S2]
Targeted [S4]
ScoX1[S2]
B1937+21[S1]
Fstat[S2]
Hough[S2]
E@H[S3]
SemiCoh[S4]
Vela
Crab
Blandford-LSC
E@H$_{opt}$[S5]
LIGO-I
Virgo
B1951+32
ScoX1
J0537-69
AdvLIGO

Summary slide

- S5 targeted pulsar search for 97 known pulsars
  - Lowest h_0 upper limit:
    PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 3.8 kpc) $h_0 = 3.4\text{x}10^{-26}$
  - Lowest ellipticity upper limit:
    PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 7.3\text{x}10^{-8}$
  - Beat spin-down upper limit for Crab pulsar
- S4 Hough search
  - No unexplained candidates
  - best h_0 upper limit = $4.3\text{x}10^{-24}$ (140.25-140.50 Hz)