# The Laser Interferometer Gravitational-Wave Observatory

A Caltech/MIT collaboration supported by the United States National Science Foundation

*http://www.ligo.caltech.edu*

# Recent Results From The LIGO Search For Periodic Gravitational Waves

**Gregory Mendell, LIGO Hanford Observatory**

**on behalf of the LIGO Scientific Collaboration**

LIGO-G070408-00-W

# Sources

Search methods can detect any type of periodic source.

Upper limits are set on gravitational-wave amplitude, $h_0$, of rotating triaxial ellipsoid.

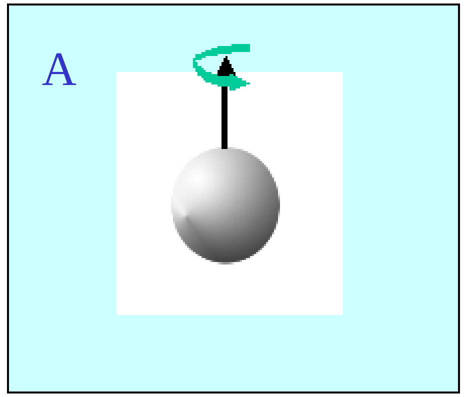
Credits:

A. image by Jolien Creighton; LIGO Lab Document G030163-03-Z.

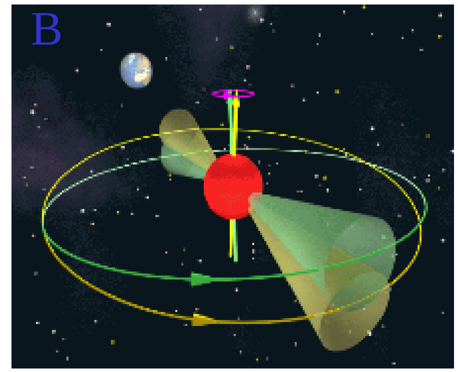
B. image by M. Kramer; Press Release PR0003, University of Manchester - Jodrell Bank Observatory, 2 August 2000.

C. image by Dana Berry/NASA; NASA News Release posted July 2, 2003 on Spaceflight Now.

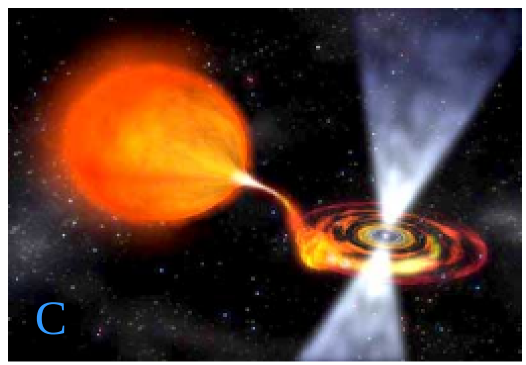
D. image from a simulation by Chad Hanna and Benjamin Owen; B. J. Owen's research page, Penn State University.



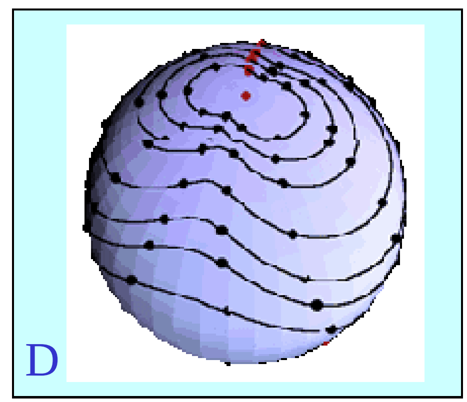

Mountain on neutron star




Precessing neutron star

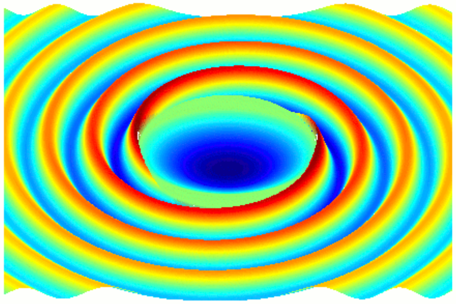



Accreting neutron star




Oscillating neutron star

# Searches

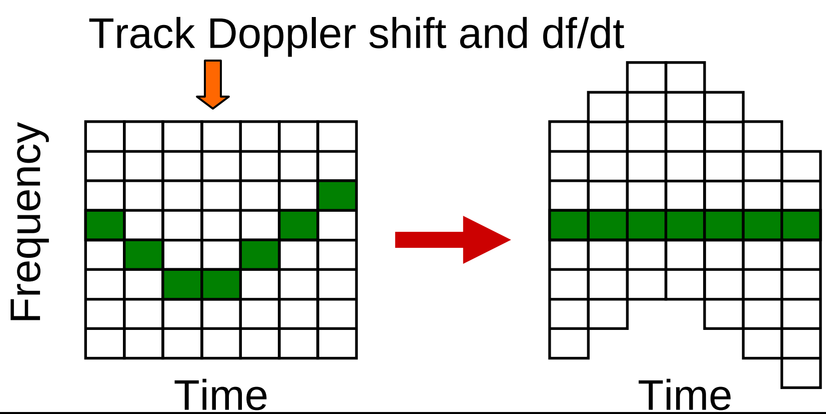


*Searches 2-4 are computationally expensive: e.g., for obs. time T a coherent search over the sky, f, and df/dt scales as $T^6$ while its sensitivity scales as $T^{1/2}$; orbital params. or higher derivs. add powers of T.

- **1. Known pulsars (radio & x-ray) (e.g., Crab pulsar)**
  - Position & frequency evolution known (including derivatives, timing noise, glitches, orbit).
- **2. Unknown neutron stars**
  - Nothing known, search over sky position, frequency & its derivatives.
- **3. Accreting neutron stars & LMXBs (e.g., Sco-X1)**
  - Position known; some need search over freq. & orbit.
- **4. Targeted sky position: galactic center, globular clusters, isolated non-pulsing neutron stars (e.g., Cas A)**
  - Search over frequency & derivatives.

# Methods

- Semicoherent Methods
  - StackSlide: add the power
  - Hough: add weighted 1 or 0
  - PowerFlux: add weighted power



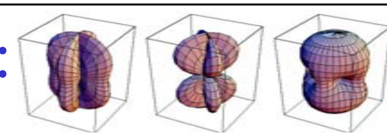

- Coherent Methods
  - Bayesian Param. Estimation
  - Maximum Likelihood & Matched Filtering

$$P(x\,|\,h) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{\frac{-(x_1-h_1)^2}{2\sigma_1^2}} \frac{1}{\sqrt{2\pi}\sigma_2} e^{\frac{-(x_2-h_2)^2}{2\sigma_2^2}} \ldots$$

$$P(h\,|\,x) = P(h)P(x\,|\,h)/P(x) \Rightarrow \text{Time Domain}$$

$$\chi^2 = \sum_j \frac{(x_j - h_j)^2}{\sigma_j^2} \Rightarrow \left( \sum_j \frac{x_j h_j}{\sigma_j^2} - \frac{1}{2} \sum_j \frac{h_j h_j}{\sigma_j^2} \right)$$

$$\Rightarrow \text{Frequency Domain} \Rightarrow (\log \Lambda)_{\max} \Rightarrow F$$

•Weights depend on both noise and antenna patterns: 

•Methods can include multi-detector data and coincidence steps.

•Hierarchical Methods: combine the above to maximize sensitivity.

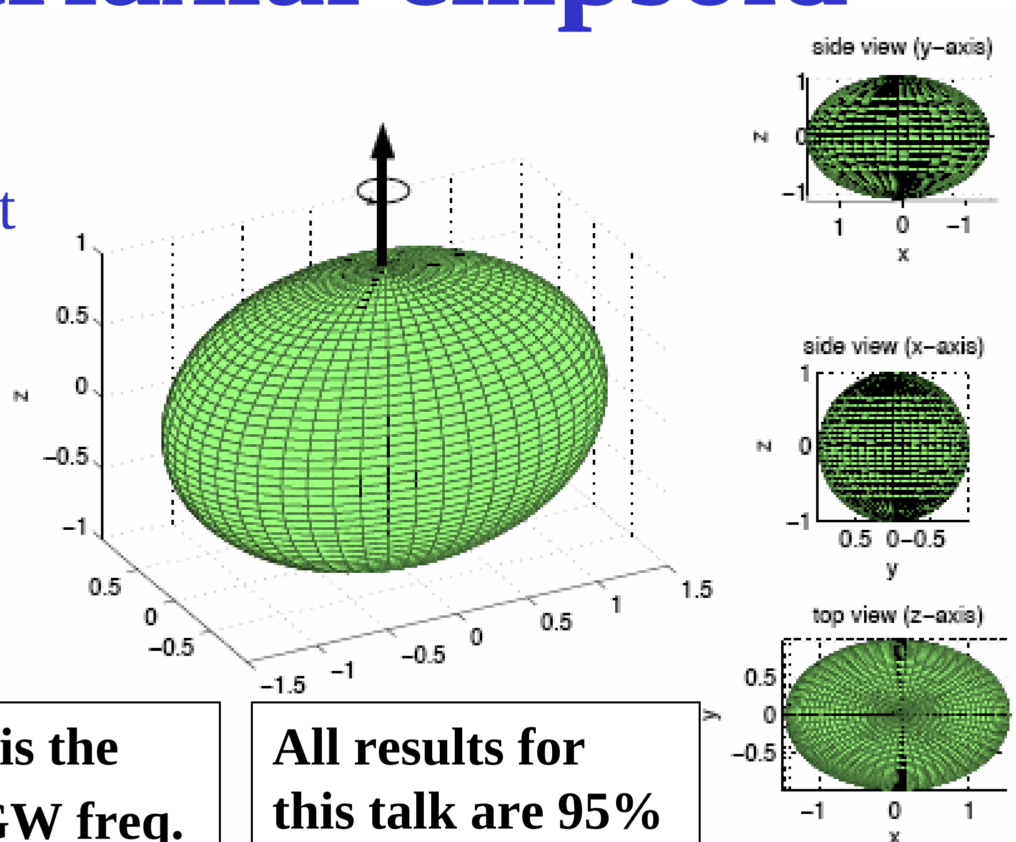
# GWs from triaxial ellipsoid

- For upper limits have to select a model. (This is not needed for detection!)
- Ellipticity, ε, measures asymmetry in triaxially shaped neutron star.

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{\varepsilon I_{zz} f^2}{r}$$

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

**Equatorial Ellipticity**




**f is the GW freq.**

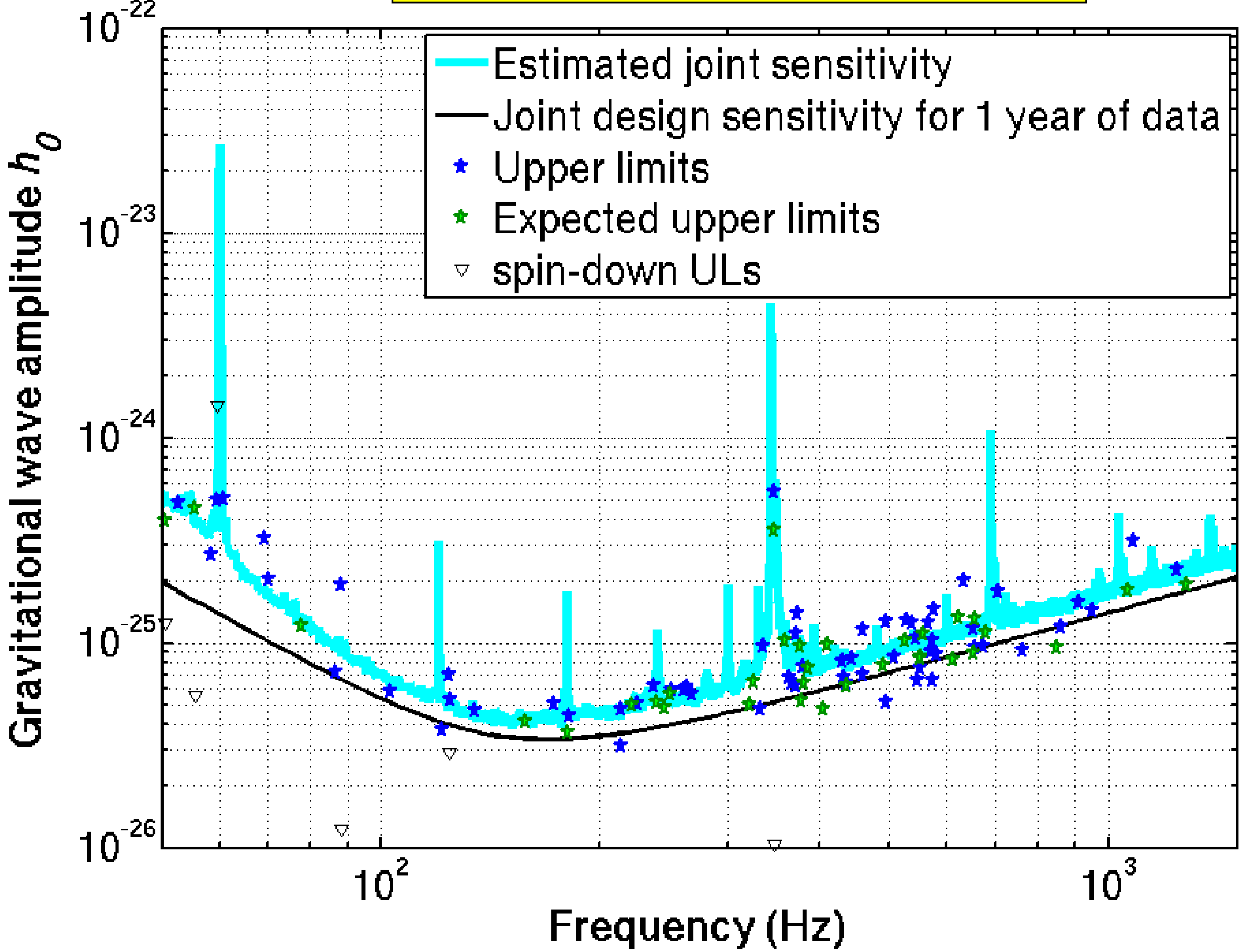
**All results for this talk are 95% confidence ULs on $h_0$ and ε.**

# Astrophysical predictions & payoff

- Neutron, hybrid or quark stars max. $\varepsilon \sim 10^{-6}, 10^{-5}, 10^{-4}$ respectively.
- Blandford/LSC statistical estimate: few $\times 10^{-24}$ $(100\text{ yrs}/\tau_{\text{birthrate}})^{1/2}$
- Age-based limits, e.g., Cas A (see K. Wette's presentation)
- Spindown limits (e.g., Crab pulsar)
- Accreting Stars
  - Torque balanced by GWs or limit cycles
  - Thermo-Elastic mountains
  - Magnetic mountains
  - R-modes
- For a summary, see: LIGO Scientific Collaboration, gr-qc/0605028, accepted by Phys. Rev. D (2007).
- For more on indirect limits and astrophysical payoff see B. Owen poster.

# S5 Known Pulsar Search

PRELIMINARY

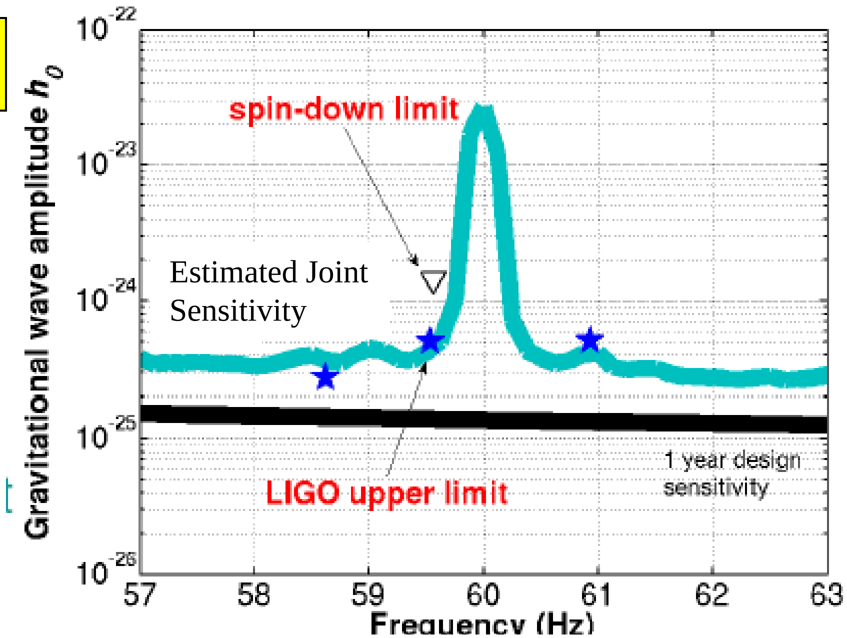


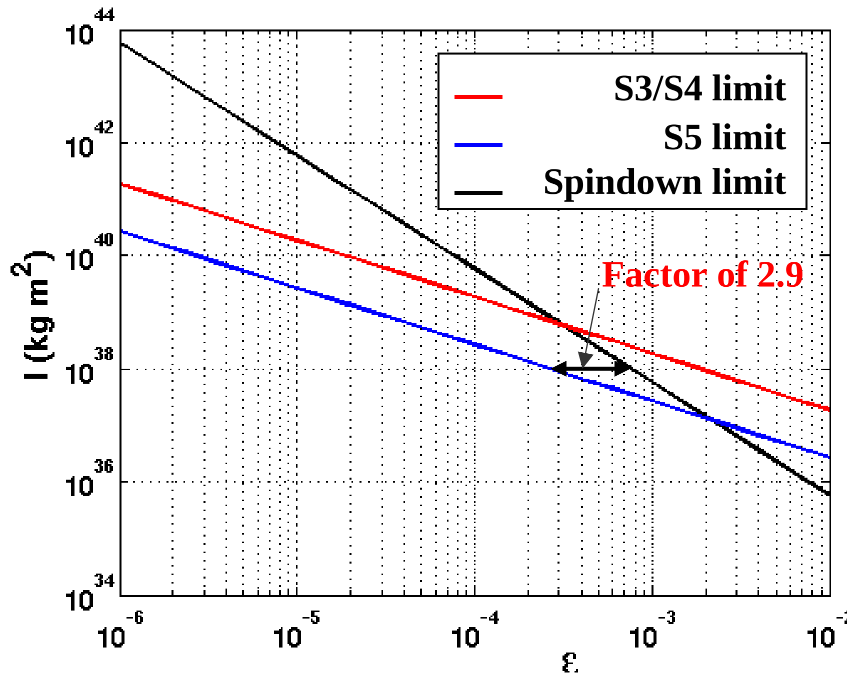

- Using data from the first thirteen months of S5
- **Black** curve represents one full year of data for all three interferometers running at design sensitivity
- **Blue** stars represent pulsars for which we are reasonably confident of having phase coherence with the signal model.
- **Green** stars represent pulsars for which there is uncertainty about phase coherence

LIGO PRELIMINARY

# S5 Crab Pulsar Result

- These results give upper limits for the Crab pulsar of $\varepsilon < 2.6\text{x}10^{-4}$, $h_0 < 5.0\text{x}10^{-25}$ using S5 data up to the glitch on 23 Aug. 2006
  - this value of the ellipticity is now in the range of some of the more speculative equations of state (Owen, 2005)
- These beat the spindown limit of $h_0 < 1.4\text{x}10^{-24}$ by a factor of 2.9 – for canonical moment of inertia I = $10^{38}$ $\text{kgm}^2$ - we even beat Palomba's limit
- Start to constrain the amount of spin-down energy in GWs to less than 10% of overall emitted and known spindown (Palomba, 2000, Santostasi)
  - This is significant: the ***uncertainties*** on all non-GW contributions ***add up to*** 80% of the total!
- Moment of inertia is uncertain by about a factor of three, but we can plot the result on the moment of inertia – ellipticity plane to give exclusion regions (Pitkin for the LSC, 2005)



UNDERWAY

# Multi-template Crab Search

•Known pulsar GW searches track phase assuming $f_{GW}=2f_{EM}$.

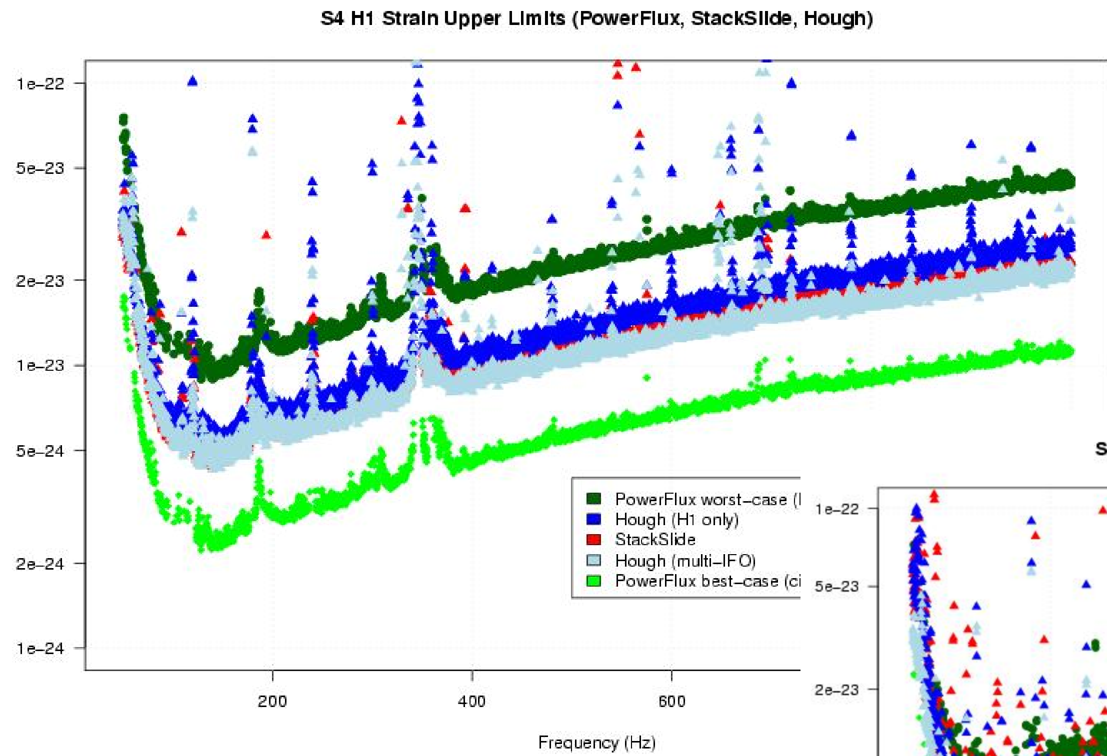
•If the gravitational radiation time evolution is different from that of the electromagnetic radiation it is possible these could miss the gravitational waves.

•We are considering mechanisms by which any emitted gravitational waves will differ from the electromagnetic.

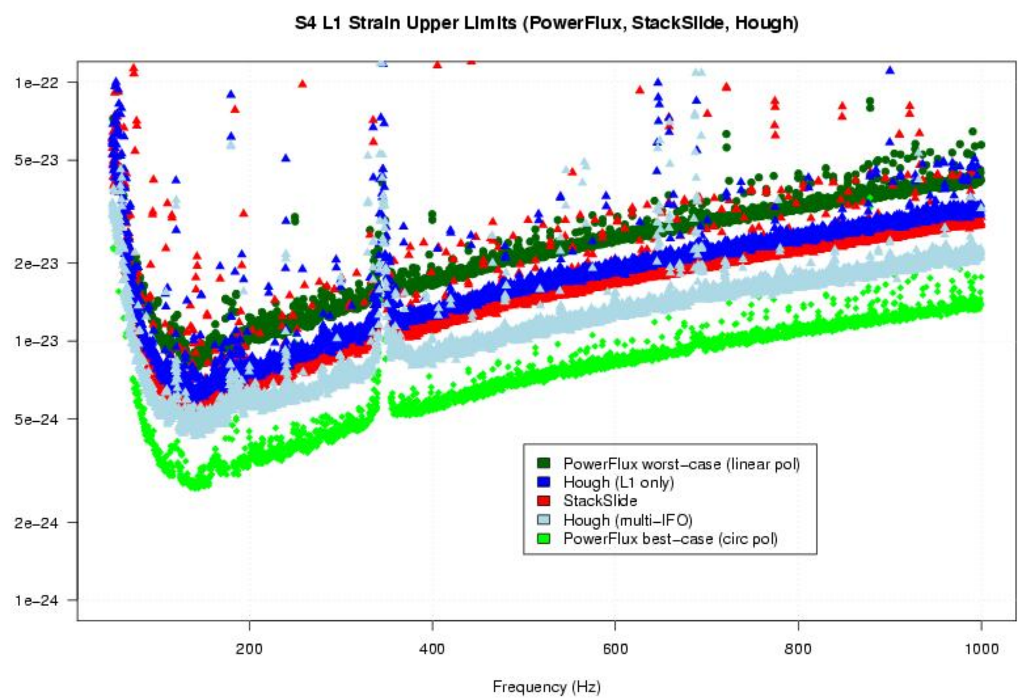
• Consideration of free precession or glitches leads to $|f_{GW}-2f_{EM}|/(2f_{EM}) \leq 10^{-4}$ and corresponding band for time derivatives of the frequency.

• Need many templates; for the Crab this is underway.

# S4 One Month All-Sky Search: Hanford, Livingston, and Multi-IFO Results



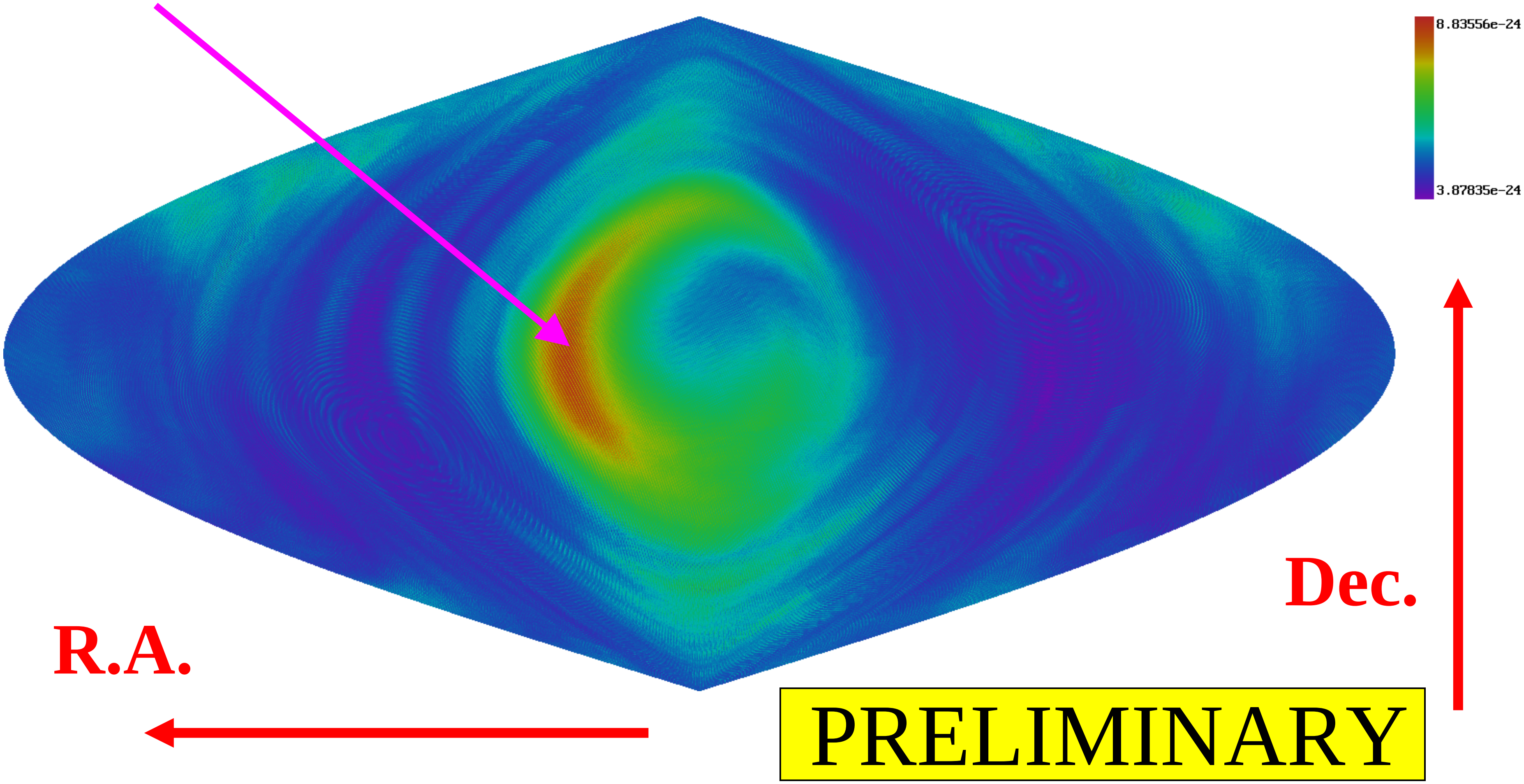

**See presentation by A. Sintes**



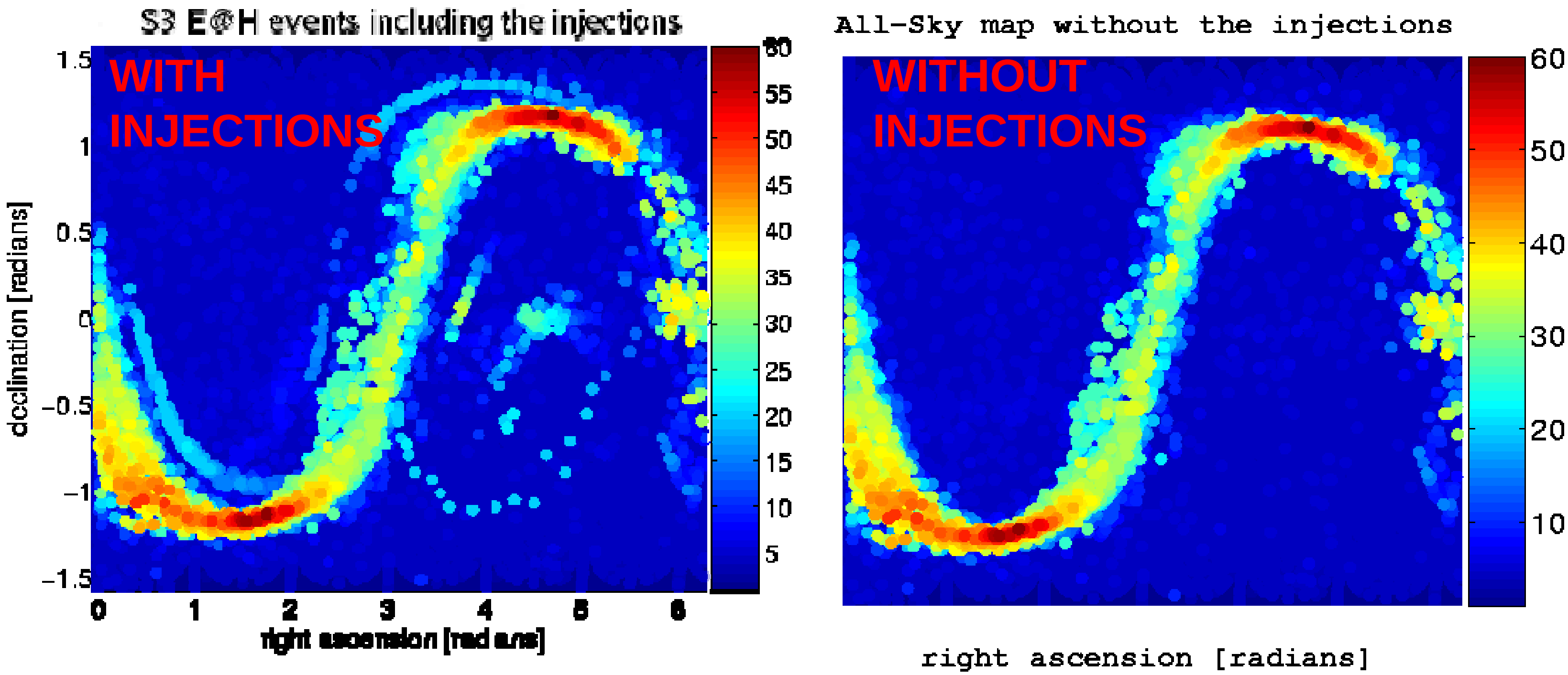

PRELIMINARY

# PowerFlux circular-polarization strain H1 S4 upper limits for band with HW Injected Signal.

**Simulated Pulsar** ($h_0$ ~ 8.4 x $10^{-24}$ → nearly circ. polarized signal)



# Einstein@home S3 Final Results




- 50-1500 Hz band shows no evidence of strong pulsar signals in sensitive part of the sky, apart from the hardware and software injections.
- Outliers are consistent with instrumental lines. All significant artifacts away from a·n=0 are ruled out by follow-up studies.

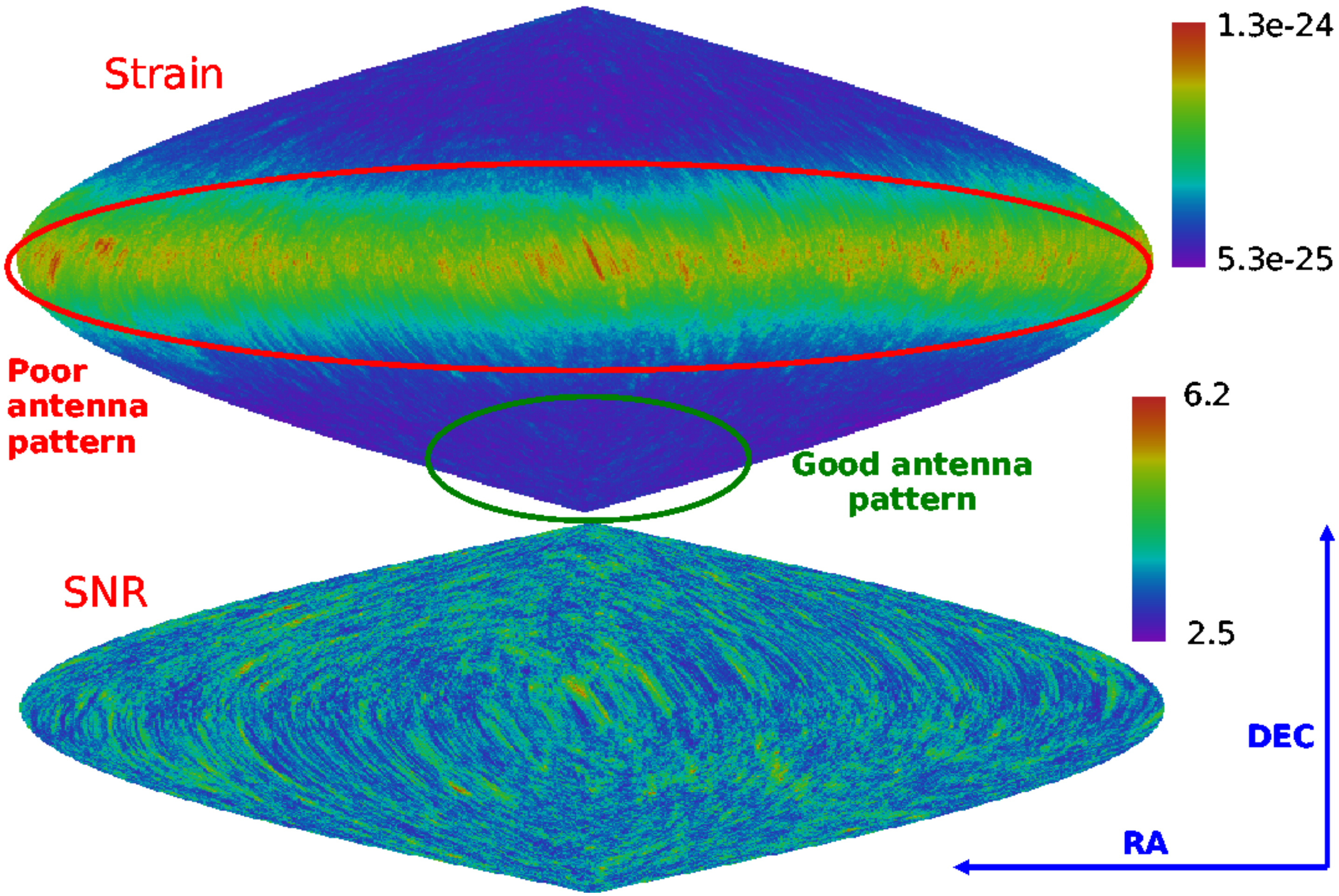
PRELIMINARY

# PowerFlux S5 Results

**(Using data from 07 Nov. 2005 through 20 July 2006)**

Hanford 4km, ~270 Hz, non-zero spindown

(equatorial coordinates)



UPDATE

# Einstein@Home S4 & S5

- S4 Post-Processing Nearly Complete!
- S5 Initial Hierarchical Search is underway:
  - computes the fully coherent multi-ifo maximum likelihood statistic for 25 hr segments containing 40 hrs of Hanford and Livingston 4km IFO data.
  - performs Hough transforms of the results.
  - will eventually include automated follow-up of candidates; could include StackSlide option.

# Summary Preliminary Results and Plans

1. S4 all-sky, 50-1000 Hz, PowerFlux, StackSlide, Hough search: results in preparation (see presentation by A. Sintes) and start of S5 preliminary all-sky PowerFlux search:

   **Best UL: $h_0 <$ few $\times 10^{-24}$.**

2. Start of S5 preliminary coherent known pulsar search:

   **Best UL $h_0 <$ few $\times 10^{-26}$; Best $\varepsilon$ UL: a little less than $\sim 10^{-7}$;**

   **Crab limits beat the spindown limit!**

3. S5 targeted sources: Cas A (youngest candidate NS) search is underway. (see presentations by K. Wette & B. Owen)

4. S5 all-sky PowerFlux & Multi-IFO initial Hierarchical Einstein@Home searches are under way.

5. More searches are under development, e.g., LMXBs.

End

# Frequency Modulation and S Parameter

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

**Relativistic corrections are included in the actual code**

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

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

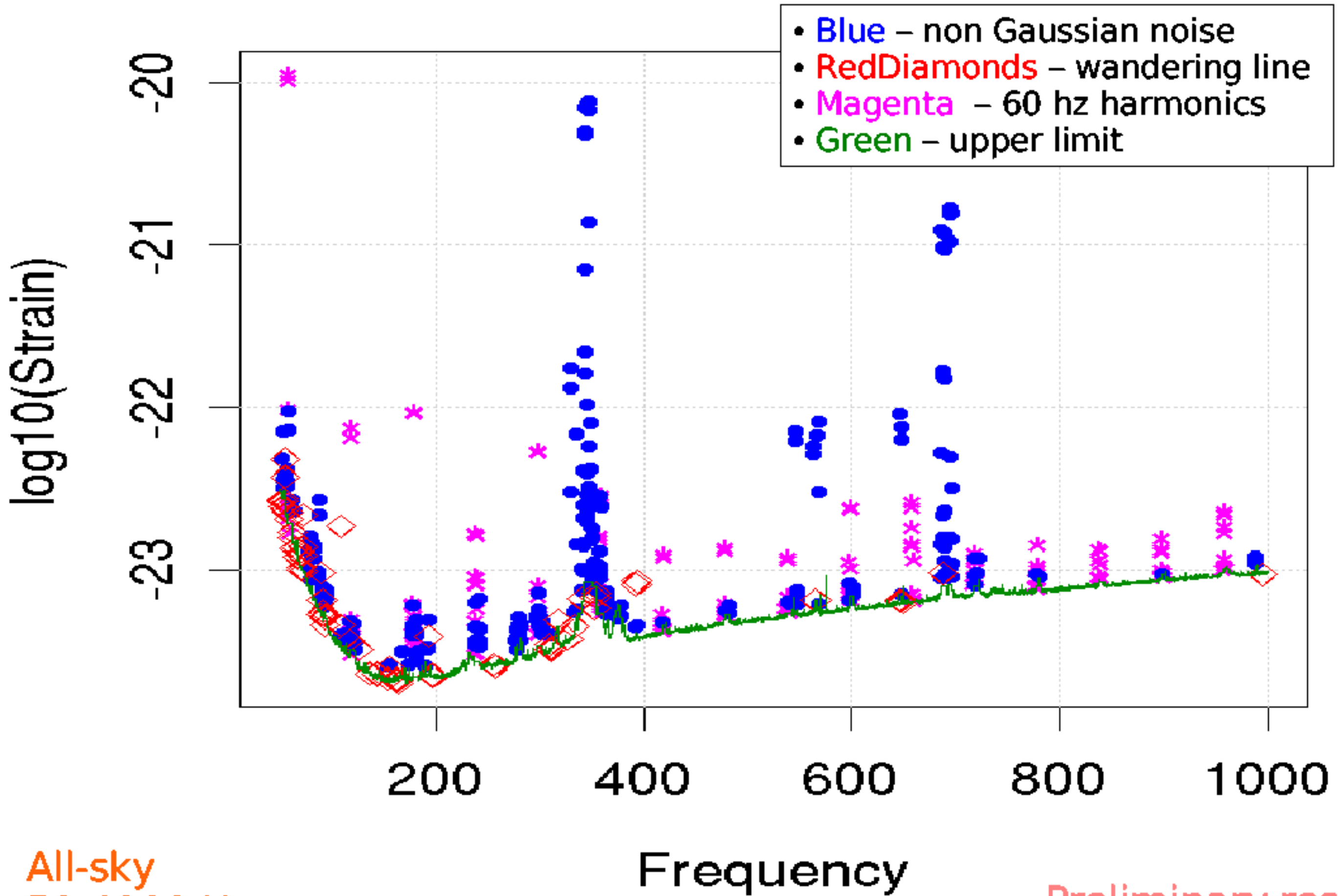
**For analysis < 1 yr sky points with small S have small doppler variation; harder to distinguish GWs from instrument lines at these points.**

PRELIMINARY

# PowerFlux S5 Preliminary Results

**(Using data from 07 Nov. 2005 through 20 July 2006)**

## H1 S5 0-spindown run




All-sky
50-1000 Hz

Preliminary results

# Published Periodic Search Results To June 2007

*. arXiv:gr-qc/0702039 [ps, pdf, other] :

Title: **Upper limits on gravitational wave emission from 78 radio pulsars**

Authors: **The LIGO Scientific Collaboration: B. Abbott, et al, M. Kramer, A. G. Lyne**

Comments: 21 pages, updated author list **(* Just accepted by Phys. Rev. D)**

1. arXiv:gr-qc/0605028 [ps, pdf, other] :

   Title: **Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run**

   Authors: **The LIGO Scientific Collaboration**

   Comments: 35 pages, 30 figures **(To appear in Phys. Rev. D)**

2. arXiv:gr-qc/0508065 [ps, pdf, other] :

   Title: **First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform**

   Authors: **LIGO Scientific Collaboration: B. Abbott, et al**

   Comments: 22 pages, 21 figures, to be submitted to Phys. Rev. D

   Journal-ref: Phys.Rev. D72 (2005) 102004

3. arXiv:gr-qc/0410007 [ps, pdf, other] :

   Title: **Limits on gravitational wave emission from selected pulsars using LIGO data**

   Authors: **The LIGO Scientific Collaboration: B. Abbott, et al, M. Kramer, A.G. Lyne**

   Comments: 6 pages, 2 figures

   Journal-ref: Phys.Rev.Lett. 94 (2005) 181103

4. arXiv:gr-qc/0308050 [ps, pdf, other] :

   Title: **Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors**

   Authors: **The LIGO Scientific Collaboration: B.Abbott, et al**

   Comments: 16 pages,8 figures

   Journal-ref: Phys.Rev. D69 (2004) 082004

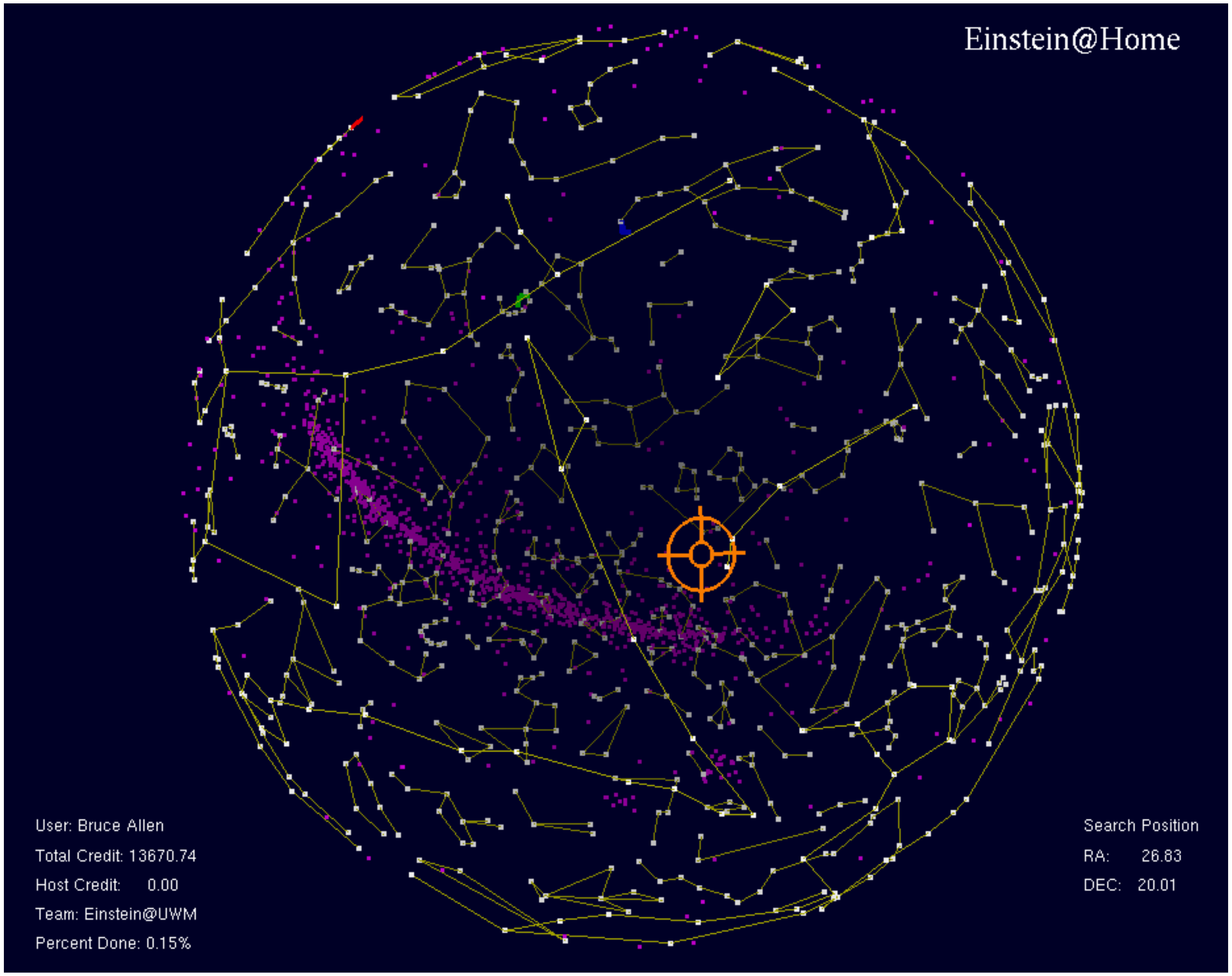
# The LIGO/VIRGO Pulsar Search Joint Working Group has started meeting!

- LIGO/Virgo MOU signed
- Weekly teleconferences
- Face-to-Face meetings in March & May 2007
- Data Sharing started in May 2007

# Einstein@home:

http://einstein.phys.uwm.edu/

- Like SETI@home, but for LIGO/GEO matched-filtered search for GWs from rotating compact stars.
- Support for Windows, Mac OSX, and Linux clients
- Our own clusters have thousands of CPUs.
- Einstein@home has many times more computing power at low cost.



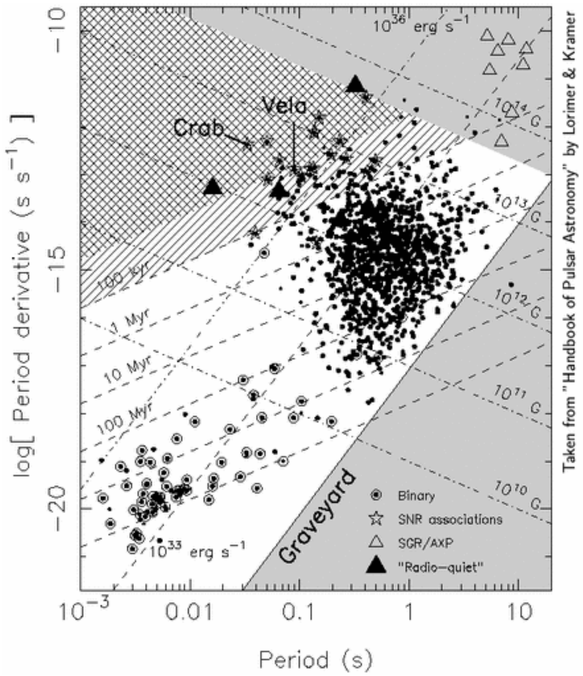
# Crab Pulsar Spindown Limit

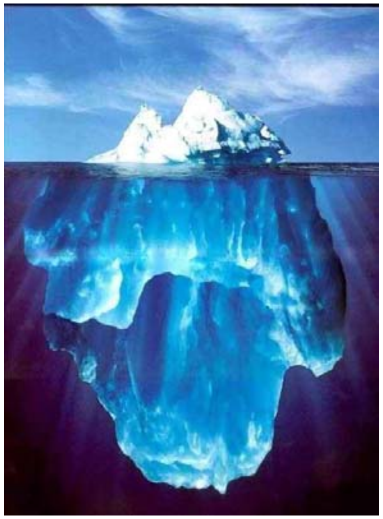
- Spindown limit assumes all the pulsars rotational energy loss is radiated by gravitational wave
- We know some energy is emitted electromagnetically and is powering the expansion of the Crab nebula
- This is poorly constrained and allows room for gravitational wave emission
- Braking index
  - The braking index of the Crab is n=2.5, not n=3 for purely magnetic dipole radiation, and not n=5 for purely gravitational radiation emission
  - Palomba (2000) allows for a combination of mechanisms to account for this braking index and ends up with a GW spin-down limit which is 2.5 times below the n=5 standard limit.

*Credits: X-ray: NASA/CXC/ASU/J. Hester et al.; Optical: NASA/HST/ASU/J. Hester et al.*

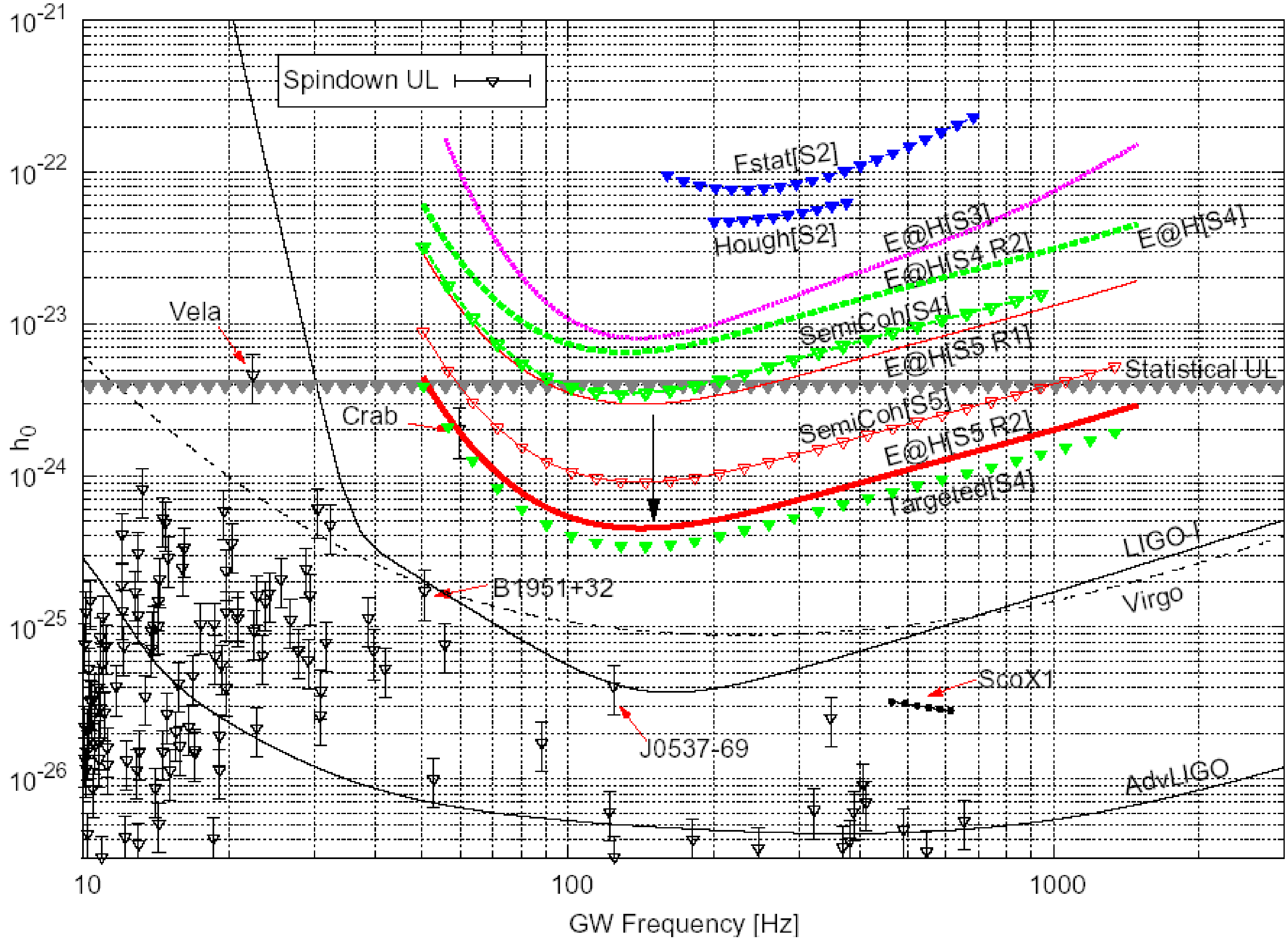
# Met with astronomers & astrophysicist in 2006 at MIT

- A. Melatos: Magnetic Mountains
- S. Ransom: Longer term, an “Arecibo in the South” would find and time *hundreds* of new cluster MSPs... (*FAST*?); Even longer term, the Square Kilometer Array will find *thousands* of new pulsars
- C. Palomba/T. Regimbau: population studies
- Dunc Lorimer: tip of the iceberg =>



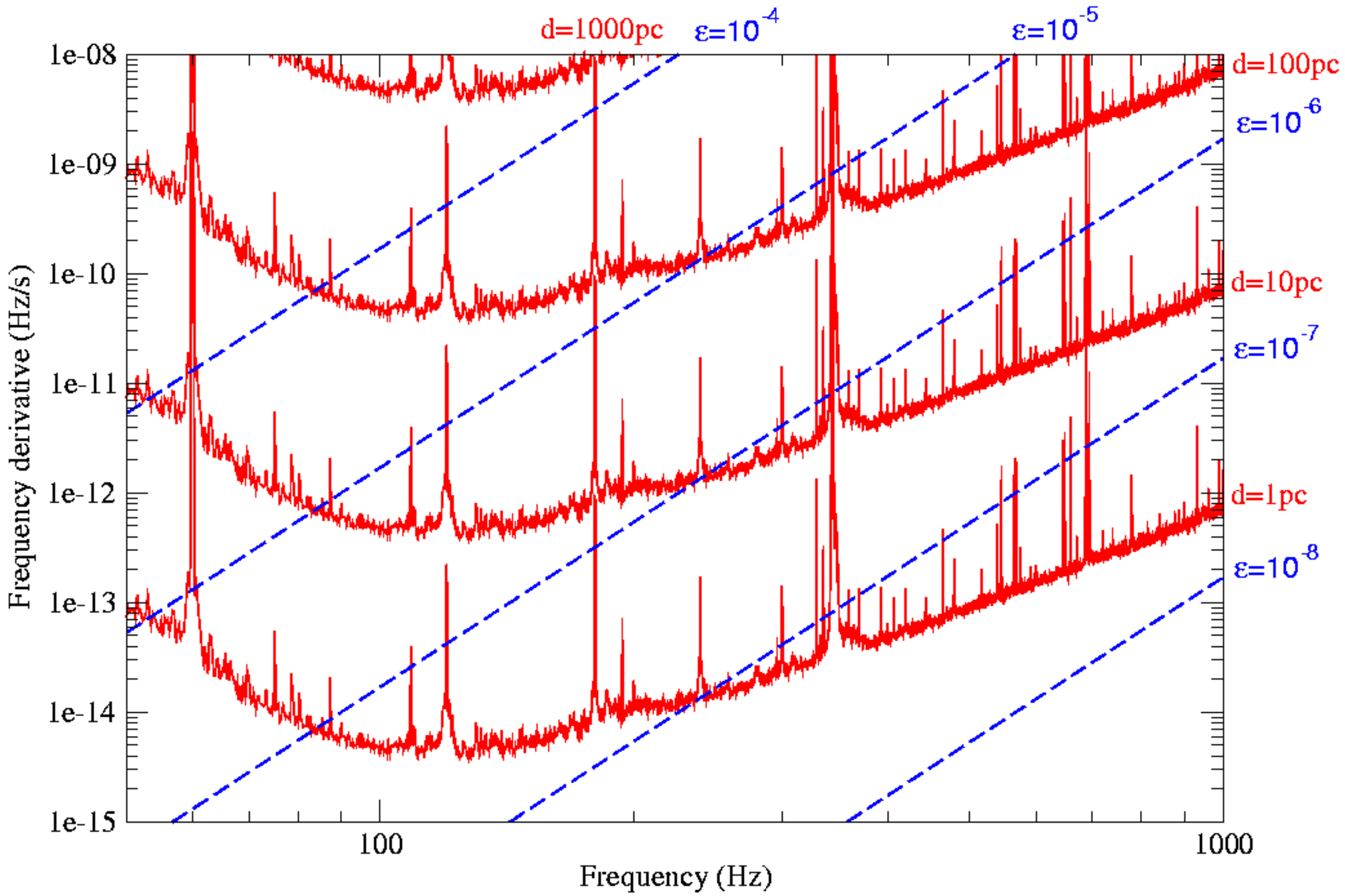
# Prospects



Spindown UL
Estat[S2]
Hough[S2]
E@H[S3]
E@H[S4]
E@H[S4 R2]
SemiCoh[S4]
E@H[S5 R1]
Statistical UL
SemiCoh[S5]
E@H[S5 R2]
Targeted[S4]
Vela
Crab
B1951+32
J0537-69
ScoX1
LIGO-I
Virgo
AdvLIGO
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$h_0$
10
100
1000
GW Frequency [Hz]

PRELIMINARY

# S4 One Month Semicoherent Search Astrophysical Reach



# Other Work:

1. X-ray pulsars (for example J0537-6910 glitchiest pulsar) Working with astronomers to get timing data.

2. LMXB Search

3. Proposed Unknown Binary Search

4. Globular cluster target

5. Code speed up

6. SN1987A

7. Generalized PowerFlux

8. LIGO/VIRGO work.

# Coherent Matched Filtering

$$X_b = \sum_{\alpha=0}^{M-1} \sum_{j=0}^{N-1} x_{\alpha j} F_{+\alpha}(0) e^{-i\Phi_{\alpha j b}} \qquad x_{\alpha j} = \frac{1}{N} \sum_{k=0}^{N-1} X_{\alpha k}^{SFT} e^{2\pi i j k / N}$$

$$\bar{X}_{+b} \cong \sum_{\alpha=0}^{M-1} F_{+\alpha}(0) e^{-i\phi_0} \sum_k \frac{X_{\alpha k}^{SFT}}{\sqrt{S_{\alpha k}}} \frac{\sin 2\pi\kappa_b - i(1-\cos 2\pi\kappa_b)}{2\pi(k-\kappa_b)}$$

$$F = \frac{4}{M} \frac{\langle F_\times^2 \rangle |\bar{X}_+|^2 + \langle F_+^2 \rangle |\bar{X}_\times|^2 - 2\langle F_+ F_\times \rangle \Re e\left(\bar{X}_+ \bar{X}_\times^*\right)}{\langle F_+^2 \rangle \langle F_\times^2 \rangle - \langle F_+ F_\times \rangle^2}$$

↑

**F-statistic**

*Jaranowski, Krolak, & Schutz gr-qc/9804014; Schutz & Papa gr-qc/9905018; Williams and Schutz gr-qc/9912029; Berukoff and Papa LAL Documentation*

# Results approaching astrophysical interest (also spindown limits/indirect limits; see B. Owen Poster.)

$$E = I\Omega\dot{\Omega} \propto |\dddot{Q}|^2 \Rightarrow \dot{f} = -Kf^5 \Rightarrow \tau_{age} = f/4|\dot{f}|$$

$$h = \frac{1}{r}\sqrt{\frac{20GI|\dot{f}|}{8c^3 f}}$$

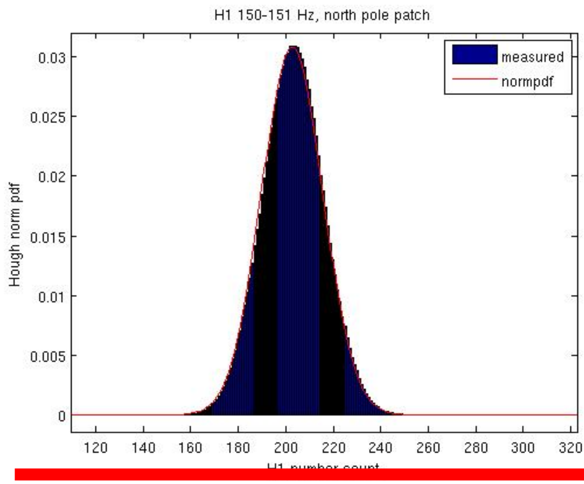
$$r_{\min} \sim \sqrt{\frac{\tau_{birthrate}}{\tau_{age}}} R_{galaxy}$$

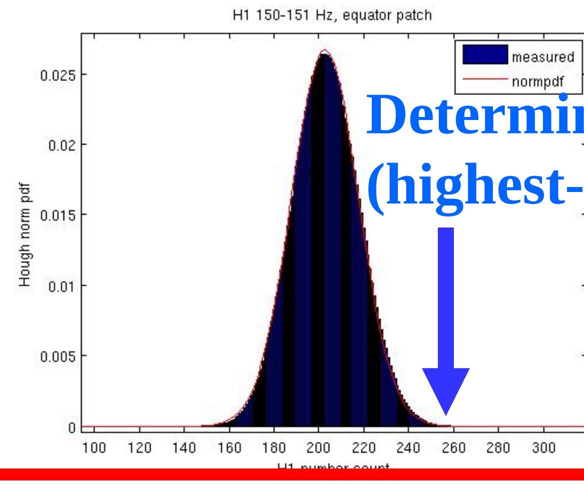
$$h \approx \frac{1}{R_{galaxy}}\sqrt{\frac{5GI}{8c^3\tau_{birthrate}}} = 10^{-24}\sqrt{\frac{100\,yrs}{\tau_{birthrate}}}$$

***Blandford (1984) as cited by Thorne in 300 Years of Gravitation; see also LIGO Scientific Collaboration, gr-qc/0508065, accepted by Phys. Rev. D (2005); and LIGO Scientific Collaboration, S2 Maximum Likelihood Search.***

# Hough (2 of 92 sky patches shown)

Sample 0.25-Hz bands



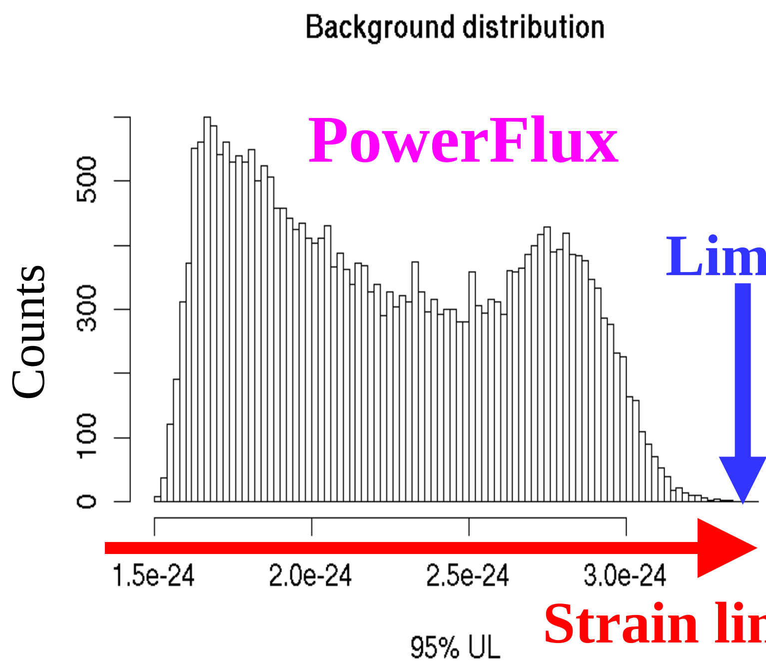




Determines limit (highest-SNR patch)

Hough count

(North Pole) (Equator)

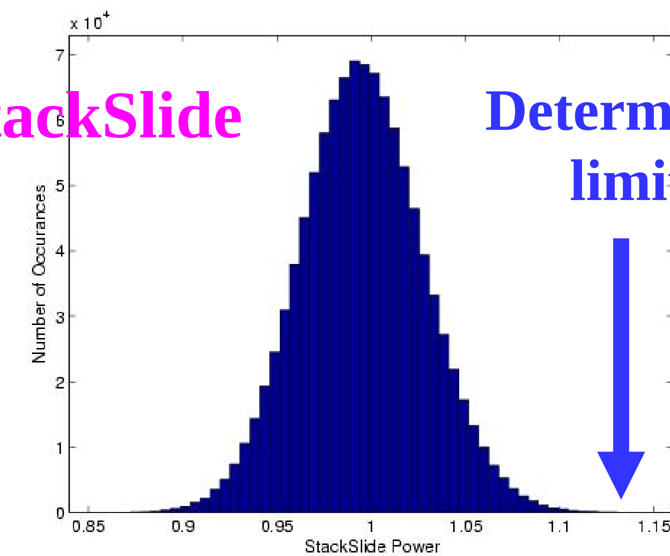
PowerFlux




Limit

Strain limit

StackSlide




Determines limit

StackSlide power

# Nature of periodic gravitational waves

- 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
  - $\psi$ - polarization angle of signal; embedded in $F_{x,+}$
  - $\iota$ - inclination angle of the pulsar
  - $\phi_0$ - initial phase of pulsar $\Phi(0)$

- In the known pulsar searches we currently look for signals at twice the rotation frequency of the pulsars

- For blind searches the location in the sky and the source's frequency and its evolution are search parameters.