Spacetime Sirens

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The University of Maryland
&
The LIGO Scientific Collaboration

*Thanks to
my hosts:*

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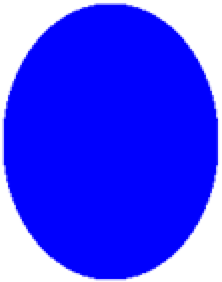
Gravitational Waves

Emitted by a massive object, or group of objects, whose shape or orientation changes rapidly with time

Perturbation of the metric of spacetime

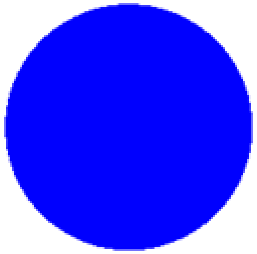
Strength and polarization depend on direction relative to source

Can be a linear combination of polarization components



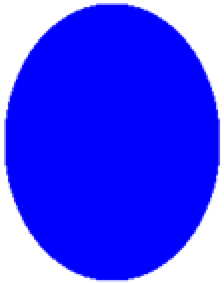
“Plus” polarization

✛



“Cross” polarization

✕



Circular polarization

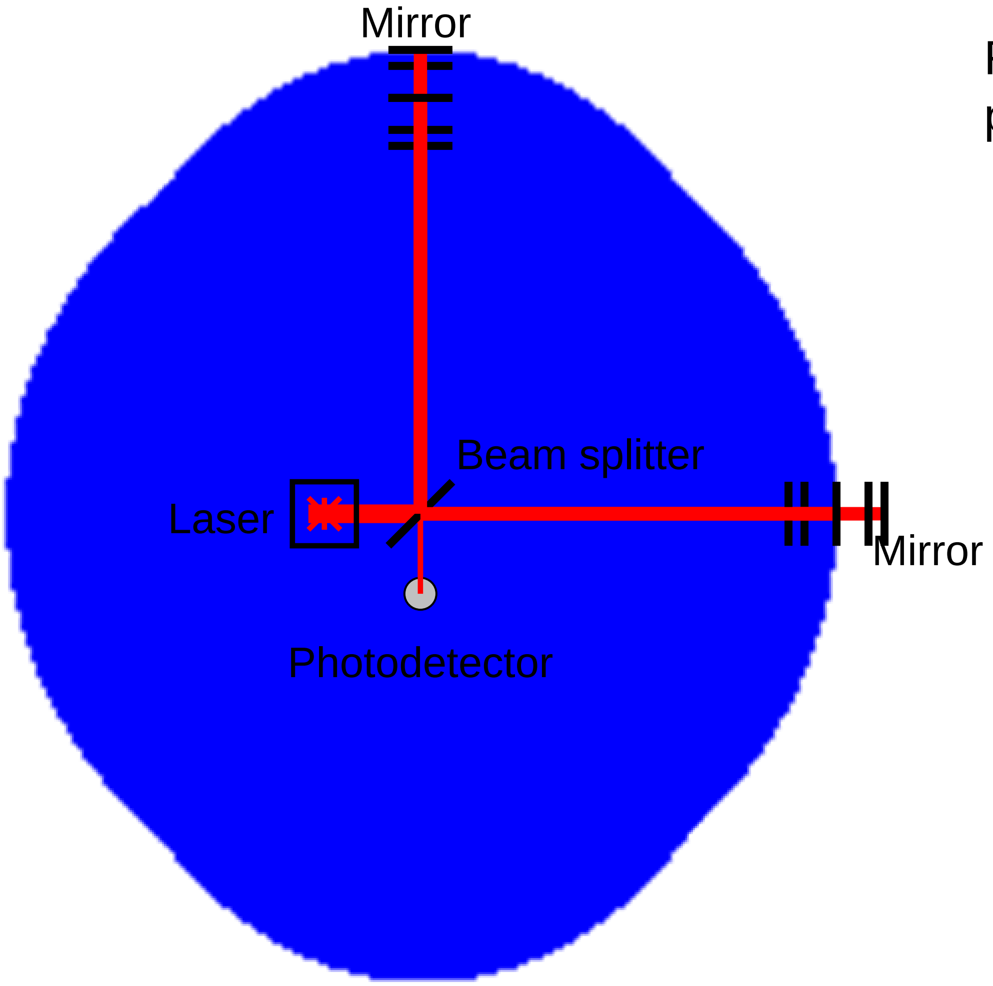
↺

…

Each component is described by a dimensionless strain, $h = \Delta L / L$, with amplitude inversely proportional to distance

A Laser Interferometer as a Gravitational Wave Detector

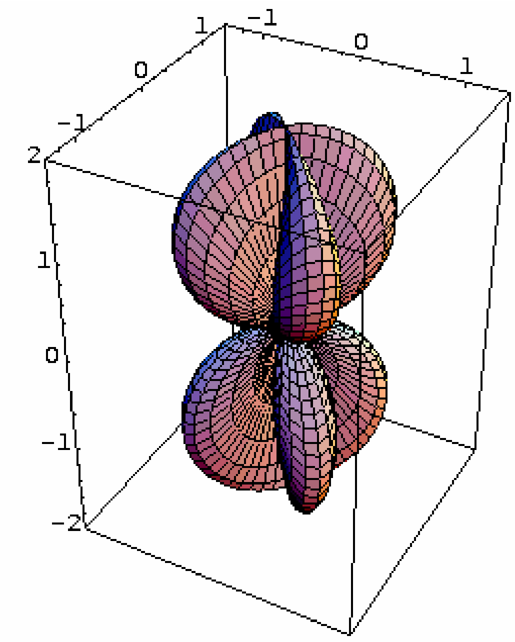
Measure *difference* in arm lengths to a fraction of a wavelength



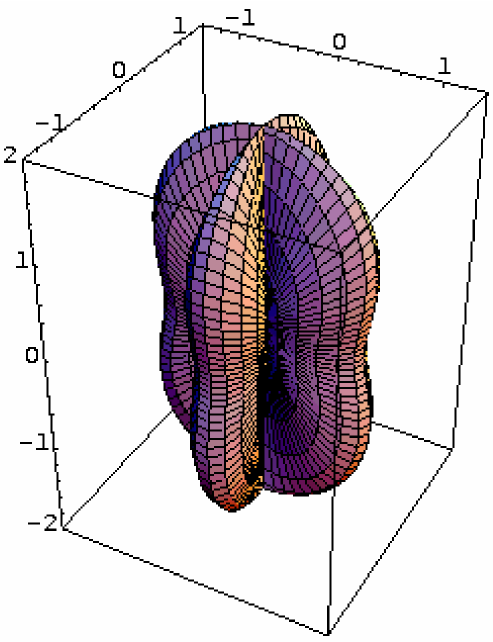
Responds to one polarization projection

Antenna Pattern of a Laser Interferometer

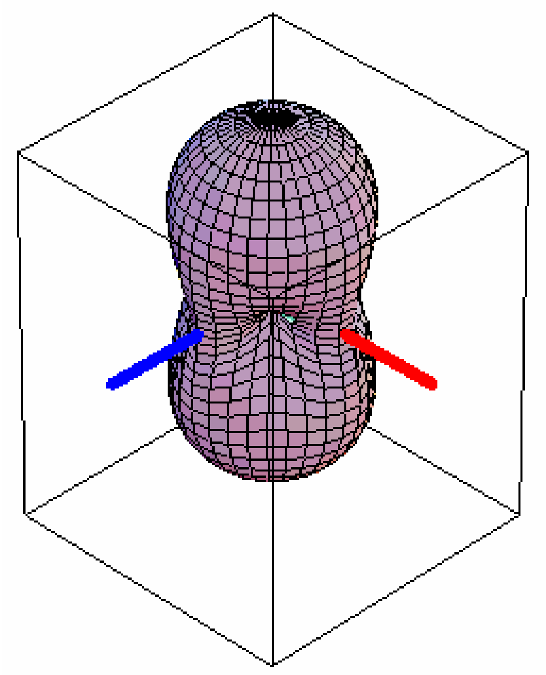
Directional sensitivity depends on polarization of waves



“×” polarization



“+” polarization



RMS sensitivity

A broad antenna pattern

⇒ More like a microphone than a telescope

The LIGO Observatories

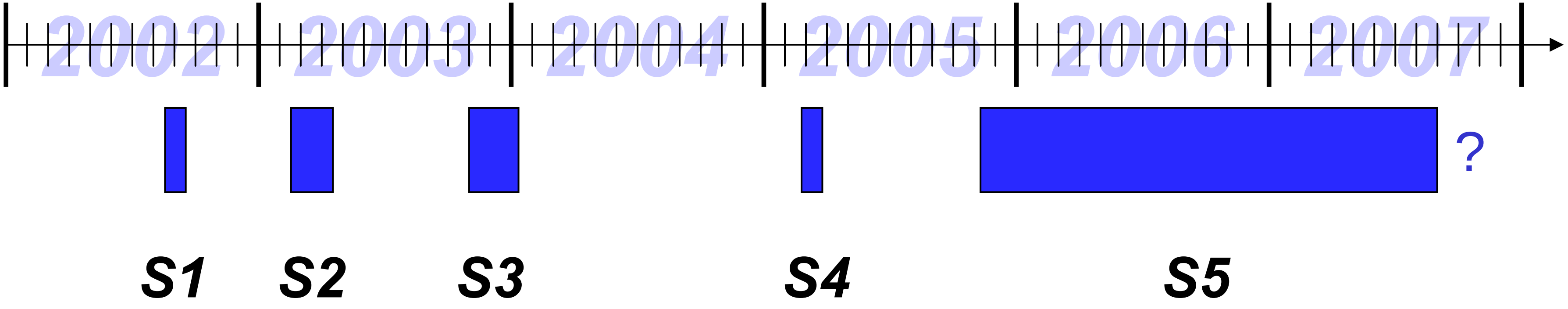
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms

LIGO Livingston Observatory (LLO)
L1 : 4 km arms

Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov

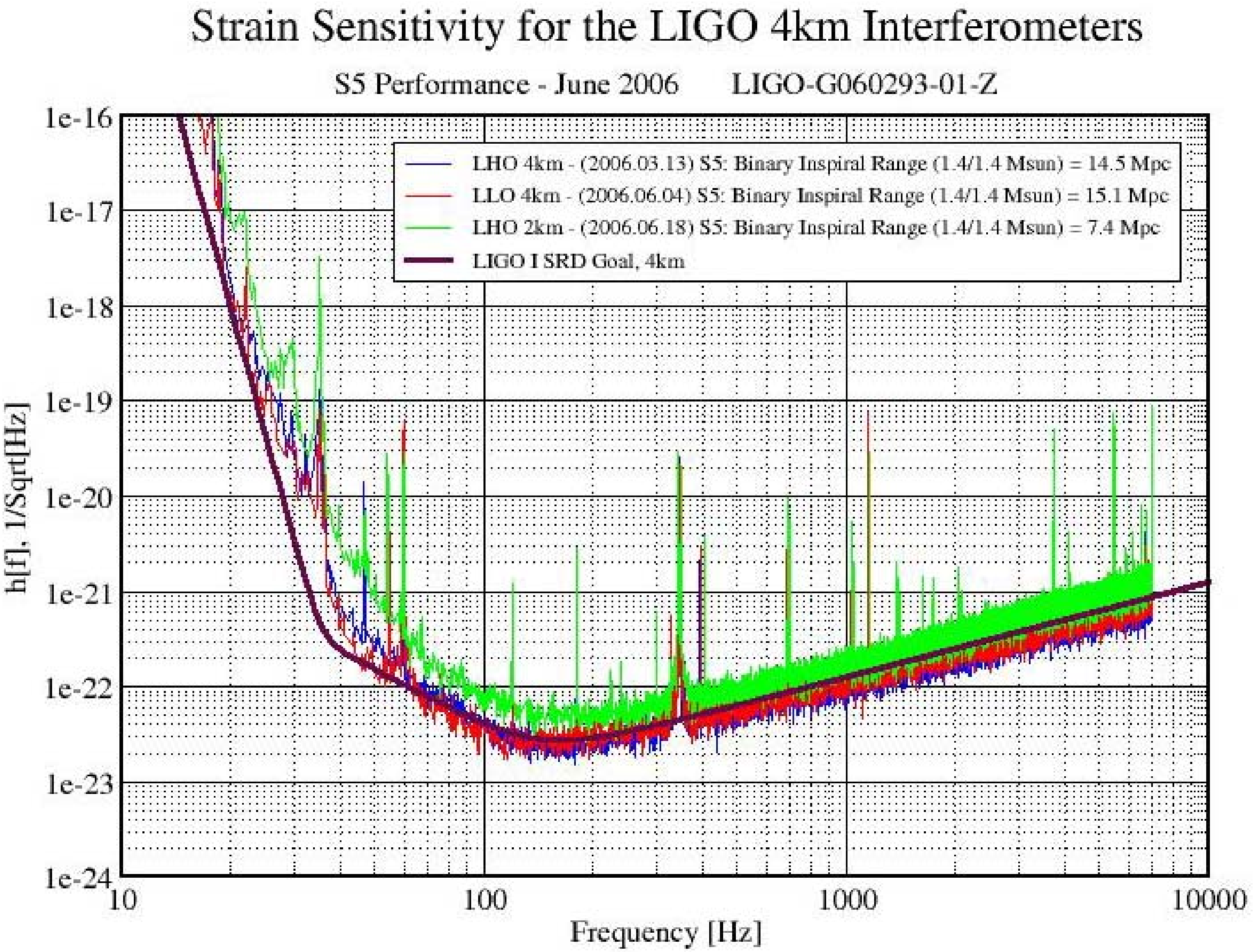
NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

LIGO Science Runs



Duty factors:					(so far)
H1	59 %	74 %	69 %	80 %	73 %
H2	73 %	58 %	63 %	81 %	77 %
L1	43 %	37 %	22 %	74 %	62 %

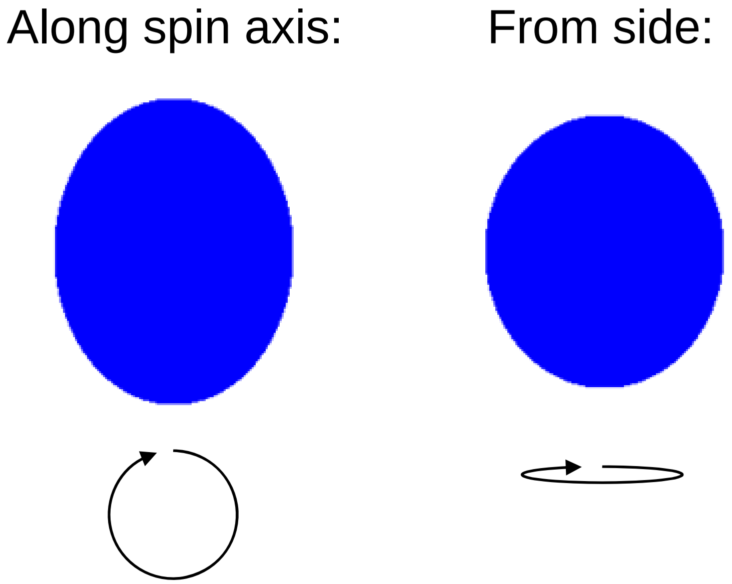
Current Sensitivity of LIGO



Potential Grav. Wave Source: Spinning Neutron Stars

If not axisymmetric, will emit gravitational waves !

Example: ellipsoid with distinct transverse axes



Review article: Reinhard Prix for the LIGO Scientific Collaboration, “The Search for Gravitational Waves from Spinning Neutron Stars”, to appear in a forthcoming volume in the Springer Lecture Notes Series. Available at **http://www.ligo.org/pdf_public/prix02.pdf**

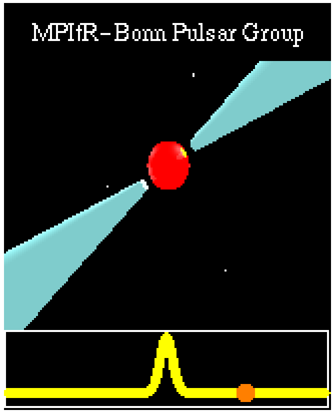
GW signal frequency is twice the rotation frequency

Other plausible emission mechanisms:
rotation-induced instabilities, free precession

The Population of Neutron Stars

Our Galaxy is thought to contain ~10^9 neutron stars

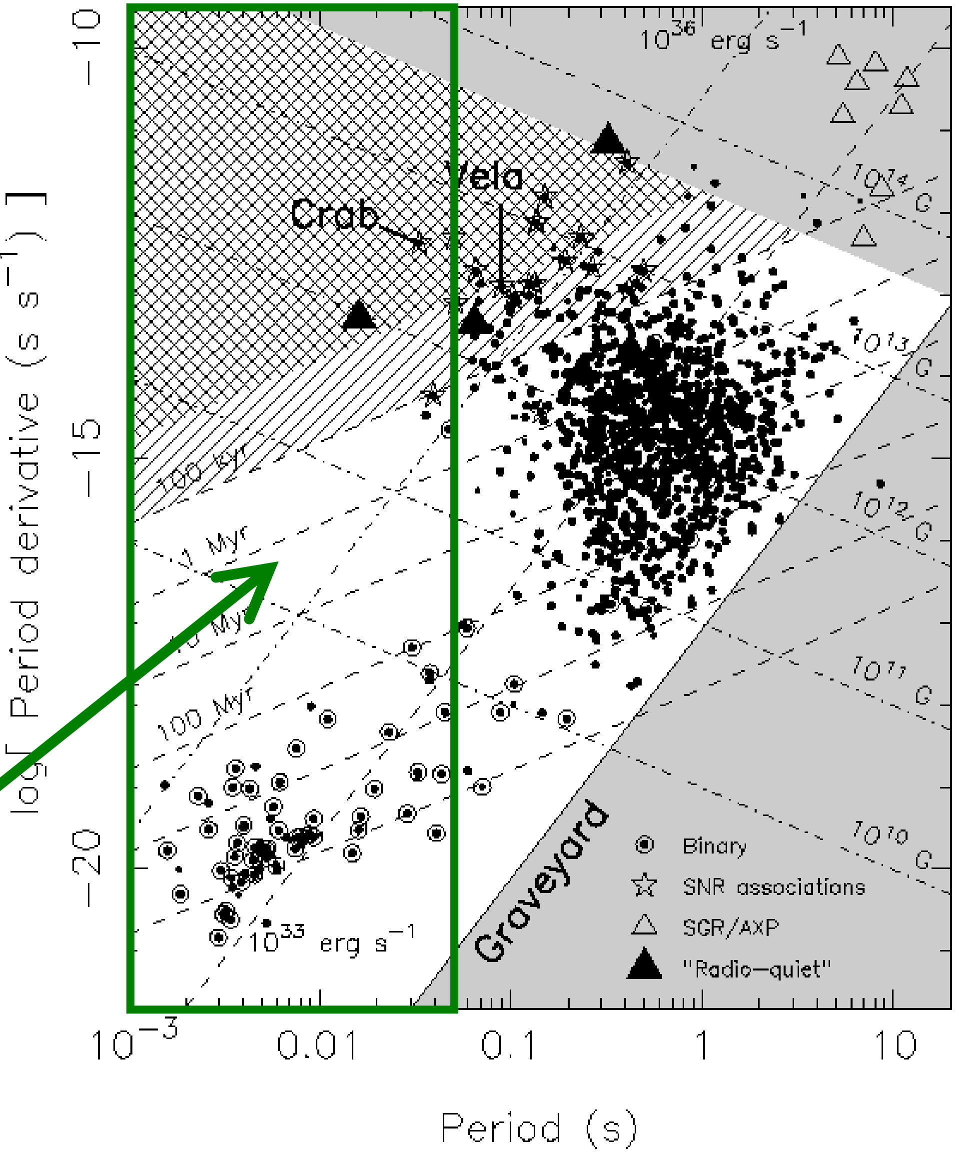
~1700 seen as pulsars



Graphic: Michael Kramer

~120 of these pulsars are within LIGO frequency band

Some pulsars have negative period derivatives



From "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Continuous GW Signals at Earth

Start with a sinusoidal signal with spin-down term(s)

Polarization content depends on orientation/inclination of spin axis

Amplitude modulation

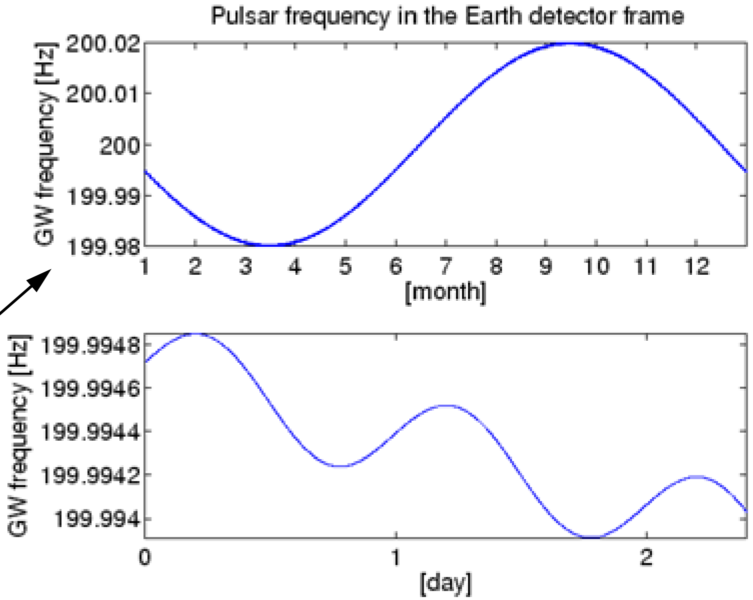
Polarization projection changes over a sidereal day

Doppler shift

$$\frac{\Delta f}{f} = \frac{\mathbf{v}\cdot\mathbf{n}}{c}$$

Annual variation: up to ~10^{-4}

Daily variation: up to ~10^{-6}



GW signals from binary systems are more complicated !

Additional Doppler shift due to orbital motion of neutron star

Varying gravitational redshift if orbit is elliptical

Shapiro time delay if GW passes near companion

Plausible Signal Amplitude

Tri-axial ellipsoid case:

Equatorial ellipticity

Moment of inertia
around spin axis

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

$$\approx\ 10^{-26} \times \left(\frac{\varepsilon}{10^{-6}}\right) \times \left(\frac{I_{zz}}{10^{45}\ \mathrm{g\,cm}^2}\right) \times \left(\frac{f}{100\ \mathrm{Hz}}\right)^2 \times \left(\frac{1\ \mathrm{kpc}}{r}\right)$$

Well below the noise ⇒ Need to integrate lots of data

Detectability of weak signals checked using long-duration hardware signal injections

~10 artificial neutron star signals injected much of the time

Overview of Searches

Several cases to consider:	*Candidates*
• Sky position and spin frequency known accurately	Radio pulsars
• Sky position and spin frequency known fairly well	X-ray pulsars
• Sky position known, but frequency and/or binary orbit parameters unknown	LMXBs
• Search for unknown sources in favored sky regions	Globular clusters Galactic center Supernova remnants
• Search for unknown sources over the whole sky	Unseen isolated neutron stars

Different computational challenges ⇒ Different approaches

Search for Gravitational Waves from Known Pulsars

Method: heterodyne time-domain data using the known spin phase of the pulsar

- Requires precise timing data from radio or X-ray observations
- Include binary systems in search when orbits known accurately
- Exclude pulsars with significant timing uncertainties
- Special treatment for the Crab and other pulsars with glitches, timing noise

Use a Bayesian approach [PRD 72, 102002 (2005)]

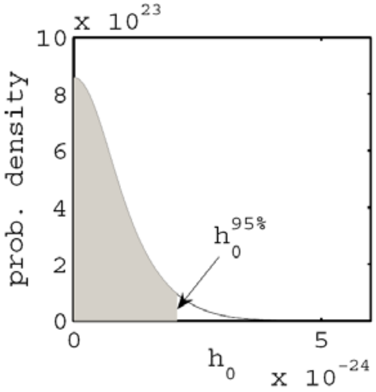
- Uniform priors on all parameters
- Combine posterior pdfs from different detectors (requires accurate time-stamping of data collected)

Marginalize over nuisance params to set 95% upper limits on GW amplitude emitted by each pulsar

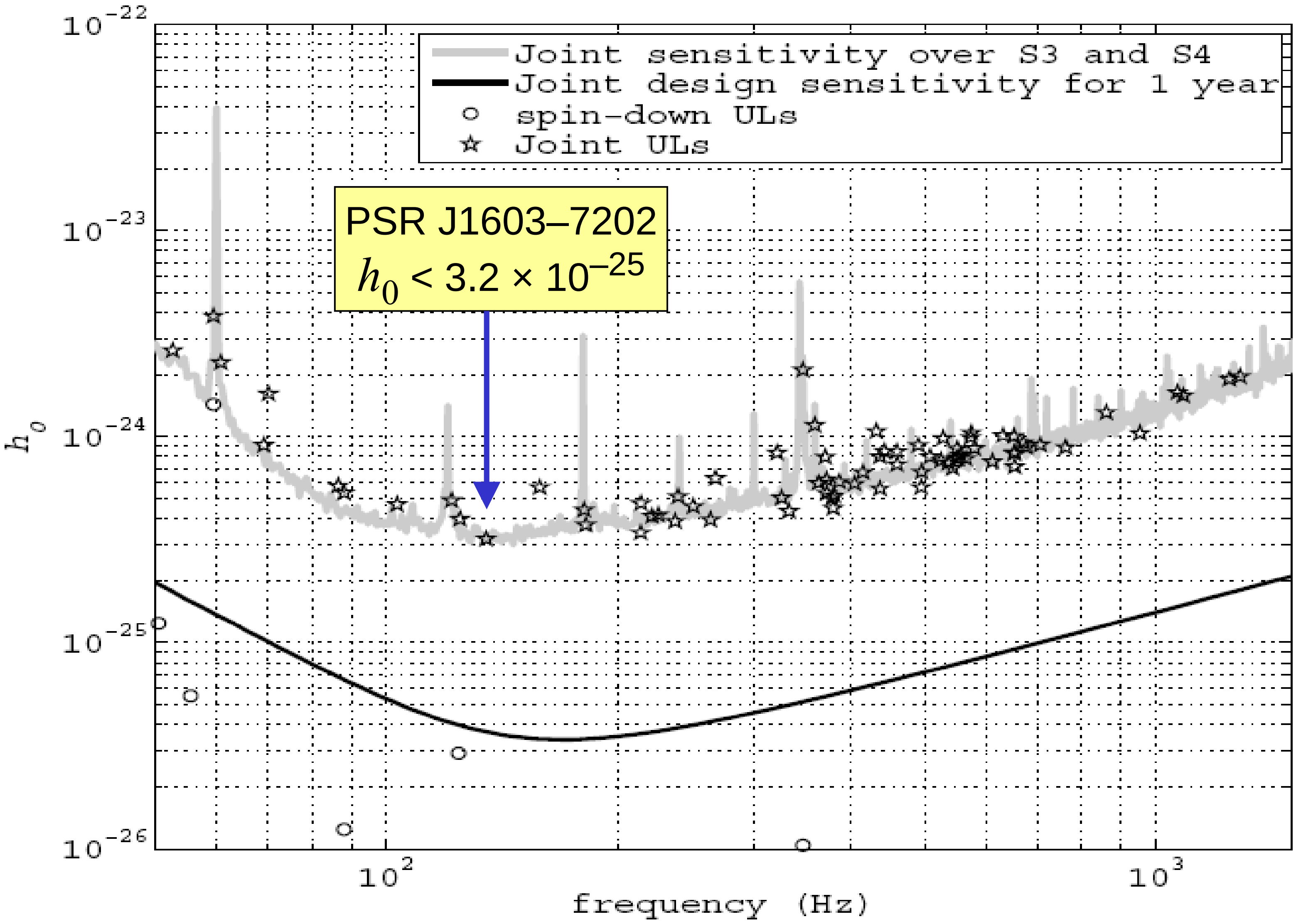
S2: 28 isolated pulsars [PRL 94, 181103 (2005)]

S3+S4: 78 isolated and binary pulsars [gr-qc/0702039]

S5: Preliminary results for 97 isolated and binary pulsars



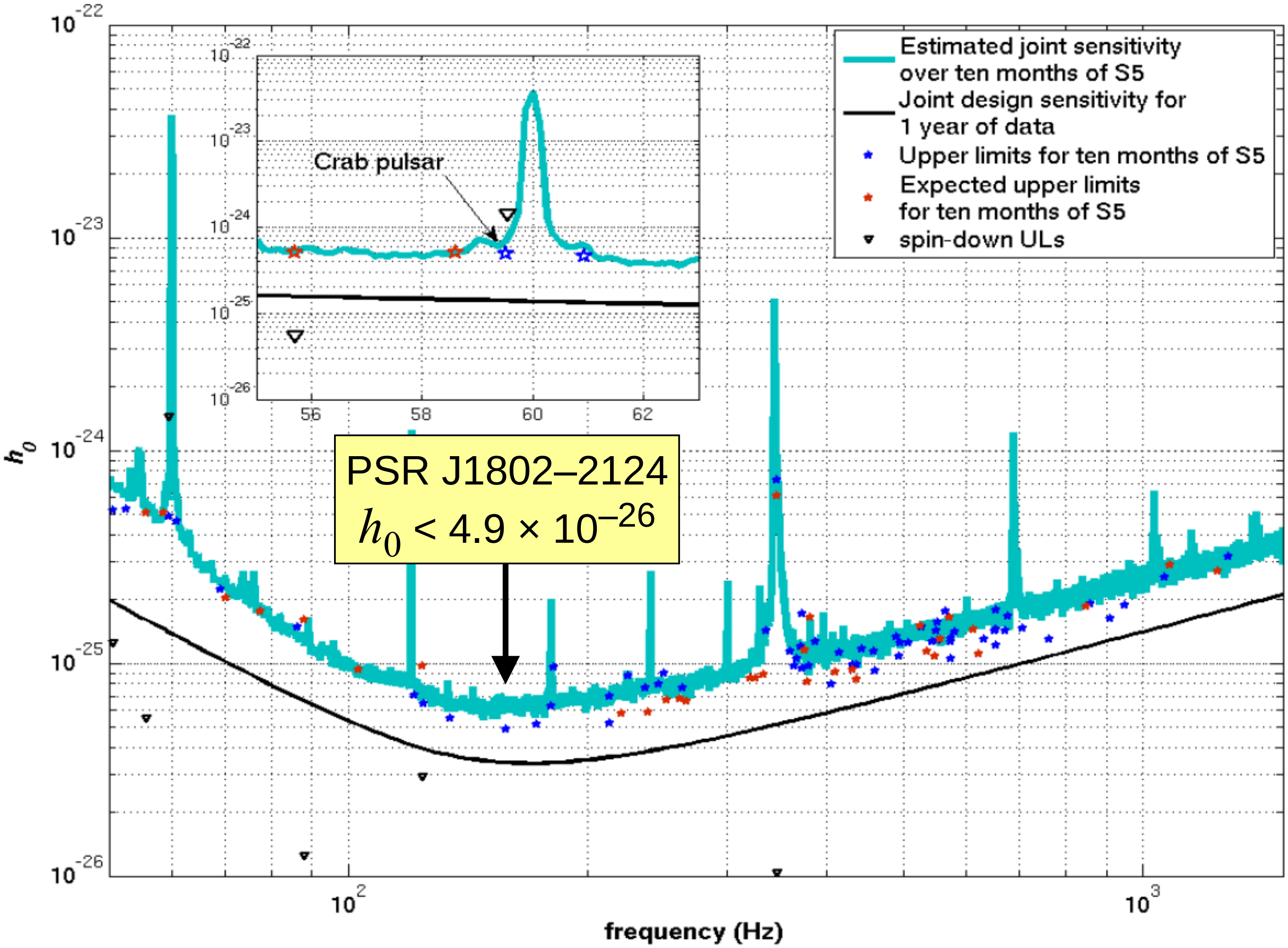
S3/S4 Upper Limits on GW Emission from 78 Radio Pulsars



PSR J1603–7202

$h_0 < 3.2 \times 10^{-25}$

Preliminary S5 Results



PSR J1802–2124
$h_0 < 4.9 \times 10^{-26}$

Connection with Neutron Star Properties

Infer limits on equatorial ellipticity ε :

$$\varepsilon = 10^{-6} \times \left(\frac{h_0}{10^{-26}}\right) \times \left(\frac{10^{45}\ \mathrm{g\ cm}^2}{I_{zz}}\right) \times \left(\frac{100\ \mathrm{Hz}}{f}\right)^2 \times \left(\frac{r}{1\ \mathrm{kpc}}\right)$$

I_{zz} probably is in the range (1 ~ 3) × 10^{45} g cm^2

Physically plausible *maximum* values of ε :

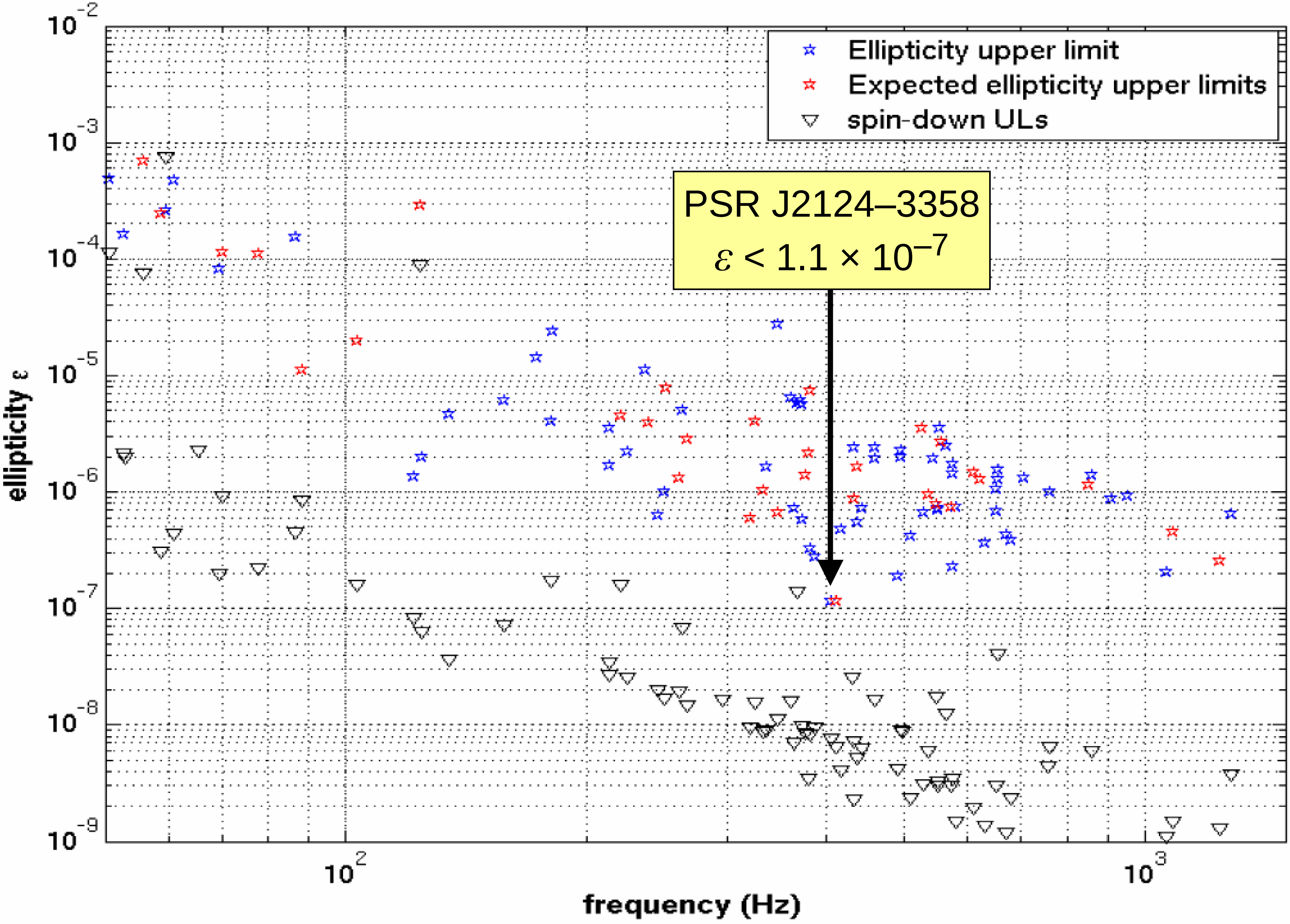
[PRL 95, 211101 (2005) ; gr-qc/0605028]

~ 10^{-6} for ordinary neutron star matter, supported by crust or by internal magnetic fields

~ 10^{-5} for a hybrid star (ordinary neutron star matter on the outside, with a core of mixed quark & baryon matter)

~ few × 10^{-4} for a solid strange quark star

Preliminary S5 Results: Ellipticity Limits



PSR J2124–3358

$\varepsilon < 1.1 \times 10^{-7}$

Wide Parameter Space Searches

Method: **apply a bank of matched filters for specific signal models**

Parameters:

- Sky position
- Spin axis inclination and azimuthal angle
- Frequency, spindown, initial phase
- Binary orbit parameters (if in a binary system)

Use a detection statistic, $\mathcal{F}$, which analytically maximizes over spin axis inclination & azimuthal angle and initial phase

- Even so, computing cost scales as ~T^6
- Detection threshold also must increase with number of filters

Check for signal consistency in multiple detectors

Wide Parameter Space Searches Using S2 Data

Submitted to PRD; preprint gr-qc/0605028

All-sky search for isolated neutron stars

Params: right ascension, declination, frequency
(neglect spindown)

Used 10 hours of data

GW from neutron star in Sco X-1

Accretion could create and sustain an eccentricity

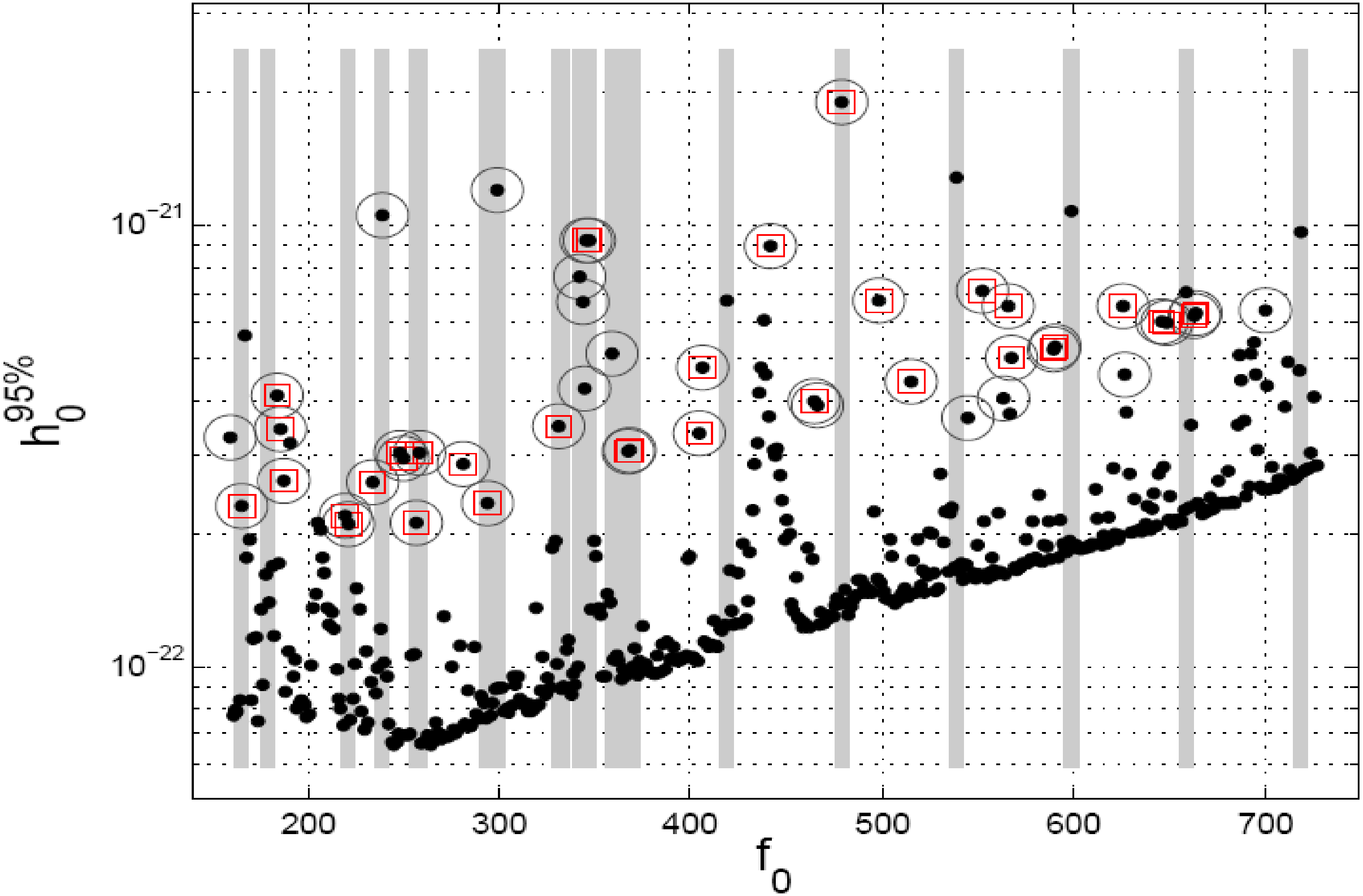
Not seen as a pulsar, but range of possible spin frequencies inferred from QPOs in X-ray emission

Params: semimajor axis of binary orbit, orbital phase at a reference time, frequency

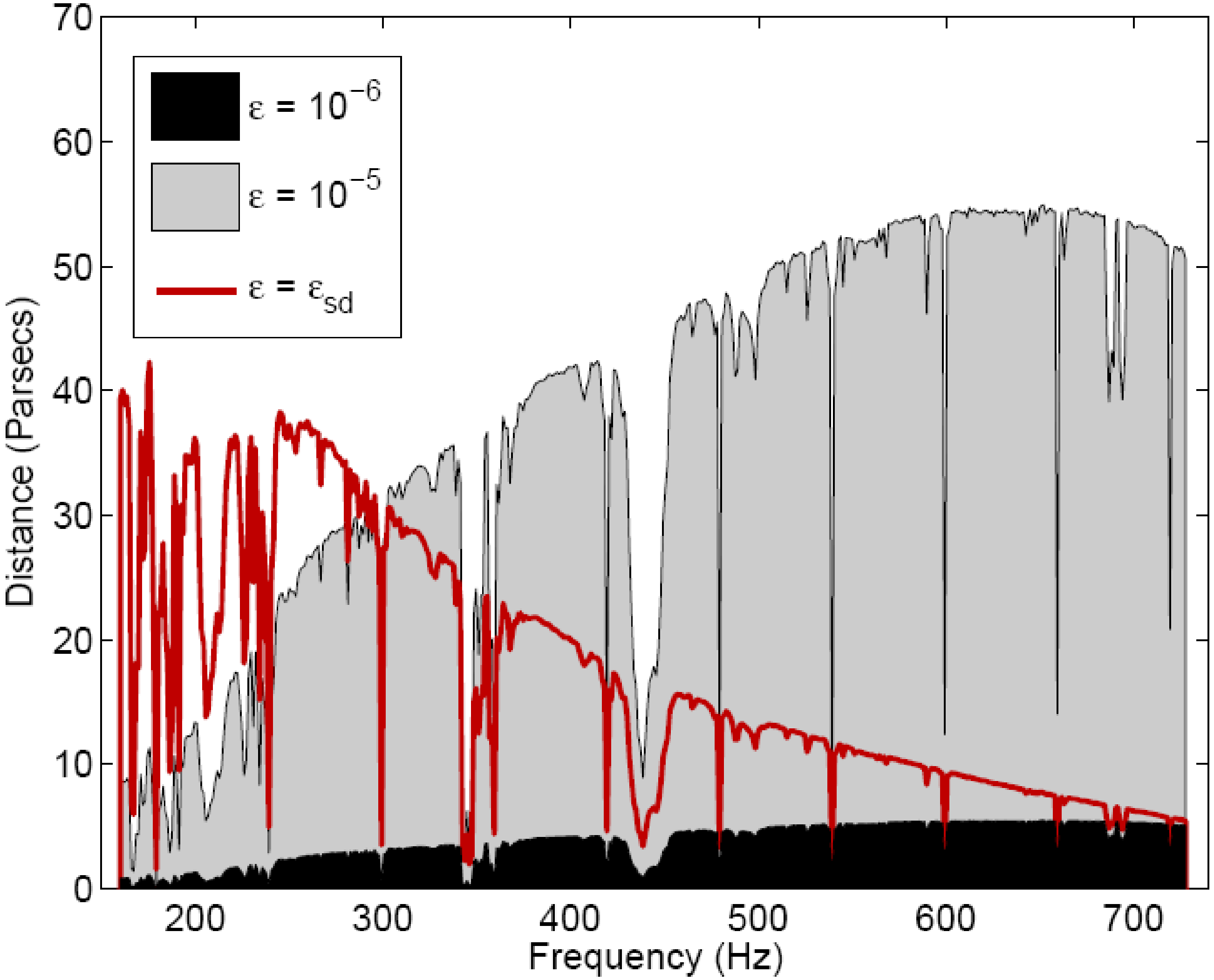
Used 6 hours of data

S2 All-Sky Search for Isolated Neutron Stars

No convincing signal detected; set upper limits in freq. bands



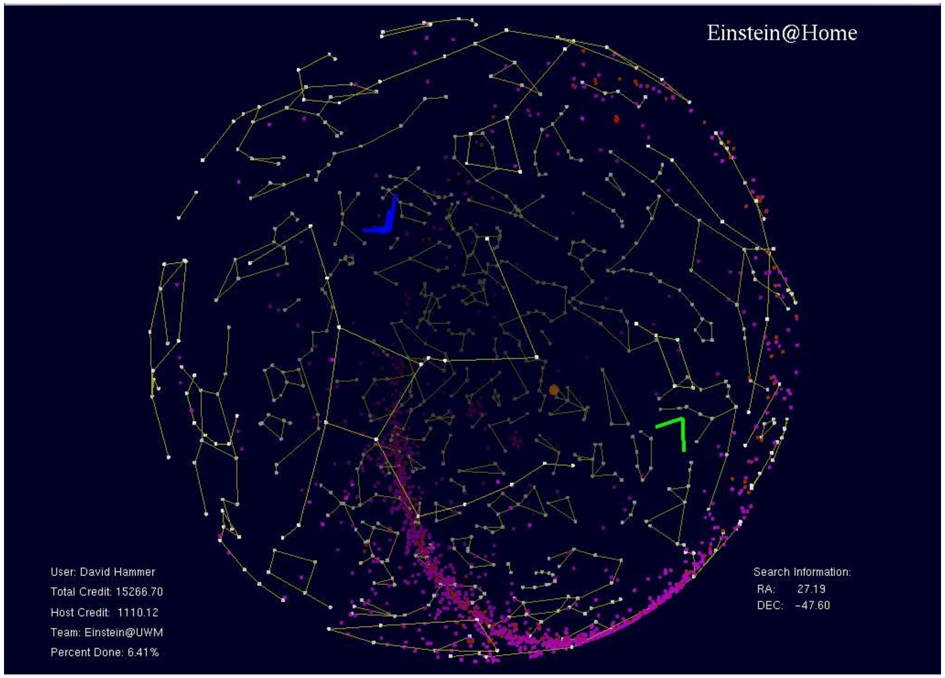
Range of the S2 All-Sky Search



Getting by with a Little Help from Our Friends

Public distributed computing project: Einstein@Home

Small bits of data distributed for processing; results collected, verified, and post-processed



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

Screen saver graphics

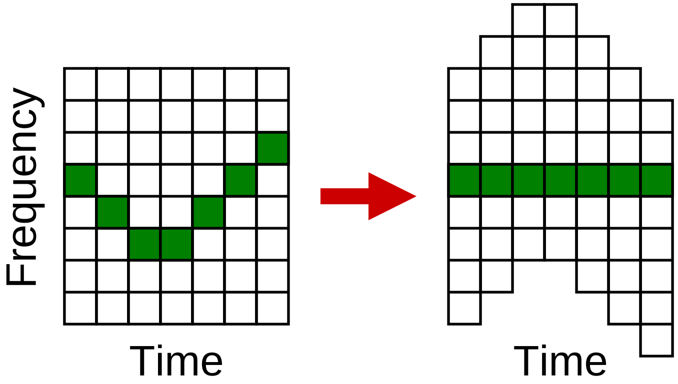
So far 156,000 users, currently providing ~77 Tflops

Semi-Coherent Search Methods

Can’t do an all-sky coherent search using all of the data

Divide data into time intervals, calculate power, sum it

- Less sensitive for a given observation time, but computationally more efficient, so can use **all** the data
- Generally use 30-minute “short Fourier transforms” (SFTs)



Different methods of adding SFTs

- “StackSlide” : sums normalized power
- “PowerFlux” : sums normalized power with weights for sky position, noise
- “Hough” : sums binary counts with weights for sky position, noise

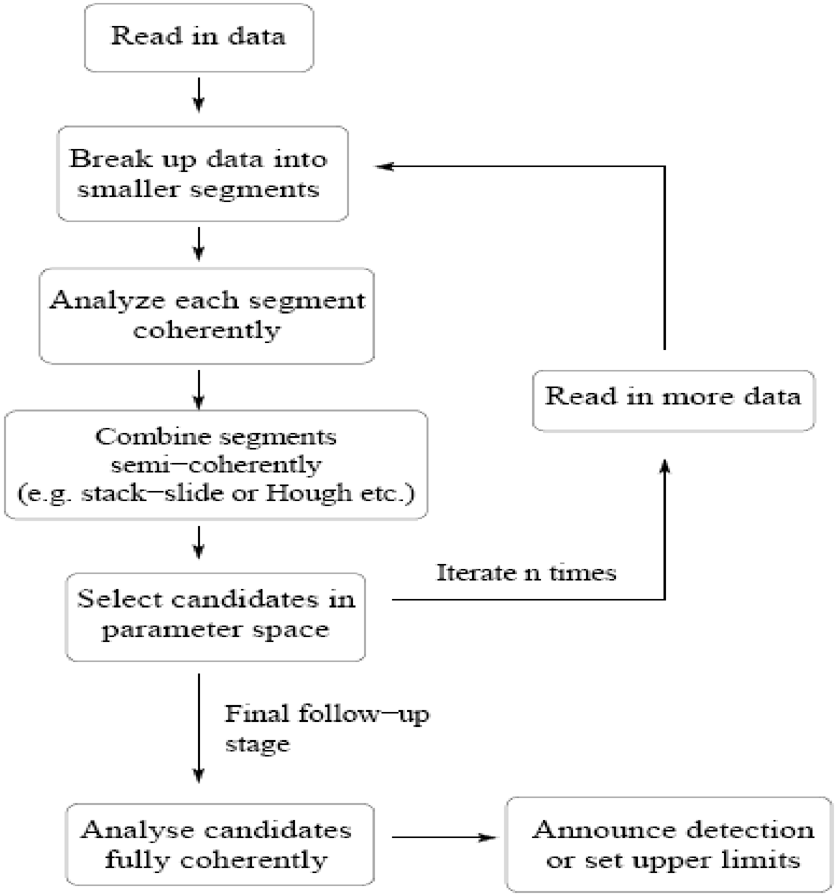
[PRD 72, 102004 (2005)]

Hierarchical Search

Alternate semi-coherent and fully coherent stages

Gets closer to optimal sensitivity, at a manageable CPU cost

Example:



Read in data

Break up data into smaller segments

Analyze each segment coherently

Combine segments semi−coherently (e.g. stack−slide or Hough etc.)

Select candidates in parameter space

Iterate n times

Read in more data

Final follow−up stage

Analyse candidates fully coherently

Announce detection or set upper limits

Detection Prospects for All-Sky Search

Estimate the strongest signal that one could hope to detect

[Unpublished argument by Blandford, developed by LSC in gr-qc/0605028]

Assume all neutron stars are born with high spin rate
and spin down due to GW emission — ***highly optimistic !***

Assume an average birth rate τ_b of 1 per 30 years

Model the Galaxy as a uniformly populated cylinder with radius R_G

For a search over the band f_{min} to f_{max} , arrive at:

$$h_0^{\mathrm{max}} = \left[\frac{5GI_{zz}}{c^3 \tau_b R_G^2} \ln \left(\frac{f_{\mathrm{max}}}{f_{\mathrm{min}}} \right) \right]^{1/2}$$

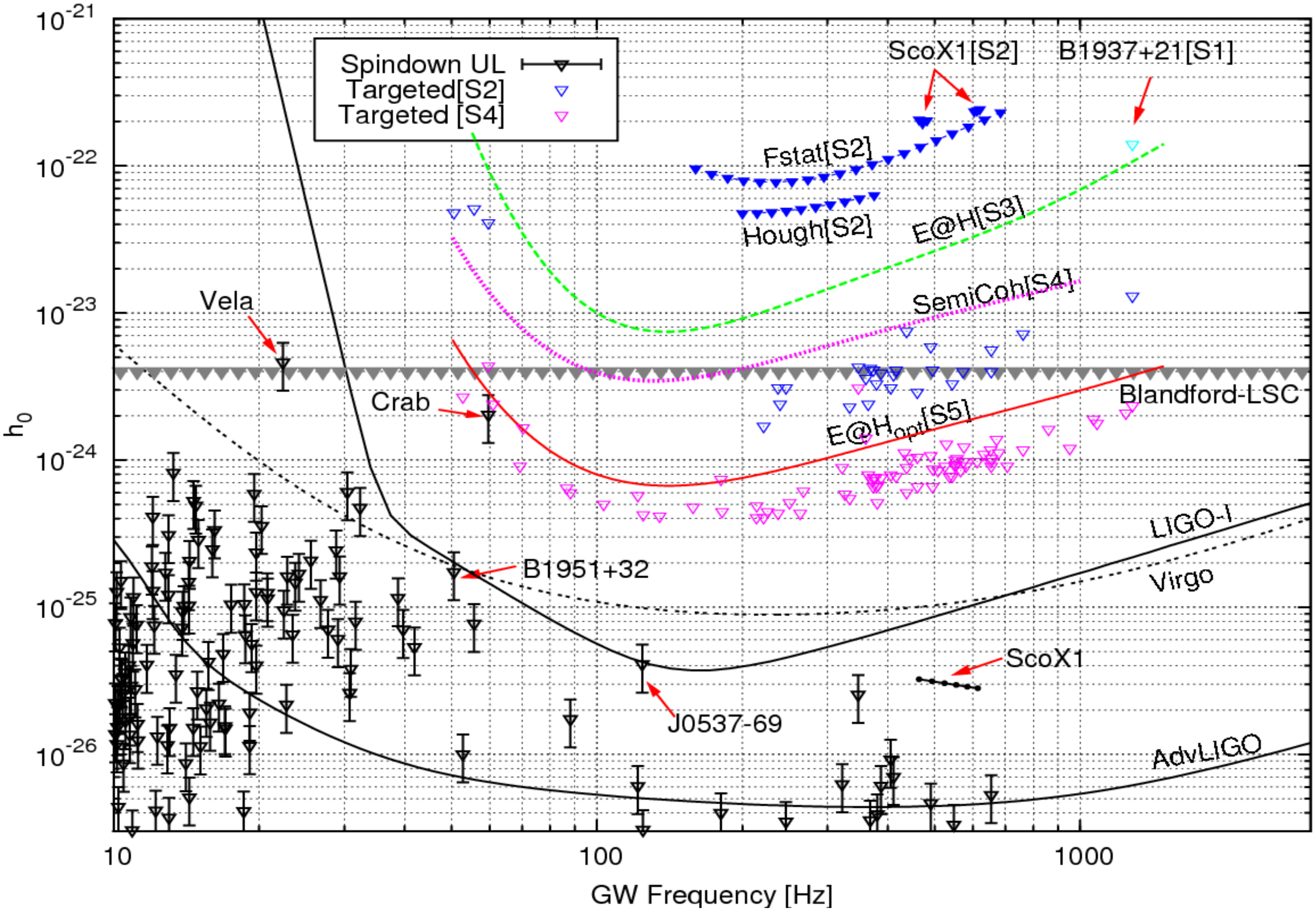
Reason:

If GW emission is strong, you can see it farther away

If GW emission is weak, it lasts for a long time

Numerically, get $h_0^{\mathrm{max}} \approx 4 \times 10^{-24}$

The Big Picture

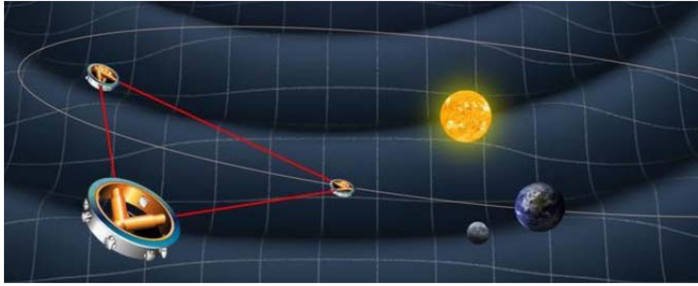


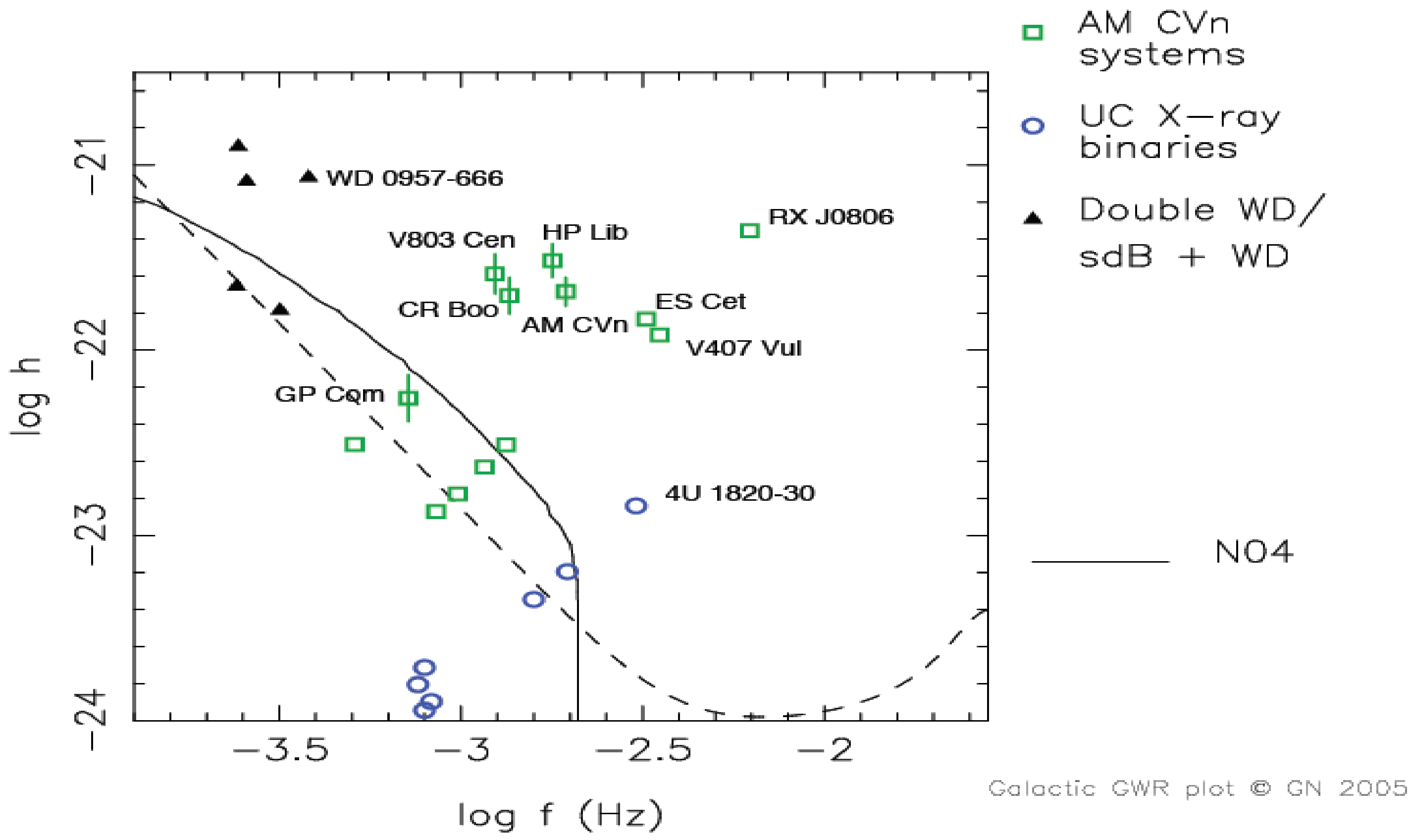
Graphic: Reinhard Prix

Contrabasso Sirens

LISA will sense much lower frequencies

Many compact binary systems will radiate well above the instrumental noise level





Galactic GWR plot © GN 2005

Epilogue

Why do we go to such great lengths to try to detect such incredibly weak signals?

> “The lovely voices in ardor appealing over the water made me crave to listen…”
>
> — *The Odyssey* (Trans. R. Fitzgerald)

Marc Chagall, “The Sirens” (lithograph, 1974)