Recent Searches for Periodic Continuous Gravitational Waves with the LIGO & Virgo Detectors

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LIGO Scientific Collaboration and the Virgo Collaboration

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LIGO-G1301090

Generation of Continuous Gravitational Waves

- Radiation generated by quadrupolar mass movements:

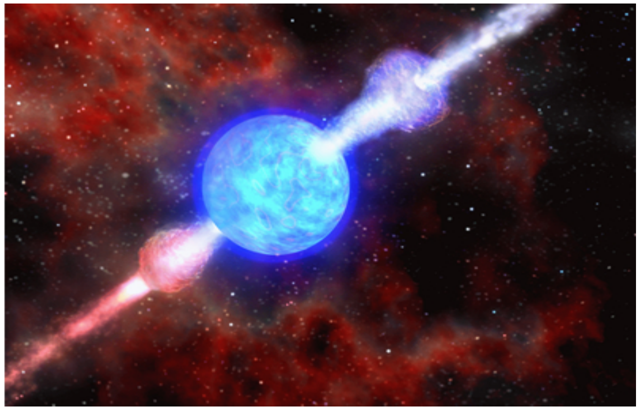
$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right]$$

No GW from axisymmetric object rotating about symmetry axis

($I_{\mu\nu}$ = quadrupole tensor, r = source distance)

- Spinning neutron star with equatorial ellipticity $\varepsilon_{\text{equat}}$

$$\varepsilon_{\text{equat}} = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$



Courtesy: U. Liverpool

gives a strain amplitude h ($f_{GW} = 2 \bullet f_{Rot}$):

$$h = 1.1 \times 10^{-24}\left[\frac{kpc}{r}\right]\left[\frac{f_{GW}}{kHz}\right]^2\left[\frac{\varepsilon}{10^{-6}}\right]\left[\frac{I_{zz}}{10^{38}\ \text{kg}\cdot\text{m}^2}\right]$$

Gravitational CW mechanisms

- **Equatorial ellipticity (e.g., – mm-high "bulge"):**

$$h \propto \varepsilon_{\text{equat}} \quad \text{with} \quad f_{GW} = 2 f_{\text{rot}}$$

- **Poloidal ellipticity (natural) + wobble angle (precessing star):**

$$h \propto \varepsilon_{poloidal} \times \theta_{\text{wobble}} \quad \text{with} \quad f_{GW} = f_{\text{rot}} \pm f_{\text{precess}}$$

(precession due to different L and Ω axes)

- **Two-component (crust+superfluid) →** $f_{\text{GW}} = f_{rot}$ and $2 f_{\text{rot}}$

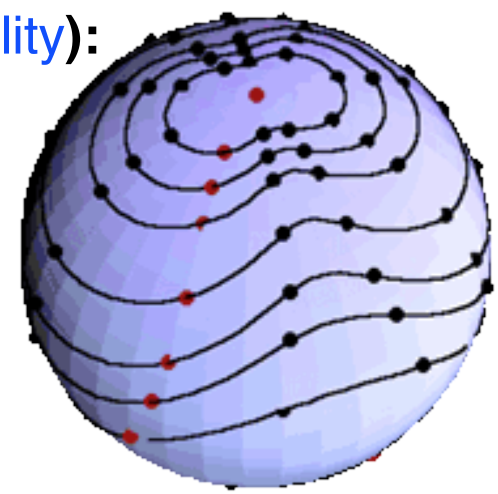
- **r modes** (rotational oscillations – CFS-driven instability)**:**

N. Andersson, ApJ 502 (1998) 708

S. Chandrasekhar PRL 24 (1970) 611

J. Friedman, B.F. Schutz, ApJ 221 (1978) 937

$$h \propto \alpha_{\text{r-mode}} \quad \text{with} \quad f_{GW} \cong \frac{4}{3} f_{\text{rot}}$$



Gravitational CW mechanisms

Assumption we (LSC, Virgo) have usually made to date:

Bulge is best bet for detection
→ Look for GW emission at twice the EM frequency

e.g., look for Crab Pulsar (29.7 Hz) at 59.5 Hz
(troublesome frequency in North America!)

What is allowed for $\boldsymbol{\varepsilon_{equat}}$?

Old maximum (?) $\approx 5 \times 10^{-7}$ $[\sigma/10^{-2}]$ ("ordinary" neutron star)
with σ = breaking strain of crust
G. Ushomirsky, C. Cutler, L. Bildsten MNRAS 319 (2000) 902

More recent finding: $\sigma \approx 10^{-1}$ supported by detailed numerical simulation
C.J. Horowitz & K. Kadau PRL 102, (2009) 191102

Recent re-evaluation: $\varepsilon_{equat} < 10^{-5}$
N.K. Johnson-McDaniel & B.J. Owen PRD 88 (2013) 044004

Gravitational CW mechanisms

Strange quark stars could support much higher ellipticities
B.J. Owen PRL 95 (2005) 211101, Johnson-McDaniel & Owen (2013)

Maximum $\varepsilon_{equat} \approx 10^{-1}$ (!)

But what $\boldsymbol{\varepsilon}_{\mathbf{equat}}$ is realistic?

What could drive $\boldsymbol{\varepsilon}_{\mathbf{equat}}$ to a high value (besides accretion)?

Millisecond pulsars have spindown-implied values
lower than 10^{-9}–10^{-6}

New papers revisiting possible GW emission mechanisms (e.g., buried magnetic fields, accretion-driven r-modes) are also intriguing

Finding a completely unknown CW Source

Serious technical difficulty: Doppler frequency shifts

- Frequency modulation from earth's rotation (v/c ~ 10^{-6})
- Frequency modulation from earth's orbital motion (v/c ~ 10^{-4})

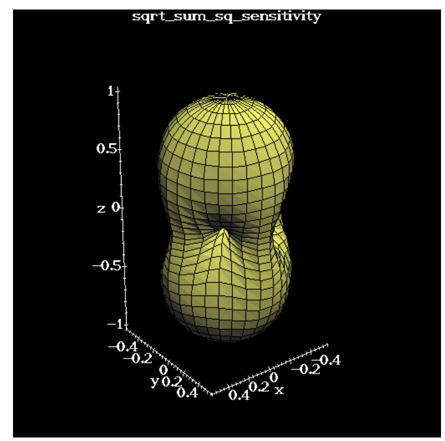
→ Coherent integration of 1 year gives frequency resolution of 30 nHz

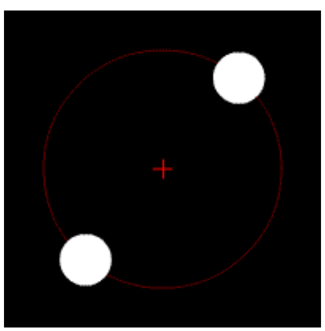
→ 1 kHz source spread over 6 million bins in ordinary FFT!

Additional, related complications:

Daily amplitude modulation of antenna pattern

Spin-down of source





Orbital motion of sources in binary systems

Finding a completely unknown CW Source

Modulations / drifts complicate analysis enormously:

- **Simple Fourier transform inadequate**
- **Every sky direction requires different demodulation**

Computational scaling:

Single coherence time – Sensitivity improves as $(T_{coherence})^{1/2}$
but cost scales with $(T_{coherence})^{6+}$
→ Restricts $T_{coherence}$ < 1-2 days for all-sky search
→ Exploit coincidence among different spans

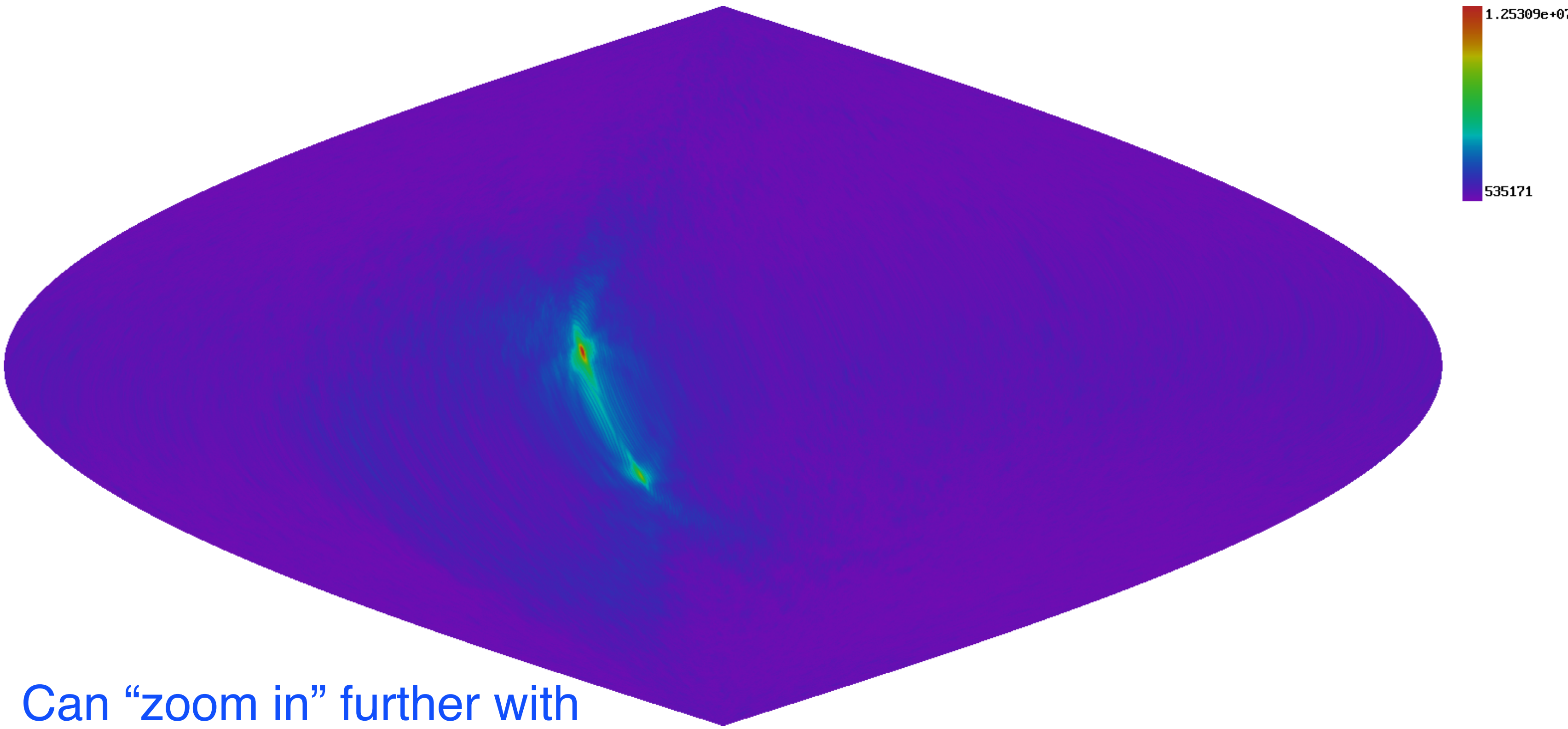
Alternative:
Semi-coherent stacking of spectra (e.g., $T_{coherence}$ = 30 min)
→ Sensitivity improves only as $(N_{stack})^{1/4}$

→ All-sky survey at full sensitivity = Formidable challenge

Impossible?

But three substantial benefits from modulations:

- **Reality of signal confirmed by need for corrections**
- **Corrections give precise direction of source**
- **Single interferometer can make definitive discovery**



Can "zoom in" further with follow-up algorithms once we lock on to source

[V. Dergachev, PRD 85 (2012) 062003
M. Shaltev & R. Prix, PRD 87 (2013) 084057]

Sky map of strain power for signal injection (semi-coherent search)

Recent results

Targeted (matched-filter) algorithm applied to 195 known pulsars over LIGO S5/S6 and Virgo VSR2/VSR4 data

Lowest (best) upper limit on strain:

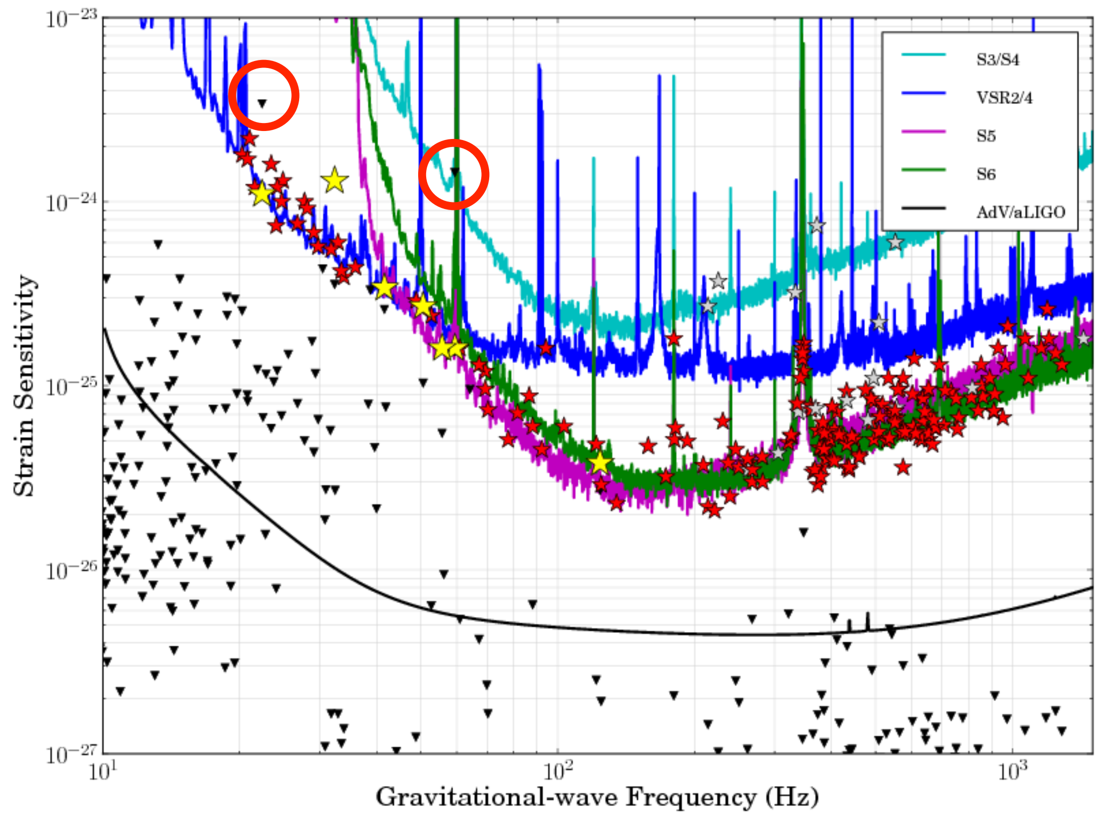
$h_0 < 2.1 \times 10^{-26}$

Lowest (best) upper limit on ellipticity:

$\varepsilon < 6.7 \times 10^{-8}$

Crab limit at 1% of total energy loss

Vela limit at 10% of total energy loss



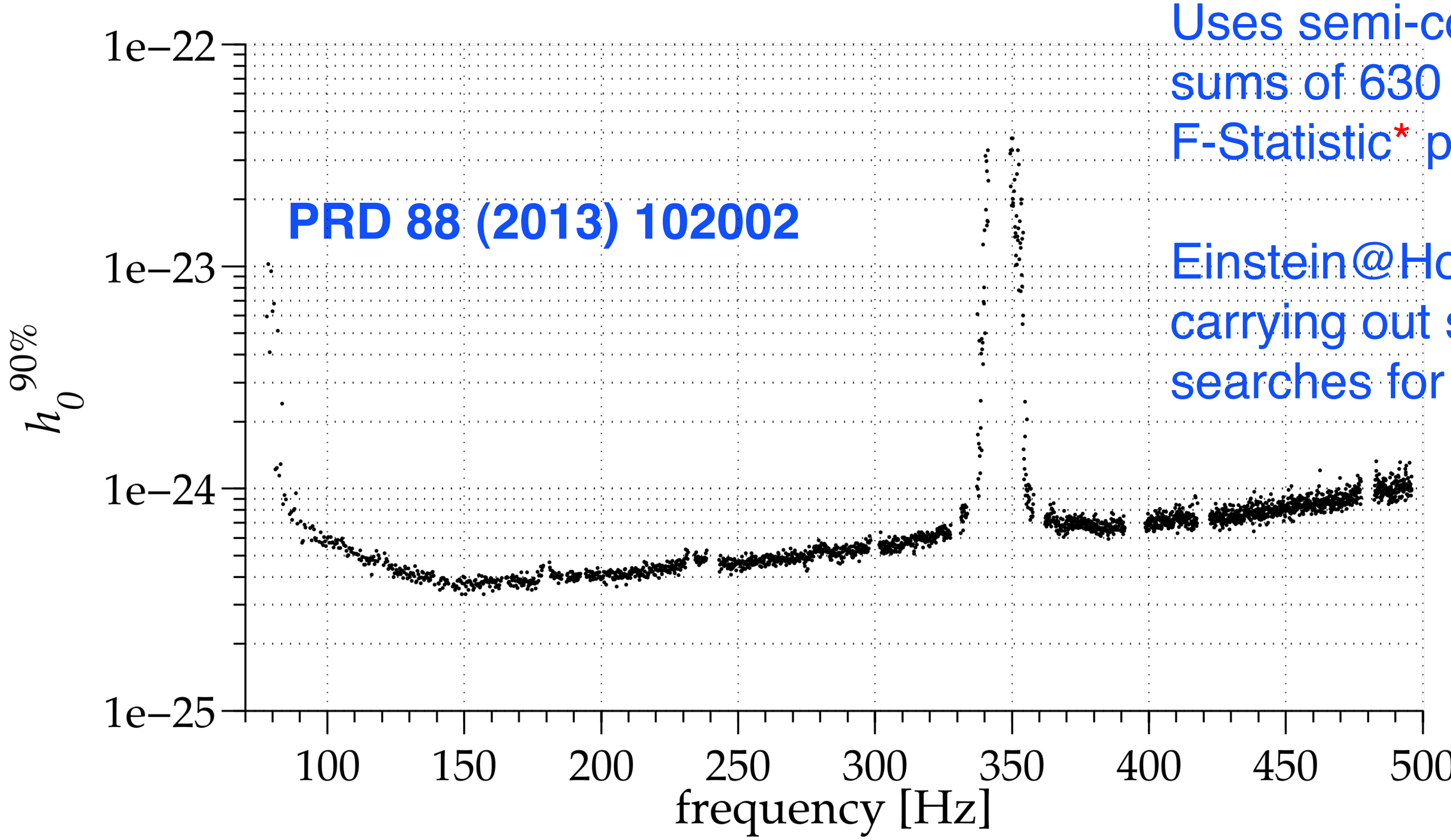
arXiv:1309.4027 (Sept 2013)

Recent results

Directed-search algorithm applied to the galactic center using LIGO S5 data (knowing direction improves sensitivity)

Uses semi-coherent sums of 630 11.5-hr F-Statistic* powers

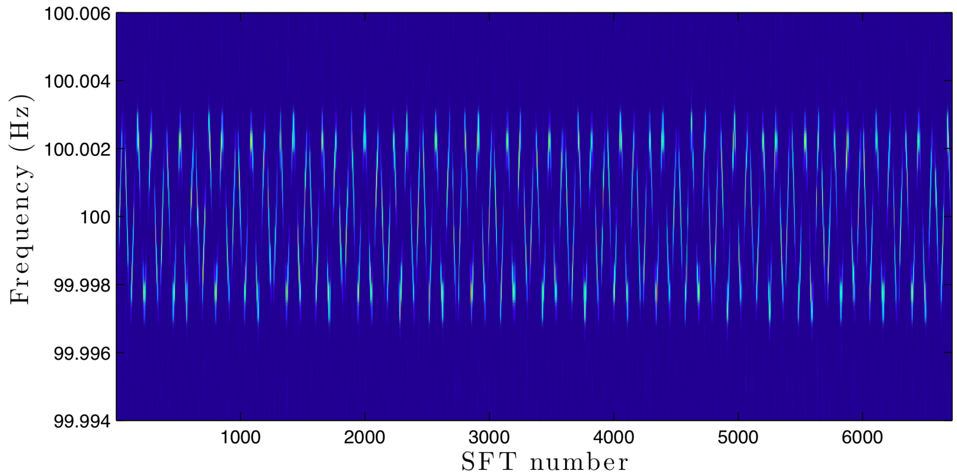
Einstein@Home now carrying out similar searches for SNRs

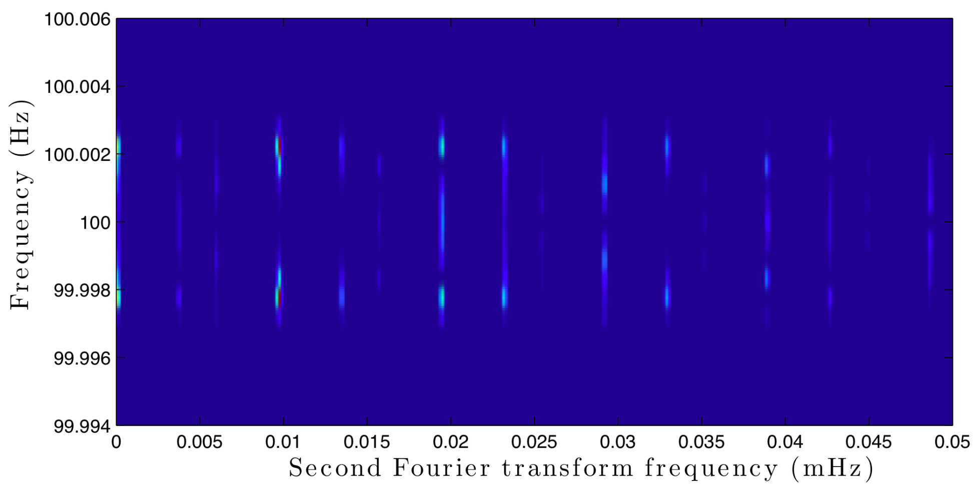


*Jaranowski, Krolak & Schutz, PRD 58 (1998) 063001

Recent results

First all-sky search for unknown binary CW sources





Uses TwoSpect* algorithm:

Sample spectrogram (30-minute FFTs) for simulated strong signal (Earth's motion already demodulated)

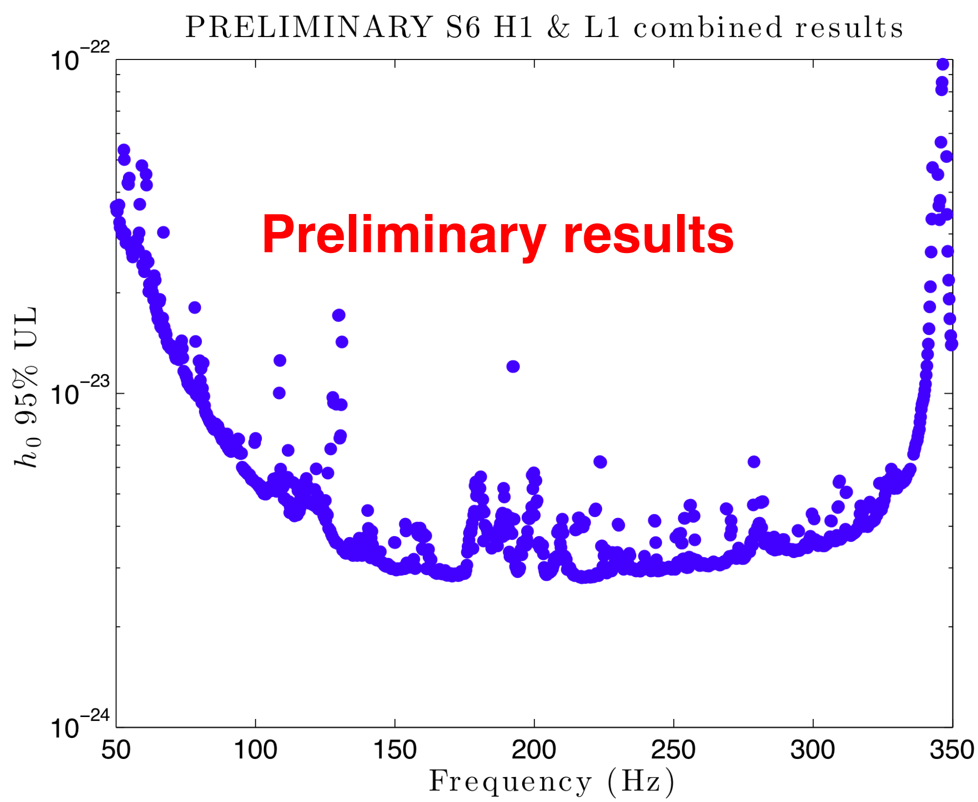
Result of Fourier transforming each row of spectrogram

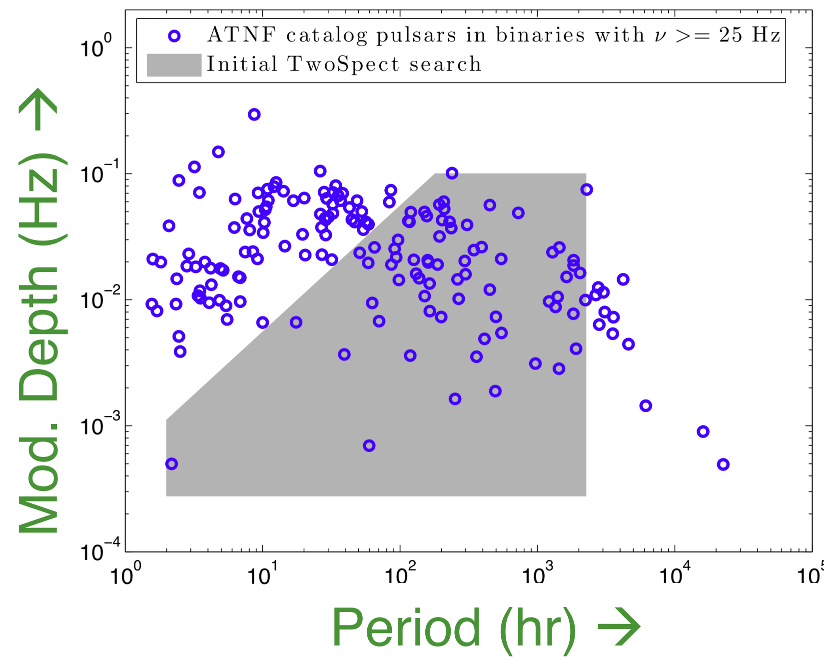
→ Concentrates power in orbital harmonics

*E. Goetz & K. Riles, CQG 28 (2011) 215006

Recent results

Initial search uses 30-minute FFTs
→ Favors longer orbital periods:





Search is severely computationally bound

Upper limits based on summing power in harmonics

Templates used only in follow-up

Not so limited in directed searches, e.g., for Scorpius X-1

Summary

No discoveries yet, but…

- Still examining data we have taken
  (computationally bound – E@H: 1 Petaflop, 100K volunteers)

- Major upgrade of LIGO & Virgo under way now
  - Advanced LIGO & Virgo
  - Improves range more than an order of magnitude
  - Moore's Law will help too…

Electromagnetic observations (radio, x-ray, γ–ray) of nearby neutron stars helpful now – and later

Extra Slides

Other results

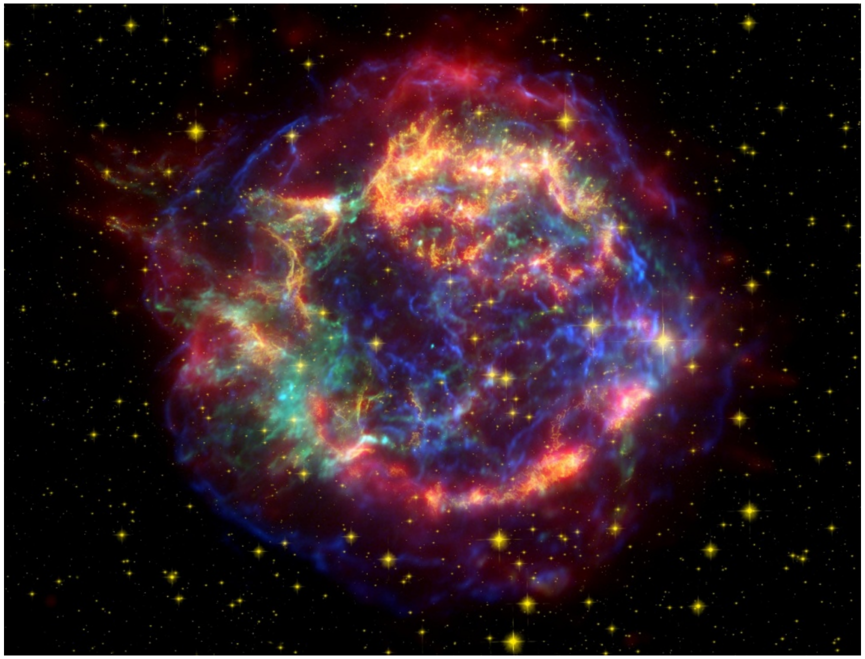
Not all known sources have measured timing

Compact central object in the Cassiopeia A supernova remnant

Birth observed in 1681 – One of the youngest neutron stars known

Star is observed in X-rays, but no pulsations observed

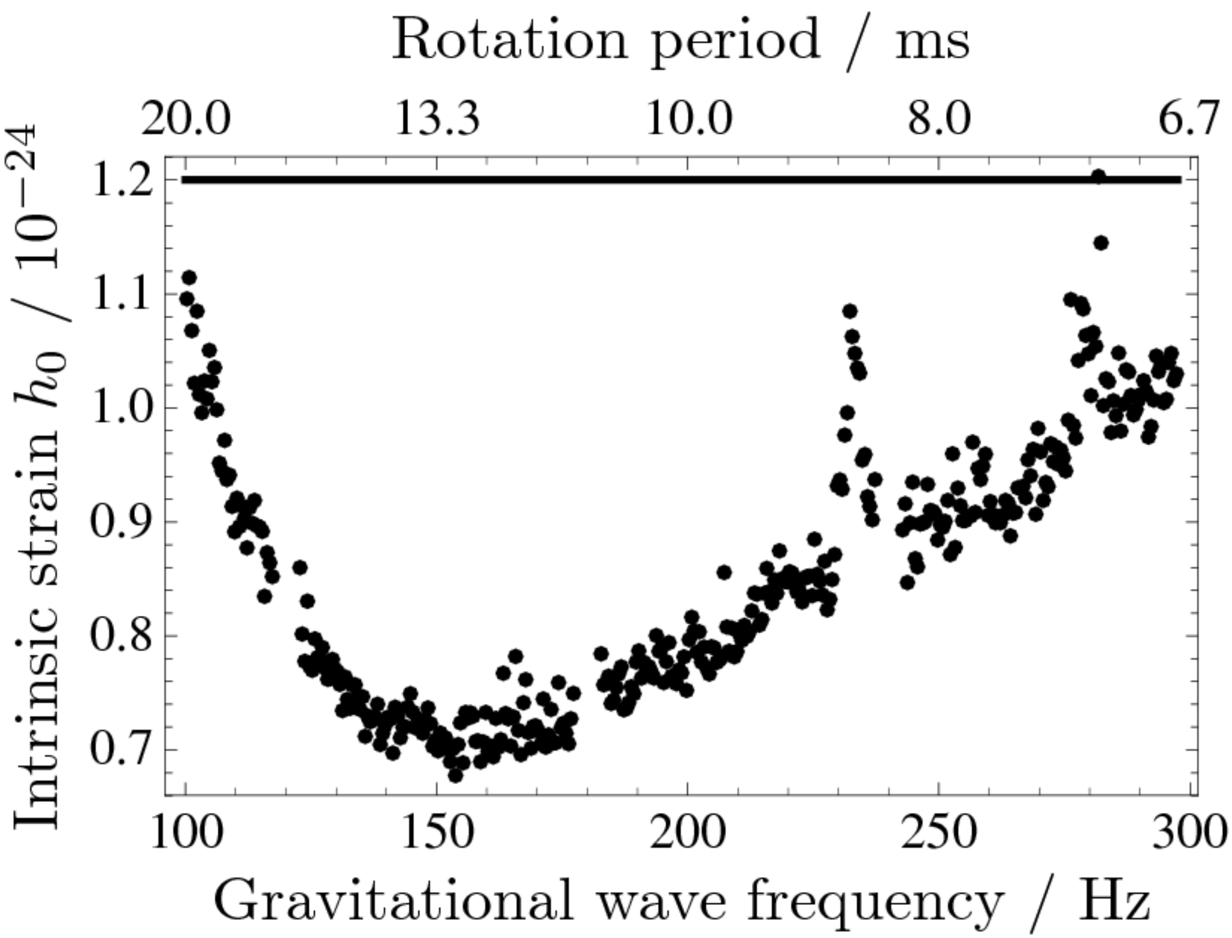
Requires a broad band search over accessible band



Cassiopeia A

Other results

Search for Cassiopeia A – Young age (~300 years) requires search over 2nd derivative

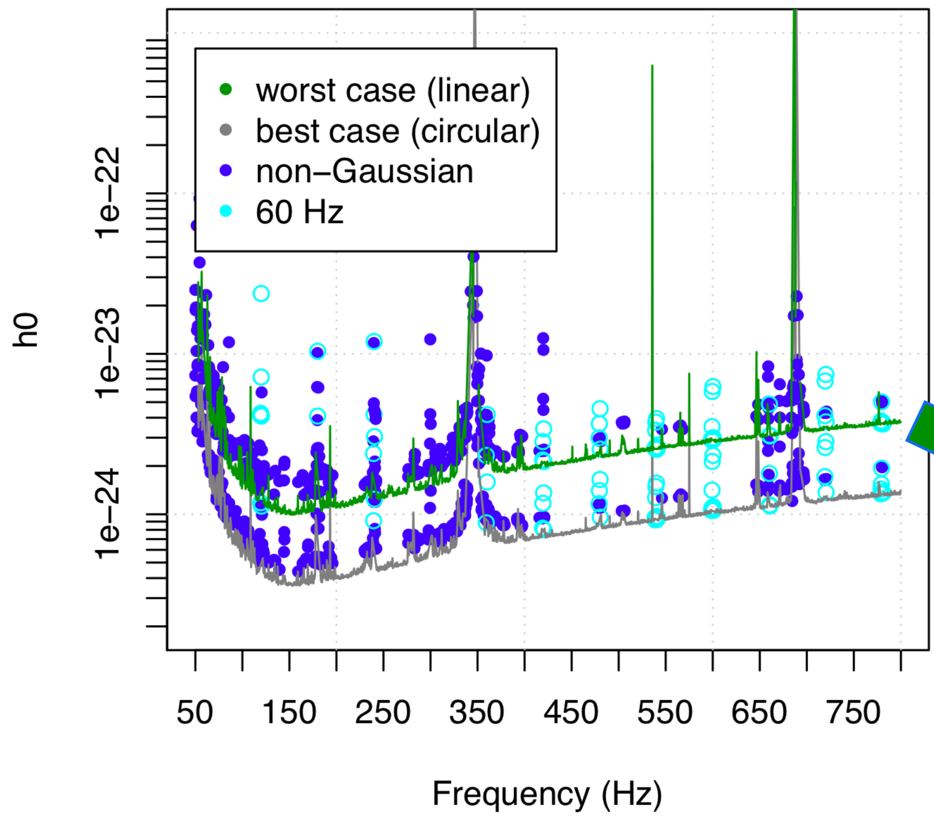


indirect upper limit (based on age, distance)

Ap. J. 722 (2010) 1504

Other results

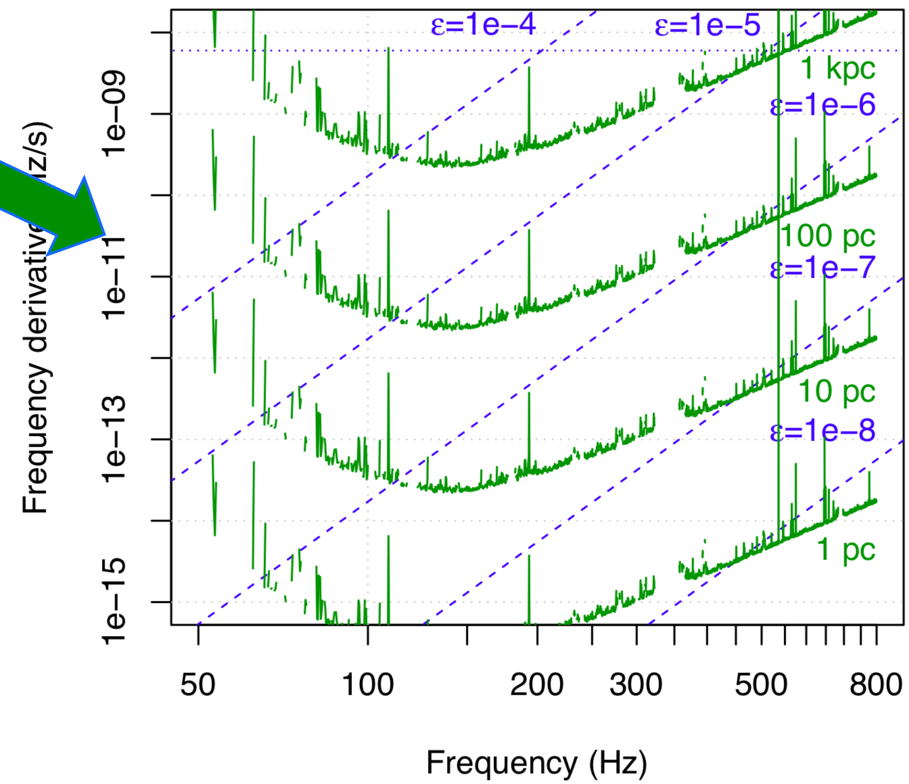
S5 all-sky results:



[PRD 85 (2012) 022001]

Semi-coherent stacks of 30-minute, demodulated power spectra ("PowerFlux")

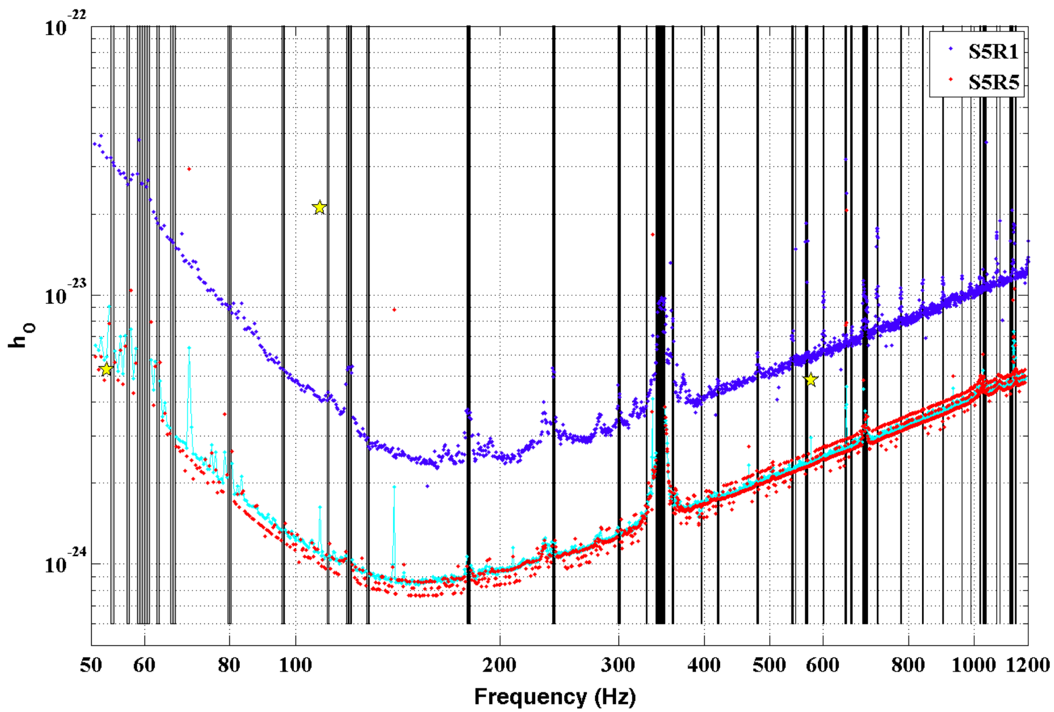
Astrophysical reach:



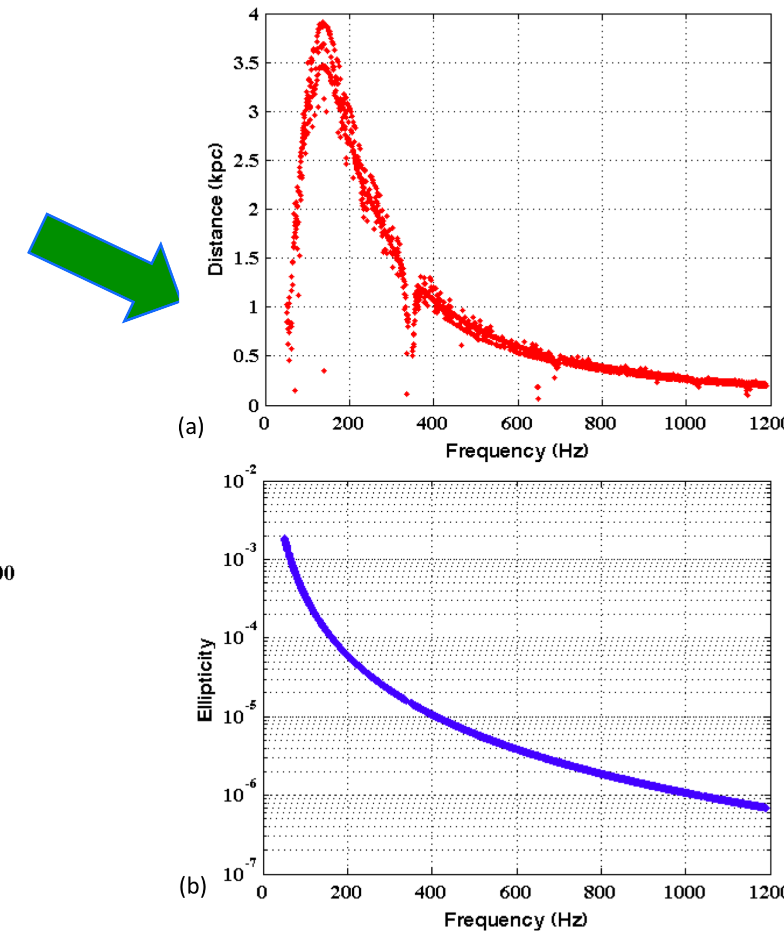
Other results

S5 all-sky results:

Einstein@Home semi-coherent sums of 121 25-hour F-Statistic powers (2 interferometers)



Astrophysical reach:

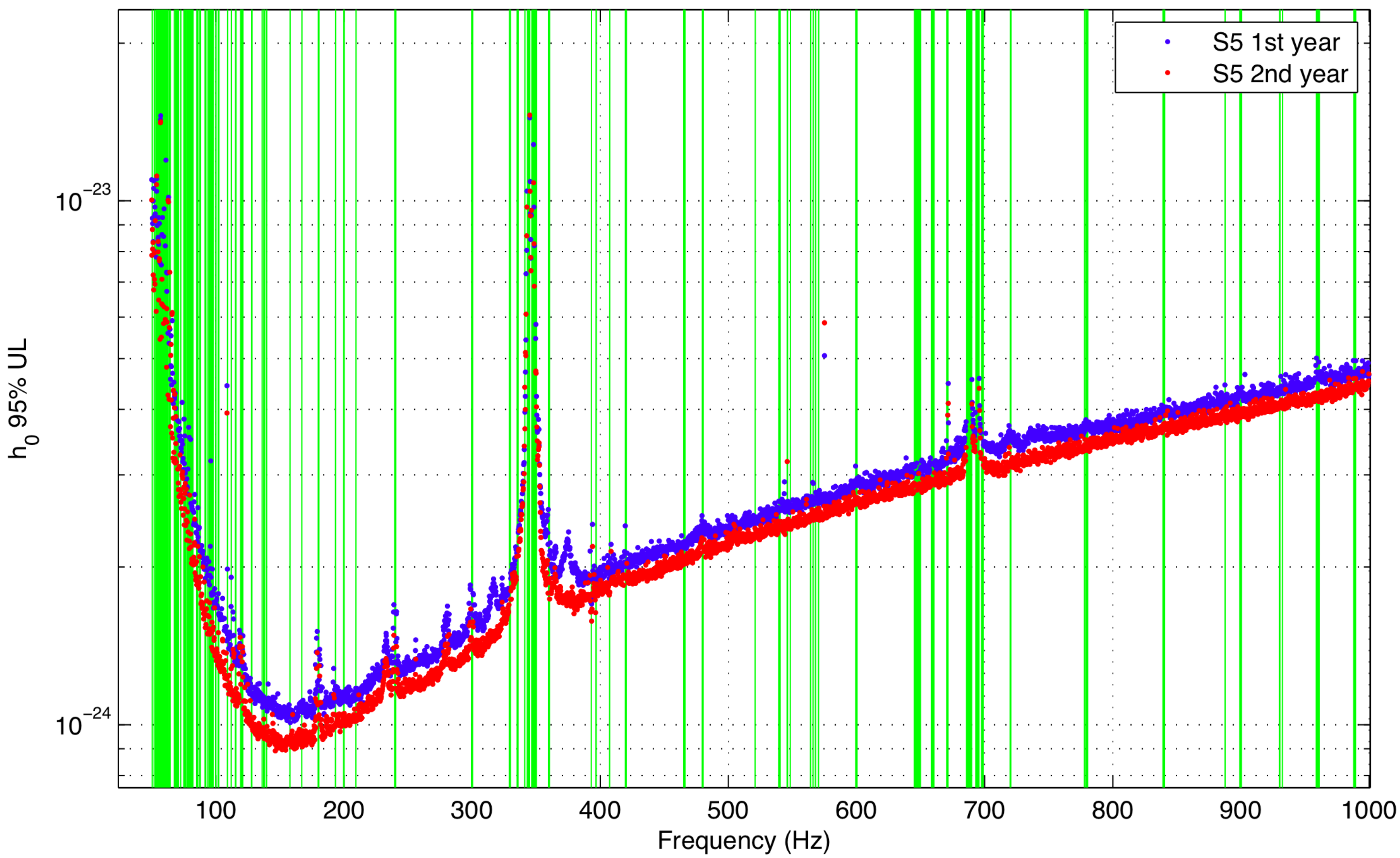


PRD 87 (2013) 042001

Other results

S5 all-sky results:

Hough-transform search based on ~68K 30-minute demodulated spectra (3 interferometers)

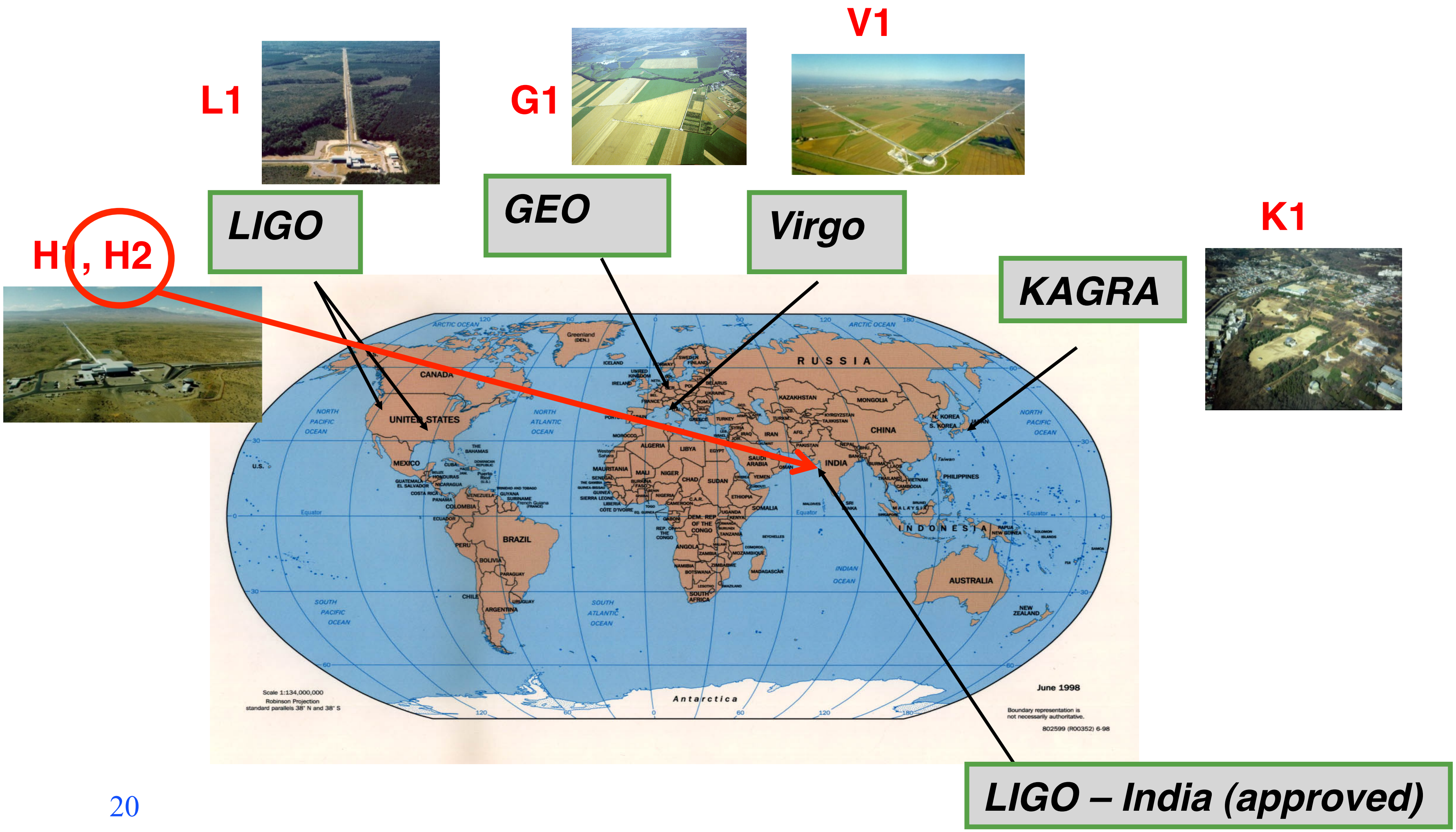


arXiv:1311.2409 (Nov 2013)

The Global Interferometer Network

The three (two) LIGO, Virgo and GEO interferometers are part of a Global Network.

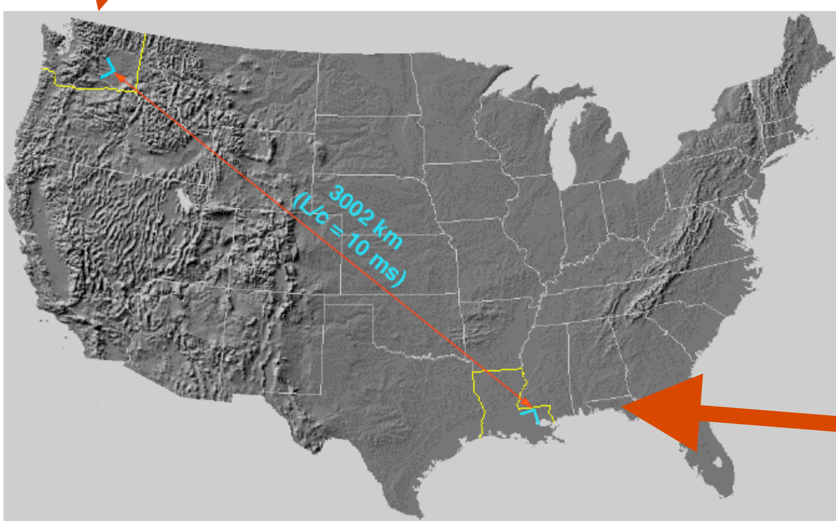
Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations



LIGO Observatories

Hanford

Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts



Livingston

Virgo

Have begun collaborating with Virgo colleagues (Italy/France)

Took data in coincidence for last ~4 months of latest science run

Data exchange and joint analysis underway

Will coordinate closely on detector upgrades and future data taking

3-km Michelson Interferometer just outside Pisa, Italy

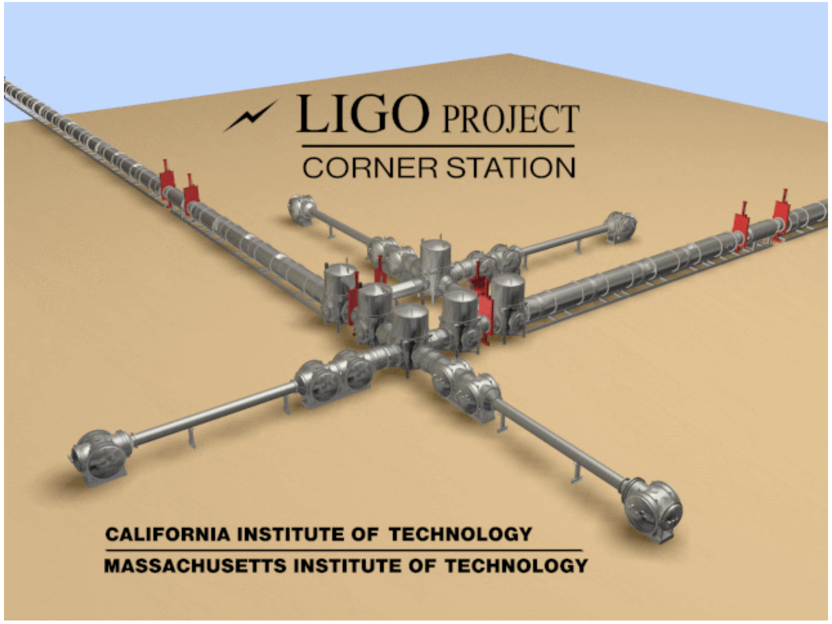
GEO600

Work closely with the GEO600 Experiment (Germany / UK / Spain)

- **Arrange coincidence data runs when commissioning schedules permit**
- **GEO members are full members of the LIGO Scientific Collaboration**
- **Data exchange and strong collaboration in analysis now routine**
- **Major partners in proposed Advanced LIGO upgrade**

600-meter Michelson Interferometer just outside Hannover, Germany

LIGO Detector Facilities



•Stainless-steel tubes

(1.24 m diameter, ~10^{-8} torr)

•Gate valves for optics isolation

•Protected by concrete enclosure

Vacuum System

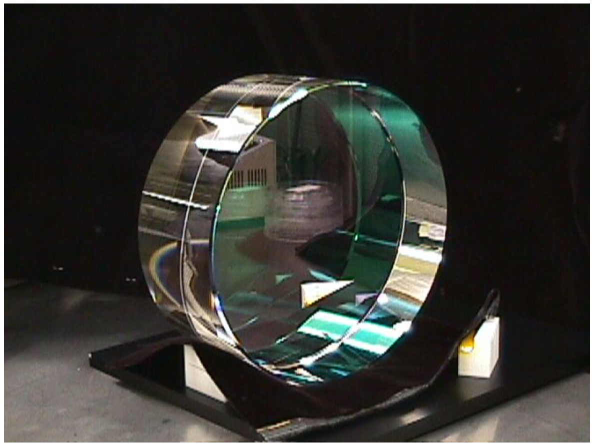
LIGO Detector Facilities

LASER

- Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- Elaborate intensity & frequency stabilization system, including feedback from main interferometer

Optics

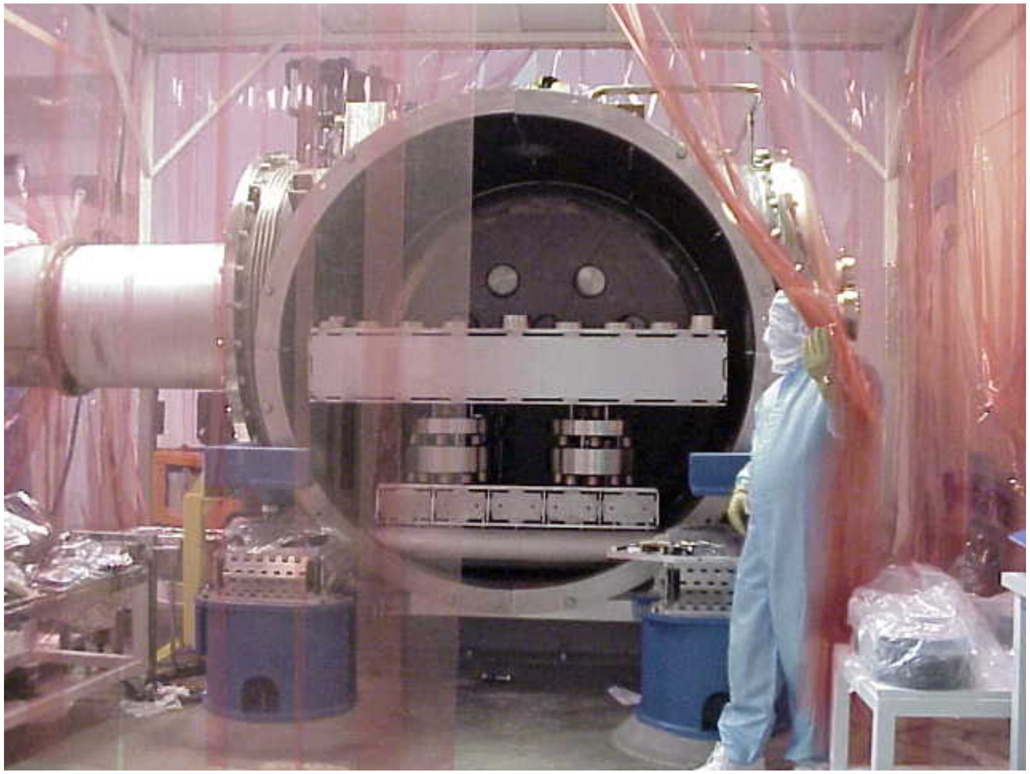
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

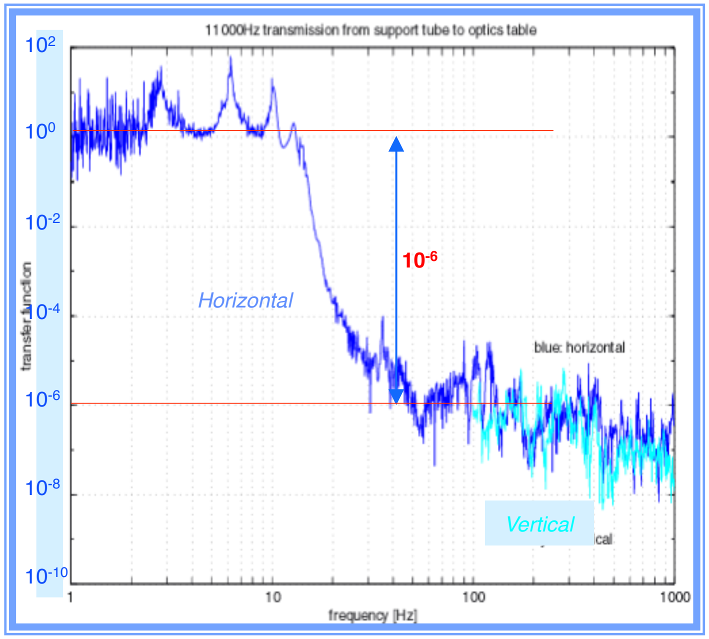


LIGO Detector Facilities

Seismic Isolation

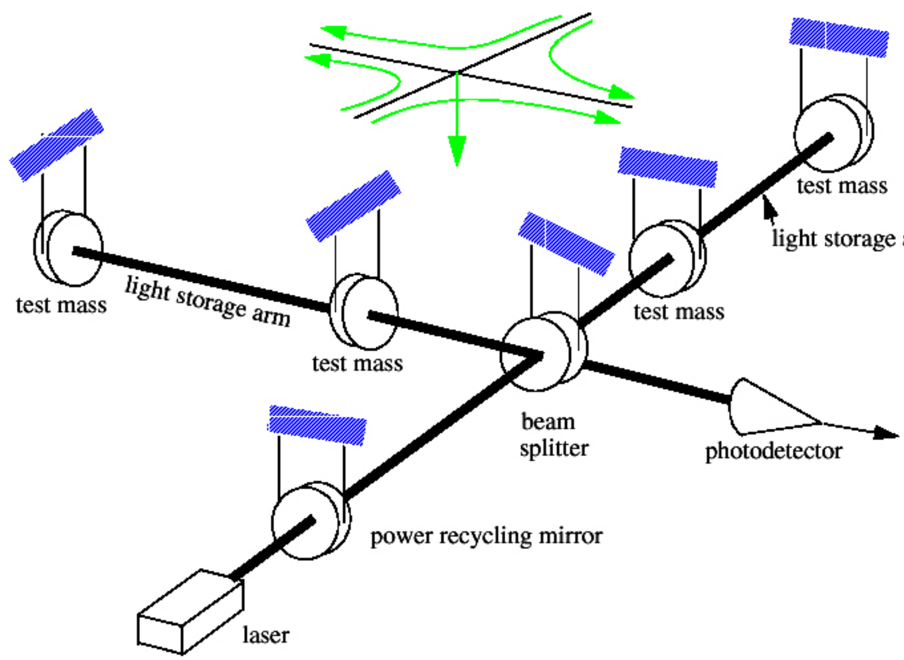
- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz





Gravitational Wave Detection

- Suspended Interferometers (IFO's)
  - **Suspended mirrors in "free-fall"**
  - **Michelson IFO is "natural" GW detector**
  - **Broad-band response (~20 Hz to few kHz)**
  - **→ Waveform information (e.g., chirp reconstruction)**

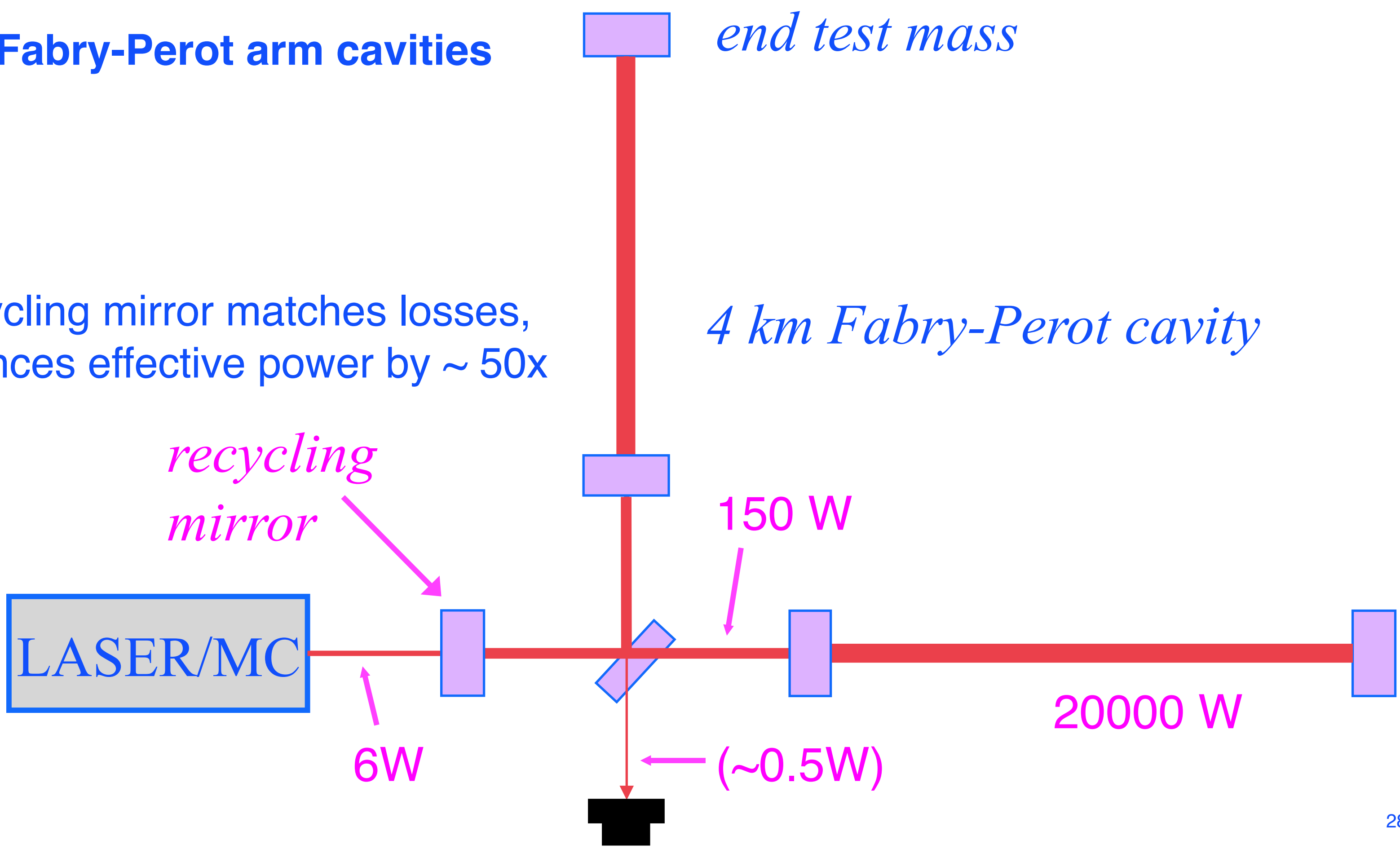


LIGO Interferometer Optical Scheme

Michelson interferometer

With Fabry-Perot arm cavities

•Recycling mirror matches losses, enhances effective power by ~ 50x

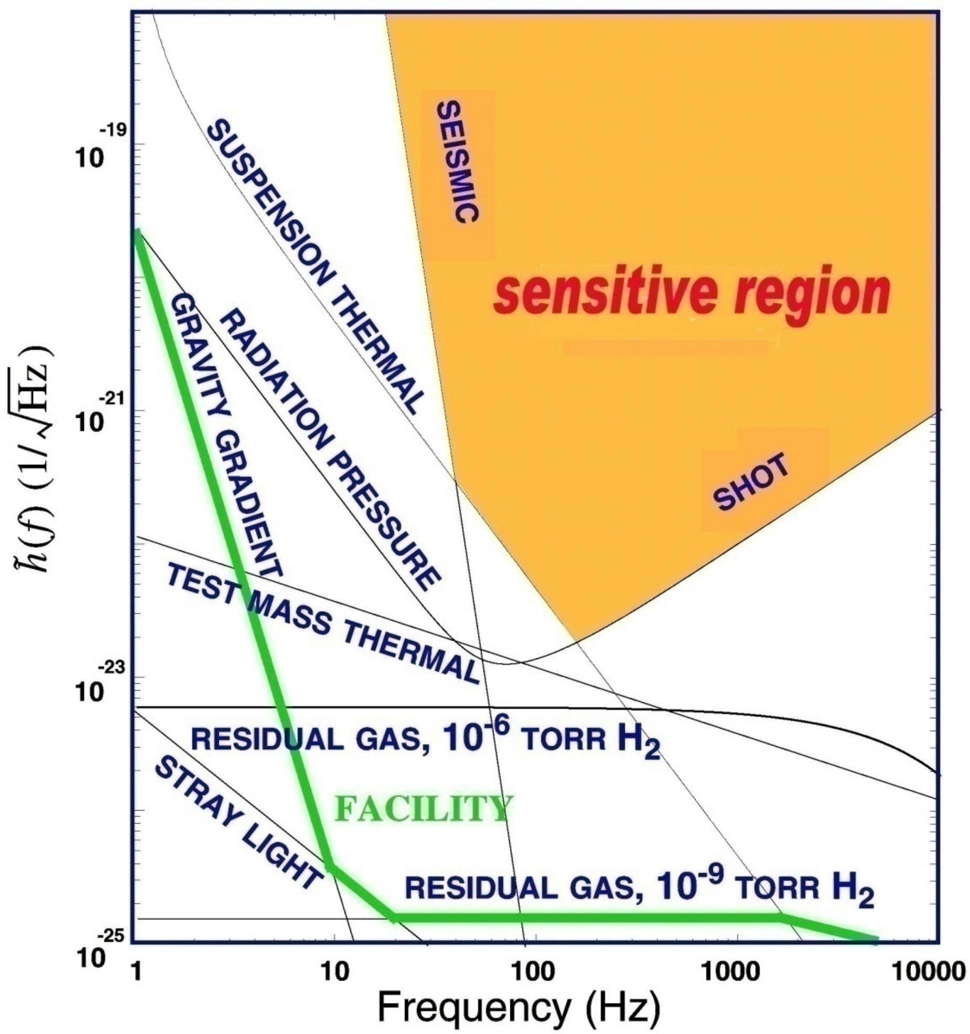


What Limits the Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

Best design sensitivity:

~ 3 x 10^{-23} $Hz^{-1/2}$ @ 150 Hz



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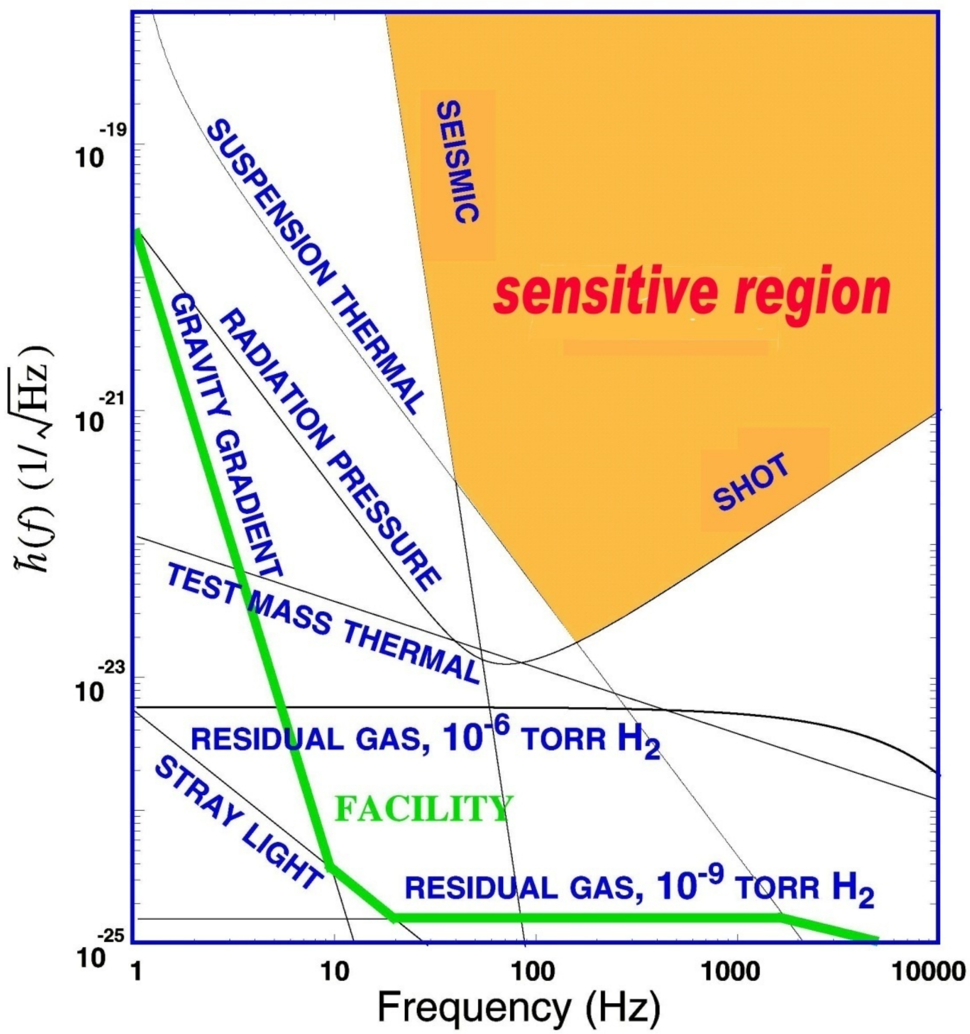


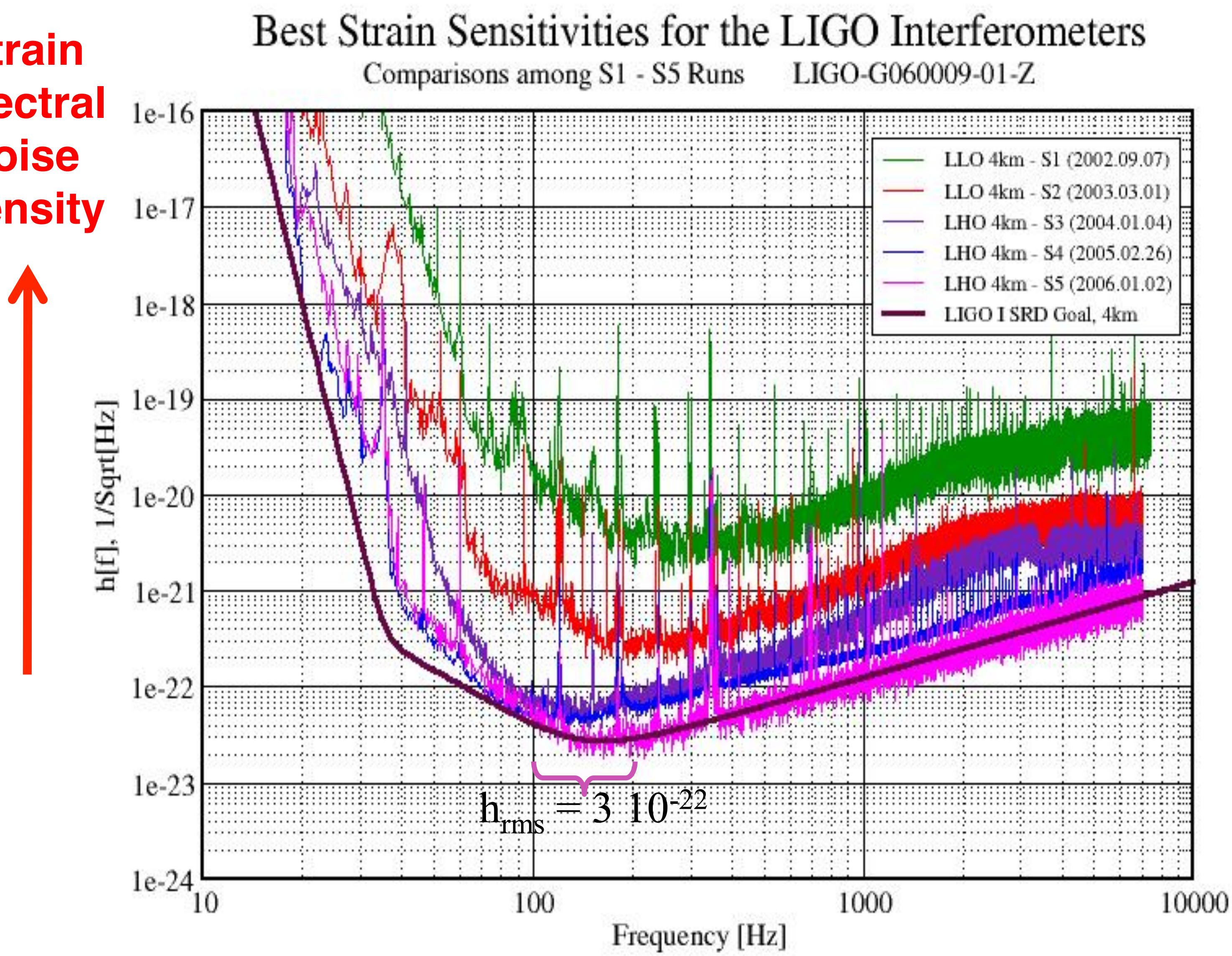
Best ~~design~~ achieved sensitivity:

~ ~~3 x 10^-23~~ $\mathrm{Hz}^{-1/2}$ @ 150 Hz

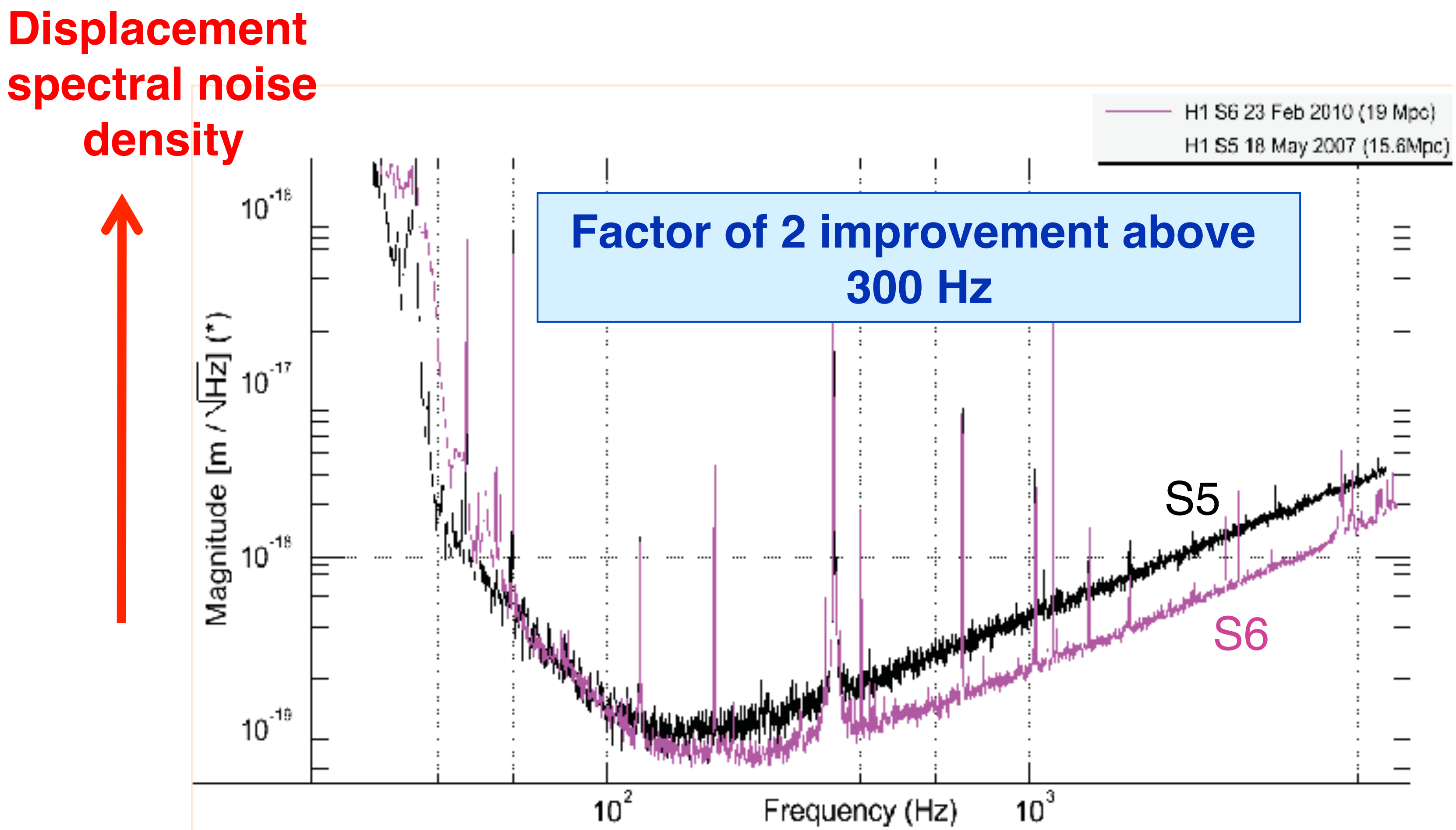
< 2×10^{-23} (enhanced LIGO)

LIGO S1 → S5 Sensitivities ("Initial LIGO")
2002-2007

Strain spectral noise density



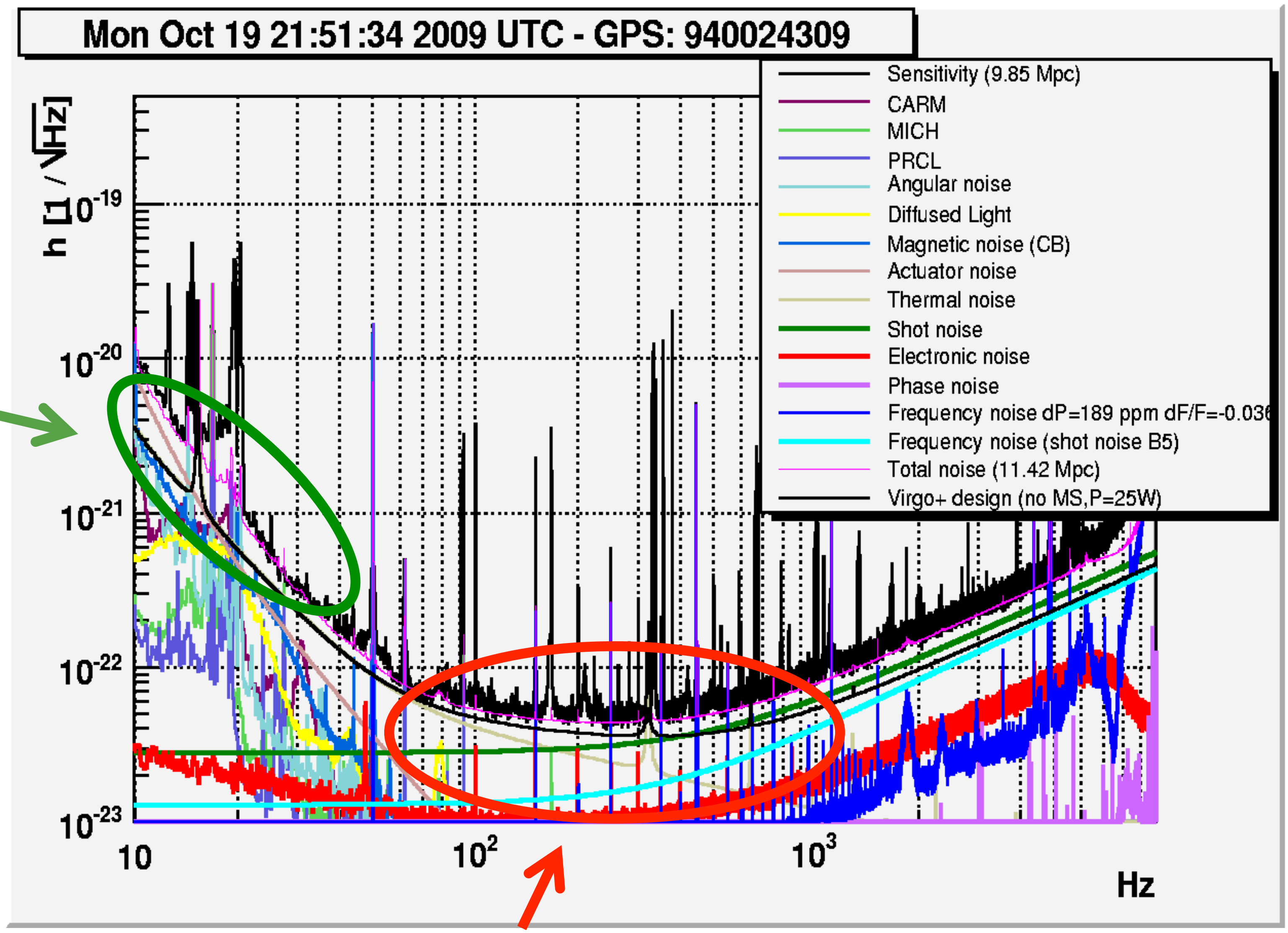
“Enhanced LIGO” (July 2009 – Oct 2010)



Virgo sensitivity in VSR2 (part of LIGO S6)

≥10^2 × better than LIGO below 30 Hz!

Enabled search for Vela at 22 Hz



Comparable to LIGO in sweet spot

“Locking” the Inteferometer

Sensing gravitational waves requires sustained resonance in the Fabry-Perot arms and in the recycling cavity

→ Need to maintain half-integer # of laser wavelengths between mirrors

→ Feedback control servo uses error signals from imposed RF sidebands

→ Four primary coupled degrees of freedom to control

→ Highly non-linear system with 5-6 orders of magnitude in light intensity

Also need to control mirror rotation (“pitch” & “yaw”)

→ Ten more DOF’s (but less coupled)

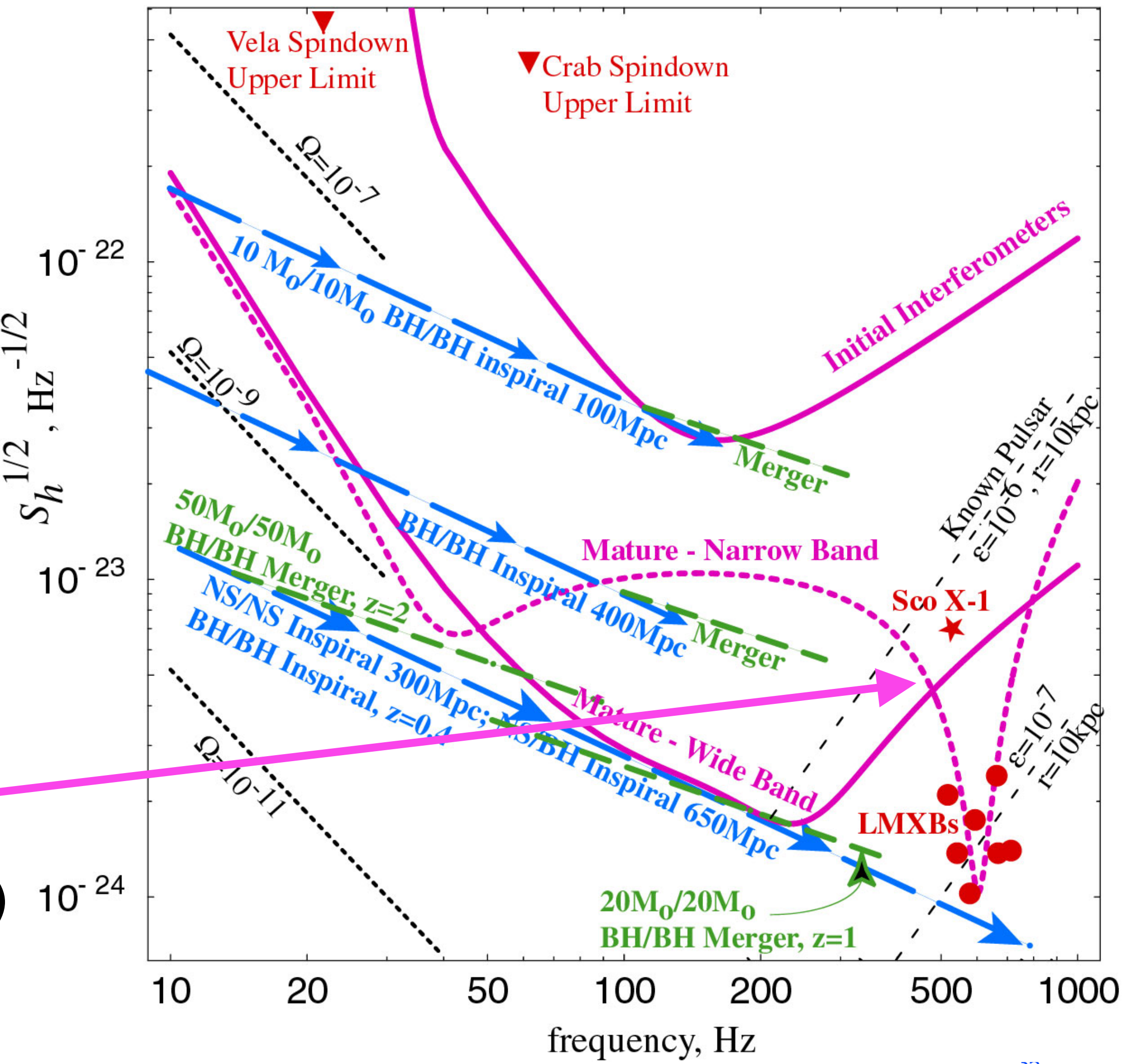
And need to stabilize laser (intensity & frequency), keep the beam pointed, damp out seismic noise, correct for tides, etc.,…

Advanced LIGO

Sampling of source strengths vis a vis Initial LIGO and Advanced LIGO

Lower h_{rms} and wider bandwidth both important

"Signal recycling" offers potential for tuning shape of noise curve to improve sensitivity in target band
(e.g., known pulsar cluster)

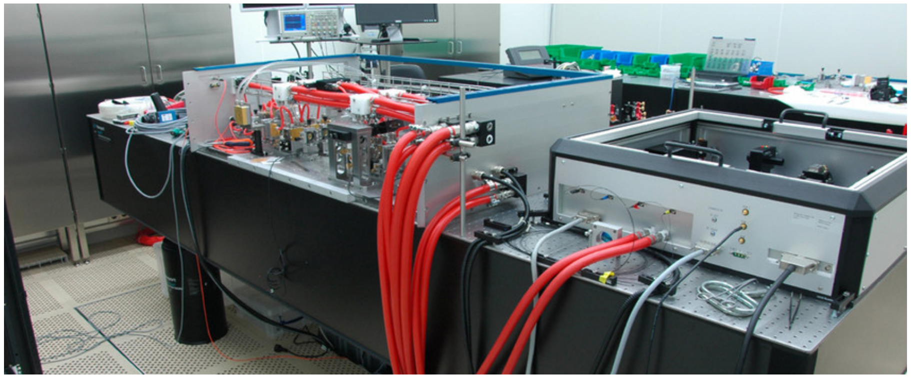


Advanced LIGO

Increased laser power:

10 W → 180 W

Improved shot noise (high freq)



Higher-Q test mass:

Fused silica with better optical coatings

Lower internal thermal noise in bandwidth

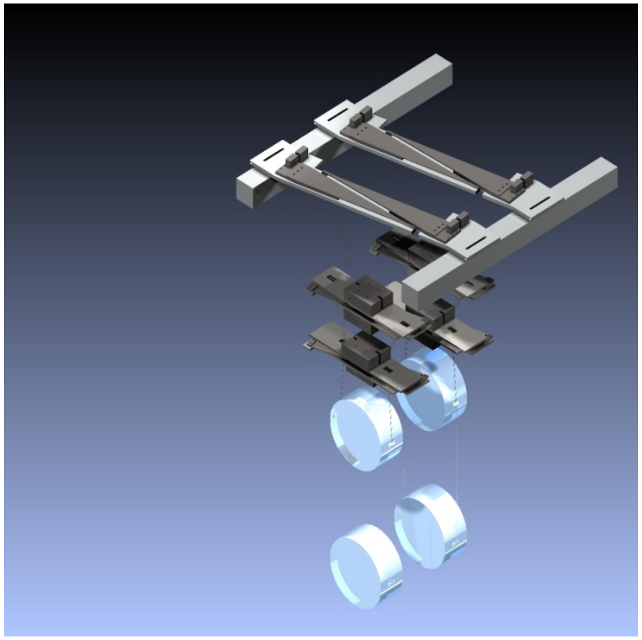
Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Advanced LIGO

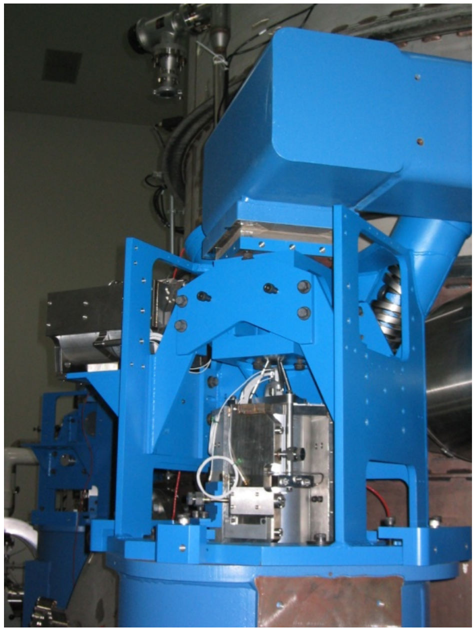
Detector Improvements:



New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth



Improved seismic isolation:

Passive → Active

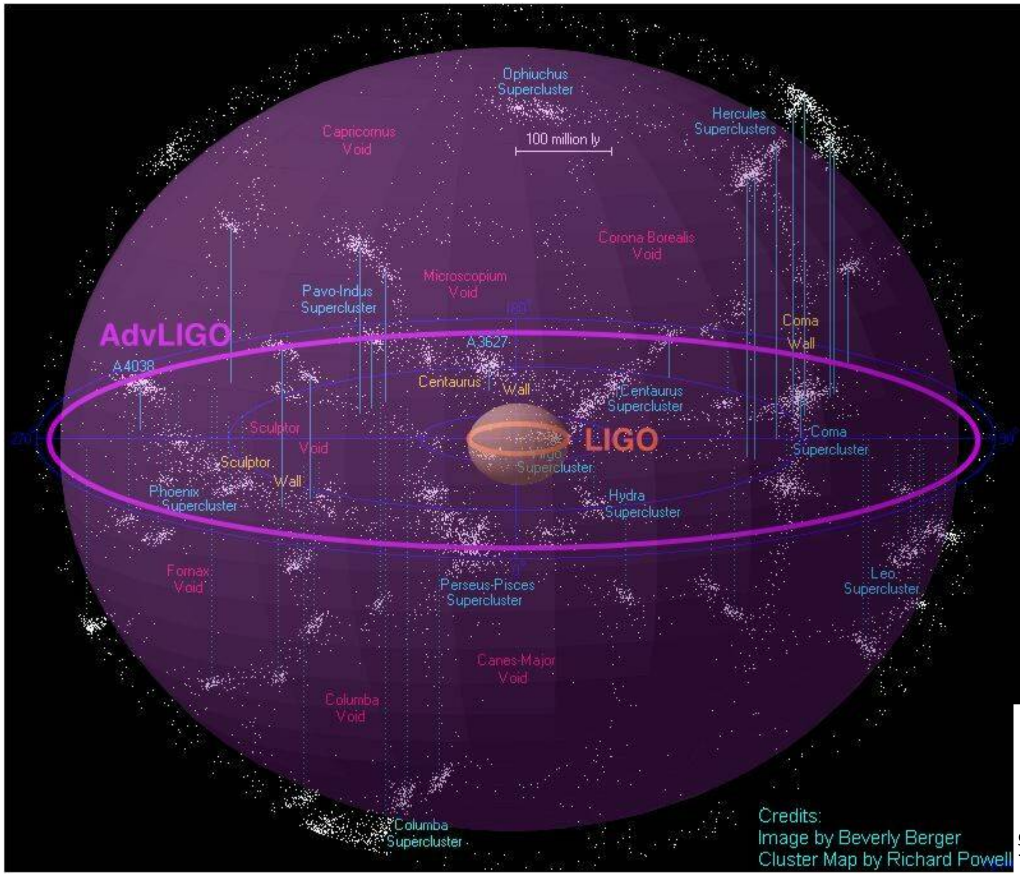
Lowers seismic "wall" to ~10 Hz

Advanced LIGO

Neutron Star Binaries:

Average range ~ 200 Mpc

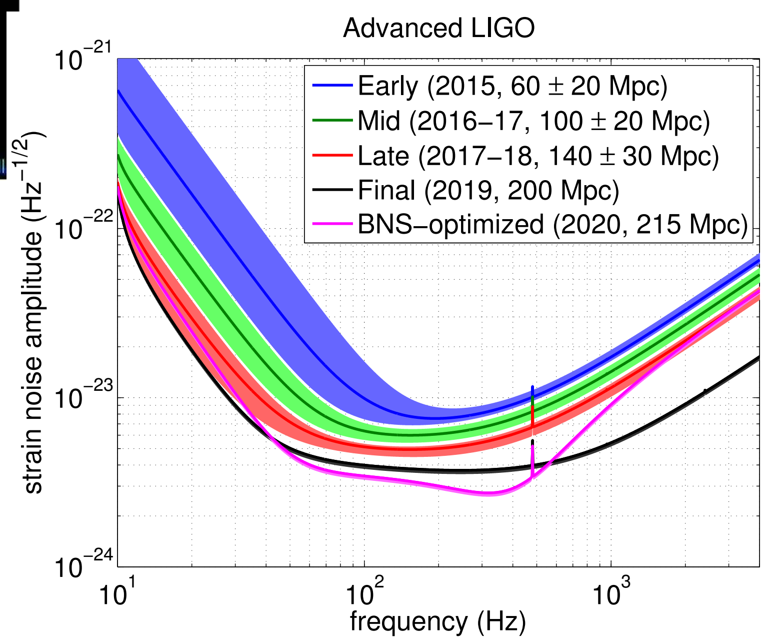
Most likely rate ~ 40/year



The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

(Range x ~10 → Volume x ~1000)

But that sensitivity will not be achieved instantly…

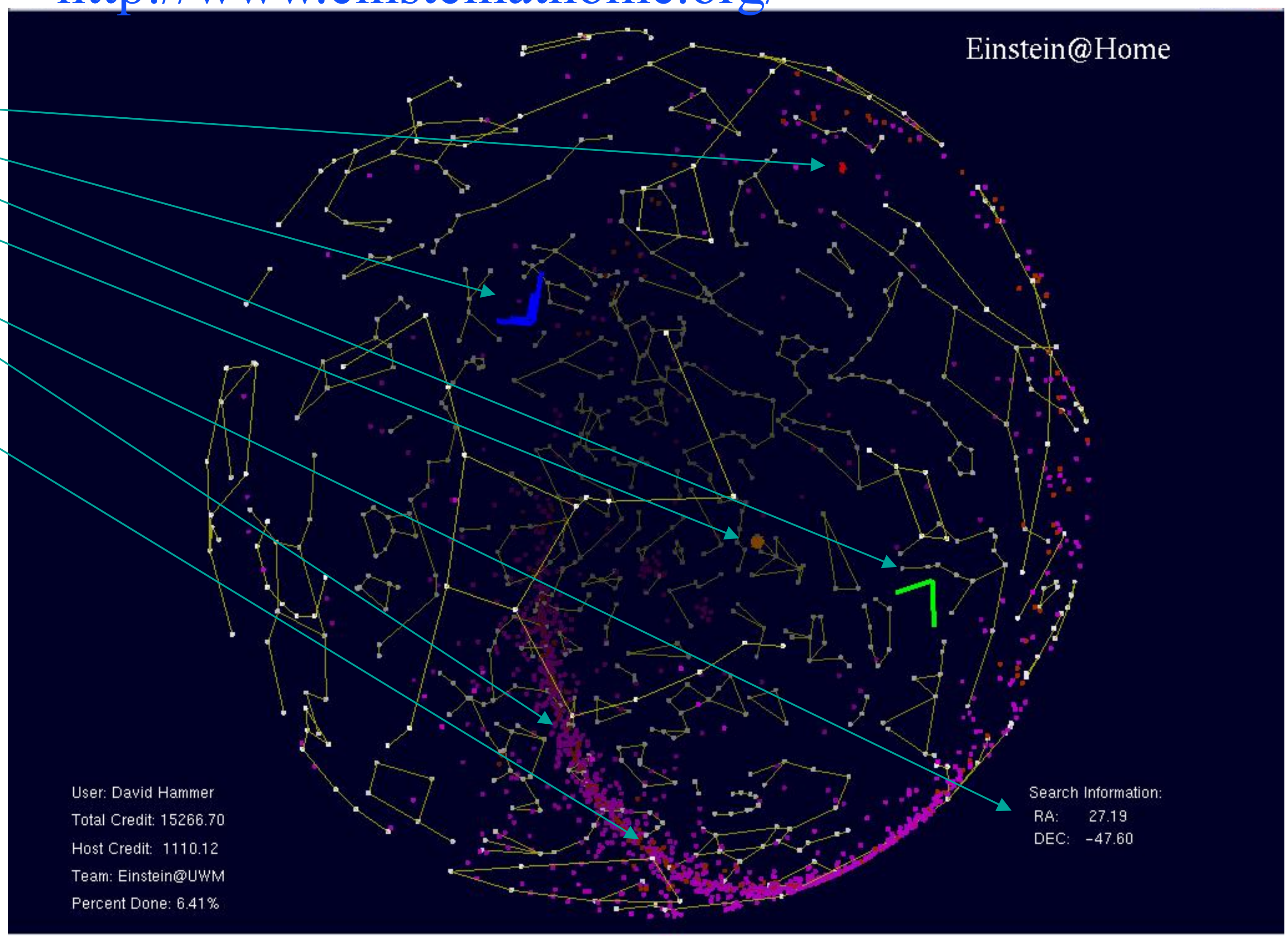


arXiv: 1304.0670

http://www.einsteinathome.org/

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants

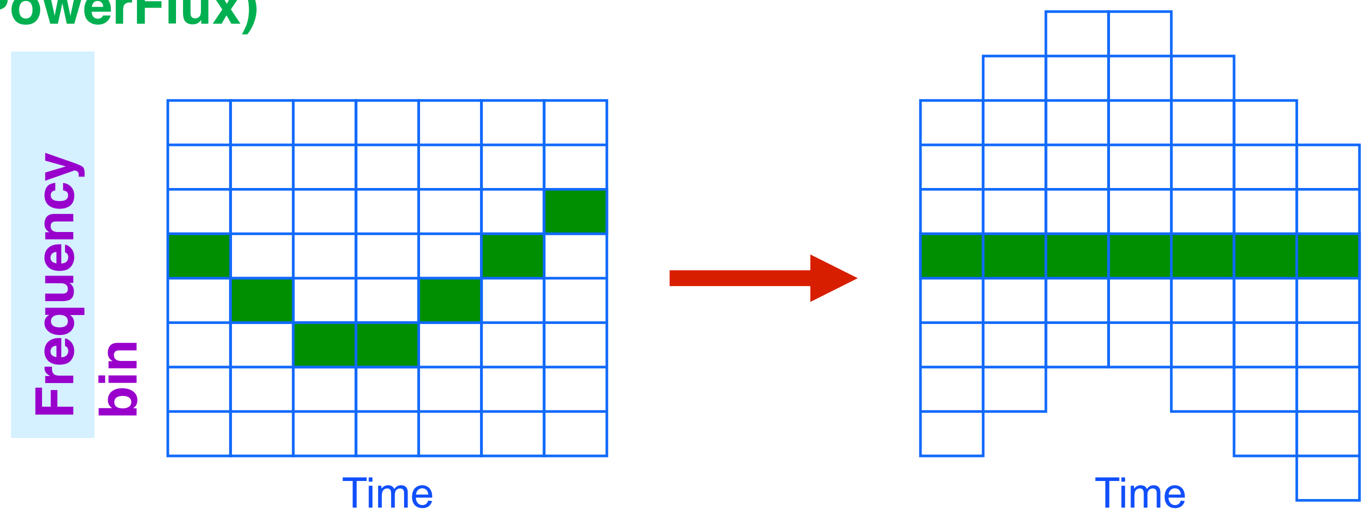
Your computer can help too!



Searching for continuous waves

Several approaches tried or in development:

- **Summed powers from many short (30-minute) FFTs with sky-dependent corrections for Doppler frequency shifts → "Semi-coherent " (StackSlide, Hough transform, PowerFlux)**



- **Push up close to longest coherence time allowed by computing resources (~1 day) and look for coincidences among outliers in different data stretches (Einstein@Home)**

What is the "direct spindown limit"?

It is useful to define the "direct spindown limit" for a known pulsar, under the assumption that it is a "gravitar", i.e., a star spinning down due to gravitational wave energy loss

Unrealistic for known stars, but serves as a useful benchmark

Equating "measured" rotational energy loss (from measured period increase and reasonable moment of inertia) to GW emission gives:

$$h_{SD} = 2.5\times10^{-25}\left[\frac{kpc}{d}\right]\sqrt{\left[\frac{1kHz}{f_{\mathrm{GW}}}\right]\left[\frac{-df_{\mathrm{GW}}/dt}{10^{-10}\,Hz/s}\right]\left[\frac{I}{10^{45}\,g\cdot cm^2}\right]}$$

Example:

Crab → $\mathbf{h_{SD} = 1.4 \times 10^{-24}}$

(d=2 kpc, f_{GW} = 59.5 Hz, $df_{GW}/dt = -7.4\times10^{-10}$ Hz/s)

What is the "indirect spindown limit"?

If a star's age is known (e.g., historical SNR), but its spin is unknown, one can still define an indirect spindown upper limit by assuming gravitar behavior has dominated its lifetime:

$$\tau = \frac{f}{4\,(df\,/\,dt)}$$

And substitute into h_{SD} to obtain
[K. Wette, B. Owen,… CQG 25 (2008) 235011]

$$h_{ISD} = 2.2\times10^{-24}\left[\frac{kpc}{d}\right]\sqrt{\left[\frac{1000\,yr}{\tau}\right]\left[\frac{I}{10^{45}\,g\cdot cm^2}\right]}$$

Example:

Cassiopeia A → **h_{ISD} = 1.2 × 10^{-24}**

(d=3.4 kpc, **τ**=328 yr**)**

What is the "X-ray flux limit"?

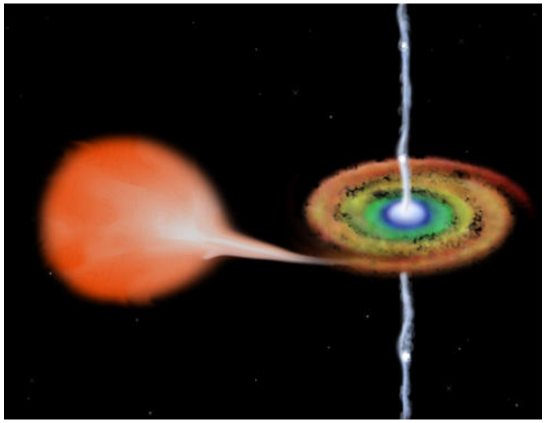
For an LMXB, equating accretion rate torque (inferred from X-ray luminosity) to gravitational wave angular momentum loss (steady state) gives: **[R.V. Wagoner ApJ 278 (1984) 345; J. Papaloizou & J.E. Pringle MNRAS 184 (1978) 501; L. Bildsten ApJ 501 (1998) L89]**

$$h_{X-ray} \approx 5\times10^{-27}\sqrt{\left[\frac{600Hz}{f_{sig}}\right]\left[\frac{F_x}{10^{-8}erg\cdot cm^{-2}\cdot s^{-1}}\right]}$$

Example: Scorpius X-1

→ $\mathbf{h_{X\text{-}ray} \approx 3 \times 10^{-26}}$ $[600\ \mathrm{Hz} / f_{sig}]^{1/2}$

($F_x = 2.5 \times 10^{-7}\ \mathrm{erg\cdot cm^{-2}\cdot s^{-1}}$)



Courtesy: McGill U.

CW observational papers to date

S1:

Setting upper limits on the strength of periodic gravitational waves from PSR J1939+2134 using the first science data from the GEO 600 and LIGO detectors - PRD 69 (2004) 082004

S2:

First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform - PRD 72 (2005) 102004

Limits on gravitational wave emission from selected pulsars using LIGO data - PRL 94 (2005) 181103 (28 pulsars)

Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run - PRD 76 (2007) 082001

CW observational papers to date

S3-S4:

Upper Limits on Gravitational Wave Emission from 78 Radio Pulsars - PRD 76 (2007) 042001

All-sky search for periodic gravitational waves in LIGO S4 data – PRD 77 (2008) 022001

The Einstein@Home search for periodic gravitational waves in LIGO S4 data – PRD **7**9 (2009) 022001

Upper limit map of a background of gravitational waves – PRD 76 (2007) 082003 (Cross-correlation – Sco X-1)

CW observational papers to date

S5:

Beating the spin-down limit on gravitational wave emission from the Crab pulsar – APJL 683 (2008) 45

All-sky LIGO Search for Periodic Gravitational Waves in the Early S5 Data – PRL 102 (2009) 111102

Einstein@Home search for periodic gravitational waves in early S5 LIGO data – PRD 80 (2009) 042003

Searches for gravitational waves from known pulsars with S5 LIGO data – APJ 713 (2010) 671 (116 pulsars)

First search for gravitational waves from the youngest known neutron star – APJ 722 (2010) 1504

All-sky search for periodic gravitational waves in the full S5 LIGO data – PRD 85 (2012) 022001

CW observational papers to date

S5:

Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data – PRD 87 (2013) 042001

A directed search for continuous Gravitational Waves from the Galactic Center – PRD 88 (2013) 102002

Application of a Hough search for continuous gravitational waves on data from the 5th LIGO science run – arXiv:1311.2409 (Nov 2013)

CW observational papers to date

S6 / VSR2 / VSR4:

Beating the spin-down limit on gravitational wave emission from the Vela pulsar – APJ 737 (2011) 93

Gravitational-waves from known pulsars: results from the initial detector – arXiv:1309.4027 (Sept 2013)