Introduction to Continuous Gravitational Wave Searches & Charge to Workshop

Workshop on Neutron Stars and Gravitational Waves:
The next steps toward detection

Keith Riles
University of Michigan

LIGO-Virgo Collaboration

Boston A.A.S. Summer Meeting
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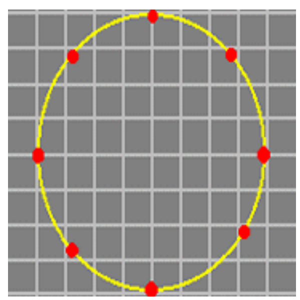
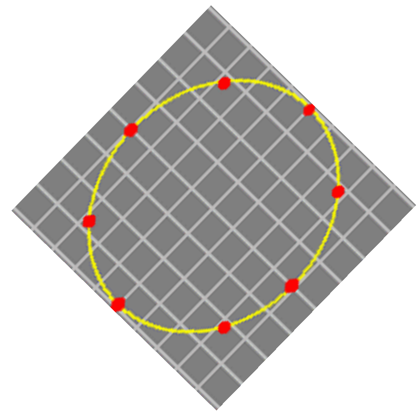
LIGO-G1100457-v1

Nature of Gravitational Waves

- Gravitational Waves = “Ripples in space-time”

- Perturbation propagation similar to light (obeys same wave equation!)
  - **Propagation speed = c**
  - **Two transverse polarizations - <u>quadrupolar</u>:** + and x





- Amplitude parameterized by (tiny) dimensionless strain h: $\Delta L \sim h(t) \times L$

Generation of Gravitational Waves

- Radiation generated by quadrupolar mass movements:

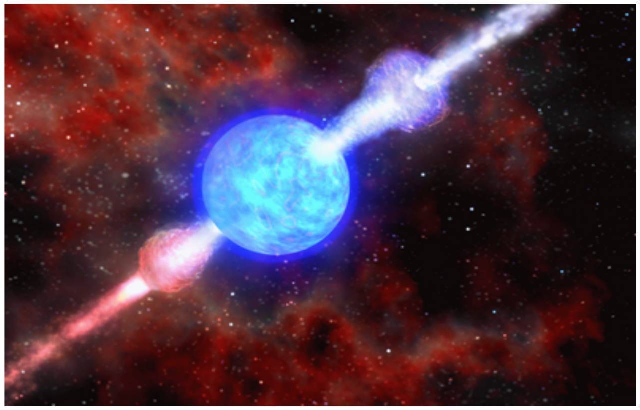
$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right]$$

No GW from axisymmetric object rotating about symmetry axis

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

- Spinning neutron star with equatorial ellipticity ε_{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 (see Ben Owen's 1st talk)

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

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

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

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

(precession due to different **L** and **Ω** axes)

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

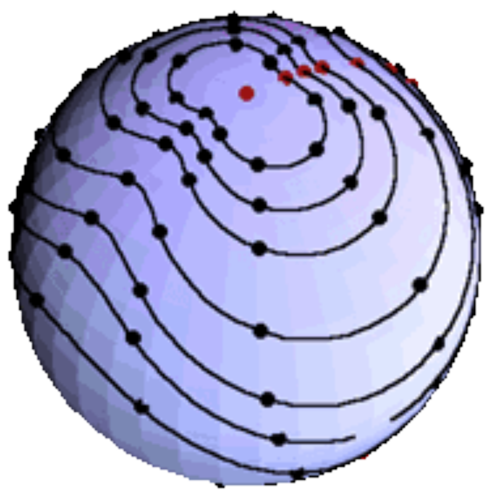
- **r modes** (Coriolis-driven instability):

N. Andersson, ApJ 502 (1998) 708

S. Chandrasekhar PRL 24 (1970) 611

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

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



Gravitational CW mechanisms

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

Mountain 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 $\boldsymbol{\varepsilon}_{\mathbf{equat}}$?

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

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

(see Madappa Prakash talk)

Gravitational CW mechanisms

Strange quark stars could support much higher ellipticities
B. Owen PRL 95 (2005) 211101

Maximum $\varepsilon_{equat} \approx 10^{-4}$

But what ε_{equat} is realistic?

What could drive ε_{equat} to a high value (besides accretion)?

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

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:

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

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]**

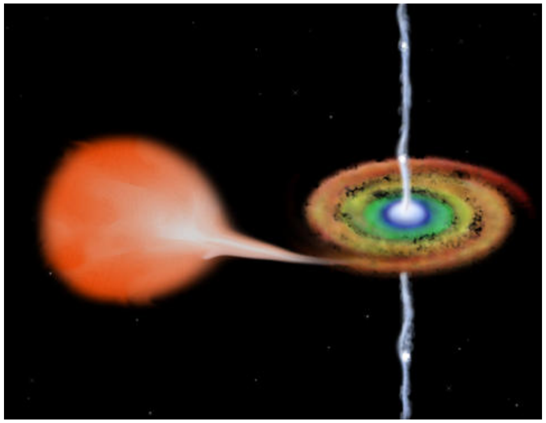
$$h_{X-ray} \approx 5\times10^{-27}\sqrt{\left[\frac{600Hz}{f_{sig}}\right]\left[\frac{F_x}{10^{-8}erg\cdot cm^{-2}\cdot s^{-1}}\right]}$$

Example: Scorpius X-1

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

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

(see Deepto Chakrabarty, Chris Messenger, Duncan Galloway talks)



Courtesy: McGill U.

Finding a completely unknown CW Source

Serious technical difficulty: Doppler frequency shifts

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

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

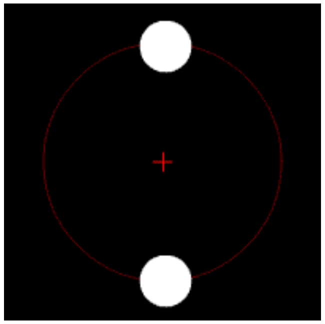
→ 1 kHz source spread over 6 million bins in ordinary FFT!

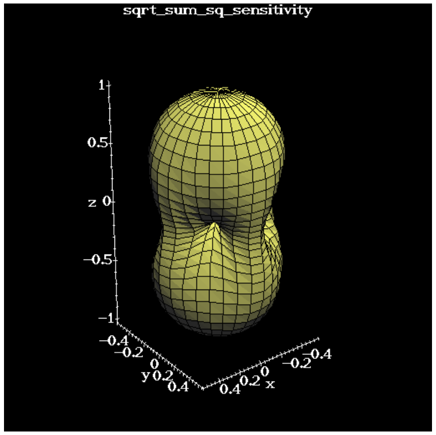
Additional, related complications:

Daily amplitude modulation of antenna pattern

Spin-down of source

Orbital motion of sources in binary systems





Finding a completely <u>unknown</u> 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 <u>coincidence</u> among different spans

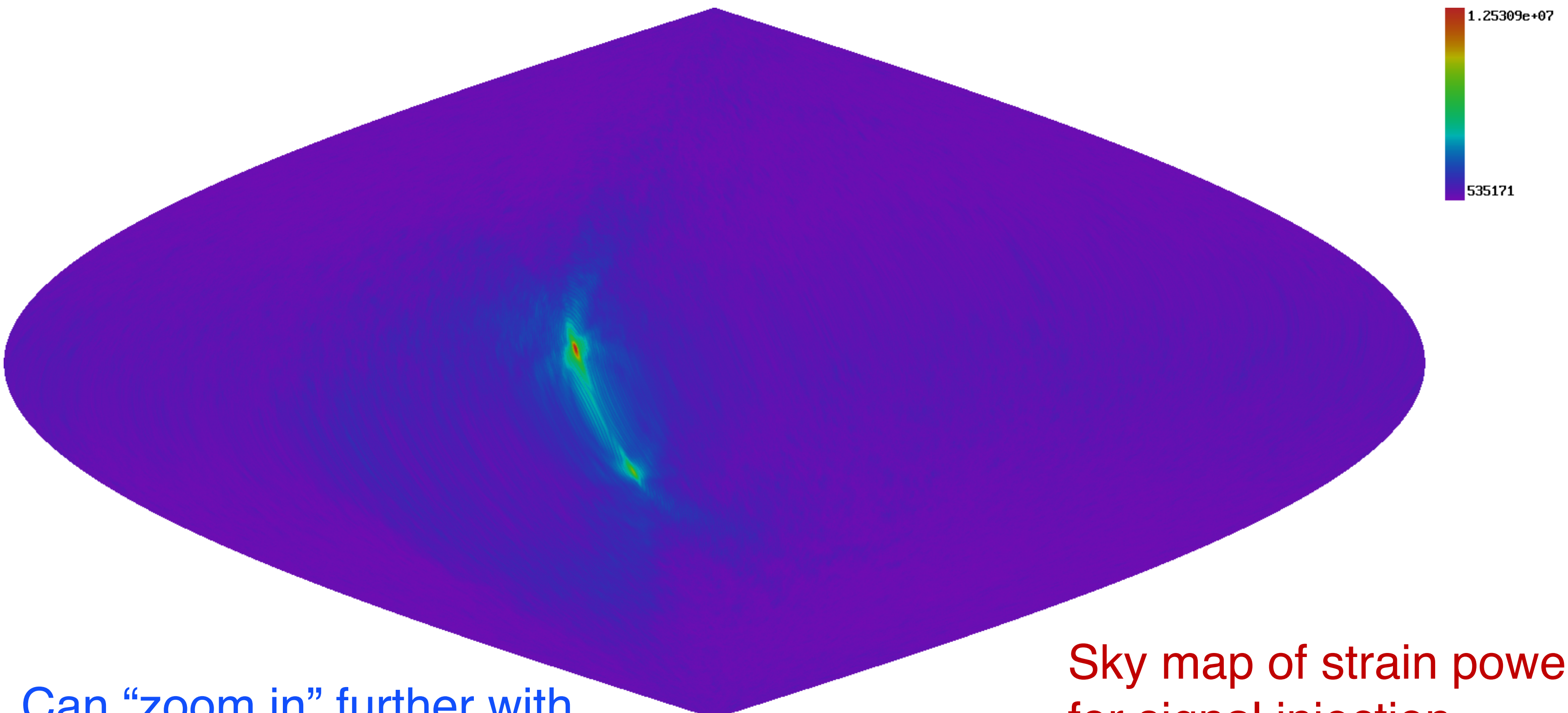
Alternative:
Semi-coherent stacking of spectra ($T_{coherence}$ = 30 min)
→ Sensitivity improves only as $(N_{stack})^{1/4}$

→ **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



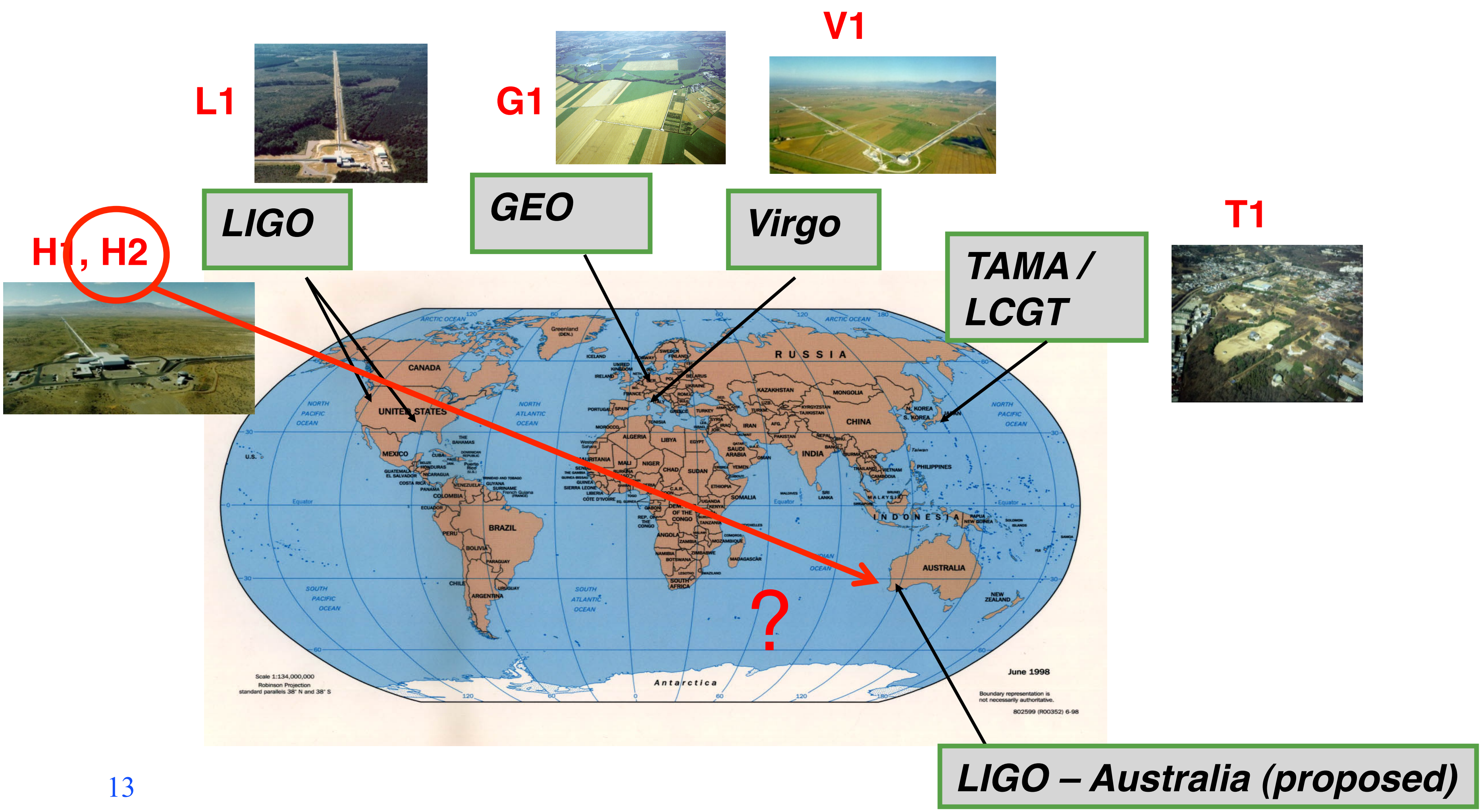
Can “zoom in” further with follow-up algorithms once we lock on to source

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

The Global Interferometer Network

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

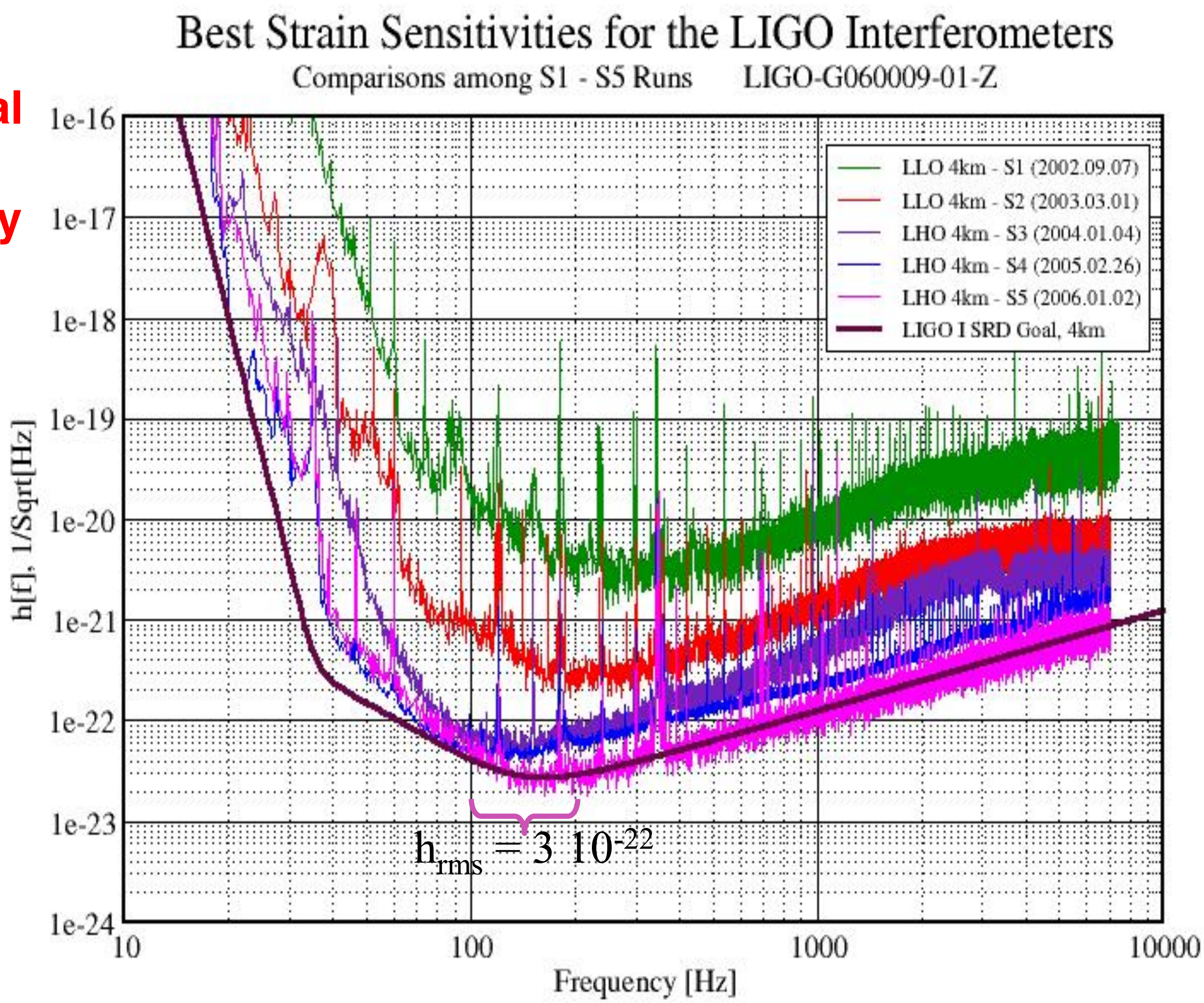
Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations



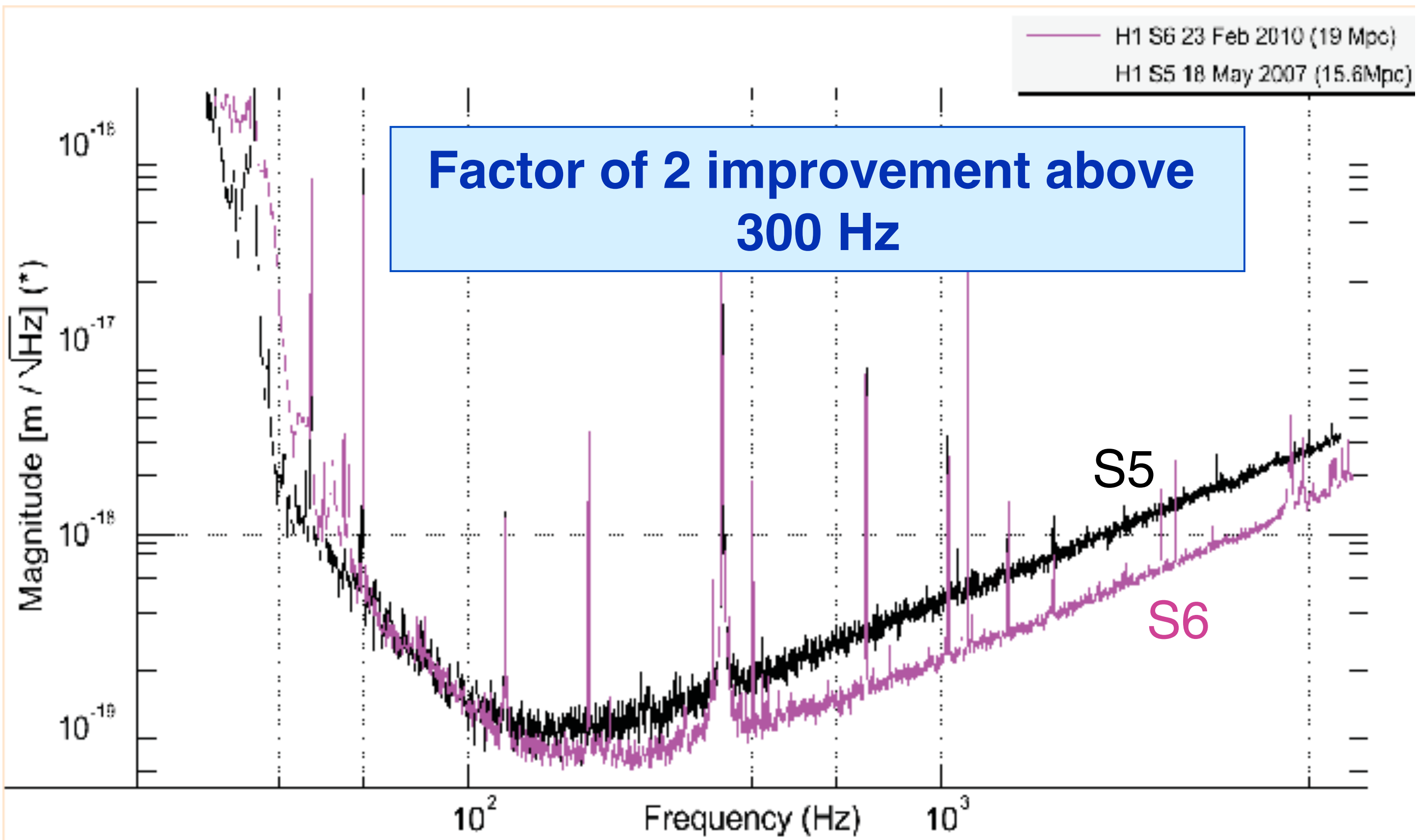
LIGO S1 → S5 Sensitivities ("Initial LIGO")

2002-2007

Strain spectral noise density



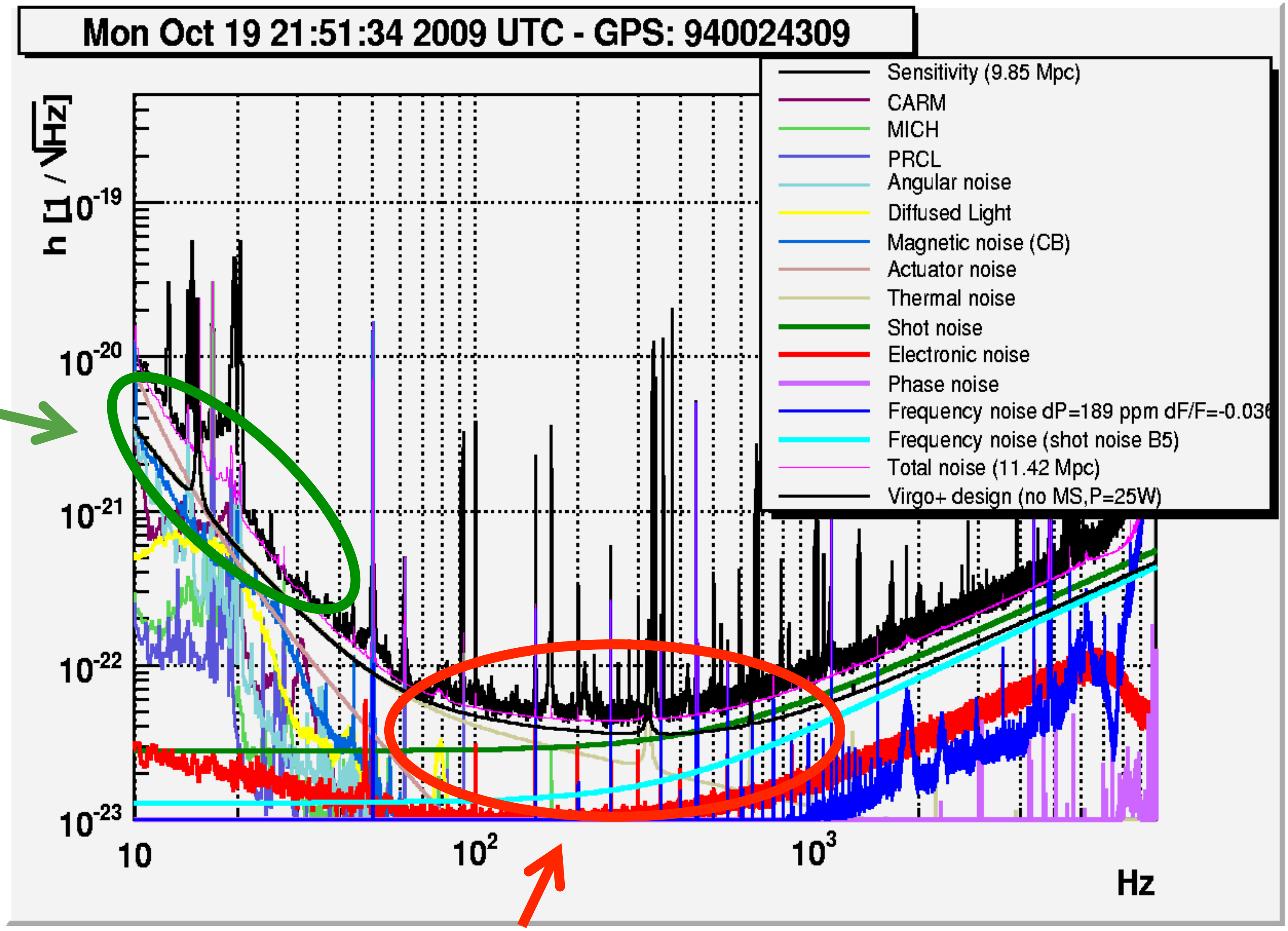
"Enhanced LIGO" (July 2009 – Oct 2010)



Virgo sensitivity in VSR2 (part of LIGO S6)

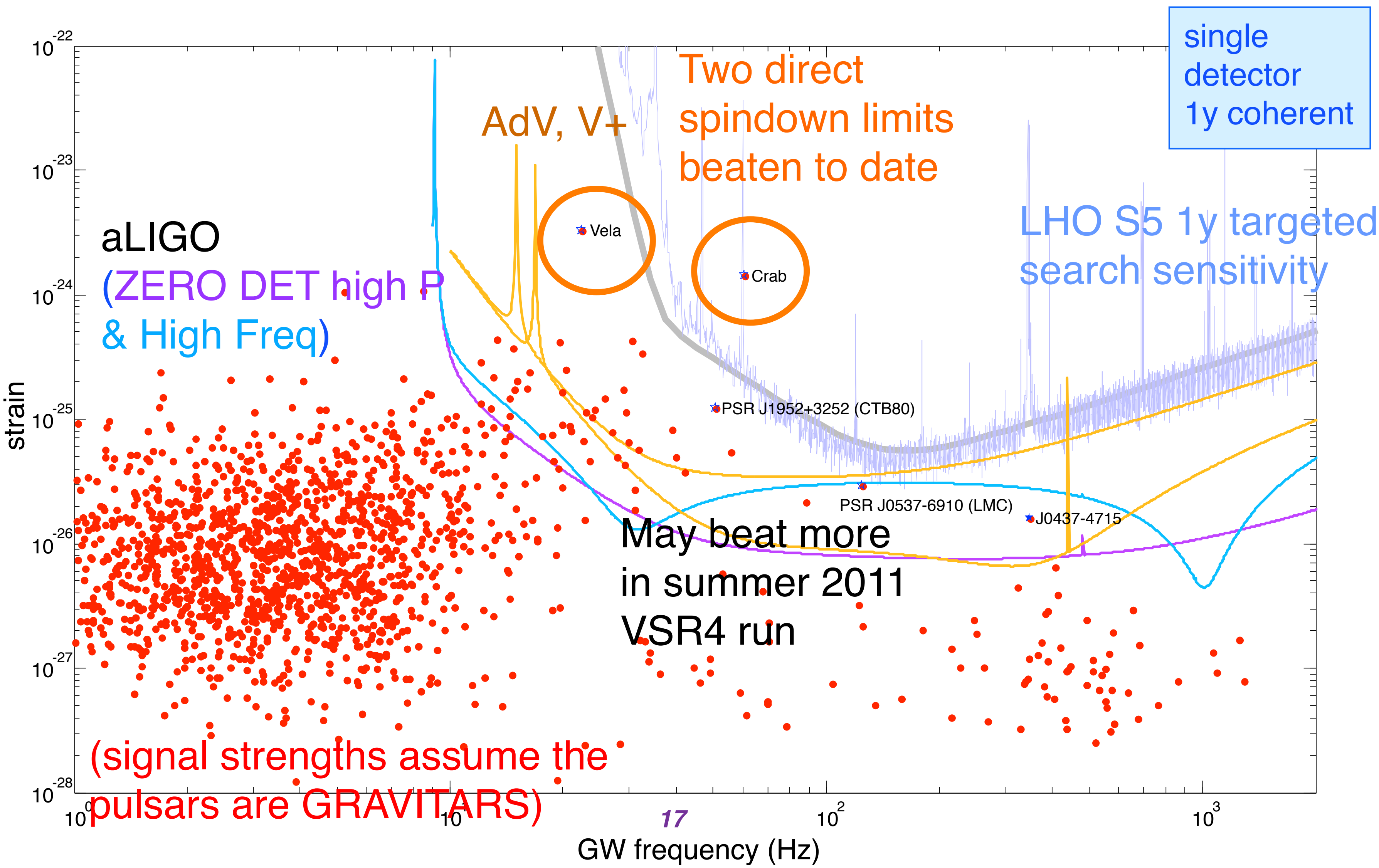
≥10^5 × better than LIGO below 40 Hz!

Enabled search for Vela at 22 Hz



Comparable to LIGO in sweet spot

Translating strain amplitude spectral noise densities into source amplitudes
→ Assumes targeted search for 1 year – see Graham Woan's talk
(all-sky search ~30 times higher)



Recent results

Targeted (matched-filter) algorithm applied to 116 known pulsars over 23 months of S5 (see Woan talk)

Vela - VSR2
(arXiv 1104.2712)

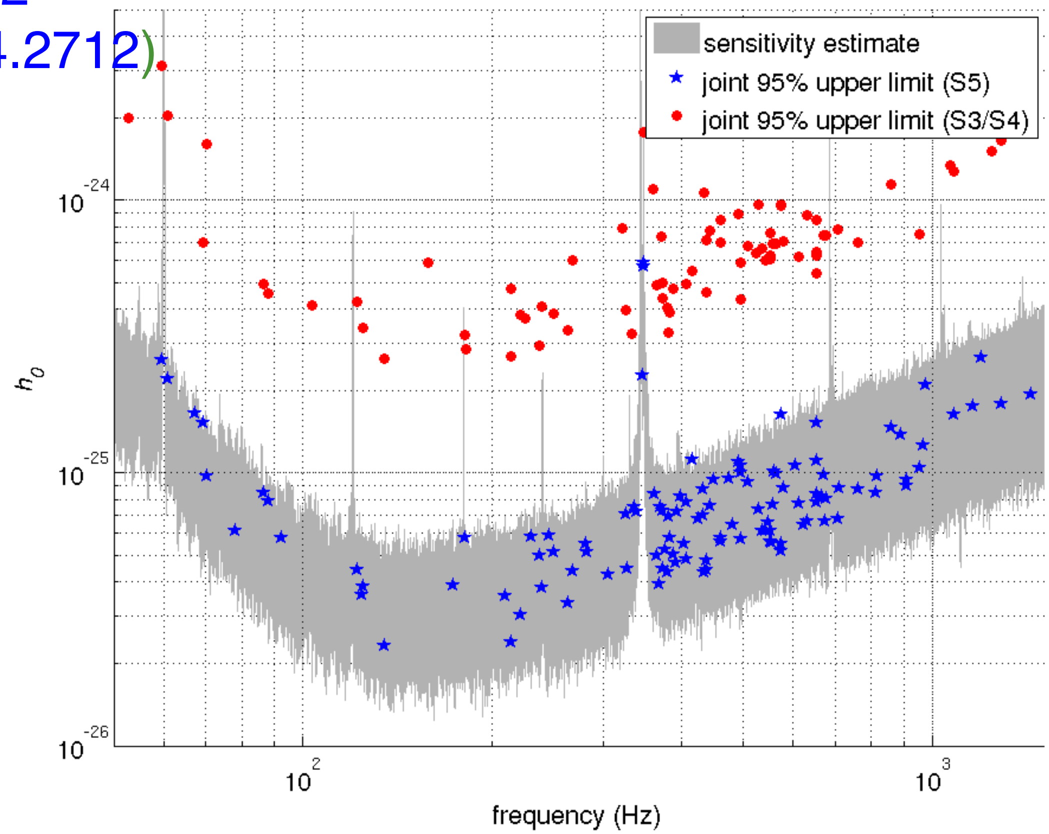
Lowest upper limit on strain:

$h_0 < 2.3 \times 10^{-26}$

Lowest upper limit on ellipticity:

$\varepsilon < 7 \times 10^{-8}$

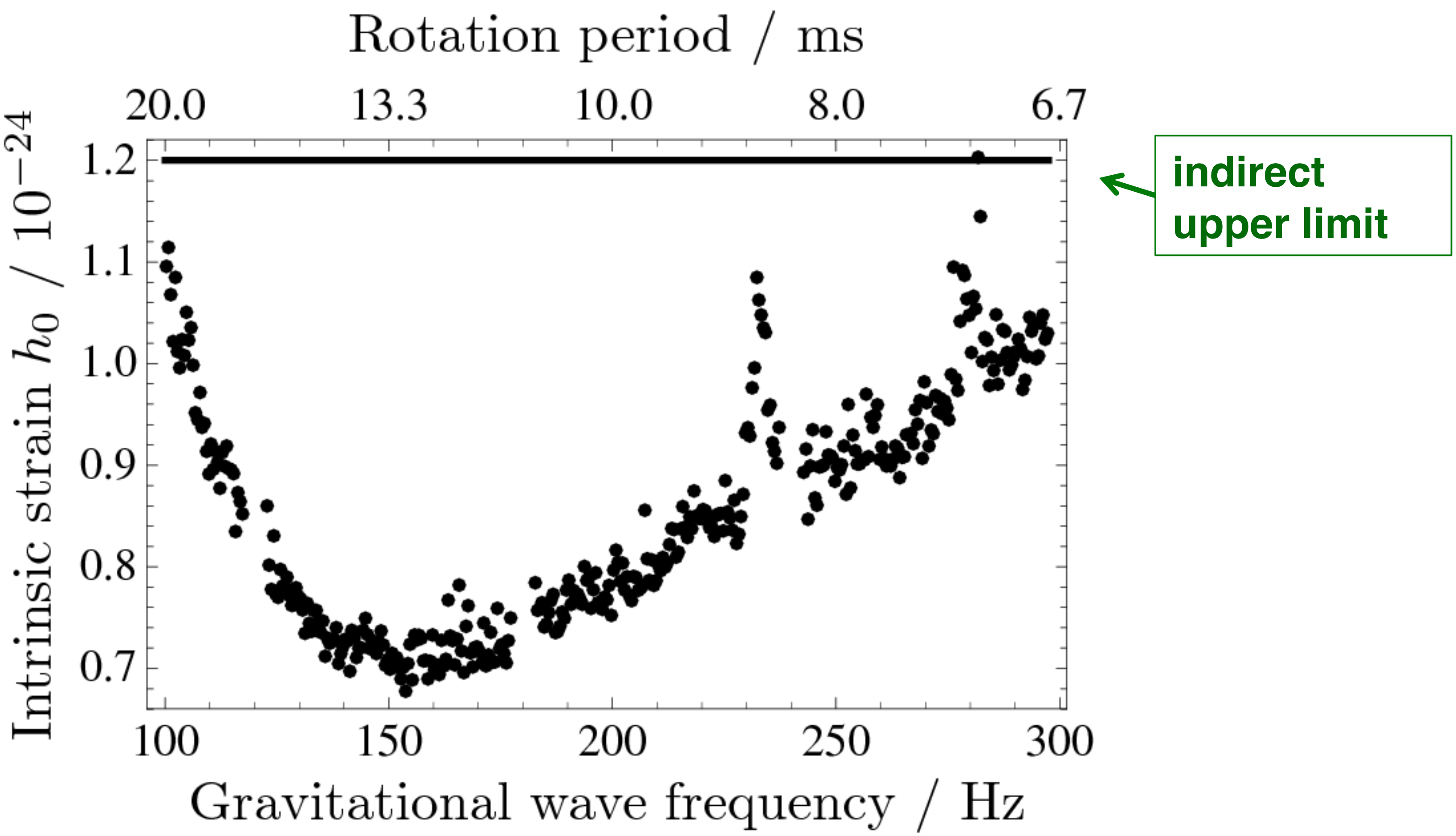
Crab limit at 2% of total energy loss



Ap. J. 713 (2010) 671

Recent results

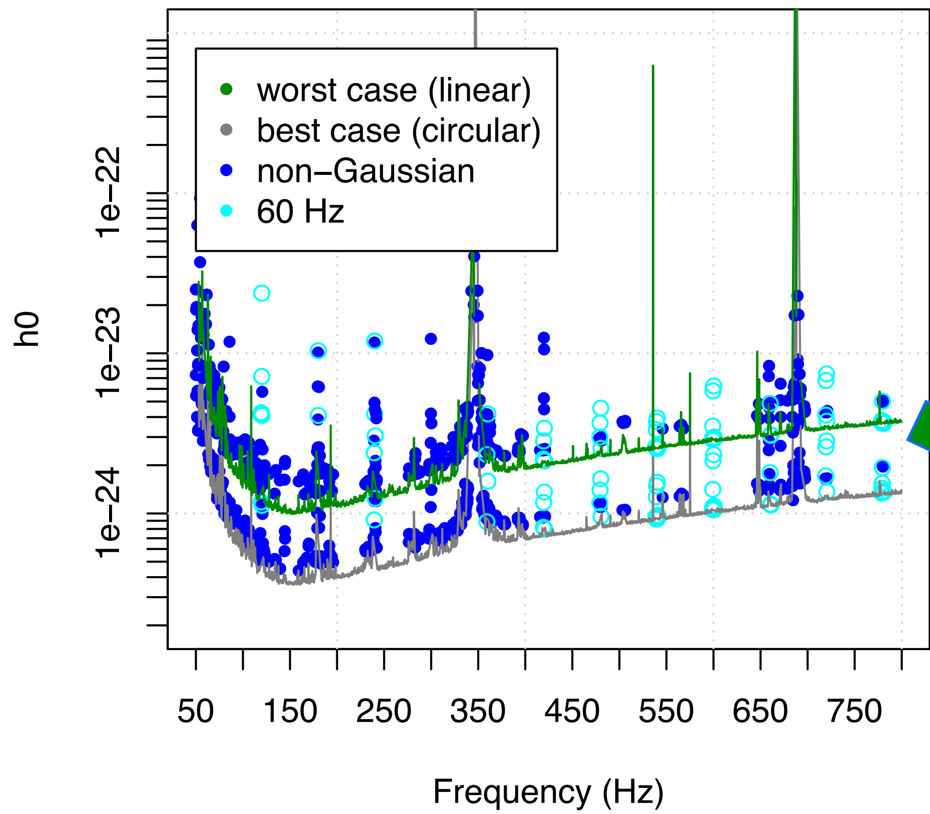
Search for Cassiopeia A – Young age (~300 years) requires search over 2nd derivative (see Ben Owen's 2nd talk)



Ap. J. 722 (2010) 1504

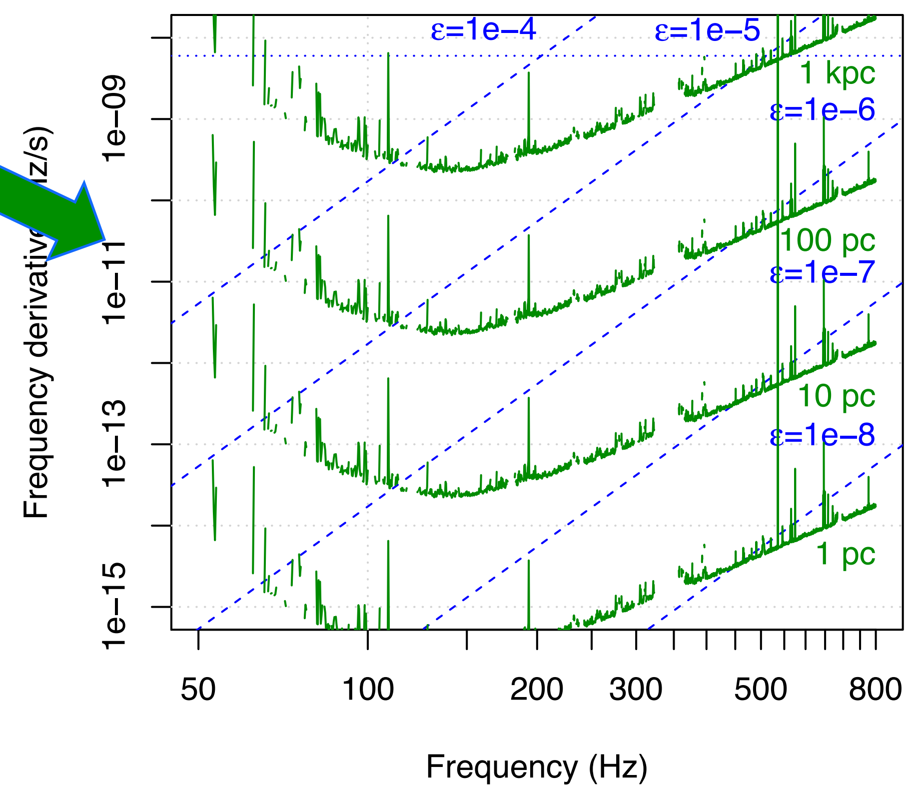
Recent results

Latest S5 all-sky results (preliminary)



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

Astrophysical reach (preliminary)



The upcoming "Dark Ages"

Most LIGO-Virgo searches entering dark ages
– no new coincidence data until ~2015

But CW searches will continue on old data
- Strive to improve sensitivity of all-sky searches
- Still room for improvement despite many years of work

More directed searches (known locations, unknown frequency)
- Supernova remnants
- Globular clusters
- Westerlund 1
- Galactic center

(see Ben Owen's 2nd talk)

Pursue narrowband searches for known pulsars, allowing mismatch of electromagnetic / gravitational wave emission
(see Ian Jones' talk)

The upcoming "Dark Ages"

More directed searches for LMXB's (e.g., Sco x-1)
– Several phase-robust algorithms in use or development
(see talks by Deepto Chakrabarty, Chris Messenger, Duncan Galloway)

All-sky searches for binaries (2 algorithms nearing maturity)

Expand LVC repertoire of post-glitch "long transient" searches
(see James Clark talk)

Some questions on our minds

What are plausible mechanisms for CW generation?
(see talks by Ben Owen, Madappa Prakash)

Directed searches:
- Which directed searches should get highest priority?
- Are we missing some promising sources?
(see talks by Ben Owen, Bob Rutledge, Scott Ransom)

Narrowband search – What is a reasonable EM/GW mismatch?
(see talk by Ian Jones)

All-sky searches:
- Should we modify all-sky searches (e.g., favor galactic plane, spiral arms)?
-What are prospects for discovery (outlier statistics)
(see talk by David Kaplan)

Some questions on our minds

Can LMXB parameters be improved?
- Better orbital parameters?
- Pulsations? **(!)**

(see talks by Chakrabarty. Duncan Galloway)

All-sky binary searches:
- What frequencies, orbital periods, modulation depths to favor?

Other questions for today

Will pulsar timing arrays find gravitational waves first? Are systematic timing uncertainties understood well enough?
(see talk by Paul Demorest)

What other General Relativity tests can be done with pulsars?
(see talk by Norbert Wex)

Leaving a record of the workshop

Slides will be stored permanently on the workshop wiki

Audio of the talks and discussion will be recorded via the EVO and also stored on the wiki

Everyone is welcome to upload auxiliary material to the wiki:
- Other relevant presentations
- Articles
- Impromptu notes or calculations
- Comments on material presented today

→ Upload as attachments to program wiki page:

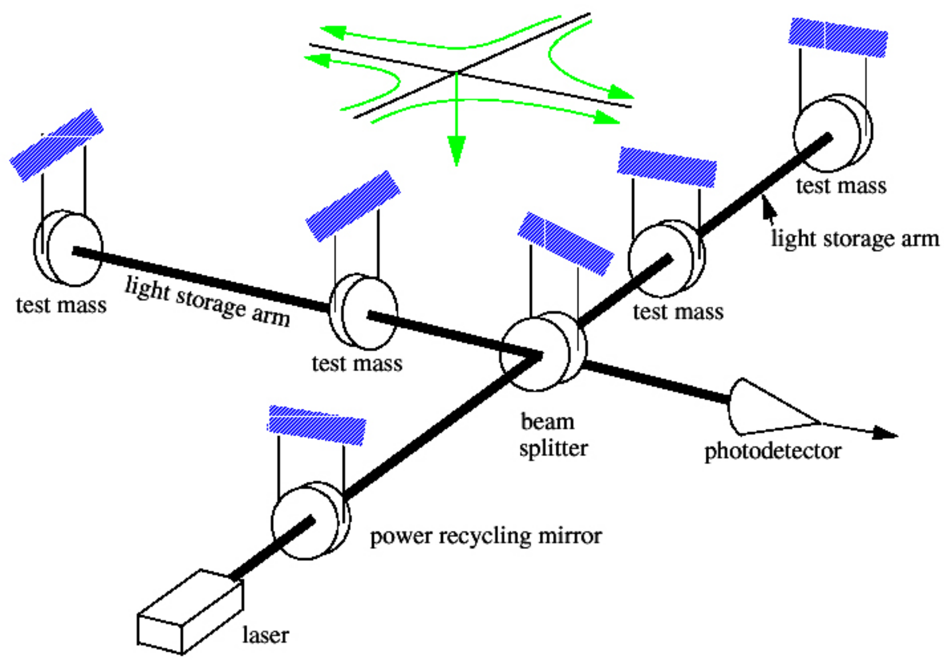
https://guest.ligo.org/foswiki/bin/view/NSWorkshop2011/MeetingProgram

Thanks for coming!

Extra Slides

Gravitational Wave Detection

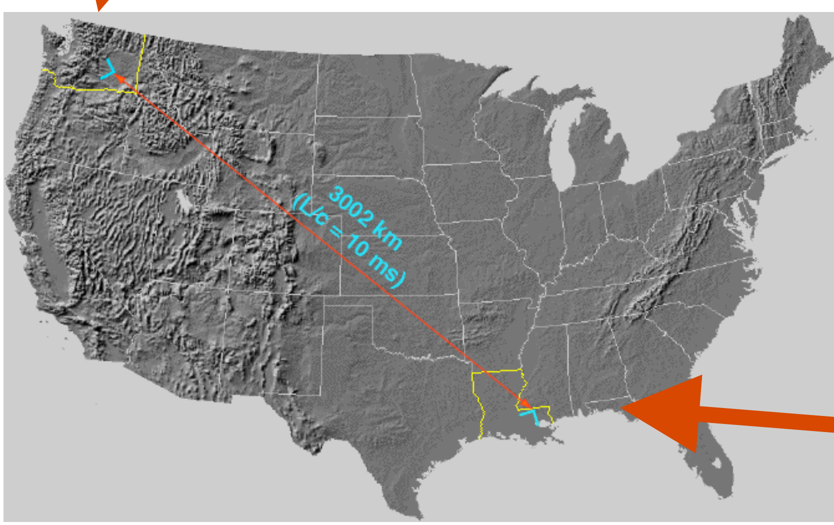
- Suspended Interferometers (IFO's)
  - **Suspended mirrors in "free-fall"**
  - **Michelson IFO is "natural" GW detector**
  - **Broad-band response (~20 Hz to few kHz)**
  - **→ Waveform information (e.g., chirp reconstruction)**



LIGO 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

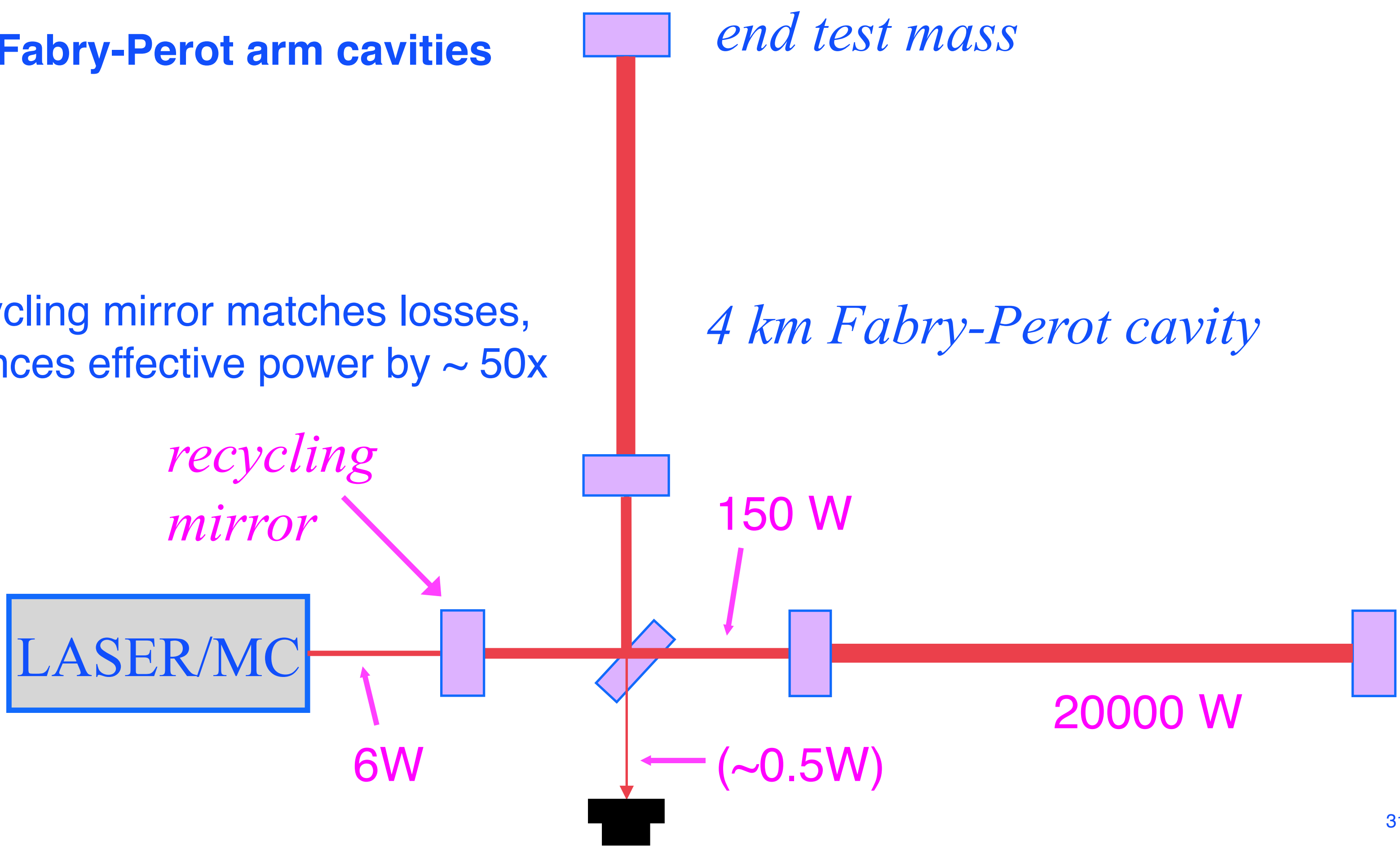
3-km Michelson Interferometer just outside Pisa, Italy

LIGO Interferometer Optical Scheme

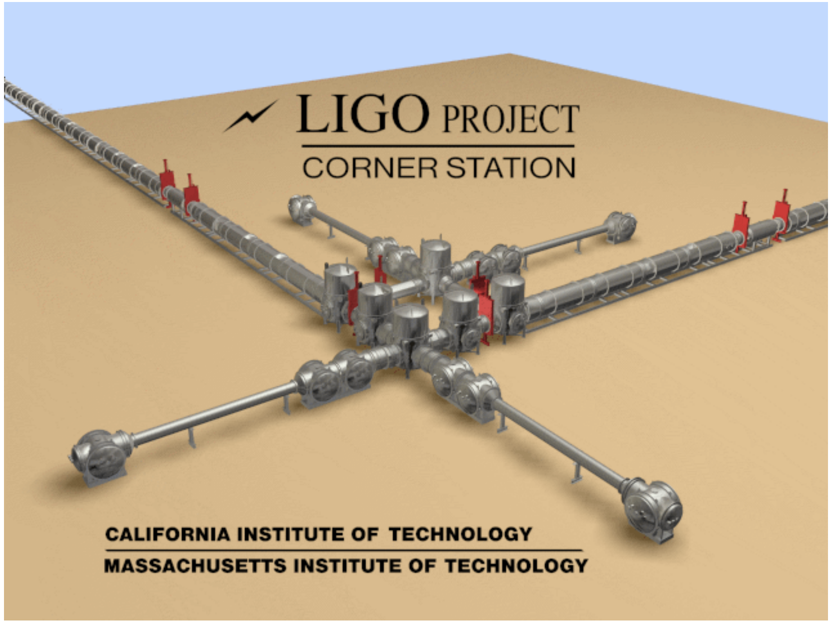
Michelson interferometer

With Fabry-Perot arm cavities

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



LIGO Detector Facilities



•Stainless-steel tubes

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

•Gate valves for optics isolation

•Protected by concrete enclosure

Vacuum System

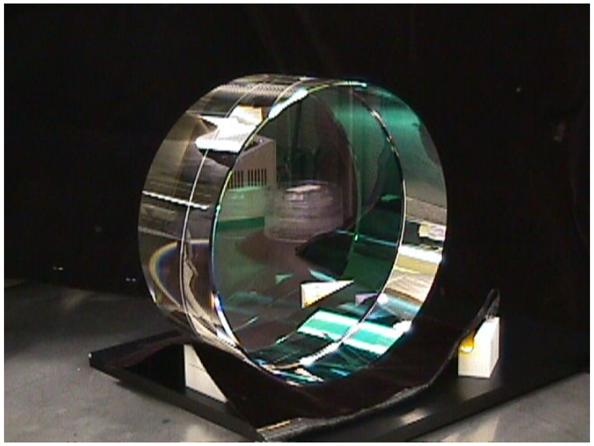
LIGO Detector Facilities

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

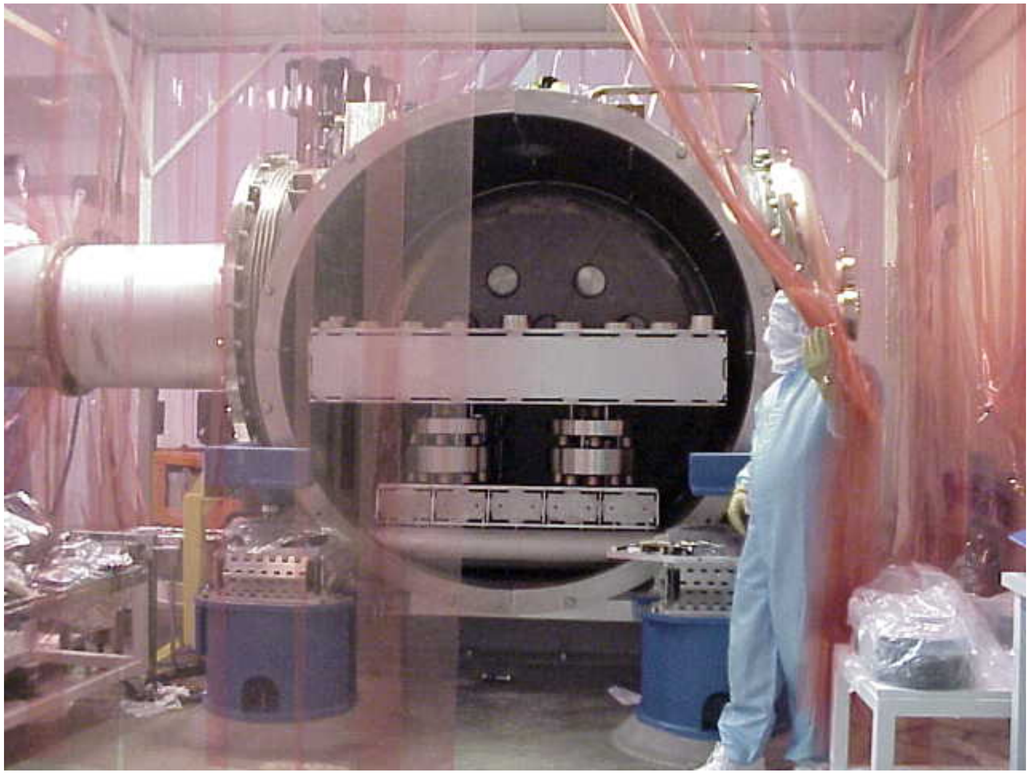
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

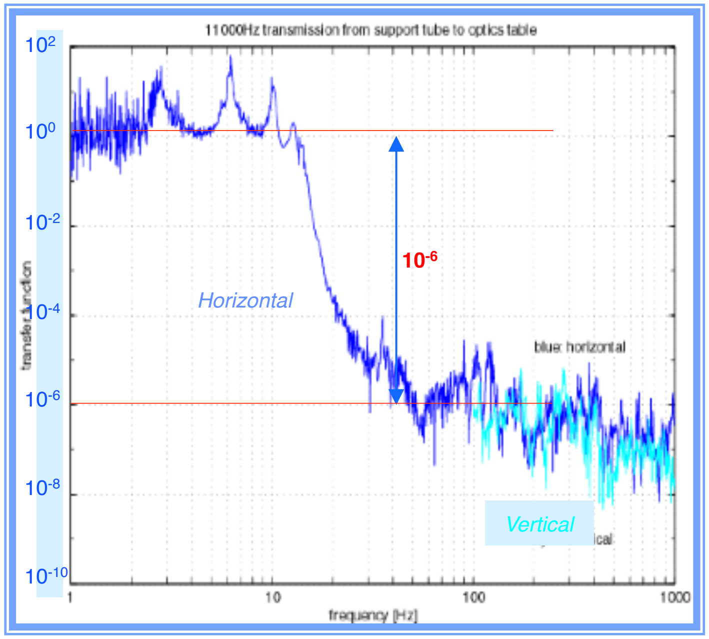


LIGO Detector Facilities

Seismic Isolation

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



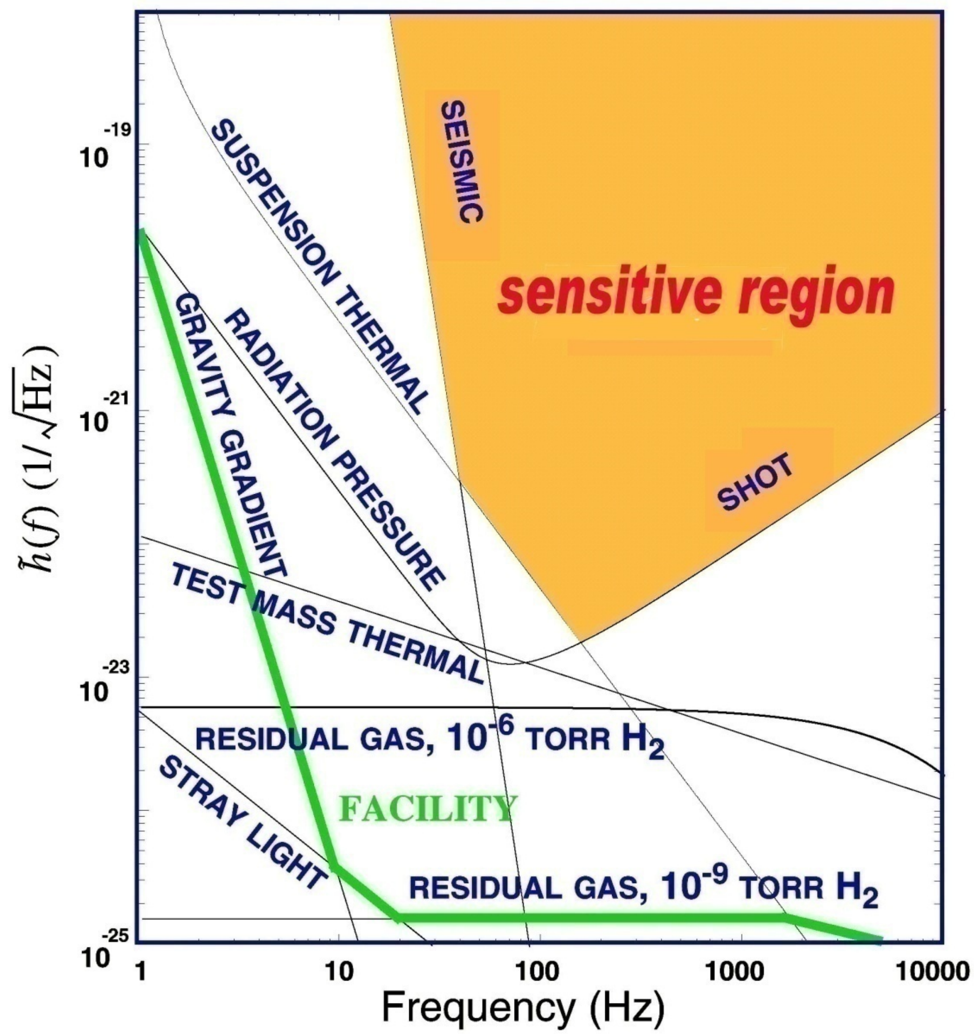


What Limits the Sensitivity of the Interferometers?

- 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



“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)

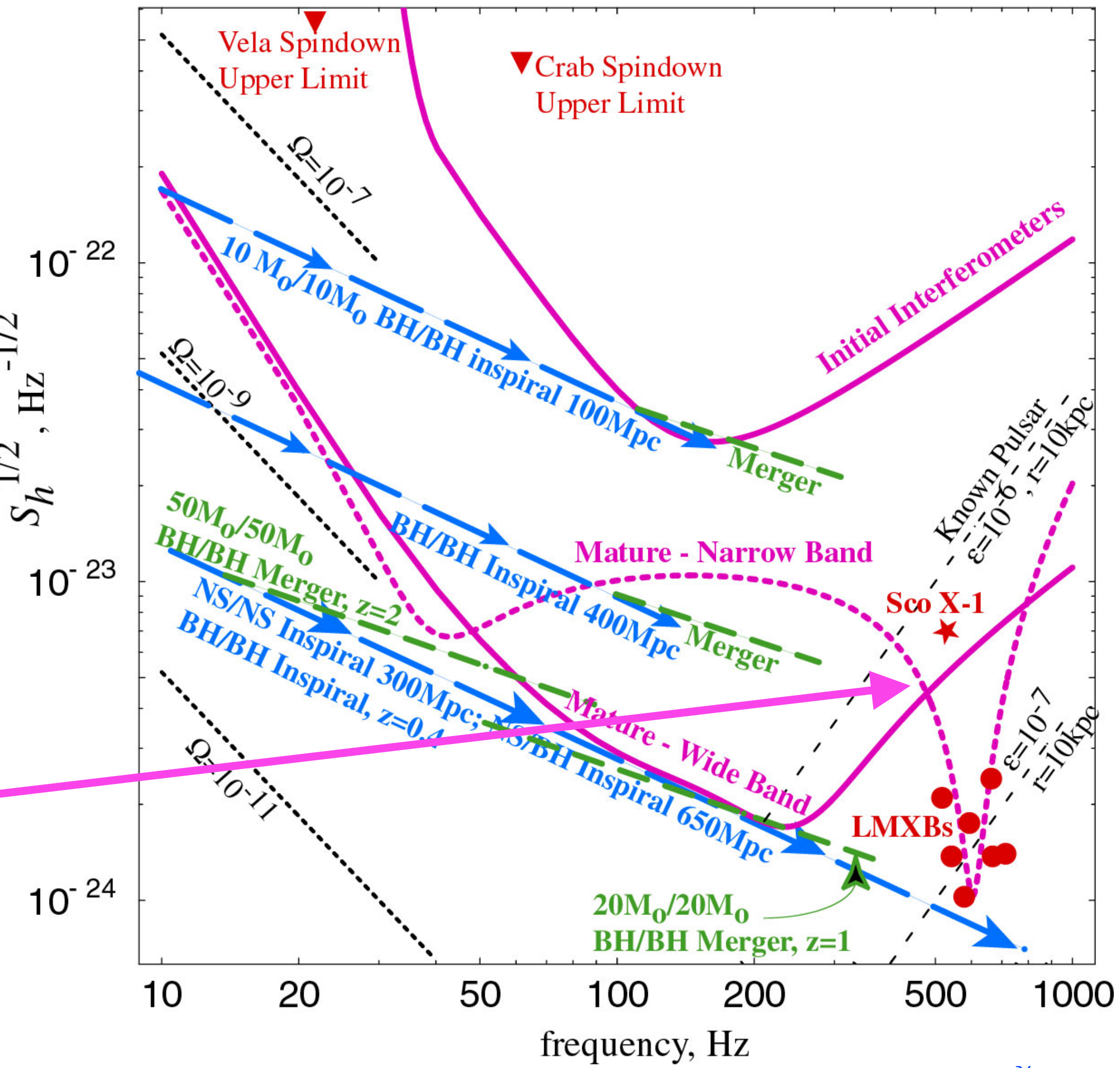
And need to stabilize laser (intensity & frequency), keep the beam pointed, damp out seismic noise, correct for tides, etc.,…

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)

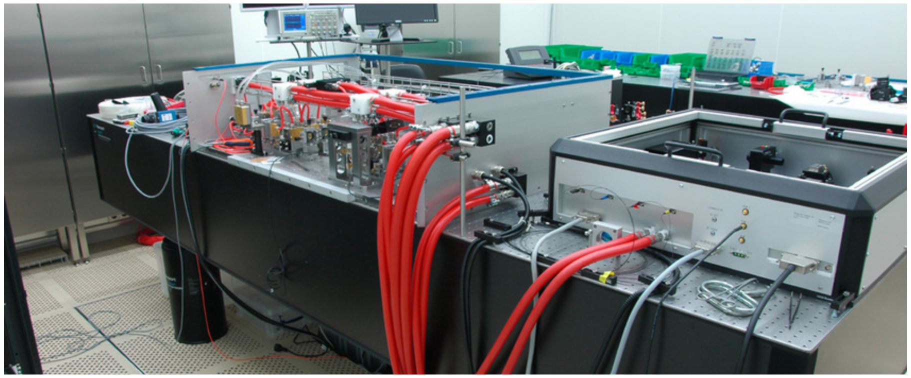


Advanced LIGO

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

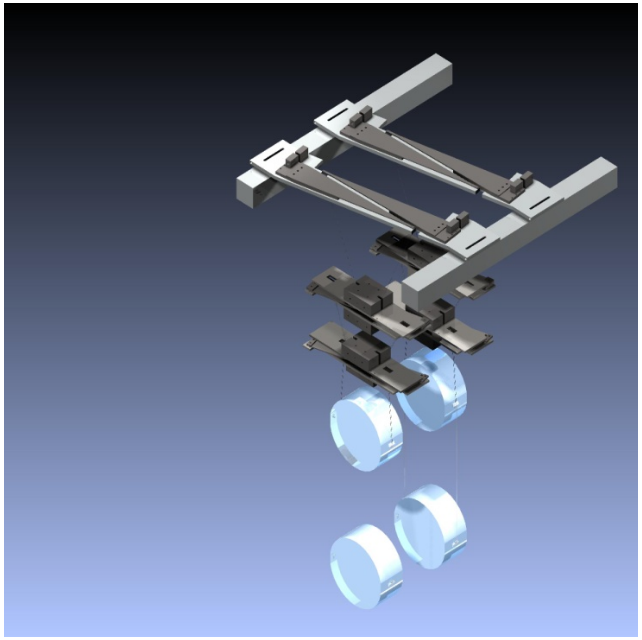
Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Advanced LIGO

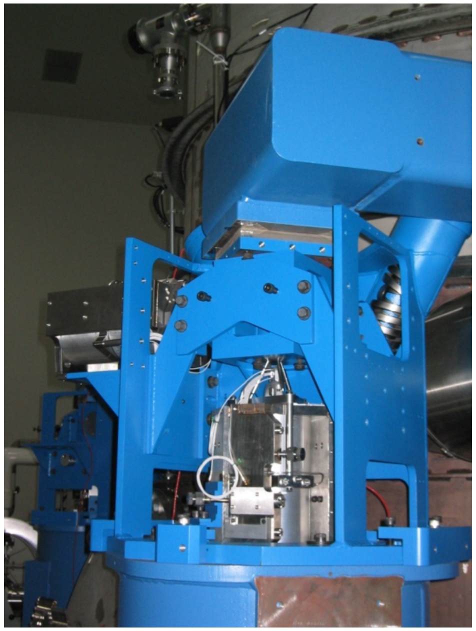
Detector Improvements:



New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth



Improved seismic isolation:

Passive → Active

Lowers seismic "wall" to ~10 Hz

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravit

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

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

Advanced LIGO

Increased laser power:

10 W → 180 W

Improved shot noise (high freq)

Higher-Q test mass:

Fused silica with better optical coatings

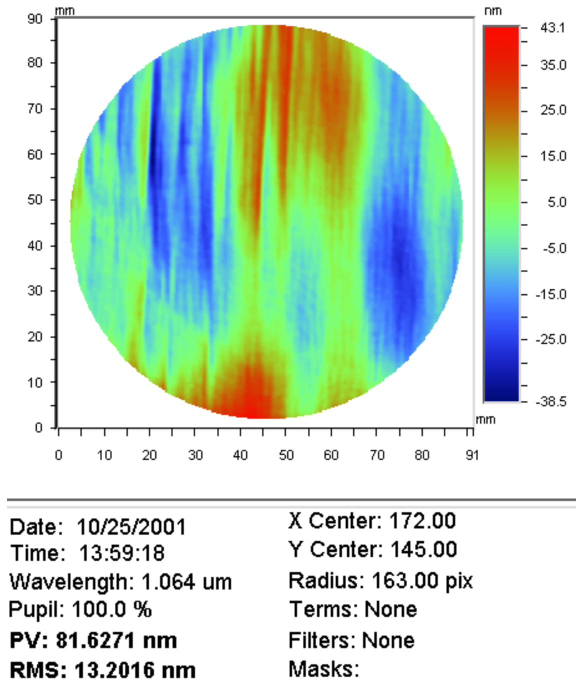
Lower internal thermal noise in bandwidth

Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Sapphire Optics



Advanced LIGO

Detector Improvements:

New suspensions:

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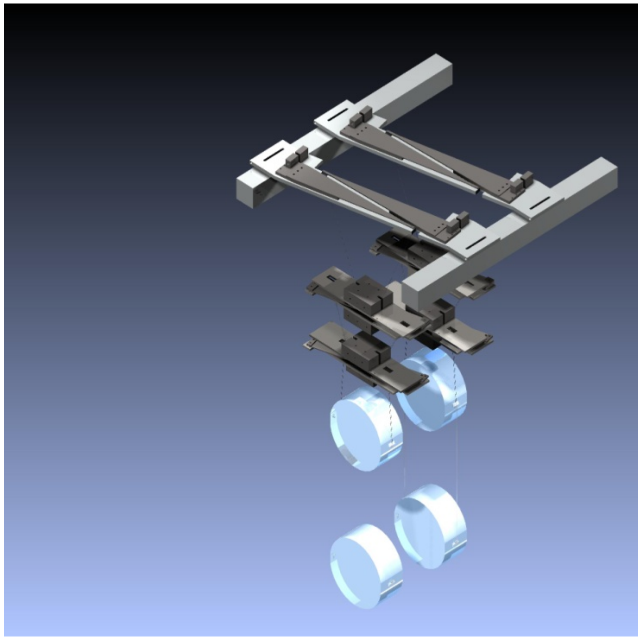
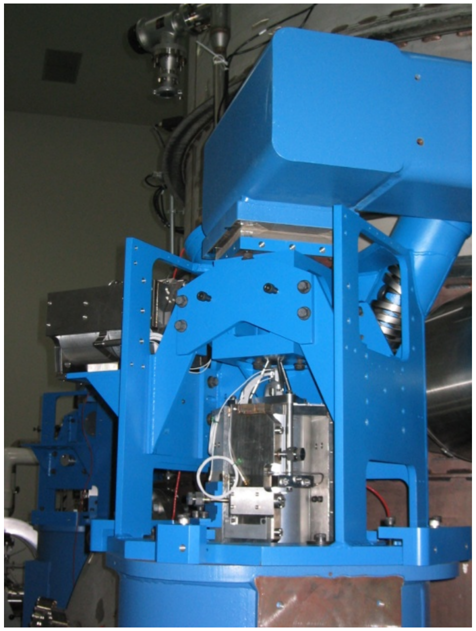
Lower suspensions thermal noise in bandwidth





Improved seismic isolation:

Passive → Active

Lowers seismic “wall” to ~10 Hz

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)

Recent results

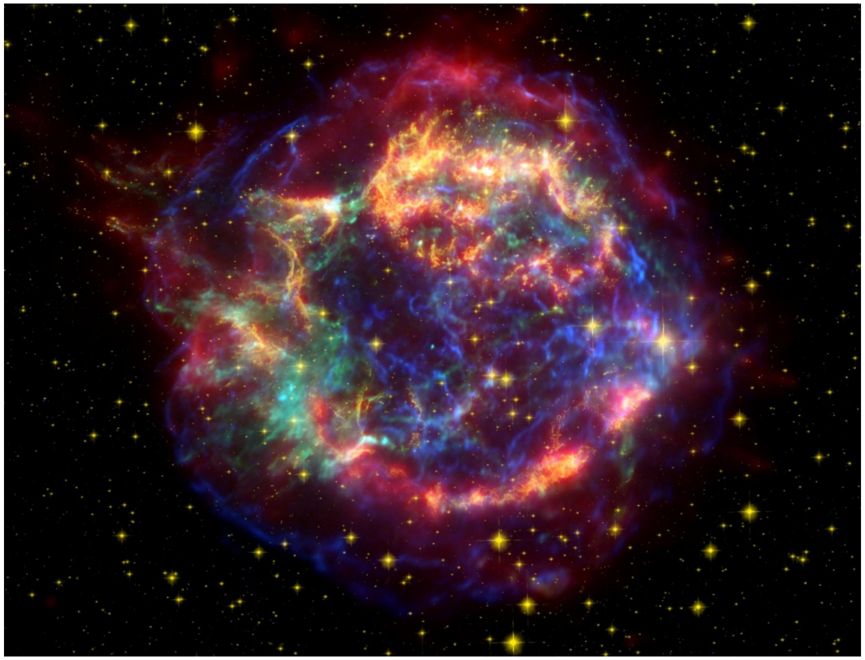
Not all known sources have measured timing

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

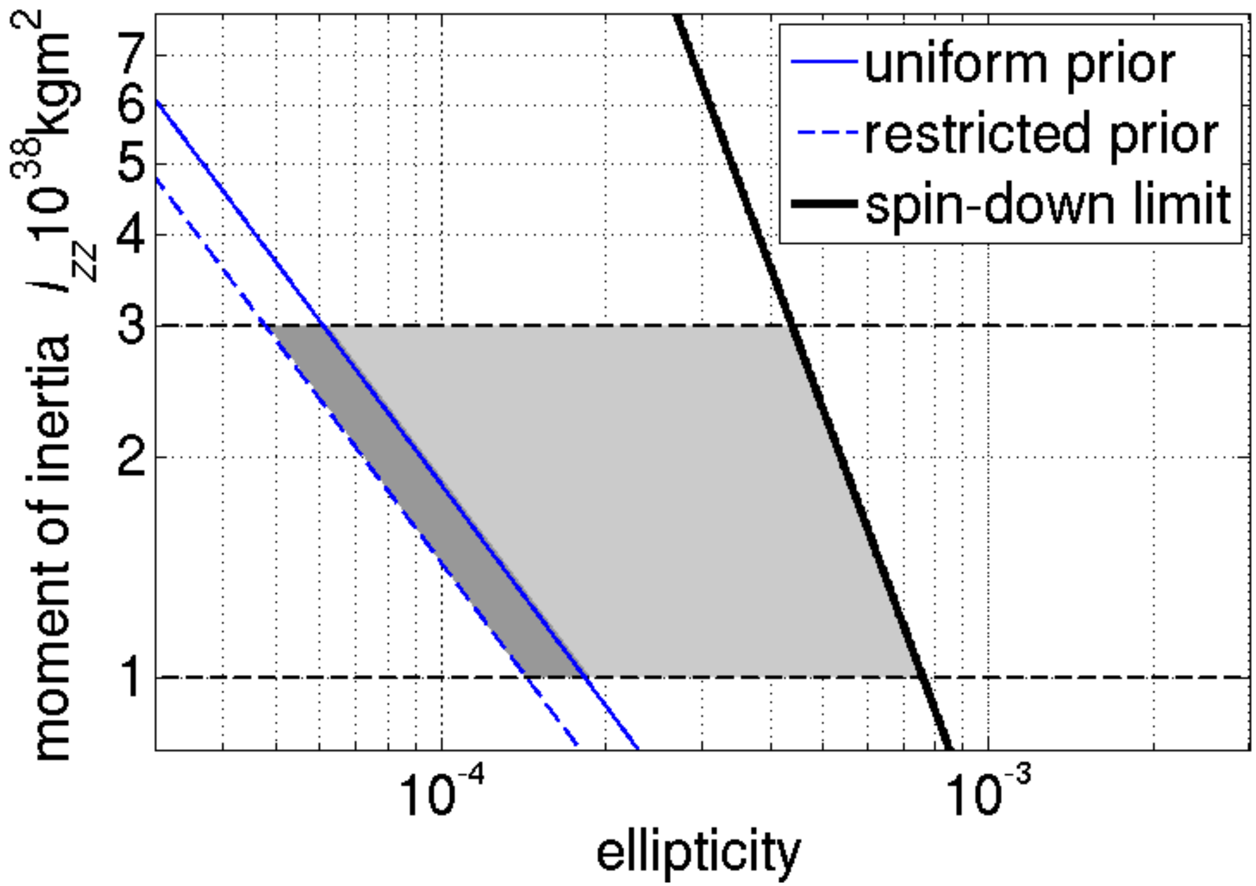


Cassiopeia A

Recent results

S5:

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

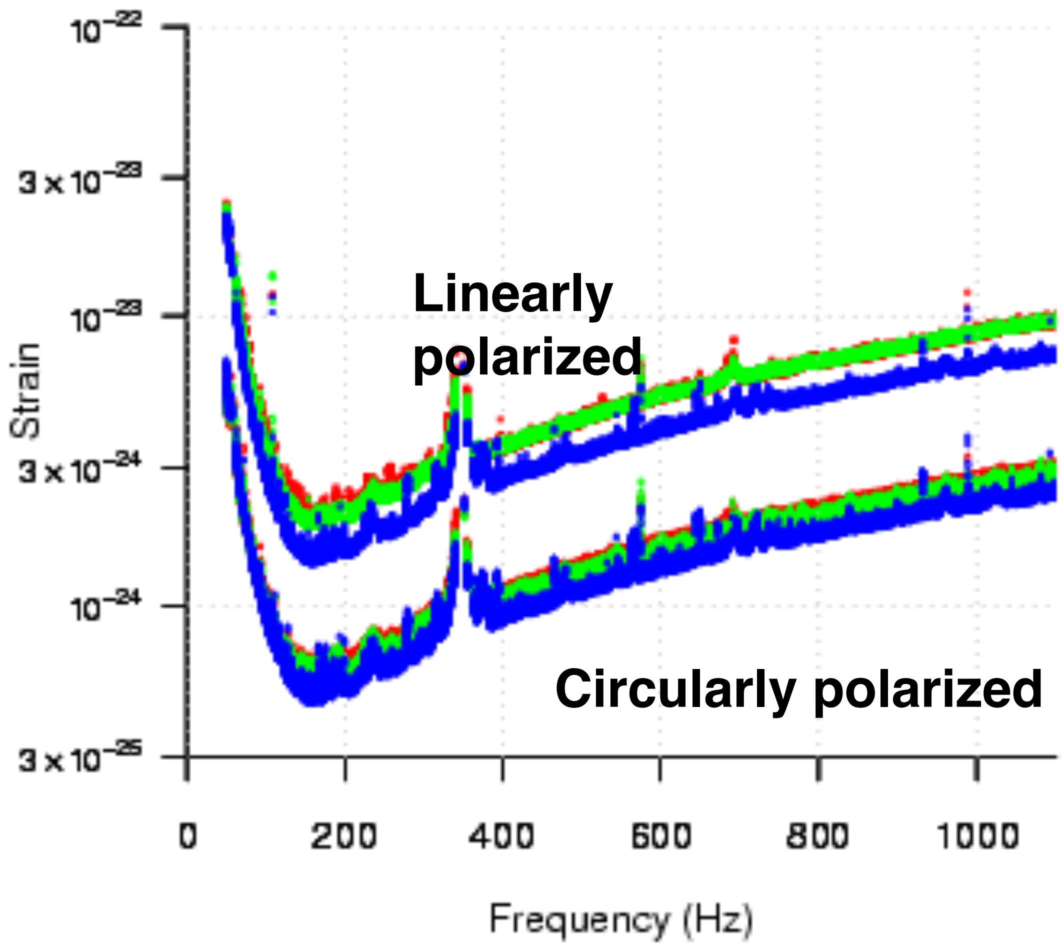


Strain limit:
2.7×10^{-25}

Spindown limit:
1.4×10^{-24}

Coherent,
9-month,
time-domain

Recent results



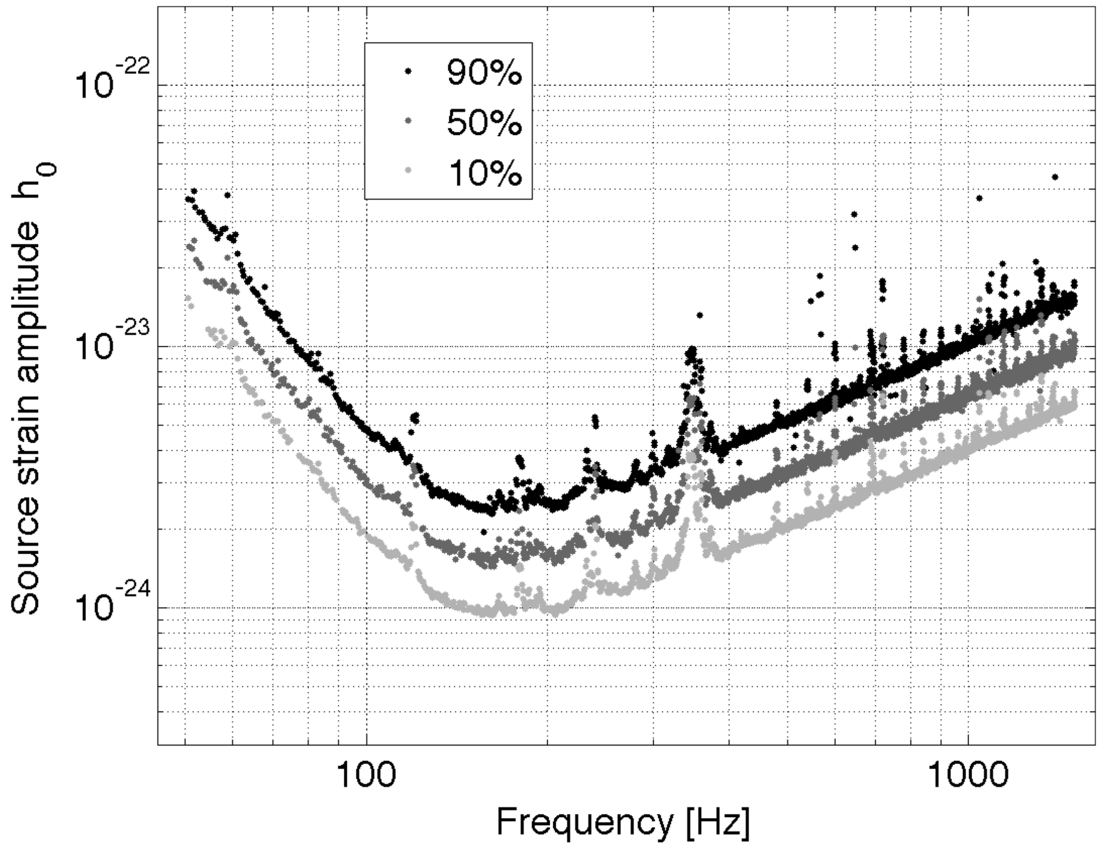
Phys. Rev. Lett. 102 (2009) 111102

All-sky search for unknown isolated neutron stars

Semi-coherent, stacks of 30-minute, demodulated power spectra

("PowerFlux")

Recent results



All-sky search for unknown isolated neutron stars

Coincidence among multiple 30-hour coherent searches

(Einstein@Home)

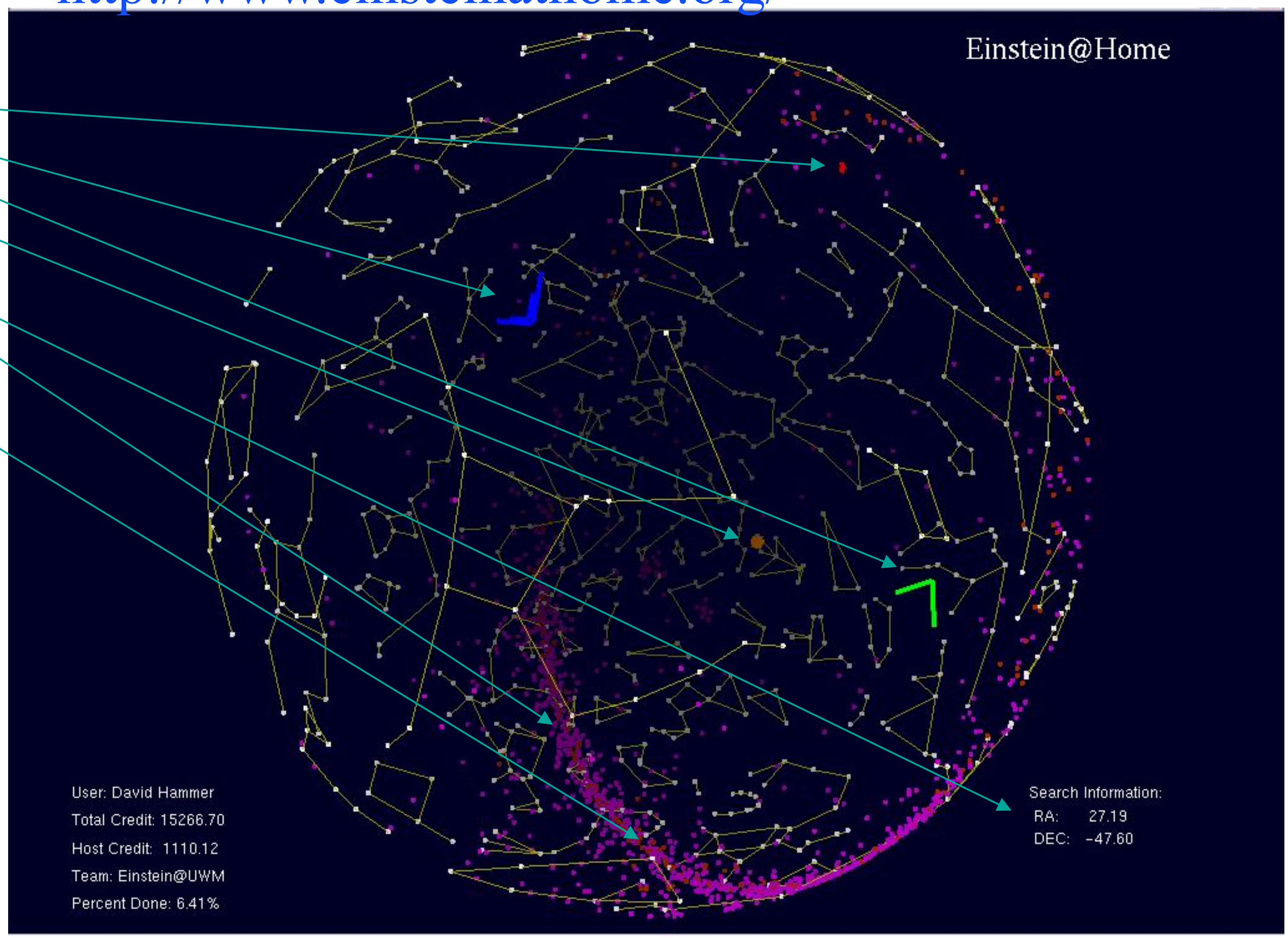
Phys. Rev. D 80 (2009) 042003

http://www.einsteinathome.org/

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

Improved (hierarchical) algorithm now running

Your computer can help too!



Searching for continuous waves

What defines separation between two "points" in the sky?

Distinct frequency bins

→ Need $\Delta\theta \times v_{orb}/c \times 1$ kHz $<$ 0.03 μHz

→ $\Delta\theta$ ~ 0.3 μrad

→ Need to search ~ 10^{14} points on the sky

Also need to search over at least one spindown derivative

→ Need to keep cumulative phase error over 1 year < 0.5 radian

→ For maximum spindown of 10^{-9} Hz/s, need ~10^{6} spindown steps

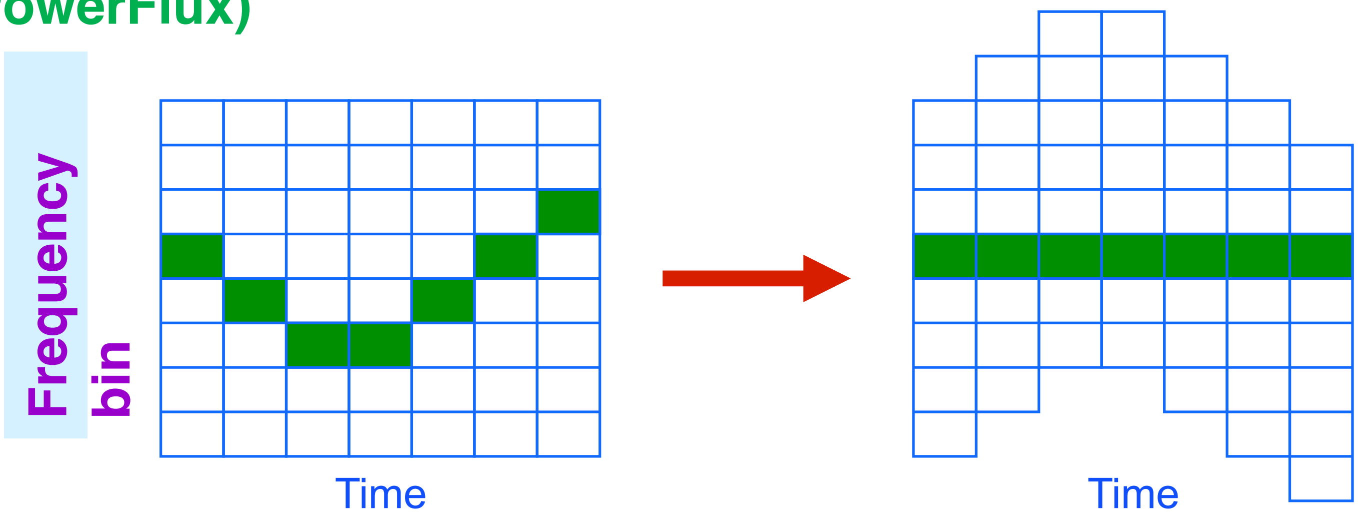
Searching a 1-Hz band at 1 kHz requires ~$10^{14} \times 10^{7} \times 10^{6}$ ~ 10^{27} templates,

→ Not enough computers in our part of the string landscape to do this

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)**