LIGO & VIRGO Continuous Wave Searches

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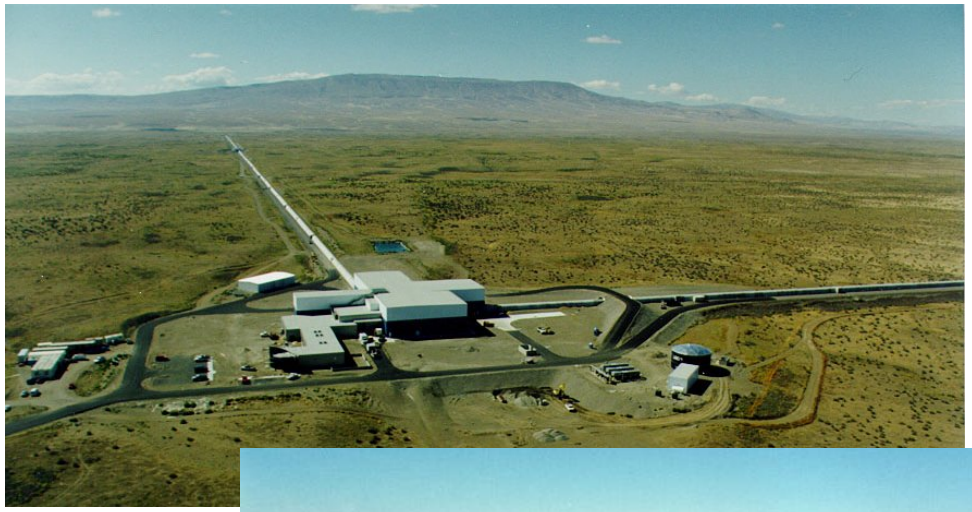
LIGO-Virgo Collaboration

Workshop on Probing Neutron Stars with Gravitational Waves

Pennsylvania State University

June 18, 2009



LIGO-G0900???

Nature of Gravitational Waves

- Gravitational Waves = “Ripples in space-time”

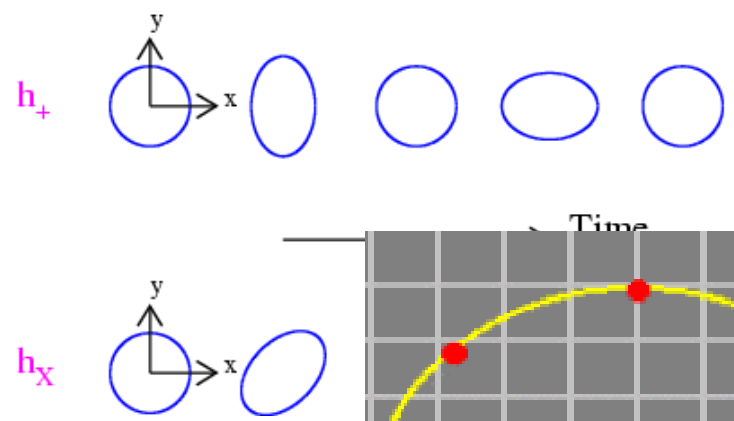
- Perturbation propagation similar to light (obeys same wave equation!)
  - **Propagation speed = c**
  - **Two transverse polarizations** - **<u>quadrupolar</u>**: + and x

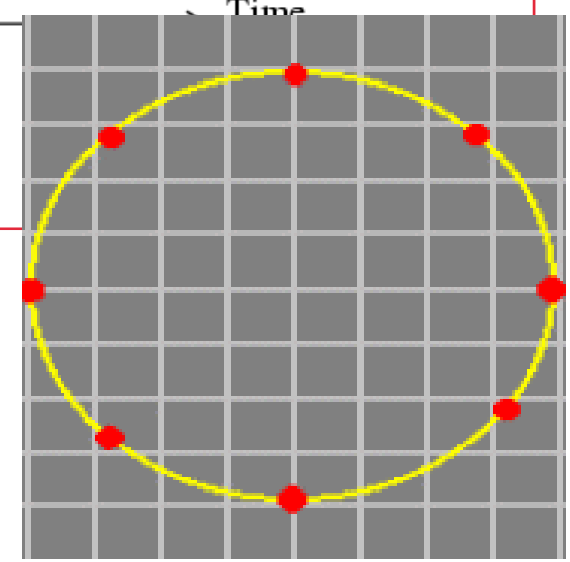
Example:

Ring of test masses

responding to wave

propagating along z





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

Generation of Gravitational Waves

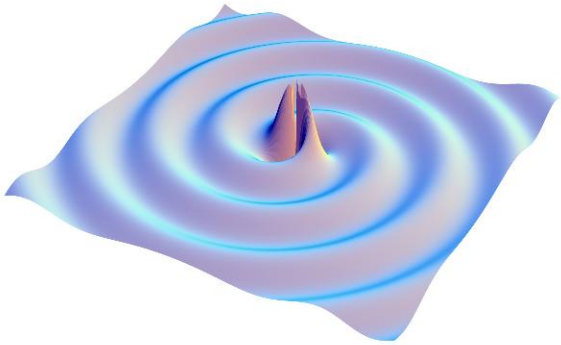
- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

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

- Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$

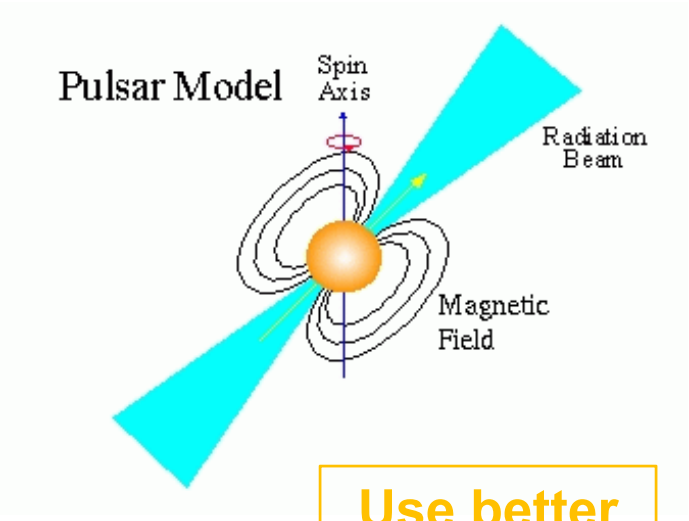


Generation of Gravitational Waves

Another quadrupole GW radiator: Spinning neutron star

Less dramatic, but still interesting(!)

Much weaker, but also much closer



Use better picture

Note:

Axisymmetric object rotating about symmetry axis generates NO radiation

Need an asymmetry or perturbation

Gravitational CW emission mechanisms

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

$$h \;\; \alpha \;\; \varepsilon_{equat}$$

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

$$h \;\; \alpha \;\; \varepsilon_{pol} \times \Theta_{wobble}$$

(precession due to different L and Ω axes)

- **r modes (Coriolis-driven instability): [add ref(s)]**

Assumption made to date:

Mountain is best bet for detection
→ Look for GW wave 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 the "direct spindown limit"?

It is useful to define the "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: **[add ref(s)]**

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

Example:

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

(d=2 kpc, f_{sig} = 59.6 Hz, $df_{sig}/dt = -7.4\times10^{-10}$ Hz/s)

Add Crab picture

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 [add ref(s)]

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

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: **[add ref(s)]**

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

Example:

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

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

Add Sco X-1 picture

Finding a new 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 3 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 new unknown CW Source

Modulations / drifts complicate analysis enormously:

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

→ All-sky survey at full sensitivity = Formidable challenge

Impossible?

Computational scaling: **[add ref(s)]**

Single coherence time -- Cost $\propto$ $(T_{coherence})^{6+}$

→ 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 $(N_{stack})^{1/4}$

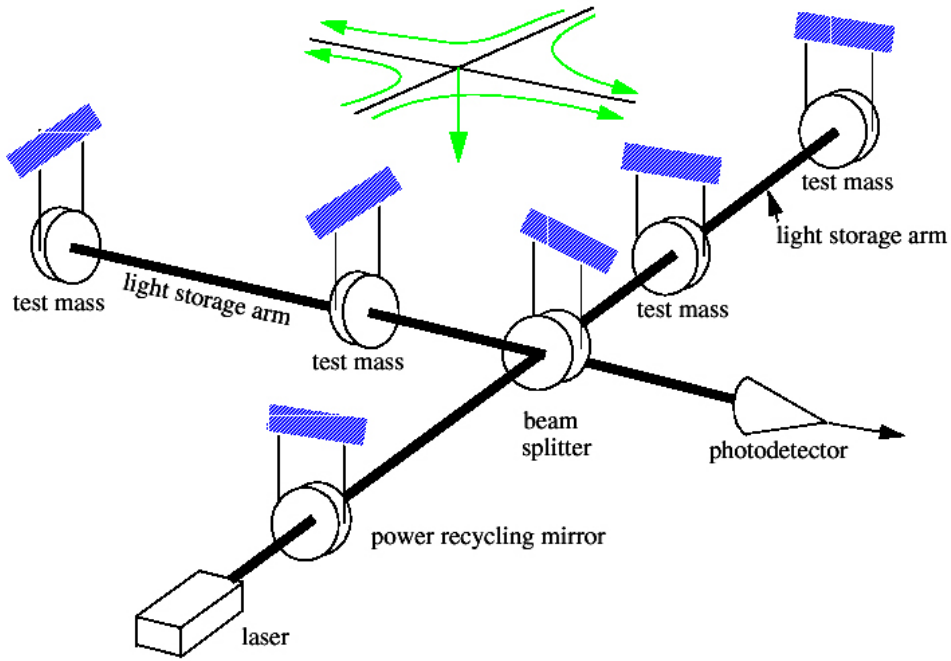
But three substantial benefits from modulations:

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

Add PowerFlux skymap showing localization of hardware injection

Gravitational Wave Detection

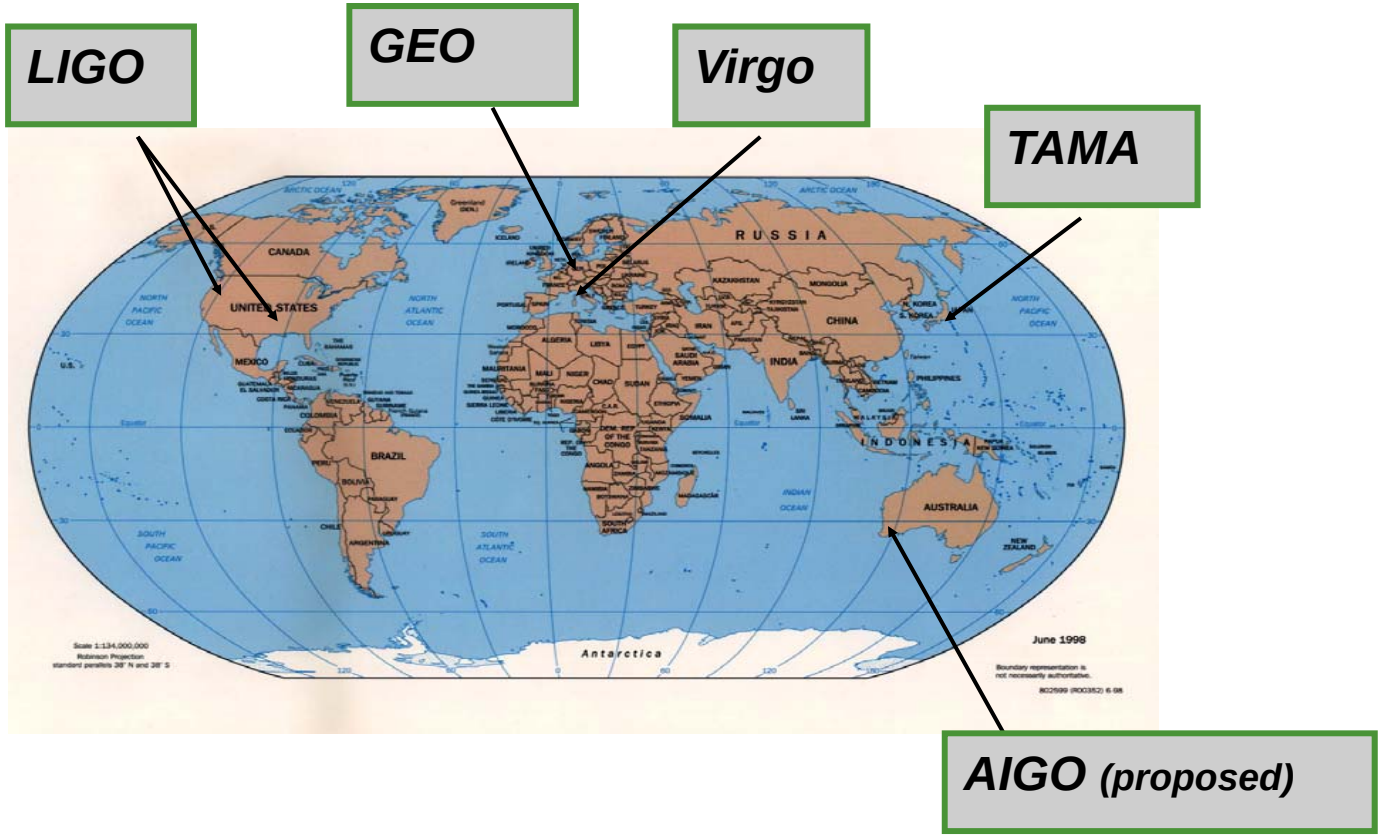
- Suspended Interferometers (IFO's)
  - **Suspended mirrors in "free-fall"**
  - **Michelson IFO is "natural" GW detector**
  - **Broad-band response (~50 Hz to few kHz)**
  - **→ Waveform information (e.g., chirp reconstruction)**



The Global Interferometer Network

The three LIGO, Virgo and GEO interferometers are part of a forming Global Network.

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



Gravitational Wave Detection

Major Interferometers world-wide

LIGO Livingston, Louisiana & Hanford, Washington	2 x 4000-m (1 x 2000-m)	Completed 2-year data run at design sensitivity – "enhancement" finishing
VIRGO Near Pisa, Italy	1 x 3000-m	Took ~4 months coincident data with LIGO – approaching design sensitivity
GEO Near Hannover, Germany	1 x 600-m	Took data during L-V downtime, about to undergo upgrade
TAMA Tokyo, Japan	1 x 300-m	Used for R&D aimed at future underground detector

Data Runs

Have carried out a series of Engineering Runs (E1–E14) and Science Runs (S1--S5) interspersed with commissioning

S1 run:

17 days (Aug / Sept 2002) – Rough but good practice

S2 run:

59 days (Feb—April 2003) – Many good results

S3 run:

70 days (Oct 2003 – Jan 2004) -- Ragged

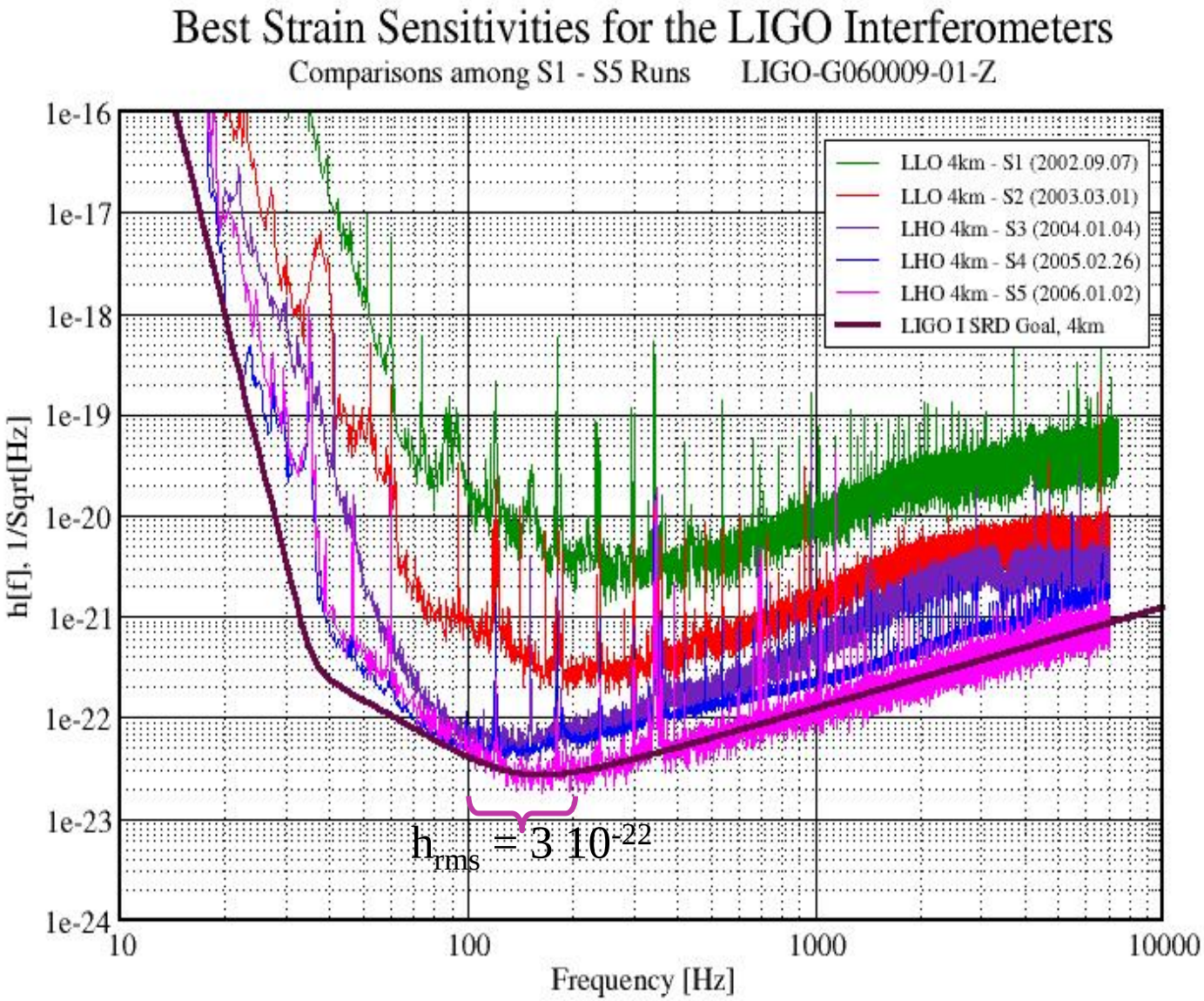
S4 run:

30 days (Feb—March 2005) – Another good run

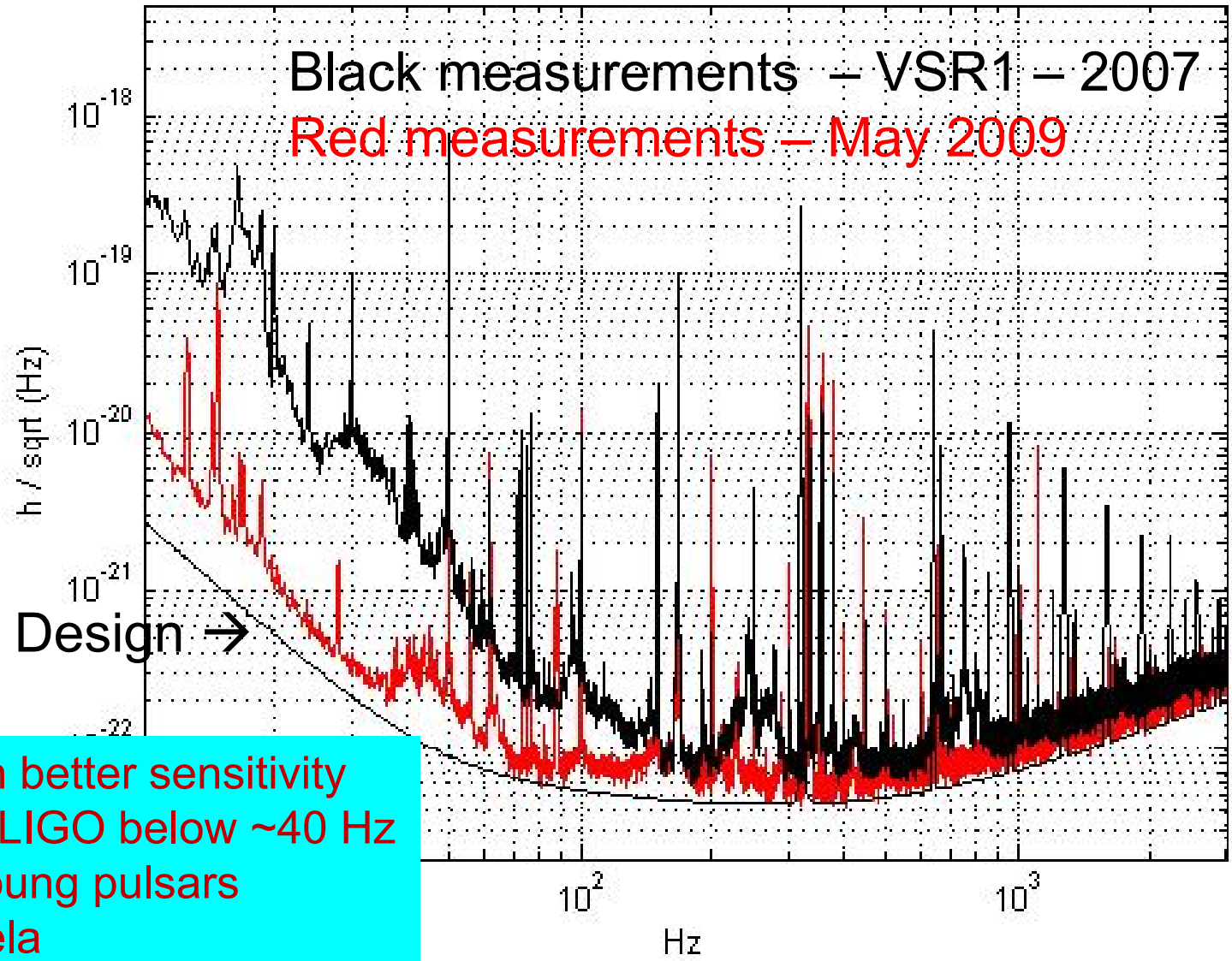
S5 run: (VSR1 for Virgo)

23 months (Nov 2005 – Sept 2007) – Great! (but no detection yet ☹)

LIGO S1 → S5 Sensitivities



Virgo Sensitivities



Much better sensitivity than LIGO below ~40 Hz
→ Young pulsars
→ Vela

Looking Ahead

Both LIGO and Virgo have undergone significant upgrades since last science run:

Initial LIGO → "Enhanced LIGO"

Initial Virgo → "Virgo +"

Data taking resumes <u>next month</u> with significant commissioning breaks scheduled to fix noise sources that sustained running reveals

→ Running/commissioning strategy worked very well for LIGO in S5

→ Aiming at up to factor of two improvement in strain sensitivity

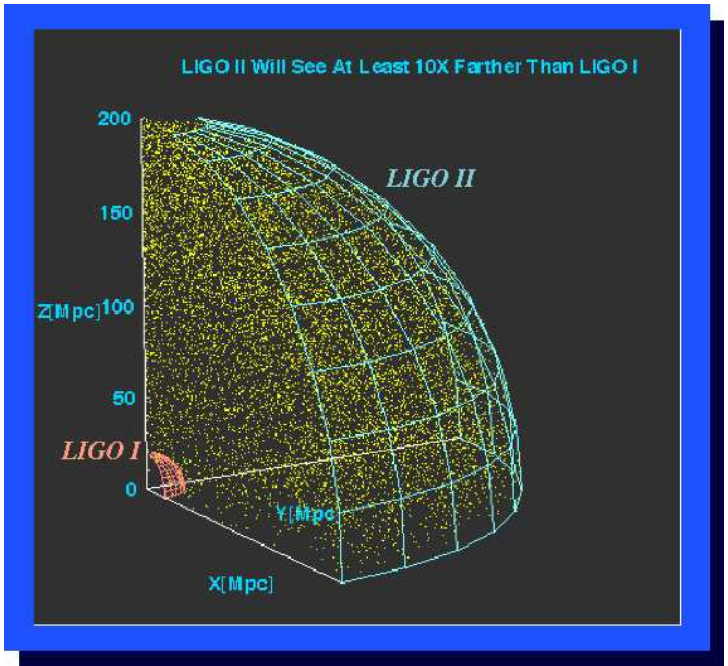
Looking Further Ahead

Despite their immense technical challenges, the initial LIGO IFO's were designed conservatively, based on "tabletop" prototypes, but with expected sensitivity gain of ~1000.

Given the expected low rate of detectable GW events, it was always planned that in engineering, building and commissioning initial LIGO, one would learn how reliably to build Advanced LIGO with another factor of ~10 improved sensitivity.

Because LIGO measures GW amplitude, an increase in sensitivity by 10 gives an increase in sampling volume, i.e, rate by ~1000

Population improvement for galactic pulsars scales like square→ cube, depending on f

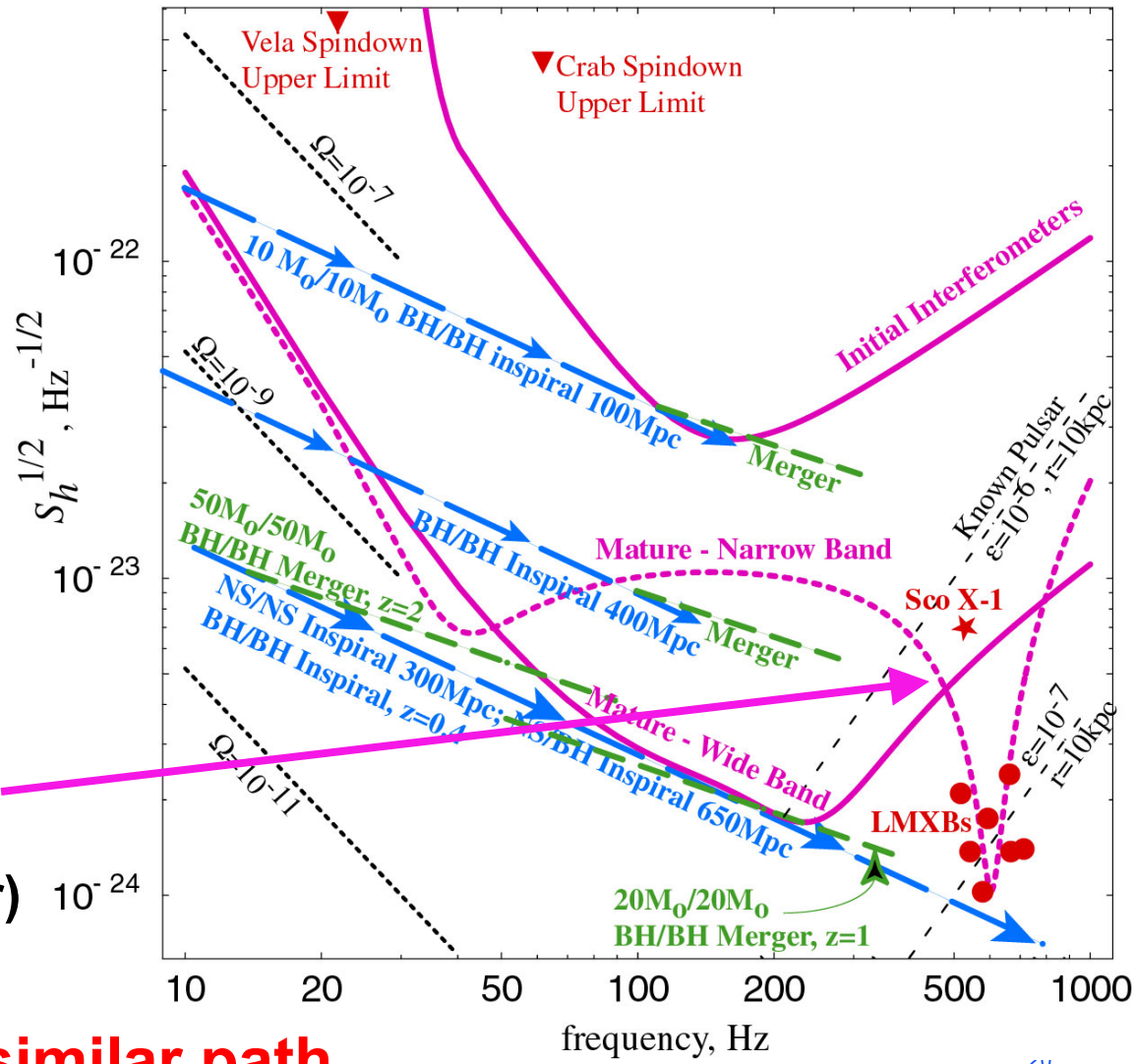


Advanced LIGO

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 Virgo on similar path

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

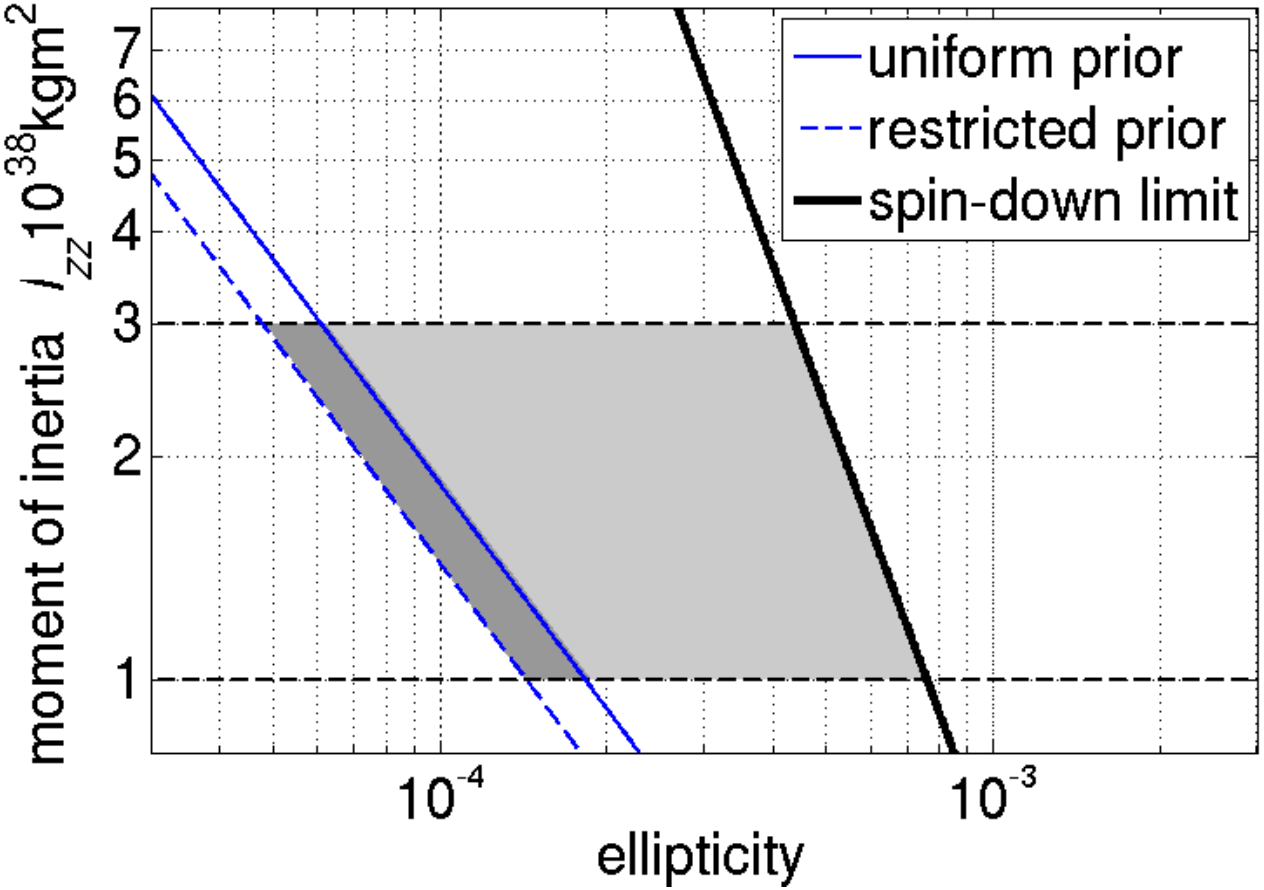
The Einstein@Home search for periodic gravitational waves in LIGO S4 data – PRD **7**9 (2009) 022001

Upper limit map of a background of gravitational waves – PRD 76 (2007) 082003

CW observational papers to date

S5:

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



Strain limit:
2.7×10^{-25}

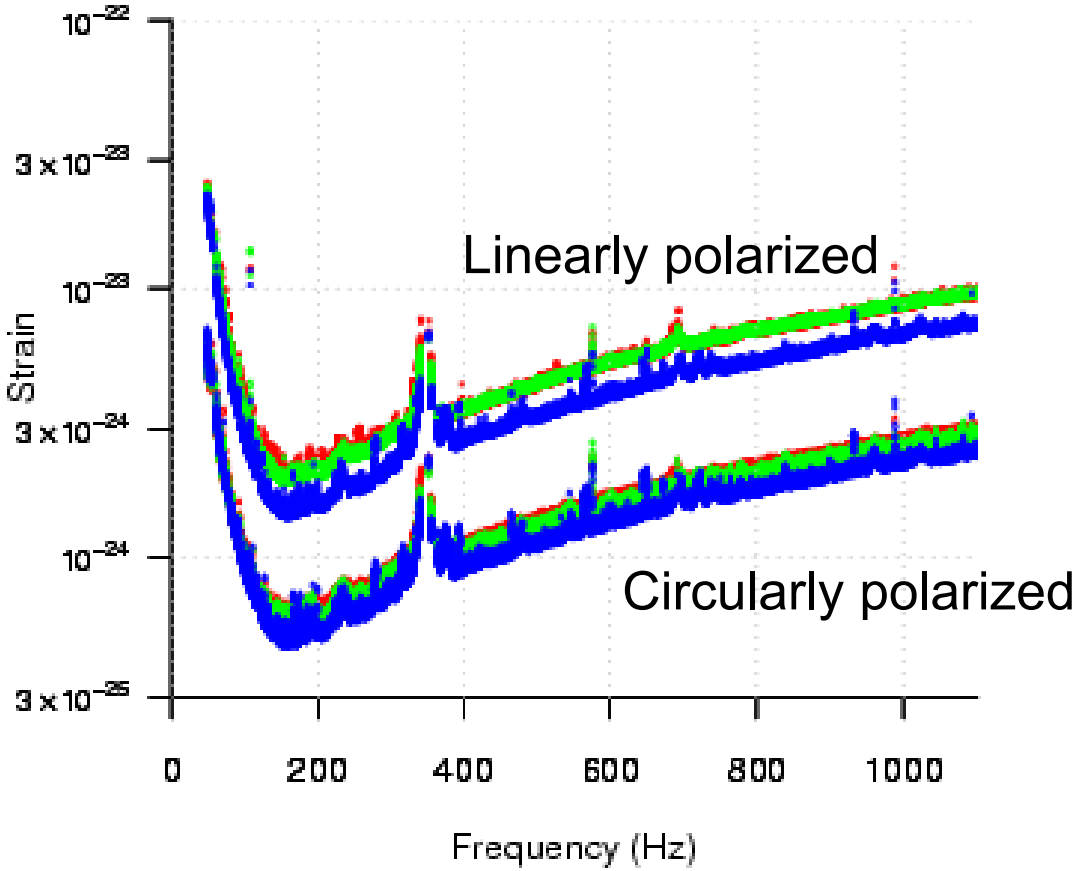
Spindown limit:
1.4×10^{-24}

Coherent,
9-month,
time-domain

CW observational papers to date

S5:

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

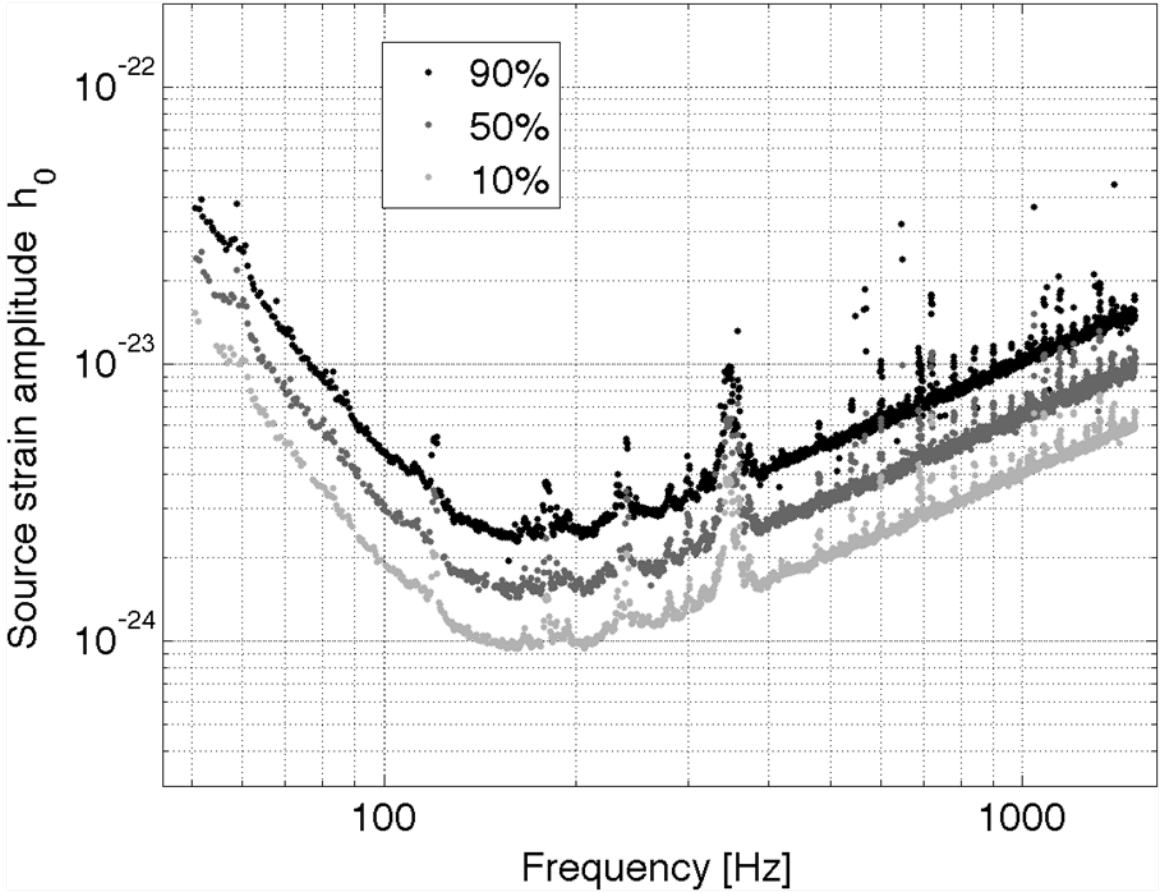


Semi-coherent, Stacks of 30-minute, demodulated power spectra

CW observational papers to date

S5:

Einstein@Home search for periodic gravitational waves in early S5 LIGO data – Submitted to PRD (arXiv:0905.1705)

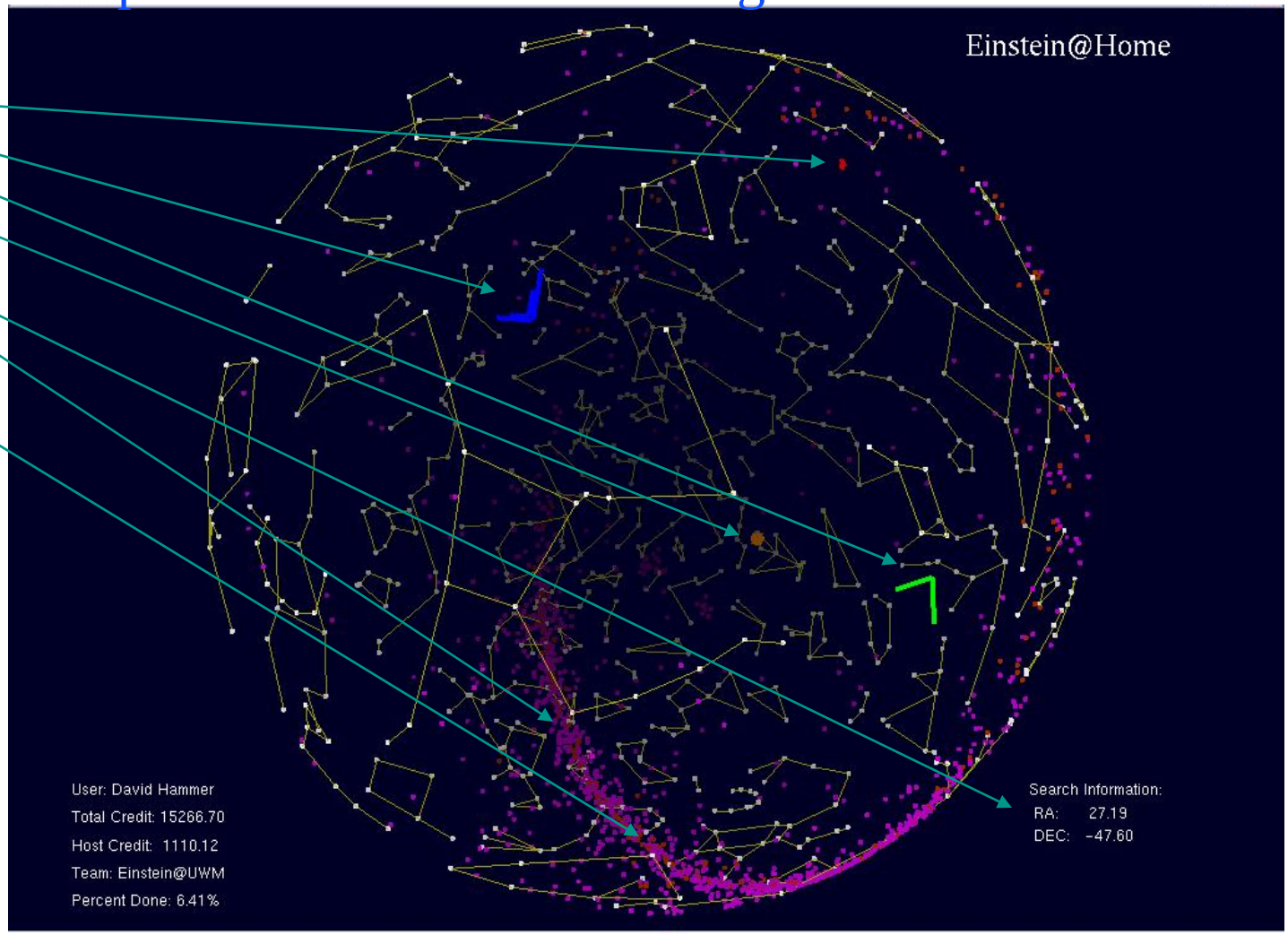


Coincidence among multiple 30-hour coherent searches

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!



Are the S5 all-sky limits interesting?

Yes, best limits are below 10^{-24}

Analytic scaling argument from Blandford (unpublished) gives an expected loudest $h_0 \approx 4 \times 10^{-24}$ (independent of ellipticity)

But argument makes assumptions, e.g., steady-state pulsar evolution, that may not be justified

Knispel & Allen [PRD 78 (2008) 044031] find with explicit simulation that loudest expected $h_0 \approx 1 \times 10^{-24}$ for $\epsilon = 10^{-6}$

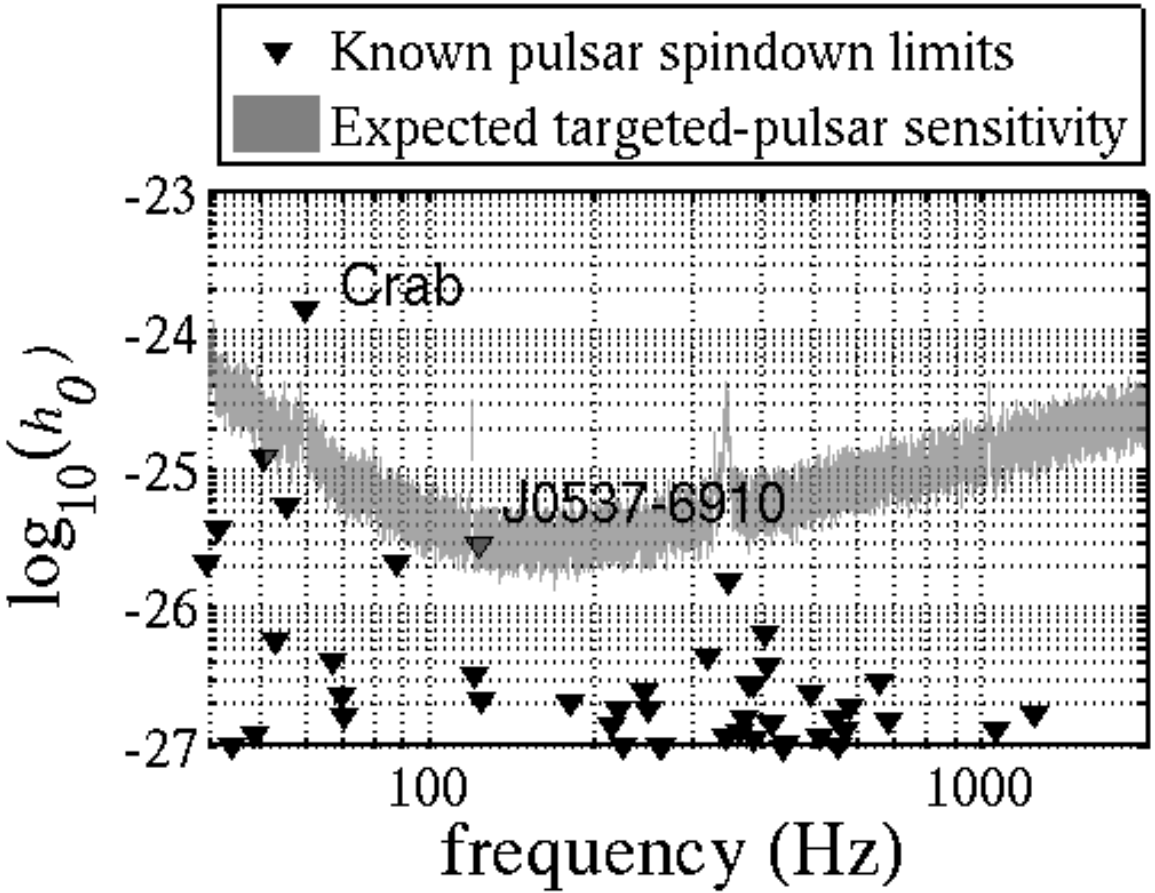
Another benchmark:

Can see out to 500 pc for $f_{sig} \approx 1$ kHz and $\epsilon \approx 10^{-6}$

Imminent CW observational papers

S5 / VSR1:

Searches for gravitational waves from known pulsars with S5 LIGO data
(116 pulsars, including full-S5 Crab result)



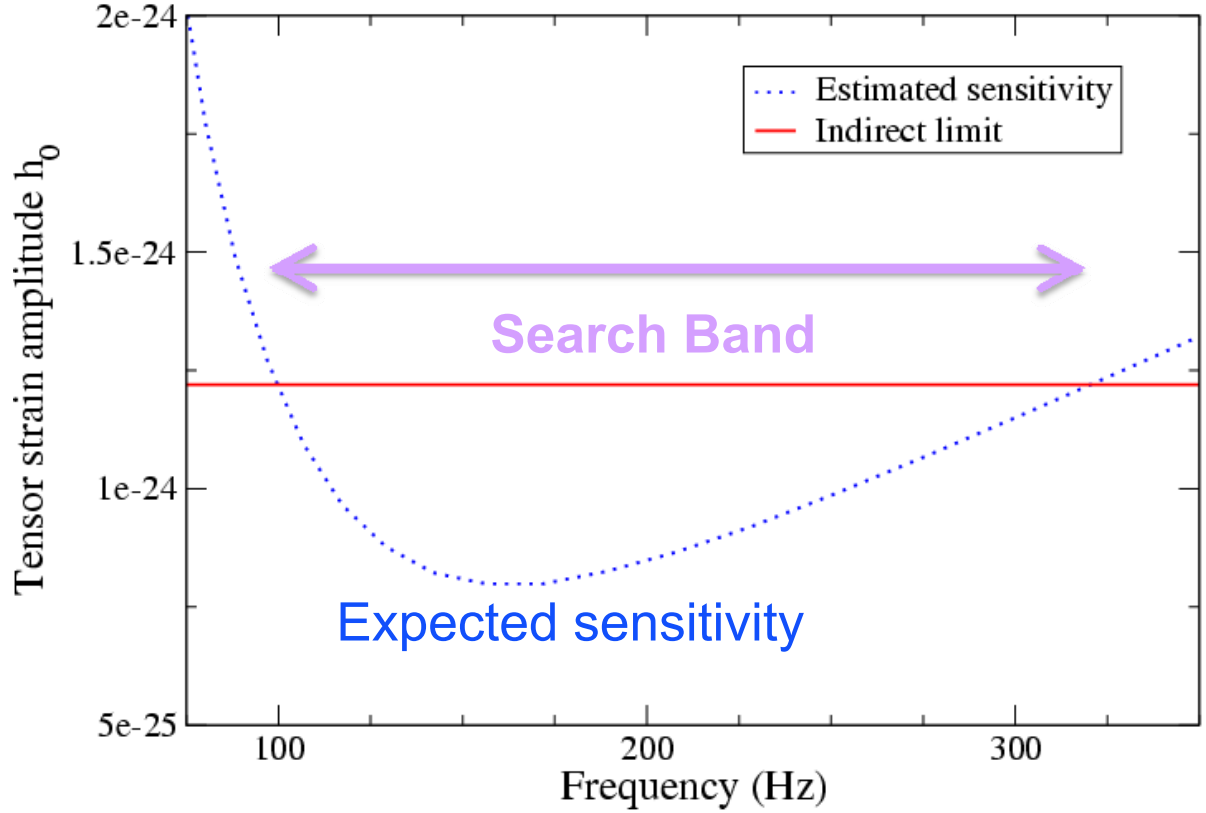
Targeted search

$T_{coherence}$ ~ 2 years

Imminent CW observational papers

S5/VSR1:

Observational upper limits on gravitational waves from Cassiopeia A



Directed search
(1 sky location)

$T_{coherence} \sim 12$ days

7×10^{12} templates

(searching over
df/dt, d^2f/dt^2)

Searches to date:

13 papers – 19 searches – 5 science runs

Recurring "themes":

- Eight targeted (direction and timing known)
- Eight all-sky (unknown, isolated, any direction)
- Three directed (known direction, but no timing info):
  - Two Sco X-1 searches ($T_{coherence}$~6 hrs, cross-correlation)
  - Cas A ($T_{coherence}$~10-12 days)

Directed searches now receiving more attention in search pipeline development:

Galactic center, globular clusters, SN1987A, Calvera, Sco X-1, SNR's

Also exploring formidable all-sky <u>binary</u> search algorithms

- Must sacrifice intrinsic sensitivity to make tractable
- But accretion as ε driver makes searches attractive

Summary

Still sorting through data from two-year S5 / VSR1 run:

- No CW signal has appeared in flagship searches so far

- Digging deeper into noise and exploring "directed searches" for interesting sky locations

- Soliciting your input on what those interesting locations ought to be

- Strong interest on LIGO-Virgo side in maximum ellipticities
    - Maximum expected vs maximum allowed
    - How seriously to treat strange quark stars
    - Affects search strategy, given computational bounds

Our Plan:

- Complete ongoing enhancements of LIGO & Virgo to "enhanced LIGO"

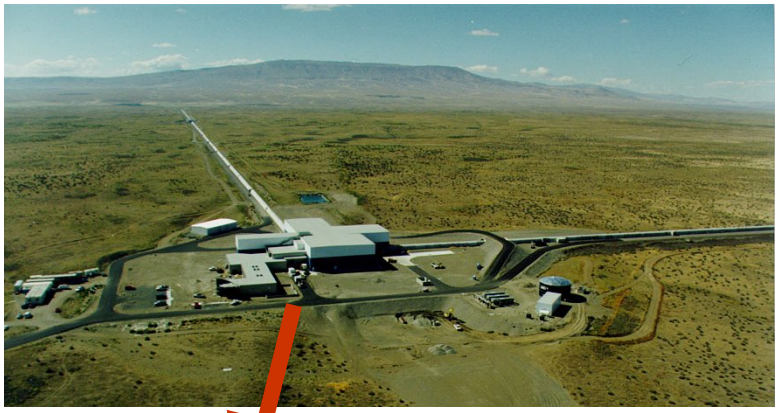
- Start ~18-month S6 / VSR2 run in July 2009 – aiming at sensitivity improvement by up to factor of two (most feasible at higher frequencies)

- Upgrade to Advanced LIGO → Return to data taking in ~2014

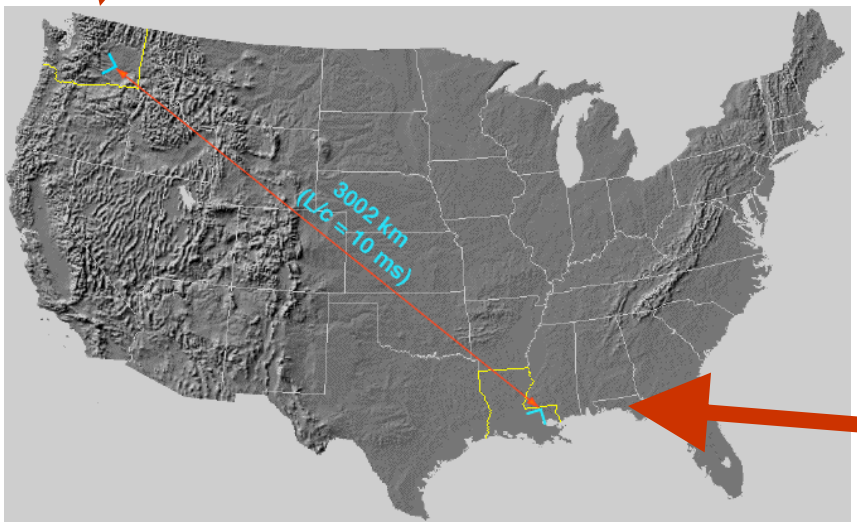
Extra Slides

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

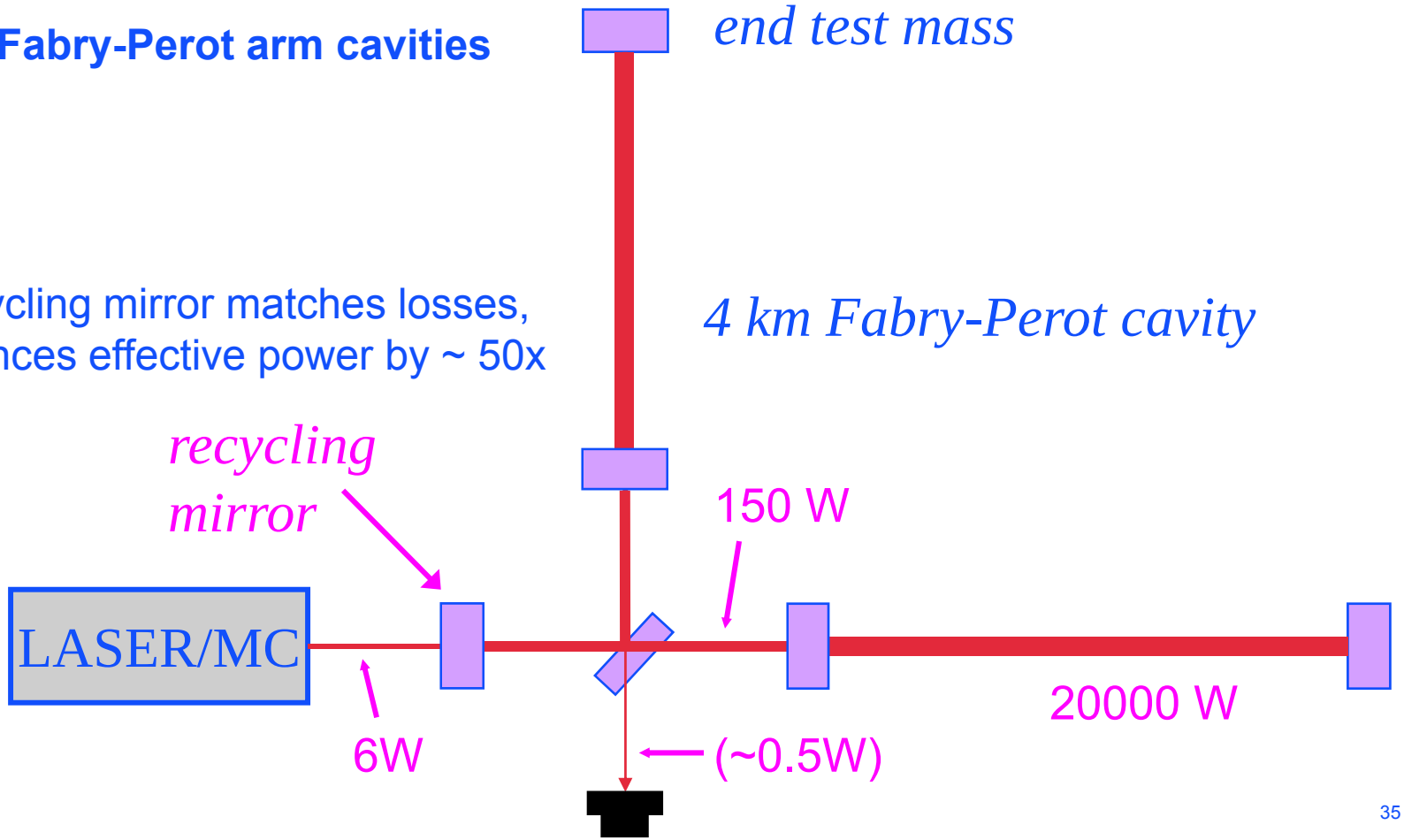
3-km Michelson Interferometer just outside Pisa, Italy

LIGO Interferometer Optical Scheme

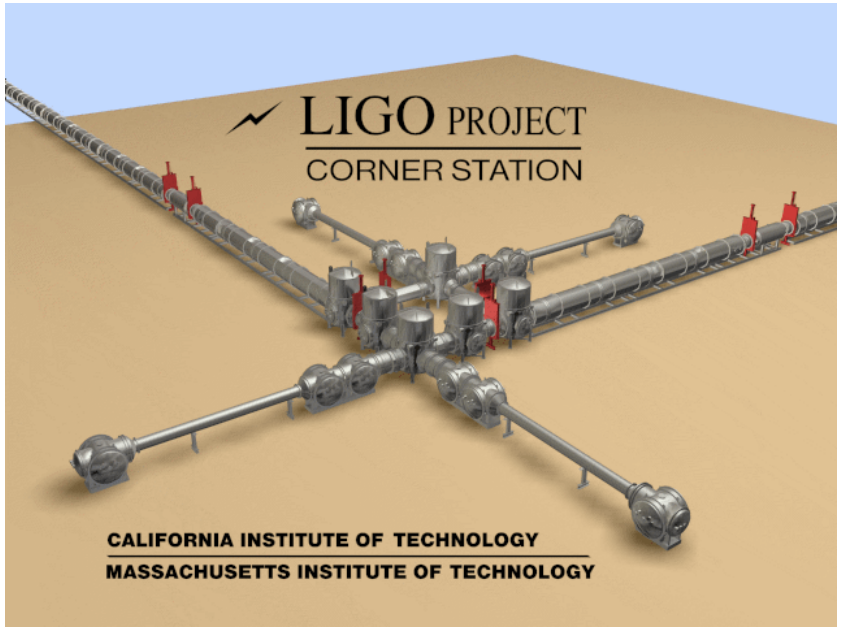
Michelson interferometer

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

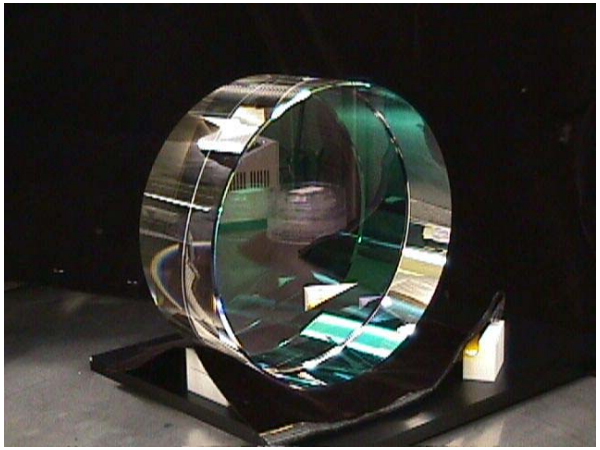
LIGO Detector Facilities

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

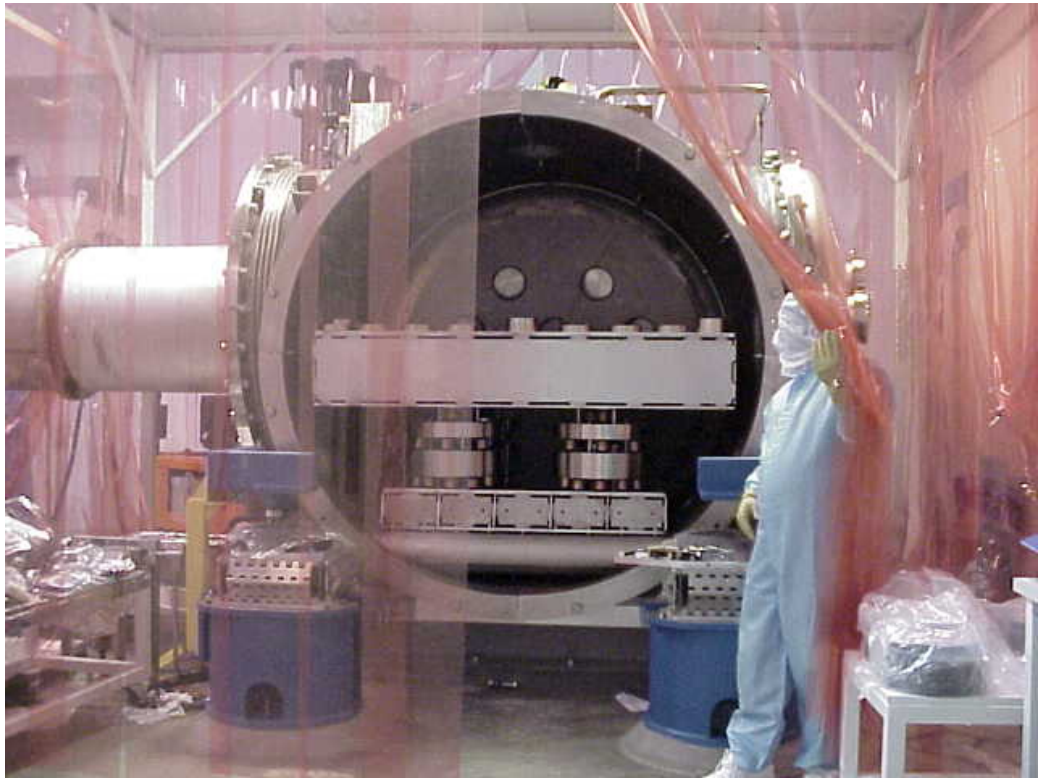
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

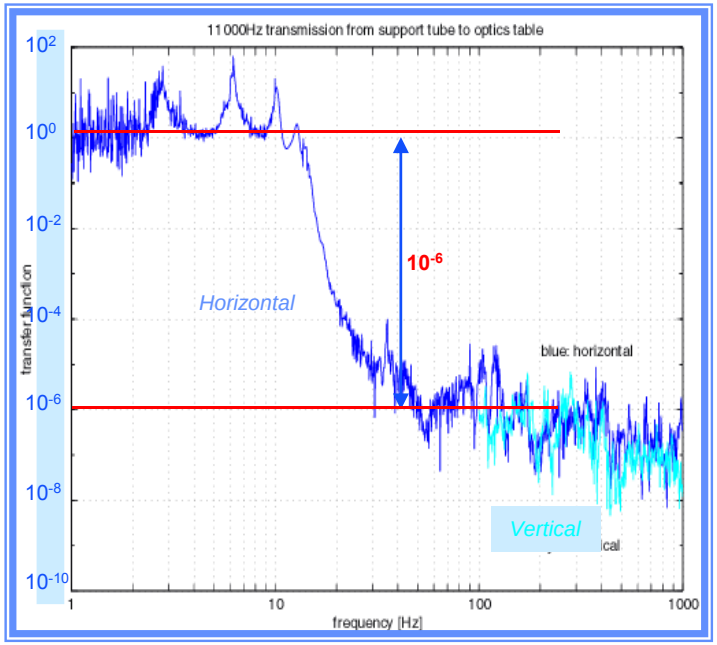


LIGO Detector Facilities

Seismic Isolation

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



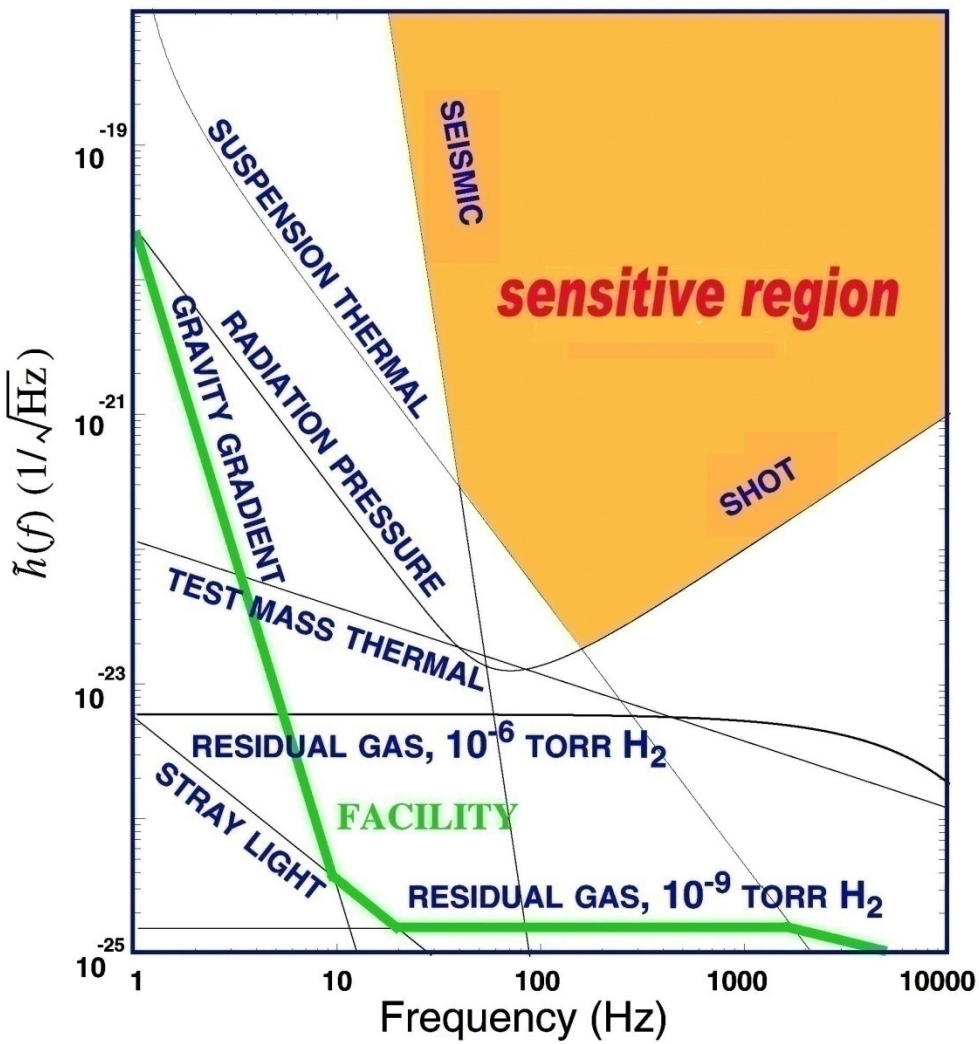


What Limits the Sensitivity of the Interferometers?

- 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.,…

LIGO Scientific Collaboration

LIGO

LSC

- 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 Gravita

- 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 Washingtor

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

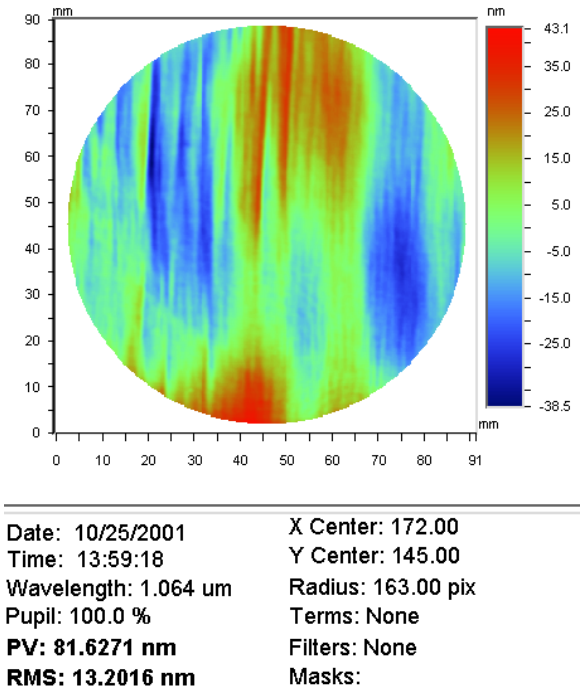
Lower internal thermal noise in bandwidth

Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Sapphire Optics



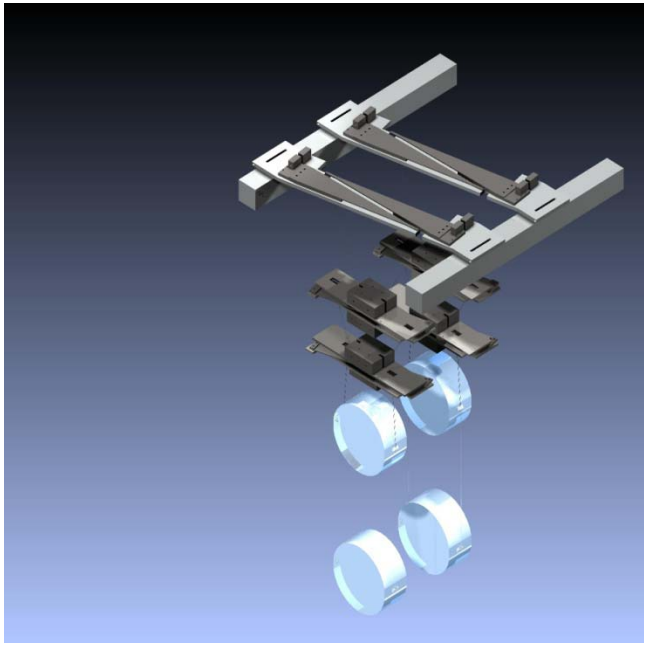
Advanced LIGO

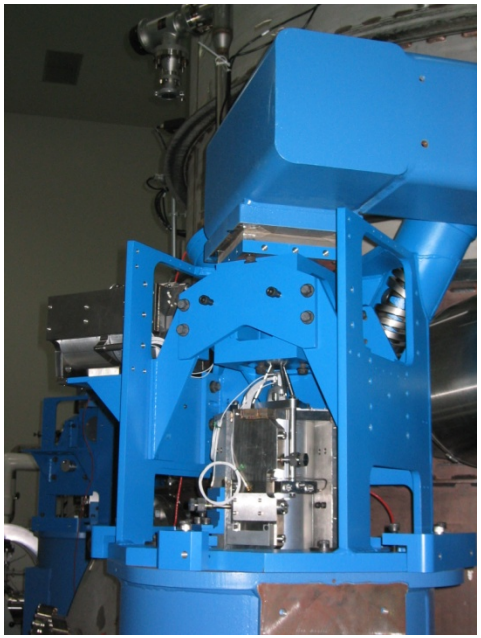
Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth





Improved seismic isolation:

Passive → Active

Lowers seismic "wall" to ~10 Hz