Gravitational Waves:
From Astrophysics to Optics

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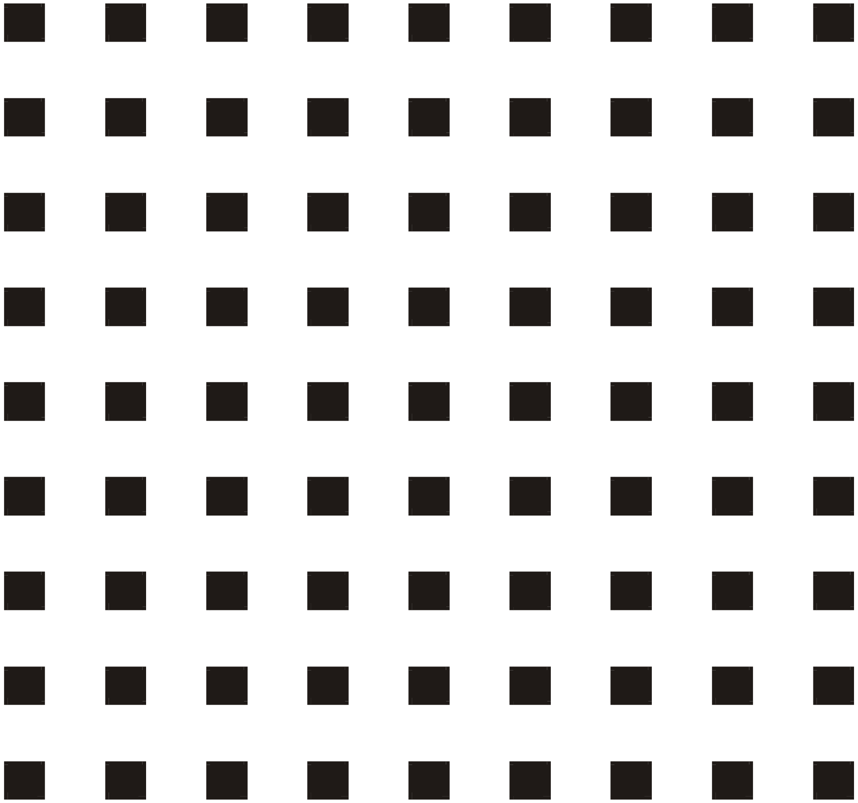
Outline

- What are gravitational waves, and why are they interesting?
- How do gravitational wave detectors work?
- Why might it seem impossible to detect gravitational waves, but why is it possible nevertheless?
- A few technical details, mainly about LIGO
- How do we look for signals in our data?

A set of freely-falling test masses



LIGO-G050252-00-Z

A gravitational wave meets some test masses

- Transverse

  No effect along direction of propagation

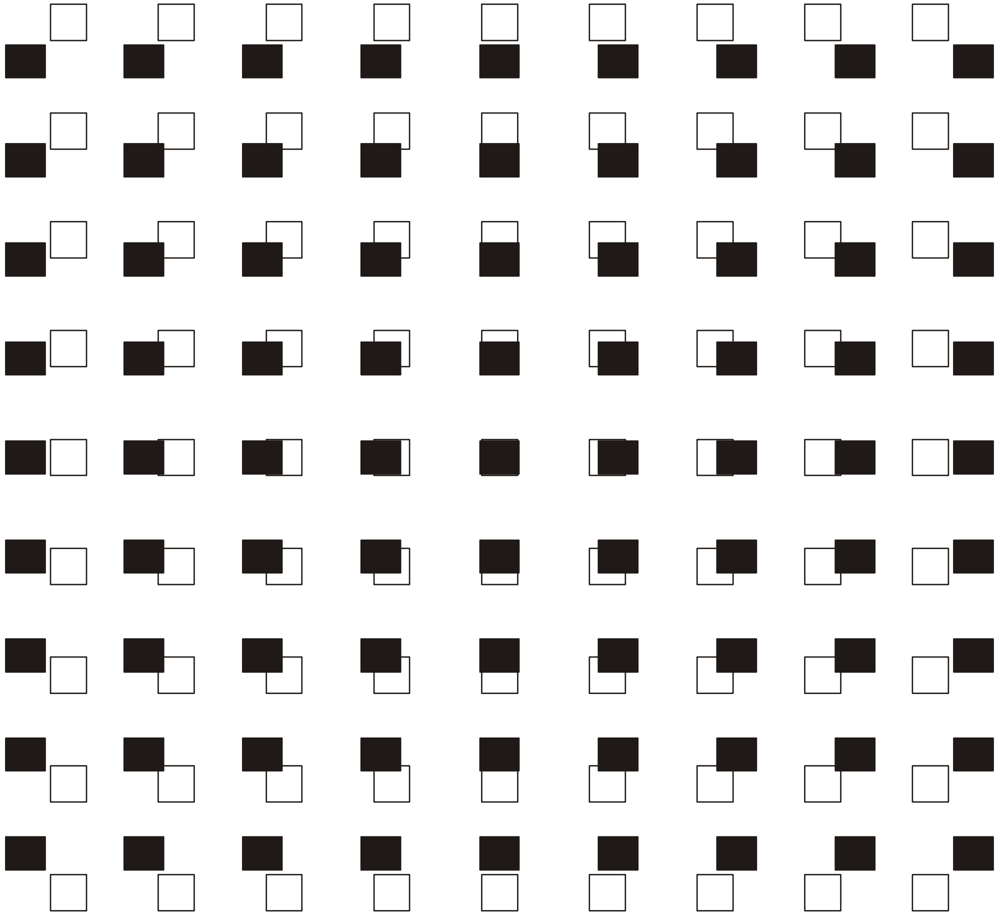
- Quadrupolar

  Opposite effects along *x* and *y* directions

- Strain

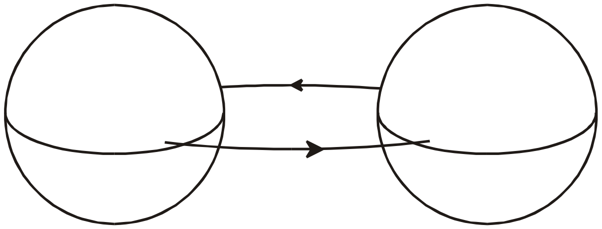
  Larger effect on longer separations

$$h \equiv 2\frac{\Delta L}{L}$$

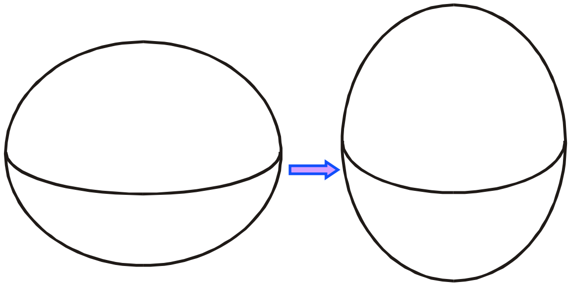


Gravitational wave sources: time-varying quadrupole moments

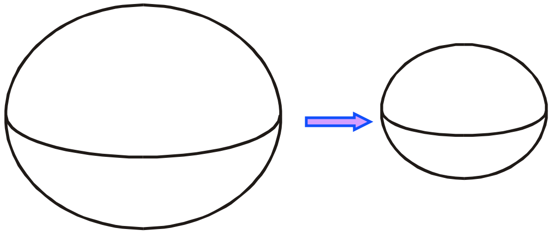
Binary stars (especially compact objects, e.g. neutron stars or black holes.)



Compact objects just after formation from core collapse.



Or anything else with a dramatic and rapid variation in its mass quadrupole moment.



Gravitational waveform lets you read out source dynamics

The evolution of the mass distribution can be read out from the gravitational waveform:

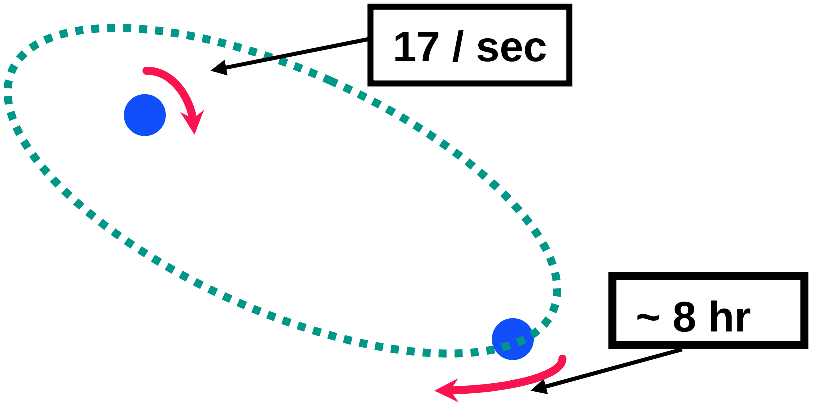
$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

I is the mass quadrupole moment of the source.

Coherent relativistic motion of large masses can be directly observed.

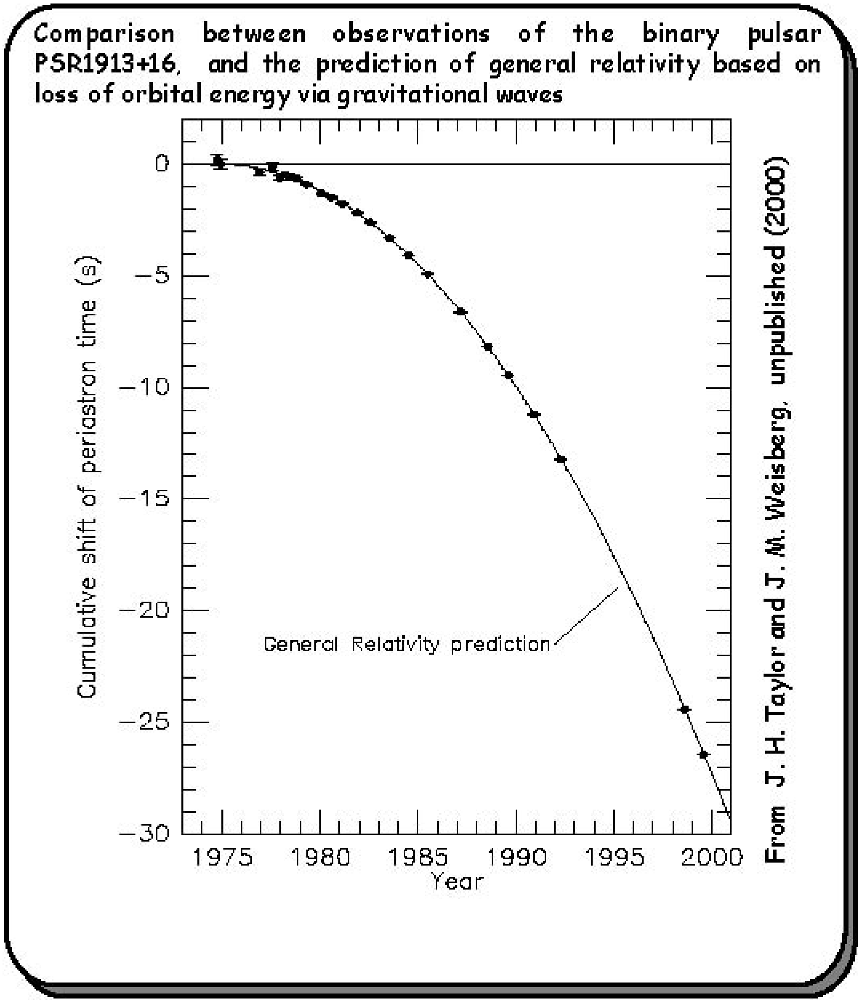
How do we know that gravitational waves exist?

Neutron Binary System – Hulse & Taylor
Timing of pulsar - Nobel prize 1993
Periastron change: 30 sec in 25 years

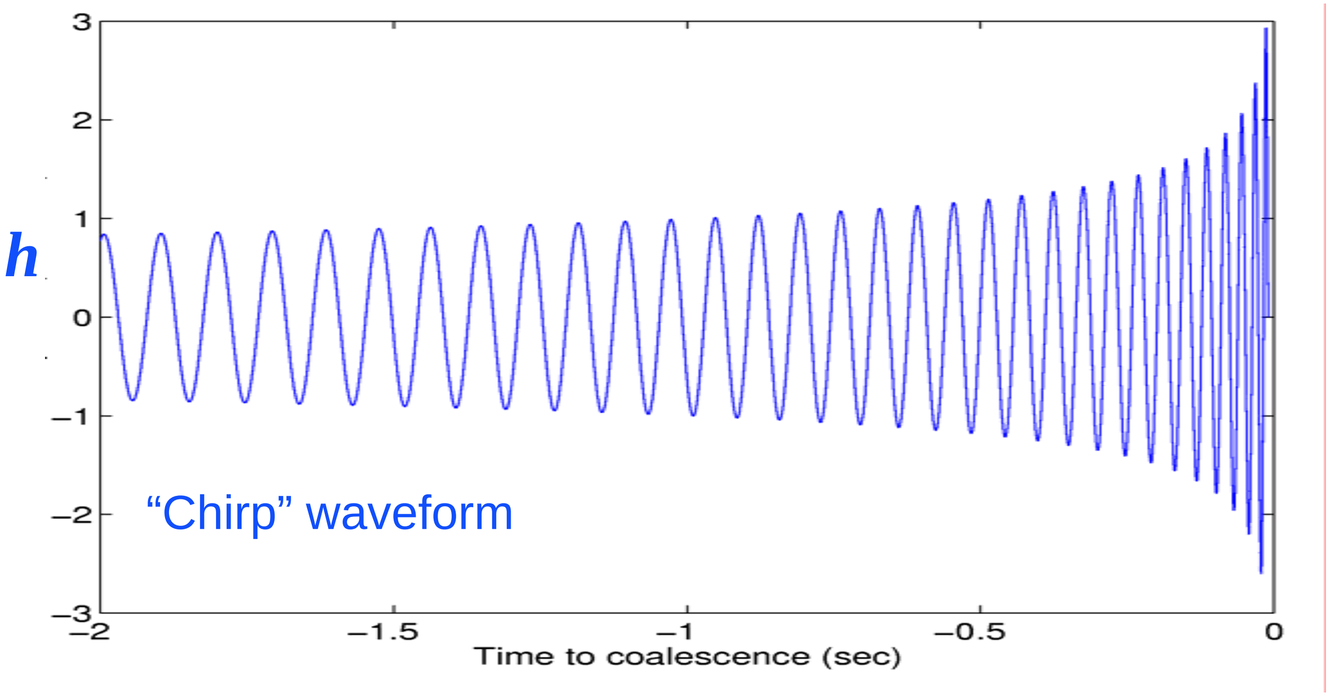


Prediction from general relativity:
spiral in by 3 mm/orbit

This is caused by the loss of energy carried away by gravitational waves, due to binary’s time varying quadrupole moment.


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

Binary pulsars end as audio-band gravity wave sources



In LIGO frequency band (40–2000 Hz) for a short time just before merging,

anywhere from a few minutes to <<1 second, depending on mass.

What is interesting about gravitational waves?

- Embody gravity’s obedience to the principle “no signal faster than light”
- Made by coherent relativistic motions of large masses
  - emitted most strongly by strong-gravity situations
- Travel through opaque matter
  - e.g., in supernovae
- Can be generated by pure space-time
  - black holes
- Dominate the dynamics of interesting systems
- Can reveal, like nothing else can, the dynamics of strongly curved space-time.

Gravitational wave detectors

Need:

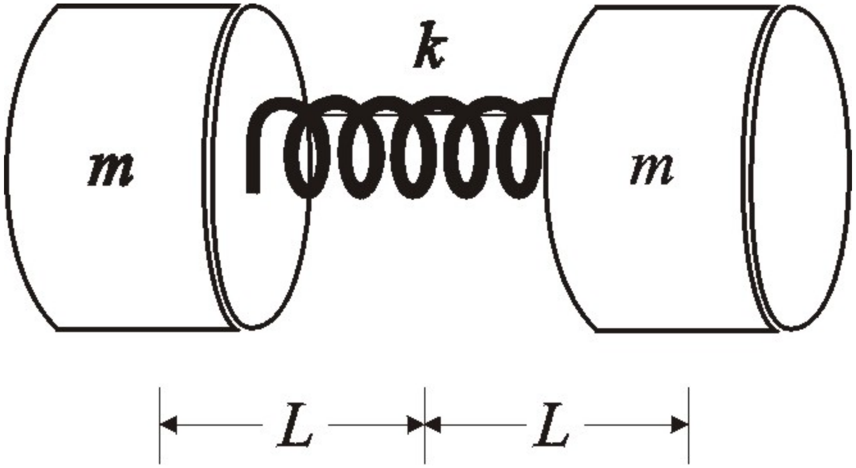
- A set of test masses,
- Instrumentation sufficient to see tiny motions,
- Isolation from other causes of motions.

Challenge:

Best astrophysical estimates predict fractional separation changes of only 1 part in 10^{21}, or less.

Resonant detector
J. Weber, 1960s

A massive (aluminum) cylinder. Vibrating in its gravest longitudinal mode, its two ends are like two test masses connected by a spring.



Today, cooled by liquid He,
rms sensitivity at/below 10^{-18}.

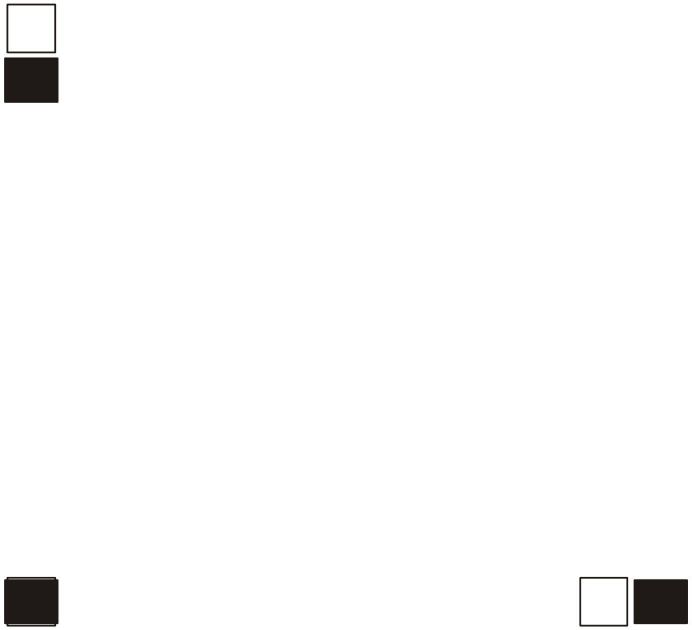
Resonant detectors

Resonant detectors have been in operation since the late 1960s.

Interferometers are just now surpassing them in sensitivity.

AURIGA

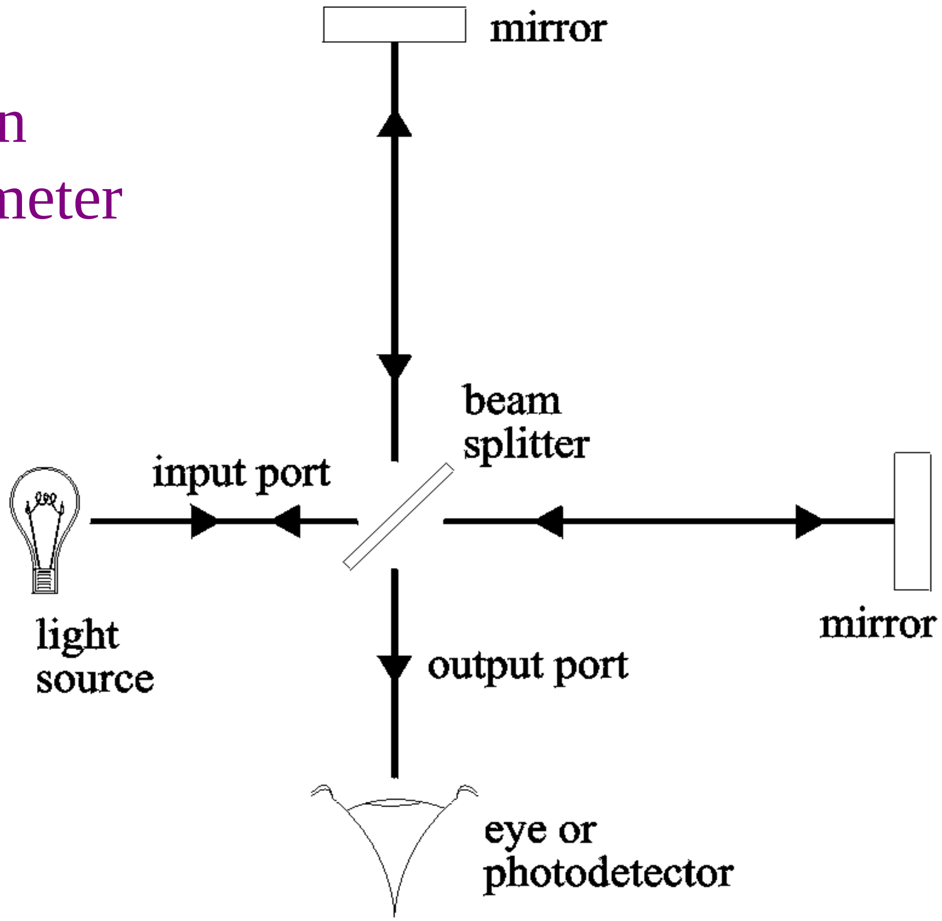
An alternative detection strategy



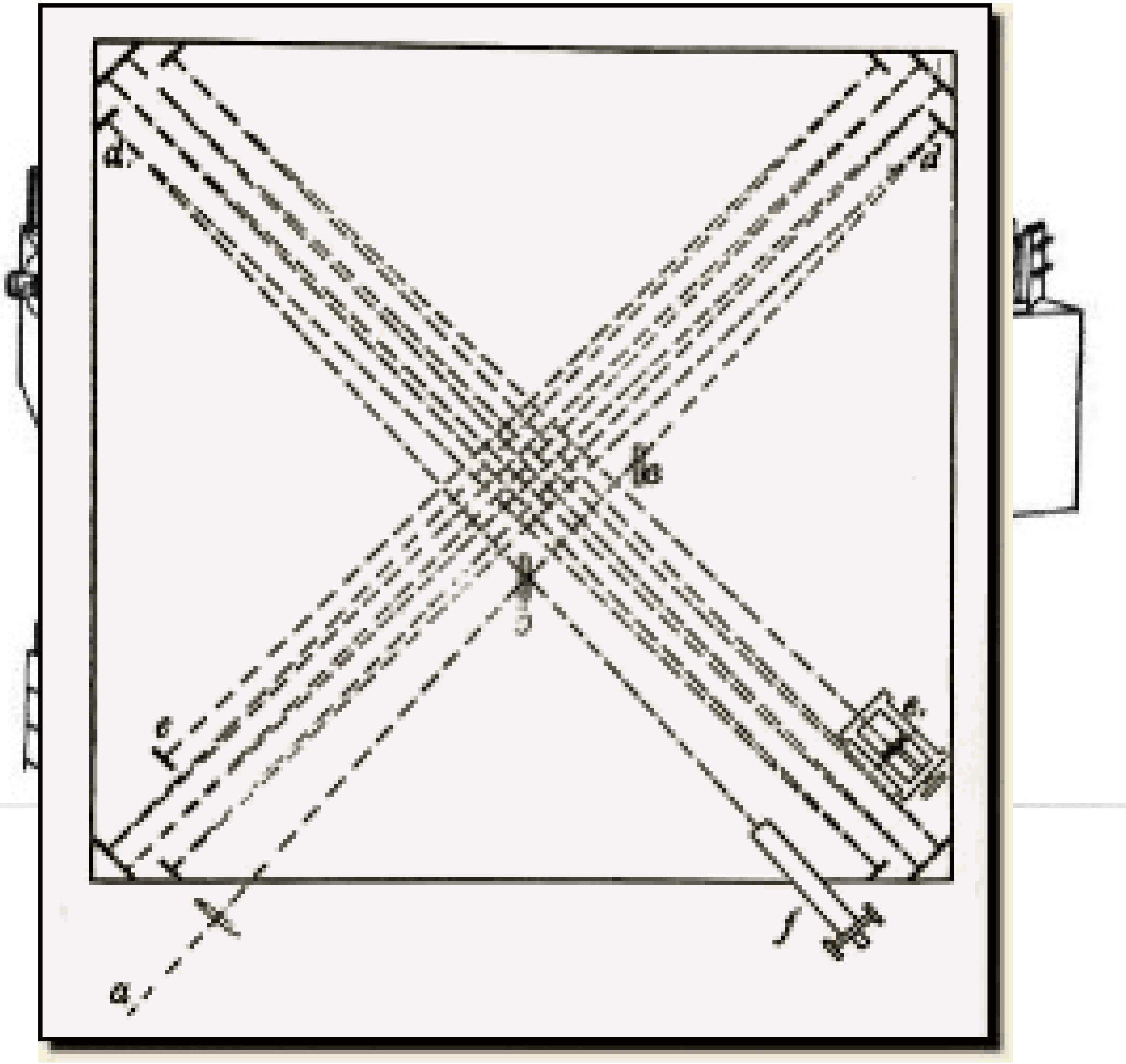
Strain character of wave argues for test masses as far apart as practicable. Perhaps masses hung as pendulums, kilometers apart.

Sensing relative motions of distant free masses

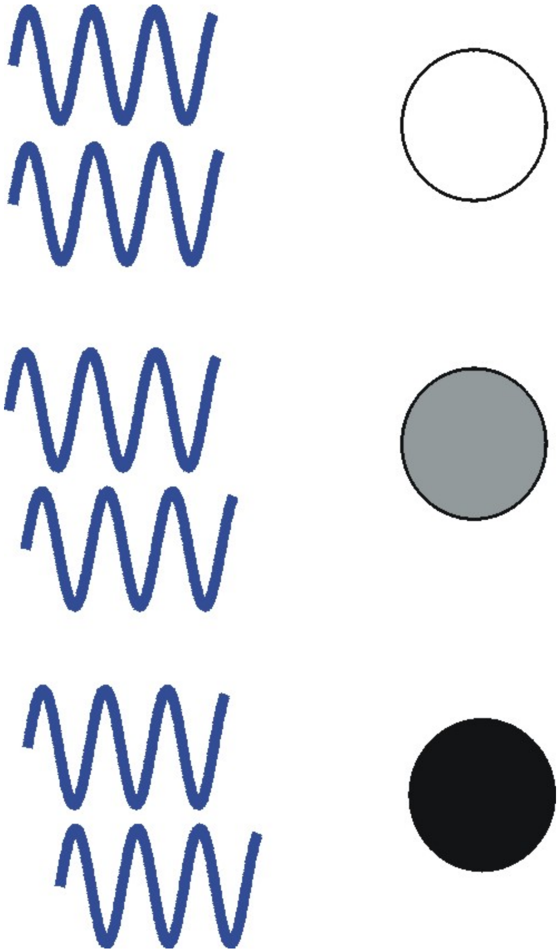
Michelson interferometer



Michelson and Morley's apparatus, 1887



A transducer from length difference to brightness



Wave from x arm.

Wave from y arm.

Light exiting from beam splitter.

As relative arm lengths change, interference causes change in brightness at output.

N.B.: This differs from Michelson’s alignment, which gave “fringes” that shift side-to-side.

Can gravitational wave detection succeed?

Challenges of gravity wave detection appear so great as to make success seem almost impossible.

from Einstein on ...

The challenges are real, but have been overcome.

Einstein on tests of General Relativity

- Classic tests:
  - Precession of Mercury’s orbit: had been already seen
  - Deflection of starlight: ~1 arcsec, O.K.
  - Gravitational redshift in a star: ~10^{-6}, doable.
- Possible future test:
  - dragging of inertial frames, 42 marcsec/yr, Einstein considered possibly feasible in future
- Gravitational waves: no comment!

Why Einstein should have worried about g.w. detection

He knew about binary stars, but not about neutron stars or black holes.

His paradigm of measuring instruments:

- » interferometer ($x_{rms} \sim \lambda/20$, $h_{rms} \sim 10^{-9}$)
- » galvanometer ($\theta_{rms} \sim 10^{-6}$ rad.)

Gap between experimental sensitivity and any conceivable wave amplitude was huge!

Gravitational wave detection is almost impossible

What is required for LIGO to succeed:

- interferometry with free masses,
- with strain sensitivity of 10^{-21} (or better!),
- equivalent to ultra-subnuclear position sensitivity,
- in the presence of much larger noise.

How is the “impossible” being made possible?

Interferometry with free masses

What's "impossible": everything!

Mirrors need to be very accurately aligned (so that beams overlap and interfere) and held very close to an operating point (so that output is a linear function of input.)

Otherwise, interferometer is dead or swinging through fringes.

Michelson bolted everything down.

Interferometry with free masses

How it became possible:

Servos

- let mirrors swing freely on pendulum suspensions (at high frequencies),
- while keeping them aimed properly and at the right interferometric operating point
  (at low frequencies.)

LIGO has dozens of servo loops.

Strain sensitivity of 10^{-21}

Why it is “impossible”:

$$h_{rms} \sim \frac{\text{precision to which we can compare arm lengths}}{\text{length of arms}}.$$

Natural “tick mark” on interferometric ruler is one wavelength.

Michelson could read a fringe to $\lambda/20$, yielding h_{rms} of a few times 10^{-9}.

Strain sensitivity of 10^{-21}

How it became possible (I): Make arms long.

LIGO has 4 km long arms.

L_{opt} is even longer, since light is stored for multiple round trips through the arms, which have the form of Fabry-Perot cavities.

Strain sensitivity of 10^{-21}

How it became possible (II): Learn to resolve very fine length differences.

Don’t rely on eye to judge sideways motion of interference fringes.

Align beams, so that entire spot varies in brightness together.

Then, interference is judged by a power measurement, and can be shot noise limited.

Strain sensitivity of 10^{-21}

How this became possible:

Minimize shot noise by using lots of light. LIGO uses a 10 W Nd:YAG laser.

Low-loss optics, dark-fringe operating point, let most light survive passage through the interferometer. Recycle that power, for even lower shot noise.

Result: Can see motions of 10^{-10} of a fringe.

$$h_{rms} \approx \frac{10^{-10} * 10^{-6}\, m}{50 * 8 * 10^{3}\, m} \approx 2.5 * 10^{-22}.$$

Ultra-subnuclear position sensitivity

Why people thought it was impossible:

- Mirrors made of atoms, 10^{-10} m.
- Mirror surfaces rough on atomic scale.
- Atoms jitter by large amounts.

Ultra-subnuclear position sensitivity

Why it is possible nevertheless:

We don't look at atoms; laser beam samples many cm^2 of mirror surface, ~ 10^{17} atoms.

We don't see atomic jitter either, but coherent motion of mirror surfaces (which is bad enough but not as bad as atom-scale motion.)

Precision better than 10^{-18} m is possible.

Large mechanical noise

How large?

Seismic: $x_{rms} \sim 1\ \mu$m.

Thermal

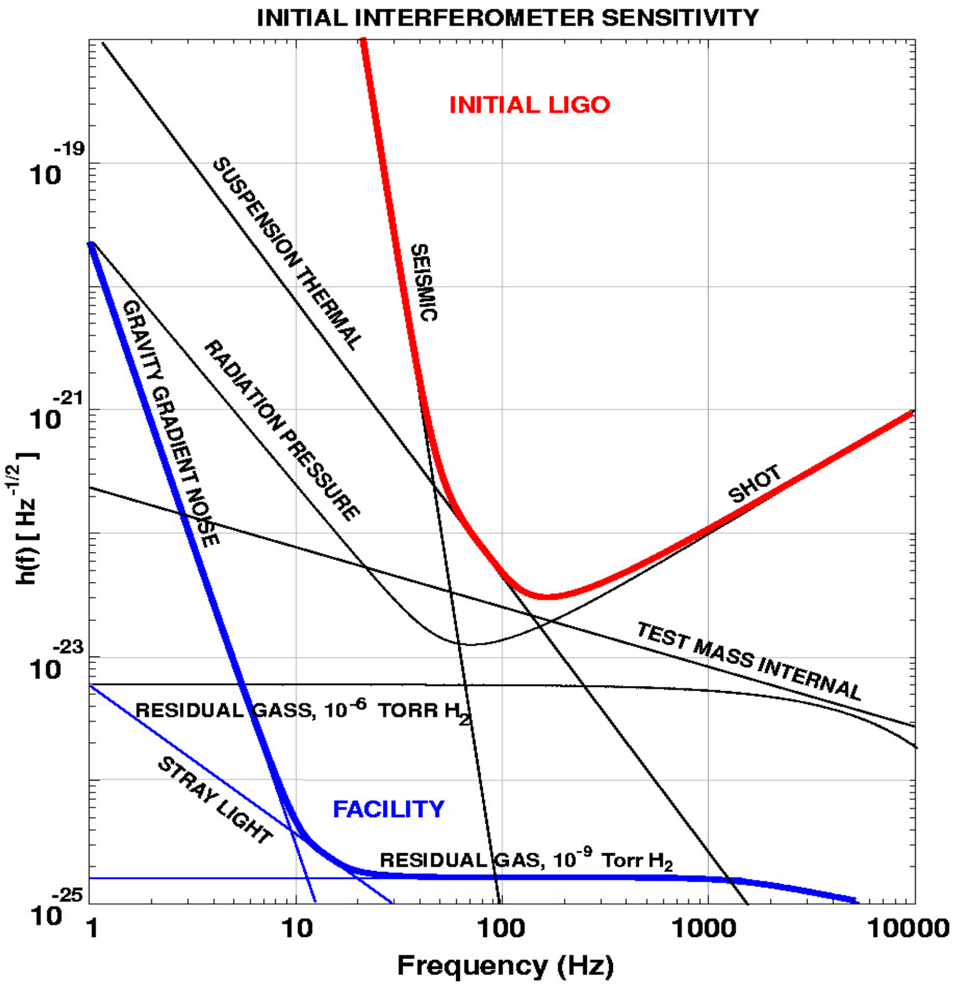
- » mirror's CM: ~ 3 x 10^{-12} m.
- » mirror's surface: ~ 3 x 10^{-16} m.

Large mechanical noise

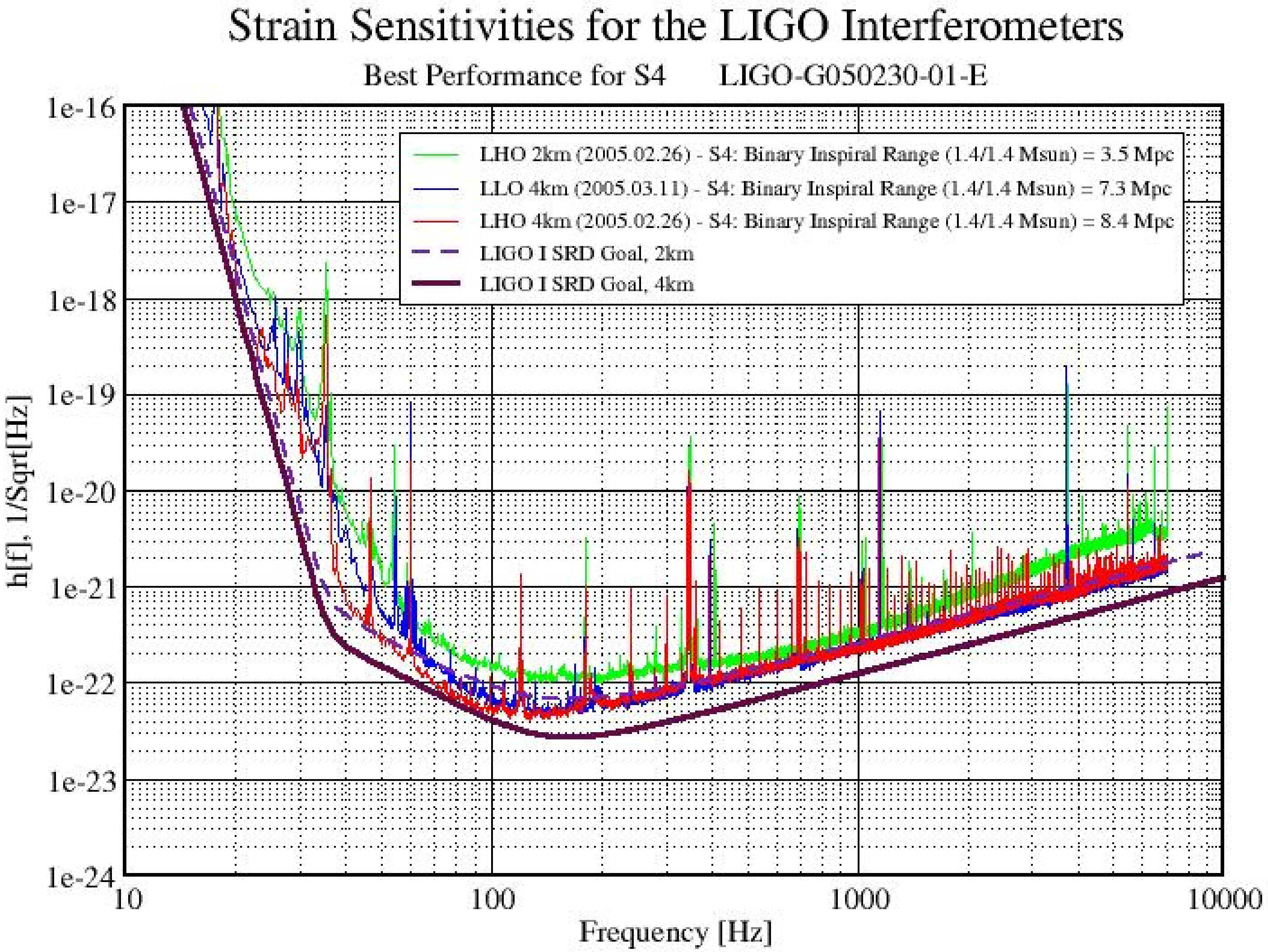
How measurement will succeed nevertheless:

- Noise is strongly frequency dependent:
    - » seismic noise falls with frequency, especially after passing through isolators, and
    - » thermal noise is peaked at resonances, especially when *Q*'s are high.
- Fringe lock servo holds interferometer at operating point, ensuring the linearity necessary for filtering.

LIGO I noise model

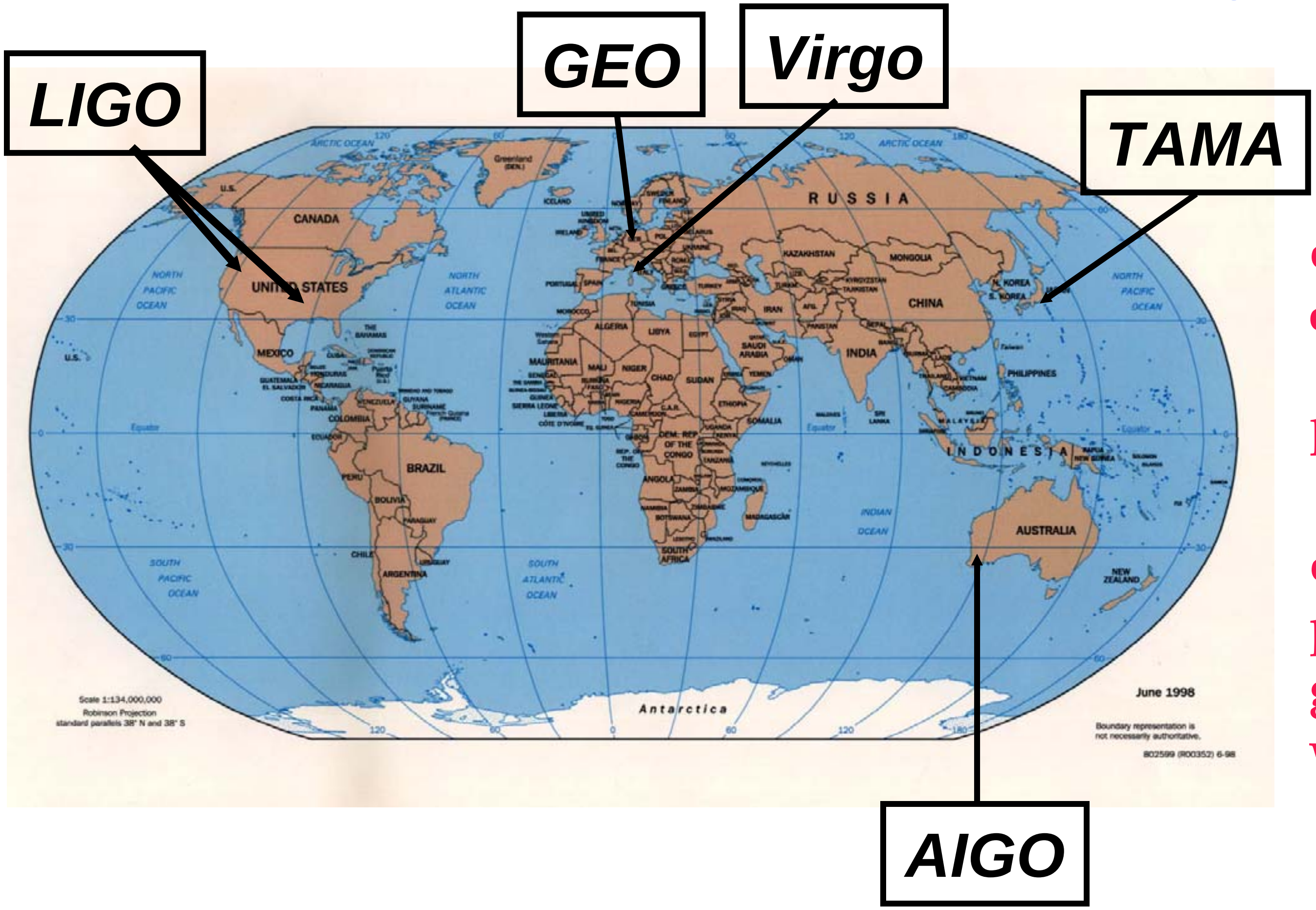


Recent noise spectrum



An International Network of Interferometers

Simultaneously detect signal (within msec)



LIGO

GEO

Virgo

TAMA

AIGO

detection confidence

locate the sources

decompose the polarization of gravitational waves

Status of interferometer projects

Virgo (3 km, Cascina (Pisa), Italy):

Installation complete. Commissioning is far advanced.

TAMA (300 m, Tokyo, Japan):

In operation, approaching design sensitivity. Coincident operation with LIGO has taken place.

GEO (600 m, Hannover, Germany):

Taking data with LIGO while approaching design sensitivity.

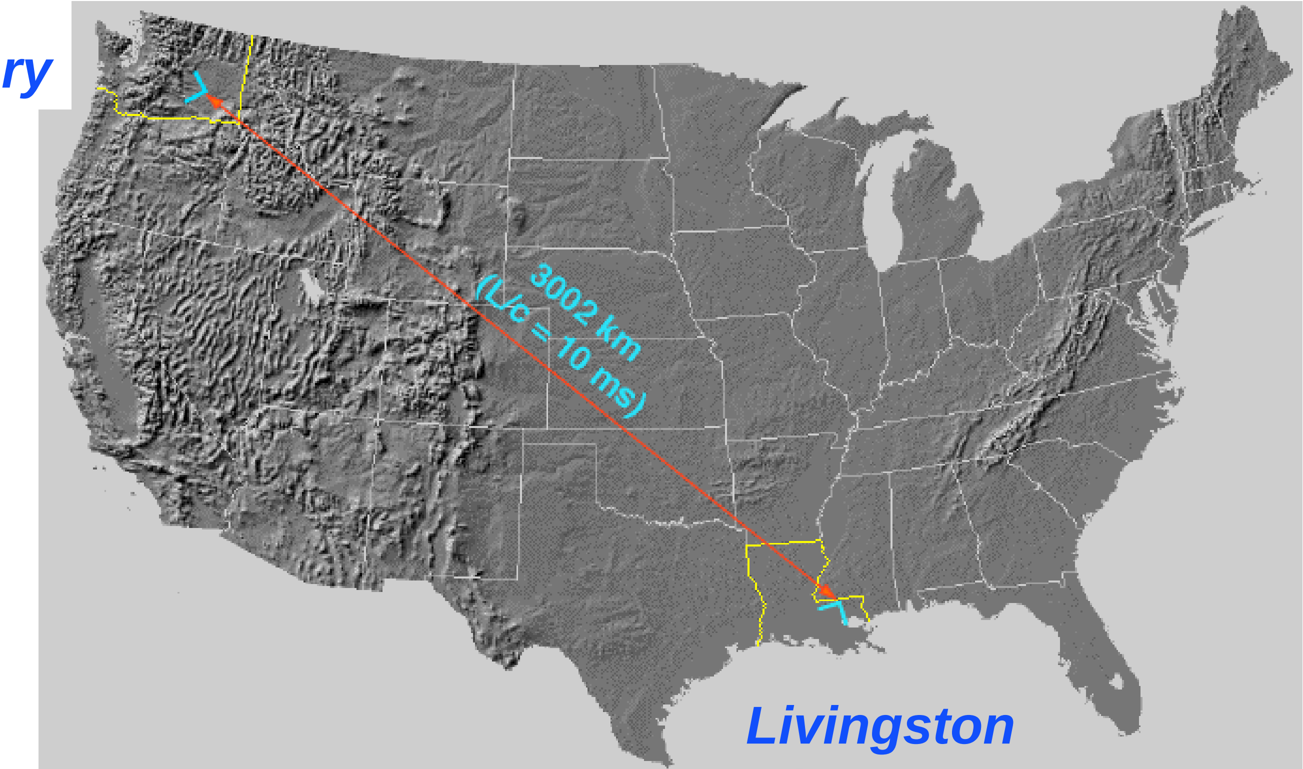
LIGO: subject of the rest of this talk

(See talks on other projects later this morning.)

LIGO Laboratory Sites

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford Observatory



Livingston Observatory

LIGO
(here, LIGO Livingston Observatory)

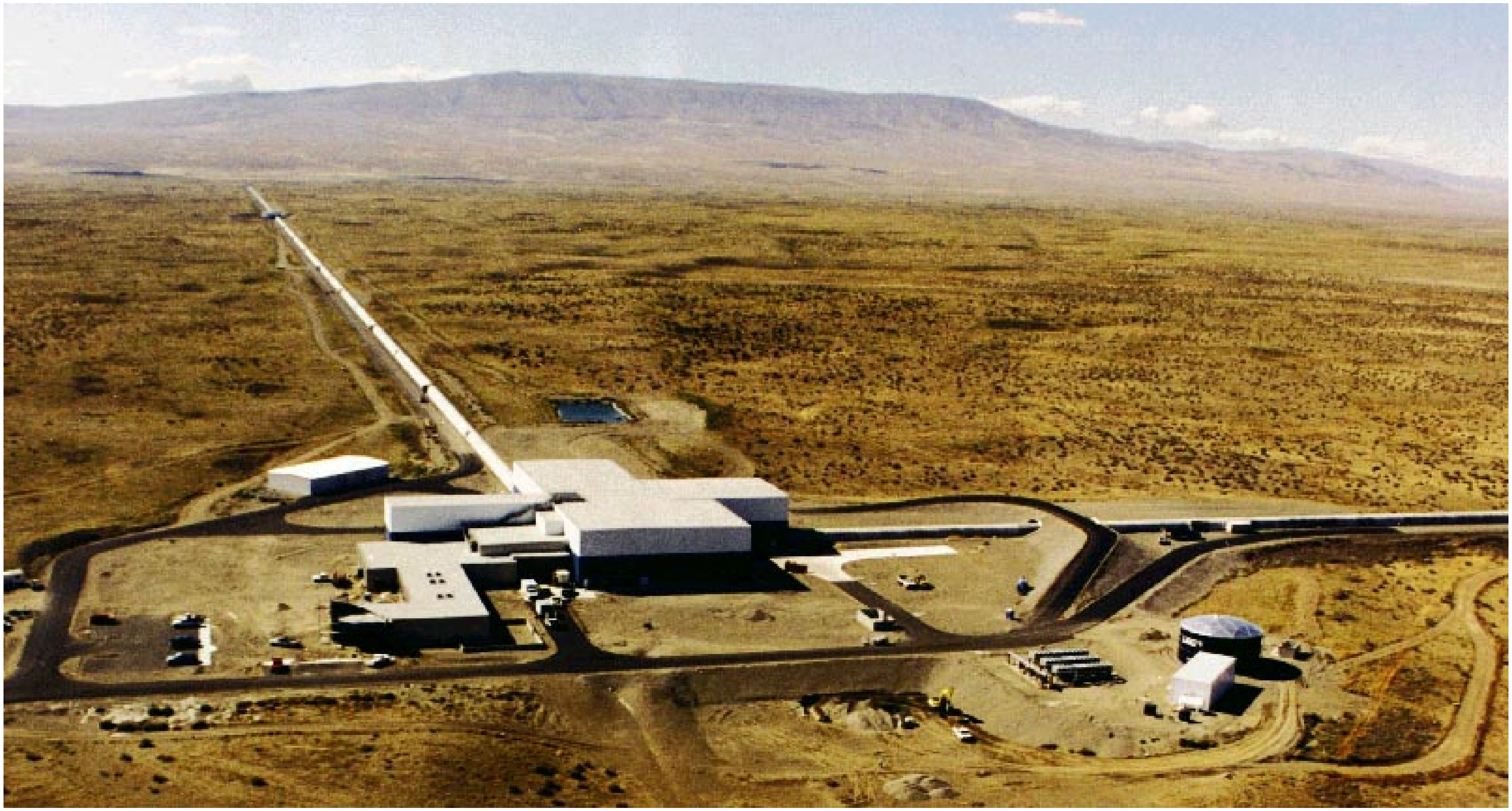
A 4-km Michelson interferometer, with mirrors on pendulum suspensions.

Site at Hanford WA has both 4-km and 2-km.

Alternate periods of data collection and commissioning.

Design sensitivity: $h_{rms} = 10^{-21}$.

LIGO Hanford Observatory



GEO 600

Vacuum Equipment

Core Optics

installation and alignment

A LIGO Mirror

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity $< 5 \times 10^{-7}$

Internal mode Q's $> 2 \times 10^{6}$

Polishing

Surface uniformity < 1 nm rms

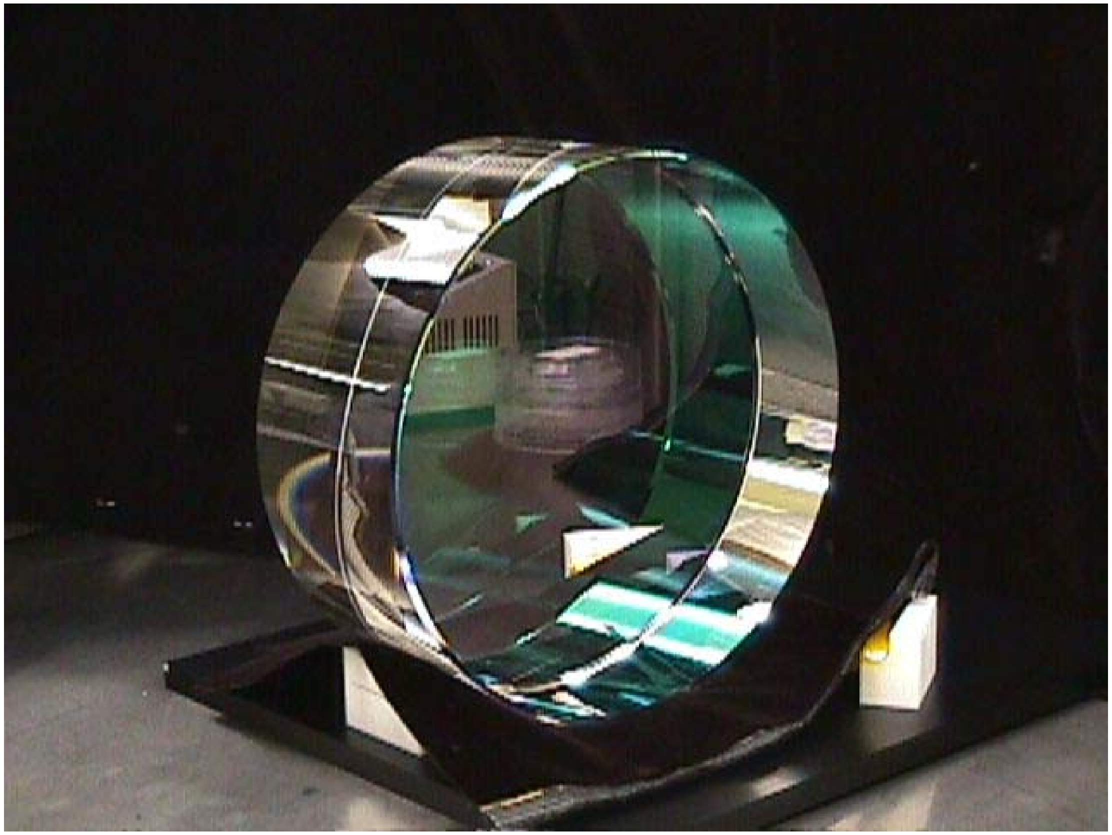
Radii of curvature matched < 3%

Coating

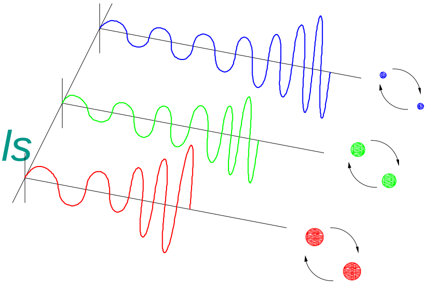
Scatter < 50 ppm

Absorption < 2 ppm

Uniformity $<10^{-3}$



We search for four classes of signals

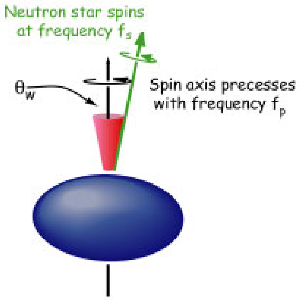


- Chirps

  "sweeping sinusoids" from compact binary inspirals

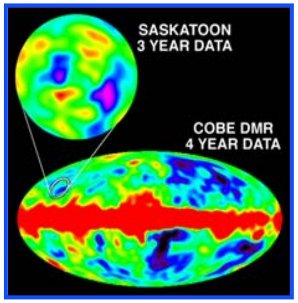
- Bursts

  transients, usually without good waveform models



- Periodic, or "CW"

  from pulsars in our galaxy

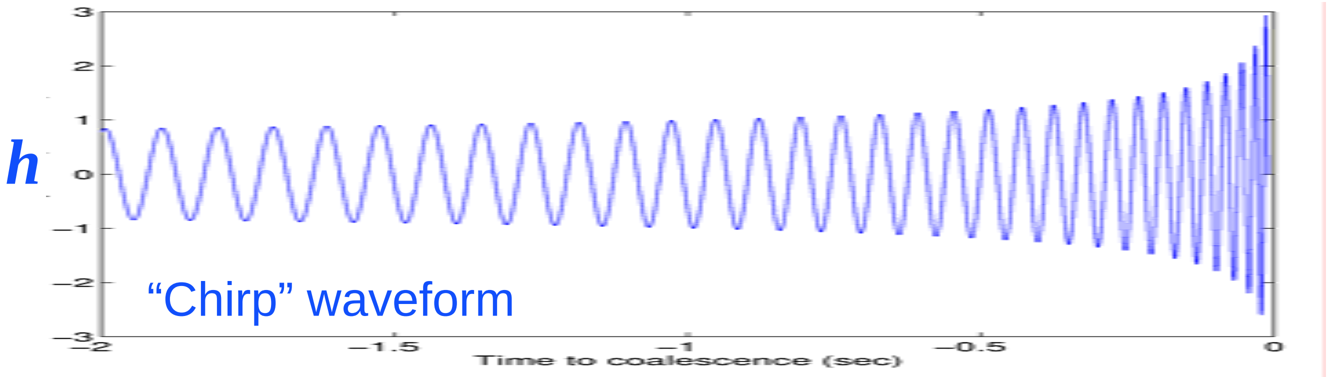


- Stochastic background

  cosmological background, or superposition of other signals

Inspiral Gravitational Waves

Compact-object binary systems lose energy due to gravitational waves. Waveform traces history.



"Chirp" waveform

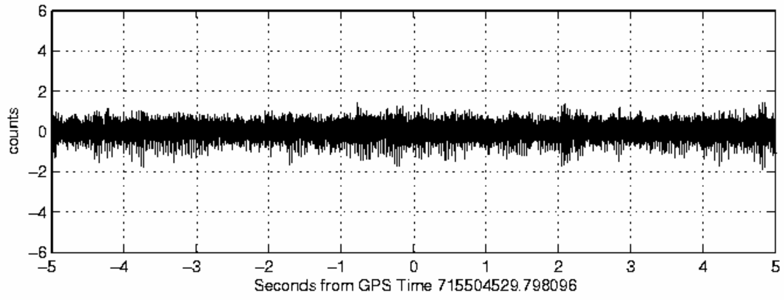
In LIGO frequency band (40–2000 Hz) for a short time just before merging:
anywhere from a few minutes to <<1 second, depending on mass.

Waveform is known accurately for objects up to ~3 $M_\odot$

➔ Use *matched filtering.*

Matched filtering

GW Channel
+ simulated inspiral



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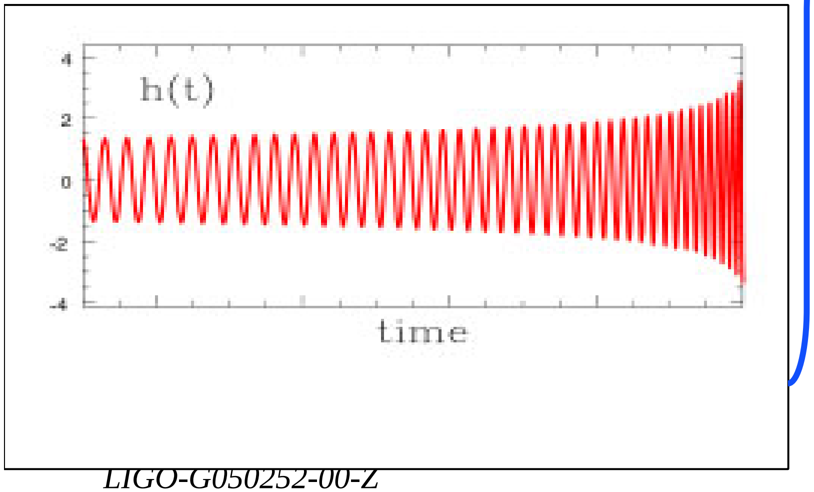
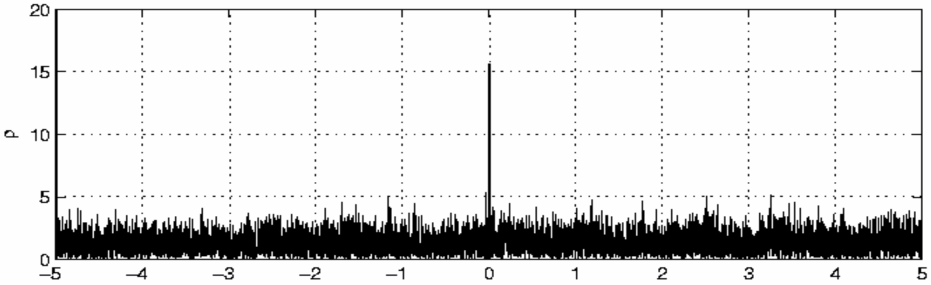
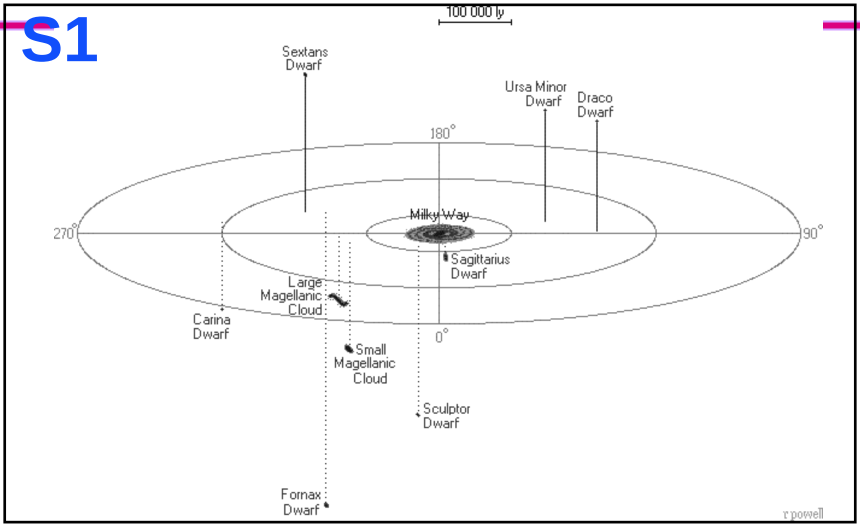


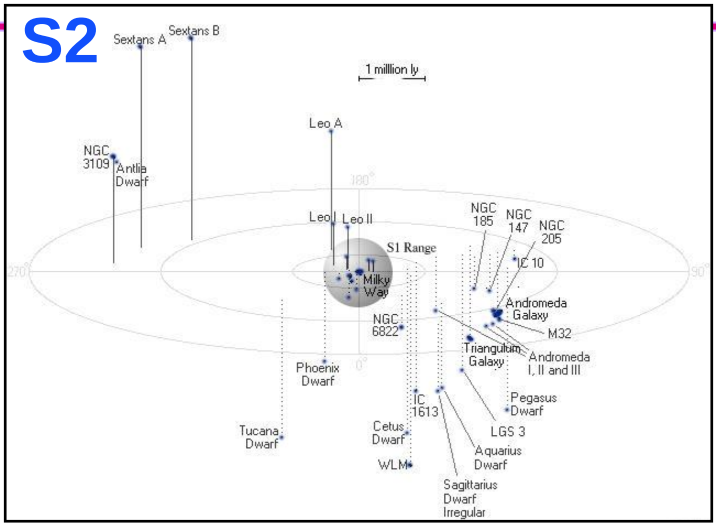
SNR

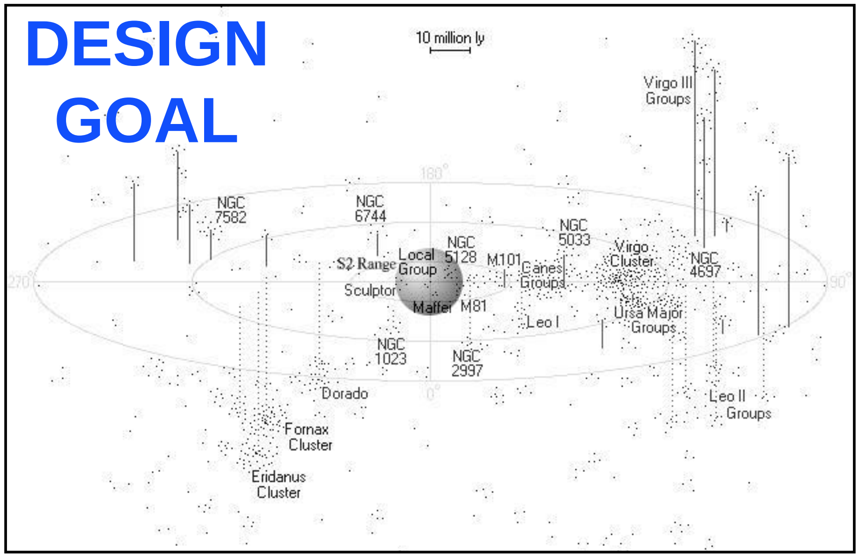


Coalescence Time

Range for Binary NS







Based on 2nd Science Run (S2), we have set a limit of fewer than 47 inspiral events per year per Milky Way Equivalent Galaxy.

Data already “in the can” should let us do much better.

Images: R. Powell

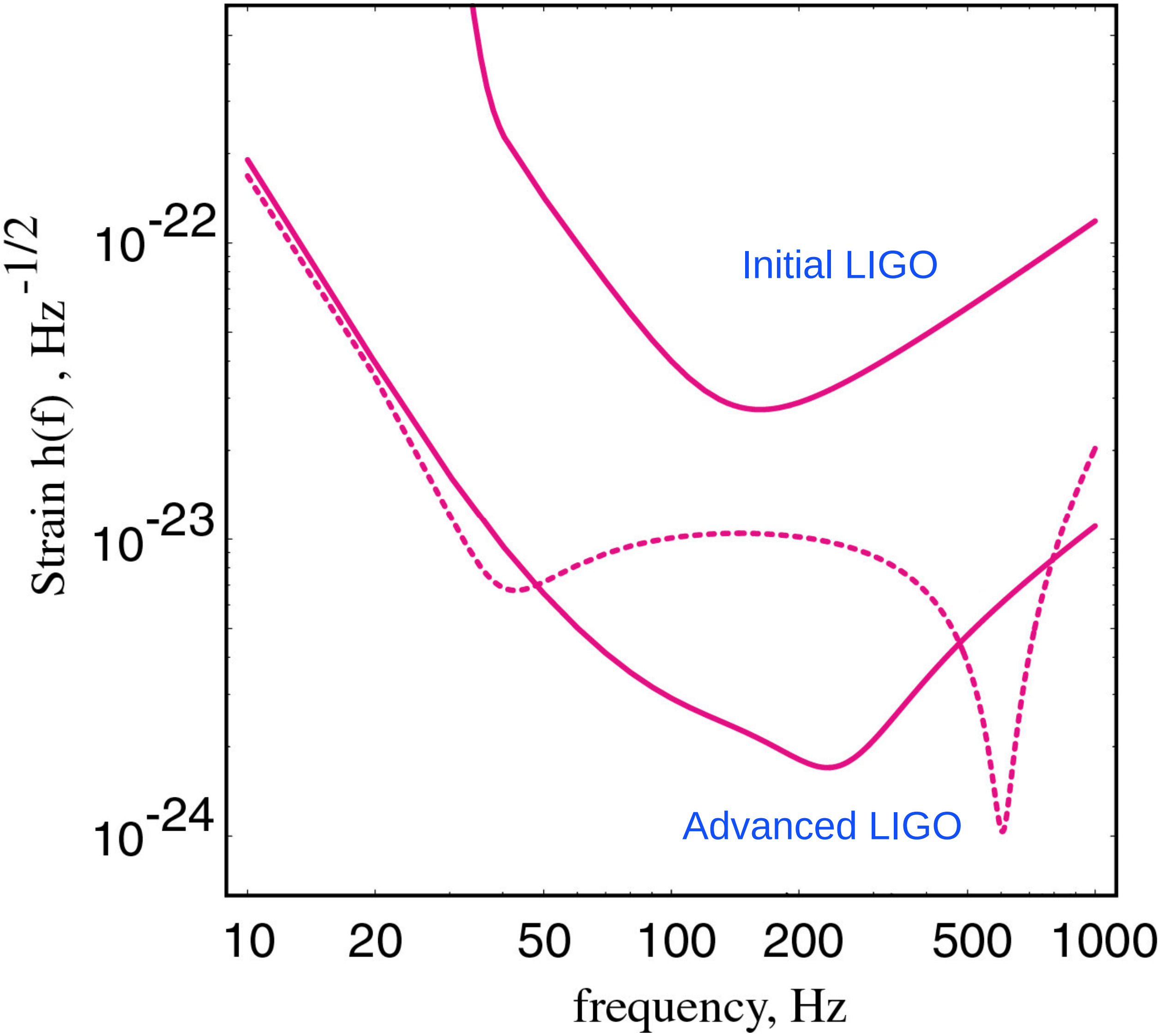
Coming Soon: Advanced LIGO

Much better sensitivity:

- ~10x lower noise
- ~4x lower frequency
- tunable

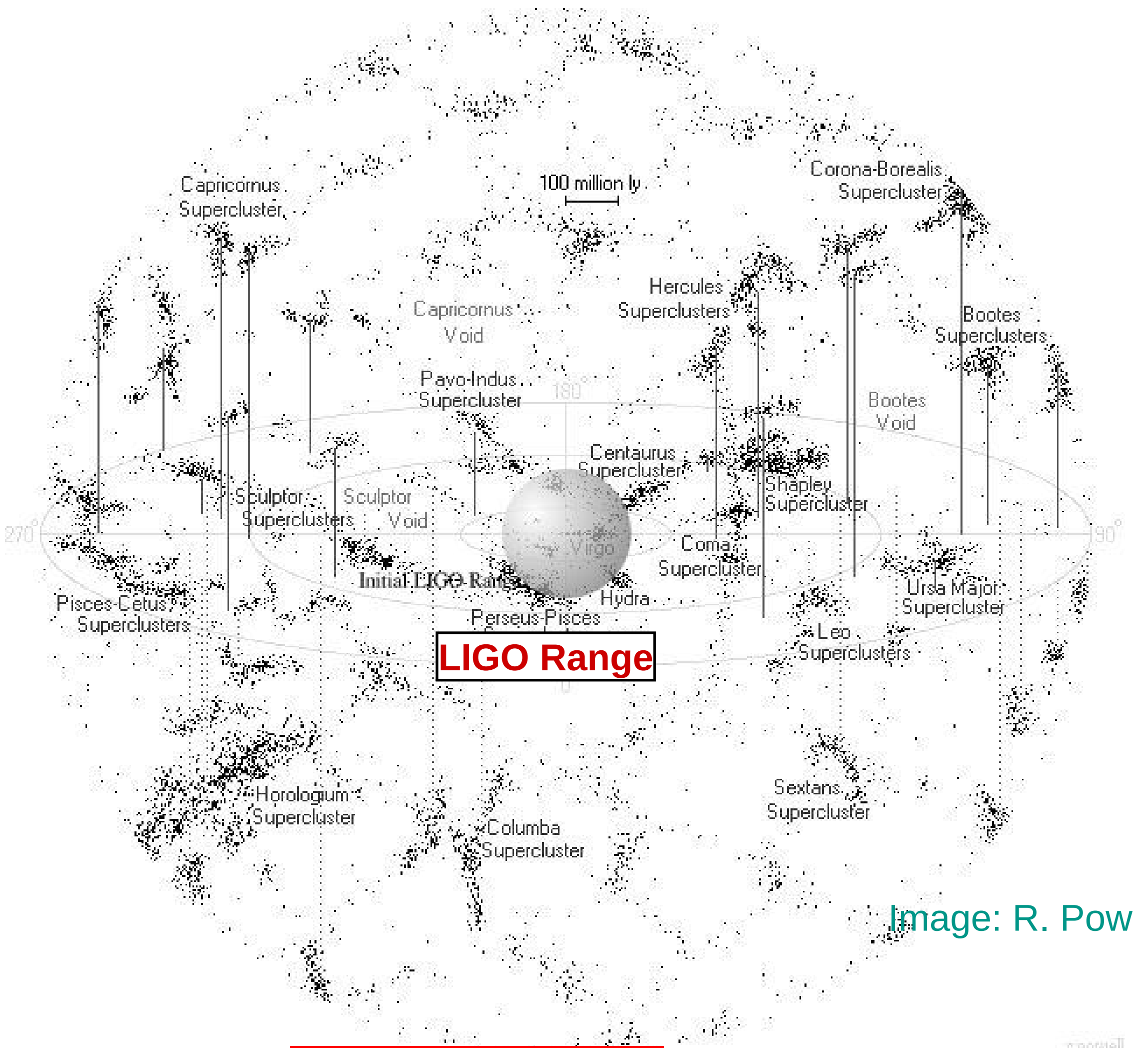
Through these features:

- Fused silica multi-stage suspension
- ~20x higher laser power
- Active seismic isolation
- Signal recycling
- Quantum engineering
  rad'n pressure *vs.* shot noise



Advanced LIGO’s reach

- Neutron star binaries
  - Range =350Mpc
  - N ~ 2/(yr) – 3/(day)
- Black hole binaries
  - Range=1.7Gpc
  - N ~ 1/(month) – 1/(hr)
- BH/NS binaries
  - Range=750Mpc
  - N ~ 1/(yr) – 1/(day)



LIGO Range

Image: R. Powell

Advanced LIGO Range