LIGO and the Search for Einstein's Gravitational Waves

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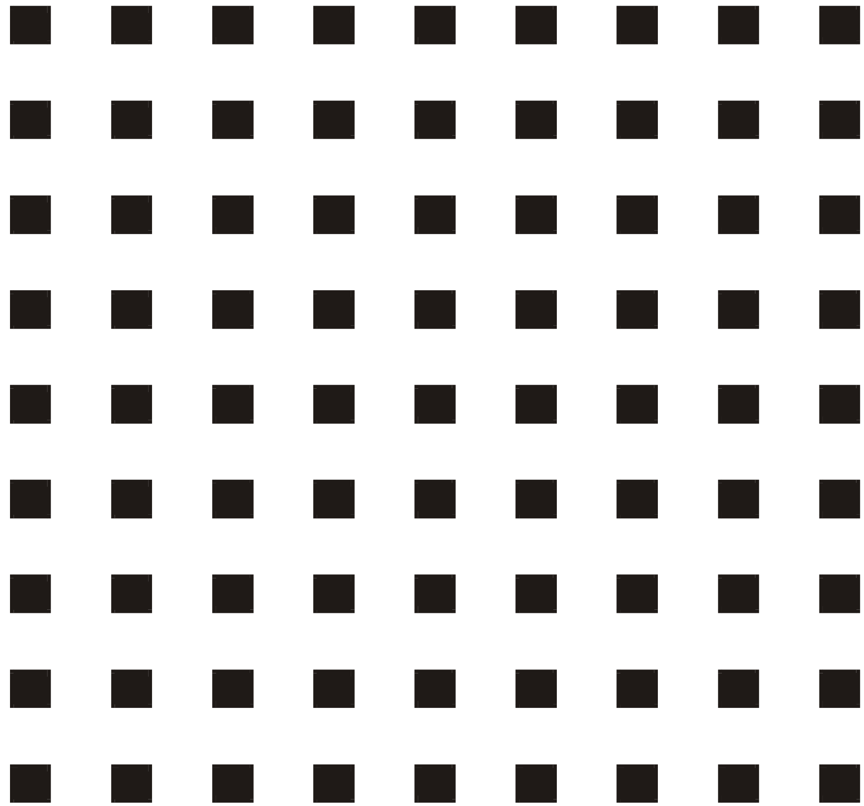
Outline

- What are gravitational waves, and
  why are they interesting?
- How do gravitational wave detectors work?
- How well do gravitational wave detectors work?
- How do we look for signals in our data?
- Prospects for the search

A set of freely-falling test masses



A gravitational wave meets some test masses

- Transverse

  No effect along direction of propagation

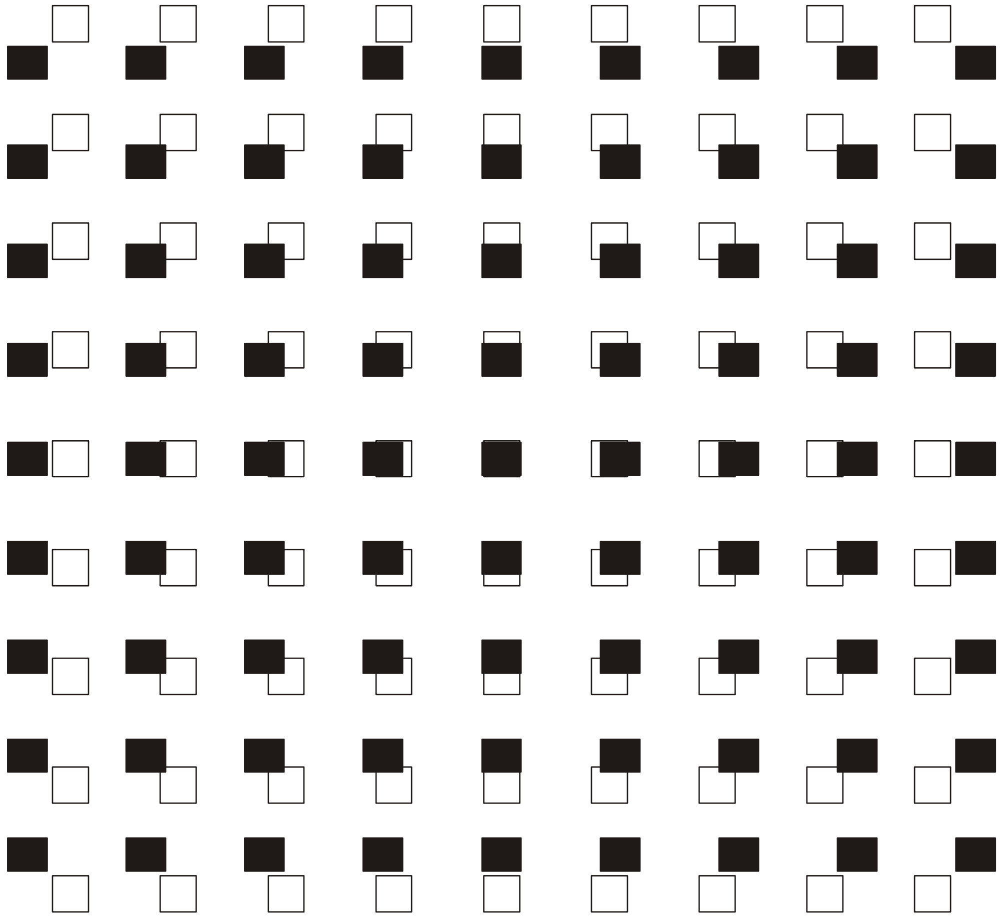
- Quadrupolar

  Opposite effects along *x* and *y* directions

- Strain

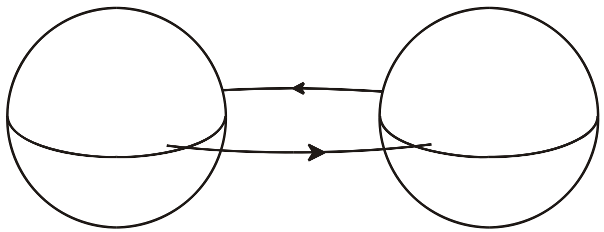
  Larger effect on longer separations

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

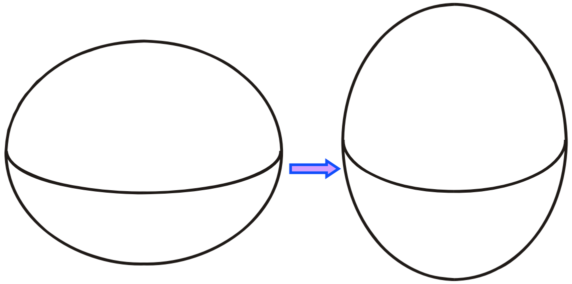


Gravitational wave sources: time-varying quadrupole moments

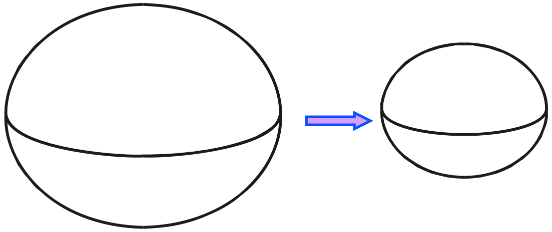
Binary stars (especially compact objects, e.g. neutron stars or black holes.)



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:

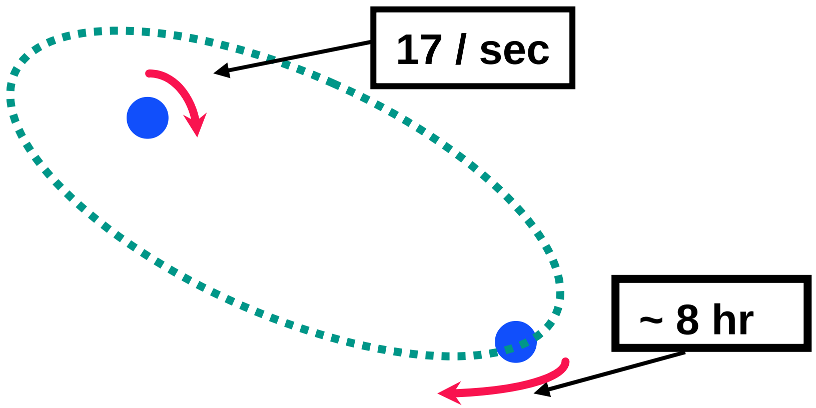
$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

I is the mass quadrupole moment of the source.

Coherent relativistic motion of large masses can be directly observed.

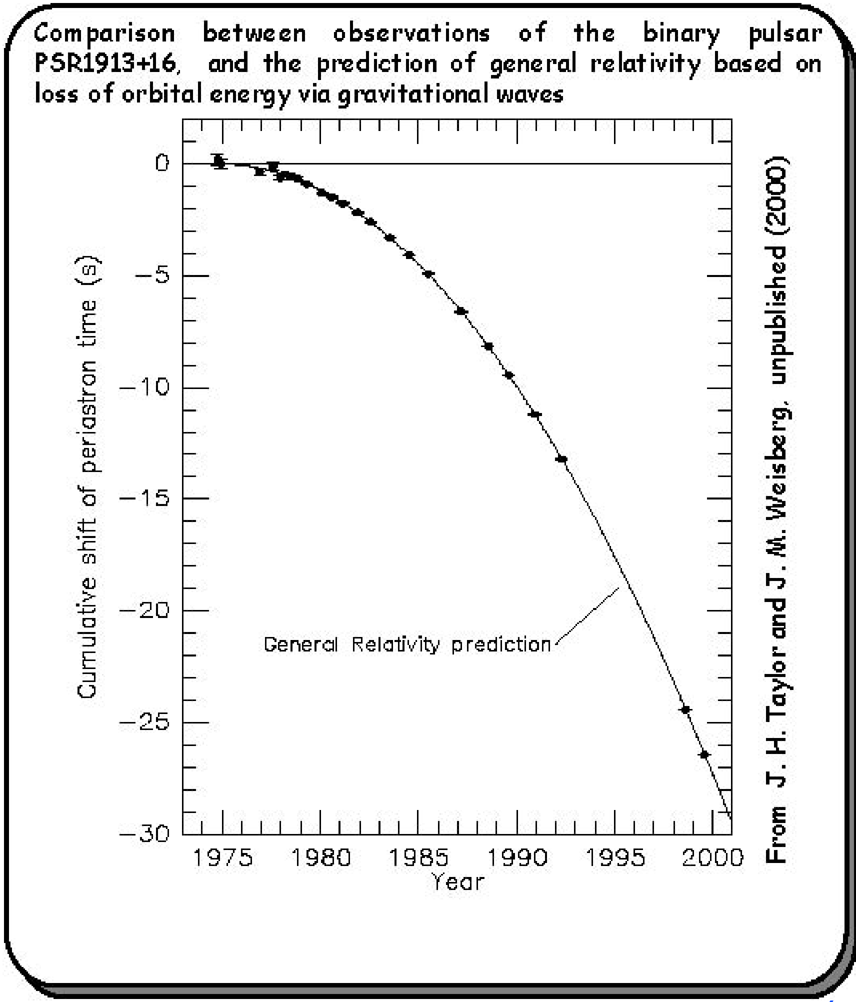
How do we know that gravitational waves exist?

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

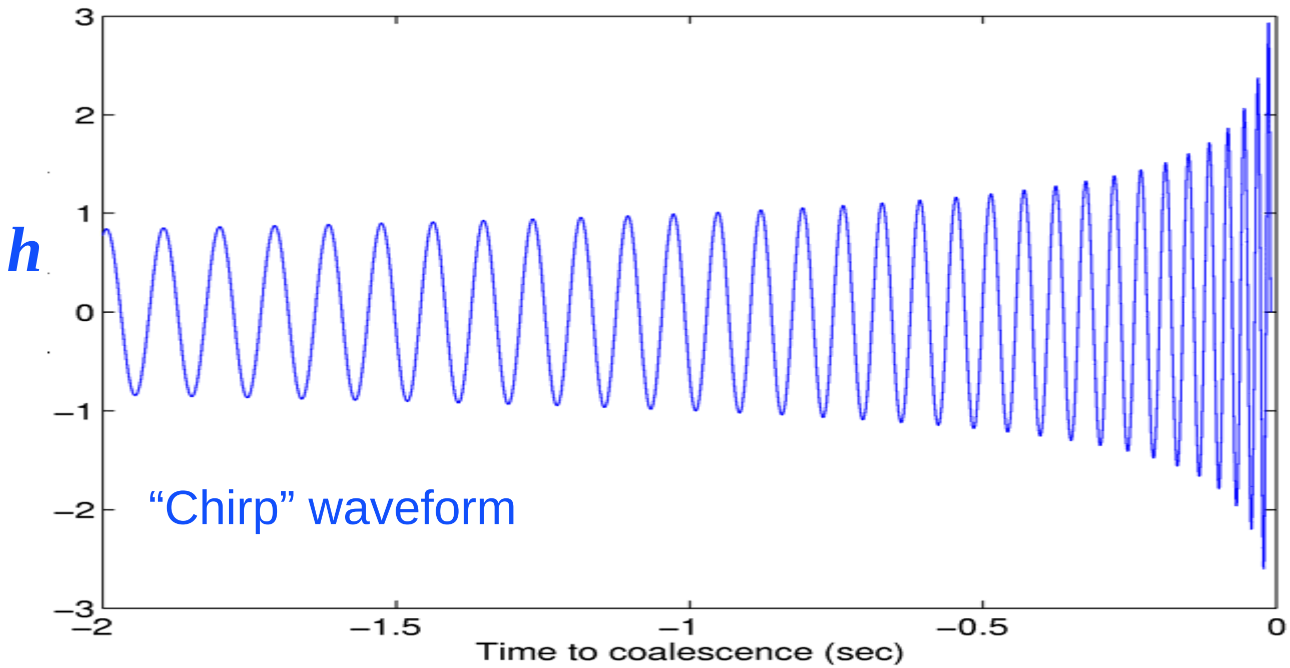


Prediction from general relativity:
spiral in by 3 mm/orbit

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



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.

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

"Post-Newtonian expansion" in powers of (Gm/rc^2) is adequate.

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
- 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.

A perfect window into the world of Einstein's gravity.

Gravitational wave detectors

Need:

» A set of test masses,

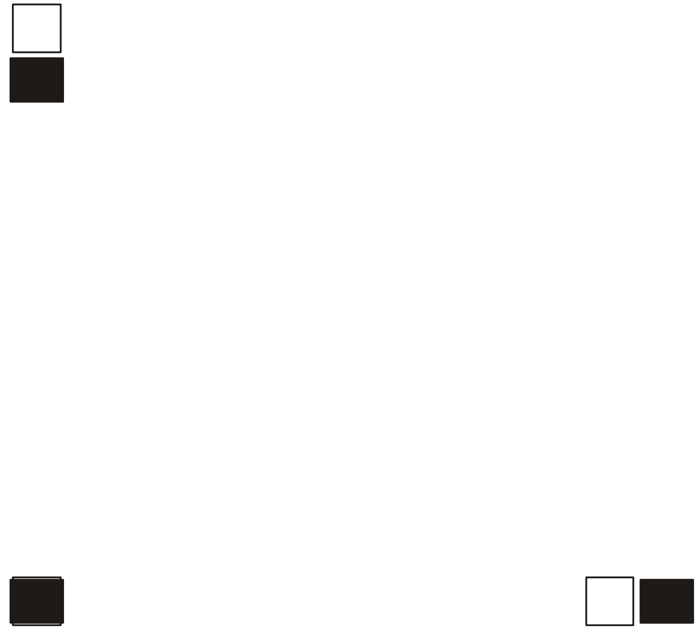
» Instrumentation sufficient to see tiny motions,

» Isolation from other causes of motions.

Challenge:

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

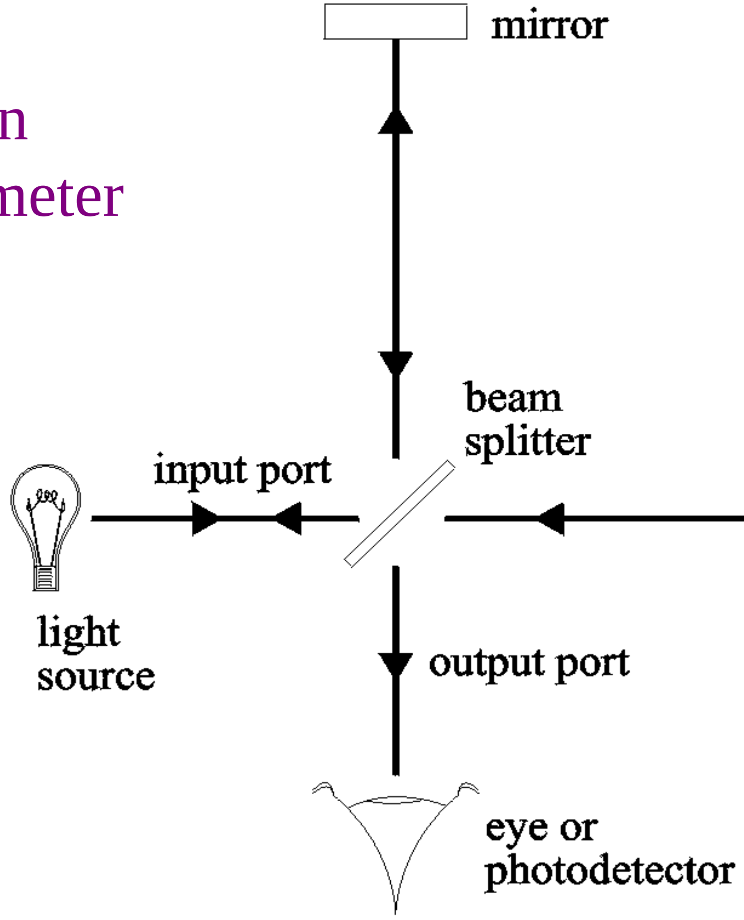
A detection strategy



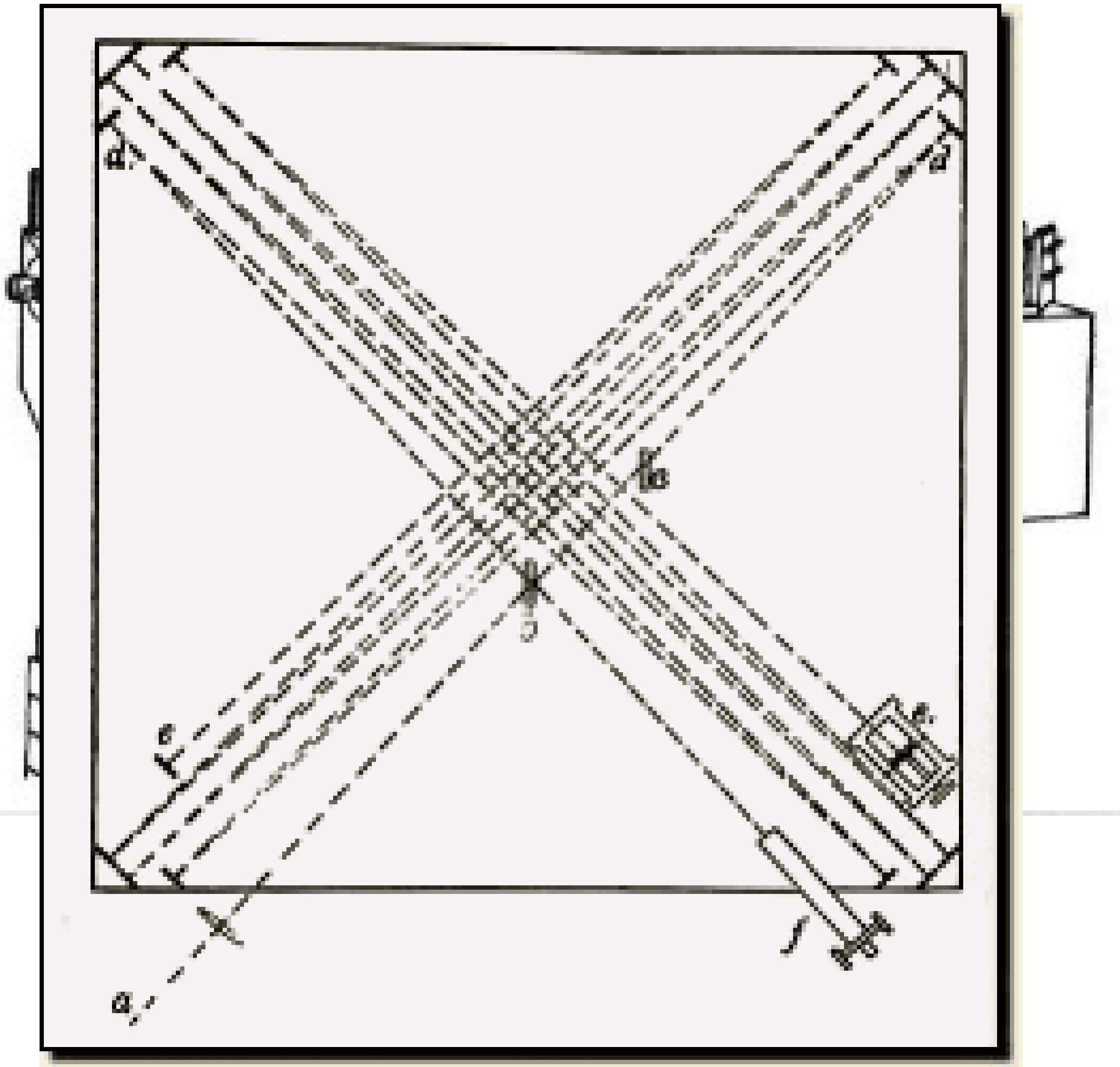
Strain character of wave argues for test masses as far apart as practicable. Perhaps masses hung as pendulums, kilometers apart.

Sensing relative motions of distant free masses

Michelson interferometer



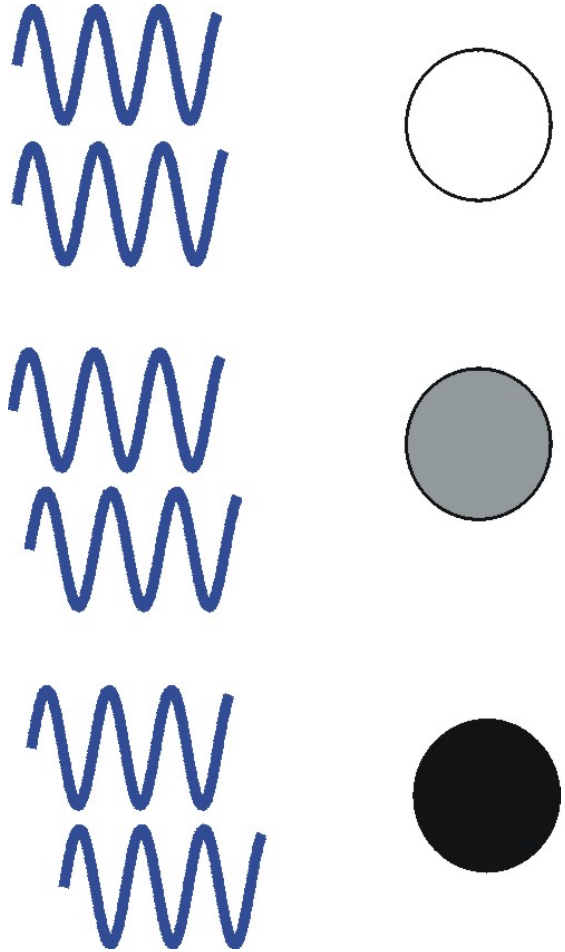
Michelson and Morley's apparatus, 1887



A transducer from length difference to brightness

Wave from x arm.

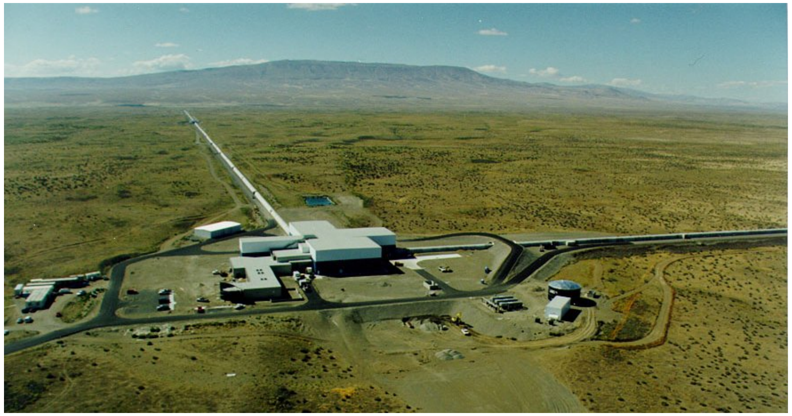
Wave from y arm.



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.

LIGO and GEO



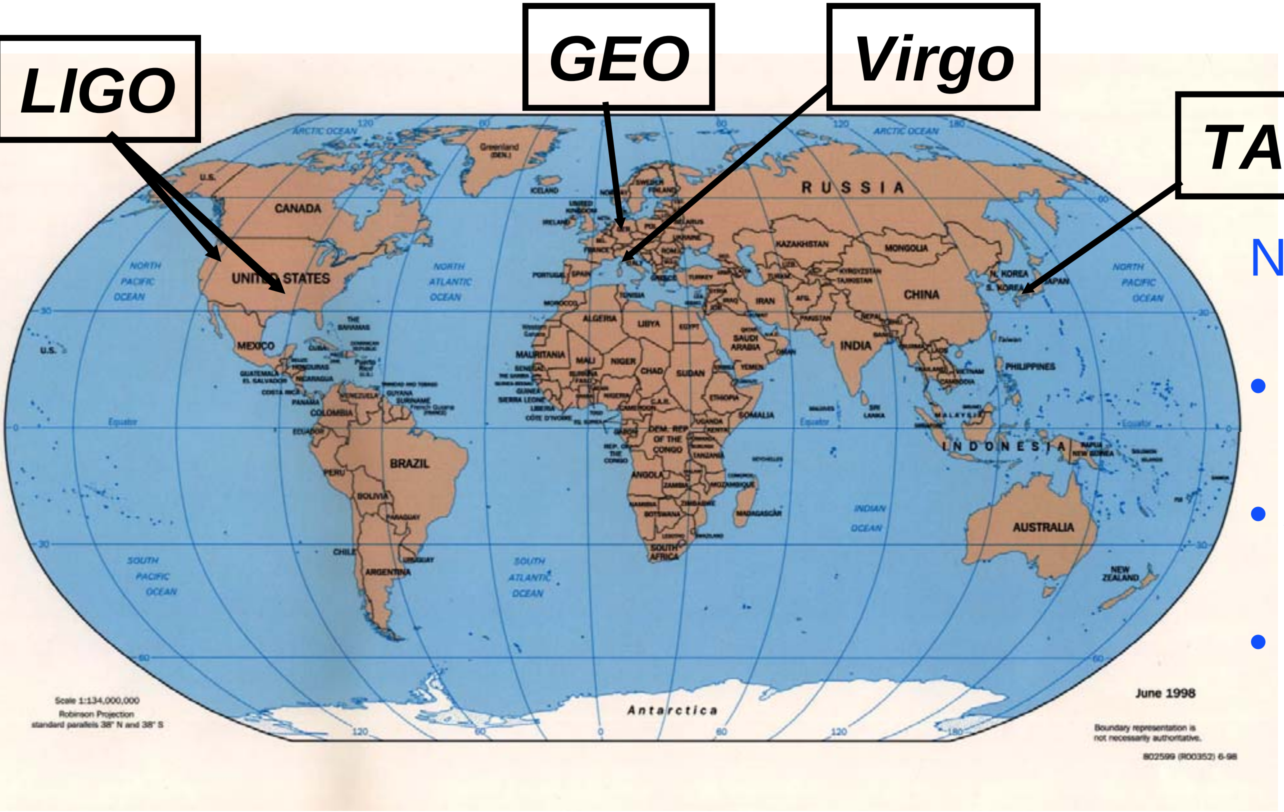
The LIGO Scientific Collaboration analyzes data from four interferometers:

•4 km and 2 km interferometers at LIGO Hanford Observatory

•4 km interferometer at LIGO Livingston Observatory

•GEO600 (U.K./Germany)

International Network of Interferometers



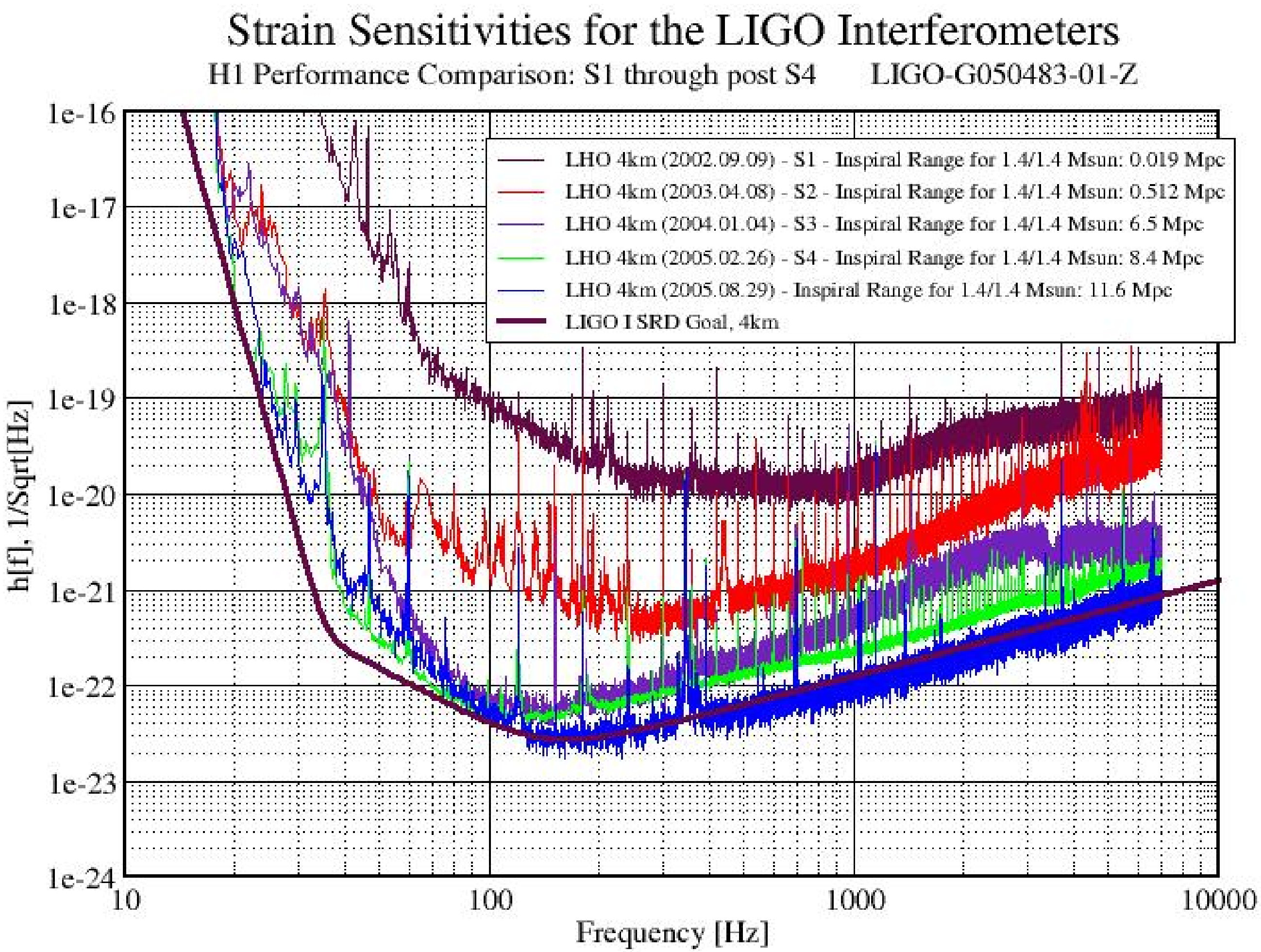
Network yields:

- detection confidence
- source localization
- polarization measurement

The state of the art

Over the past 3 years, LIGO has rapidly approached its design sensitivity.

h(f) = 10^{-22} /Sqrt[Hz]→



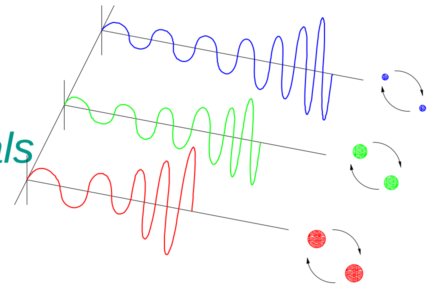
100 Hz

Frequency [Hz]

We search for four classes of signals

- Chirps

  "sweeping sinusoids" from compact binary inspirals

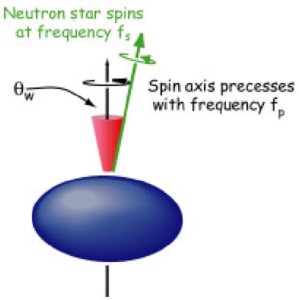


- Bursts

  transients, usually without good waveform models

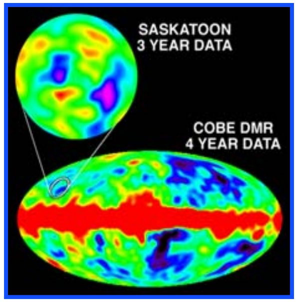
- Periodic, or "CW"

  from pulsars in our galaxy



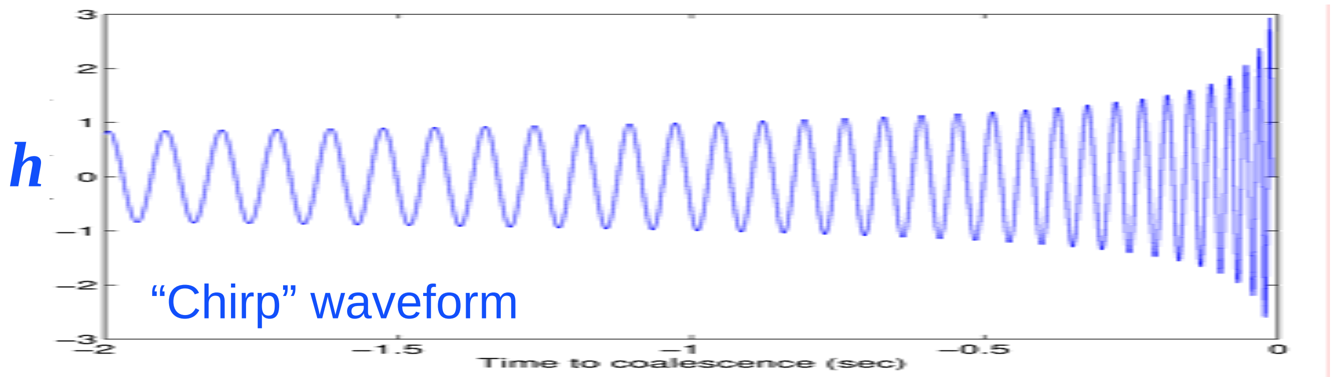
- Stochastic background

  cosmological background, or superposition of other signals



Inspiral Gravitational Waves

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



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.

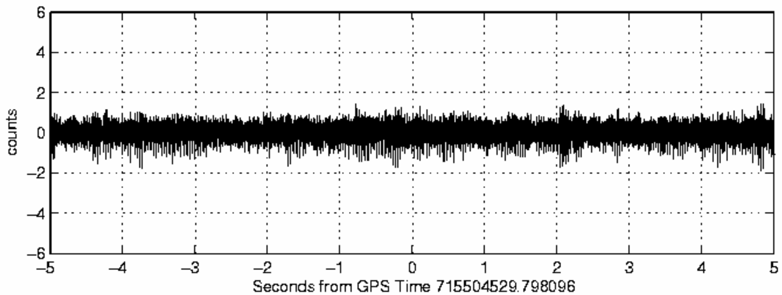
Waveform is known accurately

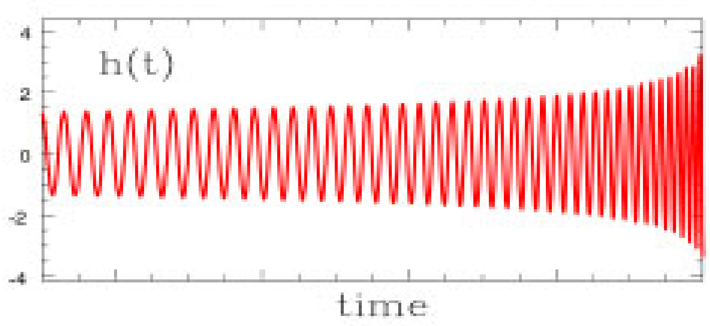
for objects up to ~3 $M_\odot$

➔ Use *matched filtering.*

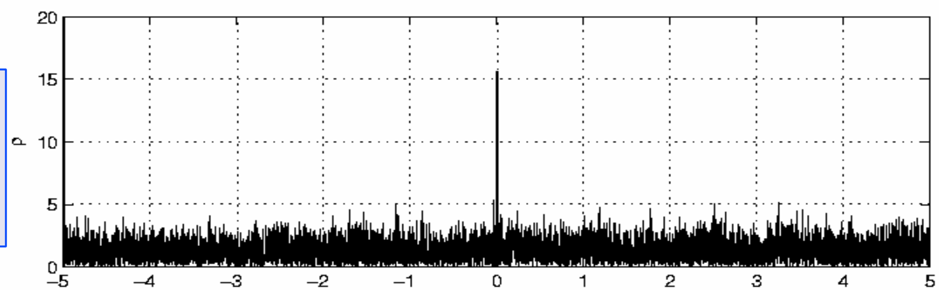
Matched filtering

GW Channel
+ simulated inspiral



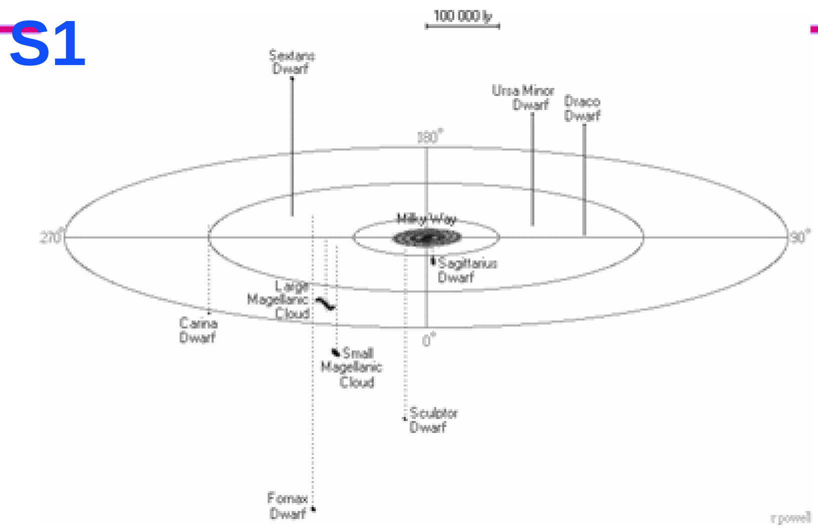


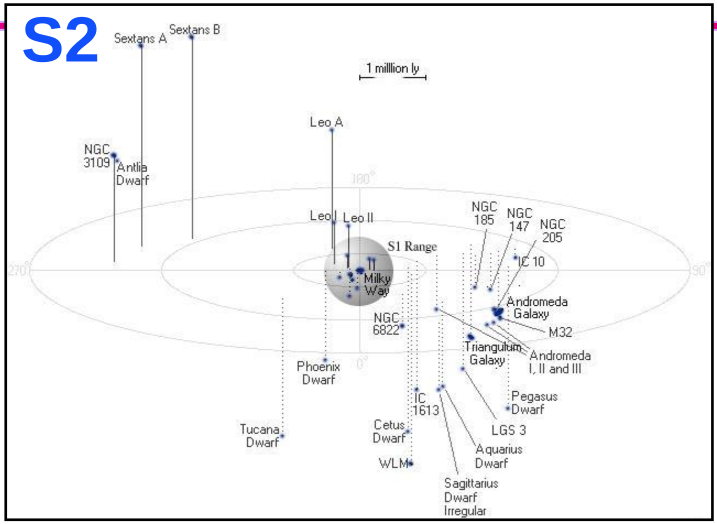
SNR

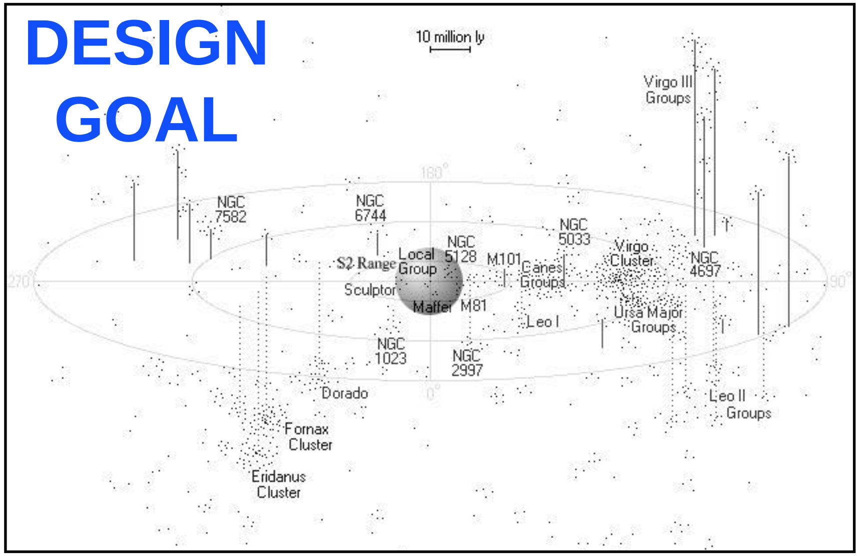


Coalescence Time

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. New results expected soon.

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Images: R. Powell

Coming Soon: Advanced LIGO

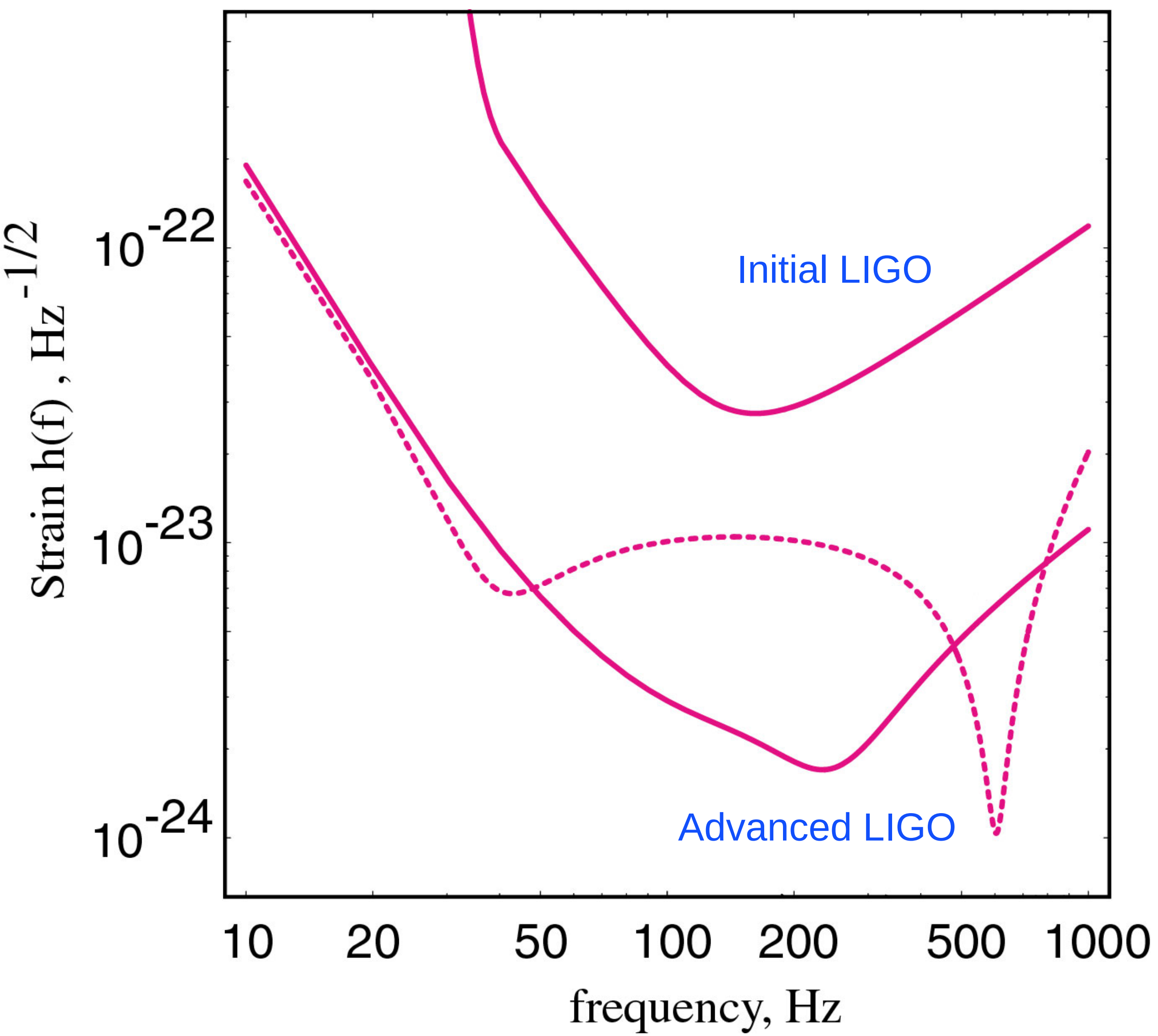
Much better sensitivity:

- ~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)

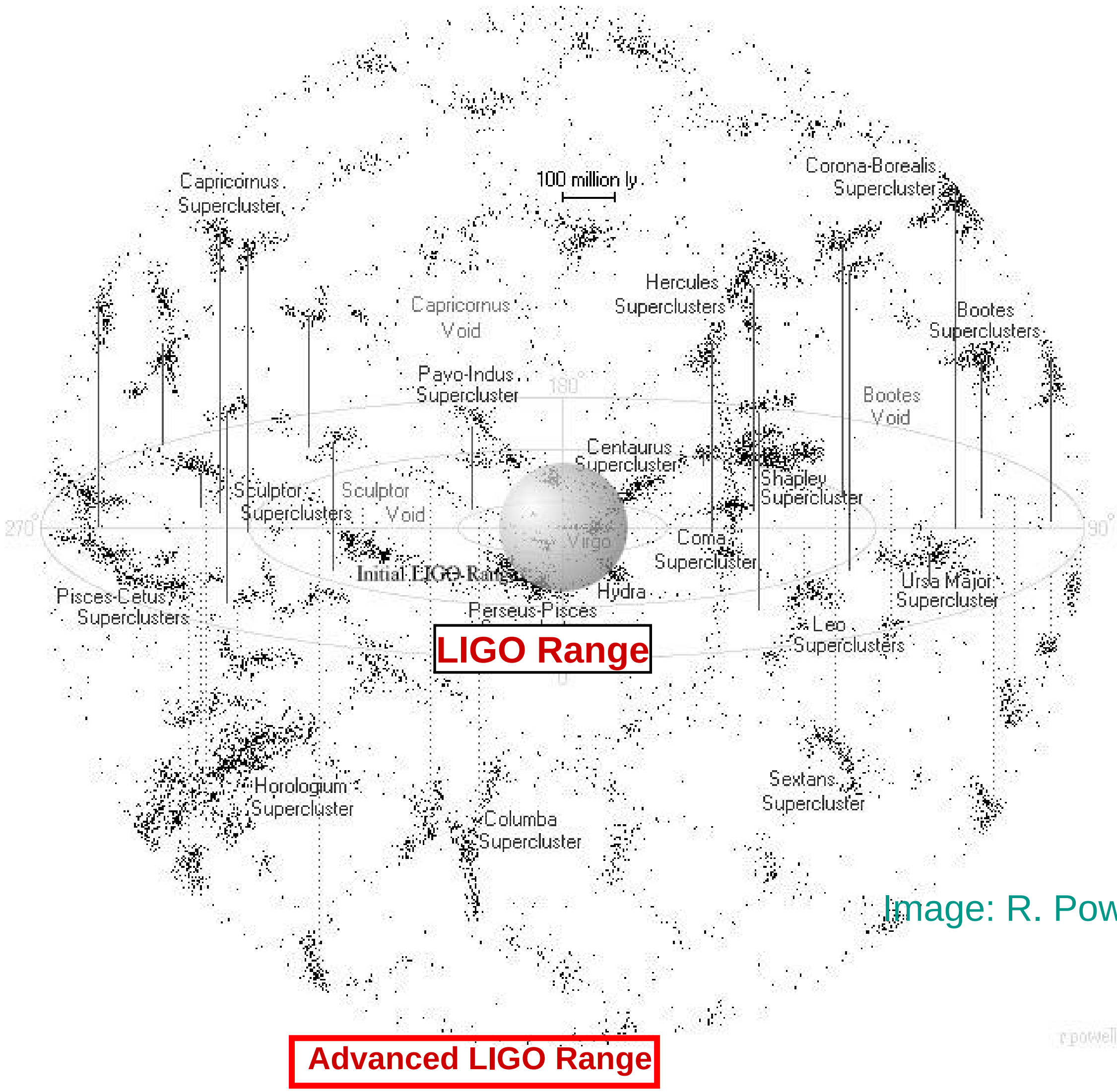


Image: R. Powell

Prospects

Next month, LIGO begins a long science run at design sensitivity. This will be the fulfillment of the investment to date.

Perhaps we'll detect signals, although it is not guaranteed.

We hope to hear soon that Advanced LIGO will be built in a few years.

If so, then the opening of the gravitational wave window is just about assured.