Status of LIGO

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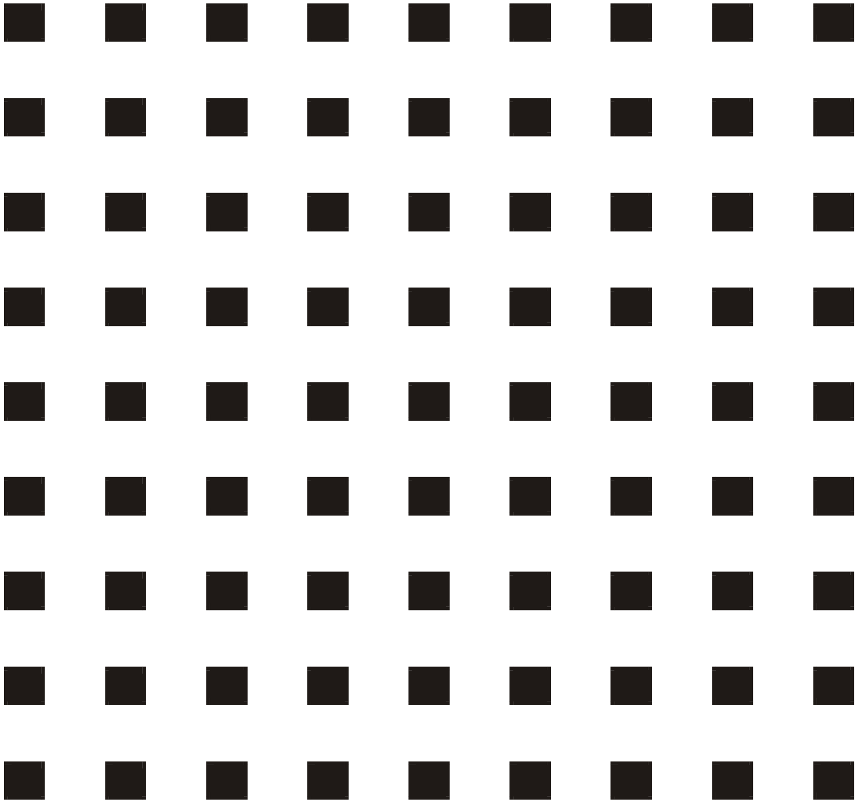
Outline

- 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

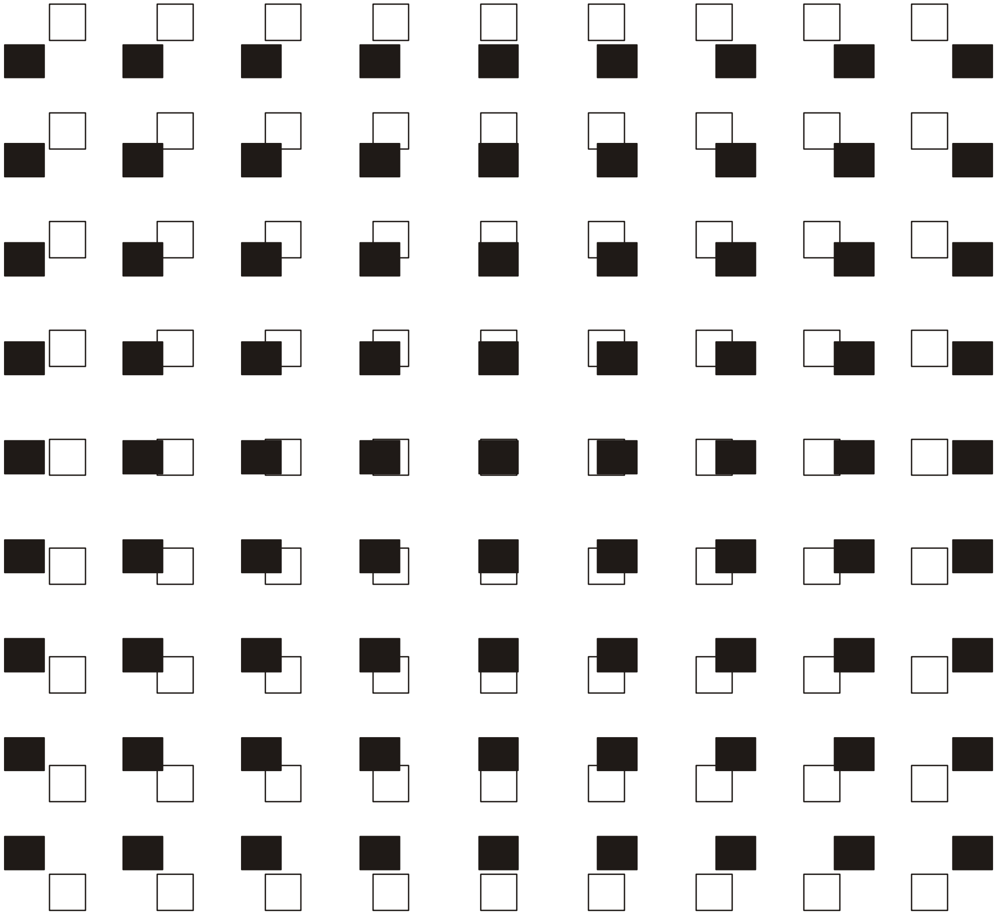
- Quadrupolar

  Opposite effects along *x* and *y* directions

- Strain

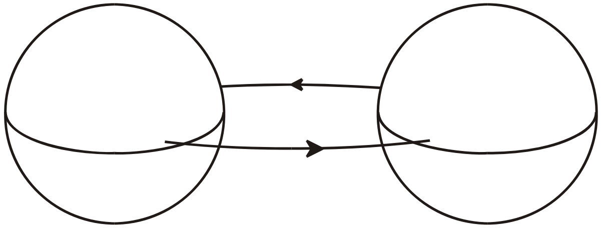
  Larger effect on longer separations

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

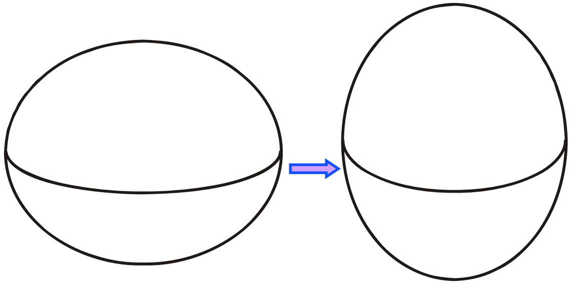


Gravitational wave sources: time-varying quadrupole moments

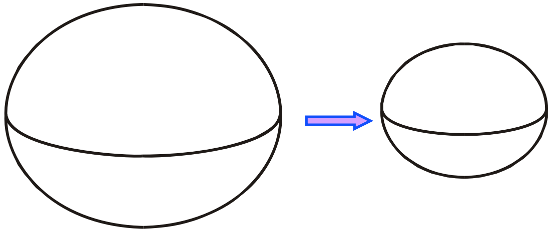
Binary stars (especially compact objects, e.g. neutron stars or black holes.)



Compact objects just after formation from core collapse.



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

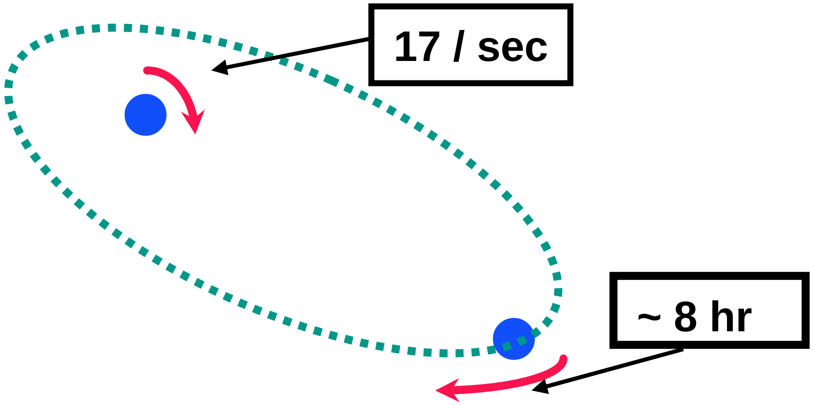


How do we know that gravitational waves exist?

Neutron Binary System – Hulse & Taylor

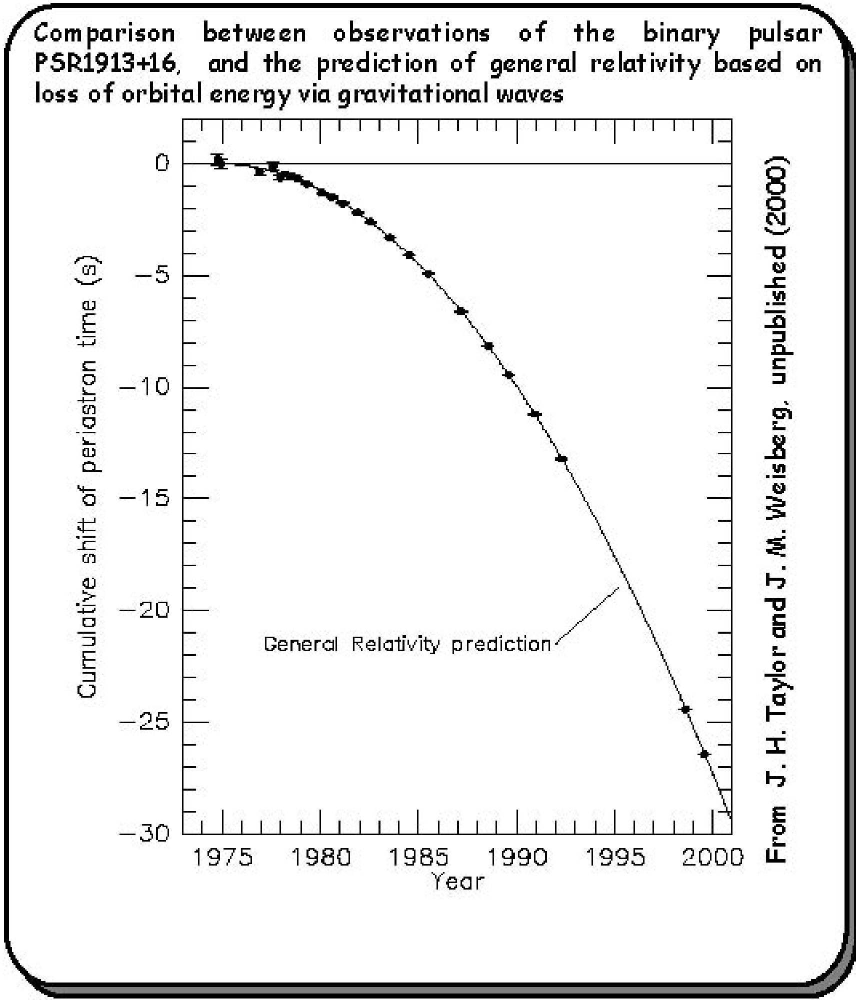
Timing of pulsar - Nobel prize 1993

Periastron change: 30 sec in 25 years



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

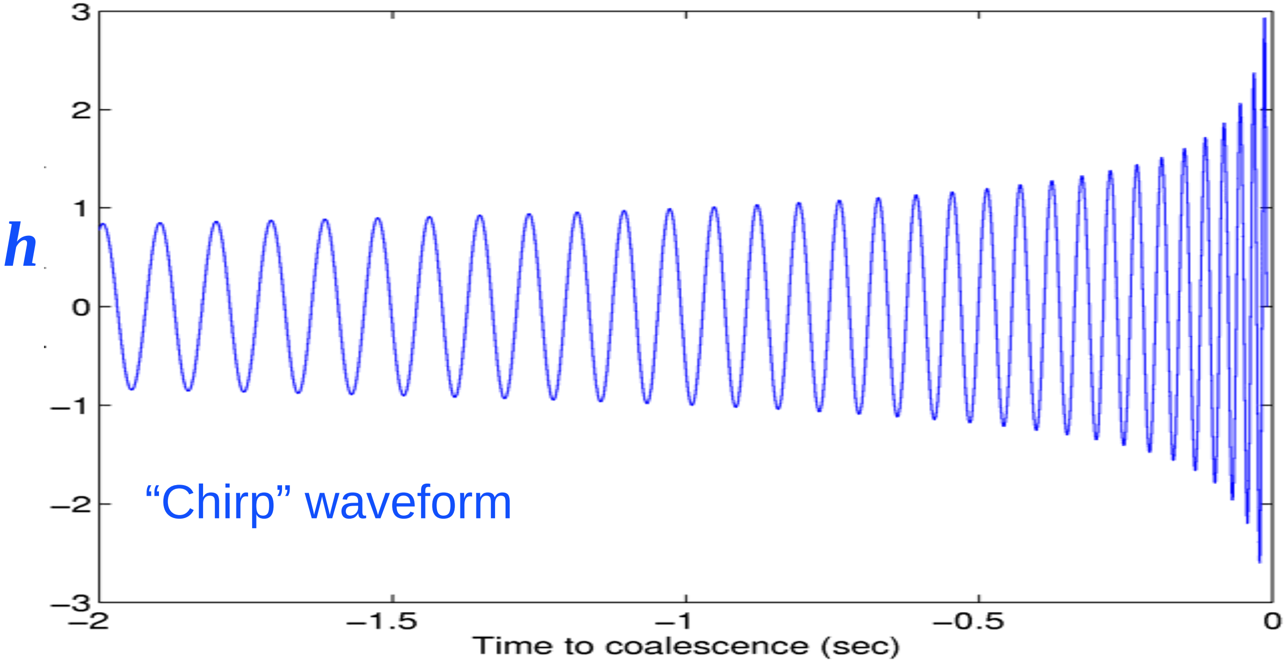
This is caused by the loss of energy carried away by gravitational waves, due to binary's time varying quadrupole moment.



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

From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Compact binaries 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

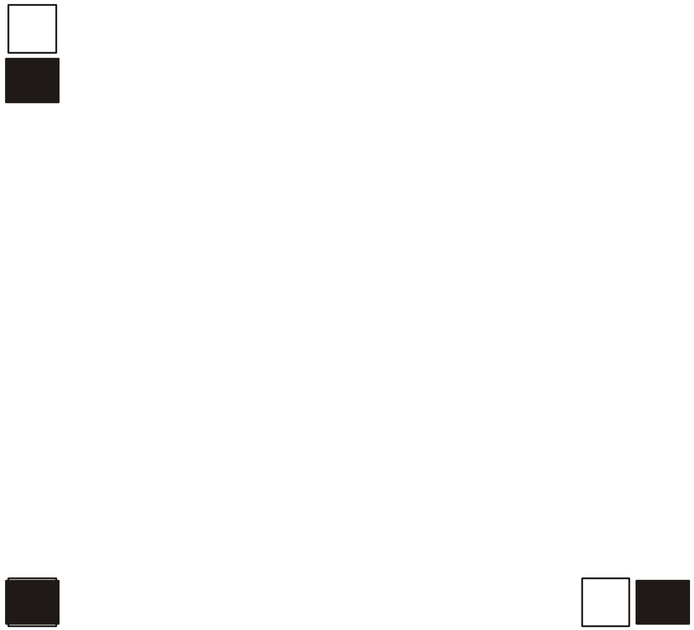
Need:

- » 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.

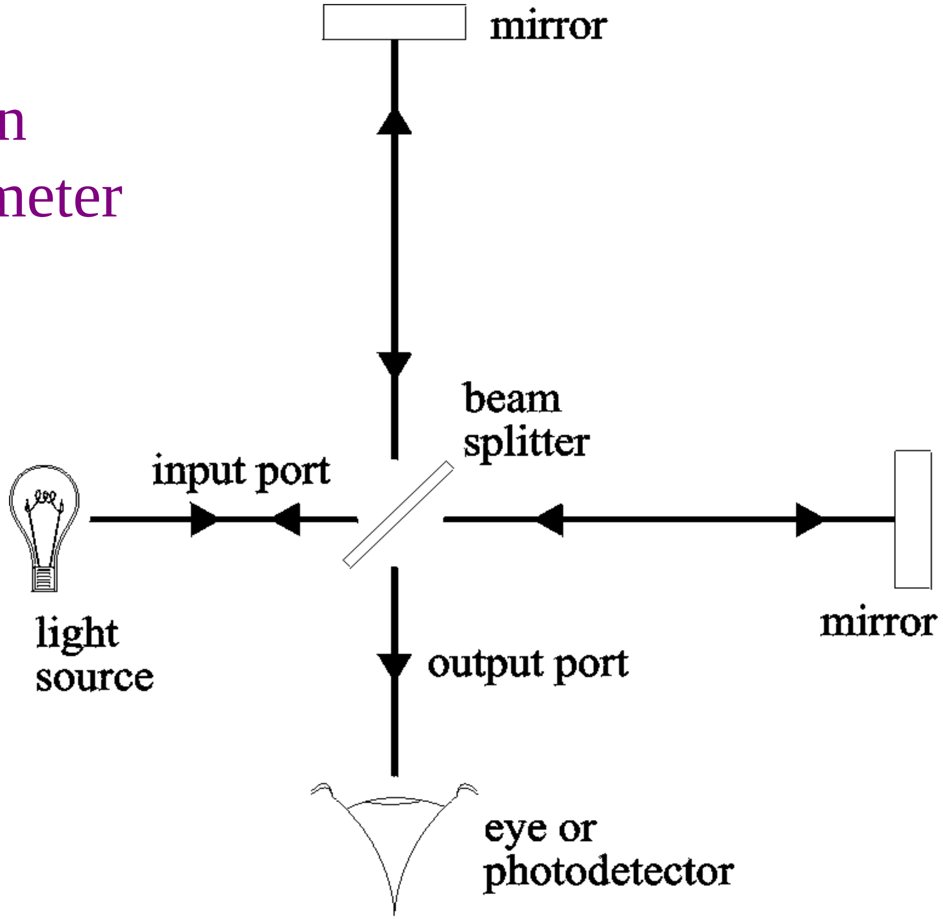
A detection strategy



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

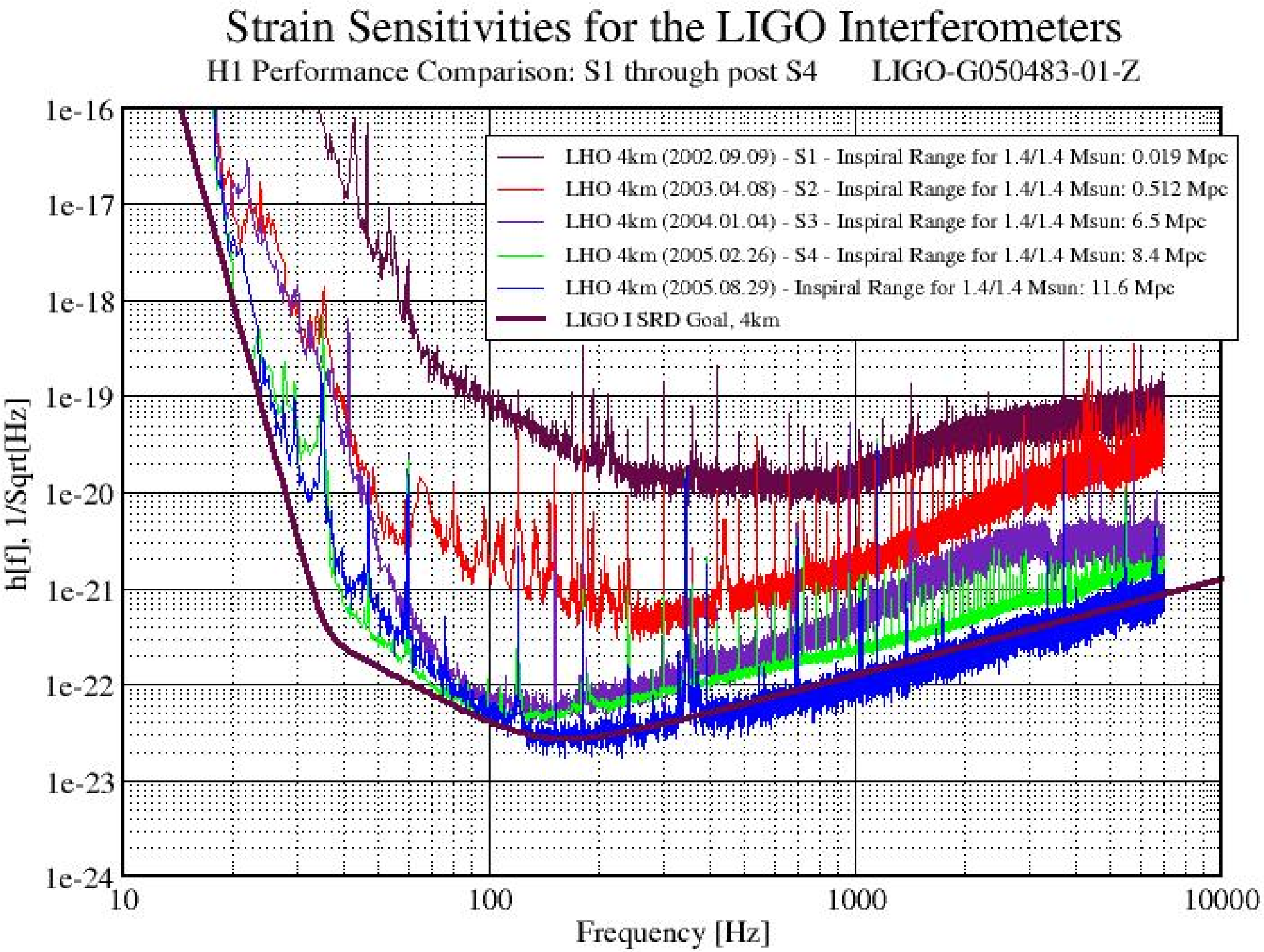
Michelson interferometer



The state of the art

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

h(f) = 10^{-22} /Sqrt[Hz]→



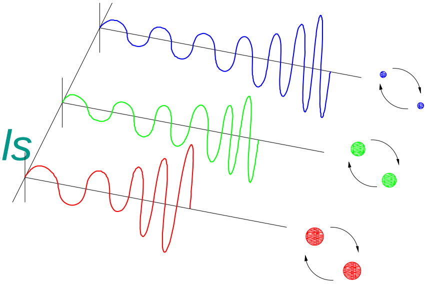
100 Hz

Frequency [Hz]

We search for four classes of signals

- Chirps

  "sweeping sinusoids" from compact binary inspirals

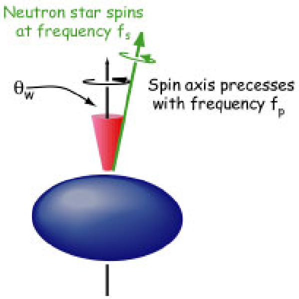


- Bursts

  transients, usually without good waveform models

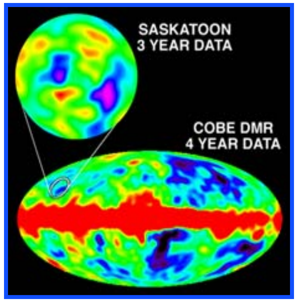
- Periodic, or "CW"

  from pulsars in our galaxy



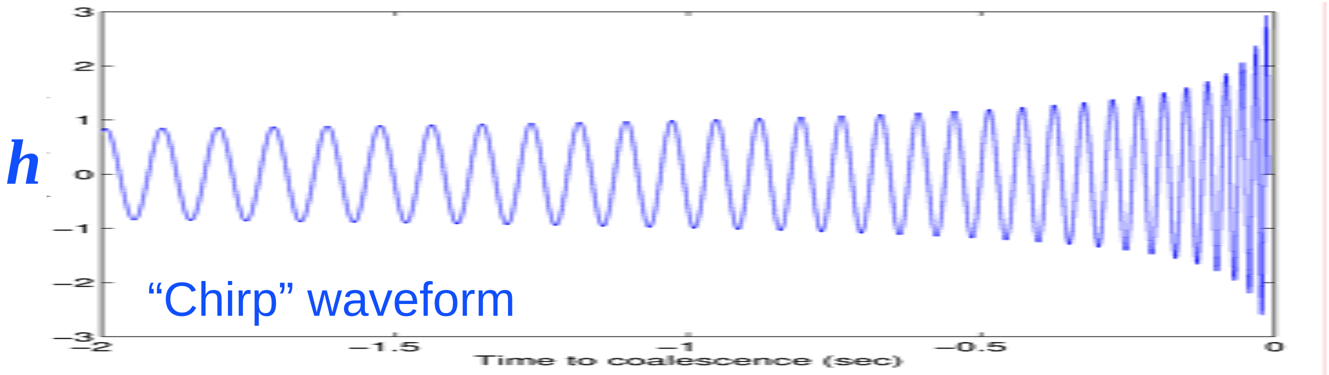
- Stochastic background

  cosmological background, or superposition of other signals



Inspiral Gravitational Waves

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



“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.

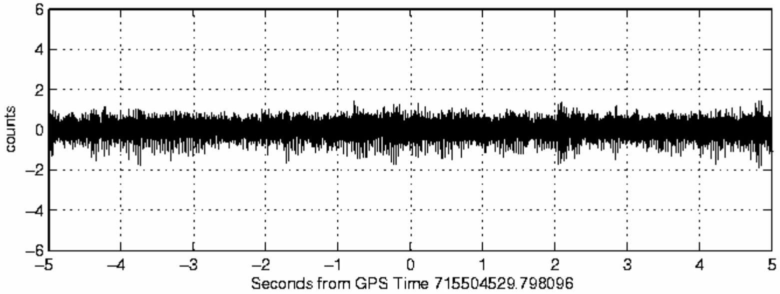
Waveform is known accurately

for objects up to ~3 $M_\odot$

➔ Use *matched filtering.*

Matched filtering

GW Channel
+ simulated inspiral



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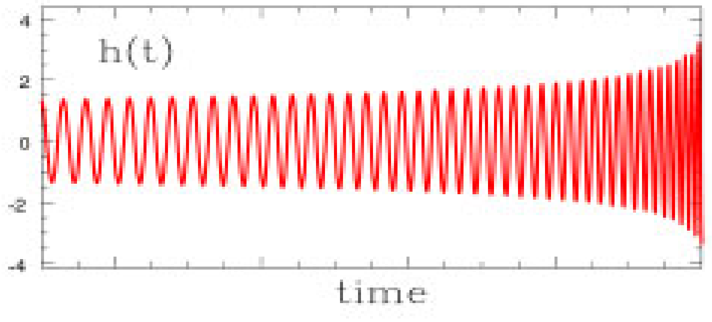
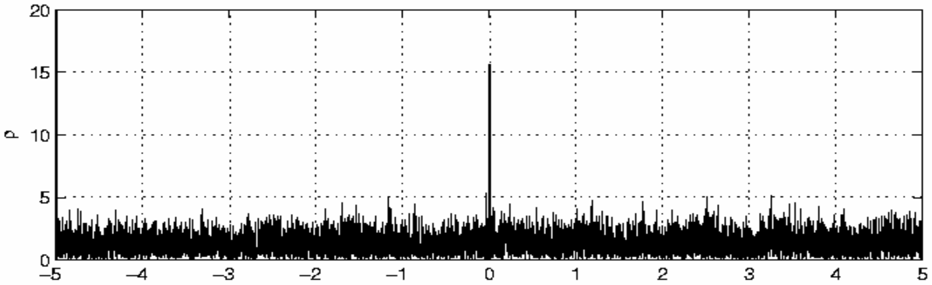


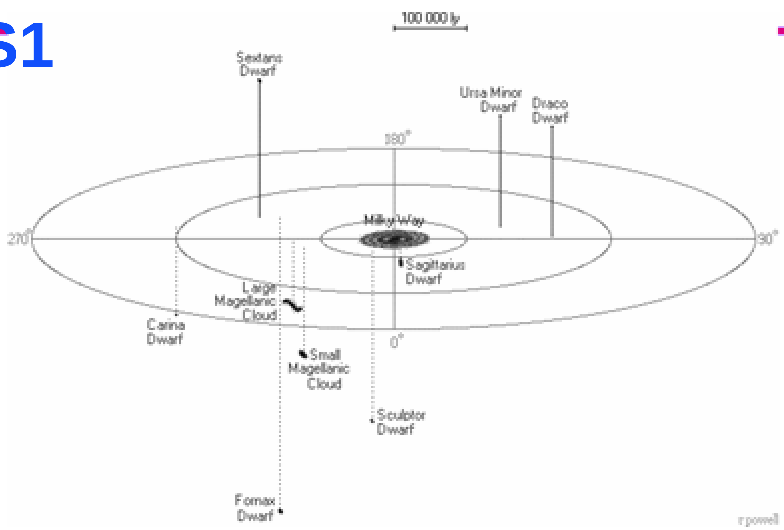
SNR



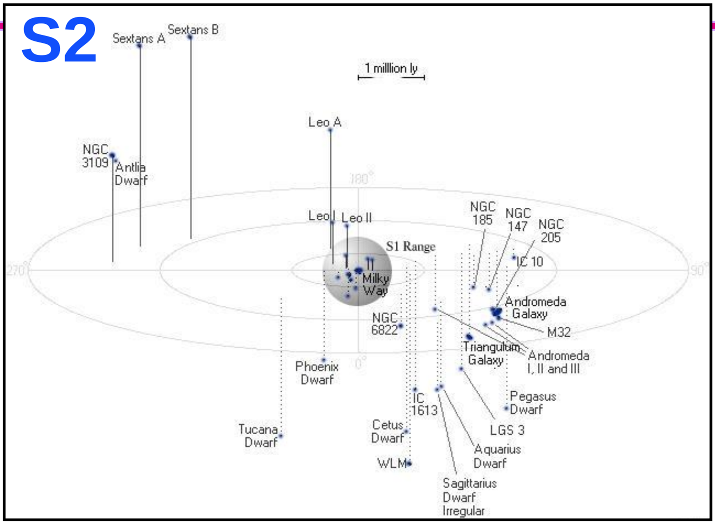
Coalescence Time

Range for Binary NS

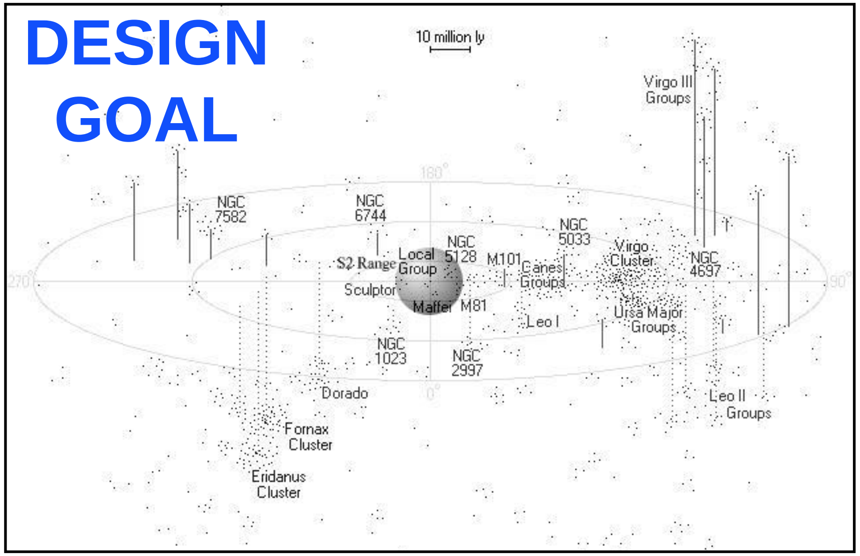
S1



S2



DESIGN GOAL



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.

LIGO-G050549-00-Z

Images: R. Powell

History of science runs

S1: 23 Aug to 9 Sept 2002

S2: 14 Feb to 14 Apr 2003

S3: 31 Oct 2003 to 9 Jan 2004

S4: 22 Feb to 23 Mar 2005

Over this period,

- » $h_{min}(f)$ decreased from 1.5 10^{-20}/$\mathrm{Hz}^{1/2}$ to 5 10^{-23}/$\mathrm{Hz}^{1/2}$
- » Noise at low frequency decreased by even larger factor
- » Duty cycle increased from ~ 20% to 57%

Observational papers

S1:

Neutron Star Binaries: *Phys. Rev. D* **69**, 122001 (2004)

Stochastic Background: *Phys. Rev. D* **69**, 122004 (2004)

Bursts: *Phys. Rev. D* **69**, 102001 (2004)

PSR J1939+2134: *Phys. Rev. D* **69**, 082004 (2004)

S2:

28 Pulsars: *PRL* **94**, 181103 (2005)

GRB030329: *Phys. Rev. D* **72**, 042002 (2005)

Bursts: *Phys. Rev. D* **72**, 062001 (2005)

Observational papers, cont.

S2:

Neutron Star Binaries: *Phys. Rev. D* in press, gr-qc/0505041

Primordial Black Holes: *Phys. Rev. D* in press, gr-qc/0505042

Bursts using LIGO+TAMA: *Phys. Rev. D* in press, gr-qc/0507081

Unknown pulsars: *Phys. Rev. D* in press, gr-qc/0508065

Binary Black Holes: gr-qc/0509129

S3:

Stochastic: *PRL* in press, astro-ph/0507254

many others in preparation

Prospects

Next month, LIGO begins S5, a long science run at design sensitivity. This will be the fulfillment of the investment to date.

- We will collect one year of coincident data.

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

We are considering some improvements after S5, which might yield x1.5 to x2 at some frequencies.

Advanced LIGO is on the horizon. This is what will guarantee that we open the field of gravitational wave astronomy.

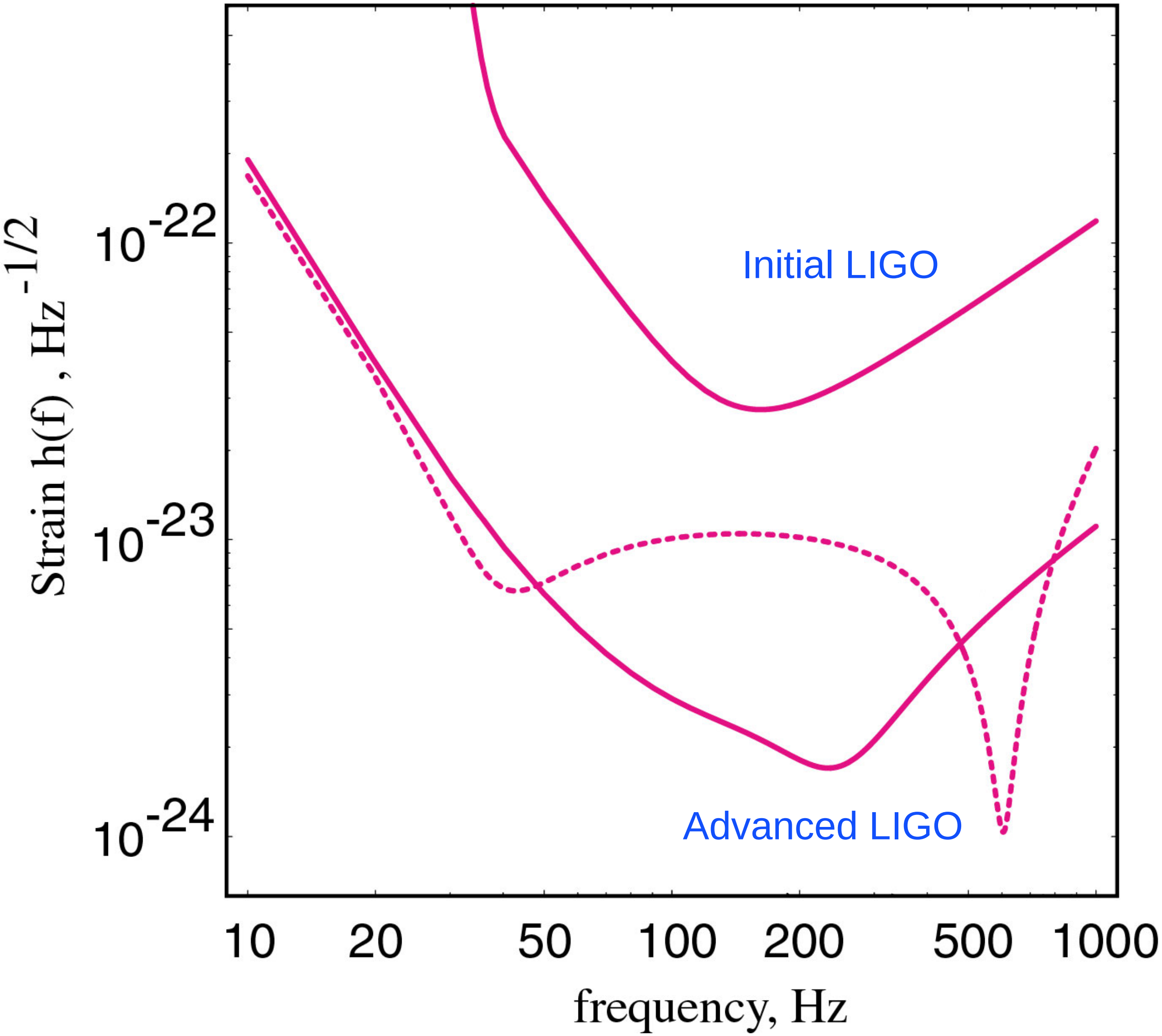
Coming Soon: Advanced LIGO

Much better sensitivity:

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

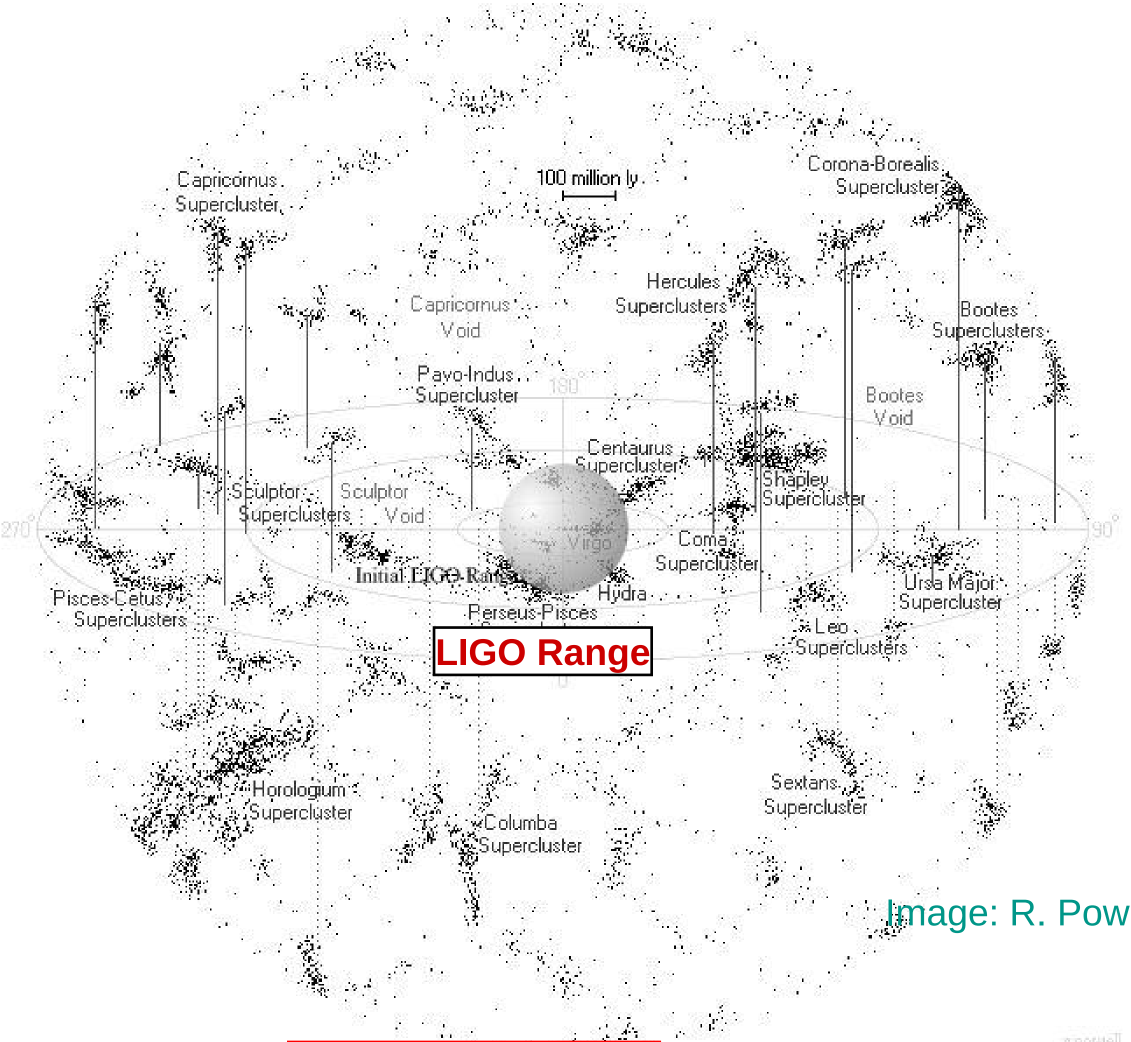
Through these features:

- 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