# Gravitational wave observations as a probe for strong gravity

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# Outline

- Gravitational waves and gravitational wave detectors
- Black holes as astrophysical objects
- Gravitational waves as a probe of black holes
- Prospects for upcoming observations

# A gravitational wave meets some test masses

- Transverse

  No effect along direction of propagation

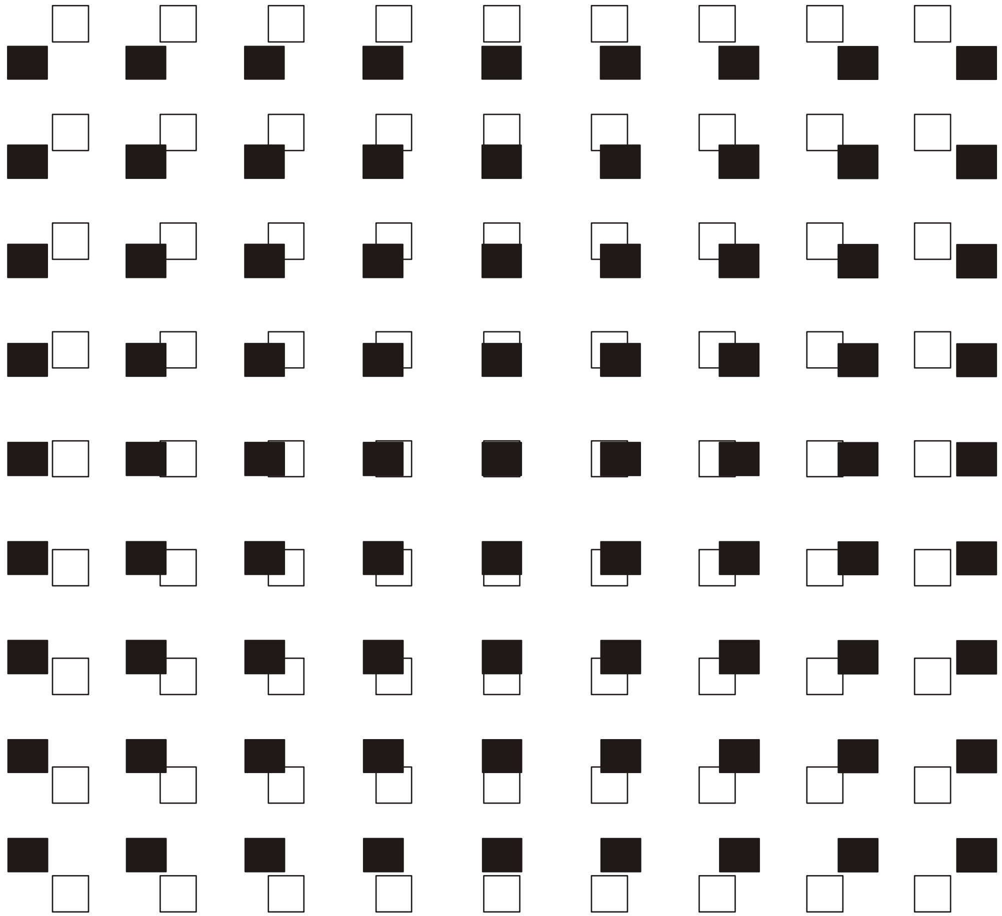
- Quadrupolar

  Opposite effects along *x* and *y* directions

- Strain

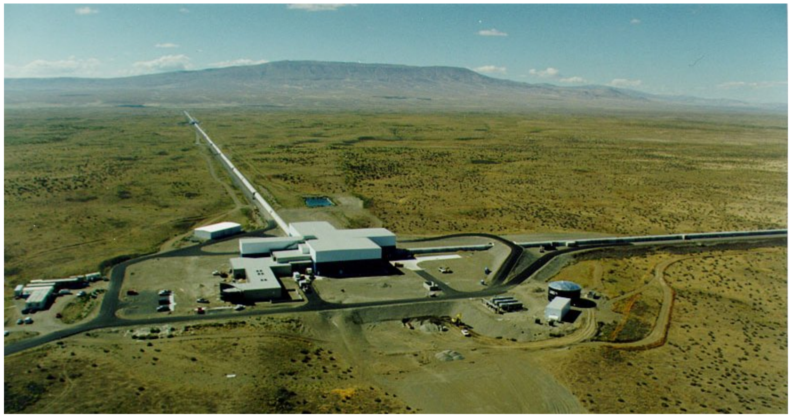
  Larger effect on longer separations

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



See Siong Heng's talk

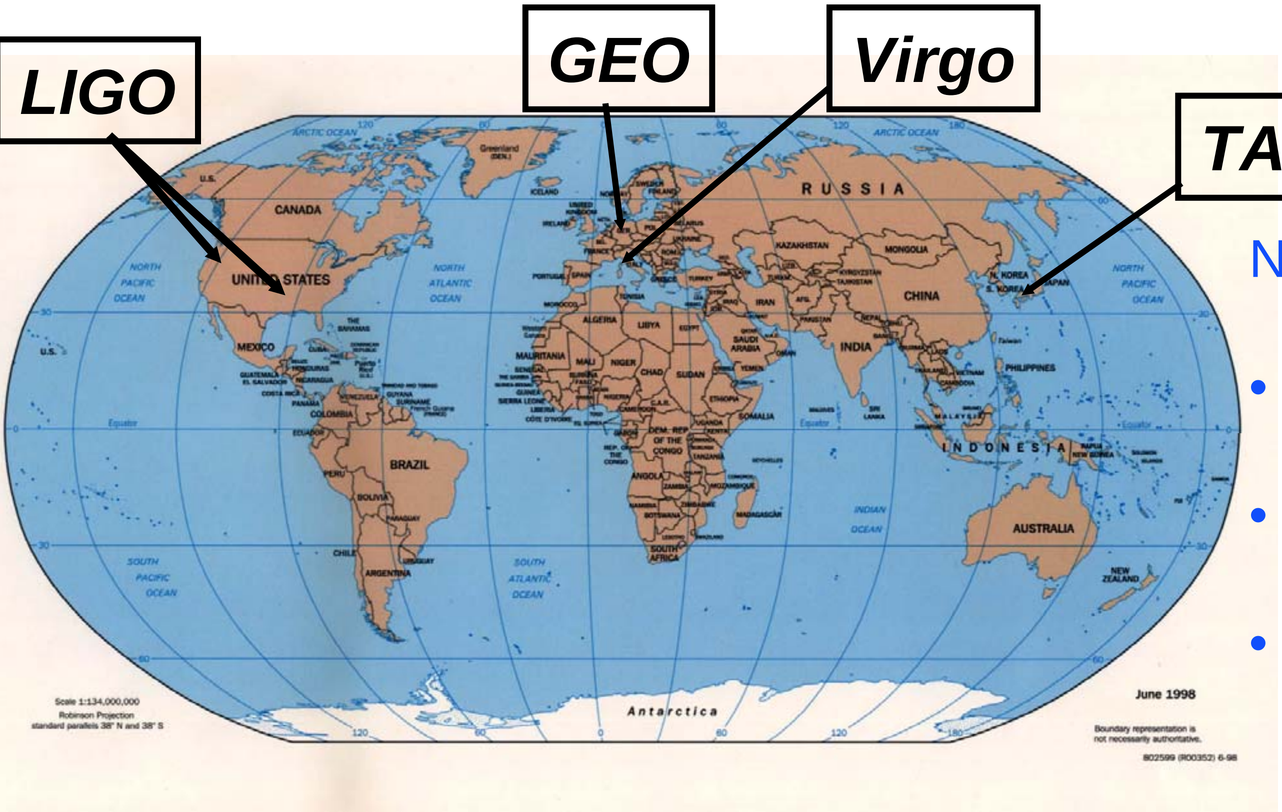
# LIGO and GEO



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

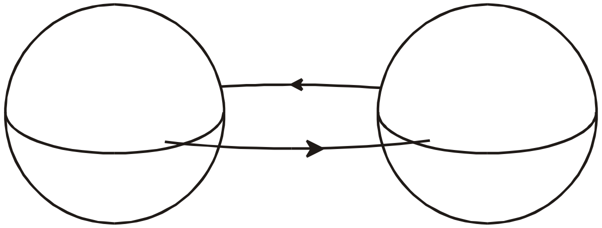
# Resonant detectors

Resonant detectors in Europe and the U.S. also form part of the network. Interferometers are just now surpassing them in sensitivity.

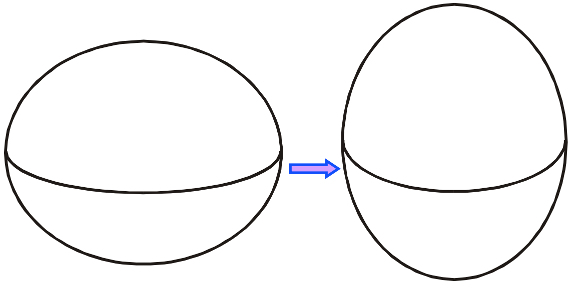
AURIGA

# Gravitational wave sources: time-varying quadrupole moments

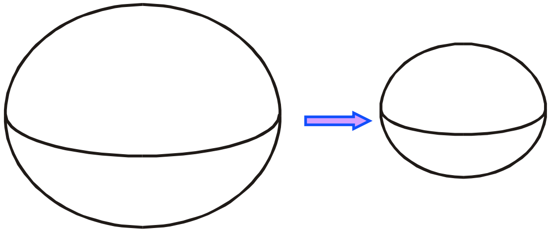
Binary stars (especially compact objects, e.g. neutron stars or black holes.)



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:

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

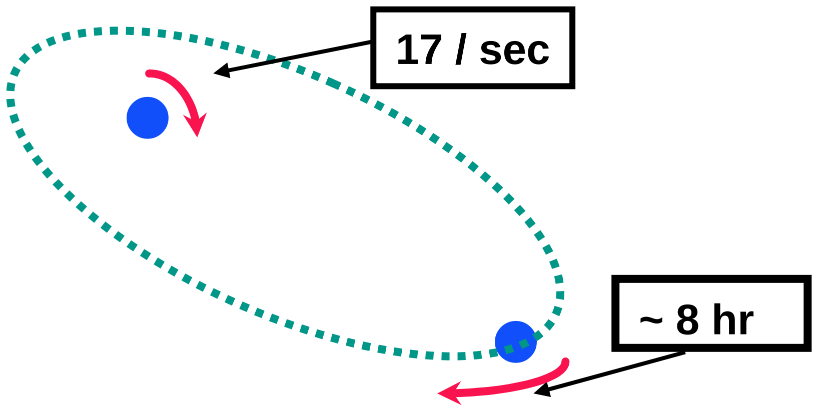
$I$ is the mass quadrupole moment of the source.

Coherent relativistic motion of large masses can be directly observed.

(True in the weak-field limit, but still good for some intuition for strong-field cases.)

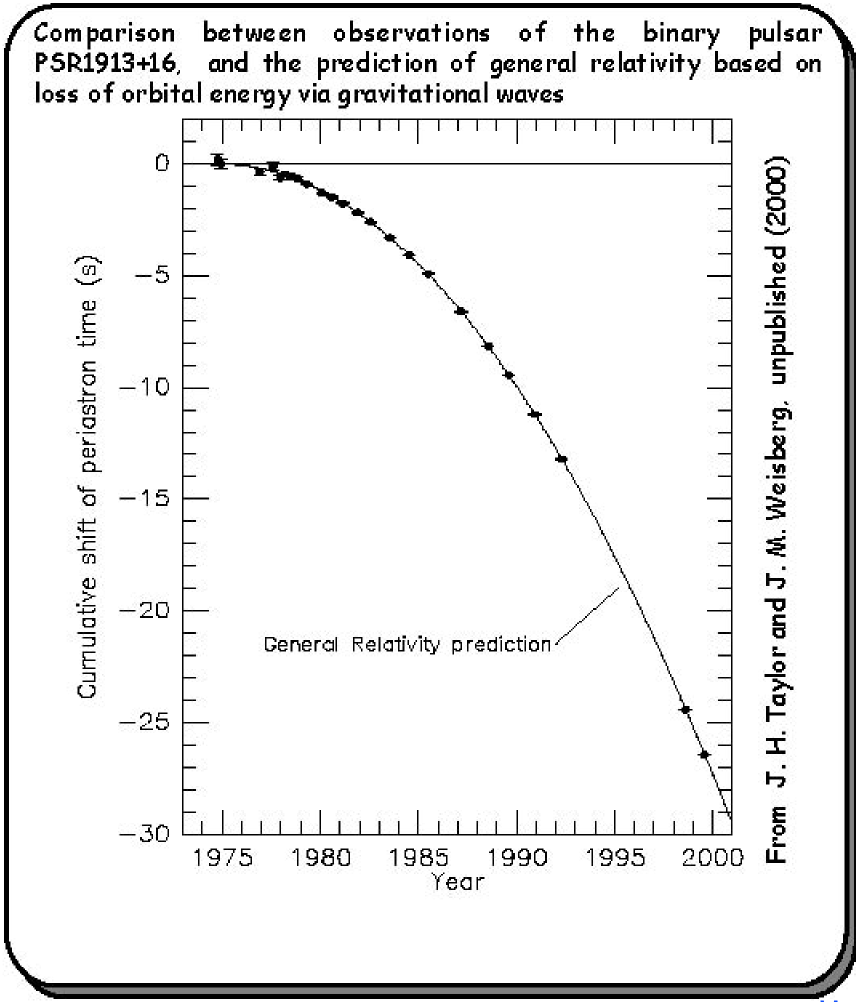
# How do we know that gravitational waves exist?

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

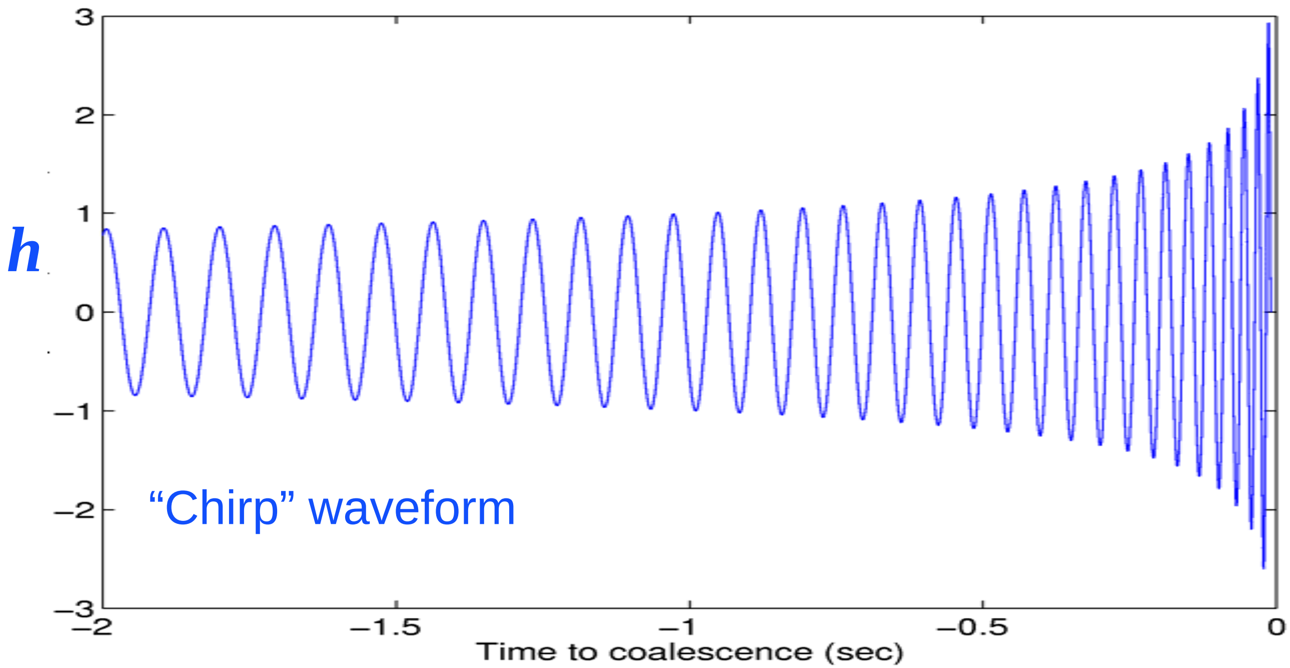



Prediction from general relativity:
spiral in by 3 mm/orbit

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.

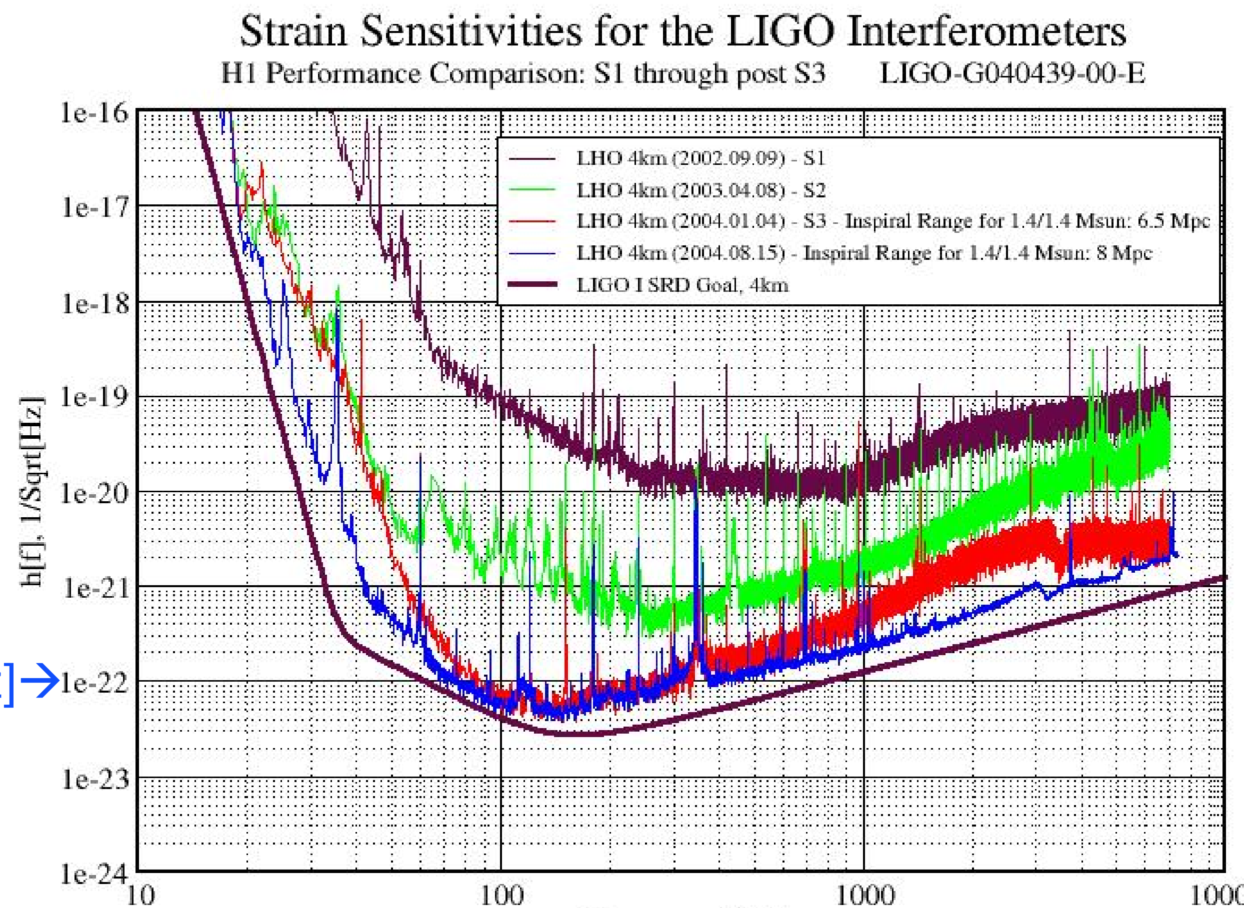
# What is interesting about gravitational waves?

- Embody gravity's obedience to the principle "no signal faster than light"
- Made by coherent relativistic motions of large masses
  - 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.

# The state of the art

Over the past 3 years, LIGO has rapidly approached its design sensitivity. Now, all three interferometers are within x2 of design.

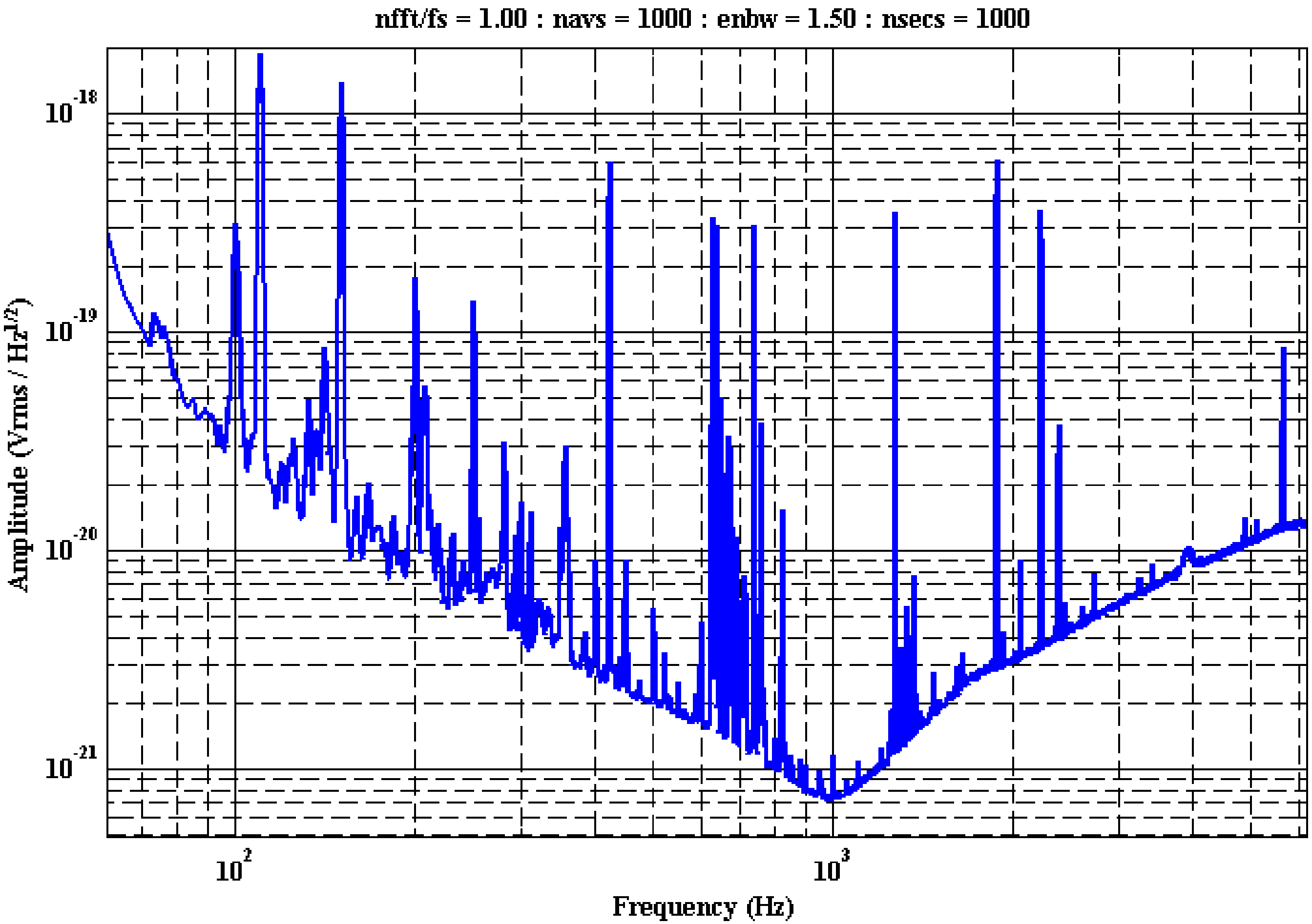
*h(f)* = $10^{-22}$ /Sqrt[Hz]→




10 100 1000 10000

Frequency [Hz]

# GEO's recent performance



# Signal strength from a neutron star binary

For a binary, the quadrupole formula can be rewritten as

$$h \approx r_{S1} r_{S2} / r_0 R,$$

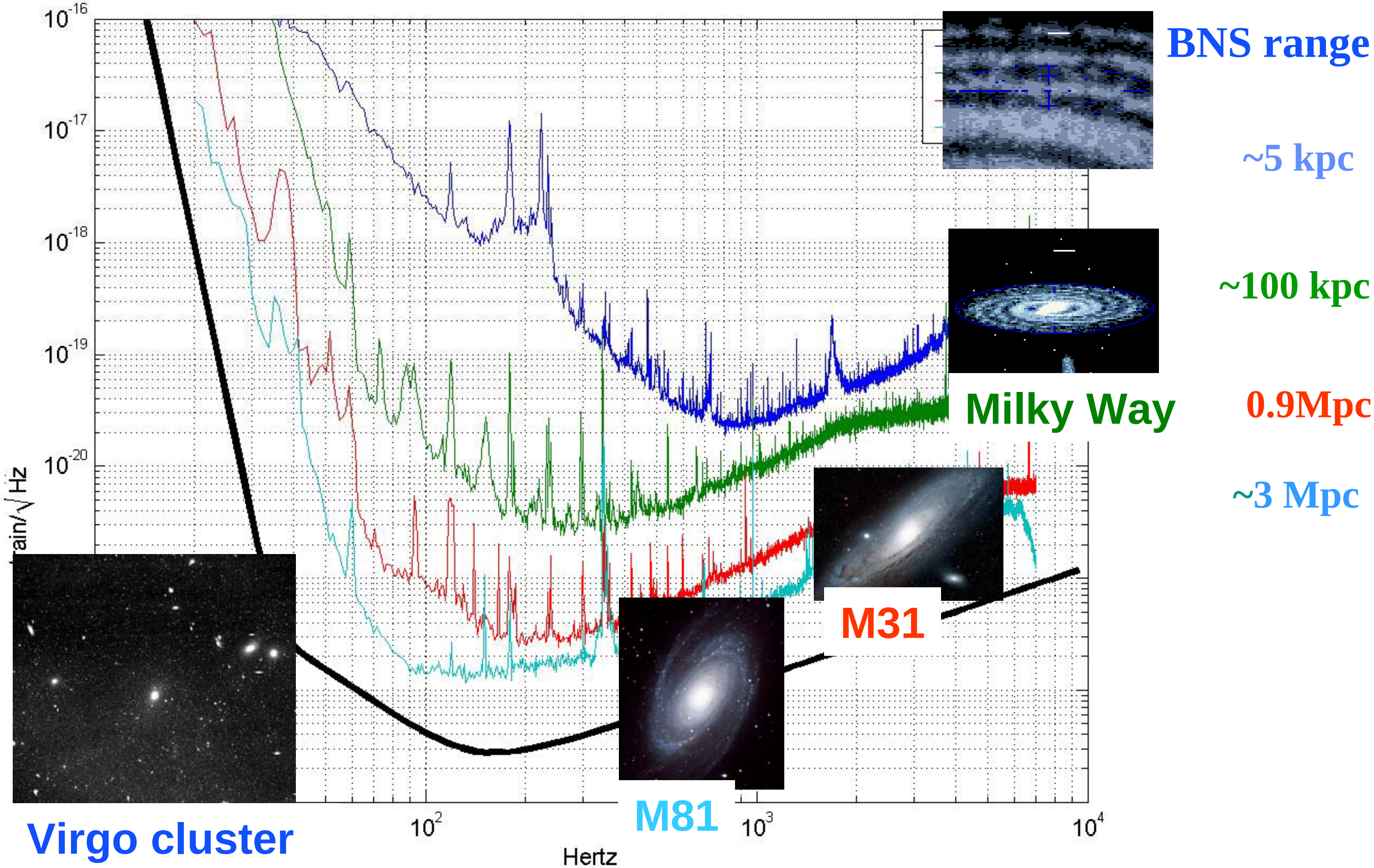
where $r_{S1}$ is the Schwarzschild radius of star 1, $2r_0$ is the stars' separation, and $R$ is the distance.

For a neutron star binary in Virgo, just before coalescence this yields

$$h \sim 2 \times 10^{-21}.$$

At design sensitivity, this is about what LIGO can see.

# A measure of progress

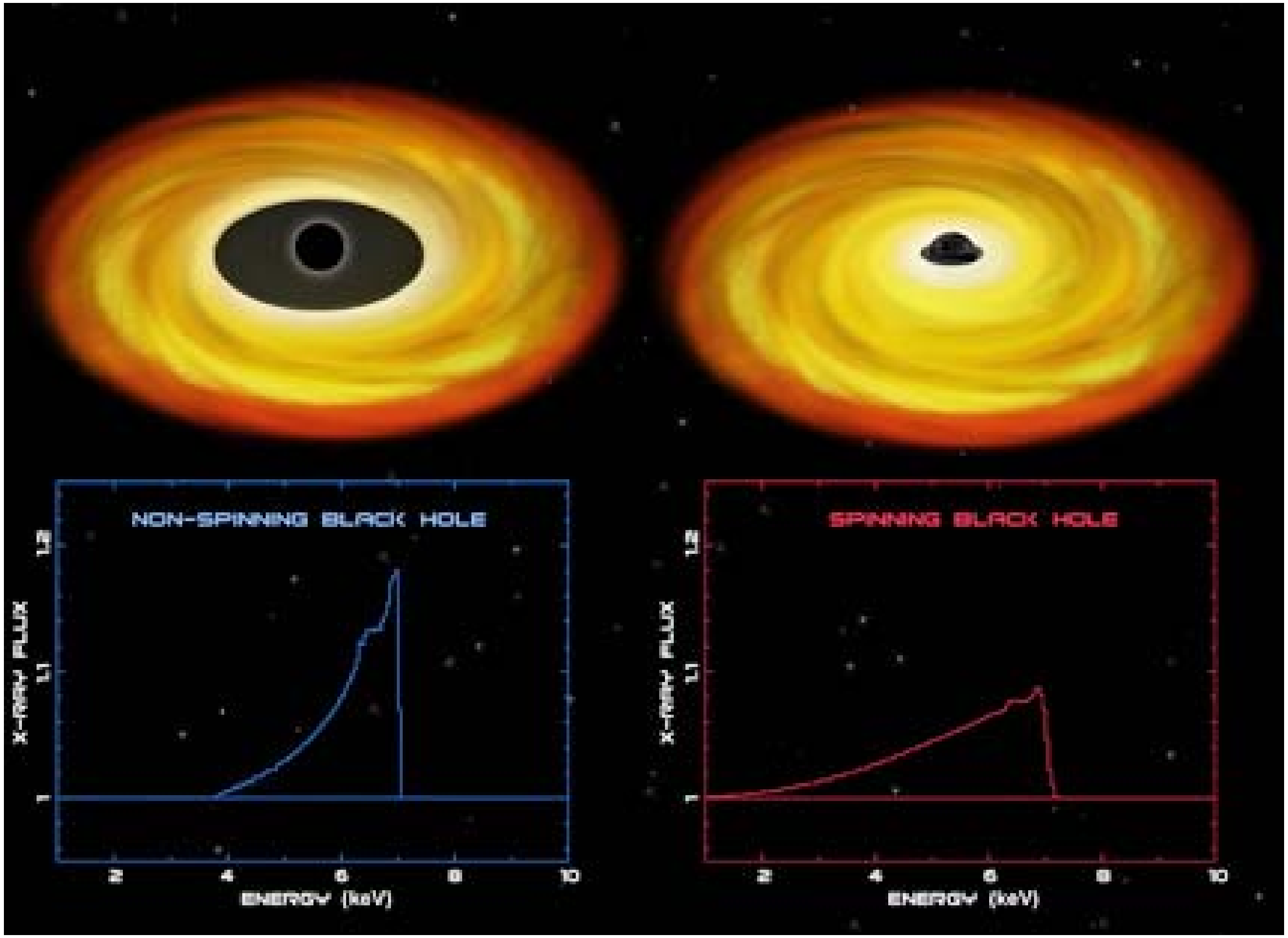


# Can we learn more about black holes?

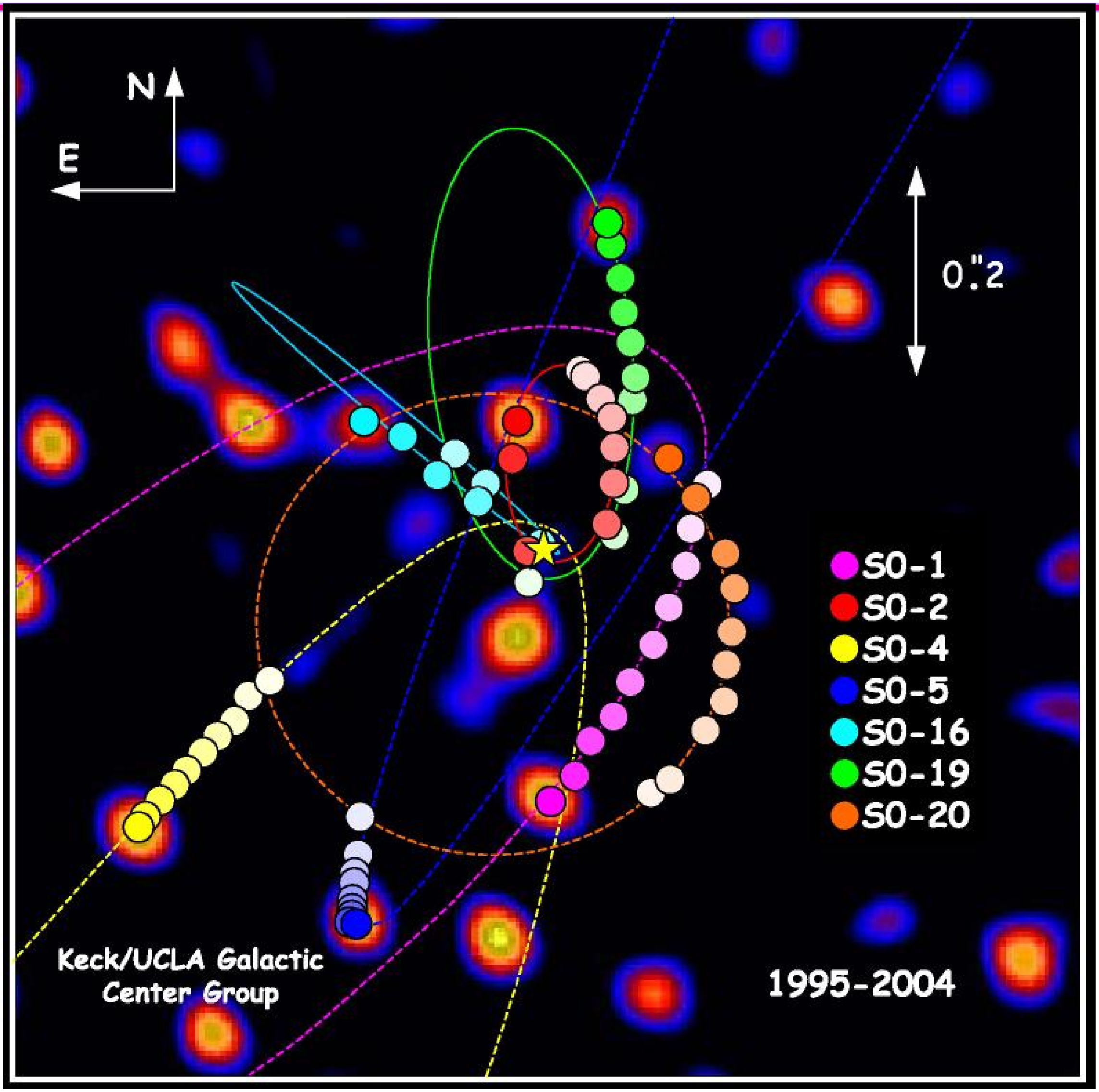
Astronomical observations already show us many systems that appear to be best explained by black holes:

- Massive dark companions in binaries
- Dense mass concentrations (millions of solar masses, or more) at the centers of galaxies, emitting little or no light.
- Central engines of active galactic nuclei

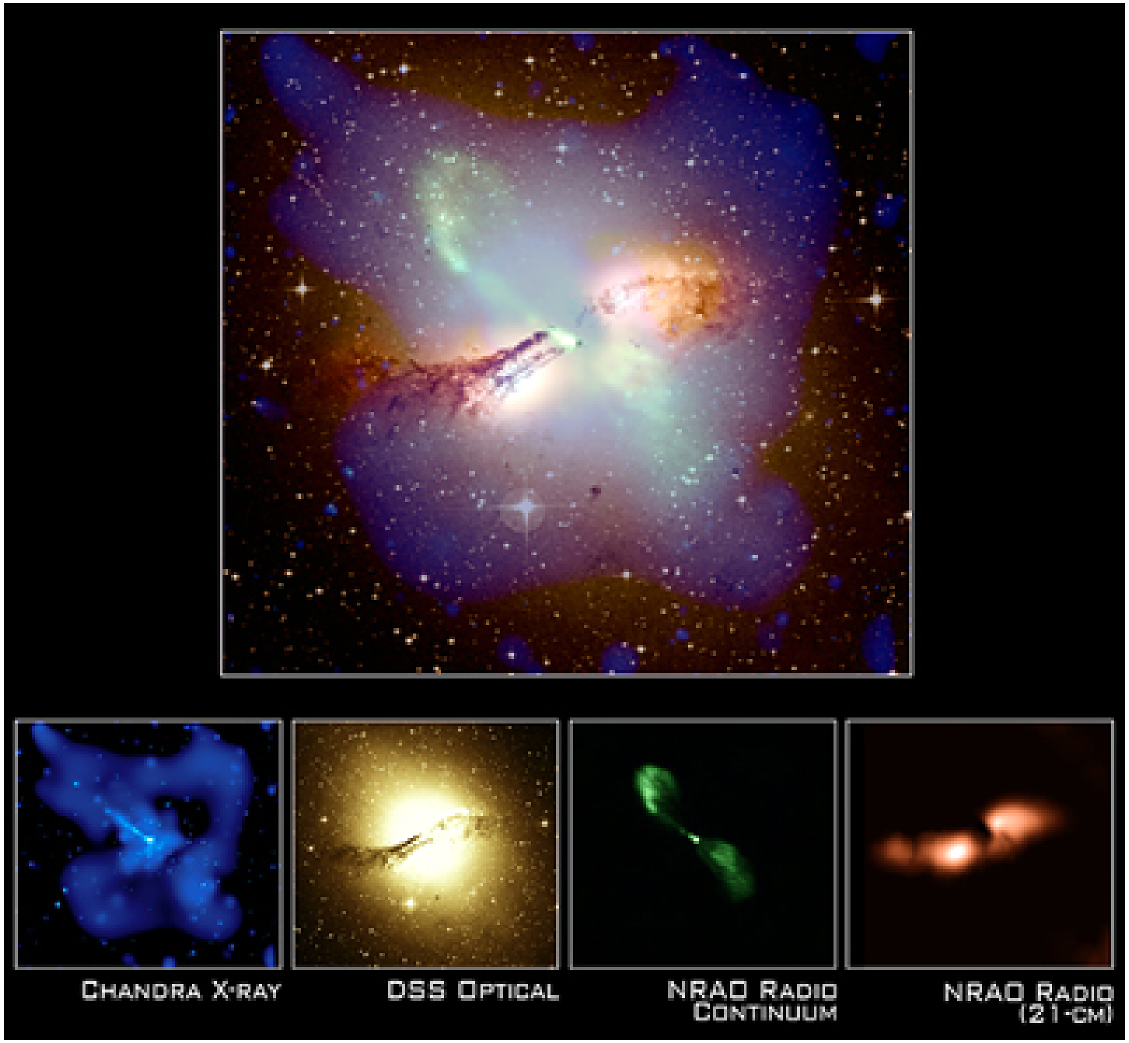
# Studies of BH X-ray binaries



# Black Hole at the center of the Galaxy



# Active Galactic Nuclei (here, Cen A)



# How to probe black hole physics?

Narayan pointed to how we can see that black holes in binaries “swallow” large amounts of energy.

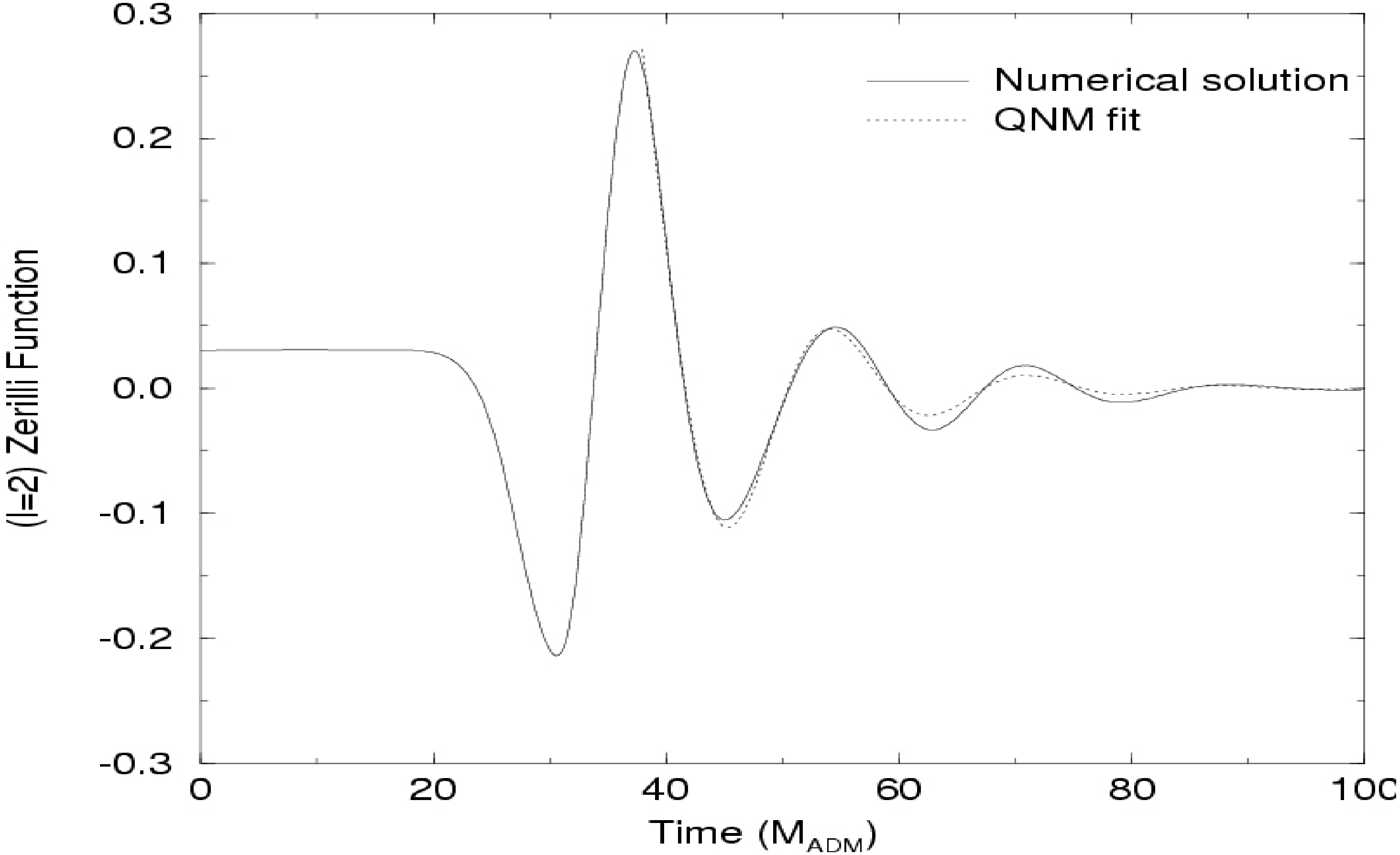
Strong evidence for existence of horizons.

But can we learn more about black holes, uncomplicated by the presence of other matter? There is much yet to be explored in the physics of black holes:

- » They are objects made of pure space-time,
- » described by very specific solutions of the Einstein Eqns.,
- » completely determined by three parameters: *M, L,* and *Q.*

# Gravitational waves will offer powerful clues

A perturbed black hole emits distinctive gravitational wave signals, representing its *quasi-normal modes*.



# Reading the waveform

We expect waveforms to be dominated by the fundamental mode,

$$f_{QNM} \approx [1-0.63(1-a)^{3/10}]\left(\frac{20\ \mathrm{M}_\Theta}{\mathrm{M}}\right)1620\ \mathrm{Hz},$$

$$Q \approx 2(1-a)^{-9/20}.$$

Angular momentum represented by dimensionless parameter *a*.

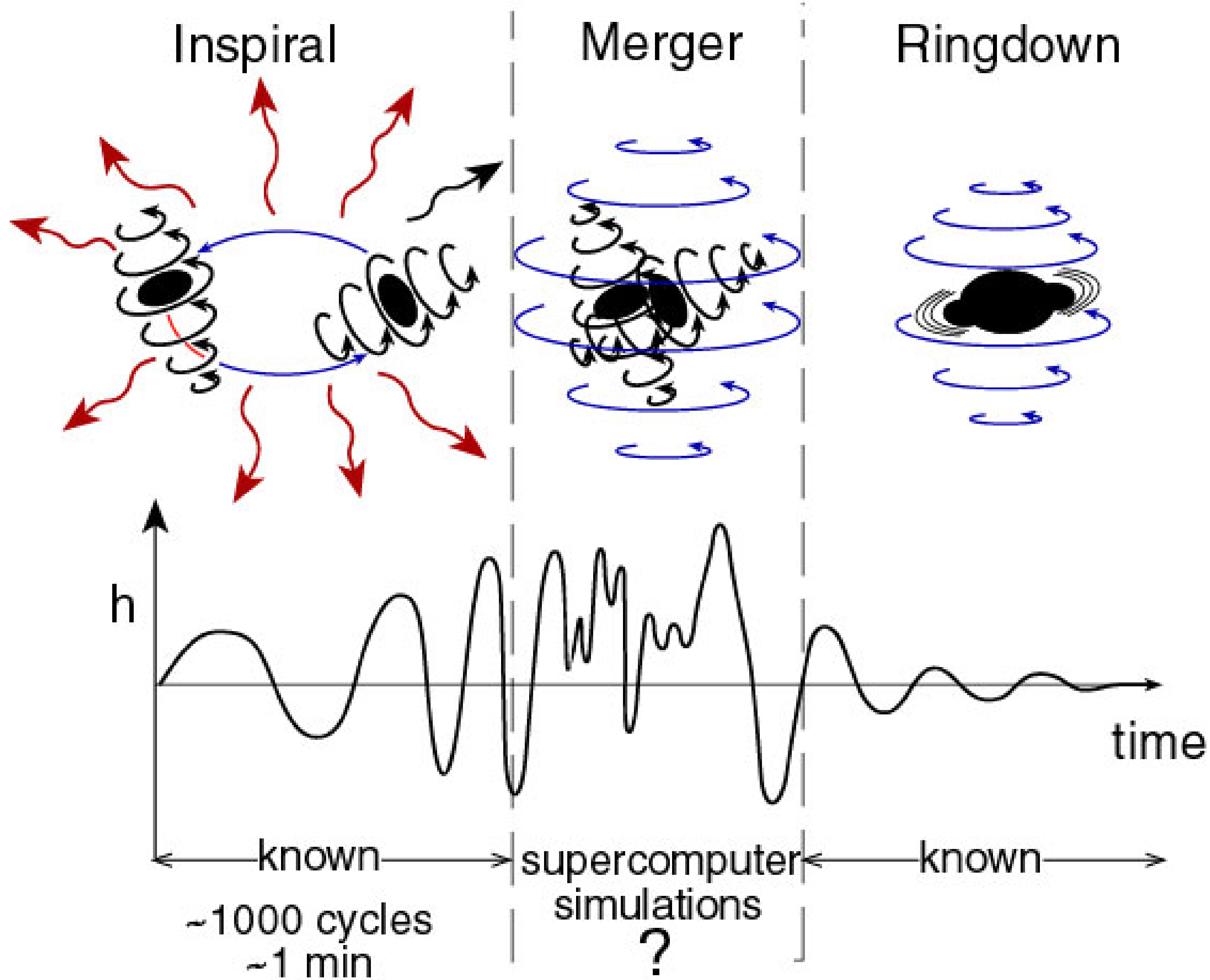
Examples:

20 solar mass, $a = 0$ → $f = 600$ Hz, $Q = 2$.

20 solar mass, $a = 0.98$ → $f = 1320$ Hz, $Q = 12$.

These very low quality factors are the diagnostic feature that these are *space-time modes*, strongly damped by emission of gravitational waves.

# QNMs are the last phase of black hole binary coalescence




**Lots of interesting physics in this waveform!**

# Interpretation, understanding

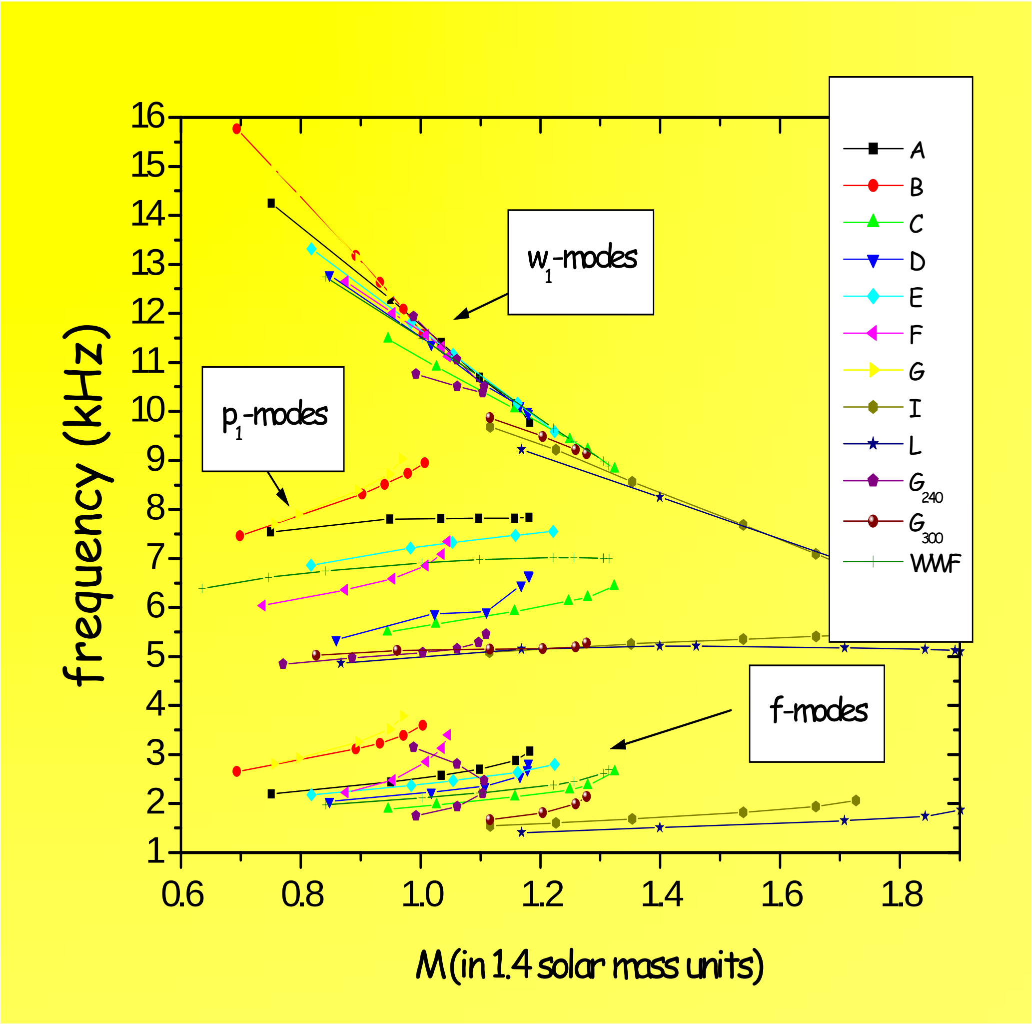
- Inspiral phase:
  - » Based on pretty well-known physics (radiation reaction)
  - » Read off (with some skill): mass, angular momentum
- Merger phase:
  - » Fully non-linear dynamics of strongly curved space-time
  - » Much work to do (numerical relativity) before we can read this part
- Ringdown phase:
  - » Well-understood (but never before seen) quasi-normal modes
  - » Check mass, angular momentum
  - » Probe the dynamics of the space-time just outside the horizon
  - » THIS IS THE DEFINITIVE BLACK HOLE SIGNATURE

# Compare to neutron star modes

Mode spectrum is VERY different.

Neutron star modes are much more lightly damped (Q ~ 1000.)

Only exception is the w-modes, analogs of a black hole's QNMs.
For a NS, *f* is very high ($f_w$~10 kHz.)




Kokkotas *et al.*

# LIGO and GEO search for these signals

- LIGO plans to start a year-long run at design sensitivity in late 2005. GEO will also participate.
- At LIGO's design sensitivity, we'd need just a bit of luck to see these signals. (Optimistic models don't quite predict 1/year at a detectable amplitude.)

- We are now running search pipelines for
  » Inspiral signals from NS binaries and BH binaries,
    (so far without spins, but will add black hole spin soon)
  » Unmodeled transients, e.g., merger waveforms, and
  » QNM "ringdowns".
- We are about to link these pipelines into an integrated coalescence search.

# Coming Soon: Advanced LIGO

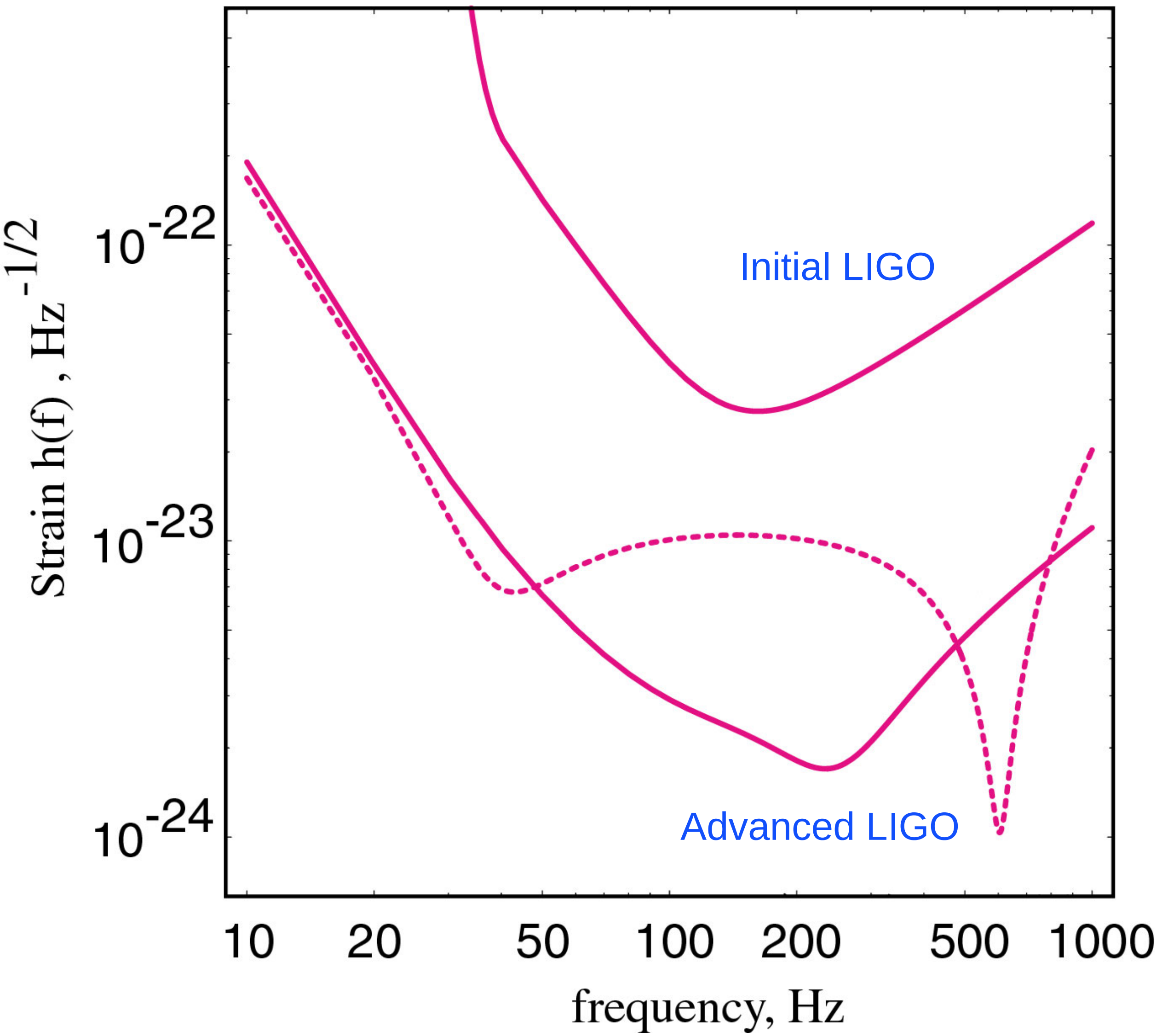
Much better sensitivity:

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

Through these features:

- Fused silica multi-stage suspension (U.K.)
- ~20x higher laser power (Germany)
- 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)

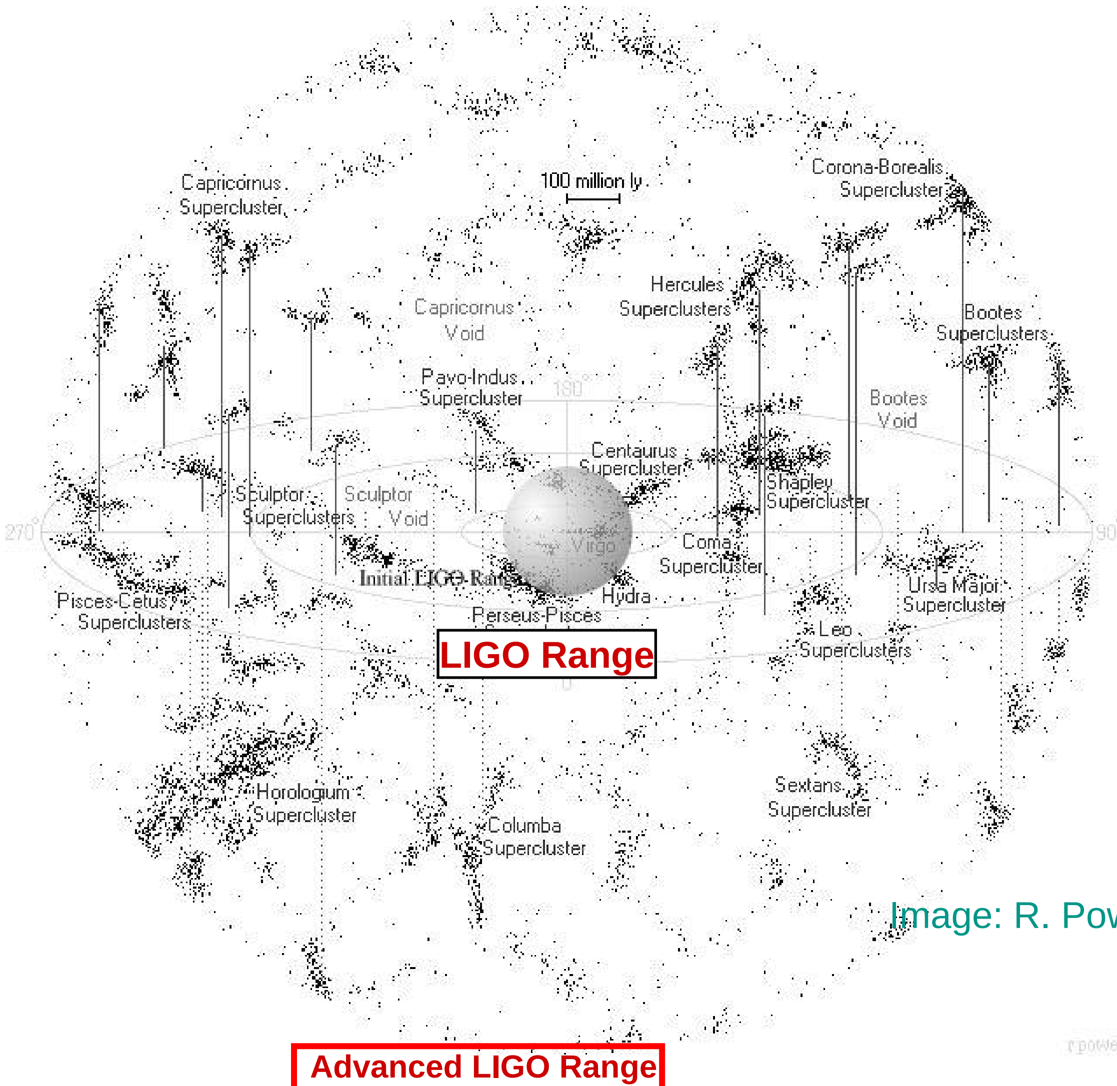



Image: R. Powell

# Status of Advanced LIGO

PPARC is funding substantial U.K. contribution (£8M),
 including multi-stage fused silica test mass suspensions.
 (See Sheila Rowan's talk.)

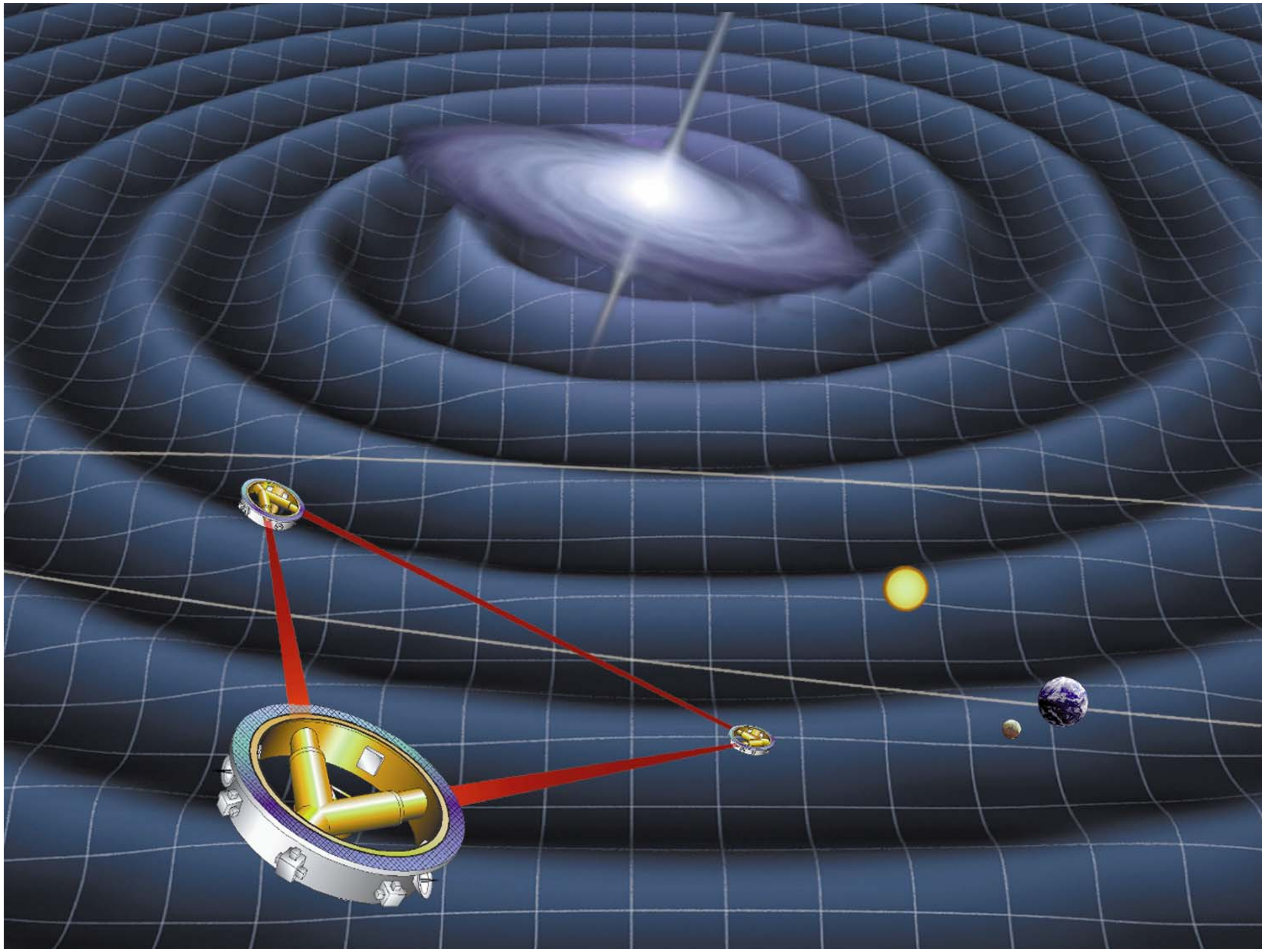
Max Planck Society has endorsed major German contribution,
 with value comparable to U.K.'s contribution,
 including 200 W laser.

U.S. National Science Board approved Advanced LIGO.
 The U.S. budget now includes Advanced LIGO start in a few years.

# LISA

A set of Michelson interferometers of astronomical dimensions,
5 million km arms.

In solar orbit, trailing the Earth by 20 degrees.



# LISA studies black hole physics

Signals from low-mass BH (~10 $M_{\odot}$) inspiral into massive (~$10^6$ $M_{\odot}$) BH.

“Maps” the space-time of the massive BH as the compact object spirals in.

- Strong test of GR “no hair” prediction

Also measures astrophysical parameters

- Masses, spins, distances

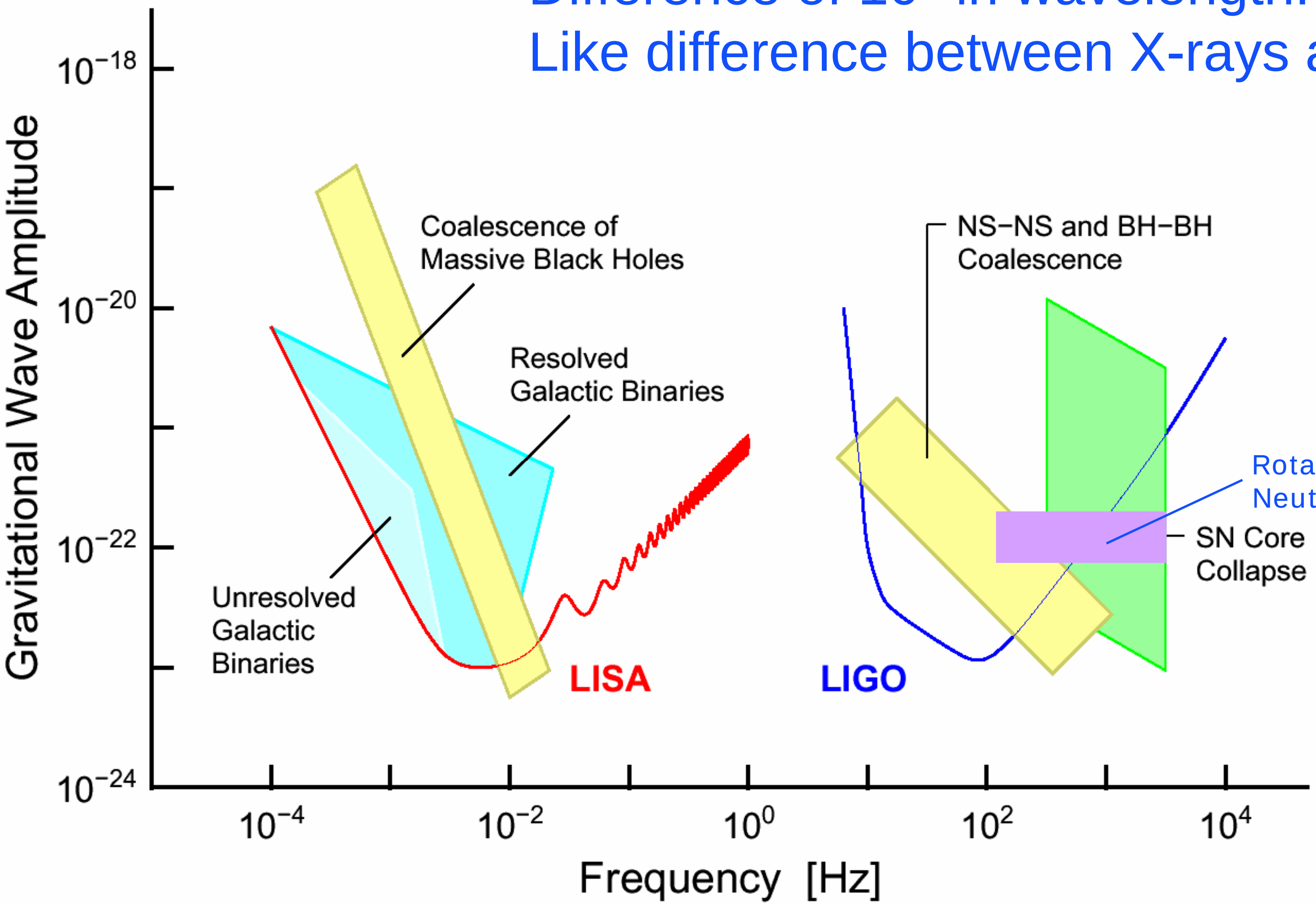
Several per year are potentially detectable.

Signal-to-noise of 1000 or more allows precision tests of General Relativity at ultra-high field strengths.

(Strong U.K. contribution to LISA Pathfinder and LISA, to be discussed in the parallel sessions.)

# LIGO and LISA probe different bands of the spectrum

Difference of $10^4$ in wavelength:
Like difference between X-rays and IR



# Another step in astronomy's golden age of observation?

- It is likely that we'll see black hole signals soon.
  - If not in the next couple of years with LIGO *et al.*, then in the next decade with Advanced LIGO and LISA.
- This will forever remove black holes from the category of "hypothetical" objects, and establish their properties unambiguously.
- It will also open up a new window for the study of strongly dynamical space-time.
  - Let's also ensure that numerical relativity advances so that we can take full advantage of these observations.