Black holes, Einstein, and space-time ripples

Peter R. Saulson

Syracuse University

Outline

- “Dark stars” in classical physics
- General relativity and the prediction of black holes
- Astronomical evidence suggests black holes
- The gravitational waves emitted by colliding black holes
- The properties of gravitational waves
- Gravitational wave detectors – LIGO
- Where we stand in the search for gravitational waves

Newton’s cannon

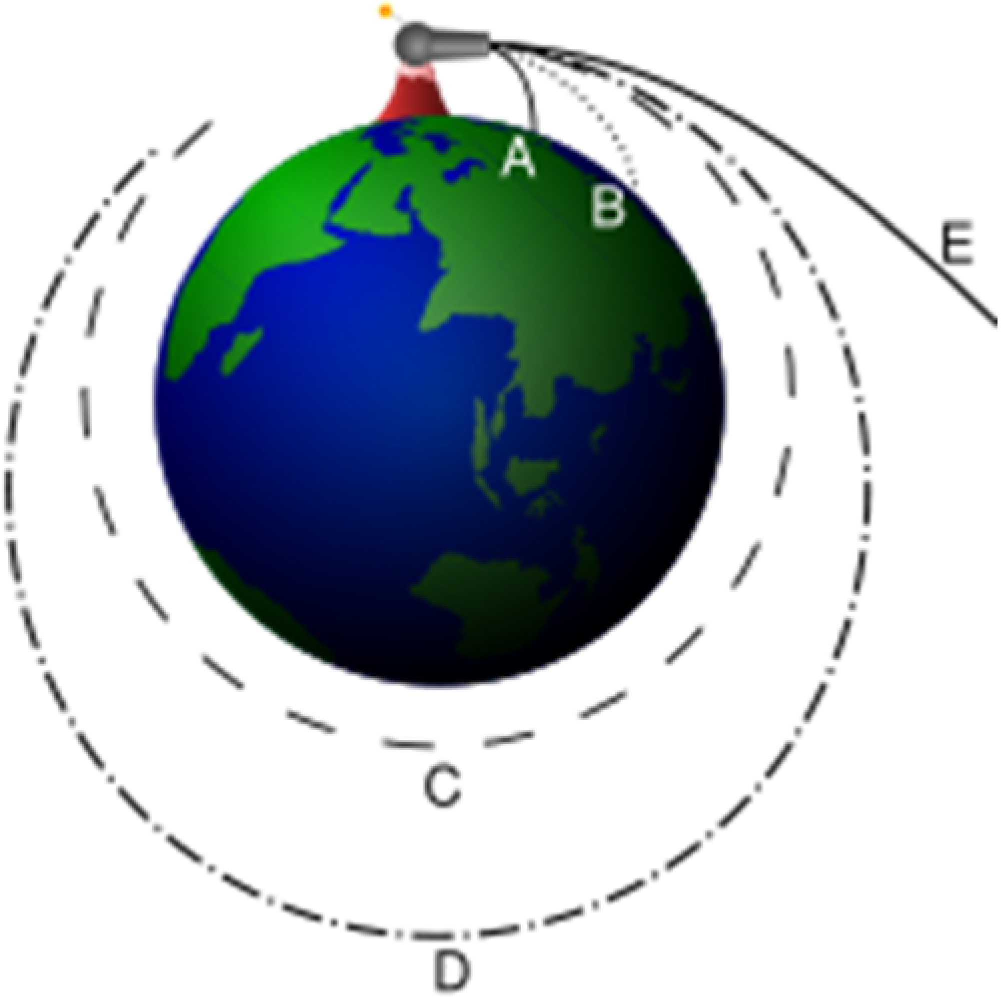
Newton unified motion on Earth and in the heavens.

A cannonball fired from a mountaintop normally falls to Earth.

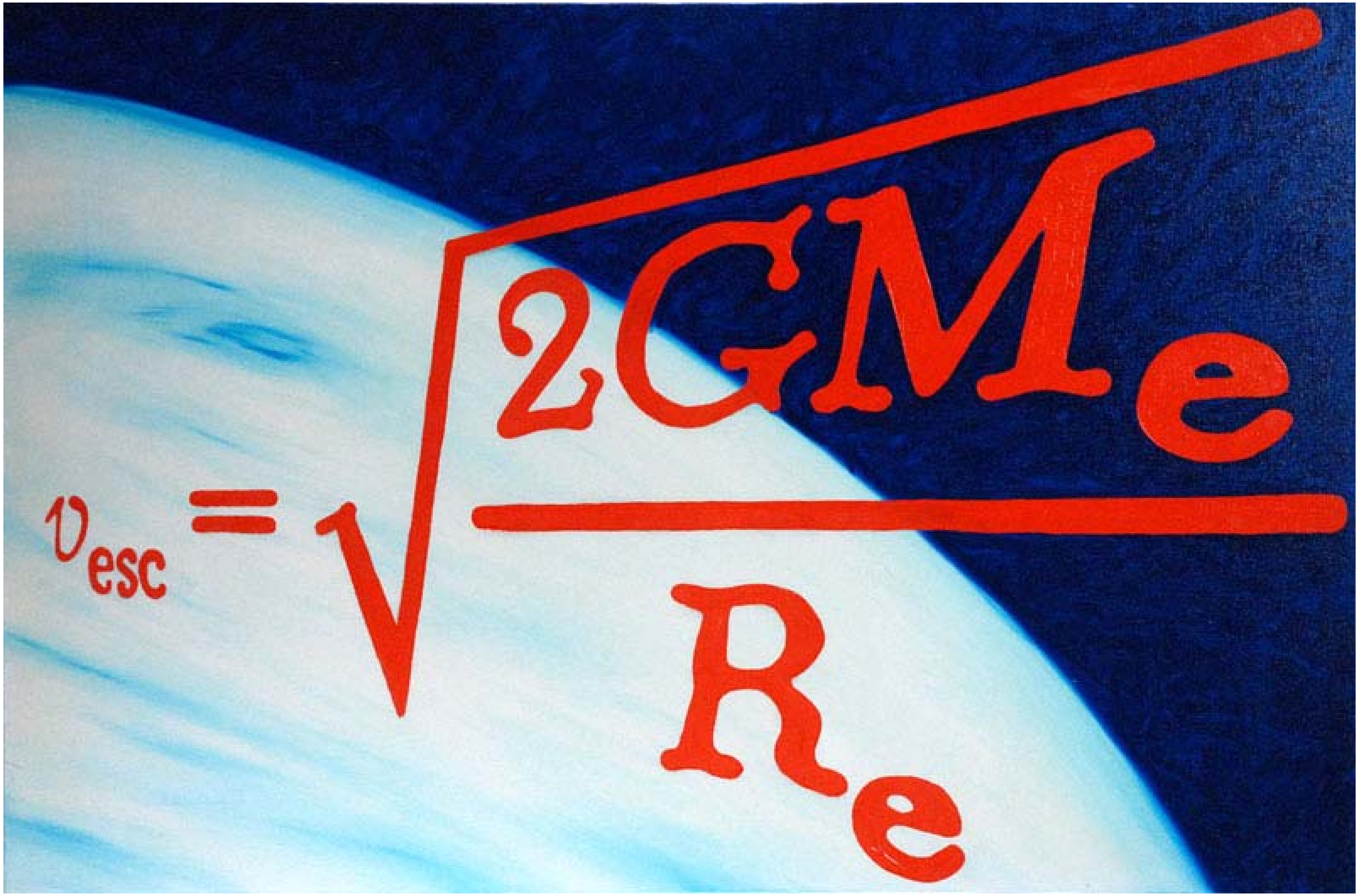
At higher speeds, it goes farther.

Higher still, it orbits.

Even higher, it escapes the Earth entirely.



Escape velocity



Escape velocities from different systems

Escape velocity from the surface of the Earth is about 11 km/sec (about 7 miles/sec)

Escape velocity from the surface of the Sun is 617 km/sec.

Imagine another Sun with the same mass, but smaller radius. The smaller the radius, the higher the escape velocity from the surface.

If the radius were small enough (about 3 km), then the escape velocity would equal the speed of light.

What if the escape velocity exceeds the speed of light?

John Michell in 1783 and Pierre-Simon Laplace in 1796 considered the possibility of a version of the Sun so compressed that light could not escape from it.

The idea of such “dark stars” remained only a curiosity until the 20th century.

New view of gravity: Einstein’s General Theory of Relativity

Starting in 1915, Albert Einstein began the development of his new theory of gravity.

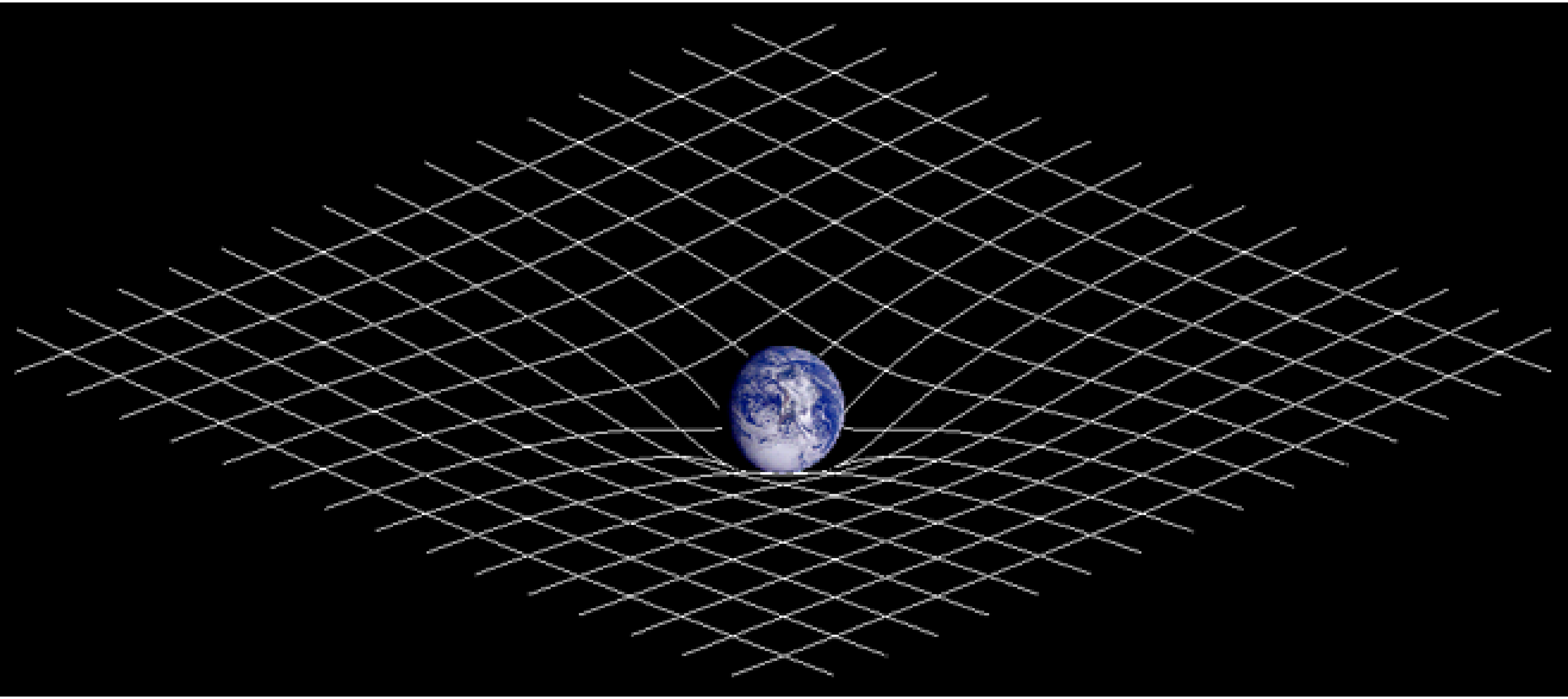
The basic idea is that gravity is not a force, but rather a manifestation of the curvature of space-time.

Space and time aren’t just a simple backdrop to the world, but have properties of their own. In particular, they can be “curved”, which means that matter can be prevented by the properties of space-time from moving uniformly in a straight line.

Space-time curvature is caused by mass.

Thus, General Relativity embodies the idea of gravity, and even “explains” it.

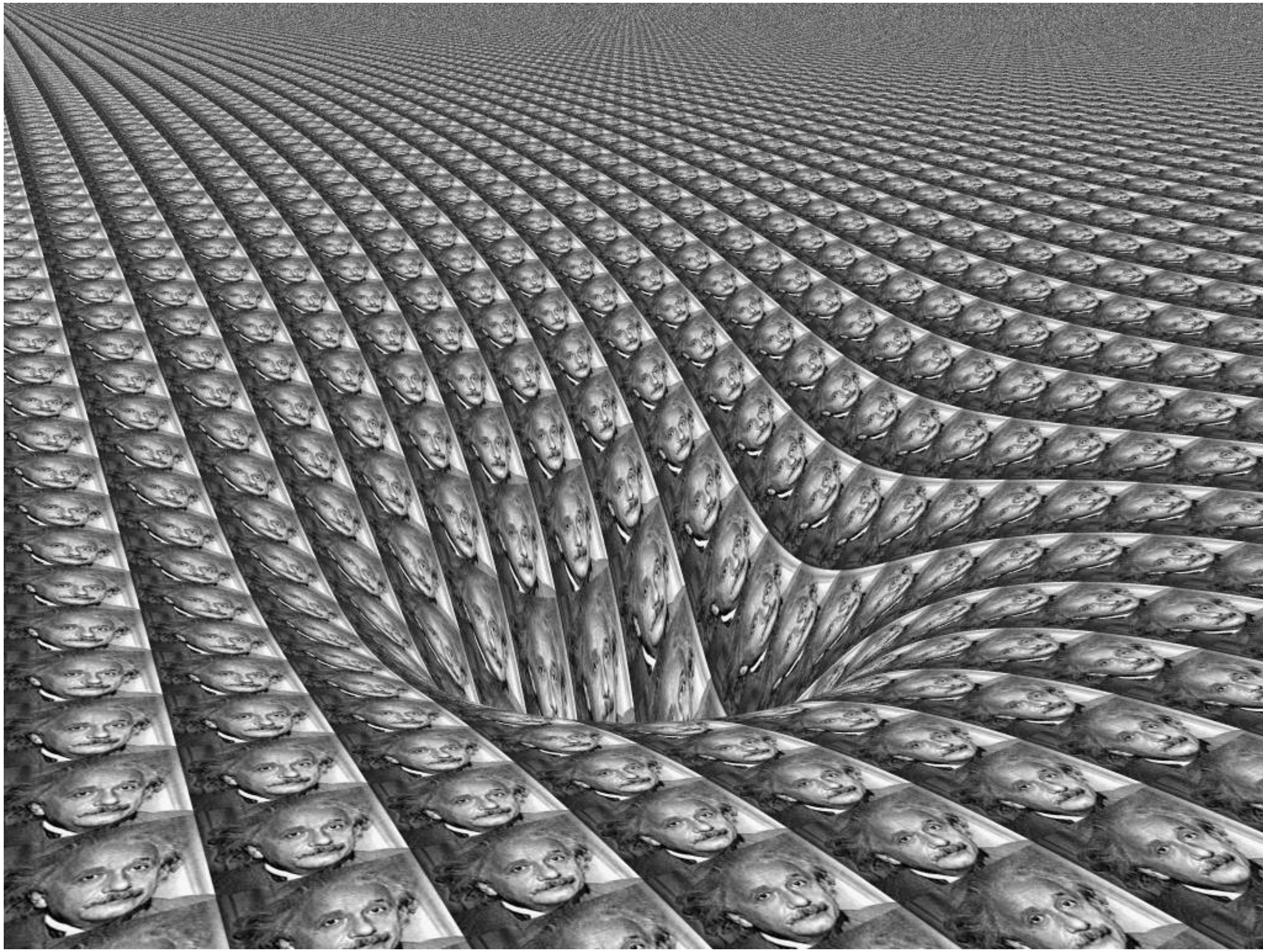
Matter tells space-time how to curve.
Space-time tells matter how to move.



Black holes, from the point of view of General Relativity

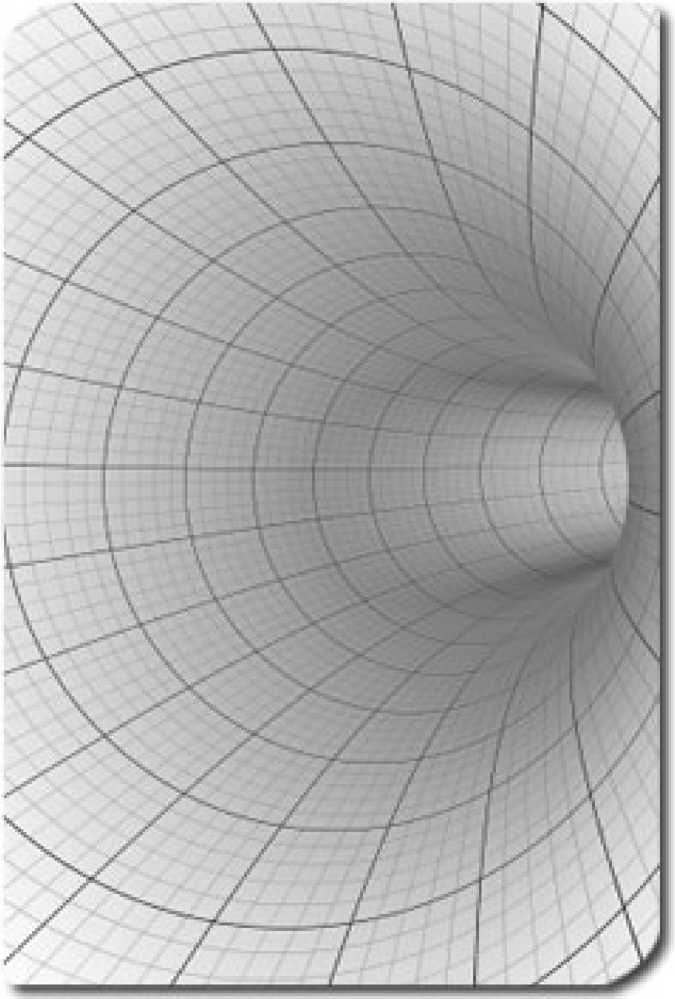
A view of the space-time in the vicinity of a black hole.

In the region where the escape velocity exceeds *c*, the geometry of the curved space-time becomes extreme.



The sad fate of matter that forms a black hole

No force can hold up the matter that forms a black hole. All of the matter inside collapses down to a point.



Are they really out there?

The idea of black holes is pretty exotic.

We'd like to know if black holes actually exist. If they do, what are their properties? How massive? How many?

At first, it seems unlikely that we could ever know. After all, if even light can't escape from a black hole, how could be observe it?

Nevertheless, evidence is accumulating that black holes do exist.

First, I'll show some exciting astronomical observations that suggest black holes are out there.

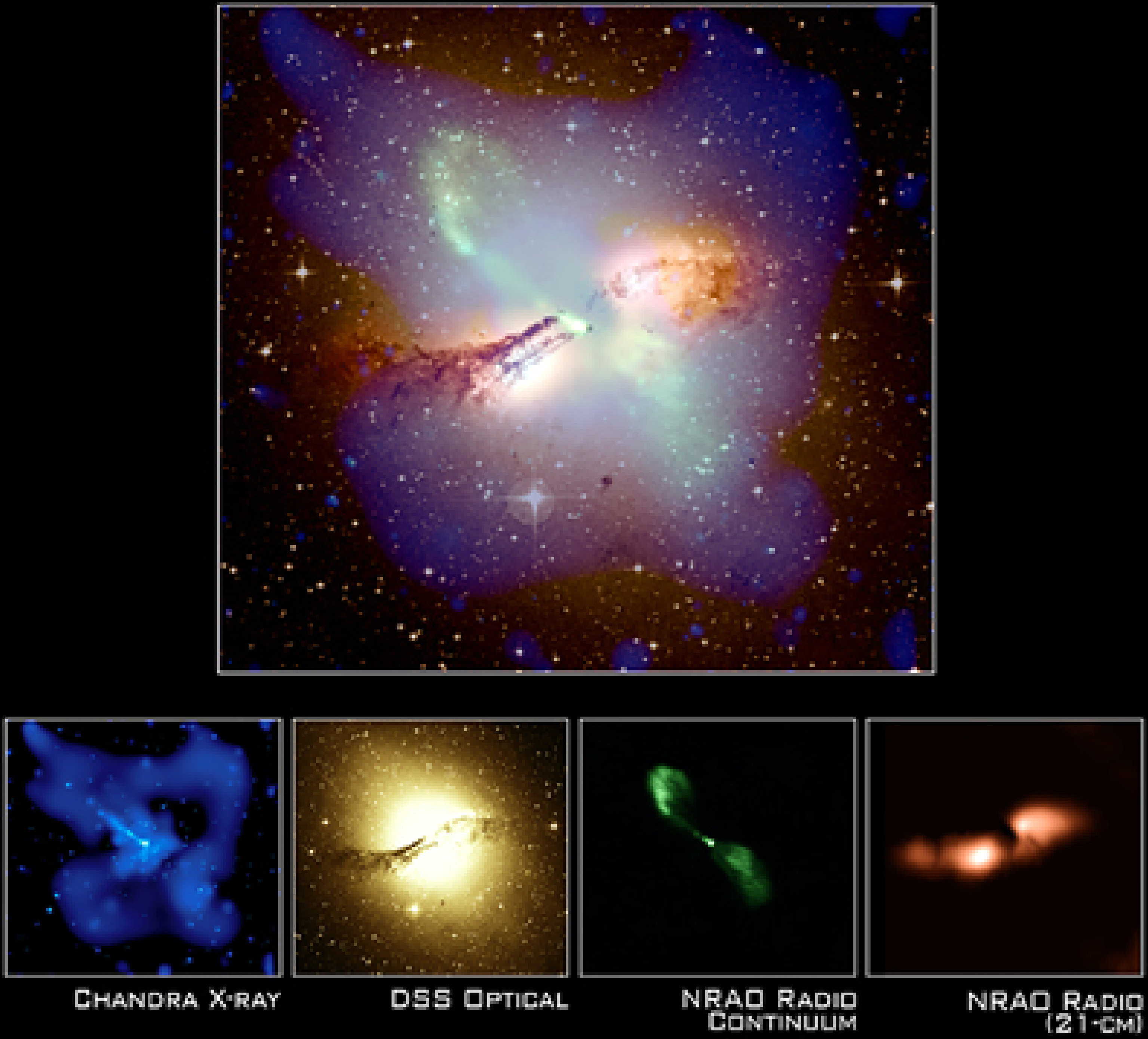
Then, I'll explain a new generation of experiments that will prove the case, using gravitational waves.

Centaurus A

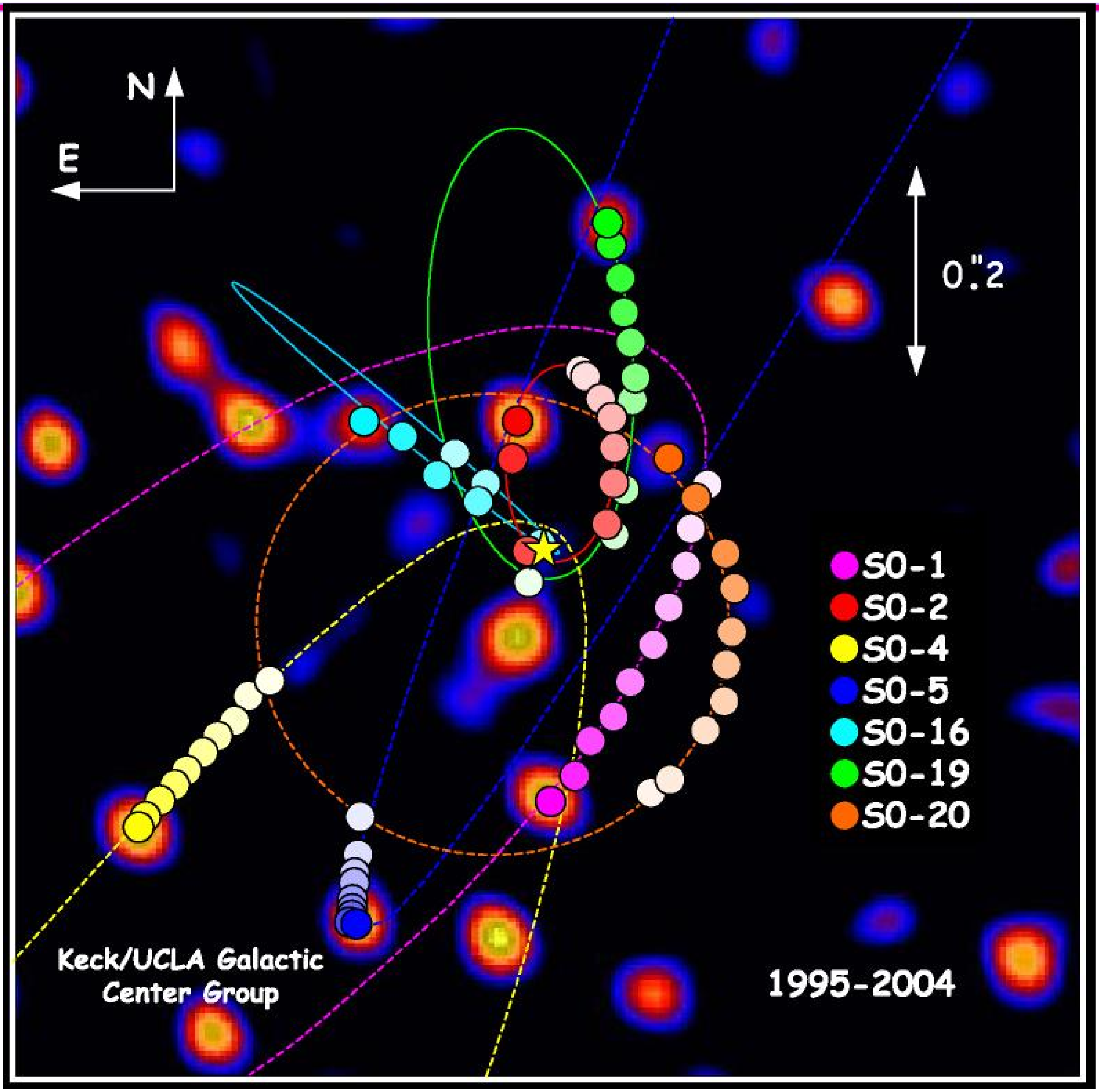
Active
Galactic
Nucleus

=

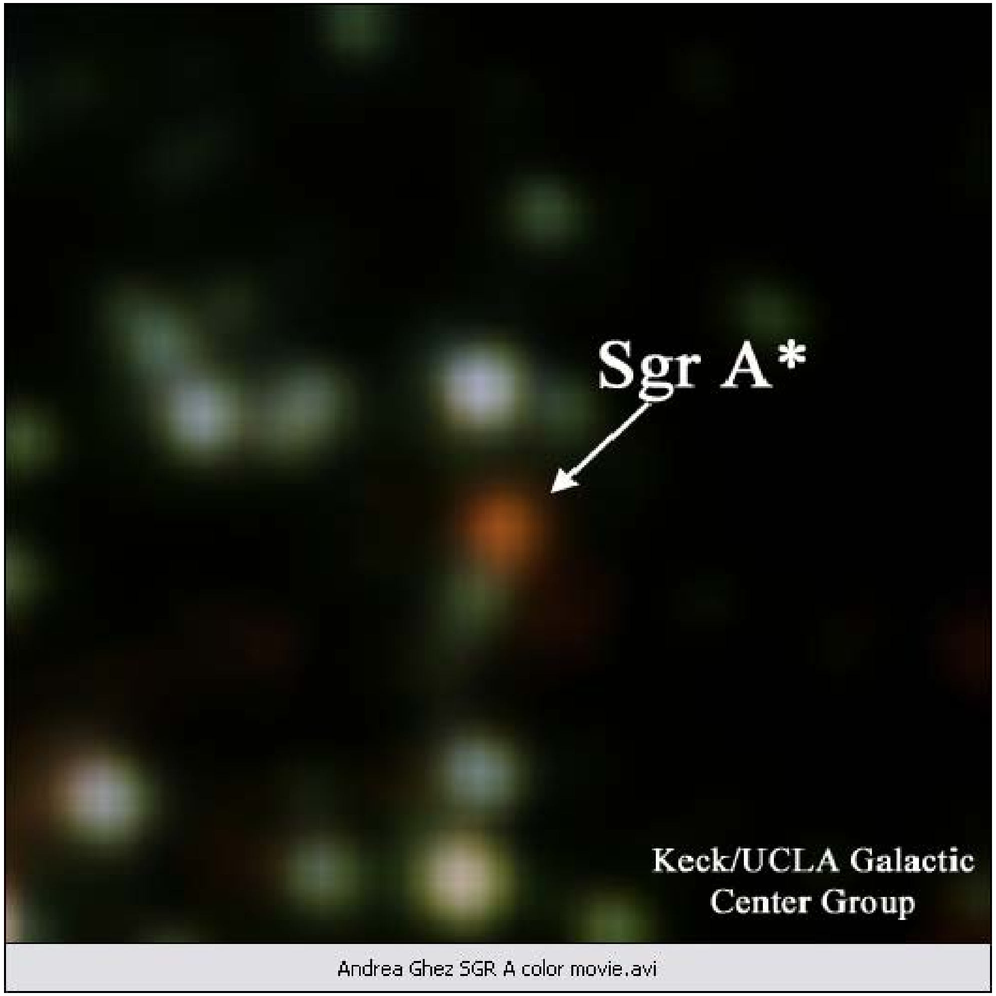
Giant
Black Hole?



Black Hole at the center of the Galaxy



Time-lapse movie
of the Milky Way’s black hole



How can we learn more?
How can we tell if this story is true?

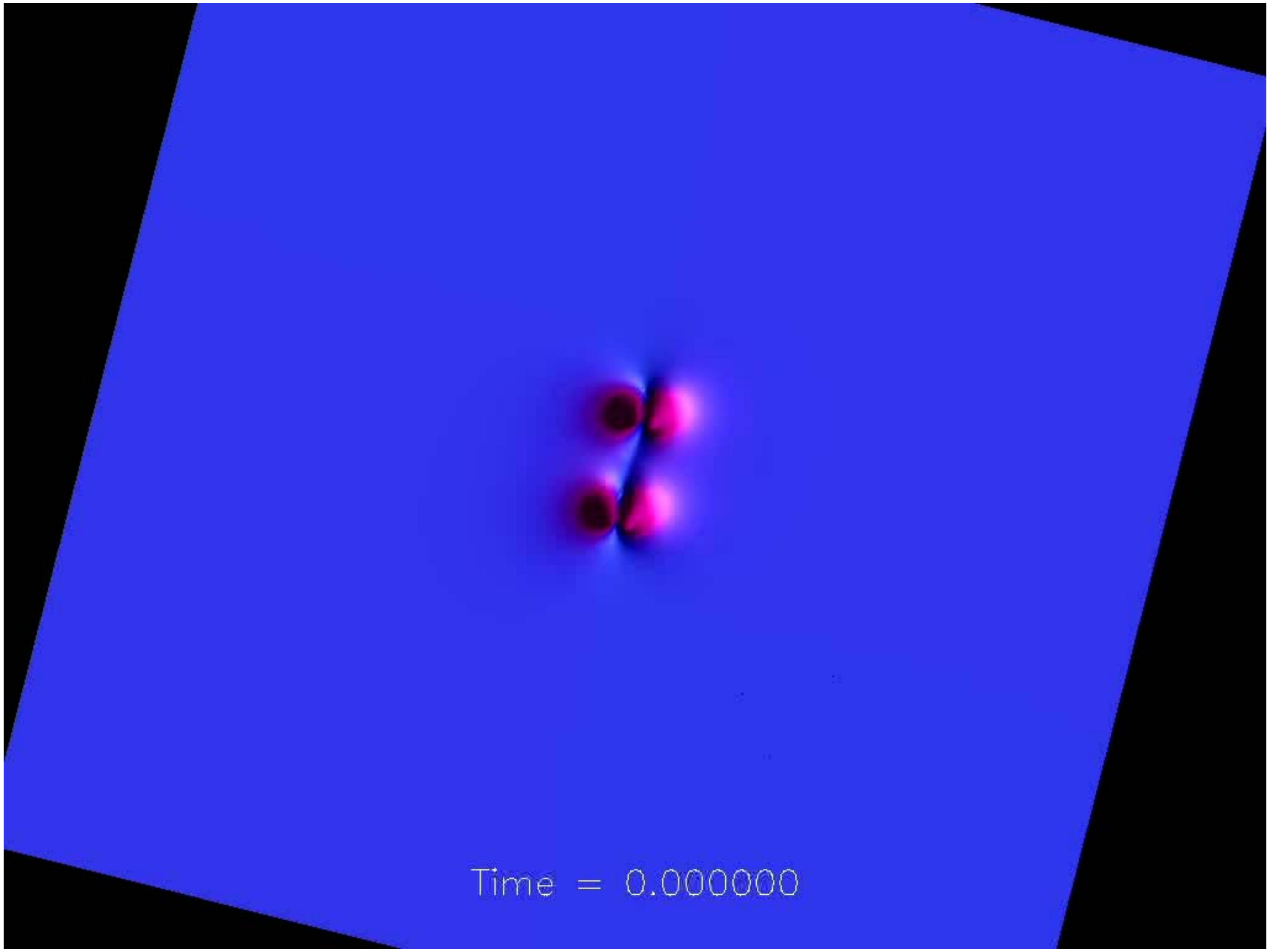
We've seen evidence that huge amounts of matter are compressed in small regions, emitting little light.

But are they really black holes?

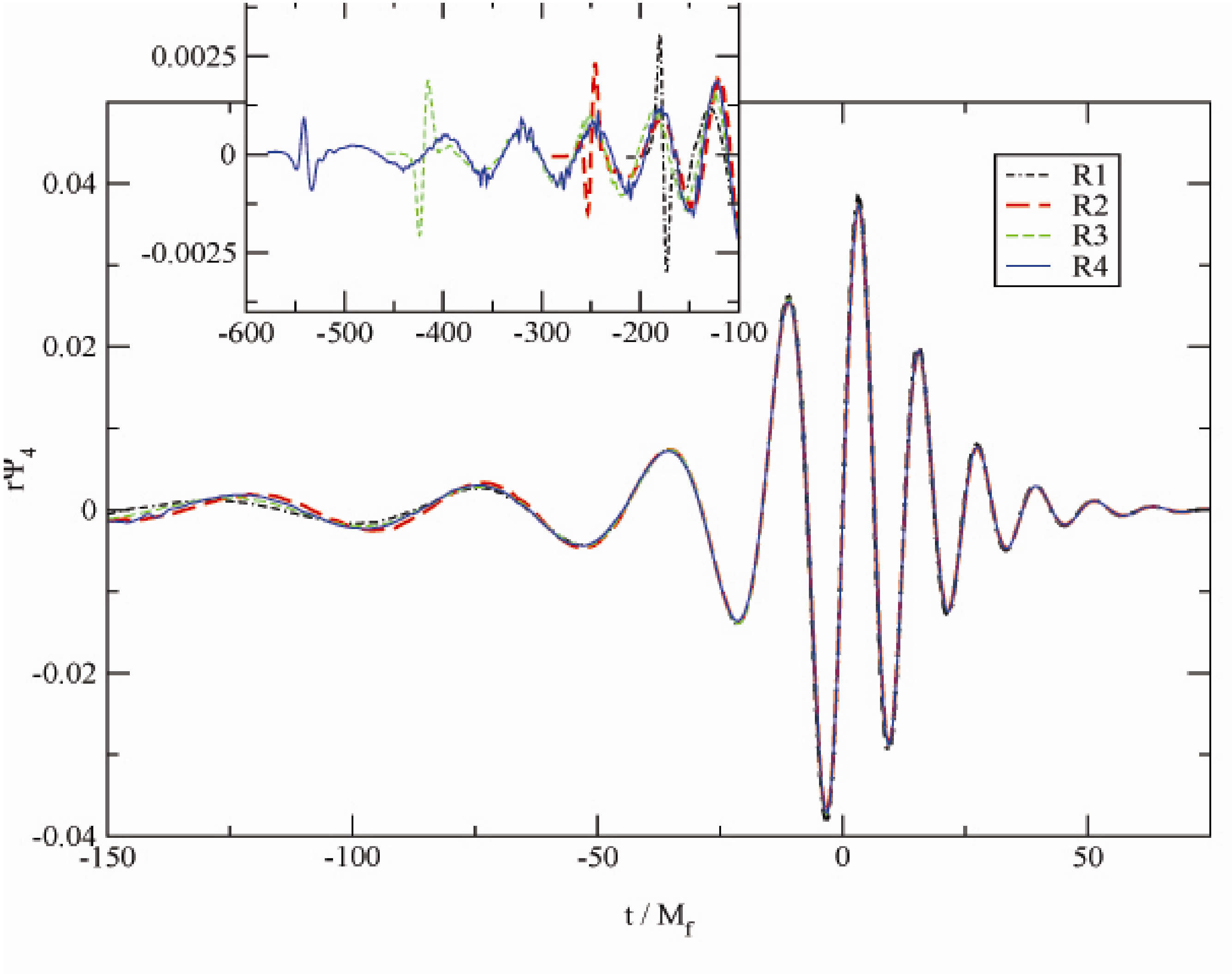
In particular, does the space-time in their vicinity do what General Relativity says it does in the vicinity of a black hole?

Soon, we'll be able to check, by looking for the characteristic vibrations of the space-time around black holes that have collided with one another.

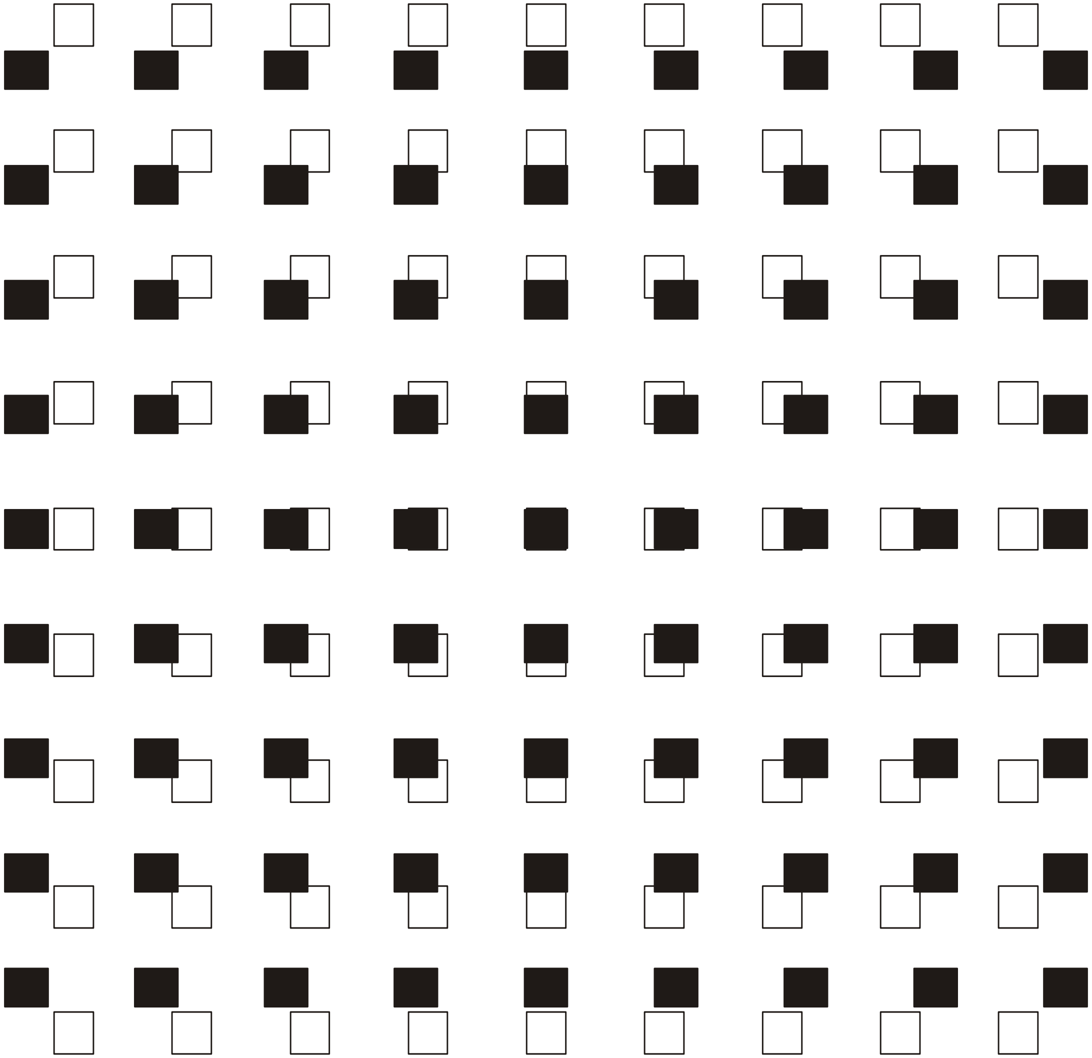
Expected space-time ripples when two black holes collide



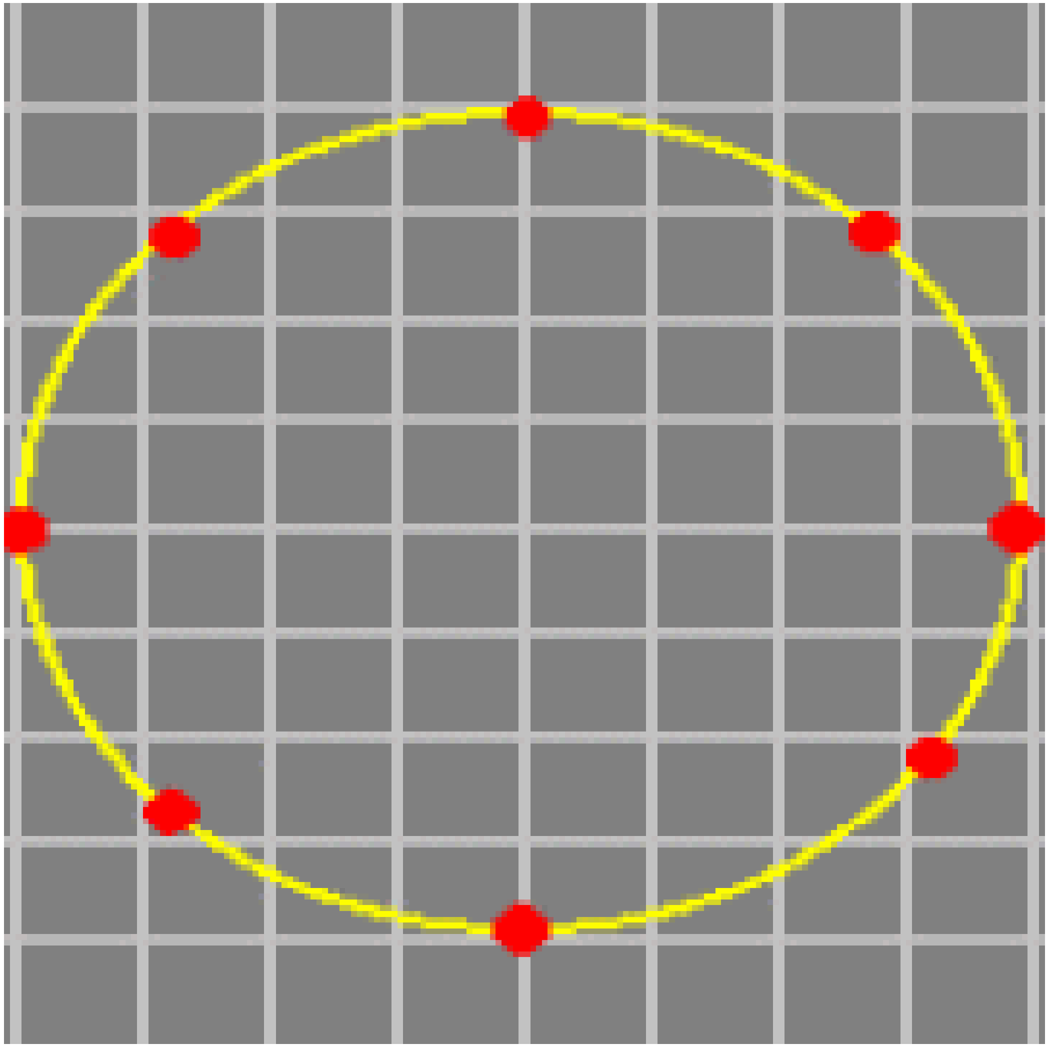
Black hole coalescence gravitational waveform



A gravitational wave meets some test masses

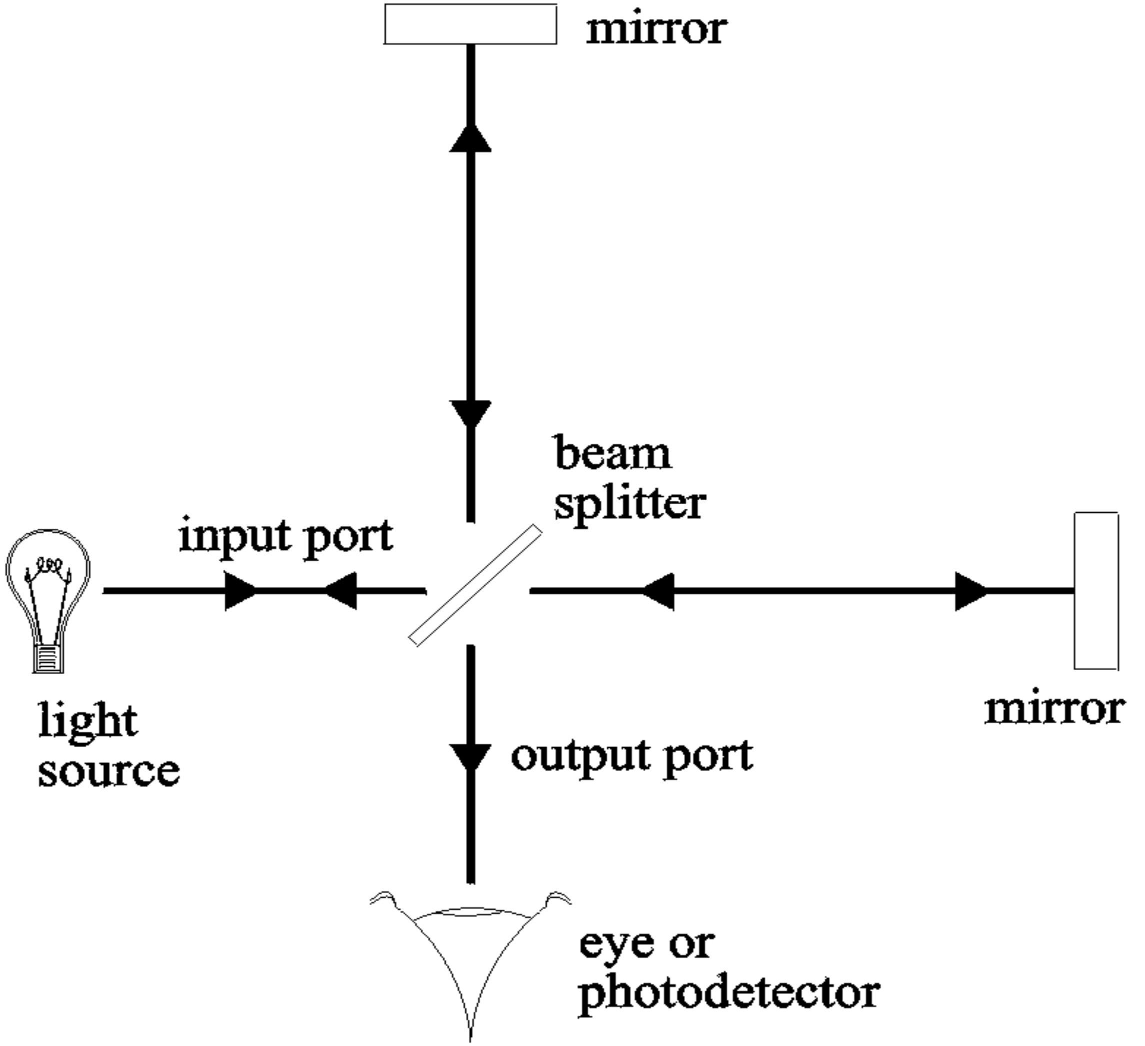


In motion …

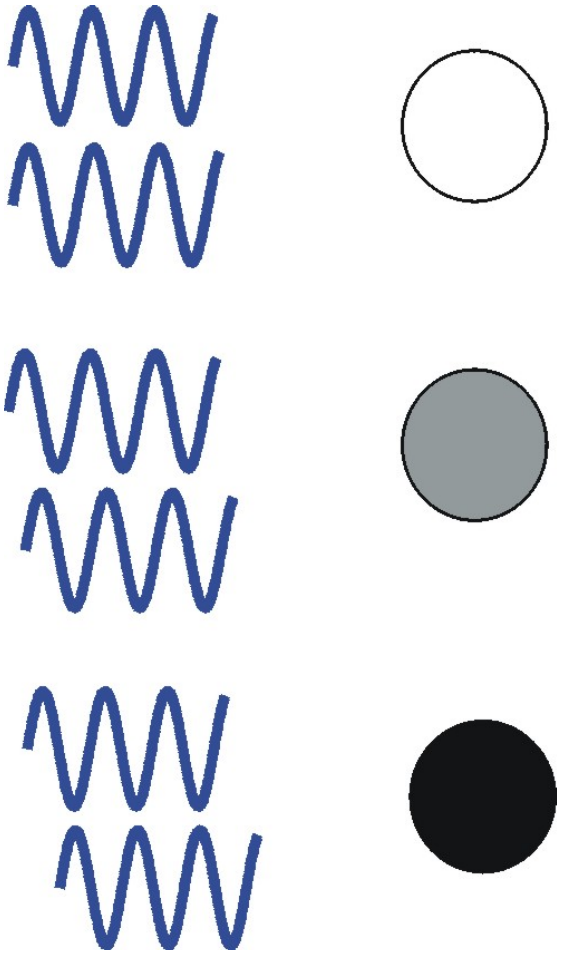


More simply …

Michelson interferometer



MI uses interference to compare the phase of light from two arms



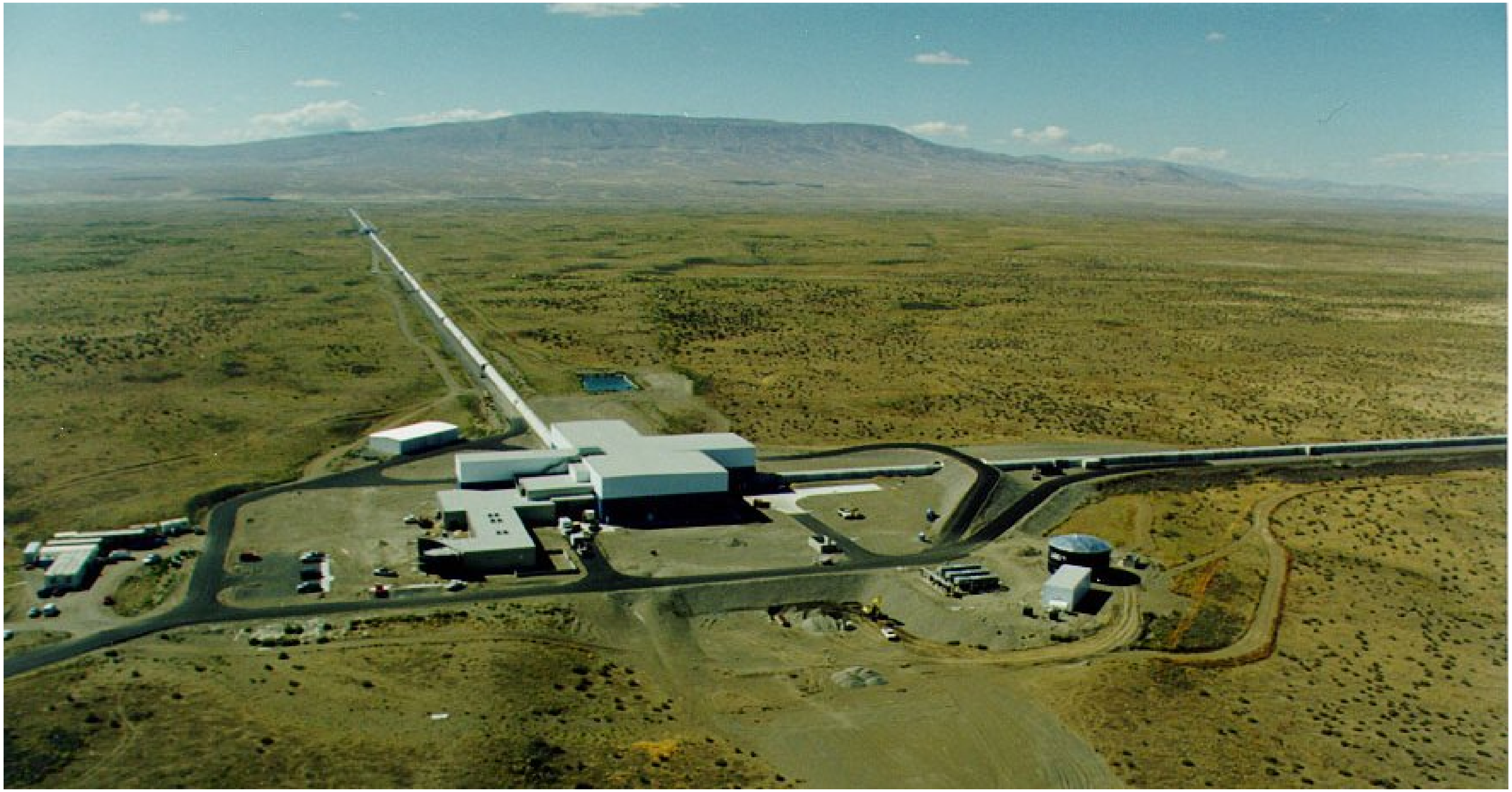
Wave from x arm.

Wave from y arm.

Light exiting from beam splitter.

LIGO Livingston

LIGO Hanford



LIGO Vacuum Equipment

A LIGO Mirror

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5×10^{-7}

Internal mode Q's > 2×10^{6}

Polishing

Surface uniformity < 1 nm rms

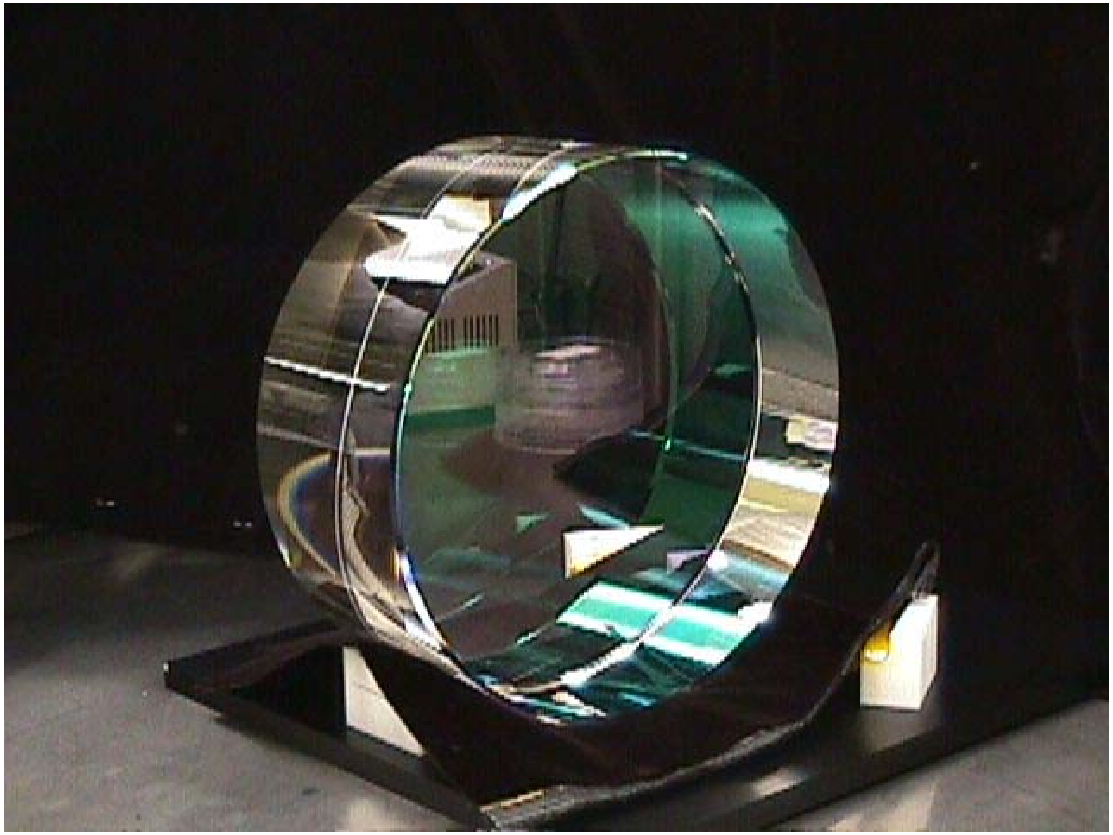
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption < 2 ppm

Uniformity <10^{-3}

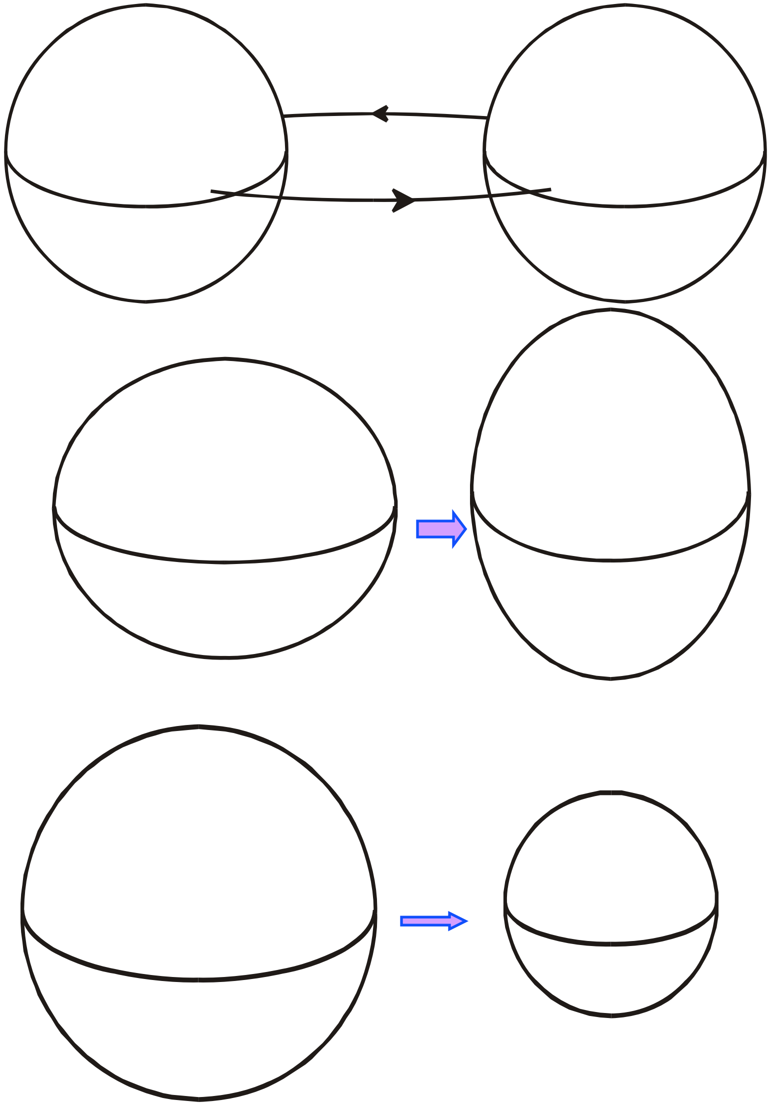


Core Optics

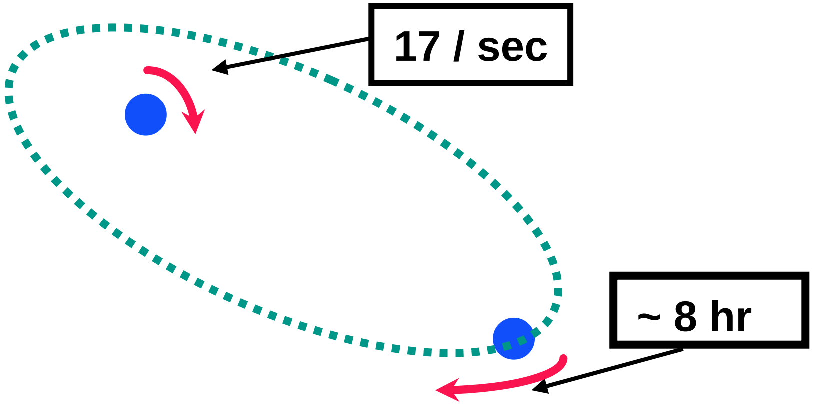
installation and alignment

LIGO-G0900289

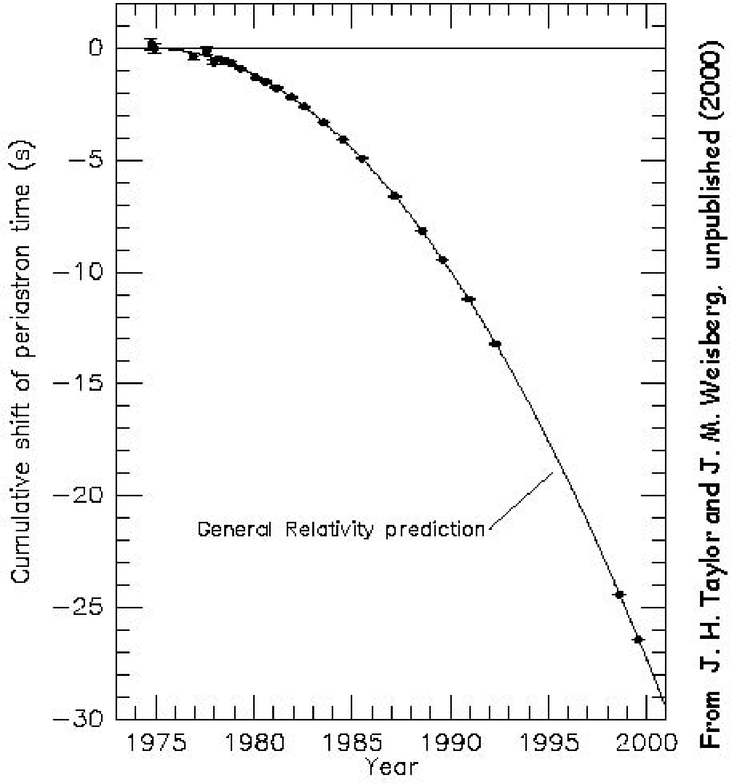
Gravitational wave sources



Binary pulsar

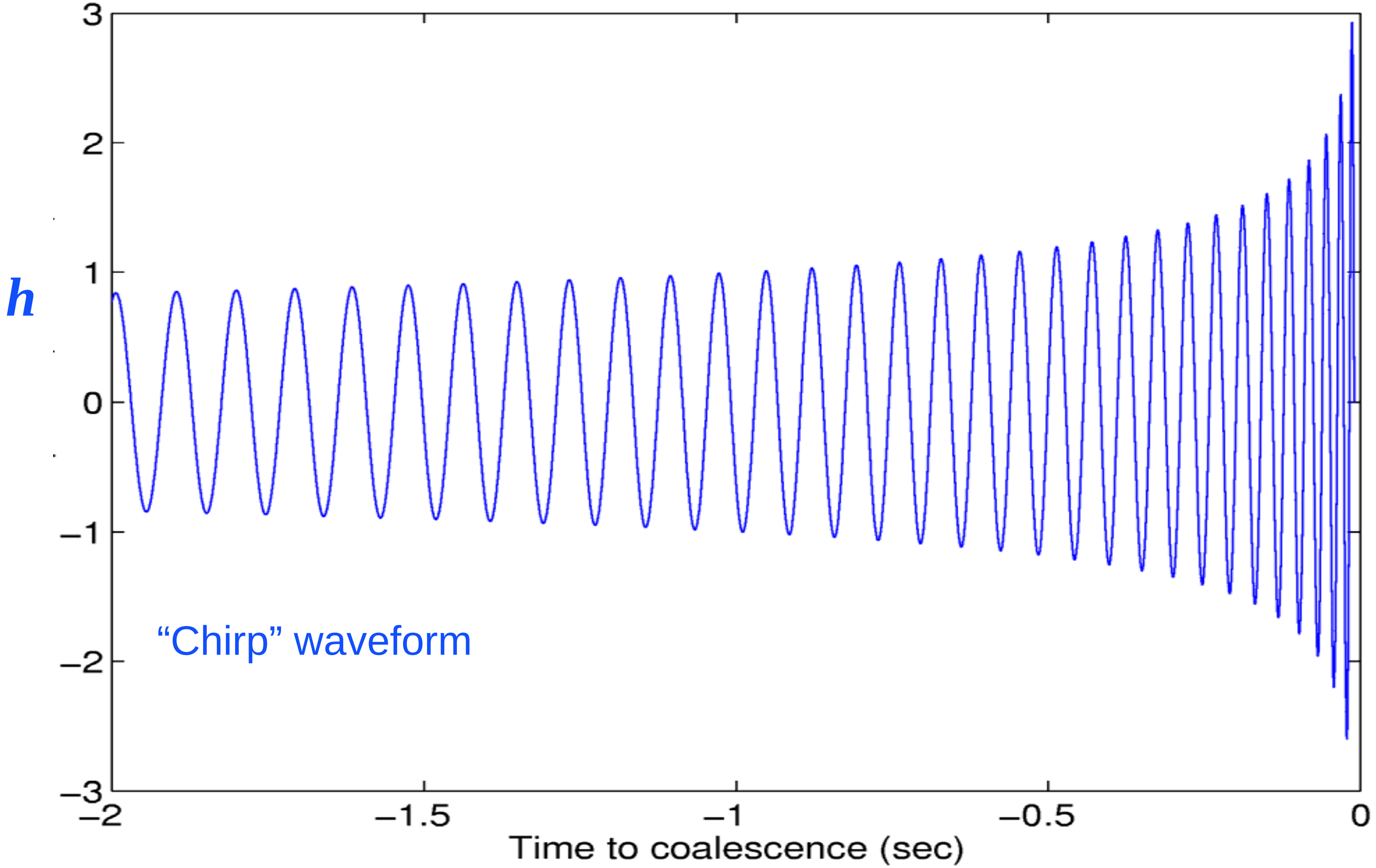


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



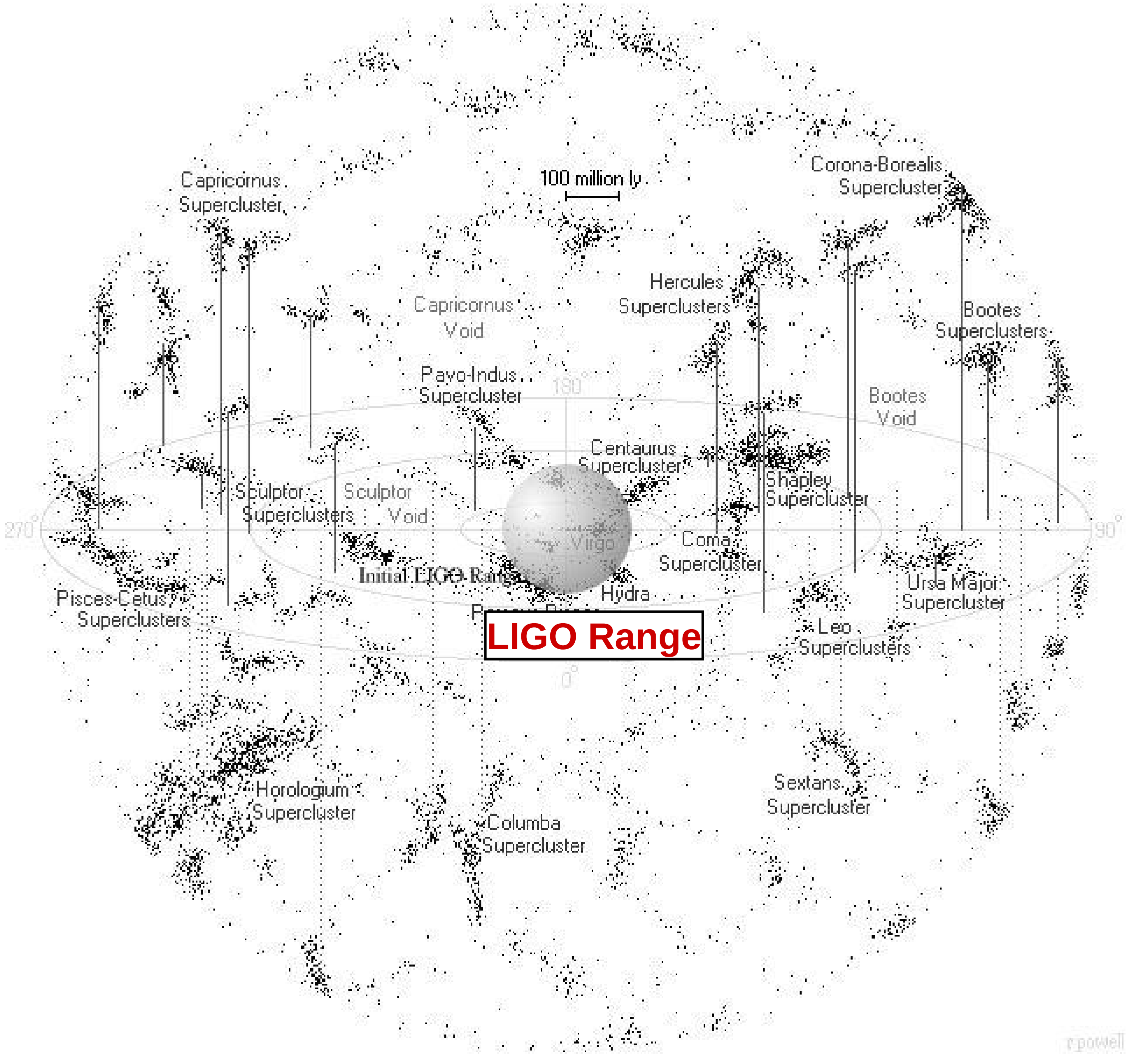
From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Binary pulsar as seen in gravitational waves



“Chirp” waveform

Initial LIGO and Advanced LIGO



LIGO Range

Image: R. Powell

Advanced LIGO Range

Where are we in the search for gravitational waves?

One year's worth of LIGO data is now being analyzed, while the instruments are upgraded.

In 2009, we'll take new data at improved sensitivity.

In 2015, we'll commission Advanced LIGO, with 10 times the present sensitivity.

All indications are that we will soon detect gravitational waves.

Then, we'll be able to use them to study black holes and other exotic phenomena across the universe.