# Black holes, Einstein, and Gravitational Waves

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# Outline

- Black holes
- Gravitation as the curvature of space-time
- Gravitational waves: ripples in the curvature of space-time
- Laser Interferometer Gravitational-wave Observatory (LIGO)

# Newton’s cannon

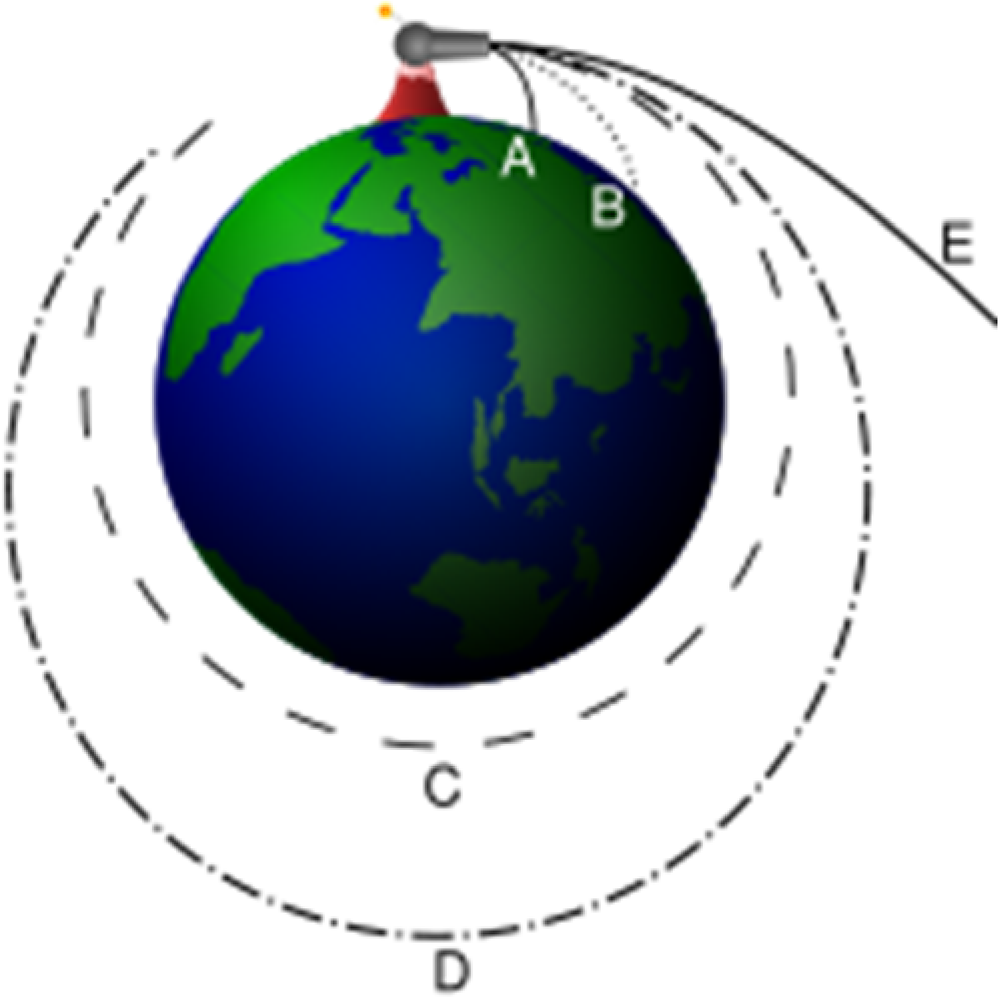
Newton unified motion on Earth and in the heavens.

A cannonball fired from a mountaintop normally falls to Earth.

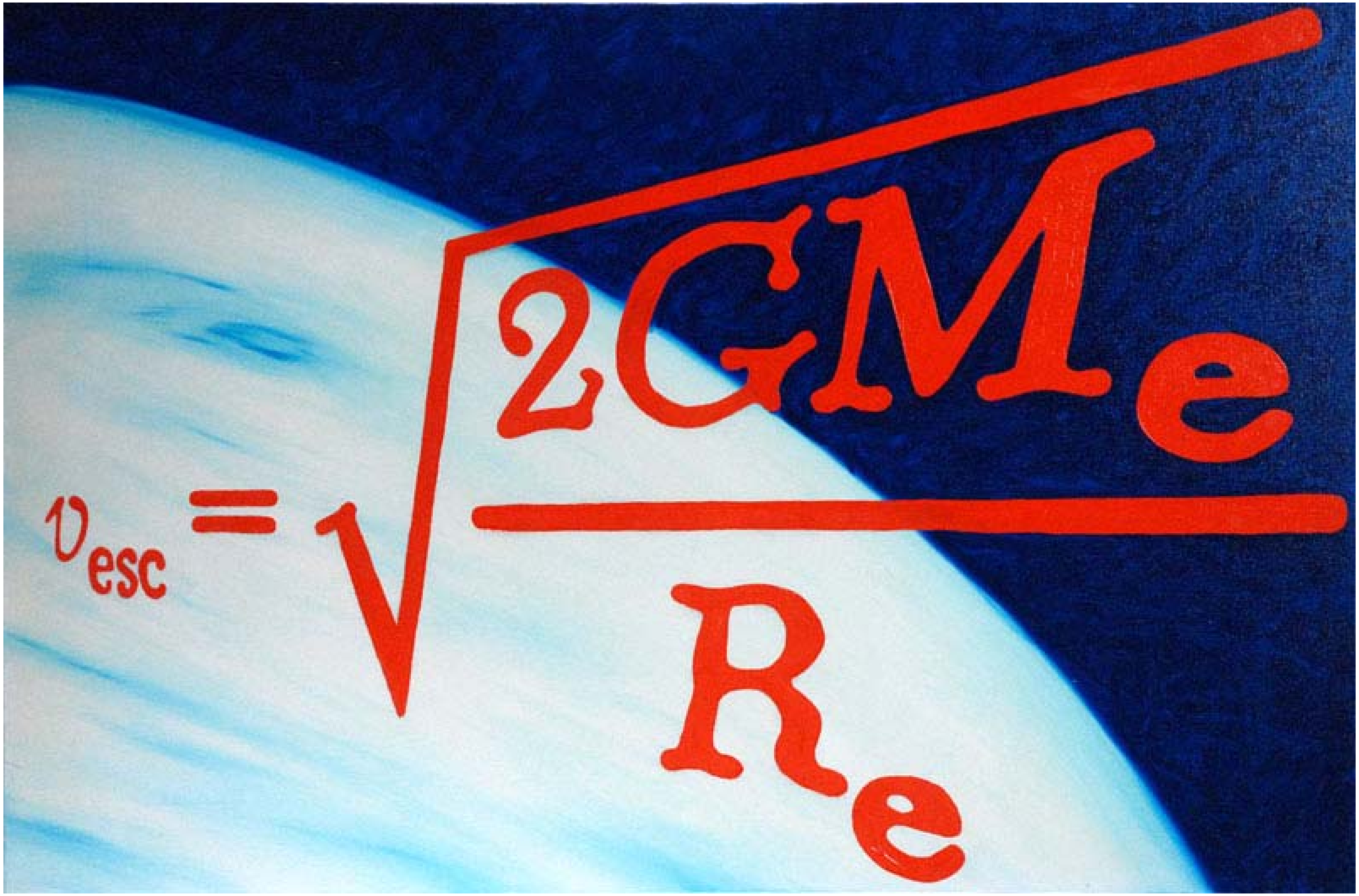
At higher speeds, it goes farther.

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.

# A mystery in the heart of the Milky Way

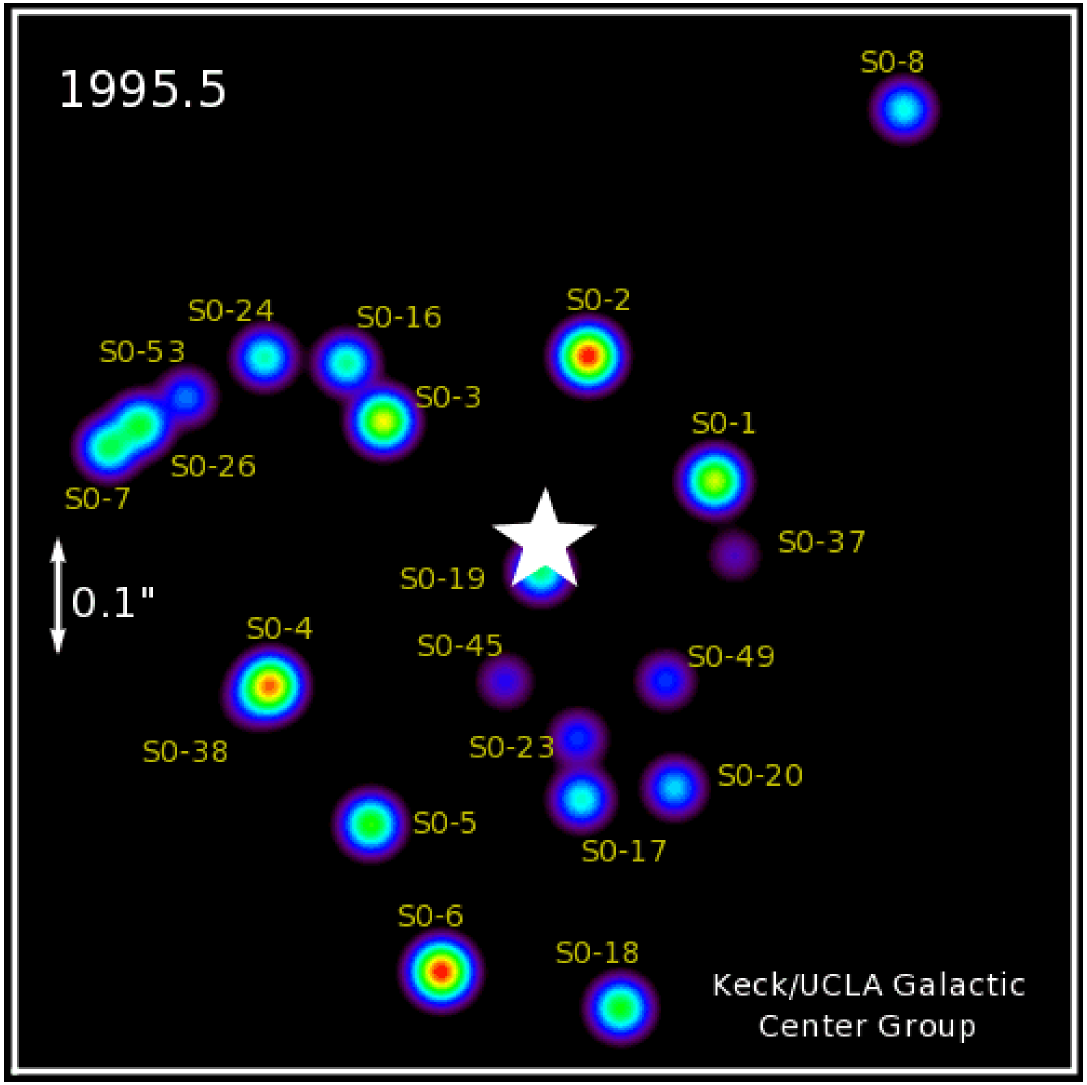
Infrared observations of the center of the Milky Way.

Time lapse movie, showing star positions from 1995 until recently.

Stars orbiting an unseen object.

From orbits, can determine the mass of the unseen object. It is about 4 million solar masses!

A black hole?



# Are black holes a threat?

Will black holes suck up everything in the Universe?

No.

Their strong gravity is only strong very close to the black hole.

The *event horizon* marks the ghostly reminder of the surface of the star that just barely can’t let light escape from it. Further away from the star, gravity falls off, getting weaker just as it would for matter in a more ordinary form.

If the Sun suddenly became a black hole, its gravity at Earth’s distance would be the same, and we’d orbit like before. (Of course, we’d miss the light!)

# Black holes are interesting!

Black holes consist of matter in one of its most extreme forms ever imagined. So dense, that it almost isn’t matter. All that is left of its character is its mass. Otherwise, “A black hole has no hair.”

Another way of looking at a black hole is that it consists of pure gravity, or in Einstein’s terms, it consists of pure “space-time curvature”.

# Einstein’s view of gravity: The General Theory of Relativity

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

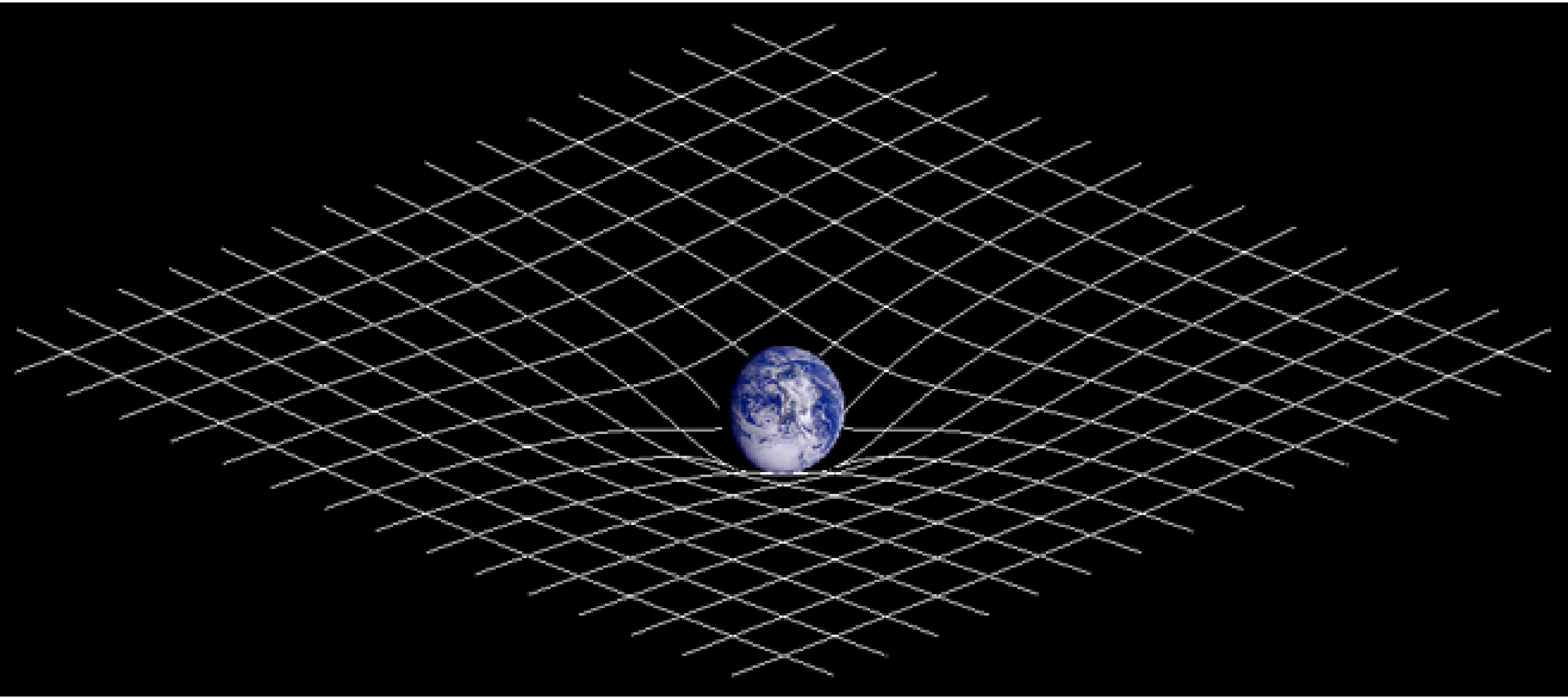
The basic idea is that gravity is not a force, but rather a manifestation of the curvature of space-time.

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.

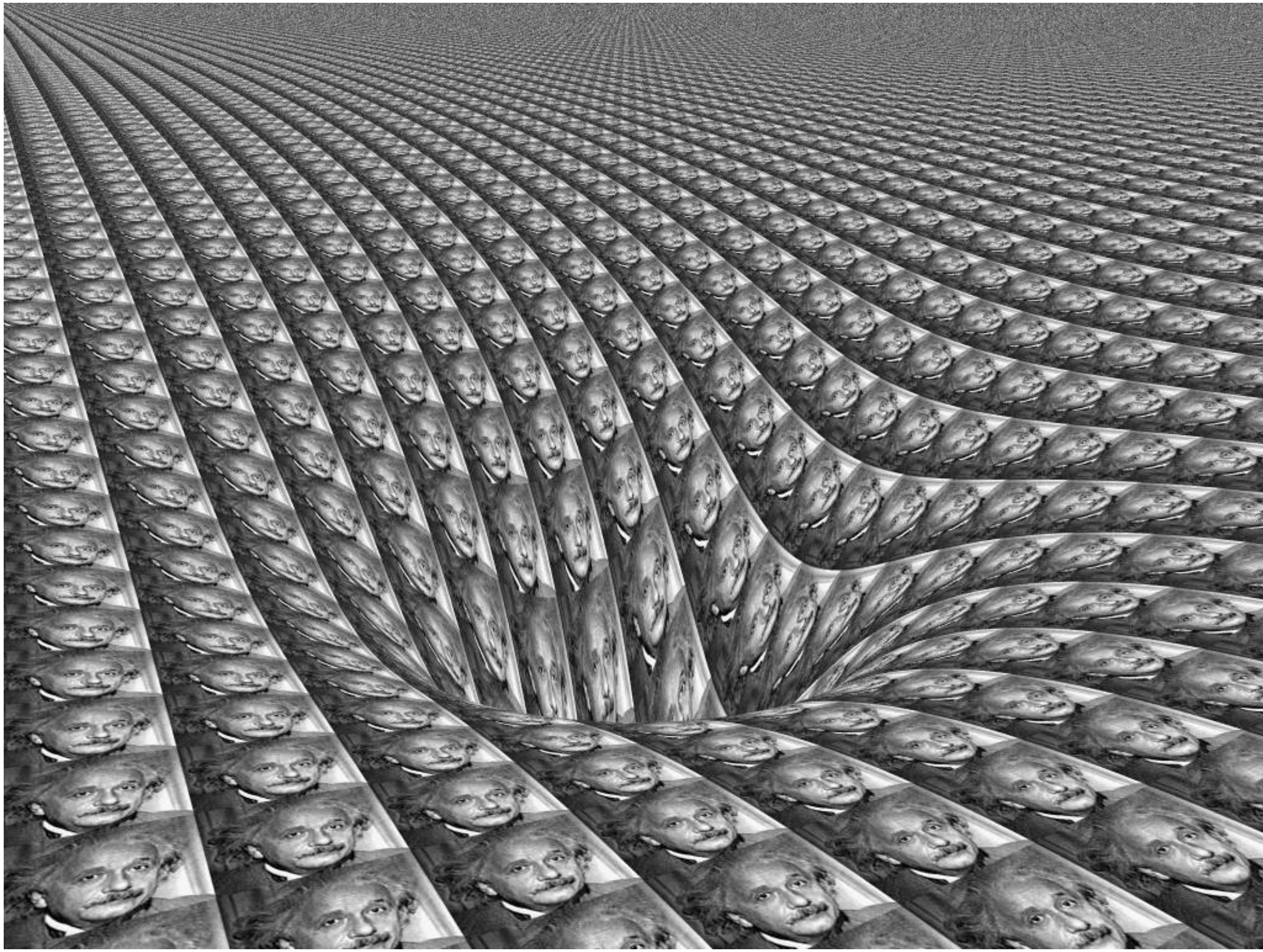
# Matter tells space-time how to curve. Space-time tells matter how to move.



# Black holes, from the point of view of General Relativity

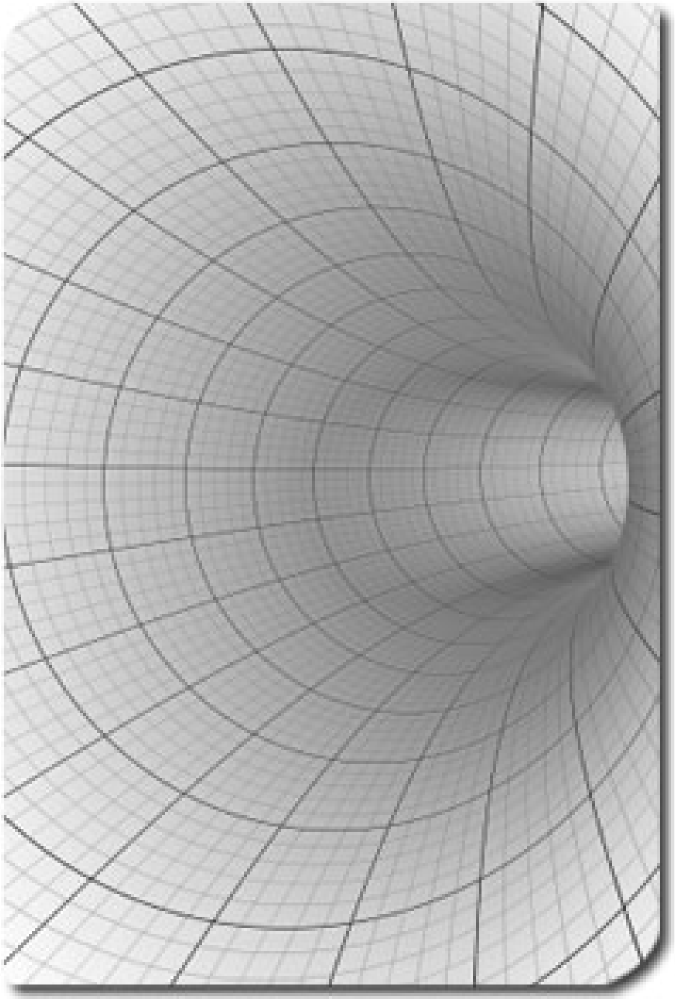
A view of the space-time in the vicinity of a black hole.

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.

Now, I'll explain a new way of looking for black holes that will let us get "up close and personal" with them.

# Black hole vibrations create space-time ripples

If a black hole is disturbed, distorted, or newly created, it will vibrate.

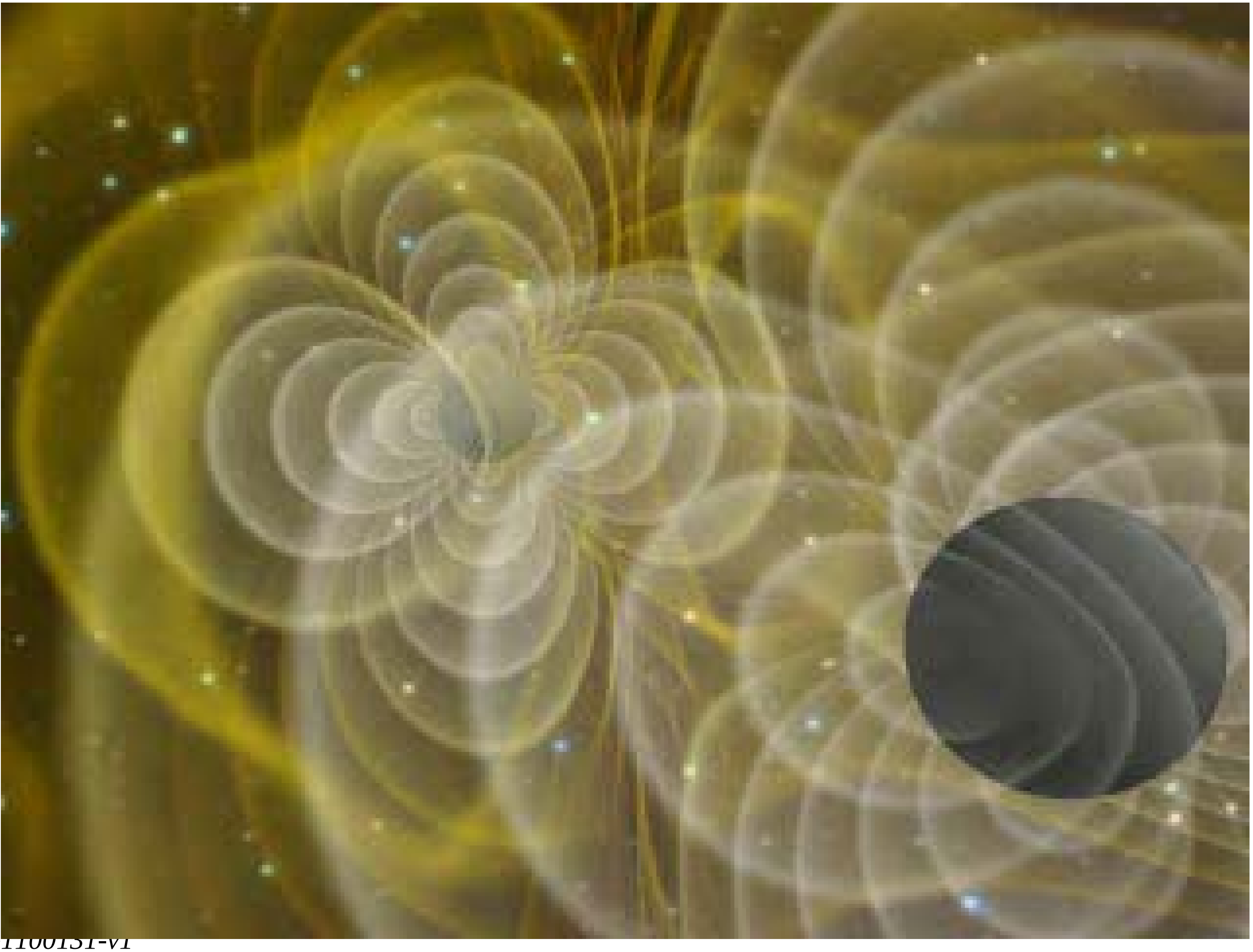
A vibrating black hole launches ripples in space-time, also known as *gravitational waves*.

If two pre-existing black holes collide, they will form a new larger (but momentarily distorted) black hole.

This happens often, from black holes in binary pairs, two black holes orbiting each other.

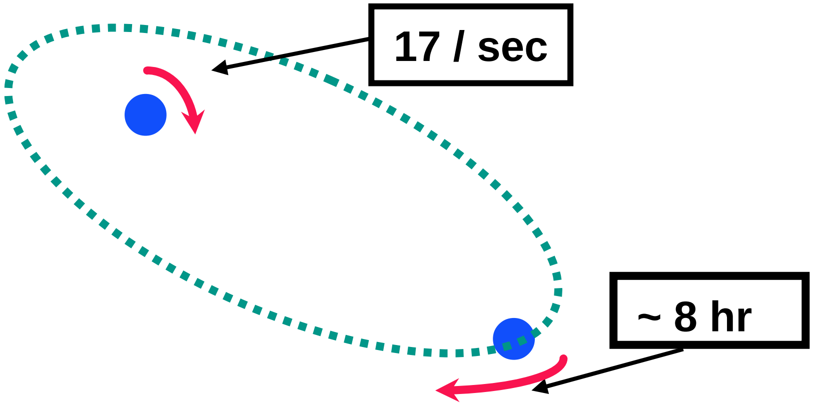
Gravitational waves are made by the orbiting black holes. This carries away energy, causing them to spiral towards each other, eventually colliding and forming a single more massive black hole.

# A simulation of two black holes colliding

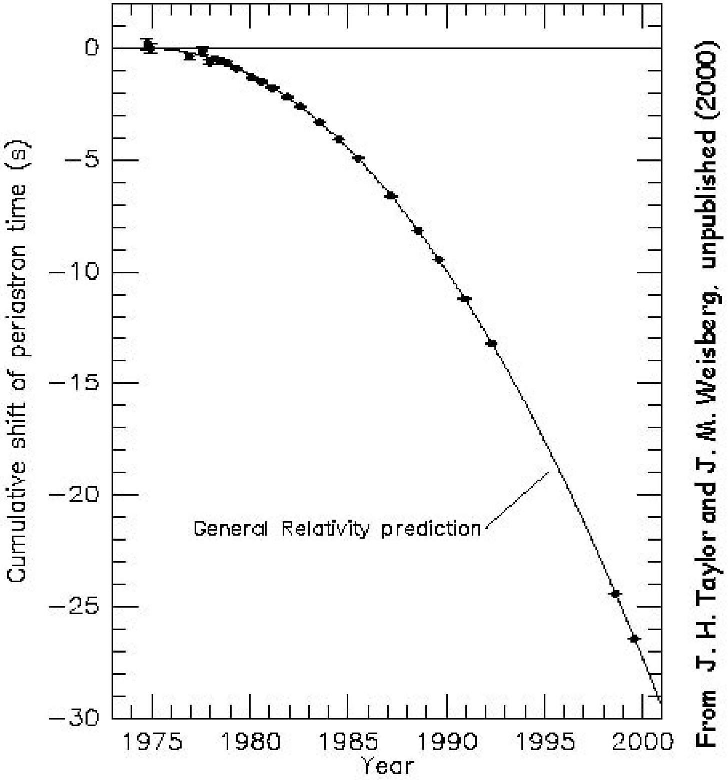


Henze, NASA

# The Binary Pulsar
# Gravitational waves are emitted by binaries

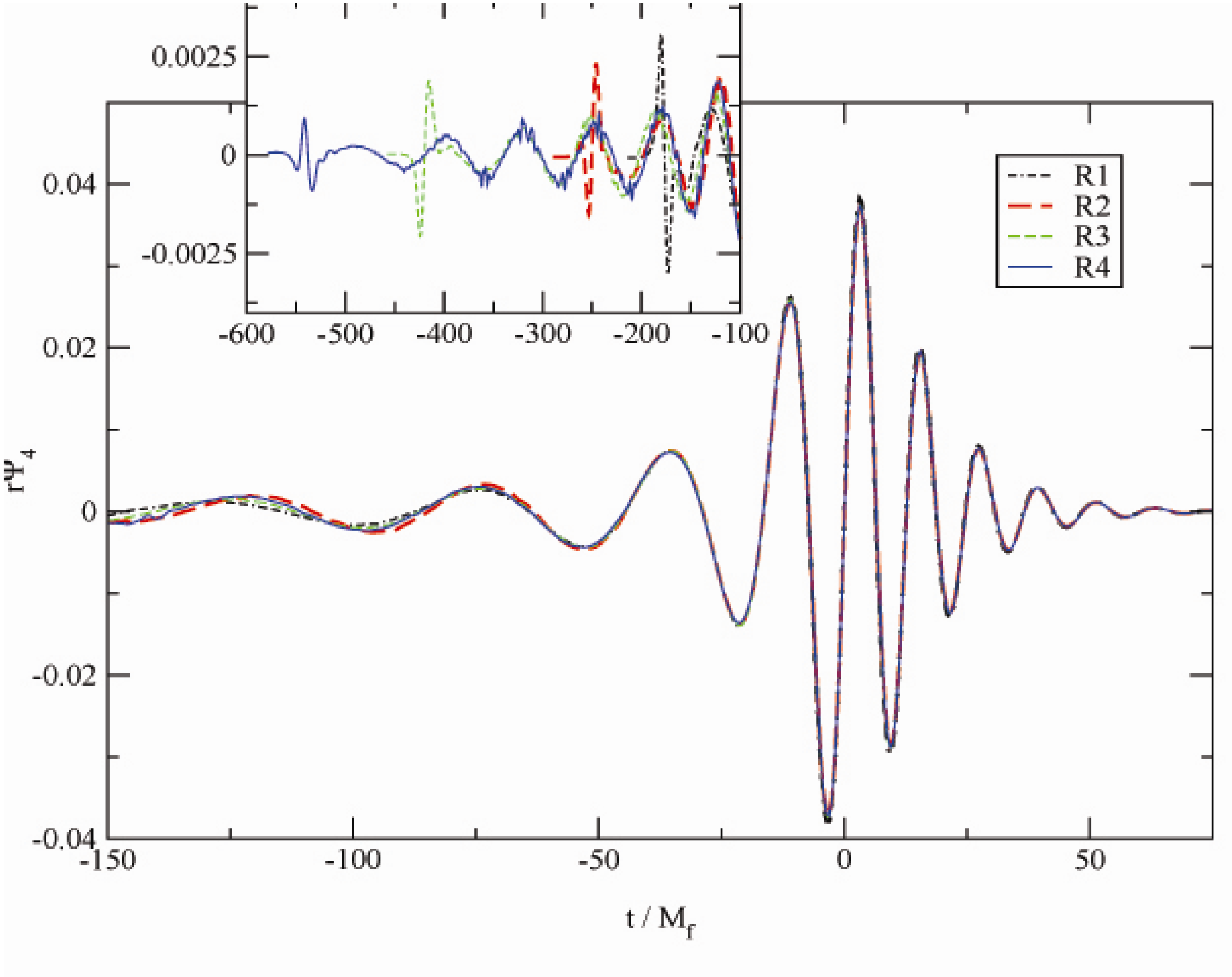


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



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

# The space-time ripple (red in simulation) as it passes us



# With the right "microphone", we could listen to these ripples

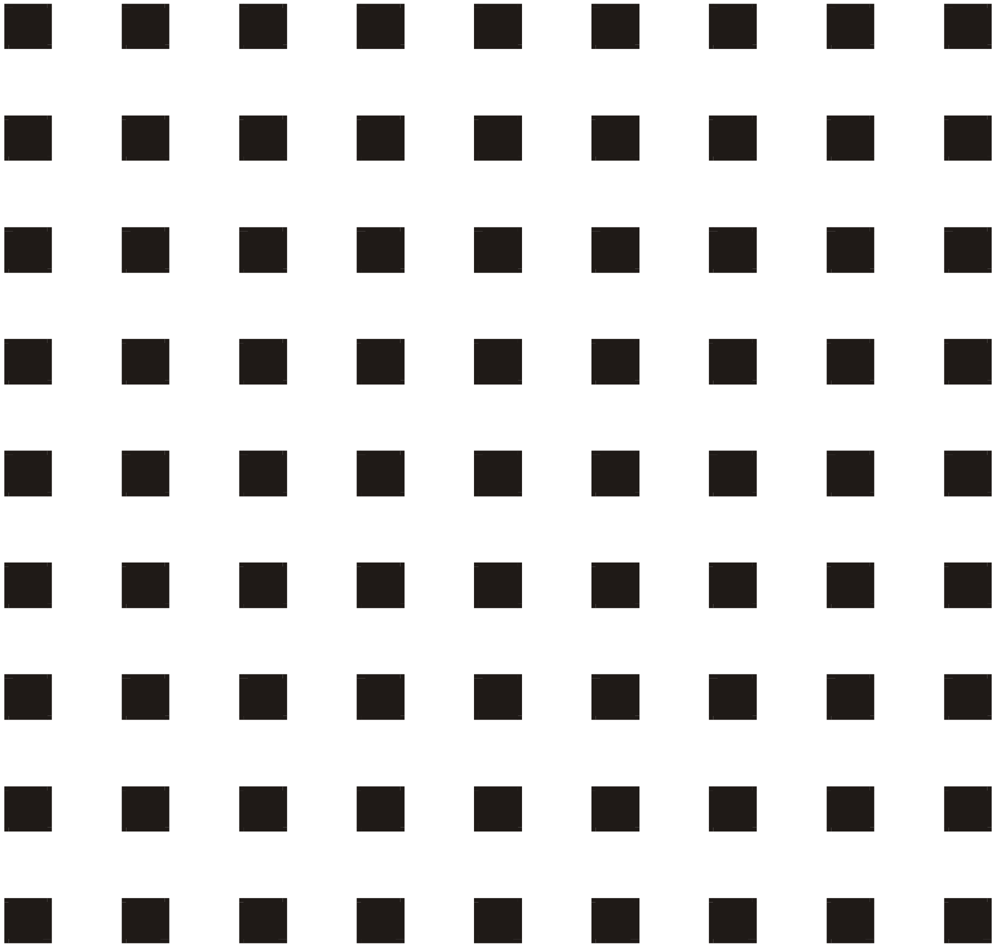
Here's a playback (based on calculation!) of the gravitational wave from the collision of two black holes, played back directly through loudspeakers.

Other than amplification, no other changes would be necessary in order to make this audible. The ripples naturally occur in the (human) audio band!

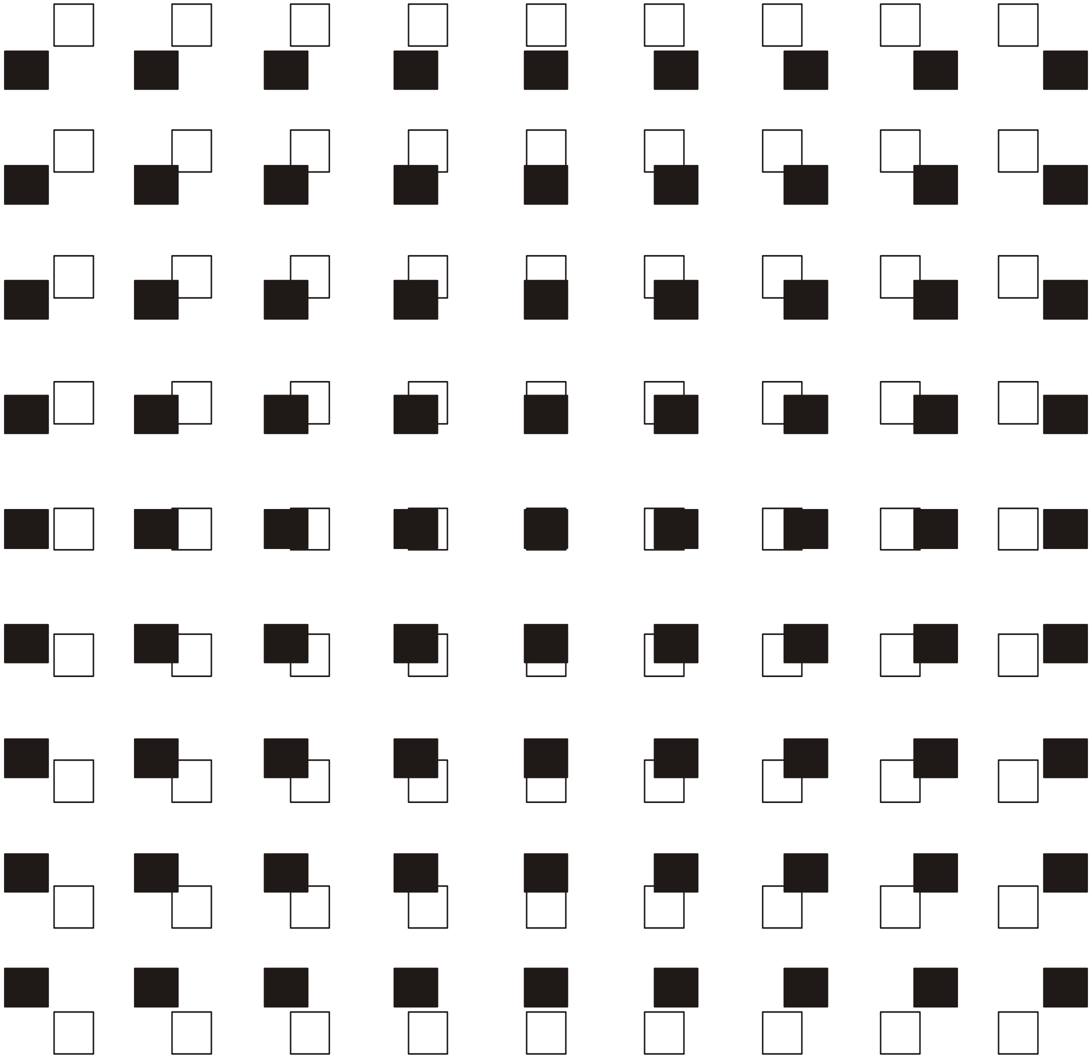
How can we make a "microphone" that could actually pick up this sound from real black hole collisions?

Firstly, we need to see what those ripples really are.

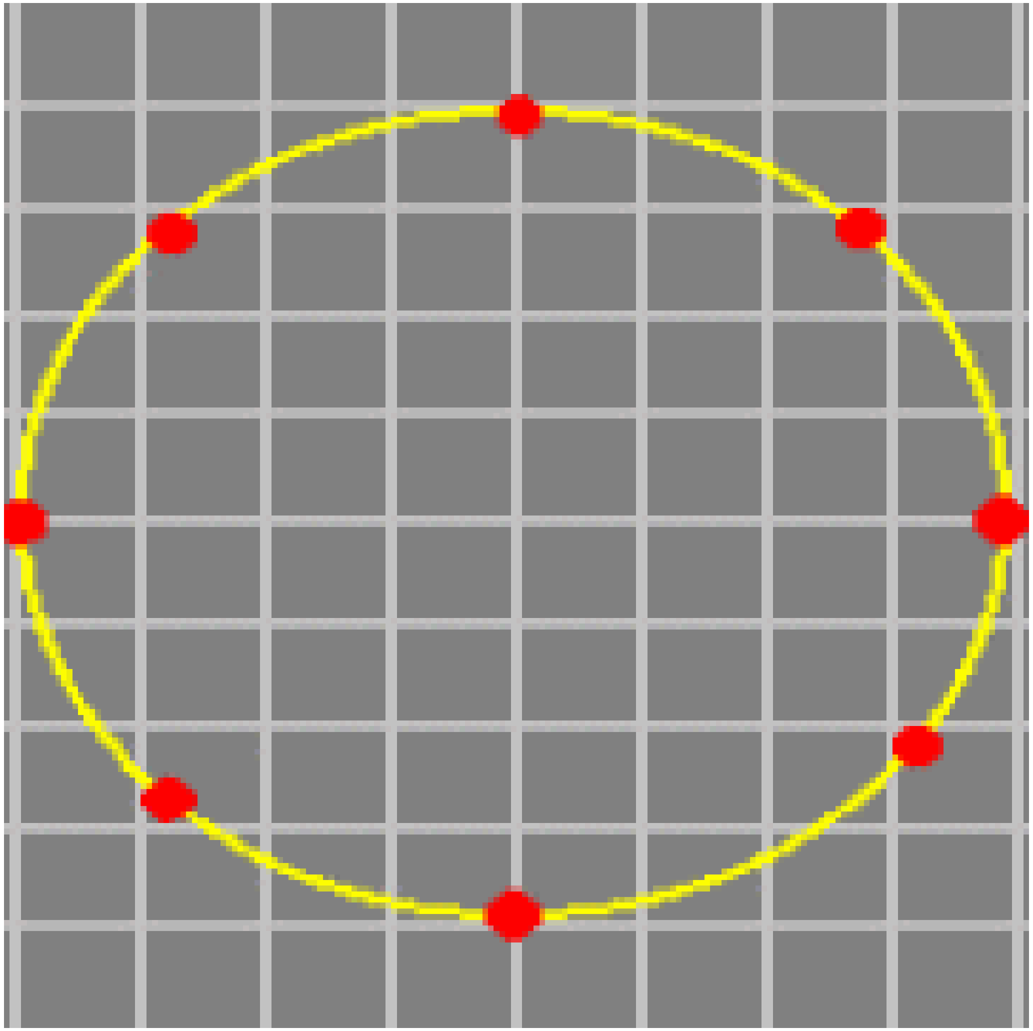
# A set of freely-falling test particles



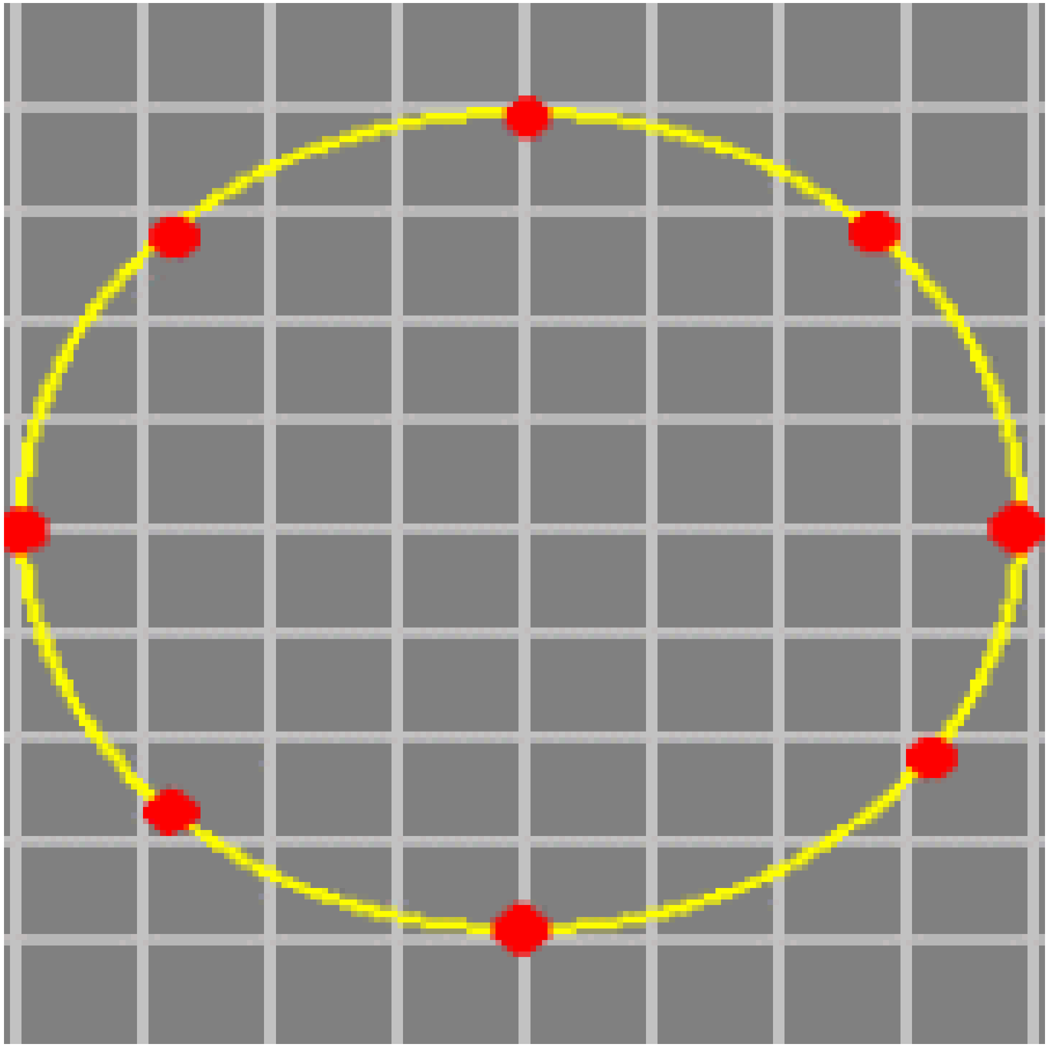
# A gravitational wave meets some test masses



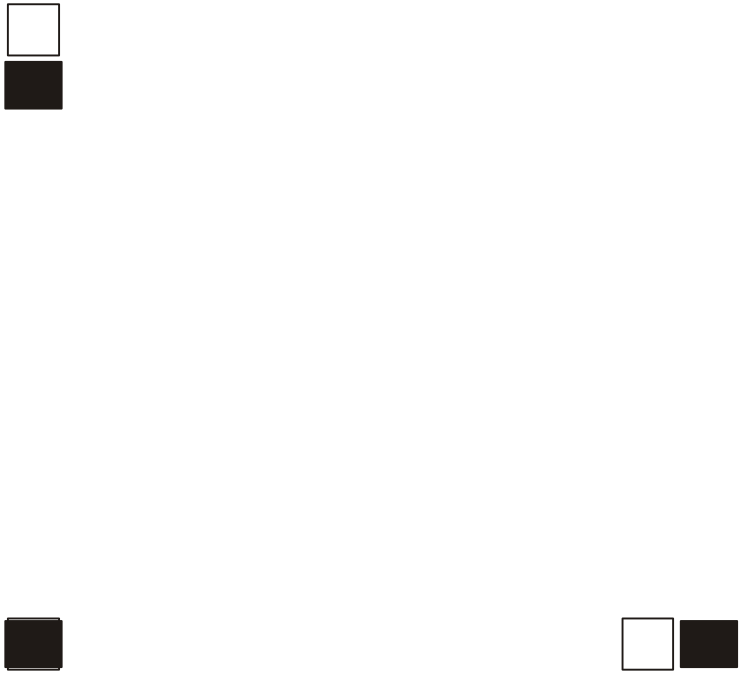
# How to make a "microphone" for space-time ripples



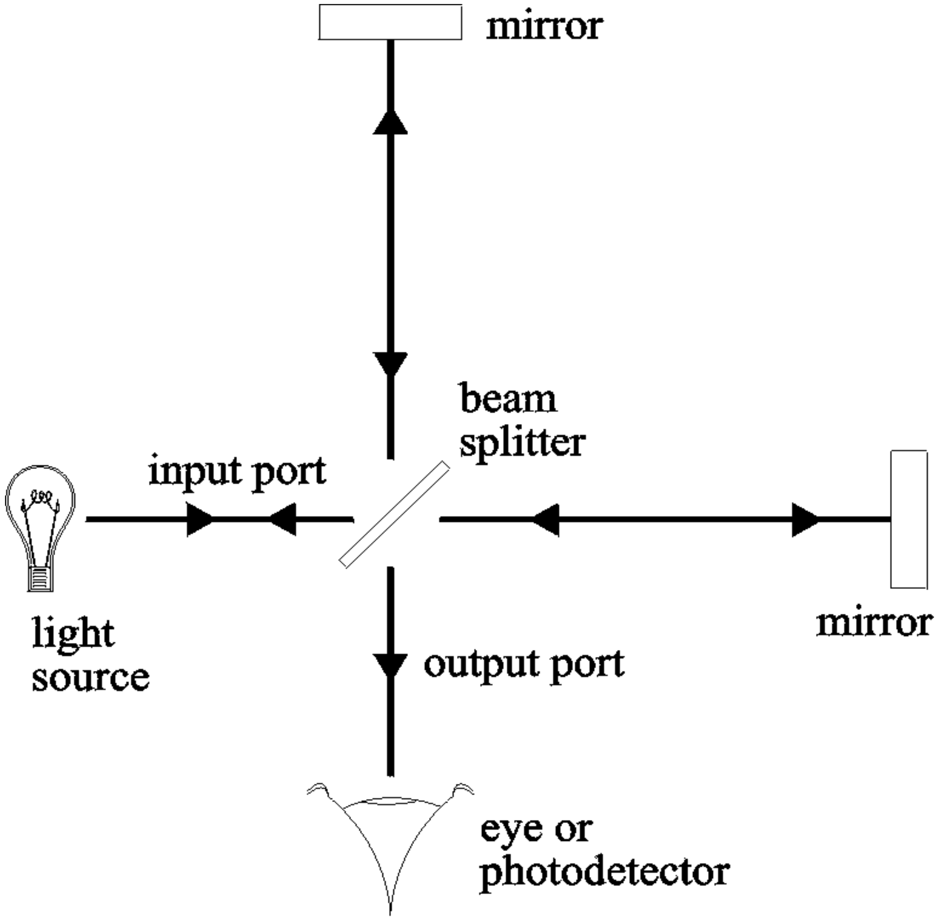
# What the ripples do



# More simply …



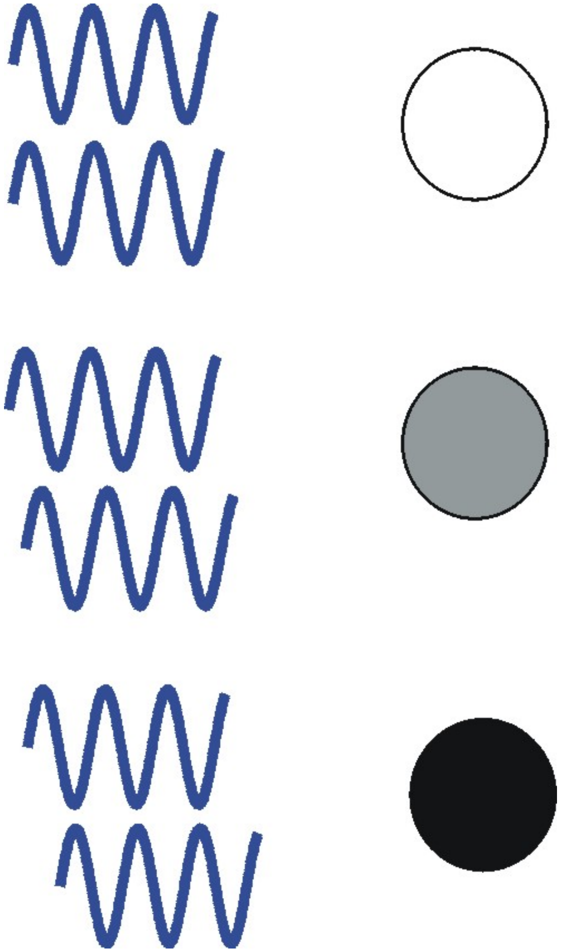
# Interferometer can serve as a microphone for space-time ripples



# How an interferometer works

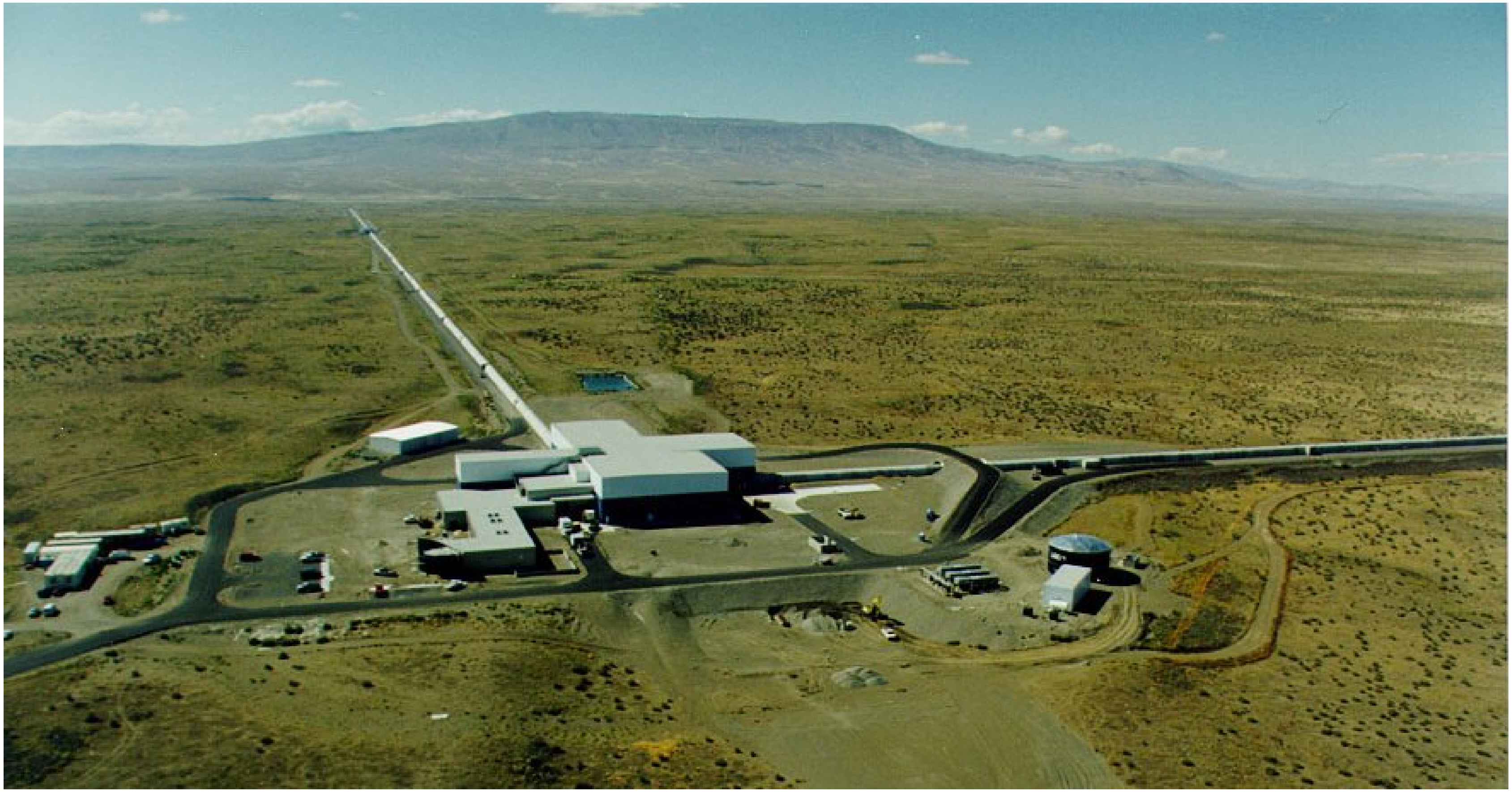
Wave from x arm.

Wave from y arm.



Light exiting from beam splitter.

# LIGO Hanford



# LIGO Livingston

# LIGO Vacuum Equipment

# 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

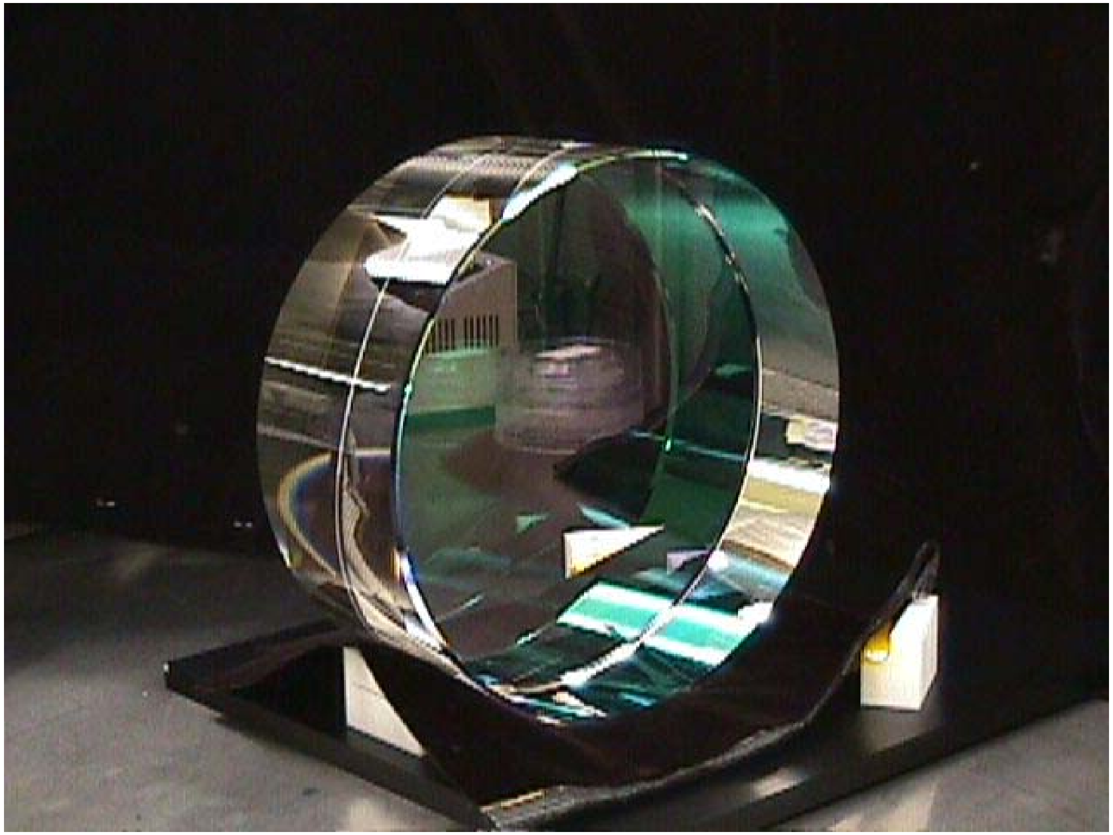
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption <  2 ppm

Uniformity $<10^{-3}$



# Core Optics

## installation and alignment

# Where are we in the search for gravitational waves?

We have been collecting observations and analyzing data with initial LIGO for several years.

So far, no luck in finding gravitational waves.

Now, we are disassembling our instruments to begin installation of Advanced LIGO, with 10 times the present sensitivity.

By 2015, Advanced LIGO will be ready. It will have enough sensitivity to find gravitational wave signals.

Then, we’ll be ready to explore the Universe using this new “ear” for gravitational waves, and to look into the nature of black holes.

# Initial LIGO and Advanced LIGO

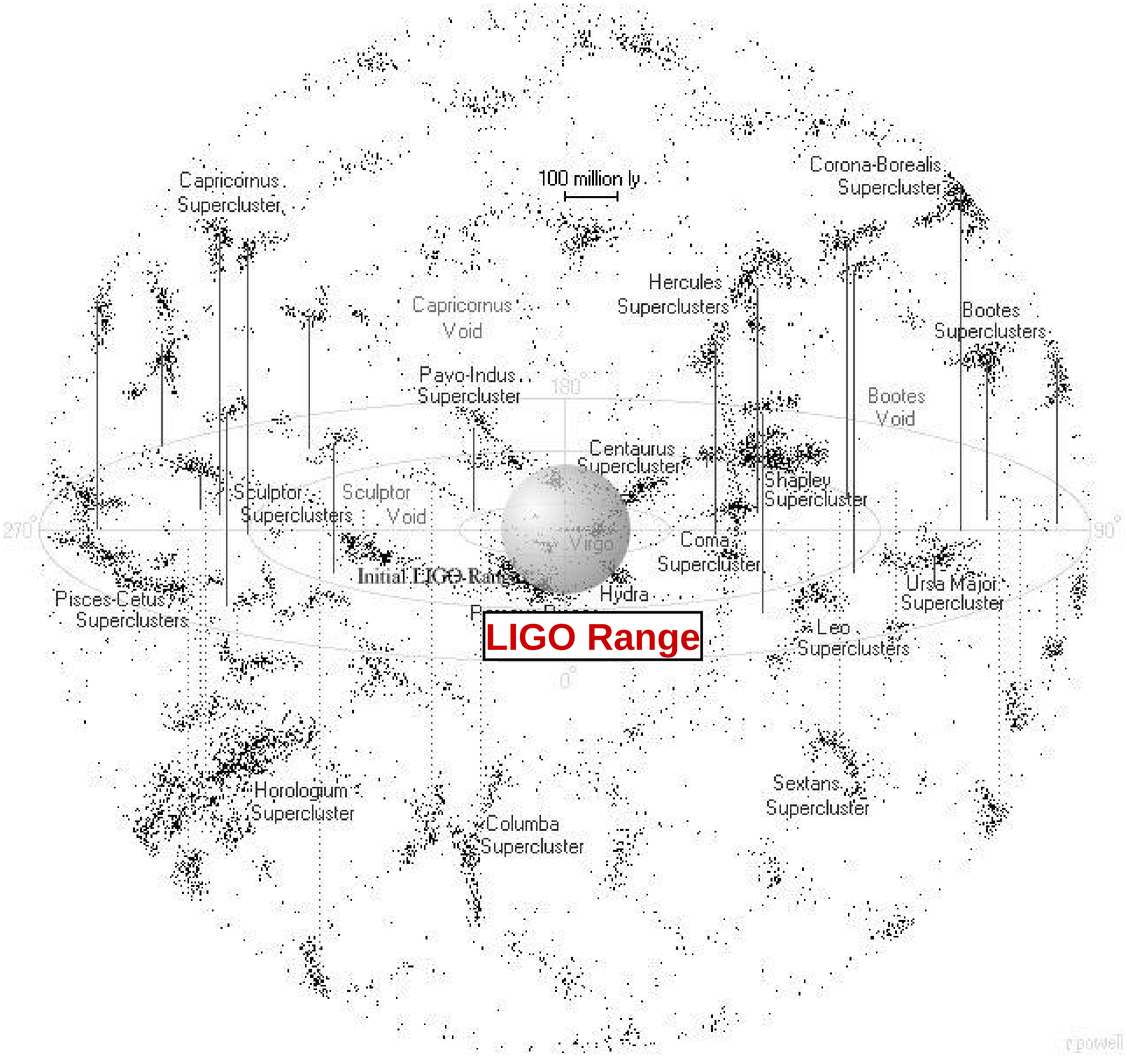


Image: R. Powell

**Advanced LIGO Range**