Black holes, Einstein, and space-time ripples

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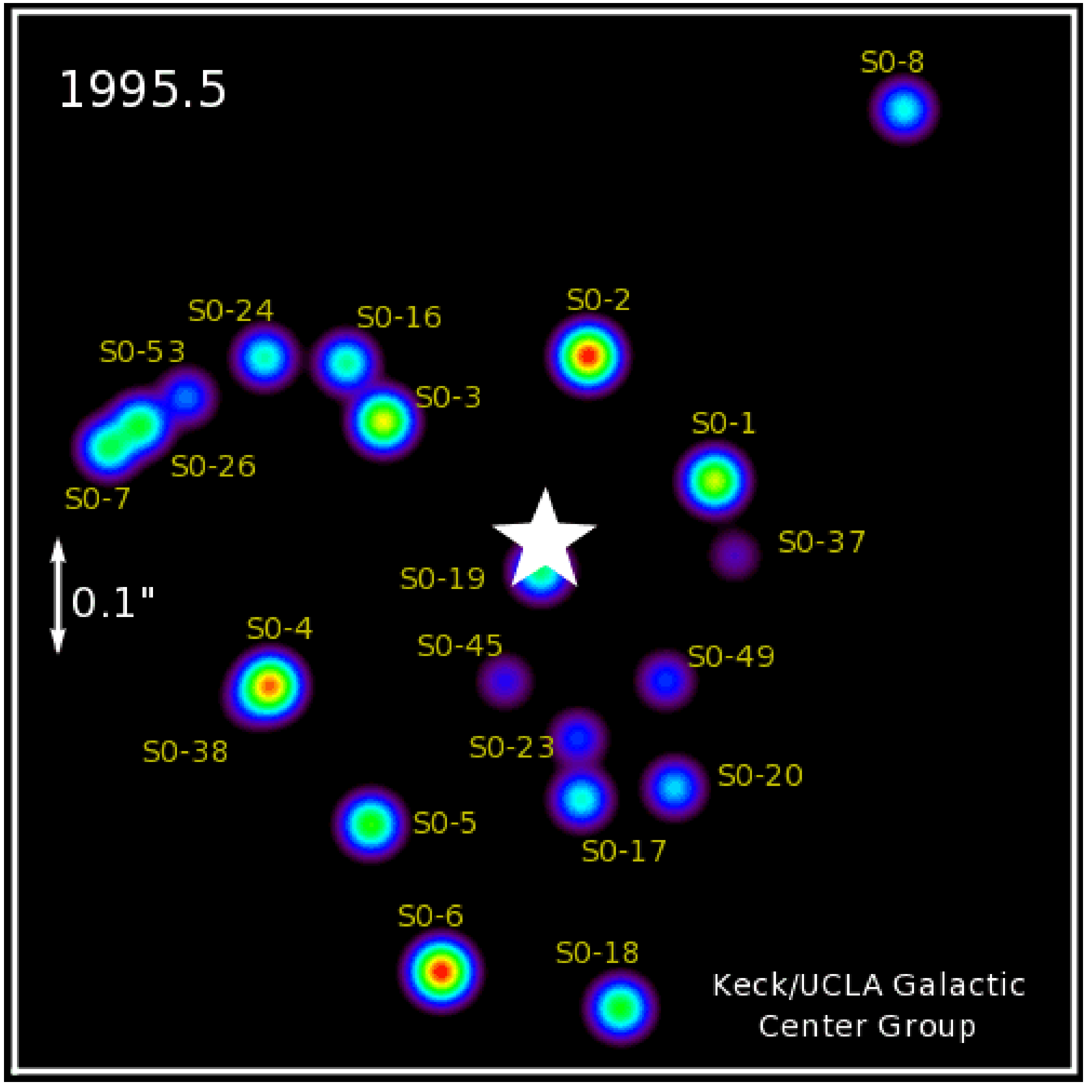
Black Hole at the center of the Galaxy



What is a black hole?

Imagine compressing all of the mass of the Sun into a sphere about four miles in diameter.

If you could do that, what would it be like?

The gravity at the surface would be so strong that nothing could escape, not even light.

Once that happened, gravity is also so strong that no force can keep the star from collapsing completely under its own weight.

It becomes a point (!), containing all of its original mass.

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.

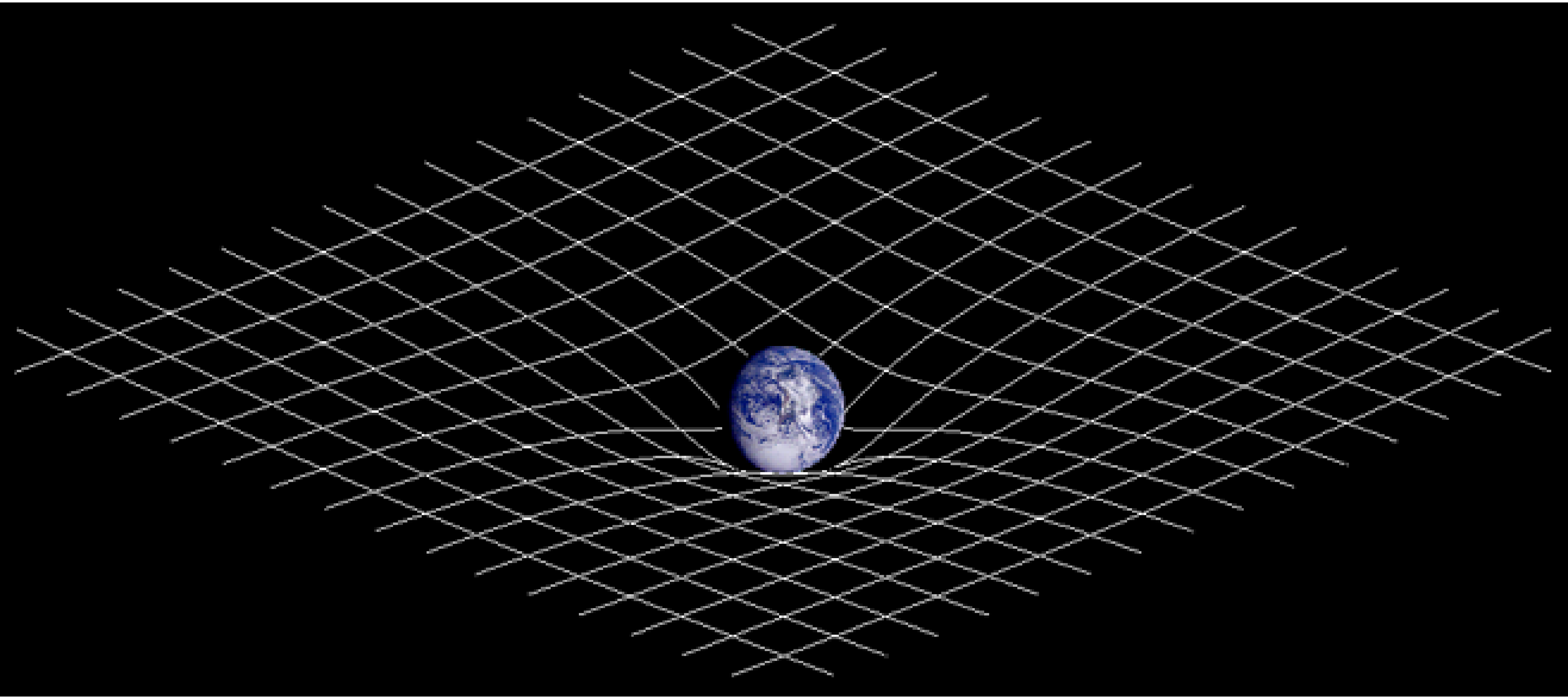
The basic idea is that gravity is not a force, but rather a manifestation of the curvature of space-time.

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.

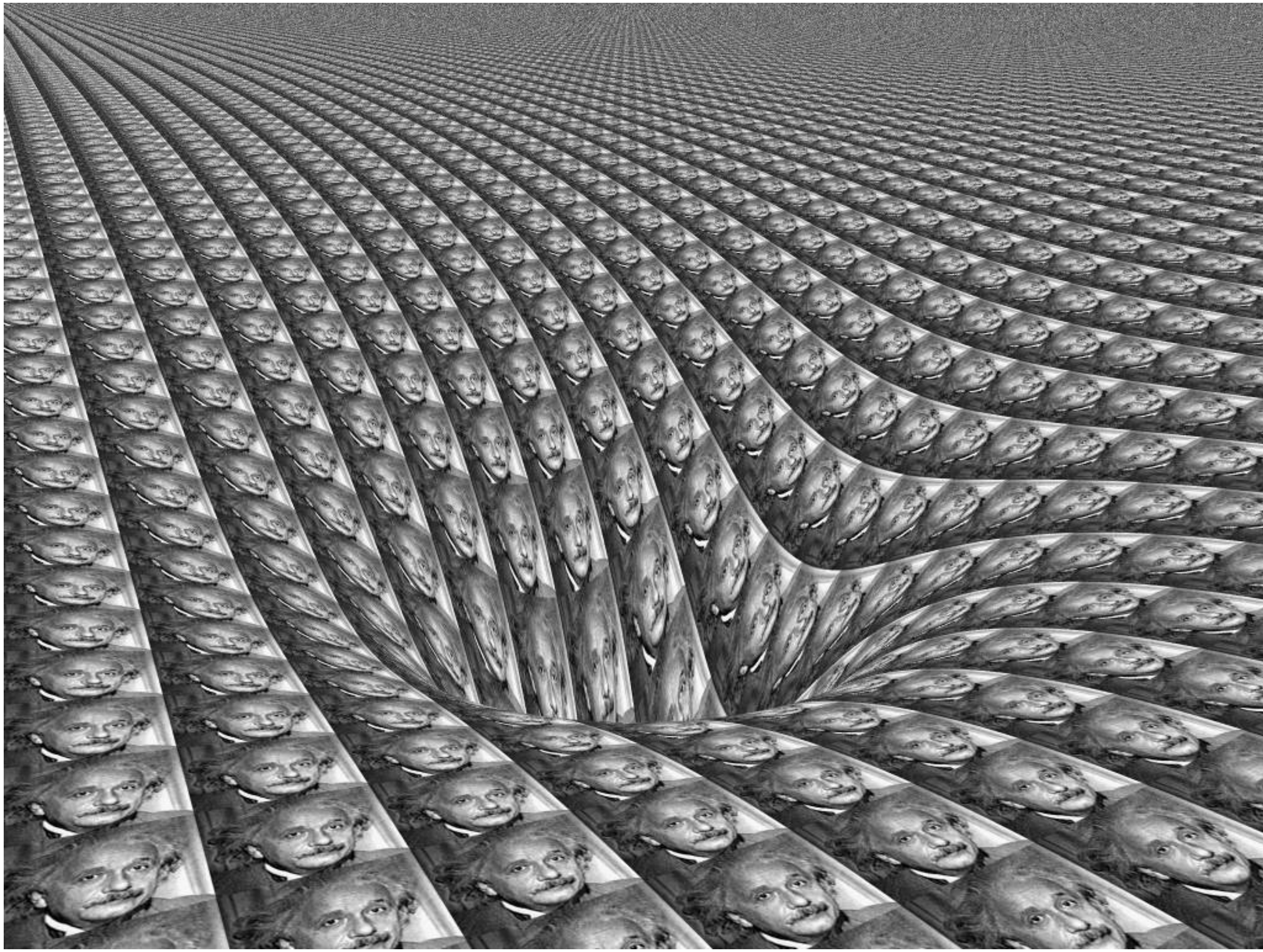
Matter tells space-time how to curve. Space-time tells matter how to move.



Black holes, from the point of view of General Relativity

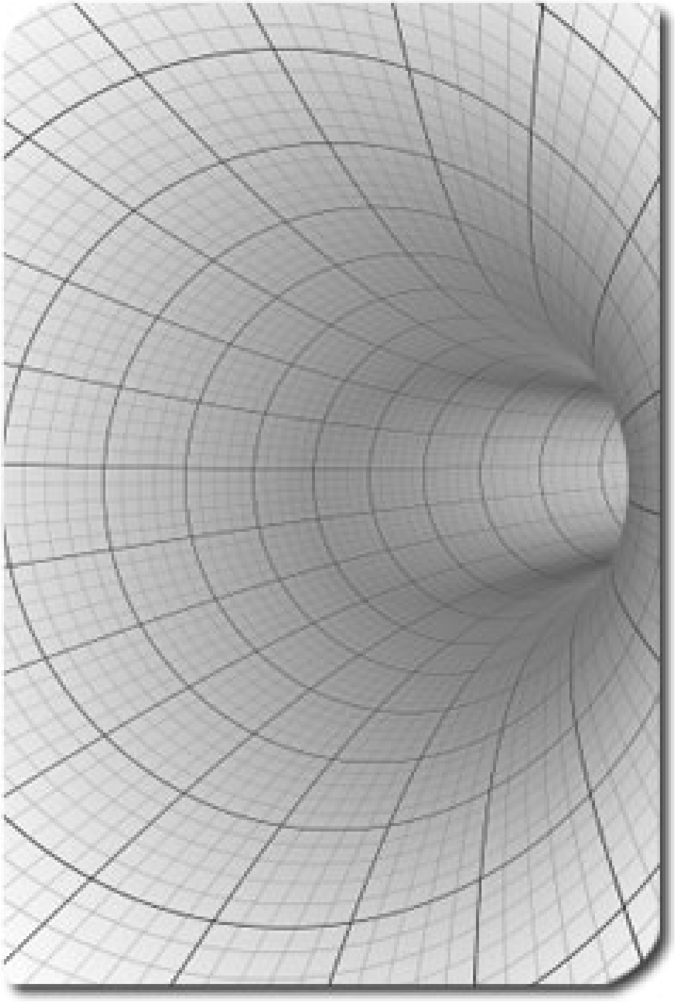
A view of the space-time in the vicinity of a black hole.

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?

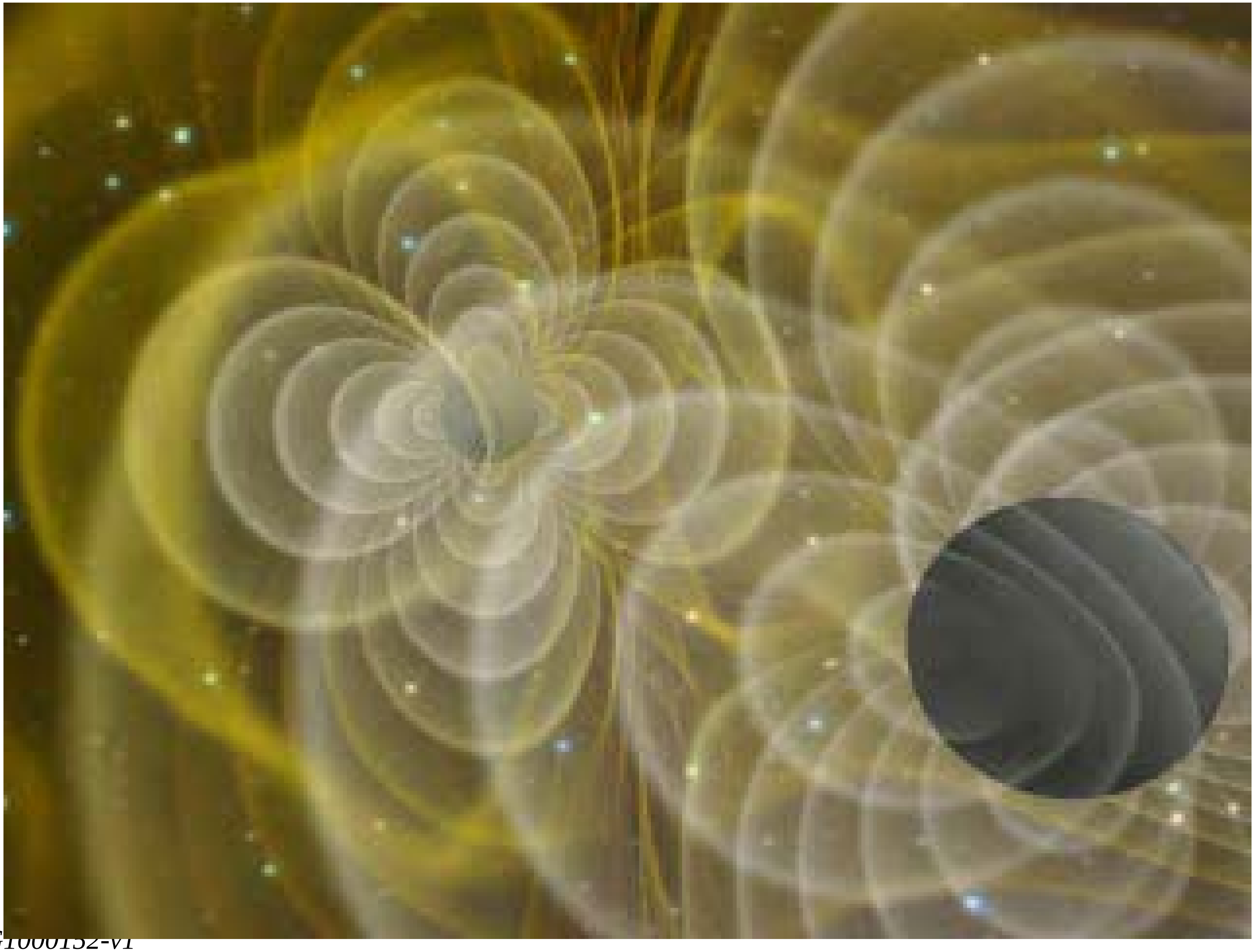
Nevertheless, evidence is accumulating that black holes do exist.

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

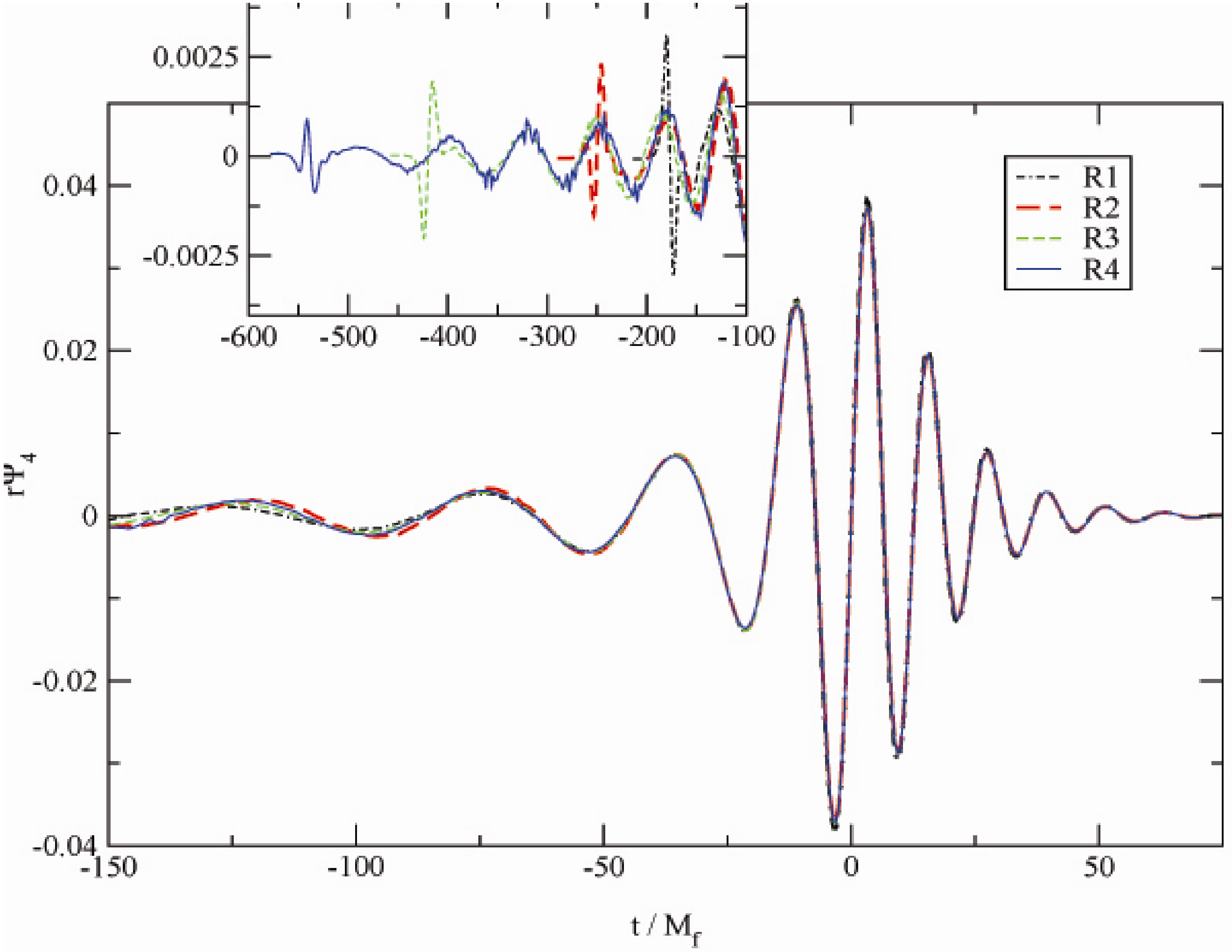
Black hole vibrations create space-time ripples

- 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



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

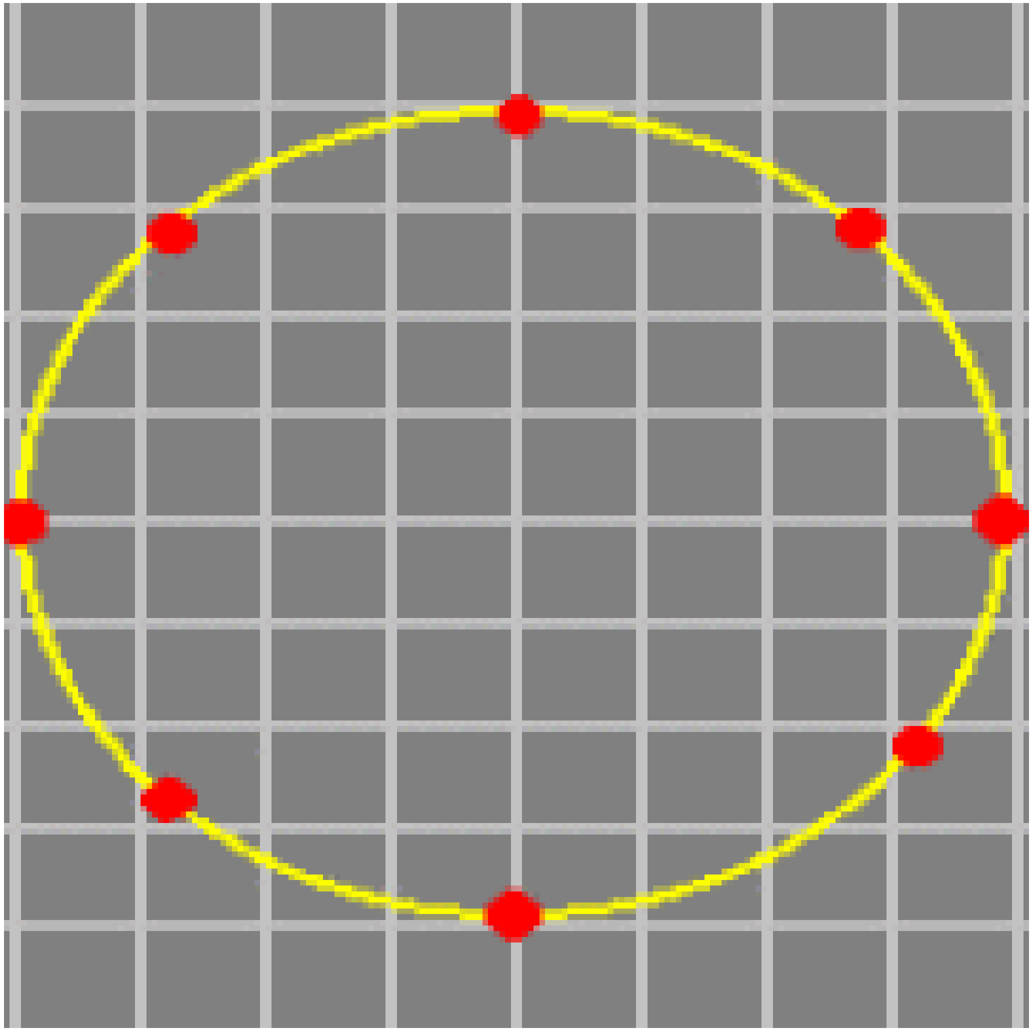


With the right "microphone", we could listen to these ripples

Here's a playback of the gravitational wave from the collision of two black holes, played back directly through loudspeakers.

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

How to make a “microphone” for space-time ripples



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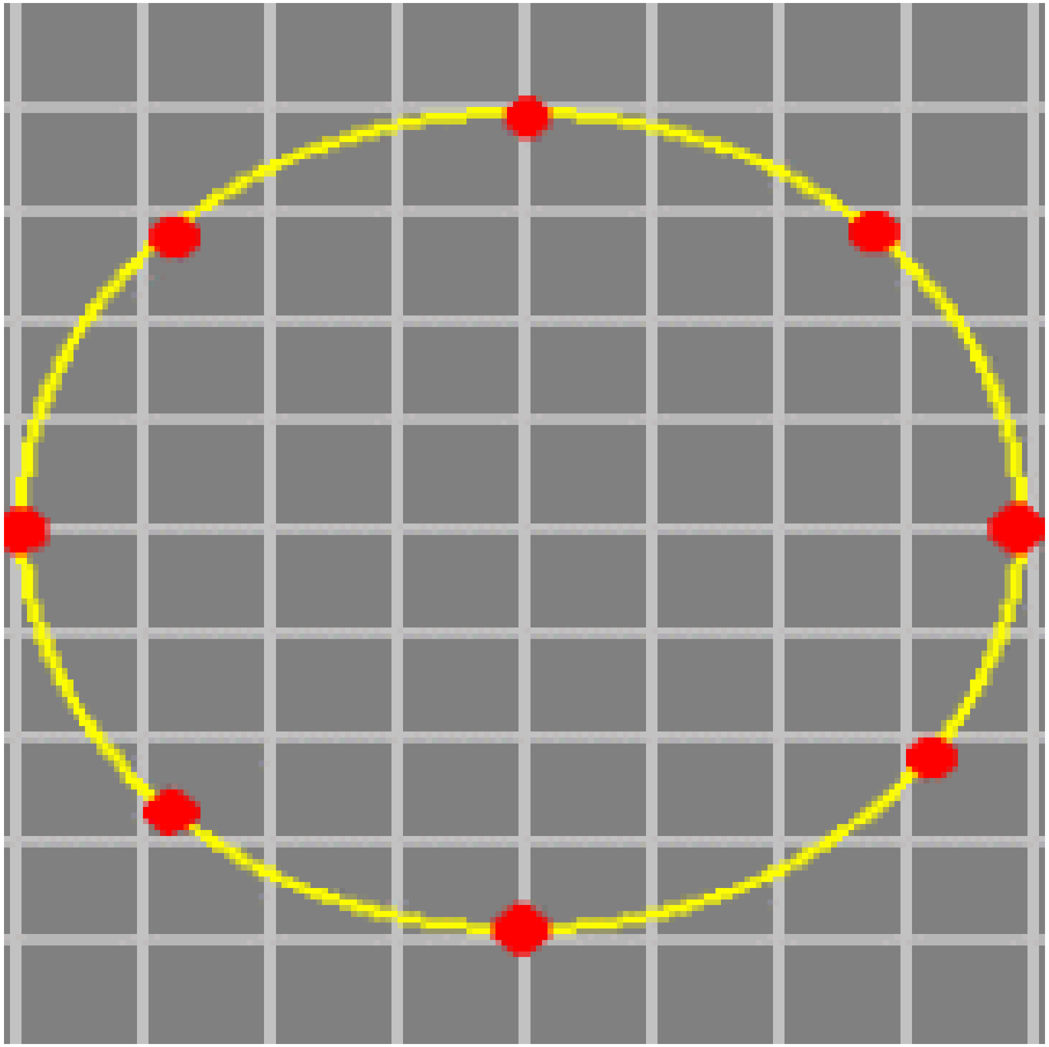
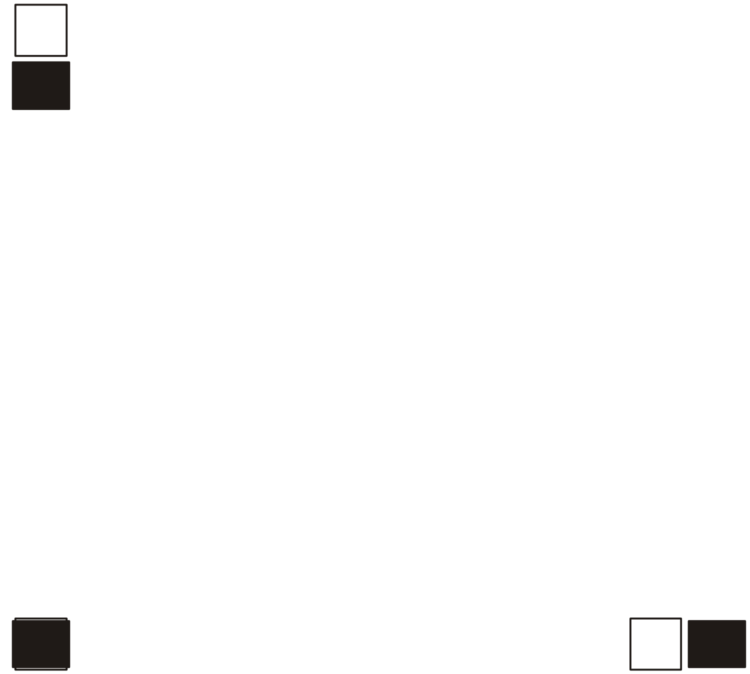
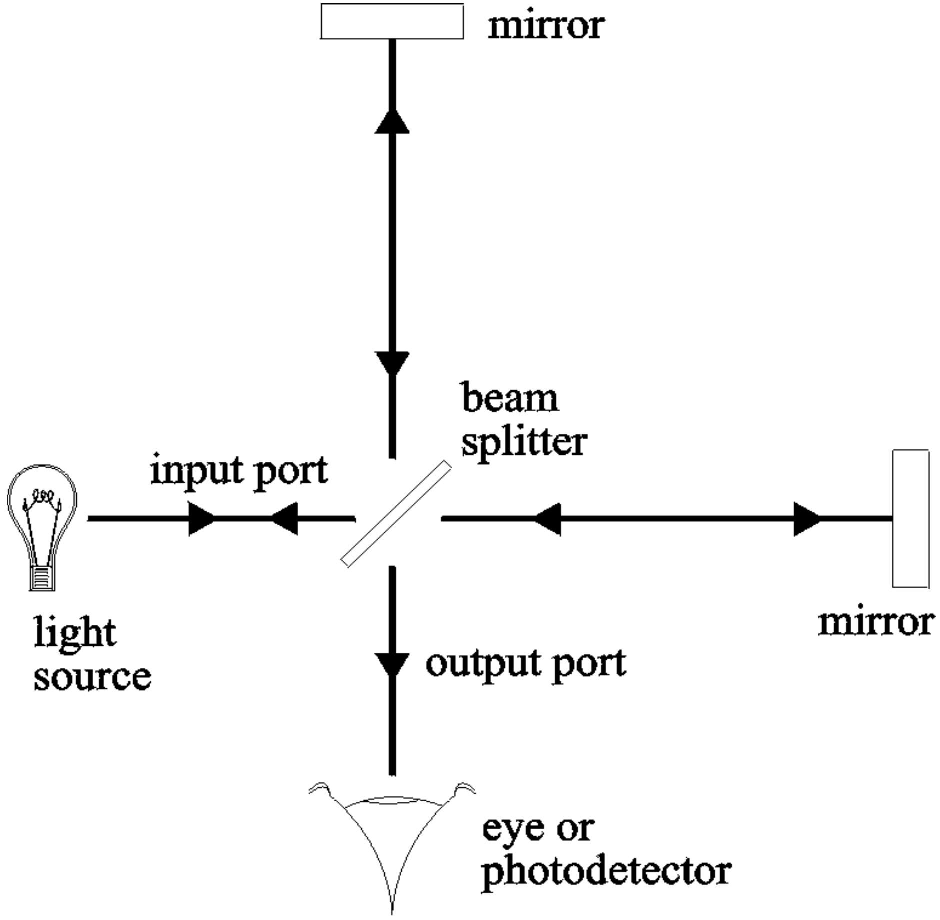
What the ripples do



More simply …



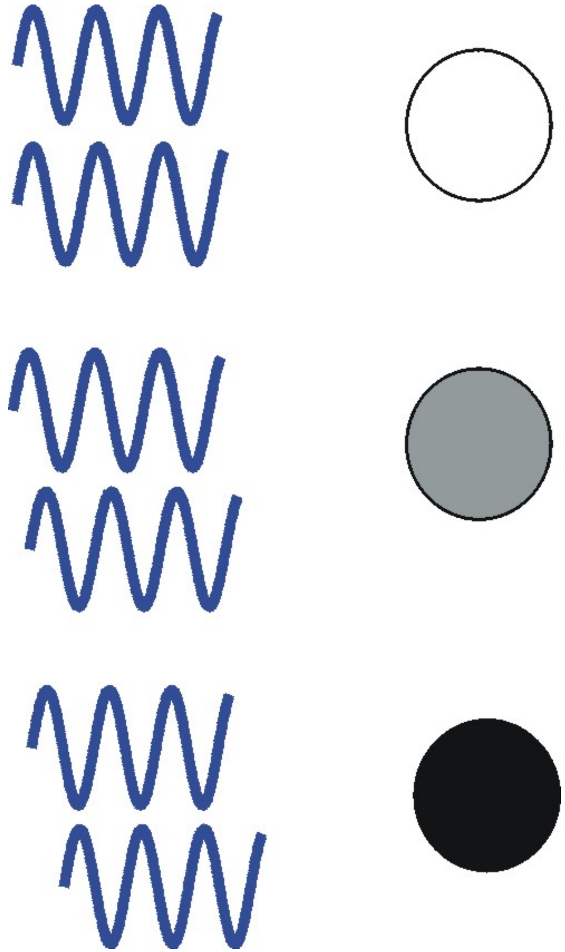
Interferometer can serve as a microphone for space-time ripples



How an interferometer works

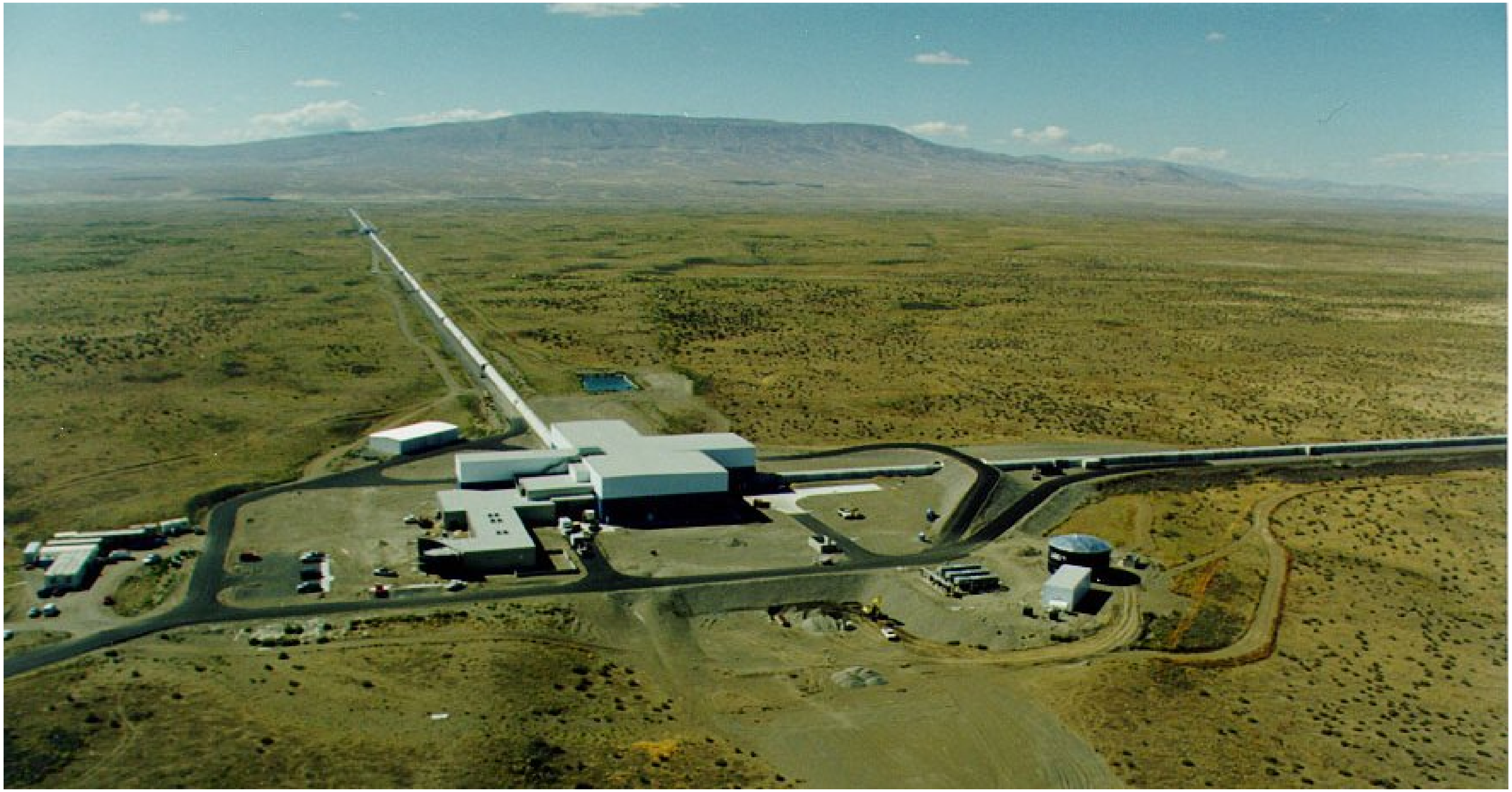
Wave from x arm.

Wave from y arm.



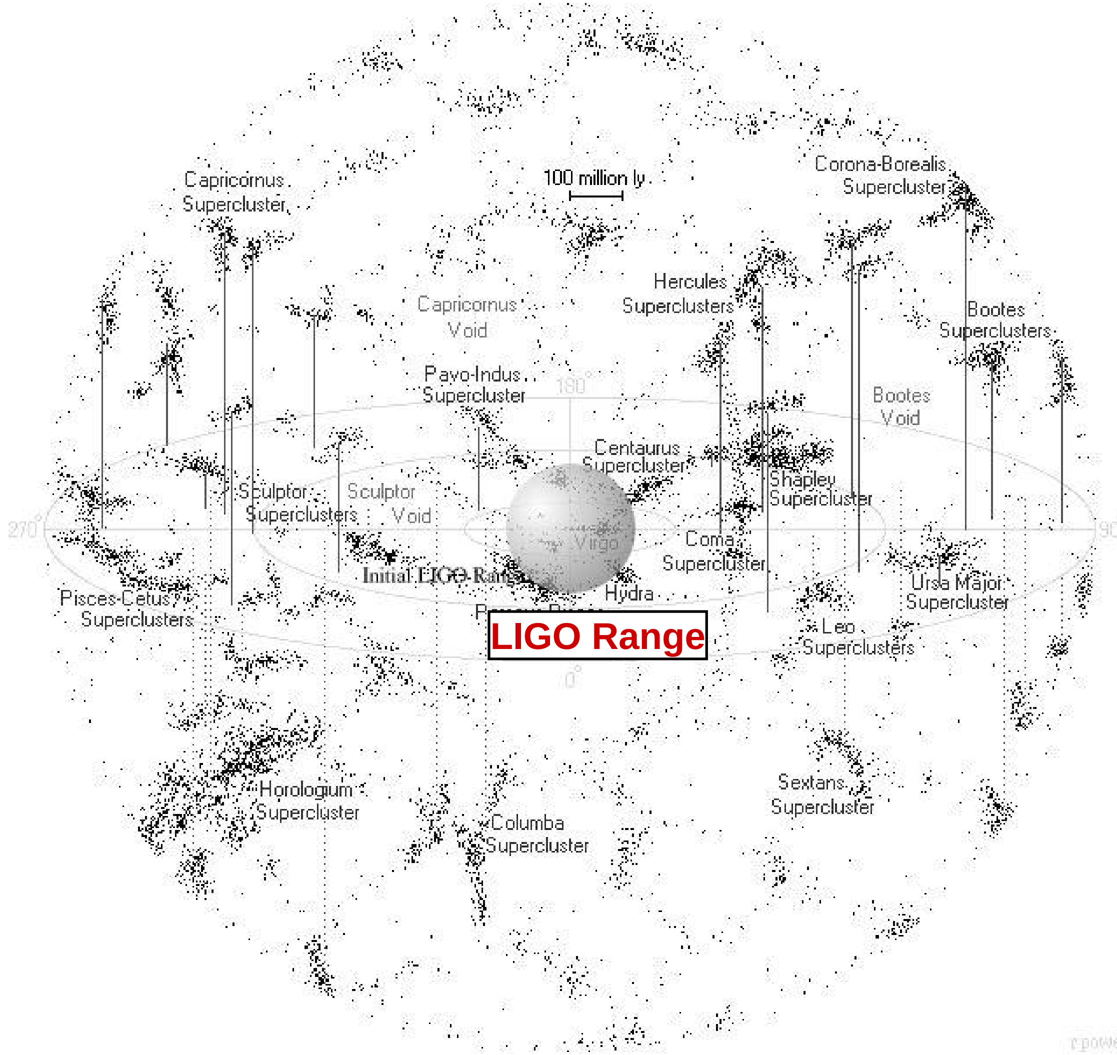
Light exiting from beam splitter.

LIGO Hanford



LIGO Livingston

Initial LIGO and Advanced LIGO



Advanced LIGO Range

Image: R. Powell

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.

Later this year, we'll disassemble 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 space-time ripples, and look into the nature of black holes.