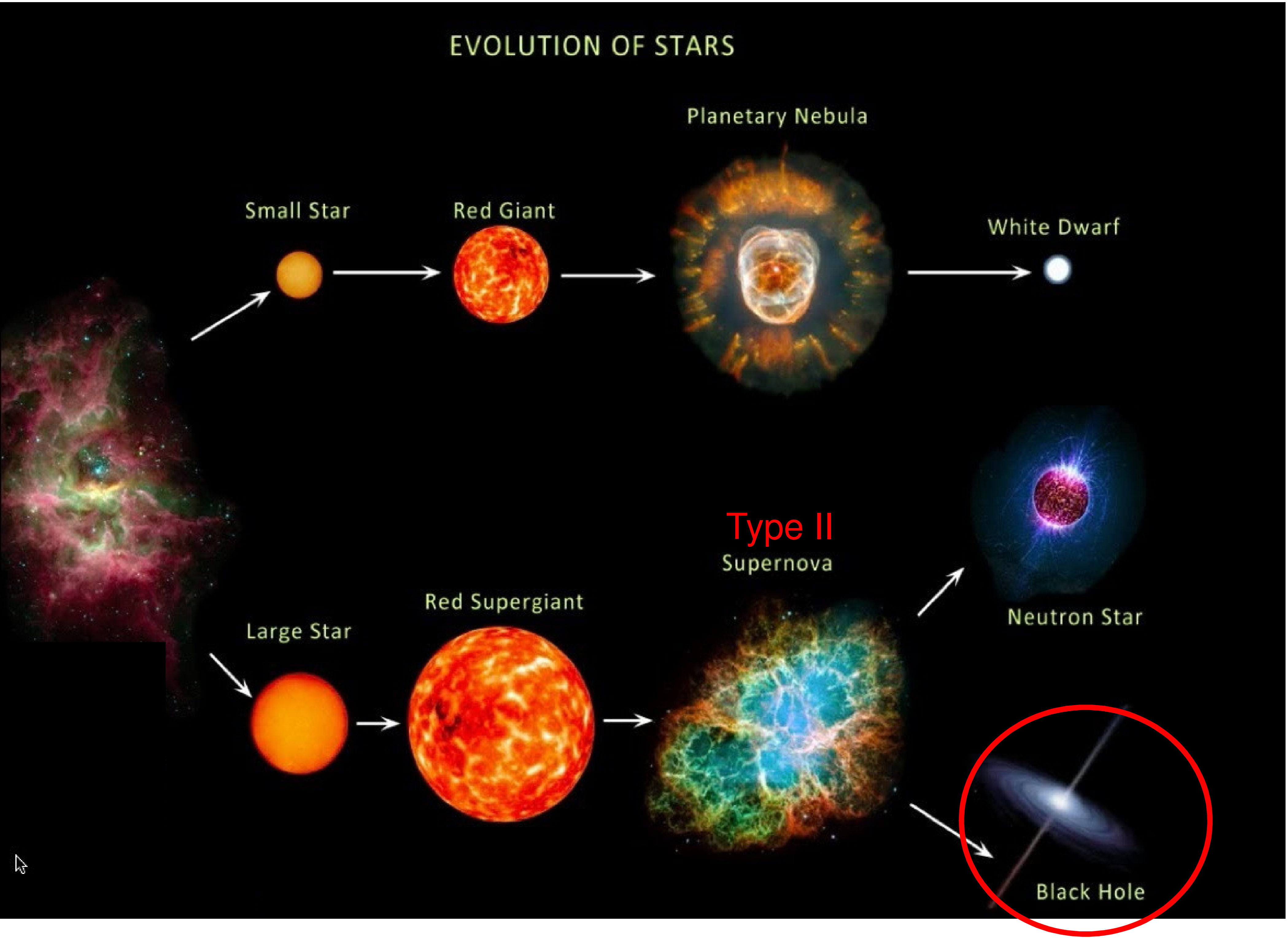
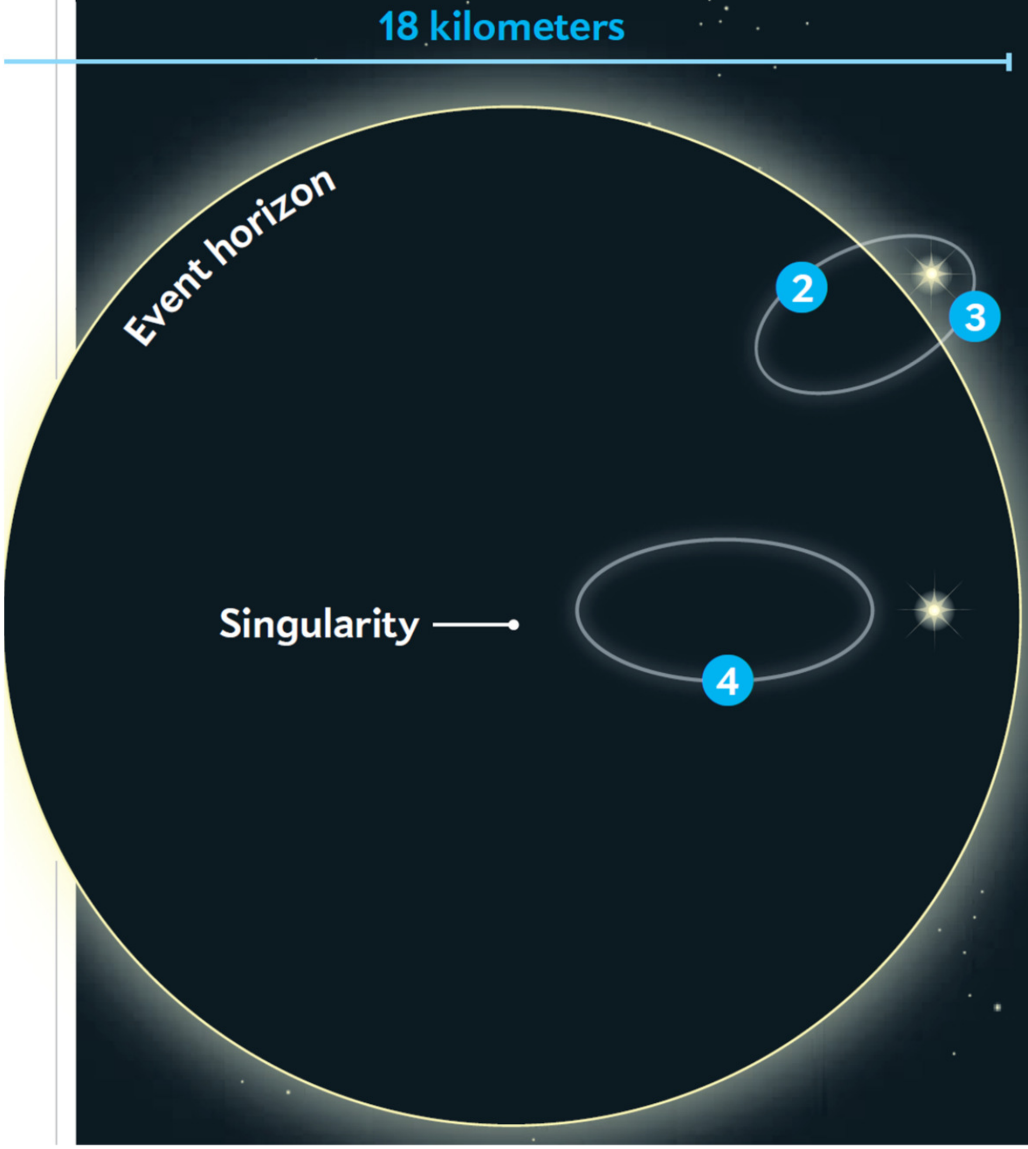
Black Holes



https://www.youtube.com/watch?v=CTNKk7TnkQ8

A black hole is a region of curved spacetime with such intense gravity that nothing can escape. Its defining feature is its event horizon: the boundary of the region of no escape. A black hole is mostly empty, its mass apparently collapsed to a location with infinite density—a "singularity"—deep inside the horizon.

A black hole with three times the mass of the sun would have a diameter of about 18 kilometers, comparable to the length of Manhattan.



Far away from large masses, a flash of light spreads out symmetrically in all directions ①.

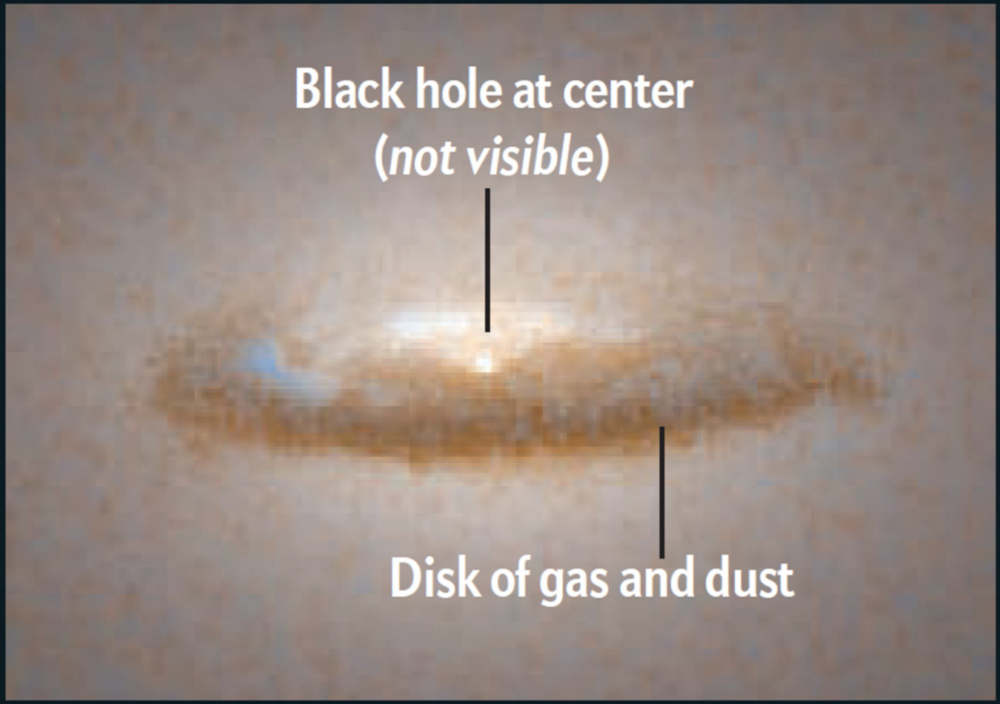
Just outside a black hole's event horizon, the gravity captures most of a flash ②.

Some light escapes, just ③.

If a flash occurs anywhere inside an event horizon, all the light is drawn into the black hole's singularity ④.

Scientific American 22, 82 (2013)

In practice, black holes can be observed via the material orbiting and falling into them. The image at the right, taken in 1998 by the Hubble Space Telescope, shows a vast disk of gas and dust believed to have a supermassive black hole at its center. Strictly speaking, however, such observations inform scientists only that an extremely compact, heavy object emitting little or no light of its own is present; they do not provide absolute proof that the object is a black hole.



Scientific American 22, 82 (2013)

First detection of gravitational waves

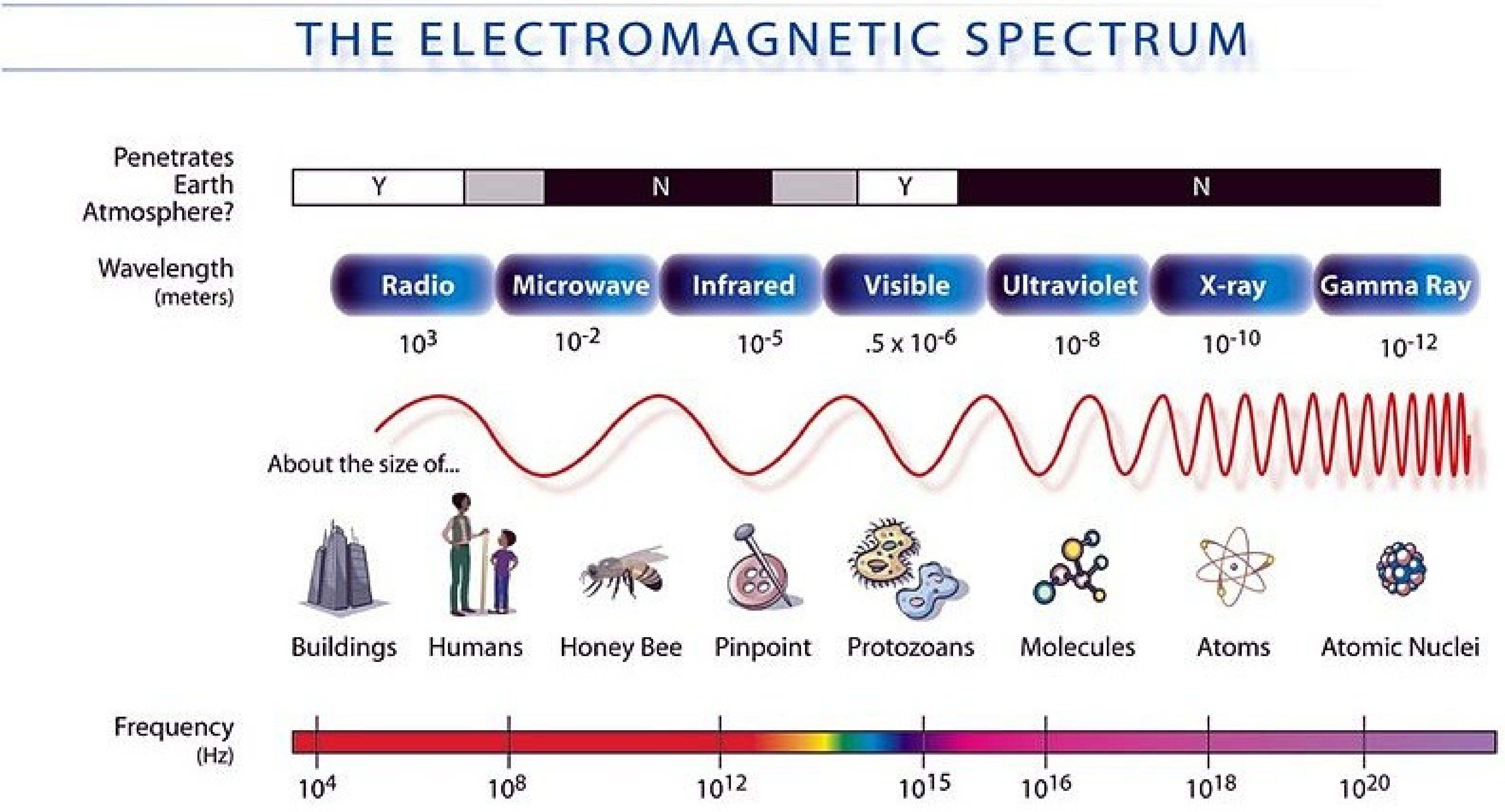
Recommended reading
Physics Viewpoint: The First Sounds of Merging Black Holes
http://physics.aps.org/articles/pdf/10.1103/Physics.9.17

Additional reading
Introduction to LIGO and gravitational waves
http://www.ligo.org/science/overview.php

Observation of Gravitational Waves from a Binary Black Hole Merger
Physical Review Letters 116, 061102 (2016) (advanced material)
http://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.116.061102

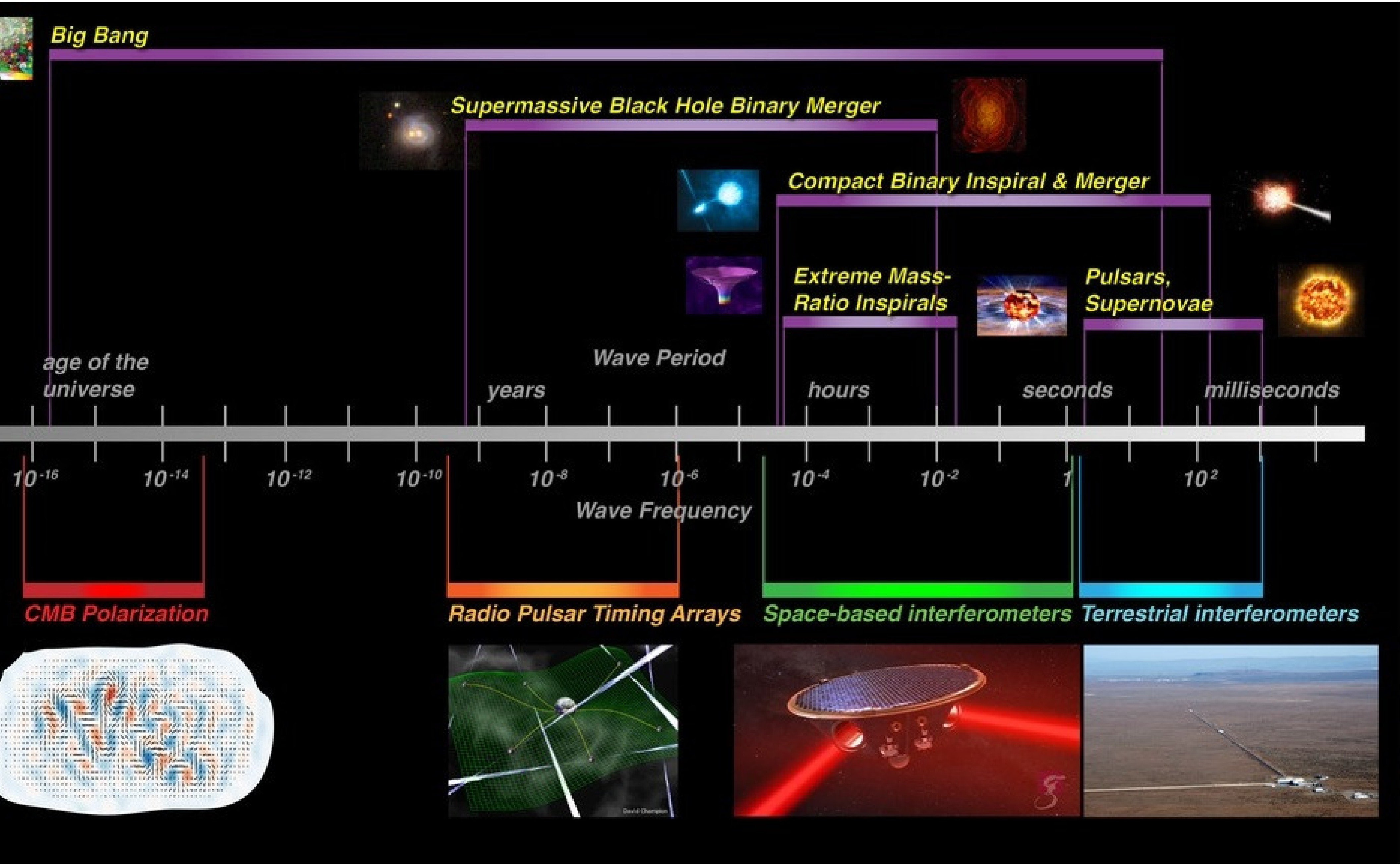
Credits to slide images:
Marit Jentoft-Nilsen: Technical Support
Eric Sokolowsky (GST): Project Support
https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=30569

So far: electromagnetic wave astronomy



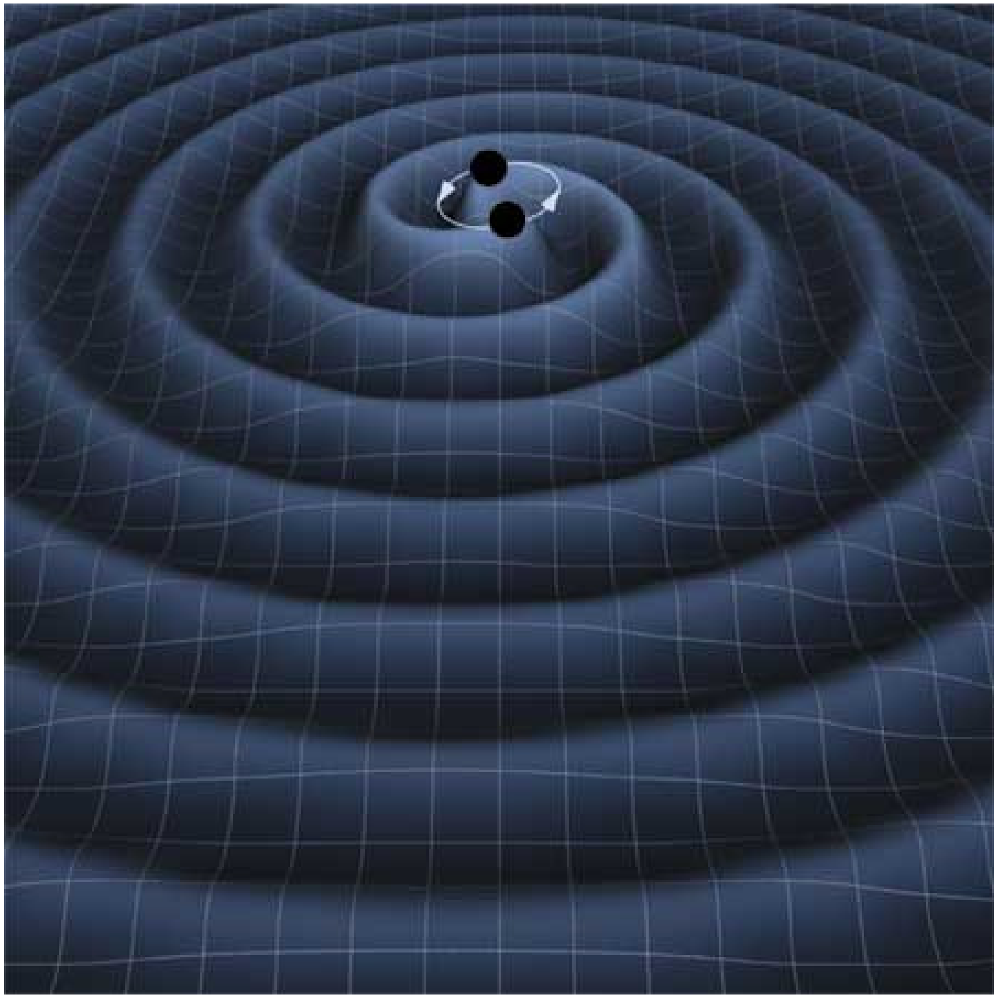
Link: Electromagnetic Spectrum Module

Add the entire new spectrum to study the Universe
Gravitational wave astronomy



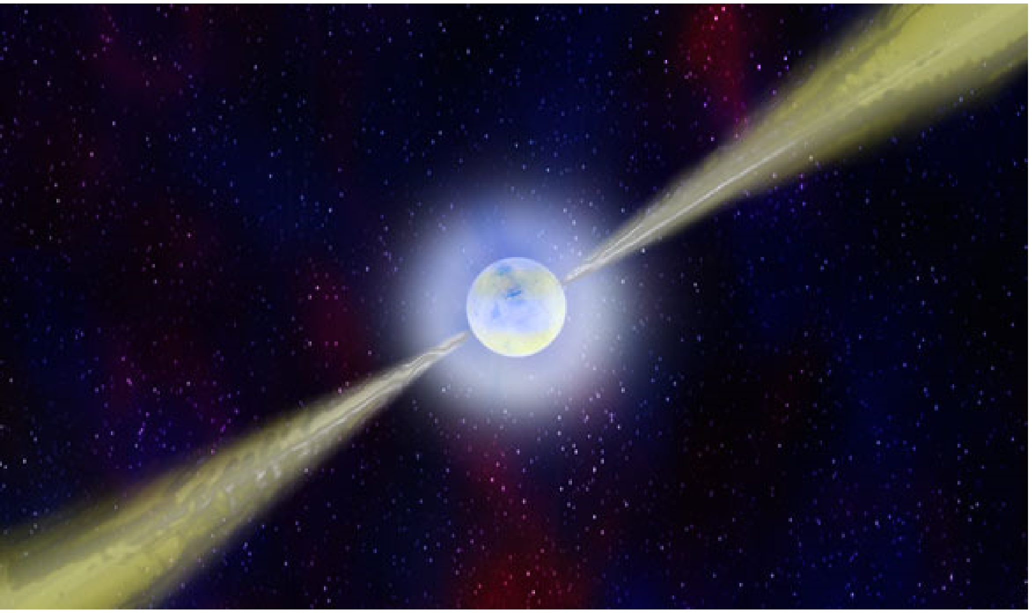
Gravitational waves

Gravitational waves: ripples on space-time, where space-time includes time as well as the 3 spatial dimensions.



http://www.ligo.org/science/GW-GW2.php

Pulsars



A **pulsar** (short for **pulsating radio star**) is a highly magnetized, rotating neutron star that emits a beam of electromagnetic radiation.

This radiation can be observed only when the beam of emission is pointing toward Earth (much the way a lighthouse can be seen only when the light is pointed in the direction of an observer), and is responsible for the pulsed appearance of emission.

A neutron star is a type of compact star that can result from the gravitational collapse of a massive star after a supernova. Neutron star radius is only about 11–11.5 km (7 miles), but they can have a mass of about twice that of the Sun.

Artist rendition of pulsar courtesy of nrao.edu

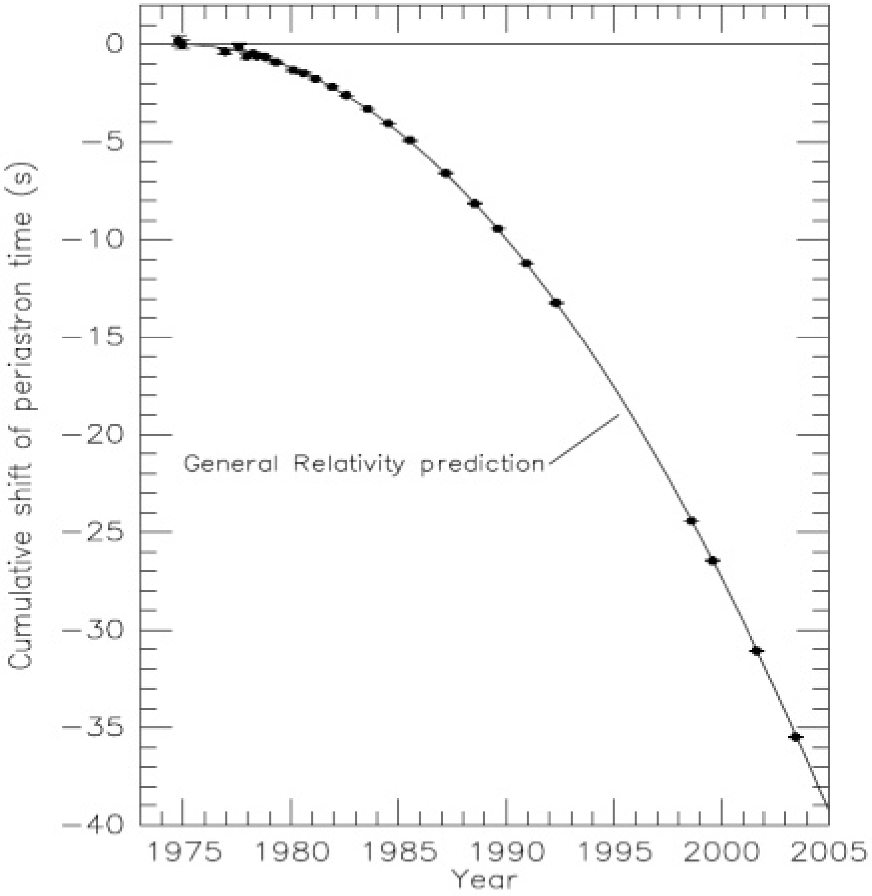
Indirect evidence for gravitational waves:

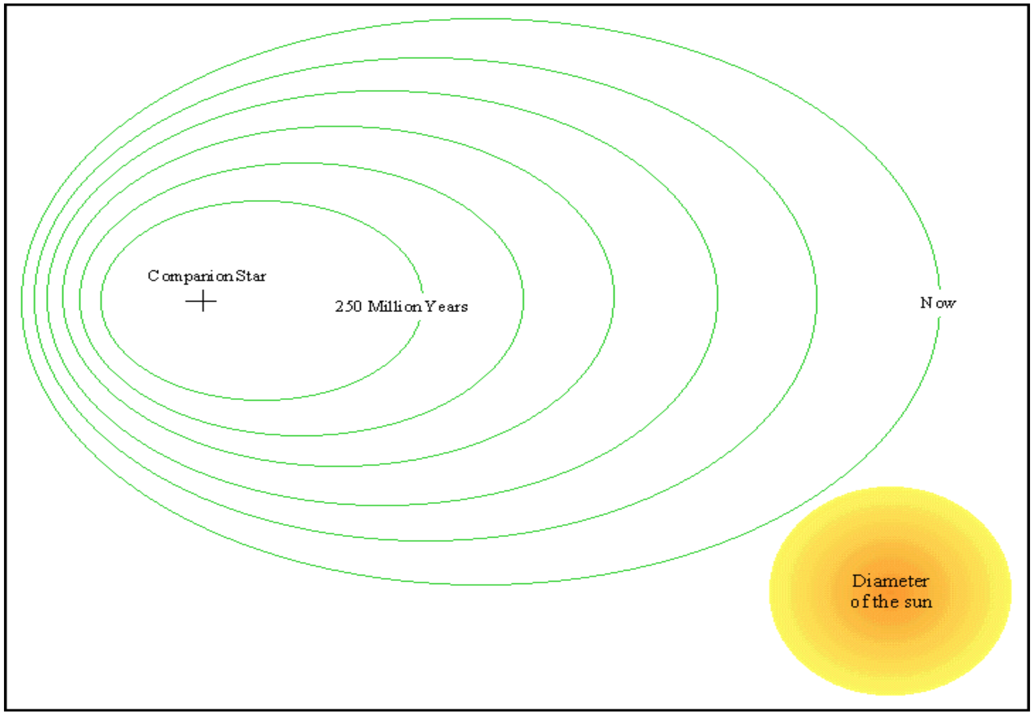
Hulse-Taylor binary pulsar (Nobel prize 1993)

Russell A. Hulse

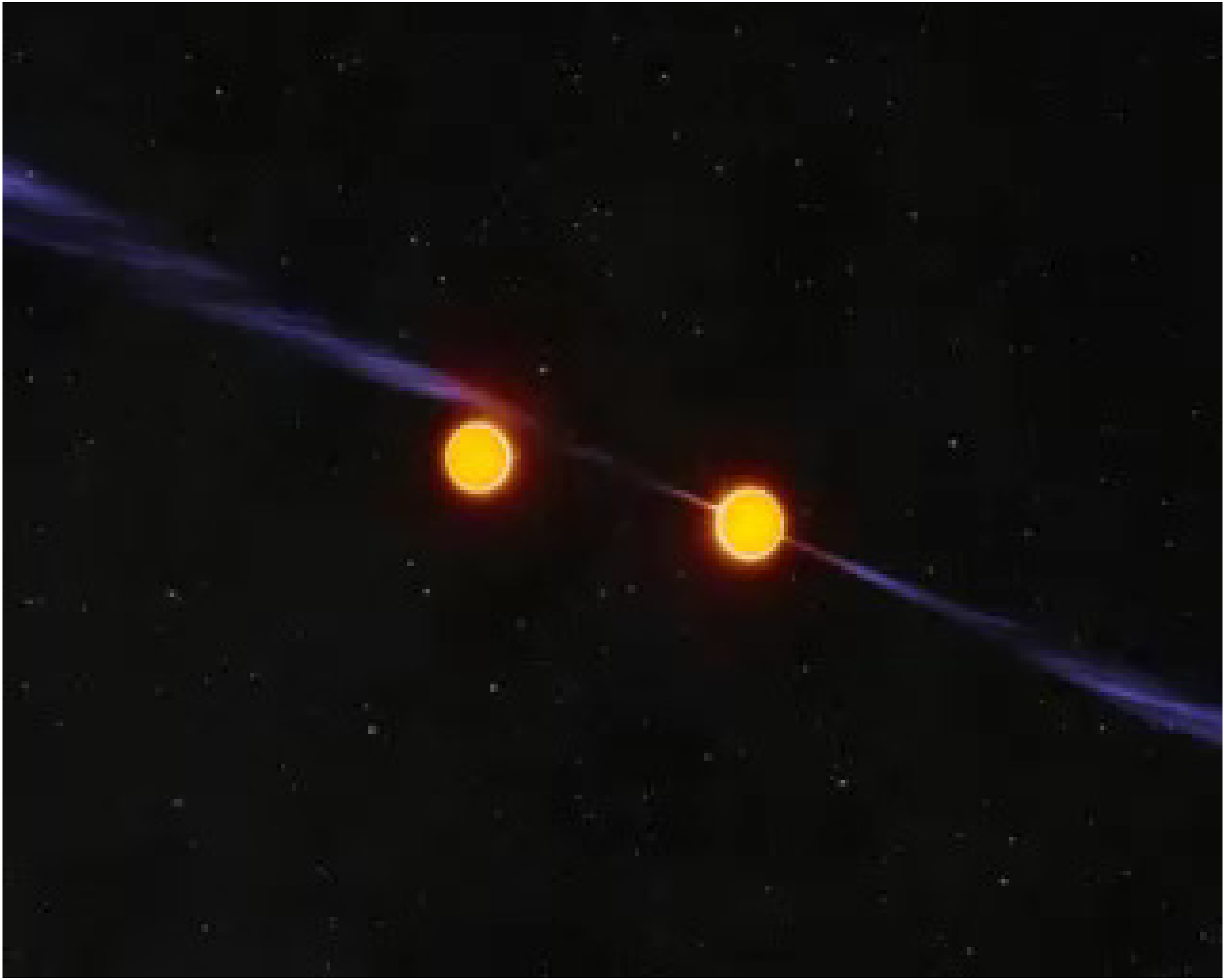
Joseph H. Taylor Jr.

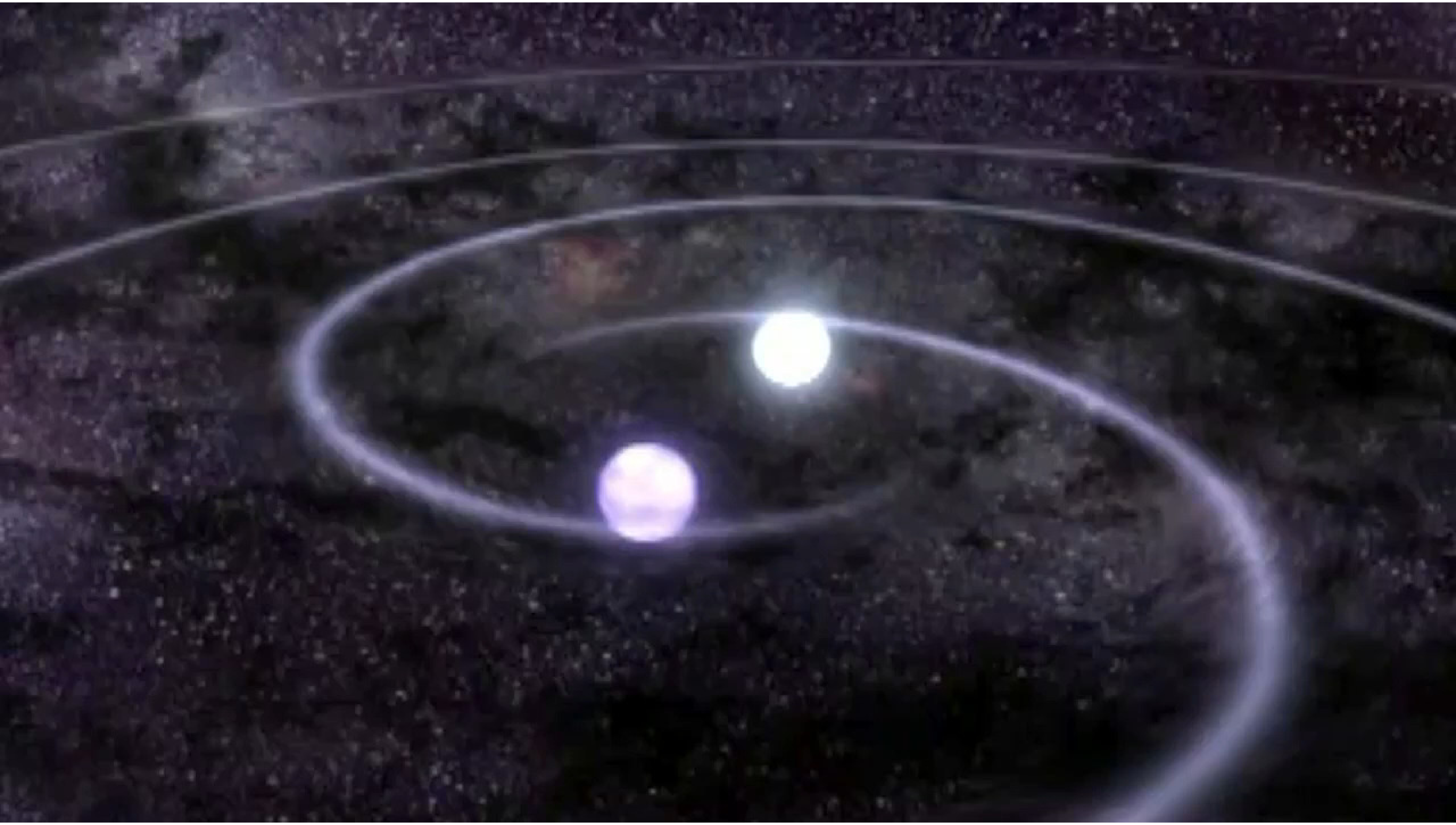
Steady decrease in orbital separation due to loss of energy through gravitational waves.

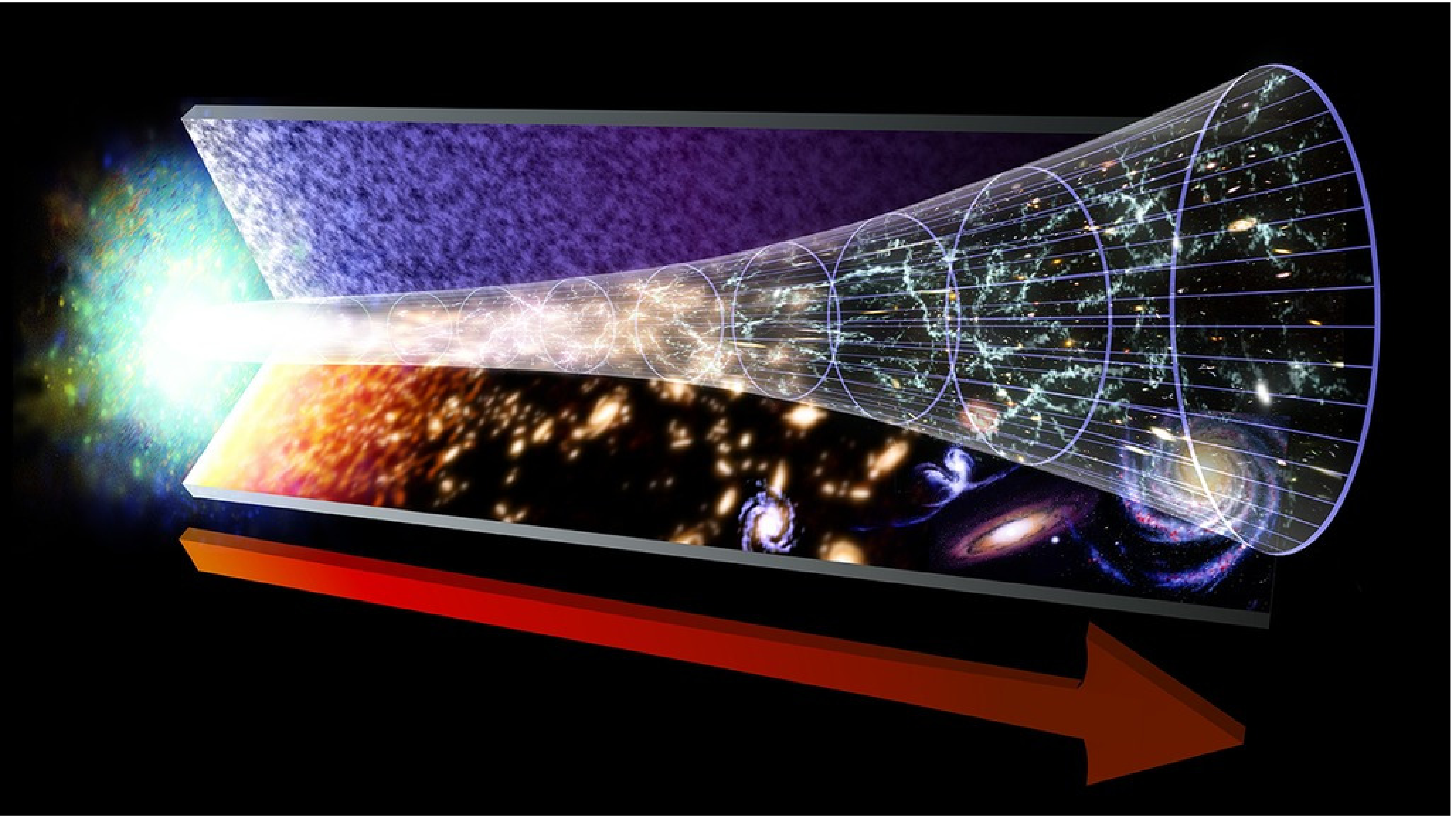


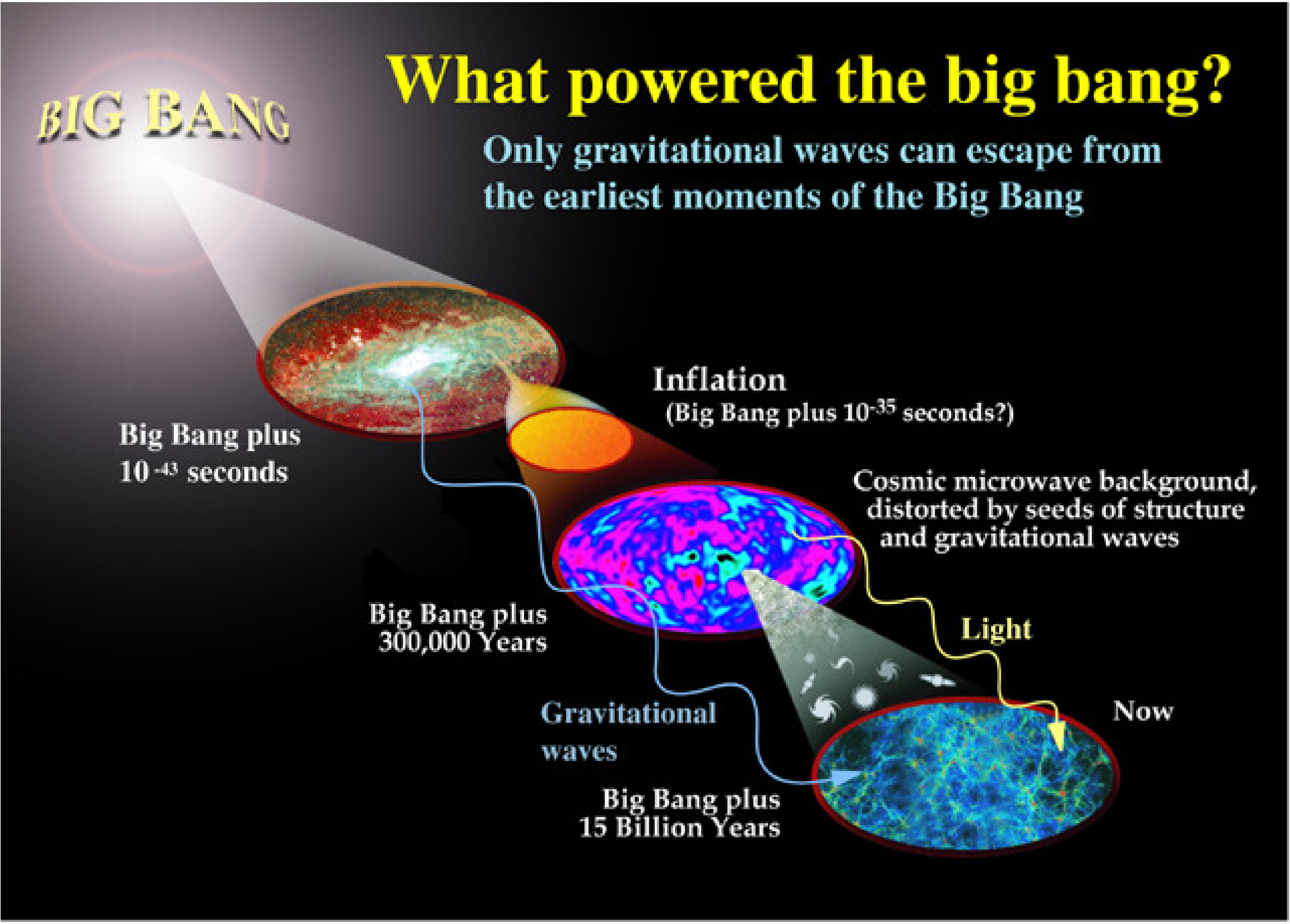


http://www.nobelprize.org/nobel_prizes/physics/laureates/1993/









BIG BANG

What powered the big bang?

Only gravitational waves can escape from the earliest moments of the Big Bang

Big Bang plus 10^{-43} seconds

Inflation
(Big Bang plus 10^{-35} seconds?)

Cosmic microwave background, distorted by seeds of structure and gravitational waves

Big Bang plus 300,000 Years

Light

Gravitational waves

Now

Big Bang plus 15 Billion Years

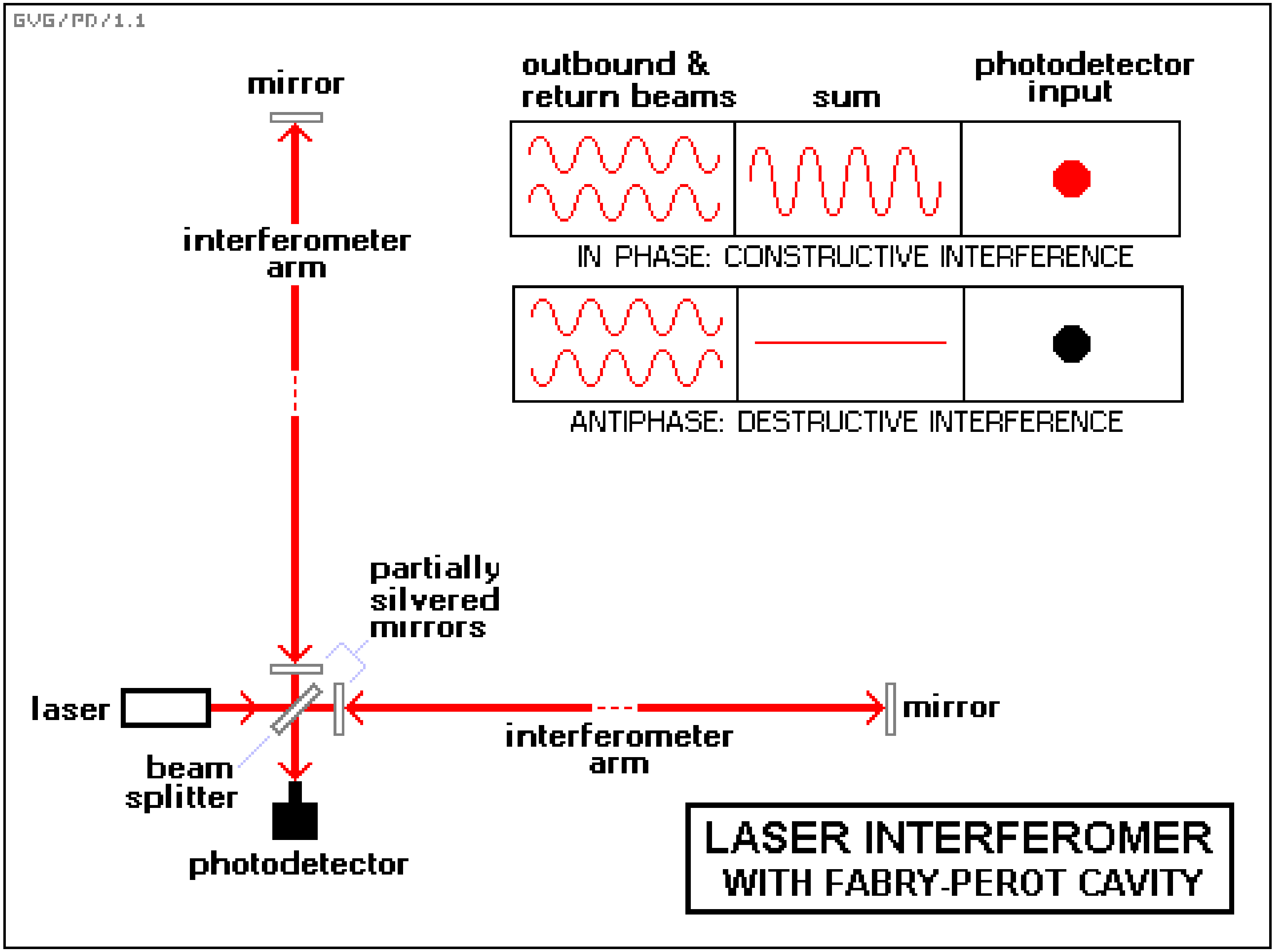
http://www.ligo.org/science/GW-Stochastic.php

Detecting Gravitational Waves: LIGO

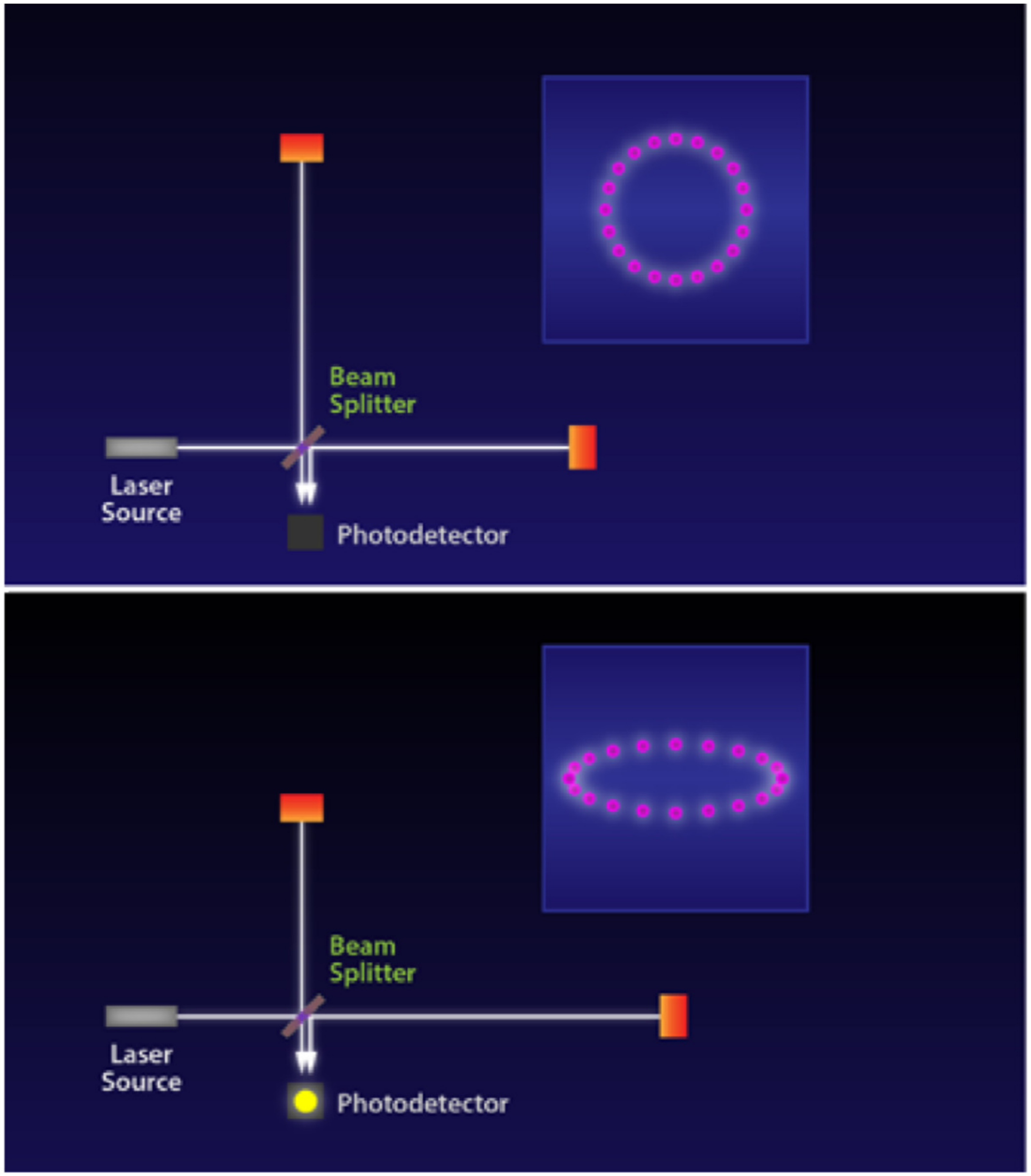
Gravitational waves interact with matter by compressing objects in one direction while stretching them in the perpendicular direction.

http://www.ligo.org/science/GW-Detecting.php

Laser interferometer: send laser beams in perpendicular directions and combine them on return to construct interference patterns.



The First Sounds of Merging Black Holes



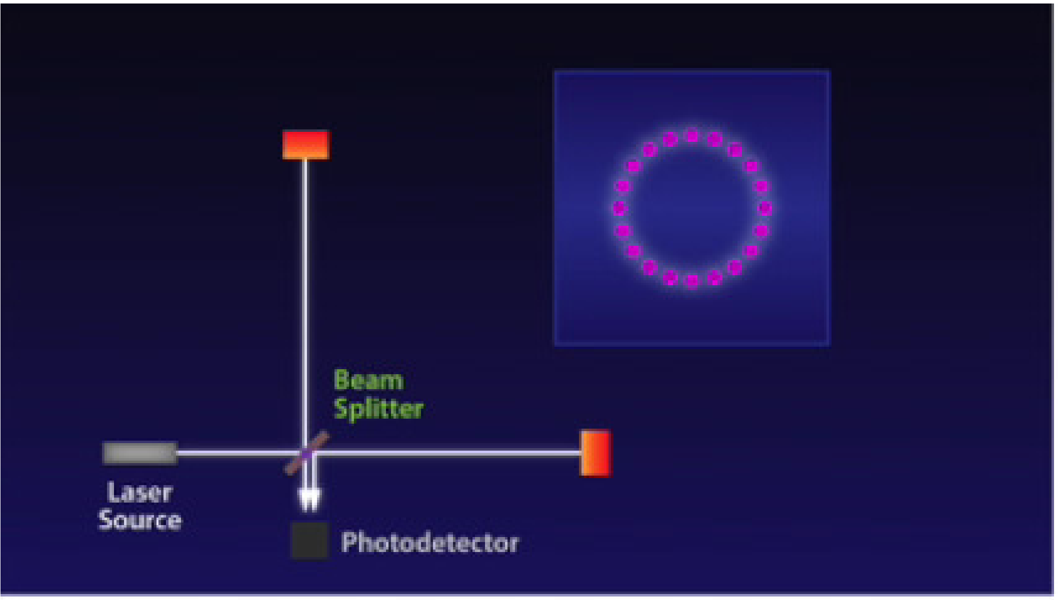
Light from a laser is split in two by a beam splitter; one half travels down the vertical arm of the interferometer, the other half travels down the horizontal arm.

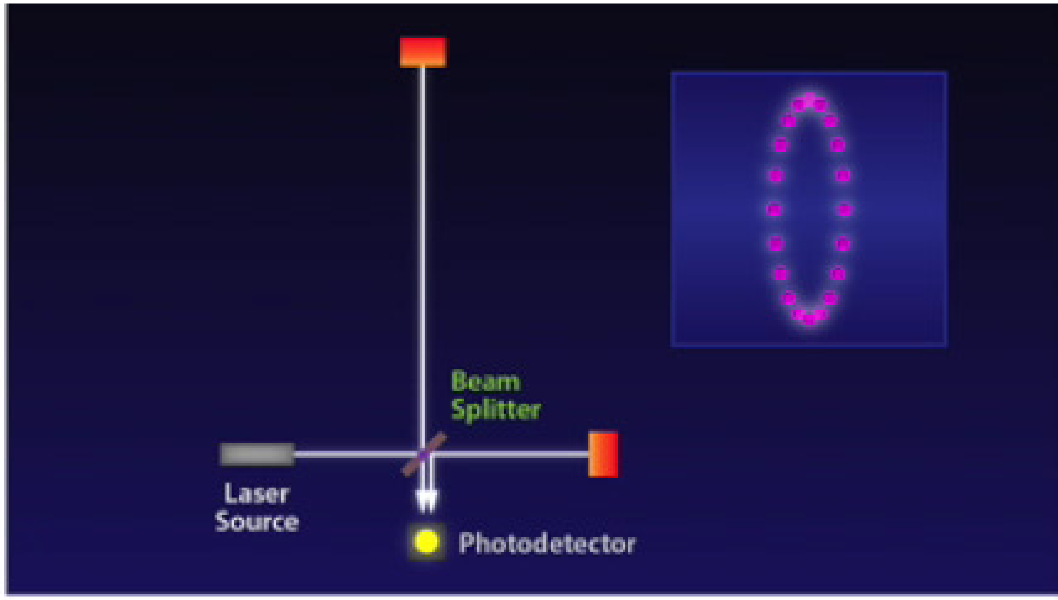
The detector is designed so that in the absence of gravitational waves (top) the light takes the same time to travel back and forth along the two arms and interferes destructively at the photodetector, producing no signal.

As the wave passes the travel times for the lasers change, and a signal appears in the photodetector.

As the wave passes (moving clockwise from top right) the travel times for the lasers change, and a signal appears in the photodetector.

Credit: APS/Alan Stonebraker https://physics.aps.org/articles/v9/17


Beam
Splitter
Laser
Source
Photodetector


Beam
Splitter
Laser
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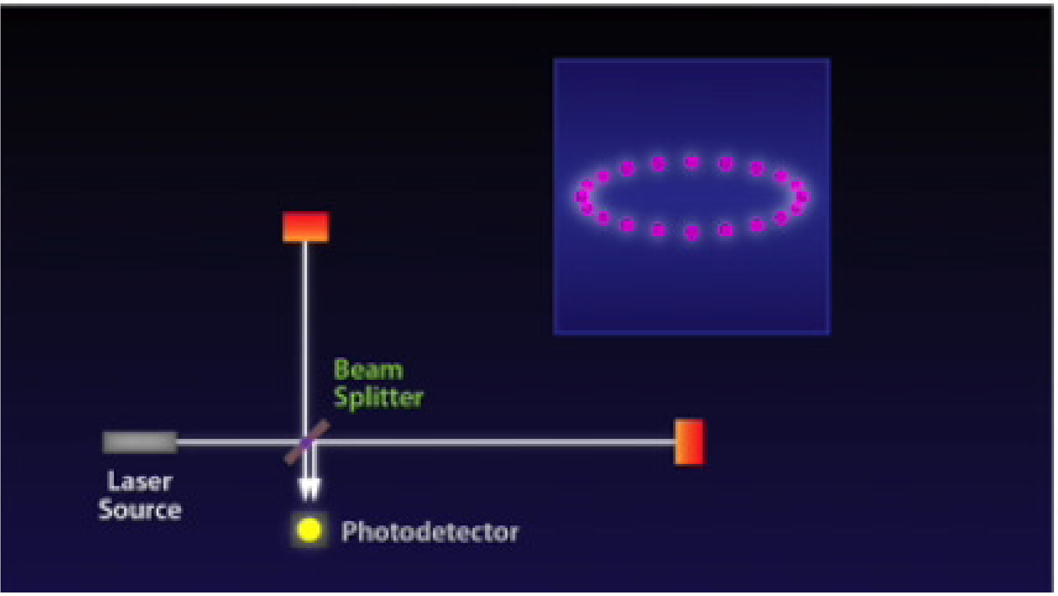
Photodetector


Beam
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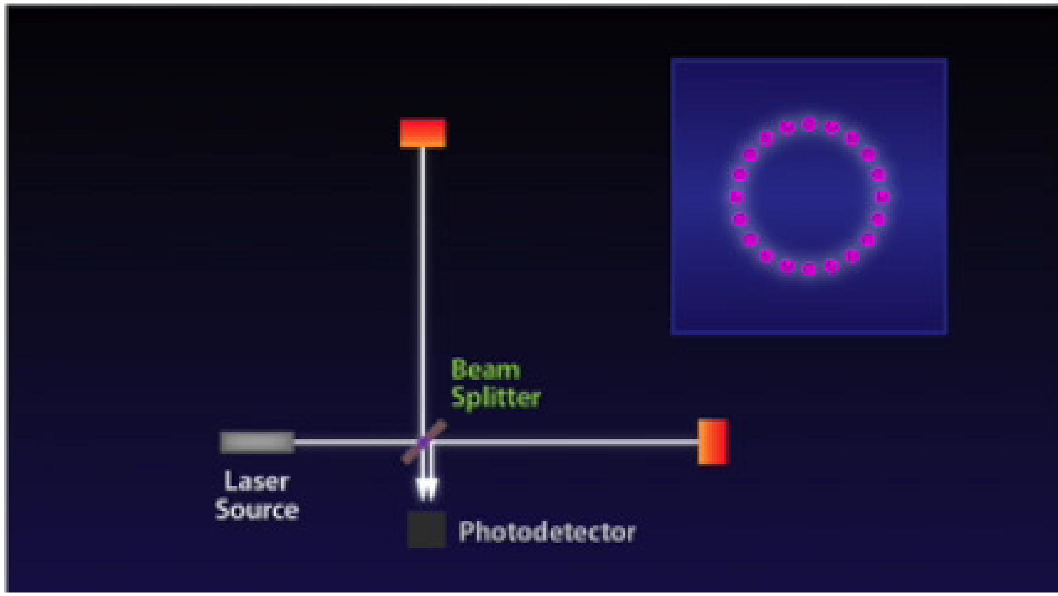

Beam
Splitter
Laser
Source
Photodetector

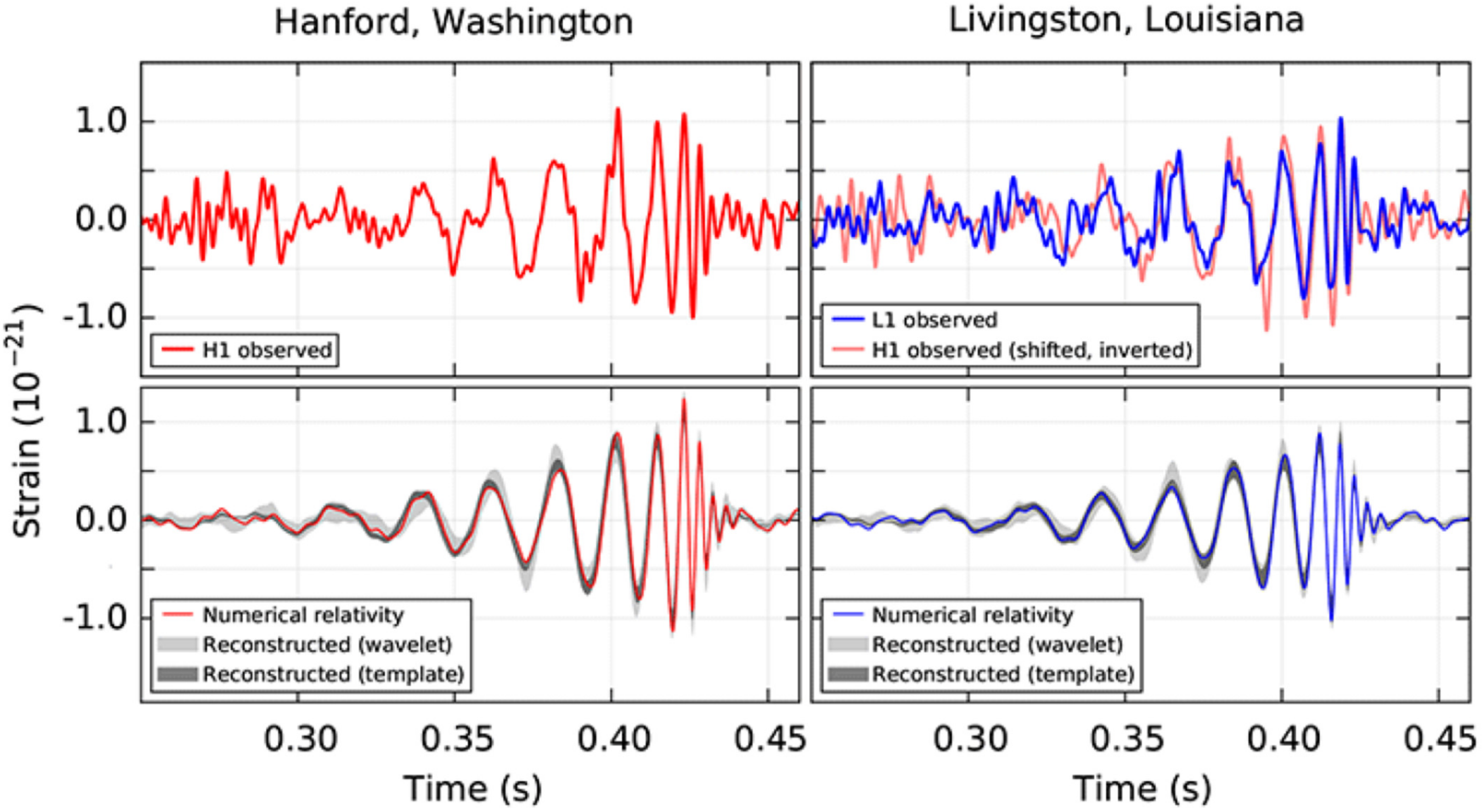
Einstein's Messengers, LIGO Documentary

http://www.nsf.gov/news/mmg/mmg_disp.jsp?med_id=58443&from=vid.htm

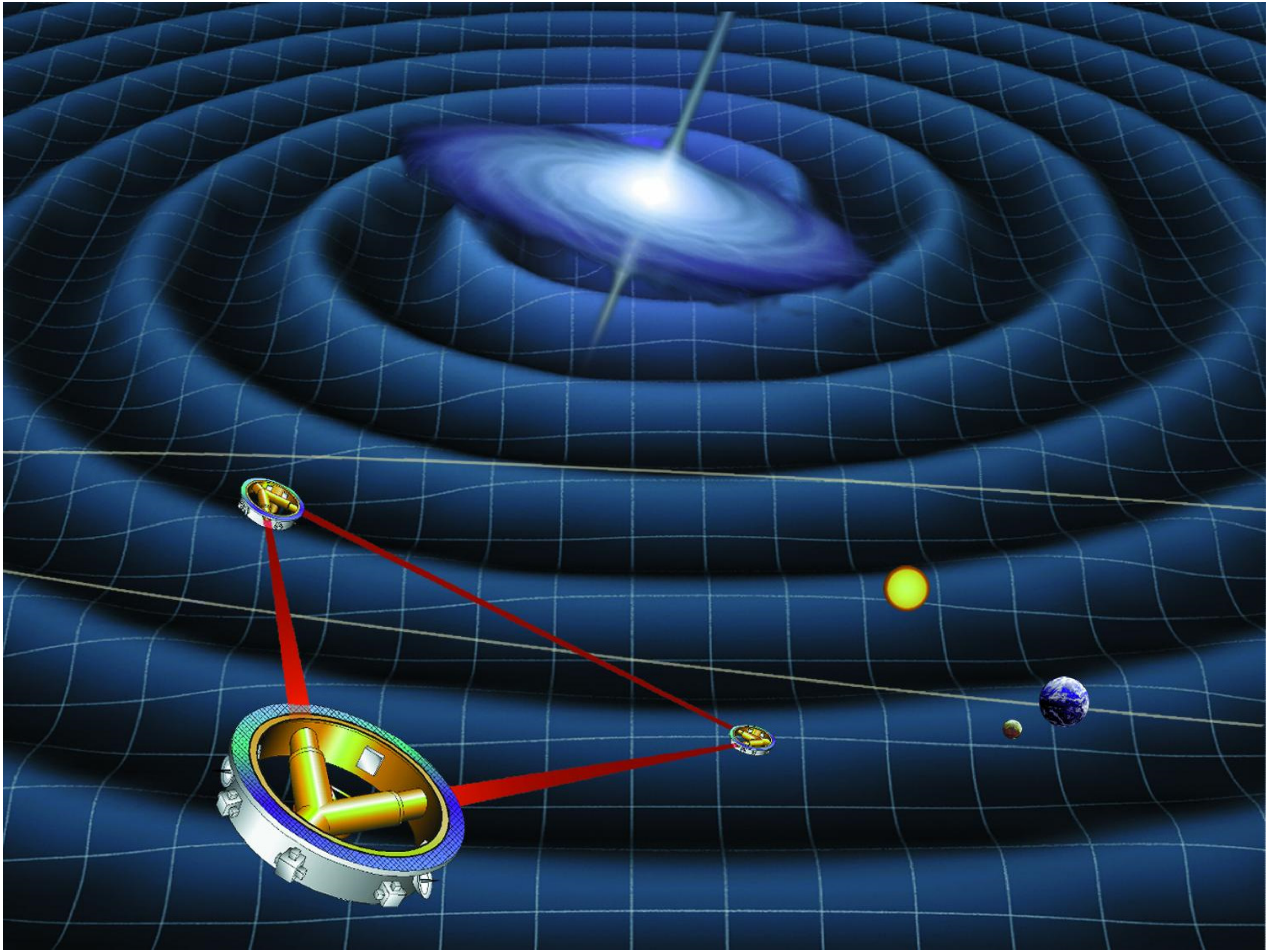
7:20 9:55 12:56

First detection of gravitational waves

On September 14, 2015, similar signals were observed in both of LIGO's interferometers. The top panels show the measured signal in the Hanford (top left) and Livingston (top right) detectors. The bottom panels show the expected signal produced by the merger of two black holes, based on numerical simulations. (B. P. Abbott et al., Phys. Rev. Lett. 116, 061102 (2016).



Laser Interferometer Space Antenna (LISA, eLISA)



http://lisa.jpl.nasa.gov/gallery/lisa-waves.html

The first monster black holes

Astronomers are puzzled about how
the oldest supermassive black holes could
have grown so big so early in cosmic history

Quasar

Quasar: "quasi-stellar radio source":

Quasar: extremely bright source, luminosity can be 100 times greater than that of the Milky Way

Compact region in the center of a massive galaxy surrounding a central supermassive (hundreds of thousands to billions of solar masses) black hole.

NASA/AP Photo, ESA/Hubble & NASA - http://www.spacetelescope.org/images/potw1403a/

To be visible at such incredible distances, these quasars must be fueled by black holes containing about a billion times the mass of the sun.

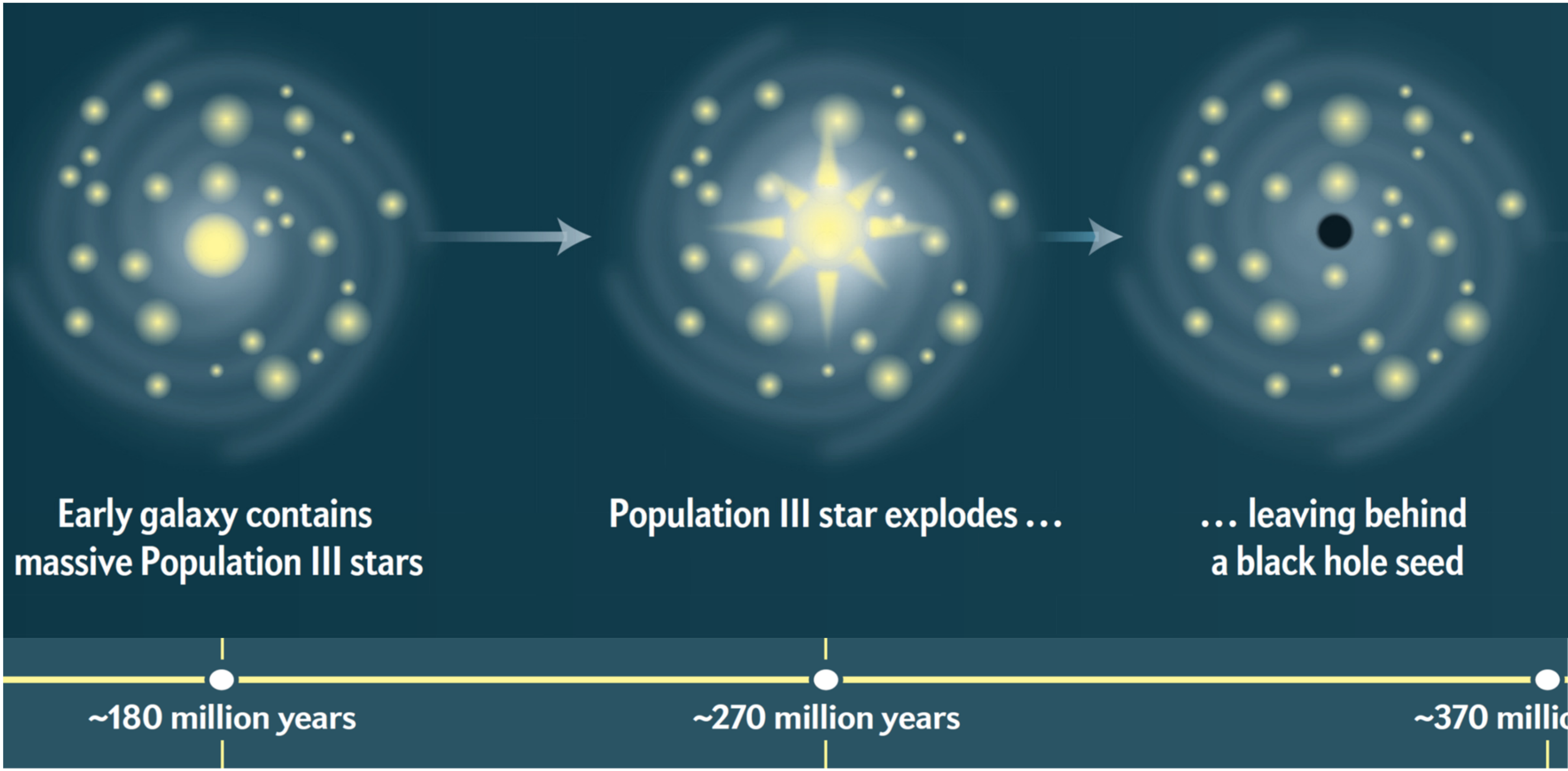
Yet conventional theories of black hole formation and growth suggest that a black hole big enough to power these quasars could not have formed in less than a billion years.

In 2001, however, with the Sloan Digital Sky Survey, astronomers began finding quasars that dated back earlier.

The oldest and most distant quasar known, which was reported last December, existed just 690 million years after the big bang. In other words, it does not seem that there had been enough time in the history of the universe for quasars like this one to form.

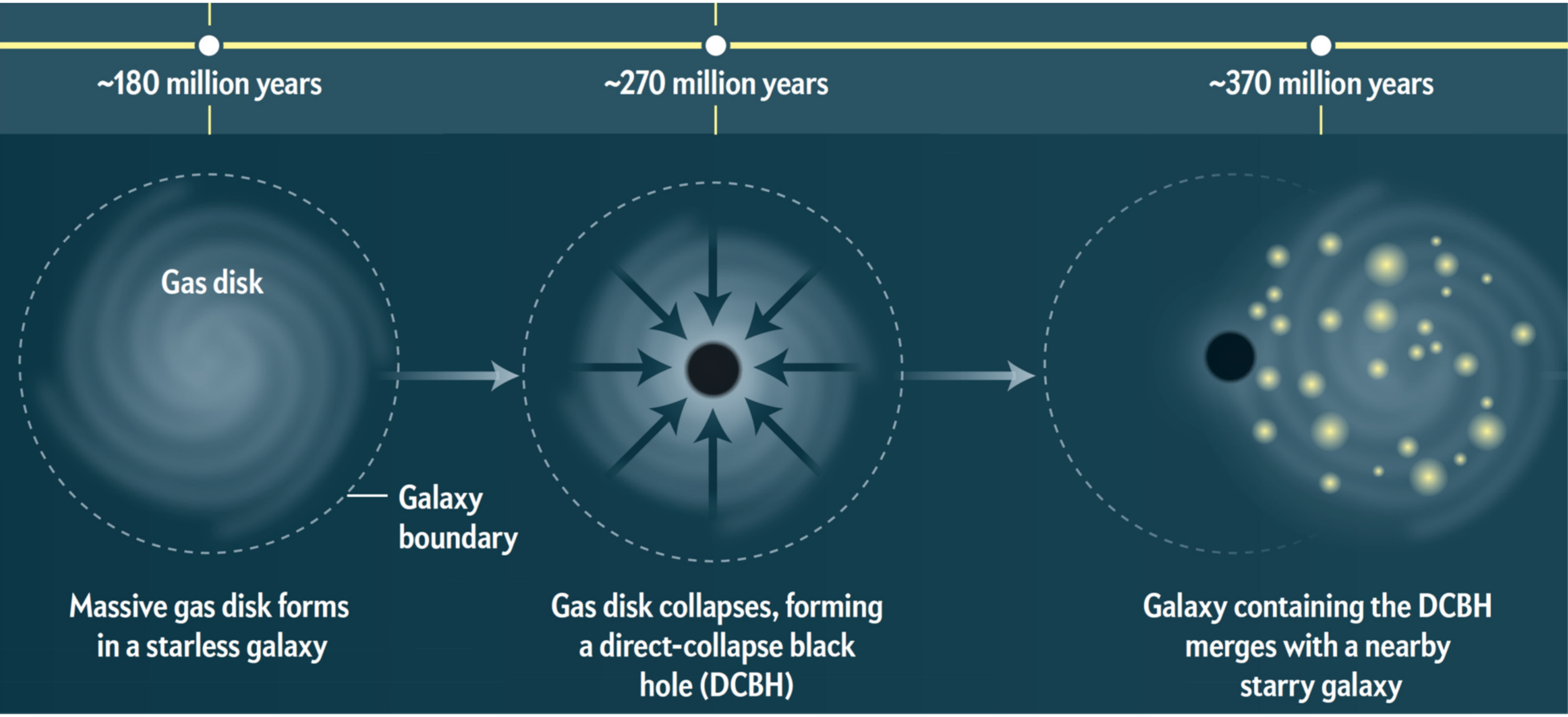
CONVENTIONAL SCENARIO

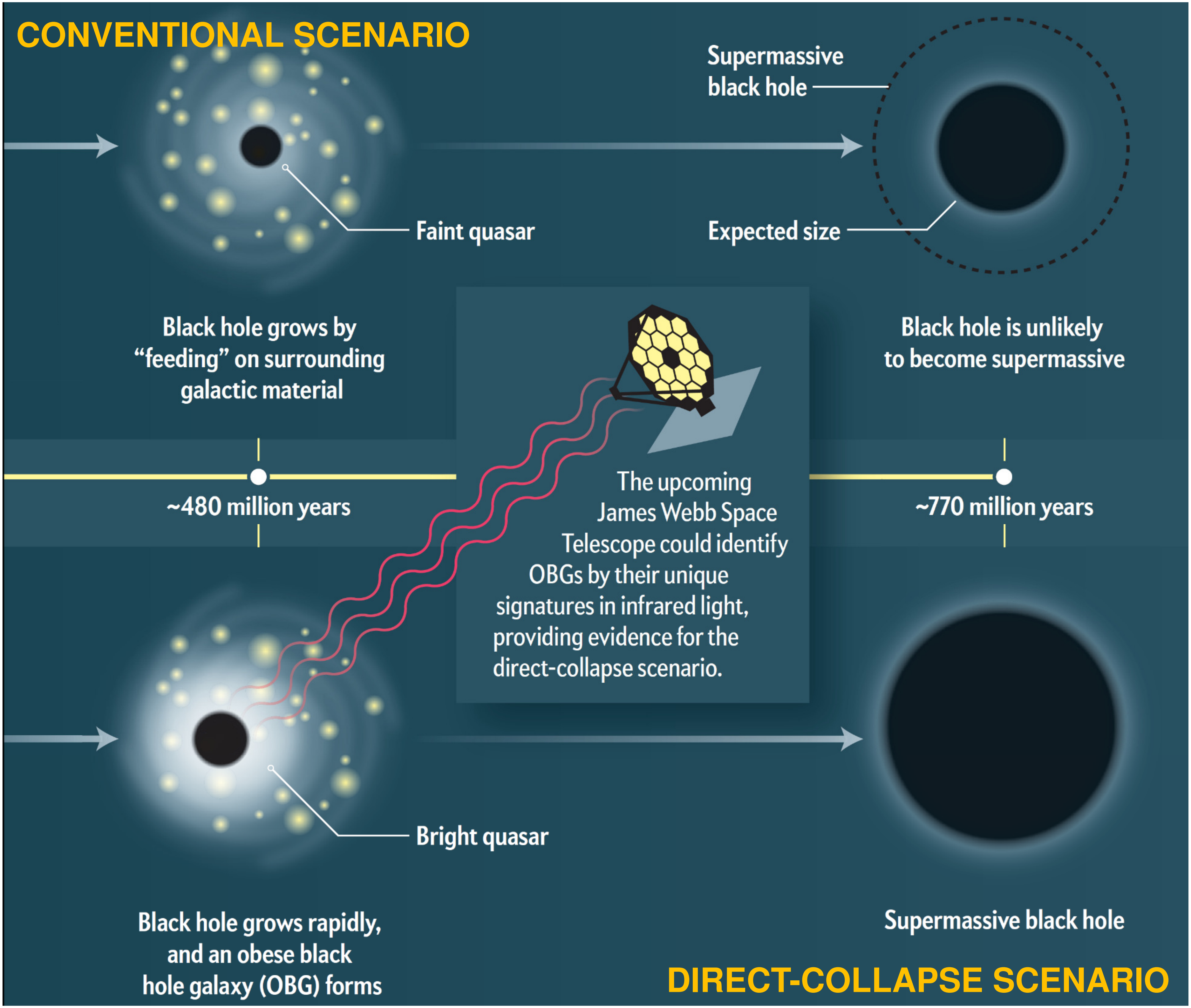
When the first (Population III) stars exhausted their nuclear fuel, they collapsed in super nova explosions, leaving behind black holes. By rapidly eating nearby stars and gas, they then grew into much larger black holes.



DIRECT-COLLAPSE SCENARIO

If star formation stalled in a budding galaxy, the entire gas disk could have collapsed into a black hole. If this black hole then collided with a nearby galaxy, it could have grown quickly by feeding on that galaxy's stars and gas, producing an "obese black hole galaxy" that telescopes could spot.





CONVENTIONAL SCENARIO

Faint quasar

Black hole grows by “feeding” on surrounding galactic material

~480 million years

Supermassive black hole

Expected size

Black hole is unlikely to become supermassive

~770 million years

The upcoming James Webb Space Telescope could identify OBGs by their unique signatures in infrared light, providing evidence for the direct-collapse scenario.

Bright quasar

Black hole grows rapidly, and an obese black hole galaxy (OBG) forms

Supermassive black hole

DIRECT-COLLAPSE SCENARIO

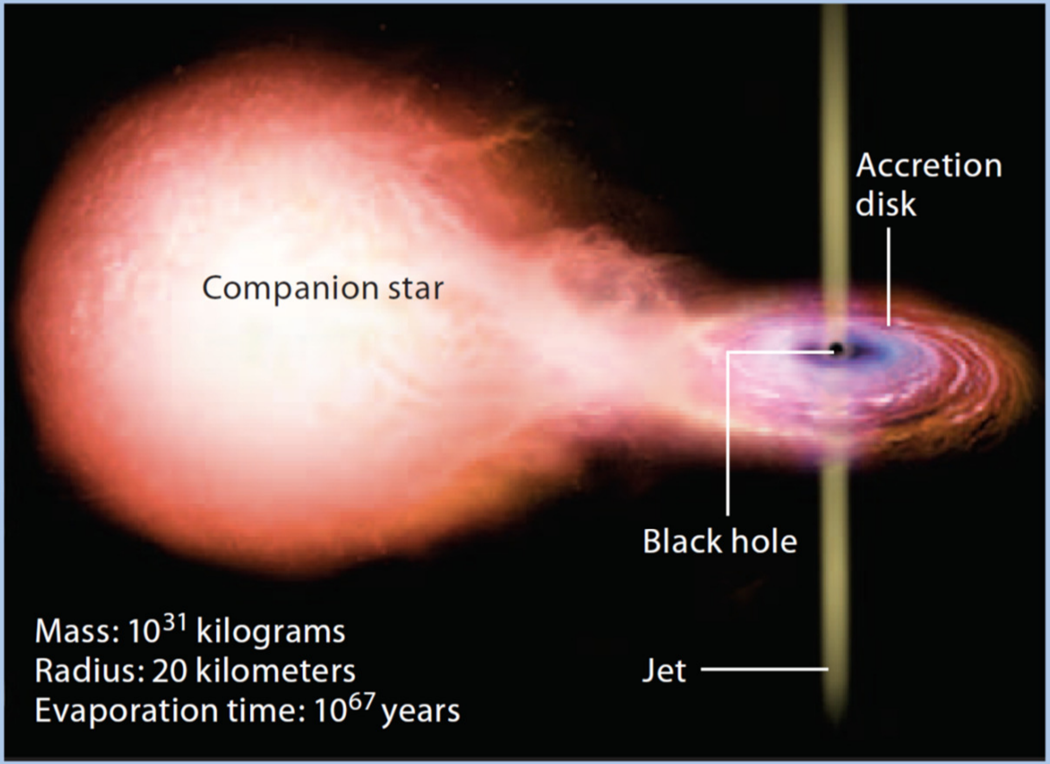
The Event Horizon Telescope is an international collaboration aiming to capture the first image of a black hole by creating a virtual Earth-sized telescope.

The EHT is an international collaboration that has formed to continue the steady long-term progress on improving the capability of Very Long Baseline Interferometry (VLBI) at short wavelengths in pursuit of this goal. This technique of linking radio dishes across the globe to create an Earth-sized interferometer, has been used to measure the size of the emission regions of the two supermassive black holes with the largest apparent event horizons: SgrA* at the center of the Milky Way and M87 in the center of the Virgo A galaxy. In both cases, the sizes match that of the predicted silhouette caused by the extreme lensing of light by the black hole. Addition of key millimeter and submillimeter wavelength facilities at high altitude sites has now opened the possibility of imaging such features and sensing the dynamic evolution of black hole accretion. The EHT project includes theoretical and simulation studies that are framing questions rooted at the black hole boundary that may soon be answered through observations.

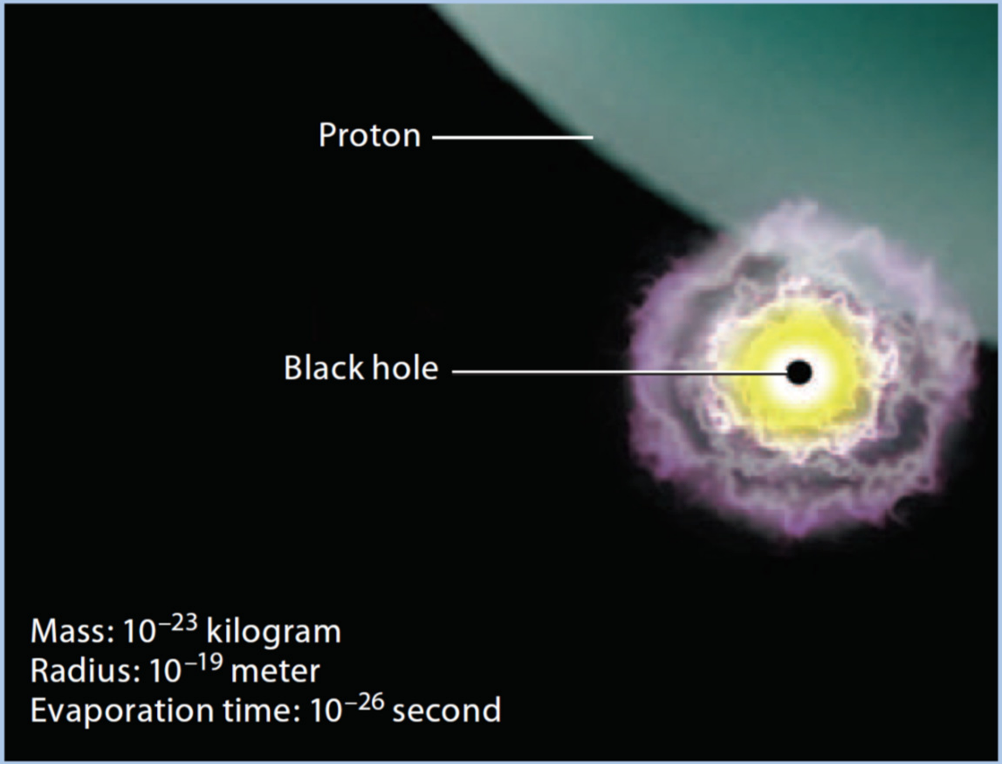
https://eventhorizontelescope.org/blog/eht-status-update-may-1-2018

Mini black holes

A Tale of Two Black Holes



Mass: 10^{31} kilograms
Radius: 20 kilometers
Evaporation time: 10^{67} years



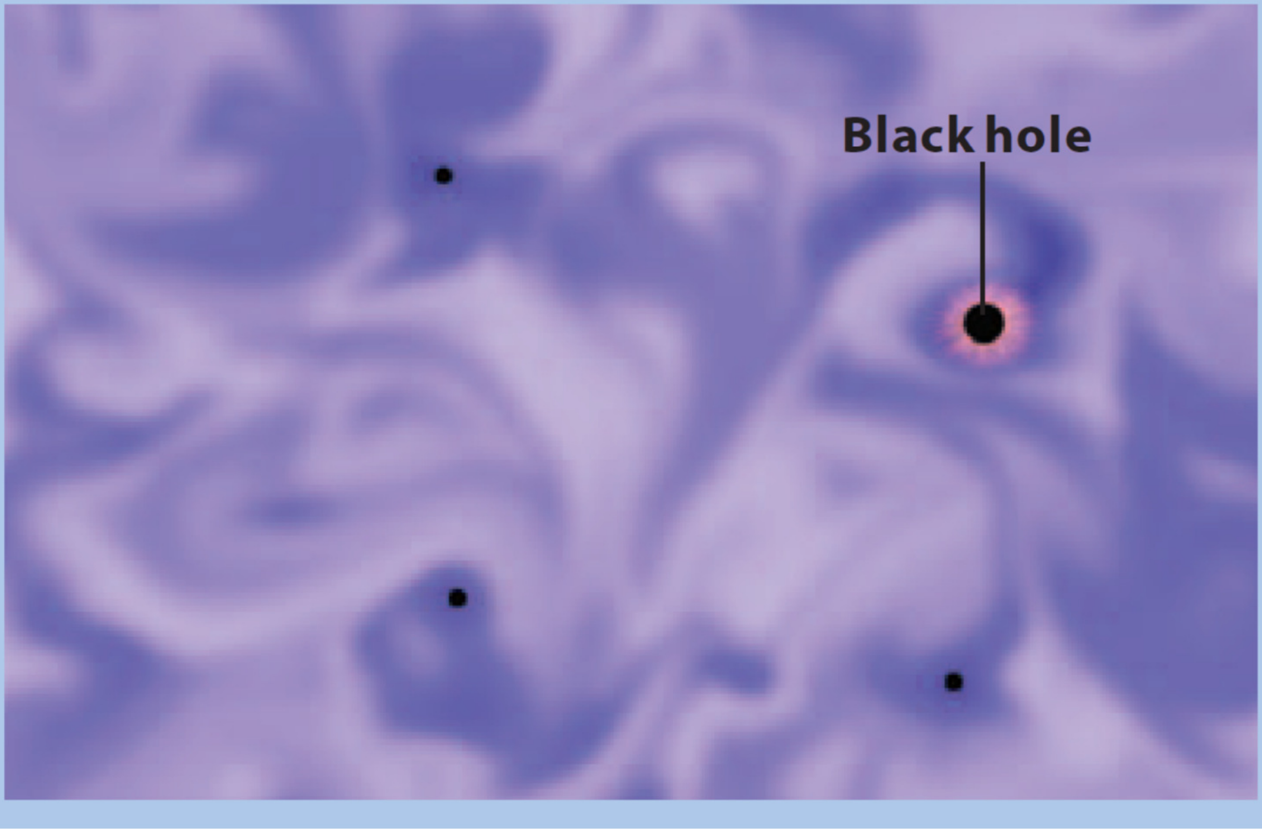
Mass: 10^{-23} kilogram
Radius: 10^{-19} meter
Evaporation time: 10^{-26} second

ASTROPHYSICAL BLACK HOLES are thought to be the corpses of massive stars that collapsed under their own weight. As matter falls into them, they act like cosmic hydroelectric plants, releasing gravitational potential energy—the only power source that can account for the intense x-rays and gaseous jets that astronomers see spurting out of celestial systems such as the x-ray binary shown here.

MICROSCOPIC BLACK HOLES have masses ranging up to that of a large asteroid. They might have been churned out by the collapse of matter early in the big bang. If space has unseen extra dimensions, they might also be created by energetic particle collisions in today's universe. Rather than swallowing matter, they would give off radiation and decay away rapidly.

Scientific American 17, 20 (2007)

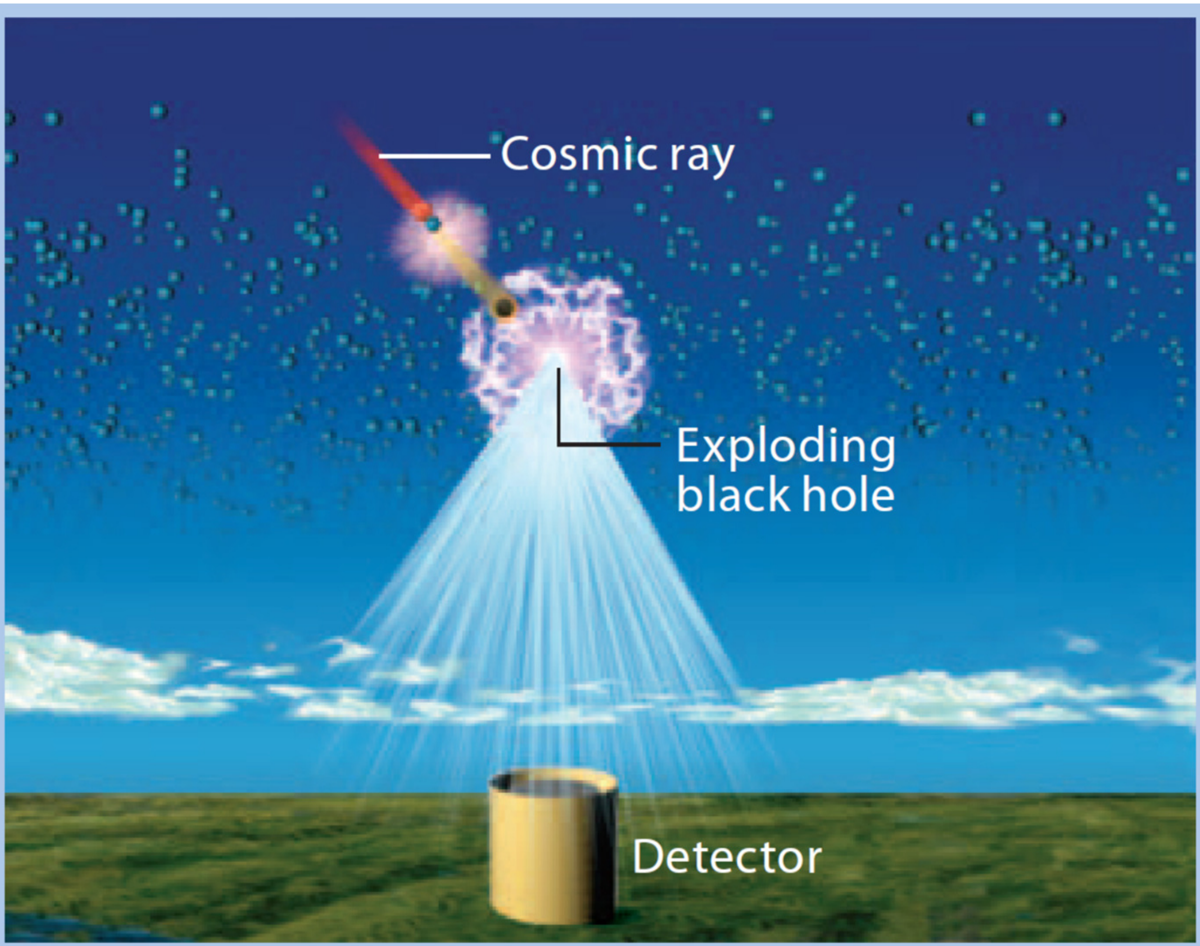
Ways to Make a Mini Black Hole



Primordial Density Fluctuations

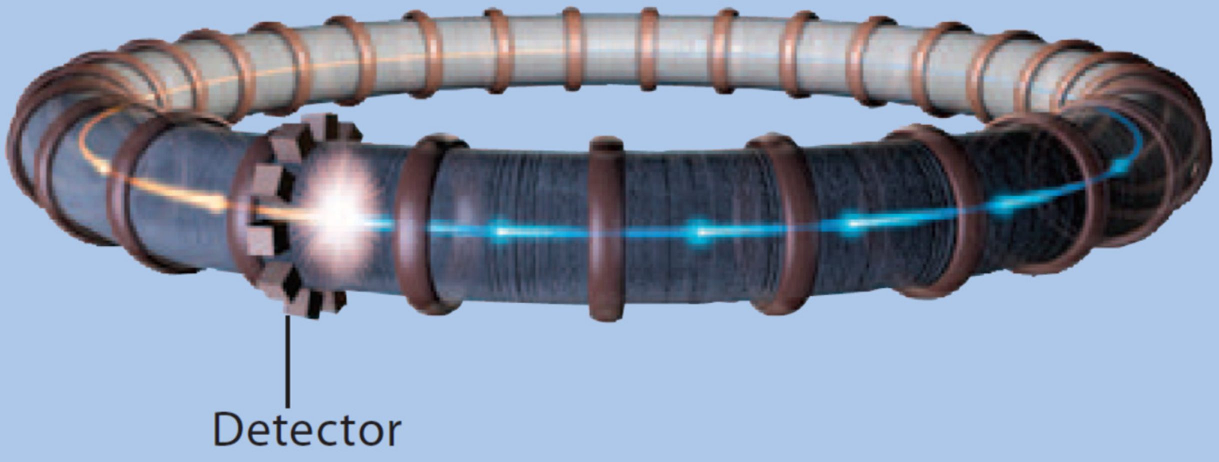
Early in the history of our universe, space was filled with hot, dense plasma. The density varied from place to place, and in locations where the relative density was sufficiently high, the plasma could collapse into a black hole.

Scientific American 17, 20 (2007)



Cosmic-Ray Collisions

Cosmic rays—highly energetic particles from celestial sources—could smack into Earth's atmosphere and form black holes. They would explode in a shower of radiation and secondary particles that could be detected on the ground.



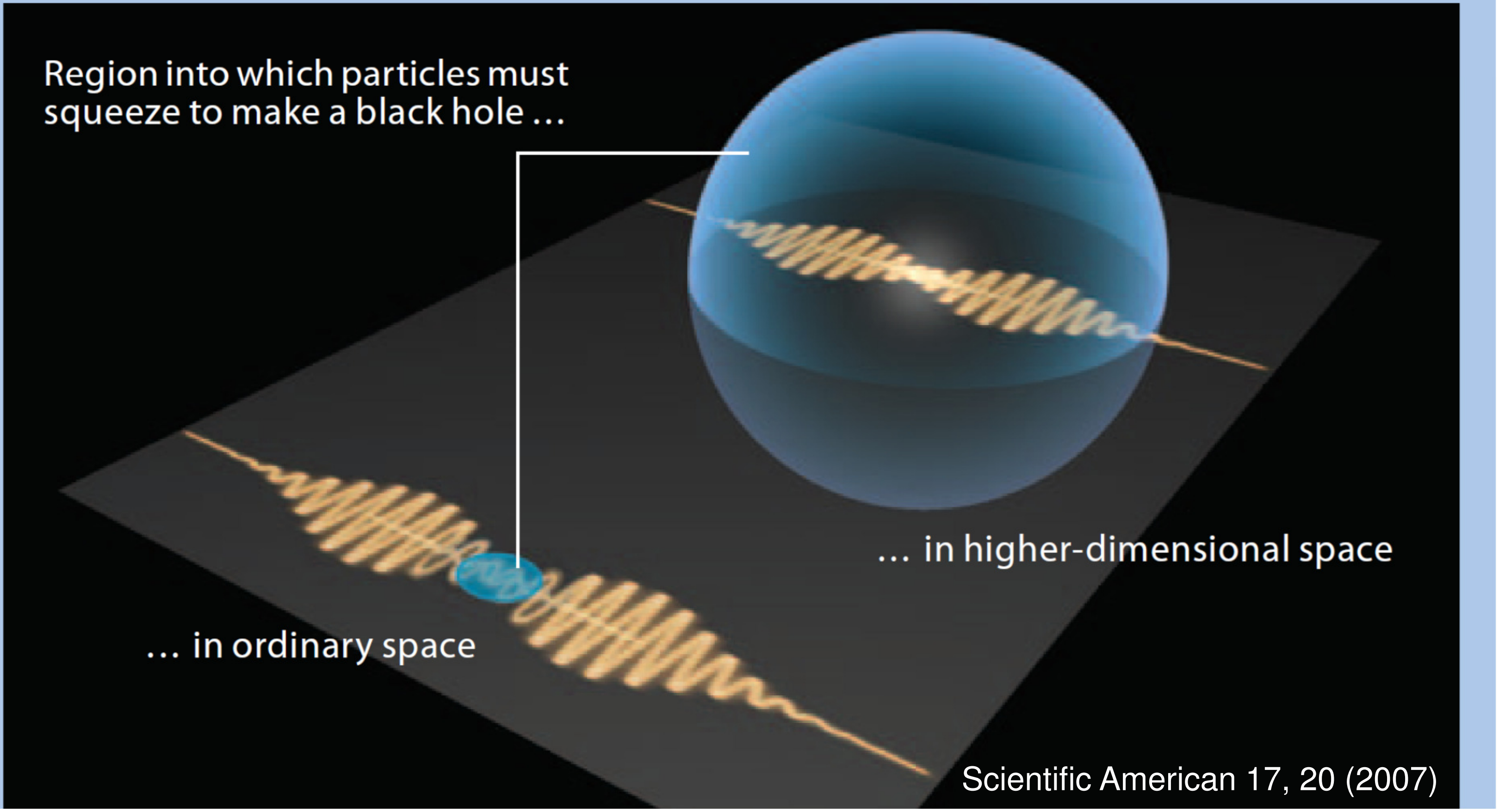
Particle Accelerator

An accelerator such as the LHC could crash two particles together at such an energy that they would collapse into a black hole. Detectors would register the subsequent decay of the hole.

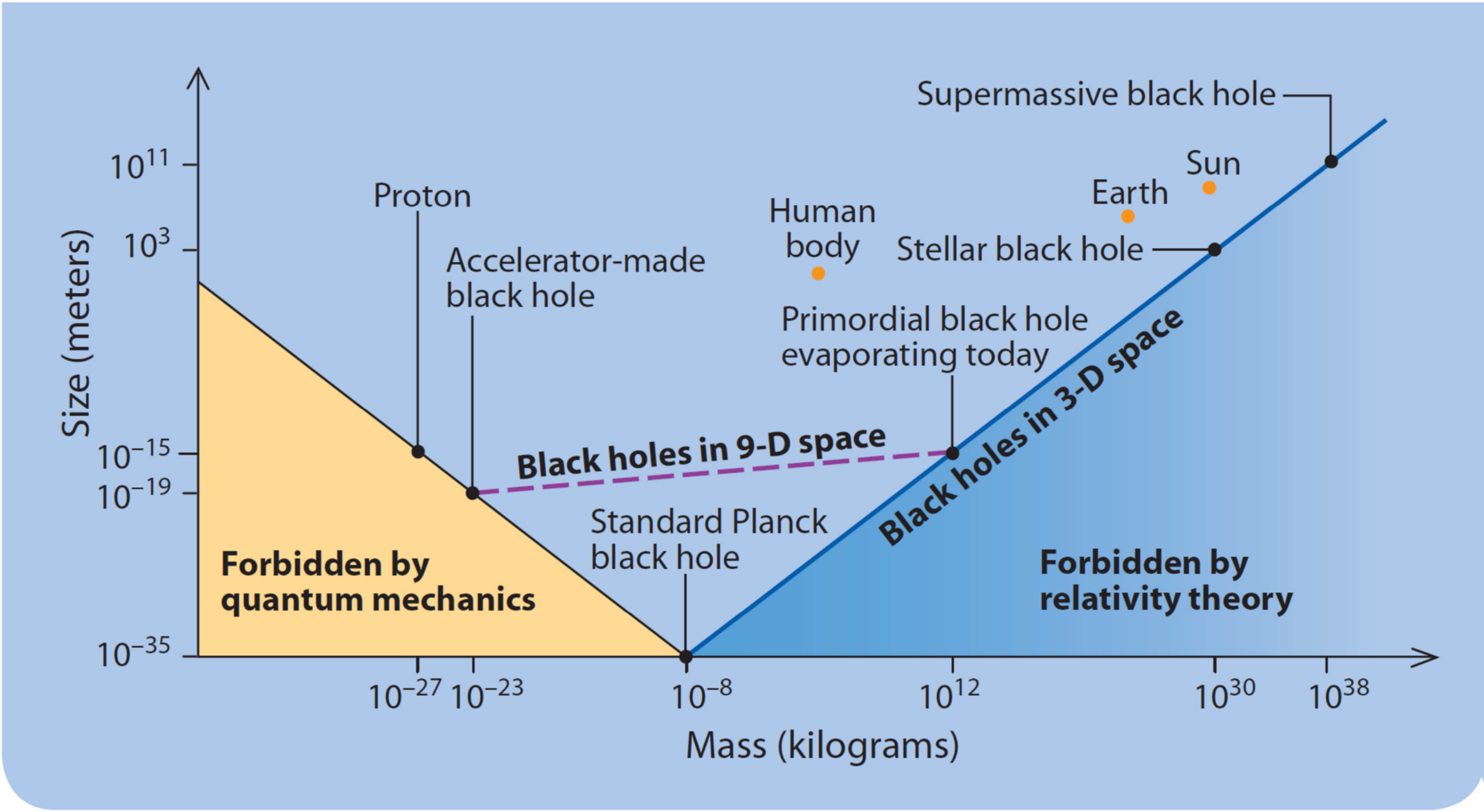
Scientific American 17, 20 (2007)

Making Holes Is Hard to Do

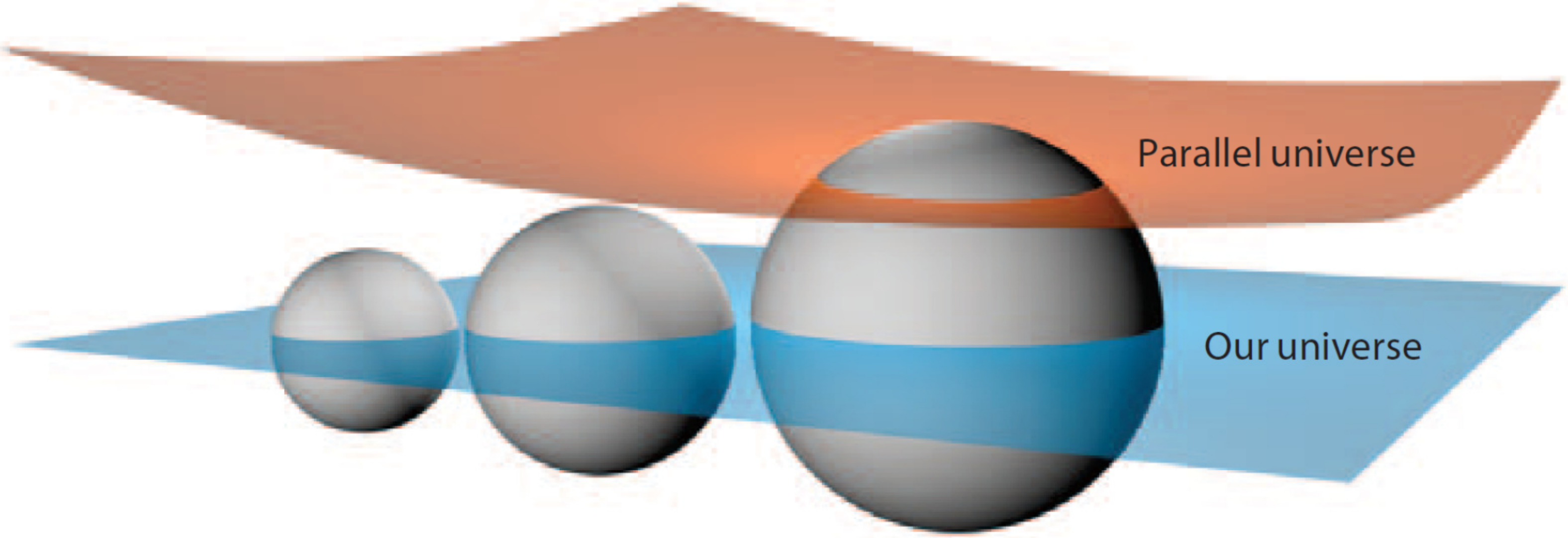
How much do you need to squeeze a piece of matter to turn it into a black hole? The lighter a body is, the more you must compress it before its gravity becomes strong enough to make a hole. Planets and people are farther from the brink than stars are (*graph*). The wave nature of matter resists compression; particles cannot be squeezed into a region smaller than their characteristic wavelength (*diagram*), suggesting that no hole could be smaller than 10^{-8} kilogram. But if space has extra dimensions, gravity would be inherently stronger over short distances and an object would not need to be squeezed as much, giving would-be hole makers hope that they might succeed in the near future.



Scientific American 17, 20 (2007)



Scientific American 17, 20 (2007)

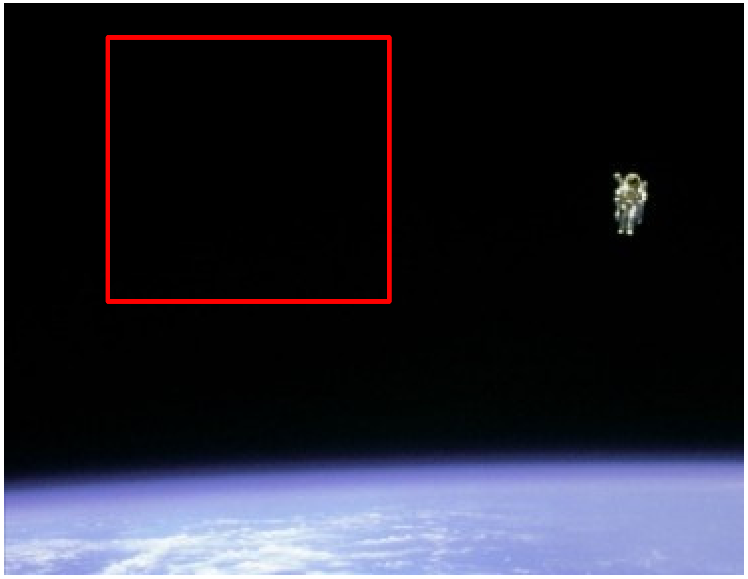


BLACK HOLES OF DIFFERENT SIZES could probe extra dimensions that are otherwise inaccessible to us. Because gravity, unlike other forces, extends into those dimensions, so do black holes. Physicists would vary their size by tuning the particle accelerator to different energies. If a hole intersects a parallel universe, it will decay faster and appear to give off less energy (because some of the energy is absorbed by that other universe).

Scientific American 17, 20 (2007)

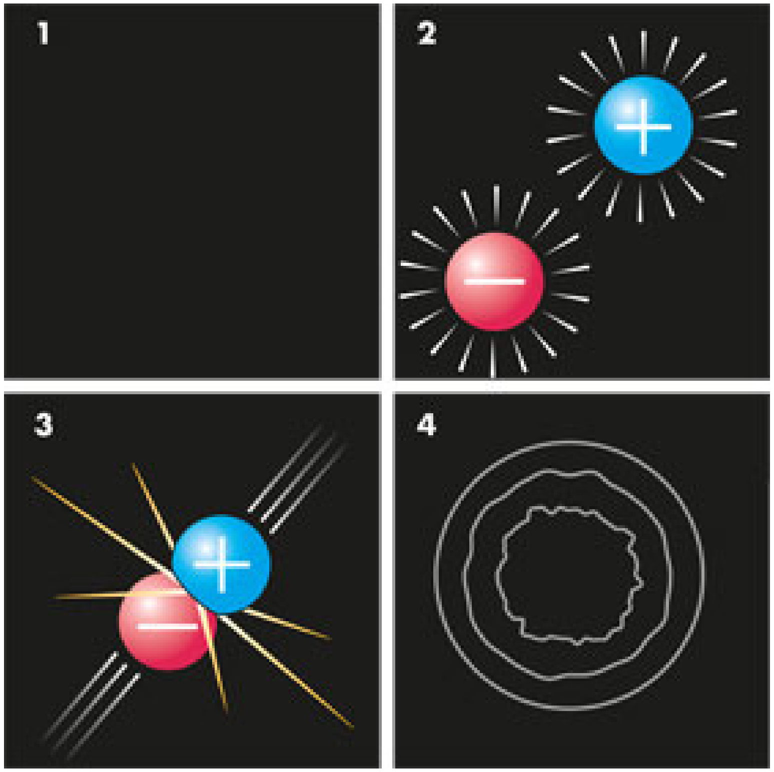
Black holes and quantum information paradox

Vacuum is not just “nothing”!



In quantum physics a vacuum is not “nothing”.

It is teeming with pairs of “virtual” particles and antiparticles that spontaneously appear and annihilate one another within a tiny fraction of a second.



http://hetdex.org/dark_energy/what_is_it/vacuum_energy.php

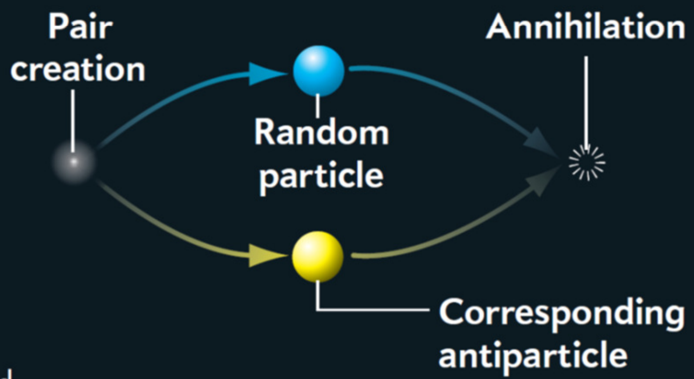
1. Empty space.
2. Two particles suddenly appear.
3. Particles ram together and annihilate each other.
4. They leave ripples of energy through space

The Trouble with Quantum Black Holes

The classical (that is, nonquantum) equations of general relativity forbid anything emerging from inside a black hole's event horizon. Yet in the 1970s Stephen Hawking carried out quantum calculations that predicted black holes would randomly emit particles at a very low rate (*left panel*). The randomness created a paradoxical scenario (*right panel*) known as the information problem.

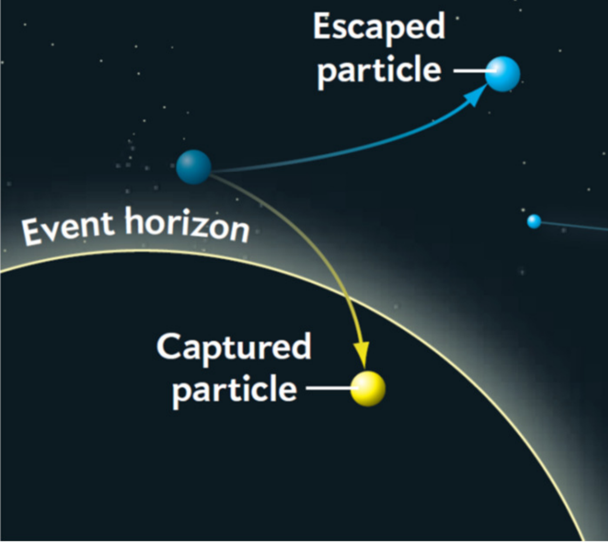
HAWKING RADIATION IS EMITTED

Even in empty space, a quantum process constantly produces pairs of so-called virtual particles and antiparticles, which immediately annihilate each other.



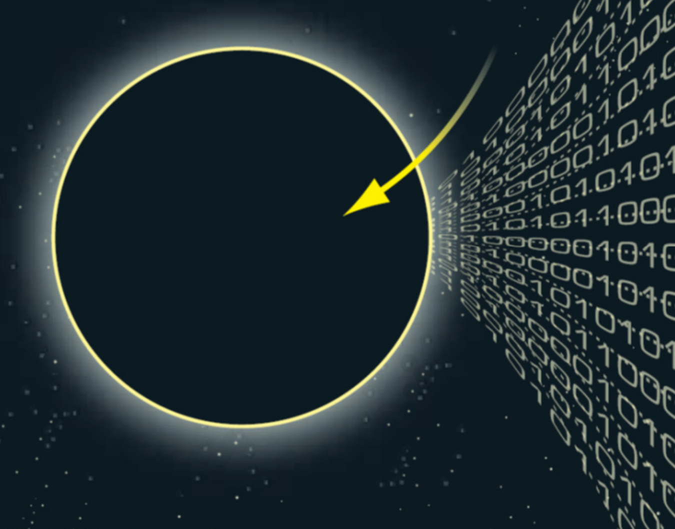
Near a black hole's event horizon, one virtual particle may be captured by the black hole, and the second may escape. The escaped particle carries away positive mass, and the captured one takes negative mass into the black hole—thereby reducing the hole's mass.

Thus, if nothing falls into the black hole, its mass and its event horizon gradually shrink. This evaporation process speeds up as the hole becomes smaller.

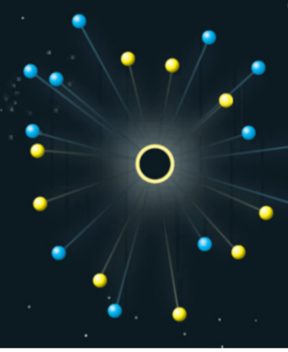


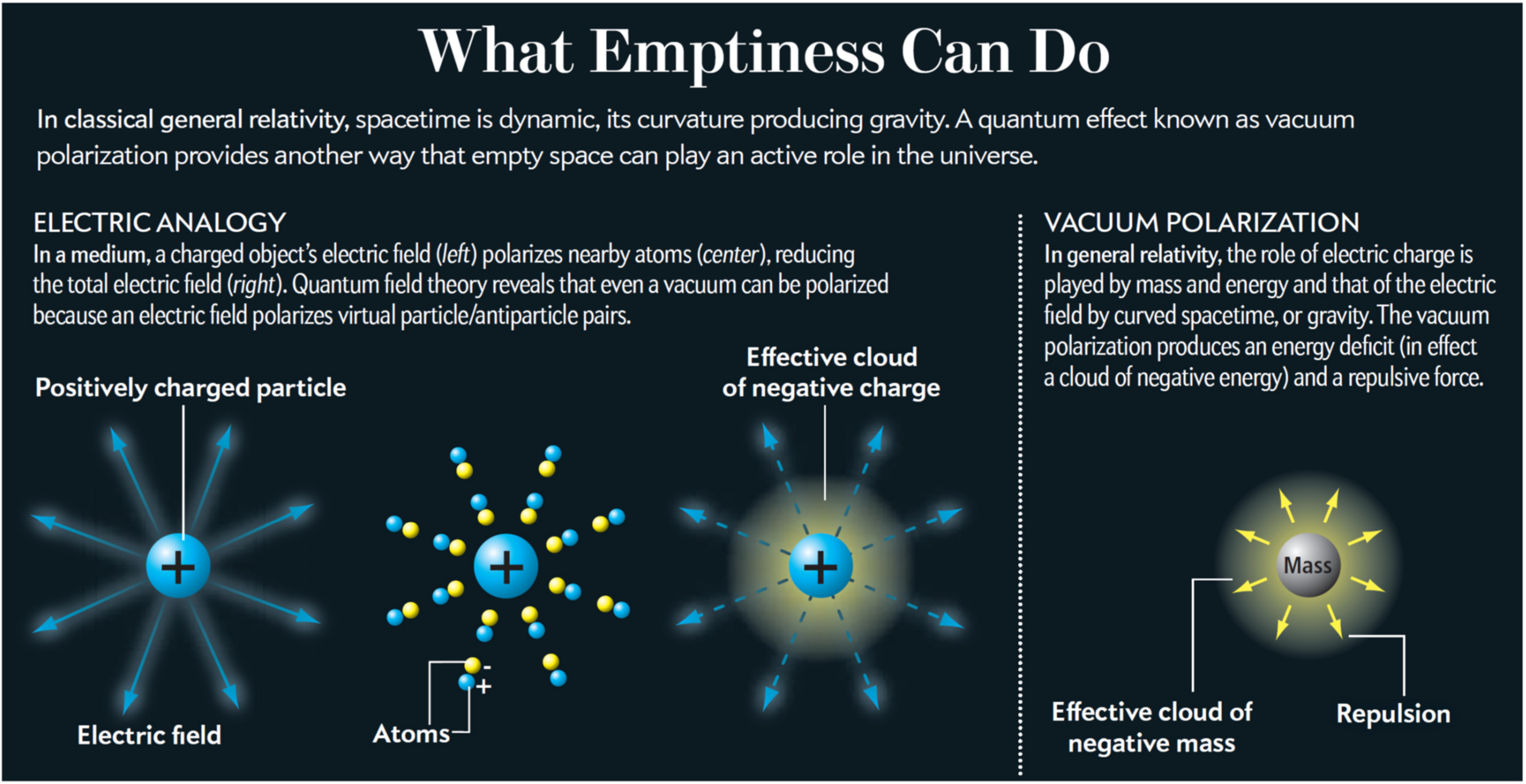
INFORMATION IS LOST

Matter that falls into a black hole carries with it a vast quantity of information.



Hawking's finding indicates that a black hole can evaporate all the way to zero mass, but the random particles it emits carry almost no information. The apparent loss of information violates a fundamental feature of quantum mechanics called unitarity. This contradiction begs for resolution.





What Emptiness Can Do

In classical general relativity, spacetime is dynamic, its curvature producing gravity. A quantum effect known as vacuum polarization provides another way that empty space can play an active role in the universe.

ELECTRIC ANALOGY

In a medium, a charged object's electric field (*left*) polarizes nearby atoms (*center*), reducing the total electric field (*right*). Quantum field theory reveals that even a vacuum can be polarized because an electric field polarizes virtual particle/antiparticle pairs.

VACUUM POLARIZATION

In general relativity, the role of electric charge is played by mass and energy and that of the electric field by curved spacetime, or gravity. The vacuum polarization produces an energy deficit (in effect a cloud of negative energy) and a repulsive force.

Scientific American 22, 82 (2013)

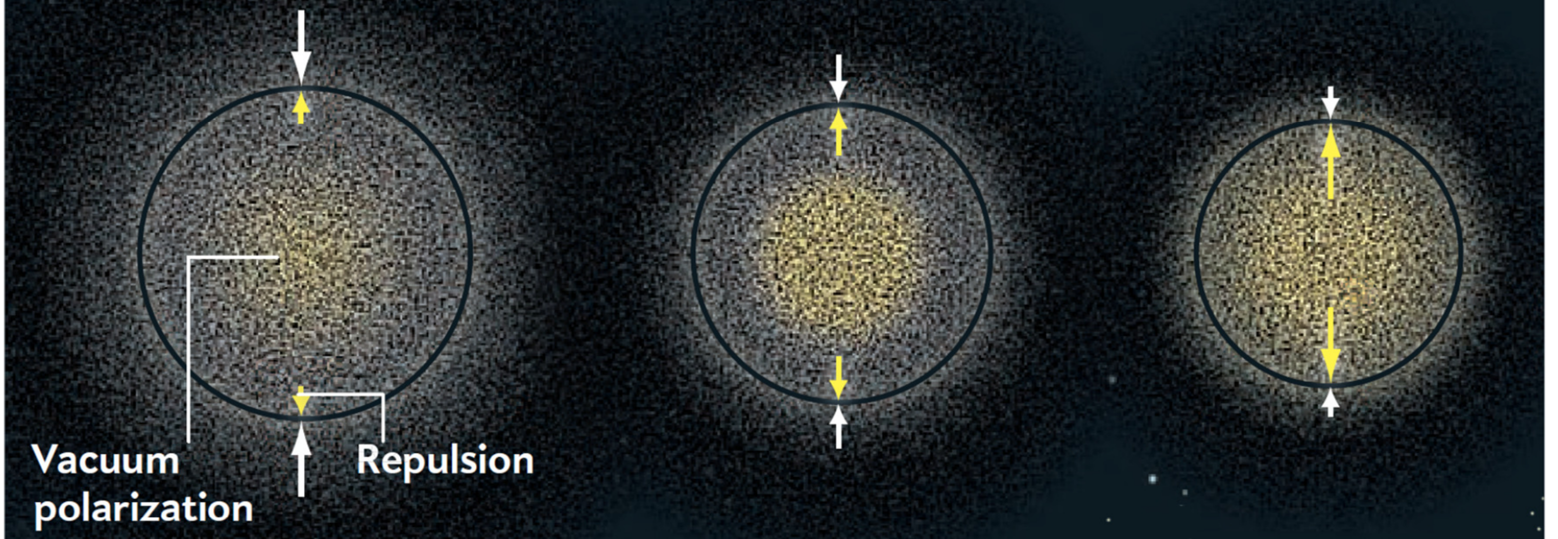
Scientific American 22, 82 (2013)

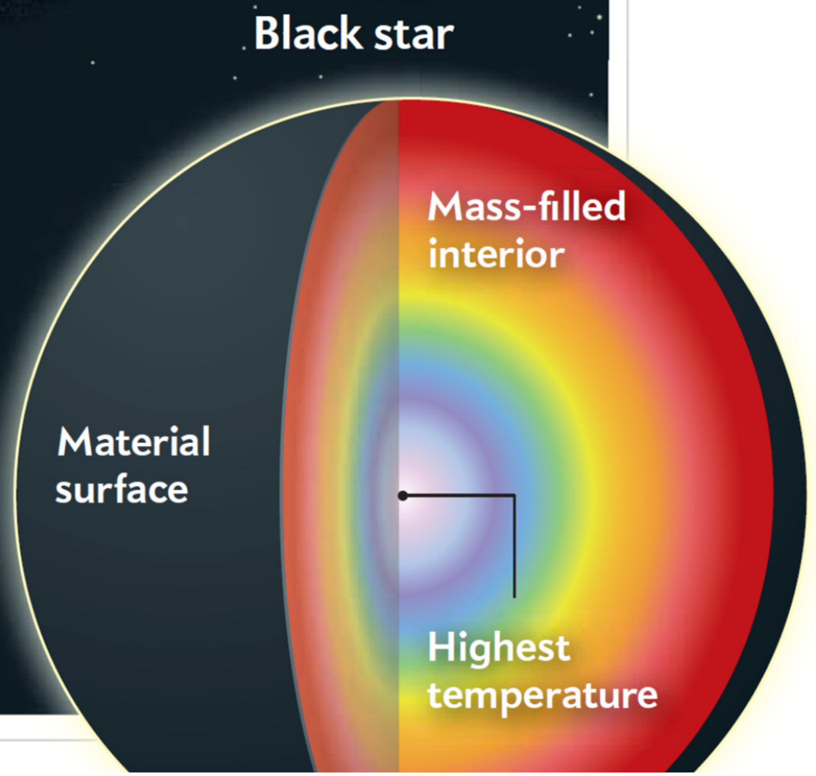
SLOWER COLLAPSES MAY BE DELAYED FOREVER

If the matter's fall is slowed, vacuum polarization may grow, producing repulsion.

The repulsion further slows the collapse, which allows the polarization to intensify.

The collapse is delayed from ever forming an event horizon.

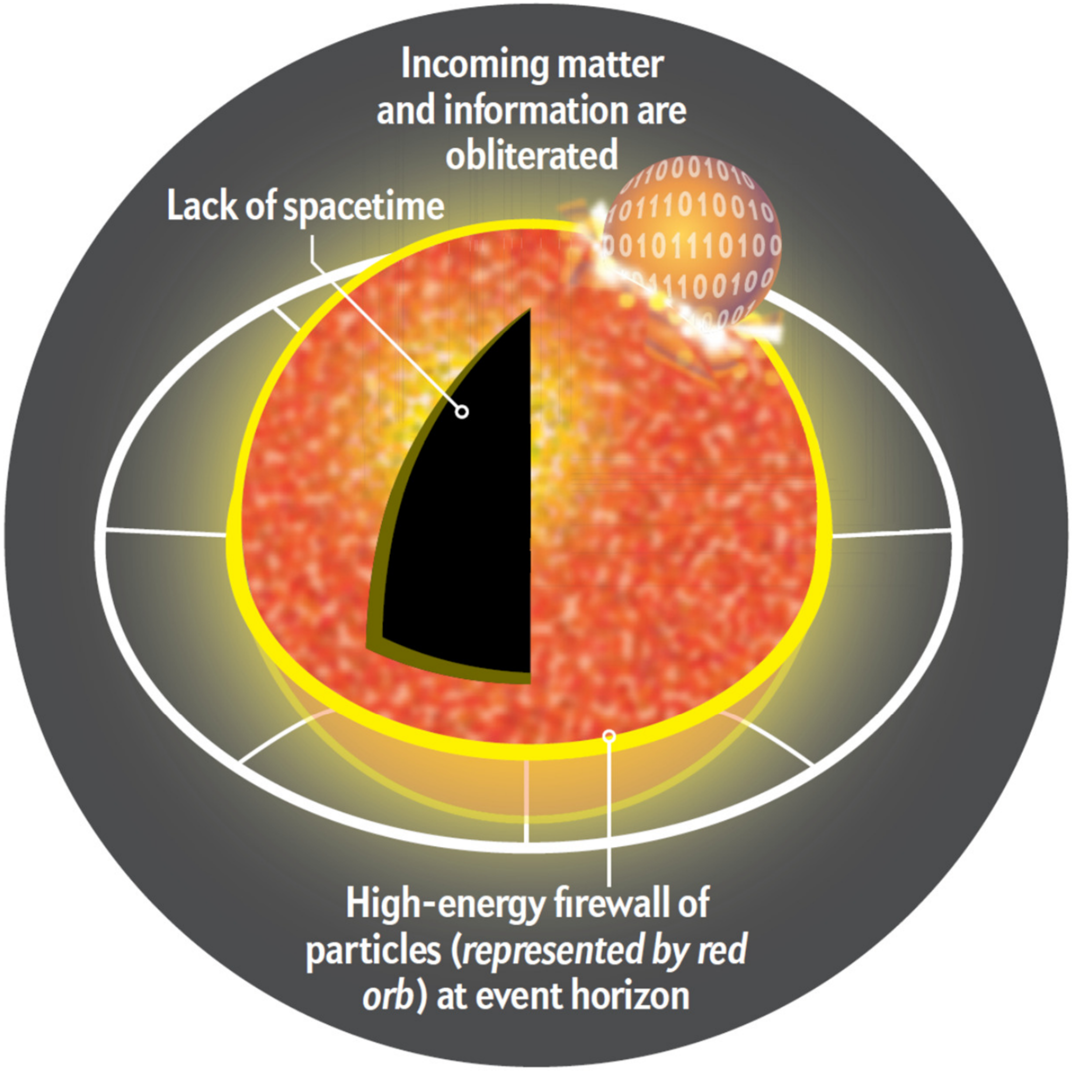




BLACK STAR

The result is a black star. The gravitational field around it is identical to that around a black hole, but the star's interior is full of matter and no event horizon forms. A black star could emit Hawking-like radiation, but this radiation carries the information that went into the black star, preserving unitarity. If a black star could be peeled layer by layer like an onion, at each stage the remaining core would be a smaller black star, also emitting radiation. Small black holes emit more radiation and have higher temperatures than larger ones, and so a black star is increasingly hot toward its center.

Firewalls



Yet the string theory solutions eventually led to a surprising conclusion: black holes might be surrounded by firewalls—walls of high-energy particles that would obliterate any object that encountered them. Firewalls seem to imply a drastic breakdown of the laws of physics at the boundary of black holes and could lead to extreme conclusions, such as the possibility that firewalls mark the end of space and time altogether.

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