Friday: review (HERE - A110)

Monday: Final Exam

2:30 – 4:20 pm

A110 (here again)

Closed book, may bring **2** double-sided sheets of hand-written notes, and a calculator.

# Physics 311
# General Relativity

Lecture 20:

Hot topics in General Relativity
(and beyond)

Field Test Version (Jan. 2003) Contact: cpepeduc@cpepweb.org

# THE HISTORY AND FATE OF THE UNIVERSE

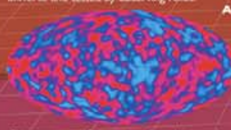
Eight major stages in the evolution of the universe are illustrated below.
The Big Bang occured everywhere in the universe. Here one region has been illuminated and followed through time. The expansion is far greater than can be shown here.

## The Big Bang and Expanding Universe

Space is expanding from an initial moment called the Big Bang. As it expands, the universe cools and becomes less dense. All distant galaxies are moving apart from each other and away from us. On large scales, the universe looks the same in all directions and all parts of space. There is no preferred center. Our current understanding of the early universe is called the Big Bang model. Much more will be learned from astronomical observations and from accelerator-based experiments in the coming years.

## Cosmology and Relics of History

**Cosmology** is the study of the universe as a whole. As in archaeology, cosmology finds clues to the past in relics. Looking out a distance d in space is looking back in time, because $t = d/c$ (light travels at a finite speed c). The laws of nature discovered on Earth can be applied to the early universe and tested by observing relics.



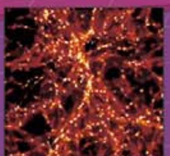
*This is an image of the universe from the time when atoms first formed. It is a map of the entire sky showing CMB light with the uniform part subtracted.*

**A Relic from the Early Universe**
The Cosmic Microwave Background (CMB) is a universal bath of lightwaves (photons) from the hot dense, early universe. They are stretched by the expansion of space. To a part in 100,000, the CMB is the same no matter where you look (it is isotropic). The remaining tiny variations (shown in figure) are images of the seeds that later form galaxies and larger cosmic structures.

**Age of the Universe** A marvelous agreement that the age of the universe is about 14 billion years comes from studying its expansion and the lifecycles of stars and also by dating meteorites.

## History of the Universe

Three major eras in the expansion history followed the hot, dense condition of the earliest universe. During each era, the expansion depended on the nature of the matter or energy that dominated the universe at that time.



*Simulated density fluctuations (ripples) in the early universe that eventually yield galaxies and clusters of galaxies.*

**Era I - Acceleration: Inflation speeds expansion**
Observations seem to imply that the very early universe underwent an extremely rapid, accelerating expansion, called ***inflation***. In a tiny fraction of a second, inflation expanded each part of space by a factor of at least $10^{27}$. Before inflation, the portion of the universe visible to us today was a smooth patch much smaller than a proton. As inflation ended, the visible universe had grown to the size of a ball (very approximately). Inflation explains how quantum fuctuations in the otherwise smooth and isotropic universe yielded tiny ripples that would eventually grow into galaxies and structures. In the 14 billion years after inflation, the universe expanded by another factor of about $10^{27}$.

**Eras 2-3 - Deceleration: Expansion slows and structure forms**
After inflation, the universe was a plasma or soup of fundamental particles. Photons and fast moving particles, generically called ***radiation***, gradually lost energy (cooled) as the universe expanded (the energy went into the expansion). Eventually, slow-moving matter became dominant over radiation. Over time, larger and larger structures grew, from galaxies to clusters of galaxies to superclusters. These began as small differences in the density of matter, but gravitational attraction made more and more matter clump together. Several interesting stages are indicated in the central figure. Stars created the higher-mass elements that eventually became part of Earth and of us. The early universe had both matter and antimatter in abundance, but today it is almost exclusively matter. How this came about is not fully understood.

**Era 4 - Acceleration: Dark energy speeds expansion**
A matter-dominated universe causes deceleration and might even reverse the expansion. So it was a great surprise in 1998 when observations showed that the expansion of the universe is now accelerating (see the "Expansion History" plot). This implies the existence of a new form of energy, referred to as ***dark energy***. Scientists are pursuing the nature of dark energy.


## Our Cosmic Address

Our sun is one of 400 billion stars in the Milky Way galaxy, which is one of more than 100 billion galaxies in the visible universe.

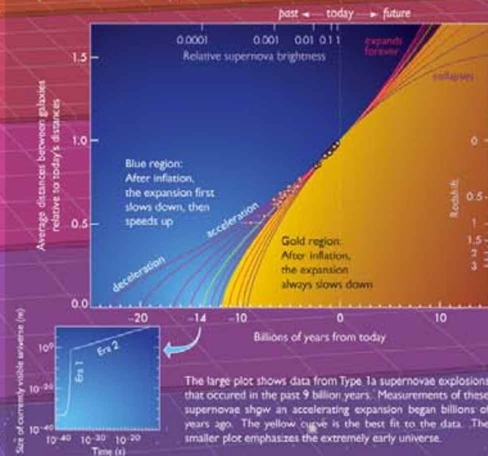

Learn more at
UniverseAdventure.org
and at CPEPweb.org

## Redshifts and Expansion

Lightwaves stretch with the expansion of space. As the wavelength of visible light increases, it becomes redder (as shown for the photons in the central figure). Measuring this redshift tells us the velocity of the source. In 1929, Hubble observed that all distant objects are receding with a velocity proportional to their distance. This information and modern telescope observations show that the universe is expanding uniformly in all directions. Objects that are bound together (such as galaxies and atoms) do not expand as space expands.

*The raisin bread represents a portion of the universe, and the raisins represent galaxies. Due to the rising of the bread (the expansion of space), wavelength increases and raisins move apart, but raisins do not expand.*

## Expansion History of the Universe




The large plot shows data from Type 1a supernovae explosions that occured in the past 9 billion years. Measurements of these supernovae show an accelerating expansion began billions of years ago. The yellow curve is the best fit to the data. The smaller plot emphasizes the extremely early universe.

## Fate of the Universe

Composition of the Universe


Whether the expansion of the universe will speed up, slow down, or even possibly reverse into collapse depends through gravity on the amount and types of matter and energy in it.

The ordinary matter – atoms and nuclei – that formed in the early universe can account for the visible mass in galaxies and clusters. But it falls far short of the total mass needed to bind them together gravitationally and explain their internal motions. So an extraordinary new type of matter, not made of atoms or nuclei, must exist; it is called ***dark matter*** because it is not directly visible.

Even stranger, recent observations of supernovae in distant galaxies show that the expansion of the universe is in fact ***accelerating***. An exotic ***dark energy*** may be causing this acceleration through a cosmic repulsion that overwhelms the pull of gravity due to matter.

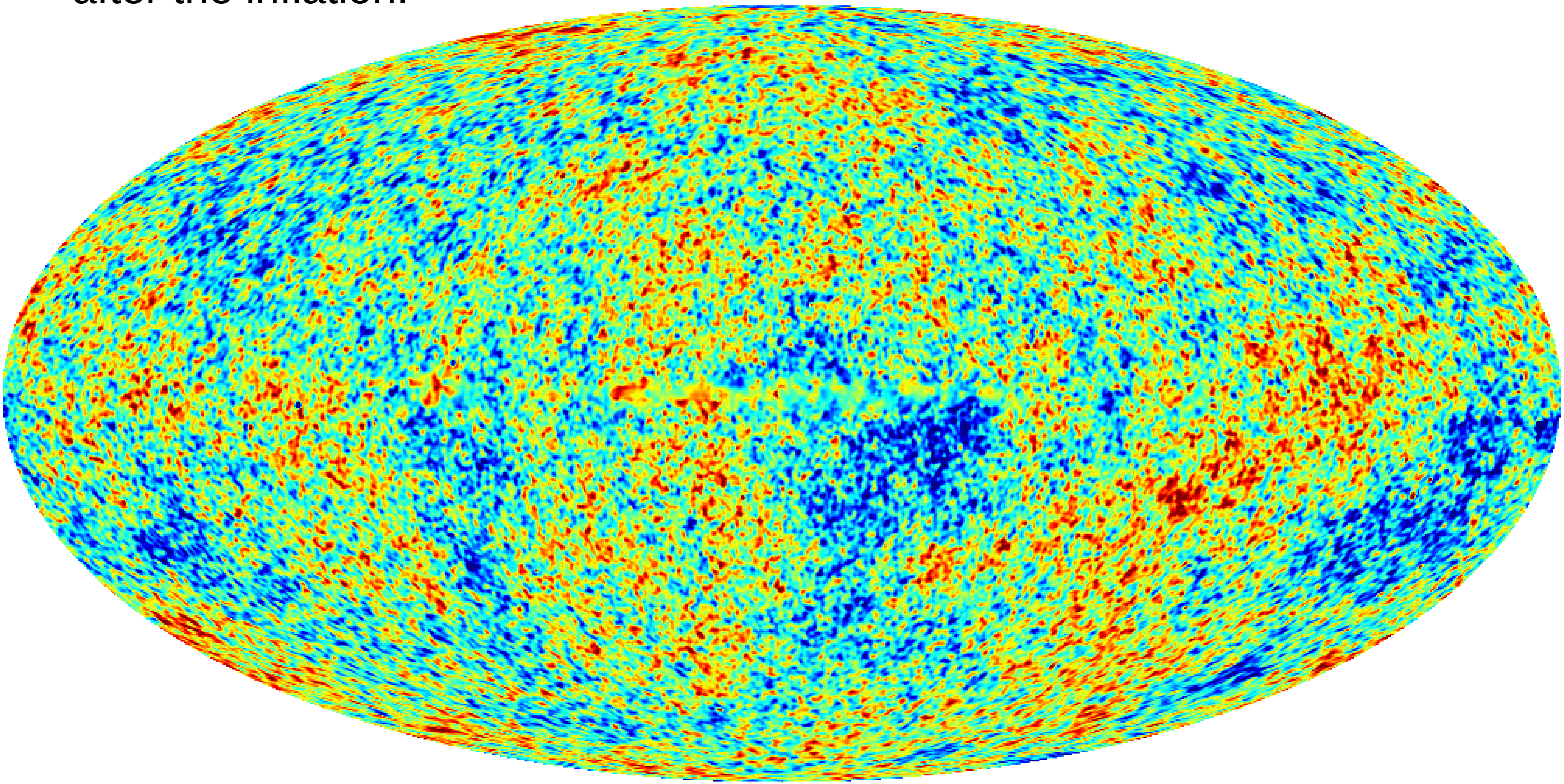
The nature of dark energy and dark matter are two of the great questions facing cosmology and particle physics. Perhaps dark energy is the cosmological constant, introduced by Einstein in 1917. Perhaps both are new parts of particle physics, tied to the very earliest moments of the universe and having to do with the nature of physics and spacetime itself.

Not all answers in science are known yet! With the research and experiments under way in astrophysics and particle physics, we may be the first generation to learn what most of the universe is made of and what is the fate of the universe.


This chart has been made possible by the generous support of: U.S. Department of Energy, U.S. National Science Foundation, Lawrence Berkeley National Laboratory. Photos courtesy of NASA.

# Microwave background map (fluctuations)

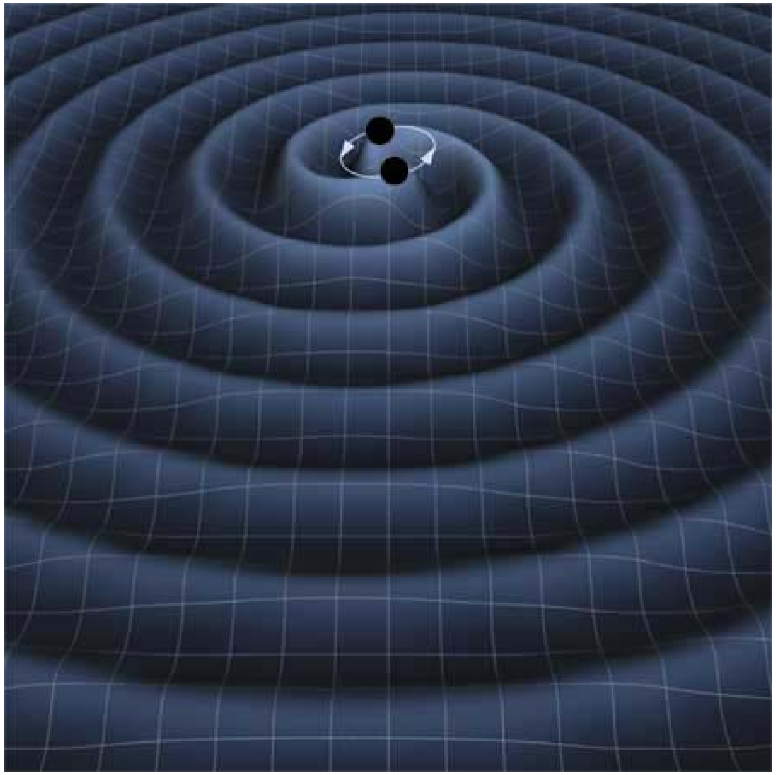
- Small ripples in the exceptionally uniform microwave background give us a glimpse at the *quantum fluctuations* in the very early Universe, just after the inflation.



# Gravitational waves

• Time-dependence in Einstein field equation leads to spacetime curvature that varies with time.

• These time-variations of spacetime curvature are expected to propagate at speed of light and are called *gravitational waves.*



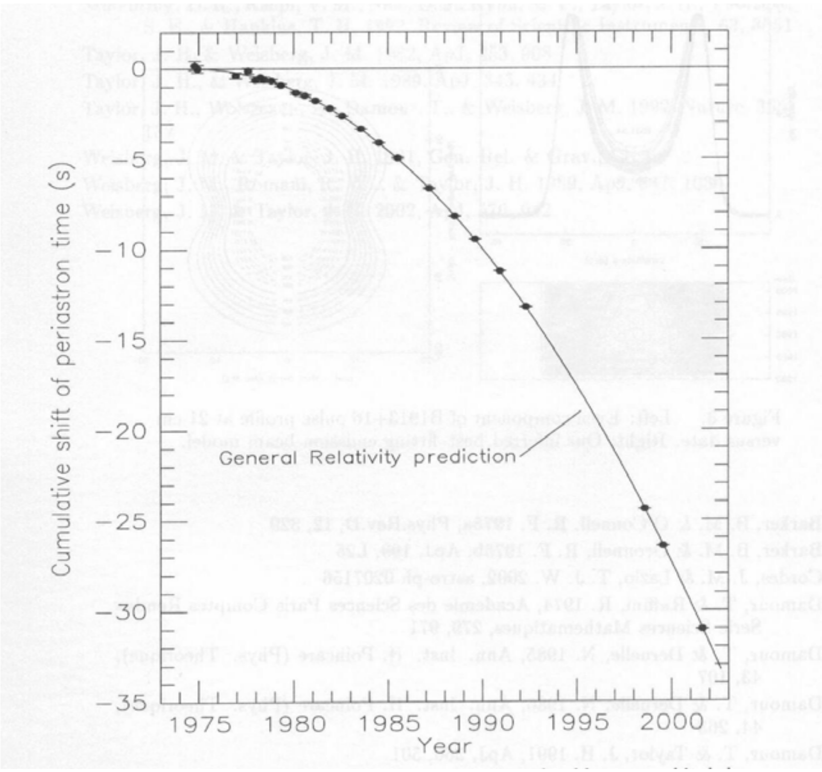
In this figure, two hypothetical black holes orbit each other at high rate.

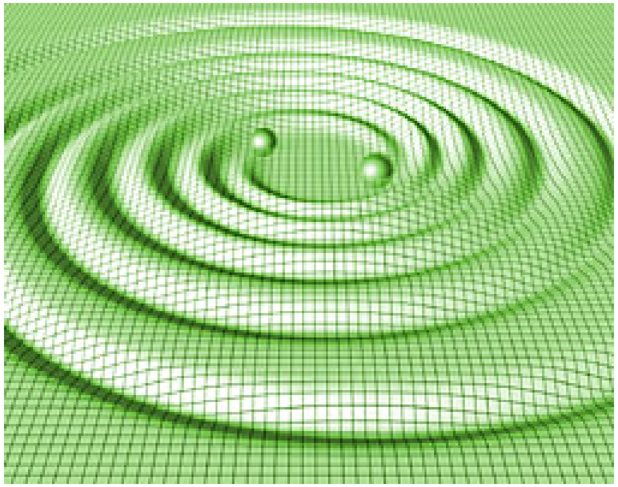
Each black hole creates its own curved spacetime around itself.

As the black holes rotate, the centers of their respective metrics move. This creates a wave pattern!

# Energy of gravitational waves

- Gravitational waves carry away energy. This energy must come from somewhere. In other words, the source of gravitational waves must lose energy.
- Looking for this loss of energy is an *indirect* way of detecting gravitational waves.



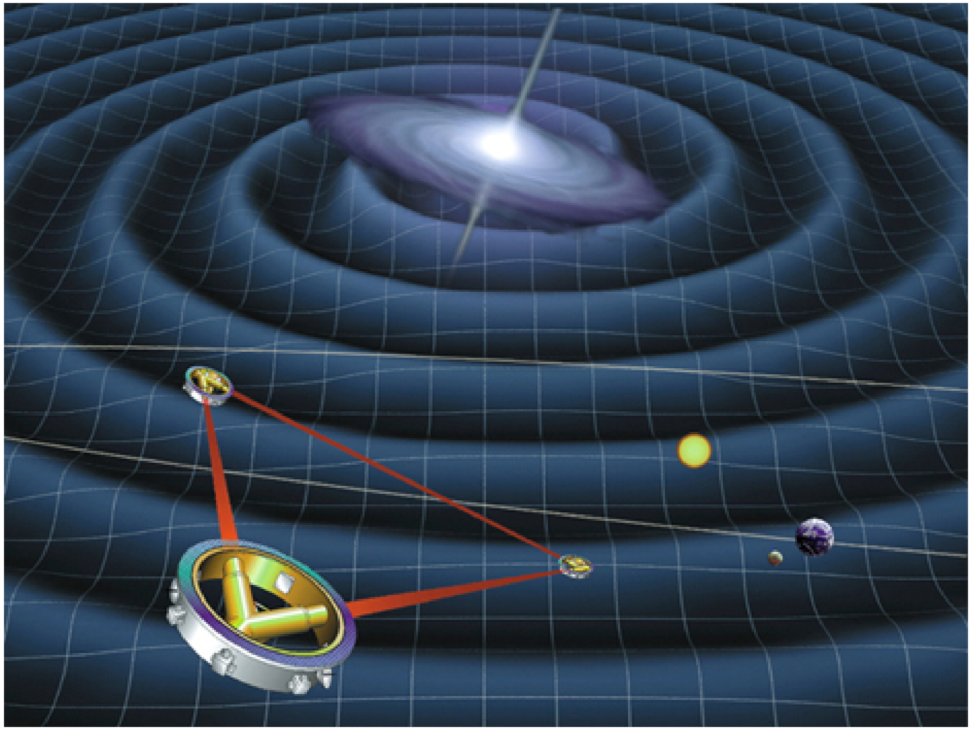
# LIGO - Laser Interferometer Gravitational wave Observatory

- Two enormous Michelson interferometers look for tiny *relative* movements of their mirrors caused by gravitational waves.

- Current sensitivity ~ $10^{-18}$ meters (1000 times smaller than the proton!), yet not sensitive enough (would probably detect waves coming from our entire Galaxy collapsing...)

# LISA - Laser Interferometer Space Antenna

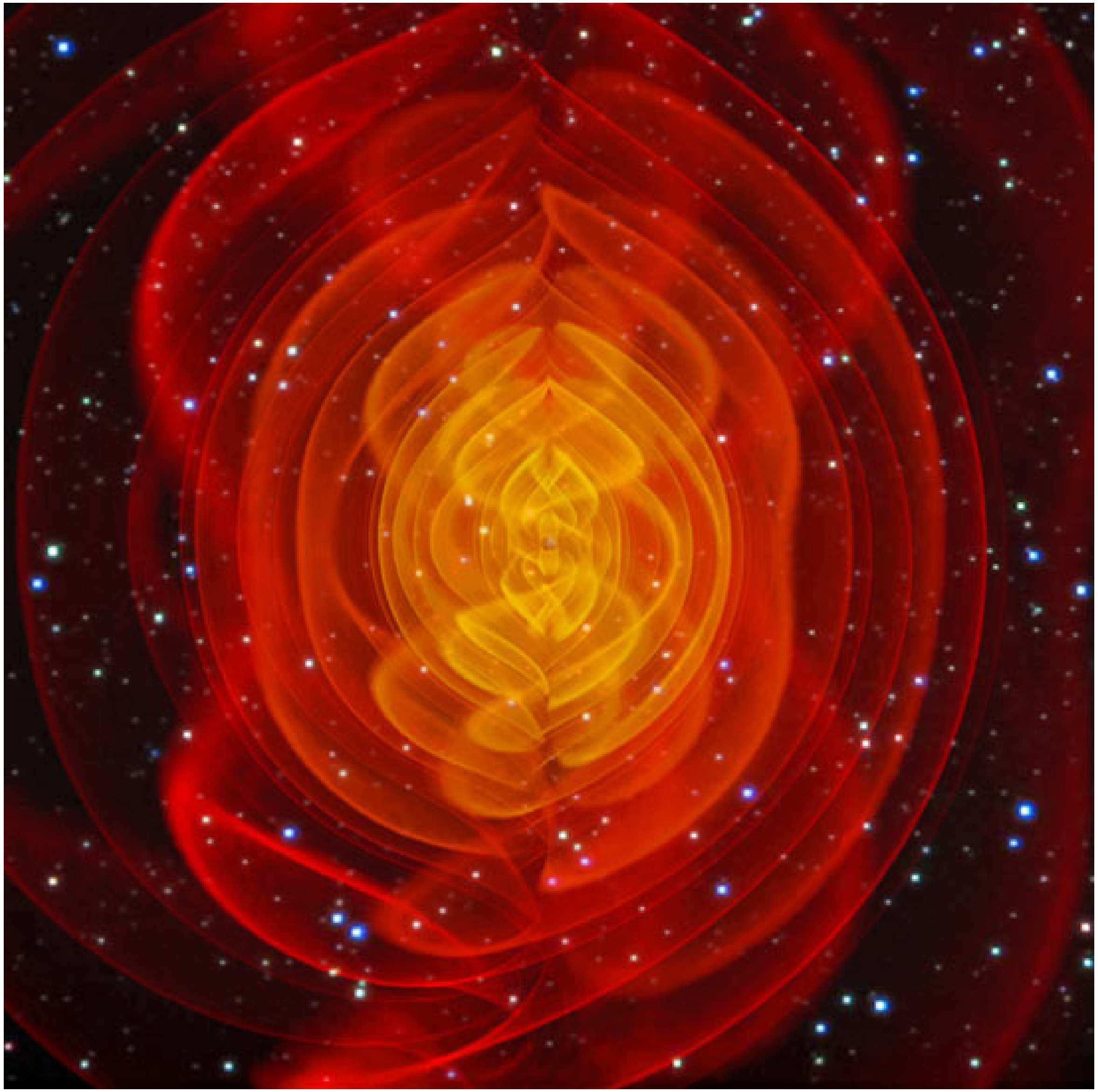
- Three satellites flying 5 million kilometers apart, with laser beams “connecting” them.
- May be launched in 2012.
- Would have sensitivity 1,000,000 times better than LIGO

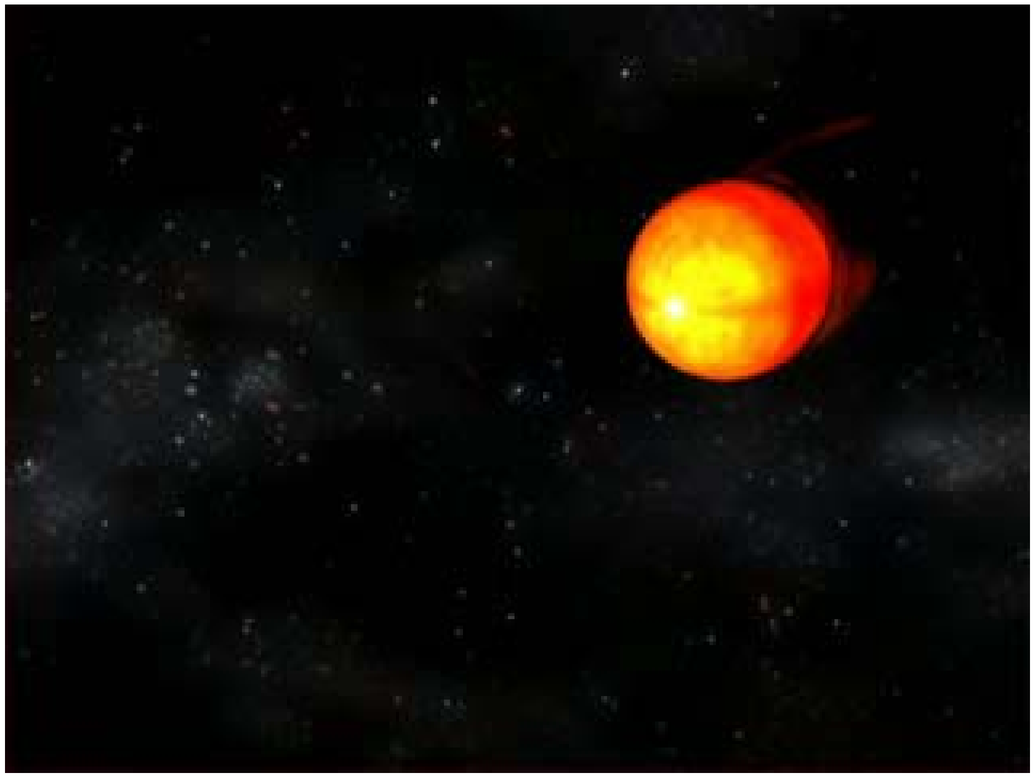


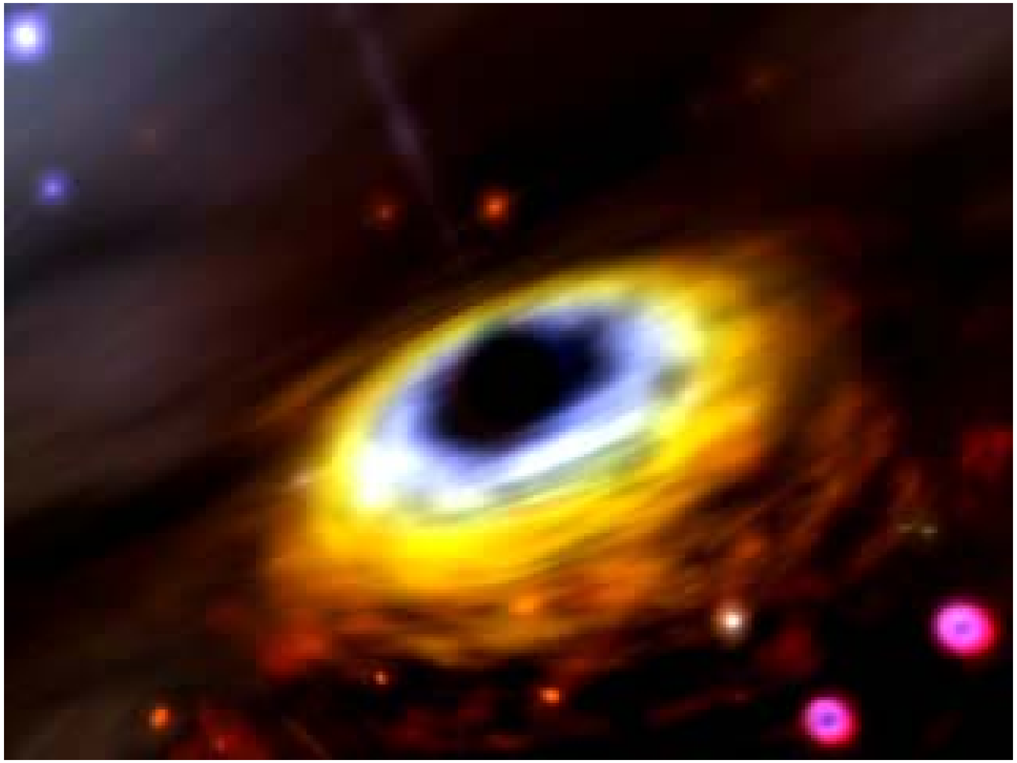
# Gravitational waves

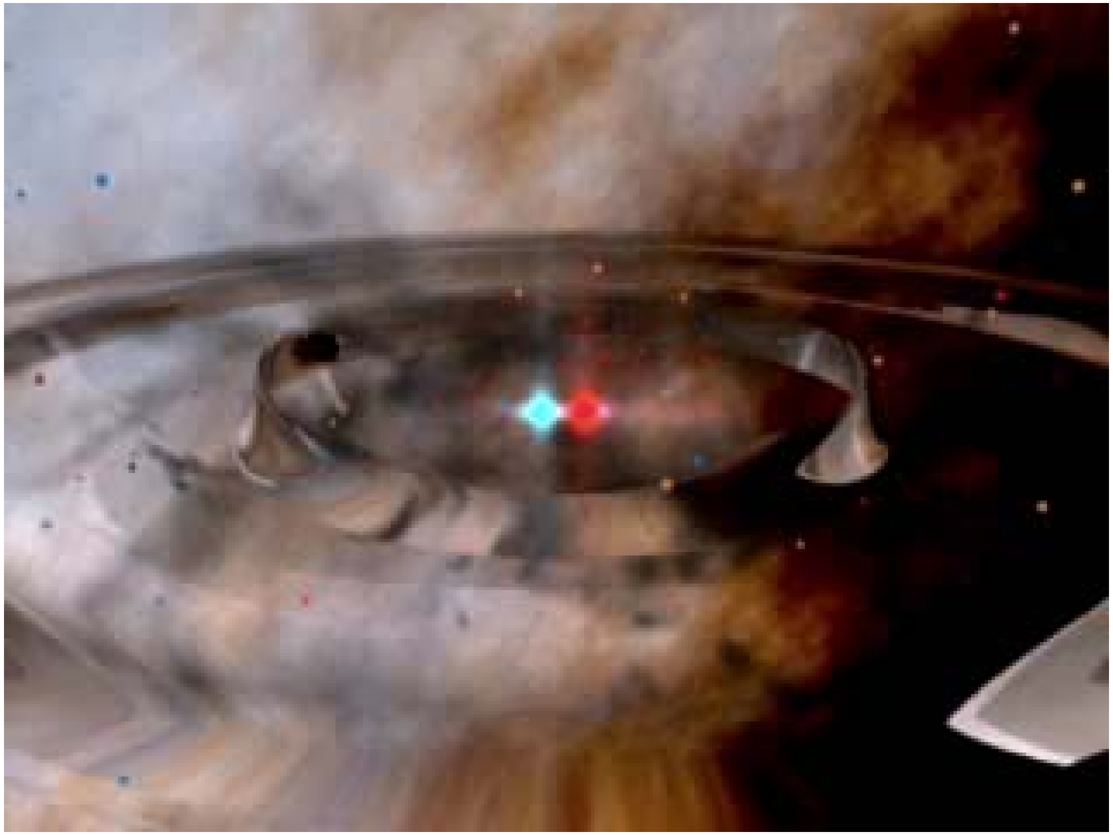
Numerical Relativity can now predict the characteristic signals sent by the merging black holes

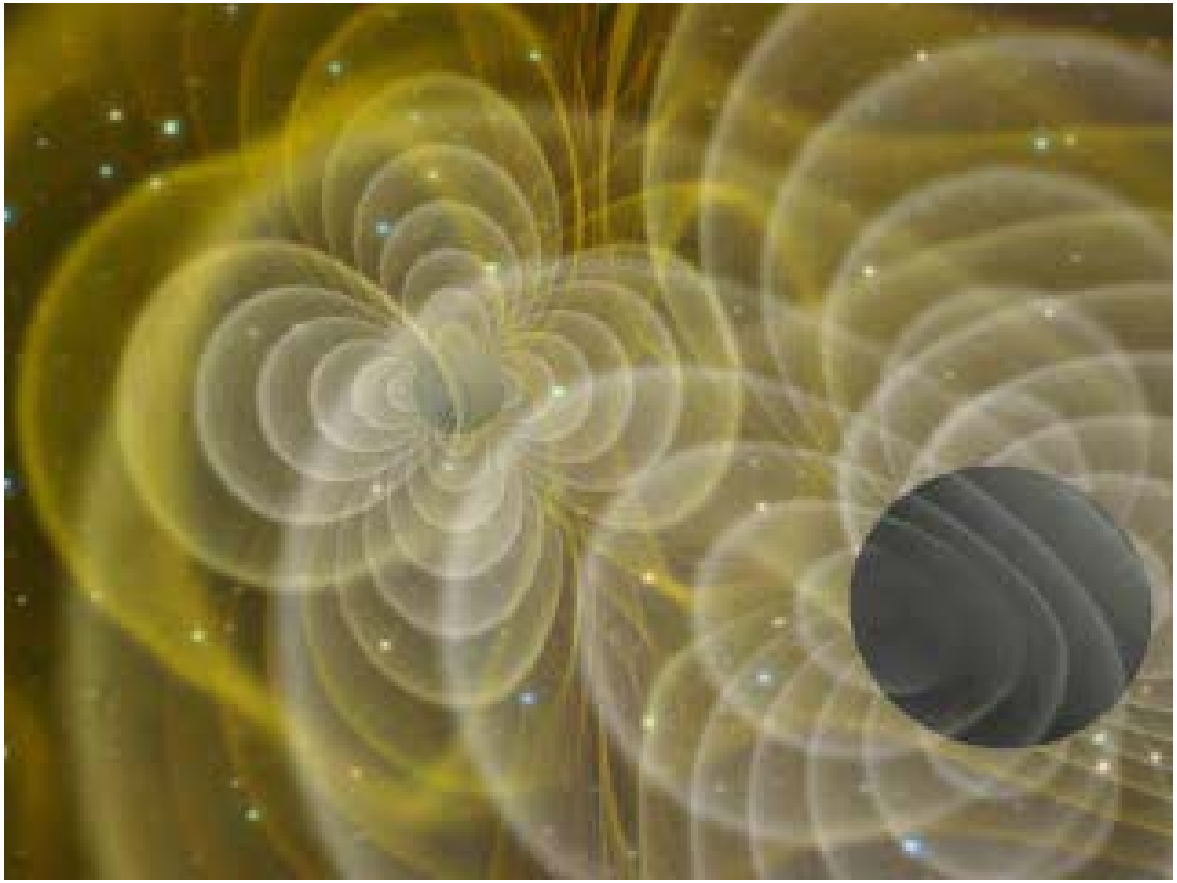
Detection of these signals – the gravitational waves – will improve and expand our understanding of the Universe.



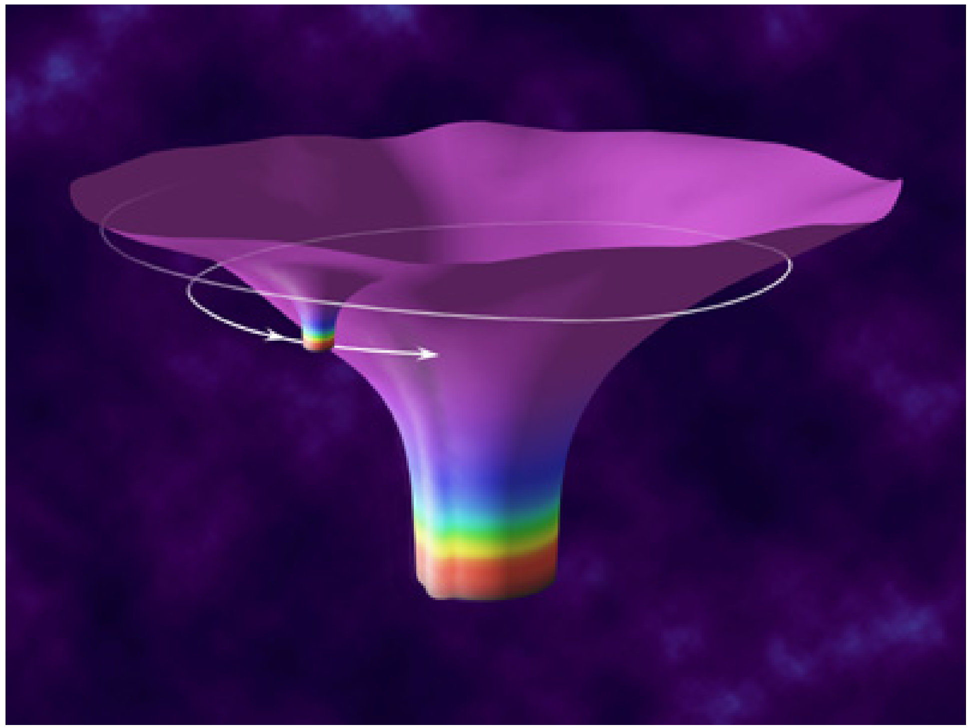








# Gravitational waves emitted by a small black hole falling onto a supermassive black hole



# BIG open questions in relativity and cosmology

- What happened before the Big Bang?
- How many dimensions of space (and time?) are there?
- What is the topology of space? (remember the balloon?)
- “Big Crunch”, “Big Rip” or …?
- What is the nature of the “Dark Energy?”
- Do “naked singularities” (i.e. singularities without the event horizon) exist?
- … and many more…