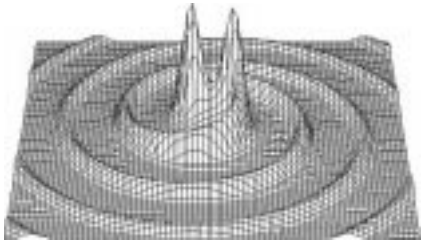

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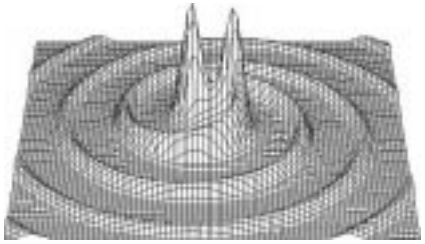
Einstein's Unfinished Symphony:

"Listening"

Barry C. Barish

LIGO-G000173-00-M



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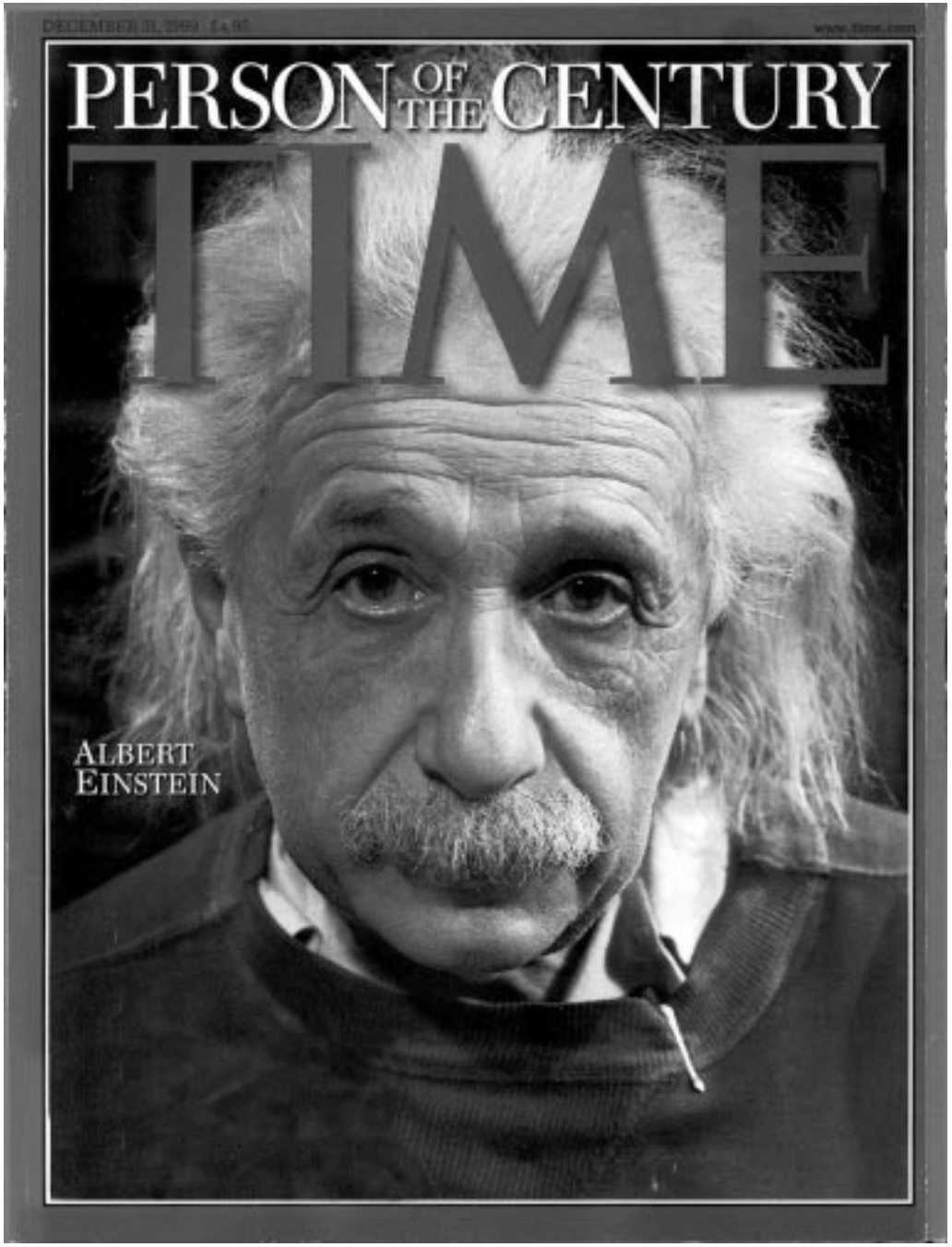
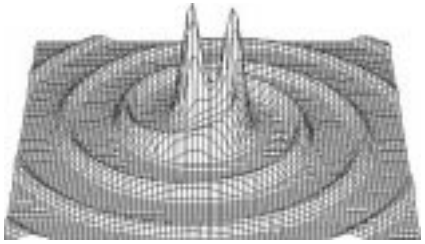
Albert Einstein





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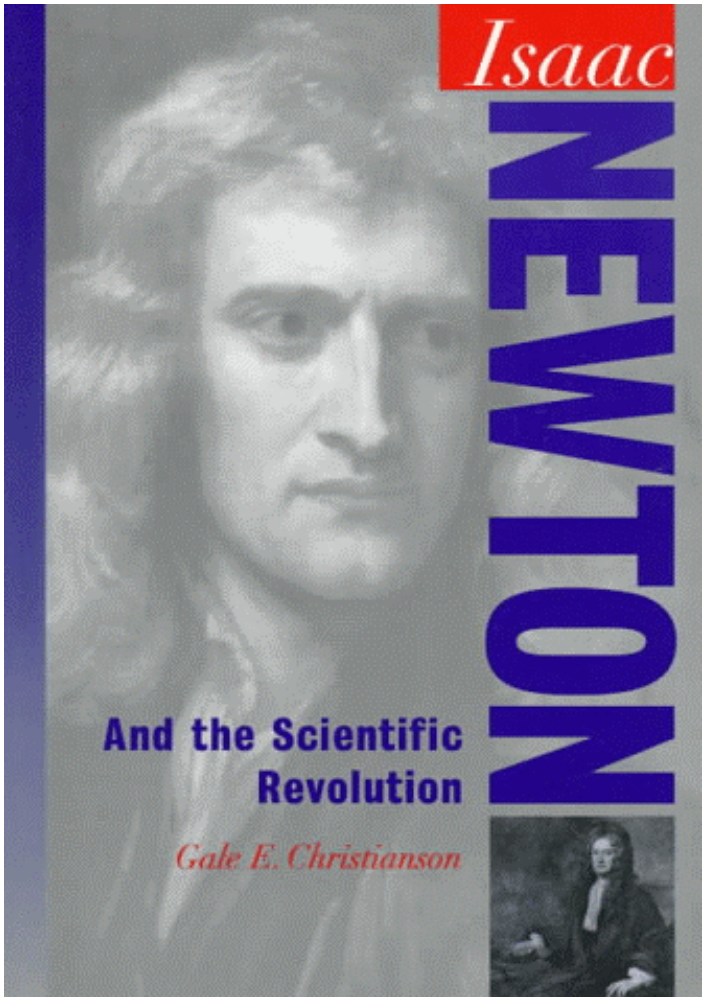
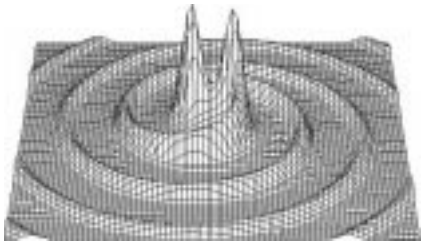
Sir Isaac Newton



- **Perhaps the most important scientist of all time!**
- **Invented the scientific method in *Principia***
- **Greatest scientific achievement: *universal gravitation***



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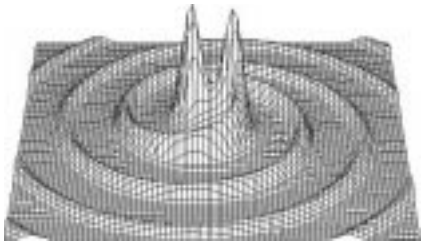
Scientific Method

Principia

- We are to admit no more causes of natural things such as are both true and sufficient to explain their appearances
- the same natural effects must be assigned to the same causes
- qualities of bodies are to be esteemed as universal
- propositions deduced from observation of phenomena should be viewed as accurate until other phenomena contradict them.



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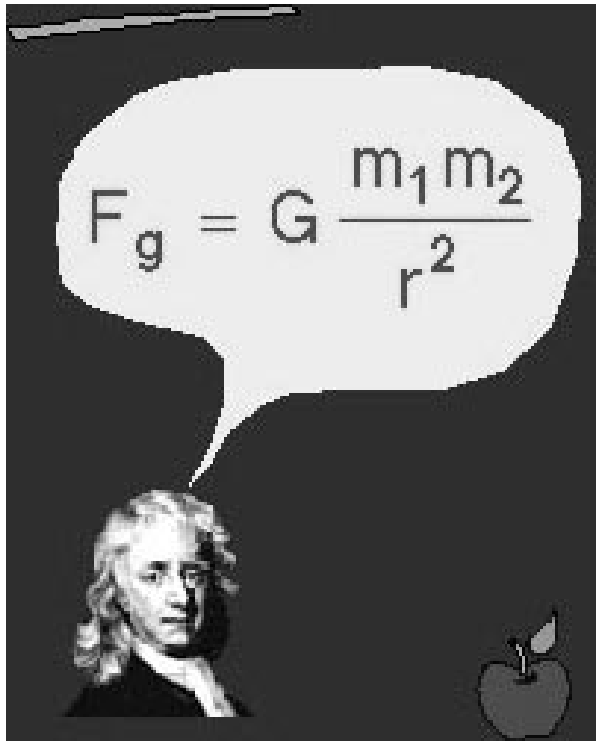
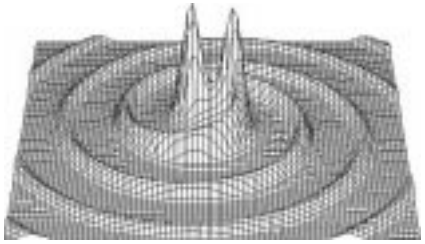
Newton
Universal Gravitation

- Three laws of motion and law of gravitation (centripetal force) disparate phenomena
  - » eccentric orbits of comets
  - » cause of tides and their variations
  - » the precession of the earth's axis
  - » the perturbation of the motion of the moon by gravity of the sun
- Solved most known problems of astronomy and terrestrial physics
  - » Work of Galileo, Copernicus and Kepler unified.





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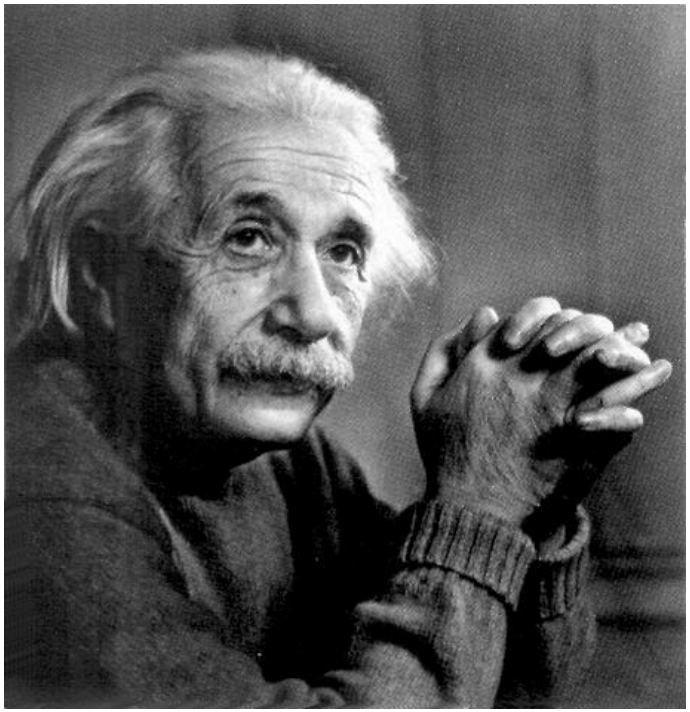
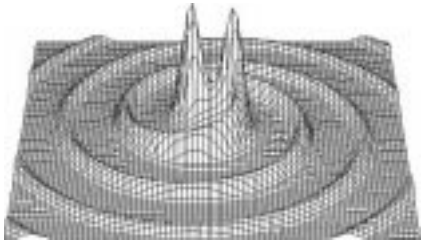
Albert Einstein



- The Special Theory of Relativity (1905) overthrew commonsense assumptions about space and time. Relative to an observer, near the speed of light, both are altered
  - » distances appear to stretch
  - » clocks tick more slowly
- The General Theory of Relativity and theory of Gravity (1916)



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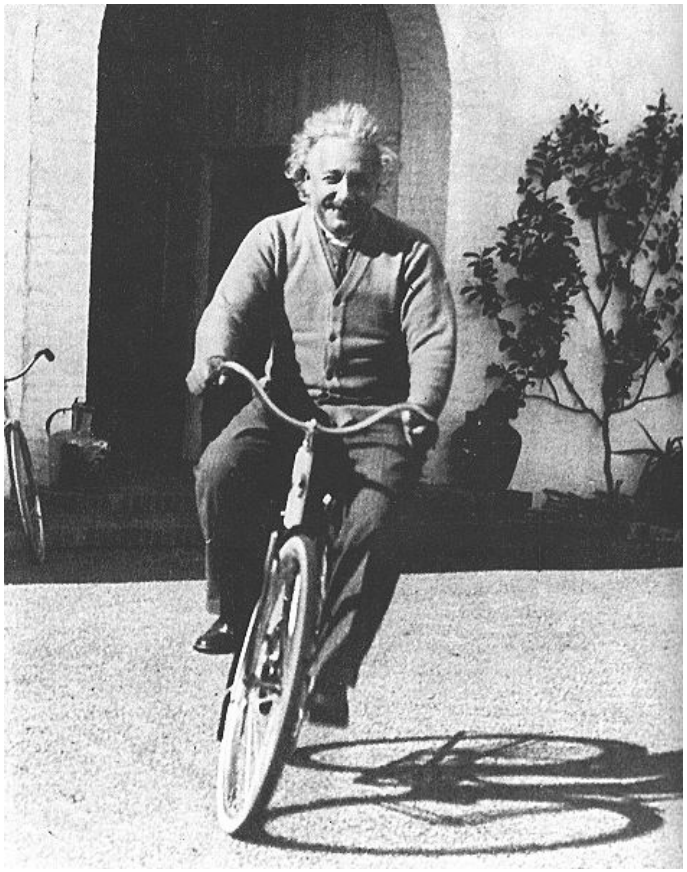
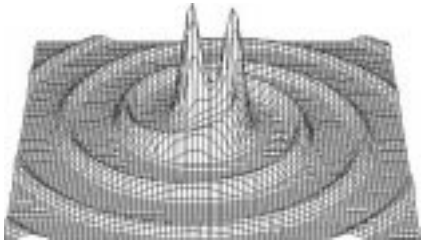
Einstein's *Spacetime Wrinkles*

- Discards concept of absolute motion; instead treats only relative motion between systems
- space and time no longer viewed as separate; rather as four dimensional space-time
- gravity described as a warpage of space-time, not a force acting at a distance





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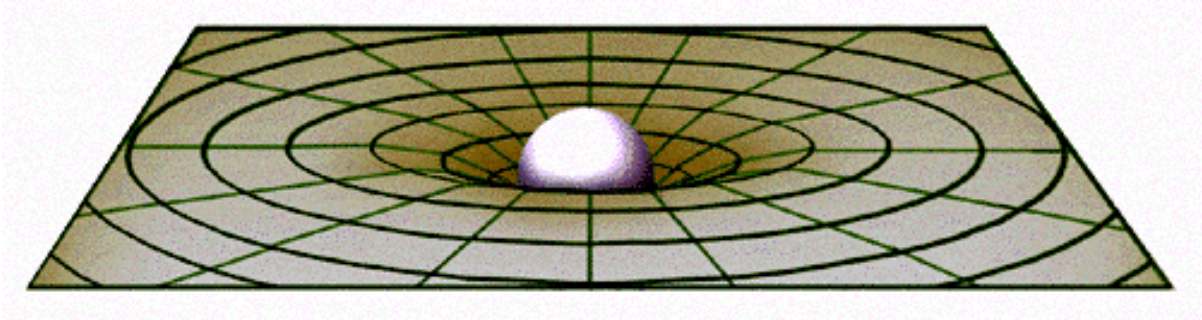
Einstein's
Warpage of Spacetime

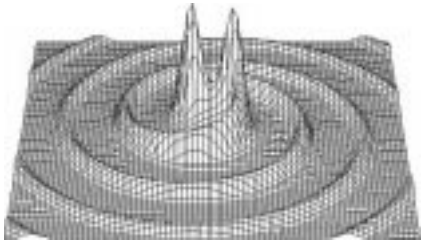
Imagine space as a stretched rubber sheet.

A mass on the surface will cause a deformation.

Another mass dropped onto the sheet will roll toward that mass.

Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object.





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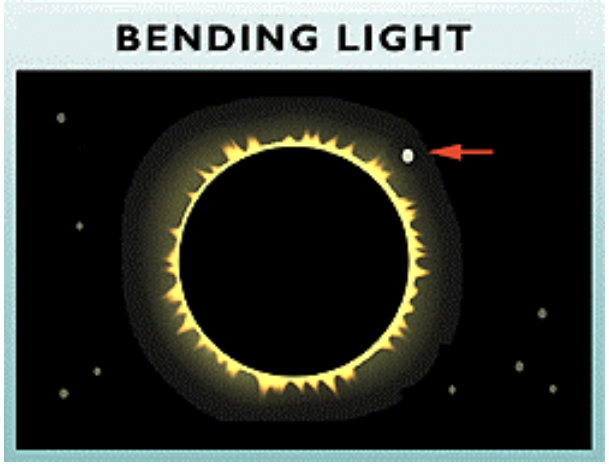
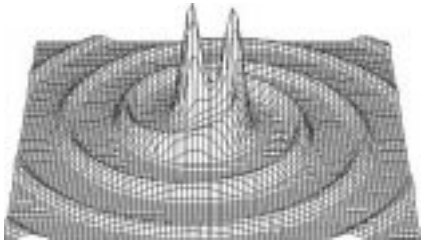


Predict the bending of light passing in the vicinity of the massive objects

First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

Their measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.

The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.



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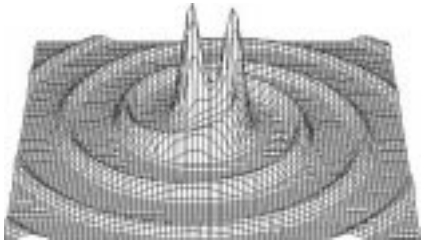
Einstein's Theory of Gravitation

experimental tests

"Einstein Cross"
The bending of light rays
gravitational lensing

Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

In modern astronomy, such gravitational lensing images are used to detect a 'dark matter' body as the central object



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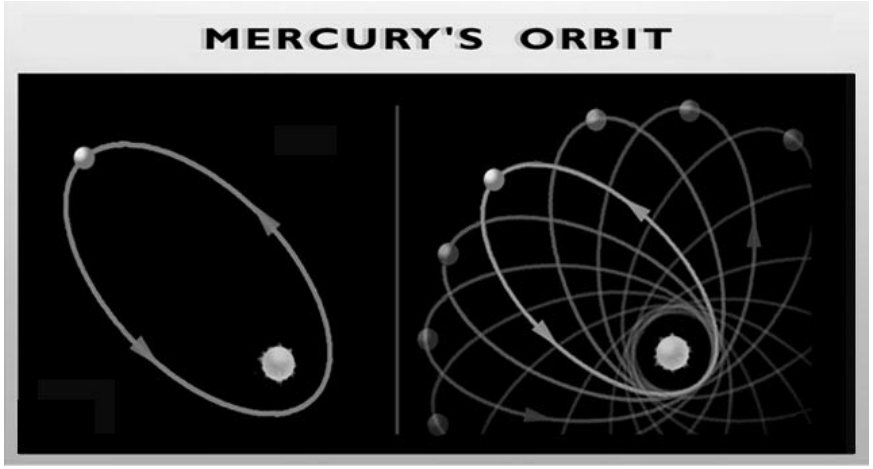
Einstein’s Theory of Gravitation

experimental tests



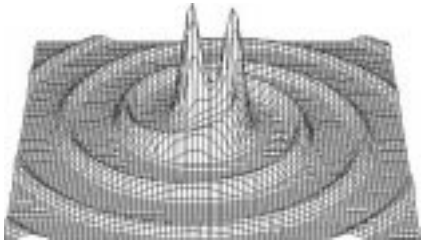
Mercury’s orbit

perihelion shifts forward twice Newton’s theory

Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

Astronomers had been aware for two centuries of a small flaw in the orbit, as predicted by Newton's laws.

Einstein's predictions exactly matched the observation.



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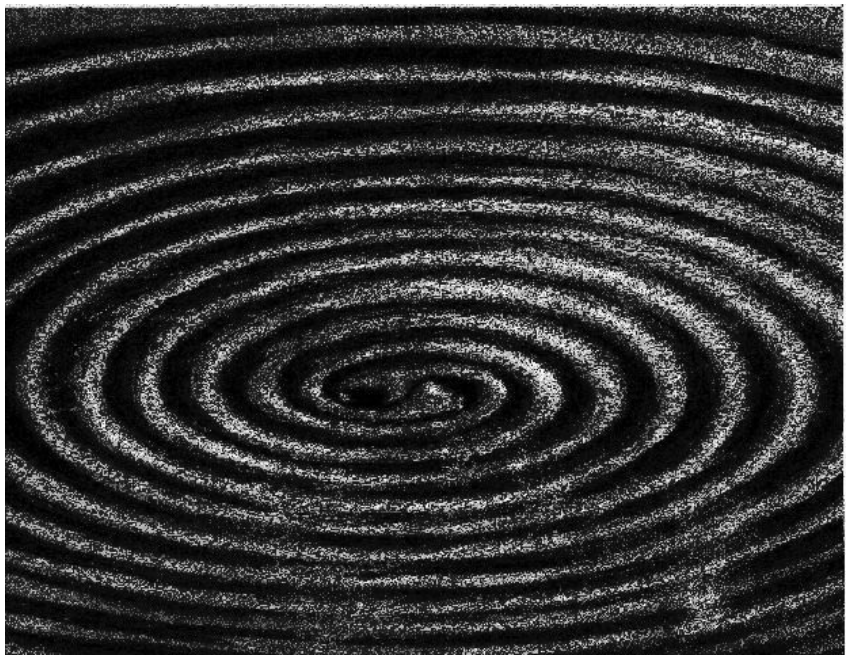
Einstein's Theory of Gravitation

experimental tests

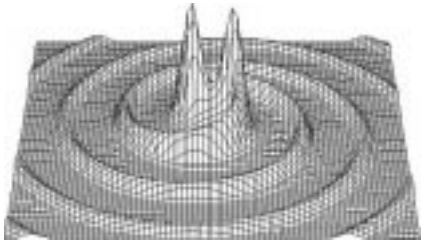
Newton's Theory

"instantaneous action at a distance"



Einstein's Theory

information carried by gravitational radiation at the speed of light



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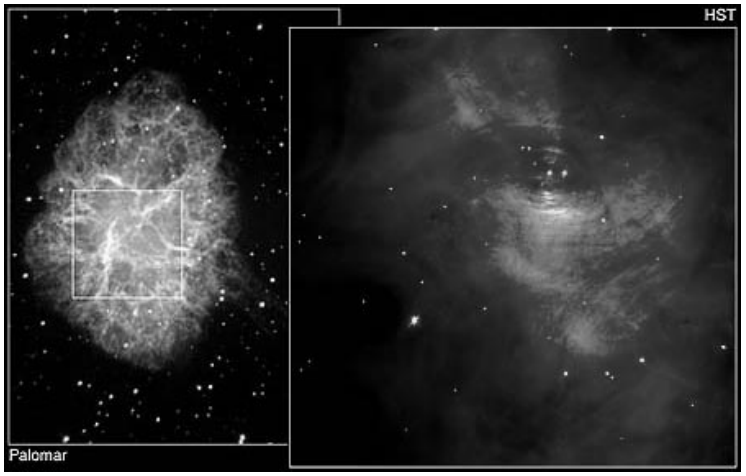
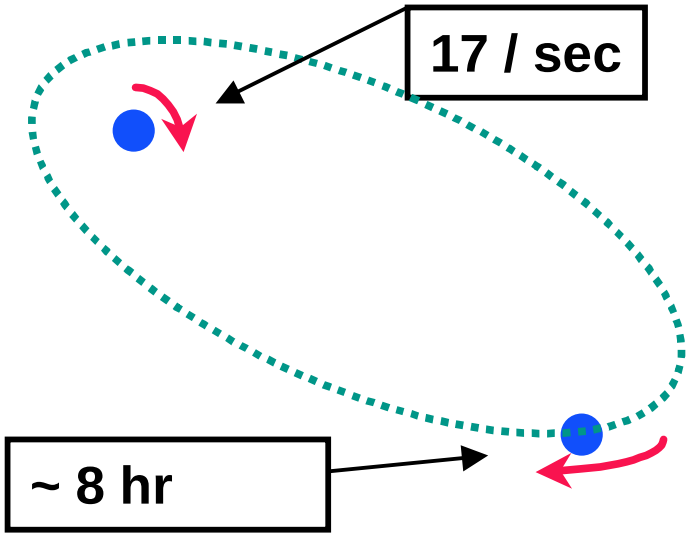
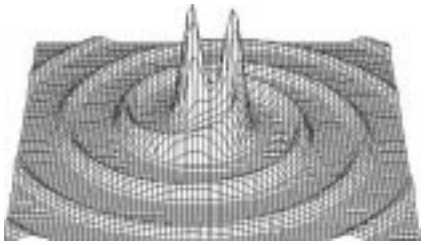
Gravitational Waves
the evidence



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars





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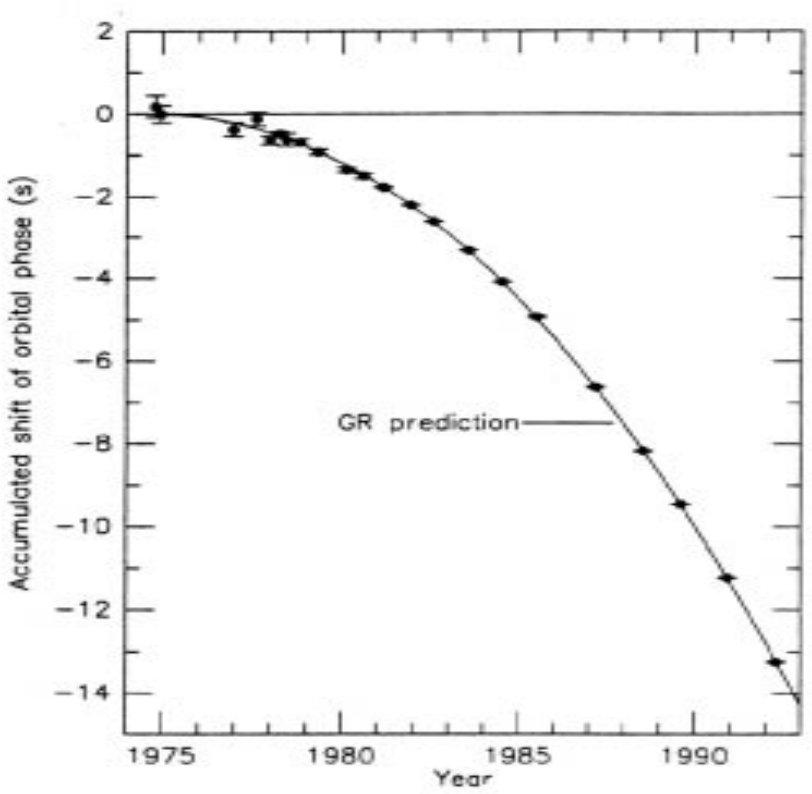
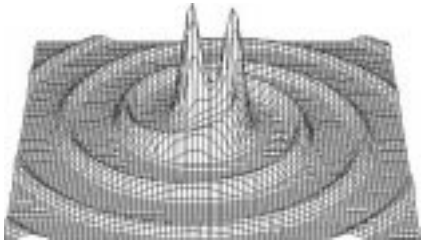
Hulse and Taylor
results

emission of gravitational waves

- due to loss of orbital energy
- period speeds up 14 sec from 1975-94
- measured to ~50 msec accuracy
- deviation grows quadratically with time





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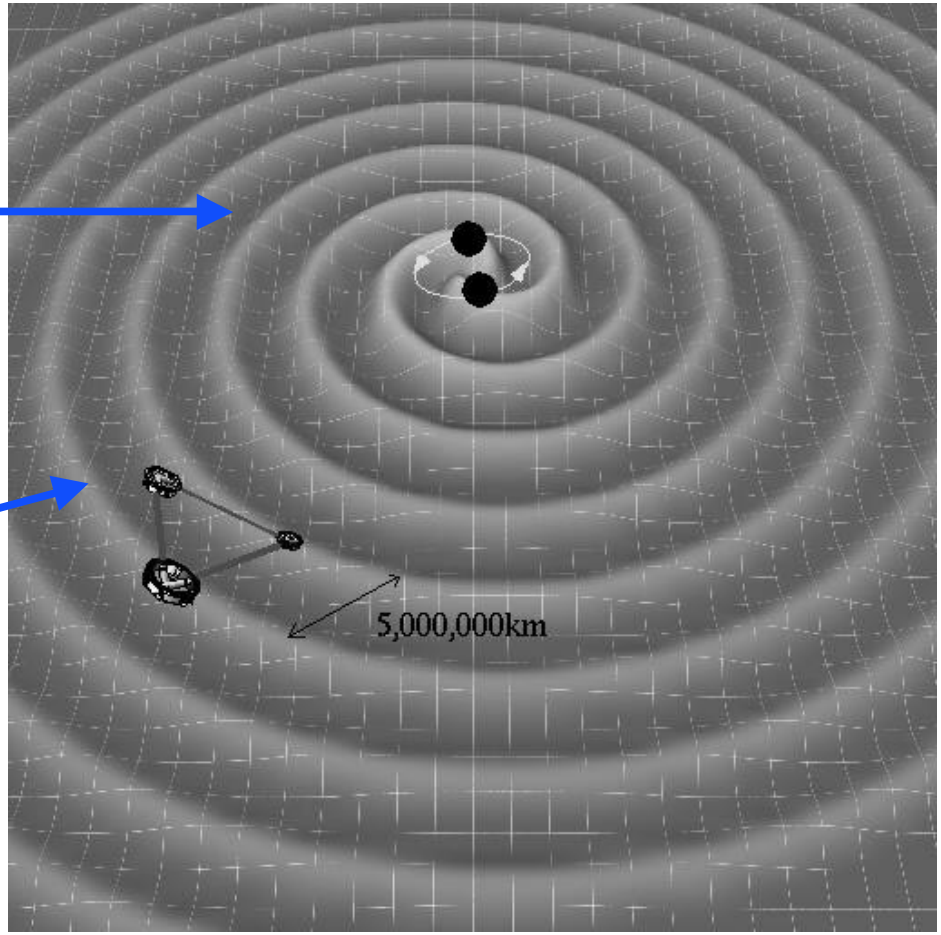
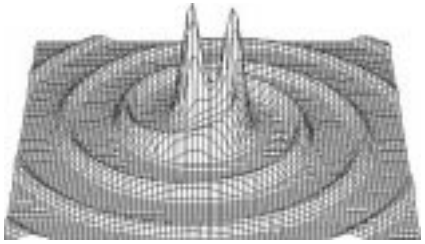
Einstein
Sounds from the Universe

Radiation of Gravitational Waves from binary inspiral system

LISA





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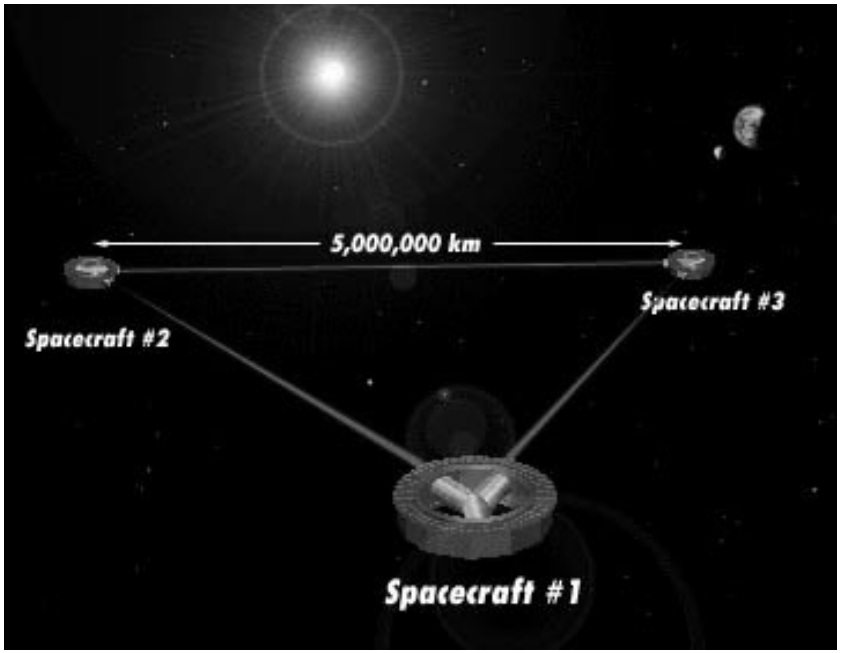
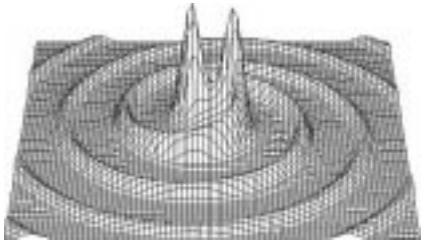
Interferometers

space

The Laser Interferometer Space Antenna (LISA)



The center of the triangle formation will be in the ecliptic plane
1 AU from the Sun and 20 degrees behind the Earth.



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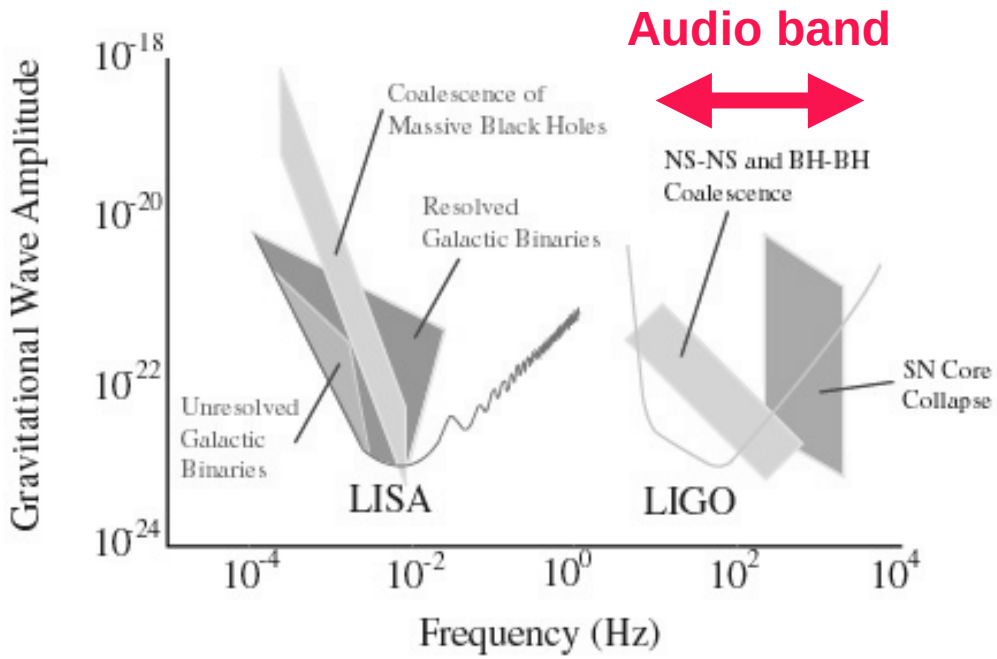
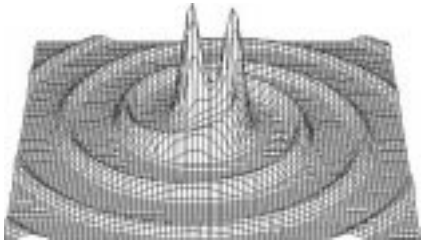
Astrophysics Sources
frequency range

- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ rays)**
- **Gravitational Waves over ~10 orders of magnitude**
  - » **(terrestrial + space)**





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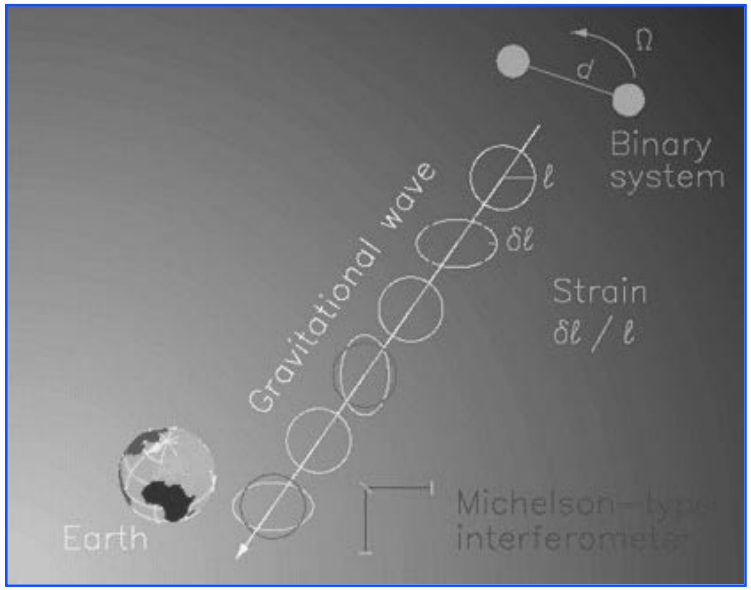
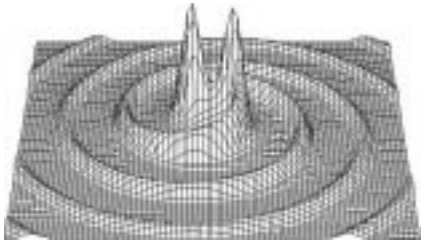
Interferometers
terrestrial

Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.





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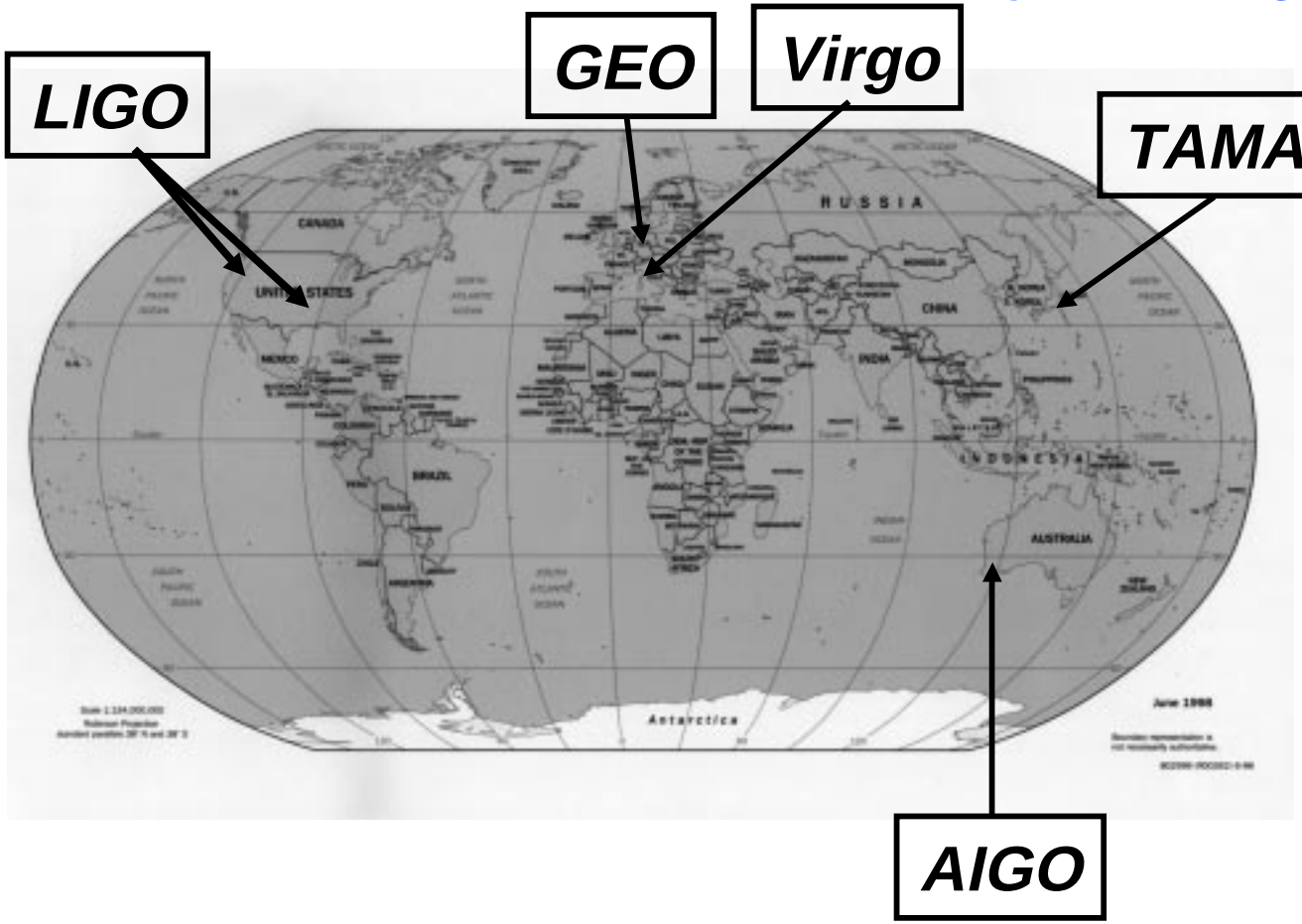
International Network

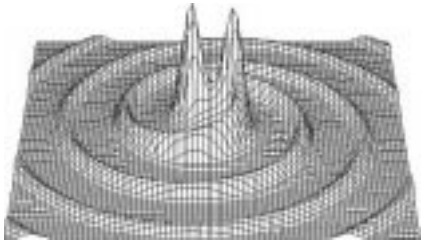
Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves



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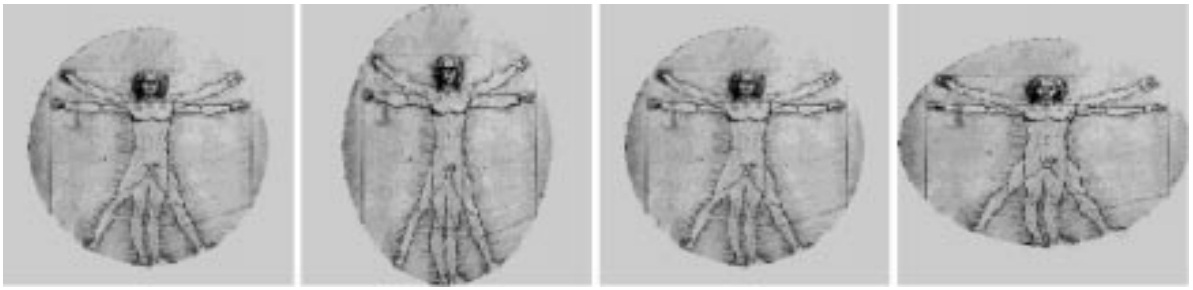
Gravitational Waves
the effect

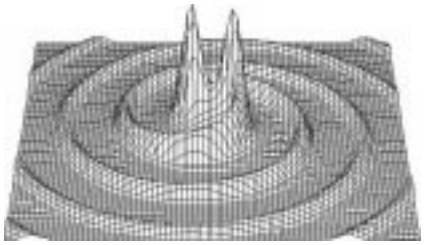
Leonardo da Vinci's Vitruvian man



- **stretch and squash in perpendicular directions at the frequency of the gravitational waves**

The effect is greatly exaggerated!!

If the man was 4.5 light years high, he would grow by only a 'hairs width'
LIGO (4 km), stretch (squash) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz. It can detect waves from a distance of 600 10^6 light years



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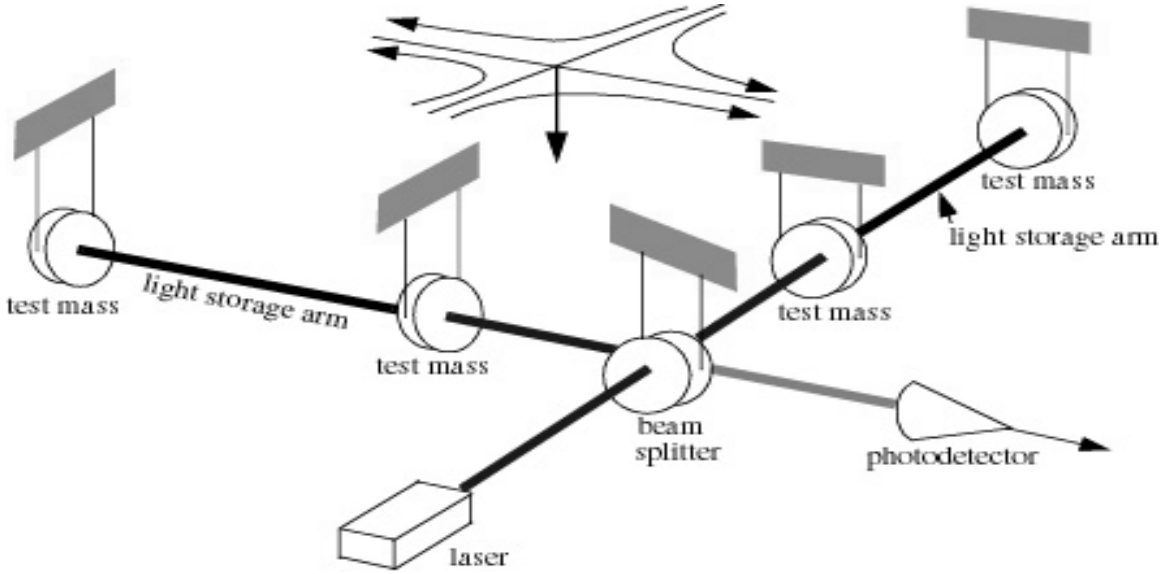
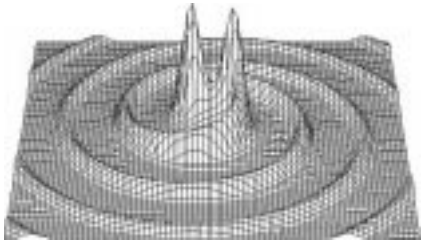


Detector
concept

- **The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.**
- **The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.**
- **The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.**



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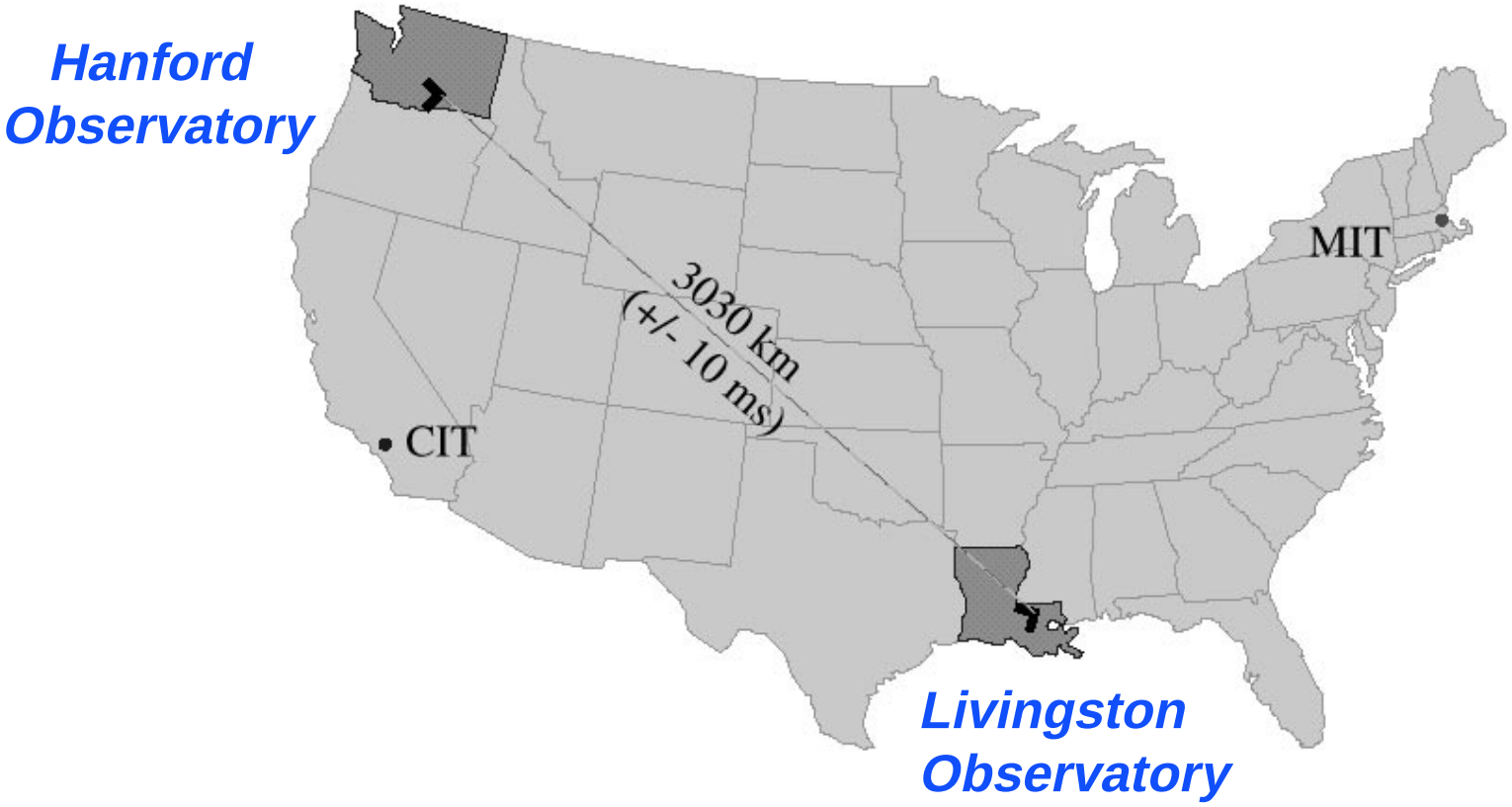
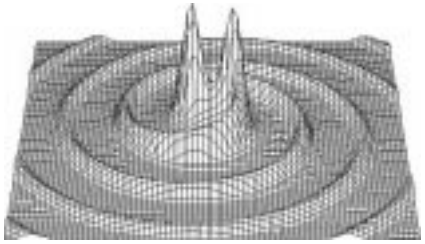
LIGO
sites





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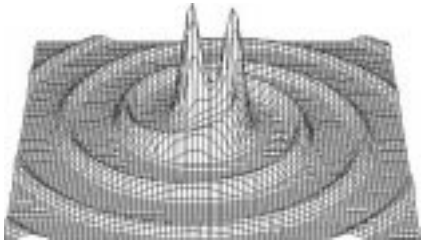
LIGO
Livingston



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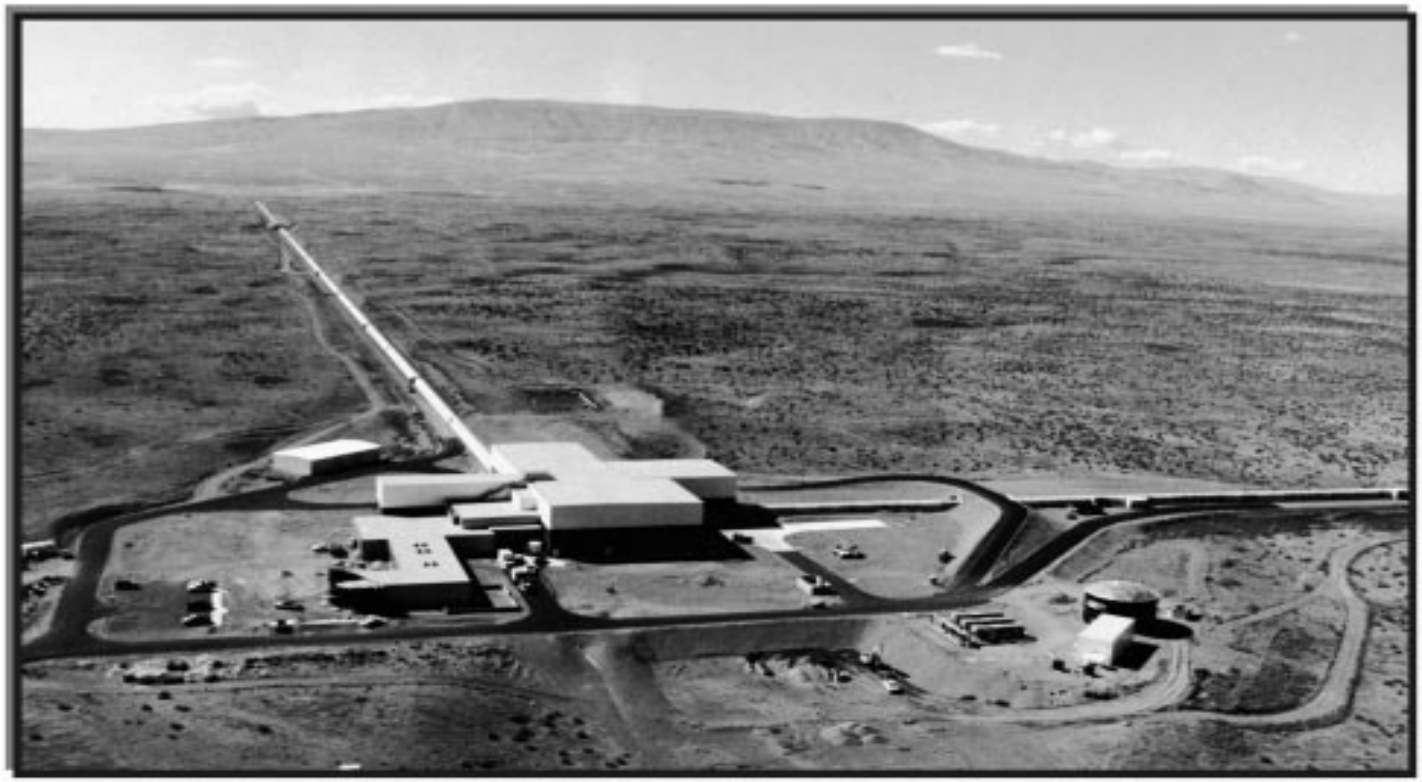
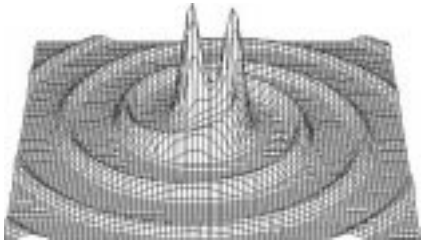
LIGO

Hanford





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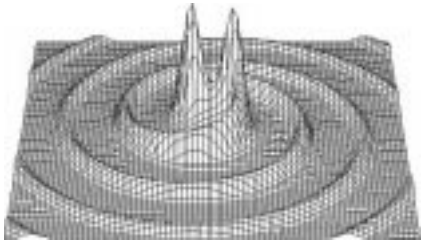
LIGO
Beam Tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field



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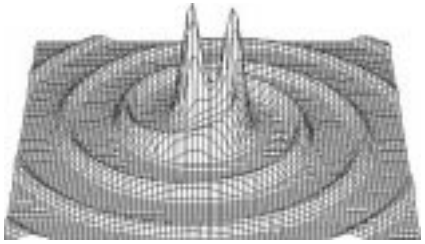
LIGO
Vacuum Systems



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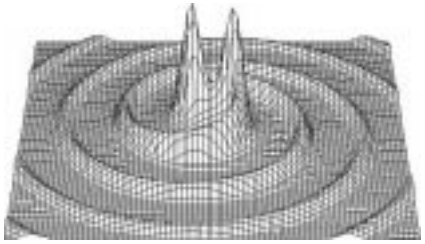
LIGO
Optics

- **Optics polished & coated**
  - » **Microroughness within spec. (<10 ppm scatter)**
  - » **ROC within spec. ($\delta R/R < 5\%$, except for BS)**
  - » **Coating defects within spec. (pt. defects < 2 ppm, 10 optics tested)**
  - » **Coating absorption within spec. (<1 ppm, 40 optics tested)**
- **Optics polished at CSIRO in Australia**



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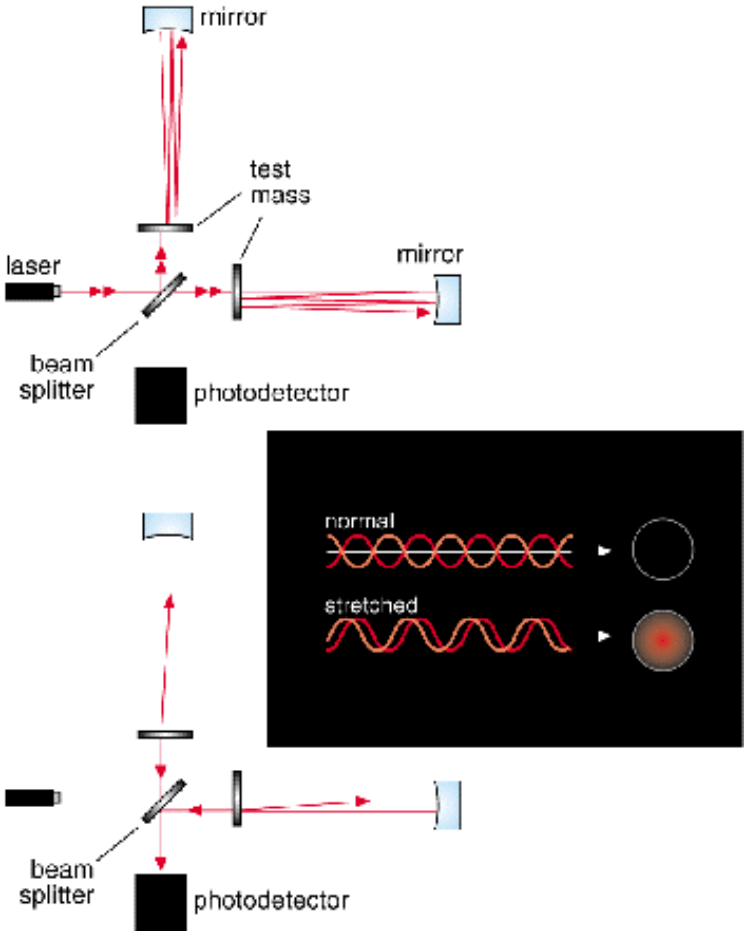
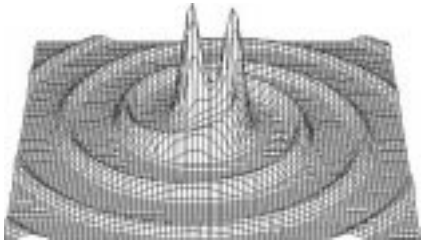
LIGO
the signals



The effects of gravitational waves appear as a fluctuation in the phase differences between two orthogonal light paths of an interferometer.



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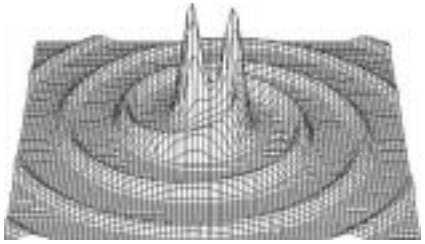
Einstein
Symphony

- **LIGO will soon ‘listen’ for Einstein’s Unfinished Symphony with gravitational waves**
- **Basic tests of General Relativity will be possible (eg. Black holes)**



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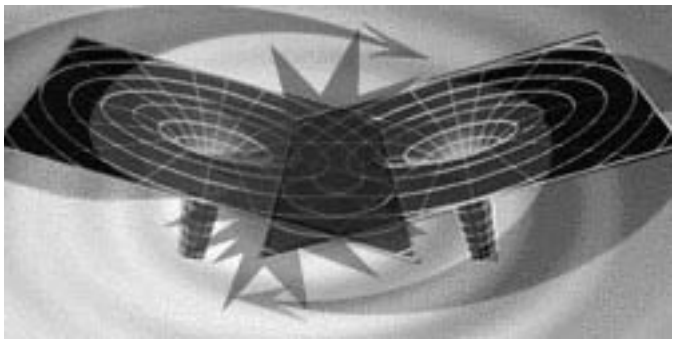
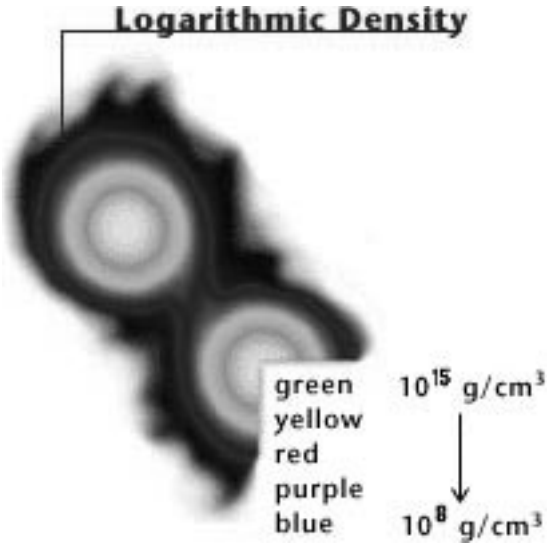
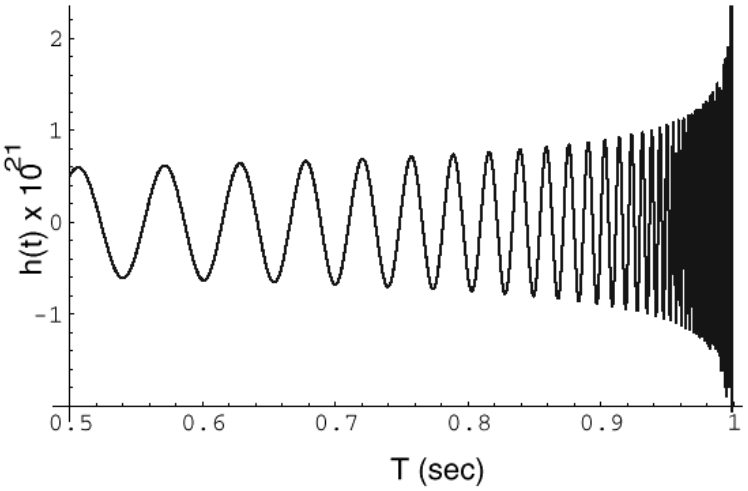
Sources of Gravitational Waves

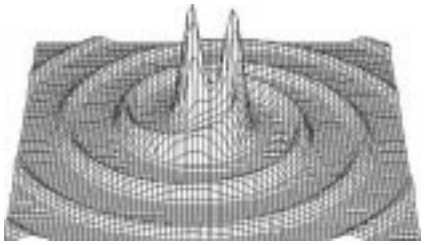
Inspiral of Neutron Stars





"Chirp Signal"





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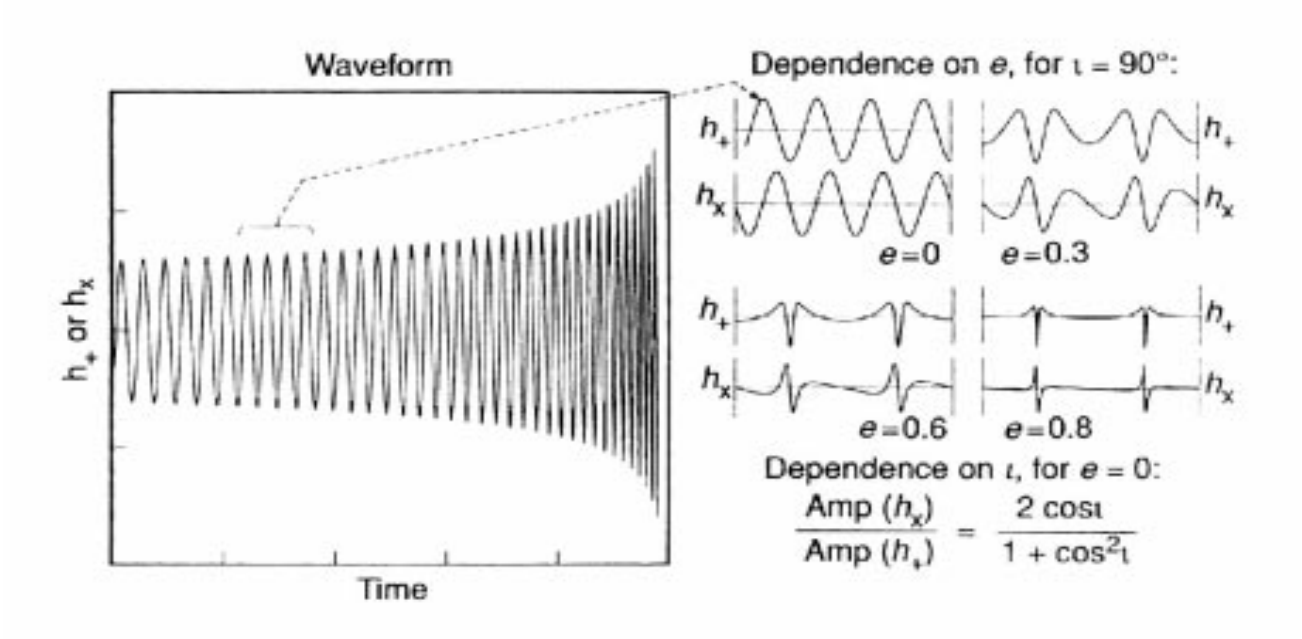
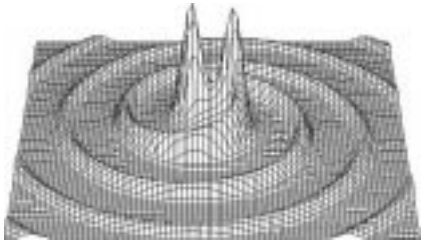
Chirp Signal

binary inspiral



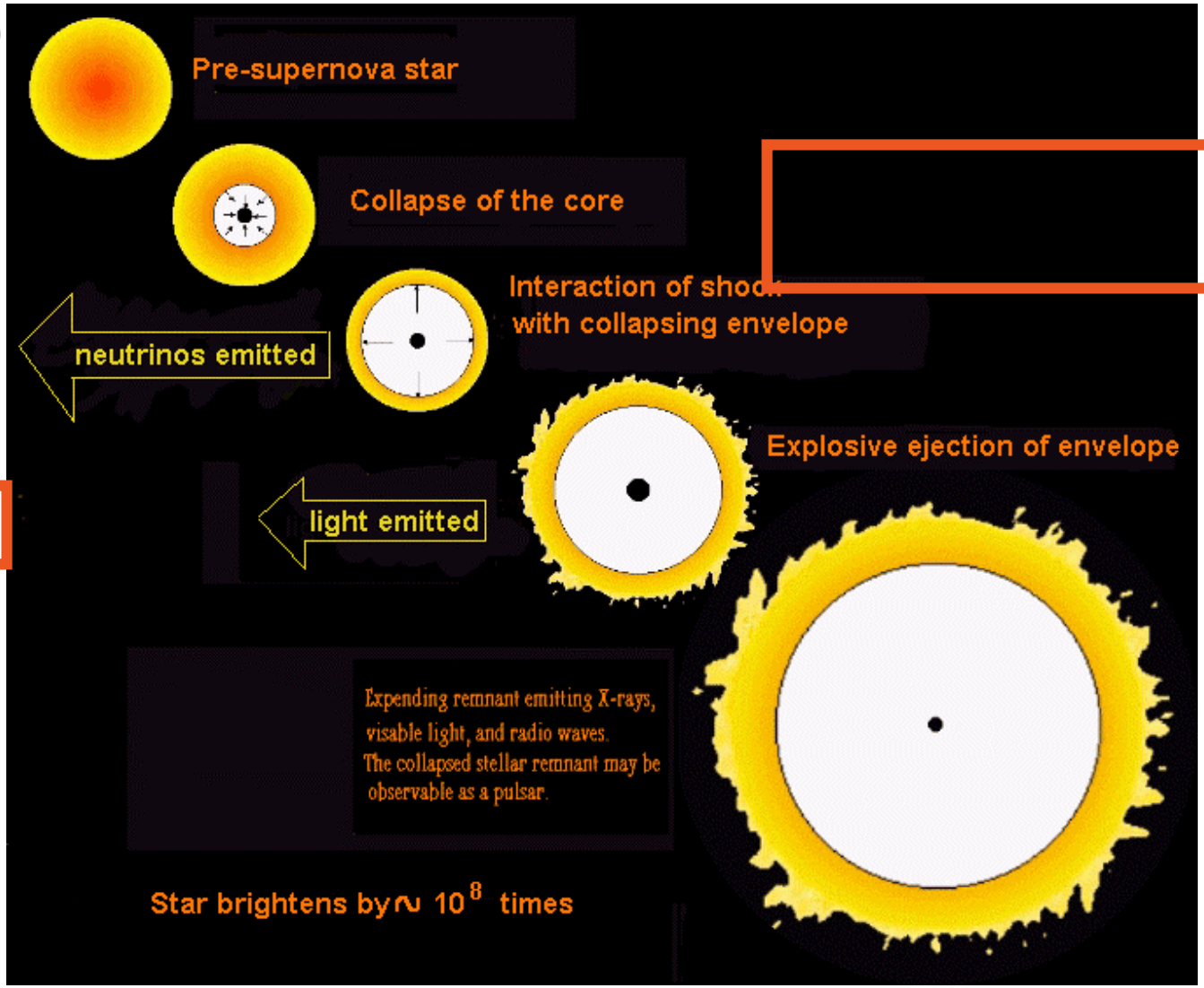
determine

- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination *i*



Supernova

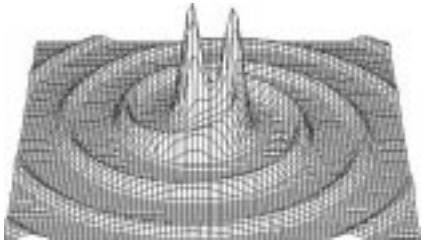
The 2000



gravitational waves

ν's

light



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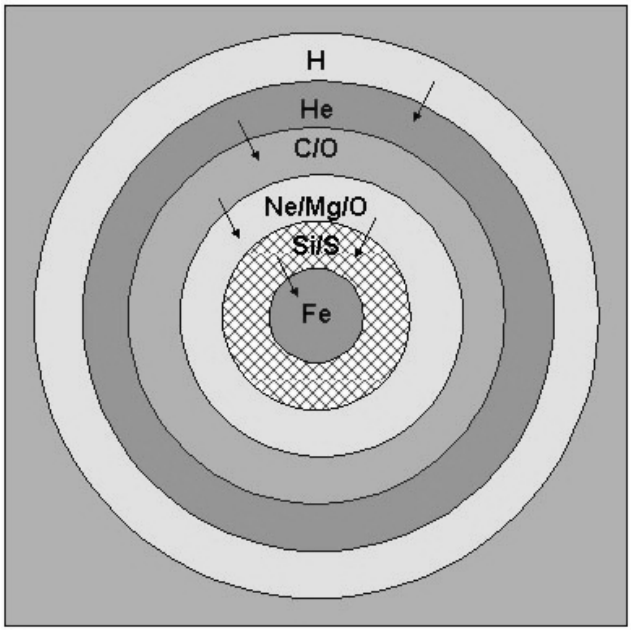
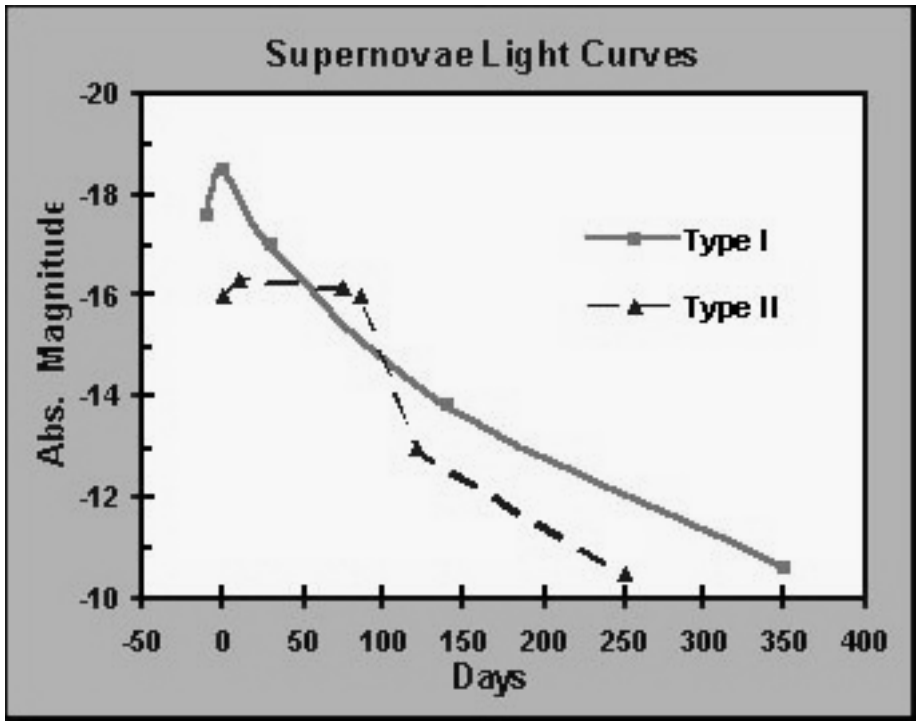
Sources of Gravitational Waves

Supernovae

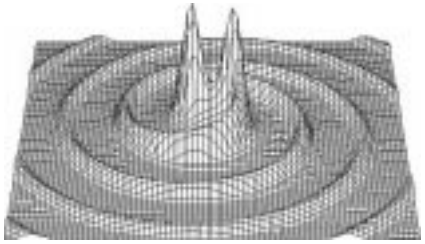
gravitational stellar collapse



The Collapse



Optical Light Curve



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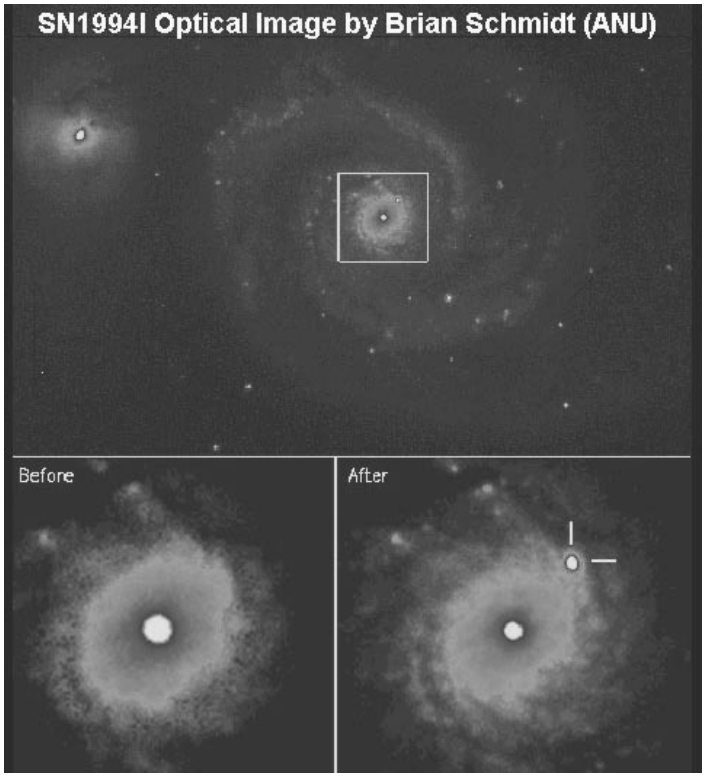
Sources of Gravitational Waves

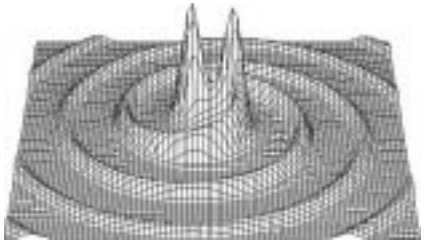
Supernovae

optical observations

Crab Nebula 1054 AD



Supernovae - SN1994I



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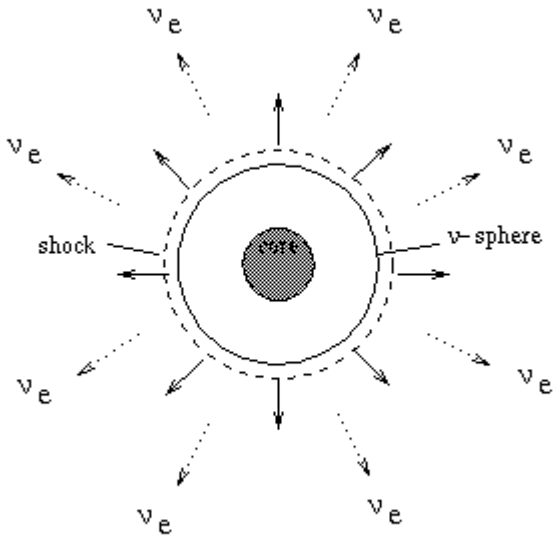
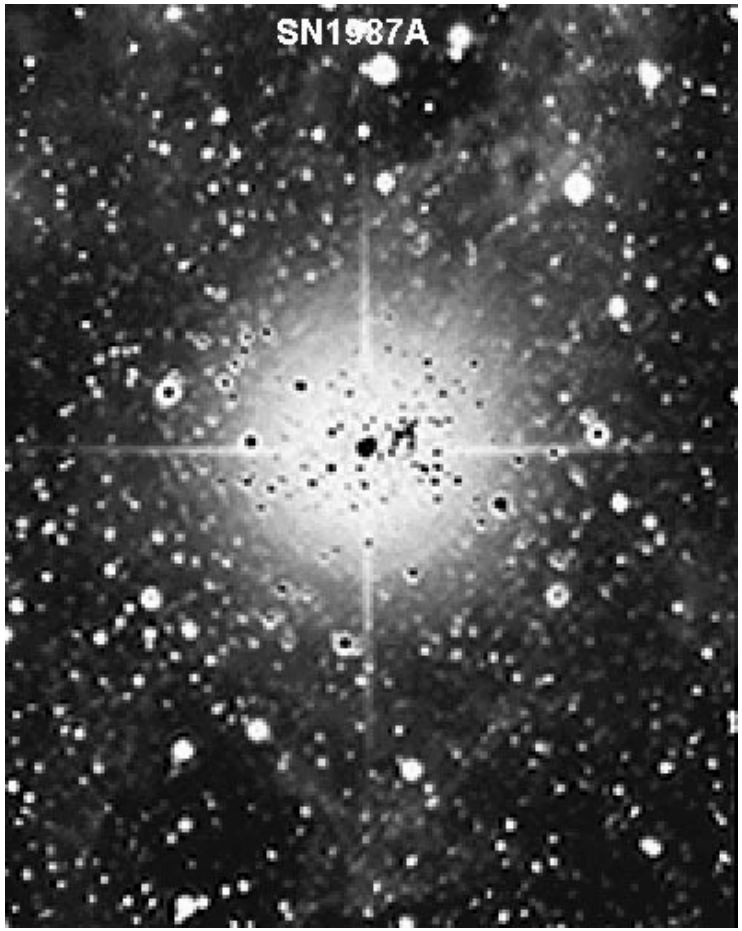
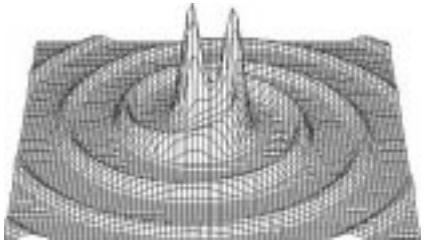
Supernovae

Neutrinos from SN1987A







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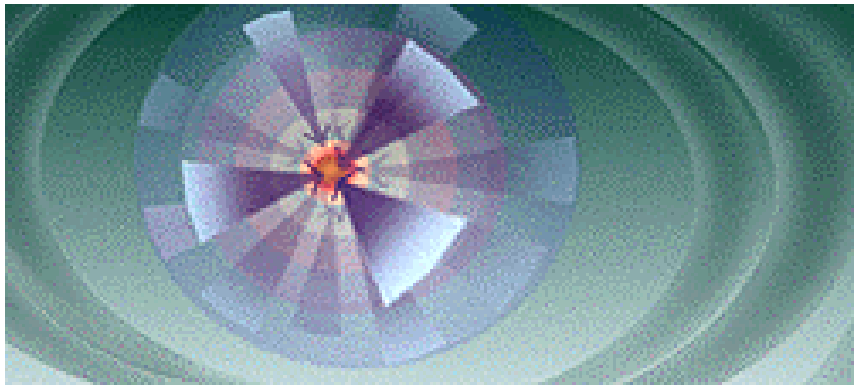
Supernovae
Gravitational Waves

Non axisymmetric collapse

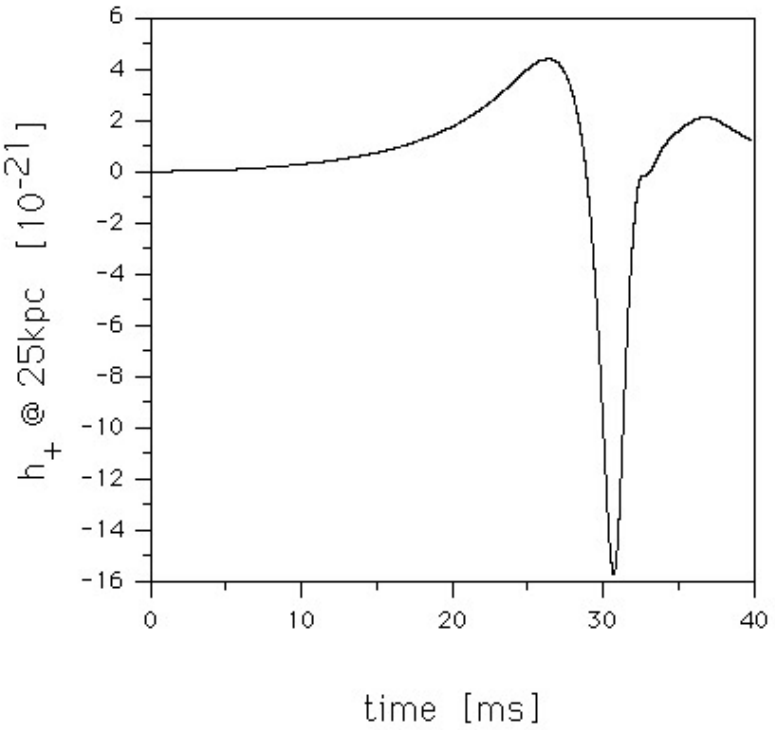


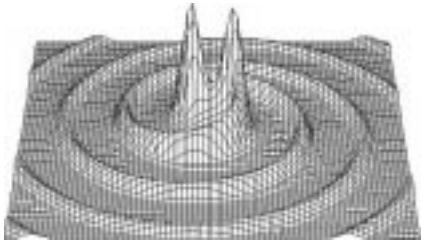
Rate

1/50 yr - our galaxy

3/yr - Virgo cluster

‘burst’ signal





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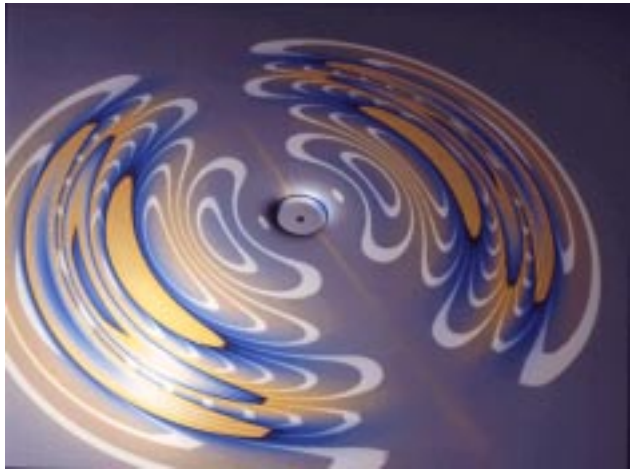
Black Holes

Computer simulations

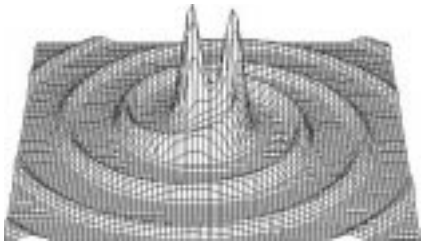
Testing General Relativity in the Strong Field Limit

Distortion of spacetime by a blackhole



Collision of two blackholes

“Grand Challenge” – Supercomputer Project



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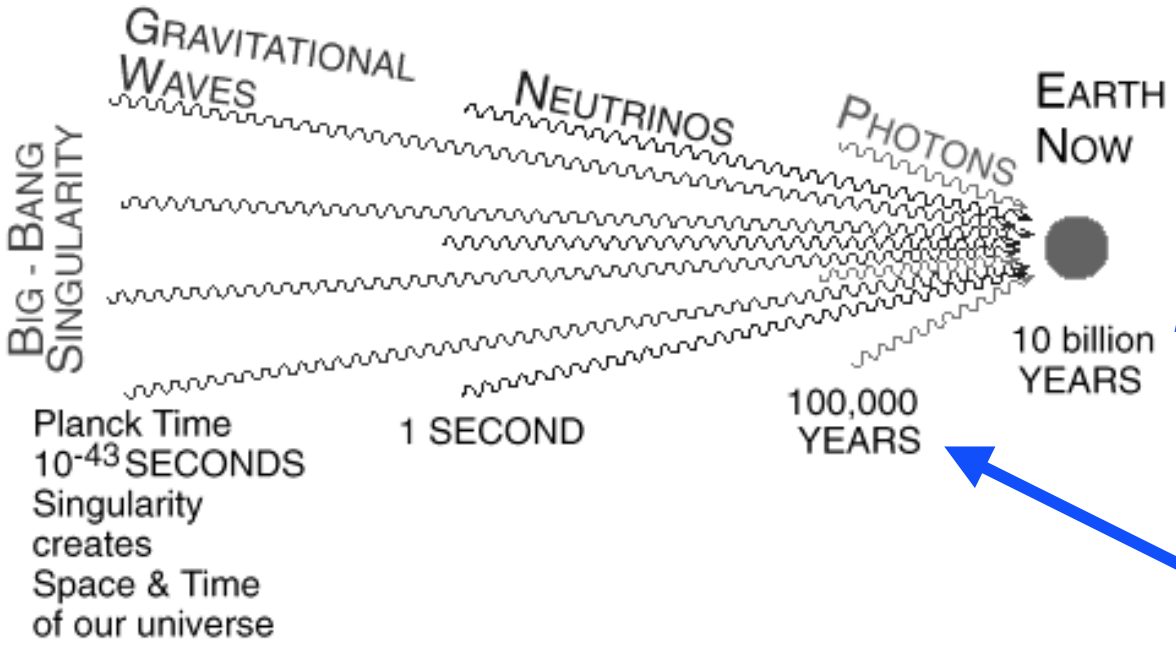
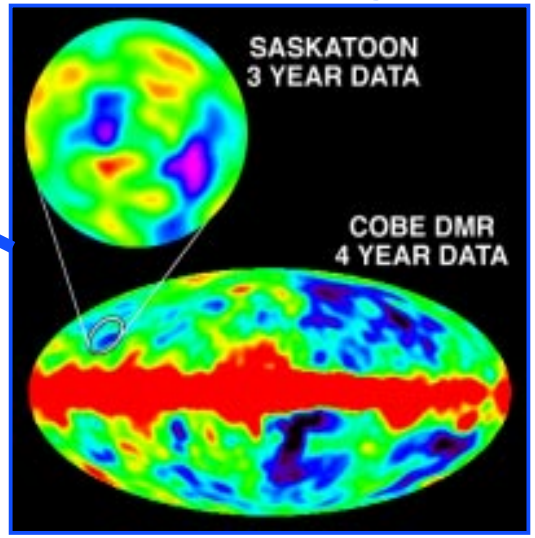
Sources of Gravitational Waves

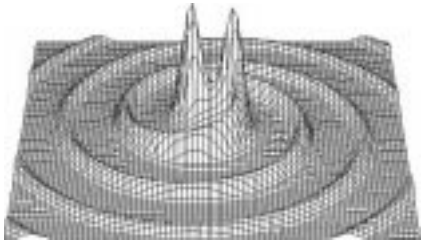
'Murmurs' from the Big Bang

signals from the early universe



Cosmic microwave background





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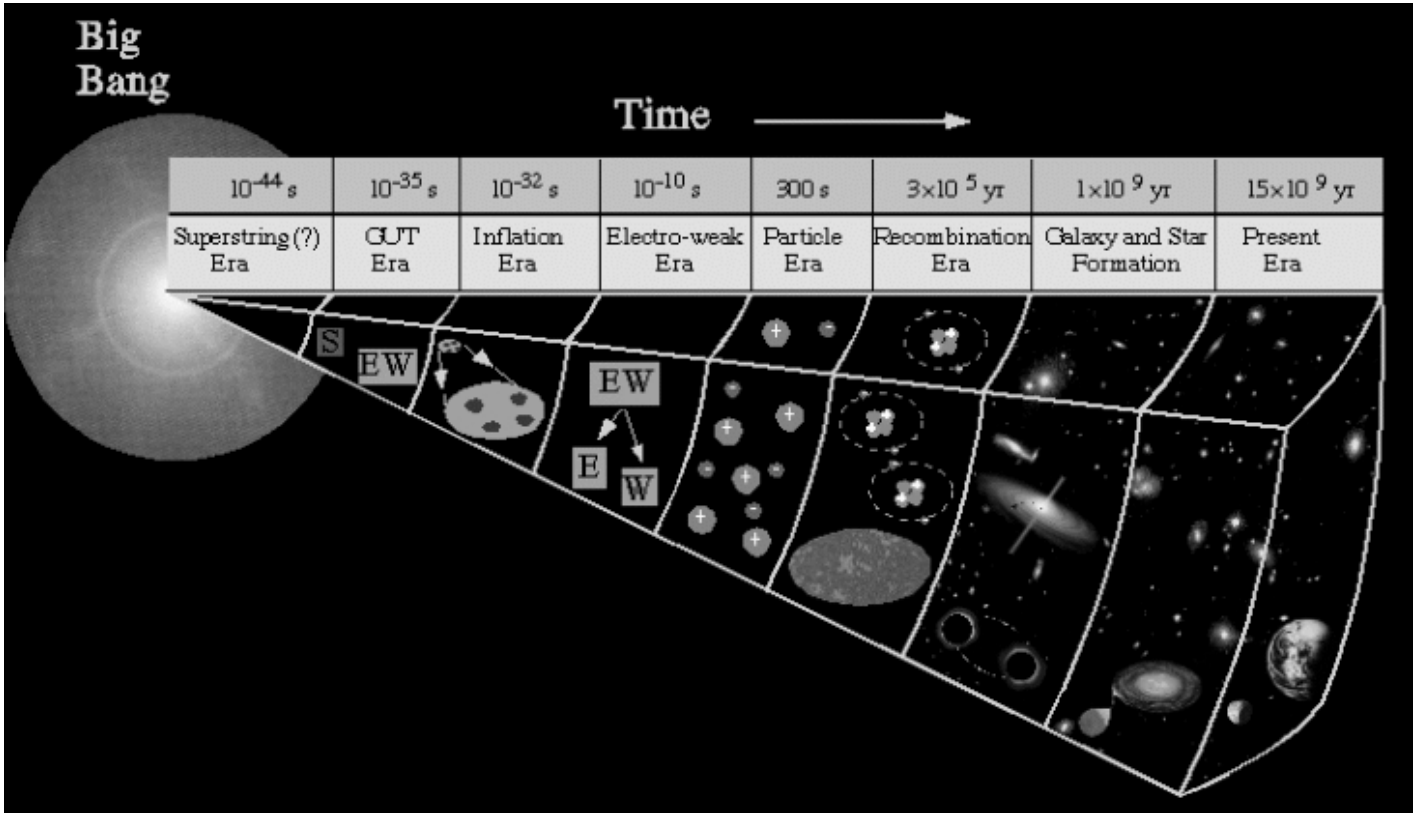
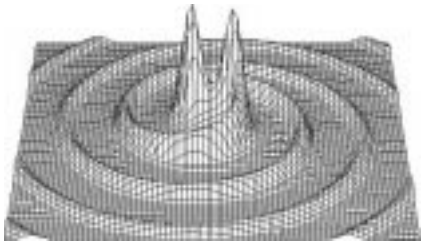
Connect the Beginning of the Universe to Fundamental Physics





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Gravitational Wave Astronomy

- More than 95% of the Universe is non luminous matter (dark matter)
- Gravitational waves will open up an entirely new window on the Universe