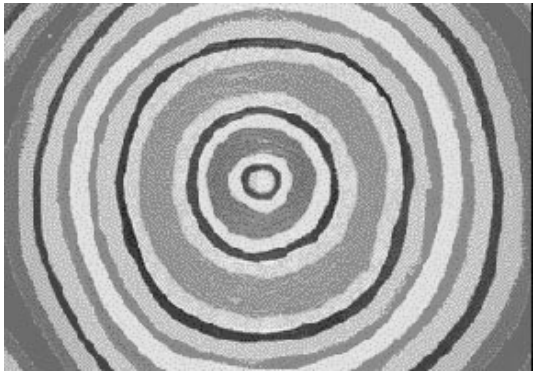


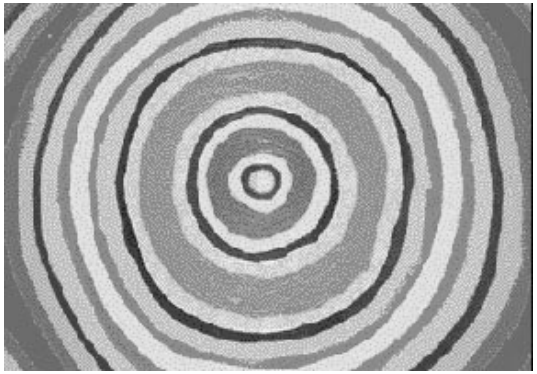
Listening to Gravitational Waves:

Einstein's Songlines from the Universe

Barry C. Barish

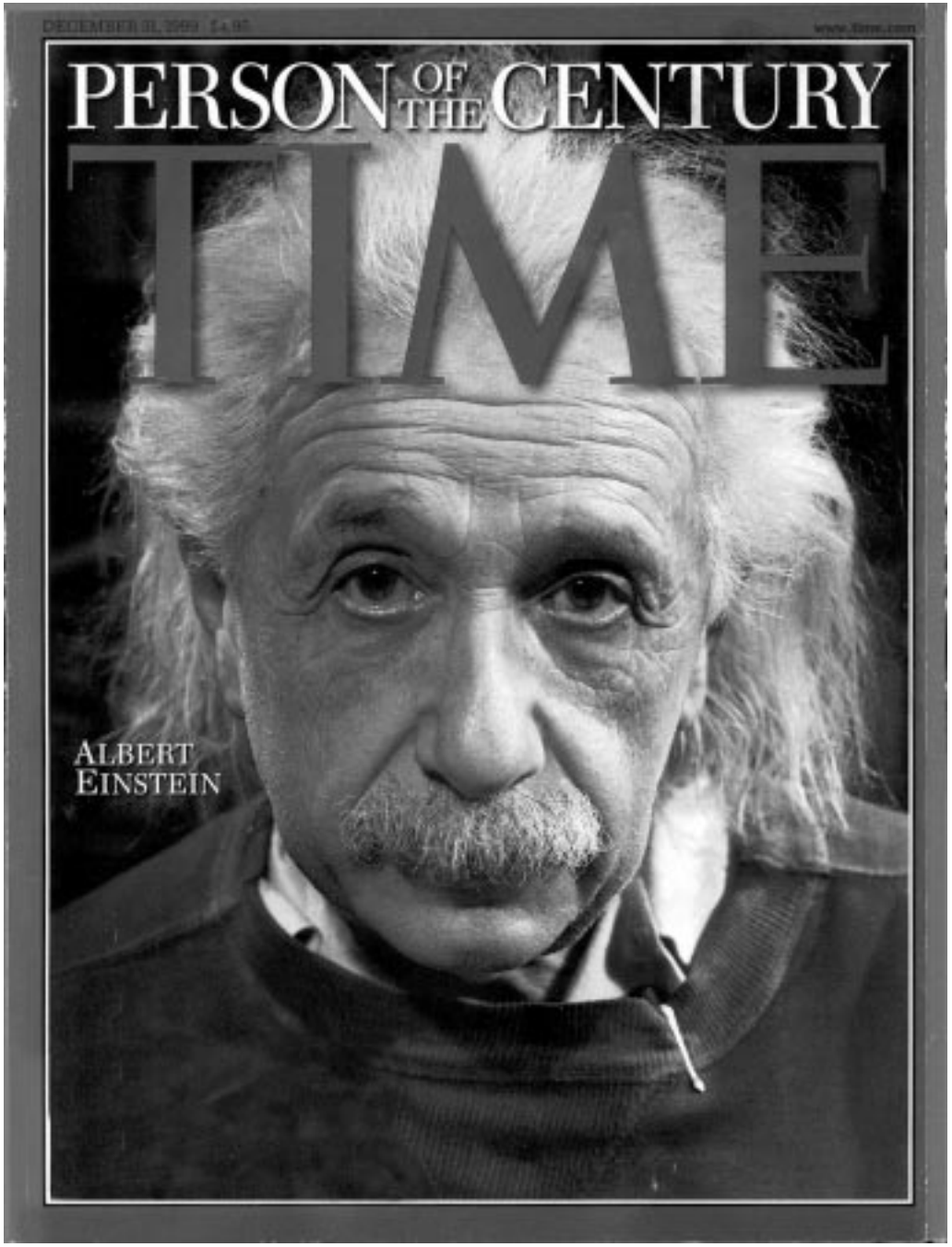
SCIENCE AT THE NEW MILLENNIUM

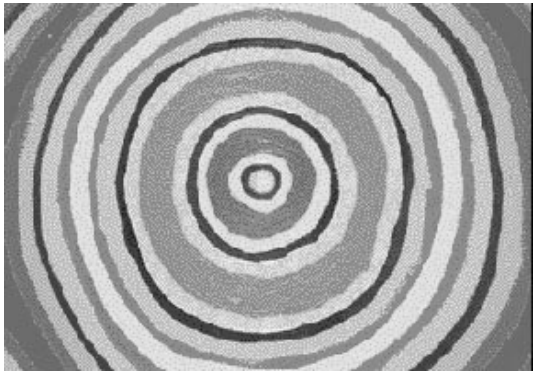
LIGO-G000171-00-M



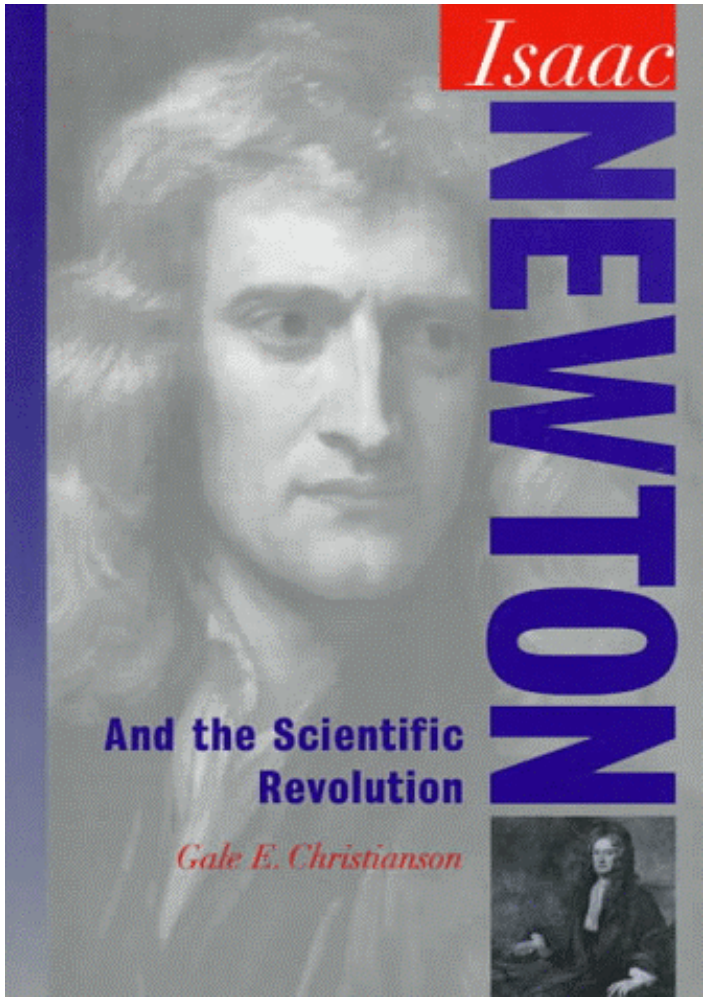
Albert Einstein

SCIENCE AT THE NEW MILLENNIUM



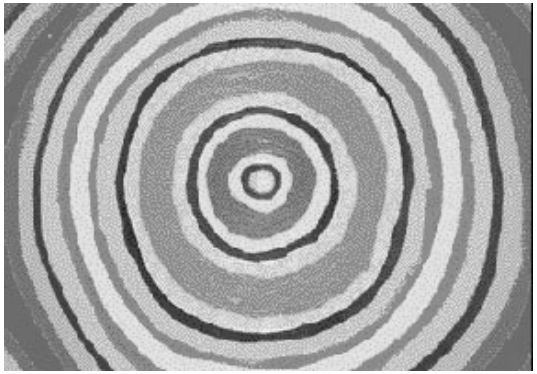


Sir Isaac Newton



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

SCIENCE AT THE NEW MILLENNIUM

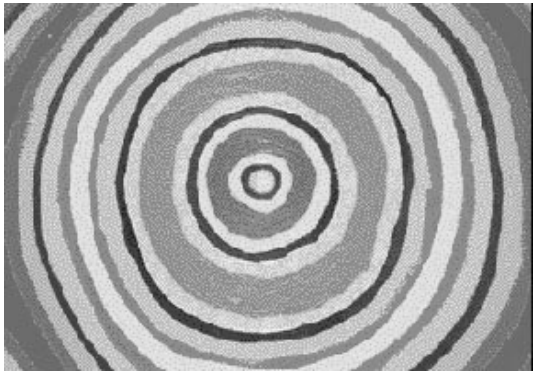


Scientific Method

Principia

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

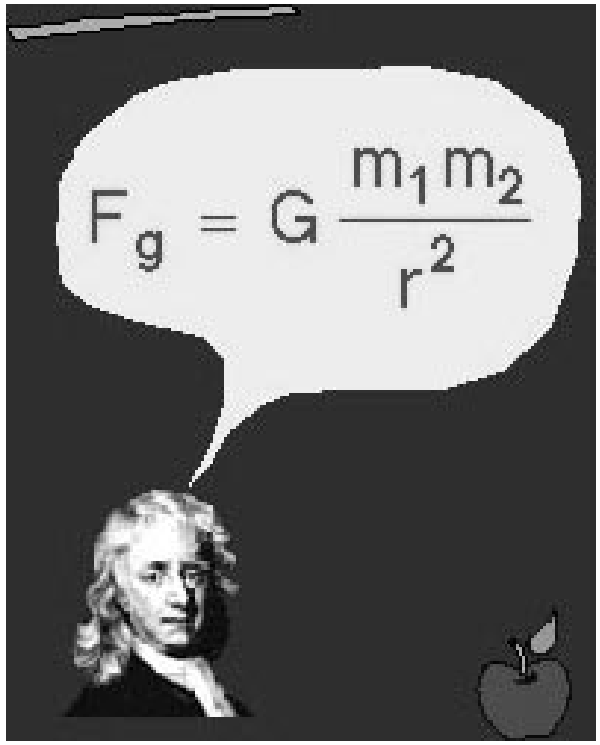
SCIENCE AT THE NEW MILLENNIUM



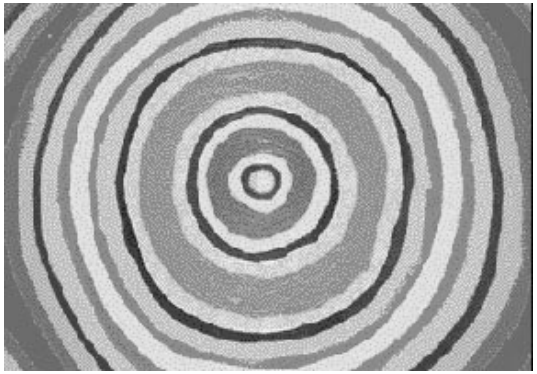
Newton

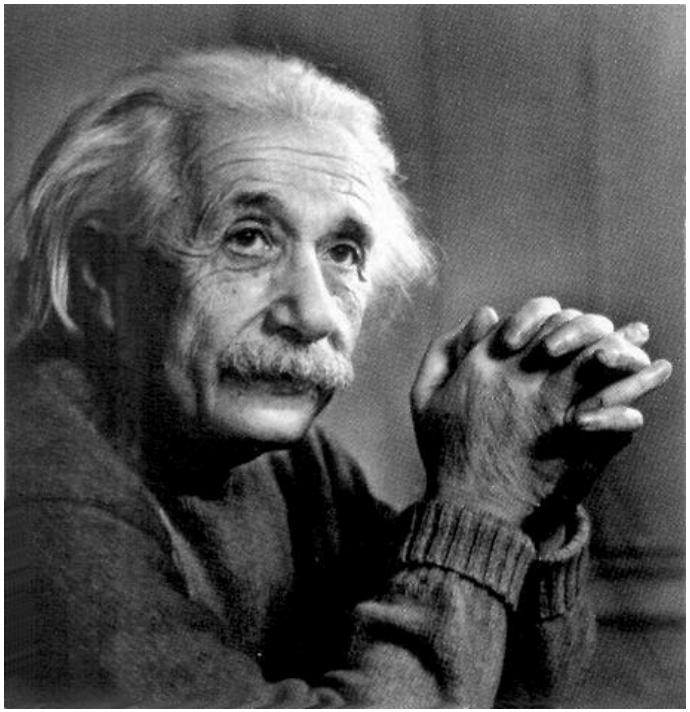
Universal Gravitation

- 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.



SCIENCE AT THE NEW MILLENNIUM

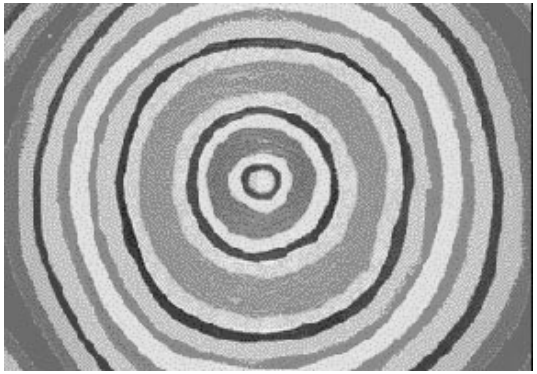




SCIENCE AT THE NEW MILLENNIUM

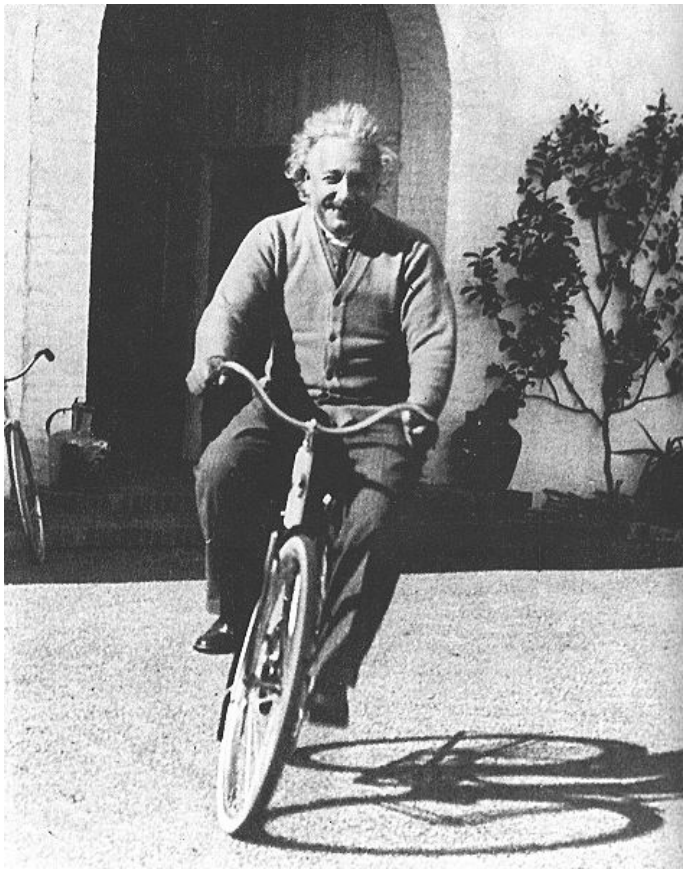
Albert Einstein

- 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)

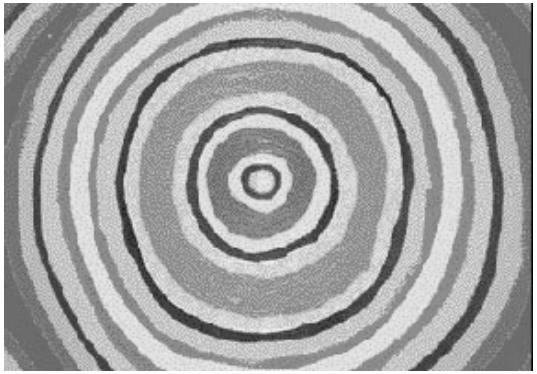


Einstein's Spacetime Wrinkles

- 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



SCIENCE AT THE NEW MILLENNIUM

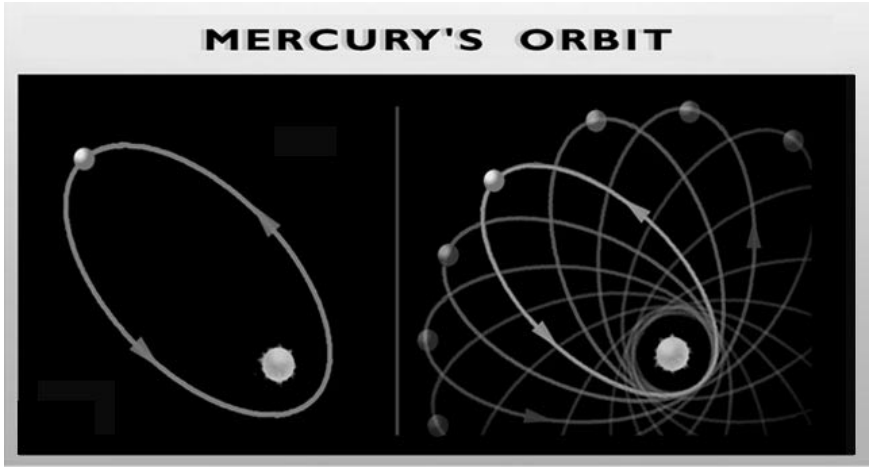


Einstein's Theory of Gravitation

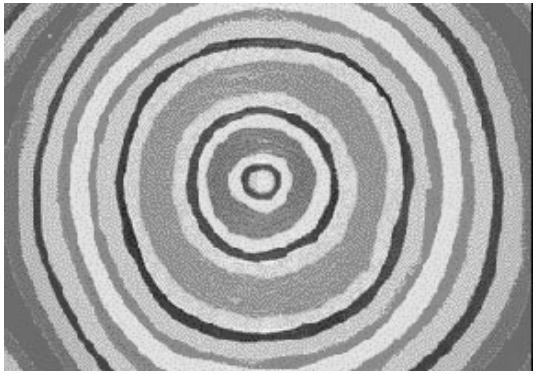
experimental tests

"Einstein Cross"
The bending of light rays
gravitational lensing

Mercury's orbit
perihelion shifts forward
twice Newton's theory



SCIENCE AT THE NEW MILLENNIUM

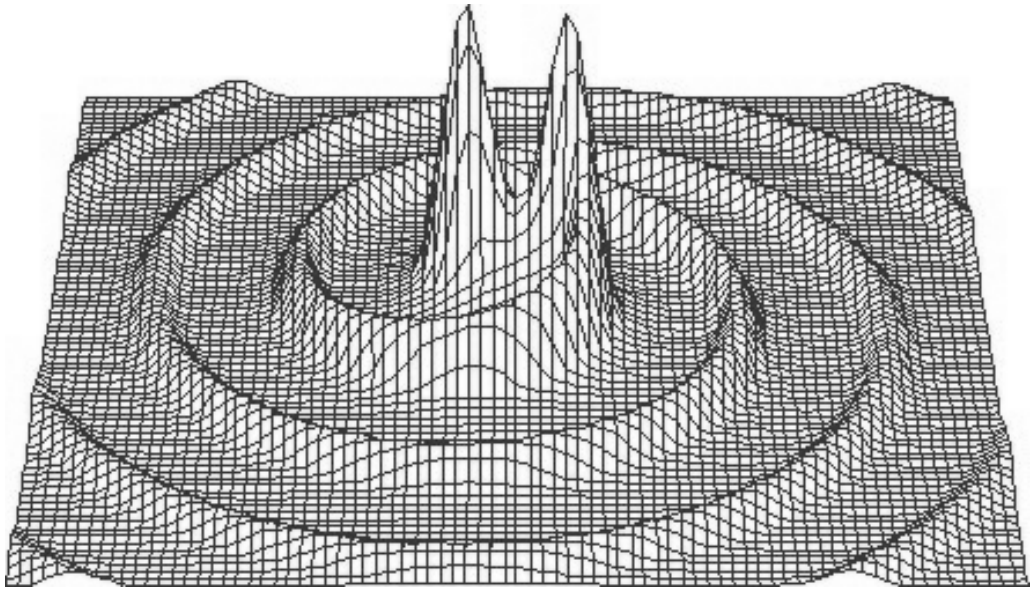


Einstein's Theory of Gravitation

experimental tests

Newton's Theory

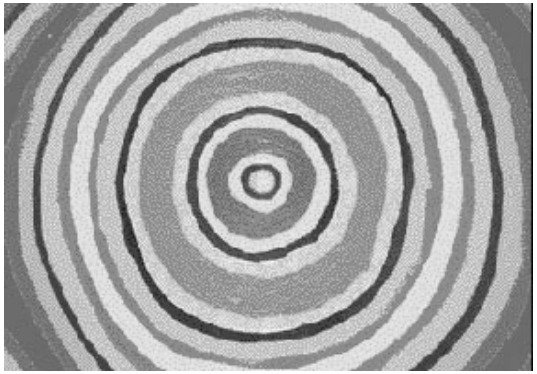
"instantaneous action at a distance"



Einstein's Theory

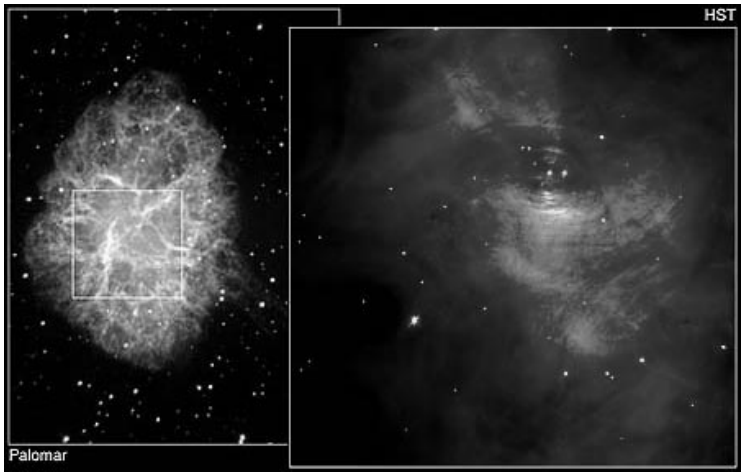
information carried by gravitational radiation at the speed of light

SCIENCE AT THE NEW MILLENNIUM



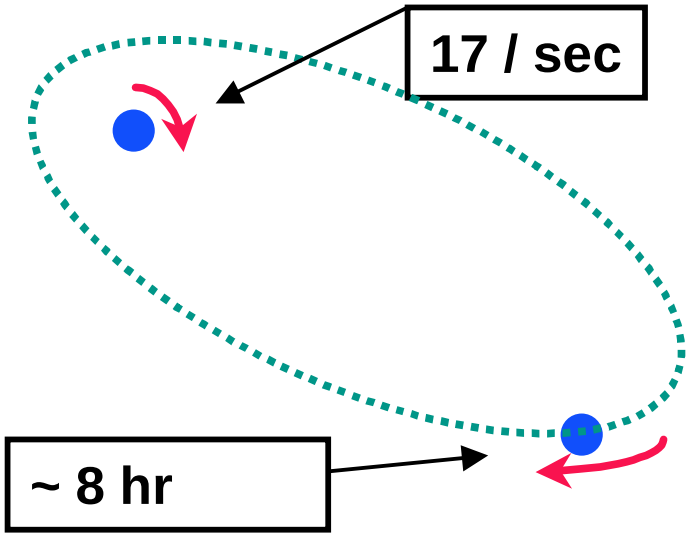
Gravitational Waves

the evidence



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars



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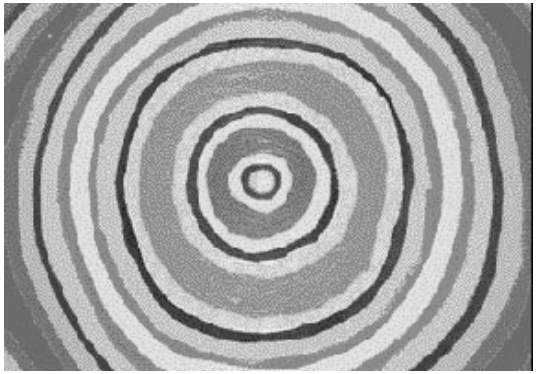
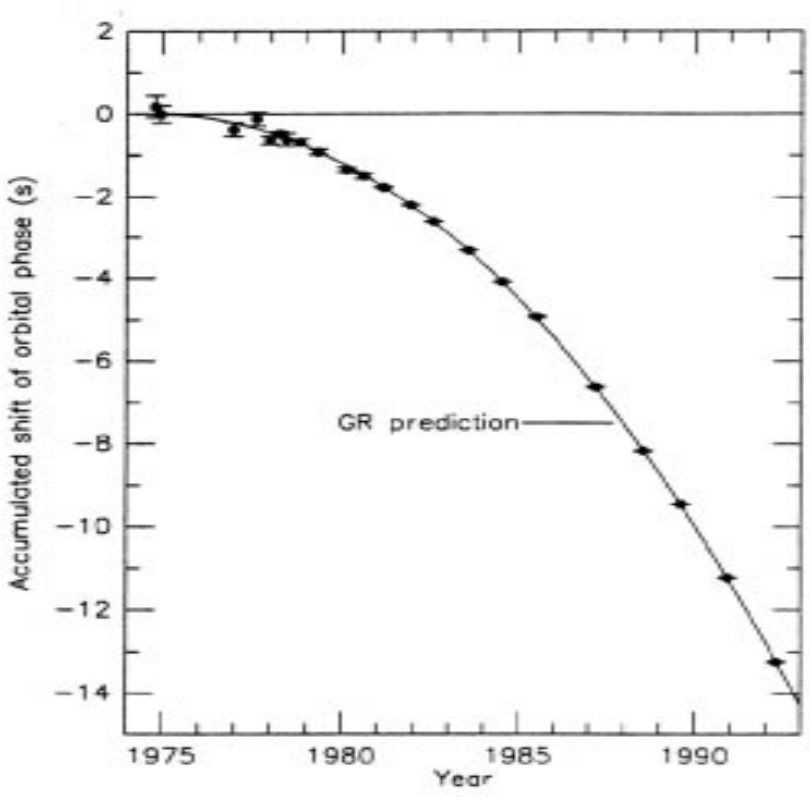


Hulse and Taylor

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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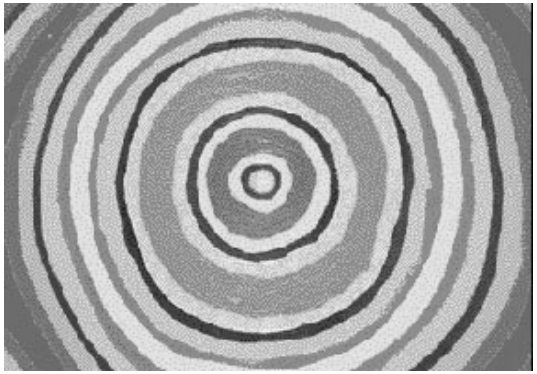
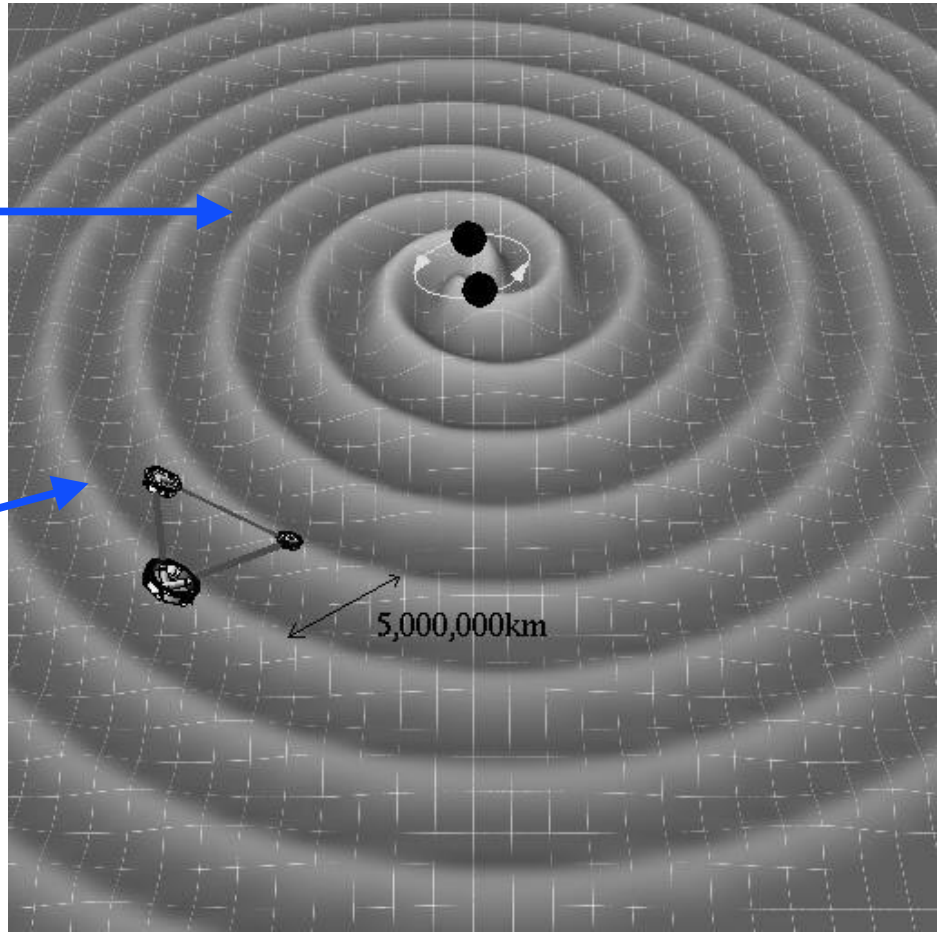


Einstein's *Songlines*

Radiation of Gravitational Waves from binary inspiral system

LISA



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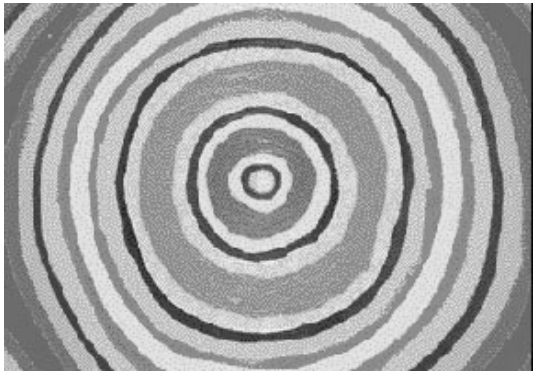
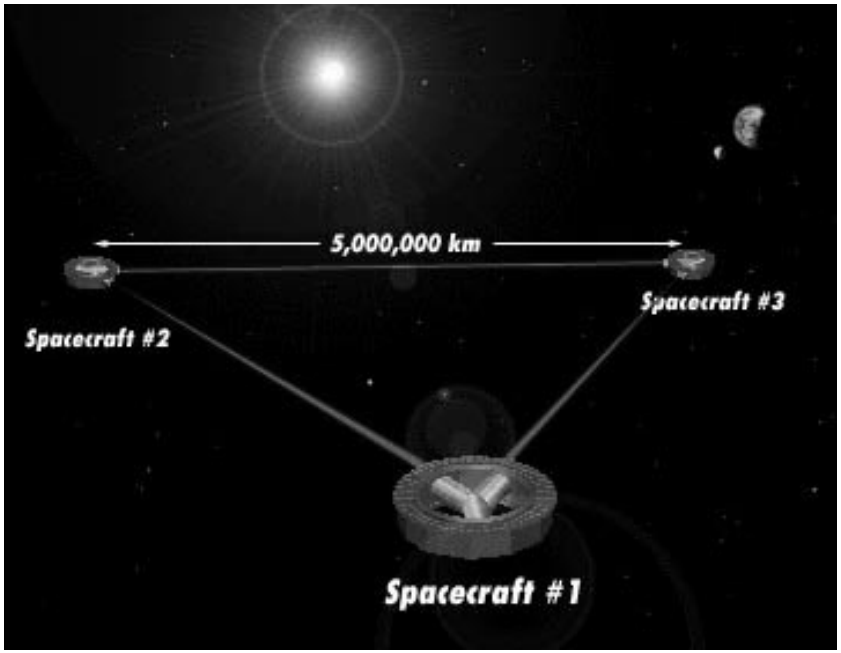


Interferometers

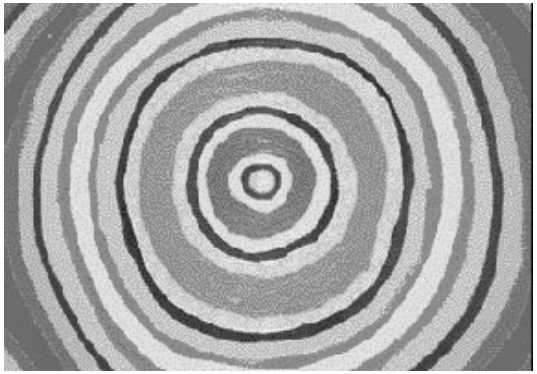
space

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.

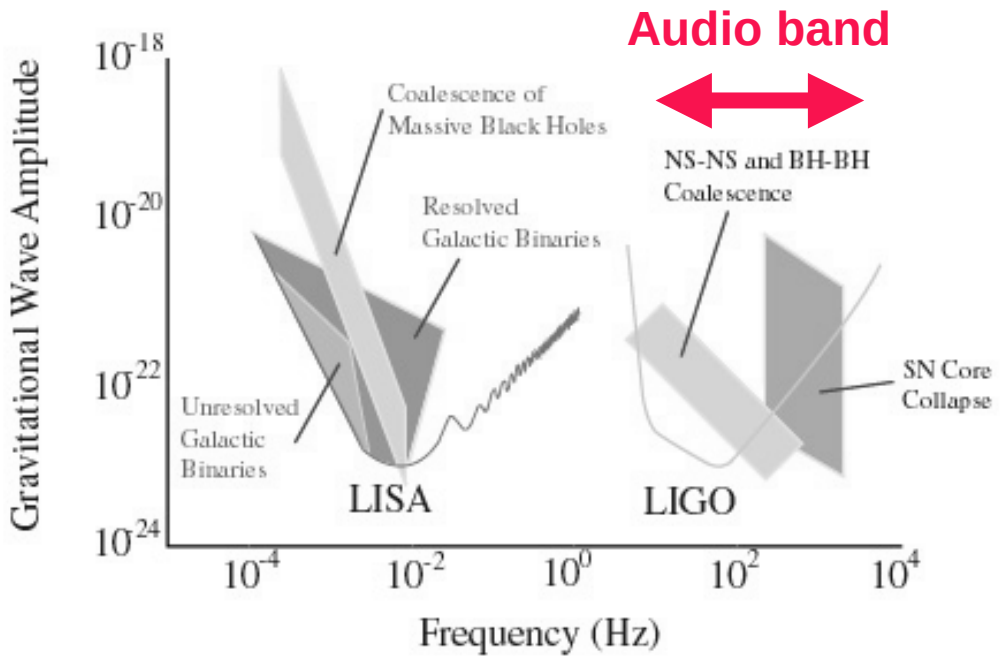
SCIENCE AT THE NEW MILLENNIUM



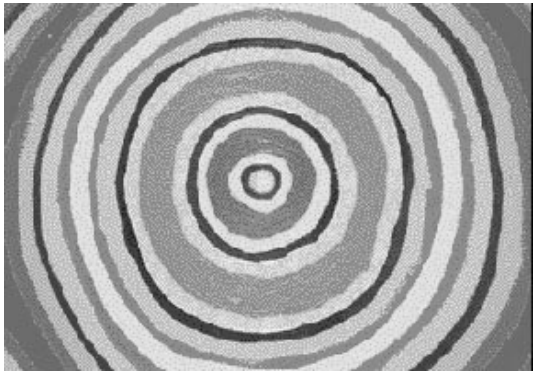
Astrophysics Sources

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)



SCIENCE AT THE NEW MILLENNIUM

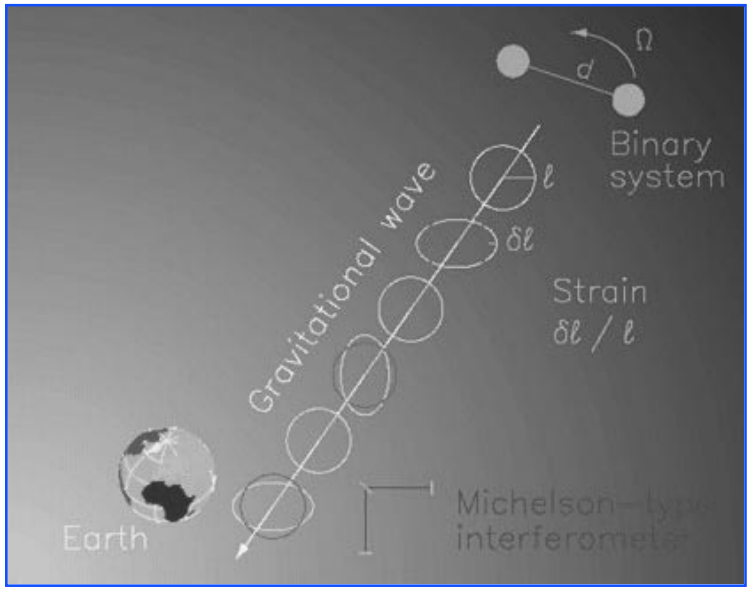


Interferometers

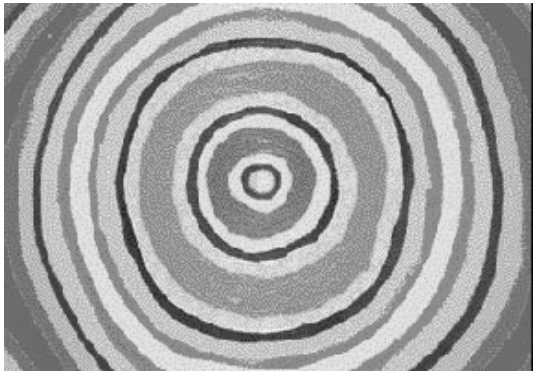
terrestrial

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.

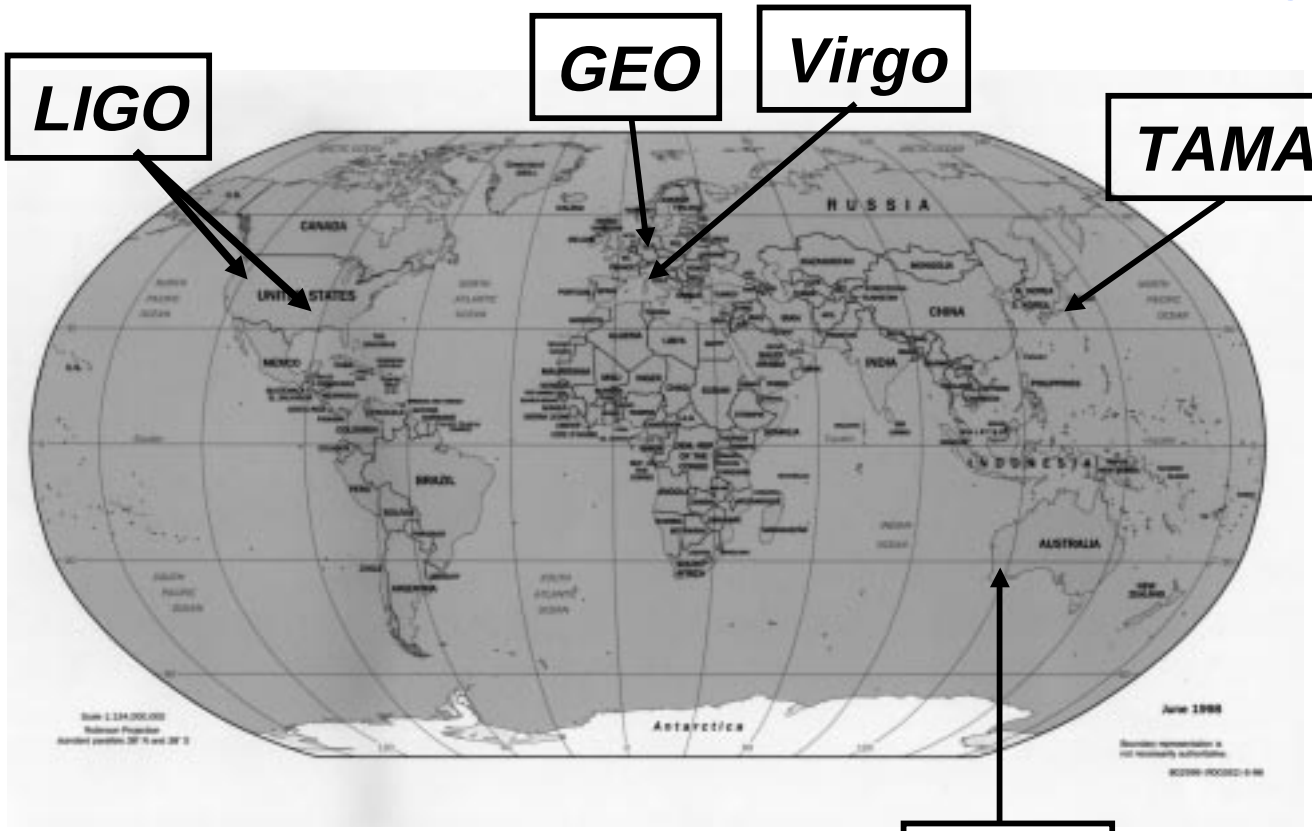


SCIENCE AT THE NEW MILLENNIUM



International Network

Simultaneously detect signal (within msec)

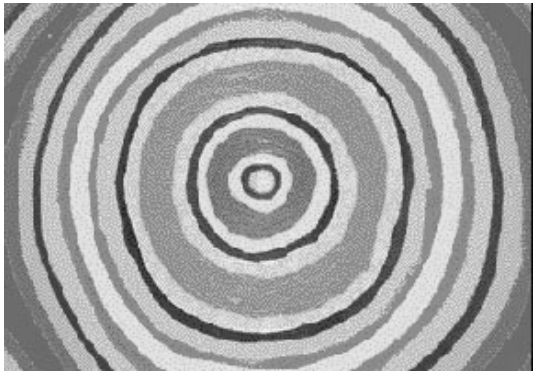


detection confidence

locate the sources

decompose the polarization of gravitational waves

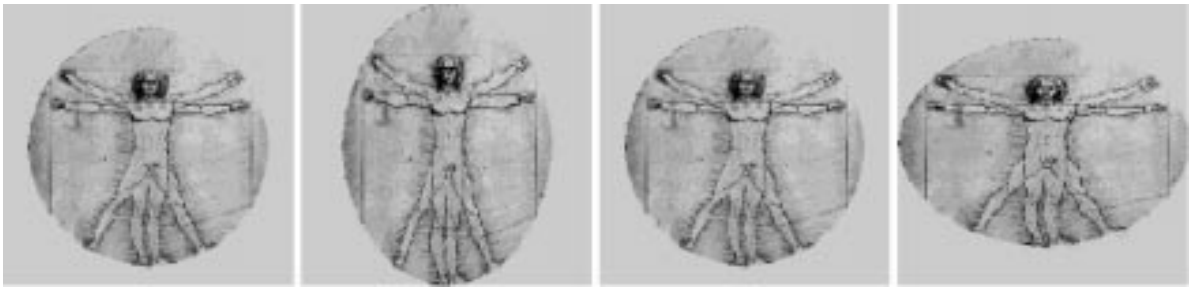
SCIENCE AT THE NEW MILLENNIUM



Gravitational Waves

the effect

Leonardo da Vinci's Vitruvian man

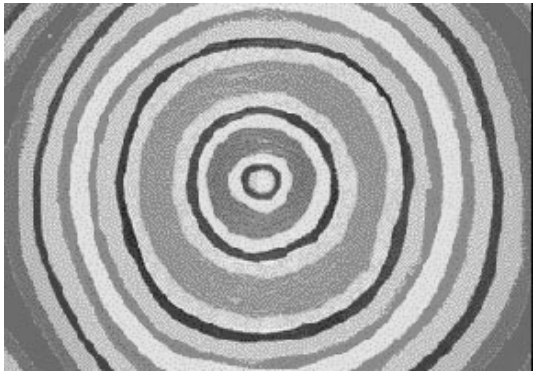


- **stretch and squash in perpendicular directions at the frequency of the gravitational waves**

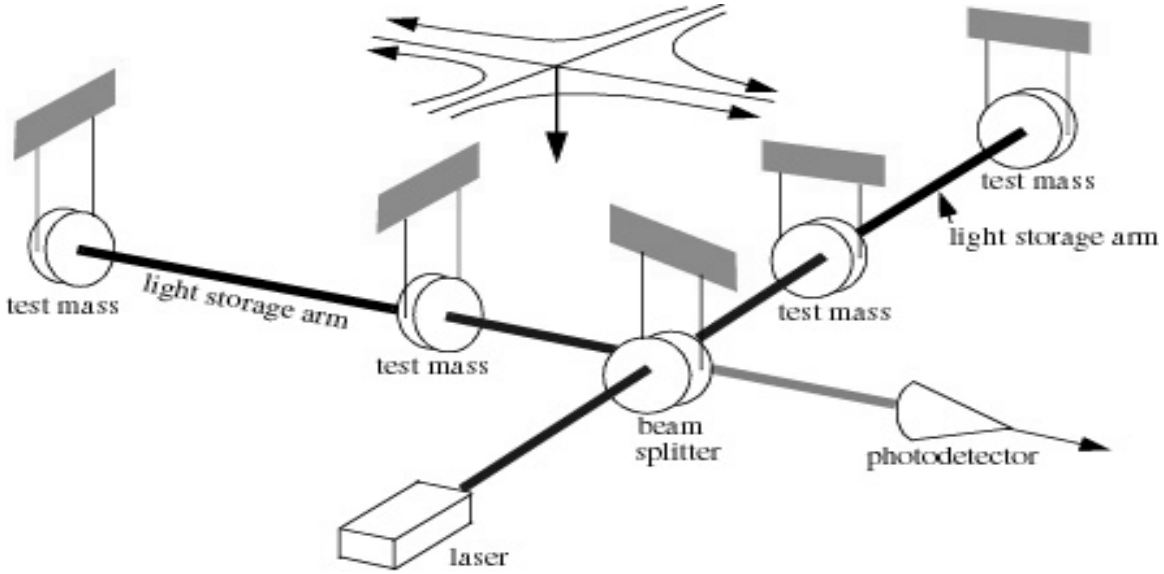
The effect is greatly exaggerated!!

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

SCIENCE AT THE NEW MILLENNIUM

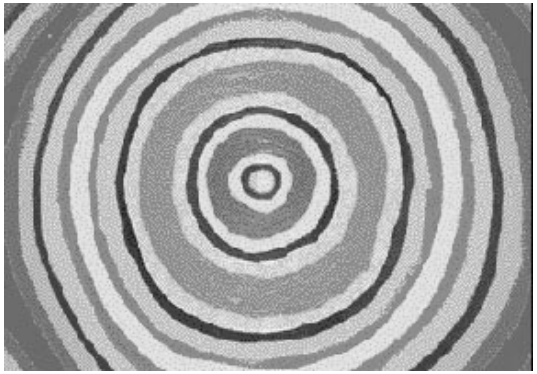


Detector concept



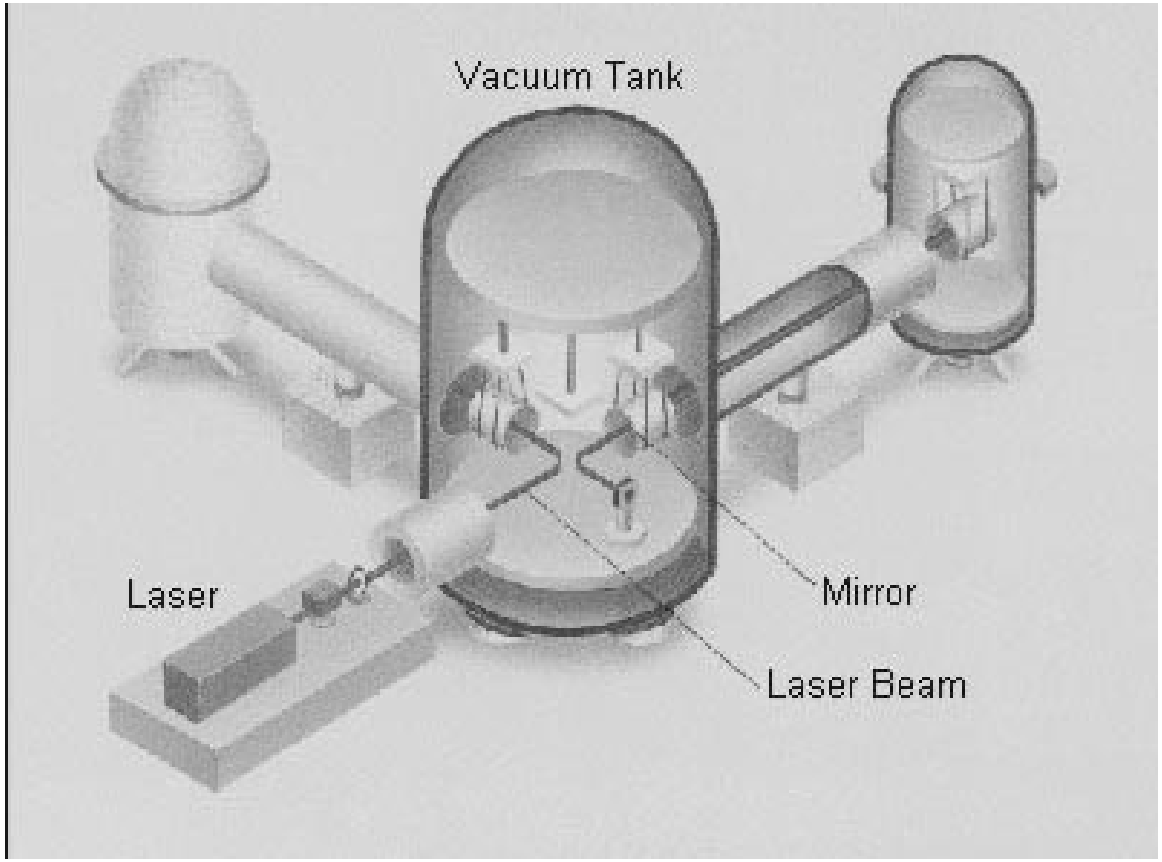
- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split)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

SCIENCE AT THE NEW MILLENNIUM



TAMA

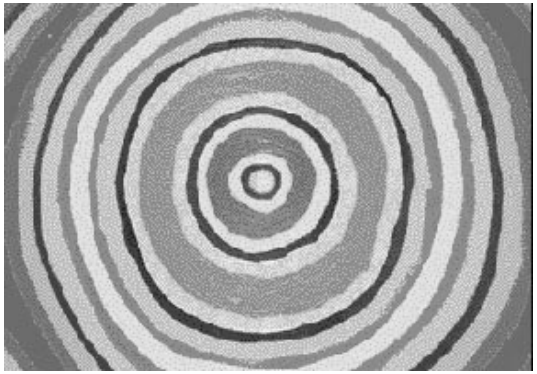
Japan



Schematic of TAMA 300m interferometer

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

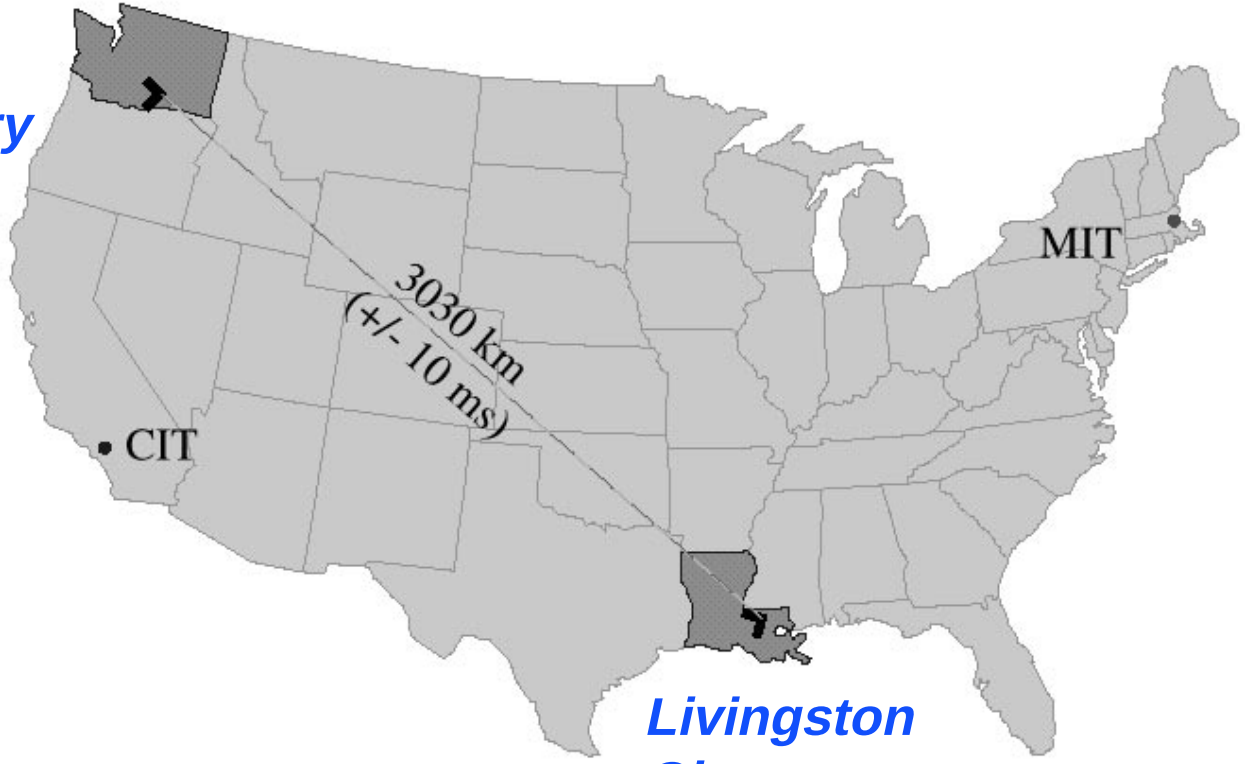
SCIENCE AT THE NEW MILLENNIUM



LIGO

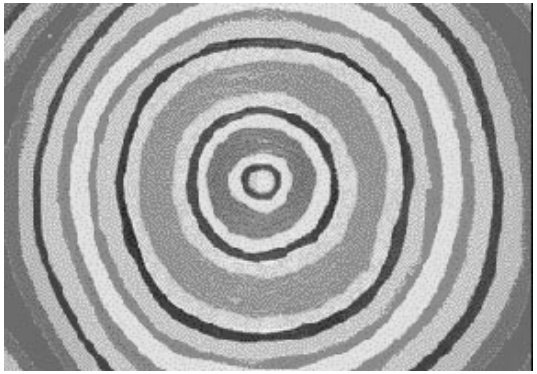
sites

Hanford Observatory



Livingston Observatory

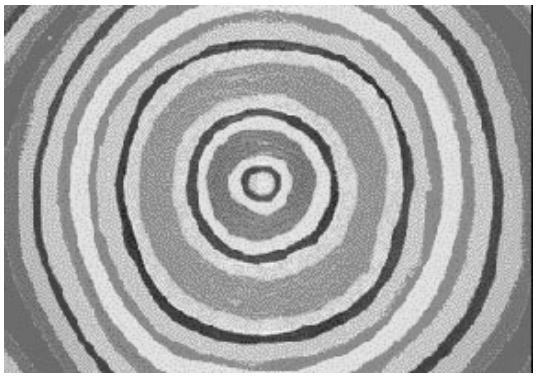
SCIENCE AT THE NEW MILLENNIUM



LIGO

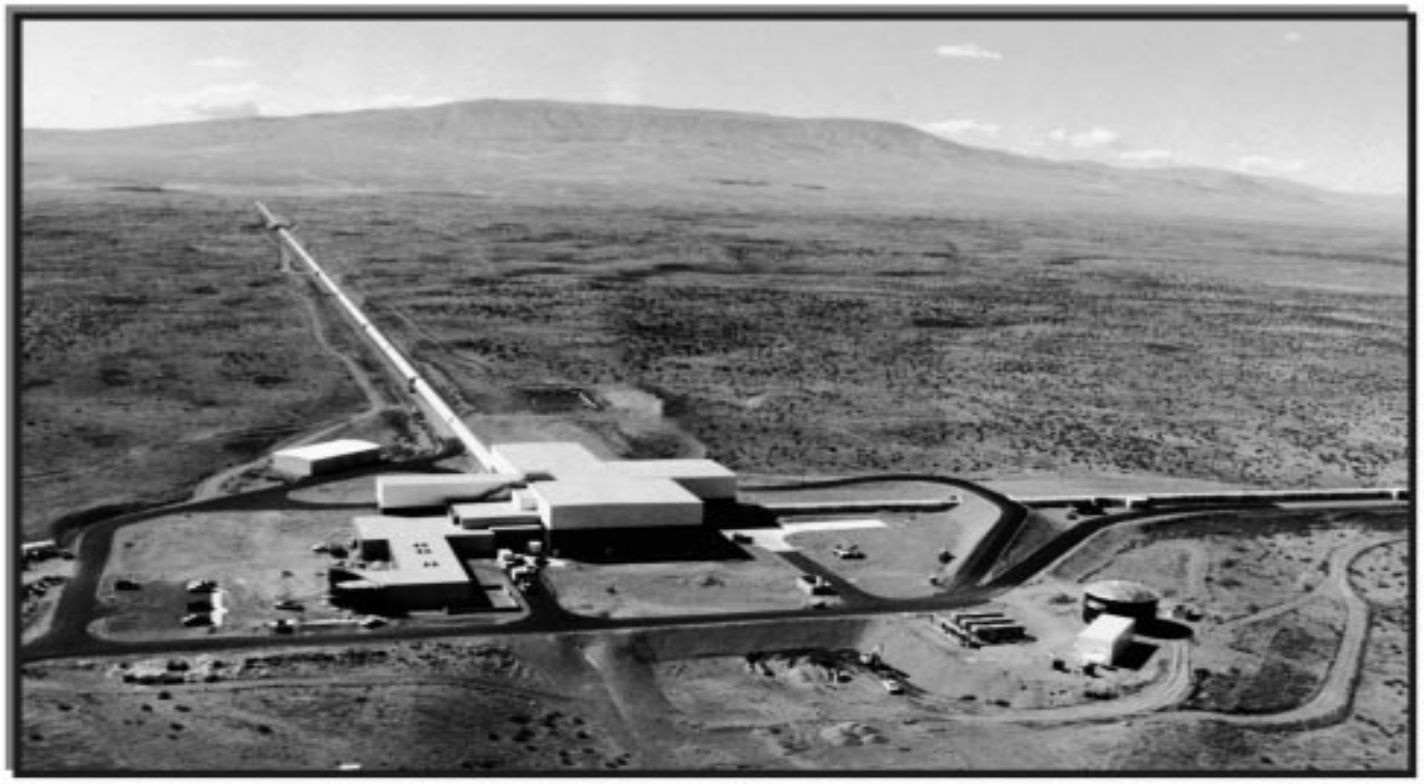
Livingston

SCIENCE AT THE NEW MILLENNIUM

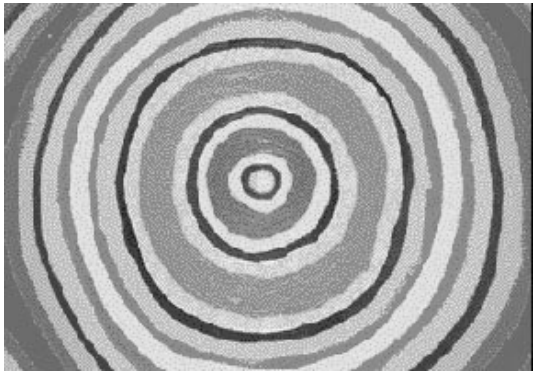


LIGO

Hanford



SCIENCE AT THE NEW MILLENNIUM

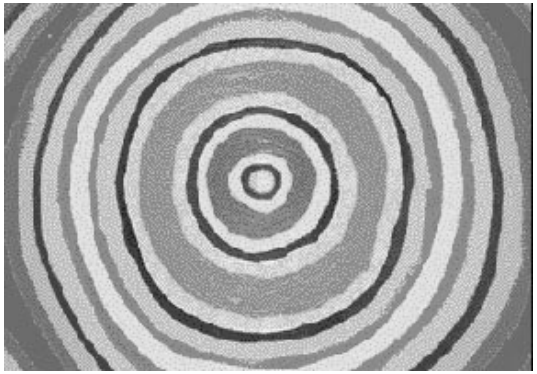


LIGO

Beam Tube

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

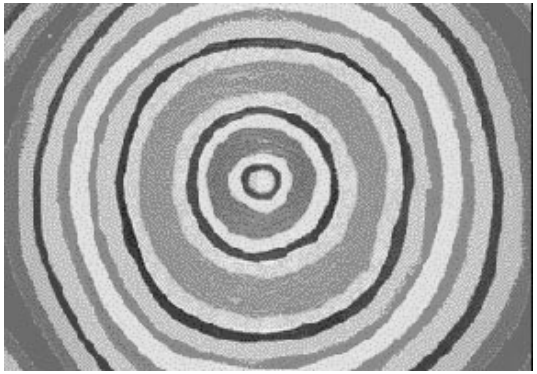
SCIENCE AT THE NEW MILLENNIUM



LIGO

vacuum equipment

SCIENCE AT THE NEW MILLENNIUM

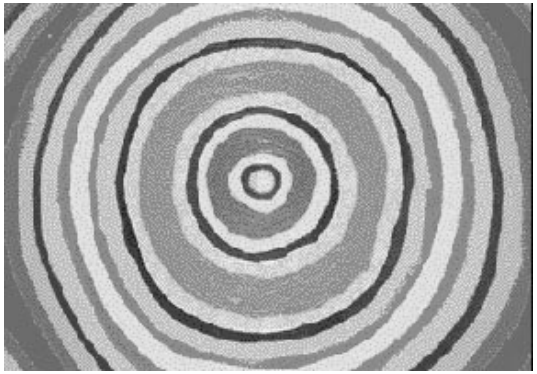


LIGO

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**

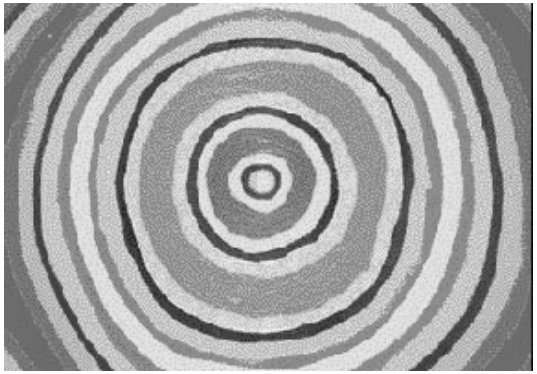
SCIENCE AT THE NEW MILLENNIUM



Einstein's *Songlines*

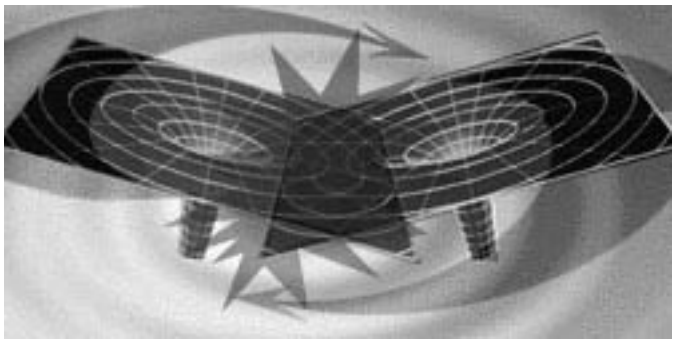
- **AIGO will soon 'listen' for Einstein's Songlines with gravitational waves**
- **Basic tests of General Relativity will be possible (eg. Black holes)**

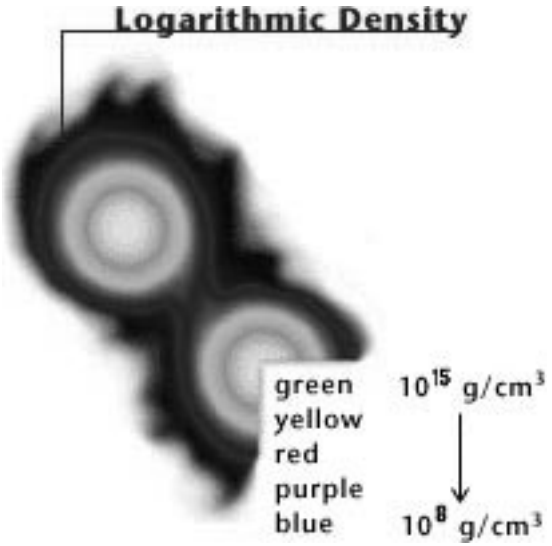
SCIENCE AT THE NEW MILLENNIUM



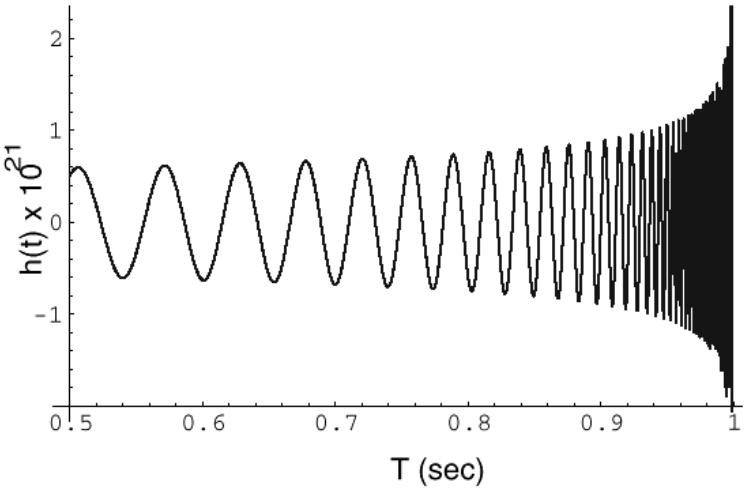
Sources of Gravitational Waves

Inspiral of Neutron Stars

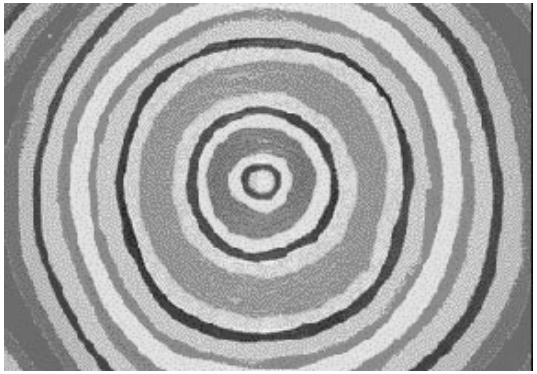




"Chirp Signal"

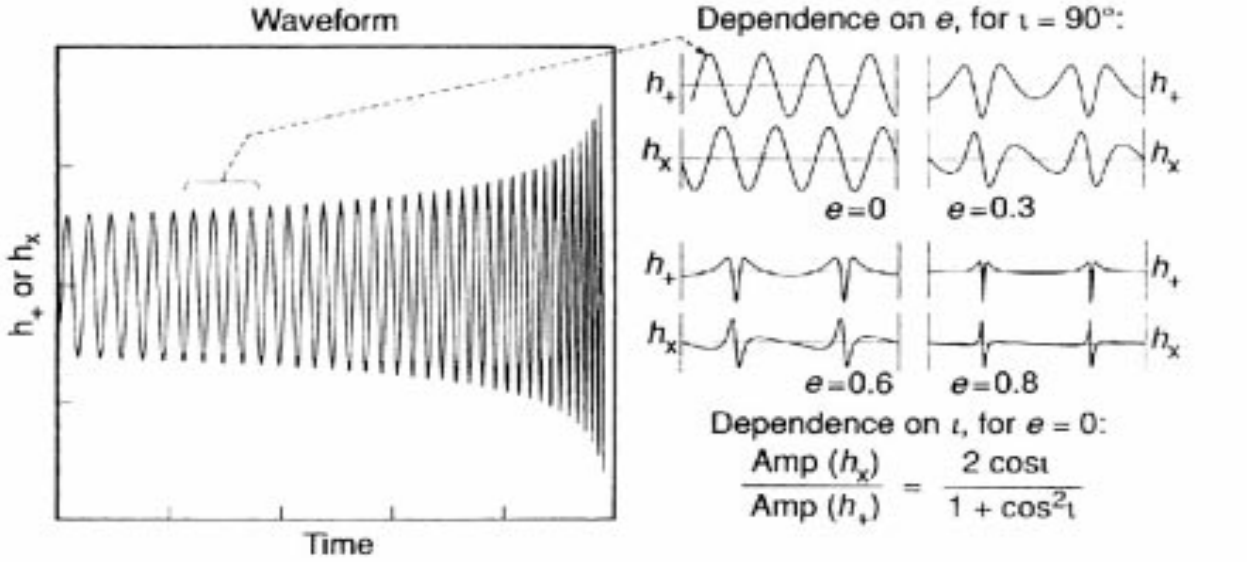


SCIENCE AT THE NEW MILLENNIUM



Chirp Signal

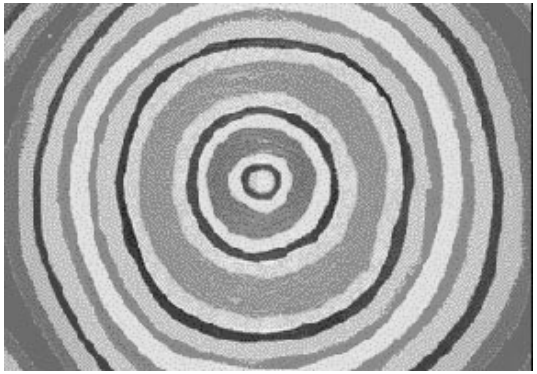
binary inspiral



determine

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

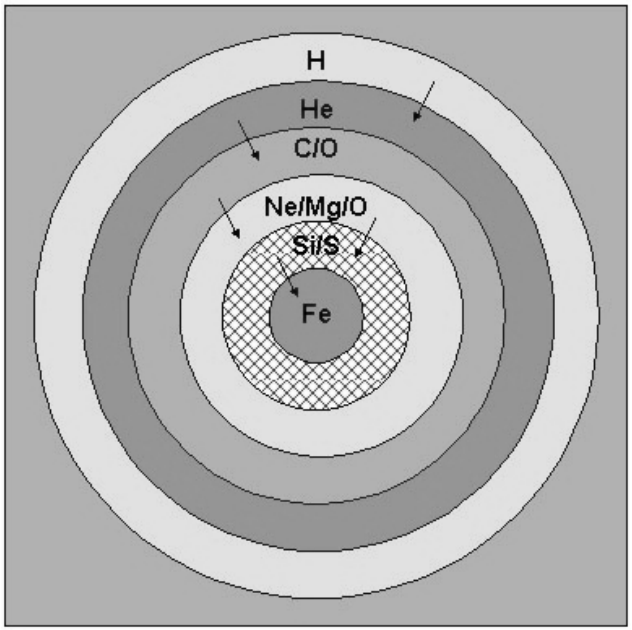
SCIENCE AT THE NEW MILLENNIUM



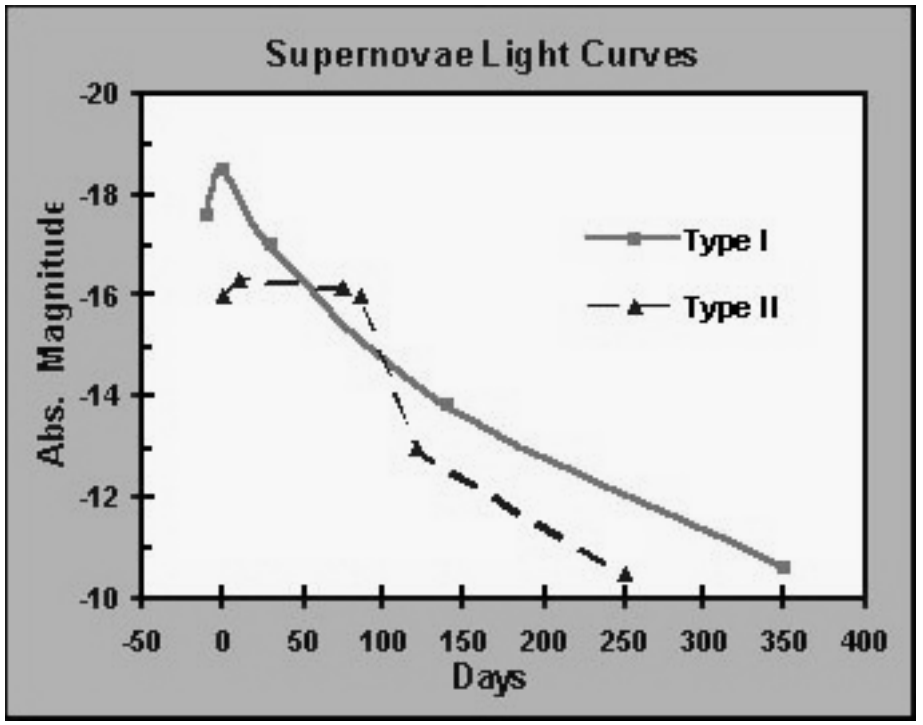
Sources of Gravitational Waves

Supernovae

gravitational stellar collapse

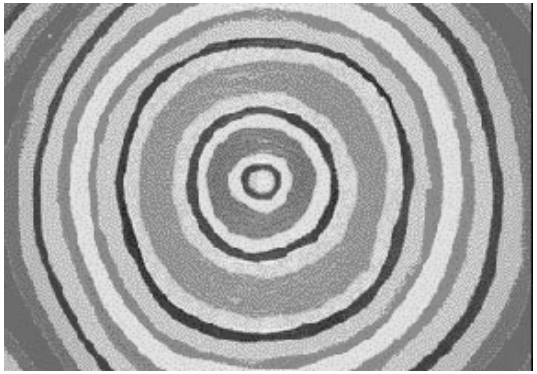


The Collapse



Optical Light Curve

SCIENCE AT THE NEW MILLENNIUM

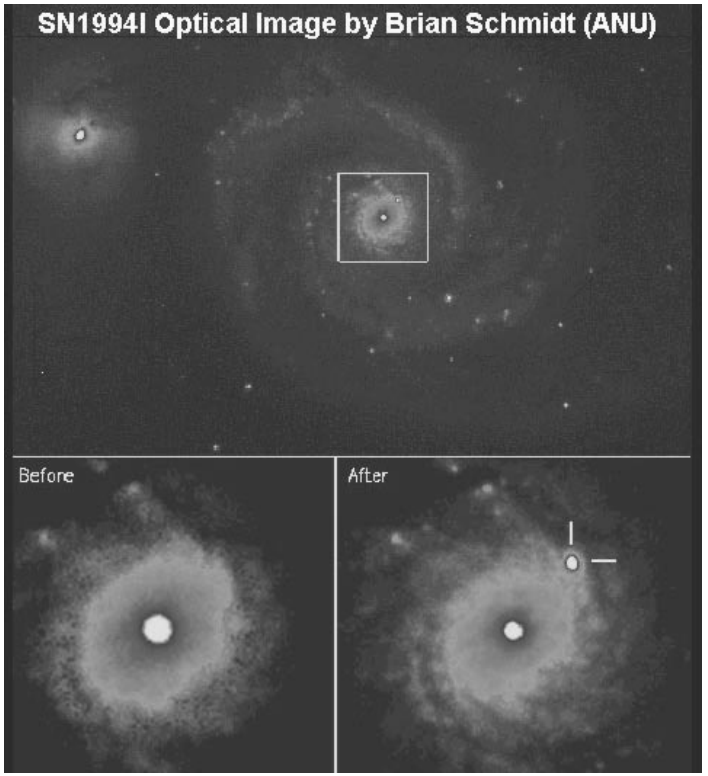


Sources of Gravitational Waves

Supernovae

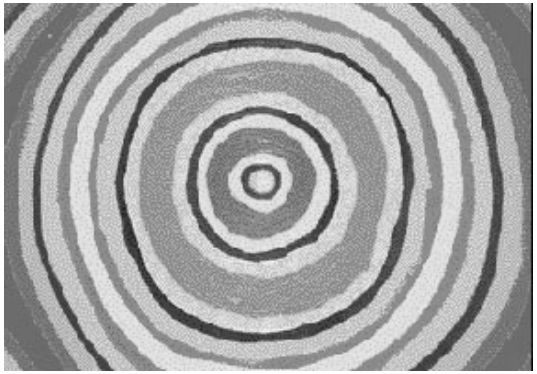
optical observations

Crab Nebula 1054 AD



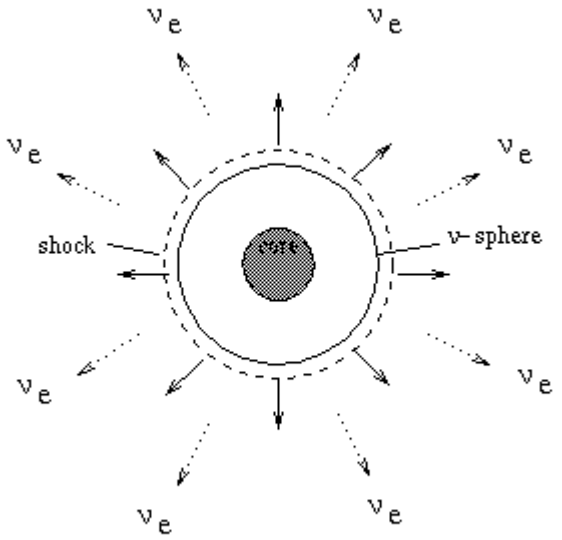
Supernovae - SN1994I

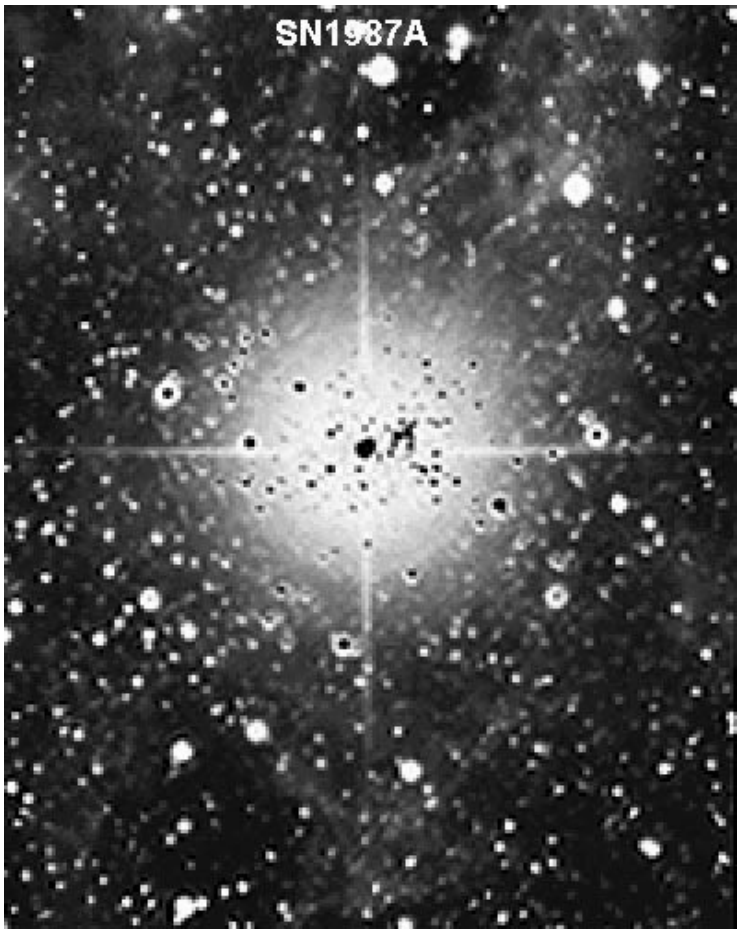
SCIENCE AT THE NEW MILLENNIUM



Supernovae

Neutrinos from SN1987A





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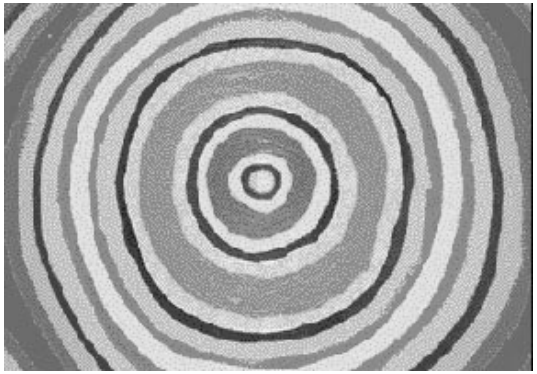
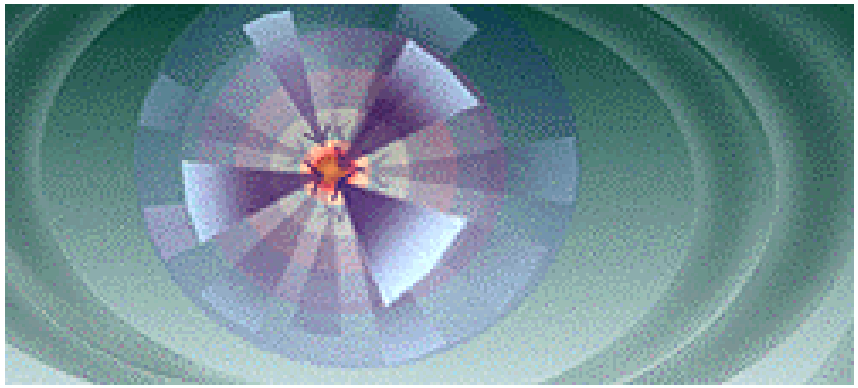


Supernovae

Gravitational Waves

Non axisymmetric collapse

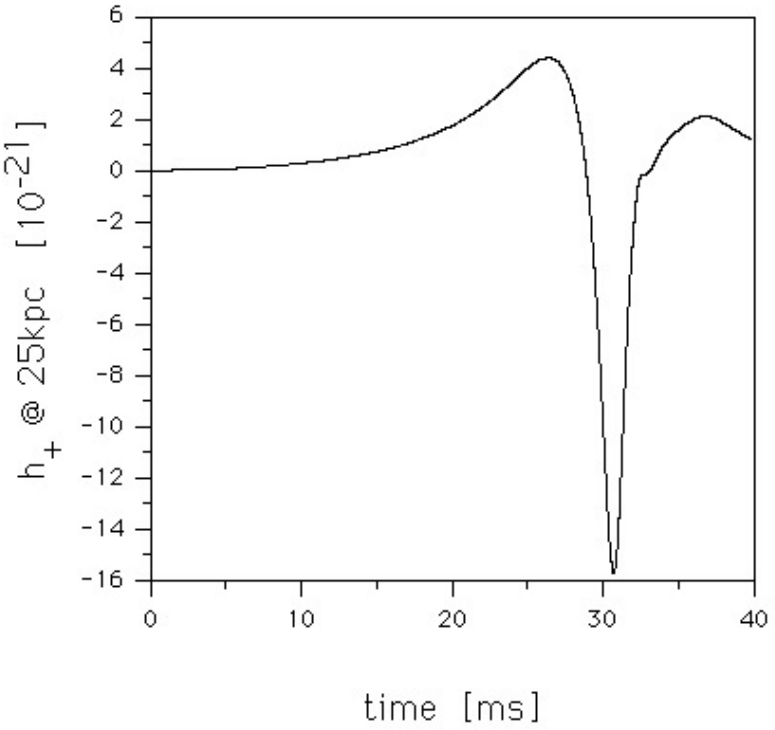


Rate

1/50 yr - our galaxy

3/yr - Virgo cluster

‘burst’ signal



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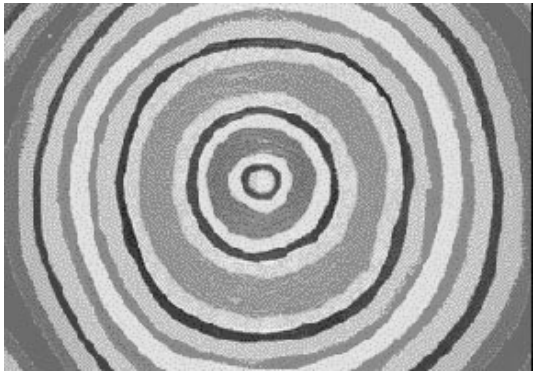
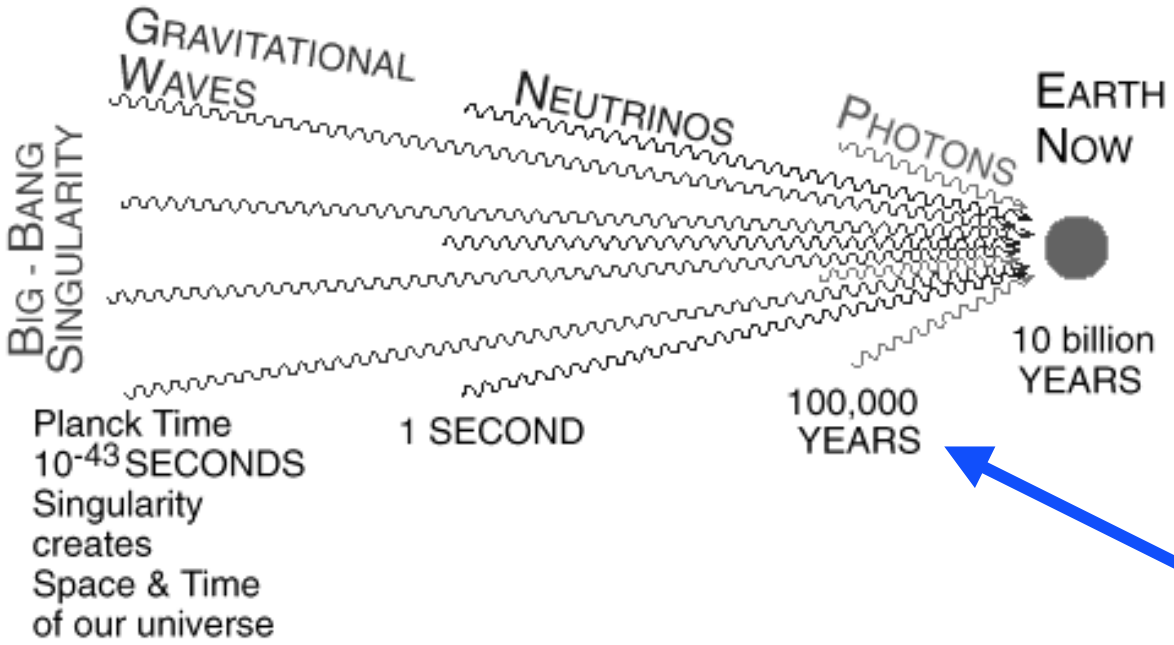


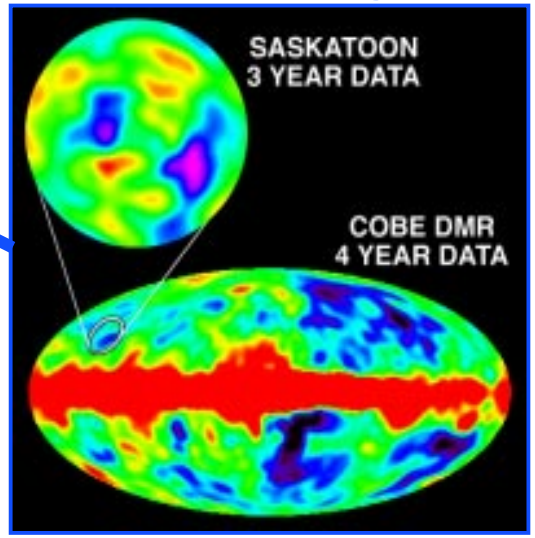
Sources of Gravitational Waves

'Murmurs' from the Big Bang

signals from the early universe



Cosmic microwave background



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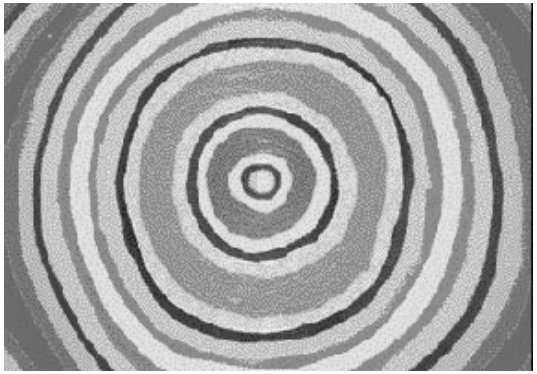
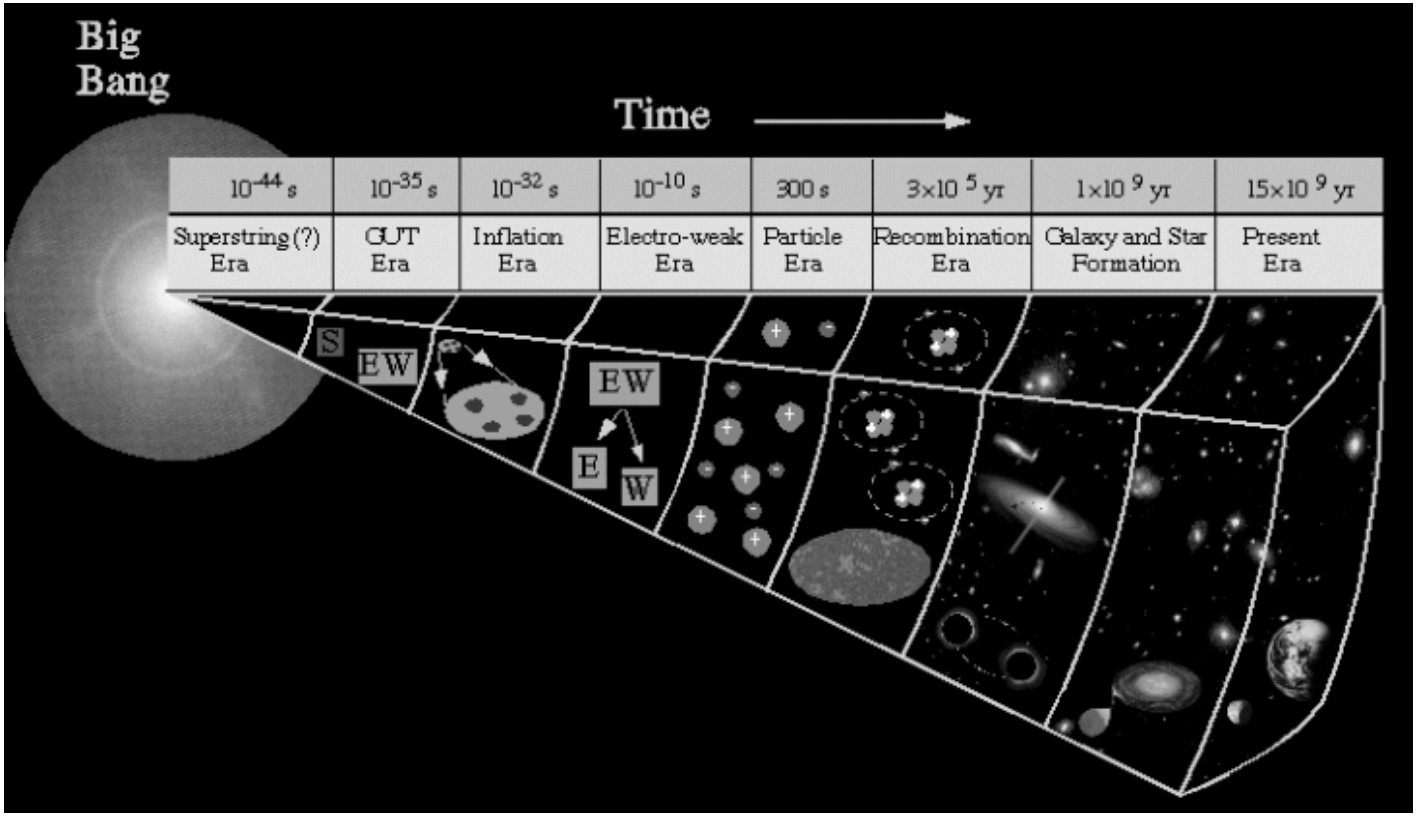


Connect the Beginning of the Universe to Fundamental Physics



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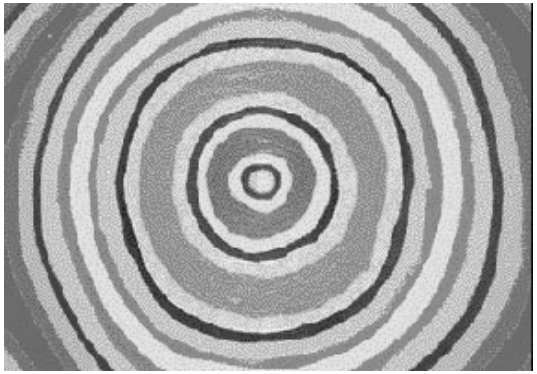
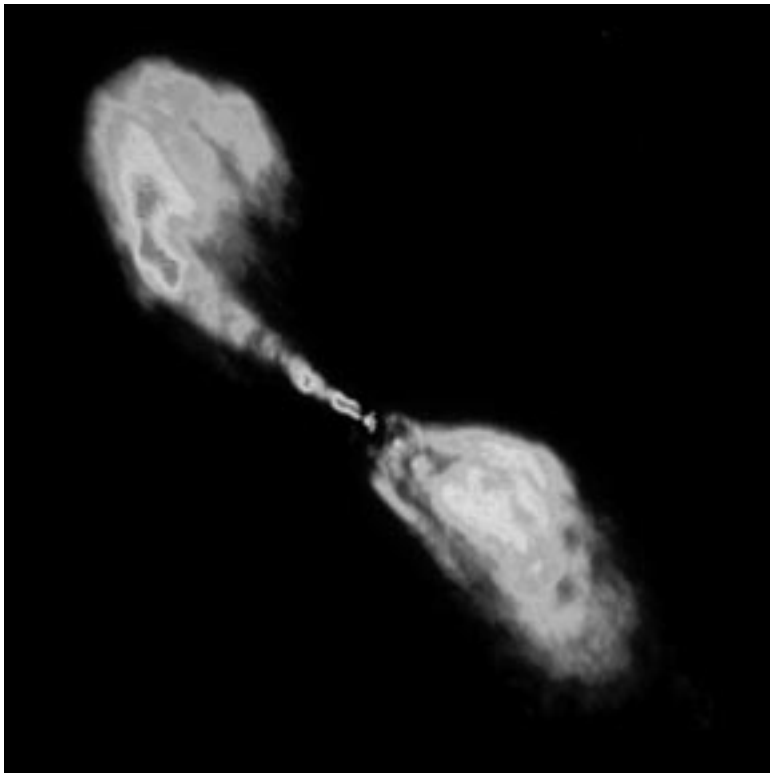
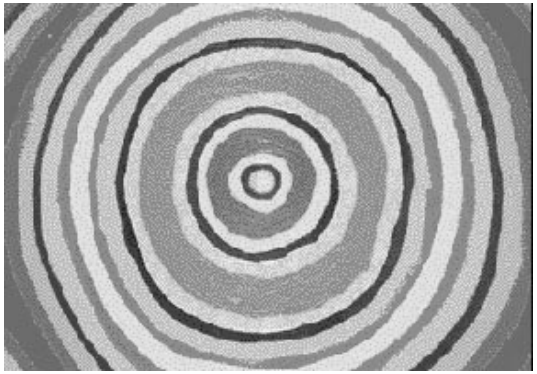


Astrophysics and Cosmology

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

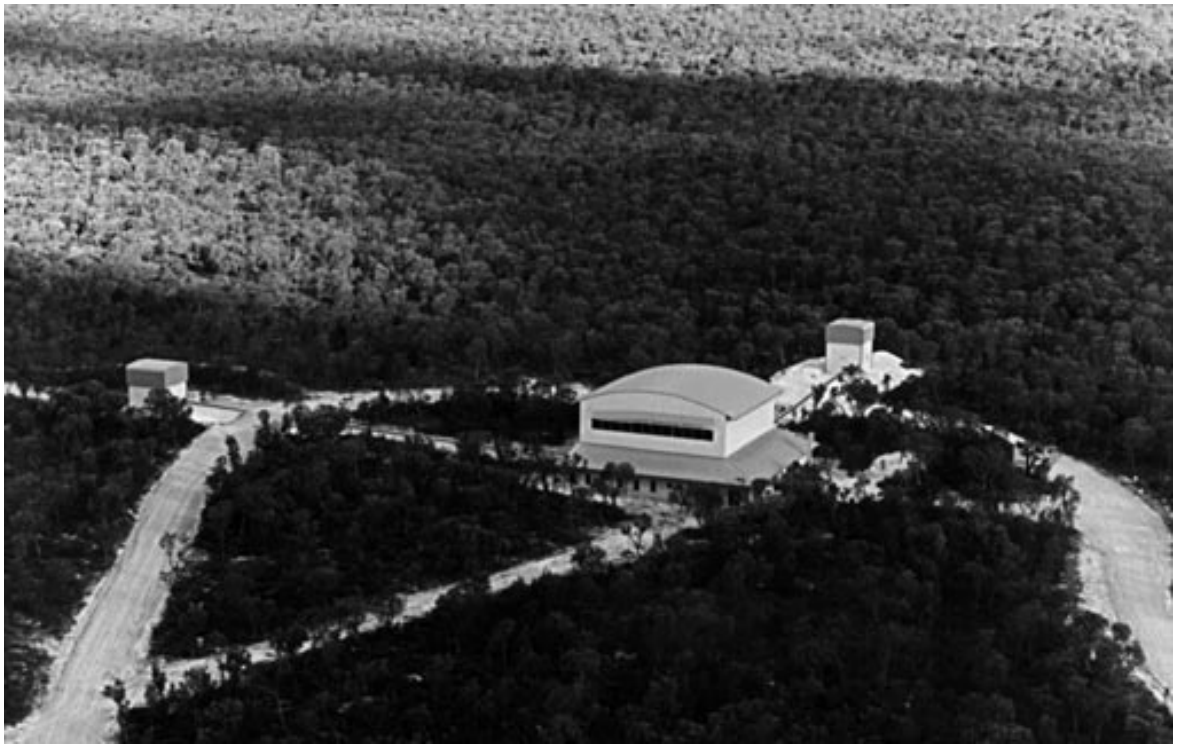


SCIENCE AT THE NEW MILLENNIUM



AIGO

Australian Consortium
for
Interferometric Gravitational Astronomy (ACIGA)



The University of Western Australia

The Australian National University

The University of Adelaide

CSIRO Lindfield

Monash University

SCIENCE AT THE NEW MILLENNIUM

The First Stage of the Laser Interferometer Gravitational Wave Observatory