Physics of LIGO

- Part 1: LIGO project, GR, GW, astrophysical sources, IFO detectors
- Part 2: IFO detector physics, noise sources
- Part 3: LIGO sub-systems; LIGO II
- Part 4: LIGO data analysis

Alan Weinstein, Caltech

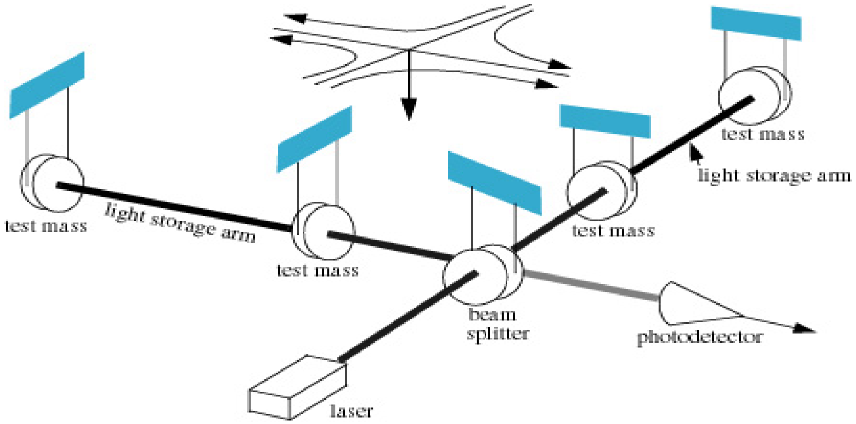
MANY THANKS to Barry Barish, Nergis Mavalvala, David Shoemaker, many others!!

Caveats

- I am a particle physicist; I'm new to LIGO
- Everything I've learned about LIGO physics (which is ε) is useful for you to know, too!
- Here I get a chance to review my understanding, and solicit comments and corrections from you

Physics of LIGO
Part I: Gravitational Waves

- The LIGO project
- Einstein's special relativity
- General relativity and curved space-time
- Gravitational waves
- Astrophysical Sources of GW's
- GW astrophysics
- GW detection via interferometry
- Practical issues with IFOs
- Scope and schedule of project



Alan Weinstein, Caltech

MANY THANKS to Barry Barish, Nergis Mavalvala, David Shoemaker!!

The LIGO Project

LIGO: Laser Interferometer Gravitational-Wave Observatory

- US project to build observatories for gravitational waves (GWs)
  - » ...and laboratory to run them
- to enable an initial detection, then an astronomy of GWs
- collaboration by MIT, Caltech; other institutions participating
  - » (LIGO Scientific Collaboration, LSC)
  - » Funded by the US National Science Foundation (NSF)

Observatory characteristics

- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers (IFOs)

Evolution of interferometers in LIGO

- establishment of a network with other interferometers
- A facility for a variety of GW searches
- lifetime of >20 years
- goal: best technology, to achieve fundamental noise limits for terrestrial IFOs

Einstein and relativity

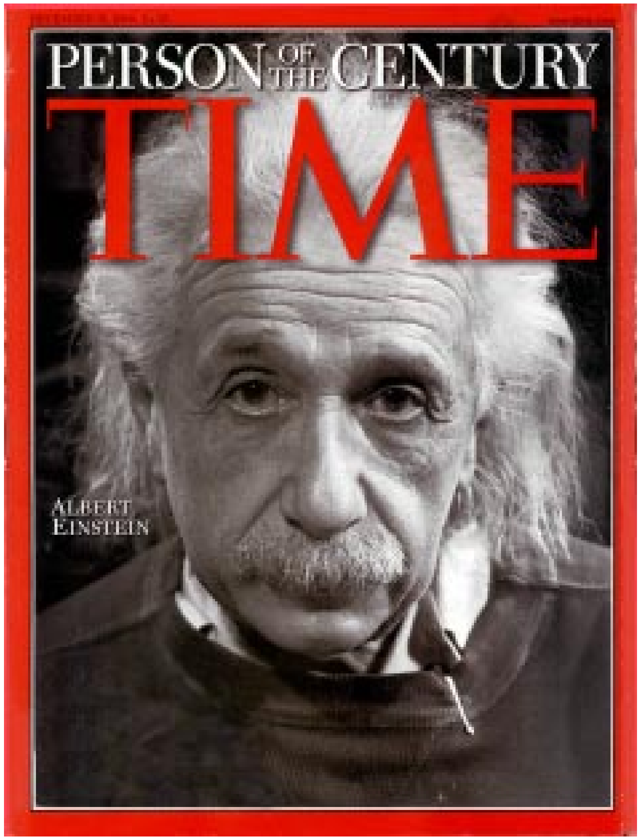
It all starts with Einstein!

- Special Relativity (1906):
  - Distances in space and time change between observers moving relative to one another, but the space-time interval remains invariant:

    $$ds^2 = dx^2+dy^2+dz^2 - c^2dt^2$$

  - space+time ⇒ 4D space-time *geometry*
  - energy and momentum form a 4D vector, with invariant (rest) mass:

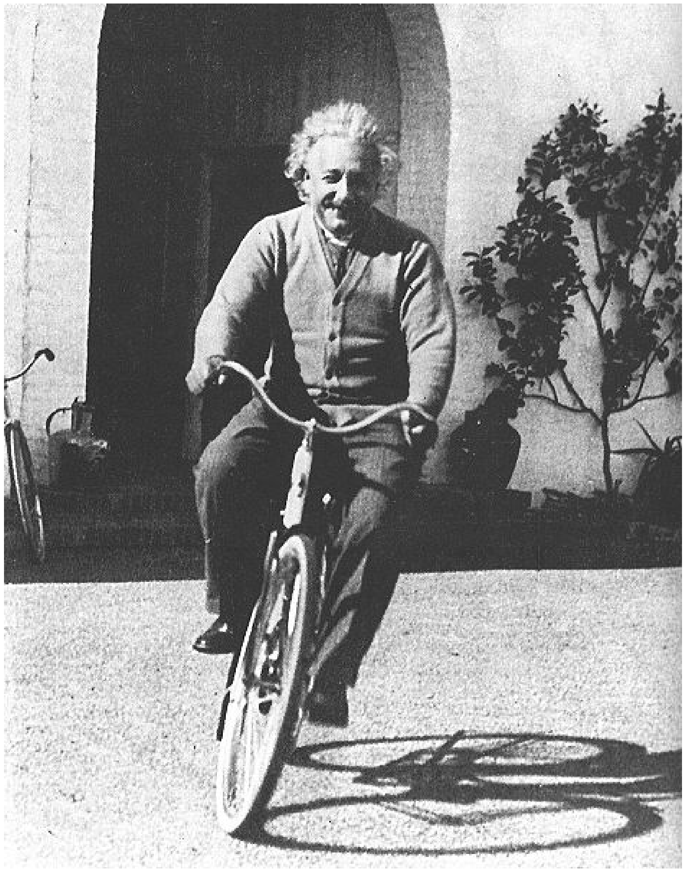
    $$(m_0c^2)^2 = E^2 - (pc)^2 \quad (\text{or } E = mc^2)$$



Space-time geometry

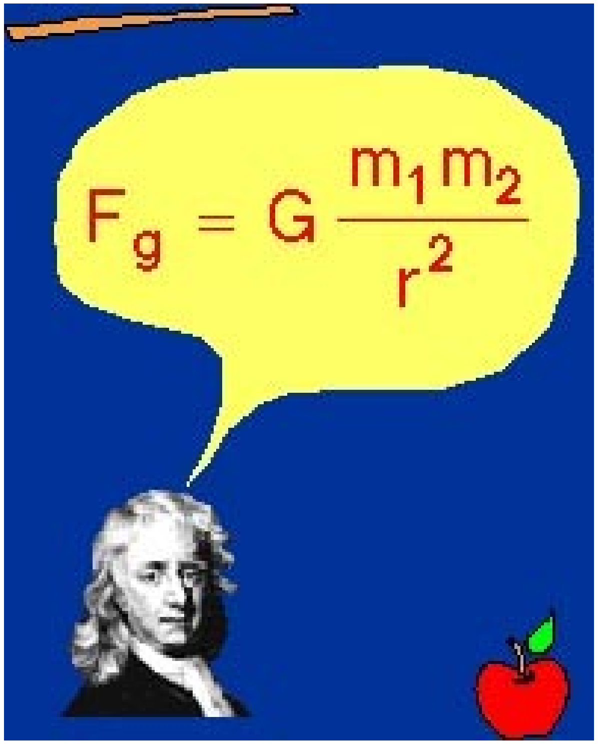
Relativity and space-time geometry:

- 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 (curving) of space-time, not a force acting at a distance



Newtonian Gravity

- Three laws of motion (F=ma) 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.
- Gravitational fields are static (or slowly changing), the force acts over large distances, "instantaneously"



Warped space-time: Einstein's General Relativity (1916)

- **A *geometric* theory of gravity**

➢ gravitational acceleration depends only on the geometry of the space that the "test mass" occupies, not any properties of the test mass itself

➢ for gravity (as opposed to all other forces), motion (acceleration) depends only on location, not mass

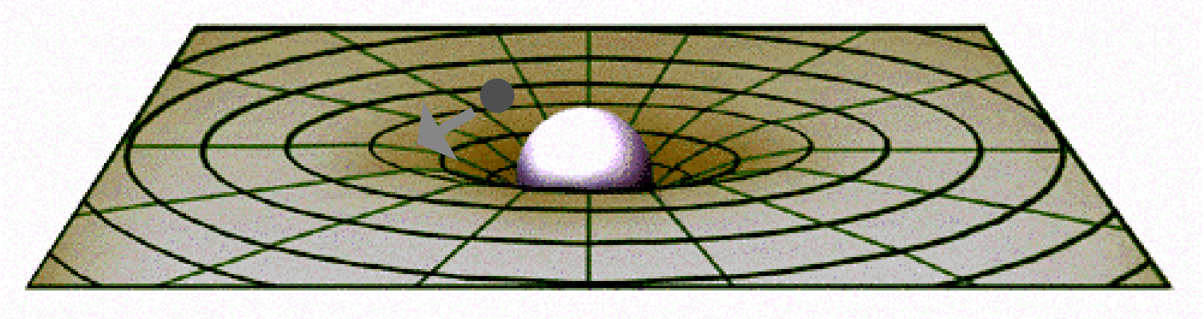
▪**Imagine space as a stretched rubber sheet.**

$$F = \cancel{m_1} a = G \cancel{m_1} m_2 / r^2$$

▪**A mass on the surface will cause a deformation.**

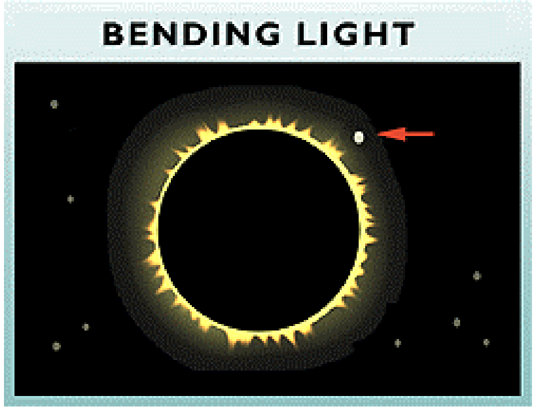
▪**Another mass dropped onto the sheet will roll toward that mass.**

▪**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.**



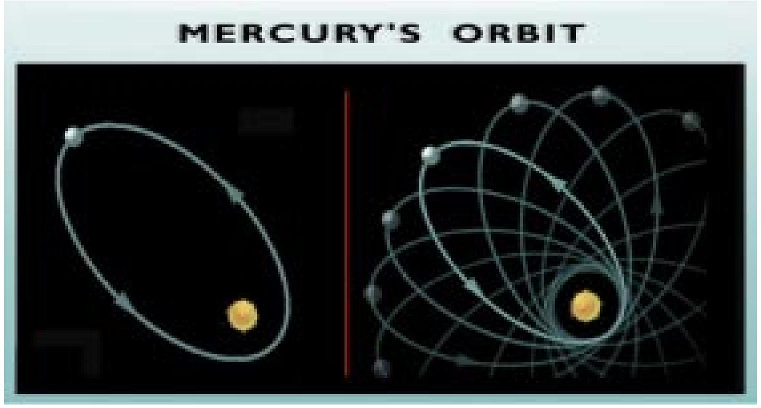
Einstein’s Theory of Gravitation

experimental tests



bending of light
As it passes in the vicinity of massive objects

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



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.

“Einstein Cross”
The bending of light rays
gravitational lensing

Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a ‘dark matter’ body as the central object

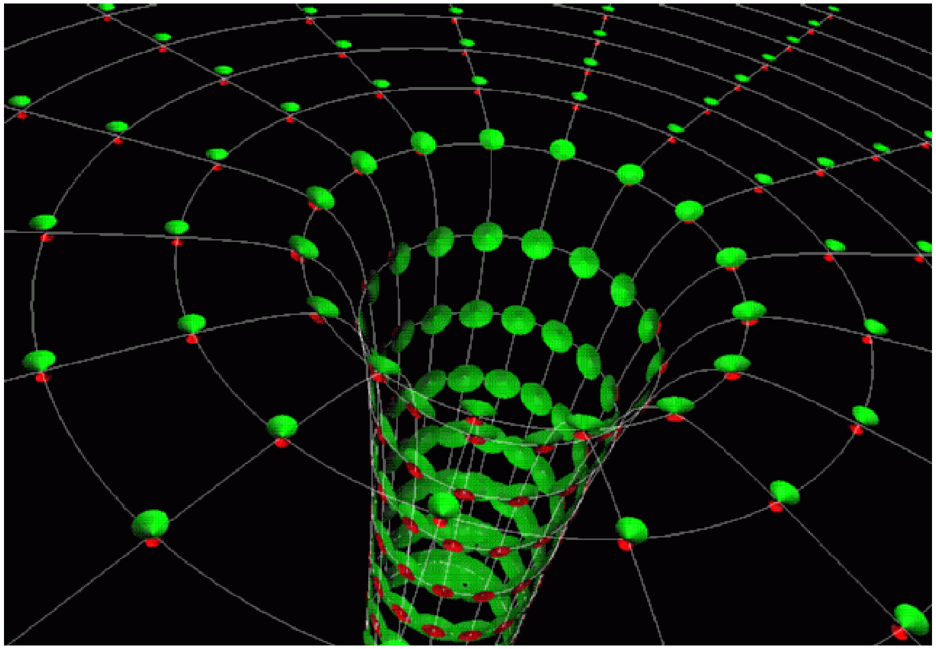
Strength of gravitational force

Interaction	Strength	Acts on	Charge	Carried by	theory
Strong nuclear	10	Quarks	Color	Gluons (*g*) (massless)	QCD
Electromagnetic	10^{-2}	Charged particles	Electric charge	Photon (γ) (massless)	QED
Weak nuclear	10^{-13}	Quarks, leptons	“flavor” charge	W^+, W^-, Z^0 (massive)	QFD
Gravitational	10^{-40}	All particles	Mass	Graviton(*G*) (massless)	GR…?

Gravitational force is very weak!
But at large scales (planets, stars, galaxies, universe) it dominates

Strong-field GR

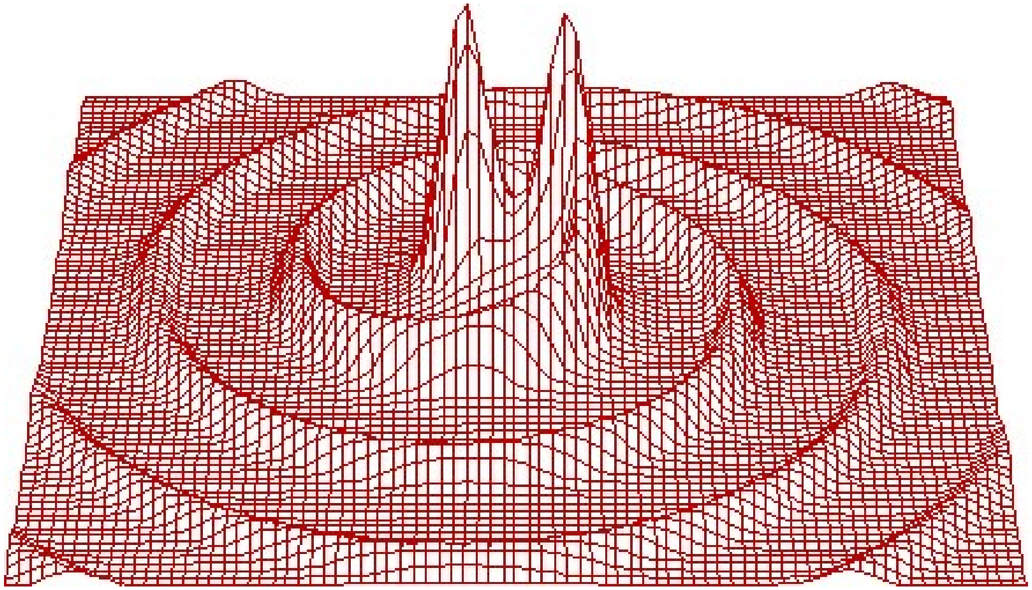
- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light



But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

Dynamics of changing Spacetime curvature

Newton's Theory
"instantaneous action at a distance"



Einstein's Theory
information carried by gravitational radiation at the speed of light

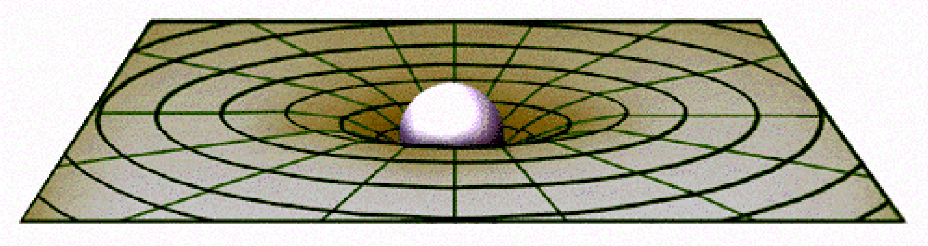
General Relativity (1916)

Einstein's field equation: ***G** = 8π**T***

spacetime curvature ⇔ matter and energy

- spacetime warps in response to the presence of matter, energy, motion
- motion of matter is determined by spacetime curvature
- for gravity (as opposed to all other forces), motion (acceleration) depends only on location, not mass
- 16 coupled non-linear differential equations; analytical solutions in only the simplest of cases (spherical symmetry, static, etc)

$$F = \cancel{m}_1 a = G\cancel{m}_1 m_2 / r^2$$



Space-time geometry metric

- Einstein field tensor *G* is a function only of the space-time metric *g* which describes local geometry
- Space-time interval *ds*

  (generalization of Pythagorean theorem to space-time):

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2$$

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- *g* is space-time metric
- η is flat space Minkowski metric,
- *h* is metric perturbation

  for weak gravitational fields, components of $h \ll 1$

Metric perturbation *h*

- In the weak-field limit (*h* << 1), Einstein's field equations can be linearized
- In the "transverse traceless" (TT) gauge, they become a wave eqn for *h* (no matter sources):

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

- The metric perturbation is interpreted as a gravitational wave amplitude, travelling at the speed of light:

$$h(2\pi ft-\mathbf{k}\bullet\mathbf{x}),\ \text{where } 2\pi f = c|\mathbf{k}|$$

- Gravitational wave metric perturbations stretch and squeeze the space they pass through (strain amplitude)

Reality of gravitational waves

- Due to non-linearity and other complexities of GR, the energy carried by a GW is ill-defined
- it was long debated whether GWs are even real!
- Finally, convincing arguments by Bondi, others (60’s)
- Alternate perspectives:
  - » GW stretches and squeezes space between two test masses
  - » GW accelerates test masses in fixed space
- Either way, we can sense effect by measuring phase advance e^{ikx} of laser beam between the masses
- Doesn’t GW stretch/squeeze the laser wavelength an equal amount, to cancel the effect?
- NO! Effect on “freely falling” test masses is different from effect on light beams; interferometers measure this difference!

Gravitational Waves from astrophysical sources

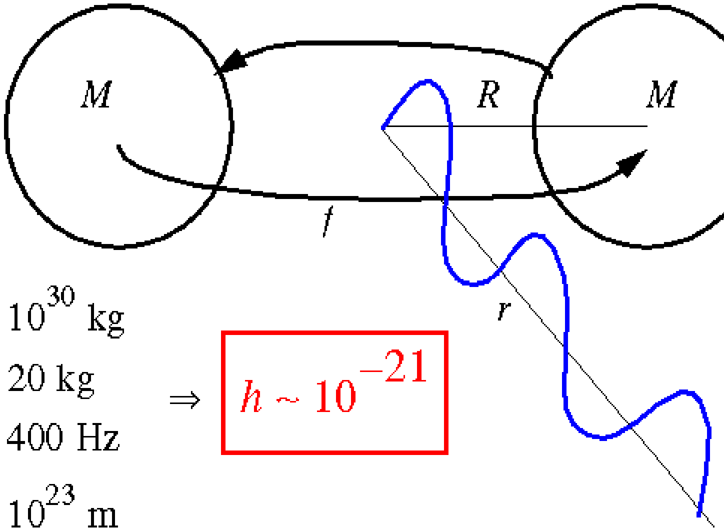
- Predicted by Einstein’s Theory of General Relativity
- Test of the strong field theory
- Radiated by astrophysical objects
  – coherent quadrupolar motion of very massive objects
- Radiated by "dark" mass distributions: black holes, dark matter
- Interacts *extremely weakly* with matter
  – can cross the universe with no attenuation
- Warps space as it passes by (changes the metric)
  – changes measured distance between two test masses
- *Extremely* weak – very hard to detect!

Sources of GWs

- Accelerating charge ⇒ electromagnetic radiation
- Accelerating mass ⇒ gravitational radiation
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy)
- G is a small number!
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:



$M \sim 10^{30}$ kg
$R \sim 20$ kg
$f \sim 400$ Hz
$r \sim 10^{23}$ m

$$\Rightarrow \boxed{h \sim 10^{-21}}$$

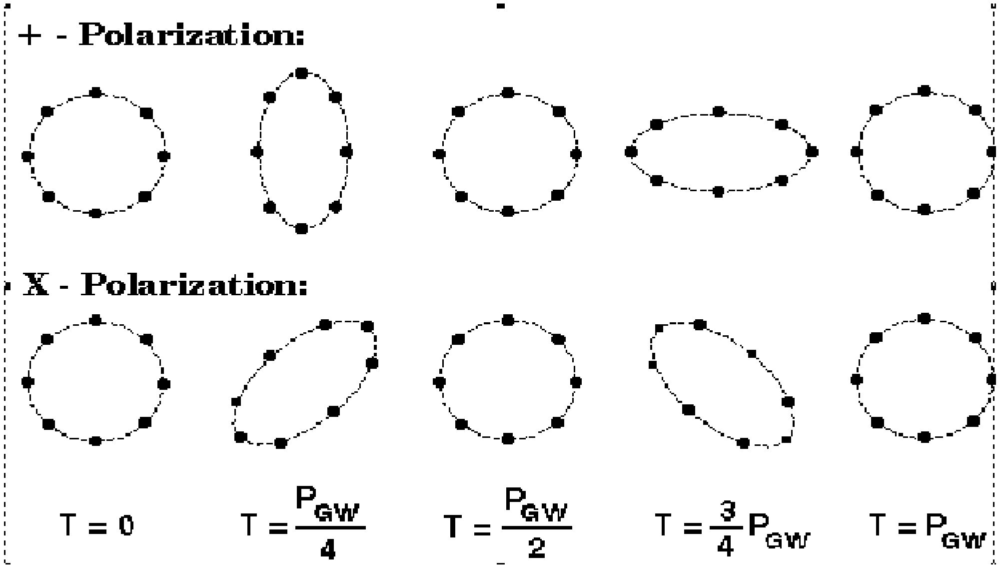
Terrestrial sources *TOO WEAK!*

Nature of Gravitational Radiation

General Relativity predicts :

- transverse space-time distortions, freely propagating at speed of light
- Conservation laws:
  - conservation of energy ⇒
    no monopole radiation
  - conservation of momentum ⇒
    no dipole radiation
  - quadrupole wave (spin 2) ⇒
    two polarizations

plus (⊕) and cross (⊗)

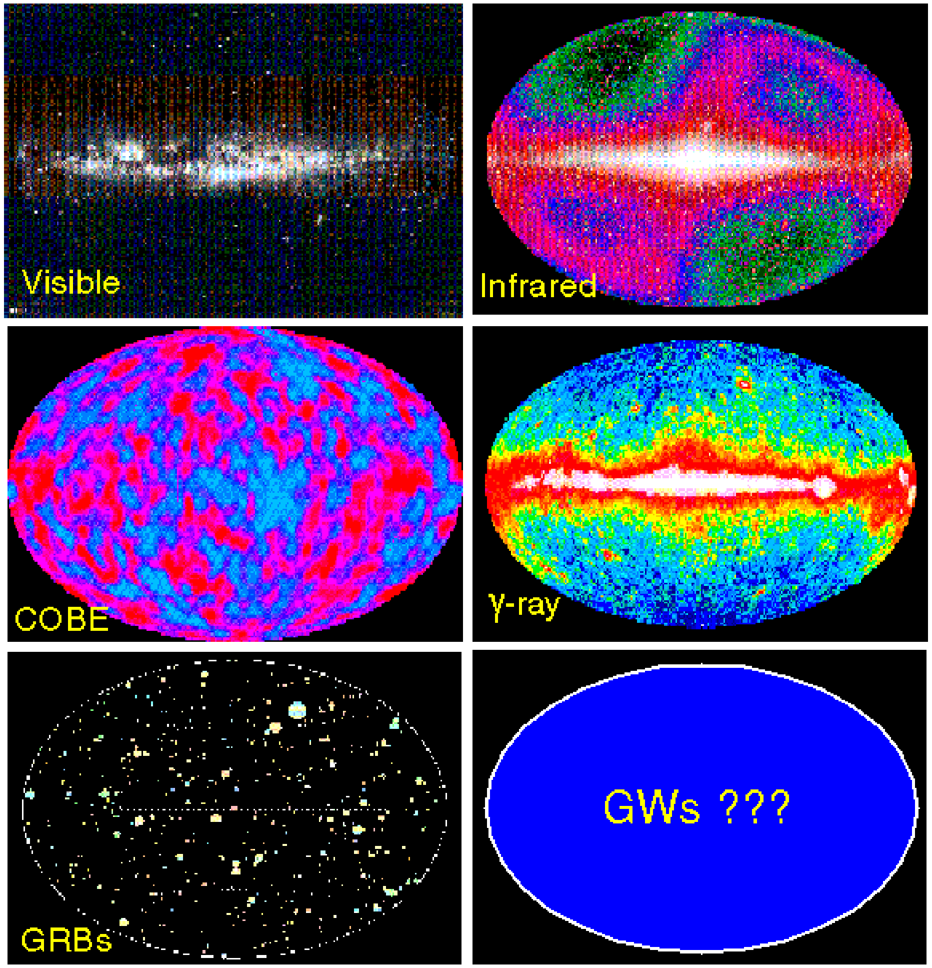


Contrast EM and GW information

E&M	GW
space as medium for field	Space-time itself
incoherent superpositions of atoms, molecules	coherent motions of huge masses (or energy)
wavelength small compared to sources - images	wavelength ~large compared to sources - poor spatial resolution
absorbed, scattered, dispersed by matter	very small interaction; no shielding
10^6 Hz and up	10^3 Hz and down
measure amplitude (radio) or intensity (light)	measure amplitude
detectors have small solid angle acceptance	detectors have large solid angle acceptance

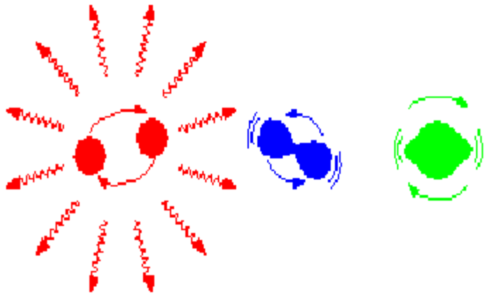
- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on E&M observations

What will we see?

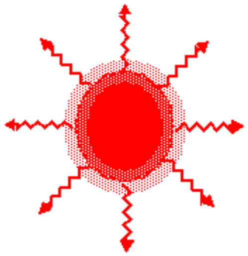


Astrophysical Sources of Gravitational Waves

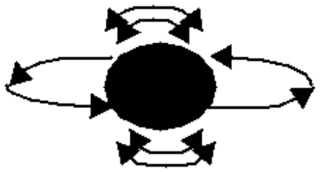
Coalescing compact binaries
(neutron stars, black holes)



Non-axi-symmetric
supernova collapse



Non-axi-symmetric pulsar
(rotating, beaming
neutron star)

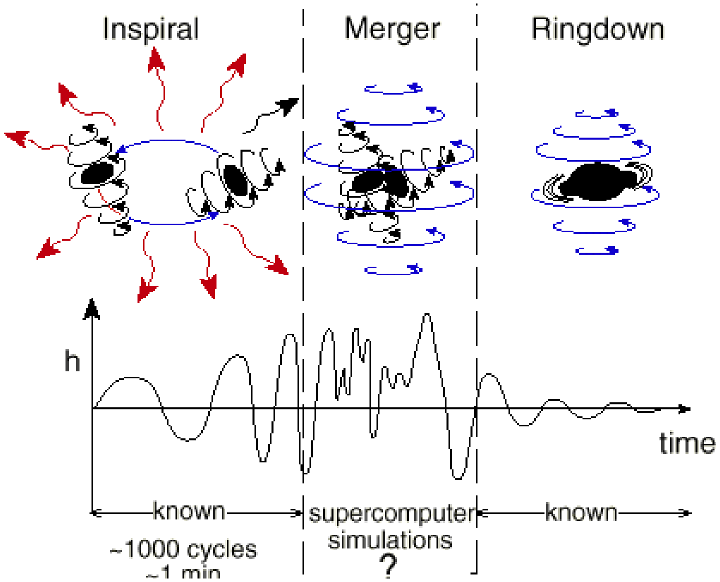


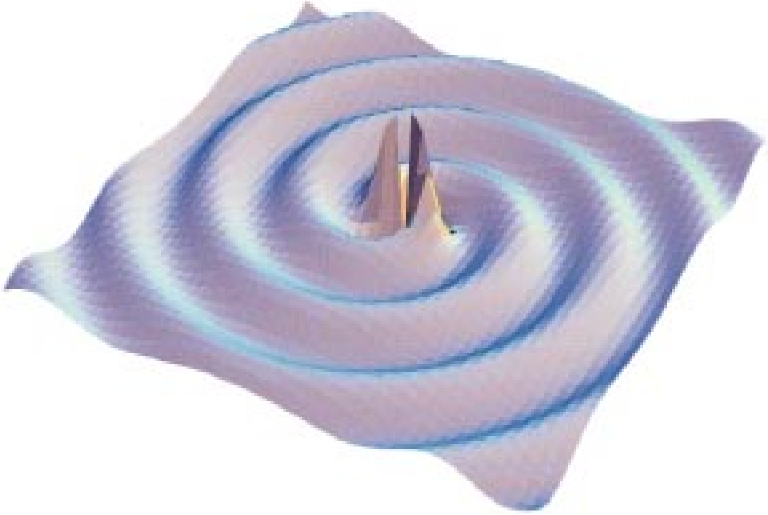
Waveforms of Gravitational Waves

- “Chirps” (reasonably known waveforms)
  - Neutron star (NS/NS) binary pairs
  - Black hole (BH/BH) binaries; NS/BH binaries
- Periodic (well defined waveforms)
  - Pulsars with ellipticity
  - "Wagoner" stars (neutron stars spinning up, with instabilities)
- Impulsive (unknown waveforms)
  - Supernova bursts
- Stochastic (random, indistinguishable from noise)
  - Background from primordial cosmological event (Big Bang)
- Unknown???
  - Rates, signal sizes, waveforms for all the above are *very* uncertain
  - Surprises are *certain*!

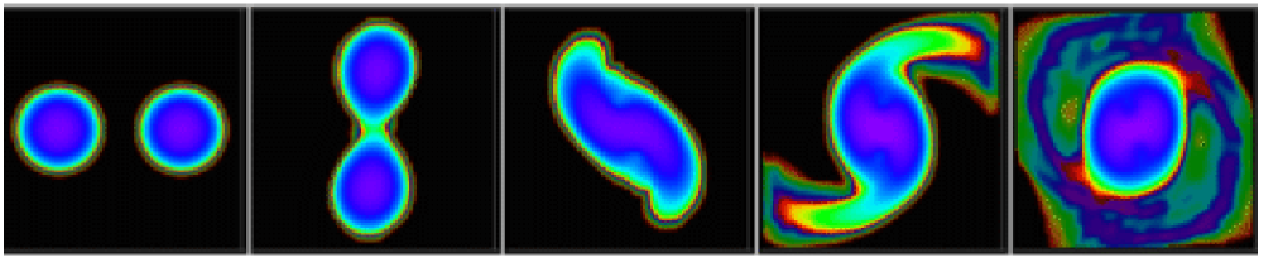
GWs from coalescing binaries

Compact binary mergers

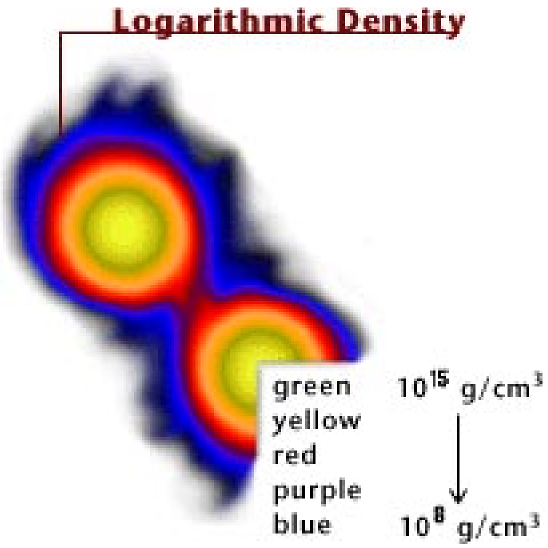


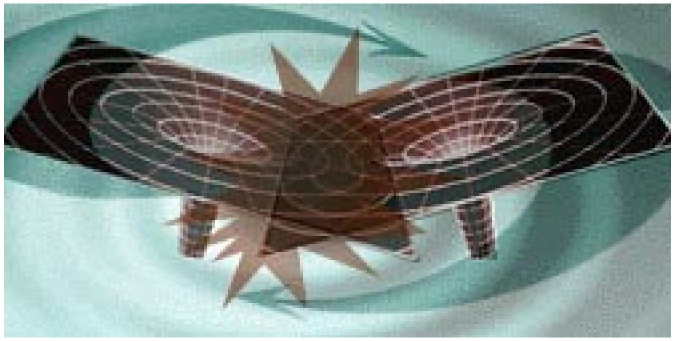


- Neutron star – neutron star (Centrella et al.)

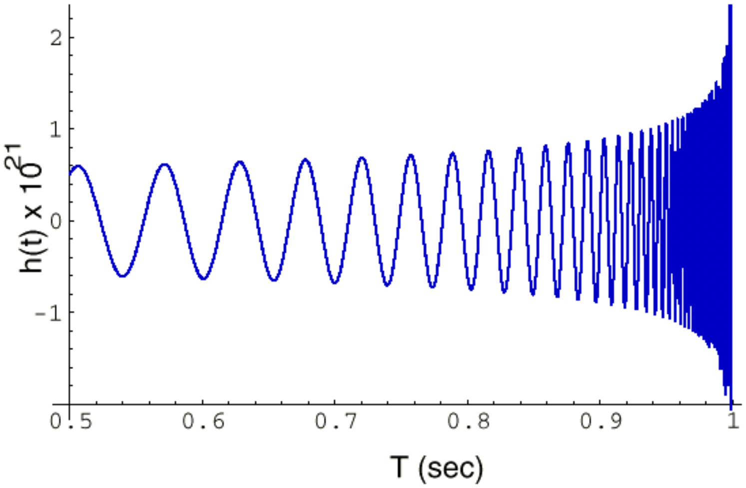


Compact Binary Inspirals

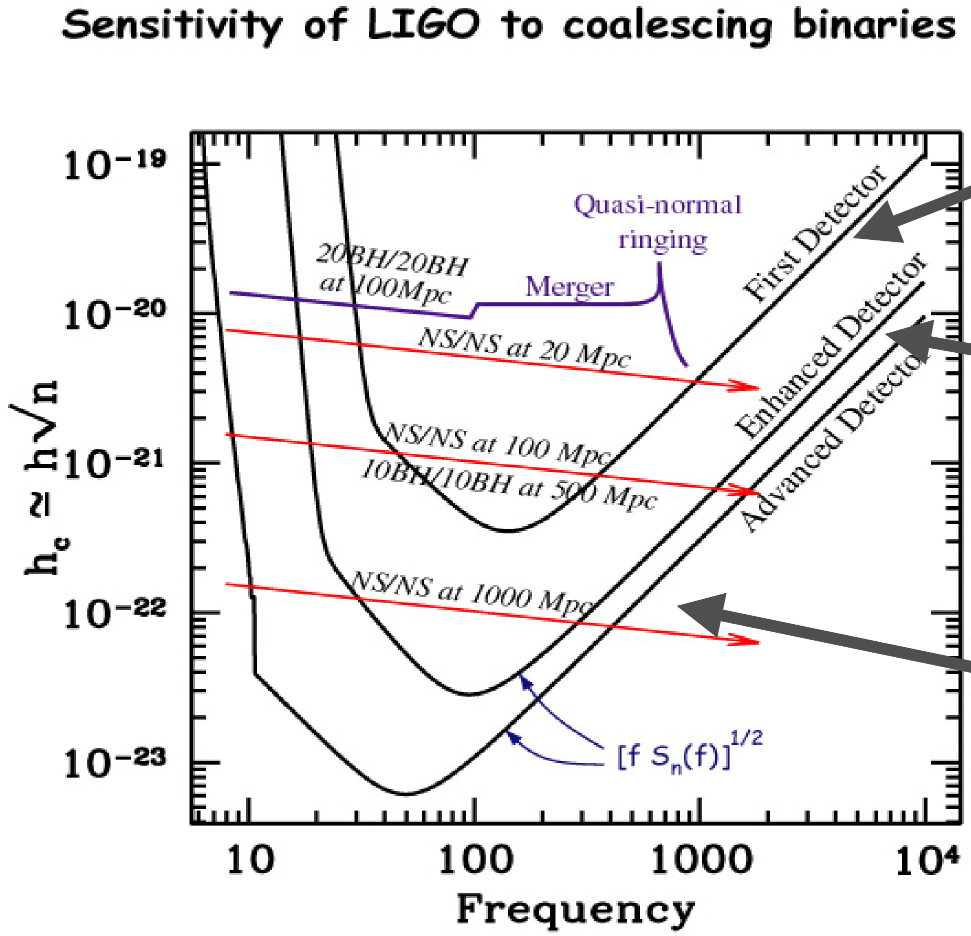




“Chirp Signal”



Astrophysical sources: Thorne diagrams



LIGO I (2002-2005)

LIGO II (2007-)

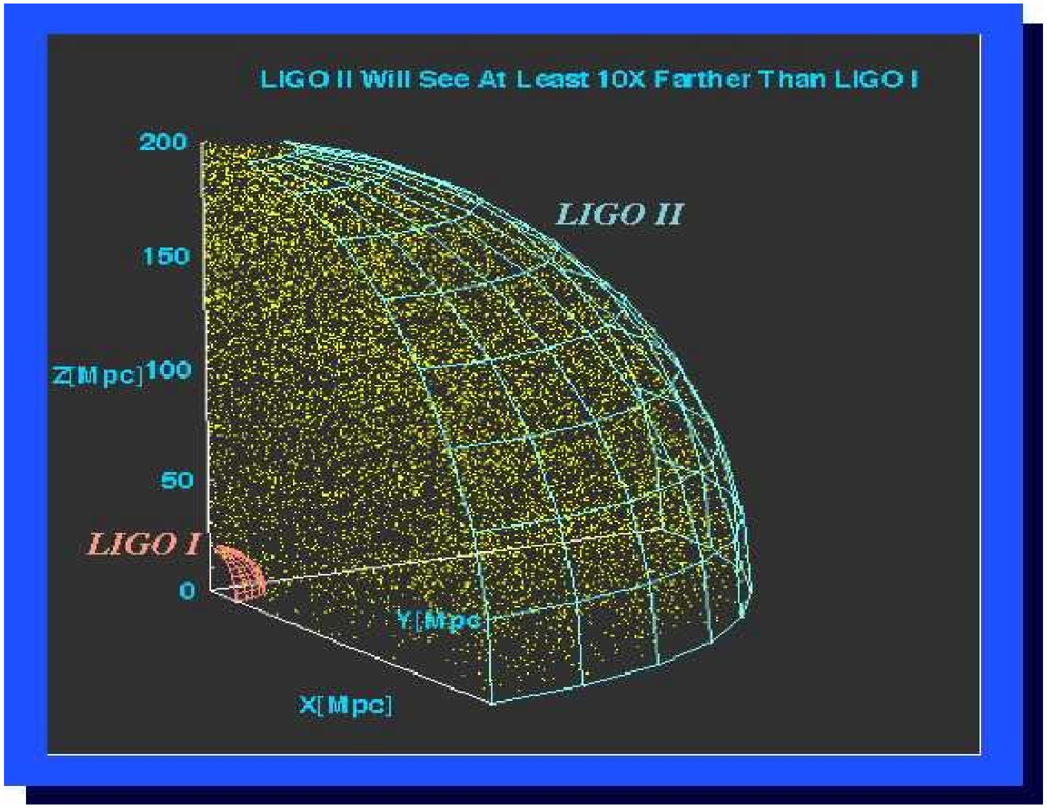
Advanced LIGO

How far out can we see?

Improve sensitivity by a factor of 2x, and…

⇒ Improve sensitivity to distance by 10x (h ~ 1/r)

⇒ Number of sources goes up 1000x ($1/r^3$) !

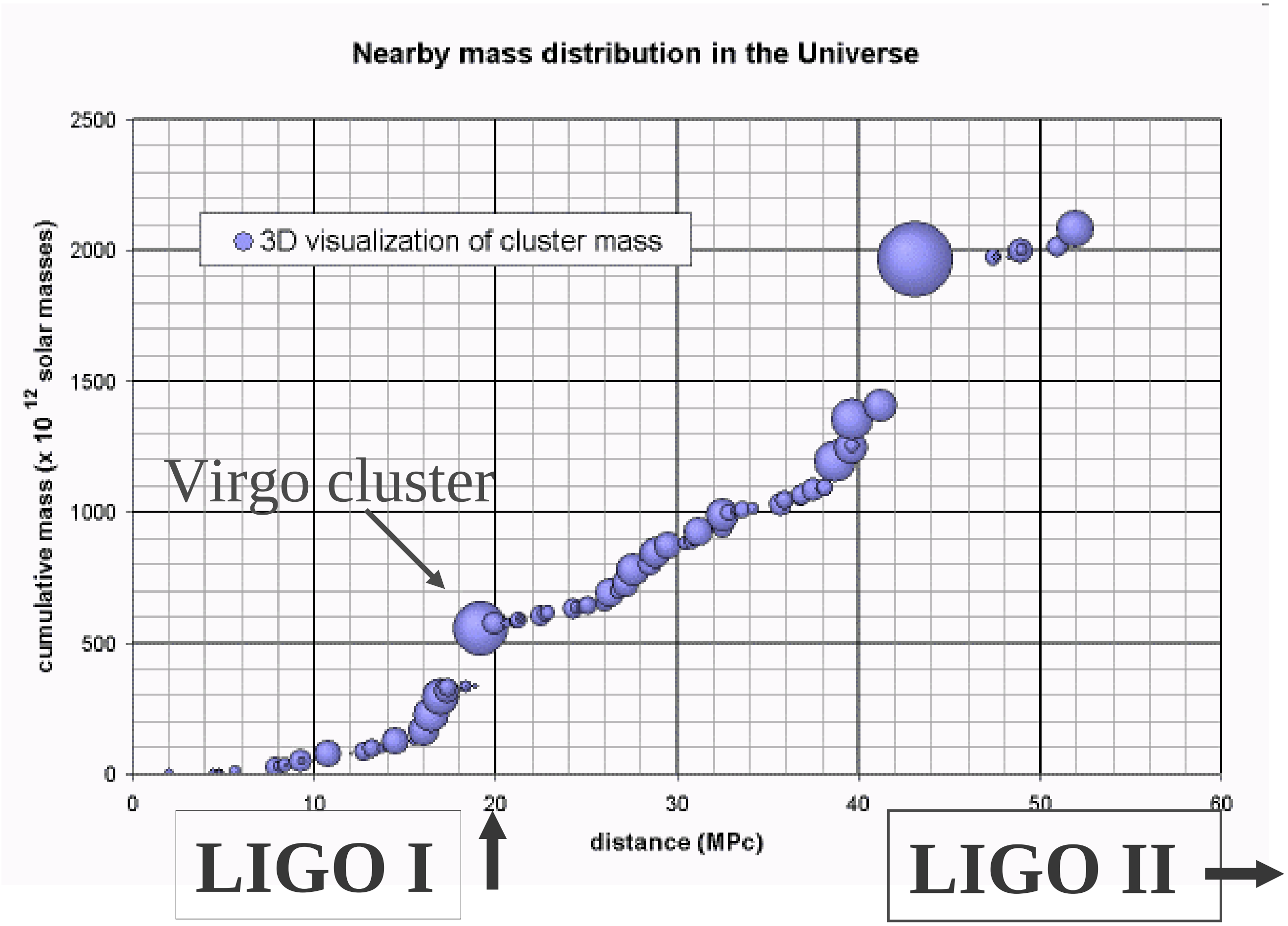


How many sources can we see?

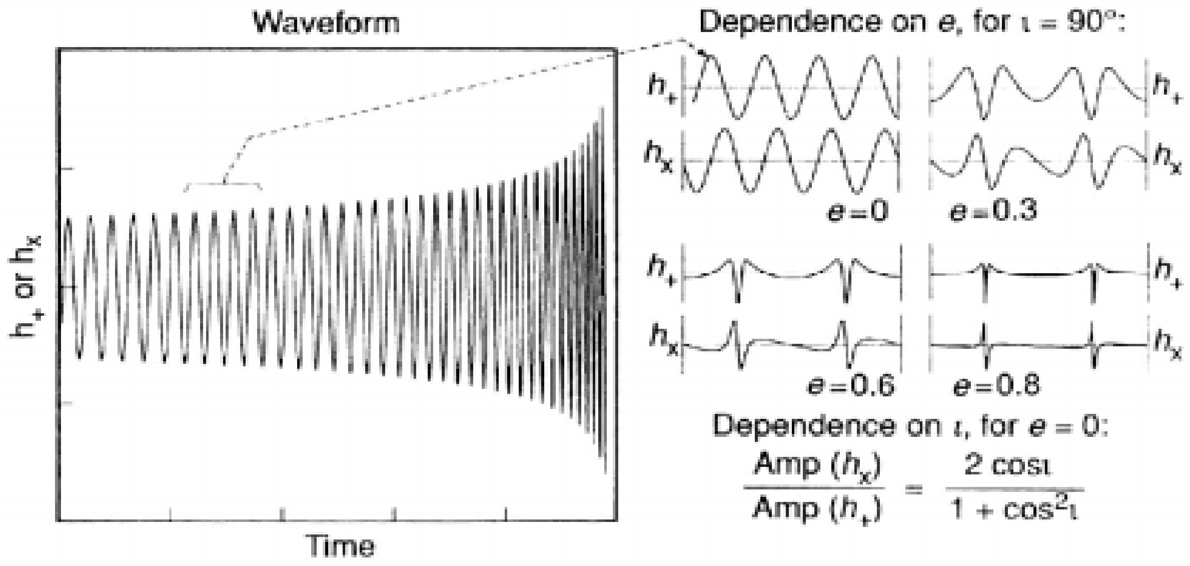
Improve sensitivity by a factor of 2x

⇒ Improve sensitivity to distance by 2x (h ~ 1/r)

⇒ Number of sources goes up 8x ($1/r^3$) !



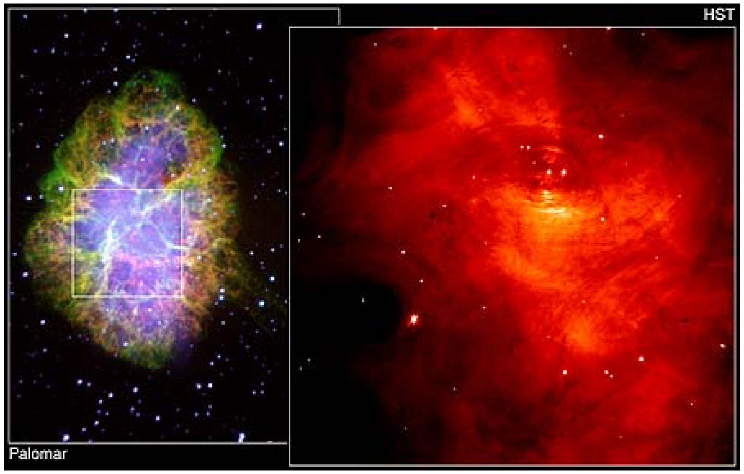
Chirp signal from Binary Inspiral



<u>determine</u>

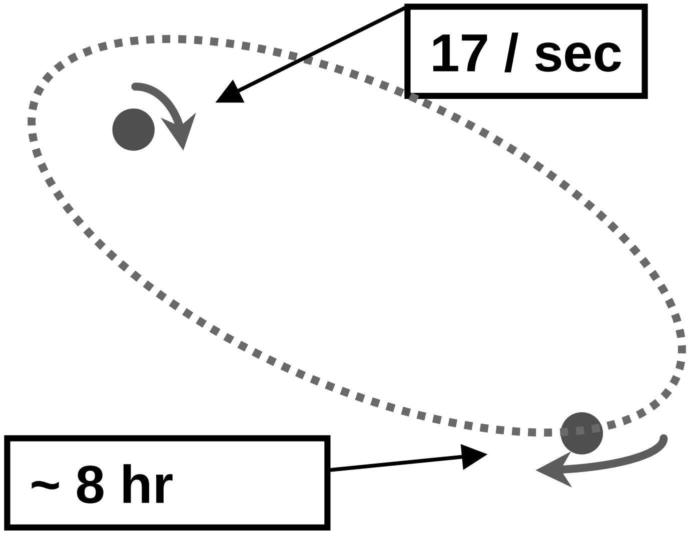
- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination *i*

Hulse-Taylor binary pulsar



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars



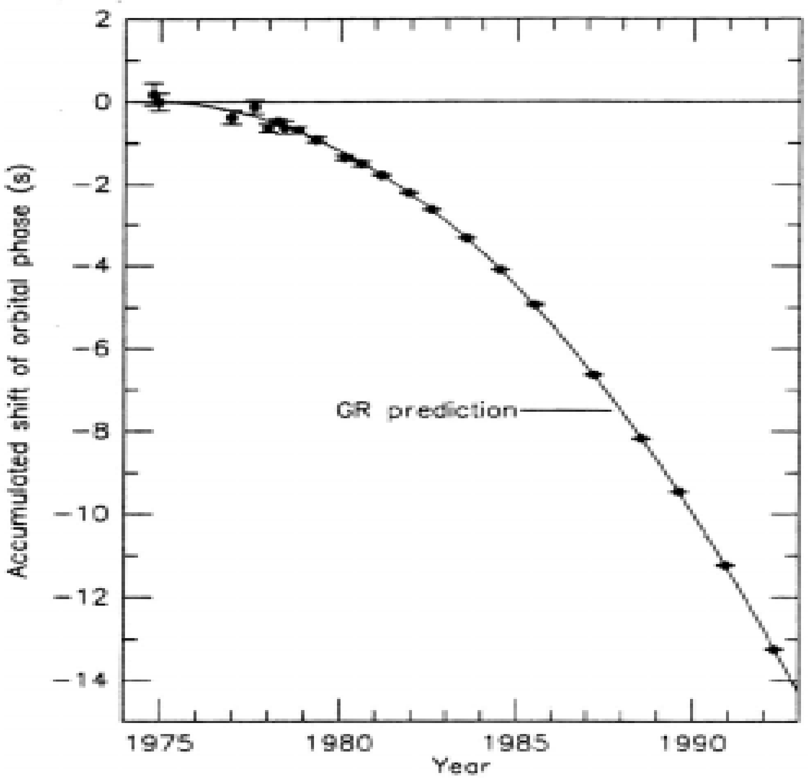
17 / sec

~ 8 hr

GWs from Hulse-Taylor binary

emission of gravitational waves by compact binary system

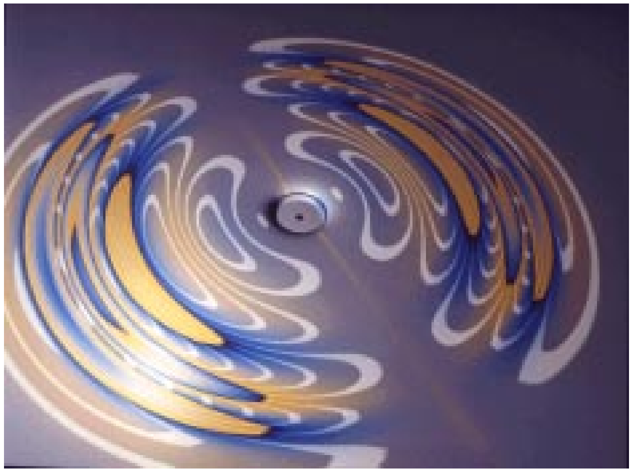
- Only 7 kpc away
- period speeds up 14 sec from 1975-94
- orbital energy loss ⇒shortening of period
- Compact system:
  - negligible loss from friction, material flow
- measured to ~50 msec accuracy
- deviation grows quadratically with time
- Merger in about 300M years
  - (<< age of universe!)
- beautiful agreement with GR prediction
- Apparently, loss is due to GWs!
- Nobel Prize, 1993



Black holes: computer simulations

Testing General Relativity in the Strong Field Limit

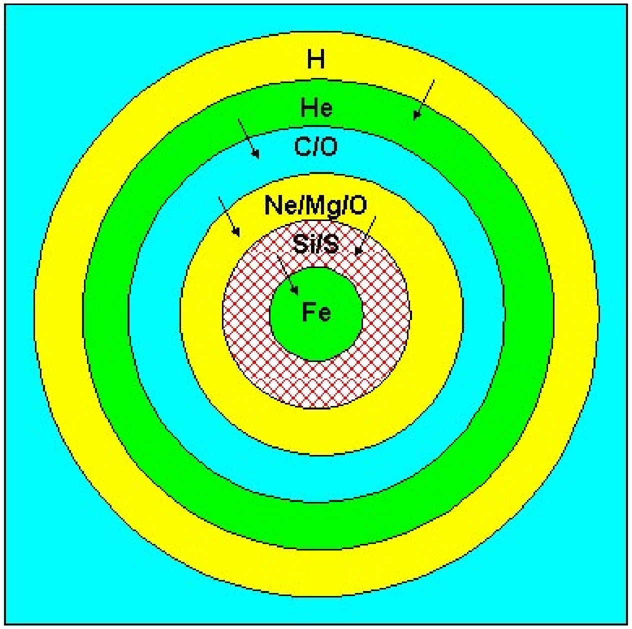
Distortion of spacetime by a blackhole

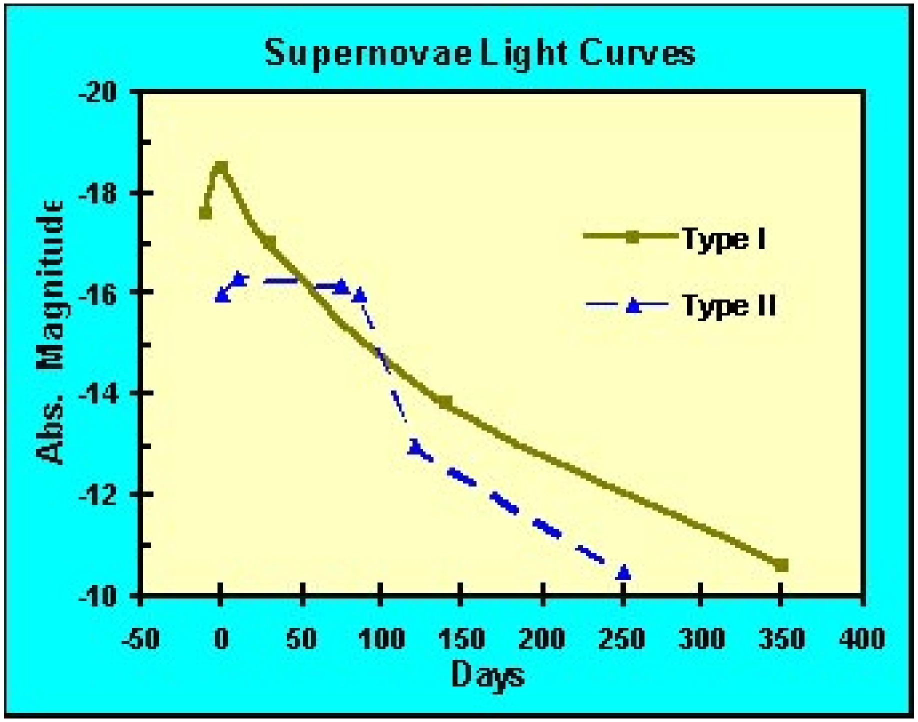


Collision of two blackholes

“Grand Challenge” – Supercomputer Project

Supernova collapse

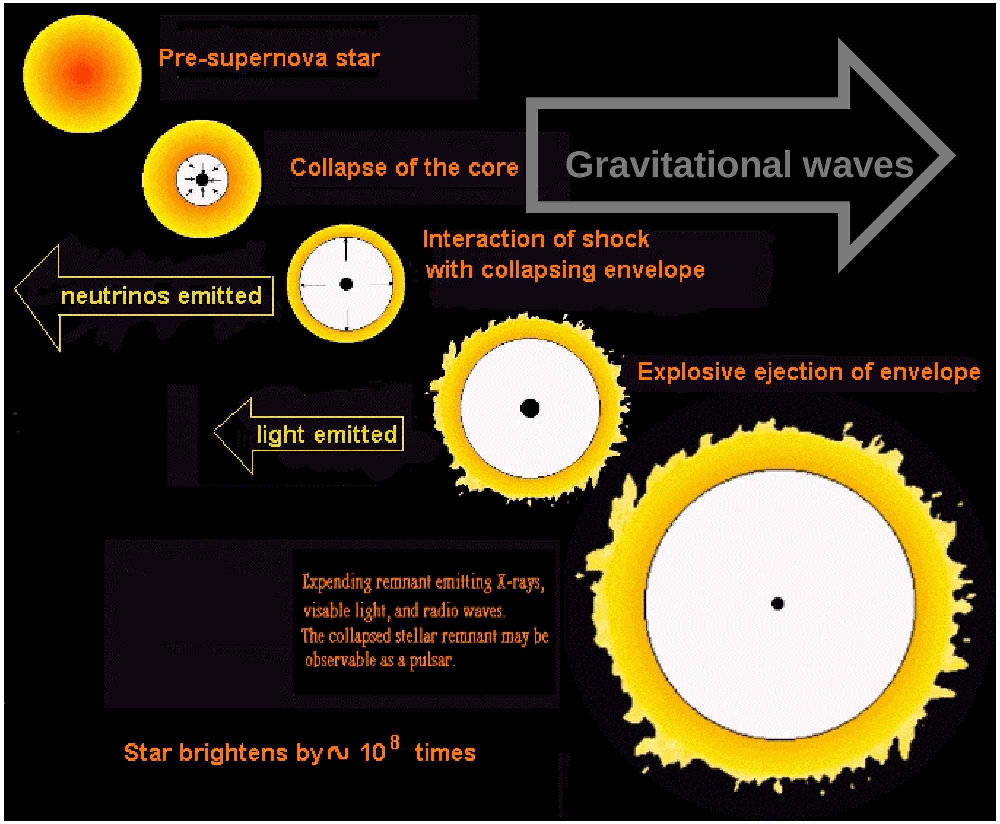




The Collapse

Optical Light Curve

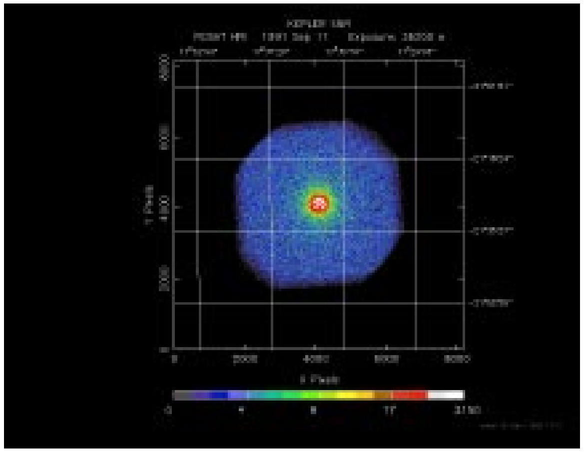
Supernova collapse sequence



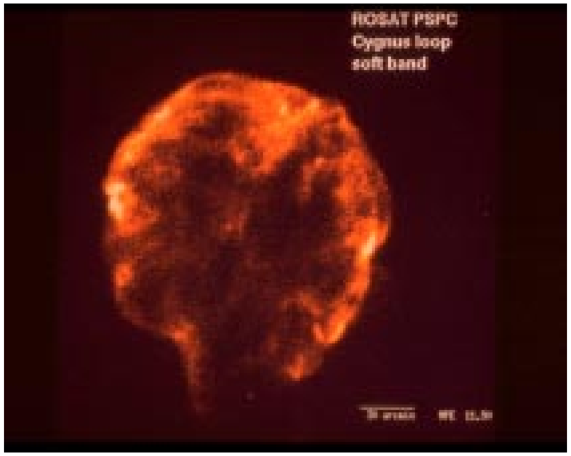
- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.

Historical Supernova (our galaxy)

Kepler SNR



Cygnus Loop Remnant



- **SN1006 in Centaurus in the southern sky**
- **SN1054 - The Crab Supernava in Taurus recorded by Chinese and Native American astronomers**
- **SN 1572 -Tycho's Supernova, studied in detail by Tycho Brahe**
- **SN 1604 Kepler's Supernava**
- **+other possible Milky Way supernovae**

- **<u>Rate</u>**

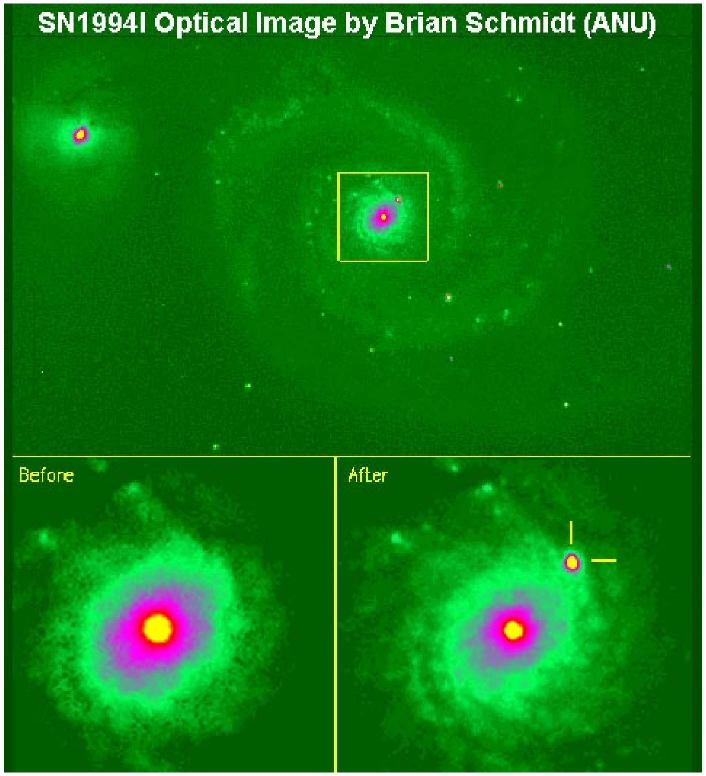
▪ **our galaxy**	**1/50 years**
▪ **within Virgo Cluster**	**~ 1 year**

Supernova optical observations

SN remnant

Crab Nebula 1054 AD

SN explosion

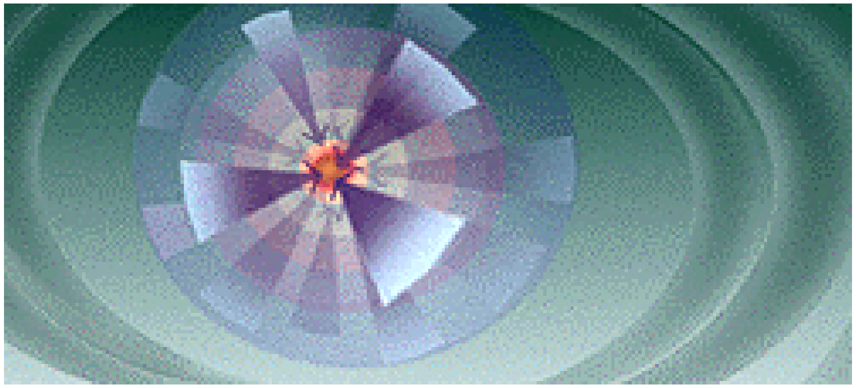


SN1994I Optical Image by Brian Schmidt (ANU)

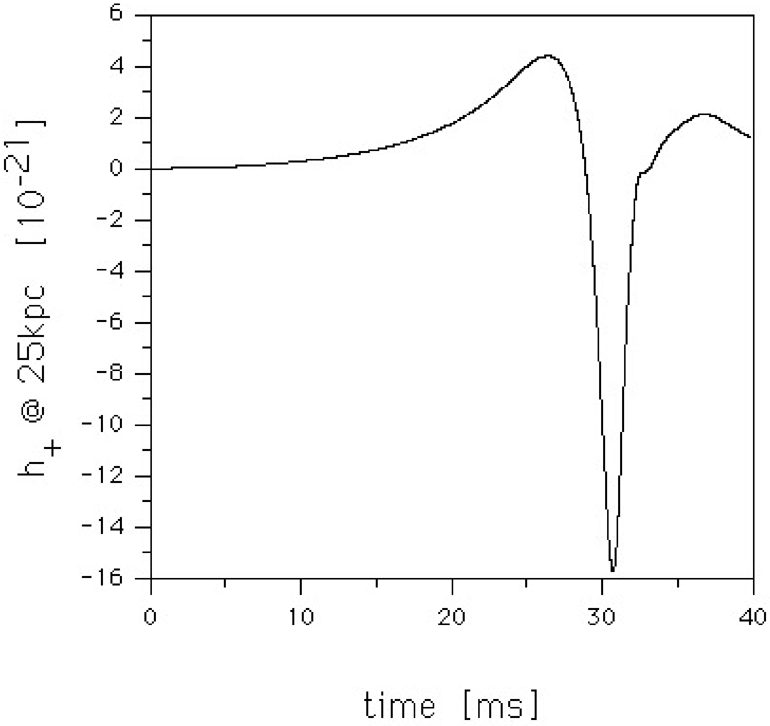
Supernovae - SN1994I

Gravitational Waves from Supernova collapse

Non axisymmetric collapse



‘burst’ signal



Rate

1/50 yr - our galaxy

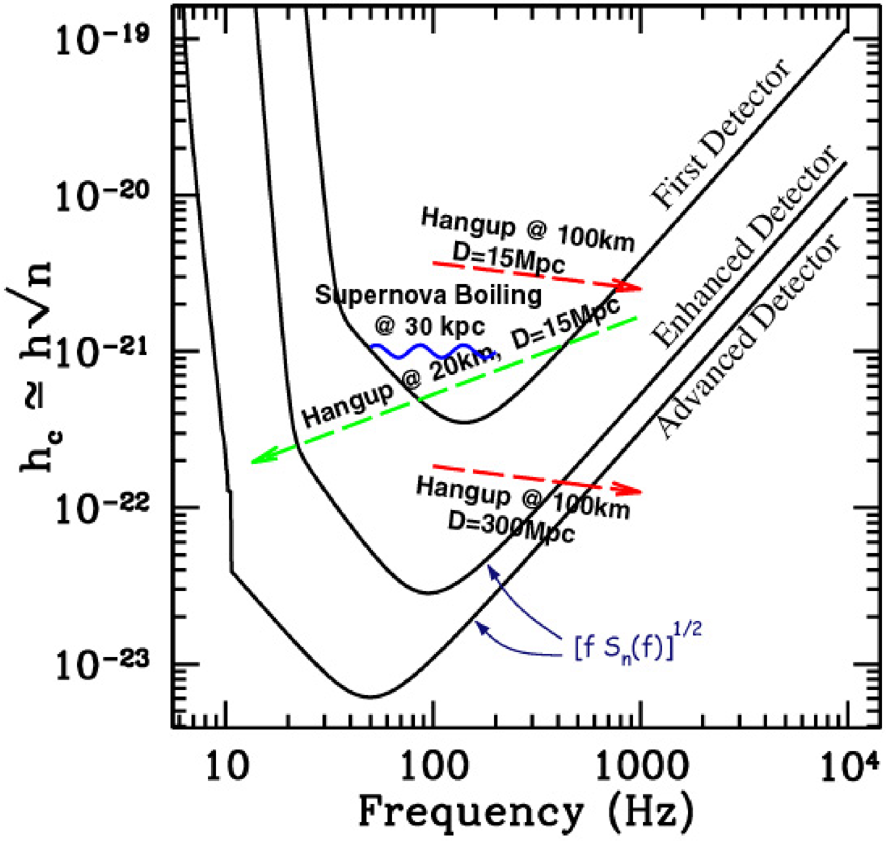
3/yr - Virgo cluster

LIGO

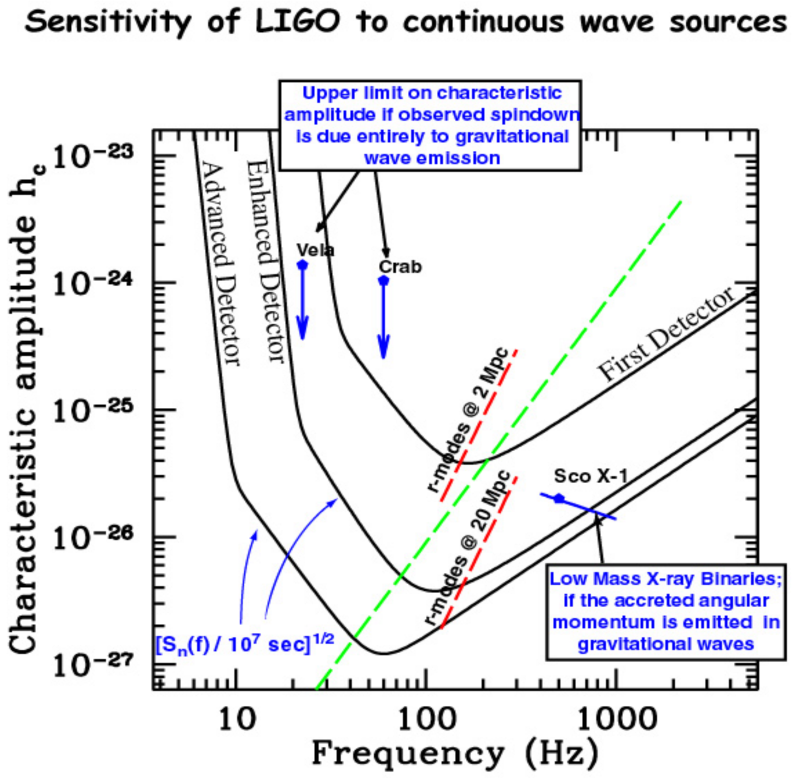
astrophysical sources

SN1987A

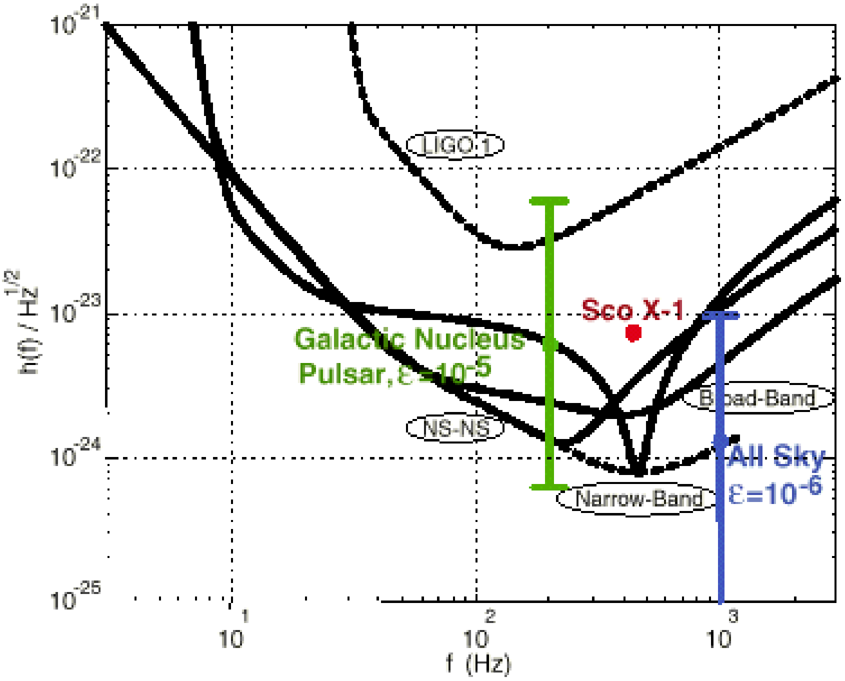
Sensitivity of LIGO to burst sources



Pulsars and continuous wave sources

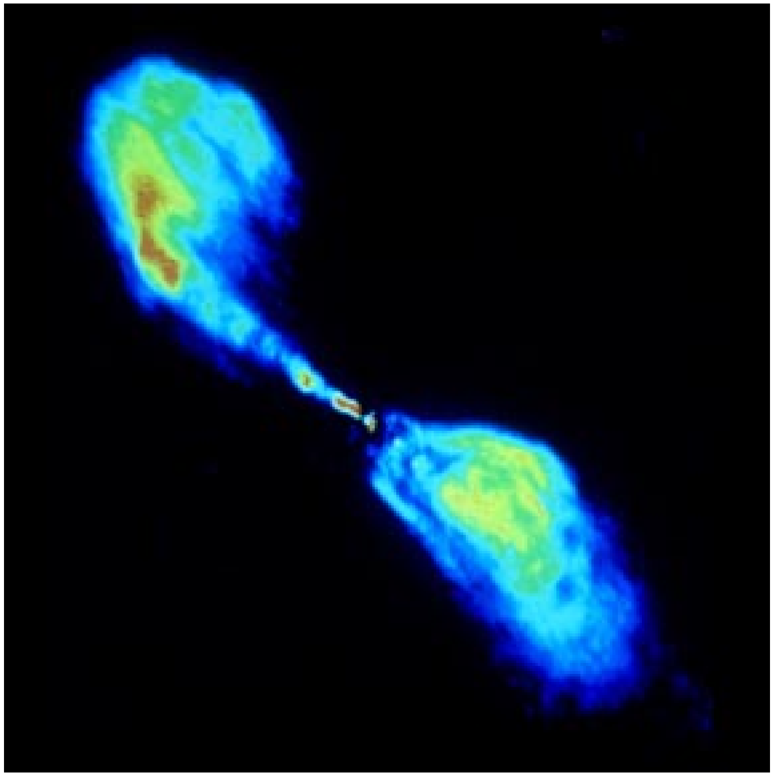


- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »“R-mode” instabilities
  - »narrow band searches best



GWs from dark matter

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

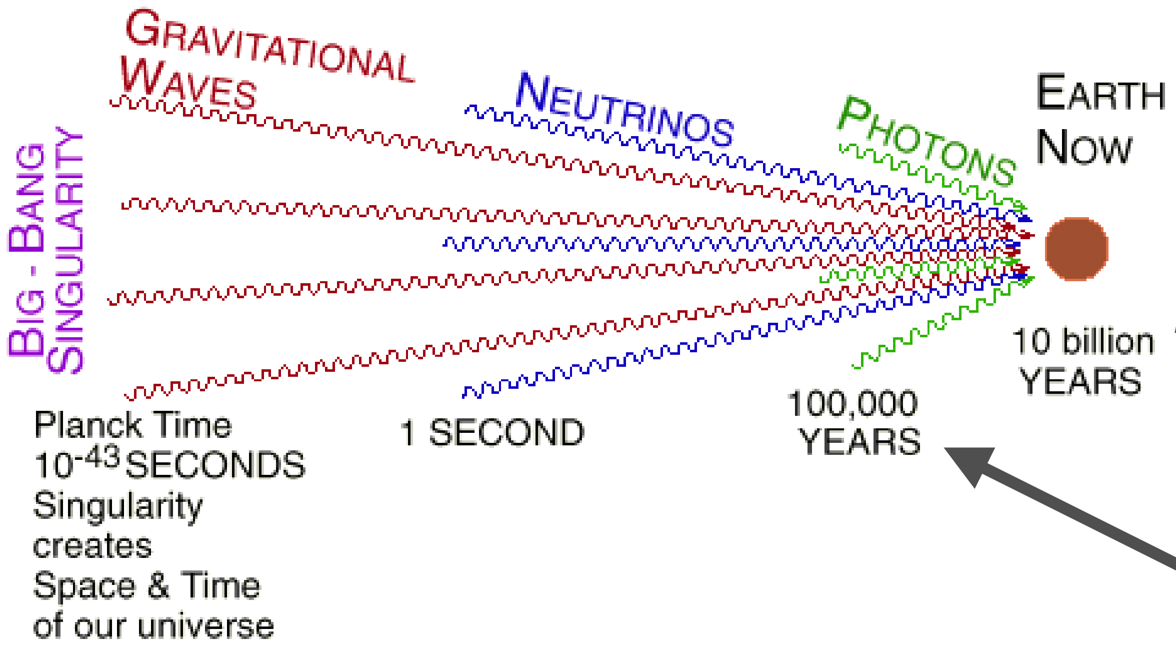


Stochastic Background

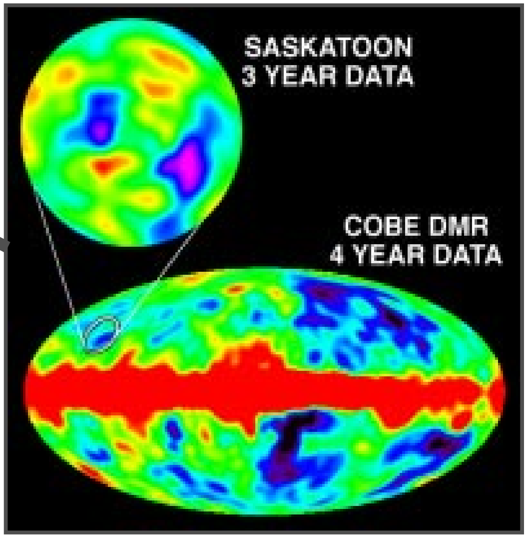
Several possible (speculative) sources:

- primordial “big-bang” background
  - Standard big bang models predict an unmeasurably small strain
- cosmic strings
  - Exotic big bang models predict large structures that radiate GWs
- Statistical properties are indistinguishable from noise
  - Must cross-correlate random “noise” between two widely separated detectors
- confusion limit
  - Incoherent sum of all the weak sources in the universe, added up.
  - Expected to be measureable at very low frequencies (LISA)

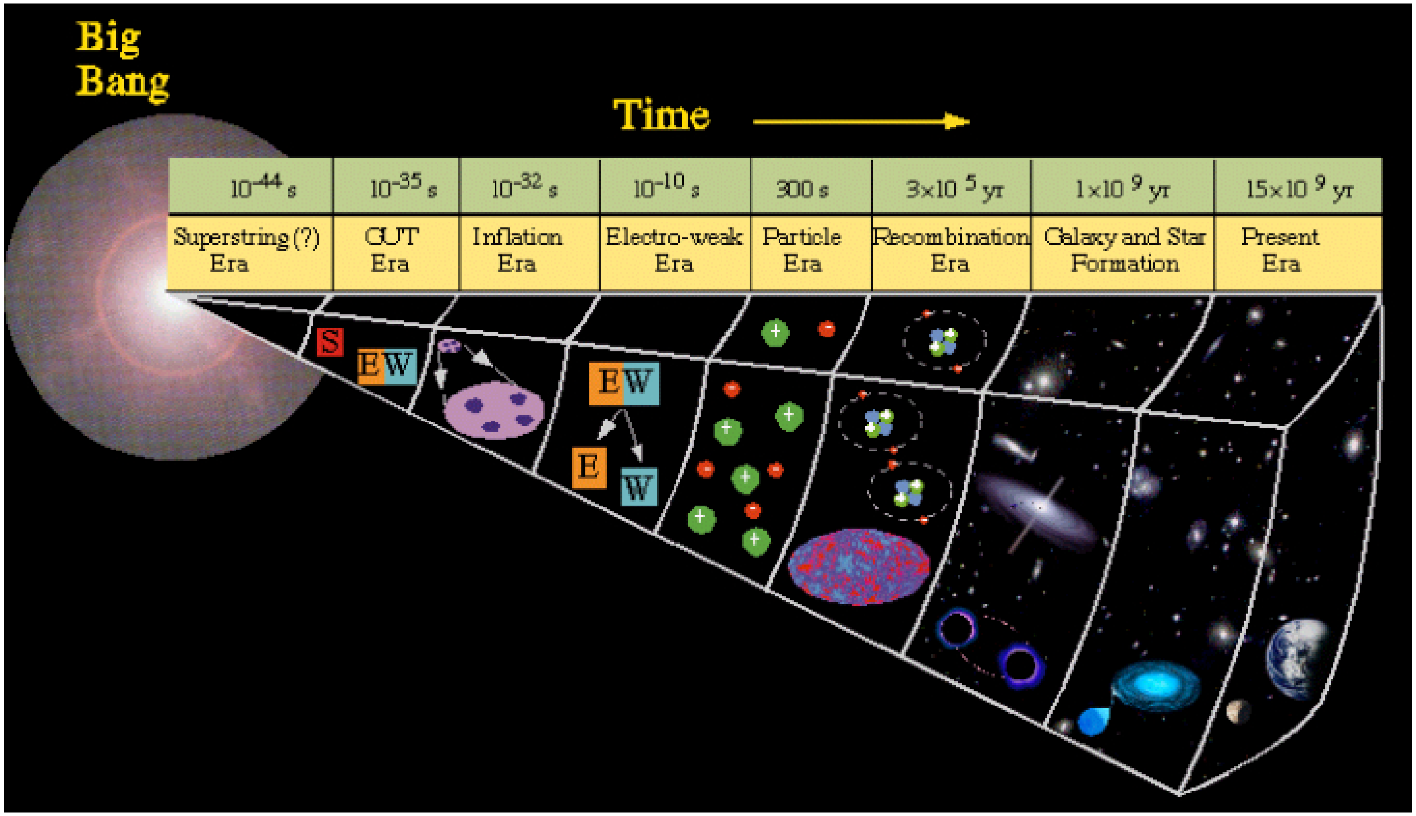
Gravitational waves from Big Bang



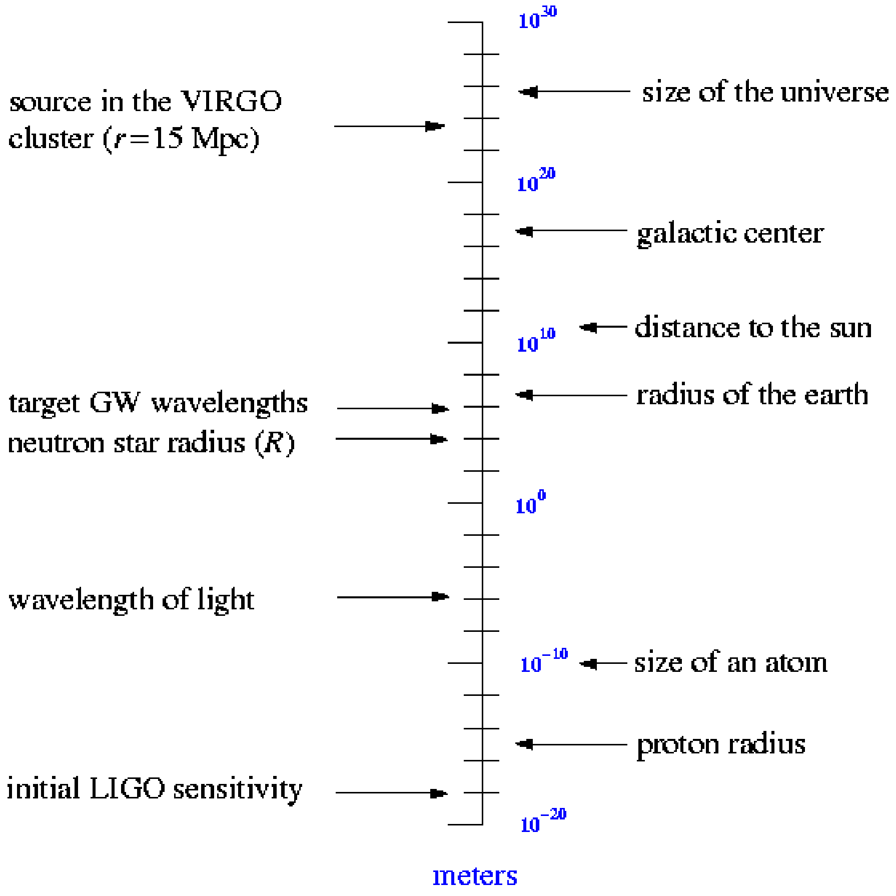
Cosmic microwave background



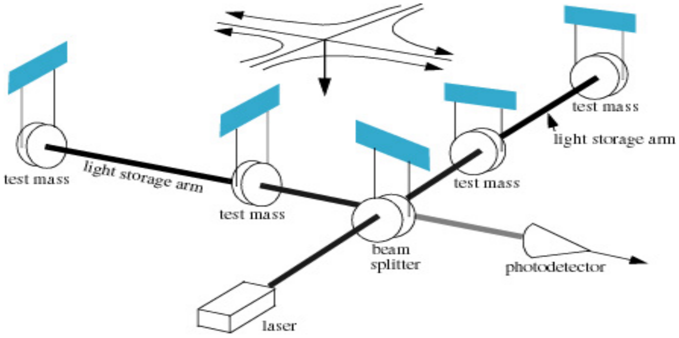
GWs probe the universe at earliest times after the Big Bang



Scales


10^{30}
size of the universe
source in the VIRGO cluster ($r = 15$ Mpc)
10^{20}
galactic center
distance to the sun
10^{10}
radius of the earth
target GW wavelengths
neutron star radius (R)
10^{0}
wavelength of light
10^{-10}
size of an atom
proton radius
initial LIGO sensitivity
10^{-20}
meters

Einstein's Songlines



- Space-time of the universe is (presumably!) filled with vibrations: Einstein's Songlines
- LIGO will soon 'listen' for Einstein's Songlines with gravitational waves, permitting
  - Basic tests of General Relativity
  - A new field of astronomy and astrophysics
- A new window on the universe!