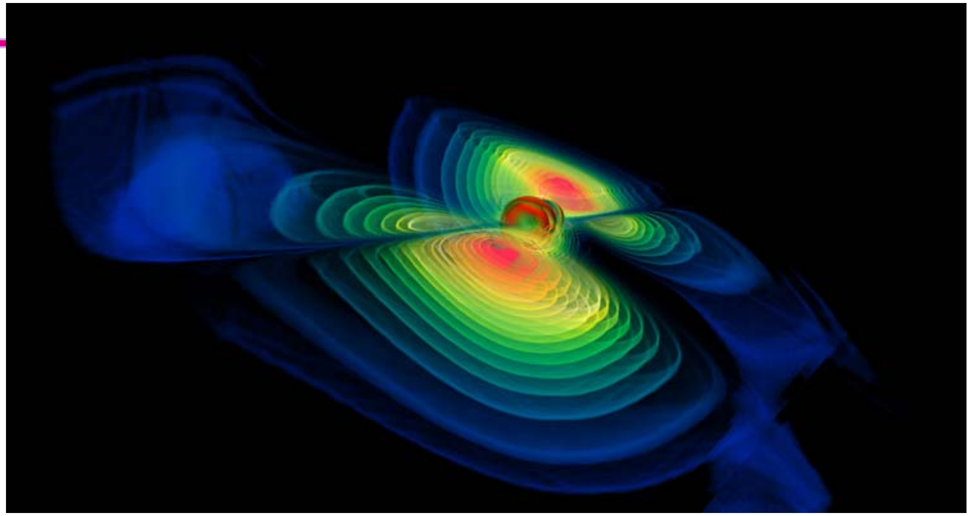
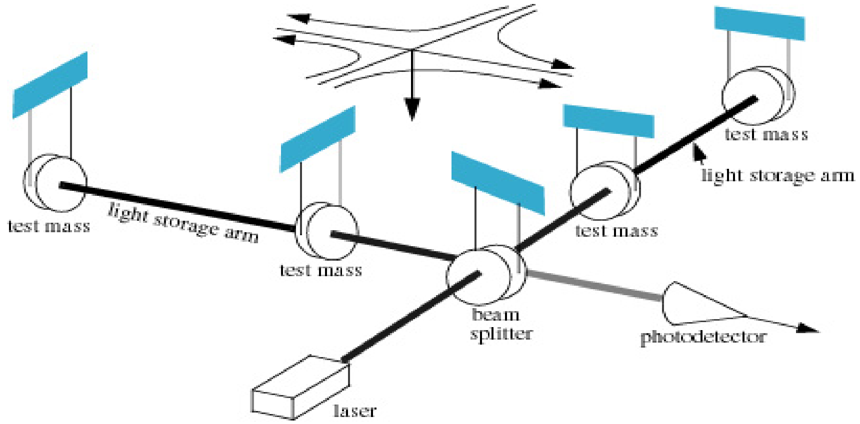
Gravitational Waves and LIGO

- Gravitational waves
- Astrophysical sources
- Detection of GW's
- The LIGO project and its sister projects
- Conclusions



"Colliding Black Holes"
National Center for Supercomputing Applications (NCSA)

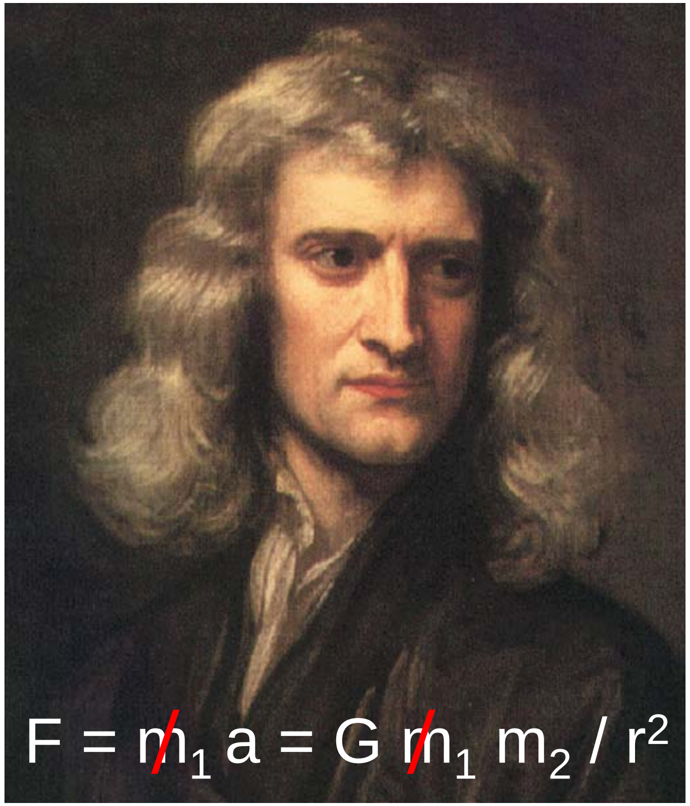


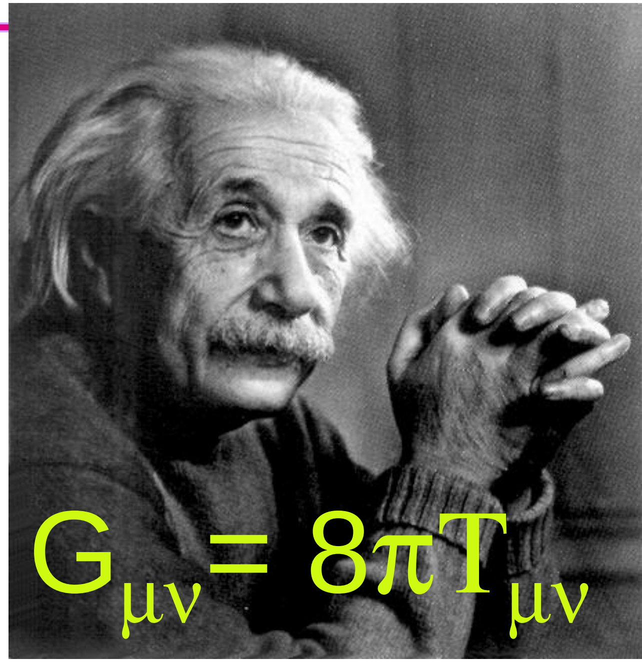
Alan Weinstein, Caltech

The nature of Gravity

Newton's Theory

"instantaneous action at a distance"



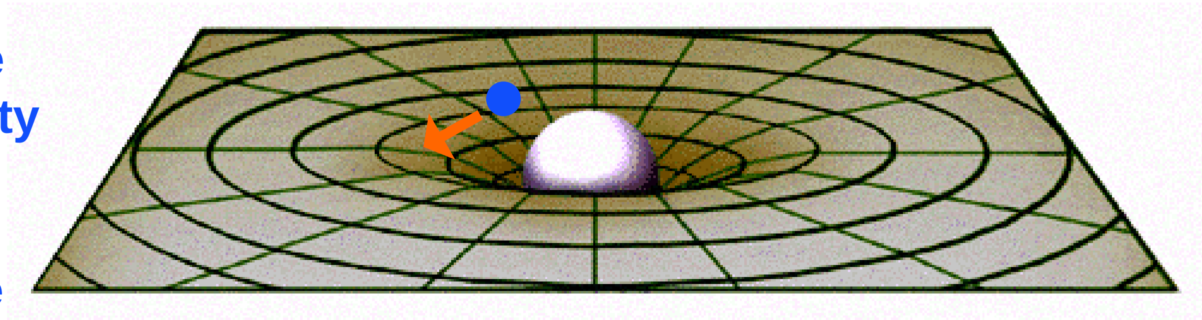


Einstein's General Theory of Relativity

Gravity is a local property of the space occupied by mass m_1, curved by the source mass m_2.

Information about changing gravitational field is carried by gravitational radiation at the speed of light

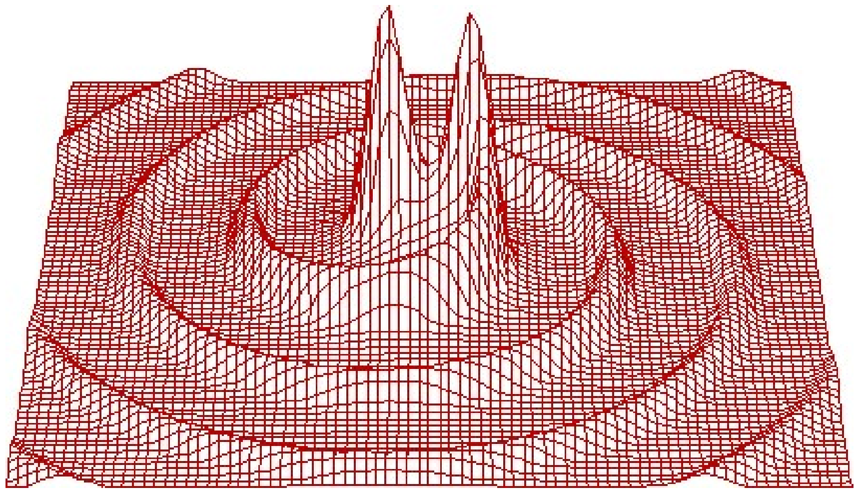
Gravitational Waves



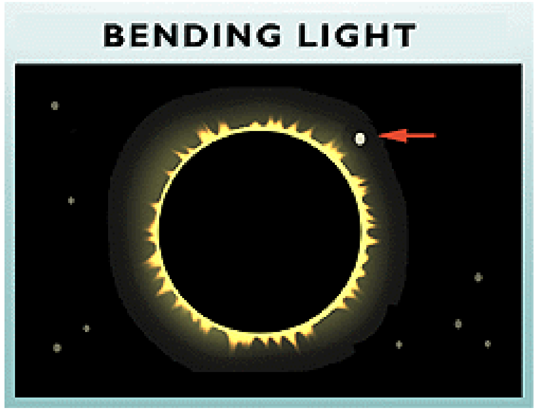
Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.

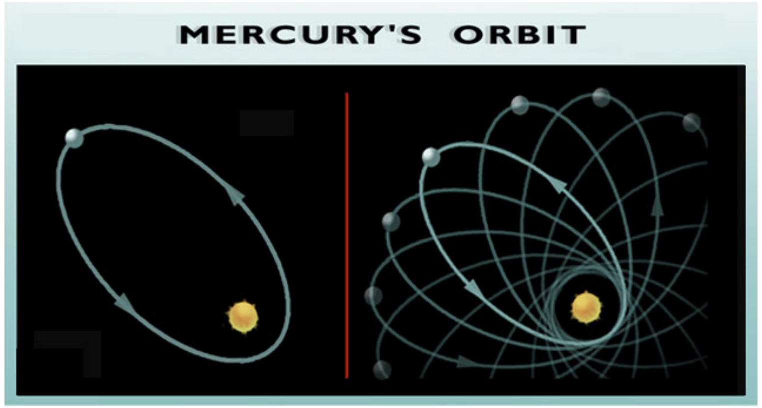
Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

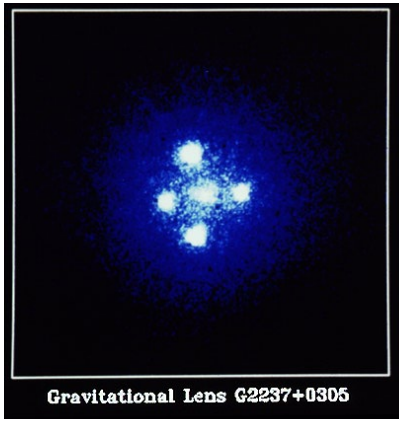
If the source is moving (at speeds close to c), *eg,* because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature



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 Post-Newton theory

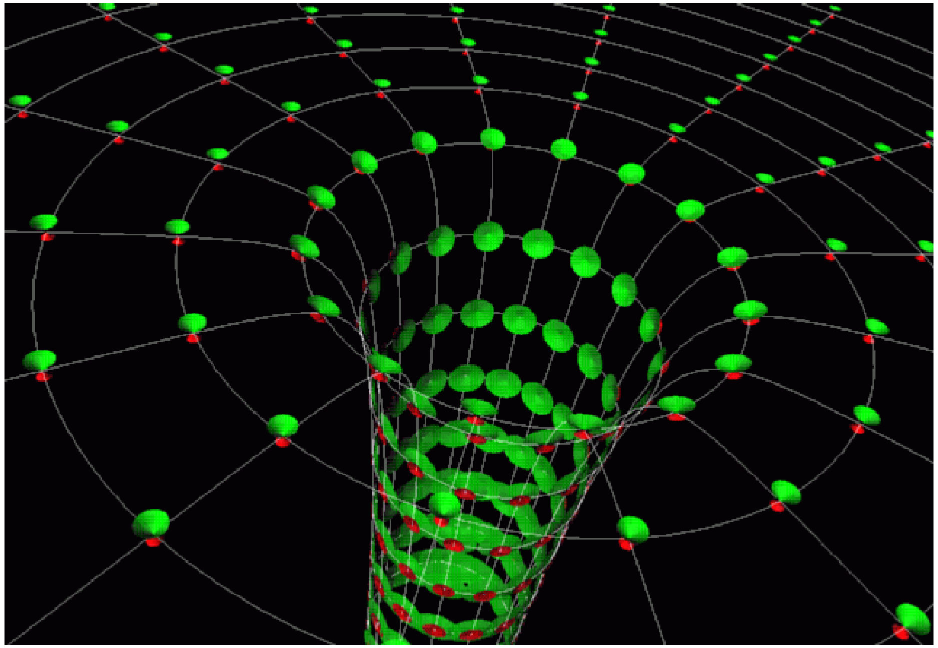
Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

"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

Strong-field

- 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



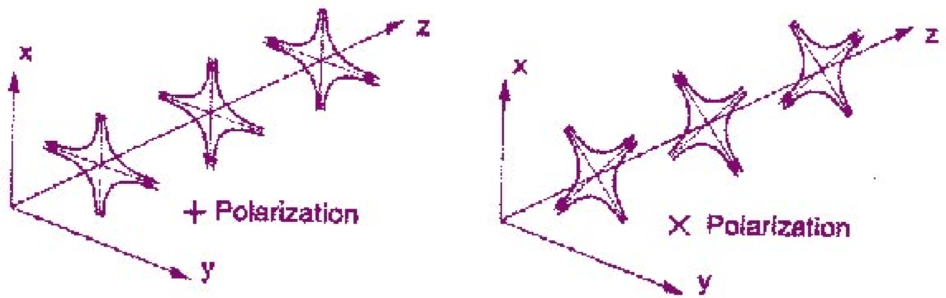
But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

Nature of Gravitational Radiation

General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in the fabric of spacetime

$h = \Delta L / L$

- transverse space-time distortions, freely propagating at speed of light
    - *mass of graviton = 0*
- Stretches and squeezes space between "test masses" – strain $h = \Delta L/L$
- GW are tensor fields (EM: vector fields) two polarizations: plus (⊕) and cross (⊗) (EM: two polarizations, *x* and *y*)
    - *Spin of graviton = 2*
- Conservation laws:
    - cons of energy ⇒ no monopole radiation
    - cons of momentum ⇒ no dipole radiation
    - lowest multipole is quadrupole wave (spin 2)



Contrast with EM dipole radiation:

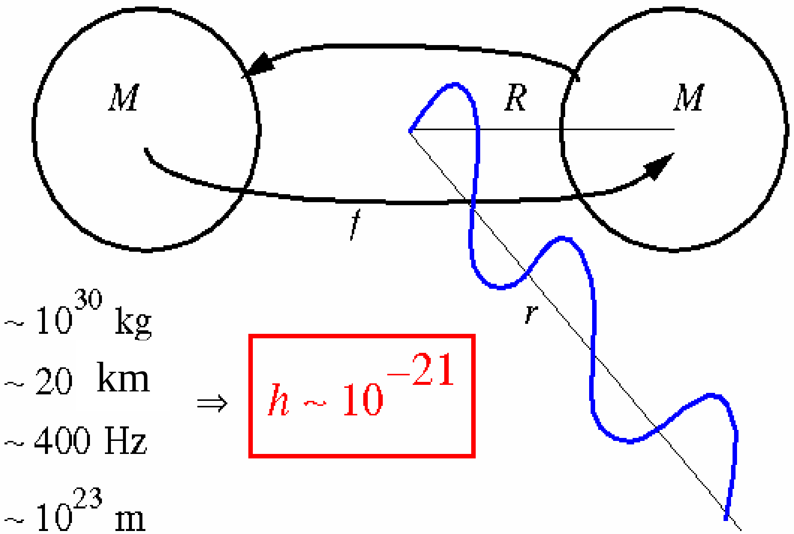
$\hat{x}$ ((⟷)) $\hat{y}$ ↕

Sources of GWs

- Accelerating charge $\Rightarrow$ electromagnetic radiation (dipole)
- Accelerating mass $\Rightarrow$ gravitational radiation (quadrupole)
- 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 – tumbling dumb-bell)
- 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:

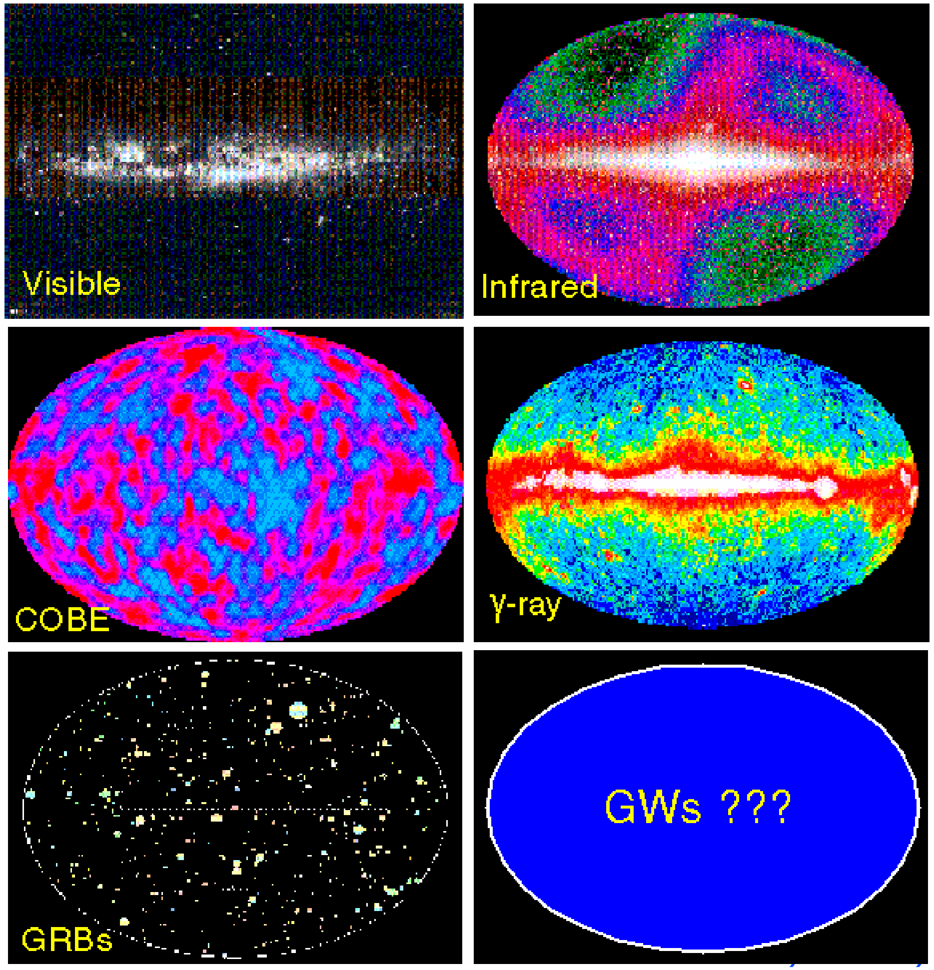


$M \sim 10^{30}$ kg
$R \sim 20$ km
$f \sim 400$ Hz
$r \sim 10^{23}$ m

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

Terrestrial sources *TOO WEAK!*

A NEW WINDOW ON THE UNIVERSE



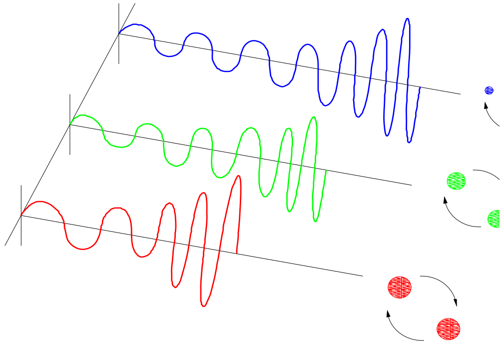
The history of Astronomy: new bands of the EM spectrum opened $\rightarrow$ major discoveries!

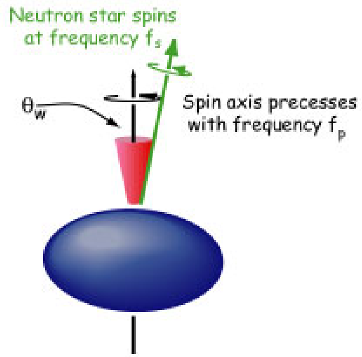
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

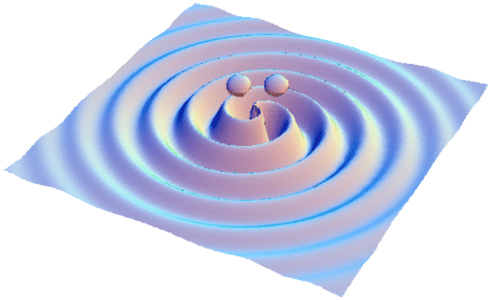
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

What will we see?

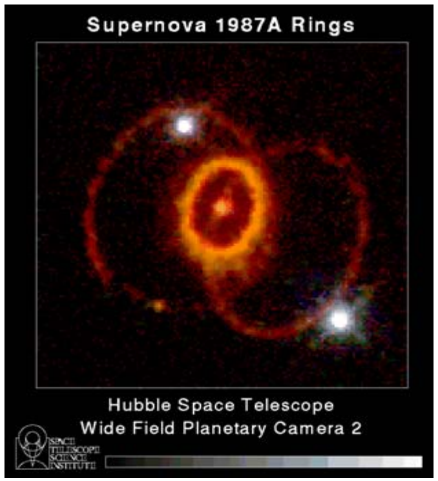


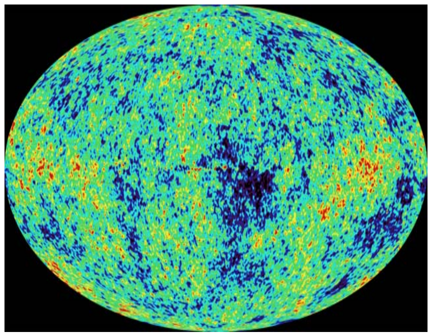




GWs from the most energetic processes in the universe!

- black holes orbiting each other and then merging together
- Supernovas, GRBs
- rapidly spinning neutron stars
- Vibrations from the Big Bang



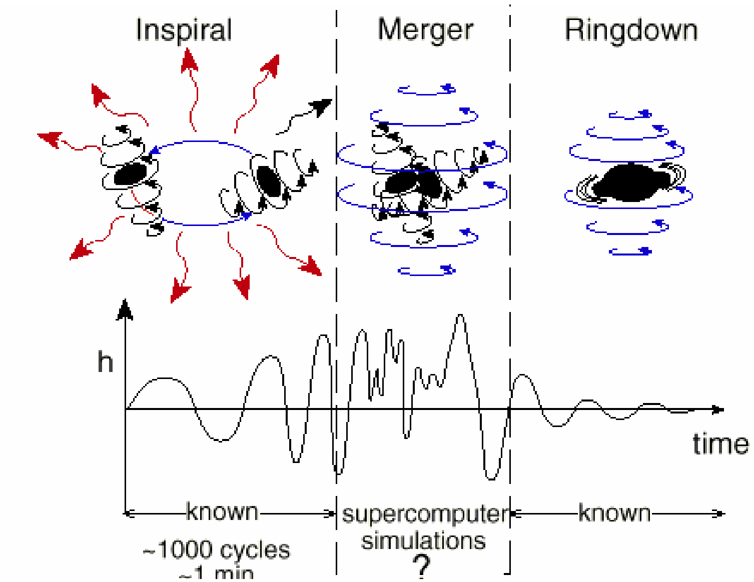


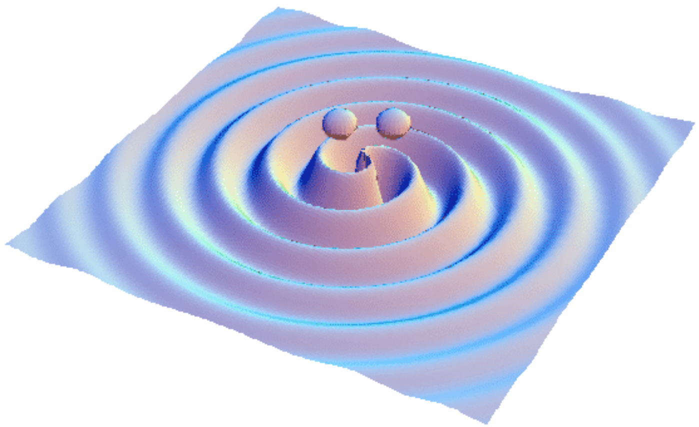
Analog from cosmic microwave background -- WMAP 2003

A NEW WINDOW ON THE UNIVERSE WILL OPEN UP FOR EXPLORATION. BE THERE!

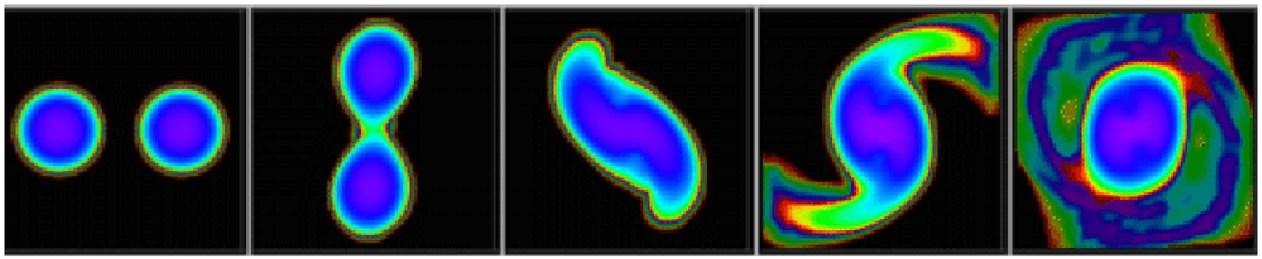
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

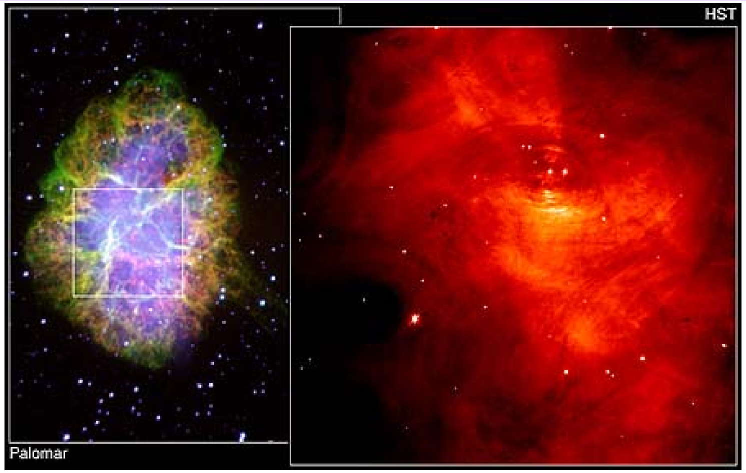




- Neutron star – neutron star (Centrella et al.)

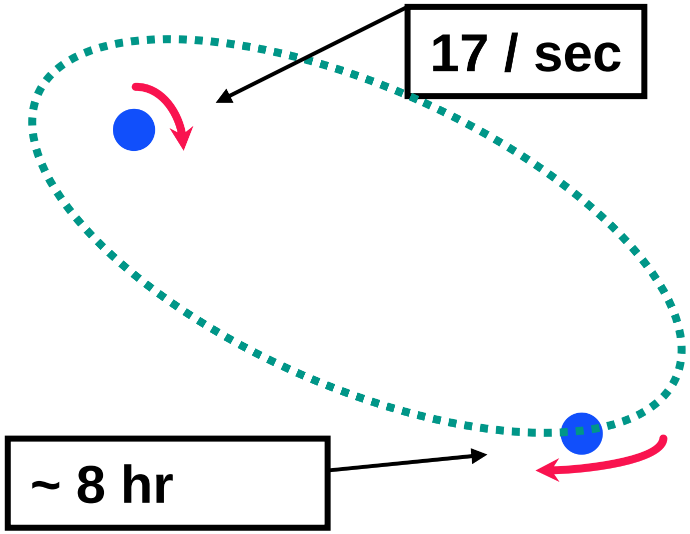


Hulse-Taylor binary pulsar



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars

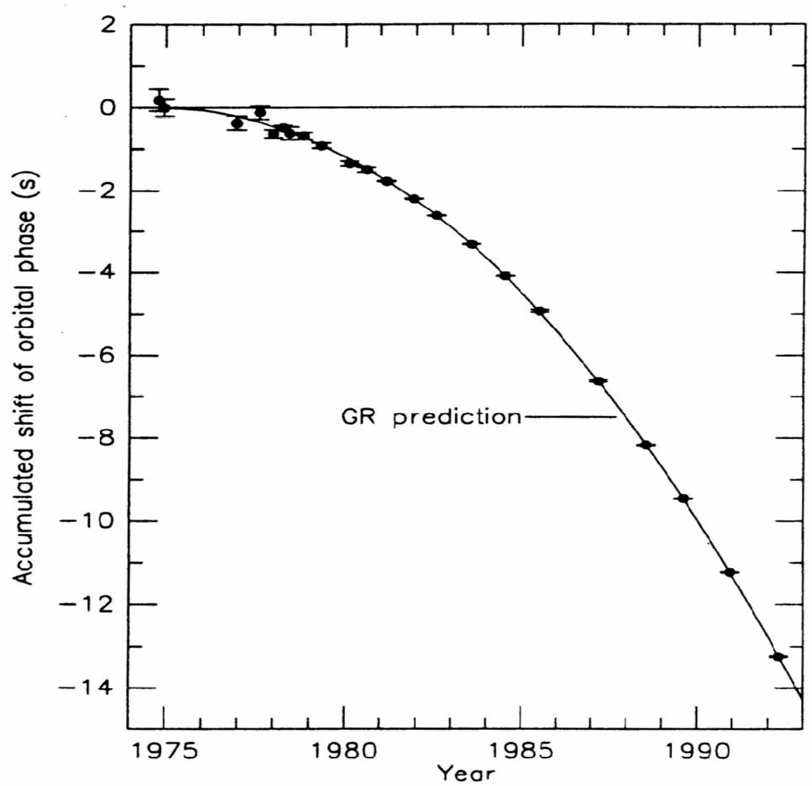


- **A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / sec)**
- **orbiting around an ordinary star with 8 hour period**
- **Only 7 kpc away**
- **discovered in 1975, orbital parameters measured**
- **continuously measured over 25 years!**

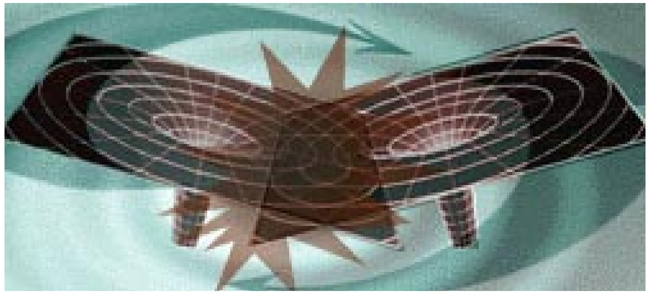
GWs from Hulse-Taylor binary

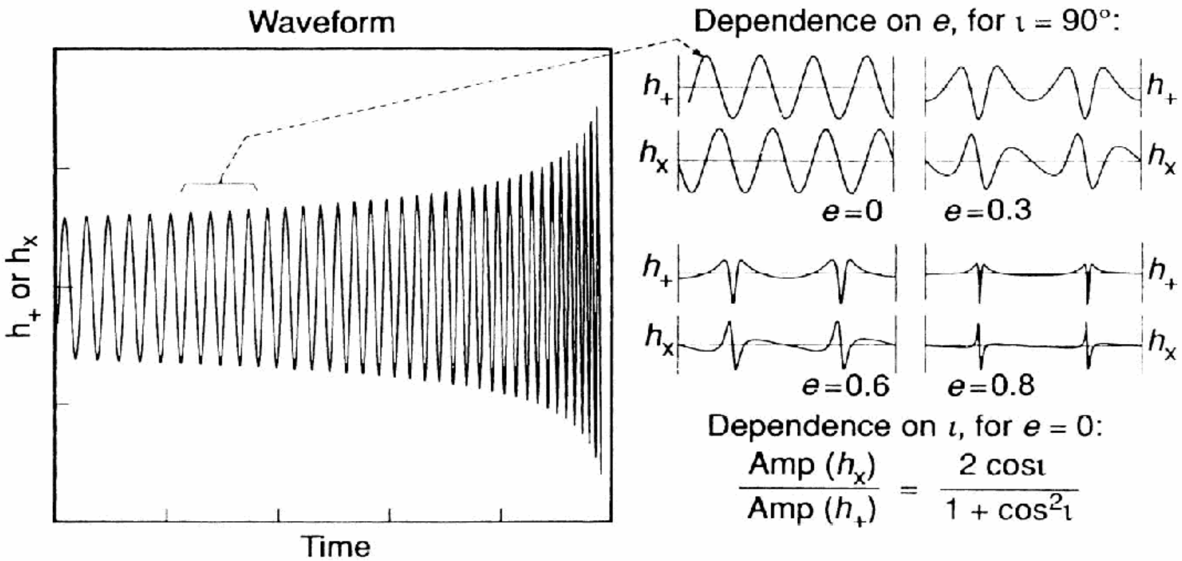
emission of gravitational waves by compact binary system

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



Chirp signal from Binary Inspiral



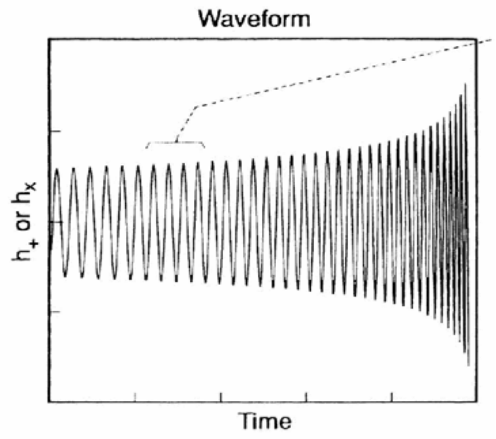


determine

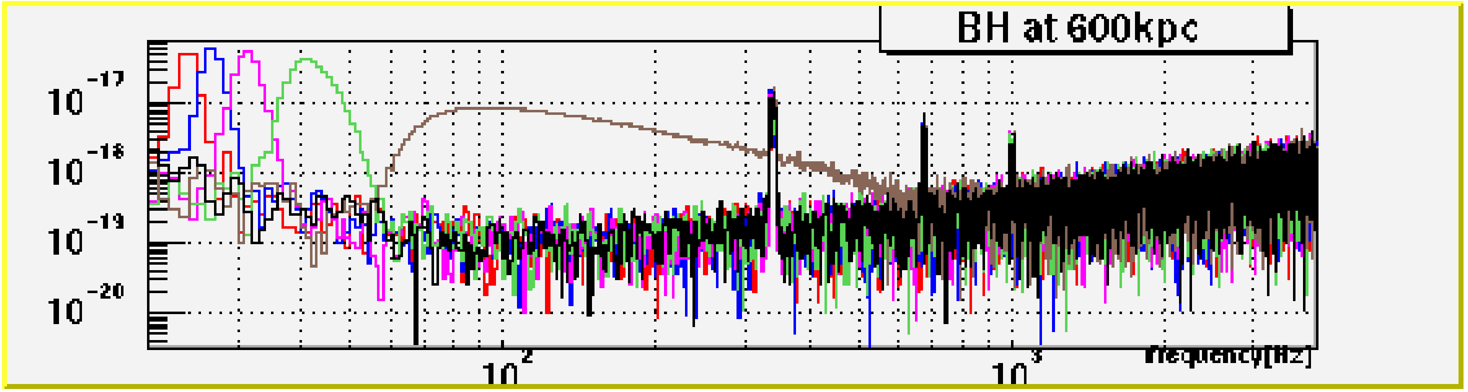
- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination *I*
- *Over-constrained parameters: TEST GR*

The sound of a chirp

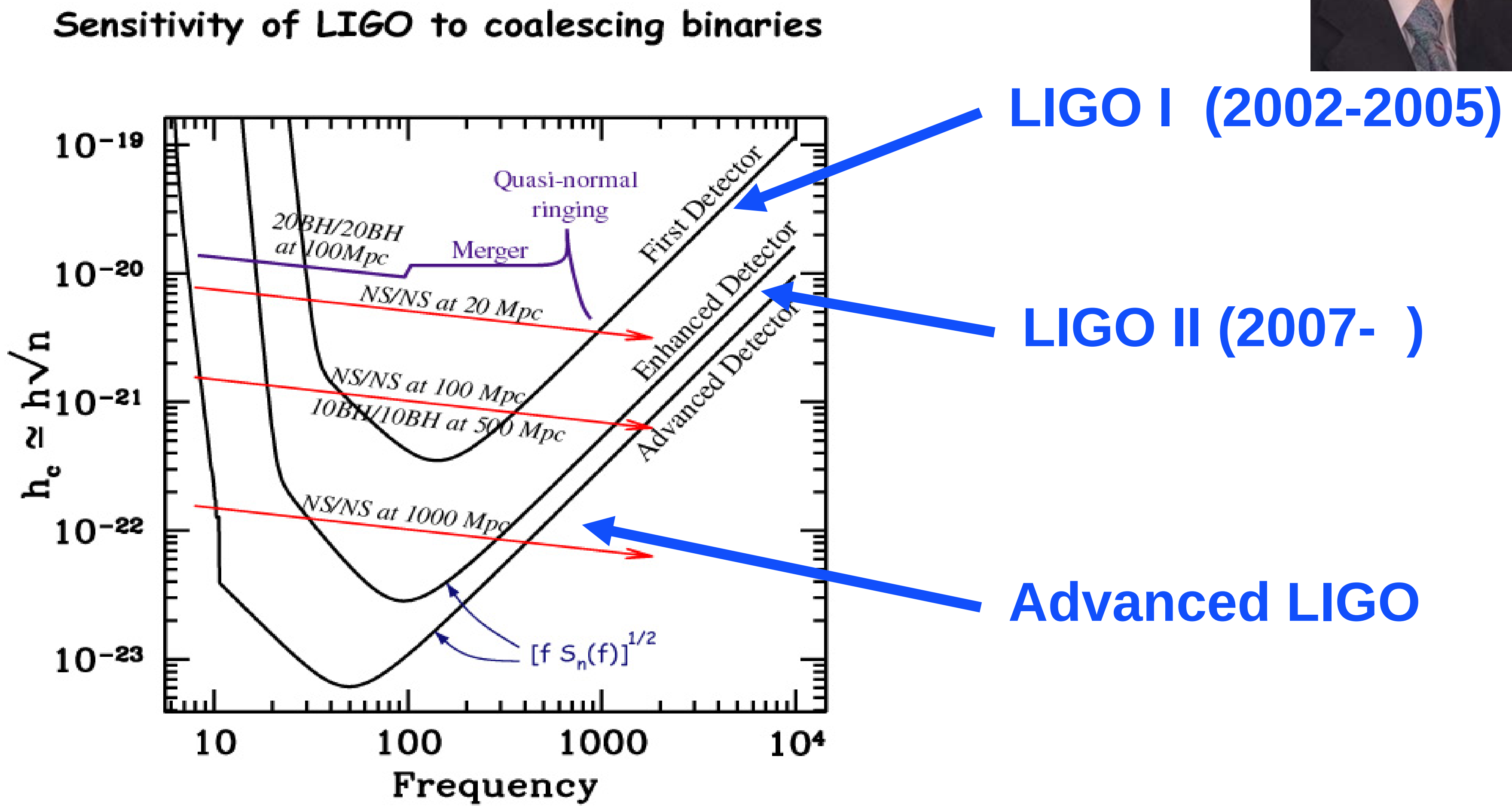
BH-BH collision, no noise



The sound of a BH-BH collision,
Fourier transformed over 5 one-second intervals
(red, blue, magenta, green, purple)
along with expected IFO noise (black)



Astrophysical sources: Thorne diagrams



Estimated detection rates for compact binary inspiral events

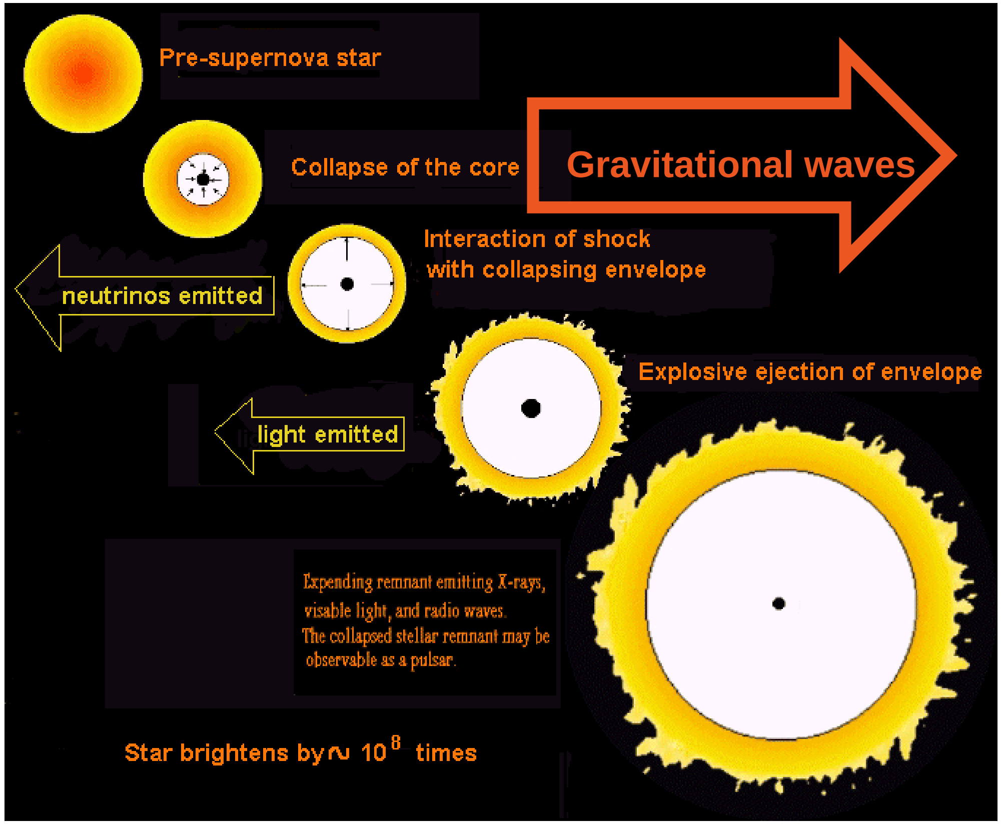
Brief Summary of Detection Capabilities of Mature LIGO Interferometers

• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4 M_\odot$ for NS and $\sim 10 M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

		NS/NS	NS/BH	BH/BH in field	BH/BH in globulars
	$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	10^{-6}–10^{-5}
	$D_{\rm I}$	20 Mpc	43 Mpc	100	100
LIGO I	$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
	$D_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
LIGO II	$\mathcal{R}_{\rm WB}$, yr^{-1}	$0.5 - 100$	$\lesssim 0.5 - 1000$	$\lesssim 10 - 2000$	$100 - 2000$

V. Kalogera (population synthesis)

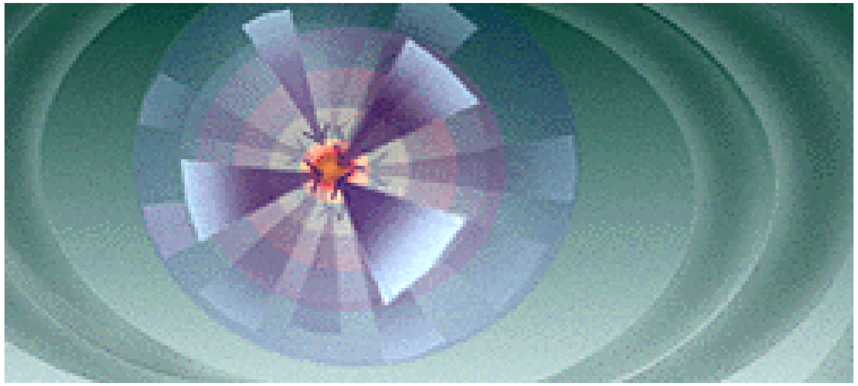
Supernova collapse sequence



- 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.

Gravitational Waves from Supernova collapse

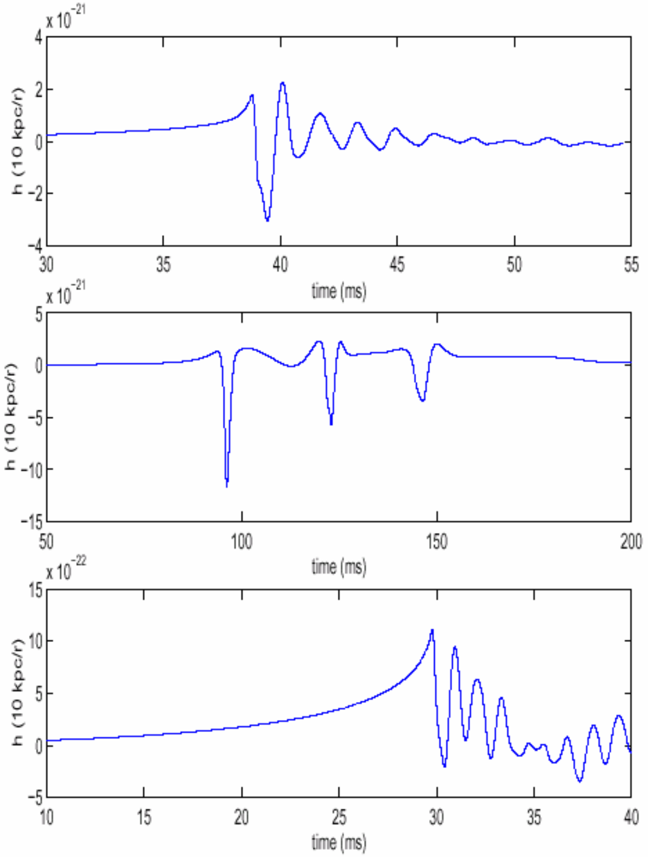
Non axisymmetric core collapse (Type II supernovae)



Rate

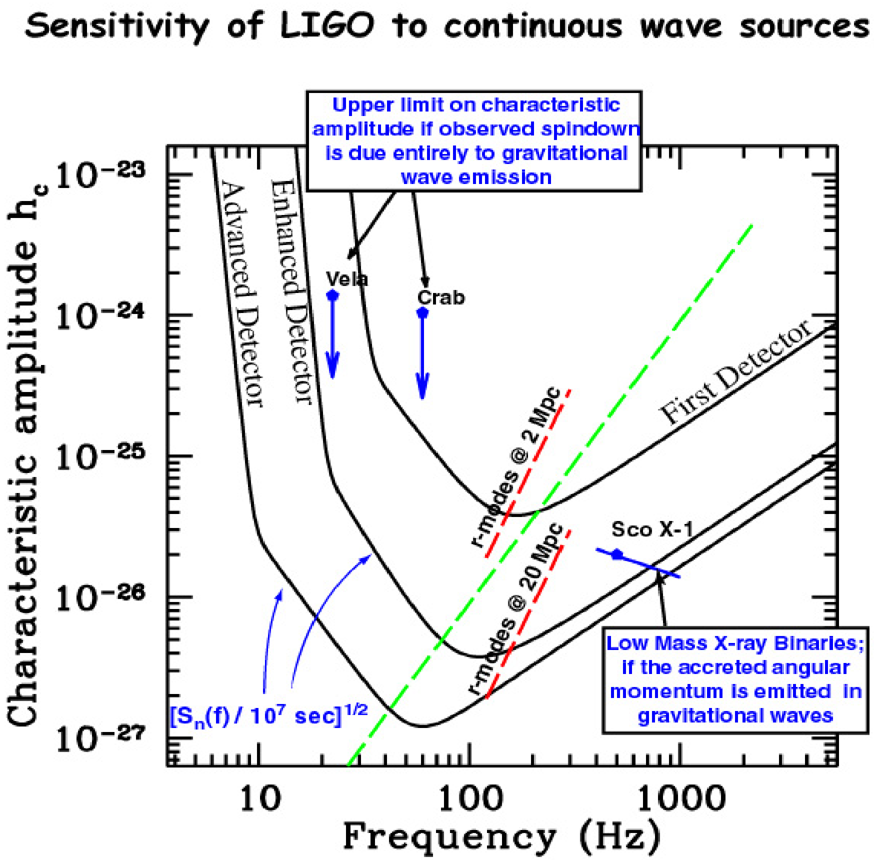
1/50 yr - our galaxy
3/yr - Virgo cluster

'burst' waveforms

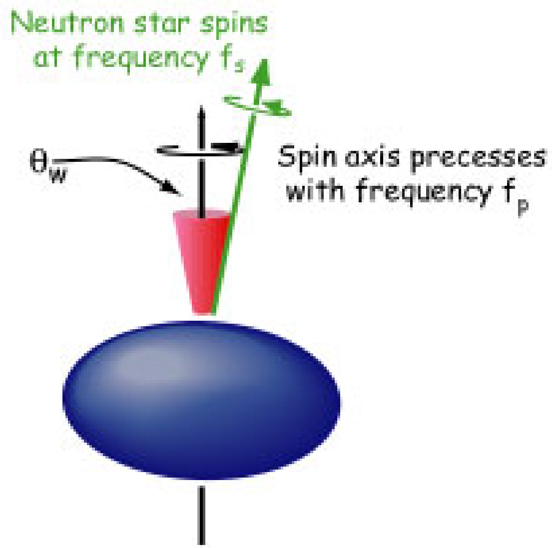


Zwerger & Muller, 1997 & 2003
simulations of axi-symmetric SN core collapse

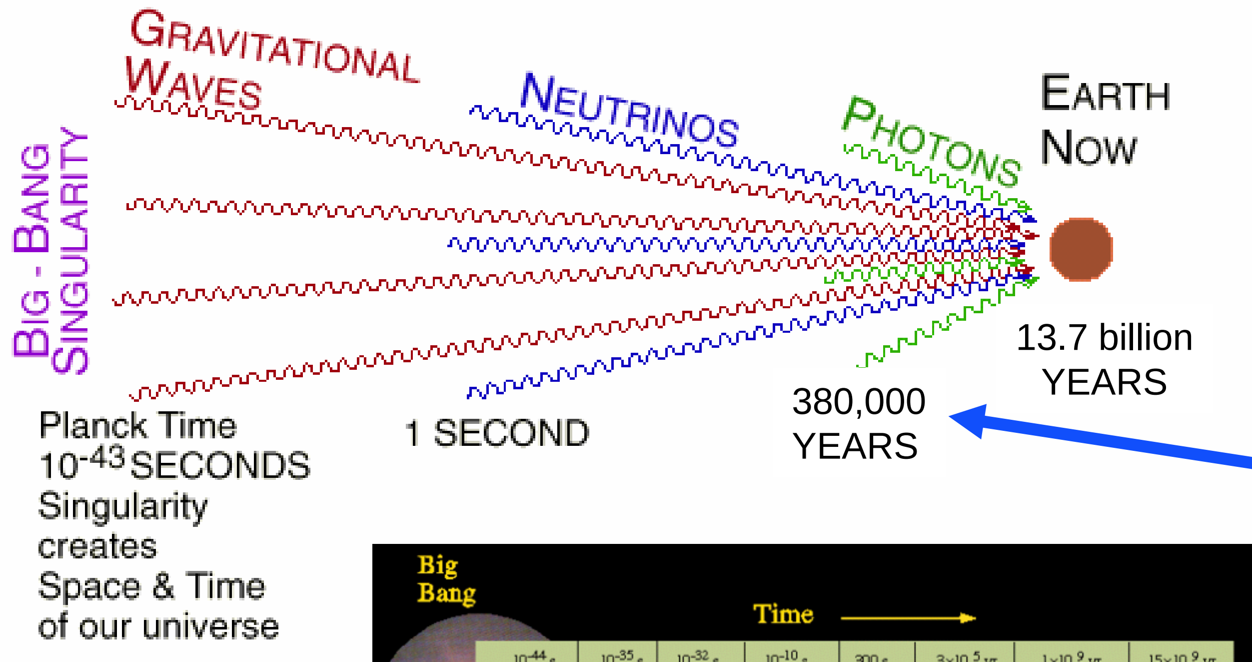
Pulsars and continuous wave sources

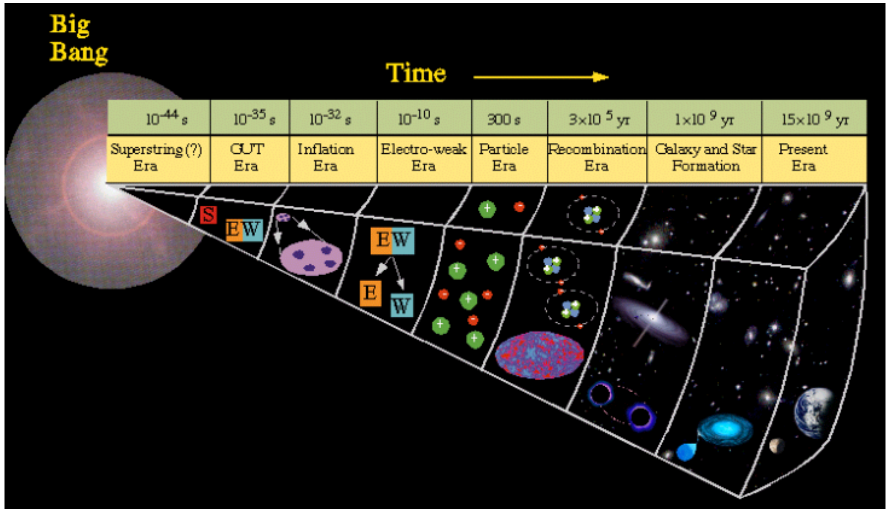


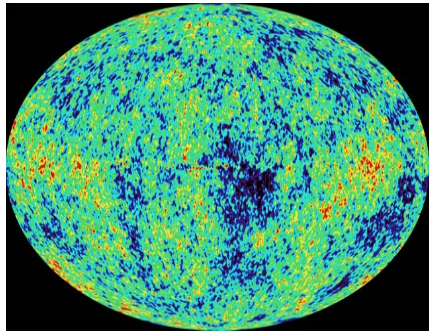
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best



Gravitational waves from Big Bang

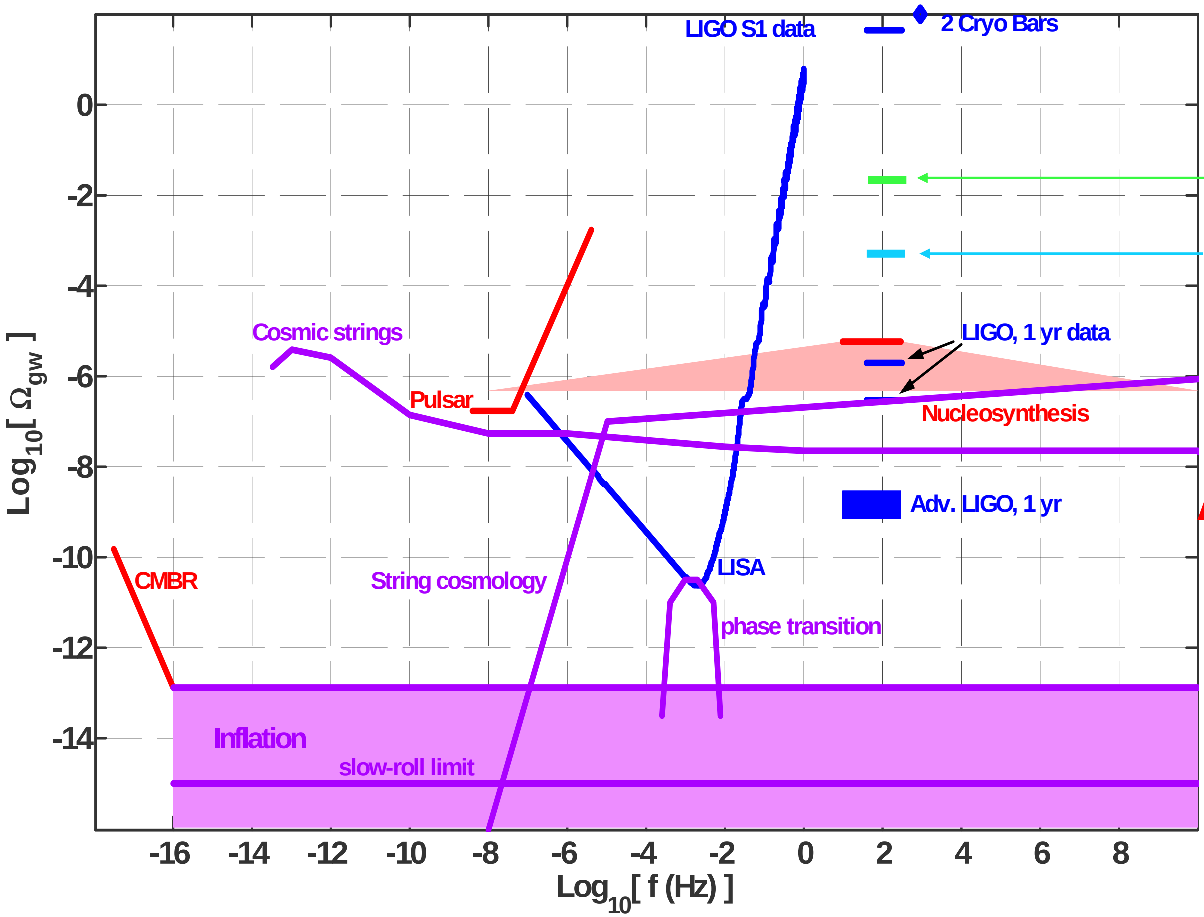






cosmic microwave background -- WMAP 2003

LIGO limits and expectations on Ω_{GW}



S1 result: $\Omega_{GW} < 23$

S2 result: $\Omega_{GW} < 0.02$

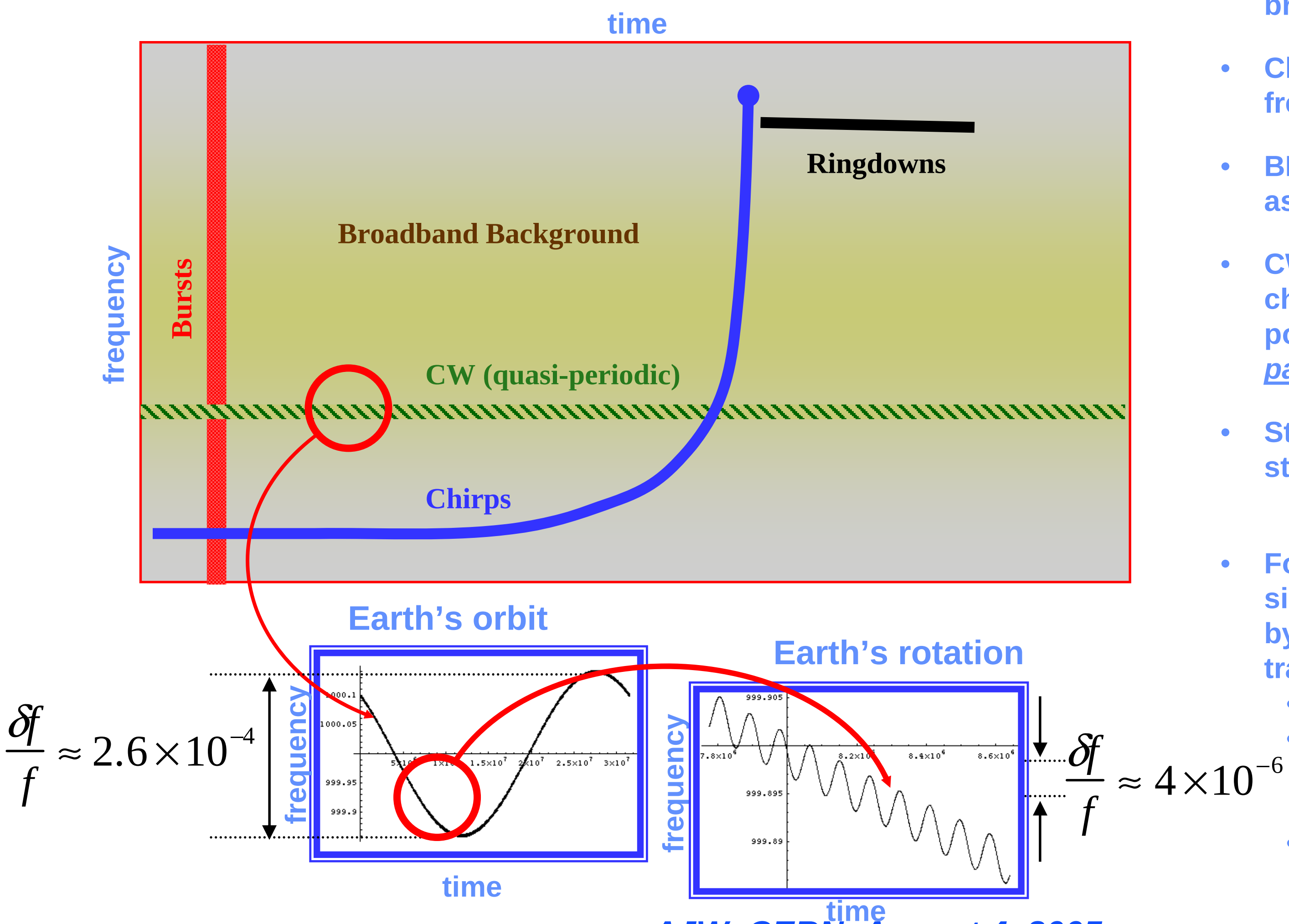
S3 result: $\Omega_{GW} < 8\times10^{-4}$

LIGO design, 1 year:
$\Omega_{GW} <\sim 10^{-5} - 10^{-6}$

Advanced LIGO, 1 year:
$\Omega_{GW} <\sim 10^{-9}$

Challenge is to identify and eliminate noise correlations between H1 and H2!

Frequency-Time Characteristics of GW Sources



- Bursts are short duration, broadband events
- Chirps explore the greatest time-frequency area
- BH Ringdowns expected to be associated with chirps
- CW sources have FM characteristics which depend on position on the sky (*and source parameters*)
- Stochastic background is stationary and broadband

- For each source, the optimal signal to noise ratio is obtained by integrating signal ***along*** the trajectory
  - If SNR >> 1, kernel ∝ |signal|^2
  - If SNR ≤ 1, kernel ∝ |template* signal| or $|signal_j^* \ signal_k|$
  - Optimal filter: kernel ∝ 1/(noise power)

Ultimate Goals for the Observation of GWs

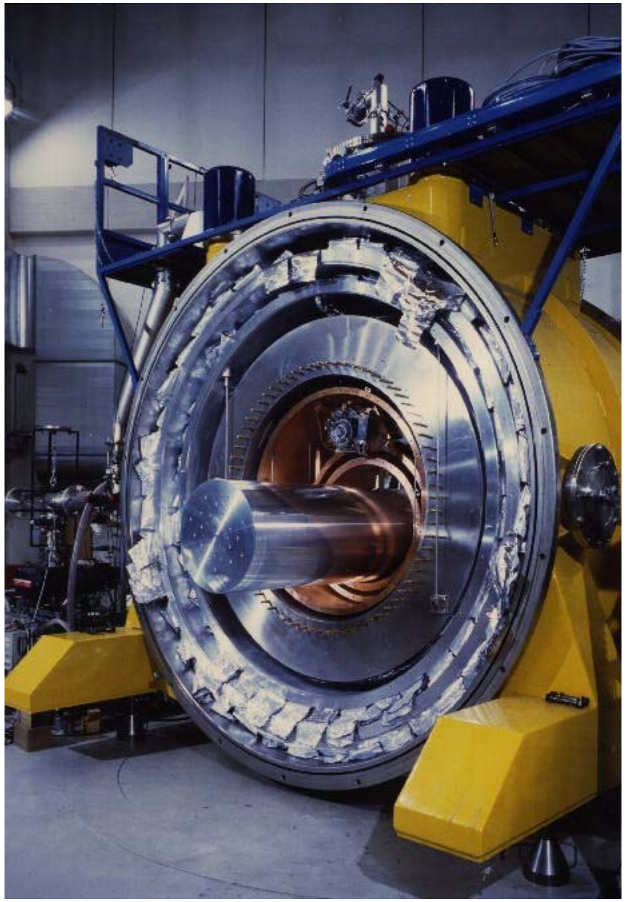
- **Tests of Relativity**
  - **Wave propagation speed (delays in arrival time of bursts)**
  - **Spin character of the radiation field (polarization of radiation from CW sources)**
  - **Detailed tests of GR in P-P-N approximation (chirp waveforms)**
  - **Black holes & strong-field gravity (merger, ringdown of excited BH)**
- **Gravitational Wave Astronomy (observation, populations, properties):**
  - **Compact binary inspirals**
  - **Gravitational waves and gamma ray burst associations**
  - **Black hole formation**
  - **Supernovae in our galaxy**
  - **Newly formed neutron stars - spin down in the first year**
  - **Pulsars and rapidly rotating neutron stars**
  - **LMXBs**
  - **Stochastic background**

Gravitational wave detectors

- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large "bell", set ringing (at ~ 900 Hz) by GW
  - Only discuss briefly, here – See EXPLORER at CERN!
- **Michelson interferometers**
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's
  - Now: large, earth-based detectors. Soon: space-based (LISA).

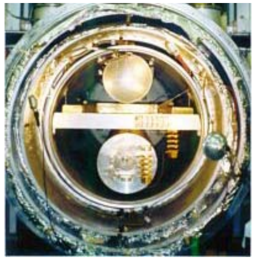
Resonant bar detectors

- AURIGA bar near Padova, Italy
  (typical of some ~5 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- $Q = 4\times10^6$ at < 1K
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive transducer and electronics (SQUID)



Resonant Bar detectors around the world

International Gravitational Event Collaboration (IGEC)

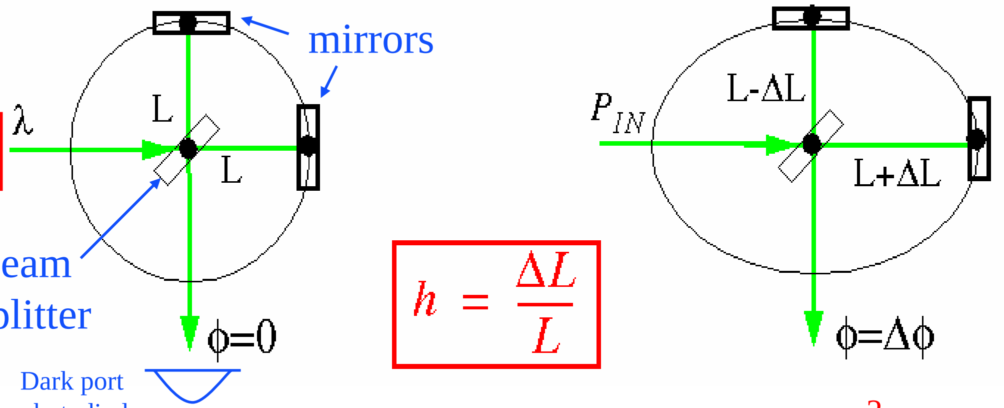


detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Mode frequencies $[Hz]$	895, 920	912, 930	905, 921	908, 924	694, 713
Bar mass M $[kg]$	2296	2230	2270	2260	1500
Bar length L $[m]$	3.0	2.9	3.0	3.0	2.75
Bar temperature $[K]$	4.2	0.2	2.6	0.1	5.0
Longitude	$91^\circ 10' 44" W$	$11^\circ 56' 54" E$	$6^\circ 12' E$	$12^\circ 40' 21" E$	$115^\circ 49' E$
Latitude	$30^\circ 27' 45" N$	$45^\circ 21' 12" N$	$46^\circ 27' N$	$41^\circ 49' 26" N$	$31^\circ 56' S$
Azimuth	$40^\circ W$	$44^\circ E$	$39^\circ E$	$44^\circ E$	0°

Baton Rouge, LA USA | **Legarno, Italy** | **CERN, Suisse** | **Frascati, Italy** | **Perth, Australia**

Interferometric detection of GWs

GW acts on freely falling masses:

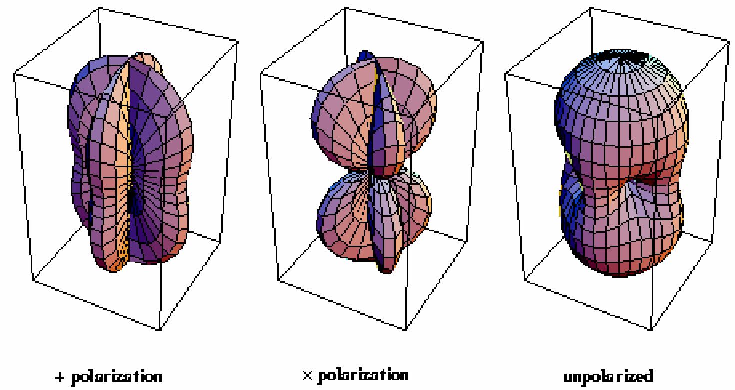


$$h = \frac{\Delta L}{L}$$

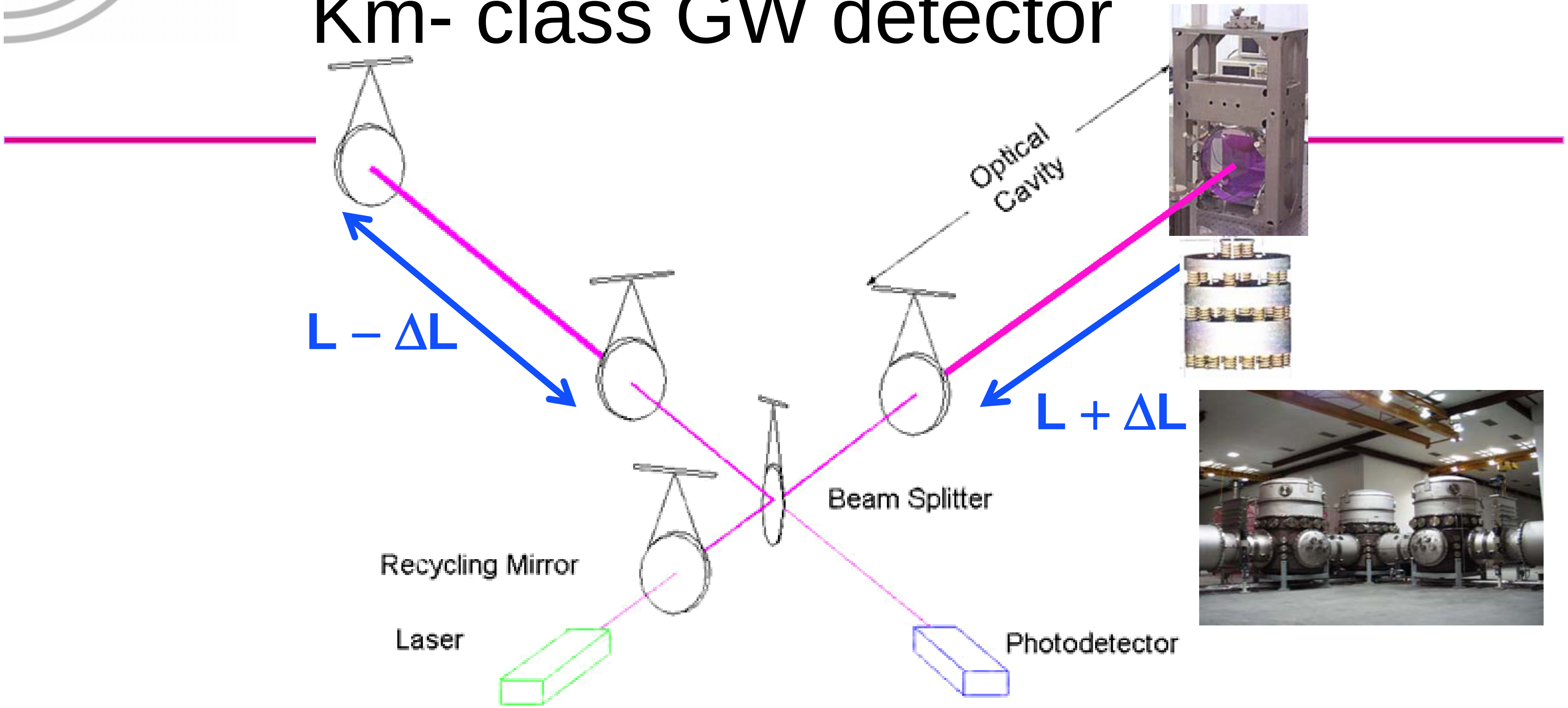
For fixed ability to measure ΔL, make L as big as possible!

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

Antenna pattern:
(not very directional!)



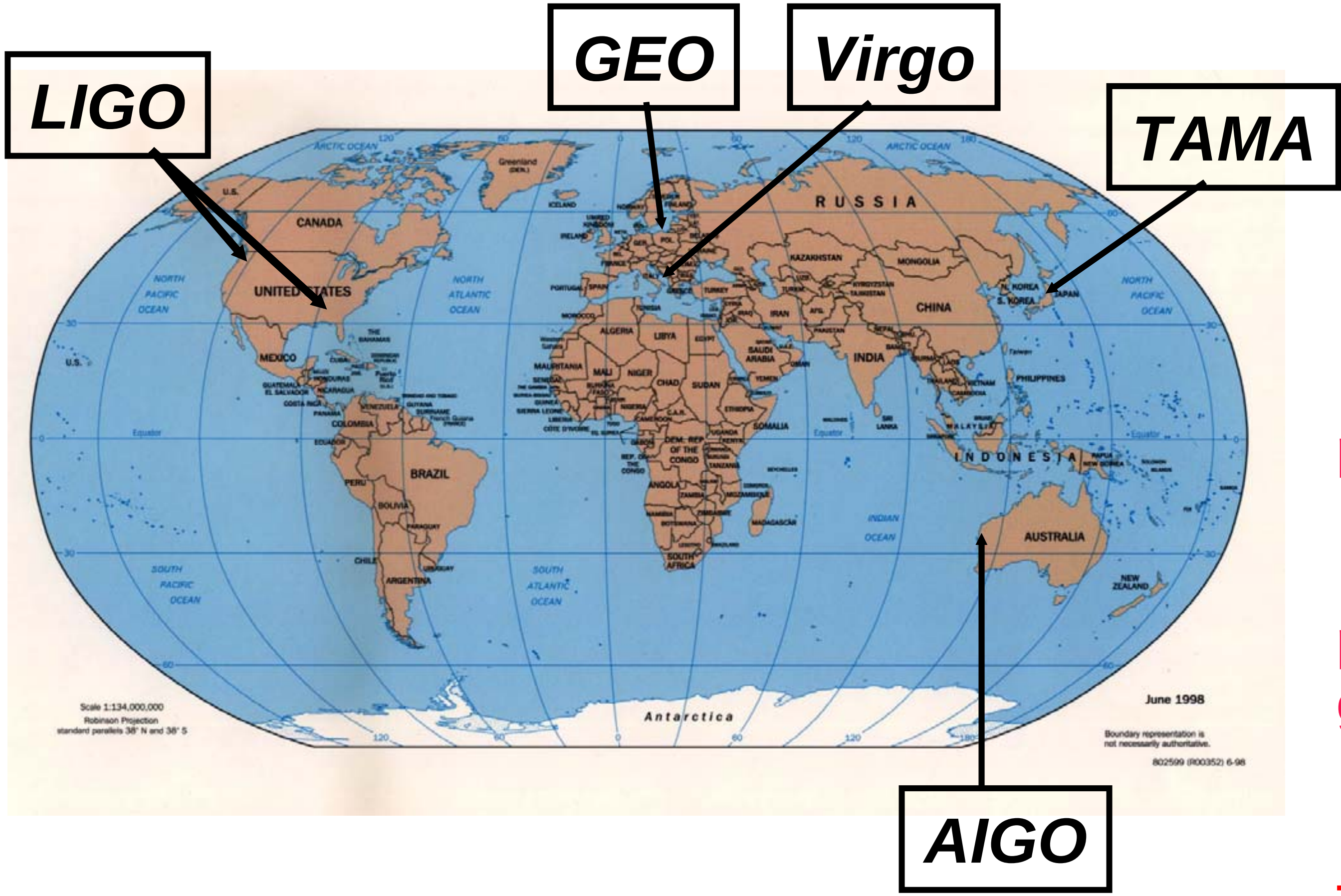
LIGO – the first Km- class GW detector



$$\Delta L = \underbrace{h}_{\lesssim 10^{-21}}\ \underbrace{L}_{4\ \text{km}} \lesssim 4\times10^{-16}\ \text{cm}$$

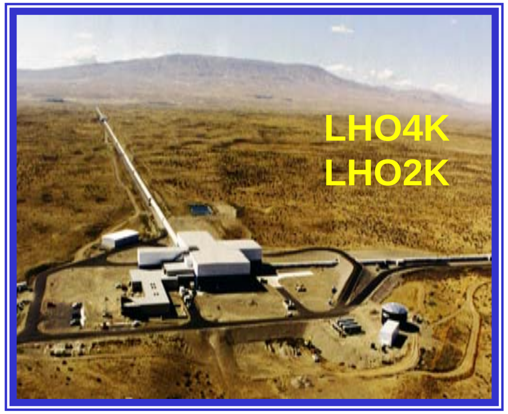
International network

Simultaneously detect signal (within msec)

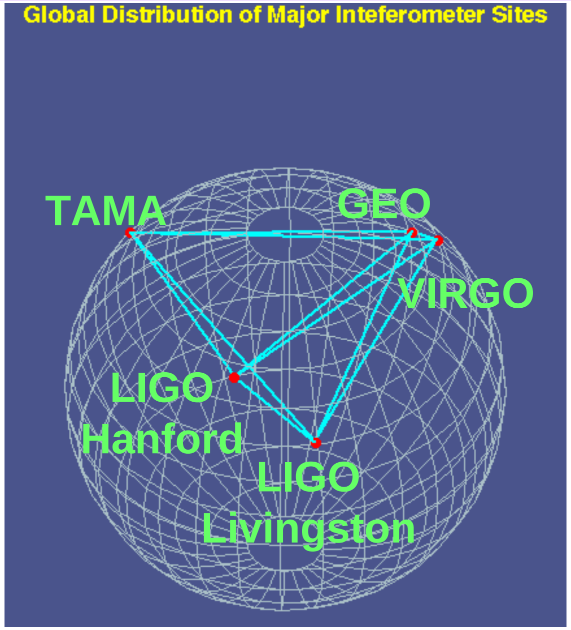


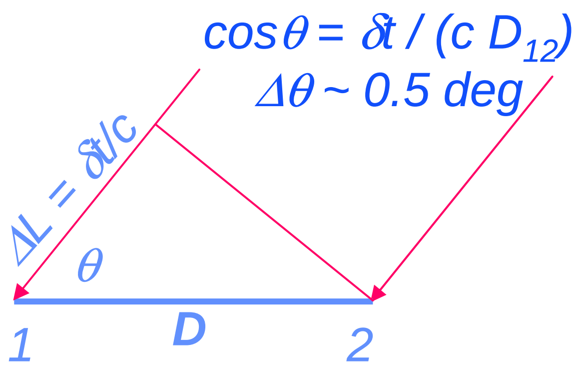
- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- **Open up a new field of astrophysics!**

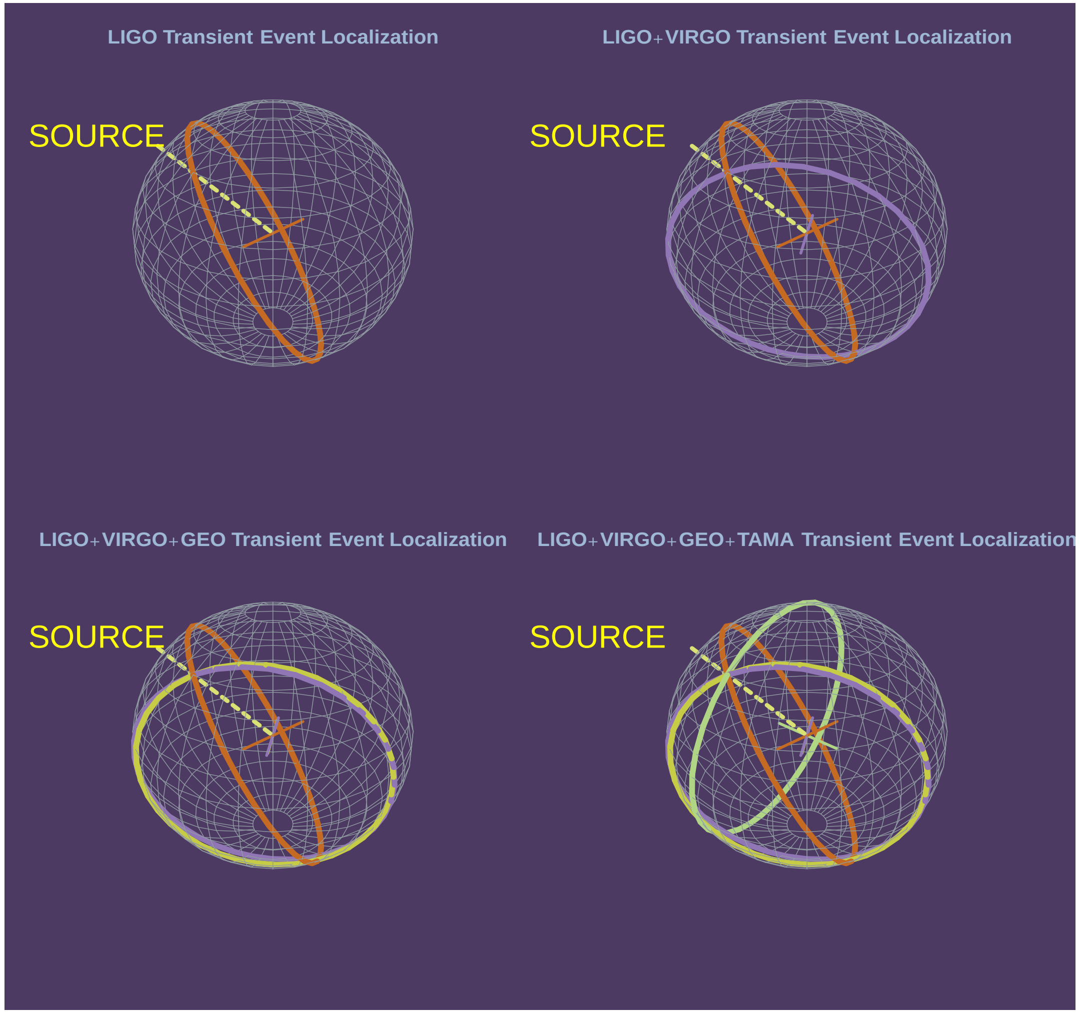
LIGO, VIRGO, GEO, TAMA …



Event Localization With An Array of GW Interferometers

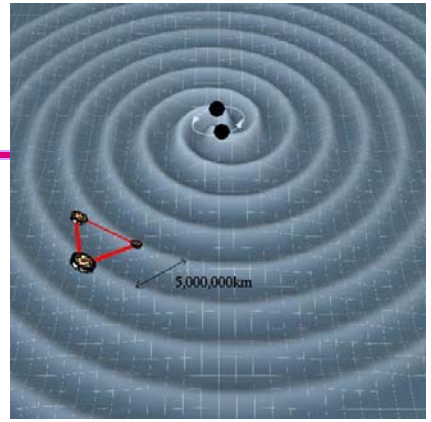






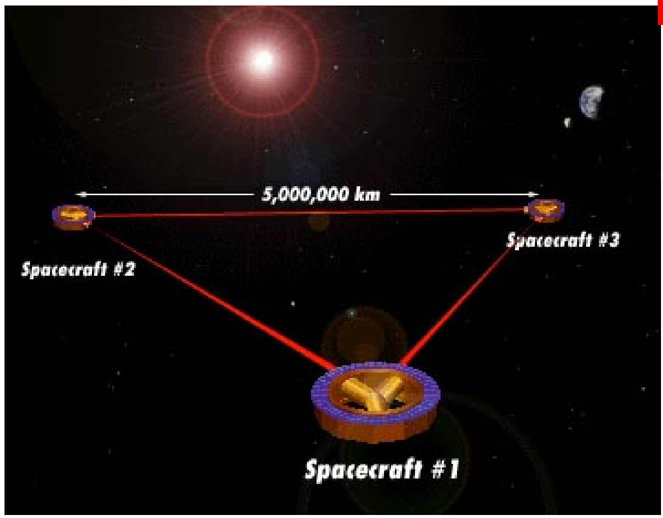
The Laser Interferometer Space Antenna

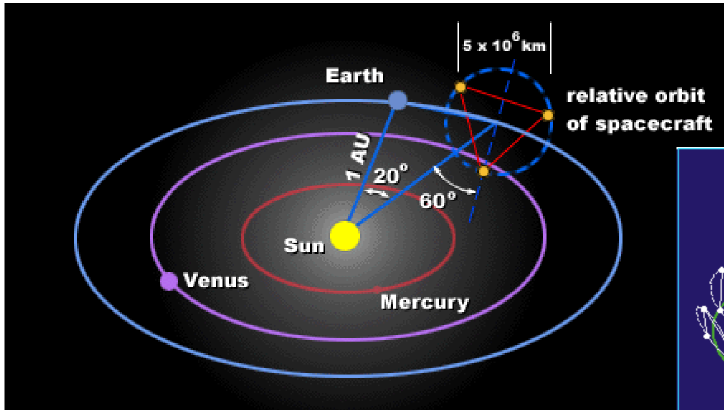
LISA

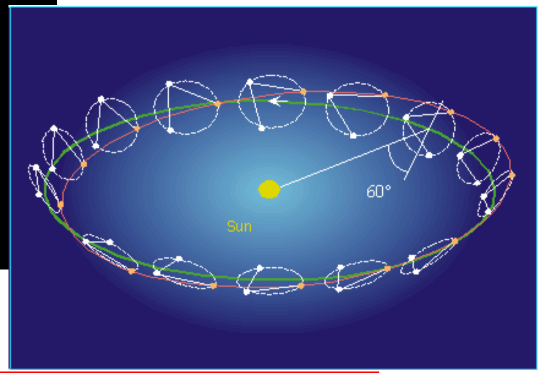


Three spacecraft in orbit about the sun,
with 5 million km baseline

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



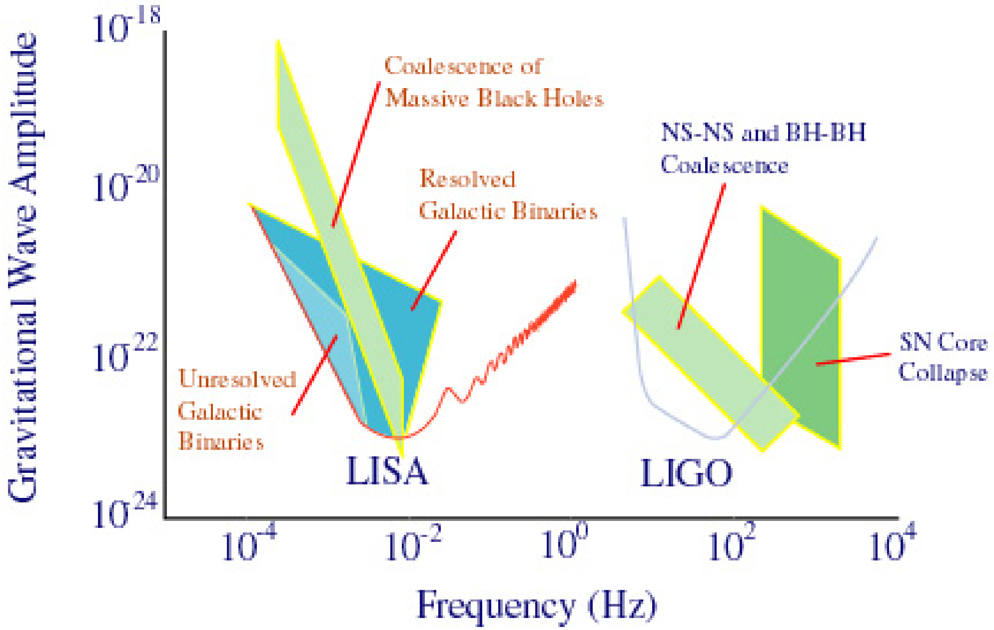




LISA (NASA/JPL, ESA) may fly in the next 10 years!

Sensitivity bandwidth

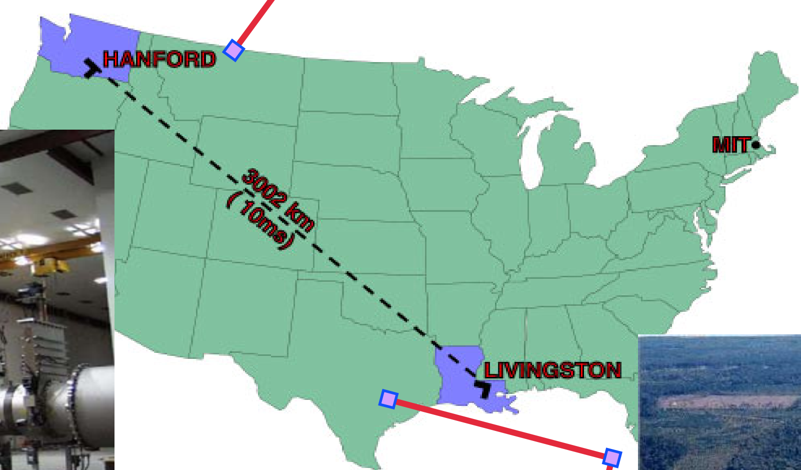
- EM waves are studied over ~20 orders of magnitude
  - » (ULF radio –> HE γ rays)
- Gravitational Waves over ~10 orders of magnitude
  - » (terrestrial + space)



LIGO Observatories

4 km (H1)
+ 2 km (H2)

Hanford (LHO) :
two interferometers in same vacuum envelope



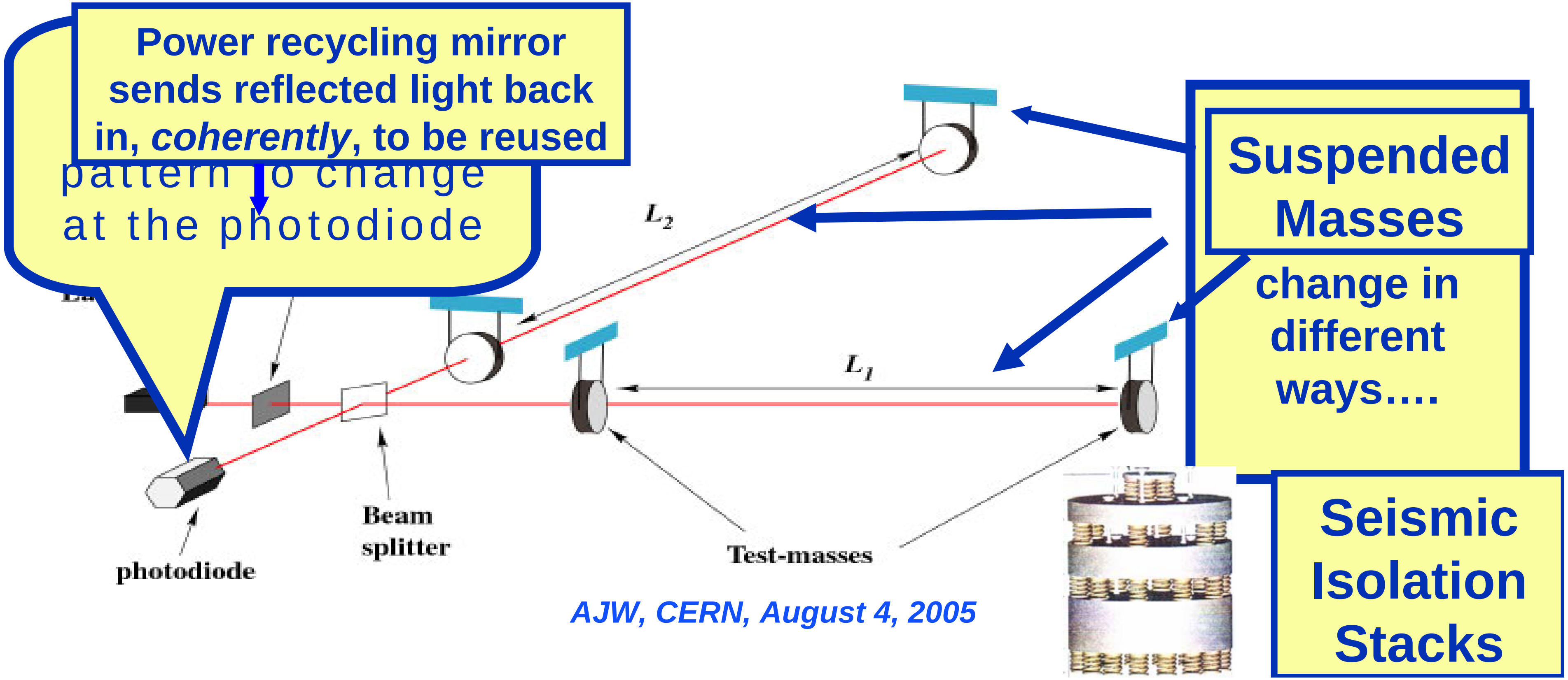
4 km
L1

Livingston (LLO):
one interferometer

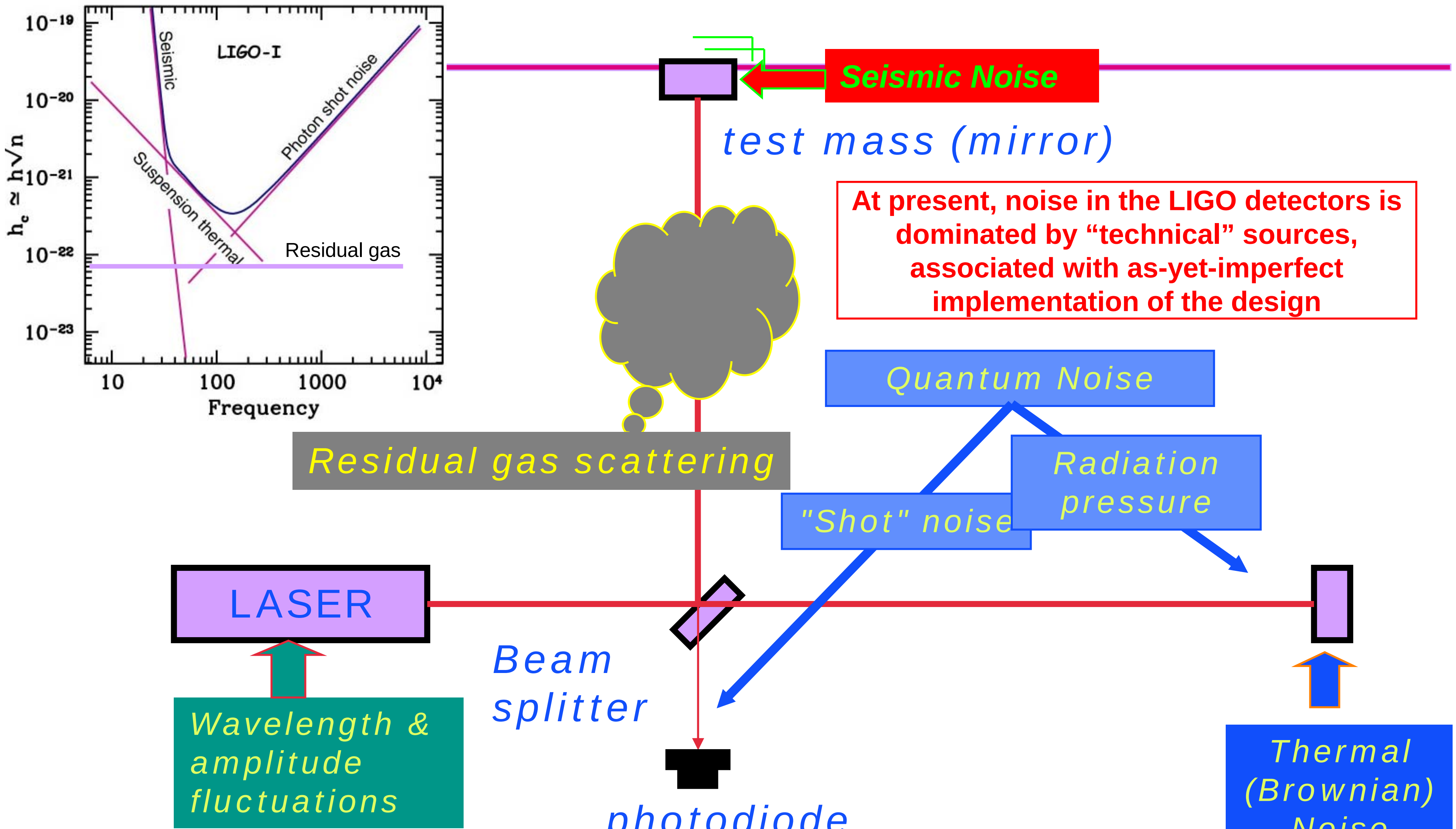
Both sites are relatively seismically quiet, low human noise

Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
- **Arms in LIGO are 4km**
- **Measure *difference in length to one part in 10^{21} or 10^{-18} meters***

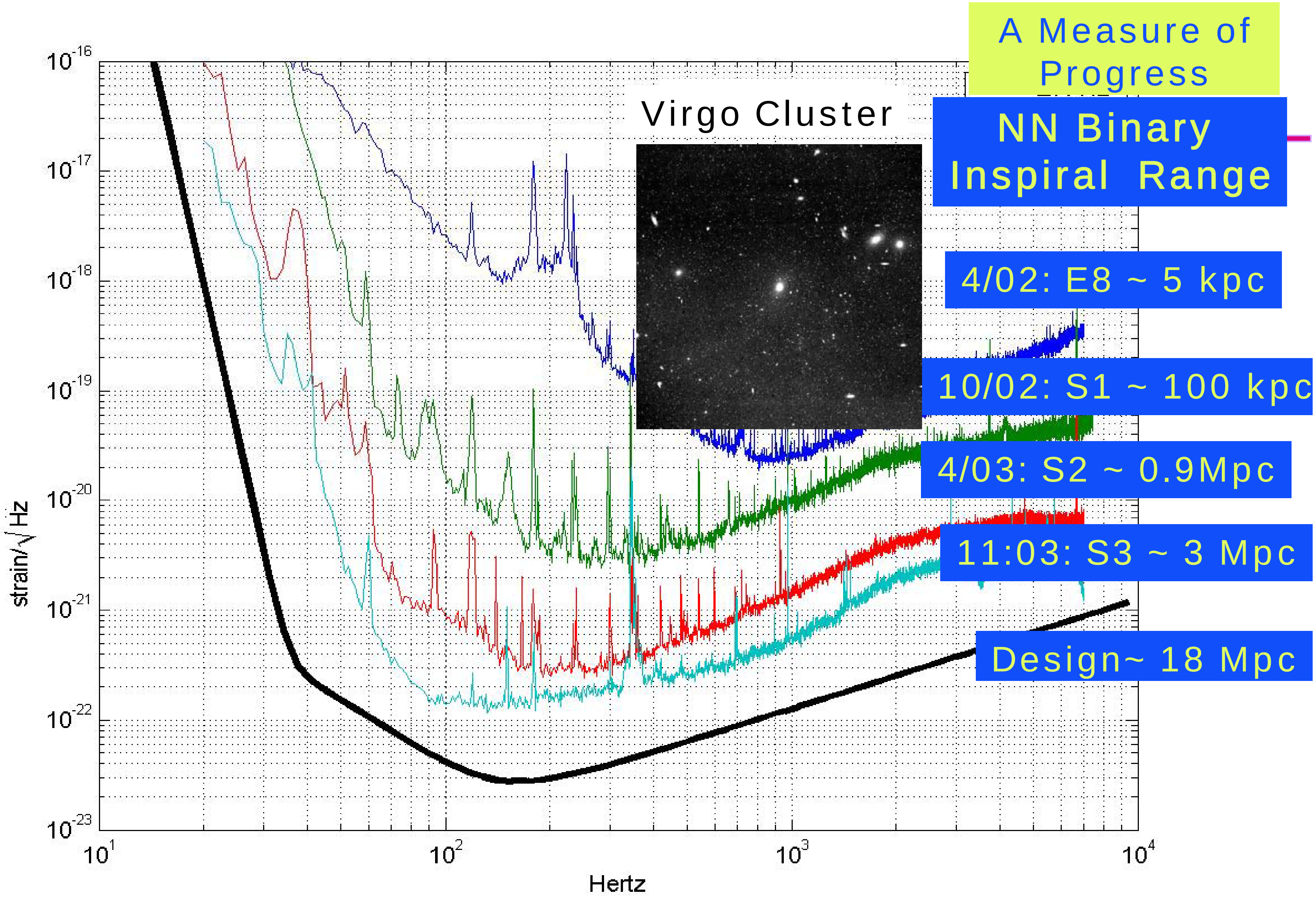


Interferometer Noise Limits

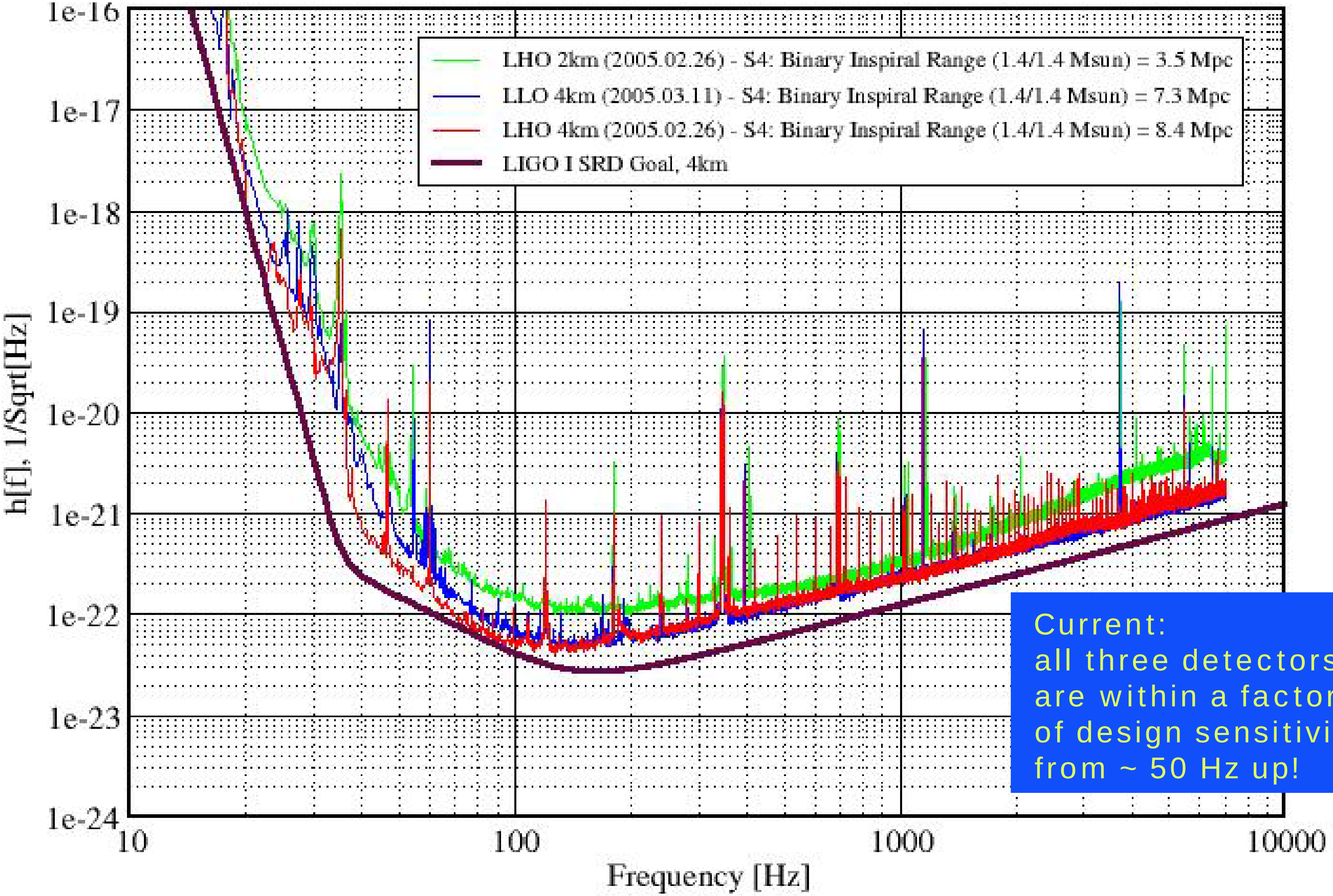


Despite a few difficulties, science runs started in 2002.

Science Runs



Best Performance to Date ….



Current:
all three detectors
are within a factor of 2
of design sensitivity
from ~ 50 Hz up!

LIGO schedule

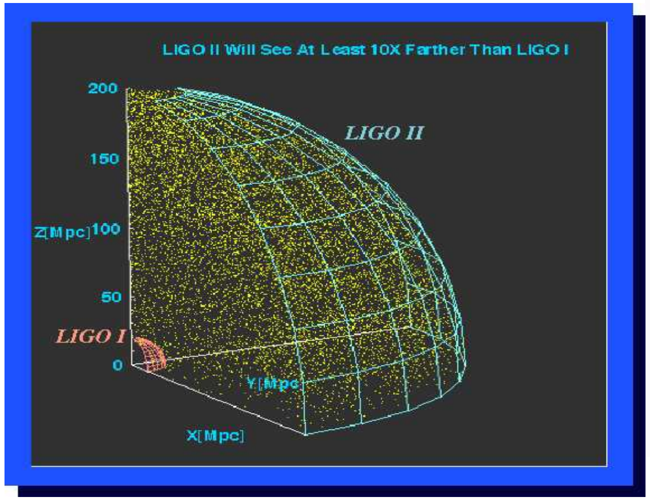
1995	NSF funding secured ($360M)
1996	Construction Underway (mostly civil)
1997	Facility Construction (vacuum system)
1998	Interferometer Construction (complete facilities)
1999	Construction Complete (interferometers in vacuum)
2000	Detector Installation (commissioning subsystems)
2001	Commission Interferometers (first coincidences)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003-4	LIGO I data runs (S1, S2, S3, S4)
2005+	LIGO I data run (one year integrated data at $h \sim 10^{-21}$)

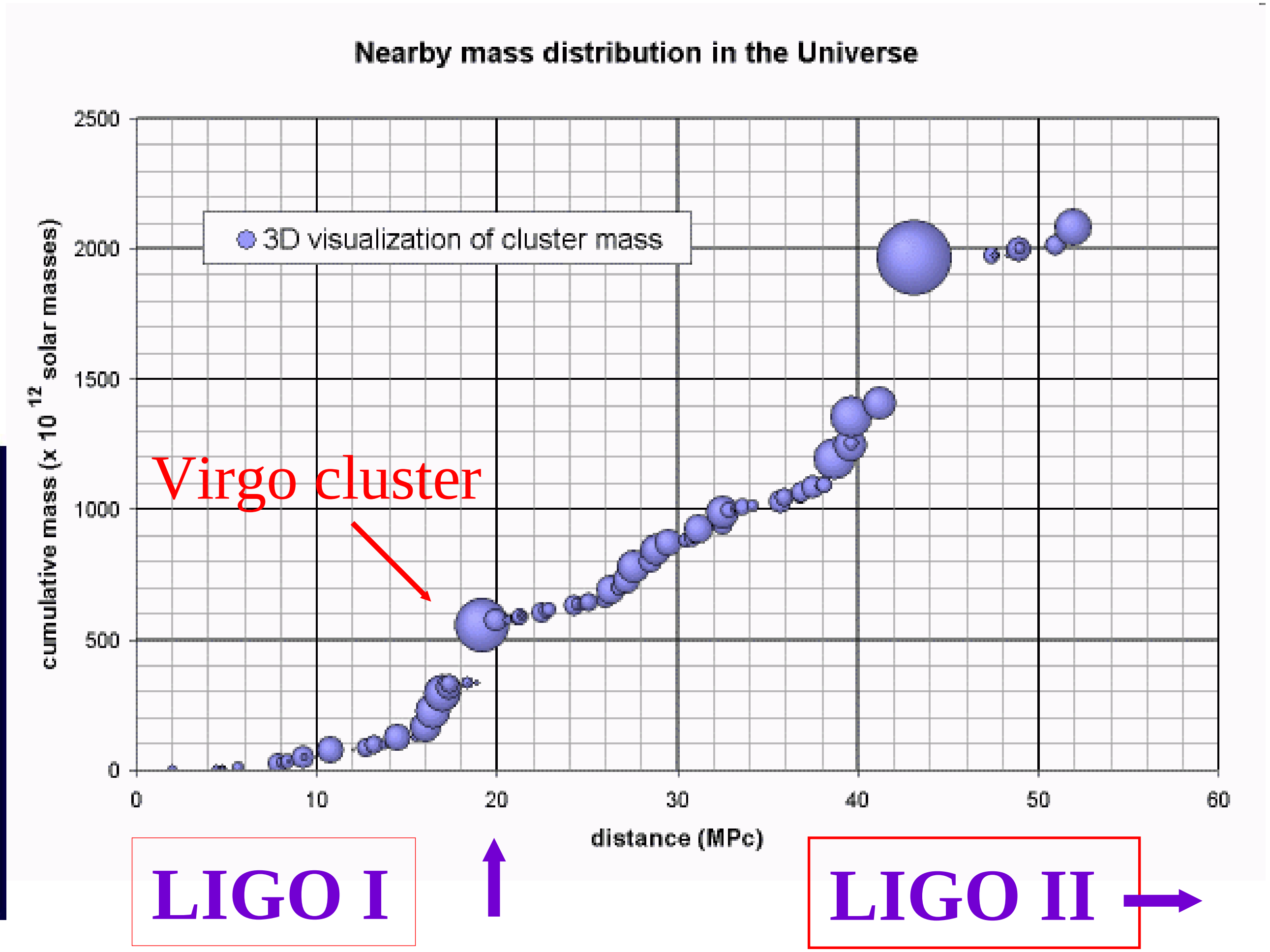
2004	Advanced LIGO approved by the NSB
2007…	Begin Advanced LIGO upgrade installation
2010…	Begin Advanced LIGO observations…

Improvement of reach with Advanced LIGO

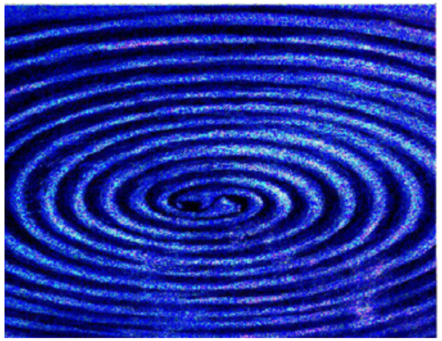
Improve amplitude sensitivity by a factor of 10x, and…

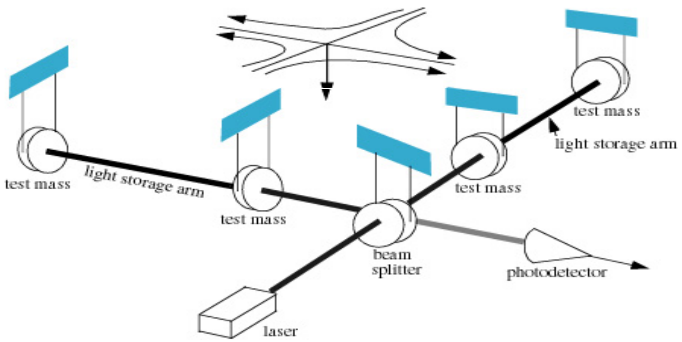
⇒ Number of sources goes up 1000x!





Einstein's Symphony



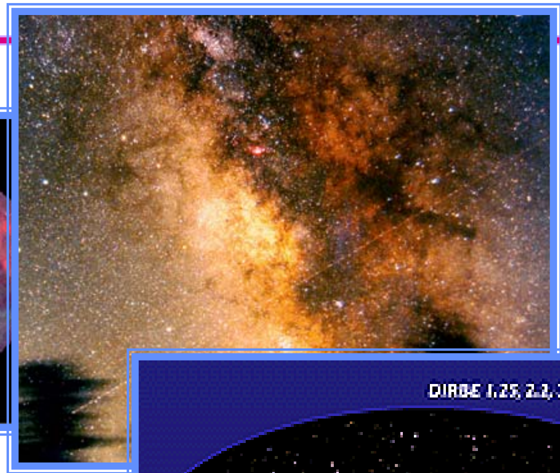


- Space-time of the universe is (presumably!) filled with vibrations: Einstein's Symphony
- LIGO will soon 'listen' for Einstein's Symphony with gravitational waves, permitting
  - » Basic tests of General Relativity
  - » A new field of astronomy and astrophysics
- A new window on the universe!

Observing the Galaxy with Different Electromagnetic Wavelengths

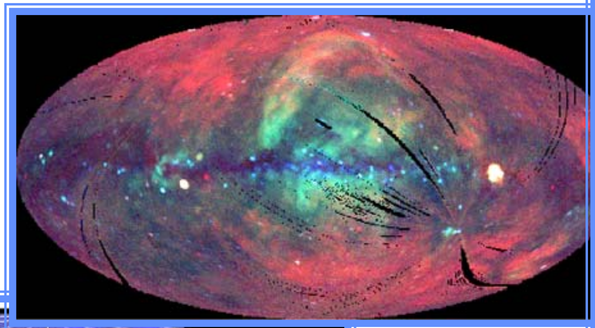
http://antwrp.gsfc.nasa.gov/apod/image/SagSumMW_dp_big.gif

$\lambda = 5 \times 10^{-7}$ m



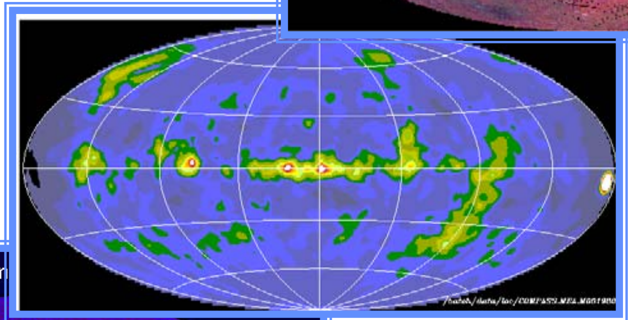
http://antwrp.gsfc.nasa.gov/apod/image/xallsky_rosat_big.gif

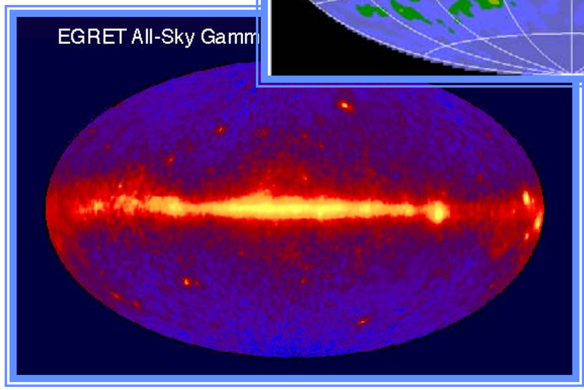
$\lambda = 5 \times 10^{-10}$ m



http://antwrp.gsfc.nasa.gov/apod/image/comptel_allsky_1to3_big.gif

$\lambda = 6 \times 10^{-13}$ m





http://cossc.gsfc.nasa.gov/cossc/egret/

$\lambda = 1 \times 10^{-14}$ m

http://www.gsfc.nasa.gov/astro/cobe

$\lambda = 2 \times 10^{-6}$ m

//rsd-www.nrl.navy.mil/7213/lazio/GC/

$\lambda = 9 \times 10^{-1}$ m

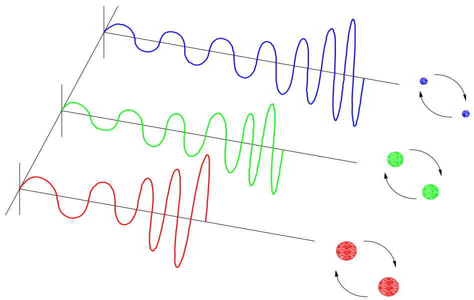
Contrast EM and GW information

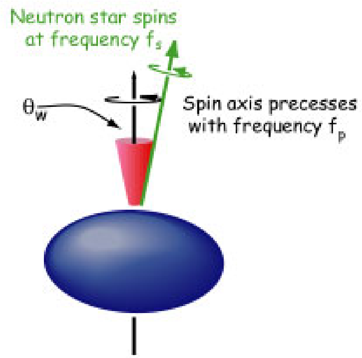
E&M	GW
space as medium for field	Space-time itself
incoherent superpositions of atoms, molecules	coherent motions of huge masses (or energy)
wavelength small compared to sources - images	wavelength ~large compared to sources - poor spatial resolution
absorbed, scattered, dispersed by matter	very small 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

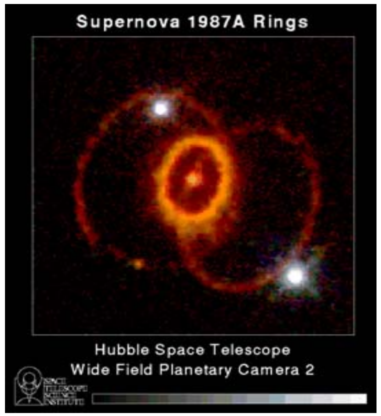
- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on E&M observations
- GW astronomy is a totally new and unique window on the universe

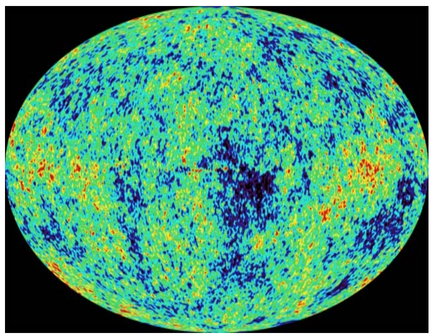
Astrophysical Sources of Gravitational Waves

- Compact binary systems
  - » Black holes and neutron stars
  - » Inspiral → merger → ringdown
  - » Probe internal structure, nuclear eqn of state of NS crust, populations, and spacetime geometry
- Spinning neutron stars
  - » known & unknown pulsars
  - » LMXBs
  - » Probe internal structure and populations
- Neutron star birth
  - » Supernova core collapse
  - » Instabilities: tumbling, convection
  - » Correlations with EM observations
- Stochastic background
  - » Big bang & other early universe
  - » Background of GW bursts









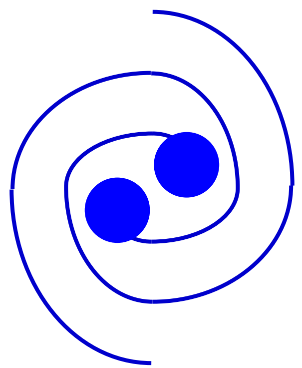
Analog from cosmic microwave background -- WMAP 2003

Binary Orbit Evolution

- A binary system in a close orbit

has a time-varying quadrupole moment
➔ emits gravitational waves

$$f_{GW} = 2\, f_{orbit}$$



Gravitational waves carry away energy and angular momentum

$$dE/dt \propto -f^{10/3}$$

➔ Frequency increases, orbit shrinks

$$df/dt \propto f^{11/3} \qquad dr/dt \propto -f^{2}$$

Objects spiral in until they finally coalesce

Additional relativistic effects kick in as (Gm/rc^2) grows away from zero

Zwerger-Müller SN waveforms

- astrophysically-motivated waveforms, computed from simulations of axi-symmetric SN core collapses.
- Almost all waveforms have duration < 0.2 sec
- A “menagerie”, revealing only crude systematic regularities. Inappropriate for matched filtering or other model-dependent approaches.
  - » Their main utility is to provide a set of signals that one could use to compare the efficacy of different filtering techniques.
- Absolute normalization/distance scale.