The Search for Gravitational Radiation from Distant Astrophysical Sources

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OUTLINE

- What is gravitational radiation?
- Indirect evidence for gravitational radiation (the Taylor-Hulse binary neutron star)
- What are the natural sources
- How to build a detector
- LIGO
- Future directions

General Relativity “predicts” the existence of gravitational radiation

- Newton’s laws assume action at a distance,
  - potential reacts instantly
  - there is no wave equation, no radiation
- General Relativity, being a relativistic theory, assumes a characteristic time for field response (c=speed of light), and yields a wave equation for this response

Einstein's Theory of General Relativity (1915)

$$\boxed{\mathbf{G} + \Lambda g = 8\pi\,(G_N/c^4)\,\mathbf{T}}$$

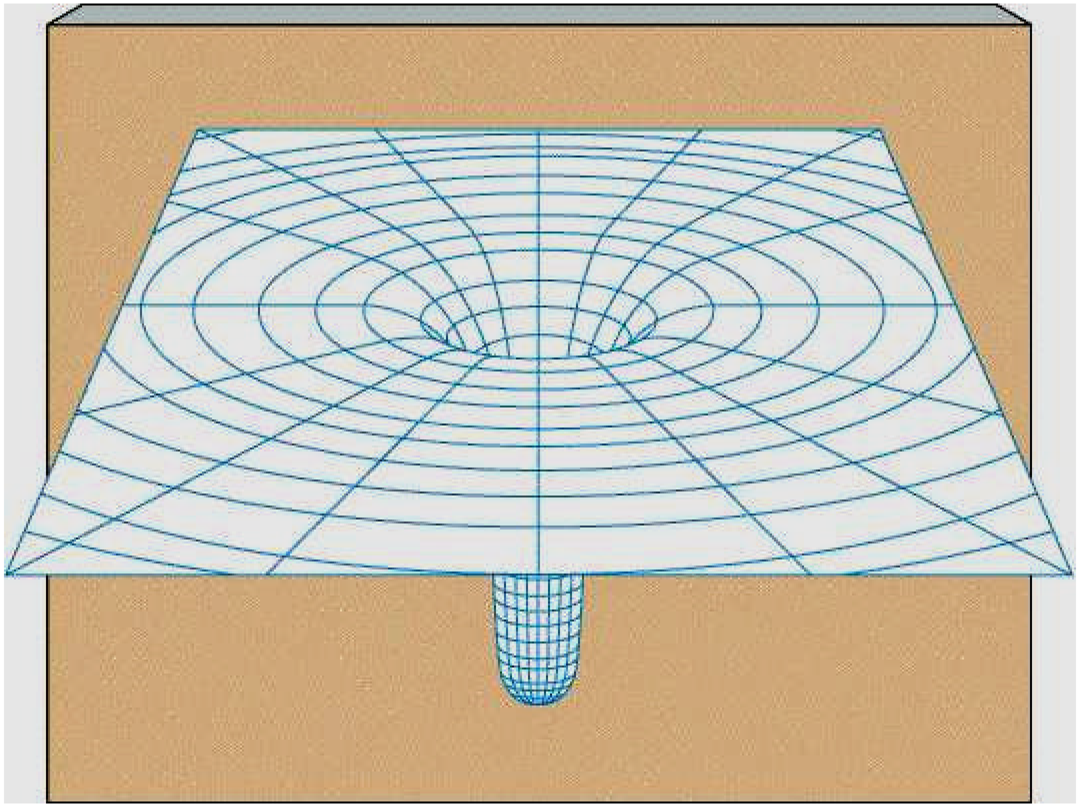
G is the curvature tensor

T is the stress-energy tensor

This equation says space-time curvature is a result of the existence of matter and energy

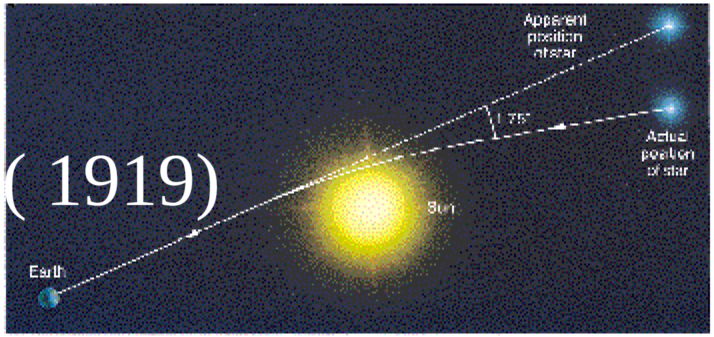
and space is stiff ($G_N/c^4 = 8.2 \times 10^{-45}\ \mathrm{s^3/kg\text{-}m}$)

Space-time is warped by matter and energy

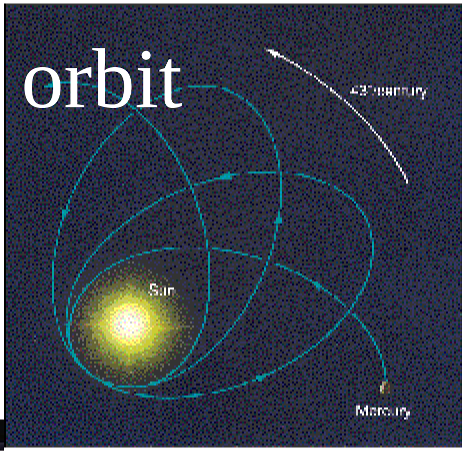


Three original predictions of GR

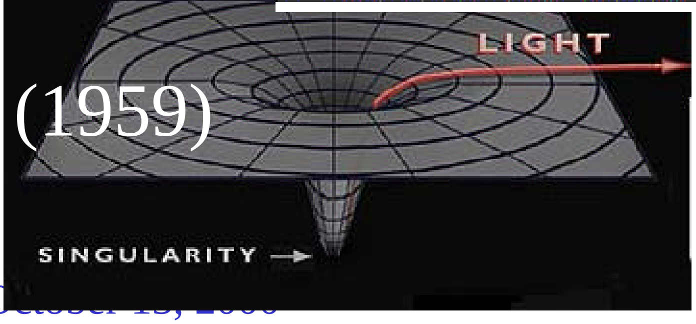
- Bending of starlight
  - 1.75″ deflection measured (1919)



- Perihelion advance of Mercury's orbit
  - 43 ″ / century (from GR)



- Gravitational redshift
  - Pound-Rebka experiment (1959)



Space-time Geometry

- The local geometry is defined by the curvature metric (G), a function of the local space-time metric (g)

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

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

$$\boxed{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}\ (h << 1)}$$

η is the flat space metric

$$\eta = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Space-time Geometry

- In the weak-field limit (h << 1), linearize equation in “transverse-traceless gauge” and arrive at wave equation for h

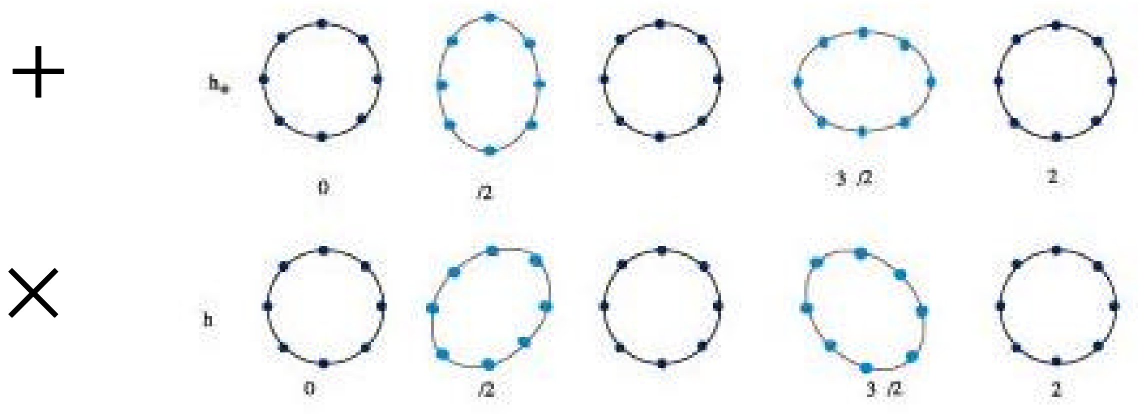
$$\nabla^2 h - \frac{\partial^2 h}{c^2 \partial t^2} = \frac{16\pi G_N}{c^4} T$$

- Quadrupole radiation
  - – monopole radiation forbidden by E conserv.
  - – dipole radiation forbidden by mom. conserv.
- There are two polarizations
  - – plus (+) and cross (×)

Two polarizations

- Wave will distort a ring of test masses like tidal deformation

- specific movement of the test masses during one period of the wave depend on polarization



Generation of gravitational radiation

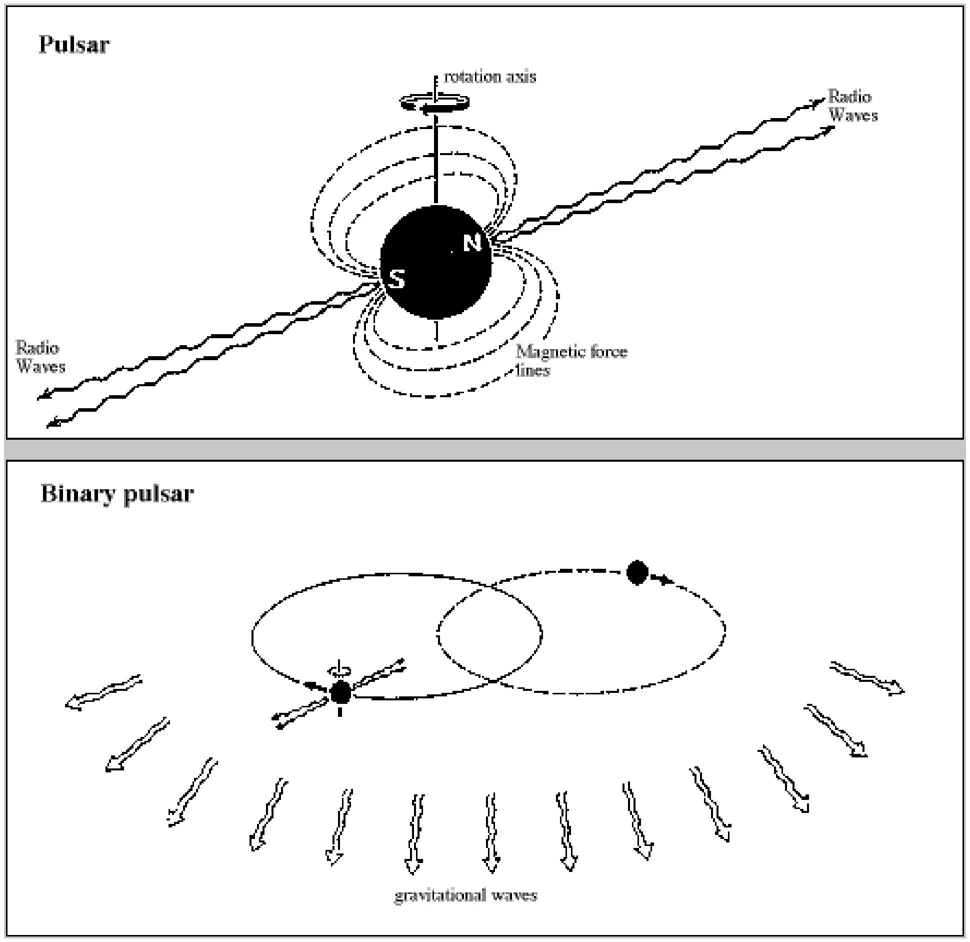
- Quadrupole radiation, requires quadrupole source
- accelerating mass generates wave, much as accelerating charge generates EM radiation

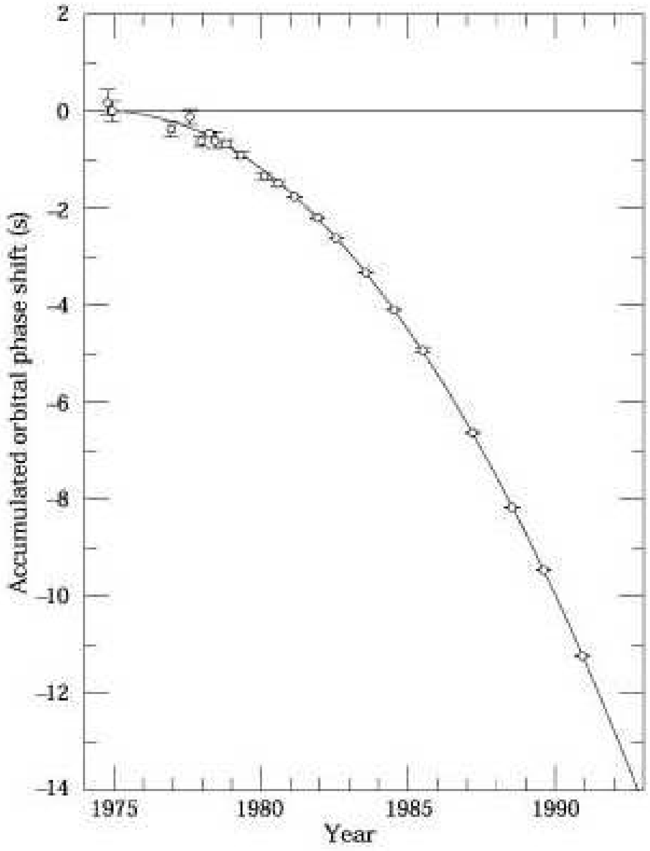
$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu}$$

EM and Grav. radiation

	Electromagnetic	Gravitational
•Source	• accelerating charge	• accelerating mass
•Nature	• oscillating field propagates thru space	• oscillating space-time
•Interactions	• absorbed, scattered by matter	• negligible interaction with matter
•Frequency	• $f > 10^7$ Hz	• $f < 10^4$ Hz
•Detector	• detectors directional	• detectors omni-directional
•Measure of strength	• measure intensity	• measure amplitude

Experimental evidence for GrRad
Taylor-Hulse Binary (PSR 1913+16)





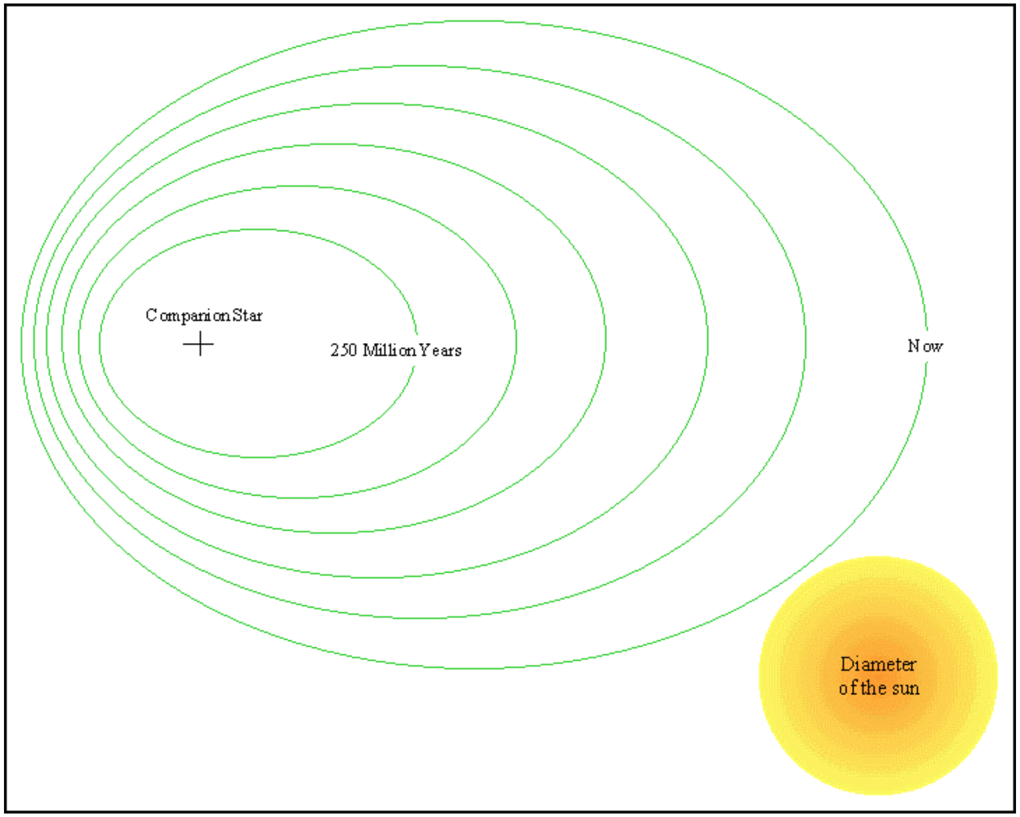
Future of the Taylor-Hulse

Radiating grav. energy

$$\frac{dE}{dt} = \frac{32GI^2w^6}{5c^5}$$

Not much today

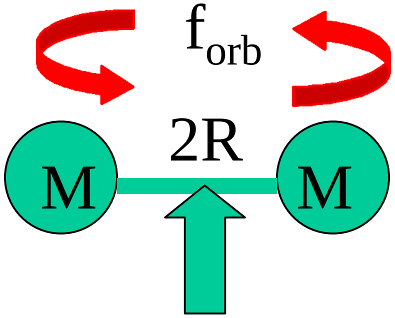
In 300,000,000 yrs
coalesce with a burst
of gravitational radiation



Generation of gravitational radiation (in the lab)

- Consider a time varying quadrupole field generated by a massive rotating dumbbell

$$h_{\mu\nu} = \frac{2G}{c^4 r} \ddot{I}_{\mu\nu}$$



M = 1000 kg (1 tonne)
R = 1 m
f = 1000 Hz
r = 1000 km (far field)

$h \approx 3 \times 10^{-39}$ – far too small a perturbation to detect!

We need larger masses - **astrophysical sources**.

Astrophysical Sources

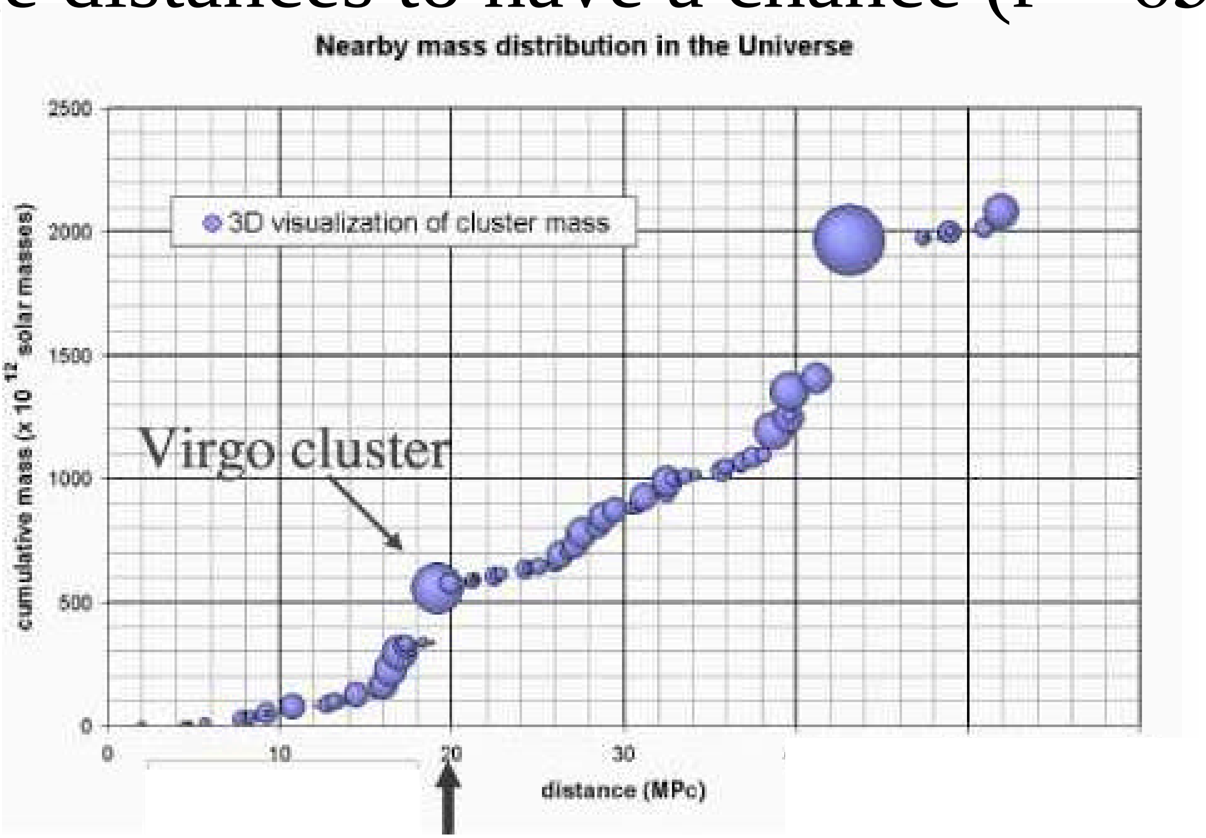
- Binary compact star systems
  - – composed of neutron stars and/or black holes
- Non-axisymmetric supernova collapse
- Non-axisymmetric pulsar (periodic)
- Early universe
  - – stochastic background radiation

⇒ most sources are not seen as EM emitters

⇒ good chance for surprises (unexpected sources)

Nearby stellar mass distribution

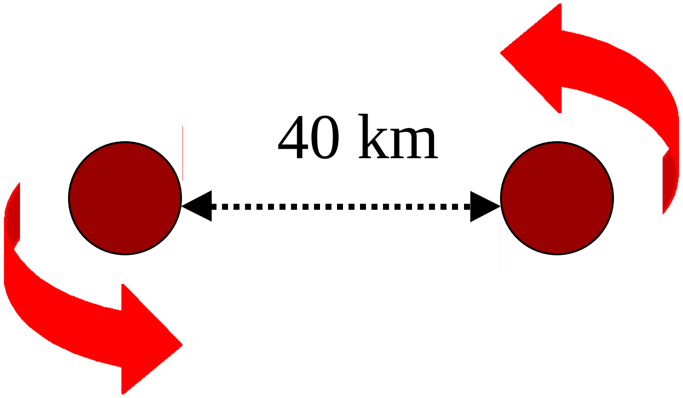
- These events are rare, so we need a reach to large distances to have a chance (r ≈ 65 Mly)



Back to the binary star system

- A benchmark system for grav. Radiation is a binary neutron star (compact)
- consider the strength

$$h_{\mu\nu} = \frac{2G}{c^4 r} \ddot{I}_{\mu\nu}$$

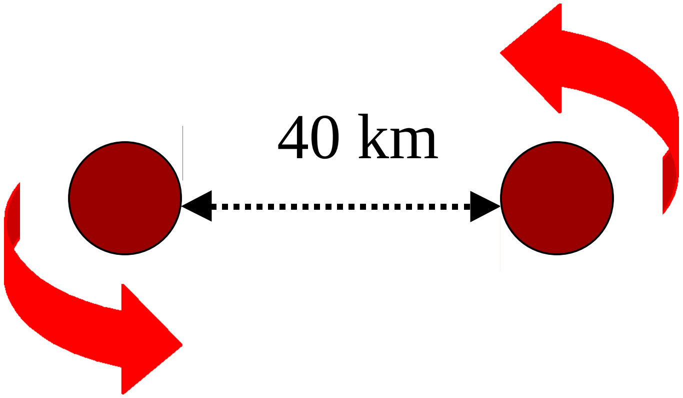


$M = 3 \times 10^{30}$ kg
R = 20 km
f = 400 Hz
$r = 10^{23}$ m (10 Mly)
$h \approx 6 \times 10^{-21}$ (10 Mly / r)

Energy flux of radiation from binary star system

- Our example binary system with f = 400 Hz radiates at a frequency of 800 Hz

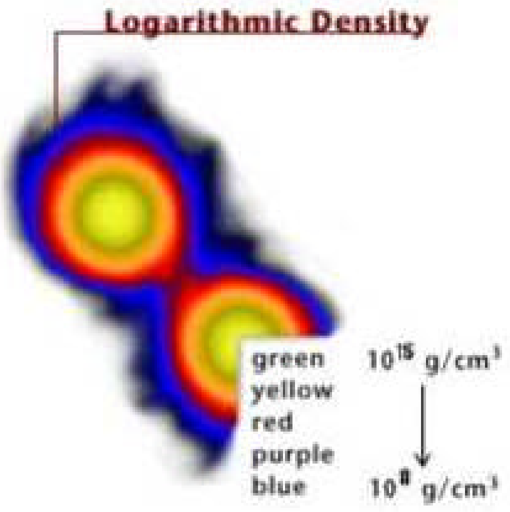
$$\frac{dE}{dt} = \frac{32 G I^2 w^6}{5c^5}$$

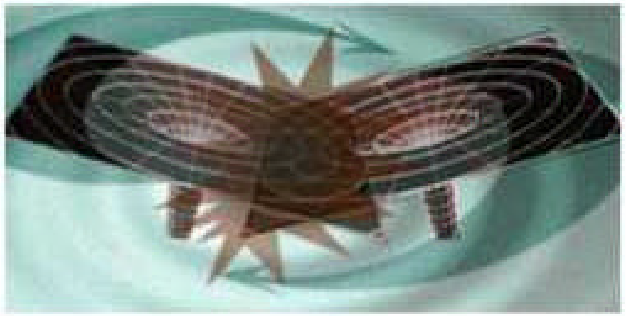


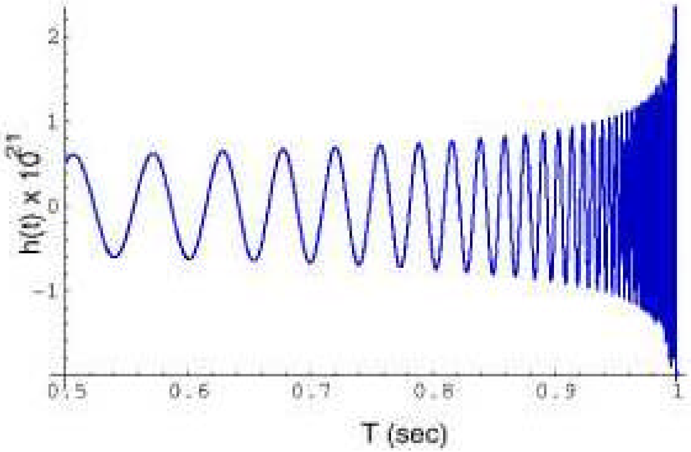
$dE/dt \approx 4 \times 10^{46}$ W

$M c^2 \approx 3 \times 10^{47}$ J

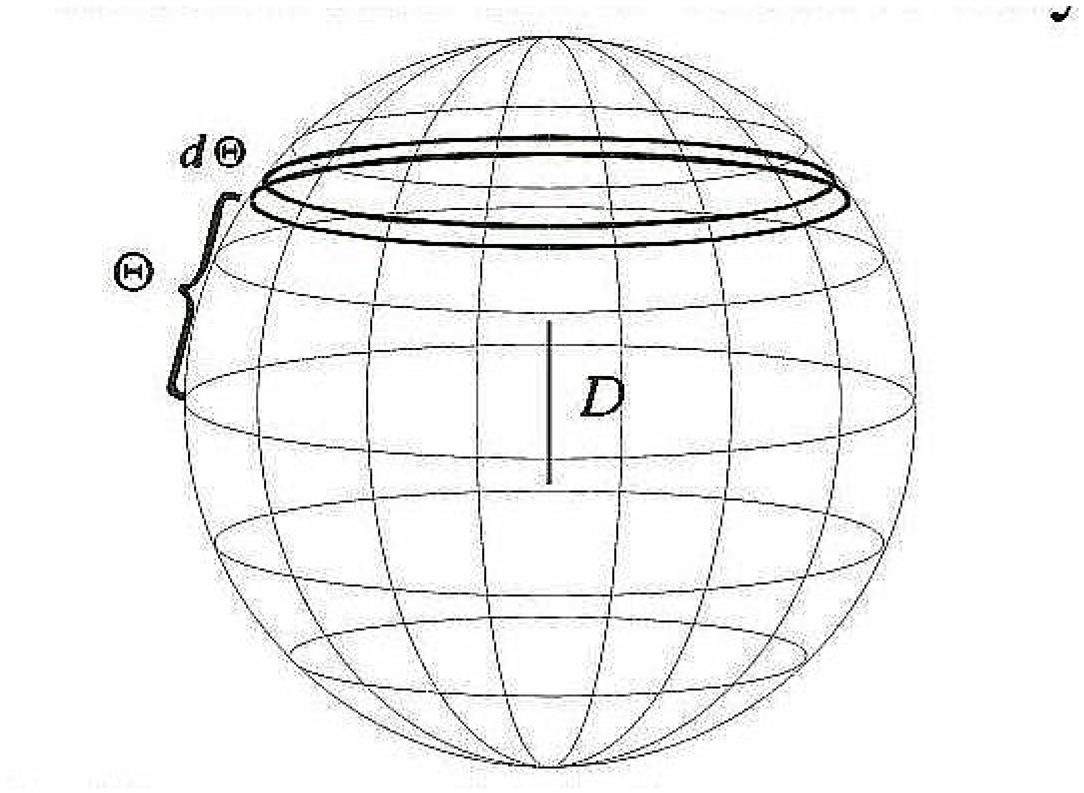
Chirp from compact binary



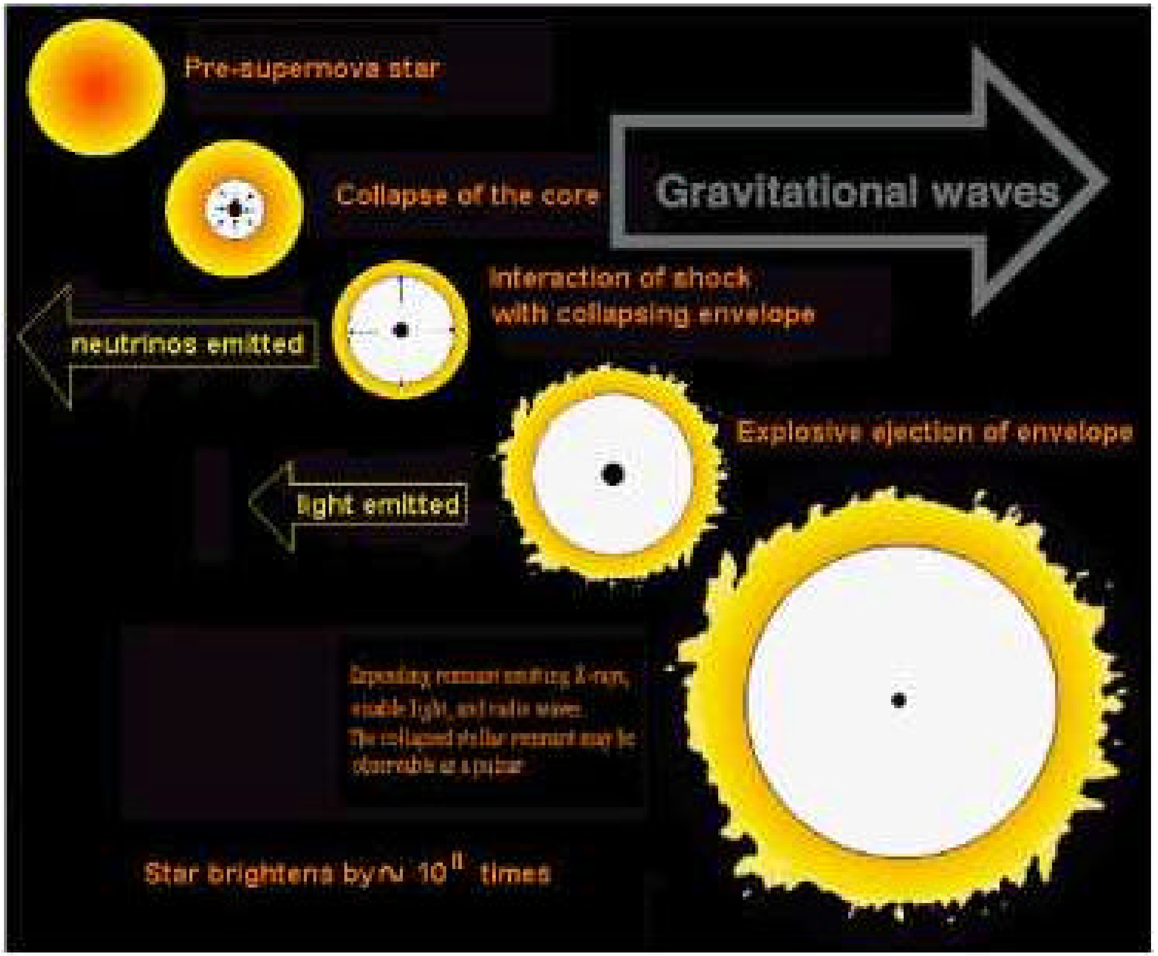




Detection at the two sites provides directional information

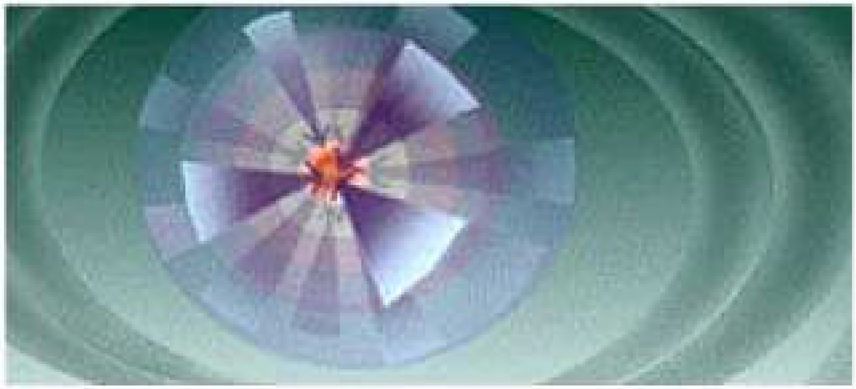


Non-axisymmetric SN collapse



Non-axisymmetric SN collapse

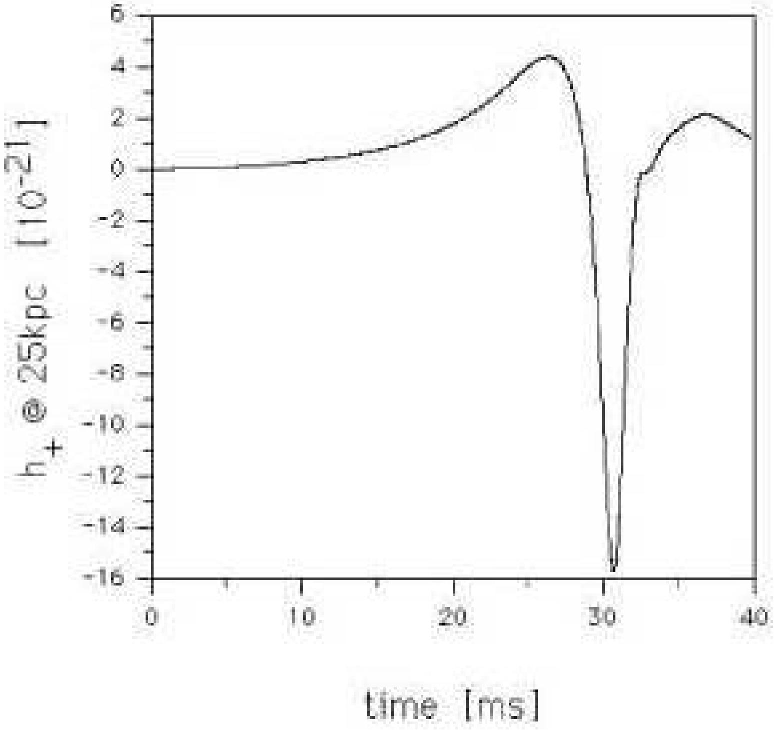
Non axisymmetric collapse



Rate

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

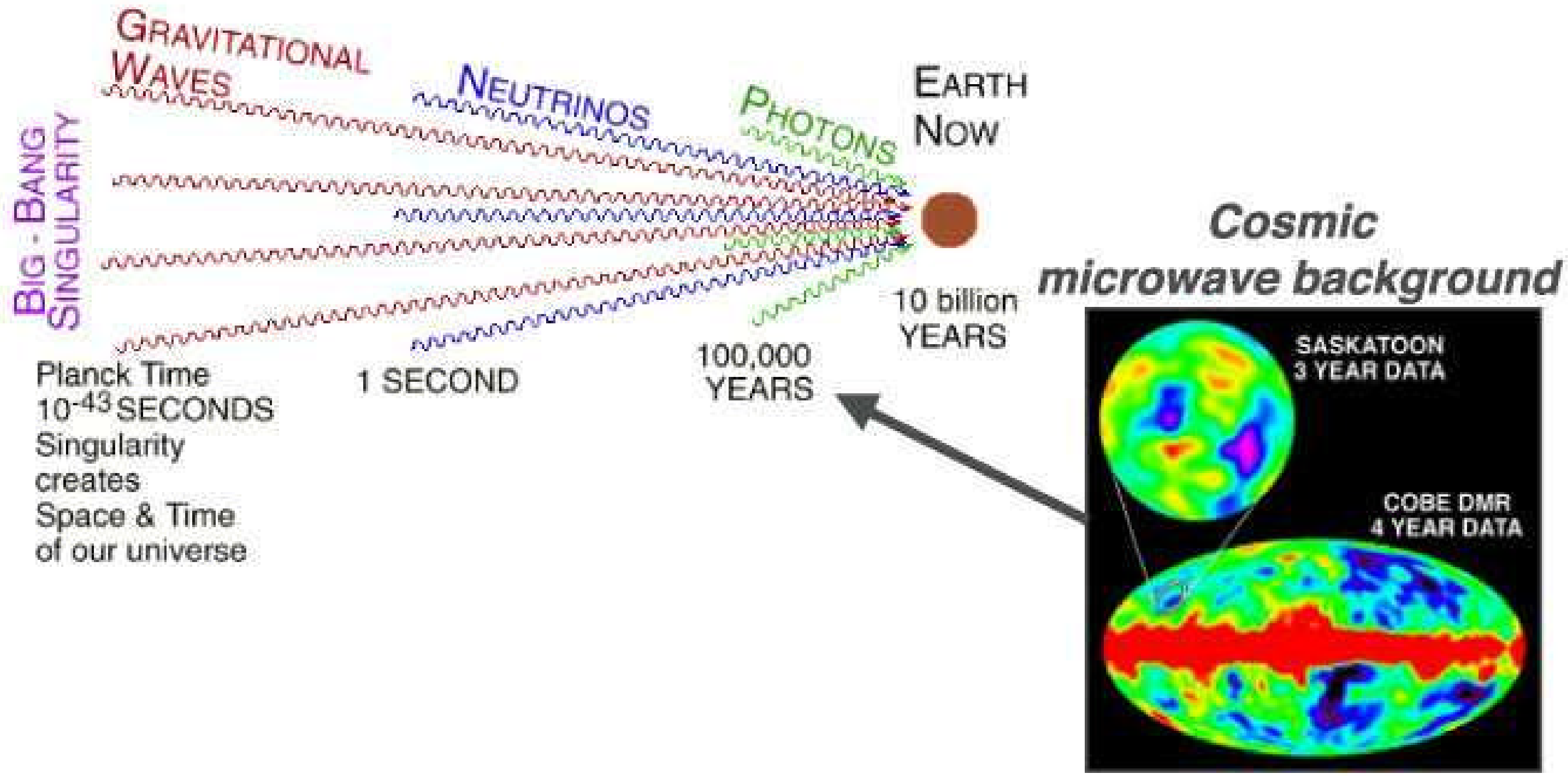
burst signal



Non-axisymmetric pulsar (periodic)

- Spinning neutron stars with asymmetric features will radiate gravity waves
- By locking on known pulsars, integrating the interferometer response over months, great sensitivity to small asymmetries are possible

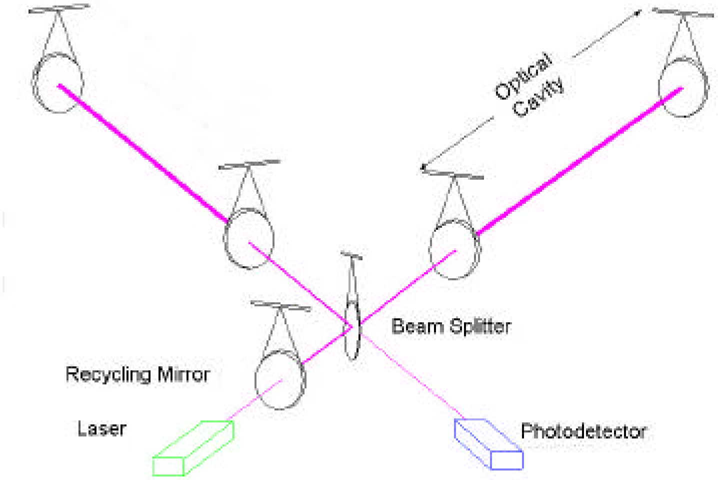
Early universe
(stochastic background radiation)



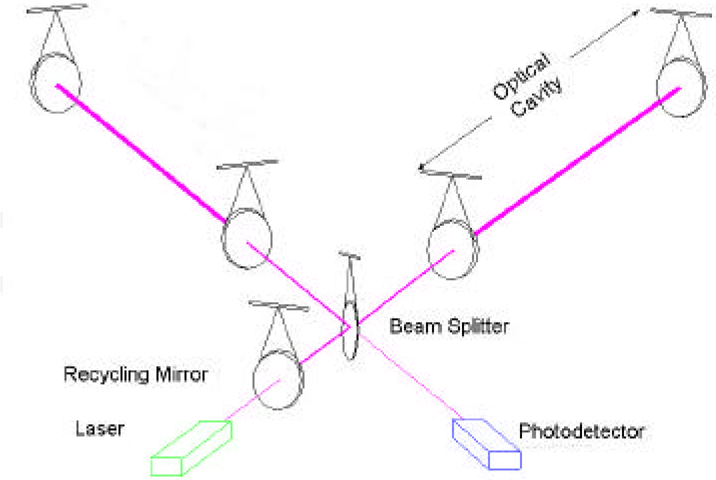
Detectors

- Bars

- Laser Interferometers



Laser Interferometer



Power recycled Michelson

$\Delta L = L_1 - L_2$ = cavity length diff.

B = number of times light bounces (effective arm length BL)

λ = laser wavelength

- Requirements for sensitivity ($h = \Delta L/L$)

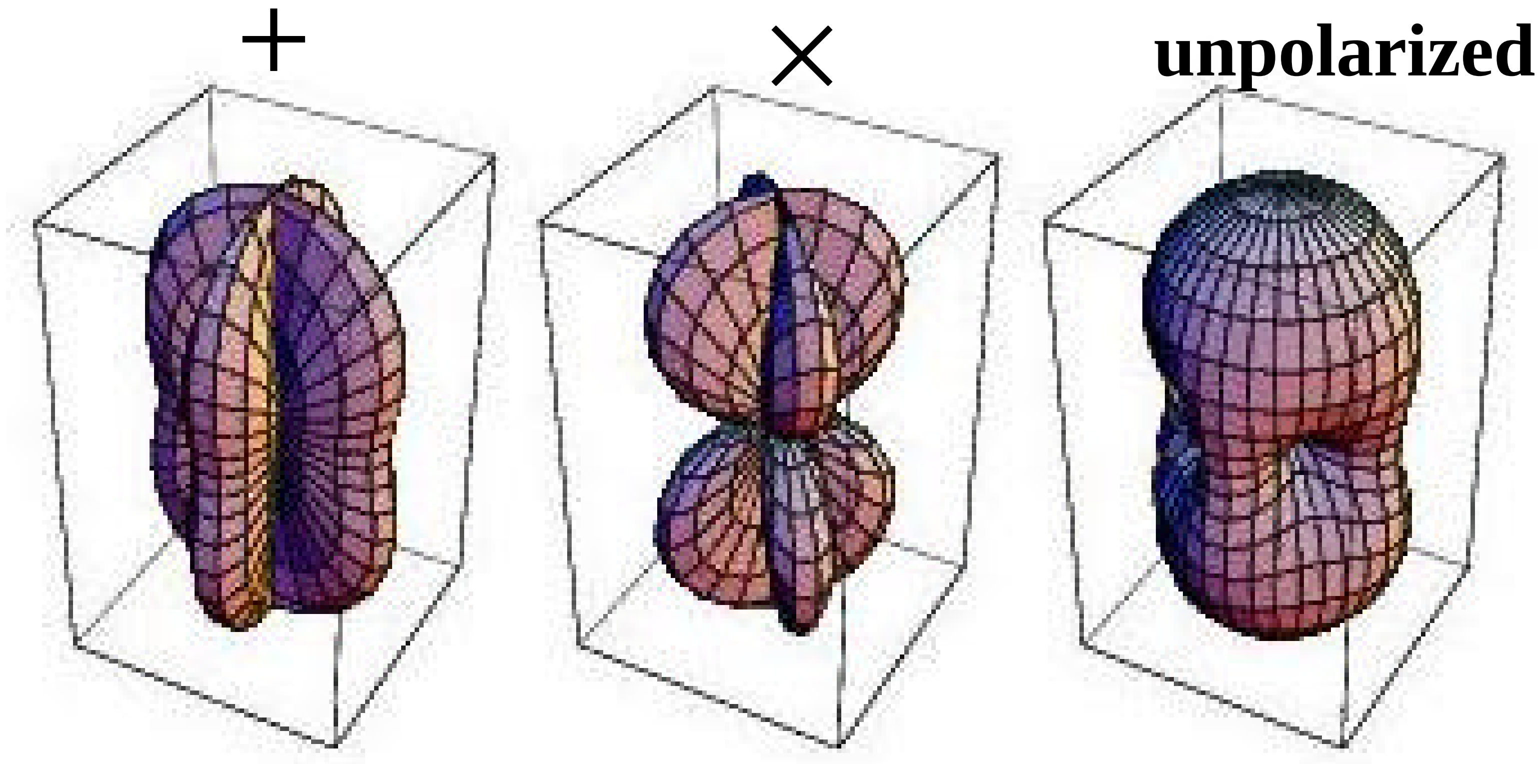
The relative phase change of light emerging from the two cavities is $\Delta\phi = B\,\Delta L / \lambda = B\,h\,L / \lambda$

So we need to maximize B and L, and minimize λ

eg. $B = 200$, $L = 4$ km, $\lambda = 1.06\ \mu m$

$\Delta\phi = 7.6 \times 10^{11}\ h$

Laser Interferometer
(antenna pattern)



(arms of interferometer are aligned along the horizontal axes)

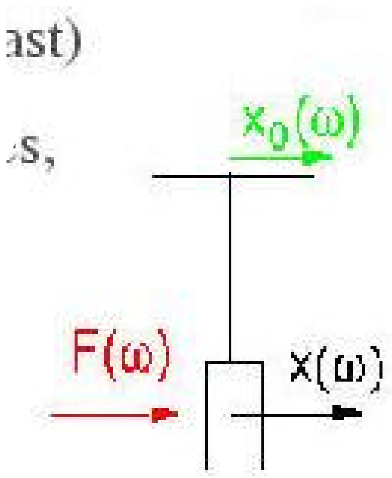
Laser Interferometer (Noise)

- Ultimately, the detection of radiation is limited by noise in the receiver (interferometer)
- Major sources of noise
  - seismic (limits low freq)
  - shot (limits high freq)
  - thermal (limits intermediate freq, difficult)

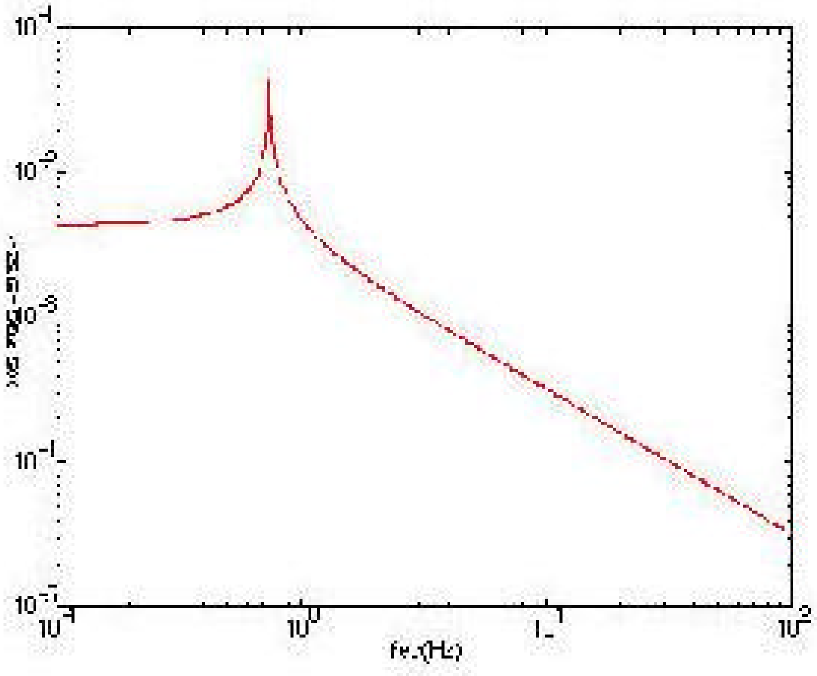
Note - other sources of noise are smaller but may limit advanced detectors

Laser Interferometer (SeismicNoise)

- Seismic noise in interferometer is suppressed by suspending test masses from pendulum



(isolated from f > 100 Hz)



Laser Interferometer (Shot Noise)

- Interesting signals are $h \sim 10^{-21}$
- Therefore, we need to measure

$$\Delta\phi \sim 7.6 \times 10^{11}\ h \sim 7.6 \times 10^{-10}$$

- The precision of this measurement is limited by the photon shot noise:

$\Delta\phi \sim 1/\sqrt{N}$, where N is the number of photons collected in a time bucket

- Or, we want want $N > 10^{19}$

Laser Interferometer (ShotNoise)

- Shot noise in interferometer is minimized by maximizing laser power in the interferometer
  - Power recycling (6 W in ⇒ ~ 240 W stored)

$$N = P\, 2\pi\, \lambda / hc \quad \tau$$

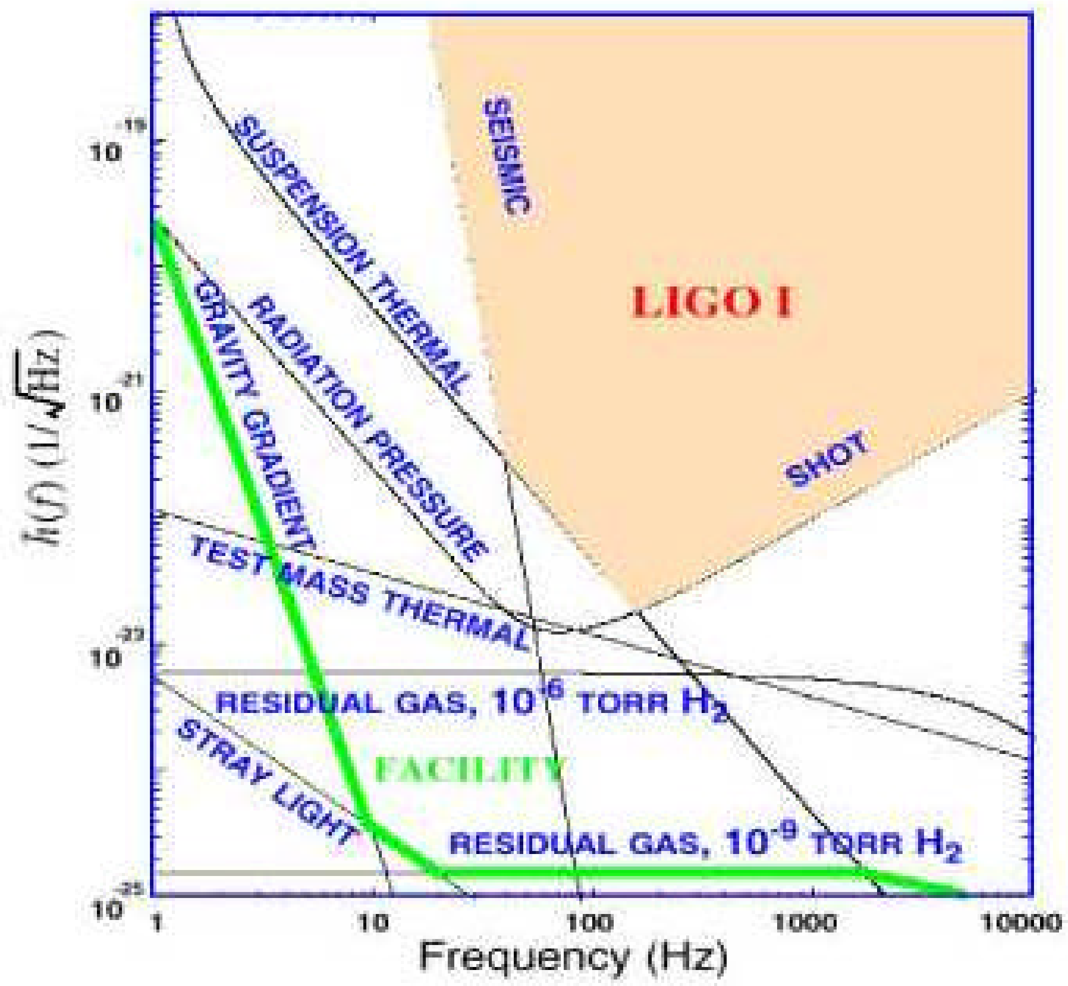
$$= 240\ \text{W}\ 1.06\ \mu\text{m} / 3.1 \times 10^{-26}\ \text{J m}\ (1\text{ms})$$

$$= 0.8 \times 10^{19} \quad \text{per millisecond}$$

Laser Interferometer (Thermal Noise)

- Thermal noise in interferometer
  - thermally induced vibrations of test masses and suspensions
  - Dissipation draws this noise into the band of sensitivity
  - minimized by choice of materials
    - high Q material (fused Si, sapphire)

Laser Interferometer (Noise)



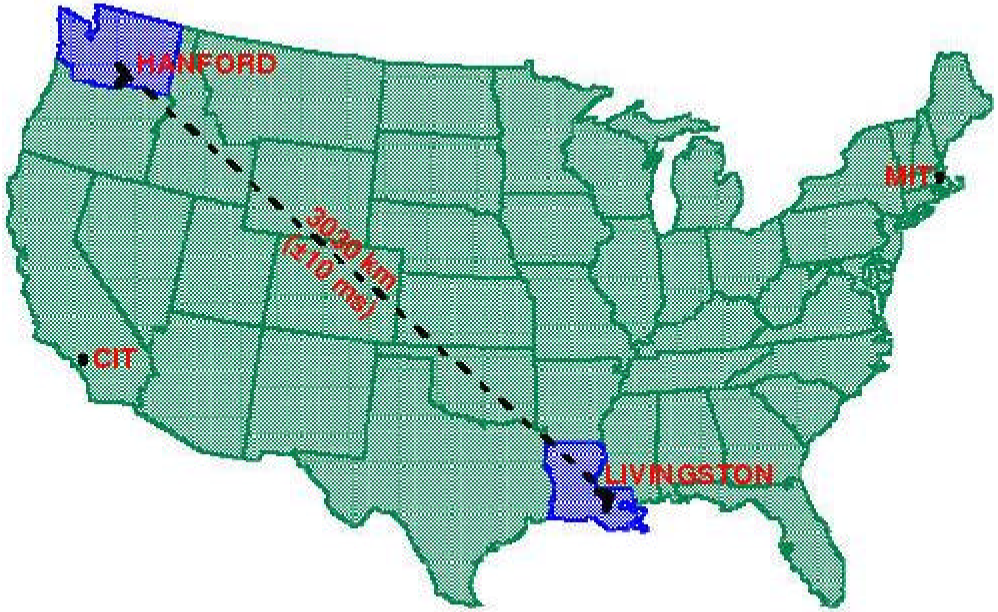
LIGO

- km-scale Laser interferometers at two sites
- Built by collaboration of Caltech and MIT
- Science will be done by LIGO Science Collaboration: ACIGA, Caltech, Carleton, Cornell, Florida, GEO, Harvard, IAP, India IUCAA, Iowa State, JILA, LSU, La. Tech, MIT, Michigan, Moscow State, NAOJ-TAMA, Oregon, Penn State, Southern, Stanford, Syracuse, Texas-Brownsville, Wisconsin-Milwaukee
- (Oregon group: JB, R. Frey, M. Ito, R. Rahkola, R. Schofield, D. Strom)

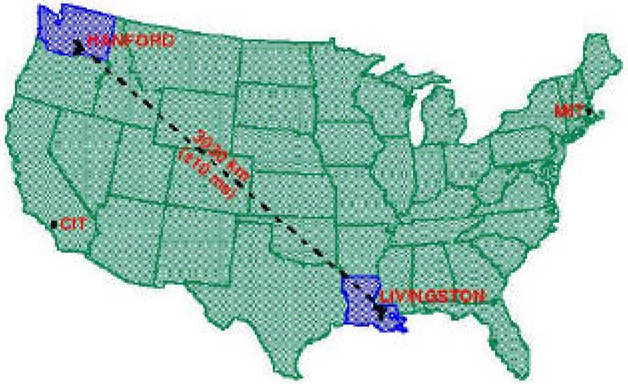
LIGO SCHEDULE

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)
	LHO 2km commissioning
	Single arm test (summer 2000)
	Power-recycled Michelson (Winter 2000)
2001	Commission Interferometers (first coincidences)
	PRM with FP arm cavities (Summer 2001)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003+	LIGO I data run (one year integrated data at h ~ 10 -21)
2005	Begin LIGO II upgrade installation

LIGO Sites



$$4 \text{ km arms} \Rightarrow h \approx 10^{-21} : \Delta L \approx 4\ 10^{-18}\ \text{m}$$



Hanford, WA

Livingston, LA

Laser Interferometer (Beam Tube)

- Light path in vacuum (10^{-6} torr initial)
- Beam tube with 1.22 meter diameter
- 10,000,000 liter vacuum systems

LIGO Vacuum Chambers

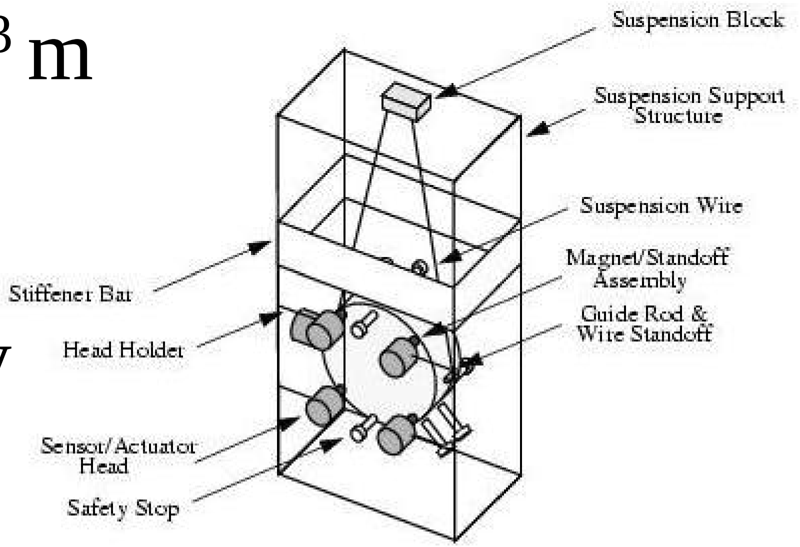
- All optical components are mounted in high vacuum chambers

LIGO Vibration Isolation

- All optical components are mounted on spring stack in high vacuum

Sensing and Control System

- 4 length and 12 alignment degrees of freedom must be controlled to maintain strain sensitivity
- Must hold lengths to 10^{-13} m in presence of 10^{-5} m seismic noise
- Test masses controlled by electromagnets driven by feedback



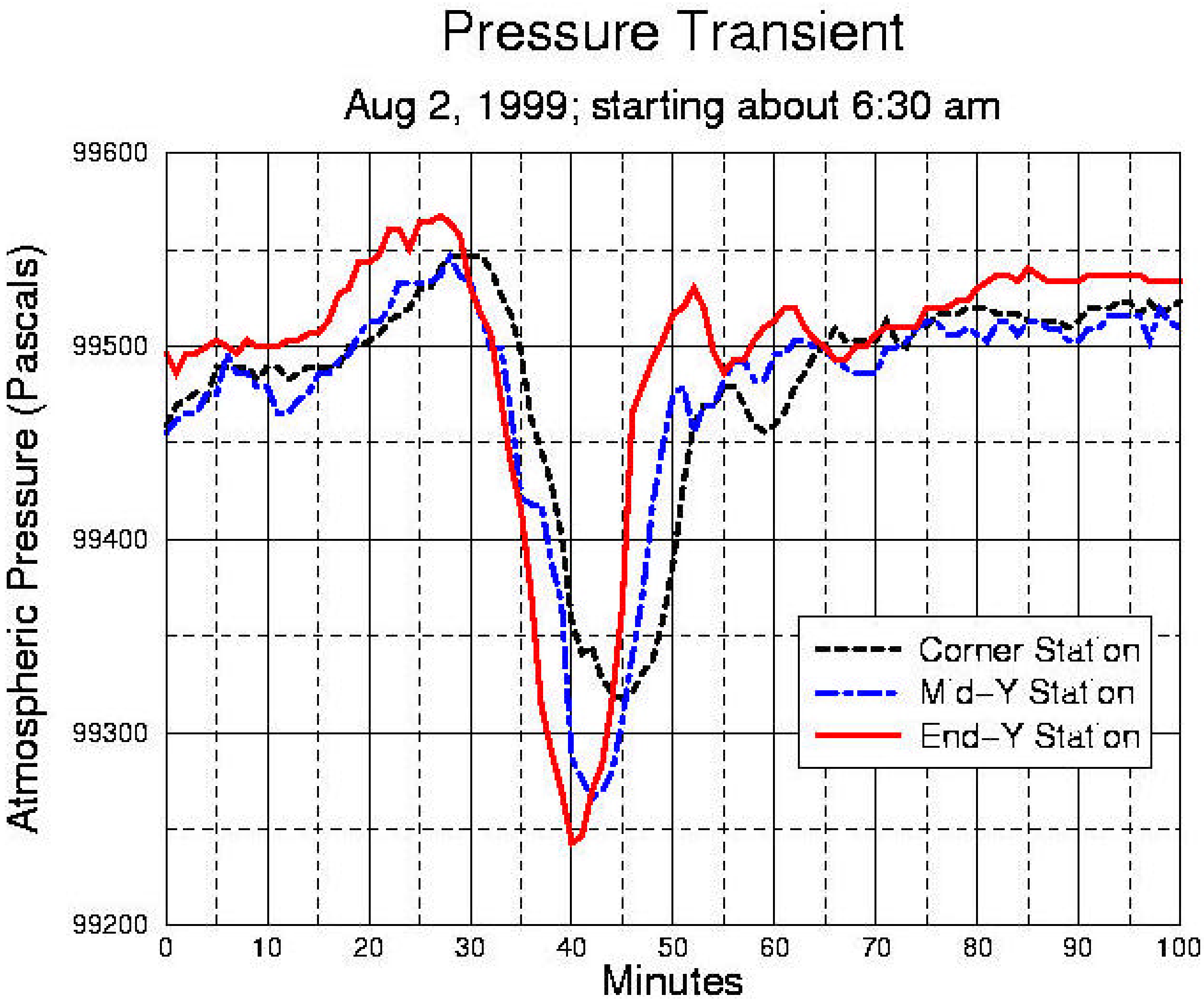
Eigenfreq. of suspension 0.5 - 0.7 Hz

Physics Environment Monitoring

- Seismometers
- Accelerometers
- Magnetometers
- Tiltmeters
- Microphones
- RFI monitors
- Cosmic Rays
- Thunderstrom service

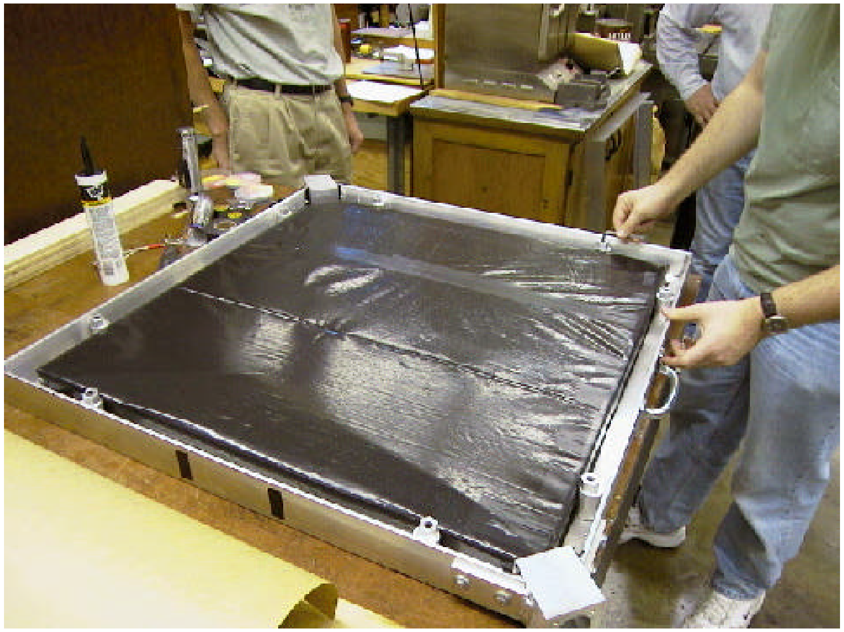
- Force Shakers
- Loudspeakers
- Magnetic field generators

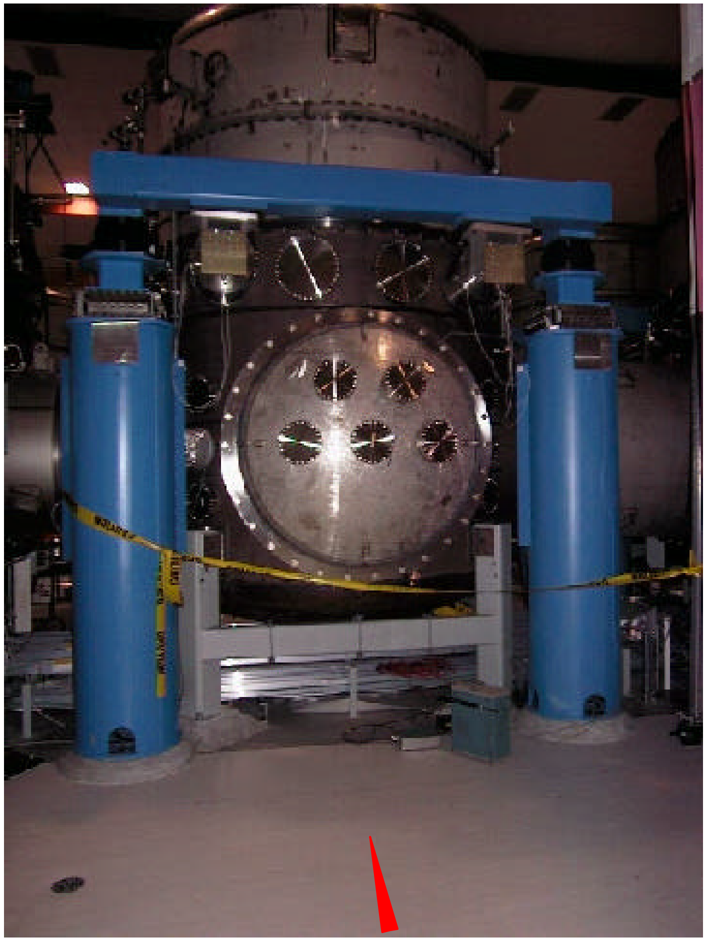
PEM (example)


Pressure Transient
Aug 2, 1999; starting about 6:30 am
Atmospheric Pressure (Pascals)
99600
99500
99400
99300
99200
0
10
20
30
40
50
60
70
80
90
100
Minutes
Corner Station
Mid-Y Station
End-Y Station

Cosmic Ray Monitor

Look for coinicidences to prevent false discovery



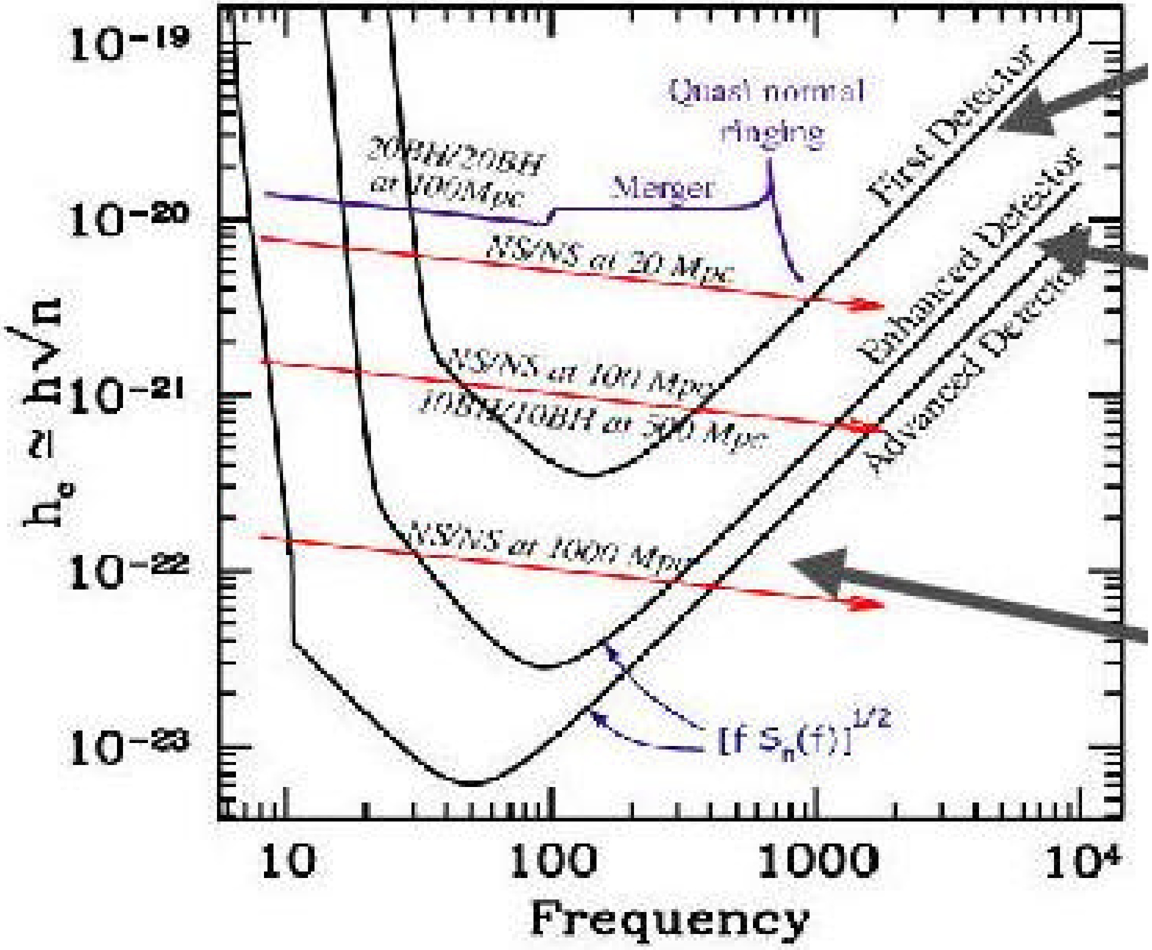


Data Acquisition

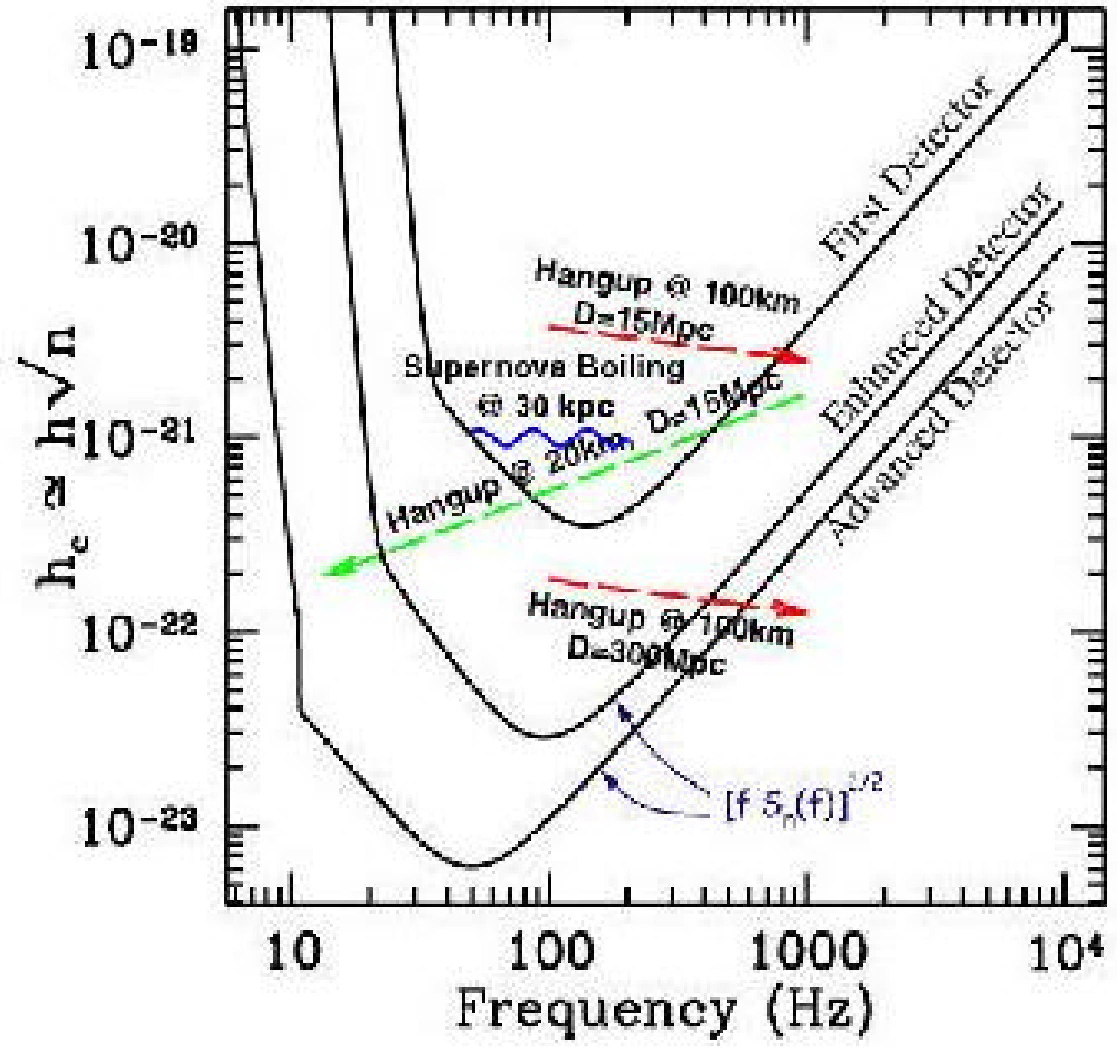
- Gravity wave channel is digitized at 16 kHz, but many other channels (about 2000 chan.)

  ⇒ very large data rate
  - monitor and control
  - PEM channels
- 14 Mbyte / sec
- store full data stream on disk for ~1 day
- reduce data to mini-data sets for analysis
  - archive rest

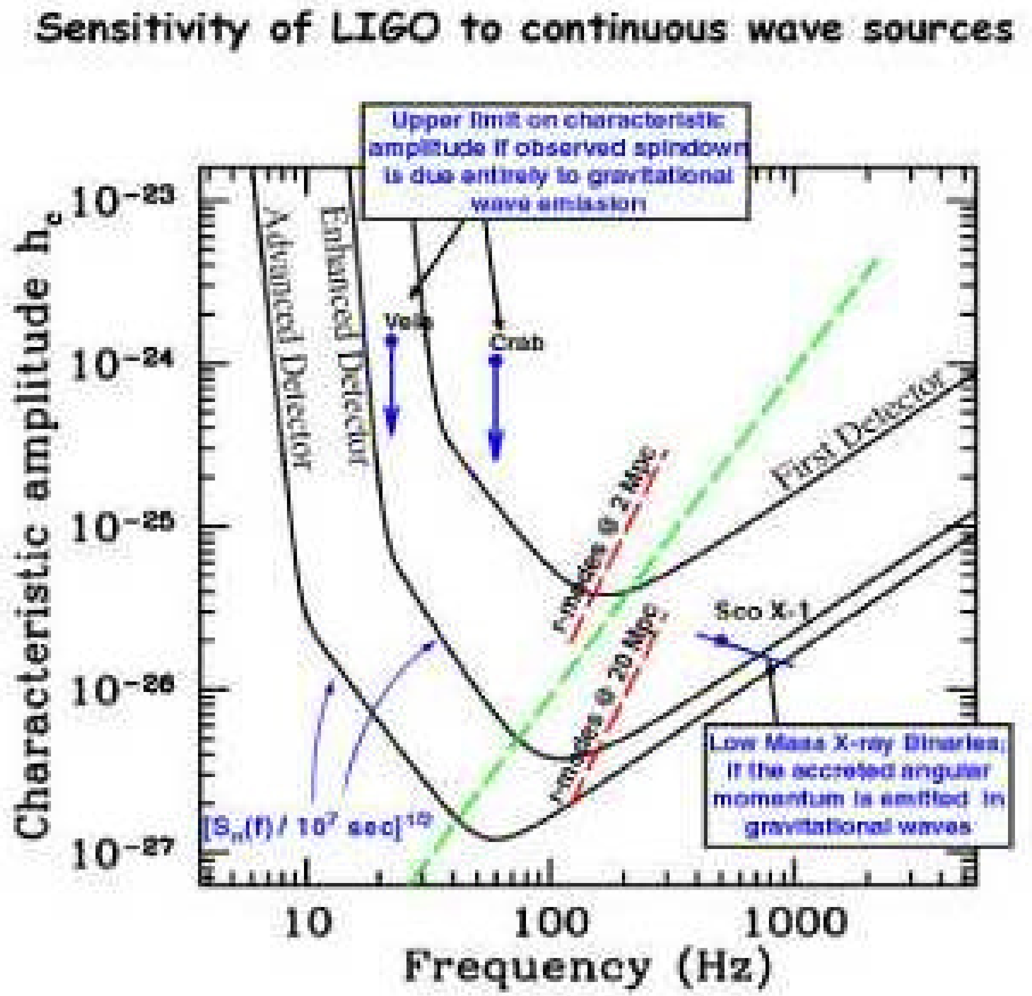
LIGO Sensitivity to Binaries



LIGO Sensitivity to Bursts



LIGO Sensitivity to Pulsars



Sensitivity of LIGO to continuous wave sources

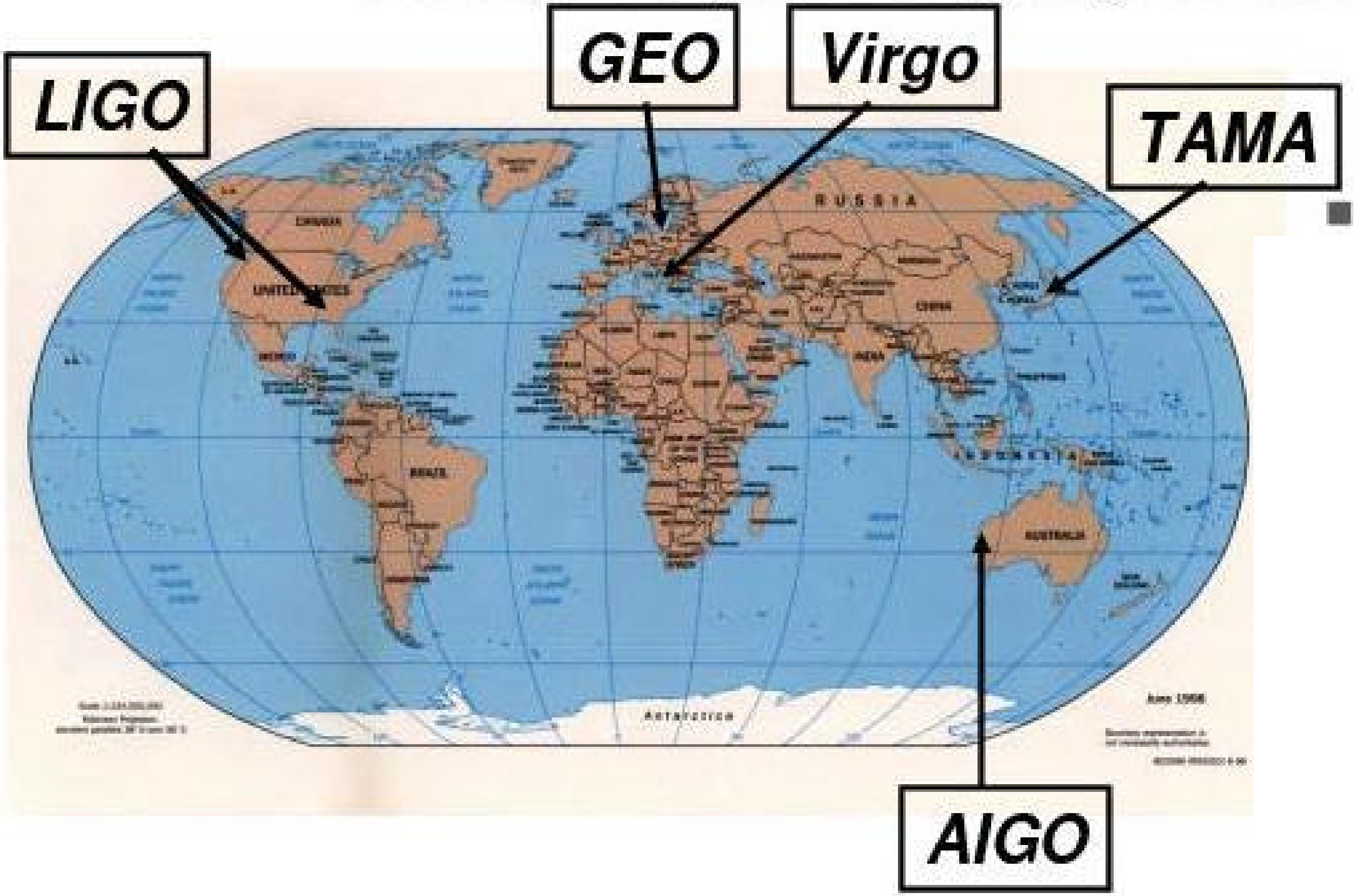
Upper limit on characteristic amplitude if observed spindown is due entirely to gravitational wave emission

Low Mass X-ray Binaries; if the accreted angular momentum is emitted in gravitational waves

Detection Strategy: Coincidences and Monitoring

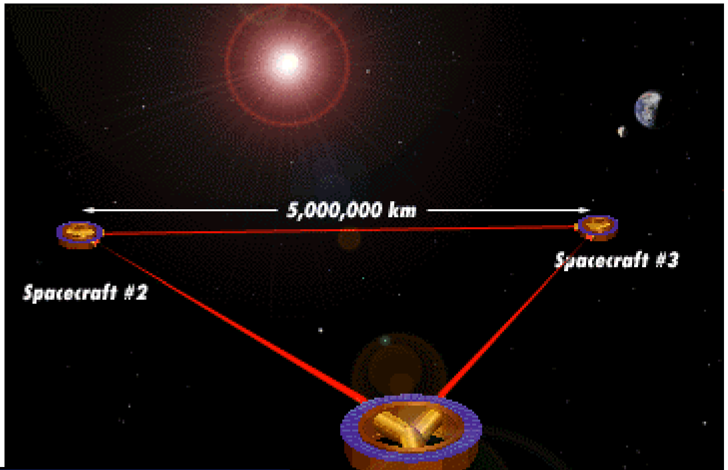
- Two sites - Three interferometers
    - absolute timing accuracy to 10 microsec
- Environmental Monitoring
    - eliminate false signals from the environment
        - such as lightening strike
- Correlate with other detectors
    - eg. optical, γ-ray, X-ray, neutrino

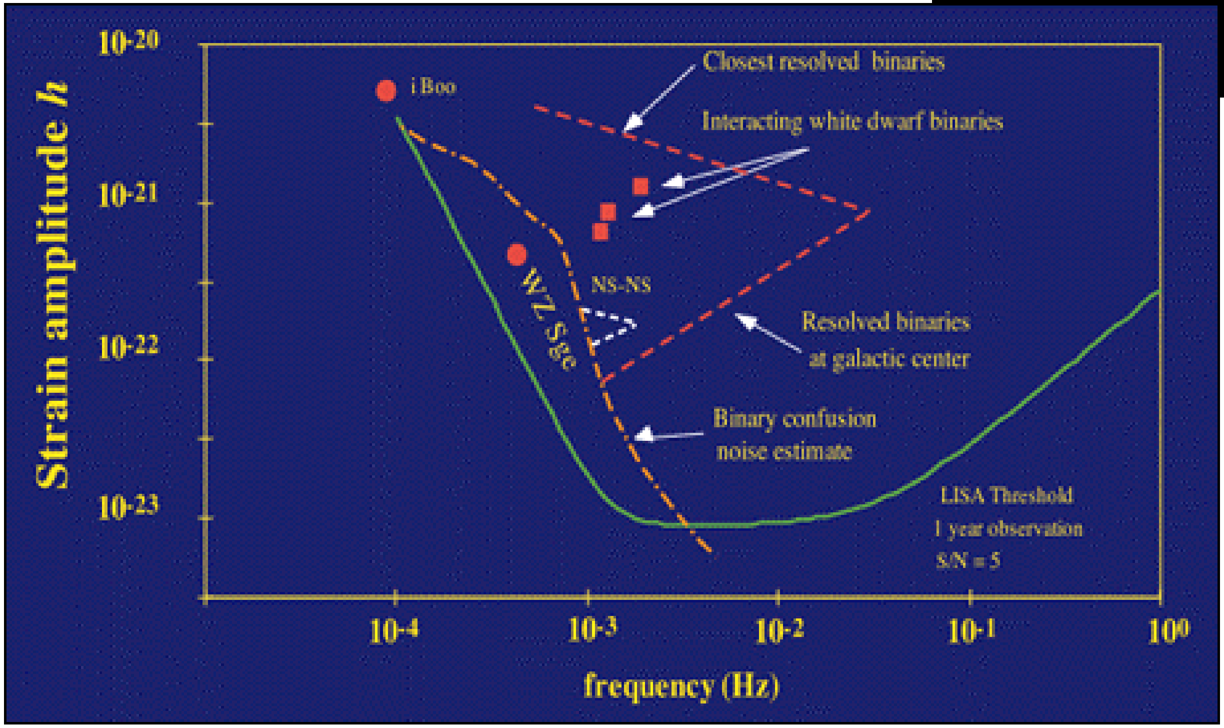
LIGO and the World-wide Network of Laser Interferometer Detectors



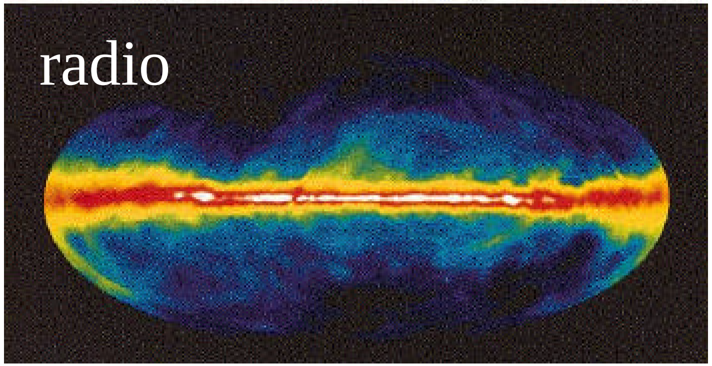
Laser Interferometer Space Antenna (LISA)

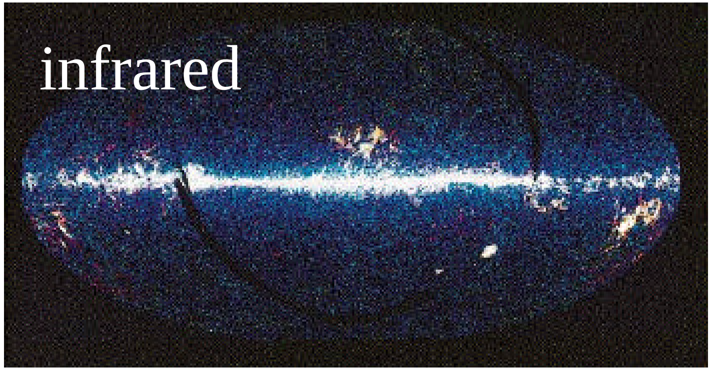
(the next generation)

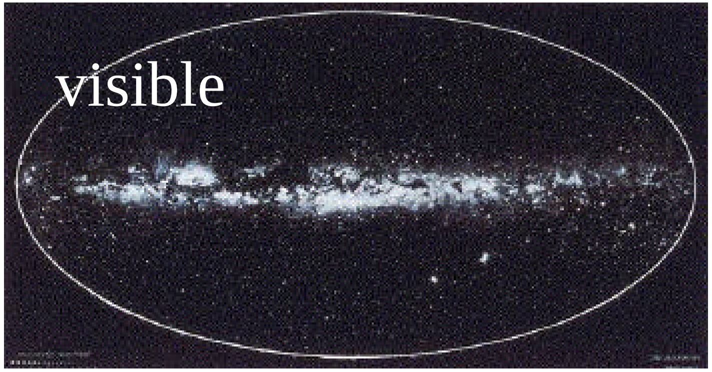


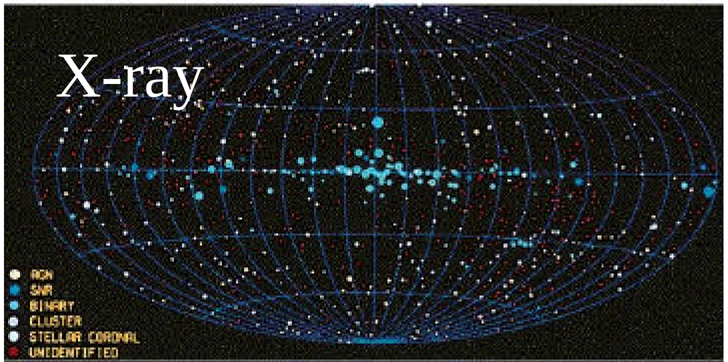


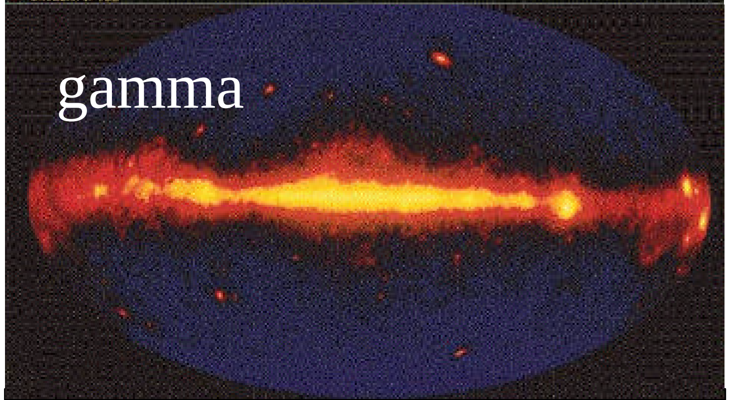
Gravity waves open a new window

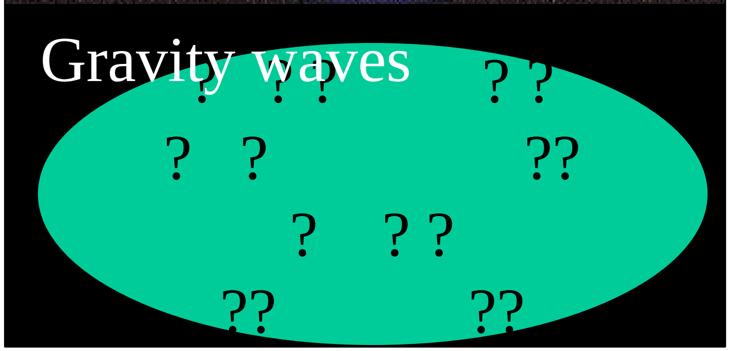

radio


infrared


visible


X-ray


gamma


Gravity waves

Invitation to Visit Hanford Site

- Fred Raab, Hanford Observatory Head, sends his personal invitation to visit
- everyone is welcome

raab_f@ligo.caltech.edu

CONCLUSIONS

- Gravitational radiation should be discovered in this decade
- With it should come advances in understanding General Relativity
- and, perhaps, discoveries of new phenomena in the universe

WATCH FOR SURPRISES