Gravitational Wave Astronomy

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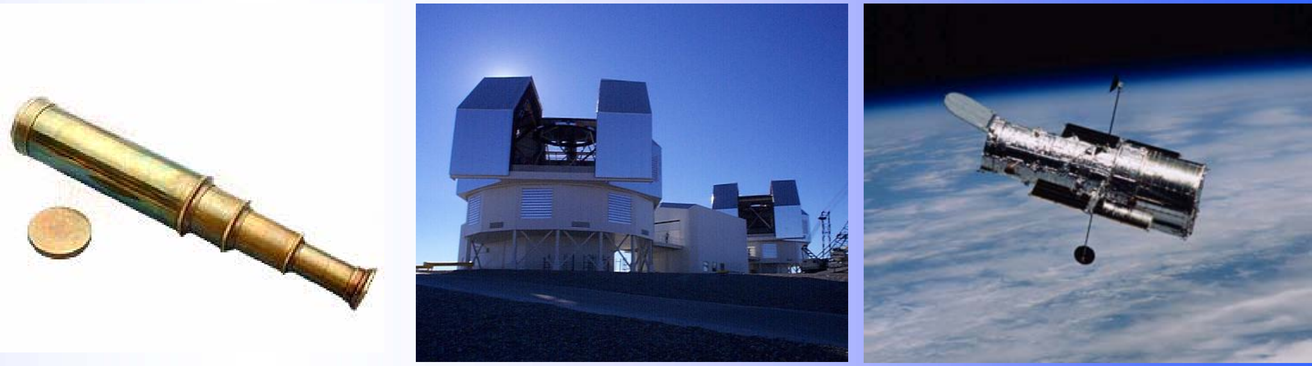
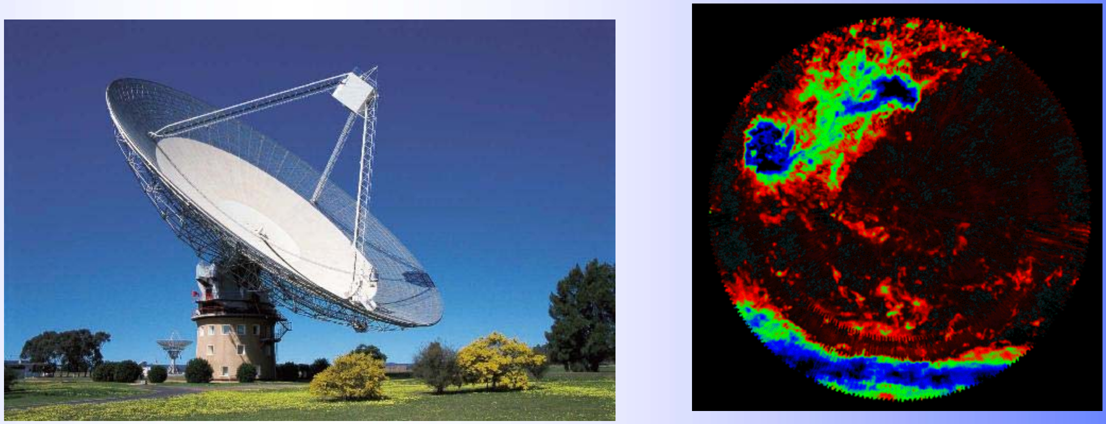
History of Astronomical Instruments

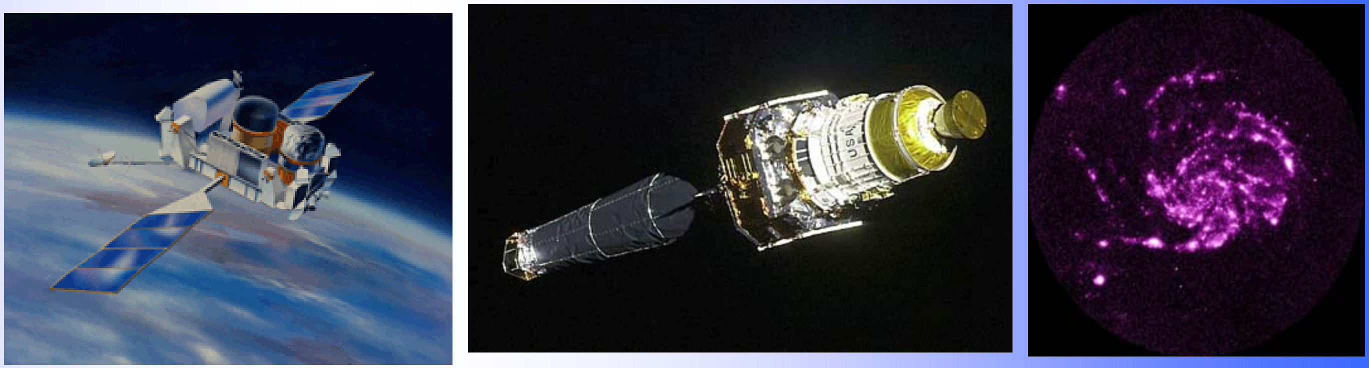
Optical Telescopes
(c. 1600 to today)



Radio Telescopes
(1932 to today)



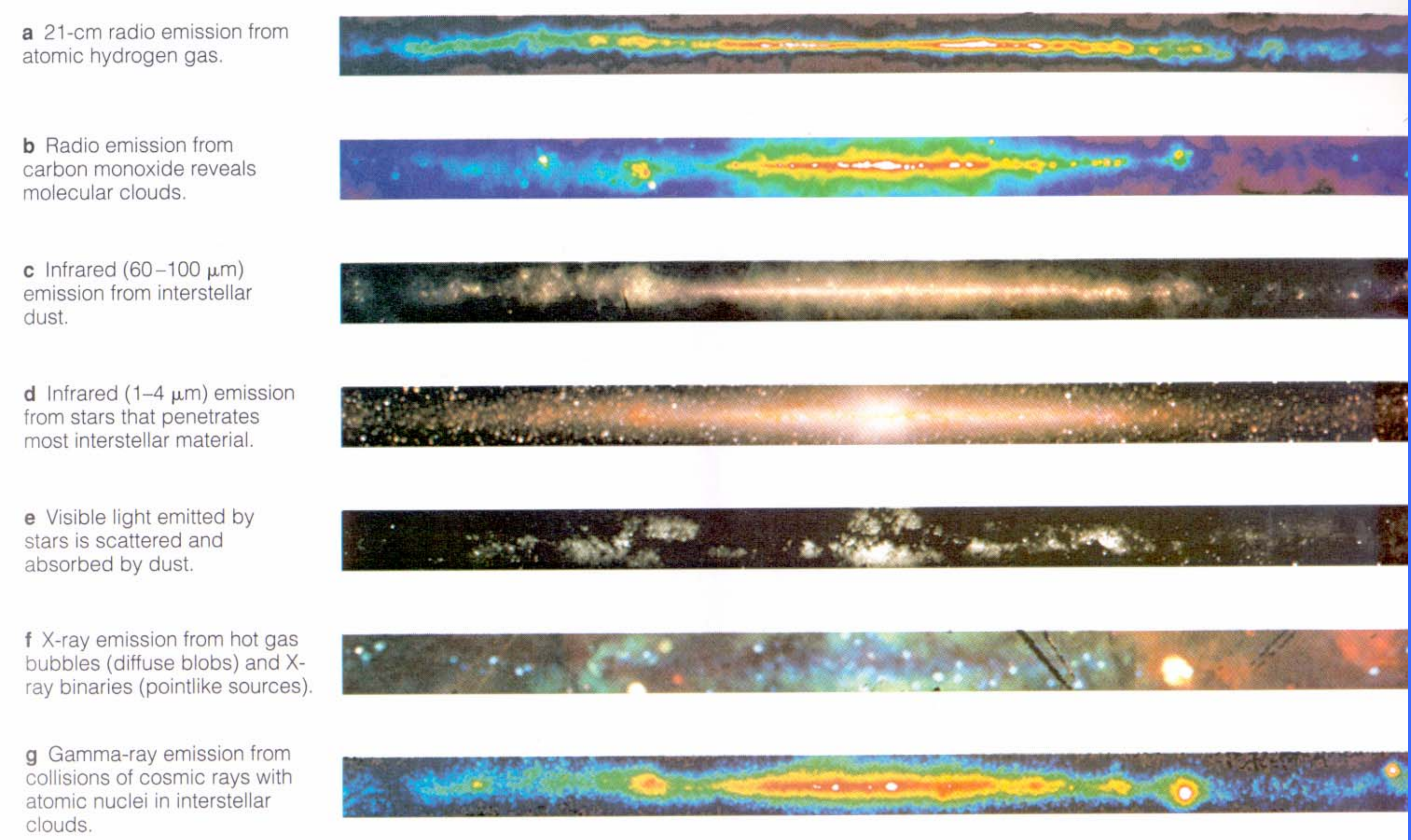
γ ray, IR, UV, X ray etc Telescopes
(c. 1960 to today)



Images of the Milky Way

All images are collected from electromagnetic waves

Primarily giving information about the temperature of source



a 21-cm radio emission from atomic hydrogen gas.

b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared (60–100 μm) emission from interstellar dust.

d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

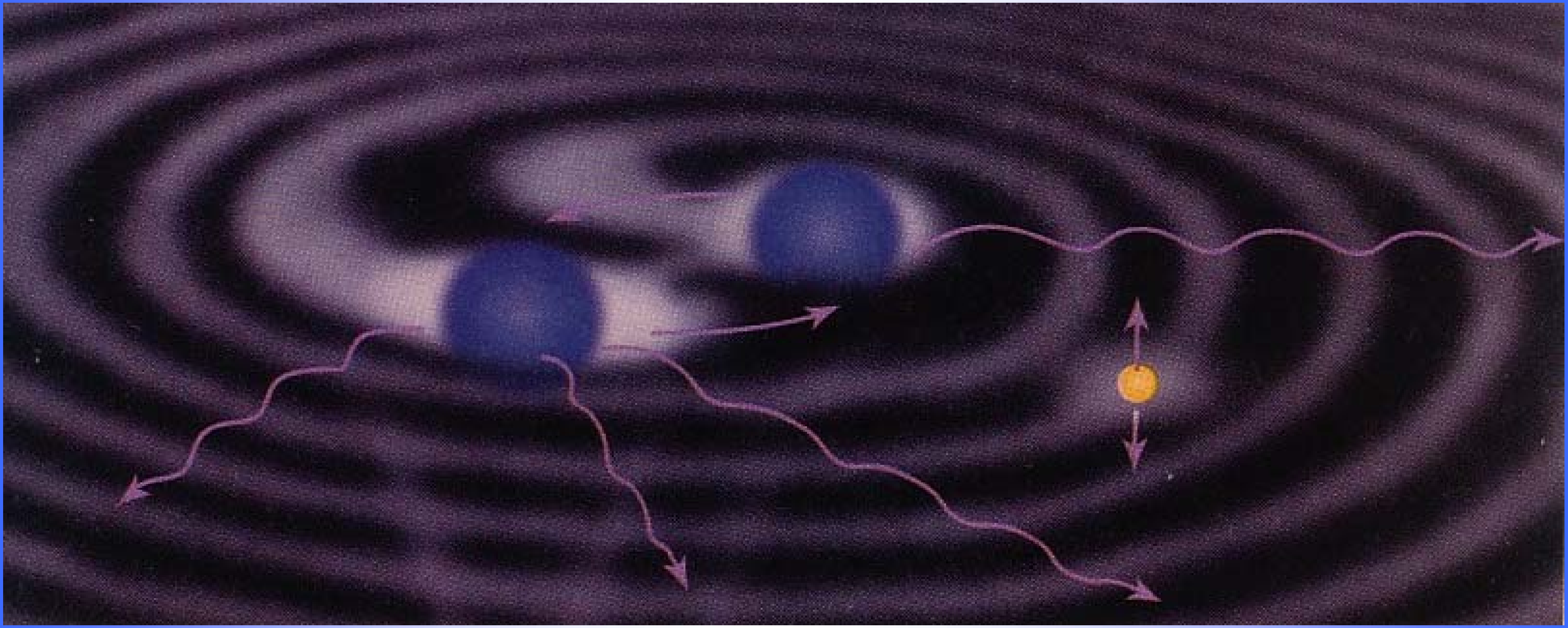
e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

Is there a way to view the universe that gives information other than what is obtained electromagnetically?

Gravitational Waves



Gravitational waves are ripples in space and time coming from the motion of large masses

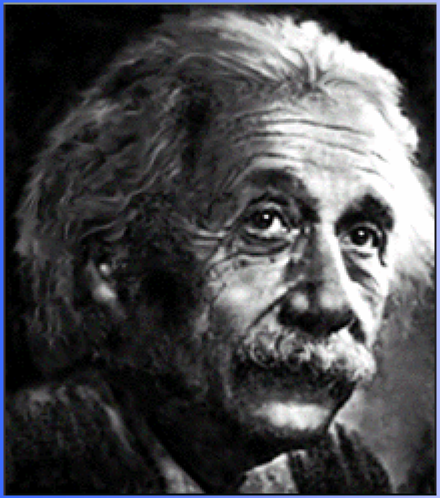
Provide information about the mass distribution of the source

Fundamentally different and complementary to view with light

Outline

- Theory of gravitation
  - Einstein’s General Theory of Relativity
  - Gravitational waves
- Detection of gravitational waves
  - Bar detectors
  - Laser Interferometer Gravitational-wave Observatory (LIGO)
  - Interferometry
  - Noise sources
- Sources of gravitational waves
  - Binary black holes and/or neutron stars
  - Asymmetric pulsars
  - Background from the Big Bang
- Current results from LIGO

Special Theory of Relativity



The speed of light c is the same for all observers

Requires time and space to change with speed

$$t' = \frac{\left(t - \frac{v}{c^2} x\right)}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \qquad x' = \frac{\left(x - vt\right)}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

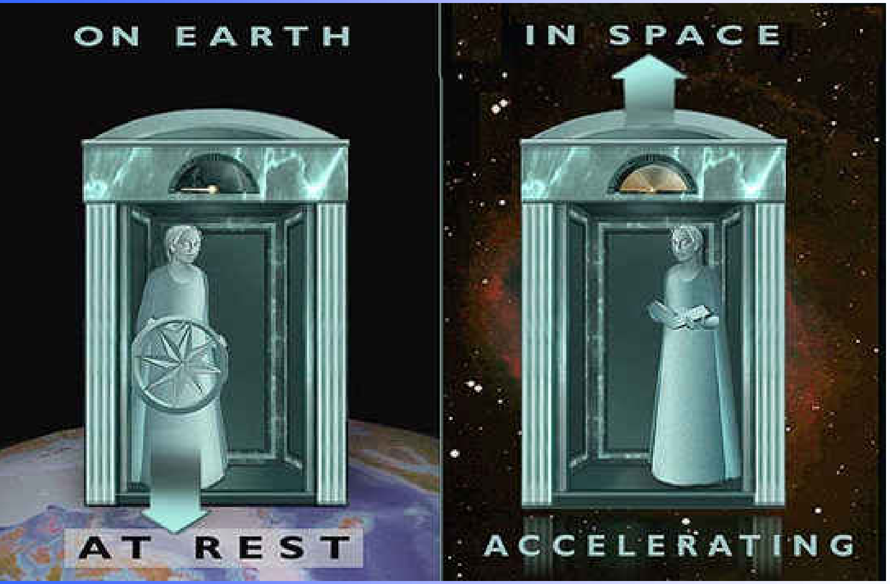
Information cannot travel faster than the c

A moving charge does not change the electric field around it instantaneously, but the effect propagates at c

Similarly with a moving mass, the effect on the surrounding gravitational field propagates out at c

This propagation is a gravitational wave

General Theory of Relativity



Gravity is indistinguishable from acceleration

Gravity is the experience of particles moving along the shortest paths through curved spacetime

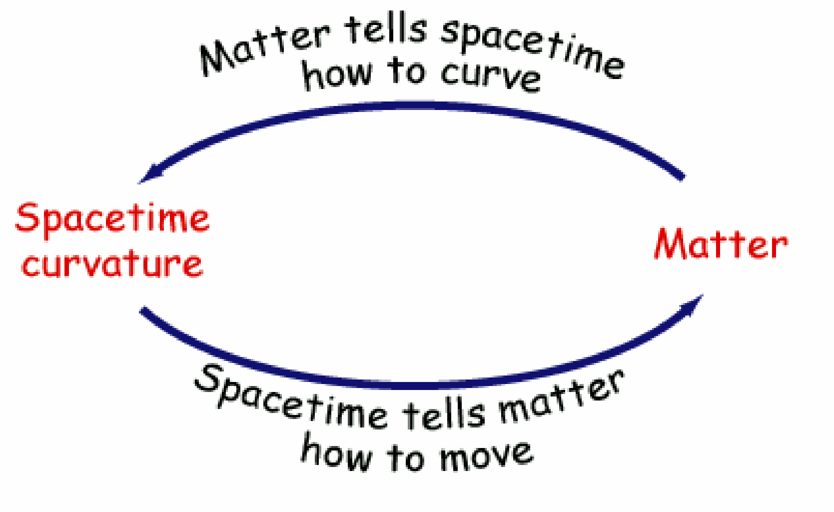
Mass is what tells spacetime how much to curve

The Einstein Equation

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$G_{\mu\nu}$ describes the gravitational field

$T_{\mu\nu}$ describes the mass/energy density



Matter tells spacetime how to curve

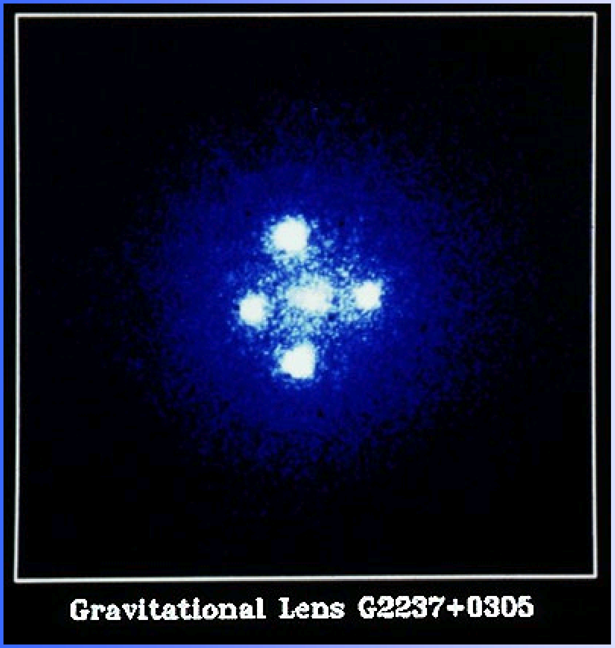
Spacetime curvature

Matter

Spacetime tells matter how to move

Astronomical Effects of Curvature

Einstein Cross


Gravitational Lens G2237+0305

Gravitational Lensing

The propagation of light follows the curvature of spacetime

If a massive object (galaxy, etc.) is lined up with a light source, can see multiple images

Einstein Ring

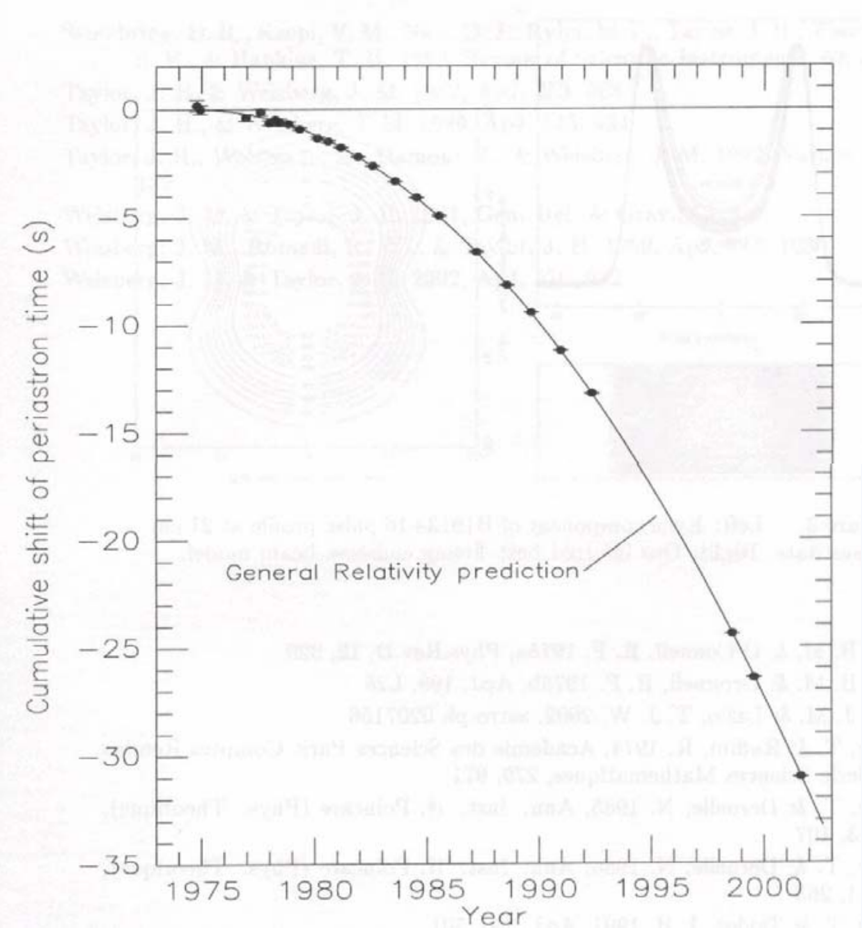
Expansion of the Universe

The universe is expanding - Big Bang

Rate seems to be accelerating, which would mean strange matter causing unusual curvature

May require addition to the Einstein Equation

Indirect Observation of Gravitational Waves



PSR 1913+16 orbital change
Black dots are observed data
Dark line is theoretical prediction

Binary Neutron Star System
PSR 1913+16 discovered by R. Hulse and J. Taylor

System has been observed for over 25 years using Arecibo radio telescope

Orbit is shrinking by a few millimeters every year

Decrease in orbit in very good agreement with gravitational wave emission predicted by General Theory of Relativity

Waves from PSR1913+16 will enter LIGO bandwidth in 300 million years

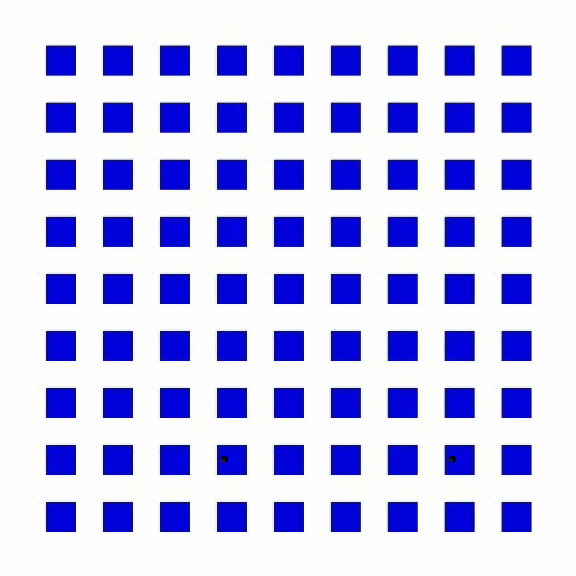
Effect of Gravitational Waves on Matter

A grid of freely floating masses

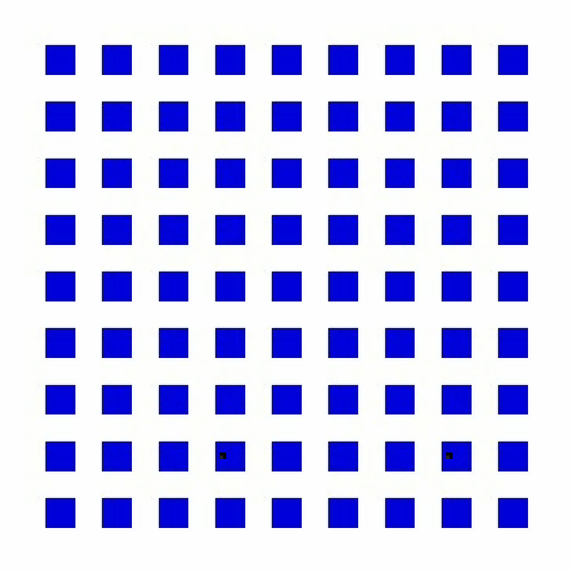
A gravitational wave passing moves all masses

Contract in one direction, expand in the perpendicular direction

This is different than the effect of an electromagnetic wave



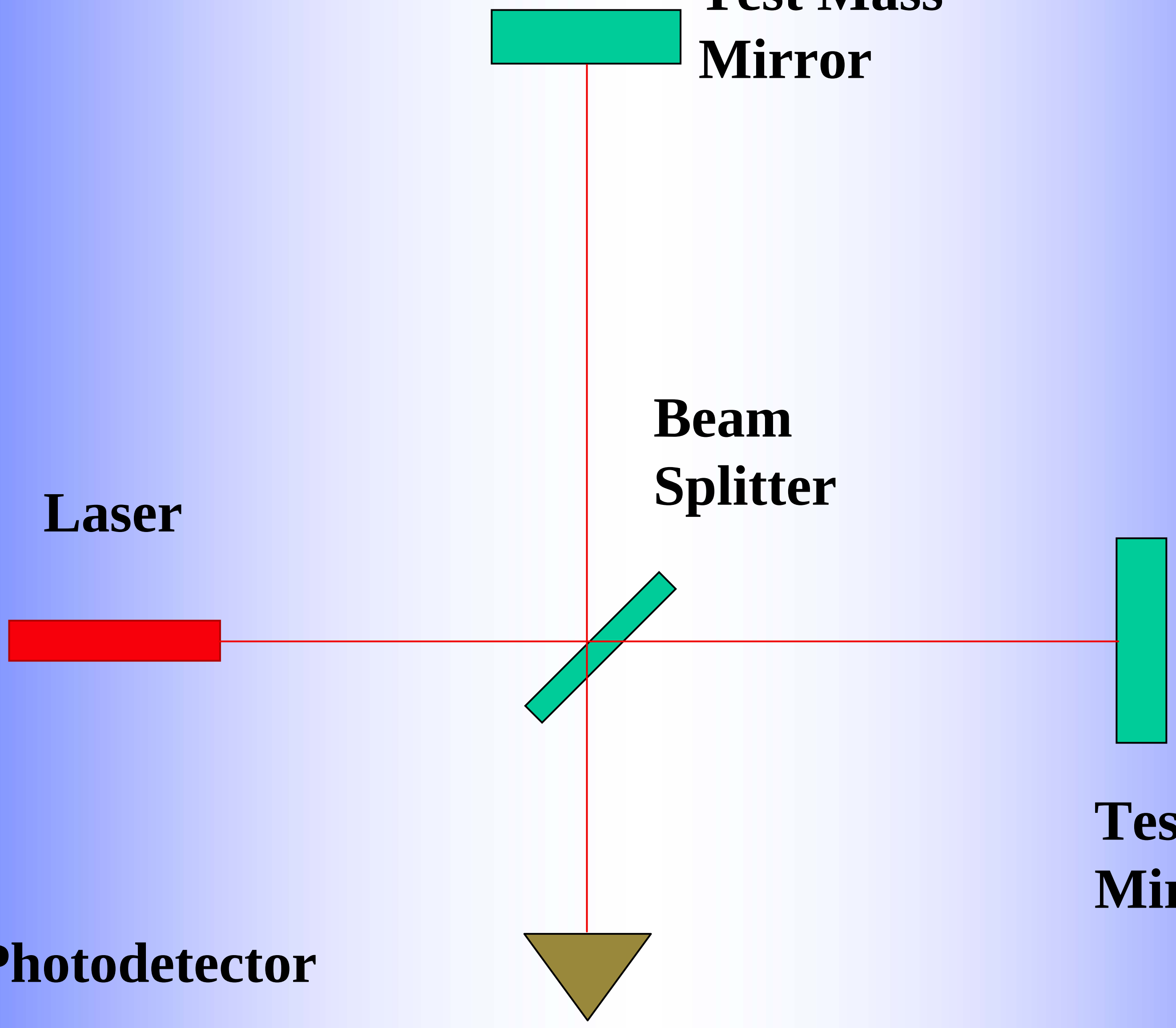
Electromagnetic Wave



Gravitational Wave

Direct Detection with Interferometer

Direct Detection with Interferometer



Test Mass
Mirror

Beam
Splitter

Laser

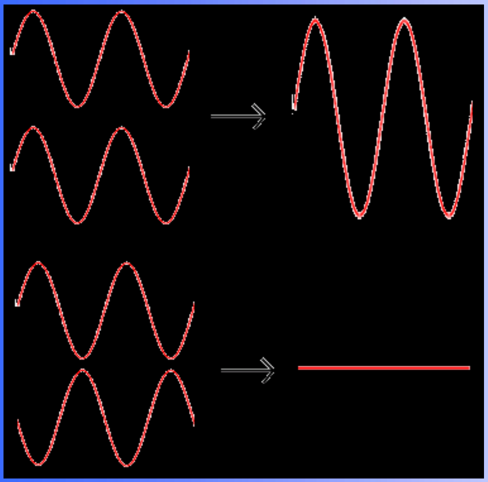
Test Mass
Mirror

Photodetector

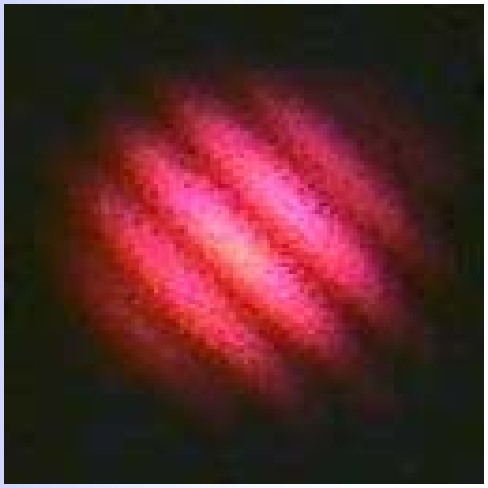
Interferometery

Laser goes down two perpendicular paths

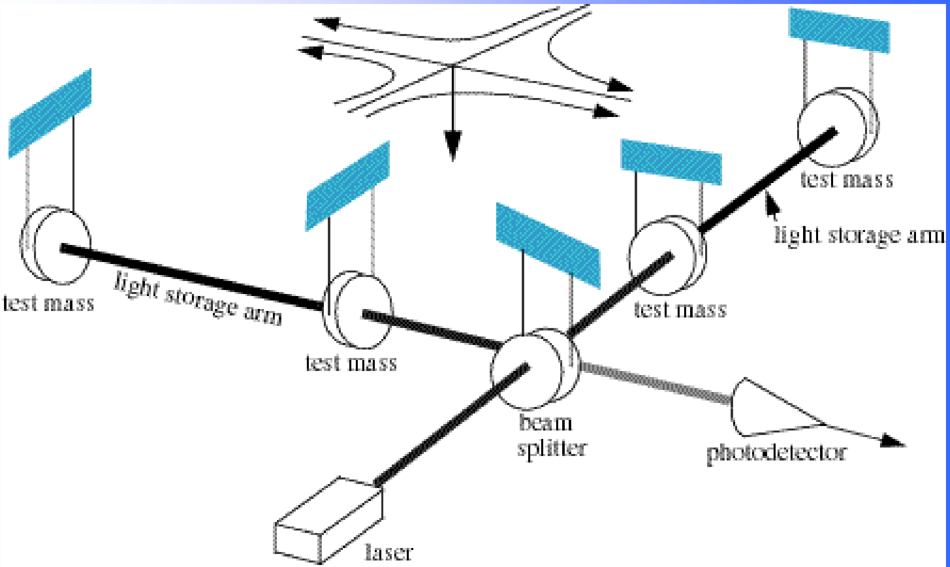
Returning beams are combined on a photodiode for detection



Constructive and destructive interference



Dark and bright fringes



If path lengths down arms is the same -> constructive interference

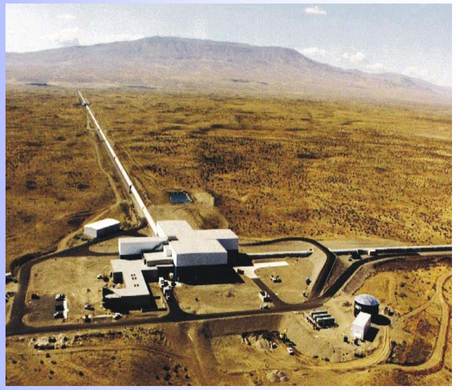
- Peaks and troughs of light waves together

If path lengths are different -> destructive interference

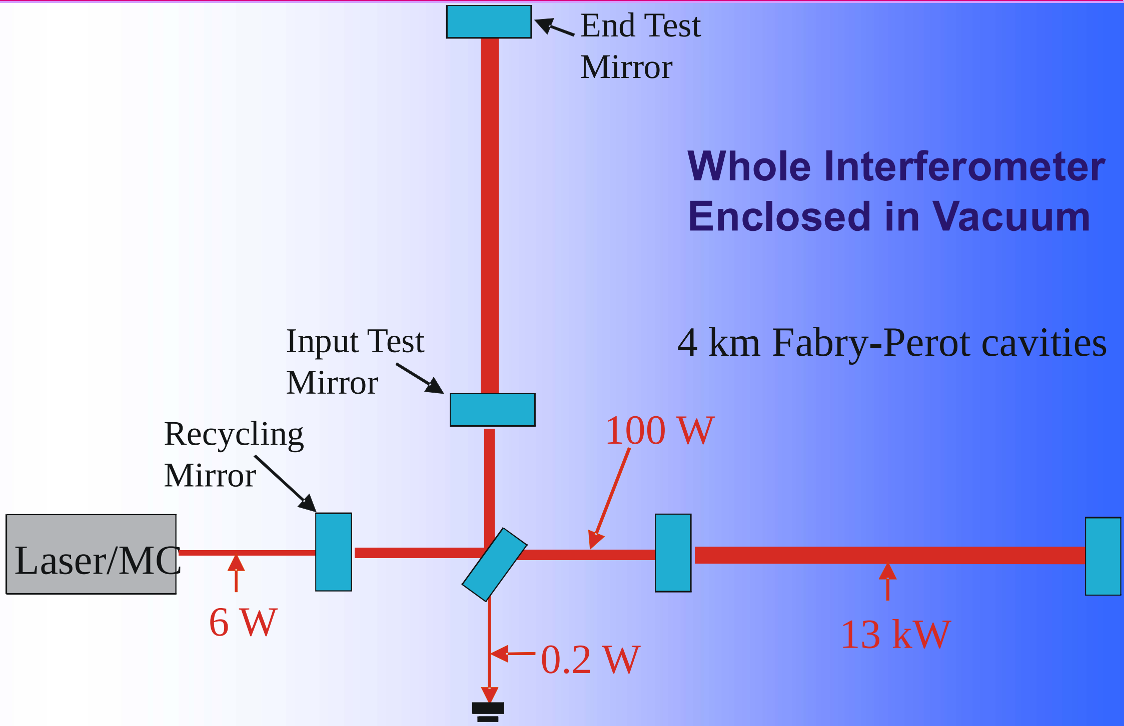
- Peaks and troughs of light waves cancel out

Laser Interferometer Gravitational-wave Observatory

LIGO Livingston Louisiana



LIGO Hanford Washington



Whole Interferometer Enclosed in Vacuum

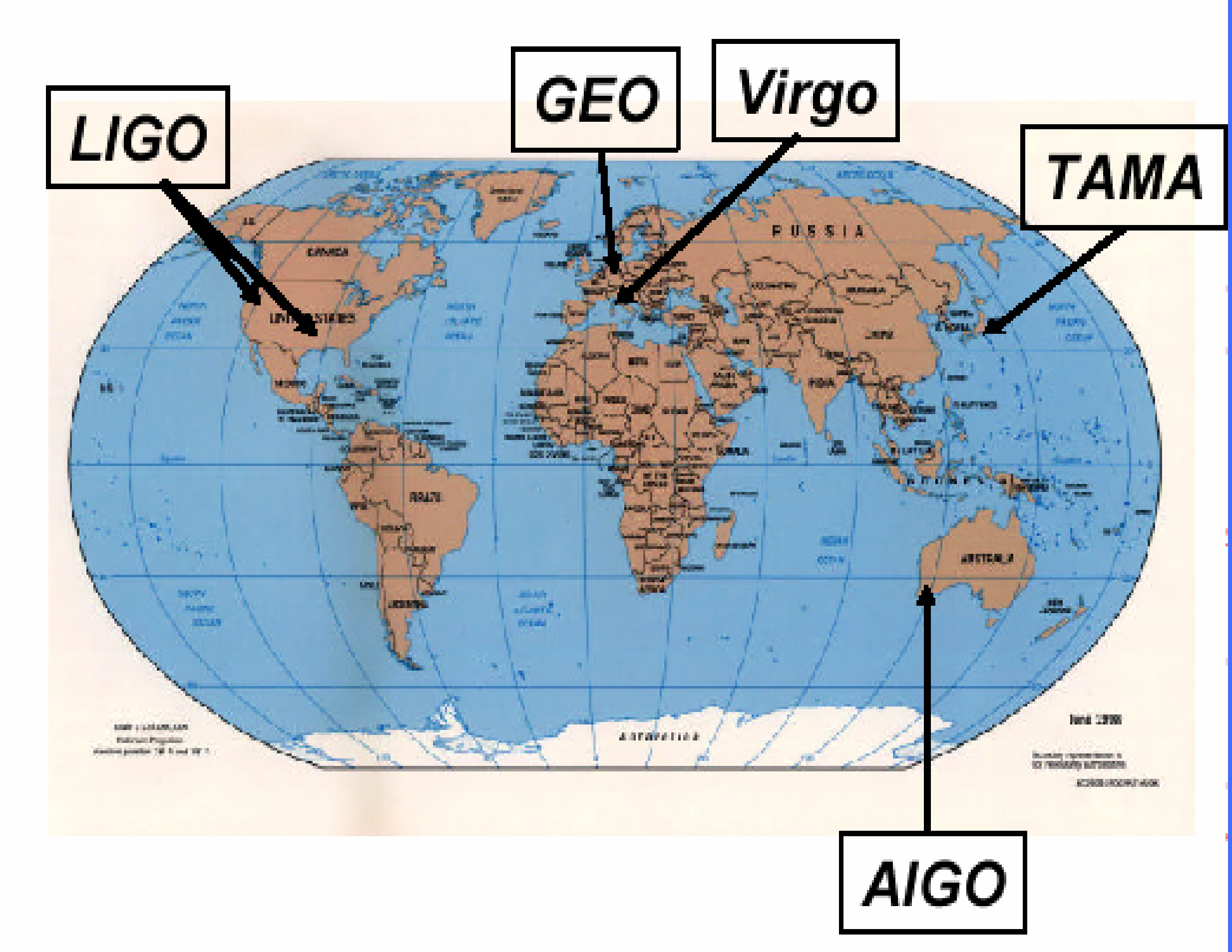
4 km Fabry-Perot cavities

LIGO Vacuum Chambers

- Two 4 km and one 2 km long interferometers
- Two sites in the US, Louisiana and Washington
- Fabry-Perot arms to store laser power
- High precision mirrors, 10 kg in mass
- Whole optical path enclosed in vacuum
- Sensitive to strains around $h = 10^{-21}$
- $\Delta L = h L \approx 10^{-18}$ m : sub-nuclear size

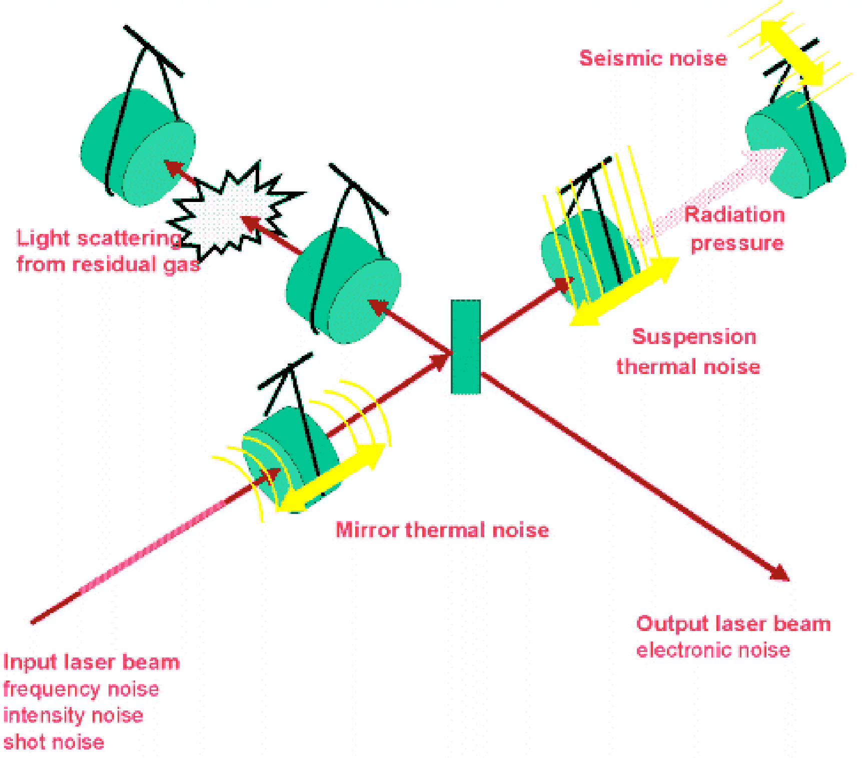
Worldwide Network of Observatories

- Increase detection confidence
- Determine polarization and source location
- Verify speed is *c*
- Try new and different technologies



Bar detectors in Louisiana and Italy

Noise in LIGO



Noise determines sensitivity

Seismic noise at low frequency f < 40 Hz

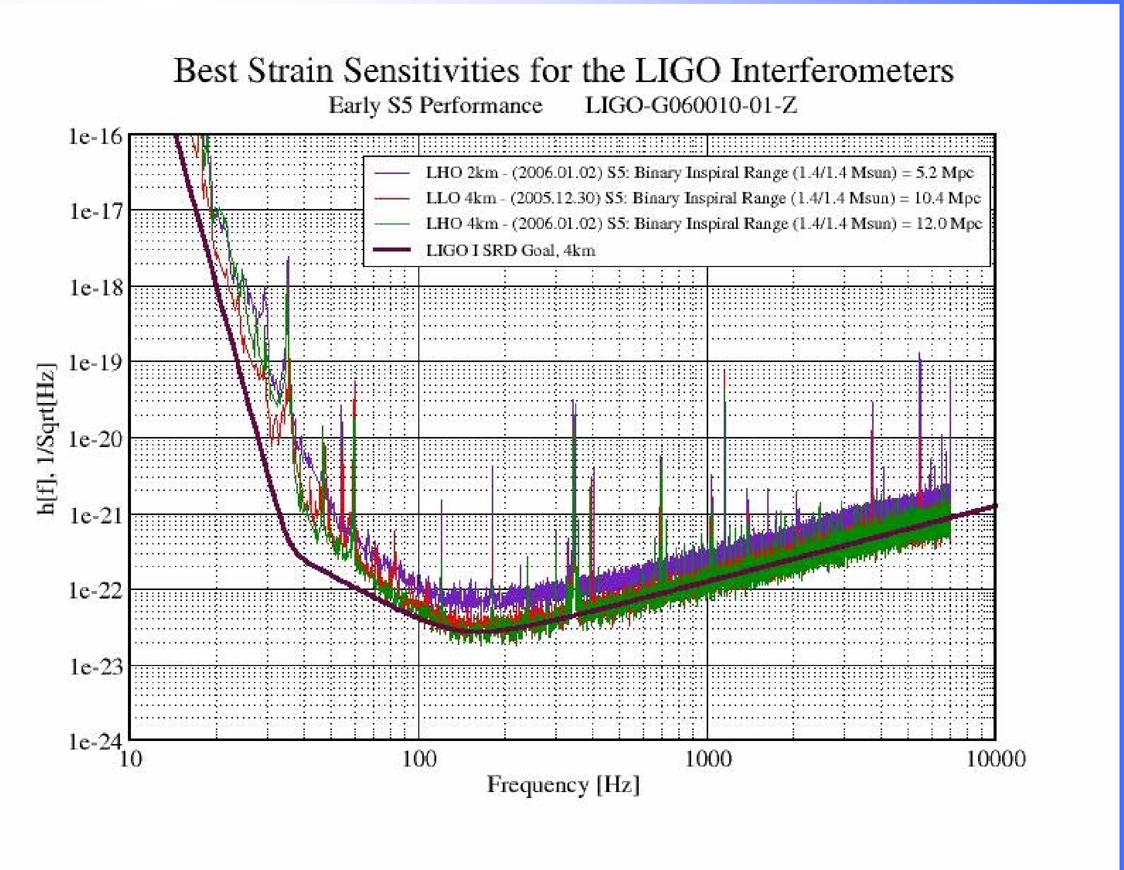
Thermal noise at intermediate frequencies 40 Hz < f < 150 Hz

Laser shot noise at high frequency f > 150 Hz

Current LIGO noise is very close to design goal

Some excess around 30 Hz

Total sensitivity currently exceeds goal

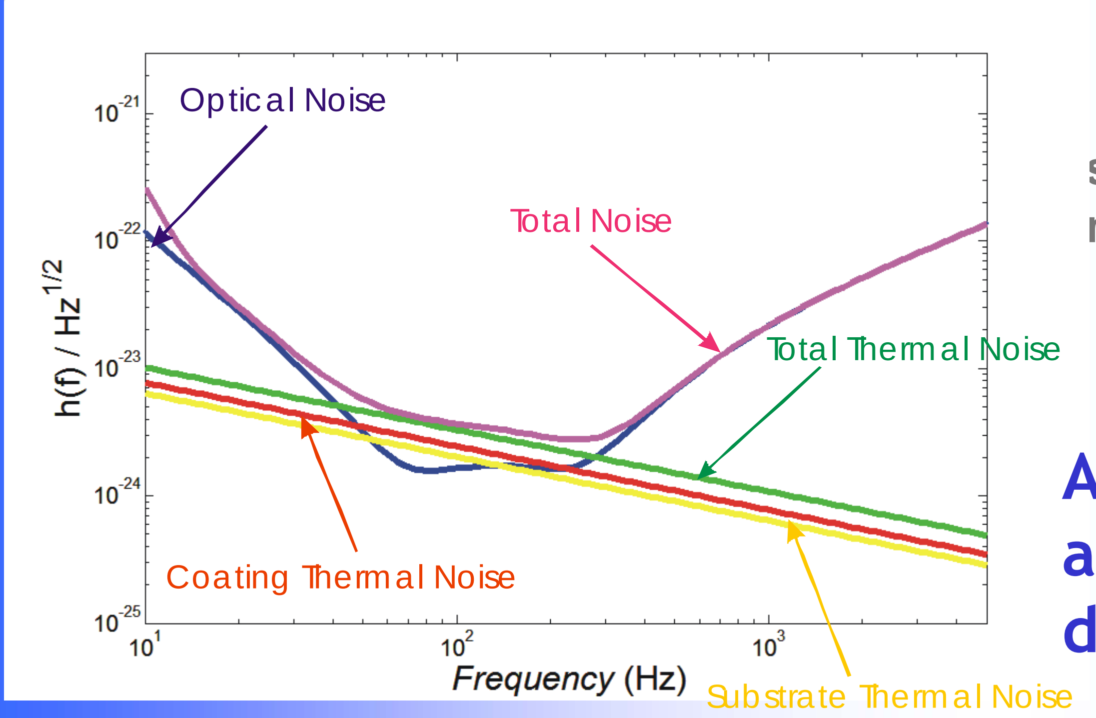


Advanced LIGO

Seismic noise removed down to 10 Hz

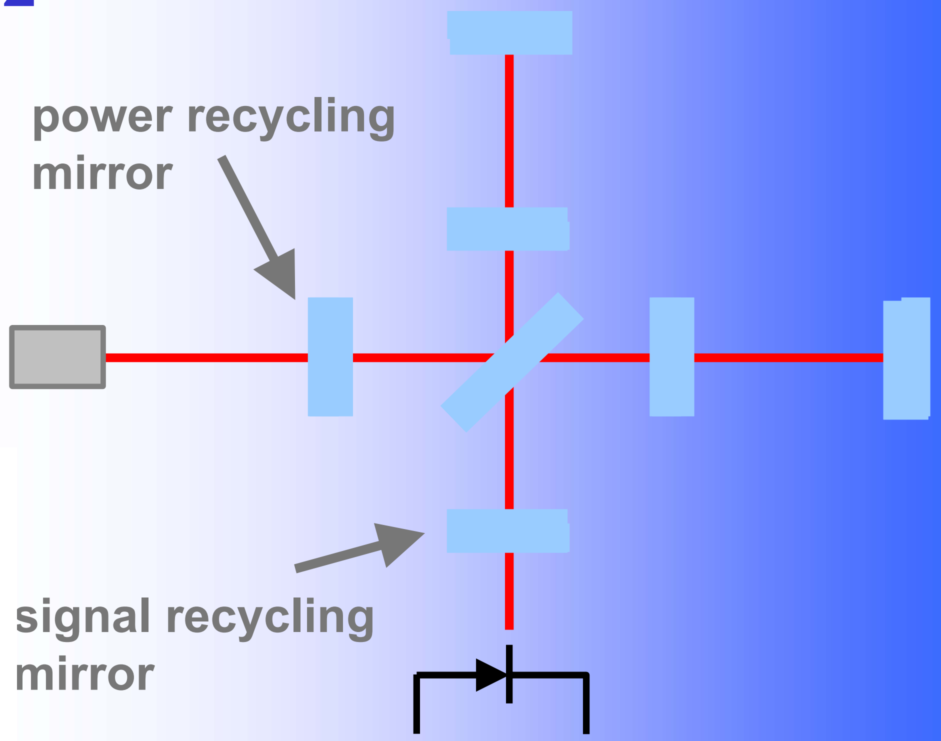
Improved mirror materials for lower thermal noise

Higher laser power to reduce shot noise, causes radiation pressure



Advanced LIGO Sensitivity

Advanced LIGO Configuration



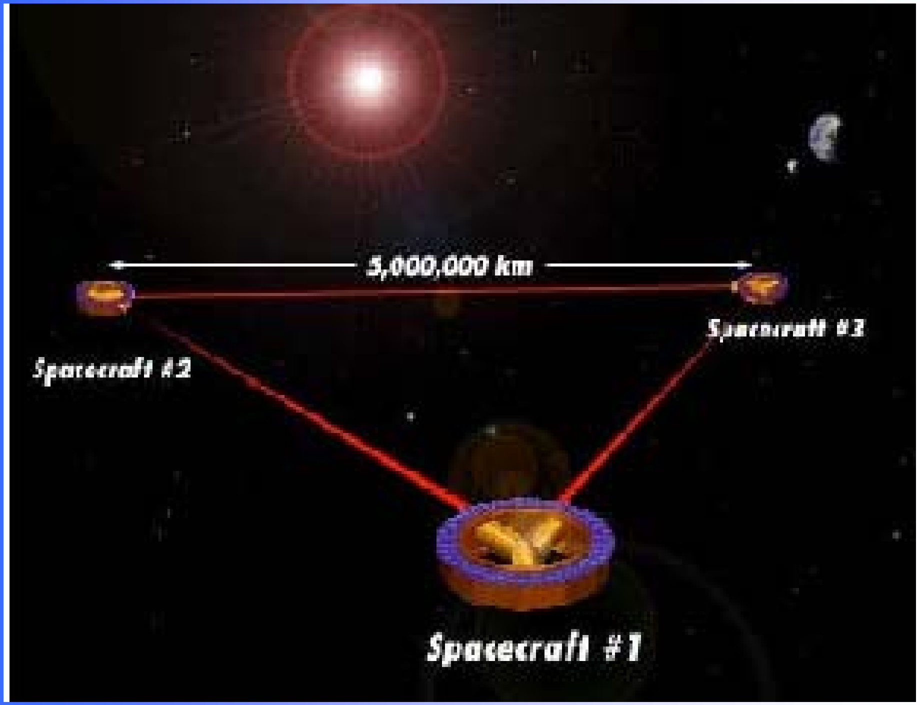
power recycling mirror

signal recycling mirror

Signal Recycling

Additional mirror at output allows for tuning of sensitivity at different frequencies

Laser Interferometer Space-based Antenna



LISA

Interferometric detector in solar orbit

Three spacecraft with two lasers each

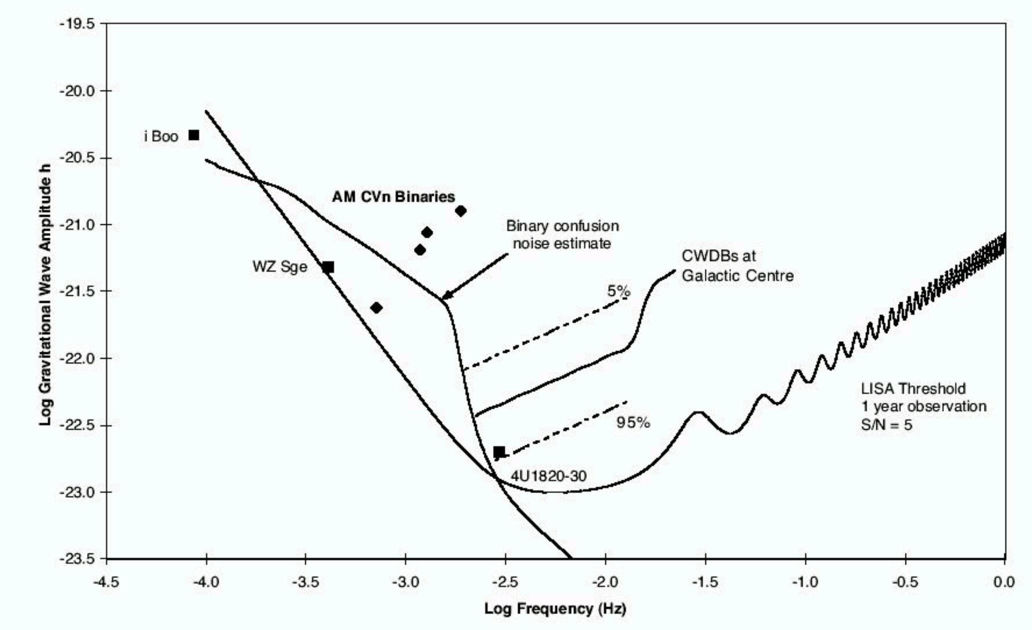
Test masses floating freely in space

LISA

Sensitive at lower frequencies than LIGO (1-100 milliHertz)

More signals at lower frequency

Limited by confusion of sources at some frequencies



Direct Detection with Resonant Mass Detectors

Weber and bar in Maryland

ALLEGRO bar in Louisiana

Early 1960s, Joseph Weber first suggests gravitational waves could be directly detected

Built room temperature aluminum bar instrumented with strain sensors

Have limited sensitivity and frequency response

From 1980s to today, cryogenic bars in vacuum with better sensitivity were built

1990s spherical detectors were analyzed

Now have prototype spheres being built

miniGRAIL in Leiden NL

Sources of Gravitational Waves

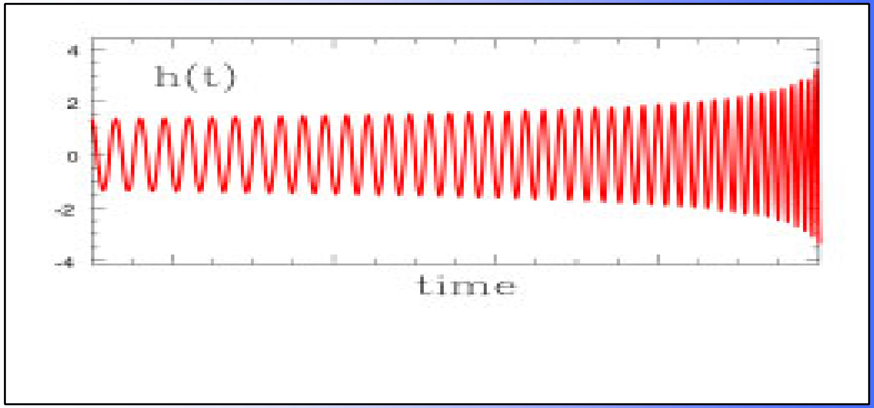
Categorization of Gravitational Wave Sources

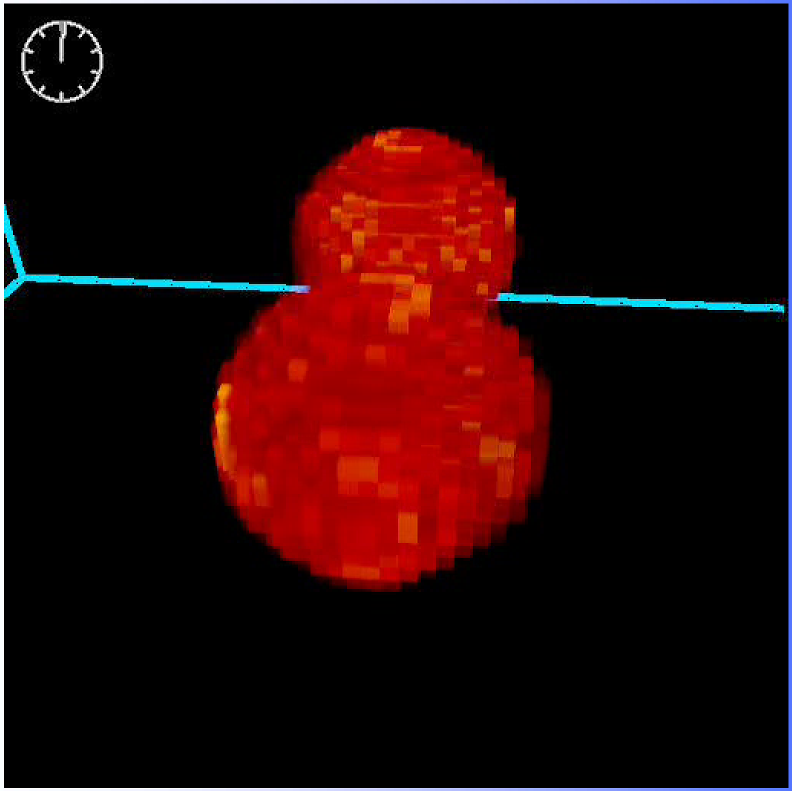
Modeling Duration	Modeled	Unmodeled
Short	Compact Body Inspirals (neutron stars, black holes)	Bursts (supernova, γ ray bursts, etc.)
Long	Asymmetric Pulsars (surface bumps, deformation from magnetic fields, etc.)	Stochastic Background (Big Bang, cacophony of other sources, etc.)

Compact Body Inspiral Sources

- Binary black holes, neutron stars, or one of each circling in on each other
- Similar to Hulse-Taylor system, but further along in their evolution
- Essentially two point masses only interacting with each other, so possible to model using General Theory of Relativity
- Makes characteristic “chirp” waveform, with both frequency and amplitude increasing with time

Chirp waveform



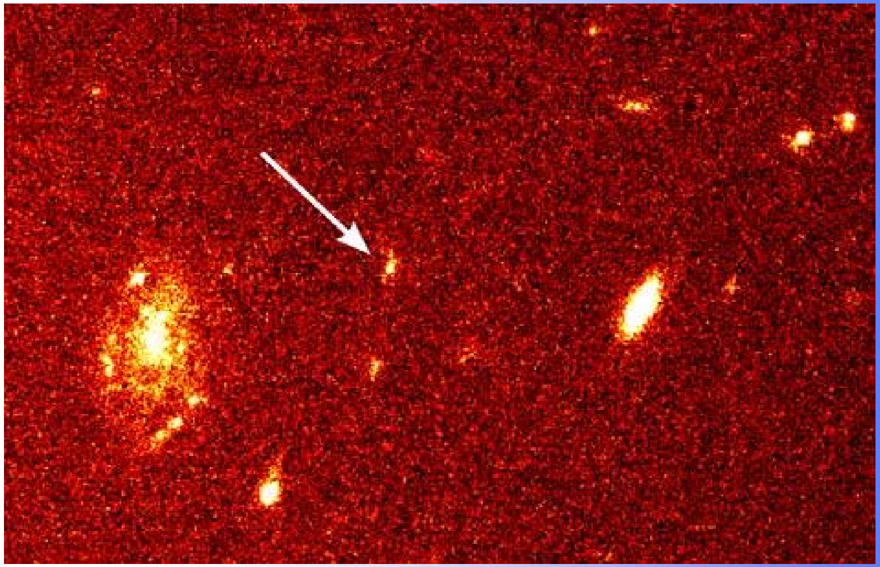


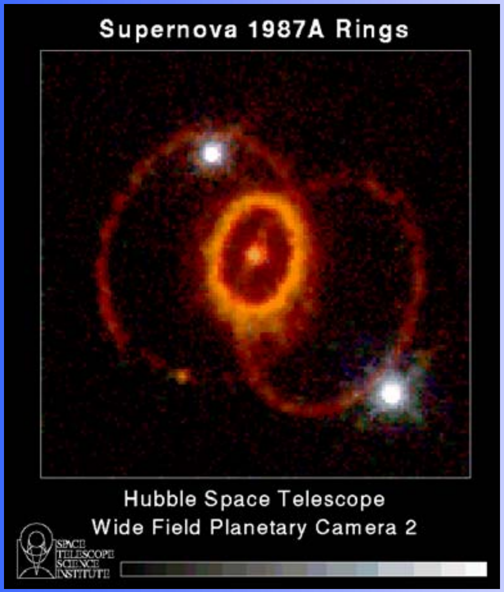
Burst Sources

Expected from catastrophic events involving roughly solar-mass (1-100 M_o) compact objects

Sources typically not well understood and therefore difficult to detect

γ ray burst





Supernova 1987A

Untriggered

Not observed core collapse supernova

Accretion onto black holes

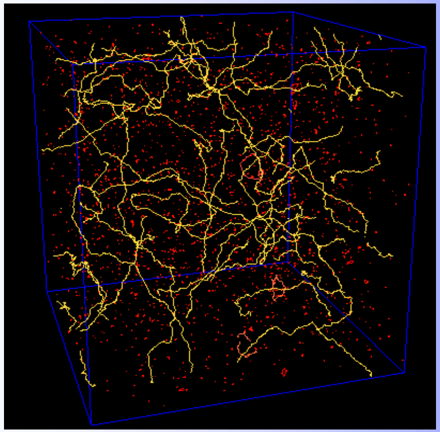
Mergers of black holes and/or neutron stars

Cusps in cosmic strings

Triggered

Visible core collapse supernova

γ-ray bursts



Network of cosmic strings

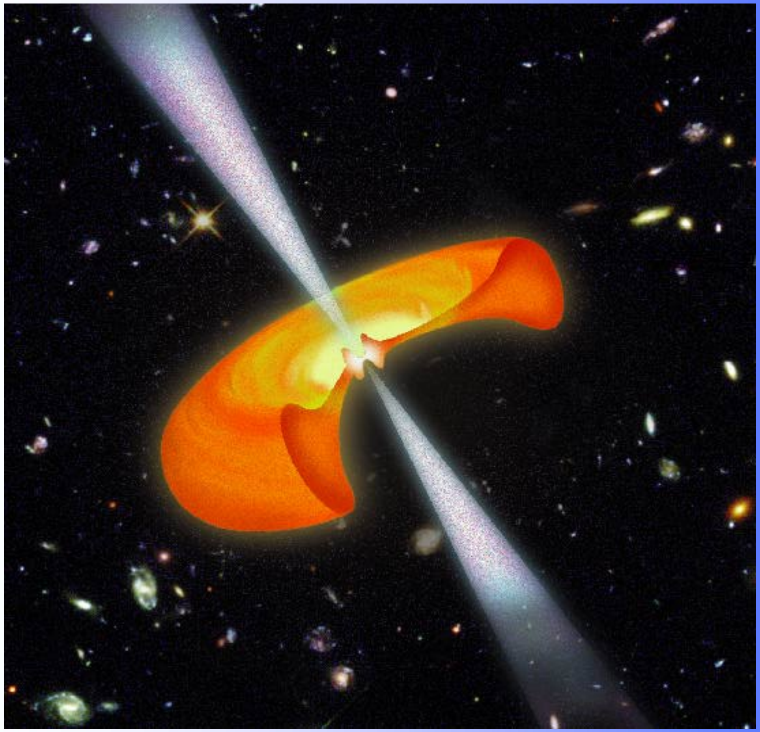
γ Ray Bursts

Bright bursts of gamma rays
- at cosmological distances
- rate of about 1/day
- last about 1ms -100 s

Long bursts (>2 seconds)
- beamed, only a few degrees wide
- about 1/year within 100 Mpc
- associated with “hypernovae” core collapse supernova forming a black hole

Short bursts (< 2 seconds)
- Binary neutron star and/or black hole inspirals (?)
- Seen by HETE to be in edges of galaxies

Strongly relativistic - high gravity, dense matter
- Likely to produce gravitational waves
- Details of waves will tell about progenitors



Hypernova (conception)

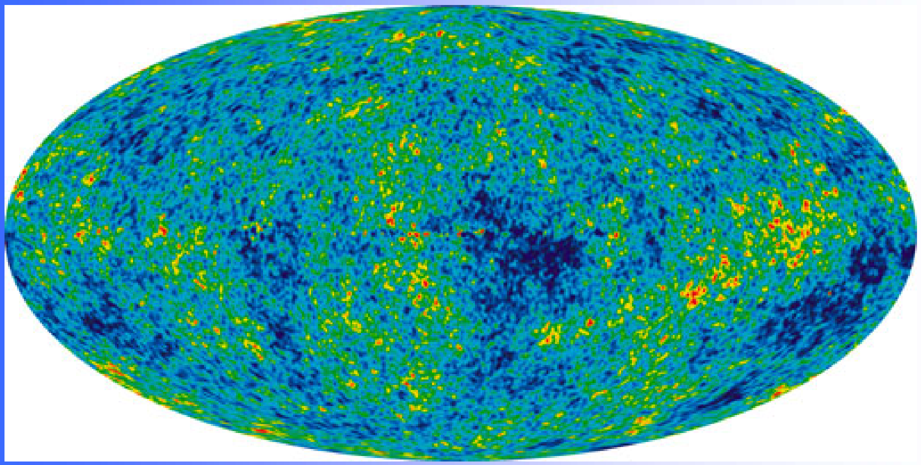
Stochastic Sources

Cosmological background from Big Bang

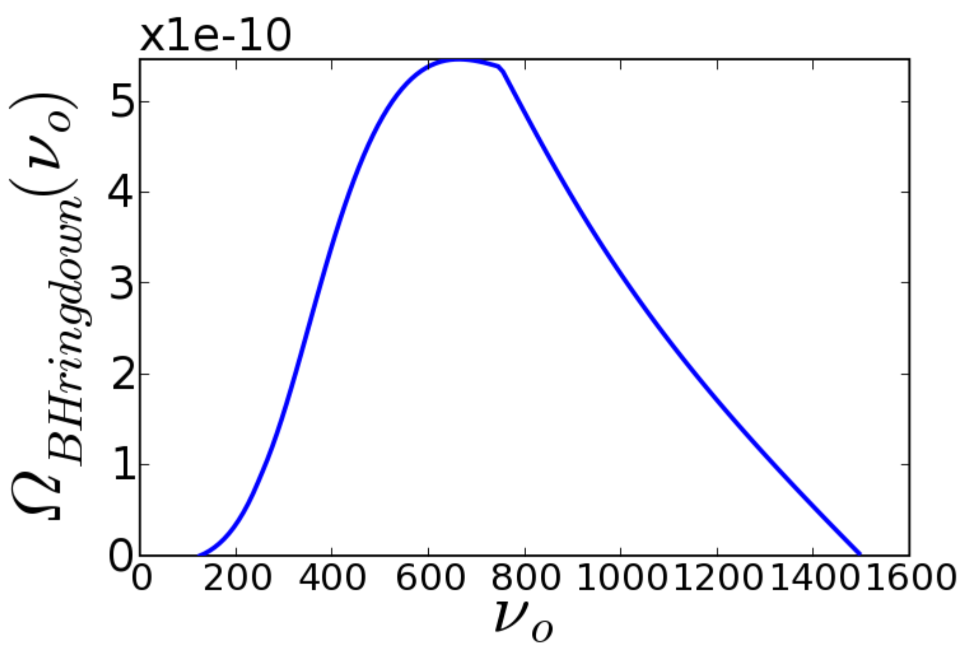
- Similar to cosmic microwave background

Astrophysical background from unresolved sources

- Distant inspirals, mergers, supernova, etc



Cosmic microwave background

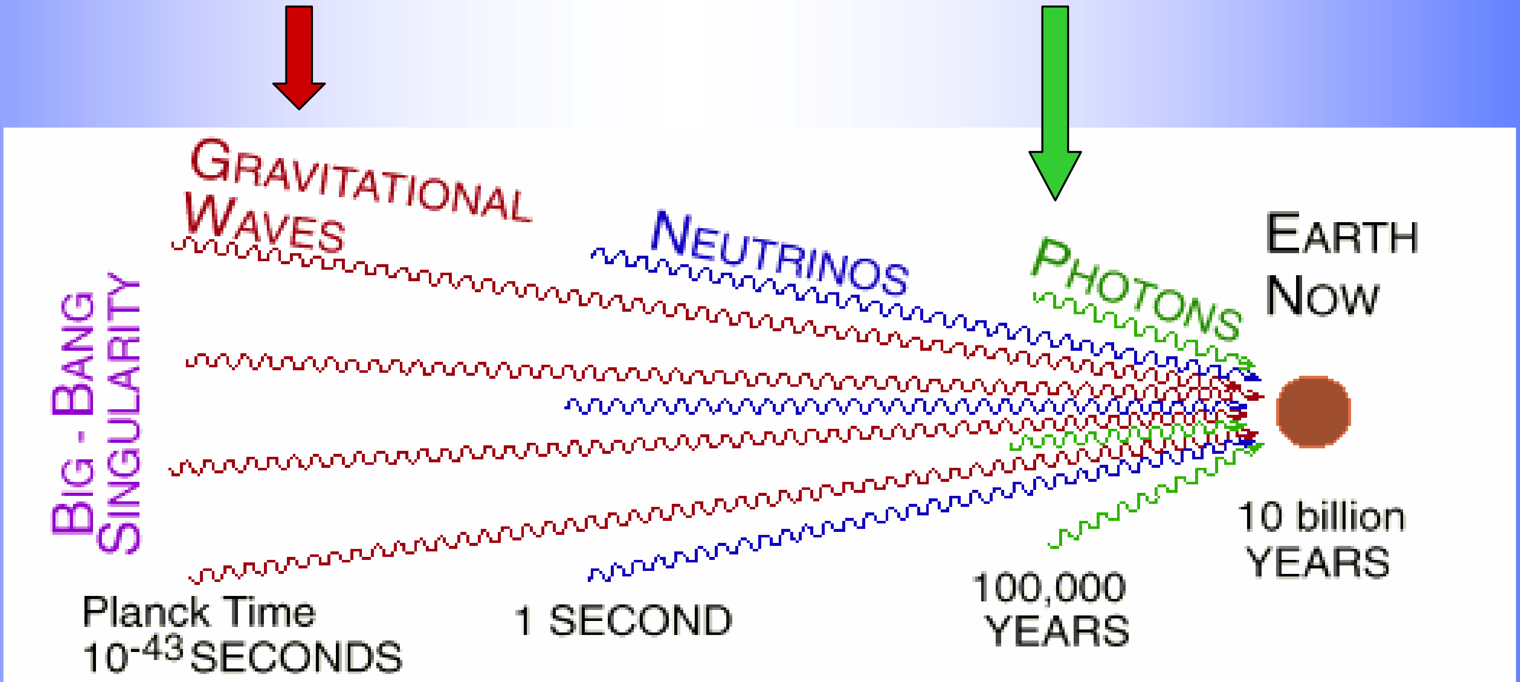


Background of black hole ringdowns

Cosmological Stochastic Sources

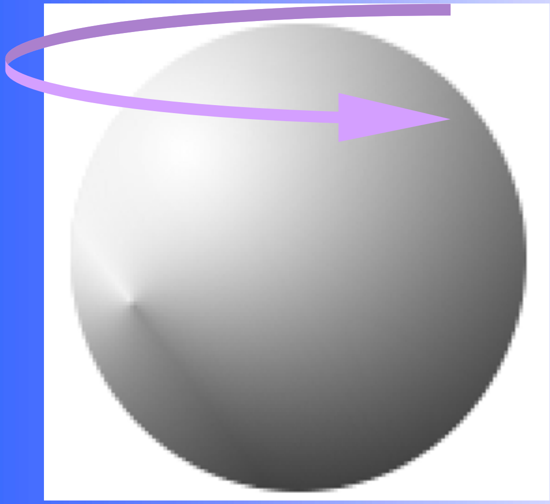
cosmic gravitational-wave background (10^{-22}s)

cosmic microwave background (10^{+12}s)



Numerous theories about what to expect from Big Bang
Some testable with LIGO

Periodic Sources



Nearly monochromatic continuous sources of gravitational waves from spinning neutron stars

- Spin precession ($f_{rotational}$)
- Oscillation (4/3 $f_{rotational}$)
- Distortions of surface (2 $f_{rotational}$)

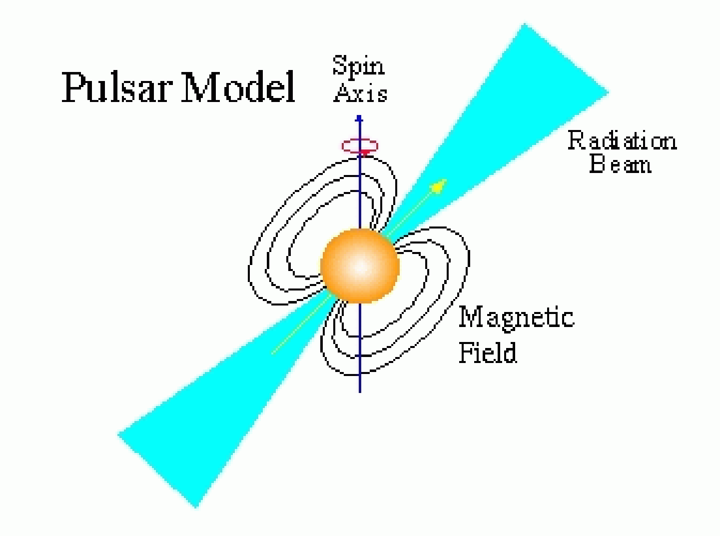
Signal is modulated by Doppler shift from motion of Earth, Sun, and source

Search known pulsars, so know

- Rotation frequency
- Position on sky
- Spin down rate
- Distance

Also search whole sky for unknown pulsars

- Need a lot of computer power

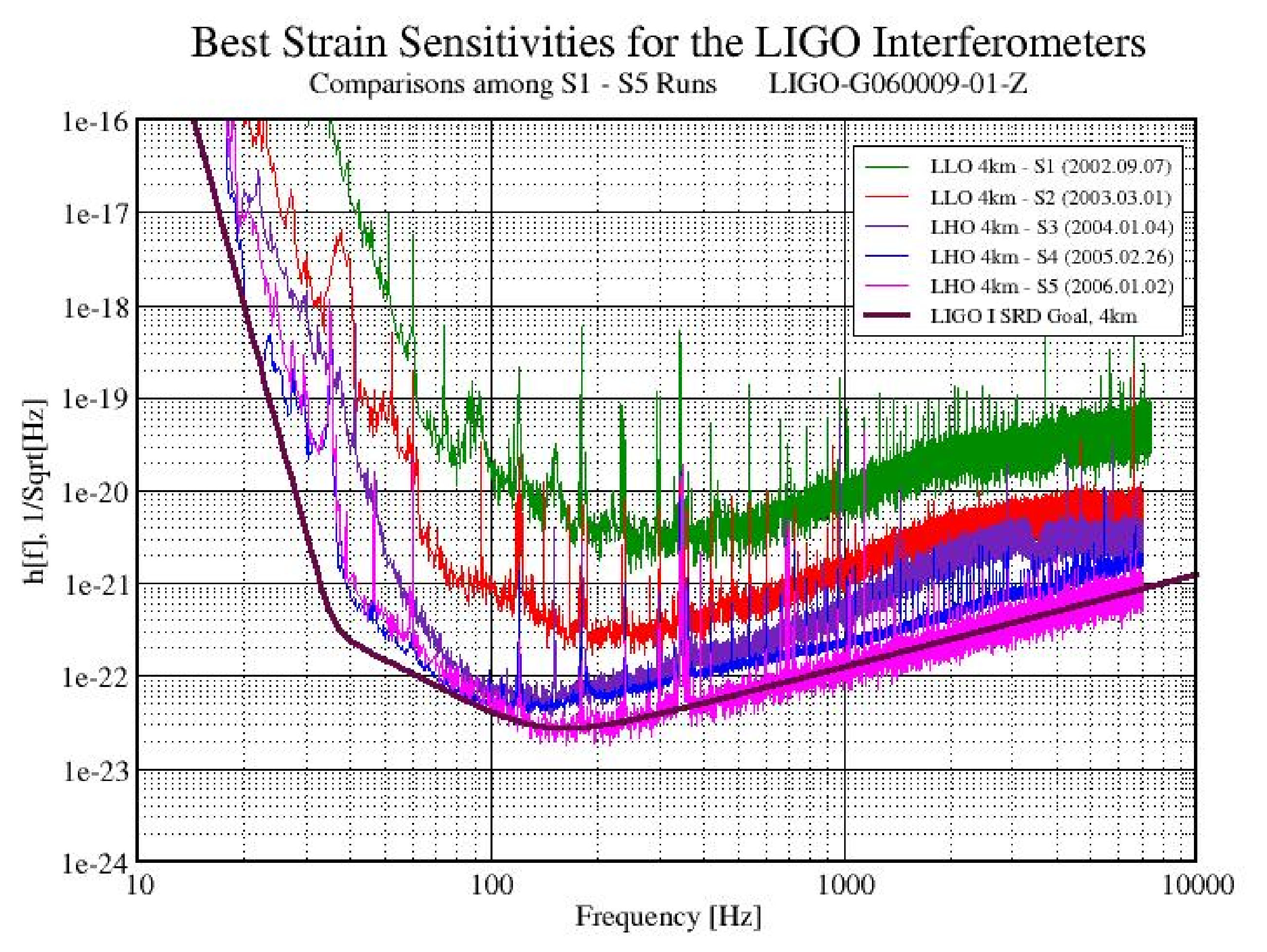


LIGO Science Runs

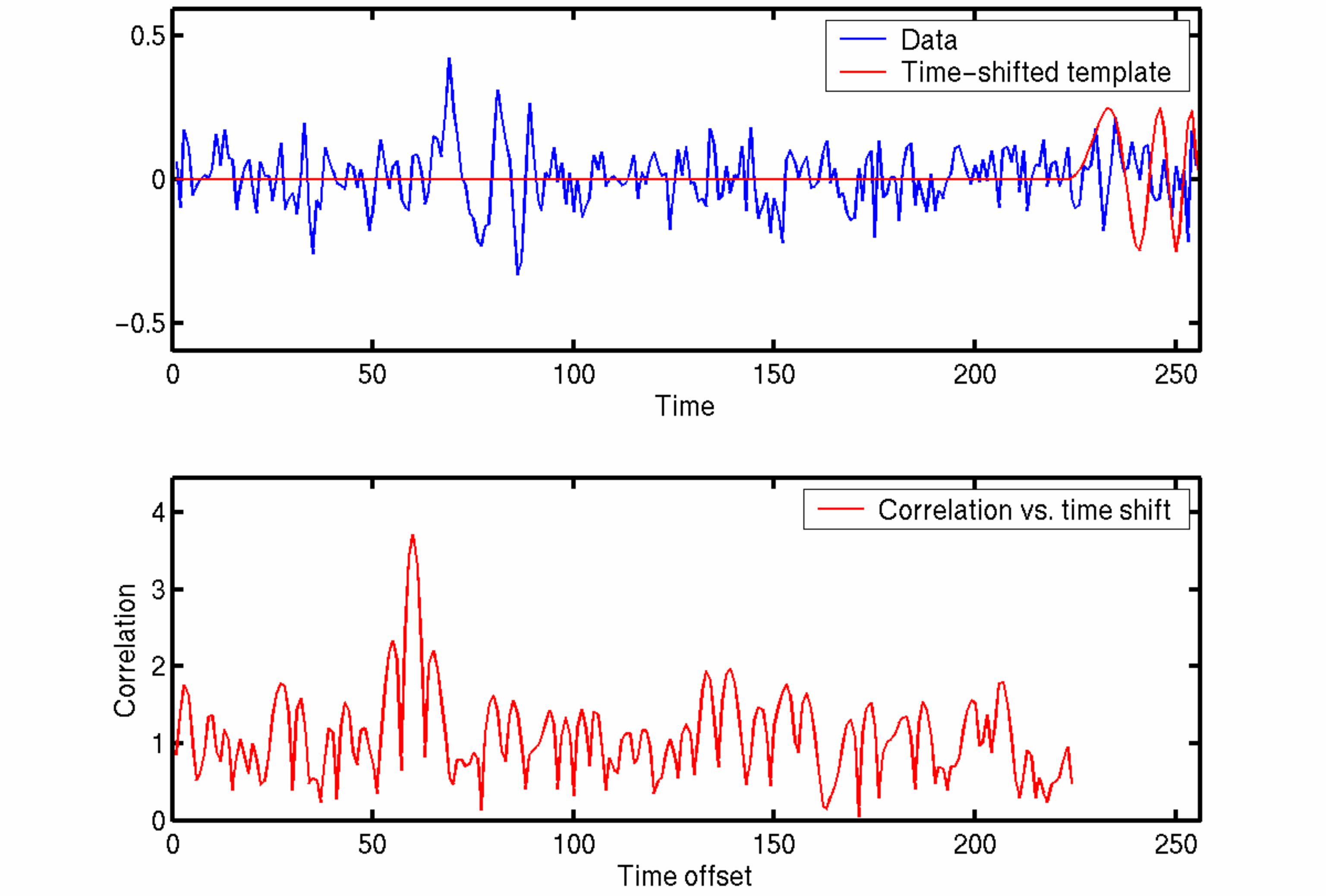
Have collected data in 5 separate science runs with LIGO

S1 2 weeks 2002
S2 8 weeks 2003
S3 9 weeks 2004
S4 4 weeks 2005
S5 23+ weeks 2006

Goal of S5 is to collect a full year of data from all three interferometers



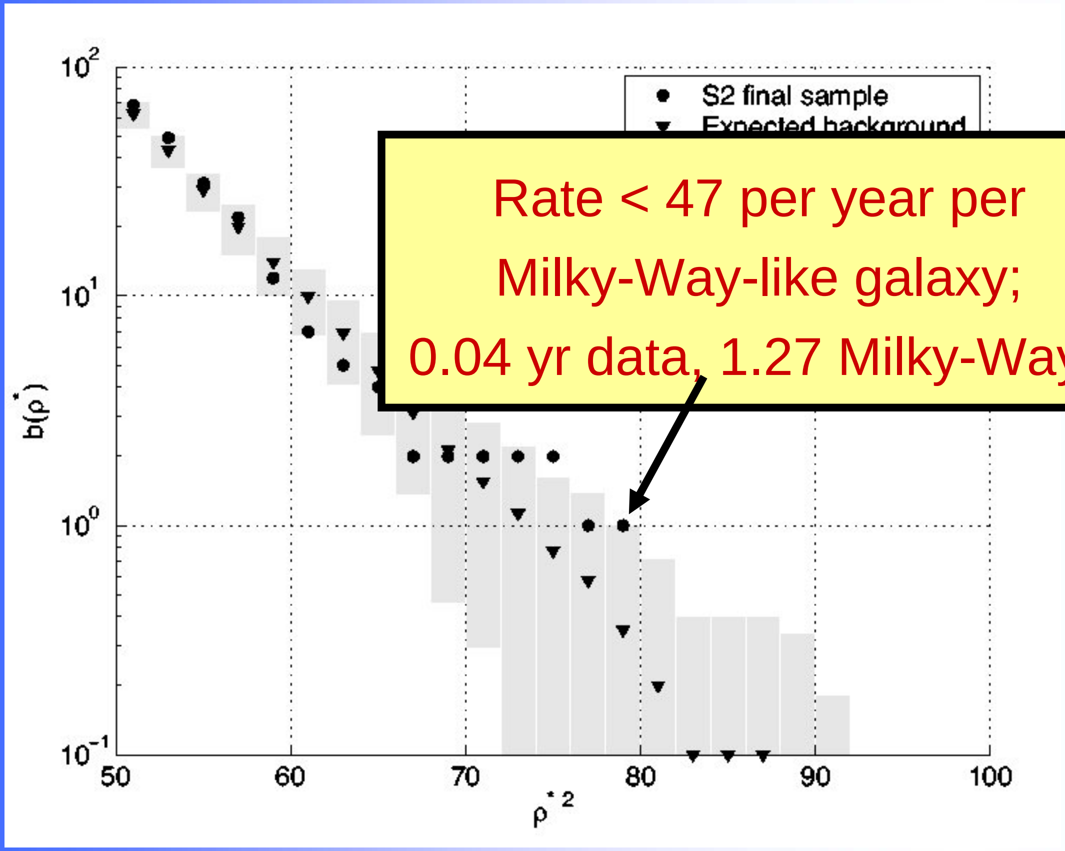
Inspiral Searches



Template based search
Compare expected signal versus data
Get maximum signal-to-noise ratio

Neutron Star Binary Results

S2 Neutron Star Binary Results



Rate < 47 per year per Milky-Way-like galaxy; 0.04 yr data, 1.27 Milky-Ways

Black points are number of events at each signal-to-noise ratio

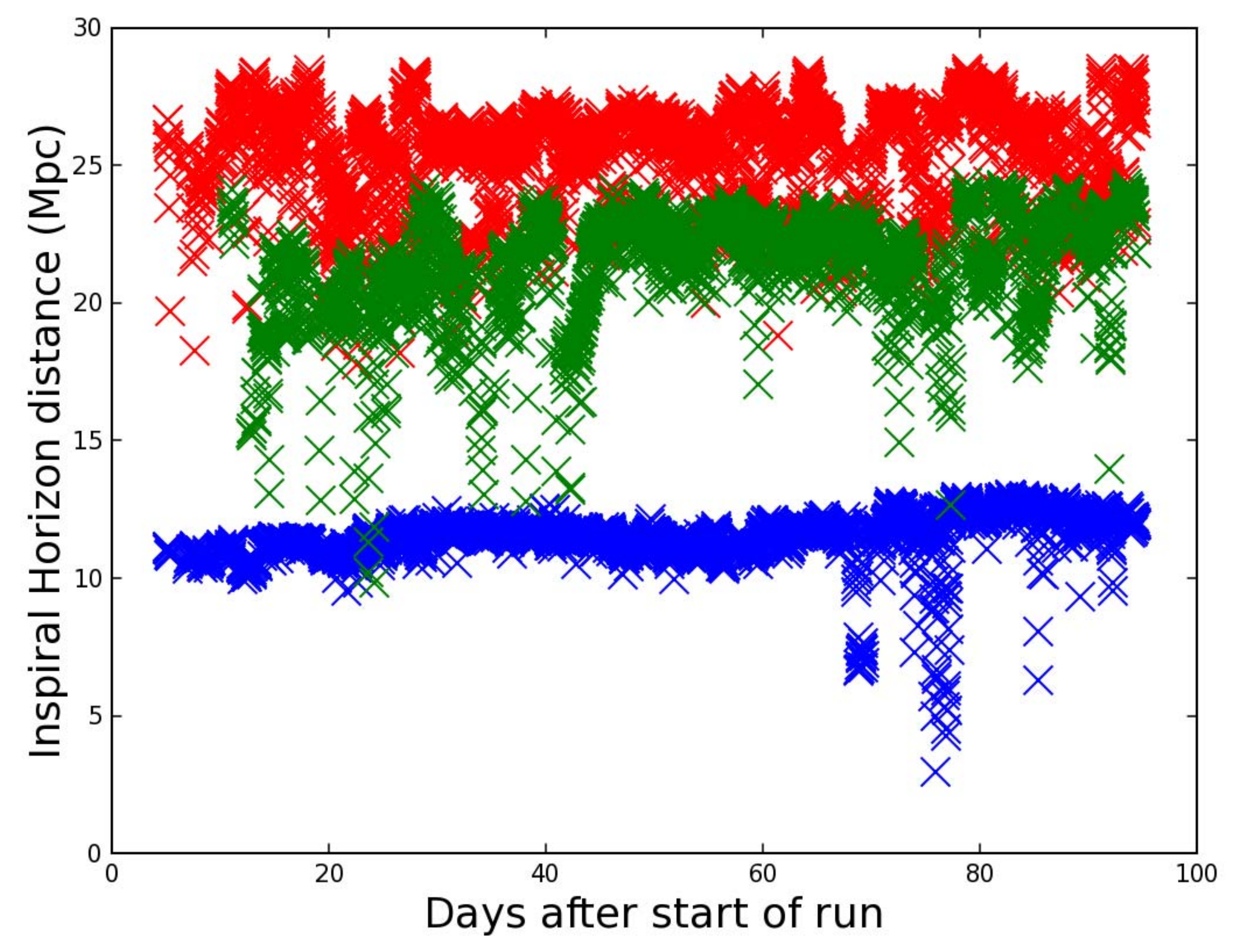
Gray bars what is expected from noise

Neutron Star Binary with Noise

S3 search complete
- Under review by LIGO
- 0.09 years of data
- about 3 Milky Way like galaxies

S4 search complete
- Under review by LIGO
- 0.05 years of data
- about 24 Milky Way like galaxies

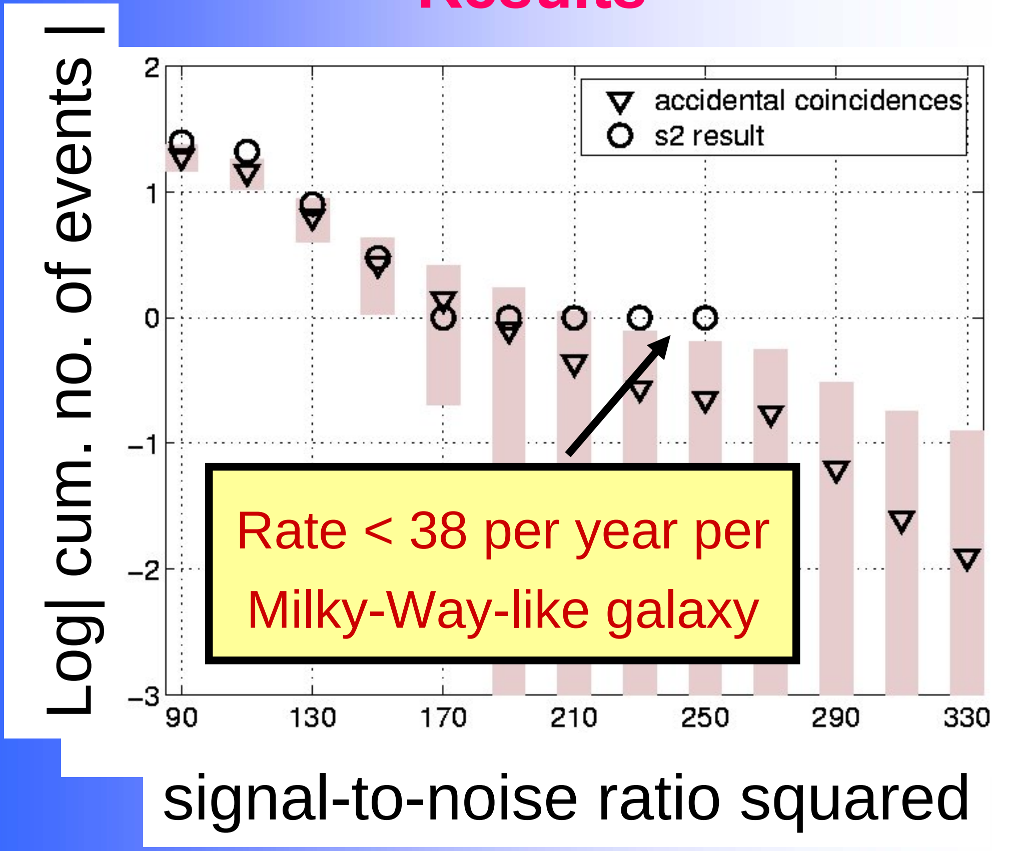
S5 Neutron Star Binary Results



Maximum range each interferometer could observe a binary neutron star inspiral

Black Hole Binary Results

S2 Black Hole Binary Results



Rate < 38 per year per Milky-Way-like galaxy

Using two 5 M_o black holes

S3 search complete

- Under review by LIGO
- 0.09 years of data
- about 5 Milky Way like galaxies

S4 search complete

- Under review by LIGO
- 0.05 years of data
- about 150 Milky Way like galaxies

Black points are number of events at each signal-to-noise ratio

Gray bars what is expected from noise

Burst Source Searches

Two main types of burst searches

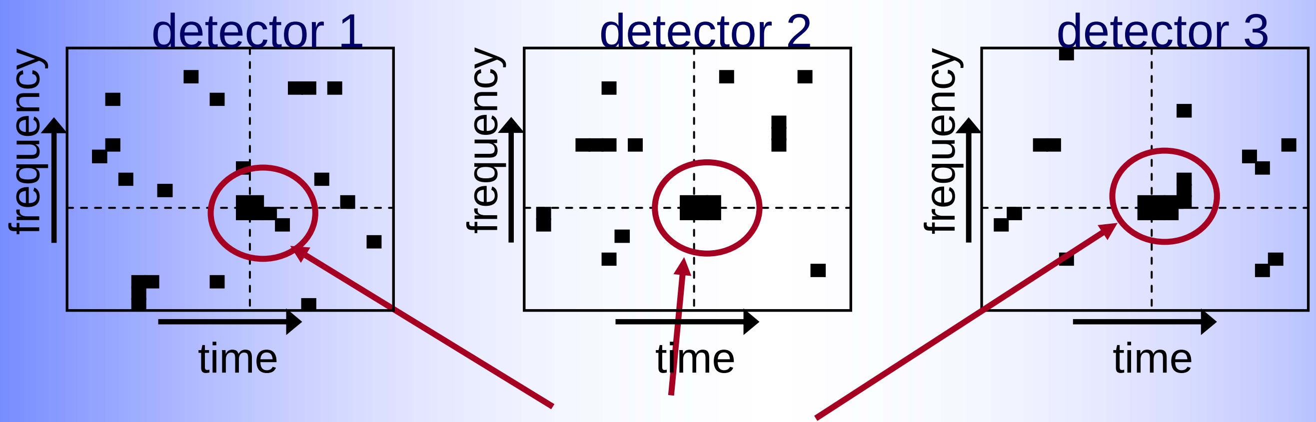
Untriggered : Scan all data, looking for excess power

Most robust way to look for bursts

Triggered : Scan data around time of known event like γ ray burst of supernova

Use knowledge of position on sky

Always make minimal assumptions about the signal.
Be open to the unexpected.

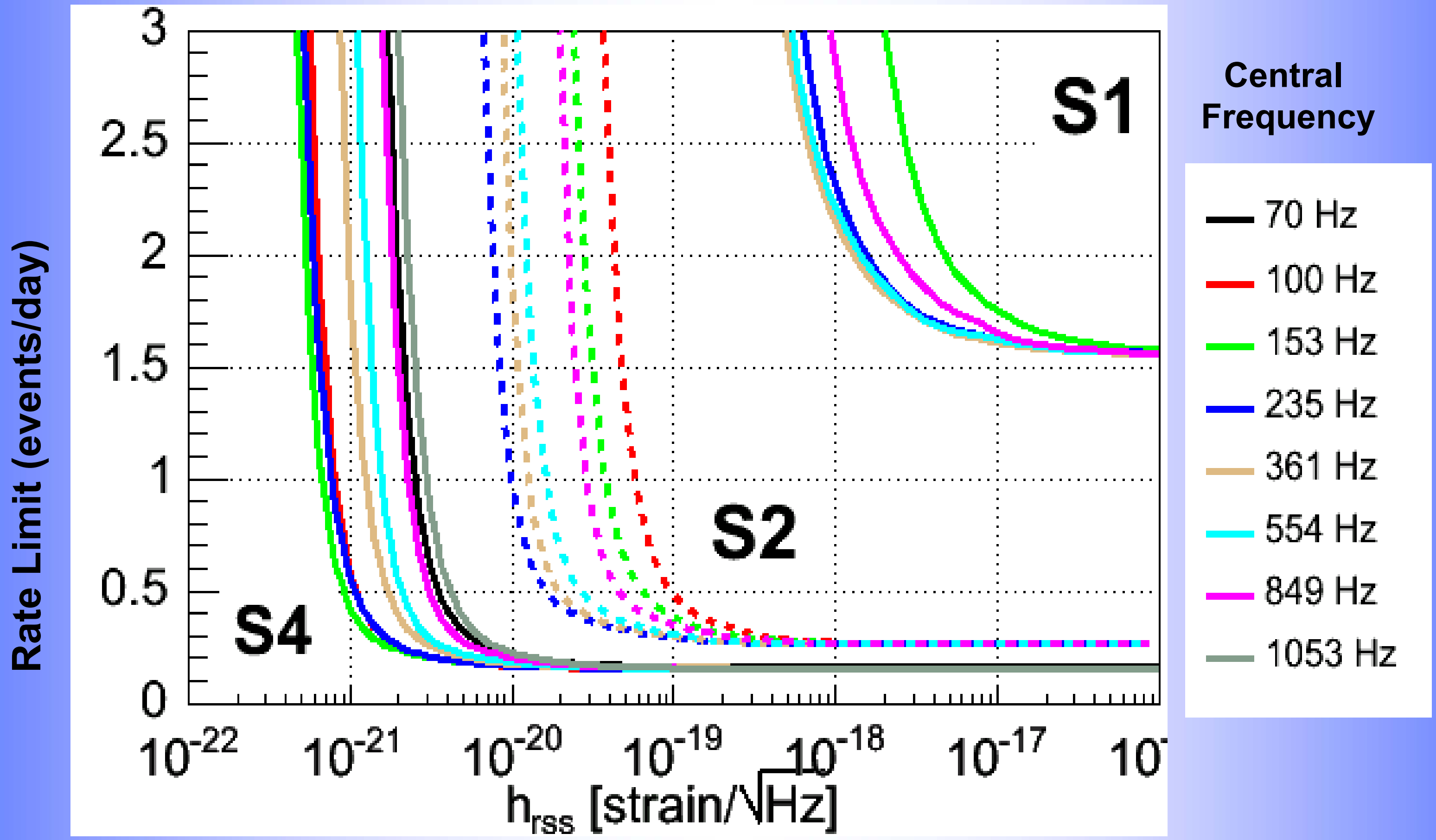


time,
frequency
coincidence

Burst Results

No gravitational wave bursts detected to date

Set limits on rates and strain amplitudes



Stochastic Search

$$S_{\mathrm{gw}}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{\mathrm{gw}}(f)$$

Stochastic signal strength parametrized as fraction of closure density of universe Ω

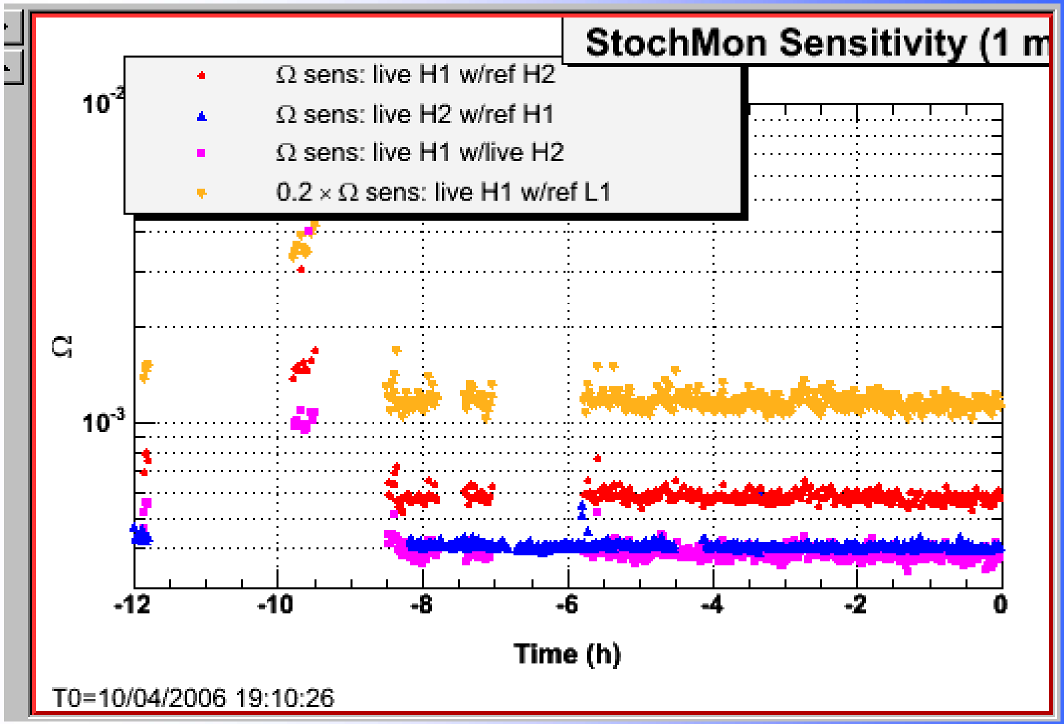
Arguments from big bang nucleosynthesis mean Ω must be less than 10^{-5}

Cross correlation of data from two interferometers

Best results from two Hanford detectors

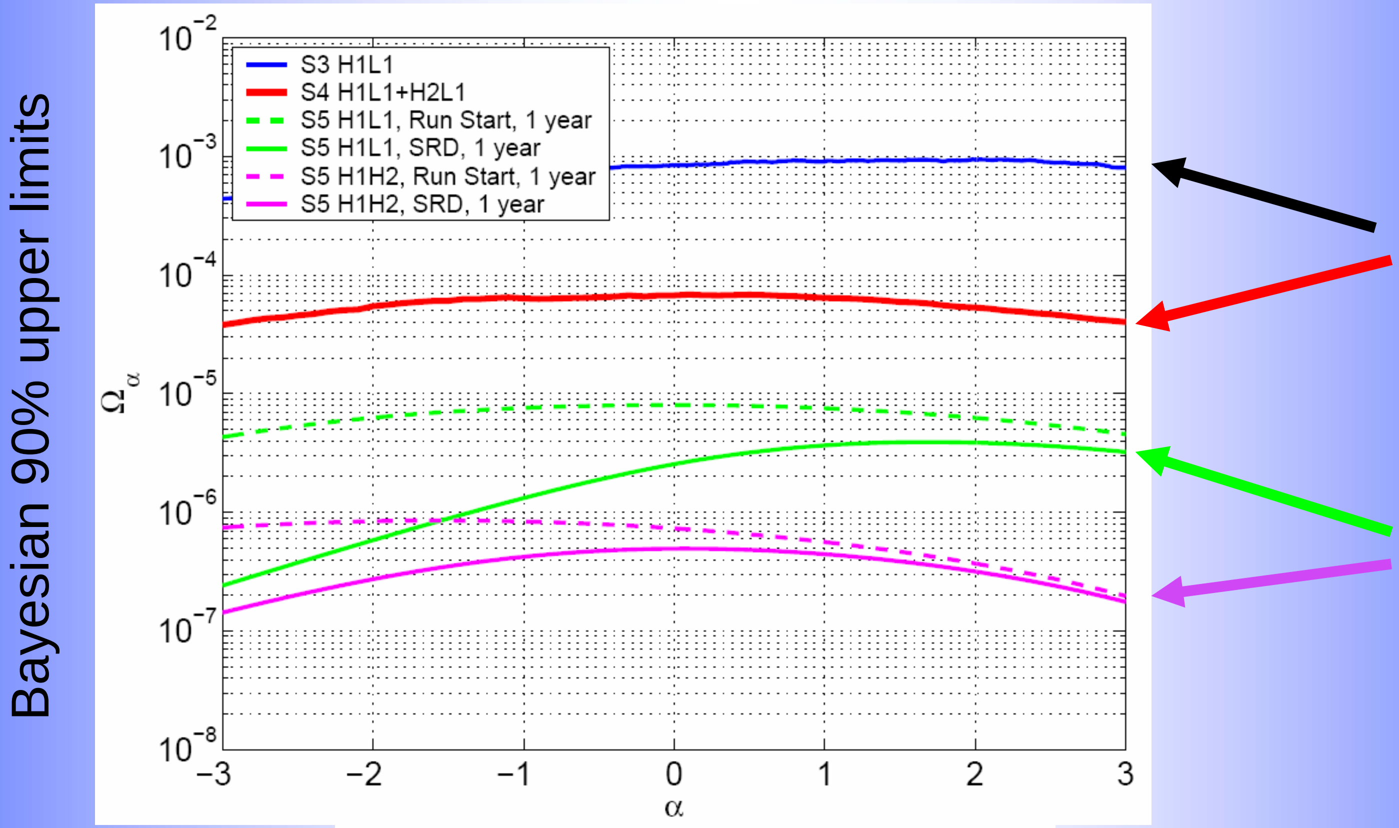
- Colocation allows for higher frequency
- Need to be sure correlations are not local noise

Longer time of correlation also increases sensitivity



S5 stochastic monitor

Stochastic Results



Measured (S3, S4)

Expected from S5

$$\Omega_t(f) = \Omega_\alpha (f/100\ \mathrm{Hz})^\alpha$$

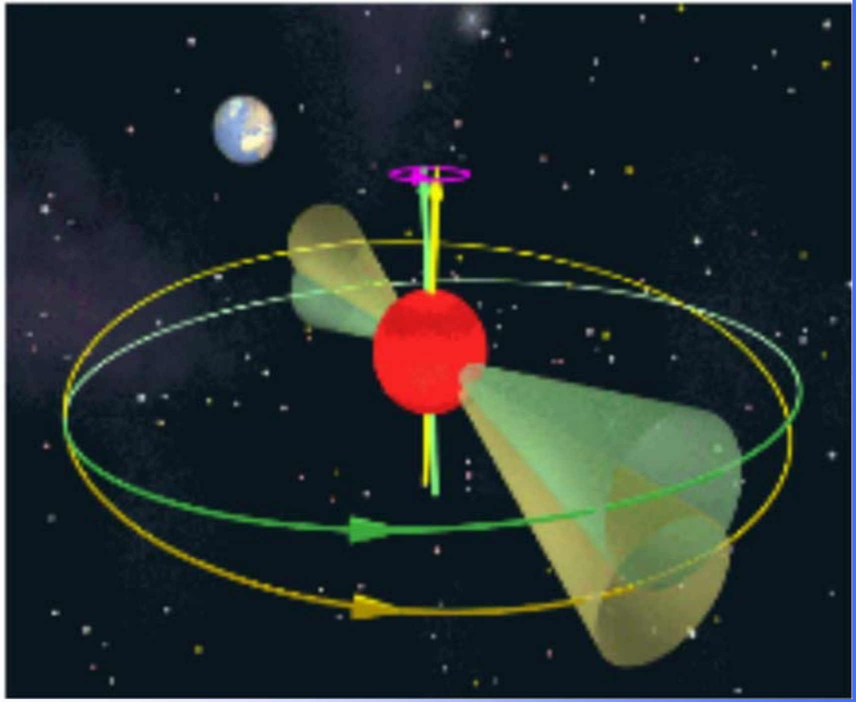
S4 results approaching astrophysically interesting limits

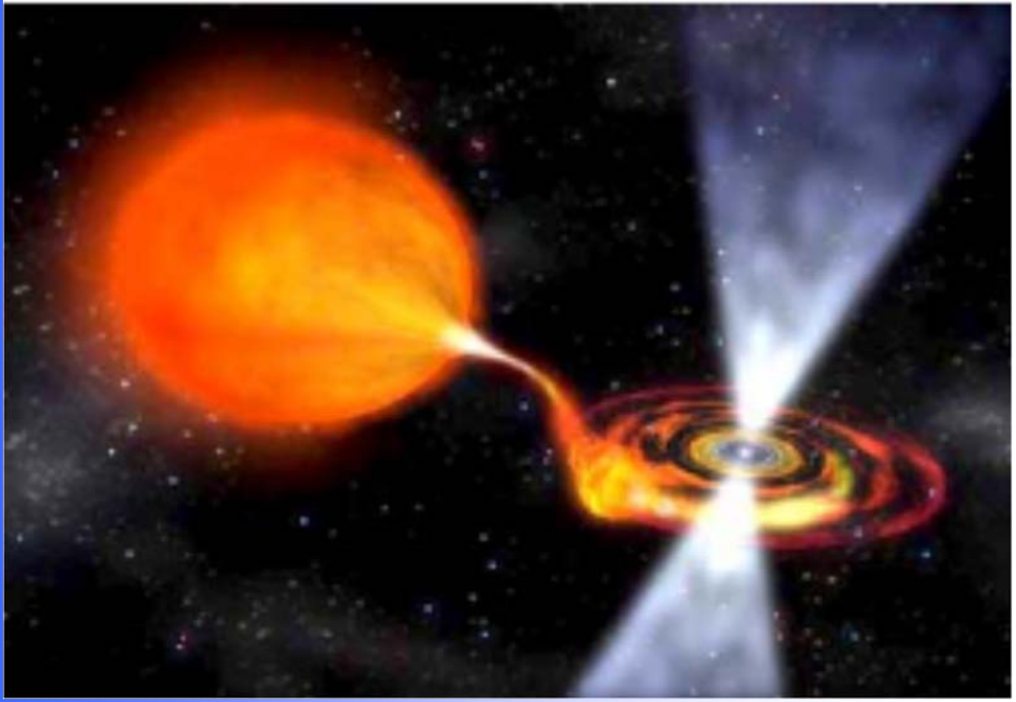
Full year of data at design sensitivity will give limit below $\Omega < 10^{-5}$

Continuous Wave Search

Search known pulsars
- Use known frequencies, positions, ringdown times, etc.

Search whole sky
- Need a lot of computer power





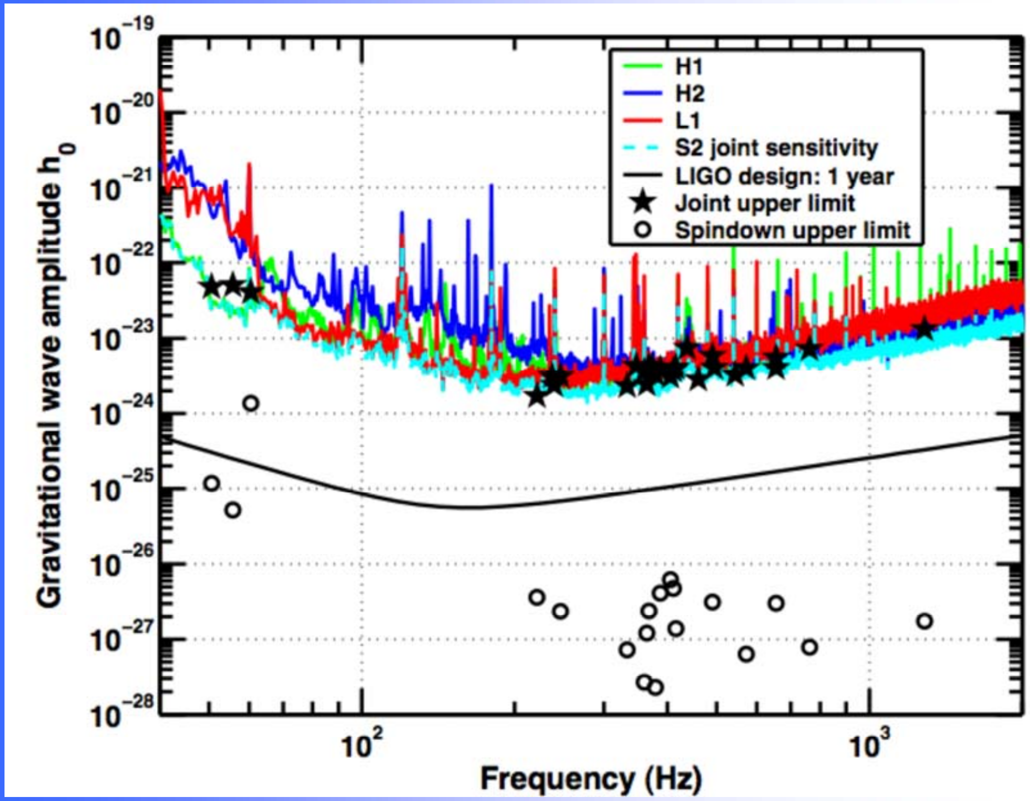
Can use template based search

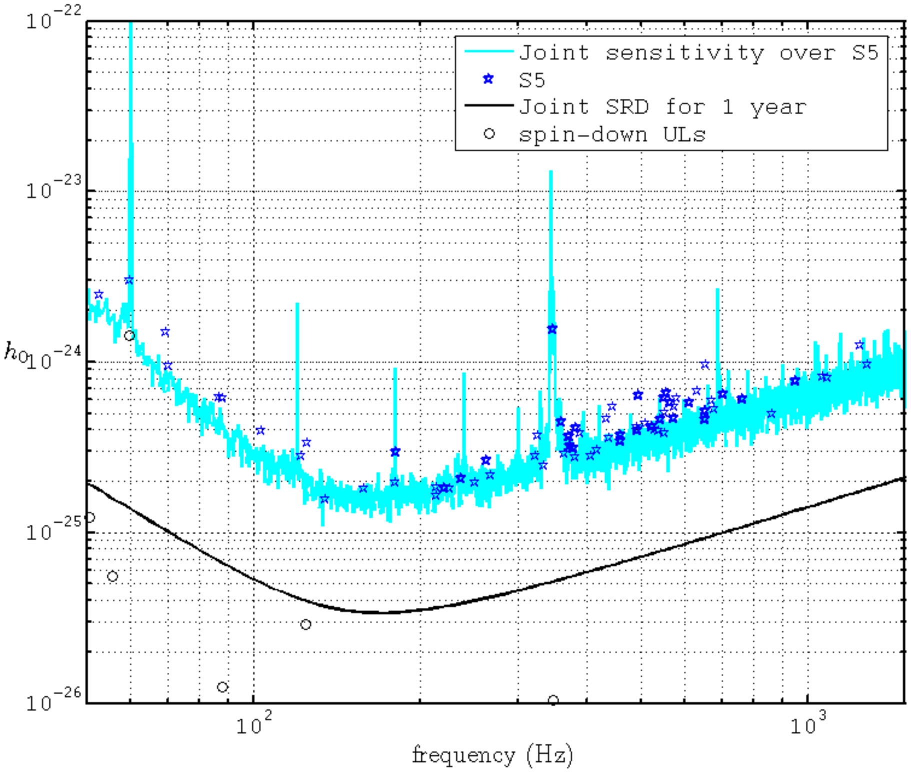
Basically sine waves, with modifications for Doppler shift, and antenna sensitivity

Continuous Wave Results

32 known isolated pulsars, 44 in binaries, 30 in globular clusters

S5 Sensitivity



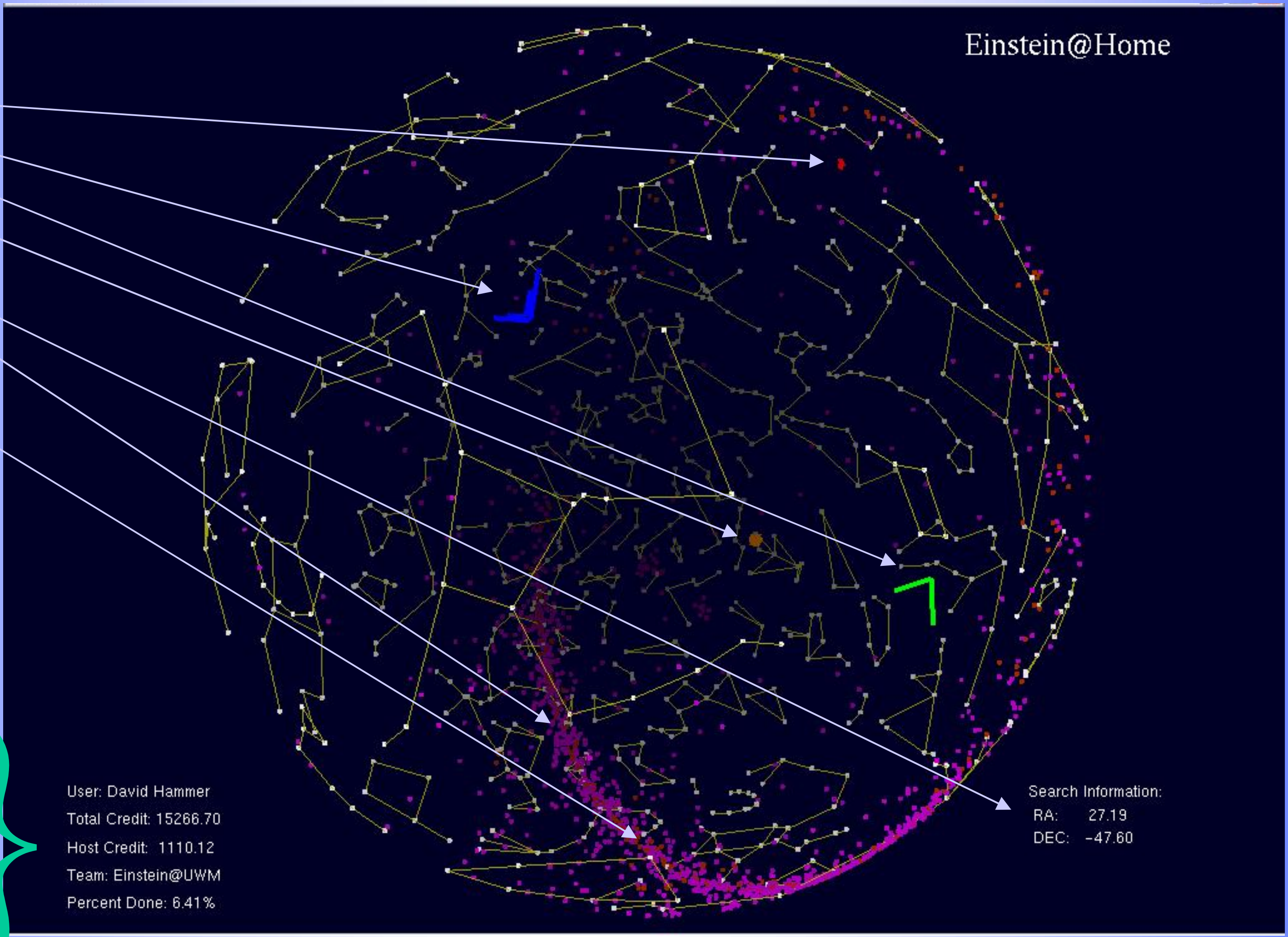


Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6Hz, r = 0.25kpc)
ellipticity = 4.0×10^{-7}

S2 Pulsar Results

Einstein @ Home

All sky, all frequency search for pulsars
Computationally limited, so uses distributed computing



Einstein@Home

User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

Search Information:
RA: 27.19
DEC: -47.60

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants

- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

http://www.einsteinathome.org/

Conclusions

Gravitational wave astronomy will open a new window on the universe

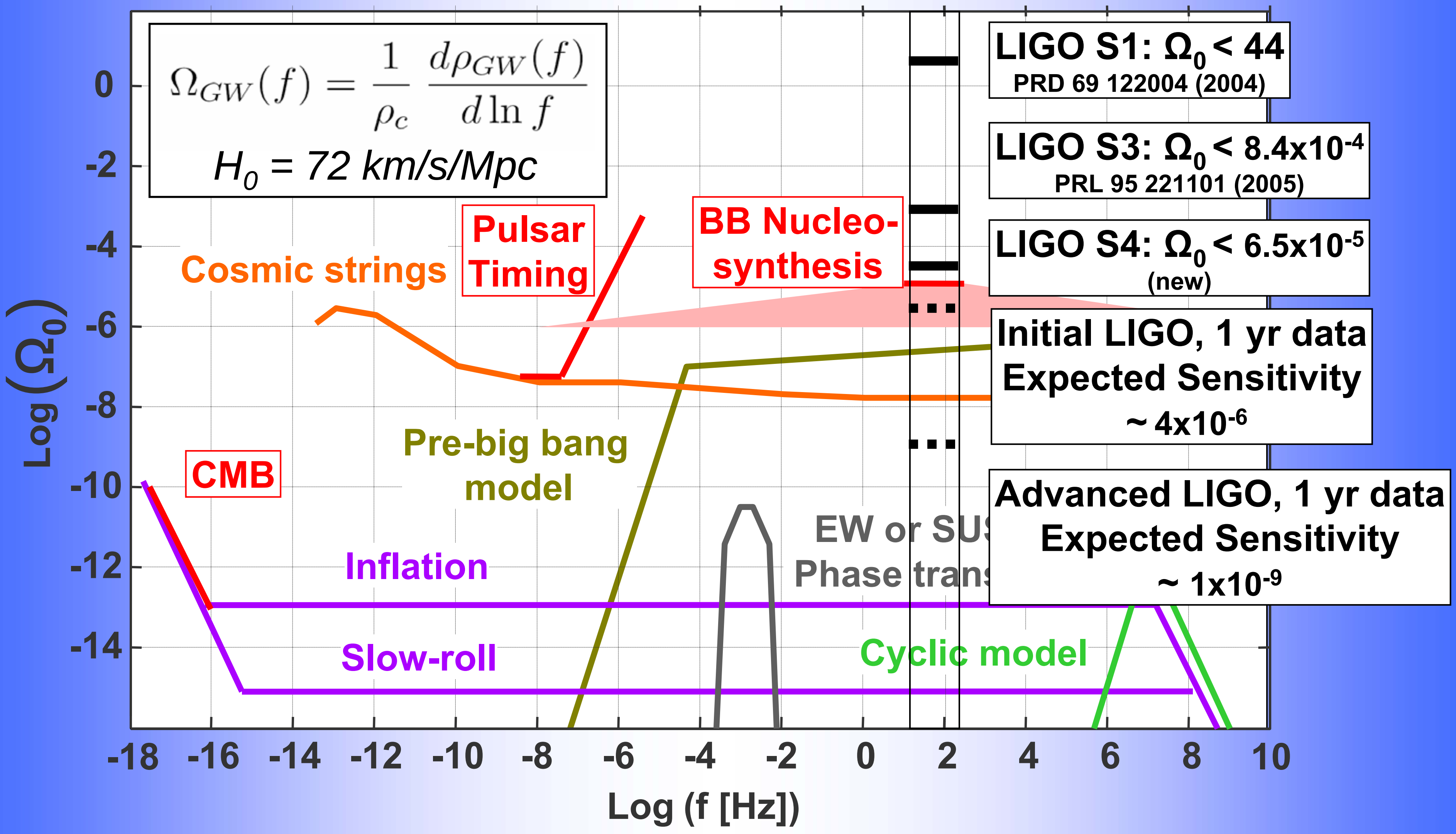
Indirect evidence has confirmed existence of gravitational waves

Attempts at direct detection have been ongoing for over 30 years

LIGO is now setting astrophysically interesting limits on multiple types of gravitational waves

First direct detection of a gravitational wave could happen any day

Models of Stochastic Sources



Gravitational Waves

Distance along a path depends on the curvature

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

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

For small curvature, the effect of gravity can be described as a perturbation from normal flat space

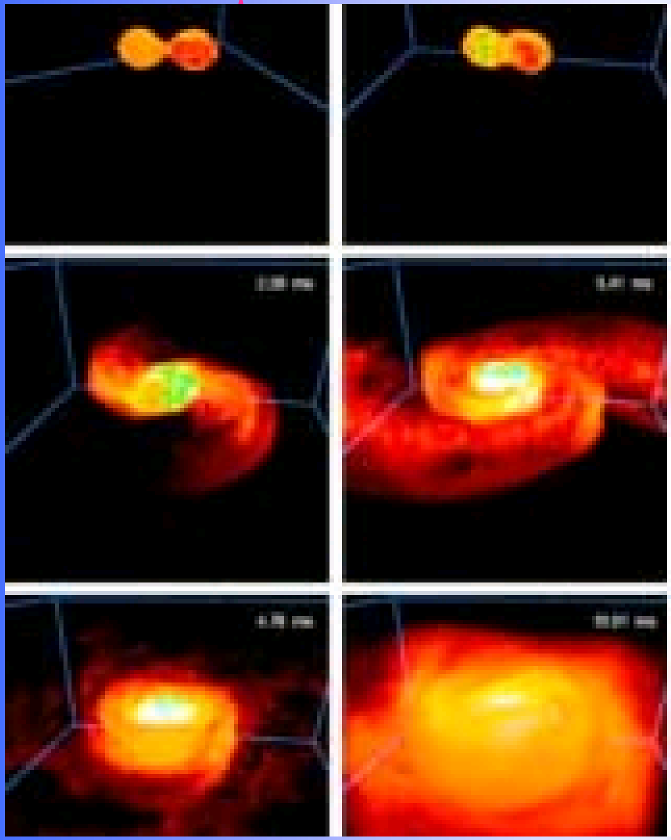
h is a strain, describes how much a length changes by: h = Δ l / l

Using the Einstein Equation, this perturbation obeys a wave equation

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

Generation of Gravitational Waves

Changes in the mass/energy density $T_{\mu\nu}$ create a corresponding change in the gravity $G_{\mu\nu}$



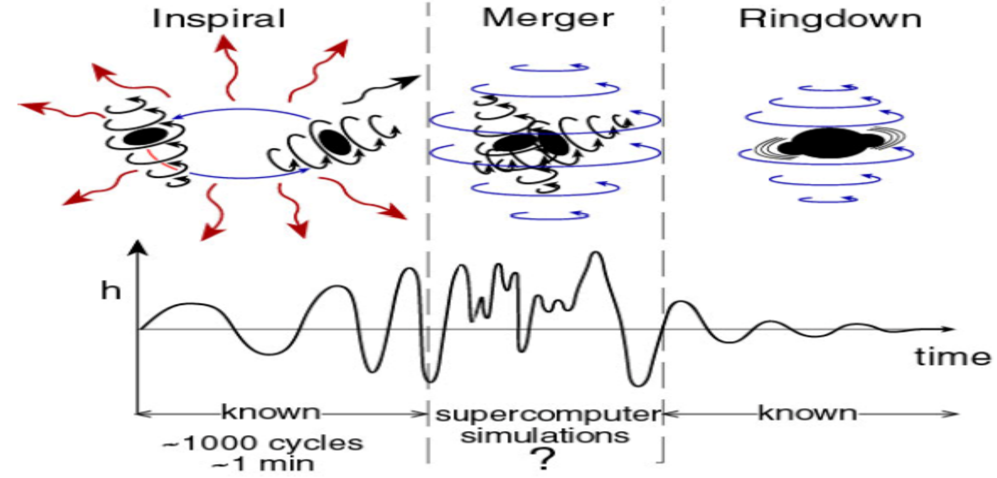
$$h_{ij} = 2\,G/(r\,c^4)\;d^2 I_{ij}/dt^2$$

h_{ij} is perturbation to spacetime
r is the distance from the source
I_{ij} is the reduced quadrupole moment of source

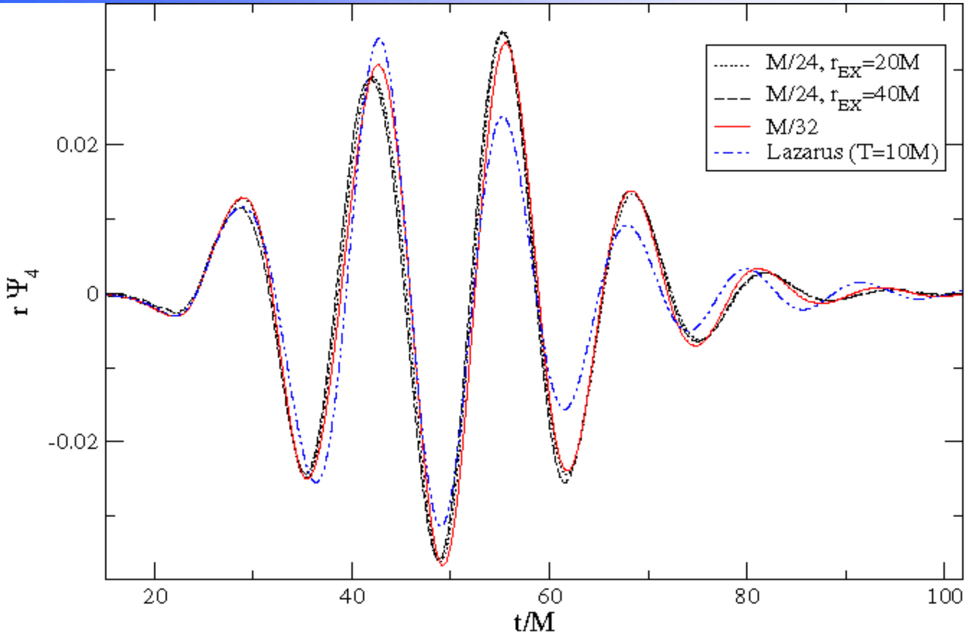
The source must not be spherically symmetric

- Makes predicting strength of supernova and pulsars difficult
- Dense object in binary systems (black holes, neutron stars) ideal

Inspiral, Merger, and Ringdown Sources



Credits: Kip Thorne



Inspiral phase well modelled

Merger very dependant on properties of object
- Neutron star - depends on equation of state of nuclear matter
- Black holes - highly nonlinear gravitational fields

Ringdown
- Only if black hole is formed
- Well modelled
- Exponentially decaying sine

Combined inspiral and burst source