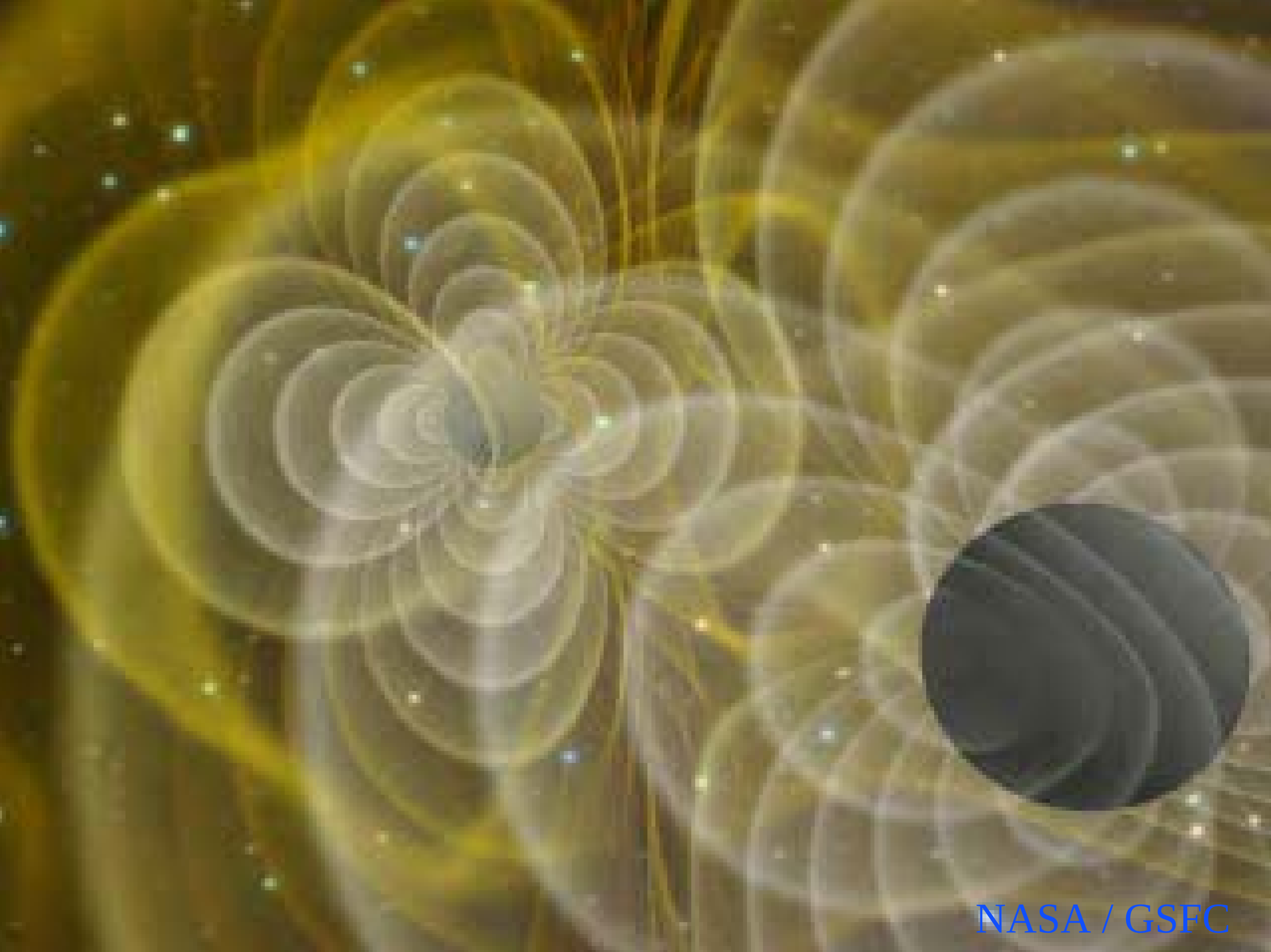
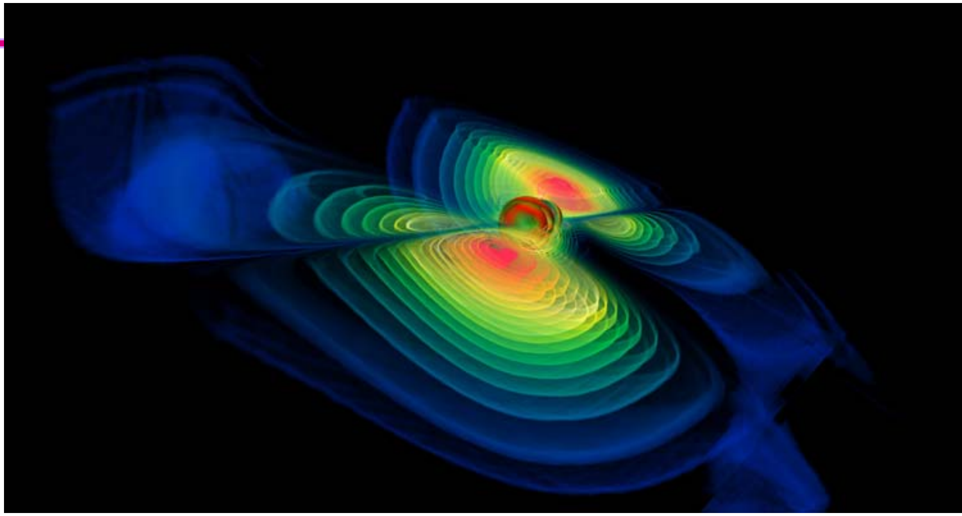


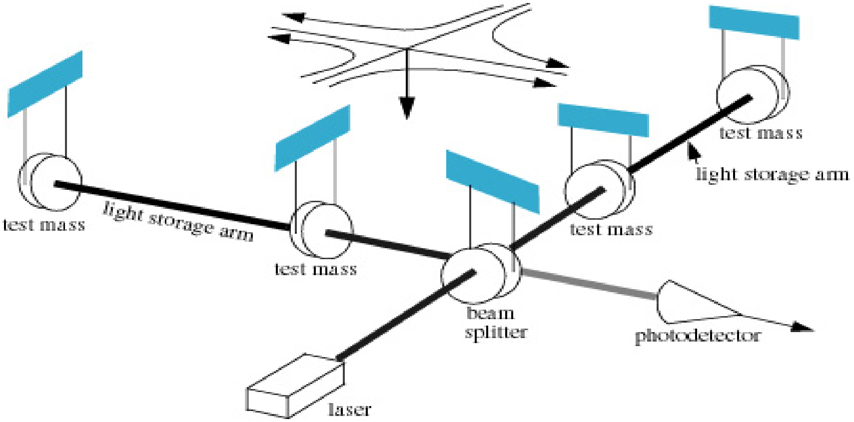
NASA / GSFC

Gravitational Waves and LIGO

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



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

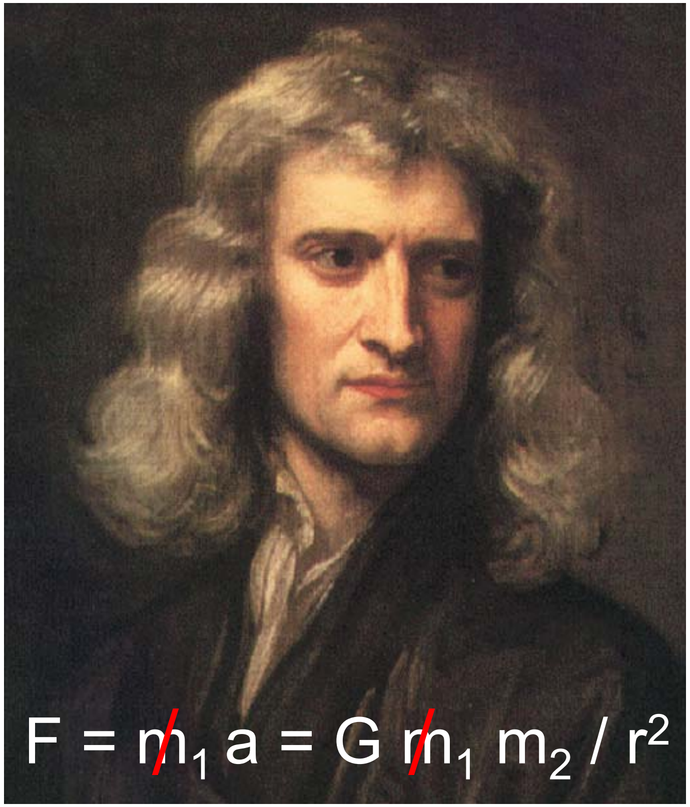


Alan Weinstein, Caltech

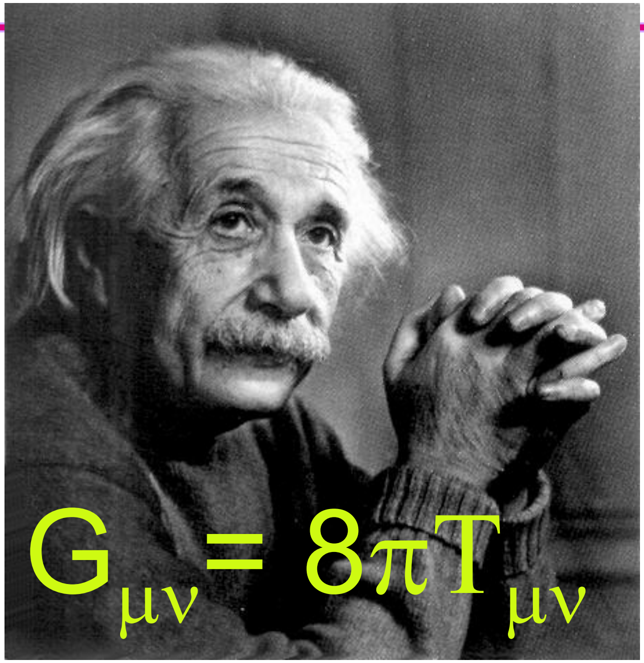
The nature of Gravity

Newton's Theory

"instantaneous action at a distance"



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



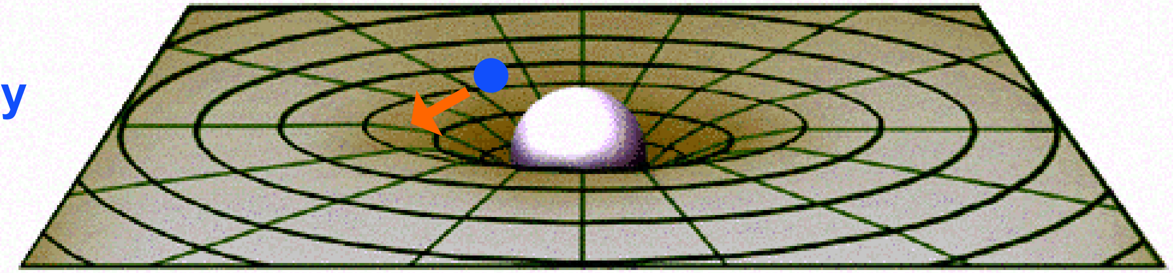
$G_{\mu\nu} = 8\pi T_{\mu\nu}$

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.

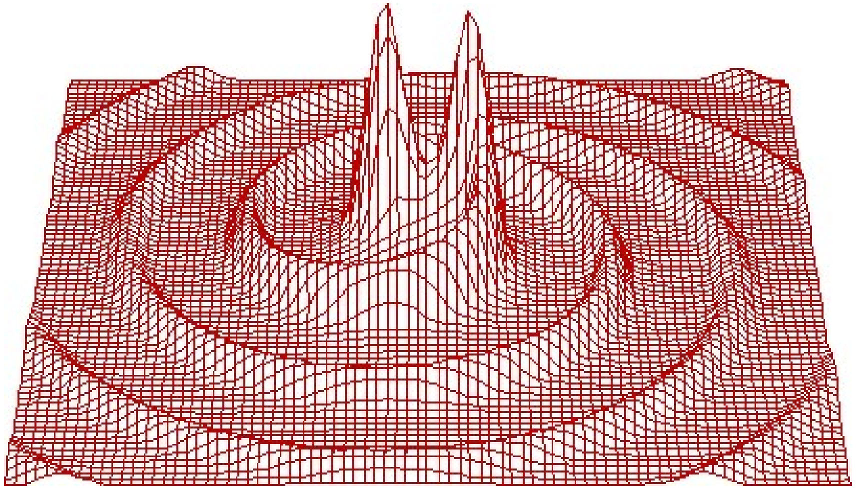
Information about changing gravitational field is carried by gravitational radiation at the speed of light

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.

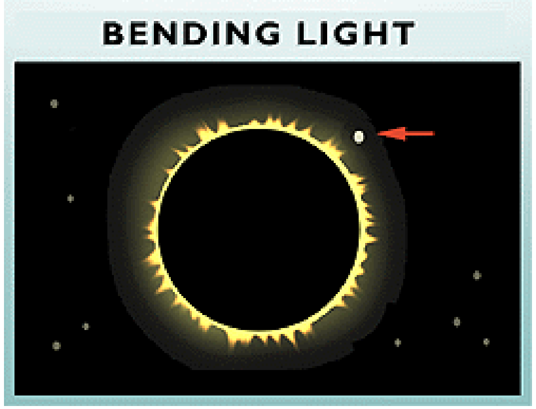
Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.



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

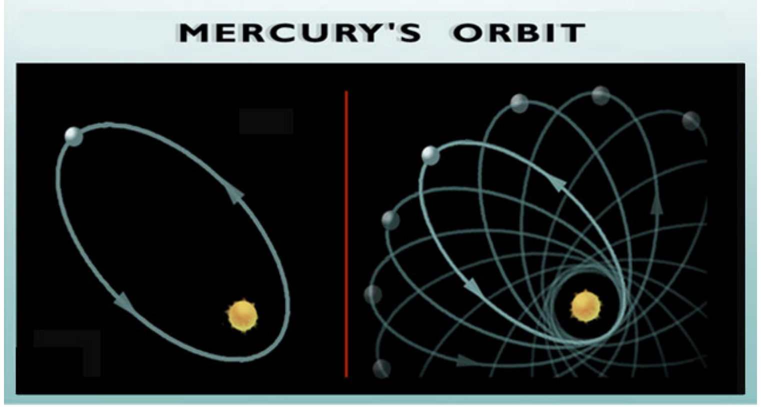
experimental tests



bending of light

As it passes in the vicinity of massive objects

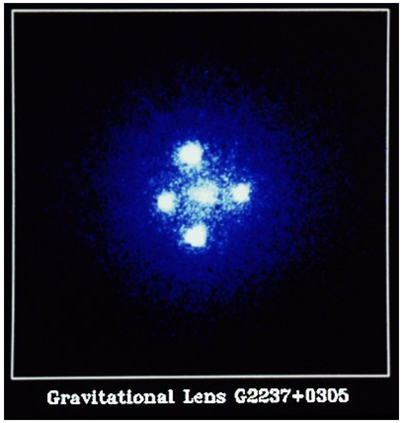
First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster



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”

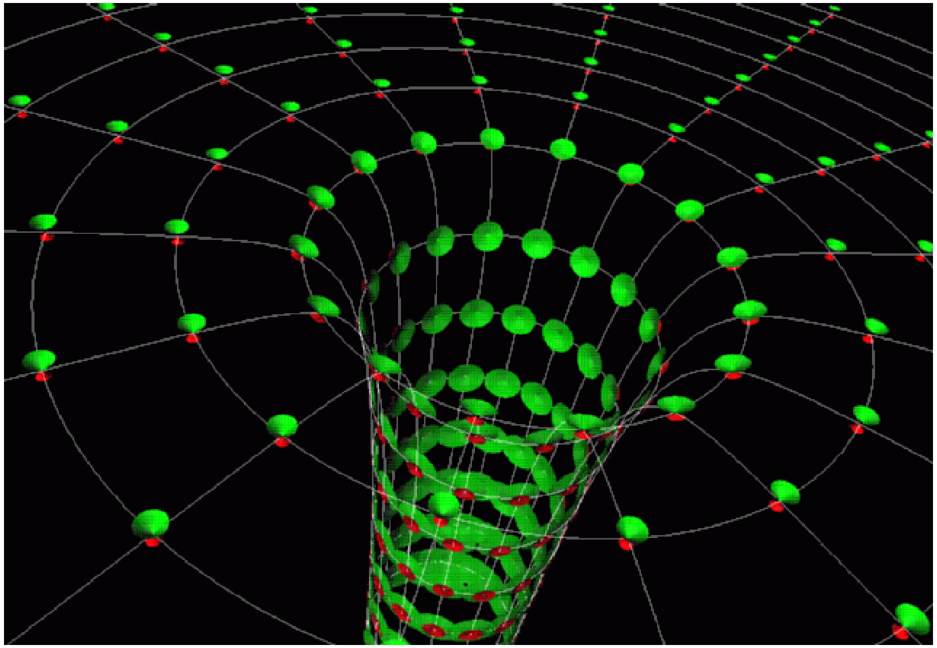
The bending of light rays

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 fabric of spacetime

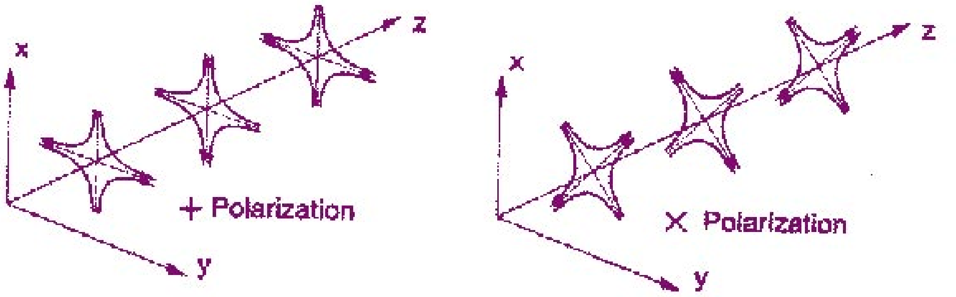
- propagating at speed of light
    - *mass of graviton = 0*
- Stretches and squeezes space between “test masses” – strain $h = \Delta L / L$
- space-time distortions are transverse to direction of propagation
- GW are tensor fields (EM: vector fields)

  two polarizations: plus (⊕) and cross (⊗)

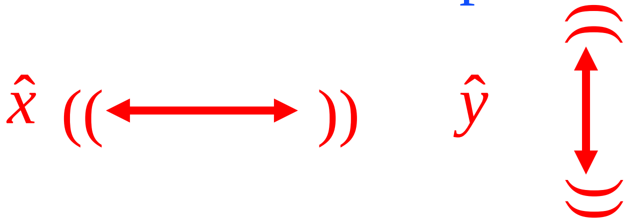
  (EM: two polarizations, *x* and *y*)

  Spin of graviton = 2

$h = \Delta L / L$



Contrast with EM dipole radiation:



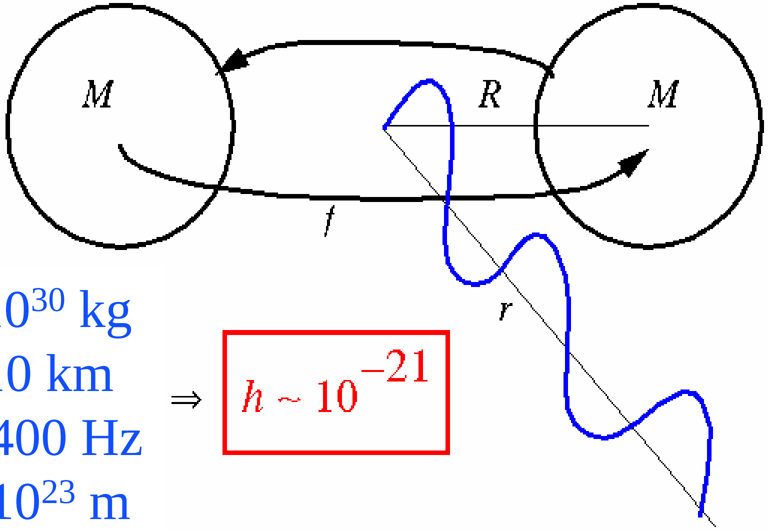
Sources of GWs

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

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

- $\ddot{I}_{\mu\nu}$ = 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:

Energy-momentum conservation:
cons of energy ⇒ no monopole radiation
cons of momentum ⇒ no dipole radiation
lowest multipole is quadrupole wave

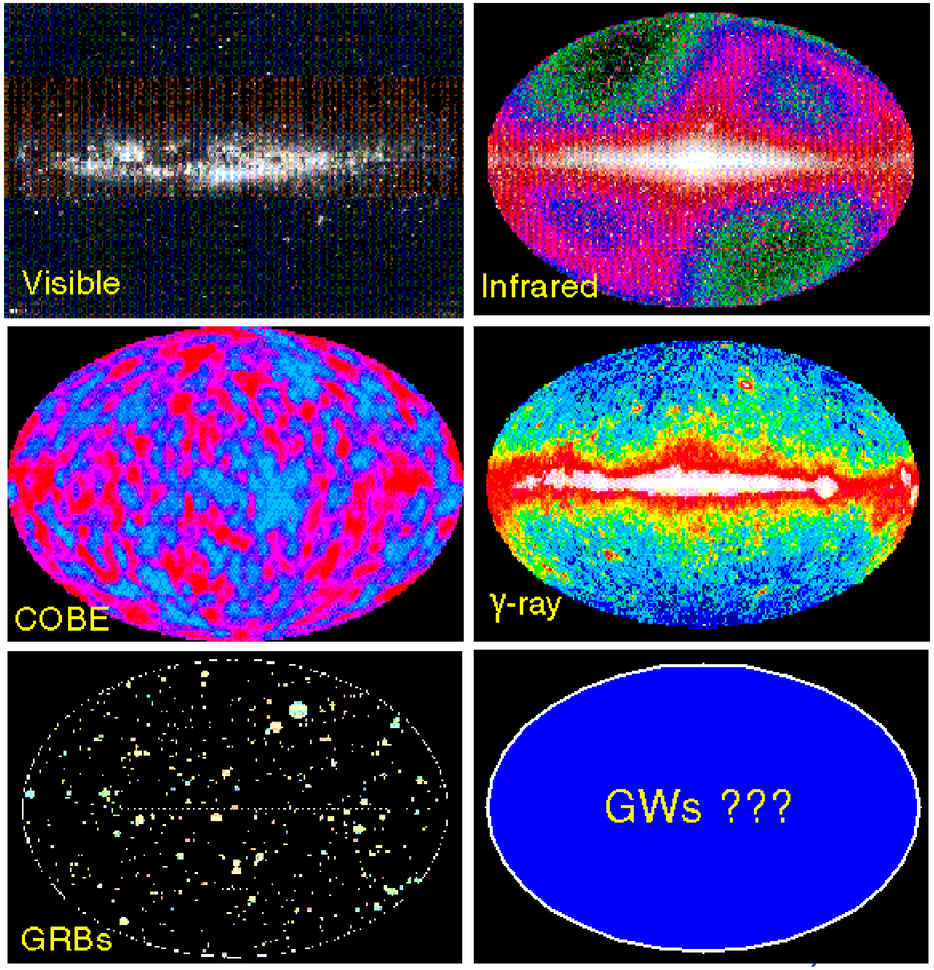


$M \sim 10^{30}$ kg
$R \sim 10$ km
$f \sim 400$ Hz
$r \sim 10^{23}$ m

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

Terrestrial sources *TOO WEAK!*

A NEW WINDOW ON THE UNIVERSE



The history of Astronomy:
new bands of the EM spectrum
opened → major discoveries!

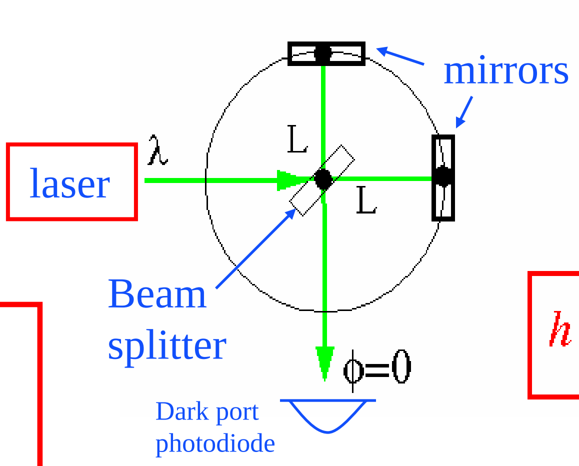
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

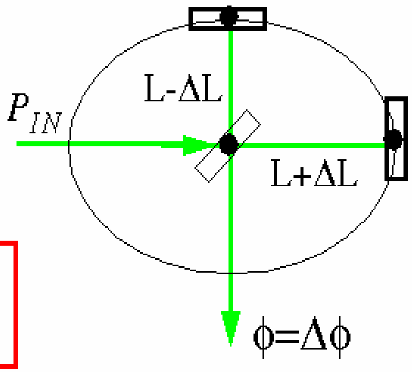
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

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

Interferometric detection of GWs

GW acts on freely falling masses:



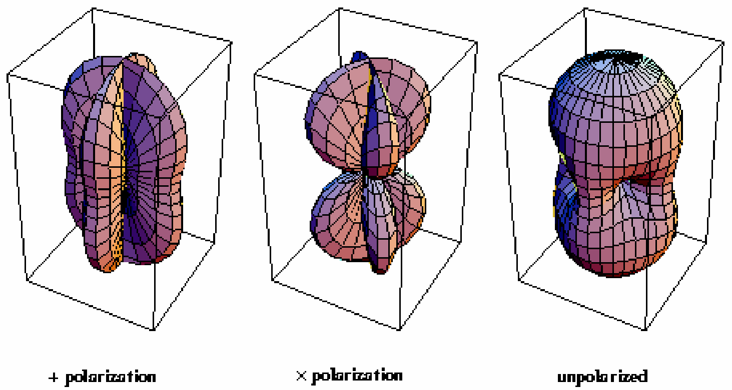


$$h = \frac{\Delta L}{L}$$

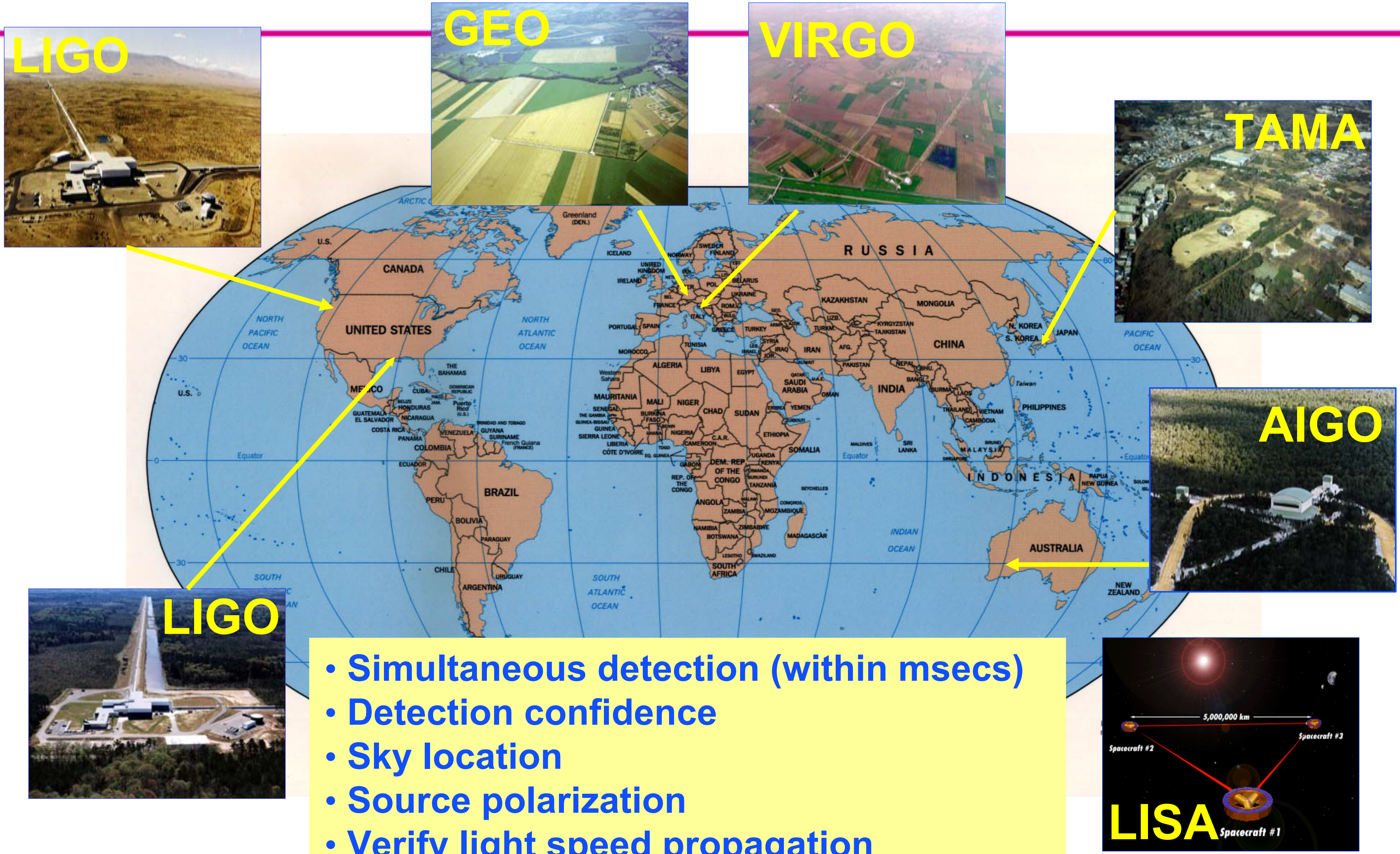
$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

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

Antenna pattern:
(not very directional!)



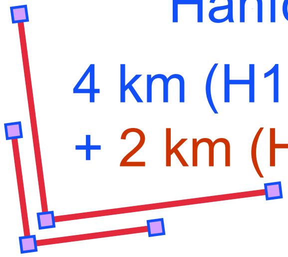
Global network of detectors



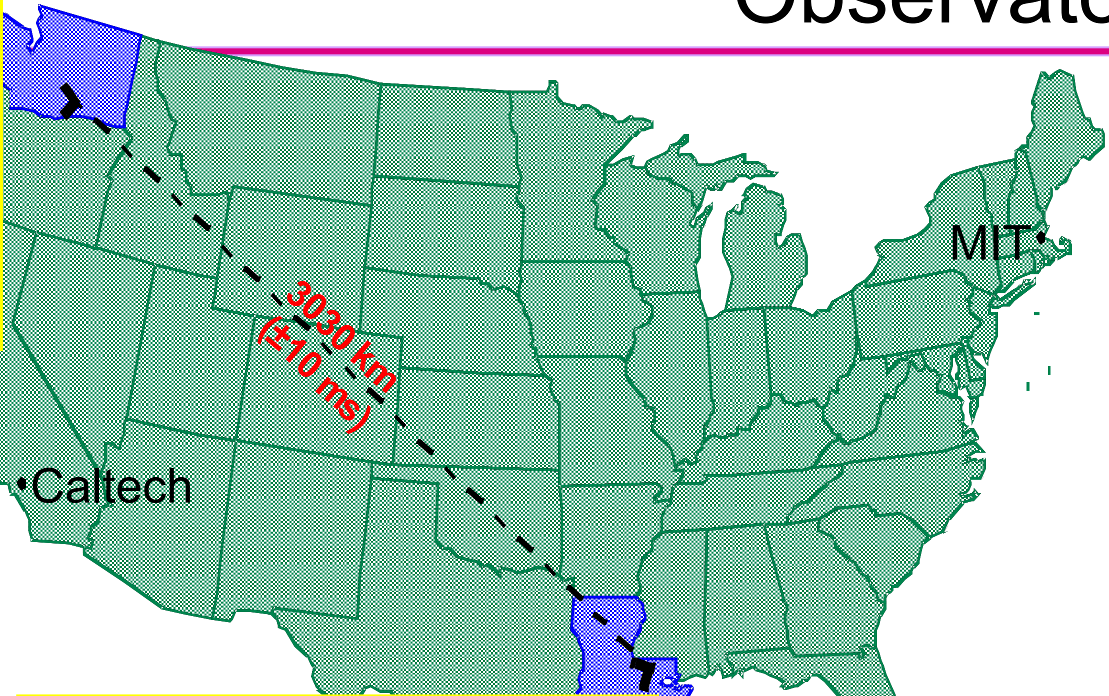
- **Simultaneous detection (within msecs)**
- **Detection confidence**
- **Sky location**
- **Source polarization**
- **Verify light speed propagation**

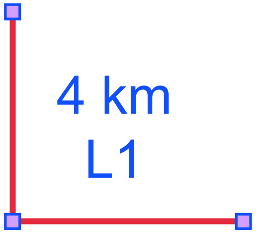
LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA



4 km (H1)
+ 2 km (H2)

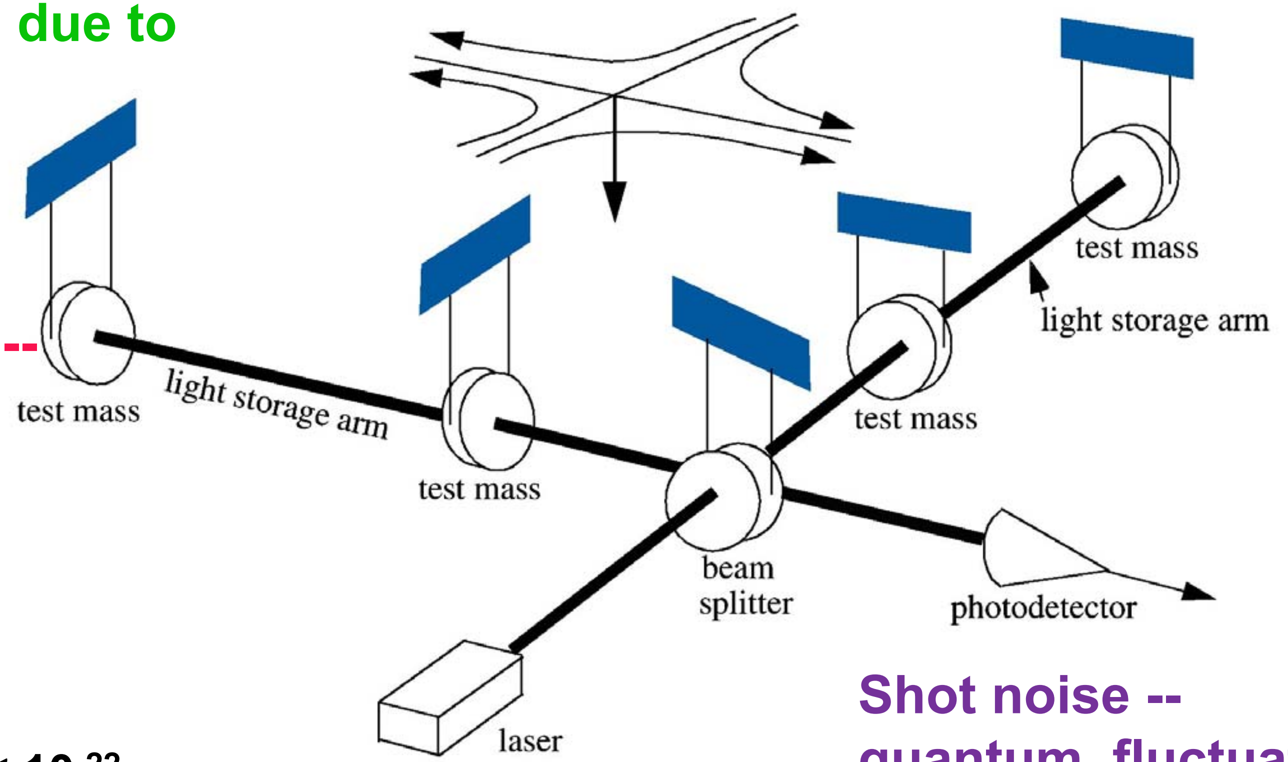




4 km
L1

Livingston, LA

GW detector at a glance



Seismic motion -- ground motion due to natural and anthropogenic sources

Thermal noise -- vibrations due to finite temperature

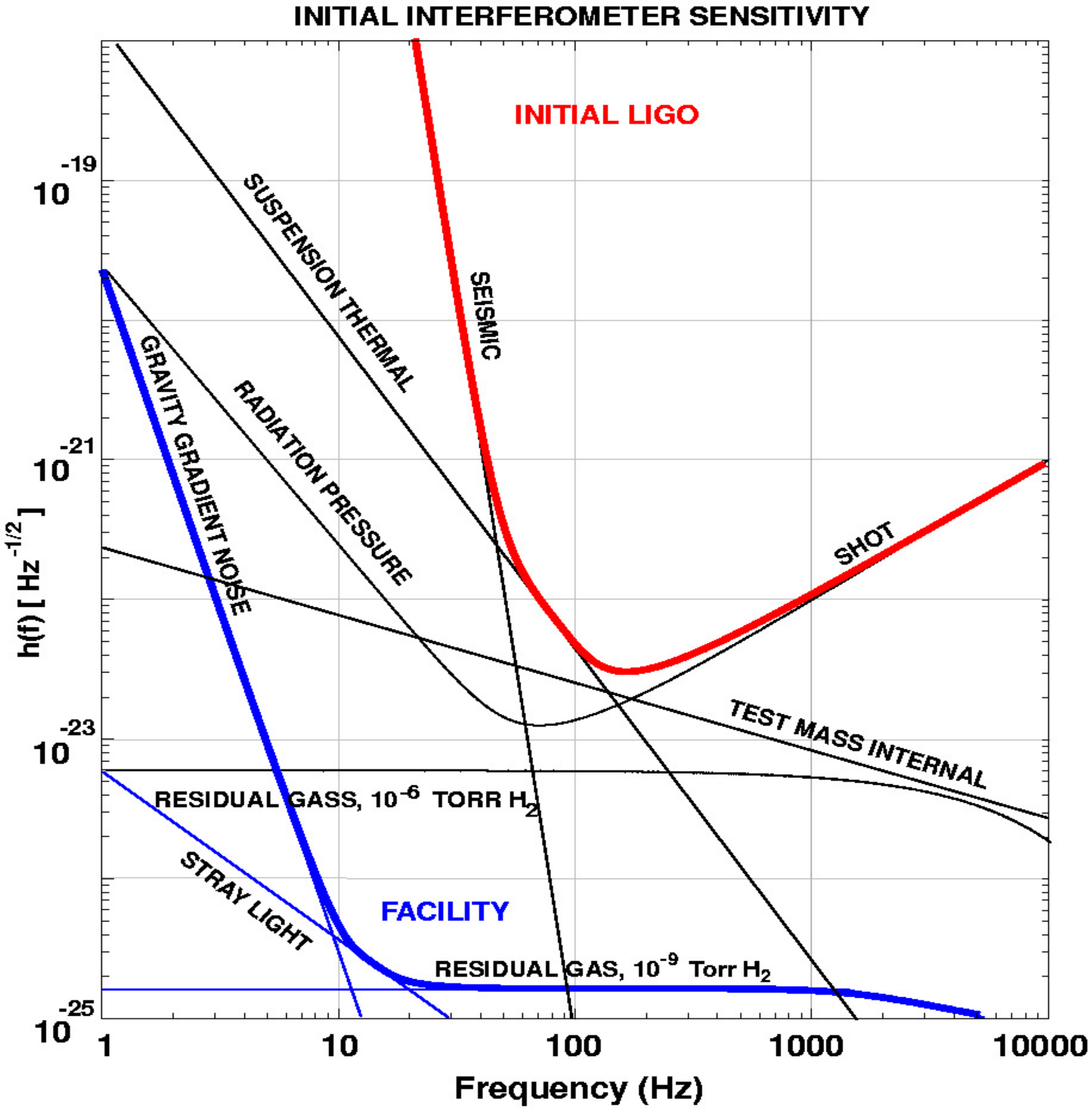
$$h = \Delta L / L$$

want to get $h \leq 10^{-22}$; can build L = 4 km; must measure $\Delta L = h\,L \leq 4\times10^{-19}$ m

Shot noise -- quantum fluctuations in the number of photons detected

AJW, LIGO SURF, 6/16/06

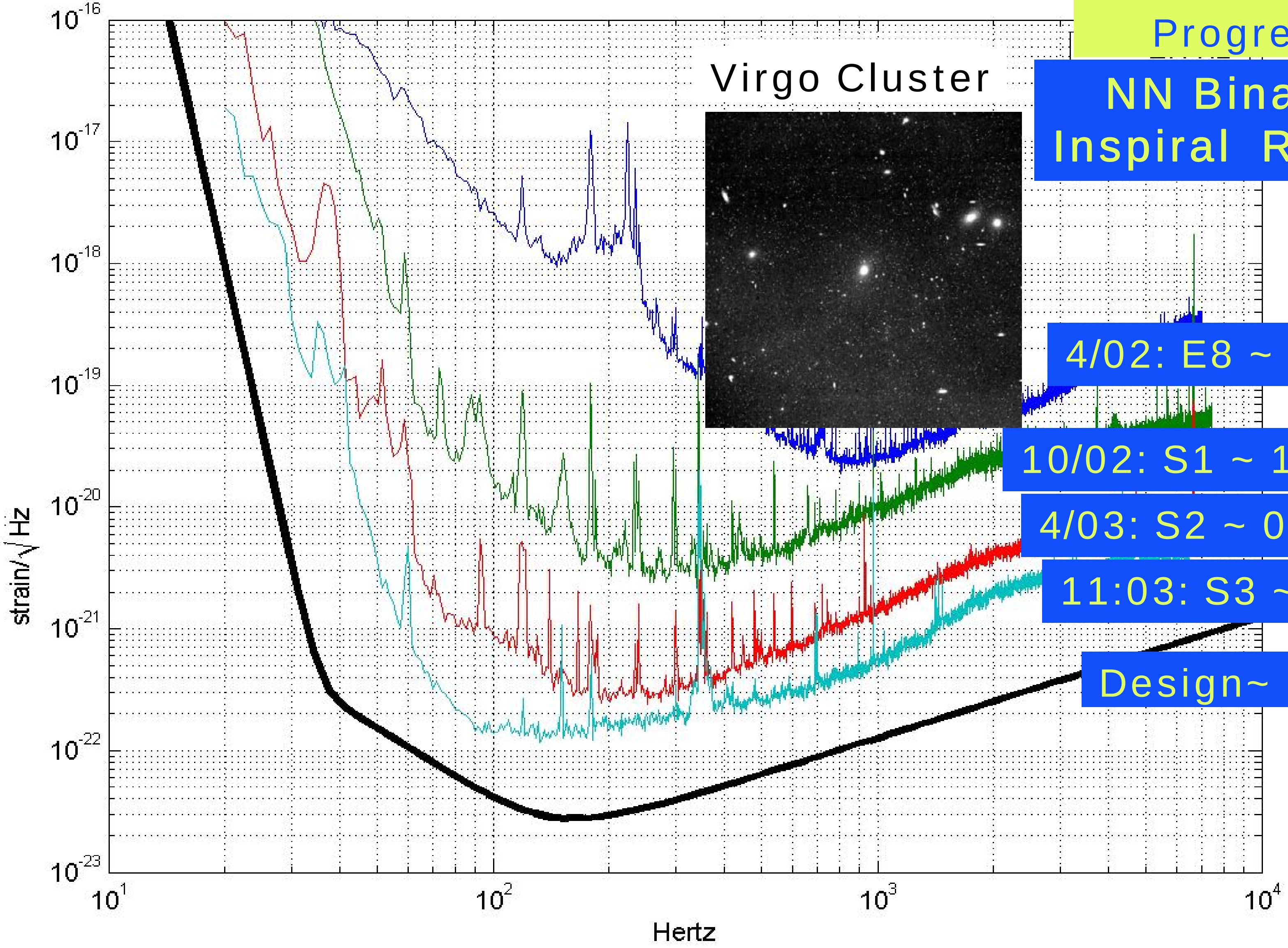
Initial LIGO Sensitivity Goal



- Strain sensitivity
  $< 3\text{x}10^{-23}$ 1/Hz$^{1/2}$
  at 200 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Facilities limits much lower
- BIG CHALLENGE:
  reduce all other (non-fundamental, or technical) noise sources to insignificance

Science Runs

A Measure of Progress



Virgo Cluster

NN Binary Inspiral Range

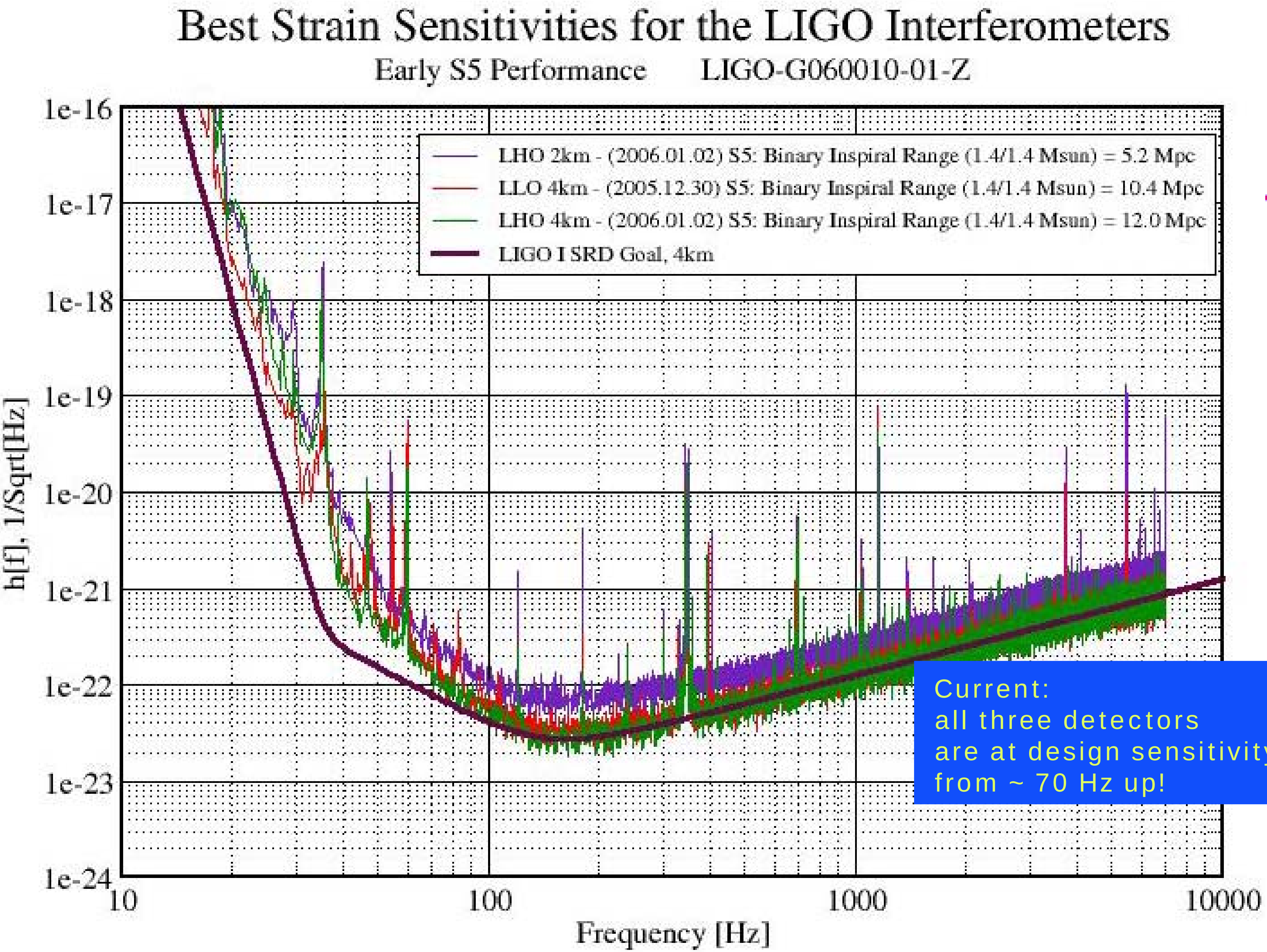
4/02: E8 ~ 5 kpc

10/02: S1 ~ 100 kpc

4/03: S2 ~ 0.9Mpc

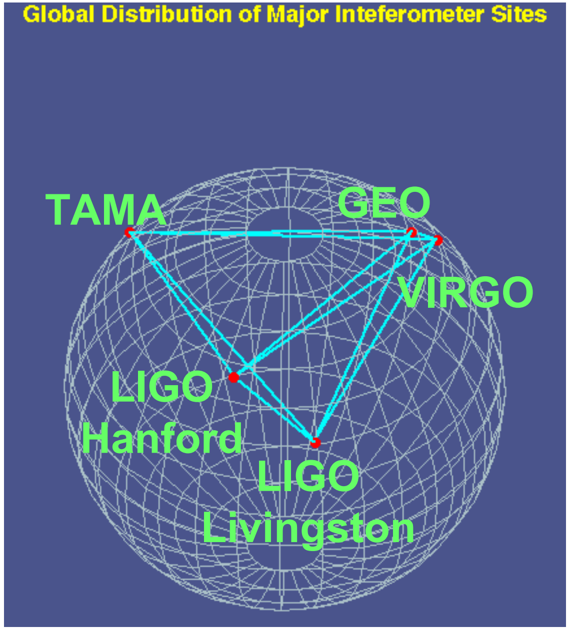
11:03: S3 ~ 3 Mpc

Design~ 18 Mpc



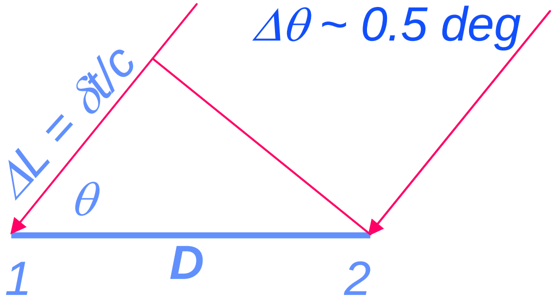
Current:
all three detectors
are at design sensitivity
from ~ 70 Hz up!

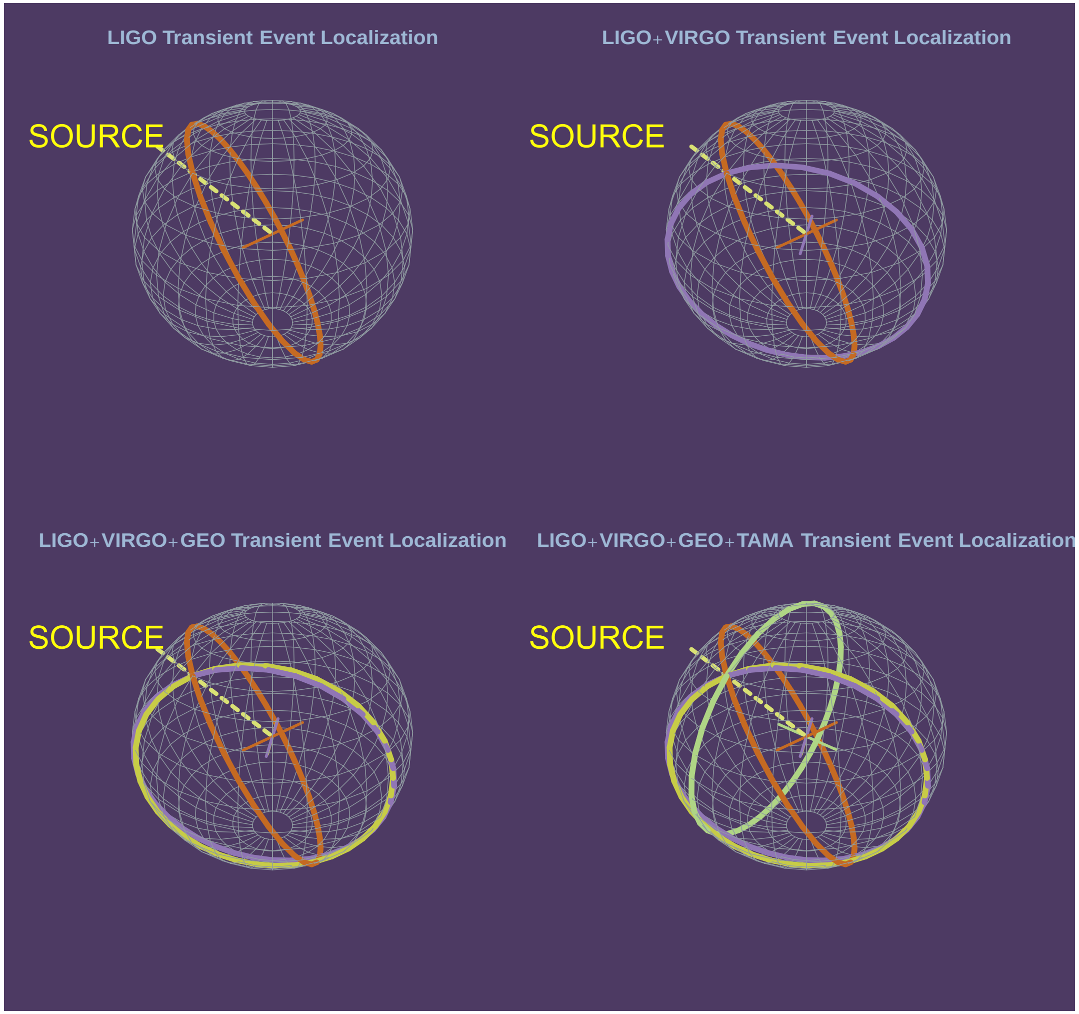
Event Localization With An Array of GW Interferometers



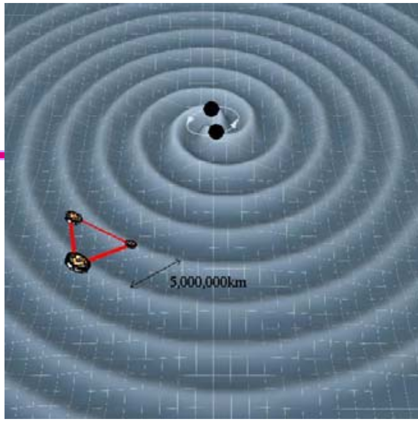
$\cos\theta = \delta t / (c\, D_{12})$

$\Delta\theta \sim 0.5$ deg



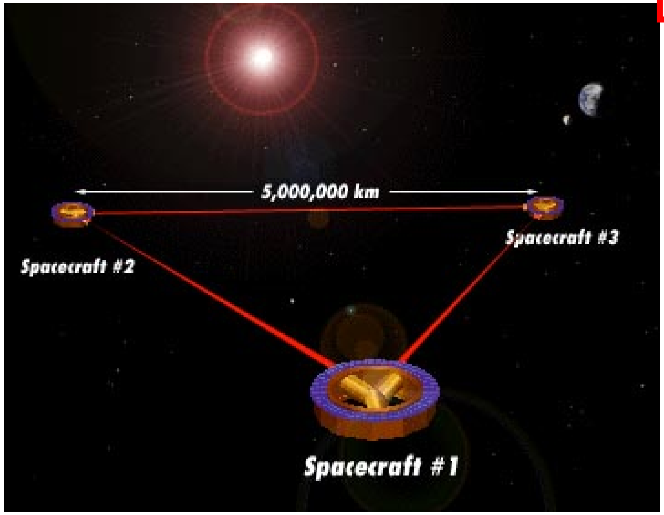


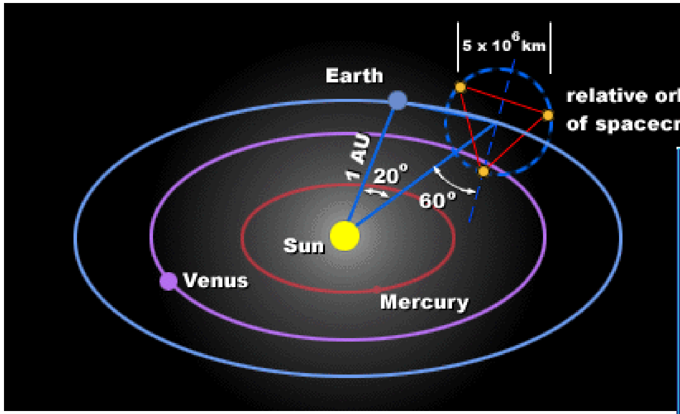
The Laser Interferometer Space Antenna
LISA

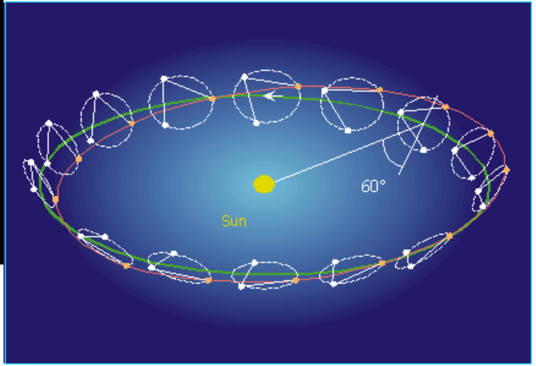


Three spacecraft in orbit about the sun,
with 5 million km baseline

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

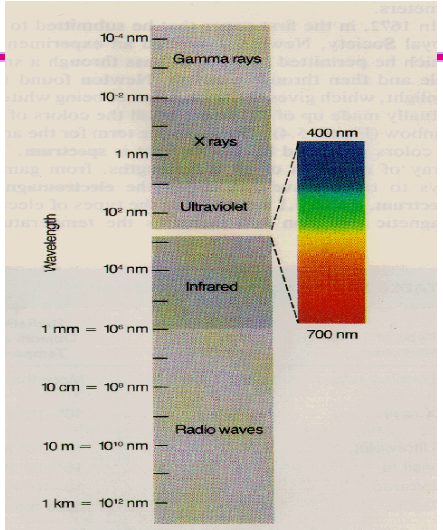






LISA (NASA/JPL, ESA) may fly in the next 10 years!

Frequency range of GW Astronomy

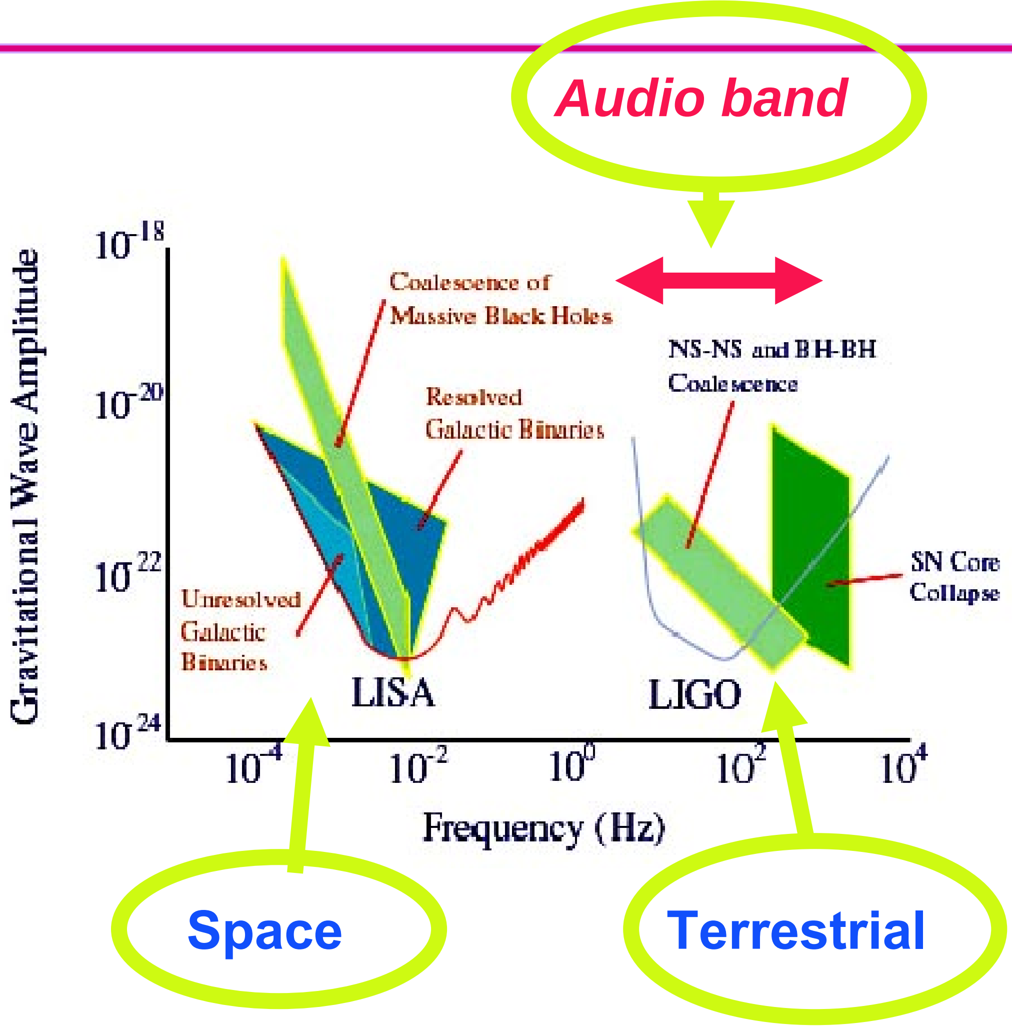


Electromagnetic waves

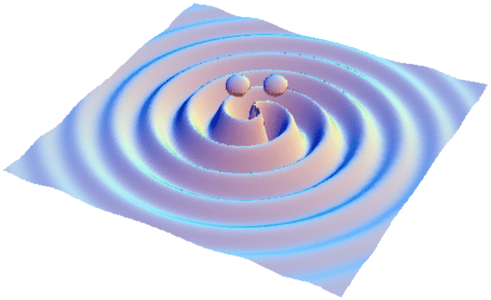
- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

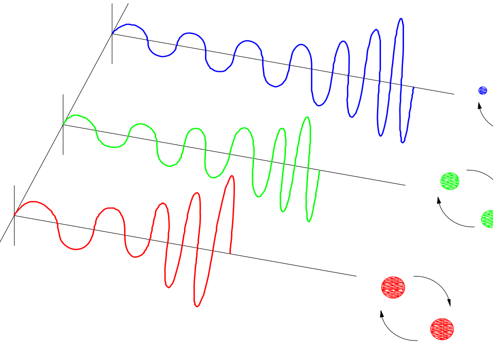
Gravitational waves

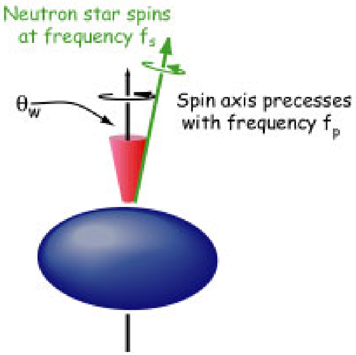
- over ~8 orders of magnitude
- Terrestrial + space detectors

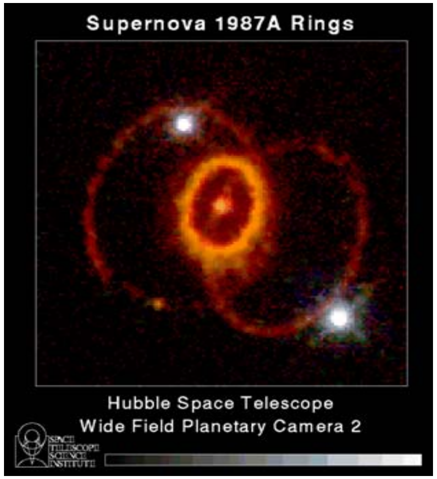


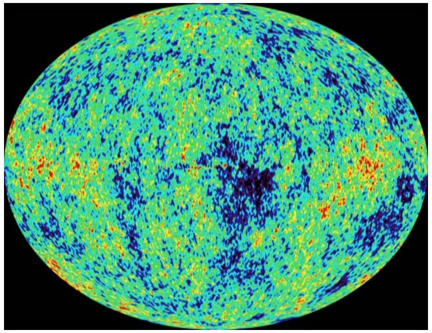
What will we see?











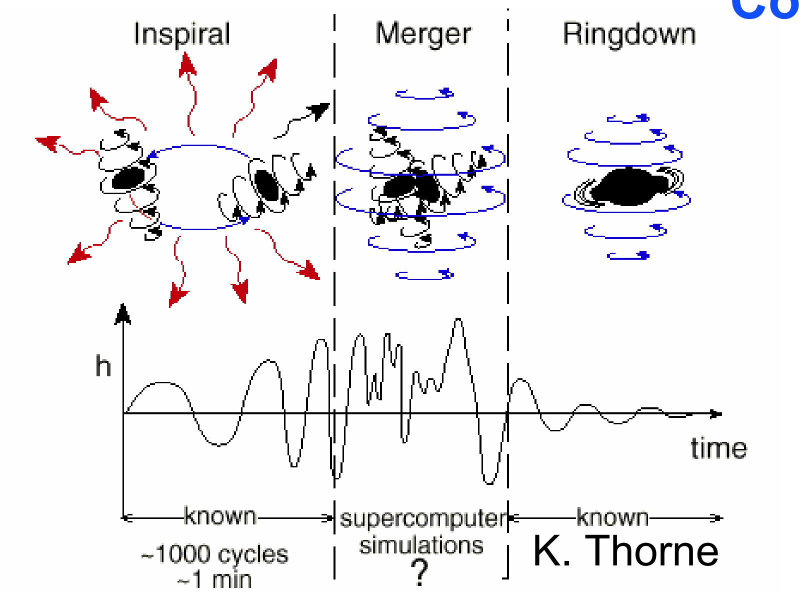
Analog from cosmic microwave background -- WMAP 2003

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

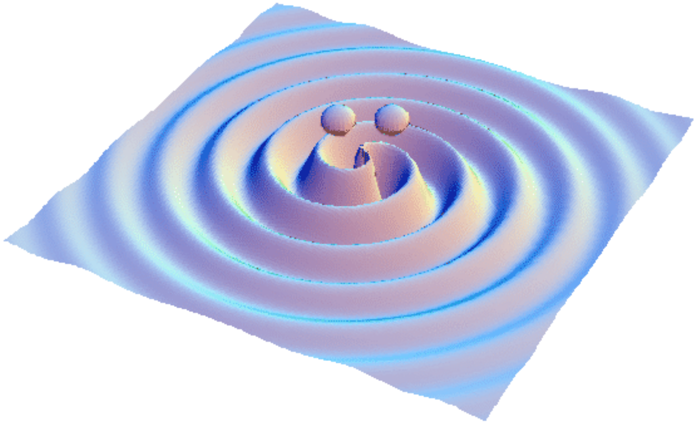
A NEW WINDOW ON THE UNIVERSE WILL OPEN UP FOR EXPLORATION. BE THERE!

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

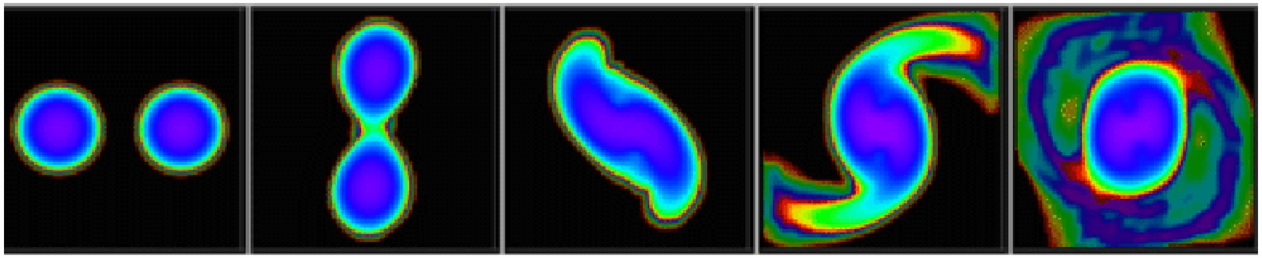


K. Thorne

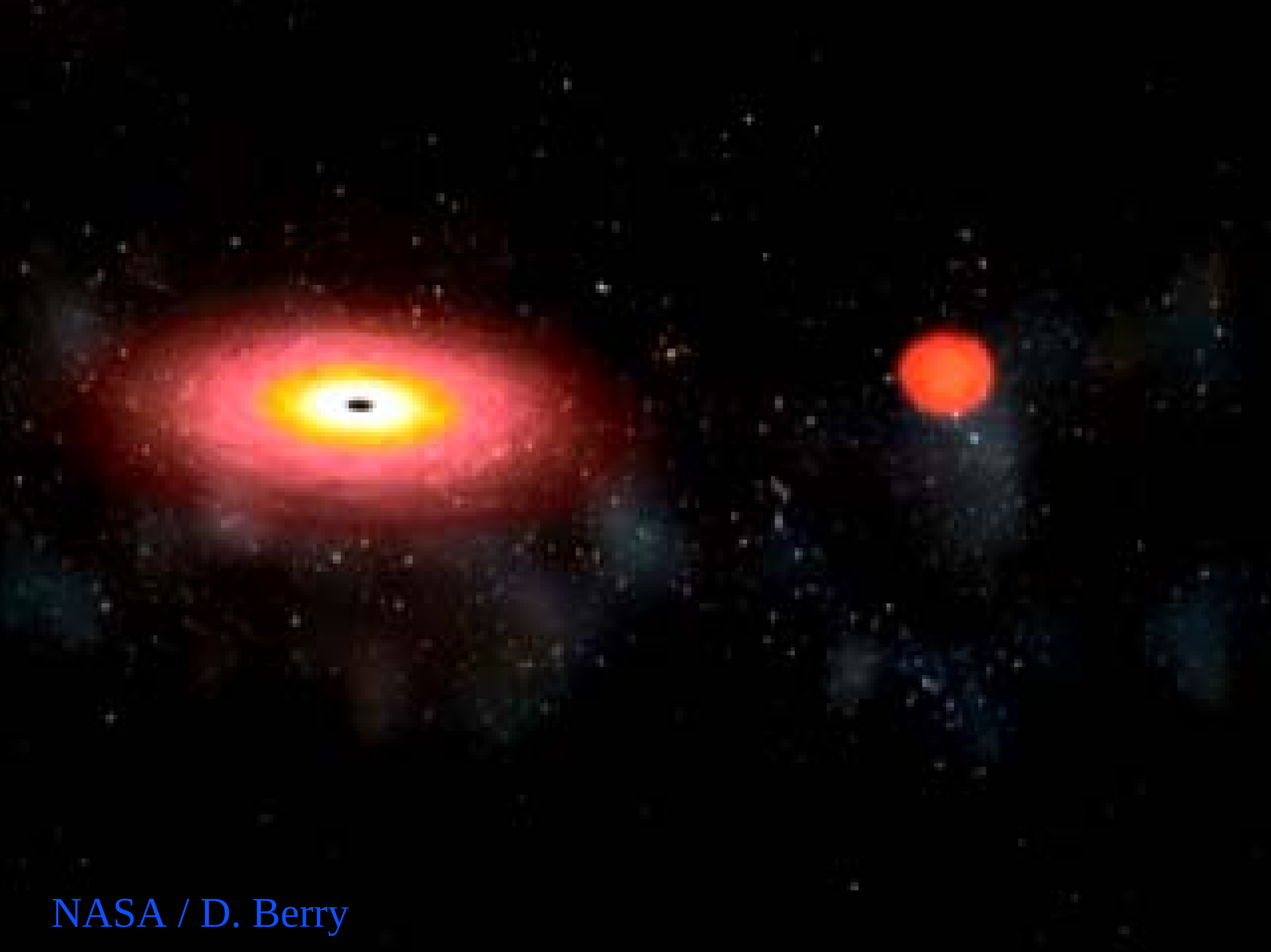
Compact binary mergers



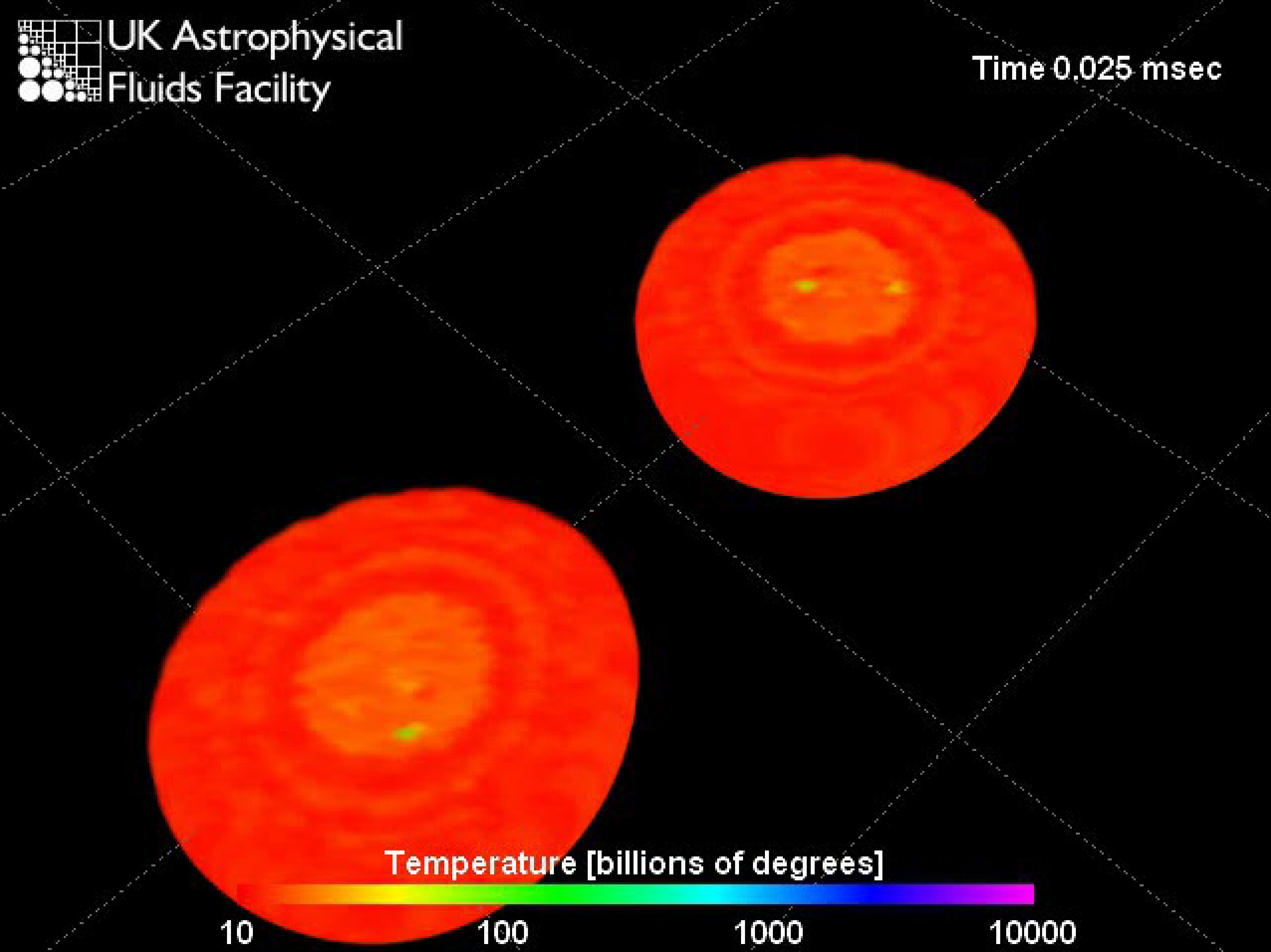
- Neutron star – neutron star (Centrella et al.)



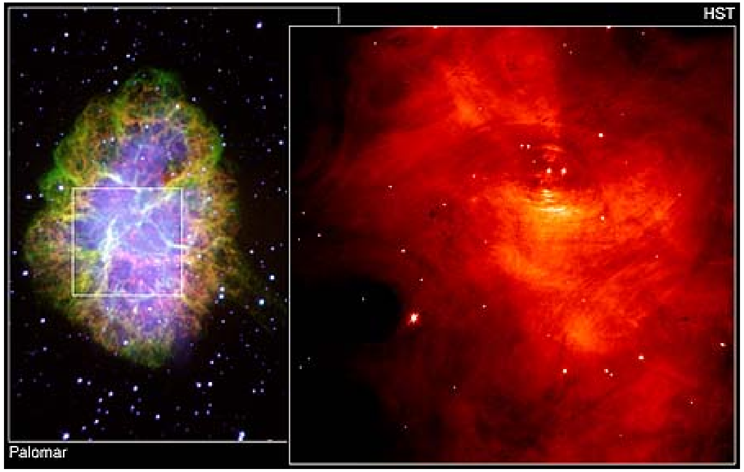
NASA / D. Berry



NASA / D. Berry

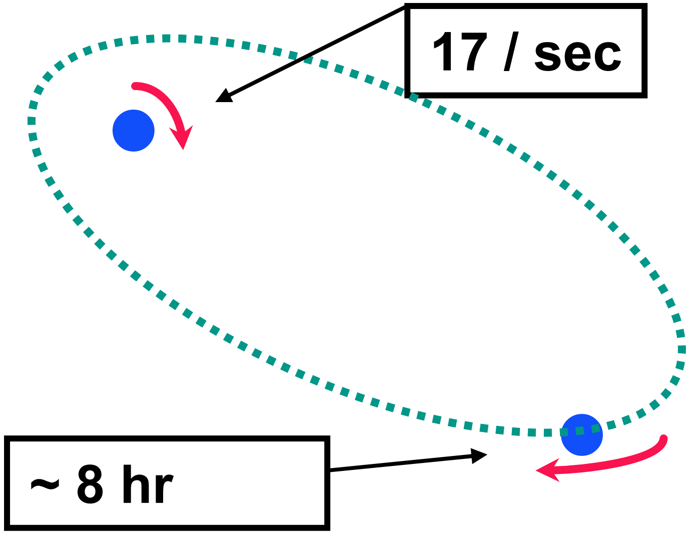

UK Astrophysical Fluids Facility
Time 0.025 msec
Temperature [billions of degrees]
10
100
1000
10000

Hulse-Taylor binary pulsar



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars



17 / sec

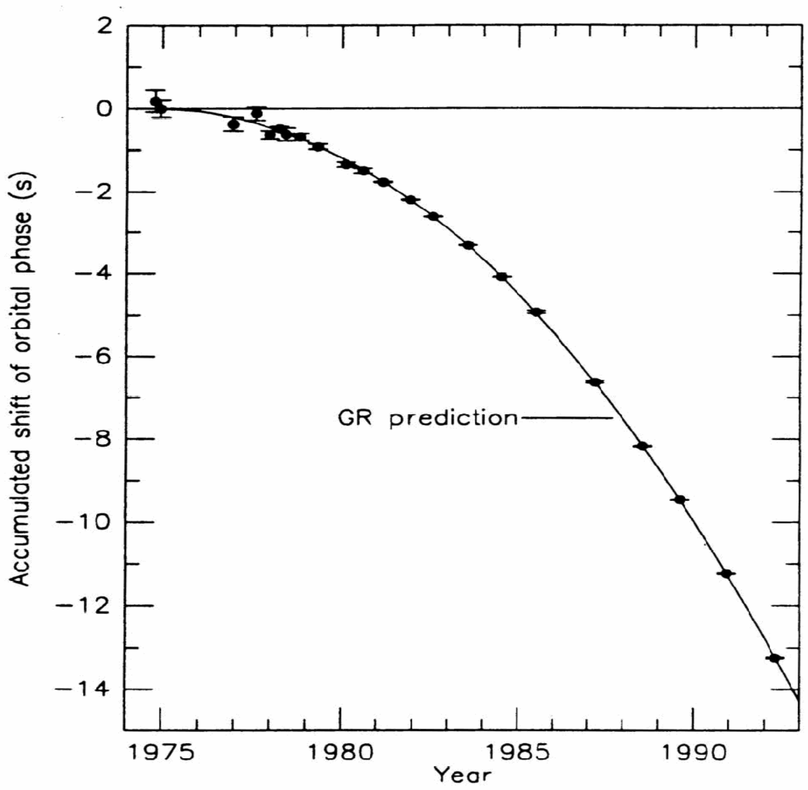
~ 8 hr

- **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!**

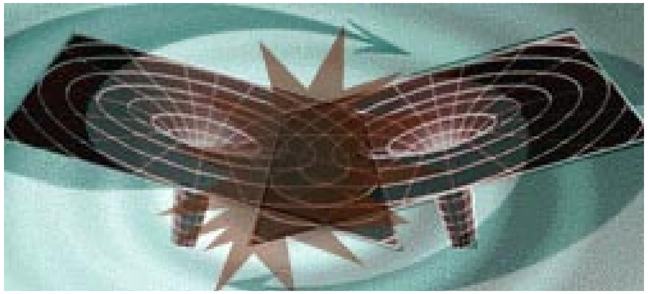
GWs from Hulse-Taylor binary

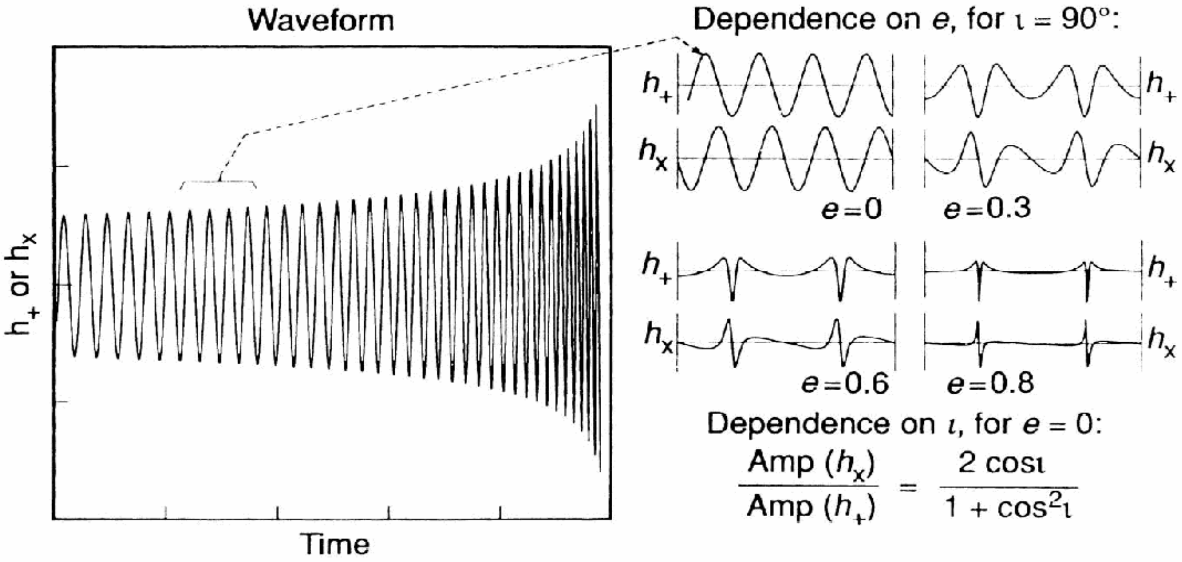
emission of gravitational waves by compact binary system

- 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





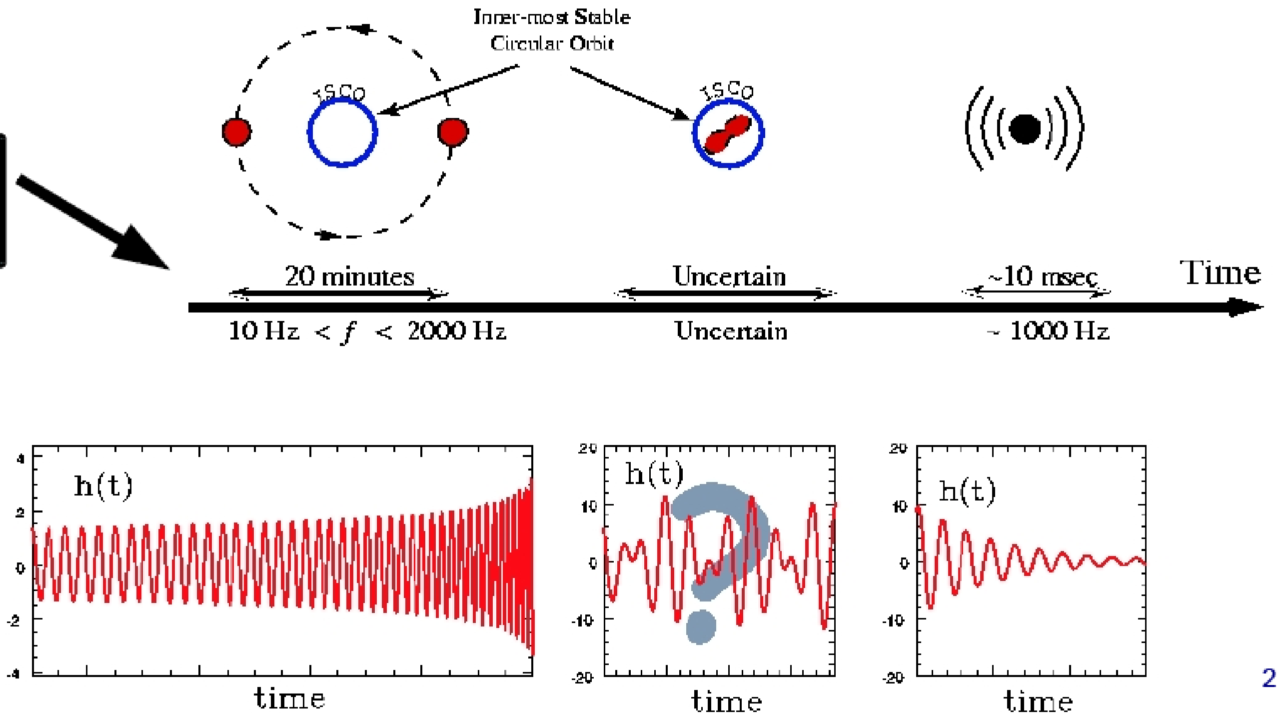
determine

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

Gravitational waves from compact binary inspiral/merger/ringdown

- LIGO is sensitive to gravitational waves from binary systems with neutron stars & black holes
  - Waveforms depend on masses, spins, eccentricity, gravitational theory, tidal coupling, magnetic fields, resonances ....

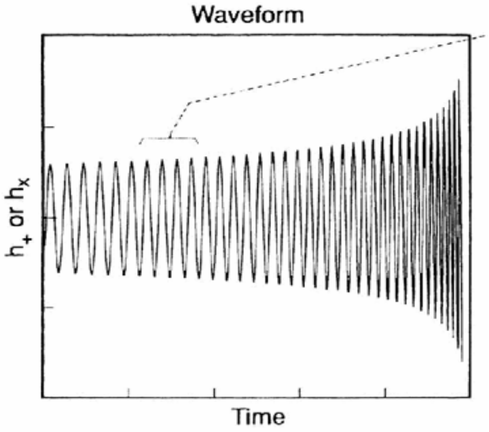
Few solar mass compact objects



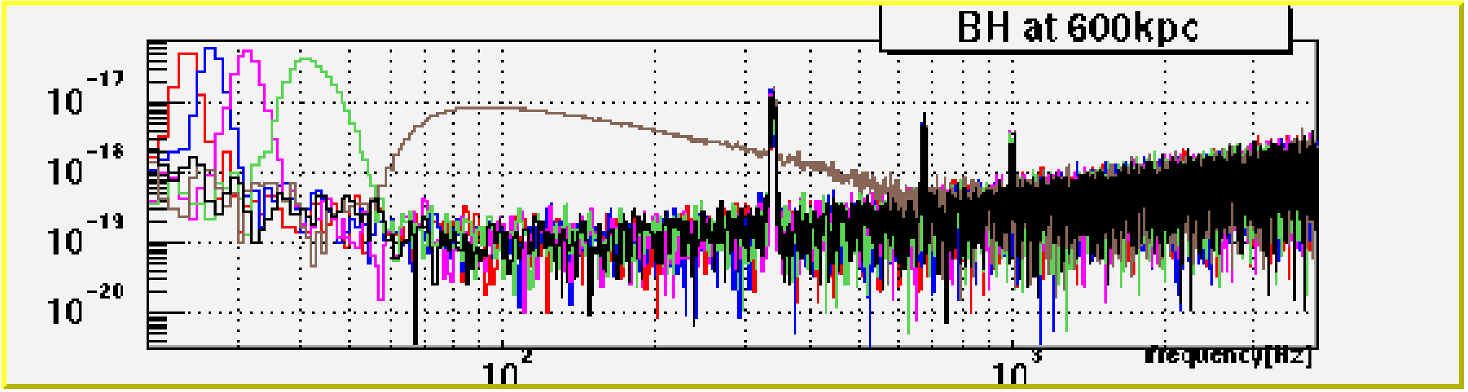
P. Brady

The sound of a chirp

BH-BH collision, no noise

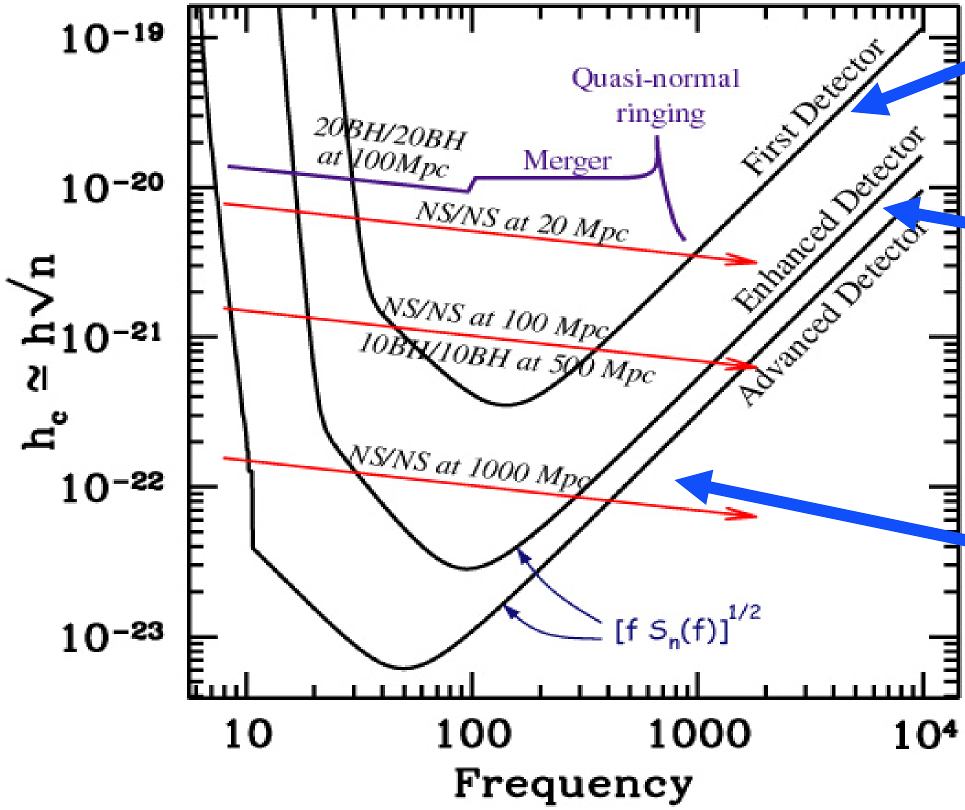


The sound of a BH-BH collision,
Fourier transformed over 5 one-second intervals
(red, blue, magenta, green, purple)
along with expected IFO noise (black)



Astrophysical sources: Thorne diagrams

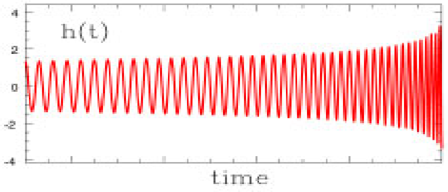
Sensitivity of LIGO to coalescing binaries



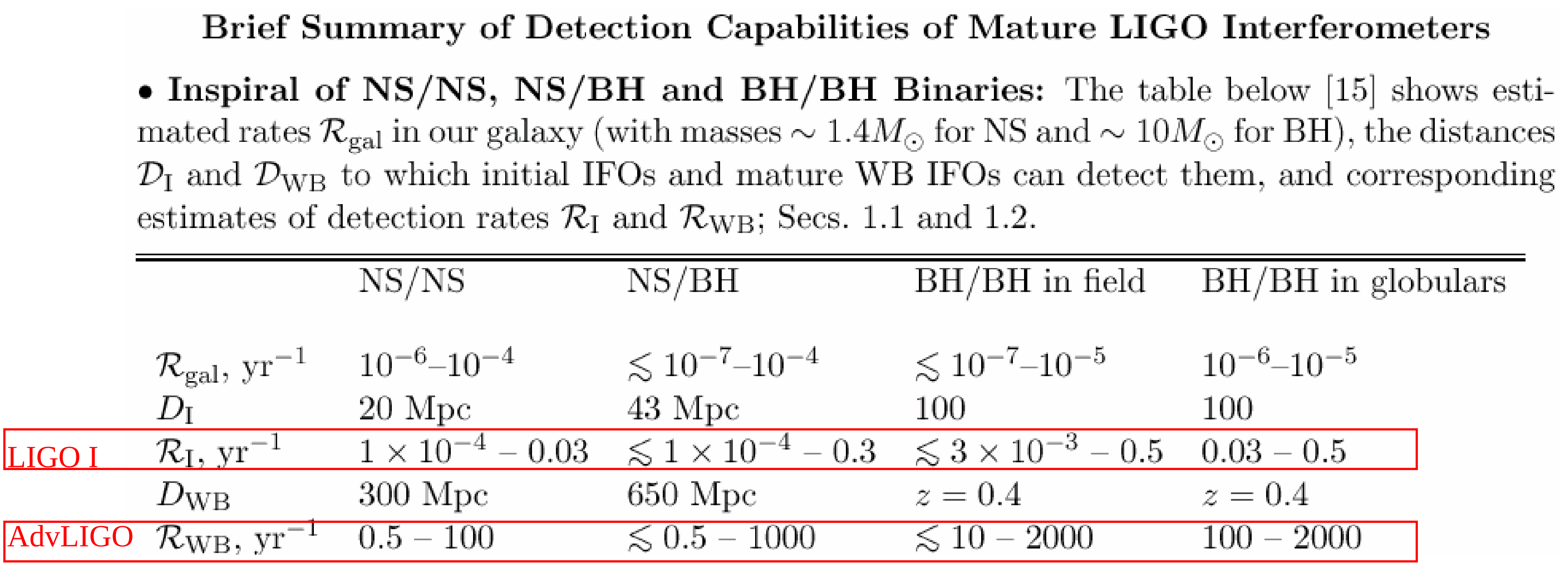
LIGO I (2002-2005)

LIGO II (2007-)

Advanced LIGO



Estimated detection rates for compact binary inspiral events



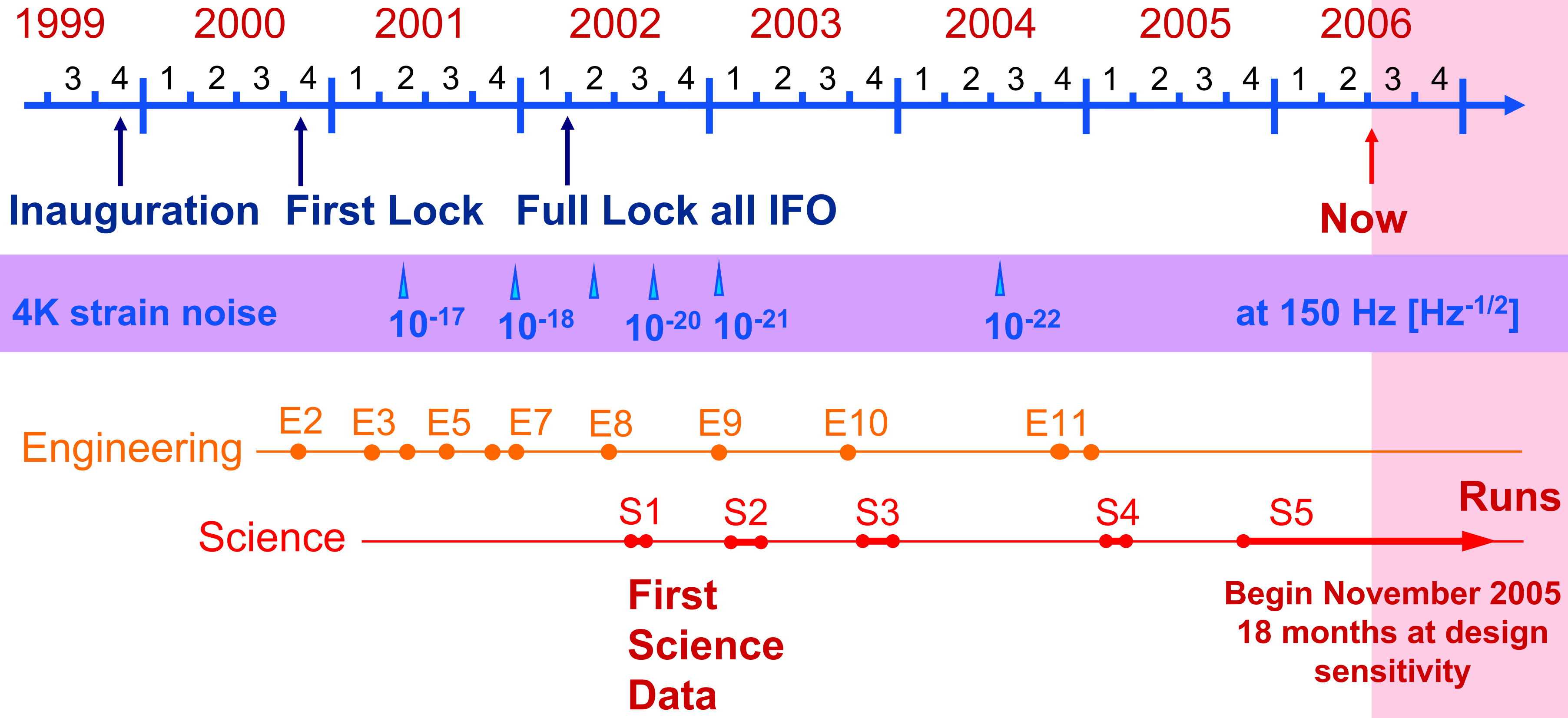
Brief Summary of Detection Capabilities of Mature LIGO Interferometers

- **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 $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ 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}
	$\mathcal{D}_{\rm I}$	20 Mpc	43 Mpc	100	100
LIGO I	$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
	$\mathcal{D}_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
AdvLIGO	$\mathcal{R}_{\rm WB}$, yr^{-1}	$0.5 - 100$	$\lesssim 0.5 - 1000$	$\lesssim 10 - 2000$	$100 - 2000$

V. Kalogera (population synthesis)

LIGO Science Runs - Time Line



1999 2000 2001 2002 2003 2004 2005 2006

Inauguration **First Lock** **Full Lock all IFO**

Now

4K strain noise **10^{-17}** **10^{-18}** **10^{-20}** **10^{-21}** **10^{-22}** **at 150 Hz [$\mathrm{Hz}^{-1/2}$]**

Engineering E2 E3 E5 E7 E8 E9 E10 E11

Science S1 S2 S3 S4 S5

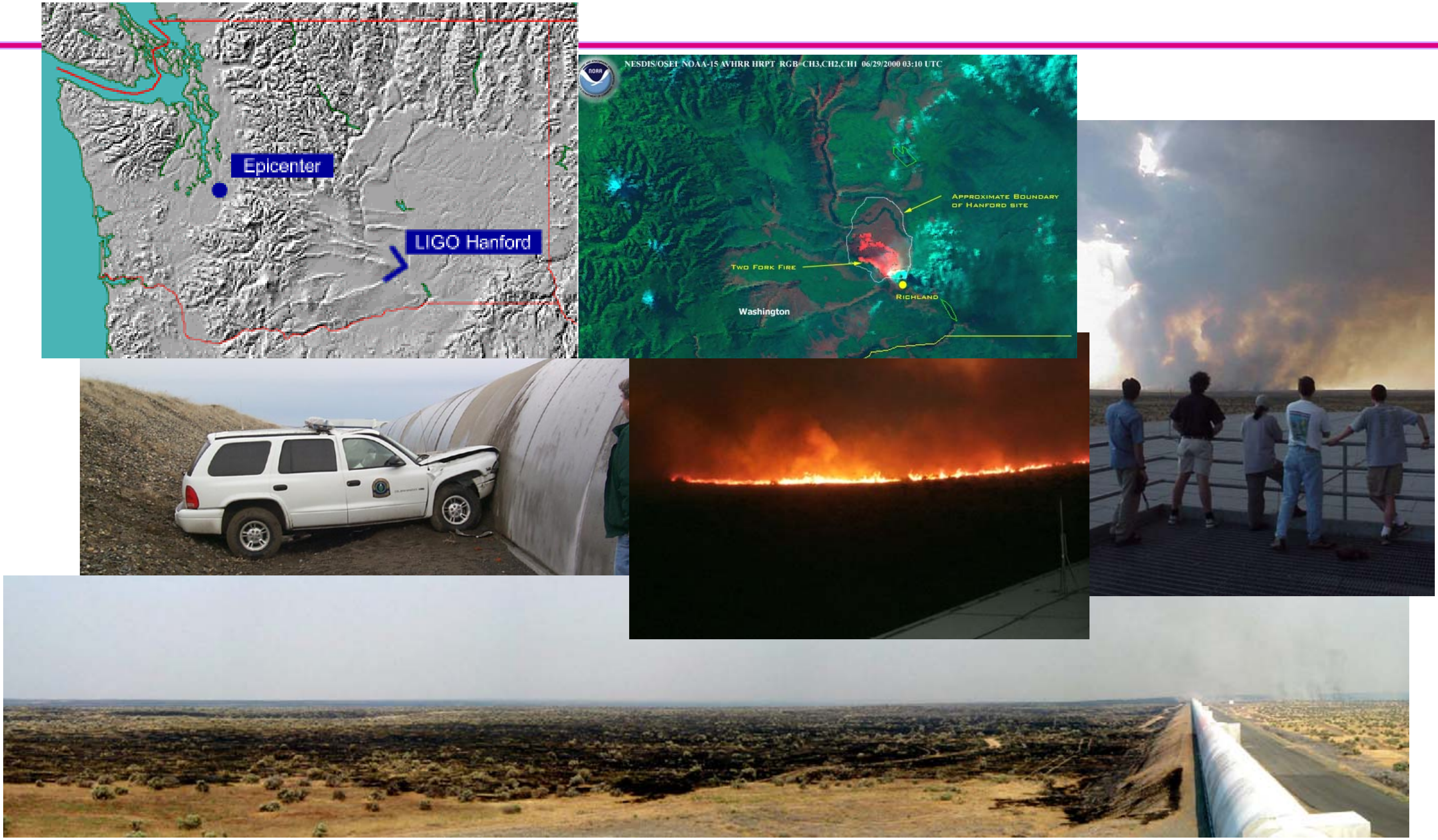
Runs

First Science Data

Begin November 2005
18 months at design sensitivity

AJW, LIGO SURF, 6/16/06

Despite a few difficulties, science runs started in 2002.

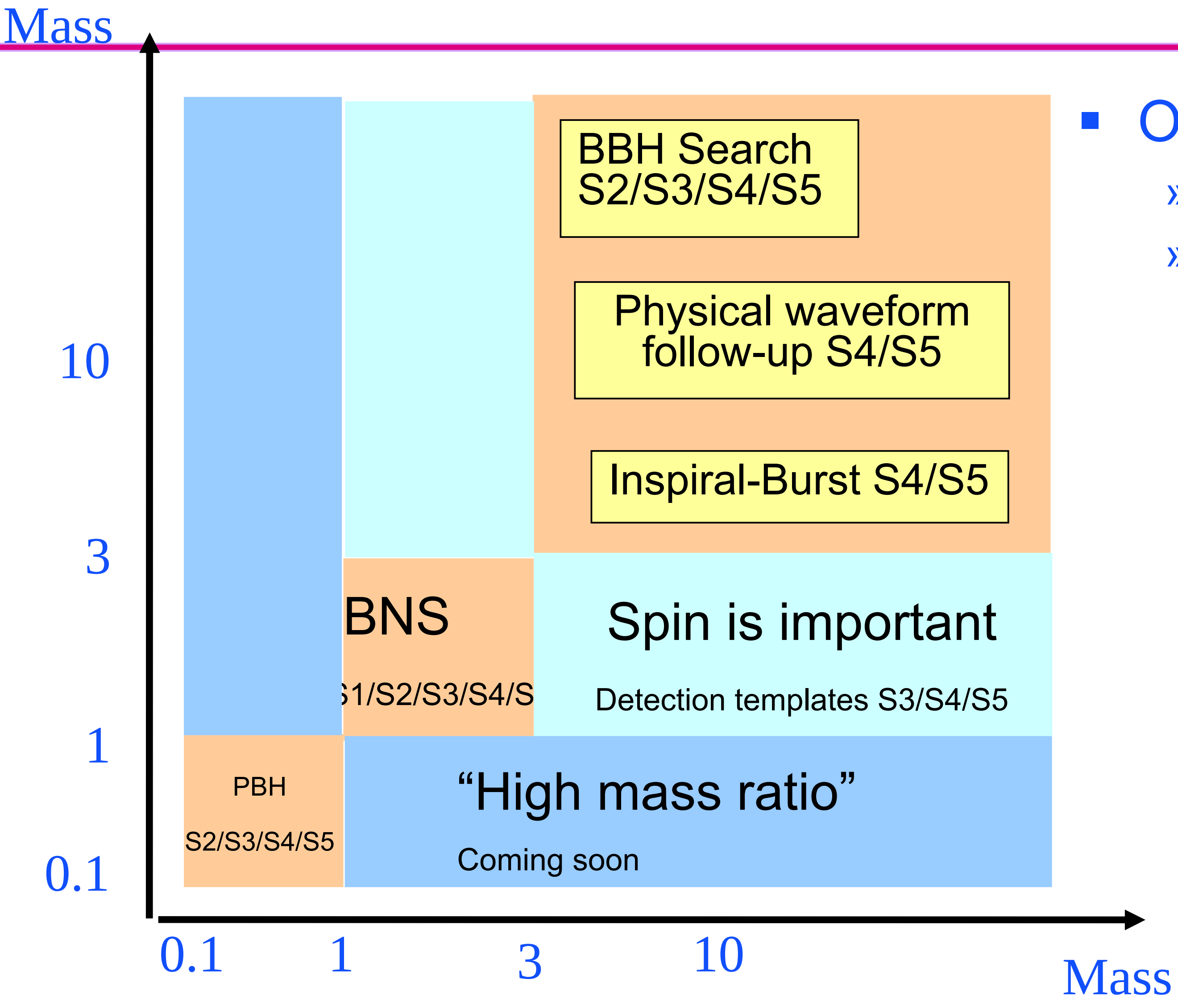


LIGO is plagued with plagues

- man-made
- natural
- biblical!

LIGO Hanford, 6/05:
grasshoppers overrun the site.

Binary Mass Plane



BBH Search
S2/S3/S4/S5

Physical waveform
follow-up S4/S5

Inspiral-Burst S4/S5

BNS

S1/S2/S3/S4/S

Spin is important

Detection templates S3/S4/S5

PBH

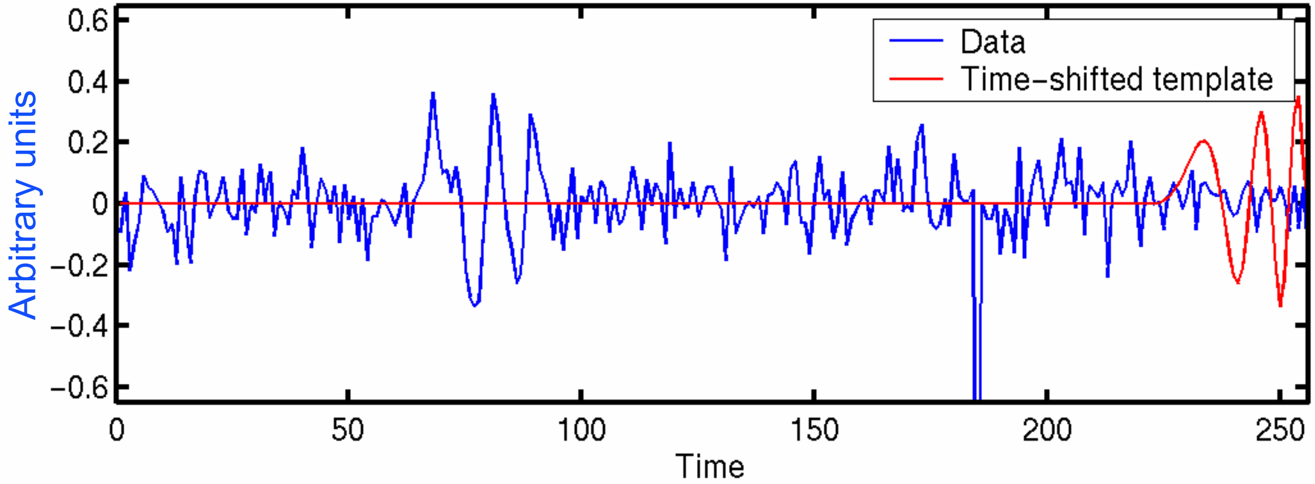
S2/S3/S4/S5

“High mass ratio”

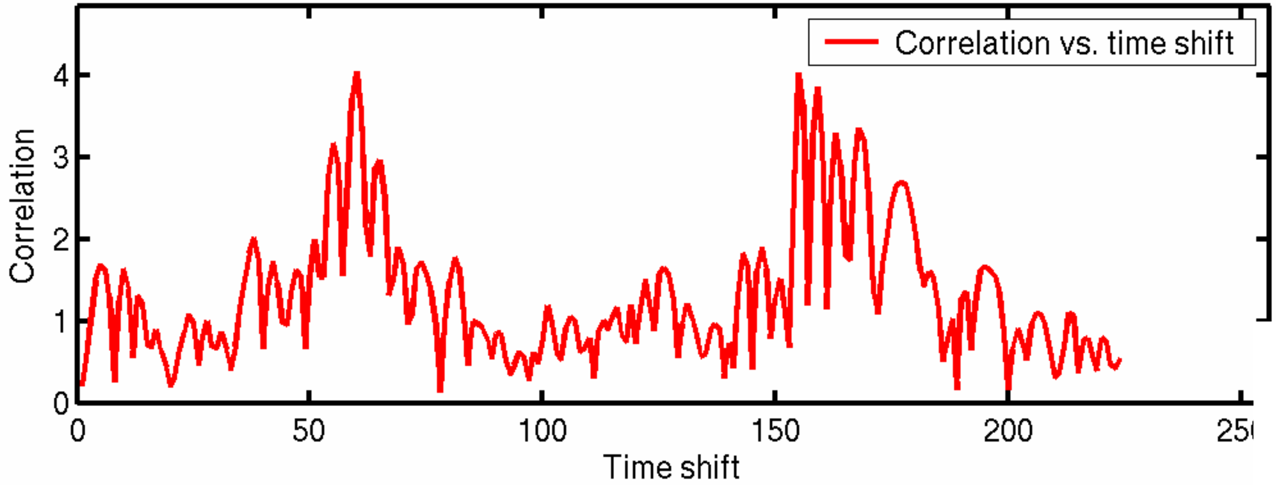
Coming soon

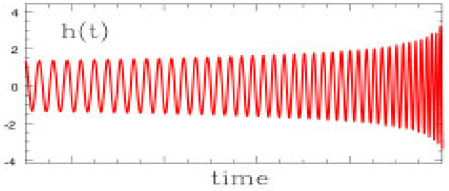
- Other activities
  - LIGO-VIRGO analysis
  - GRB trigger follow-up

Illustration of Matched Filtering

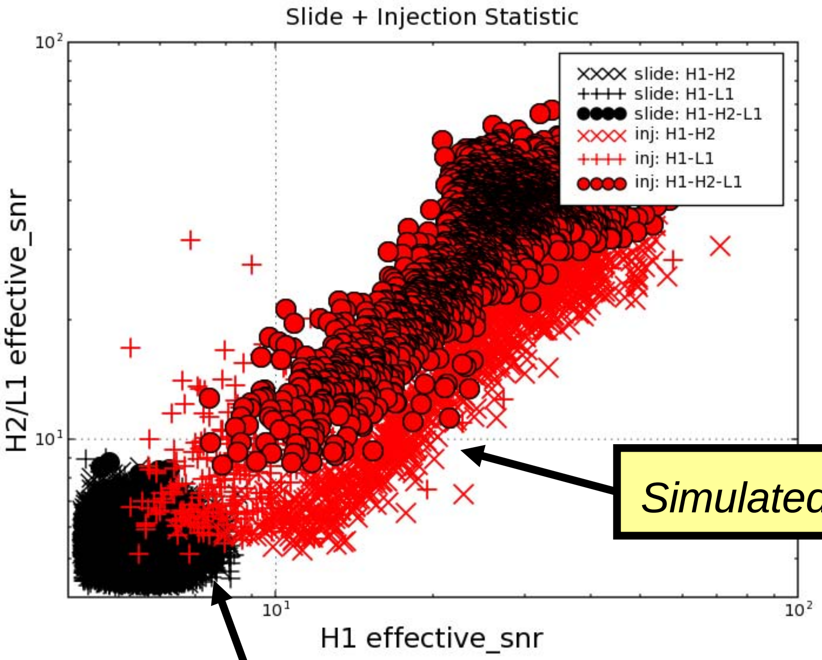


- Bank of 2110 post^2 –Newtonian stationary-phase templates for $1 < m_1 \leq m_2 < 3\ M_\odot$ with 3% maximum mismatch





Coincident detection



Simulated signals

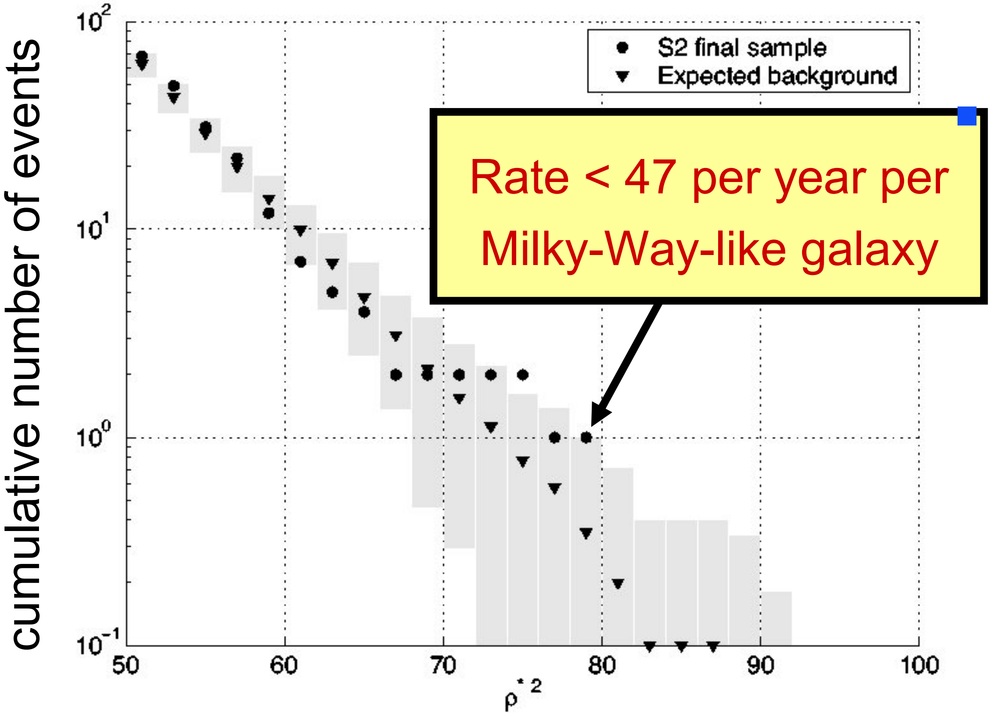
Estimate background accidentals in time-slides

- Estimate fake rate using "time slides"
- Suppress noise (fake triggers) using environmental and instrumental vetoes
- Estimate efficiency for detection using injections
  - » Follow-ups on loudest triggers at end of each search as "fire drill"
  - » Evaluate efficiency versus distance to source, mass of source binary
  - » Assume some astrophysical population of sources, eg, binary neutron stars in Milky-Way-like galaxies
  - » Evaluate number of milky-way-like galaxies to which we are sensitive
- If no signal is seen, quote upper limit on number of inspirals per year per MWEG

Binary Neutron Stars

S2 Observational Result

Phys. Rev. D. 72, 082001 (2005)



Rate < 47 per year per Milky-Way-like galaxy

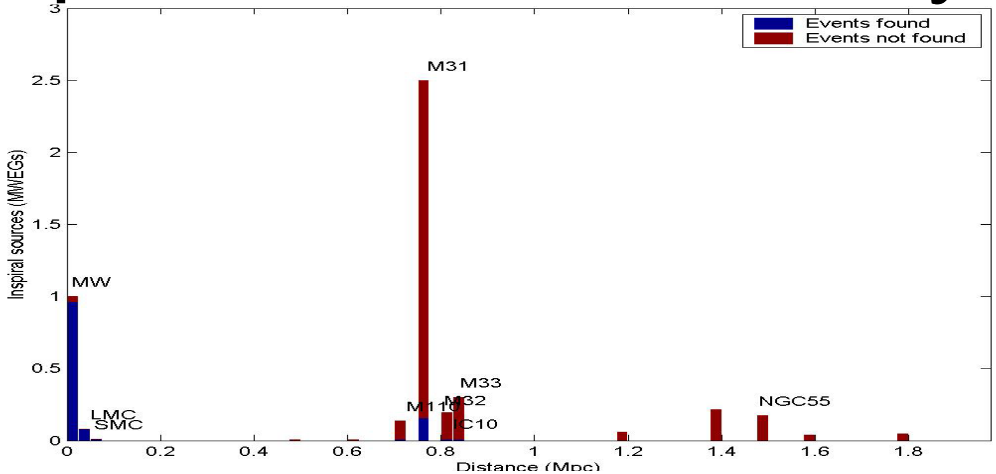
signal-to-noise ratio squared

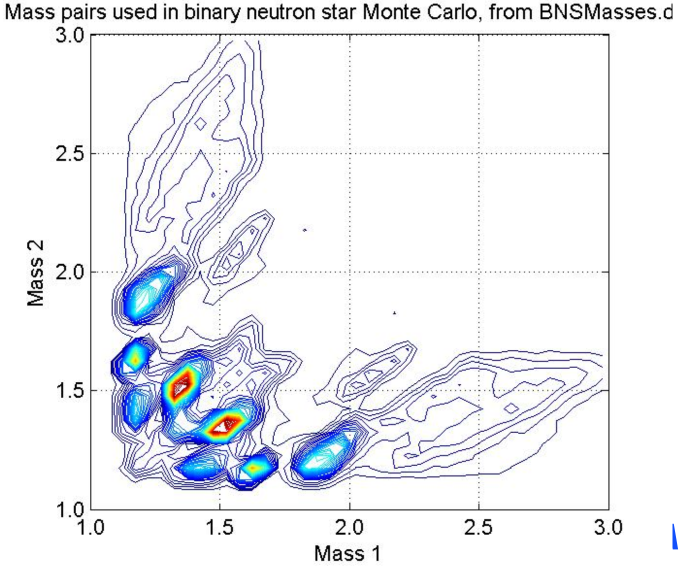
- S3 search complete
  - » Under internal review
  - » XX yr of data
  - » YY Milky-Way like galaxies
- S4 search complete
  - » Under internal review
  - » XX yr of data
  - » YY Milky-Way like galaxies

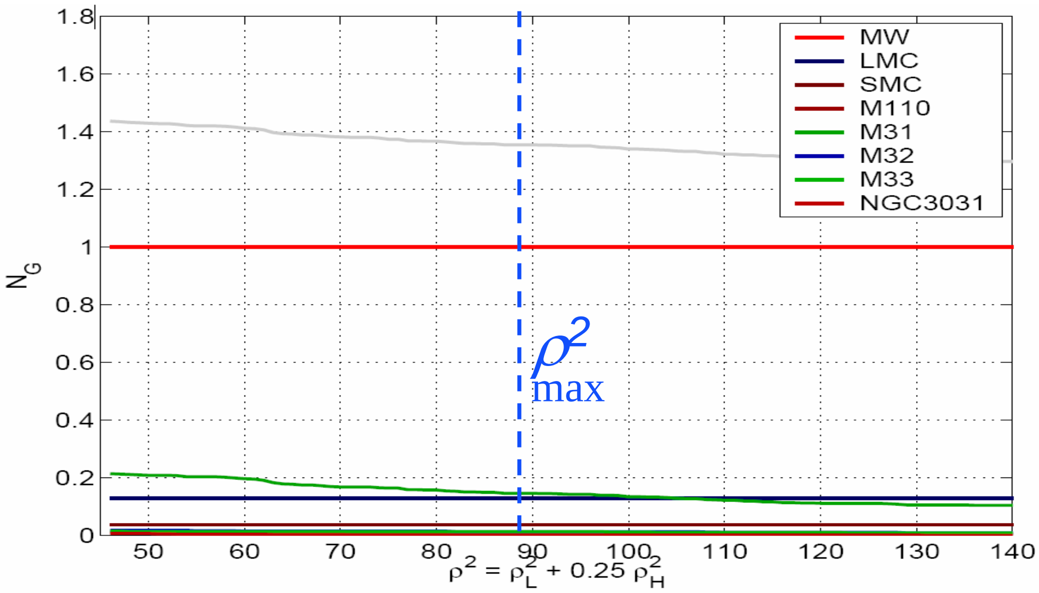
S2 BNS inspiral search efficiency

From detailed simulations:

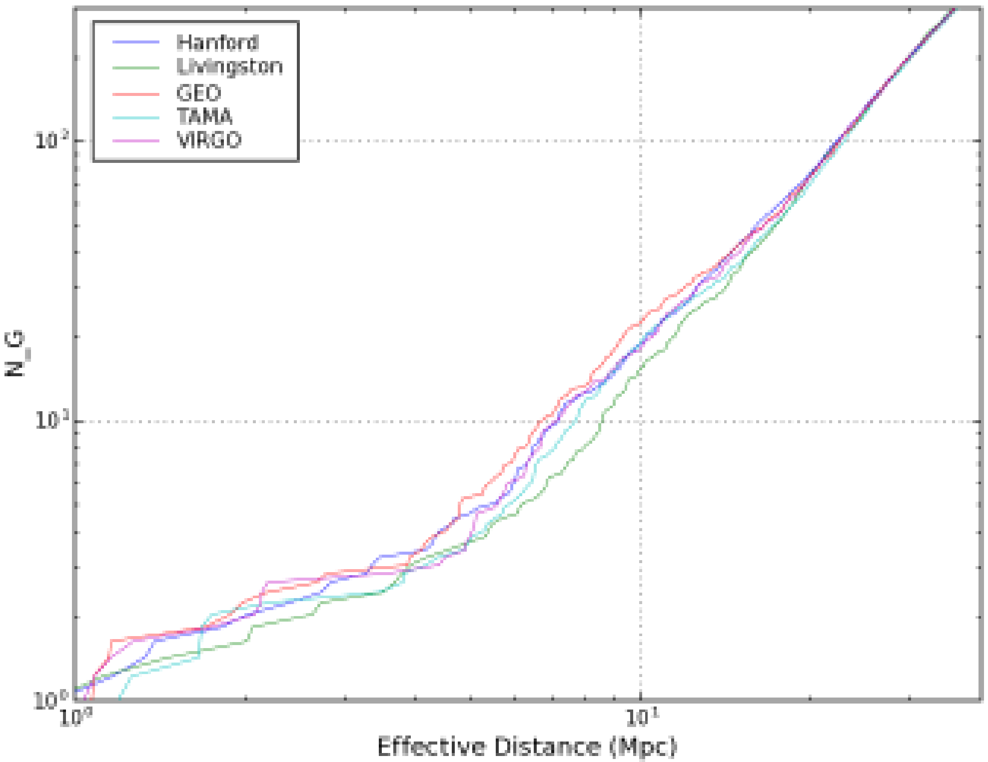
- waveform injection into S2 data
- Galactic and extra-galactic source distribution
- m_1/m_2 distribution (pop synth)
- antenna pattern response
- full search pipeline







Number of galaxies to which we are sensitive

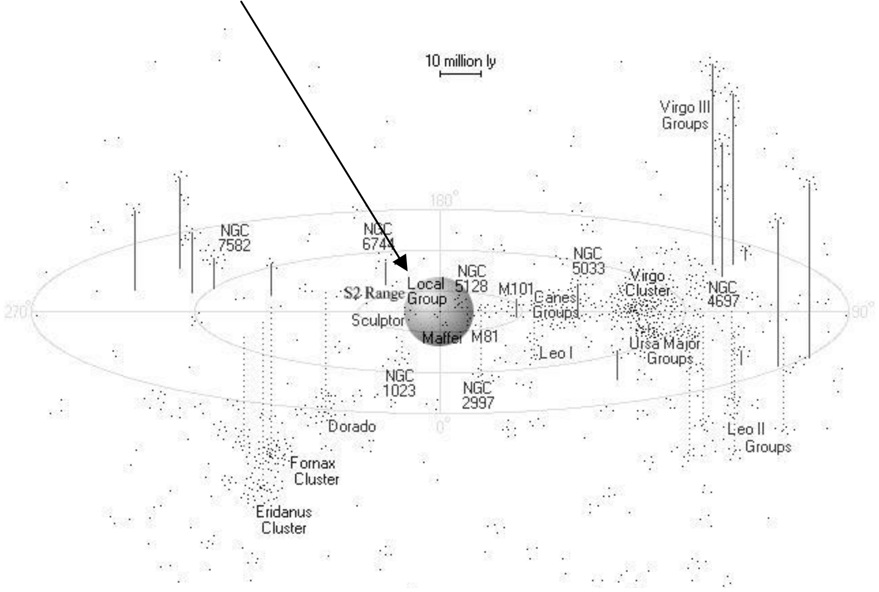


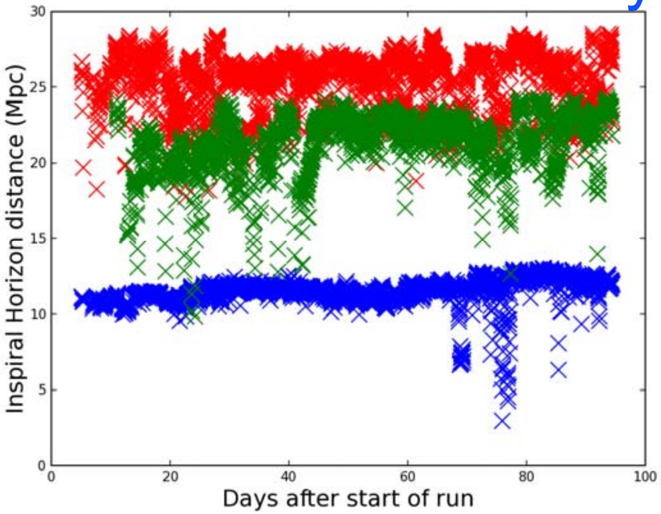
- Things get astrophysically interesting when we are sensitive to 100's of MWEG's (S5) or 10,000's (AdvLIGO) – for binary neutron stars (BNS)
- For binary black holes (BBH) and black hole ringdowns, we can see much further out – depends on mass of BH, and astrophysics can't yet tell us the expected mass distribution (we will tell them!).
- Beyond S5, number of galaxies start to go like d^3

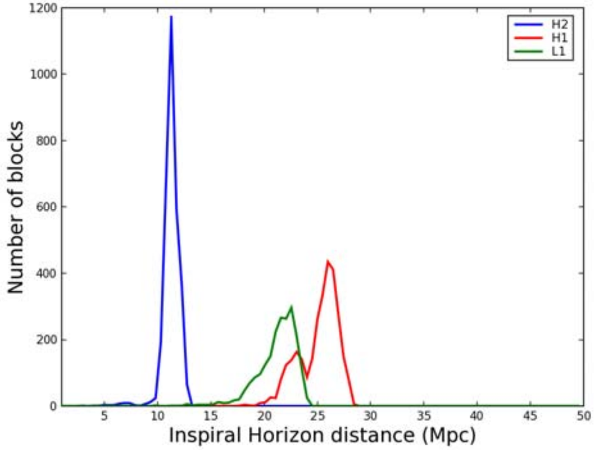
Binary Neutron Stars
S5 Search Reach

First 3 months has been analyzed

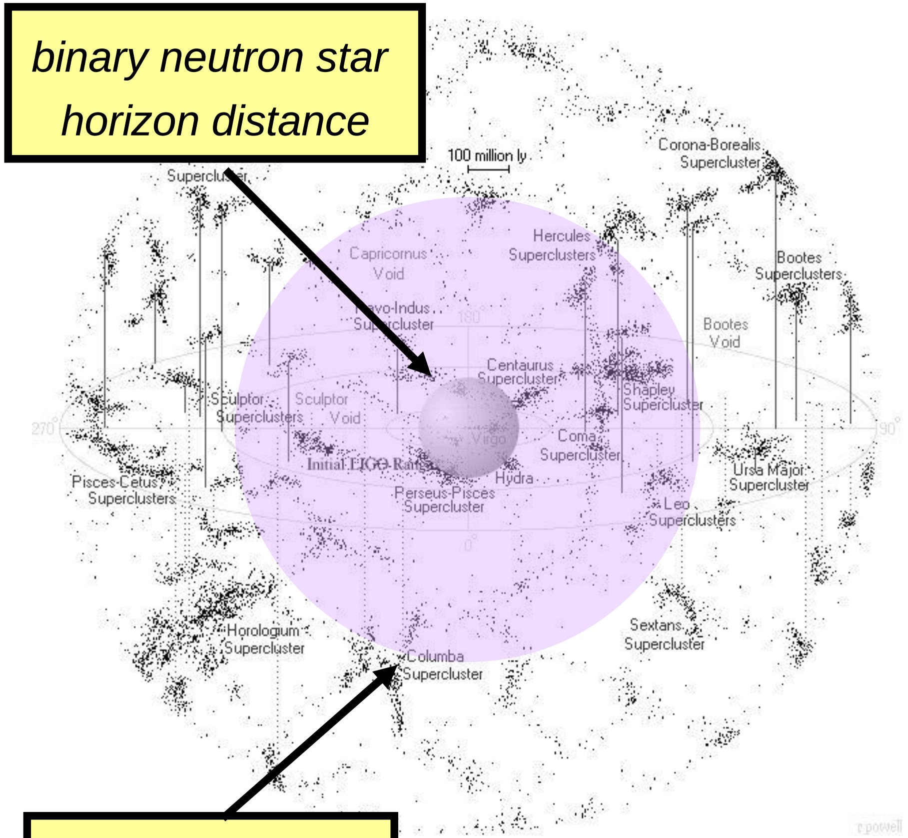
S2 Range







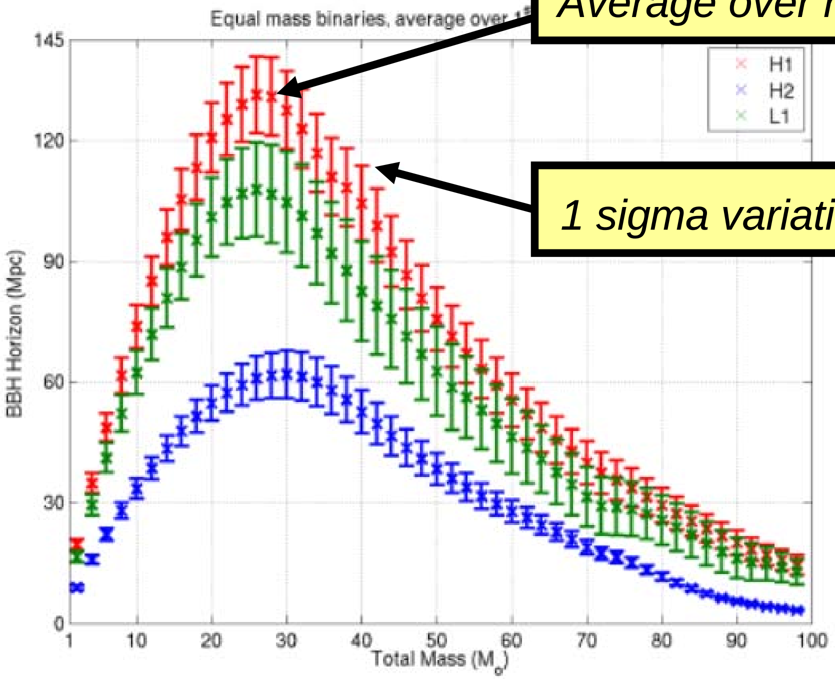
Binary Black Holes
S5 Search



binary neutron star horizon distance

binary black hole horizon distance

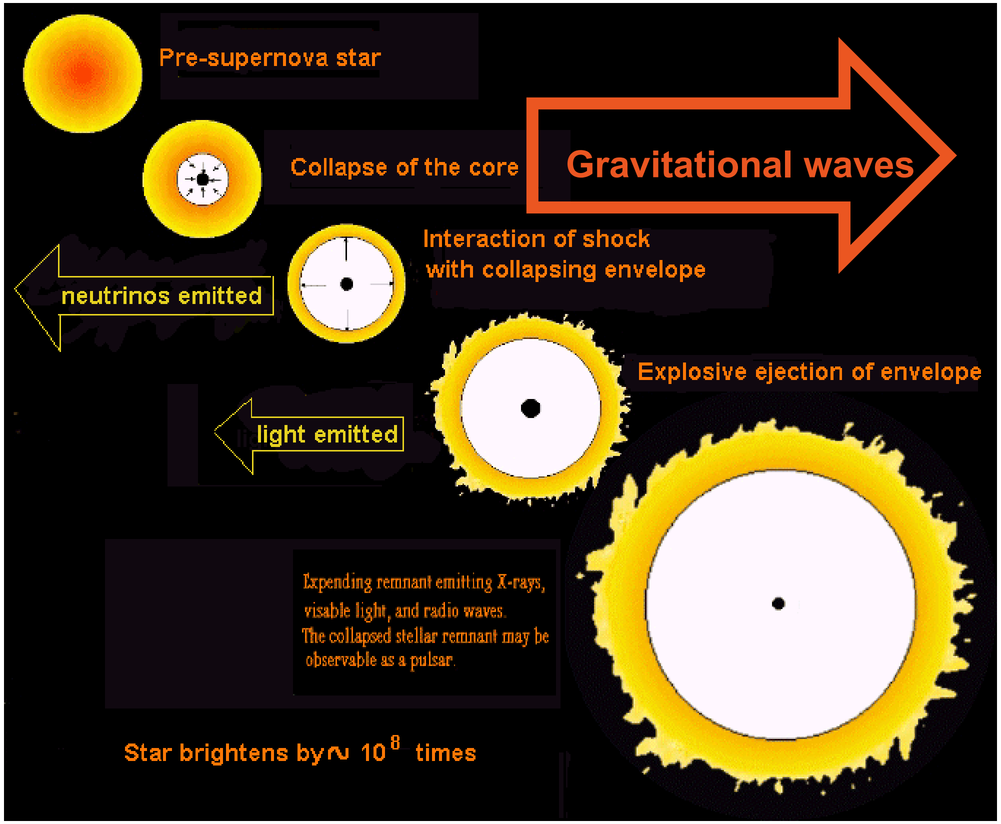
- 3 months analyzed
- Horizon distance (detector sensitivity) versus mass



Average over run

1 sigma variation

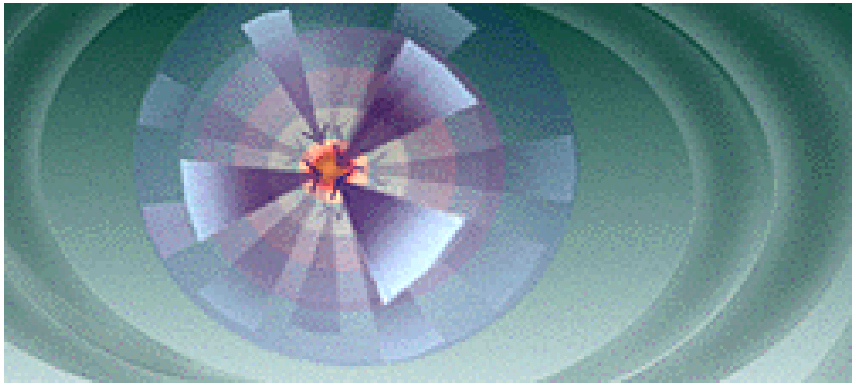
Supernova collapse sequence



- 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

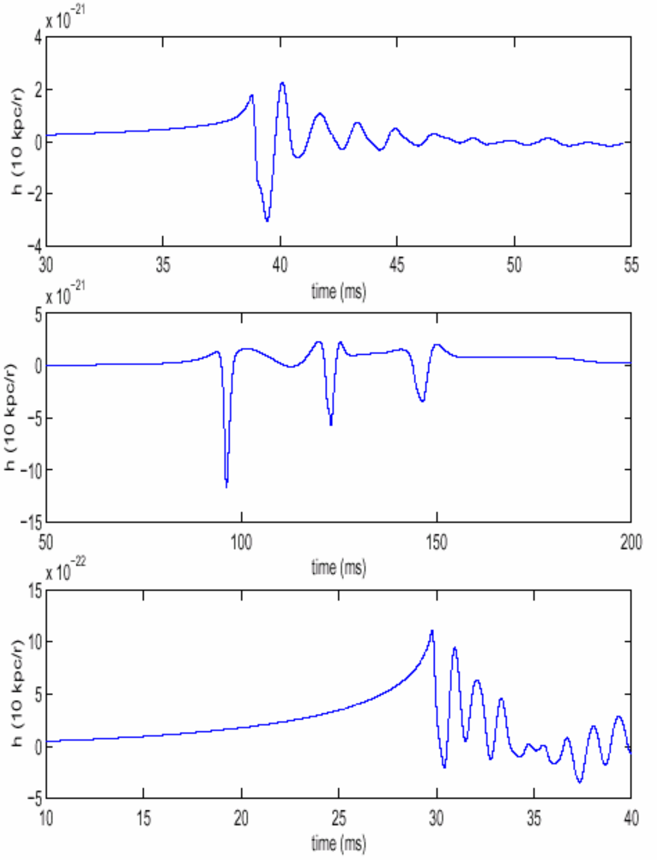
Non axisymmetric core collapse (Type II supernovae)



Rate

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

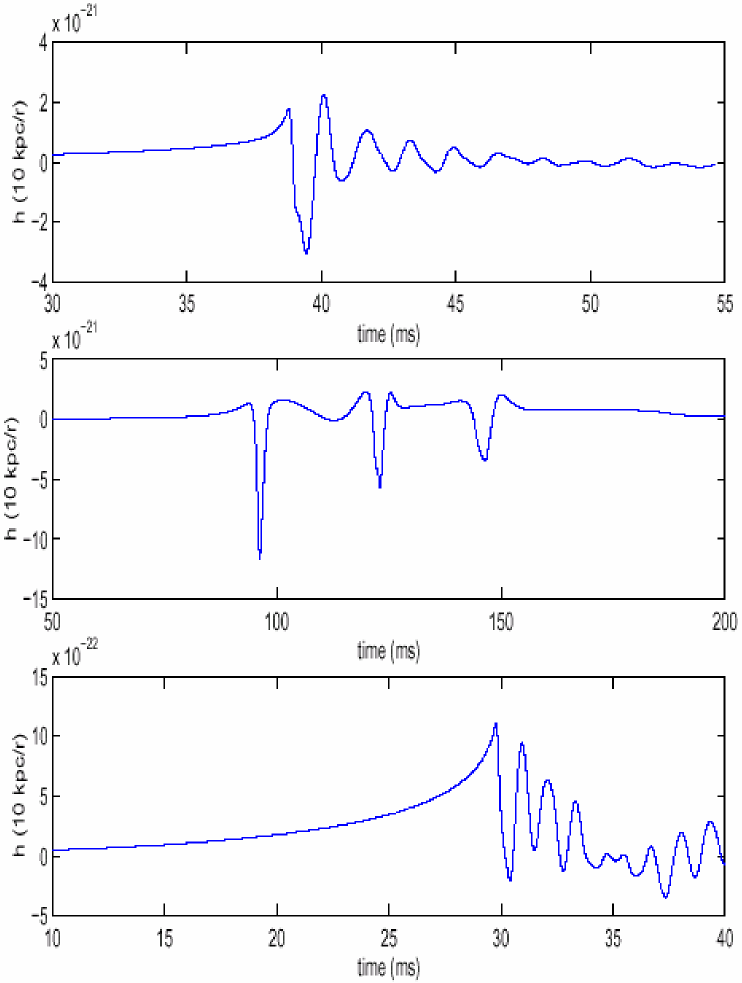
‘burst’ waveforms

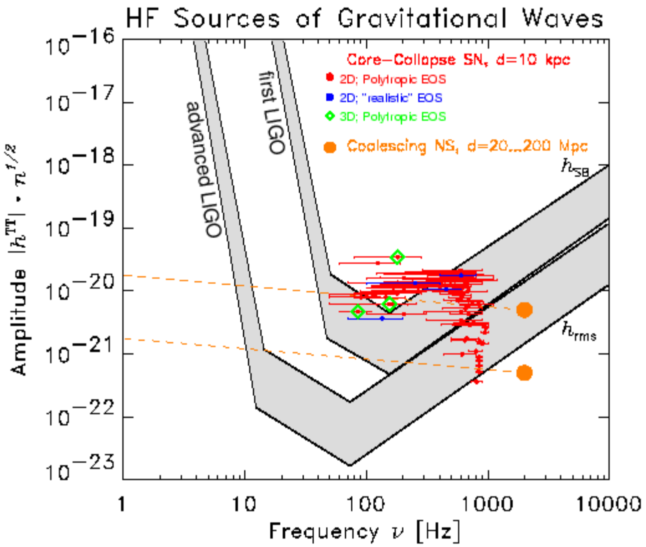


Zwerger & Muller, 1997 & 2003
simulations of axi-symmetric SN core collapse

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.





Burst Search Techniques

Two main types of burst searches:

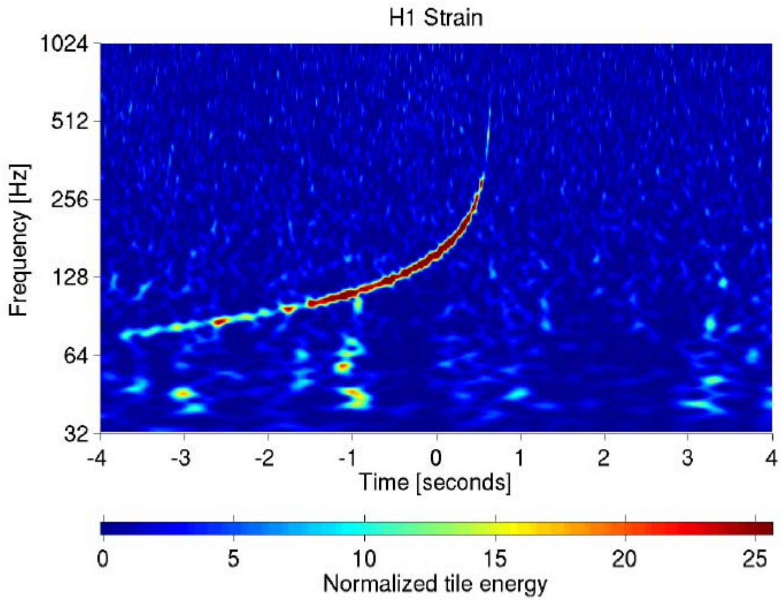
- Untriggered: Scan ~all data, looking for excess power indicative of a transient signal.
  - Robust way to detect generic waveforms.
- Triggered: Scan small amount of data around time of astronomical event (e.g., GRB), by cross-correlating data from pairs of detectors.
  - Exploits knowledge of time of and direction to astronomical event.

Always: Use techniques that make minimal assumptions about the signal. Be open to the unexpected!

Excess-Power Detection

- Look for transient jump in power in some time-frequency region:
  - frequency ~ [60,2000] Hz (determined by noise curves of instruments)
  - duration ~ [1,100] ms (time scale associated with solar-mass COs)
  - Anderson et al. PRD **63** 042003 (2001).
- Many different implementations in LIGO:
  - Fourier modes, wavelets, Gaussian-modulated sinusoids.
  - Multiple time-frequency resolutions.
  - Provide redundancy & robustness.
  - Also time-domain & optimal filter searches.

Simulated binary inspiral signal in S5 data

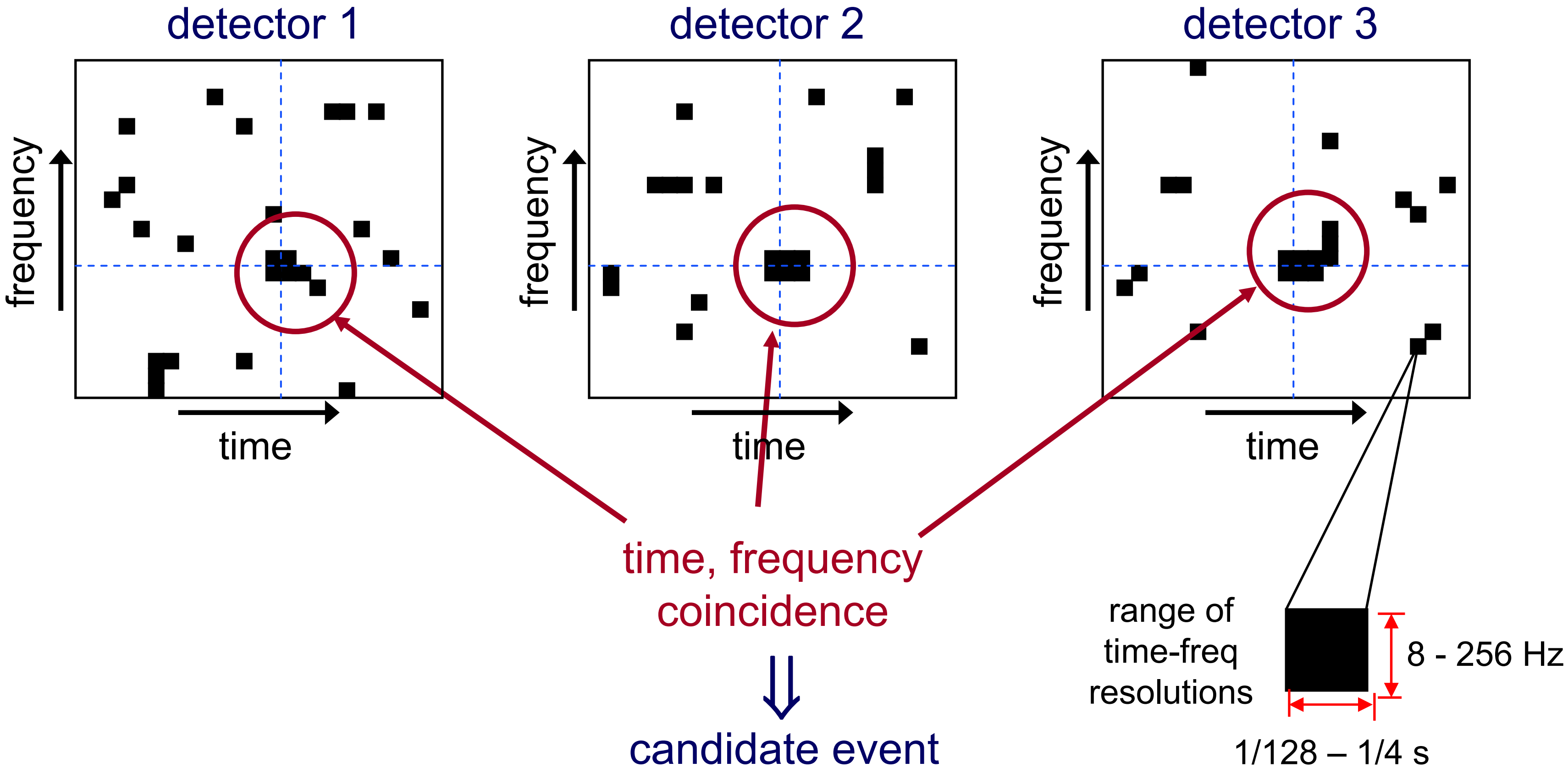


from Chatterji, session W11:

The Q Pipeline search for GWBs with LIGO

Schematic

Typically require coincident detection in all 3 LIGO interferometers:



time, frequency
coincidence

⇓

candidate event

Removing Spurious Events

- Waveform-independent detection algorithms also pick up noise “glitches”.
- Follow up with tests for consistency with GWs:
  - » time coincidence
  - » frequency overlap
  - » amplitude consistency (in the two Hanford detectors H1 & H2)
  - » require cross-correlation of data from pairs of detectors exceed threshold:

$$r_k = \frac{\sum_i (x_i-\bar{x})(y_{i+k}-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2}\sqrt{\sum_i (y_{i+k}-\bar{y})^2}}$$

Cadonati CQG *21* S1695 (2004)

- Also apply cuts on data quality, and “veto” candidate GWs occurring in coincidence with identifiable noise events.

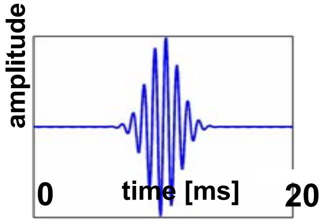
Tuning & Testing

- Tuning ground rules:
  - “Blind tuning” for statistical purity of upper limits.
  - Target low background rate from noise (<0.1 event / observation time).
- Test sensitivity of analysis by adding simulated signals to the data.
- Estimate background rate by repeating analysis with large (5+ sec) time shifts between detector sites.

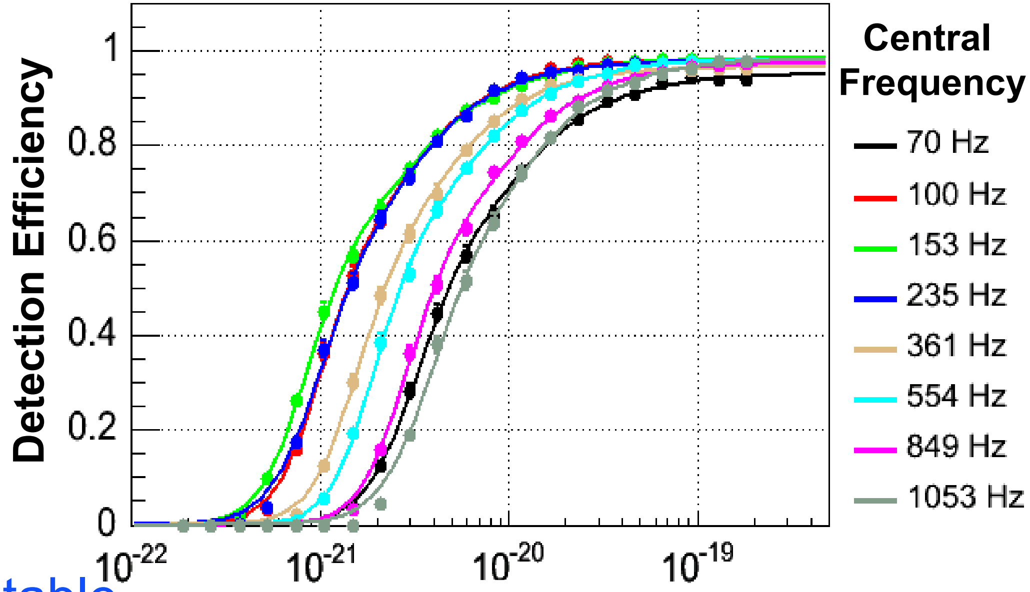
Detection Efficiency

Test sensitivity by adding simulated GWBs to the data.

- » Typical test waveform: Gaussian-modulated sinusoid.



Science Run 4 (Shawhan, Session W11)



$$h_{rss} = \sqrt{\int |h(t)|^2 \, dt}$$

Astrophysics - minimum detectable in-band energy in GWs (in S5):

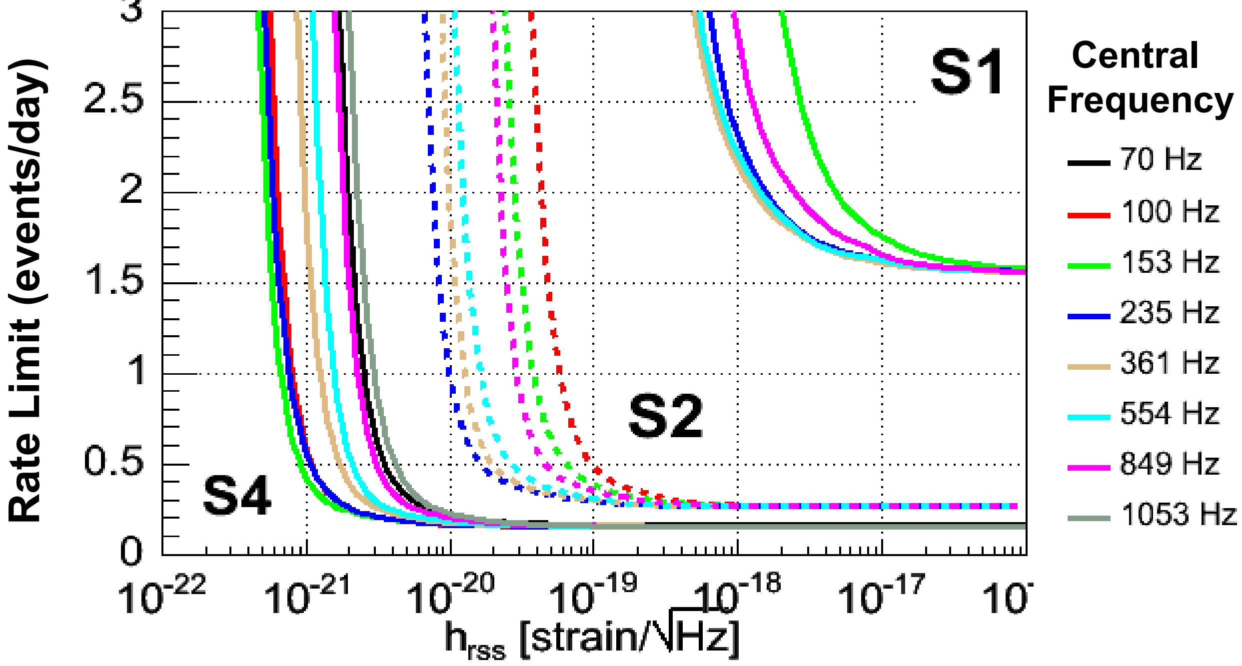
- » $E_{GW} >$ 1 M_o at r ~ 75 Mpc
- » $E_{GW} >$ 0.05 M_o at r ~ 15 Mpc (~ distance to Virgo cluster)

Progress in Upper Limits

No GWBs detected through S4. So, set limit on GWB rate vs. signal strength:

$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η = upper limit on event number
T = observation time
$\varepsilon(h_{rss})$ = efficiency vs strength



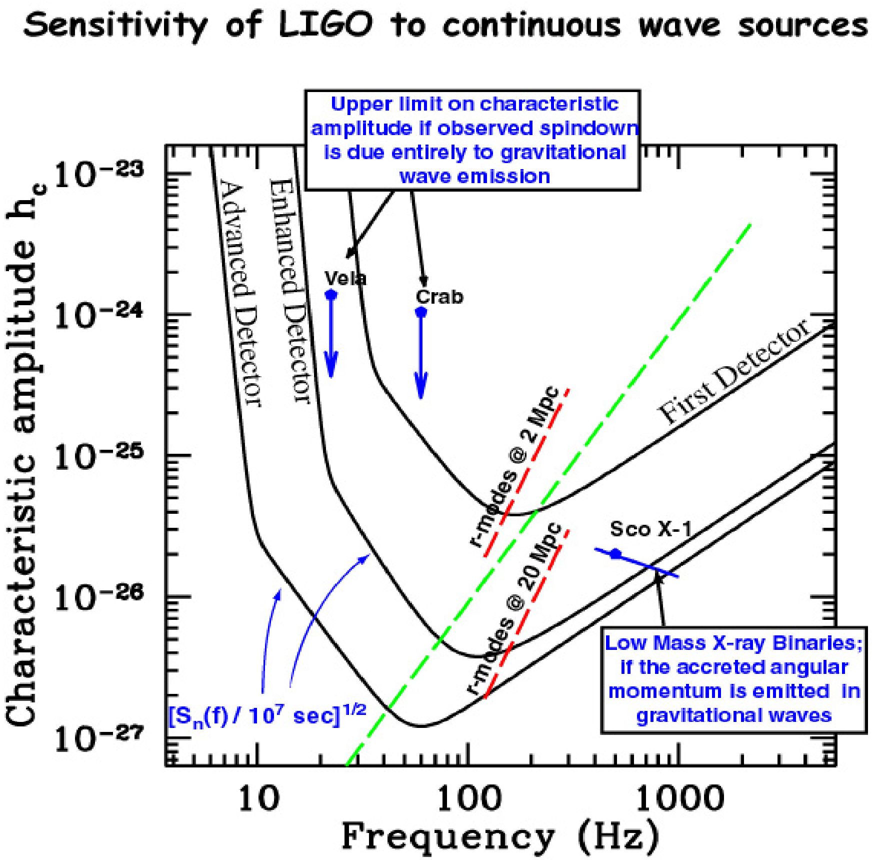
Progress:

Lower rate limits from longer observation times

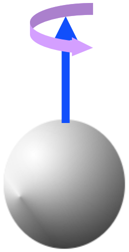
Lower amplitude limits from lower detector noise

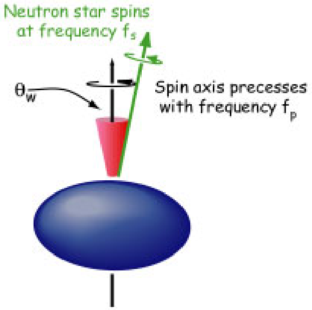
Latest (unpublished) results in Session W11: Shawhan – Science Run 4
Yakushin – Science Run 5

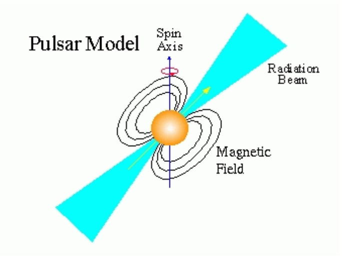
Pulsars and continuous wave sources

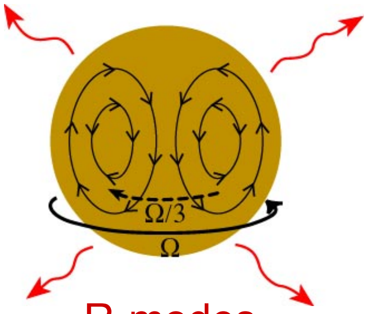


- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »“R-mode” instabilities
  - »narrow band searches best



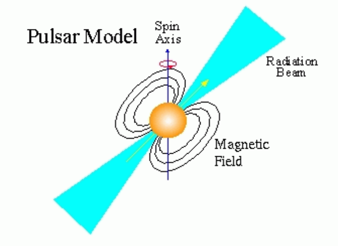




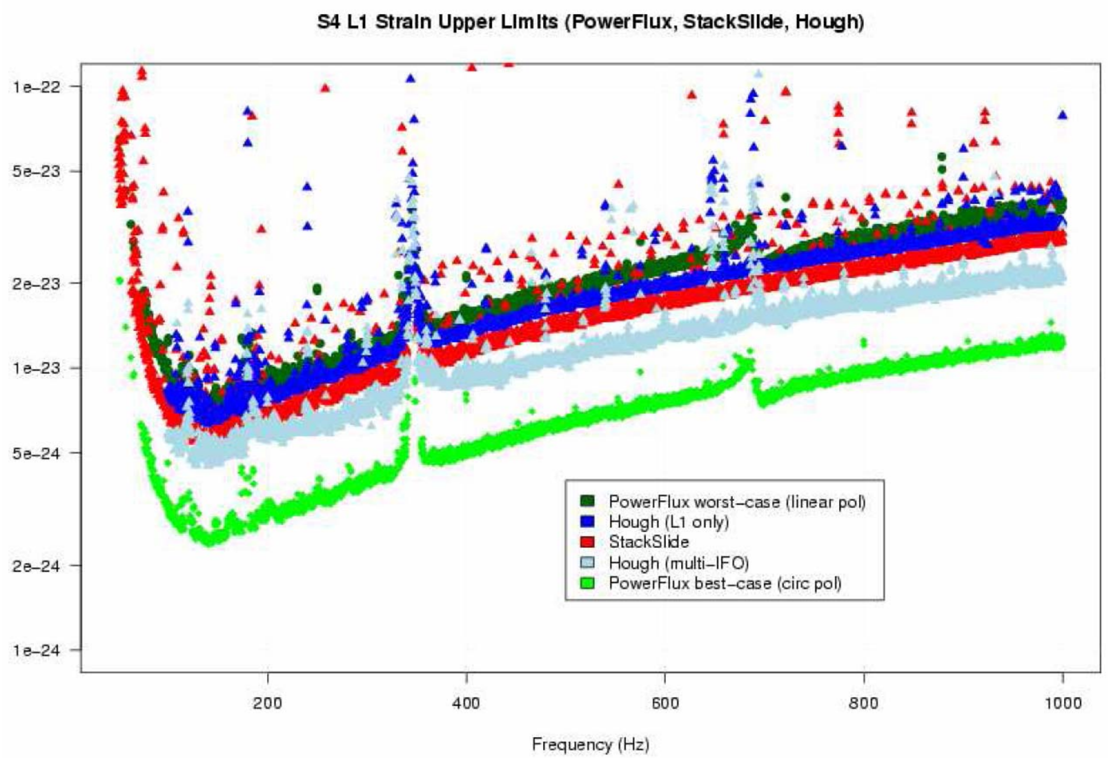


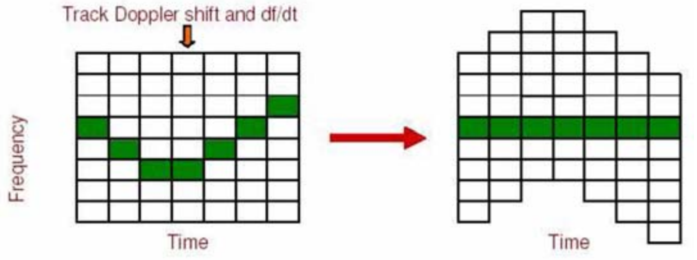
R-modes

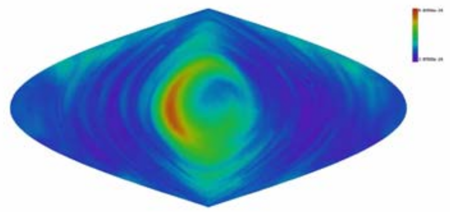
All sky searches
for spinning neutron stars



- Most spinning neutron stars are not pulsars; EM dim and hard to find.
- But they all emit GWs in all directions (at some level)
- Some might be very close and GW-loud!
- Must search over huge parameter space:
  - » sky position: 150,000 points @ 300 Hz, more at higher frequency or longer integration times
  - » frequency bins: 0.5 mHz over hundreds of Hertz band, more for longer integration times
  - » df/dt: tens(s) of bins
- Computationally limited! Full coherent approach requires ~100,000 computers (Einstein@Home)



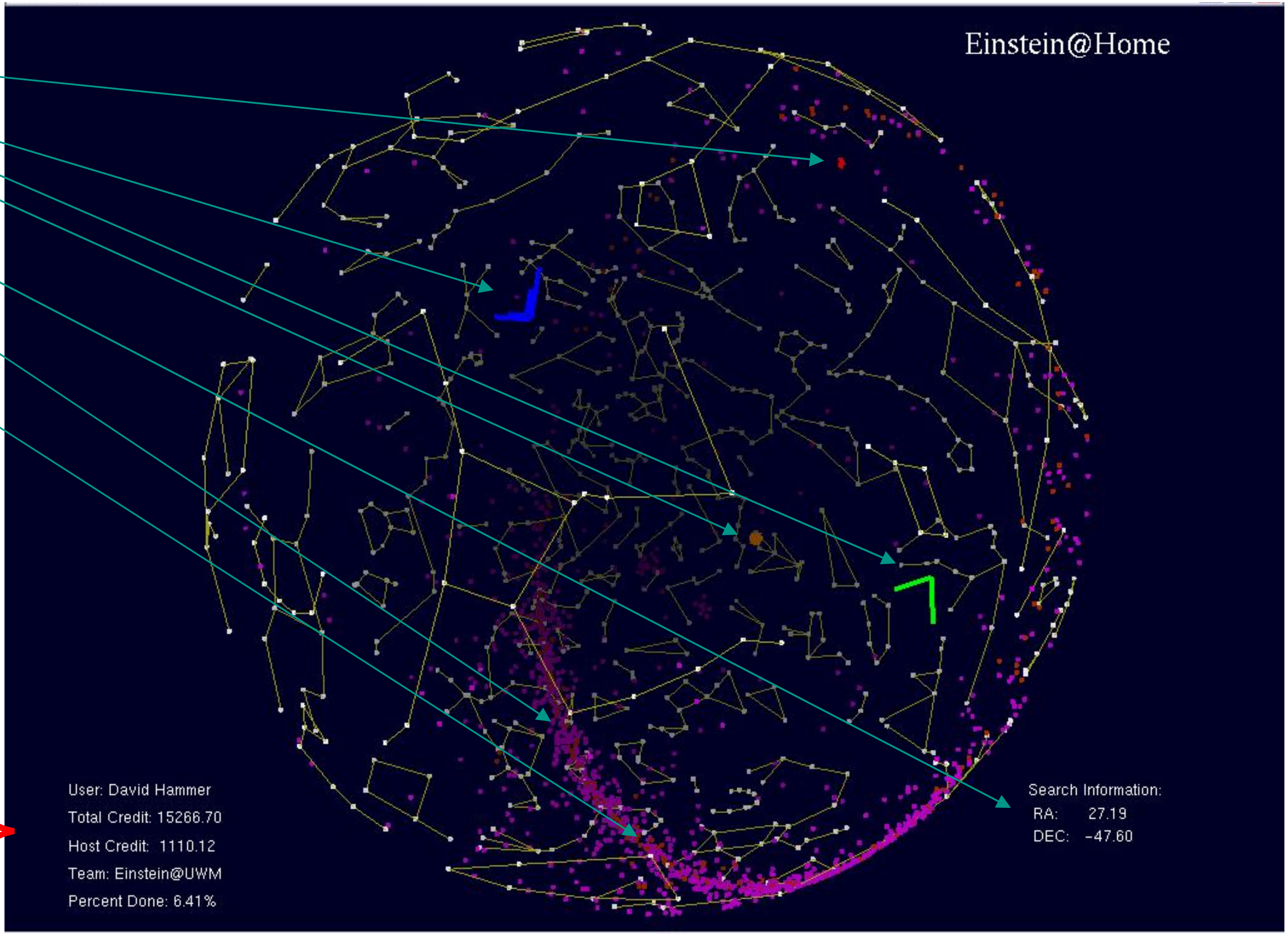




LIGO Einstein@Home: the Screensaver

- 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



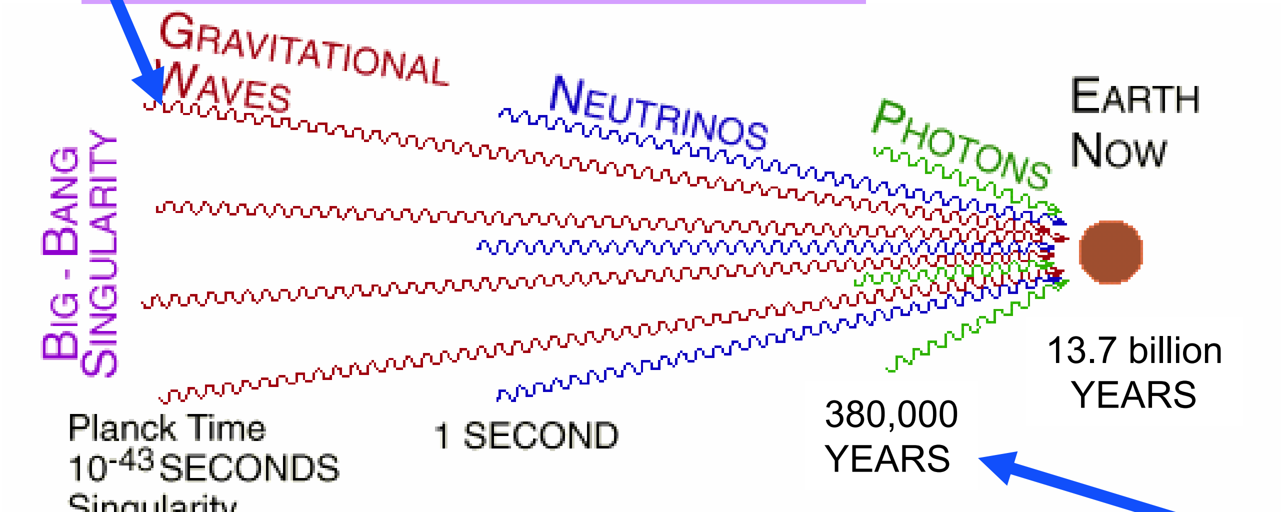
Einstein@Home

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

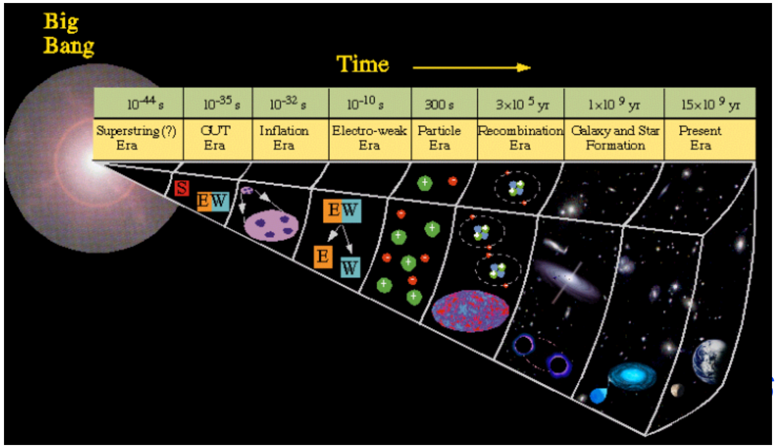
Search Information:
RA: 27.19
DEC: -47.60

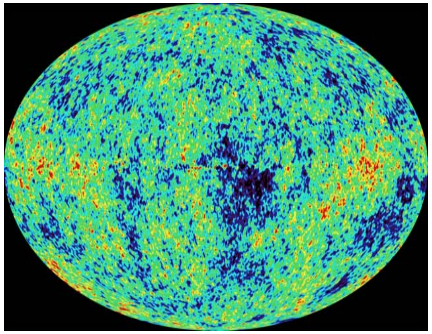
Gravitational waves from Big Bang

Waves now in the LIGO band were produced 10^{-22} sec after the big bang



Planck Time
10^{-43} SECONDS
Singularity
creates
Space & Time
of our universe





cosmic microwave background -- WMAP 2003

Stochastic Background of Gravitational Waves

- Energy density:

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\, \dot{h}^{ab} >$$

- Characterized by log-frequency spectrum:

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln f}$$

- Related to the strain power spectrum:

$$S(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}$$

- Strain scale:

$$h(f) = 6.3 \times 10^{-22} \sqrt{\Omega_{GW}(f)} \left(\frac{100\ \mathrm{Hz}}{f}\right)^{3/2} \mathrm{Hz}^{-1/2}$$

Detection via cross-correlation of data streams from 2 detectors

- Cross-correlation estimator

$$Y = \int_{-T/2}^{+T/2} dt_1 \int_{-T/2}^{+T/2} dt_2 \; s_1(t_1)\; s_2(t_2)\; Q(t_2 - t_1)$$

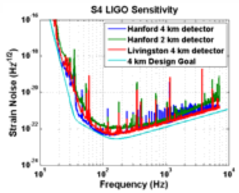
$$Y = \int_{-\infty}^{+\infty} df \; \tilde{s}_1^*(f) \; \tilde{s}_2(f) \; \tilde{Q}(f)$$

- Theoretical variance

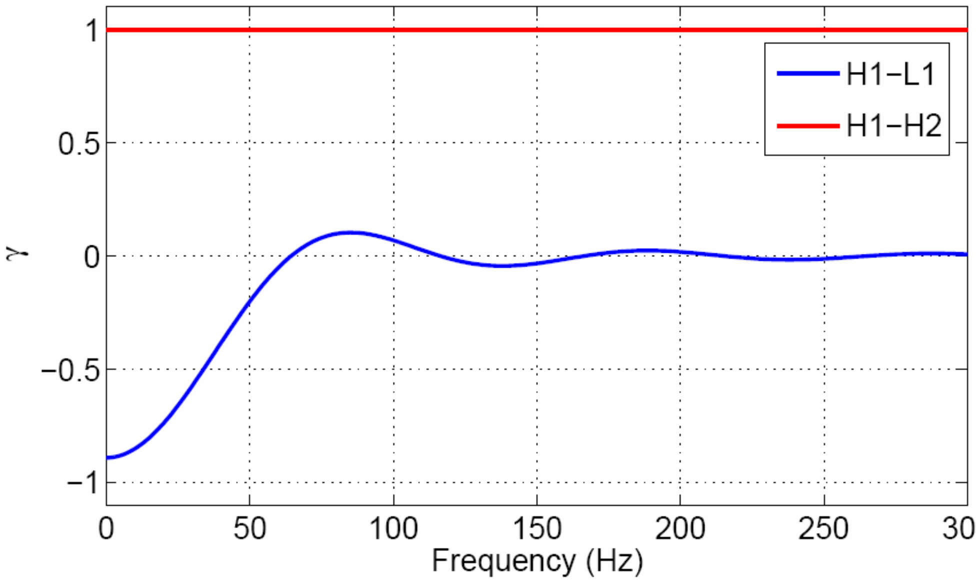
$$\sigma_Y^2 \approx \frac{T}{2} \int_0^{+\infty} df \; P_1(f) \; P_2(f) \; | \; \tilde{Q}(f) \; |^2$$

- Optimal Filter

$$\tilde{Q}(f) = \frac{1}{N} \frac{\gamma(f)\; \Omega_t(f)}{f^3 \; P_1(f) \; P_2(f)}$$



Overlap Reduction Function

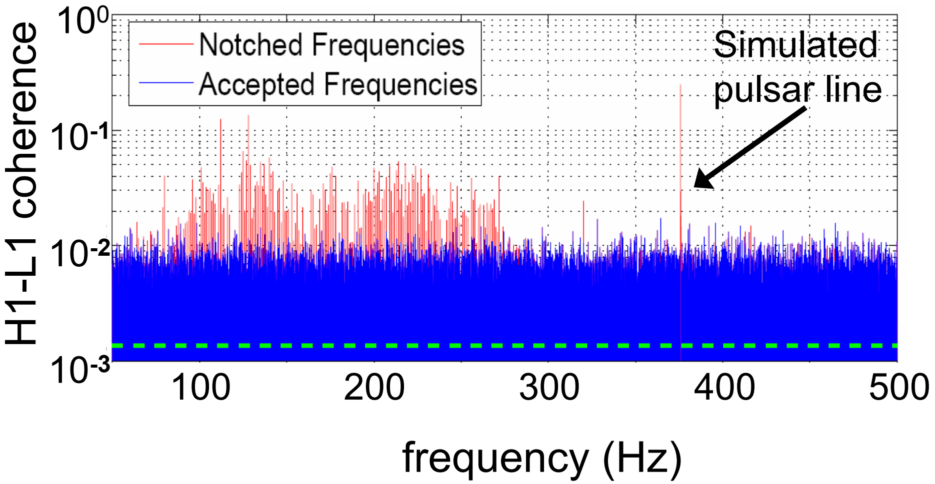


For template: $\Omega_t(f) = \Omega_\alpha (f/100 \text{ Hz})^\alpha$

Choose *N* such that: $< Y >= \Omega_\alpha T$

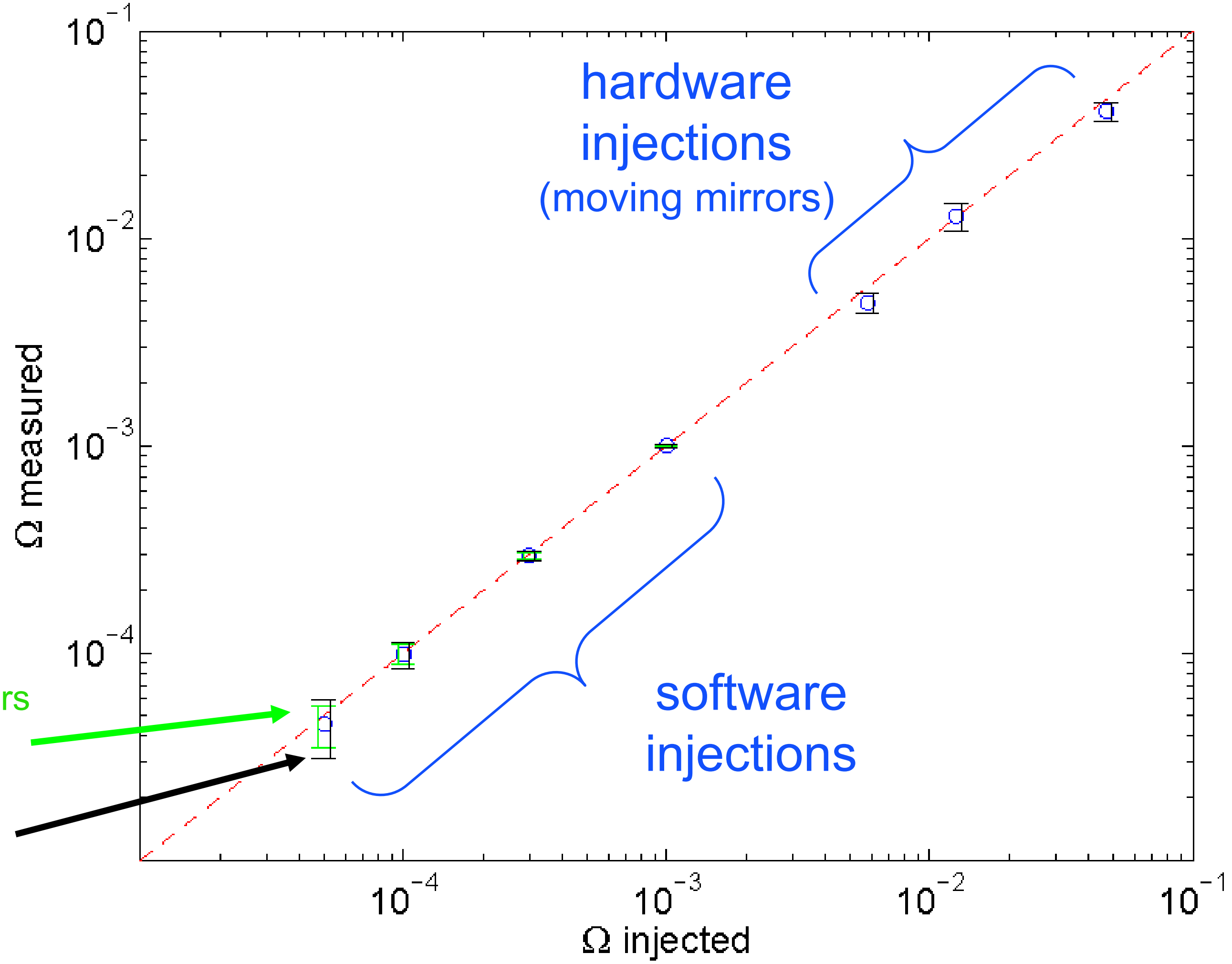
Technical Challenges

- Digging deep into instrumental noise looking for small correlations.
- Need to be mindful of possible non-GW correlations
  - common environment (H1-H2)
  - common equipment (e.g. DAQ – could affect any IFO pair!)
- Example:
  - Correlations at harmonics of 1 Hz.
  - Due to GPS timing system.
  - Lose ~3% of the total bandwidth (1/32 Hz resolution).



Signal Recovery

Demonstrated ability to estimate Ω_{GW} accurately:



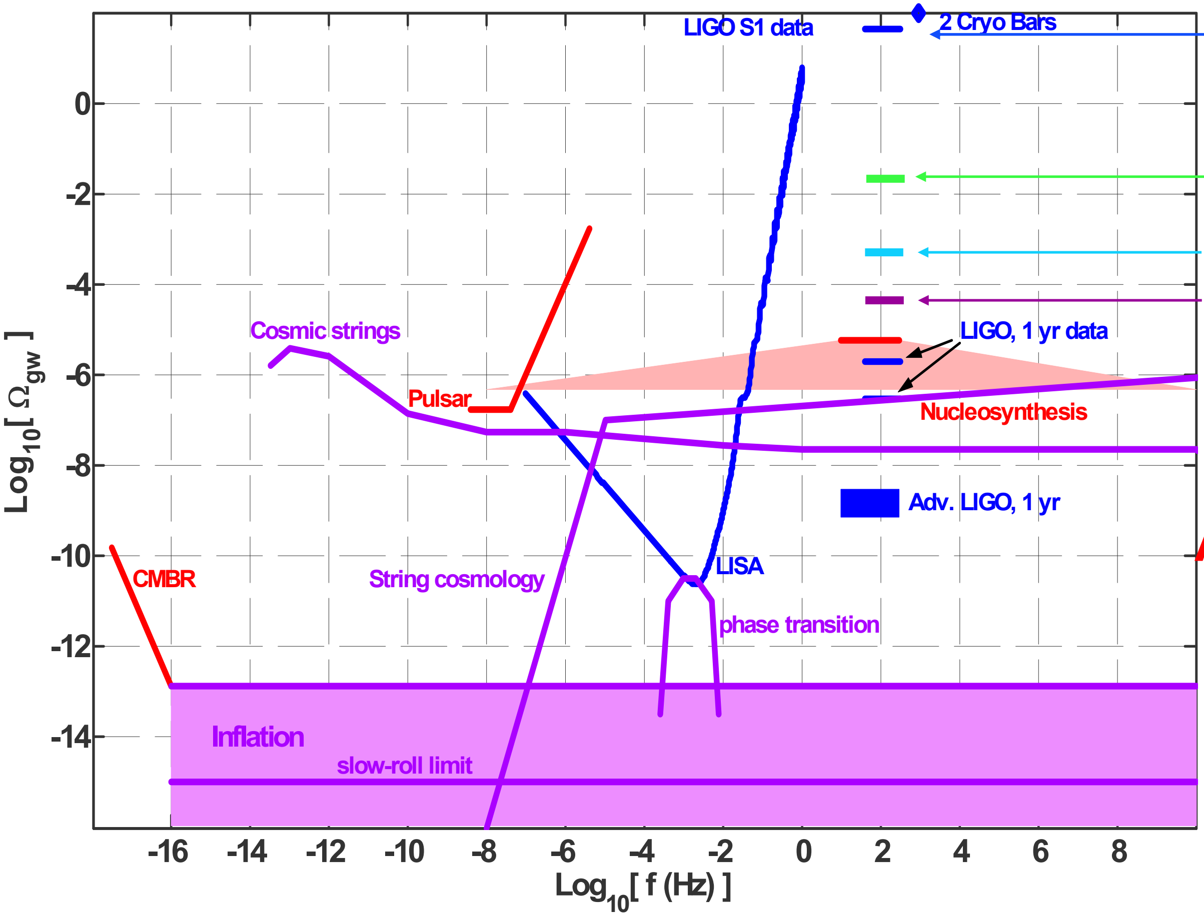
hardware injections (moving mirrors)

software injections

standard errors (10 trials)

theoretical errors

LIGO limits and expectations on Ω_{GW}



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

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

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

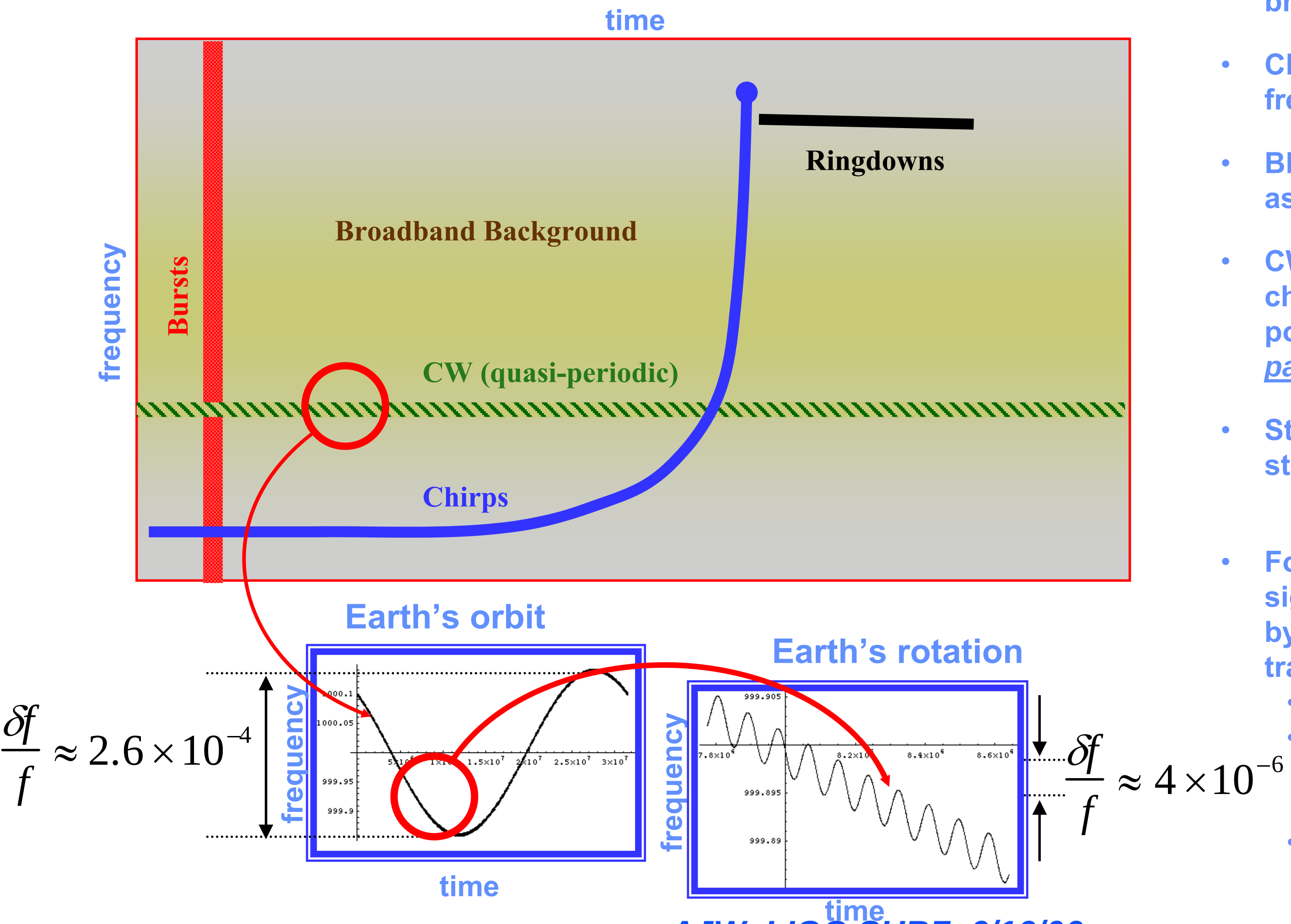
S4 result: $\Omega_{GW} < 6\times10^{-5}$

LIGO design, 1 year:
Ω_{GW} <~ 10^{-5} - 10^{-6}

Advanced LIGO, 1 year:
Ω_{GW} <~ 10^{-9}

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

Frequency-Time Characteristics of GW Sources



$$\frac{\delta f}{f} \approx 2.6\times 10^{-4}$$

$$\frac{\delta f}{f} \approx 4\times 10^{-6}$$

- 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 $|\text{signal}_j{}^{*}\ \text{signal}_k|$
  - Optimal filter: kernel ∝ 1/(noise power)

Ultimate Goals for the Observation of GWs

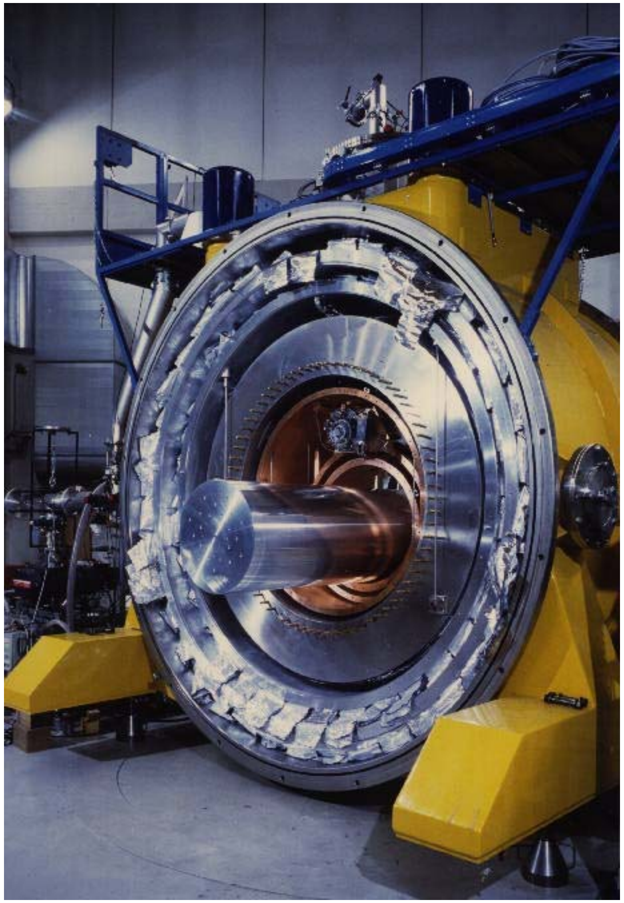
- **Tests of General Relativity – Gravity as space-time curvature**
  - Wave propagation speed (delays in arrival time of bursts)
  - Spin character of the radiation field (polarization of radiation from sources)
  - Detailed tests of GR in P-P-N approximation (chirp waveforms)
  - Black holes & strong-field gravity (merger, ringdown of excited BH)
- **Gravitational Wave Astronomy** (observation, populations, properties of **the most energetic processes in the universe**):
  - Compact binary inspirals
  - Gamma ray burst engines
  - Black hole formation
  - Supernovae in our galaxy
  - Newly formed neutron stars - spin down in the first year
  - Pulsars, 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).

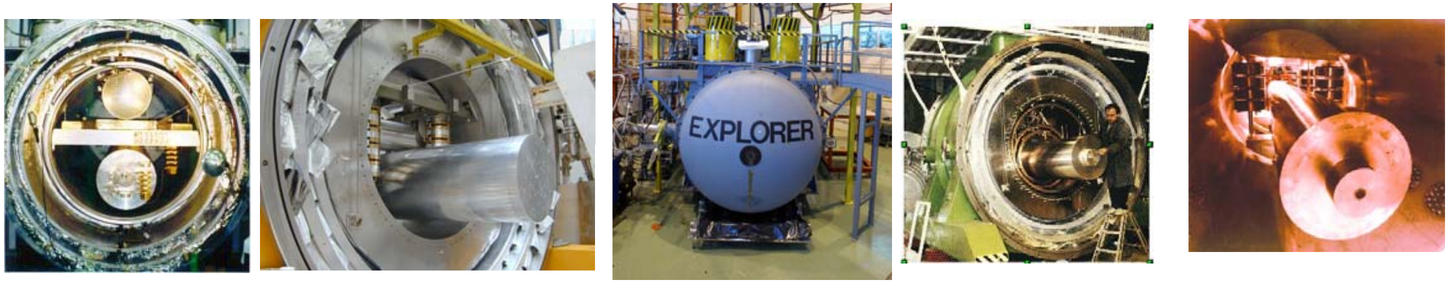
Resonant bar detectors

- 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)

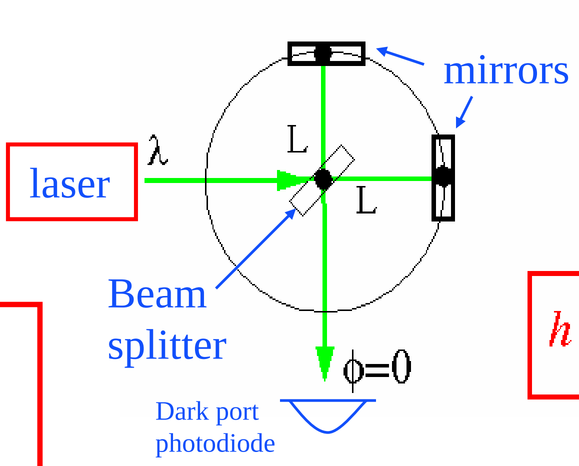


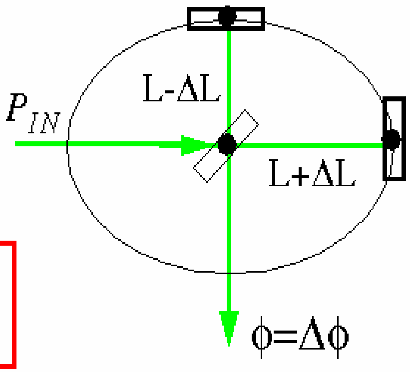
detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Mode frequencies $[Hz]$	895, 920	912, 930	905, 921	908, 924	694, 713
Bar mass M $[kg]$	2296	2230	2270	2260	1500
Bar length L $[m]$	3.0	2.9	3.0	3.0	2.75
Bar temperature $[K]$	4.2	0.2	2.6	0.1	5.0
Longitude	$91°10'44"W$	$11°56'54"E$	$6°12'E$	$12°40'21"E$	$115°49'E$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

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

Interferometric detection of GWs

GW acts on freely falling masses:



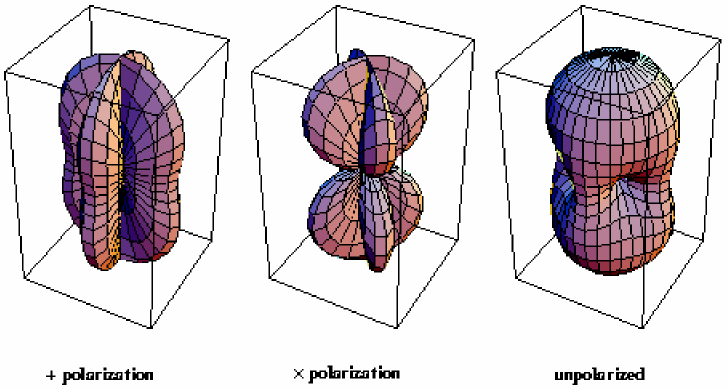


$$h = \frac{\Delta L}{L}$$

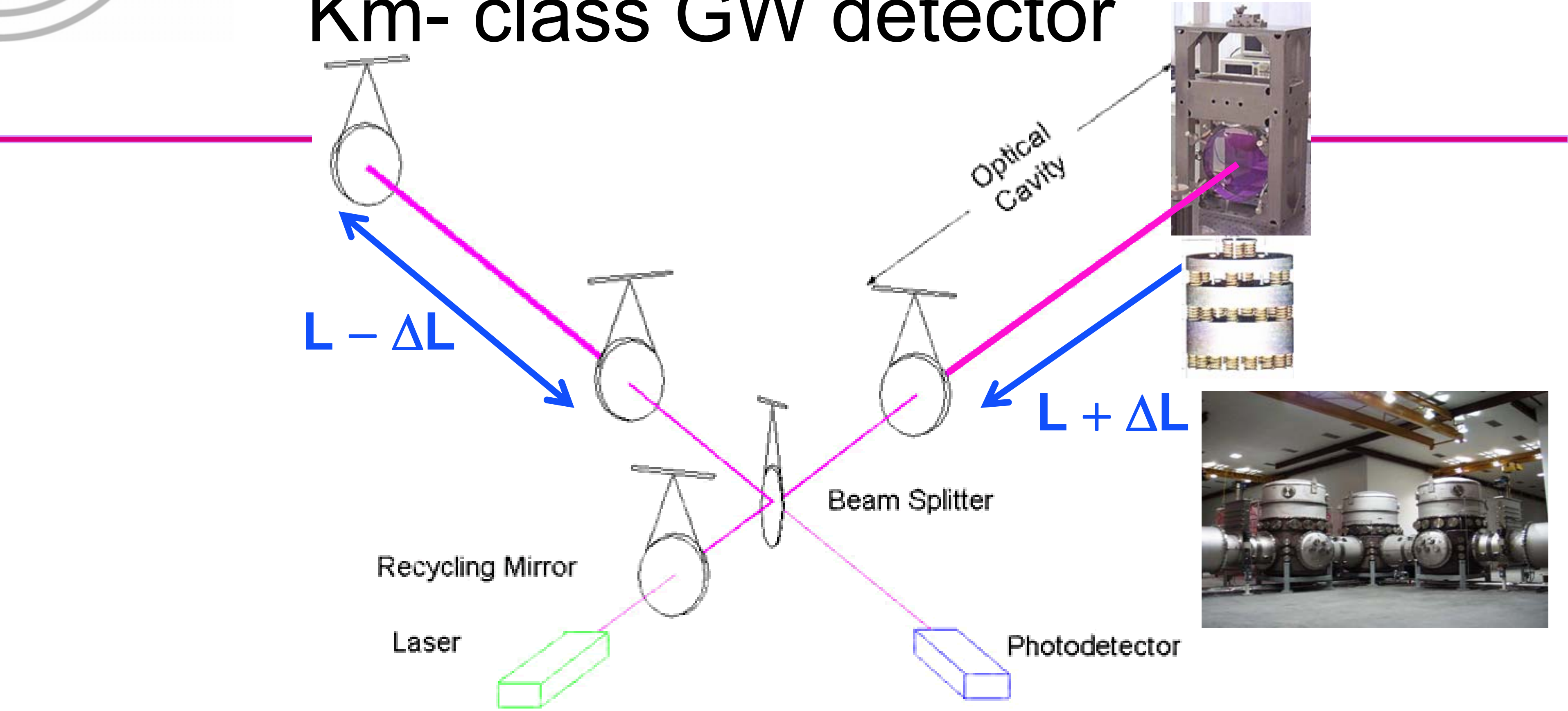
For fixed ability to measure *ΔL*, make *L* as big as possible!

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

Antenna pattern:
(not very directional!)



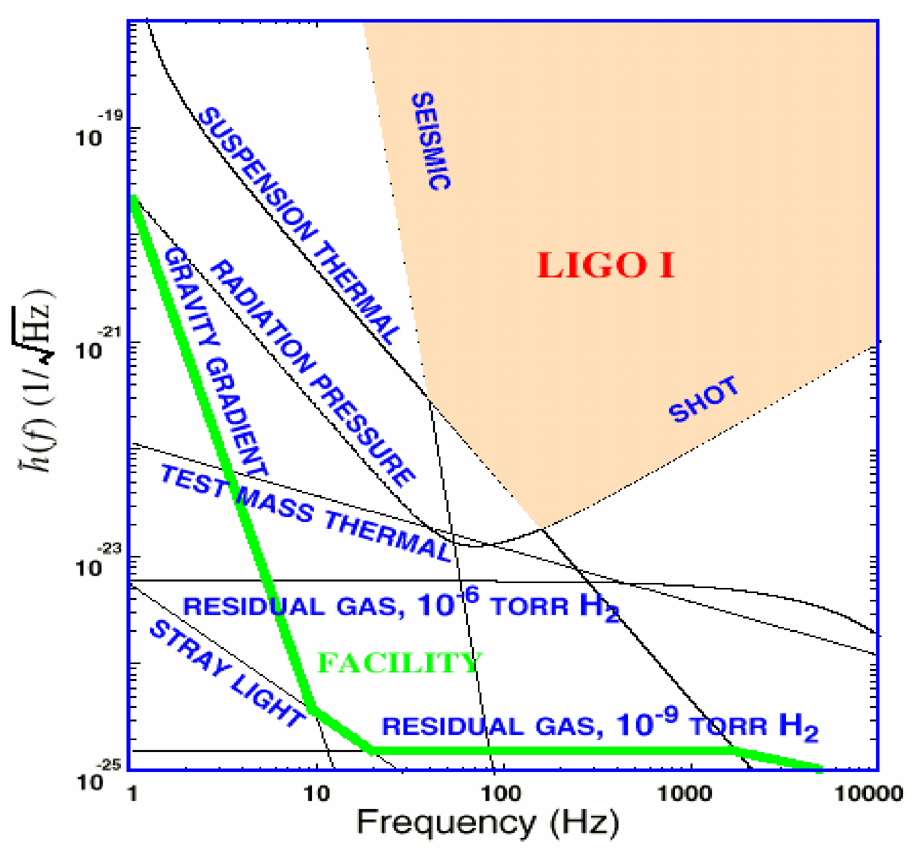
LIGO – the first Km- class GW detector



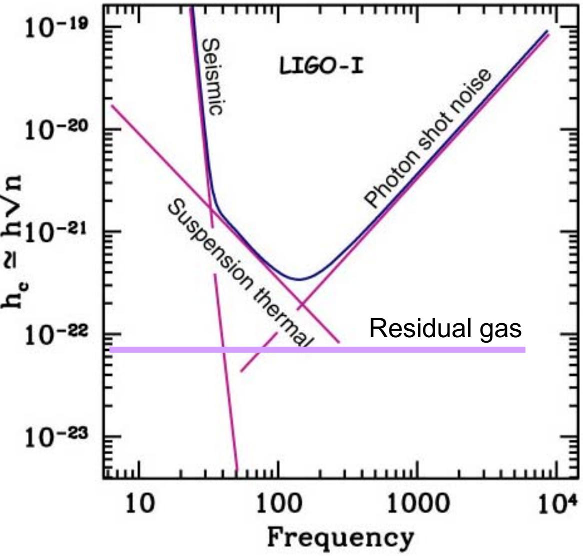
want to get h ≤ 10^{-22};
can build L = 4 km;
must measure ΔL = h L ≤ 4×10^{-19} m

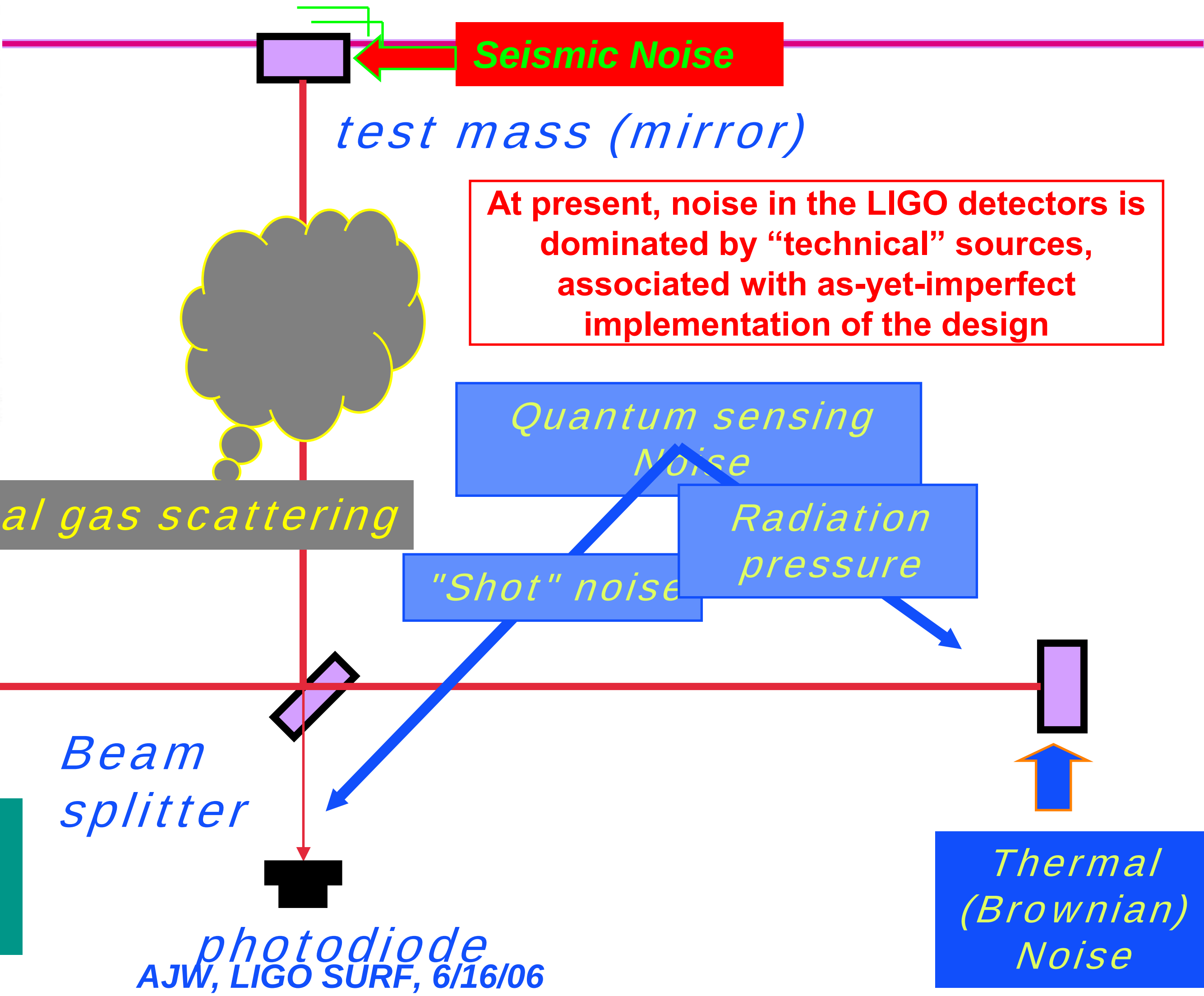
LIGO I noise floor

- **The LIGO detectors are limited by three fundamental noise sources**
  - **seismic noise at the lowest frequencies**
  - **thermal noise at intermediate frequencies**
  - **shot noise (*quantum sensing* noise) at high frequencies**
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**
- **The LIGO sites and vacuum systems are designed to accomadate the next generation of Advanced detectors.**



Interferometer Noise Limits





Seismic Noise

test mass (mirror)

At present, noise in the LIGO detectors is dominated by "technical" sources, associated with as-yet-imperfect implementation of the design

Quantum sensing Noise

Radiation pressure

"Shot" noise

Residual gas scattering

LASER

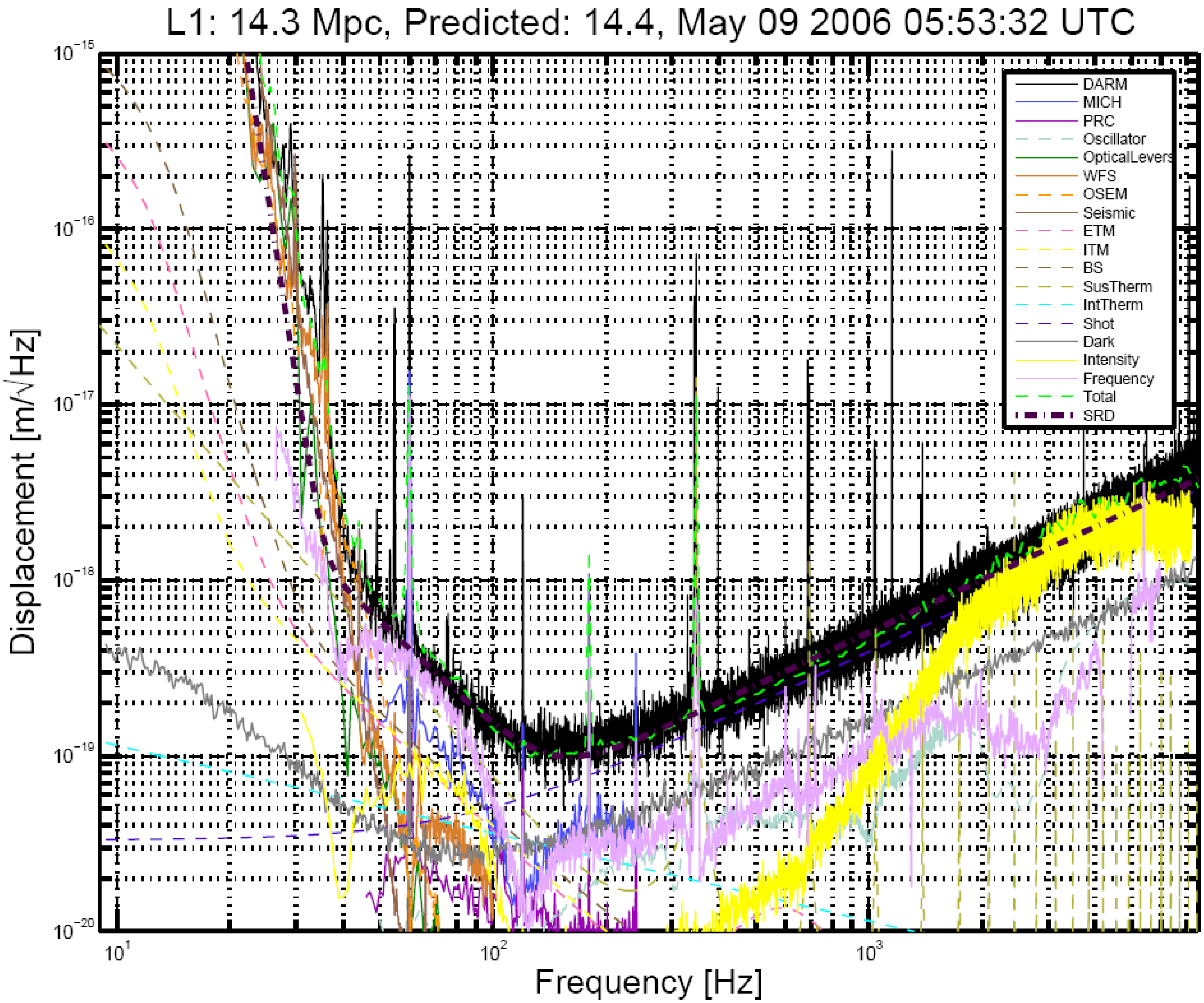
Wavelength & amplitude fluctuations

Beam splitter

photodiode

Thermal (Brownian) Noise

Noise budget

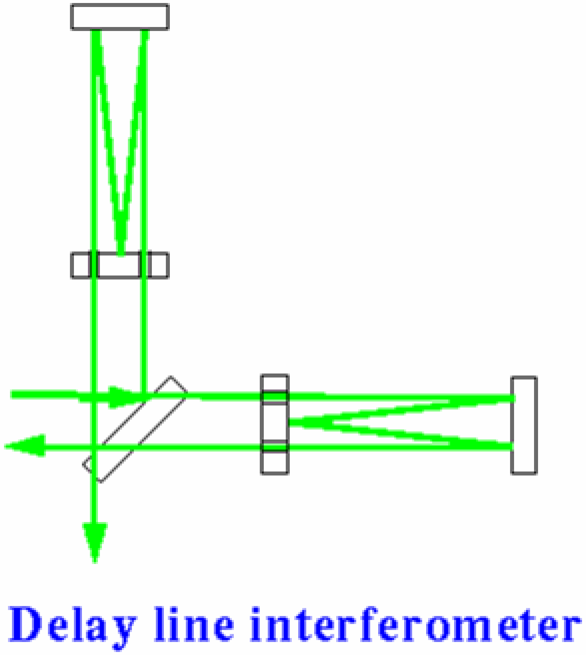


Light storage: folding the arms

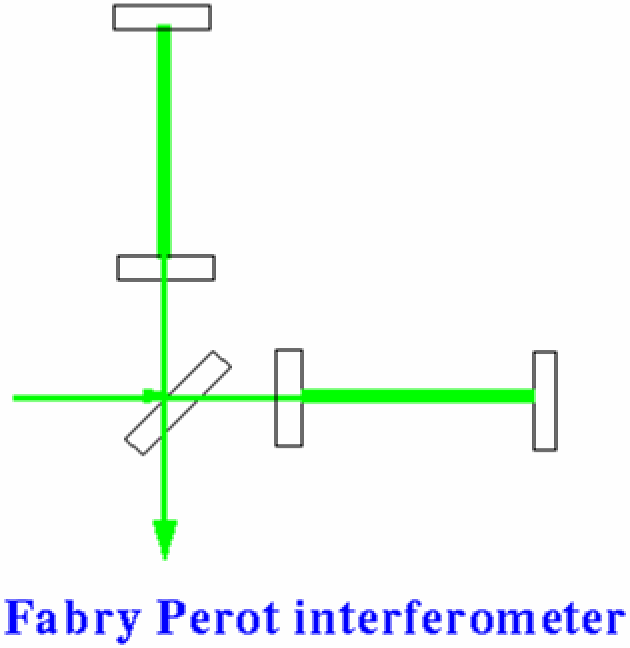
How to get long light paths without making *huge* detectors:

Fold the light path!

The laser measures the displaced mirrors many times before returning to the beamsplitter.



Delay line interferometer



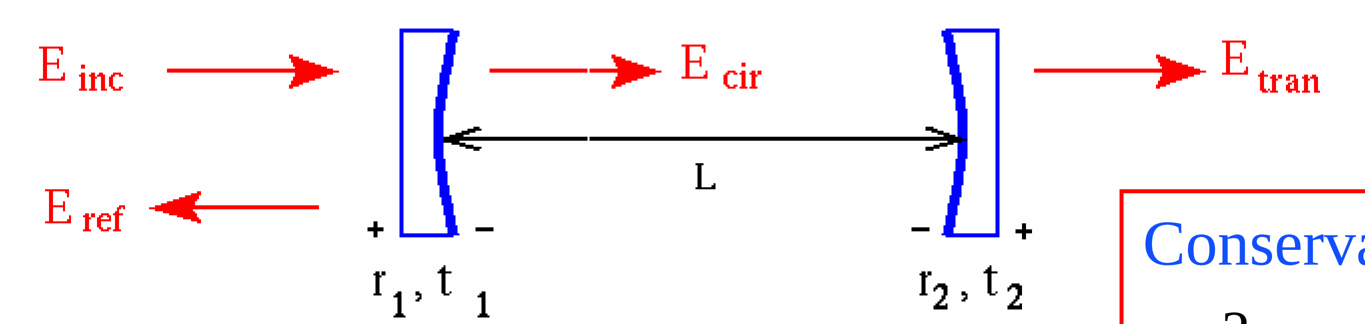
Fabry Perot interferometer

Simple, but requires large mirrors; limited τ_{stor}

(LIGO design) $\tau_{stor} \sim 10$ msec

More compact, but harder to control

Fabry-Perot Optical Resonator Cavities



$$E_{cir} = t_1 E_{inc} + r_1 r_2 e^{-2ikL} E_{cir} = \frac{t_1}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{ref} = r_1 E_{inc} - t_1 r_2 e^{-2ikL} E_{cir} = \frac{r_1 - r_2 (1 - L) e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{tran} = t_2 \; e^{-ikL} E_{cir} = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

Conservation of energy:

$$r_i^2 + t_i^2 + L_i = 1$$

$$R_i + T_i + L_i = 1$$

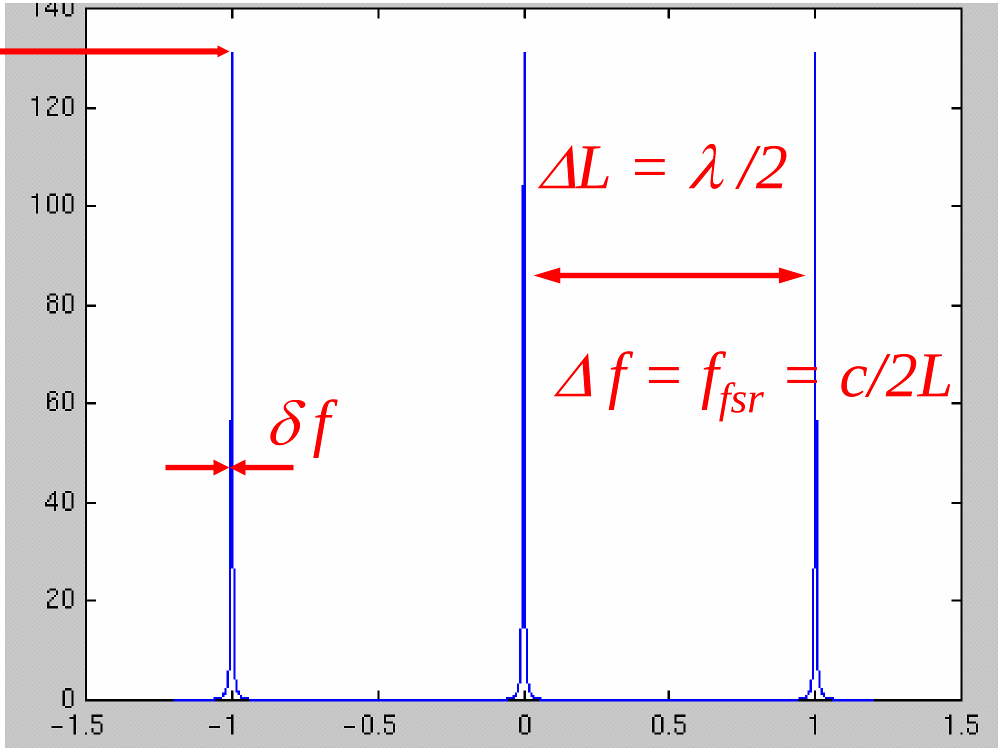
When $2kL = n(2\pi)$, (ie, $L = n\lambda/2$),

E_{cir} , E_{tran} maximized ⇒ resonance!

FP circulating field

Power Gain

$$\left|\frac{E_{circ}}{E_{in}}\right|^2$$



$\Delta L = \lambda/2$

$\Delta f = f_{fsr} = c/2L$

δf

Free Spectral Range:

$f_{FSR} = c/2L$

$\text{Finesse} = \delta f / f_{fsr}$

$$\Delta\nu = \Delta(2kL)/2\pi = \Delta f/f_{fsr} = \Delta L/(\lambda/2)$$

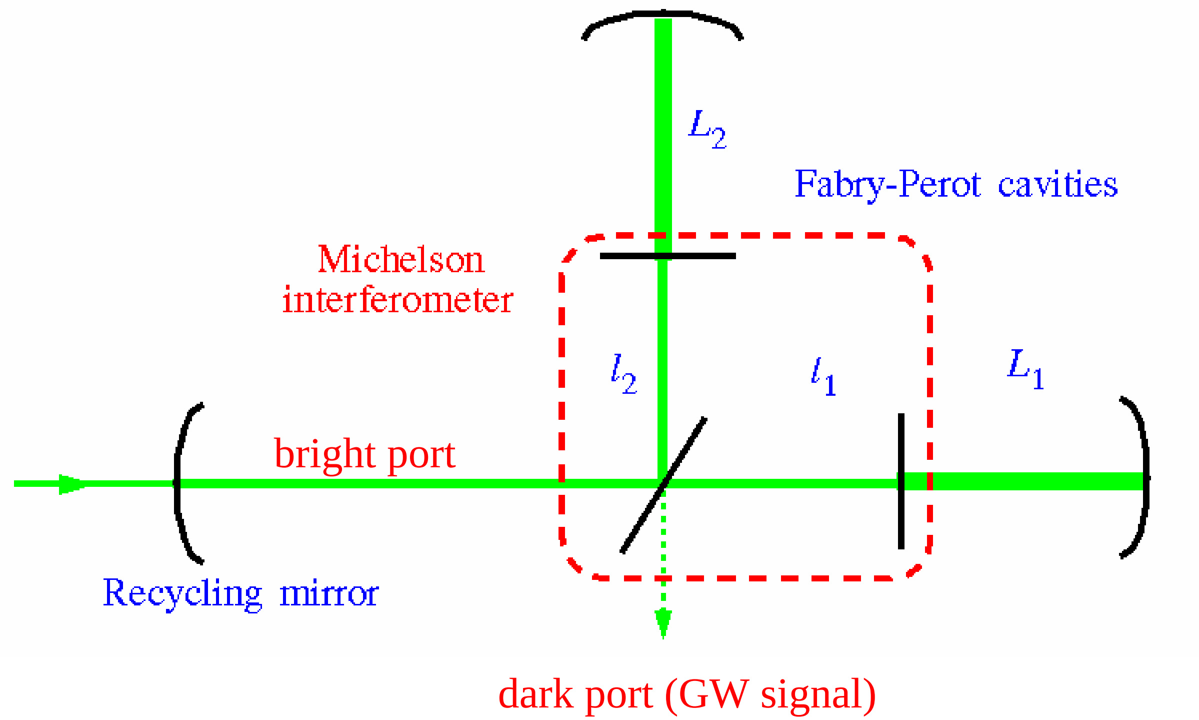
What do high-finesse optical cavities do for you?

- They are incredibly sensitive measuring devices and/or filters!
- They measure $\Delta\nu = \Delta(2kL)/2\pi = \Delta f/f_{fsr} = \Delta L/(\lambda/2)$
- If you know L very well (a *length reference*), they measure the frequency of your laser very accurately!
  - In LIGO, we use a sequence of ever-longer optical cavities to measure Δf from the laser, then feed back on the laser to stabilize it. Utlimately, we use the 4-km arms (in *common mode*) to make the world's most stable laser.
- If you have a very stable laser frequency, can measure ΔL very accurately!
  - In LIGO, we use the 4-km arms (in differential mode) to measure ΔL to an accuracy of 10^{-19} m
  - We accentuate the effect of ΔL on the phase shift of the light in the arms, by having the light bounce back and forth many times
  - Can't have arbitrarily large number of bounces: when light storage time > GW period, the effect cancels and we lose sensitivity! For LIGO, this starts happening at ~ 100 Hz.
- If you know both L and f very well, can measure *optical thickness* of sample placed in one arm – often used in materials science, etc.
- If you send in light with a broad range of frequencies, or the light has noisy frequency fluctuations, it only transmits one frequency: a filter!
- If one of the mirrors is curved, and you send in light with a messy transverse profile, it only transmits light with a single transverse *mode*: a *mode cleaner*.

LIGO I configuration

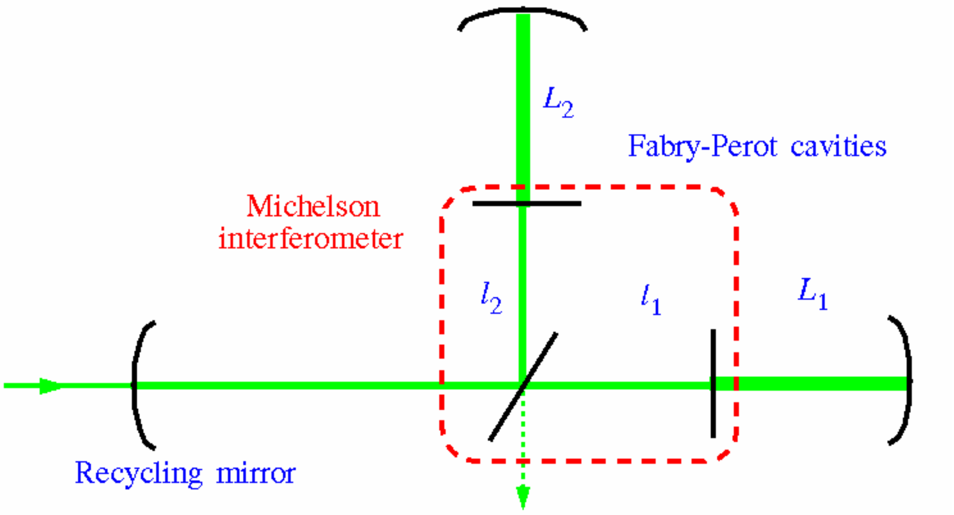
Power-recycled Michelson with Fabry-Perot arms:

- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in (coherently!) to be reused

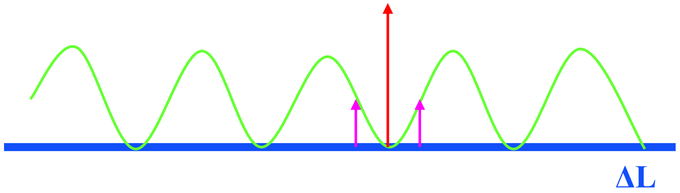


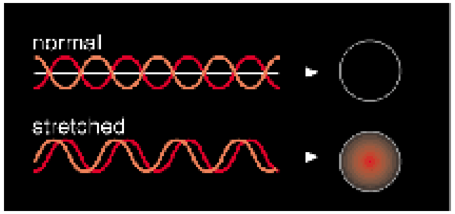
LIGO as a “Null” instrument

- **Power at output port of the Michelson depends most sensitively on ΔL at “mid-fringe”**
- **But LIGO operates the Michelson on a dark fringe, where power depends on $(\Delta L)^2$!**
- **Why? Because at mid-fringe, power fluctuations would “fake” the GW signal, and they are a *huge* source of noise**
- **Instead, we extract a signal from the light at the dark fringe, which is linear in ΔL, using a clever technique invented by Pound, Drever, Hall (Nobel 2005), to be described in a bit.**
- **Now we are insensitive to power fluctuations, and sensitive to ΔL.**
- **We want to stay dark, even when the GW signal is present: so we servo out the signal!**
- **That’s fine; the servo correction signal is neatly linear with ΔL.**
- **Null instrument: one of the many powerful techniques in precision measurement science that makes LIGO possible.**



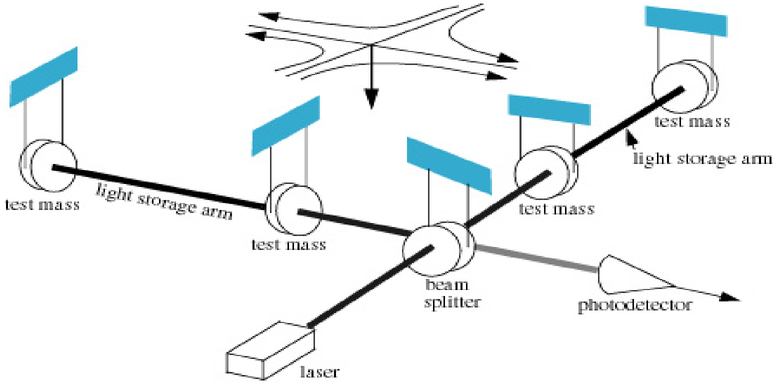
$$P_{out} = P_{in}\sin^2(2k\Delta L)$$



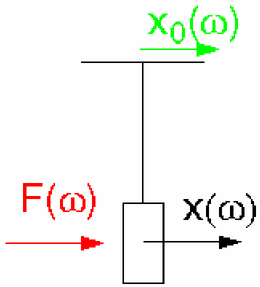


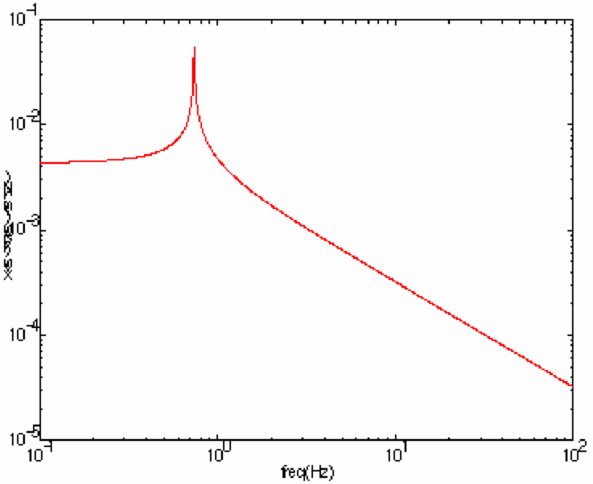
Suspended test masses

- To respond to the GW, test masses must be “free falling”
- On Earth, test masses must be supported against DC gravity field
- The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical);
  - can’t simply bolt the masses to the table (as in typical ifo’s in physics labs)
- So, IFO is insensitive to low frequency GW’s
- Test masses are suspended on a pendulum resting on a seismic isolation stack
  - “fixed” against gravity at low frequencies, but
  - “free” to move at frequencies above ~ 100 Hz



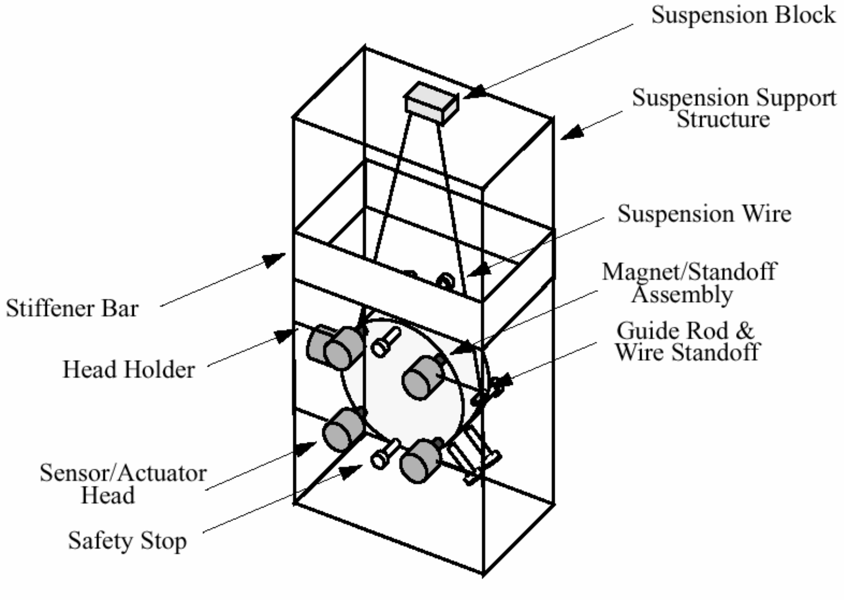
“Free” mass: pendulum at $f \gg f_0$

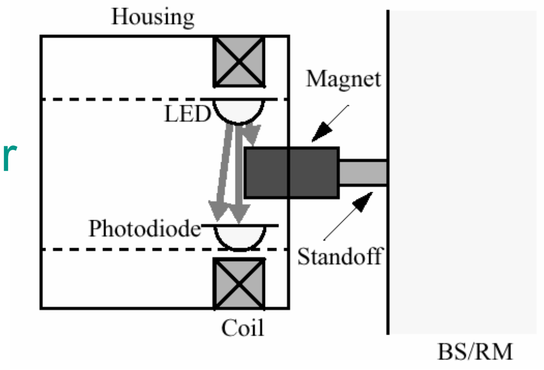




Mirror control

- Seismic isolation system, and pendulum, keep the mirror motion to a minimum.
- Now the mirrors are not being kicked around by the environment (at high frequencies) – “free” masses!
- But, being free, they may not be where you need them to be to keep the laser resonant in the cavities.
- Instead, they’re swinging back and forth at the pendulum frequency (~ 0.8 Hz).
- Need active control system to keep mirrors at set points (at/near DC), to keep F-P cavities resonant, without injecting noise at high frequencies
- ⇒ Carefully designed feedback servo loops

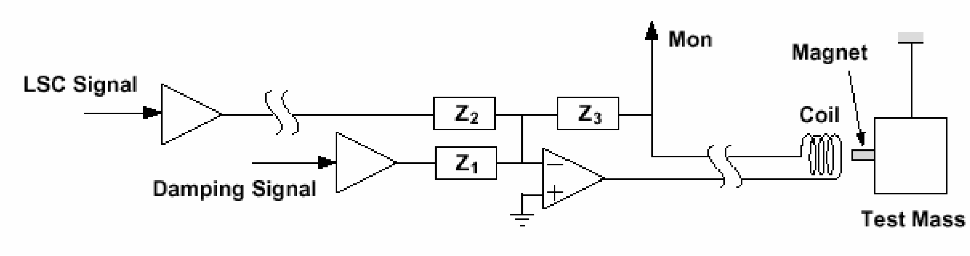


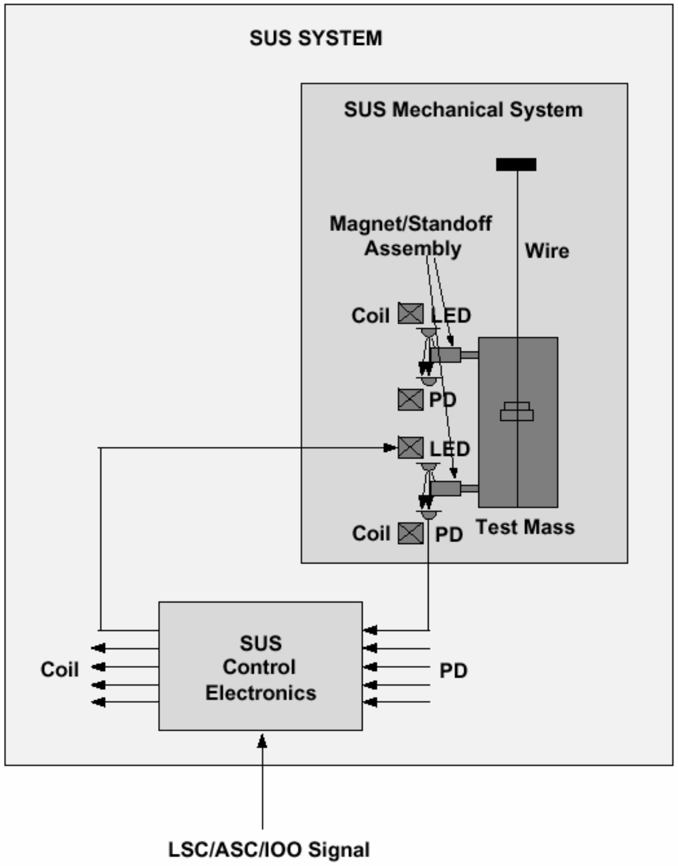


sensor/actuator head (OSEM)

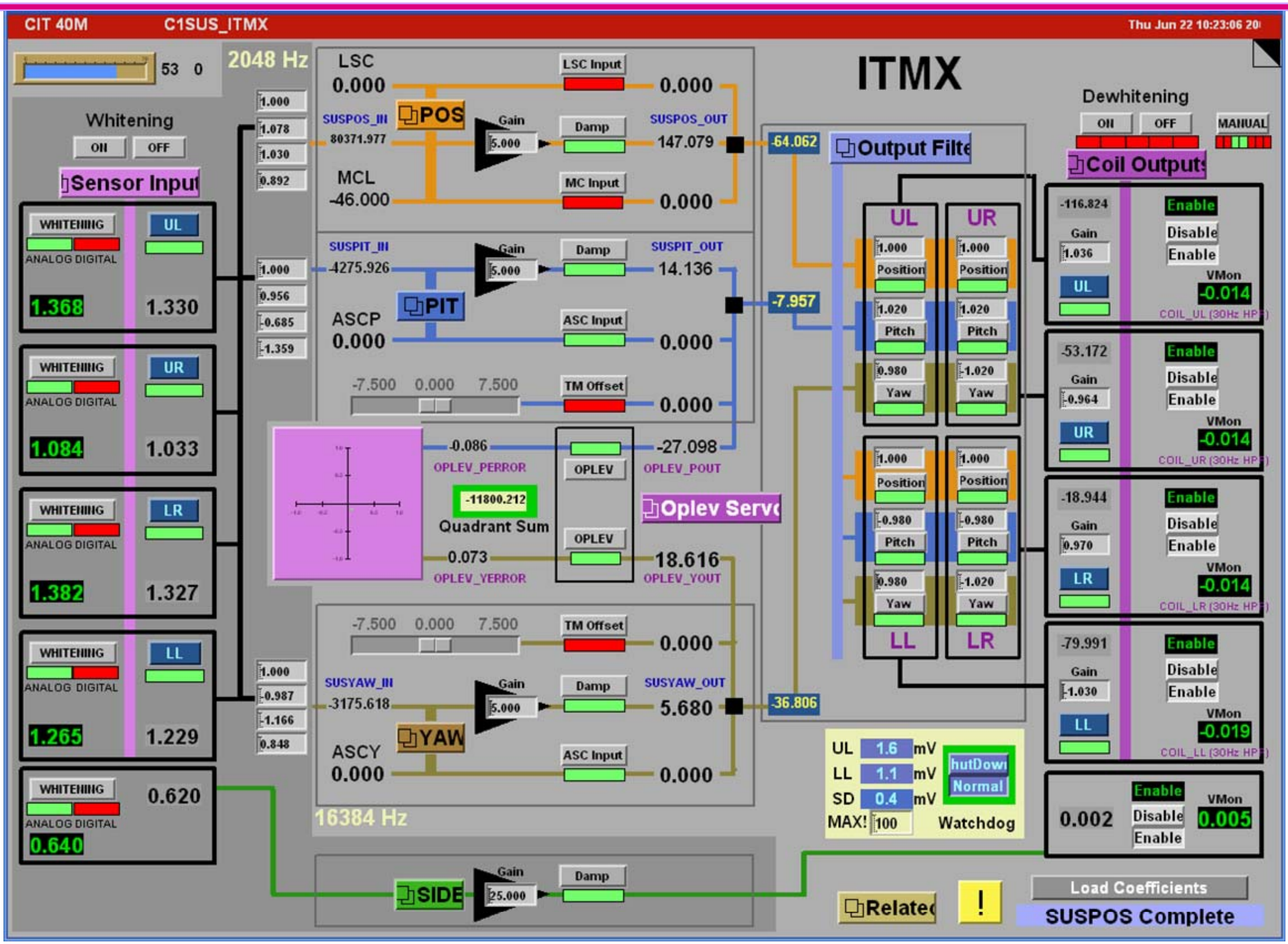
Suspension control system

- Each suspension controller handles one suspension (5 OSEMs)
- Local velocity damping
- Input from LSC and ASC to fix absolute position, pitch, yaw of mirror to keep cavity in resonance





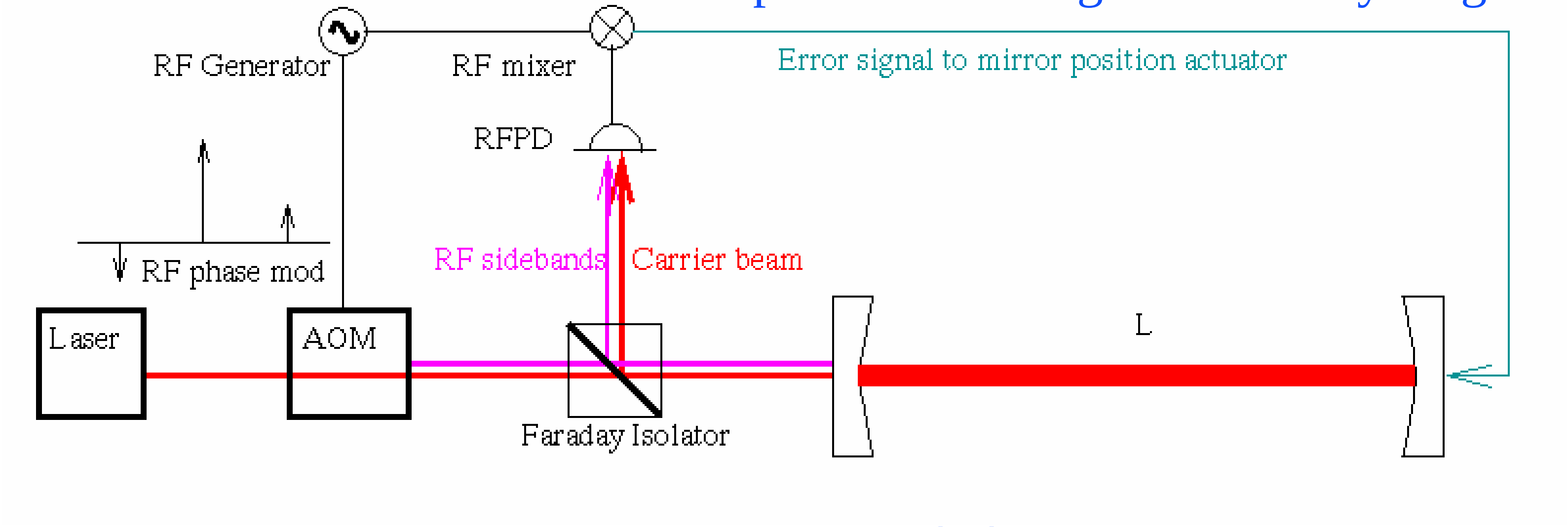
Digital suspension controls



Cavity control

Pound-Drever (reflection) locking used to control lengths of all the optical cavities in LIGO

- Phase modulate incoming laser light, producing RF sidebands
- Carrier is resonant in cavity, sidebands are not
- Beats between carrier and sidebands provide error signal for cavity length



Phase modulation of input beam

Phase modulation adds sidebands to the beam:

$$E_{inc} = E_{laser} e^{i(\omega t + \Gamma \cos \Omega t)} \approx E_{laser} e^{i\omega t}\left(J_0(\Gamma) + J_{+1}(\Gamma)e^{i\Omega t} + J_{-1}(\Gamma)e^{-i\Omega t}\right)$$

Ω = RF modulation frequency ($\Omega/2\pi$ ~ 30 MHz)

Γ = modulation depth

J_i = Bessel functions; $J_{\pm 1} \approx \pm \Gamma/2$ for $\Gamma<1$

$$E_{ref} = \left(E_0^{ref} + E_{+1}^{ref} e^{i\Omega t} + E_{-1}^{ref} e^{-i\Omega t}\right) e^{i\omega t}$$

Arrange the length of the cavity, and the value of Ω, so that

- carrier is resonant in FP cavity, sidebands are not,
- so they have different reflection coefficients
- phase of carrier is sensitive to length changes in cavity, sidebands are not

Demodulation

$$S_{ref} = \left(\left|E_0\right|^2 + \left|E_+\right|^2 + \left|E_-\right|^2 \right) + 2\,\mathrm{Re}\left(\left(E_0^* E_+ + E_0 E_-^* \right) e^{i\Omega t} \right) + 2\,\mathrm{Re}\left(E_+^* E_- e^{i2\Omega t} \right)$$

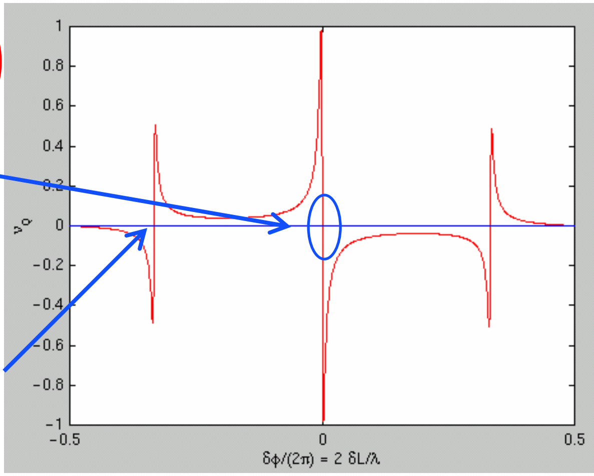
Use an electronic “mixer” to multiply this by

cosΩt or sinΩt, average over many RF cycles, to get:

- In-phase demodulated signal $v_I = 2\,\mathrm{Re}\left(E_0^* E_+ + E_0 E_-^* \right)$
- Quad-phase demodulated signal $v_Q = 2\,\mathrm{Im}\left(E_0^* E_+ + E_0 E_-^* \right)$

Which are sensitive to length of cavity (very near resonance)

And can be used as an *error signal* to control cavity length



Sideband resonant - error signal has wrong sign

Schnupp Asymmetry

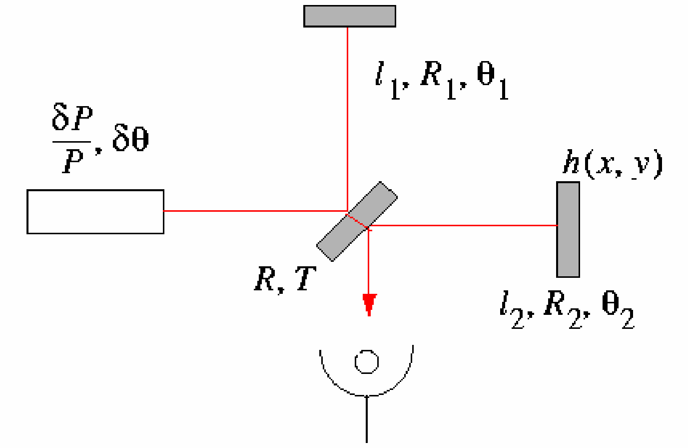
GW signal (L_-) is measured using light *transmitted* to dark port. Signal power is quadratic in L_- ; not as sensitive as linear dependence.

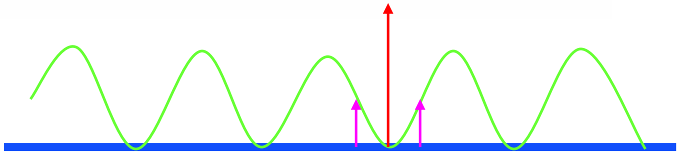
To keep the dark port dark for the main (carrier) laser light, use Schnupp (tranmission) locking as opposed to reflection locking, for l_- signal.

- **In absence of GW, dark port is *dark*;**
  carrier power ~ $\sin^2(\Delta\phi)$,
  quadratic in $\Delta\phi = 2k\, l_-$ for small signal

- **Add Schnupp (Michelson) asymmetry: $l_1 \neq l_2$ ($l_- \neq 0$); port still dark for carrier ($l_1 = l_2 \mod \lambda_c$), but sidebands leak out to dark port PD to act as local oscillator for RF-detection of GW signal.**

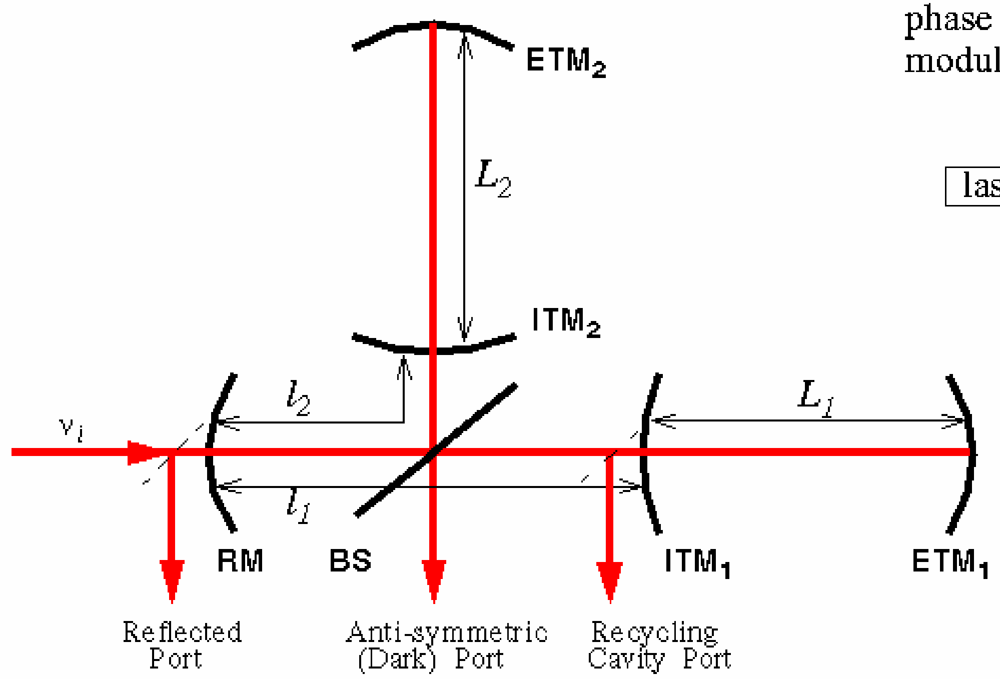
- **Error signal is then *linearly* proportional to amount of carrier light (GW signal)**

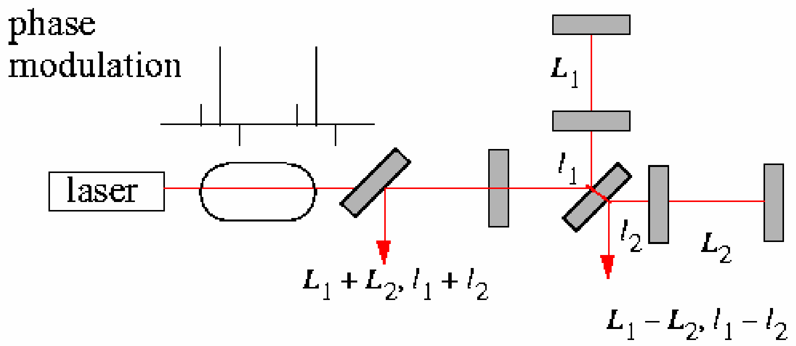




$$\nu_Q = 2\,\mathrm{Im}\left(E_0^* E_+ + E_0 E_-^*\right)$$

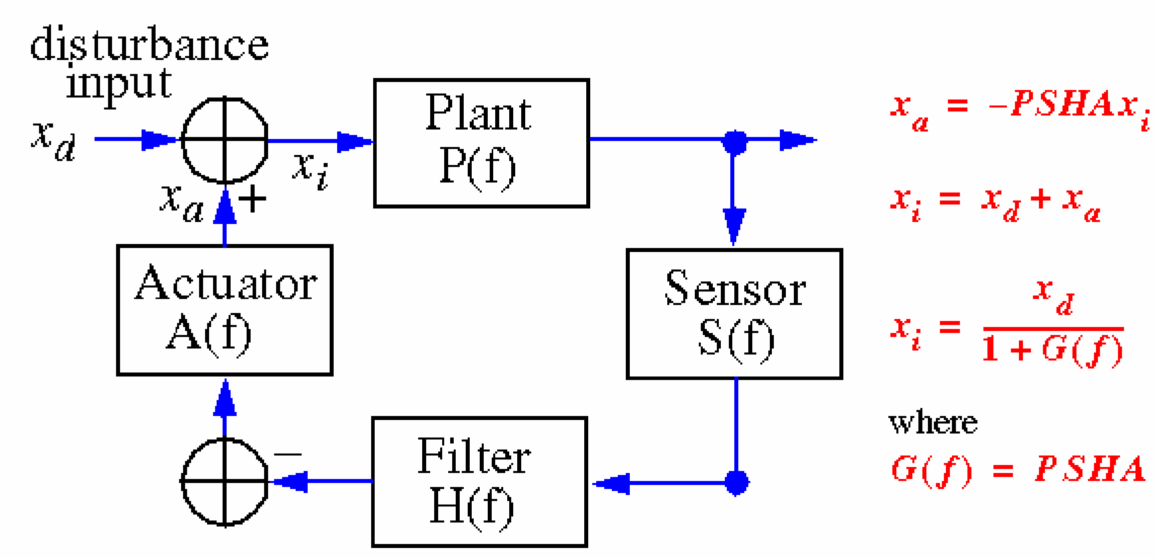
The control problem in LIGO





- **Four interferometer lengths ⇒ four sensors/actuators**
- **Ten mirror angles ⇒ ten sensors/actuators**

Elements of a control system



$x_a = -PSHAx_i$

$x_i = x_d + x_a$

$x_i = \frac{x_d}{1+G(f)}$

where

$G(f) = PSHA$

- Time delays are inevitable; Plant, and control system, response is best characterized in *frequency domain* (as in communication engineering)

- When $G(f) >> 1$ then $x_i << x_d$,

  Plant input is much smaller than original disturbance

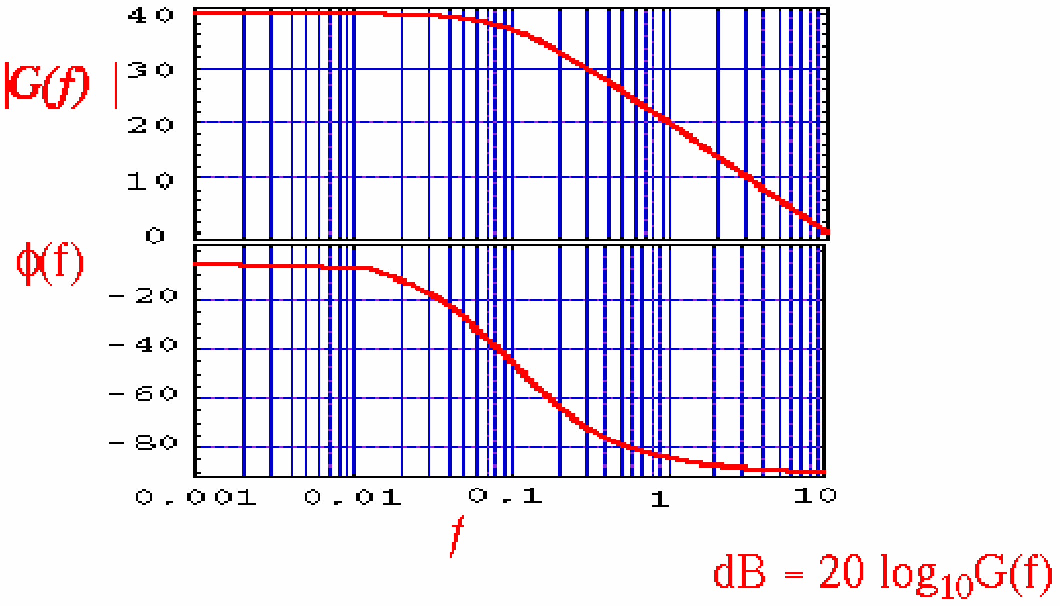
Controls terminology

- Transfer function (frequency response) magnitude [$|G(f)|$] and phase [$\phi(f)$] of output when input is a sinusoid of unit magnitude at frequency f

- Bode Diagram:

- Pole: magnitude falls off with f ($f>f_o$), phase lags

- Zero: magnitude increases with f ($f<f_o$), phase leads



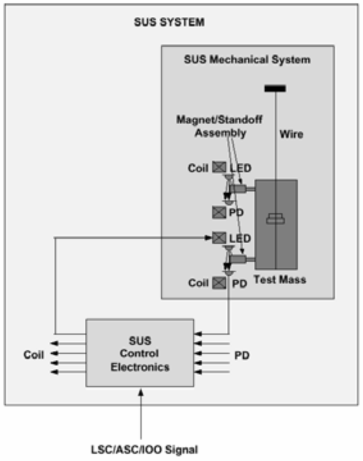
dB = 20 $\log_{10}$G(f)

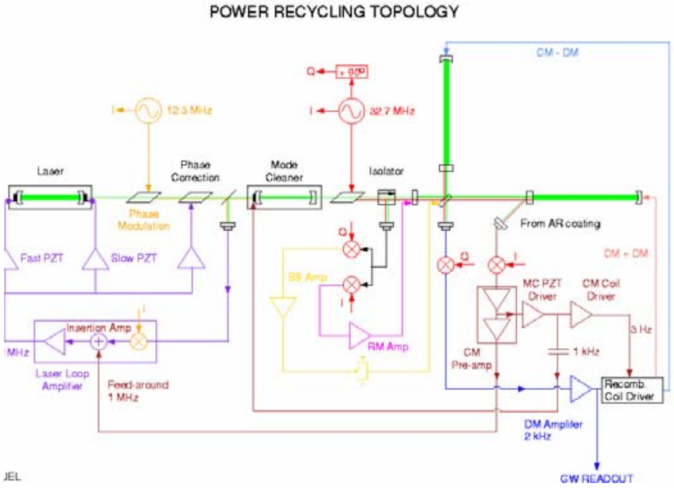
Want high gain at frequencies where control is effective (sensor fidelity, actuator response), and phase < 90°;

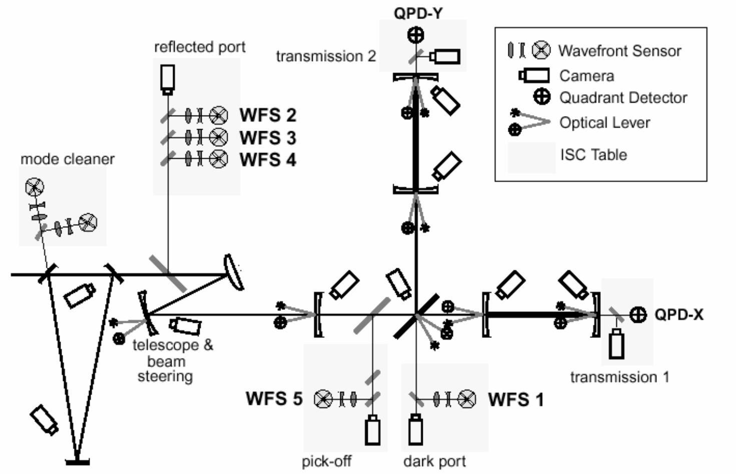
Then fast rolloff of gain to avoid injecting noise

LIGO Control systems

- Start with a “simple” system: control of a mirror (AKA “optic” or “test mass”) suspended on a pendulum
- Control of a Fabry-Perot optical cavity (P-D-H reflection locking)
- Control of a Michelson IFO (Schnupp tranmission locking)
- Controlling all the length degrees of freedom in a LIGO IFO
- Controlling all the alignment degrees of freedom in a LIGO IFO





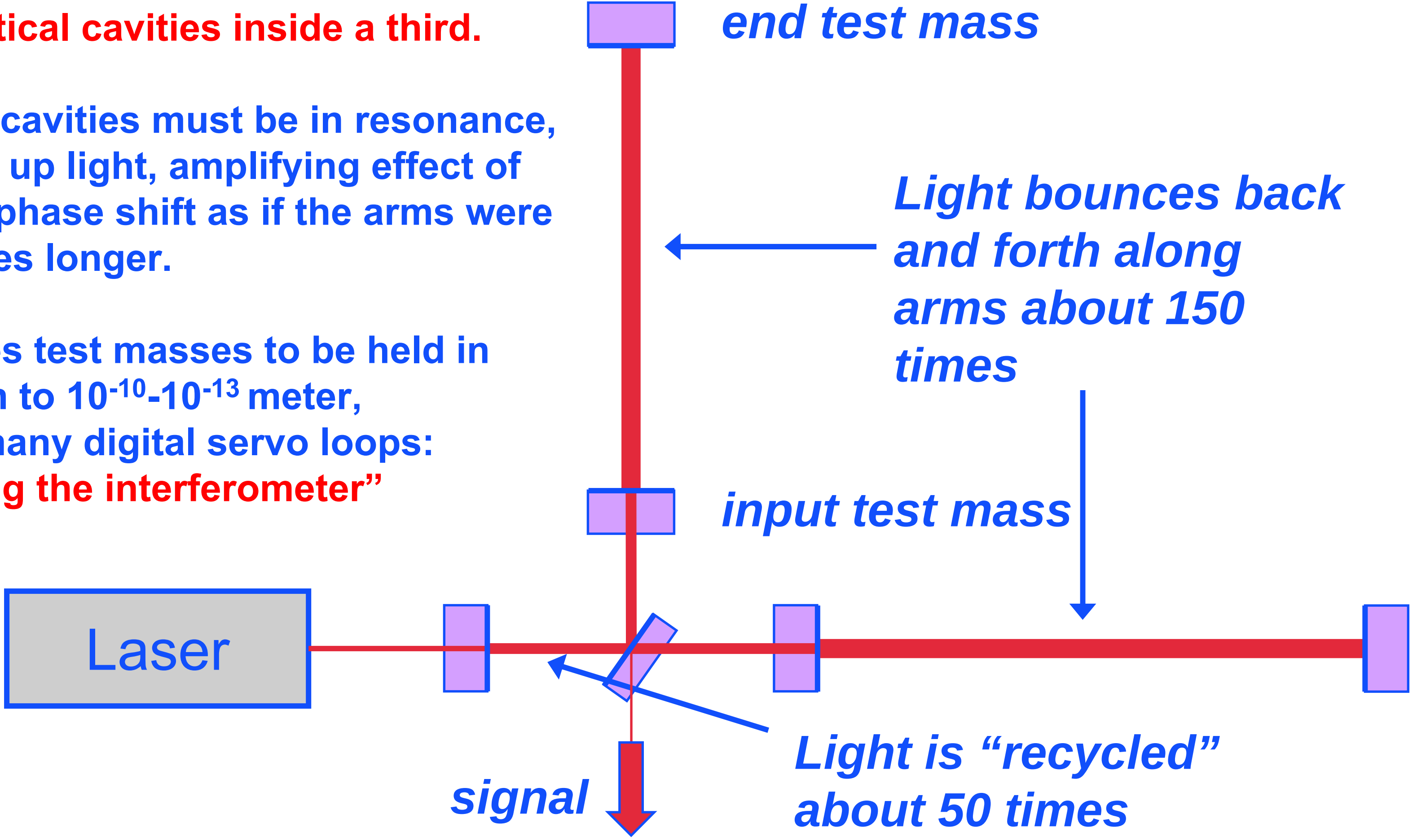


Interferometer
locking

Two optical cavities inside a third.

Optical cavities must be in resonance, to build up light, amplifying effect of GW on phase shift as if the arms were 150 times longer.

Requires test masses to be held in position to 10^{-10}-10^{-13} meter, using many digital servo loops: "Locking the interferometer"



end test mass

Light bounces back and forth along arms about 150 times

input test mass

signal

Light is "recycled" about 50 times

NOISE in GW detectors

- After ~ 40 years of effort, no one has detected a GW!
- Why? Noise levels in detectors exceed expected signal; *insufficient sensitivity*
- Want to detect GW strain *h*; can express detector noise in terms of equivalent *h* sensitivity
- Most of the effort in GW detection has gone into *understanding and reducing noise* to the fundamental quantum limit (and beyond!)
- We are the beneficiaries of that pioneering and frustrating work: on the threshold of doing what sounds almost impossibly hard!

NOISE SOURCES IN THE DETECTOR

- Noise ⇒ signals which appear in detector as GWs but are imposters
- Three categories:
- Displacement noise ⇒ moves mirrors (path length changes)

$\delta x = L\ \delta h$, so to achieve $h \approx 10^{-21}/\sqrt{\mathit{Hz}}$ with $L = 4$km,

$$\Rightarrow \delta x \approx 10^{-18}\ m/\sqrt{Hz}$$

(*cf*: diameter of proton is 10^{-15} m)

- Phase noise ⇒ changes the phase of the light:

$\delta\phi = 4\pi\ NL\ \delta h / \lambda$, with $N \approx 100$ and $\lambda \approx 1.064\ \mu$m,

$$\Rightarrow \delta\varphi \approx 10^{-10}\ rad/\sqrt{Hz}$$

- Technical or instrumental noise (laser, electronics, EMF pickup, *etc*)

must engineer IFO to keep this *below* the fundamental noise!

Sensing limits

Photon shot noise:

$$E_{APD} = P_{APD}\tau_{\text{int}} = N_{photon}\left(h_{Pl}\, c/\lambda\right)$$

uncertainty in intensity due to counting statistics: $\Rightarrow \delta P_{APD} = \sqrt{P_{APD} h_{Pl}\, c/\lambda\, \tau_{\text{int}}}$

can solve for equivalent strain:

Note: scaling with $1/\sqrt{P_{laser}}$; gives requirement for laser power

$$h_{shot} = \frac{\delta L}{L} = \frac{1}{L}\sqrt{\frac{h_{Pl}c\lambda}{2\pi T(f)P_{laser}}}$$

Radiation Pressure

quantum limited intensity fluctuations anti-correlated in two arms

photons exert a time varying force, spectral density

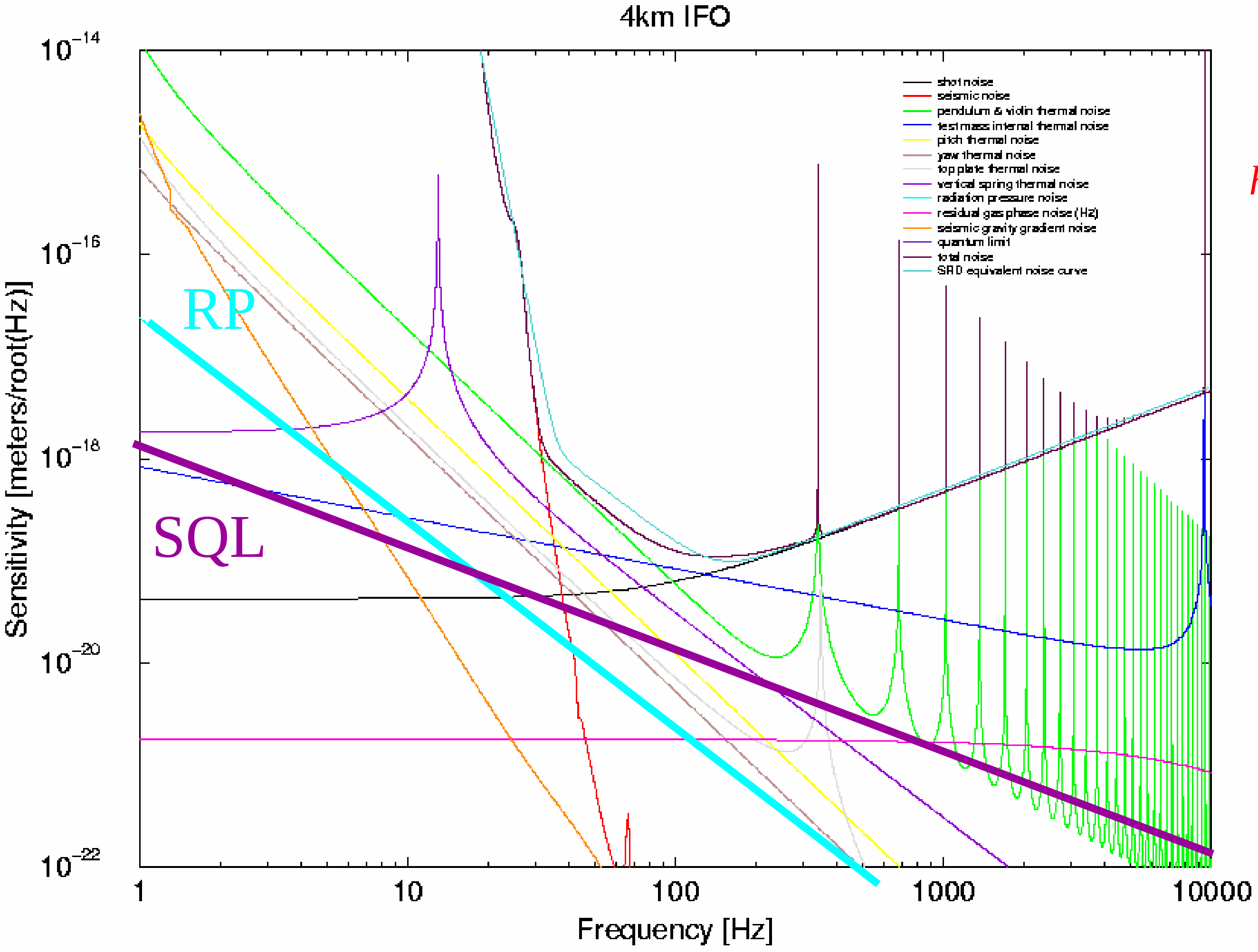
results in opposite displacements of *each* of the masses; strain $h_{rp} = \frac{\delta L}{L} = \frac{2}{L}\frac{1}{mf^2}\sqrt{\frac{h_{Pl}T(f)P_{laser}}{8\pi^3 c\lambda}}$

NOTE: scaling with $\sqrt{P_{laser}}$, scaling with the arm length

Total optical readout, or quantum noise:

quadrature sum $h_q = \left(h_{shot}^2 + h_{rp}^2\right)^{1/2}$; can be optimized

Optical readout noise



Optical readout noise:

$$h_{ro}(f) = \sqrt{h_{shot}^2(f) + h_{rp}^2(f)}$$

Optimize h_{ro} wrt P_{laser} at each point in f; Locus of points is the Standard Quantum Limit, Obtainable from Heisenberg Uncertainty

$$h_{SQL} = \frac{1}{\pi f L}\sqrt{\frac{\hbar}{m}}$$

Thermal displacement noise

Mechanical systems excited by the thermal environment results in physical motions of the tests masses

Each normal mode of vibration has $k_B T$ of energy; for a SHO, $x_{rms} = \sqrt{\langle (\delta x)^2 \rangle} = \sqrt{k_B T / k_{spring}}$

An extended object has many normal modes at discrete frequencies; each will experience thermal excitation.

Dissipation causes the energy, and fluctuations in position, to spread over a range of frequencies, according to Fluctuation-Dissipation theorem:

$\tilde{x}(f) = \frac{1}{\pi f} \sqrt{\frac{k_B T}{\Re(Z(f))}}$, $\Re(Z)$ is the real (lossy) impedance

e.g., damping term in an oscillator: $m\ddot{x} = F_{ext} - \Re(Z)\dot{x} - k_{spring} x$

- viscous damping: $\Re(Z) = b$ = constant. Recall, at a definite f, $\dot{x} = i\,2\pi f\; x$
- internal friction: $F = -kx \quad \Rightarrow \quad F = -k(1 + i\phi(f))x$

$\phi(f)$ is often a constant, = 1/Q

Minimize thermal motion ⇒ materials and techniques for very low loss (high Q)

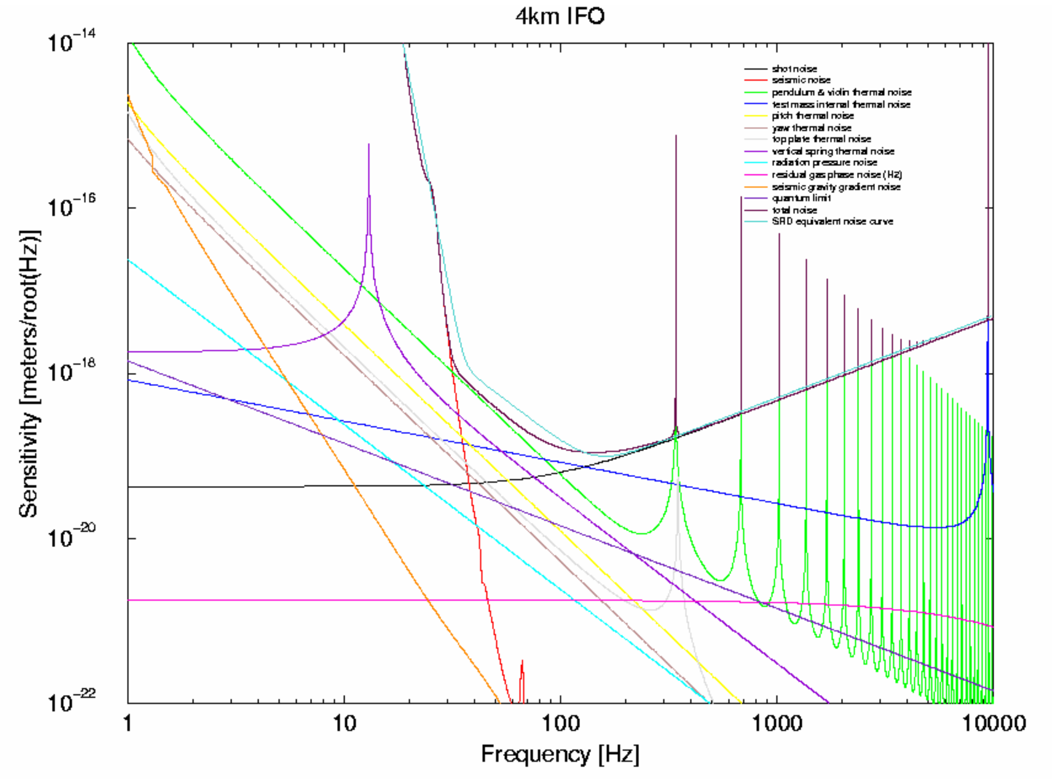
Thermal displacement noise

Sum of many normal modes, $x_{thermal}^2 = \frac{4kT}{2\pi f}\sum_n \frac{\phi_n(f)}{m_n(2\pi f_n)^2}\left\{\frac{1}{\left(1-(f/f_n)^2\right)^2+\phi_n^2(f)}\right\}$

Each with loss $\phi_n(f)$:

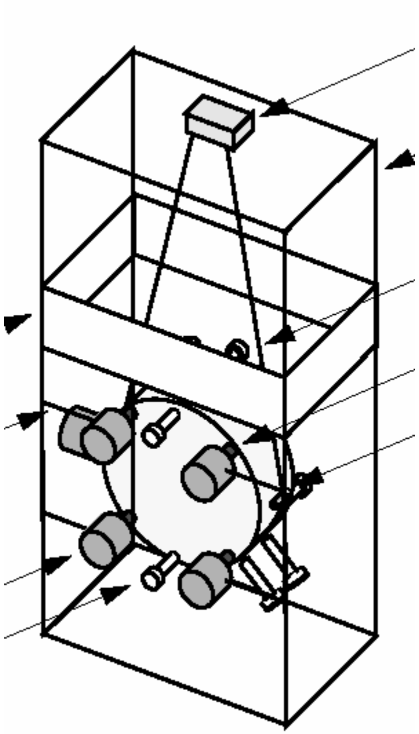
Equivalent strain (noise):

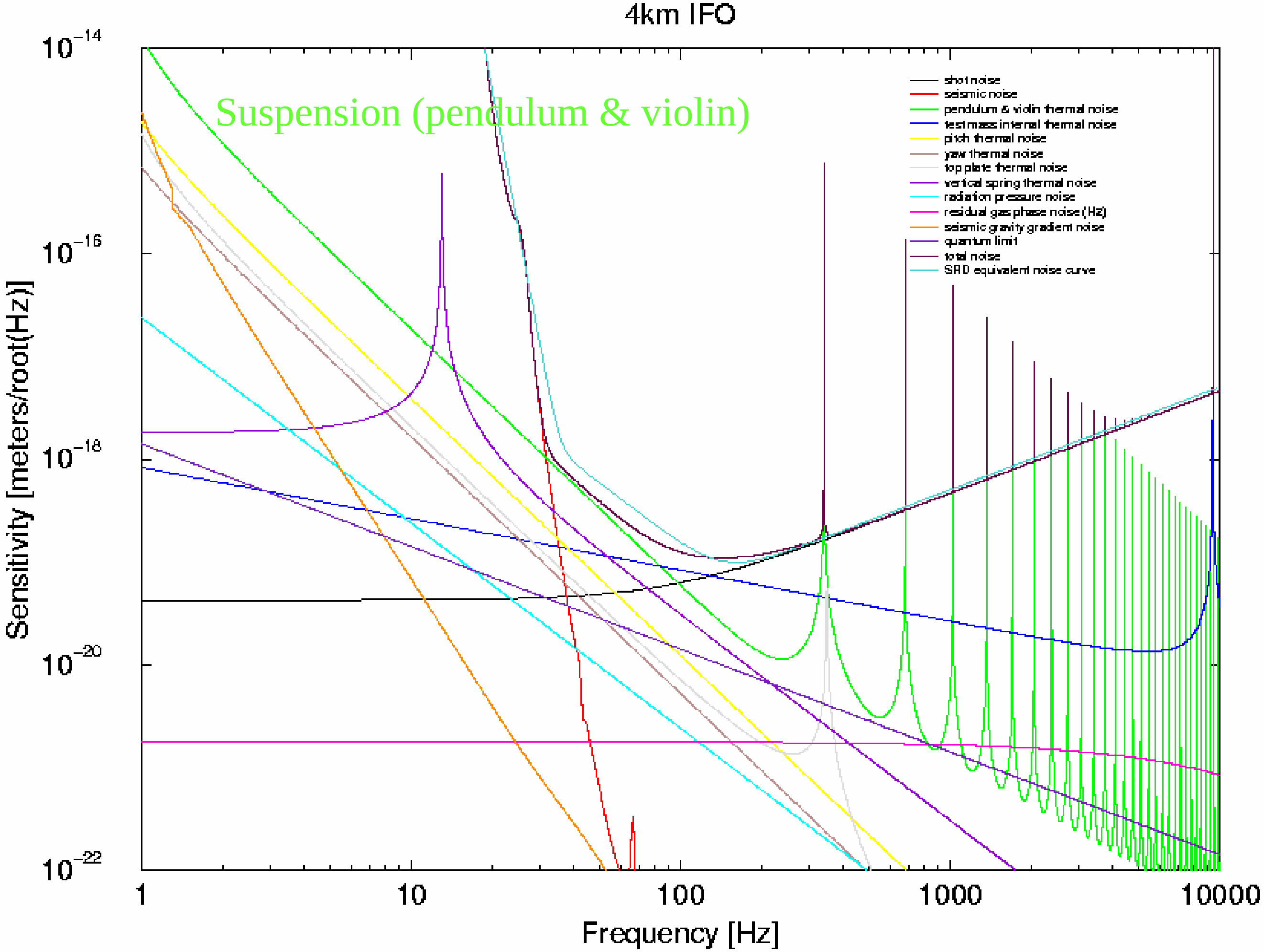
$$h_{thermal}(f) = \frac{2}{L}\sqrt{x_{thermal}^2}$$



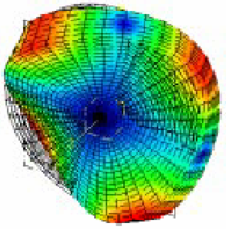
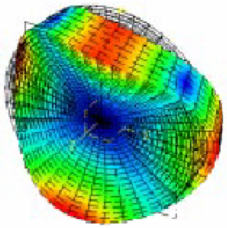
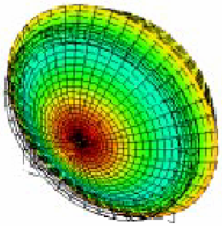
Suspension thermal noise

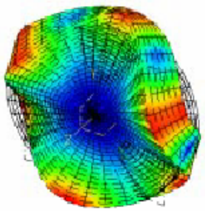
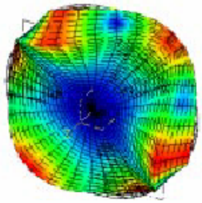
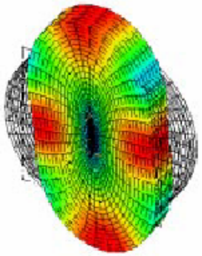
Suspension wires vibrate (violin modes, stretch/bounce modes), kick the test mass around, introducing an harmonic series of noise lines



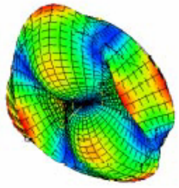
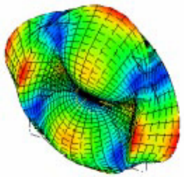
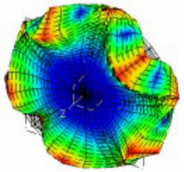
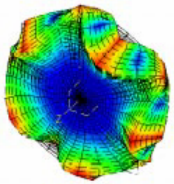


Vibrational modes of test masses

Mode Shape	Frequency (Hz)
	3785
	3785
	5578

Mode Shape	Frequency (Hz)
	7975
	7975
	11259

. . .

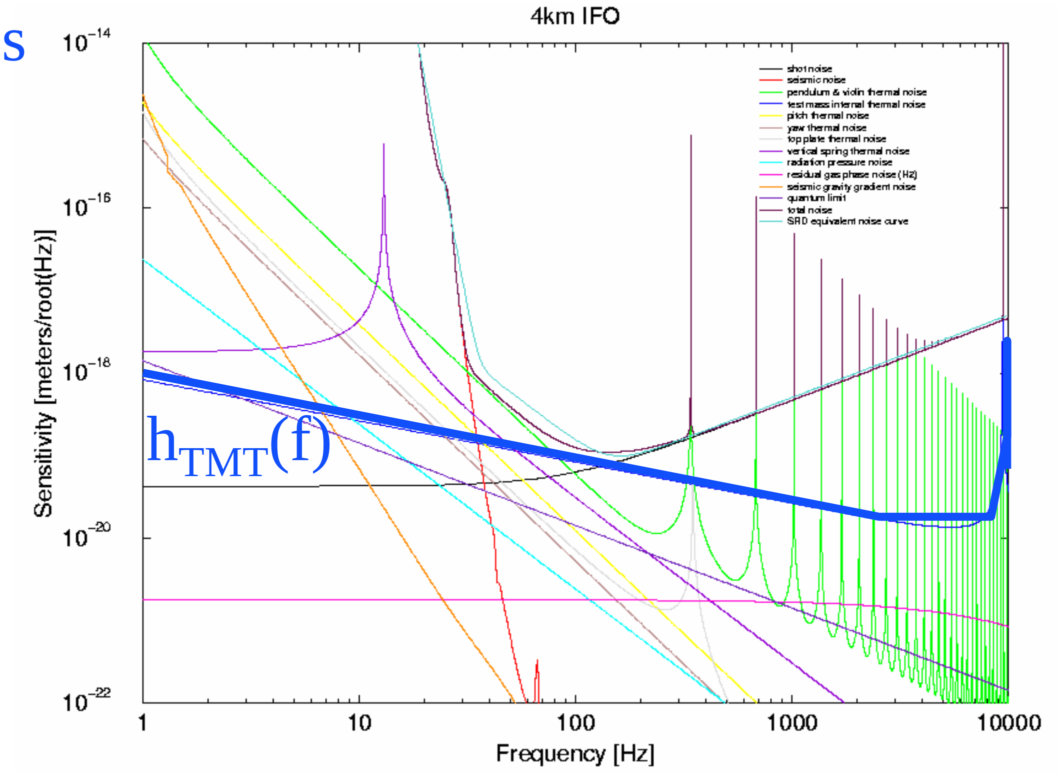
Mode Shape	Frequency (Hz)
	17388
	17388
	17958
	17958

This is for beam splitter. Test masses have no resonances below ~8KHz (?).

Test mass internal thermal noise

$$x_{TMT}^2 = \frac{4kT}{2\pi f} \sum_n \frac{\phi_n(f)}{m_n (2\pi f_n)^2} \left\{ \frac{1}{\left(1 - (f/f_n)^2\right)^2 + \phi_n^{\,2}(f)} \right\}$$

Test masses have normal modes
Above the LIGO band



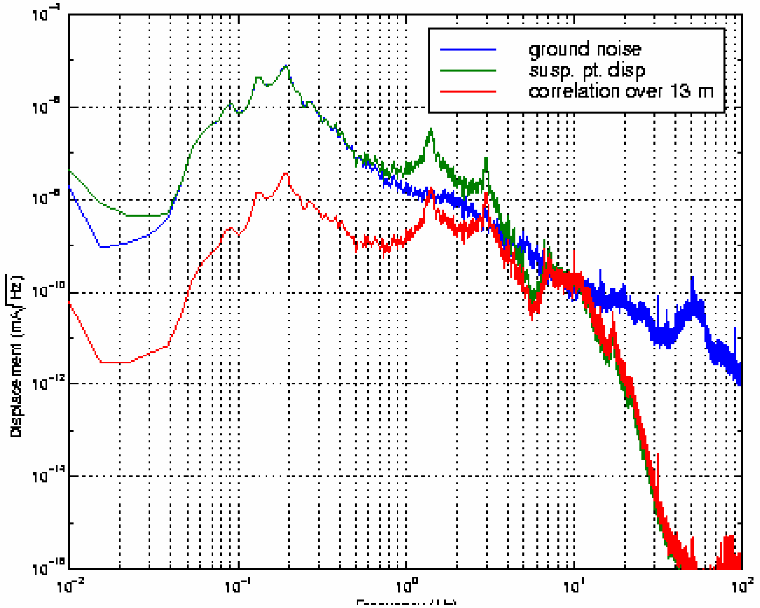
Equivalent strain:

$$h_{TMT}(f) = \frac{2}{L}\sqrt{x_{TMT}^2}$$

Seismic displacement noise

Motion of the earth

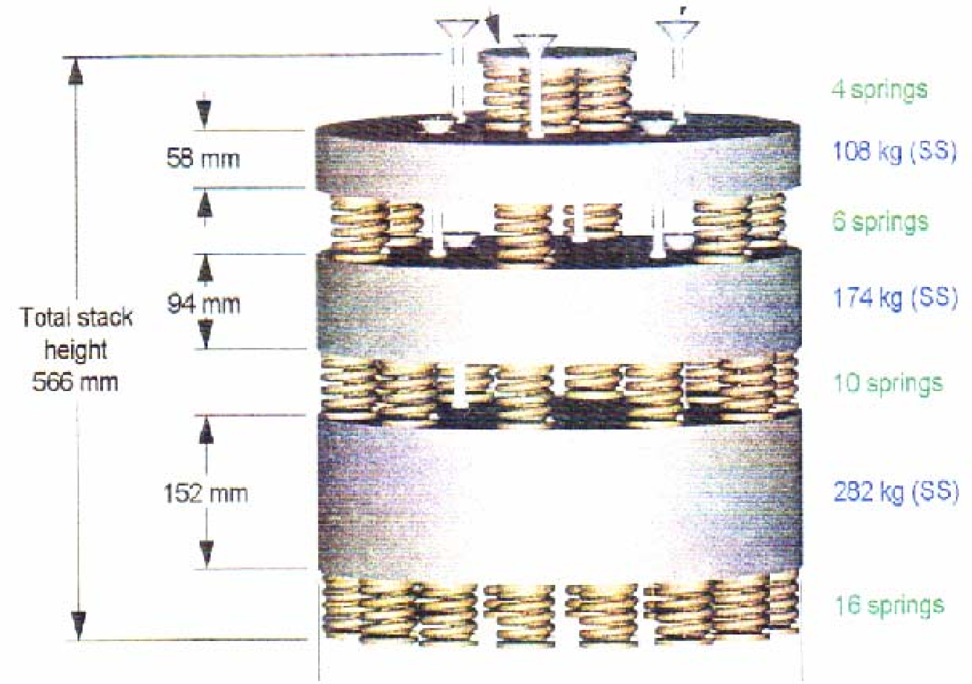
- driven by wind, volcanic/seismic activity, ocean tides, humans
- requires *e.g.*, roughly 10^9 attenuation at 100 Hz
- ~300 micron tidal motion, microseismic peak at 0.16 Hz.
- At low frequencies, motion is correlated over two mirrors

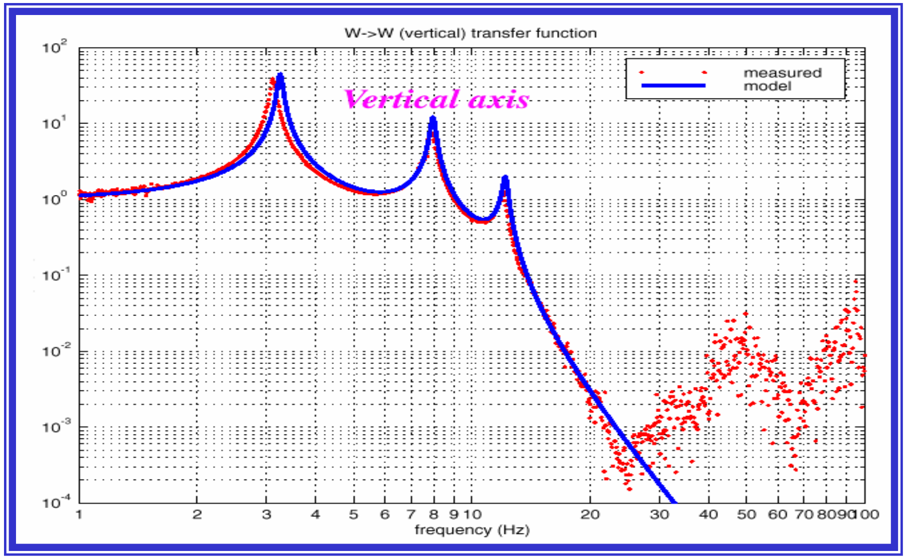


Approaches to limiting seismic noise

- careful site selection
    - far from ocean, significant human activity, seismic activity
- active control systems (only microseismic peak for now)
    - seismometers, regression, feedback to test masses
- simple damped harmonic oscillators in series
    - \`stacks', constrained layer springs and SS masses
- one or more low-loss pendulums for final suspension
    - gives $1/f^2$ for each pendulum

Seismic isolation stacks





Seismic Isolation Systems

Support Tube Installation

Stack Installation

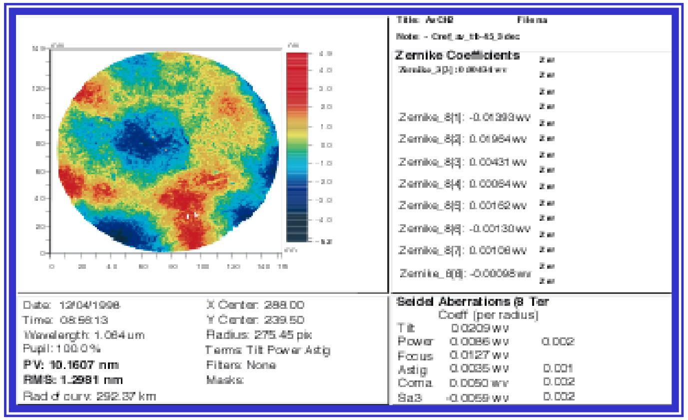
Coarse Actuation System

Noise from imperfect Optics

Highly efficient optical system:

~50 ppm lost per round-trip

- optics are 25 cm diameter, 10 cm thick fused silica cylinders
- light beam ~10 cm diameter; 1ppm scattered, ~1ppm absorbed



Title: AvOIR Filena

Note: - Cref_av_tilt-45_3dec

Zernike Coefficients

Zernike_8[1]: -0.01393 wv

Zernike_8[2]: 0.01964 wv

Zernike_8[3]: 0.00431 wv

Zernike_8[4]: 0.00084 wv

Zernike_8[5]: 0.00162 wv

Zernike_8[6]: -0.00130 wv

Zernike_8[7]: 0.00108 wv

Zernike_8[8]: -0.00098 wv

Date: 12/04/1998
Time: 08:58:13
Wavelength: 1.064 um
Pupil: 100.0%
PV: 10.1607 nm
RMS: 1.2981 nm
Rad of curv: 292.37 km

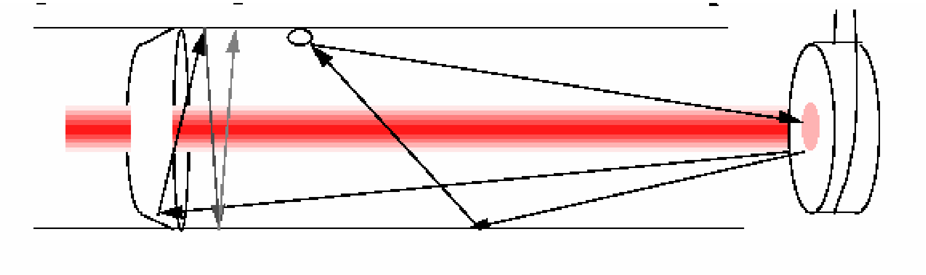
X Center: 288.00
Y Center: 239.50
Radius: 275.45 pix
Terms: Tilt Power Astig
Filters: None
Masks:

Seidel Aberrations (8 Ter

	Coeff (per radius)	
Tilt	0.0209 wv	
Power	0.0086 wv	0.002
Focus	0.0127 wv	
Astig	0.0035 wv	0.001
Coma	0.0050 wv	0.002
Sa3	-0.0059 wv	0.002

Constraints on optical surface due to noise requirements:

- minimize scatter (power loss ⇒ phase noise)
- minimize absorption (thermal distortions, lensing ⇒ phase noise)
- minimize scattering out of beam, onto tube, back into beam (phase noise)
- minimize wavefront distortions (*contrast defect* at dark port ⇒ phase noise)



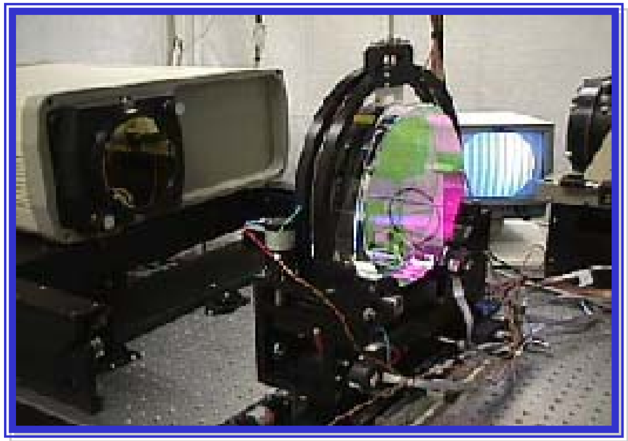
Results

- **λ/800** over central 10 cm (~1 nm rms); fine scale `superpolish‘
- Sophisticated *baffling*

LIGO Optics

mirrors, coating and polishing

- SUPERmirrors:
  - » High uniformity fused silica quartz
  - » reflectivity as high as 99.999%
  - » losses < 1 ppm in coating, 10 ppm in substrate
  - » polished with mircoroughness < $\lambda/1800 \approx 0.5$ nm
  - » and ROC within spec.
  - ≈ ($\delta R/R < 5\%$, except for BS)
- Suspensions: hang 10kg optic by a single loop of wire, and hold it steady with feedback system

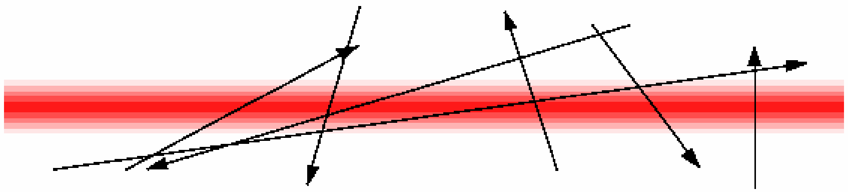


Residual gas in beam tube

Light must travel 4 km without attenuation or degradation

- refractive index fluctuations in gas cause variations in optical path, phase noise
- residual gas scatters light out of, then back into, beam; phase noise
- Residual gas pressure fluctuations buffet mirror; displacement noise
- Contamination: low-loss optics can not tolerate surface 'dirt';

  High circulating powers of ~10-50 kW burns dirt onto optic surface



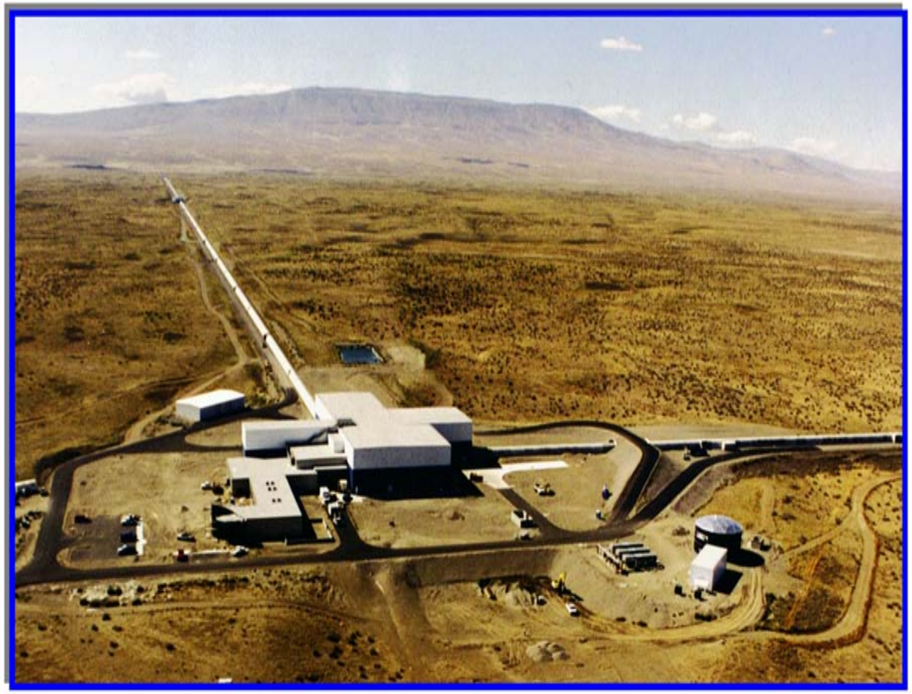
requirement for vacuum in 4 km tubes:

- H_2 at 10^{-6} torr initial, 10^{-9} torr ultimate
- H_2O at 10^{-7} torr initial, 10^{-10} ultimate
- Hydro-, flourocarbons < 10^{-10} torr
- vacuum system, 1.22 m diameter, ~10,000 m^3
- strict control on in-vacuum components, cleaning

LIGO beam tubes

LIGO Livingston Observatory
LLO

LIGO Hanford Observatory
LHO



LIGO *Beam Tube*

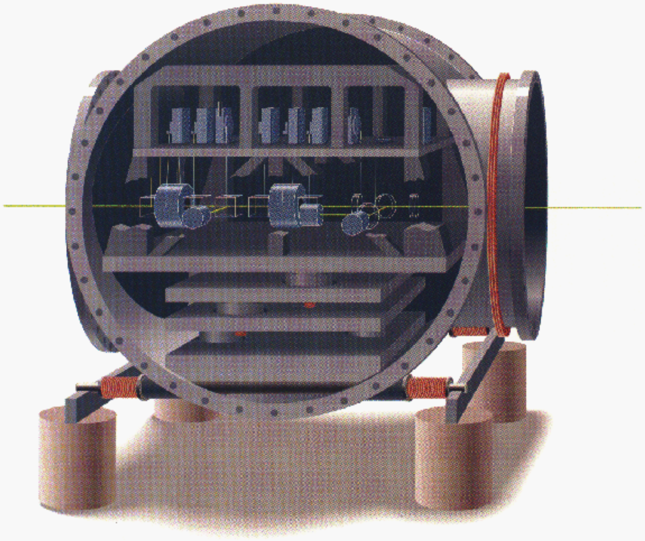
Beam light path must be high vacuum, to minimize "phase noise"

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

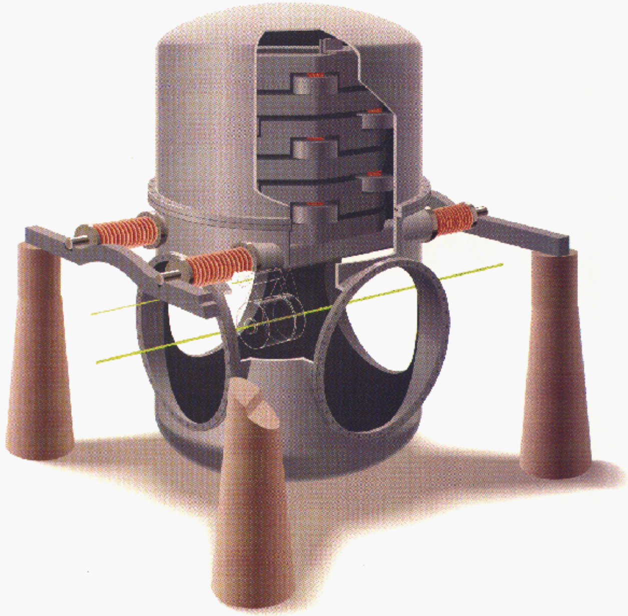
LIGO vacuum equipment

All optical components must be in high vacuum, so mirrors are not “knocked around” by gas pressure

LIGO Vacuum Chambers



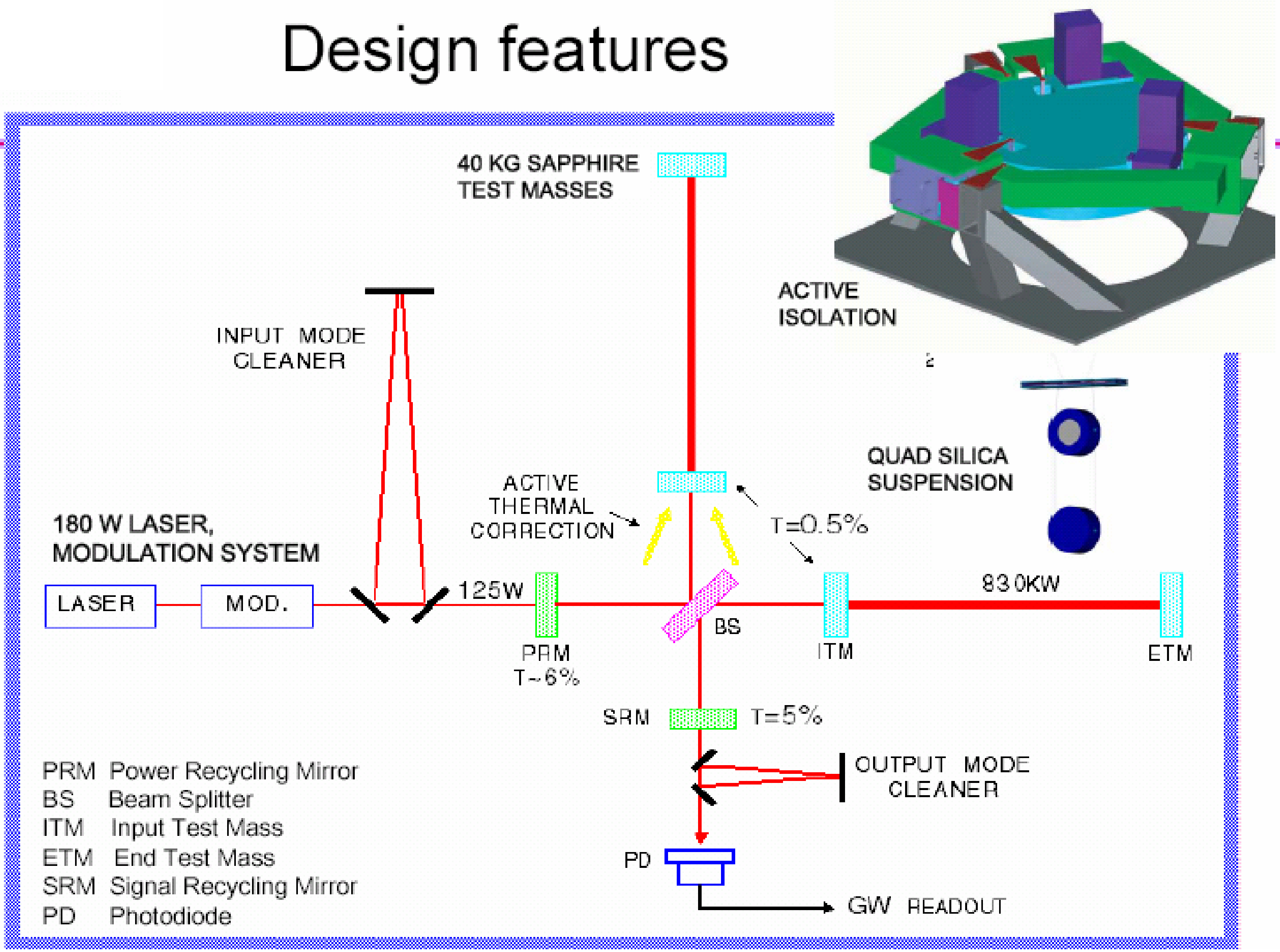
HAM Chambers



BSC Chambers

Advanced LIGO

Design features

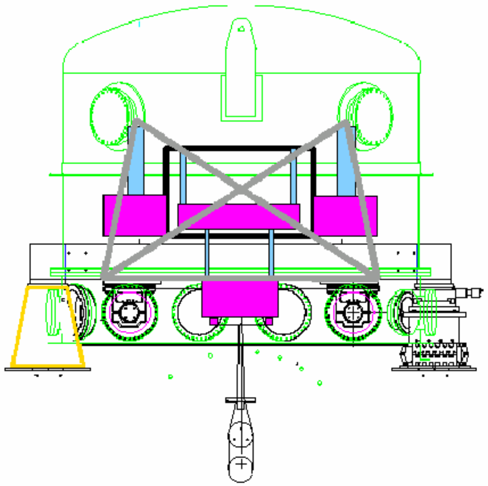


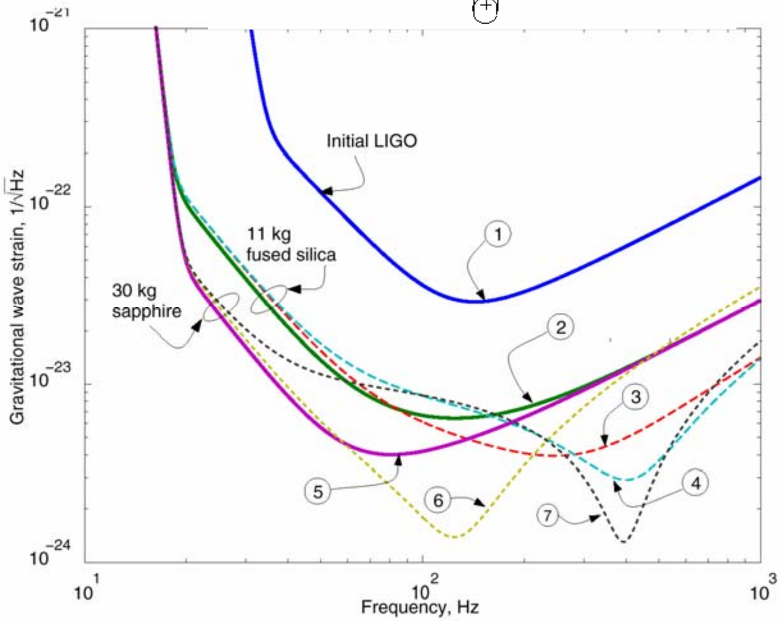
PRM	Power Recycling Mirror
BS	Beam Splitter
ITM	Input Test Mass
ETM	End Test Mass
SRM	Signal Recycling Mirror
PD	Photodiode

Advanced LIGO

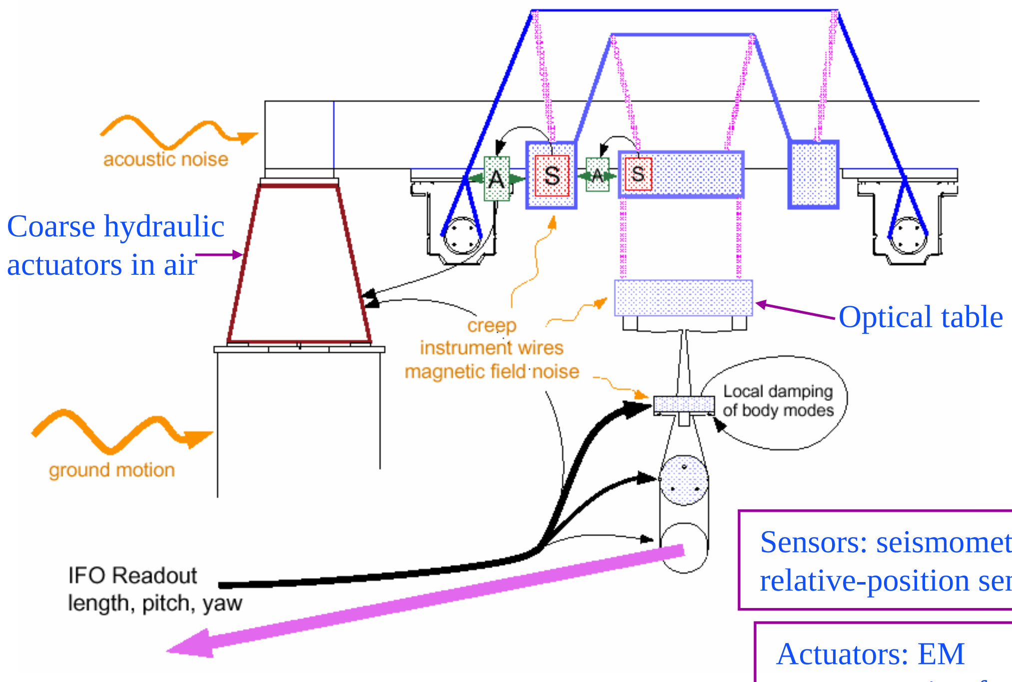
incremental improvements

- Reduce shot noise:
  higher power CW-laser: 12 watts ⇒120 watts
- Reduce shot noise: Advanced optical configuration: signal recycling mirror (7th suspended optic) to tune shot-noise response in frequency
- To handle thermal distortions due to beam heating: advanced mirror materials, coatings, thermal de-lensing compensation (heating mirror at edges)
- Reduce seismic noise: Active seismic isolation.
  Seismic wall moved from 40 Hz ⇒ ~ 10 Hz.
- Reduce seismic and suspension noise: Multiple pendulum suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise: Last pendulum stage (test mass) is controlled via photonic and/or electrostatic forces (no magnets).
- Reduce test mass thermal noise:
  High-Q material (40 kg of single-crystal sapphire).



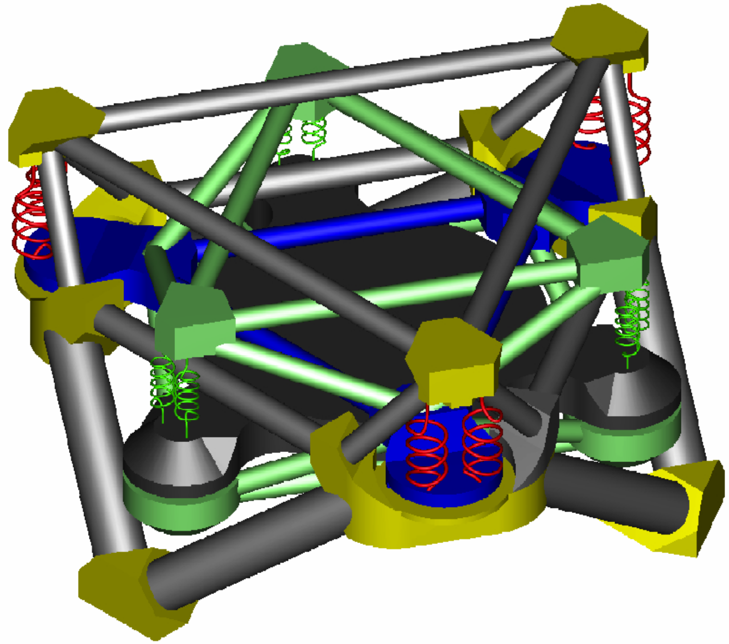


Active control of SEI system



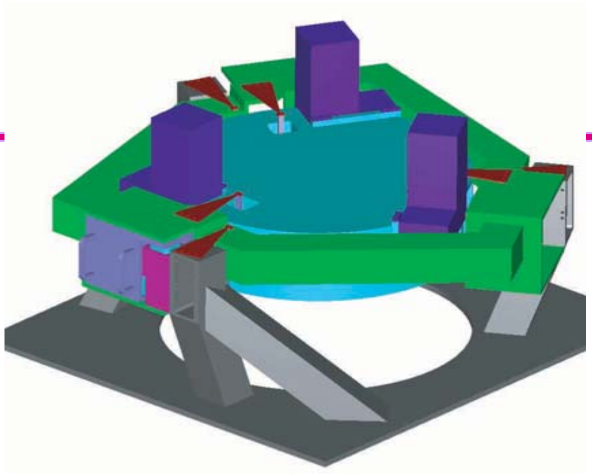
Sensors: seismometers, relative-position sensors

Actuators: EM non-contacting forcers

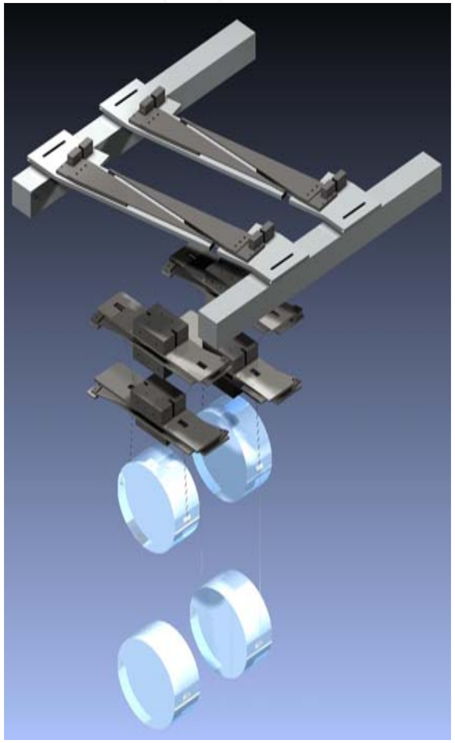


Two active stages: cages, masses, springs, S/A pairs.
All DOF under active control.

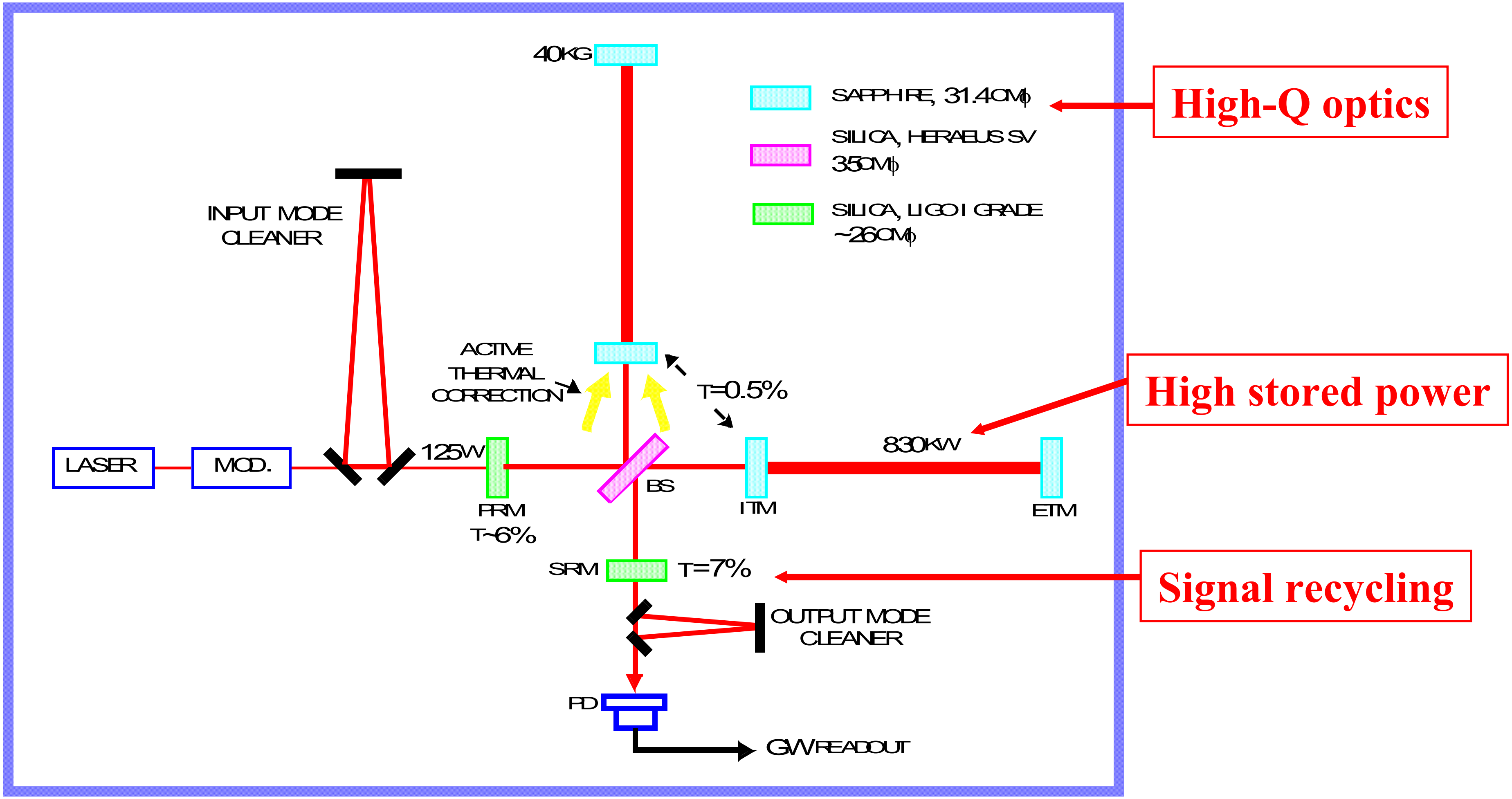
Advanced LIGO R&D



- Development of multiple pendulum suspensions with silica fibers
    - » Willems et al
- Development of advanced seismic isolation and suspension systems
    - » de Salvo et al
- Advanced interferometer techniques, detection of gravity at DC
    - » Drever et al
- Simulations of complex interferometer behavior
    - » Yamamoto et al
- Quantum-nondemolition optical techniques to reduce quantum readout noise
    - » Whitcomb et al



LIGO II Optics



High-Q optics

High stored power

Signal recycling

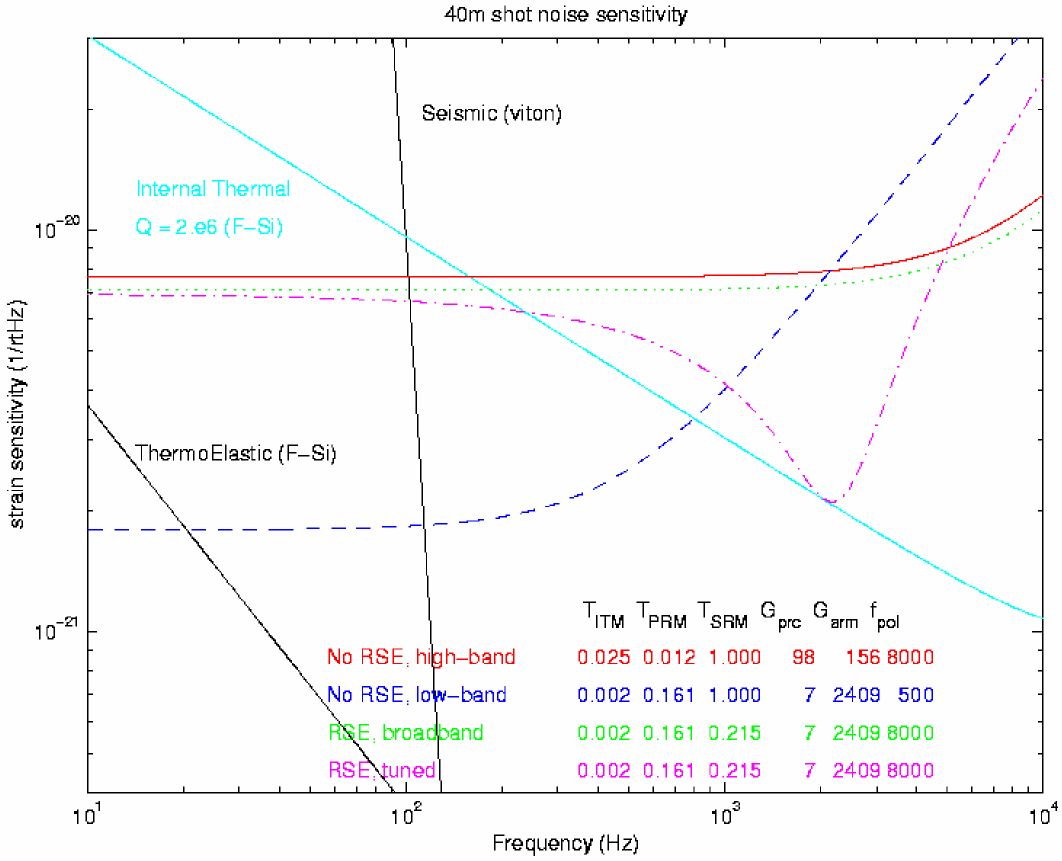
Signal recycling mirror to optimize sensitivity

- The signal mirror is NOT used to store the laser light; all it sees is light generated by the GW signal.

- The signal recycling cavity allows one to tune the response of the IFO to the signal, as a function of its frequency, independently of the light storage in the arms (the “reservoir” of light available to be converted into signal light.

- The frequency response of the IFO can be tuned to put the sensitivity where it is most needed (at high frequencies).

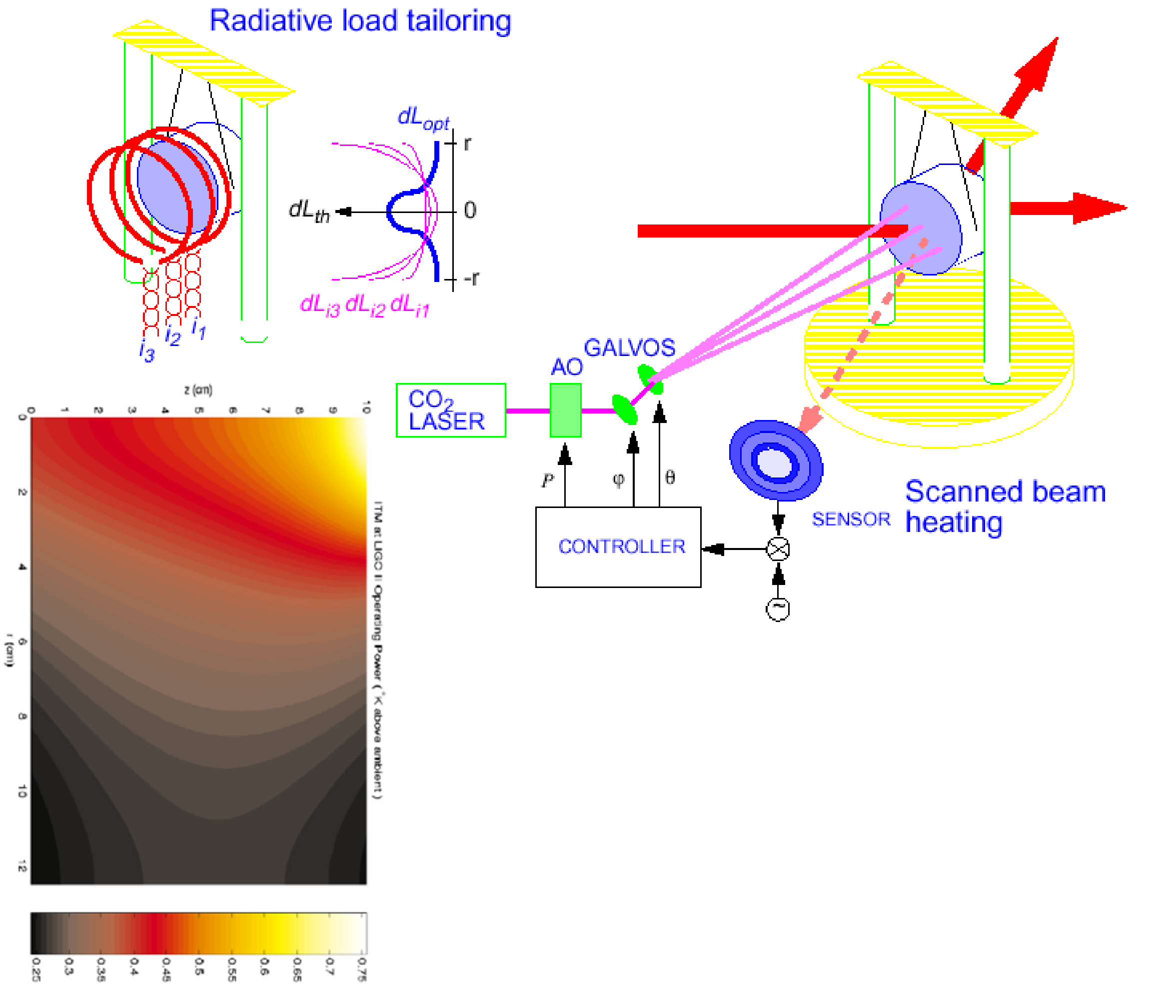
- Net result:
  - 2× sensitivity for CBI;
  - or ~ 10 × in event rate.



Thermal compensation (de-lensing) methods

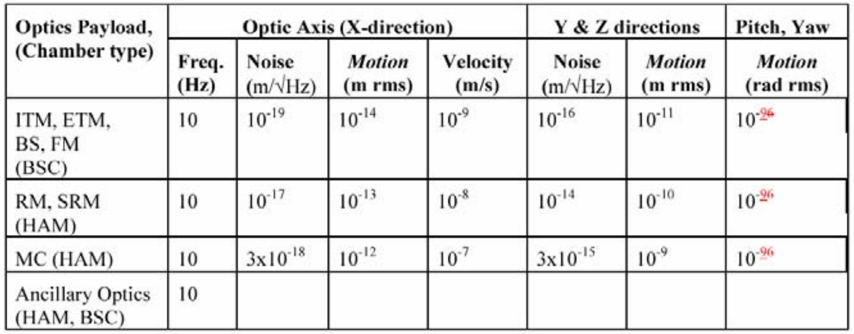
- Beam heating at center of optic distorts the optic due to thermal expansion, changing ROC, index of refraction, etc.

- Compensate by heating the optic from the circumference in, to give uniform and constant-in-time thermal loading as the IFO is operated.

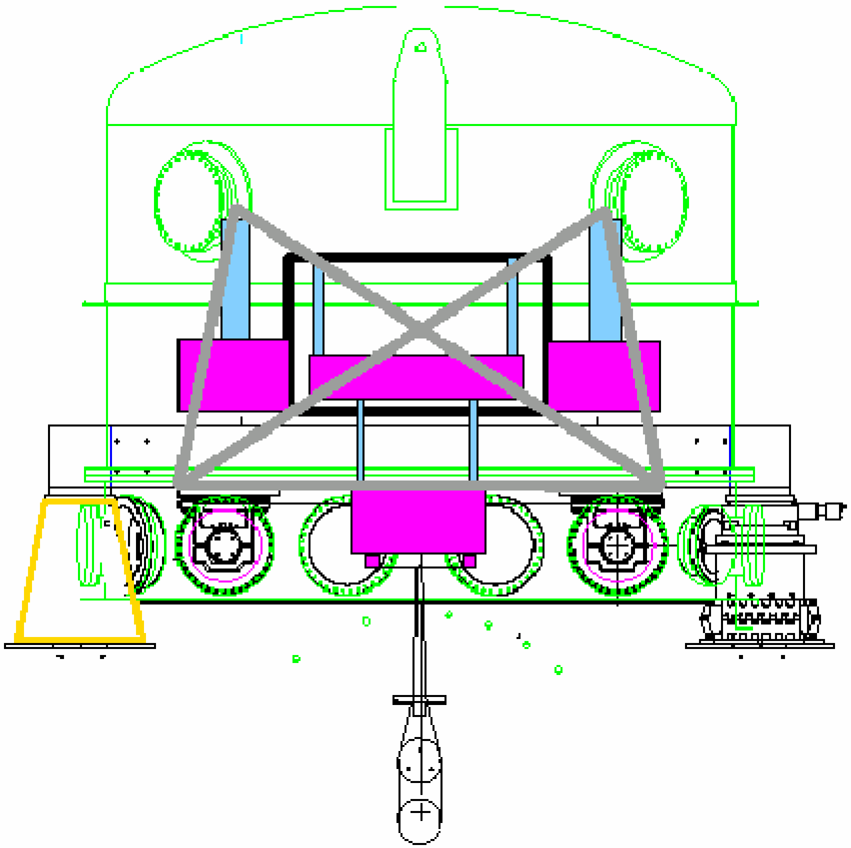


LIGO II Active seismic isolation and multiple pendulum suspension

- Must support LIGO test mass optic at the beamline.
- Must fit inside existing vacuum chambers, and be fully vacuum compatible.
- Must provide full control system.
- Must satisfy specs:

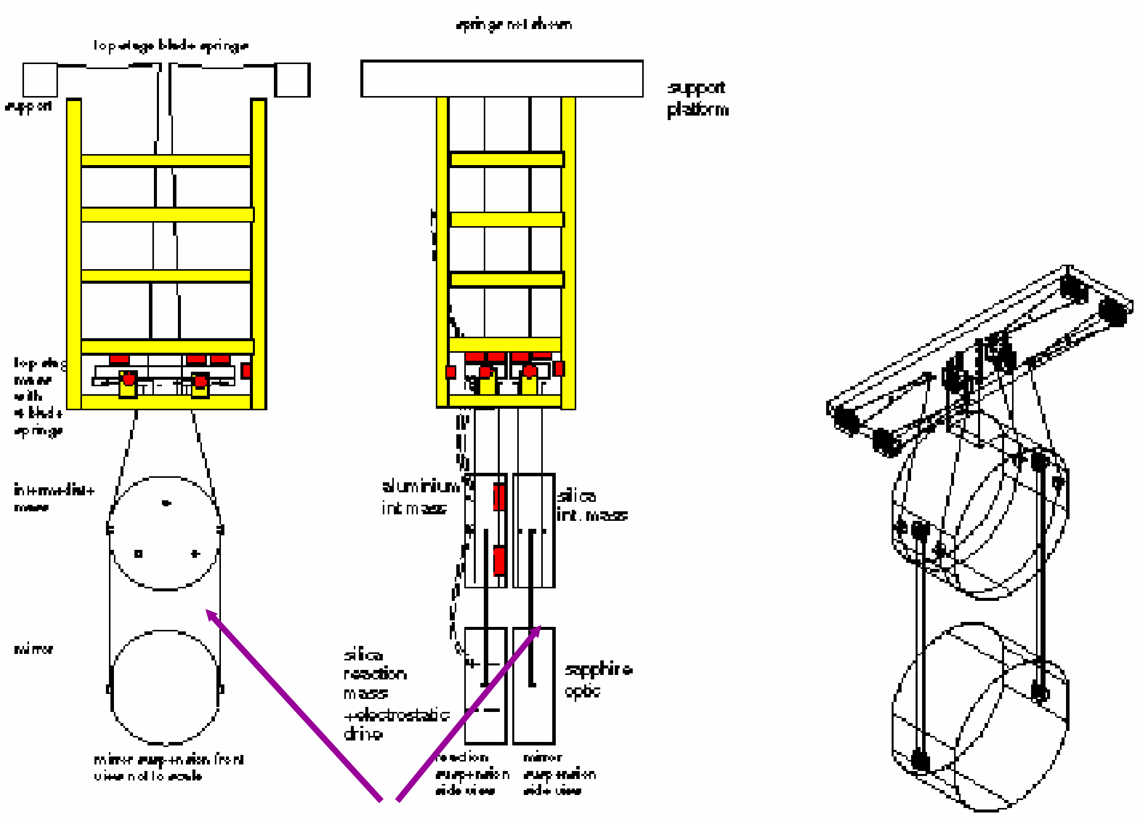


Optics Payload, (Chamber type)	Optic Axis (X-direction)				Y & Z directions		Pitch, Yaw
	Freq. (Hz)	Noise (m/√Hz)	*Motion* (m rms)	Velocity (m/s)	Noise (m/√Hz)	*Motion* (m rms)	*Motion* (rad rms)
ITM, ETM, BS, FM (BSC)	10	10^{-19}	10^{-14}	10^{-9}	10^{-16}	10^{-11}	10^{-96}
RM, SRM (HAM)	10	10^{-17}	10^{-13}	10^{-8}	10^{-14}	10^{-10}	10^{-96}
MC (HAM)	10	$3x10^{-18}$	10^{-12}	10^{-7}	$3x10^{-15}$	10^{-9}	10^{-96}
Ancillary Optics (HAM, BSC)	10						



GEO multiple pendulum design

- 3 or 4 pendulum stages; each provides $1 / f^2$ filtering for $f > f_0$
- Top stage has 6 OSEMs for 6-dof control (“marionetta”), relative to support cage.
- Normal modes of the multiple pendulum (~24) must not have nodes at the top, so they can be controlled from the top.
- Blade springs at the very top provide tuned vertical isolation.
- Lower stages must control w.r.t. stage above it; so the actuators must push against a “reaction mass” which is as quiet as the stage above it
- lowest stage (test mass optic) is attached to stage above it with fused silica fibers.



Fused silica fibers

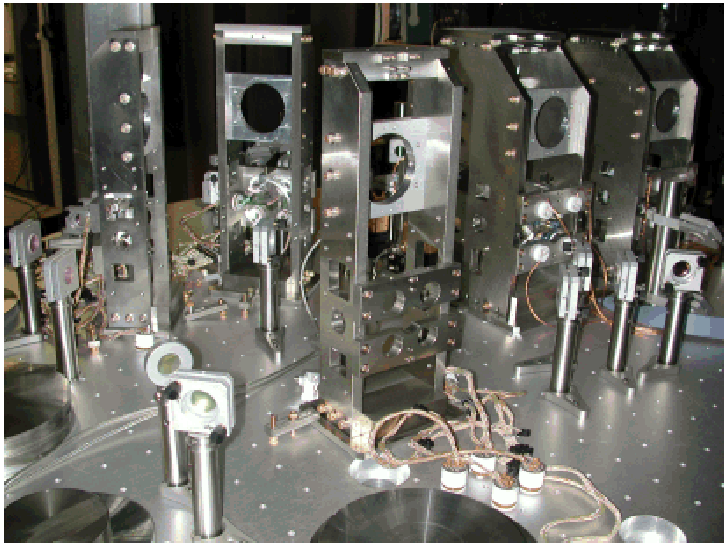
Prototype IFOs

- **40 meter (Caltech)** :
  full engineering prototype for optical and control plant for AdvLIGO
- **Thermal Noise Interferometer (TNI, Caltech)** :
  measure thermal noise in AdvLIGO test masses
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** :
  full-scale prototyping of AdvLIGO seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford) :**
  advanced IFO configs (Sagnac)
- **10 meter IFO at Glasgow** : prototype optics and control of RSE
- **TAMA 30 meter (Tokyo) :** Advanced technologies
  (SAS, RSE, control schemes, sapphire, cryogenic mirrors)
- **AIGO (Gingin, Western Australia)** : high powered lasers, thermal effects and compensation

Advanced LIGO prototyping

- Caltech LIGO 40 Meter Gravitational Wave Interferometer (Weinstein)
  - » Full engineering prototype of the Advanced LIGO optical configuration and controls

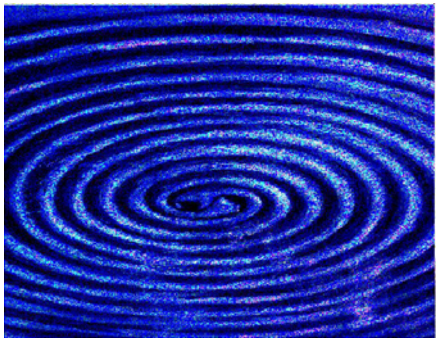
- Thermal Noise Interferometer (Libbrecht)
  - » Direct measurement of thermal noise in mirrors made of advanced materials

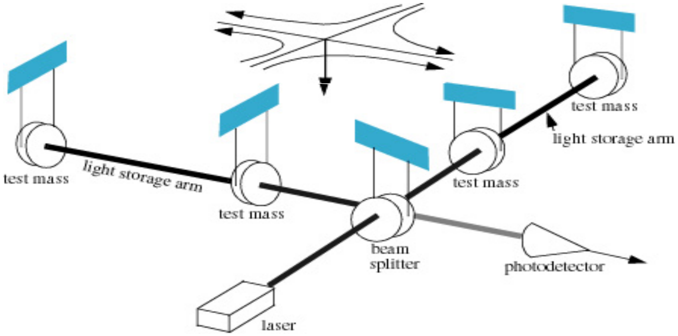


The LIGO detectors

- They employ a wide range of clever techniques to overcome the noise that surrounds us, ultimately limited by quantum effects.
- They are great examples of the art and science of precision measurement.
- They are marvels of engineering, in service to marvelous science.
- They *work*, and they will detect GWs soon!

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!