Gravitational Waves: Next Window on the Universe

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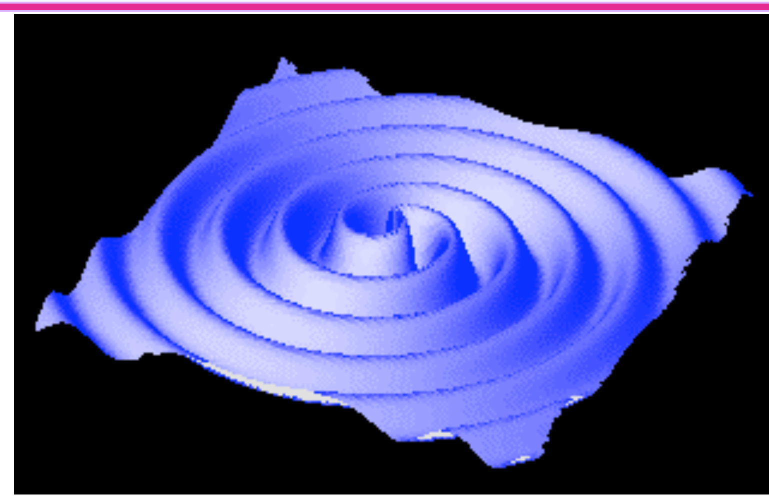
Gravity Waves?

- Einstein's General Relativity is *the* gauge theory of gravity
- Just like Electromagnetism …

  … well, not quite …

  … Graviton spin = 2



LISA

- Einstein's gravity describes curvature of space-time
- Waves are "ripples in the fabric of space-time"
- Newton: instantaneous action at a distance
- Einstein: dynamic gravity information travels at light speed

Of course!

Gravity is Geometry

- Newton: $F = ma = \frac{GmM}{r^2}$

  Unlike other forces, effect on *a* is independent of object property *m*

- Einstein: $\boldsymbol{G} = 8\pi \boldsymbol{T}$

  Wheeler's tensor notation - Einstein curvature tensor $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$

  - Stress energy tensor $T_{\mu\nu}$

  Curvature of space-time depends on local stress-energy (mass)

- California Department of Motor Vehicles

  License Plate ***GEQ8PIT*** is offensive to good taste!

Unfortunately, we are unable to approve the requested license plate configuration for the following reason(s):

1. California Vehicle Code, Section 5105(a), states, we must refuse any license plate configuration which carries connotations offensive to good taste and decency, or which may be misleading to some of our citizens.

Conservation Laws Rule!

- Conservation of energy-momentum : $\nabla \boldsymbol{T} = 0$
- So, by construction: $\nabla \boldsymbol{G} = 0$
- Conservation of mass-energy: no monopole source
  - » Just like E&M - conservation of charge
- Conservation of momentum: no mass dipole source!

$$\ddot{d} = \frac{\partial^2}{\partial t^2} \sum mx = \frac{\partial}{\partial t} \sum m\dot{x} = \dot{p} = 0$$

  - » Conservation of angular momentum: no “magnetic” dipole source
  - » No spherical sources of Gravity Waves
- Gravity waves are quadrupole (& higher)
  - » Graviton spin = 2
- Gravity wave detectors must be quadrupole antennas

Quadrupole Sources & Waves …

- Coalescing binary
  - » Black holes and/or neutron stars
- Aspherical pulsar
- Aspherical supernova collapse
- Big Bang

- Linearize General Relativity in weak field limit, $h_{\mu\upsilon}$ small

  metric: $g_{\mu\upsilon} = \eta_{\mu\upsilon} + h_{\mu\upsilon}$

  transverse traceless gauge: $\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\upsilon} = 0$

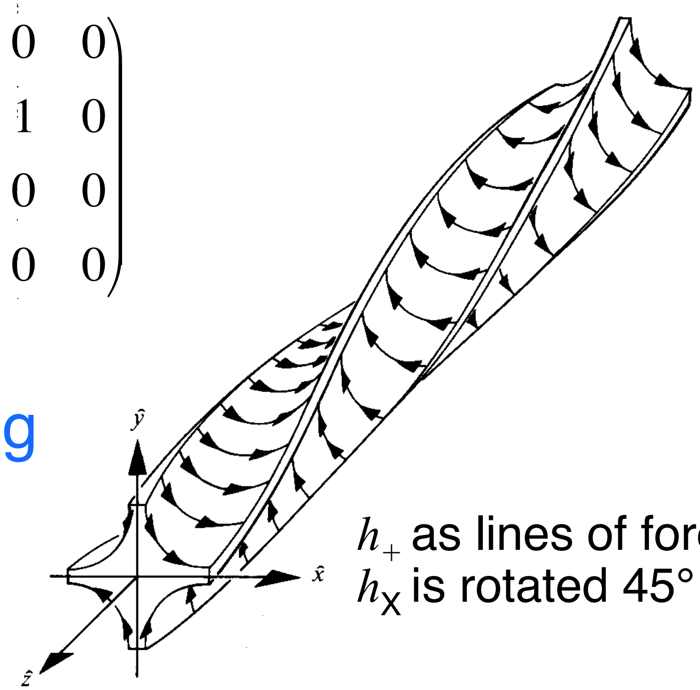
… Quadrupole Sources & Waves …

- Elements of $h_{\mu\upsilon}$ are waves, $h(\omega t - \boldsymbol{k} \bullet \boldsymbol{x})$
- Transverse, traceless with 2 polarizations: $h = ah_{+} + bh_{x}$

$$h_{+} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_{X} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- Resonant bar detectors are rung by effective force

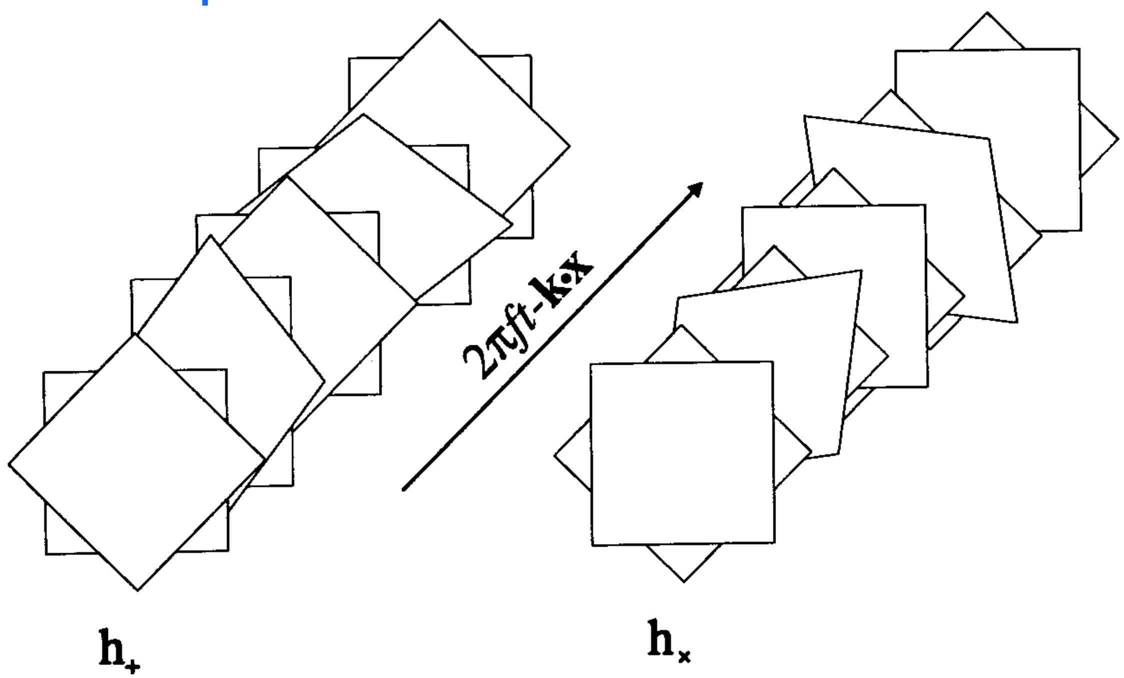
  Early GW detector design
  ~ 6 are still in use ~900 Hz (typ)



h_{+} as lines of force
h_{X} is rotated 45°

… Quadrupole Sources & Waves

- In this "TT" gauge, coordinates are worldlines of freely falling bodies
- Distance between masses at corners of a square change as gravity wave passes
- h_+ polarization:
  - X expands
    Y shrinks
  - Y expands
    X shrinks
    …
- $h_\times$ polarization
  - Rotated 45°

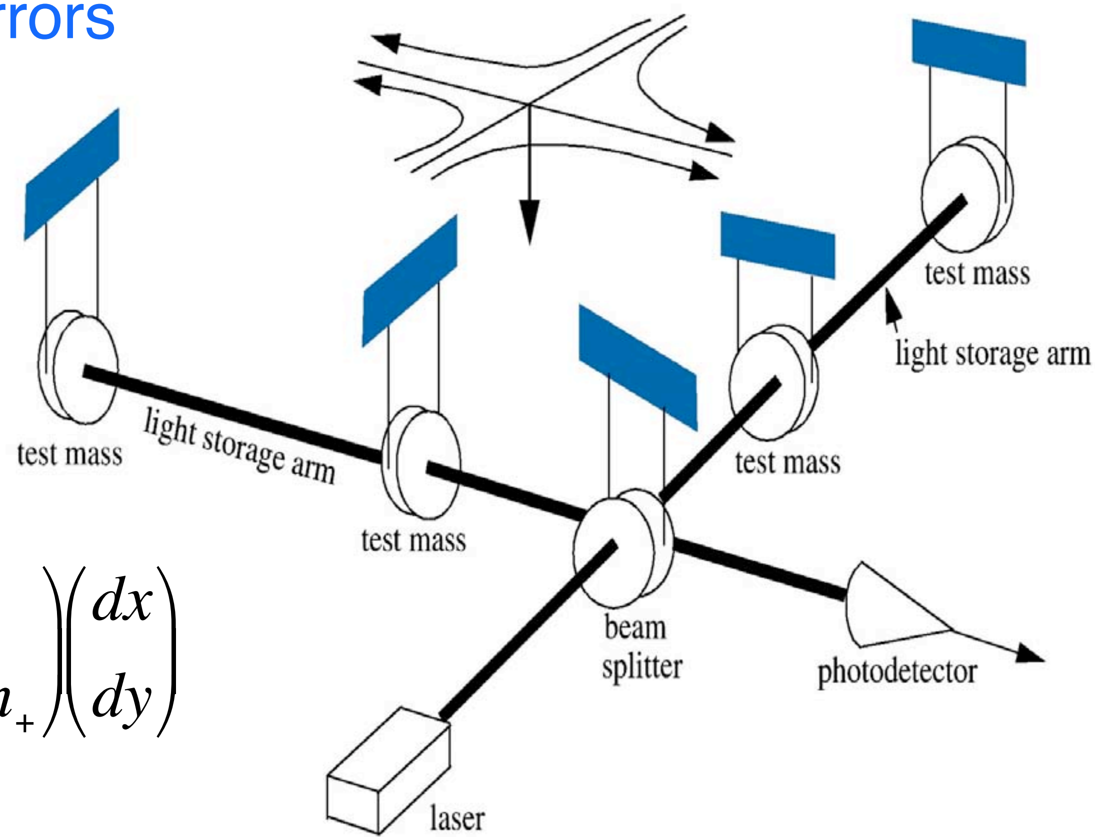


Quadrupole GW Antennas

- A natural detector: interferometers measure length
- Test masses are mirrors

$$dL^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$$

$$= \begin{pmatrix} dx & dy \end{pmatrix} \begin{pmatrix} 1 + h_+ & h_X \\ h_X & 1 - h_+ \end{pmatrix} \begin{pmatrix} dx \\ dy \end{pmatrix}$$

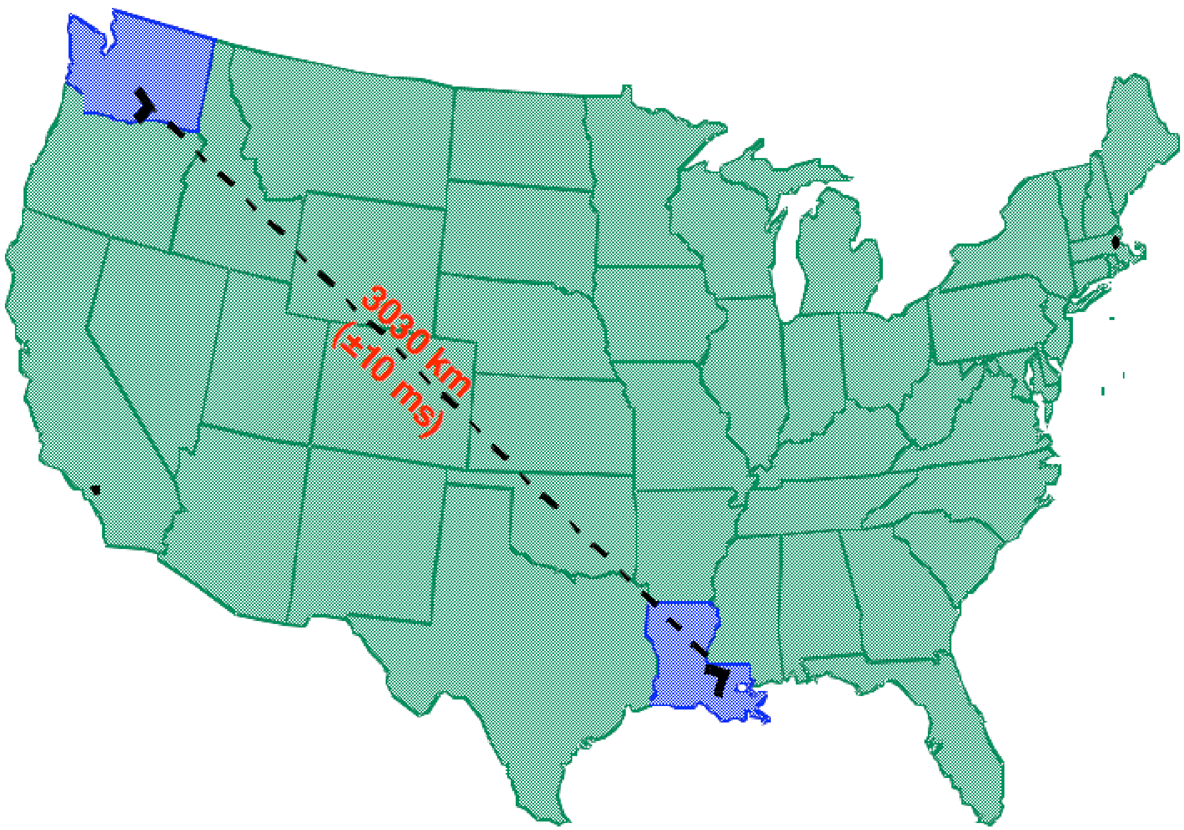


LIGO Laser Interferometer Gravitational-wave Observatory

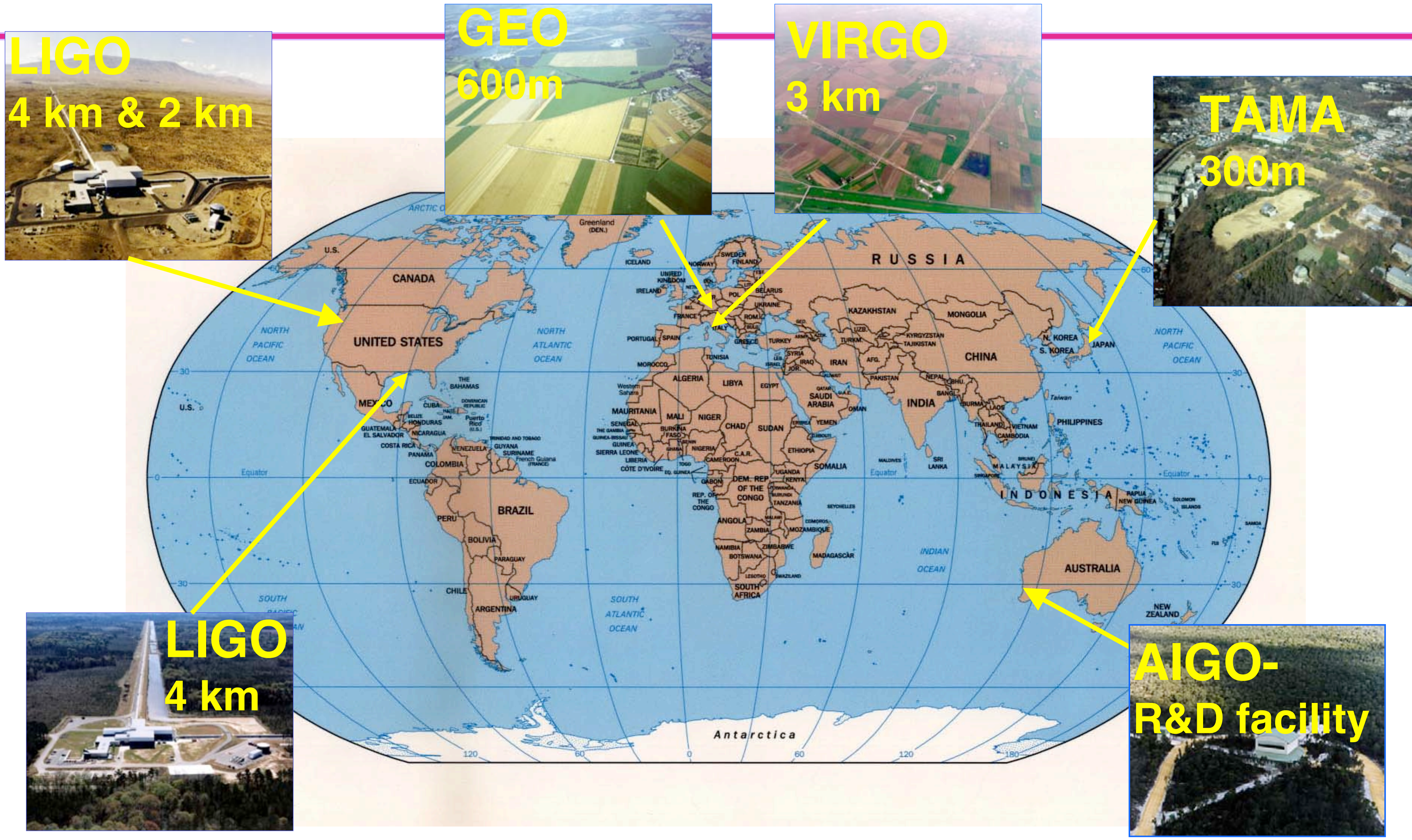
Hanford, Washington State
2 km and 4 km

Livingston, Louisiana
4 km

Two locations, far apart



Global network of interferometers

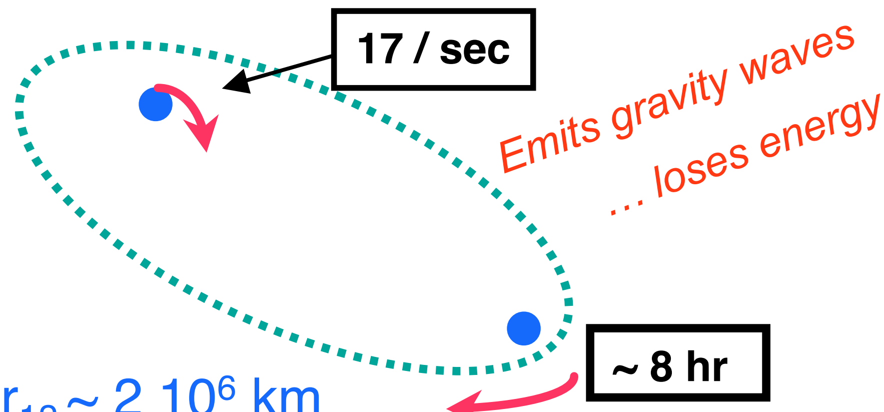


Worldwide Network Gravity Wave Observatories

- Why so large?
  - Gravity waves affect $\delta L/L \sim h$
  - Need large L for high sensitivity
- Why so far apart?
  - Sensitivity is extremely high (as we shall see)
  - Require coincidence of at least 2 detectors
  - Different local noise sources (seismic, electric, audio, …)
- Why so many?
  - Antennas are somewhat directional
  - Multiple observatories can triangulate sources
  - Detector duty factors <100%. Missed SN1987A. Not to happen again.

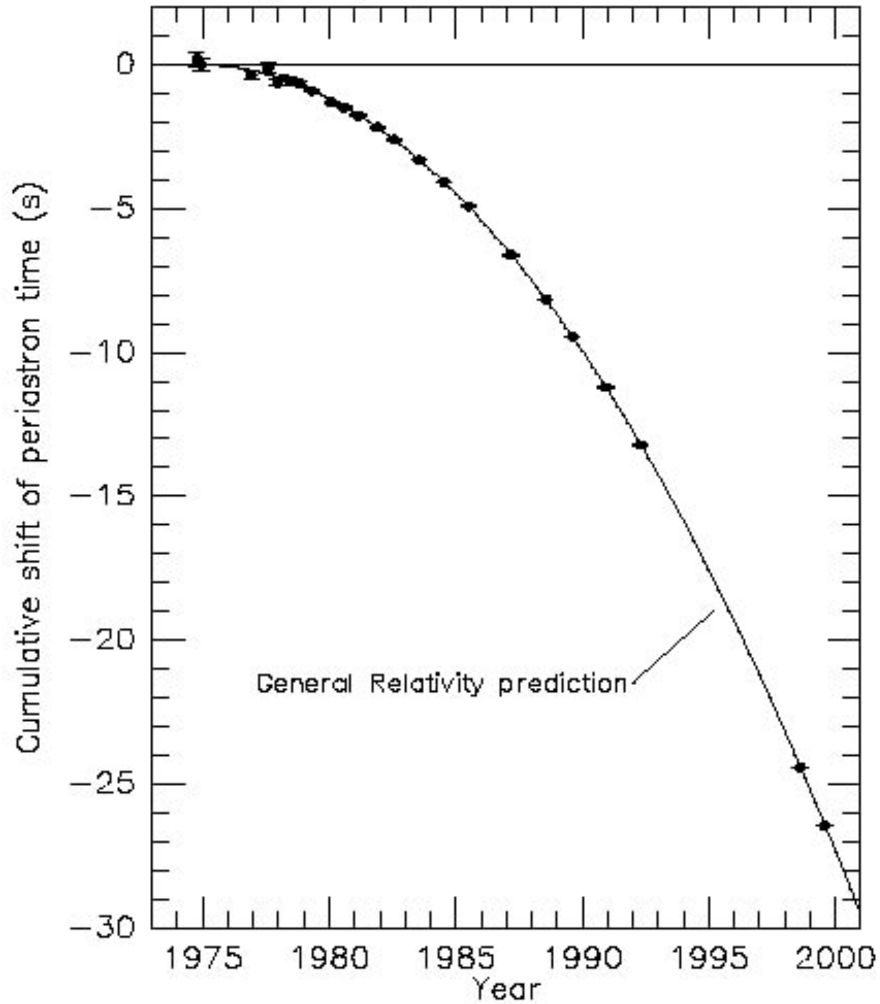
Indirect Detection of Gravity Waves
Hulse & Taylor Nobel Prize

Neutron Binary Pulsar System
PSR 1913 + 16



$r_{12} \sim 2\ 10^6$ km
$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

General Relativity prediction:
spiral in by 3 mm/orbit
slowing orbital period



Direct Detection Sensitivity Requirement

- $h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$ with $I_{\mu\nu}$ the quadrupole moment

- Binary Star $h_{xx} = -h_{yy} \approx \frac{r_{s_1} r_{s_2}}{r_{orbit} R}\cos[2(2\pi f_{orbit})t]$

  where $r_s = \frac{2GM}{c^2}$ are Schwarzschild radii

- Real numbers: $M \approx 1.4\, M_\odot$

  $r_{orbit} \approx 20$ km $f_{orbit} \approx 400$ Hz

  $R_{Virgo\ Cluster} \approx 15$ Mpc

- $h \approx 10^{-21}$

  $\delta L_X - \delta L_Y \approx 4\ 10^{-16}$ cm $\approx .003\ r_{H\ nucleus}$ over 4 km !!

Much Longer than 4 km!

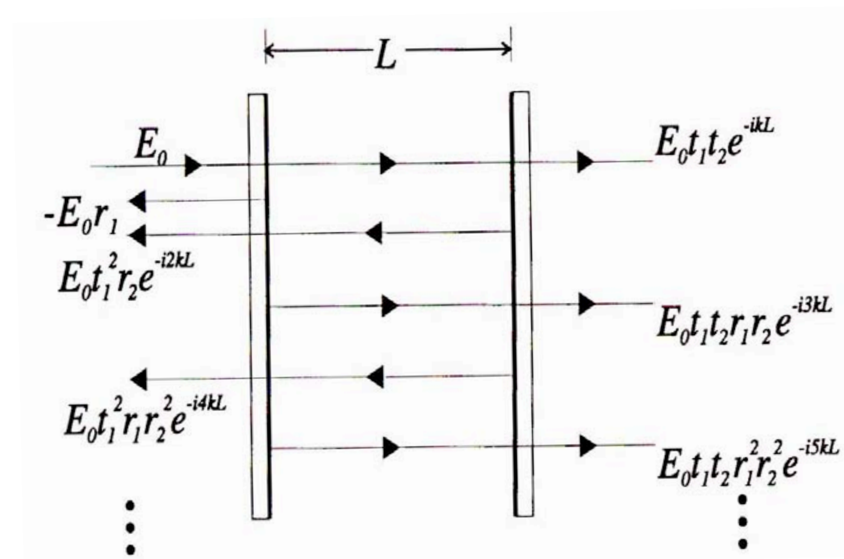
- Michelson interferometer with a "light storage arm"

Fabry-Perot Cavity

- Escaping light ($r_2=1$)

$$E_{esc} = E_O \frac{t_1^2}{1 - r_1 e^{-2kL}}$$

$$\approx E_O \frac{t_1^2}{1 - r_1(1 - i2kL)}$$ near resonance.



- Phase is sensitive to δL

$$\delta\phi \approx \frac{4\sqrt{r_1}}{1 - r_1} k\delta L \equiv \frac{4}{\pi} Fk\delta L = \frac{4}{\pi} F\delta\phi_{Michelson}$$

- "Finesse" of LIGO cavities $F \sim 200$ so like 800/π x 4 km

How to Detect Phase

- 1.064 μm laser light is resonant in Michelson and Fabry Perot Cavities, so phase is sensitive to gravity wave h
- RF phase modulate laser light at f_{mod}= 24.463 MHz through a “Pockels Cell” crystal which converts V to ϕ
- Sidebands are non-resonant and so not sensitive to h
- Lengths are locked on laser carrier dark fringe
- Only sidebands come out of the interferometer with power $2\Phi_{GW}$ X the phase modulation:

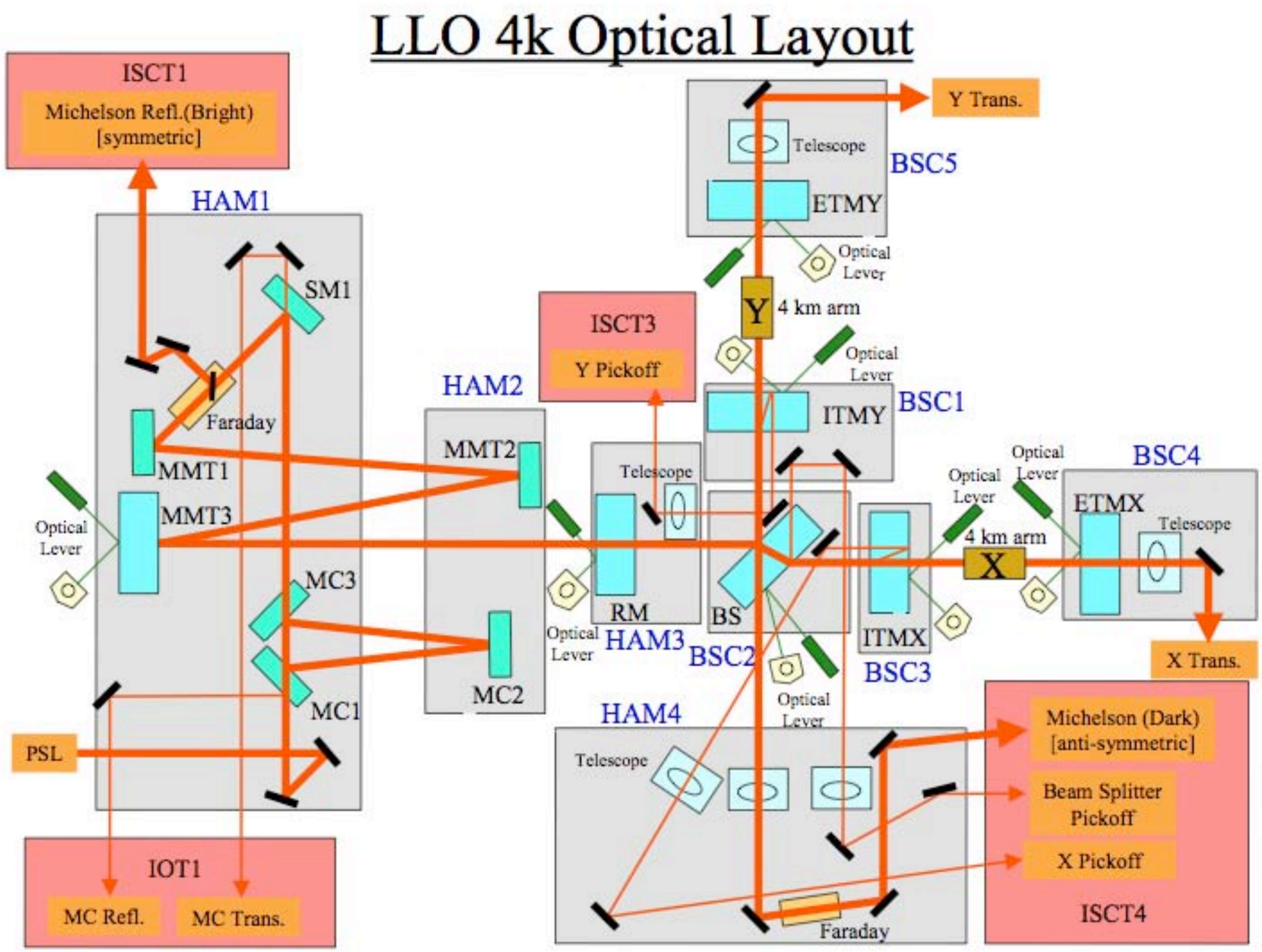
$$P_{OUT} \approx 2\Phi_{GW}\delta \sin 2\pi f_{\mathrm{mod}} t$$

- Demodulate --> audio frequency Gravity Wave signal.

How to Lock the Interferometer

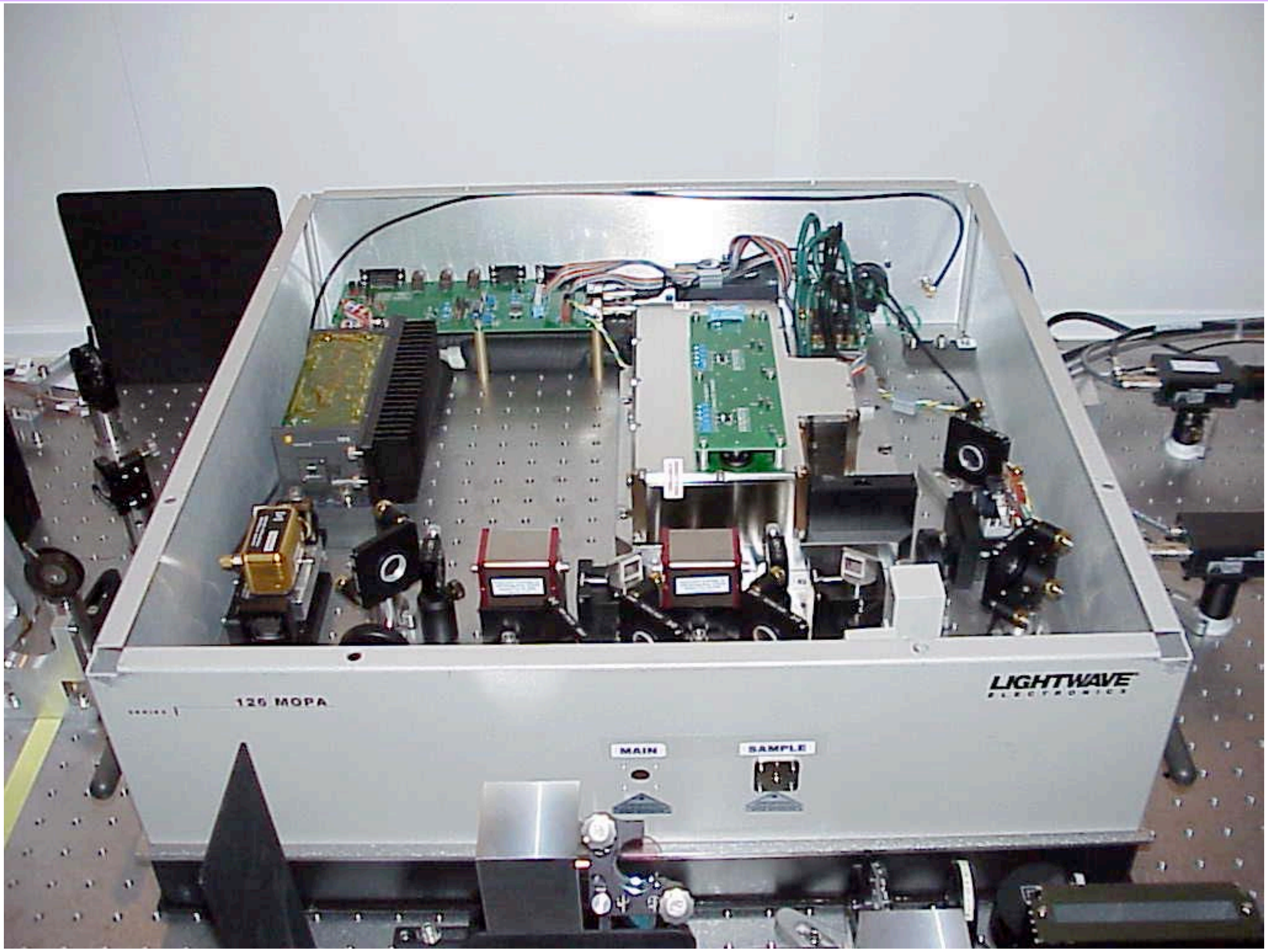
- Suspended mirrors each have 4 magnetic sensor/controllers to adjust angles and position
- One Fabry-Perot arm is length reference for laser frequency in a feed back loop locked to arm resonance
- Second arm mirror positions adjusted so cavity length is locked to this frequency
- Beam splitter is moved to lock on dark fringe
- Mirror/beam angle alignments sensed and locked at 2nd RF modulation frequency on quad photodetectors
- … and more complications and locking
  - » Input (&output) mode cleaners. Power recycling. Future signal recycling.

Simple diagram. Complex System.



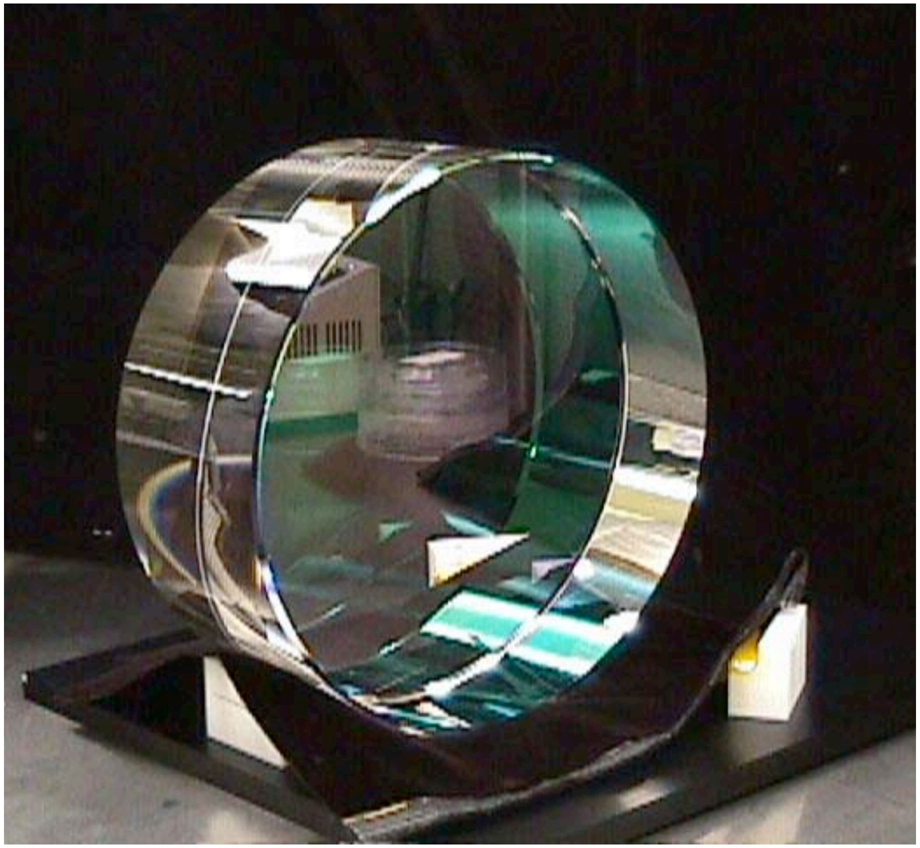
All-Solid-State Nd:YAG Laser

Custom-built
10 W Nd:YAG Laser

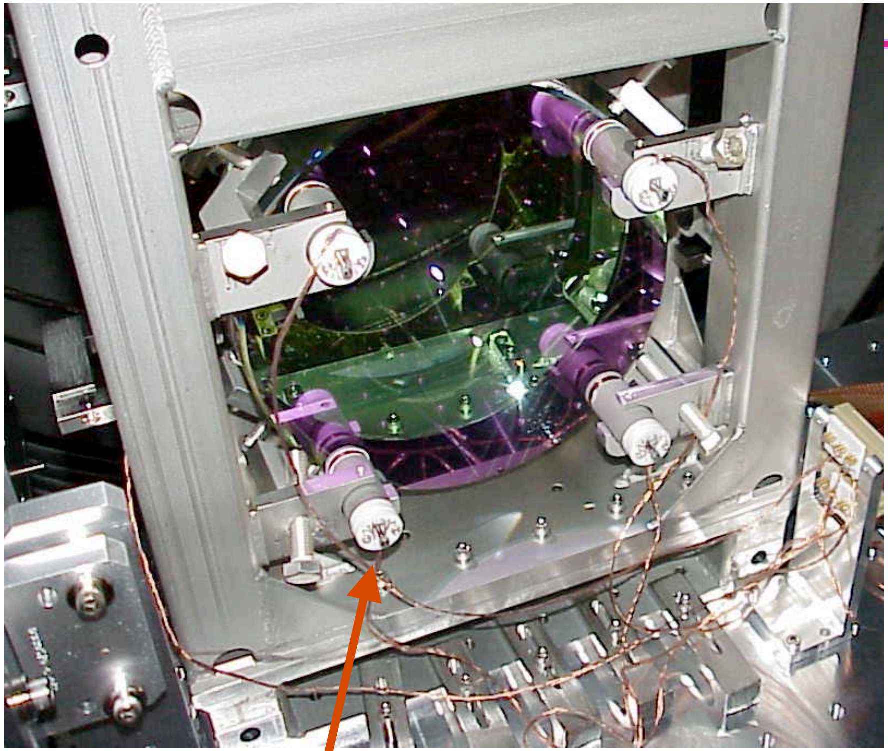


Test Mass Mirrors

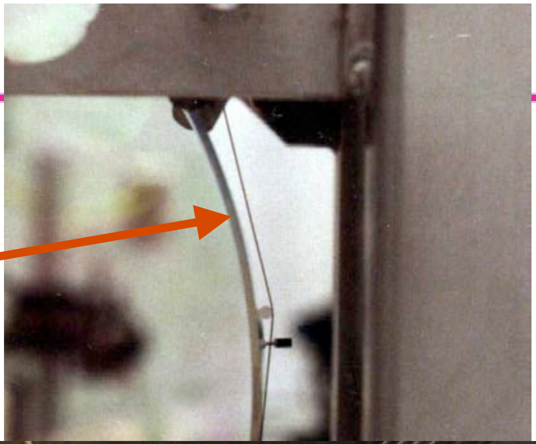
- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}



Mirror Suspension & Control

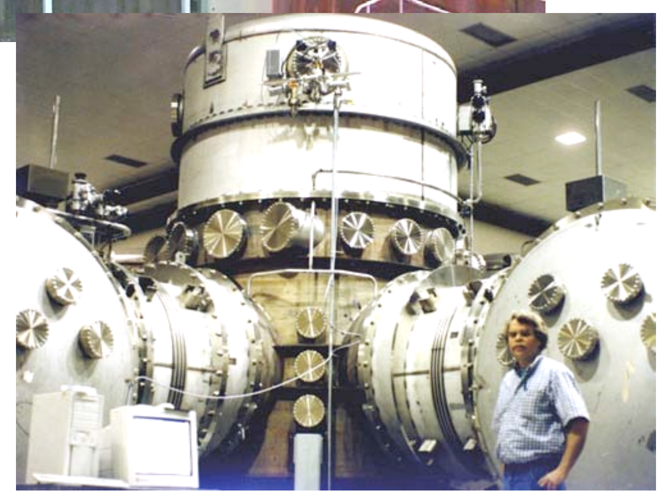


Local sensors/actuators provide damping and control forces



Optics suspended as simple pendulums on 0.25 mm wire

Corner Station Vacuum Chambers



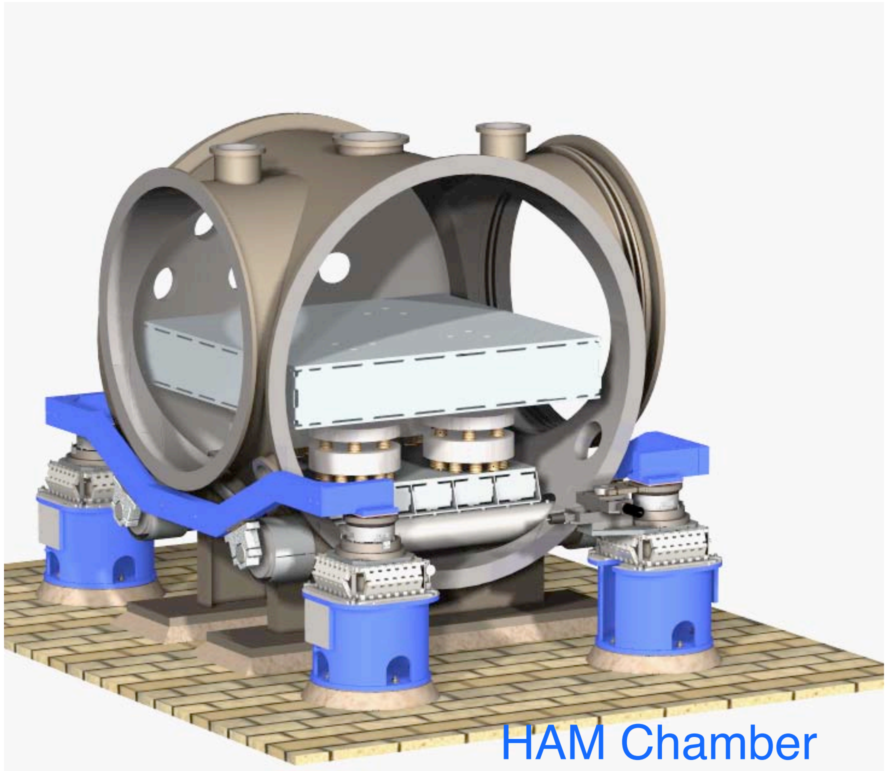
Vacuum: 10^{-6} torr

~1m diameter   2 x 4 km long

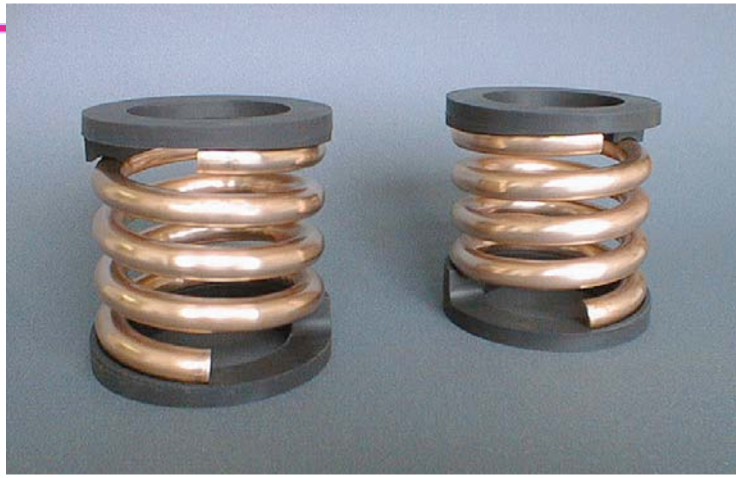
Adapted from Fred Raab slide

Vibration Isolation Systems

- Reduce in-band seismic motion by 10^4 to 10^6
- Actuation corrects Earth tides and microseismic at 0.15 Hz

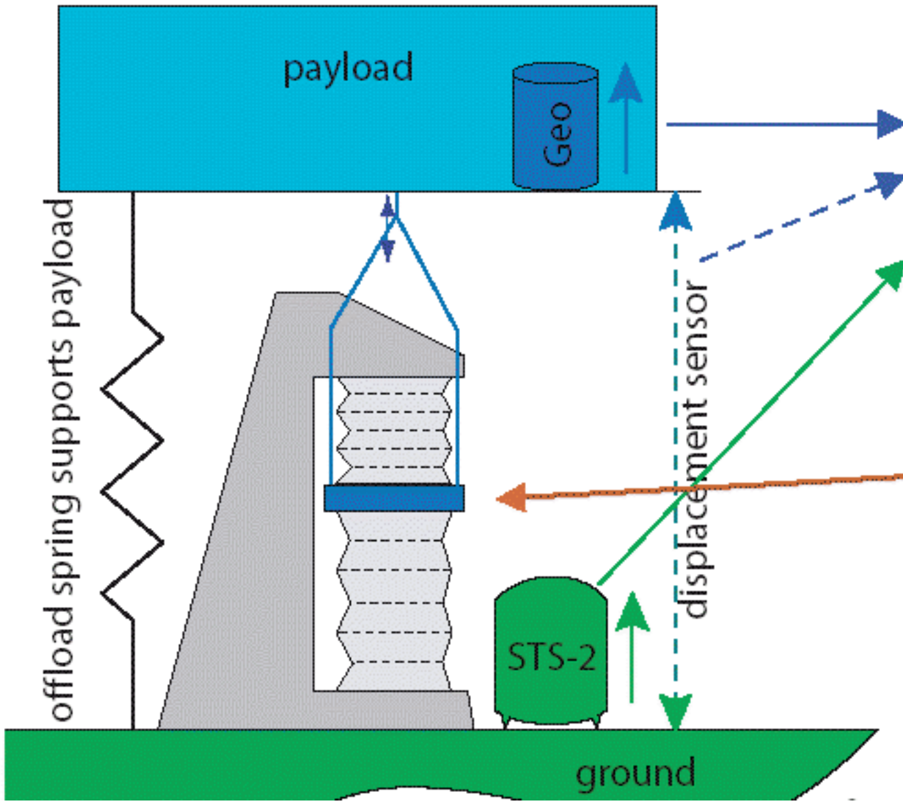


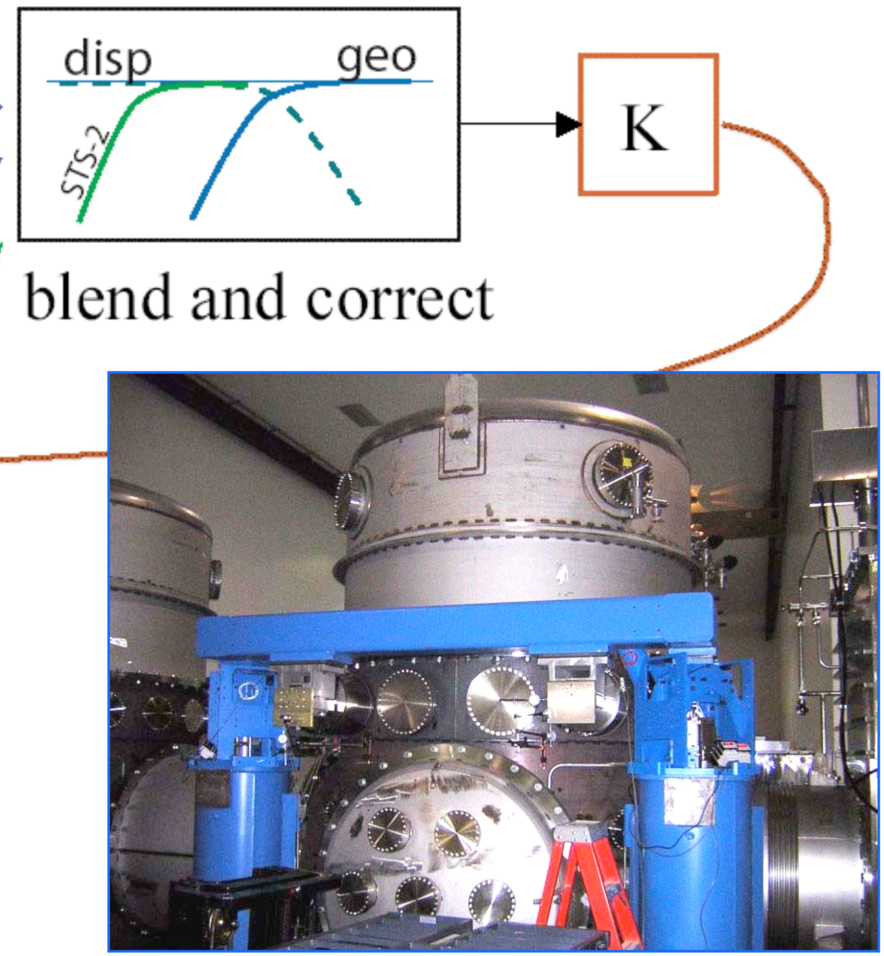
Seismic Isolation
Springs and Masses



damped spring
cross section

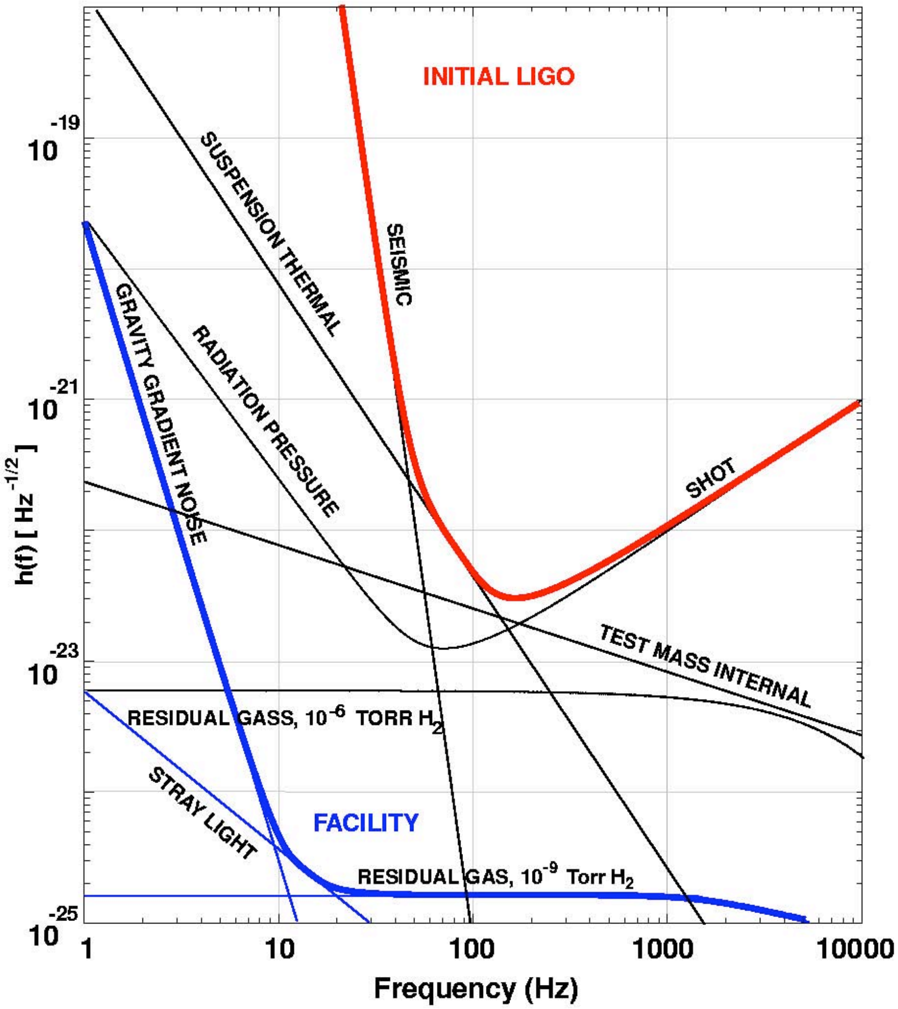
Advanced Dynamic Seismic Isolation





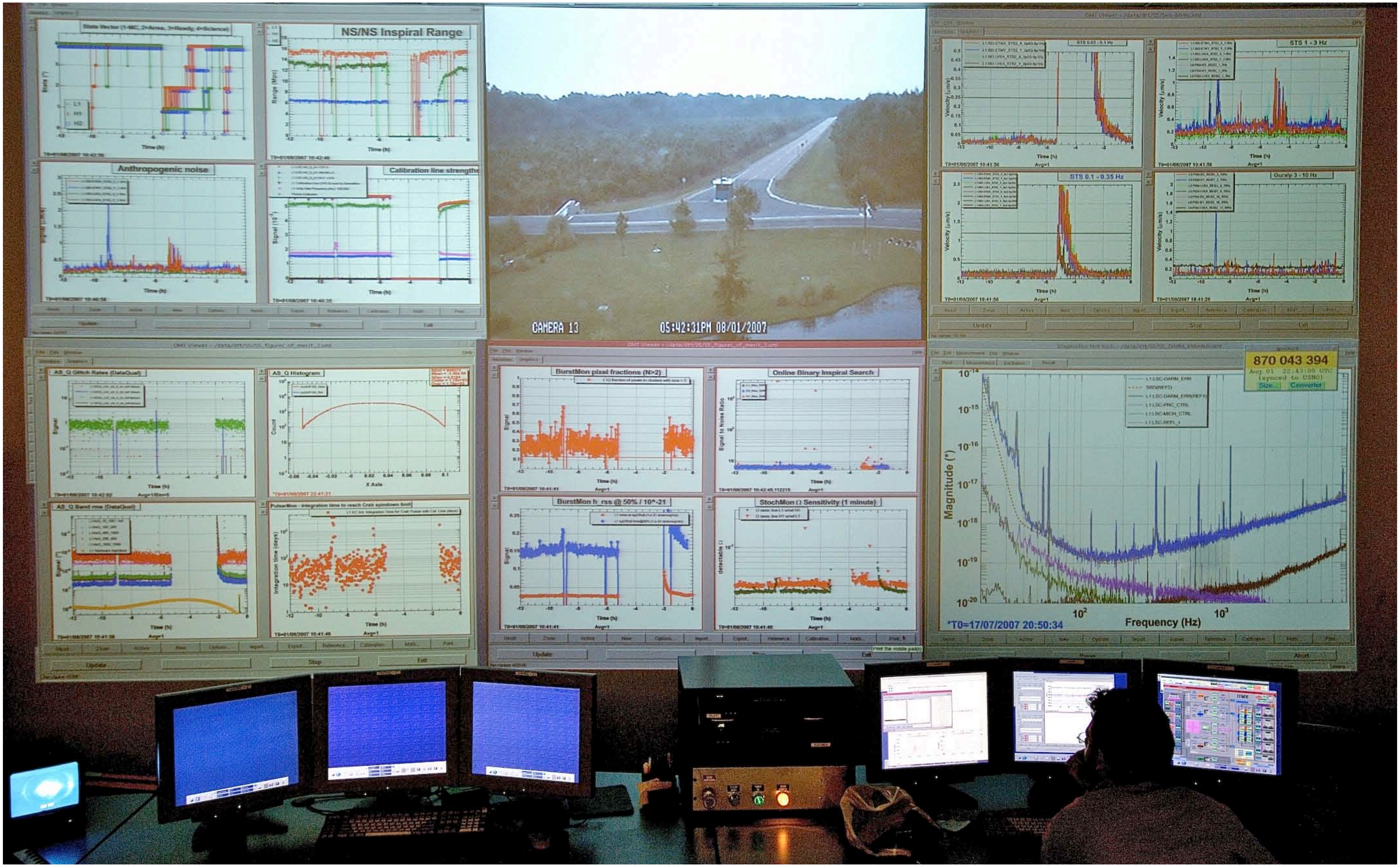
First installed in Louisiana
to reduce anthropogenic noise

Major noise sources for LIGO



- Displacement Noise
  - Seismic
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
- Facilities limits
  - Residual Gas (scattering)
- Inherent limit on ground
  - Gravity gradient noise

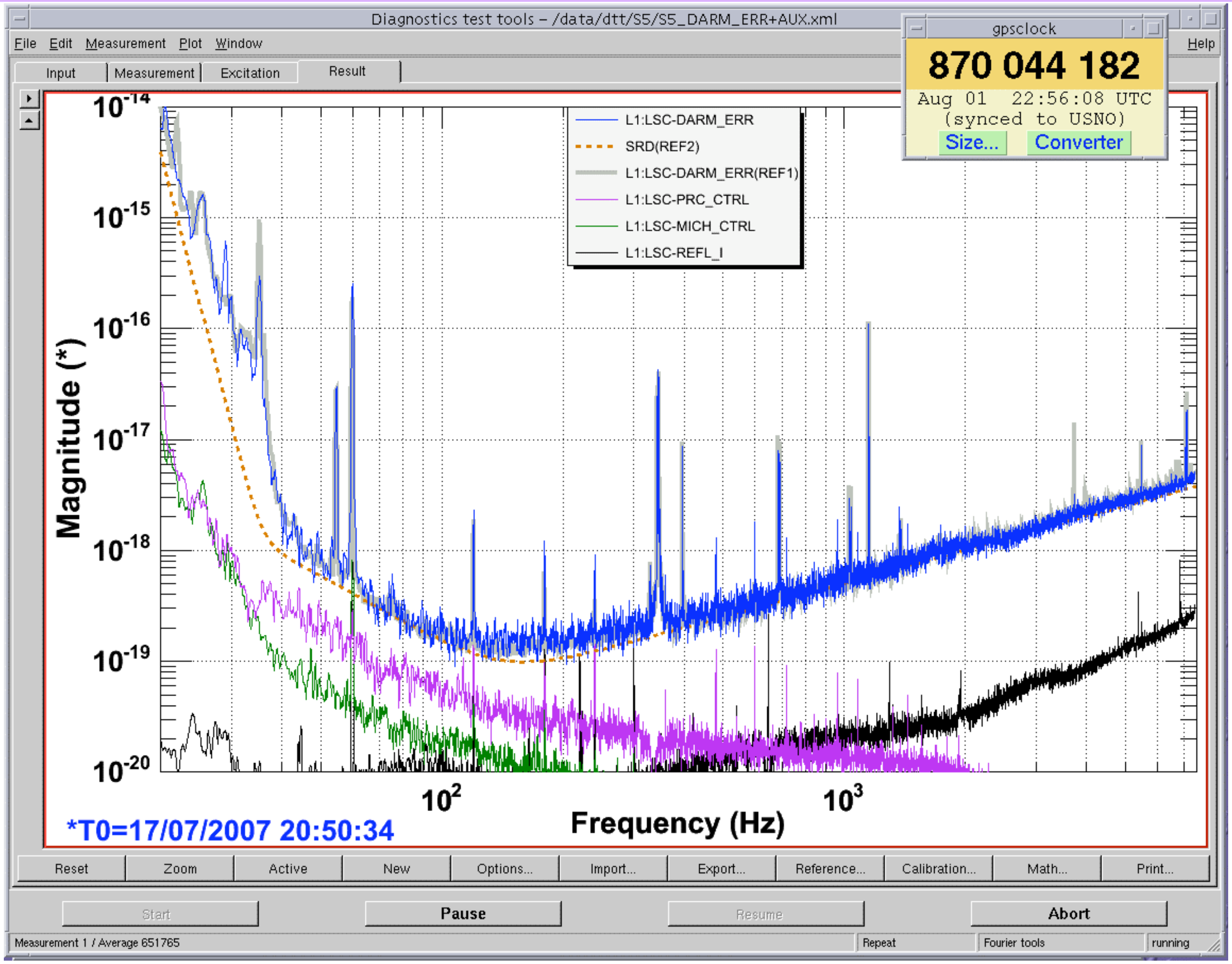
Louisiana Control Room…



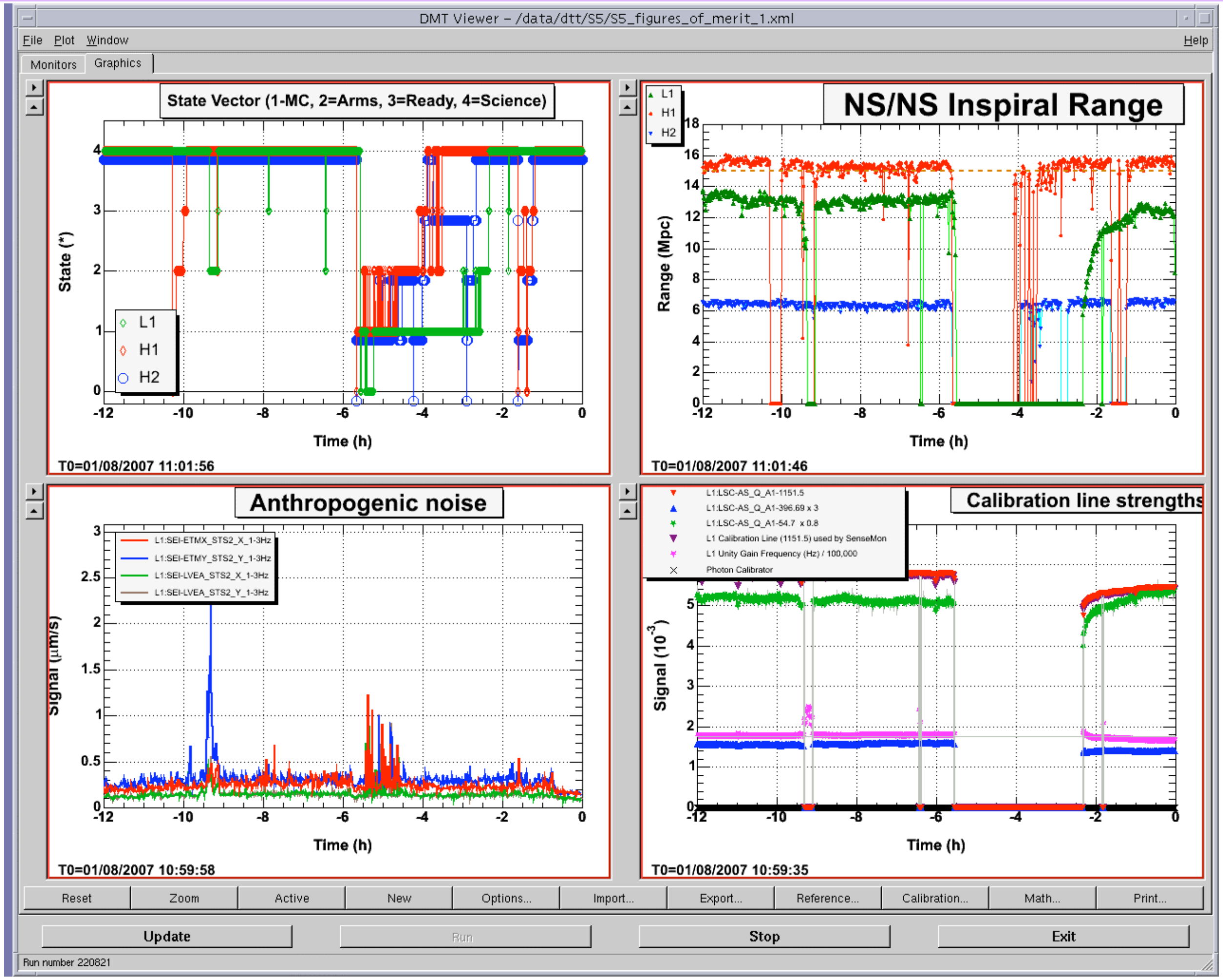
…Louisiana Control Room…

Y-arm Test Mass TV images

…Louisiana Control Room…



…Louisiana Control Room…



What happened 6 hours ago?

Magnitude 7.2 - VANUATU

2007 August 1 17:08:54 UTC

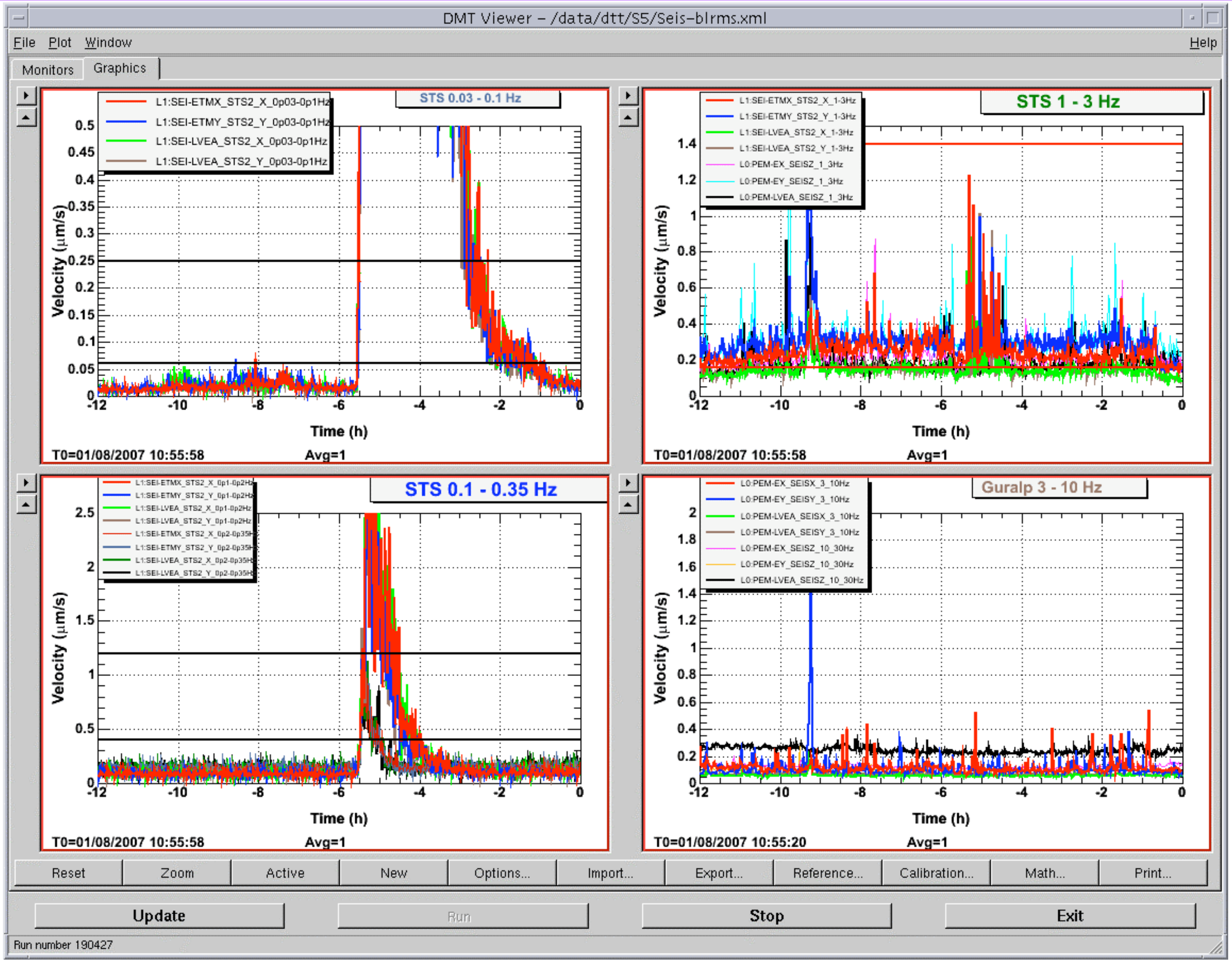
Versíon en Español

Details | Summary | Maps | Scientific & Technical | Where can I find...?

Earthquake Details

Magnitude	**7.2**
Date-Time	**Wednesday, August 1, 2007 at 17:08:54 (UTC)** = Coordinated Universal Time **Thursday, August 2, 2007 at 4:08:54 AM** = local time at epicenter Time of Earthquake in other Time Zones
Location	15.671°S, 167.602°E
Depth	144.8 km (90.0 miles) set by location program
Region	VANUATU

…Louisiana Control Room…



Observational Searches

- Science Run 5: ***1 year coincident running at design luminosity 2006-7***
- S5 sensitivity improved by ~10x
  - » Volume observed = Sensitivity^3 = 1000x

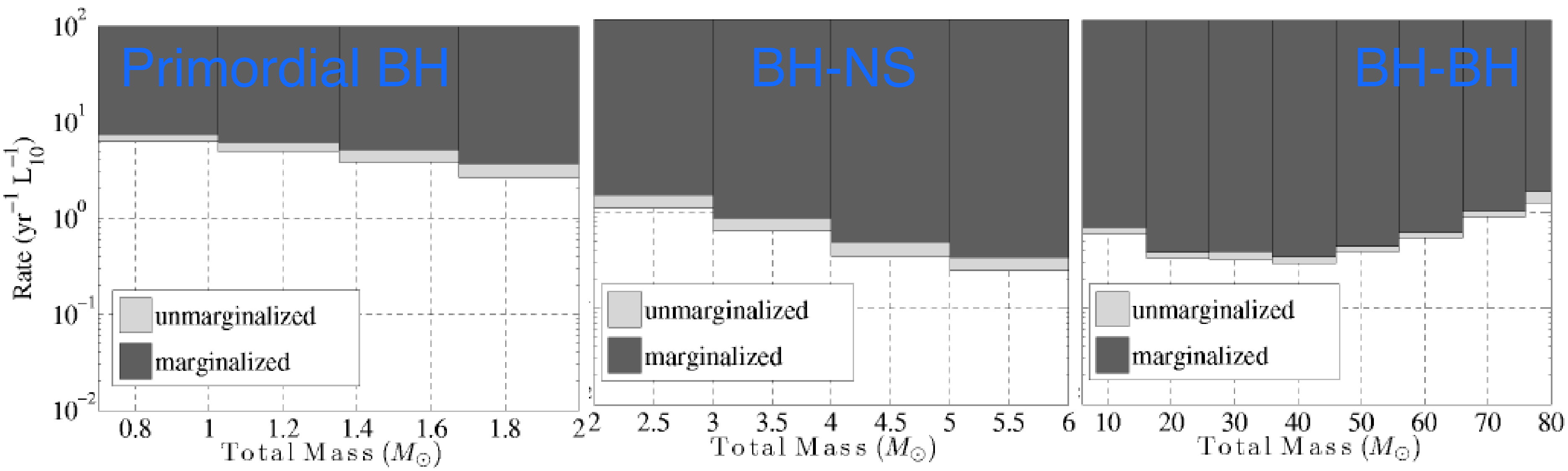
- Binary inspirals: ***chirp signal***
- Pulsars: ***wobbling, accreting, mountainous stars known frequency***
- Bursts: ***listening for supernova…***
- Stochastic: *Cosmological Background* ***early universe***
  Astrophysical background ***noisy present day***

How not to be fooled

- Require at least 2 independent signals
  - » 2 non-local site coincidences for inspiral and burst
  - » External trigger for GRB or nearby supernova
- Known constraints
  - » Pulsar ephemeris
  - » Inspiral waveform from Post-Newtonian GR numerical calculations
  - » Time difference between sites
- Veto on environmental monitors
  - » Seismometers, accelerometers, wind-monitors
  - » Microphones, magnetometers, line-volt meters
- Monitor detector response
  - » Hardware injections of pseudo signals (actuators move mirrors)
  - » Software signal injections

Upper limits now have physics significance…

Binary Coalescence S4 Upper Limits



Rate/L_{10} vs. binary total mass

$L_{10} = 10^{10} L_{\odot,B}$ (1 Milky Way = 1.7 L_{10})

Dark region excluded at 90% confidence

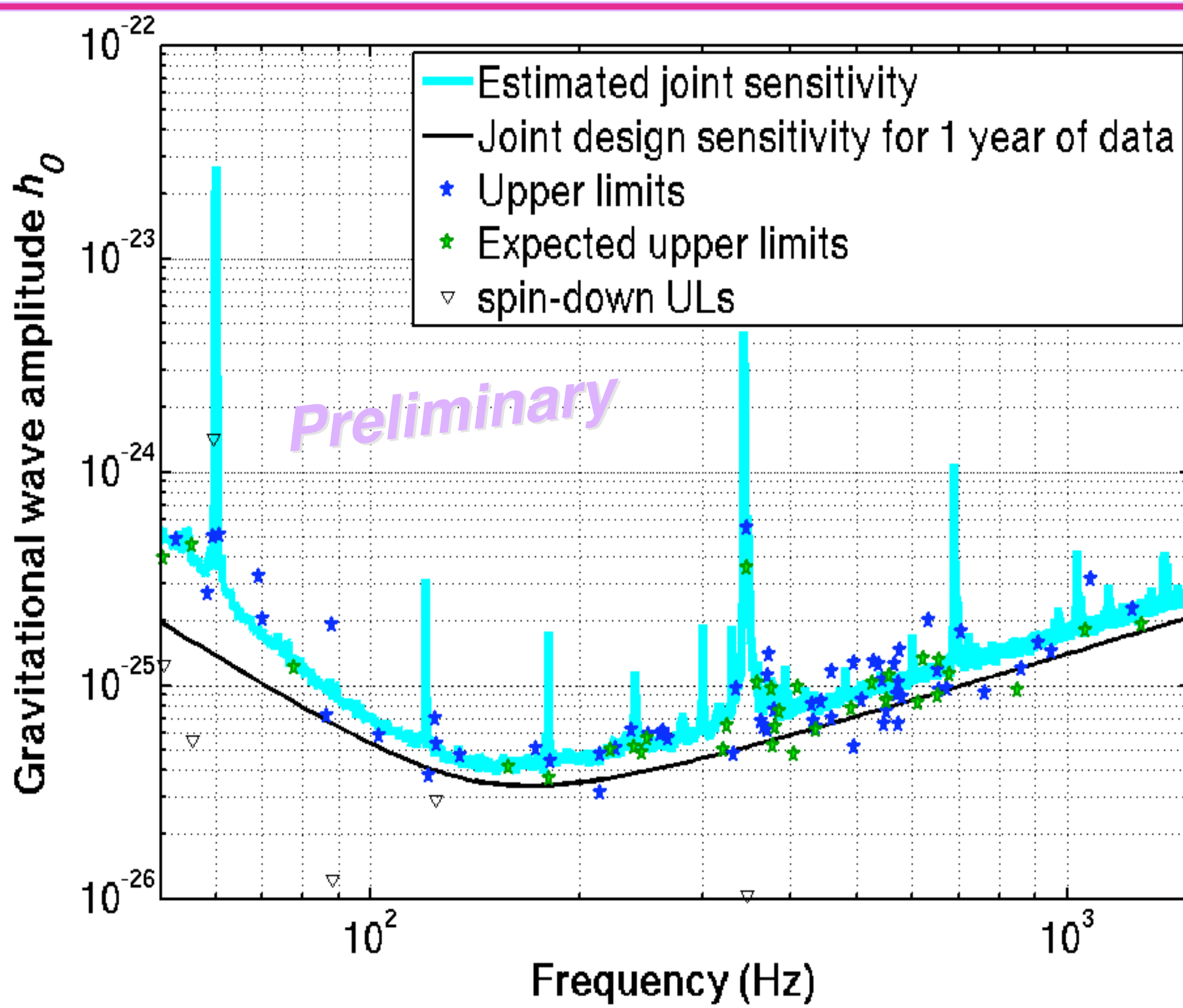
arXiv:0704-3368

Known Pulsars (~13 months S5)

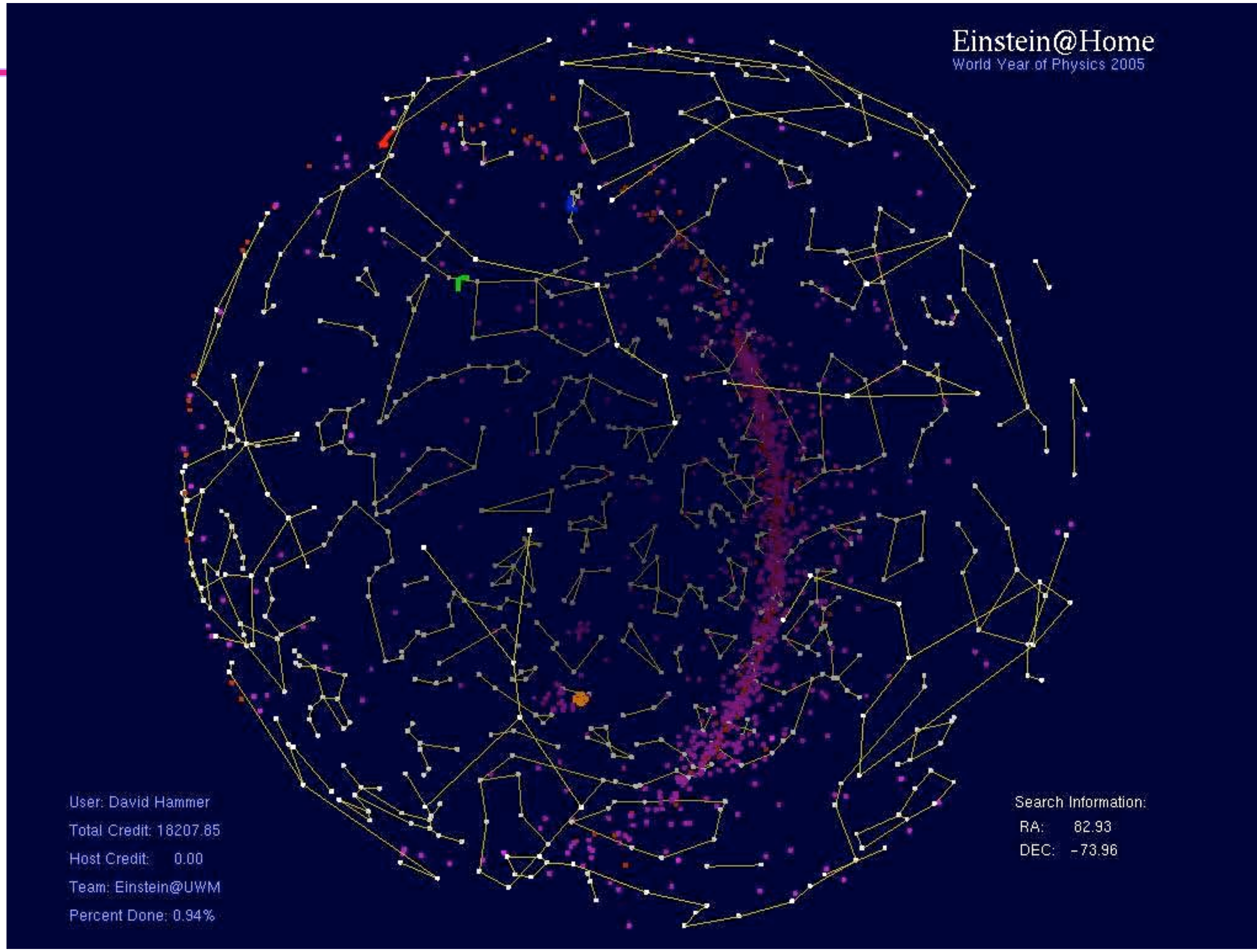
$$\epsilon = (I_{xx} - I_{yy})/I_{zz}$$

Lowest ellipticity upper limit:
PSR J2124-3358
@405.6 Hz

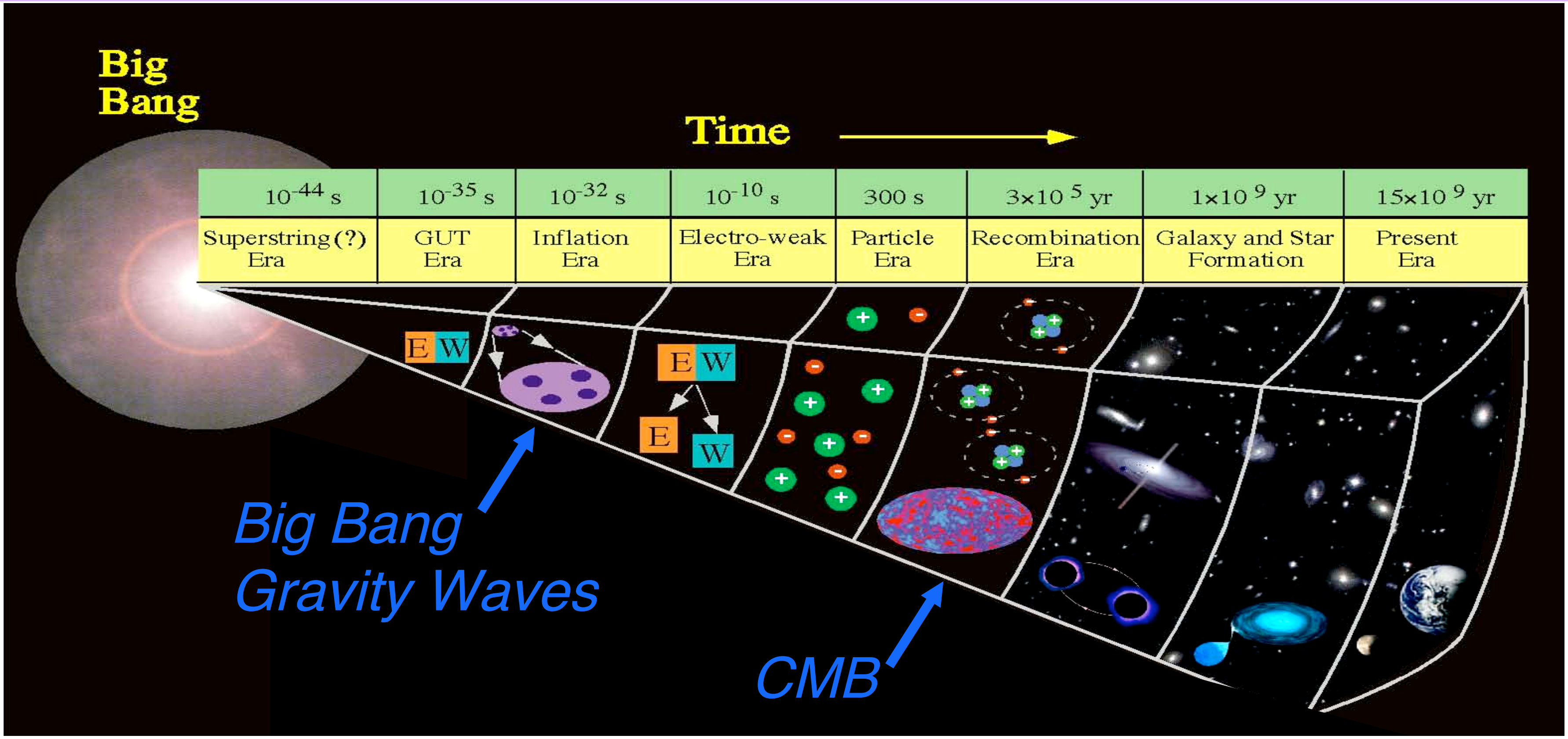
$\varepsilon = 7.3 \times 10^{-8}$



Einstein @ Home



Stochastic Gravity Waves
Our Only Window to the Big Bang



Adapted from LISA slide

Stochastic Upper Limits

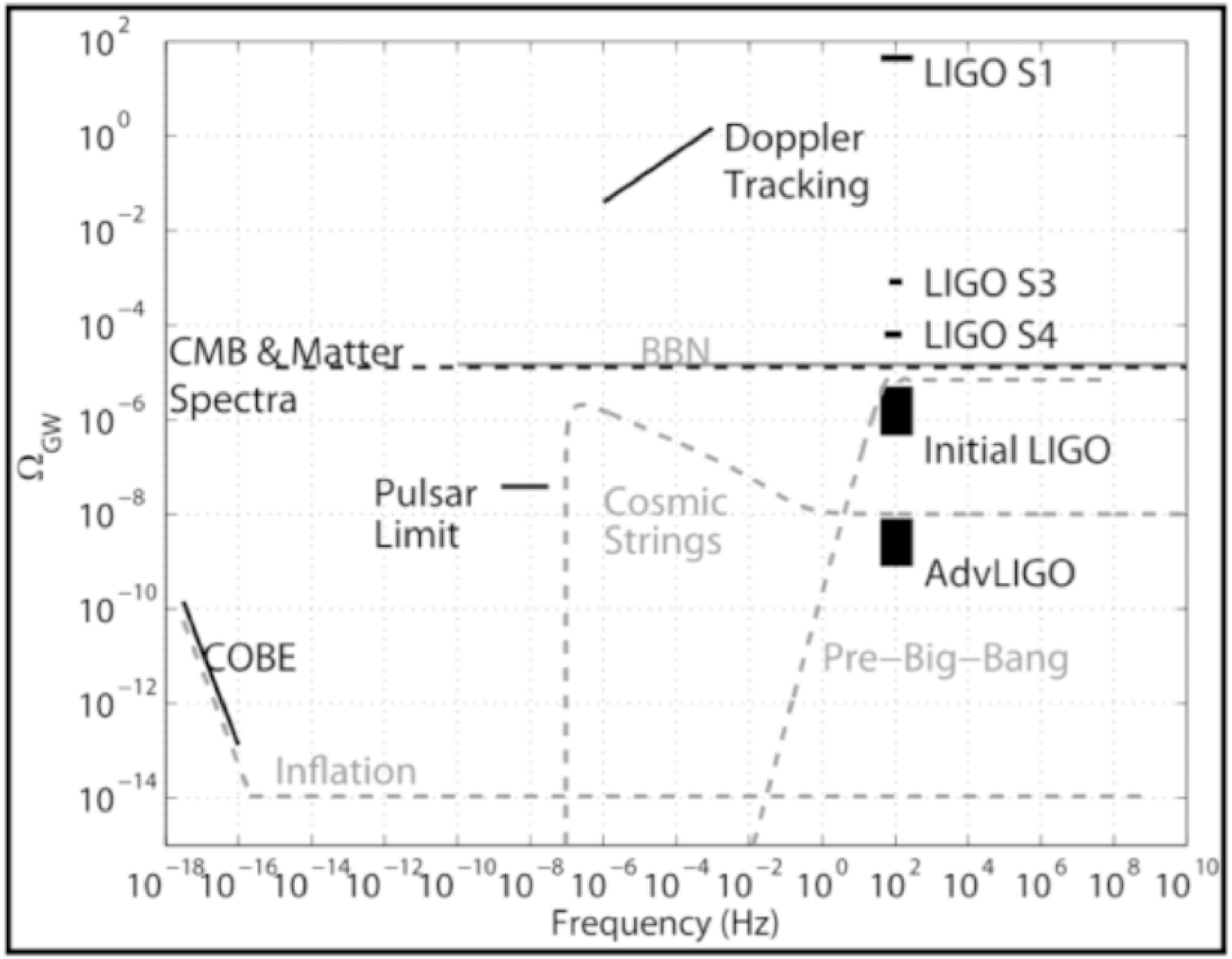
Cross-correlate 2 data streams: e.g. Louisiana-Wash.

S4: $\Omega_{GW} < 6.5\ 10^{-5}$ (90% CL)

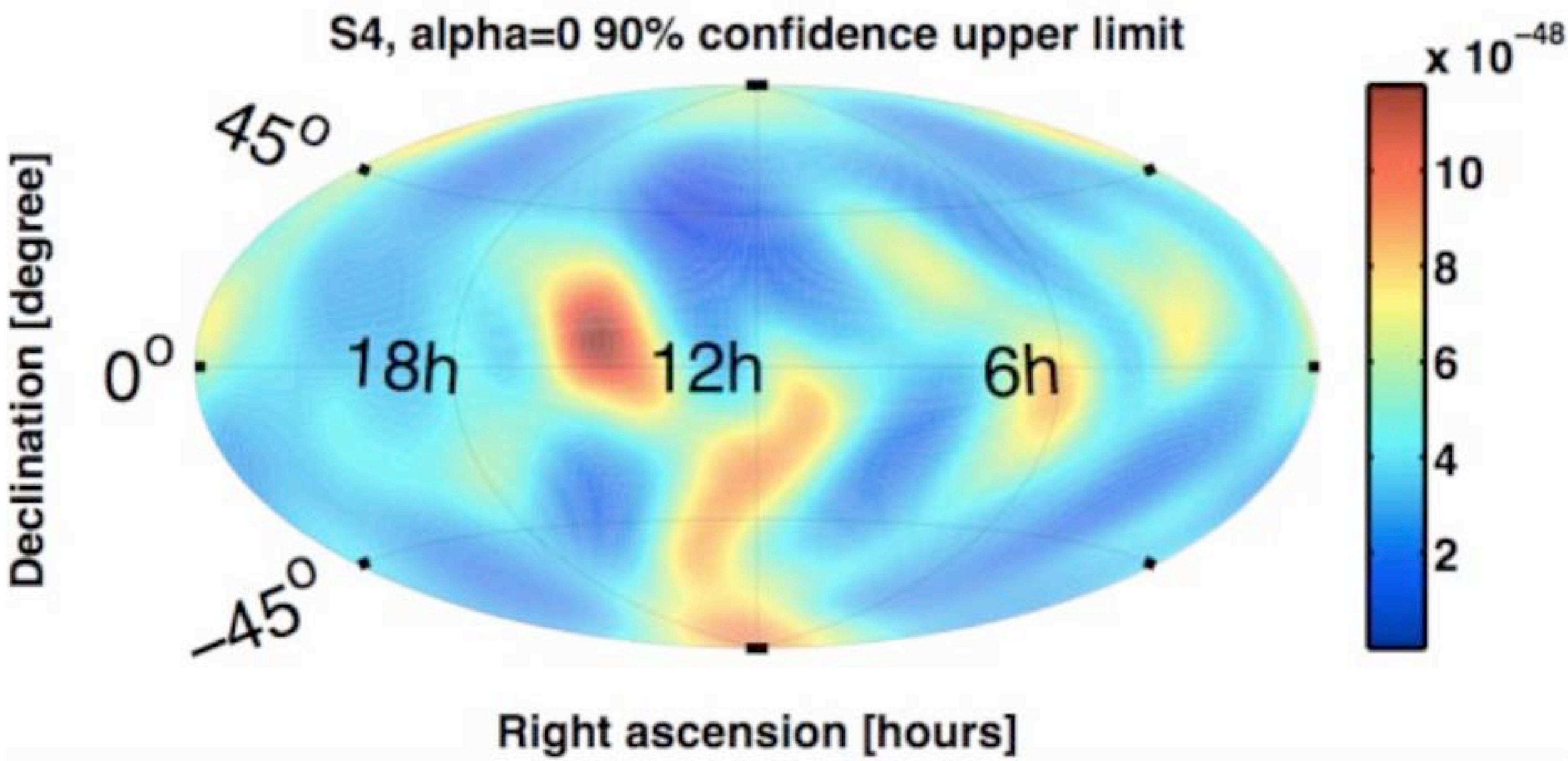
S5: expect

$\Omega_{GW} < 10^{-5}$
below nuclear-synthesis limit

ApJ **659**(2007)918



First Gravity Wave Upper Limit All Sky Map



Point sources with flat power spectrum

The Future: Advanced LIGO
Major installation: 2011

Active anti-seismic
lower frequencies

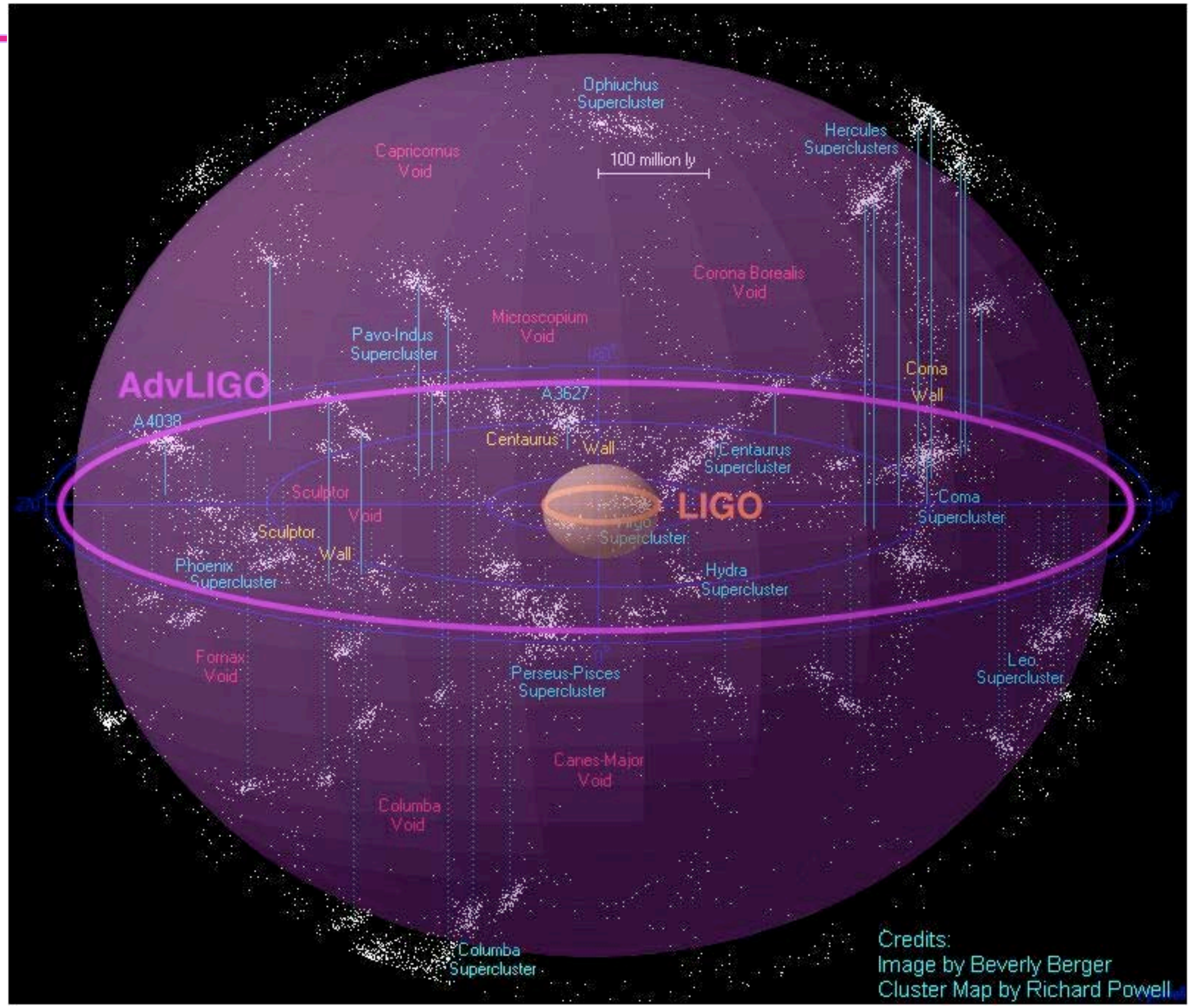
Lower noise optics
& suspensions

Increased mass
mirrors (40 kg)

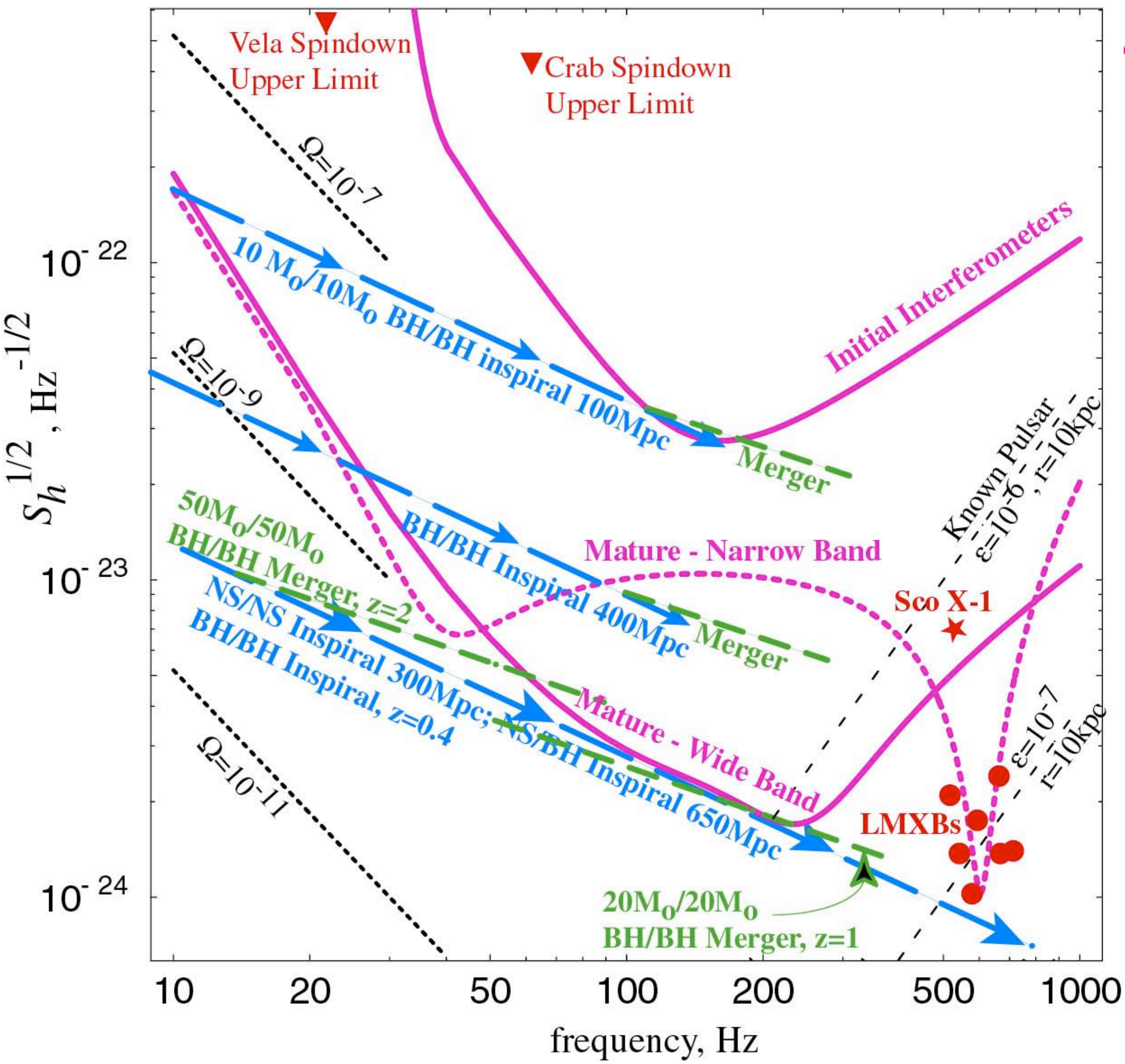
Higher Laser power
(180 W)

Signal recycling

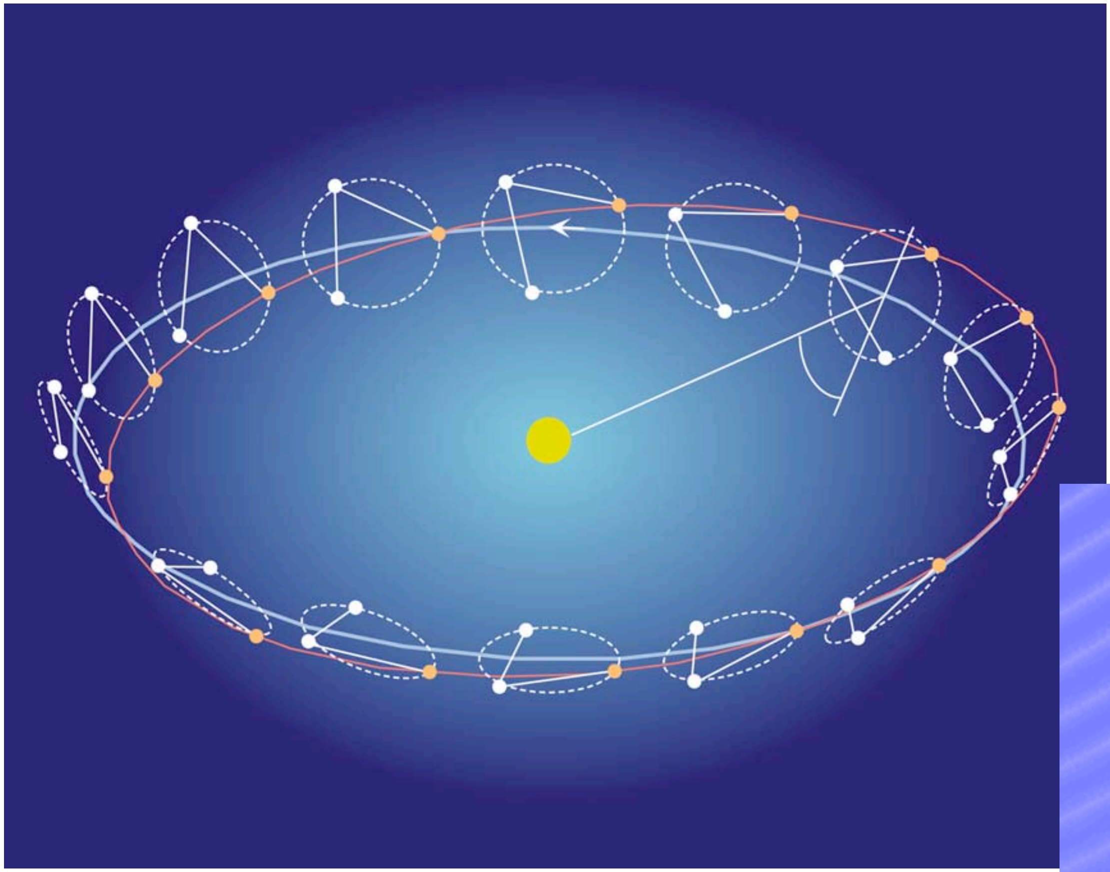
DC readout



Difficult to hide from Advanced LIGO

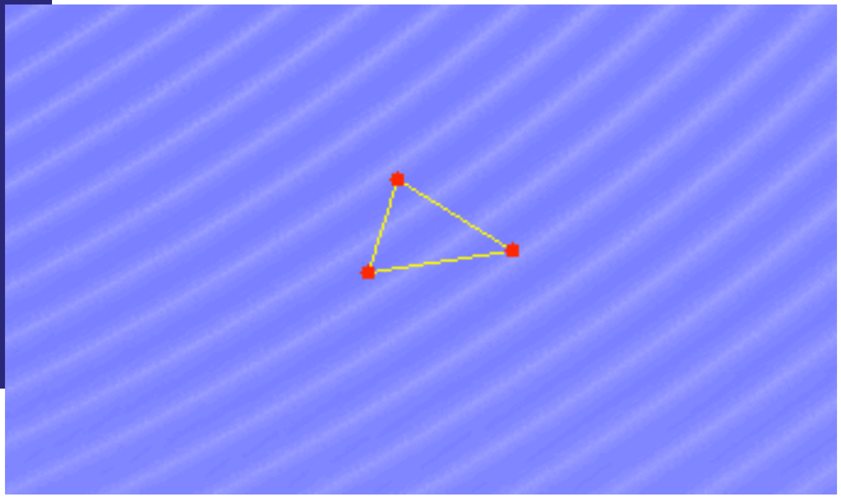


Space based interferometer: LISA



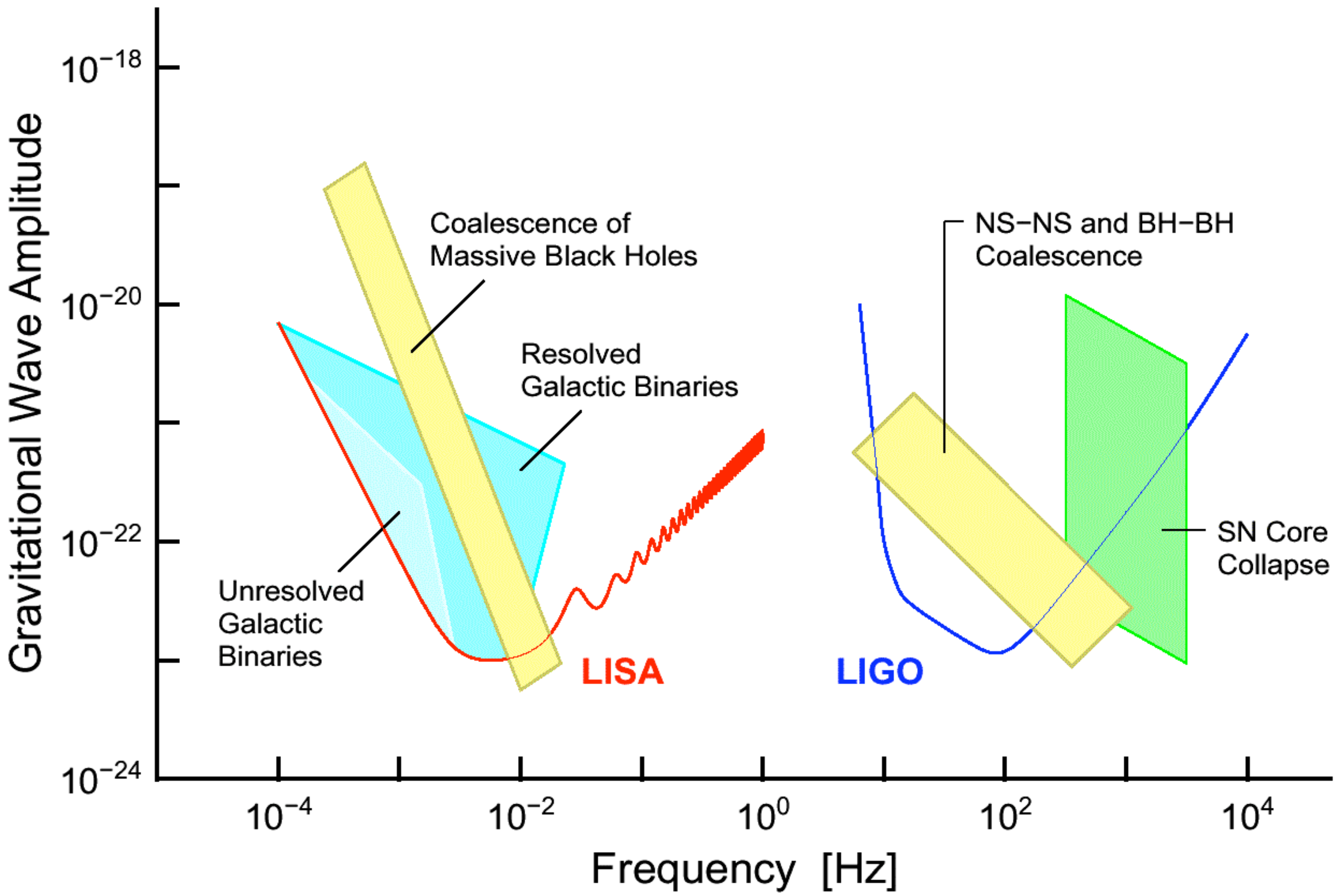
3 satellites 5 10^6 km apart
Heliocentric orbit
20° behind the earth

LISA surfing
a gravity wave



NASA-ESA Launch 2013?

LIGO and LISA are Complementary



Universe full of surprises
Need to keep our eyes open

References = Acknowledgement

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  - » Misner, Thorne, Wheeler, *Gravitation*, W.H. Freeman 1973
  - » Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors,* World Scientific 1994
- LIGO Papers and Talks
  http://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html
  http://admdbsrv.ligo.caltech.edu/dcc/
  http://www.lsc-group.phys.uwm.edu/ppcomm/Talks2007.html
  - » Fred Raab LIGO-G070024-01-W
  - » Alan Weinstein {LIGO-G000162-00-R … LIGO-G000167-00-R},
  - » Daniel Sigg LIGO-P980007-00 - D
  - » Laura Cardonati LIGO-G070458-00
  - » Gabriela Gonzalez LIGO-G070013-00
  - » Jay Marx LIGO-G060579-00-D
  - » Bernard Whiting LIGO-G070239-00-Z
  - » Stan Whitcomb LIGO-G070417-01-D