Gravitational Waves: Next Window on the Universe

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LIGO Scientific Collaboration

Sobral Meeting

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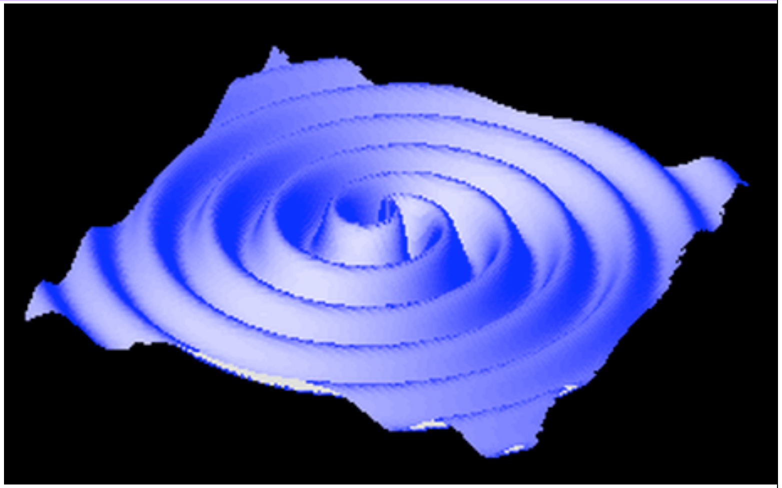
Gravity Waves?

- 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)

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!

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

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

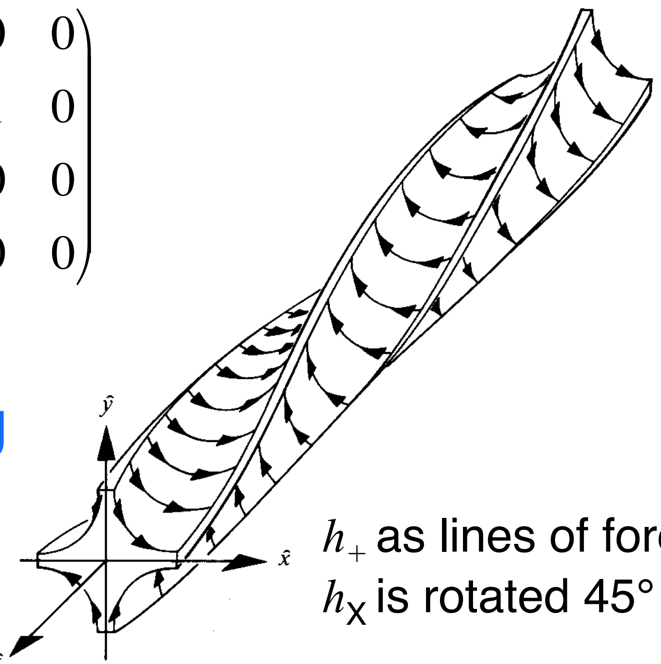
… Quadrupole Sources & Waves …

- Elements of $h_{\mu\upsilon}$ are waves, $h(\omega\, t - \boldsymbol{k \bullet x})$
- 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

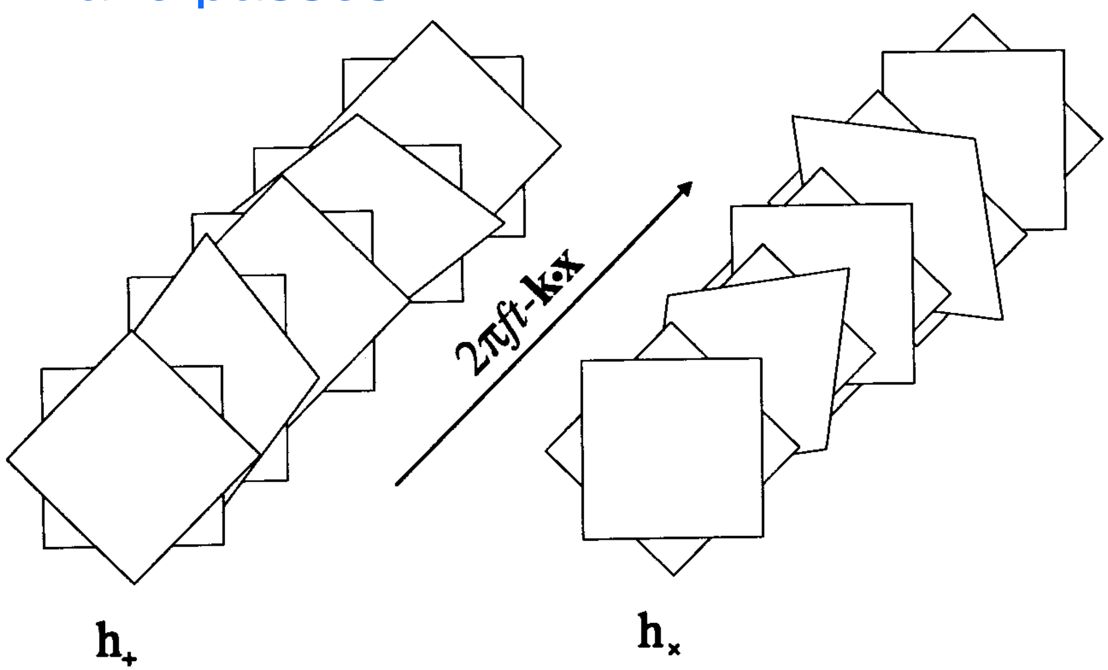
  Early GW detector design
  ~ 6 are still in use ~900 Hz (typ)



h_+ as lines of force
h_X is rotated 45°

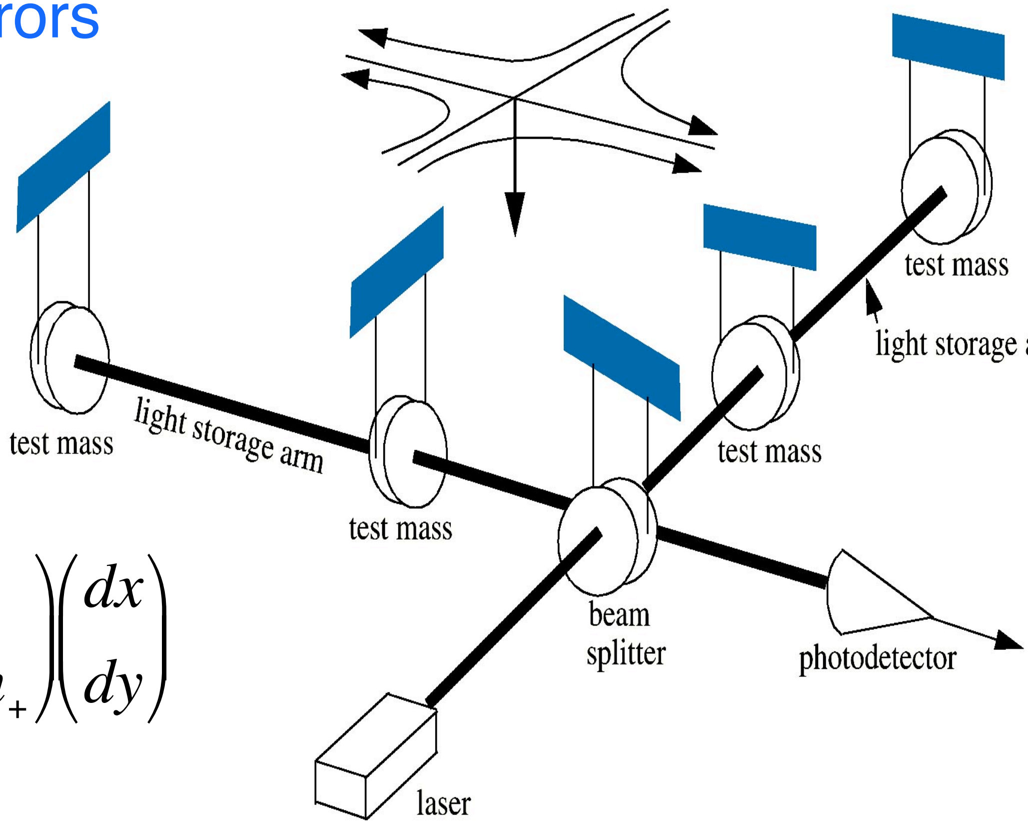
… Quadrupole Sources & Waves

- 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

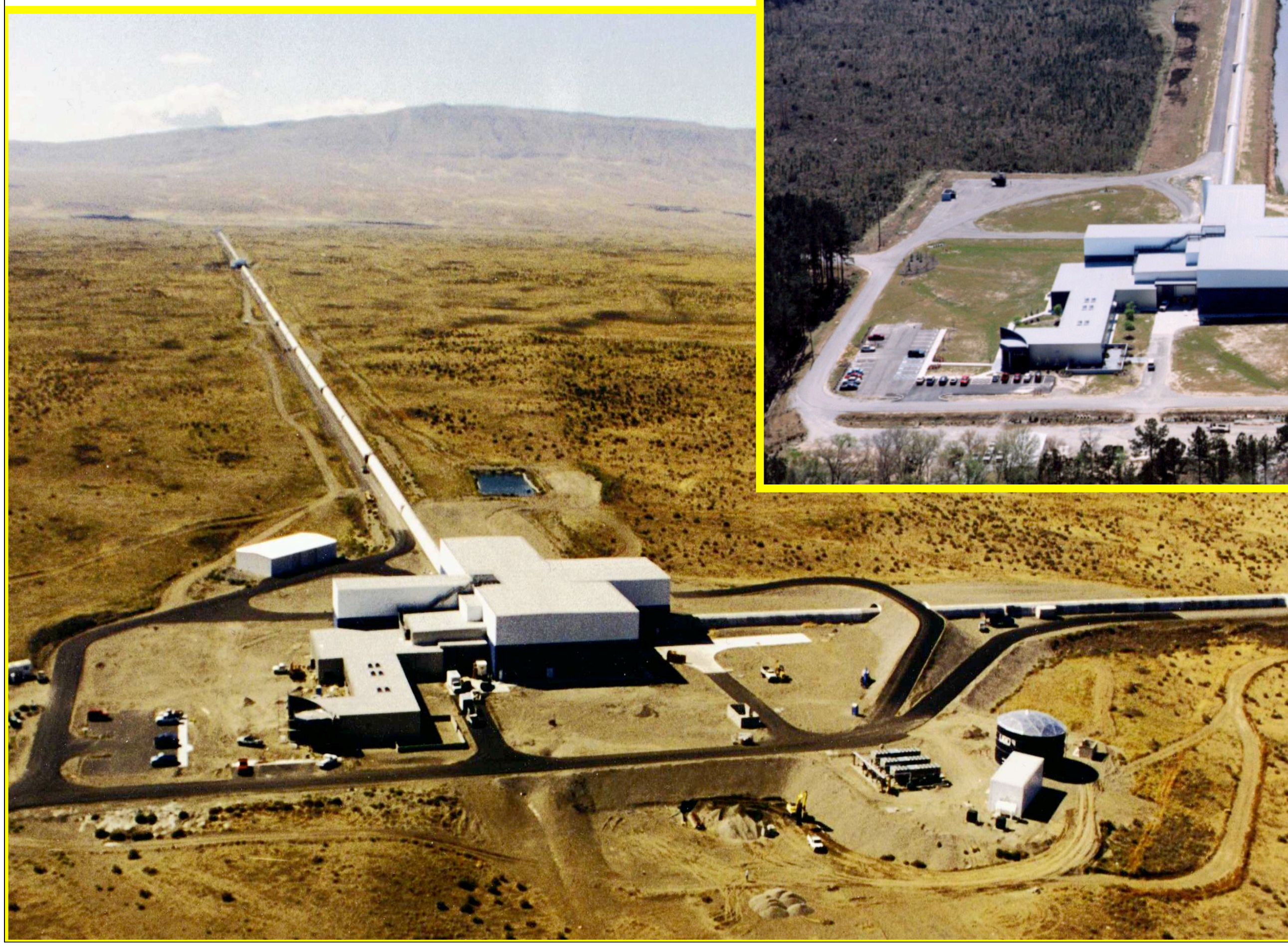


$$dL^2 = g_{\mu\nu} dx^\mu dx^\nu$$

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

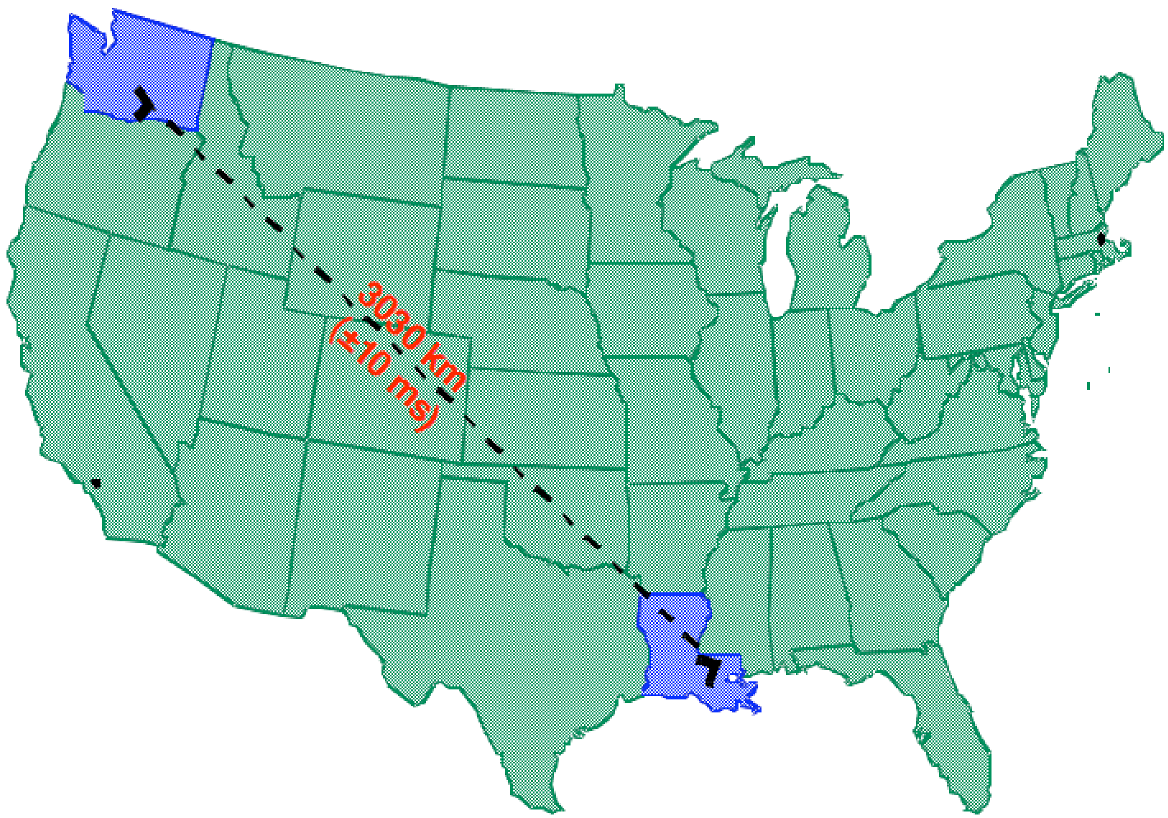
LIGO Laser Interferometer Gravitational-wave Observatory

Hanford, Washington State
2 km and 4 km

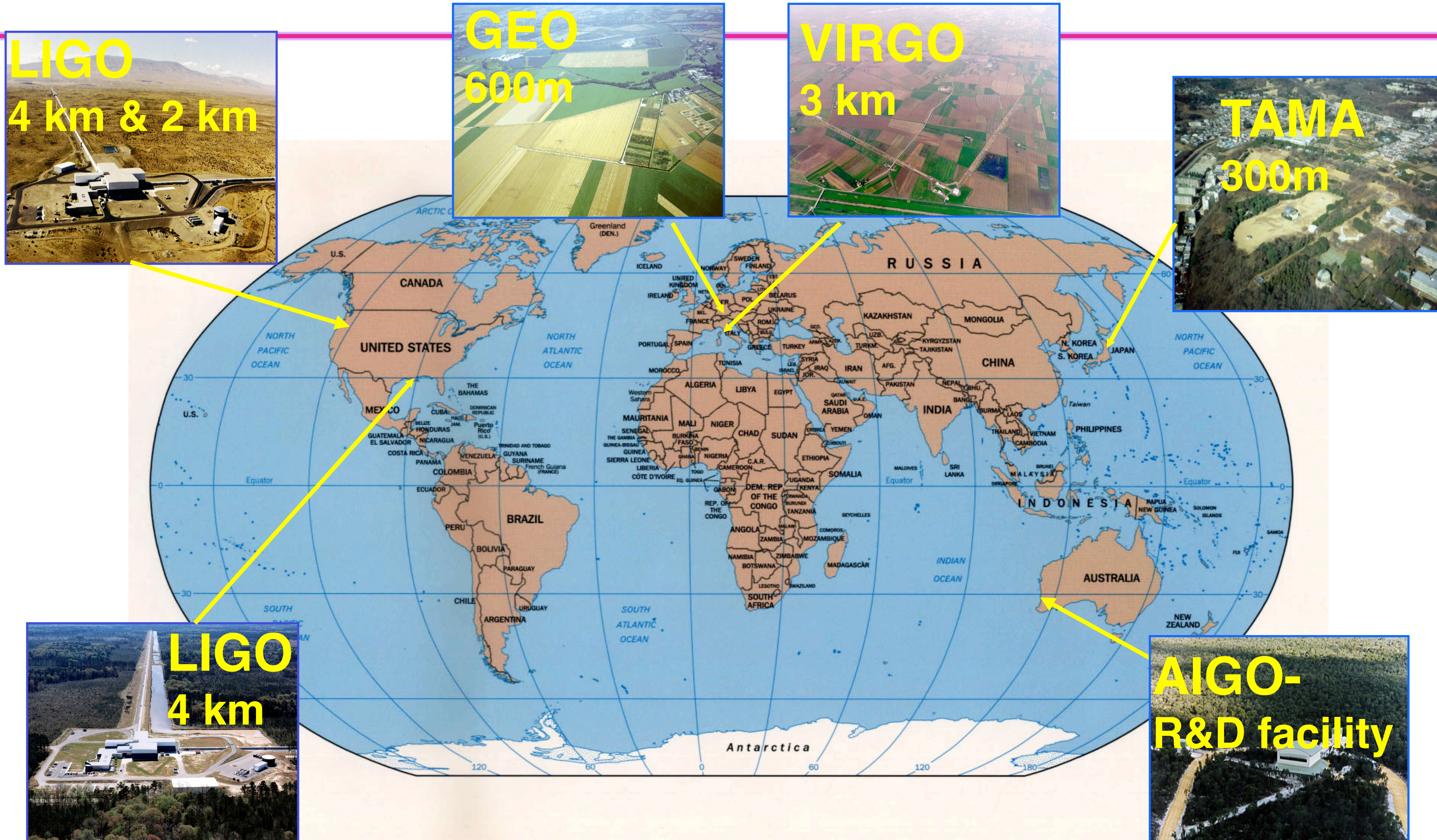


Livingston, Louisiana
4 km

Two locations, far apart



Global network of interferometers



Worldwide Network Gravity Wave Observatories

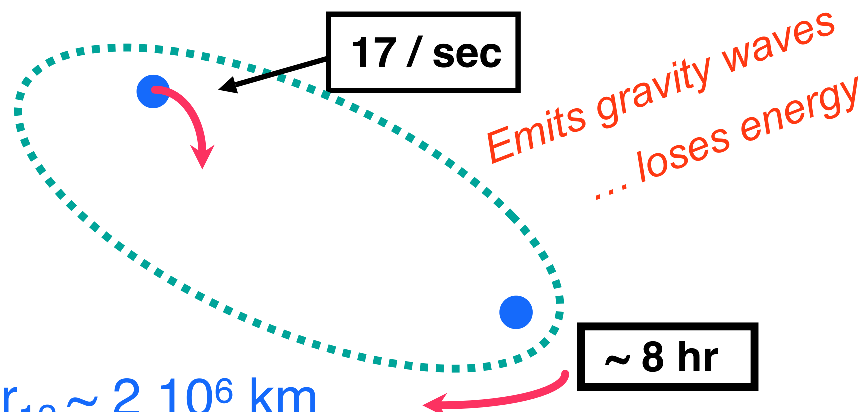
- Why so large?
  - » Gravity waves affect $\delta L/L \sim h$
  - » Need large L for high sensitivity
- Why so far apart?
  - » Sensitivity is extremely high (as we shall see)
  - » Require coincidence of at least 2 detectors
  - » Different local noise sources (seismic, electric, audio, …)
- Why so 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

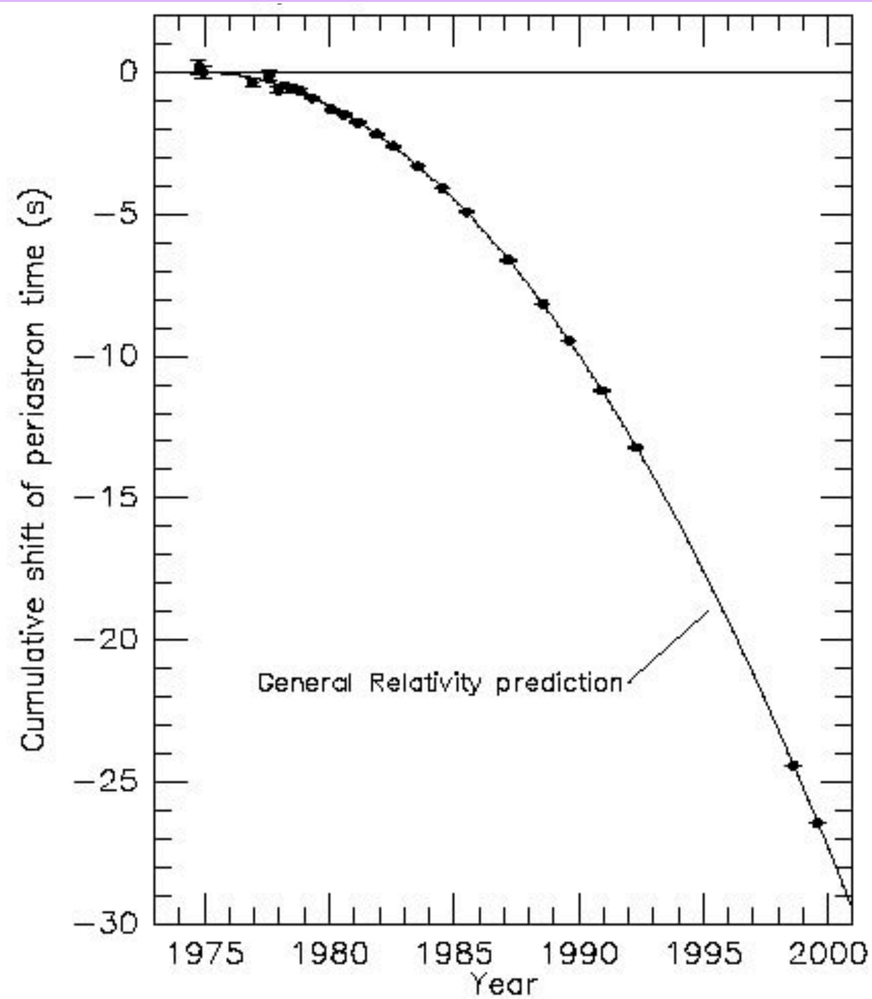
PSR 1913 + 16



$r_{12} \sim 2\ 10^6$ km

$m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$

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



Direct Detection Sensitivity Requirement

- $h_{\mu\nu} = \dfrac{2G}{Rc^4}\ddot{I}_{\mu\nu}$ with $I_{\mu\nu}$ the quadrupole moment
- Binary Star $h_{xx} = -h_{yy} \approx \dfrac{r_{s_1} r_{s_2}}{r_{orbit} R}\cos\left[2(2\pi f_{orbit})t\right]$

  where $r_s = \dfrac{2GM}{c^2}$ 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 $\approx .003\ r_{\mathrm{H\ nucleus}}$ over 4 km !!

Much Longer than 4 km!

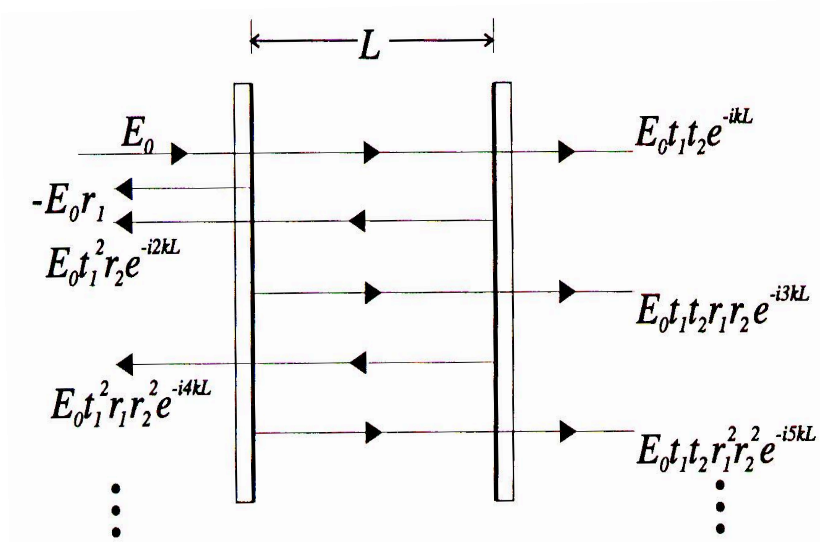
- Michelson interferometer with a “light storage arm”

Fabry-Perot Cavity

- Escaping light $(r_2=1)$

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

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



- Phase is sensitive to δL

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

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

How to Detect Phase - Initial LIGO

- 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:

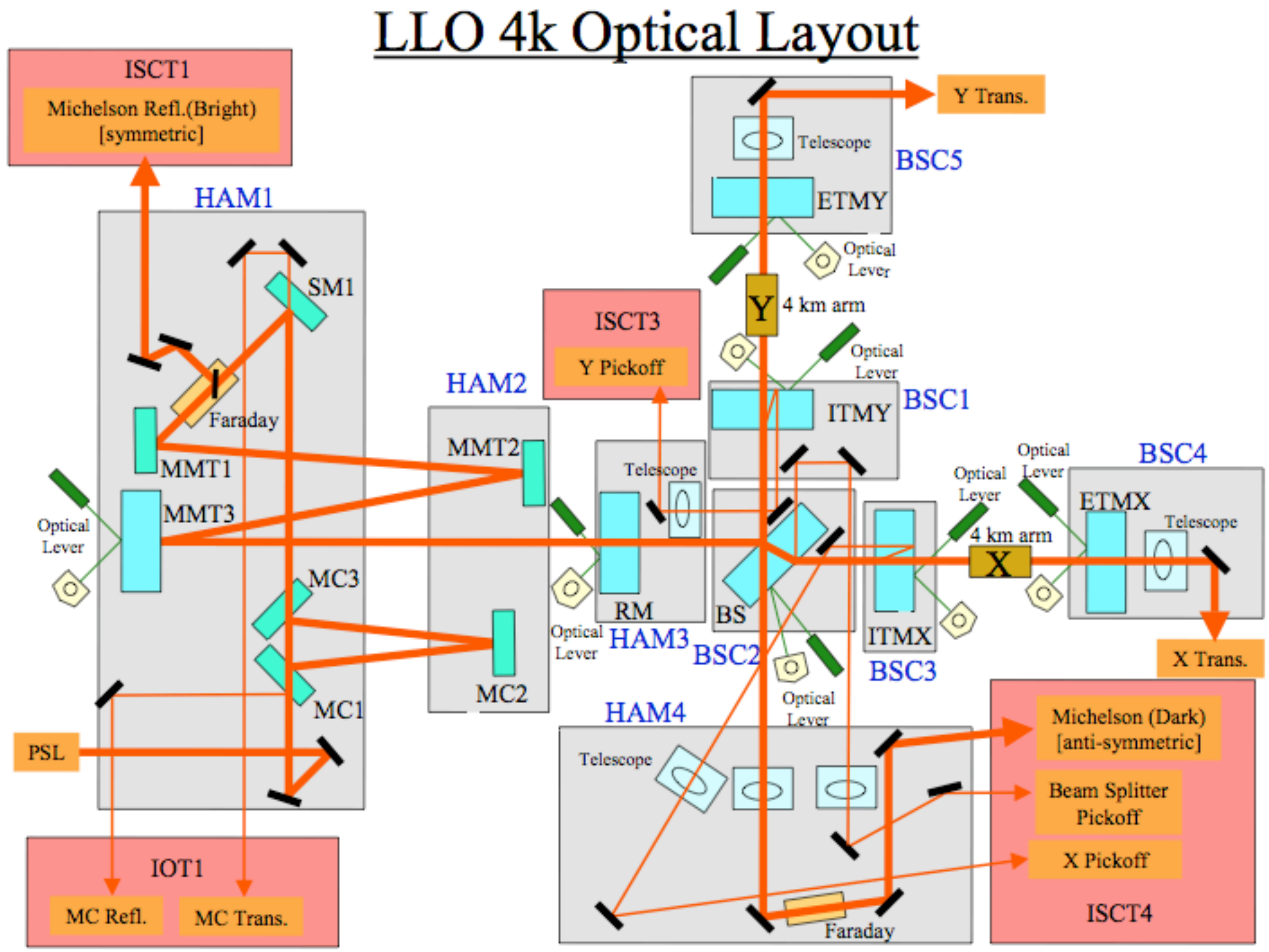
$$P_{OUT} \approx 2\Phi_{GW}\delta\sin 2\pi f_{\mathrm{mod}} t$$

- Demodulate --> audio frequency Gravity Wave signal.

How to Lock the Interferometer

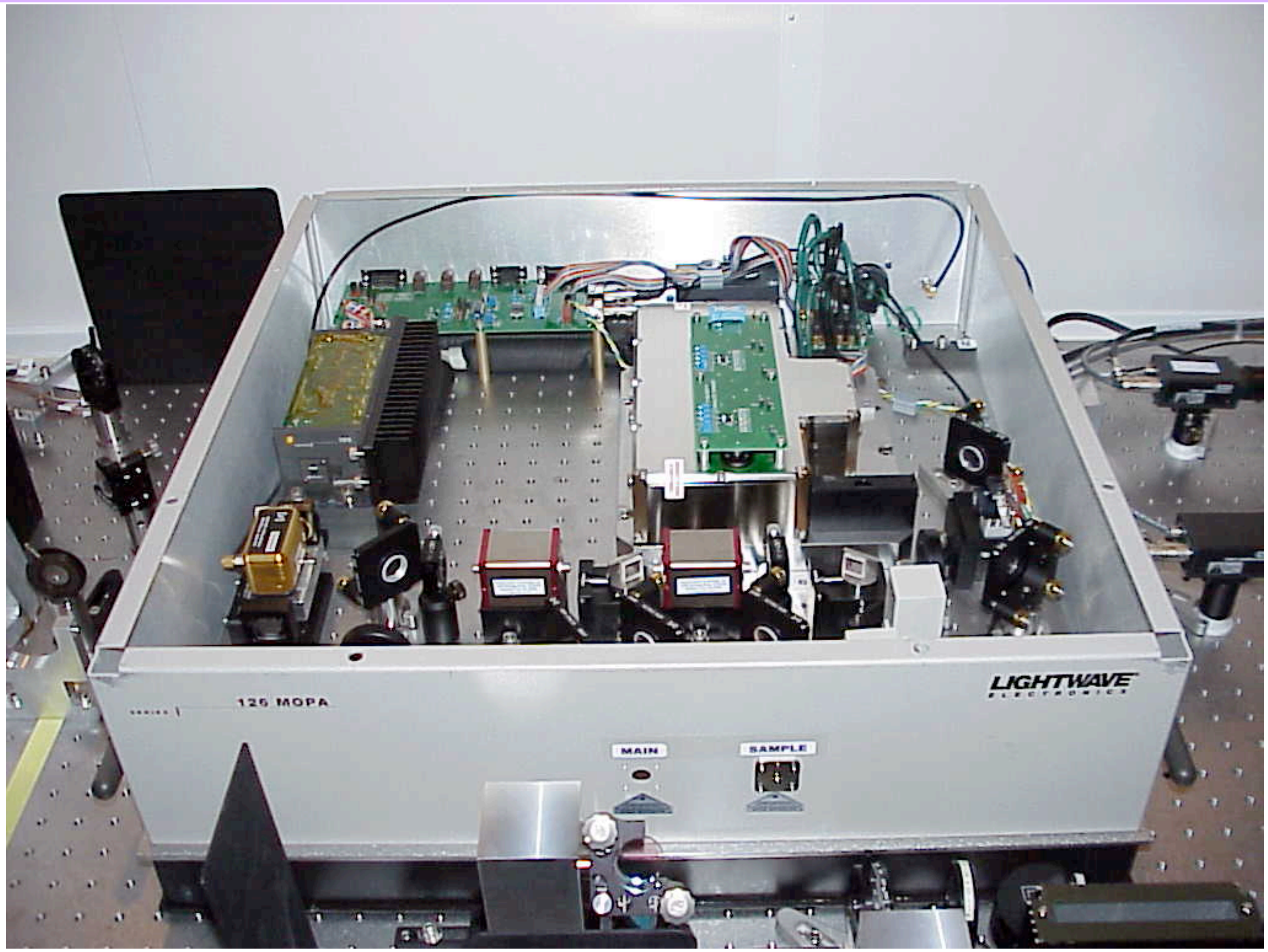
- Suspended mirrors each have 4 magnetic sensor/ controllers to adjust angles and position
- One Fabry-Perot arm is length reference for laser frequency in a feed back loop locked to arm resonance
- Second arm mirror positions are adjusted so cavity length is locked to this frequency
- Beam splitter 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.



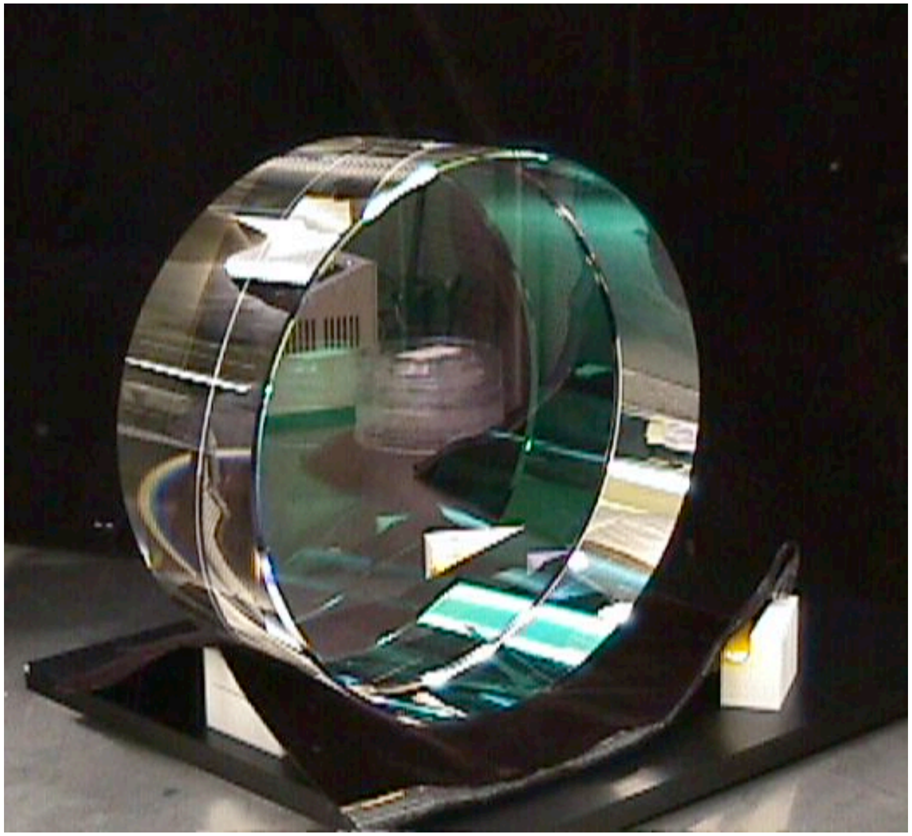
All-Solid-State Nd:YAG Laser

Custom-built
10 W Nd:YAG Laser

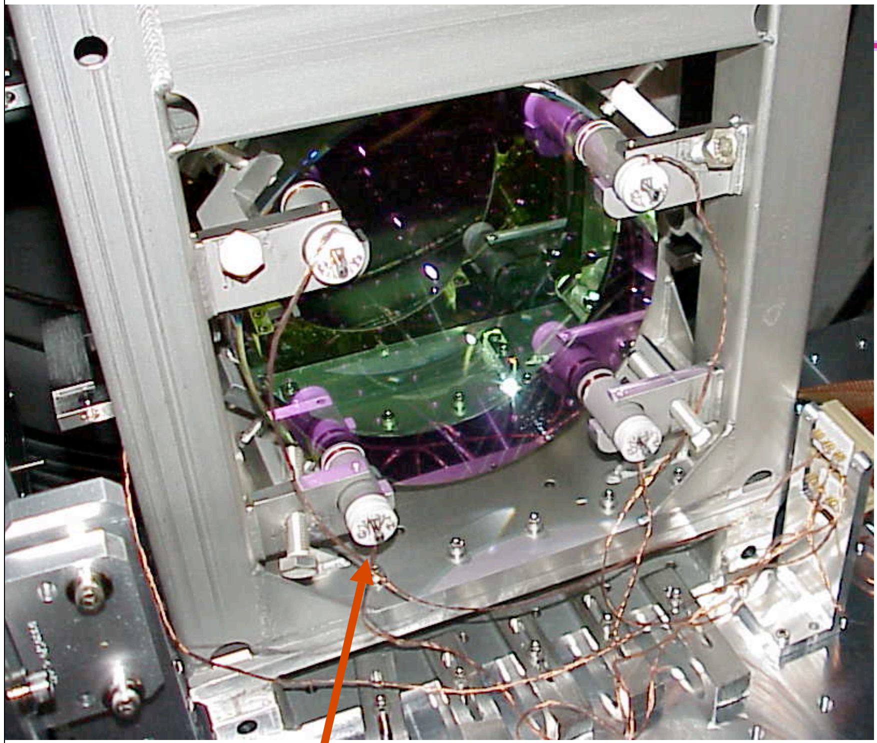


Test Mass Mirrors

- 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}

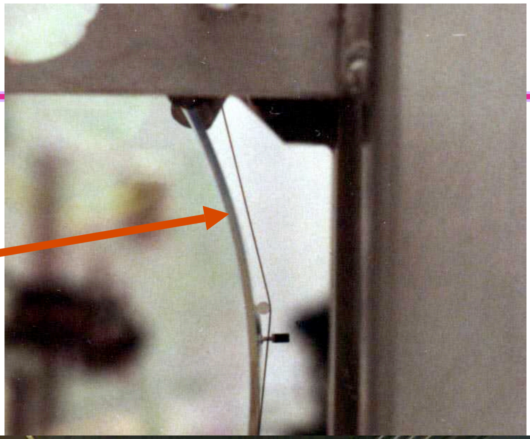


Mirror Suspension & Control



Local sensors/actuators provide damping and control forces

Optics suspended as simple pendulums on 0.25 mm wire

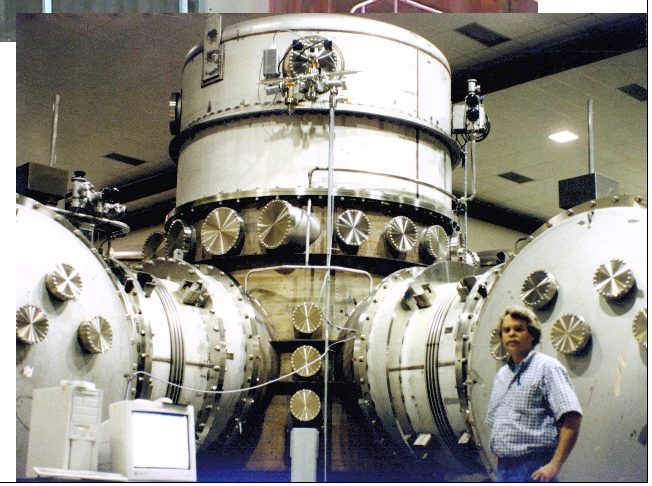


LIGO

Corner Station Vacuum Chambers

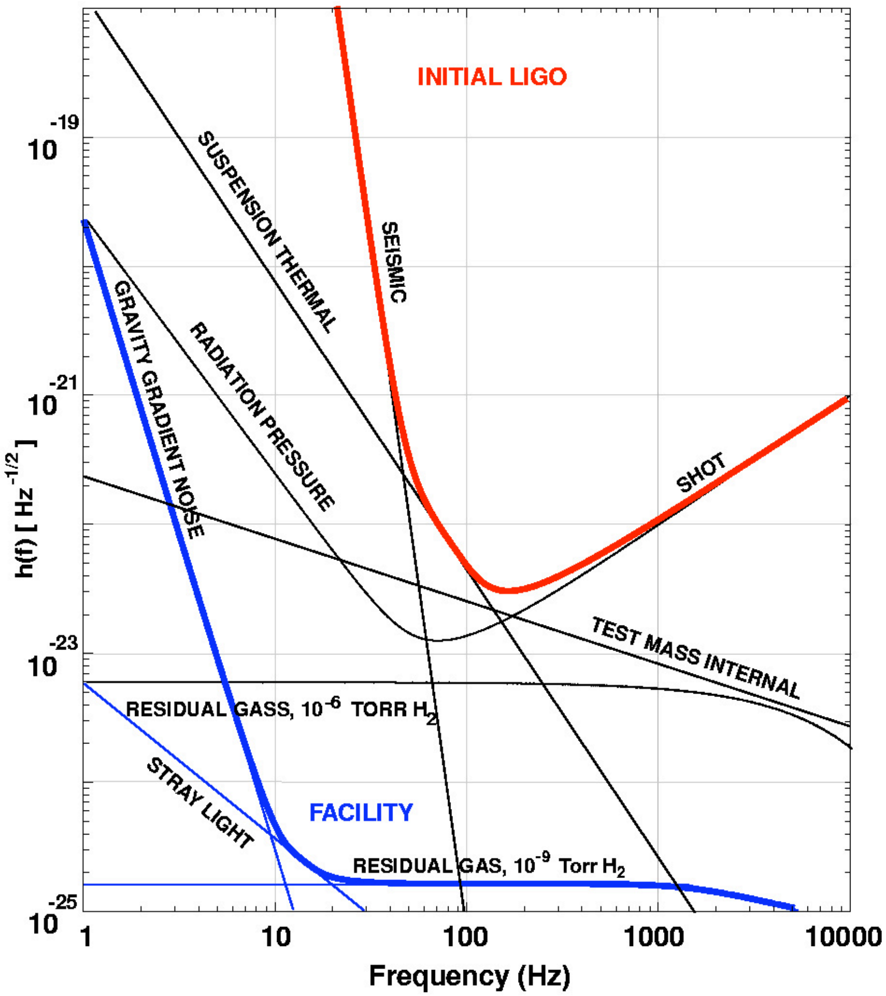
Vacuum: 10^{-6} torr

~1m diameter   2 x 4 km long



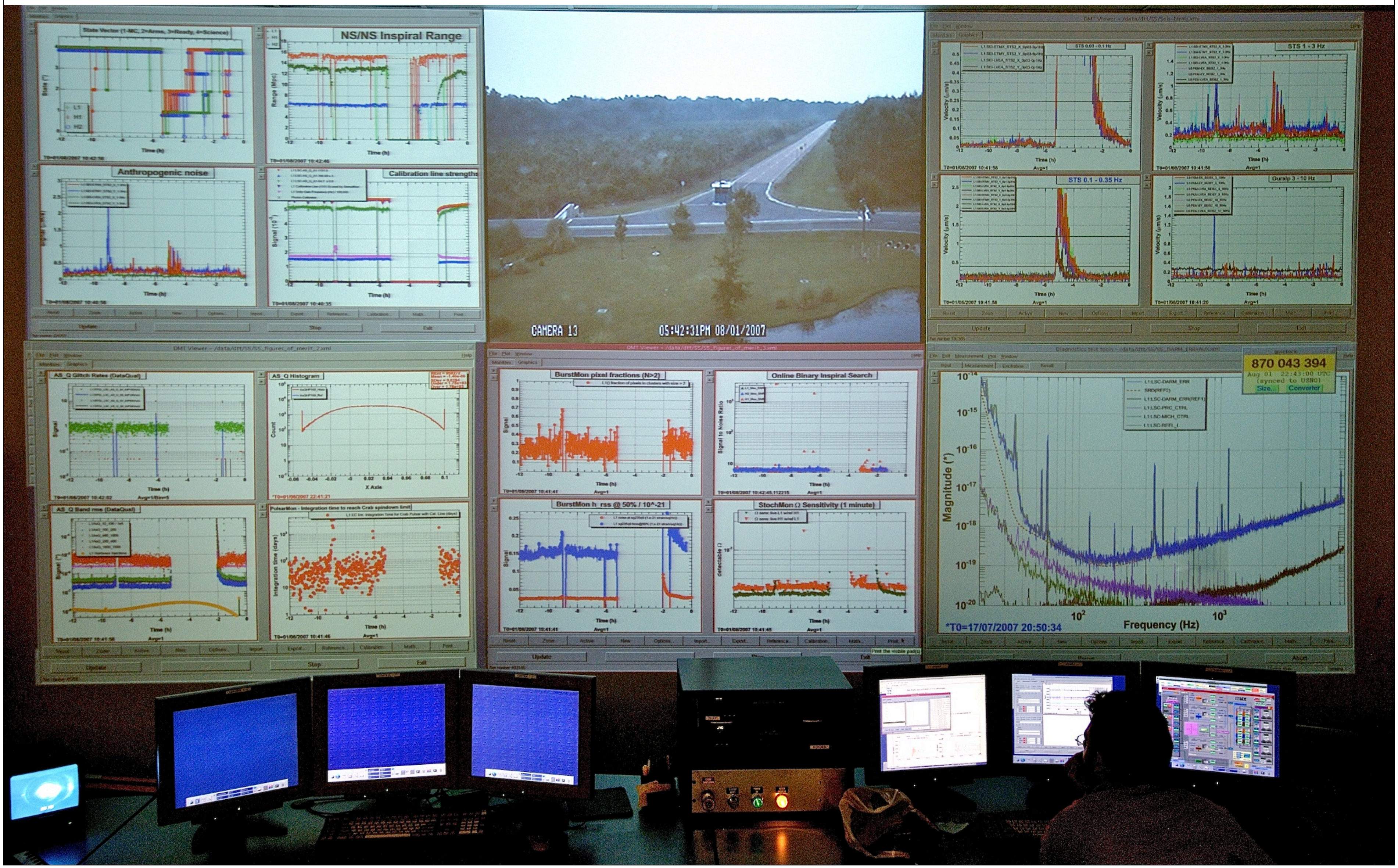
Adapted from Fred Raab slide

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

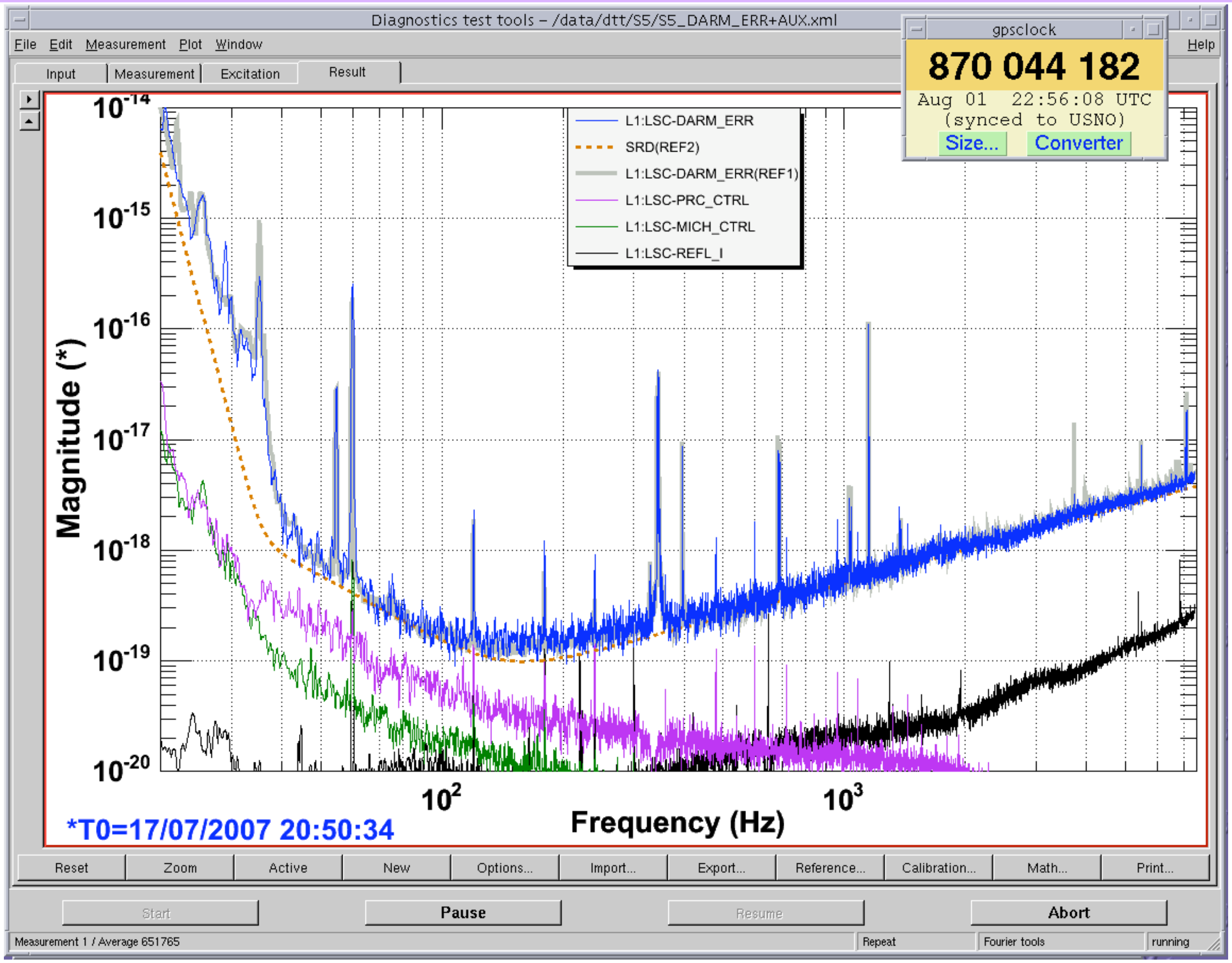
Louisiana Control Room…



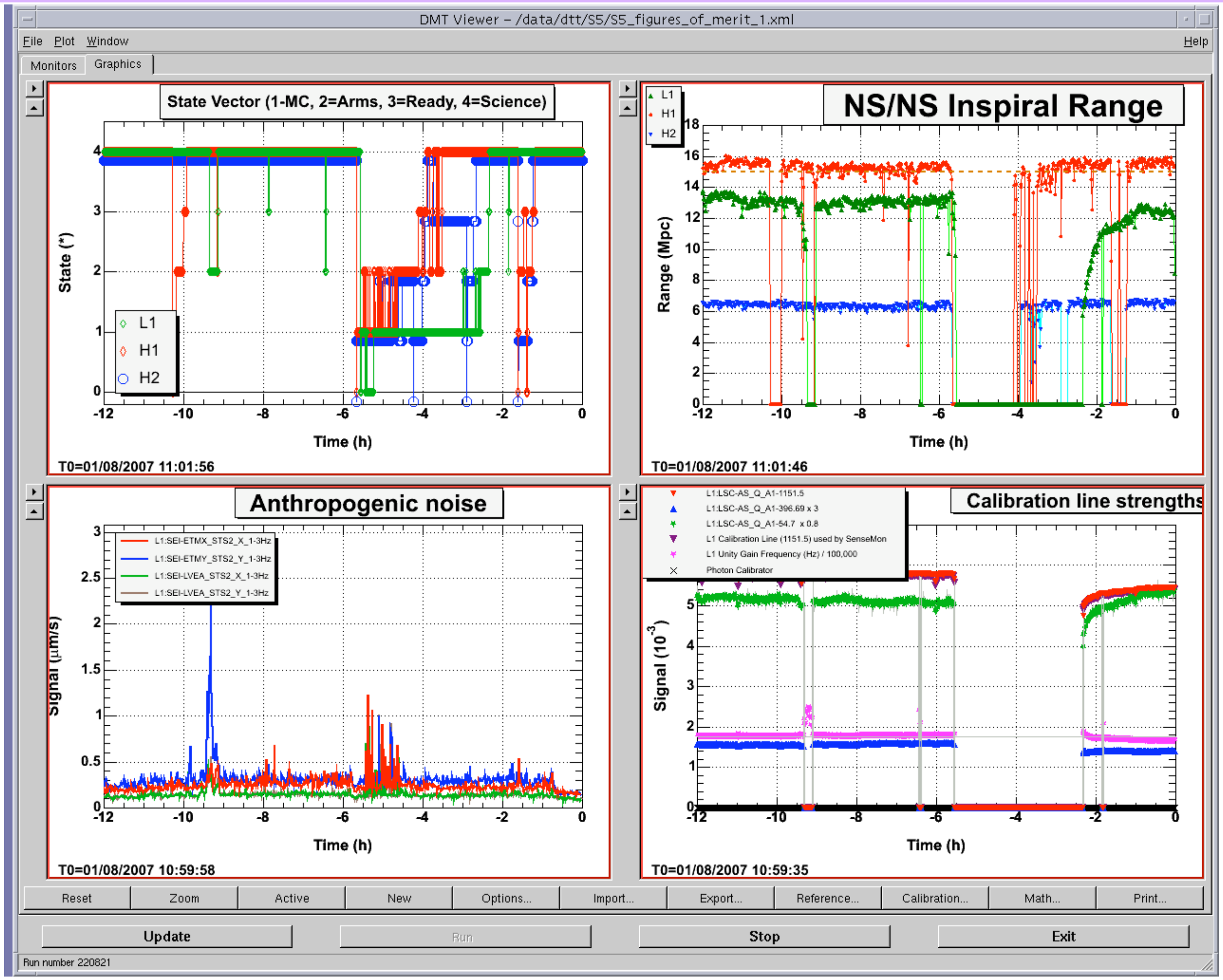
…Louisiana Control Room…

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

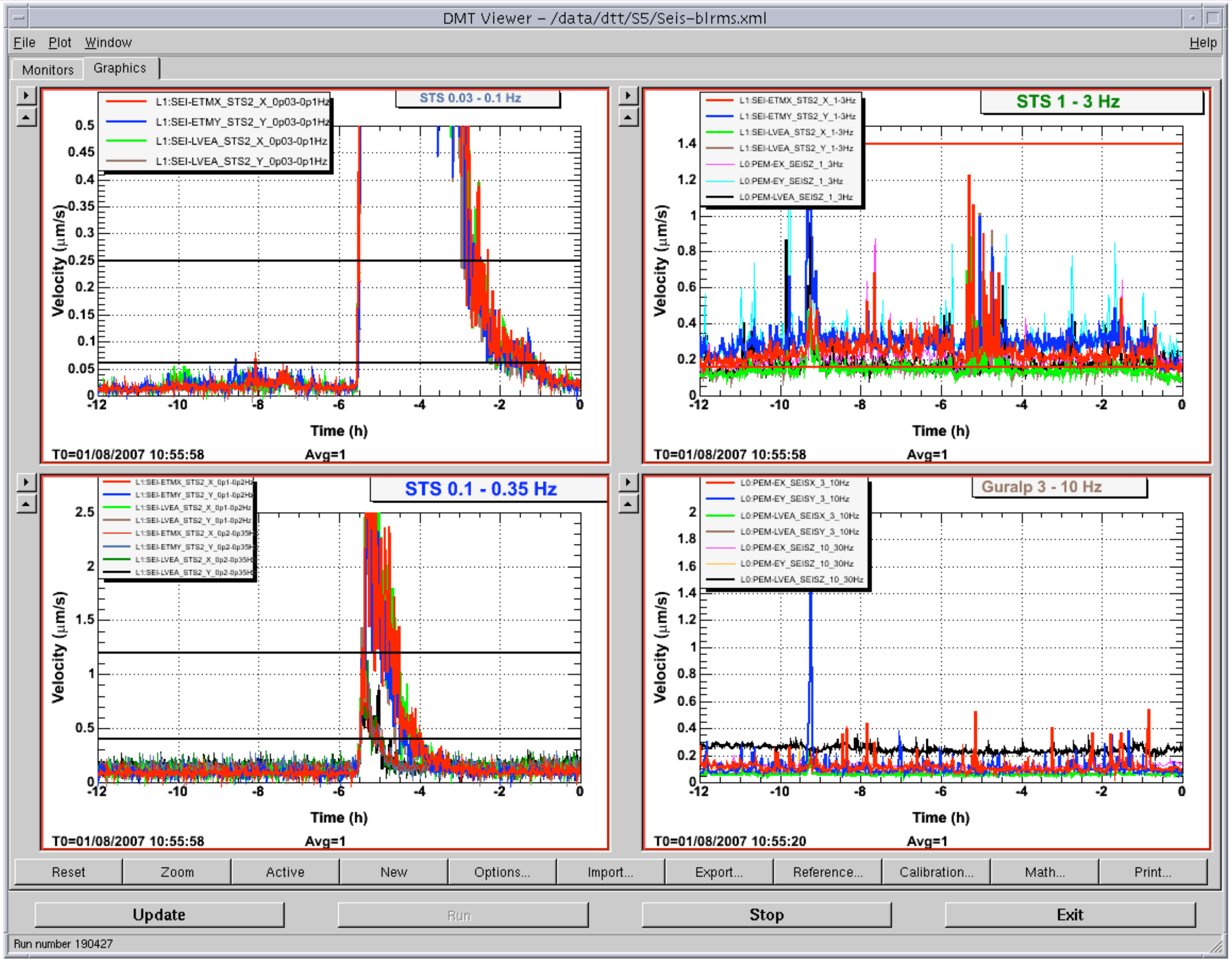
Versíon en Español

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 - design sensitivity 2006-7*
- Science Run 6: *Sensitivity goal ~2x 2009-11*
- *Enhanced LIGO*
  - » *Increase Laser Power*
  - » *DC Readout of GW phase - set length just off dark fringe*
  - » *Output Mode Cleaner*
  - » *Volume observed = Sensitivity ^{3} ~ 8X*
  - » *Preparing to start this summer*

Potential Sources

- Binary inspirals: **chirp signal of mergers and ring-down**
  numerical relativity black hole binaries templates
- Pulsars: **wobbling, accreting, mountainous stars**
  known frequency
- Bursts: **listening for supernova, GRBs, hi mass mergers**
- Stochastic: **Cosmological Background**
  early universe
  Astrophysical background
  noisy present day
  cosmic strings

How not to be fooled

- Require at least 2 independent signals
  - 2 non-local site coincidences for inspiral and burst
  - Time and position of electromagnetic signal - "multi-messenger"
    - External trigger from GRB or nearby supernova
    - Electromagnetic follow-up of GW trigger (gamma ray, radio, optical)
- 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 approach physics significance…

Binary Coalescence S5 90% Upper Limits

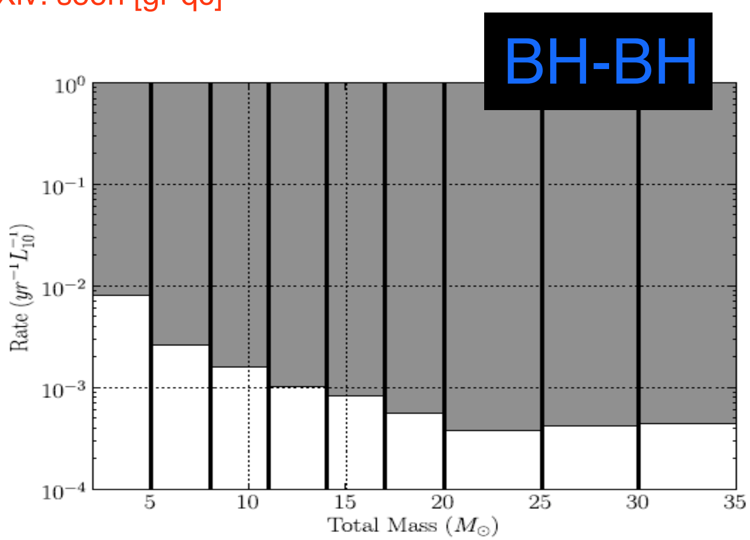
NS-NS 1.35/1.35M$_\odot$
~30 Mpc
1.4 $10^{-2}/L_{10}$-yr

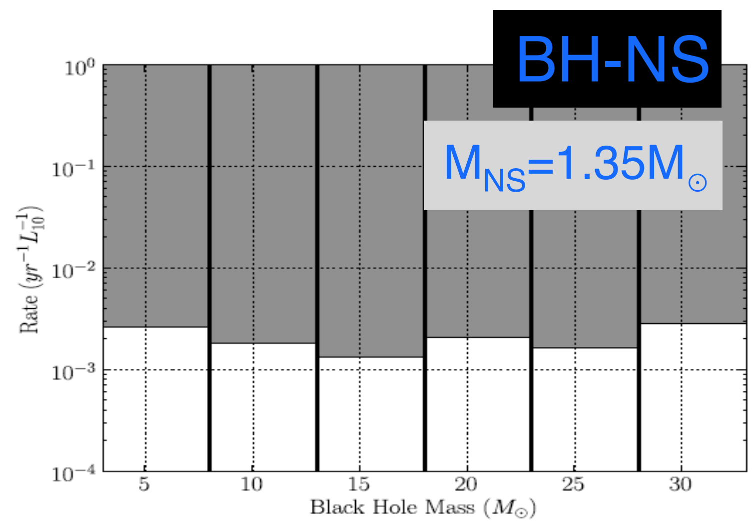
BH-BH 5/5M$_\odot$
~100 Mpc
7.4 $10^{-4}/L_{10}$-yr

BH-NS 5/1.35M$_\odot$
~60 Mpc
4.2 $10^{-3}/L_{10}$-yr

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

arXiv: soon [gr-qc]





113 Known Pulsars (S5)

Lowest ellipticity limit:

PSR J2124-3358 @405.6 Hz, 0.2 kpc

$\varepsilon < 7.0\text{x}10^{-8}$

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

Smallest limit:

PSR J1603-7202 @135Hz

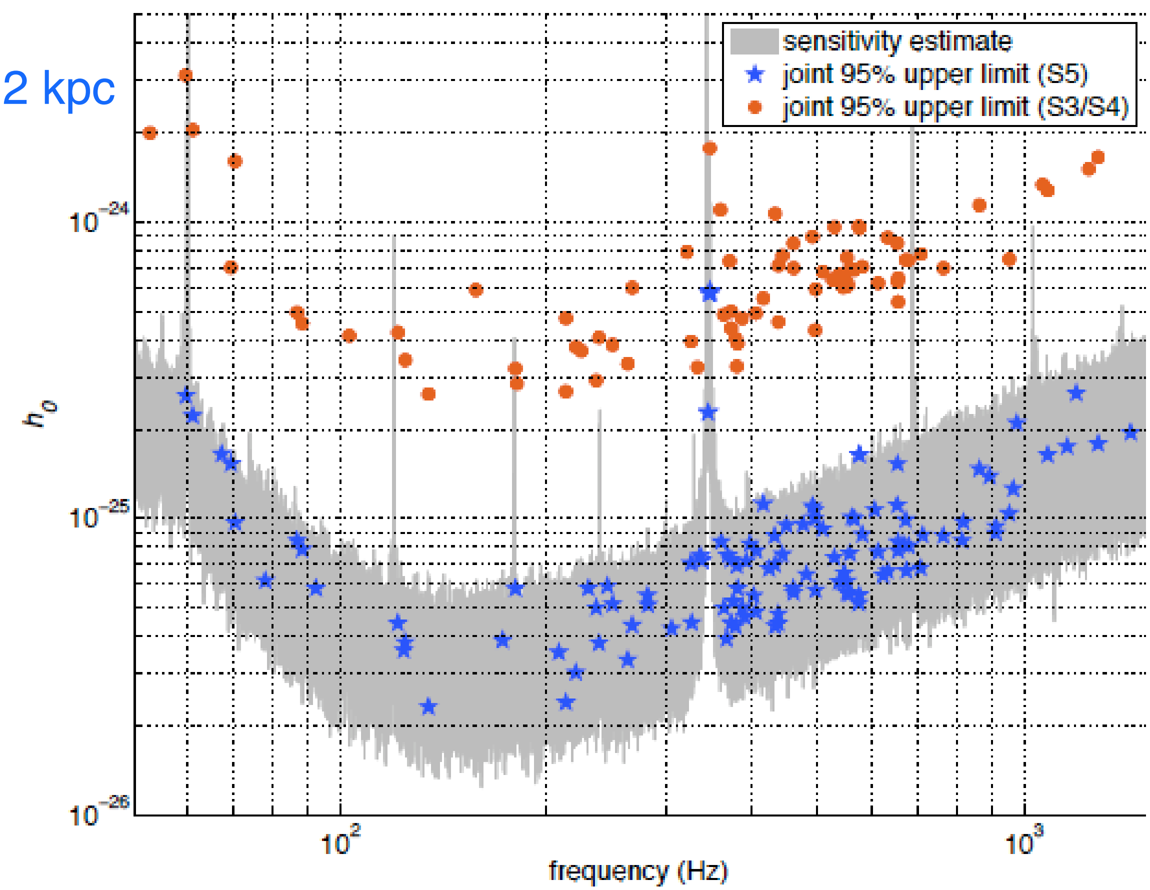
$h_0 < 2.3 \times 10^{-26}$

Crab pulsar

now well below spin down limit

< 2% spin down power in GW

ApJ 683 (2008), L45



Gamma Ray Burst Triggered Gravity Wave Search

LIGO and VIRGO

Most GRBs from Swift

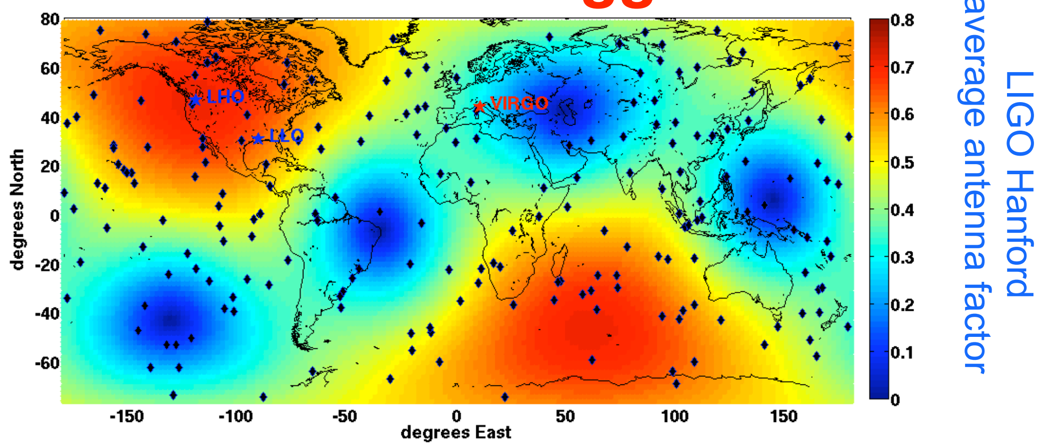
Also IPN3, INTEGRAL, HETE-2

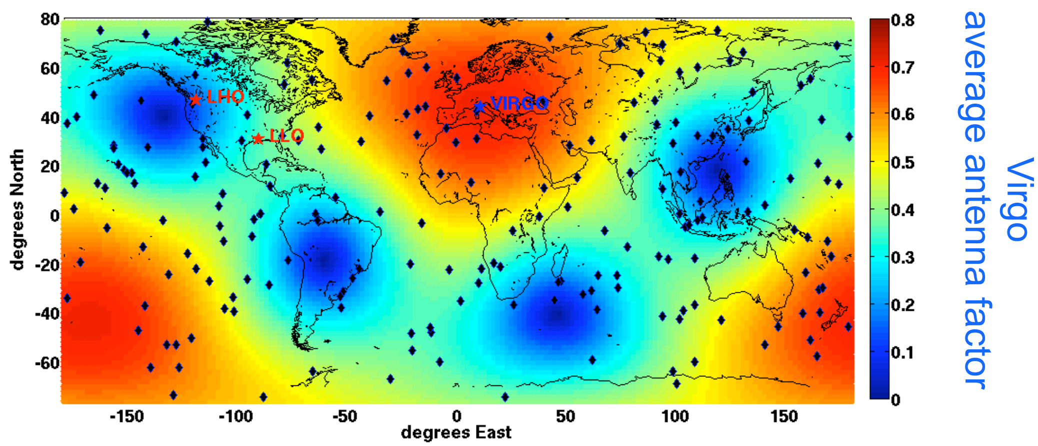
Nov 2005 to Oct 2007

- ~70% double-IFO coincidence LIGO data
- ~45% with triple-IFO coincidence LIGO data
- ~15% short-duration GRBs
- ~25% with redshift
- ~20% fall in joint LIGO-Virgo times

Paper in preparation

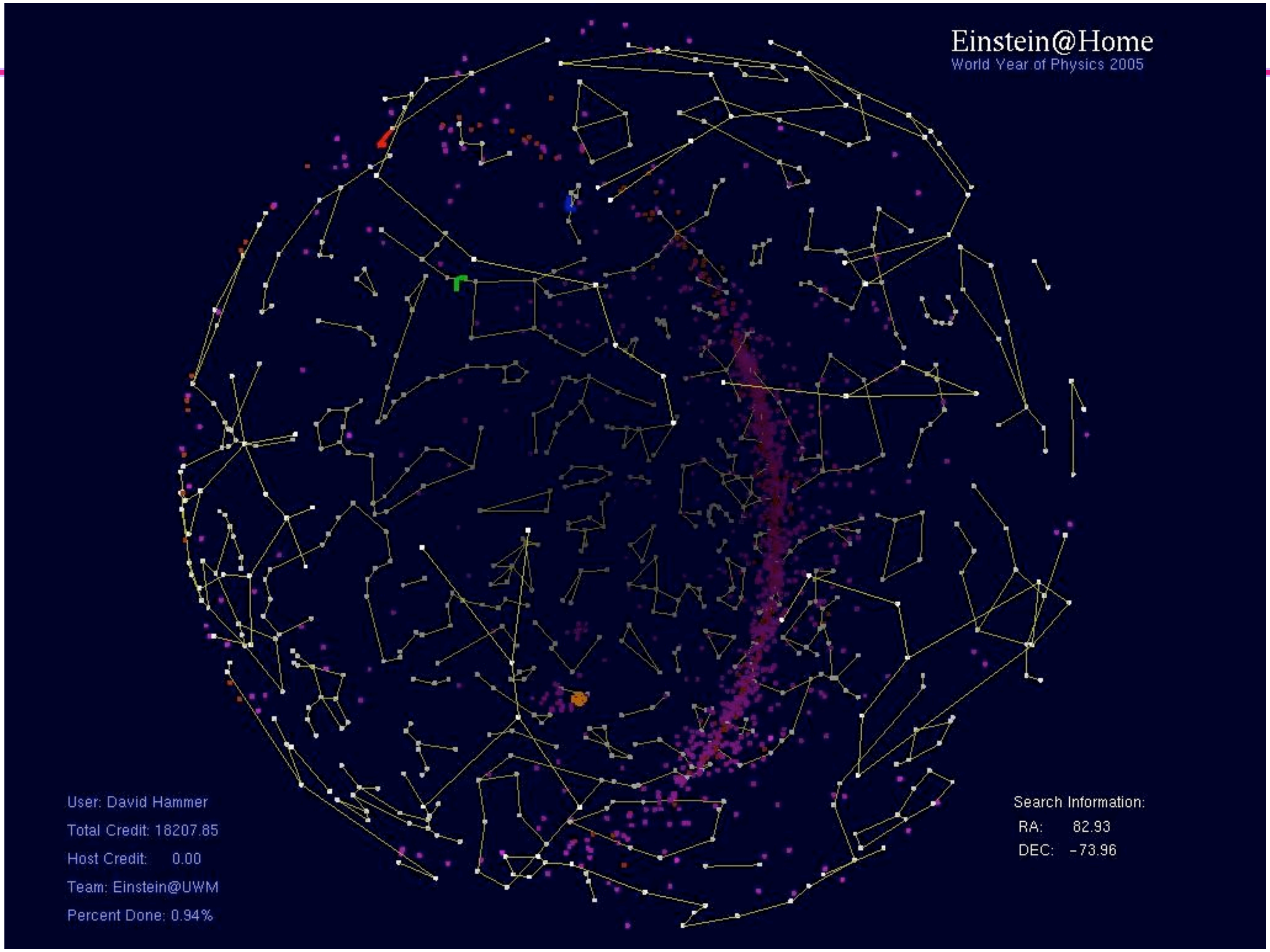
212 GRB Triggers



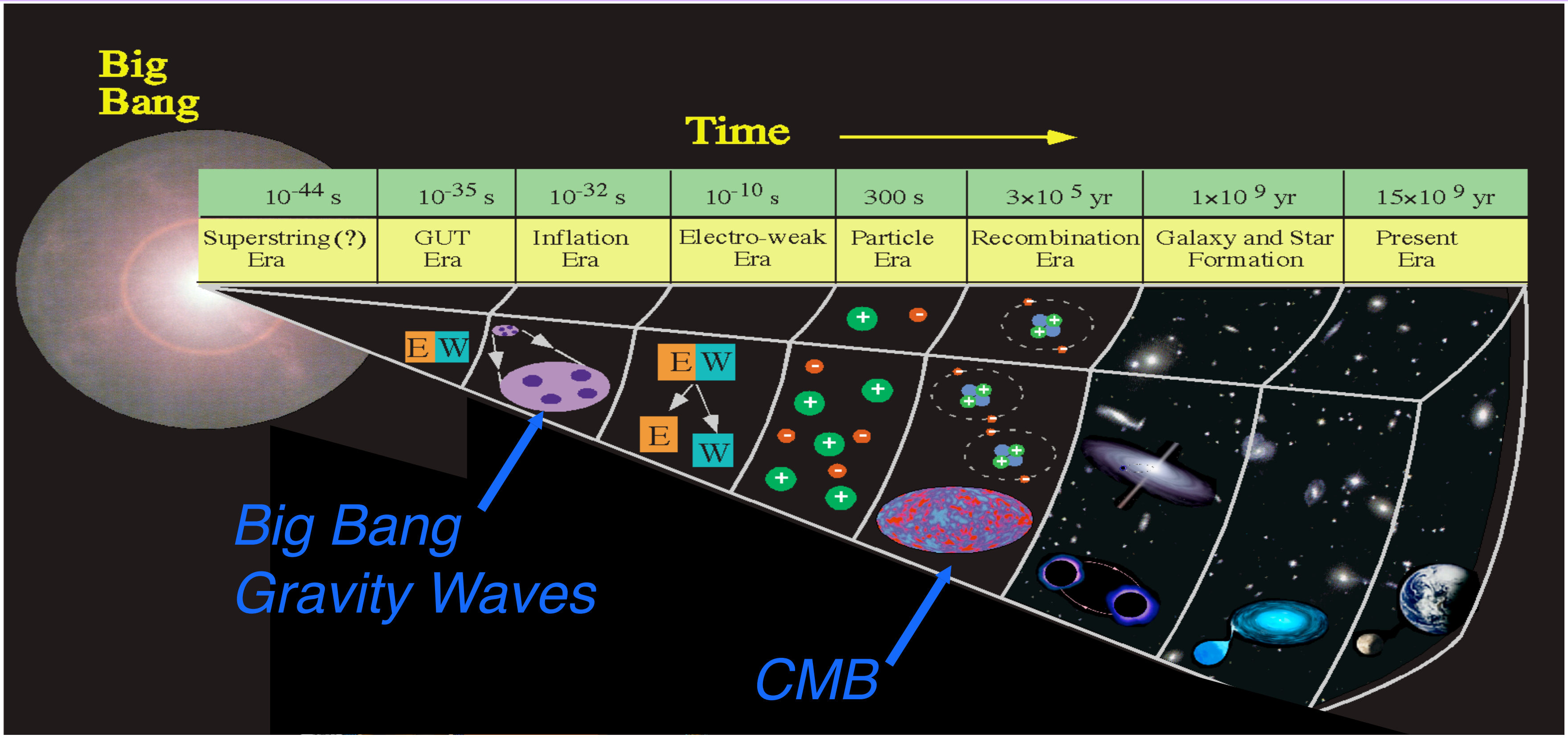


Slide adapted from Isabel Leonor talk at Denver APS LIGO-G0900392

Einstein @ Home



Stochastic Gravity Waves
Our Only Window to the Big



Adapted from LISA slide

Stochastic Upper Limits

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

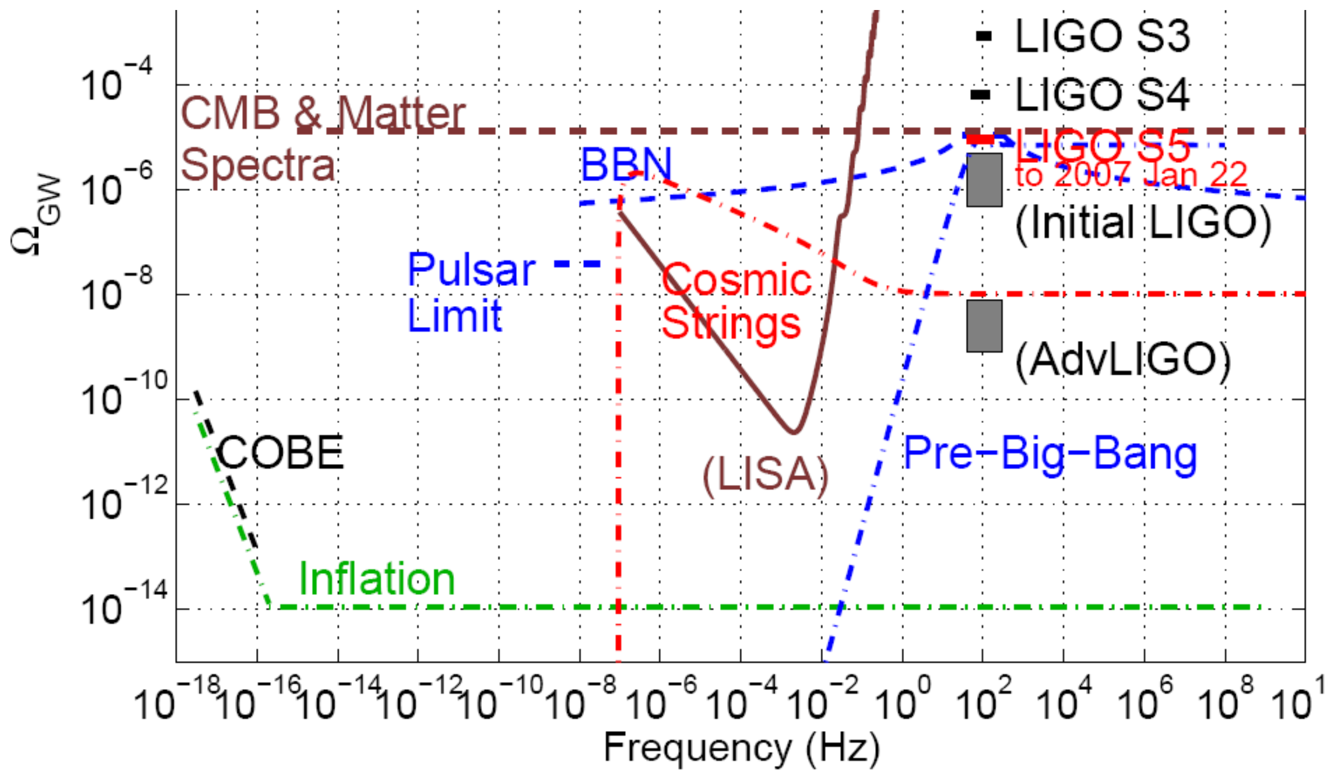
Partial, preliminary S5 result comparable to *Big Bang Nuclear-synthesis Limit*

$\Omega_{BBN} < 1.1\ 10^{-5}$

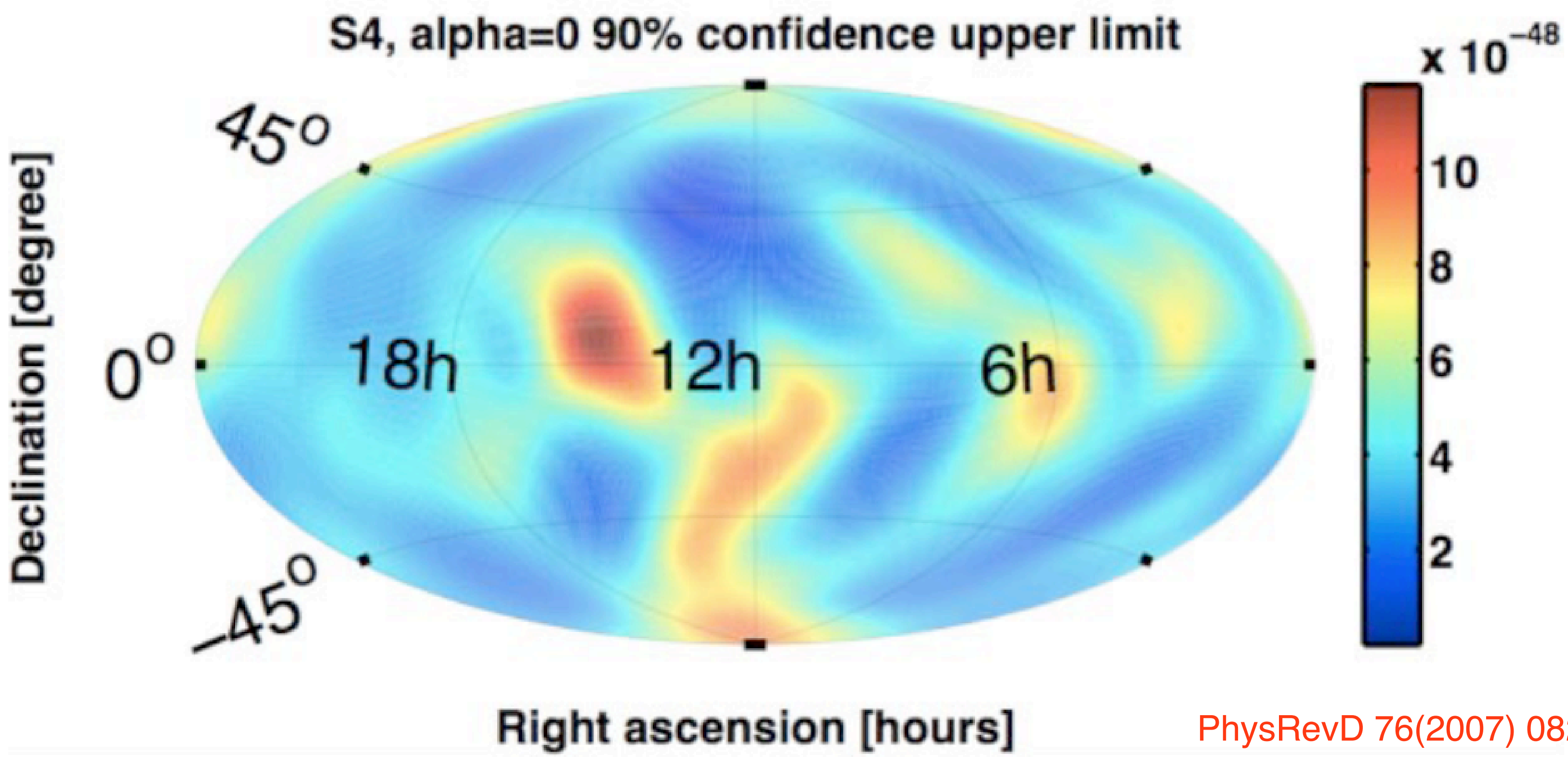
ApJ **659**(2007)918

Full S5 result soon

VIRGO will improve joint sensitivity in future runs



First Gravity Wave Upper Limit All Sky Map



PhysRevD 76(2007) 082003

Point sources with flat power spectrum

LIGO The Future: Advanced LIGO

Major installation: 2011 Run:

Active anti-seismic lower frequencies

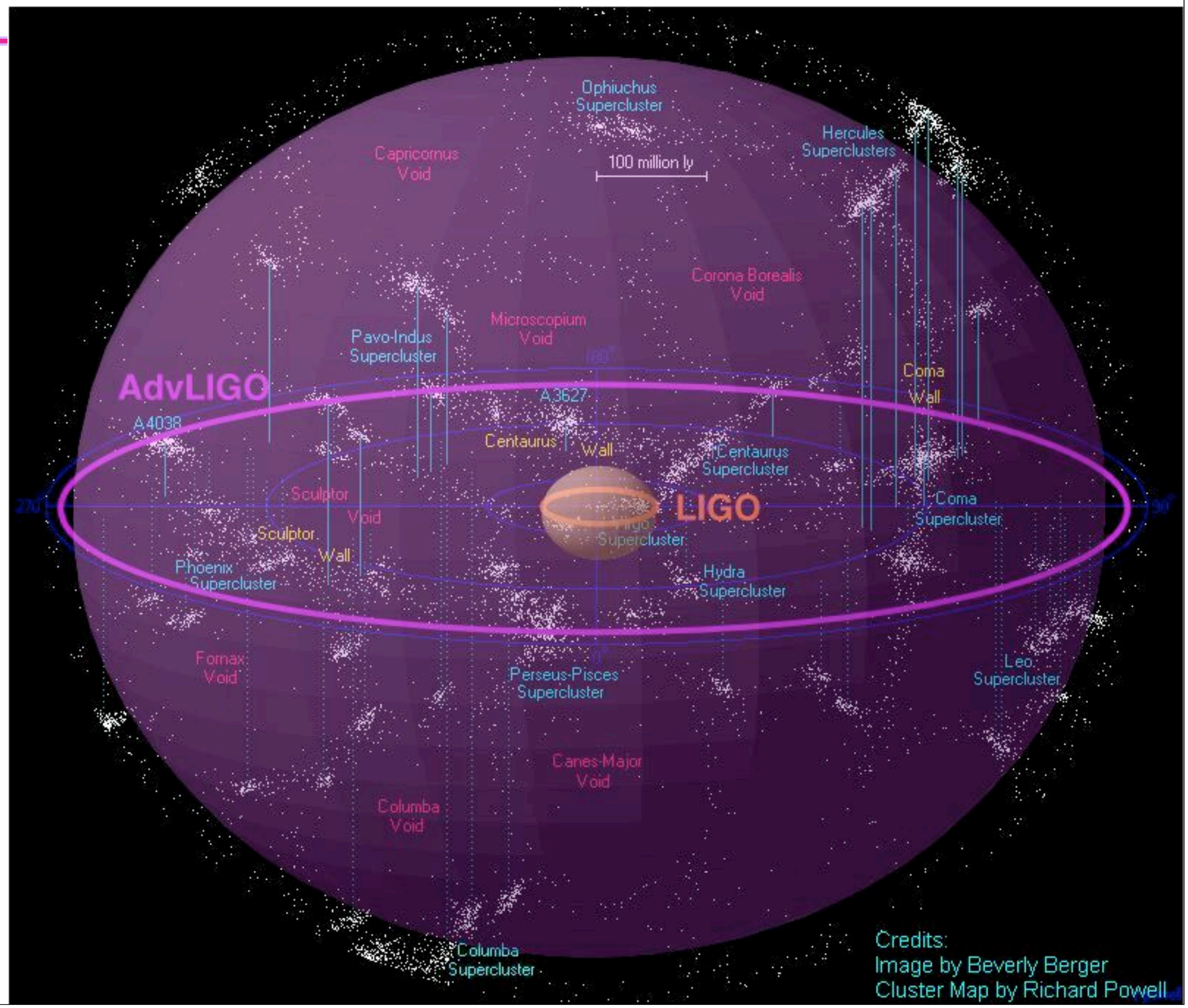
Lower noise optics & suspensions

Increased mass mirrors (40 kg)

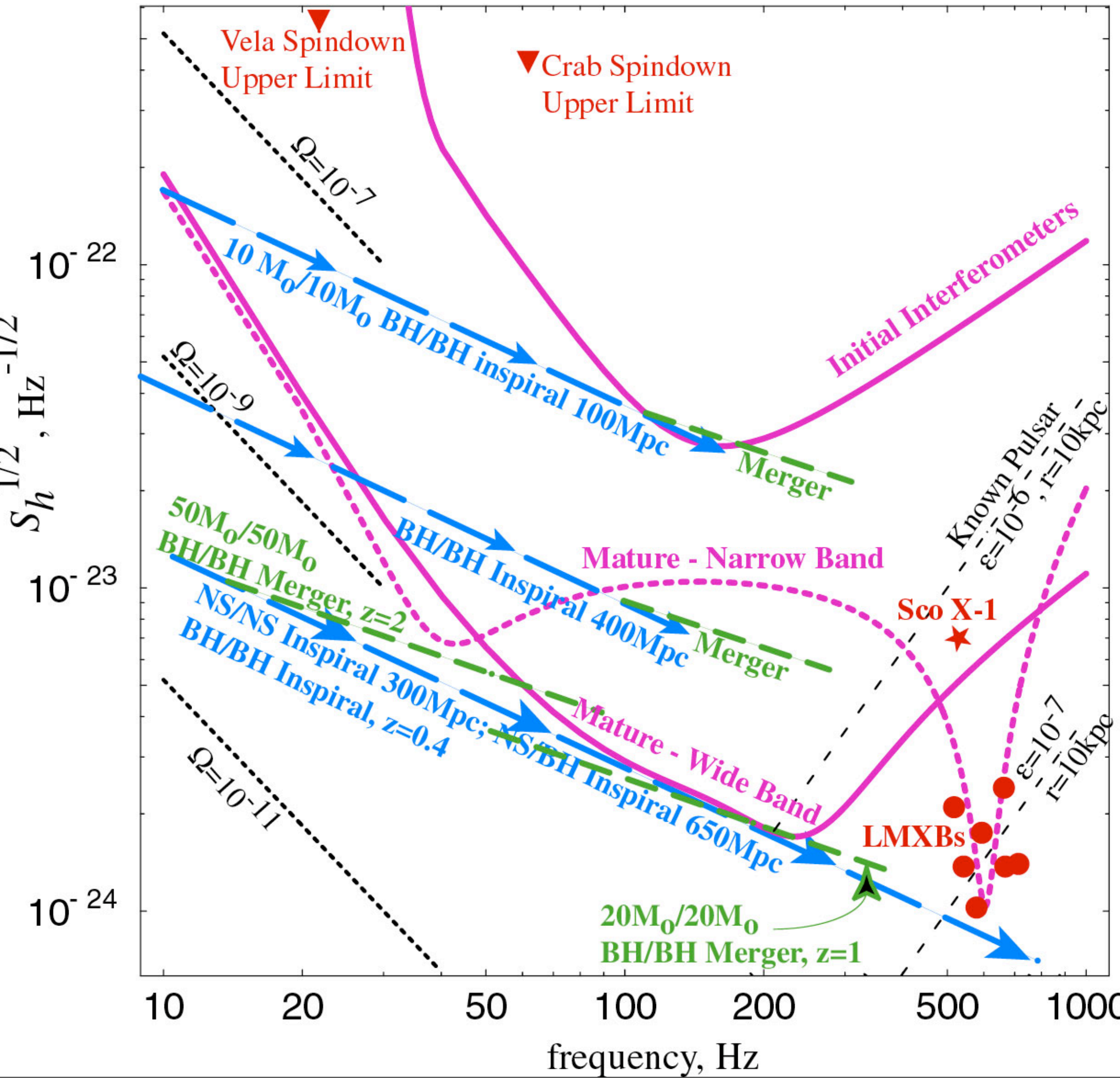
Higher Laser power (180 W)

Signal recycling

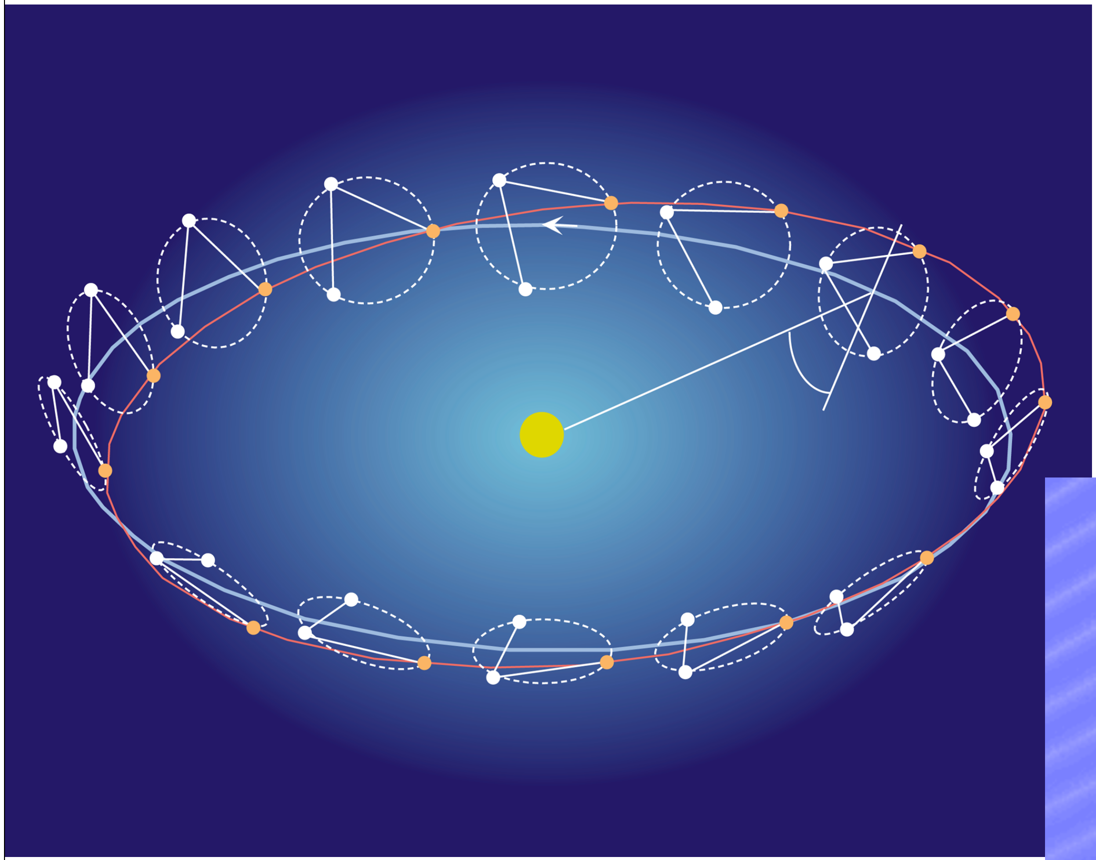
DC readout



Difficult to hide from Advanced LIGO

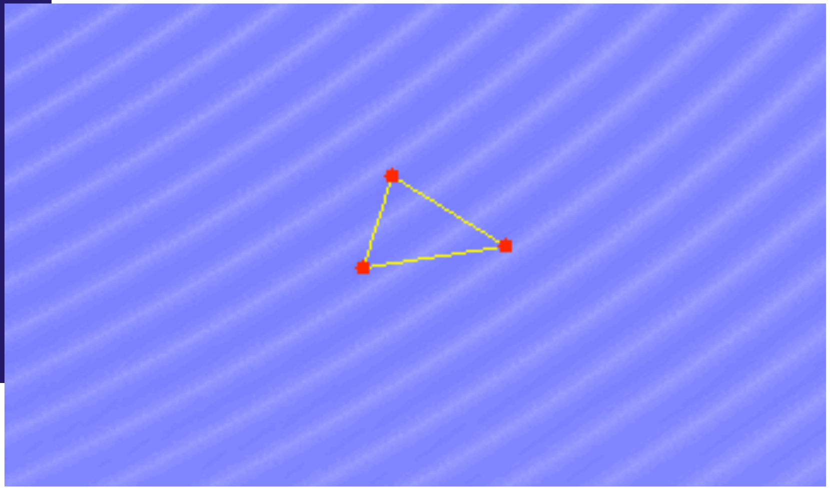


Space based interferometer: LISA



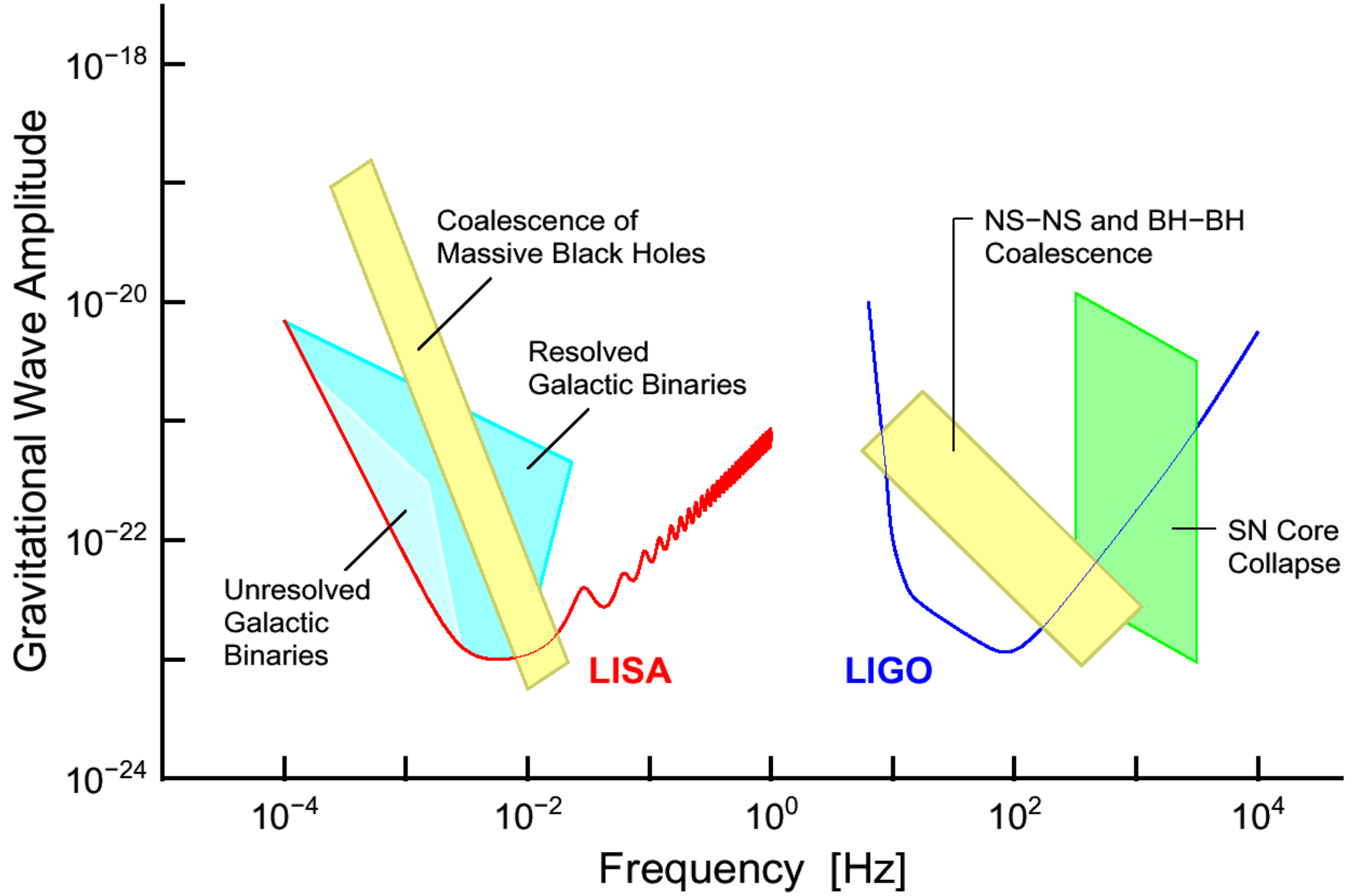
3 satellites 5 10^6 km apart
Heliocentric orbit
20° behind the earth

LISA surfing
a gravity wave



NASA-ESA Launch 2013?

LIGO and LISA are Complementary



LIGO Universe full of surprises
Need to keep our eyes open

References = Acknowledgement

- Books
  - » 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