# Gravitational Waves: Next Window on the Universe

Thomas Nash
California Institute of Technology
LIGO Scientific Collaboration

*Sobral Meeting*

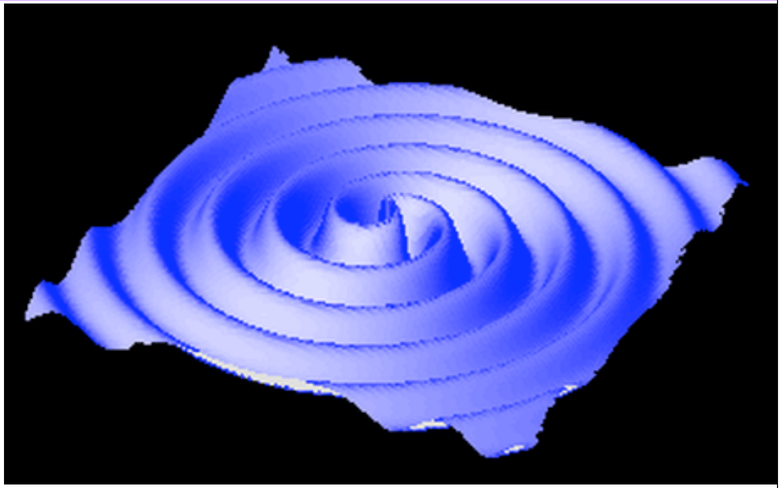
*Fortaleza, 27 de maio de 2009*

# 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: $G = 8\pi T$

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

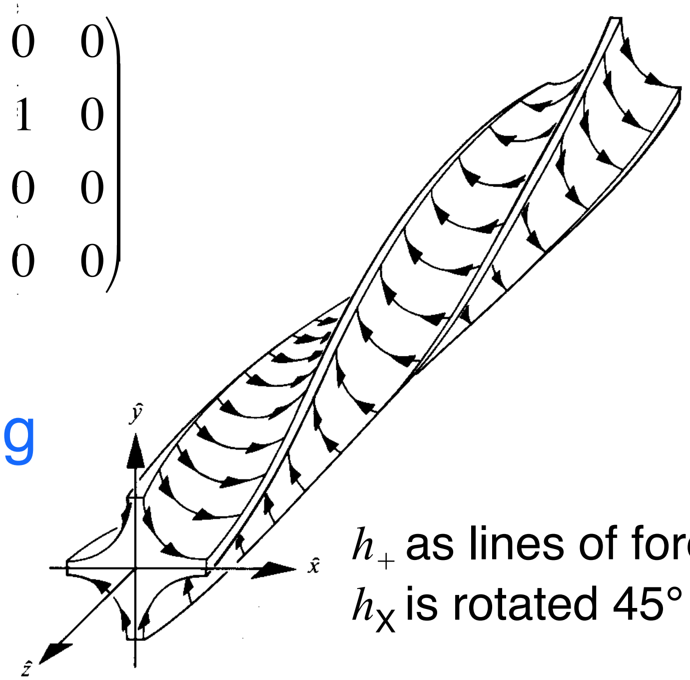
# … Quadrupole Sources & Waves …

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

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

- Resonant bar detectors are rung by effective force

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

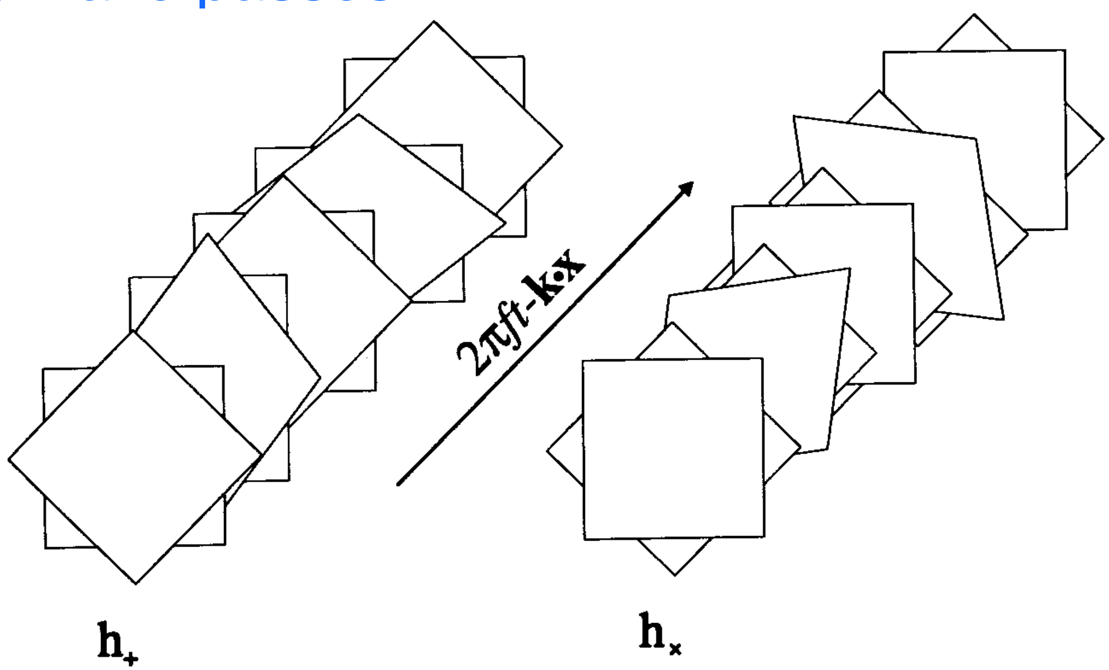



$h_{+}$ as lines of force
$h_{\mathrm{X}}$ is rotated 45°

# … 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°

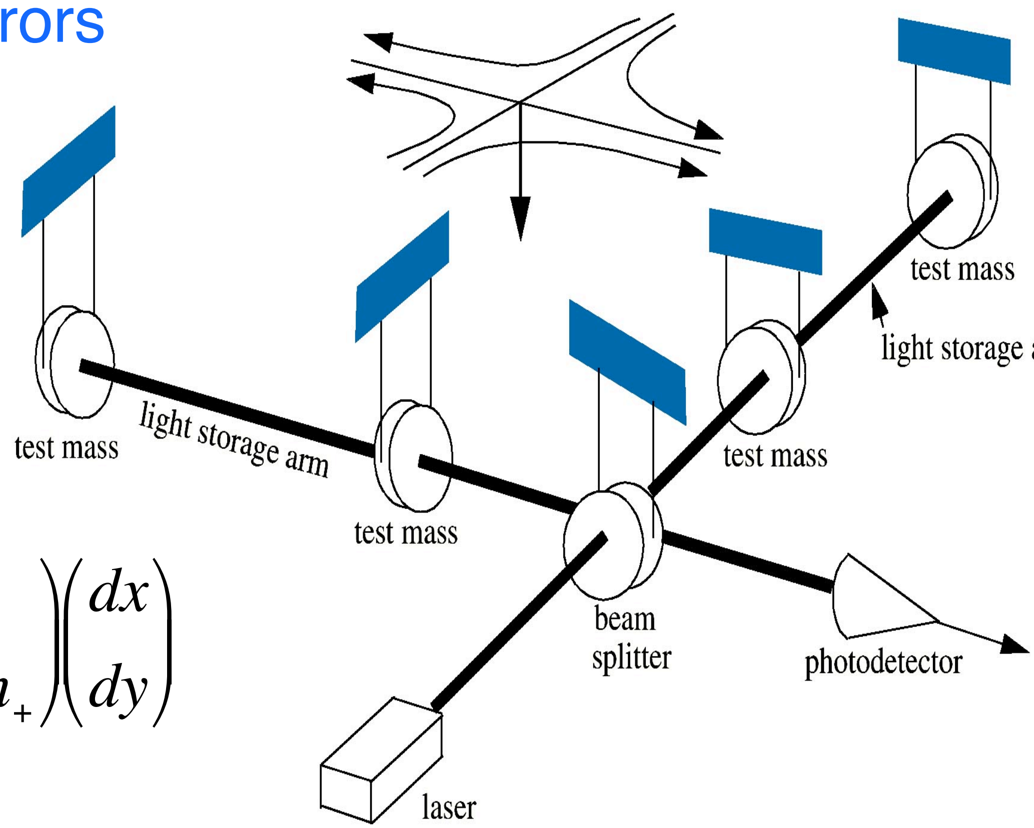


# Quadrupole GW Antennas

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

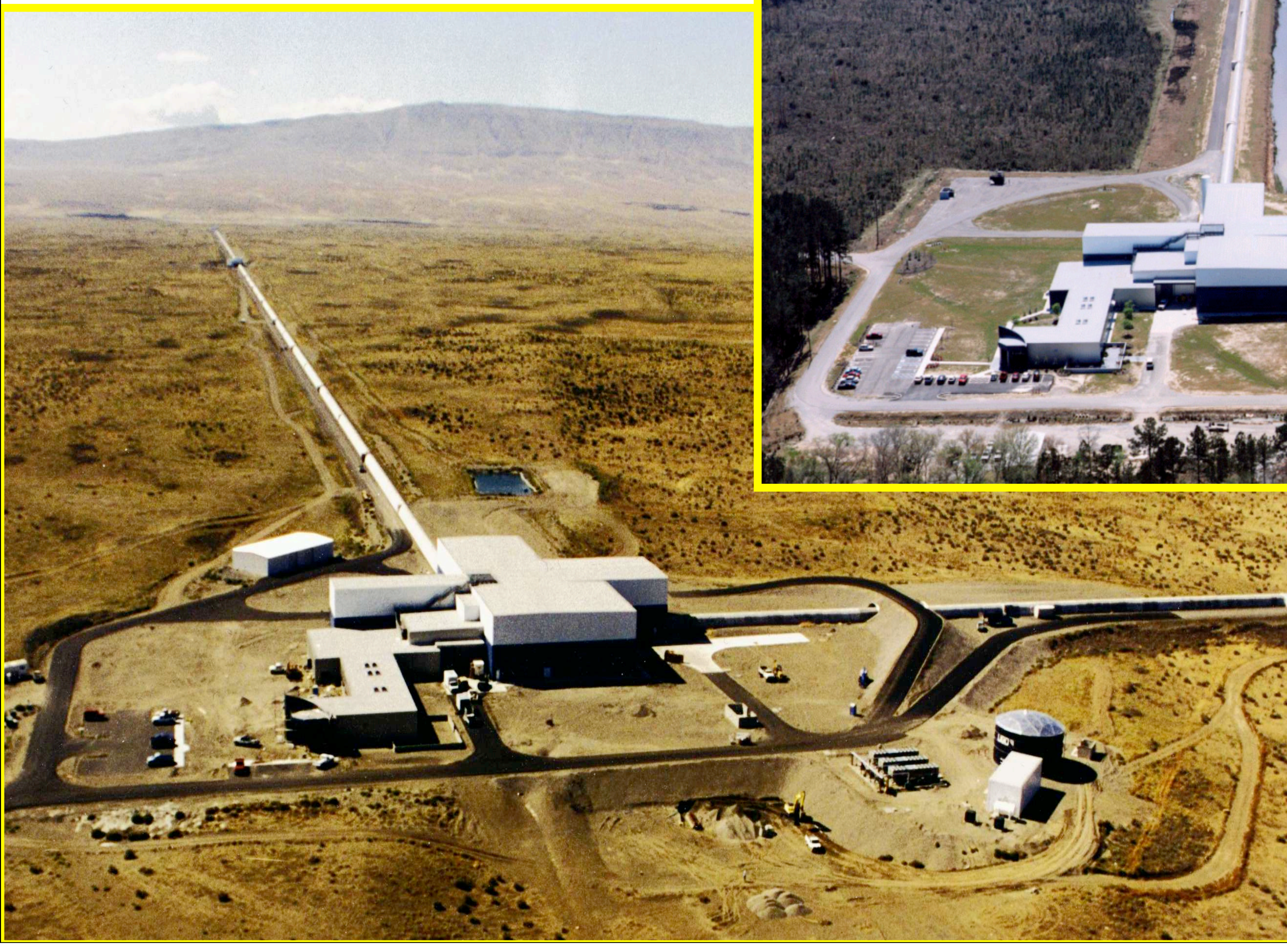
$$dL^2 = g_{\mu\nu} dx^\mu dx^\nu$$

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



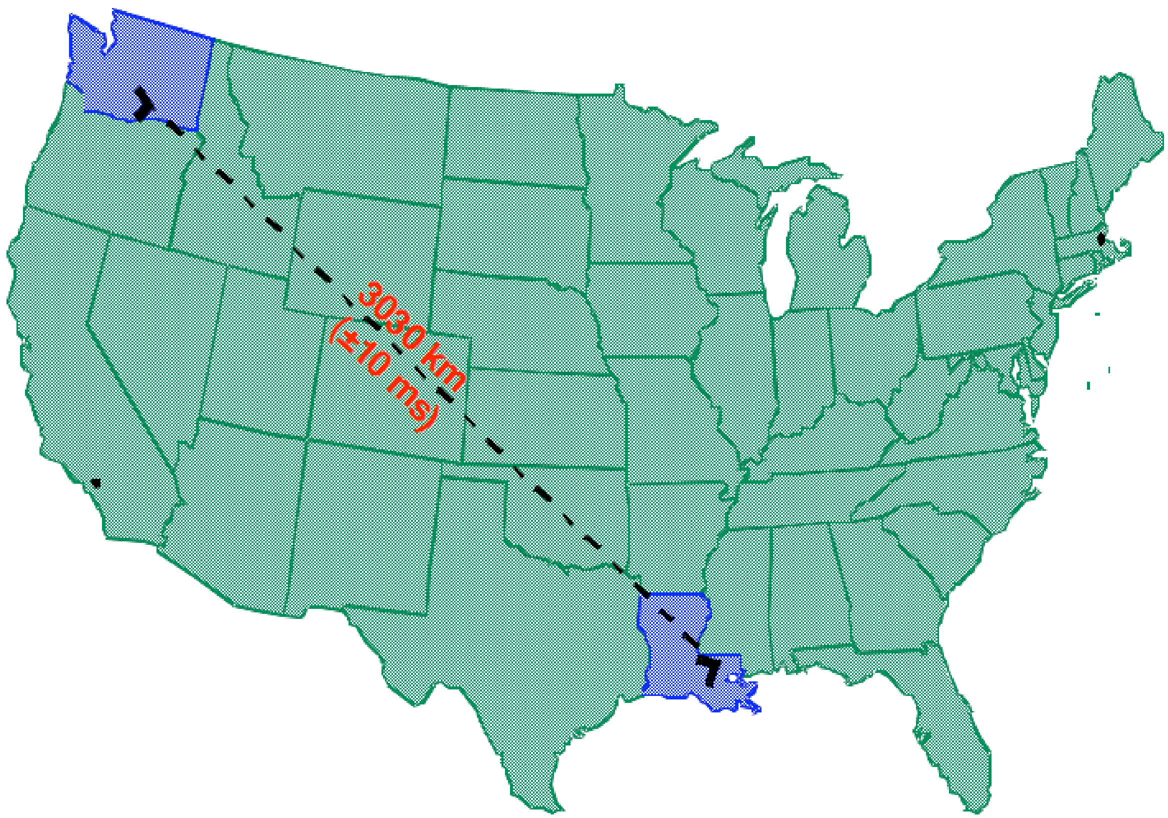
# LIGO Laser Interferometer Gravitational-wave Observatory

*Hanford, Washington State*
*2 km and 4 km*

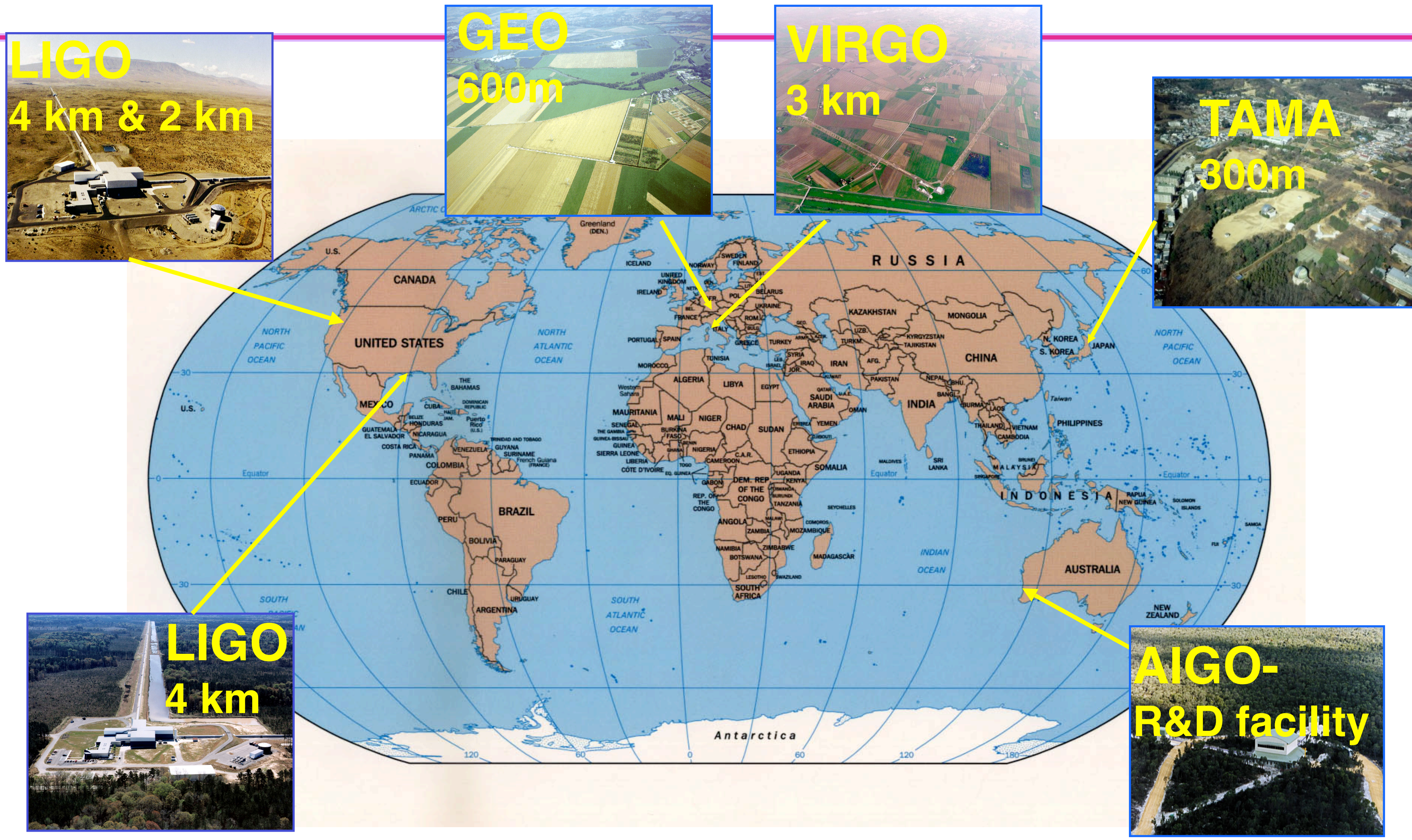


*Livingston, Louisiana*
*4 km*

# Two locations, far apart



# Global network of interferometers



# Worldwide Network Gravity Wave Observatories

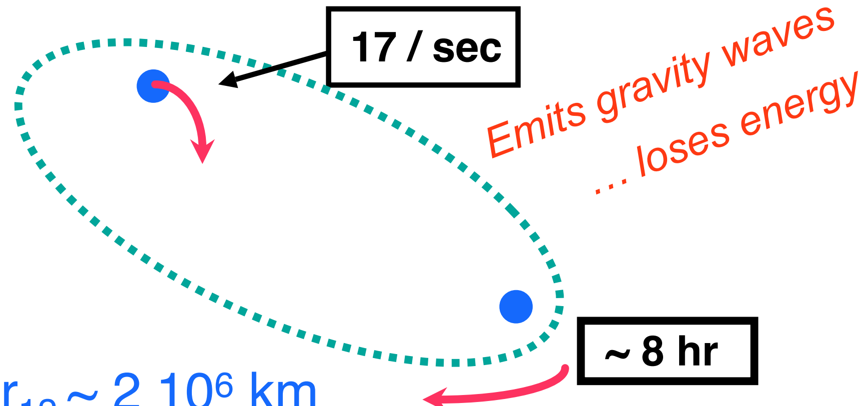
- Why so large?
  - Gravity waves affect $\delta L/L \sim h$
  - Need large $L$ for high sensitivity
- Why so far apart?
  - Sensitivity is extremely high (as we shall see)
  - Require coincidence of at least 2 detectors
  - Different local noise sources (seismic, electric, audio, …)
- Why so many?
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

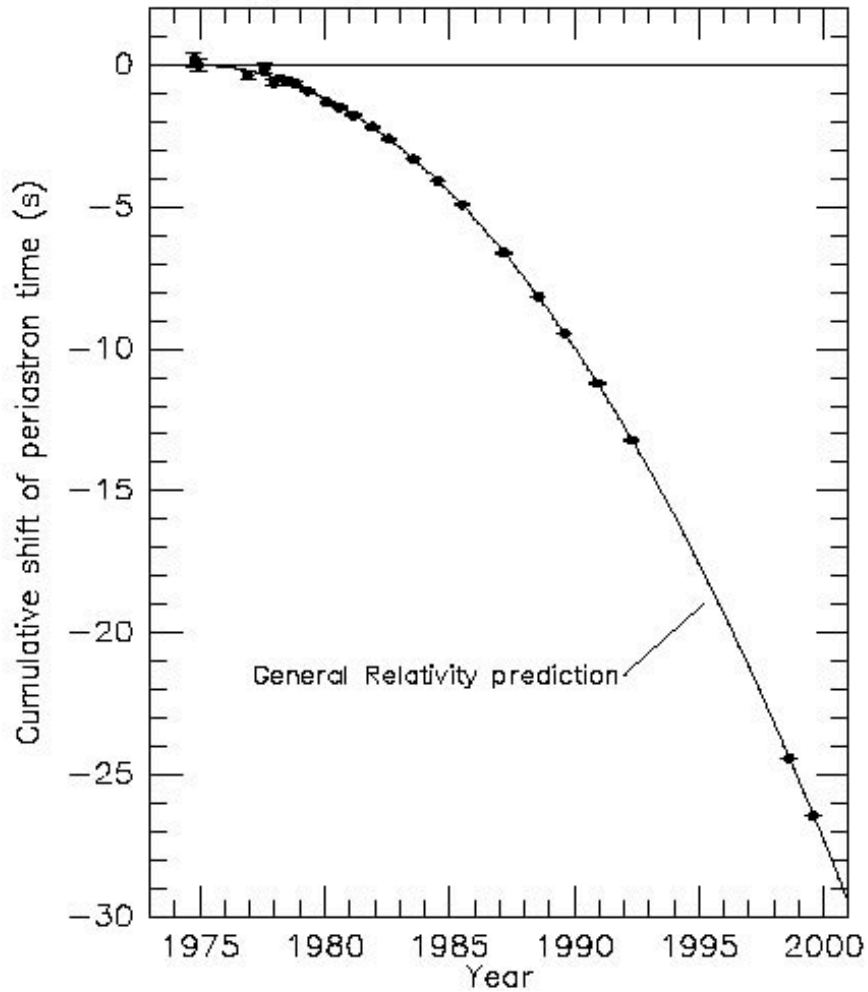
PSR 1913 + 16




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

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

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

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

  $r_{orbit} \approx 20$ km $\quad f_{orbit} \approx 400$ 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!

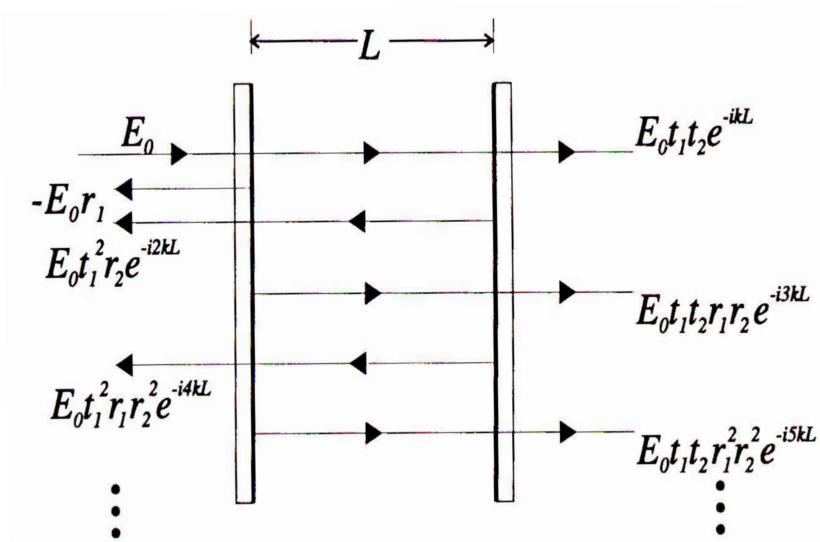
- Michelson interferometer with a "light storage arm"

Fabry-Perot Cavity

- Escaping light $(r_2=1)$

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

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




- Phase is sensitive to $\delta L$

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

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

# How to Detect Phase - Initial LIGO

- 1.064 $\mu$m 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:

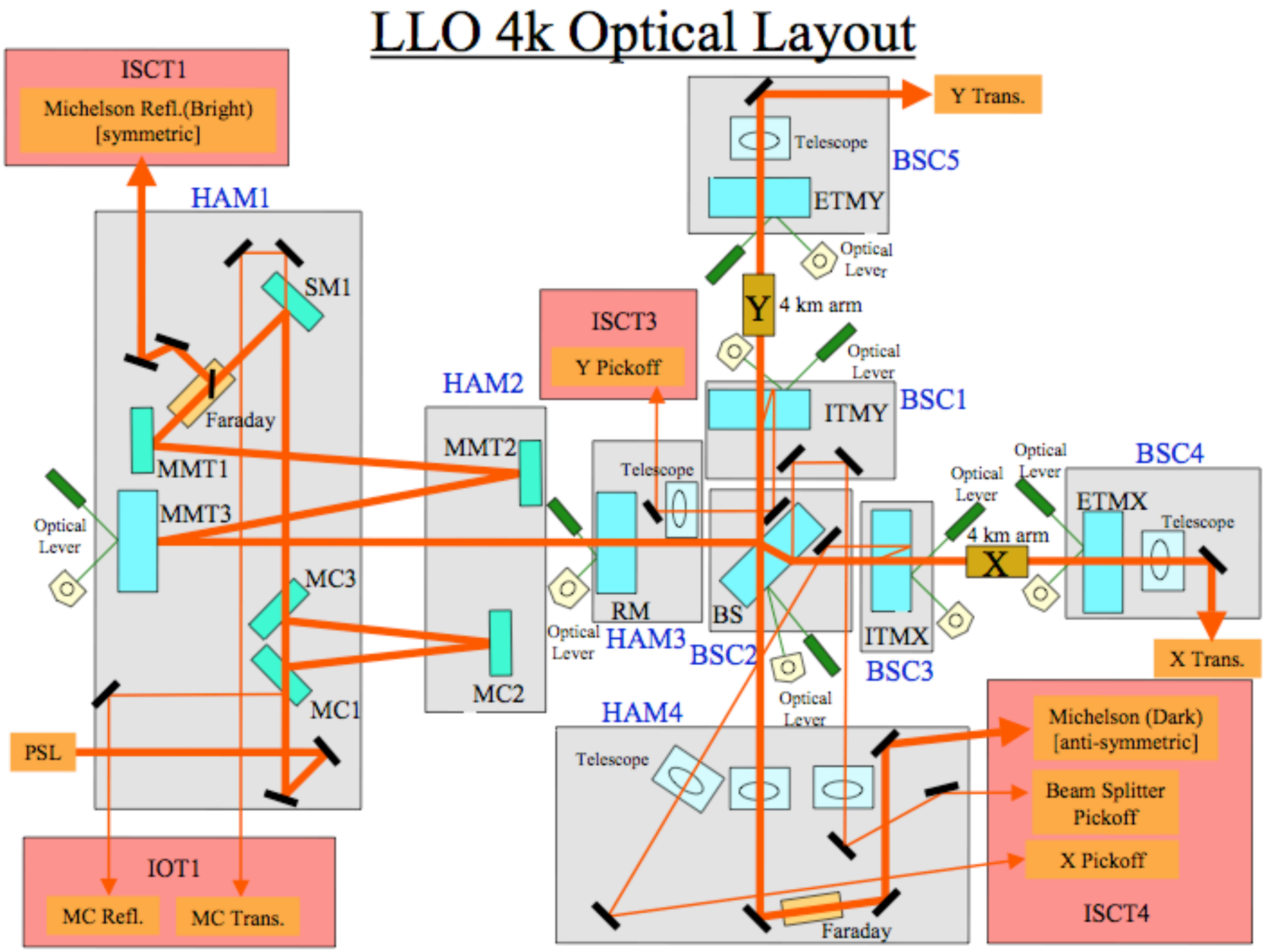
$$P_{OUT} \approx 2\Phi_{GW}\delta\sin 2\pi f_{\mathrm{mod}} t$$

- Demodulate --> audio frequency Gravity Wave signal.

# How to Lock the Interferometer

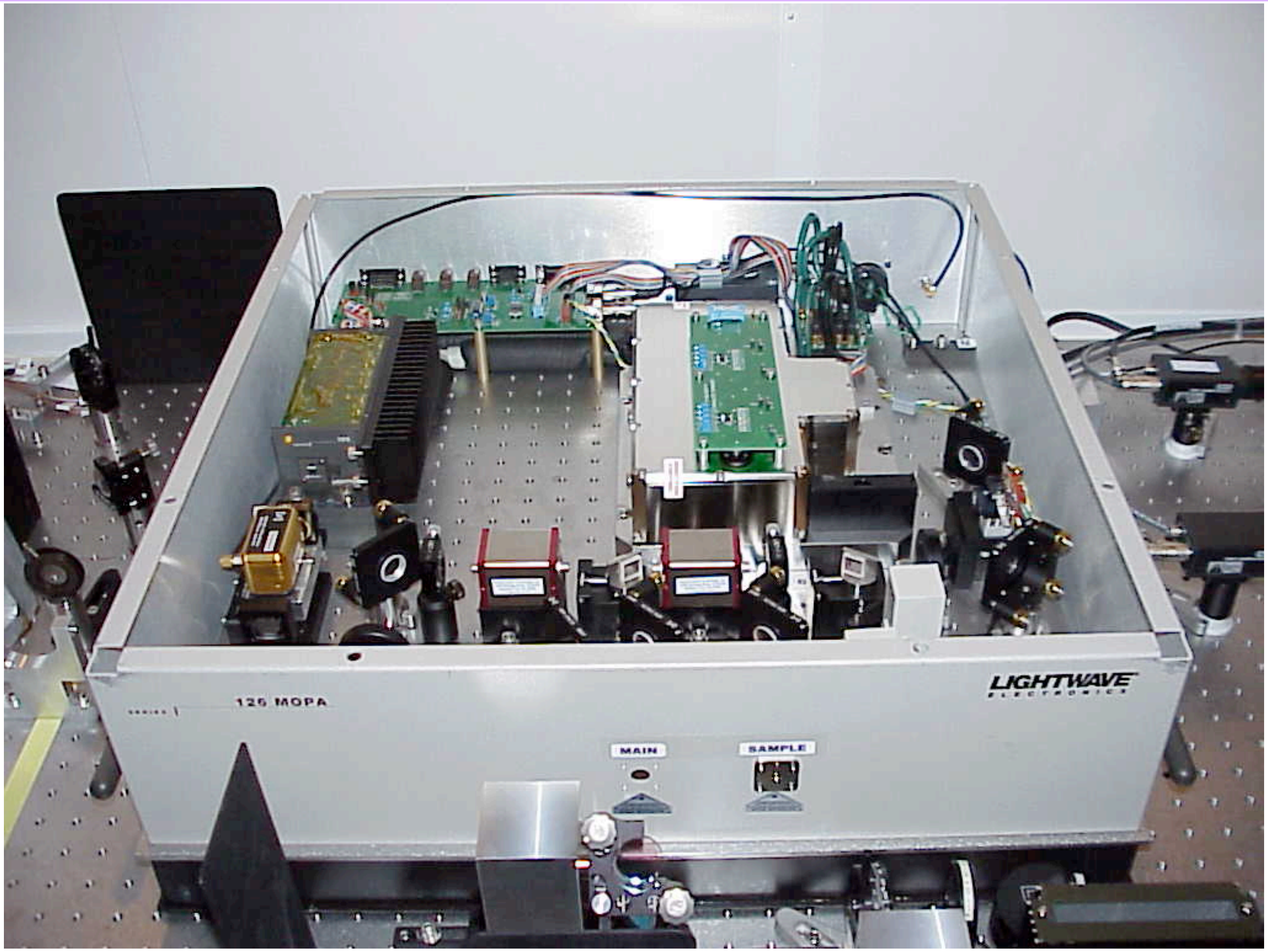
- Suspended mirrors each have 4 magnetic sensor/ controllers to adjust angles and position
- One Fabry-Perot arm is length reference for laser frequency in a feed back loop locked to arm resonance
- Second arm mirror positions are adjusted so cavity length is locked to this frequency
- Beam splitter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



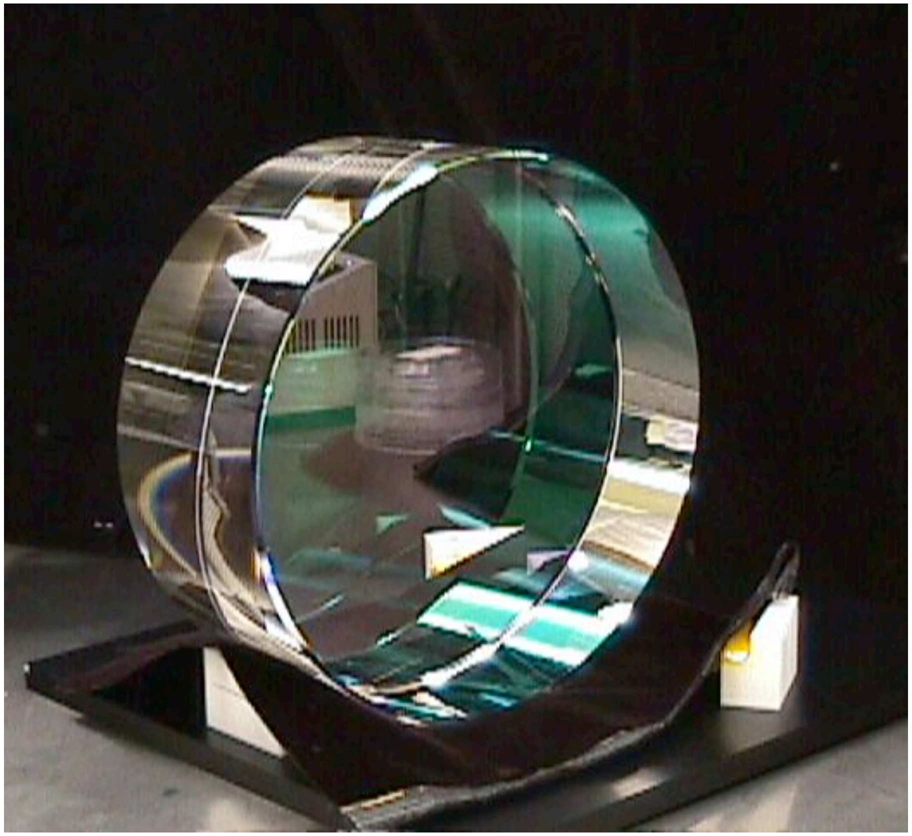
# All-Solid-State Nd:YAG Laser

Custom-built
10 W Nd:YAG Laser

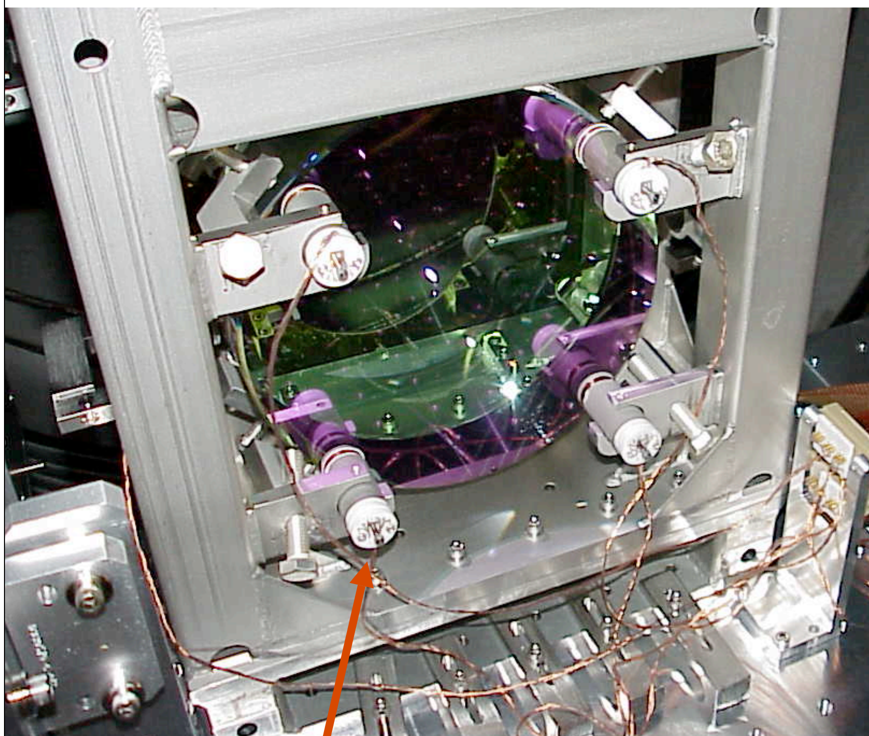


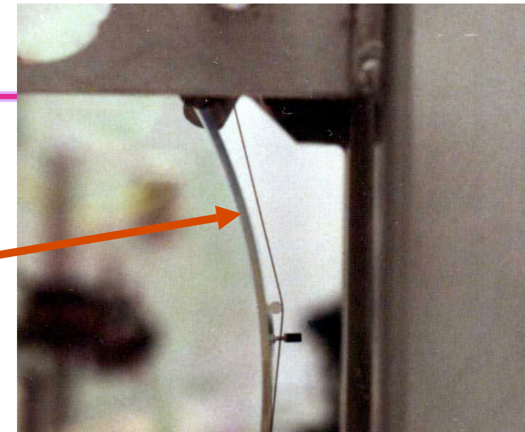
# Test Mass Mirrors

- 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





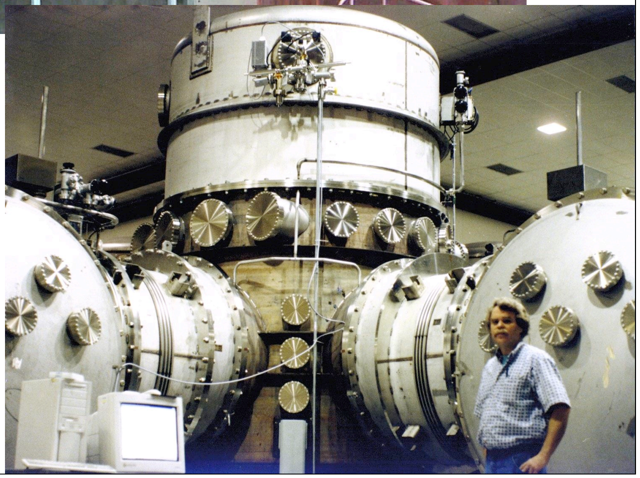
*Optics suspended as simple pendulums on 0.25 mm wire*

*Local sensors/actuators provide damping and control forces*

# Corner Station Vacuum Chambers

Vacuum: $10^{-6}$ torr

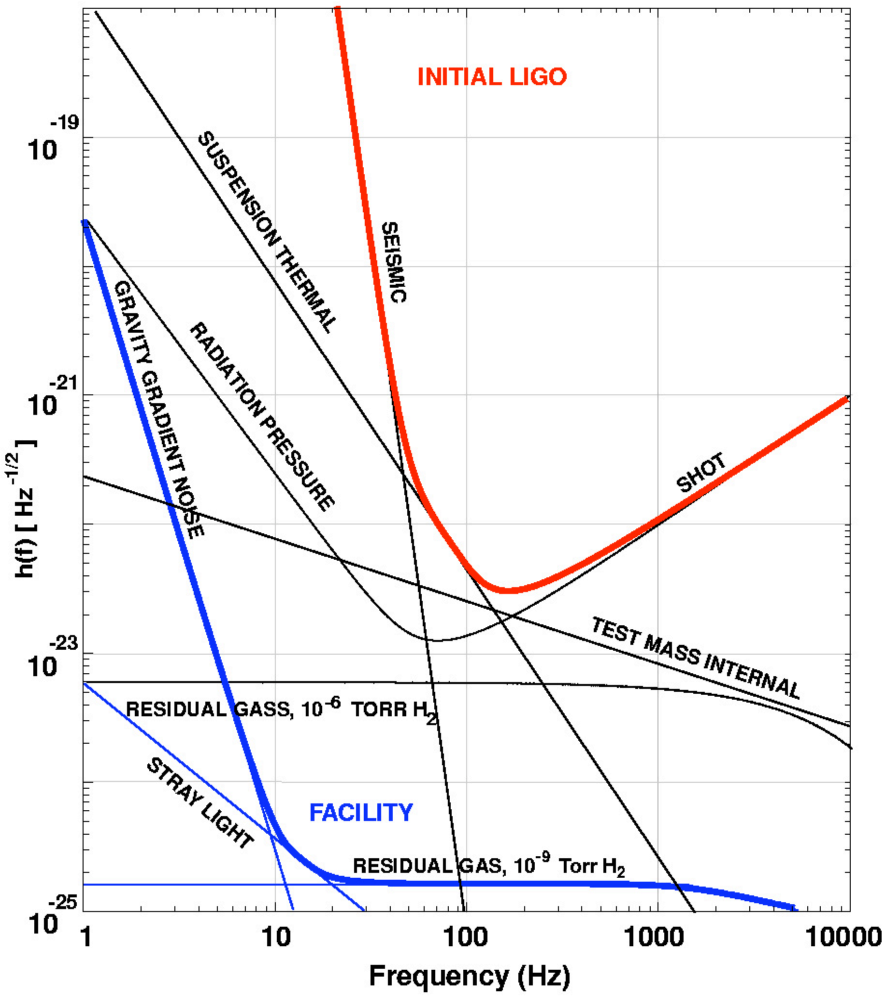
~1m diameter   2 x 4 km long





*Adapted from Fred Raab slide*

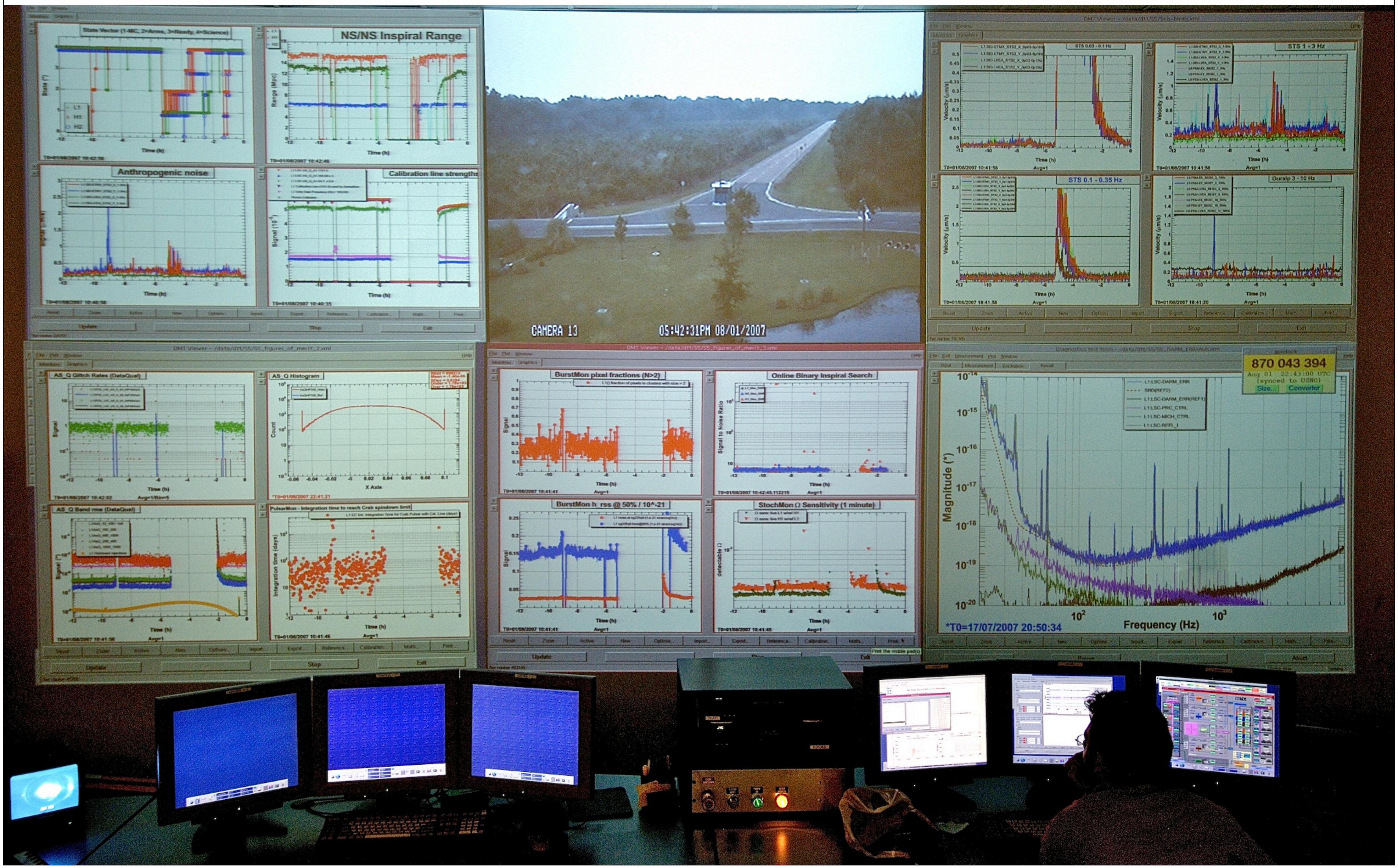
# Major noise sources for LIGO




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

LIGO

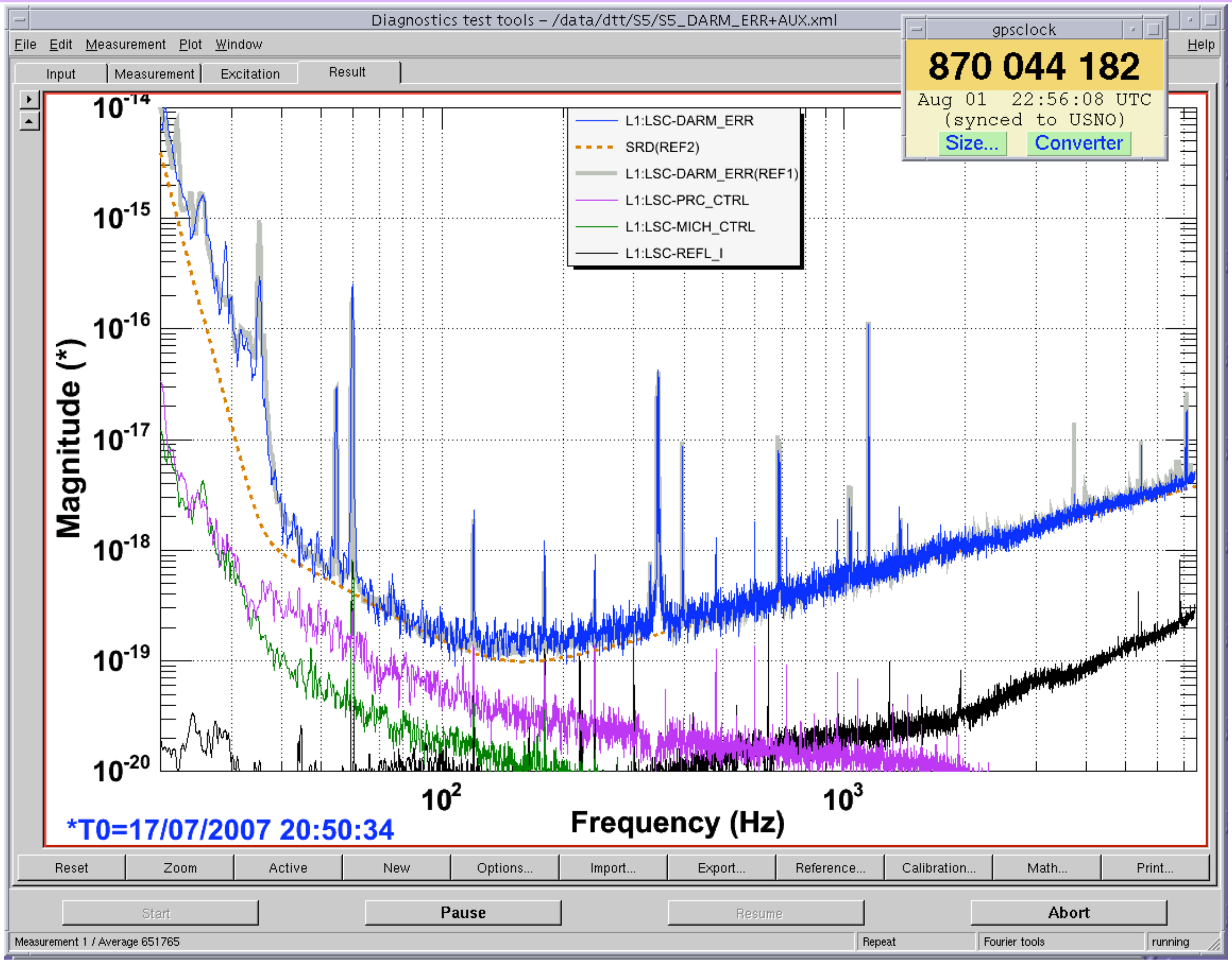
# Louisiana Control Room…



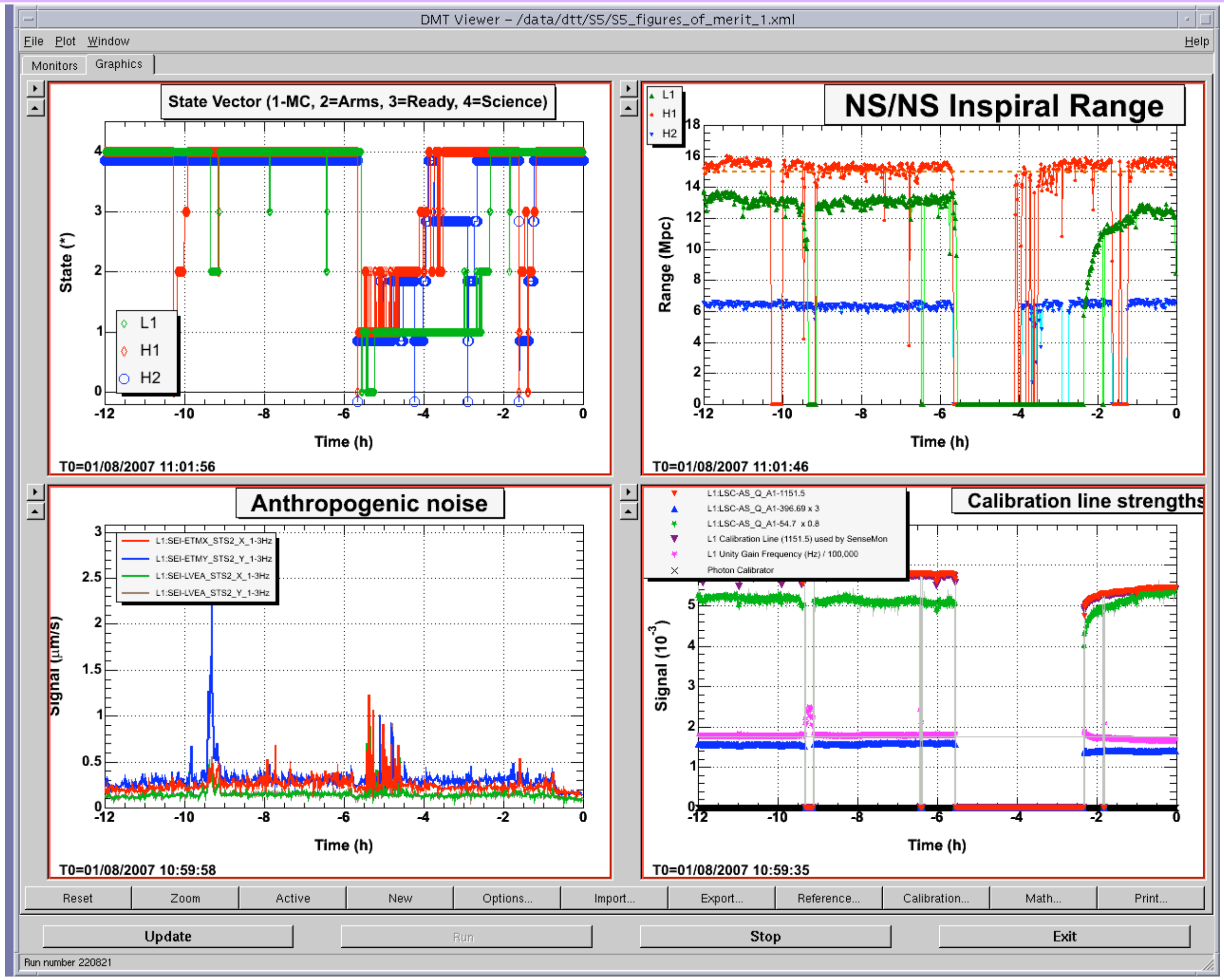
# …Louisiana Control Room…


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**

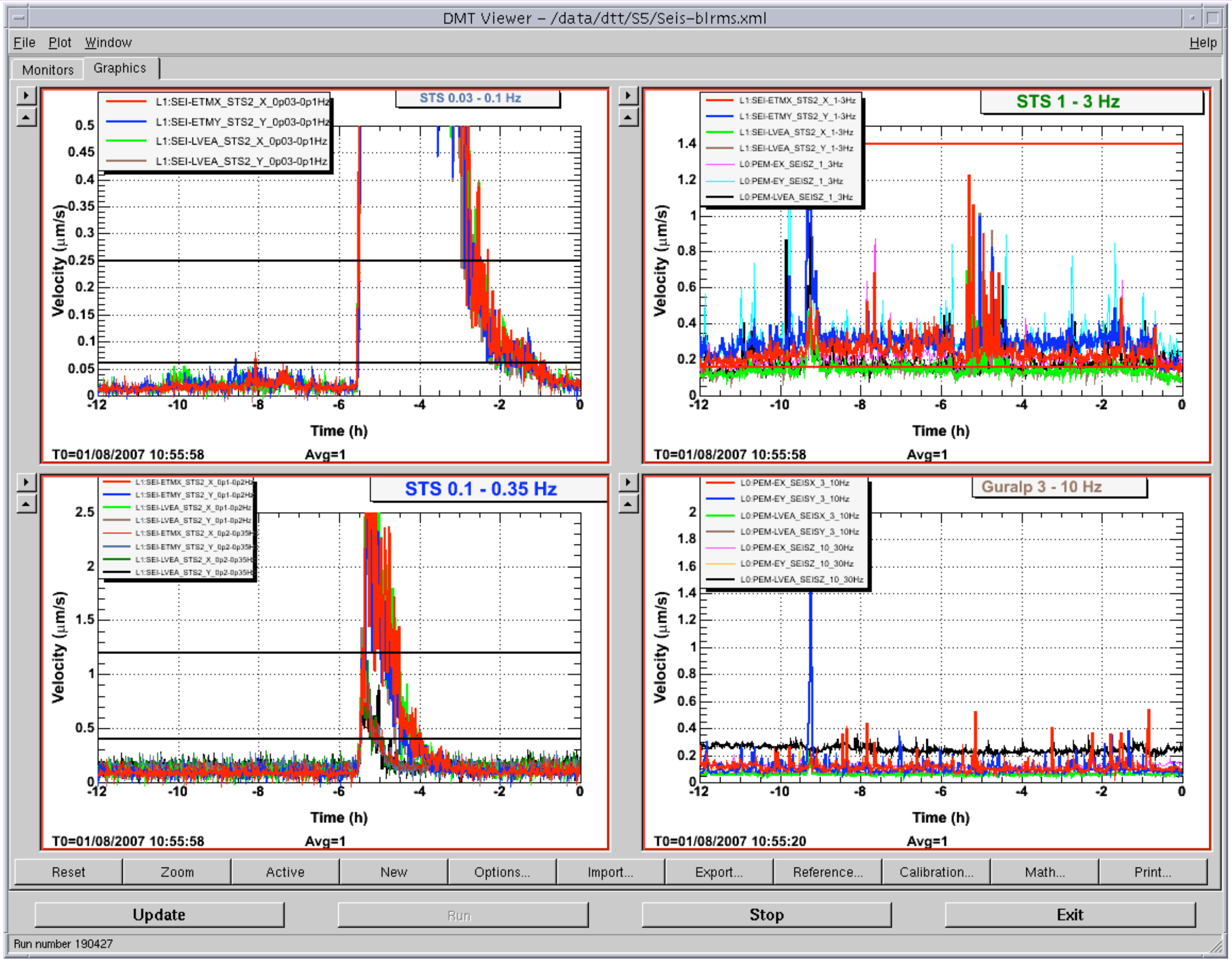
Versíon en Español

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)**<br>= Coordinated Universal Time<br>**Thursday, August 2, 2007 at 4:08:54 AM**<br>= local time at epicenter<br>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

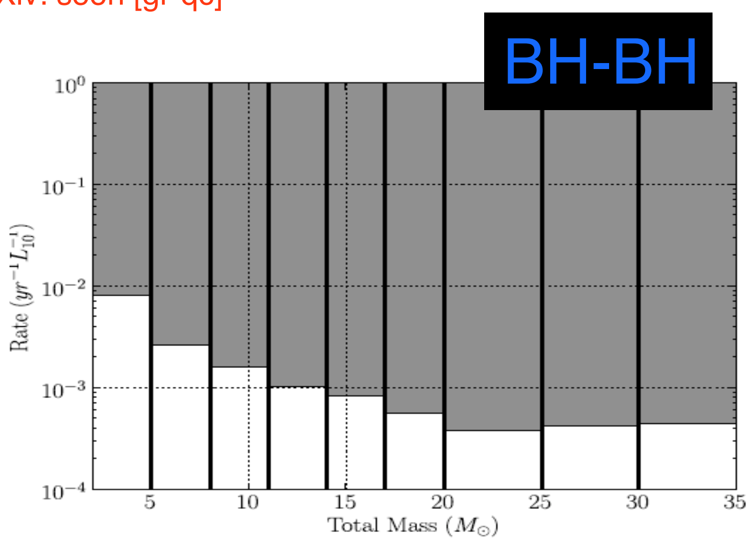
# Upper limits now approach physics significance…

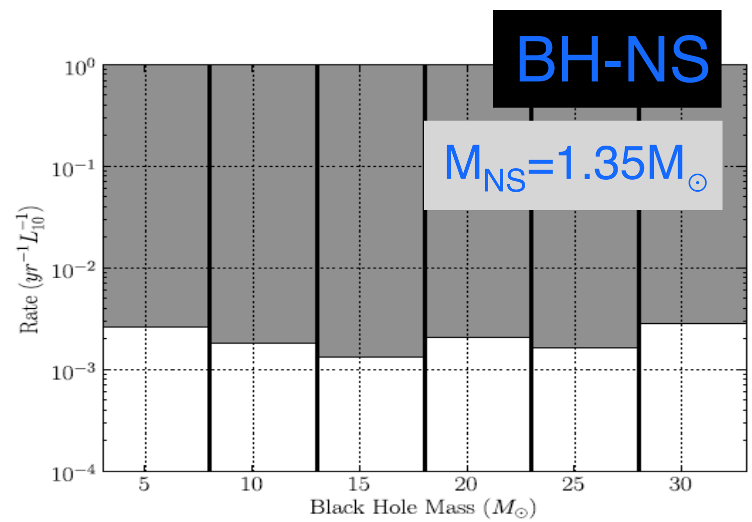
## Binary Coalescence S5 90% Upper Limits

| **NS-NS 1.35/1.35$M_\odot$** | **BH-BH 5/5$M_\odot$** | **BH-NS 5/1.35$M_\odot$** |
|---|---|---|
| ~30 Mpc | ~100 Mpc | ~60 Mpc |
| $1.4\ 10^{-2}/L_{10}$-yr | $7.4\ 10^{-4}/L_{10}$-yr | $4.2\ 10^{-3}/L_{10}$-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

ε < 7.0x10$^{-8}$

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

## Smallest limit:

PSR J1603-7202 @135Hz

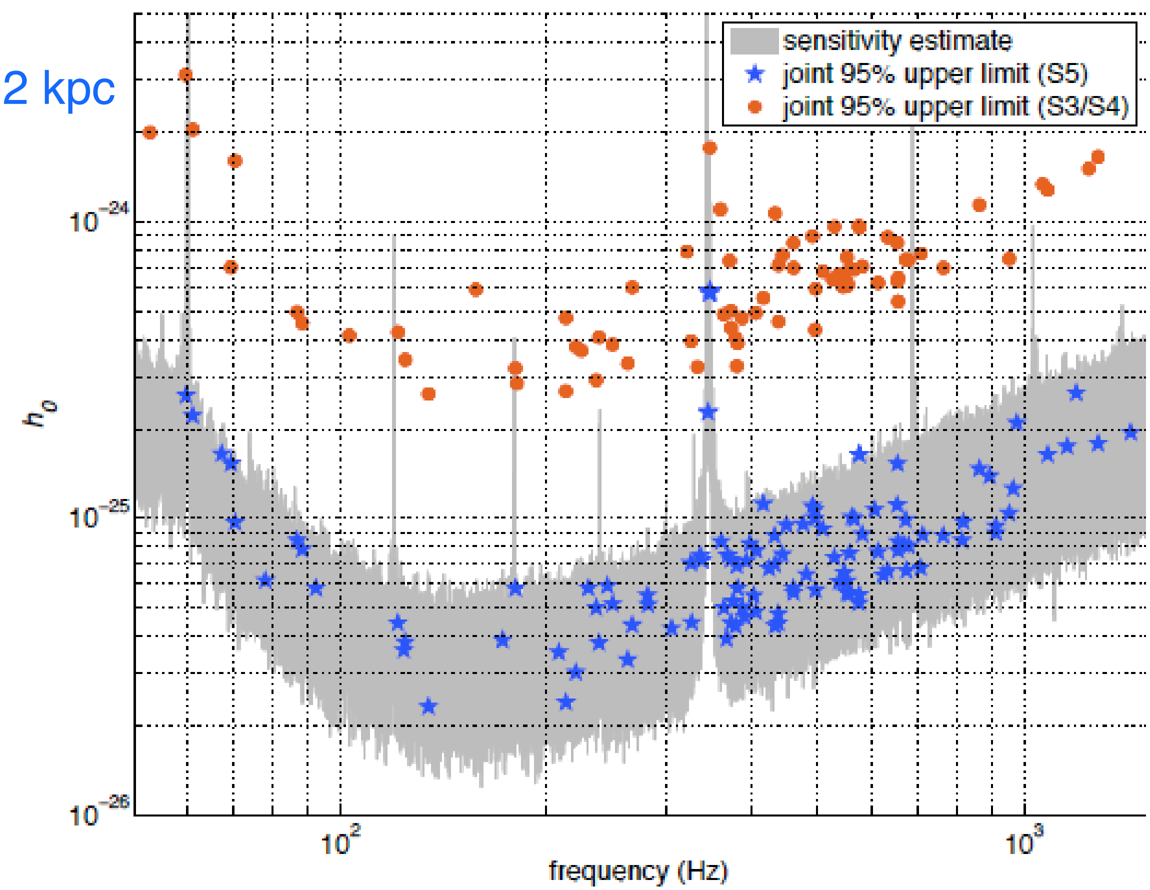
$h_0 < 2.3 \times 10^{-26}$

## 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

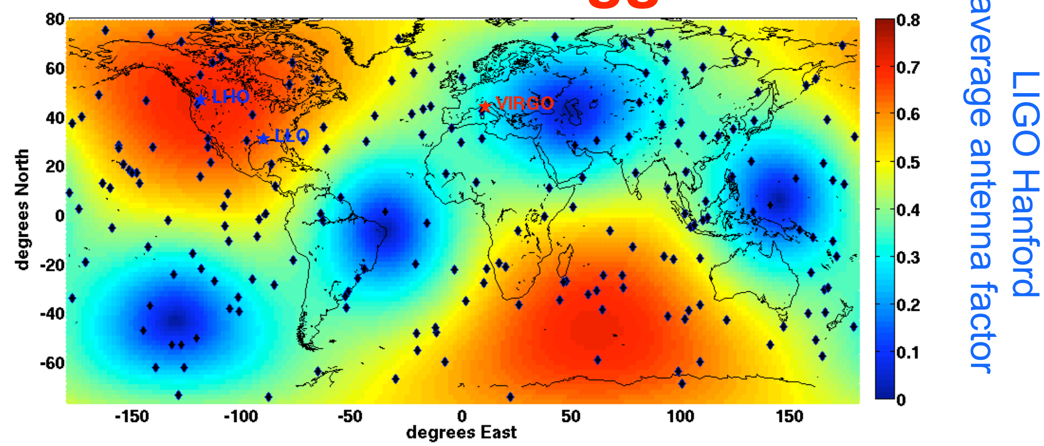
Also IPN3, INTEGRAL, HETE-2

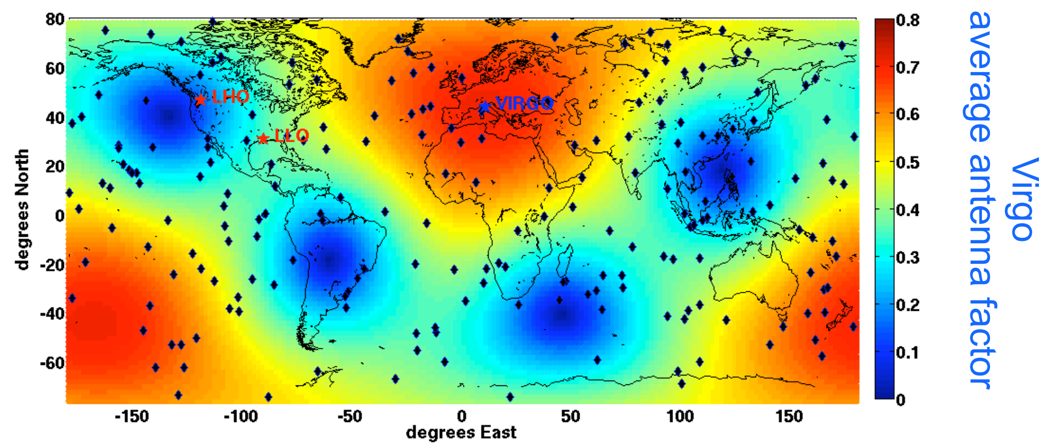
Nov 2005 to Oct 2007

- ~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

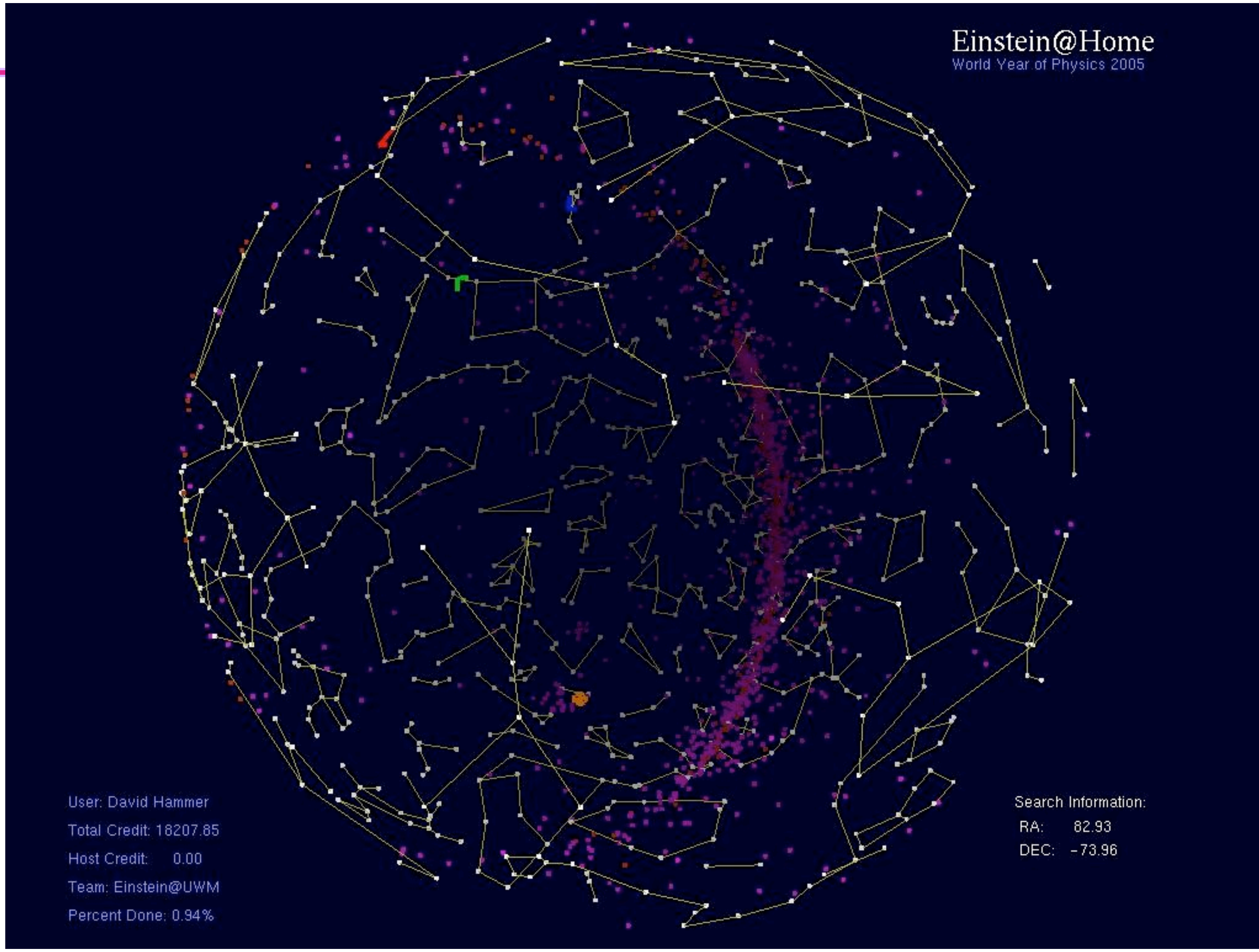


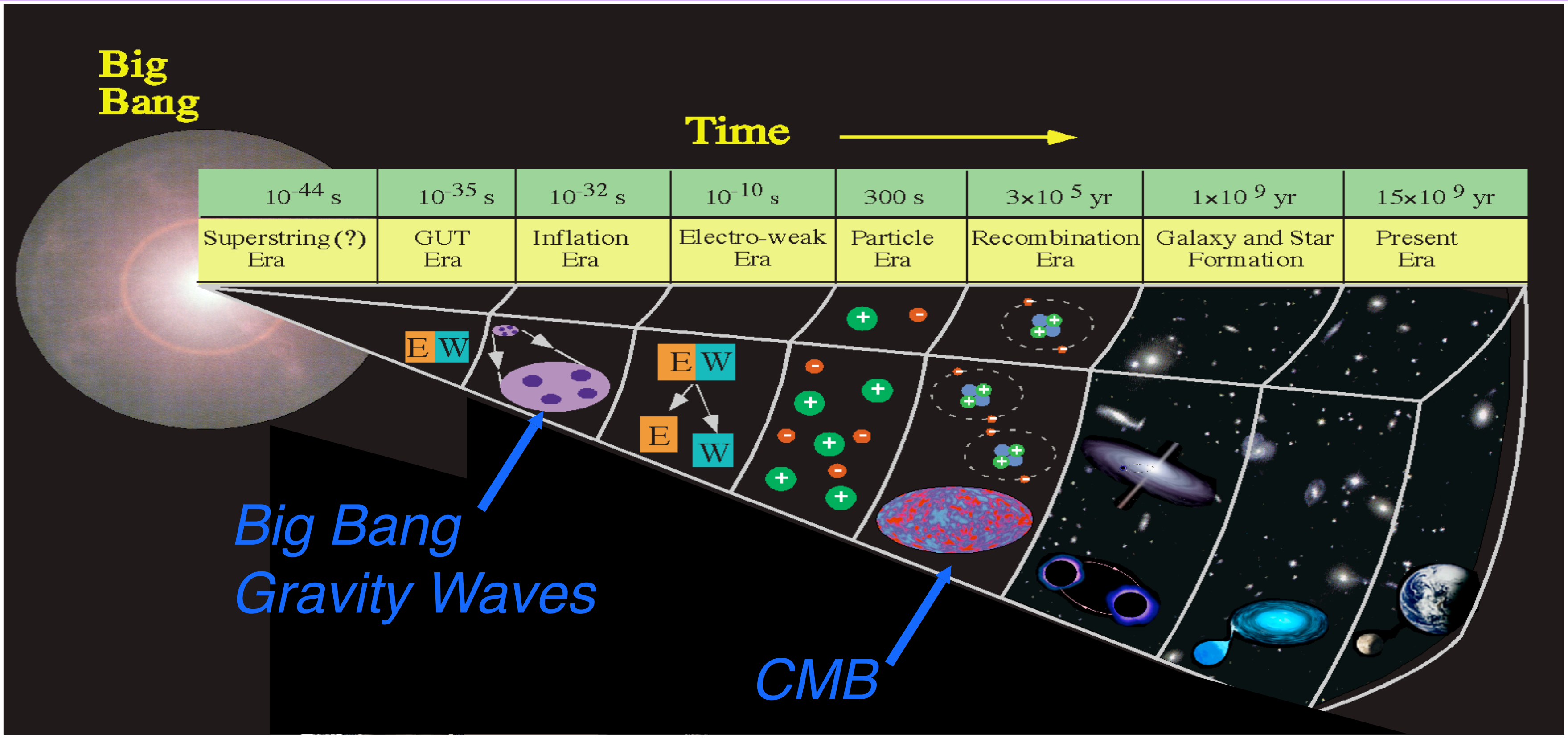



*Slide adapted from Isabel Leonor talk at Denver APS LIGO-G0900392*

# 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.

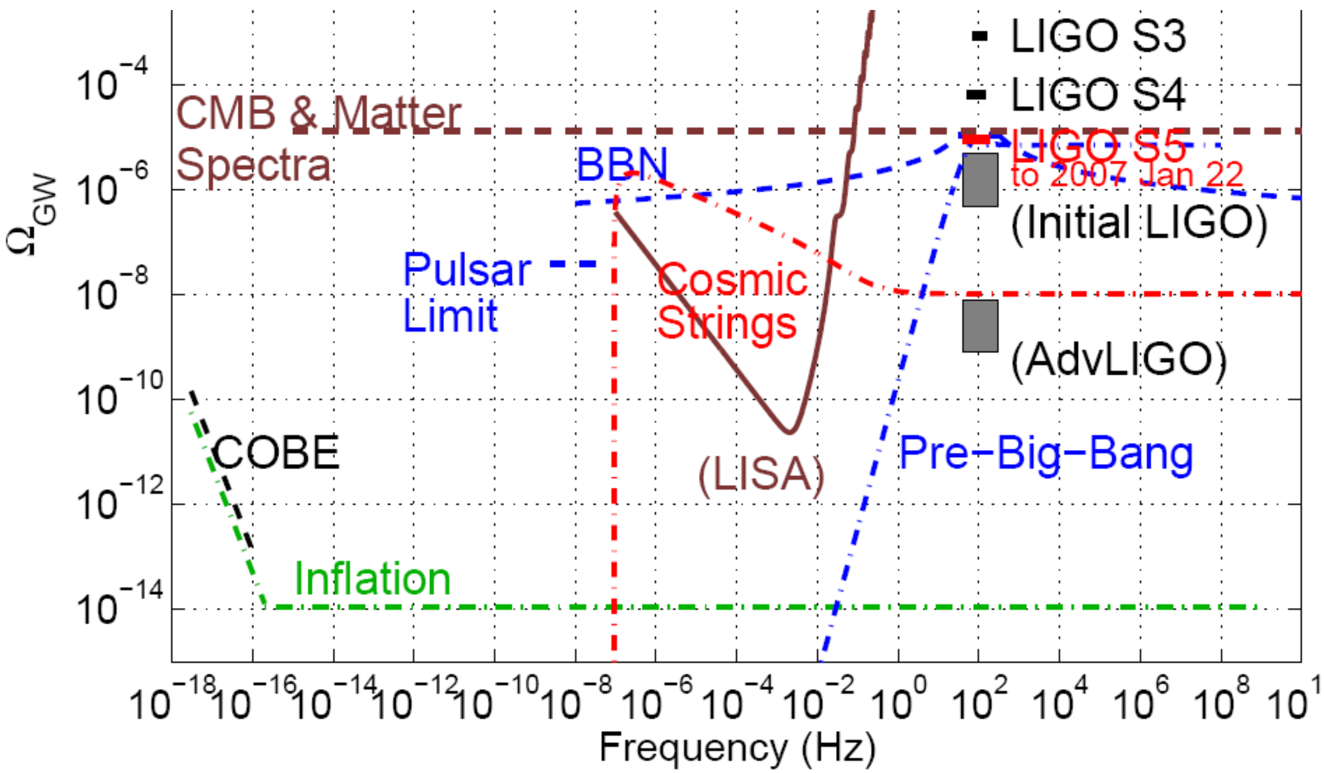
Partial, preliminary S5 result comparable to *Big Bang Nuclear-synthesis Limit*

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

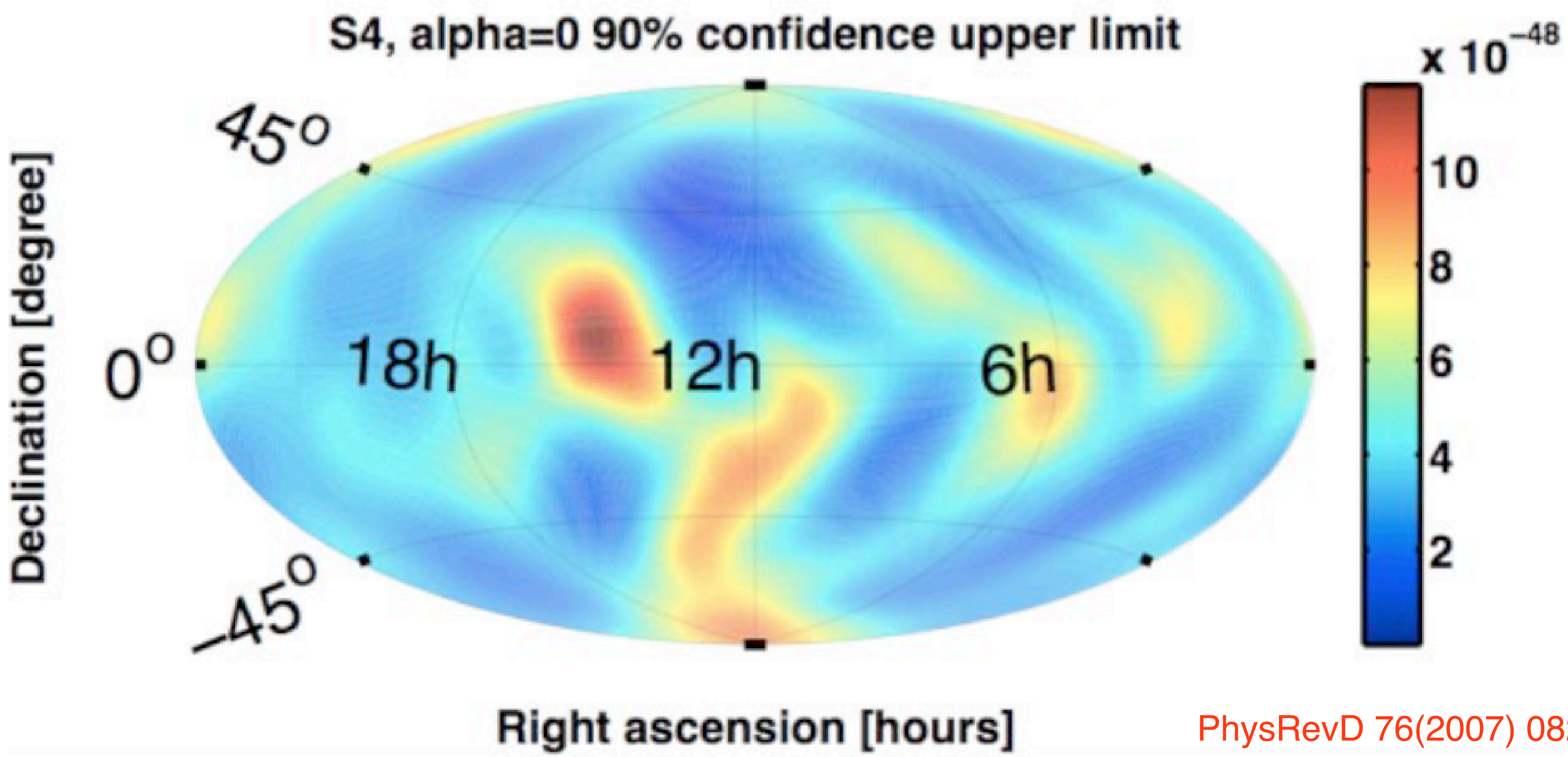
ApJ **659**(2007)918

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

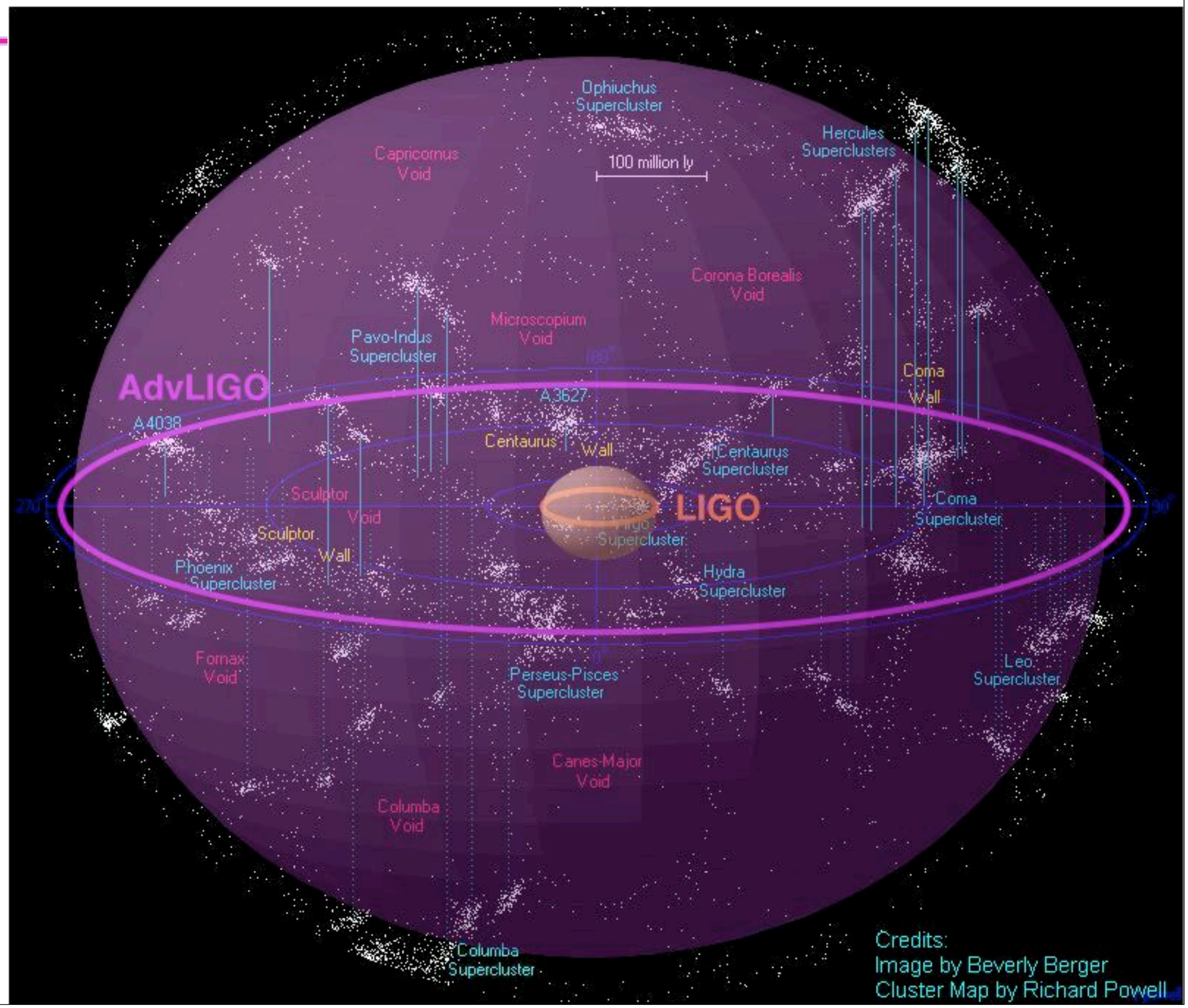
Lower noise optics & suspensions

Increased mass mirrors (40 kg)

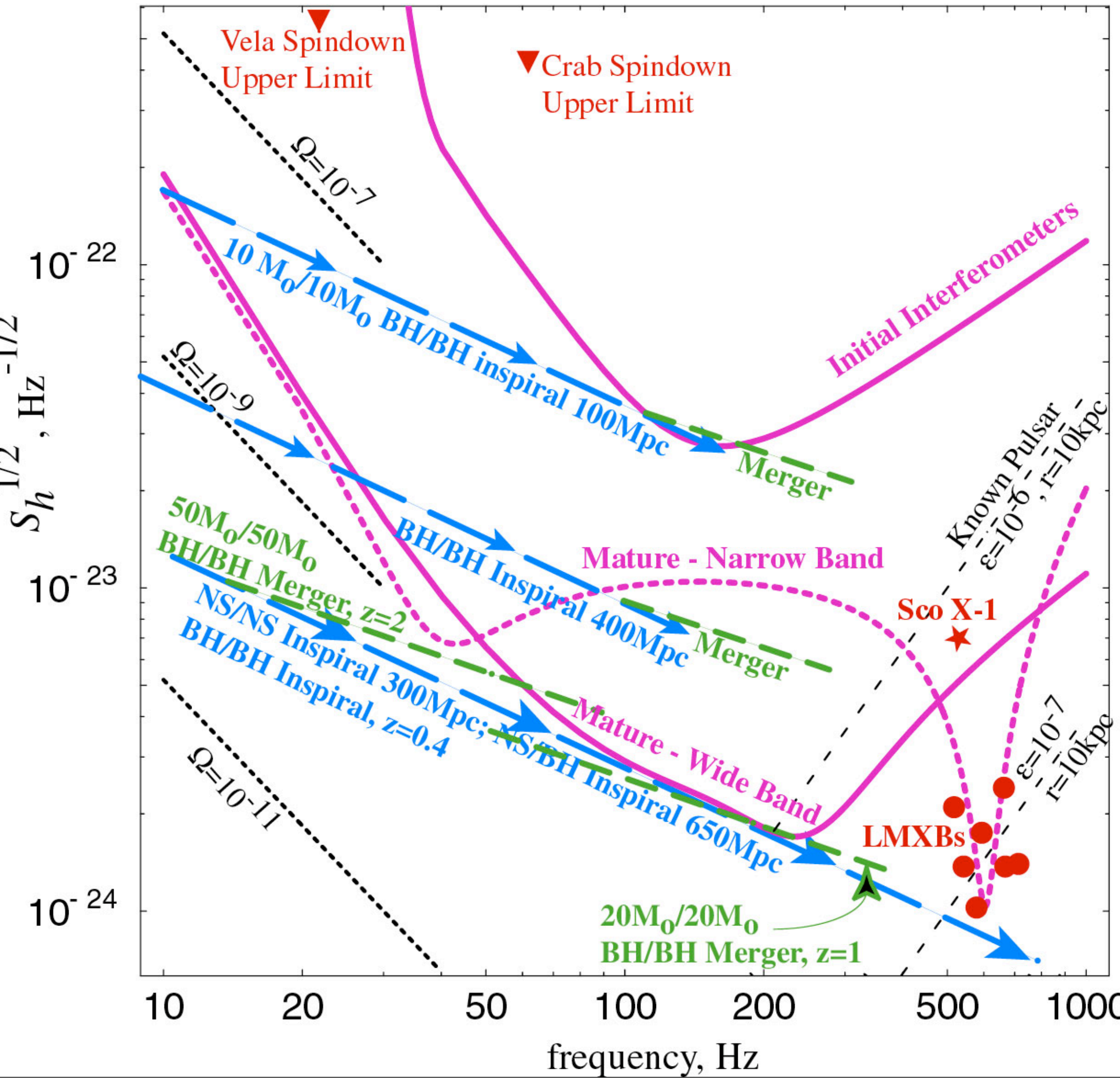
Higher Laser power (180 W)

Signal recycling

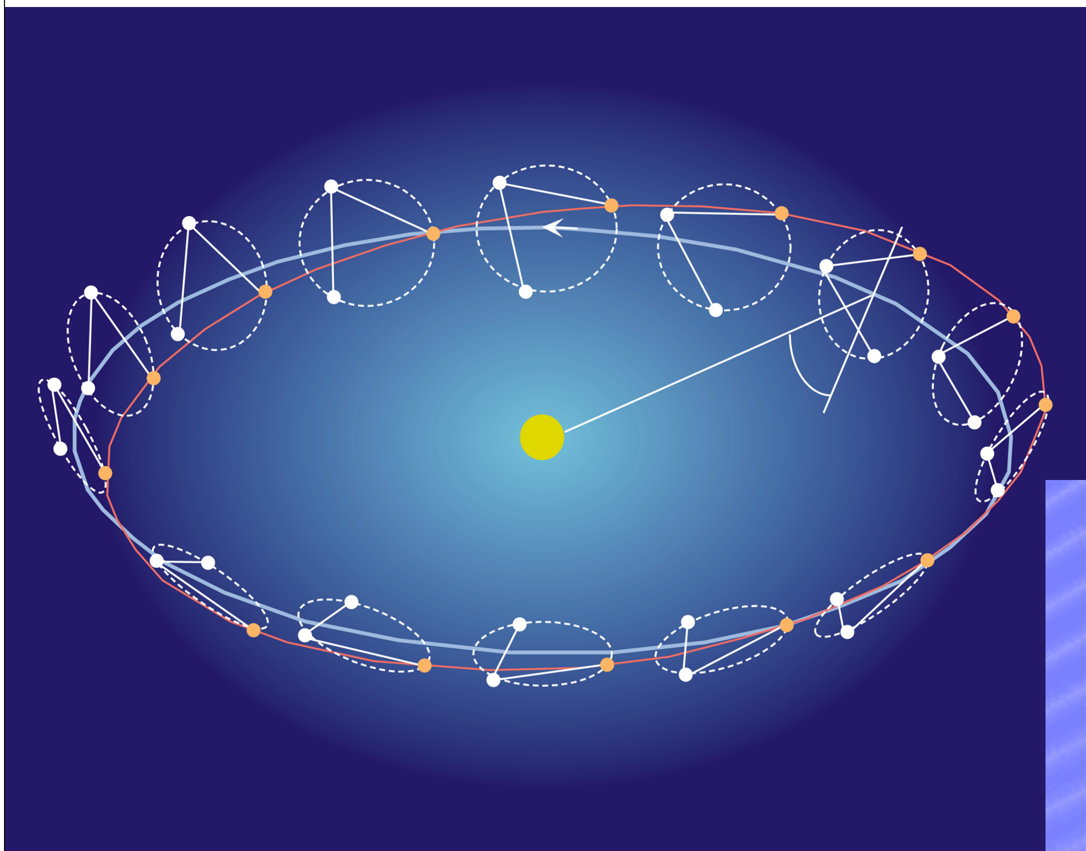
DC readout



# Difficult to hide from Advanced LIGO

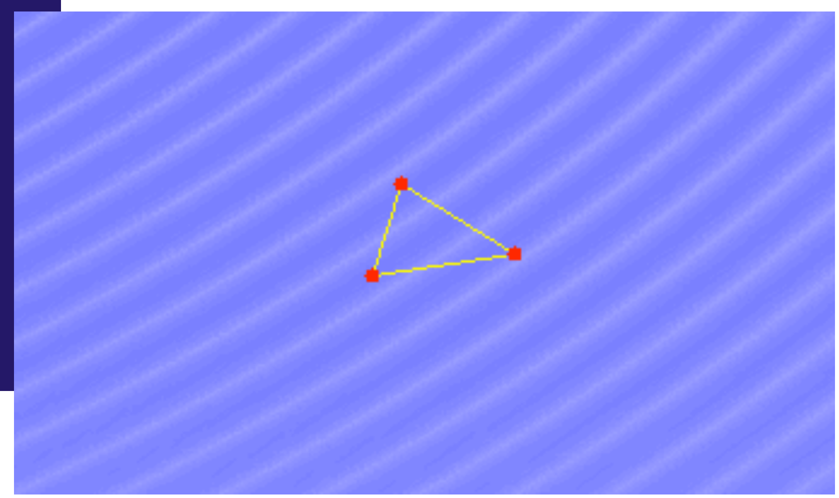


# Space based interferometer: LISA



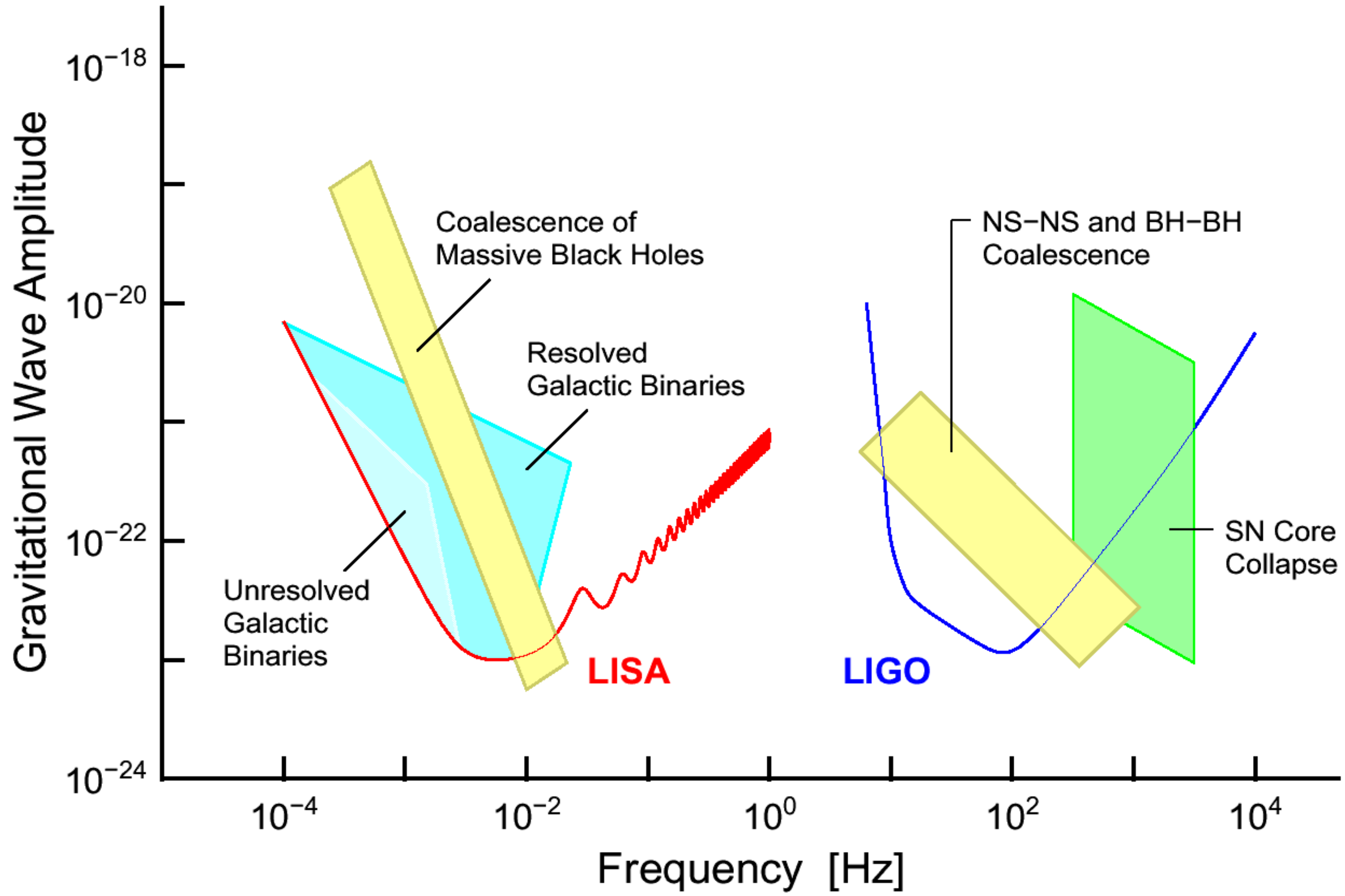
3 satellites 5 $10^6$ km apart
Heliocentric orbit
20° behind the earth

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