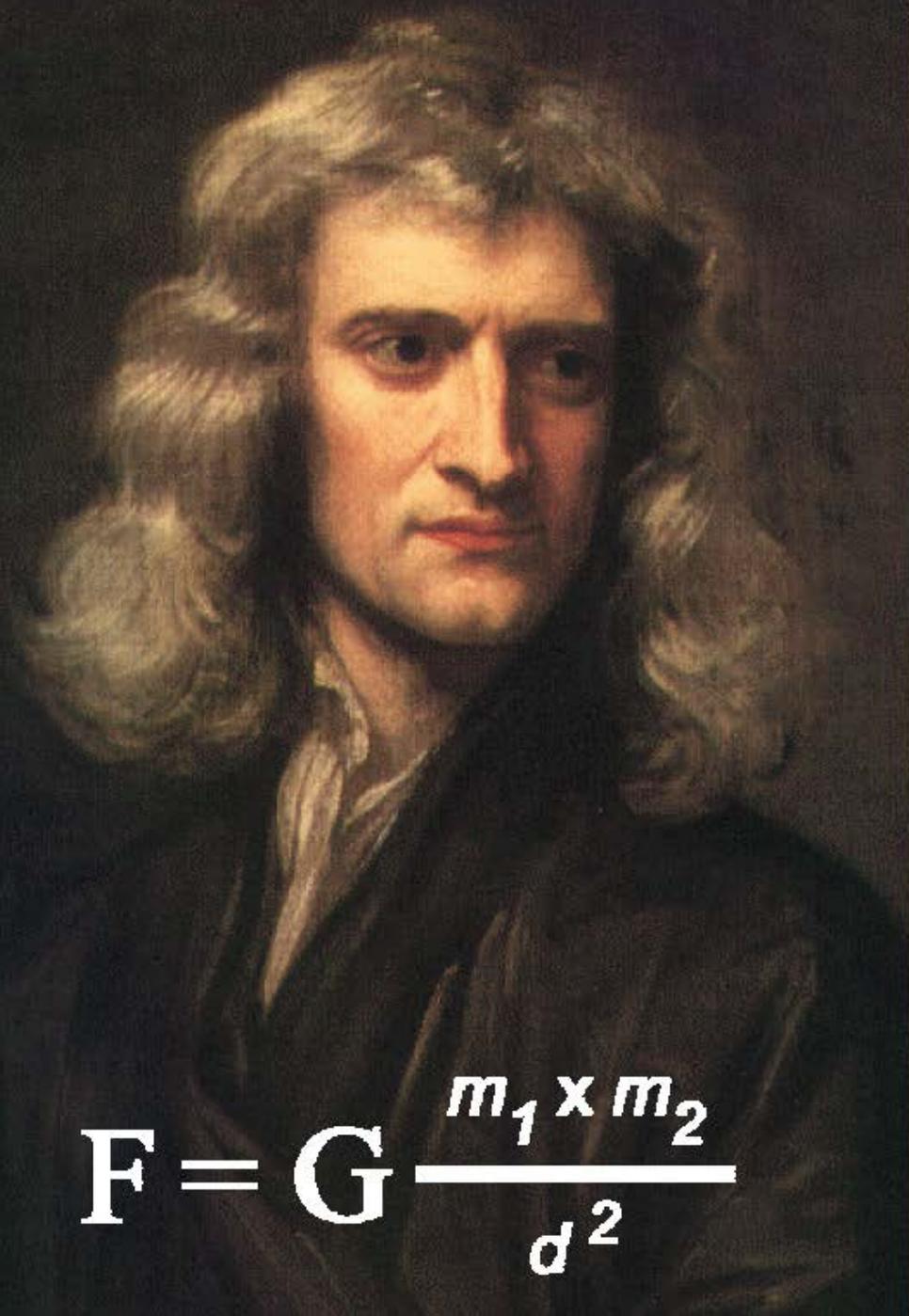


# Probing the Universe with Gravitational Waves

R.Weiss, MIT on behalf of the LIGO Scientific  
Collaboration

International Congress on Mathematical Physics

Montreal, Canada, July 23, 2018



$$F = G \frac{m_1 \times m_2}{d^2}$$

Handwritten signature or mark at the top right corner.

PHILOSOPHIÆ  
NATURALIS  
PRINCIPIA  
MATHEMATICÆ.

Autore J. S. NEWTON, Trin. Coll. Cantab. Soc. Mathefeos  
Professore *Lucasiano*, & Societatis Regalis Sodali.

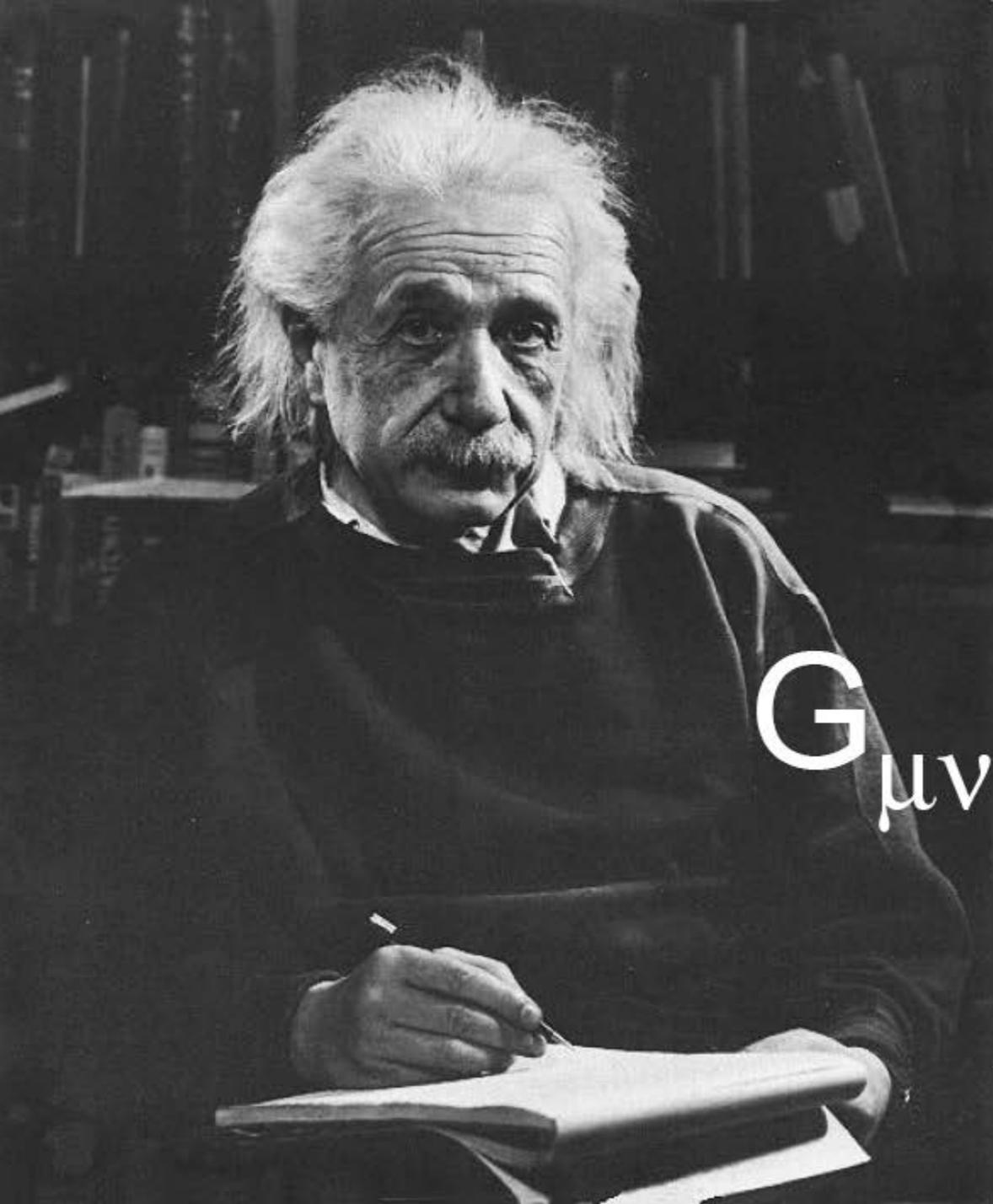
IMPRIMATUR.  
S. PEPYS, Reg. Soc. PRÆSES.  
Julii 5. 1686.



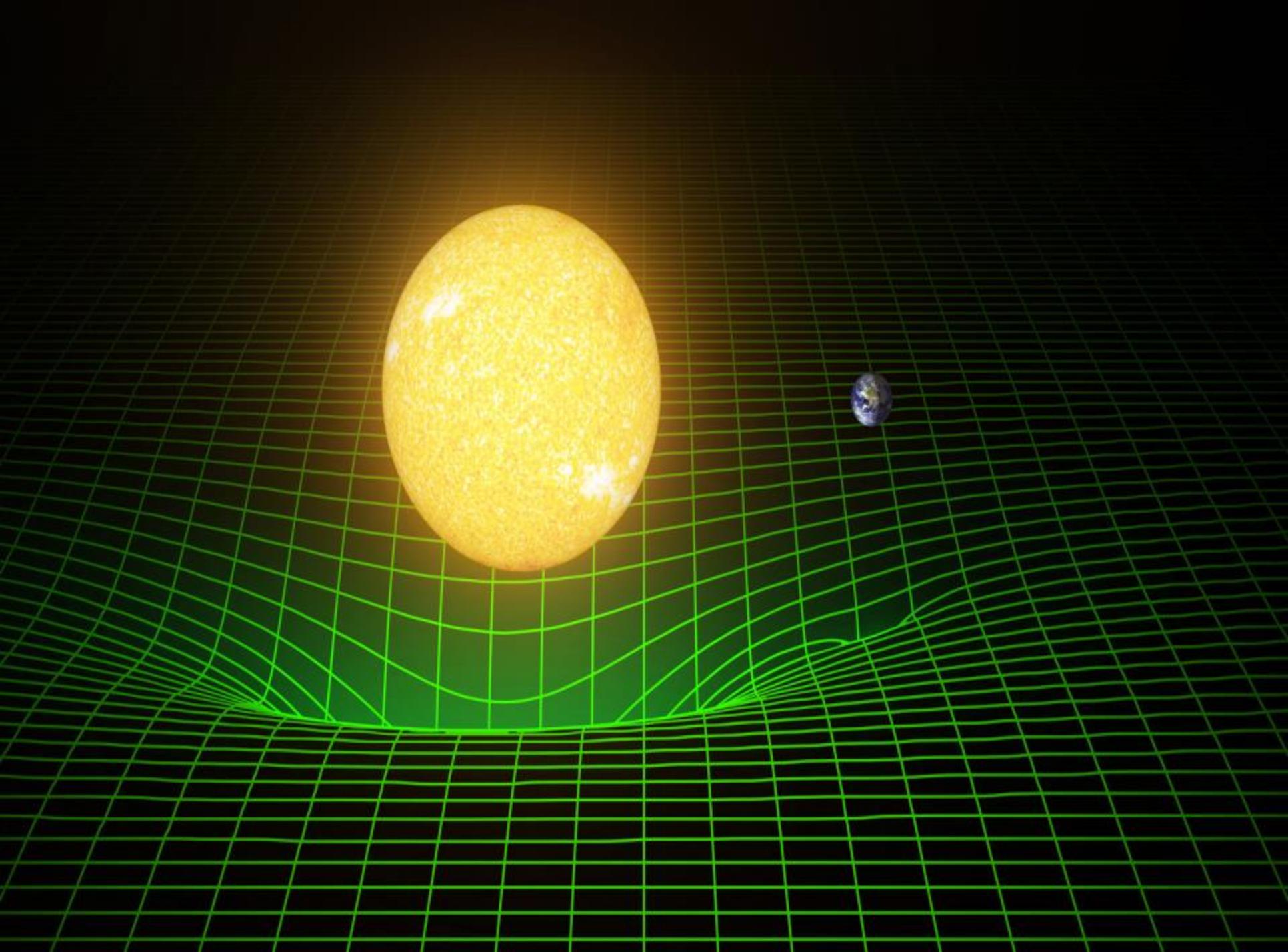
LONDINI,

Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud  
plures Bibliopolas. Anno MDCLXXXVII.





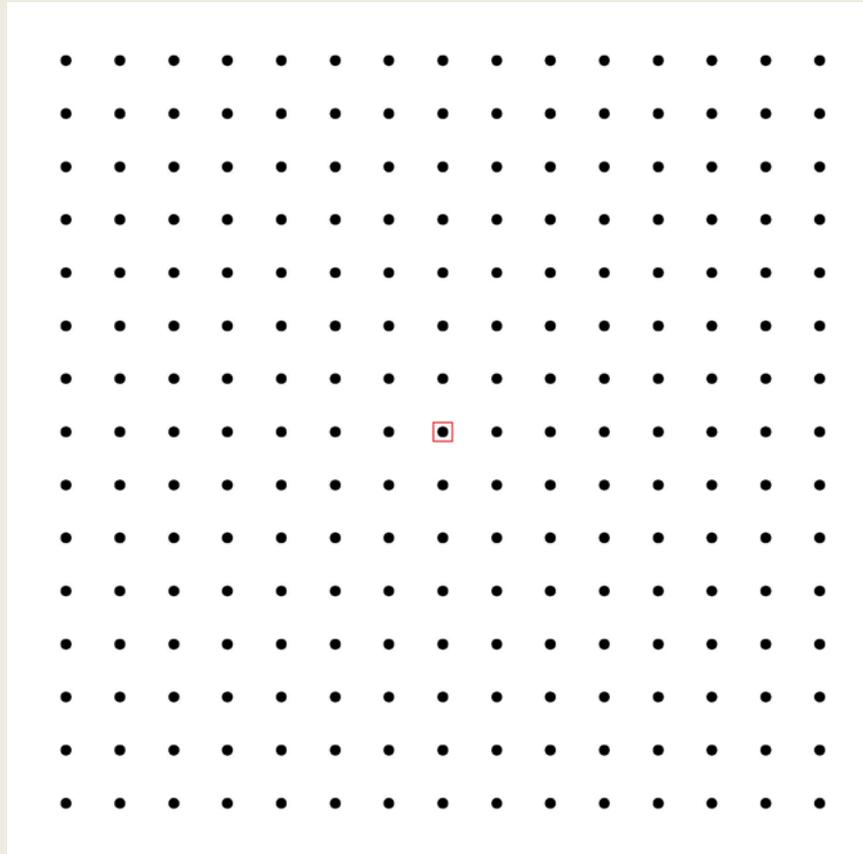
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



# Gravitational waves

Einstein 1916 and 1918

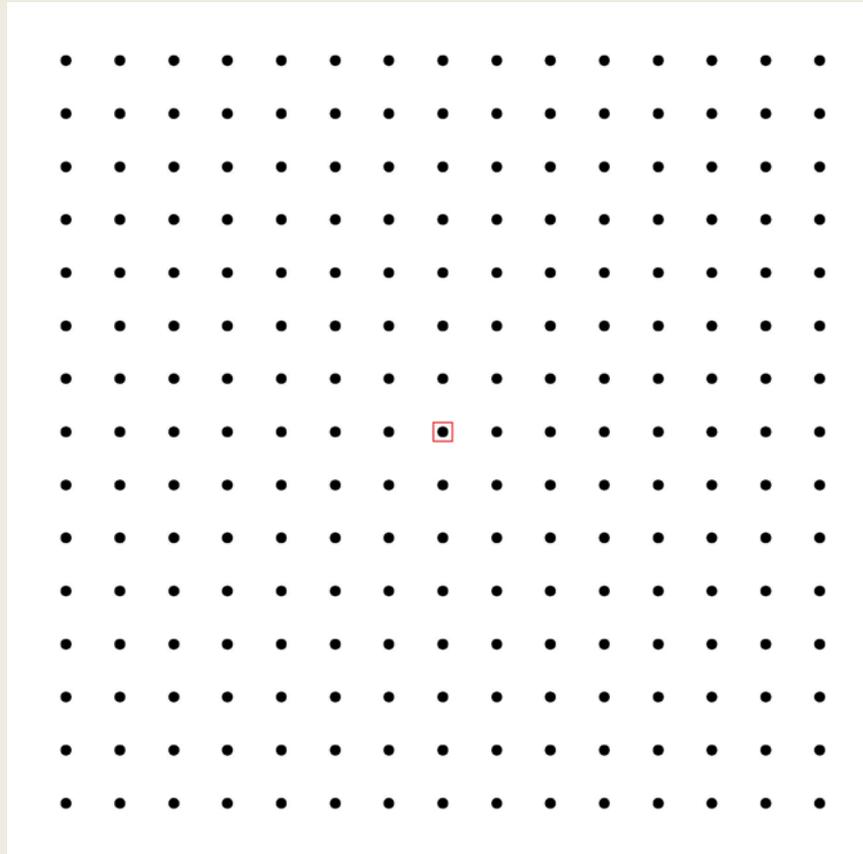
- Sources: non-spherically symmetric accelerated masses
- Kinematics:
  - propagate at speed of light
  - transverse waves, strains in space (tension and compression)



# Gravitational waves

Einstein 1916 and 1918

- Sources: non-spherically symmetric accelerated masses
- Kinematics:
  - propagate at speed of light
  - transverse waves, strains in space (tension and compression)





Russel A. Hulse



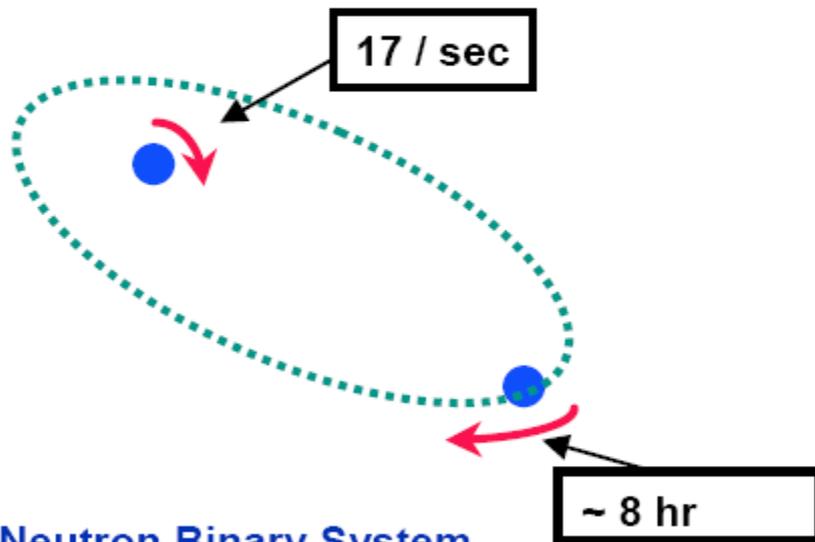
Joseph H. Taylor Jr

# Gravitational Waves

## *the evidence*

### Neutron Binary System – Hulse & Taylor

**PSR 1913 + 16 -- Timing of pulsars**



### Neutron Binary System

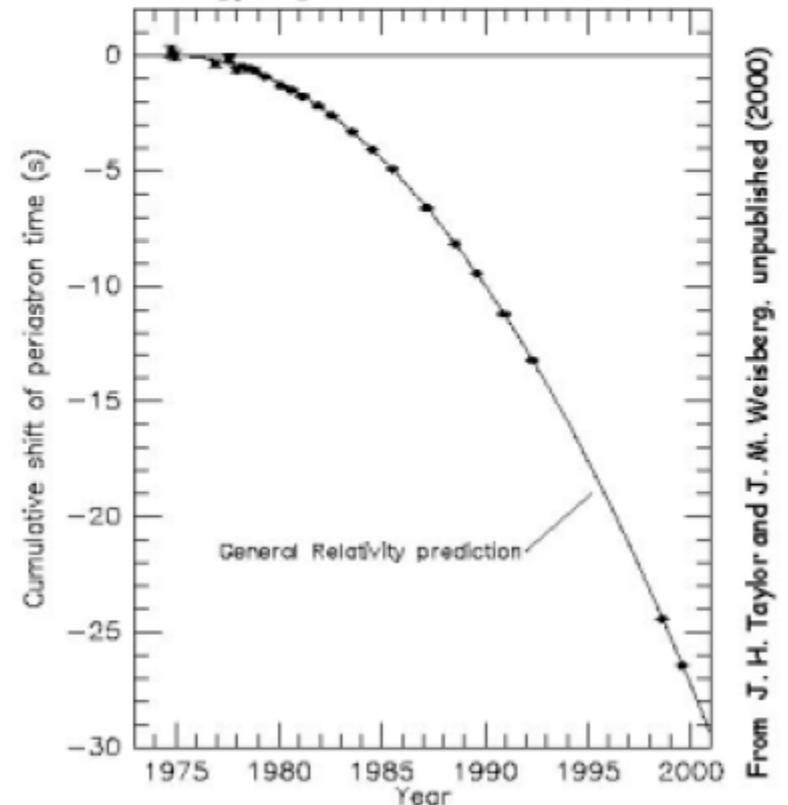
- separated by  $10^6$  miles
- $m_1 = 1.4m_{\odot}$ ;  $m_2 = 1.36m_{\odot}$ ;  $\epsilon = 0.617$

### Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

### Emission of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves





Joseph Weber 1919-2000







# The measurement challenge

$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

$$L = 4\text{km} \quad \Delta L \leq 4 \times 10^{-18} \text{ meters}$$

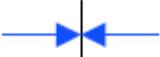
$\Delta L \approx 10^{-12}$  wavelength of light

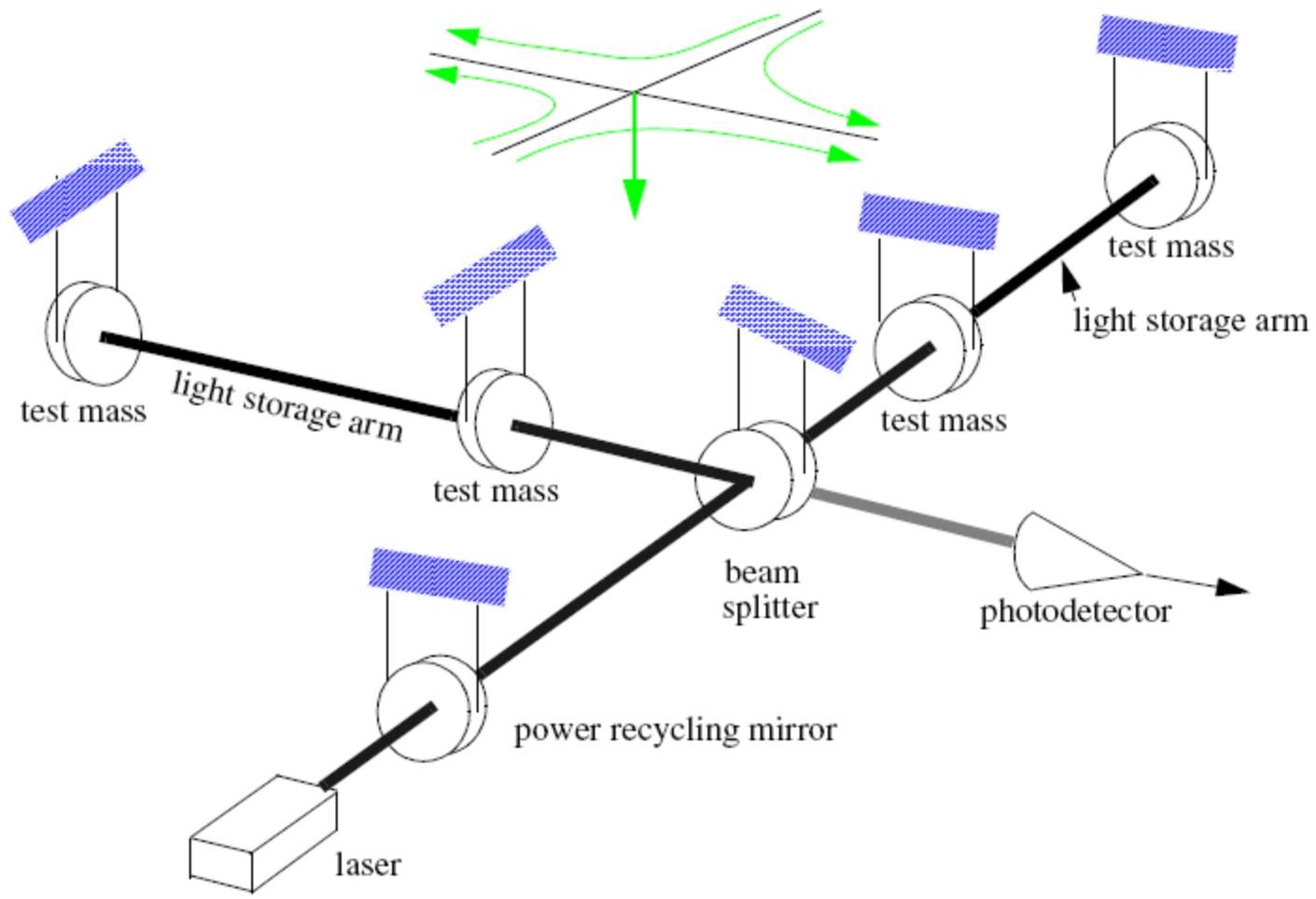
$\Delta L \approx 10^{-12}$  vibrations at earth's surface

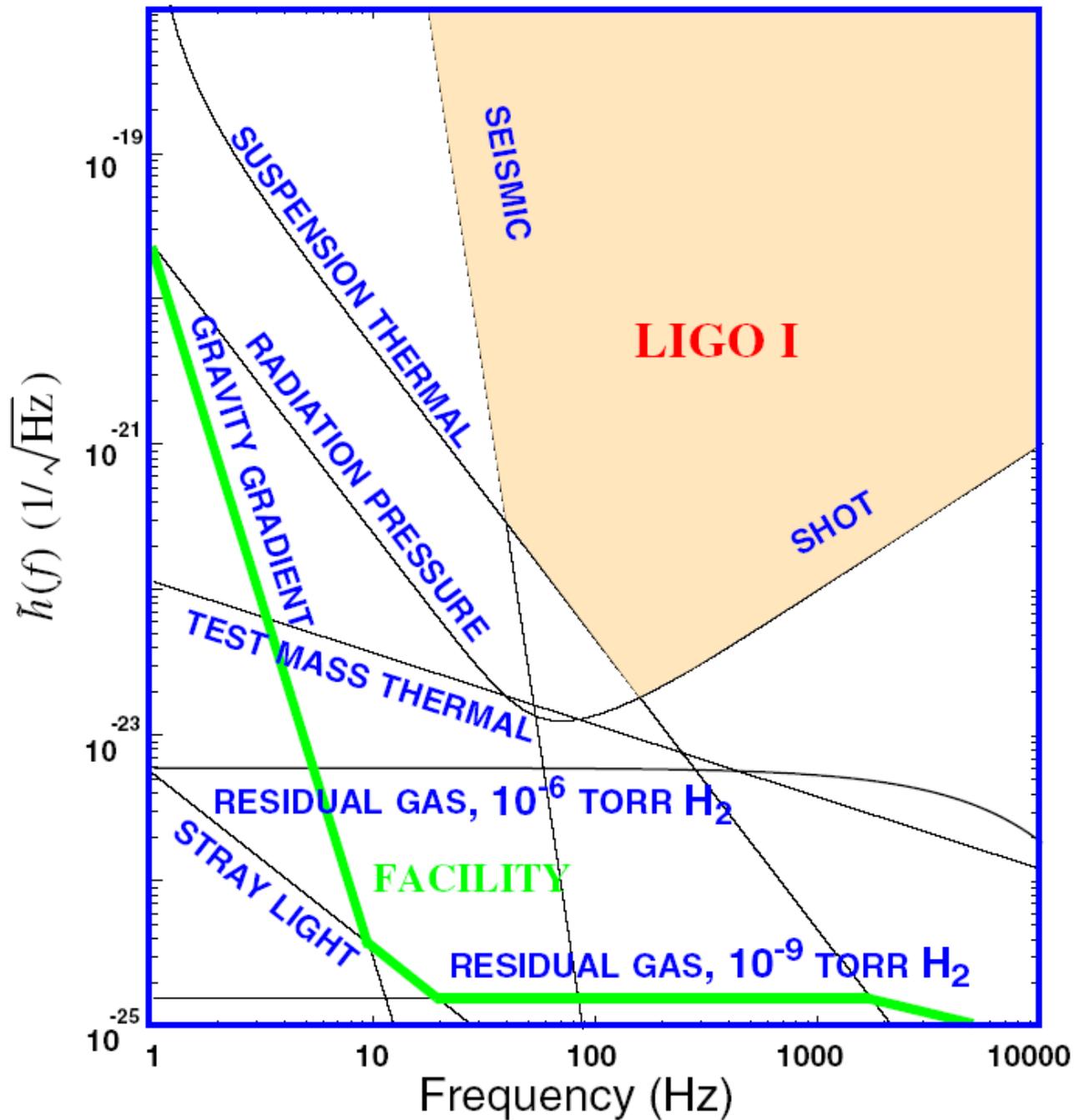


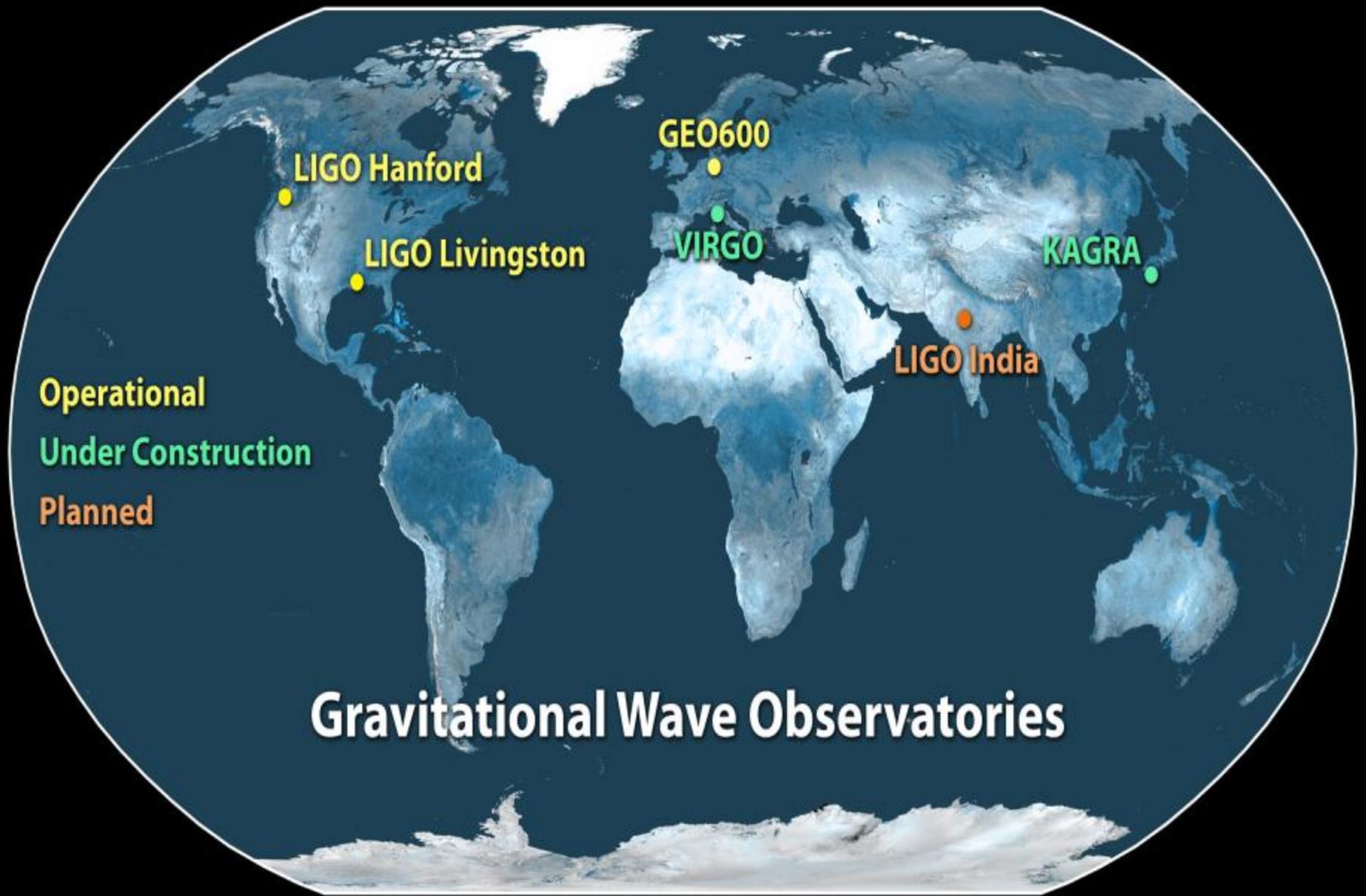
Kip Thorne

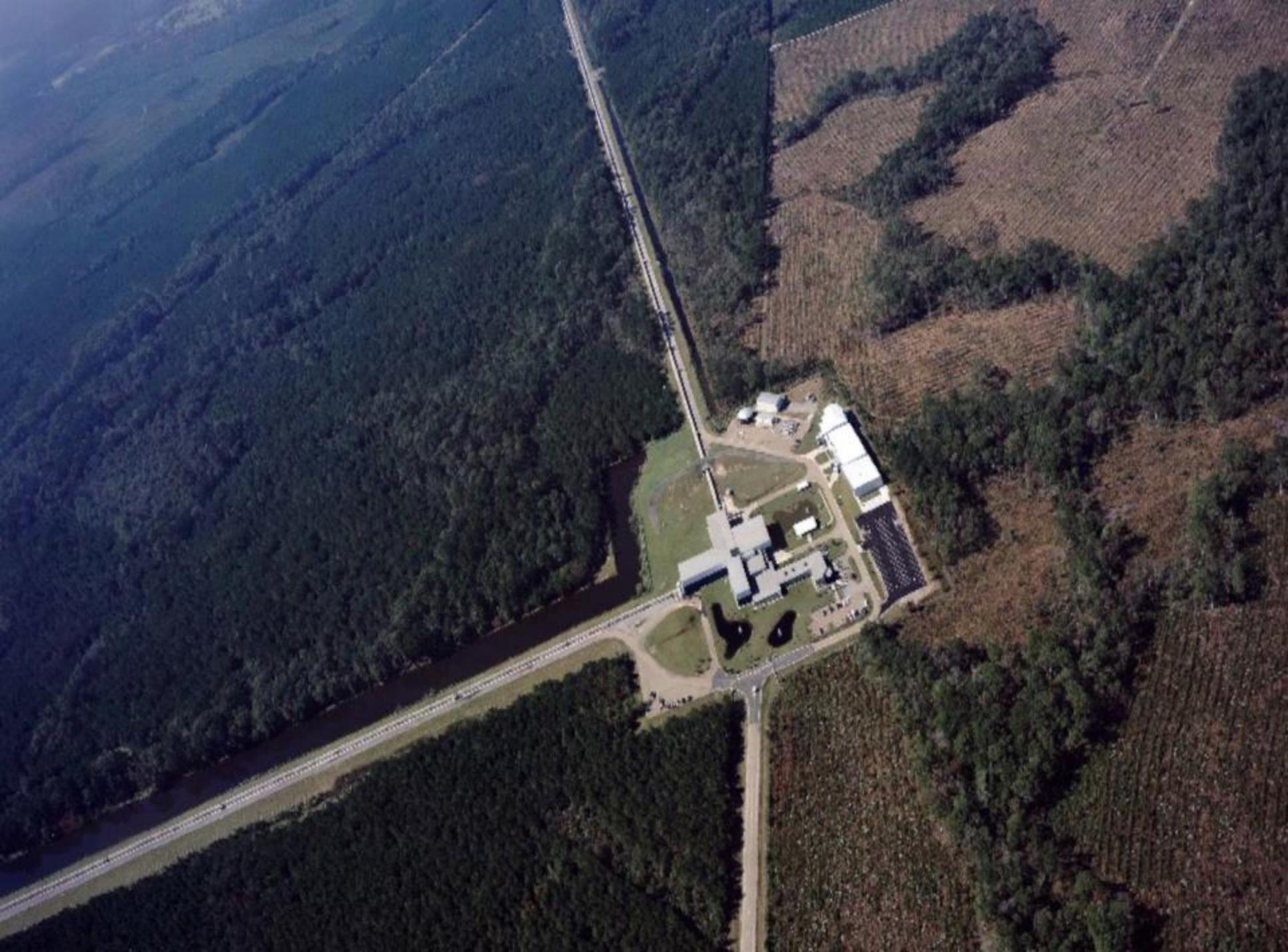
# How Small is $10^{-18}$ Meter?

		<i>One meter, about 40 inches</i>
$\div 10,000$		<i>Human hair, about 100 microns</i>
$\div 100$		<i>Wavelength of light, about 1 micron</i>
$\div 10,000$		<i>Atomic diameter, <math>10^{-10}</math> meter</i>
$\div 100,000$		<i>Nuclear diameter, <math>10^{-15}</math> meter</i>
$\div 1,000$		<i>LIGO sensitivity, <math>10^{-18}</math> meter</i>



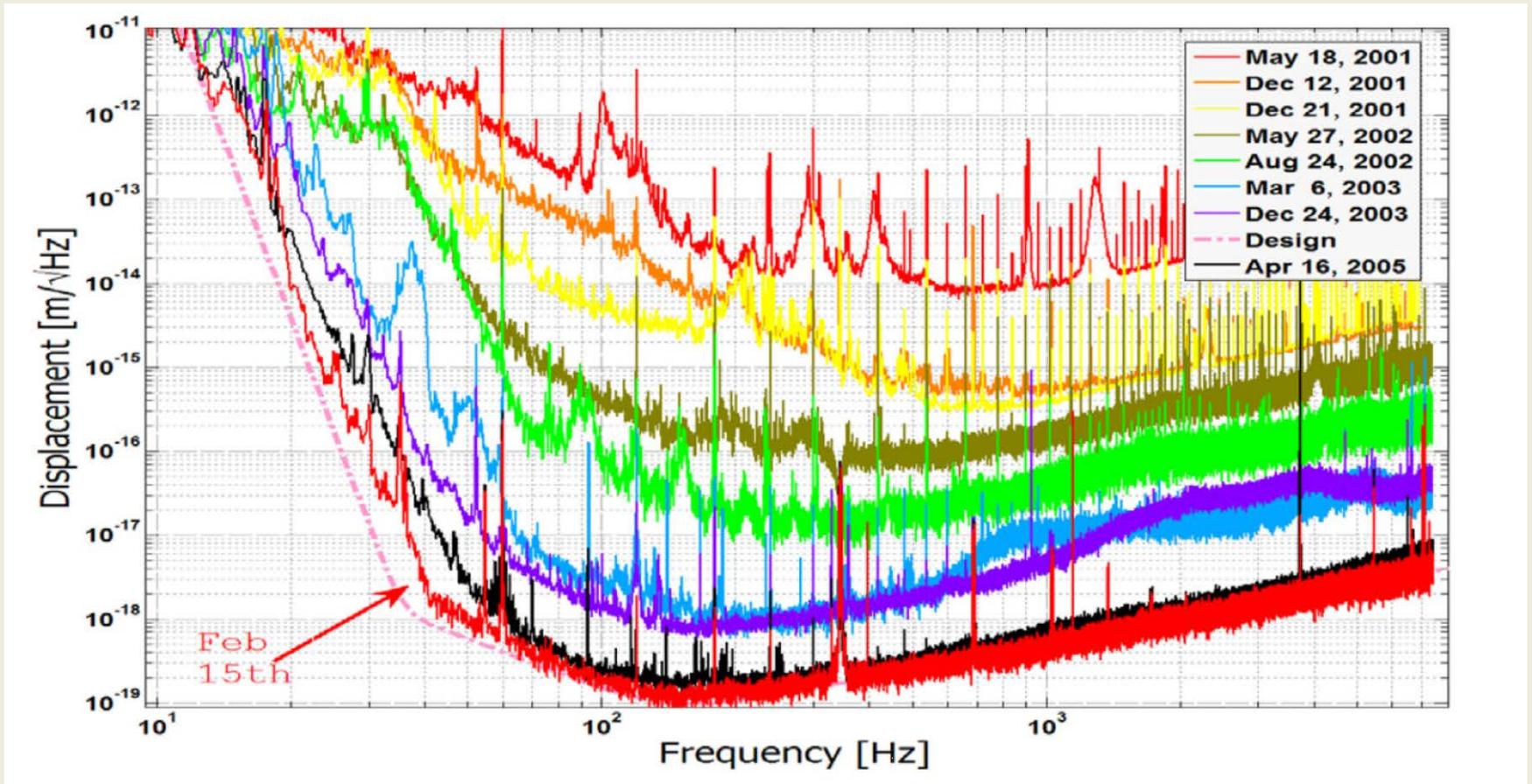




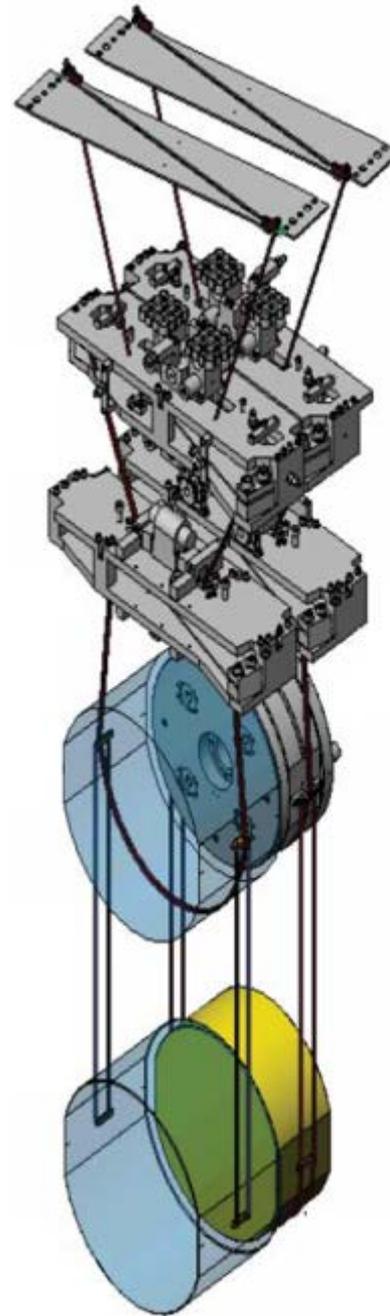
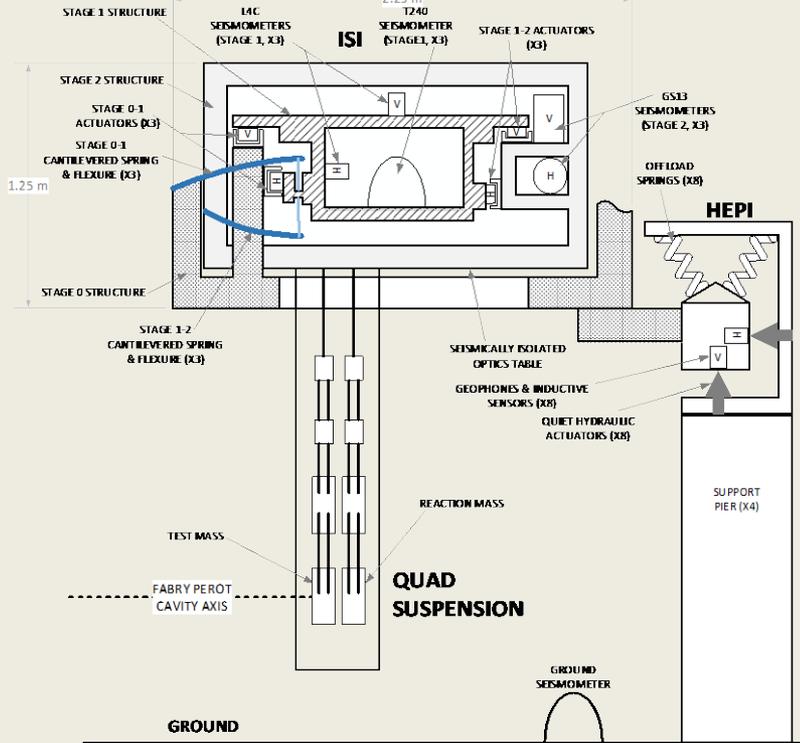




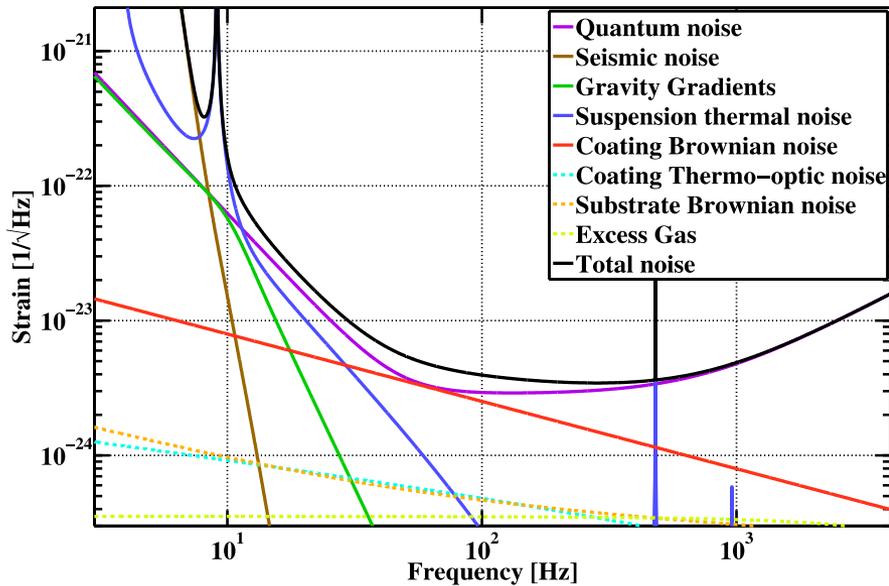
# Evolution of the initial detector 2001 - 2006

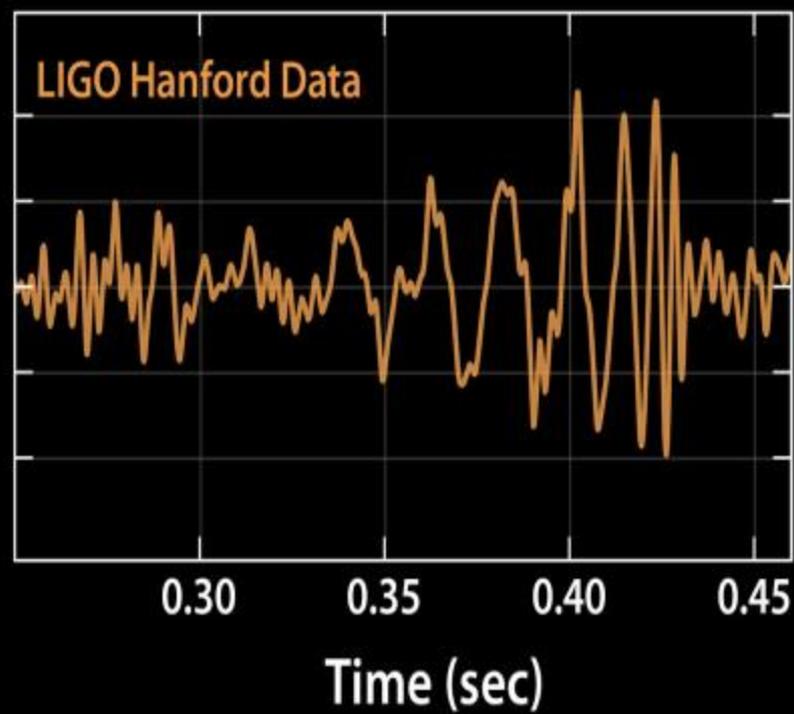
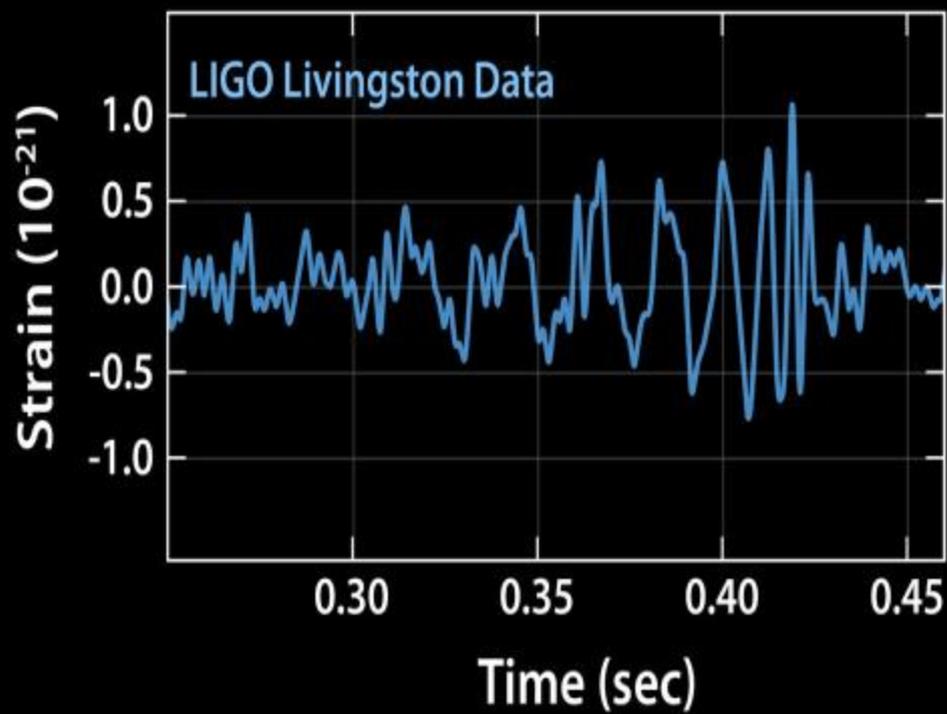


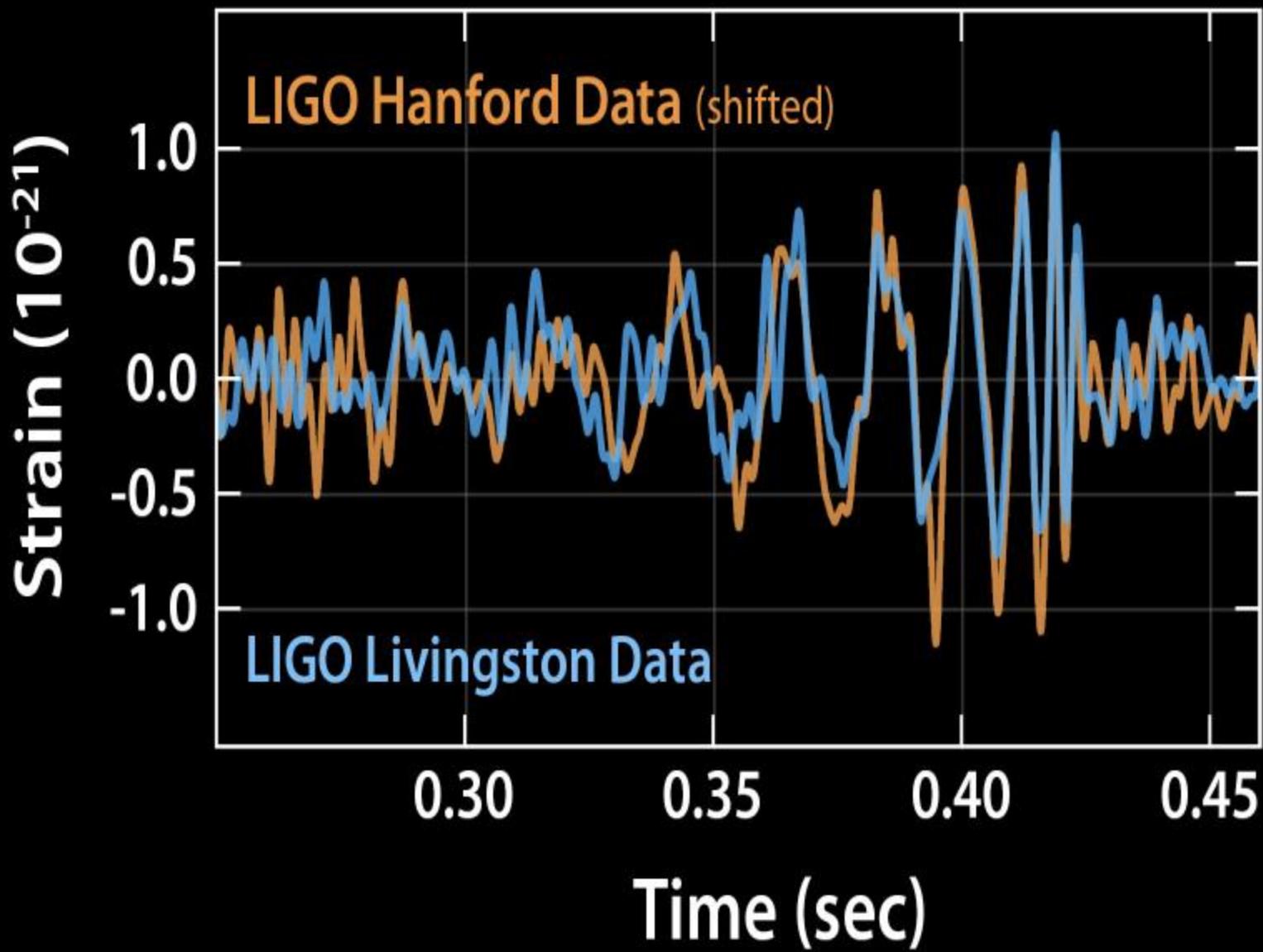
A clean non-detection

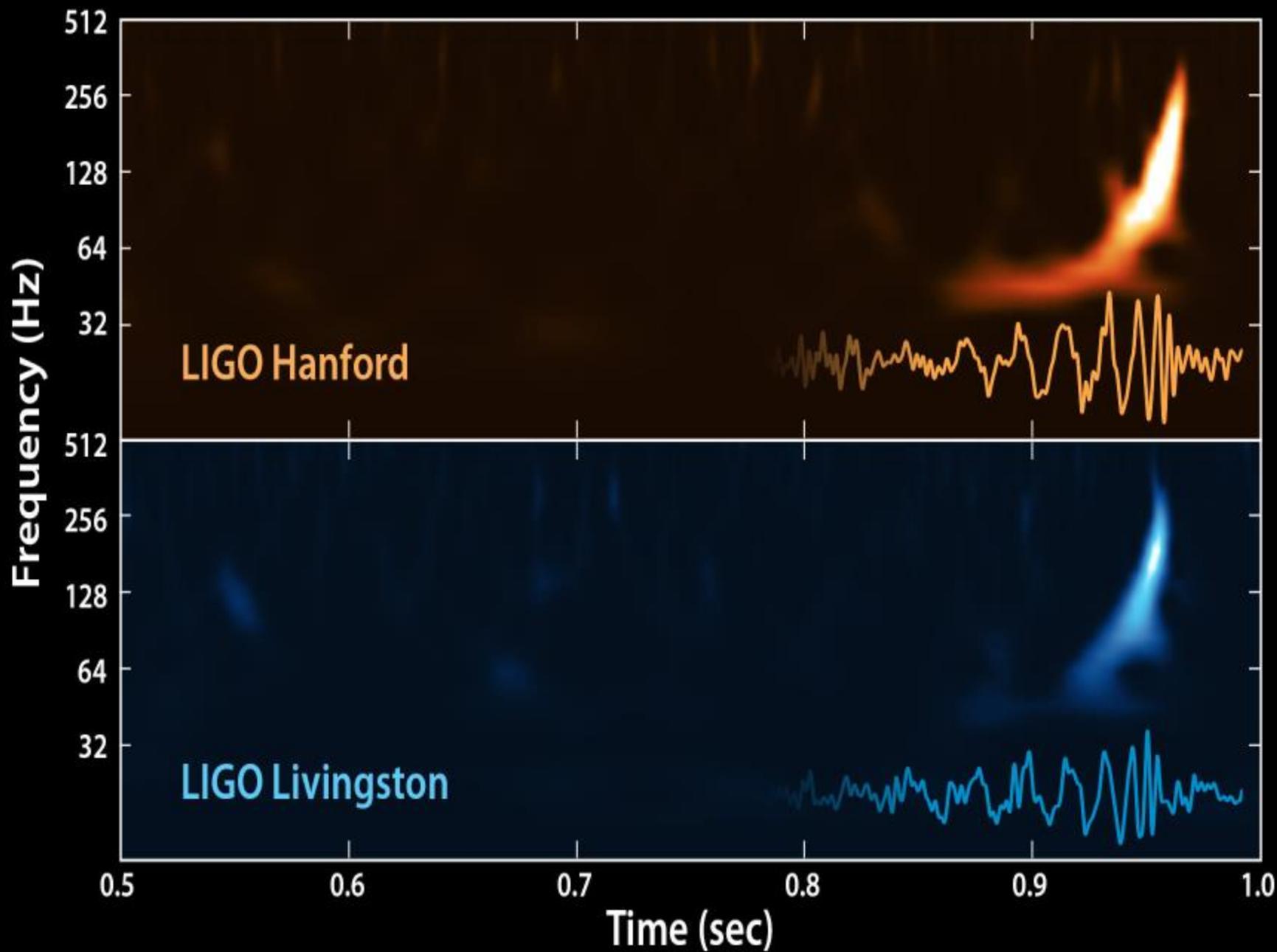


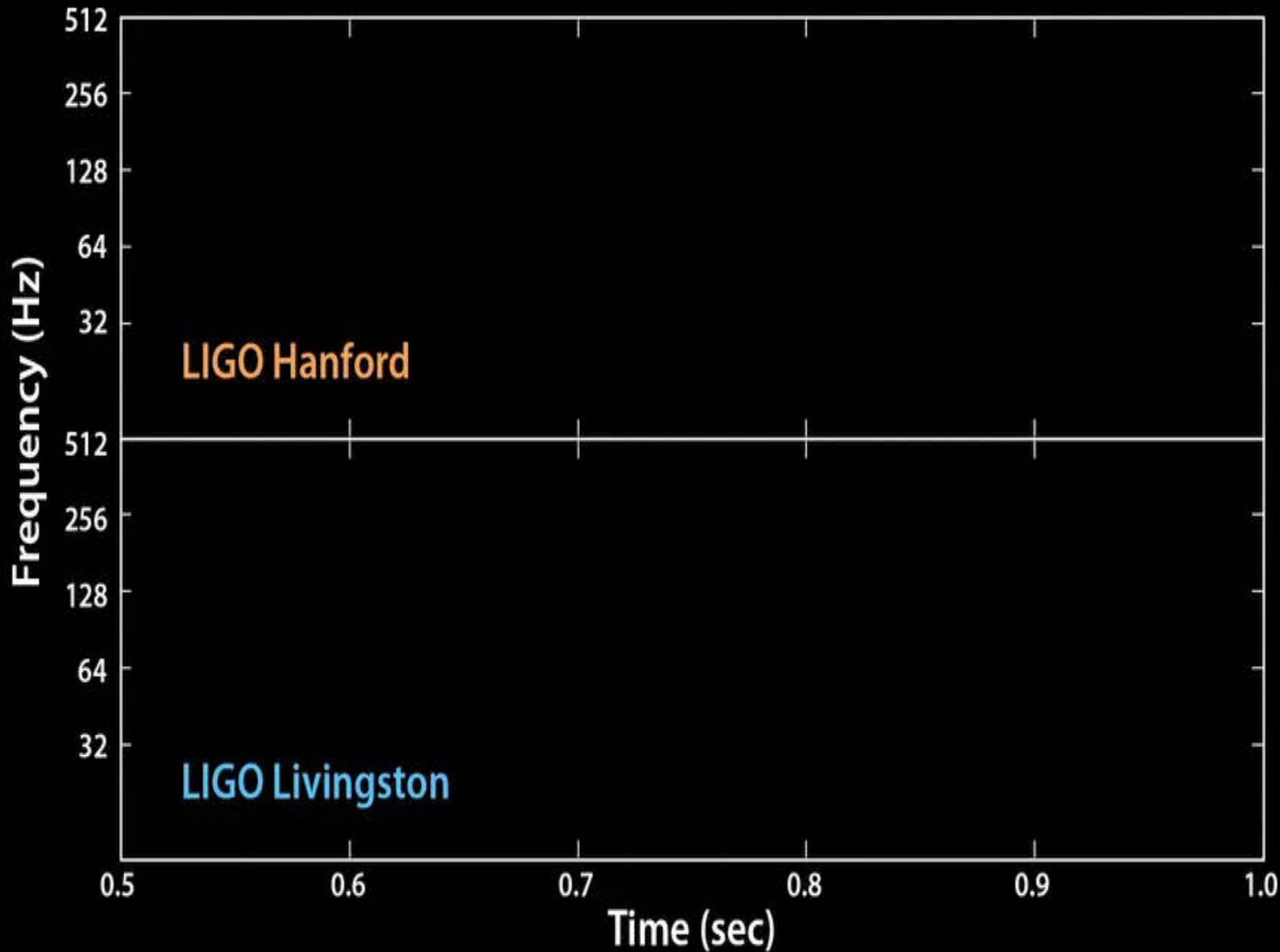
Advanced LIGO design noise budget

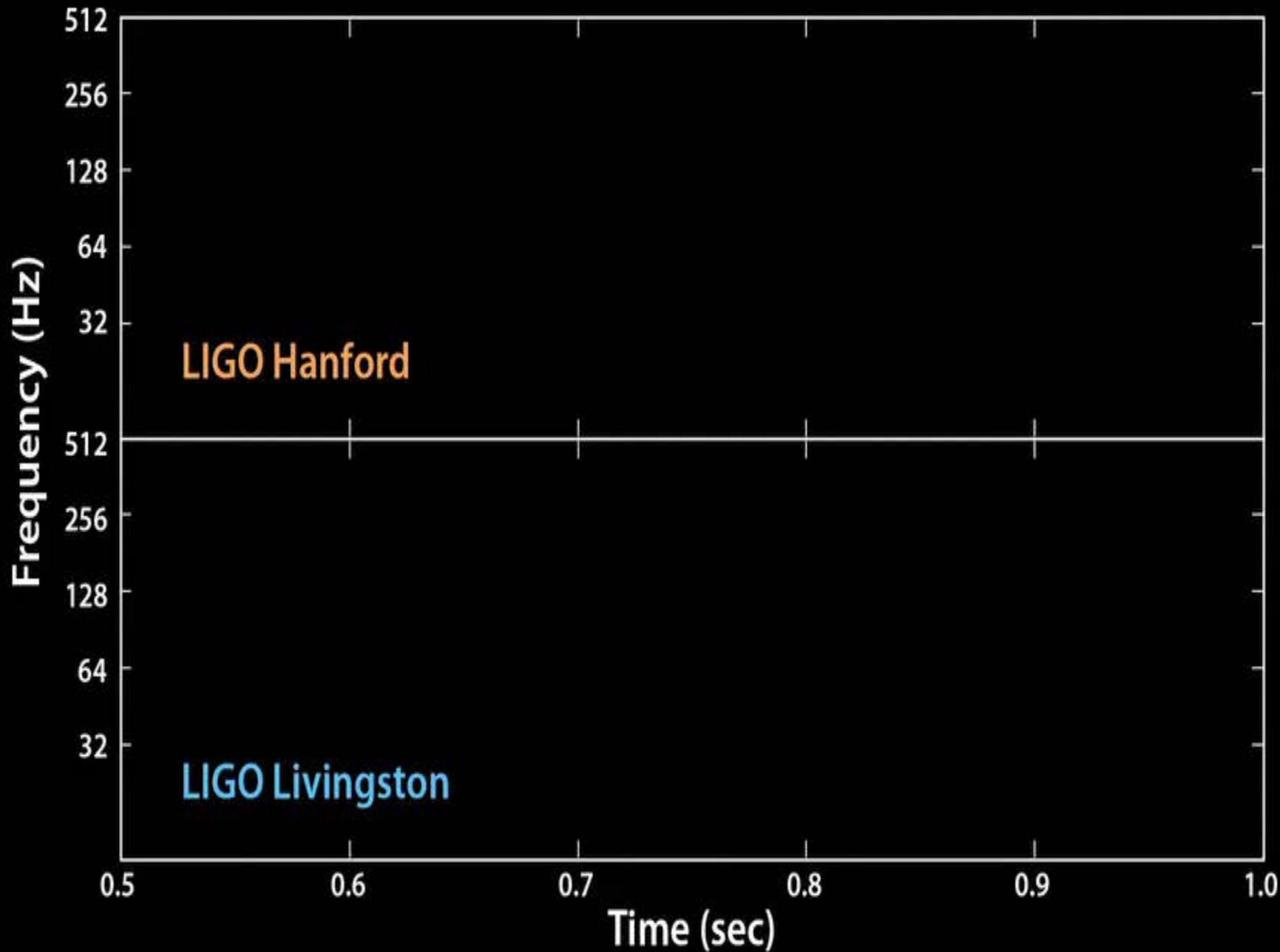




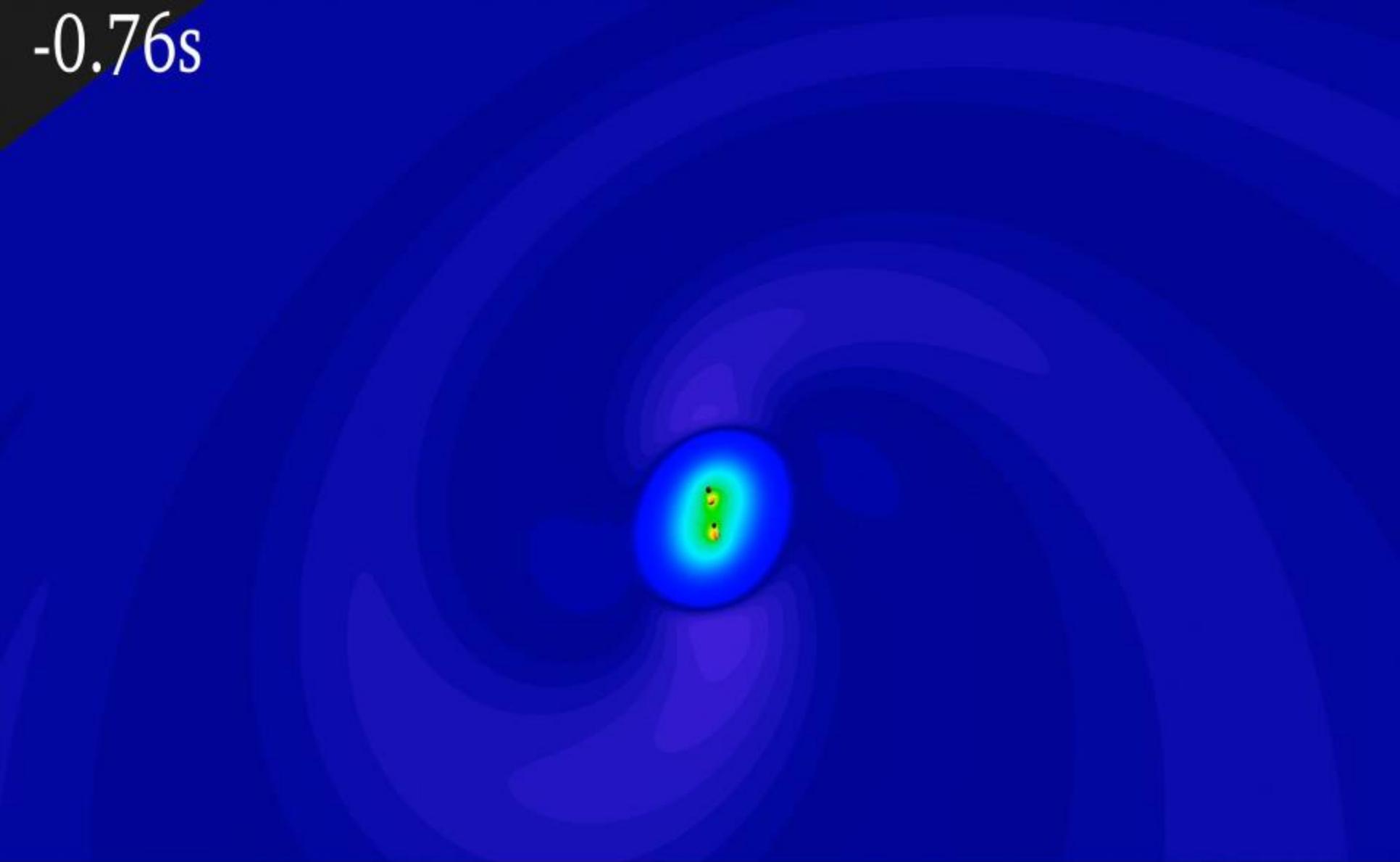




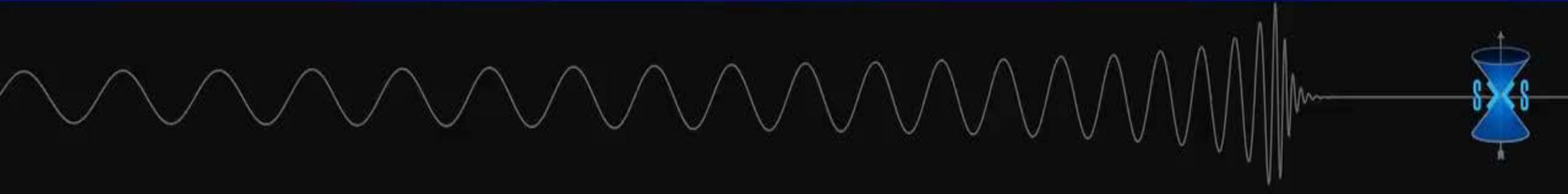
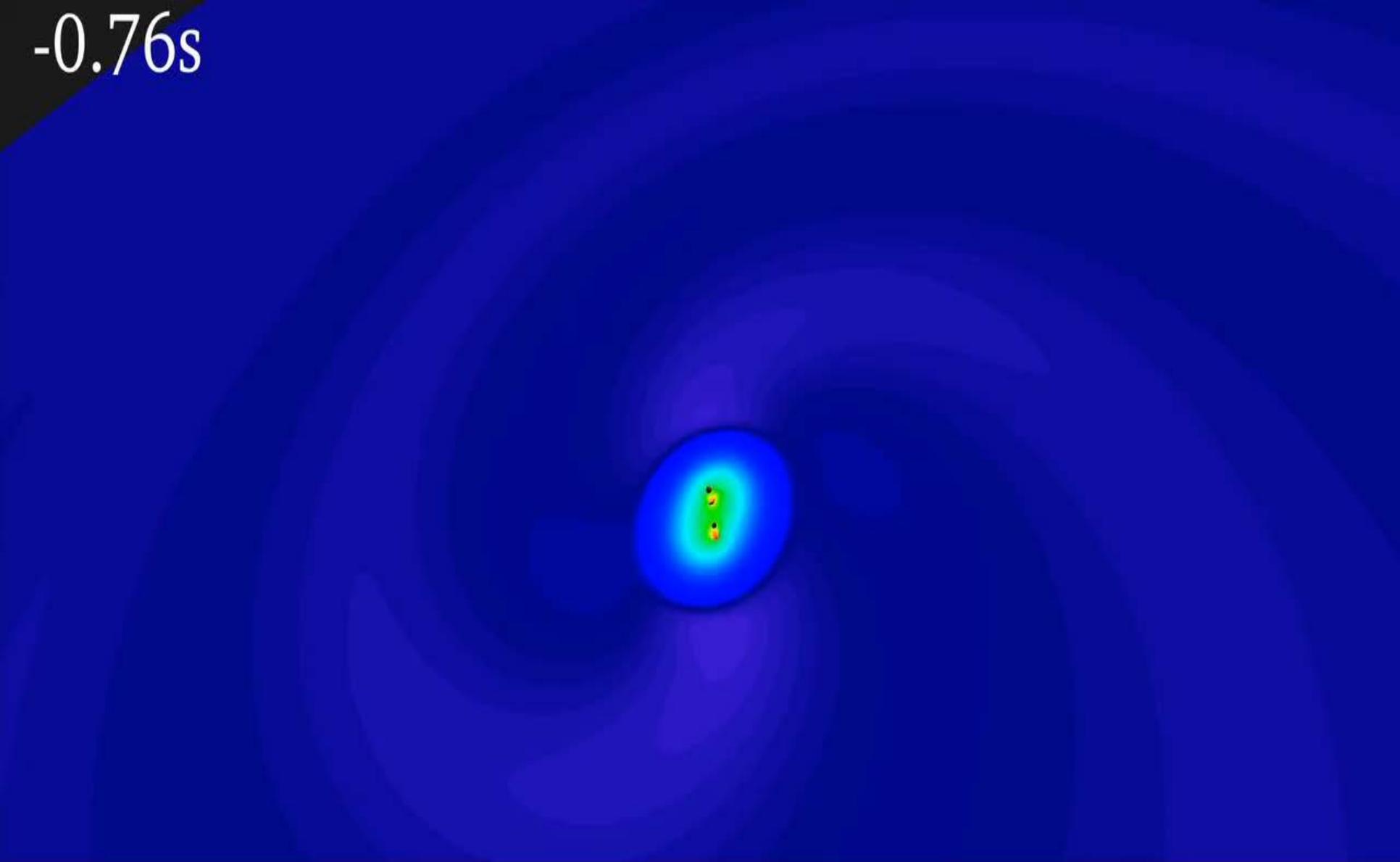




-0.76s



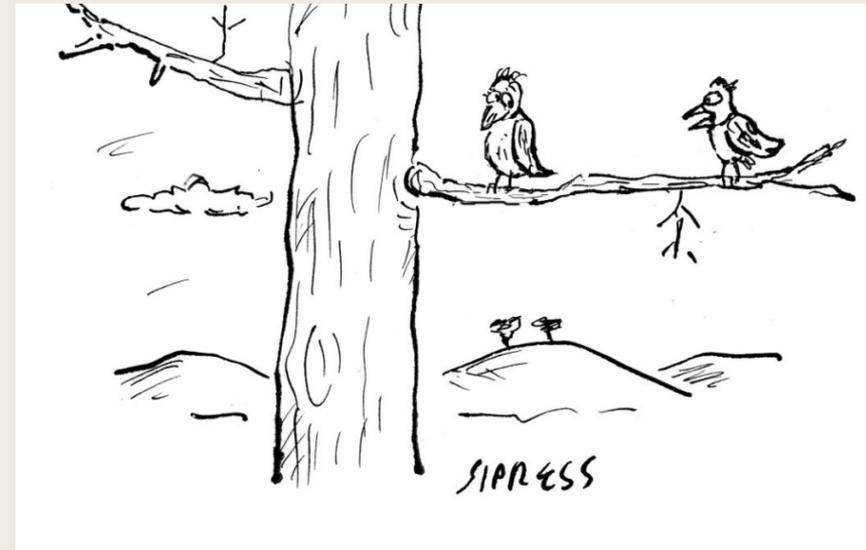
-0.76s



# After Feb 11, 2016



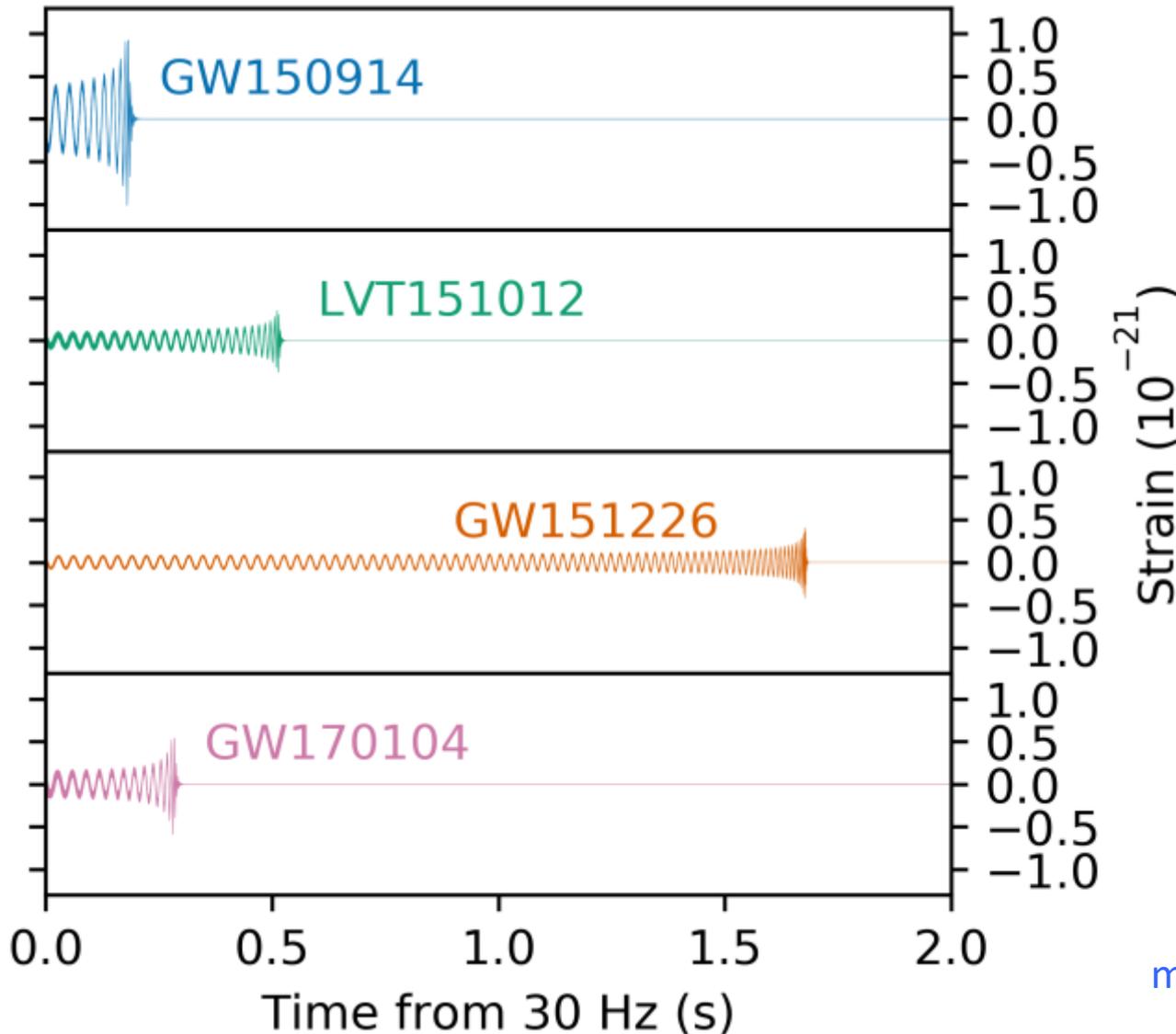
Matt Weber



*“Was that you I heard just now,  
or was it two black holes colliding*

New Yorker Feb 12,, 2016

# Results of O1 and O2 run announced June 1, 2017



$m_1=36, m_2= 29, \Delta m=3$

if at 1 au

$h \sim 10^{-6}$

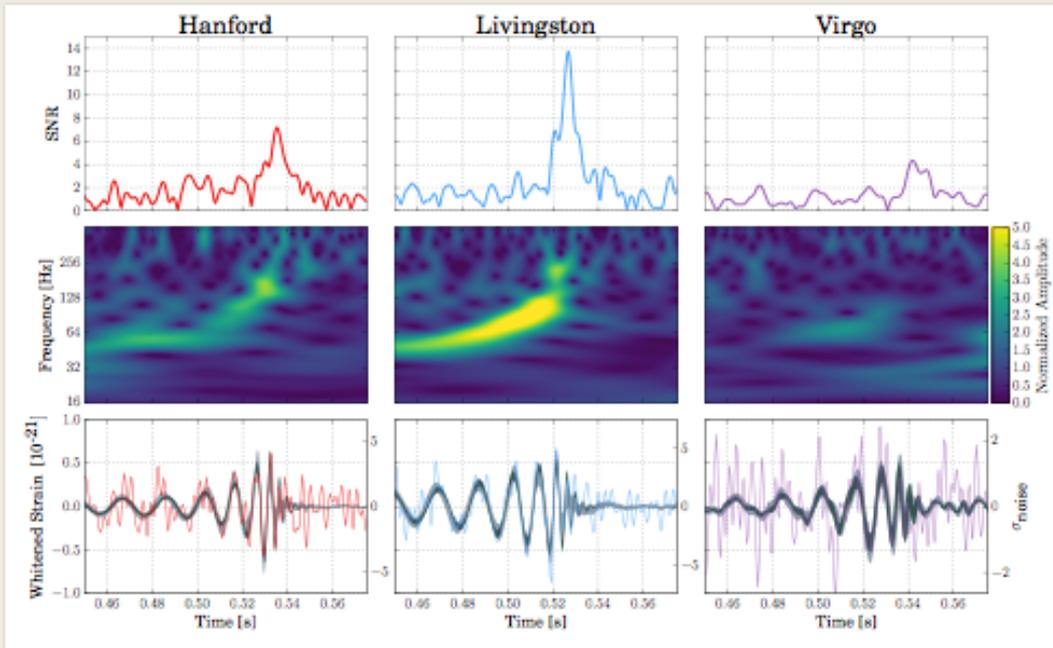
$I_g \sim 10^{25} \text{ w/m}^2$

$m_1=23, m_2= 13, \Delta m=1.5$

$m_1=14.2, m_2= 7.5, \Delta m=1$

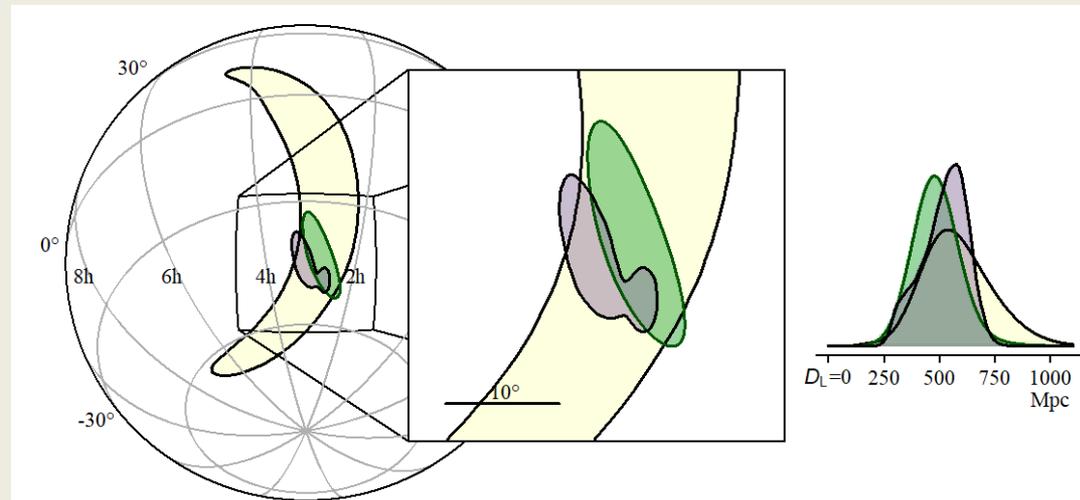
$m_1=31, m_2= 19, \Delta m=2$

masses in source frame

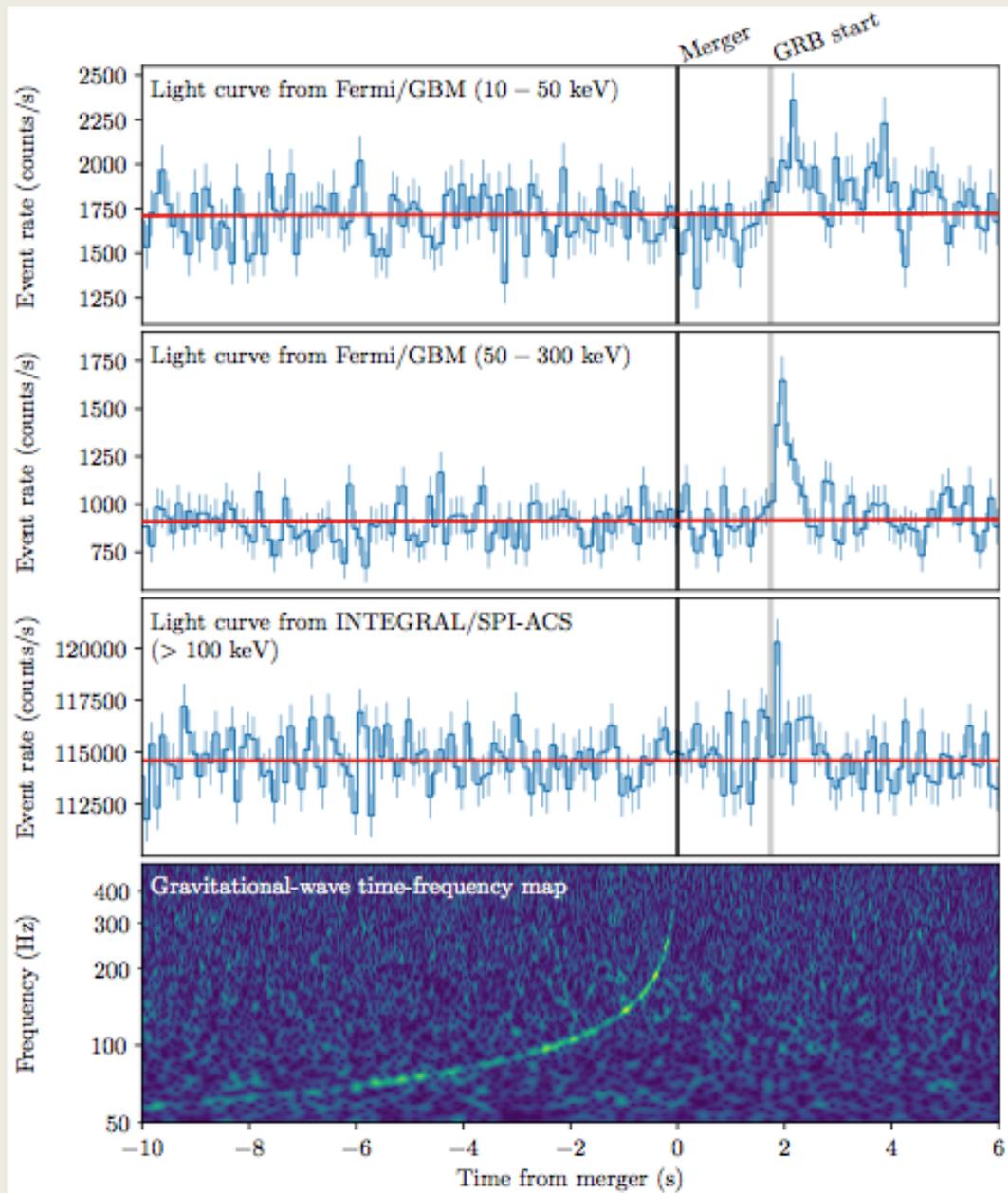


Triple coincidence  
GW 170814

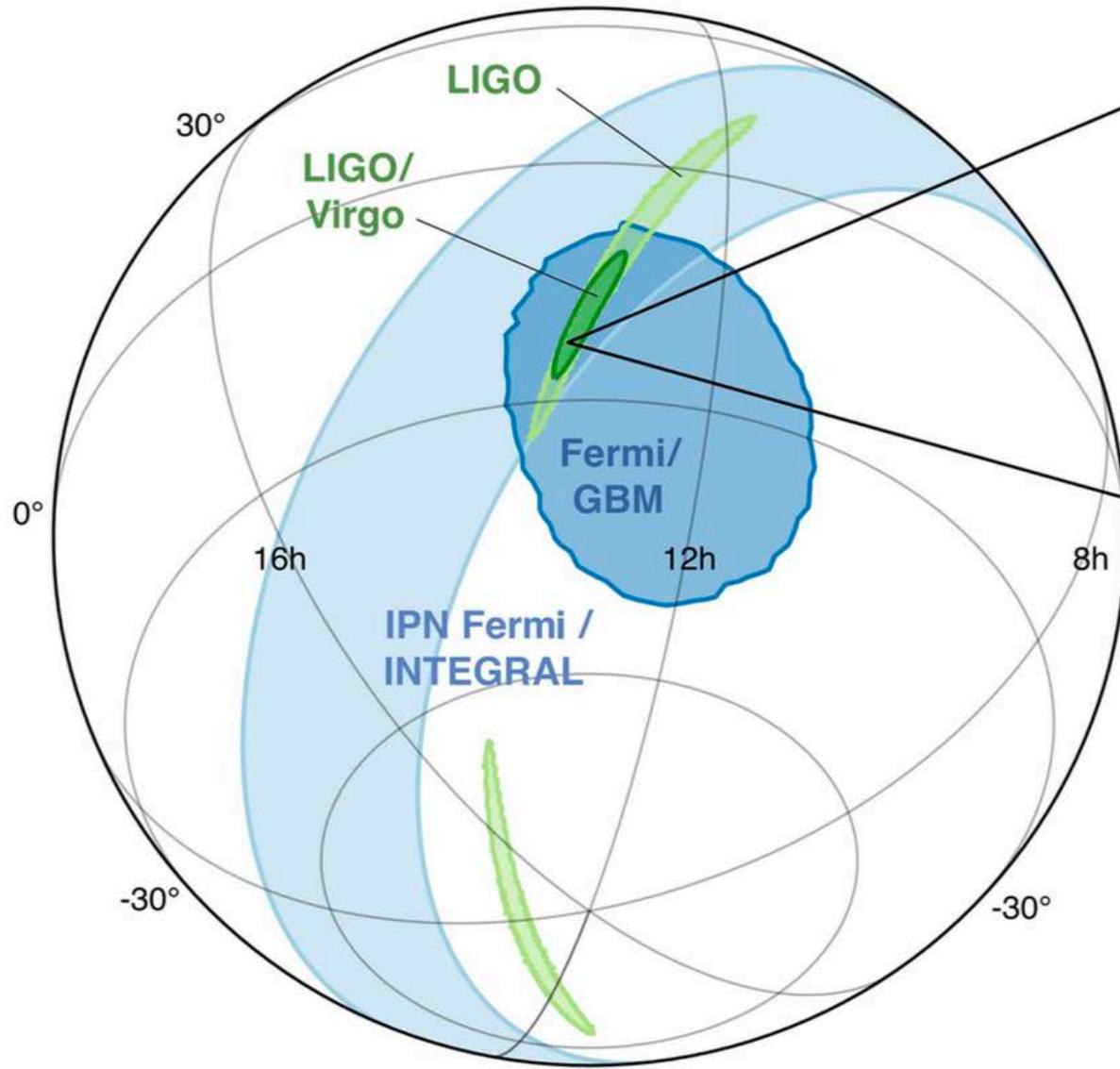
$M_1 = 30$   
 $M_2 = 25$   
 $\Delta M = 2.7$



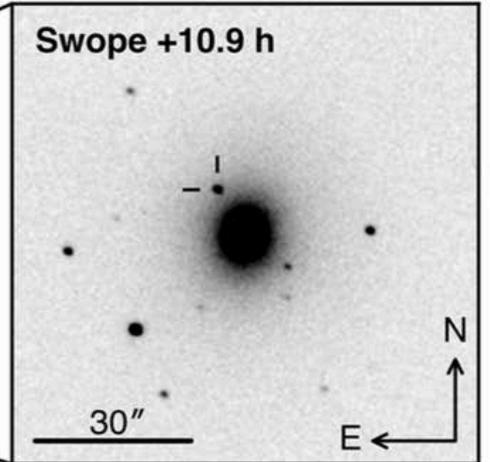
Localization on sky and distance



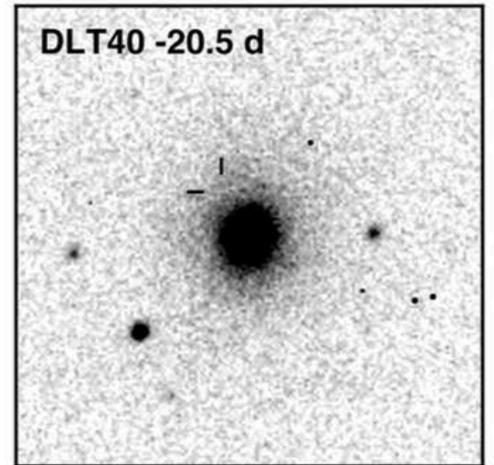
NGC4493

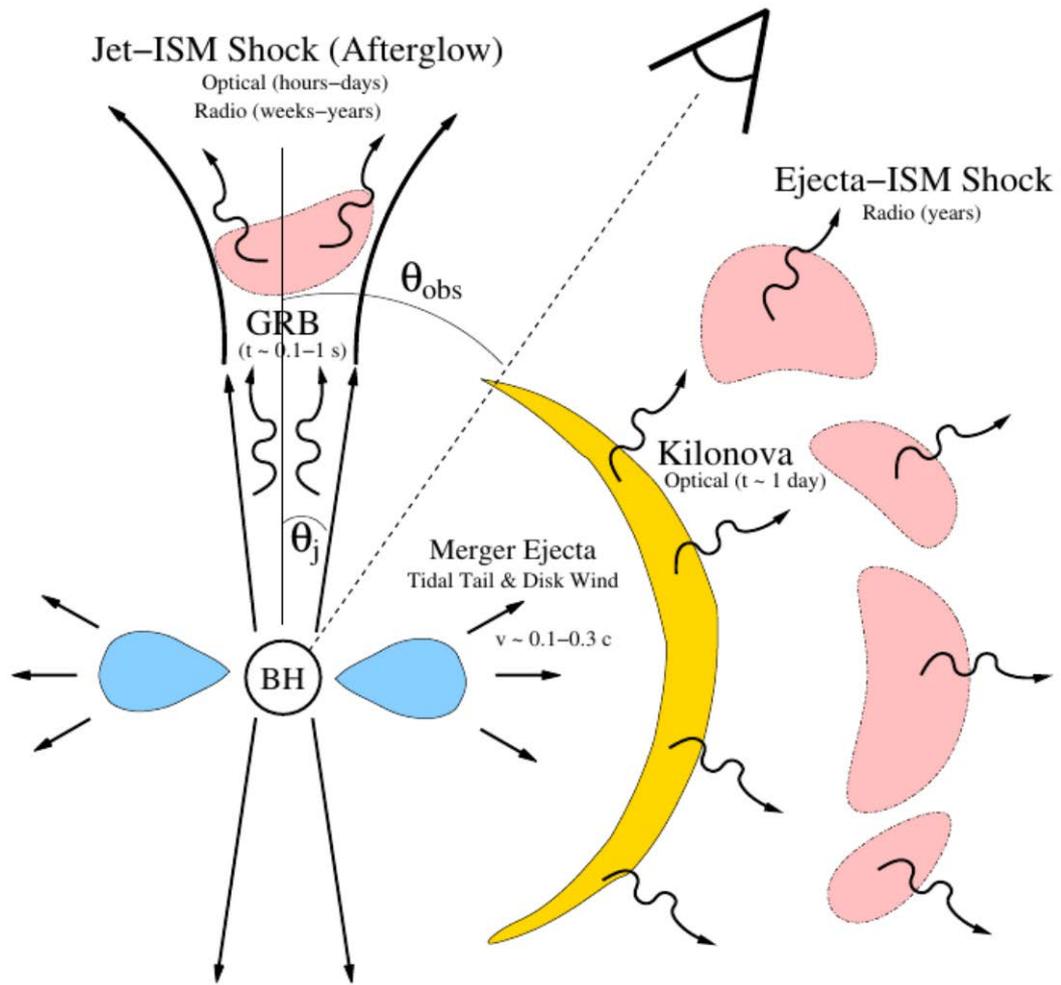


Swope +10.9 h



DLT40 -20.5 d





# Multi-messenger Astronomy with Gravitational Waves



*Gravitational Waves*

*Binary Neutron Star Merger*



*Visible/Infrared Light*



*Radio Waves*

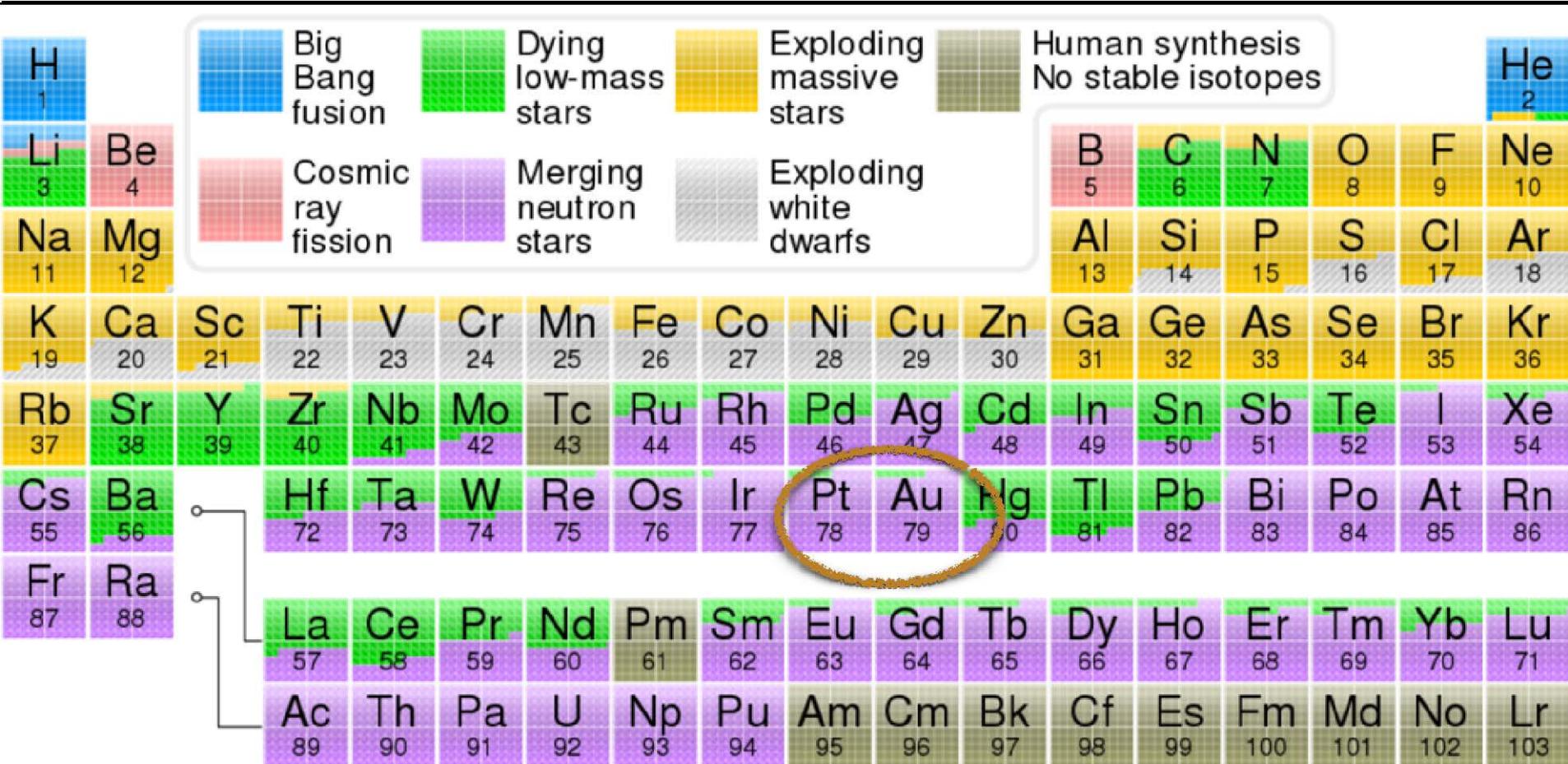


*X-rays/Gamma-rays*

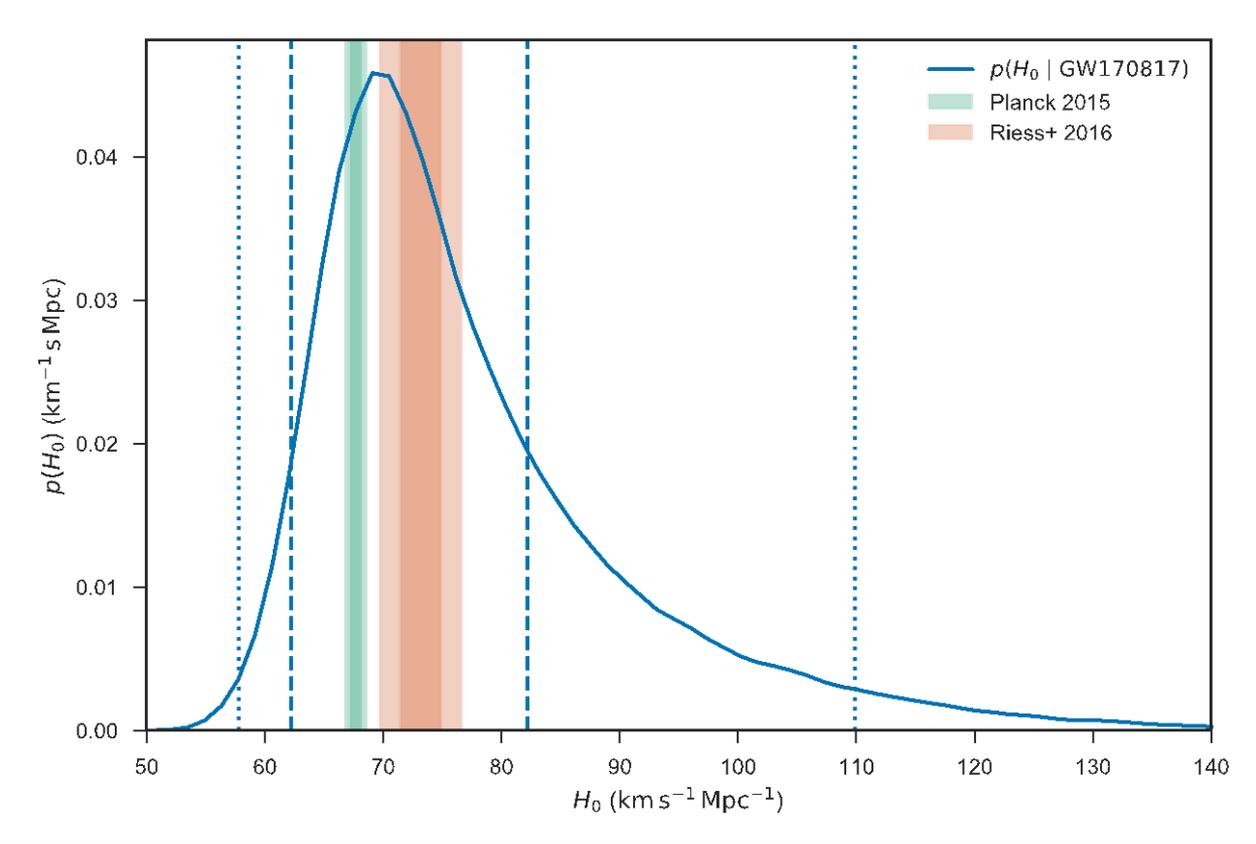


*Neutrinos*

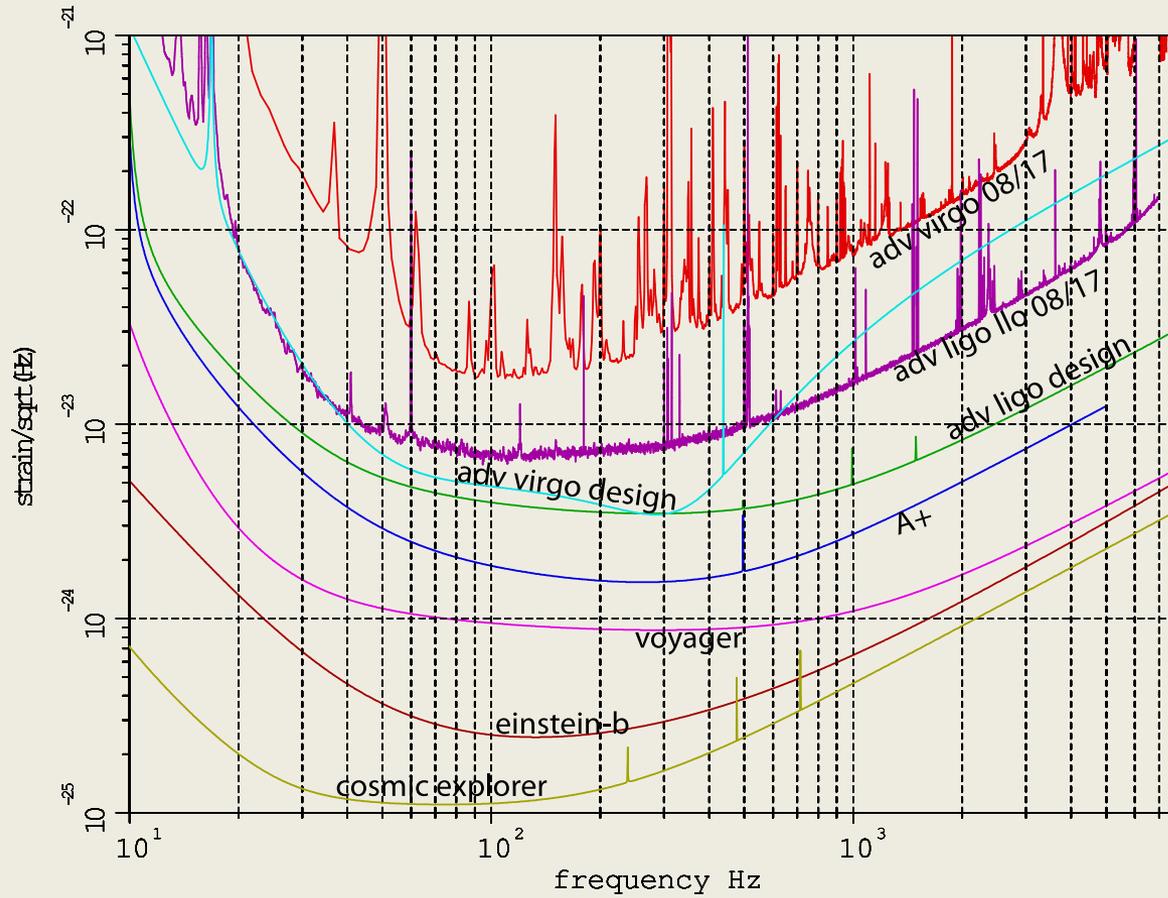
# Origin of the elements



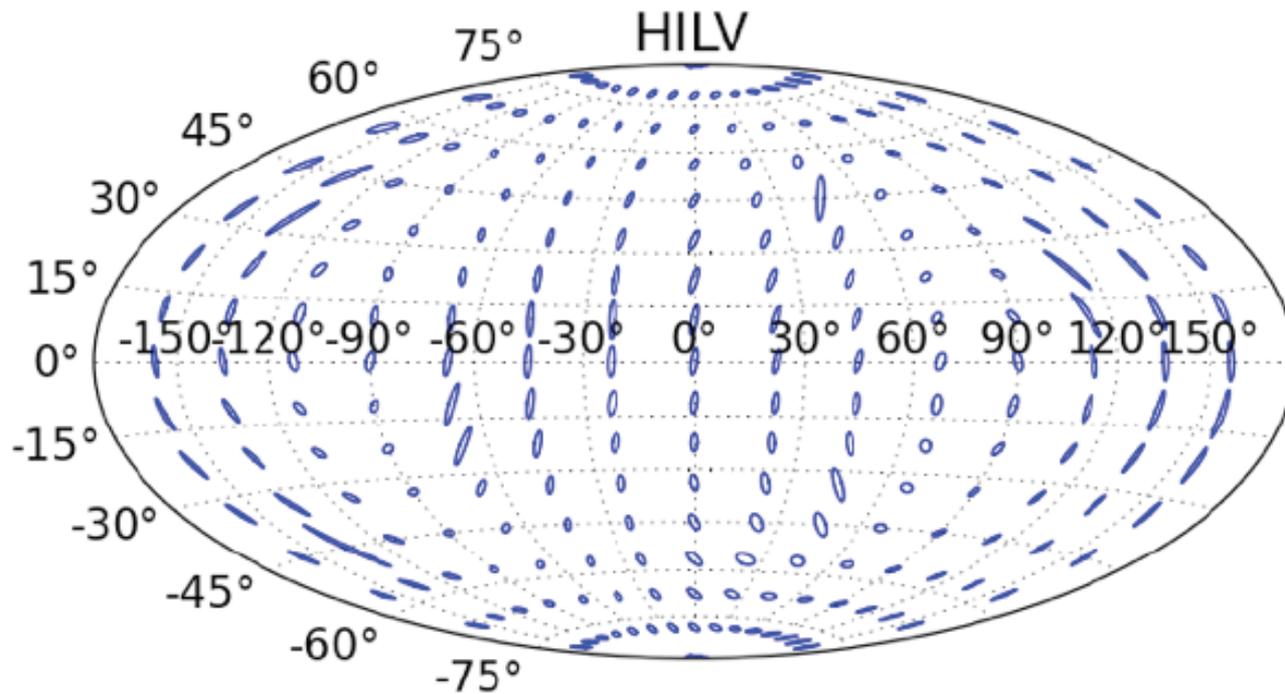
# Hubble constant measurement: Galaxy z and distance from GW amplitude



# Interferometer Evolution



# Localization with more detectors



Fairhurst 2011

age of universe

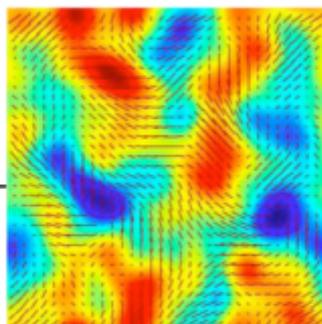
years

hours

minutes

1/10 to 1/1000 sec

*Cosmic Microwave Background  
Polarization B Modes*



h  
10<sup>-5</sup>  
10<sup>-10</sup>  
10<sup>-15</sup>  
10<sup>-20</sup>  
10<sup>-25</sup>

Primeval gravitational waves from inflationary epoch  
Measured at epoch of recombination  $z \sim 1000$  and reionization  $z \sim 6$

## Gravitational Wave Spectrum

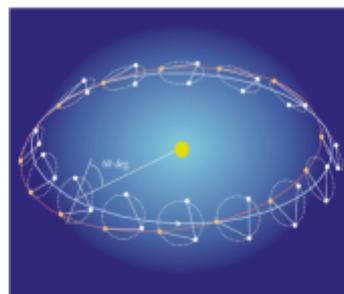
*Pulsar Timing*



Supermassive BH coalescences  
Isotropic GW background from unresolved sources

Massive BH coalescences  
Small mass/BH infalls  
White dwarf binaries in our galaxy

*Space-based Interferometers*



Compact binary coalescences: neutron stars and black holes  
Asymmetric pulsar rotations

*Ground-based Interferometers*



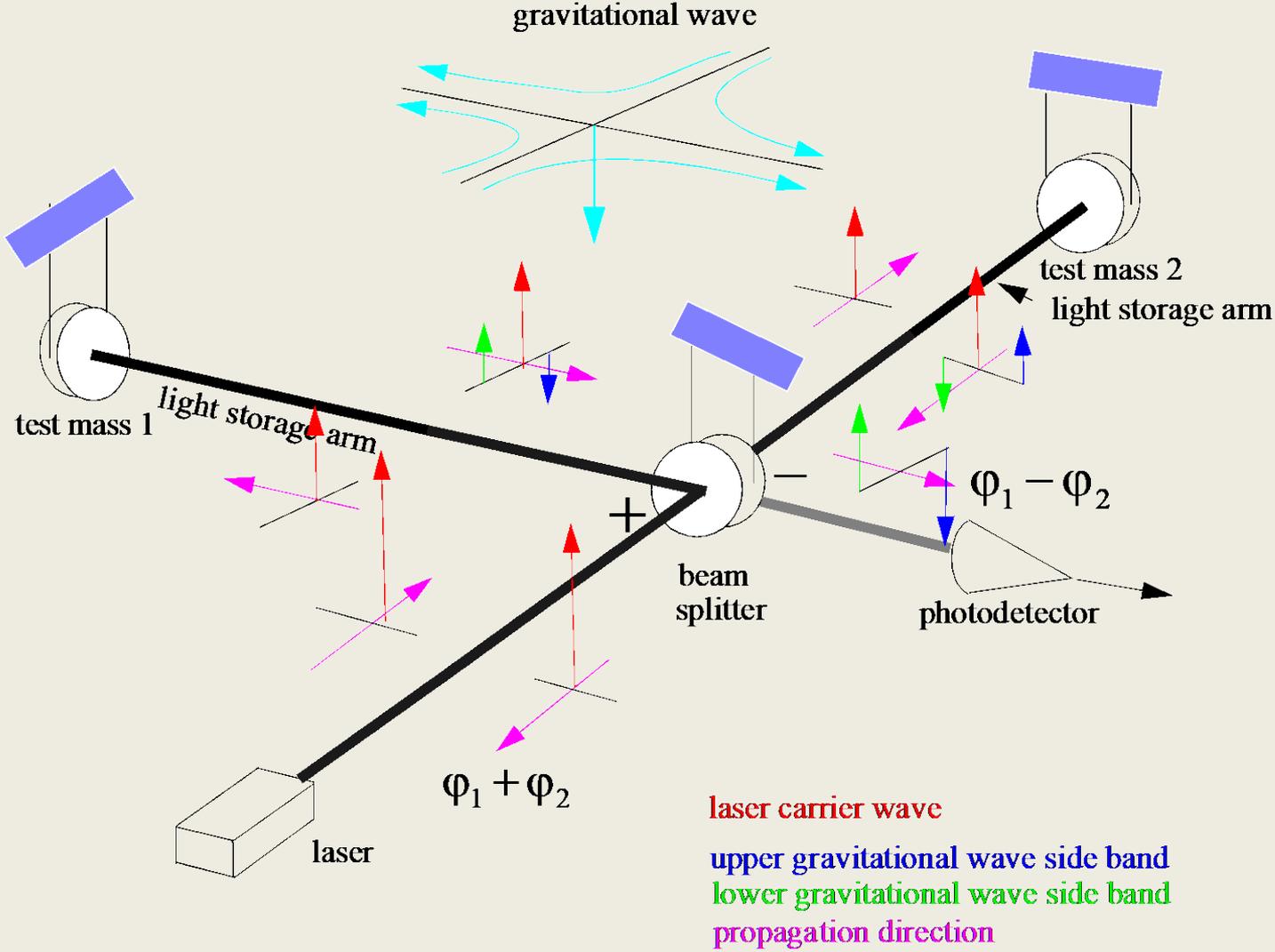
10<sup>-16</sup> 10<sup>-12</sup> 10<sup>-8</sup> 10<sup>-4</sup> 10<sup>0</sup> 10<sup>4</sup>  
Frequency Hz

# LIGO LIGO Scientific Collaboration



Extra slides

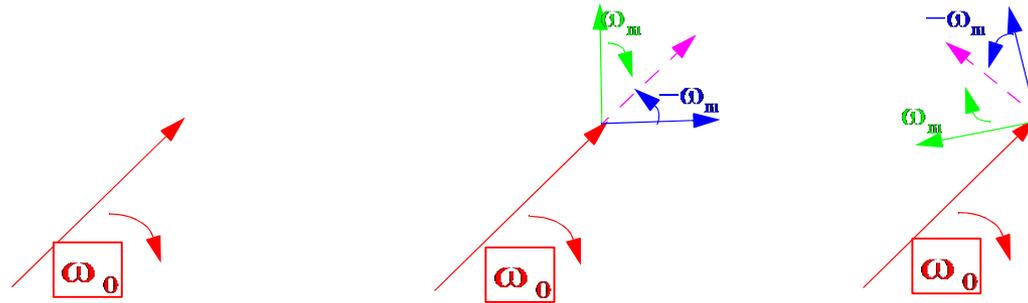
# Michelson Interferometer Schematic and GW sidebands



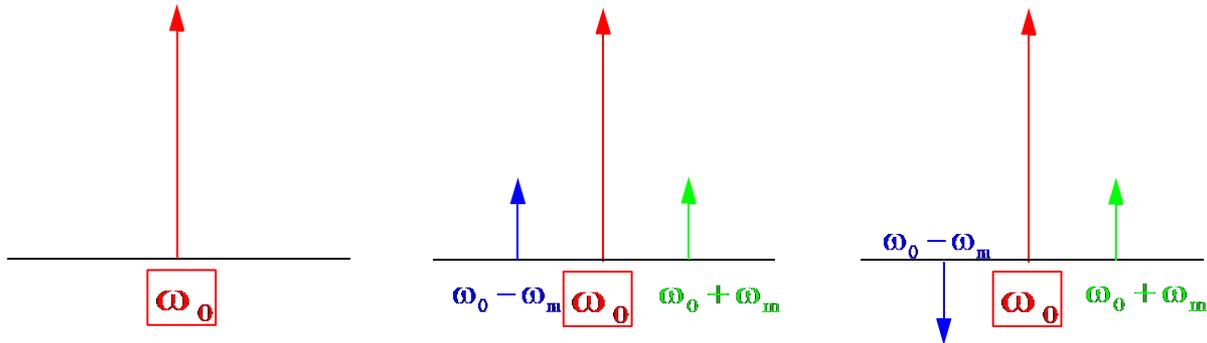


waveforms

phasors



spectrum



modulation

amplitude

phase

$$E(t) = \text{Re}(e^{i\omega_0 t})$$

$$\text{Re}(e^{i\omega_0 t} [1 + \Gamma(e^{-i\omega_m t} + e^{i\omega_m t})])$$

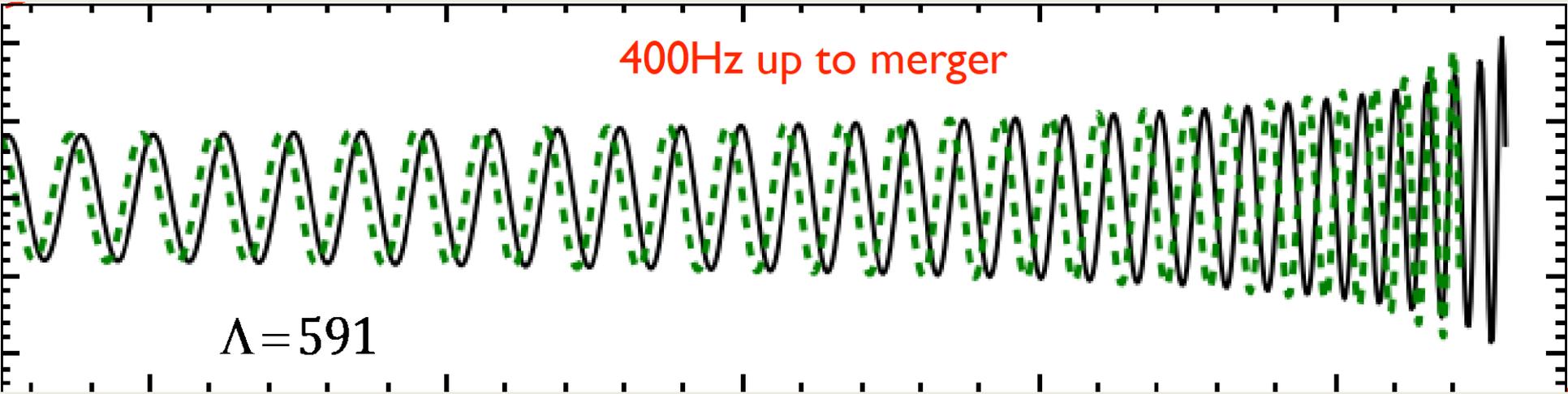
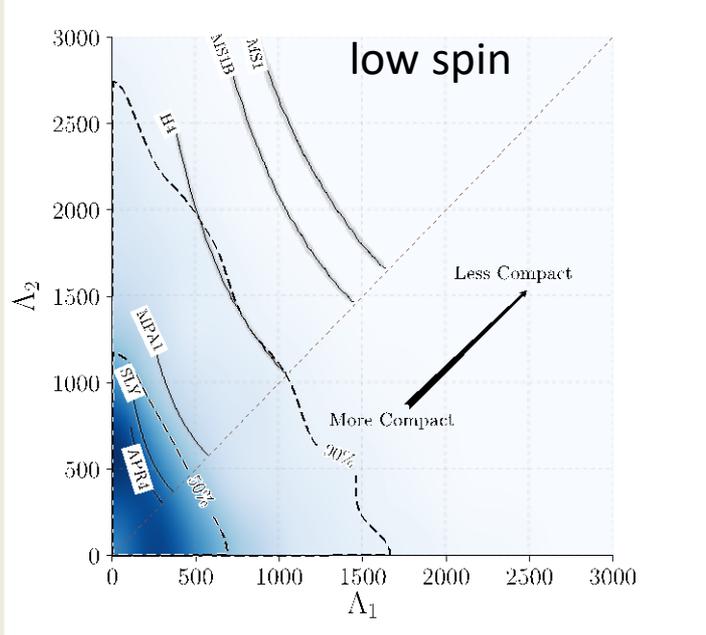
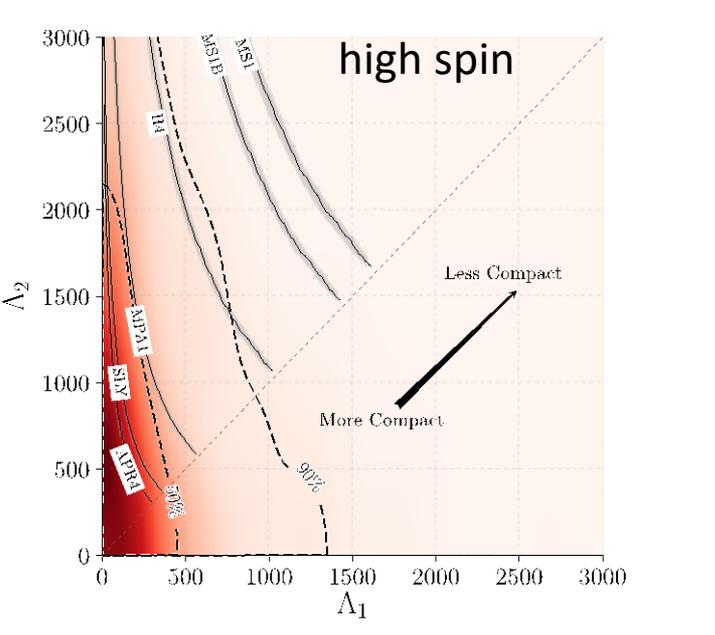
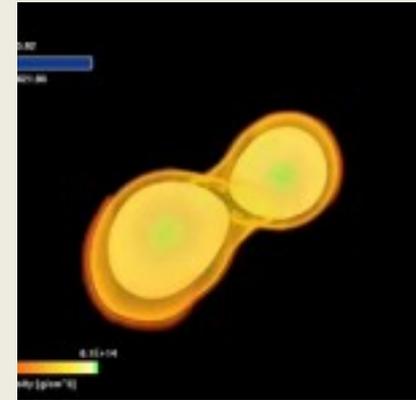
$$\text{Re}(e^{i\omega_0 t} [1 + \Gamma(e^{-i\omega_m t} - e^{i\omega_m t})])$$

## MODULATION: Amplitude and Phase

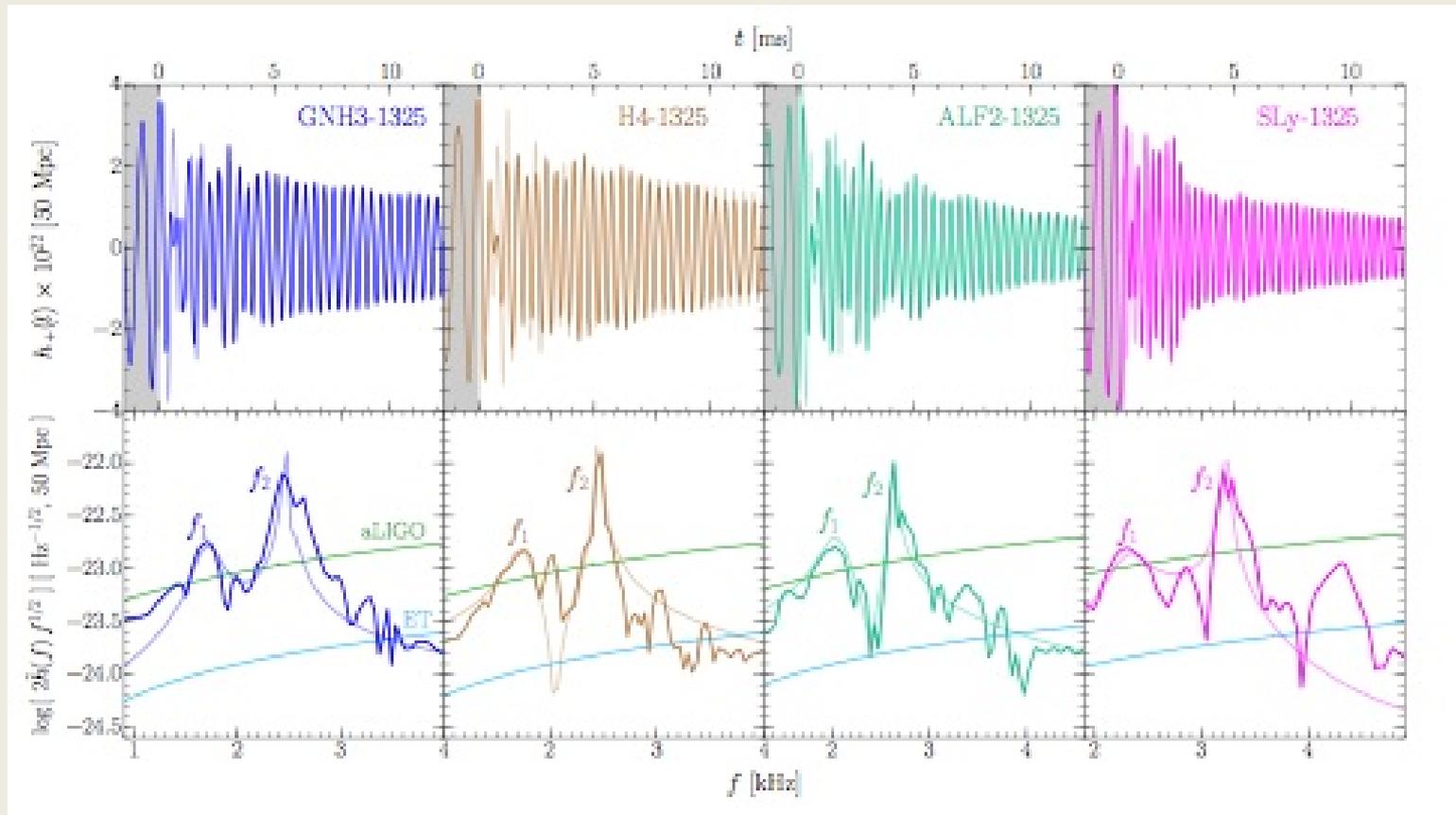
# Neutron Star Tidal Distortion

$$Q_{ij} = \lambda \frac{d^2 V(\mathbf{r})}{dx_i dx_j}$$

tidal distortion



# Binary neutron star spectroscopy



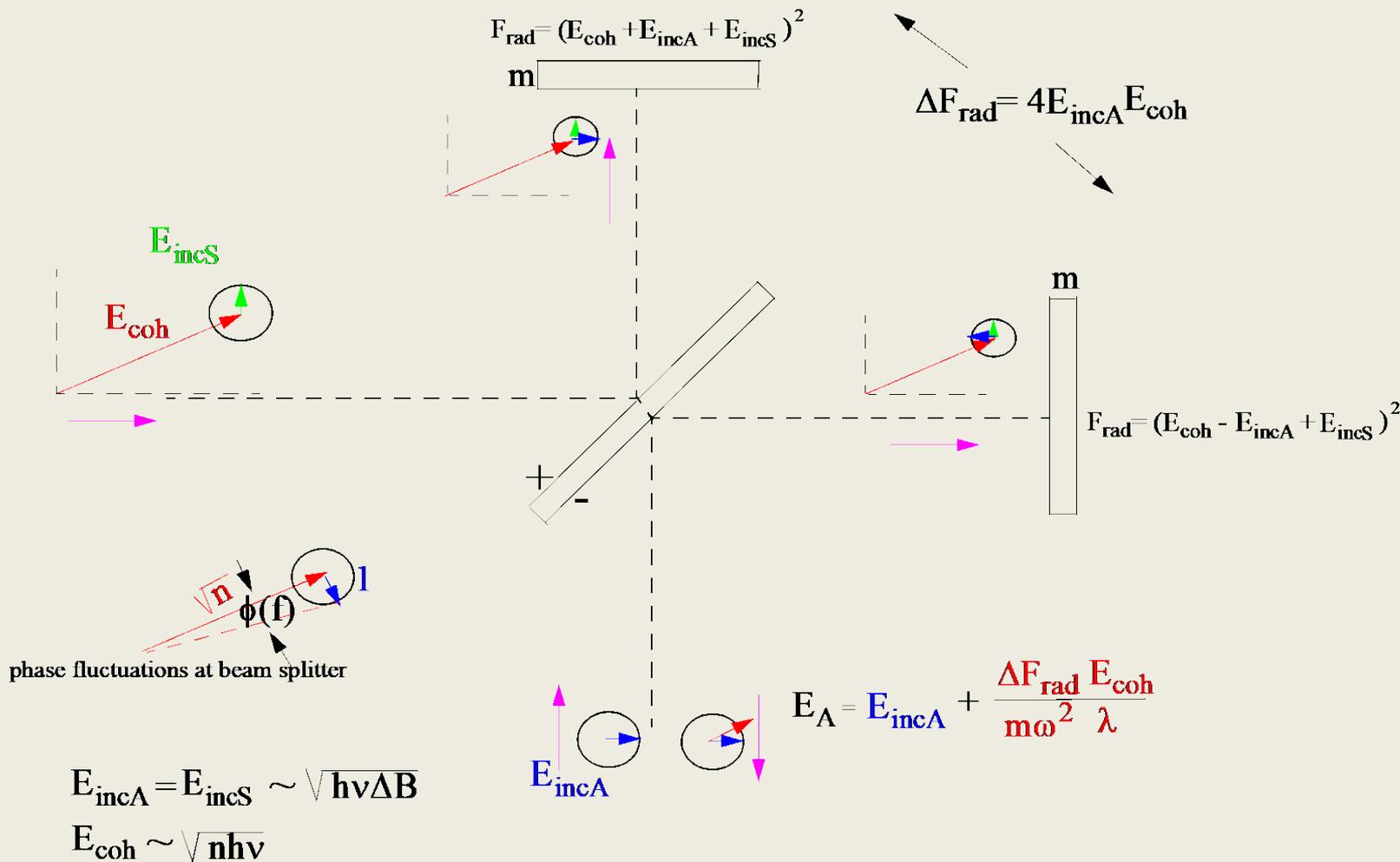
S. Bose, K. Chakravarti, L. Rezzolla, B. S. Sathyaprakash, K. Takami

# Quantum-mechanical noise in an interferometer

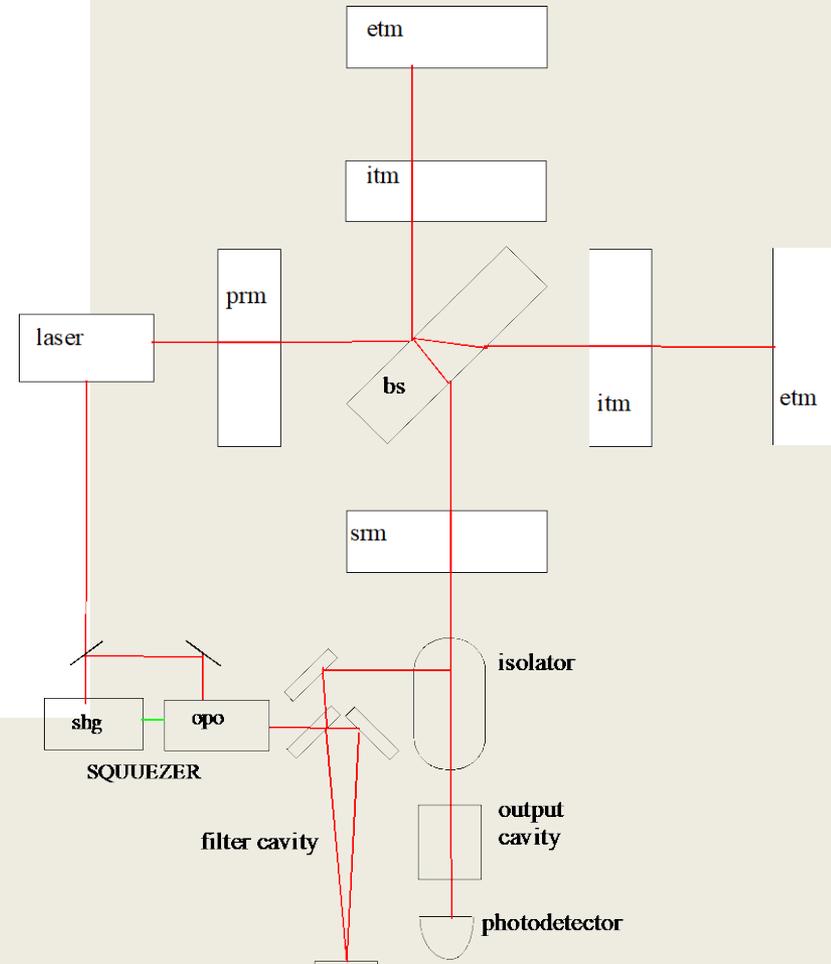
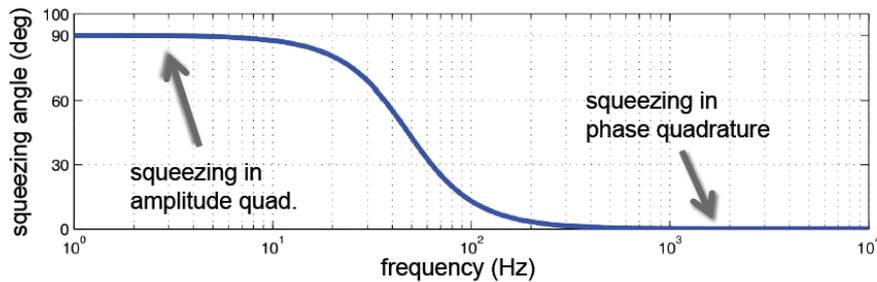
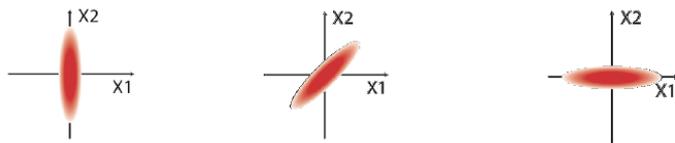
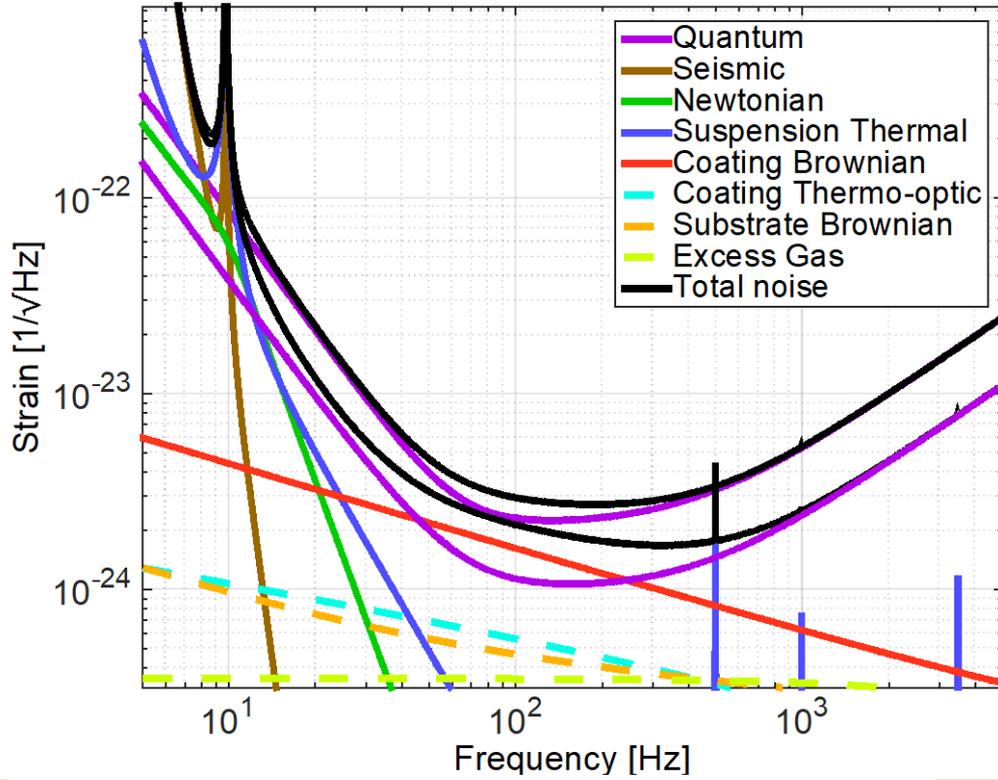
Carlton M. Caves

*W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125*

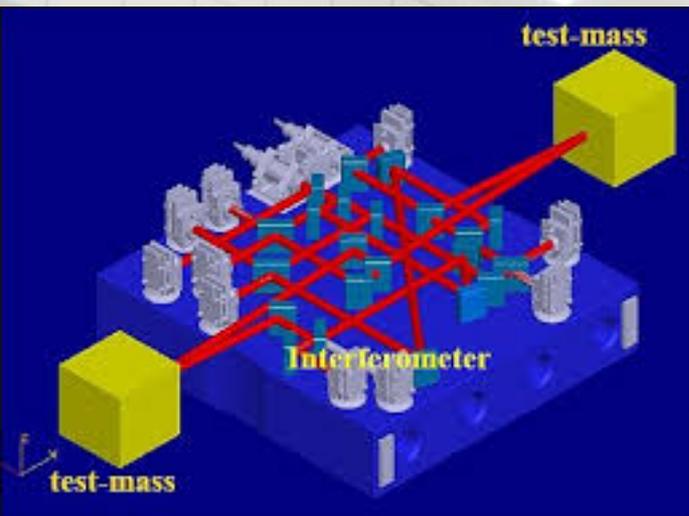
(Received 15 August 1980)



A plus without squeezing and with squeezing



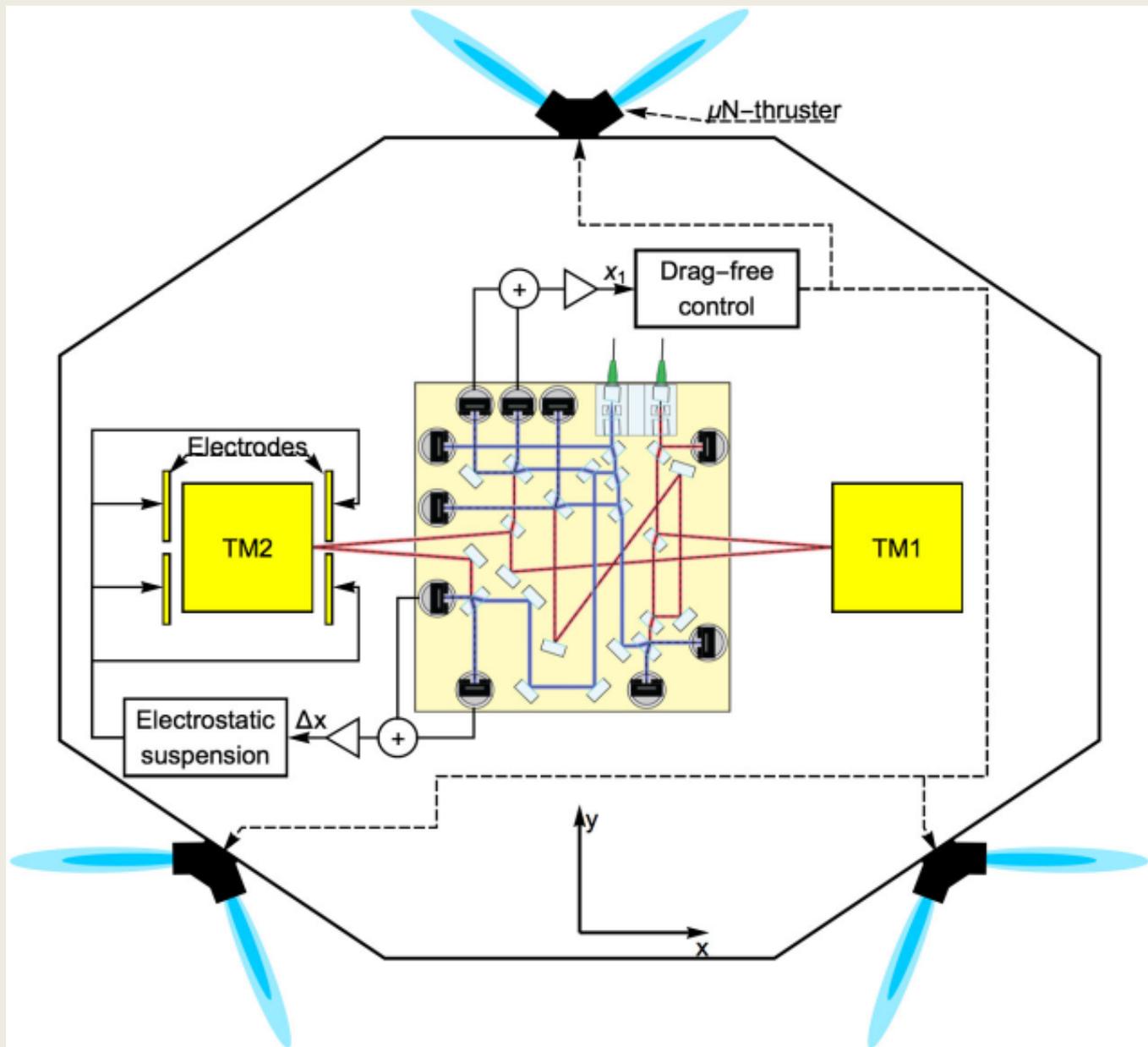
# LISA Pathfinder

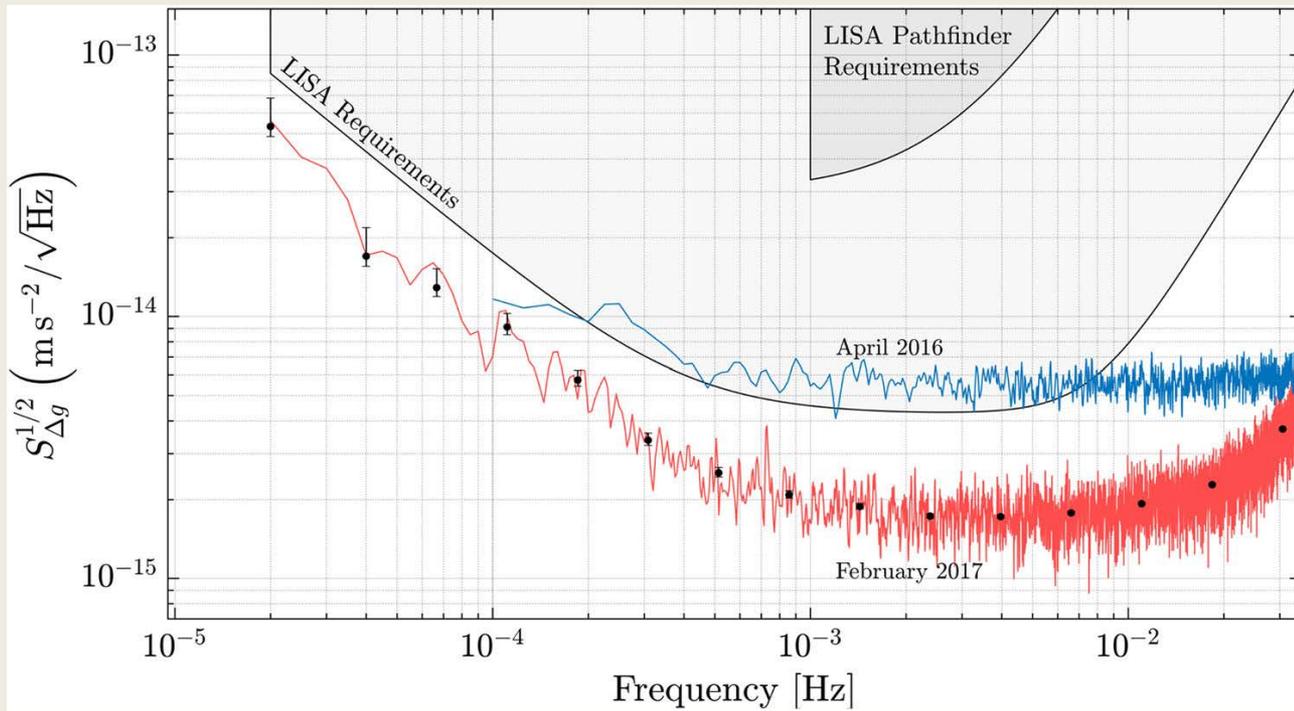


Launched 12/03/2015  
At L1, masses released  
Passed acceleration tests  
Next, thruster tests

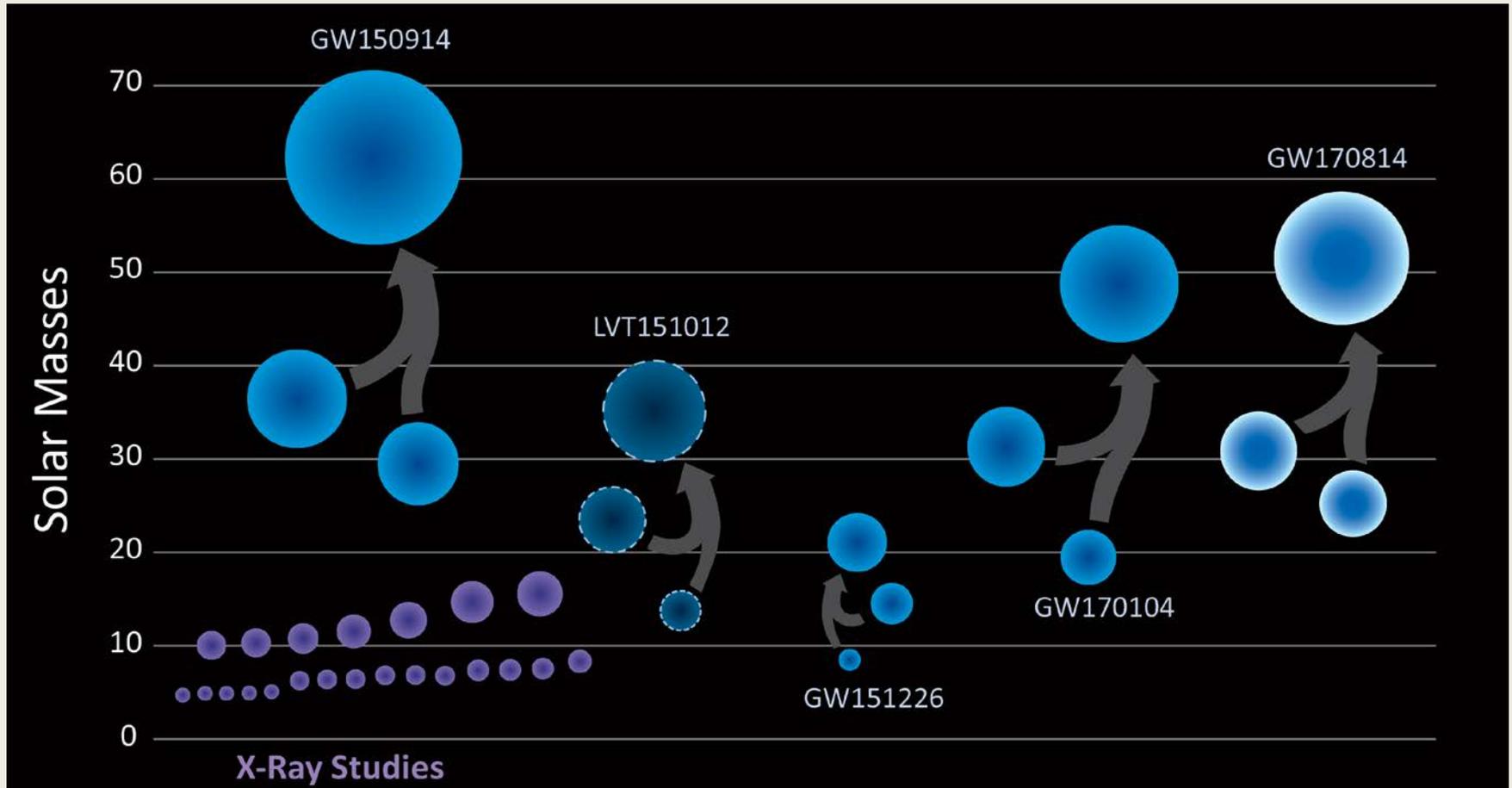


**iABG**  
**lisa pathfinder**  
**AIRBUS** DEFENCE & SPACE  
**esa**  
WEIGHT EMPTY 7700 kg  
MAXIMUM GROSS WEIGHT 2500 kg SWL 2500 kg  
DIMENSIONS: L x W x H = 6467 x 2884 x 3302 mm (25 050 in)  
HANDLE WITH CARE  
DO NOT DROP  
IF A REPRESENTATIVE OF QUALITY CONTROL  
FIND IN ACCORDANCE WITH OPERATING INSTRUCTIONS  
DO NOT OPEN IN ANY CONDITIONS WHICH MAY CAUSE  
CORROSION TO OCCUR ON THE PACKAGED EQUIPMENT  
➔ ONLY LABORATORY USE  
➔ CHD LAB/INT-101





# “Solar Mass” Black Holes



Credit: LIGO/Caltech/Sonoma State (Simonnet)