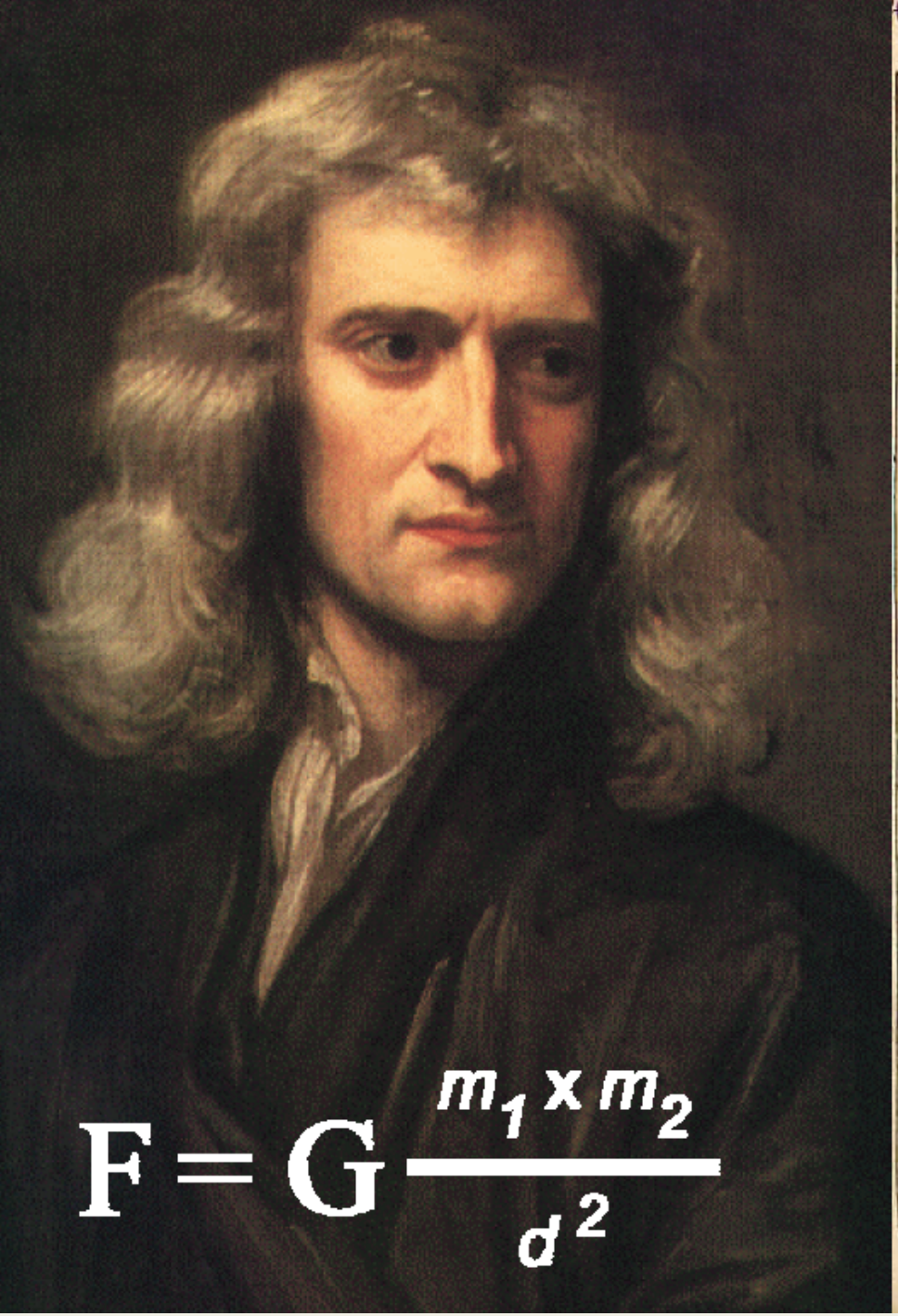
Probing the Universe with Gravitational Waves

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

TED^{X} Natick

Natick High School

January 26, 2019



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

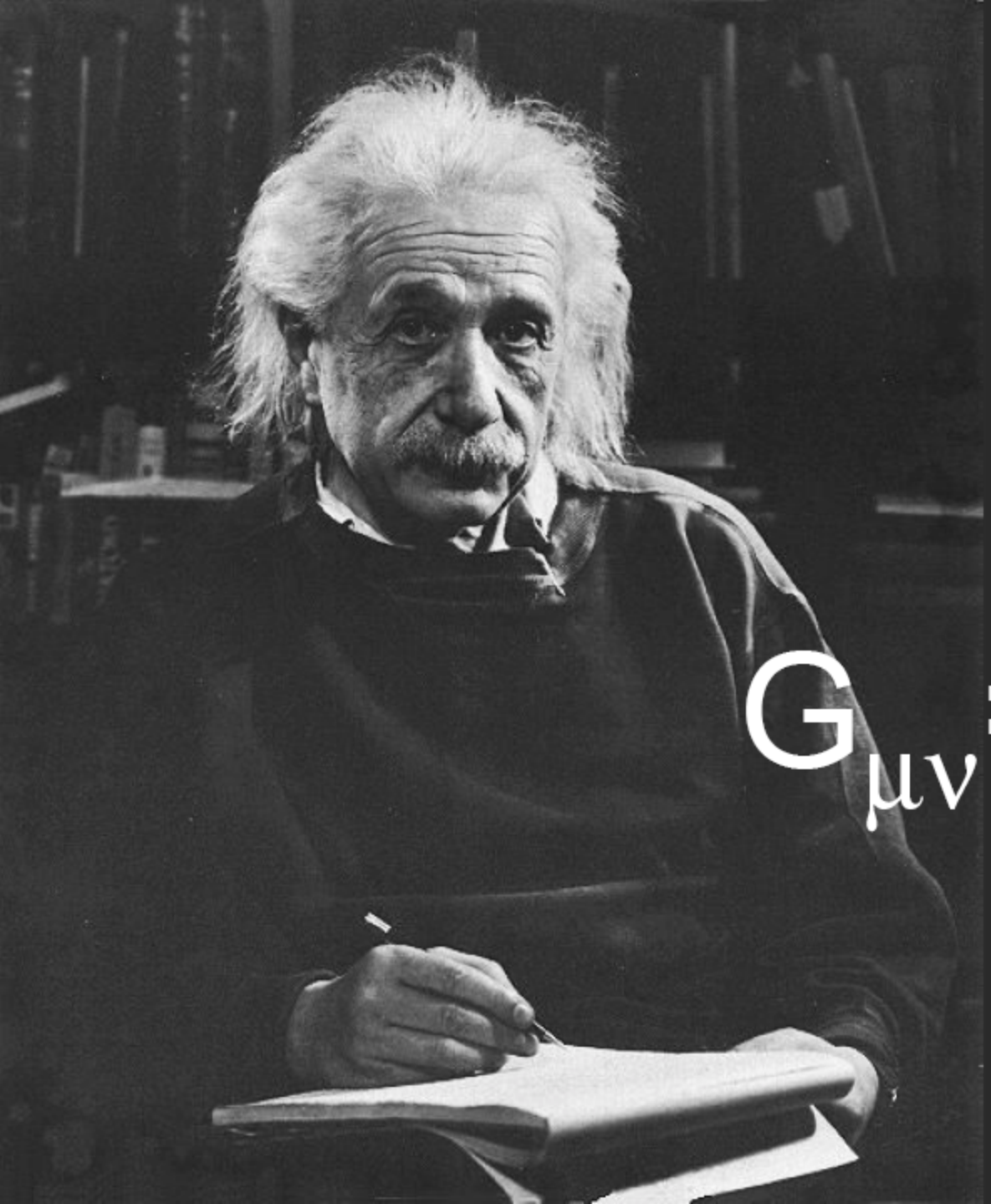
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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

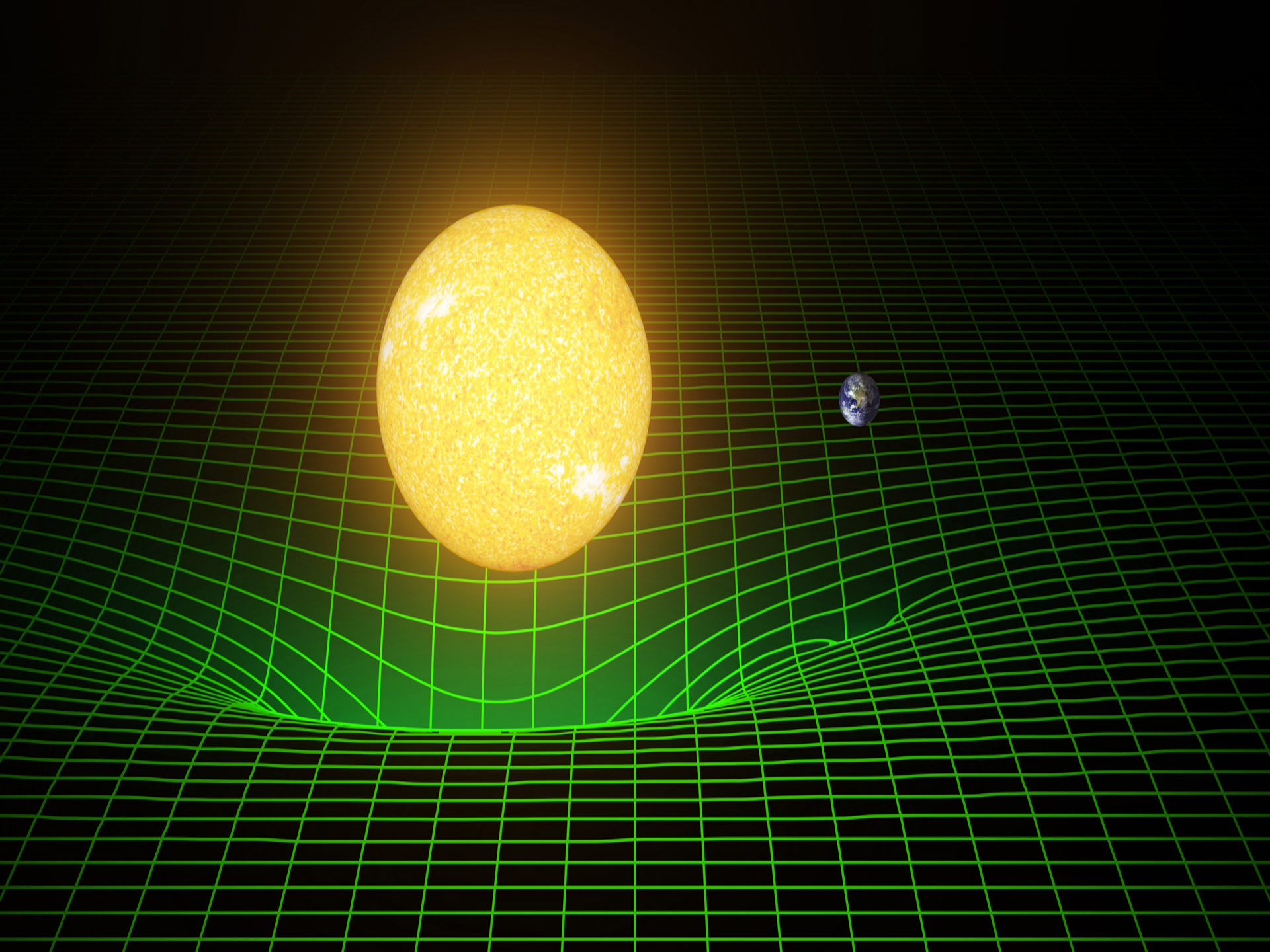
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

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



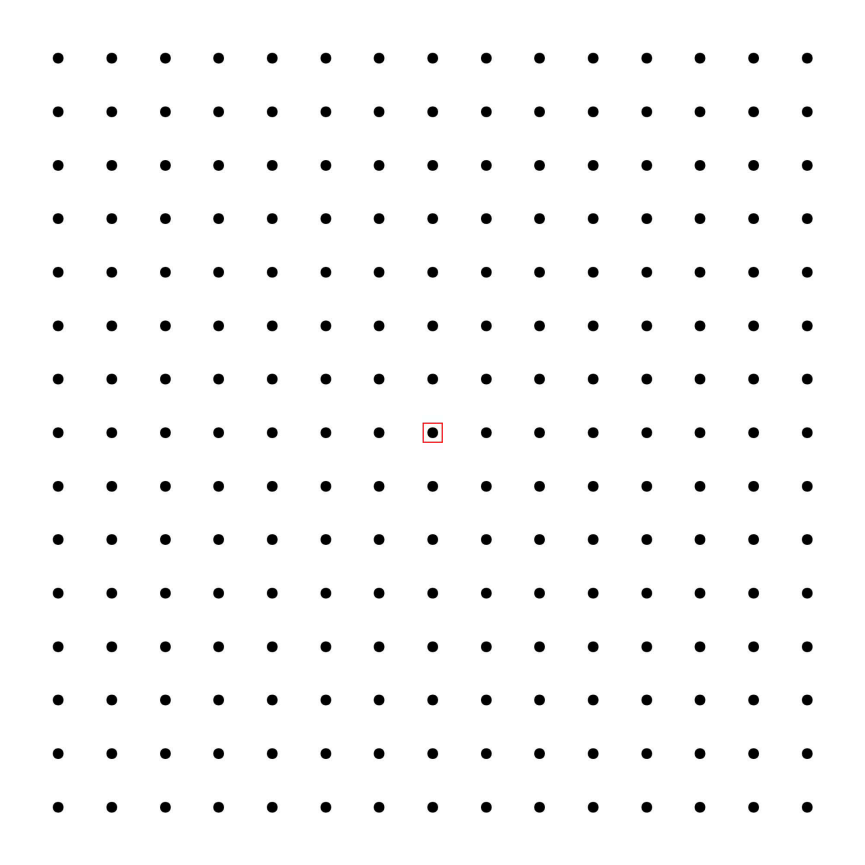
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



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)



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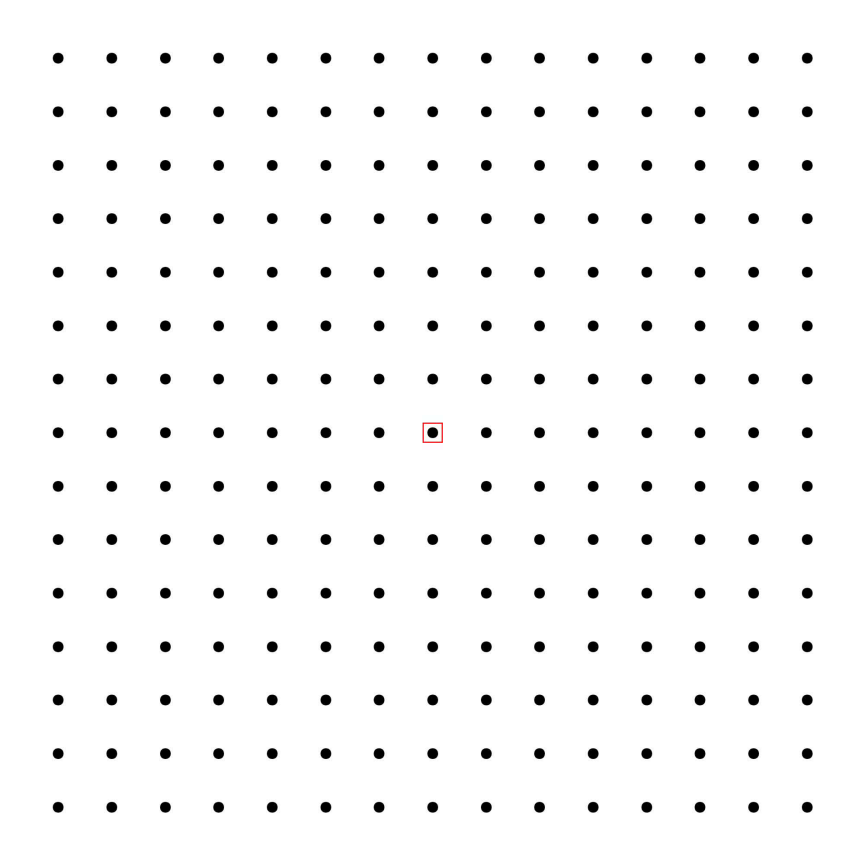
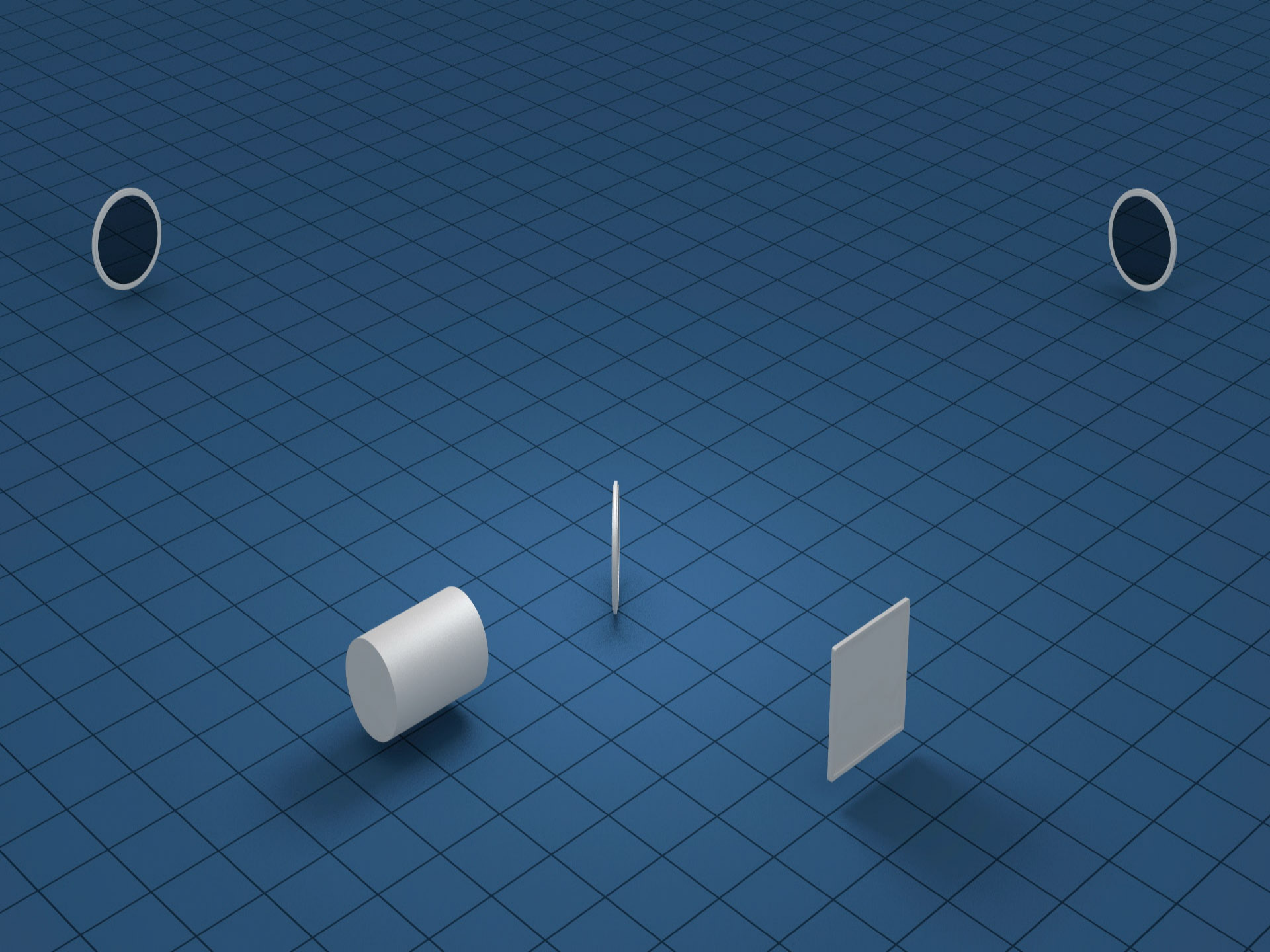
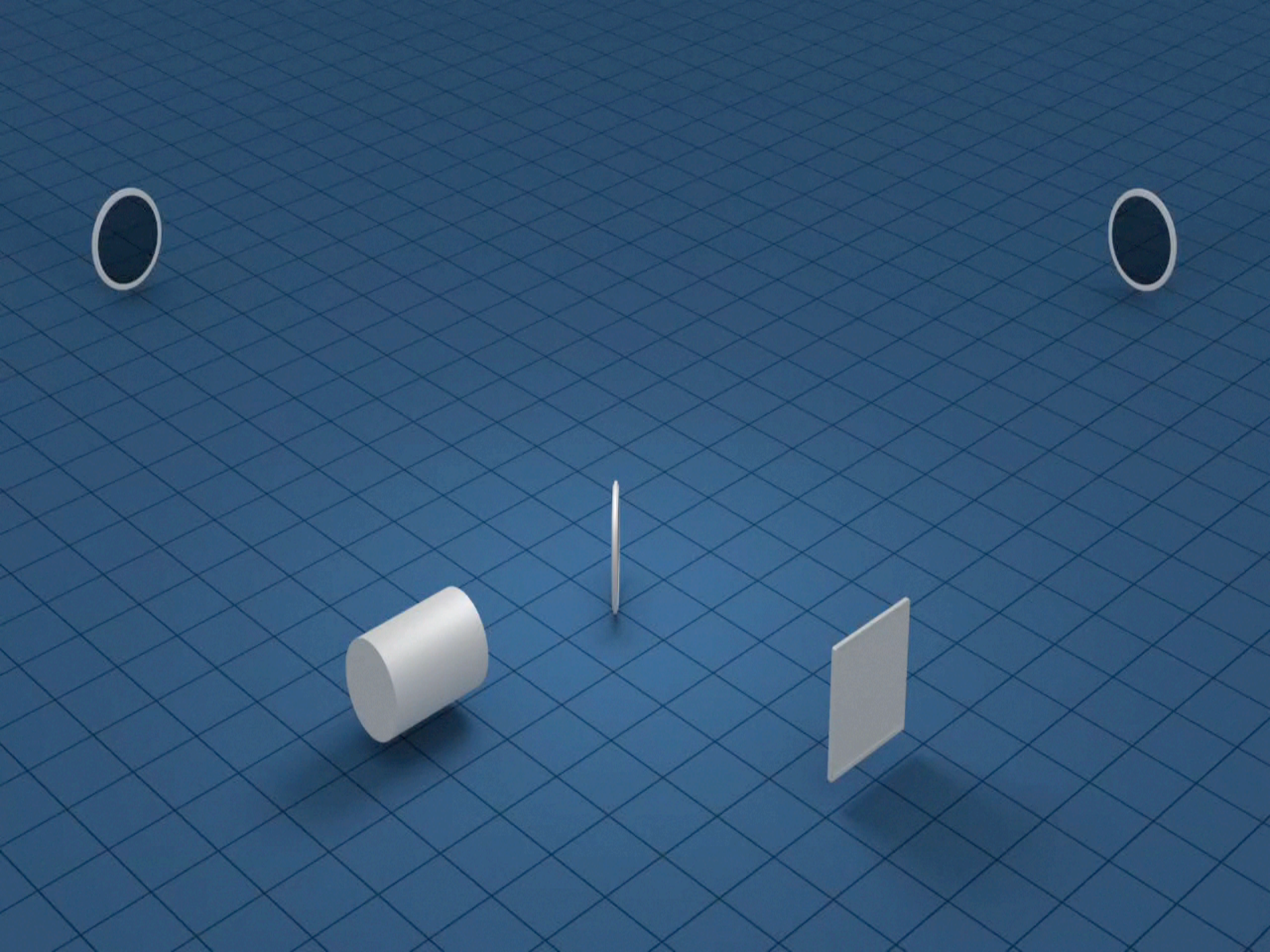






The measurement challenge

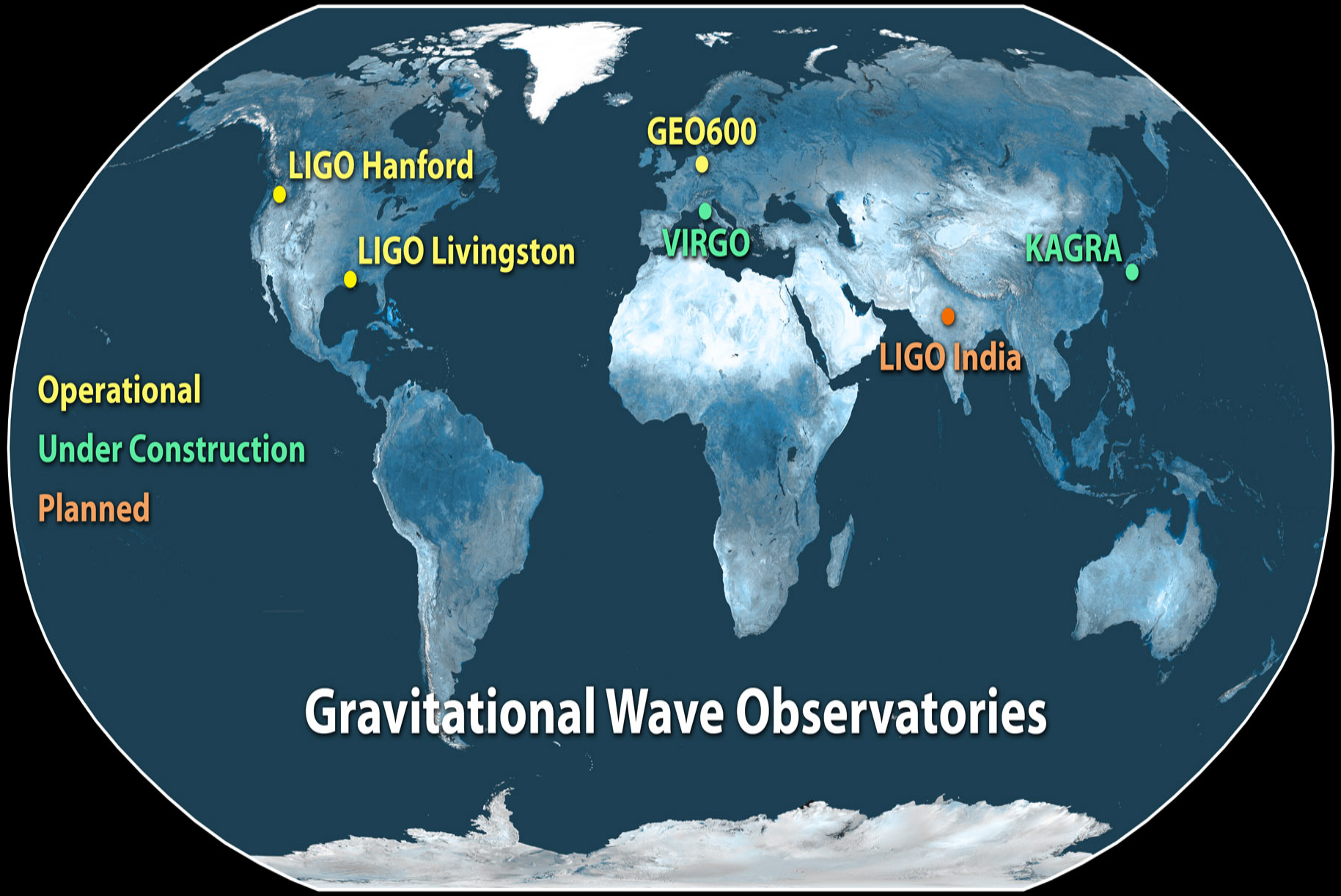
Kip Thorne

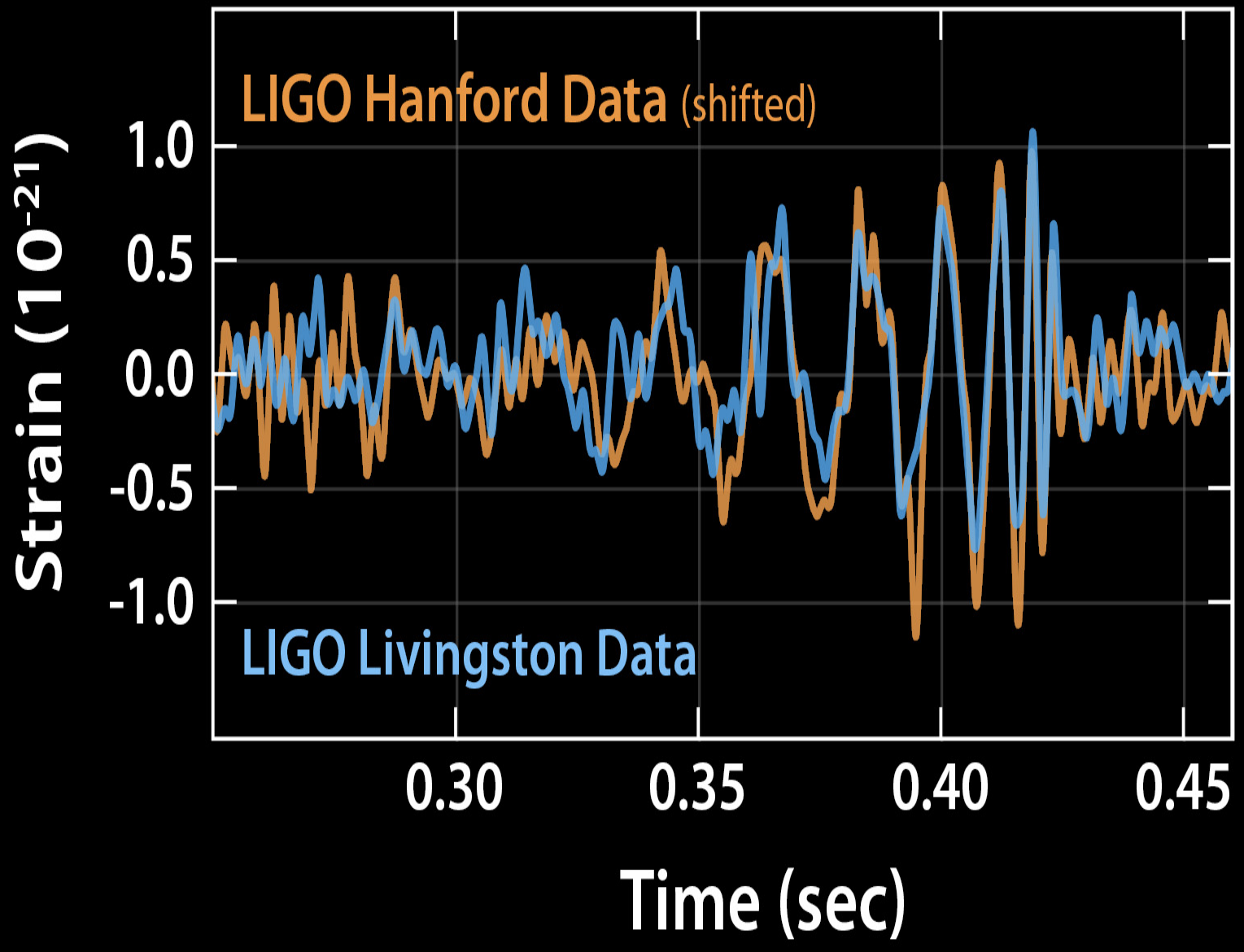
$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

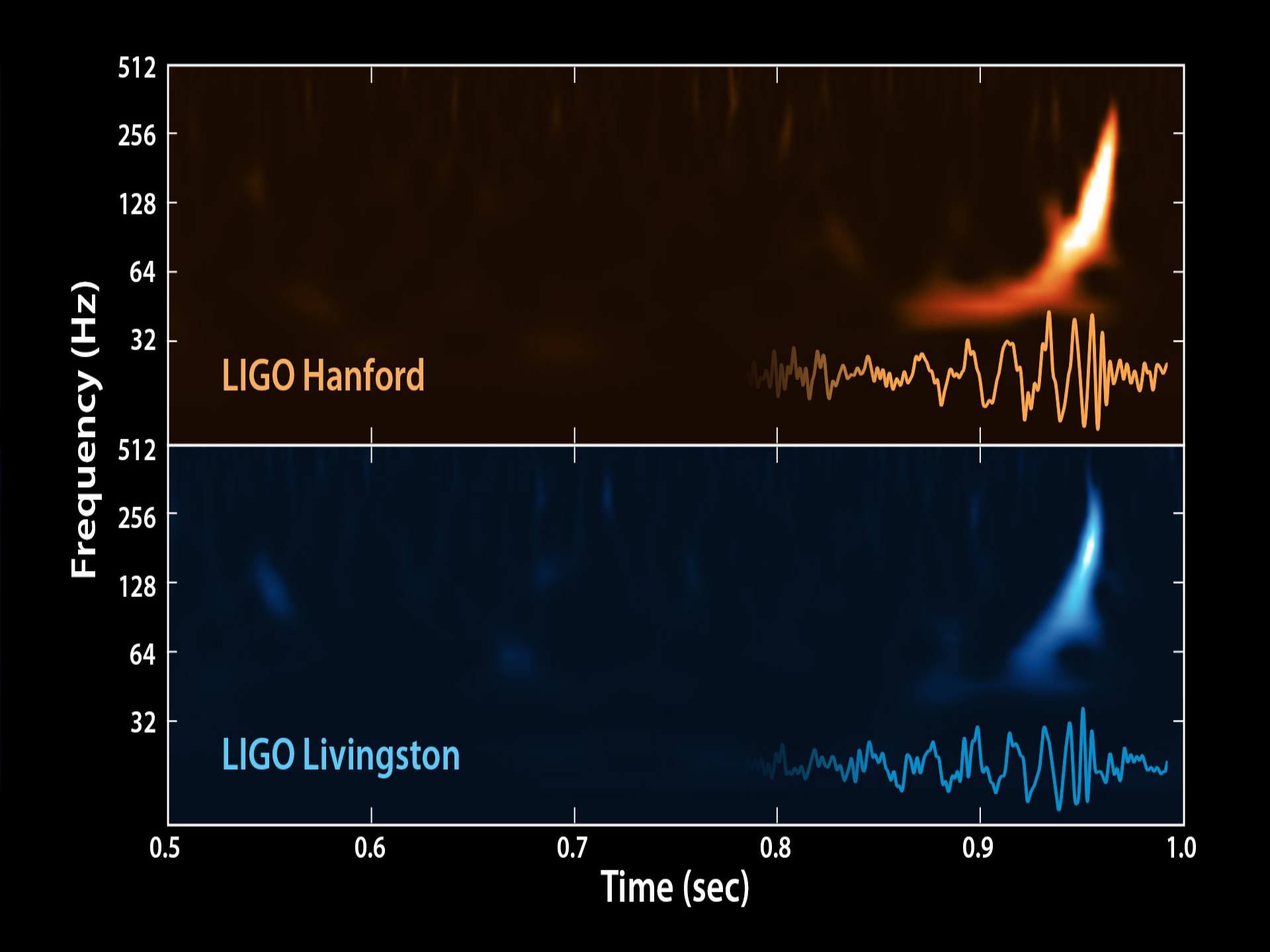
$$L = 4\text{km} \quad \Delta L \leq 4\text{x}10^{-18}\ \text{meters}$$

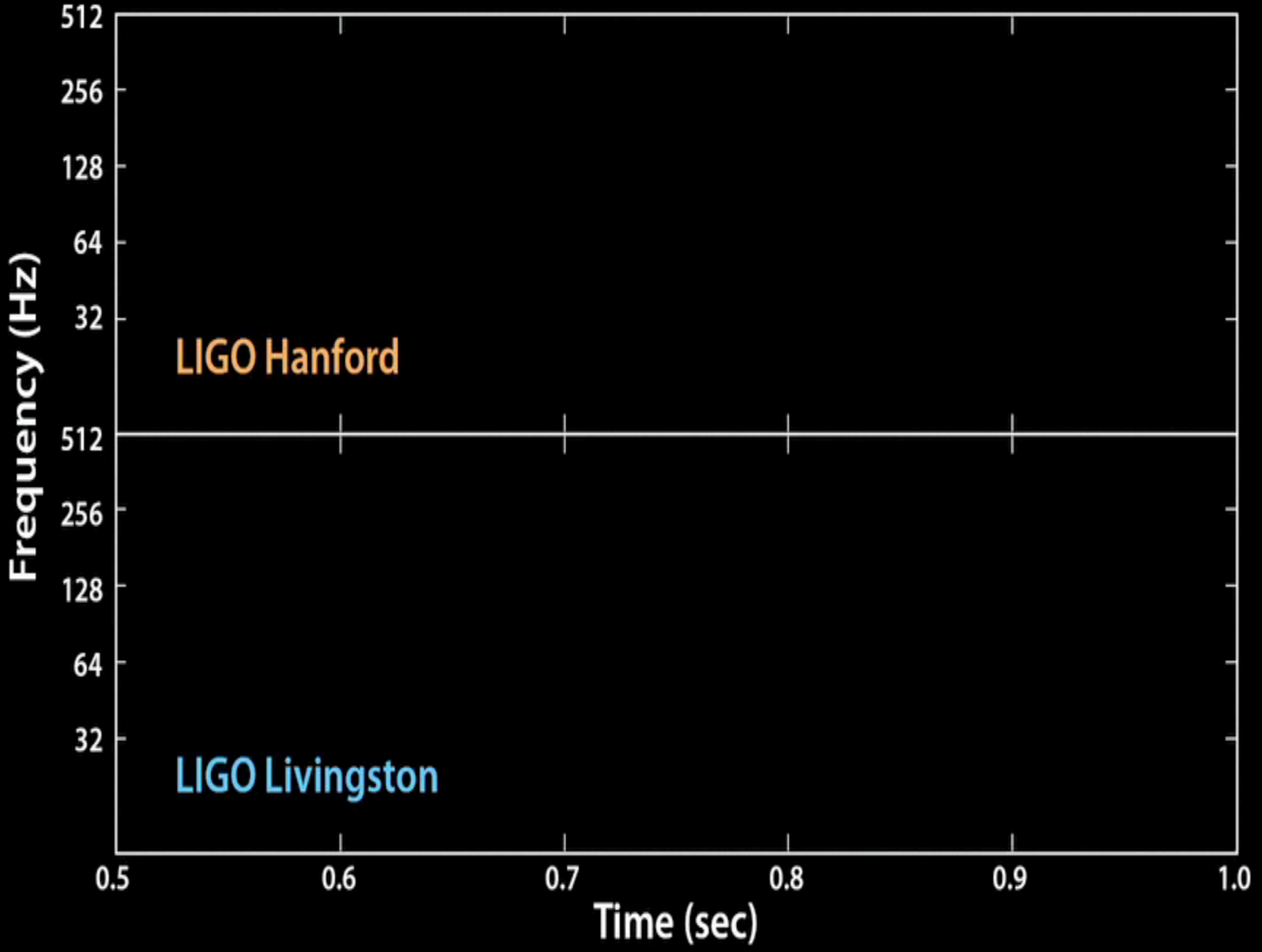
$$\Delta L \sim 10^{-12}\ \text{wavelength of light}$$

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


LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories


LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


512
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LIGO Hanford
512
256
128
64
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LIGO Livingston
Frequency (Hz)
0.5
0.6
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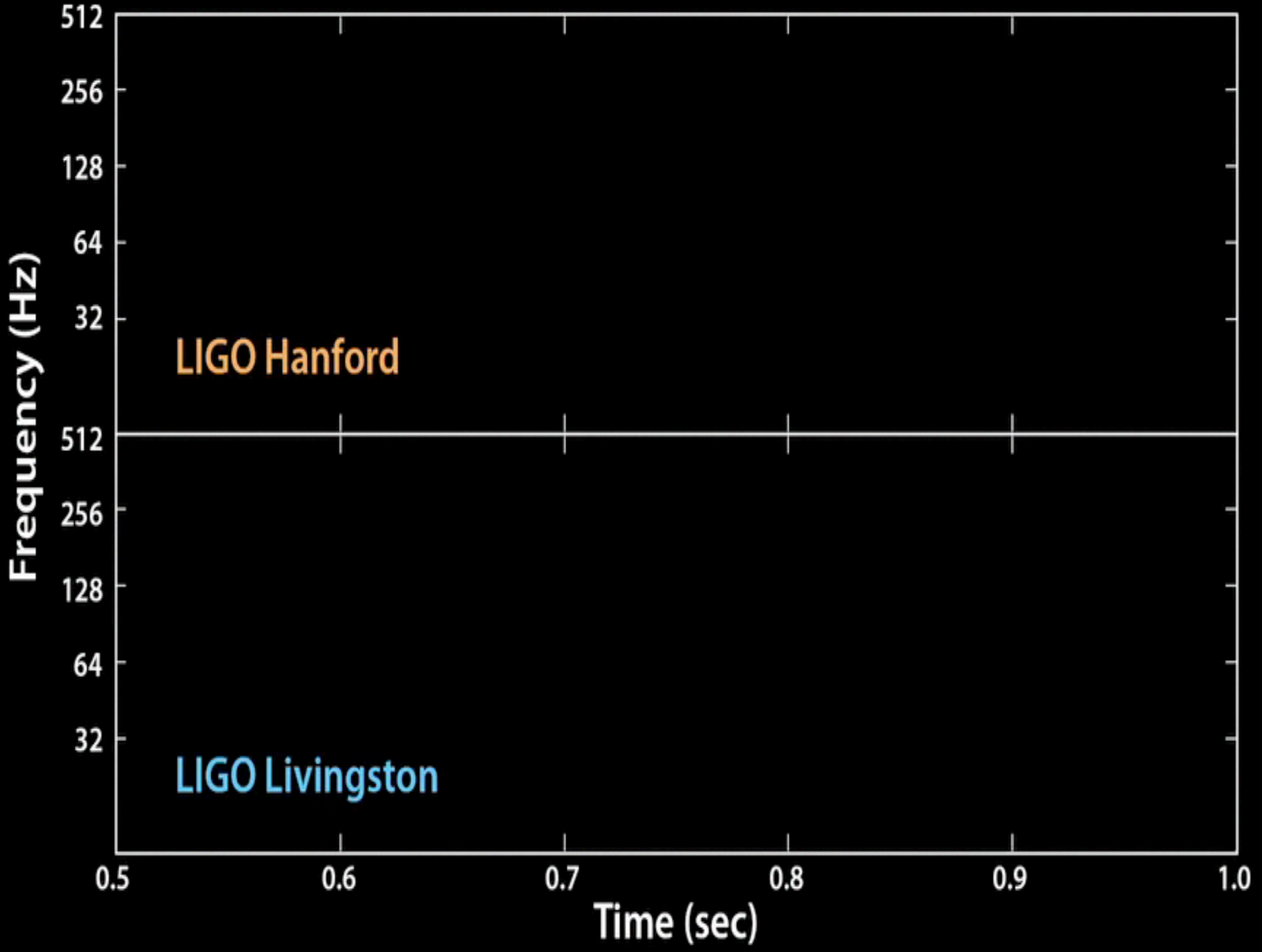
1.0
Time (sec)


512
256
128
64
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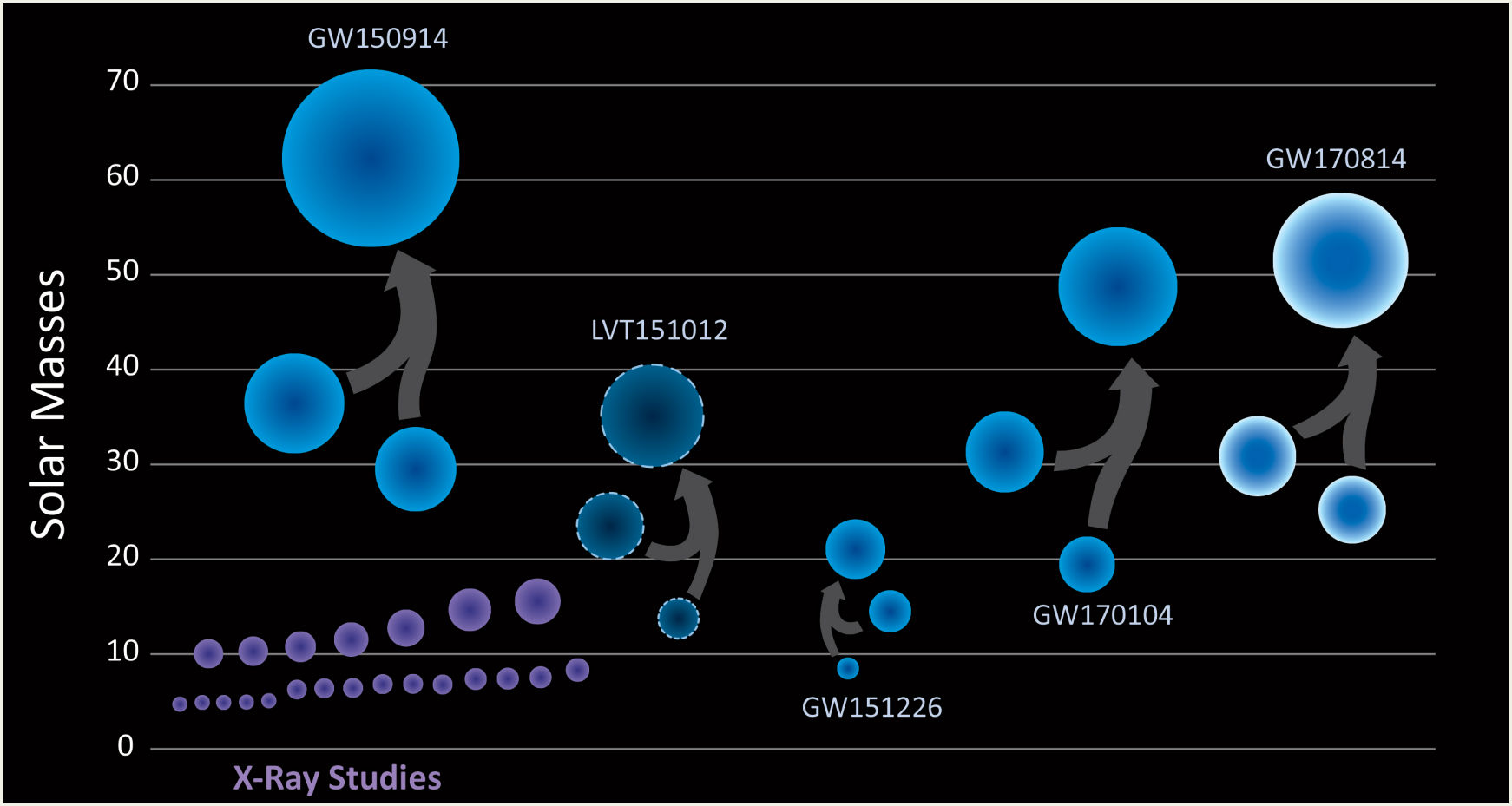
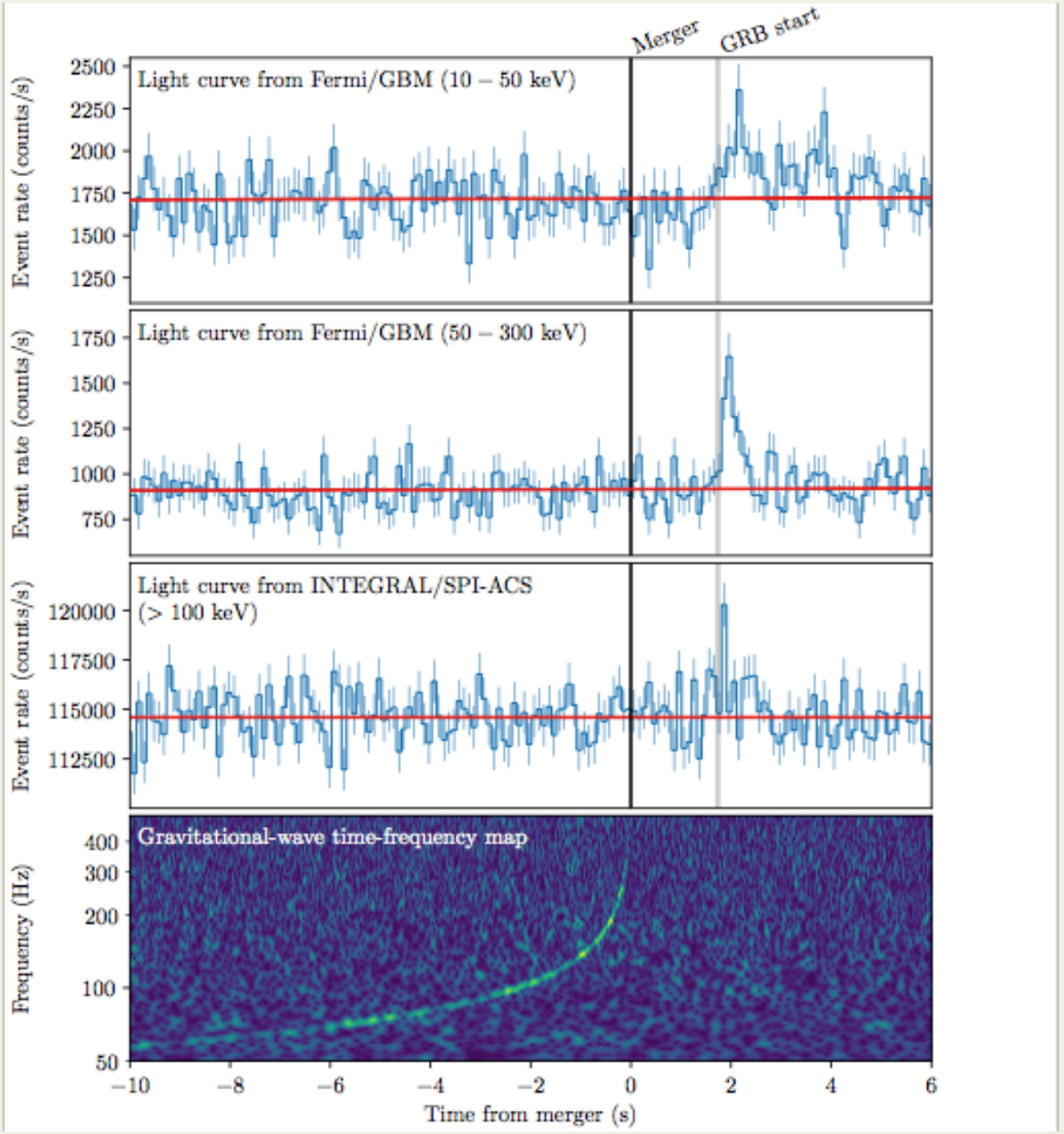
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

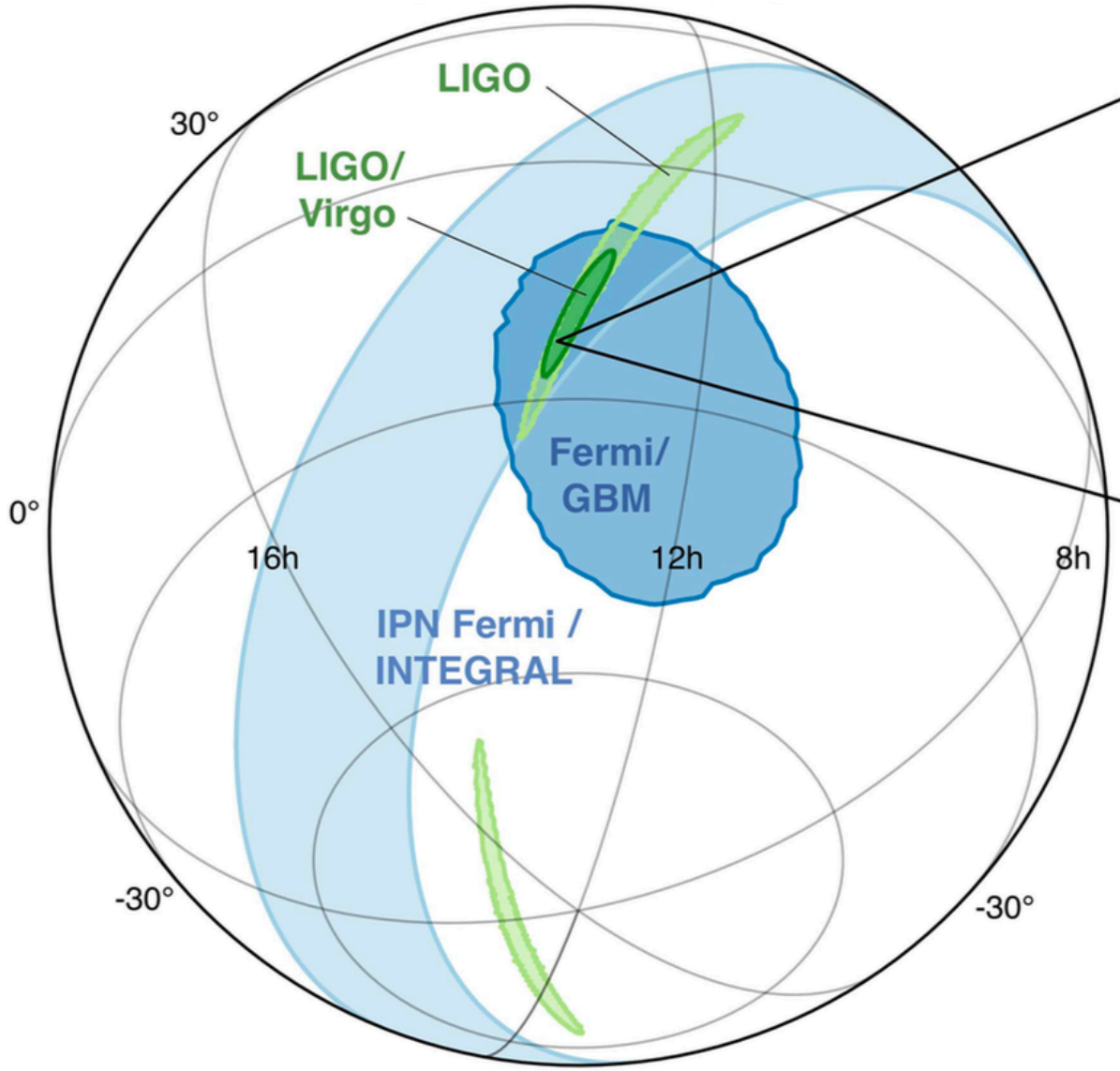
“Solar Mass” Black Holes

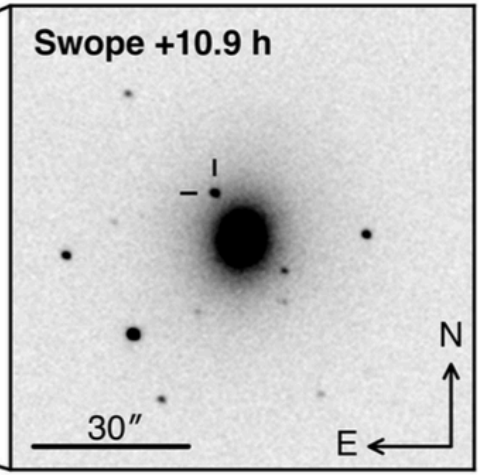


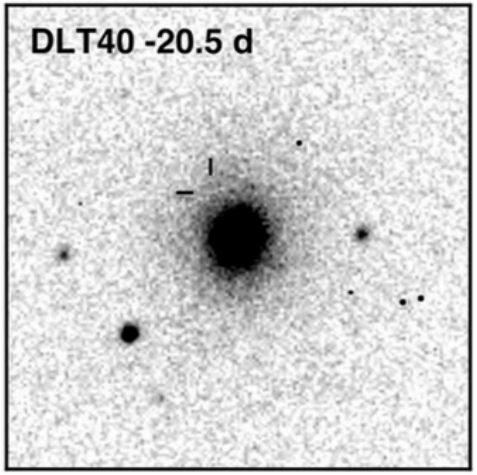
Credit: LIGO/Caltech/Sonoma State (Simonnet)

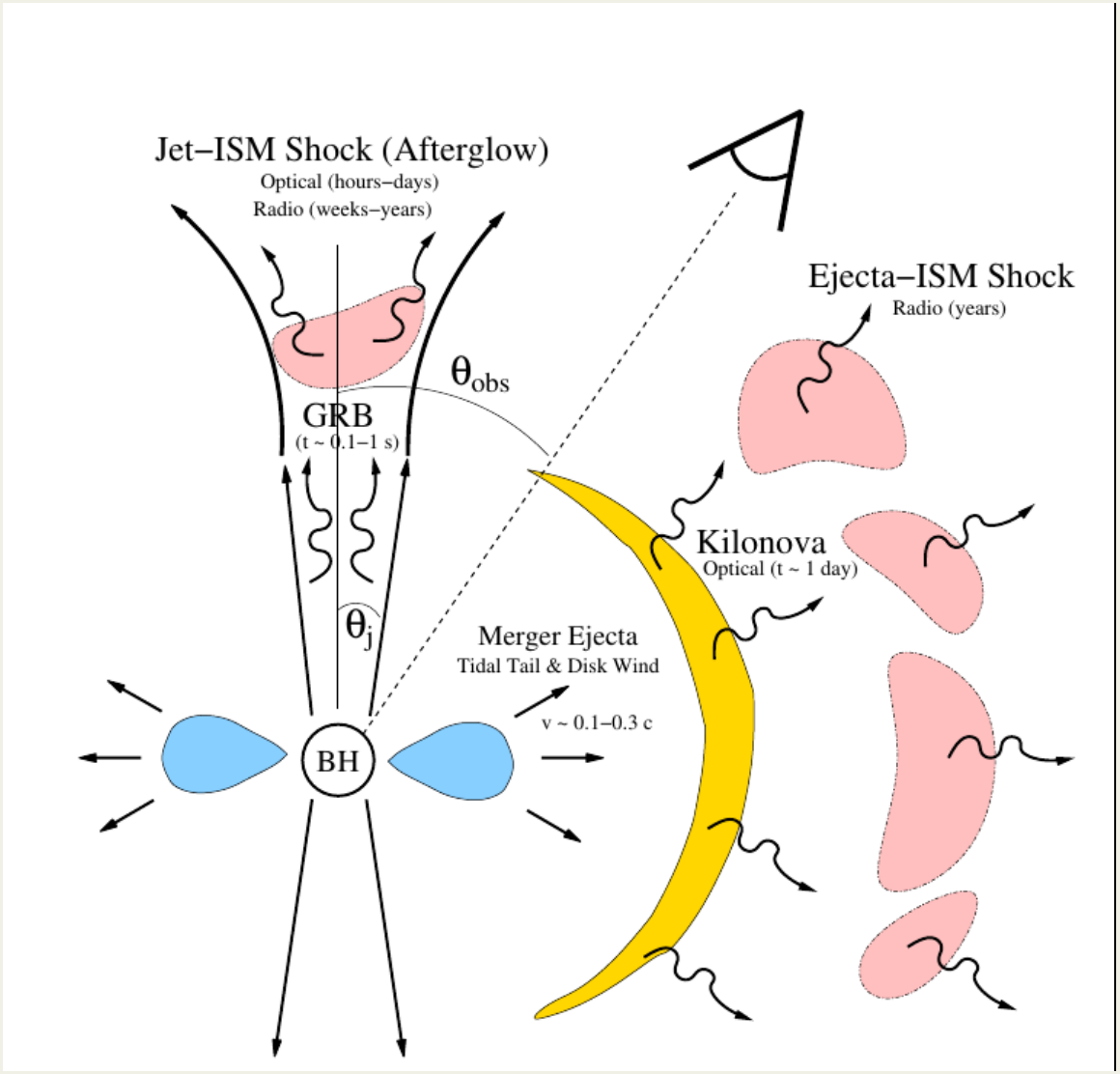

Merger
GRB start
Light curve from Fermi/GBM (10 – 50 keV)
Light curve from Fermi/GBM (50 – 300 keV)
Light curve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)

NGC4493


LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
16h
12h
8h
-30°


Swope +10.9 h
N
E
30″

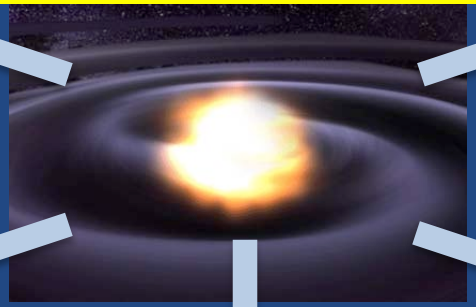

DLT40 -20.5 d


Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM Shock
Radio (years)
θobs
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
θj
Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c
BH

Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

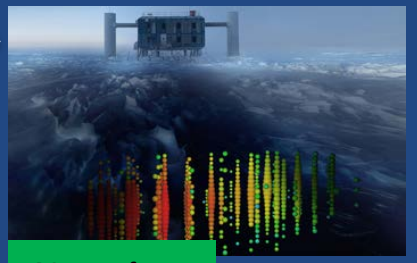
Binary Neutron Star Merger



X-rays/Gamma-rays

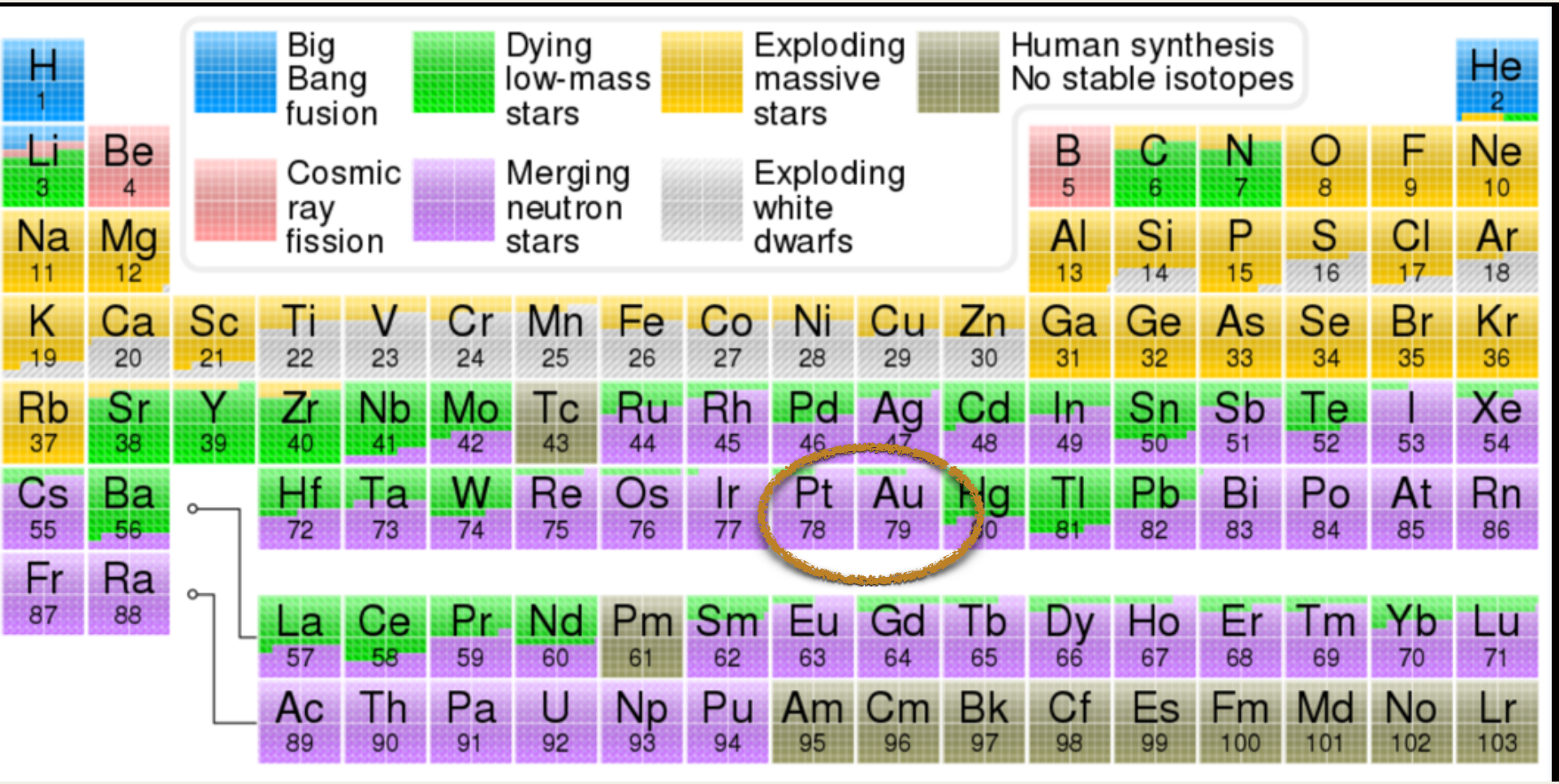
Visible/Infrared Light

Radio Waves



Neutrinos

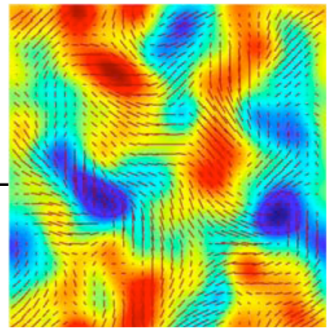
Origin of the elements



age of universe years hours minutes 1/10 to 1/1000 sec

Gravitational Wave Spectrum

Cosmic Microwave Background Polarization B Modes



Primeval gravitational waves from inflationary epoch

Measured at epoch of recombination z ~ 1000 and reionization z ~ 6

Pulsar Timing

Supermassive BH coalescences

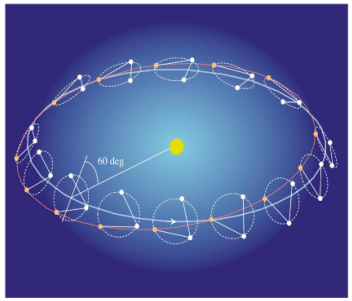
Isotropic GW background from unresolved sources

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

h

10^{-5}

10^{-10}

10^{-15}

10^{-20}

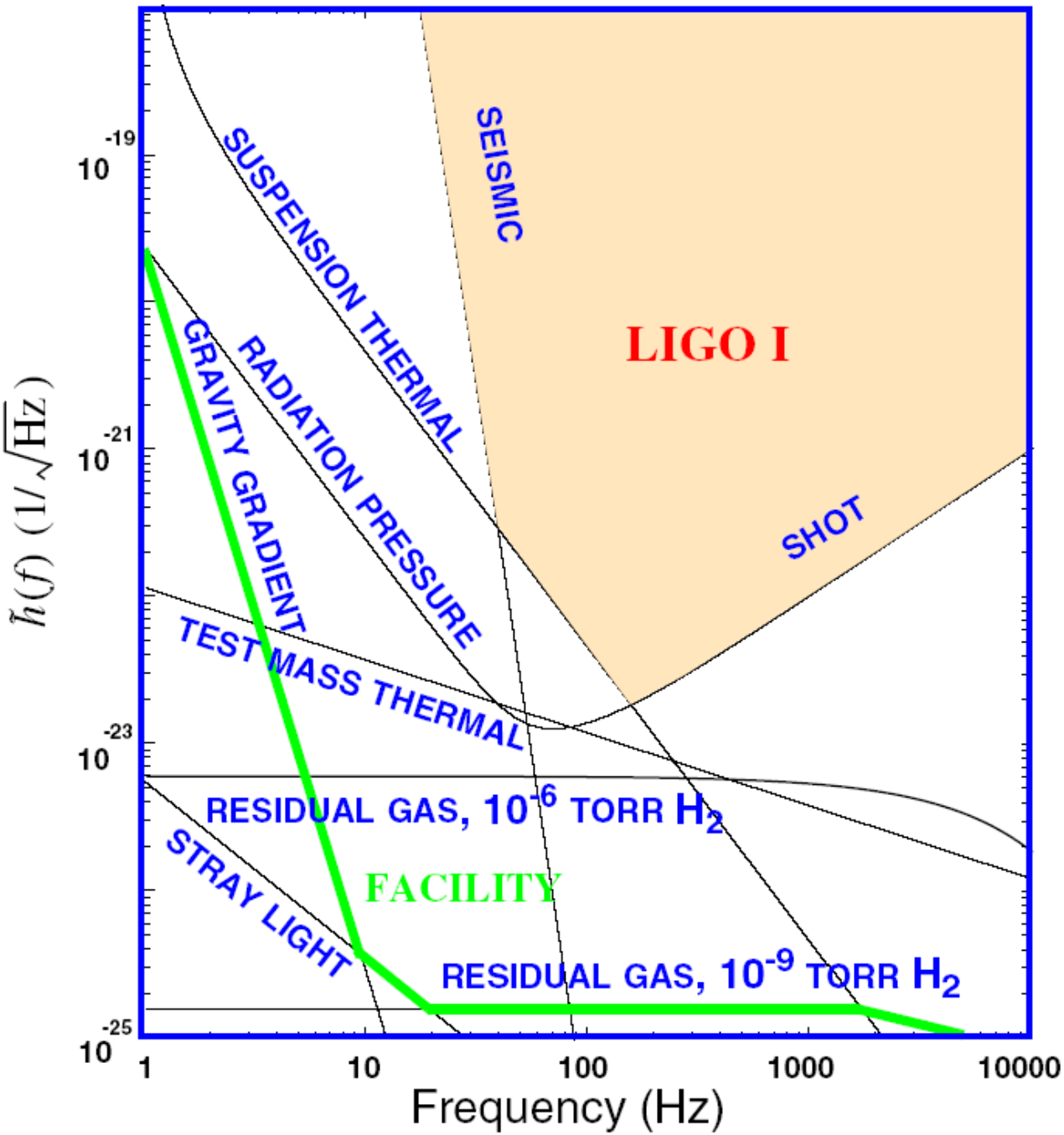
10^{-25}

10^{-16} 10^{-12} 10^{-8} 10^{-4} 10^{0} 10^{4}

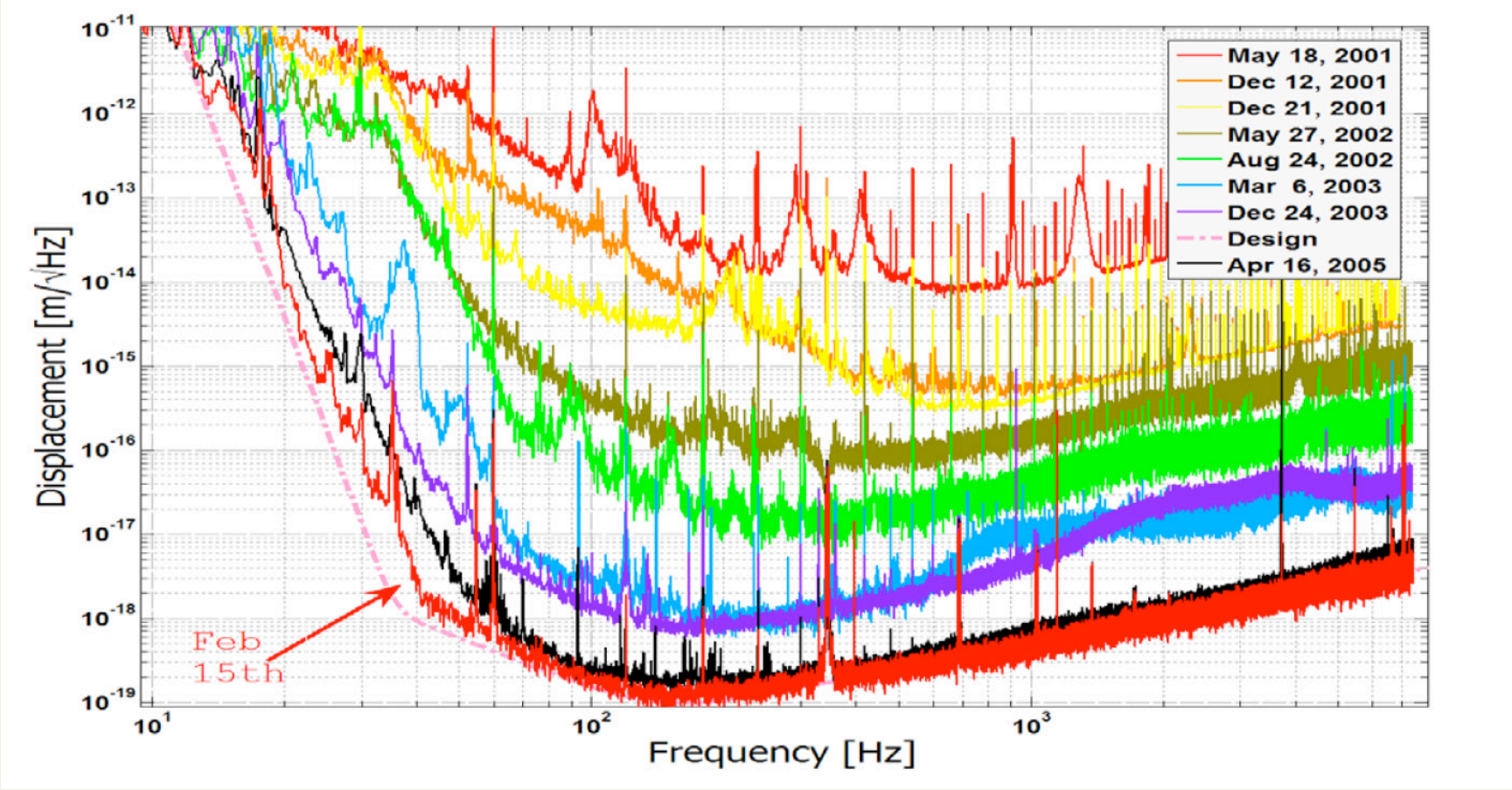
Frequency Hz

LIGO LIGO Scientific Collaboration

Spare slides after this one


LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
TEST MASS THERMAL
SHOT
RESIDUAL GAS, 10-6 TORR H2
FACILITY
STRAY LIGHT
RESIDUAL GAS, 10-9 TORR H2
h(f) (1/√Hz)
10-19
10-21
10-23
10-25
1
10
100
1000
10000
Frequency (Hz)

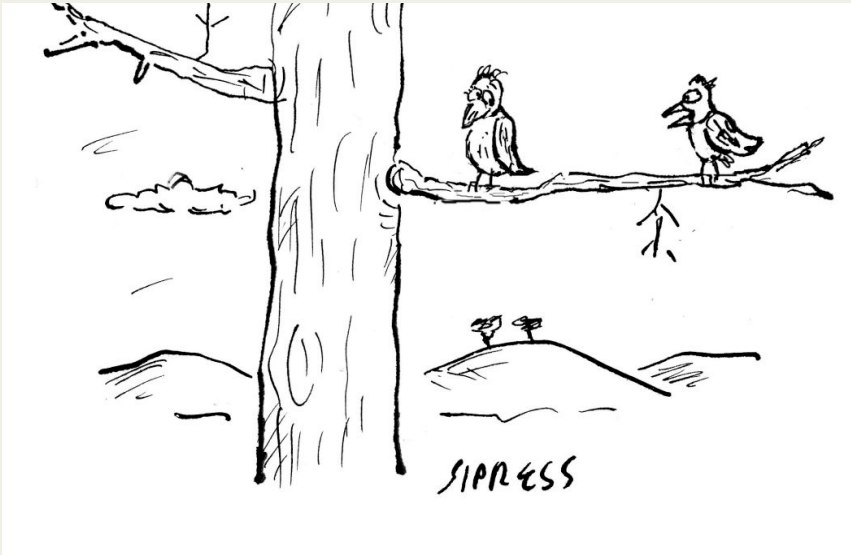
Evolution of the initial detector 2001 - 2006



A clean non-detection

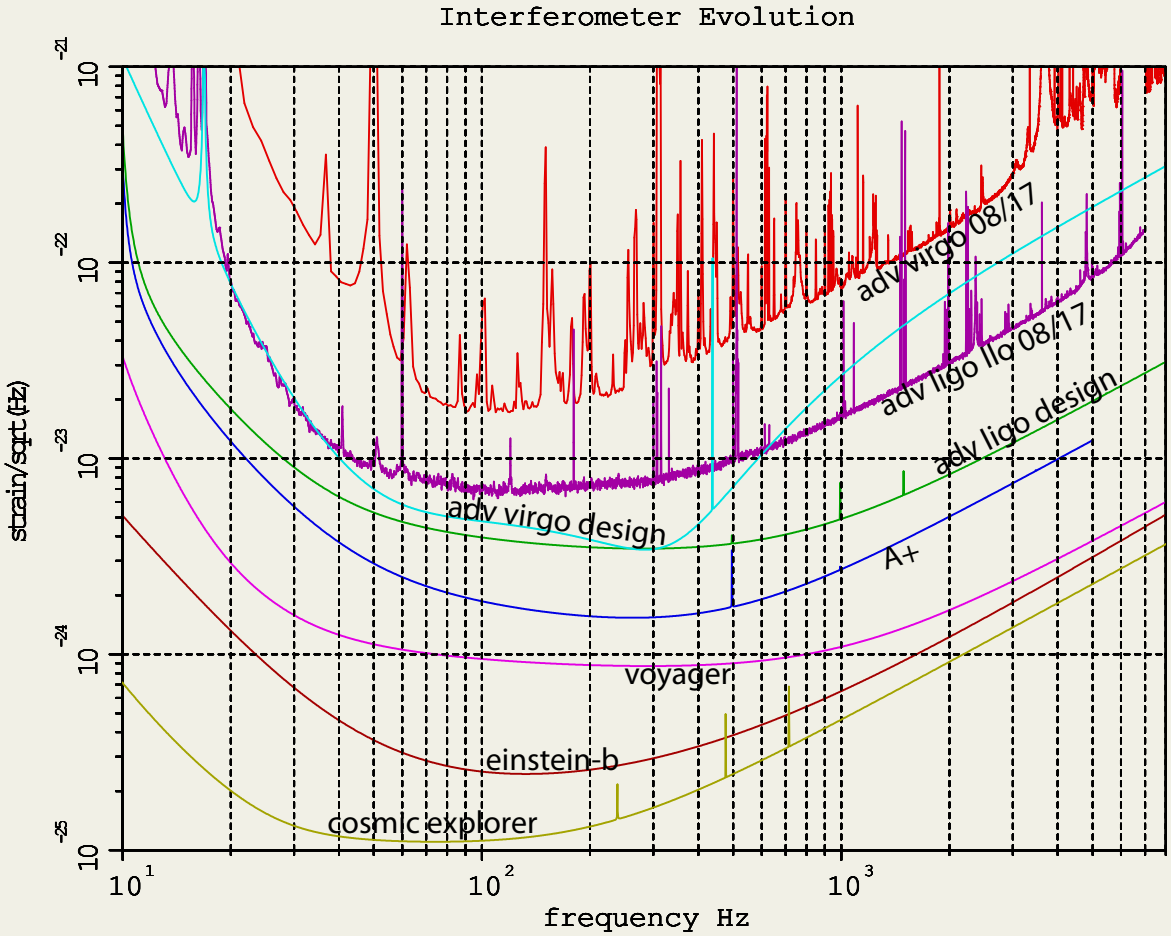
After Feb 11, 2016

Matt Weber

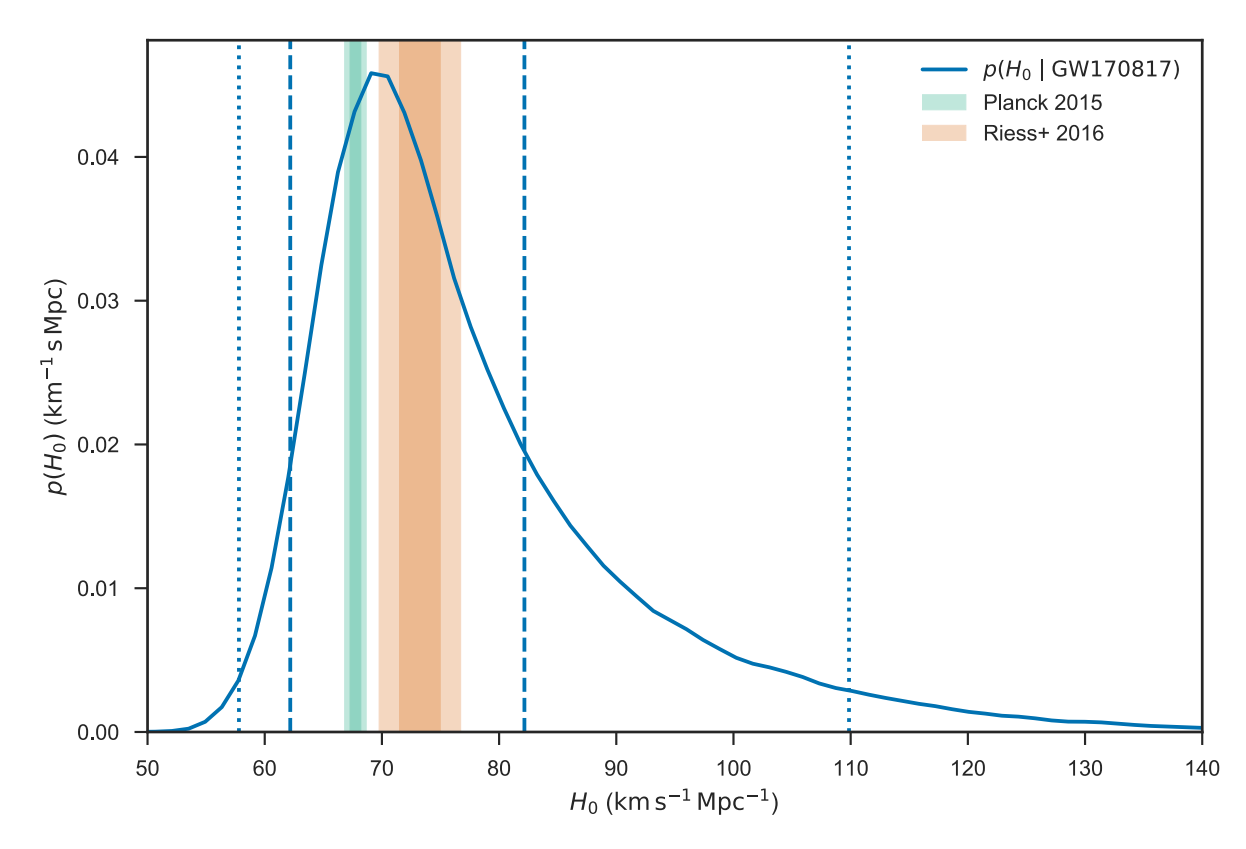


"Was that you I heard just now,
or was it two black holes colliding

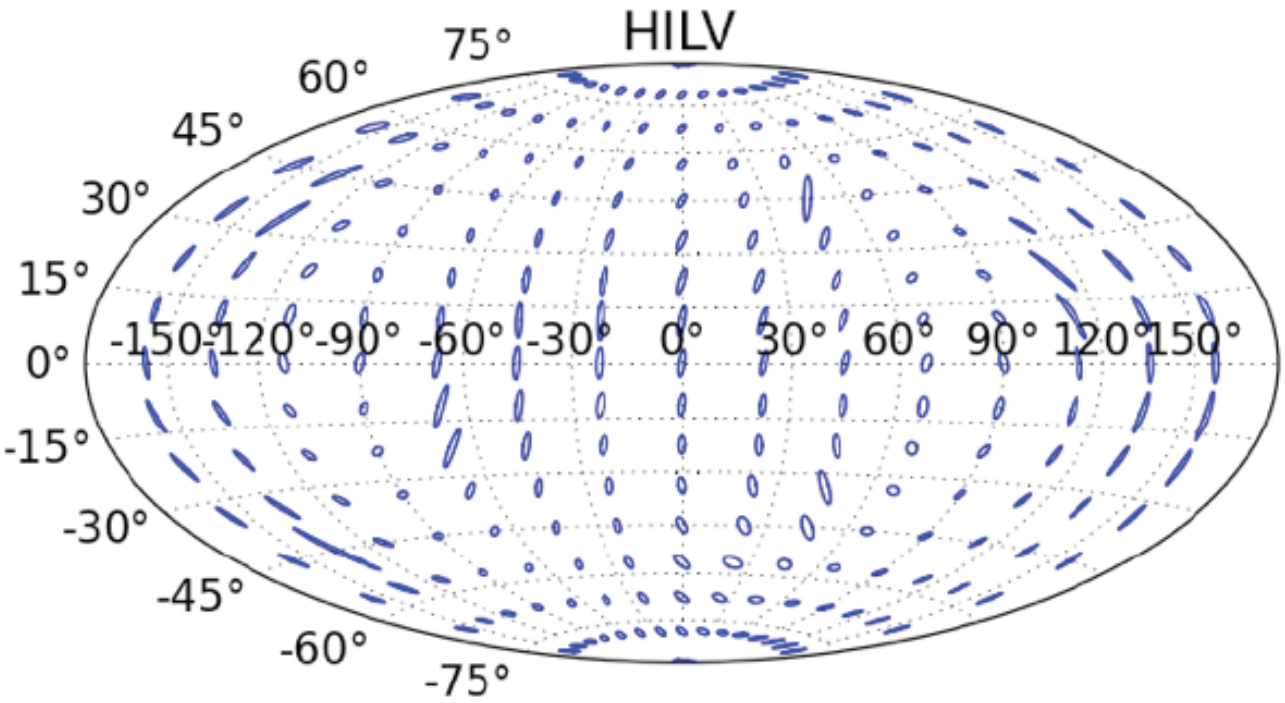
New Yorker Feb 12,, 2016


Interferometer Evolution
strain/sqrt(Hz)
frequency Hz
adv virgo 08/17
adv ligo llo 08/17
adv ligo design
adv virgo design
A+
voyager
einstein-b
cosmic explorer

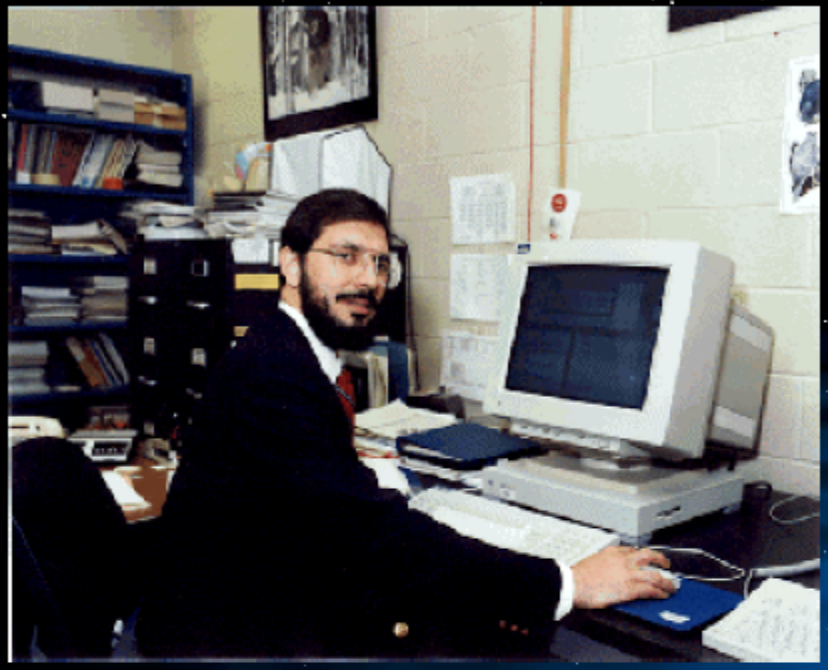
Hubble constant measurement: Galaxy z and distance from GW amplitude



Localization with more detectors



Fairhurst 2011



Russel A. Hulse

Joseph H.Taylor Jr

Source: www.NSF.gov

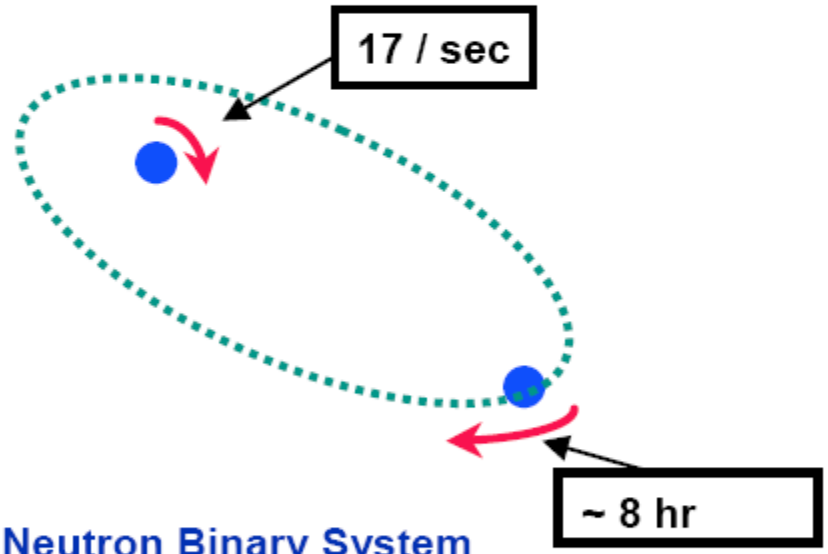
LIGO

Gravitational Waves

the evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



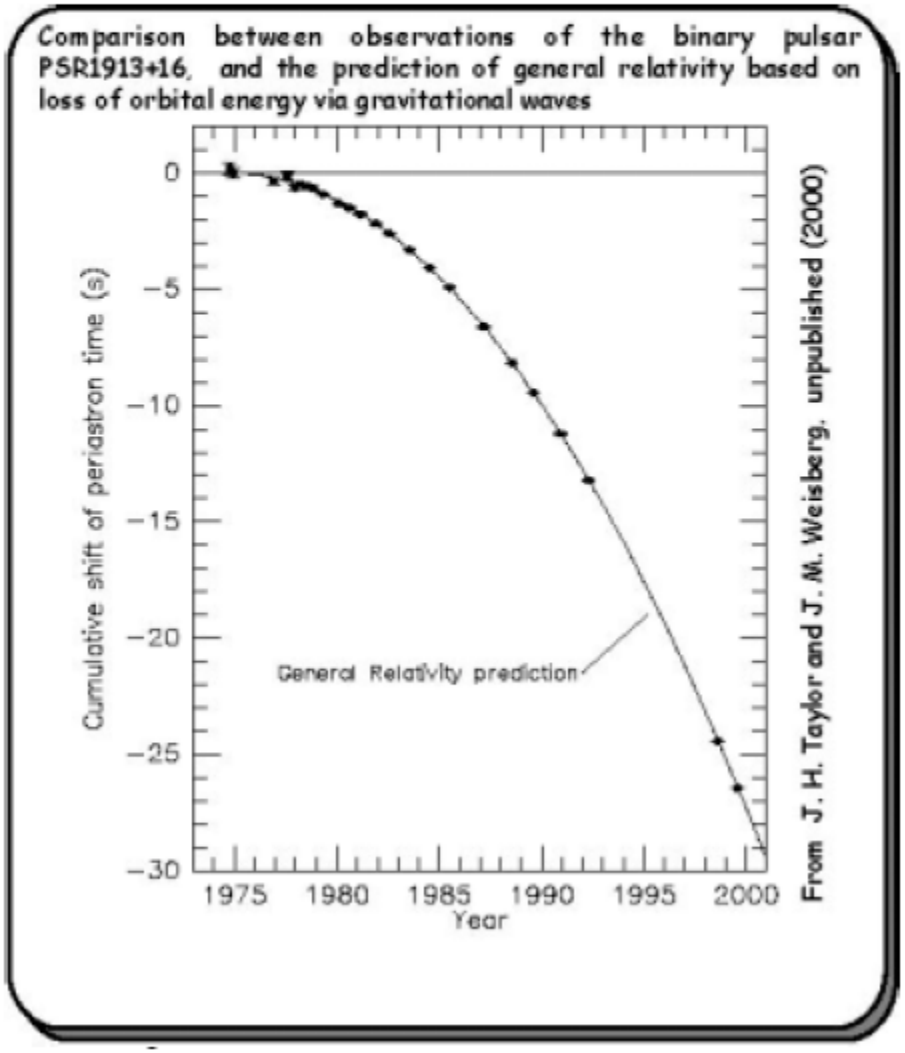
Neutron Binary System

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

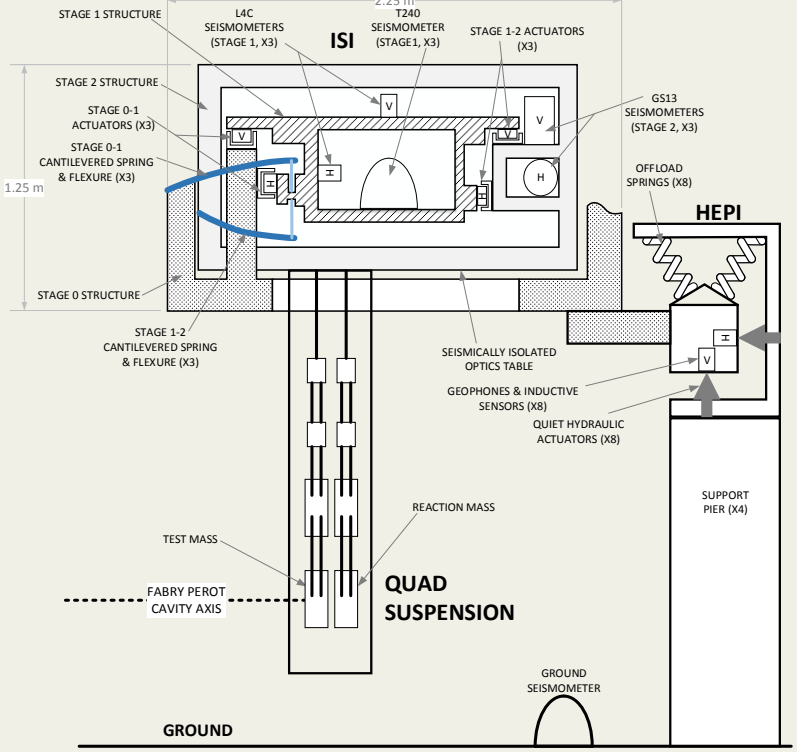
Prediction from general relativity

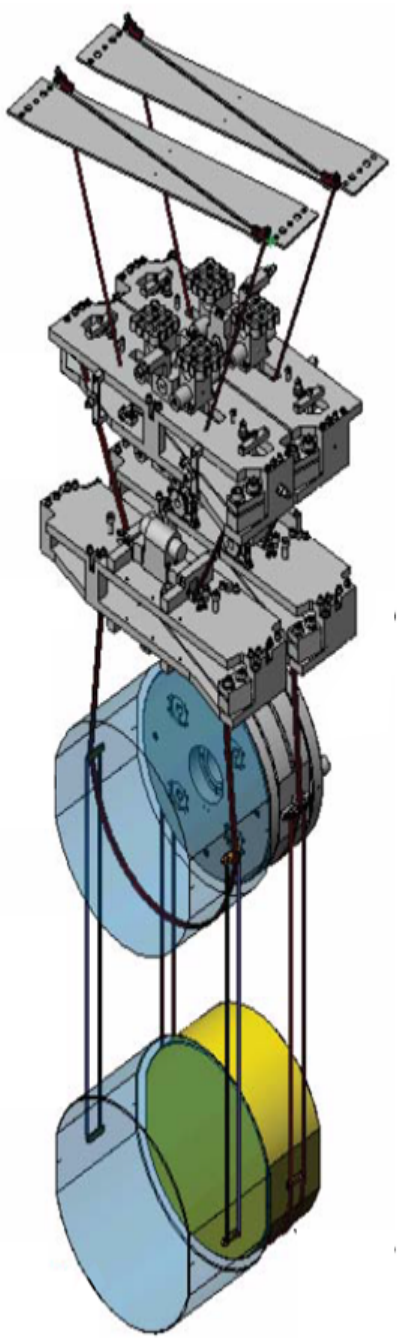
- spiral in by 3 mm/orbit
- rate of change orbital period

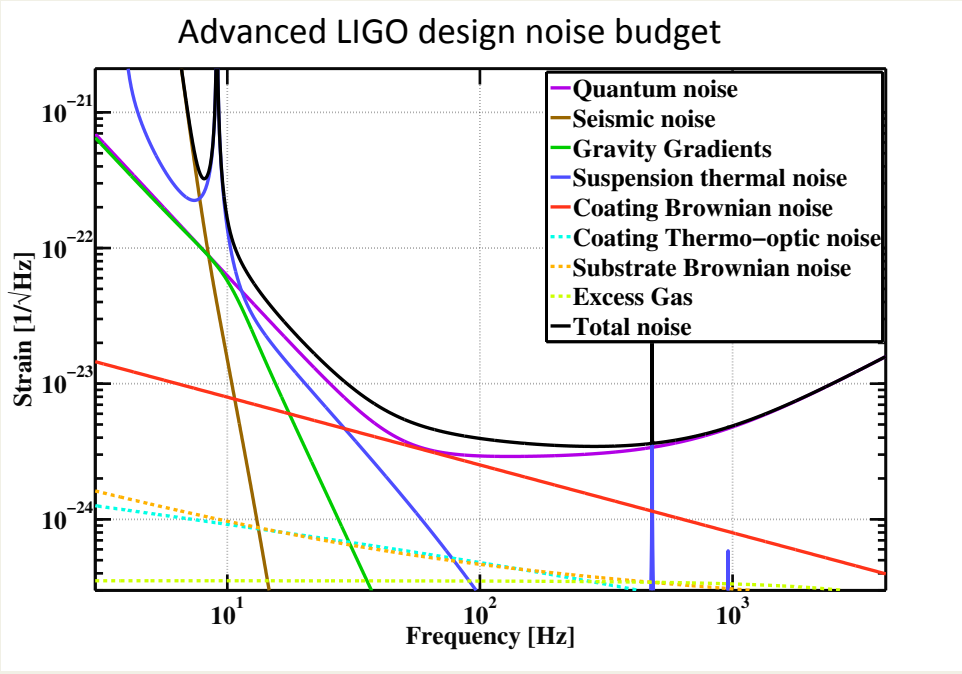
Emission of gravitational waves



Joseph Weber 1919-2000


STAGE 1 STRUCTURE
L4C SEISMOMETERS (STAGE 1, X3)
ISI
T240 SEISMOMETER (STAGE1, X3)
STAGE 1-2 ACTUATORS (X3)
STAGE 2 STRUCTURE
STAGE 0-1 ACTUATORS (X3)
STAGE 0-1 CANTILEVERED SPRING & FLEXURE (X3)
1.25 m
GS13 SEISMOMETERS (STAGE 2, X3)
OFFLOAD SPRINGS (X8)
HEPI
STAGE 0 STRUCTURE
STAGE 1-2 CANTILEVERED SPRING & FLEXURE (X3)
SEISMICALLY ISOLATED OPTICS TABLE
GEOPHONES & INDUCTIVE SENSORS (X8)
QUIET HYDRAULIC ACTUATORS (X8)
SUPPORT PIER (X4)
REACTION MASS
TEST MASS
FABRY PEROT CAVITY AXIS
QUAD SUSPENSION
GROUND SEISMOMETER
GROUND




Advanced LIGO design noise budget
Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Excess Gas
Total noise
Strain [1/√Hz]
Frequency [Hz]

LIGO

How Small is 10^{-18} Meter?

One meter, about 40 inches

÷10,000

Human hair, about 100 microns

÷100

Wavelength of light, about 1 micron

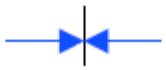
÷10,000

Atomic diameter, 10^{-10} meter

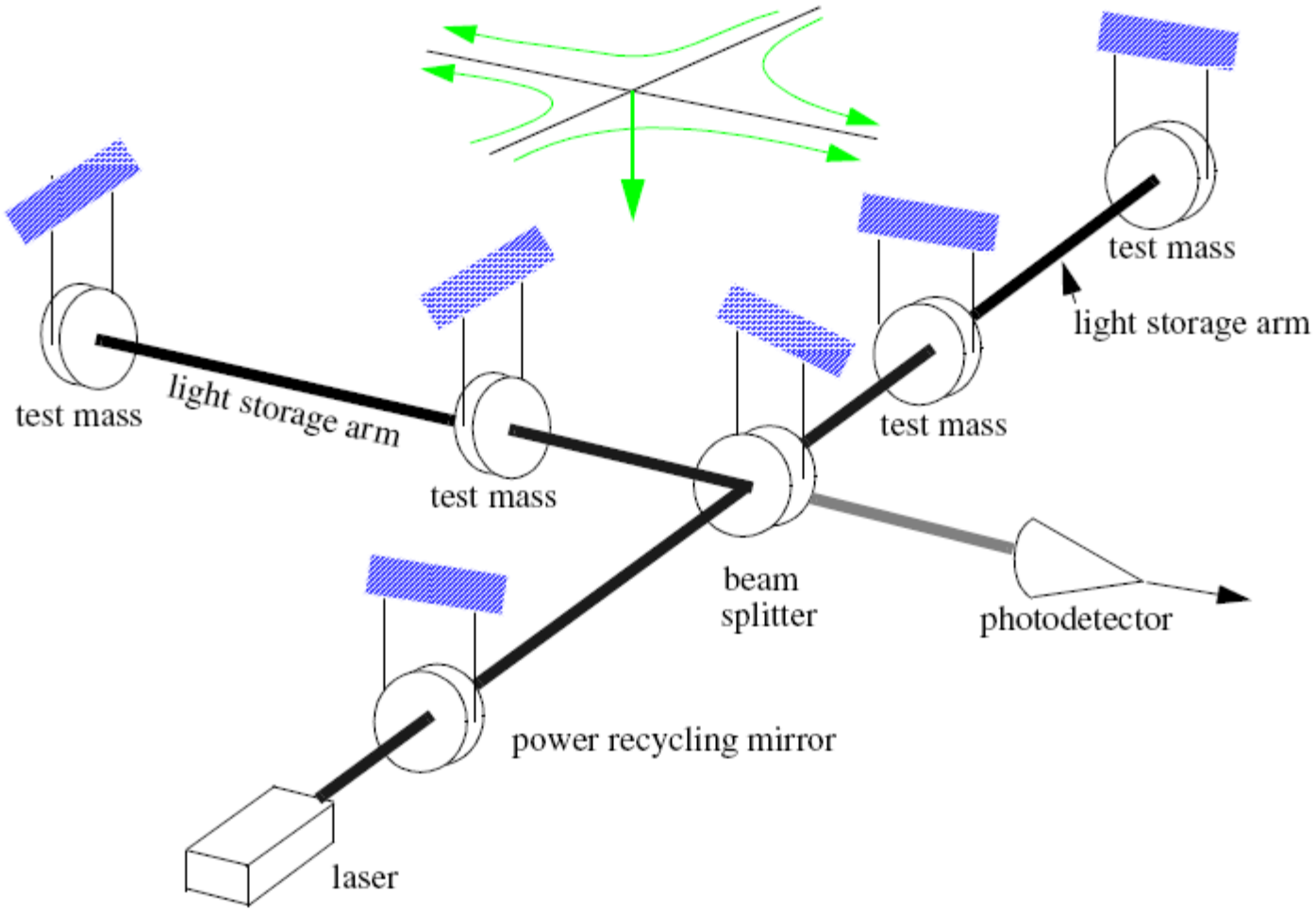
÷100,000

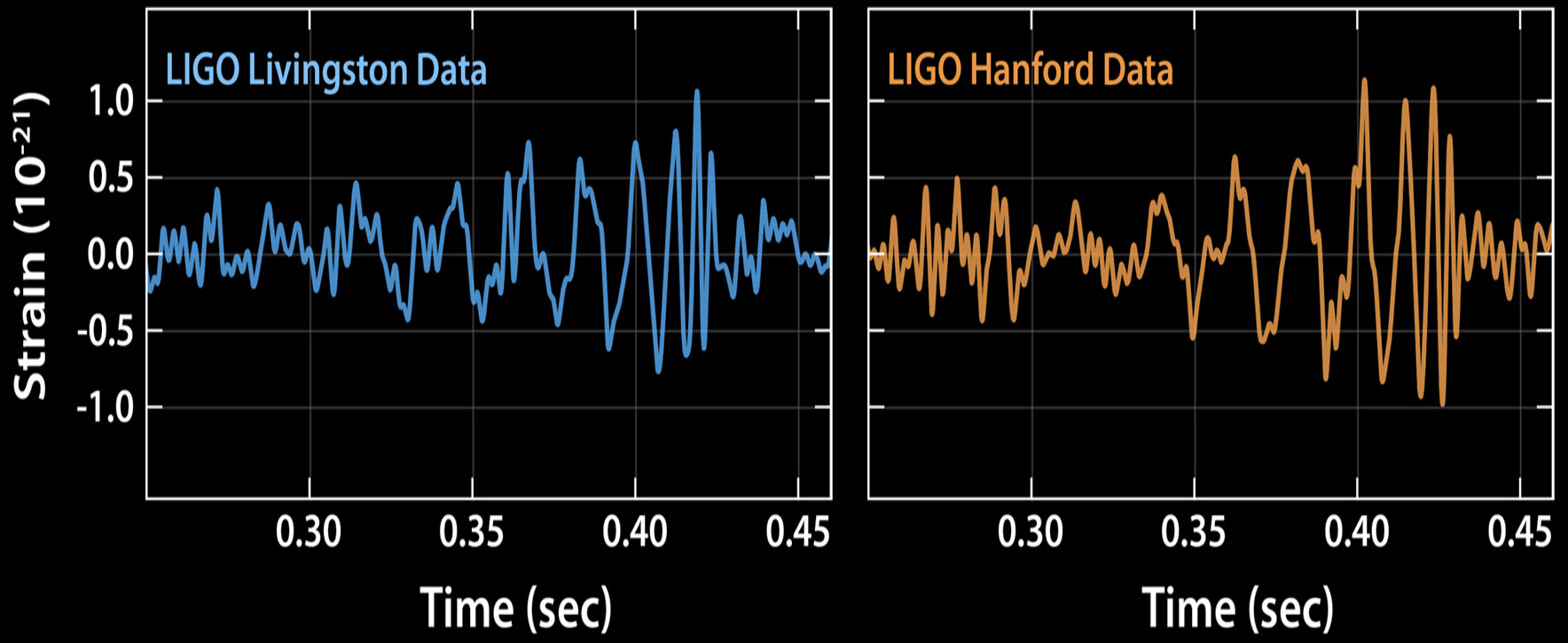
Nuclear diameter, 10^{-15} meter

÷1,000



LIGO sensitivity, 10^{-18} meter


test mass
light storage arm
test mass
test mass
light storage arm
test mass
beam
splitter
photodetector
power recycling mirror
laser


LIGO Livingston Data
LIGO Hanford Data
Strain (10-21)
1.0
0.5
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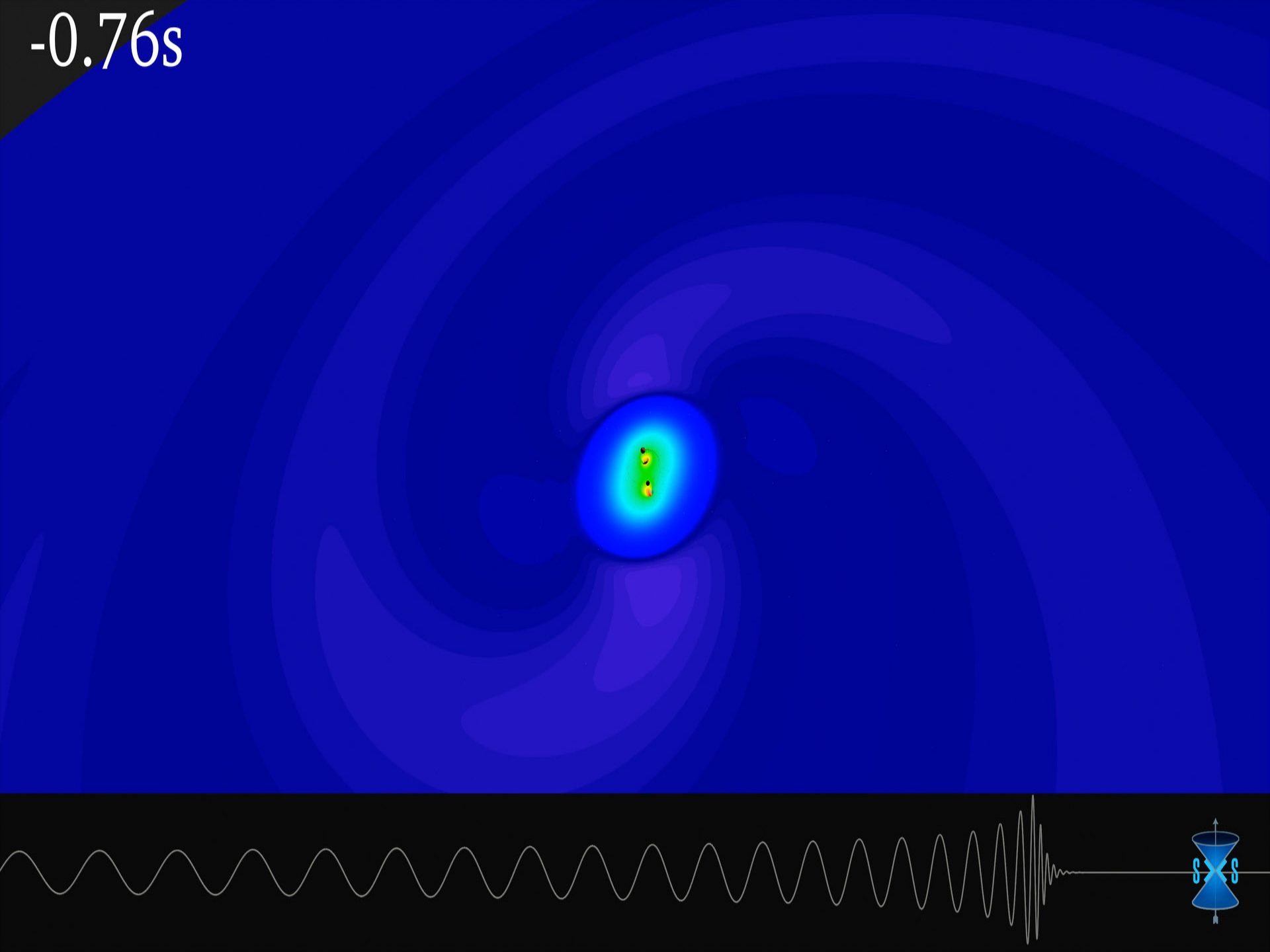
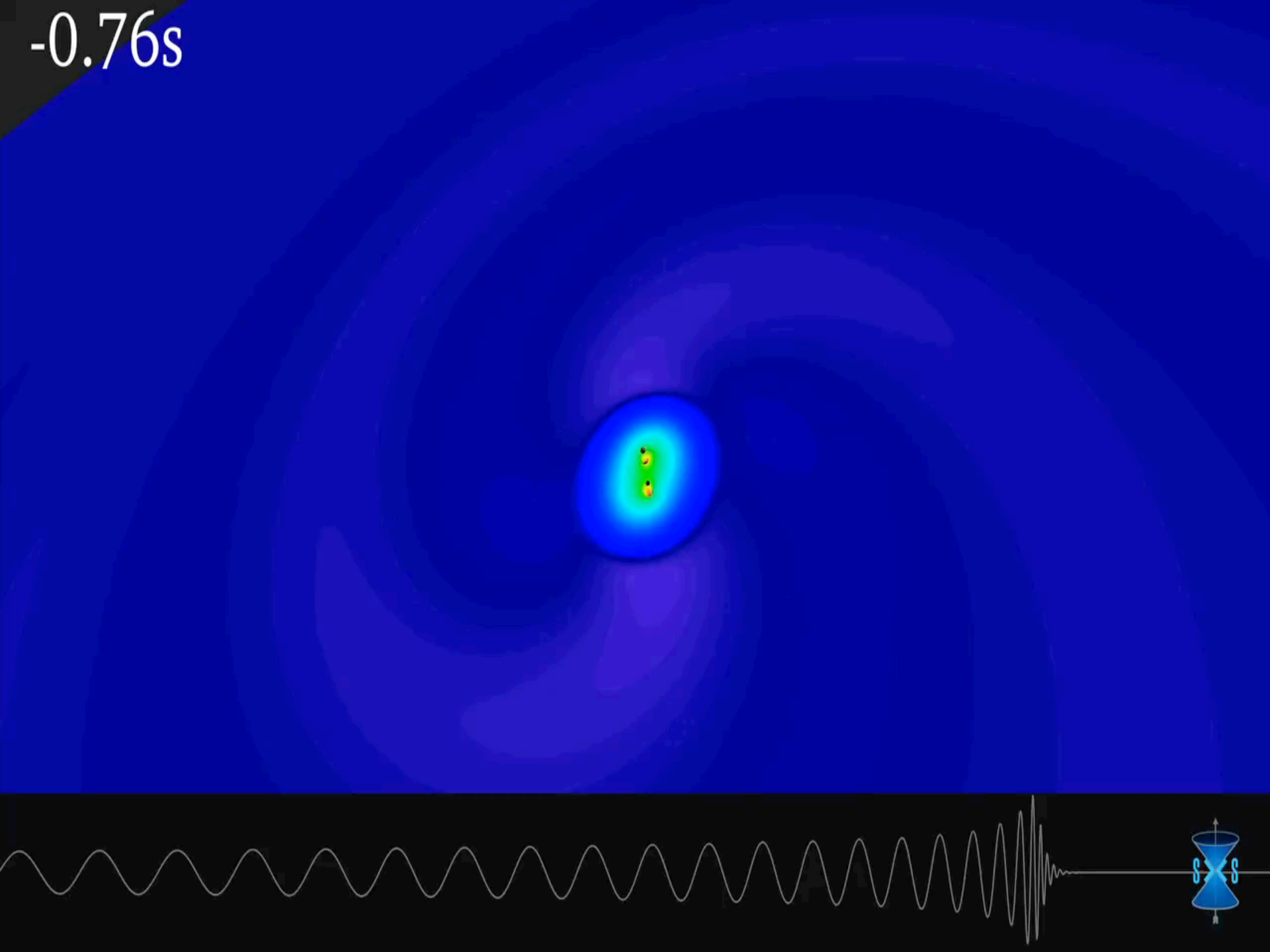
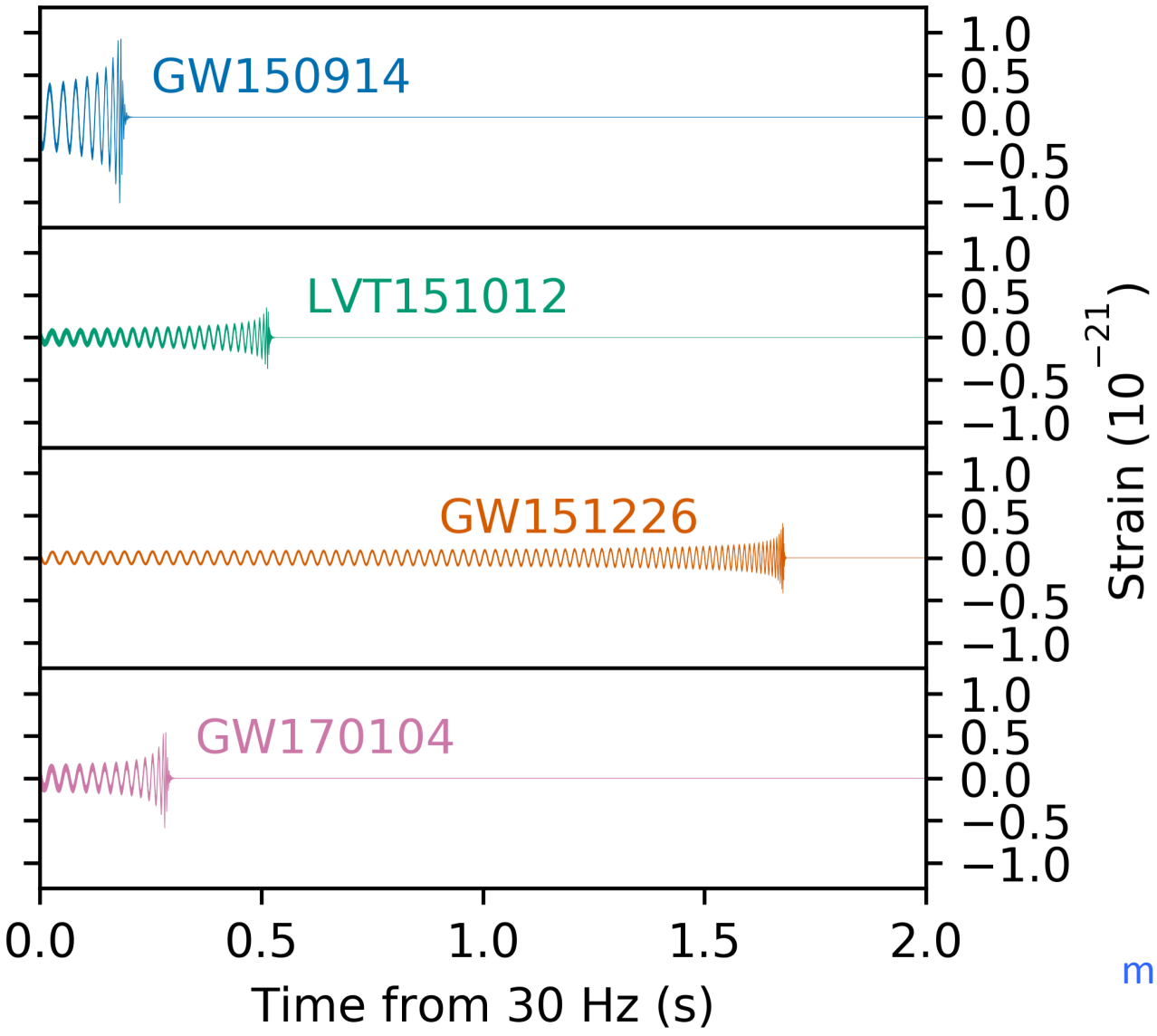
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)


-0.76s


-0.76s

Results of O1 and O2 run announced June 1, 2017



m1=36, m2= 29, Δm=3

if at 1 au

h ~10^{-6}

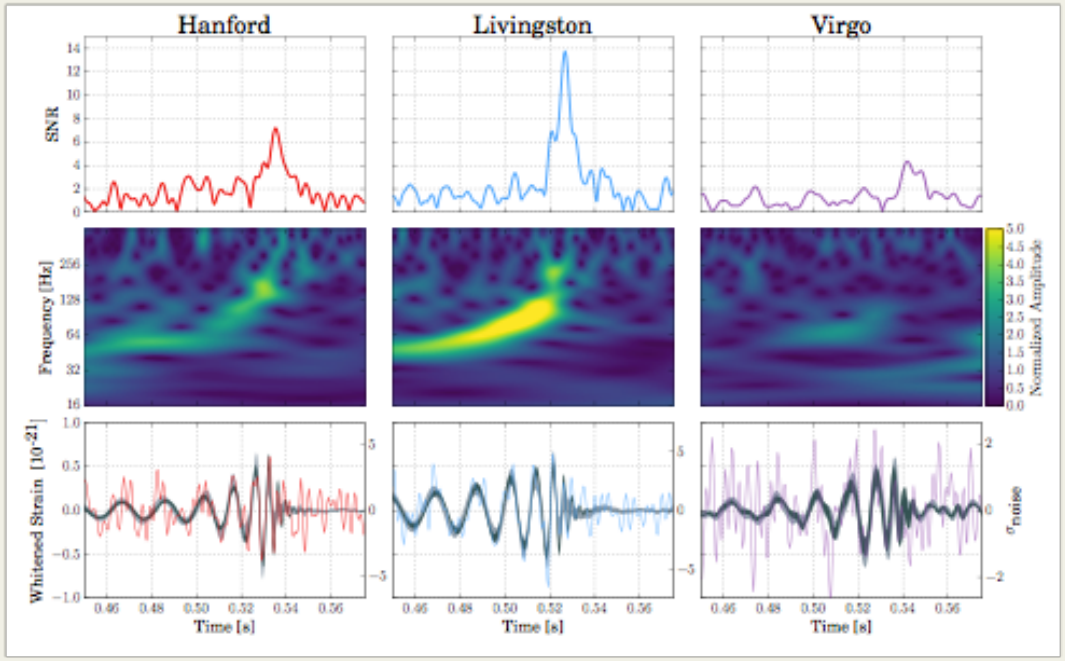
I_g~ 10^{25} w/m^2

m1=23, m2= 13, Δm=1.5

m1=14.2, m2= 7.5, Δm=1

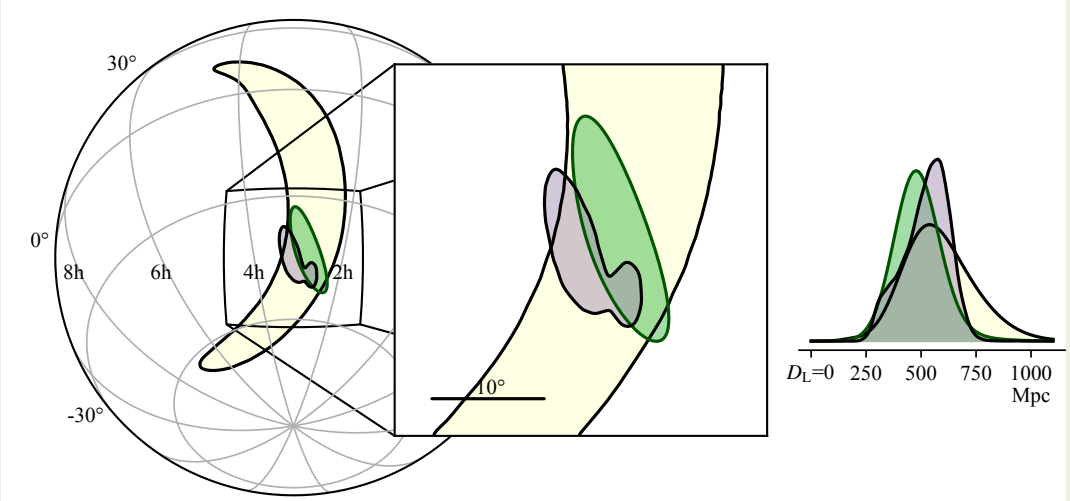
m1=31, m2= 19, Δm=2

masses in source frame



Triple coincidence
GW 170814

M_1 = 30
M_2 = 25
ΔM = 2.7



Localization on sky and distance