DETECTING GRAVITATIONAL WAVES

RICHARD MITTLEMAN ON BEHALF OF THE
LIGO VIRGO COLLABORATION

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LIGO

LSC

LIGO Scientific Collaboration

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University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
Whitman College
American University
University of the West of Scotland UWS
Texas Tech University
清華大學 Tsinghua University
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University of Strathclyde
Michigan
CITA ICAT
Università degli Studi del Sannio
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
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Montana State University
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
University of Birmingham
The University of Melbourne
UIB Universitat de les Illes Balears
University of Washington
UTRGV
UW Milwaukee University of Wisconsin
Northwestern
Syracuse University
Cardiff University Prifysgol Caerdydd
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council Rutherford Appleton Laboratory

Gravity

The history of our understanding of gravity goes back to a long time ago…

Aristotle (350 BC)

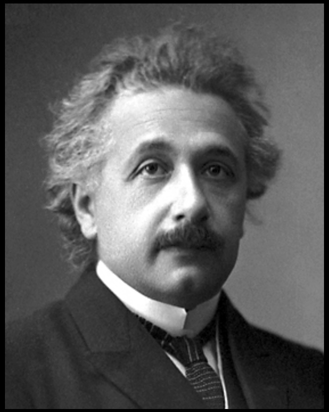
All that is earthly tends toward the center of the Universe, i.e., the center of the Earth

Galileo Galilei (1638)

All unequal weights would fall with the same finite speed in a vacuum

Isaac Newton (1687)

All bodies are subject to an attractive force described in mathematical terms

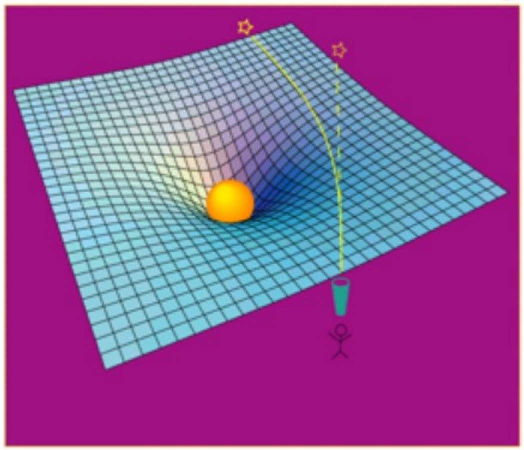


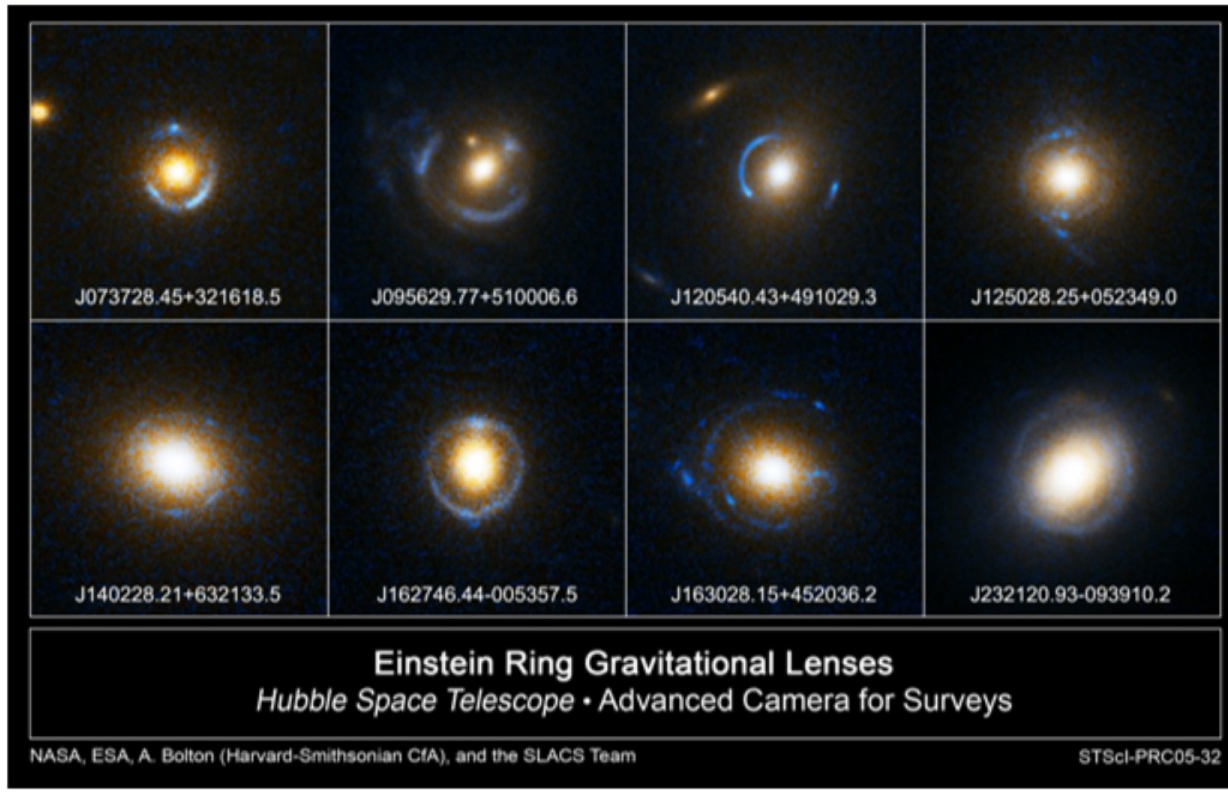
Albert Einstein (1915)

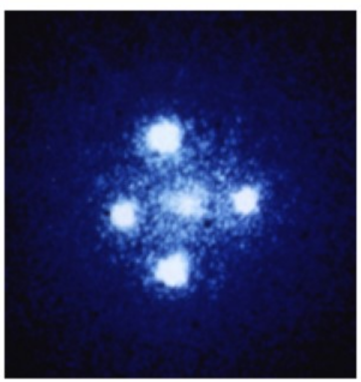
Gravity is a property of space and time, modified by the presence of matter

Observed Effects of Gravity's Distortion of Space

Gravitational Lensing – light bends around massive object

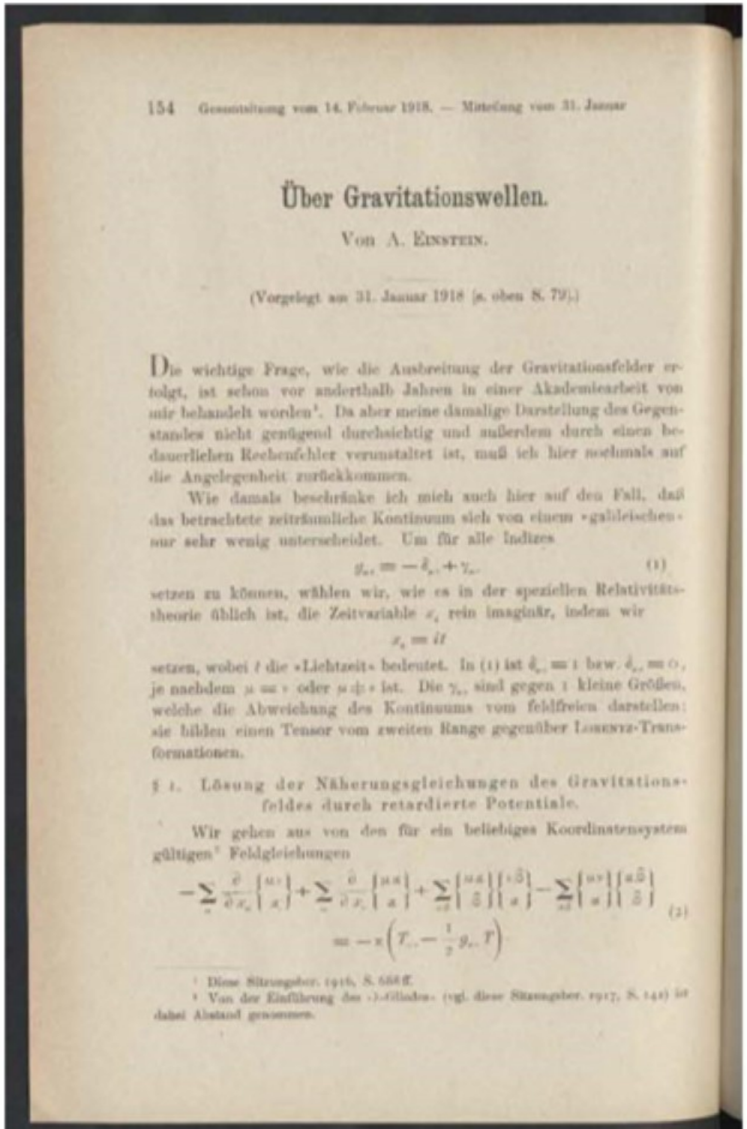






"Einstein's Cross" – quasar's light bends around a galaxy.

Gravitational Waves in General Relativity (Einstein 1916,1918)



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_\alpha \frac{\partial}{\partial x_\alpha}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix} + \sum_\alpha \frac{\partial}{\partial x_\nu}\begin{Bmatrix}\mu\alpha\\ \alpha\end{Bmatrix} + \sum_{\alpha\beta}\begin{Bmatrix}\mu\alpha\\ \beta\end{Bmatrix}\begin{Bmatrix}\nu\beta\\ \alpha\end{Bmatrix} - \sum_{\alpha\beta}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix}\begin{Bmatrix}\alpha\beta\\ \beta\end{Bmatrix} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right) \qquad (2)$$

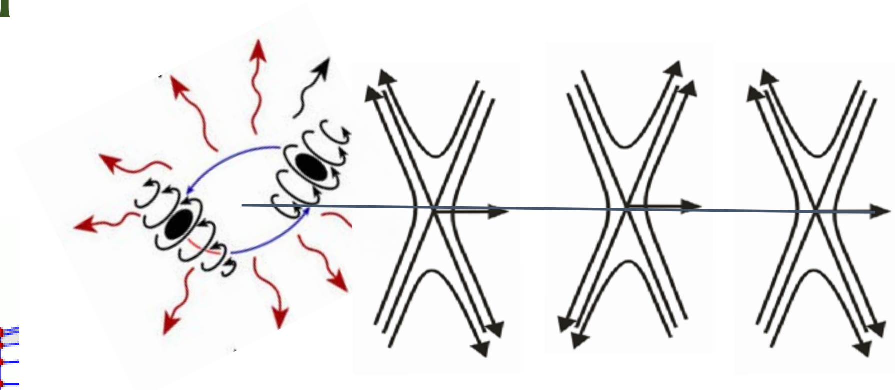
[1] Diese Sitzungsber. 1916, S. 688ff.

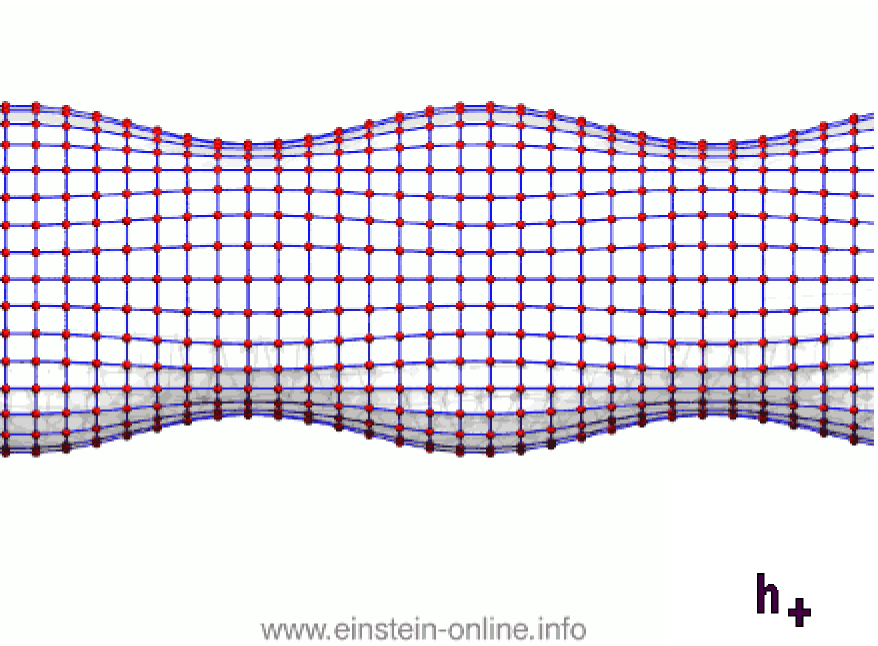
[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

$$g_{ij} = \delta_{ij} + h_{ij}$$

h_{ij}: transverse, traceless and propagates at v=c

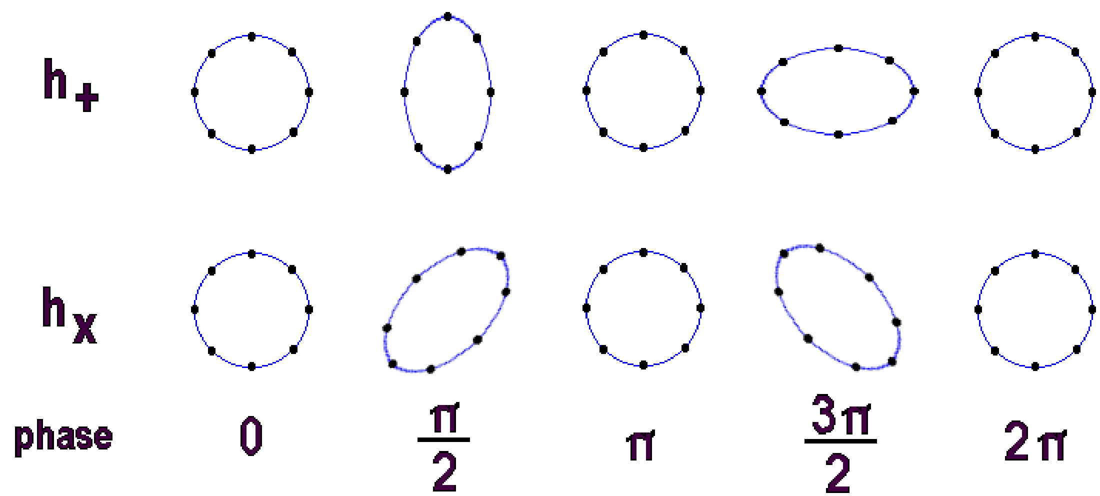
Gravitational Radiation is a Quadrupolar Strain in space-time



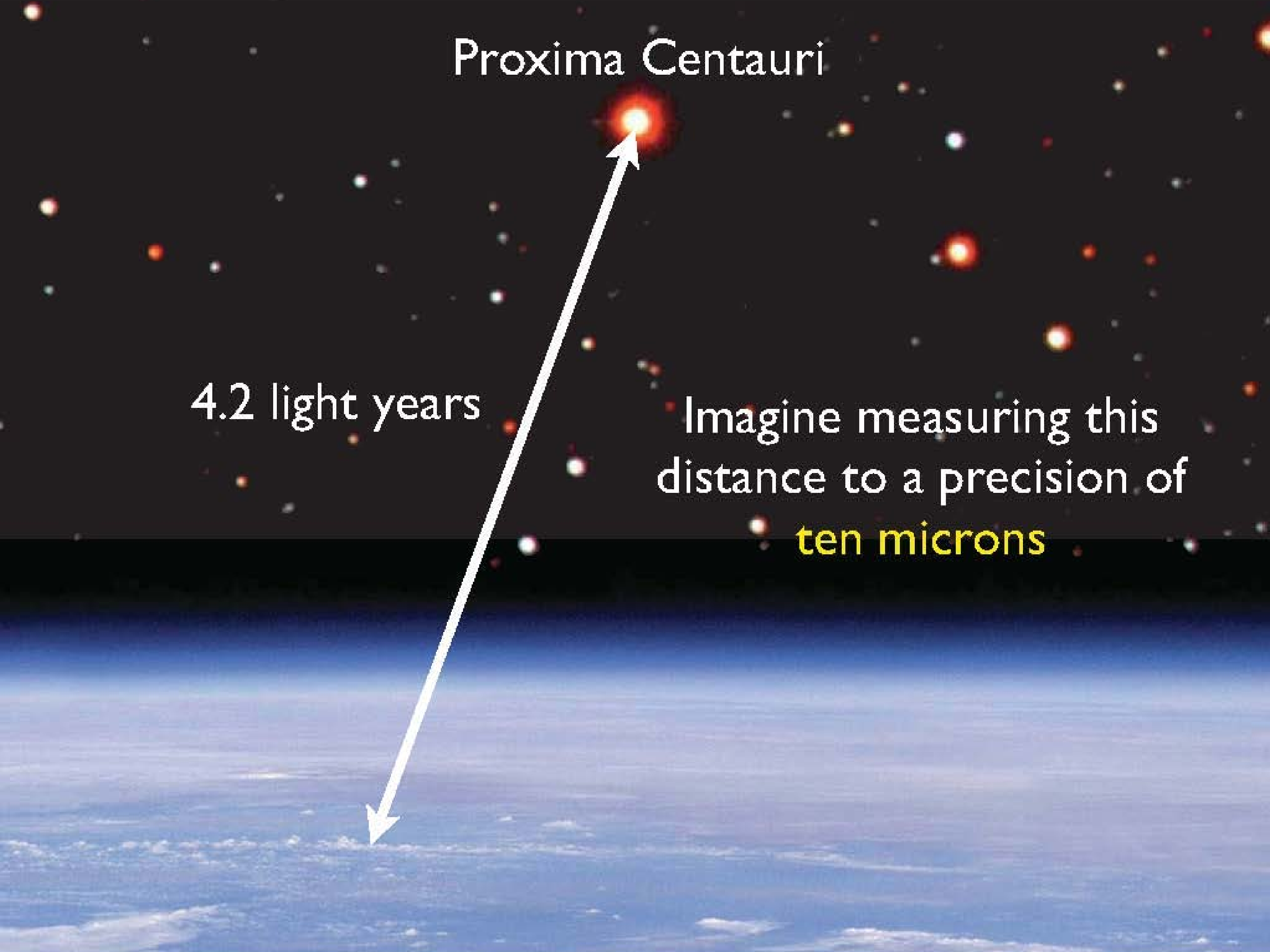


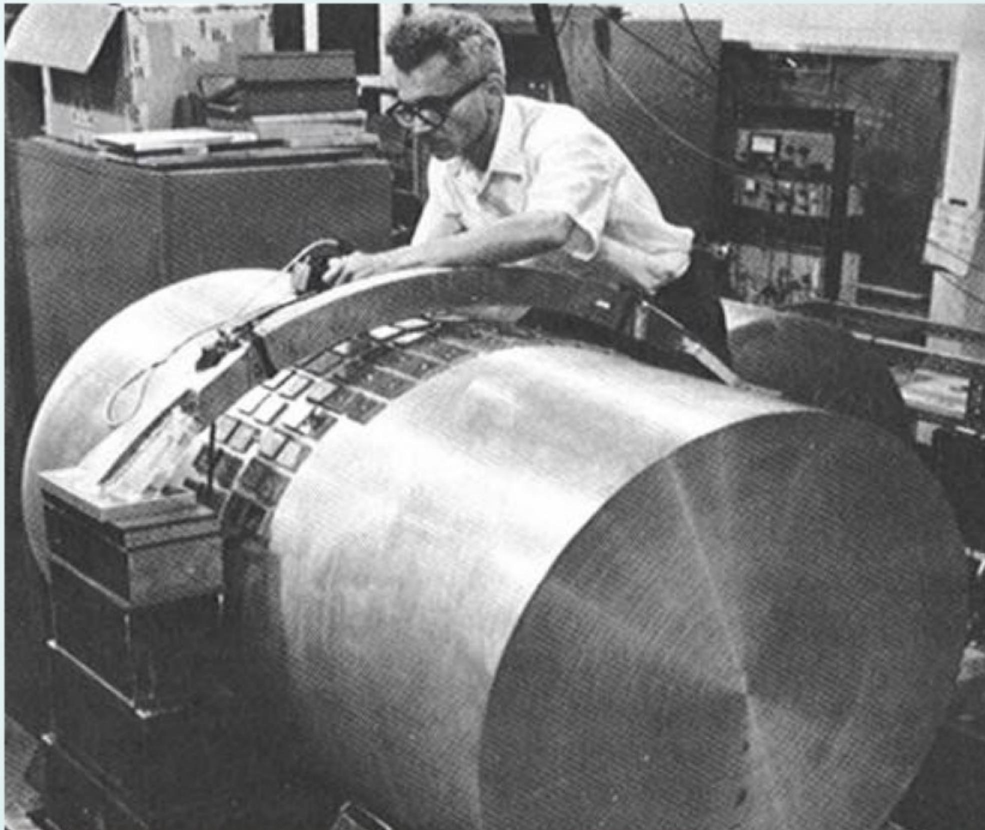
Space is very stiff
For astrophysical sources you might expect h~1e-21

There are two polarizations

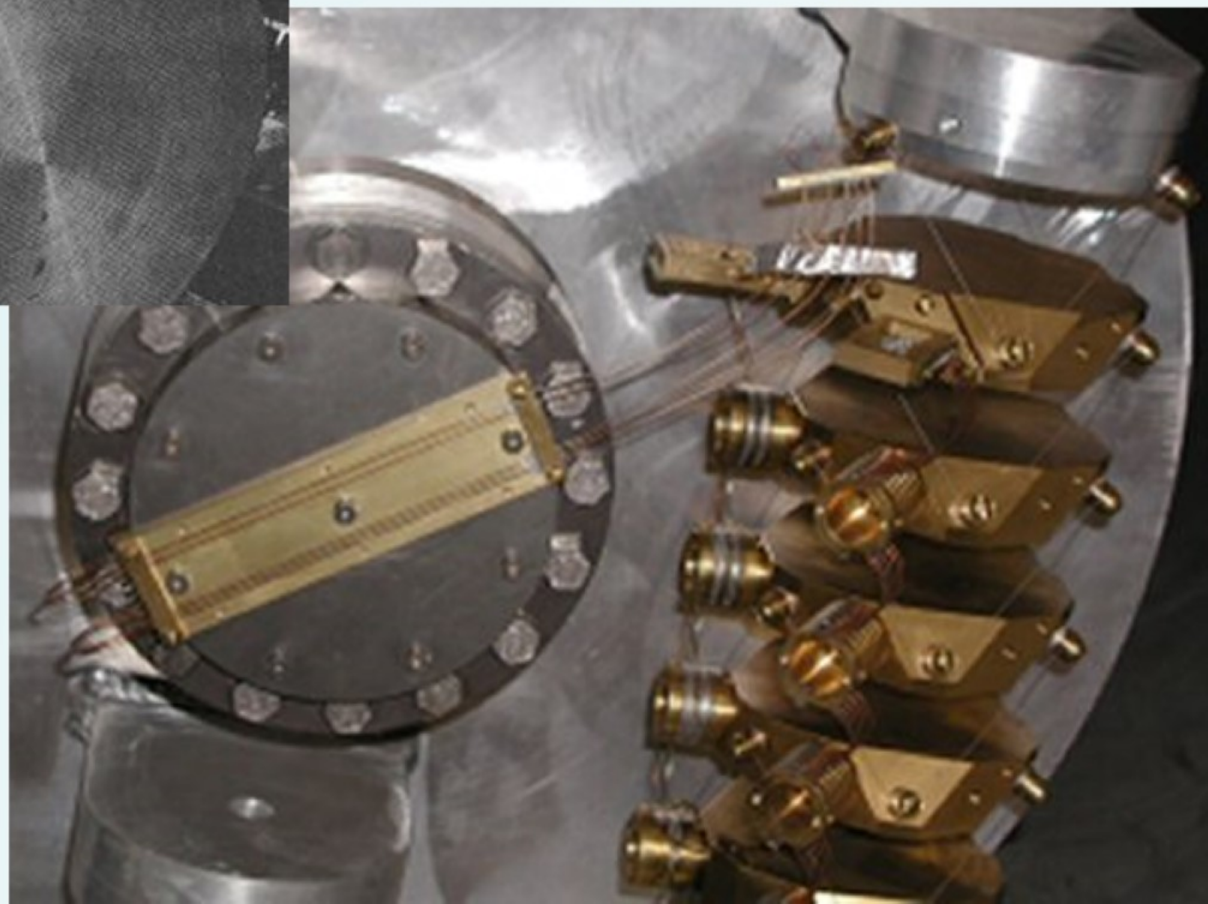


How big is the effect? Zooming into an Atom


Proxima Centauri
4.2 light years
Imagine measuring this distance to a precision of ten microns



In the 1960-70's Joseph Weber built a bar to directly detect gravity waves



Bars are resonant detector designs to detect the energy left by a passing gravity wave

Modern bars are cryogenic, see Nautilus and MiniGrail

An Early LIGO proposal

Rai Weiss of MIT was teaching a course on GR in the late '60s

Wanted a good homework problem for the students

Why not ask them to work out how to use laser interferometry to detect gravitational waves?

Weiss wrote the instruction book we have been following ever since

(V. GRAVITATION RESEARCH)

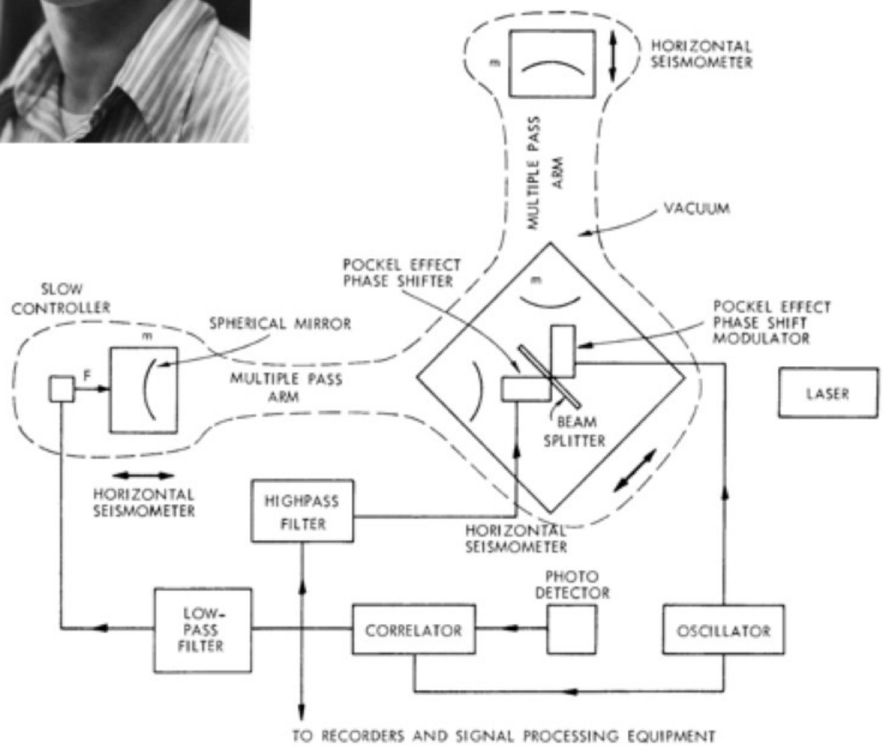


Fig. V-20. Proposed antenna.

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

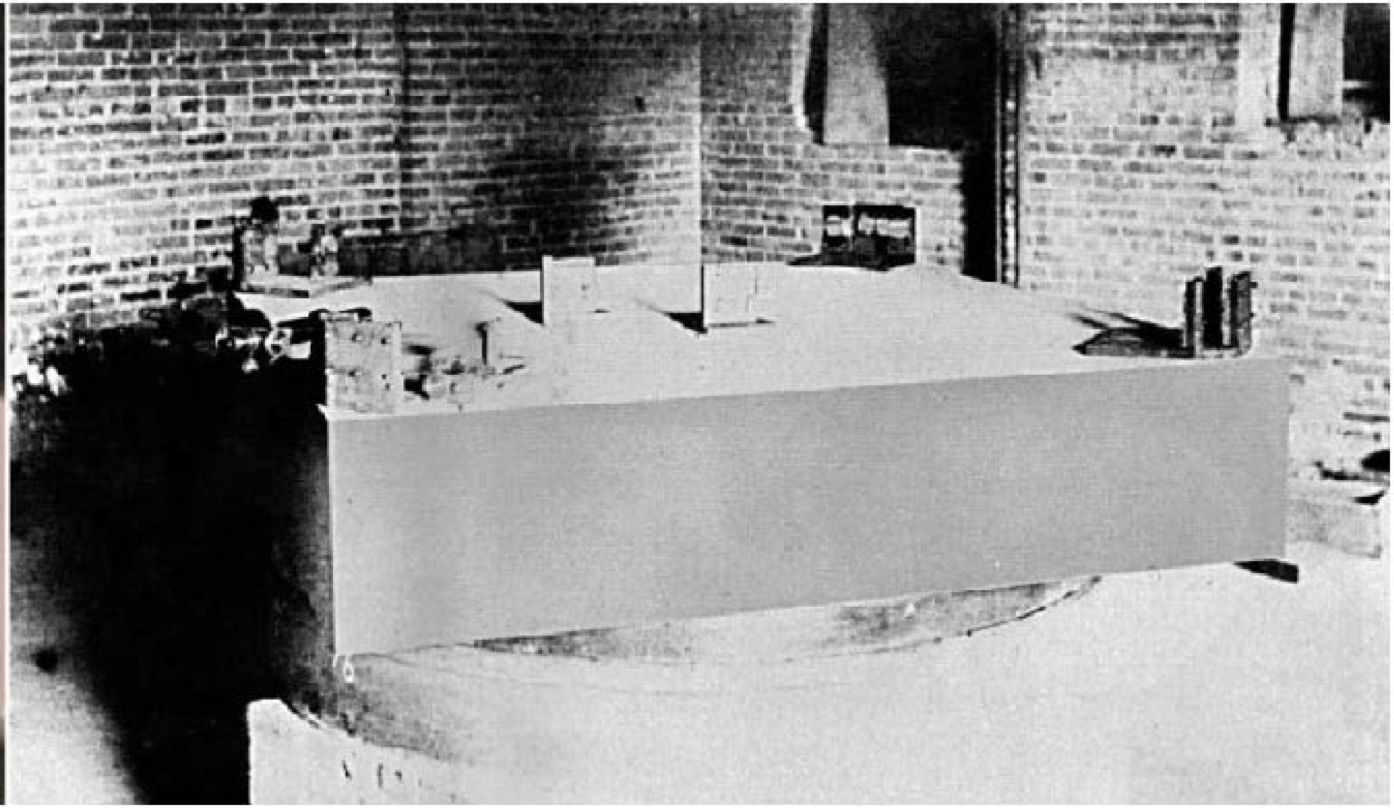
B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

The prediction of gravitational radiation that travels at the speed of light has been

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

American Journal of Science, Nov 1887 vol. Series 3 Vol. 34 no. 203 333-345



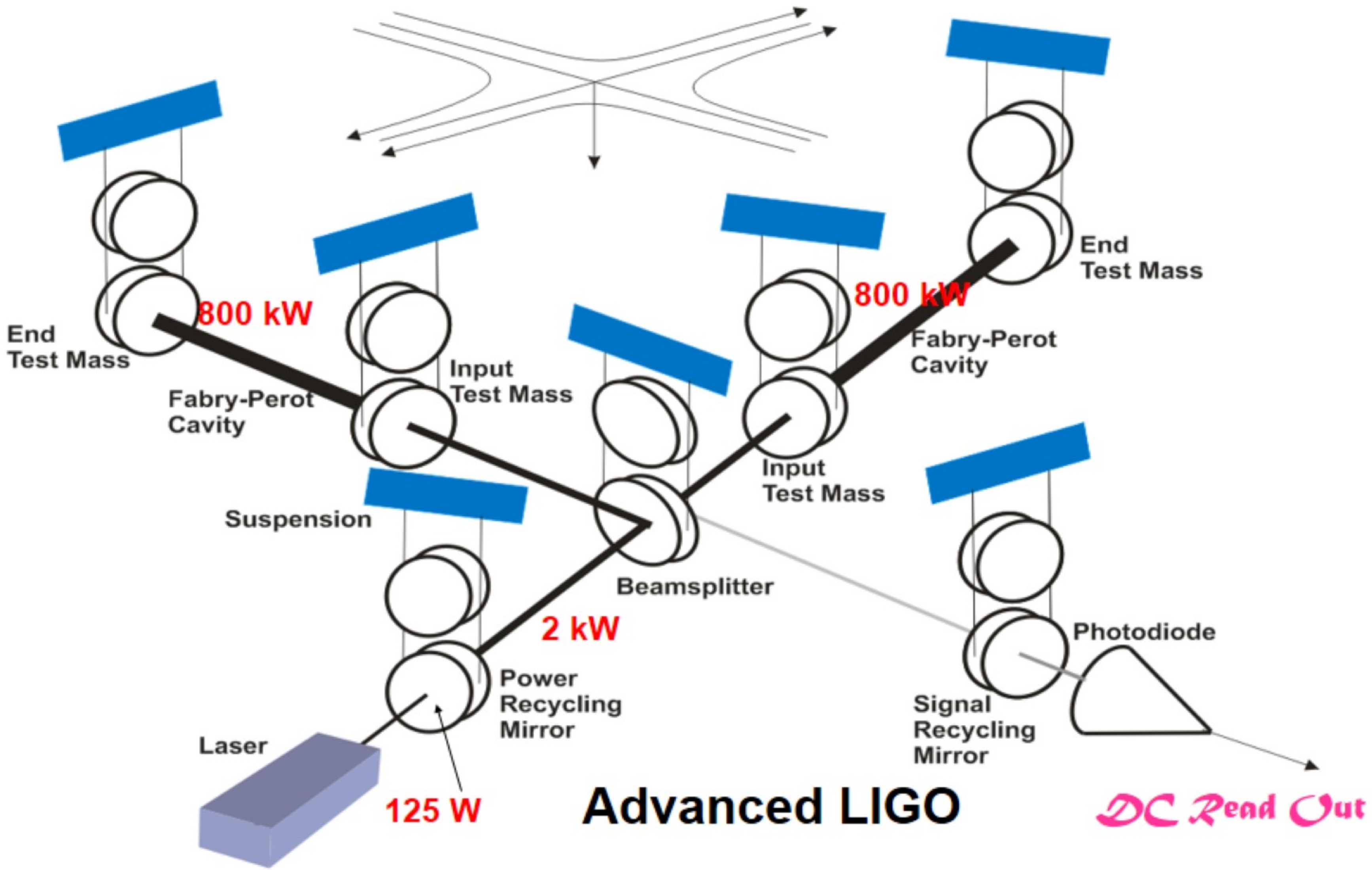
Used light interferometry to achieve sensitivity in measuring distances down to 0.01 λ or ~5×10^{-9} m = 0.000000005 m

1907 Nobel Prize in Physics to A. Michelson

SIMPLE MICHAELSON INTERFEROMETER

Simple Michaelson Interferometer

ADVANCED LIGO




LIGO HANFORD OBSERVATORY

LIGO Hanford

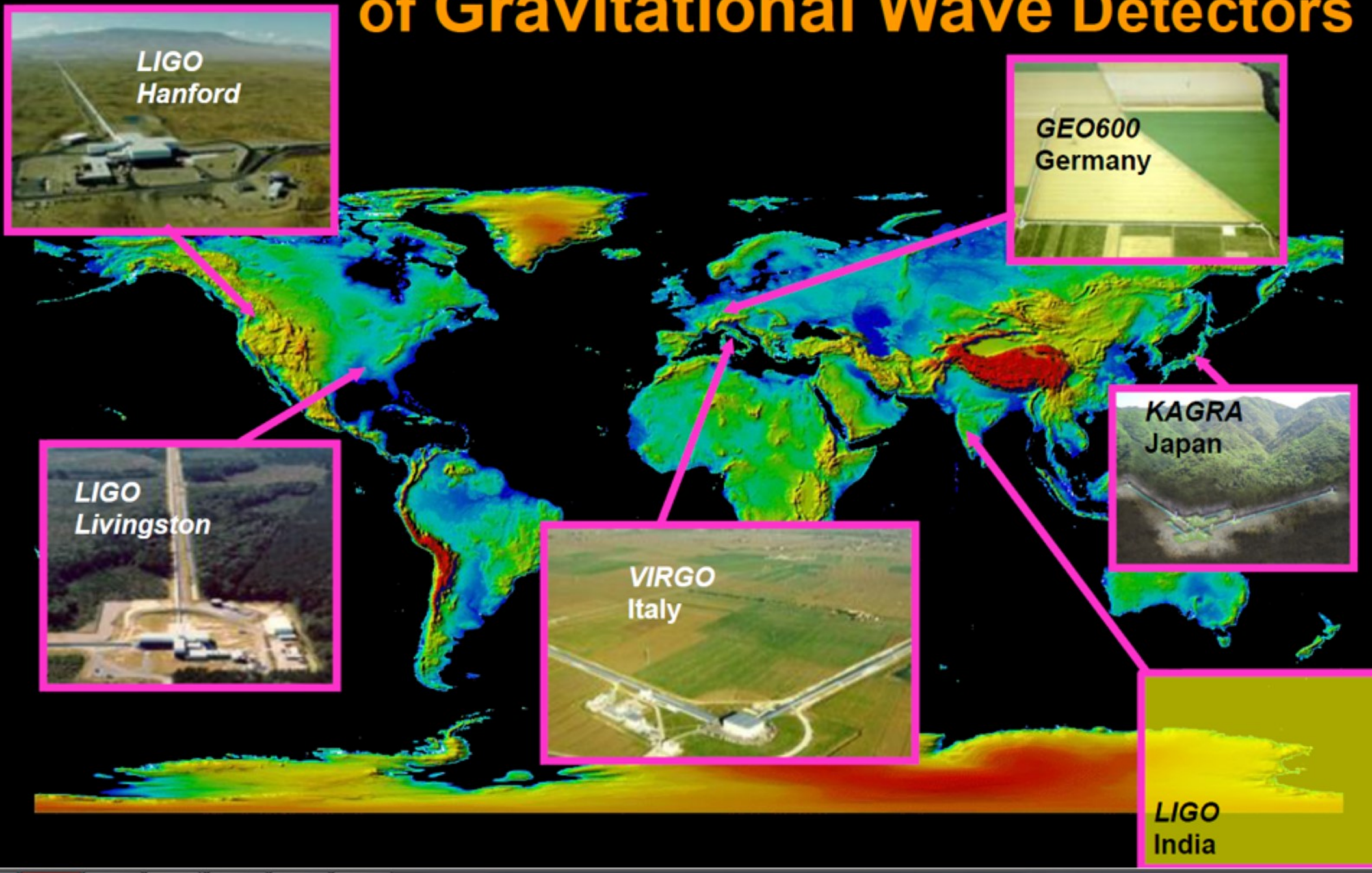

LIGO Livingston Observatory


LIGO Livingston


~3000 km
New York
Livingston
Nassau
Gulf of Mexico
1475 km
© 2010 Europa Technologies
© 2010 Tele Atlas
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2010 Google
©2009 Google


VIRGO
CASCINA, ITALY

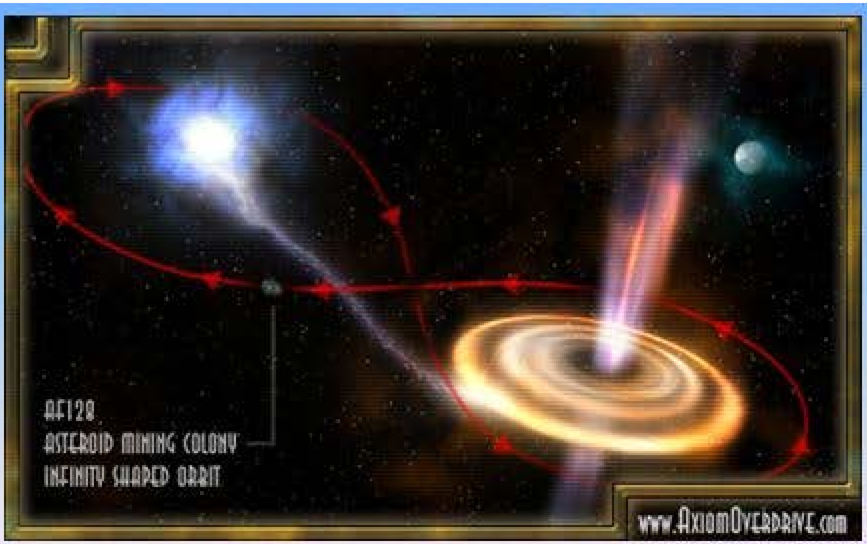
The Global Network of Gravitational Wave Detectors

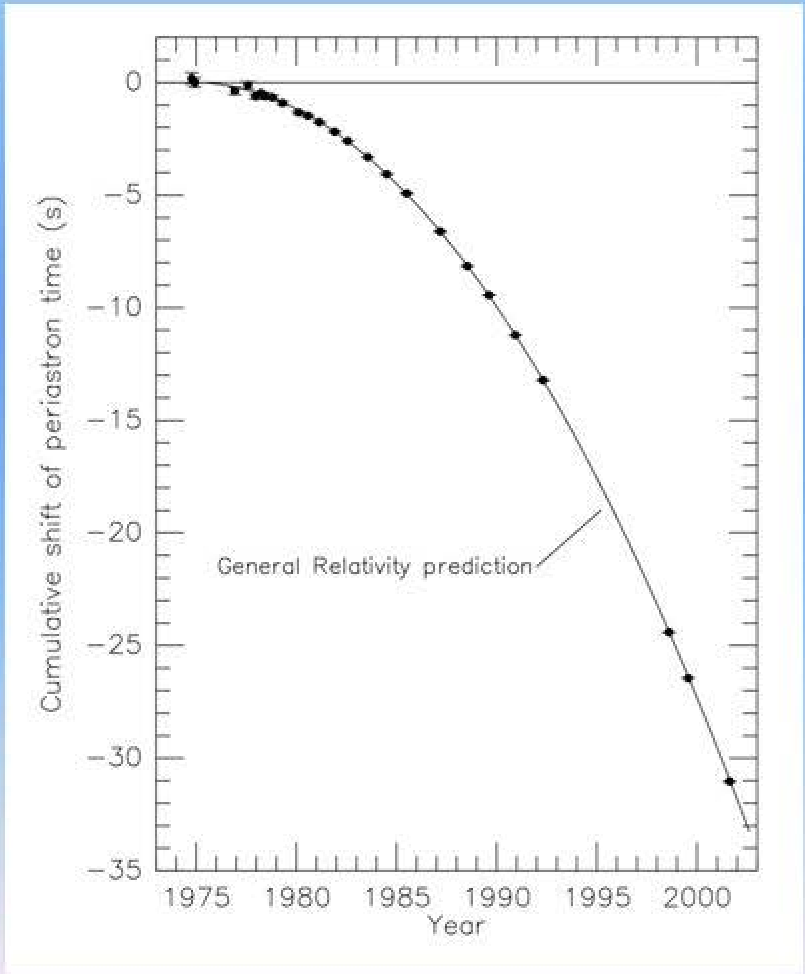



Neutron Star Inspiral

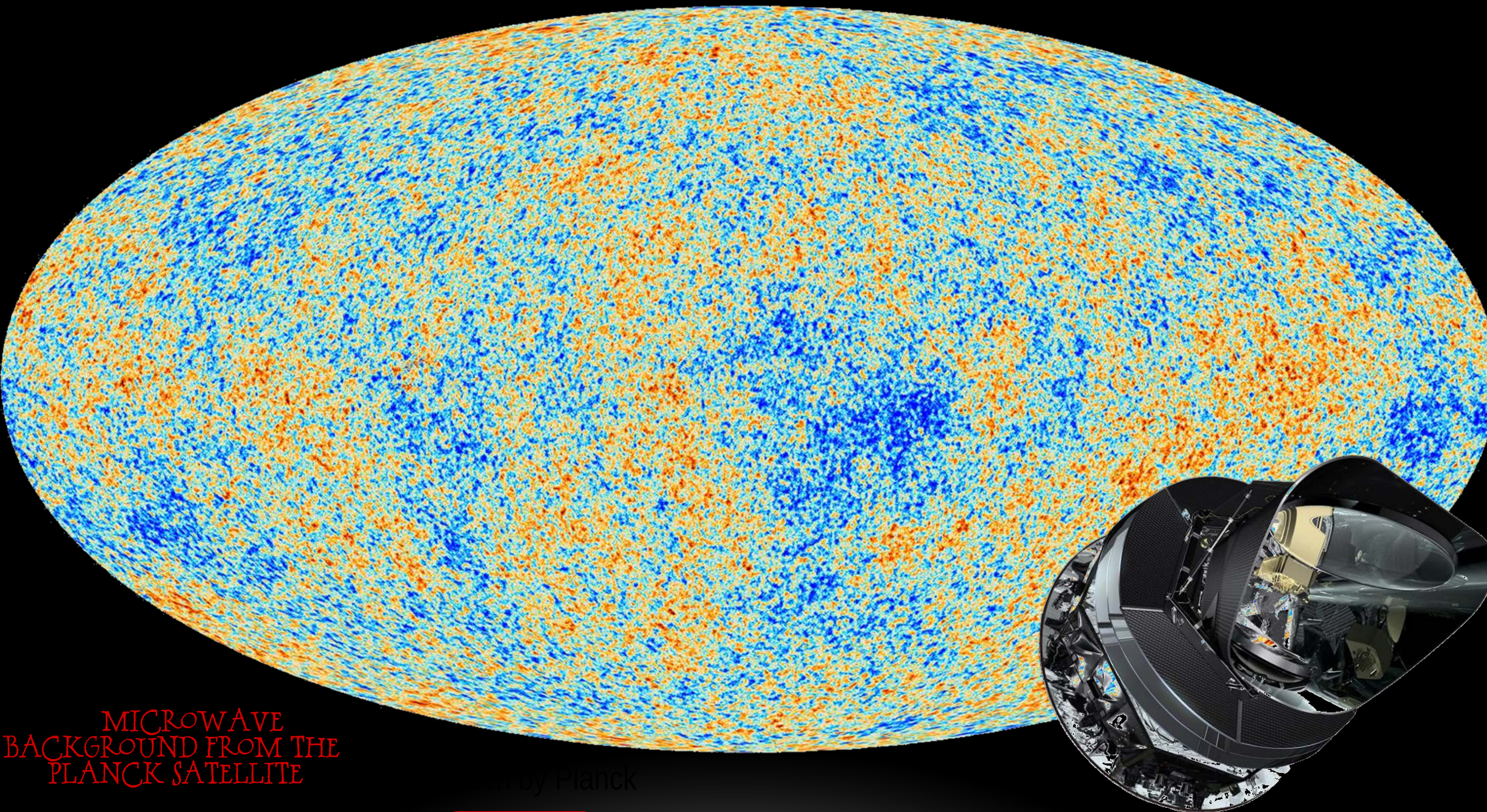
The binary pulsar

- Period speeds up 14 sec from 1975-94
- Measured to ~50 msec accuracy
- Deviation grows quadratically with time
- Merger in about 300M years
  (<< age of universe!)
- shortening of period ⇐ orbital energy loss
- Compact system:
  negligible loss from friction, material flow
- Beautiful agreement with GR prediction
- Apparently, loss is due to GWs!
- GW emission will be strongest near the end:
  – Coalescence of neutron stars!
- Nobel Prize, 1993
- By 2013, there are ~8

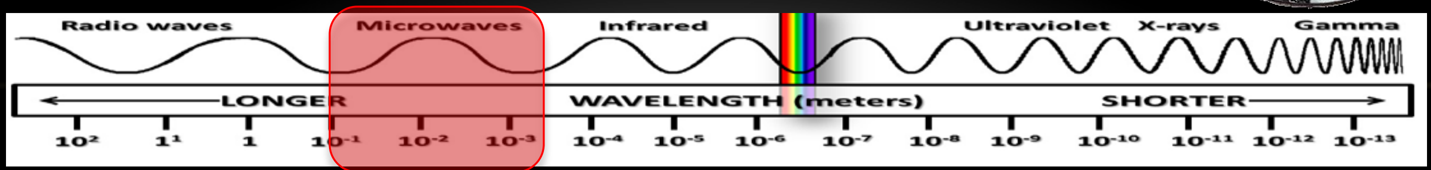


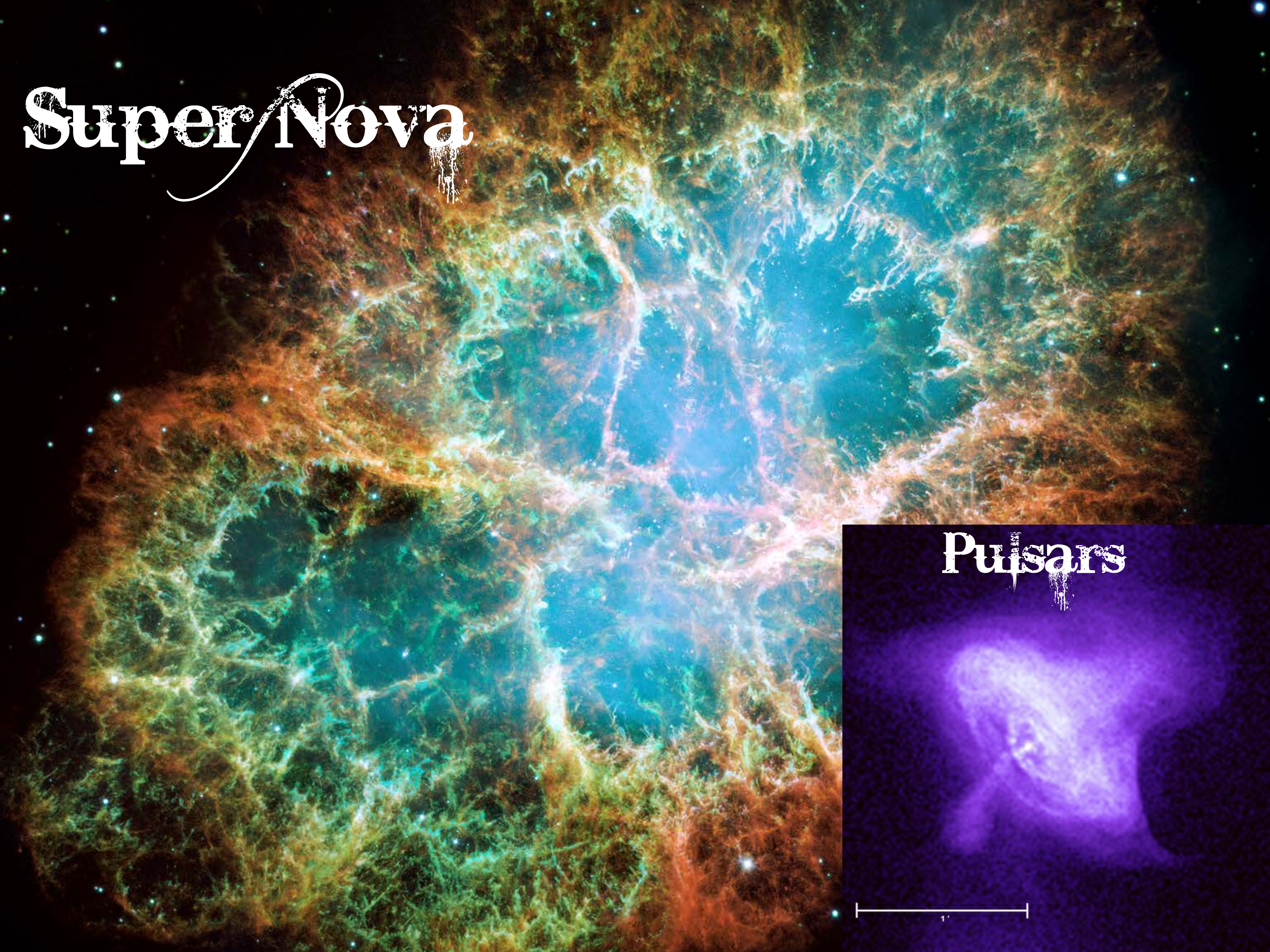


STOCHASTIC BACKGROUND*

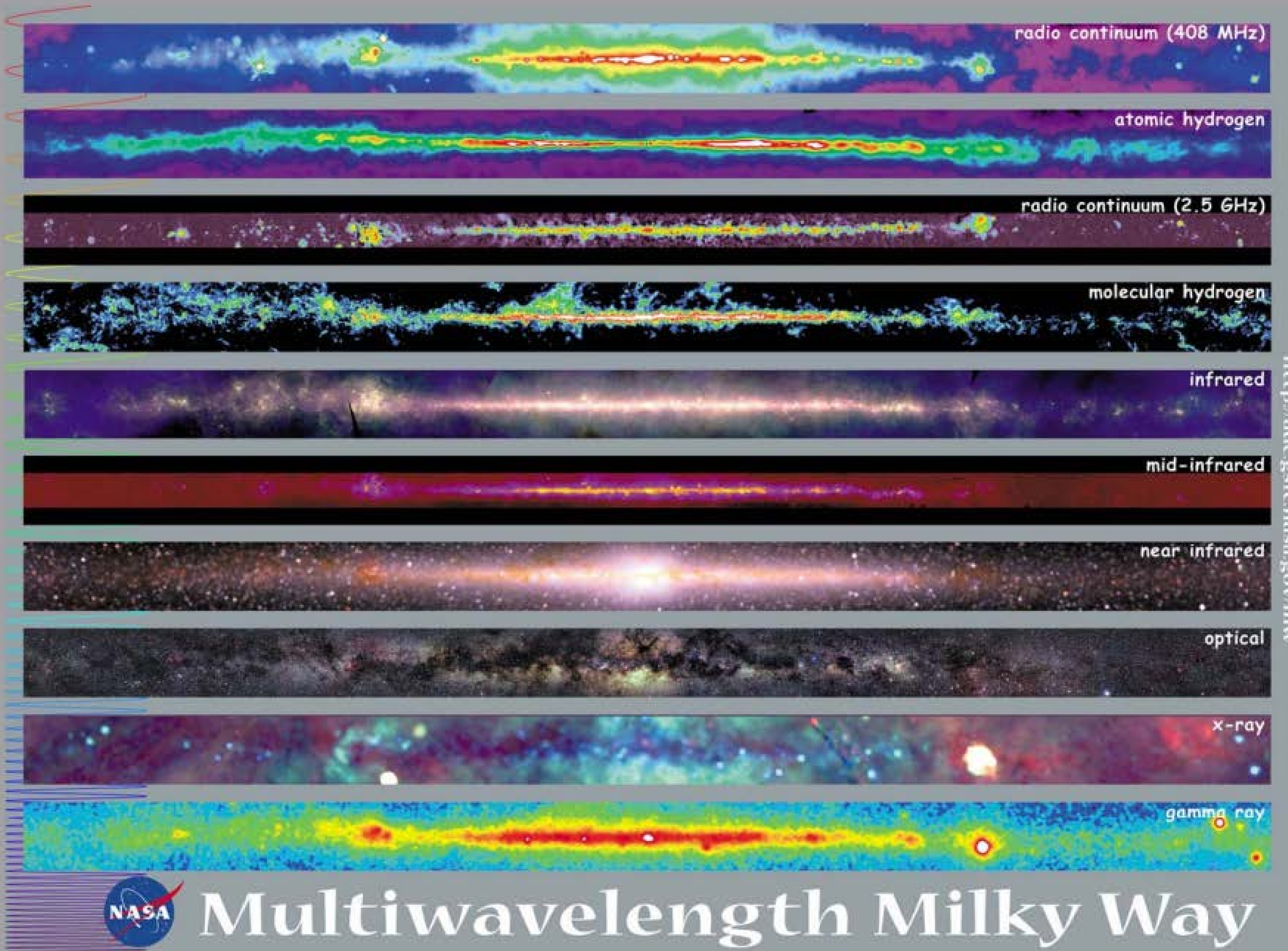


MICROWAVE BACKGROUND FROM THE PLANCK SATELLITE

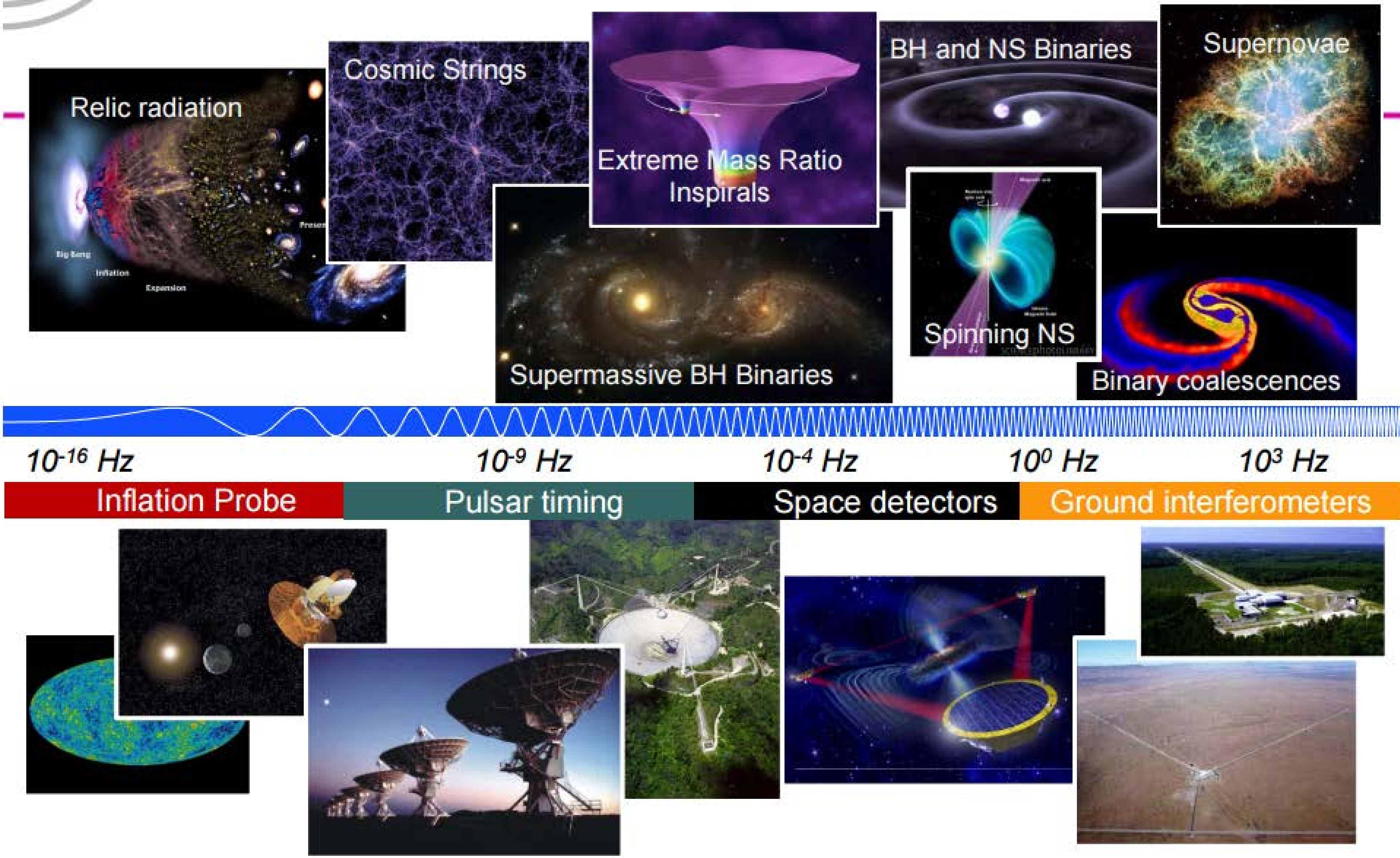



Super Nova
Pulsars
1'

Electromagnetic Astronomy

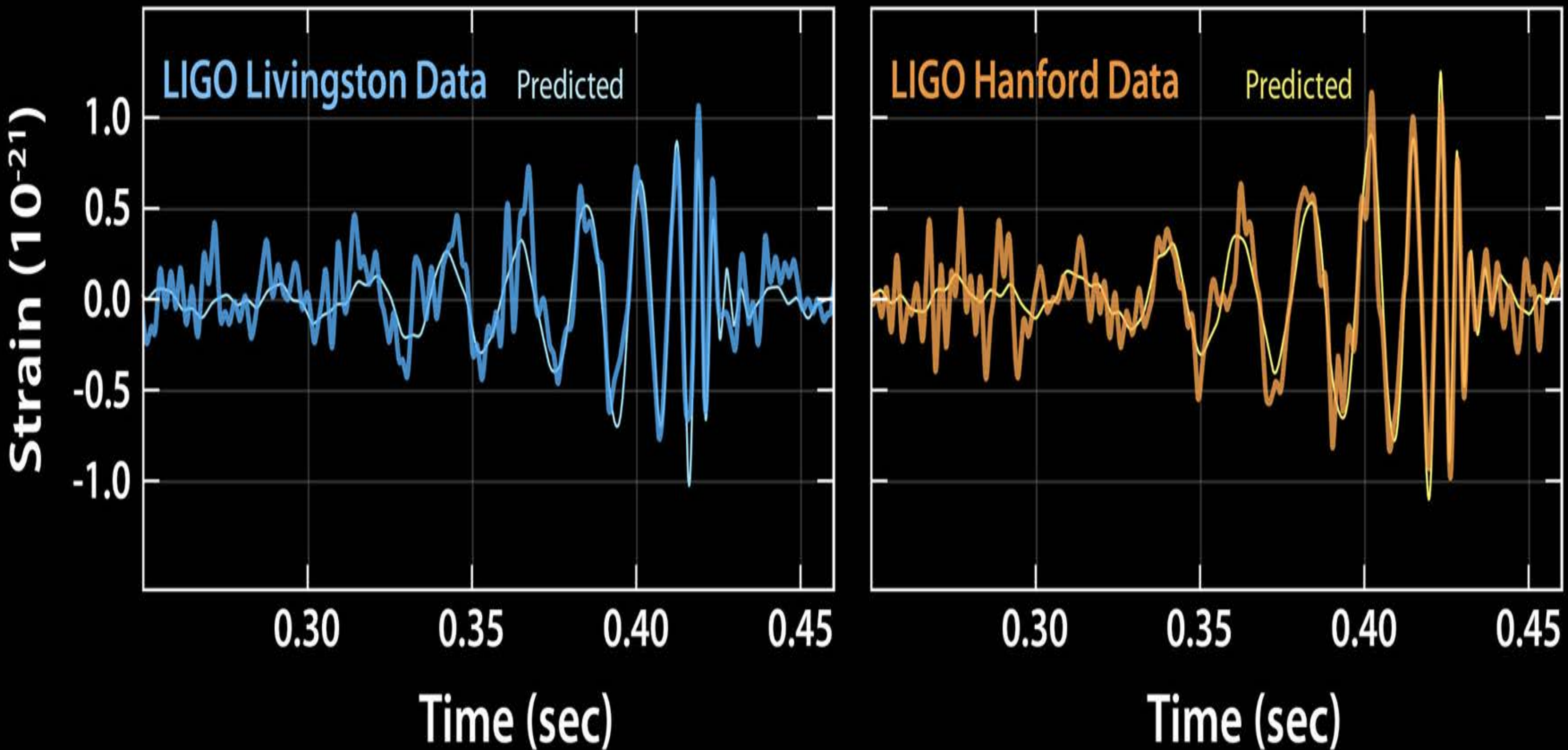


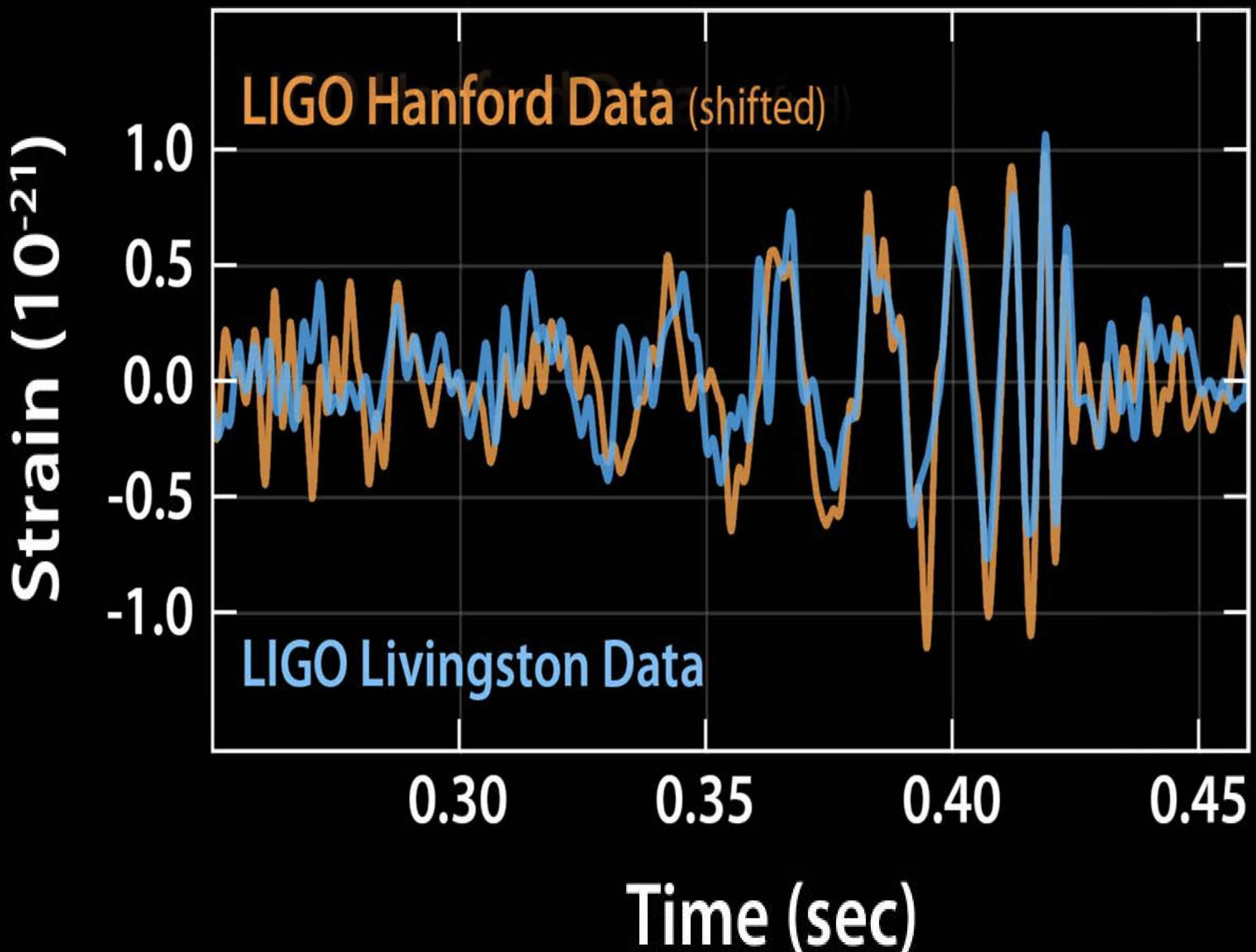
The GW Spectrum



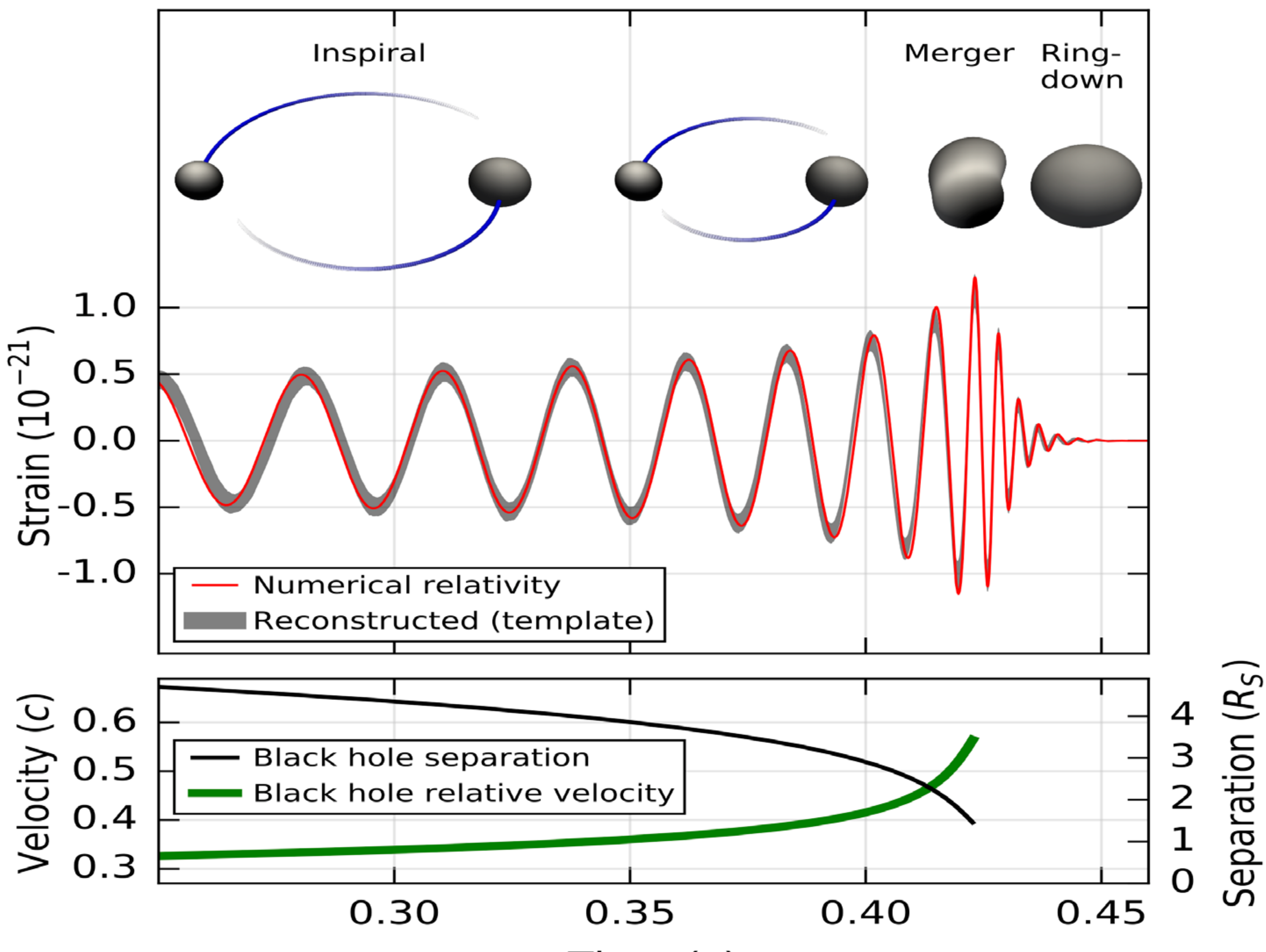
Simulation of the merging of two black holes

150914


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)



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)



Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45

Warped Space and Time Around Colliding Black Holes

Image Credit: SXS, the Simulating eXtreme Spacetimes (SXS) project (https://www.ligo.caltech.edu/video/ligo20160211v10)

GW 150914: FACTSHEET

date	14 Sept 2015
time	09:50:45 UTC
observatory	LIGO WA, LA
source type	black hole binary
SNR	24
false alarm prob.	< 2 x 10^{-7}
false alarm rate	1 in 200,000 yr
chirptime at 35 Hz	200 ms
cycles from 35 Hz	8
remnant size, area	210 km,
inferred rate	2-400 Gpc^{-3} yr^{-1}
BH spins	
primary	< 0.7
secondary	< 0.9
remnant	0.7
graviton mass	< 1.2 x 10^{-22} eV
resolved to	600 sq. deg.
orientation	face-on/off
sky location	southern hemisphere
CPU hours used	~ 50 million

distance, redshift	410 Mpc, 0.09
peak frequency	150 Hz
QNM frequency	250 Hz
peak strain	10^{-21}
peak luminosity	3.6 x 10^{56} erg s^{-1}
peak speed	0.6 c
radiated energy	3 M⊙, 5% of mass
Detector Frame Masses M⊙	
total mass	70
chirpmass	30
primary BH	39
secondary BH	31
remnant BH	67
Source Frame Masses M⊙	
total mass	65
chirpmass	28
primary BH	36
secondary BH	29
remnant BH	62
mass ratio	0.8

How much energy was radiated away in GW?

- The two black hole merged to form a single black hole of 62 times the mass of the sun
- As they merged, the equivalent of ~3 times the mass of our Sun was emitted in gravitational waves

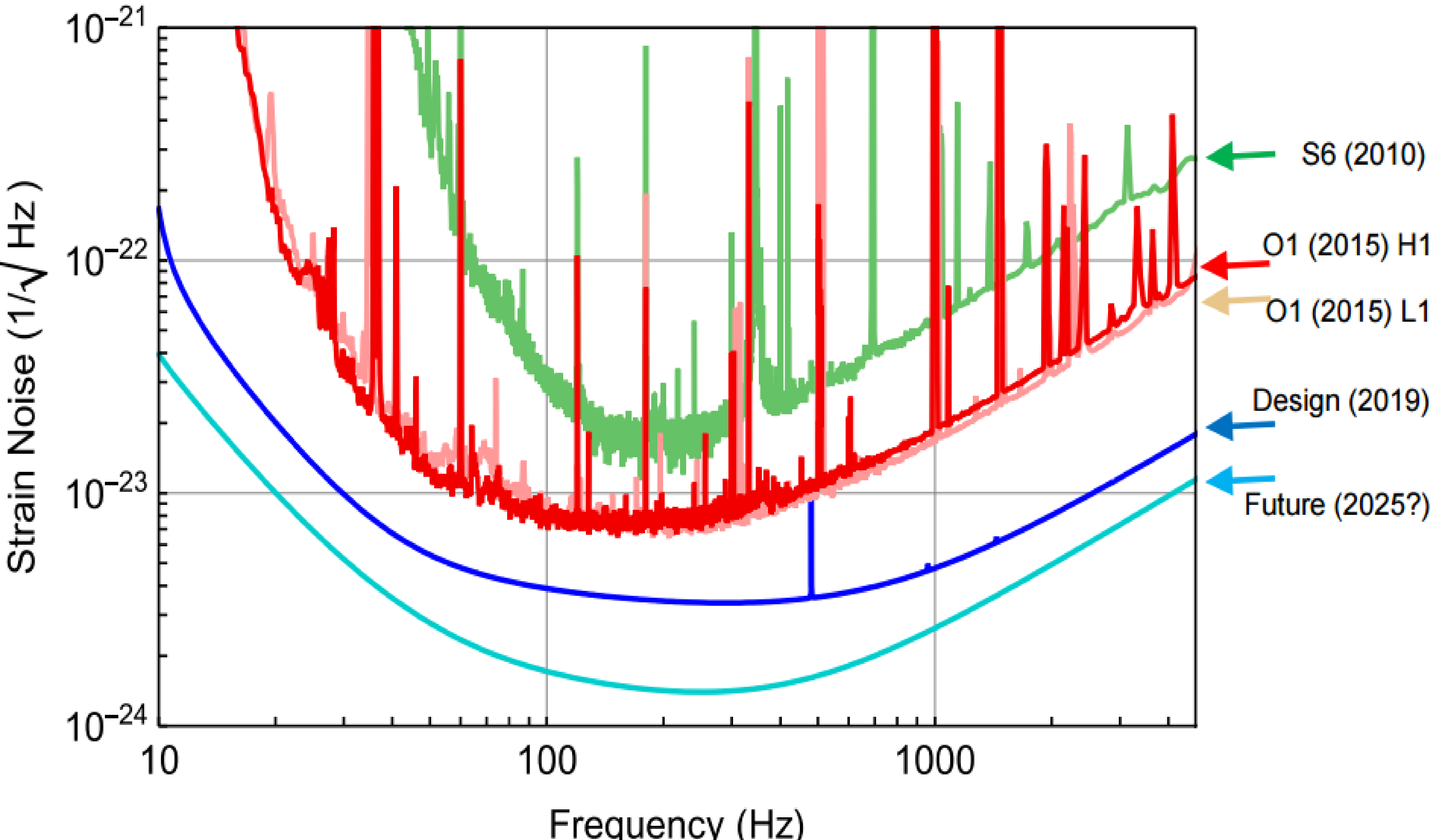


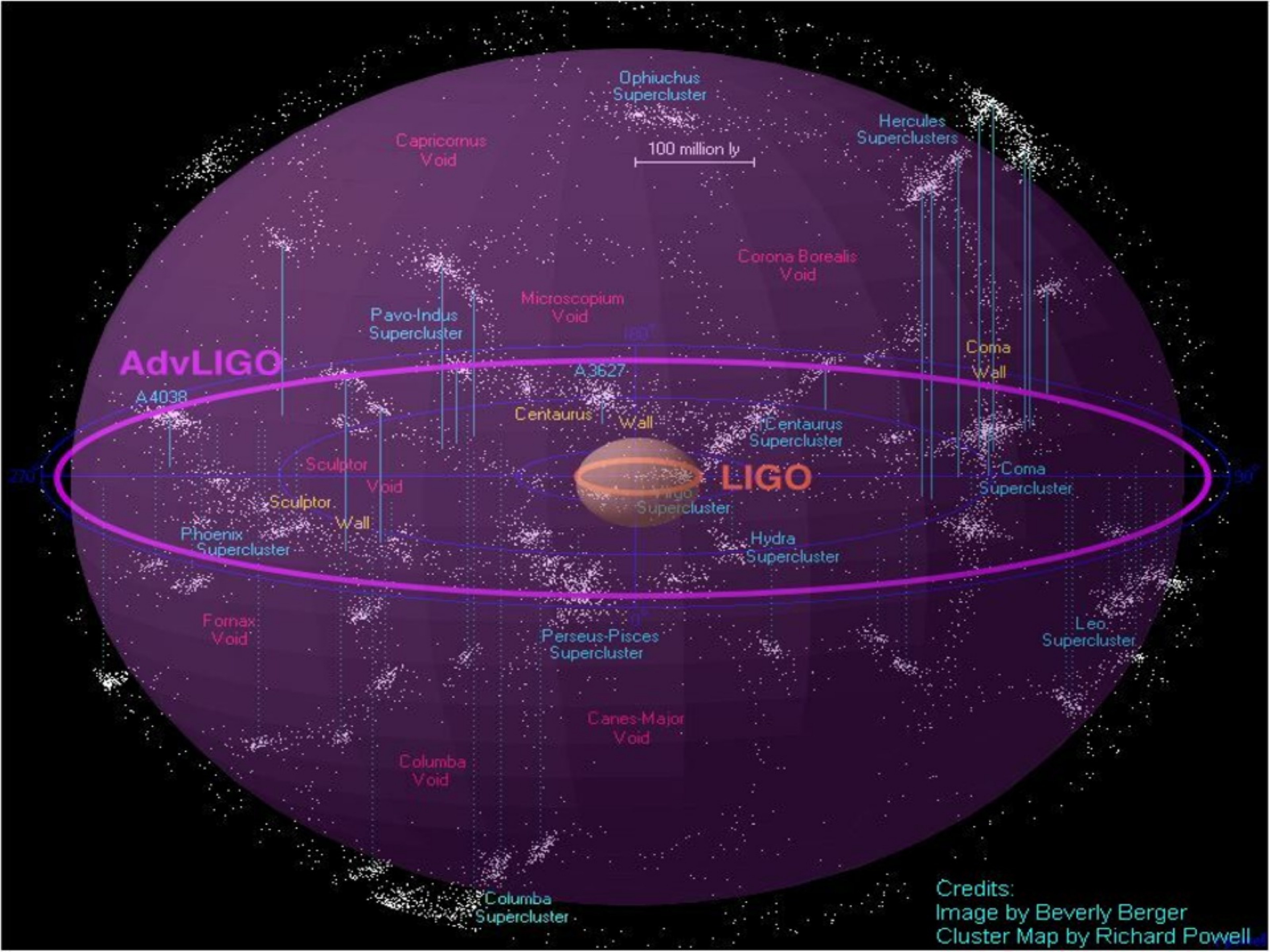
- That is a lot!!! Let's compare:

> 1 PeV / m^2 at Earth!

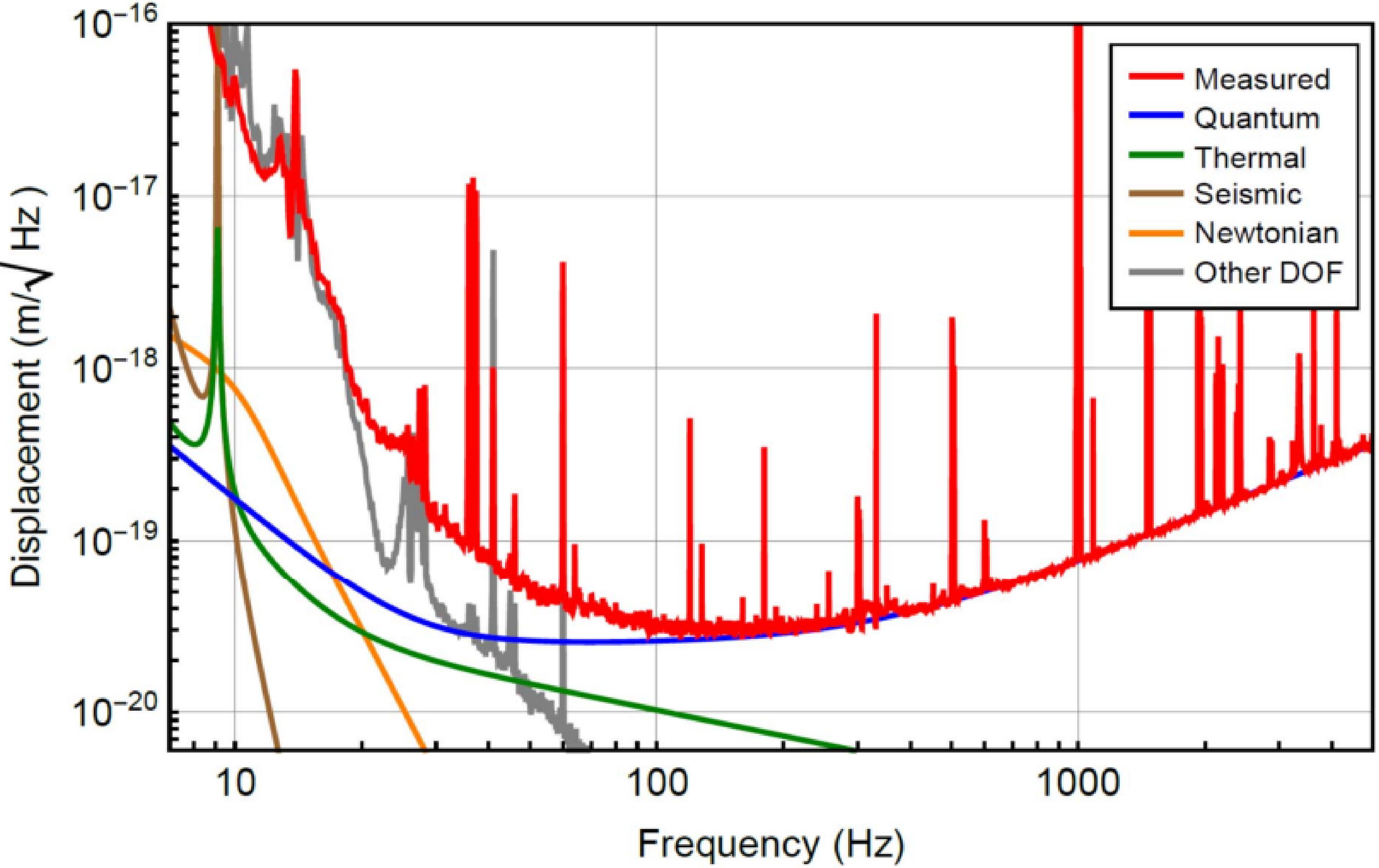
  - Our Sun has lost 0.03% of its mass in 5 billion years, through electromagnetic emission (so this was 10,000 times more, in < 1s)
  - The power output was briefly large than all of the light from all of the stars in the visible universe
- And still, it produced only a tiny distortion here on Earth: space-time is very, very stiff (roughly 10^{22} times stiffer than steel)

Sensitivity: past, present and future



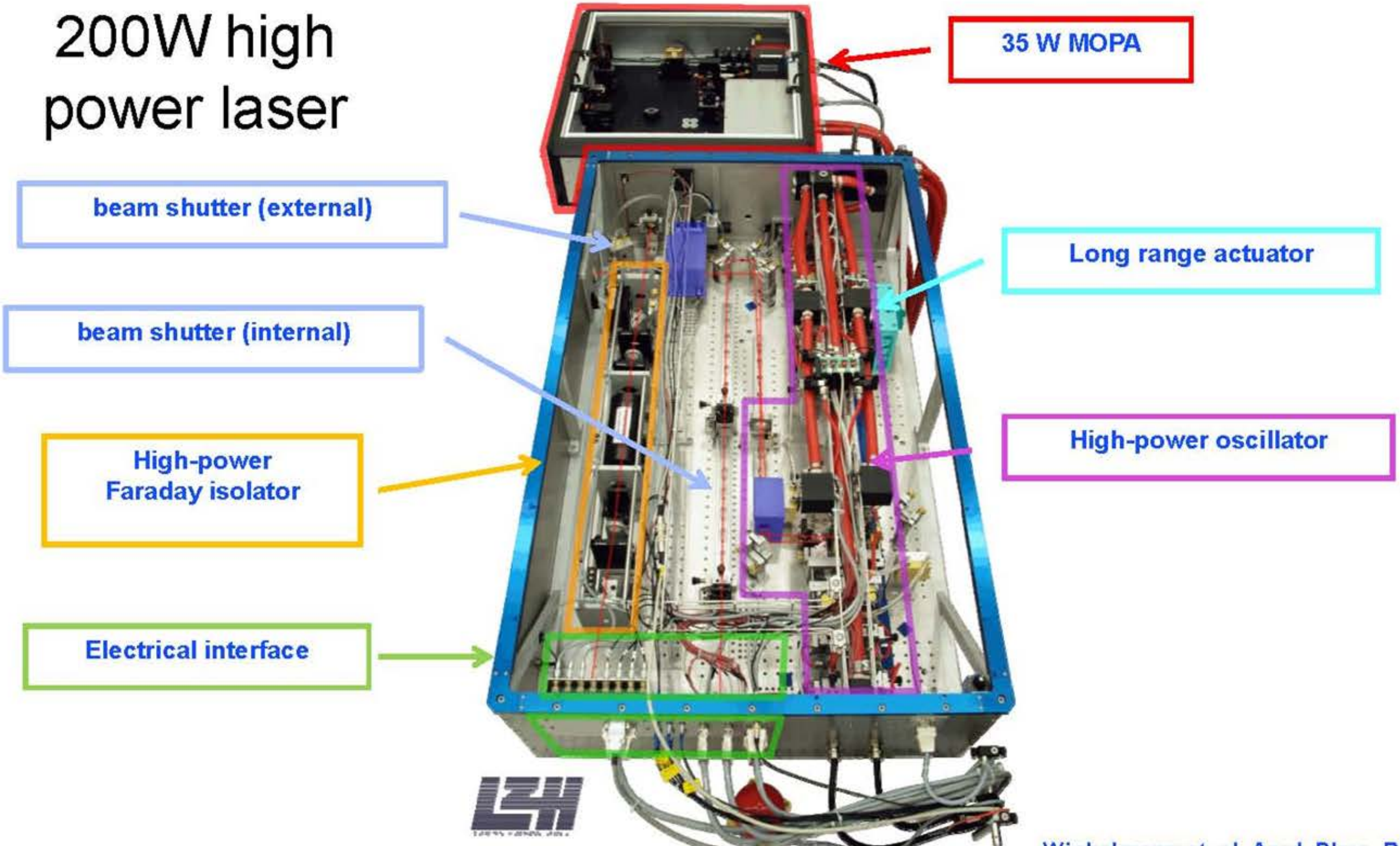

Ophiuchus
Supercluster
Capricornus
Void
100 million ly
Hercules
Superclusters
Corona Borealis
Void
Microscopium
Void
Pavo-Indus
Supercluster
AdvLIGO
A3627
Coma
Wall
A4038
Centaurus
Wall
Centaurus
Supercluster
Sculptor
Void
LIGO
Coma
Supercluster
Virgo
Supercluster
Sculptor
Wall
Phoenix
Supercluster
Hydra
Supercluster
Fornax
Void
Perseus-Pisces
Supercluster
Leo
Supercluster
Canes-Major
Void
Columba
Void
Columba
Supercluster
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Noise sources: the O1 budget



More Photons

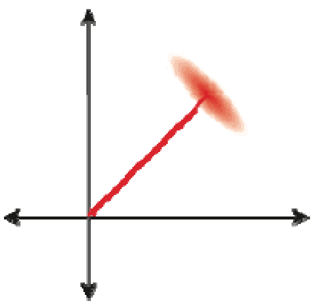
200W high power laser



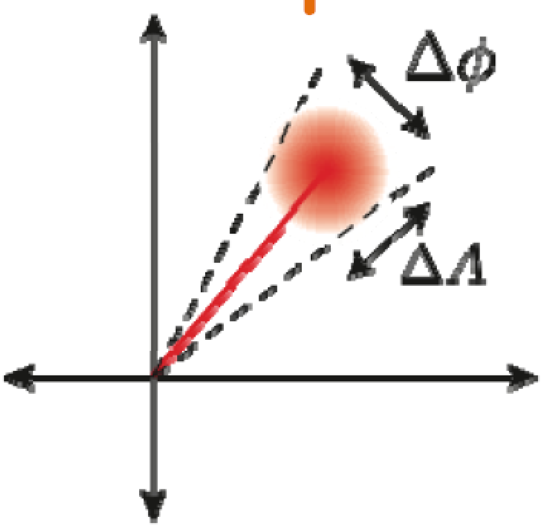
Winkelmann et. al, Appl. Phys. B. (2011)
DOI 10.1007/s00340-011-4411-9

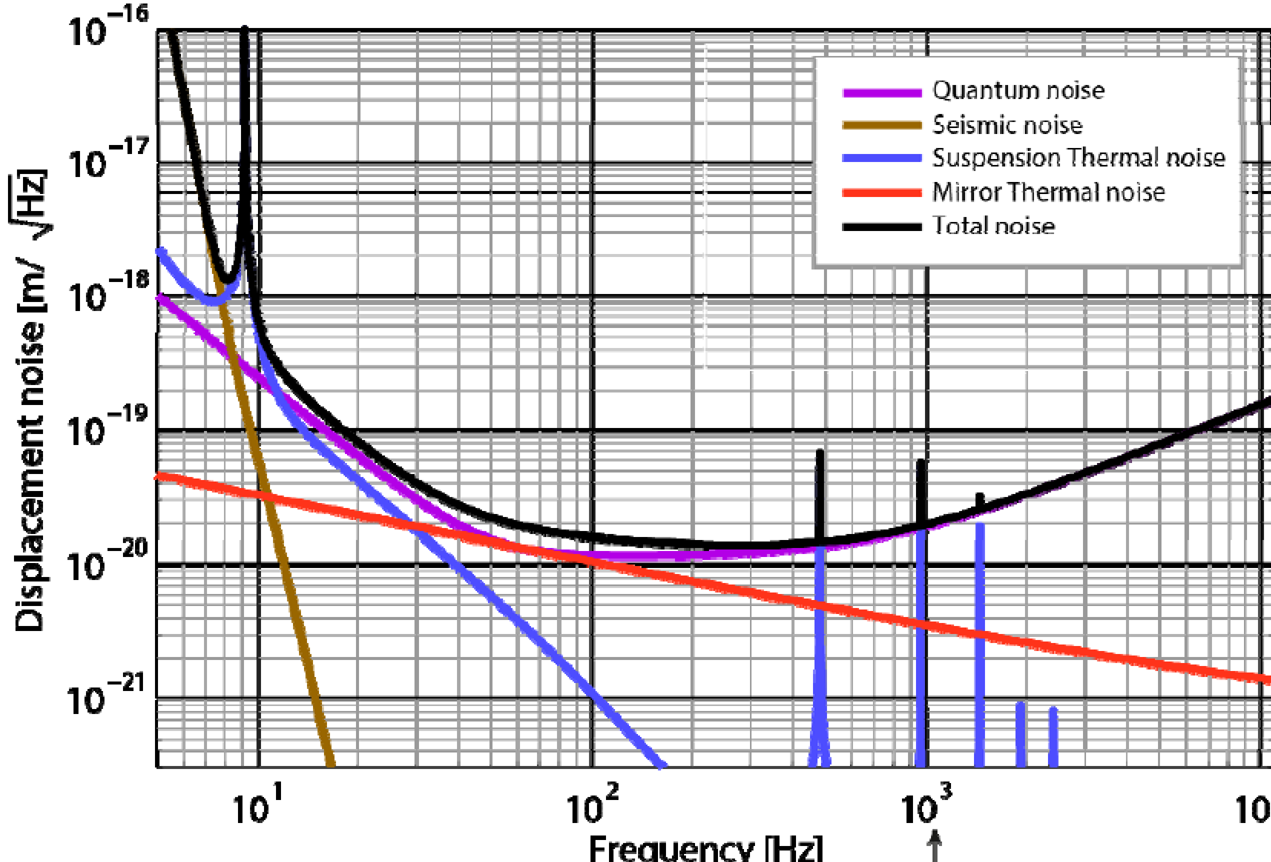

LESS THERMAL
NOISE
MONOLITHIC CONSTRUCTION
HIGH Q MATERIAL – SILICA
NO MAGNETS
LARGE SPOT SIZE

How to Beat the Quantum Limit

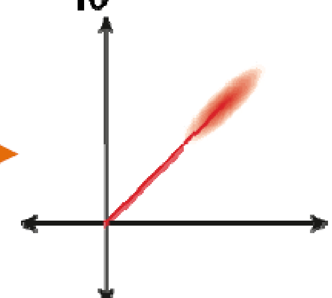


Reduced Amplitude Noise



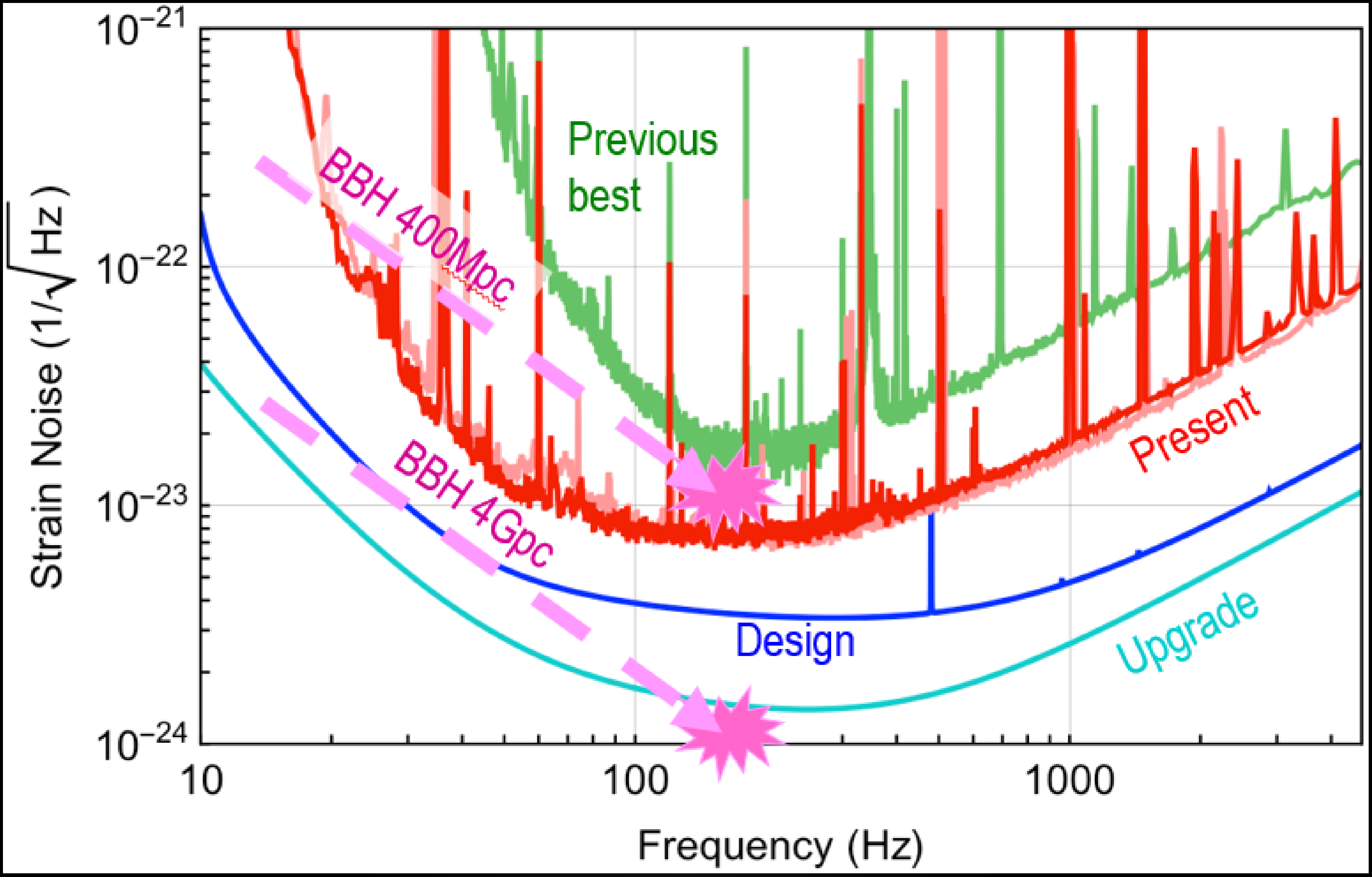


Reduced Phase Noise

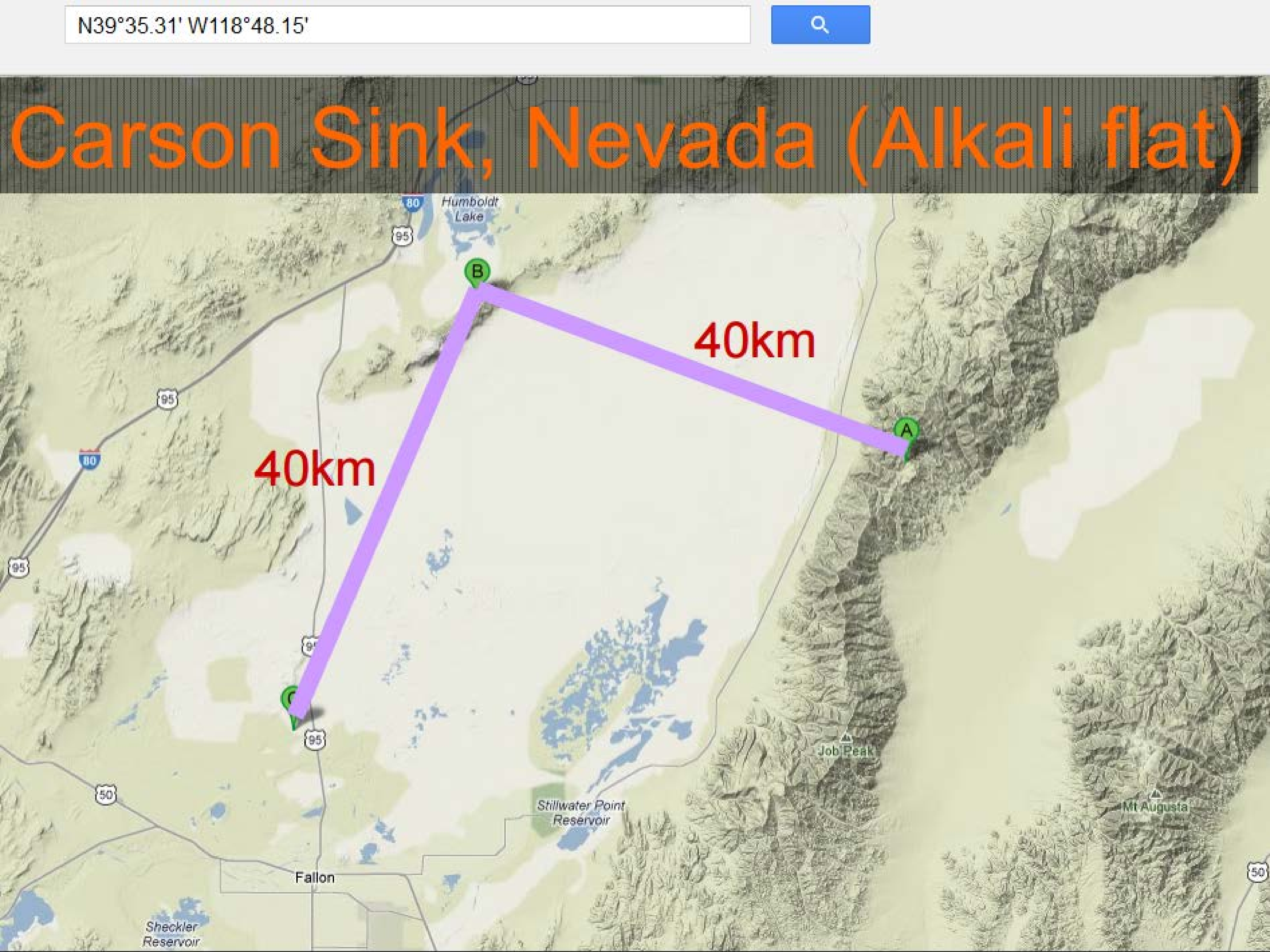


Why were there vacuum leaks?

LIGO Noise: "Range"

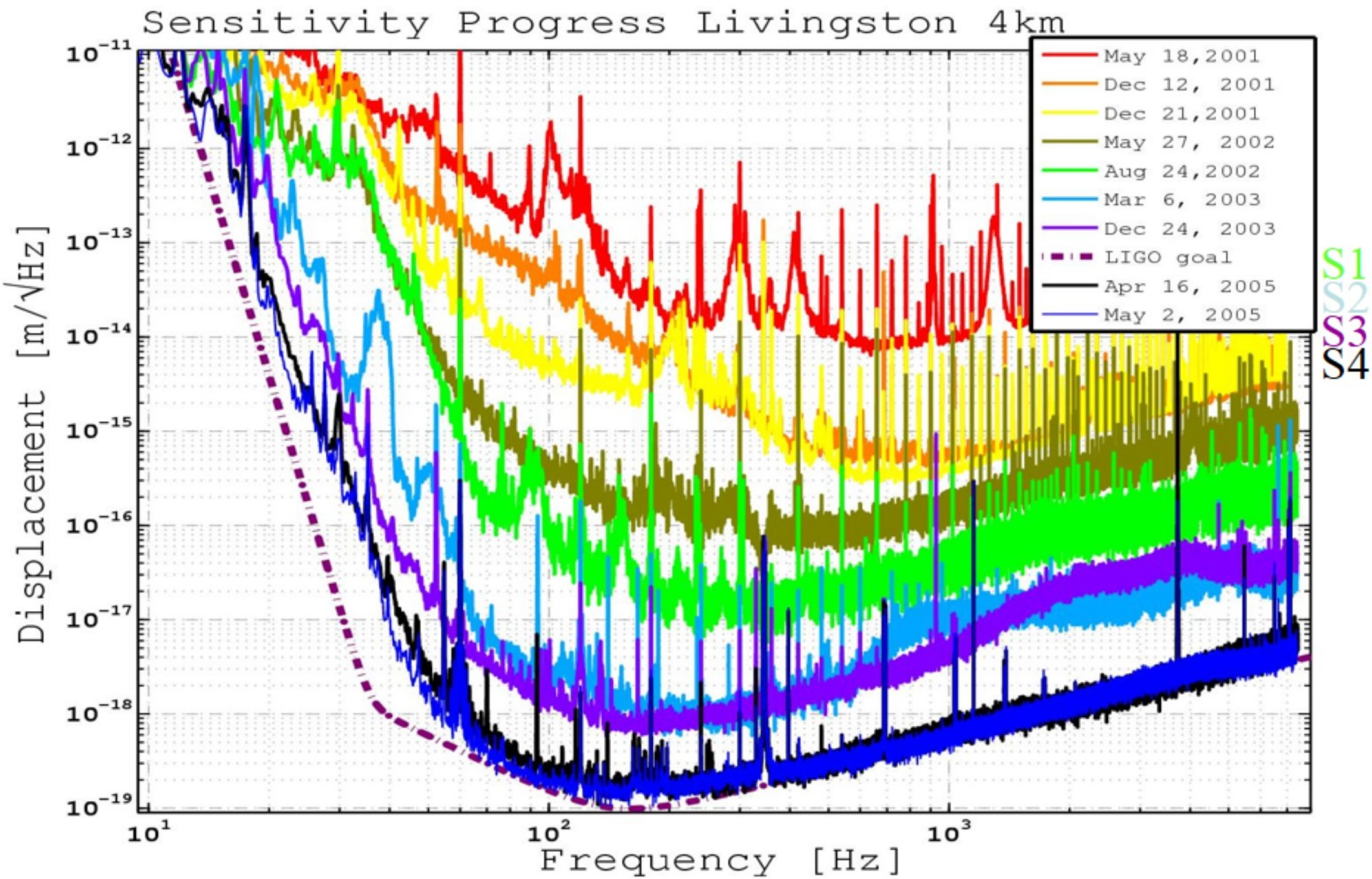


Carson Sink, Nevada (Alkali flat)



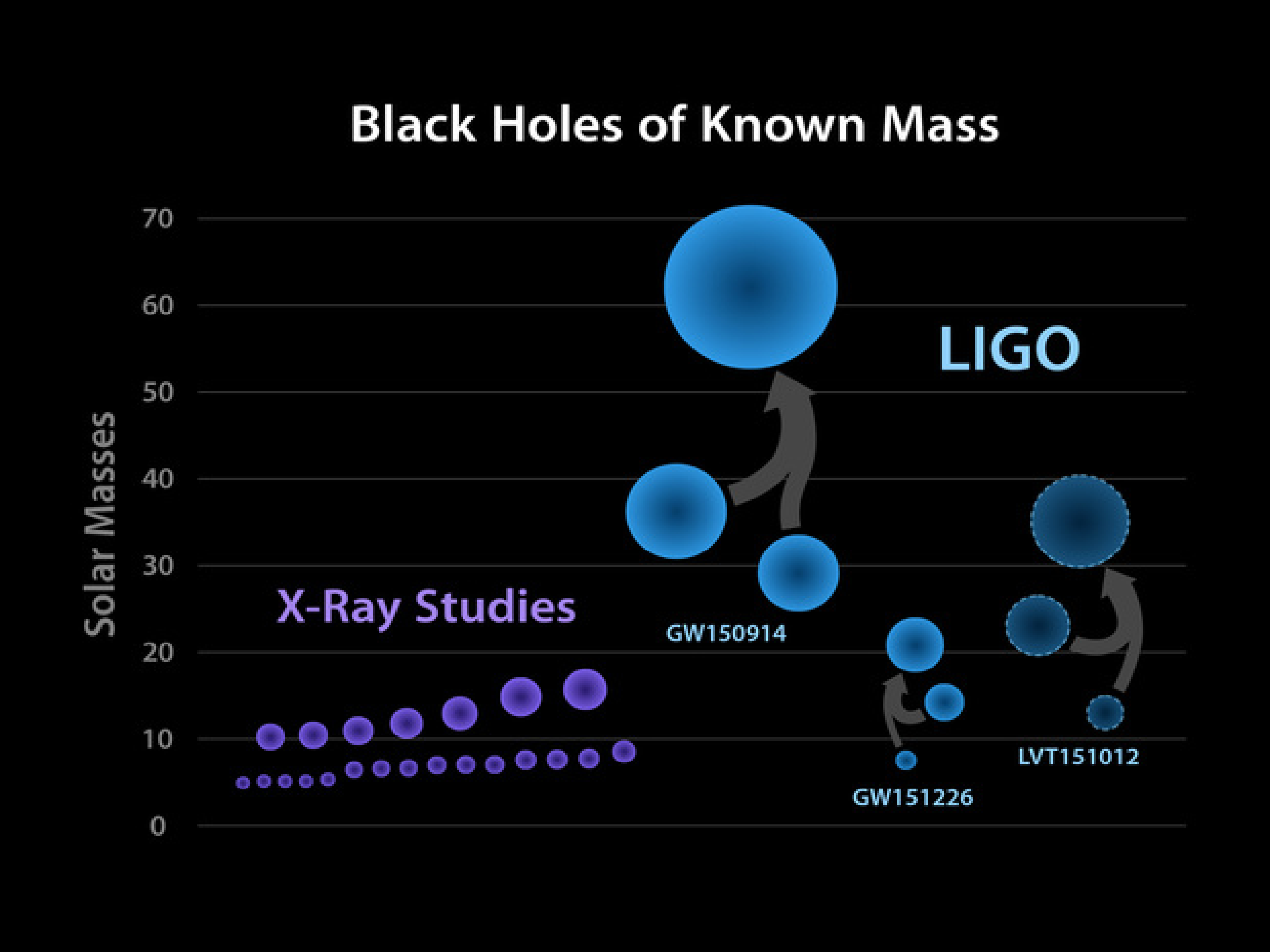

Thank You for your
attention

Early Noise Progression Livingston 4km

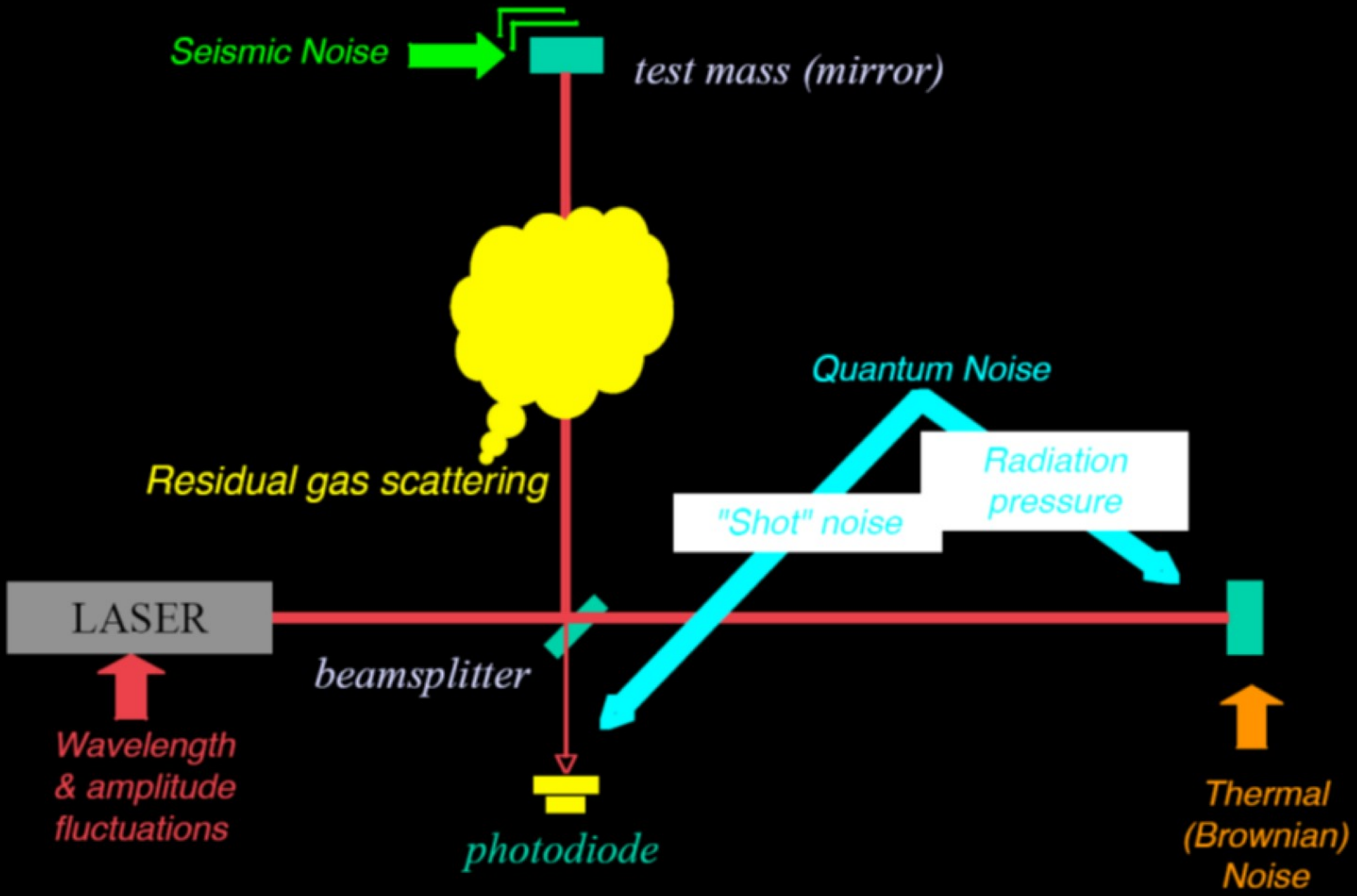


Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5.8 \times 10^{-7}$	7×10^{-8} ($> 5.3\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
GW151226	26 December 2015 03:38:53	$< 5.8 \times 10^{-7}$	7.4×10^{-8} ($> 5.3\,\sigma$)	$8.8^{+0.4}_{-0.3}$	14^{+9}_{-3}	8^{+2}_{-3}	$0.20^{+0.21}_{-0.10}$	490^{+180}_{-210}
LVT151012	12 October 2015 09:54:43	0.44	0.05 ($1.9\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

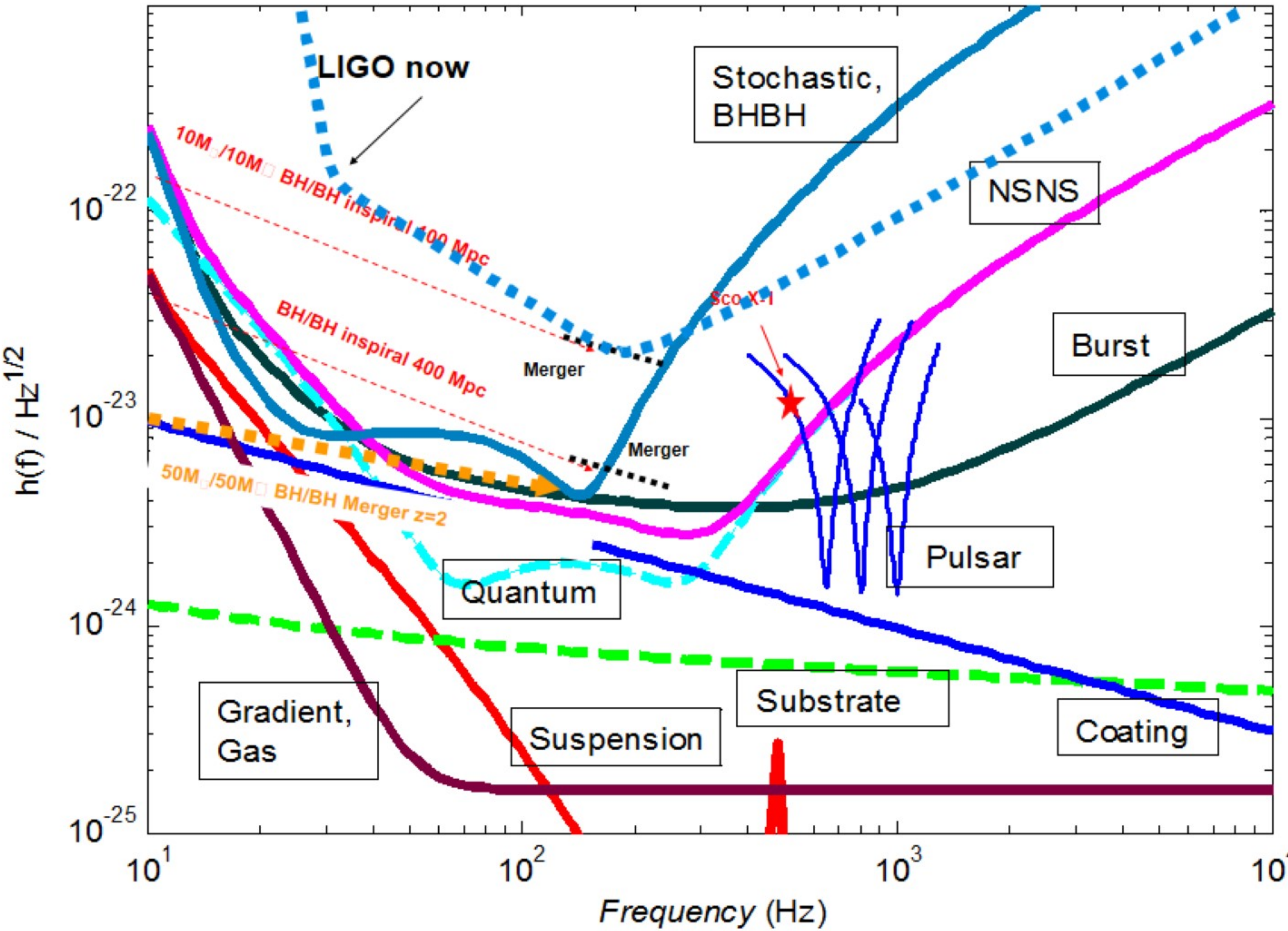
TABLE I. Parameters of the three most significant events. The false alarm rate (FAR) and false alarm probability ($\mathscr{F}$) given here were determined by the PyCBC pipeline; the GstLAL results are consistent with this. The values for the second and third events are calculated after the more significant events are removed from the background. The source-frame chirp mass $\mathscr{M}$, component masses $m_{1,2}$, effective spin χ_{eff}, and luminosity distance D_L are determined using a parameter estimation method that assumes the presence of a coherent compact binary coalescence signal starting at 20 Hz in the data [59]. The results are computed by averaging the posteriors for two model waveforms. Quoted uncertainties include both the 90% credible interval and an estimate for the 90% range of systematic error determined from the variance between waveform models. Further parameter estimates of GW150914 are presented in [19], GW151226 in [2] and LVT151012 in Appendix A.

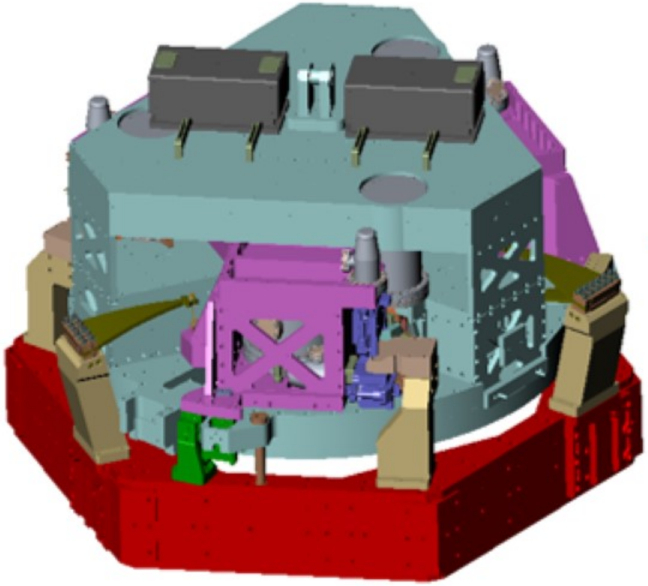

Black Holes of Known Mass
70
60
50
40
30
20
10
0
Solar Masses
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012

Noise Cartoon

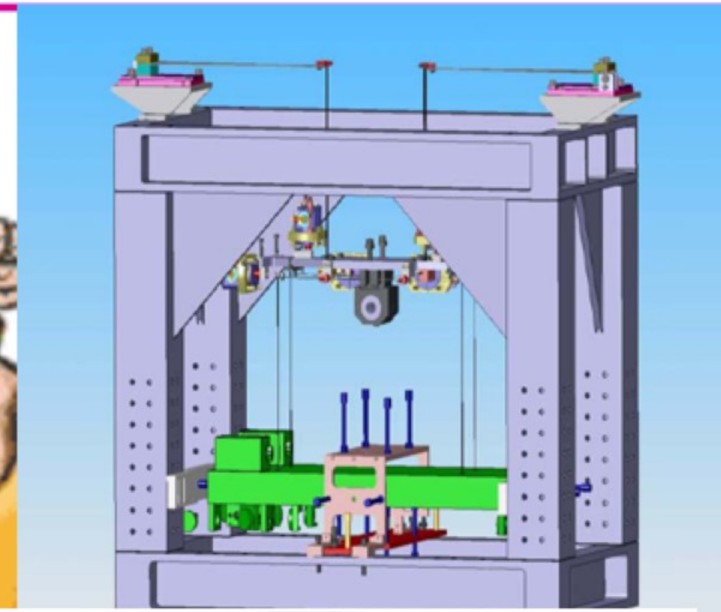


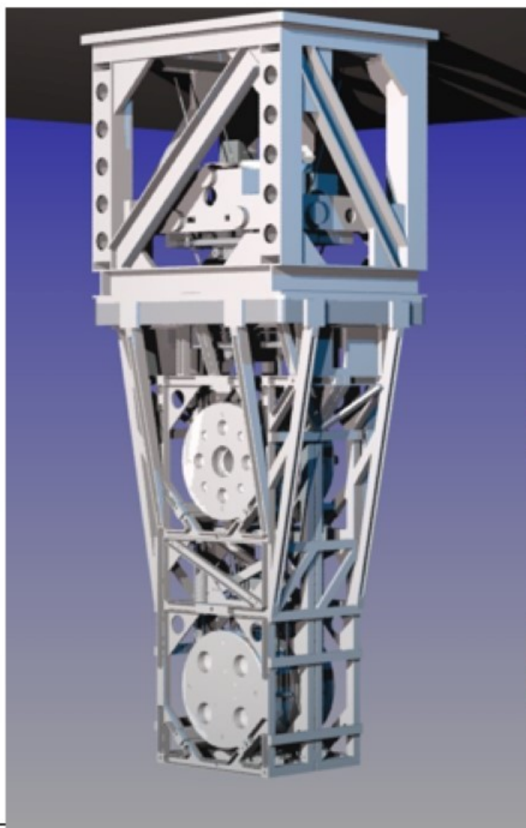
Advanced Ligo

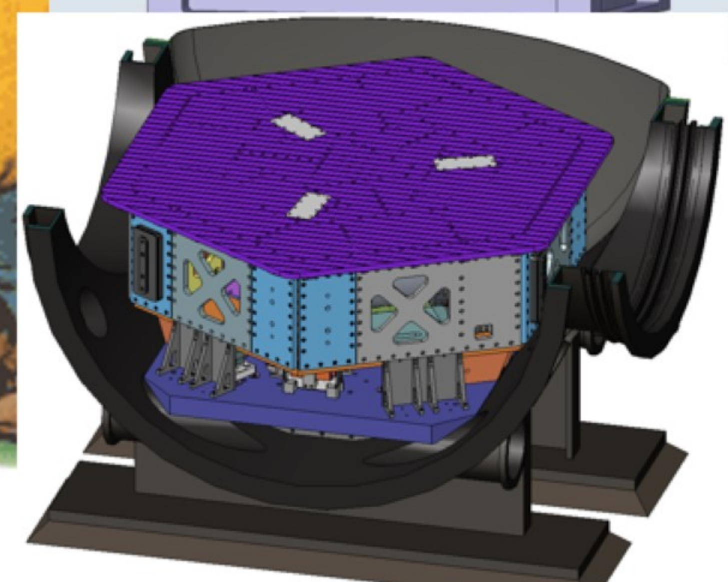


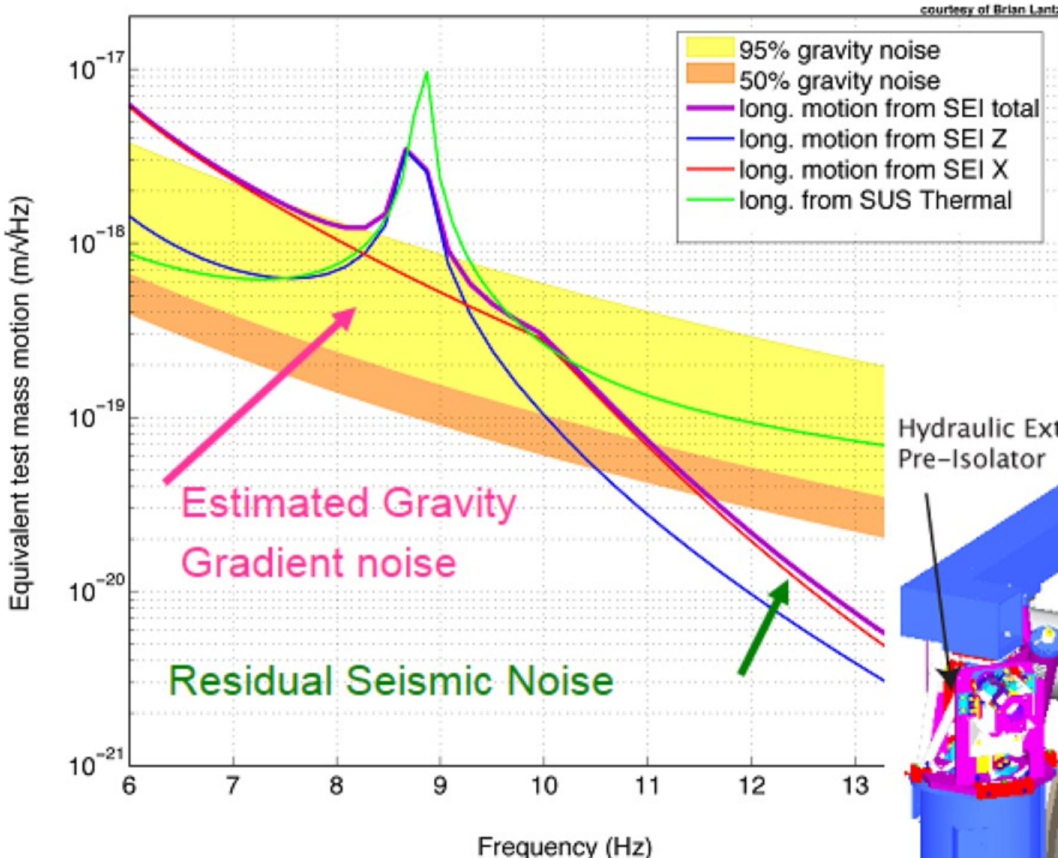


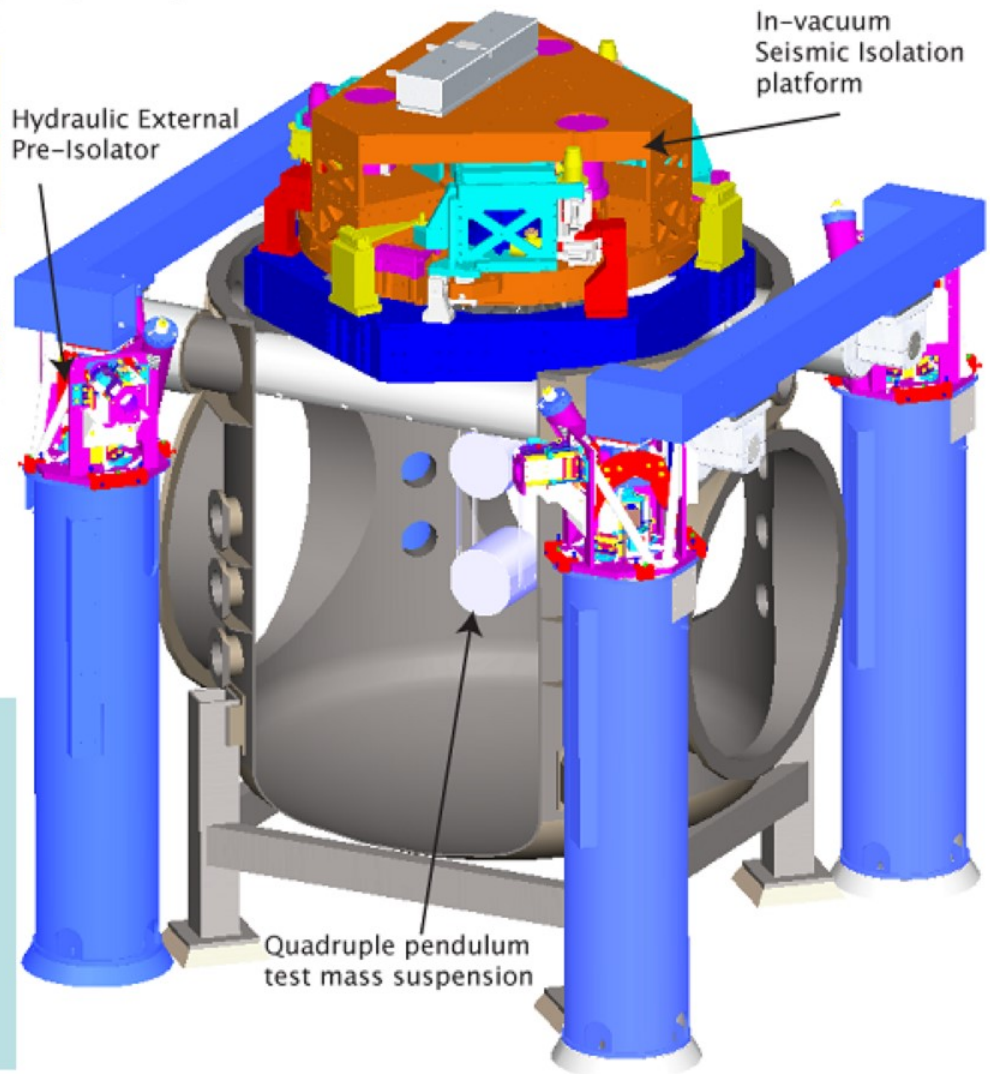
Seismic Noise







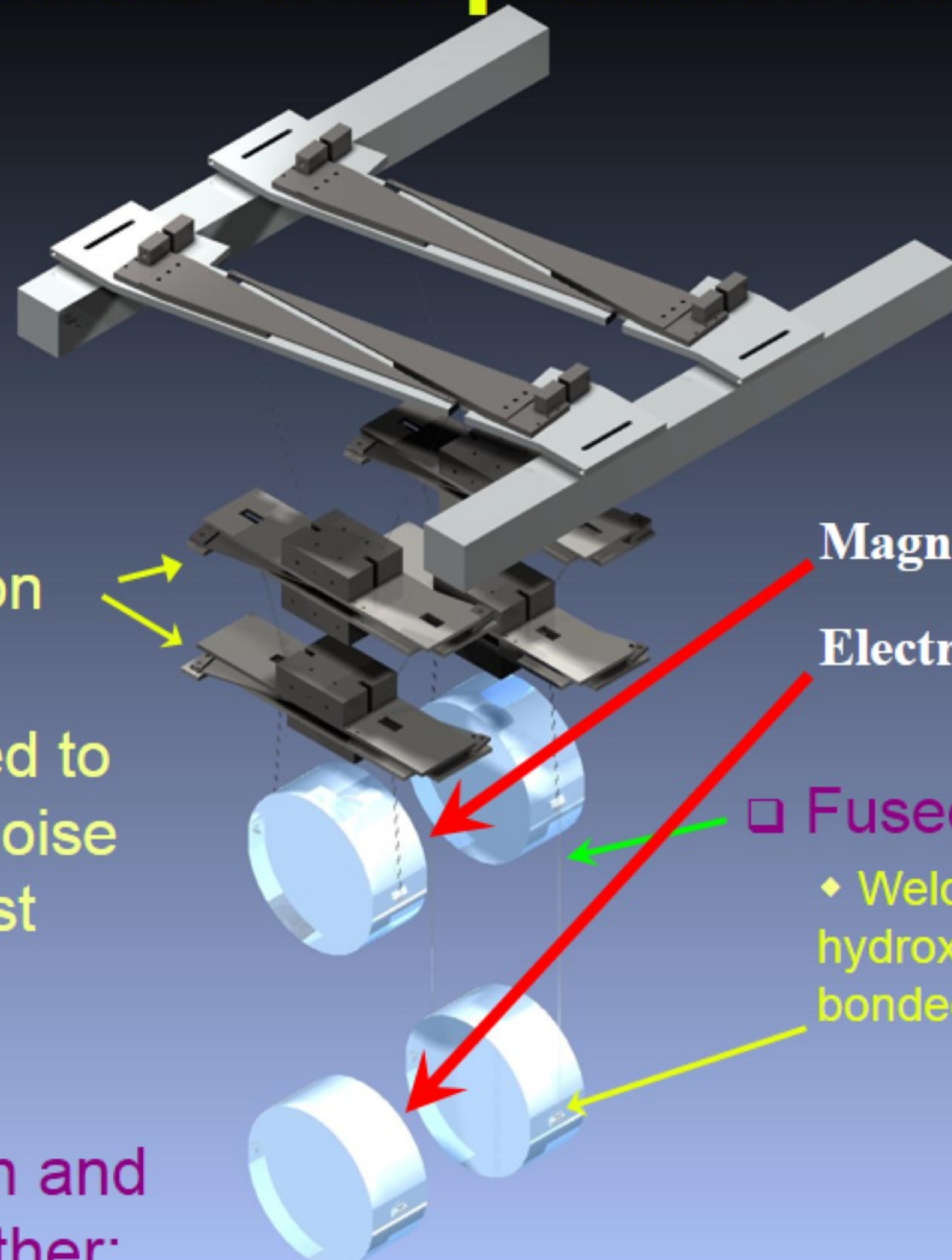




Advance Ligo Seismic Isolation is designed so as not to be a limiting noise source

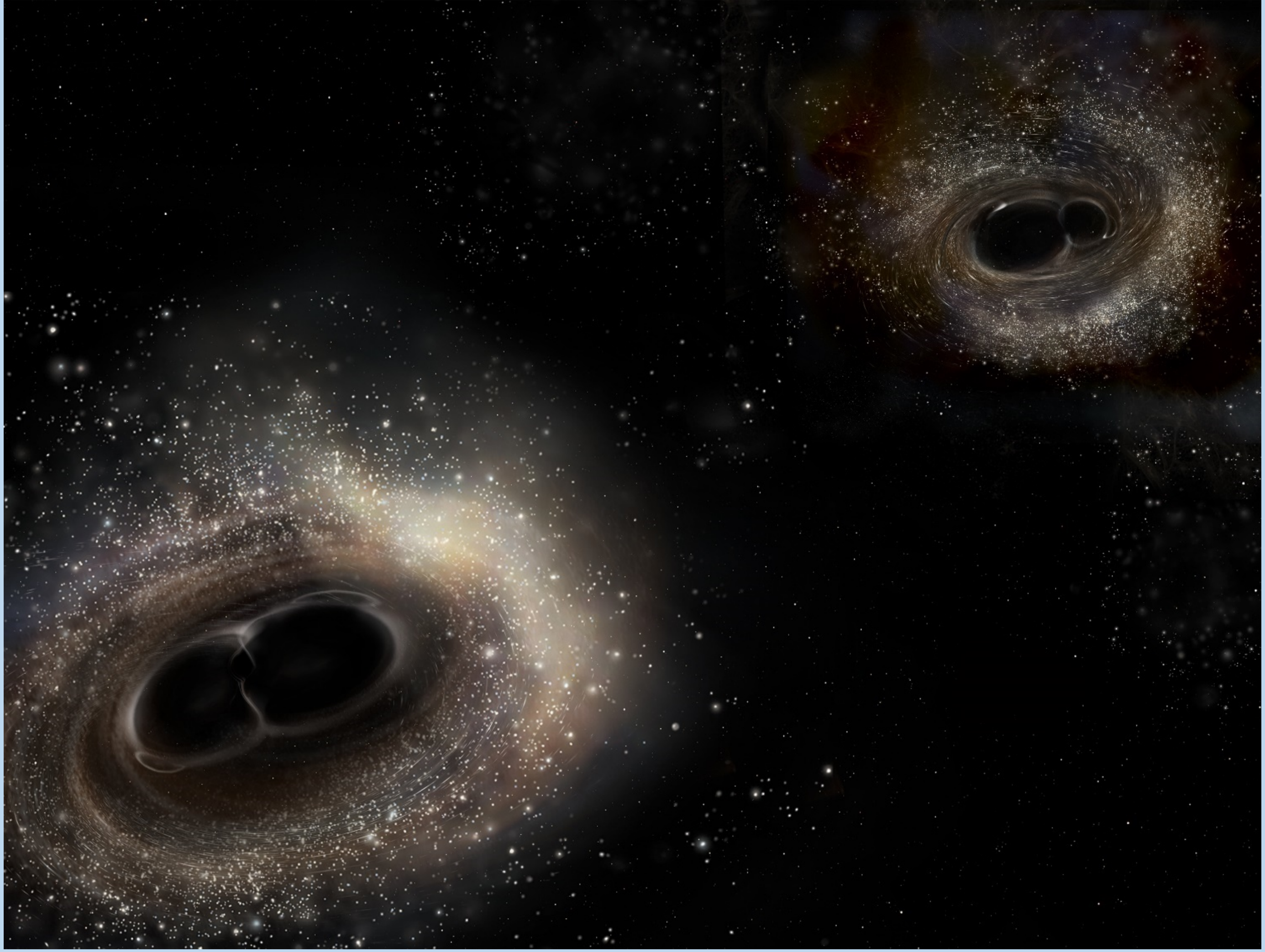
Quad Suspensions

- Quadruple pendulum:
  - ~10^7 attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses



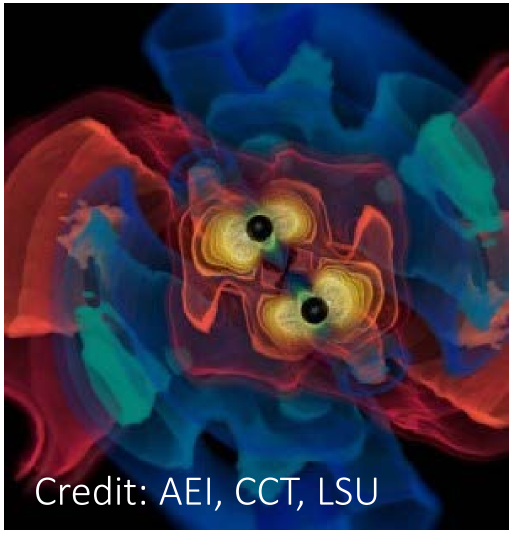
- Fused silica fiber
  - Welded to ‘ears’, hydroxy-catalysis bonded to optic

- Seismic isolation and suspension together:



A comparison of the GW150914 and GW151226 merging black hole binary systems: This artist's illustration depicts the merging black hole binary systems for GW150914 (left image) and GW151226 (right image). In the GW150914 event, the black holes were 29 and 36 times that of our Sun, while in GW151226, the two black holes weighed in at 14 and 8 solar masses. Image credit: LIGO/A. Simonnet. - See more at: http://ligo.org/detections.php#sthash.drzqF9rW.dpuf

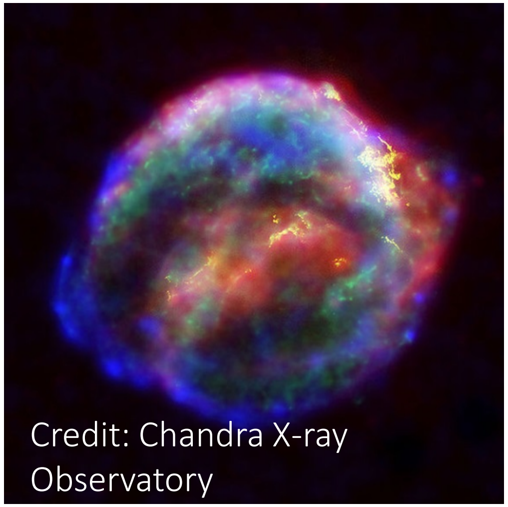
GW sources for ground-based detectors: The most energetic processes in the universe



<u>Coalescing Compact Binary Systems</u>: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

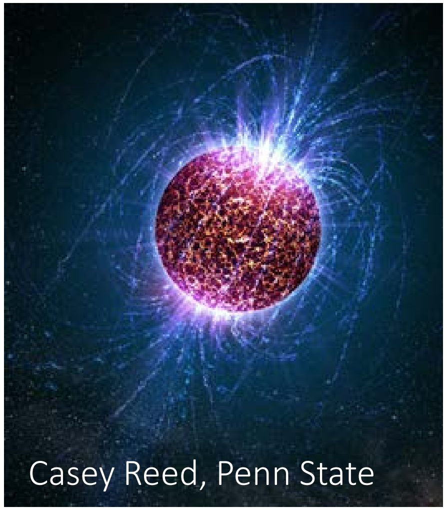
- (effectively) transient



<u>Asymmetric Core Collapse Supernovae</u>

- Weak emitters, not well-modeled ('bursts'), transient

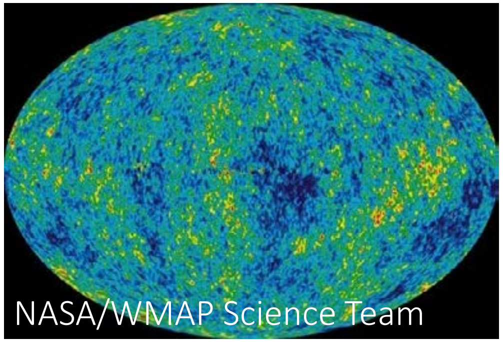
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



<u>Spinning neutron stars</u>

- (effectively) monotonic waveform

- Long duration

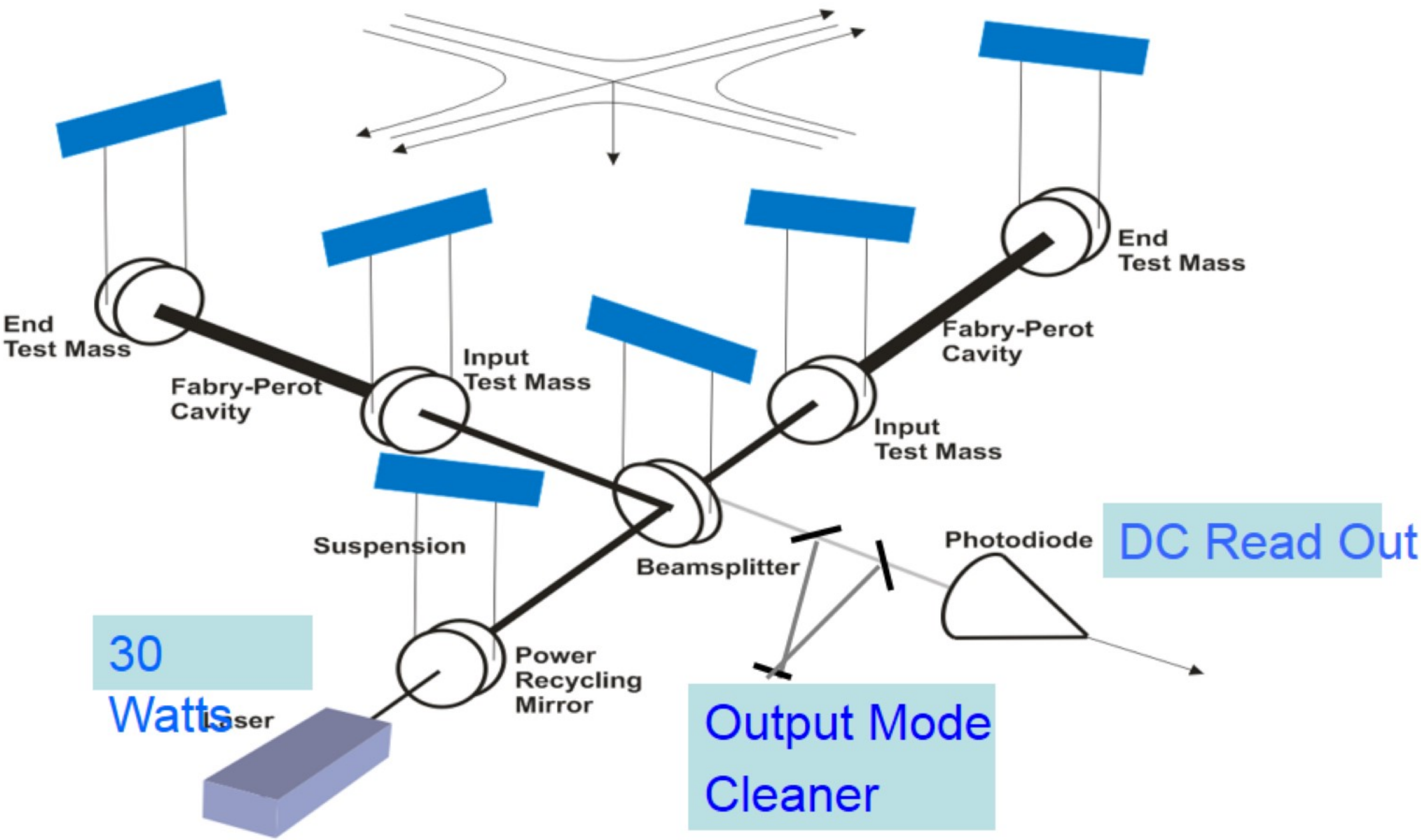


<u>Cosmic Gravitational-wave Background</u>

- Residue of the Big Bang, long duration

- Long duration, stochastic background

ENHANCED LIGO



New Internal Seismic Isolation System