Science and technology at LIGO

Joseph A. Giaime
LIGO Livingston observatory head (Caltech),
Prof. of physics and astronomy (LSU),
for the LIGO Scientific Collaboration

LIGO LIGO

LIGO Scientific Collaboration

LSC

TRINITY UNIVERSITY

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 WASHINGTON, DC

UNIVERSITY OF THE WEST of SCOTLAND UWS

TEXAS TECH UNIVERSITY

清華大學 Tsinghua University

R·I·T

Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE

UNIVERSITY OF STRATHCLYDE

MICHIGAN

CITA ICAT

Università degli Studi del Sannio

NASA GODDARD SPACE FLIGHT CENTER

ICTP SAIFR

THE UNIVERSITY OF WESTERN AUSTRALIA

PAH

UNIVERSITY OF CAMBRIDGE

THE UNIVERSITY OF CHICAGO

MONTANA STATE UNIVERSITY

Caltech

UNIVERSITY OF MINNESOTA

THE UNIVERSITY of MISSISSIPPI

THE UNIVERSITY OF ADELAIDE AUSTRALIA

SOUTHERN UNIVERSITY Agricultural & Mechanical College

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF MELBOURNE

UIB Universitat de les Illes Balears

UNIVERSITY OF WASHINGTON

GEO 600

UTRGV

UNIVERSITY of WISCONSIN UWMILWAUKEE

SYRACUSE UNIVERSITY FOUNDED AD 1870

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Northwestern

UNIVERSITÄT HAMBURG

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

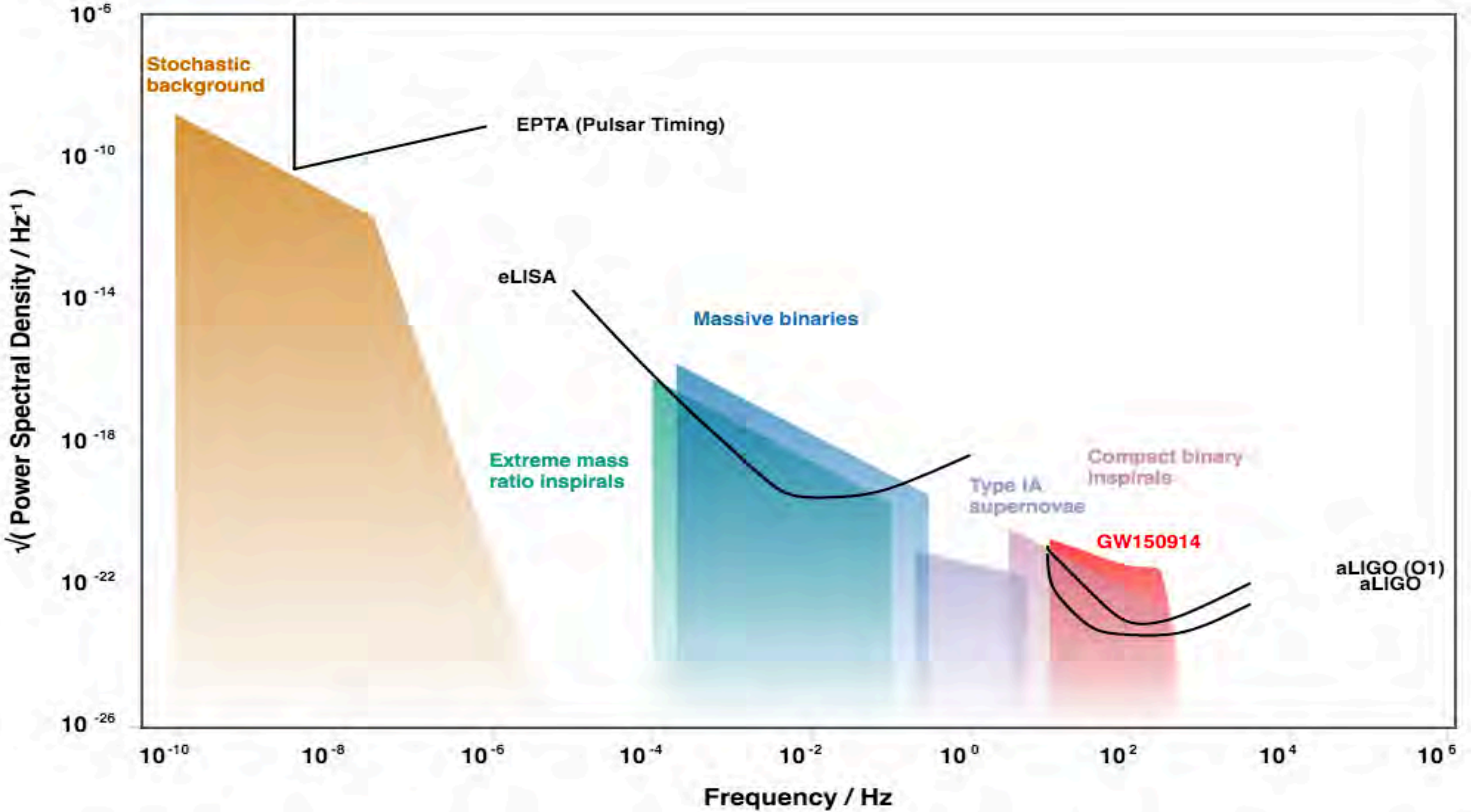
Leibniz Universität Hannover

PennState

WILLIAM SMITH COLLEGE

Science & Technology Facilities Council Rutherford Appleton Laboratory

Efforts to observe gravitational waves



http://rhcole.com/apps/GWplotter/,

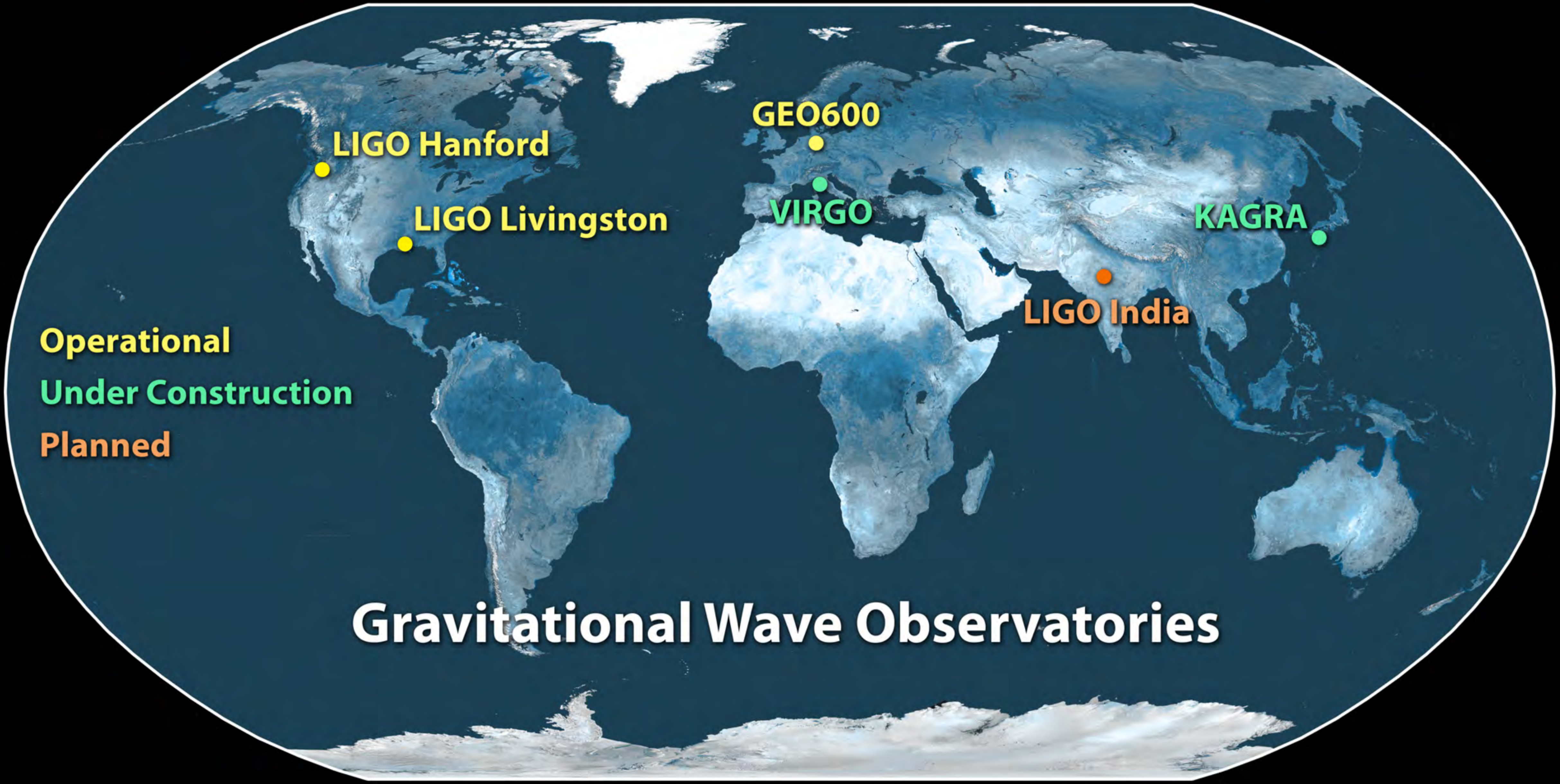
Generation of GW’s

- GW radiation requires a time-varying non-zero quadrupole moment of the source’s mass.
- Constants of nature come together to make the effect very tiny, even for enormous sources.
- ‘Hertzian’ experiment probably impossible.
- Sources include inspiraling binary compact objects, non-spherical core implosion, driven or relaxing normal modes of compact objects, …

$$h \simeq \frac{GM}{c^4}\frac{E_k^{\mathrm{ns}}}{r} \simeq 10^{-20}\left(\frac{E_k^{\mathrm{ns}}}{M_\odot c^2}\right)\left(\frac{10\,\mathrm{Mpc}}{r}\right)$$

where $E_{\mathrm{k}}^{\mathrm{ns}}$ is the non-spherical kinetic energy of the source. This formula is roughly the best-case, with optimal orientation.

How LIGO sees the waves



Gravitational Wave Observatories

Patience and stewardship over generations:

~100 years ago: Albert Einstein published his theory of General Relativity, including prediction of gravitational waves.

~50 years ago: Weber builds bar antennas to attempt detection of the waves.

~45 years ago: Key ideas for interferometric antennas developed by Weiss and others. Bar antenna work continues, including cryogenics.

~40 years ago: (U.S.) National Science Foundation funding of pre-LIGO R&D, continued GW detector research internationally, including Glasgow in the U.K. and MPQ in Germany.

~25 years ago: LIGO proposed to the NSF by MIT and Caltech.

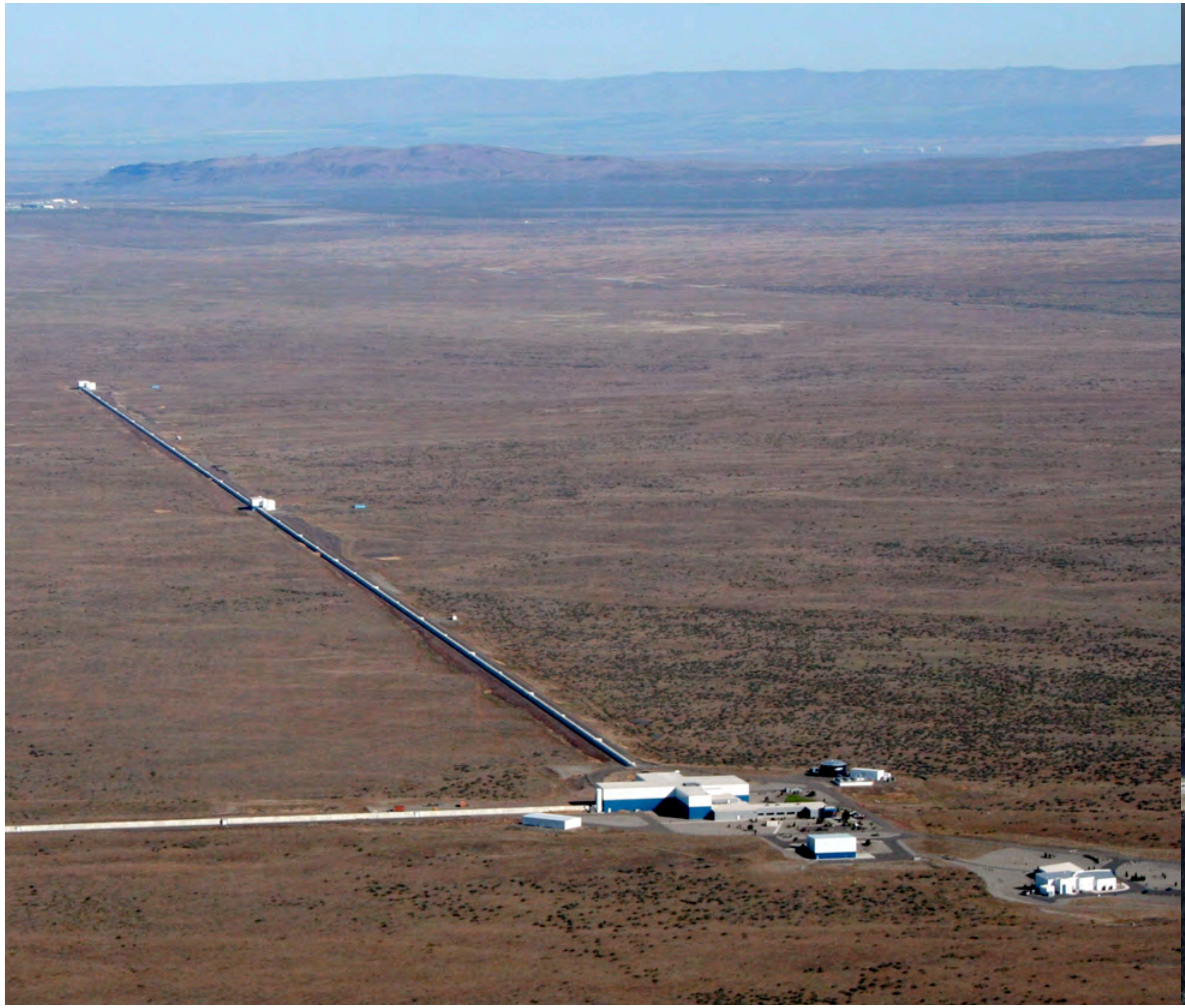
~20 years ago: LIGO site construction began.

~15 years ago: initial LIGO running at design sensitivity.

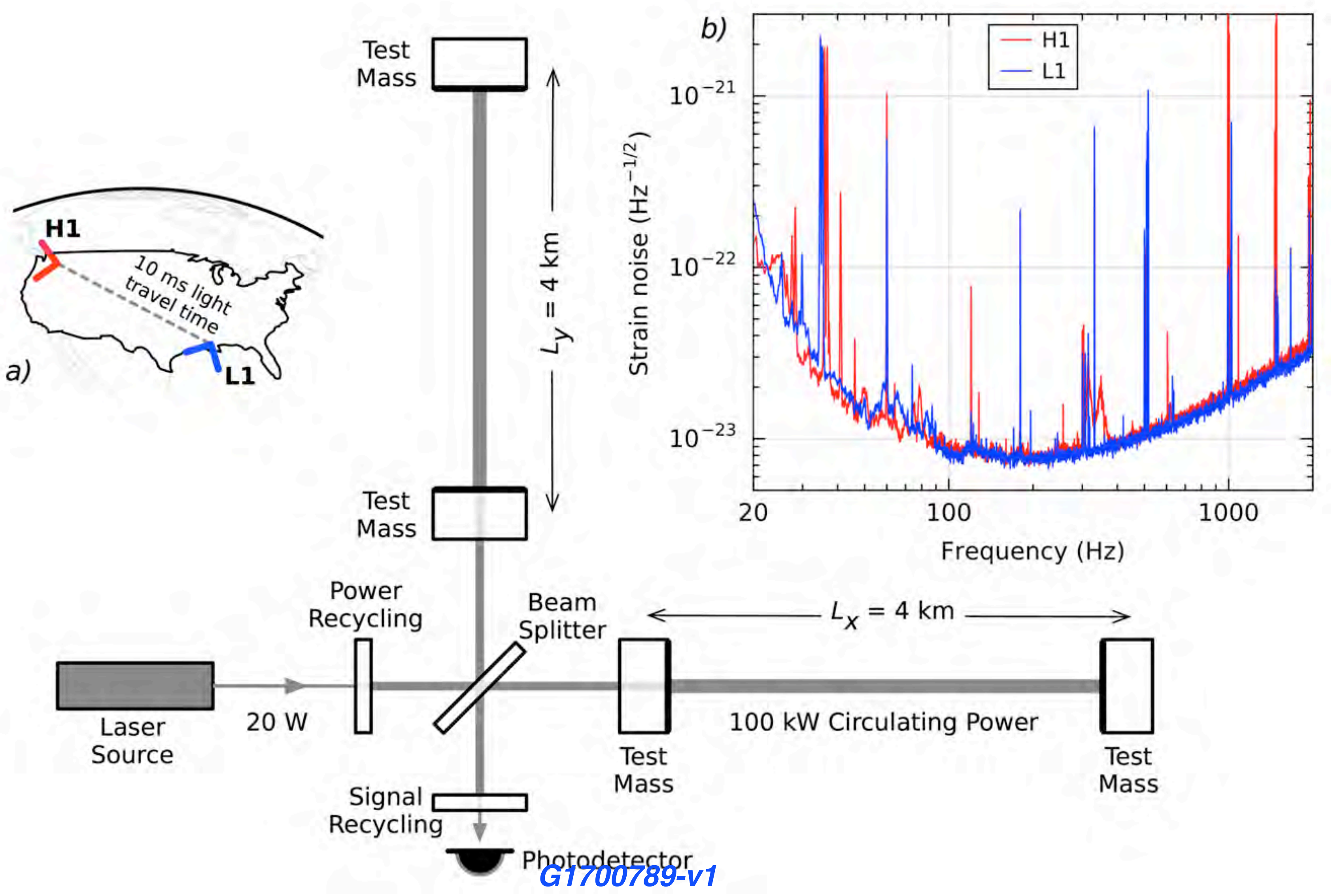
~6 years ago: Advanced LIGO installation began with major international contributions, including from the U.K. and Germany.

~now: Advanced LIGO detectors see astrophysical signals.

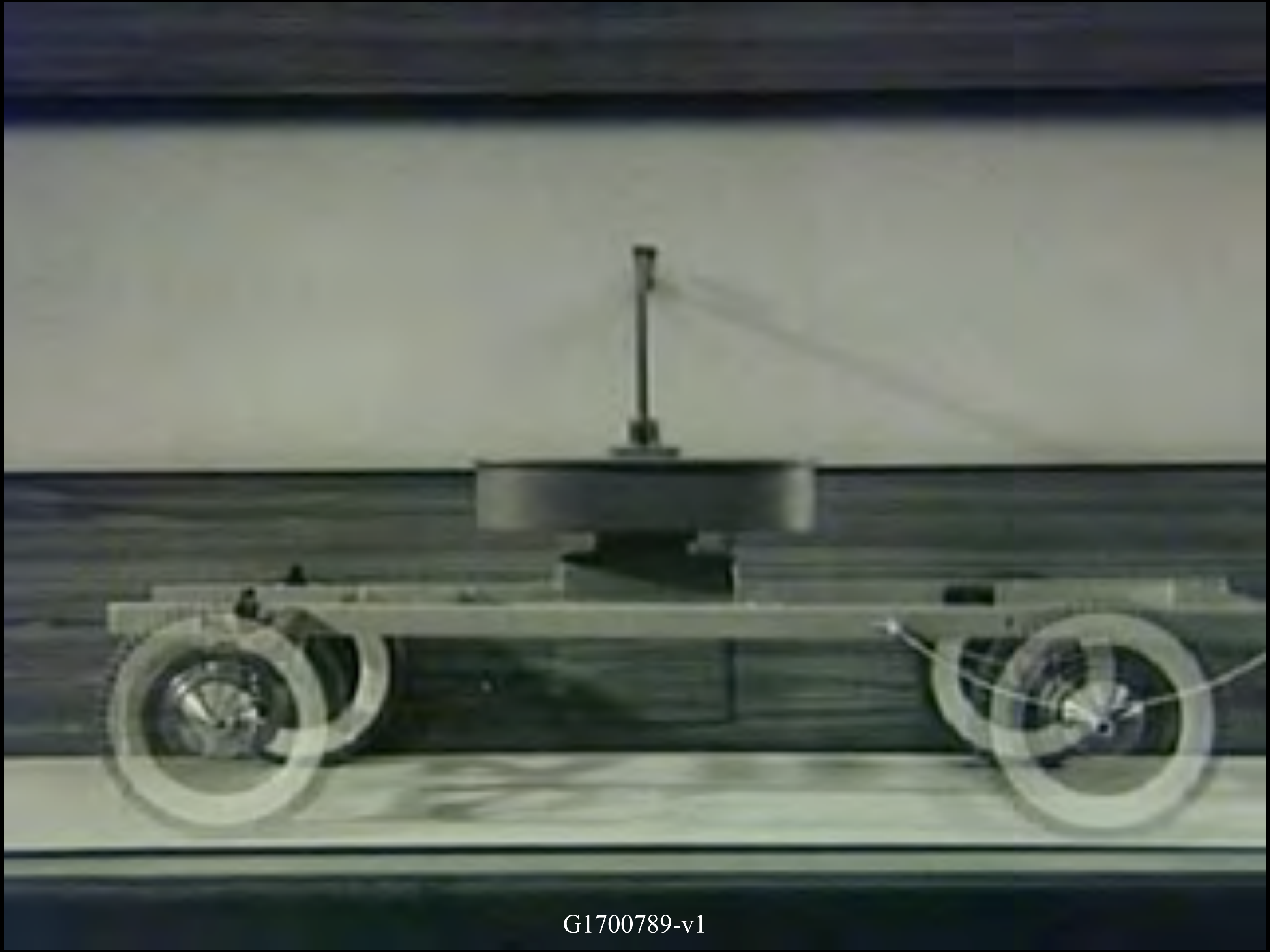
LIGO Hanford and LIGO Livingston



Advanced LIGO Detectors: installation 2010, first run fall 2015

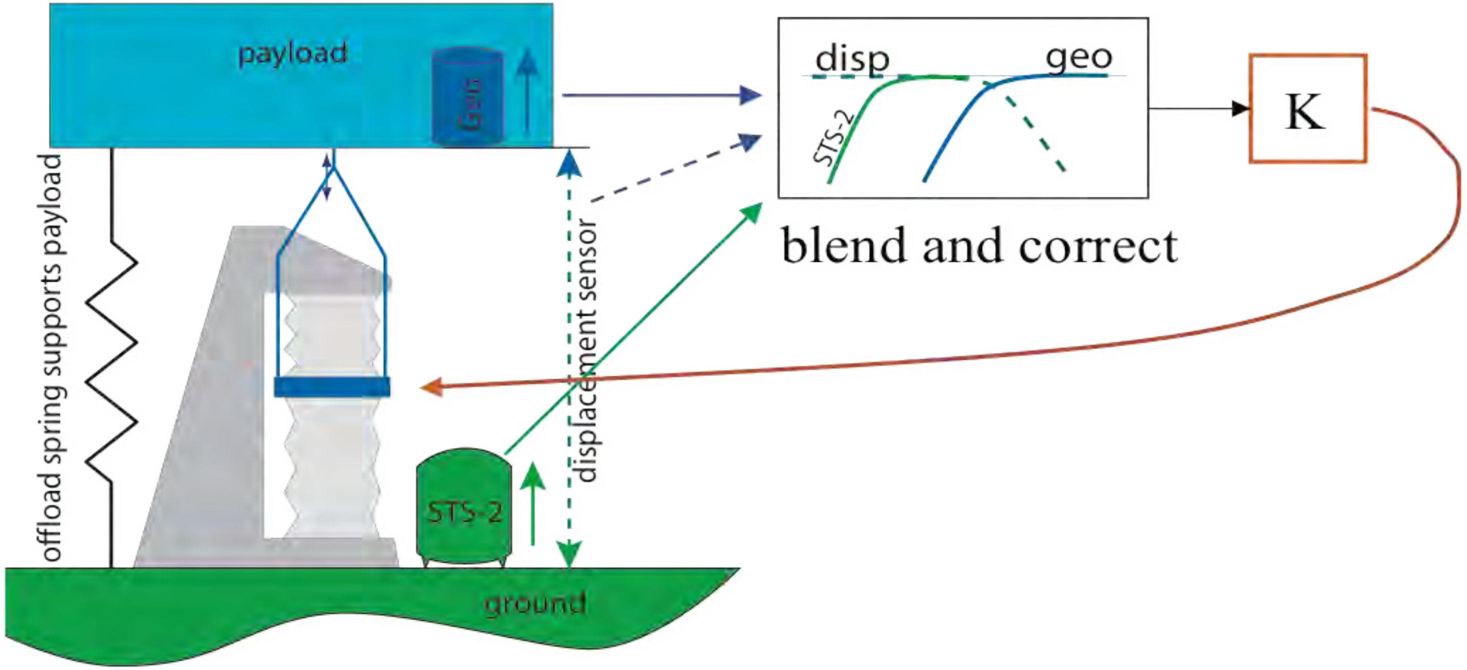


1938 seismic isolation technology

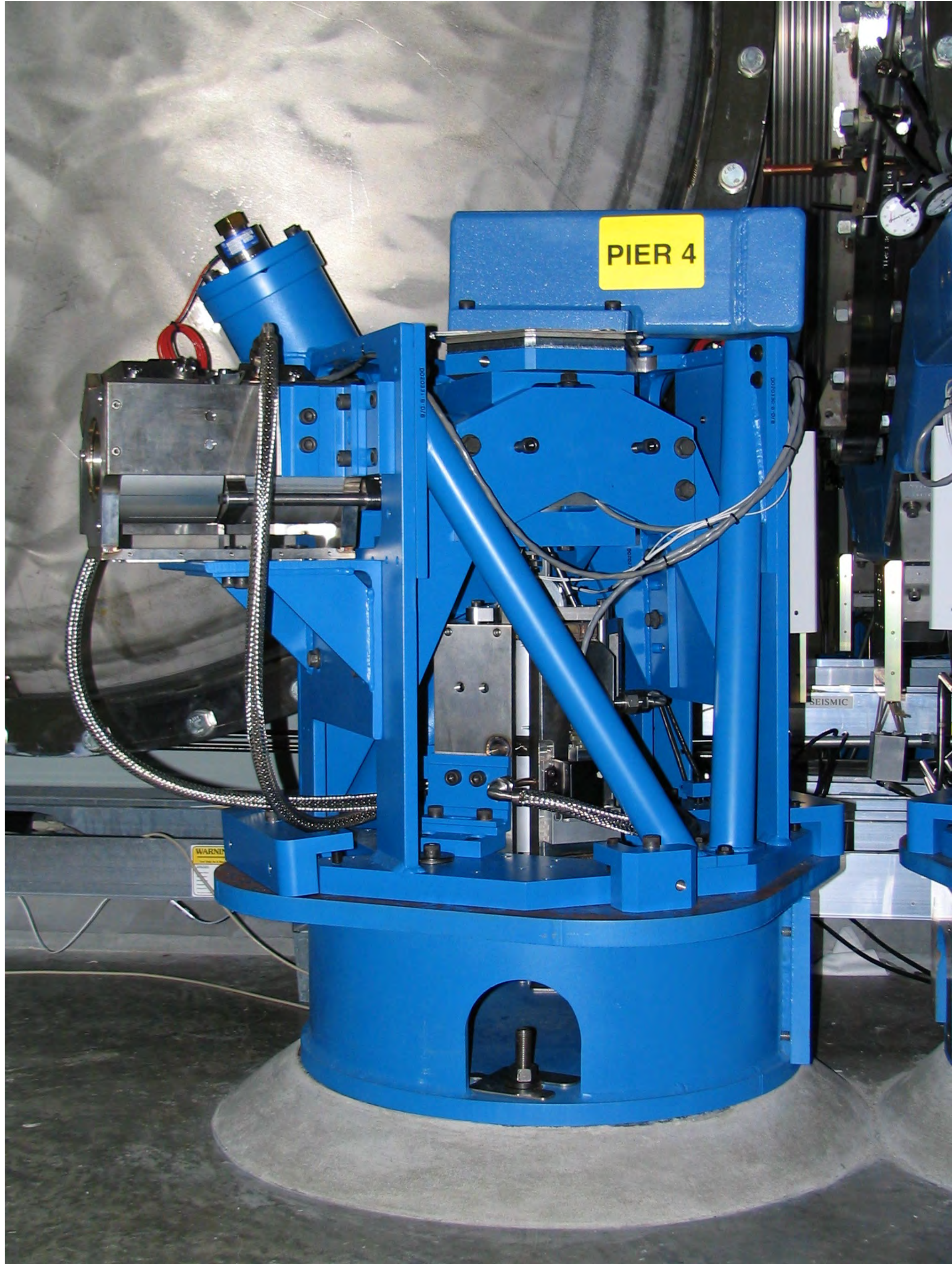


General Motors

Active Seismic Isolation

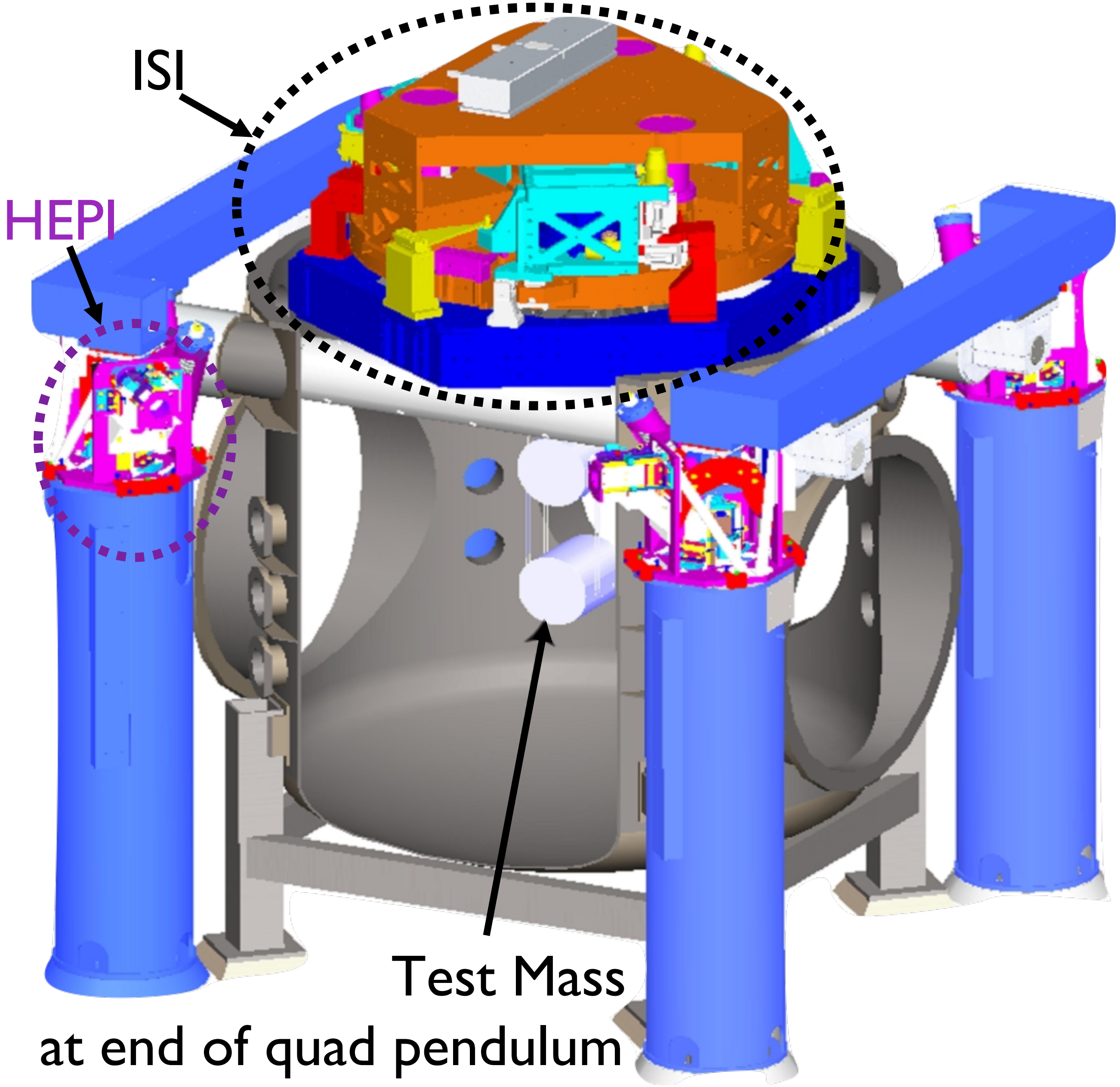


blend and correct



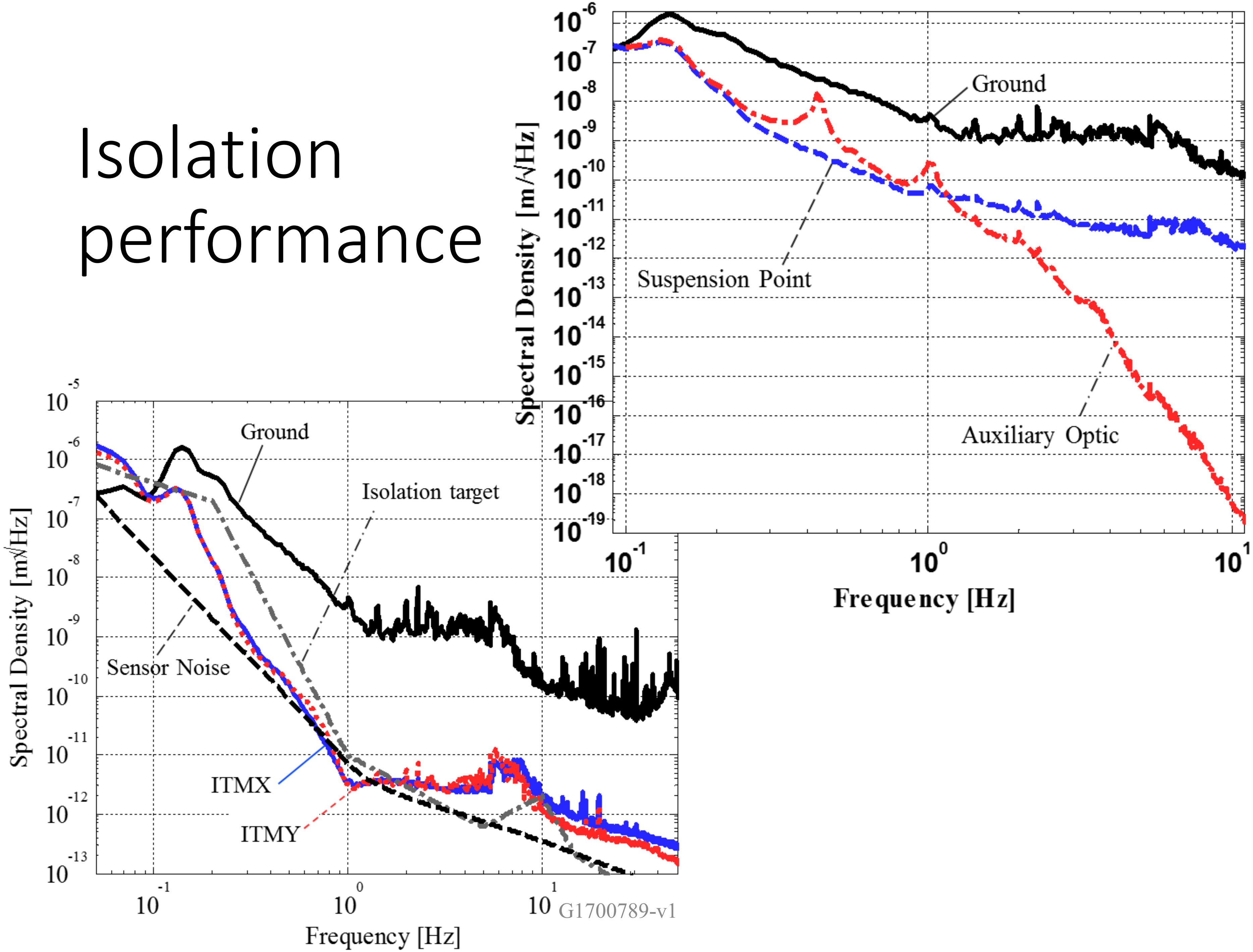
21st Century Seismic Isolation

- HEPI: Hydraulic External Pre-Isolator
  large throw, isolation below ~5 Hz
- ISI: Internal Seismic Isolation
  Isolates above ~0.2 Hz
- Quadruple pendulum: superior performance at 10 Hz and above



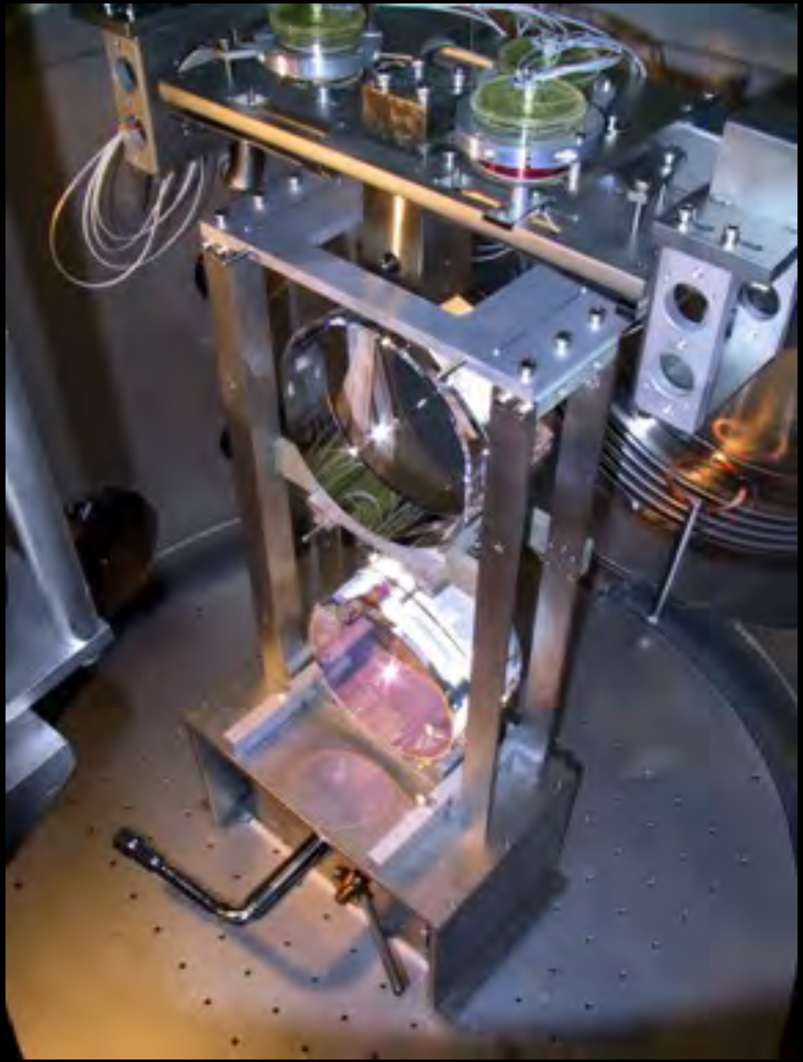
Test Mass
at end of quad pendulum

Isolation performance



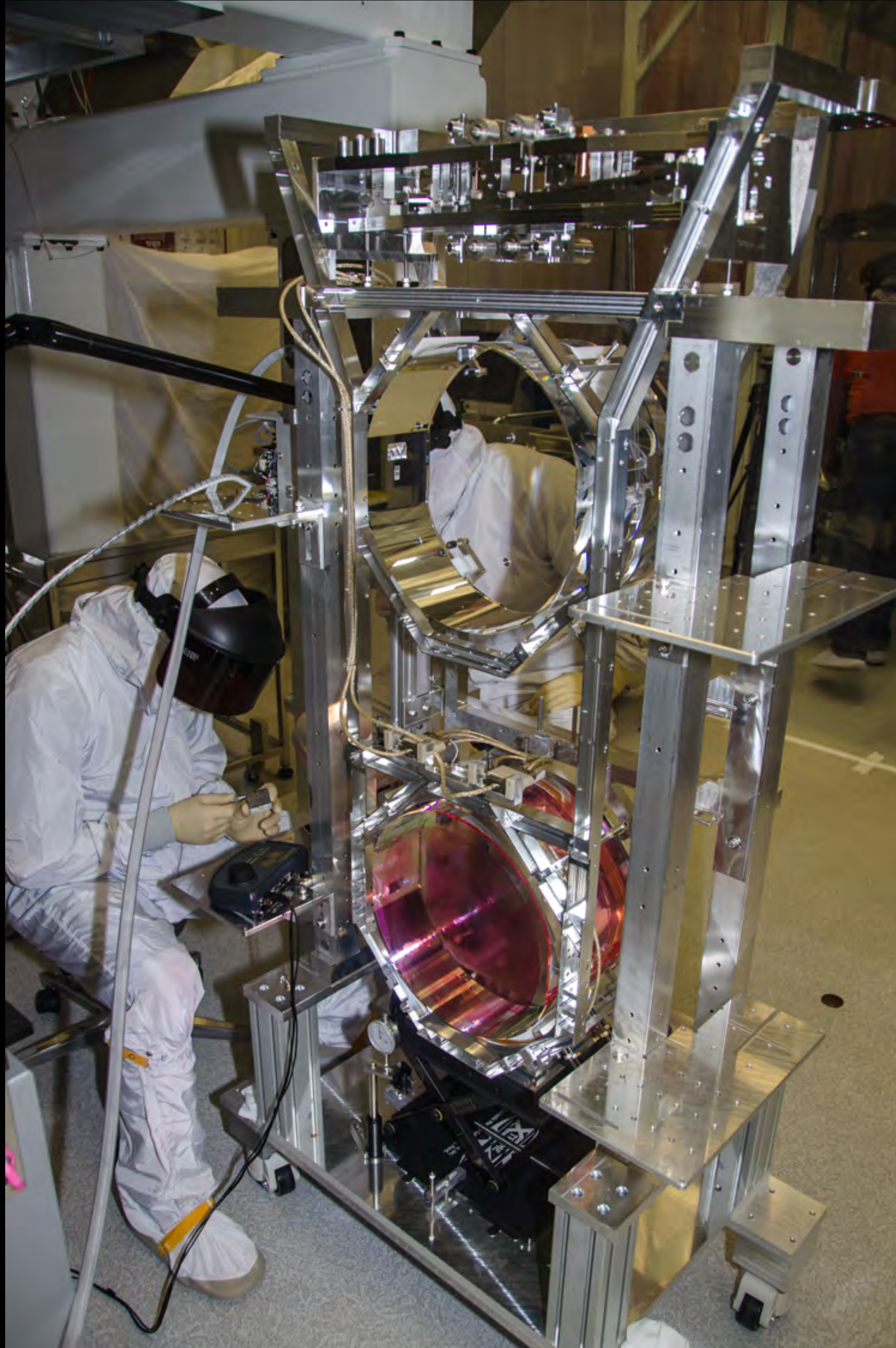
Monolithic Mirror Suspensions:

Fused silica test mass, hung from similar mass via pure silica fiber and ‘ears.’

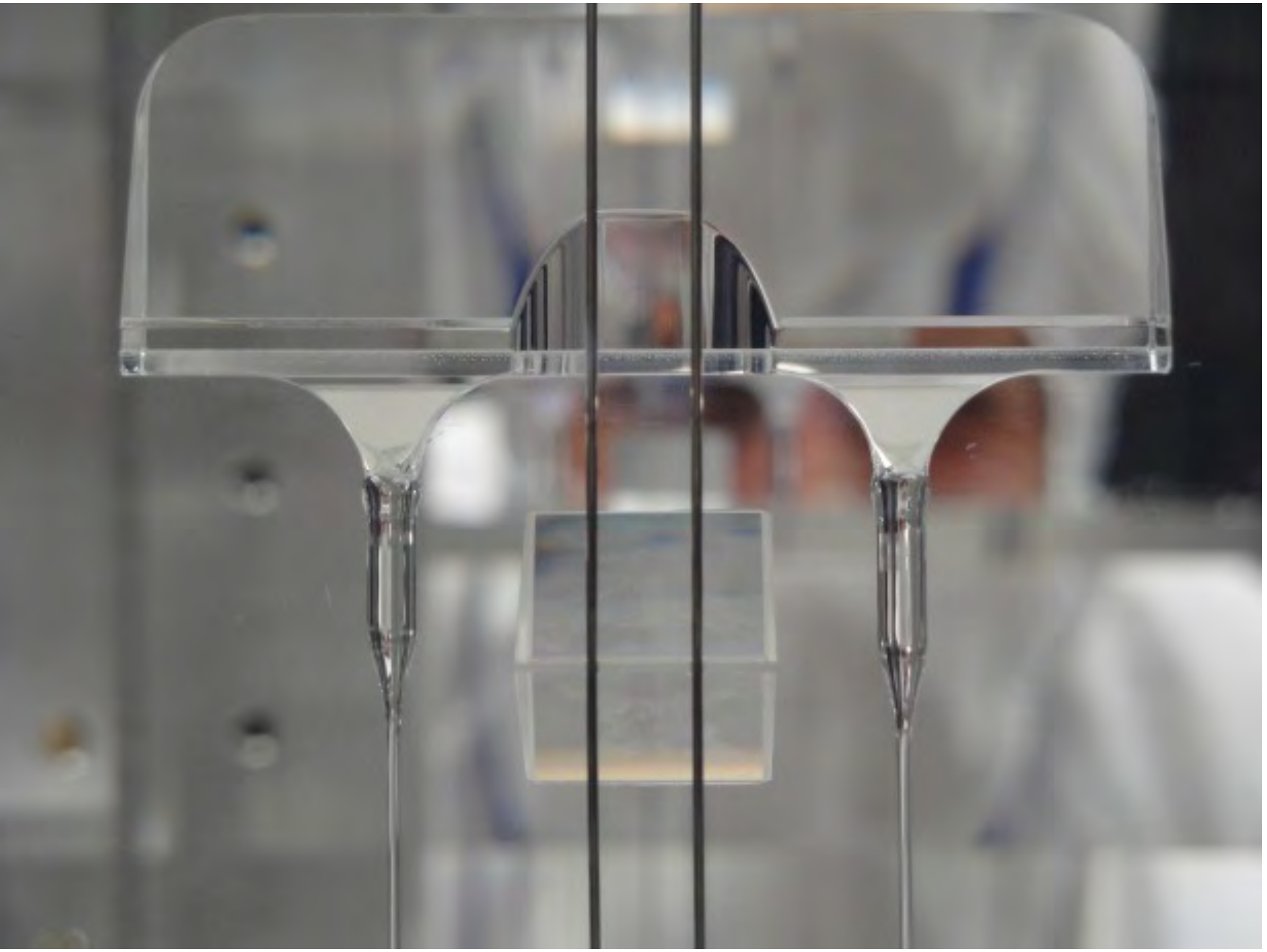


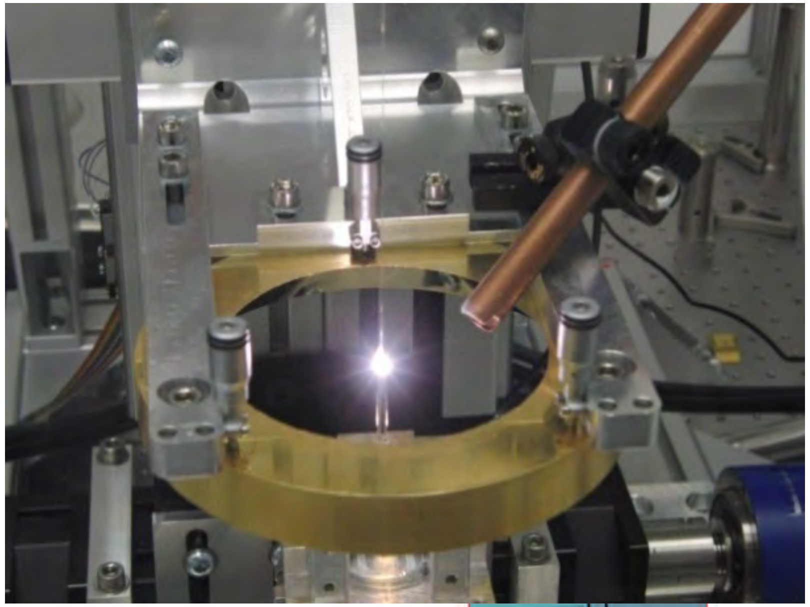
GEO 600 photo

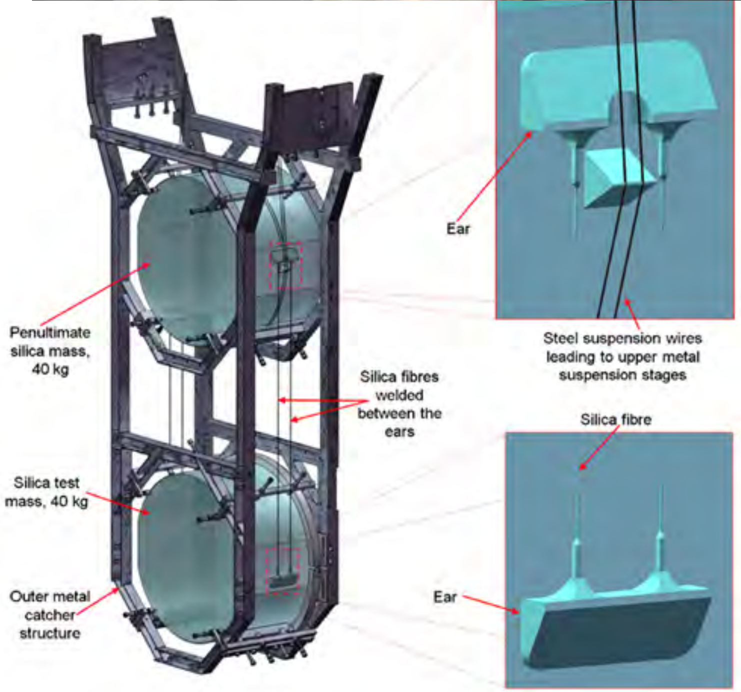
Design from U.K.-German GEO 600 suspension



Quadruple Pendulum for test mass mirrors

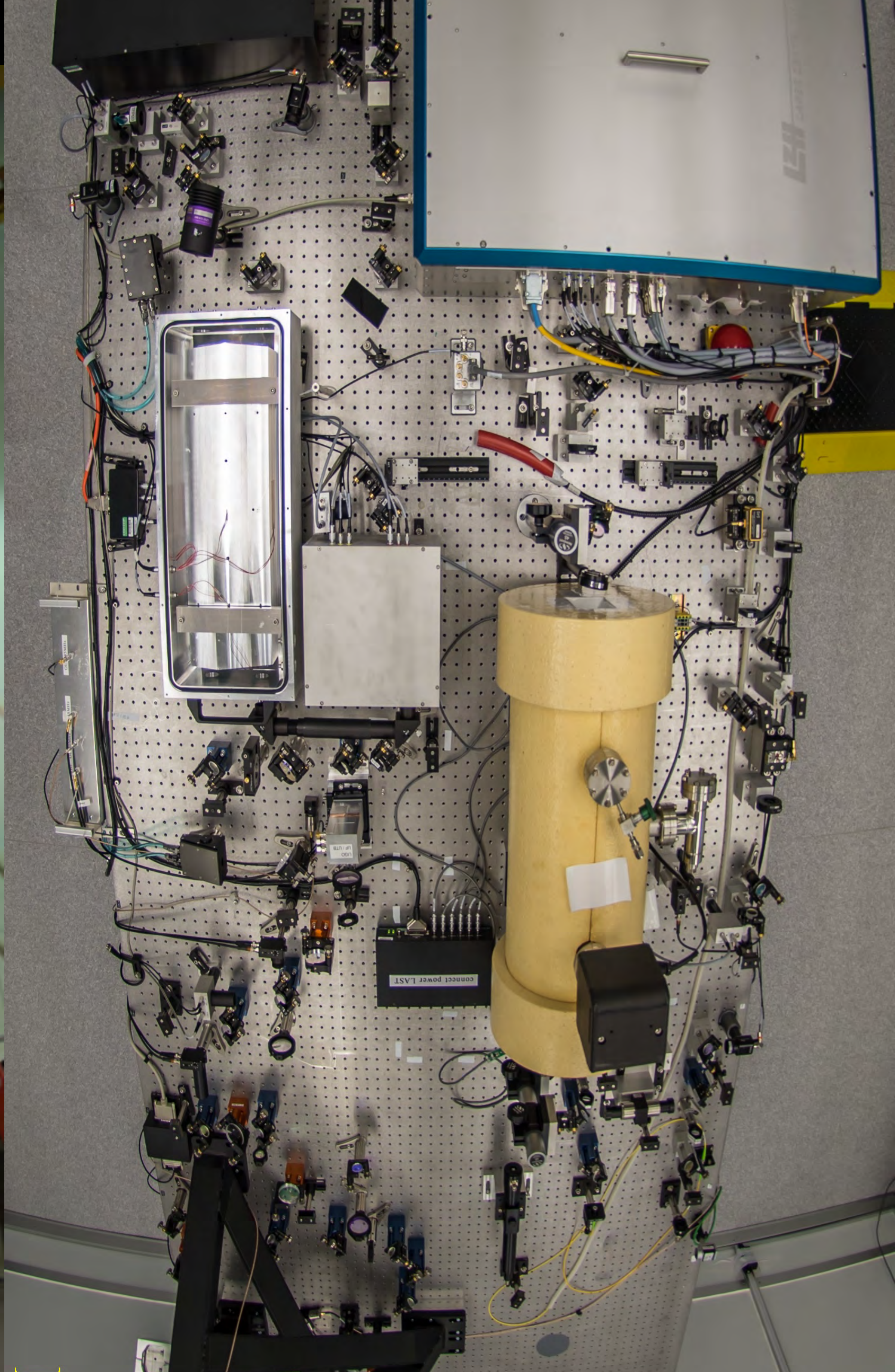




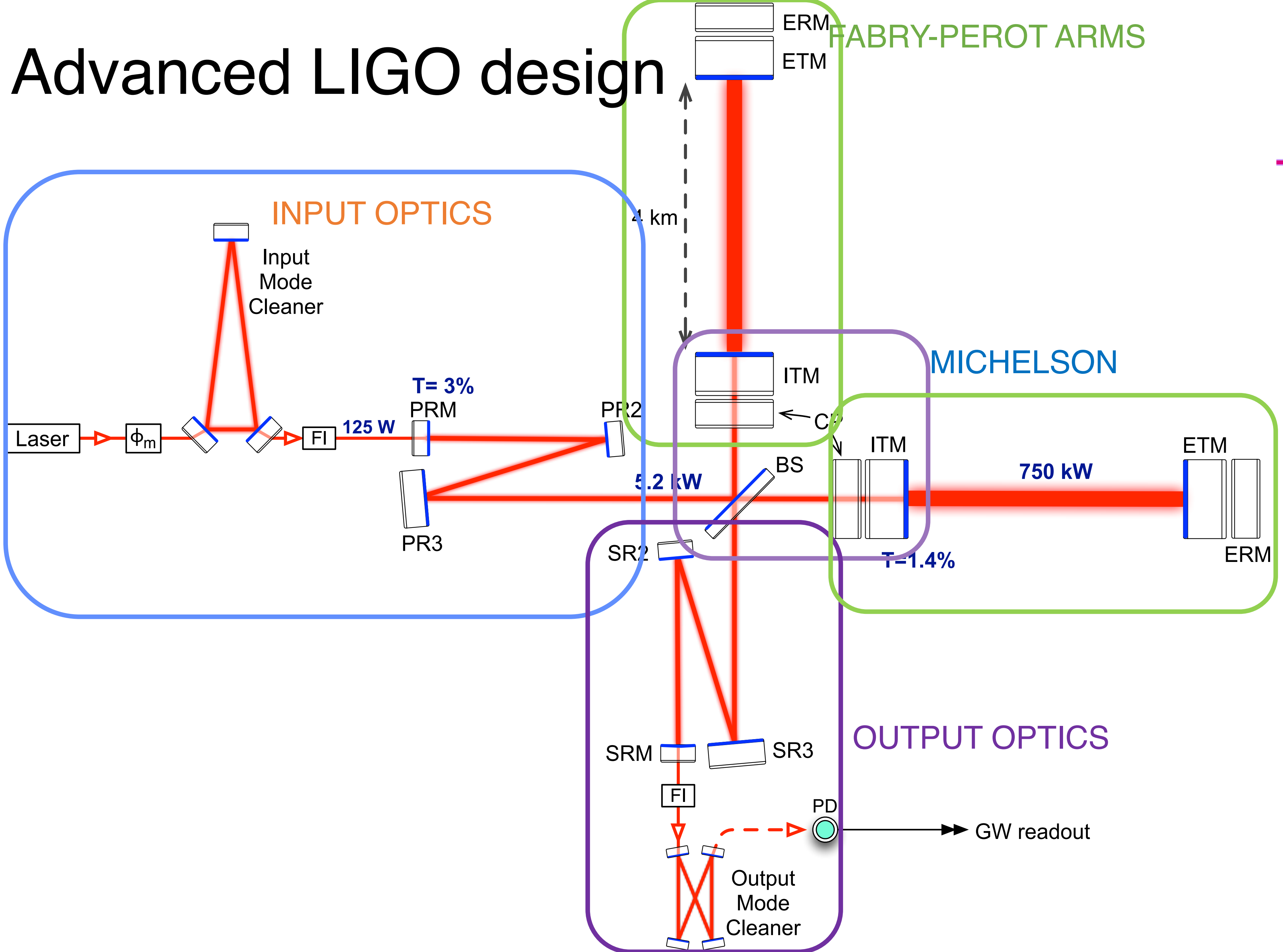


- UK supplied, Glasgow IGR-developed
- Fused silica suspensions, fibre-pulling, bonding and welding
- Coating R&D, major Glasgow activity

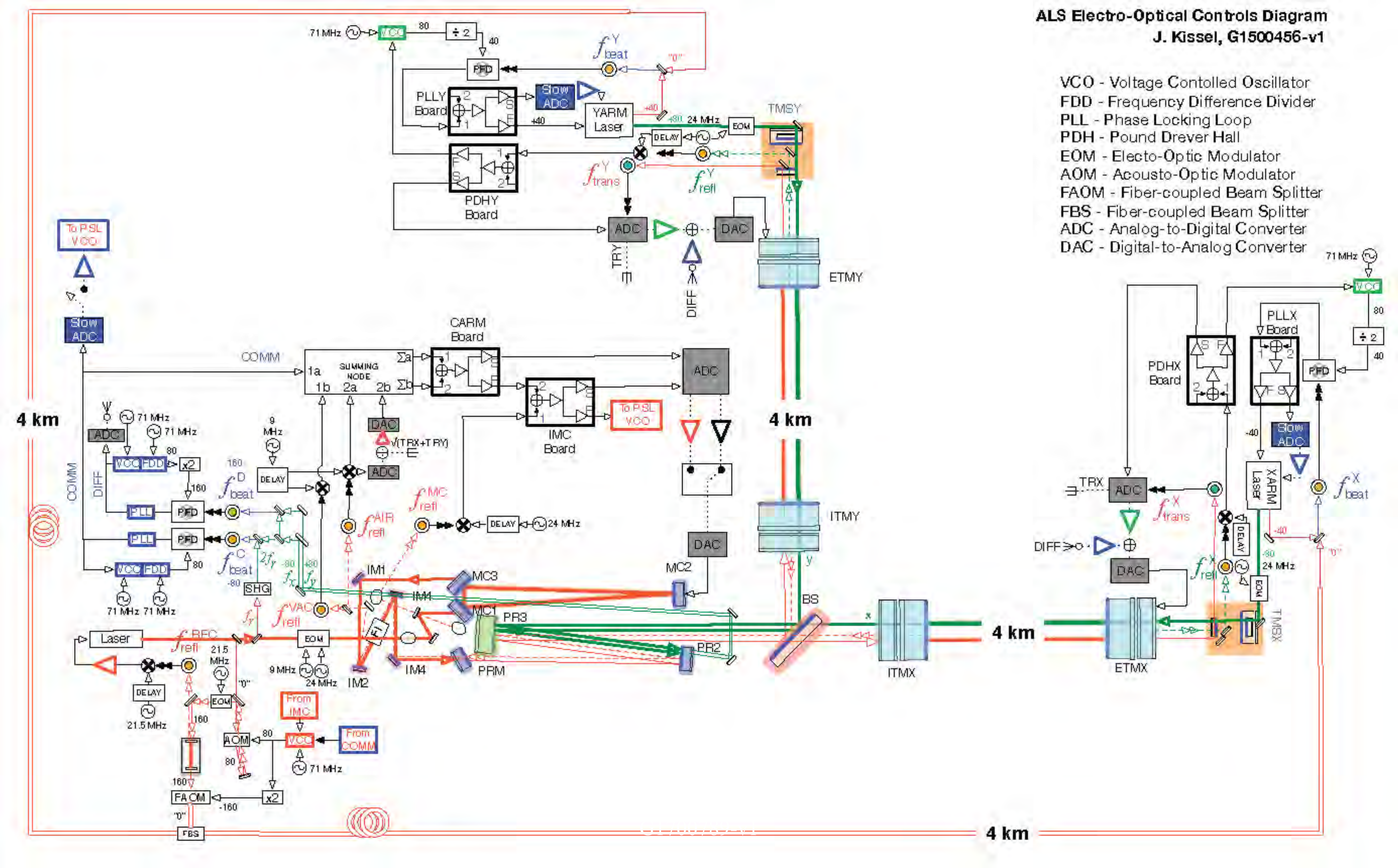
Installation



Advanced LIGO design



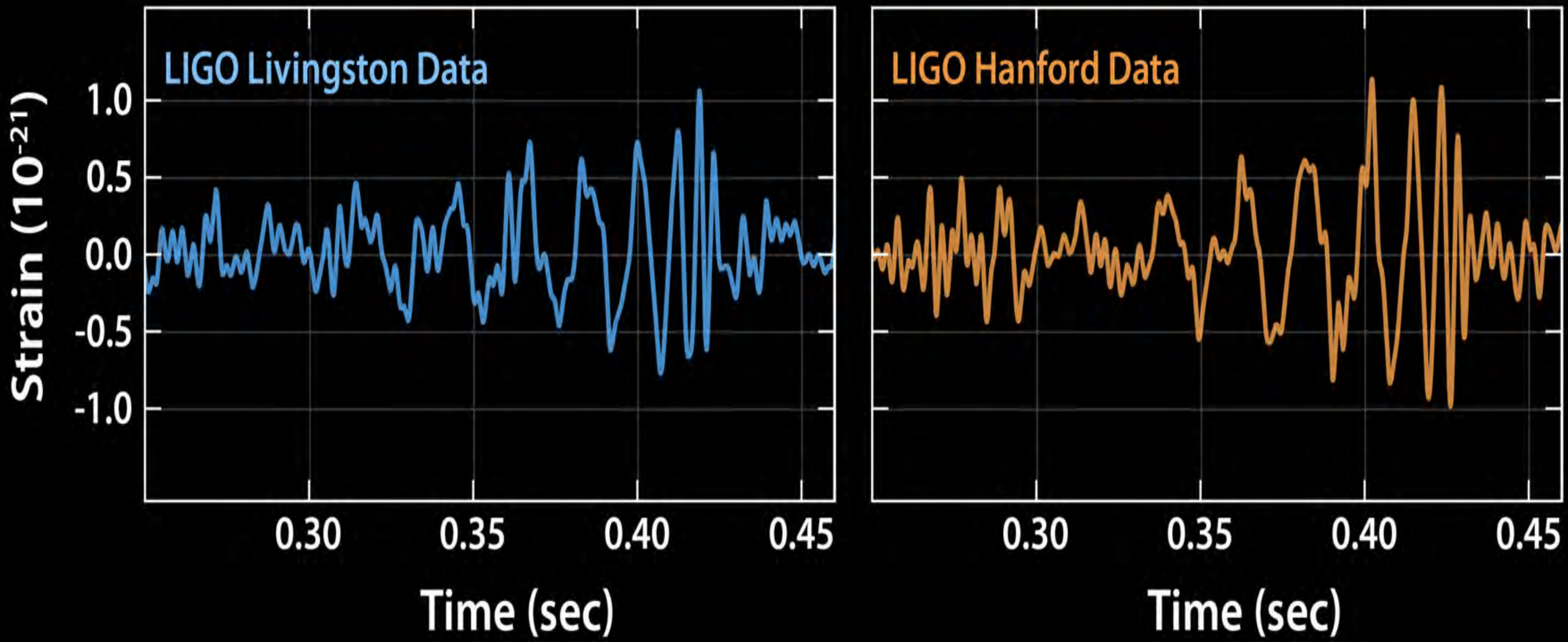
Optical alignment and control… just one part:



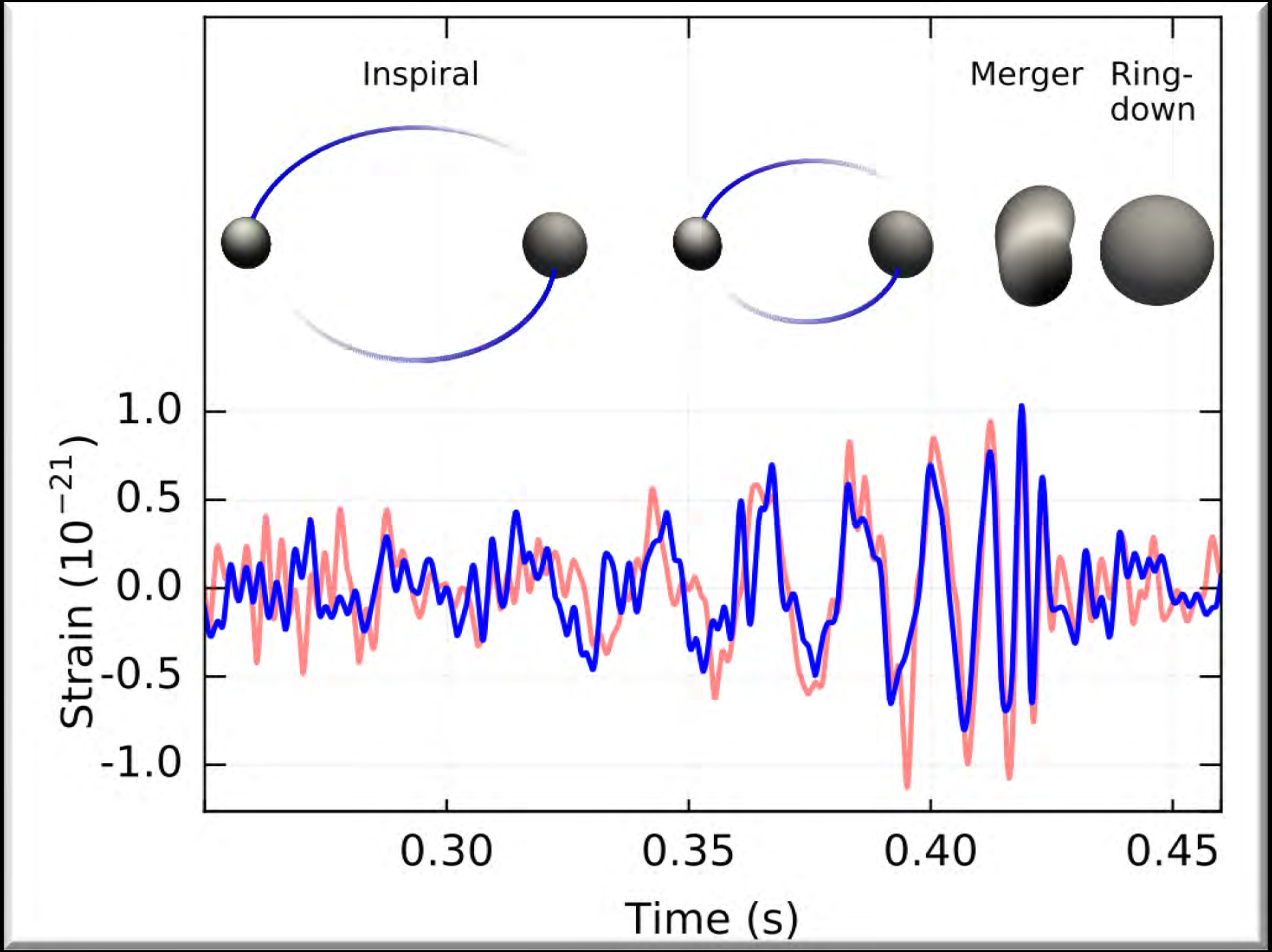
ALS Electro-Optical Controls Diagram
J. Kissel, G1500456-v1

VCO - Voltage Contolled Oscillator
FDD - Frequency Difference Divider
PLL - Phase Locking Loop
PDH - Pound Drever Hall
EOM - Electo-Optic Modulator
AOM - Acousto-Optic Modulator
FAOM - Fiber-coupled Beam Splitter
FBS - Fiber-coupled Beam Splitter
ADC - Analog-to-Digital Converter
DAC - Digital-to-Analog Converter

LIGO control room: lock acquisition

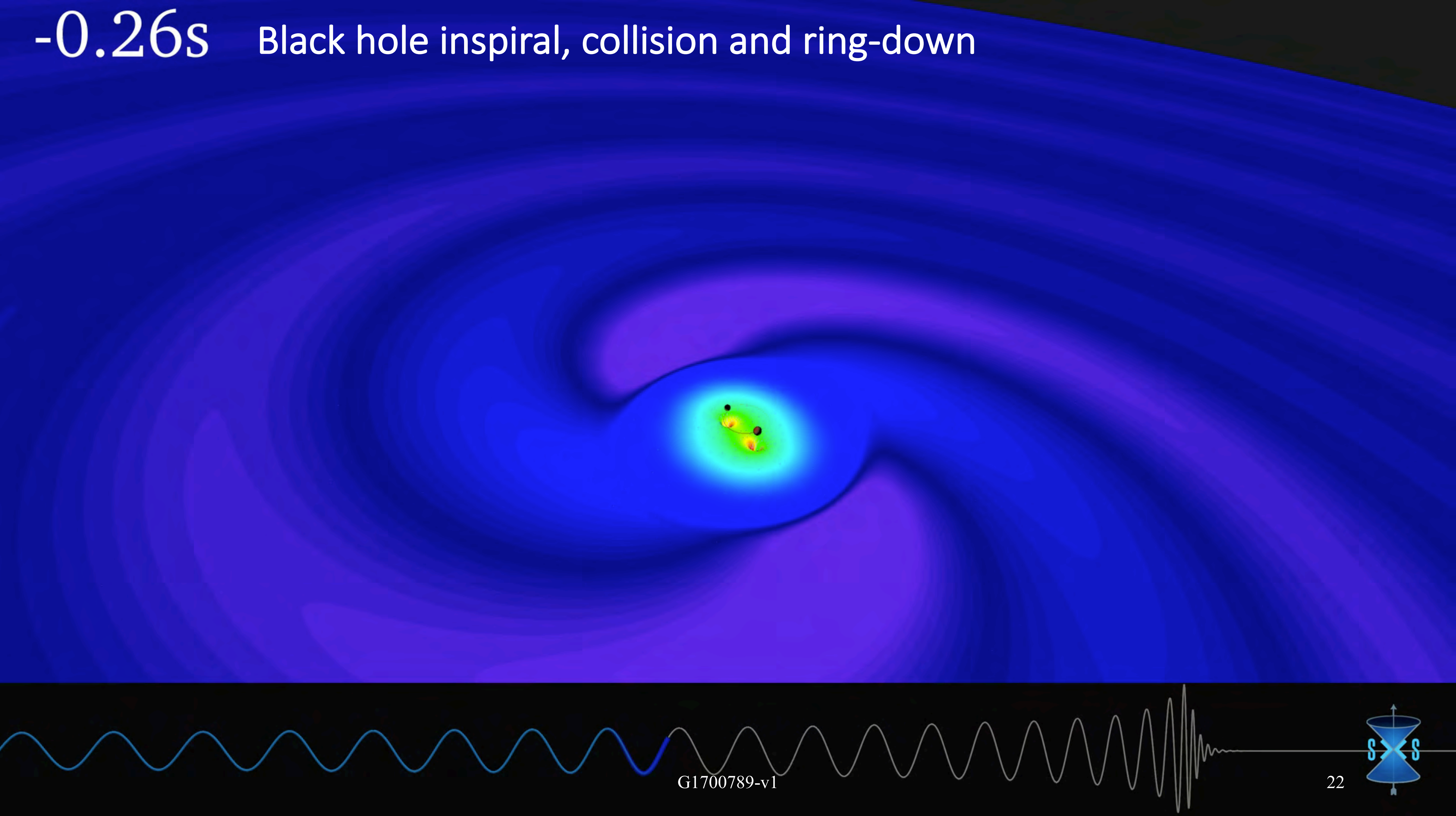


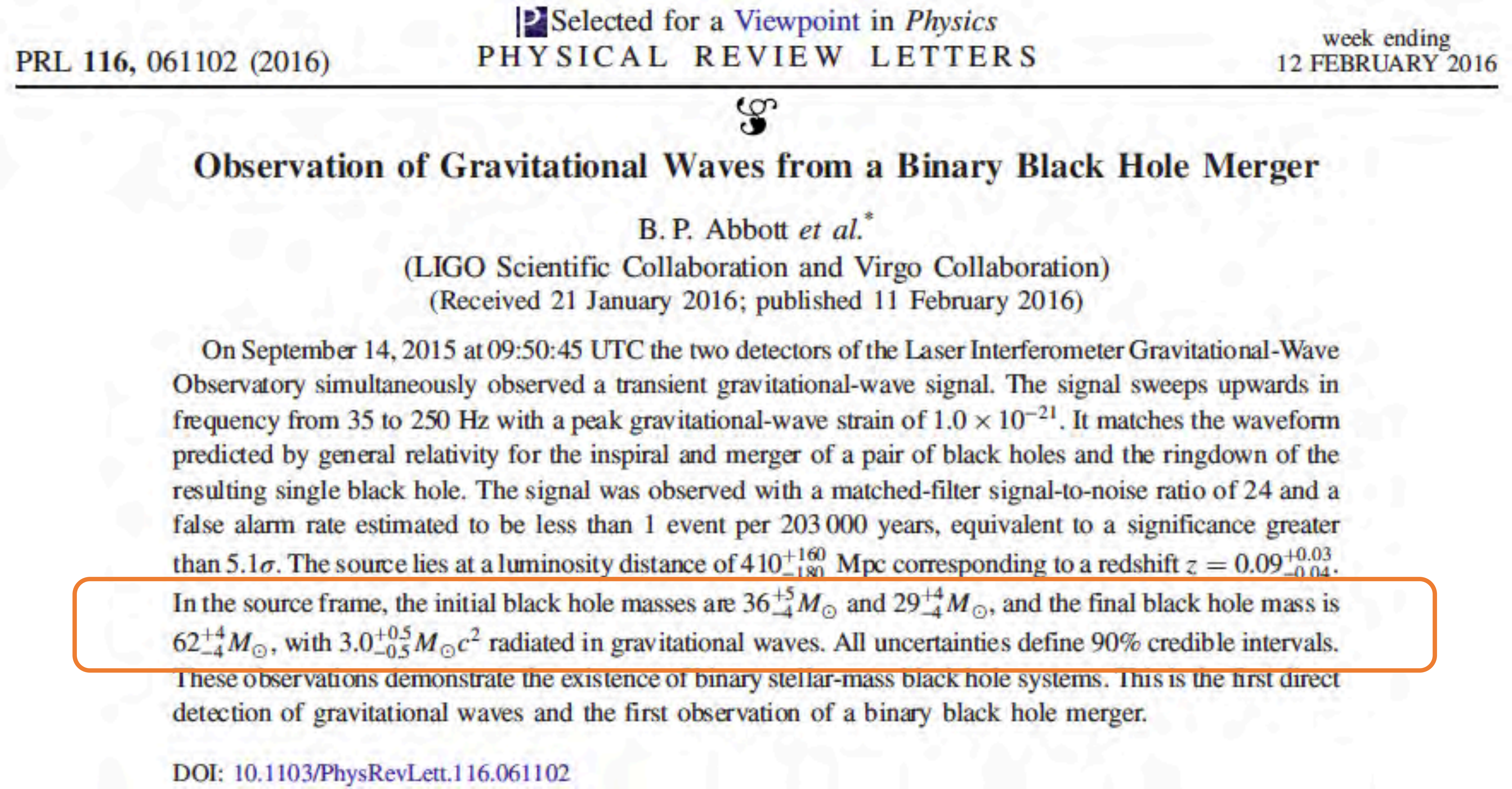
PRL **116**, 06112 (2016)



PRL **116**, 06112 (2016)

-0.26s Black hole inspiral, collision and ring-down





Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

PRL **116**, 06112 (2016)

4×10^{49} J/s peak power of source, 40 yotta yotta watt.

1×10^{25} meter distance to source, 10 yotta meter.

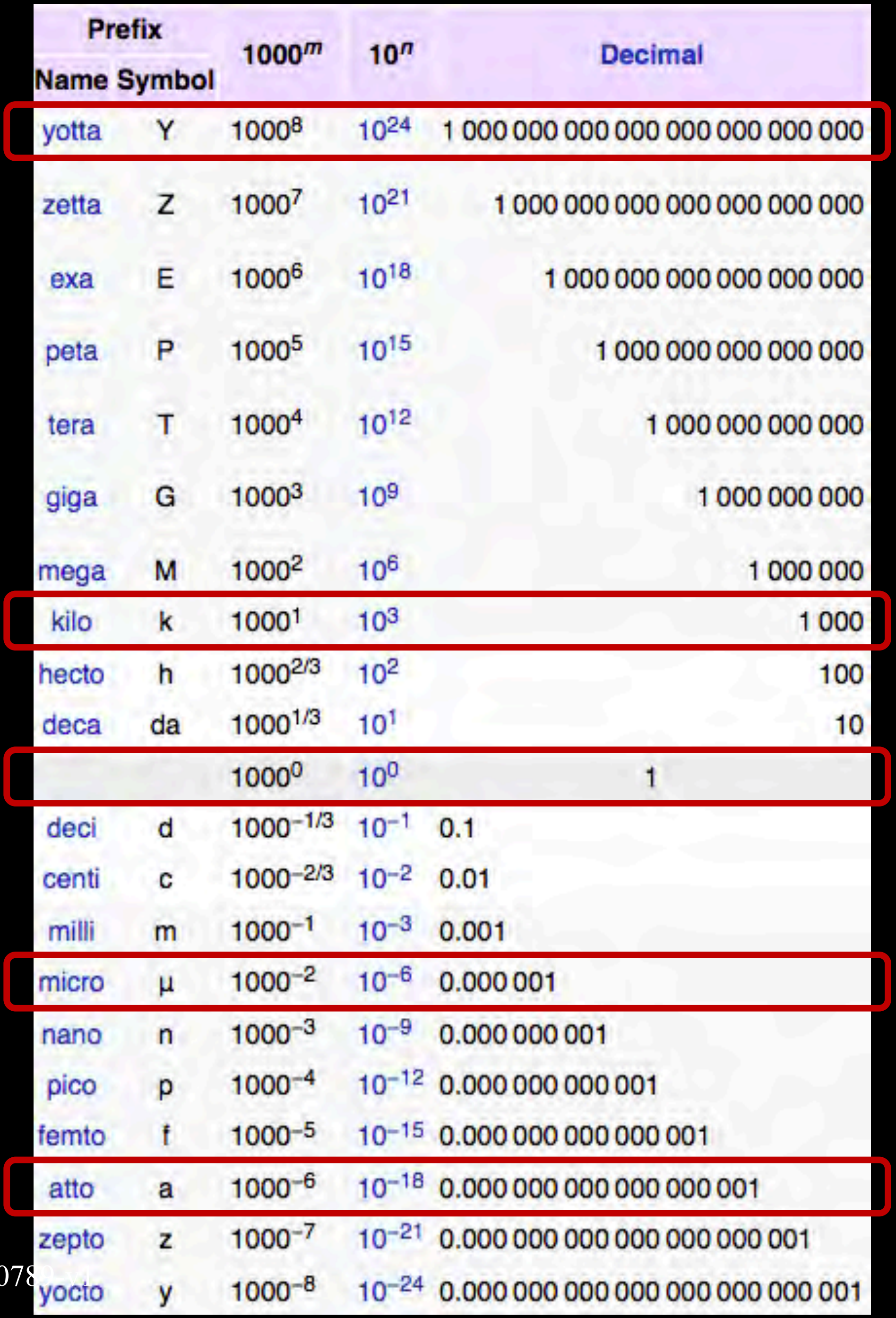
S.I. prefix chart … kind of dull.

4×10^{3} meter LIGO arm length, 4 kilometer.

2×10^{0} meter test mass suspension length, 2 meter.

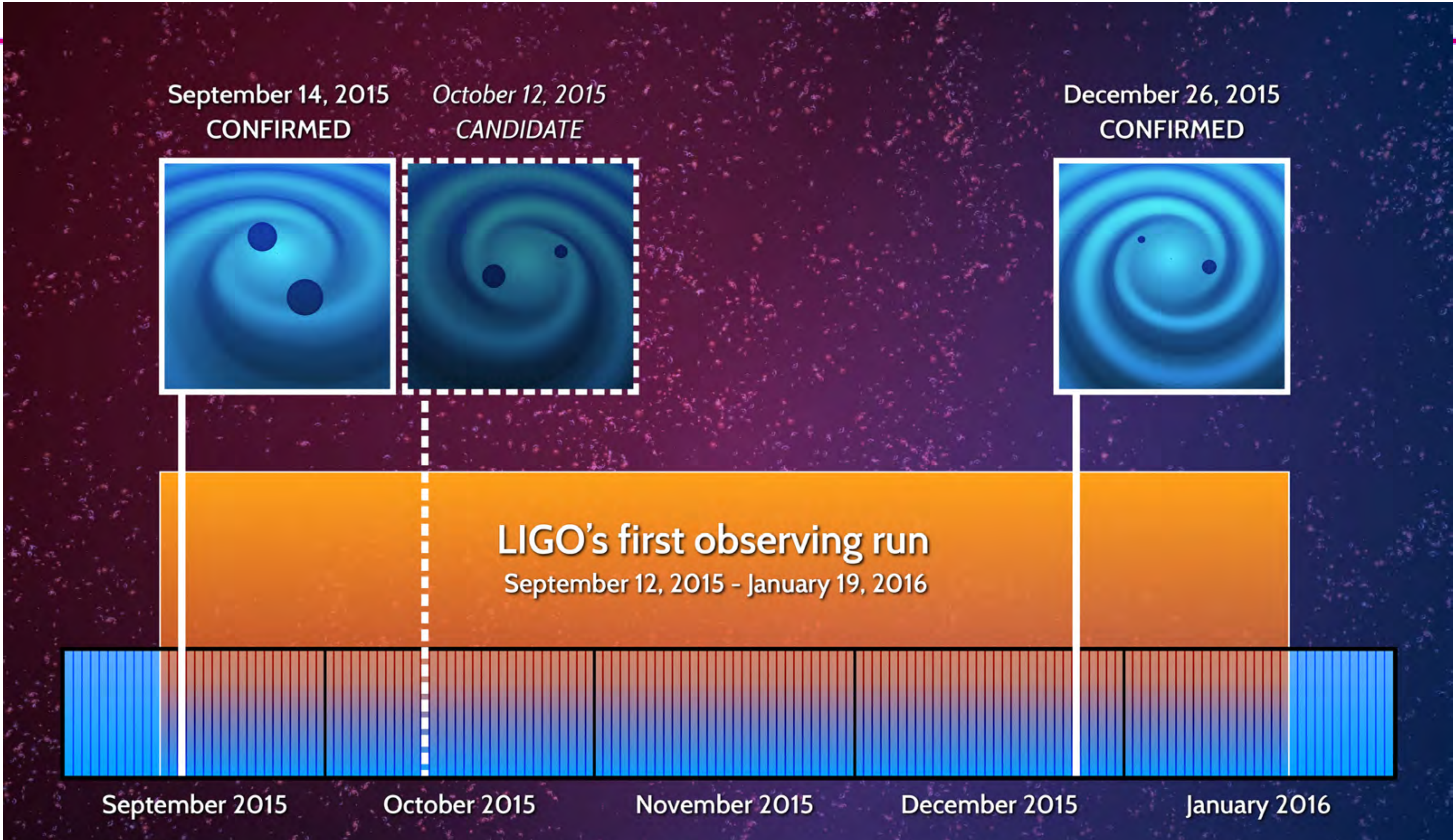
1×10^{-6} meter ground vibration, 1 micrometer.

1×10^{-18} meter arm difference at peak signal, 1 attometer.



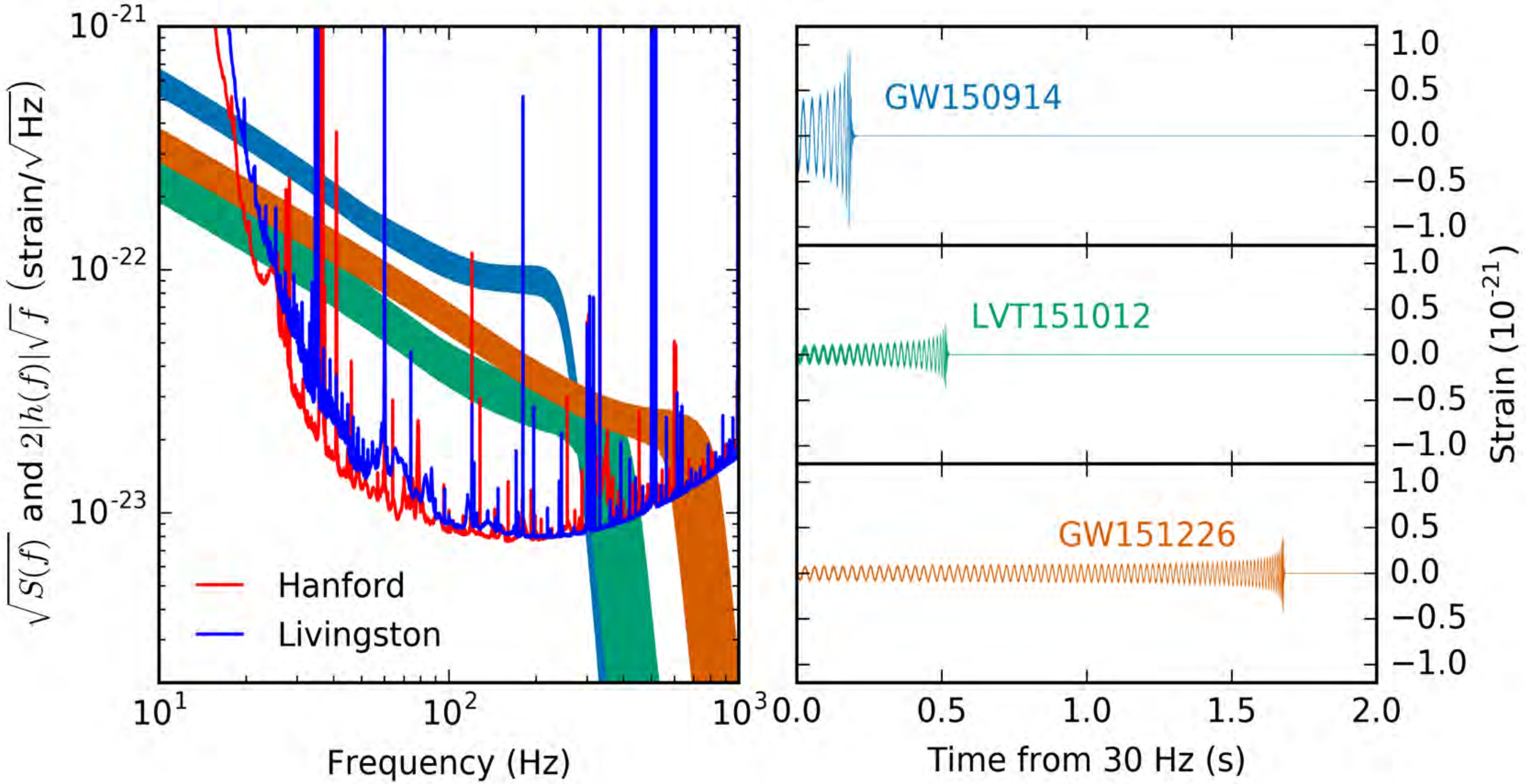
Prefix Name	Prefix Symbol	1000^m	10^n	Decimal
yotta	Y	1000^8	10^{24}	1 000 000 000 000 000 000 000 000
zetta	Z	1000^7	10^{21}	1 000 000 000 000 000 000 000
exa	E	1000^6	10^{18}	1 000 000 000 000 000 000
peta	P	1000^5	10^{15}	1 000 000 000 000 000
tera	T	1000^4	10^{12}	1 000 000 000 000
giga	G	1000^3	10^{9}	1 000 000 000
mega	M	1000^2	10^{6}	1 000 000
kilo	k	1000^1	10^{3}	1 000
hecto	h	$1000^{2/3}$	10^{2}	100
deca	da	$1000^{1/3}$	10^{1}	10
		1000^0	10^{0}	1
deci	d	$1000^{-1/3}$	10^{-1}	0.1
centi	c	$1000^{-2/3}$	10^{-2}	0.01
milli	m	1000^{-1}	10^{-3}	0.001
micro	µ	1000^{-2}	10^{-6}	0.000 001
nano	n	1000^{-3}	10^{-9}	0.000 000 001
pico	p	1000^{-4}	10^{-12}	0.000 000 000 001
femto	f	1000^{-5}	10^{-15}	0.000 000 000 000 001
atto	a	1000^{-6}	10^{-18}	0.000 000 000 000 000 001
zepto	z	1000^{-7}	10^{-21}	0.000 000 000 000 000 000 001
yocto	y	1000^{-8}	10^{-24}	0.000 000 000 000 000 000 000 001

Events during Advanced LIGO's first observational run:



LIGO & Caltech Press Office

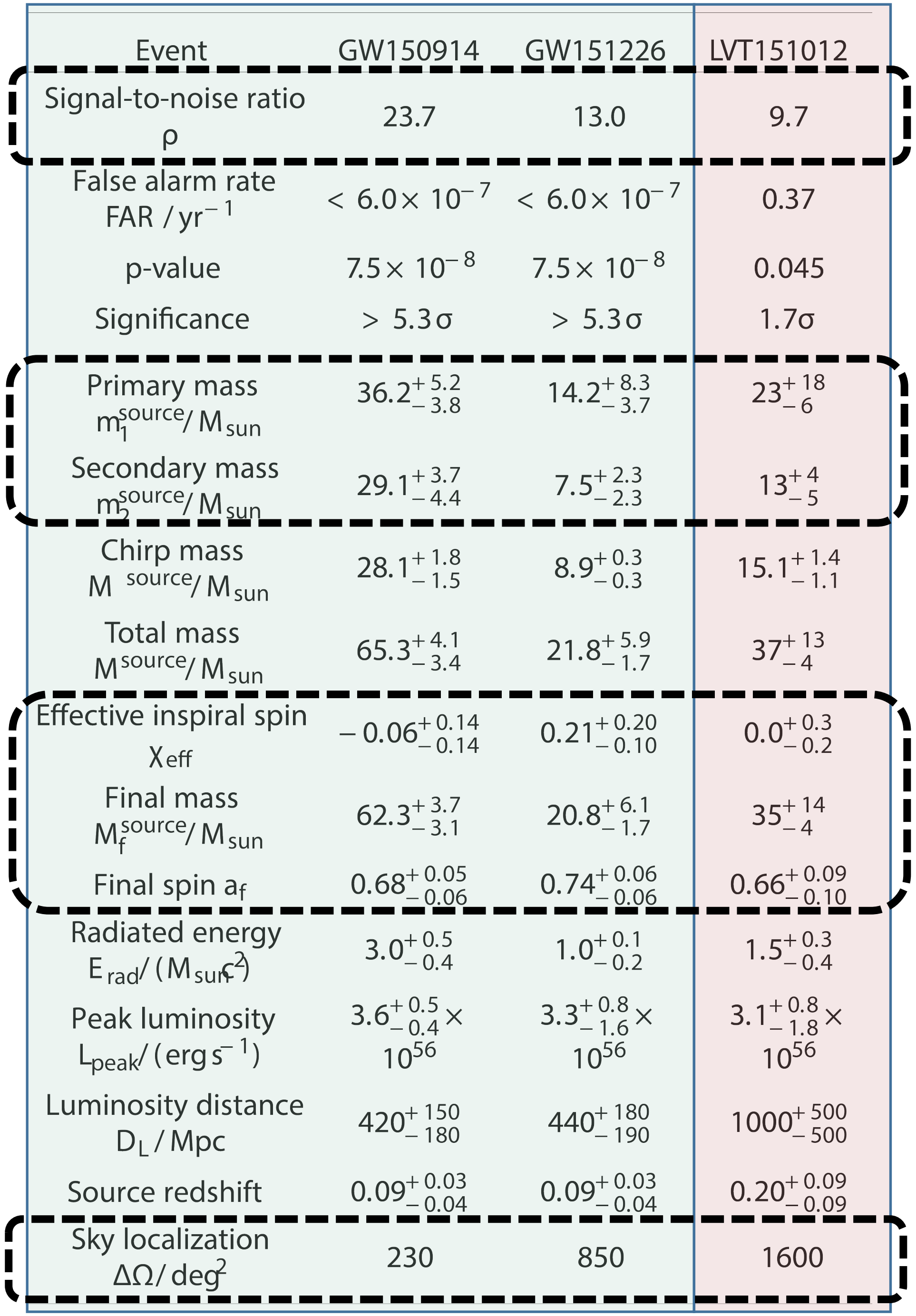
Three events compared



Phys. Rev. Lett. **116**, 241103, Phys. Rev. X 6, 041015 (2016)

What have we learned about the systems that emitted the waves? How do we learn more?

- Accuracy of most parameters improves with signal-to-noise ratio.
- Sky localization improves as more observatories are added.
- Some parameters, like spin, are hard to measure!



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR $/ \mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/M_{\mathrm{sun}}$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/M_{\mathrm{sun}}$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $M^{\mathrm{source}}/M_{\mathrm{sun}}$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/M_{\mathrm{sun}}$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\mathrm{source}}/M_{\mathrm{sun}}$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(M_{\mathrm{sun}}c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $L_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

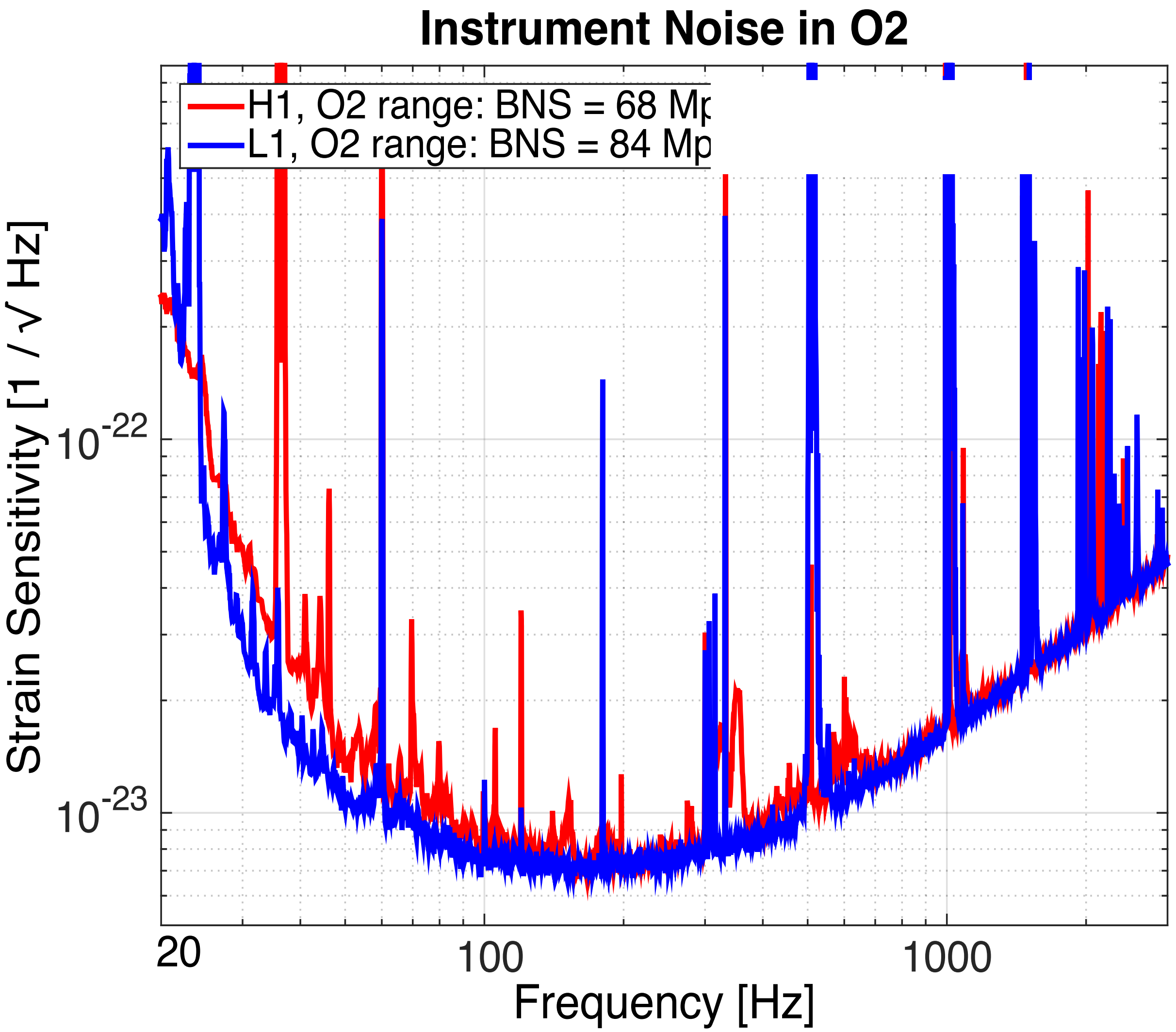
journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.241103,
arxiv.org/abs/1606.04856 (accepted to PRX)

Commissioning between O1 and O2 runs

- High power stage of LIGO Hanford laser activated.
  - Development of techniques to reduce buildup of opto-mechanical parametric instabilities.
  - Thermal compensation and higher power.
  - Study of beam jitter/geometry noise coupling to detector.
- Diagnosis and reduction of noise from scattered light off moving surfaces
  - Several scattering sites identified in LIGO Livingston.
  - Compensation plate now “correctly” misaligned.
  - Scattering from photon calibrator periscope mirror identified, will be addressed later.
  - Scattering and relative motion among one end station optics partially addressed.
- Test-mass bounce/roll dampers, new photodiodes, new pre-mode cleaner, Faraday isolator, etc., in L1.
- Removed accidental noise from temperature sensor instrumentation in L1

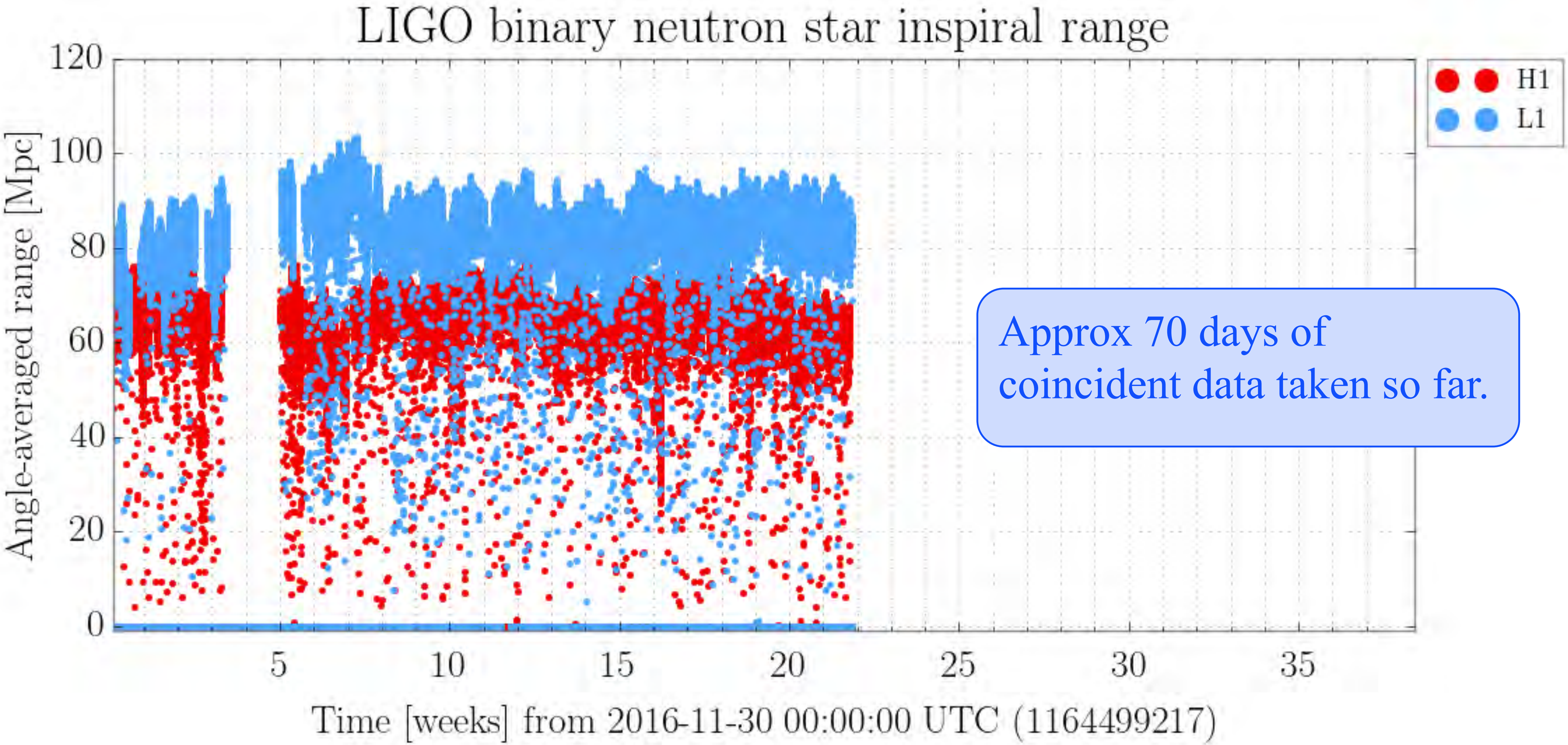
Second aLIGO observational run

- The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of March 1, 2017, approx. 34 days (0.093 year) of cumulative coincident data have been taken with L1 and H1, with a scheduled break between December 22, 2016 and January 4, 2017.
- Average reach of the LIGO network for binary merger events have been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.



NS-NS range in O2 run …

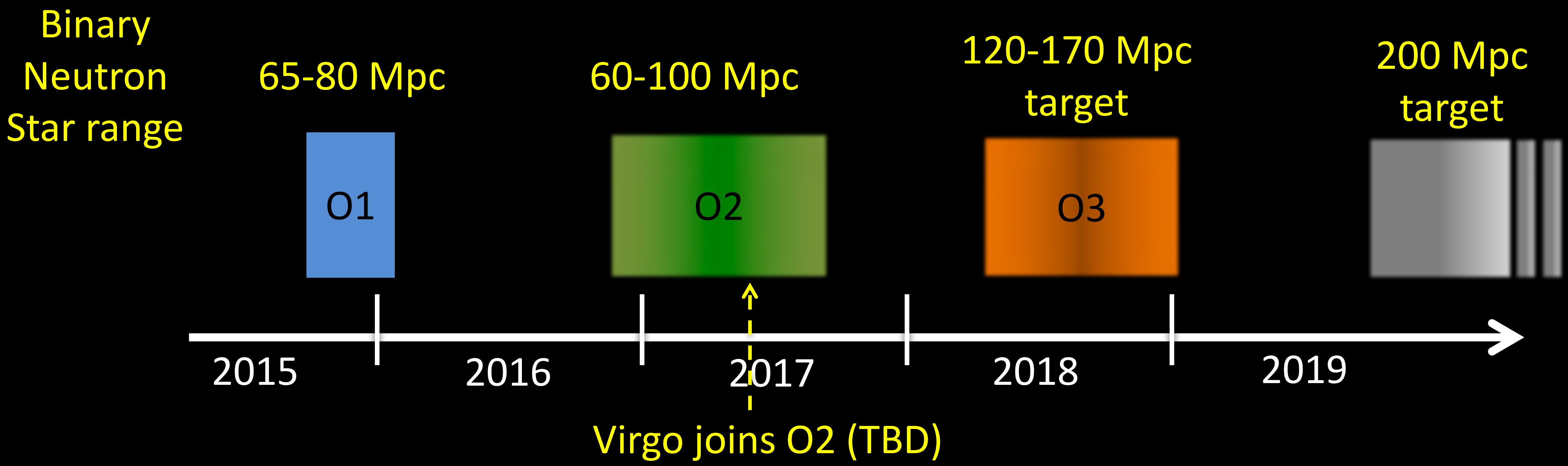
rough online calibration (±10%)



Approx 70 days of coincident data taken so far.

Plausible Observing Run Timeline

(plans still under development within the LIGO and Virgo Collaborations)



Binary Neutron Star range

65-80 Mpc

60-100 Mpc

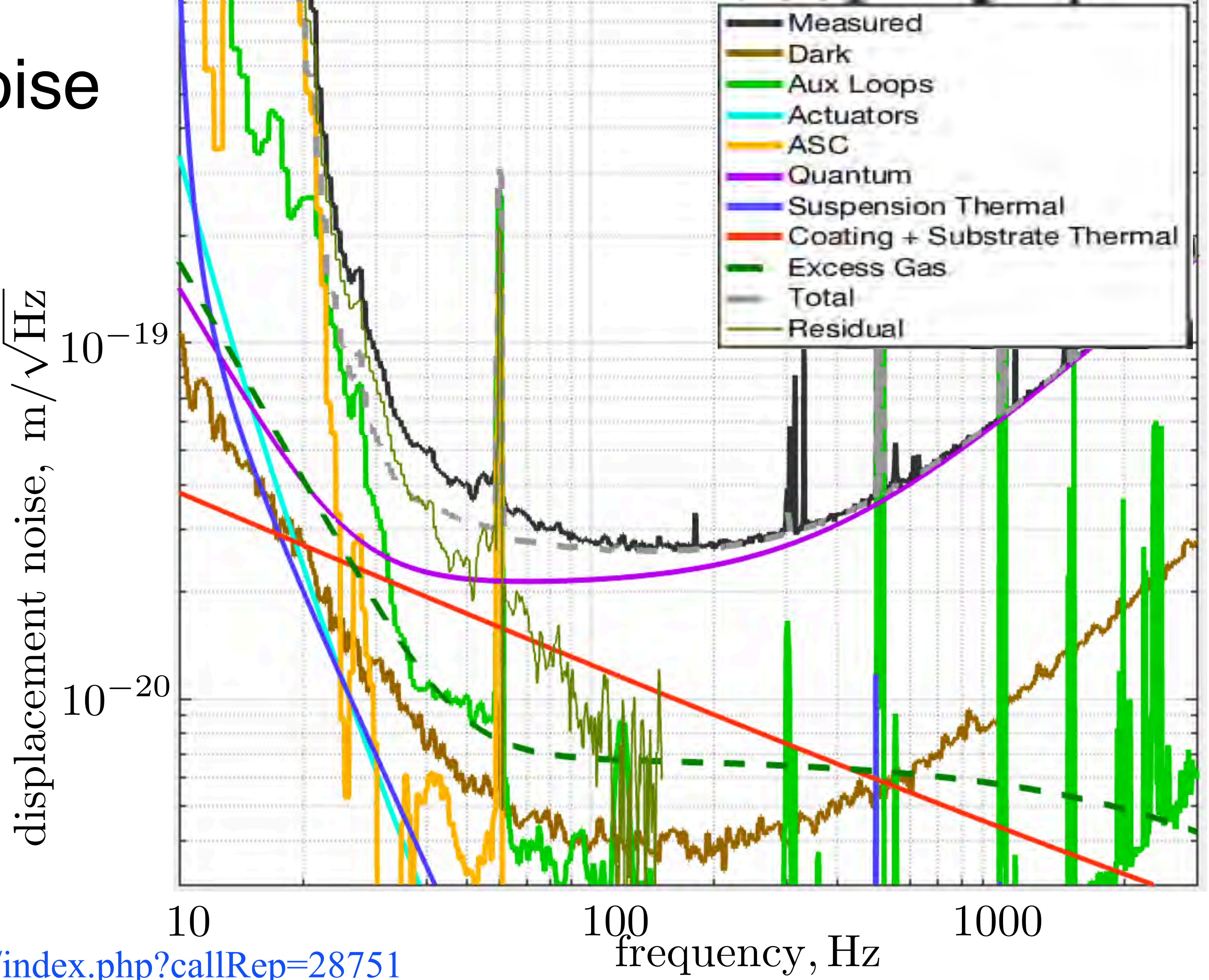
120-170 Mpc target

200 Mpc target

Virgo joins O2 (TBD)

Displacement noise

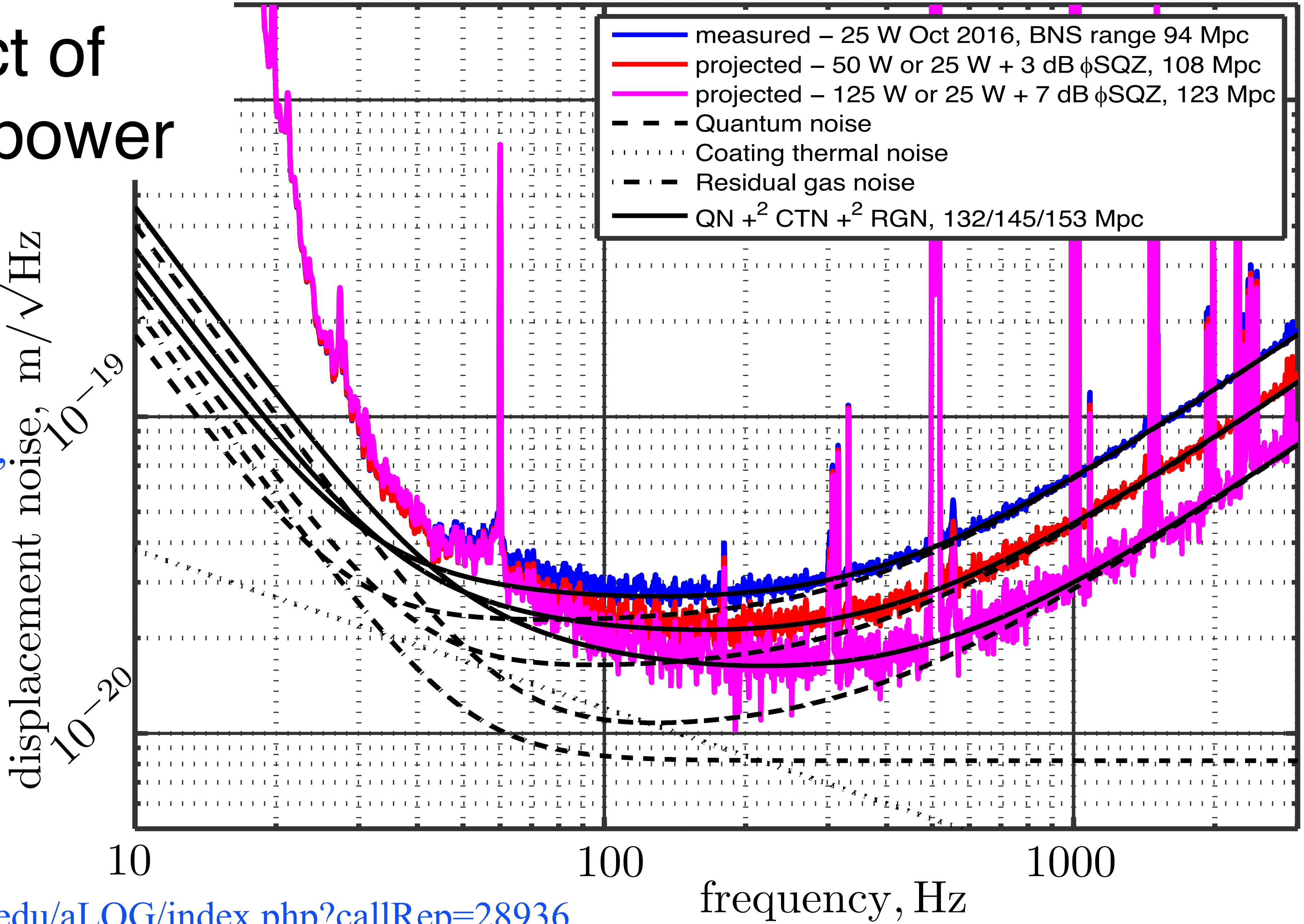
- Noise model of high-range data segment in Livingston (M. Evans).
- Tracks shot noise at high frequencies.
- Tracks servo-induced noise at low frequencies.
- Slight excess 30-100 Hz, attributed to light scattering from moving surfaces.



https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=28751

Potential effect of additional laser power

- V. Frolov’s noise model of current best-case detector with higher laser power.
- Assumes current excess, coating and gas noises. Quantum adjusted.
- Current 25 W range, 94Mpc, might reach 108/123 Mpc with 50/125 W or 3/7 dB phase squeezing.



https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=28936

LIGO Science Education Center: a partnership with Southern University, the SF Exploratorium, and educators.

- The U.S. NSF has funded Southern Univ. BR, Caltech and the Baton Rouge Area Foundation to build and carry out educational programs related to LIGO science and inquiry-based learning.
- The LIGO SEC programs reach over 20,000 people each year, focusing on classroom visits and teacher training.
- Docents serve as role models for children who wish to pursue science and technology careers.

Recent LSU and Southern graduates at the helms of both LIGO detectors as the wave was detected

Nutsinee Kijbunchoo and William Parker

Thank you!