ICHEP2016CHICAGO

38th INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS
AUGUST 3 - 10, 2016
CHICAGO

The Advanced LIGO detectors at the beginning of the new gravitational wave era

Lisa Barsotti
MIT Kavli Institute – LIGO Laboratory
on behalf of the
LIGO Scientific Collaboration

LIGO Document G1600324

LIGO

LIGO Scientific Collaboration

LSC

TRINITY UNIVERSITY

UNIVERSITY OF MARYLAND 56

Andrews University

WASHINGTON STATE UNIVERSITY

CALIFORNIA STATE UNIVERSI FULLERTO

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

SONOMA STATE UNIVERSITY

indigo

MONTCLAIR STATE UNIVERSITY

University of Glasgow

VIA VERITAS VITA

Australian National University

NATURAM PRIMUM COGNOSCERE RERUM

WHITMAN COLLEGE

AMERICAN UNIVERSITY WASHINGTON, DC

RERUM COGNOSCERE CAUSAS

UNIVERSITY OF STRATHCLYDE

UNIVERSITY OF THE WEST of SCOTLAND UWS

TEXAS TECH UNIVERSITY

清华大学 Tsinghua University

RIT

LELAND STANFORD JUNIOR UNIVERSITY 1891

Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE

MICHIGAN

PAH

Università degli Studi del Sannio

CITA ICA

Canadian Institute for Theoretical Astrophysics

L'institut Ca d'astrophysi

SCIENTIA VINCERE TENEBRAS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861

NASA GODDARD SPACE FLIGHT CENTER

ICTP SAIFR

THE UNIVERSITY OF WESTERN AUSTRALIA

SEEK WISDOM

ACU

MONASH University

UNIVERSITY OF CAMBRIDGE

SOUTHERN UNIVERSITY Agricultural & Mechanical College

MONTANA

THE UNIVERSITY OF CHICAGO

1848 THE UNIVERSITY of MISSISSIPPI

THE UNIVERSITY OF ADELAIDE AUSTRALIA

SUB CRUCE LUMEN

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

UNIVERSITAS SCIENTIARUM SZEGEDIENSIS SZEGEDI TUDOMÁNYEGYETEM

Caltech

UNIVERSITY OF MINNESOTA

UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF MELBOURNE

POSTERA CRESCAM LAUDE

UIB Universitat de les Illes Balears

UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA

UNIVERSITY OF WASHINGTON

GEO 600

TSING HUA UNIVERSITY

UTRGV

SIGILL: COLL: CARLETON NORTHFIELD, MINN. A.D. 1866

UNIVERSITY of WISCONSIN UWMILWAUKEE

UNIVERSITÄT HAMBURG

SYRACUSE UNIVERSITY FOUNDED AD 1870 SUOS CULTORES SCIENTIA CORONAT

CARDIFF UNIVERSITY PRIFYSGOL CAERDYD

Northwestern

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

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

Leibniz Universität Hannover

PennState

HOBART COLLEGE

WILLIAM SMITH COLLEGE 1908

Science & Technology Facilities Council Rutherford Appleton Laboratory

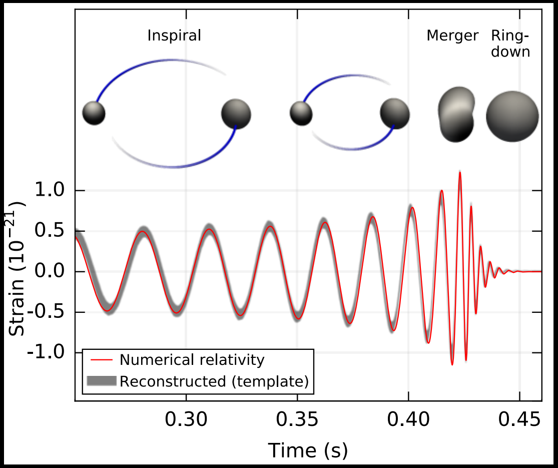
In this talk

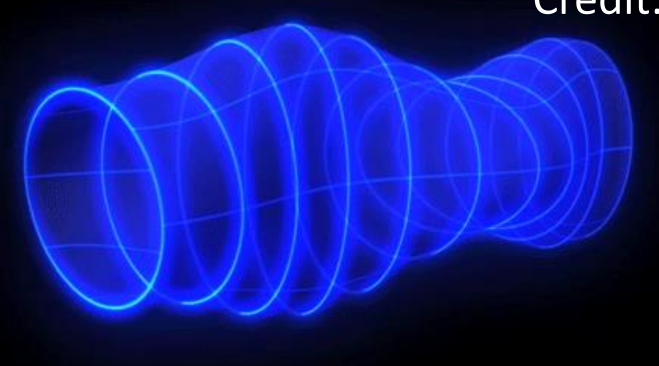
- The Advanced LIGO detectors
- Plans towards the next observing run
- Growing the gravitational wave network
- What’s next – going beyond Advanced LIGO

Gravitational waves cause strain distortion of space-time, Michelson interferometer can measure it

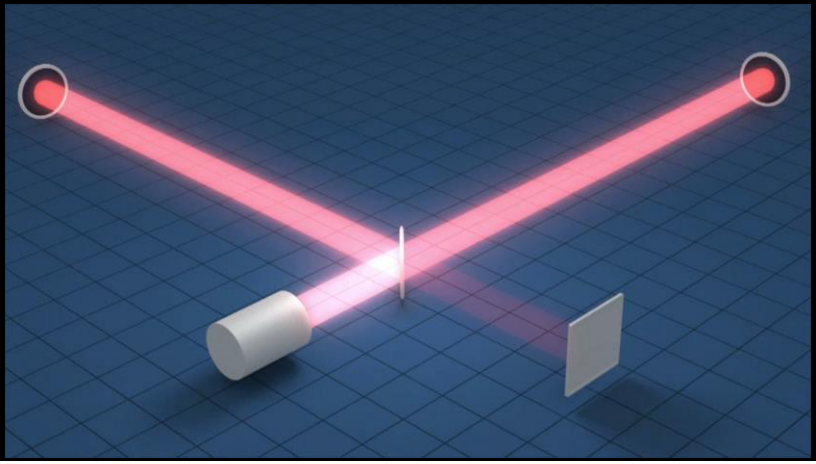
GW Amplitude

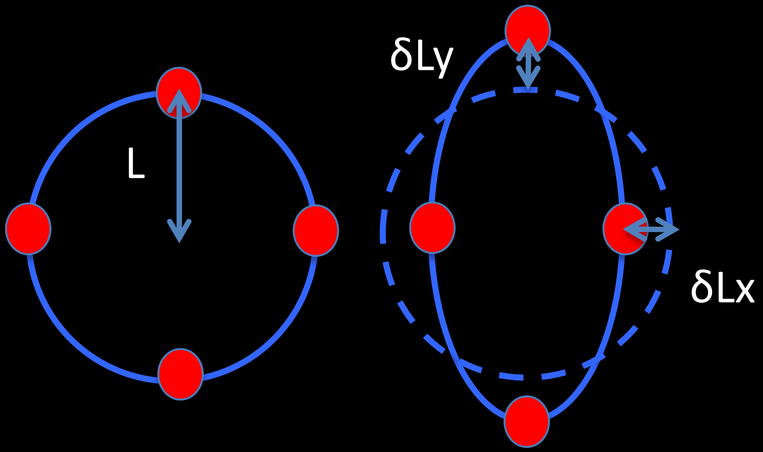
$$h \sim 10^{-21}$$





Credit: ESA





$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18}\,m$$

$$\frac{\Delta L}{L} = \frac{\delta L_x - \delta L_y}{L} = h$$

Advanced LIGO: 2 twins 4 km laser interferometers

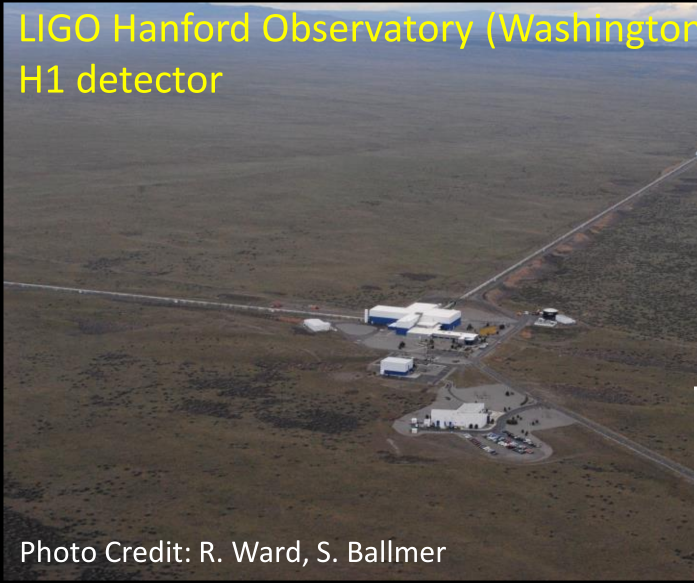
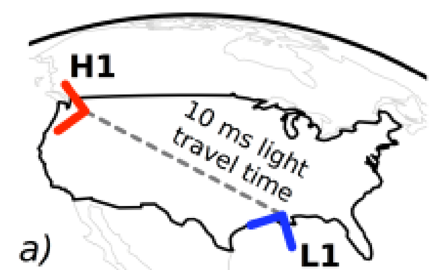
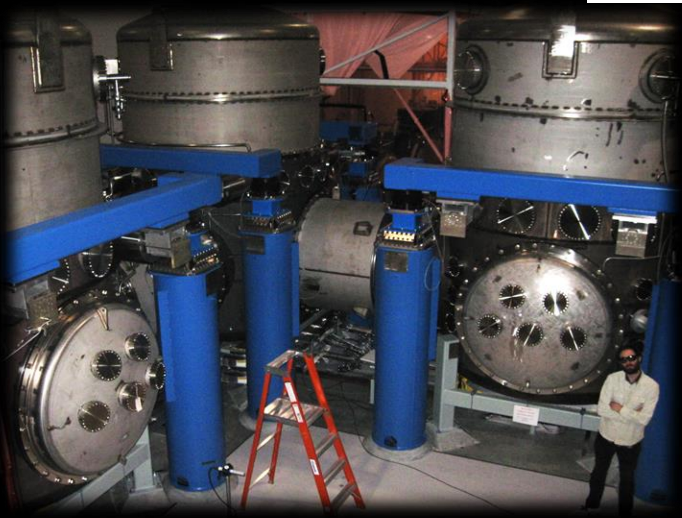

LIGO Hanford Observatory (Washington State)
H1 detector

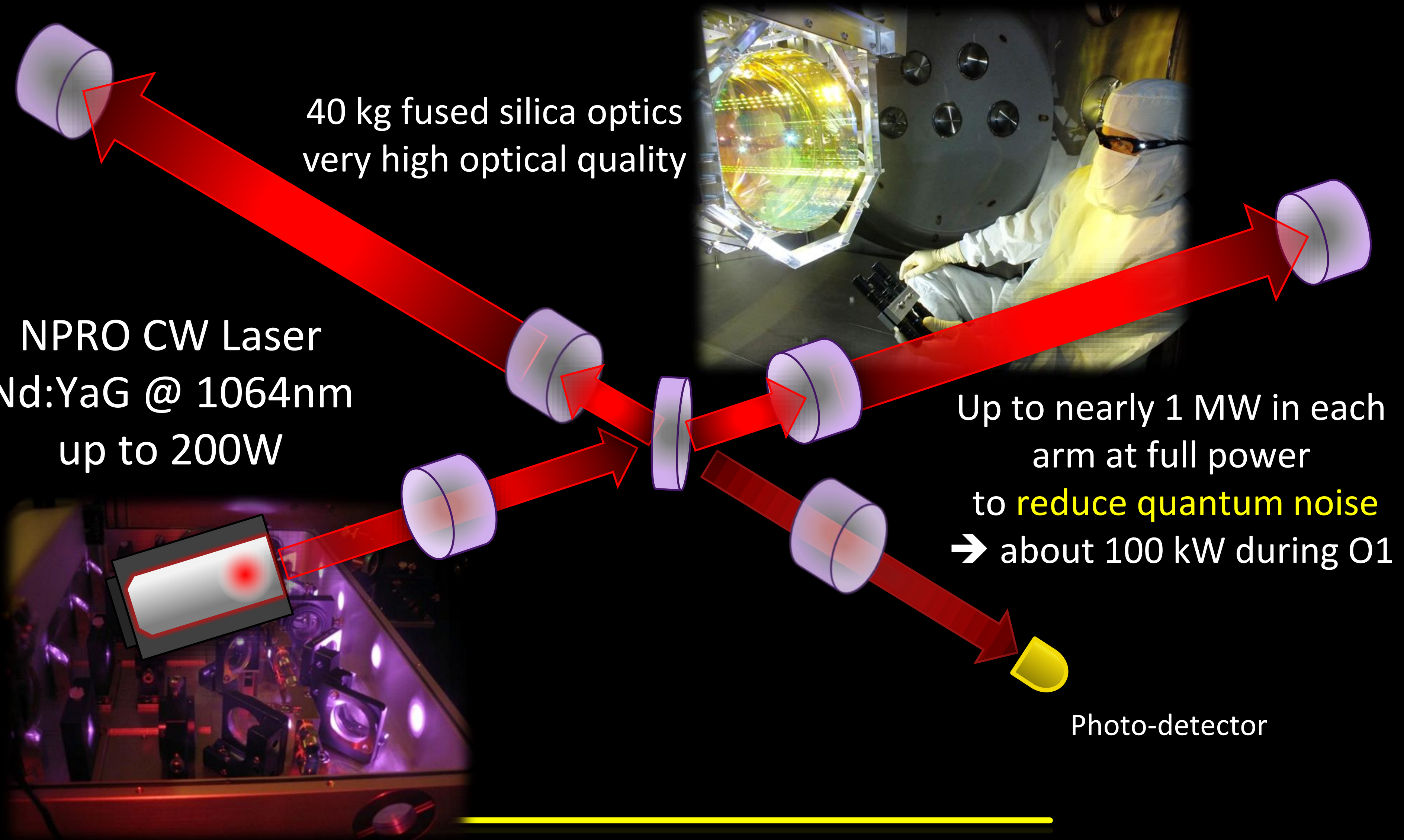
Photo Credit: R. Ward, S. Ballmer






LIGO Livingston Observatory (Louisiana)
L1 detector

The Advanced LIGO detectors

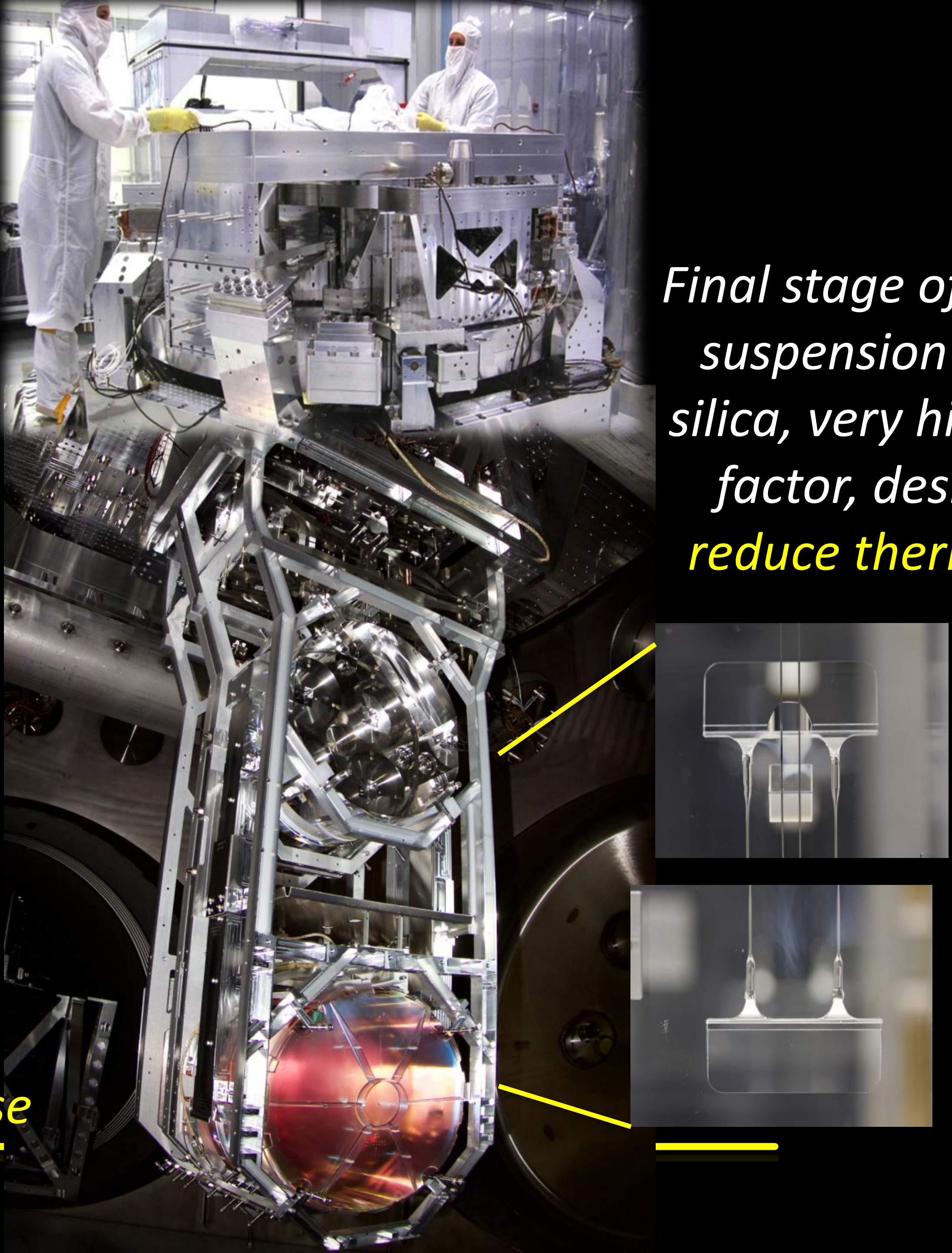


40 kg fused silica optics
very high optical quality

NPRO CW Laser
Nd:YaG @ 1064nm
up to 200W

Up to nearly 1 MW in each arm at full power
to **reduce quantum noise**
→ about 100 kW during O1

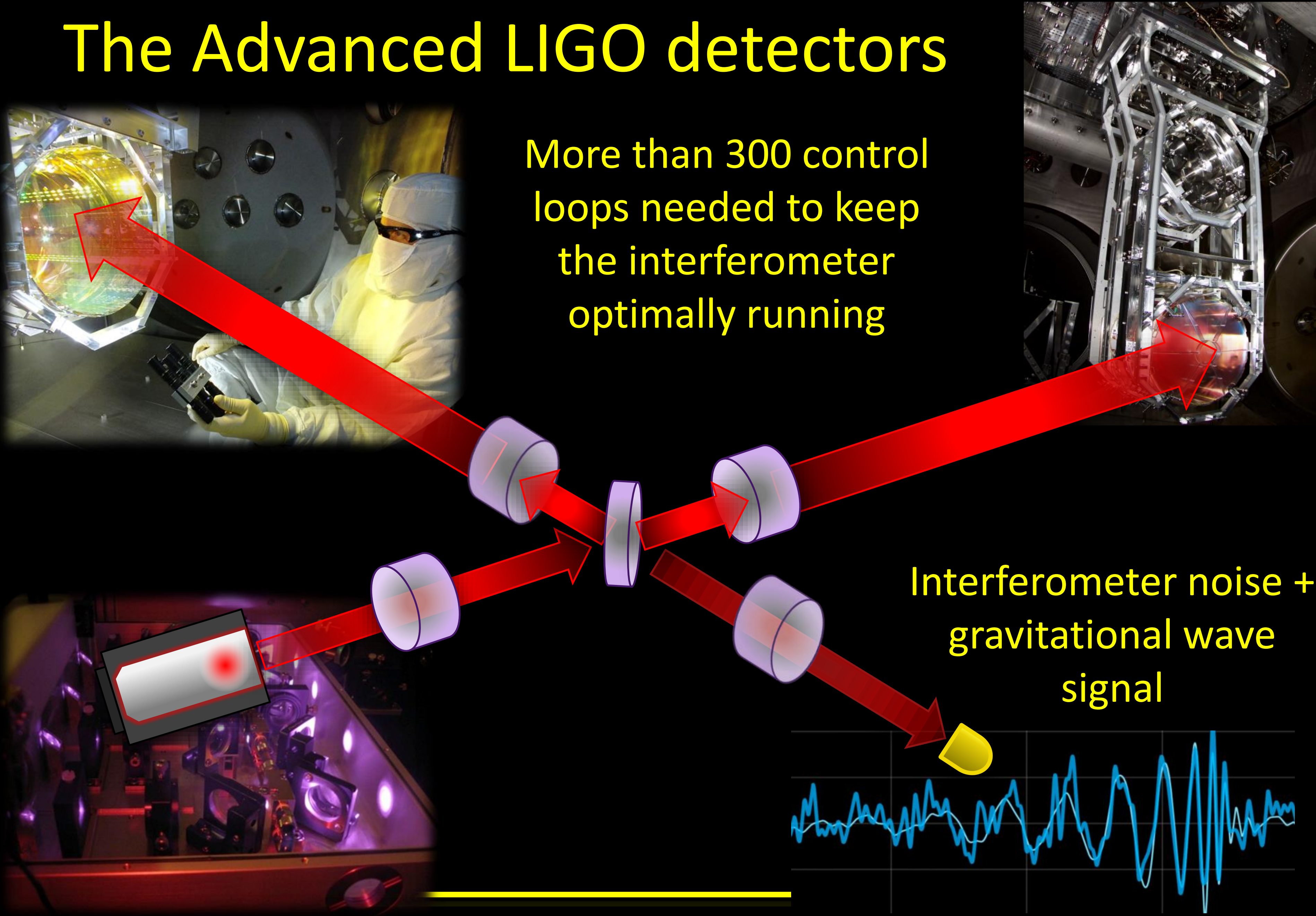
Test mass suspended by a quadruple pendulum, attached to two stages of active isolation to reduce seismic noise



Final stage of test mass suspension all fused silica, very high quality factor, designed to reduce thermal noise

Test masses have dielectric coating material with low mechanical loss to reduce thermal noise

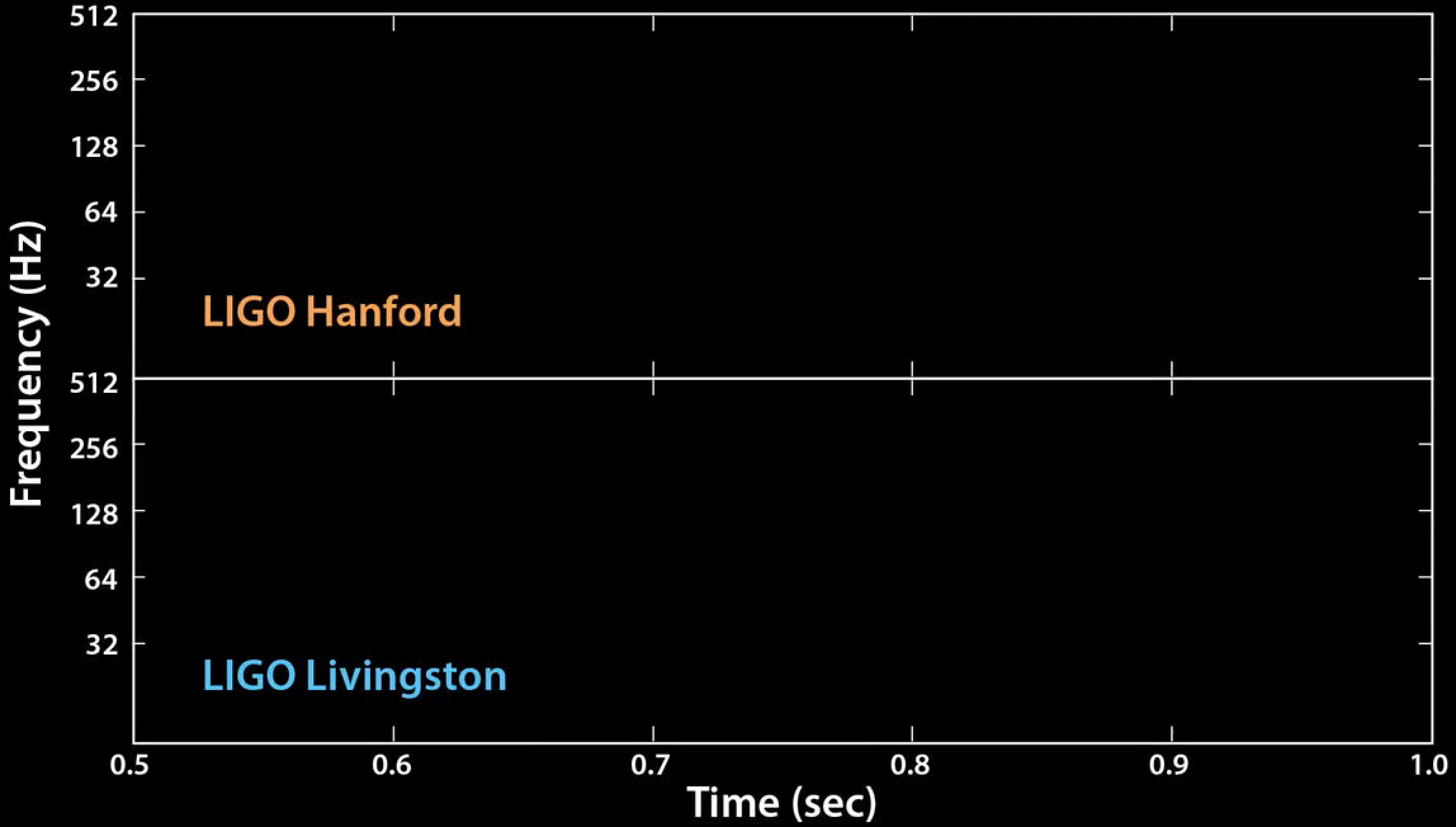
The Advanced LIGO detectors



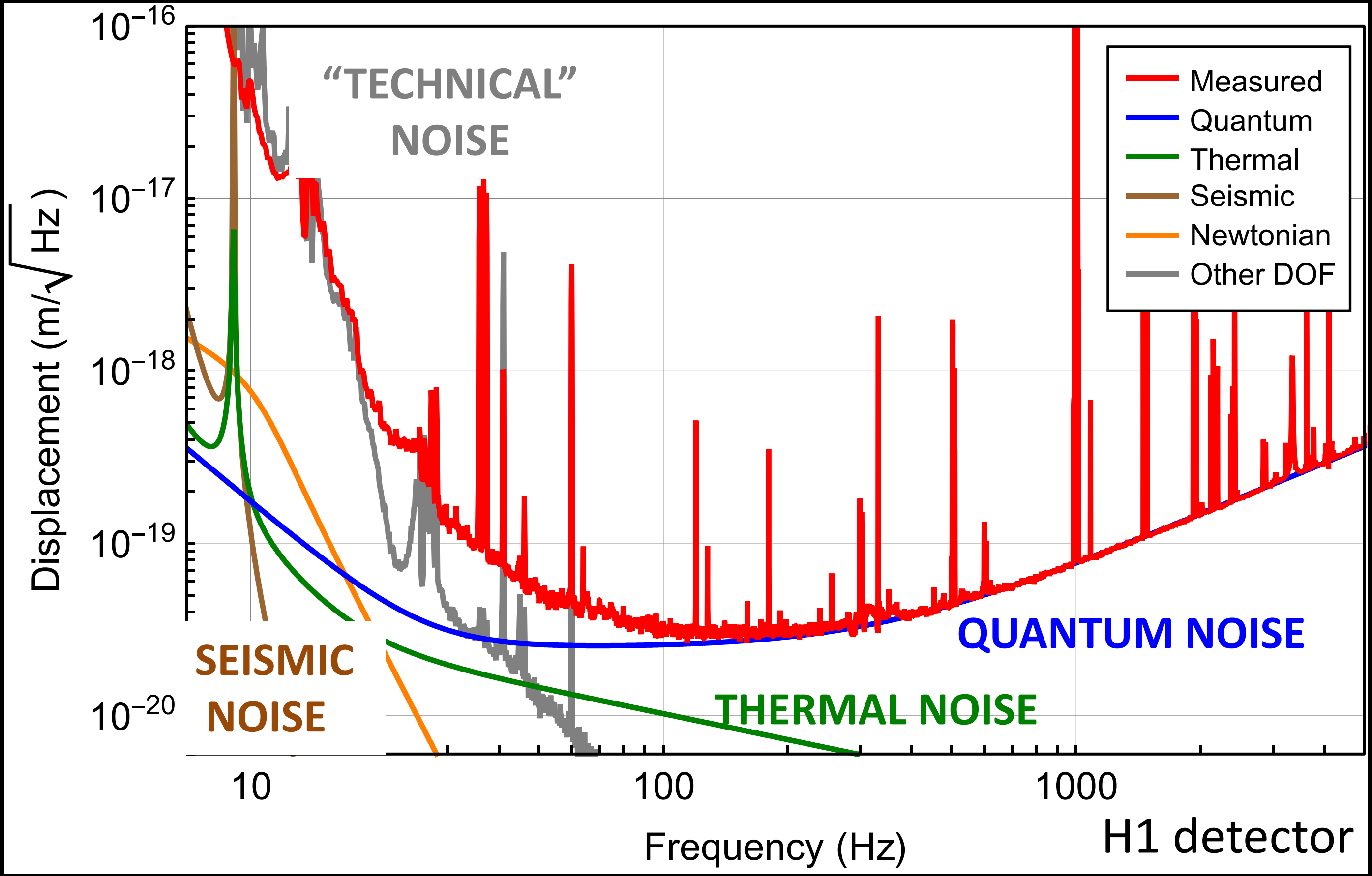
More than 300 control loops needed to keep the interferometer optimally running

Interferometer noise + gravitational wave signal

GW 150914

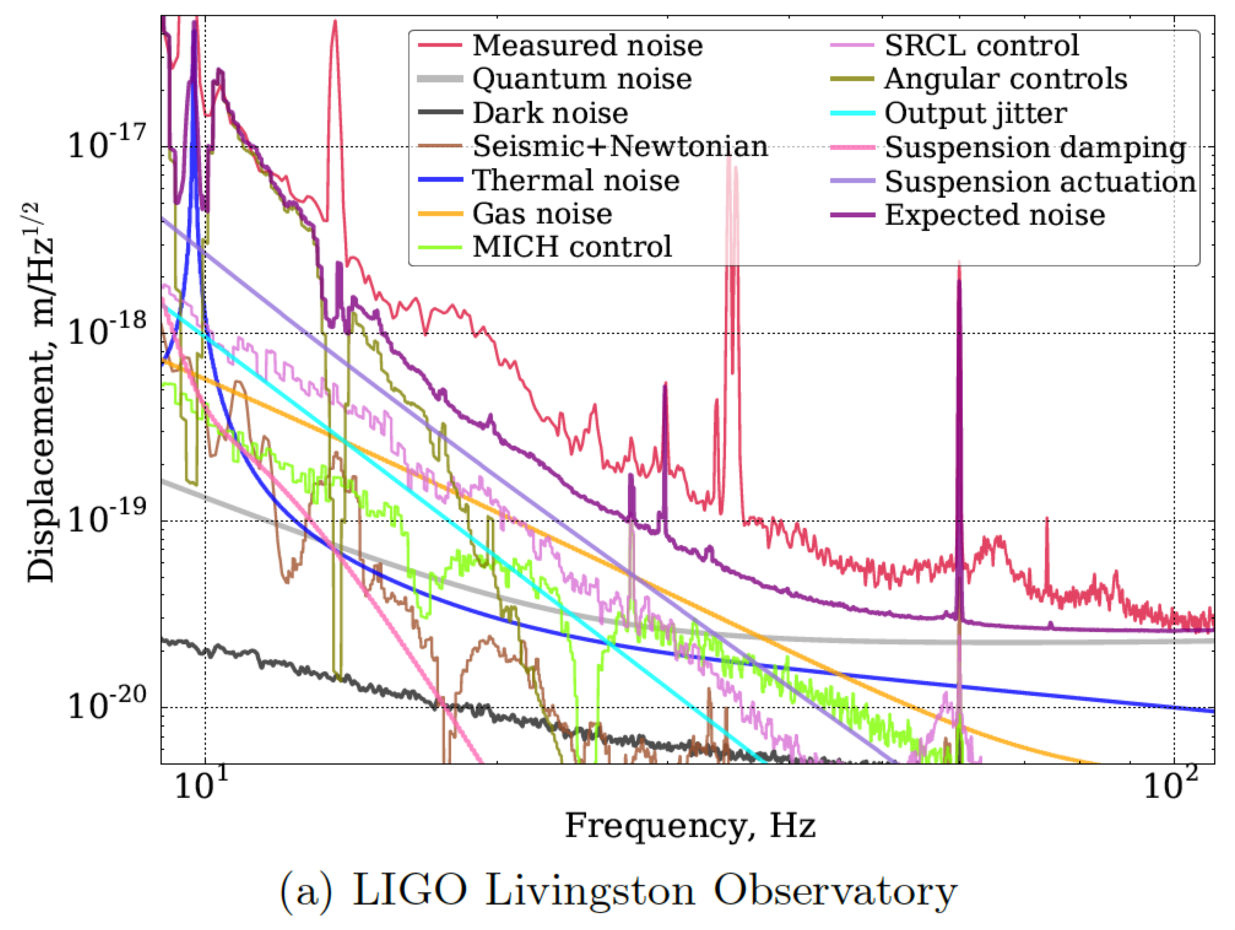

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

Interferometer Displacement Noise



GW150914: The Advanced LIGO Detectors in the Era of First Discoveries (Phys. Rev. Lett. 116, 131103)

Many noise sources in the 10-100 Hz band



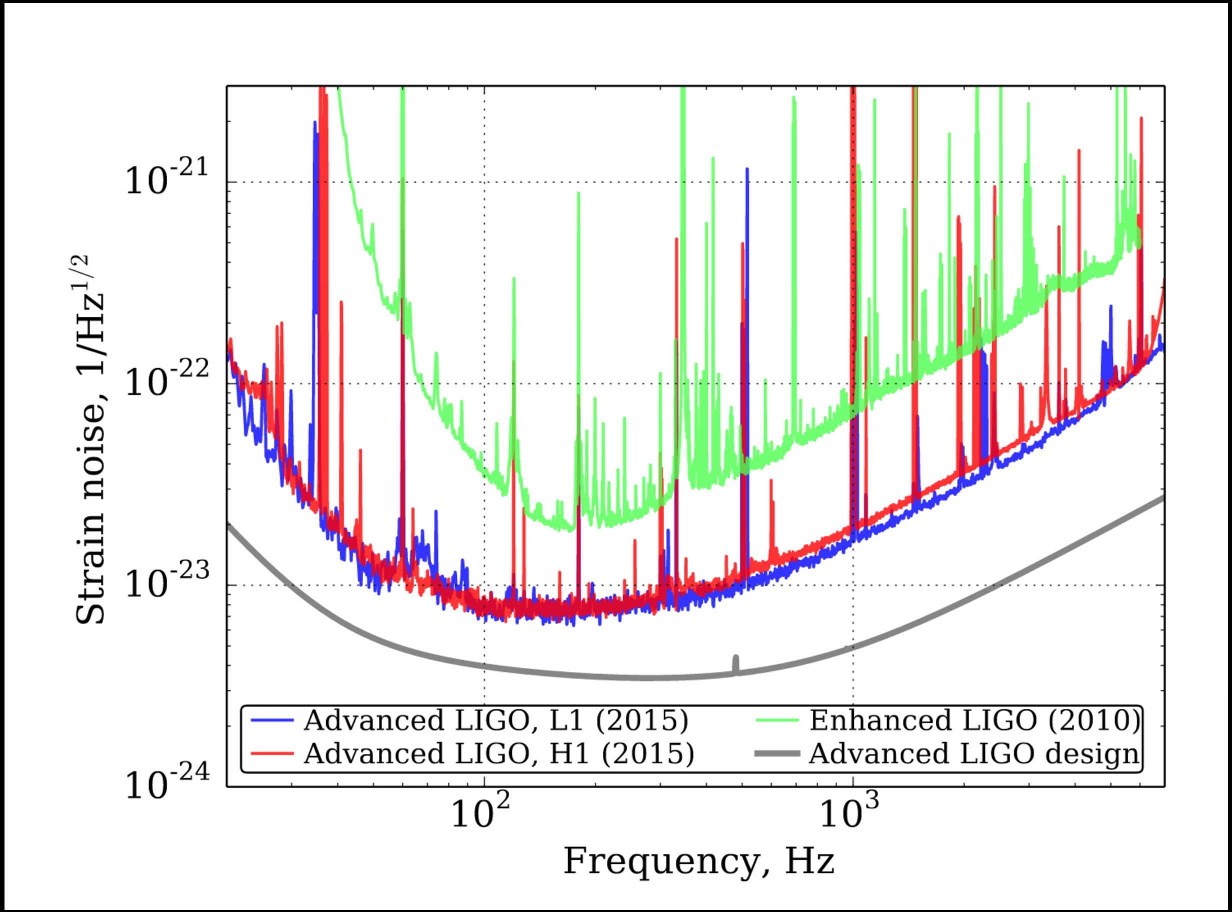
(a) LIGO Livingston Observatory

Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy D. V. Martynov et al. Phys. Rev. D 93, 112004

Strain noise during O1:

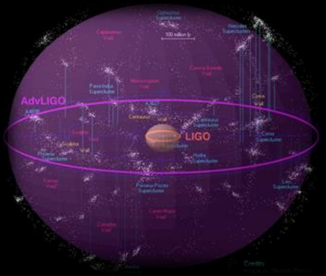
better than ever, not at design sensitivity yet

"Strain Noise"
=
Detector noise
expressed as
equivalent
GW strain



Initial LIGO
(2010)

Advanced
LIGO Design



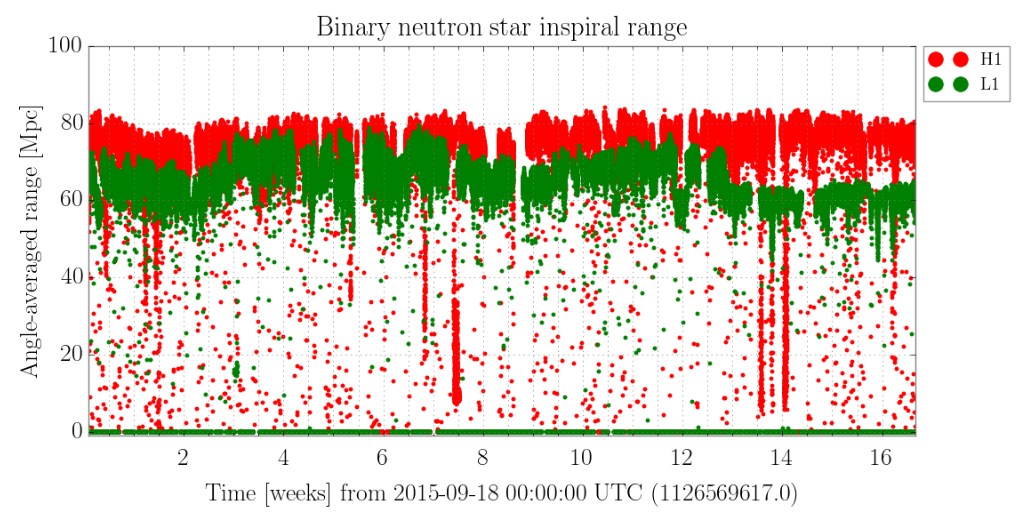
Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy D. V. Martynov et al. Phys. Rev. D 93, 112004

Observing Run O1

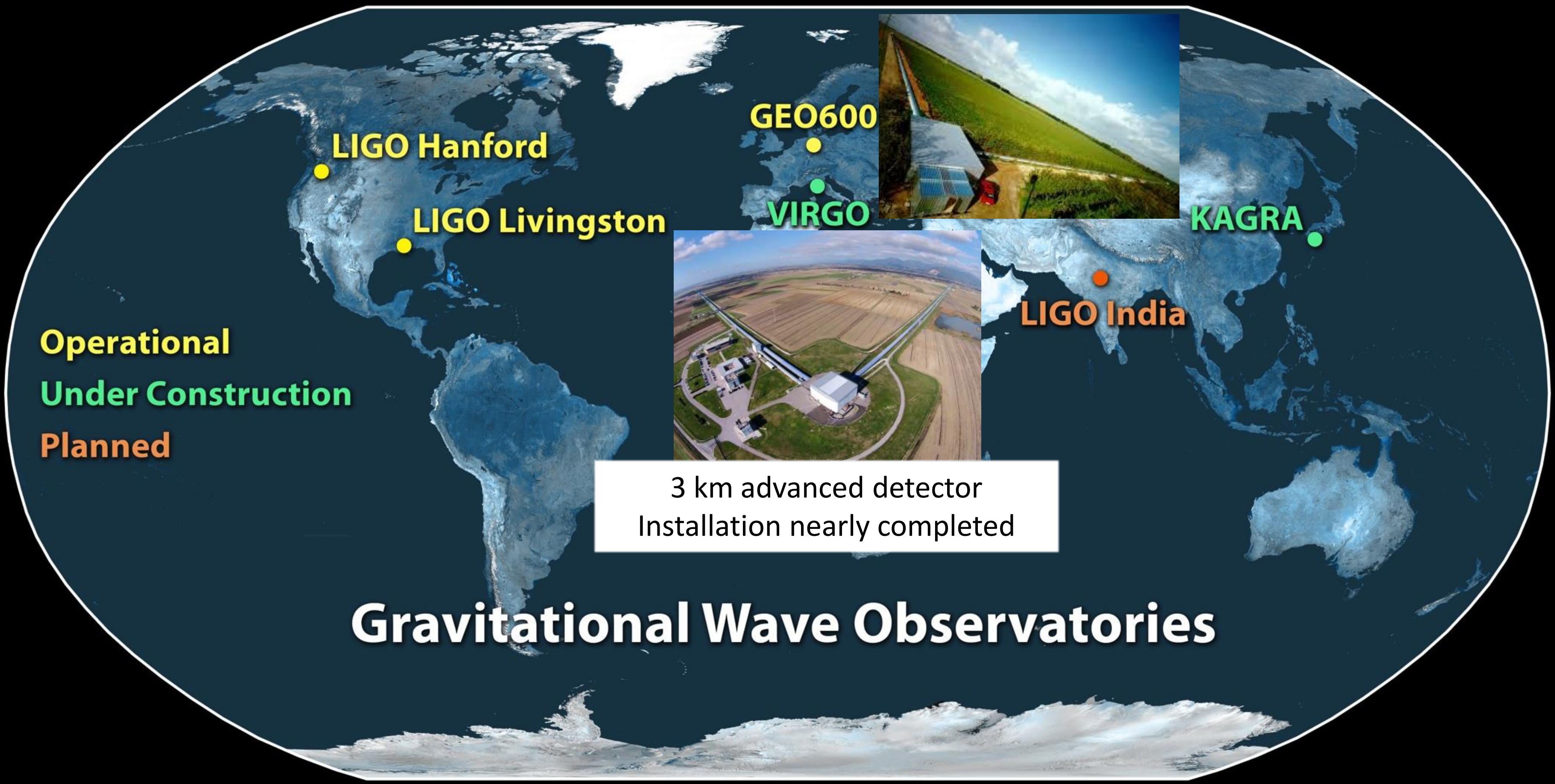
(from mid-September 2015 to mid-January 2016)

- ✓ During O1: H1 and L1 operational for ~4 calendar months
- ✓ Duty cycle: H1 = 62%, L1 = 55% ➔ H1&L1 = 43%
- ✓ 51.5 days of coincident time, 48.6 days after data quality process

The product of <u>observable volume</u> and <u>measurement time</u> exceeded that of all previous runs within the first 16 days of coincident observation



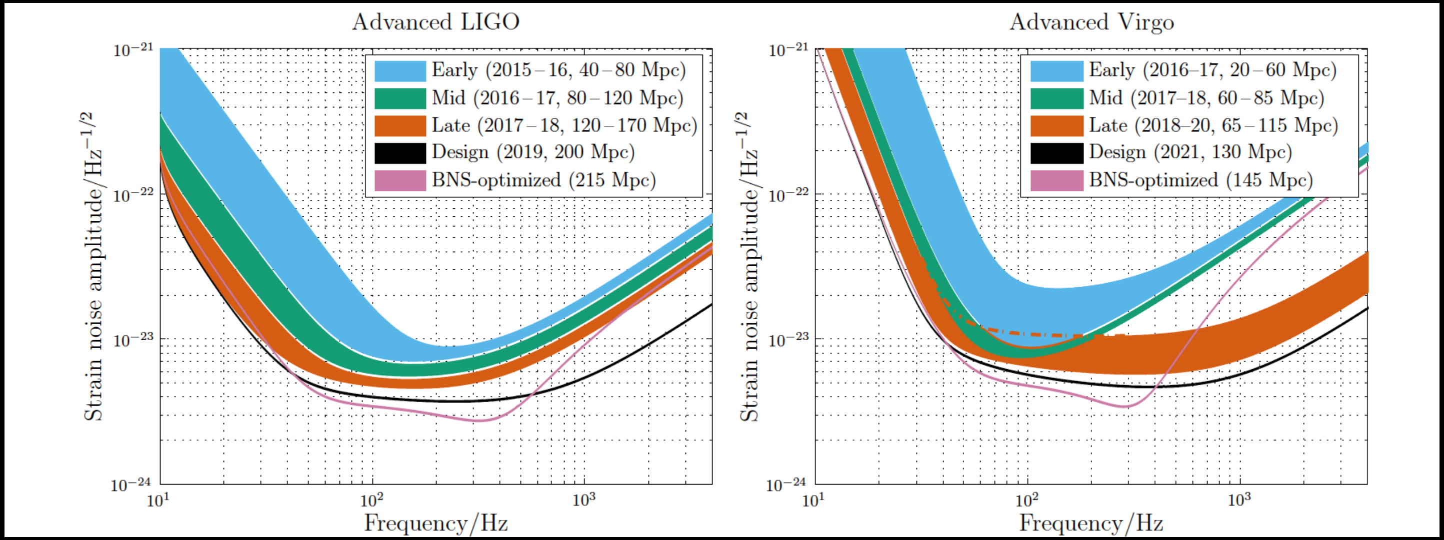
VIRGO expected to join the network soon



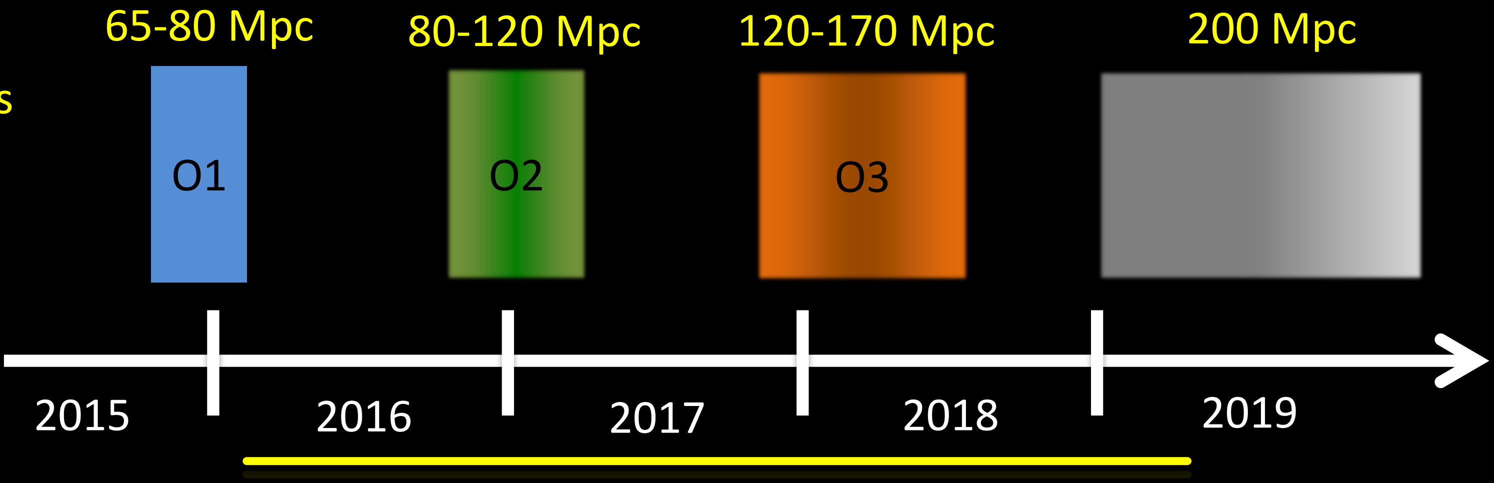
3 km advanced detector
Installation nearly completed

LIGO-Virgo Observing Plan Overview

Live Observing document http://arxiv.org/abs/1304.0670



Binary
Neutron
Star ranges

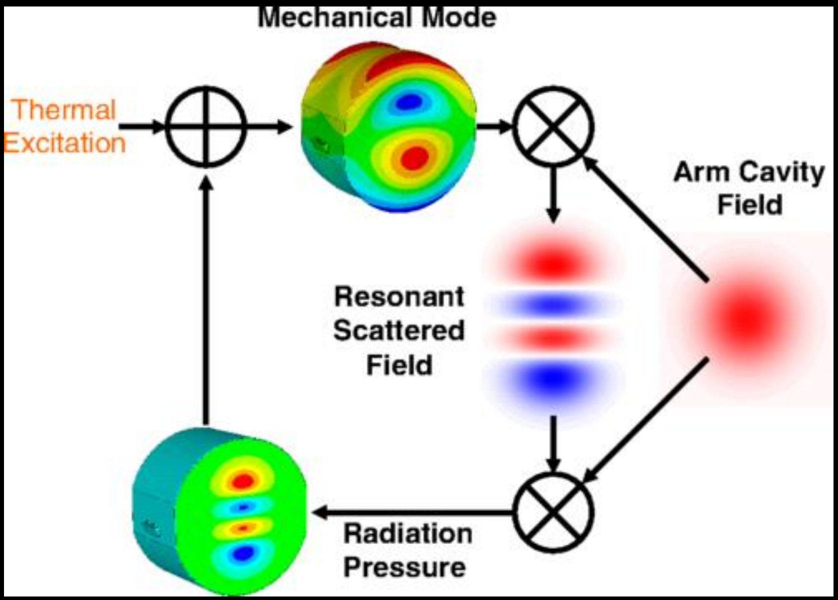


Since the end of the first Observing Run O1

- Work to improve the sensitivity:
  - Noise “hunting”: understand and reduce the noise at low frequency
  - Increase the circulating power to reduce quantum noise (several challenges associated with that)
- Data quality improvements
- Interferometer robustness

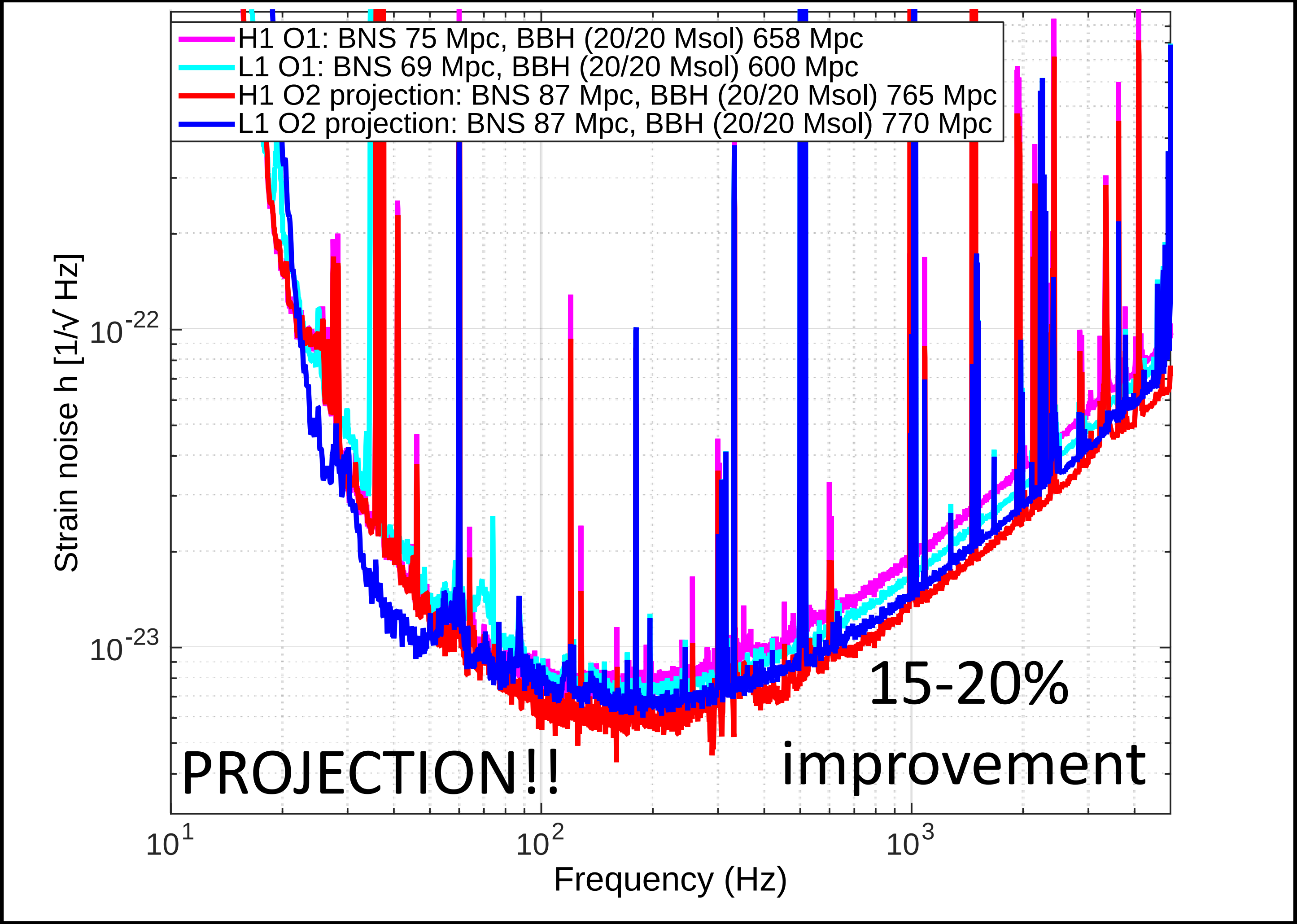
(Some of) the challenges with high circulating laser power

- Thermal lens in the interferometer mirrors induced by high circulating power require active thermal compensation
- Mirror alignment control
- “Parametric” instabilities: acoustic modes of the mirrors get excited and pump light in high order optical modes, that become resonant in the arms



Observation of Parametric Instability in Advanced LIGO
Matthew Evans et al. Phys. Rev. Lett. 114, 161102 (2015)

Projected sensitivity for O2 (this Fall)

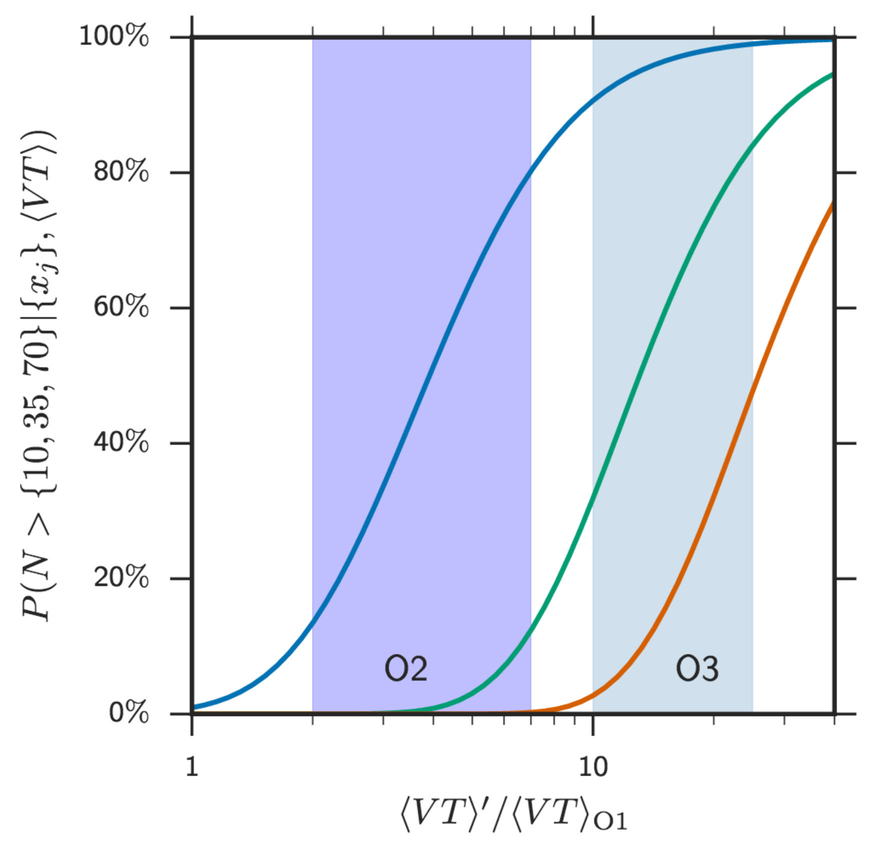


PROJECTION!!

15-20% improvement

Binary Black Holes Rates

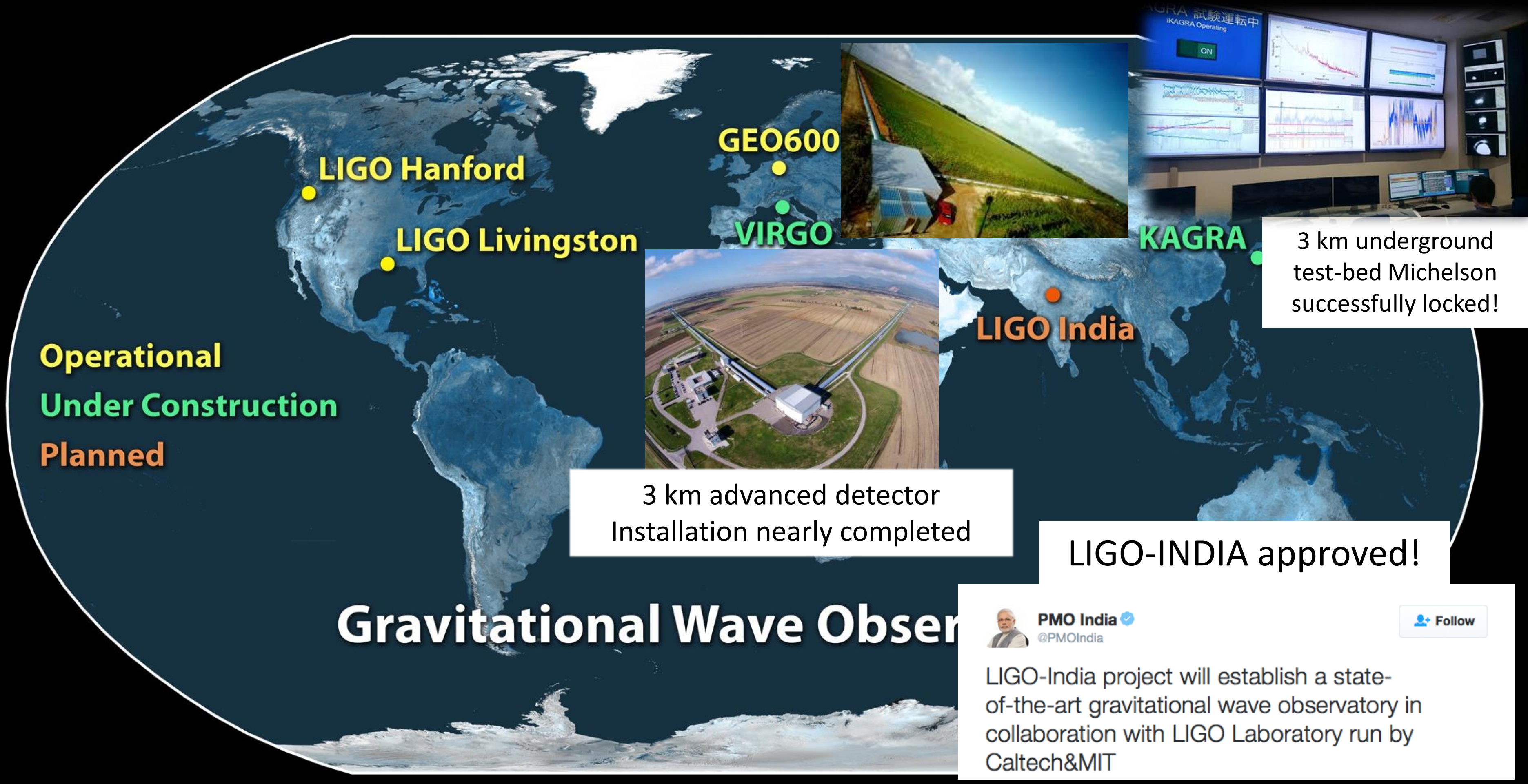
https://arxiv.org/abs/1606.04856



surveyed time-volume (shown as multiple of VT analyzed for O1)

- O2: projected time volume at least 2/2.5 larger wrt O1
- Expect to see (at least) a few significant events by the end of O2
- Ten(s) of events by the end of O3

The upcoming world-wide network of advanced detectors



3 km underground test-bed Michelson successfully locked!

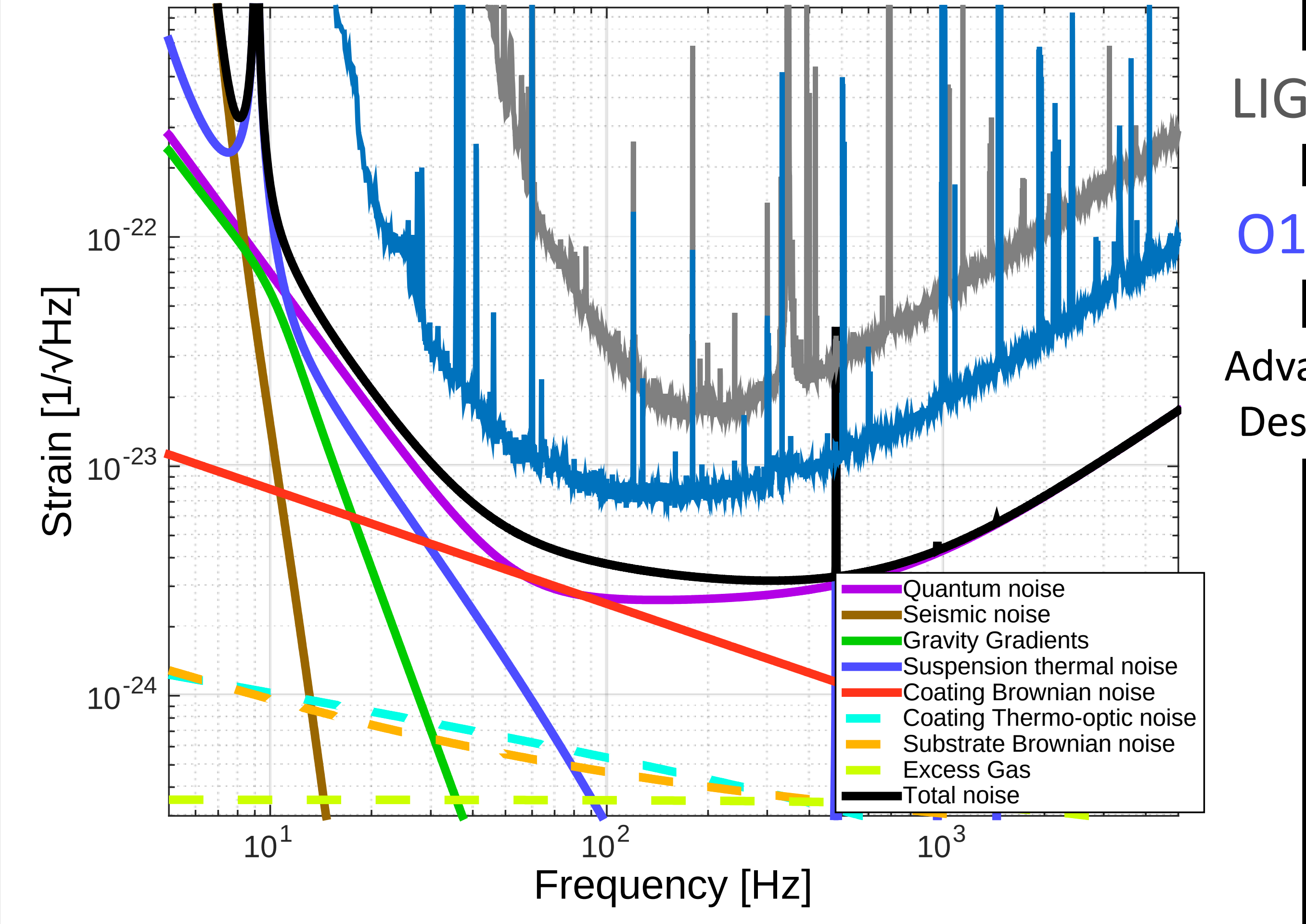
3 km advanced detector
Installation nearly completed

LIGO-INDIA approved!

PMO India @PMOIndia

LIGO-India project will establish a state-of-the-art gravitational wave observatory in collaboration with LIGO Laboratory run by Caltech&MIT

Can we do better than advanced detectors?

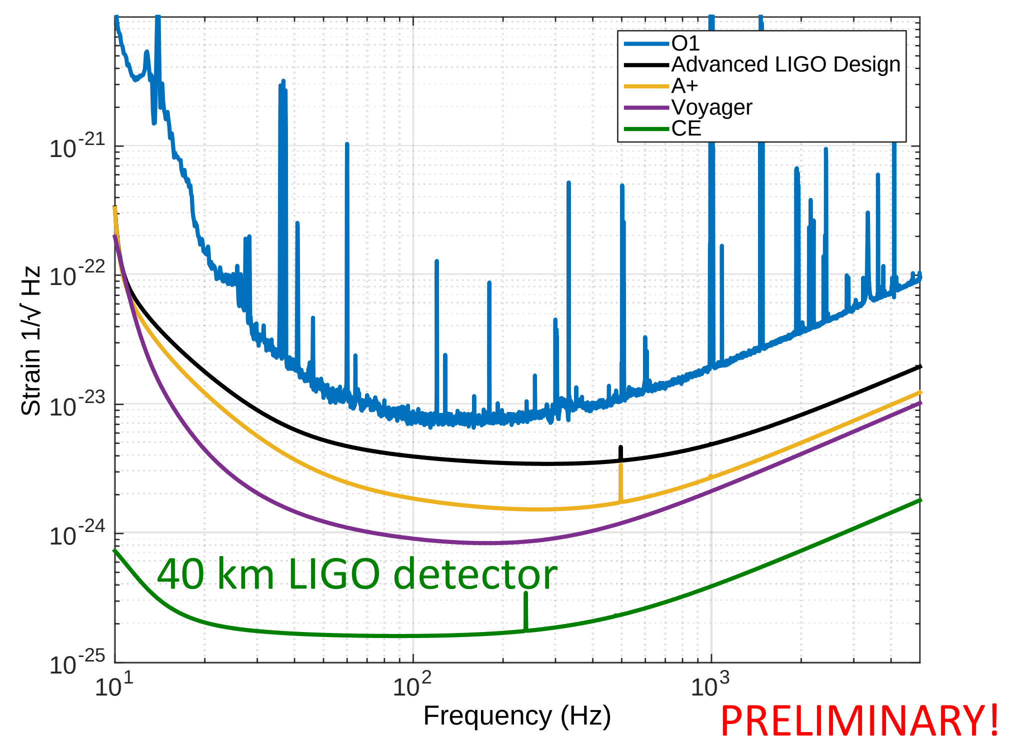


LIGO 2010

O1 (2015)

Advanced LIGO Design (2019)

Beyond advanced detectors

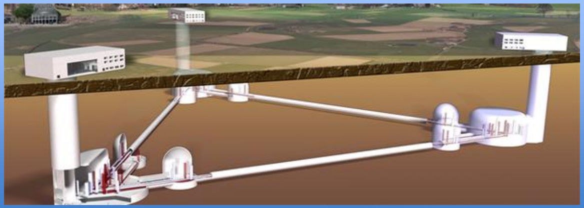


- ✓ Two complementary strategies: better technologies and longer interferometer arms
- ✓ Up to a factor of 2-4 better sensitivity than design in current facility
- ✓ Ultimately need new facility with longer baseline for factor of 10+ improvements

European design study: **Einstein telescope**

Triangular shape, underground

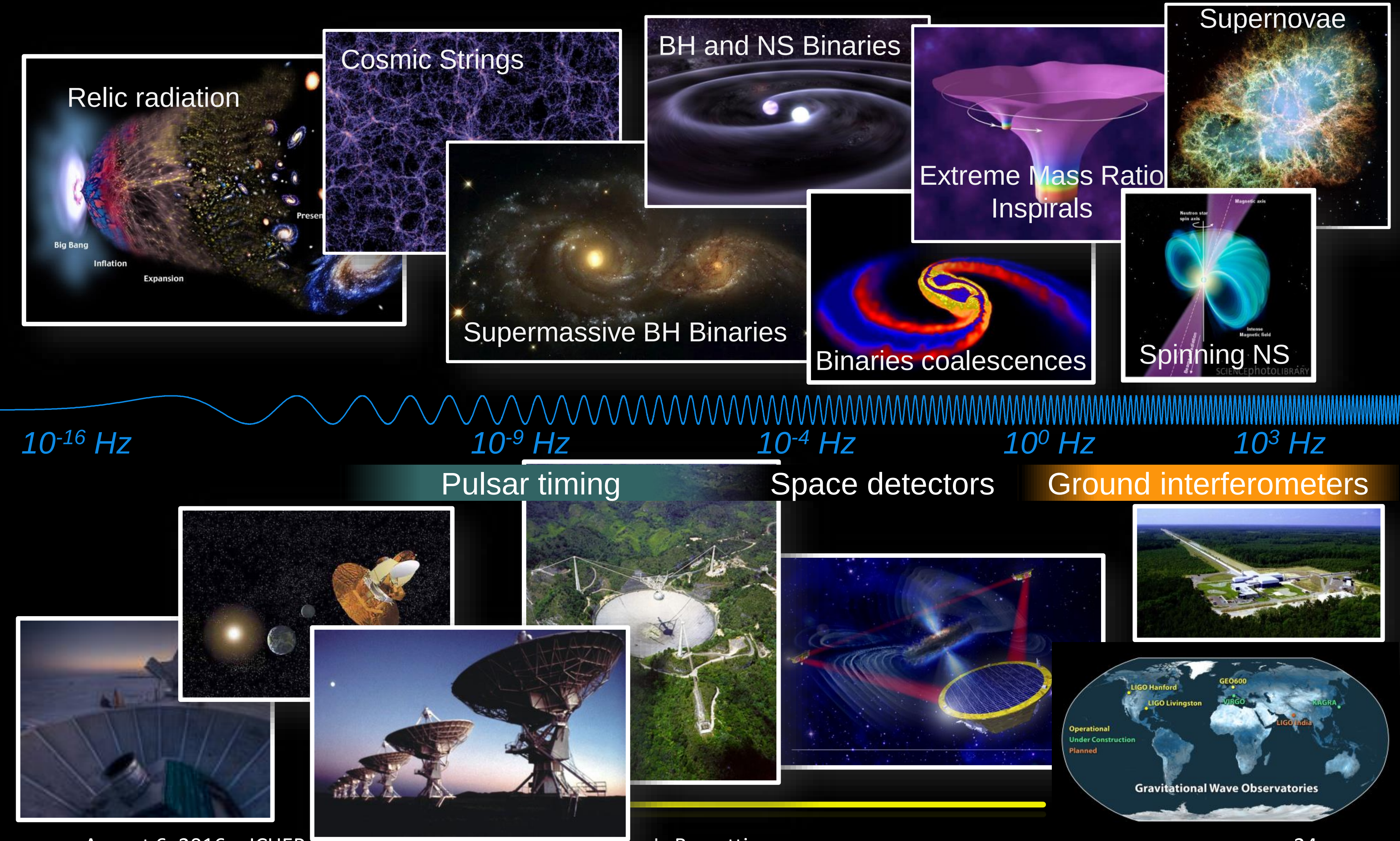
(see: http://www.et-gw.eu/)



Conclusions

- Advanced LIGO works, and there are gravitational wave signals out there to detect!
- Progression of sensitivity improvements interleaved with observing runs in the near future
- Network of advanced detectors coming on-line in the upcoming years (Virgo, Kagra, LIGO-India)
- World-wide gravitational wave community working to further extend the reach of ground based detectors, for many events and very high SNR

It is just the beginning: the Gravitational Wave Spectrum



Relic radiation

Cosmic Strings

BH and NS Binaries

Extreme Mass Ratio Inspirals

Supernovae

Supermassive BH Binaries

Binaries coalescences

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

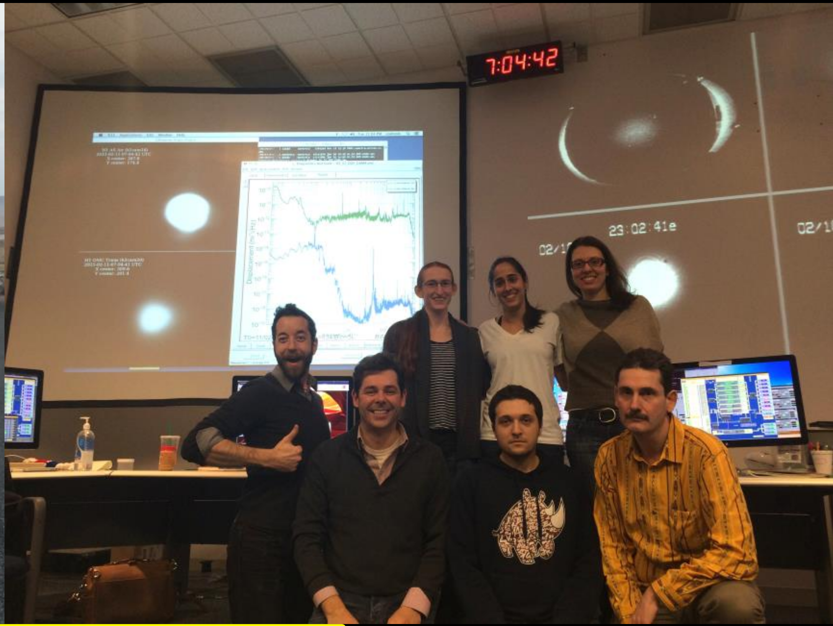
10^{3} Hz

Pulsar timing

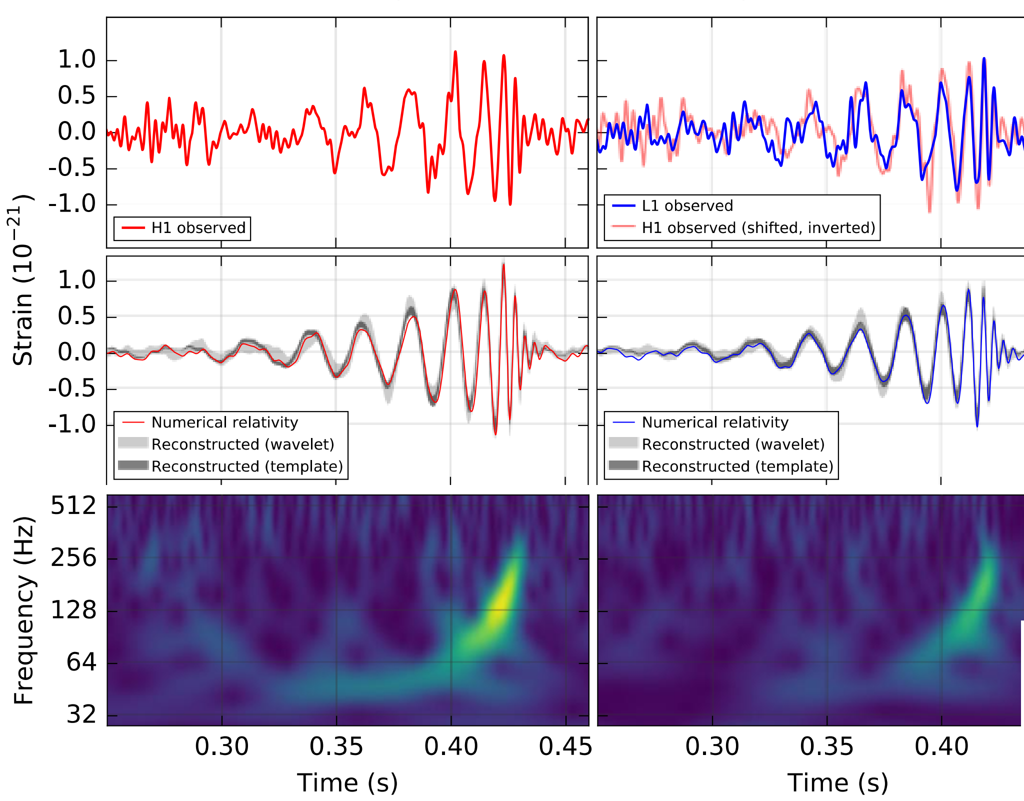
Space detectors

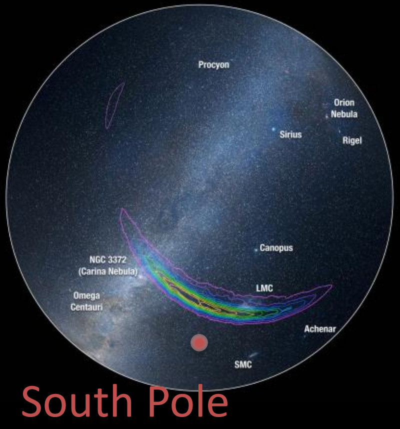
Ground interferometers

THANKS!

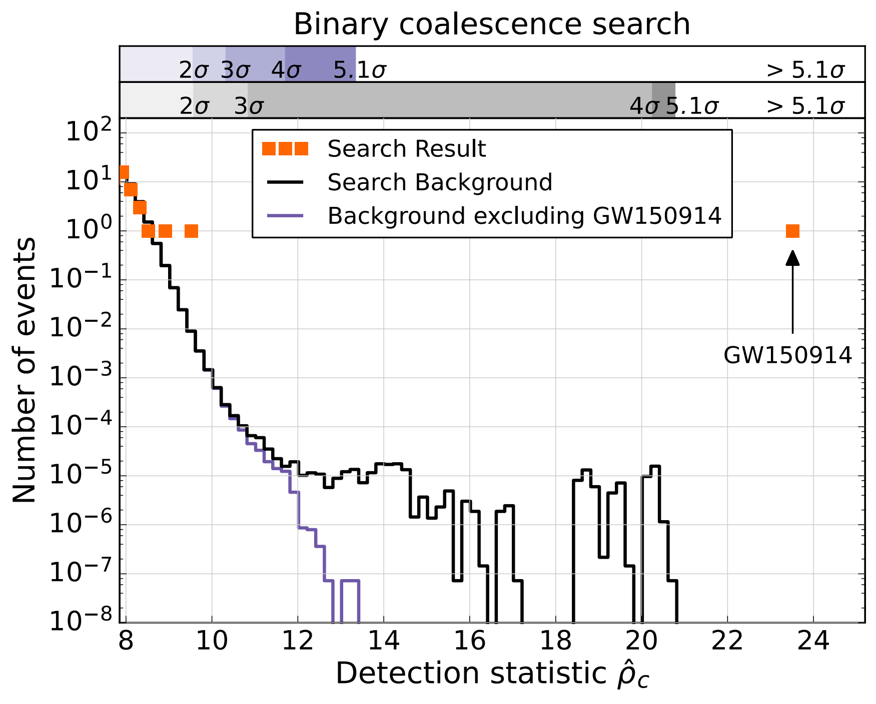


GW150914, a discovery in one slide...





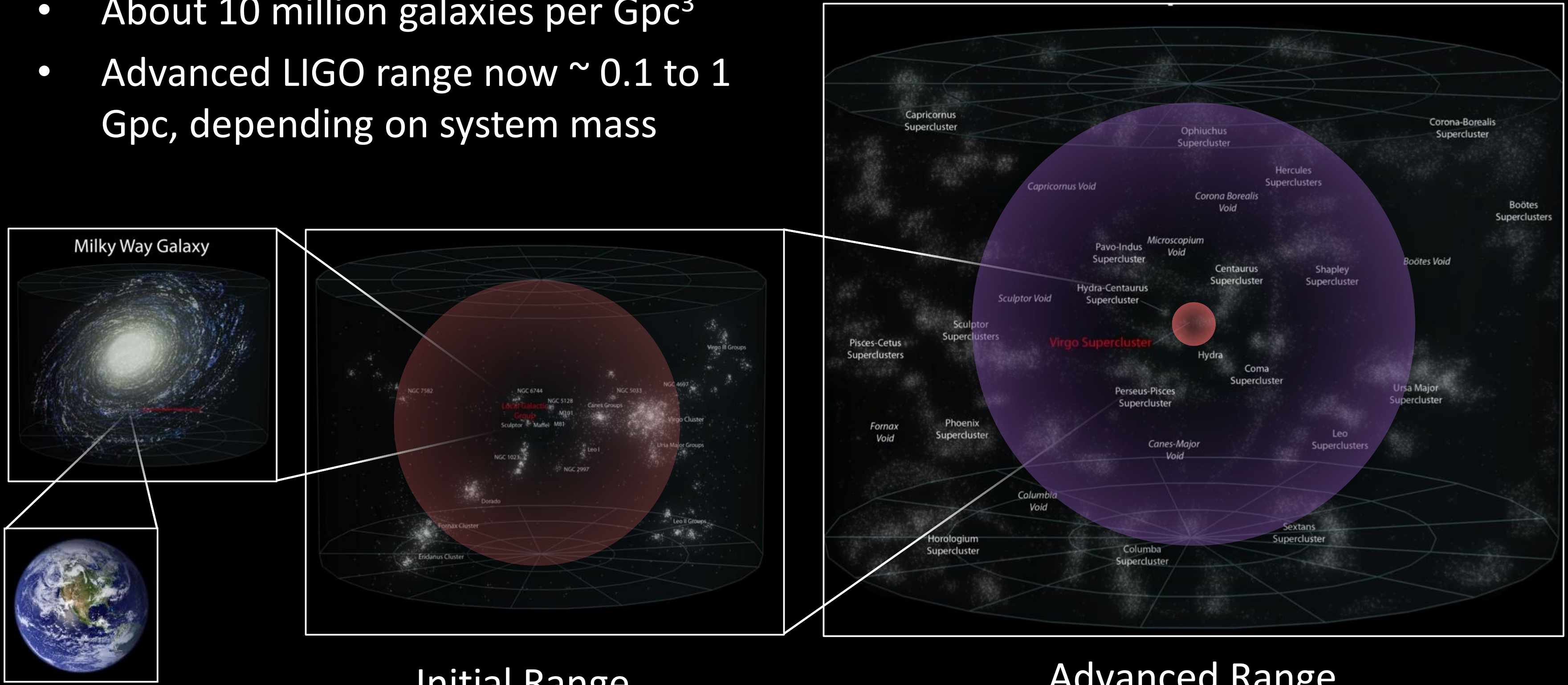
Primary black hole mass	$36^{+5}_{-4}\,\mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$



Advanced LIGO Sensitive Volume

- Rate roughly 50 BBH mergers each year in a volume of 1 Gpc^3
- About 10 million galaxies per Gpc^3
- Advanced LIGO range now ~ 0.1 to 1 Gpc, depending on system mass

We can expect 5 or more BBH events in the next observing run



Initial Range

Advanced Range

A+: a factor of 2 sensitivity improvement over Advanced LIGO

- Mature technologies available to reduce quantum noise and improve aLIGO sensitivity by ~35% beyond design ➔ x1.35^3=2.5 in rate
  - Squeezed light for gravitational wave detectors:

    Nature Physics 7, 962–965 (2011)
    Nature Photonics 7, 613–619 (2013)
    Phys. Rev. Lett. 116, 041102 (2016)

- Need to reduce thermal noise for maximal benefit:
  - Reducing coating thermal noise as well can lead to a reduction in the noise by a factor of 2
  - Remember: detection rate scales with cube..

    ➔ x2^3 = 8 in rate!

frequency dependent squeezing experiment @ MIT