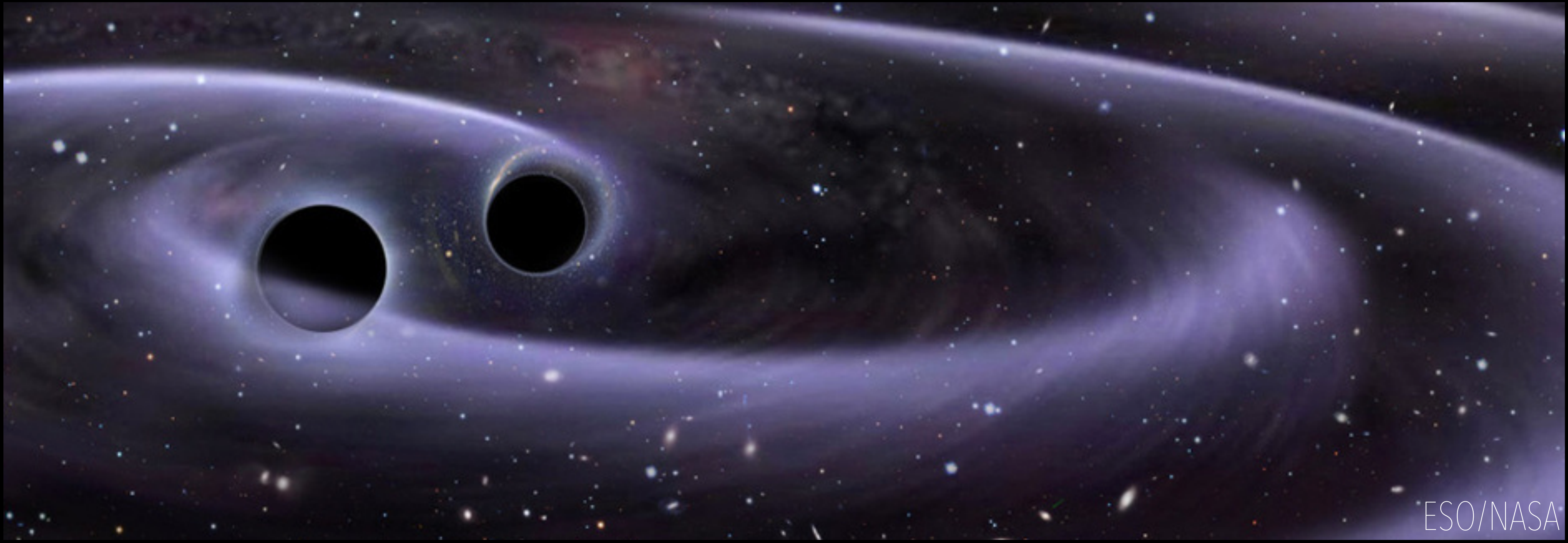
LIGO and the Beginning of Gravitational Wave Astronomy



Dr. Jess McIver, Caltech

Brookhaven National Lab
September 22, 2016
LIGO DCC G1601664

LSC

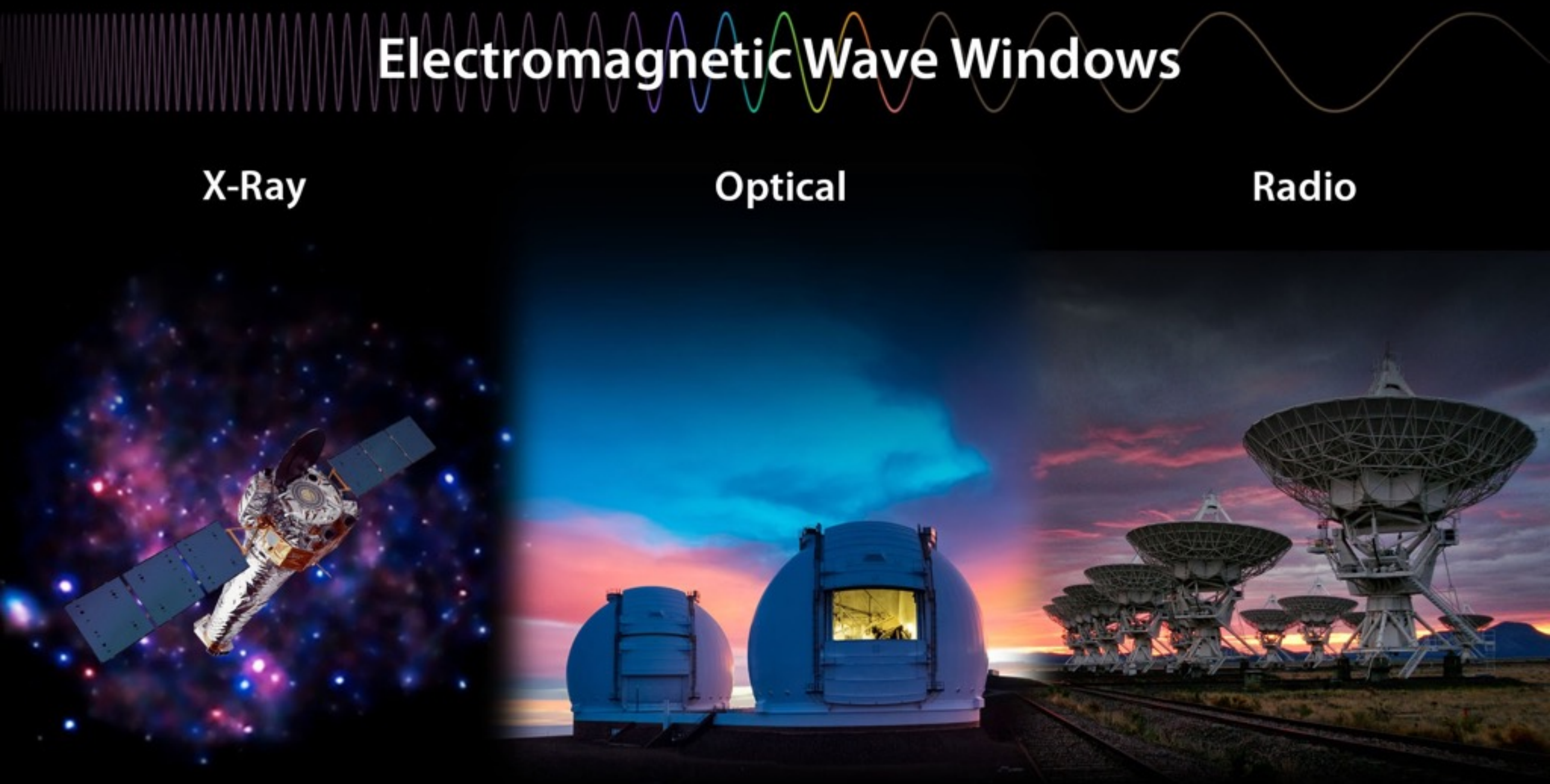
Caltech

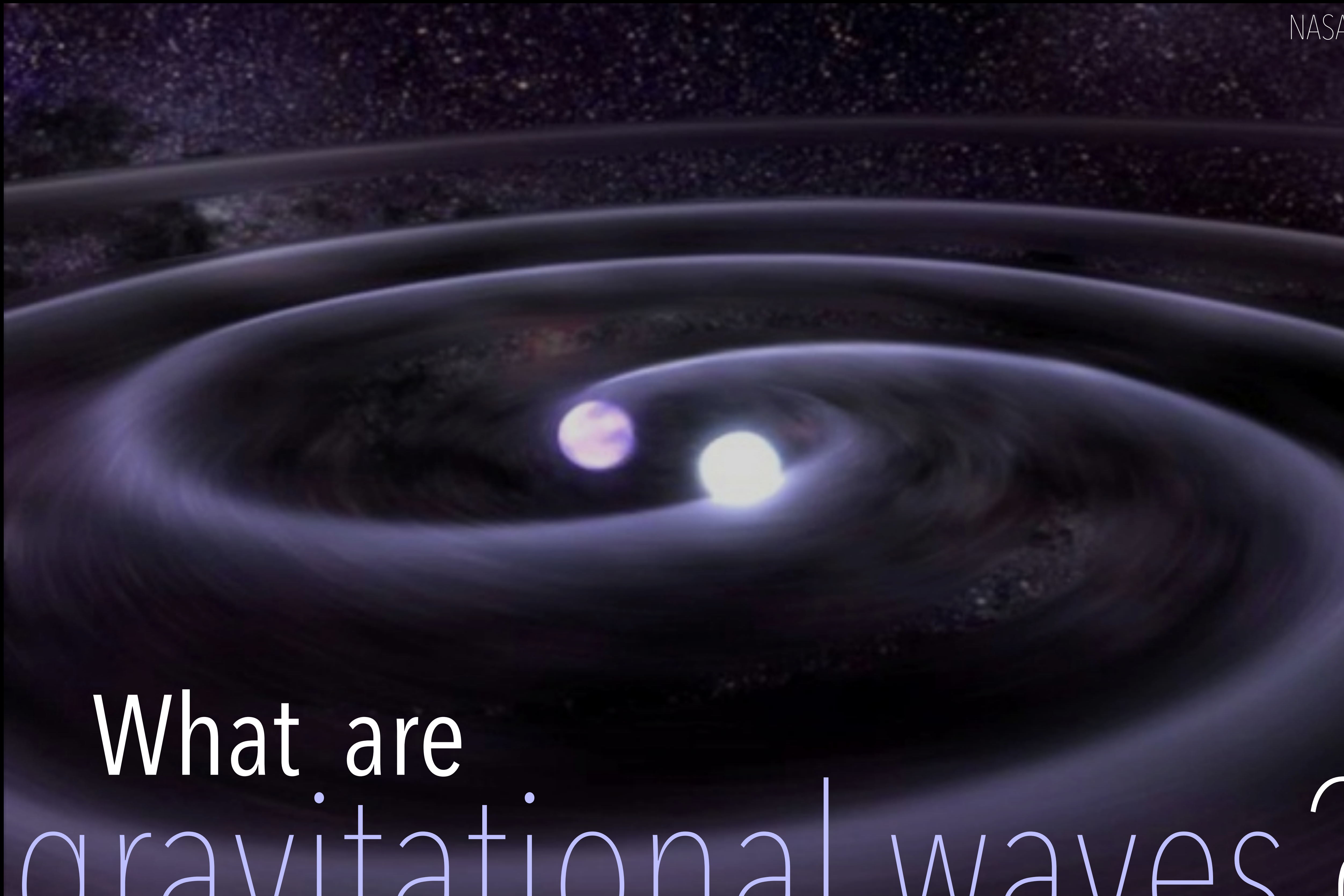
What *are* gravitational waves?

waves come in many forms

Waves occur naturally nearly *everywhere*

Astronomy with light

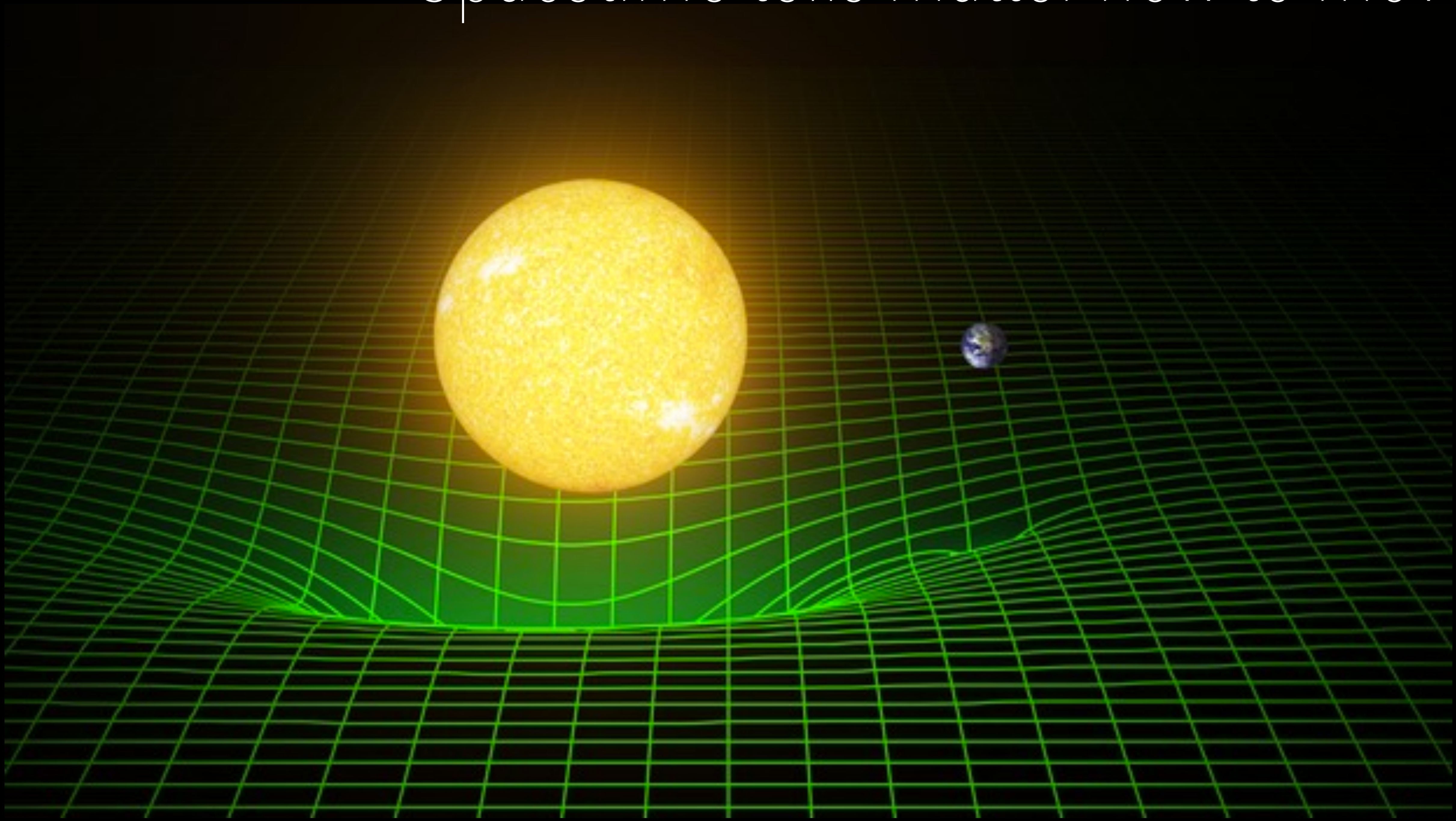




What are gravitational waves?

General Relativity

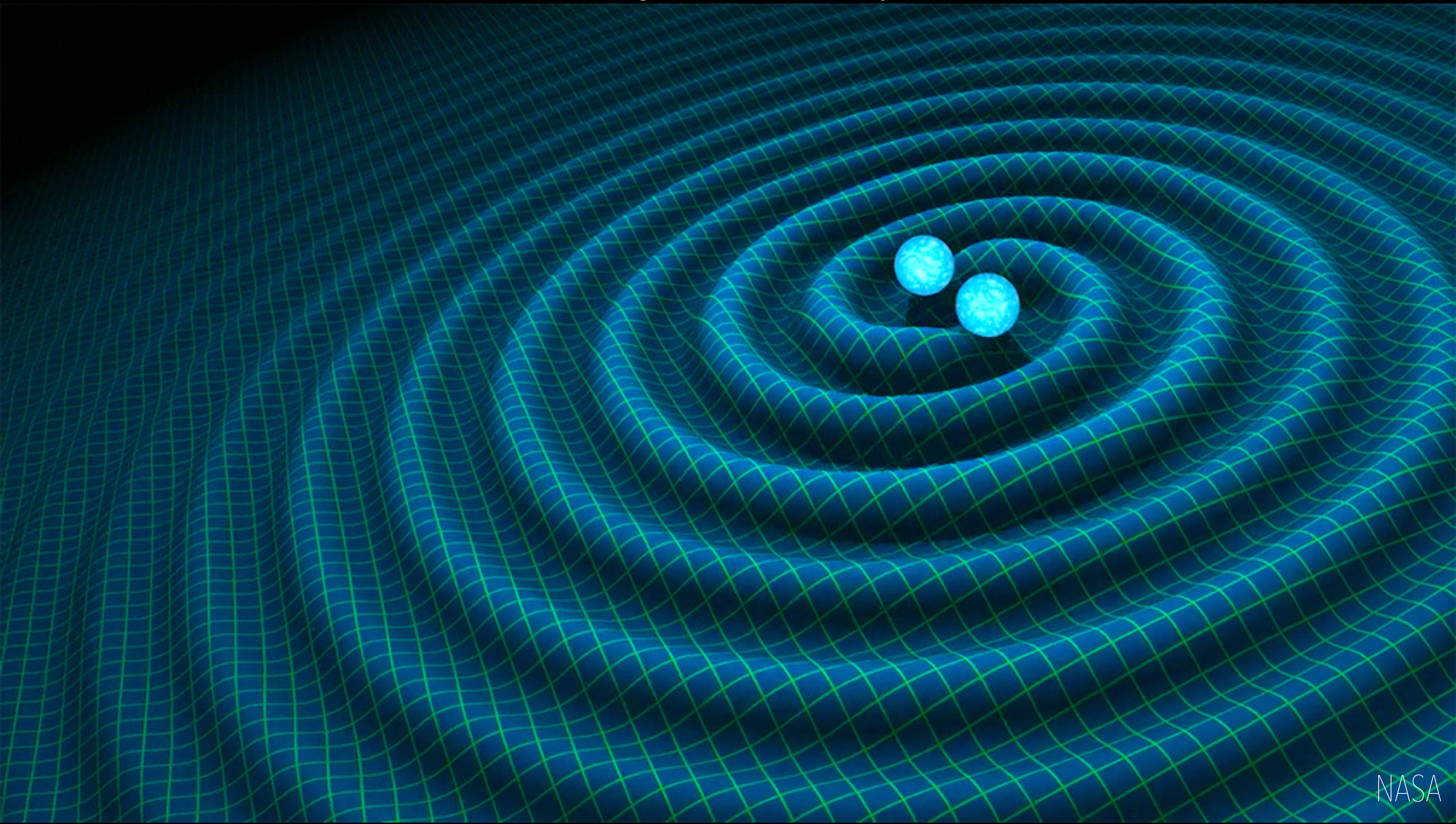
Matter tells spacetime how to curve
Spacetime tells matter how to move



Gravitational waves

Ripples in the fabric of spacetime

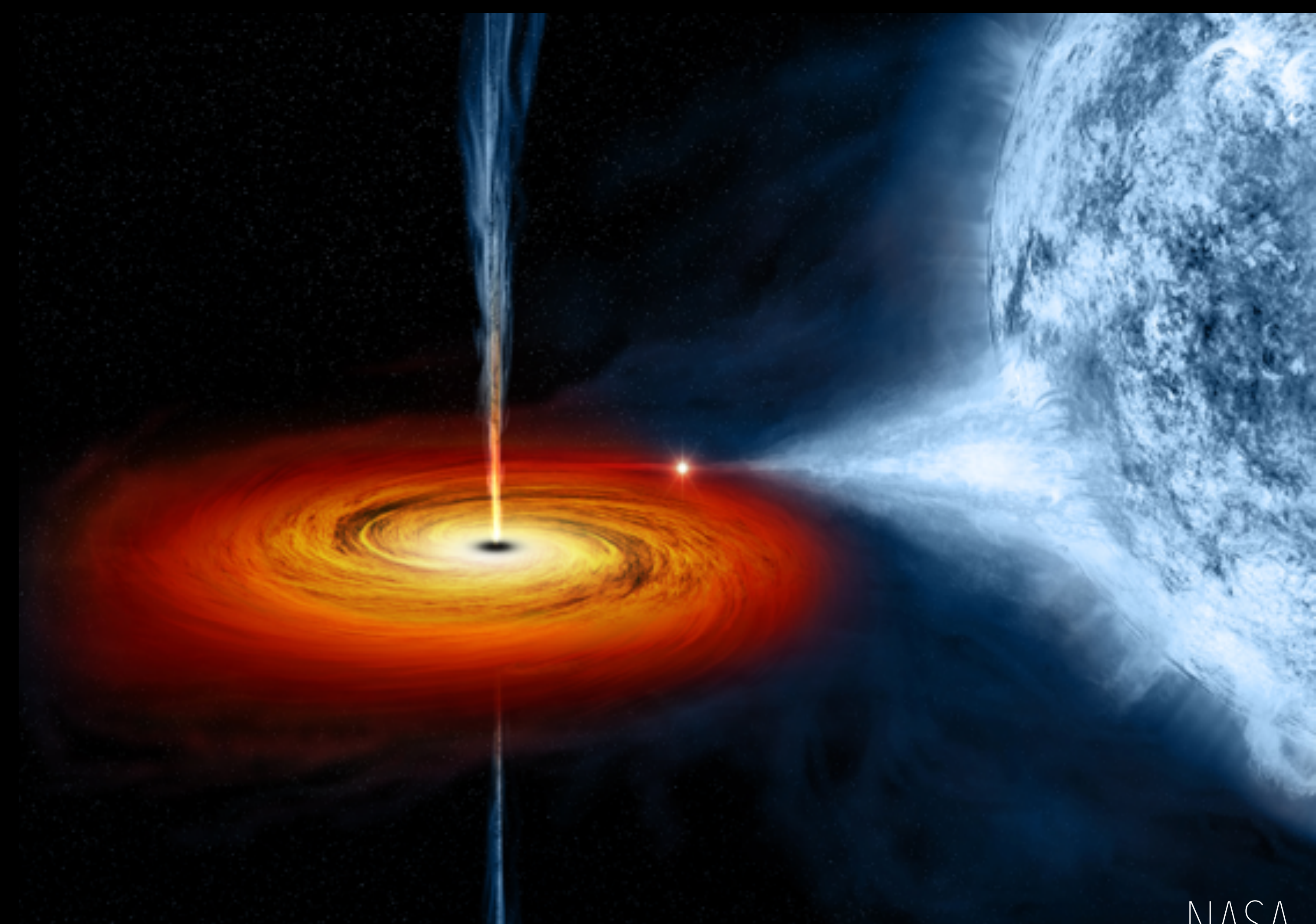
generated by the acceleration of matter



Gravitational waves

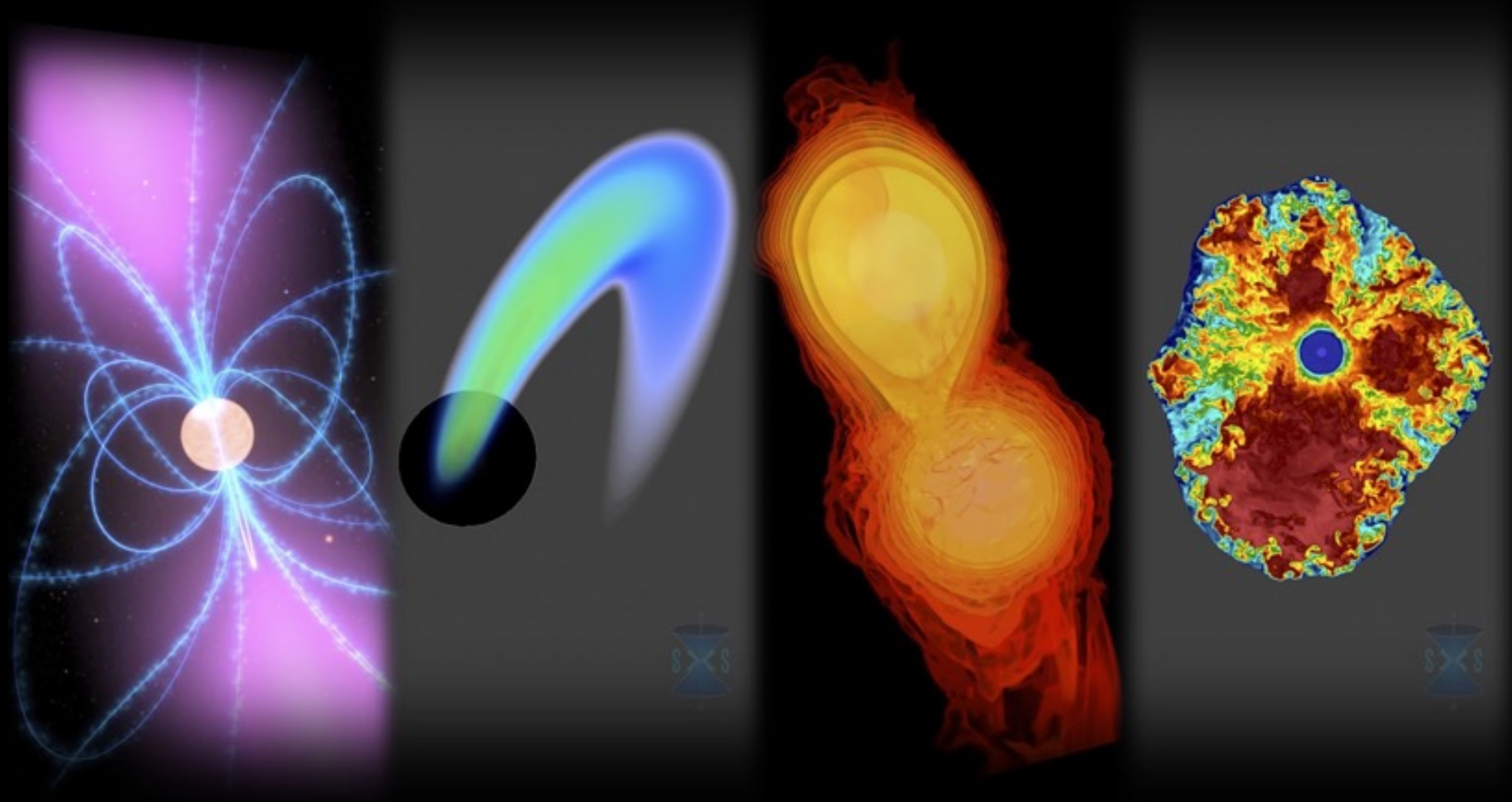
cause very tiny distortions to space.

Only **VERY MASSIVE** objects moving ***REALLY FAST***
emit gravitational waves strong enough to detect their passing.

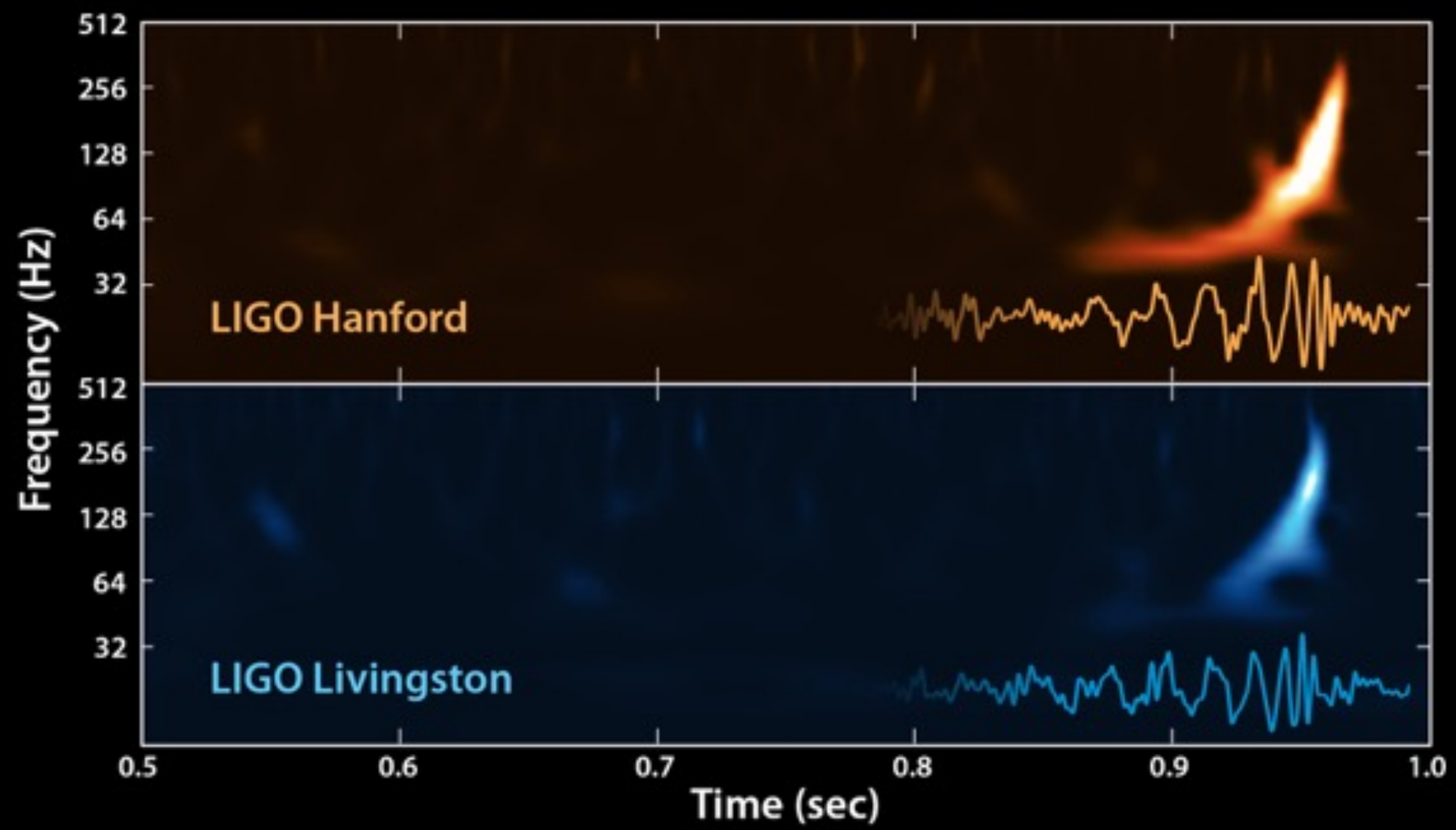


NASA

What makes detectable gravitational waves ?



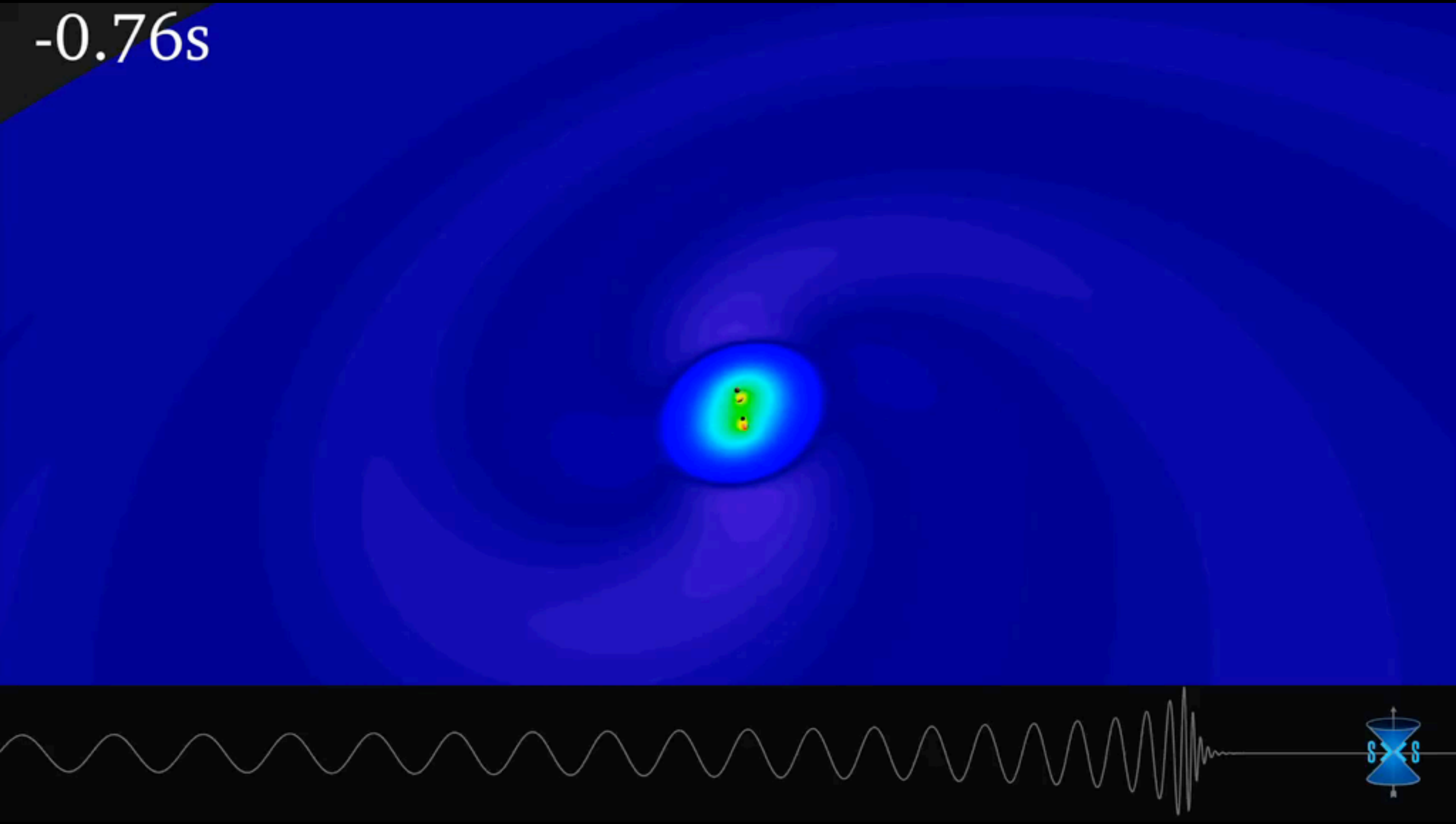
September 14, 2015

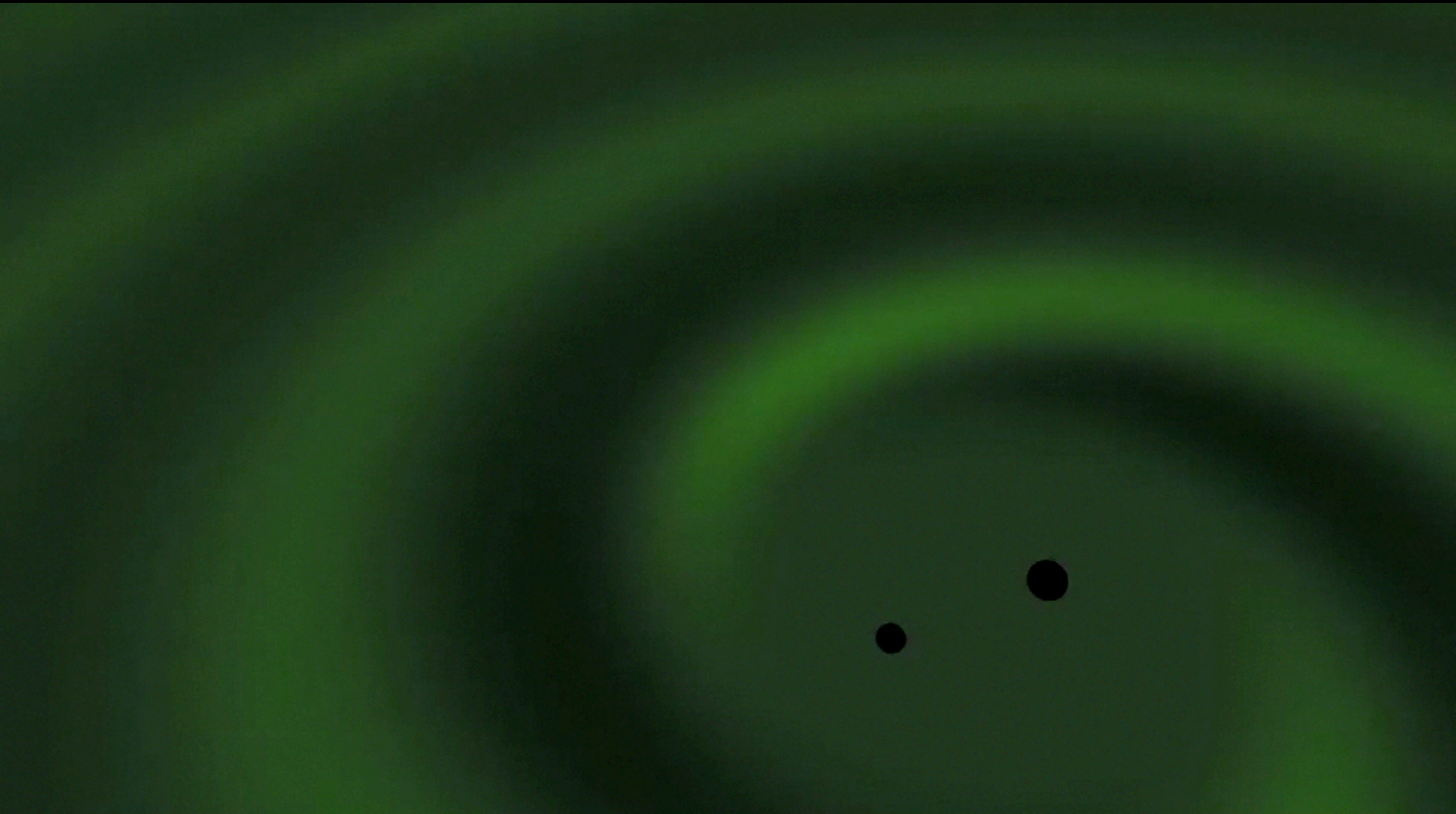


What did LIGO detect?

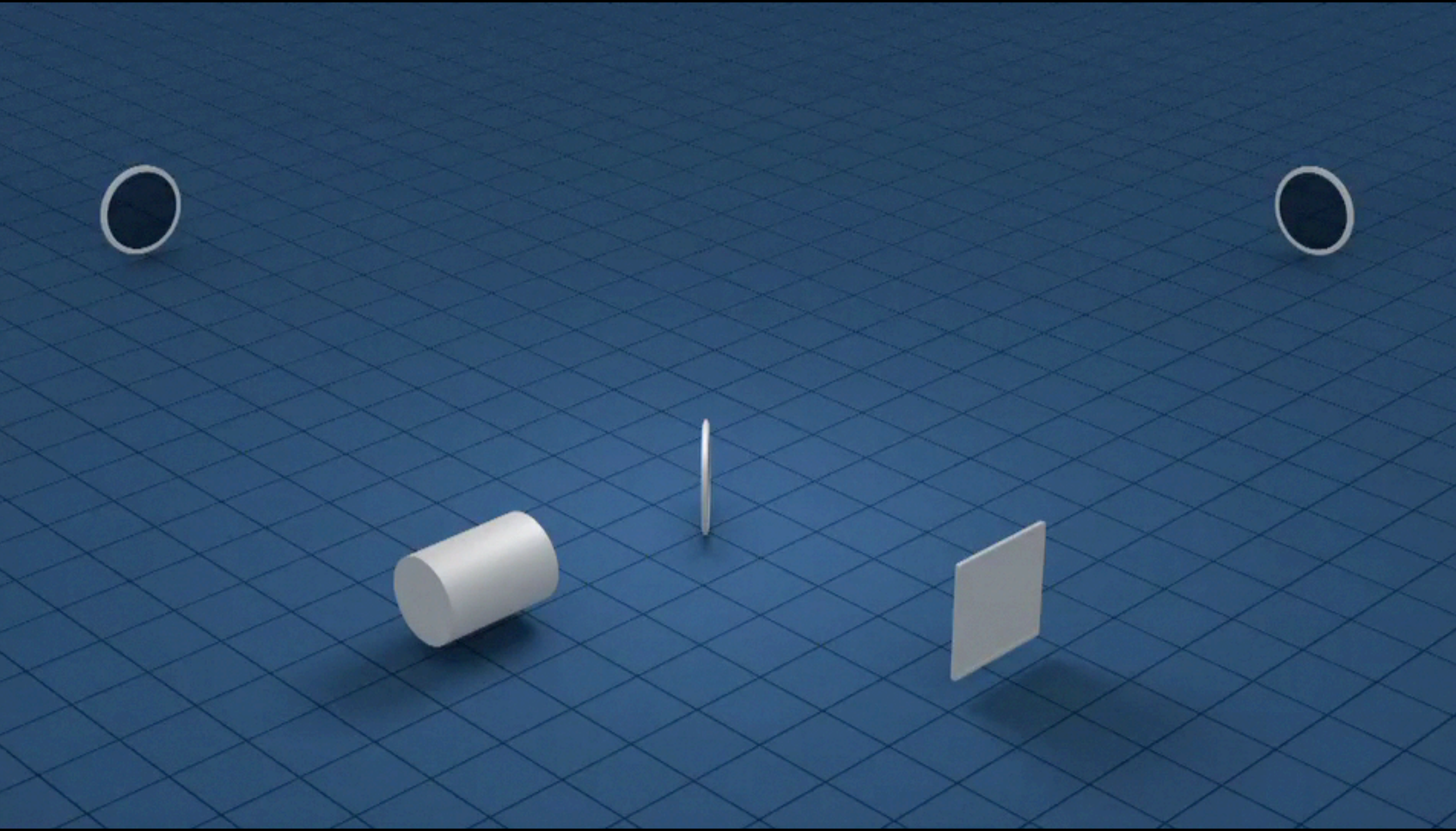
A binary black hole coalescence

A binary black hole coalescence

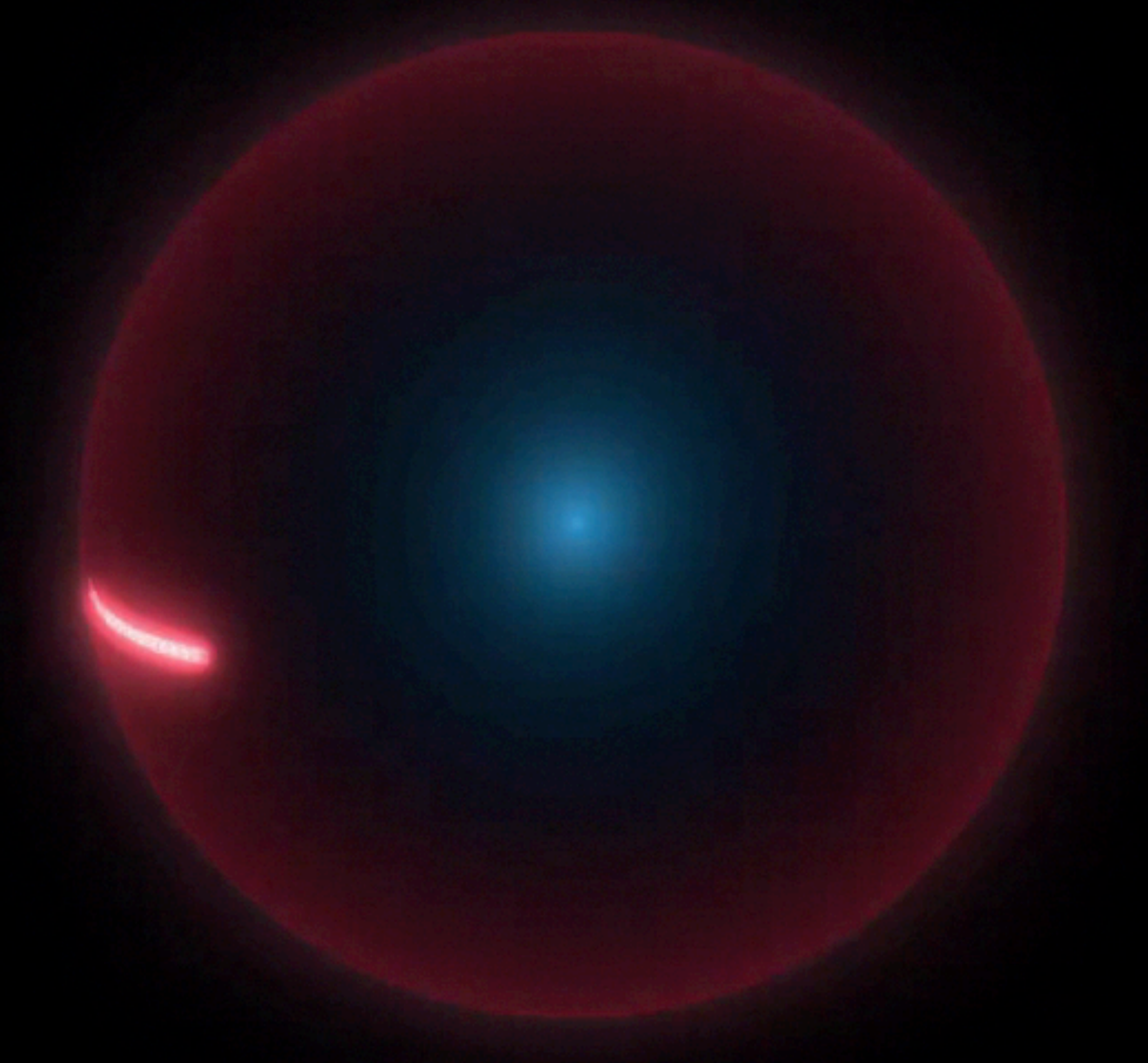




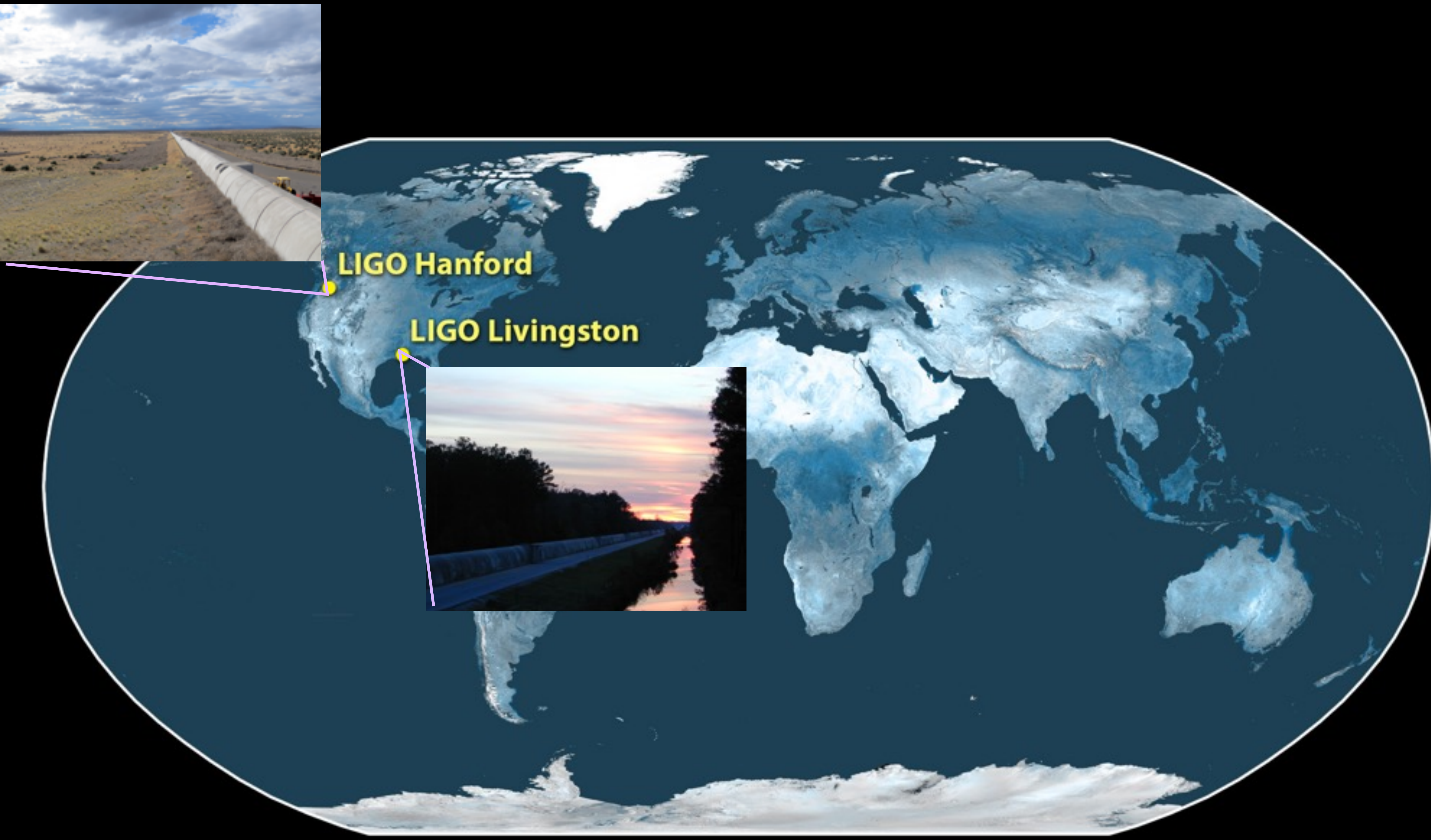
How does LIGO detect gravitational waves?

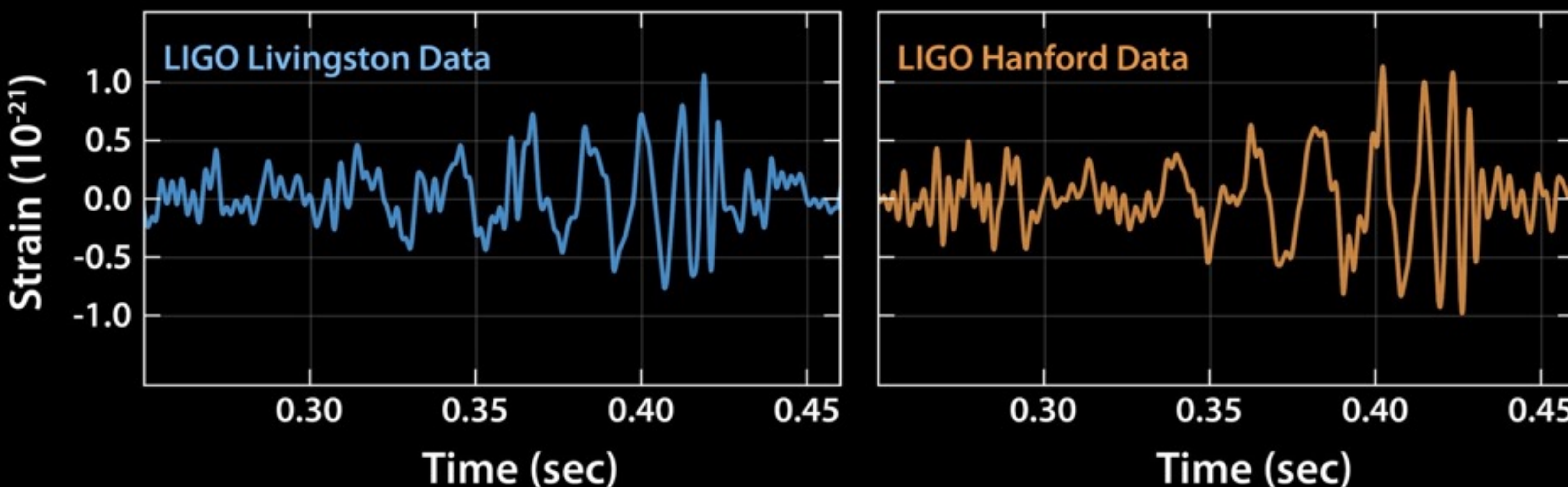


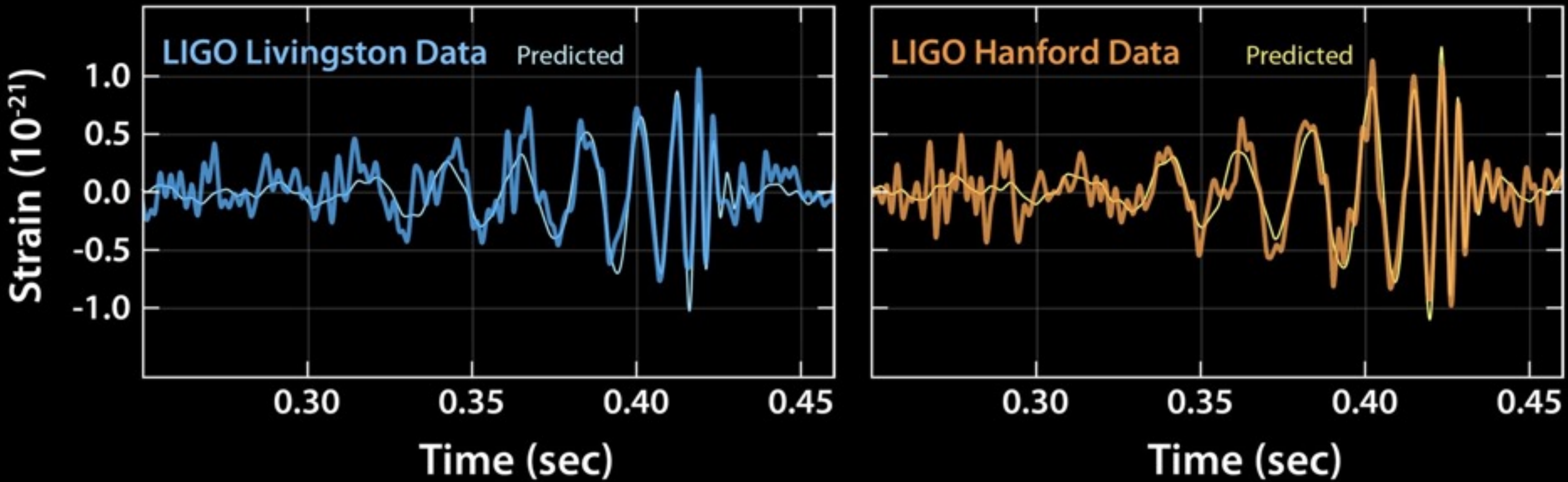
How sensitive is the LIGO experiment?



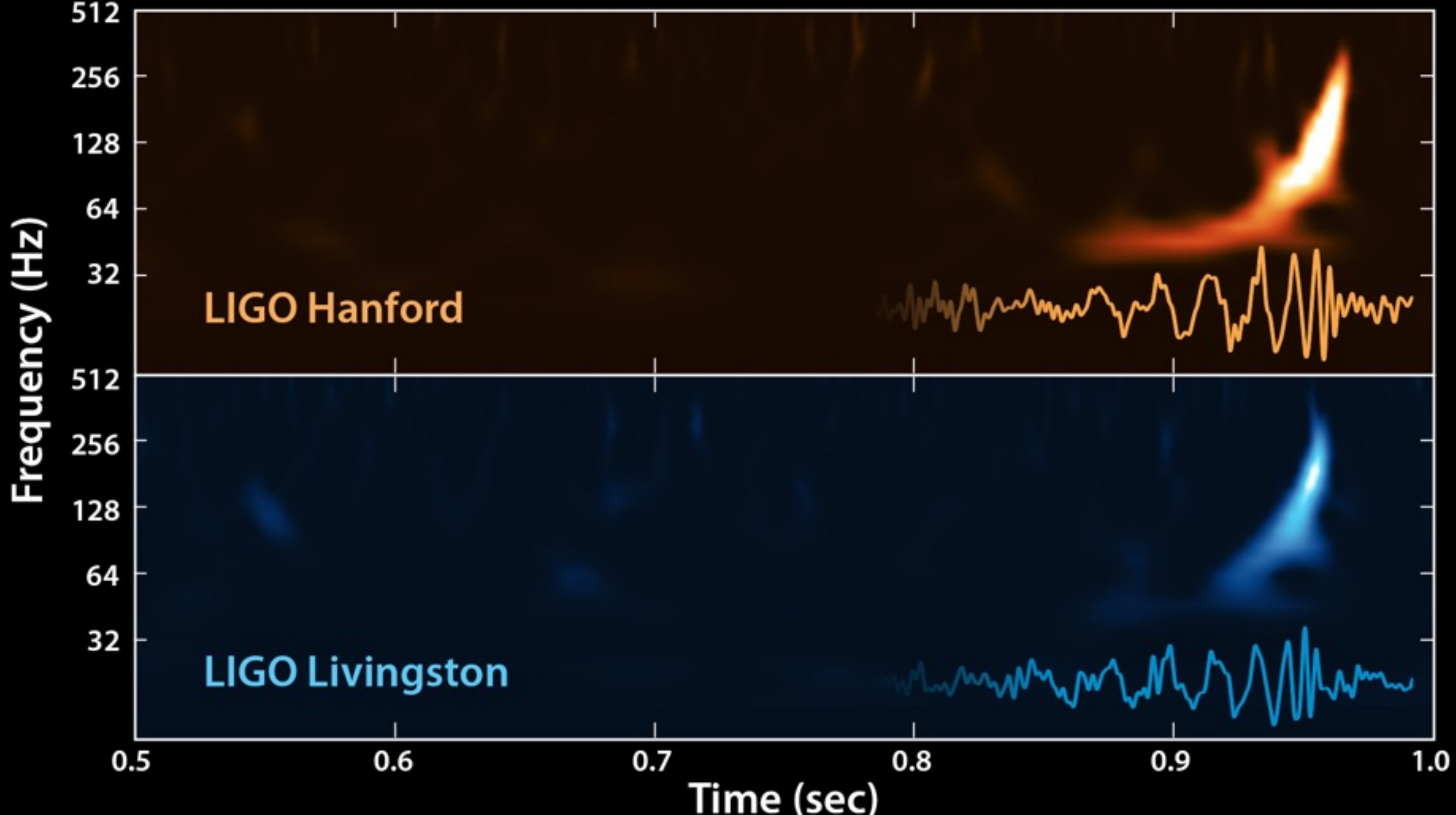
Where are the LIGO detectors?



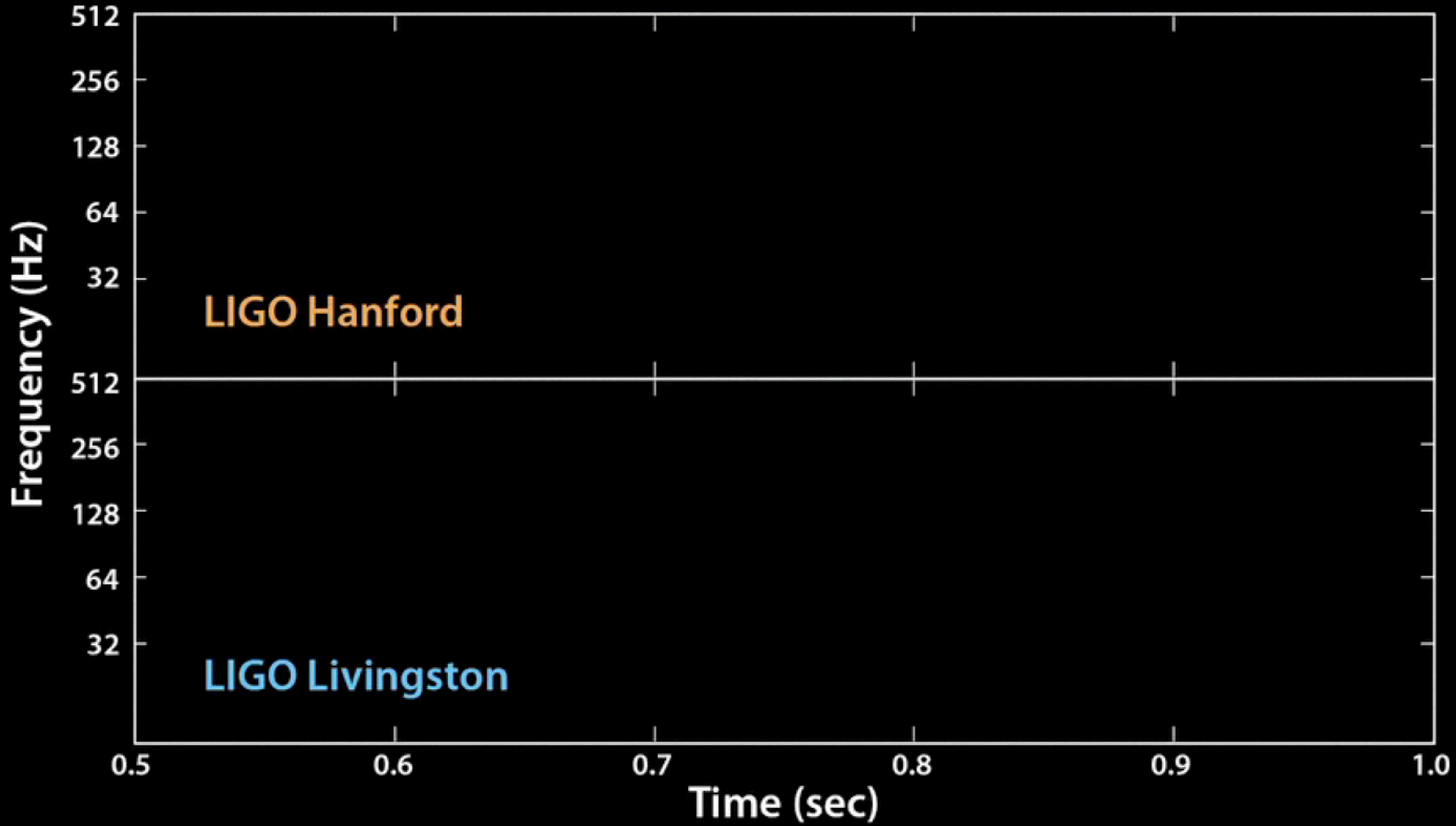

LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)



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
0.30
0.35
0.40
0.45
Time (sec)
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)



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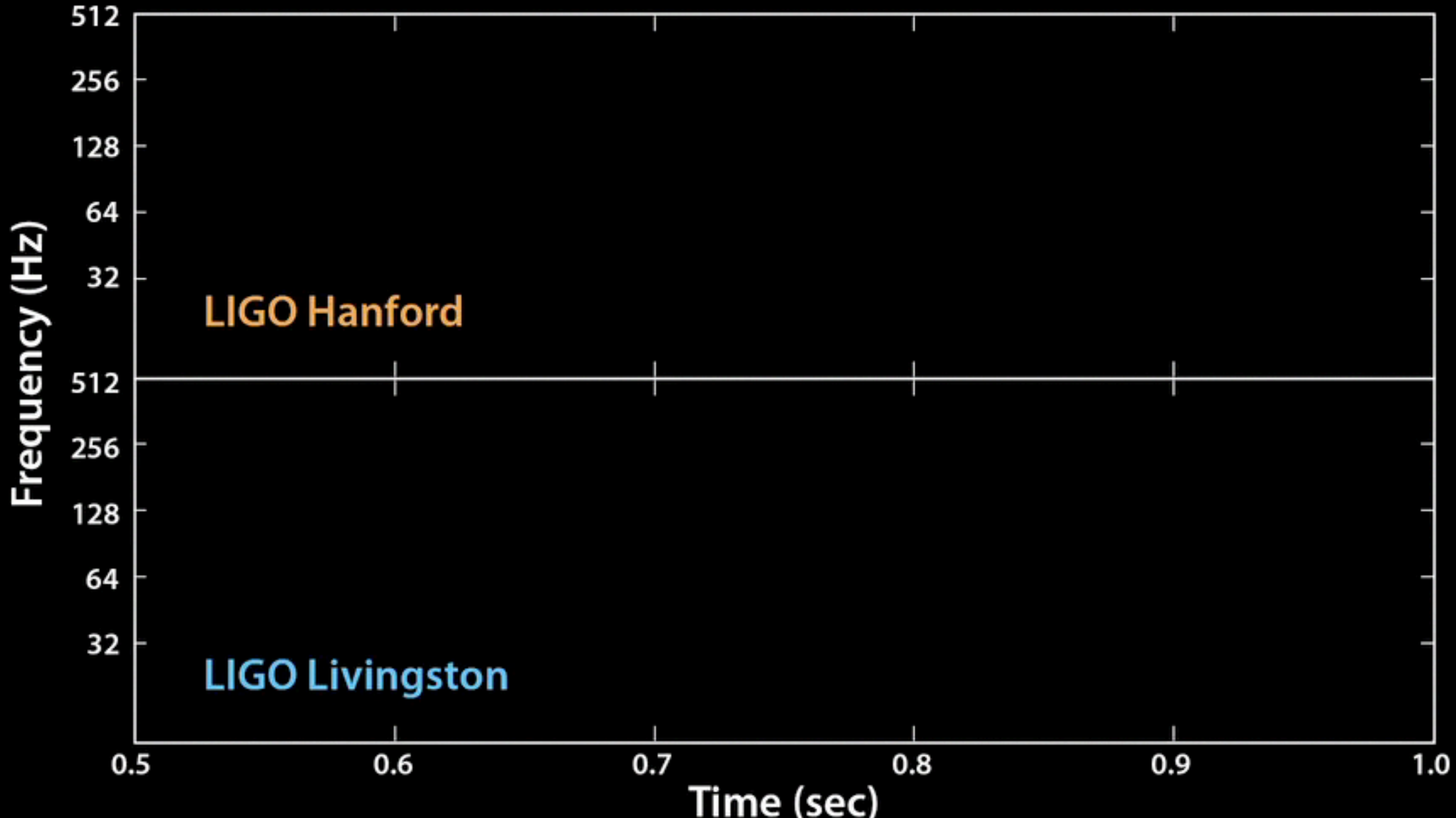

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LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
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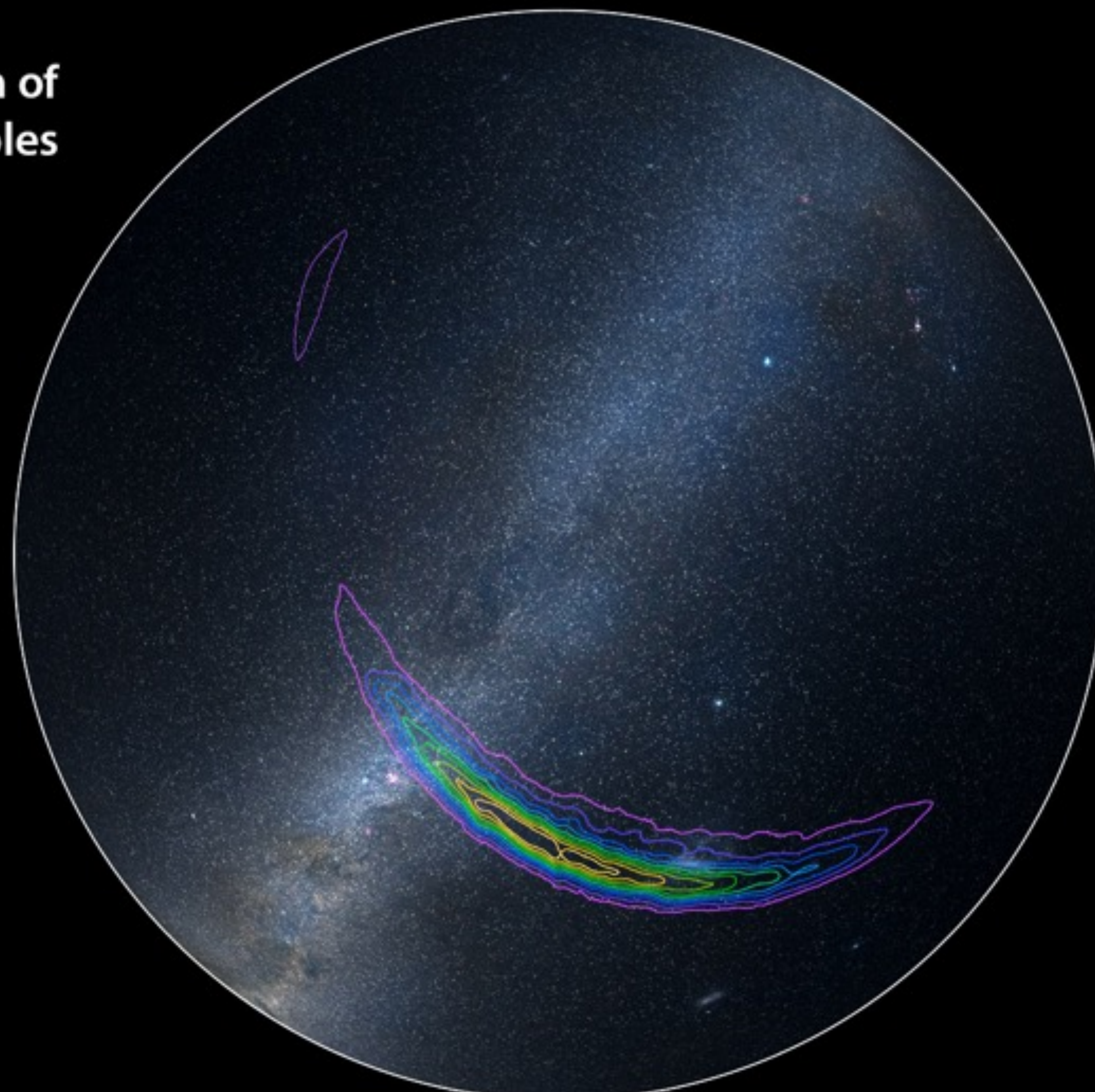
0.9
1.0
Time (sec)

Localizing the GW signal in the sky

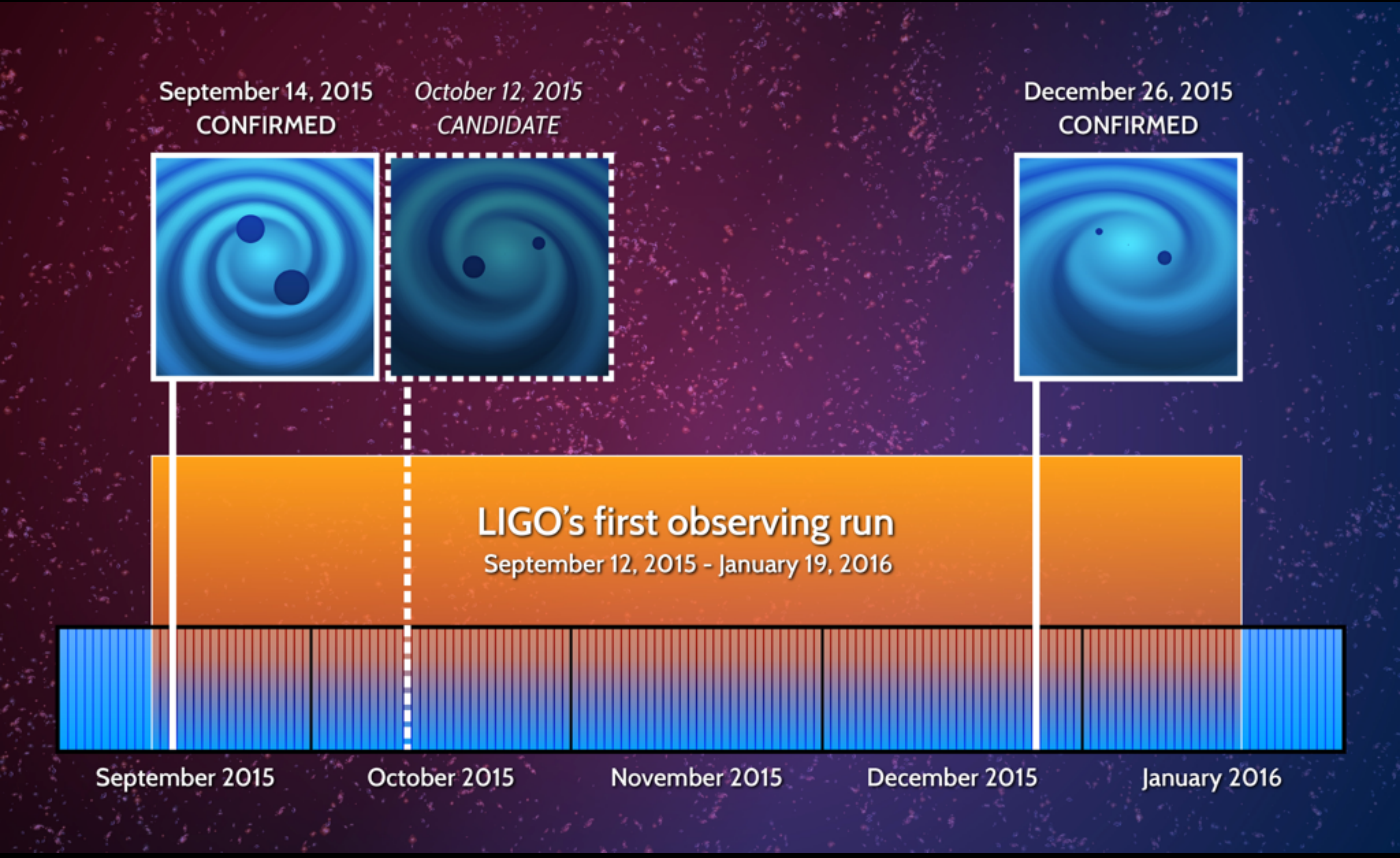
Probable location of merging black holes



The world heralds a new era of astronomy!

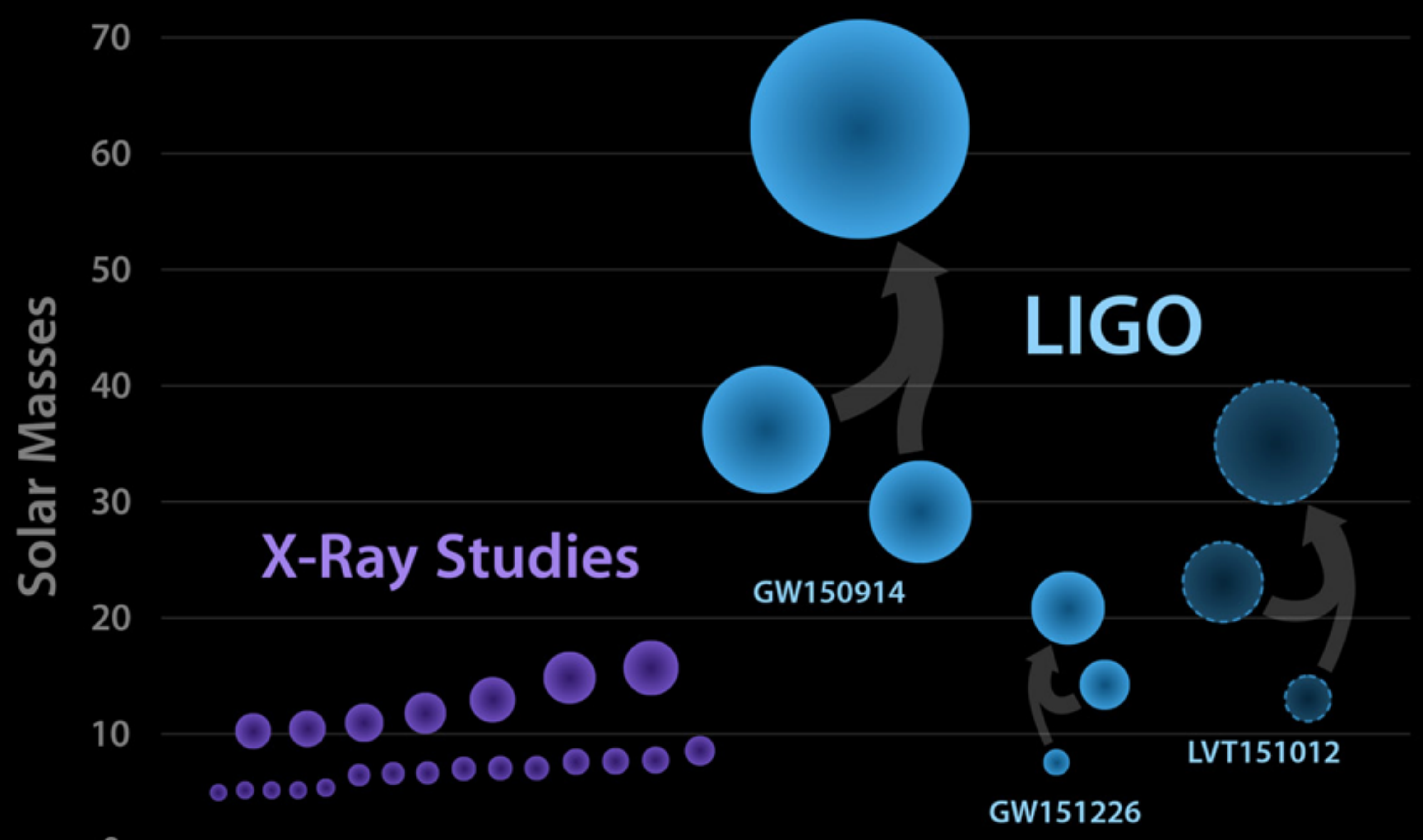
GWs on the subway!

Results from the first observing run

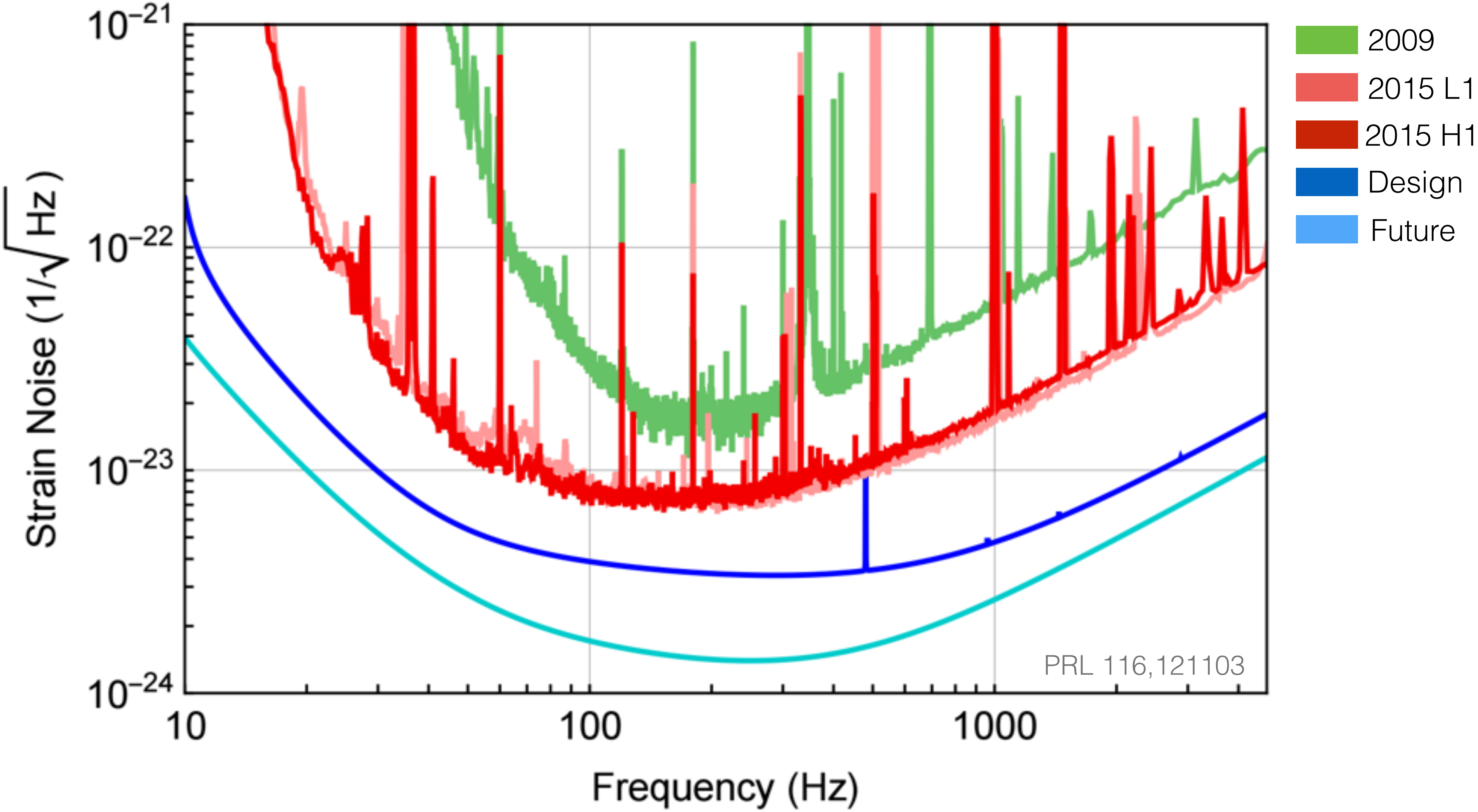


Results from the first observing run

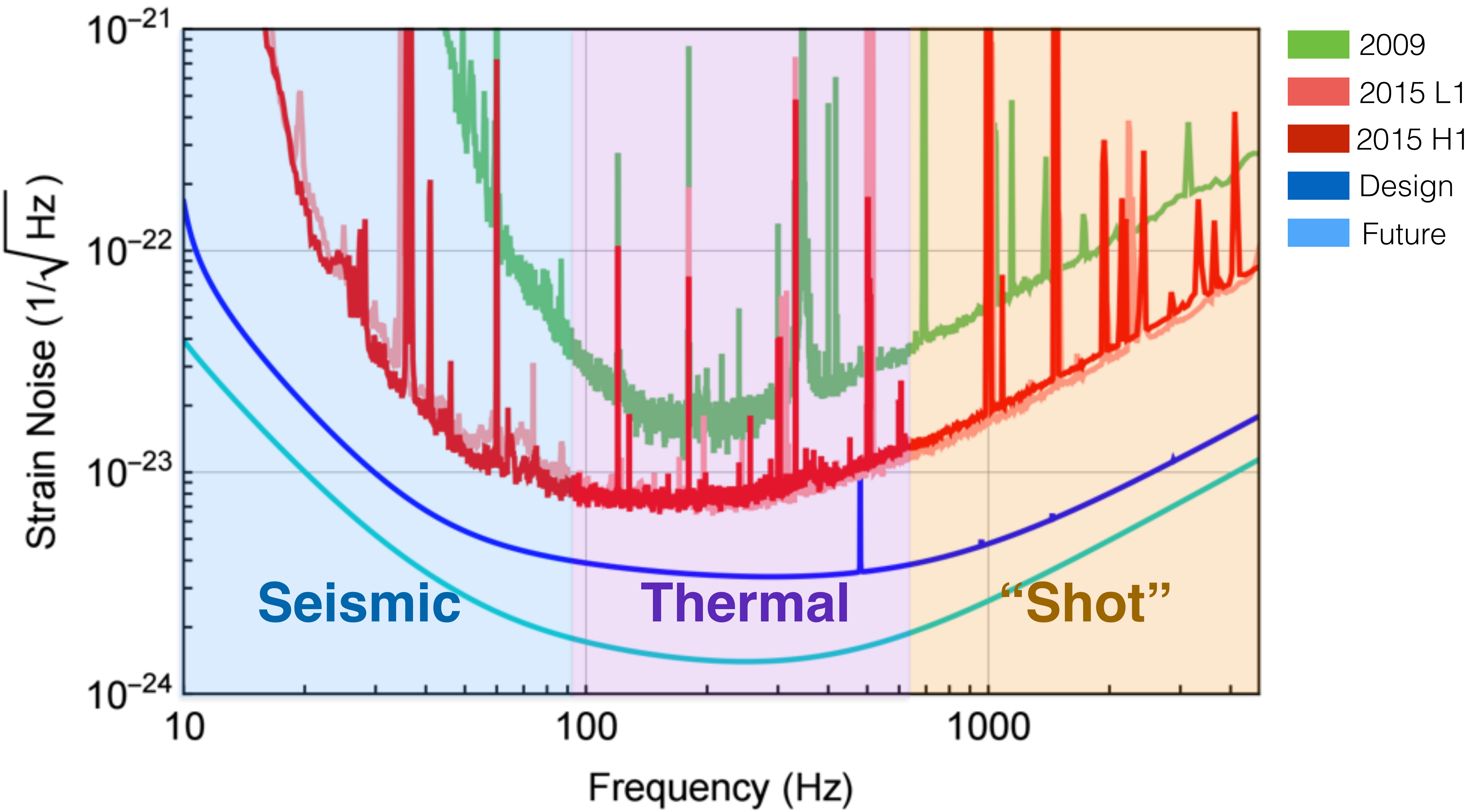
Black Holes of Known Mass



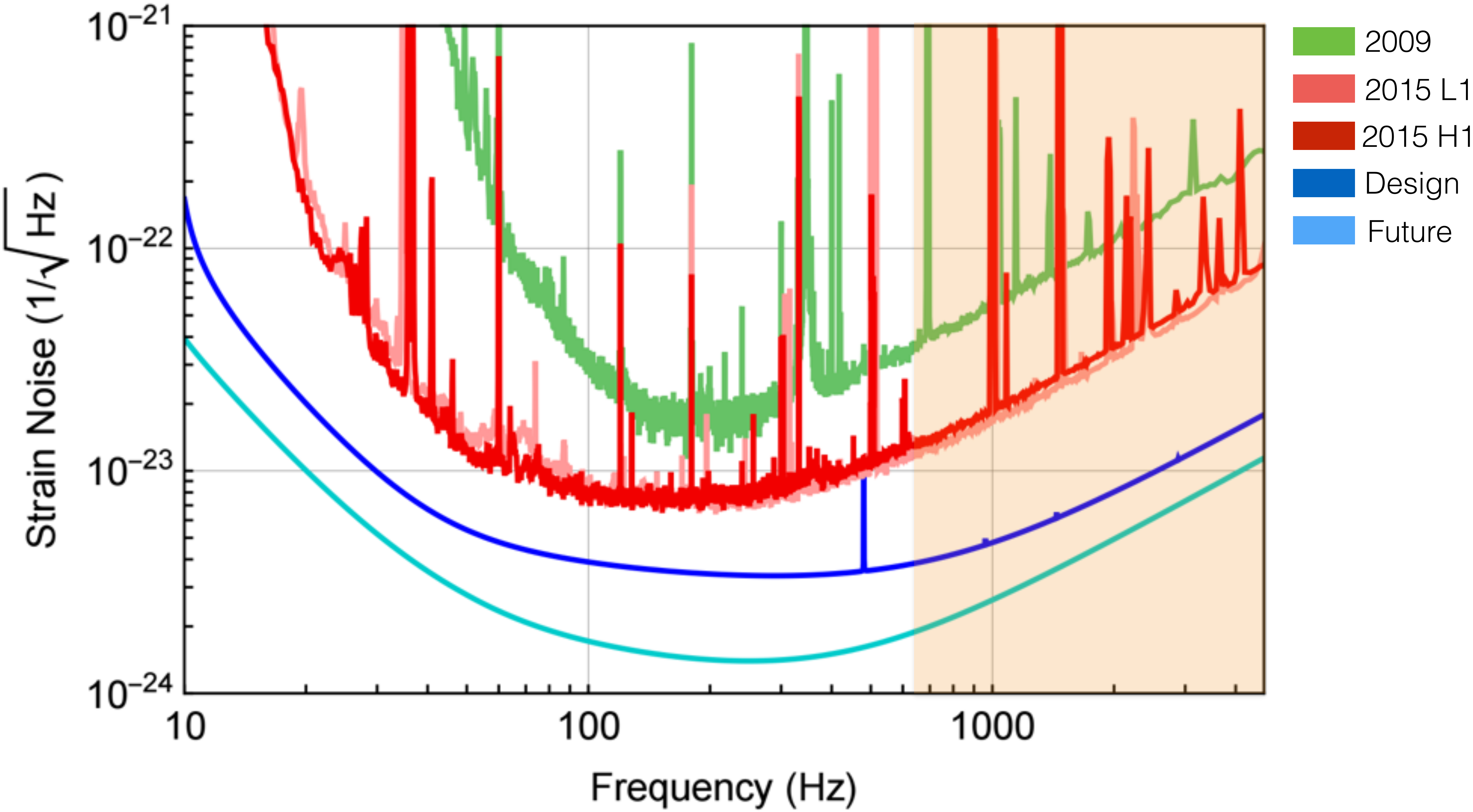
LIGO sensitivity: past, present, and future



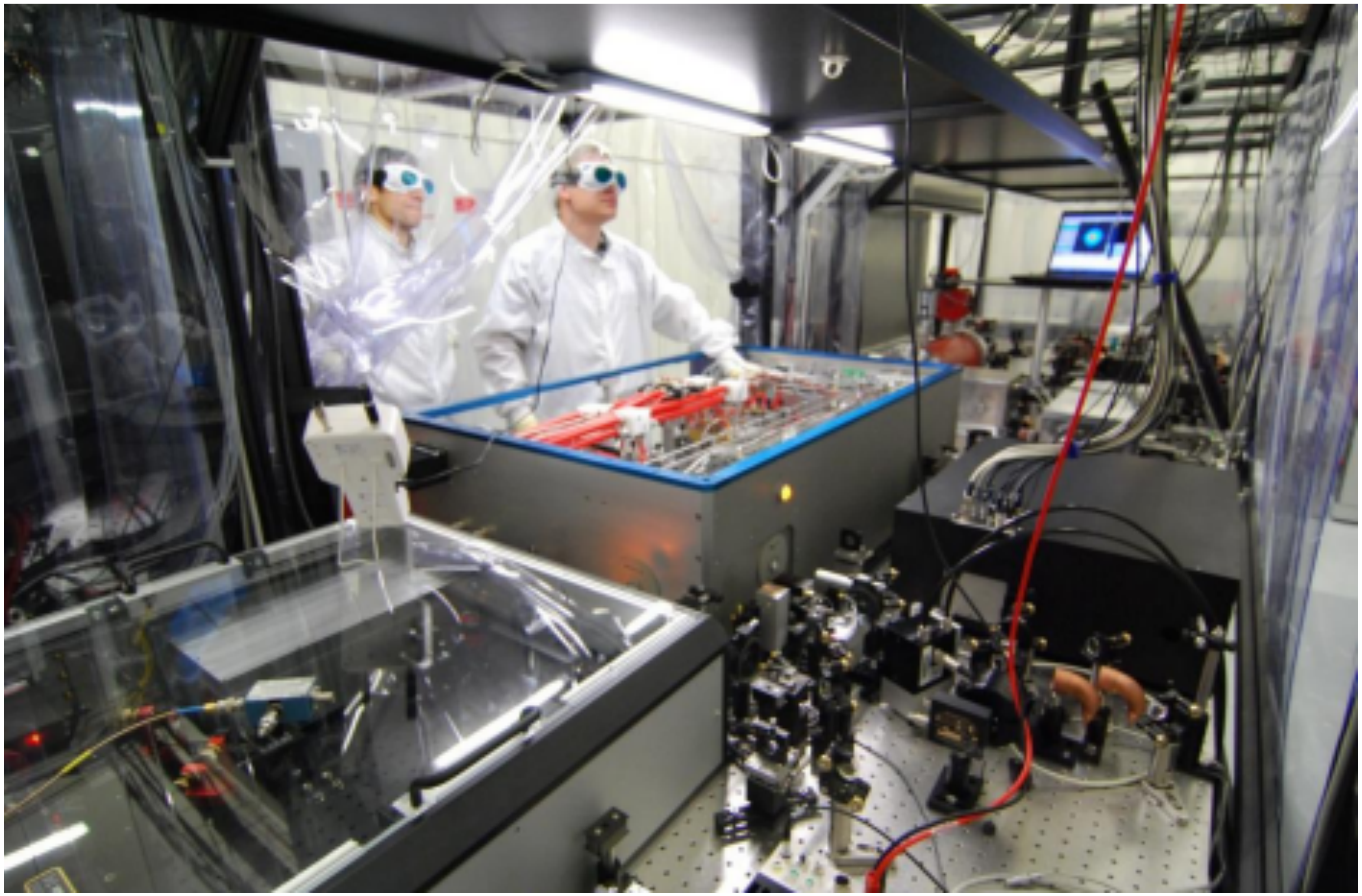
LIGO sensitivity: traditional noise regimes



Technology to combat shot noise: increasing circulating laser power



LIGO’s lasers

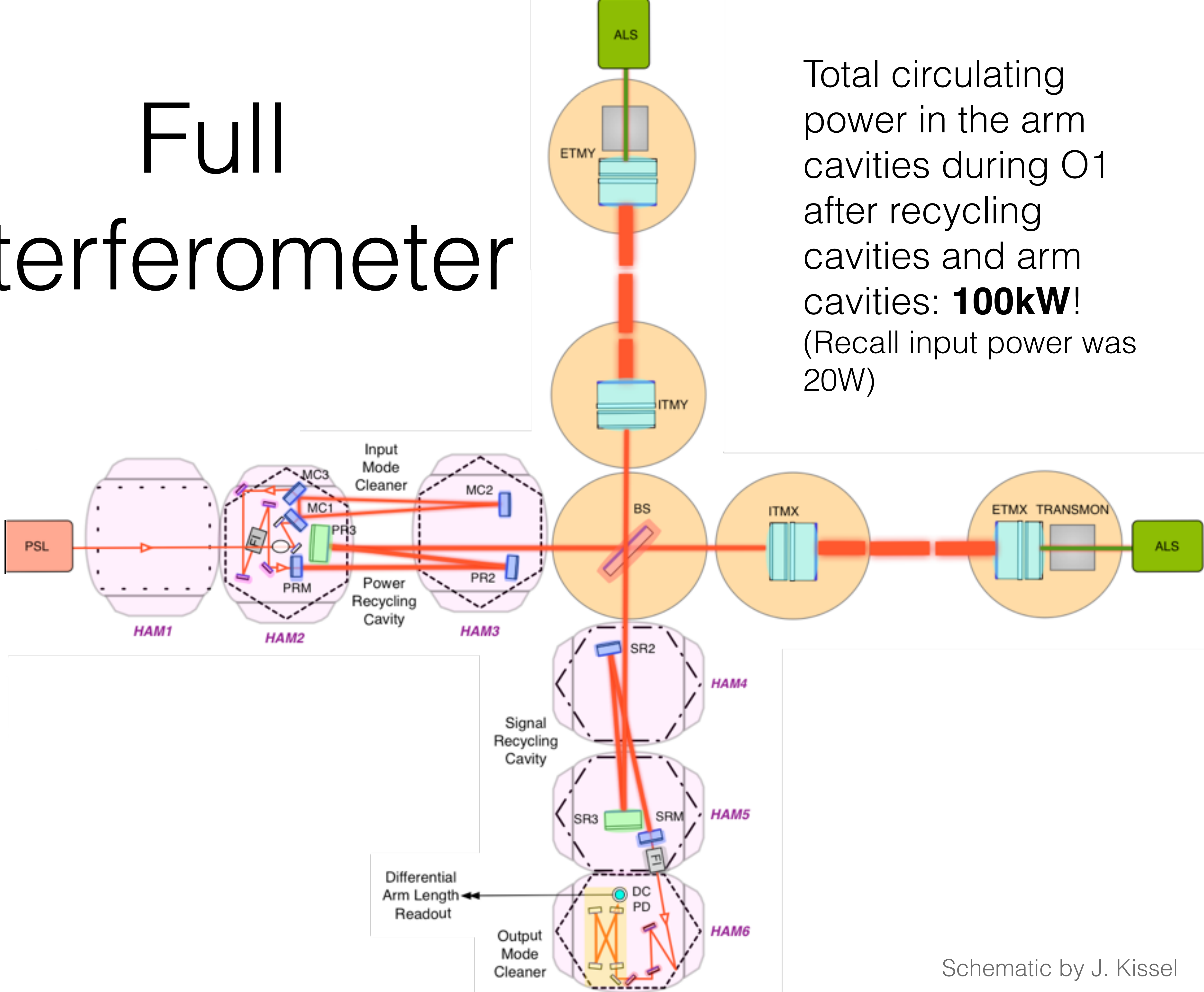


- Nd:YAG 1064nm pre-stabilized laser
- Designed to input power into the interferometer of up to 180 Watts
- **O1 input power: 20W**

Control loops stabilize laser light in both frequency and intensity to reduce the introduction of noise into the interferometer

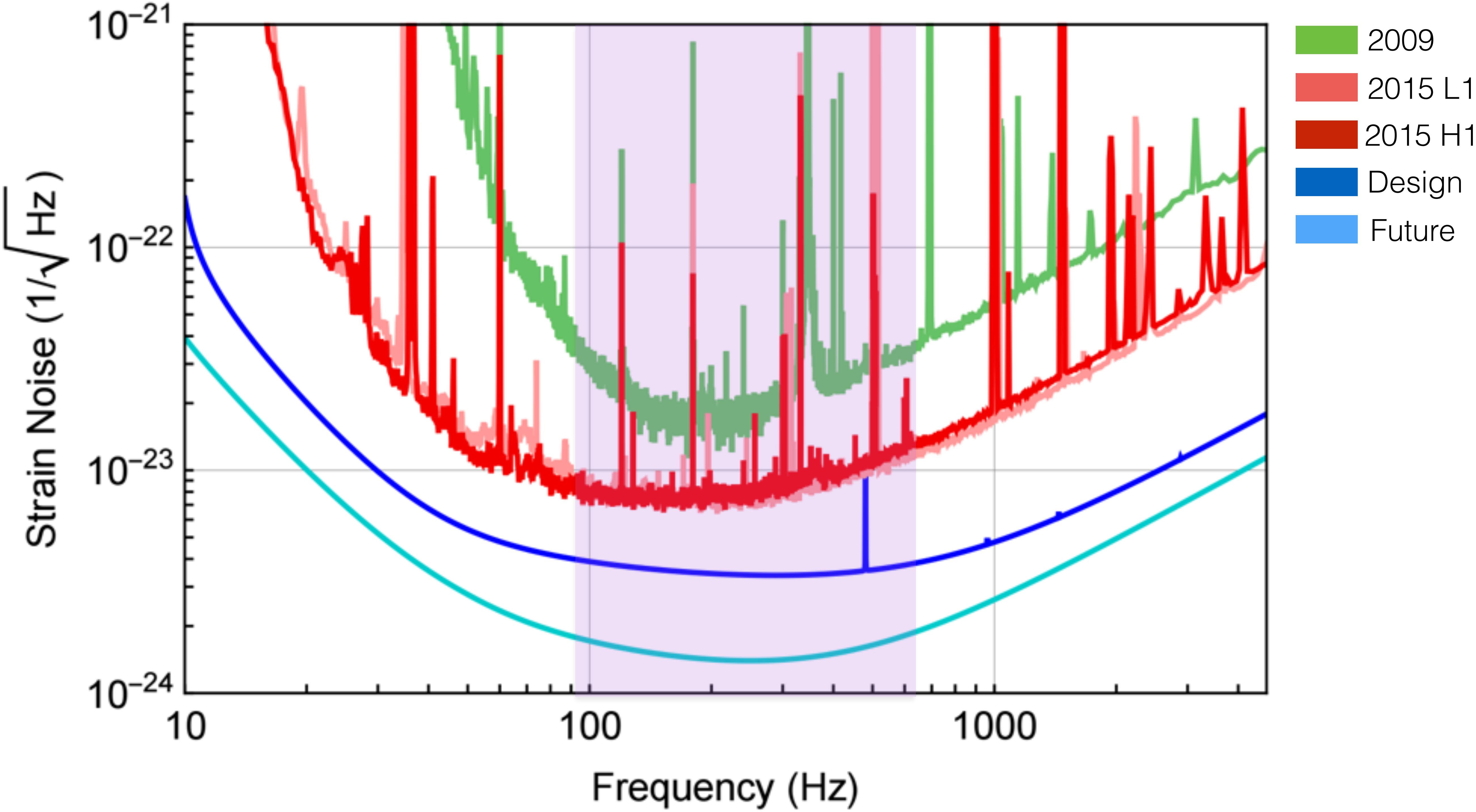
Full interferometer

Total circulating power in the arm cavities during O1 after recycling cavities and arm cavities: **100kW**!
(Recall input power was 20W)

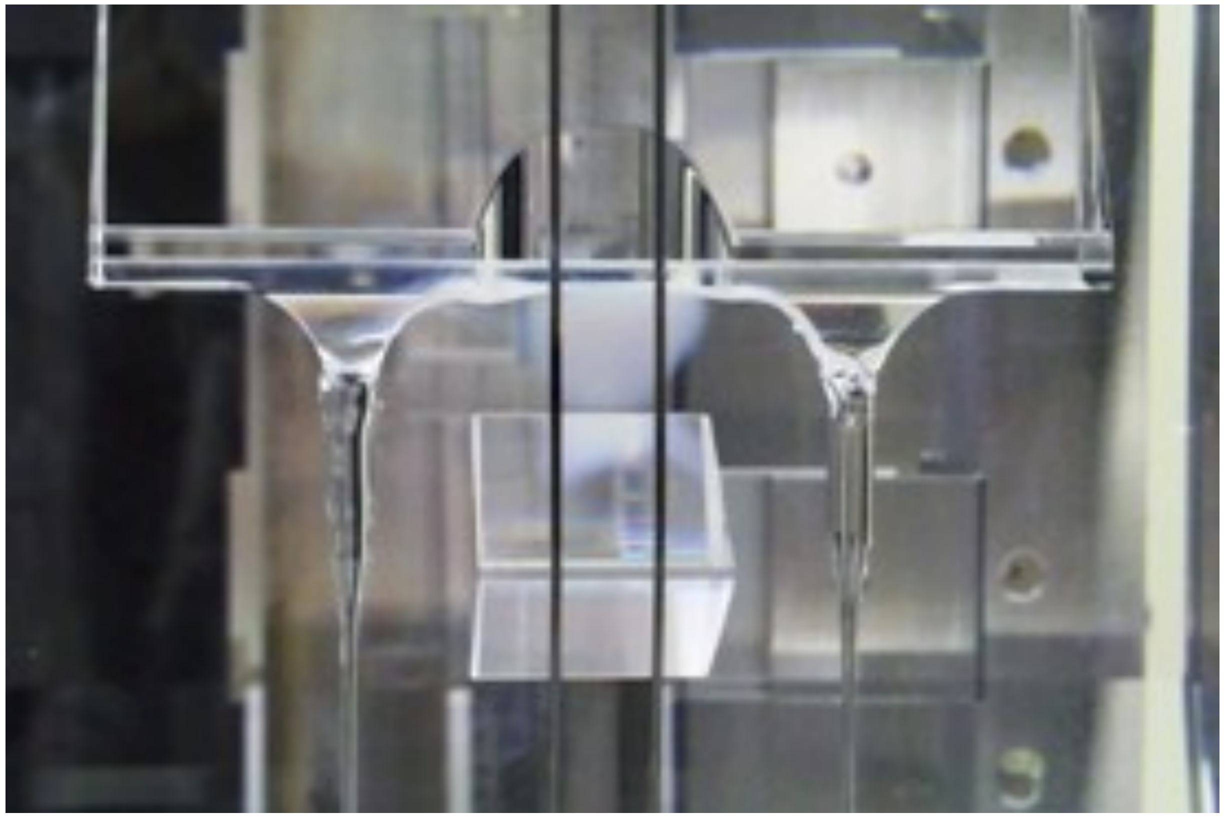


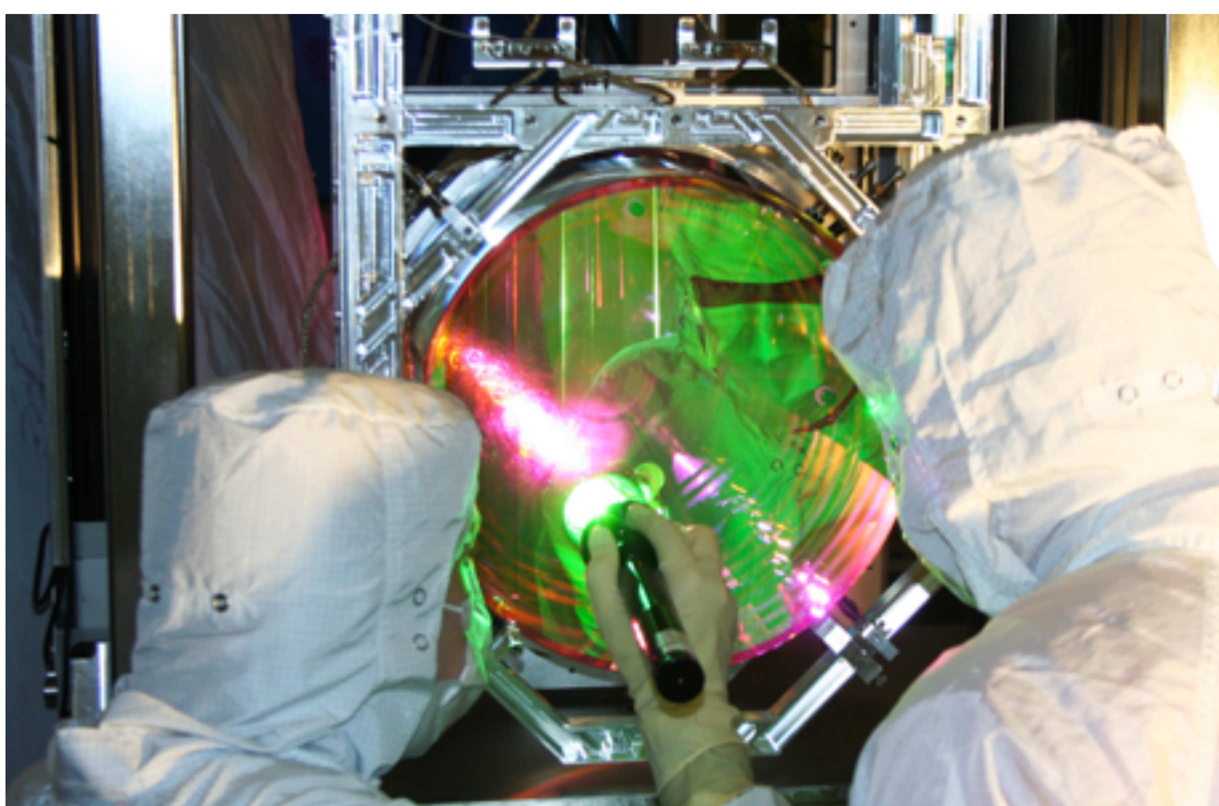
Schematic by J. Kissel

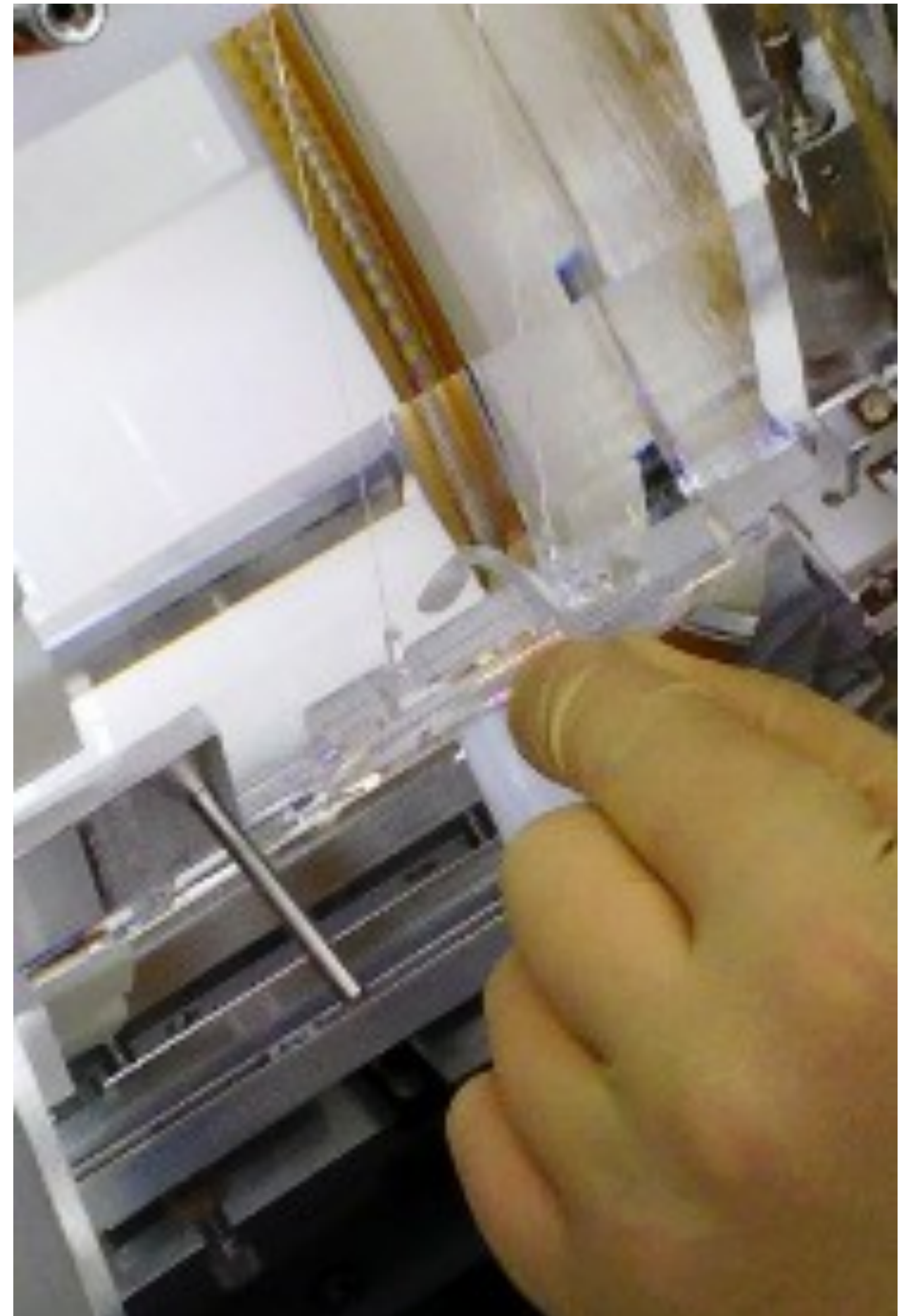
Technology to combat thermal noise



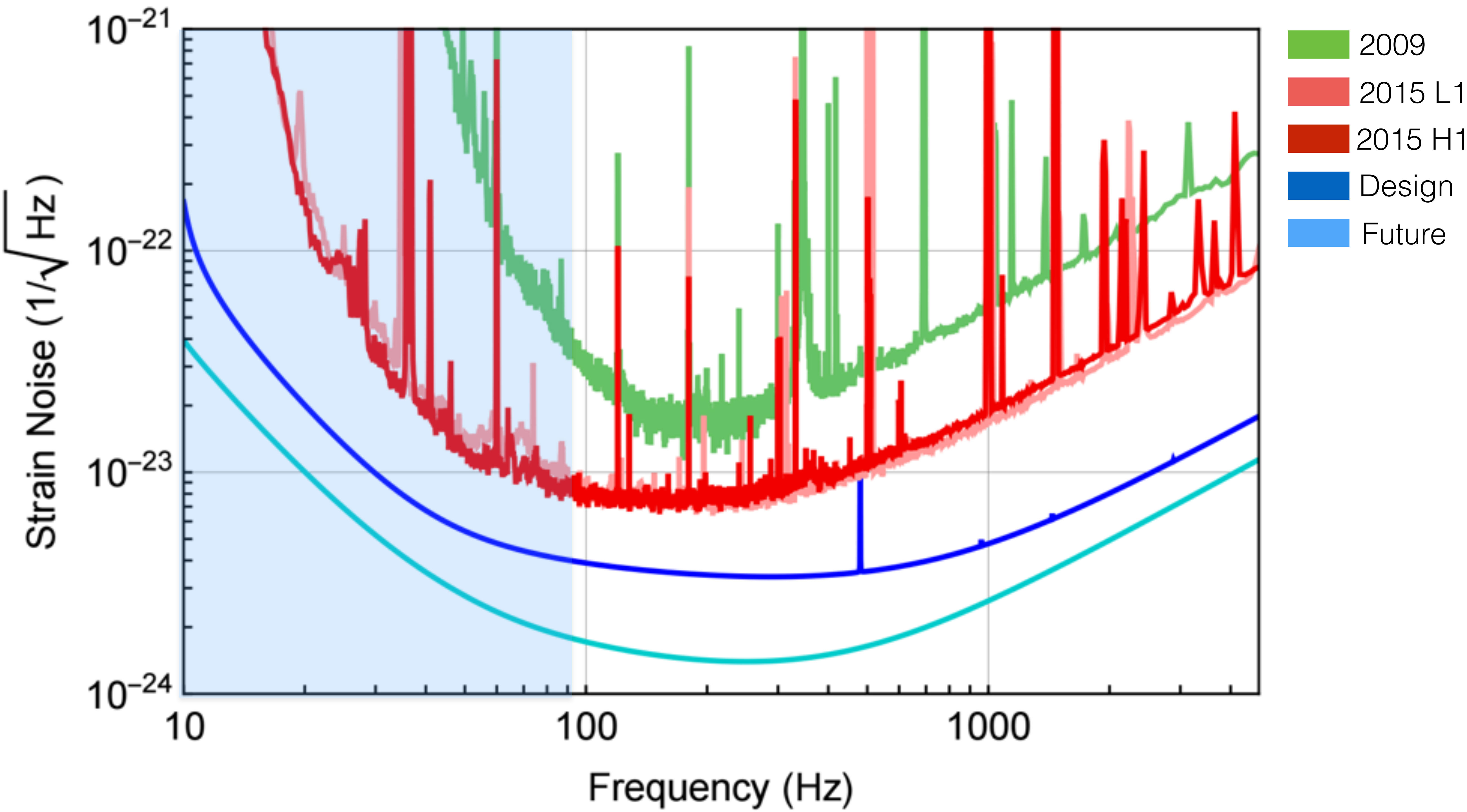
Material science:
Improved optic coatings and optic suspensions



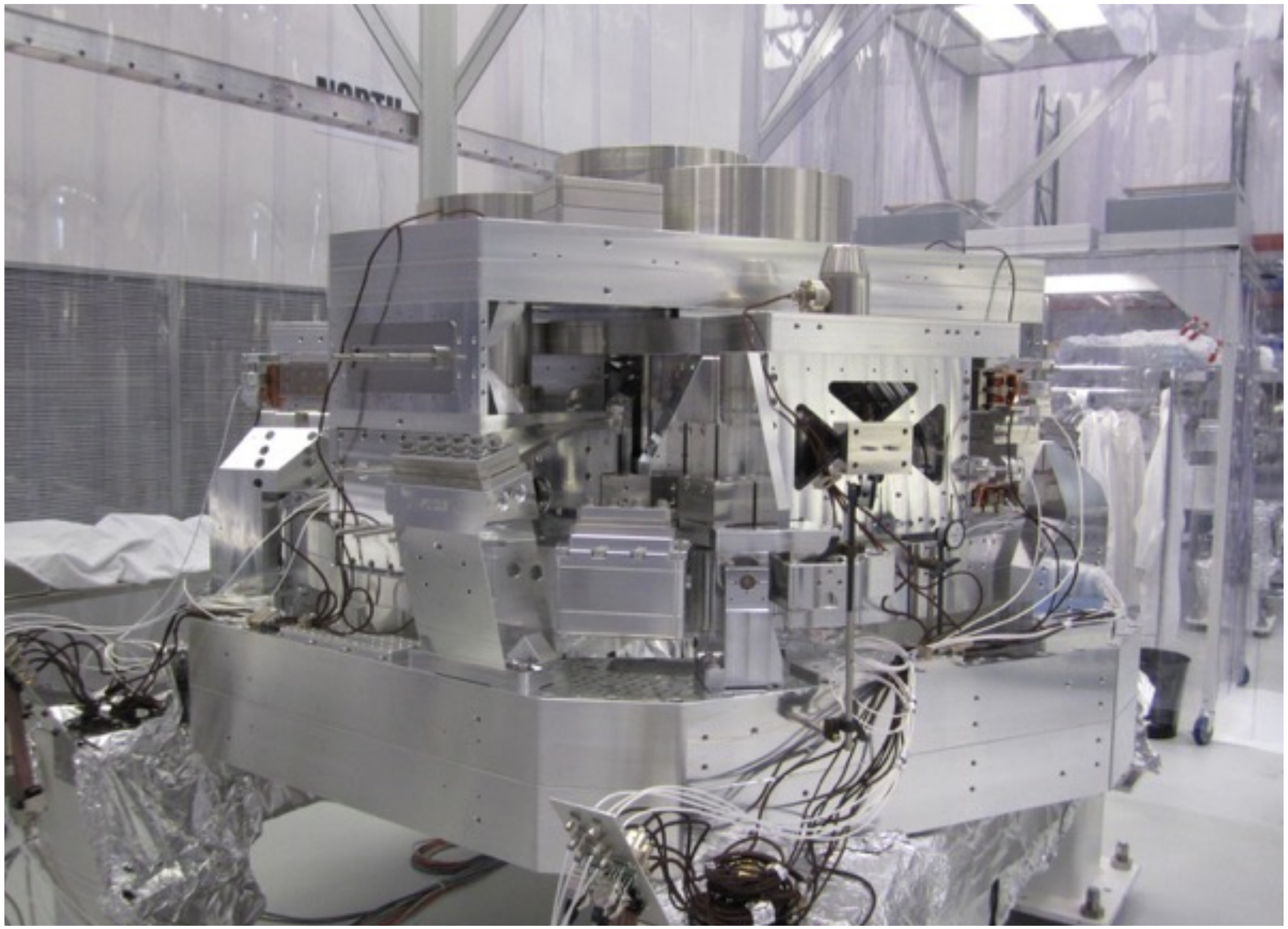




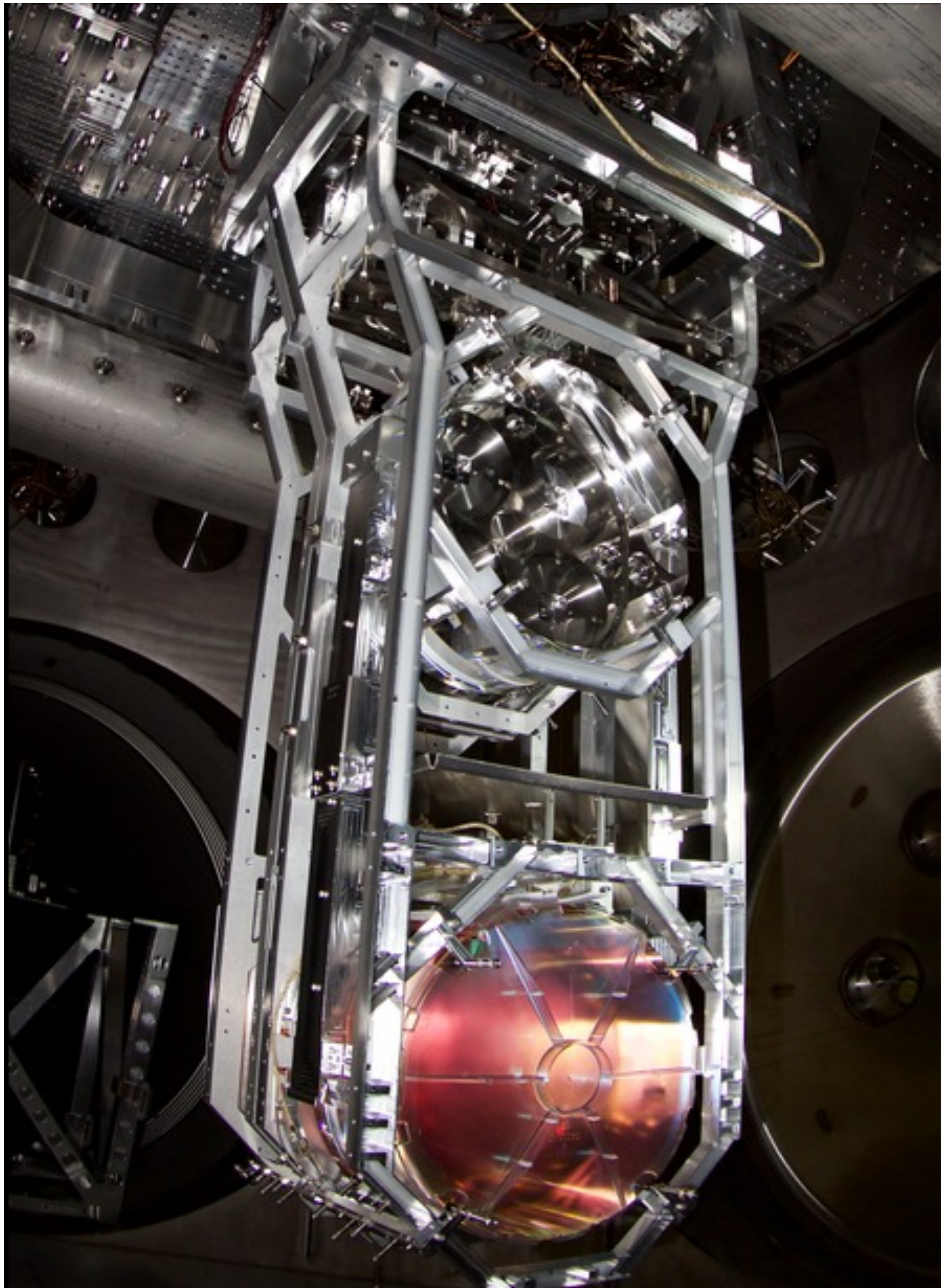
Technology to combat seismic noise

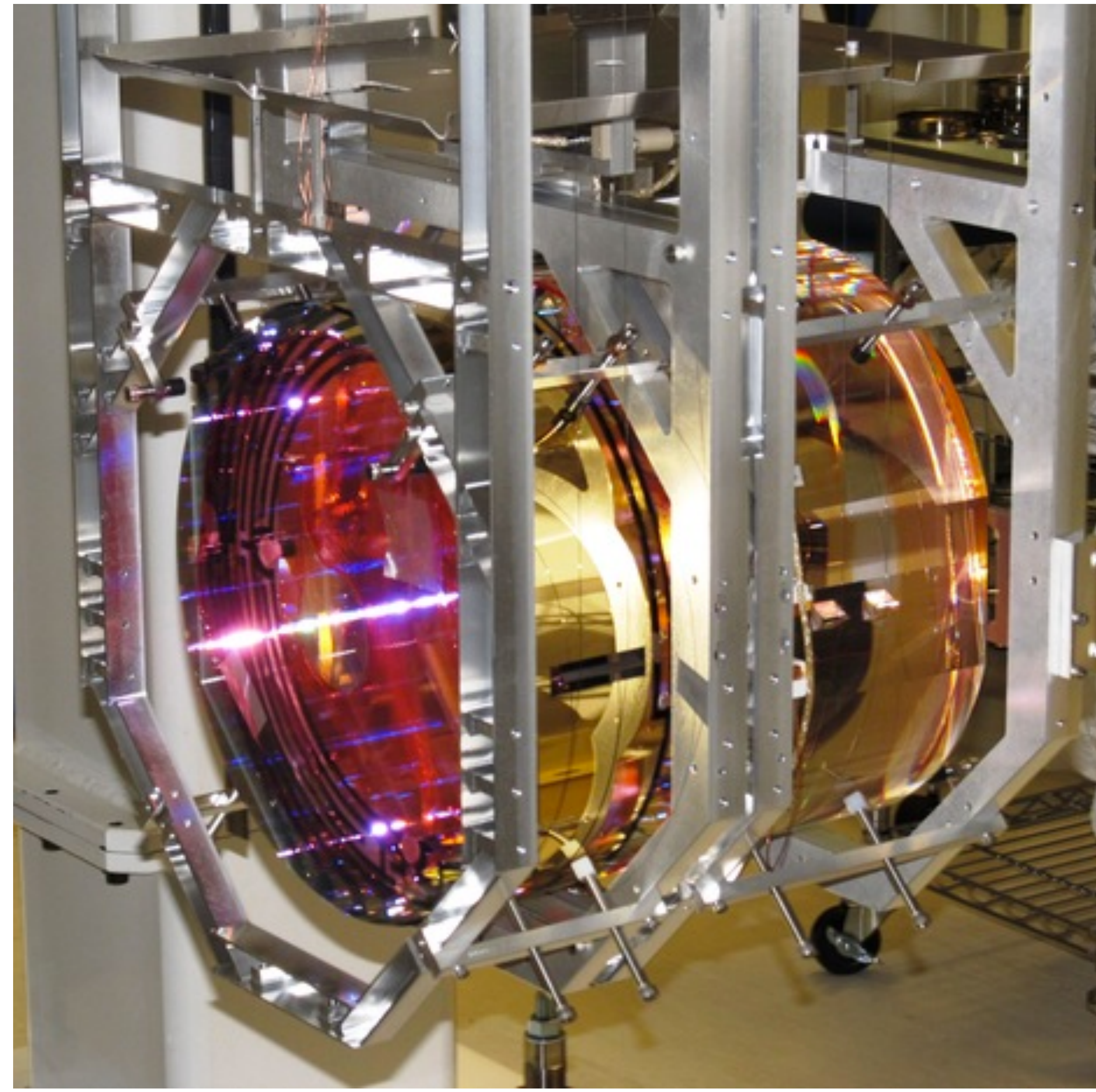


Seismic isolation: active isolation

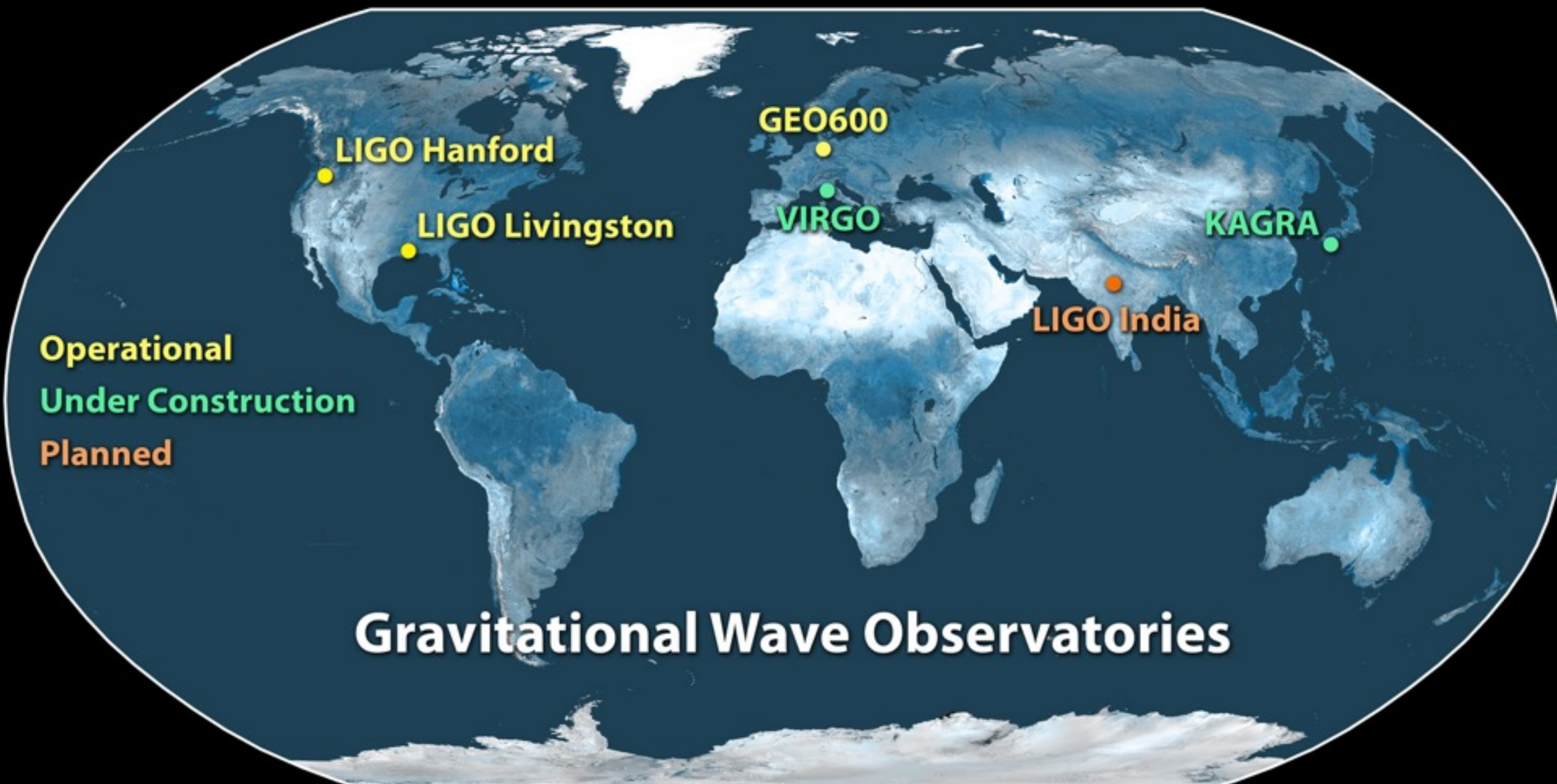


Seismic isolation: suspensions





Future prospects: the global GW network



LIGO

LSC

LIGO Scientific Collaboration

Trinity University
University of Maryland 1856
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
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
The University of Chicago
Montana State University
The University of Mississippi
The University of Adelaide Australia
Caltech
University of Minnesota
University of Birmingham
The University of Melbourne
UIB Universitat de les Illes Balears
University of Washington
GEO 600
UTRGV
University of Wisconsin Milwaukee
Cardiff University Prifysgol Caerdydd
Northwestern
Syracuse University Founded AD 1870
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

Coming Fall 2016

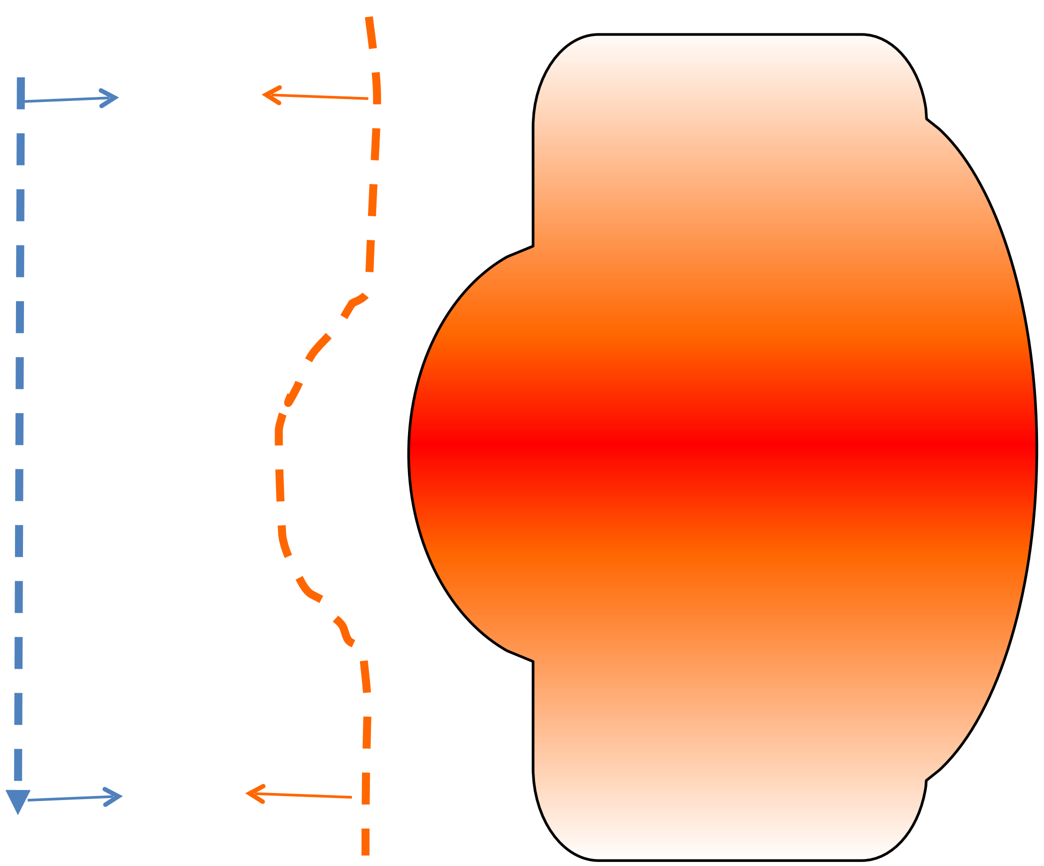
The second LIGO observing run

Challenge for higher power: thermal distortion

A small fraction of laser power (on the order of 10-100 mW) is absorbed by the arm cavity mirrors as heat.

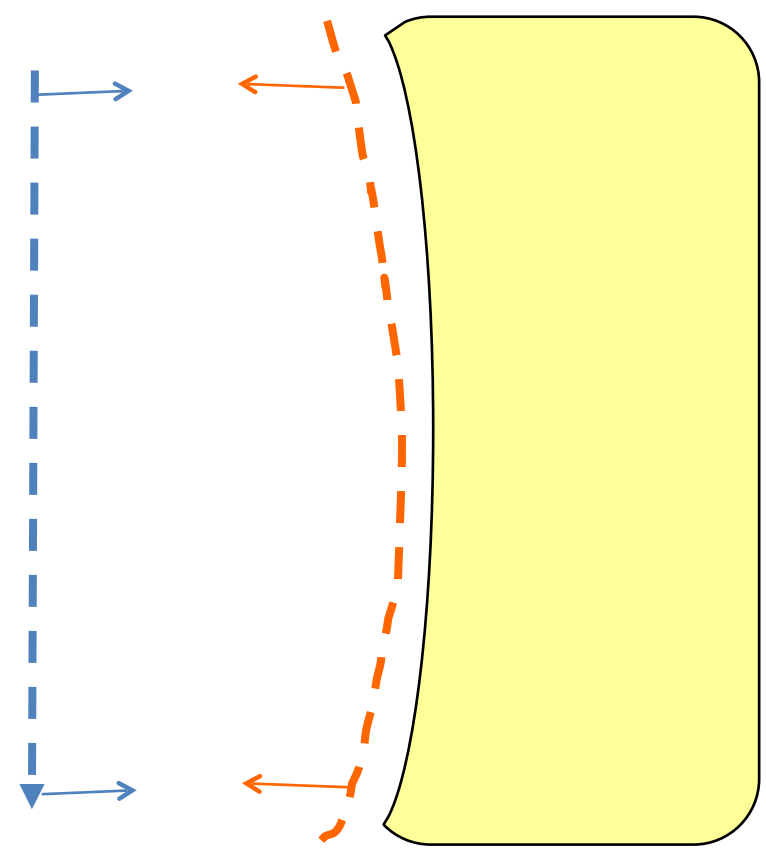
Uneven heating over the mirror surfaces induces **thermal lensing** which cases the shape of the mirrors to distort.

Thermally-distorted wavefront:



Bumps & temperature gradients

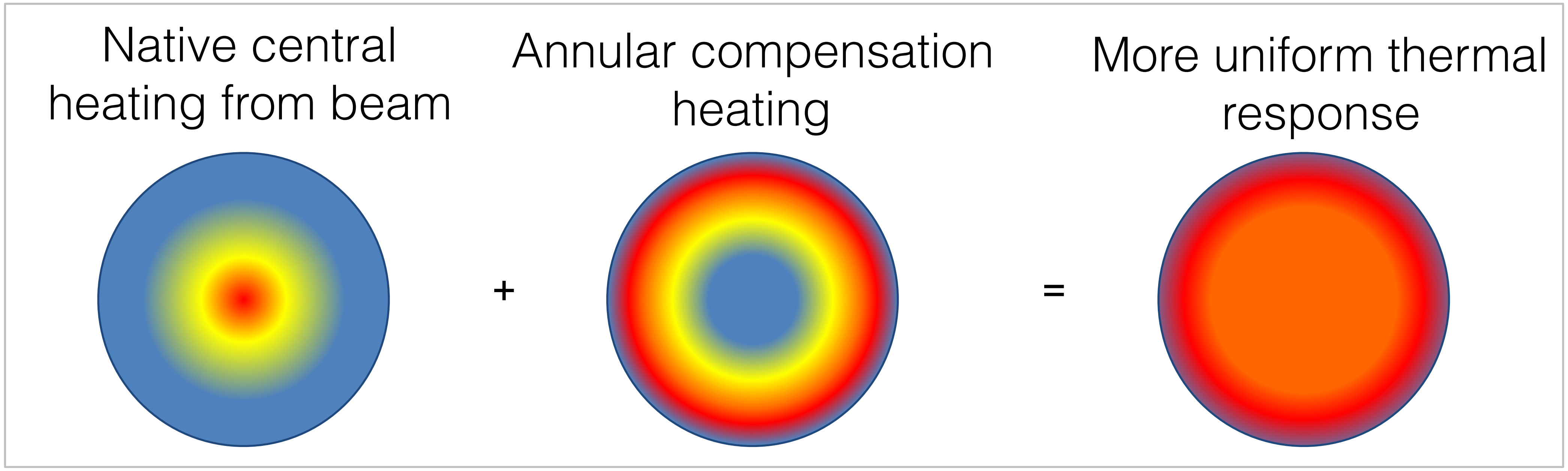
Wavefronts should ideally look like:



Uniform temperature & smooth curved faces

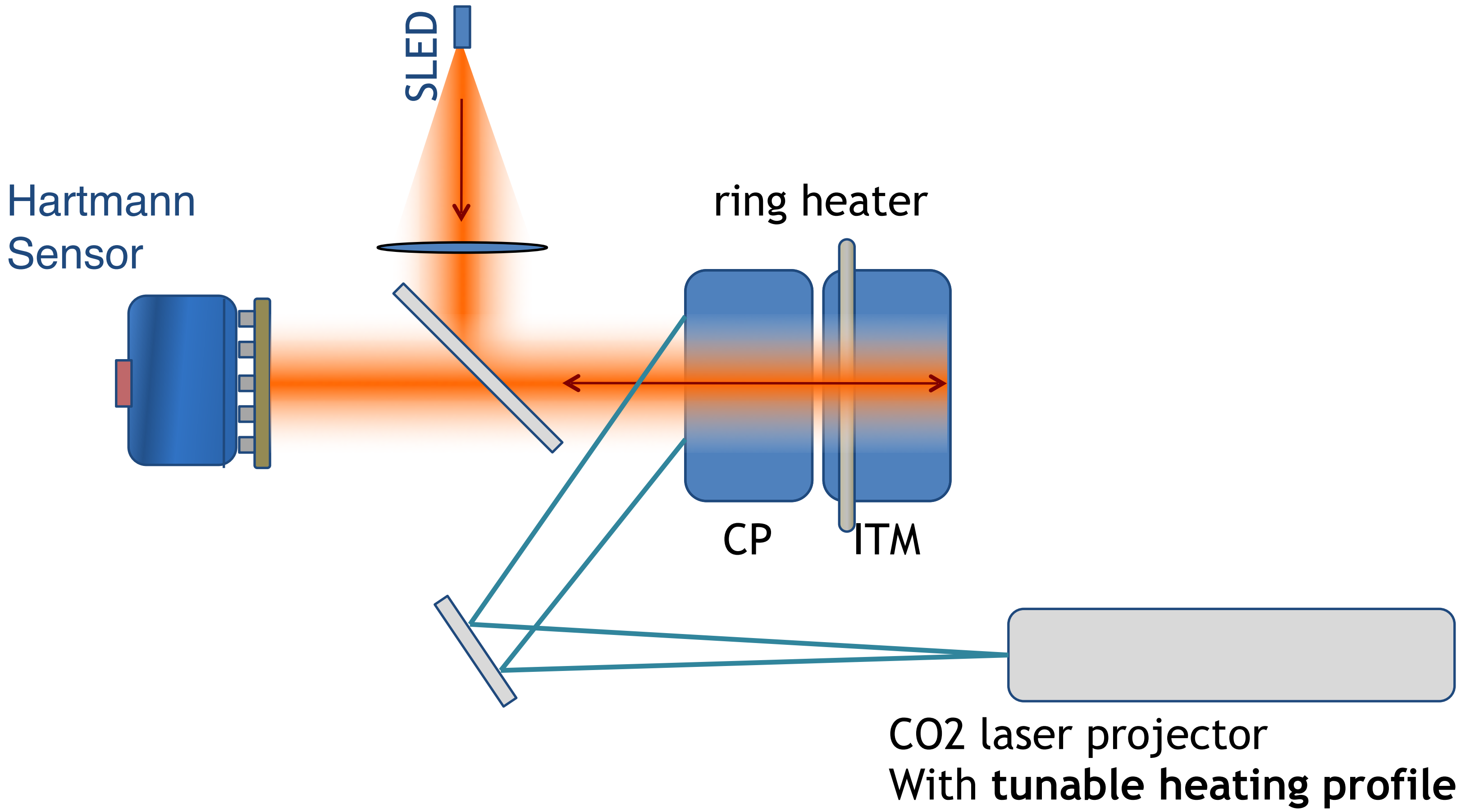
Adapted from A. Brooks G1300218

Thermal compensation



The thermal compensation system mitigates thermal lensing effects from light absorbed by the optics using:

- Ring heaters
- Laser projection

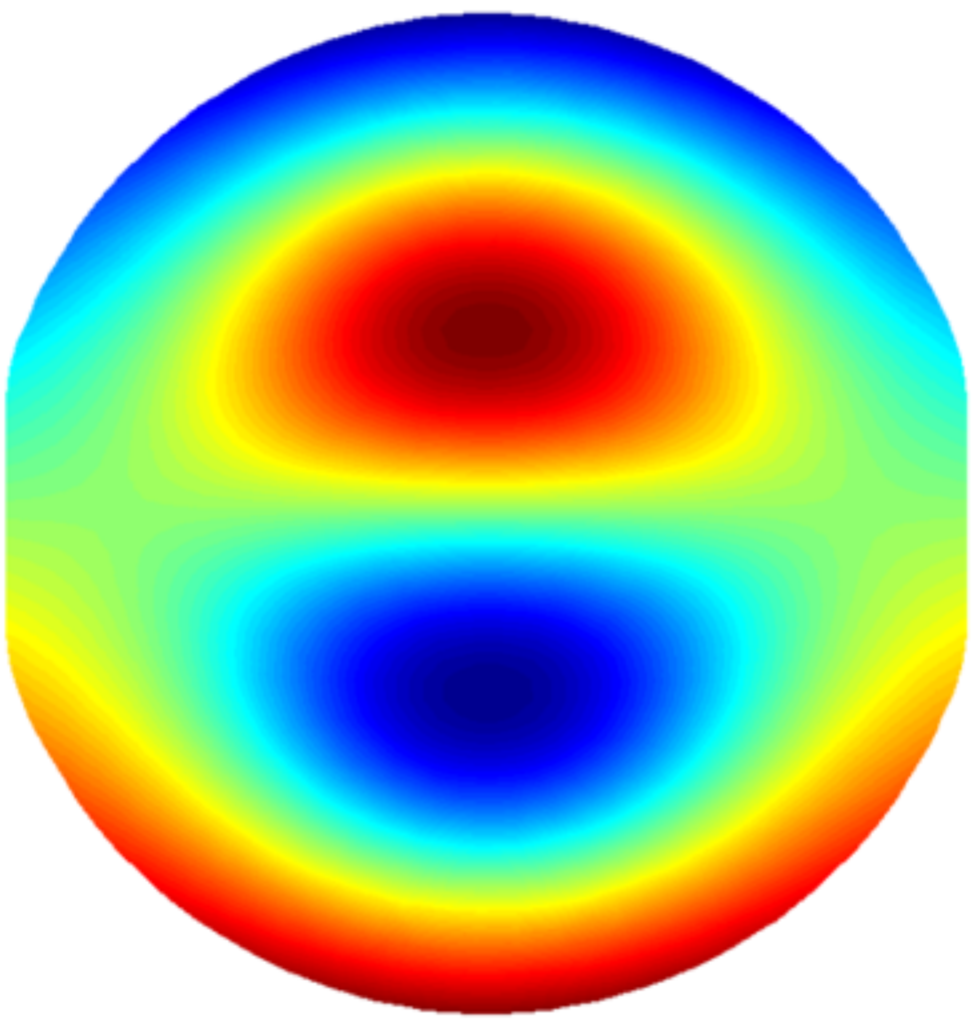


Adapted from A. Brooks G1300218

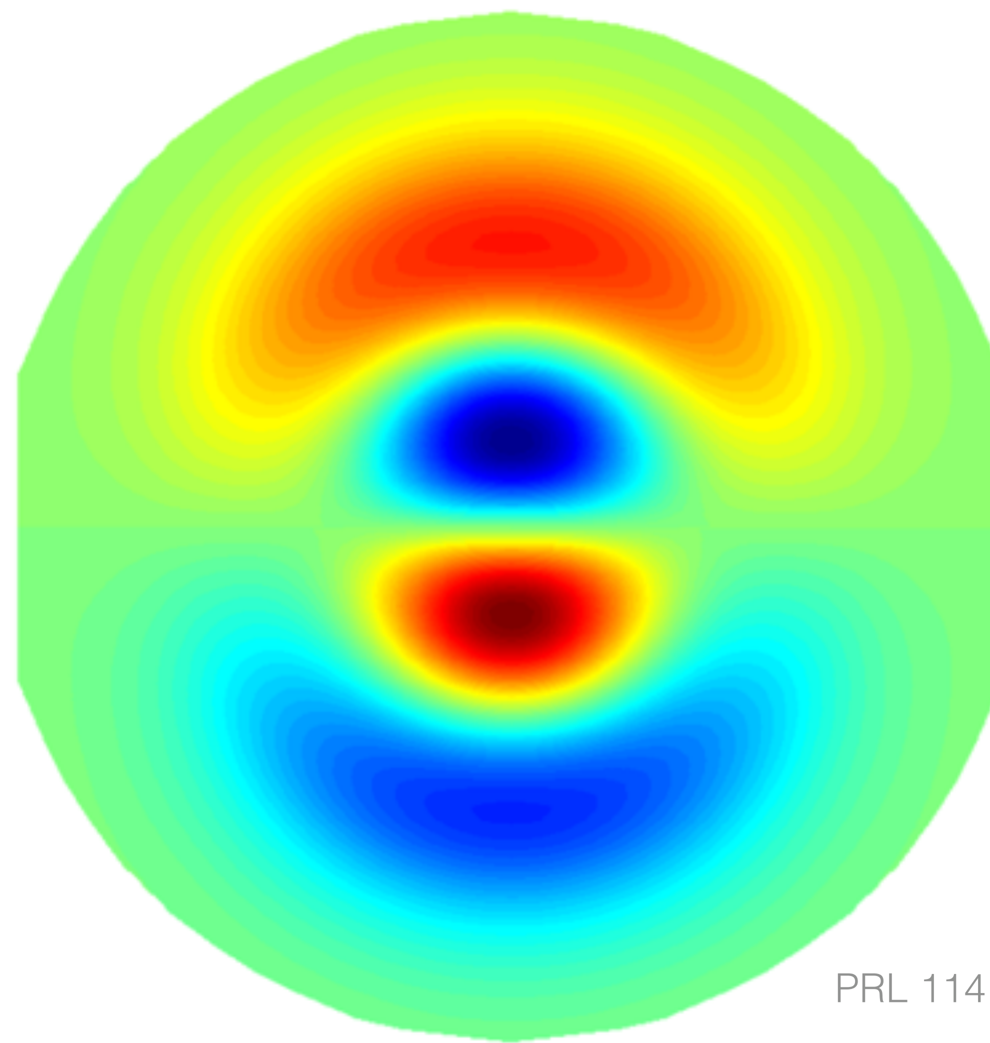
Challenge for higher power: parametric instabilities

Transfer energy from the laser light arm cavity field to the mechanical mode(s) of a mirror through radiation pressure

Mirror mechanical mode



Light cavity optical mode

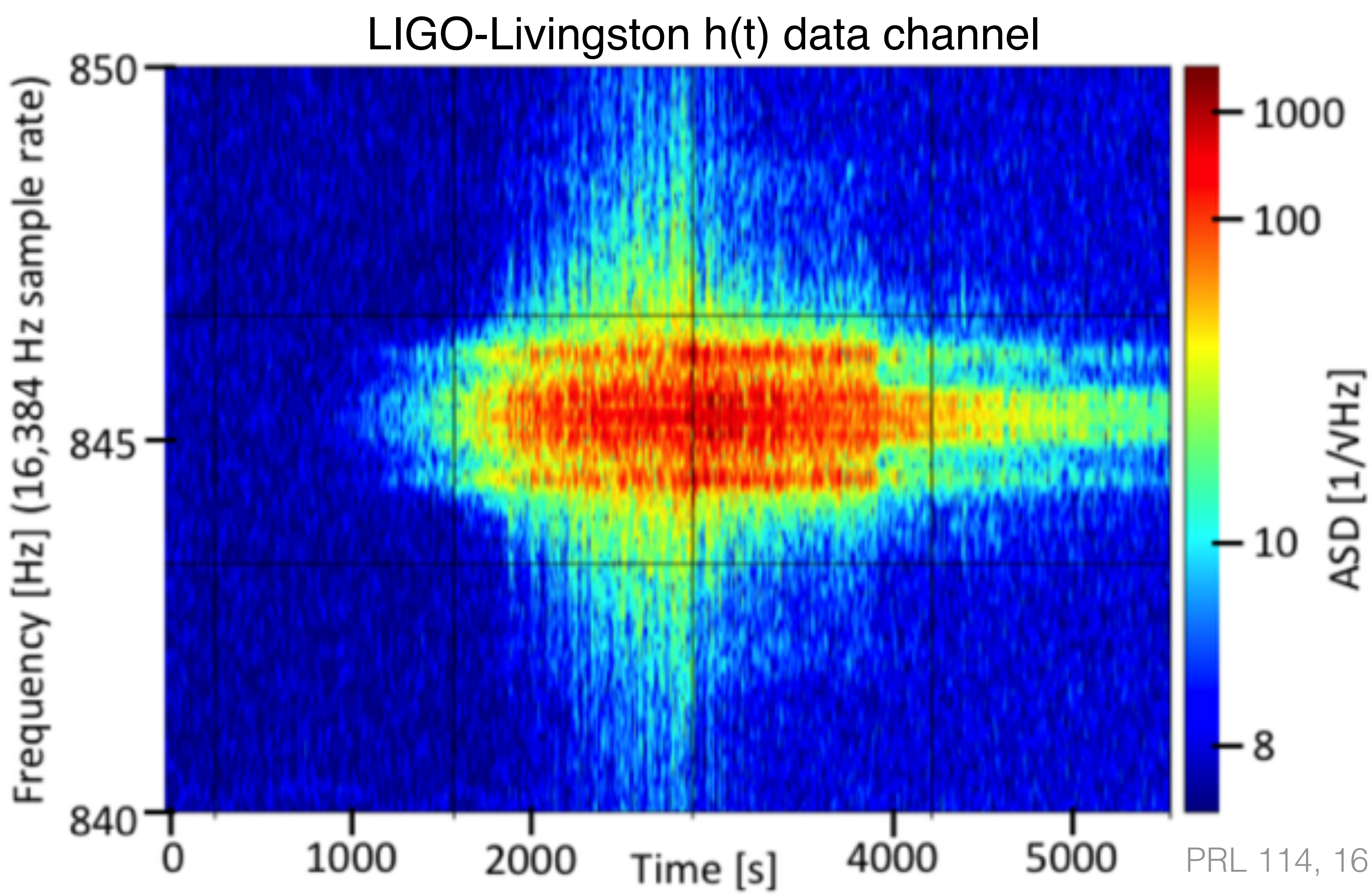


PRL 114, 161102

An example of a mode set with resonance at 15.54 kHz that produced a runaway feedback effect at LIGO-Livingston at 25W circulating power.

Parametric Instabilities

What effect do they have on the data?



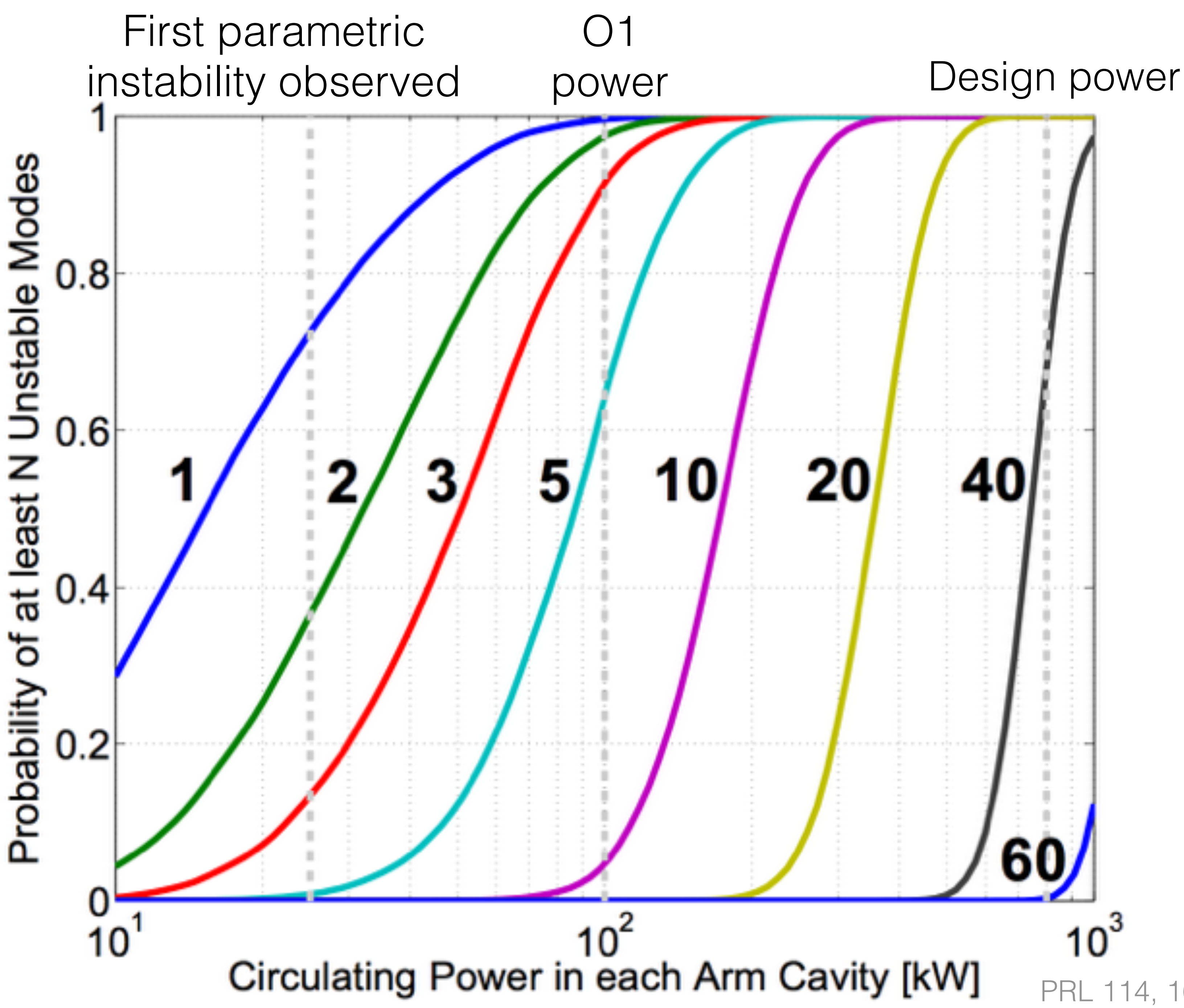
PRL 114, 161102

- Data pollution
- Loss of control of the interferometer cavities (“lock loss”) when actuators are saturated

How did we deal with these during O1?

Thermal compensation! Change the radius of curvature of the mirror enough so that the resonance mode frequency is shifted.

Parametric Instabilities



PRL 114, 161102

Thermal compensation alone won't be enough at higher power!

Will need active damping, which we are equipped to do

Thank you!