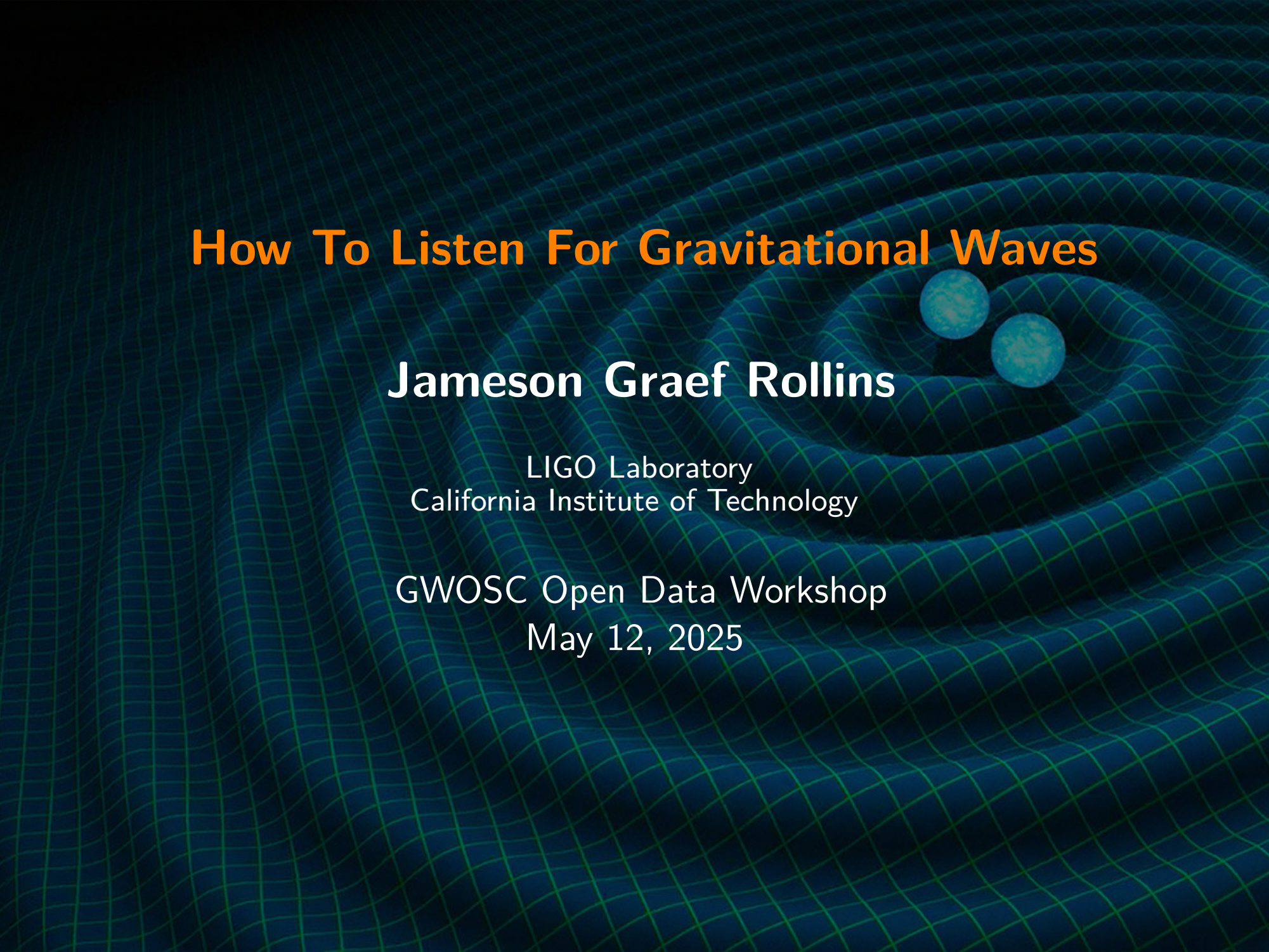


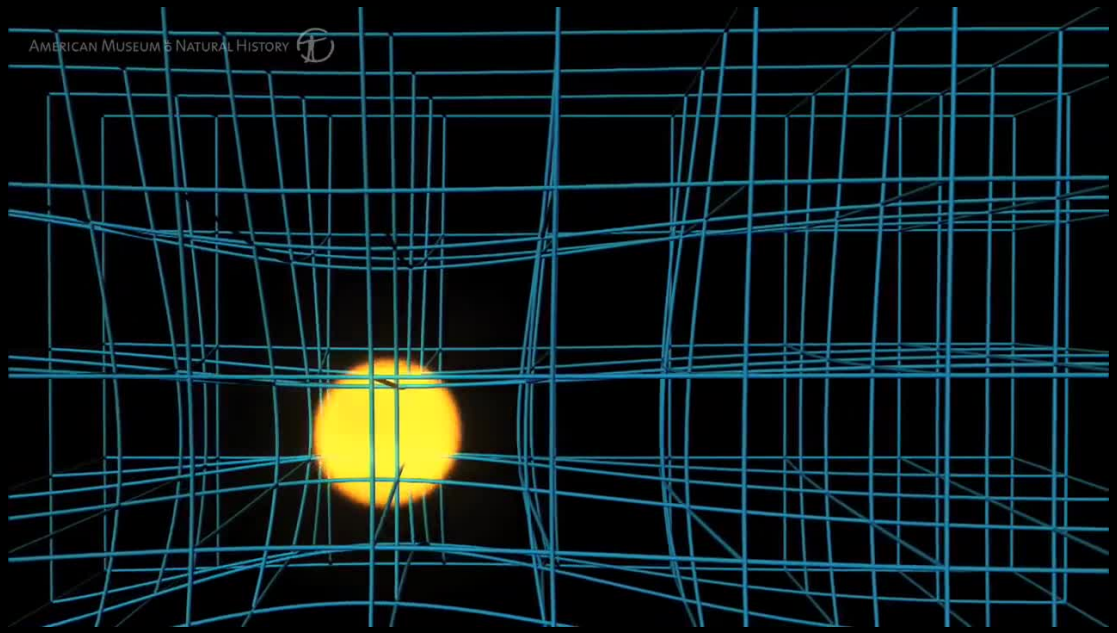
How To Listen For Gravitational Waves

Jameson Graef Rollins

LIGO Laboratory
California Institute of Technology

GWOSC Open Data Workshop
May 12, 2025

General Relativity: gravity is curved spacetime



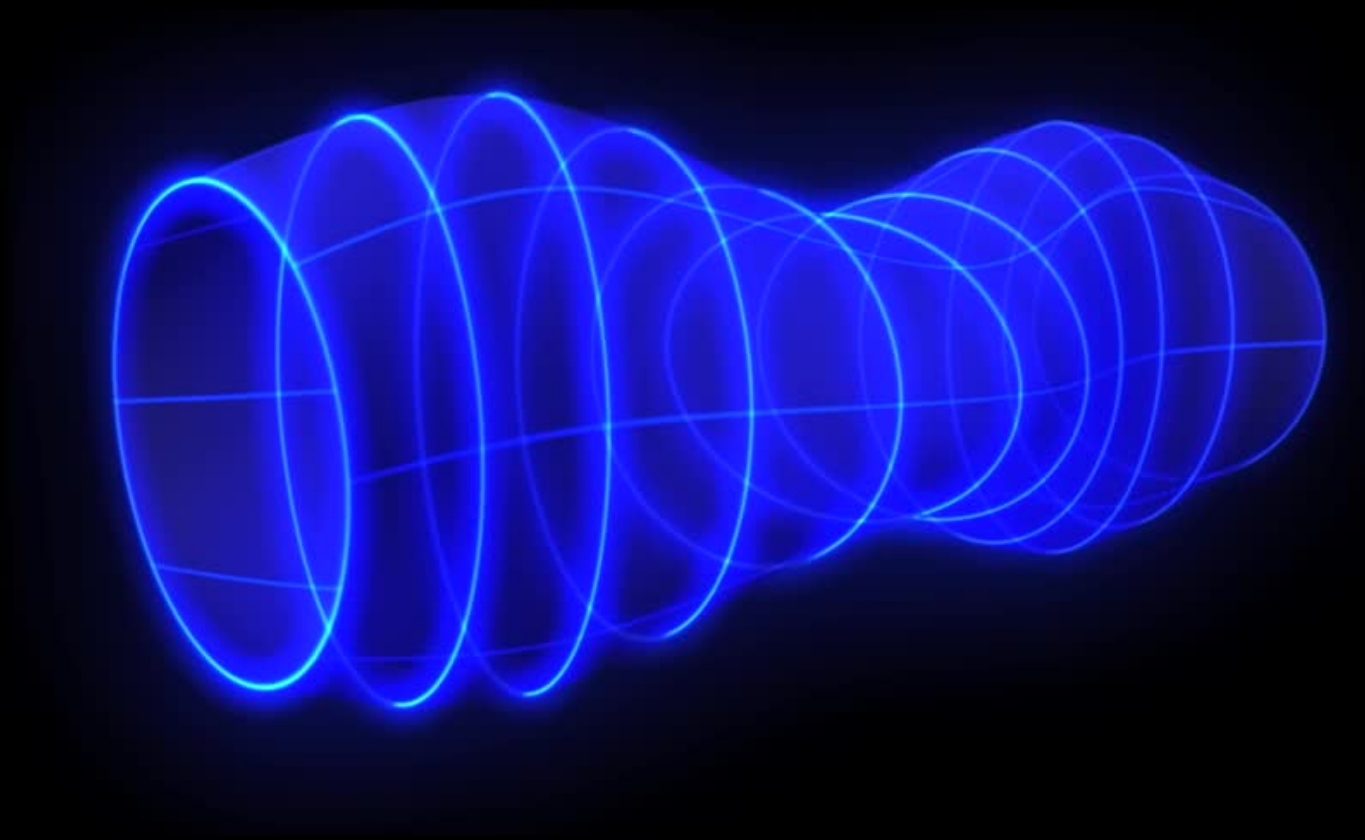
"Mass tells spacetime how to curve, spacetime tells mass how to move."

- J. Wheeler

$$G_{\mu\nu} = 8\pi\frac{G}{c^4} T_{\mu\nu}$$

curvature of spacetime $= \sim 10^{-43}$ mass-energy content

GR predicts *gravitational waves*: ripples in spacetime



Effect on local spacetime

Gravitational waves cause a peculiar motion of spacetime as they pass:

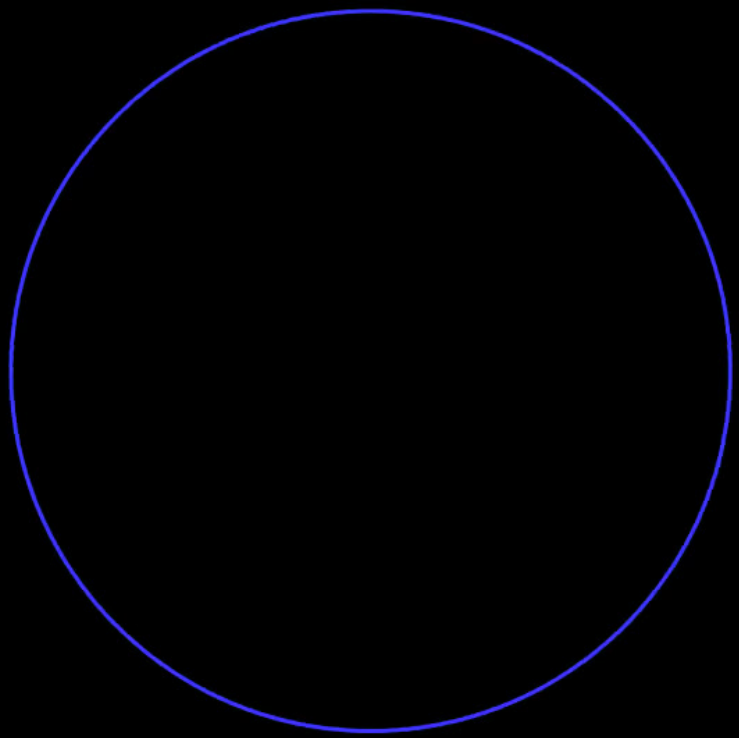
differential strain

$$h = \frac{\Delta L}{L}$$

For wave traveling z direction, x stretches while y contracts, then vice versa.

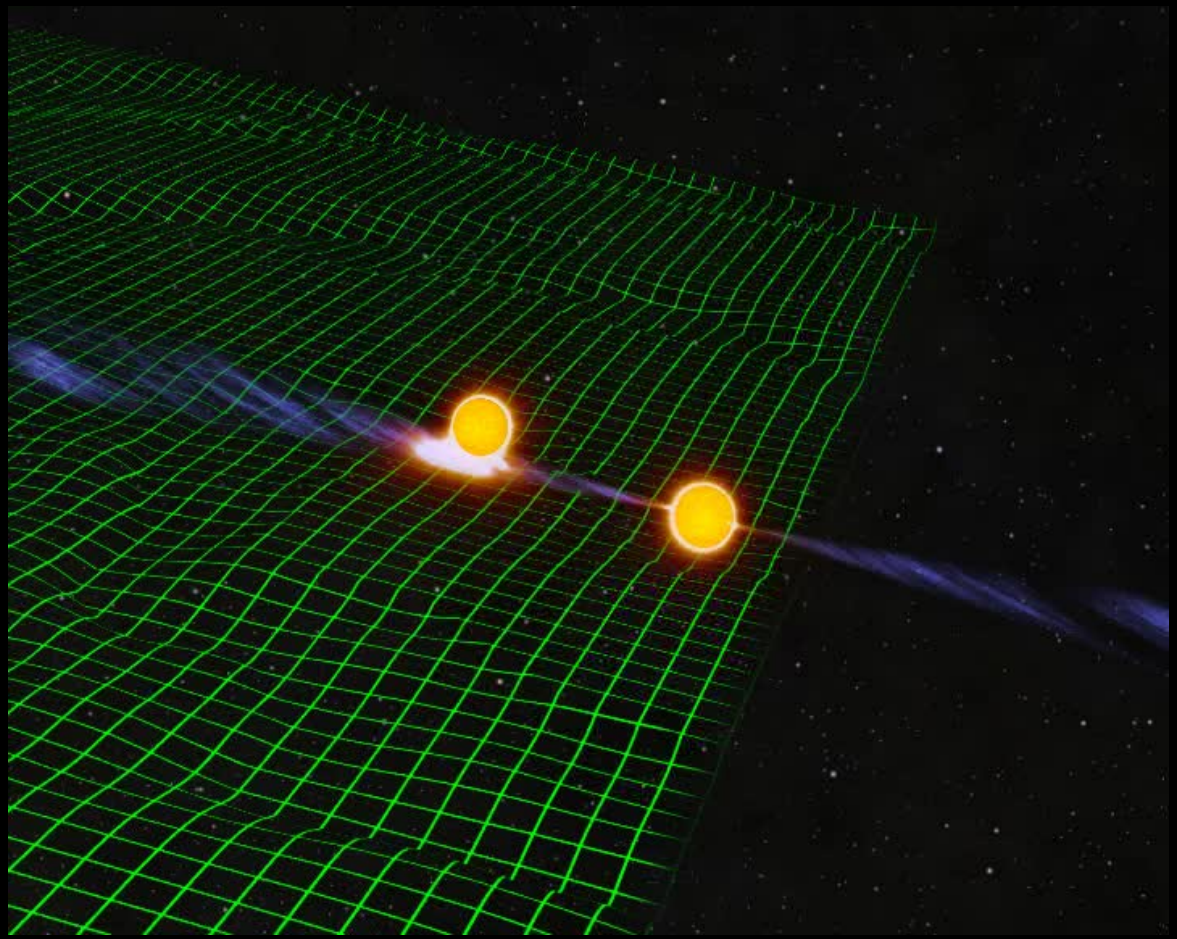
Test masses placed on the ring will move with the spacetime.

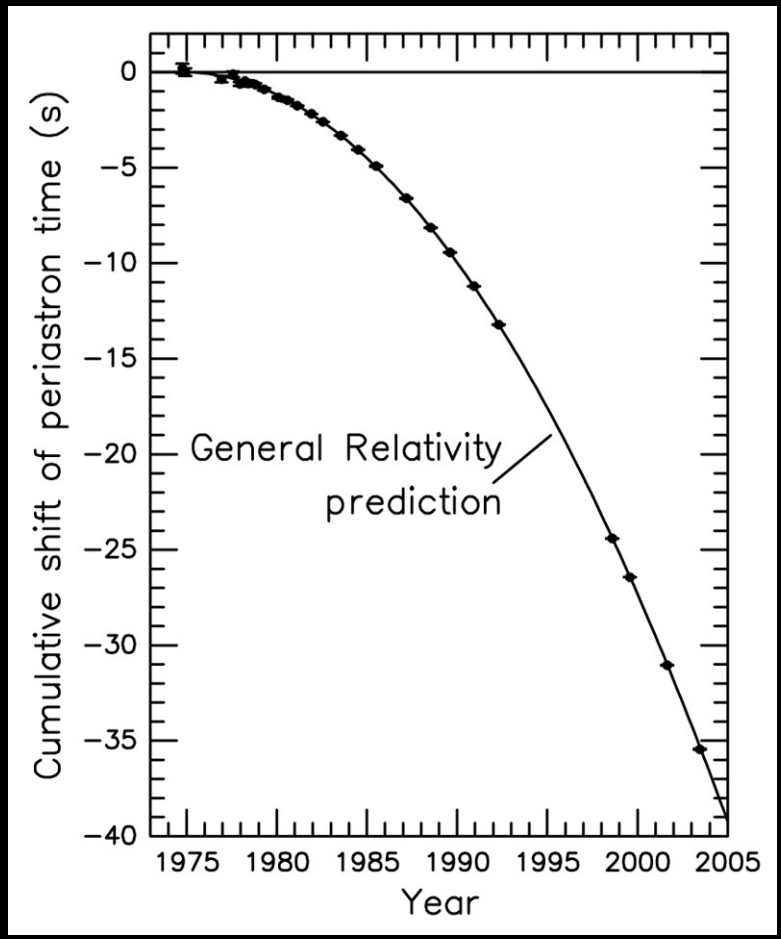
Cross section of tube:



GW produced by accelerating asymmetric mass distributions

1993 Nobel Prize in Physics: pulsar in binary system





Russell Hulse and Joseph Taylor
(decay measurement with J. Weisberg)

Joseph Weber: pioneer of GW experiment

Weber built the first ever gravitational wave detectors in the 1960s.

resonant mass detector

Designed to ring like a bell when struck by a gravitational wave.

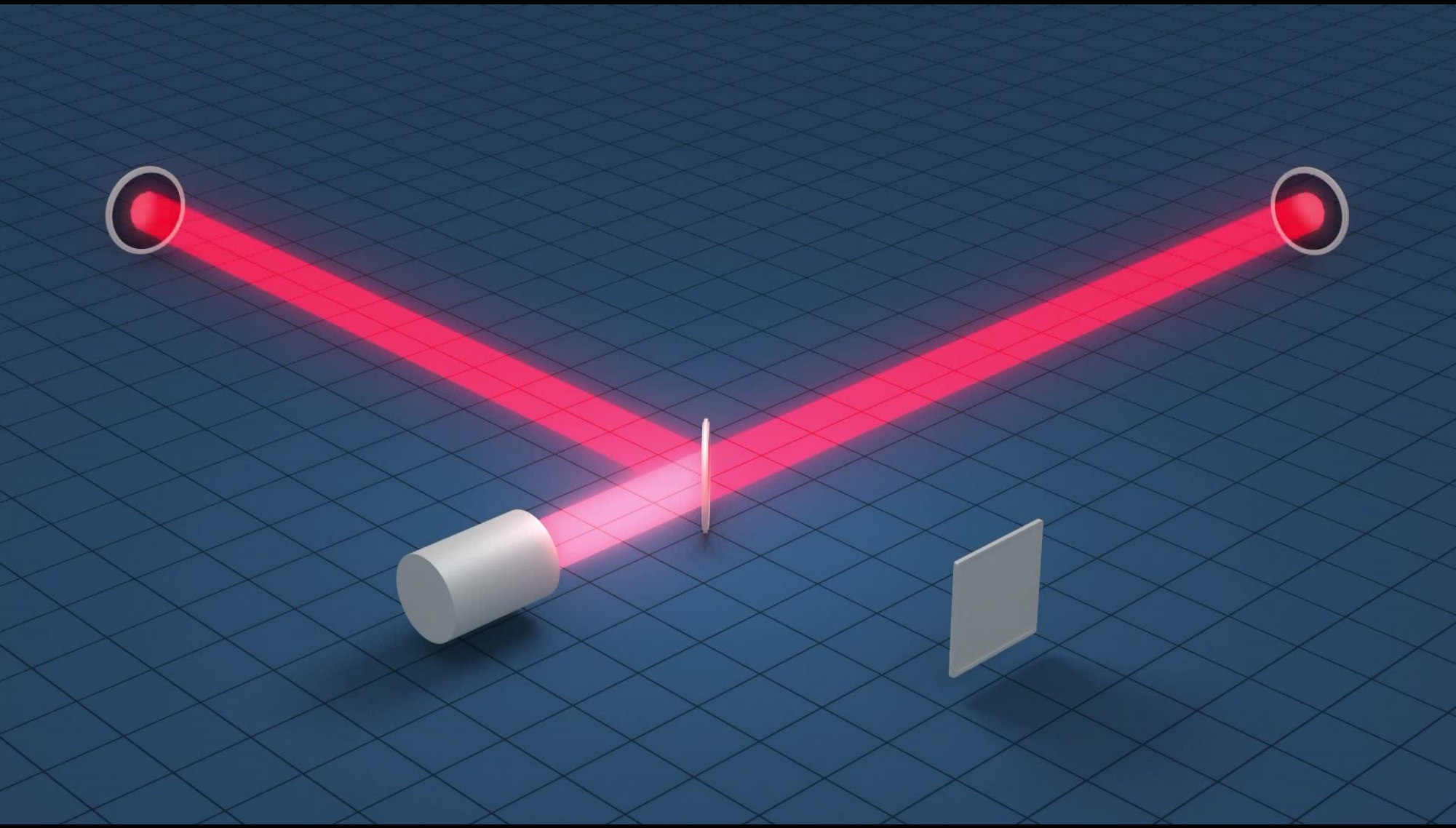
He thought he detected something (but probably didn't).

In 1970s a new detection paradigm was conceived

Rainer Weiss
(MIT)

Kipp Thorne, Ronald Drever,
Rochus Voigt (Caltech)

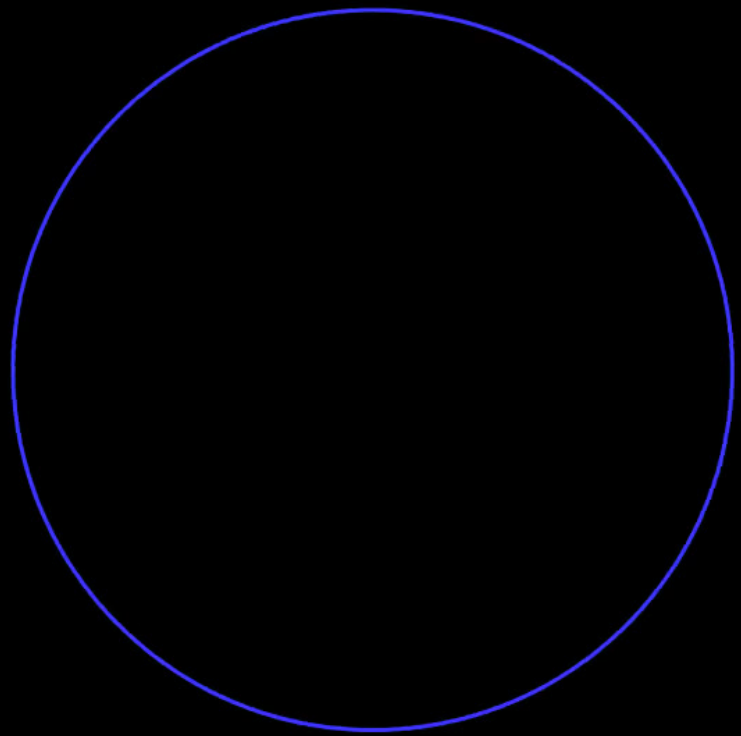
Use light to measure the strain: Michelson interferometer



Effect on local spacetime

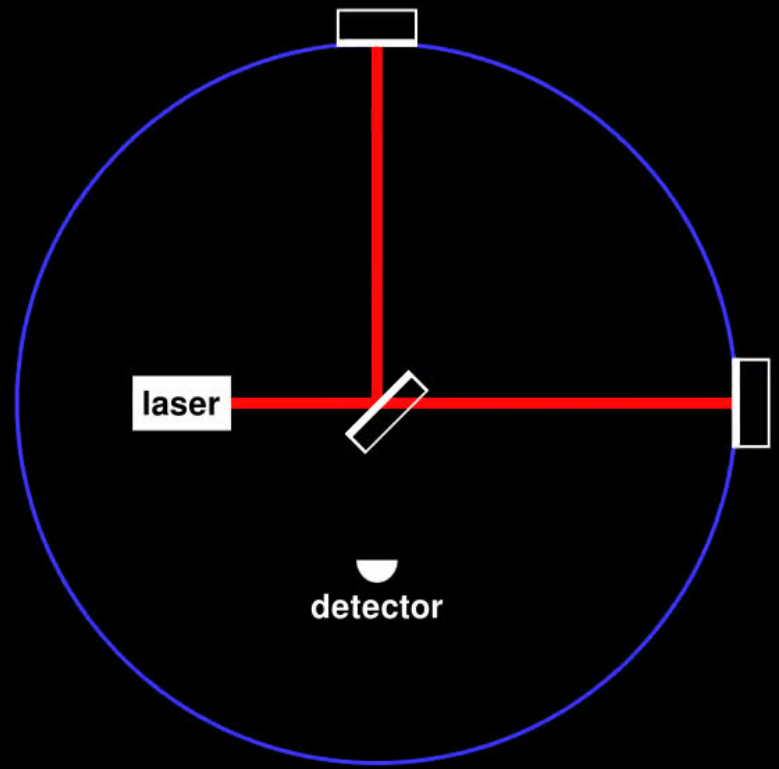
How can we use Michelson interferometer to measure the strain?

Remember: test masses placed on the ring will move with the spacetime.

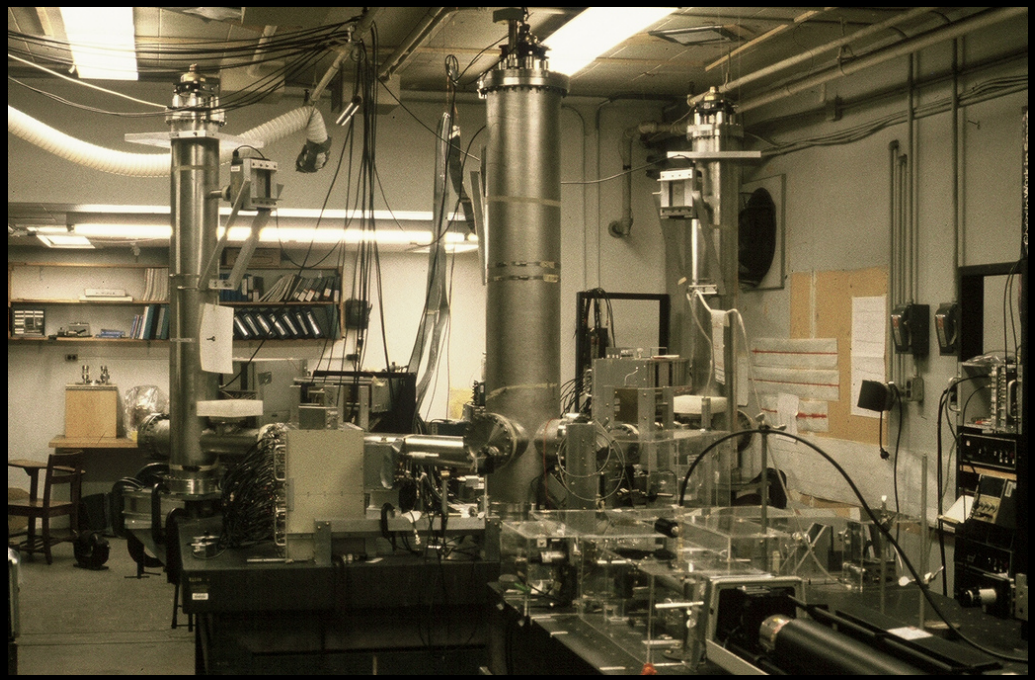


Michelson interferometer gives direct measure of strain

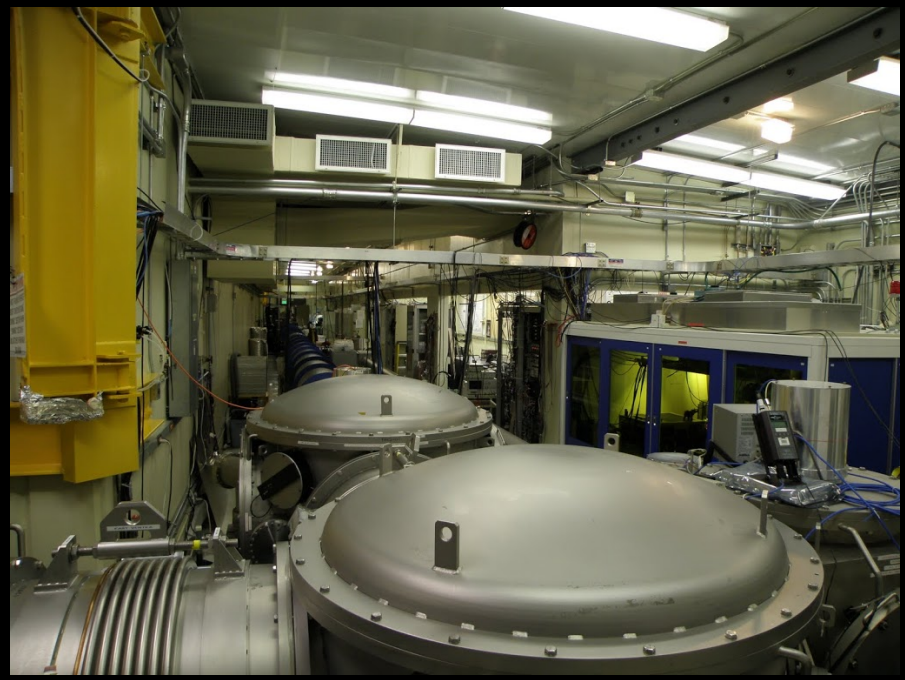
If we place Michelson end mirrors on the ring, the interferometer *directly measures* the strain of the passing gravitational wave.



Prototype interferometric detectors were built

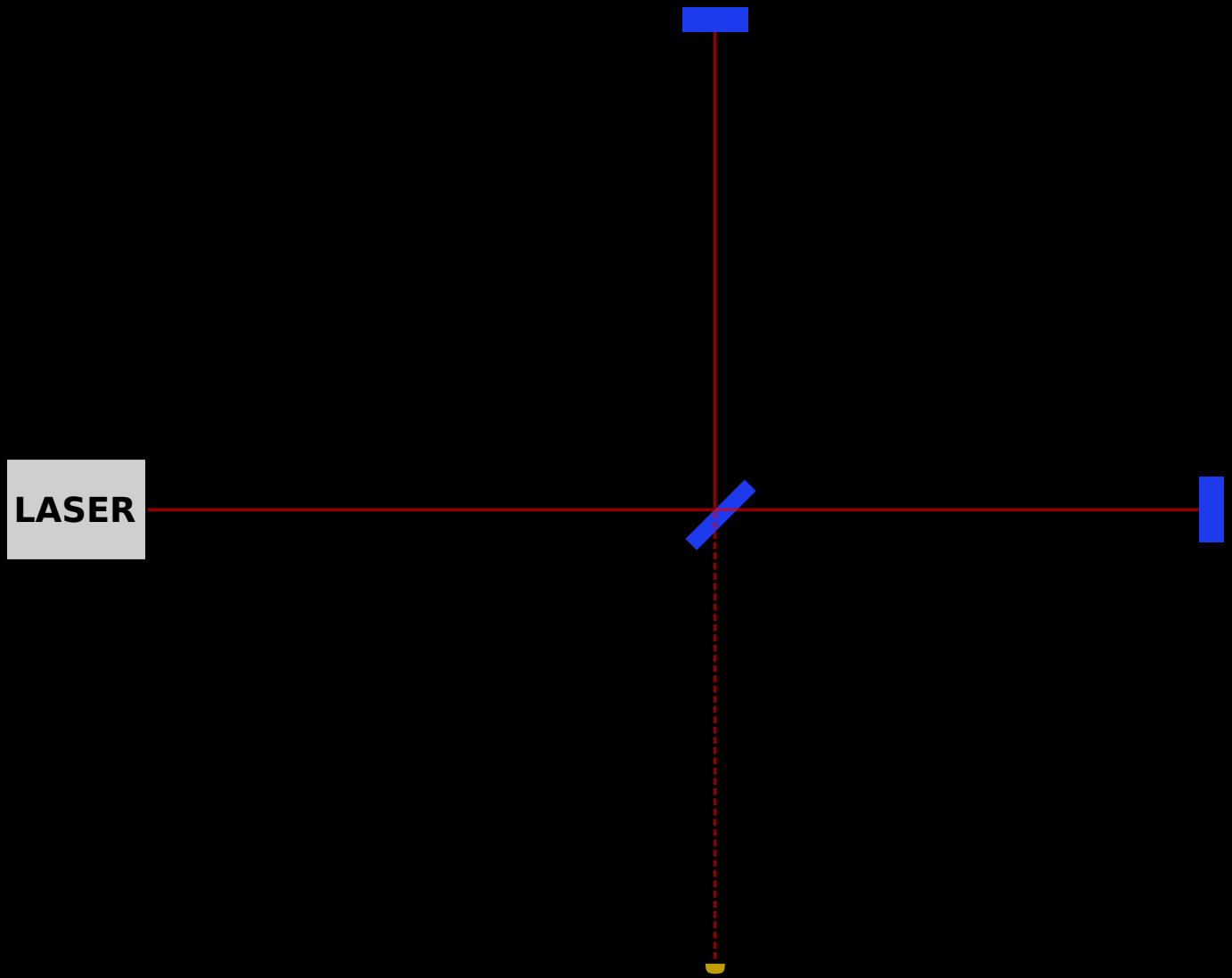


MIT 1.5m prototype

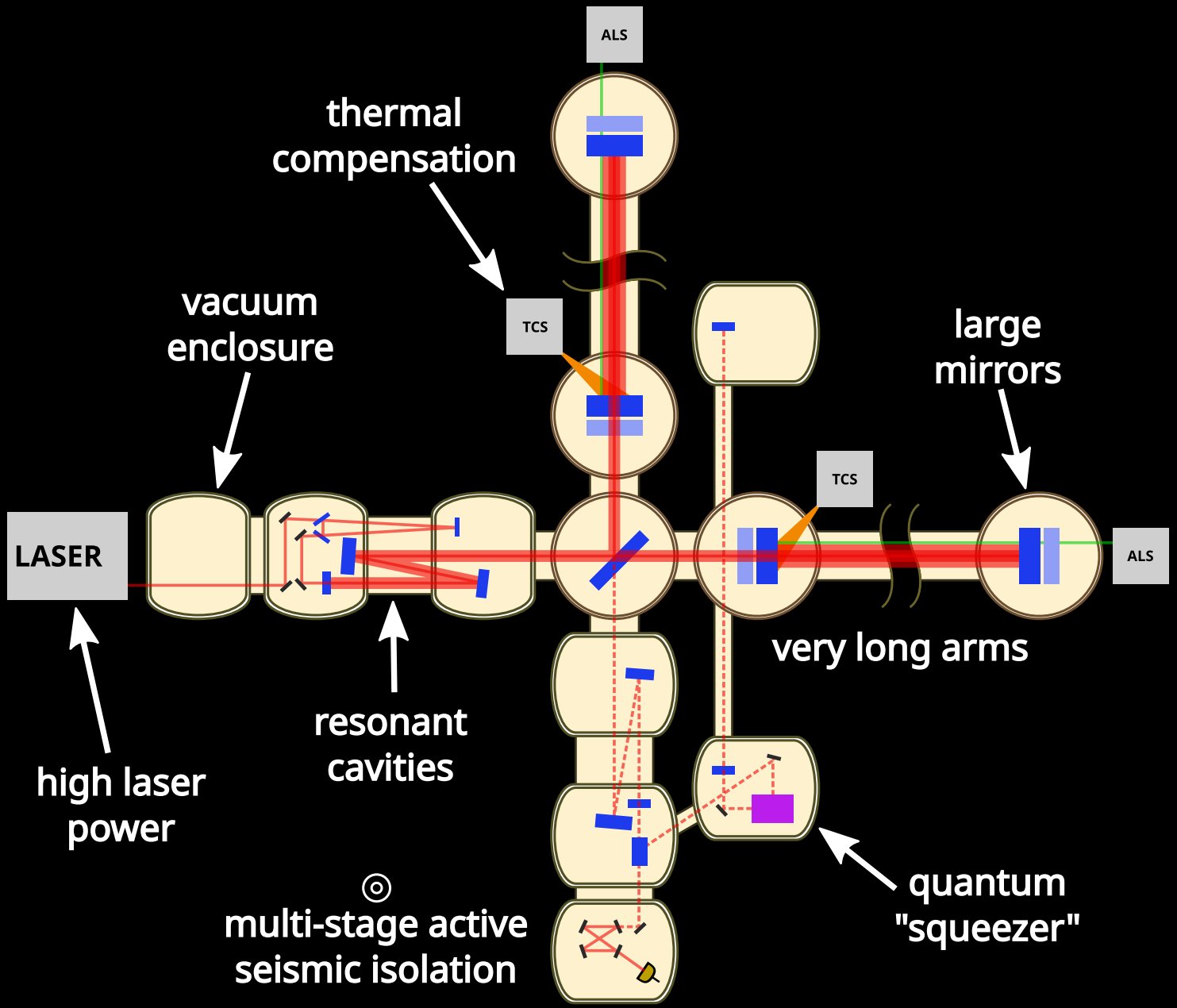


Caltech 40m prototype

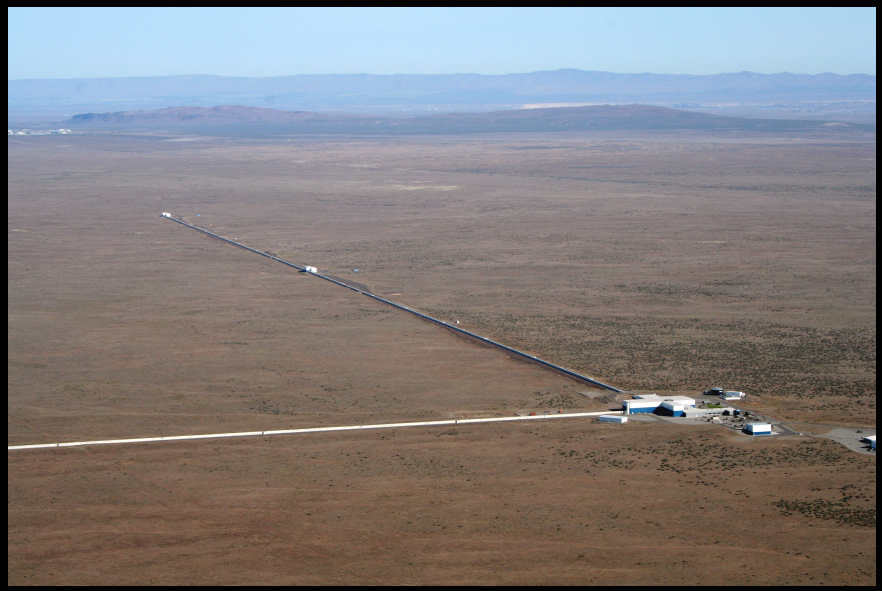
After much research, simple Michelson concept...



...evolved into something much more sensitive



Laser Interferometer Gravitational-wave Observatory

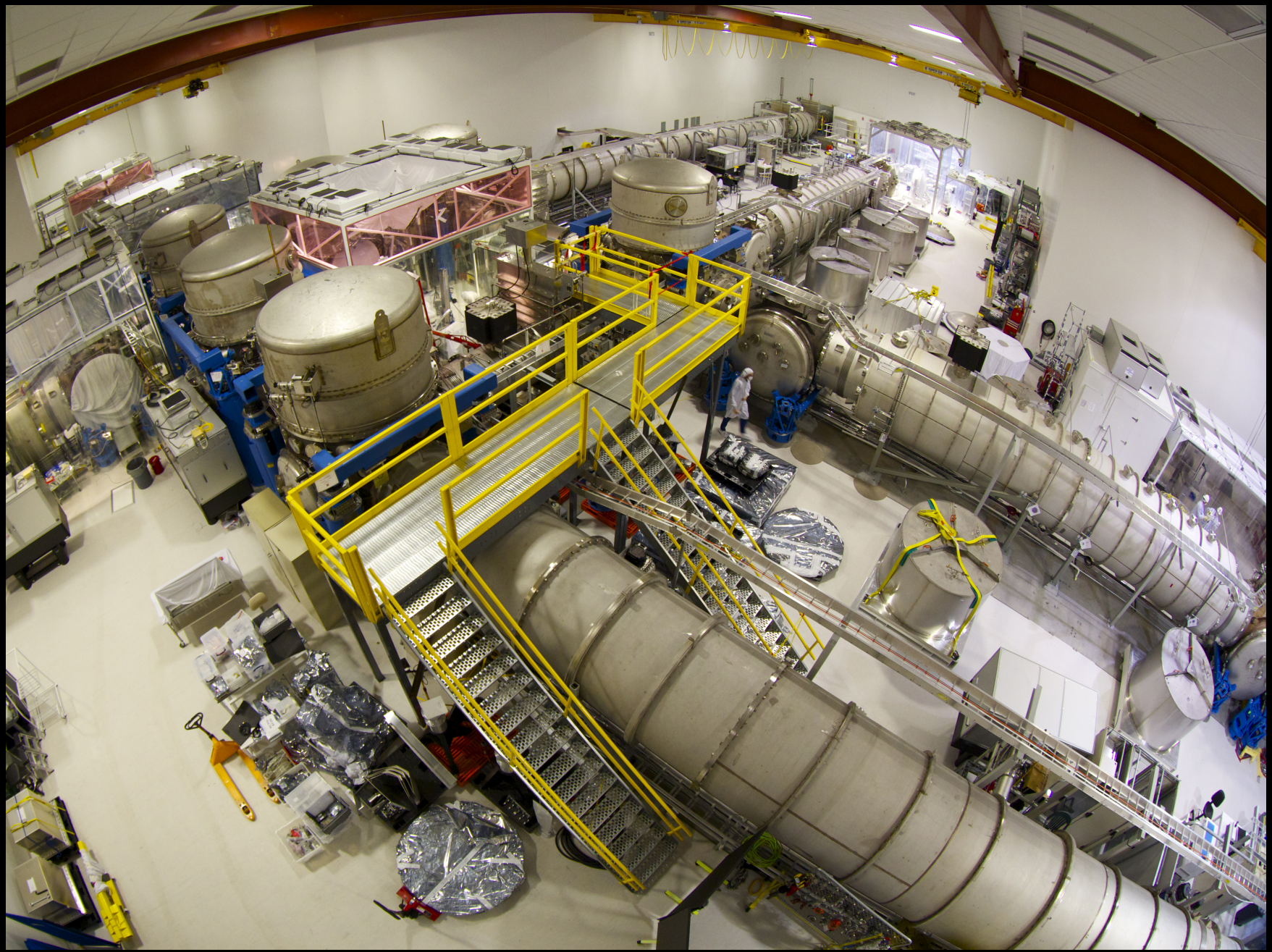


Hanford, WA (LHO)

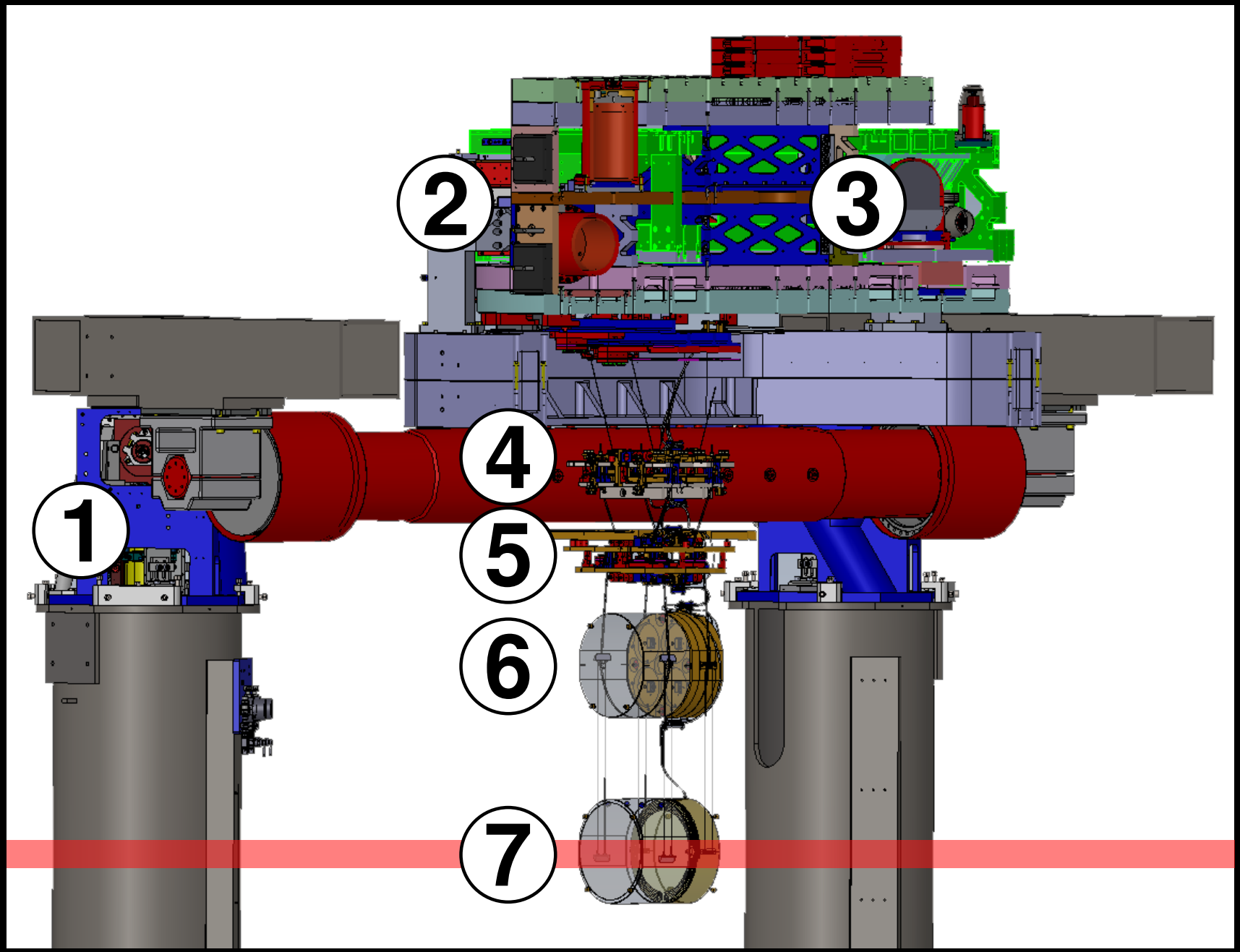
Livingston, LA (LLO)

Laser Interferometer Gravitational-wave Observatory

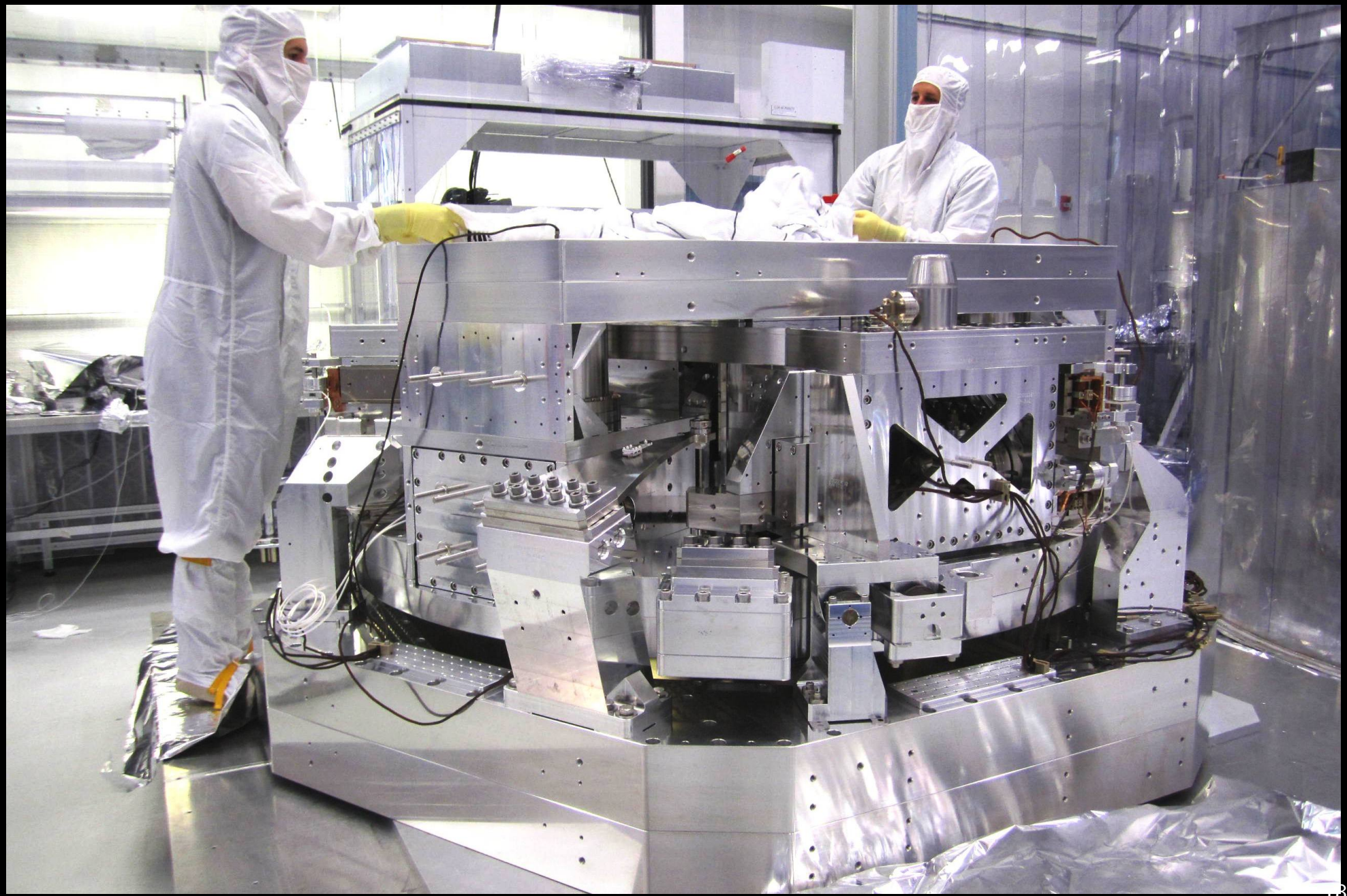
Very large ultra-high vacuum enclosure



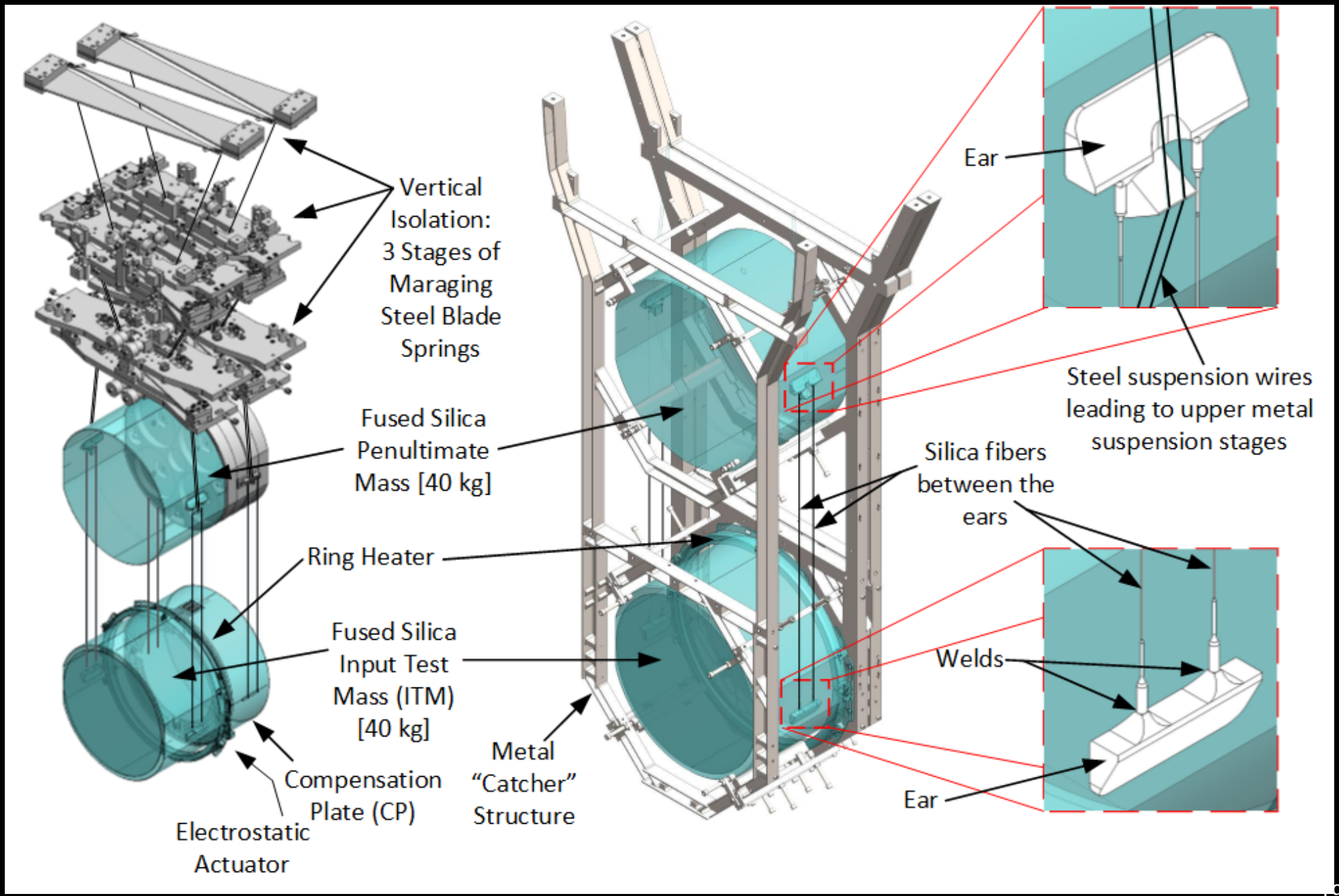
Seven stages of active seismic isolation



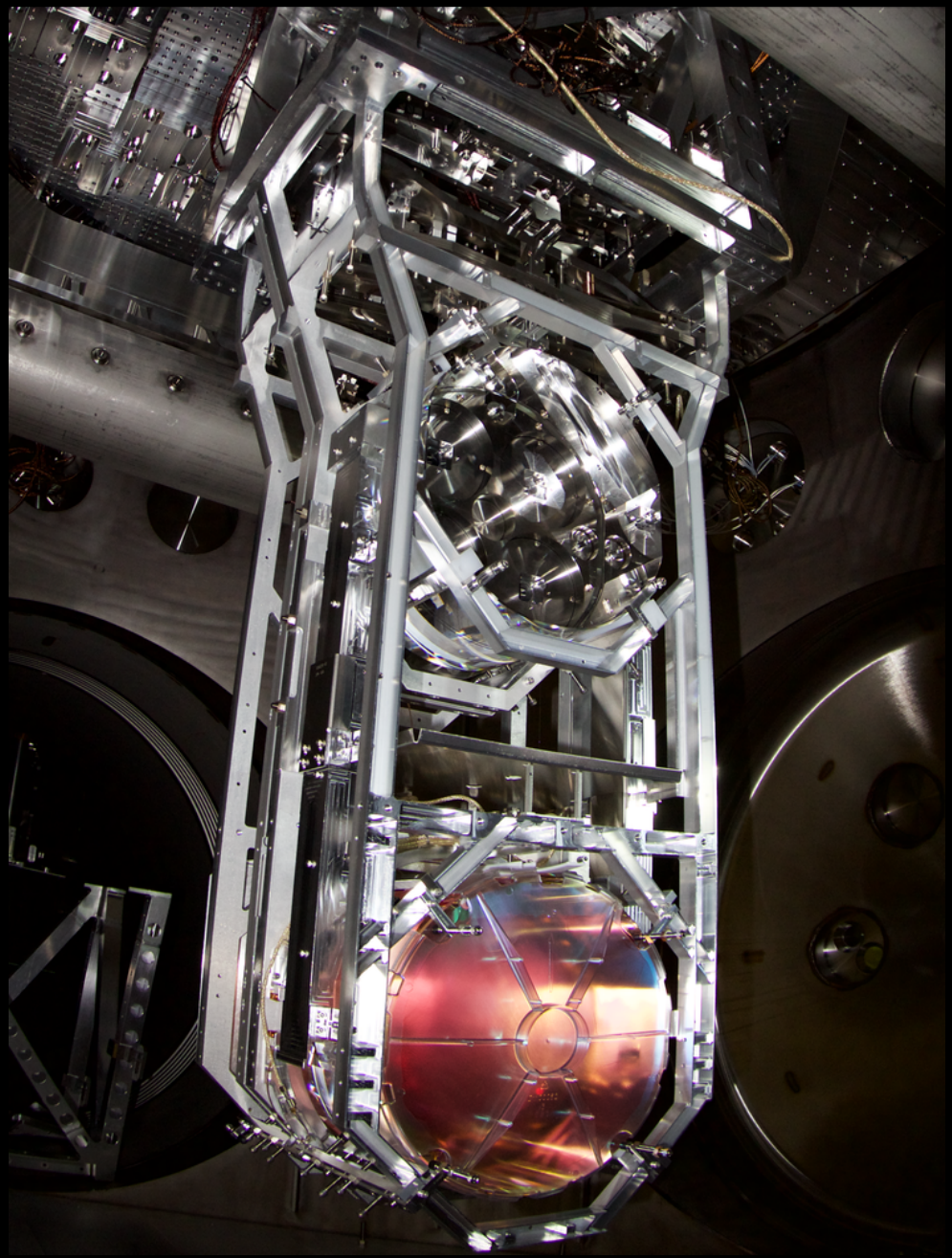
Seismic isolation platform



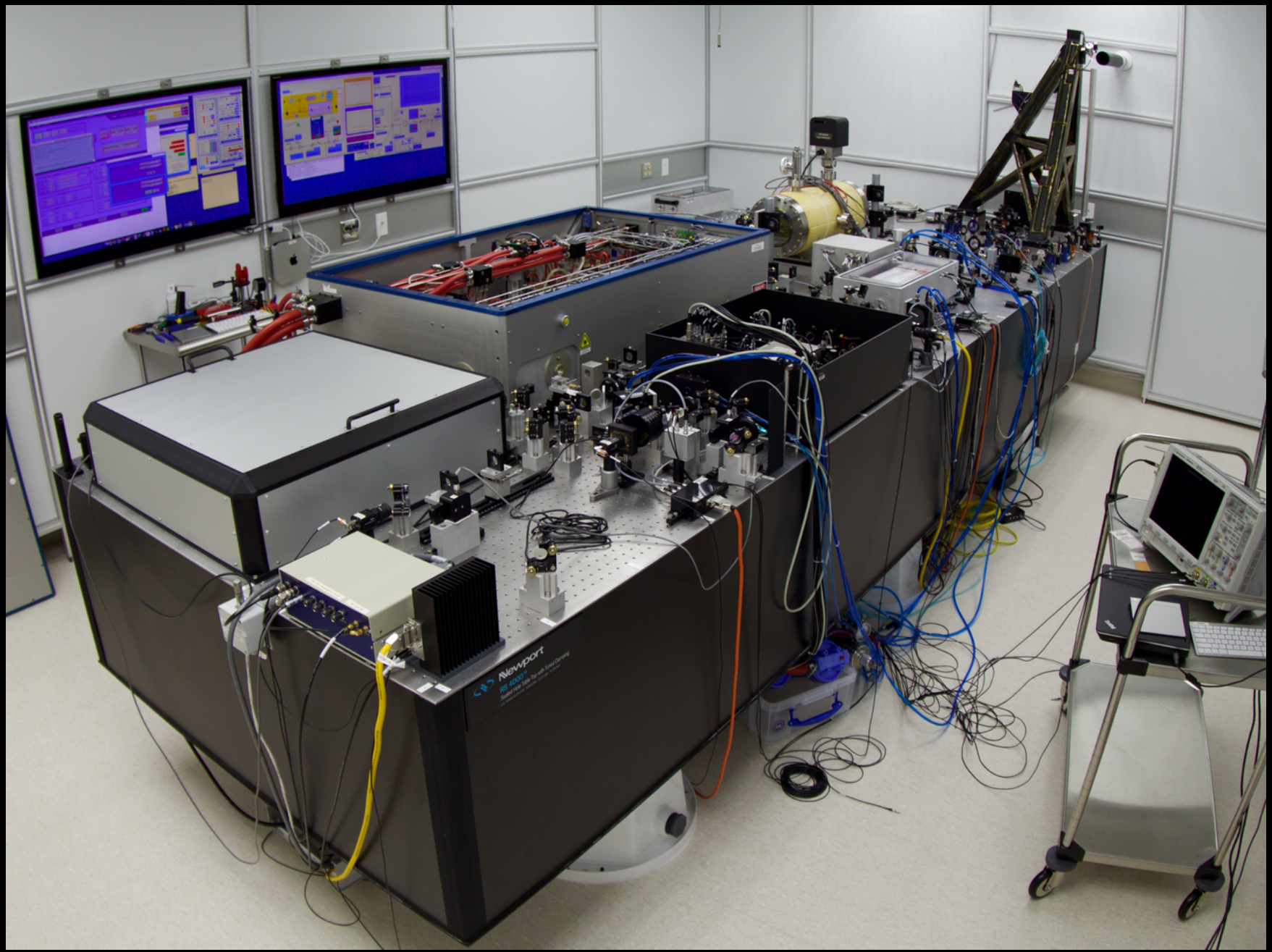
Large test masses and monolithic suspensions



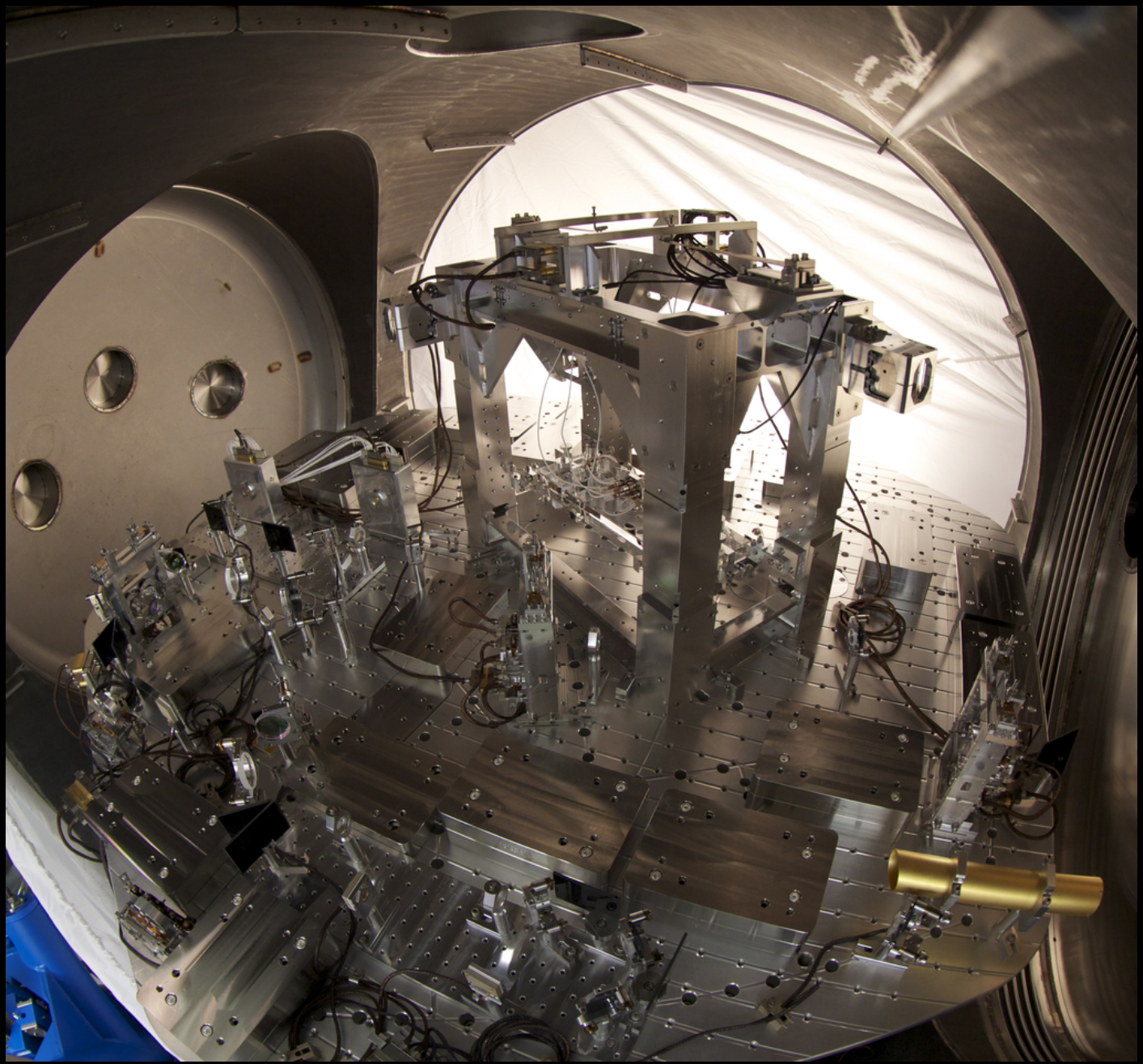
Large test masses and monolithic suspensions



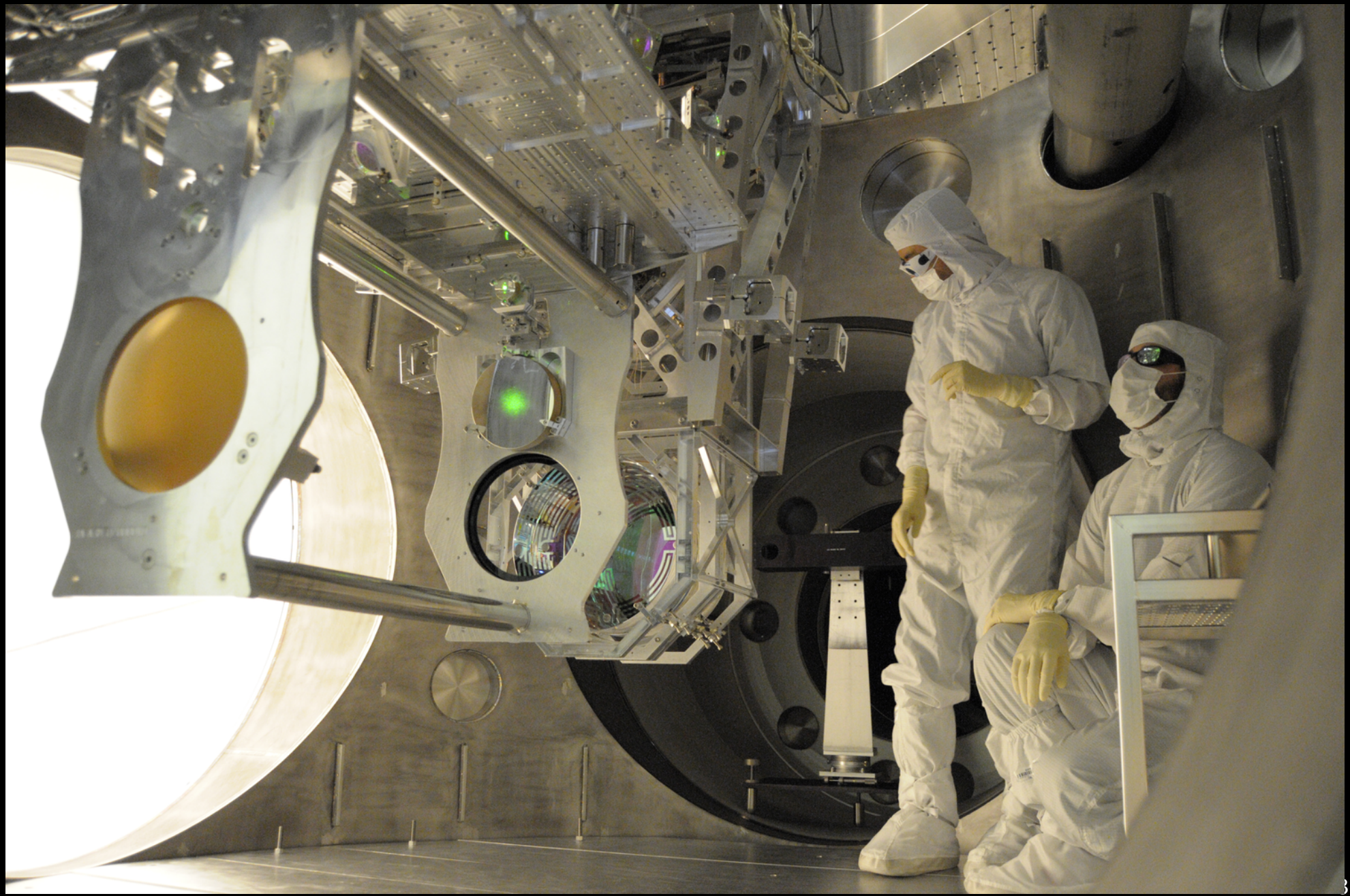
High power pre-stabilized laser source



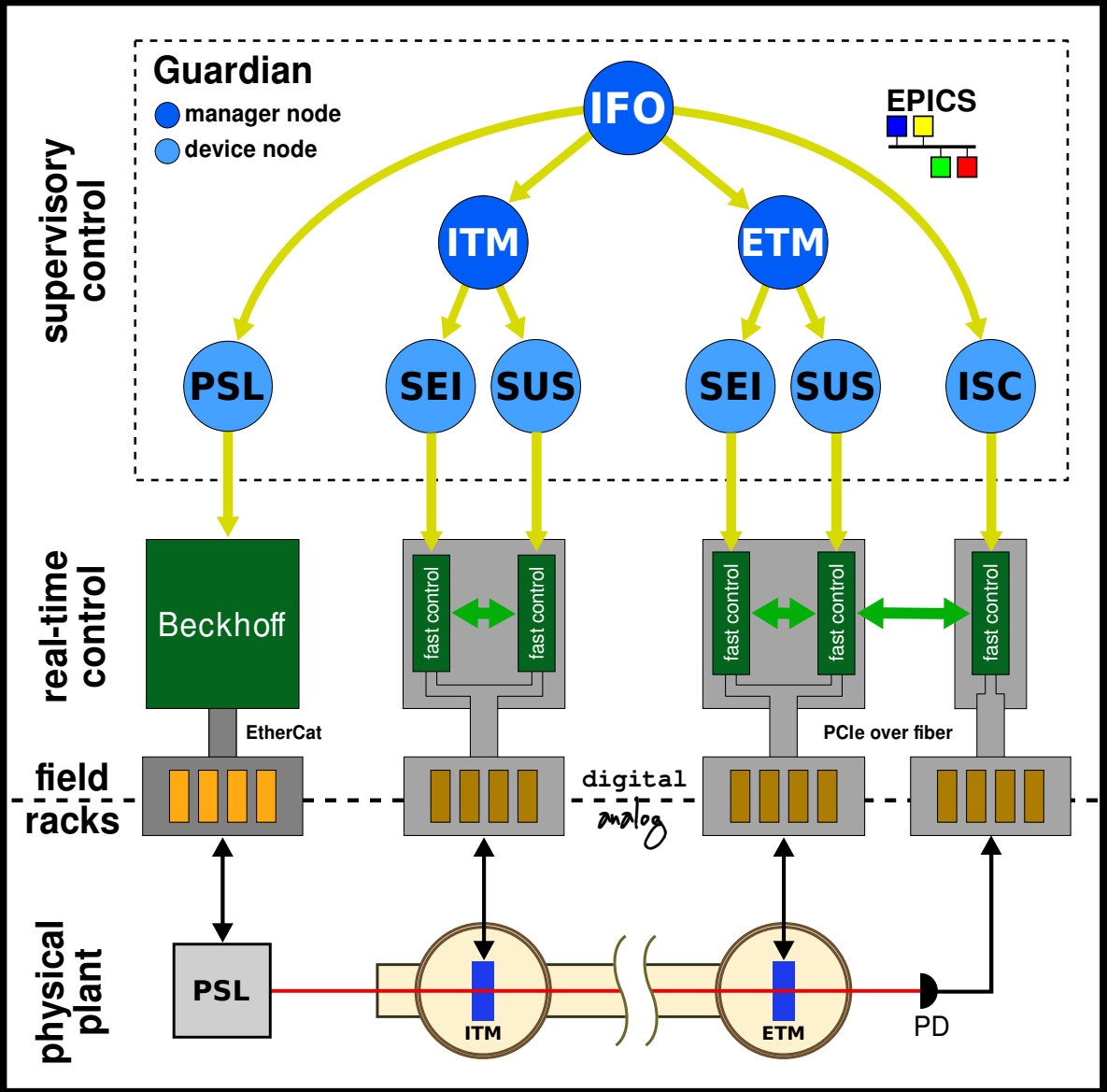
Readout optics and electronics



End test mass chamber assembly



Digital control systems



Hundreds of feedback loops:

suspensions active damping of 3-24 DOF per suspension ($\times 18$)

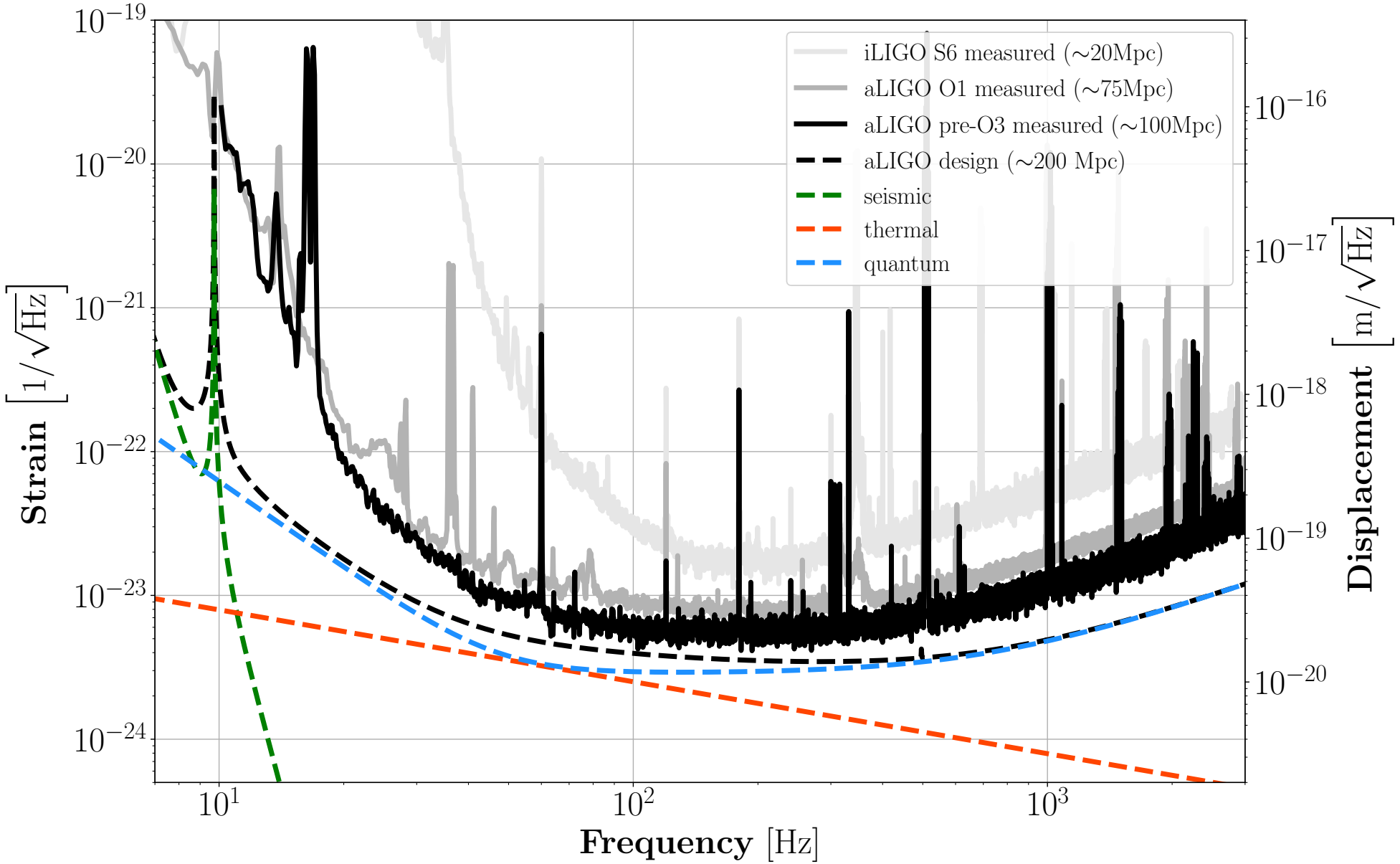
seismic isolation active damping and isolation of 18 DOF per seismic platform ($\times 9$)

global control 5 length and 10 angular global DOF

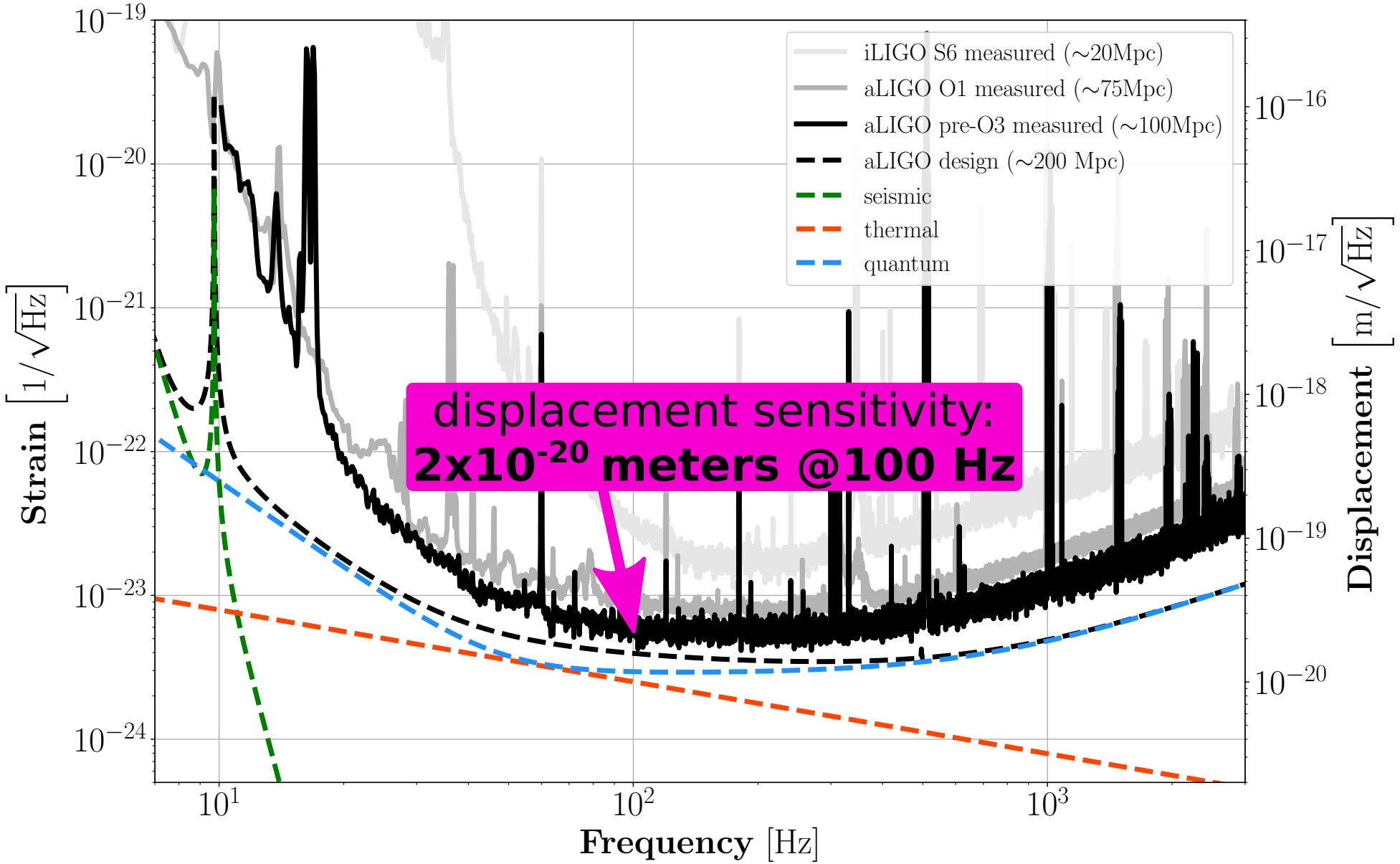
LIGO is a transducer of spacetime strain to electrical signals.

a “microphone” of spacetime waves

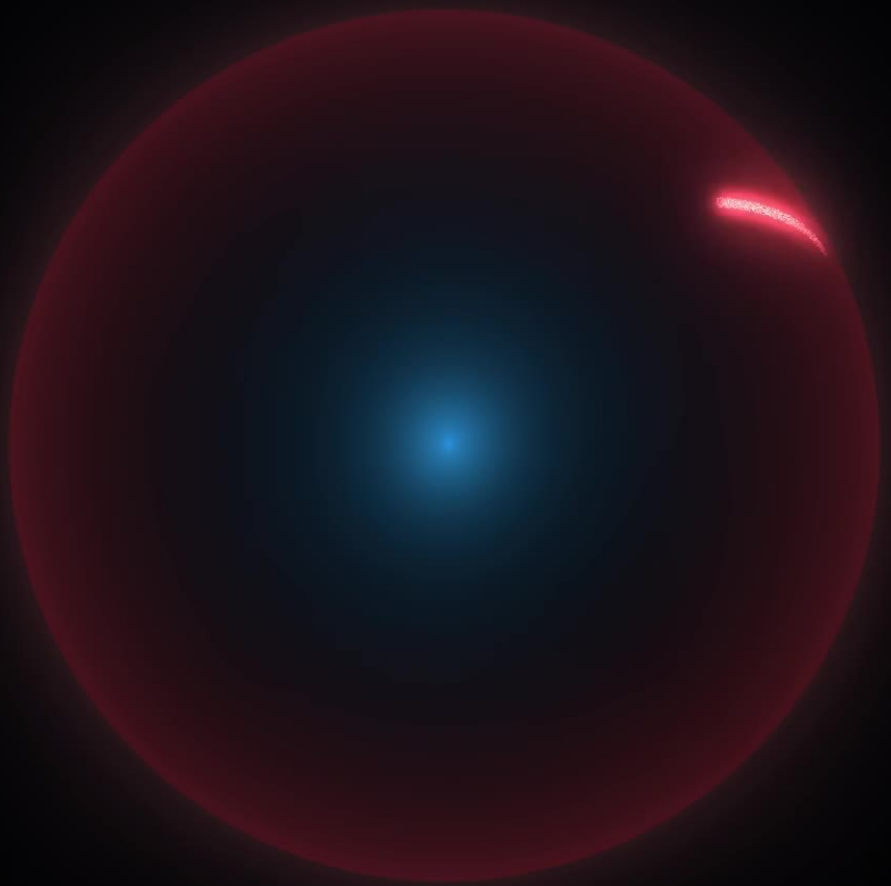
LIGO sensitivity and noise budget



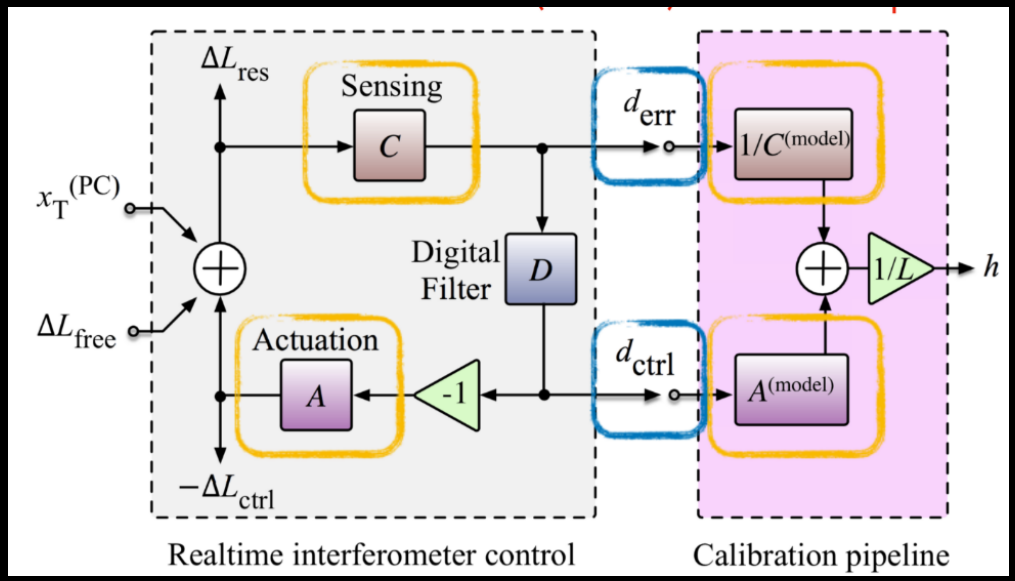
LIGO sensitivity and noise budget



How small *is* that?!

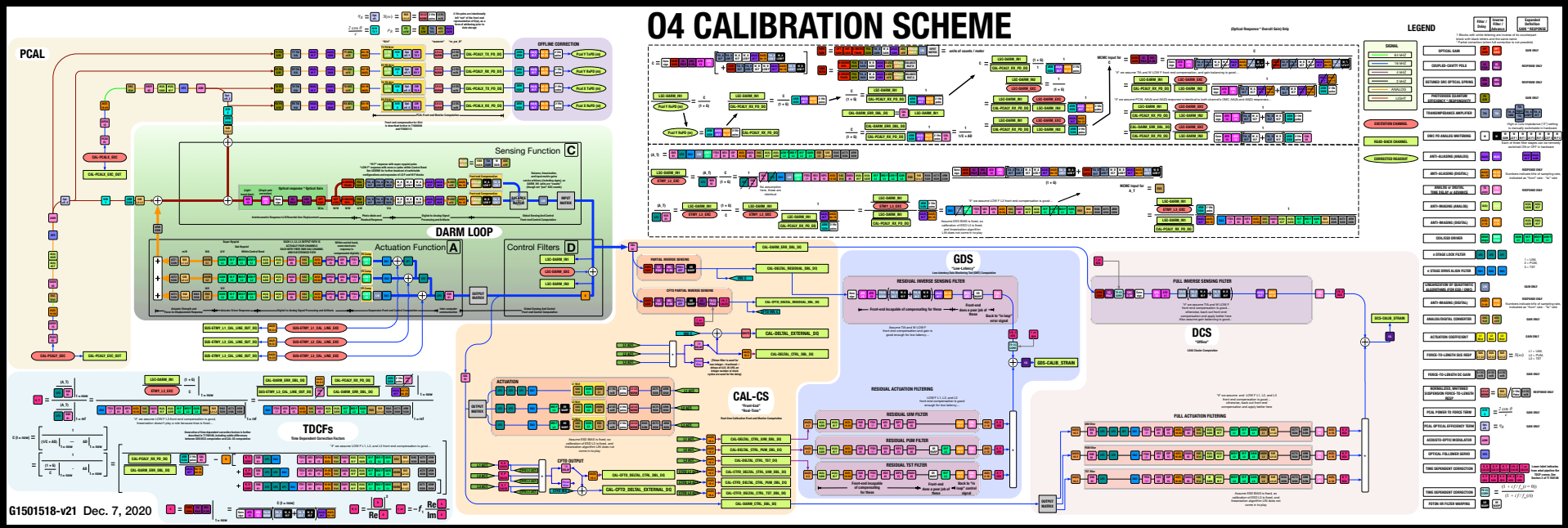


Turning measurement into strain



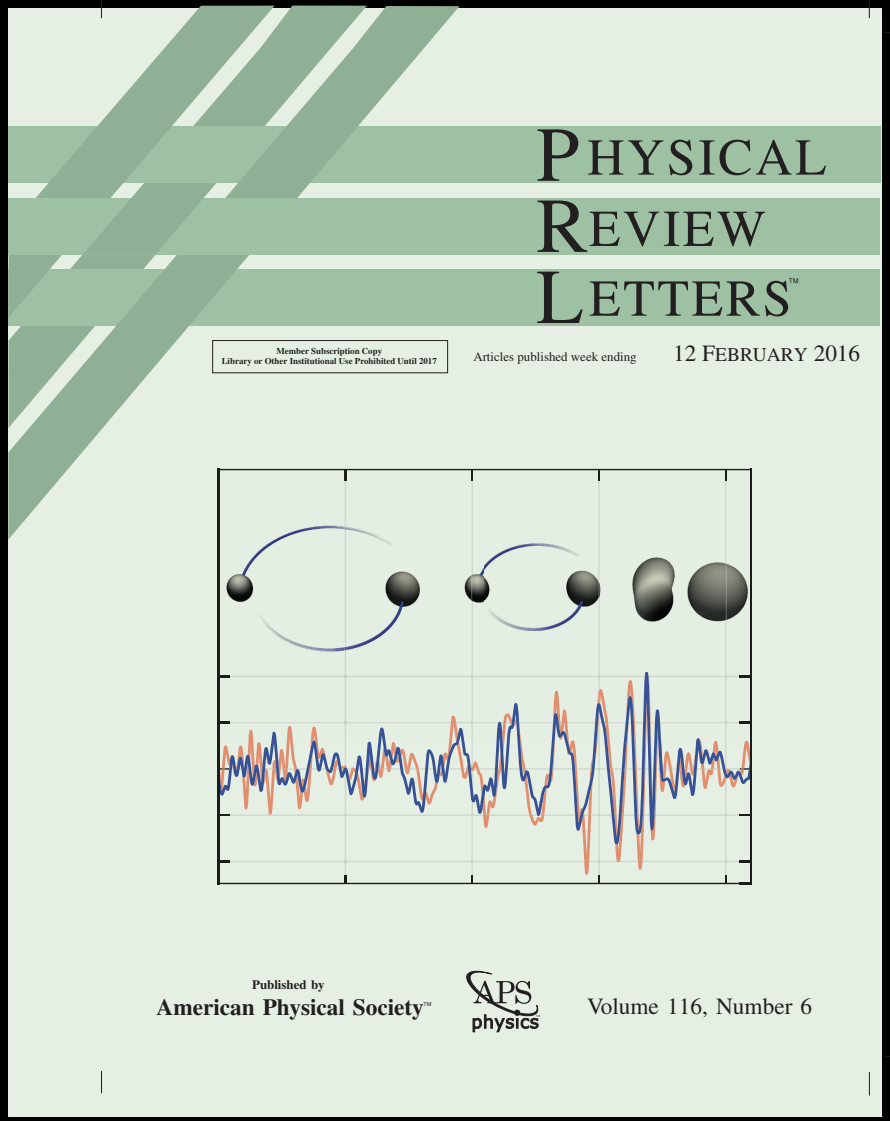
Calibrating the measurement into *strain* requires a precise understanding of the interferometer.

← create a model of the *differential arm length control loop*.



GW150914

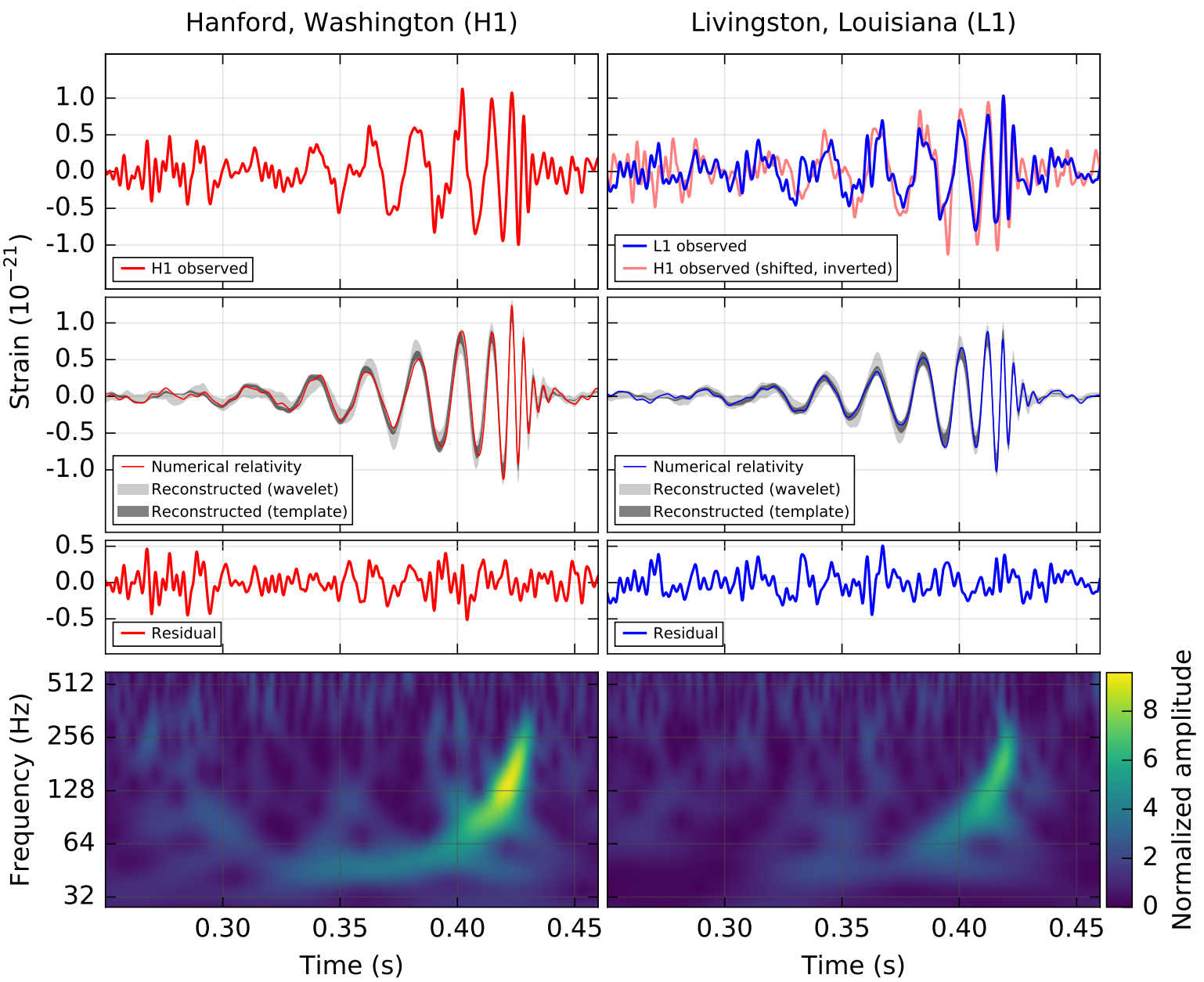
Observation of Gravitational Waves from a Binary Black Hole Merger



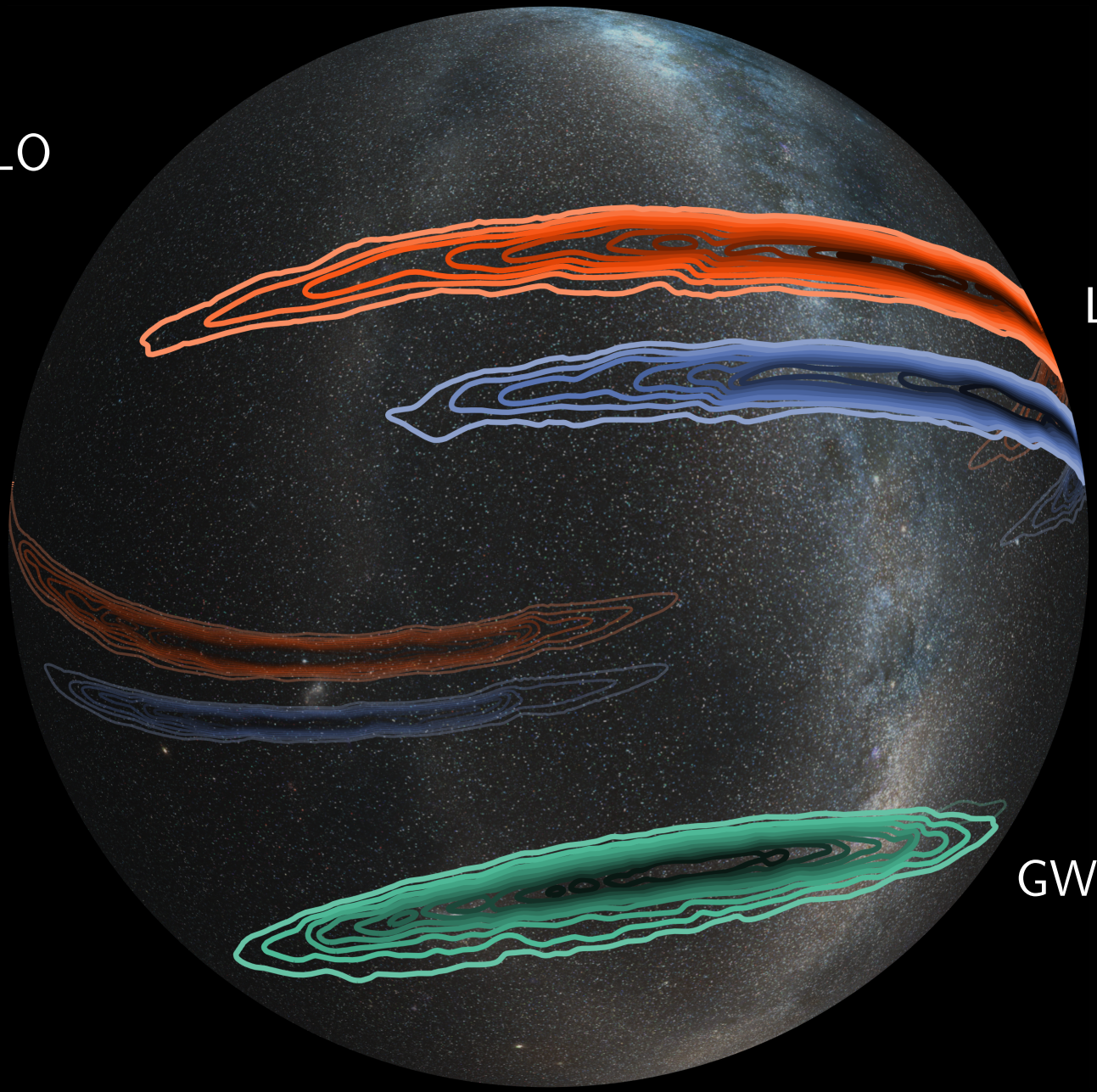
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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.

`https://papers.ligo.org/`

GW150914 – Observed strain

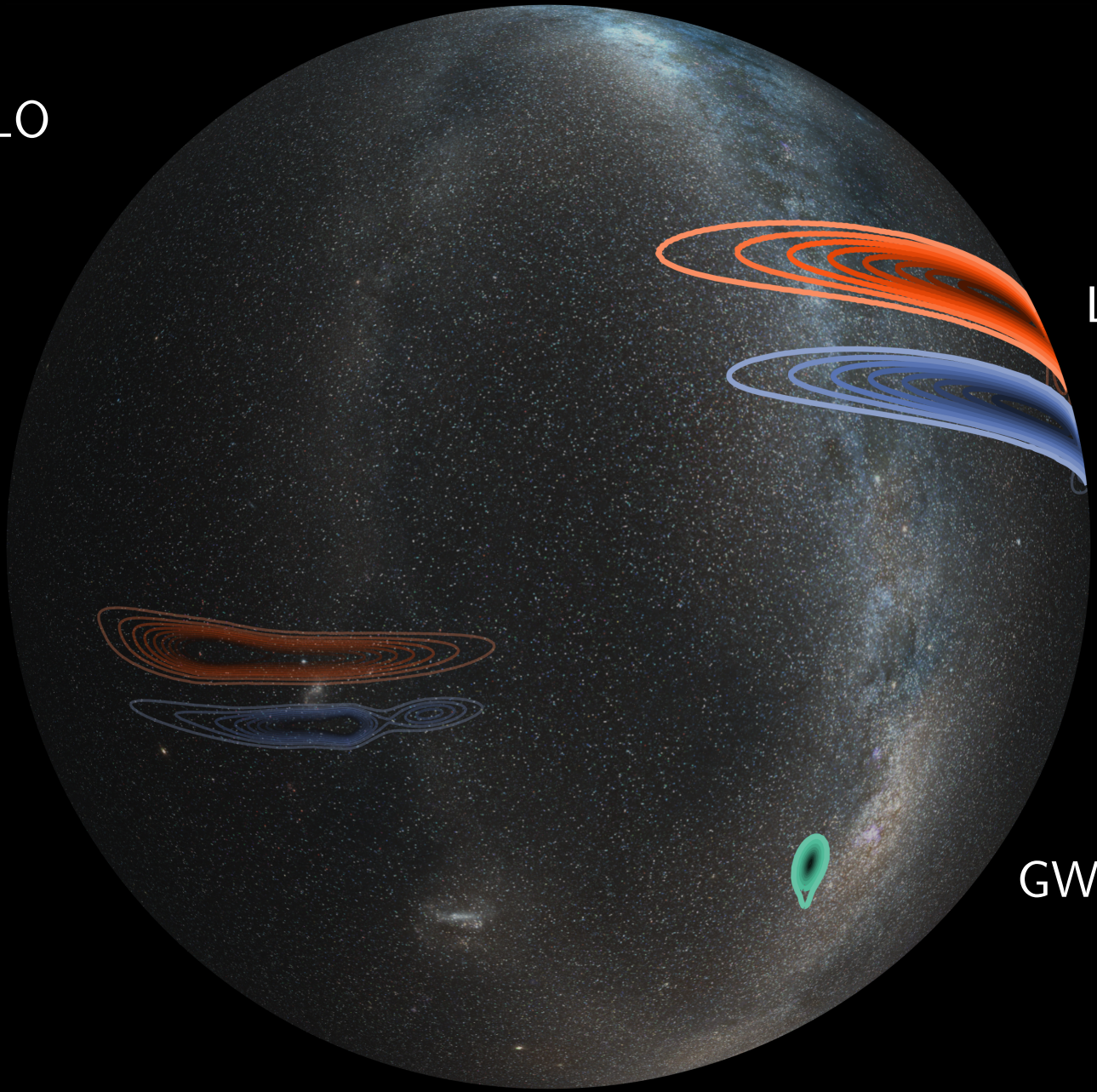


Adding detectors to the network...

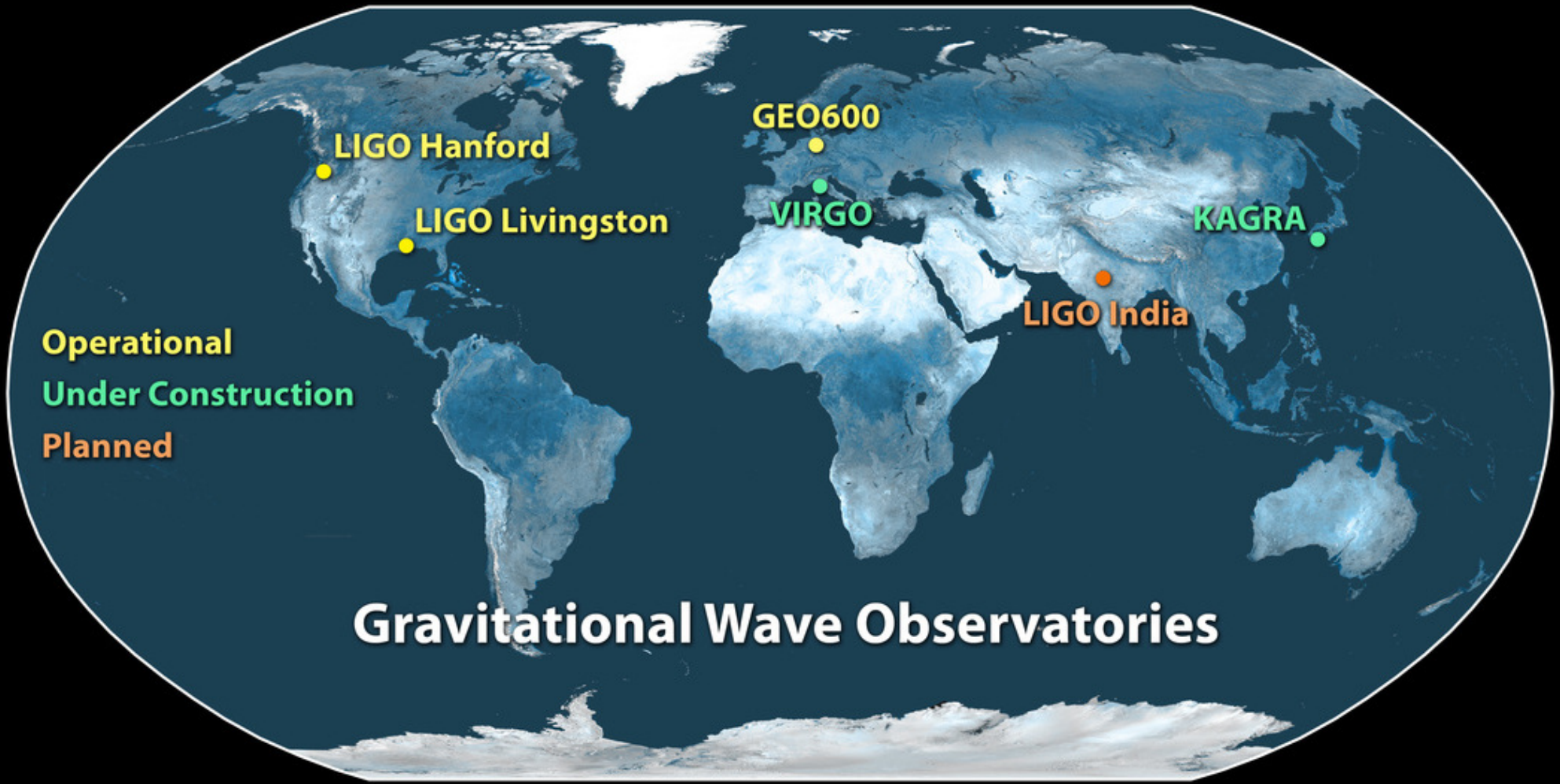


Adding detectors to the network...

LHO + LLO
+ Virgo

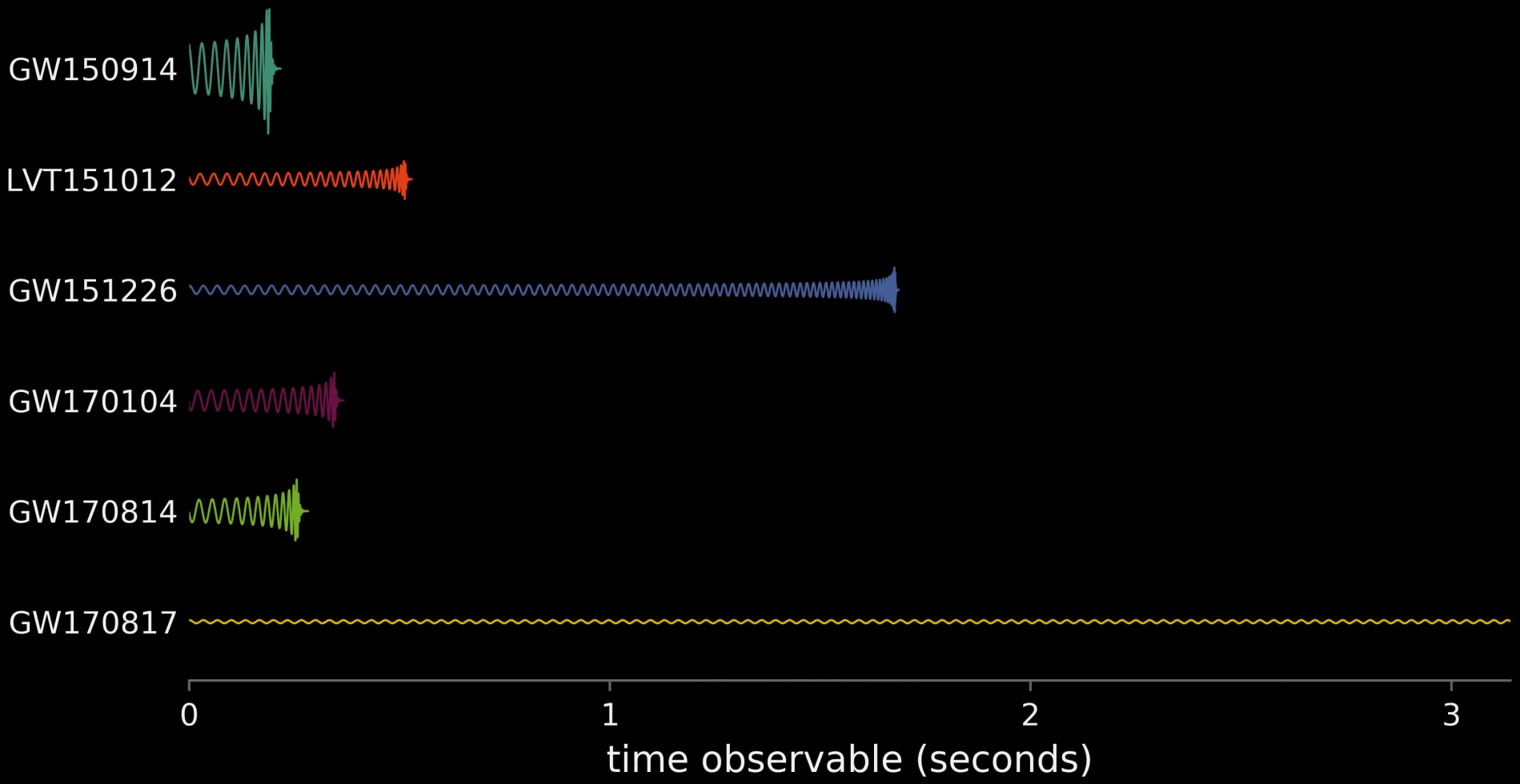


World-wide network needed for better sky localization



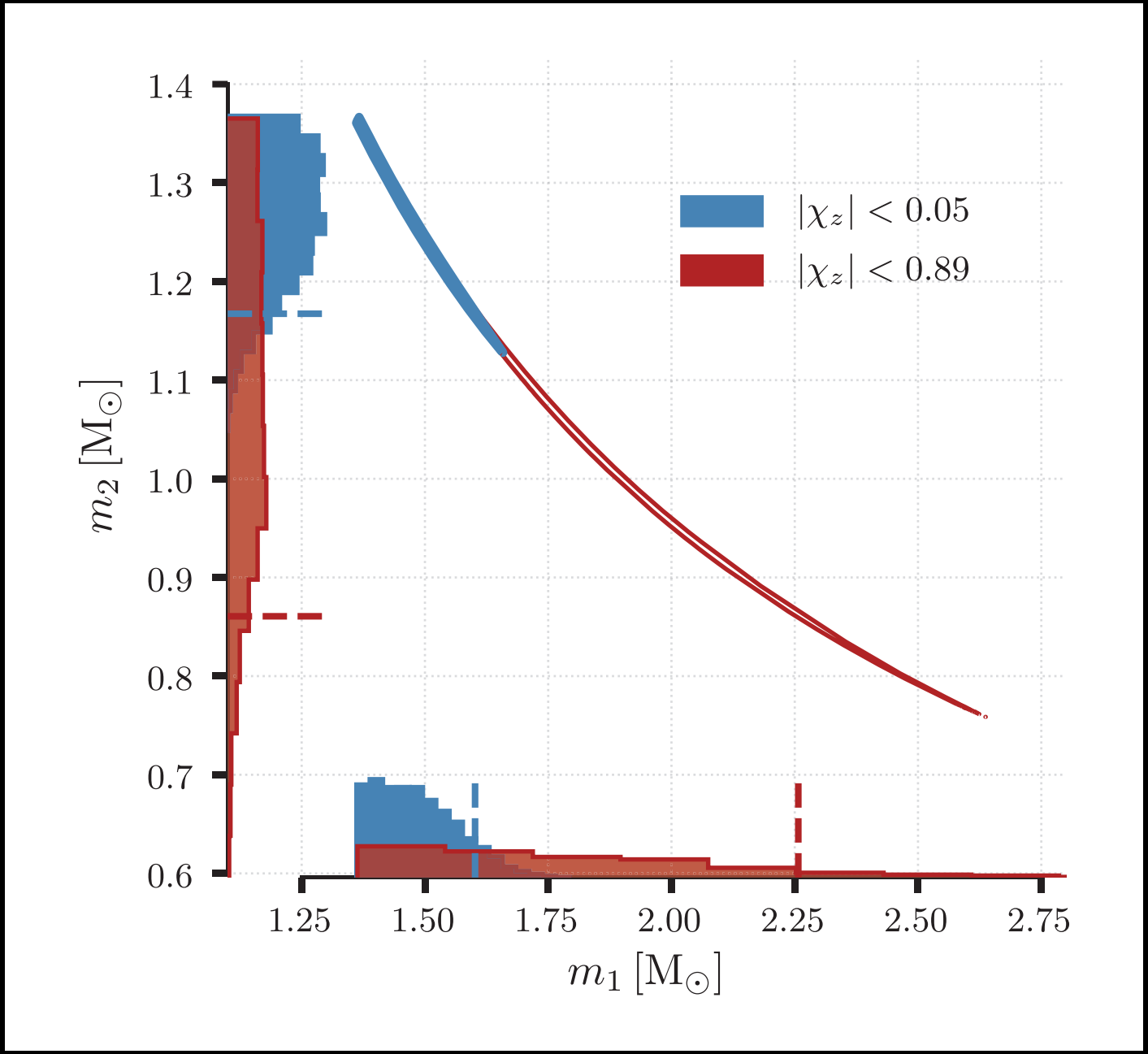
GW170817

GW170817 timeseries relative to past events

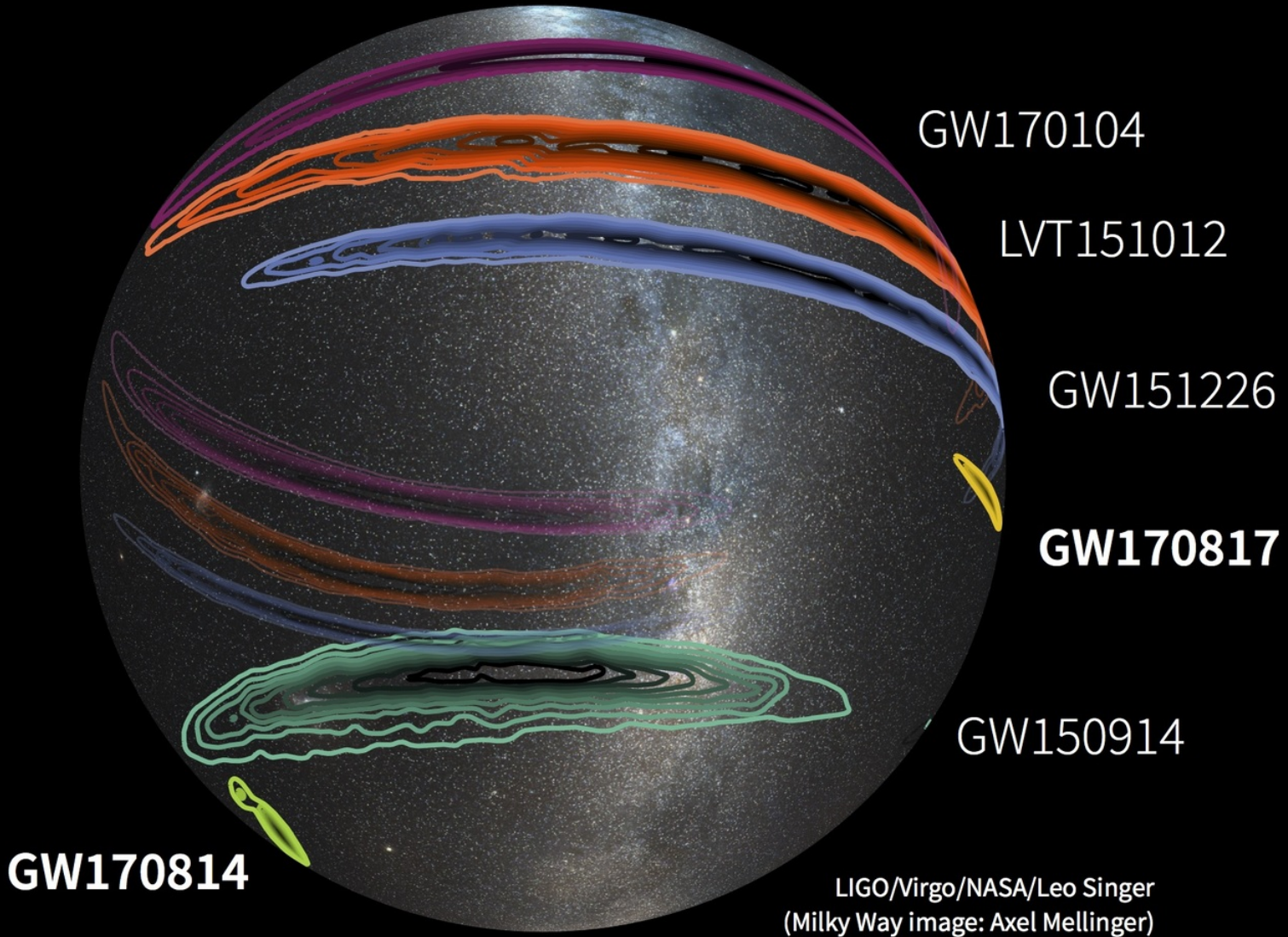


LIGO/University of Oregon/Ben Farr

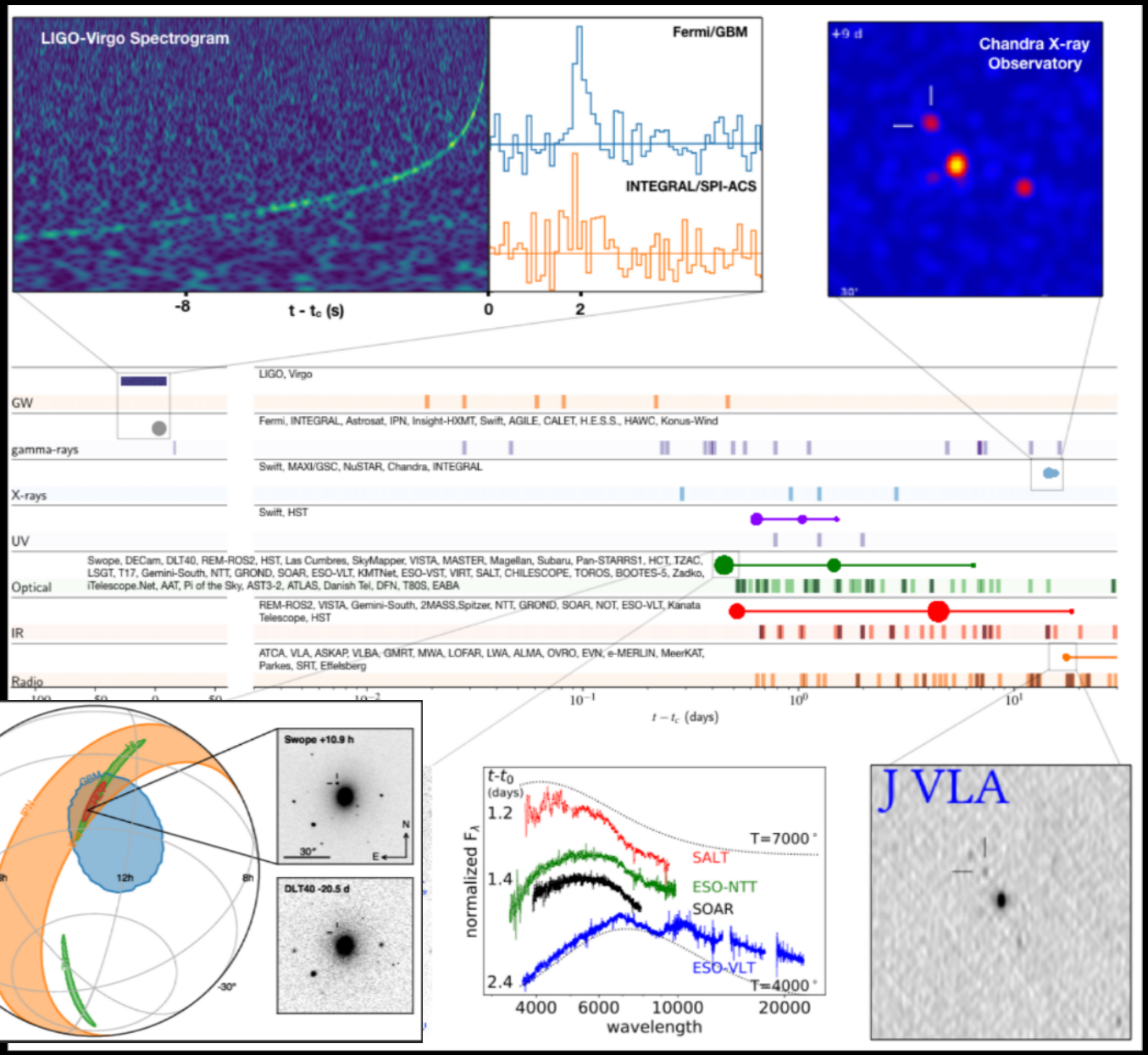
GW170817 progenitor masses



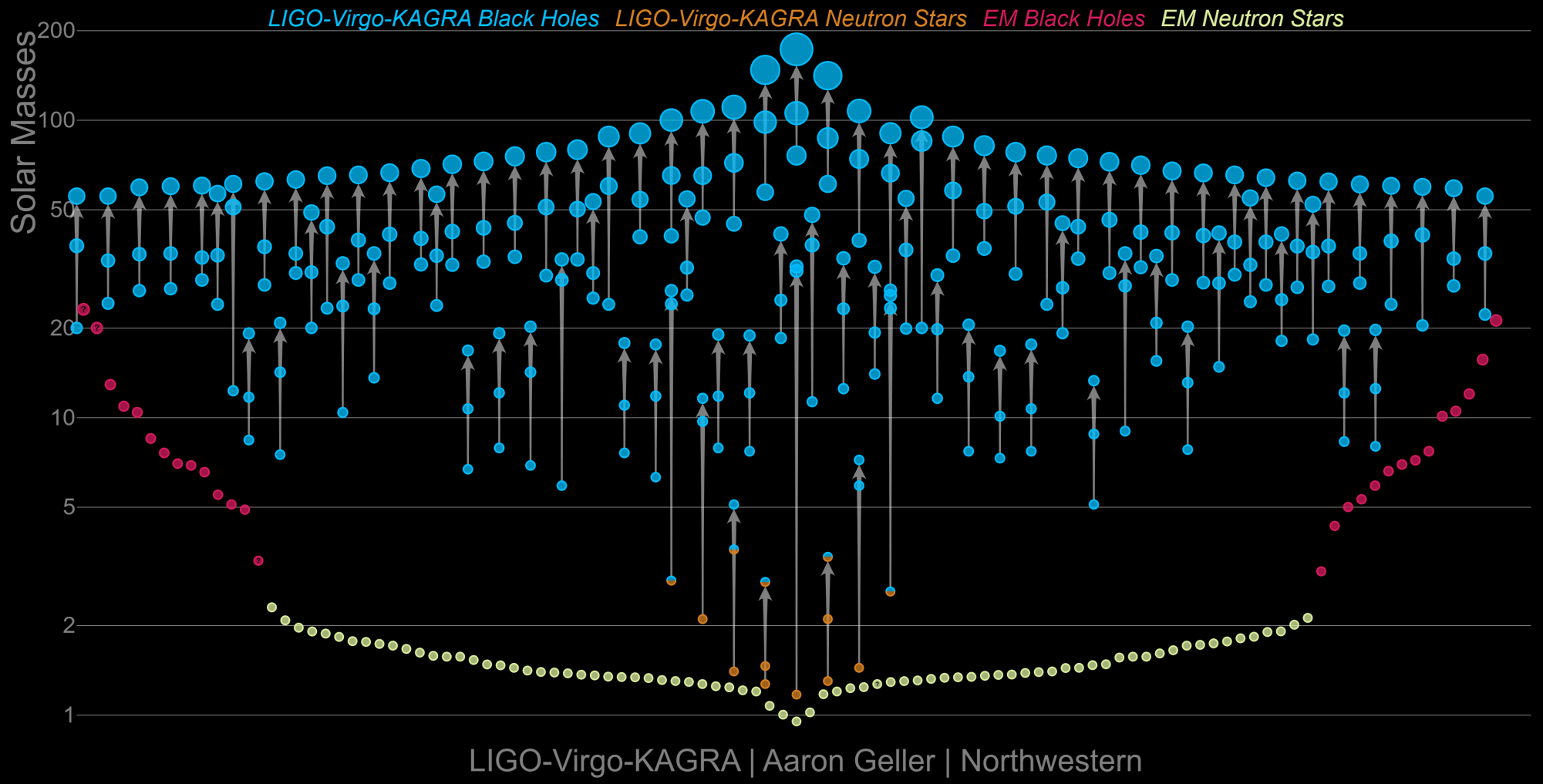
Very small sky localization region



Multi-messenger Observations of a Binary Neutron Star Merger



Masses in the Stellar Graveyard



https://media.ligo.northwestern.edu/gallery/mass-plot