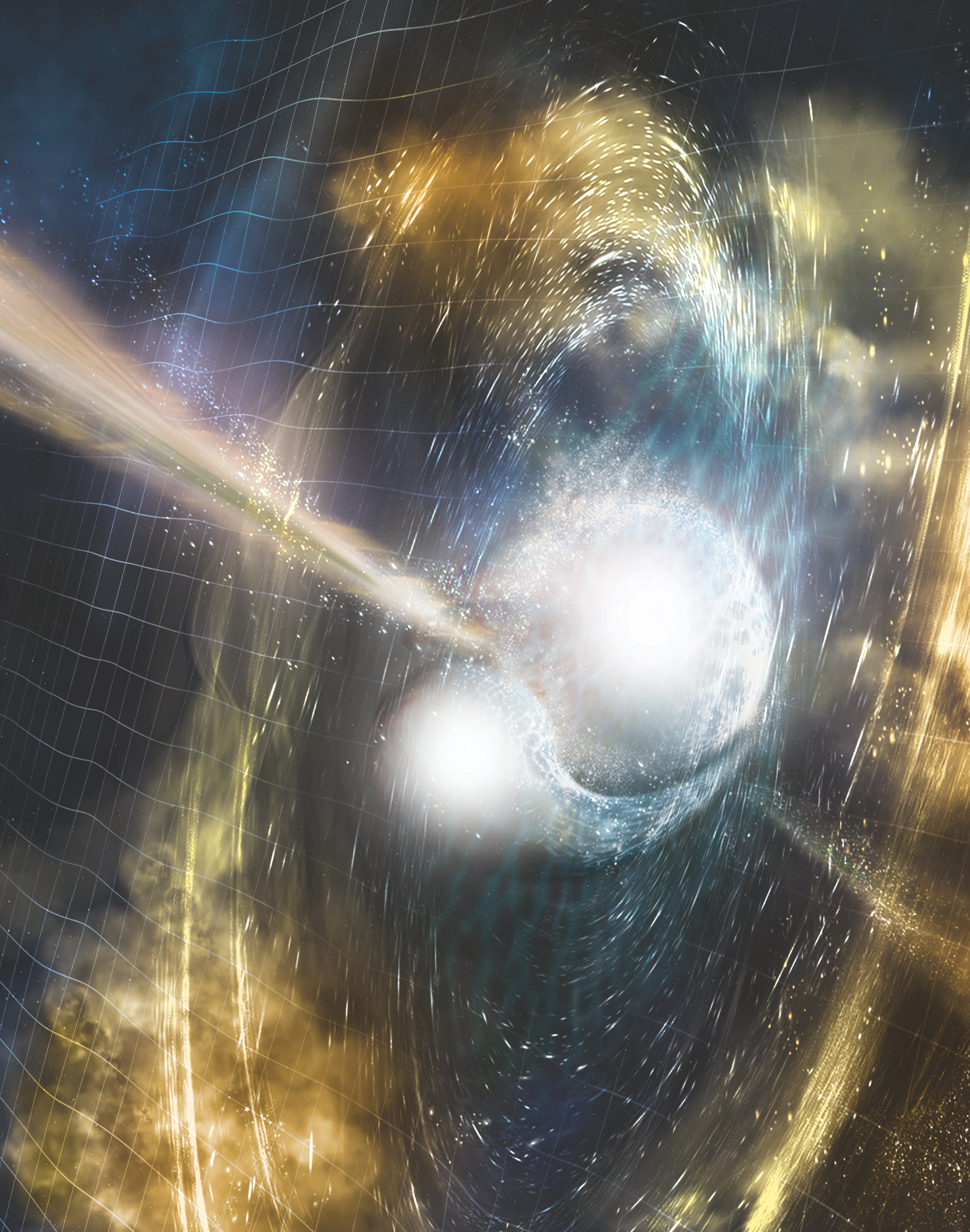
Advanced LIGO:
Today and Tomorrow



Brian Lantz

work by the LSC & Virgo

May 27, 2020

Ph. 364

G20000830

LIGO Scientific Collaboration

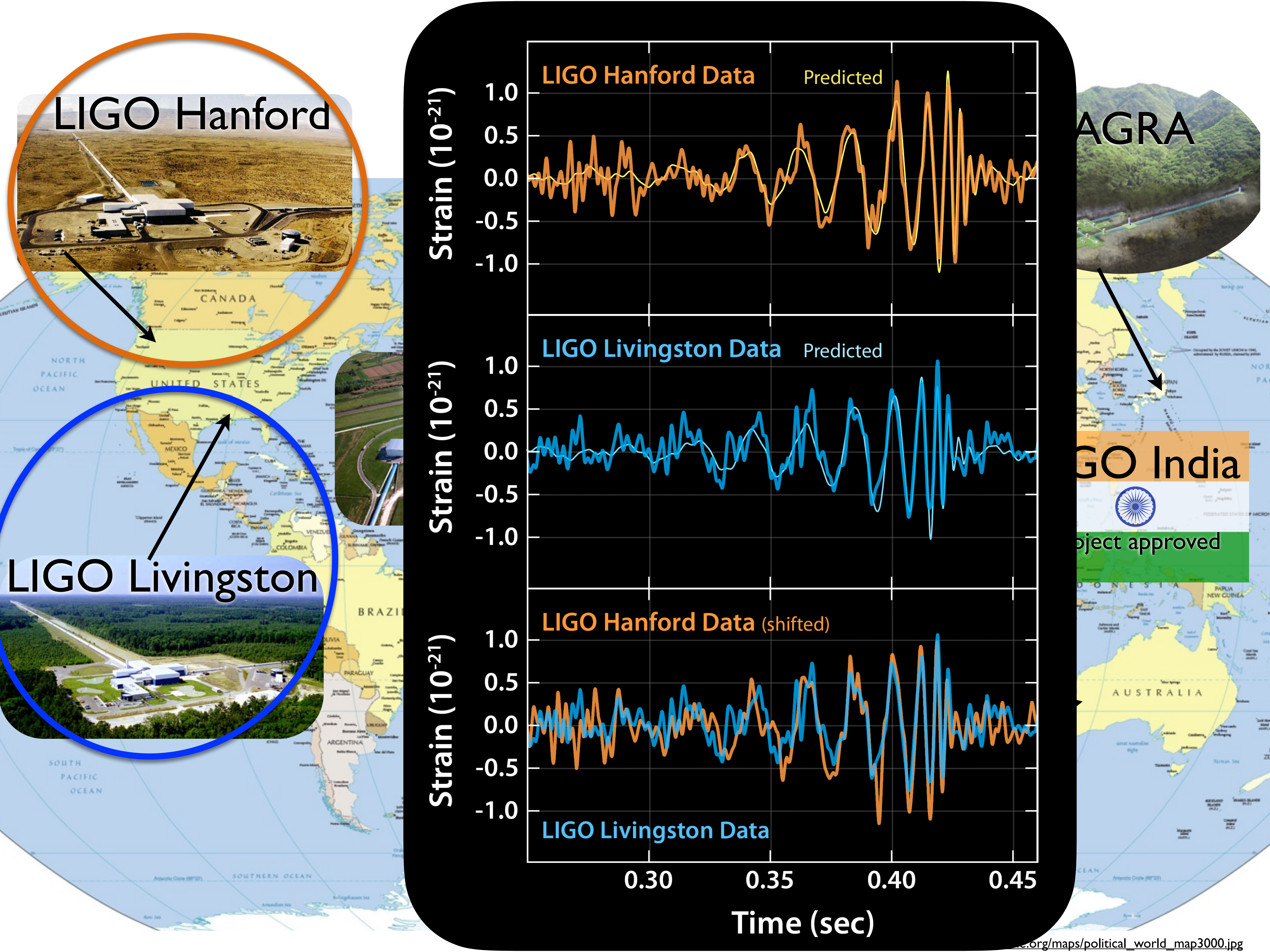
LIGO

LSC

Caltech
American University Washington, DC
Andrews University
Washington State University
California State University Fullerton
PennState
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University 1891
The University Of Sheffield.
University of Maryland
indigo
Texas Tech University
Hillsdale College
Montclair State University
清華大学 Tsinghua University
Universitat de les Illes Balears
International Institute of Physics
Cal State LA
Bellevue College
Montana State University
University of Cambridge
University of Southampton
Université de Montréal
Monash University
Polytechnique Montréal
The University of Adelaide Australia
NCSA
W Bothell
Michigan
University of Wisconsin Milwaukee
Trinity University
Australian National University
UWS University of the West of Scotland
University of Strathclyde
University of Glasgow
Indian Institute of Technology Madras
Columbia University in the City of New York
Lomonosov Moscow State University
Syracuse University
OzGrav
Cardiff University Prifysgol Caerdydd
The University of Western Australia
R·I·T
Sonoma State University
University of Minnesota
Carleton College
RRCAT
Cornell University
NASA
The University of Chicago
IIT Hyderabad
University of Washington
東京大学 The University of Tokyo
Università degli Studi del Sannio
LSU Louisiana State University
Colorado State University
Charles Sturt University
Marshall Space Flight Center
cmi Chennai Mathematical Institute
ICTS International Centre for Theoretical Sciences
Tata Institute of Fundamental Research
University of Birmingham
Georgia Institute of Technology
Korean Gravitational-Wave Group
ACIGA
UH Universität Hamburg
Der Forschung | Der Lehre | Der Bildung
The University of Melbourne
Embry-Riddle Aeronautical University
Villanova University
Whitman College
Northwestern
UF University of Florida
tifr
IUCAA
UTRGV
University and Institute of Advanced Research
The Puri Foundation for Education in India
Swinburne University of Technology
The University of Mississippi
INPE
GEO 600
Max Planck Institute for Gravitational Physics
Albert Einstein Institute
Leibniz Universität Hannover
University of Zurich
IISER Thiruvananthapuram
CITA ICAT
King's College London
IISER Kolkata
NASA Goddard Space Flight Center

International Network

map from http://www.nationsonline.org/maps/political_world_map3000.jpg

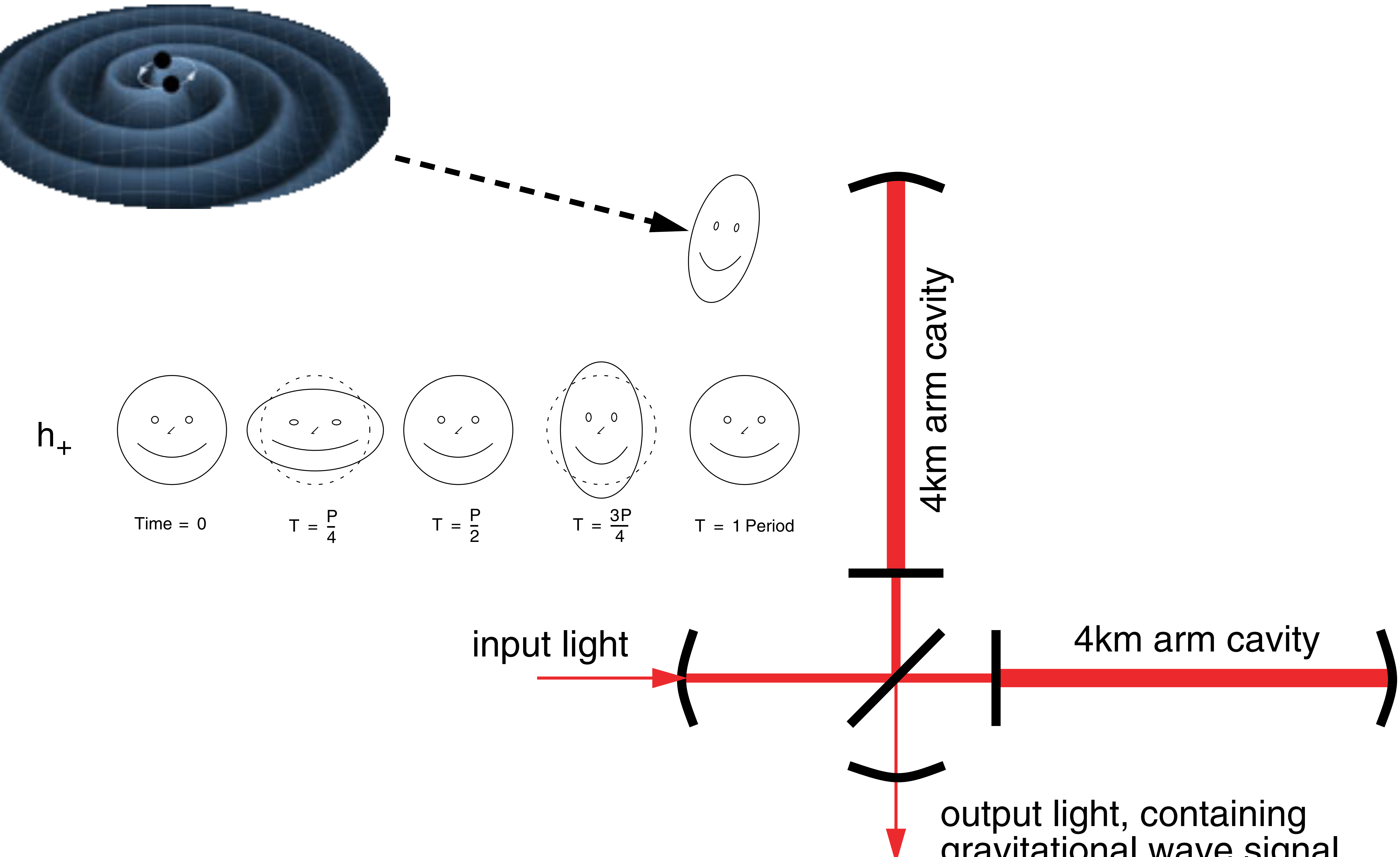


LIGO Hanford
LIGO Livingston
AGRA
GO India
oject approved
CANADA
NORTH PACIFIC OCEAN
UNITED STATES
MEXICO
COLOMBIA
BRAZI
PARAGUAY
ARGENTINA
SOUTH PACIFIC OCEAN
SOUTHERN OCEAN
AUSTRALIA
PAPUA NEW GUINEA
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
e.org/maps/political_world_map3000.jpg

For today

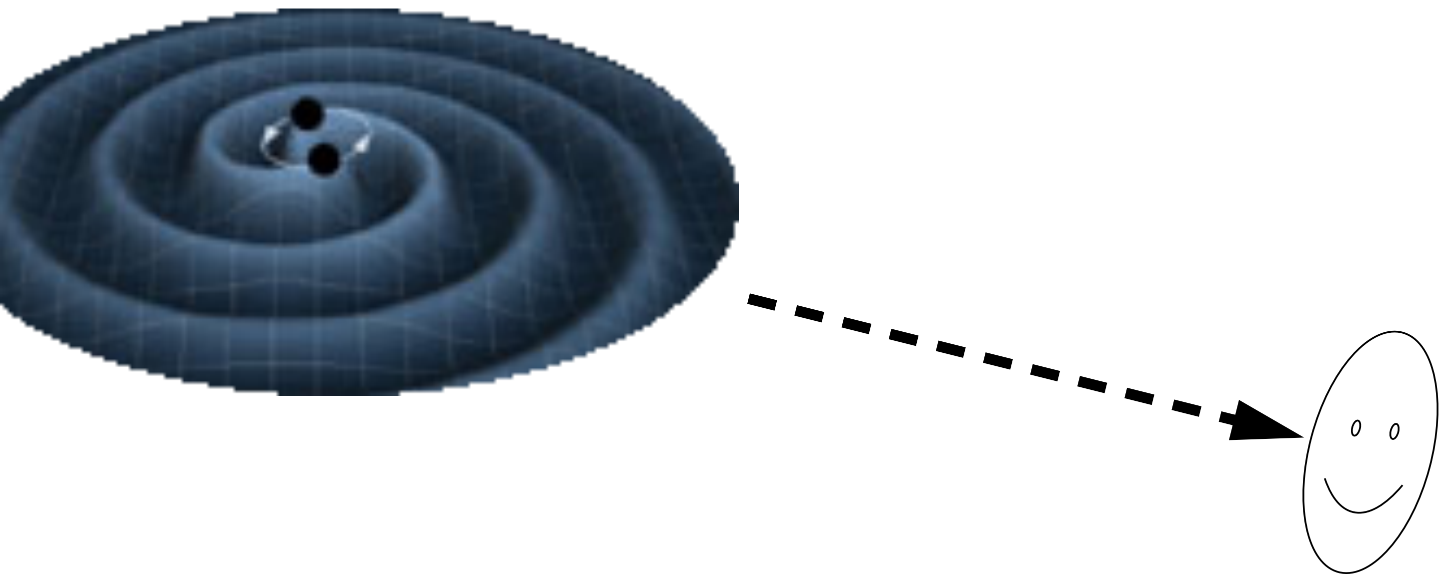
- A bit about how the detector works
- Measurements of the Hubble constant
- How improvements to the detector network lead to improvements in the astrophysics / cosmology.
- More than just range - stability, bandwidth, a good network are also key.
- Finish with advertising for the future

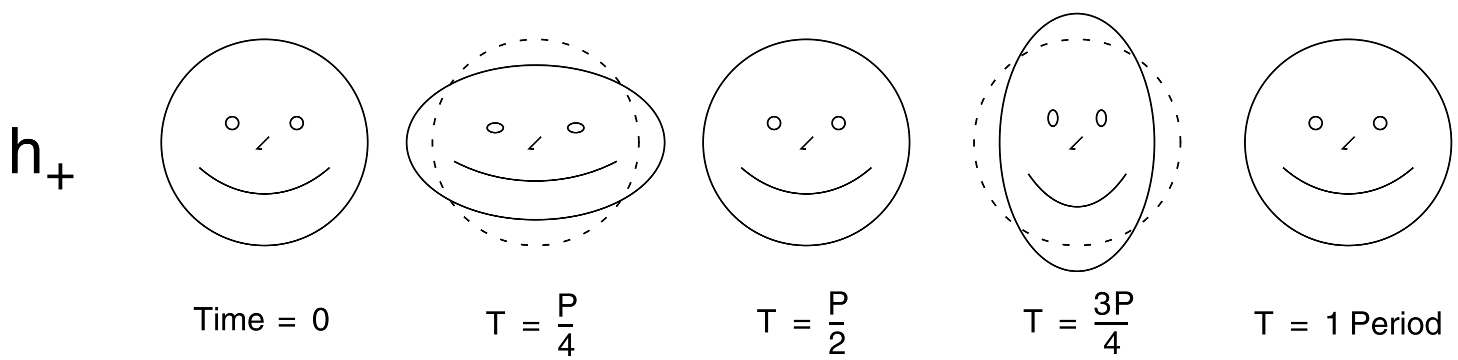
The LIGO concept

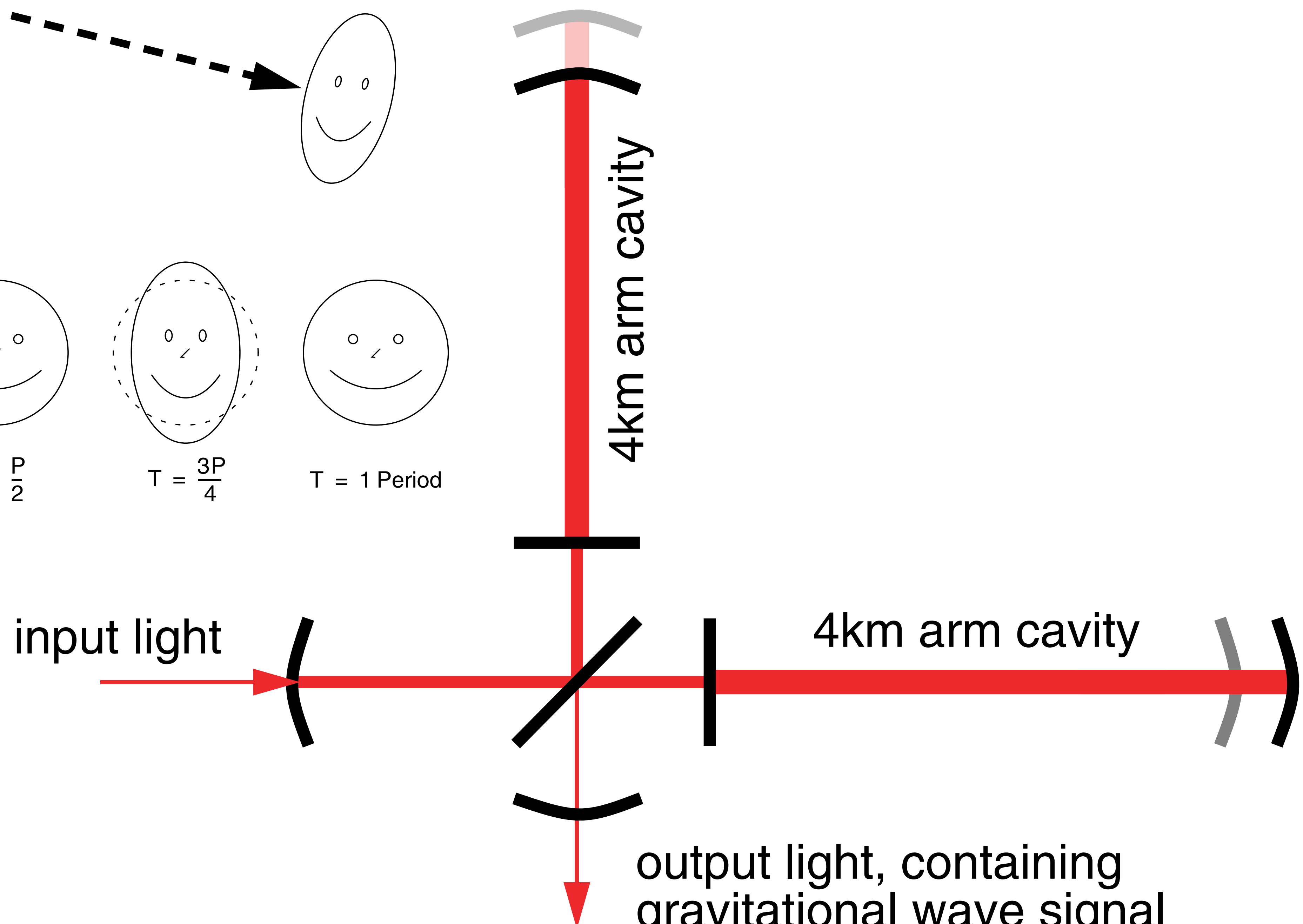


The LIGO concept

It's sort of like this,

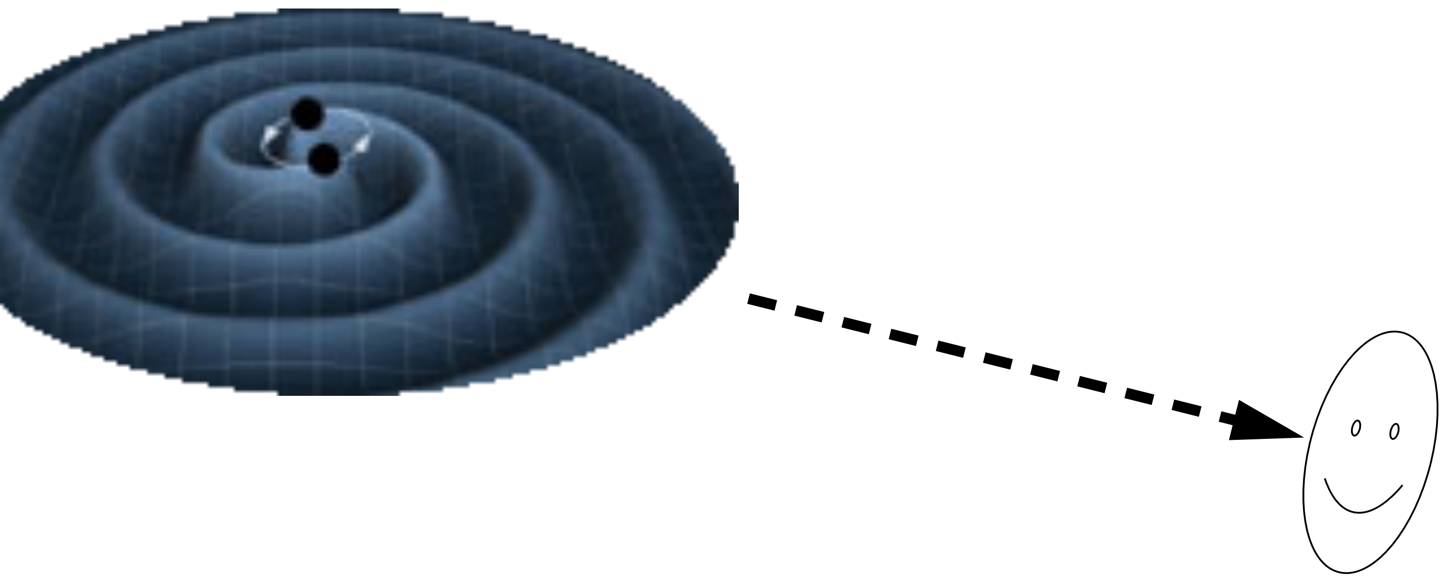


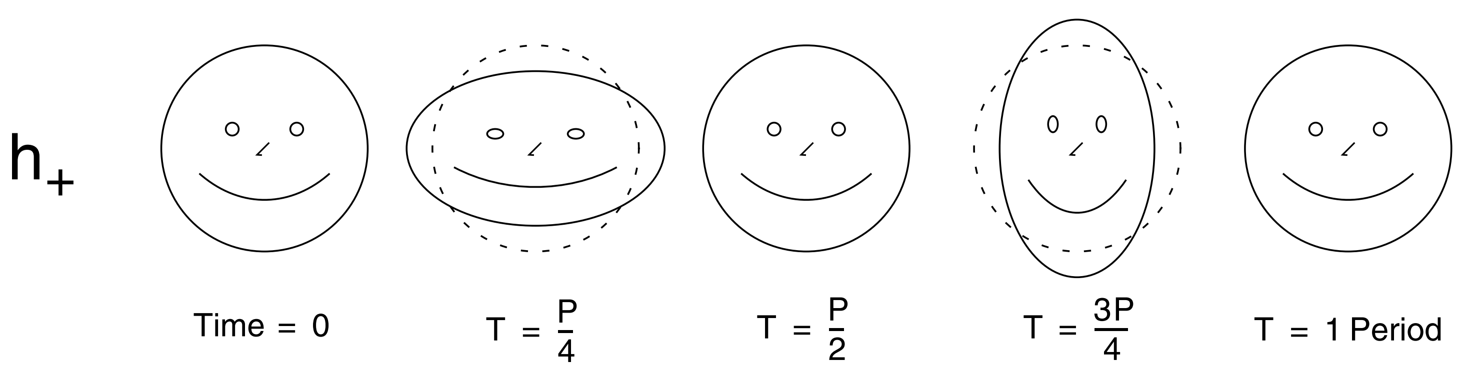


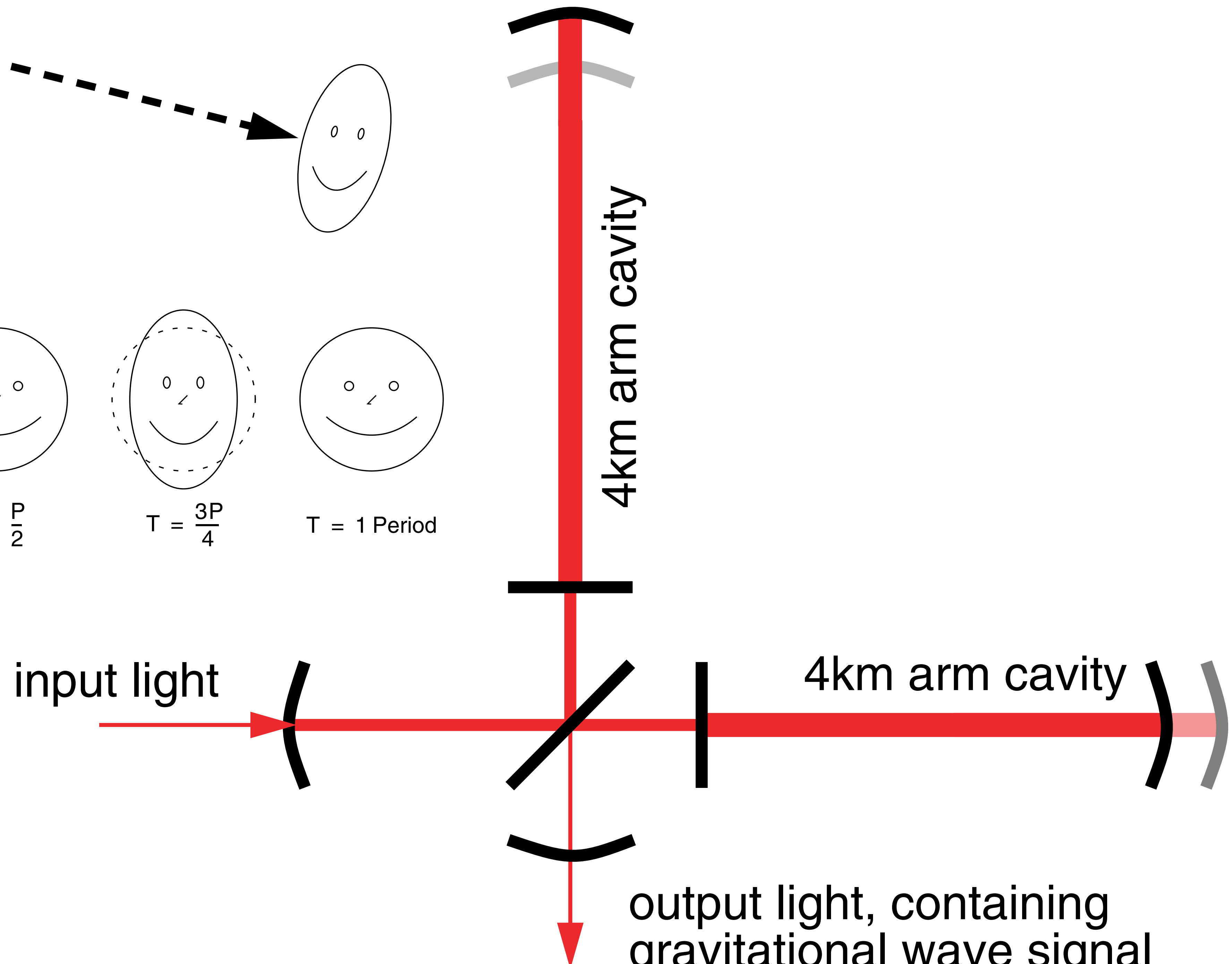


The LIGO concept

It's sort of like this,

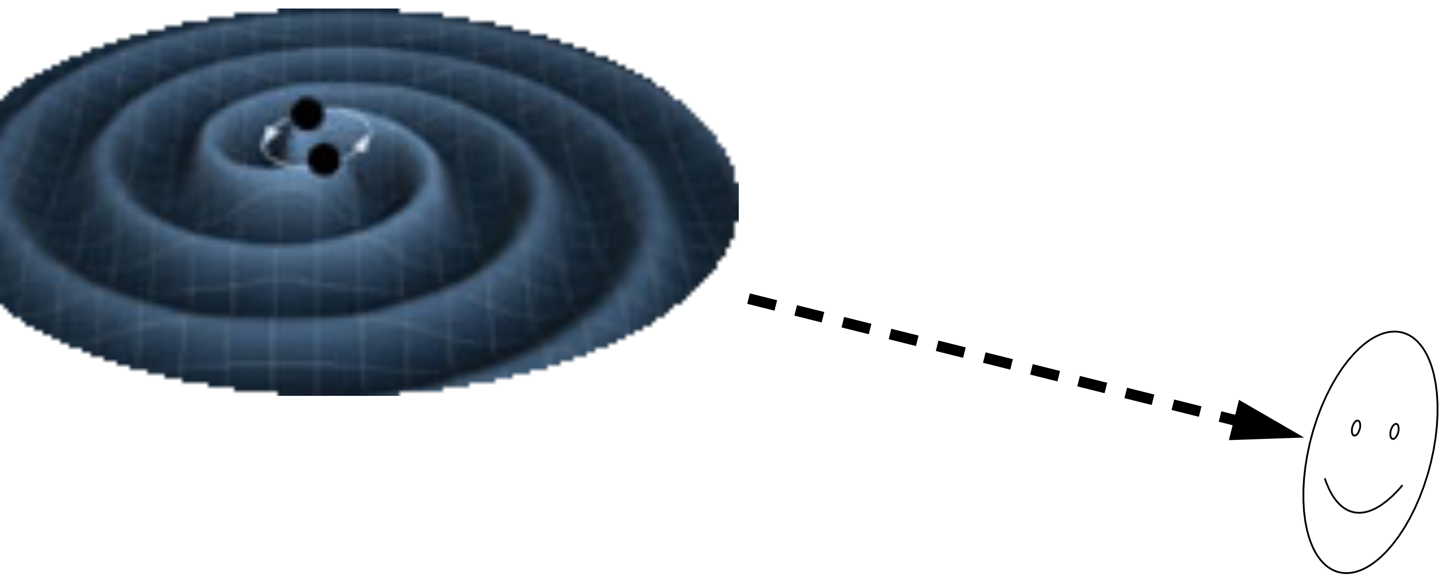


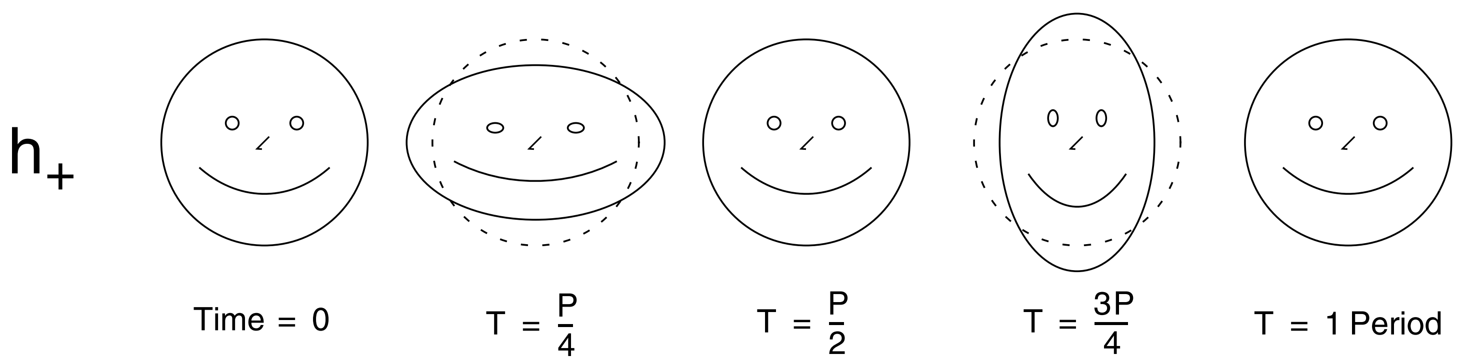


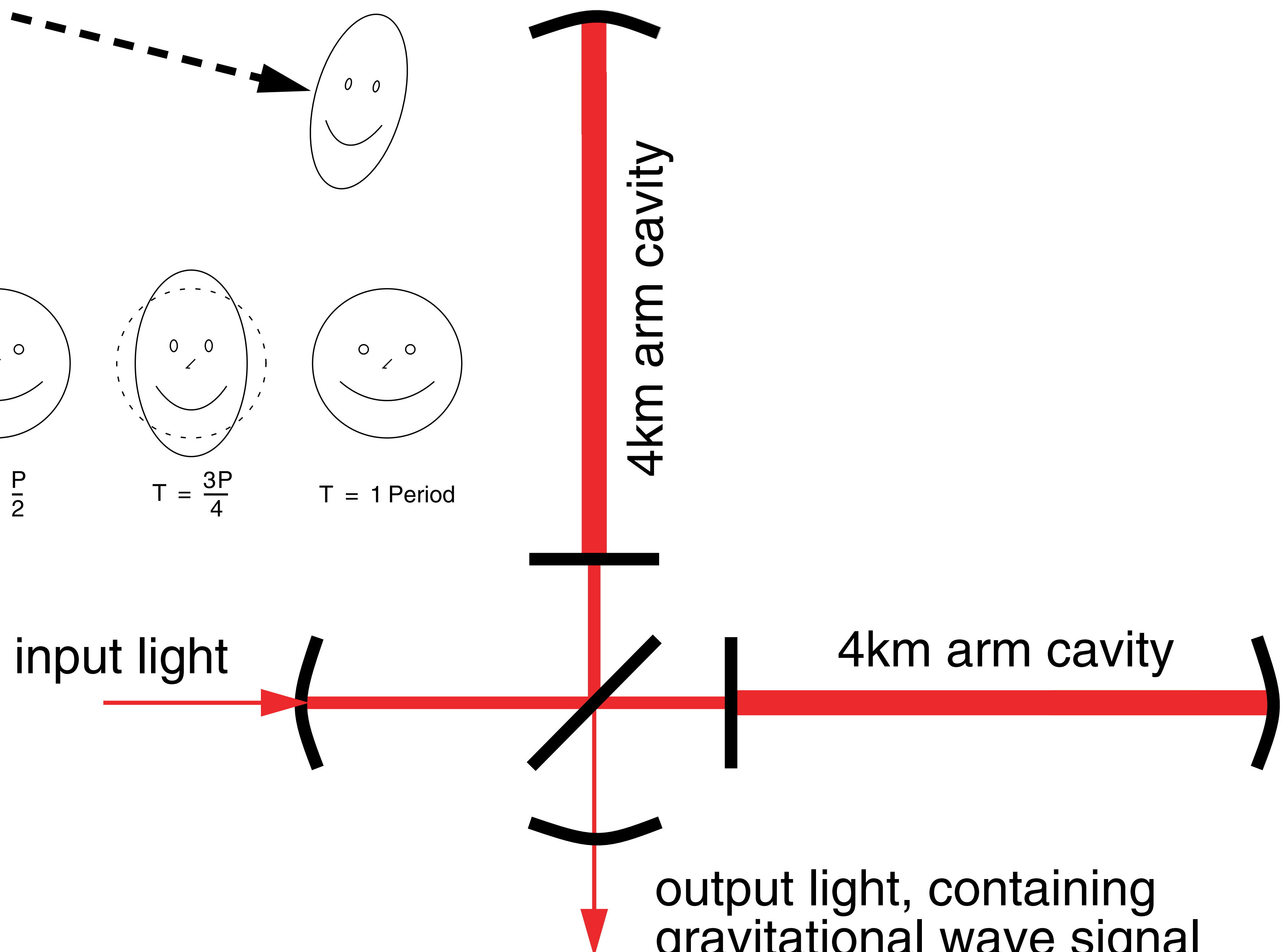


The LIGO concept

It's sort of like this,
except spacetime is stretching,
and the mirrors don't move.





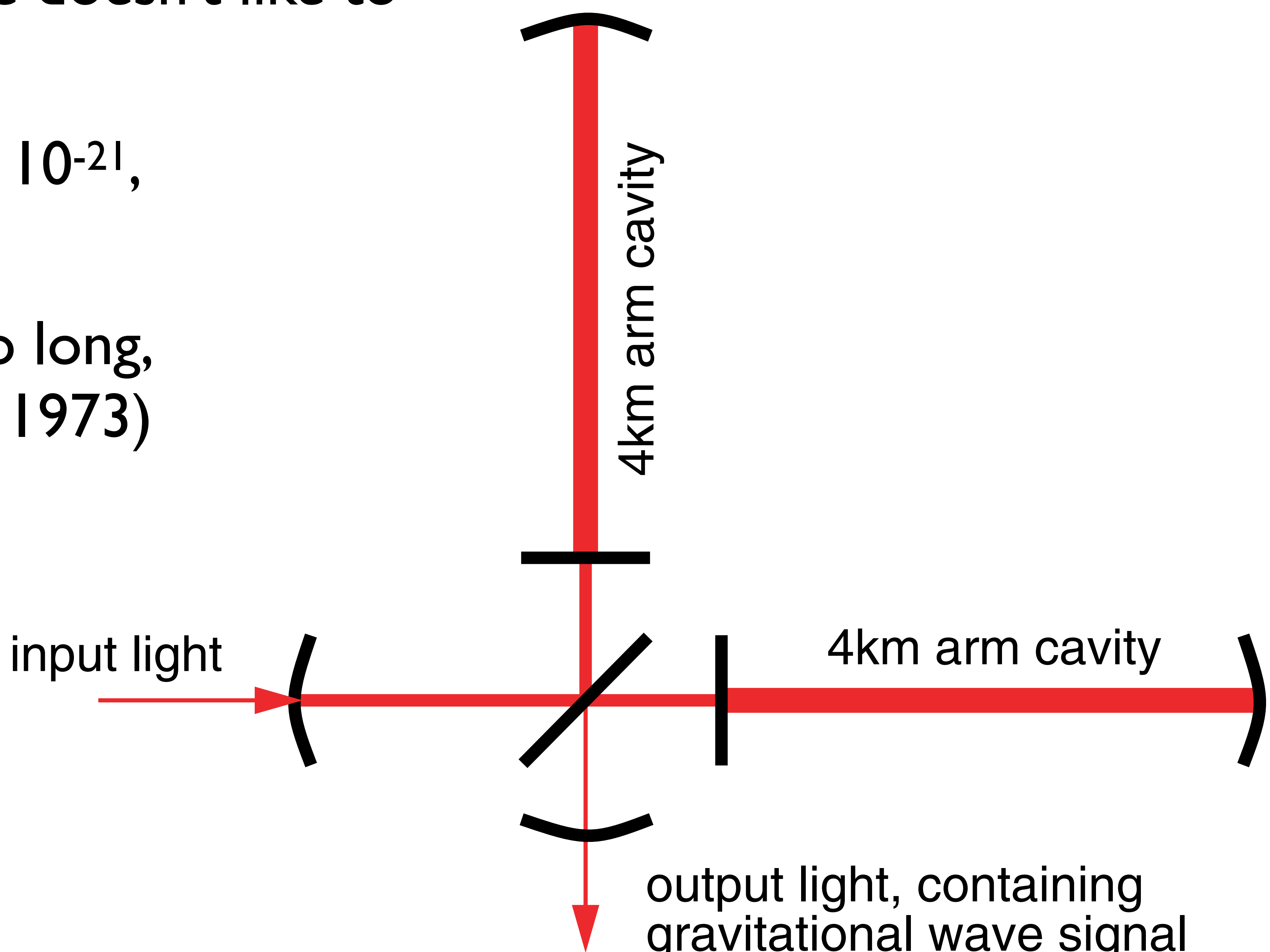


The LIGO concept

Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

(that's why it's taken so long,
Einstein 1916, Weiss 1973)



The LIGO concept

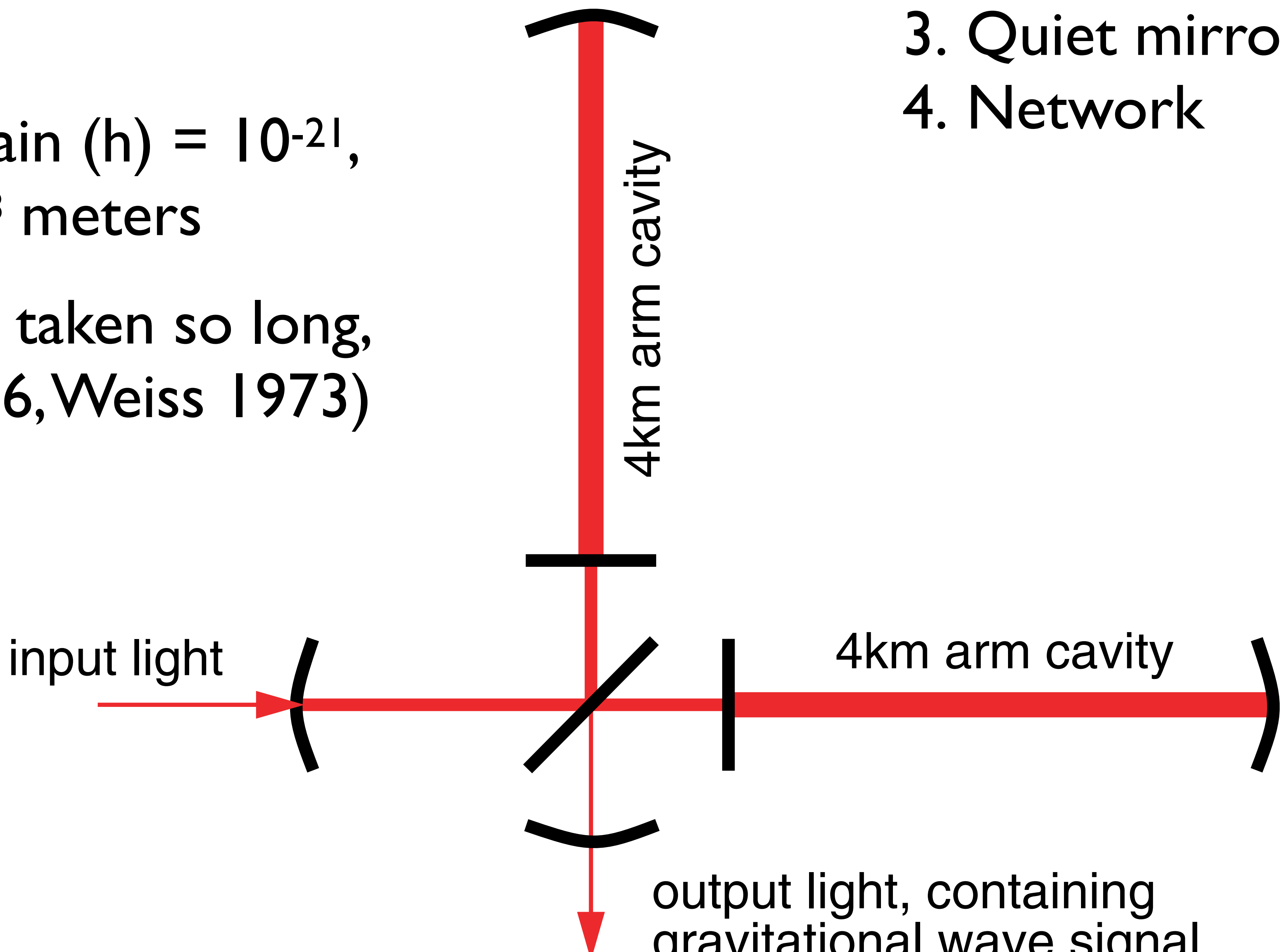
How it really works

Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

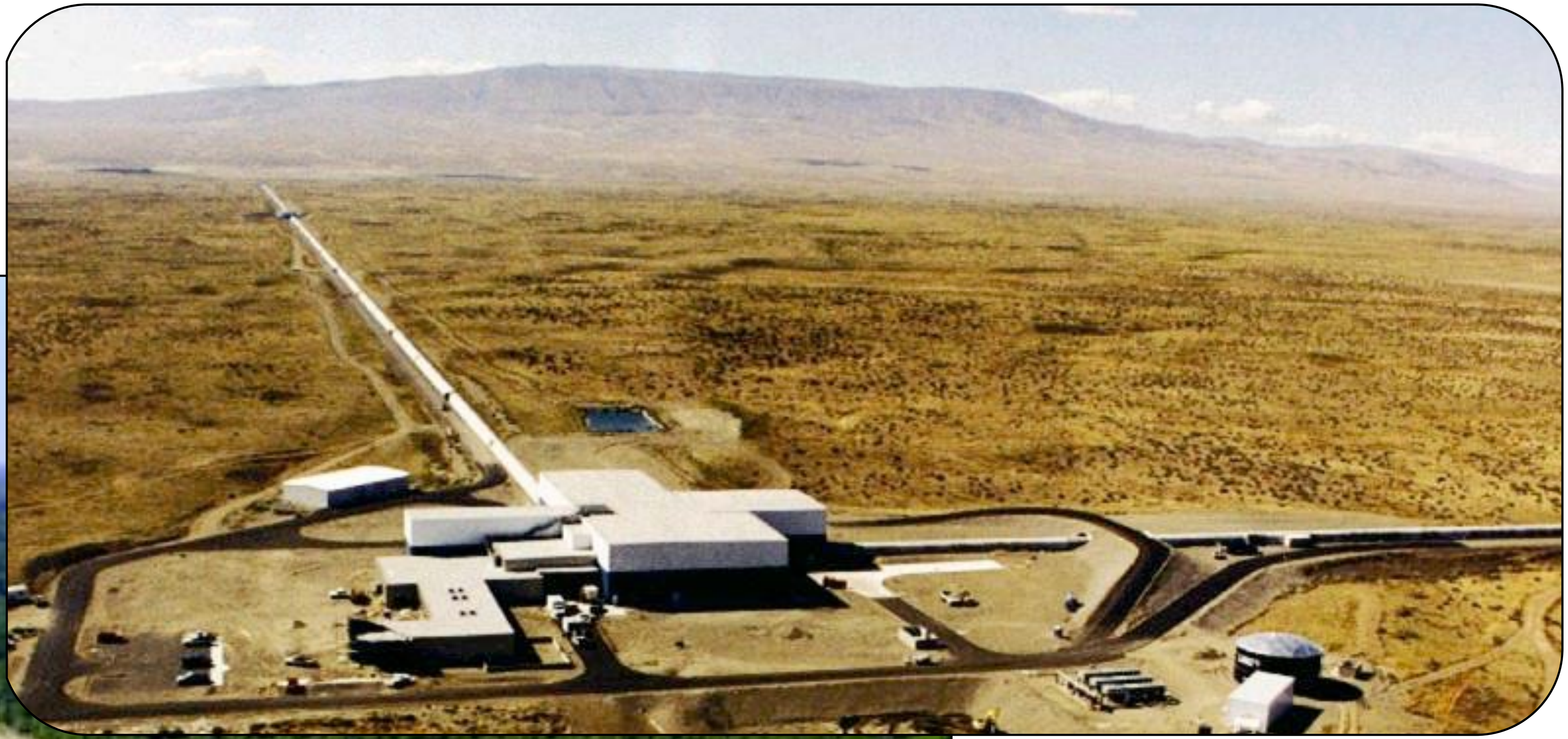
(that's why it's taken so long,
Einstein 1916, Weiss 1973)

1. Long arms
2. Precise measurement
3. Quiet mirrors
4. Network



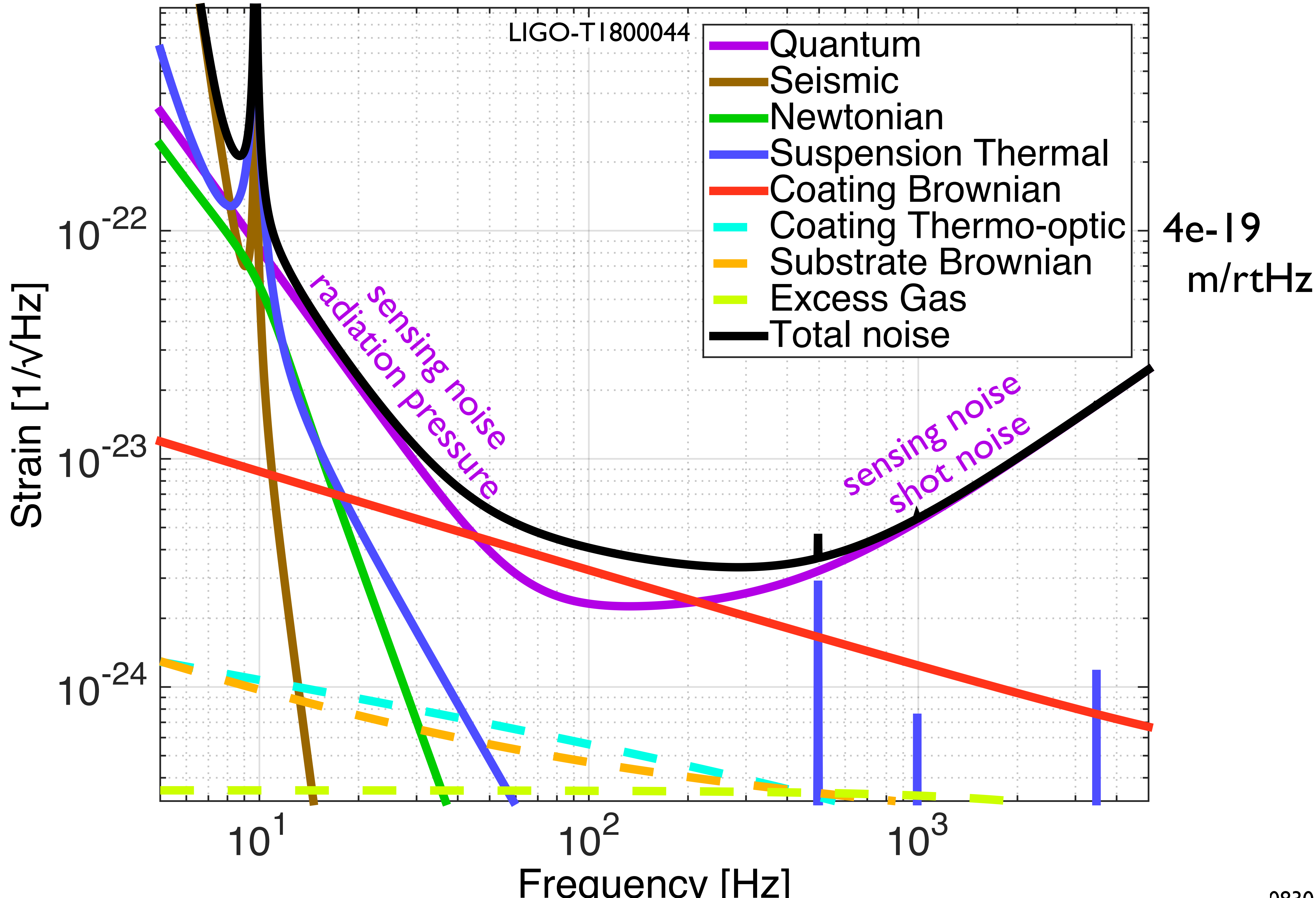
Long arms

Since h = dL/L, more L gives you more dL of signal (below cavity pole)
Many low frequency noise sources are fixed dL of noise.
More L = better signal to noise at low frequency.
World's largest UHV system - each arm is 4 km long, 4 ft. diameter



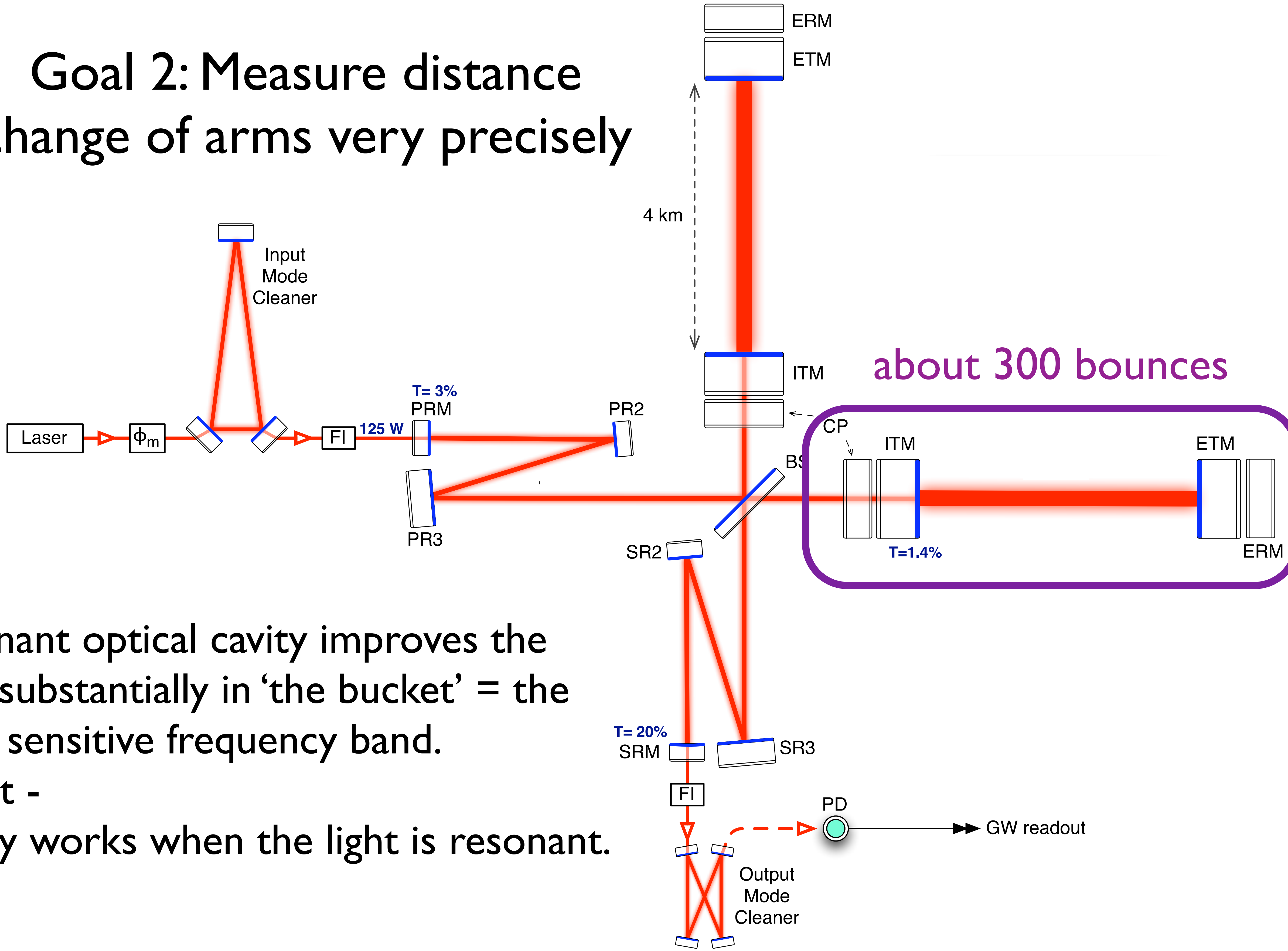
Detector Noise (design)

aLIGO new design curve: NSNS (1.4/1.4 $M_\odot$) 173 Mpc and BHBH (30/30 $M_\odot$) 1606 Mpc



Fabry-Perot arms

Goal 2: Measure distance change of arms very precisely



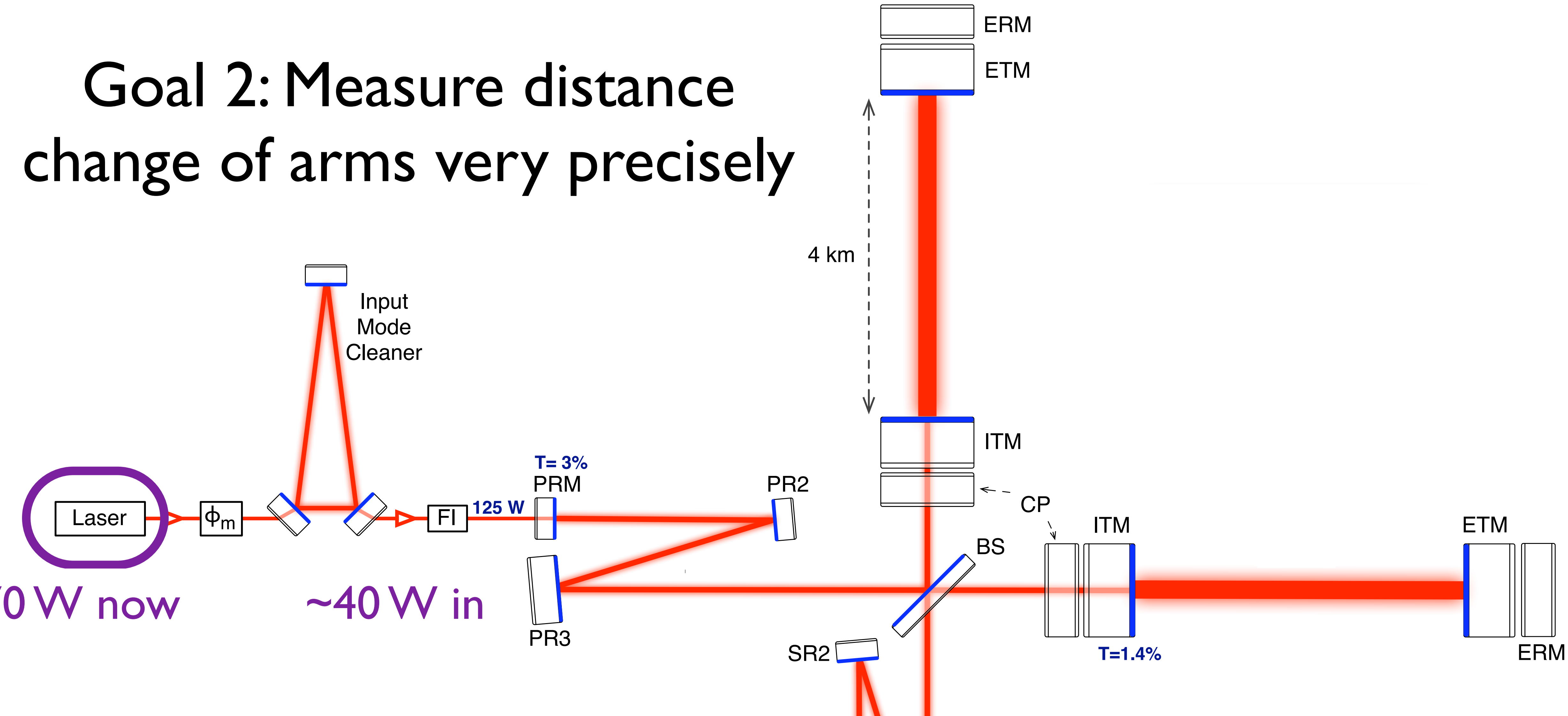
Resonant optical cavity improves the SNR substantially in 'the bucket' = the most sensitive frequency band.

- but -

It only works when the light is resonant.

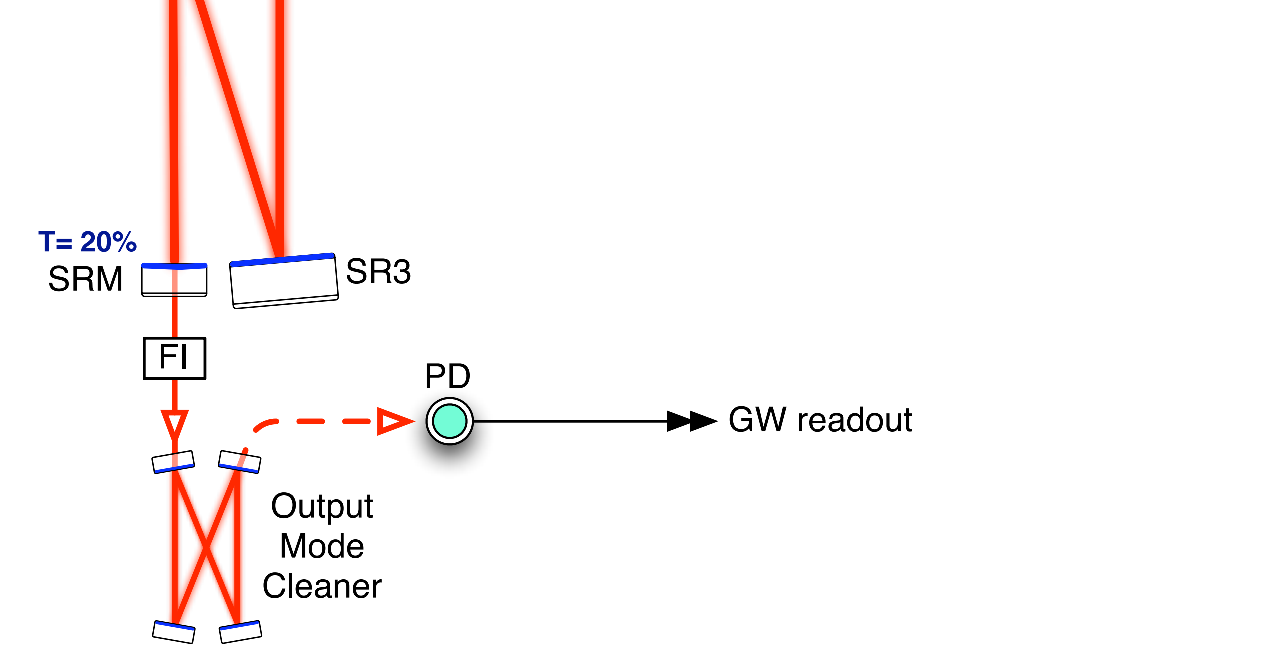
Lots of photons

Goal 2: Measure distance change of arms very precisely



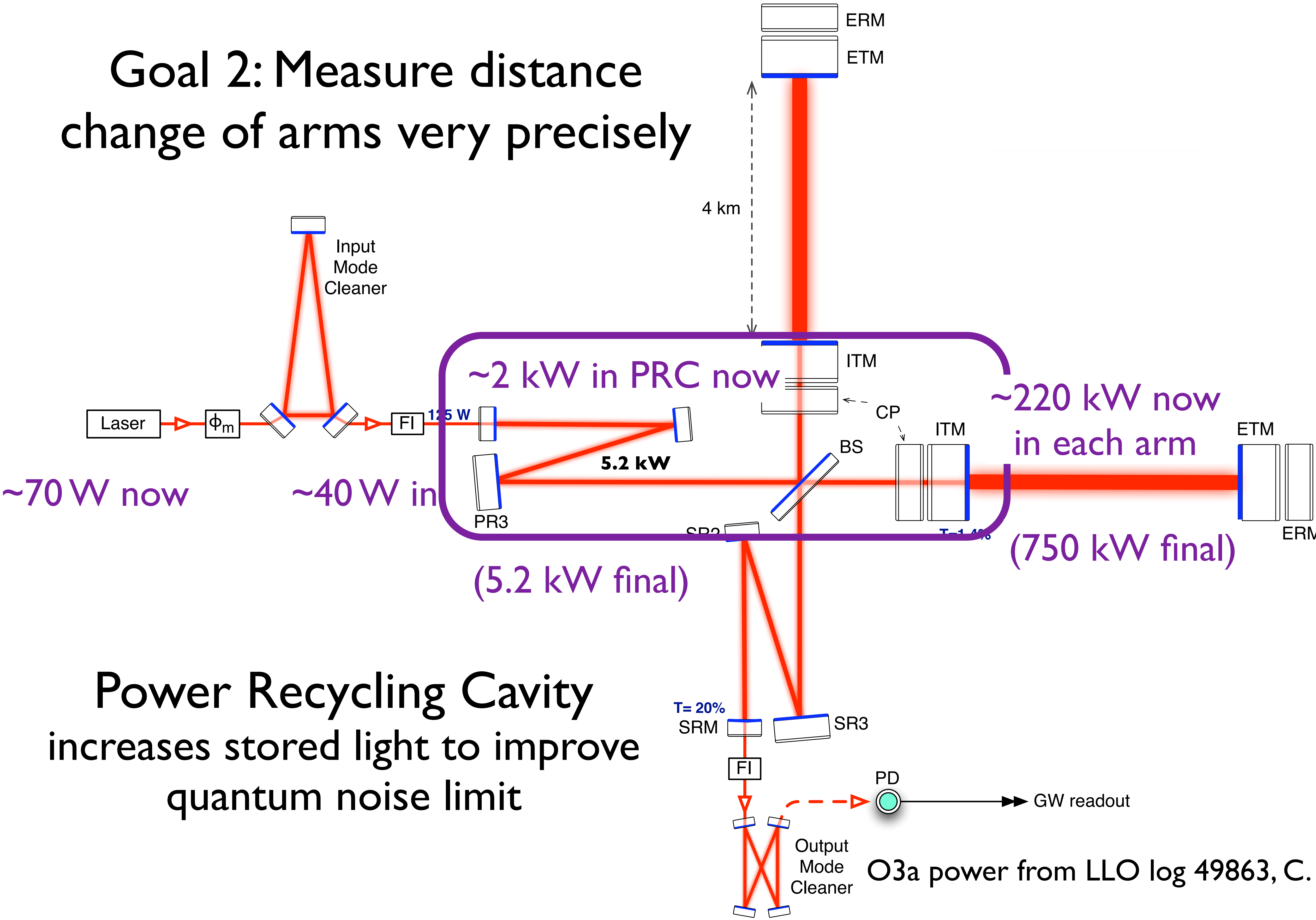
~70 W now

~40 W in



Lots of photons

Goal 2: Measure distance change of arms very precisely



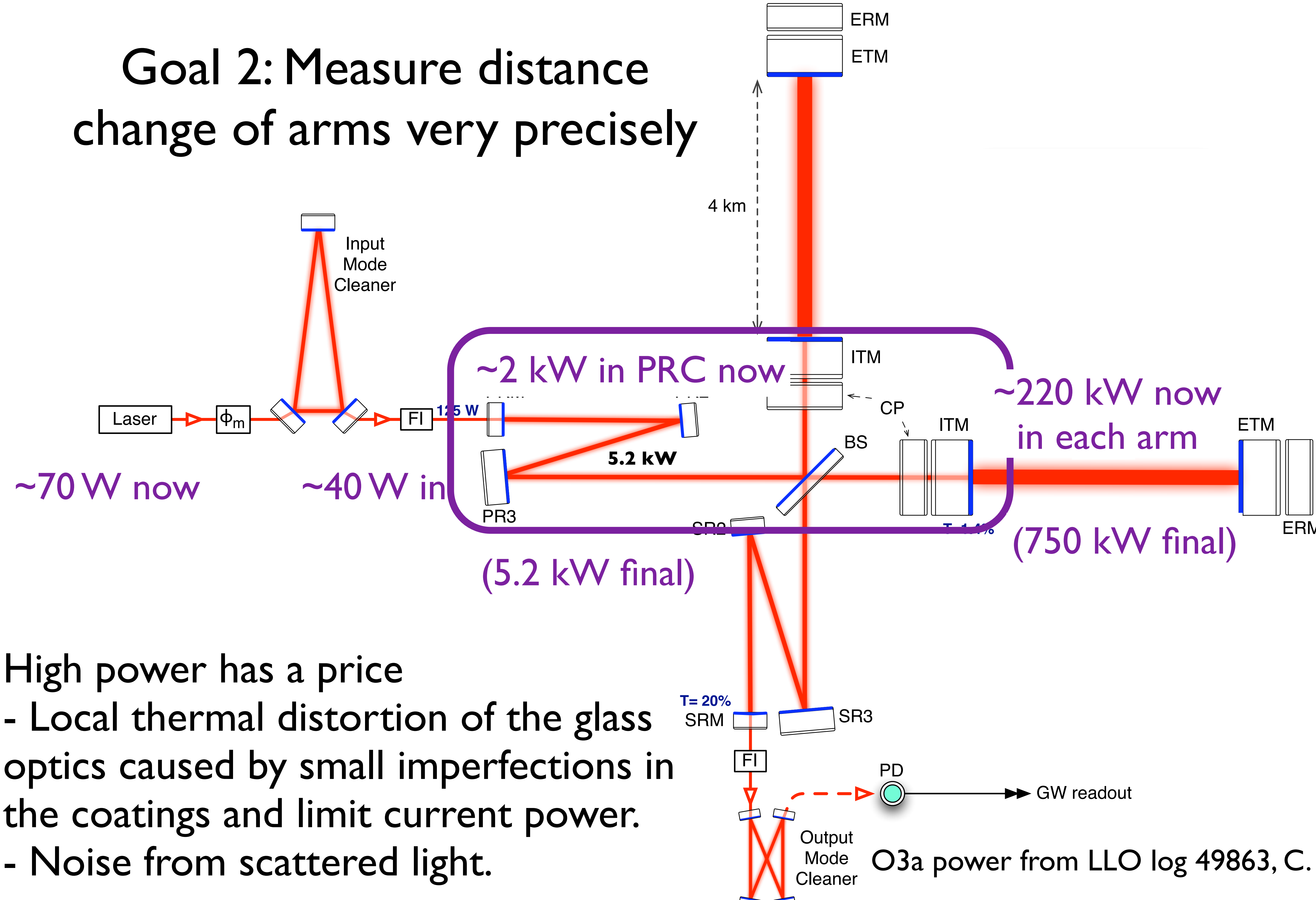
Power Recycling Cavity

increases stored light to improve quantum noise limit

O3a power from LLO log 49863, C. Blair

Lots of photons

Goal 2: Measure distance change of arms very precisely

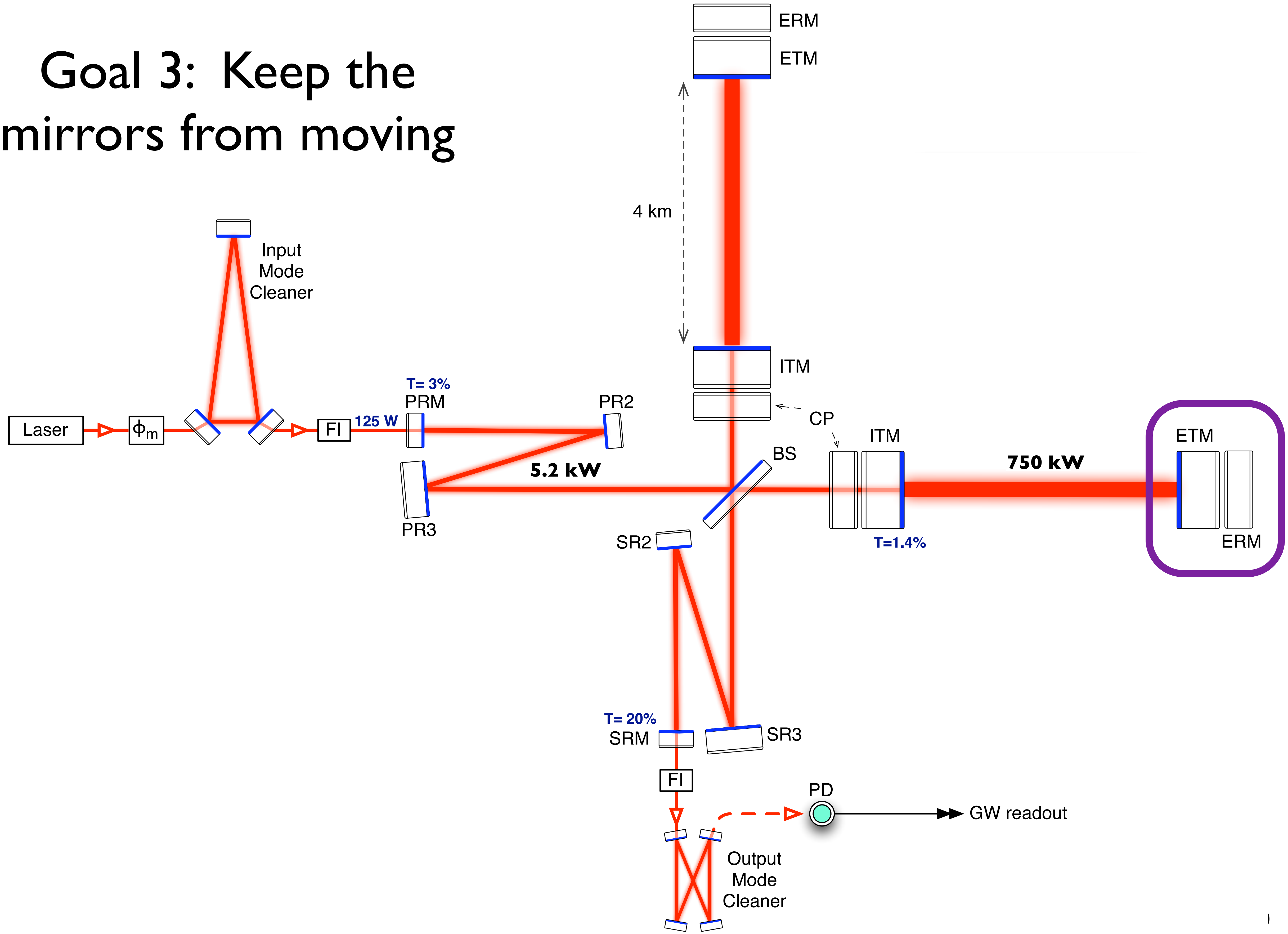


High power has a price
- Local thermal distortion of the glass optics caused by small imperfections in the coatings and limit current power.
- Noise from scattered light.

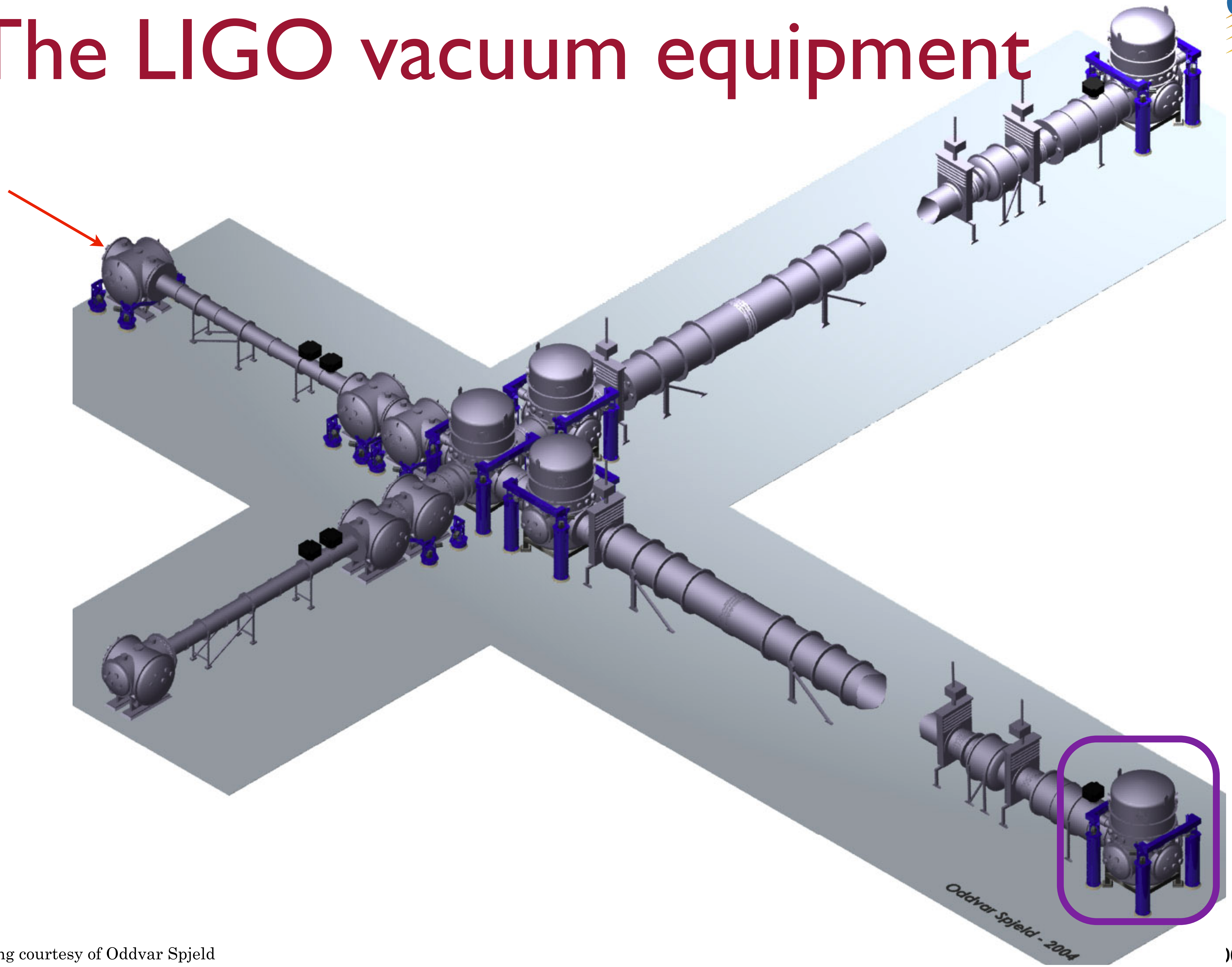
O3a power from LLO log 49863, C. Blair

Quiet Mirrors

Goal 3: Keep the mirrors from moving

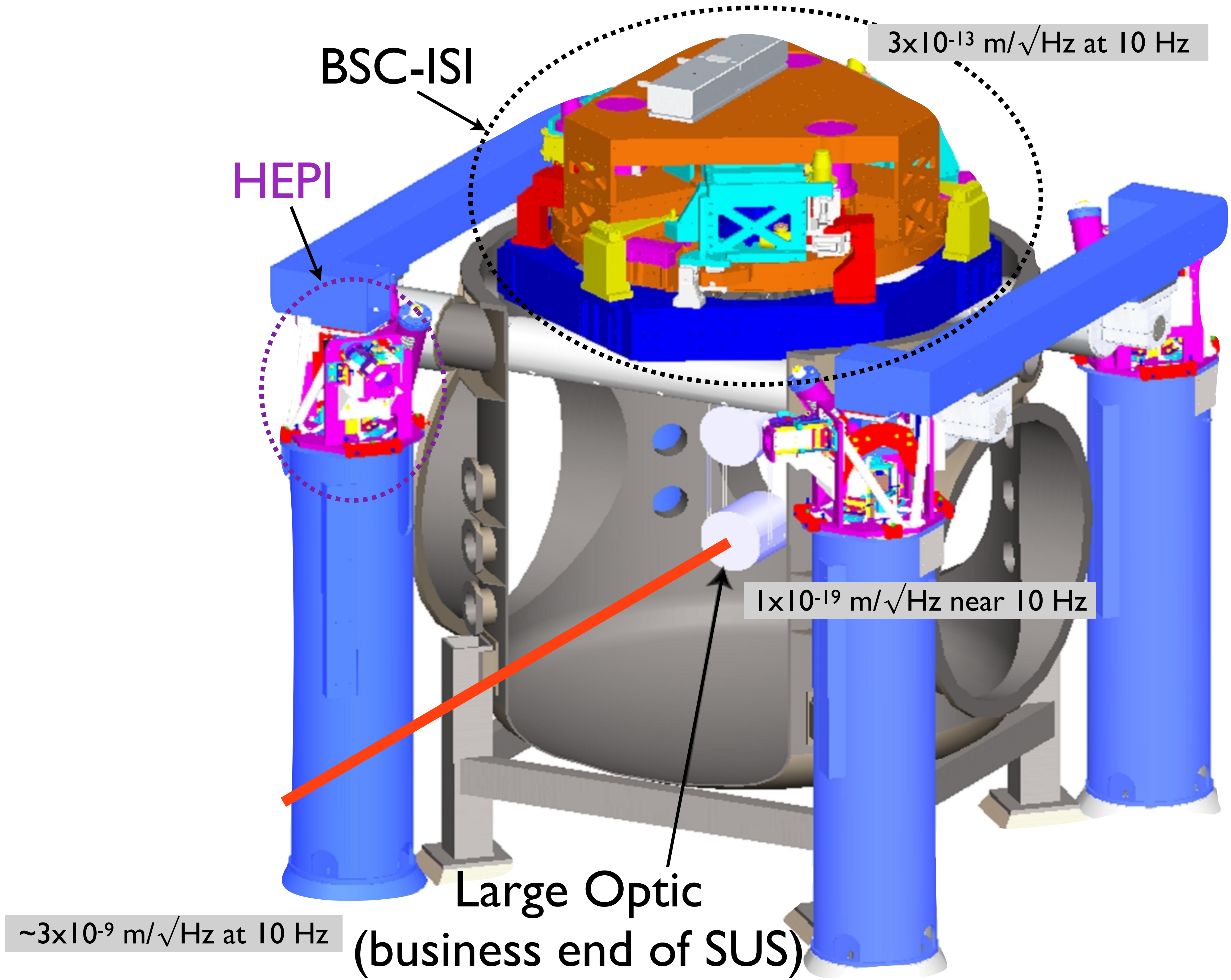


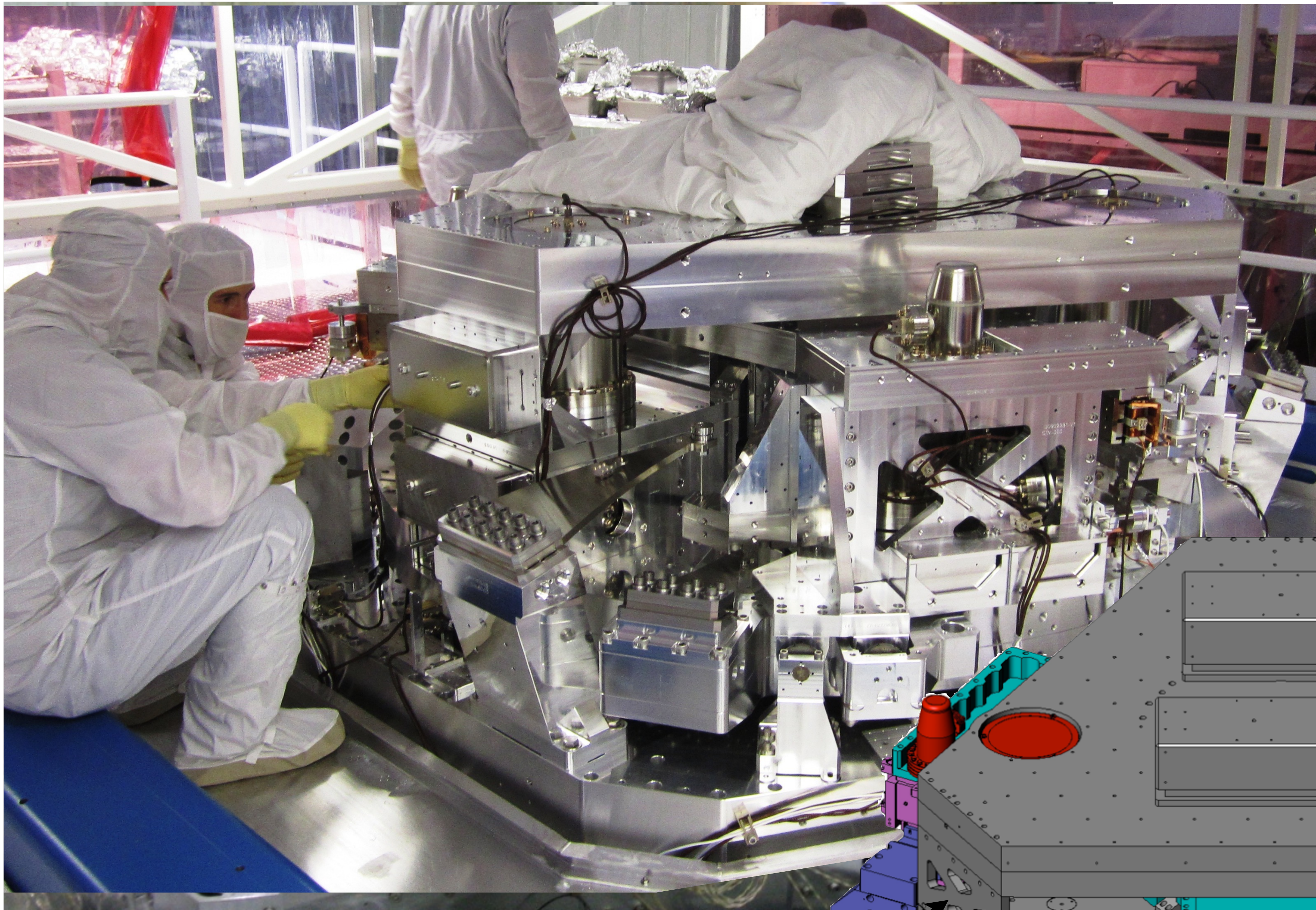
The LIGO vacuum equipment

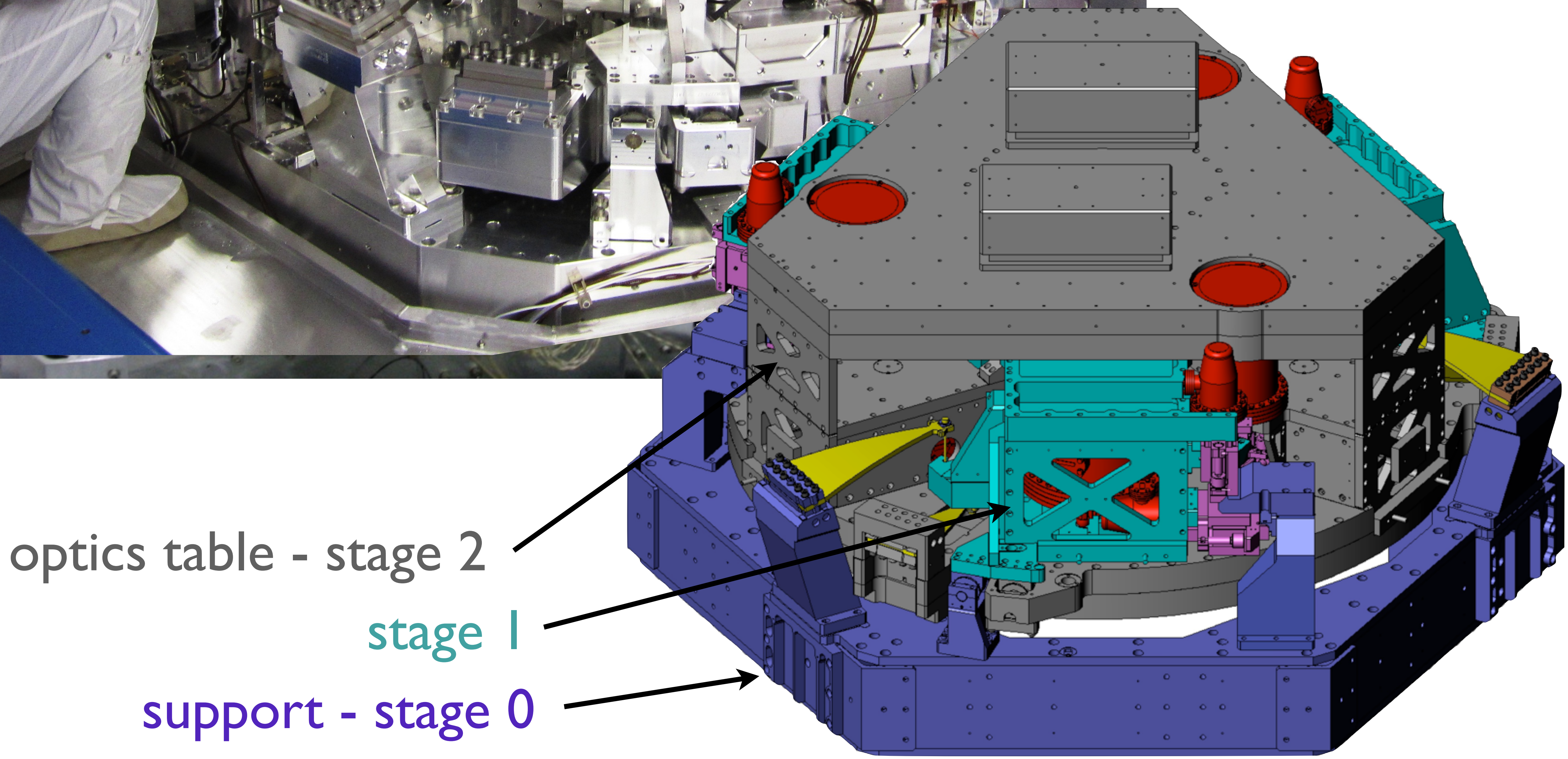


drawing courtesy of Oddvar Spjeld

Isolation of the Mirrors






optics table - stage 2
stage 1
support - stage 0

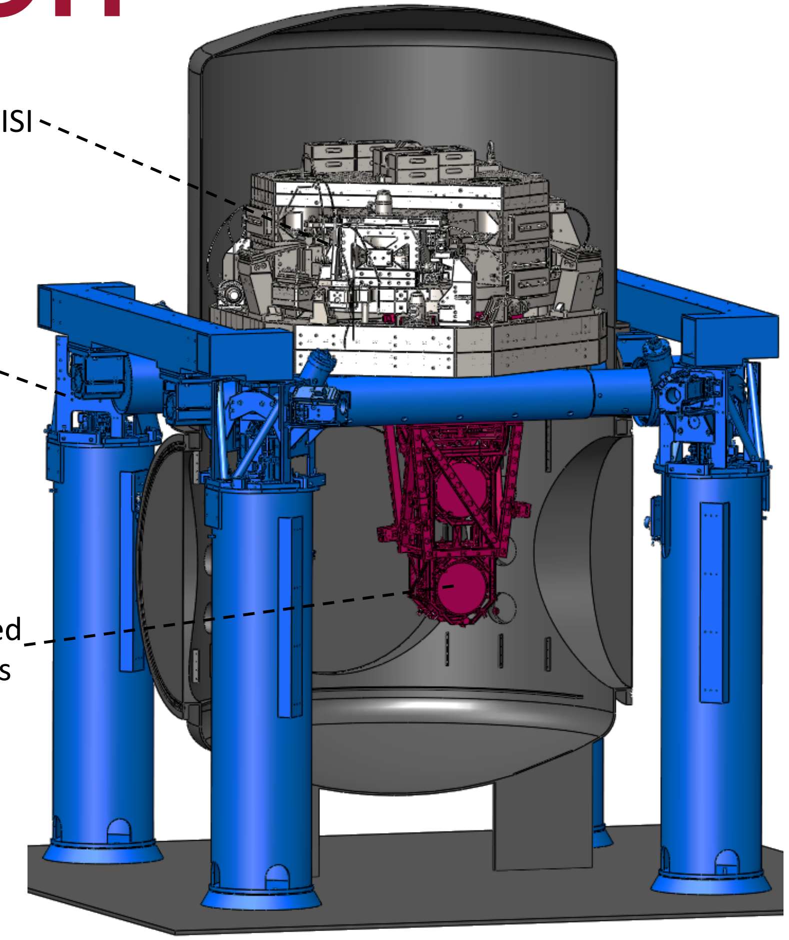
Pendulum Suspension

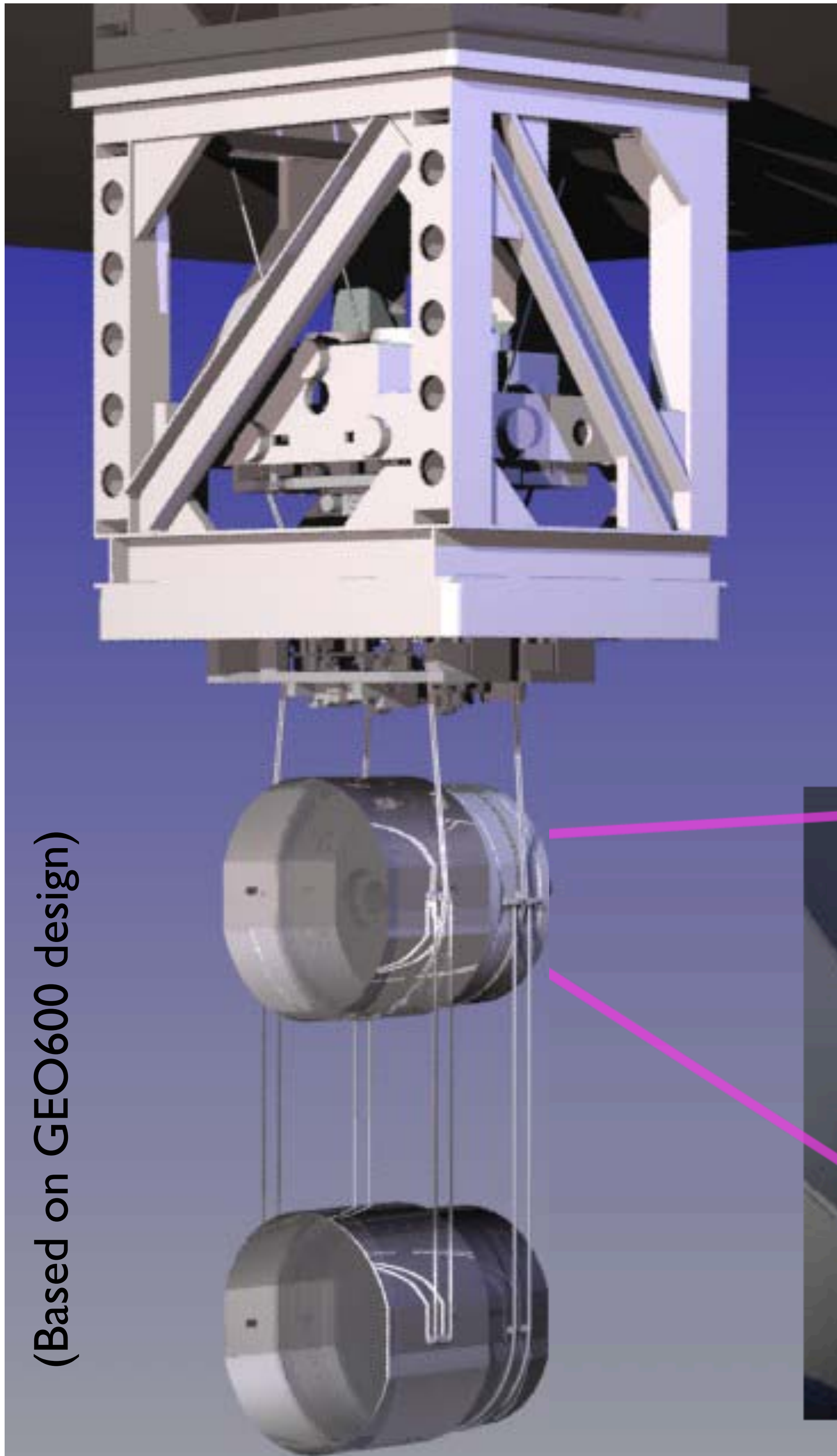
LIGO Mirrors:
Synthetic fused silica,
- 40 kg mass
- 34 cm diameter
- 20 cm thick

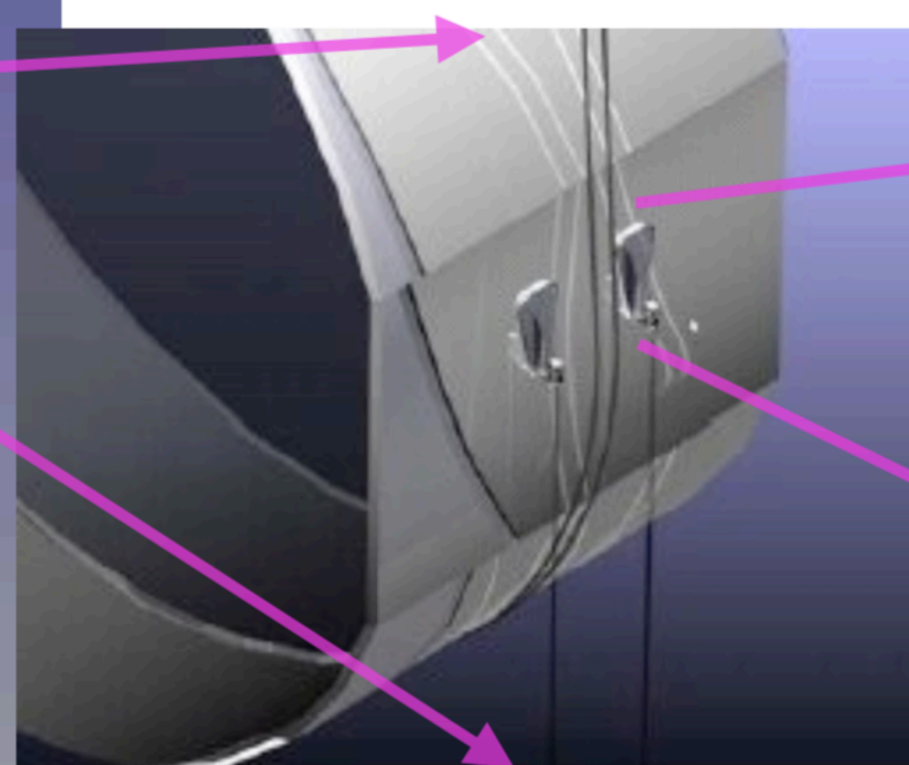
Suspended as a
4 stage pendulum

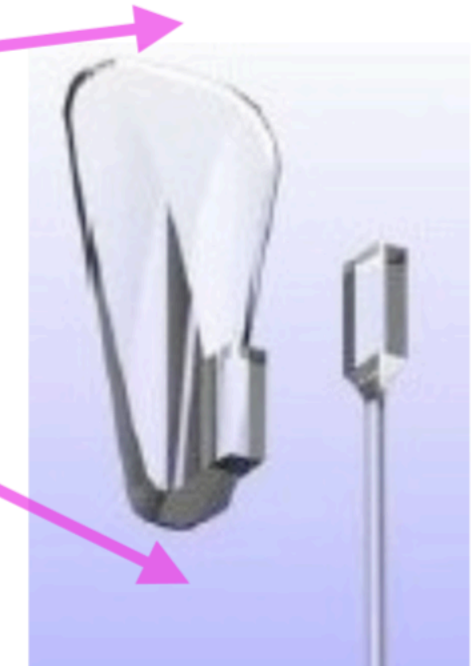
Best coatings available

Motion at 10 Hz set by
thermal driven vibration



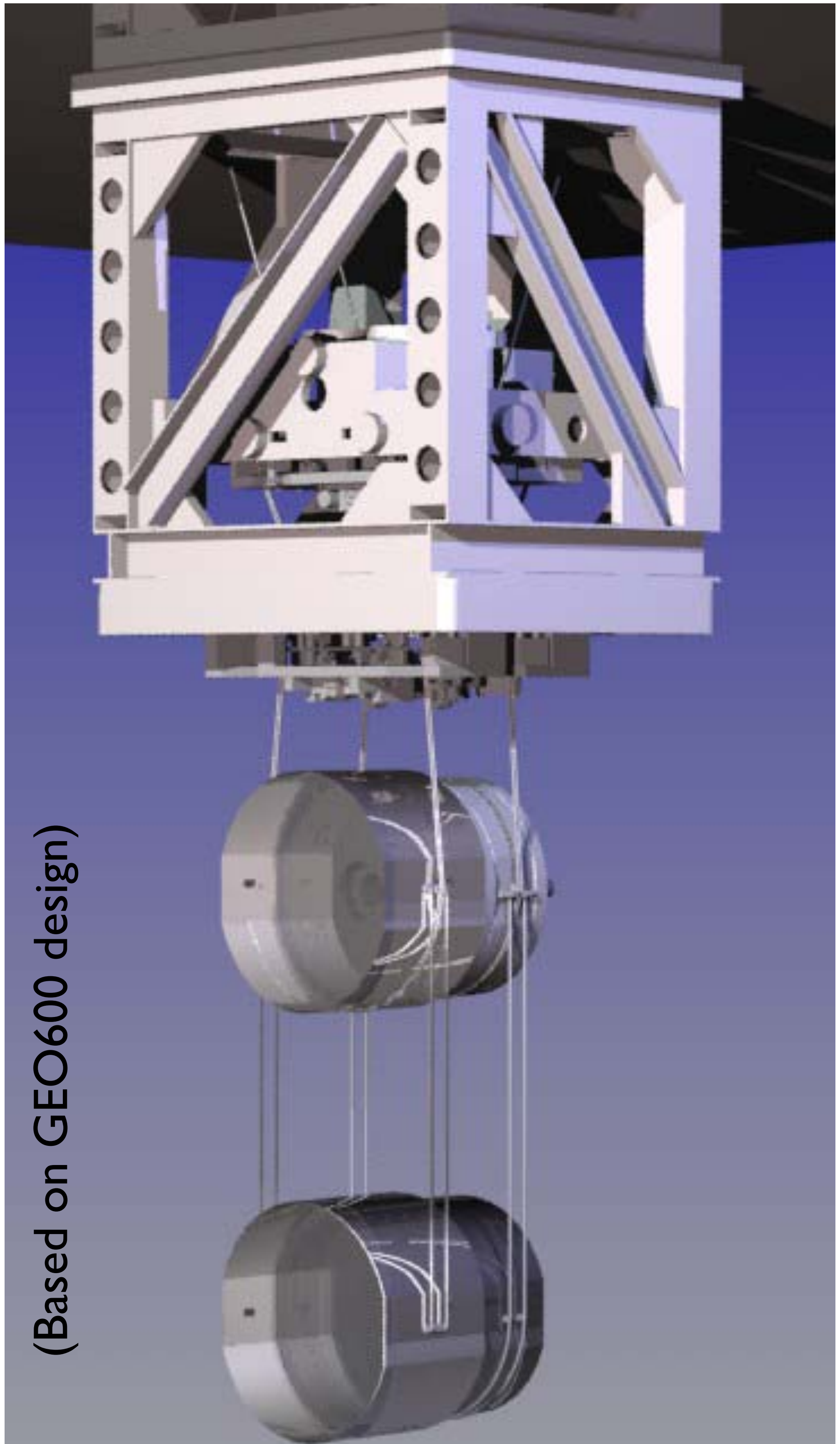


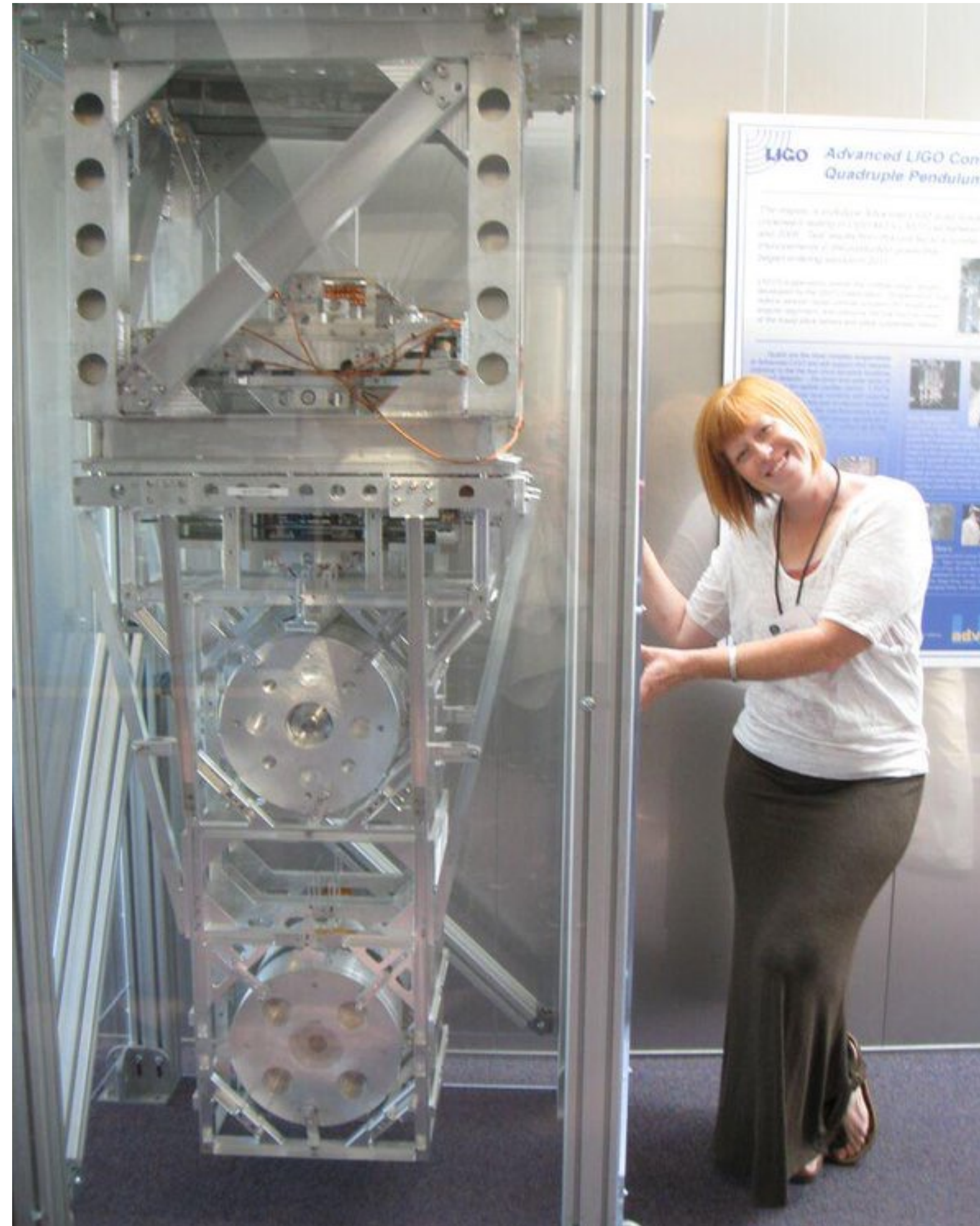




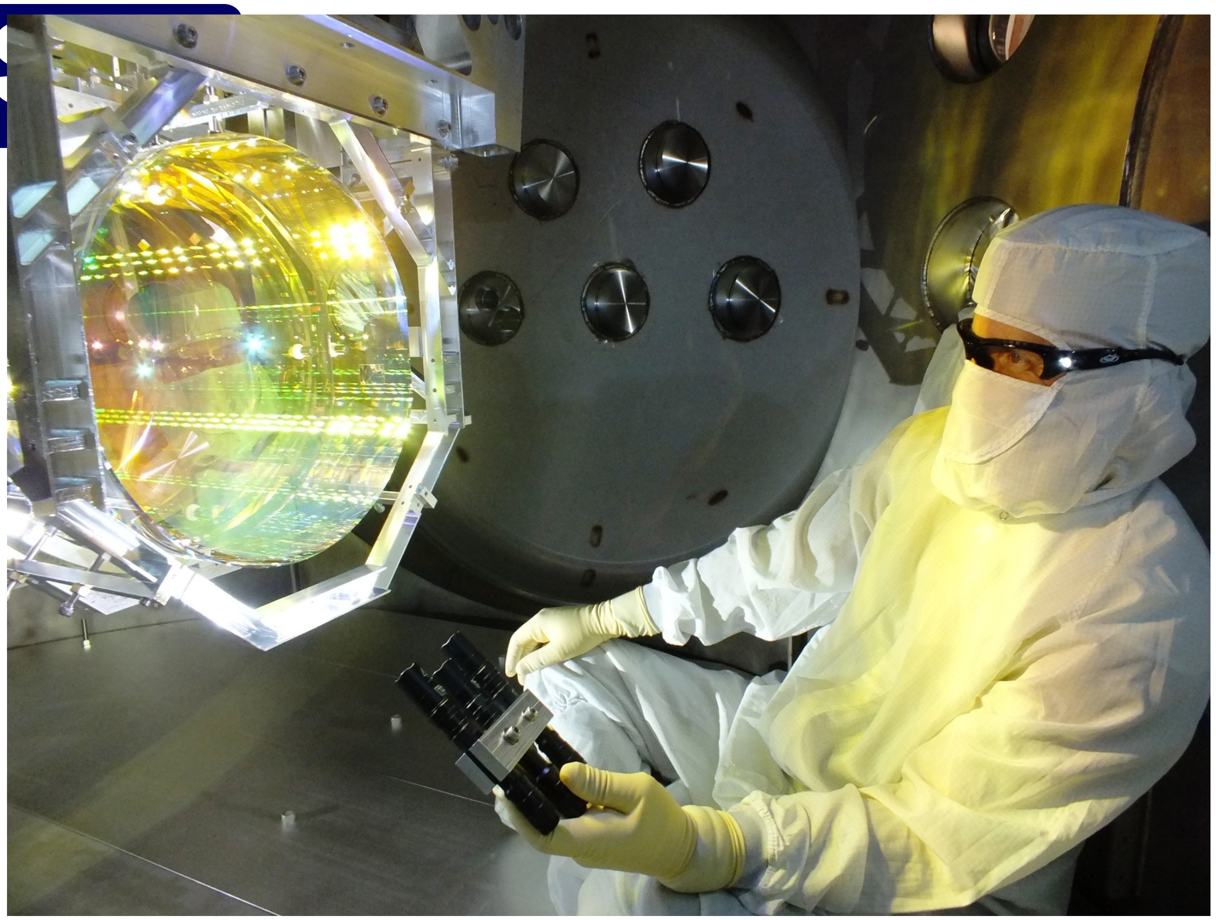
silicate bonding creates a monolithic final stage

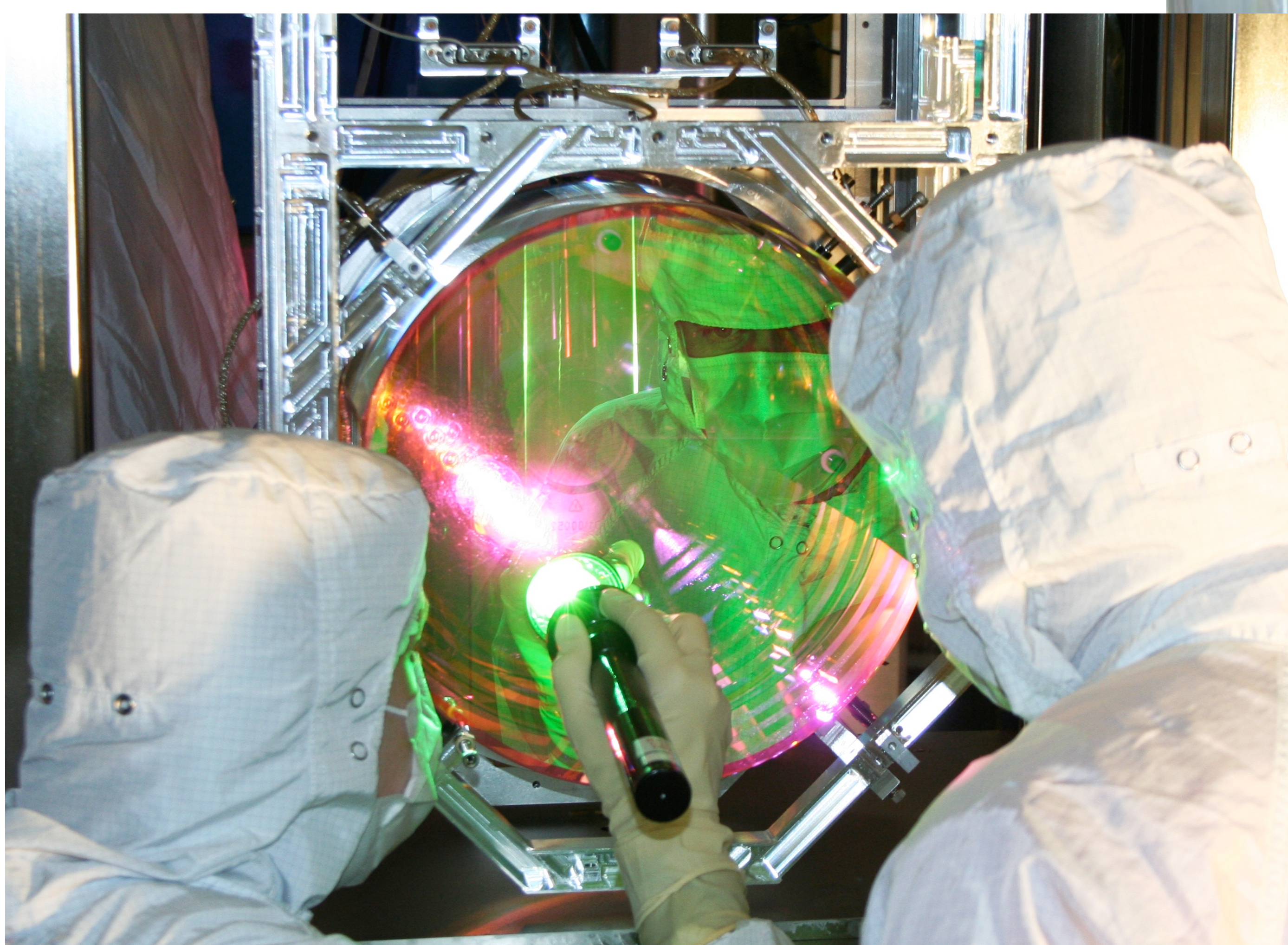
LHO suspension expert, Betsy Weaver with the Engineering prototype

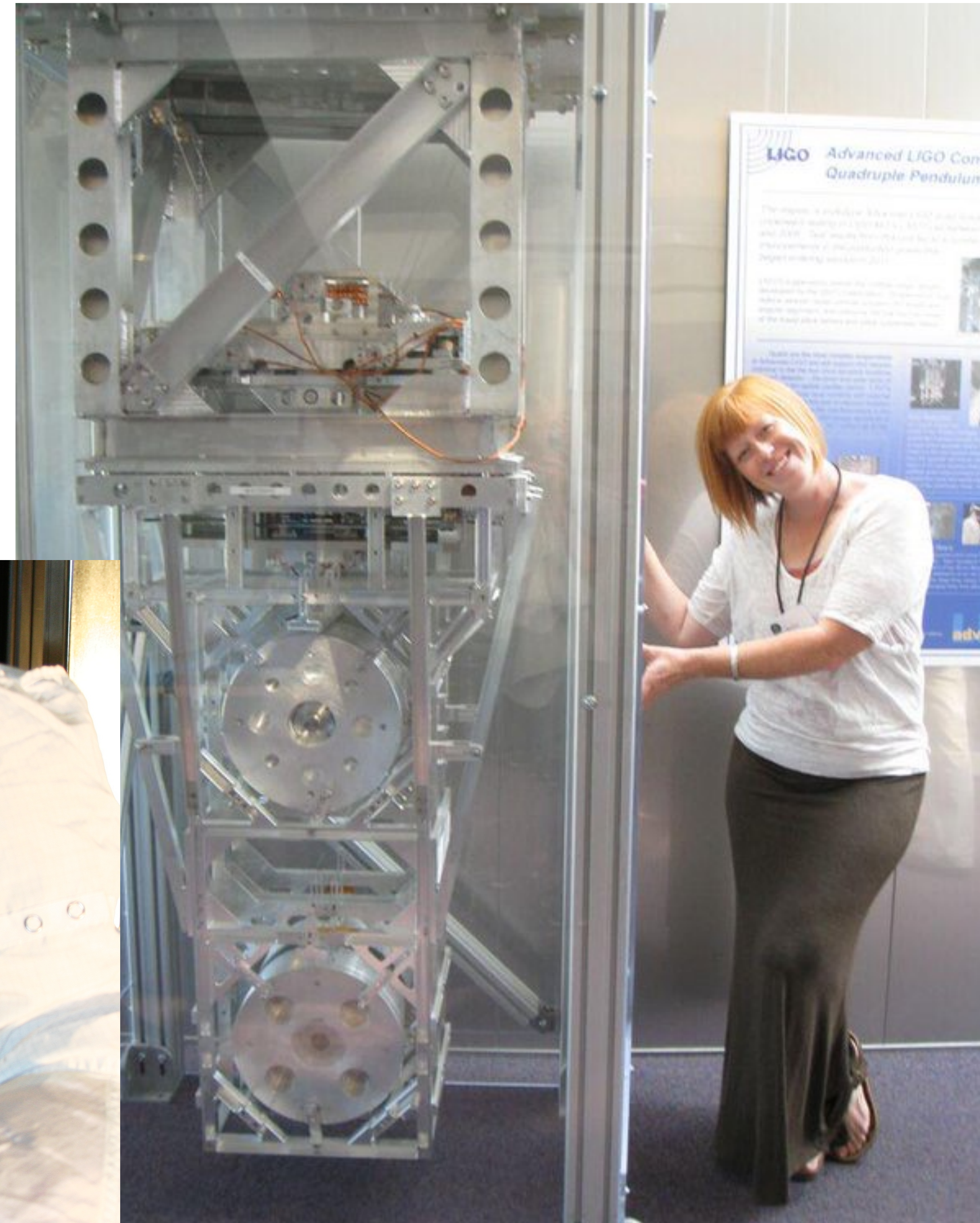




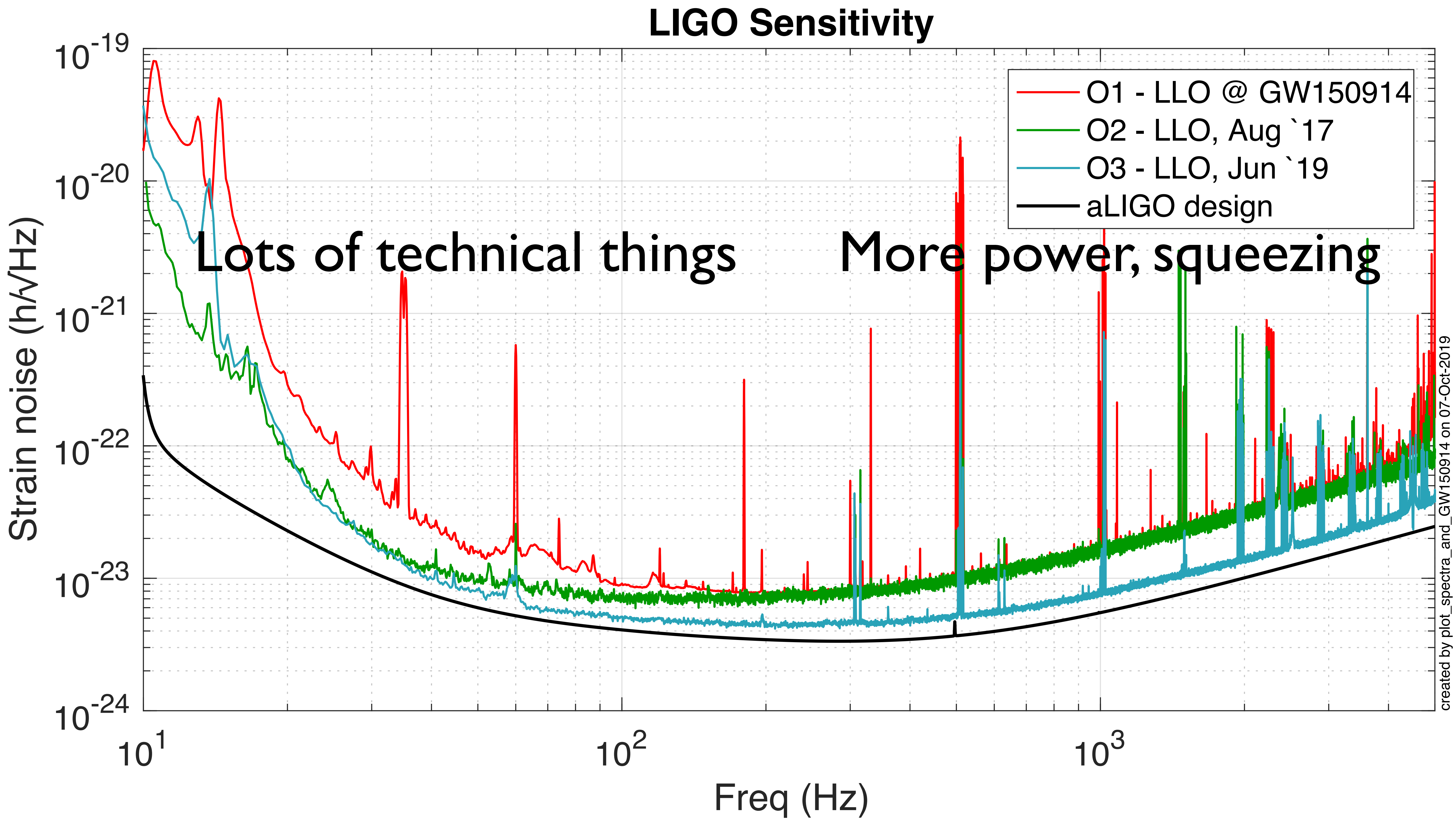
Mirror picts





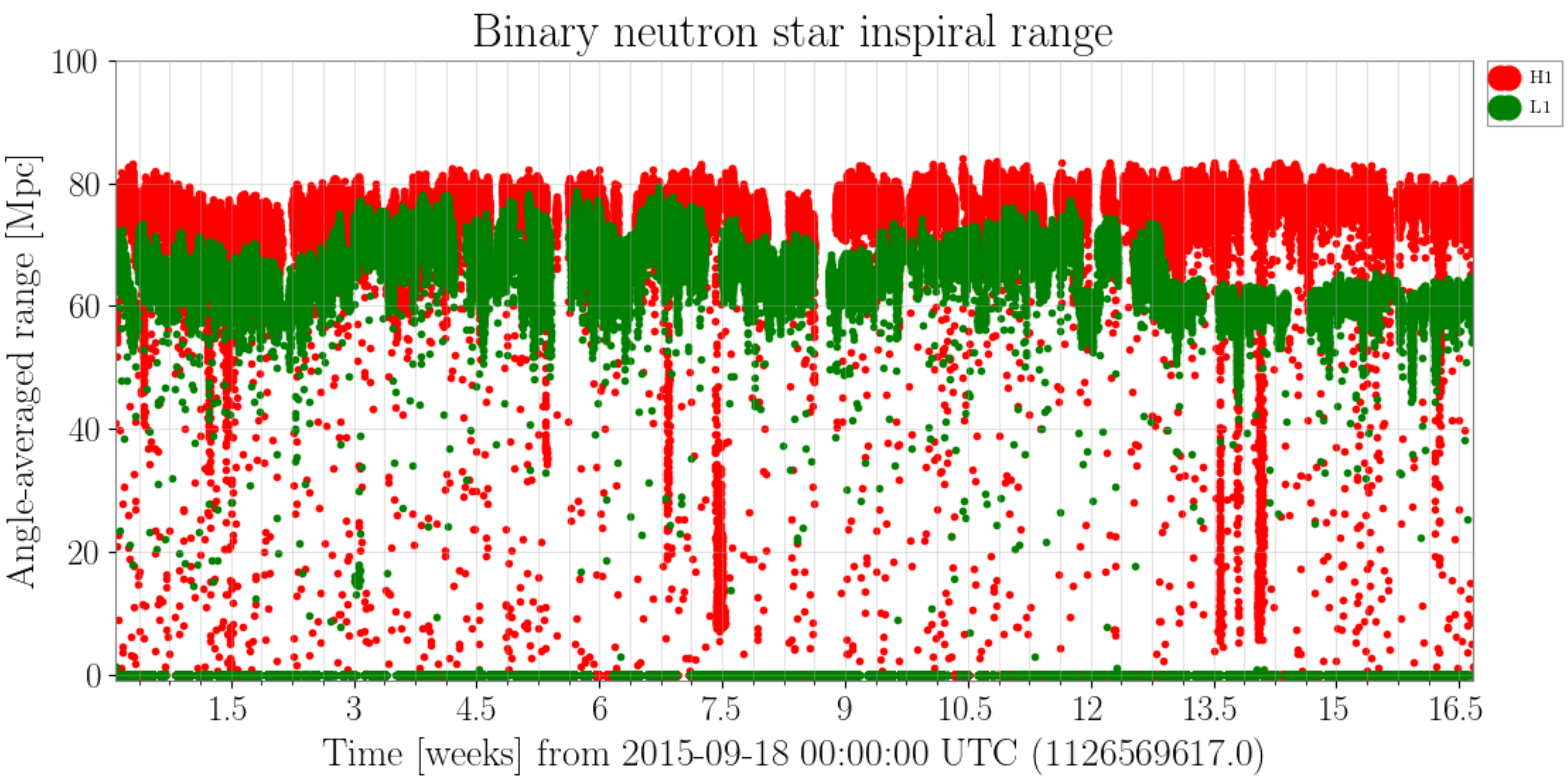


O1 to O3



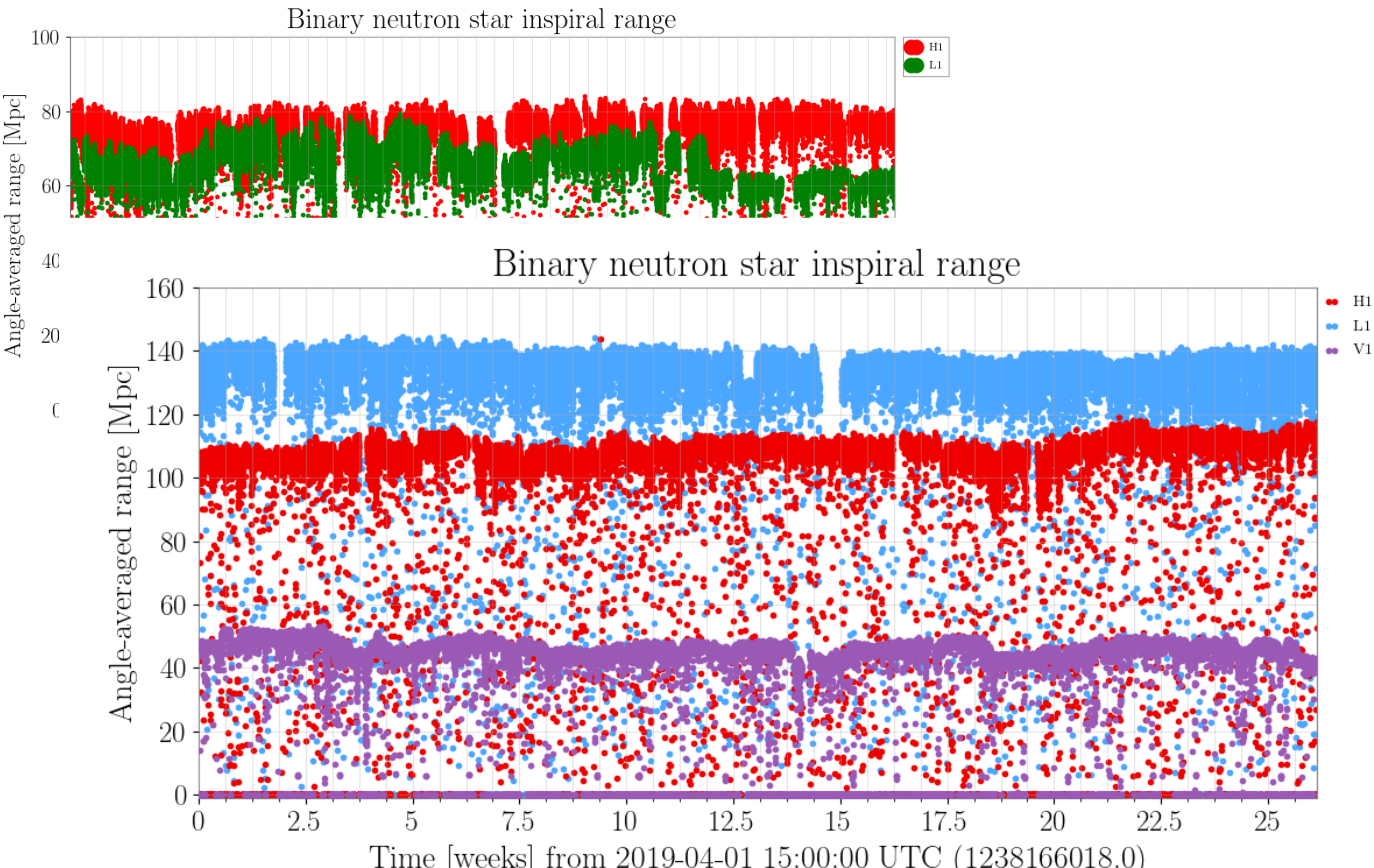
LIGO Sensitivity
Strain noise (h/√Hz)
Freq (Hz)
O1 - LLO @ GW150914
O2 - LLO, Aug `17
O3 - LLO, Jun `19
aLIGO design
Lots of technical things
More power, squeezing
created by plot_spectra_and_GW150914 on 07-Oct-2019

Range

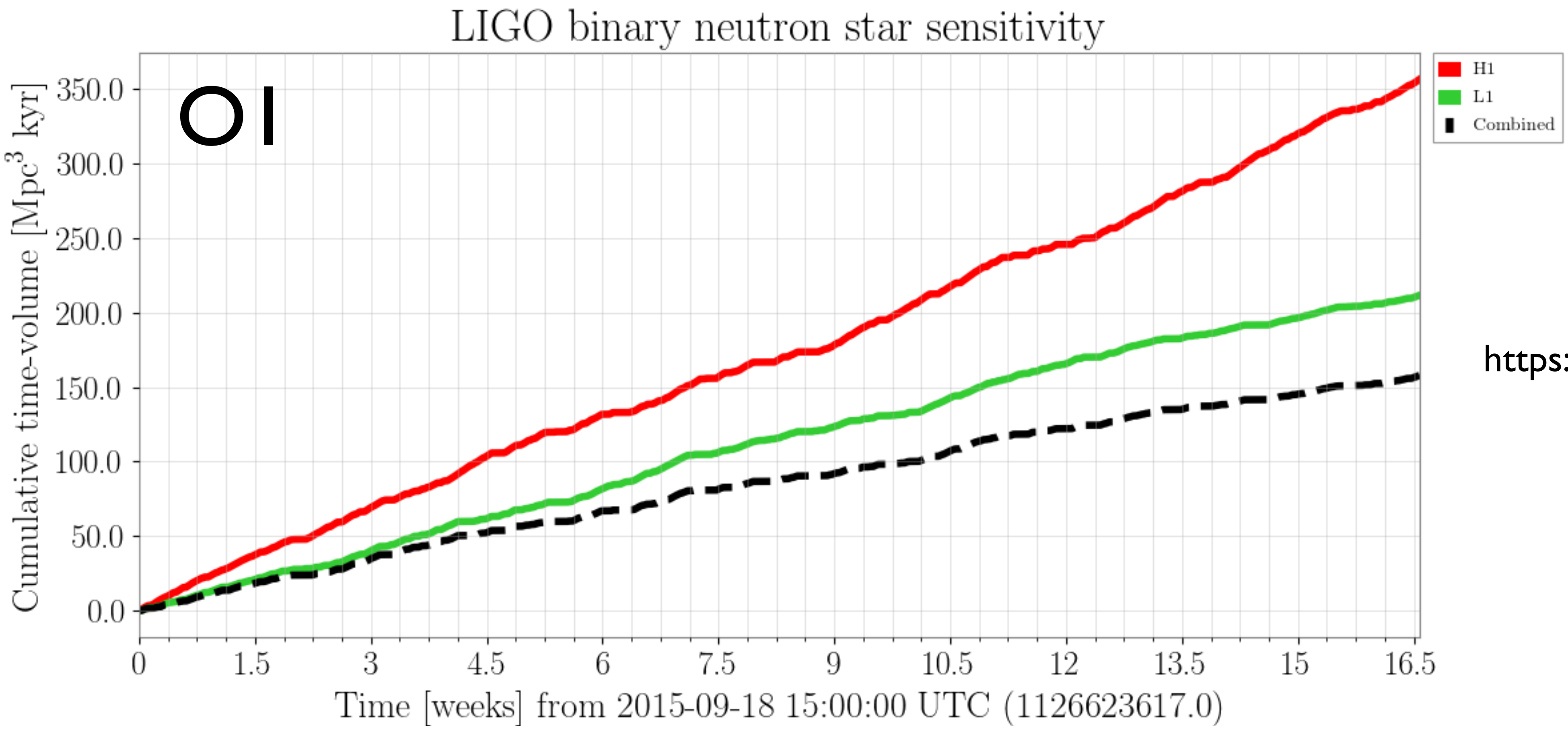


O3a network range: <https://summary.ligo.org/~detchar/summary/1238166018-1253977218/range/>
O2 network range: <https://summary.ligo.org/~detchar/summary/1164556817-1187733618/range/>
O1 network range: <https://summary.ligo.org/~detchar/summary/1126623617-1136649617/range/>

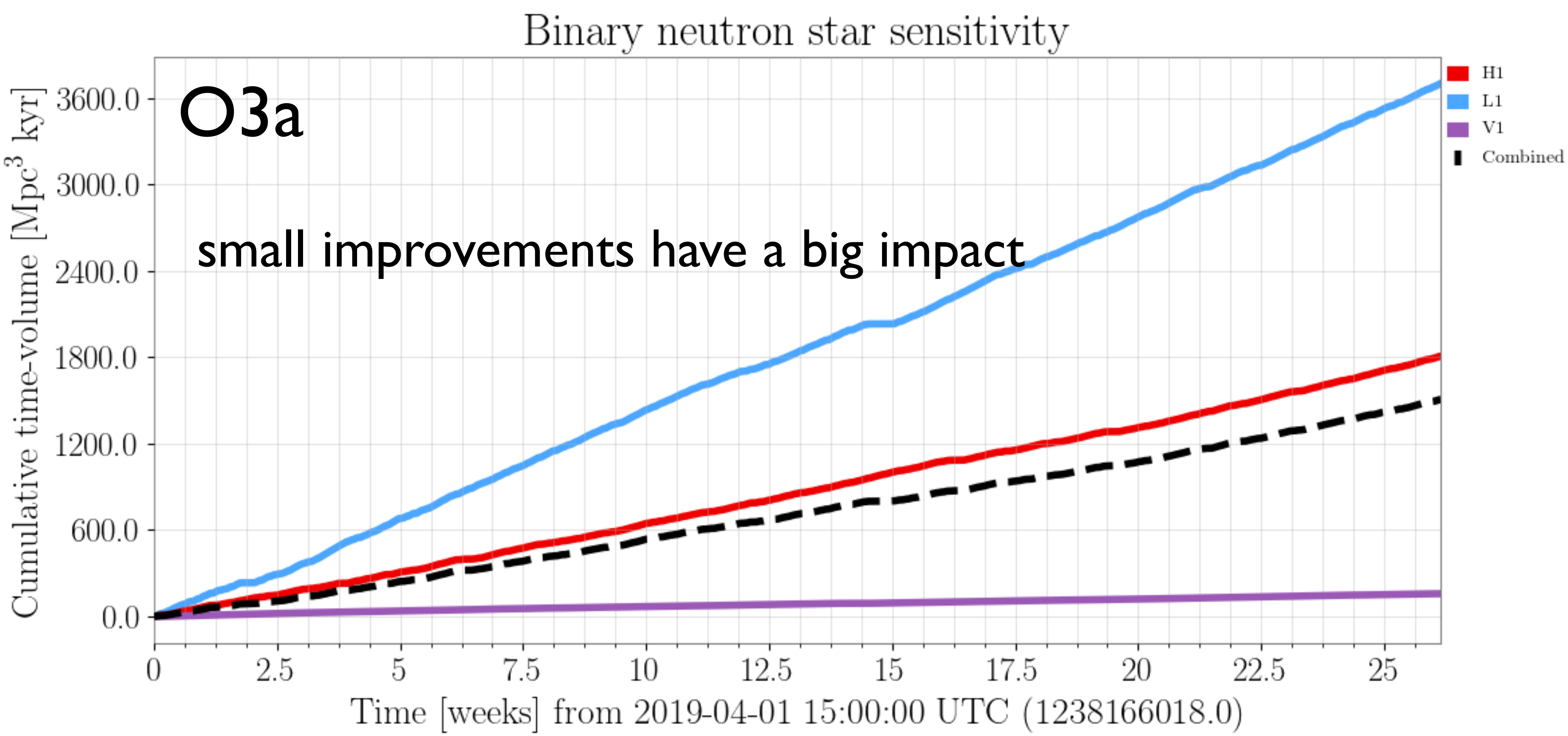
Range



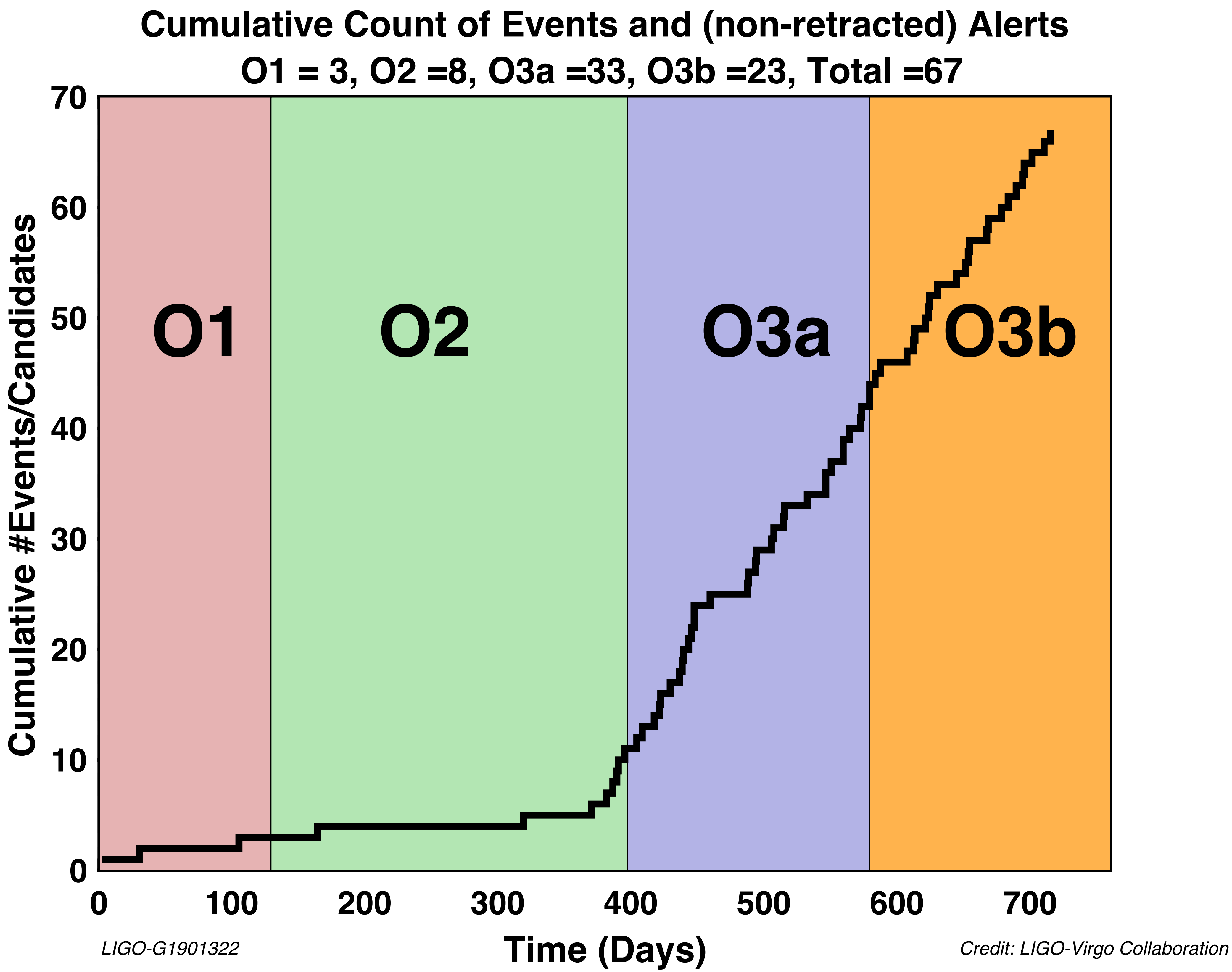
Binary neutron star inspiral range
100
80
60
40
20
H1
L1
Angle-averaged range [Mpc]
Binary neutron star inspiral range
160
140
120
100
80
60
40
20
0
H1
L1
V1
Angle-averaged range [Mpc]
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Time [weeks] from 2019-04-01 15:00:00 UTC (1238166018.0)



rates: GWTC-1:
BNS: 1.1e-4 - 3.8e-3 /MPc^3-kYr
https://doi.org/10.1103/PhysRevX.9.031040



Events!



LIGO-G1901322

Measuring H0

H0 - need to measure Distance and redshift (velocity)
GWs offer new ways to do this.
Amplitude of the GW is set by chirp mass, orientation, distance, and more
Velocity is set by redshift of the event's host galaxy.
- with visible counterparts like a BNS
    e.g. GW170817 & visible kilonova
- without a unique counterpart, e.g. a BBH
    e.g. GW170814 & DES galaxy catalog

References

B. Schutz,
Determining the Hubble constant from gravitational wave observations, 1986
https://doi.org/10.1038/323310a0

N. Dalal, D. Holz, S. Hughes,B. Jain,
Short GRB and binary black hole standard sirens as a probe of dark energy, 2006,
https://link.aps.org/doi/10.1103/PhysRevD.74.063006

DES, LSC, and Virgo collaborations,
First Measurement of the Hubble Constant from a Dark Standard Siren using the Dark Energy Survey Galaxies and the LIGO/Virgo Binary-Black-hole Merger GW170814, 2019,
https://doi.org/10.3847%2F2041-8213%2Fab14f1

The LIGO Scientific Collaboration and The Virgo Collaboration, the 1M2H Collaboration, the Dark Energy Camera GW-EM Collaboration and the DES Collaboration, the DLT40 Collaboration, the Las Cumbres Observatory Collaboration, the VINROUGE Collaboration & the MASTER Collaboration,
A gravitational-wave standard siren measurement of the Hubble constant, 2017,
https://doi-org.stanford.idm.oclc.org/10.1038/nature24471

H-Y Chen, M. Fishbach, D. Holz,
A two per cent Hubble constant measurement from standard sirens within five years, 2018
https://doi.org/10.1038/s41586-018-0606-0

GW170817

Binary Neutron Star merger with kilonova and GRB.
Measure of H0 is 70.0 +12/- 8 km/sec/MPc
Distance from GW alone is 43.8 +2.9/-6.9
Largest uncertainty still inclination angle [144,180]
Angle/ inclination degeneracy reduced by fitting waveforms, and knowing true angular location.

Velocity inferred from redshift of the associated galaxy NGC 4993. largest uncertainty from the peculiar (non-Hubble flow) velocity. (3,017 +/- 166 km/sec)

Multiple events are a good way to improve both of these.

Analysis says: improved range = events with good (useful) SNR at greater distance. Recent experience is more cruel.

Result from 1 event

Figure 1. GW170817 measurement of H_0

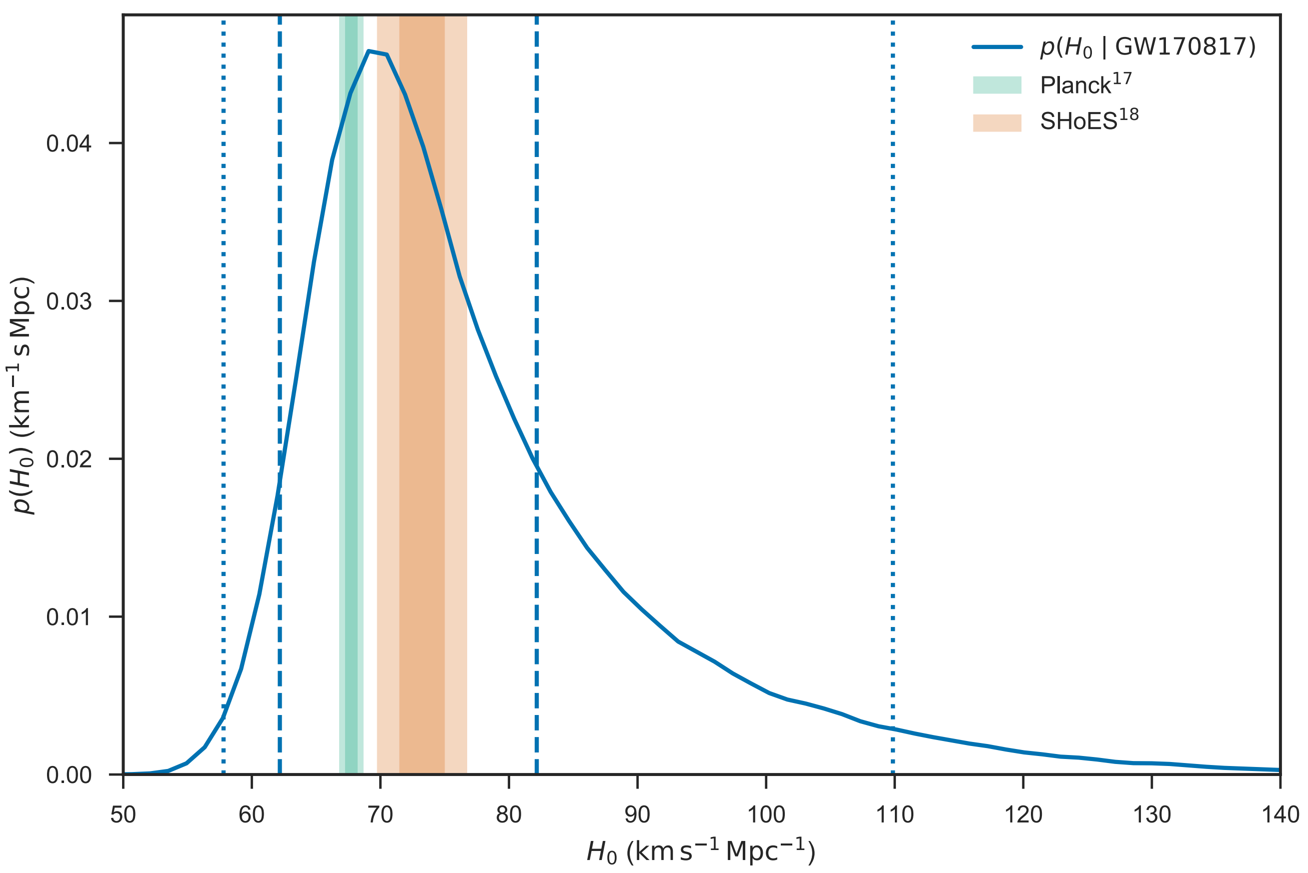
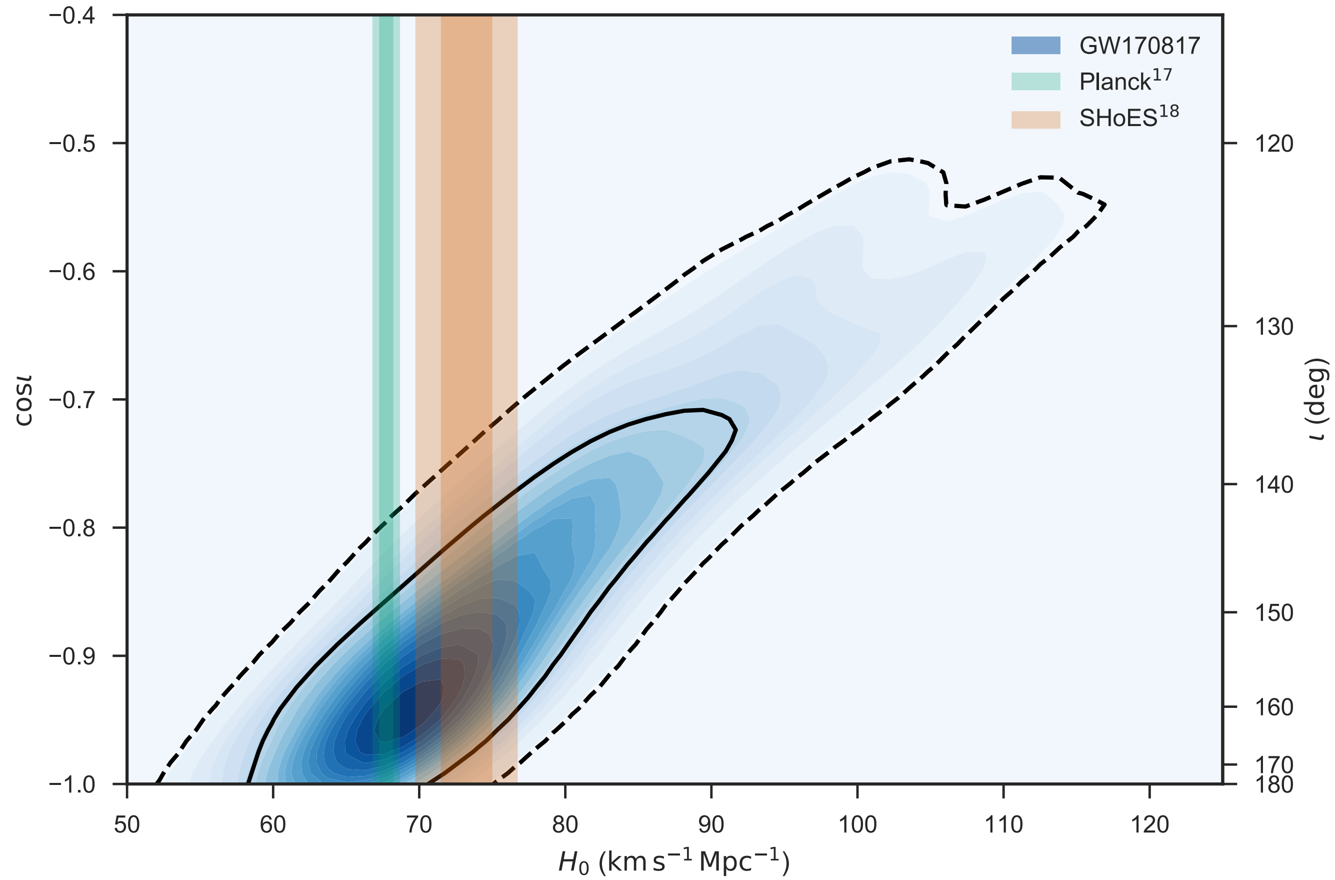


Figure 2. Inference on H_0 and inclination



The LIGO Scientific Collaboration and The Virgo Collaboration, the 1M2H Collaboration, the Dark Energy Camera GW-EM Collaboration and the DES Collaboration, the DLT40 Collaboration, the Las Cumbres Observatory Collaboration, the VINROUGE Collaboration & the MASTER Collaboration, *A gravitational-wave standard siren measurement of the Hubble constant*, 2017, https://doi-org.stanford.idm.oclc.org/10.1038/nature24471

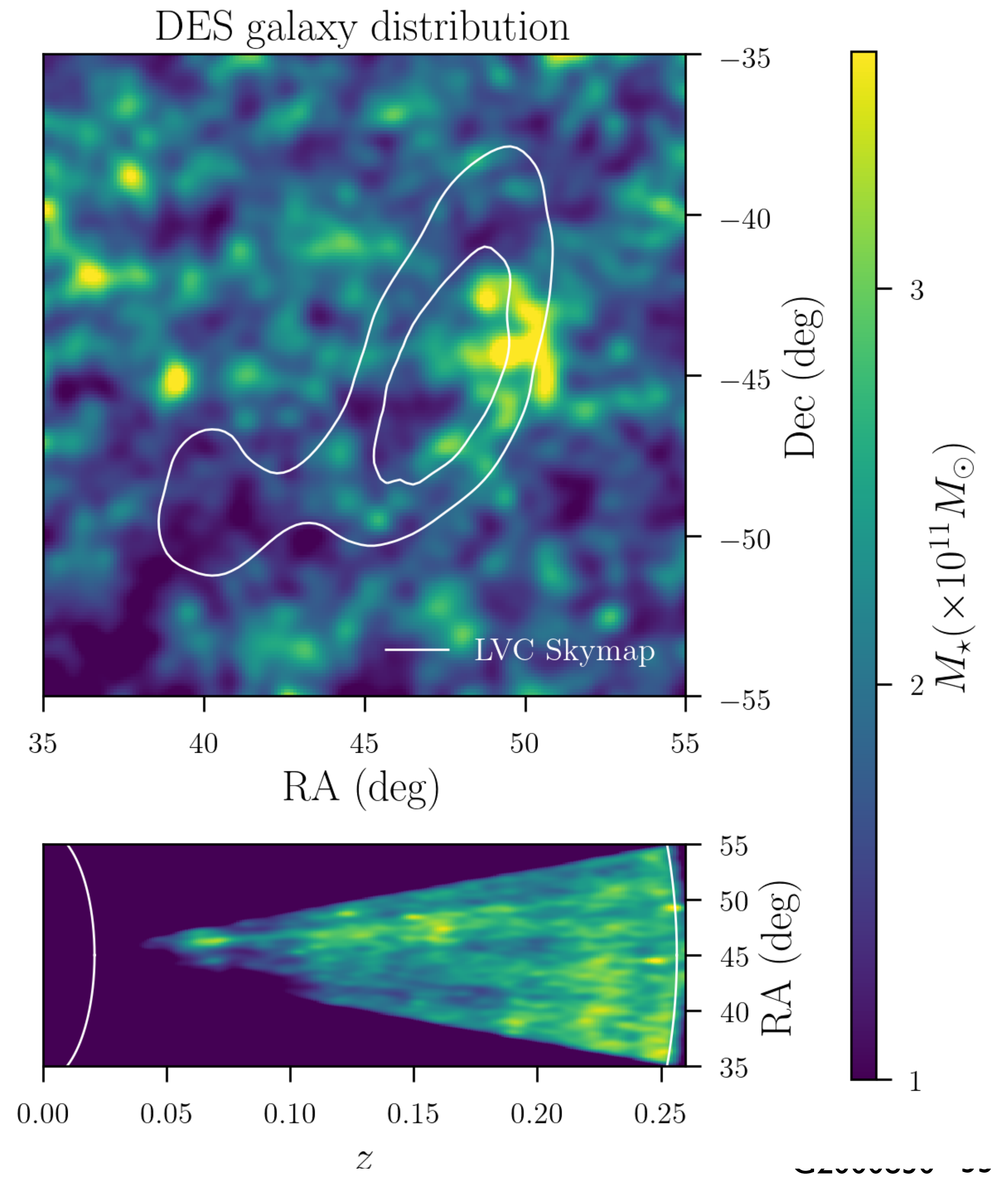
GW170814

Measure of H0 is 75.2 +39.5/-32.4 km/sec/MPc
Distance from GW alone is 540 +130/ -210

Possible location on the sky constrained to 61.66 deg^2.

Velocity inferred statistically from the redshift of the ~77,000 galaxies (~6,000 have measured redshifts) in the 90% credible volume.

Improvements from multiple measurements, better localization, and improved galaxy catalogs.



H_0 from 1 BBH event

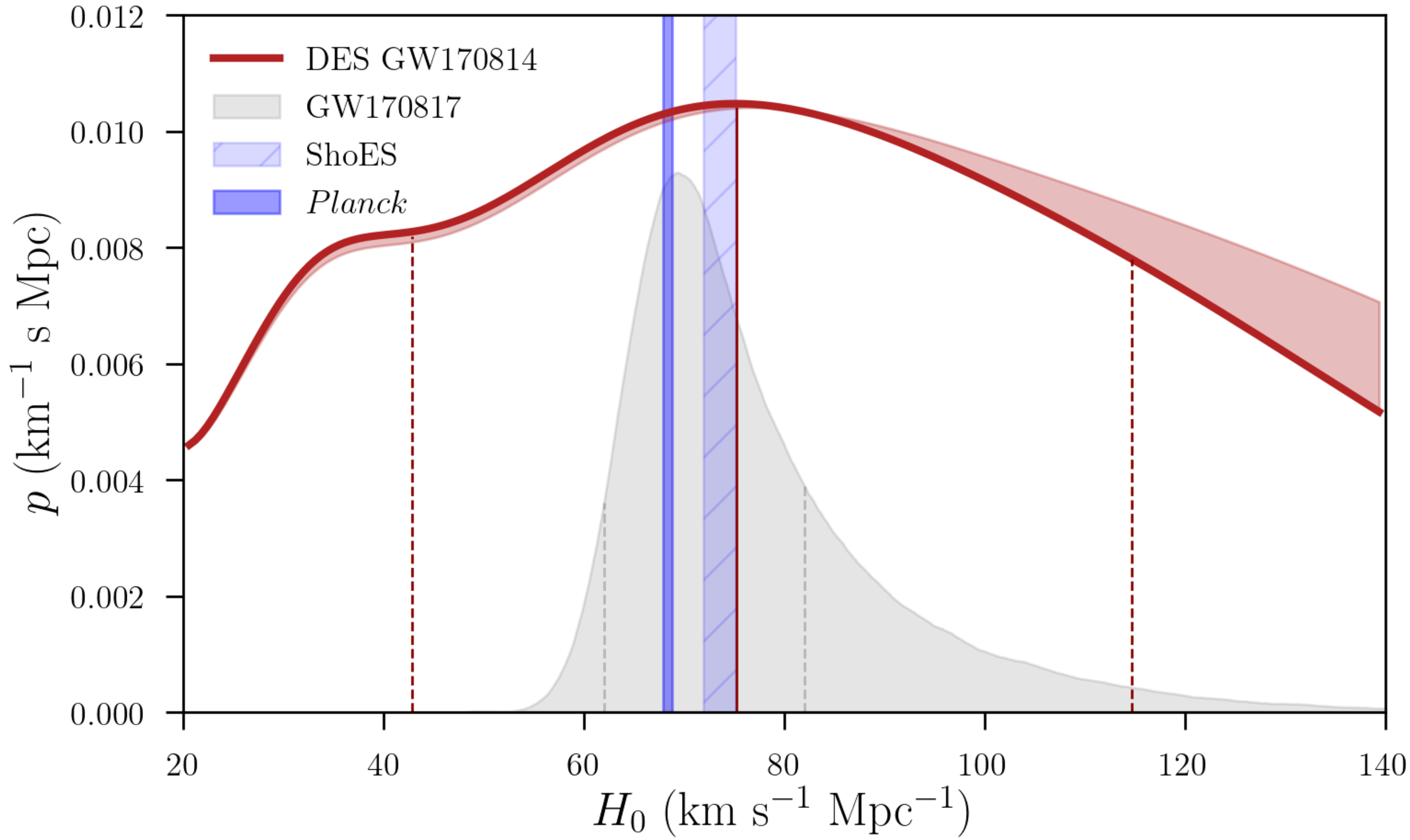


Figure 3. Hubble constant posterior distribution obtained by marginalizing over ∼ 77,000 possible host galaxies (red line), showing the maximum value (solid vertical line). The maximum a posteriori and its 68% confidence level is $H_0 = 75.2^{+39.5}_{-32.4}$ km s^{-1} Mpc^{-1} for a flat prior in

Multiple collaborations,
A gravitational-wave standard siren measurement of the Hubble constant, 2017,
https://doi-org.stanford.idm.oclc.org/10.1038/nature24471

Predictions

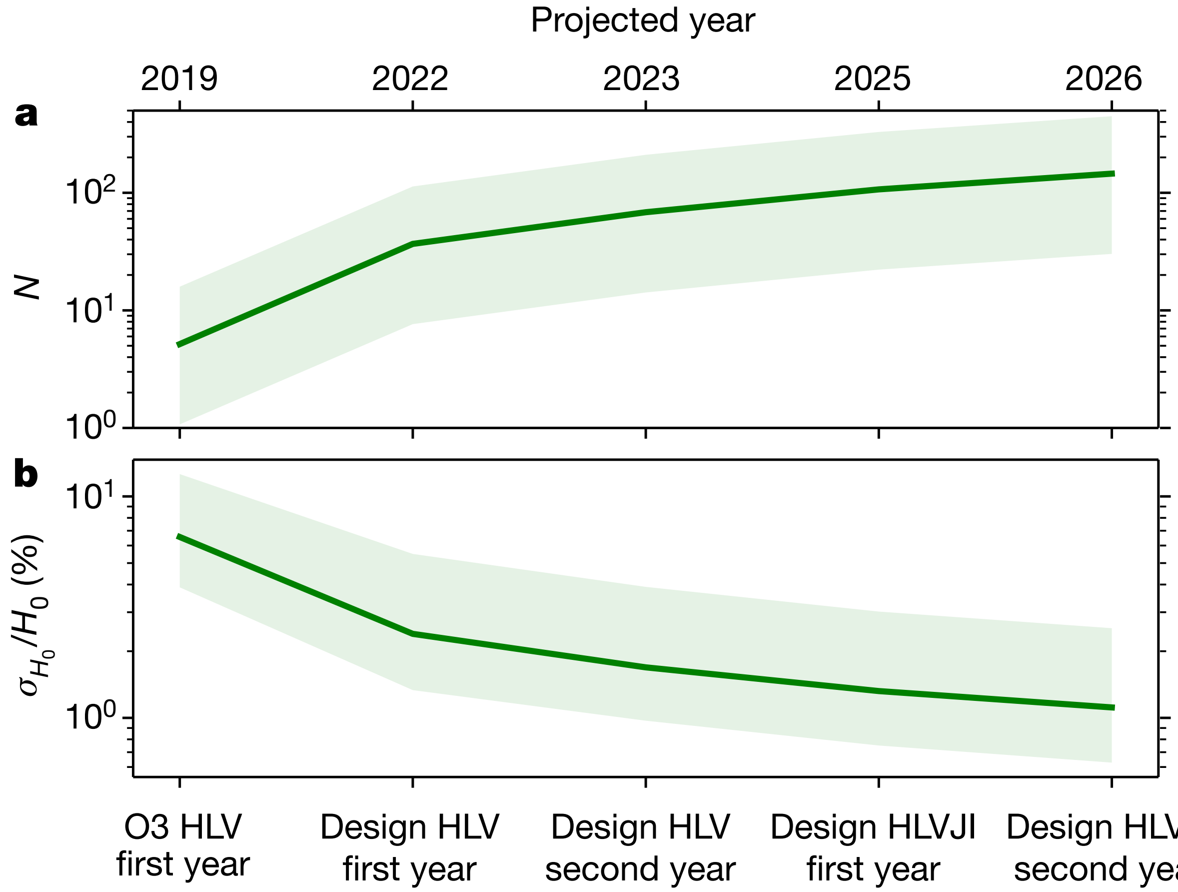


Fig. 1 | Projected number of BNS detections and corresponding fractional error for the standard siren H_0 measurement. a, The expected total number N of BNS detections for future observing runs, using the median merger rate (solid green curve) and upper and lower rate bounds (shaded band). **b**, The corresponding H_0 measurement error, defined as half of the width of the 68% symmetric credible interval divided by the posterior median. The band corresponds to the uncertainty in the merger rate shown in **a**. These measurements assume an optical counterpart, and the associated redshift, for all BNS systems detected with gravitational waves.

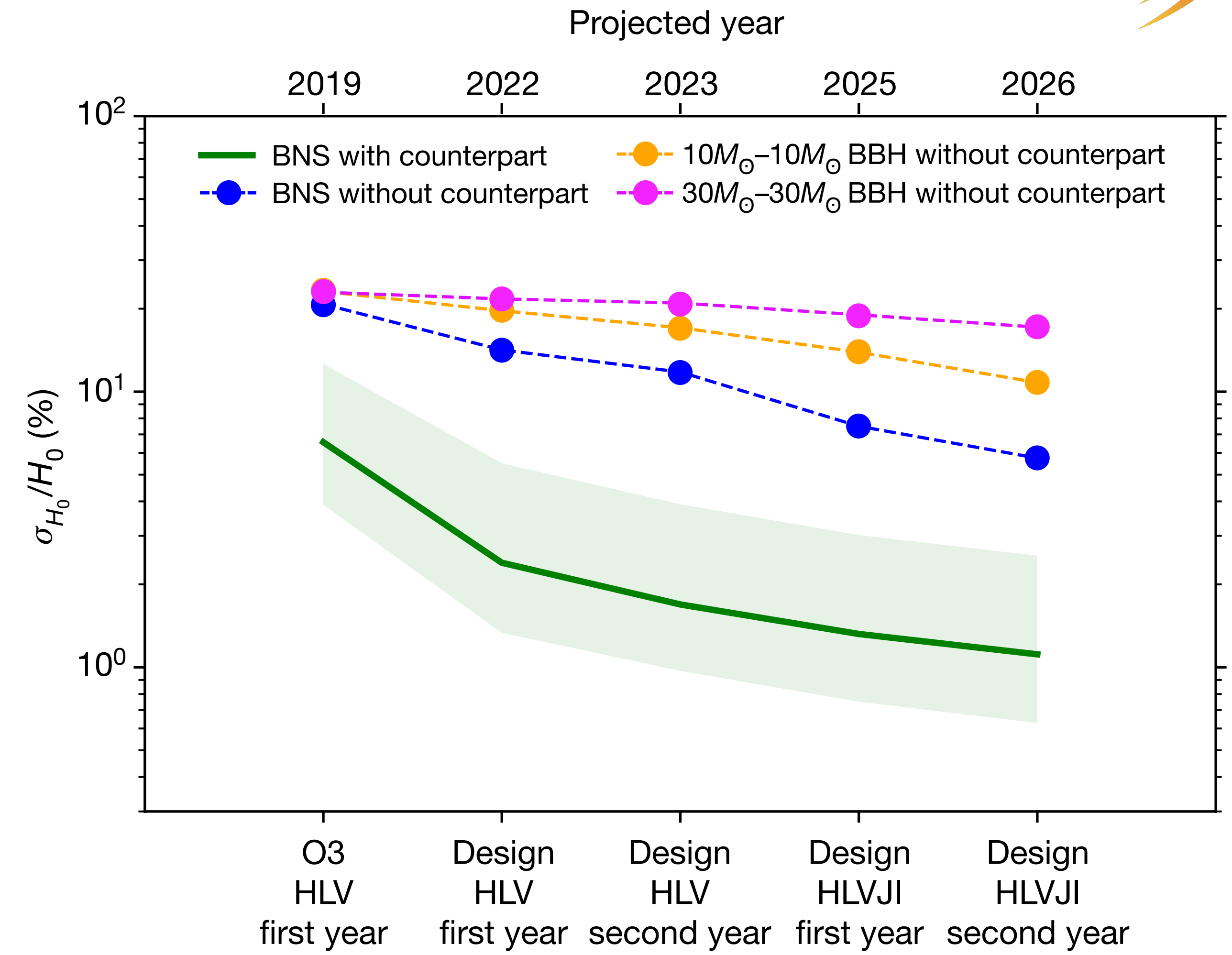
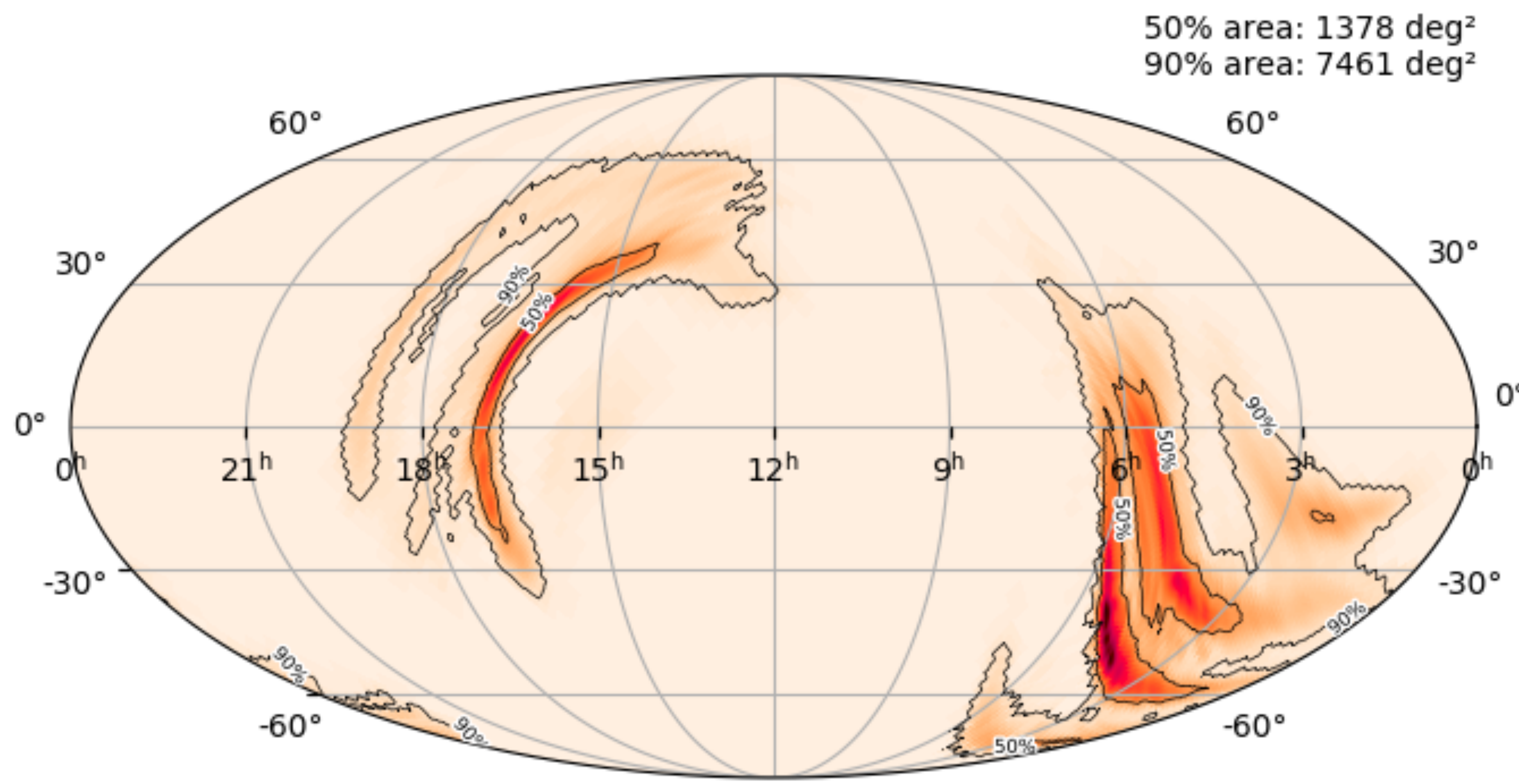


Fig. 2 | Projected fractional error for the standard siren H_0 measurement for BNSs and BBHs for future gravitational-wave detector networks. The green shaded band corresponds to the BNS rate uncertainty (see Fig. 1); the same uncertainty applies to the 'BNS without counterpart' curve. For the 'without counterpart' curves, we adopt a statistical standard siren approach using only events localized to within 10,000 Mpc^3; events with larger volumes do not contribute noticeably (see the text). Constraints from BBH systems without counterparts are inferior, despite higher rates, owing to the larger numbers of potential host galaxies per event.

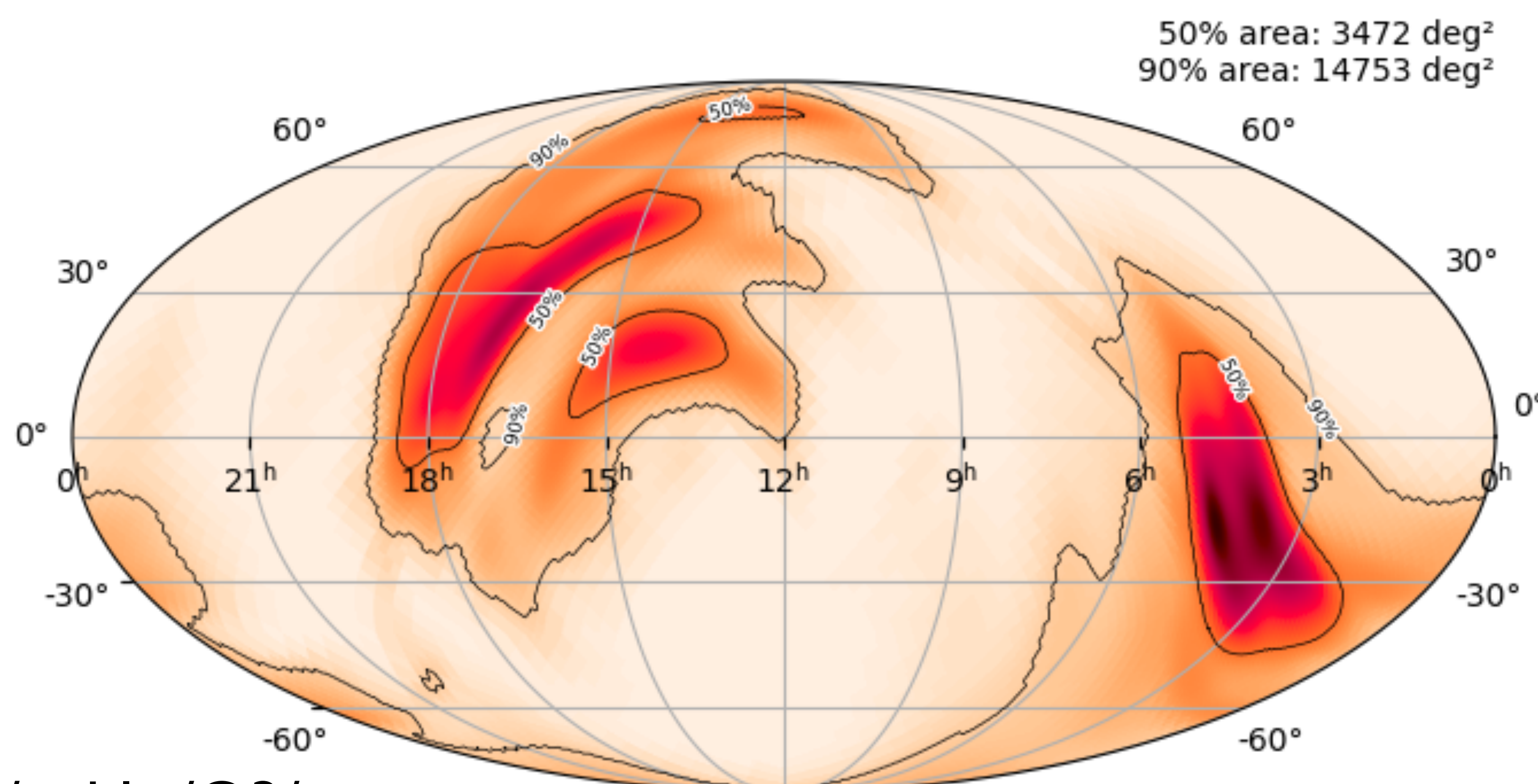
H-Y Chen, M. Fishbach, D. Holz,
A two per cent Hubble constant measurement from standard sirens within five years, 2018
https://doi.org/10.1038/s41586-018-0606-0

No EM counterparts in O3.

S190425z
BNS (>99%)
FAR 1/79,000 years
distance: 156 +/- 41 MPc
L1,V1 only



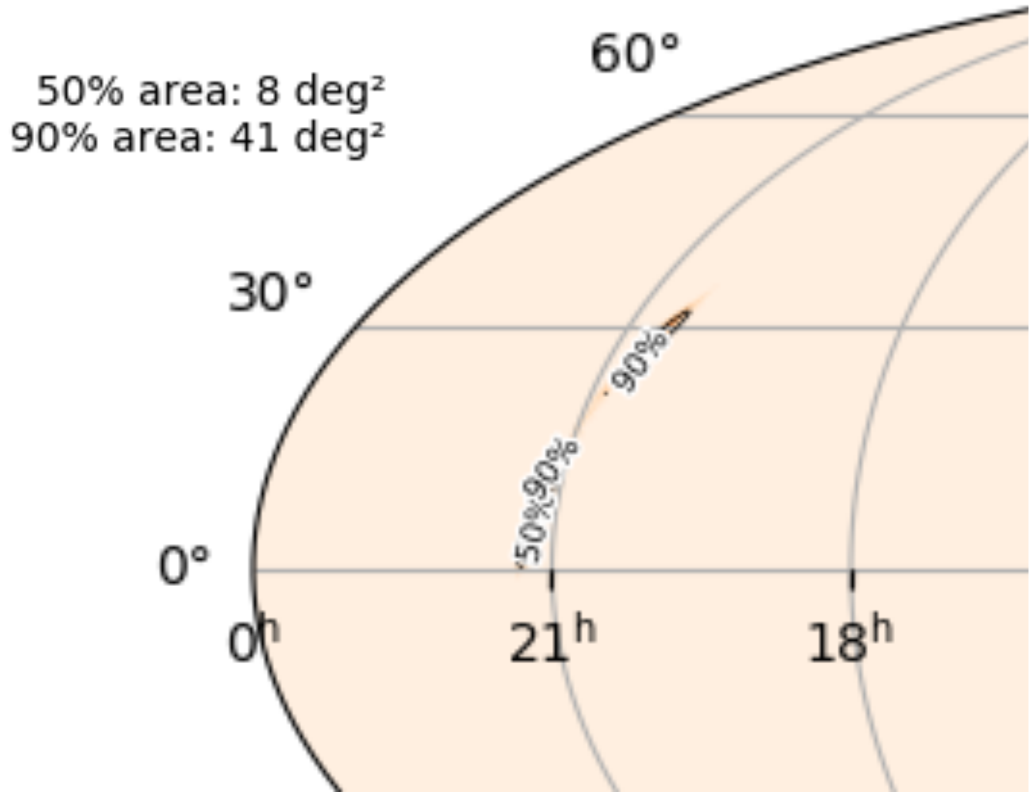
S190901ap
BNS (86%), Terrestrial (14%)
FAR 1/4.5 years,
distance: 241 +/- 79 MPc,
L1,V1 only



https://gracedb.ligo.org/superevents/public/O3/

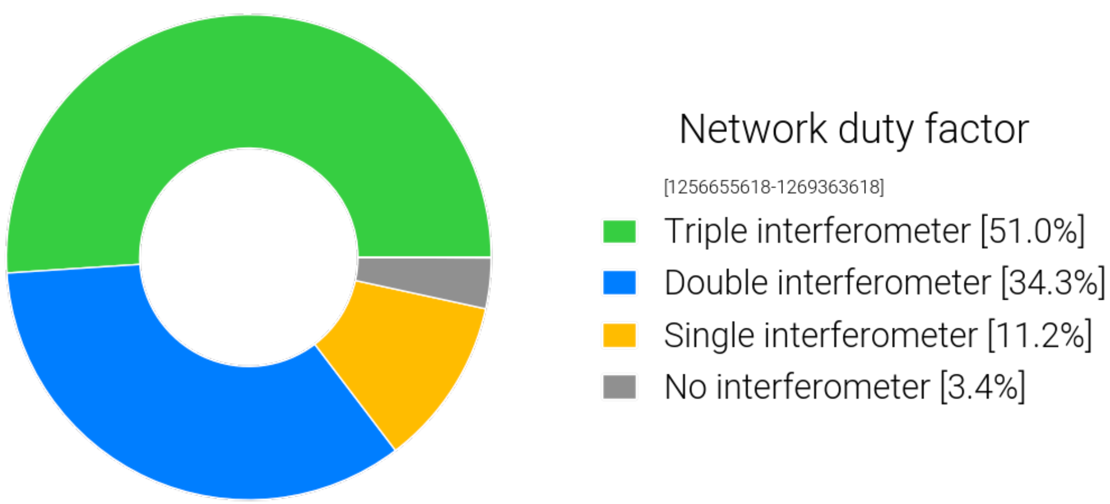
It should look like this

<u>S200129m</u>
BBH >99%
d: 755 +/- 194 MPc
FAR 1/ 4.7e23 years
H1, L1, V1

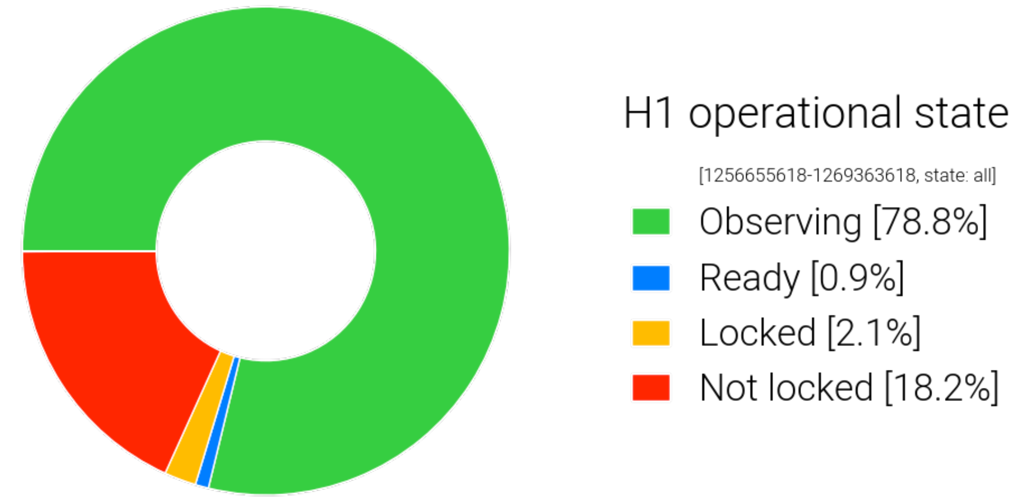


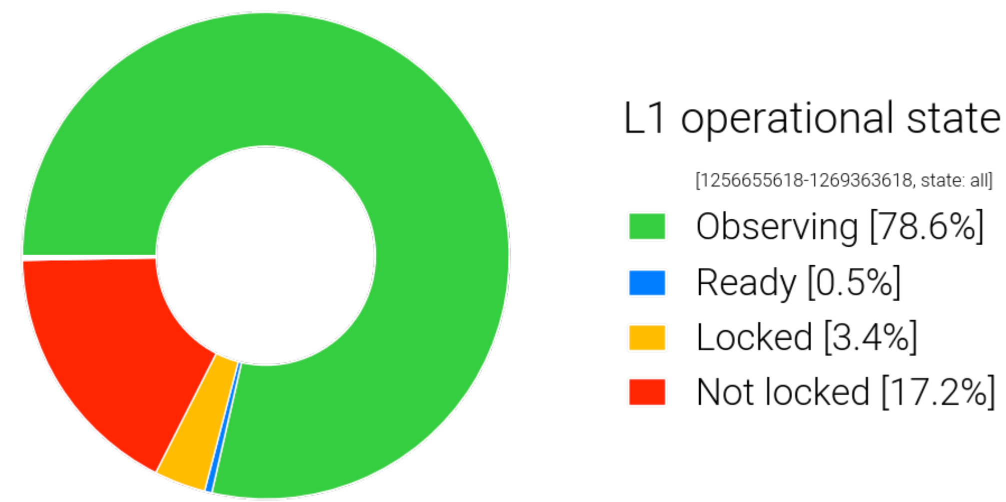
Operational State in O3b

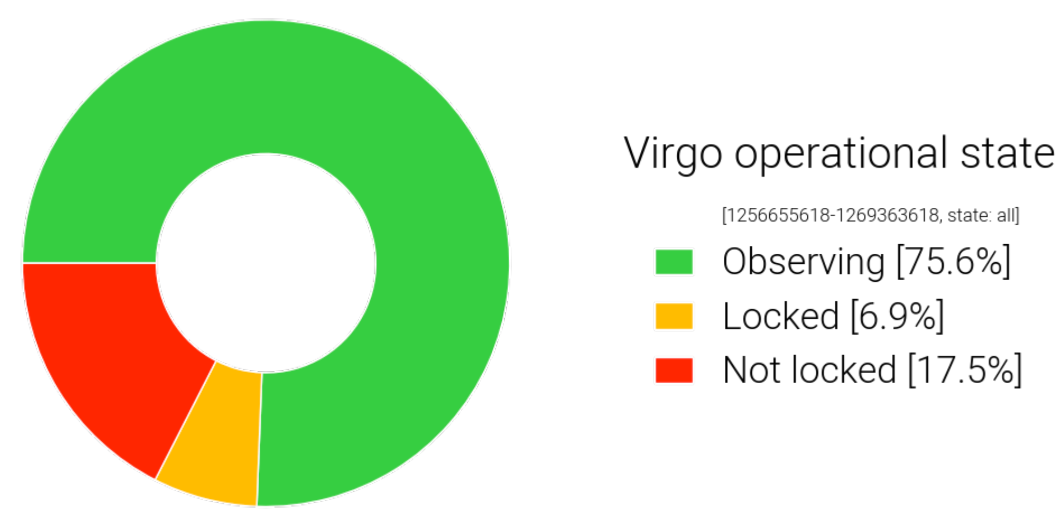
With only 3 detectors, localization is compromised ~50% of the time



When LIGO-India comes online and as KAGRA performance improves, you get
1) Better polarization info,
2) Much better chance of 3-detector coverage of the sky.





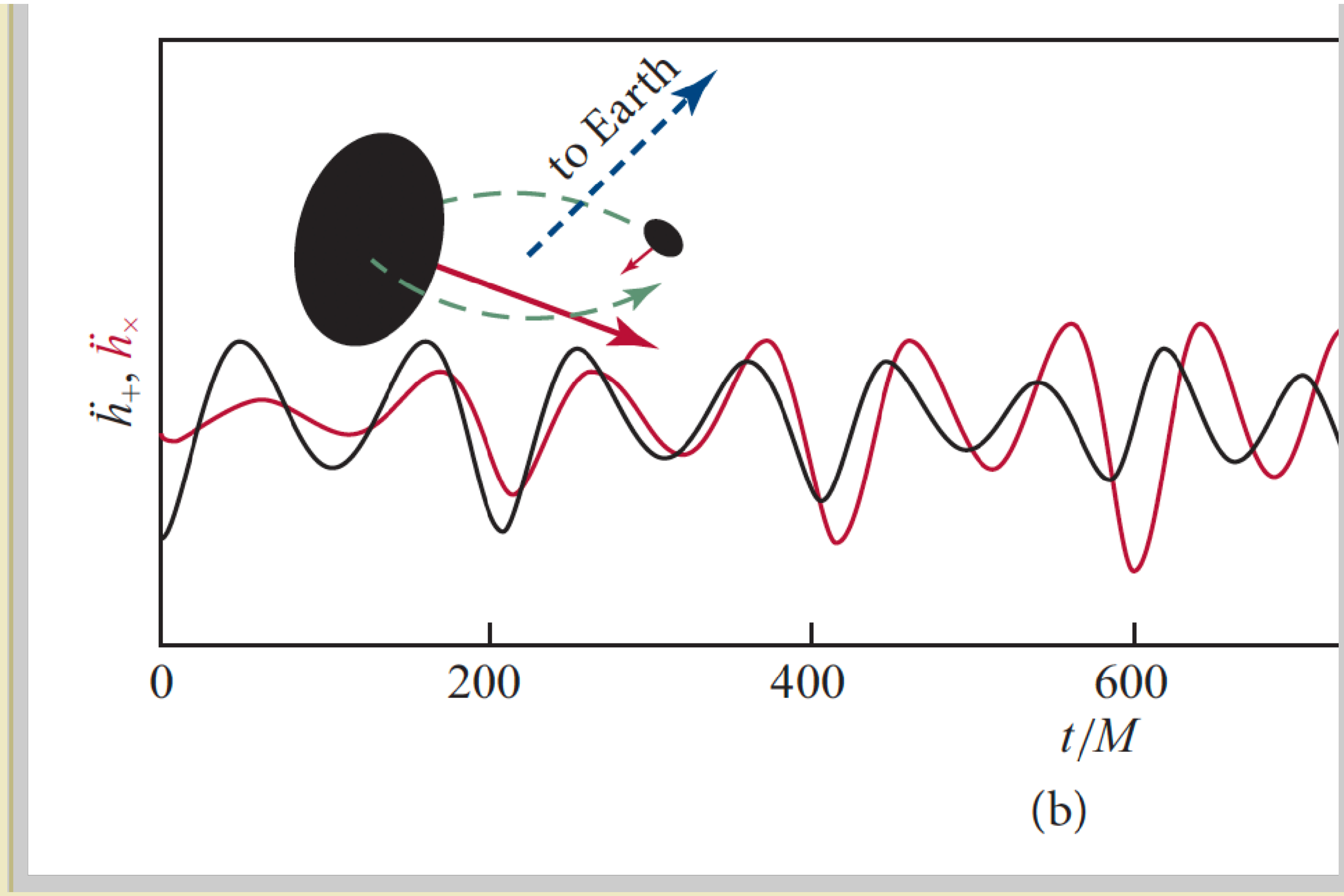


https://summary.ligo.org/~detchar/summary/O3b/

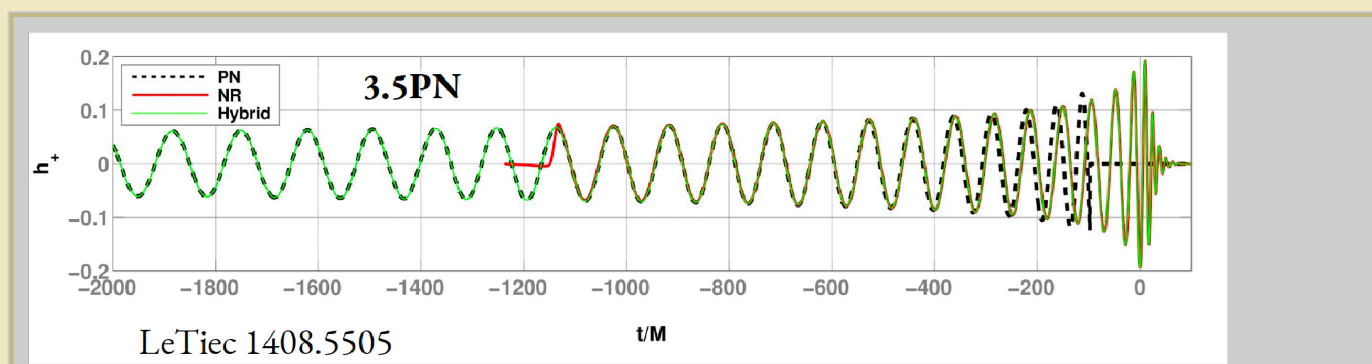
the hope

‘borrowed’ from last week, information about spin, etc, encoded in polarization and waveform evolution.

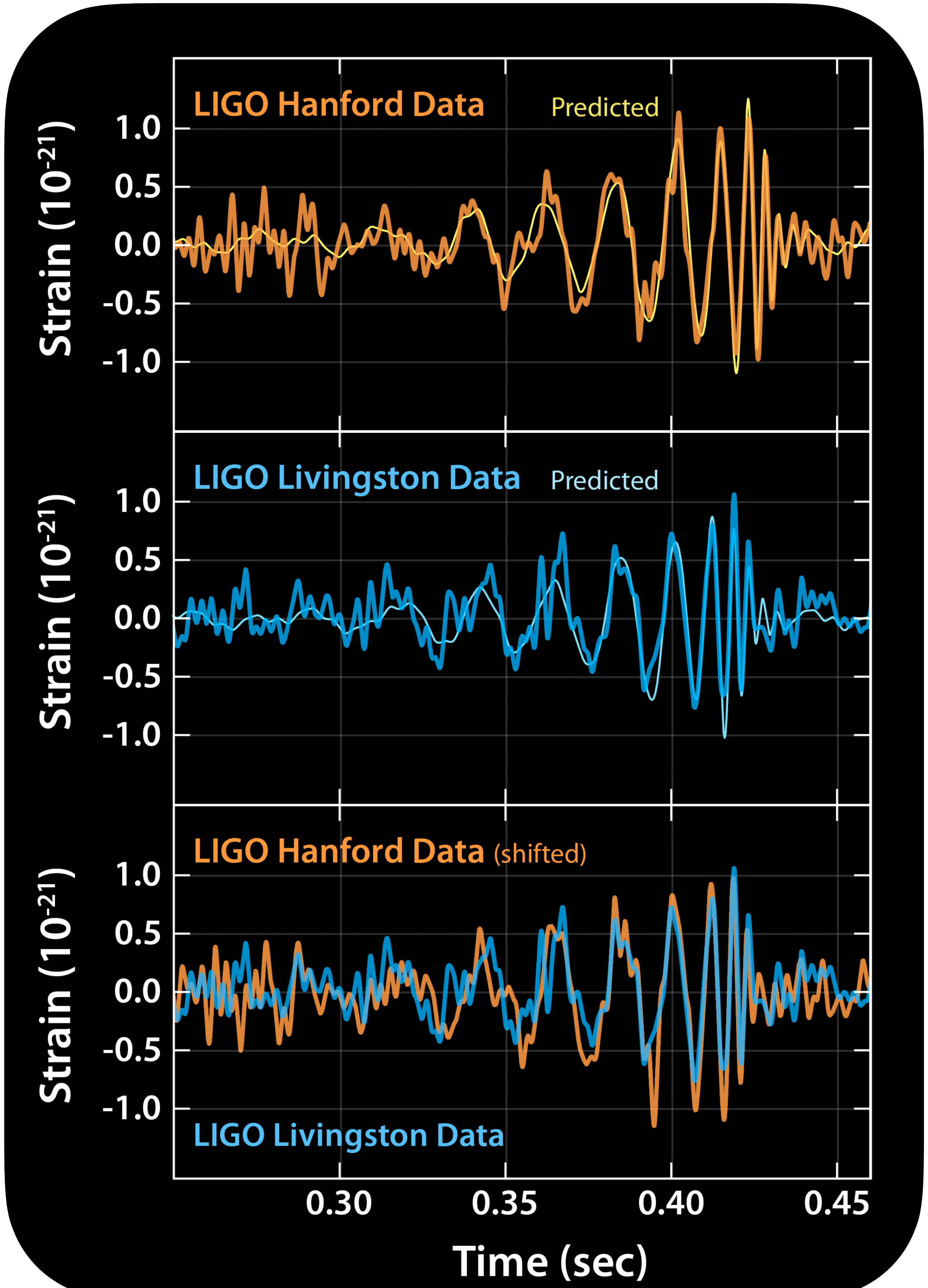
In addition to the physics encoded in the BH spin, this can break the distance/ inclination degeneracy.

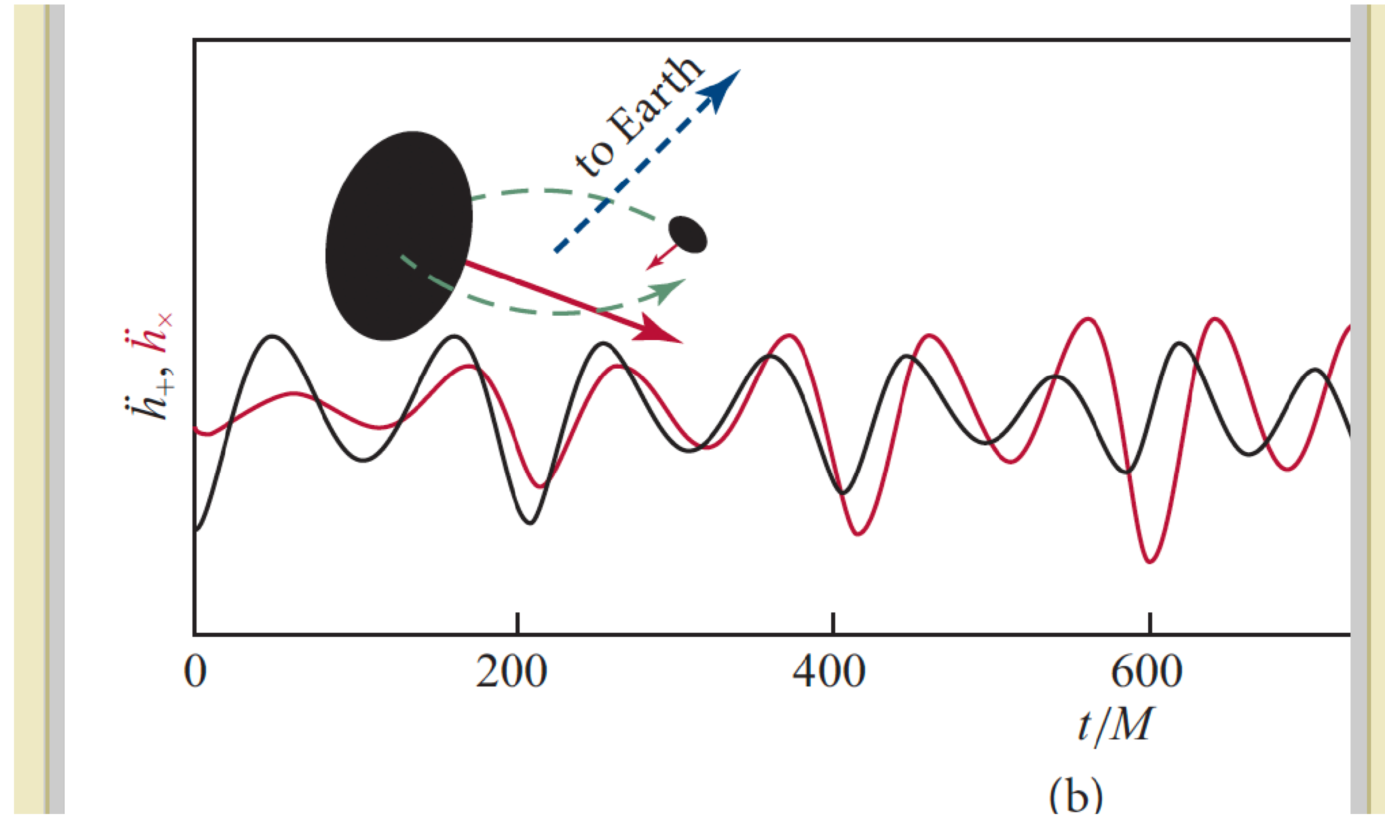


- Perturbation theory
  - Post Newtonian expansion in powers of v ≡ $(m/a)^{1/2}$
  - 1.5 PN is $O(v^3)$ etc- algebraically rich even with symbolic manipulation
  - Perturb near, wave zone metrics and match
  - Different groups getting different answers at the highest order due to subtleties in regularization

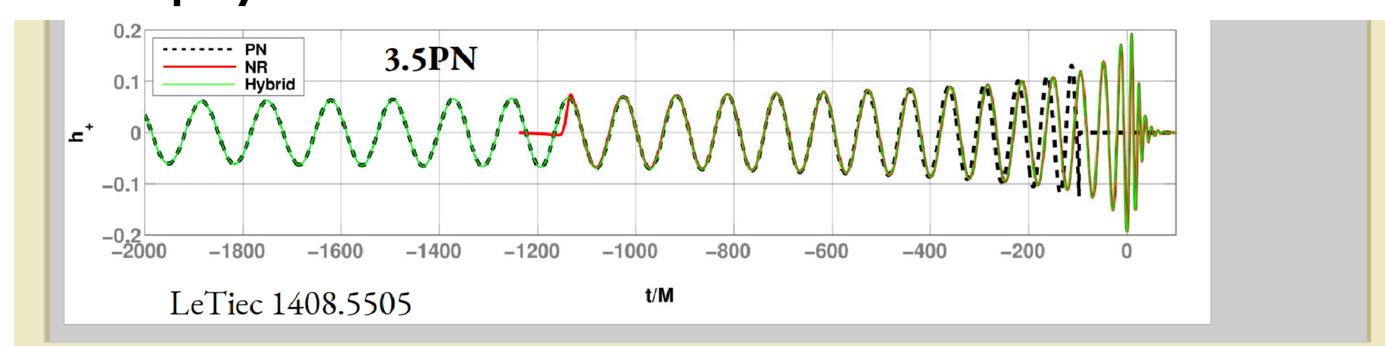


The current capability



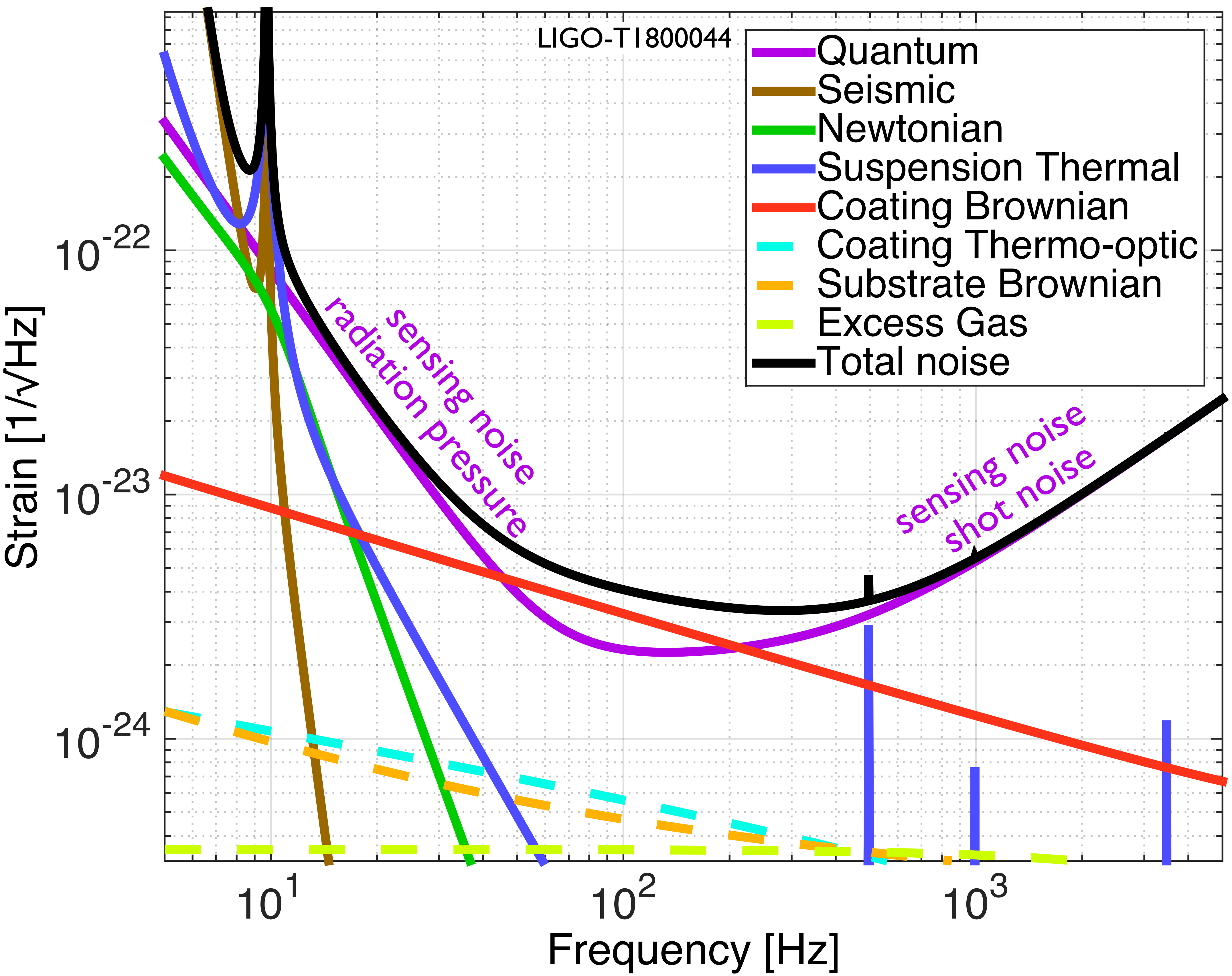


Roughly 8 cycles of good data,
Currently, we don't do much with the data below ~30 Hz.
Better low-frequency noise = better astrophysics.



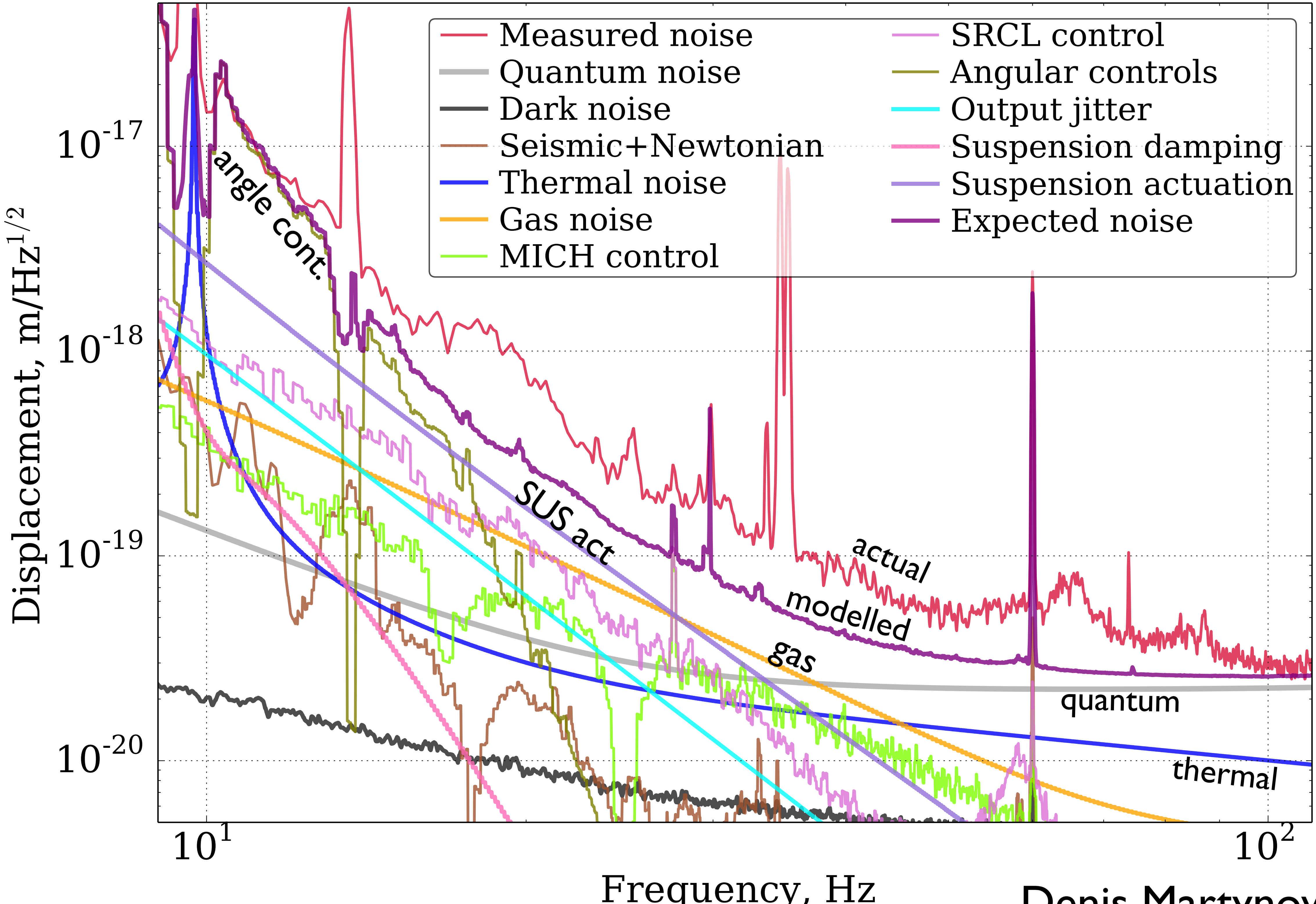
Detector Noise (design)

aLIGO new design curve: NSNS (1.4/1.4 $M_{\odot}$) 173 Mpc and BHBH (30/30 $M_{\odot}$) 1606 Mpc



4e-19 m/rtHz

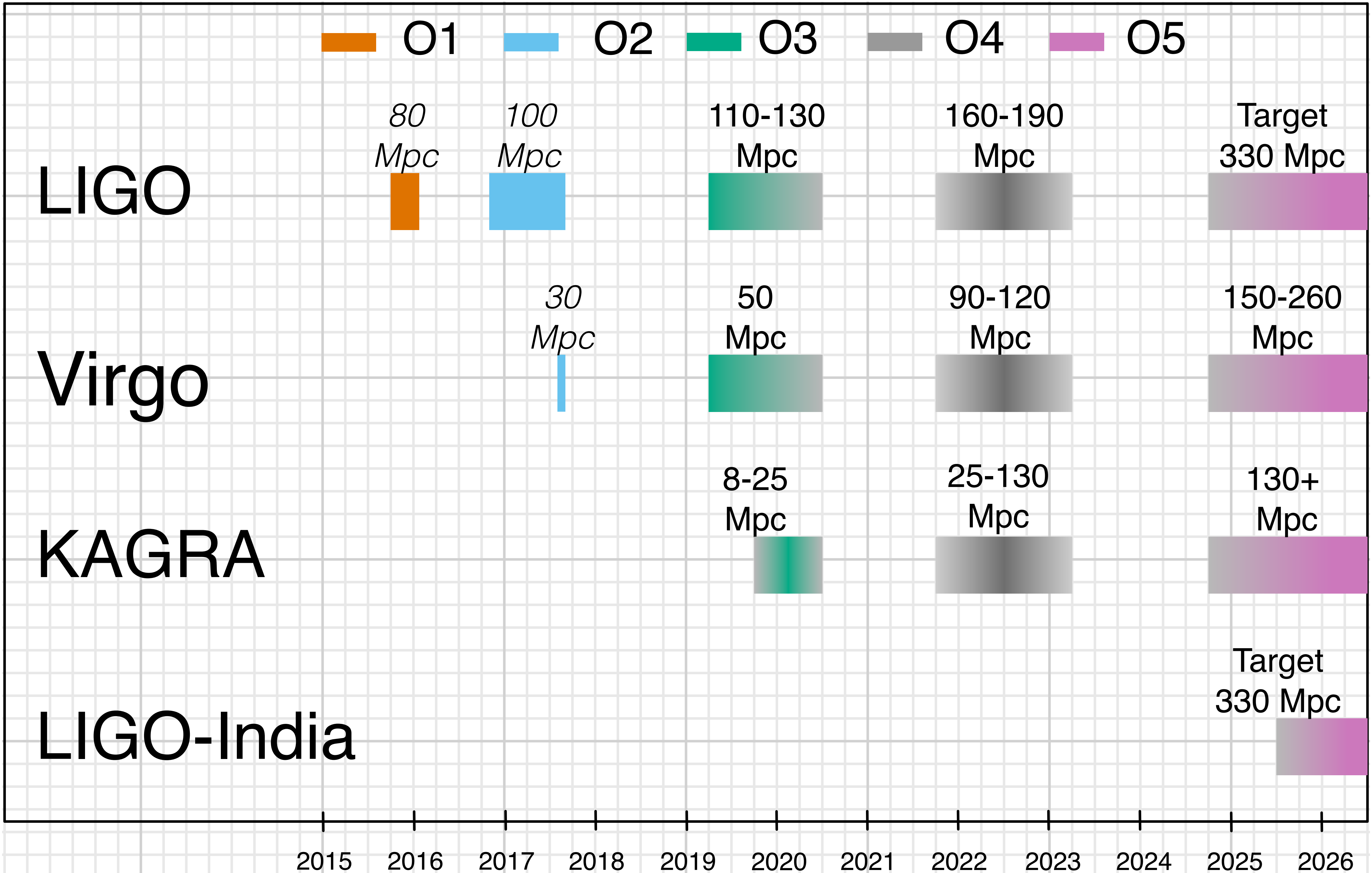
Noise at 10-100 Hz



Denis Martynov, et. al.

(a) LIGO Livingston Observatory

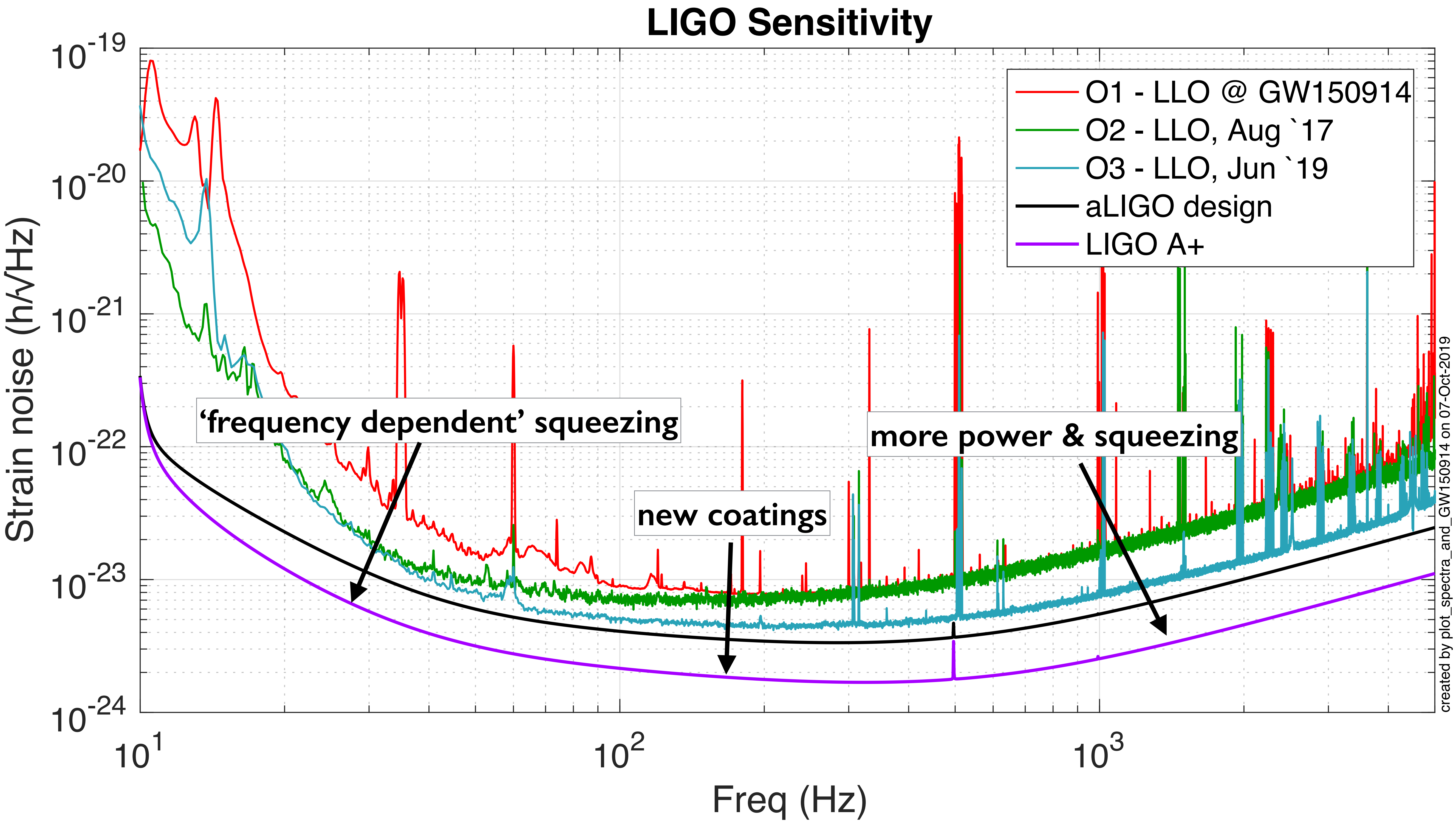
What's next?



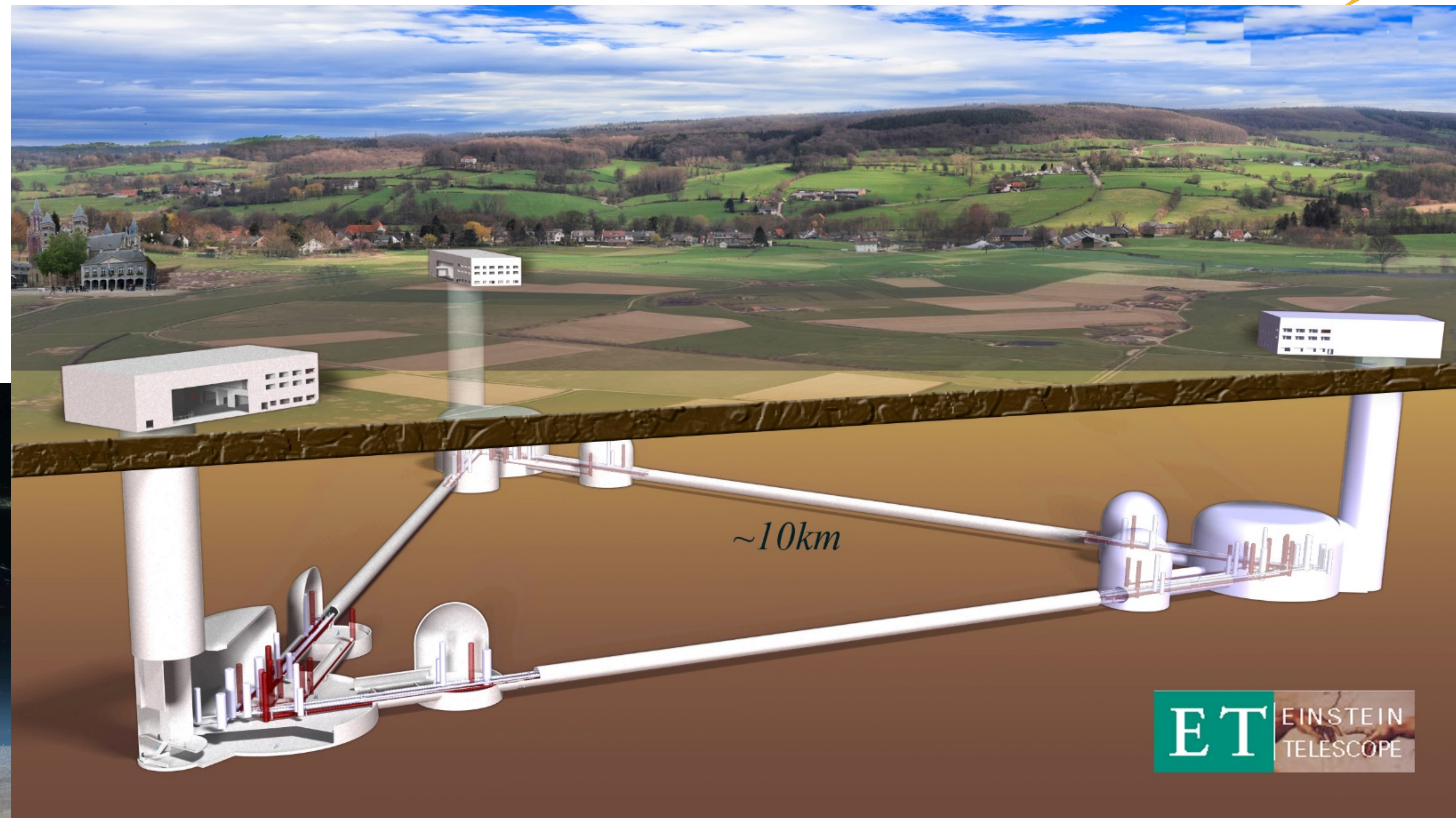
Timeline from: Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA

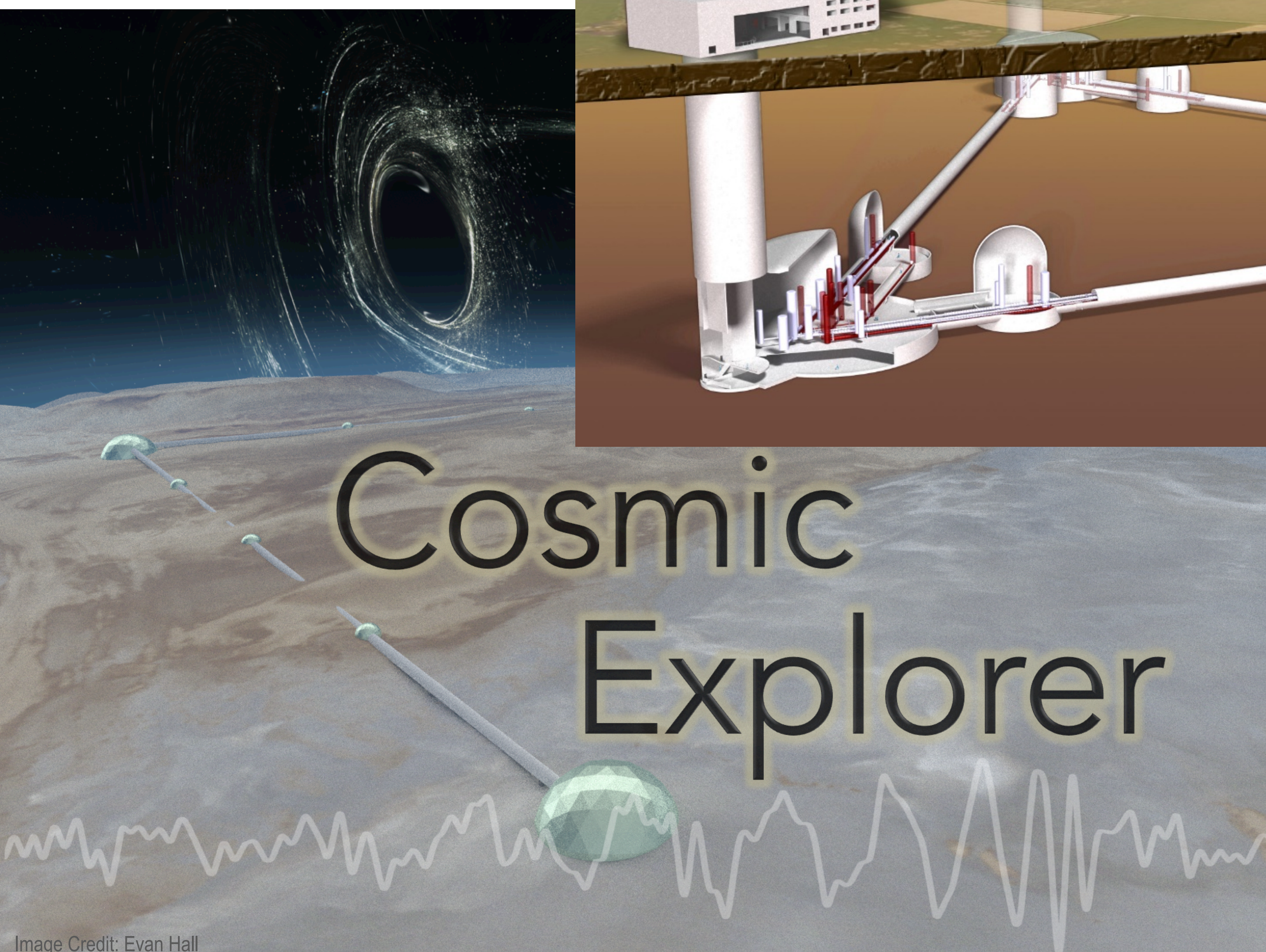
https://doi.org/10.1007/s41114-018-0012-9

LIGO A+ (for O5)

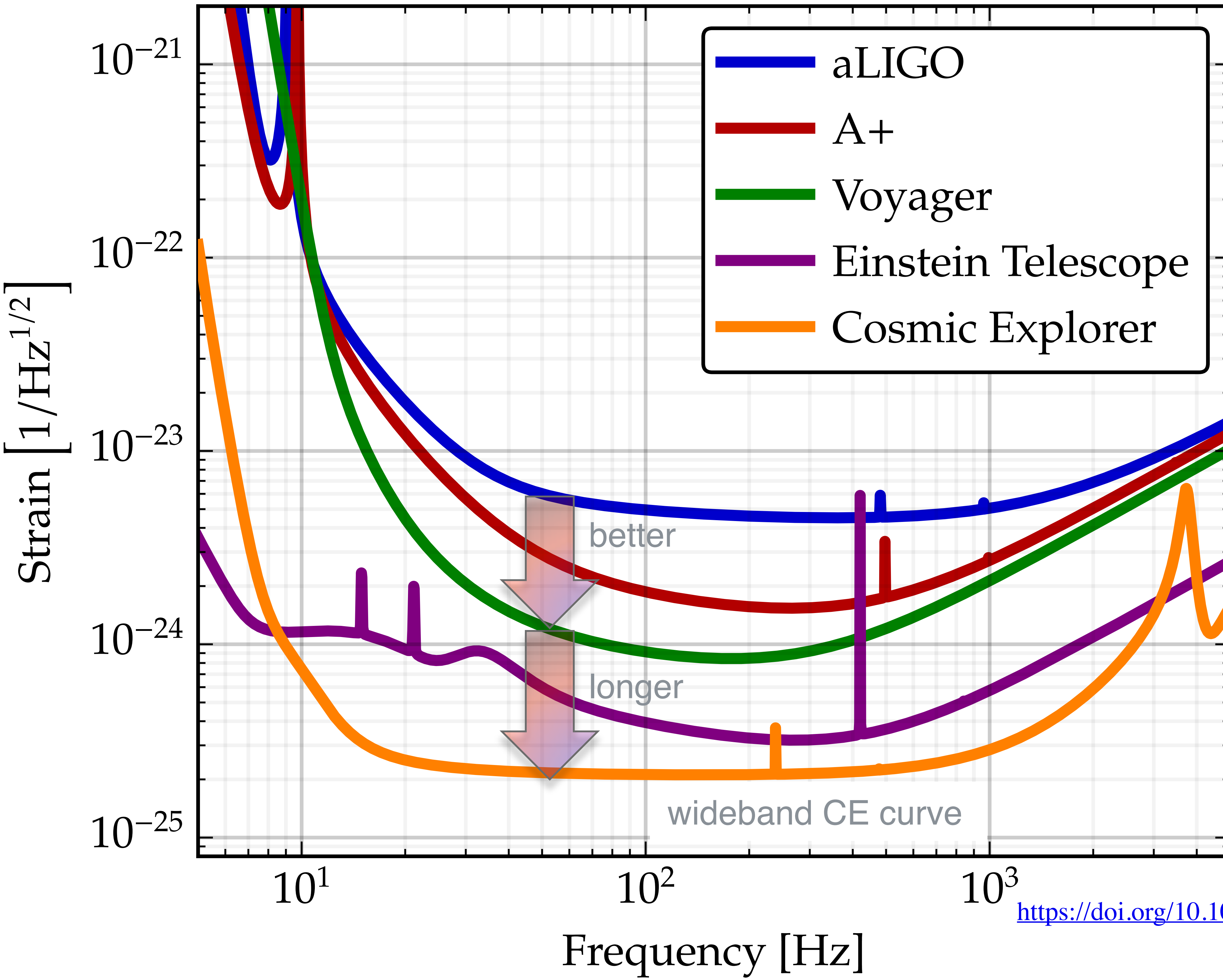

LIGO Sensitivity
Strain noise (h/√Hz)
Freq (Hz)
O1 - LLO @ GW150914
O2 - LLO, Aug `17
O3 - LLO, Jun `19
aLIGO design
LIGO A+
'frequency dependent' squeezing
new coatings
more power & squeezing
created by plot_spectra_and_GW150914 on 07-Oct-2019

3G detectors



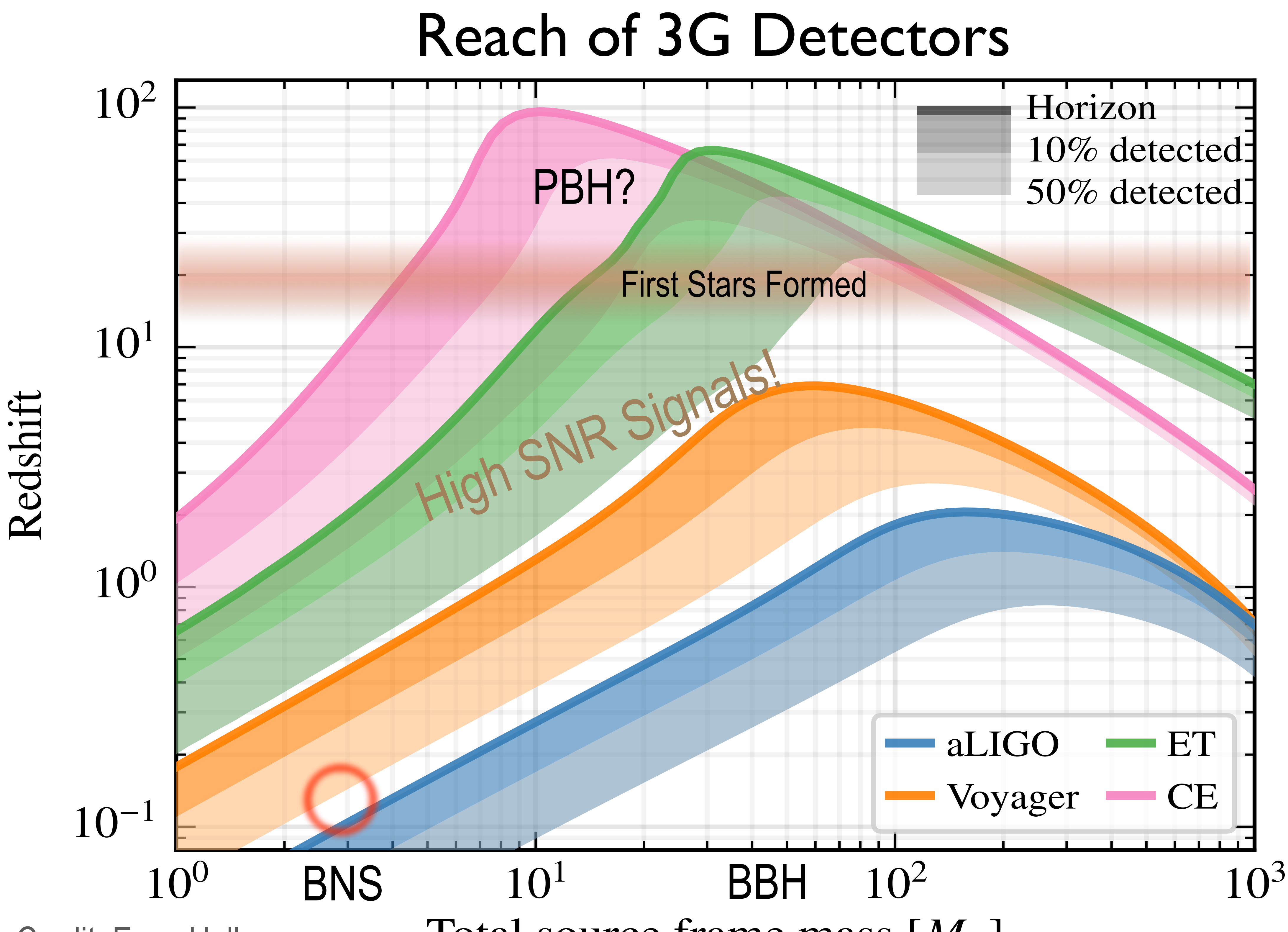


3G detectors



https://doi.org/10.1088/1361-6382/aa51f4

How much could we see?



Credit: Evan Hall