LIGO: The Current Observation Run and Future Upgrades

Daniel Sigg

LIGO Hanford Observatory
California Institute of Technology

February 2020

For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G2000229-v2

Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.

LIGO Scientific Collaboration

Albert-Einstein-Institut
American University
Andrews University
Bar-Ilan University
Bard College
Bellevue College
California Institute of Technology
California State Univ., Fullerton
California State Univ., Los Angeles
Carleton College
Chinese University of Hong Kong
Christopher Newport University
Colorado State University
Columbia U. in the City of New York
Concordia University, Wisconsin
Cornell University
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
GW-INPE, Sao Jose Brasil
Haverford College
Hillsdale College
Hobart & William Smith Colleges
IAP – Nizhny Novogorod
IIP-UFRN
Kenyon College
Louisiana State University
Maastricht University
Marquette University
Marshall Space Flight Center
Missouri University of Science & Technology
Montana State University
Montclair State University
Moscow State University
National Tsing Hua University

NCSARG – Univ. of Illinois, Urbana-Champaign
Northwestern University
Penn State University
Rochester Institute of Technology
Sonoma State University
Southern University
Stanford University
Stony Brook / CCA
Syracuse University
Texas Tech University
Tsinghua University
U. Montreal / Polytechnique
University of Arizona
University of Brussels
University of California, Berkeley
University of Chicago
University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Oregon
University of Rhode Island
University of Sannio
University of Santiago de Compostela
University of Szeged
University of Texas at Austin
University of Texas Rio Grande Valley
University of the Balearic Islands
University of Tokyo
University of Utah
University of Washington
University of Washington Bothell
University of Wisconsin – Milwaukee
USC – Information Sciences Institute
Villanova University
West Virginia University

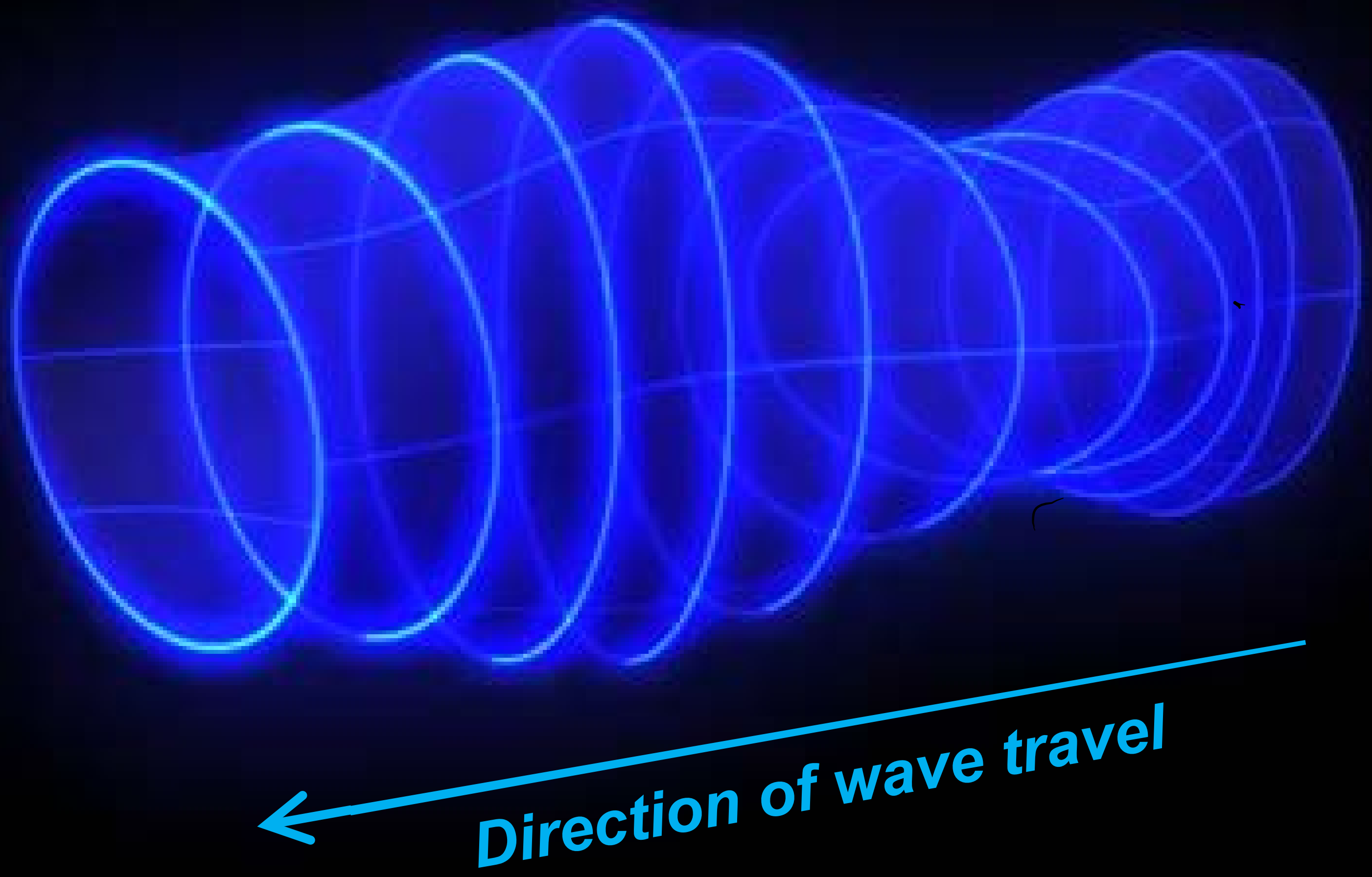
LIGO Laboratory: California Institute of Technology; Massachusetts Institute of Technology; LIGO Hanford Observatory; LIGO Livingston Observatory

ARC Centre of Excellence For Gravitational Wave Discovery (OzGrav):
Australian National University; Charles Sturt University; Monash University; Swinburne University of Technology; University of Adelaide; The University of Melbourne; University of Western Australia

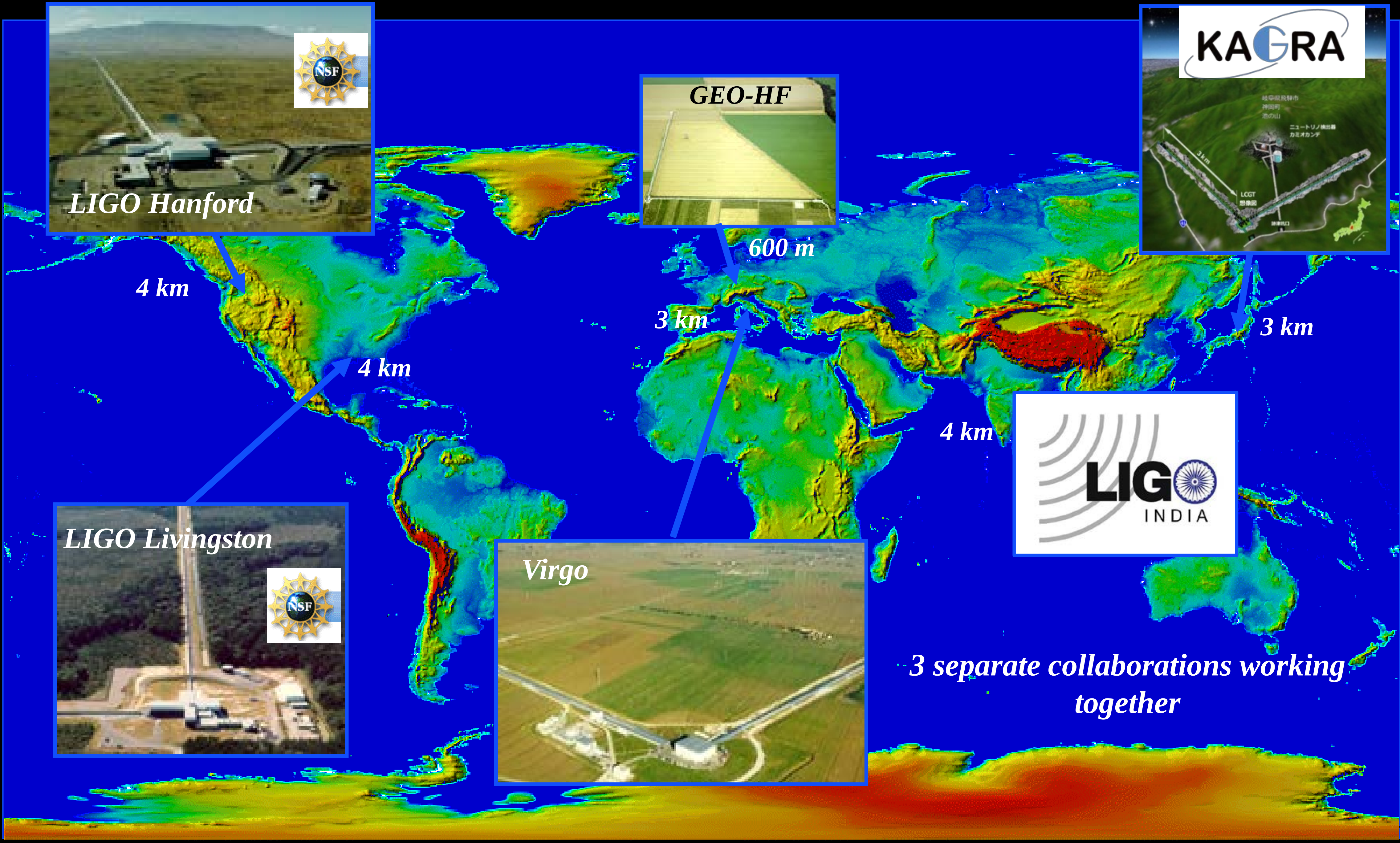
German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Albert-Einstein-Institut, Hannover; Cardiff University; King's College, University of London; Lancaster University, Leibniz Universität, Hannover; Rutherford Appleton Laboratory; University of Birmingham; University of Cambridge; University of Glasgow; University of Hamburg; University of Portsmouth; The University of Sheffield; University of Southampton; University of Strathclyde; University of the West of Scotland; University of Zurich

Korean Gravitational Wave Group (KGWG)
Ewha Womans University; Hanyang University; Inje University; Korea Astronomy and Space Science Institute; Korea Institute of Science and Technology Information;
National Institute for Mathematical Sciences; Pusan National University; Seoul National University; Ulsan National Institute of Science and Technology

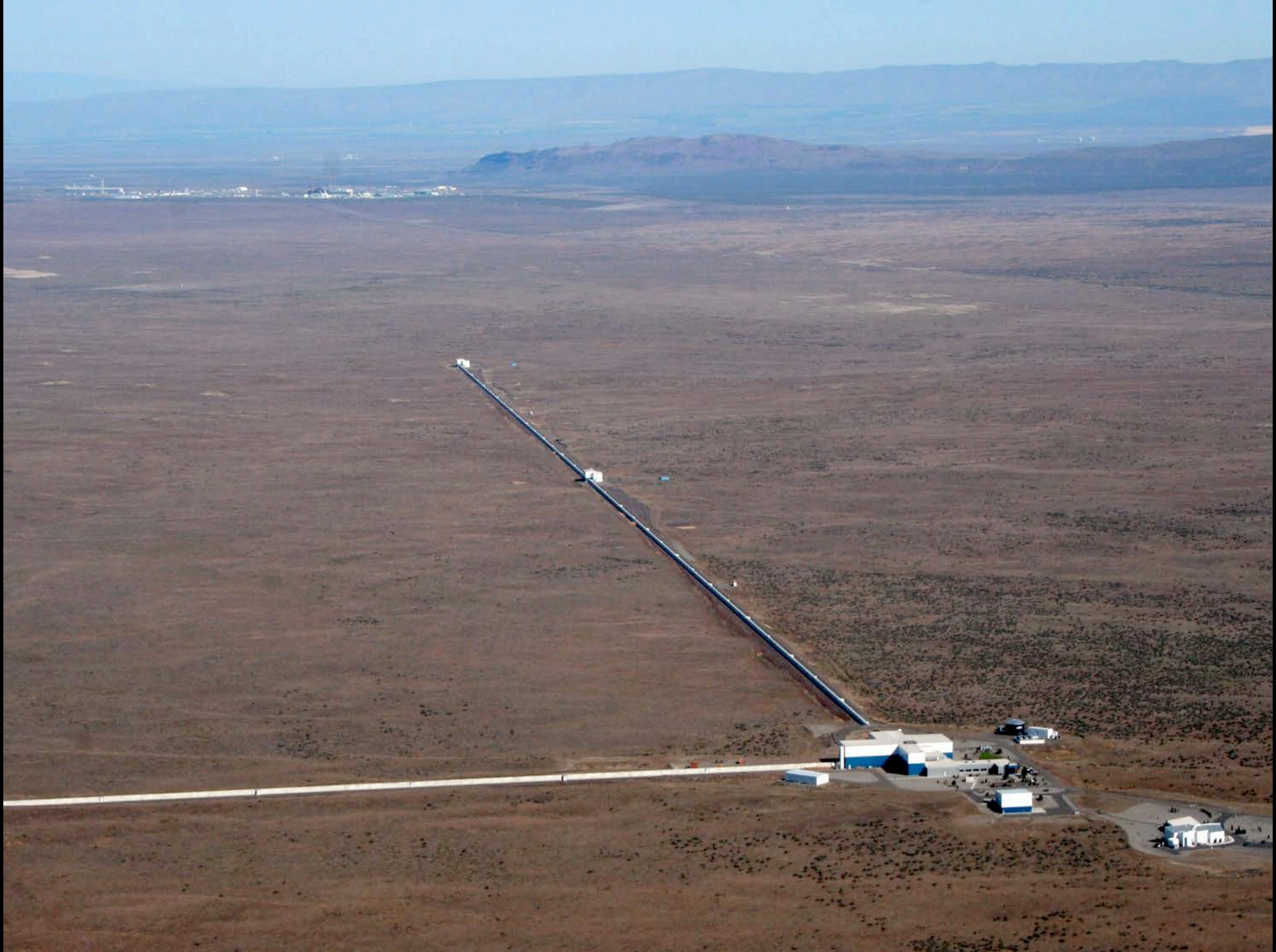
LIGO India Scientific Collaboration (LISC)
Chennai Mathematical Institute; DCSEM, Mumbai; IISER-Kolkata; IISER-Pune; IIT-Bombay; IIT-Gandhinagar; IIT-Hyderabad; IIT-Madras; IPR-Gandhinagar; ICTS-TIFR, Bengaluru; IUCAA, Pune; RRCAT, Indore; TIFR, Mumbai


Direction of wave travel

The Growing Network



Hanford Observatory



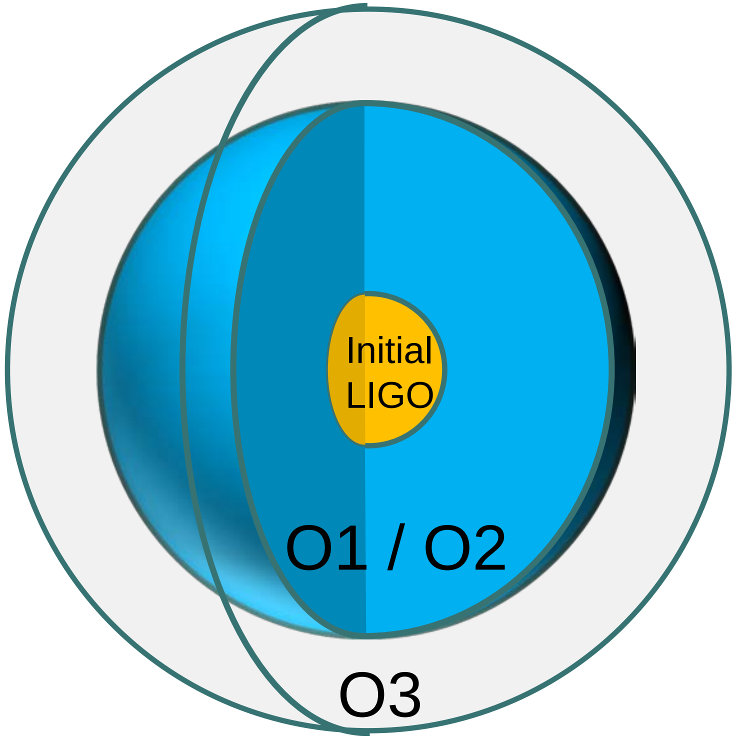
Livingston Observatory

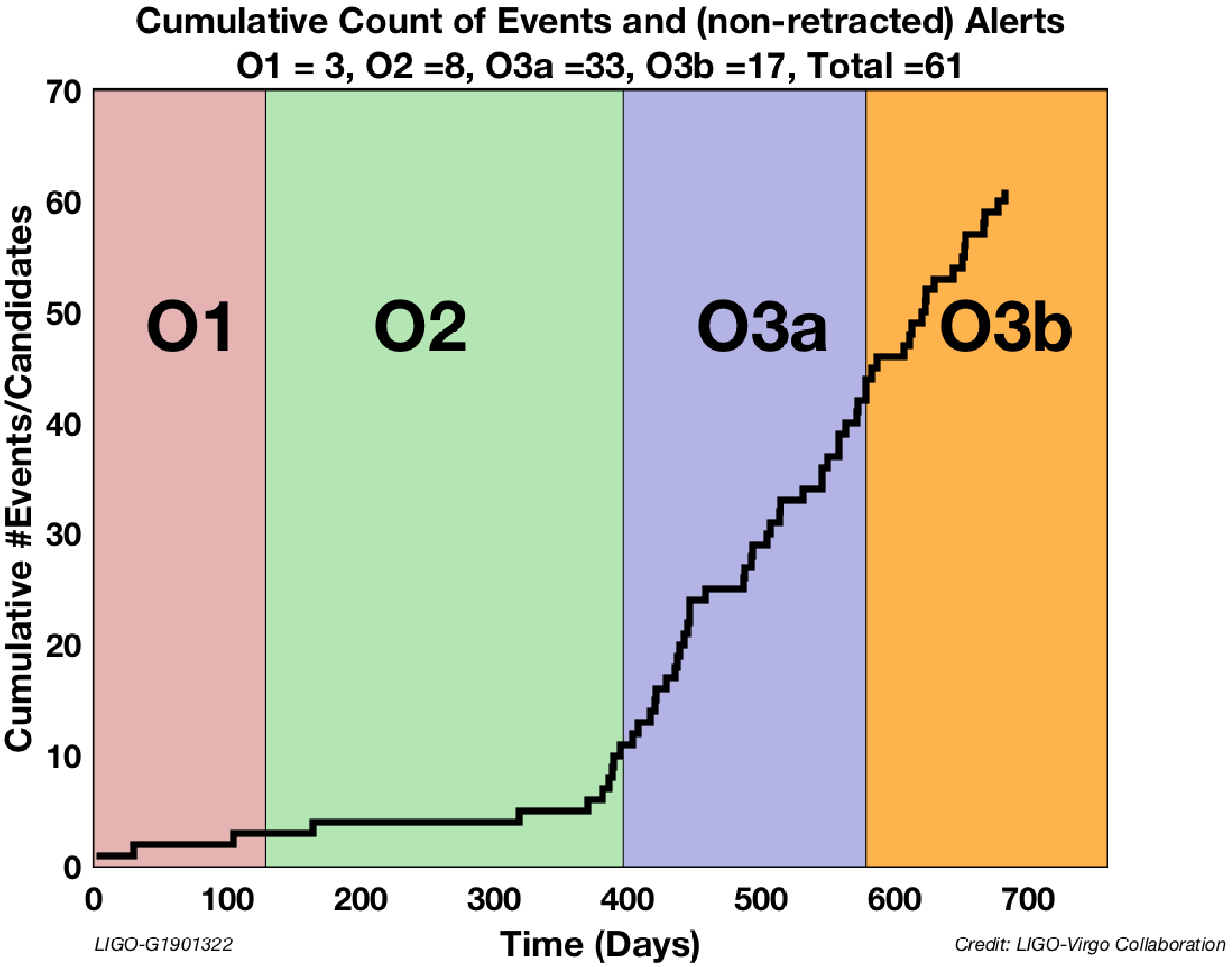
Events / Public Alerts

Events: 61 / O3: 50

Sharp increase of event rate in O3 due to sensitivity improvements

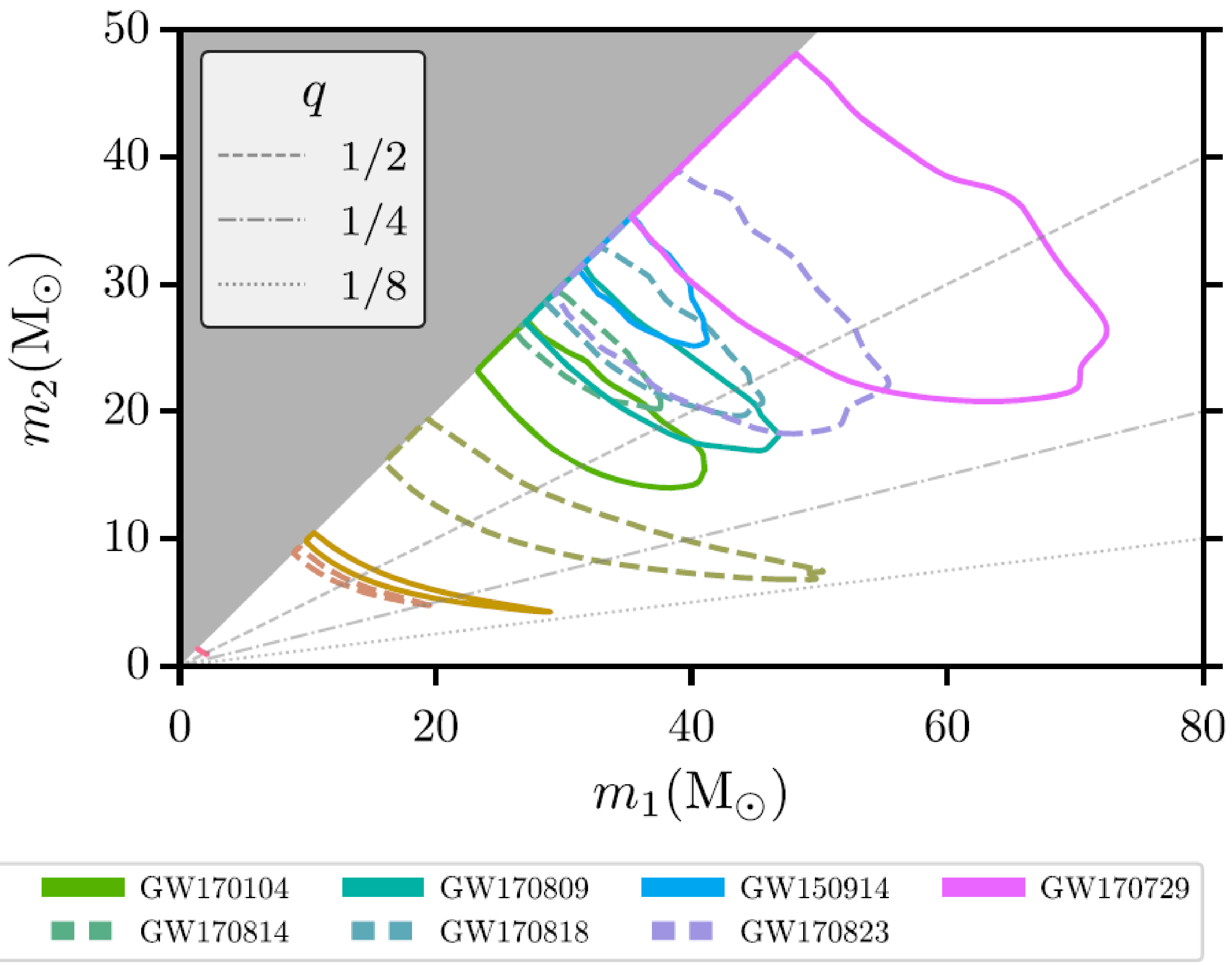
gracedb.ligo.org

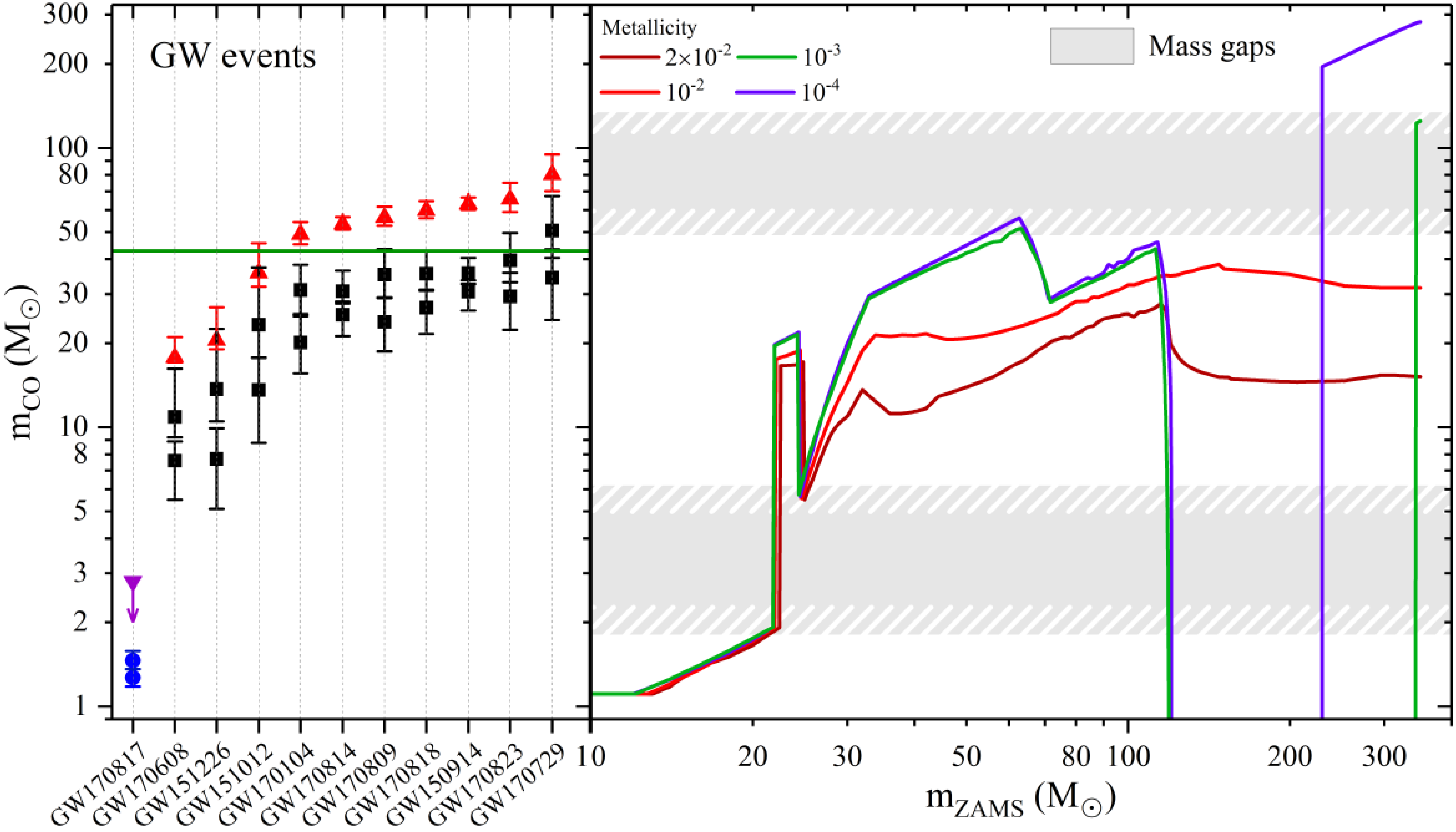




Events confidently detected in O1+O2: the GWTC-1 catalog

- Abbott et al. (LSC+Virgo) 2019, Phys Rev X 9, 031040
- Ten binary black hole (BBH) mergers plus one binary neutron star (BNS) merger!
- Mass ratio (***q***) consistent with 1 for all these events, but with significant uncertainty



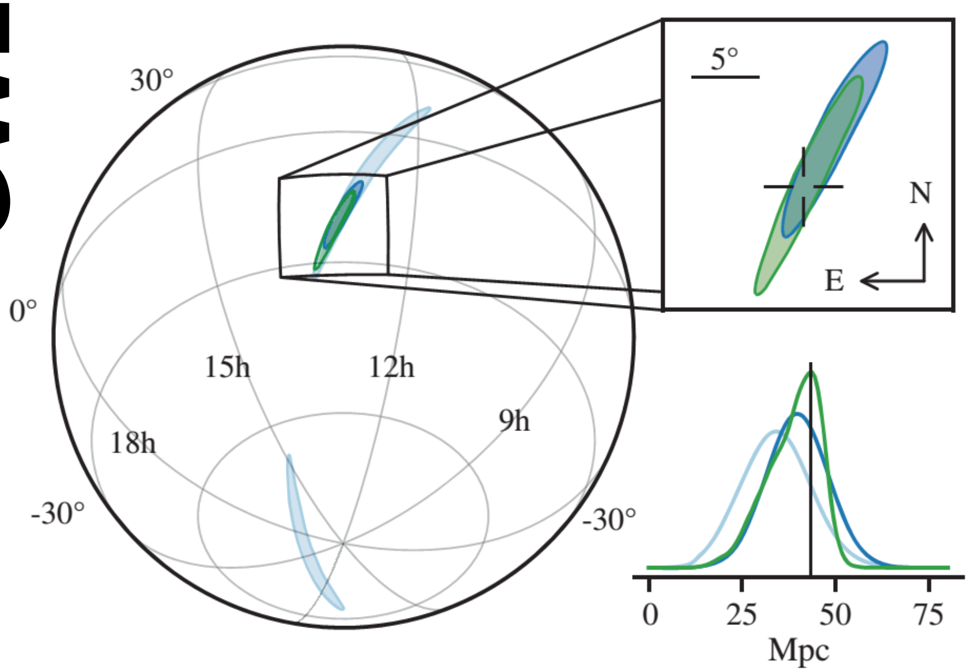

GW events
Metallicity
2×10⁻²
10⁻³
10⁻²
10⁻⁴
Mass gaps
m_{CO} ($M_\odot$)
m_{ZAMS} ($M_\odot$)
GW170817
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729

Binary Neutron Star Merger

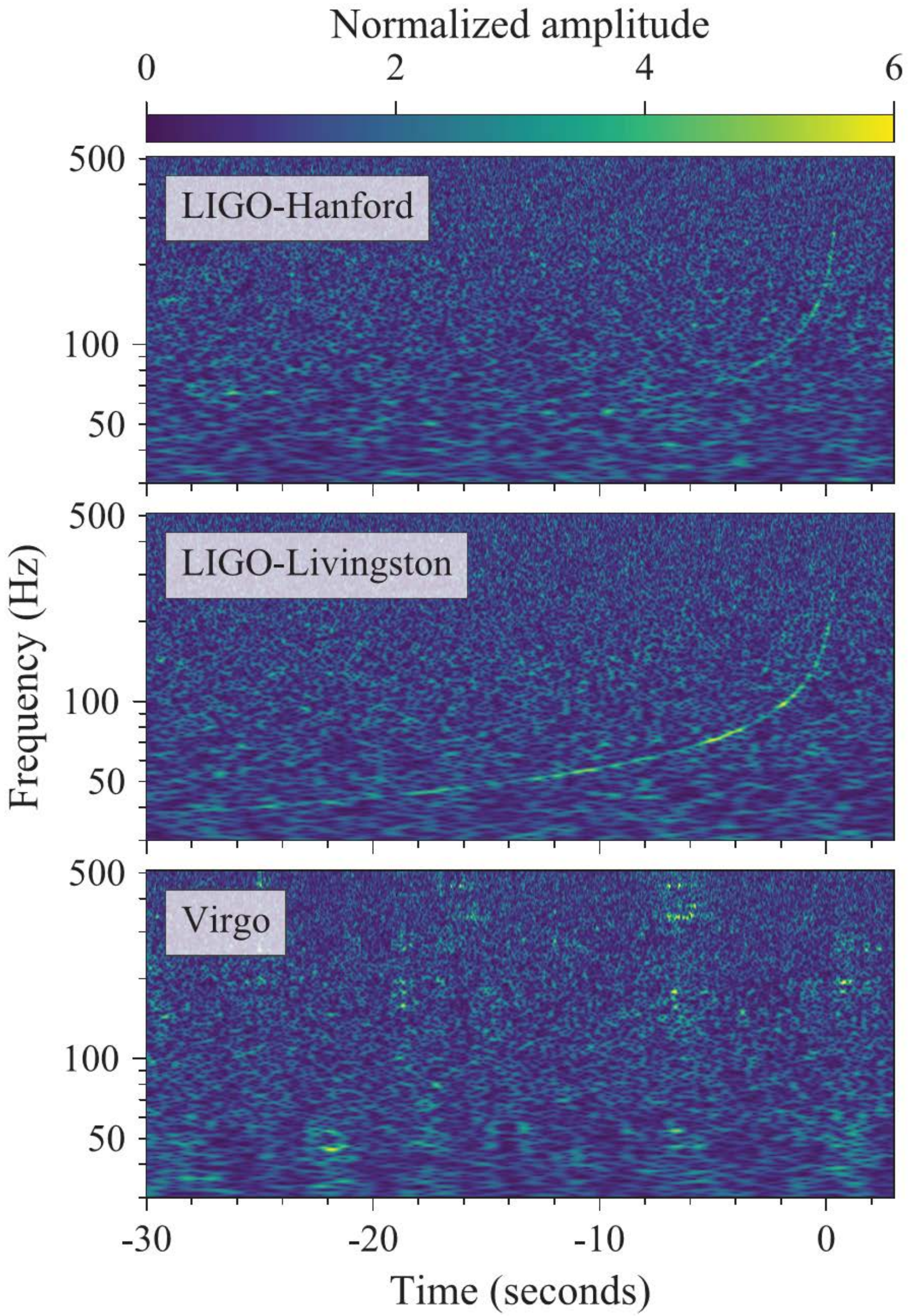
- Initially found using a template with typical neutron star masses
- And coincident (within ~2 sec) with a short GRB!

GW170817

- ❑ Visible in LIGO spectrograms!
- ❑ We localized it pretty well in the sky
  - Initially to an area of ~31 deg, ultimately to ~16 deg^2

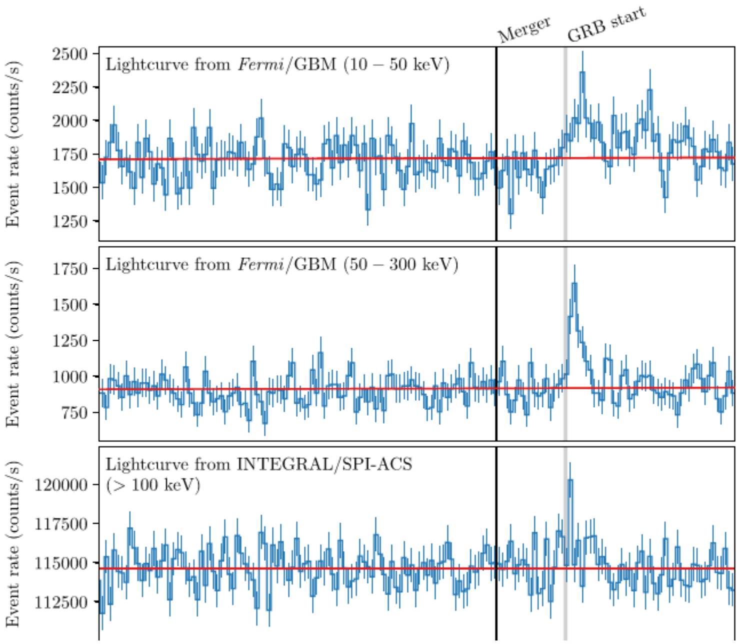


[Abbott et al. 2017, PRL 119, 161101]



GRB 170817A / AT2017gfo Electromagnetic Signatures

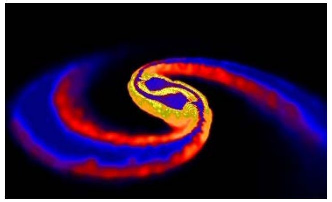
Gamma-Ray Burst



[LSC, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

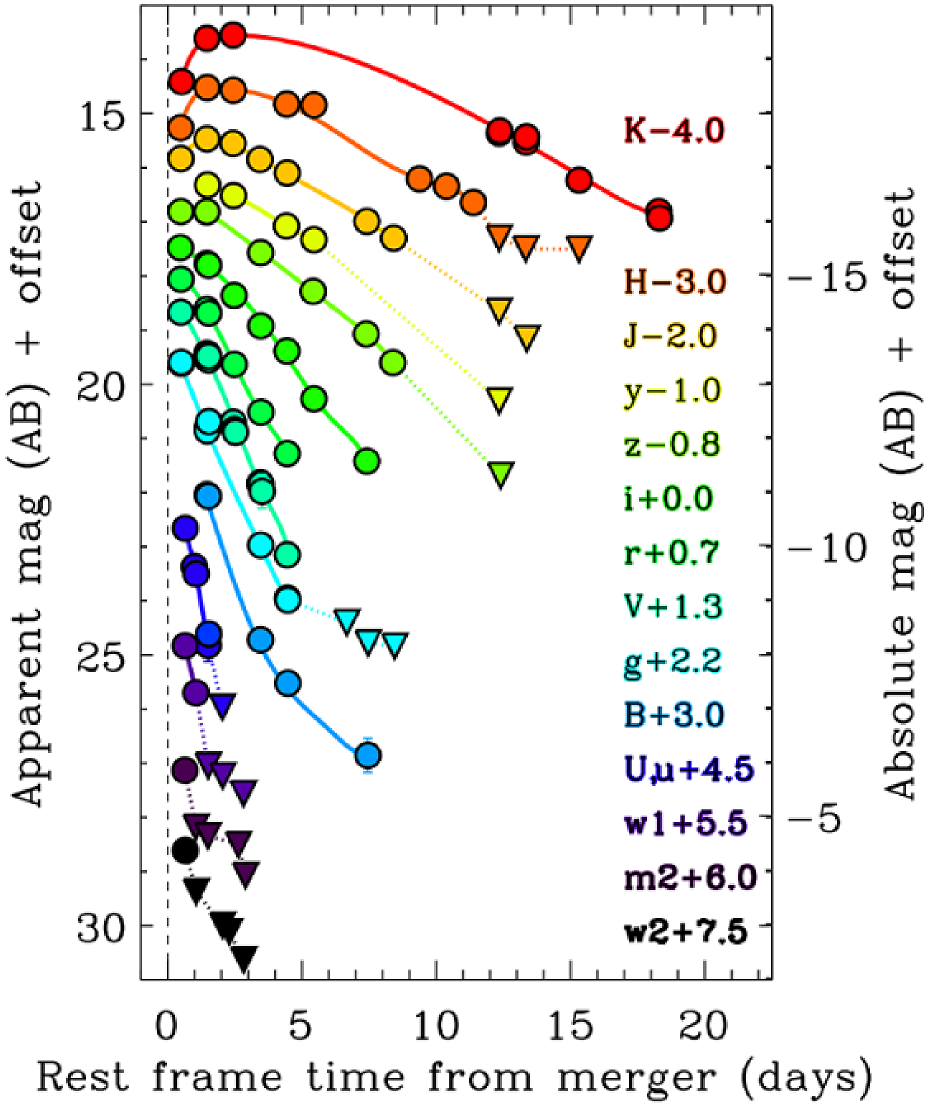
Pretty typical observed properties, but very dim (i.e., low E_{iso}) considering how close it was

Kilonova



[Price/Rosswog/Press]

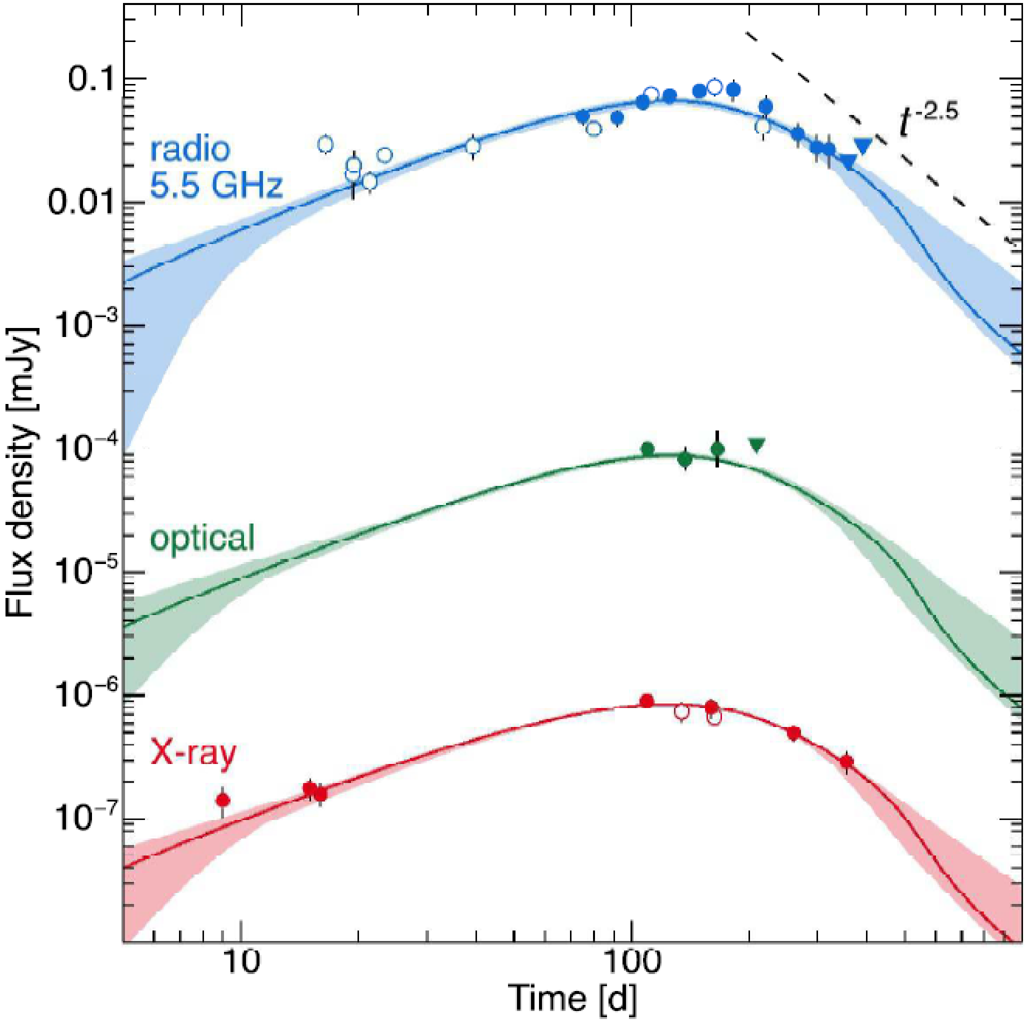
Thermal emission from ejected material, heated by decay of r-process elements formed in event



[Drout et al. 2017, Science 10.1126/science.aaq0049]

GRB 170817A / AT2017gfo Electromagnetic Signatures

[Troja et al. 2019, MNRAS 489, 1919]

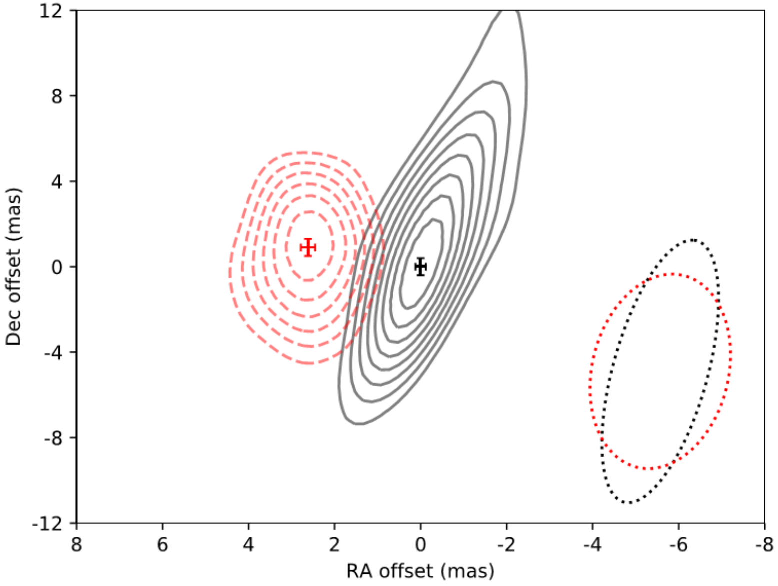


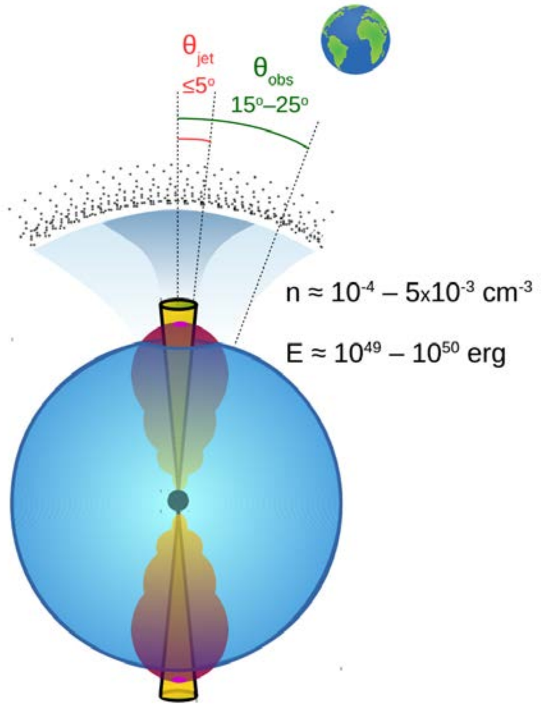
X-ray and radio signals appeared after several days, then brightened for months before fading!

Very-high-resolution radio imaging of the remnant saw the expanding jet!

[Mooley et al., arXiv:1806.09693]

From 75 to 230 days after merger, position shifted ~2.7 milli-arcseconds





Afterglow

Consistent with a relativistic jet viewed ~20 degrees off-axis

GW190425

First published O3 event

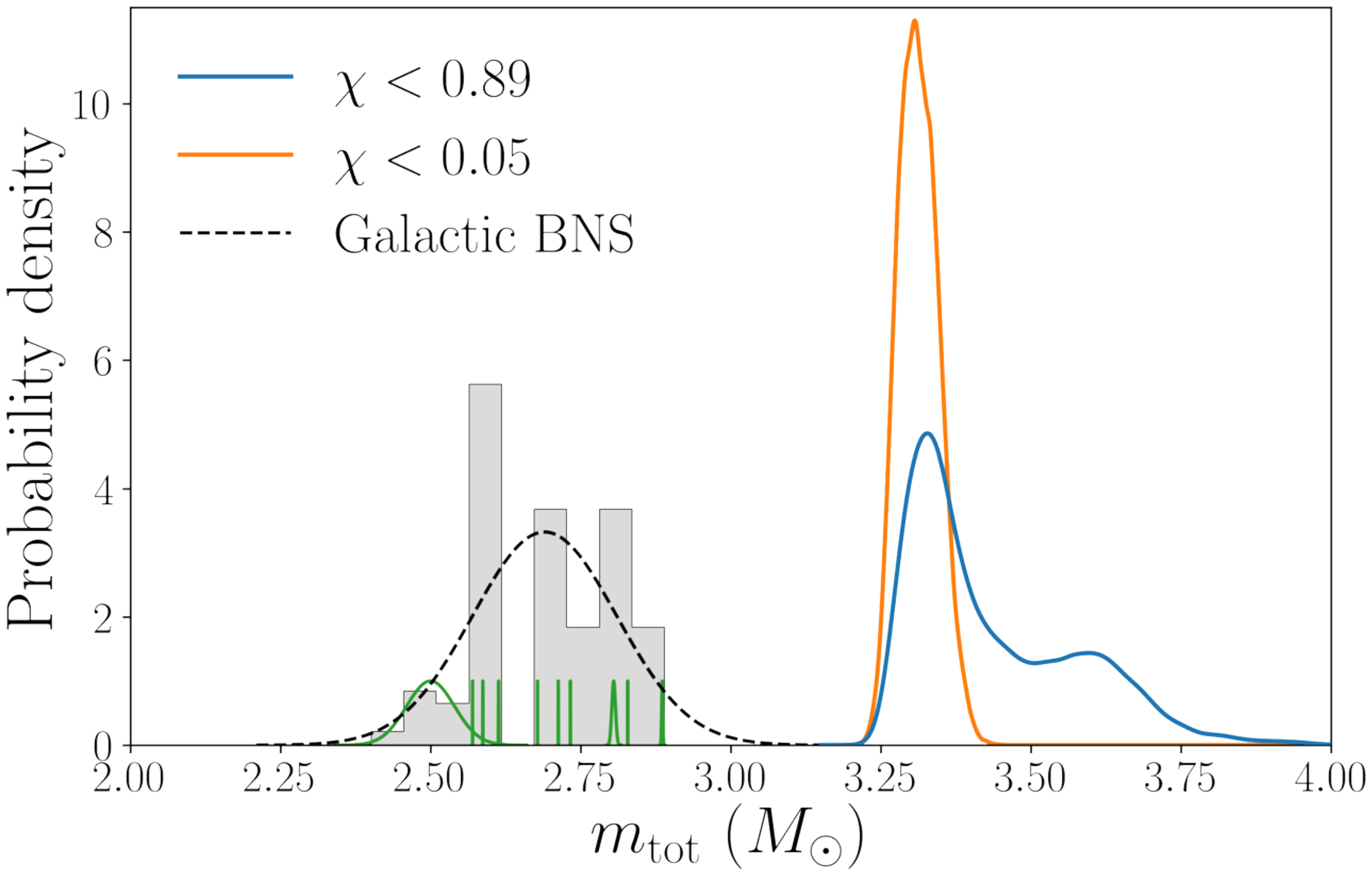
2^{nd} Binary Neutron Star Merger

Distinguished from galactic distribution

Overall heavier

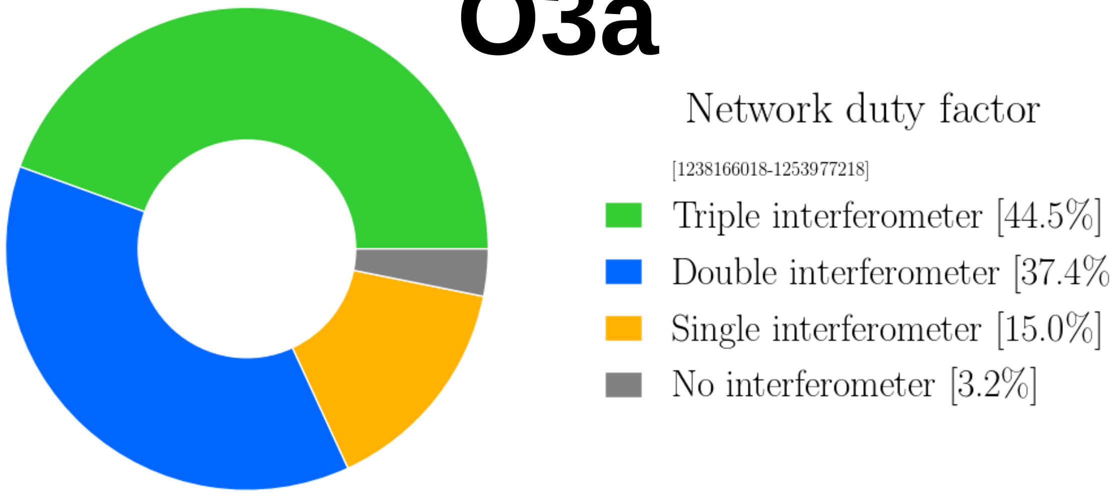
No EM counterpart observed

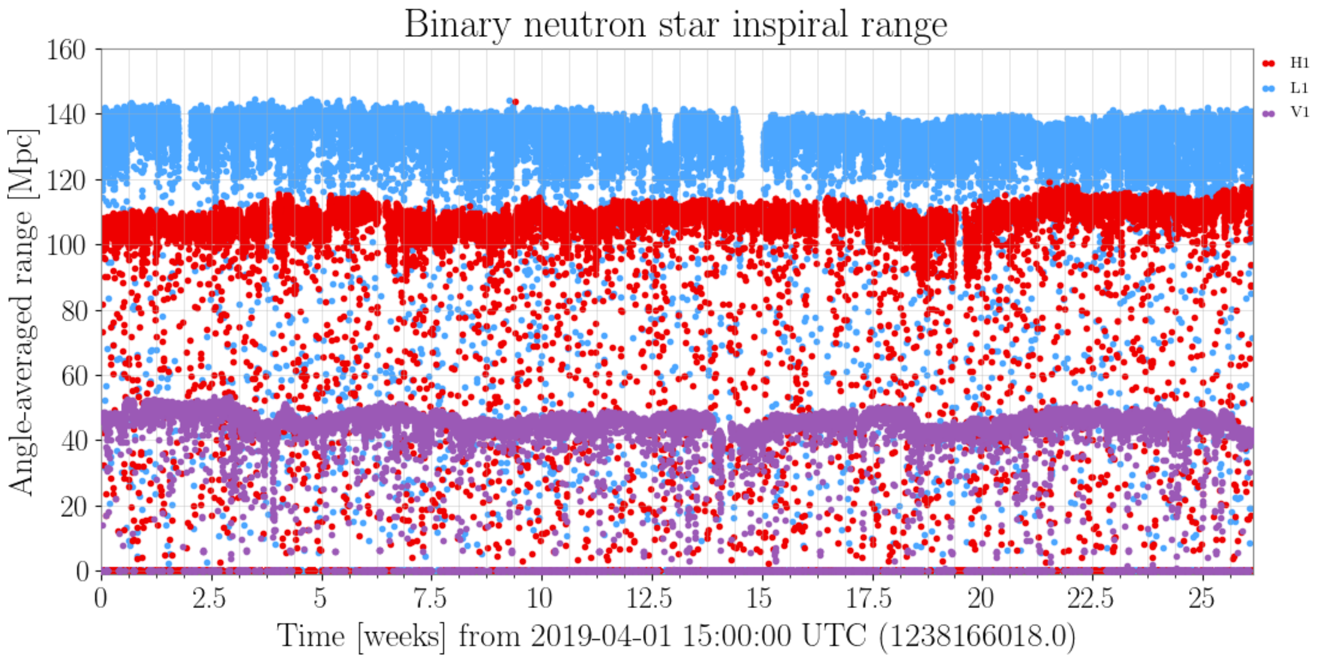
Black hole?



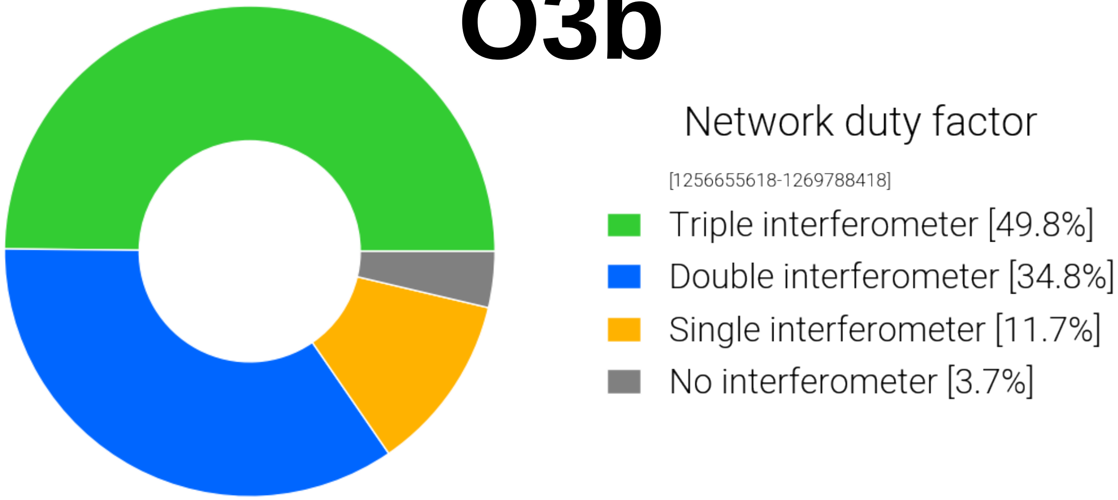
arXiv:2001.01761

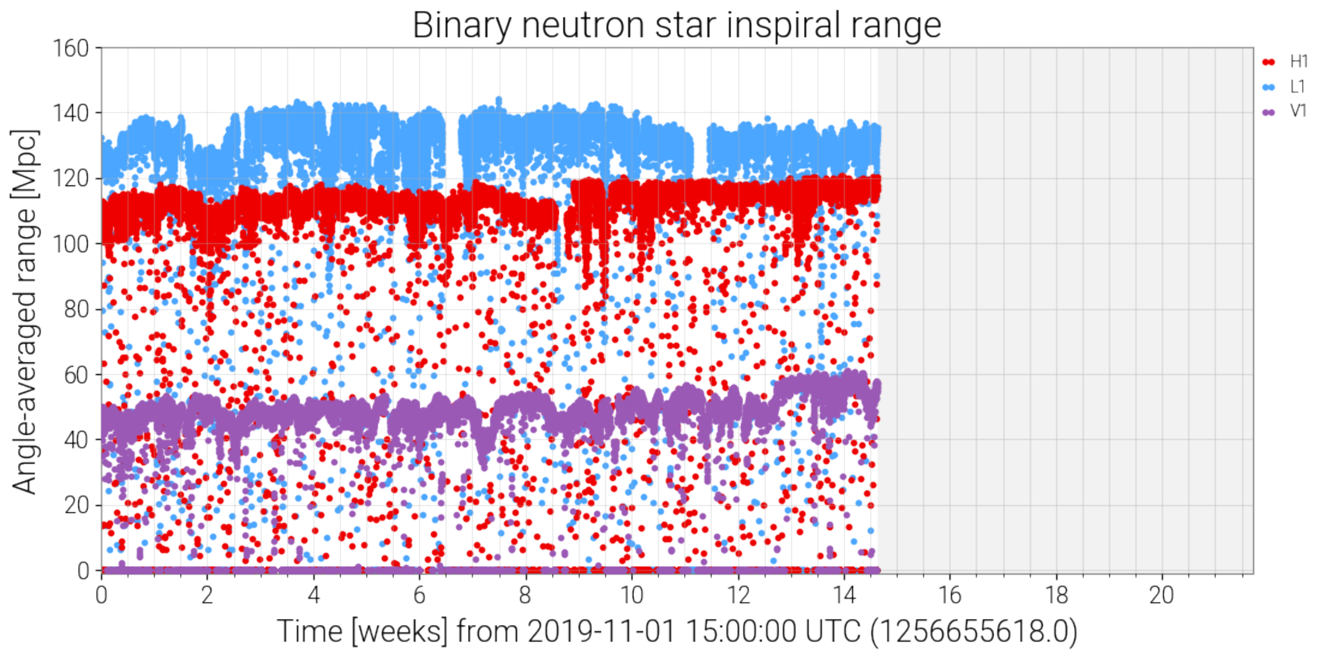
O3a

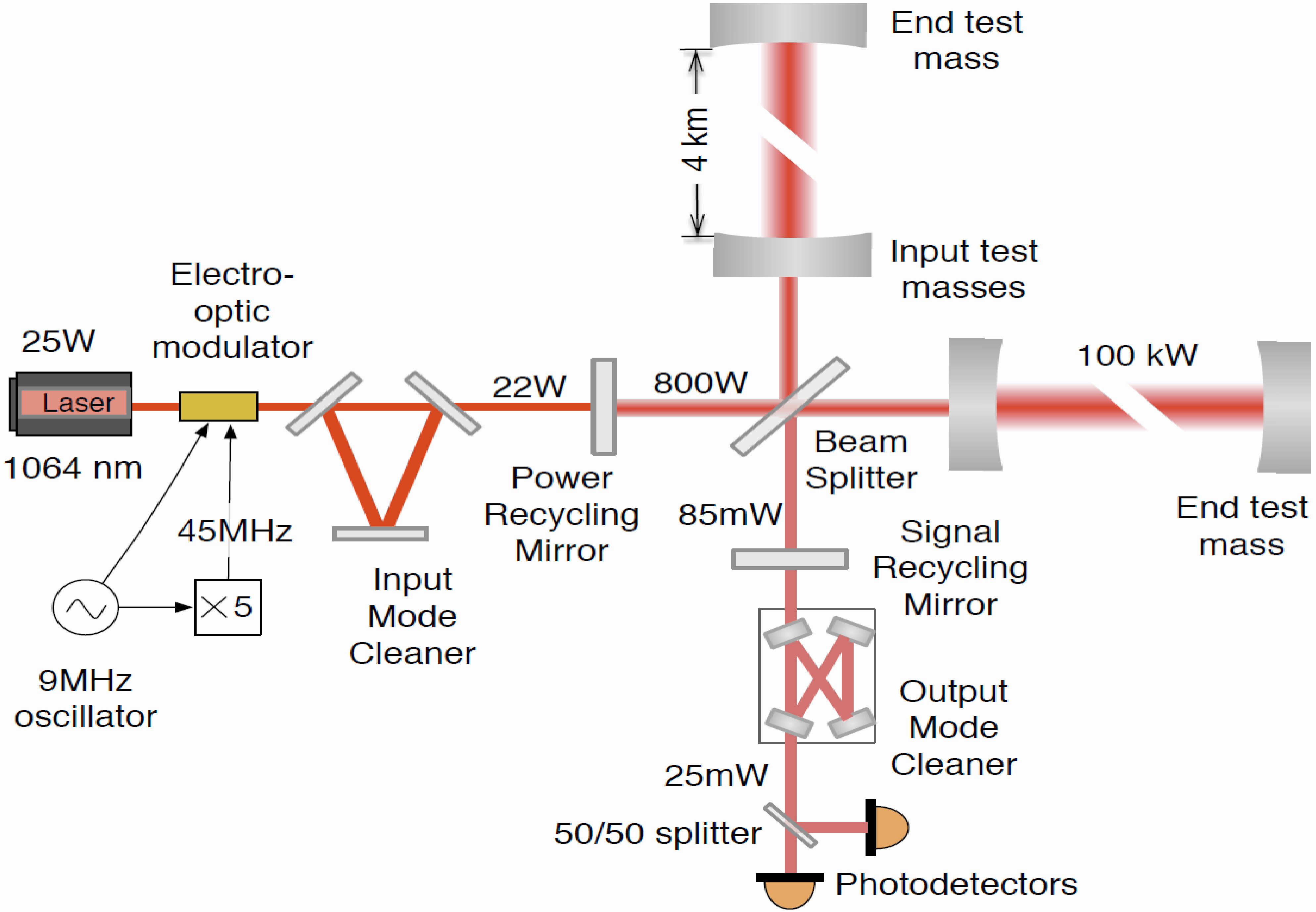

Network duty factor
[1238166018-1253977218]
Triple interferometer [44.5%]
Double interferometer [37.4%]
Single interferometer [15.0%]
No interferometer [3.2%]

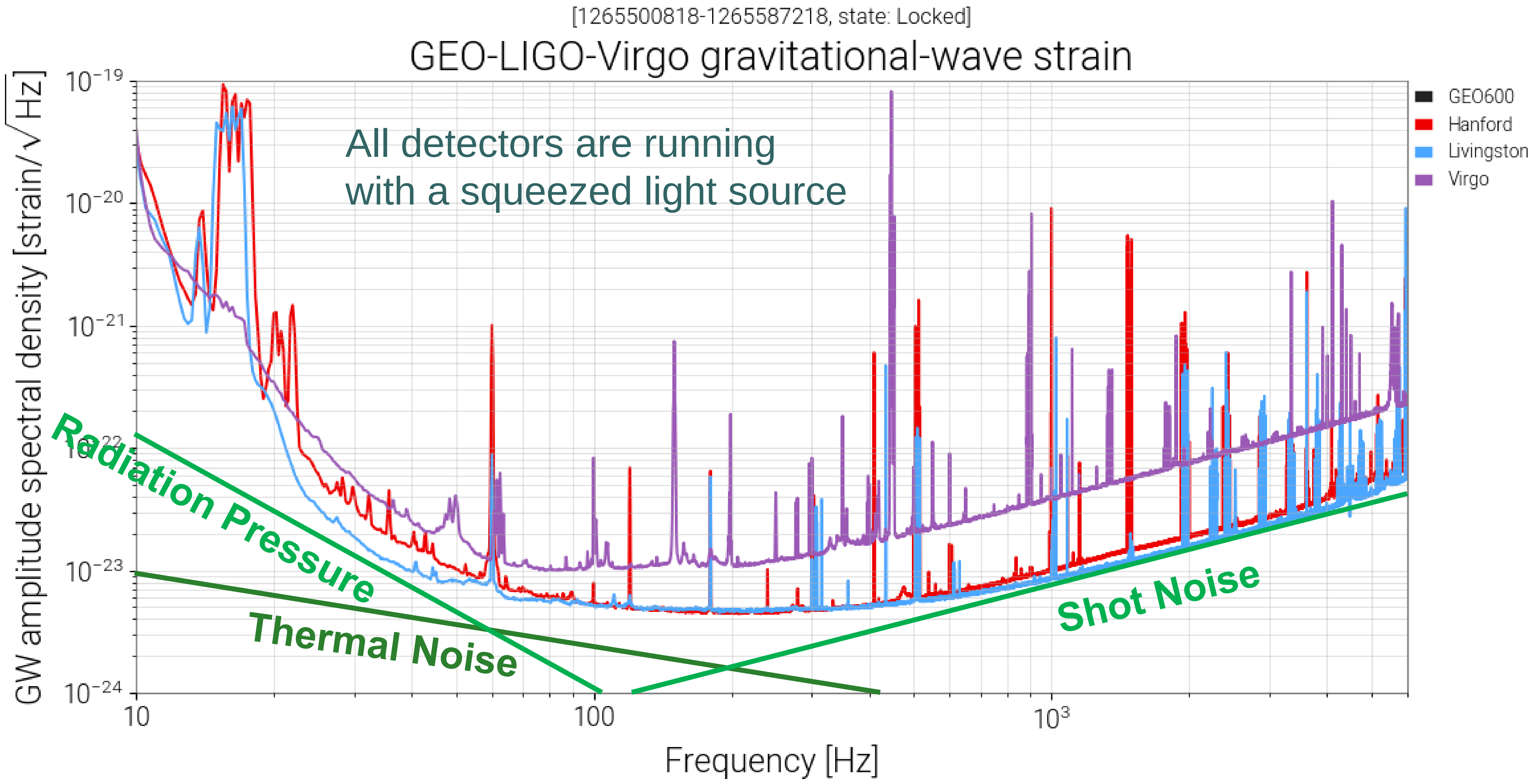

Binary neutron star inspiral range
Angle-averaged range [Mpc]
Time [weeks] from 2019-04-01 15:00:00 UTC (1238166018.0)
H1
L1
V1

O3b


Network duty factor
[1256655618-1269788418]
Triple interferometer [49.8%]
Double interferometer [34.8%]
Single interferometer [11.7%]
No interferometer [3.7%]


Binary neutron star inspiral range
Angle-averaged range [Mpc]
Time [weeks] from 2019-11-01 15:00:00 UTC (1256655618.0)
H1
L1
V1


End test mass
4 km
Input test masses
Electro-optic modulator
25W
Laser
1064 nm
45MHz
×5
9MHz oscillator
Input Mode Cleaner
22W
Power Recycling Mirror
800W
Beam Splitter
100 kW
End test mass
85mW
Signal Recycling Mirror
Output Mode Cleaner
25mW
50/50 splitter
Photodetectors

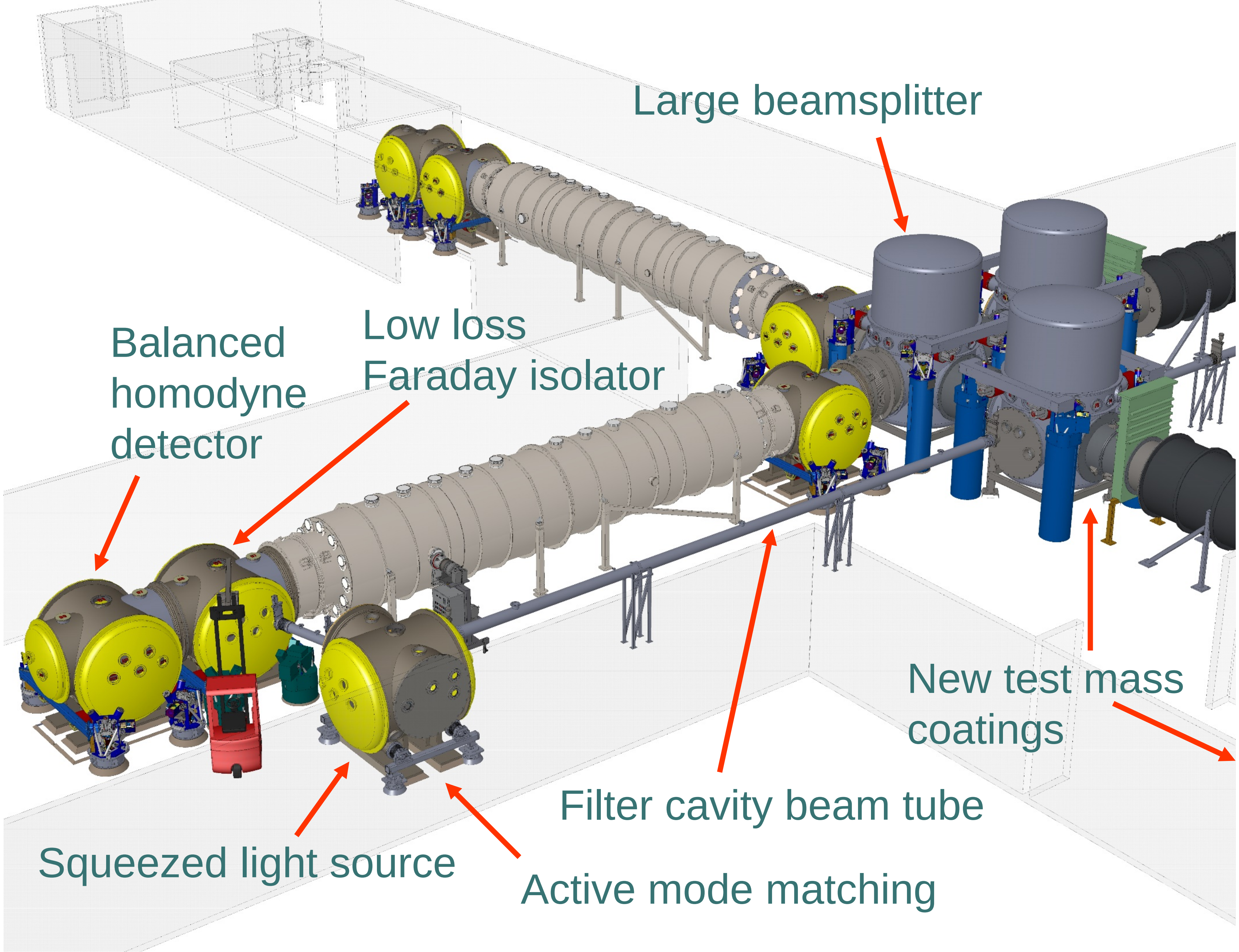


[1265500818-1265587218, state: Locked]
GEO-LIGO-Virgo gravitational-wave strain
All detectors are running
with a squeezed light source
GEO600
Hanford
Livingston
Virgo
GW amplitude spectral density [strain/√Hz]
Frequency [Hz]
Radiation Pressure
Thermal Noise
Shot Noise

The A+ Upgrade

- Goal:
  - Projected inspiral range: 325 Mpc (almost doubling of Advanced LIGO design)
- First stage: May 2020 to end of 2021
  - Add frequency depended squeezing to suppress both shot and radiation pressure noise
  - 300 m filter cavity to rotate squeezer phase
  - Low loss Faraday isolator
  - Active wavefront control to improve mode matching
- Second state: after O4
  - New mirror coatings with 4 times lower thermal noise (2x improvement in displacement)
  - Add a balanced homodyne detector to improve sensing and reduce noise couplings
  - Larger beamsplitter to reduce losses

A+ Layout



Large beamsplitter
Low loss
Faraday isolator
Balanced
homodyne
detector
New test mass
coatings
Filter cavity beam tube
Squeezed light source
Active mode matching

Voyager

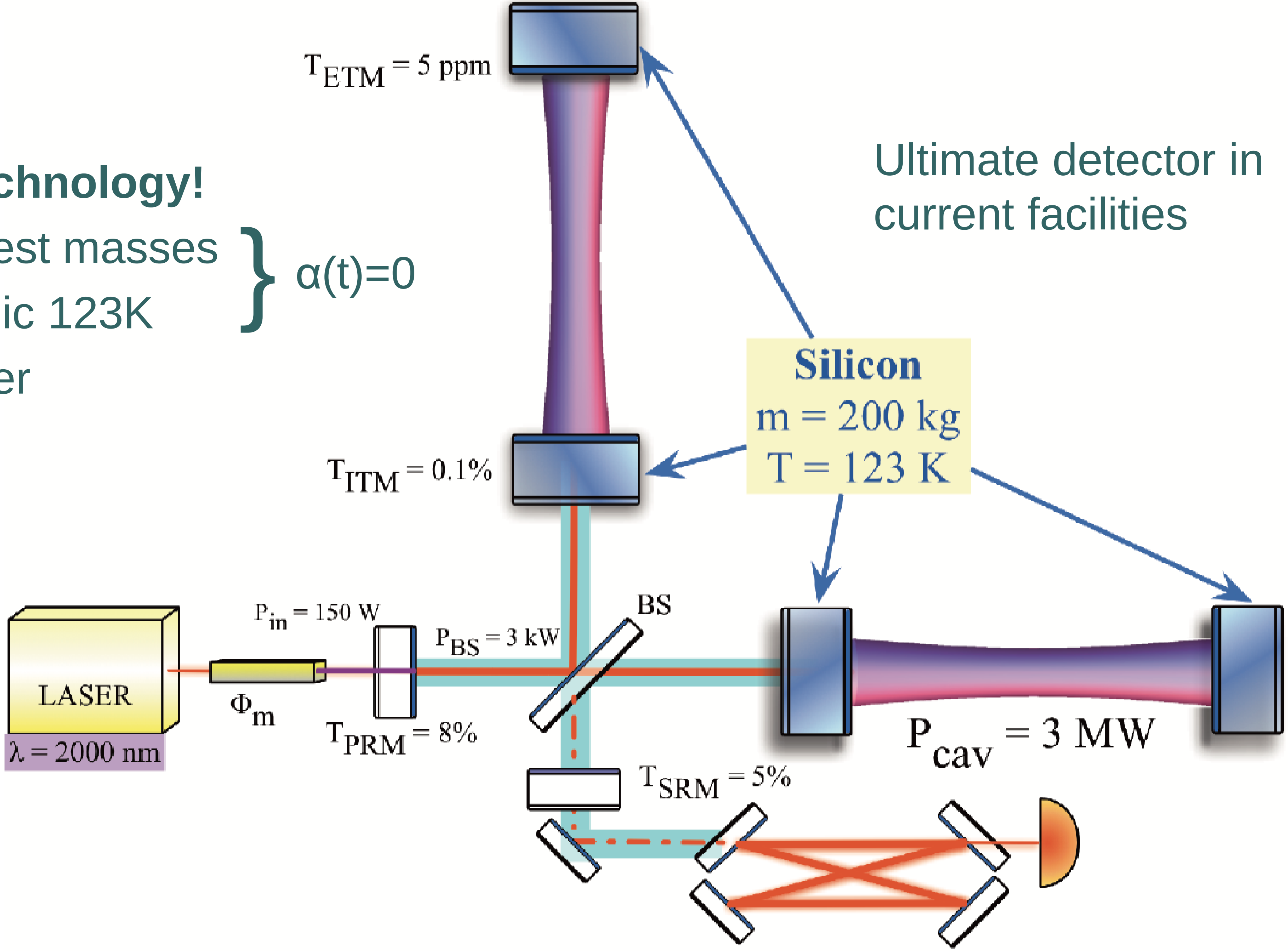
New Technology!

Silicon test masses } $\alpha(t)=0$

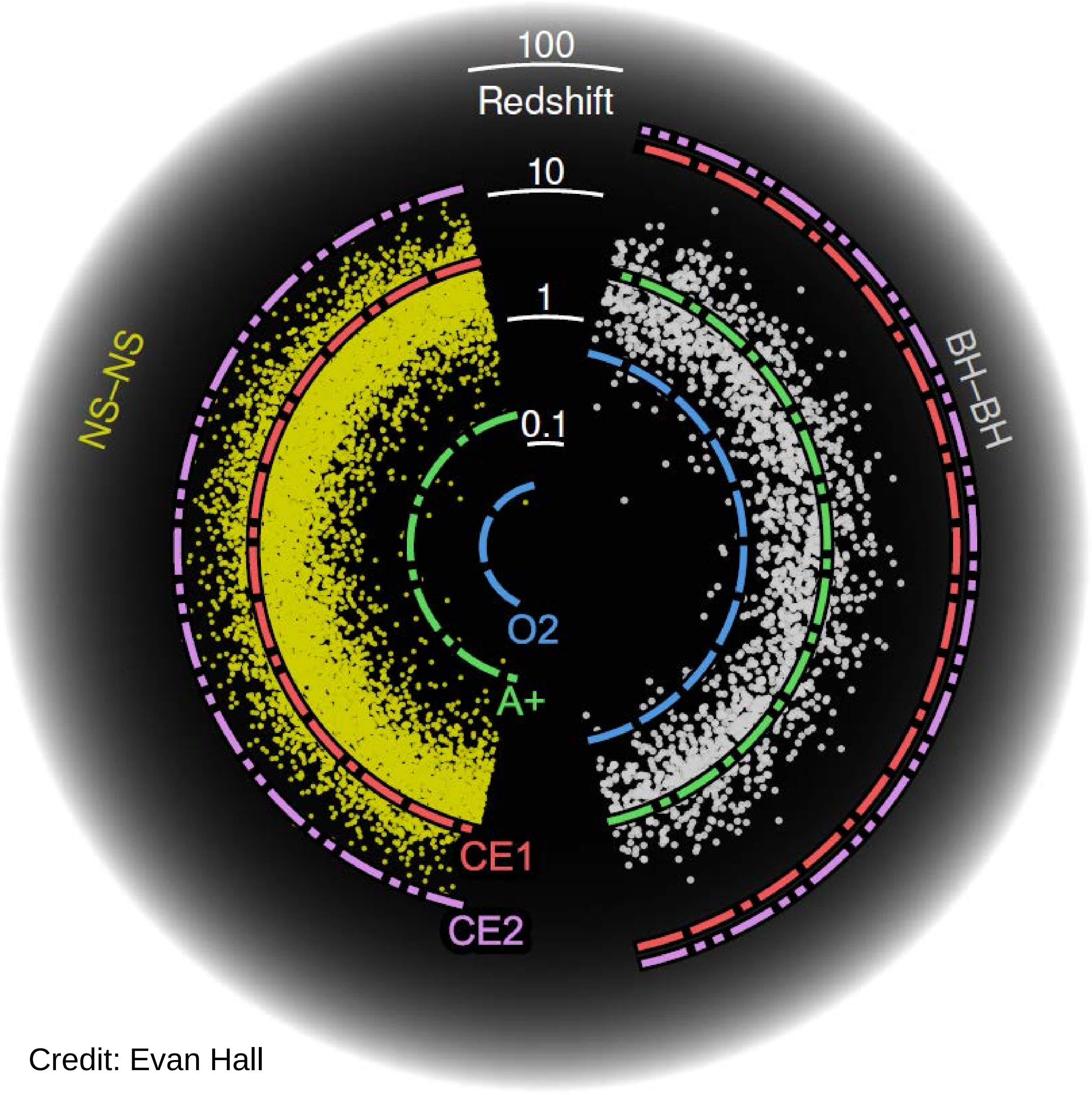
Cryogenic 123K

2µm laser

Ultimate detector in current facilities



3rd Generation Detectors



Credit: Evan Hall

Einstein Telescope

- ❑ 10 km triangular shape
- ❑ Underground
- ❑ Xylophone
- ❑ Cryogenic

Cosmic Explorer

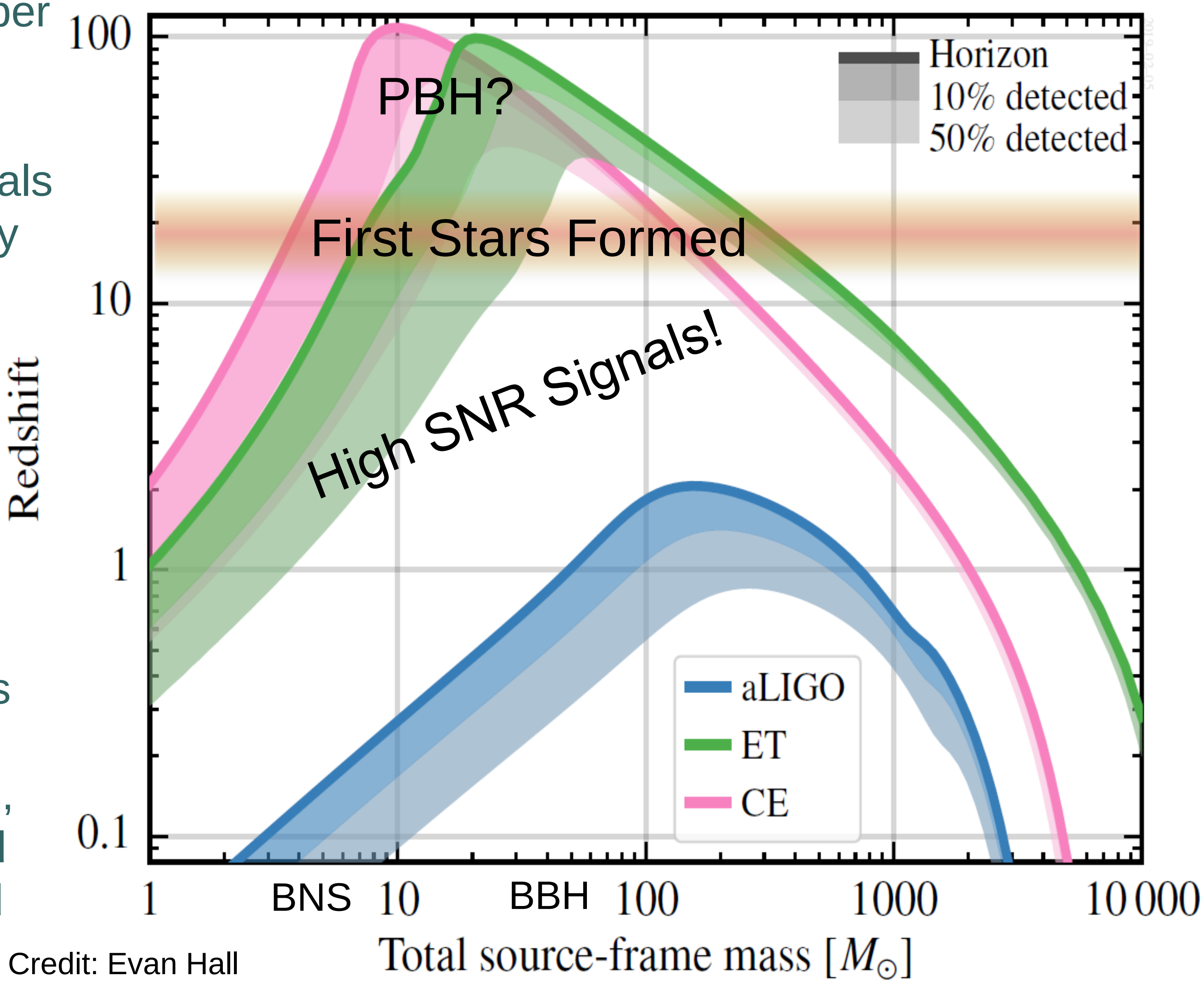
- ❑ 40 km L-shape
- ❑ Above ground
- ❑ CE1: Fused silica, room temperature
- ❑ CE2: Silicon @ 120K

Need a network of 3+ detectors for triangulation/source direction

O(100 000) events per year

3rd Generation Detectors

- Enormously increase the number of compact binary mergers detected
- Provide samples of “loud” signals measured with very high fidelity
- Greatly improve tests of cosmology and fundamental physics
- Trace the cosmic evolution of compact binary mergers, inferring their origins and evolution
- Search more deeply for signals other than binary mergers — such as spinning neutron stars, core-collapse supernovae, and the stochastic GW background



Credit: Evan Hall

Key Science Goals

Determining the Nature of the Densest Matter in the Universe

- Quark matter, equation of state, strange quark stars, radius vs. mass
- Magnetic fields, pulsar glitches

Multi-messenger Observations of Binary Systems

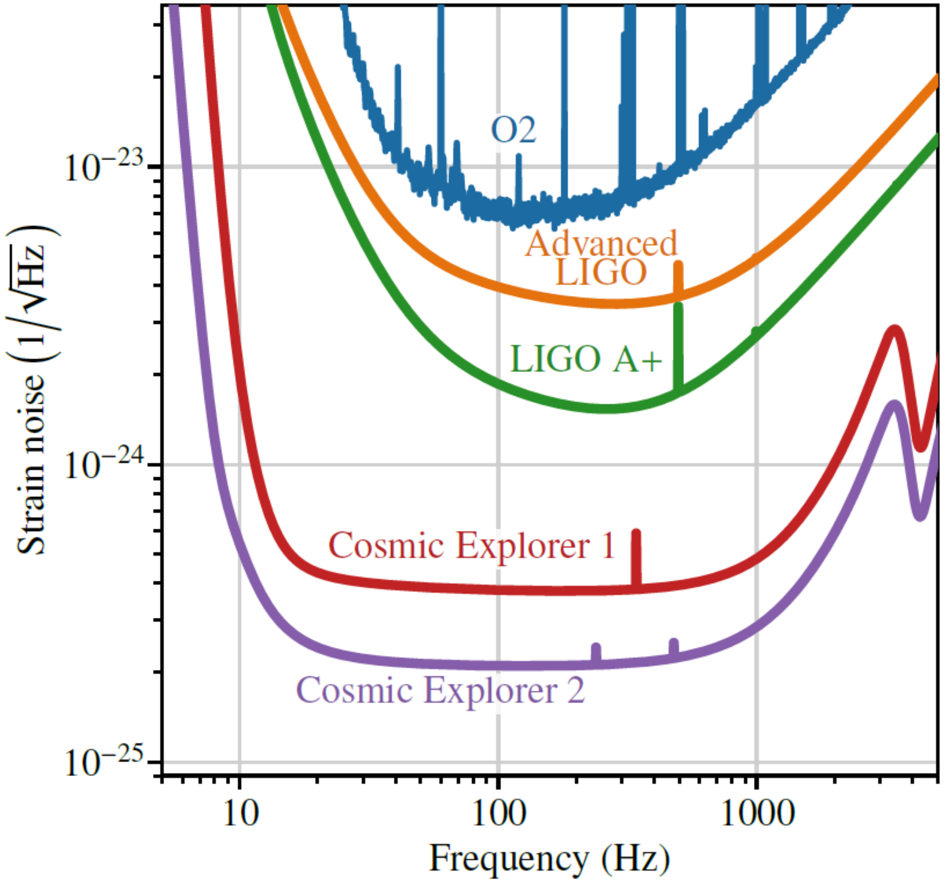
- Dynamics of the collision, Jet formation
- Heavy element production
- Localize sources prior to merger!

Seeing Black Holes Merge throughout Cosmic Time

- First stars, star formation rate, galaxy evolution

Probing the Evolution of the Universe

- Expansion of the Universe, Hubble constant, dark energy density



Key Science Goals

Exploring the Nature of Gravity and Compact Objects

- High-fidelity observations, GR tests
- Multi-band: Observation with LISA
- Rare objects: high spin, neutron star/IMBH, black hole with matter, etc.

The Life and Death of Massive Stars

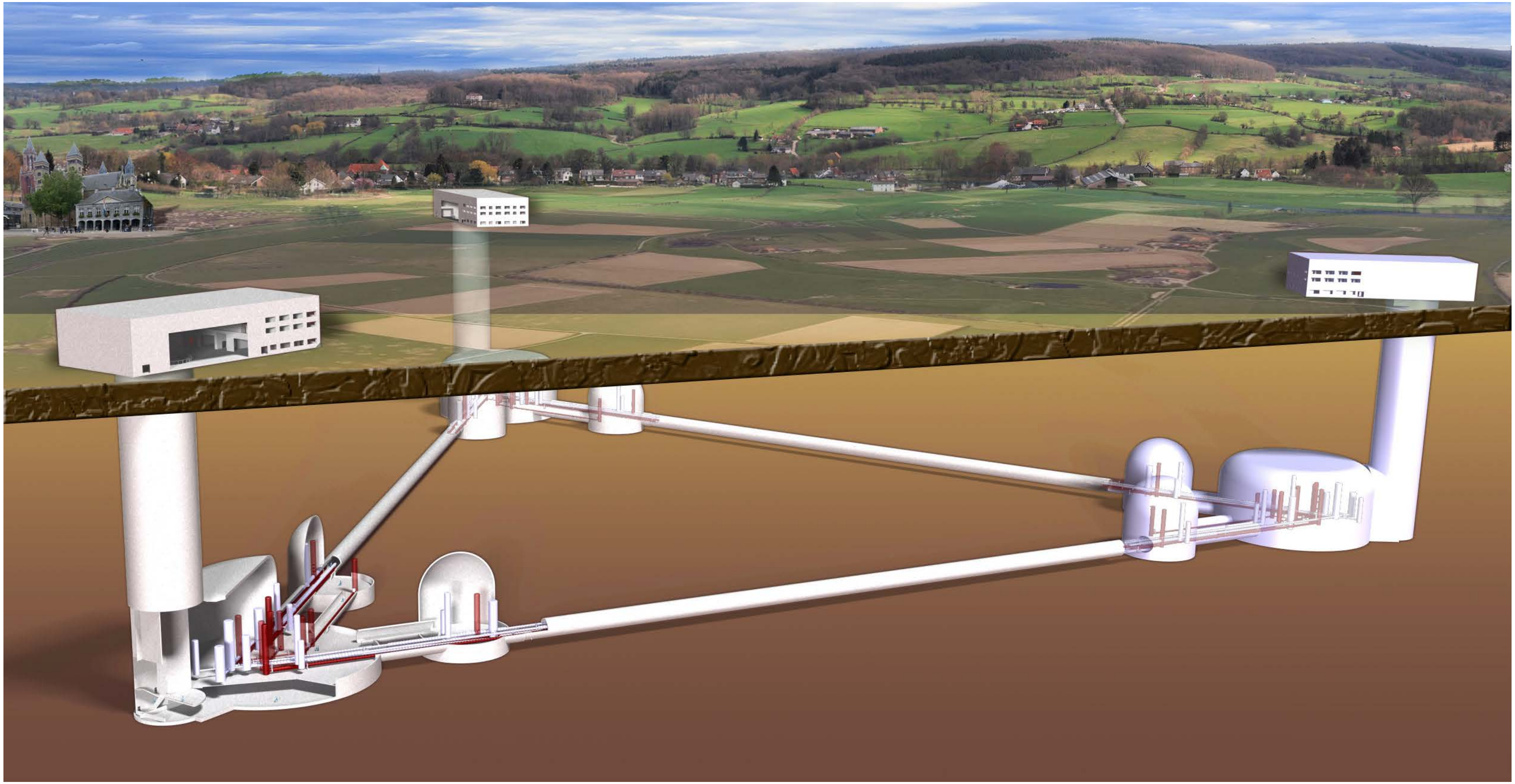
- Evolution of massive stars throughout cosmic history
- Core collapse/ magnetar glitches in the Milky Way or Magellanic Clouds

Sources at the Frontier of Observations

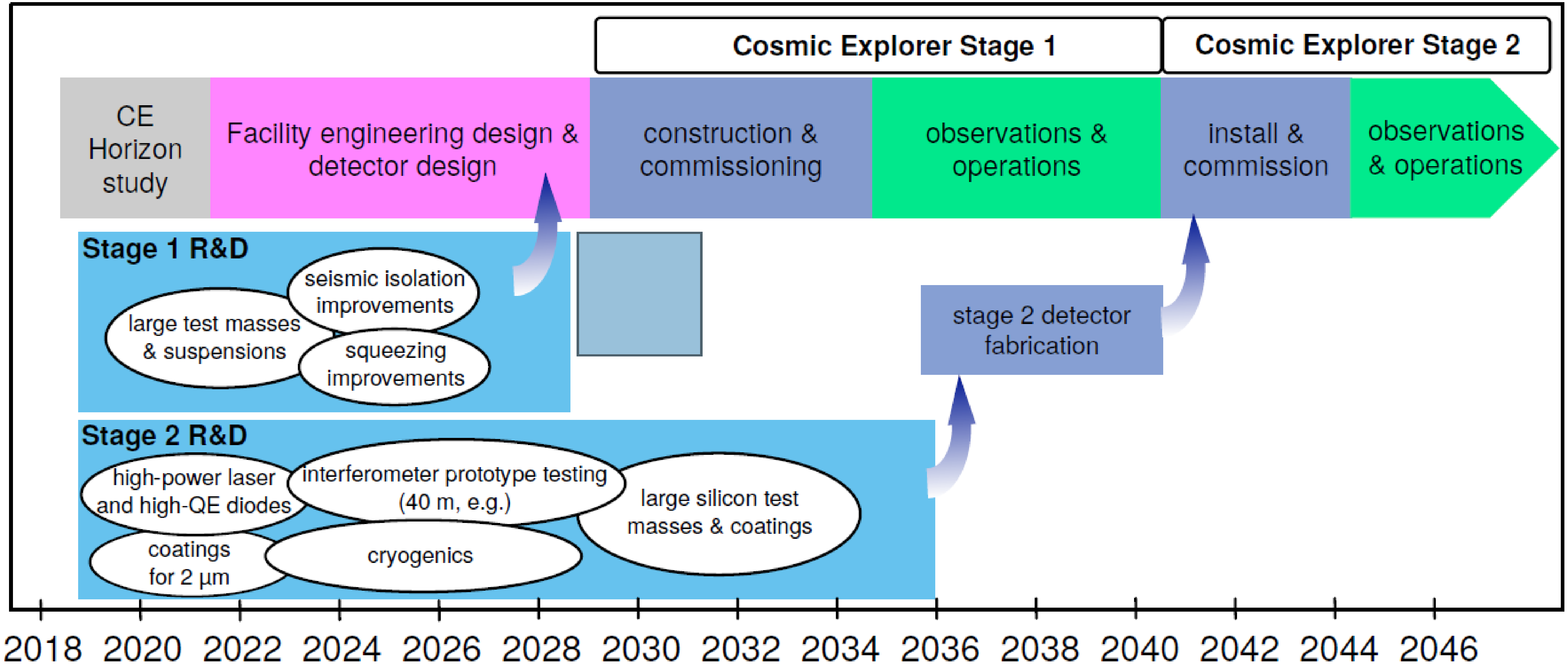
- Potential for discoveries beyond neutron stars and black holes
- Dark and exotic matter including axionic and other dark matter fields around black holes or in the cores of neutron stars,
- Mergers of primordial black holes formed in the early Universe
- Gravitational-wave emission from cosmic (super)strings.

https://gwic.ligo.org/3Gsubcomm/

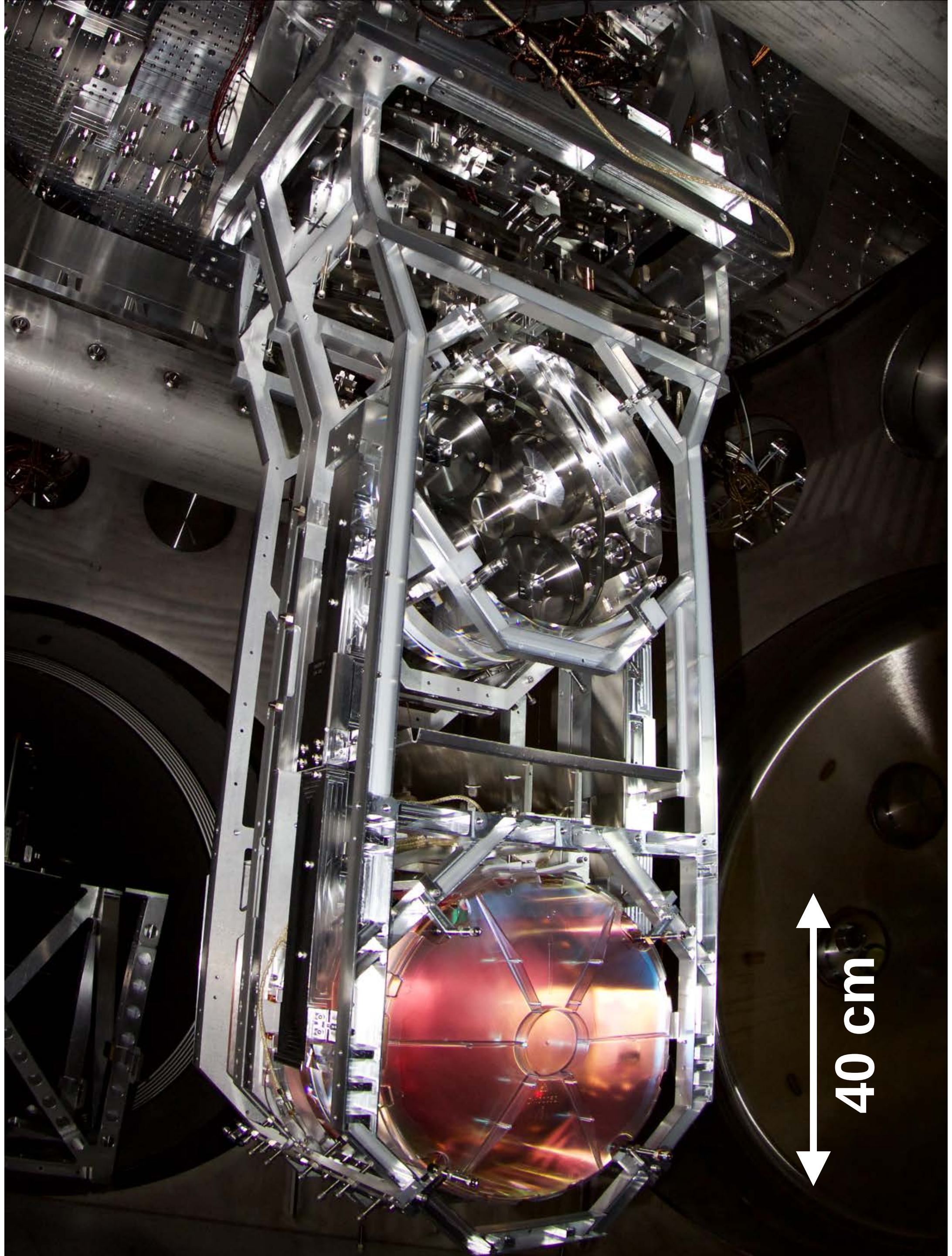
Einstein Telescope

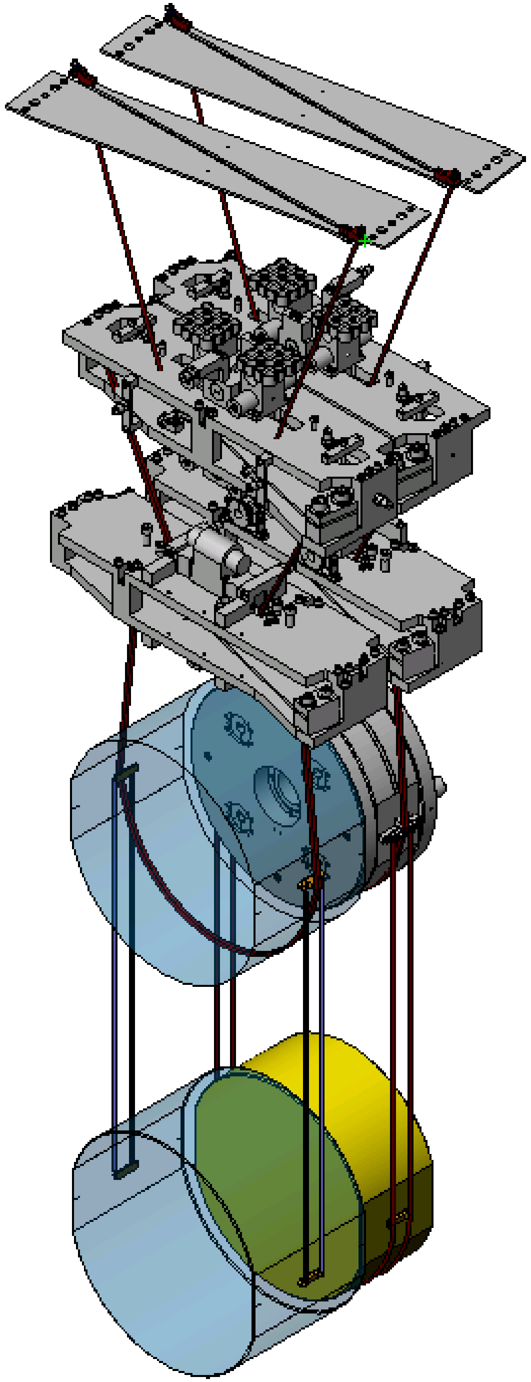


Cosmic Explorer



Test Mass Suspension

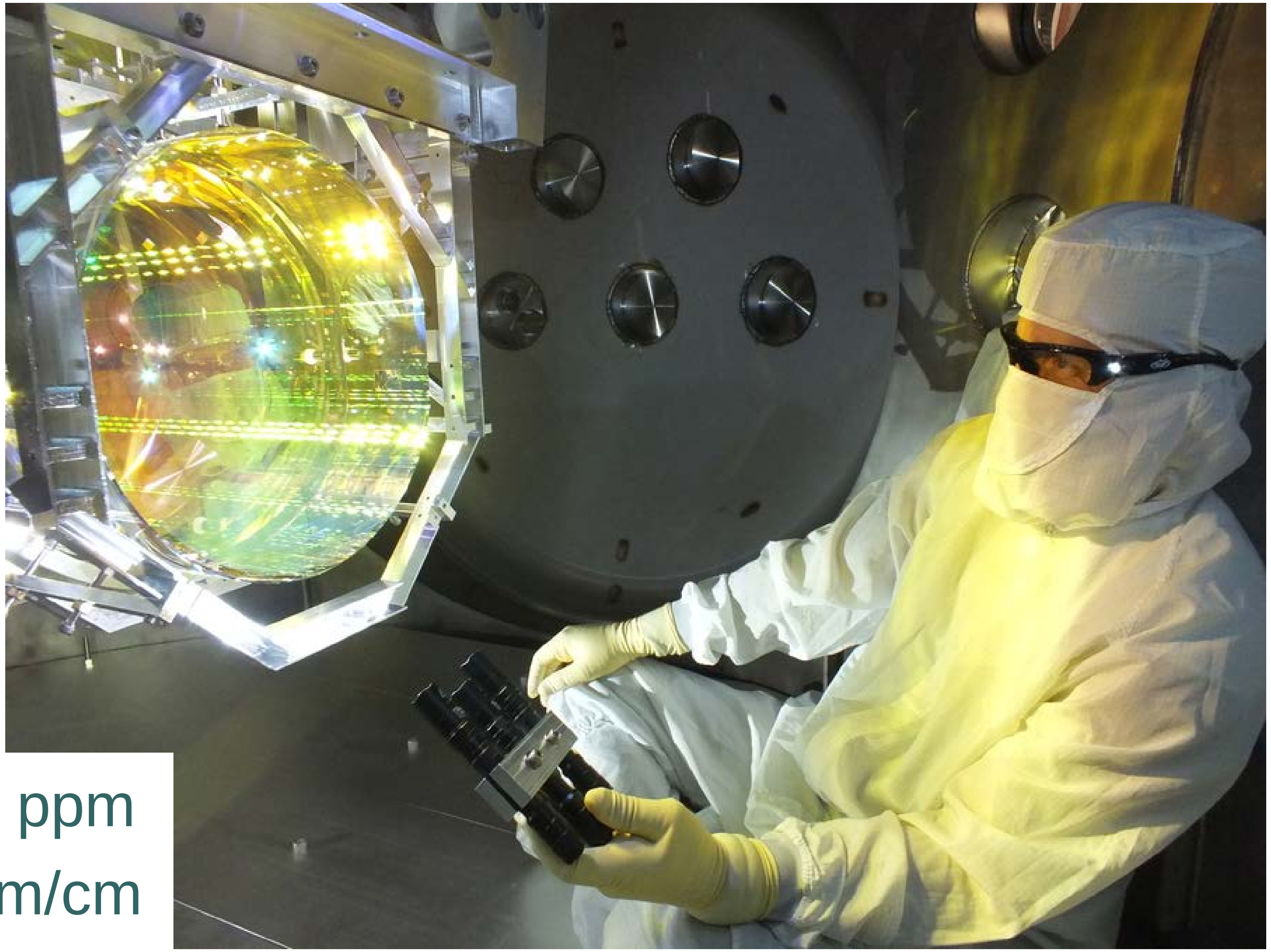




Large Test Mass Optics

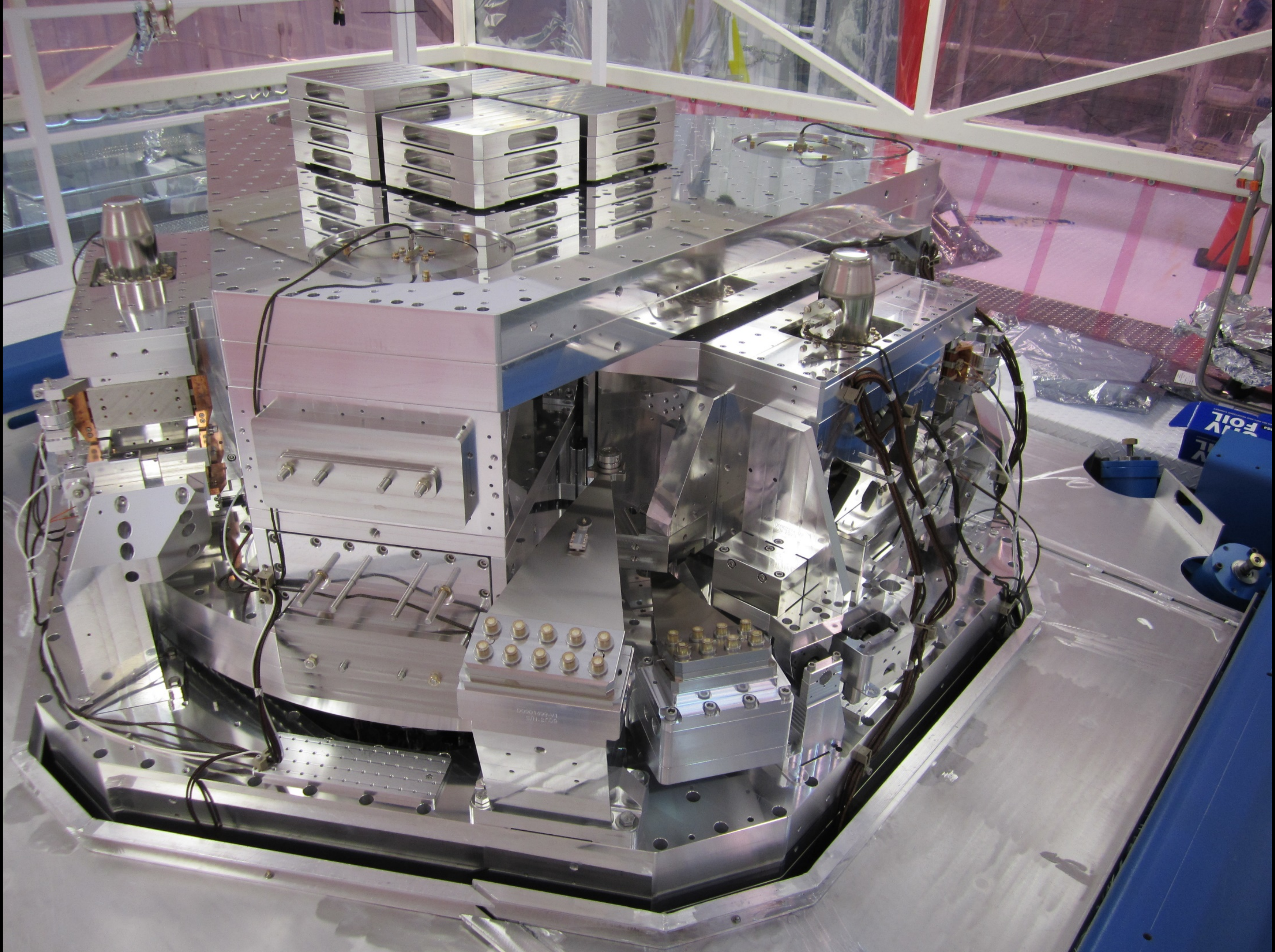
Specifications:

- Diameter: 340 mm
- Thickness: 200 mm
- Mass: 39.6 kg
- ROC: 2250 m / 1940 m
- Figure: <1 nm rms
- Scatter: ~10 ppm
- Surface absorption: ~0.3 ppm
- Bulk absorption: ~0.2 ppm/cm
- HR transmission: ~4 ppm
- AR reflectivity: ~200 ppm

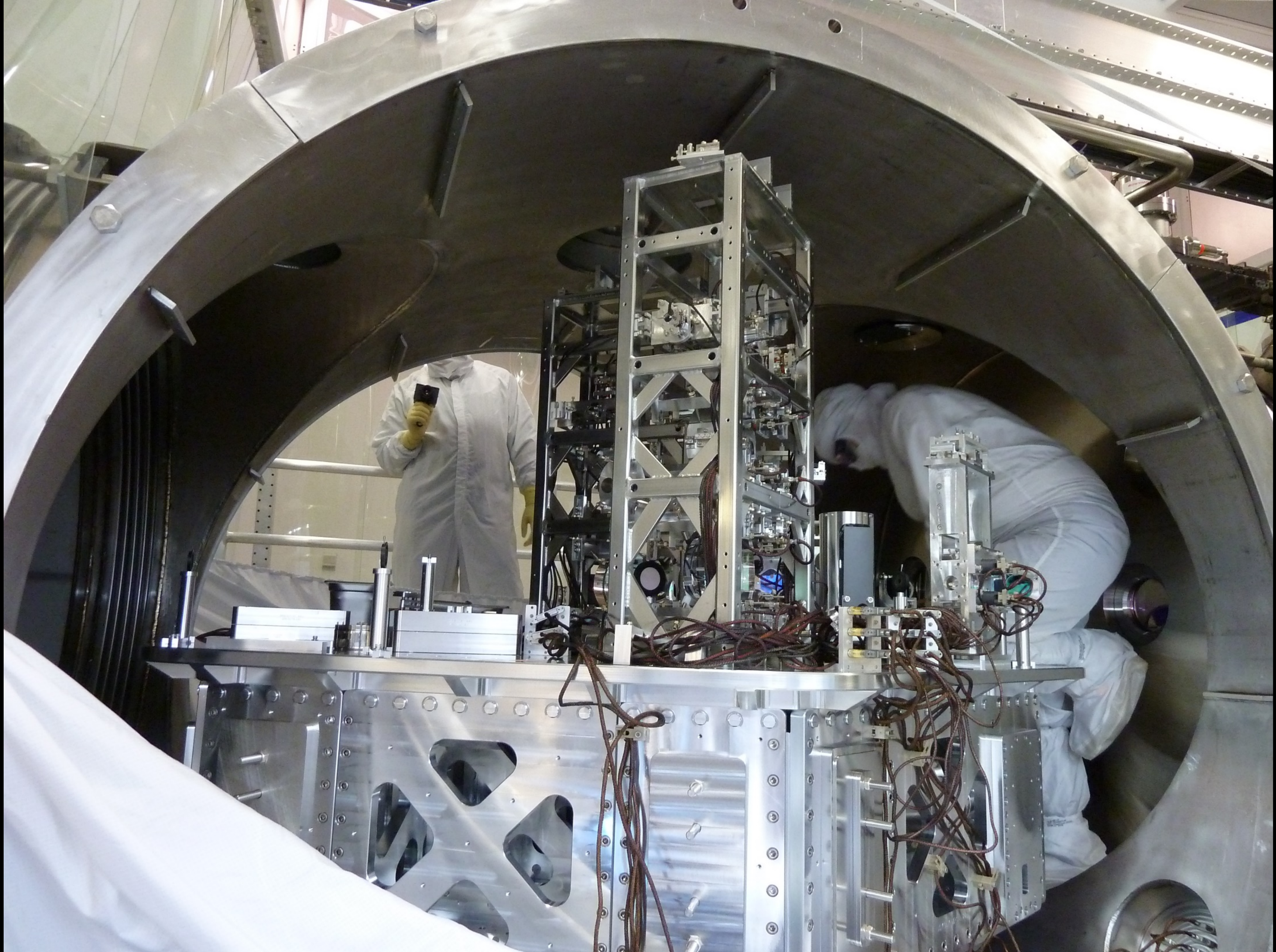


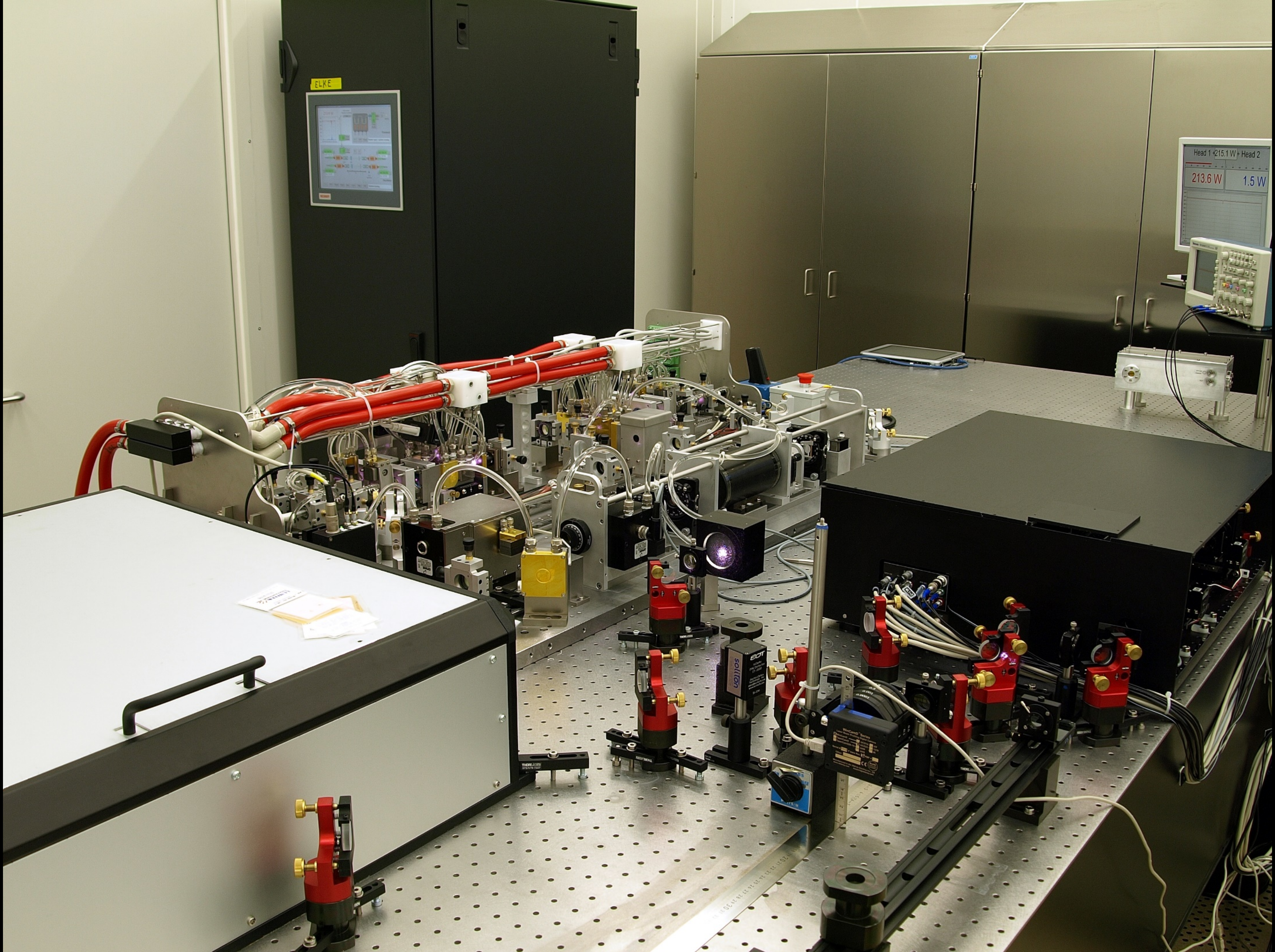
Vacuum System Vertex

Seismic Isolation Platform



Input Optics Table





200W Pre-Stabilized Laser


Control Room