Results and status of joint LIGO/Virgo/KAGRA observational runs and of the LIGO detectors

Joe Giaime
Head, LIGO Livingston Observatory (Caltech)
Prof of Physics & Astronomy (Louisiana State University)

LIGO-G2400279-v2
12 February 2024
Nishinomiya-Yukawa Symposium

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
IFT-UNESP
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 Central University
National Tsing Hua University
Northwestern University
Penn State University
Perimeter Institute
Rochester Institute of Technology

Sonoma State University
Stanford University
Stony Brook / CCA
Syracuse University
Szeged University
Texas A&M University
Texas Tech University
Tsinghua University
U. Montreal / Polytechnique
University of Antioquia
University of Arizona
University of Arkansas
University of Bonn and AIP
University of British Columbia
University of Brussels
University of California, Berkeley
University of California, Riverside
University of Chicago
University of Florida
University of Maryland
University of Massachusetts Dartmouth
University of Michigan
University of Minnesota
University of Mississippi
University of Oregon
University of Rhode Island
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University of Santiago de Compostela
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
Vanderbilt University
Villanova University
Vrije Universiteit Amsterdam
West Virginia University
Western Washington University

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

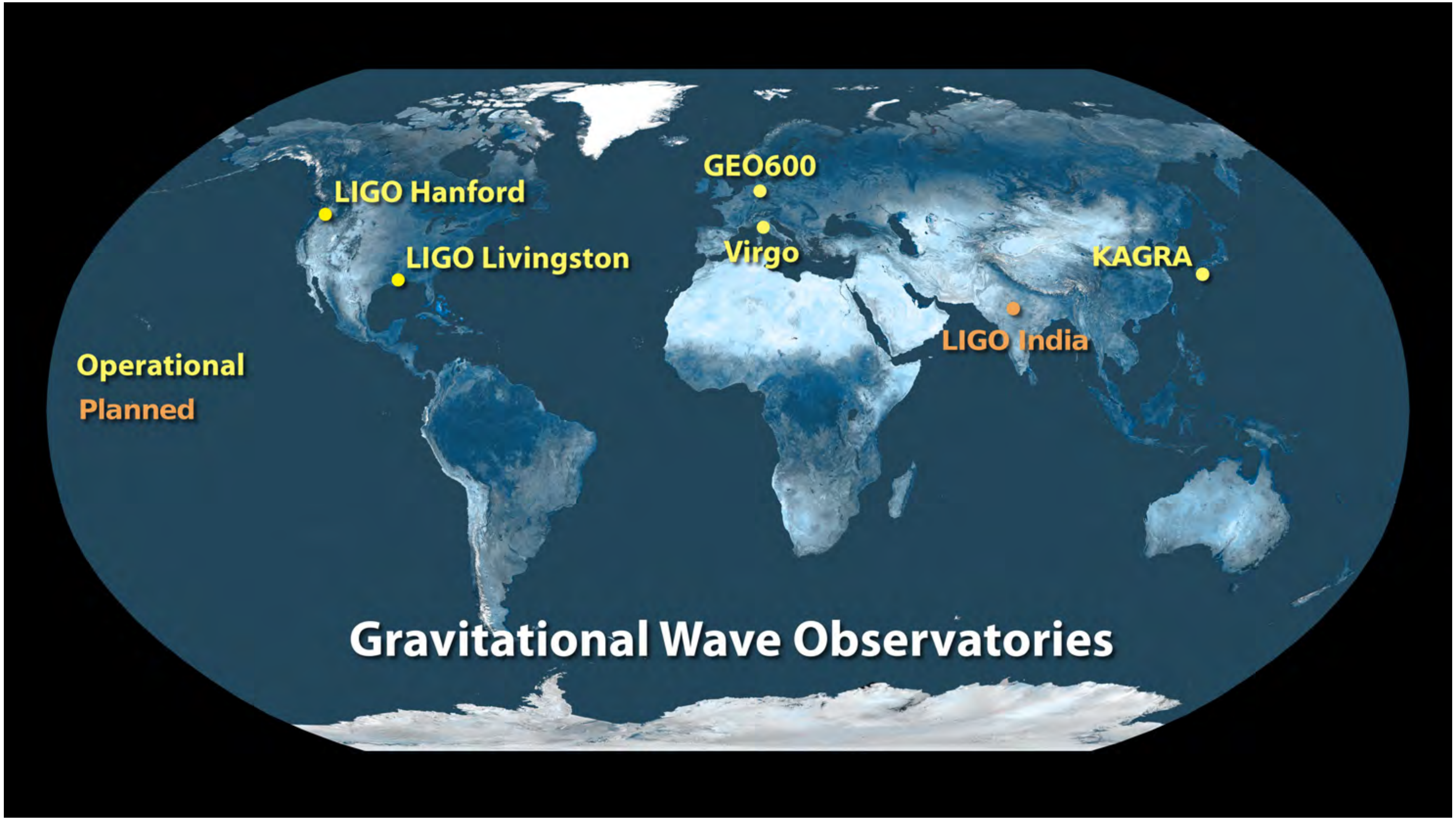
ARC Centre of Excellence For Gravitational Wave Discovery (OzGrav):
Australian National University; Charles Sturt University; Monash University; Swinburne University of Technology; University of Adelaide; The University of Melbourne; University of Western Australia

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; Royal Holloway, University of London; 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 Warwick; University of the West of Scotland; University of Zurich

Korean Gravitational Wave Group (KGWG)
Chung-Ang University; 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; Sungkyunkwan University; Ulsan National Institute of Science and Technology

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

Worldwide network



Gravitational plane waves in flat spacetime

Tiny perturbation to flat space metric:

$$g_{\mu\nu} \simeq \eta_{\mu\nu} + h_{\mu\nu} \qquad \eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Solution to the Einstein eqn. for plane waves, in Transverse Traceless gauge:

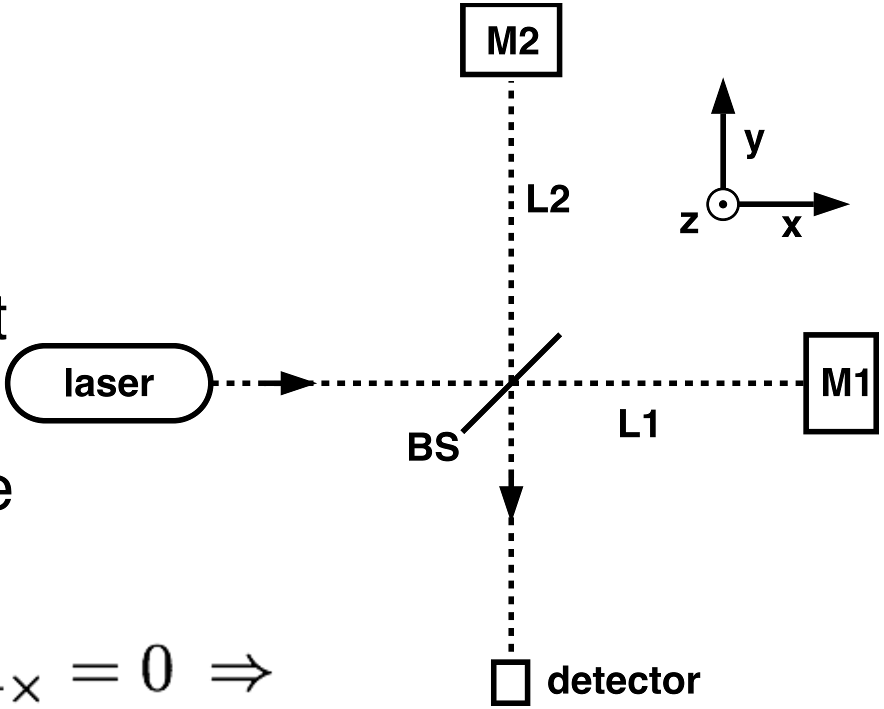
$$h_{\mu\nu} = \Re\left\{A_{\mu\nu} e^{i\left(k_0 x^0 + k_z x^z\right)}\right\}$$

Two polarizations, 45° apart, (for z propagation):

$$A_{\mu\nu} = A_+ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + A_\times \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

GW detection with a Michelson interferometer

- Assume that GW wavelength is much longer than arms, and that light traverses arms quickly compared with GW period.
- Calculate spacetime interval between test mass and beamsplitter.
- Use arm-arm difference in light travel time (phase) to measure strain.



$$\Delta t \ll 2\pi/\omega,\; h \ll 1,\; A_+ = h, A_\times = 0 \;\Rightarrow$$

$$ds^2 = 0 = g_{\mu\nu} dx^\mu dx^\nu = -c^2 dt^2 + dz^2 + \left[1 + h\sin\left(k_z z - \omega t\right)\right] dx^2 .$$

$$\int_{\rm BS}^{\rm M1} dt = \Delta t \simeq \int_{\rm BS}^{\rm M1} dx \left[1 - \frac{h}{2}\sin\left(k_z z - \omega t\right)\right] \simeq \frac{L}{c}\left[1 - \frac{h}{2}\sin(\omega t)\right] .$$

$$\frac{\Delta L}{L} = h\sin(\omega t)$$

Weiss 1972, MIT RLE Report No. 105, https://dcc.ligo.org/LIGO-P720002/public/main

How LIGO sees the waves, in cartoon form

Generation of Gravitational Waves, or the experimentalist nightmare math

- GW radiation requires a time-varying non-zero quadrupole moment of the source’s mass.
- Constants of nature come together to make the effect very tiny, even for enormous sources.
- ‘Hertzian’ experiment probably impossible.
- Sources include inspiraling binary compact objects, non-spherical core implosion, driven or relaxing normal modes of compact objects, …

$$h \simeq \frac{GM}{c^4}\frac{E_k^{\rm ns}}{r} \simeq 10^{-20}\left(\frac{E_k^{\rm ns}}{M_\odot c^2}\right)\left(\frac{10\,\rm Mpc}{r}\right)$$

where $E_{\rm k}^{\rm ns}$ is the non-spherical kinetic energy of the source. This formula is roughly the best-case, with optimal orientation.

Patience and stewardship over generations:

~110 years ago: Albert Einstein published his theory of General Relativity, including prediction of gravitational waves.

~60 years ago: Weber builds bar antennas to attempt detection of the waves.

~50 years ago: Key ideas for interferometric antennas developed by Weiss and others. Bar antenna work continues, including cryogenics. ALLEGRO cryo. detector work underway at LSU.

~45 years ago: (U.S.) National Science Foundation funding of pre-LIGO R&D, continued GW detector research internationally, including Glasgow in the U.K. and MPQ in Germany.

~35 years ago: LIGO proposed to the NSF by MIT and Caltech.

~30 years ago: LIGO site construction began.

~20 years ago: initial LIGO running at design sensitivity.

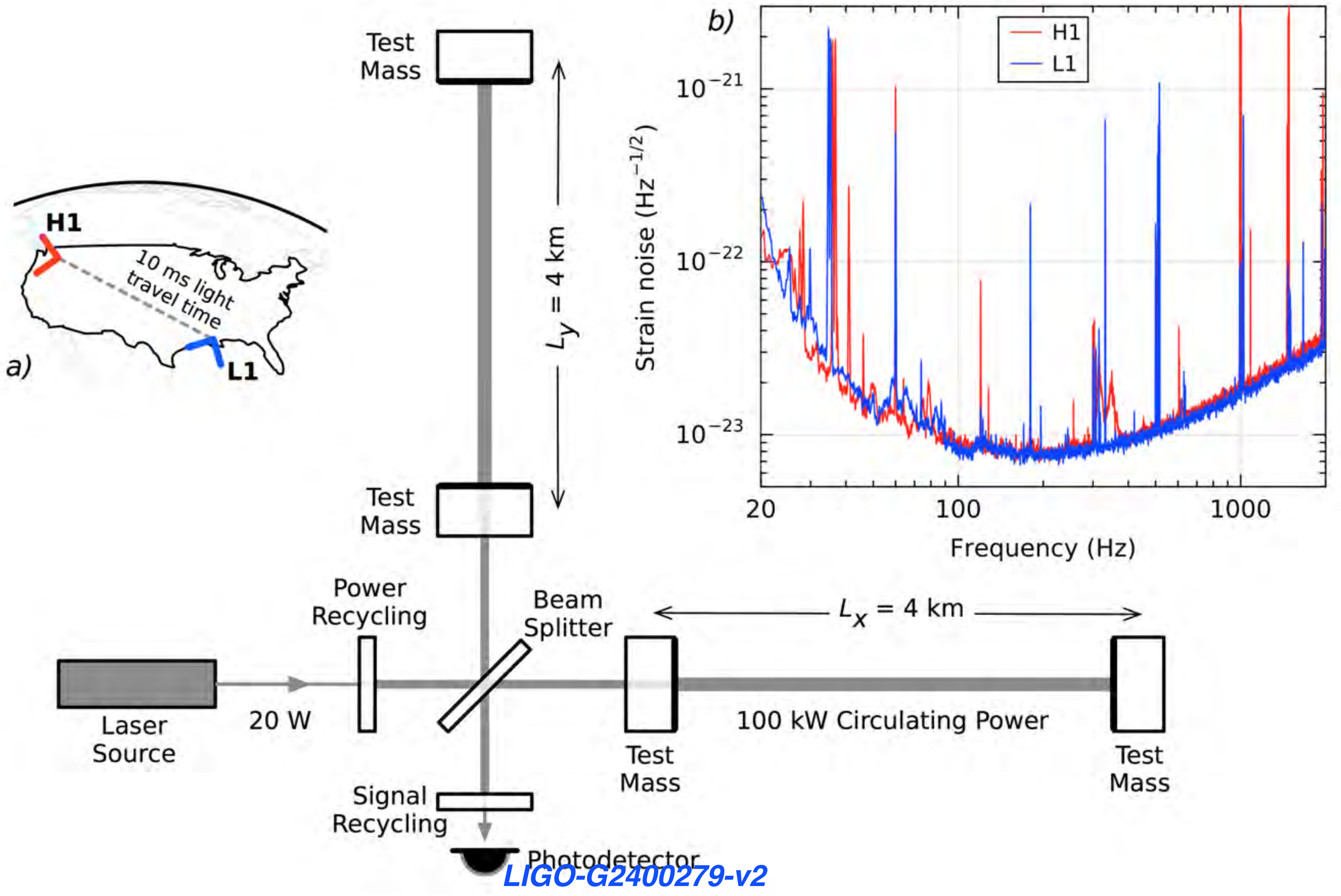
~13 years ago: Advanced LIGO installation began with major international contributions, including from the U.K. and Germany.

September 2015: Advanced LIGO detectors see astrophysical signal from Black Holes.

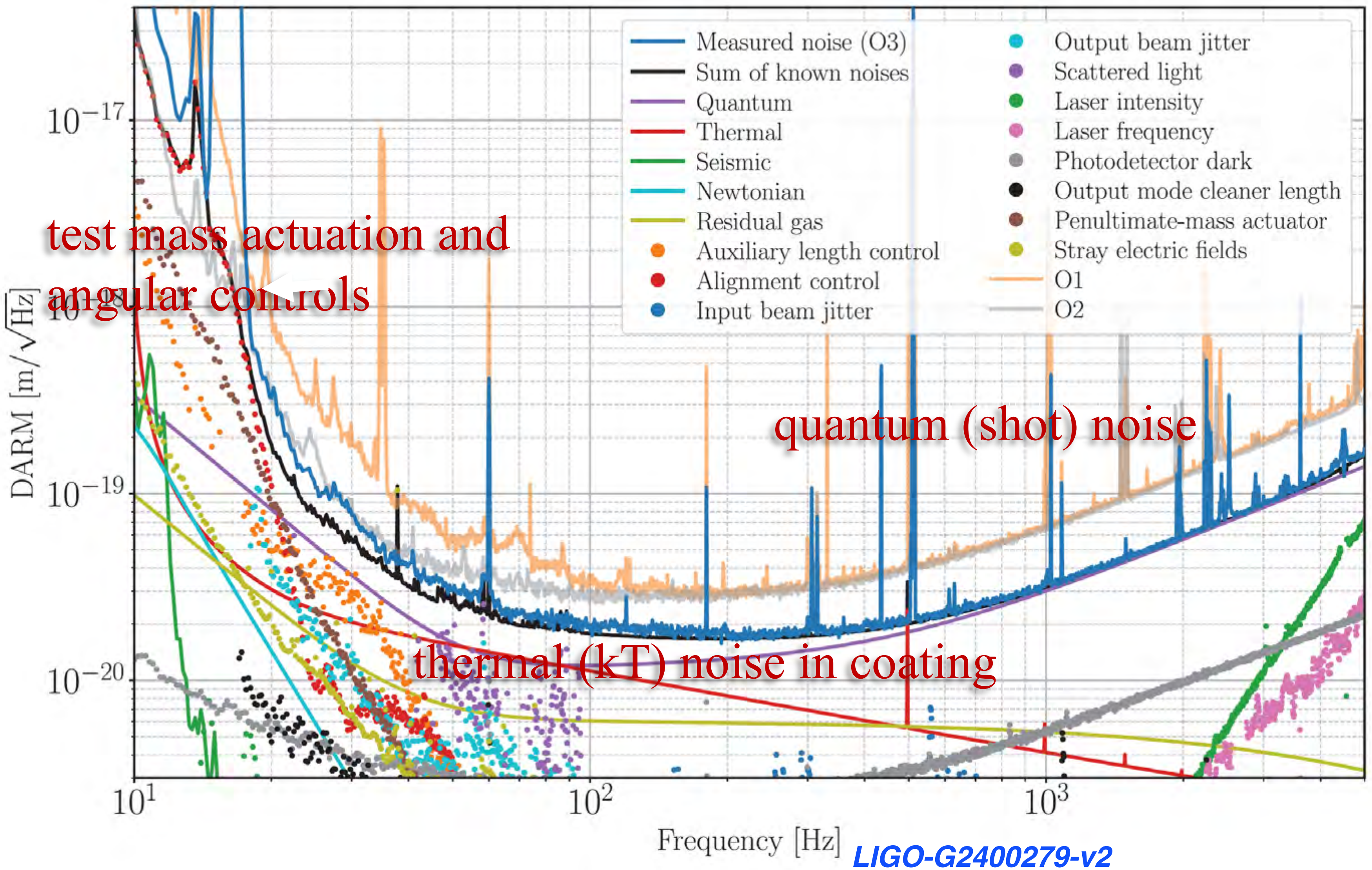
August 2017: Advanced LIGO and Virgo detectors see signal from Neutron Stars.

June 2018: LIGO Livingston and Hanford recognized as APS historic physics sites.

Advanced LIGO Detectors: installation 2010, first run fall 2015

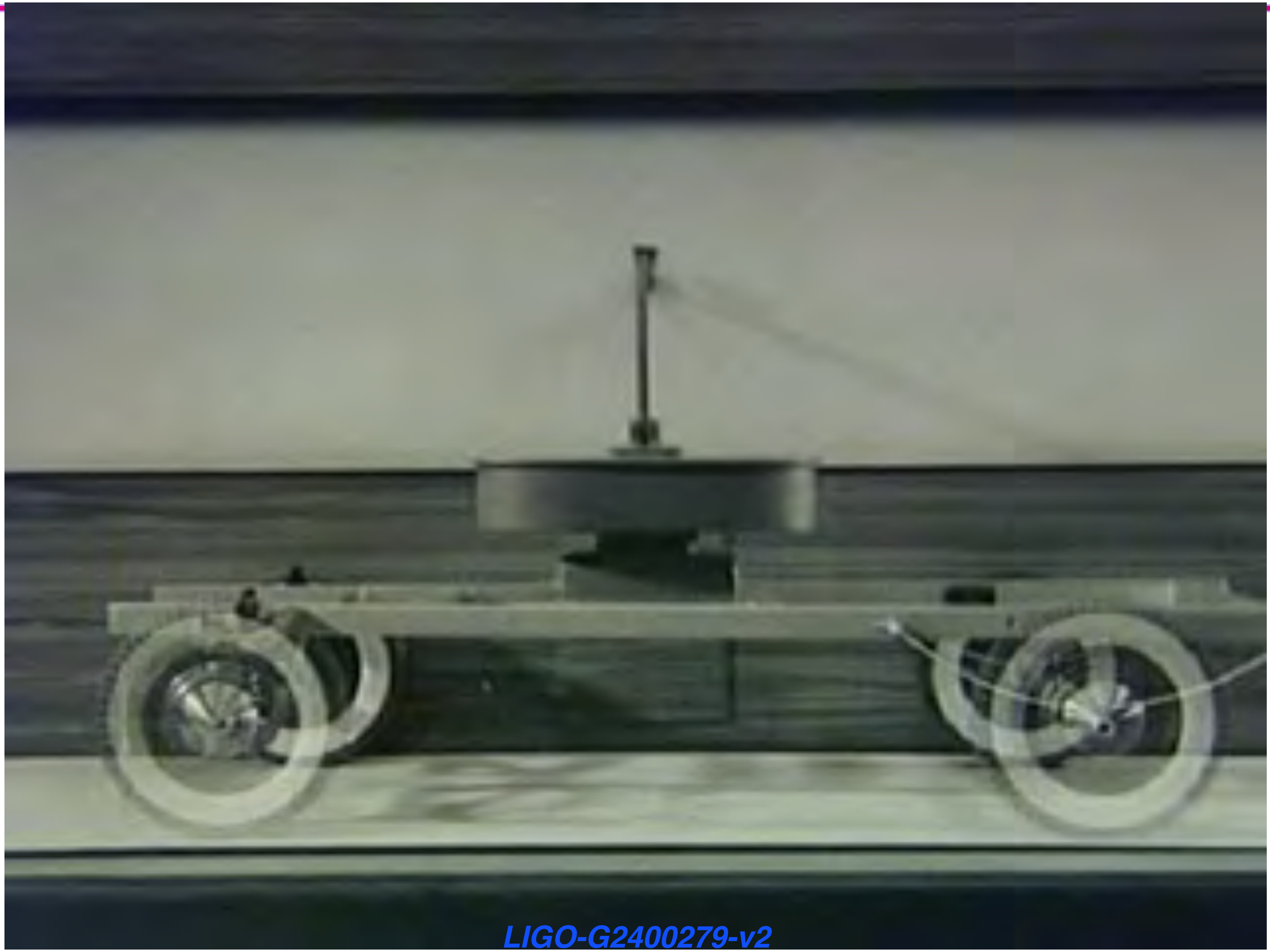


Detector noise sources



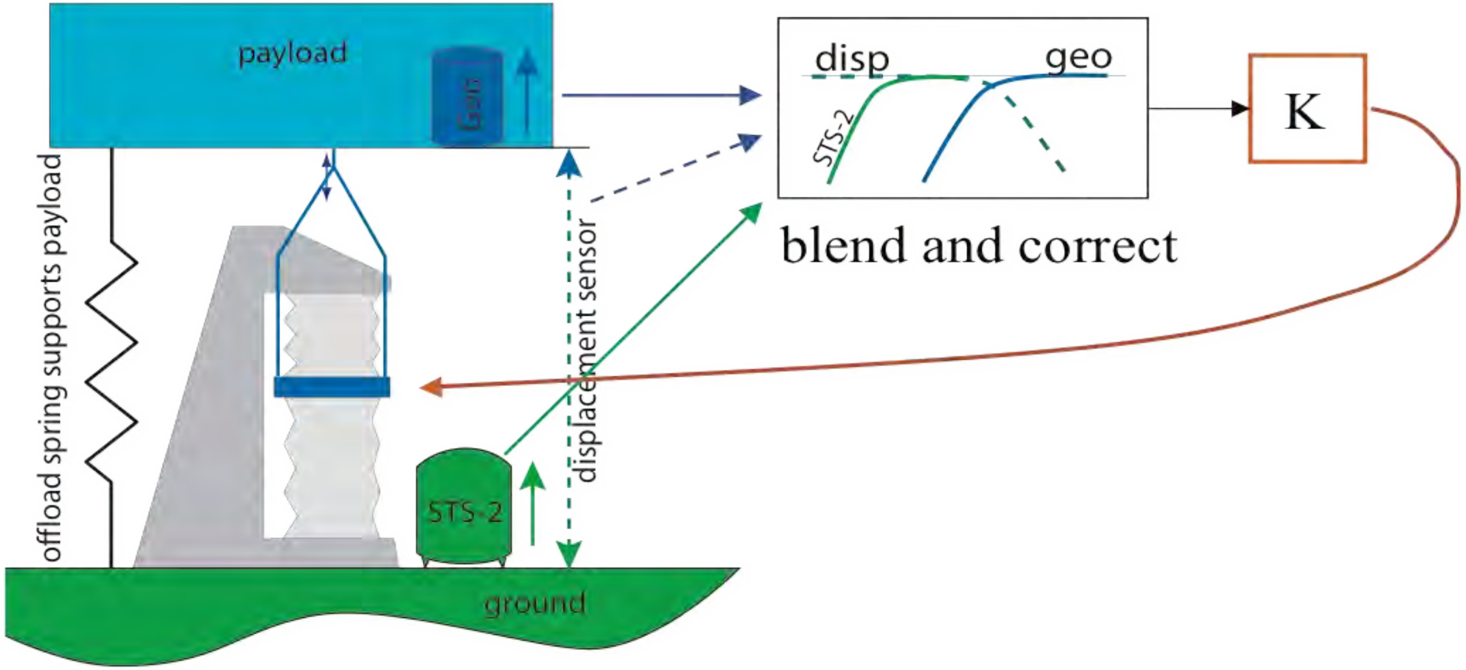
- Lowest frequencies: noise dominated by control actuation necessary to maintain optical alignment, resonance and balance
- Mid frequencies: noise dominated by kT (thermal) noise in test mass coatings
- High frequencies: quantum (shot) noise.

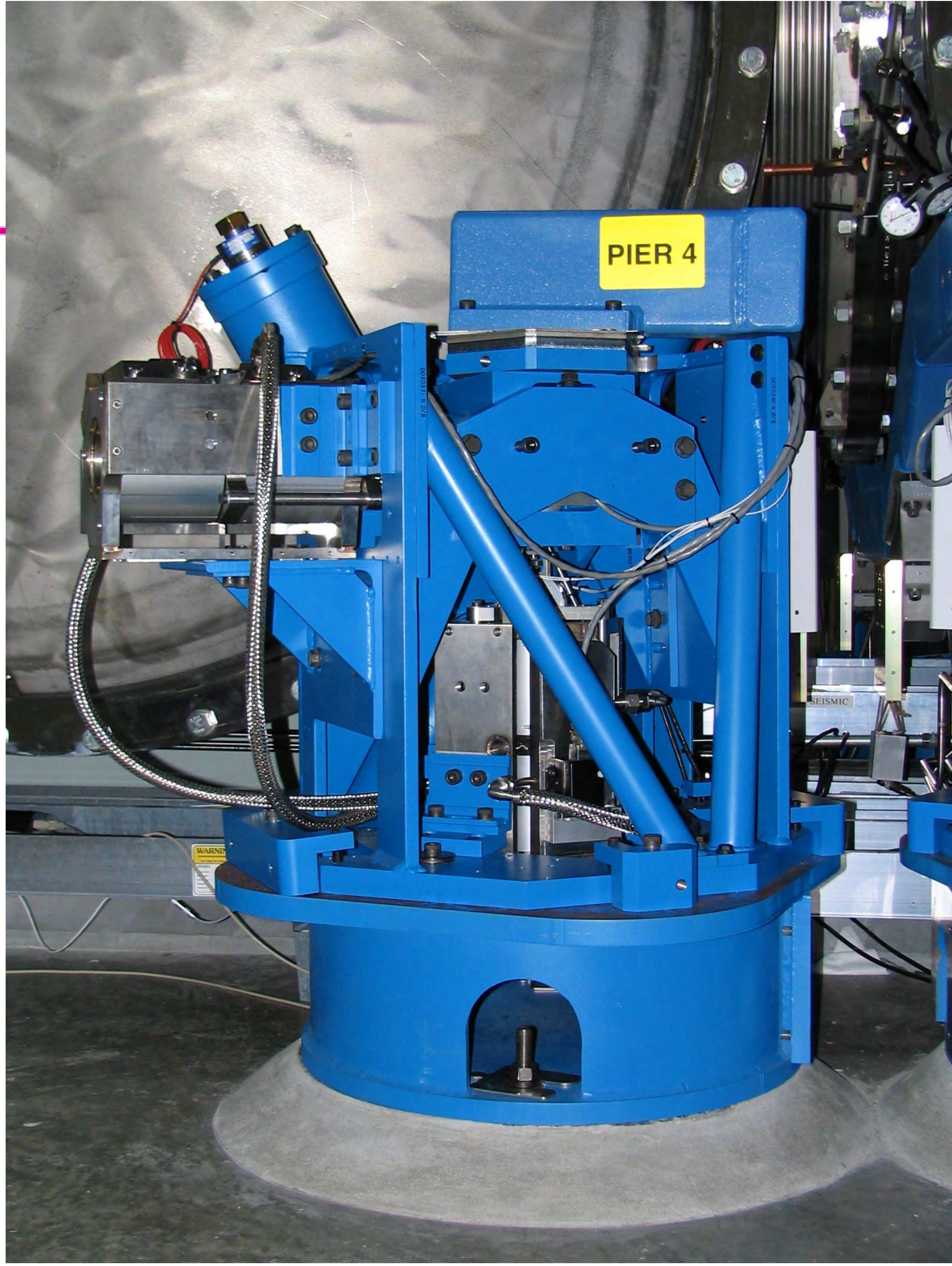
1938 seismic isolation technology



General Motors

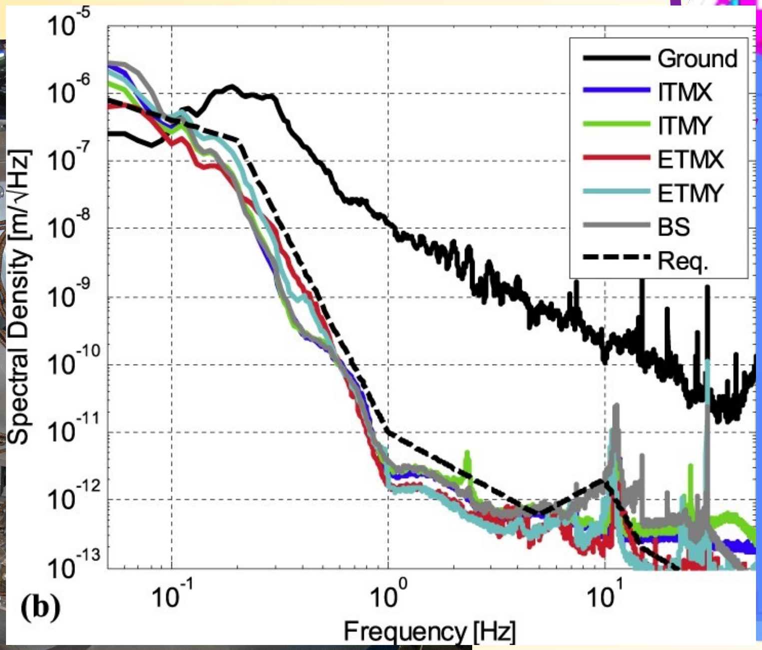
Active Seismic Isolation

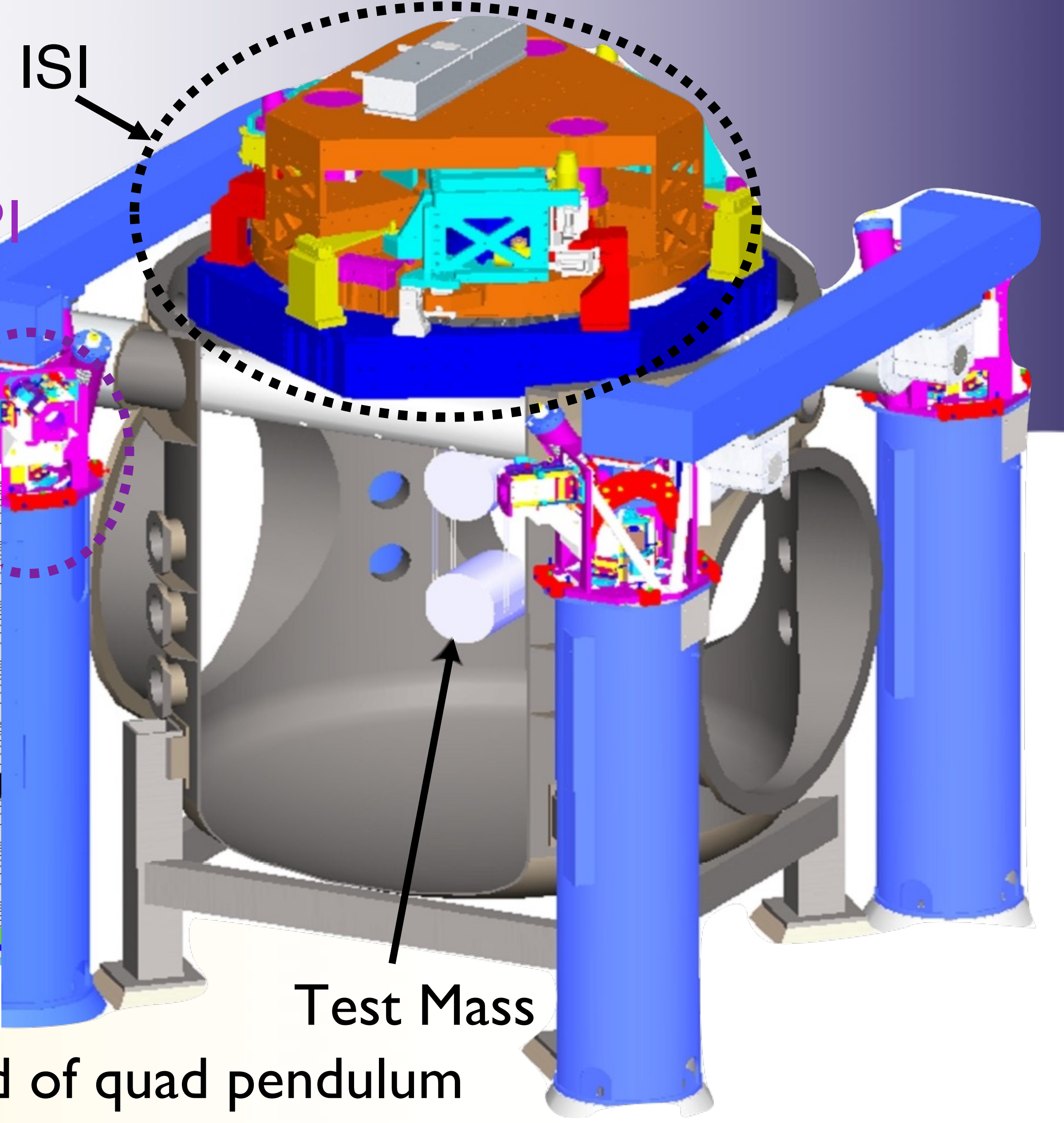




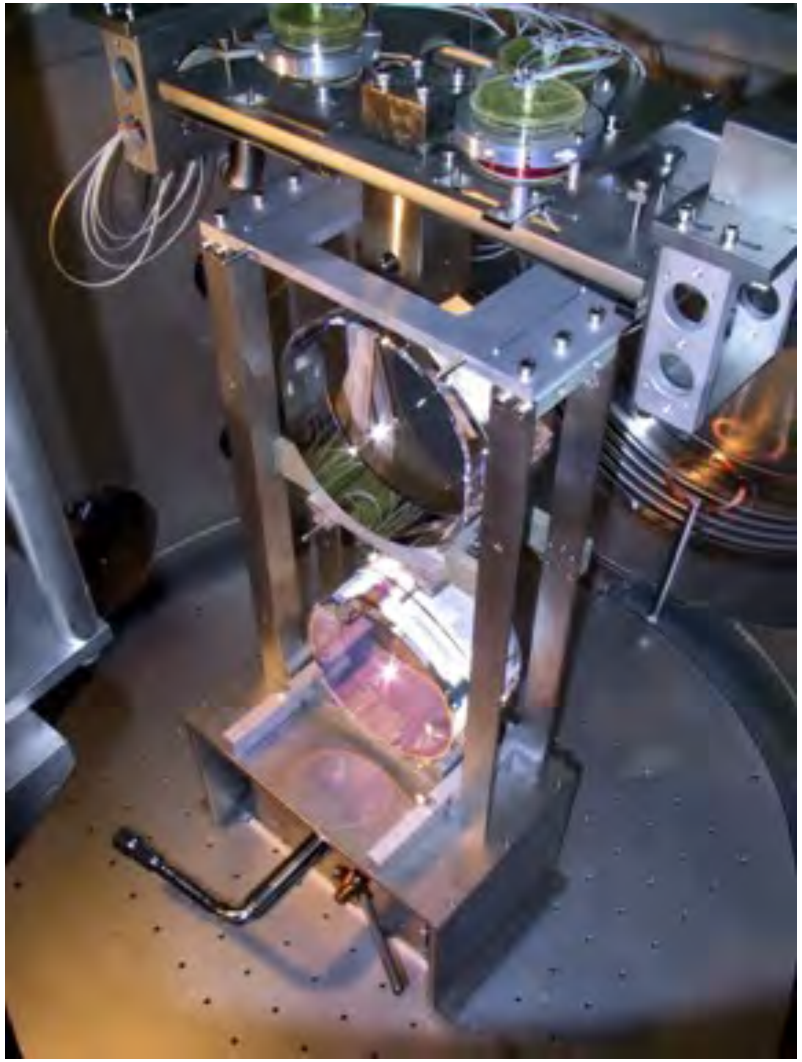
Seismic Isolation

- HEPI: Hydraulic External Pre-Isolator
  large throw, isolation below ~5 Hz
- ISI: Internal Seismic Isolation
  Isolates above ~0.2 Hz
- Quadruple pendulum: superior performance at 10 Hz and above



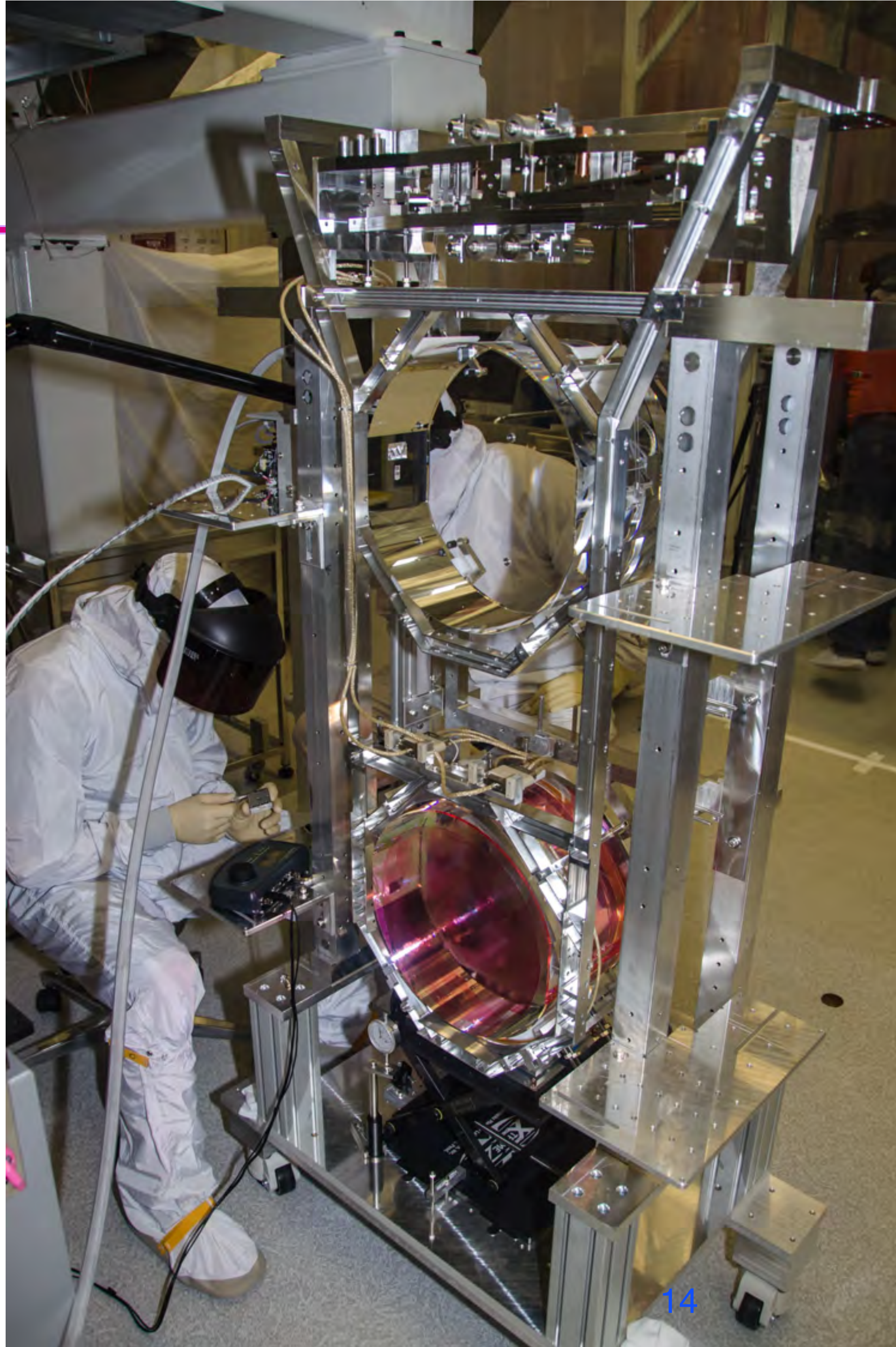


LIGO Monolithic Mirror Suspensions:
Fused silica test mass, hung from similar mass via pure silica fiber and 'ears.'



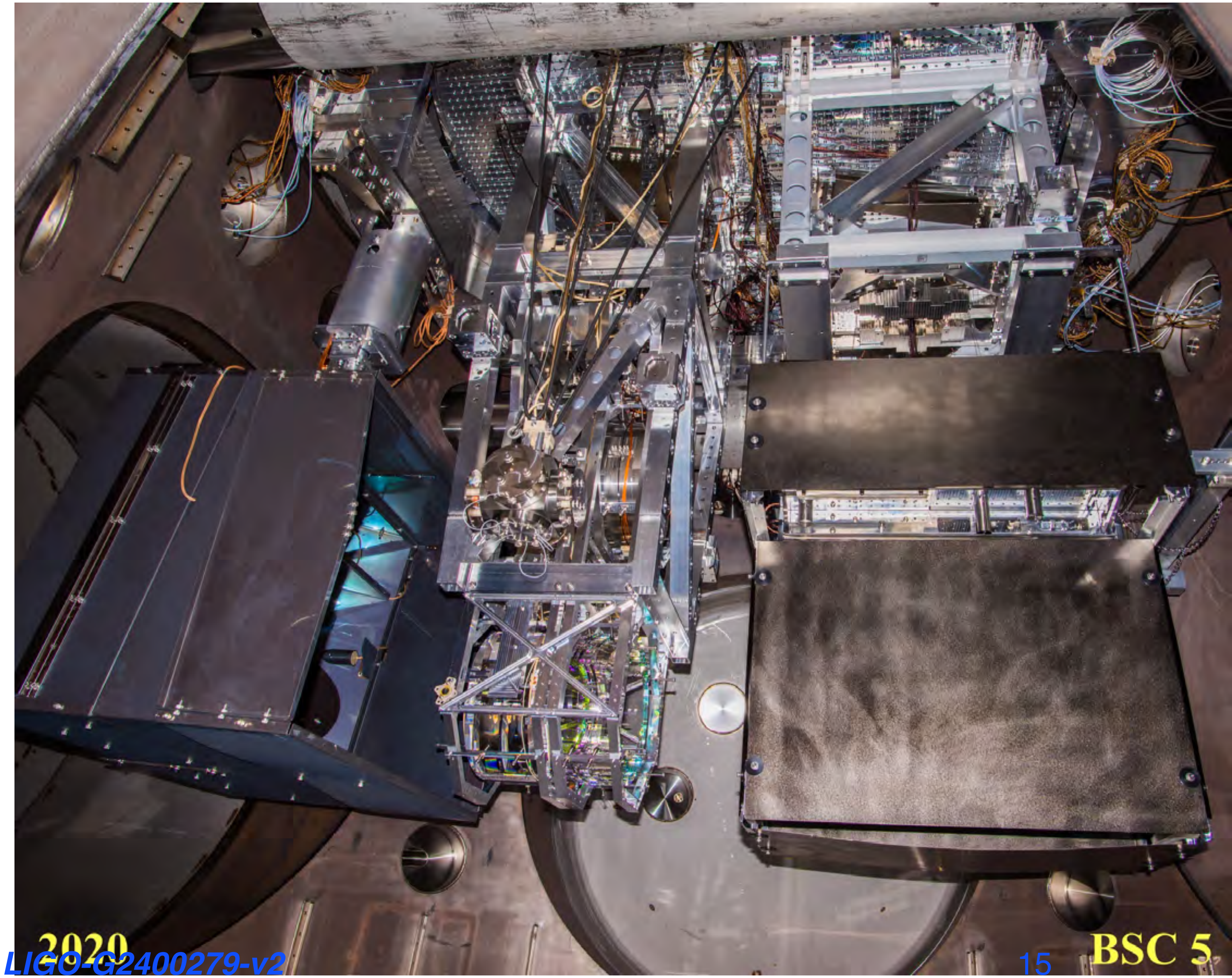
Goal: thermal noise from mechanical dissipation as low as possible

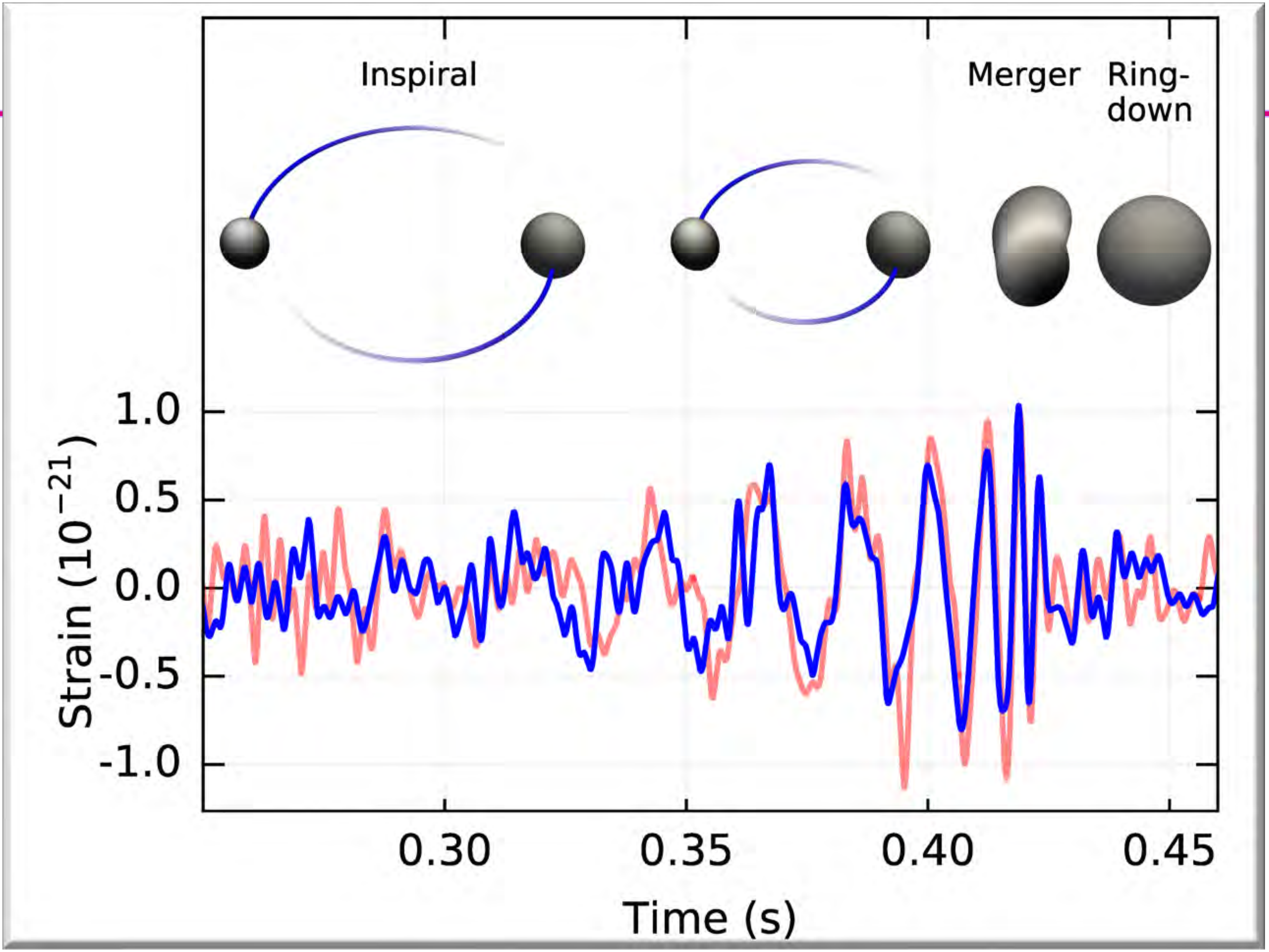
GEO 600 photo



End station test mass

- Baffle assembly
- Quad pendulum, with reaction chain
- High reflectivity test mass mirror
- Transmission light telescope and instrumentation.





PRL **116**, 06112 (2016)

PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

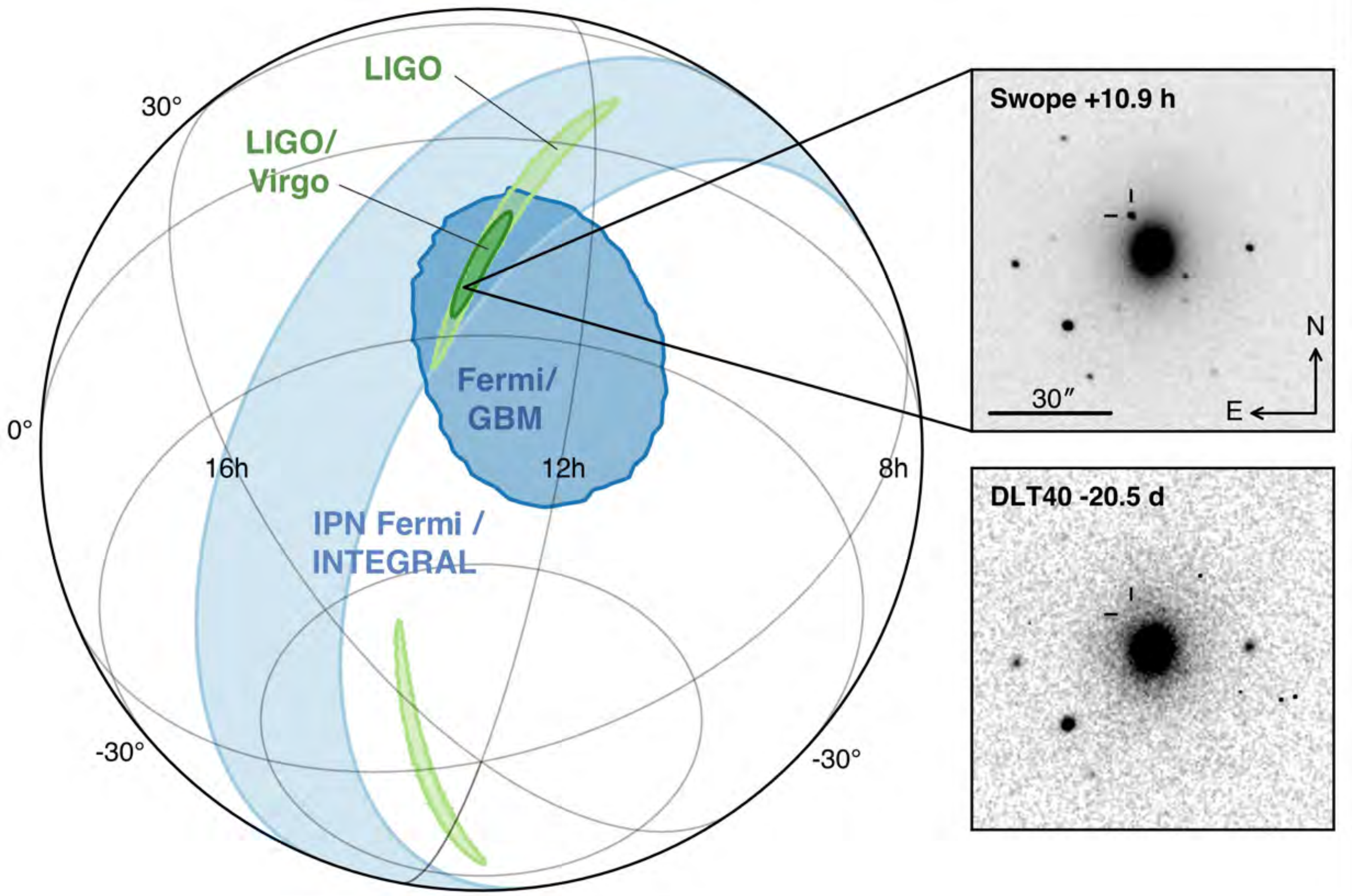
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

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. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

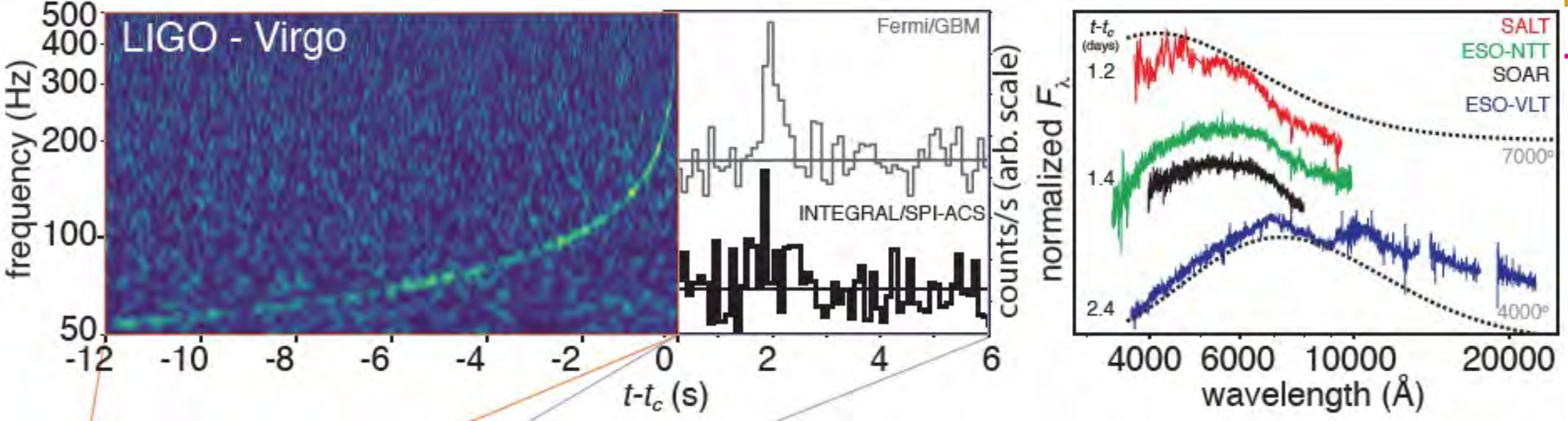
DOI: 10.1103/PhysRevLett.116.061102

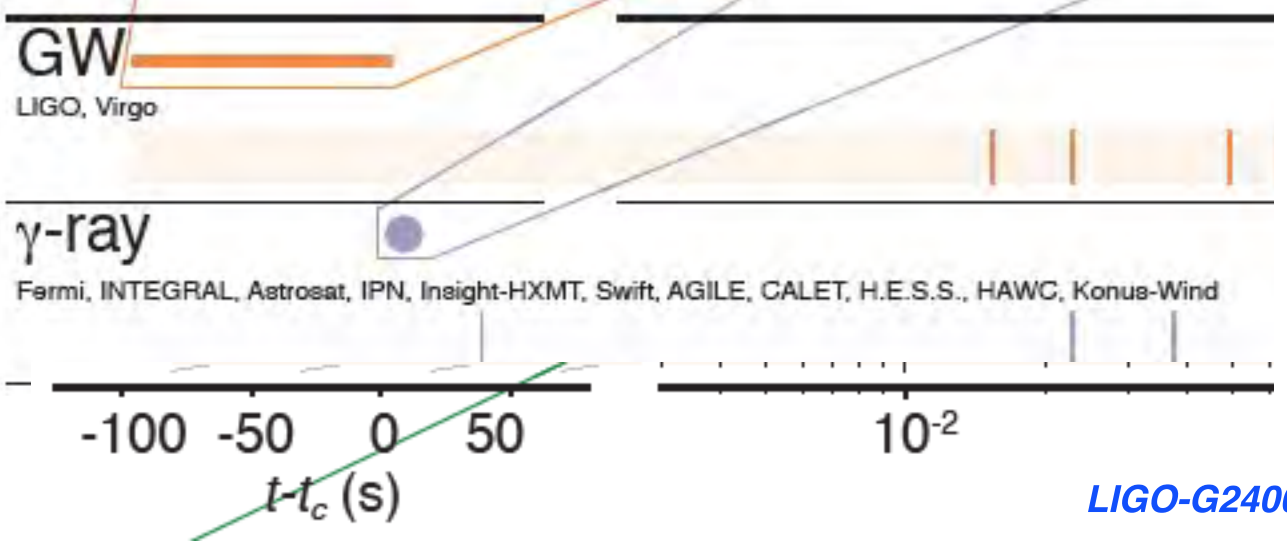
GW170817: Localization and optical counterpart discovery or, why astrophysics need a global GW network.



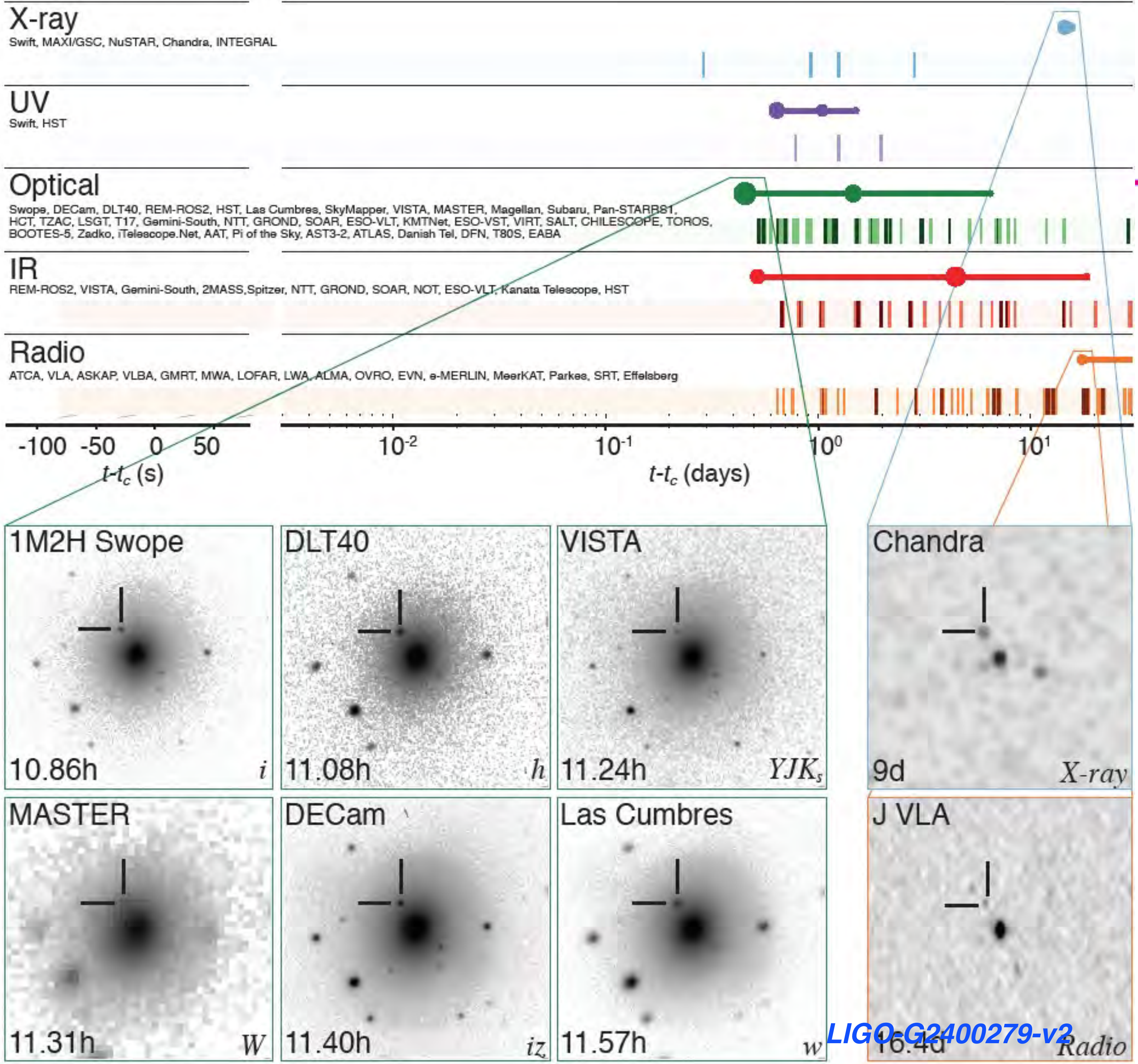
- From LIGO/Virgo/Many partners Multi-messenger paper, https://doi.org/10.3847/2041-8213/aa91c9
- Fermi/GBM, LIGO/Virgo localization areas nicely intersect.
- 1M2H team using Swope telescope found counterpart and galaxy 10 hours later.

Gamma-ray bursts seen





- Strong evidence connecting short GRBs with NS mergers.
- https://doi.org/10.3847/2041-8213/aa920c
- ~2 s delay between GW and GRB signal can be used to limit theories that would make speed of GW and Gamma rays differ.



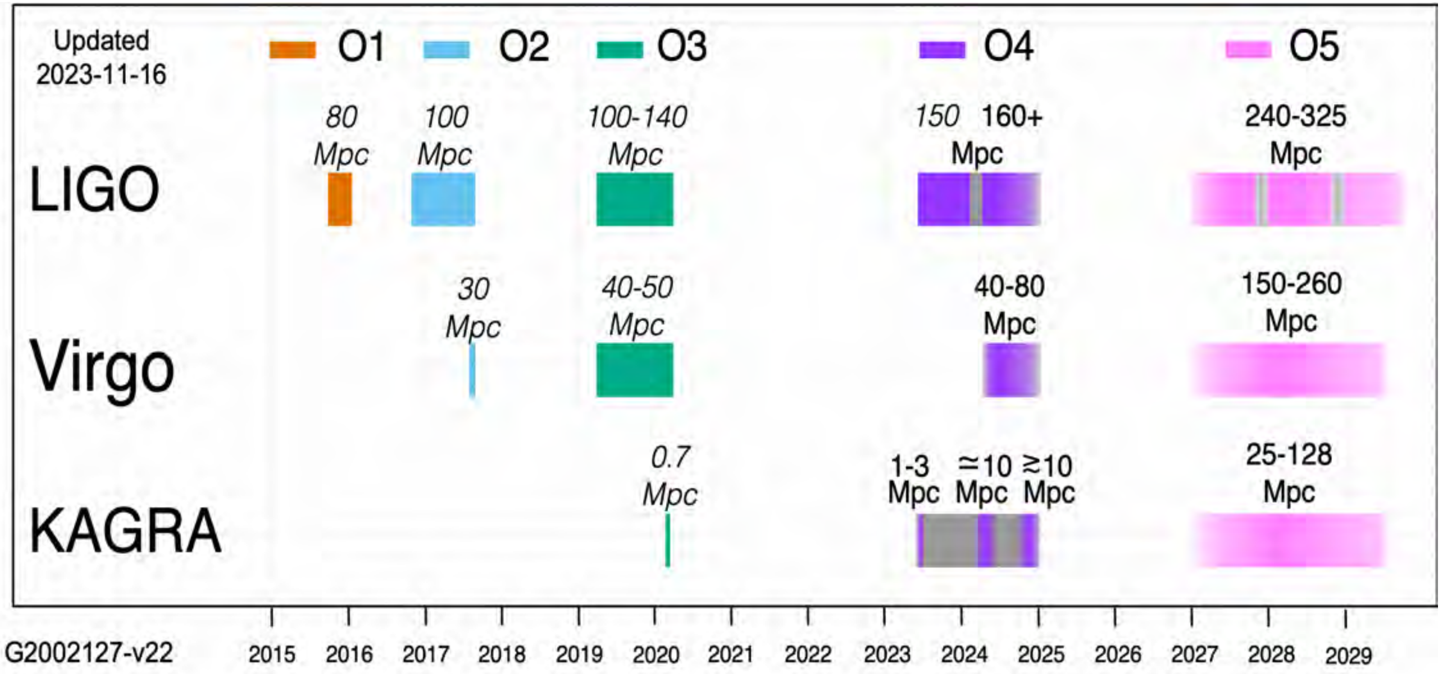
Light, X-ray, radio

- First optical counterpart ID’d by 1M2H team using Swope: DOI: 10.1126/science.aap9811
- Object was near the Sun, making it hard work.
- Light dimmed and reddened over days.
- X-ray data taken with Chandra’s 3-10 keV band: https://doi.org/10.3847/2041-8213/aa8ede
- J VLA radio data, 3 and 6 GHz: DOI: 10.1126/science.aap9855

LIGO

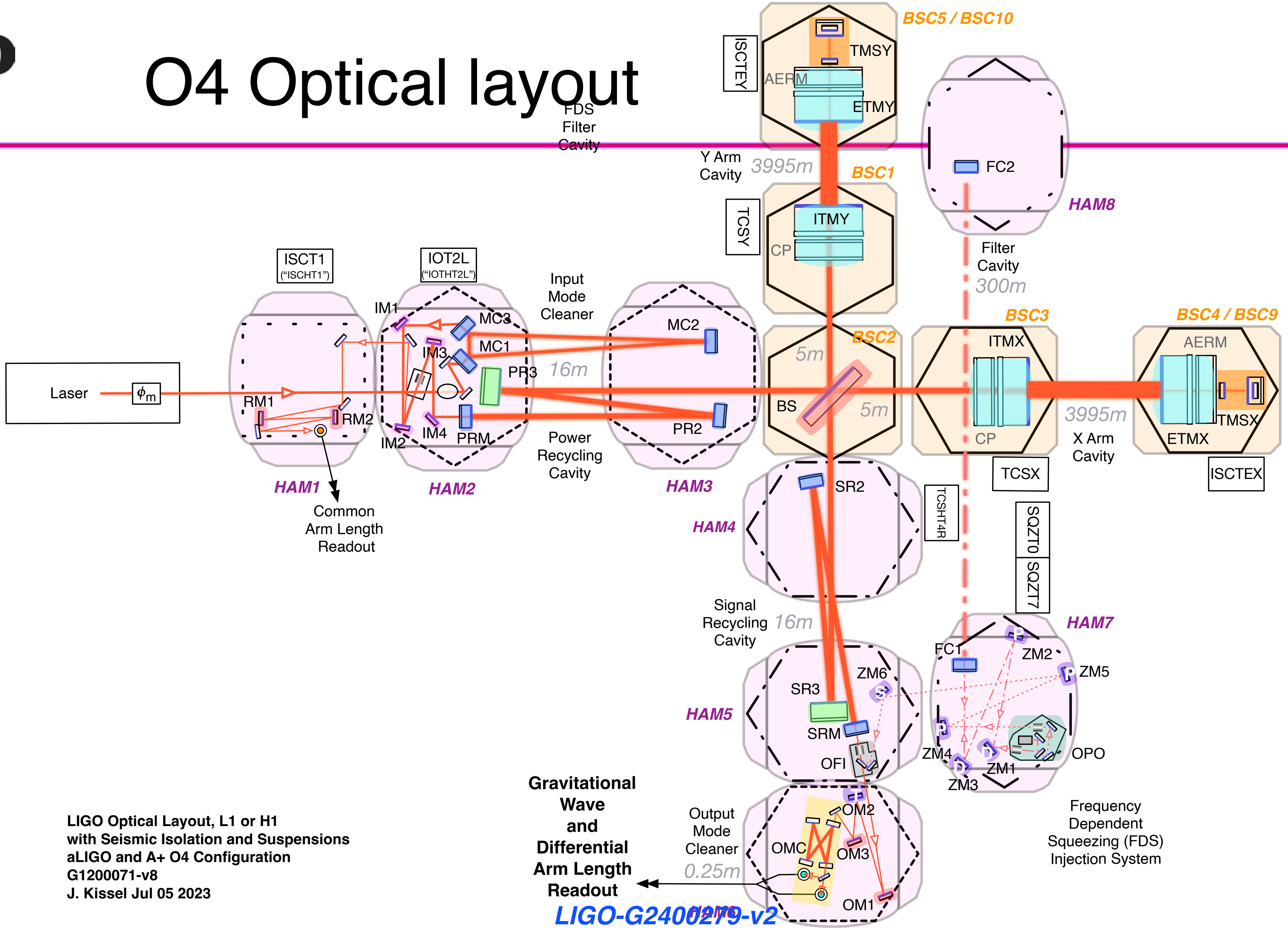
LVK runs and plans

Past (O1, O2, O3); Present (O4); future (O5)



- O4b is to begin early April, 2024 and run until around the end of the year.
- Installation, commissioning and tests leading to O5 will occupy 2025 and 2026.
    - ➢ key feature is coatings with less mechanical dissipation and fluctuation, allowing other upgrades to be effective.

O4 Optical layout



Gravitational Wave and Differential Arm Length Readout

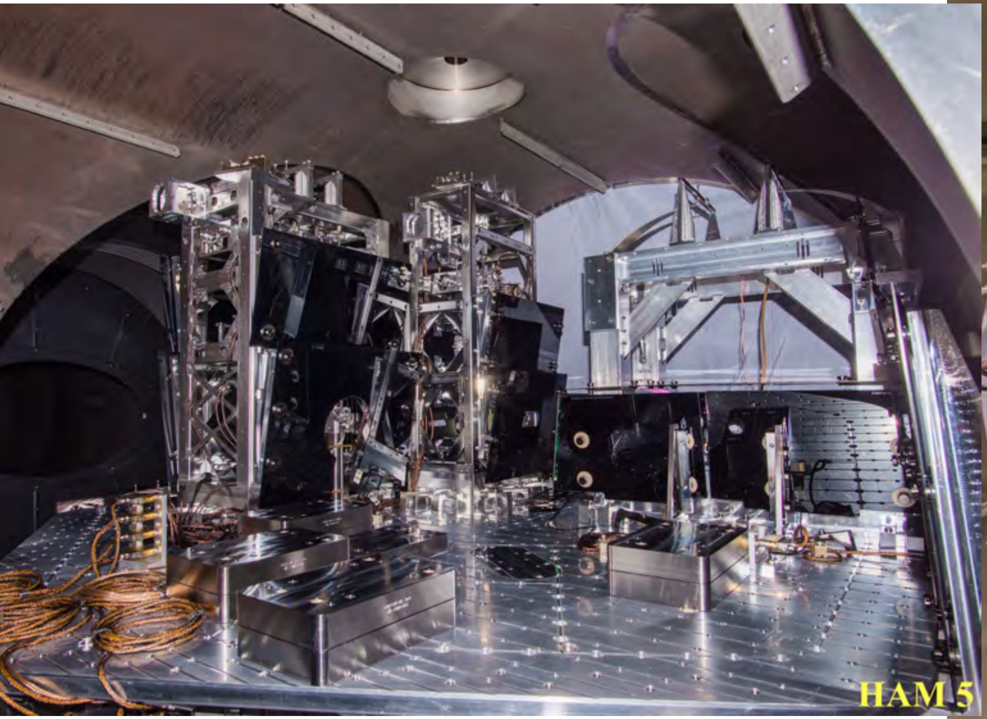
LIGO Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
aLIGO and A+ O4 Configuration
G1200071-v8
J. Kissel Jul 05 2023

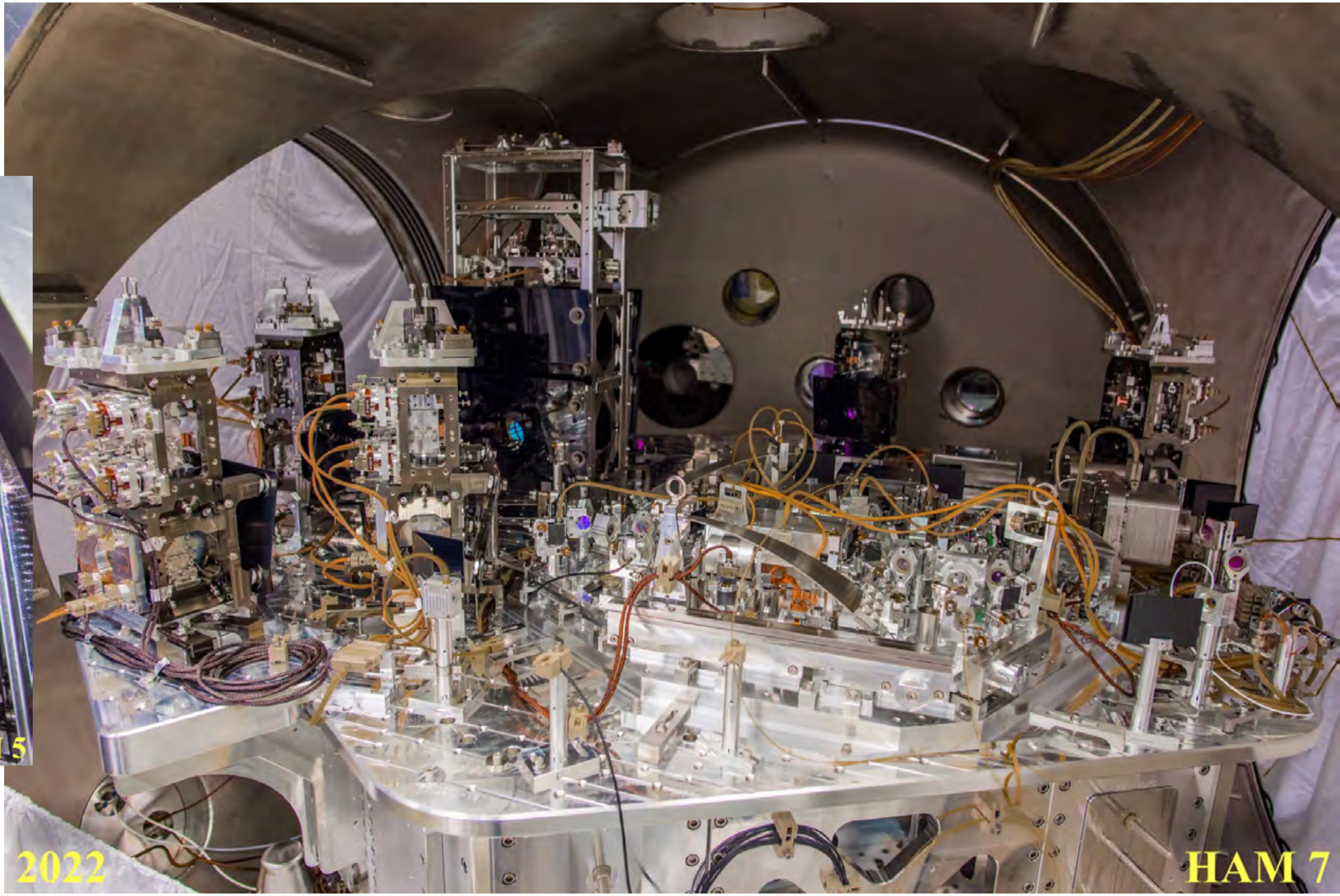
Frequency-dependent squeezed vacuum

- Between O3 and O4, both LIGO detectors were outfitted with a frequency-dependent squeezed source.
  - For the first time since LIGO was built, we added new piece of major detector-related architecture, a new 300 m enclosure beside Y arm, with a pass-through to the main (LVEA) high-bay space.
  - This was a critical part of the A+ project, intended to augment and improve the Advanced LIGO detectors.
  - Briefly, an improved version of the O3-era squeezed state was reflected from a 300 m Fabry-Perot filter cavity. Opto-mechanical interactions rotated the squeeze angle.
  - At high frequencies, > 5 dB of squeezing in phase noise and anti-squeezing on amplitude noise
  - At low frequencies, modest squeezing (or absence of anti-squeezing) in amplitude noise.
- The squeezed vacuum state is injected into the antisymmetric Michelson port, in place of unaltered vacuum.
- The filter cavity length/ alignment and various squeezer degrees of freedom are stably controlled for performance and stability

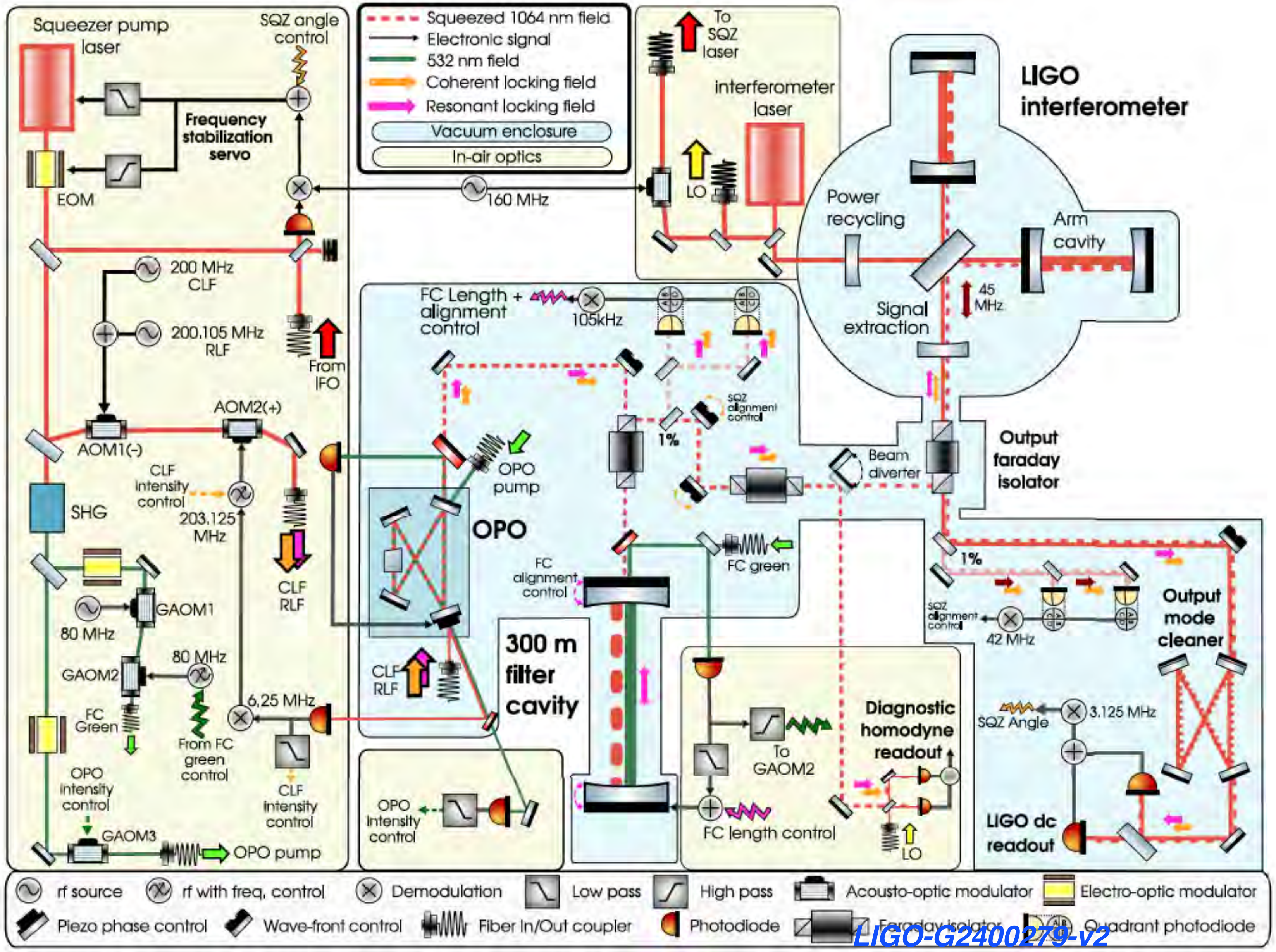
- https://doi.org/10.1103/PhysRevX.13.041021 D. Ganapathy, W. Jia, M. Nakano, et. al. (LIGO O4 Detector Collaboration)

New-for-O4 frequency-dependent squeezed vacuum preparation and injection





Squeezing overview



- https://doi.org/10.1103/PhysRevX.13.041021 D. Ganapathy, W. Jia, M. Nakano, et. al. (LIGO O4 Detector Collaboration)
- The squeezer generates squeezed vacuum at 1064 nm using a subthreshold optical parametric oscillator, pumped at 532 nm stabilized from main laser.
- Two sidebands are added, to allow extraction of error signals for the squeeze angle and filter cavity length with offset.
- Long-term angle and length stability is controlled globally with main interferometer degrees of freedom.
- Various diagnostic states are available.

Scattered light

$$h_{sc} = G \cdot \sin(2k \cdot x_{sc})$$

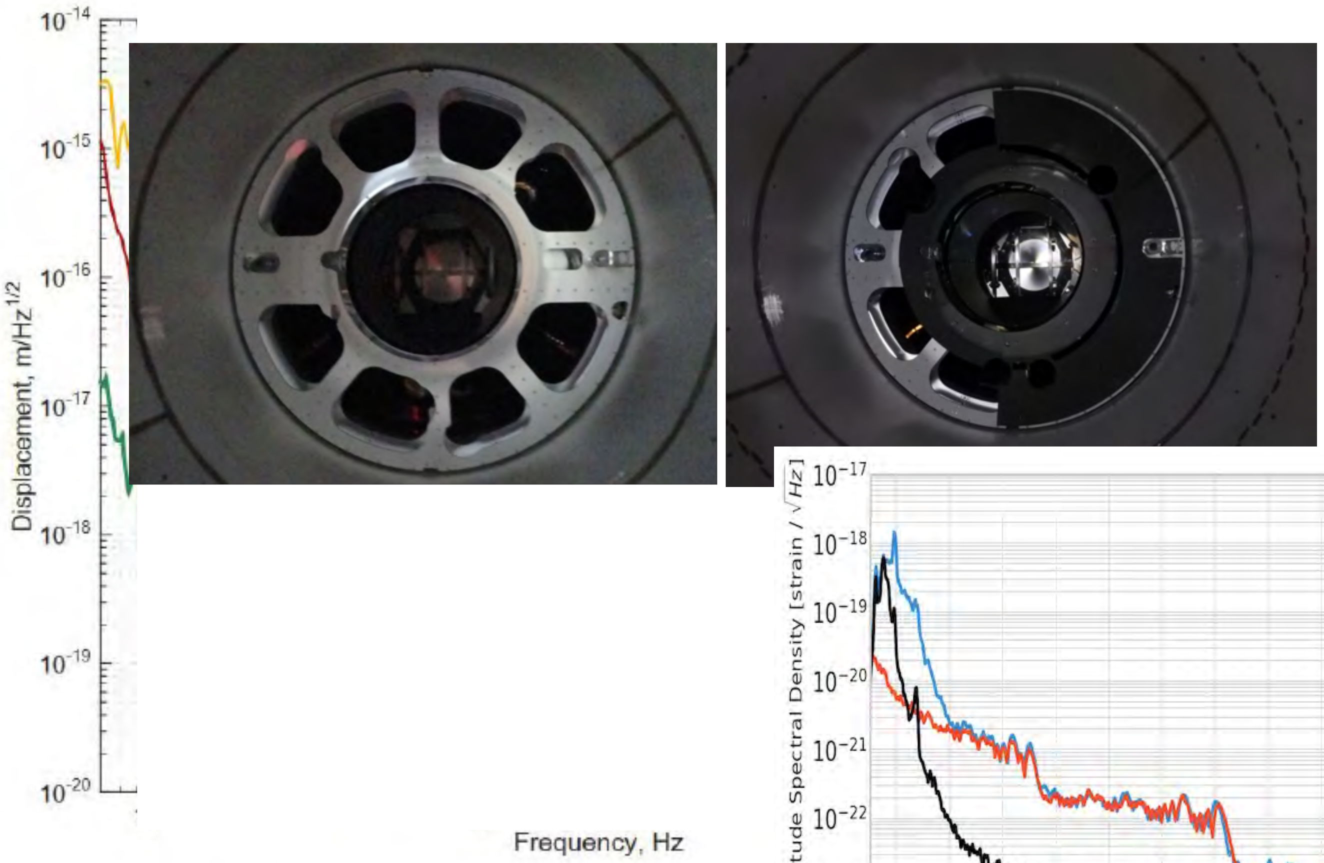
View of the effect of one of the baffles

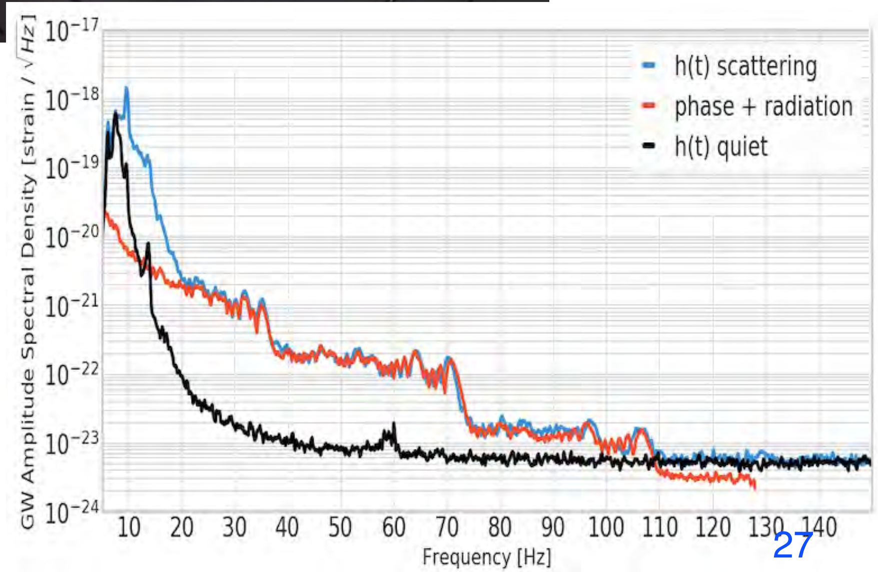
When $kx_{scat} \ll 1$, phase modulation at the frequency of the backscattering surface

When $kx_{scat} \gg 1$, noise is upconverted to higher frequencies up to a maximum:

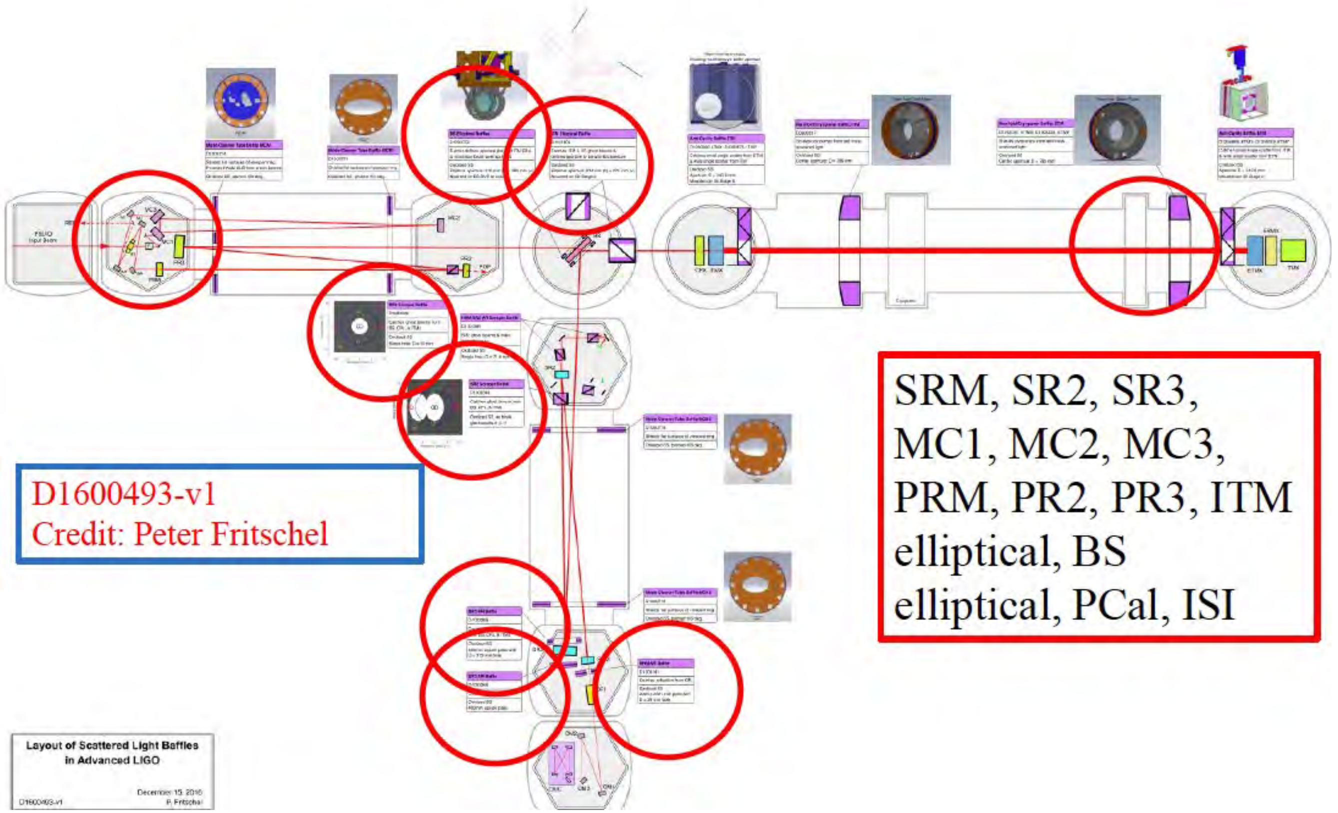
$$\omega_{max} = 2kx_{scat}\omega_{scat}$$

This maximum sets the 'knee' of scattering shelves

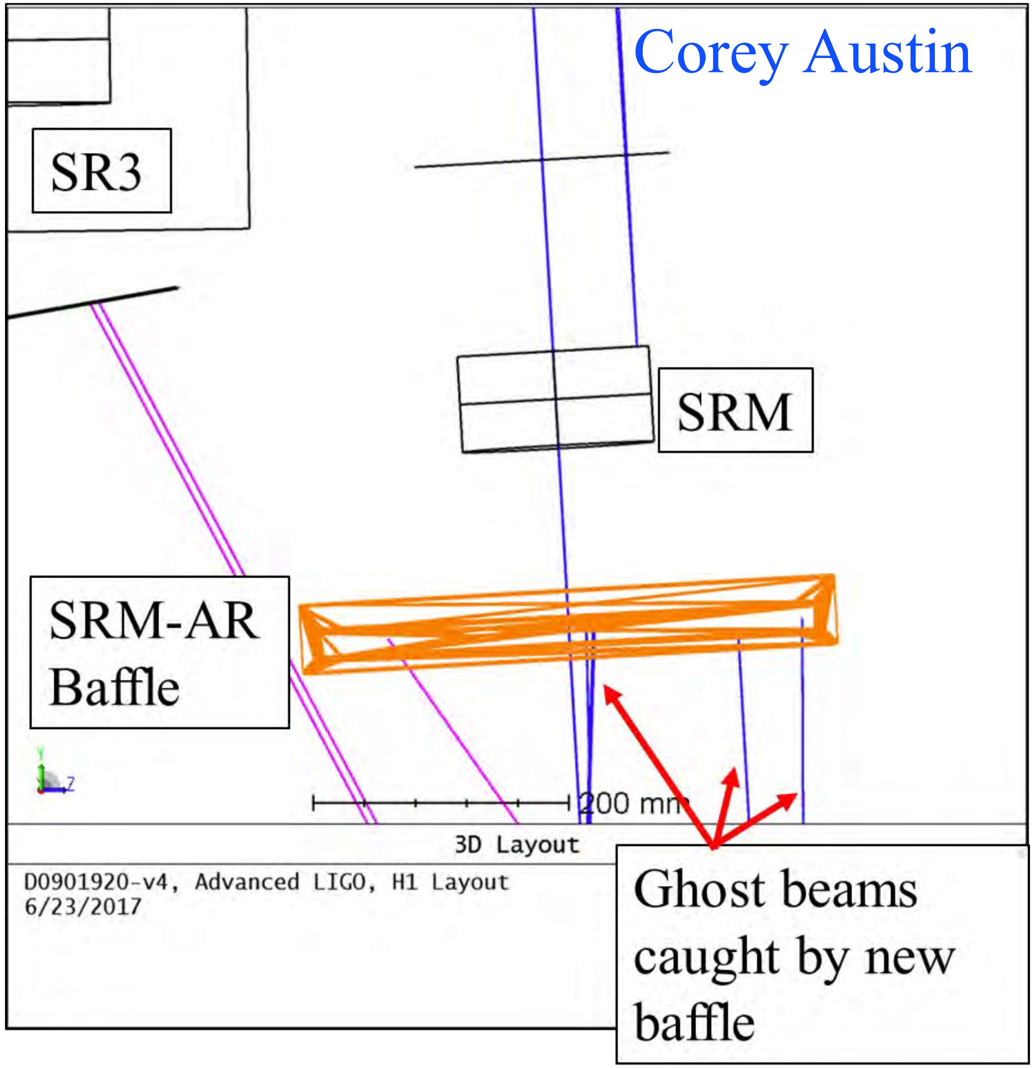




Scattered light abatement (Corey Austin, LSU Ph.D. ’20)

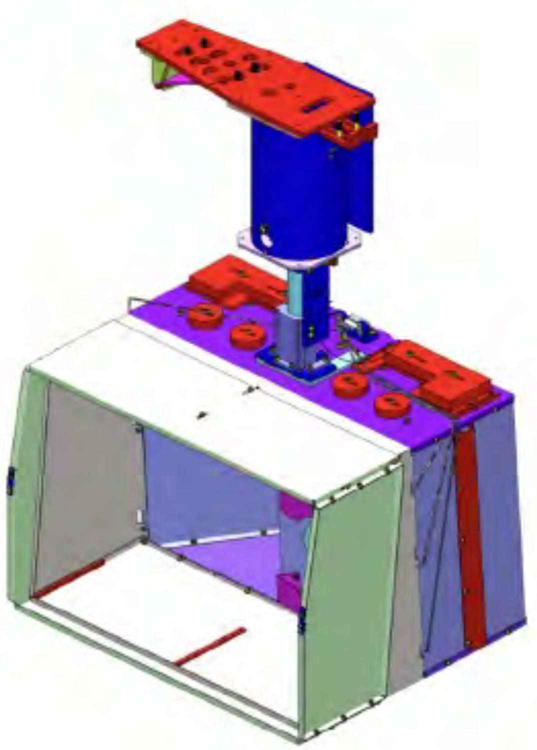


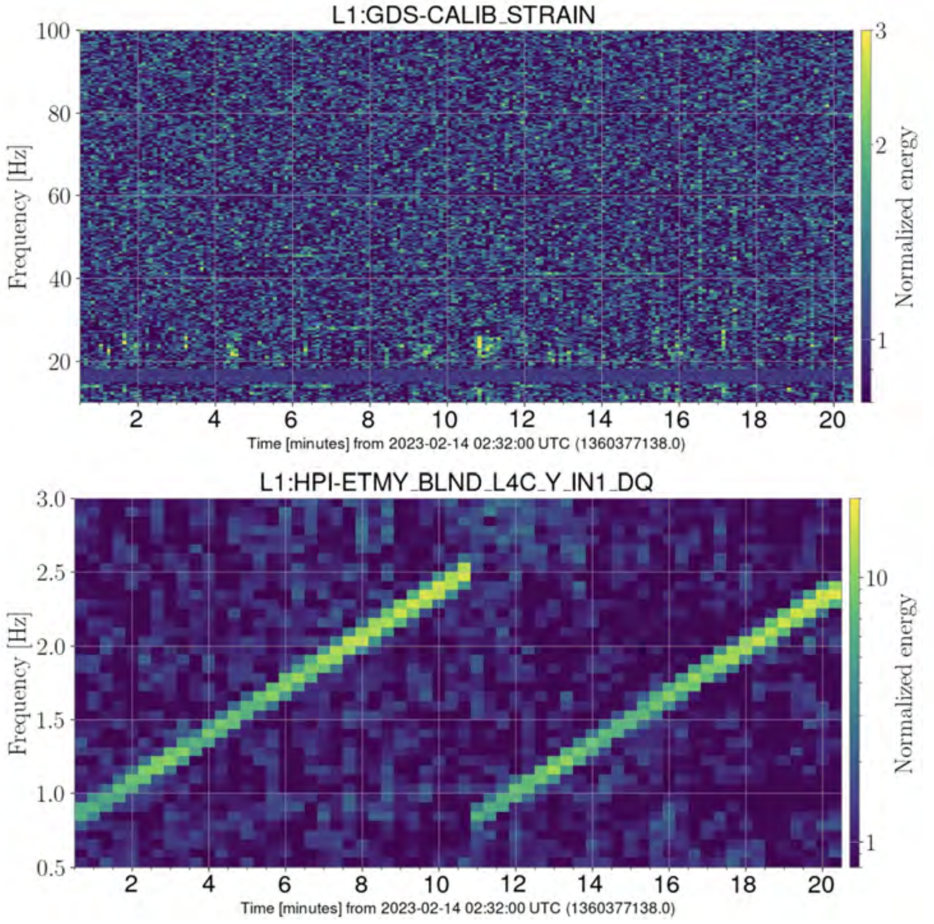
SRM, SR2, SR3, MC1, MC2, MC3, PRM, PR2, PR3, ITM elliptical, BS elliptical, PCal, ISI



Reduction of noise from scattered light

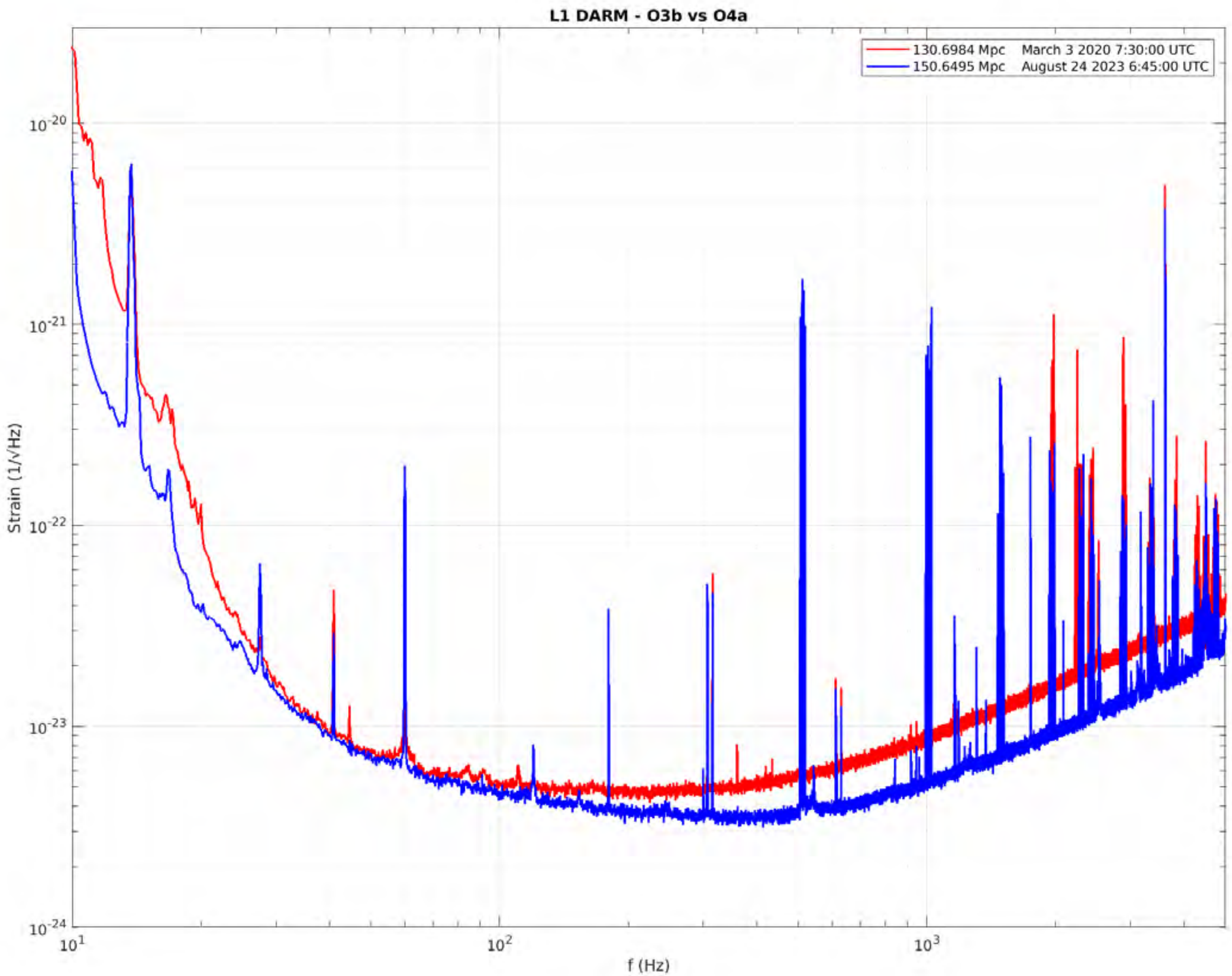
- Search for coupling of out-of-band ground motion to detector output implicated undamped resonance in beam cavity baffle. This was damped, and a short removed, leading to reduced coupling
- arXiv:2401.17495v1 [gr-qc] 30 Jan 2024. S. Soni, J. Glanzer, A. Effler, V. Frolov, G. González, A. Pele, R. Schofield.
- D Davis et al 2021 Class. Quantum Grav. 38 135014 DOI 10.1088/1361-6382/abfd85





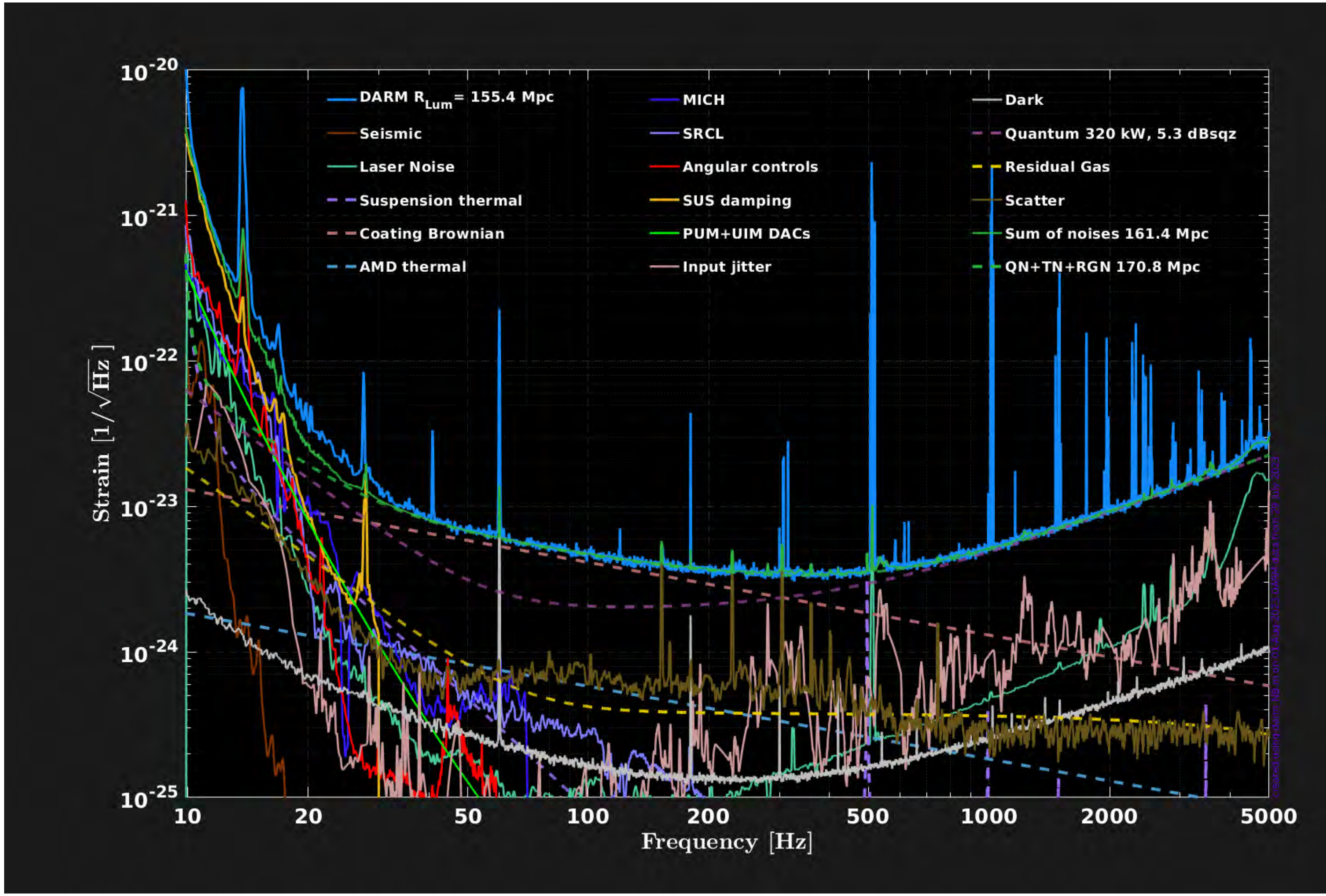
Comparison between O3b and O4a

- Overlay of typical O3b and early O4a Livingston noise
- Changes:
  - Arm power increase 250 kW/200 kW (O3a/O3b) to 320 kW O4a, and due to the higher level of (frequency dependent) squeezing ~2.5 dB -> 5.3 dB, which also reduces the radiation pressure noise.
  - The DARM noise reduction at low frequency is due to the following improvements:
    - change of the TM spot position control scheme: dither->camera
    - rework of the subtraction and cut off filters of the LSC/ASC/BOSEM noises
    - **removing the mechanical shorting on the arm cavity baffles**
    - reduction of the HAM1 table motion
    - reduction of the AS port back scatter: **removal of the HAM5/6 septum plate, cleaning of the output mode cleaner, and new output Faraday isolator**
- V. Frolov. https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=66948



LIGO O4a noise performance

- Typical O4a Livingston noise spectrum, with modeled contributions, 29 Jul 2023
- Interesting contributions include
  - ➢ Quantum sensing
  - ➢ Coating Brownian
  - ➢ Angular controls
  - ➢ Mystery (near 20 Hz)
- Range for NS/NS mergers, averaged over pol. and angles: 155 Mpc.
- A. Effler, V. Frolov. https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=66532

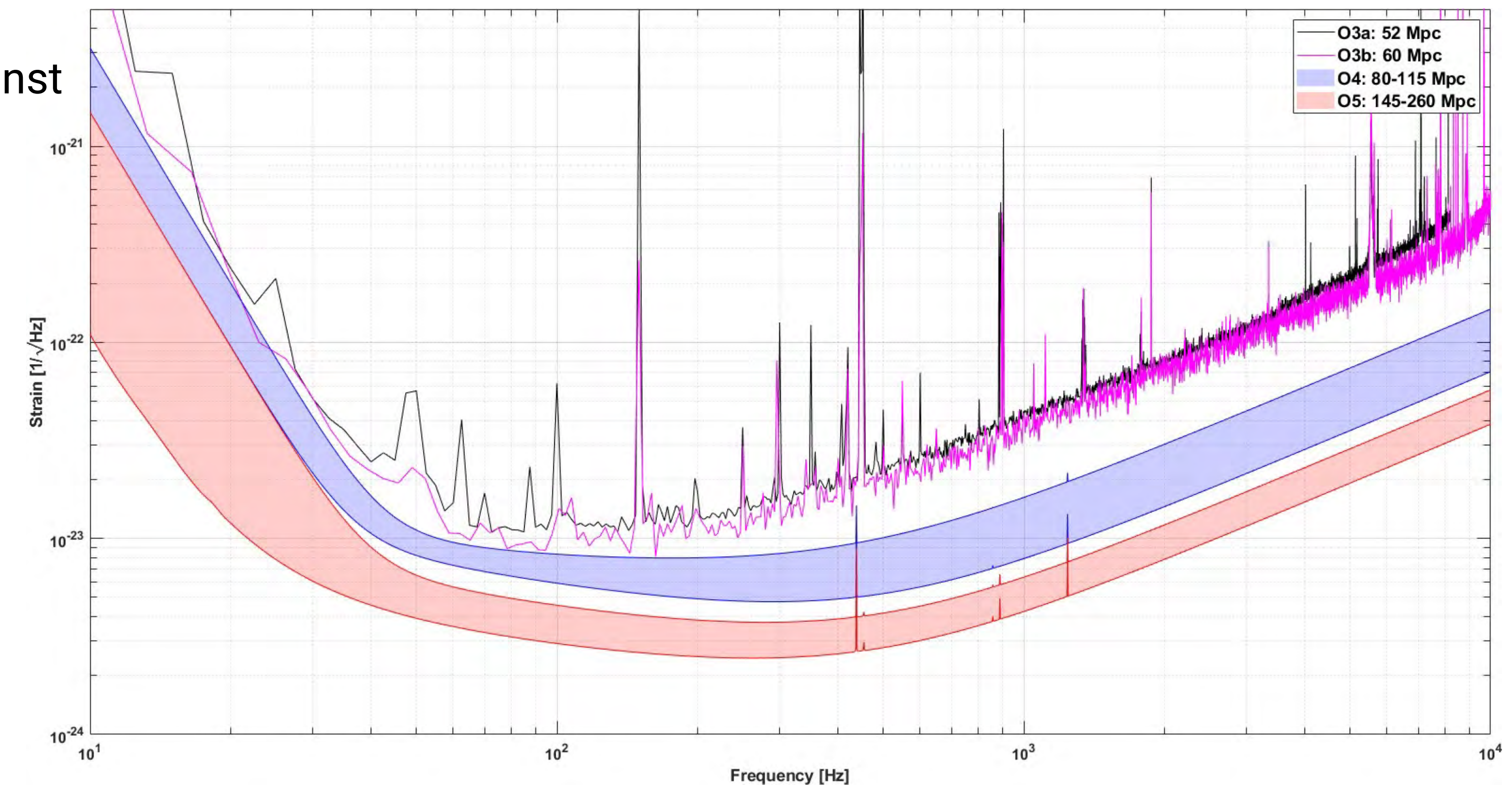


FROM O3 TO O4: ADV+ DESIGN SENSITIVITY

Virgo Status,
from Gianlucca Gemme

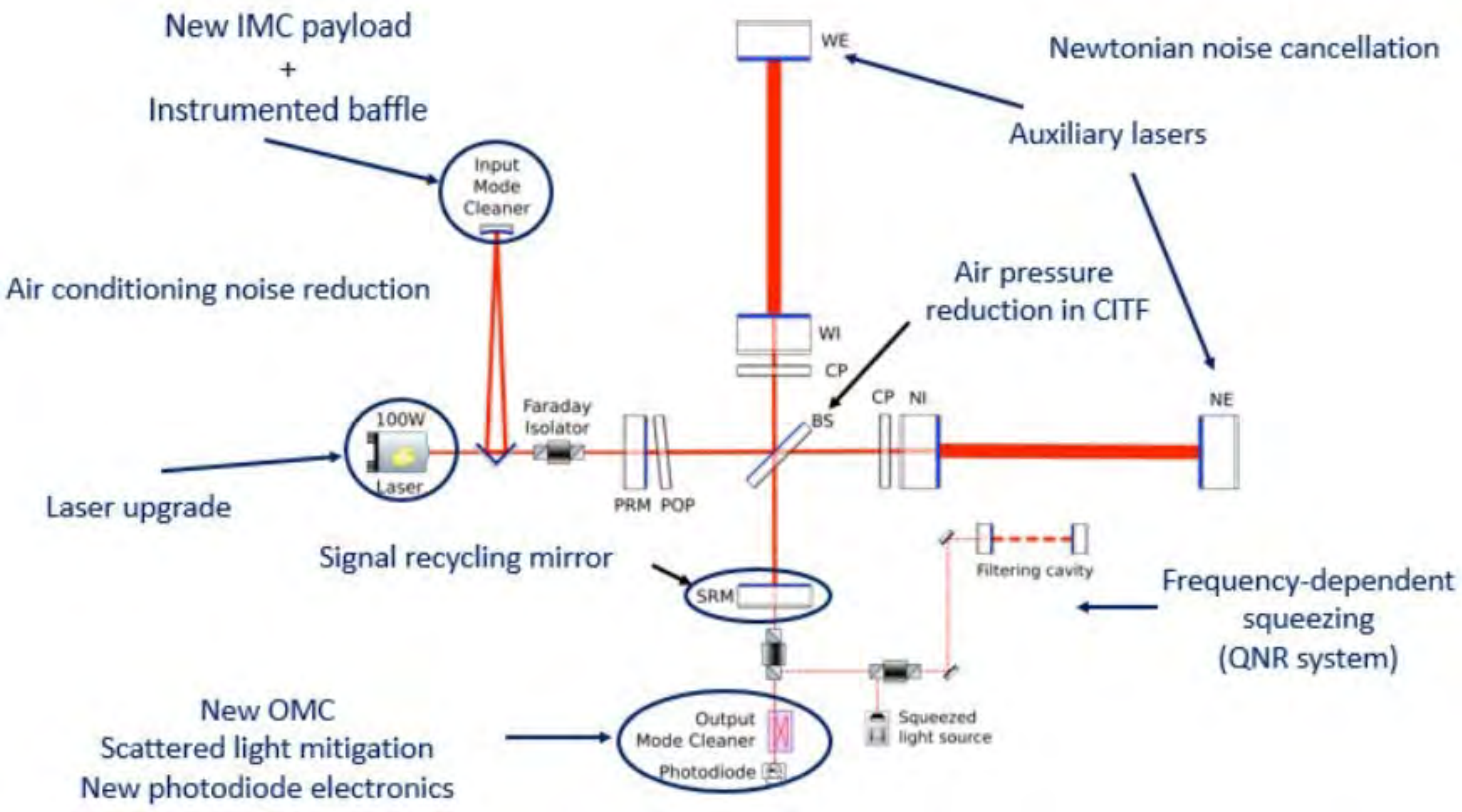
- Phase I (before O4: 2023-24)
  - Reduce quantum noise, hit against thermal noise
  - Reduction of technical noises
  - Preparation of Phase II
  - **BNS range ~ 100 Mpc**

- Phase II (before O5: 2027-28)
  - Lower thermal noise wall
  - **BNS range ~ 200 Mpc**



ADVANCED VIRGO+ PHASE I

Virgo Status,
from Gianlucca Gemme



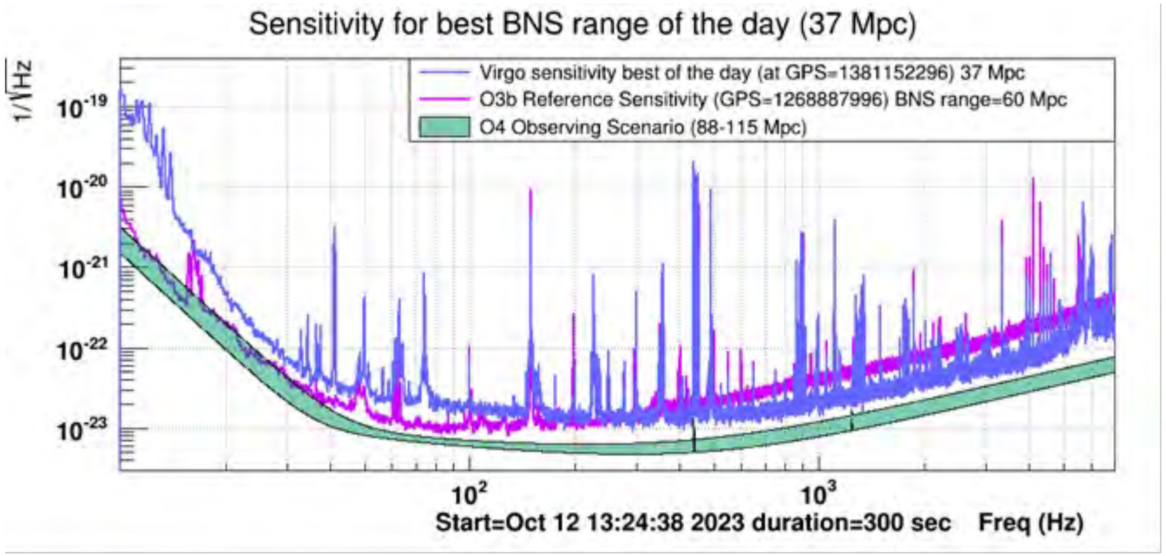
- Installation within a year despite pandemic
  - Main interferometer complete in December 2020
  - Quantum noise reduction system complete in April 2021
- Commissioning
  - Started in January/May 2021 for main ITF/QNR system
- Two aspects fundamentally new (in Virgo)
  - Signal recycling
  - Frequency-dependent squeezing

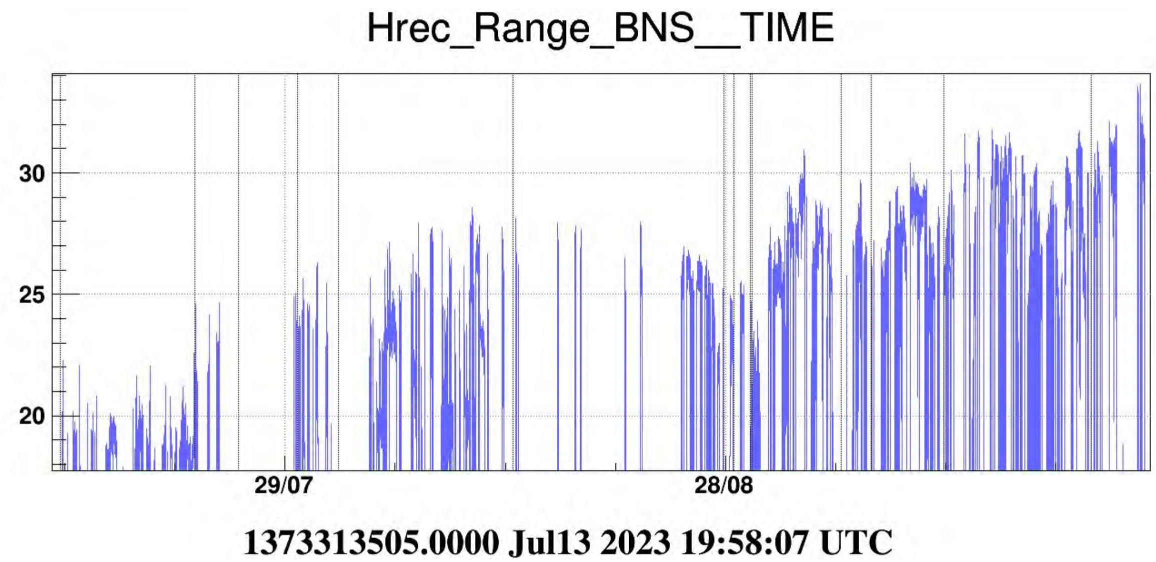
O4 COMMISSIONING

Virgo Status, from Gianlucca Gemme

- Stable and reproducible control of interferometer mostly achieved in fall 2022, after
  - Lowering input power from nominal 40 W to 33 W (further reduced to 23 W in Feb 2023)
  - Installing new thermal actuator to correct power-recycling mirror curvature
  - Learning to deal with signal-recycling cavity with resonating higher-order modes
    - **Due to Virgo specific optical configuration: marginally-stable recycling cavities**

- Commissioning took (and is taking) much longer than expected





- Virgo will join O4 in March 2024 and with a worse sensitivity than expected
  (mitigation of known noise sources: around 50 Mpc)

STABLE VS. MARGINALLY STABLE OPTICAL CAVITIES

Virgo Status,
from Gianlucca Gemme

Stable optical recycling cavities

Marginally stable optical recycling cavities

WHAT'S NEXT? O5, POST-O5 AND 3RD GEN

Virgo Status,
from Gianlucca Gemme

- Plans for O5 being revised

- **Install stable recycling cavities in Virgo?**
  - Realistic options, timing, cost, impact on ongoing activities, impact on observing timeline

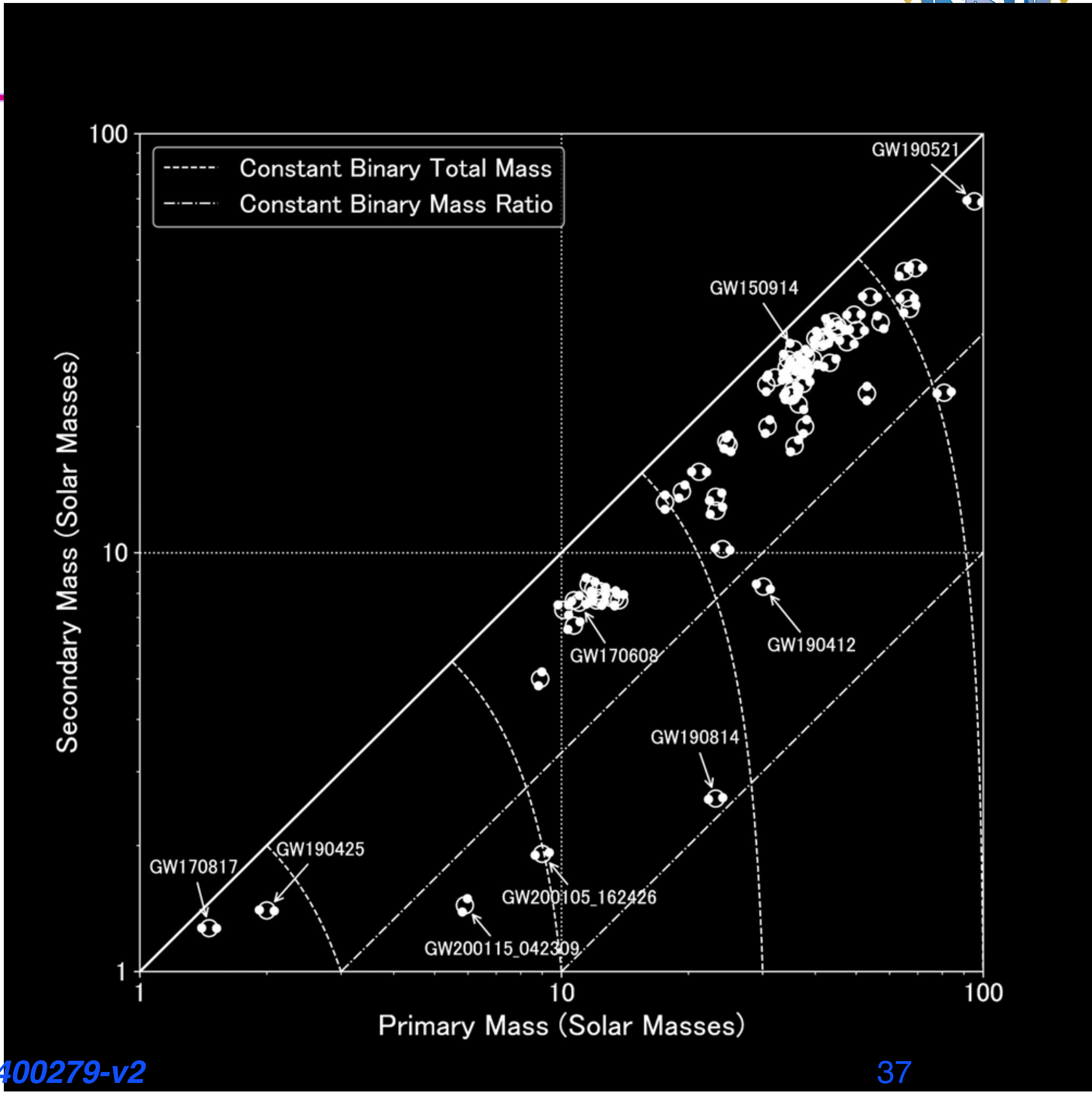
- Post-O5 [not funded yet]
  - Goal: another x 2 astrophysical range
  - In progress: A# and Virgo_nEXT
  - Conceptual design by the end of 2024
  - Target: early 2030's

- **LIGO India approved**
  - The Government of India approved the construction of the LIGO India Observatory with ~$315M (US $ equivalent) in funding
  - LIGO Lab/NSF is providing the components for one Advanced LIGO detector to be housed at the LIGO Aundha Observatory (LAO) as well as technical advice & support
  - The facility's construction is expected to be completed by 2030 (Post-O5 era)

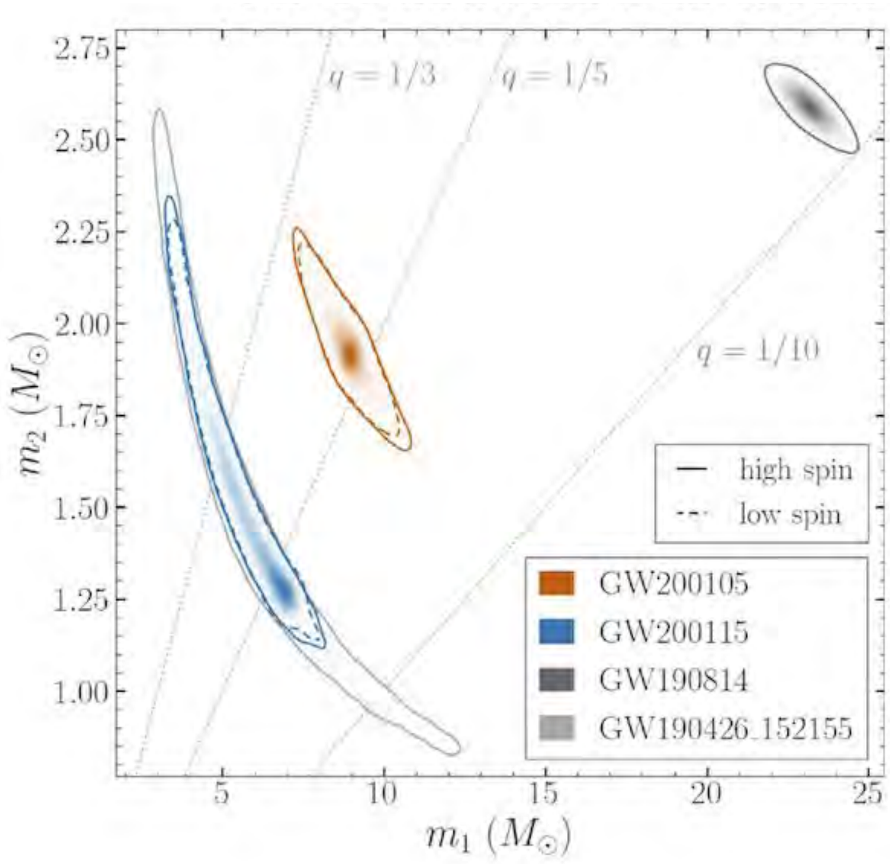
- 3rd generation detectors
  - x10 sensitivity improvement
  - **Einstein telescope in Europe**
    - 10 km arm, underground, cryogenics, triangle
  - Exceptional science reach

Science overview through O3

- GW150914
  - ➢ First astrophysical source
  - ➢ Binary black holes exist
- GW170817
  - ➢ Binary neutron star mergers are gamma-ray burst progenitors
- GW190521
  - ➢ Black holes exist in pair instability mass gap
- GW190814
  - ➢ Compact objects exist with masses between 2-5 $M_\odot$
- This short summary based on P. Brady: https://dcc.ligo.org/LIGO-G2302128/public



Previous NS-NS mergers

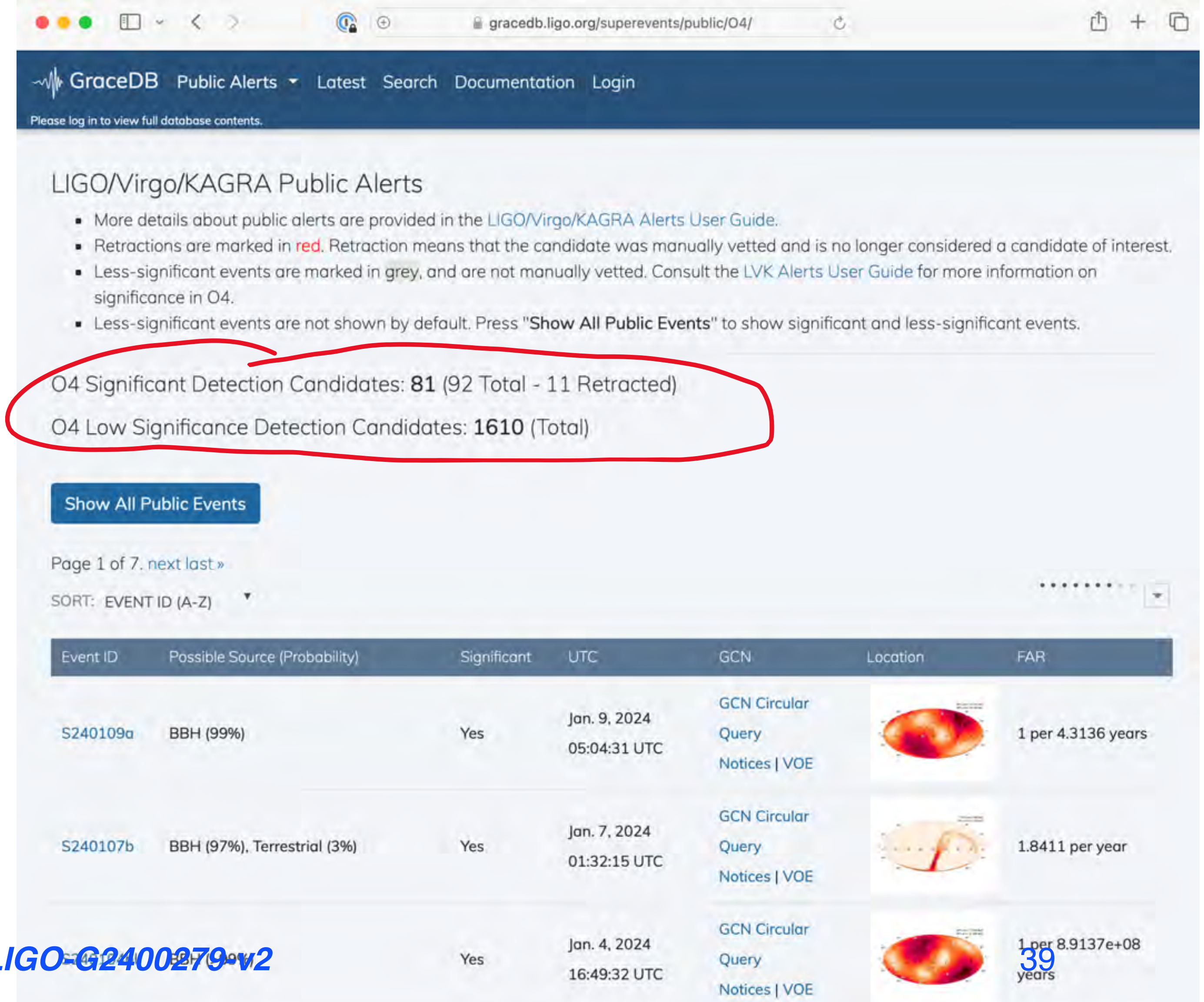


New features entries from GWTC-3 and O3b

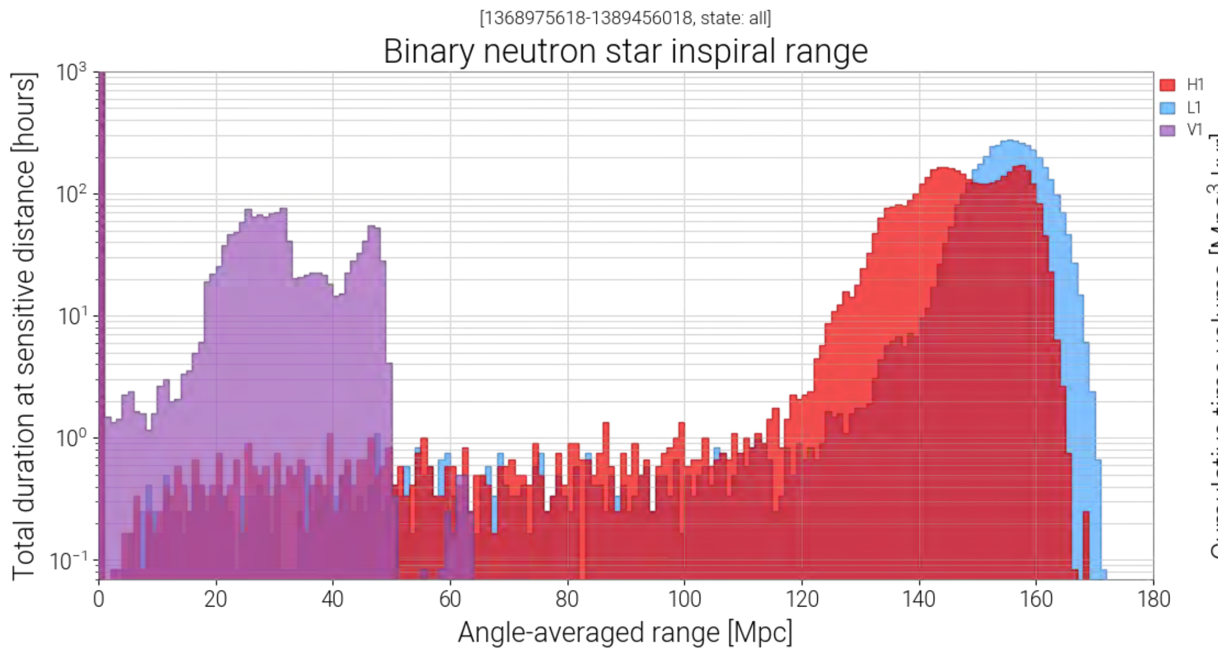
- Recently published GWTC-3 catalog paper lists a total of 90 compact object mergers from O1, 02 and both halves of O3.
  - new criteria for signals with probability of astrophysical origin greater than 50%.
  - it is likely that a handful will be false and a handful of the unlisted are true.
- New objects from O3b include:
  - two NS-NS mergers (alas, no non-GW signals): GW191219_163120 and GW200115_042309.
  - a few BH-BH mergers that seem to have spin > 0.8.
- https://doi.org/10.1103/PhysRevX.13.041039

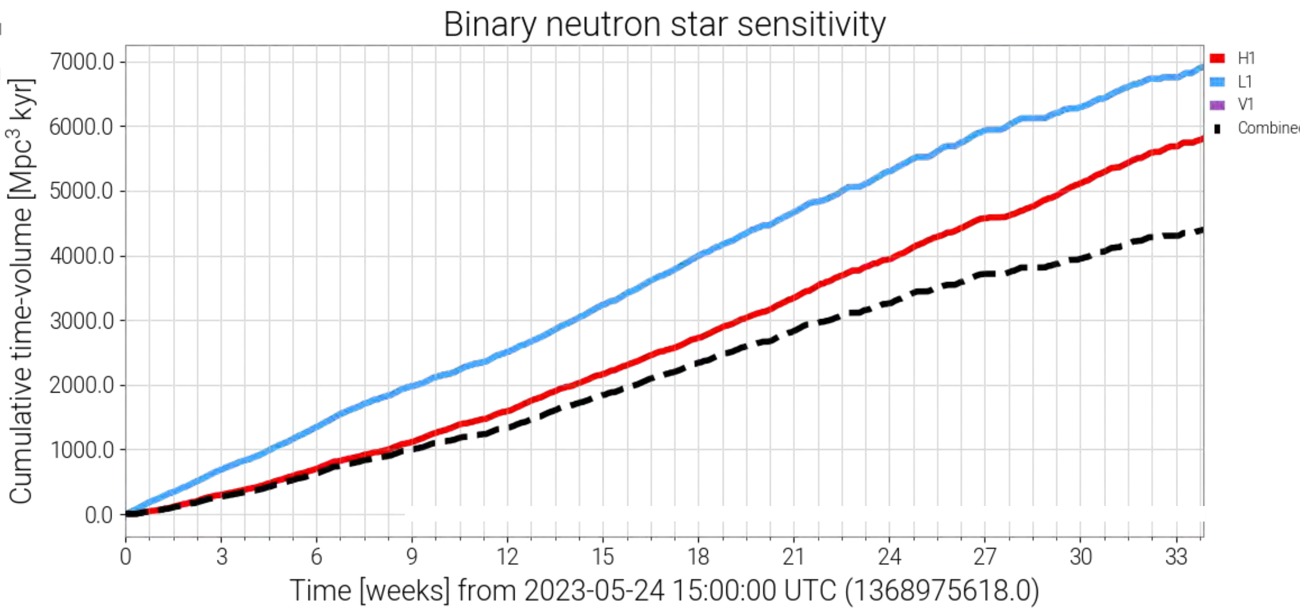
O4a is complete; O4b is to begin after commissioning.

- The 8-month run brought **81** non-retracted public alerts for compact object mergers, and 11 retractions.
  - ➢ The astro community likes that ratio, preferring not to miss anything.
  - ➢ We also had 1610 low significance ‘events.’
- O4a is the first run for which we began with calibration that wasn’t intended to need updates and refinements.
  - ➢ The goal is to avoid analysis projects waiting for calibration to be set.
  - ➢ Calibration error estimates began a bit later.



O4a

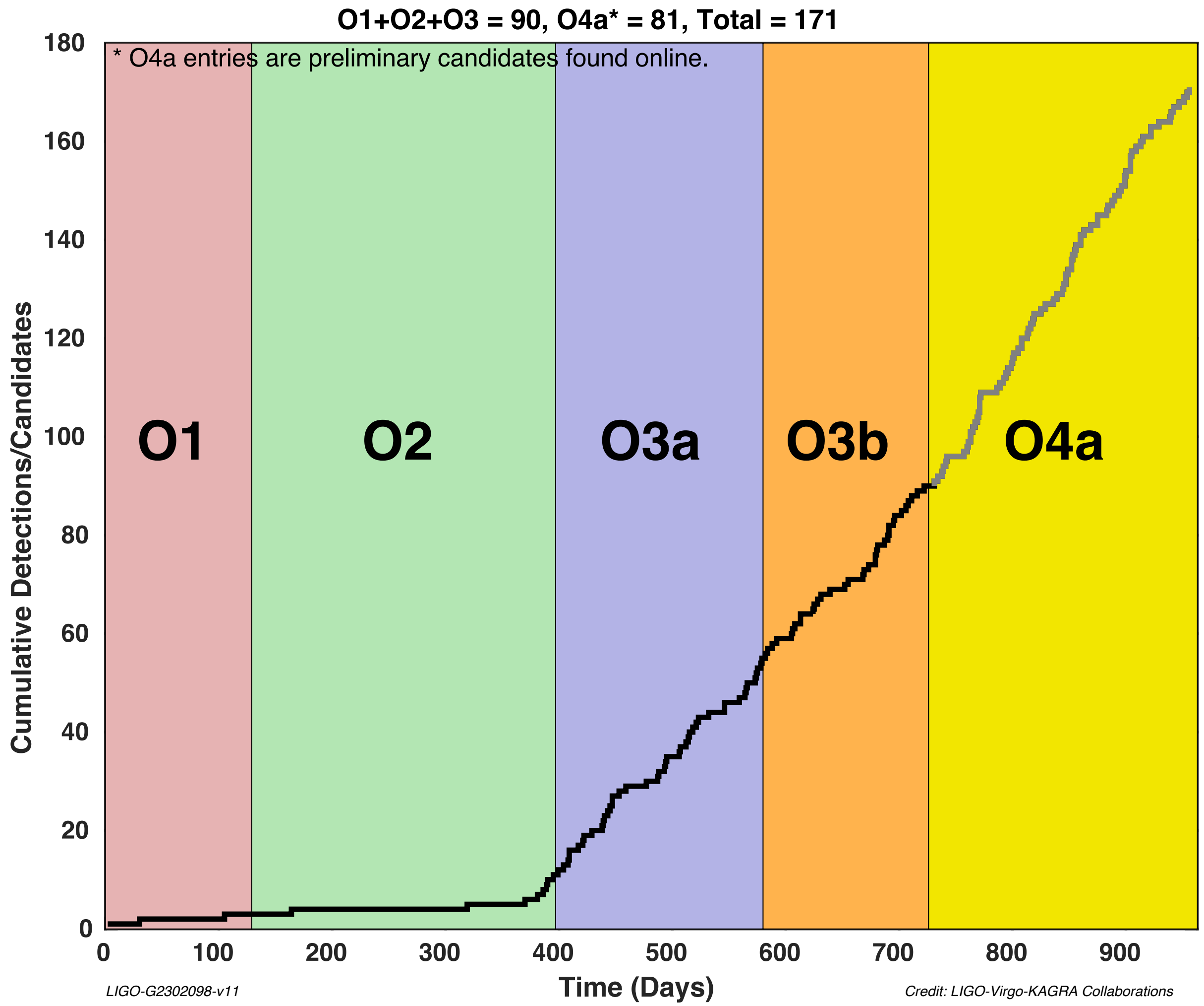




- For the bulk of O3b, both sites had passed the 160 Mpc range intended for the run.
- Integrated spacetime search volume was approximately equivalent to all prior runs combined.
- Stay tuned for careful data analysis and astrophysical interpretation!

Usually (but not always), commissioning pays off

- When detector improvements and commissioning make even modest improvements in range, the event rate disproportionately rises.
- We carefully plan and optimize this work during scheduled breaks between runs.
- Sometimes the improvements happen as a result of careful work **during** the runs; see late O2.



LIGO

- http://gw-openscience.org/

  Easy point & click downloads of calibrated strain data

  Includes:

  - Data Discovery
  - Documentation
  - Examples
  - Data Quality
  - Segments
  - Injections

- https://papers.ligo.org

  LSC publications

LIGO Science Education Center: a partnership with Southern University, the SF Exploratorium, and educators.

- The U.S. NSF has funded SUBR, Caltech and the Baton Rouge Area Foundation to build and carry out educational programs related to LIGO science and inquiry-based learning.
- The LIGO SEC programs reach over 20,000 people each year, focusing on classroom visits and teacher training.
- Docents serve as role models for children who wish to pursue science and technology careers.

LSU and Southern inter/docents at the helms of both LIGO detectors as the wave was detected

Nutsinee Kijbunchoo and William Parker

Thank you!