

Black-Hole Hunters: from Millwrights to Scientists, Jobs on the Frontier of Physics and Astronomy

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Senior Advisor to the Directorate
LIGO Laboratory
Caltech

Outline

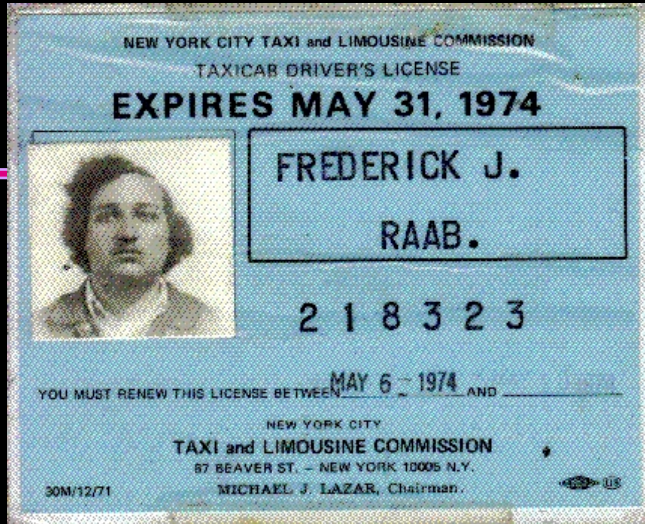
- What do we do? Who are we?
- Basics of Gravitational Waves (GWs)
- What does it take to operate a LIGO observatory?
- Working at an Observatory
- Perspective



What do we do at LIGO and how do we do it? (elevator version)

The LIGO team works to explore the most extreme regions of space and time and the most extreme forms of matter in the universe.

We do this by detecting the ripples in space-time, called gravitational waves, that are produced by black holes and neutron stars in some of the most violent events in our universe.



- Born to immigrants in NY City in 1951.
- Had an “OK” but not “strong” high school science background.
- Fan of space; fell in love with Physics.
- Struggled in my first college physics course, but persevered.
- BS-Manhattan College, PhD-SUNY Stony Brook (1980). U. Washington research scientist.
- Kip Thorne recruited me to Caltech in 1988.
- First LIGO Observatory Head (for 20+ years)

Proposal to the National Science Foundation

**THE CONSTRUCTION, OPERATION, AND
SUPPORTING RESEARCH AND DEVELOPMENT
OF A**

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

*Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
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Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

Who else is working on terrestrial GW detectors

- LIGO Laboratory: 180 members.
- LIGO Scientific Collaboration: 1600+ members in 19 countries on 5 continents.
- Virgo Collaboration: 800+ members in 15 countries, mostly in Europe.
- KAGRA Collaboration: 400+ members from 110+ institutions in 17 countries.
- Science is a team sport!

LIGO

The advanced GW detector network: 2015-2030

Advanced LIGO
Hanford
2015

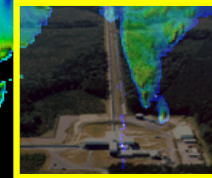


GEO600 (HF)
2011



Advanced LIGO
Livingston
2015

Advanced
Virgo
2017



LIGO-India
2030

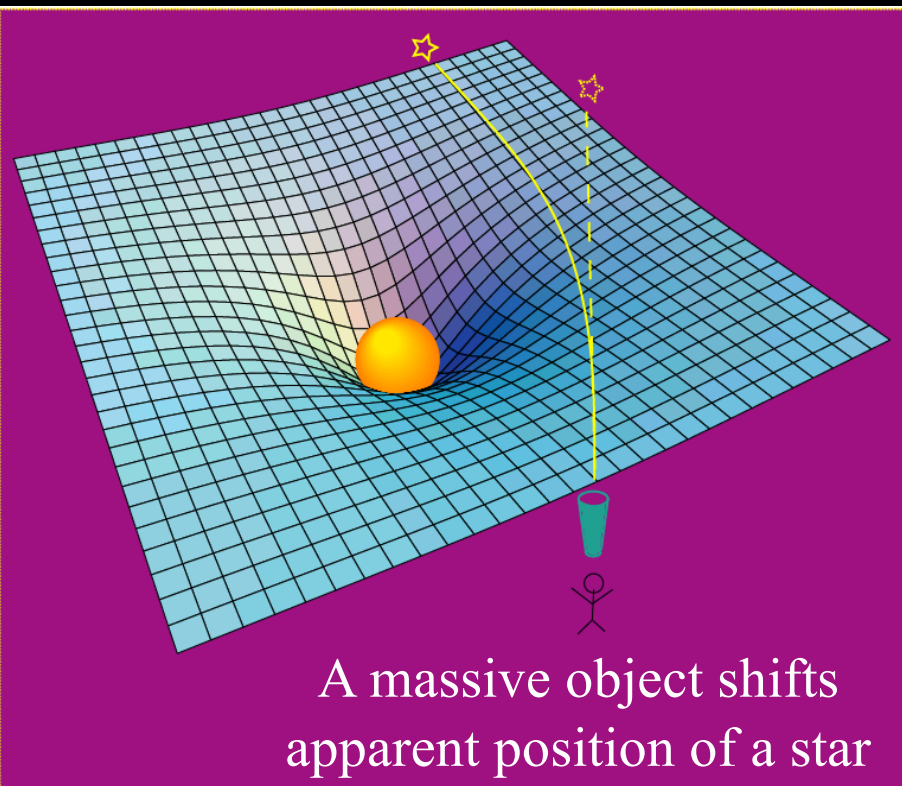


KAGRA
2020

Basics of Gravitational-Waves

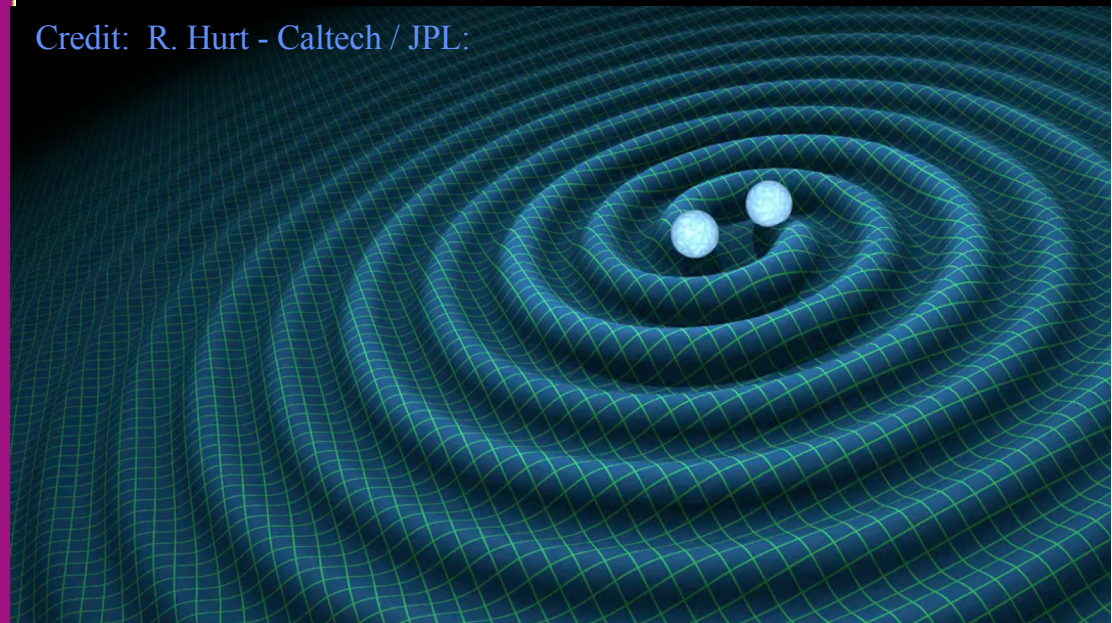
Einstein's General Relativity: gravity is a manifestation of space-time curvature

curved spacetime can bend light, too!

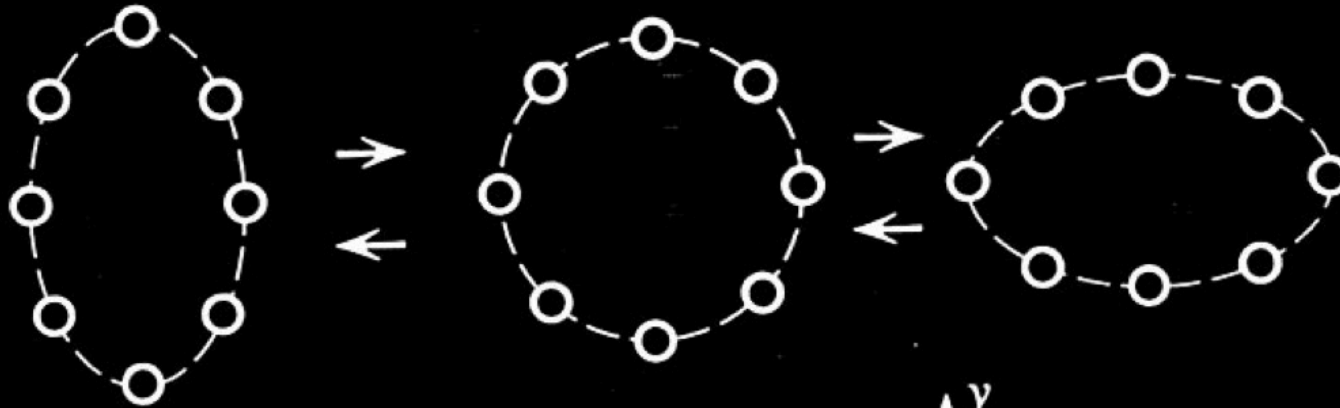


dynamic deformation of
spacetime

Credit: R. Hurt - Caltech / JPL:

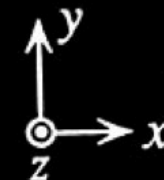


Basic idea for GW detection is simple

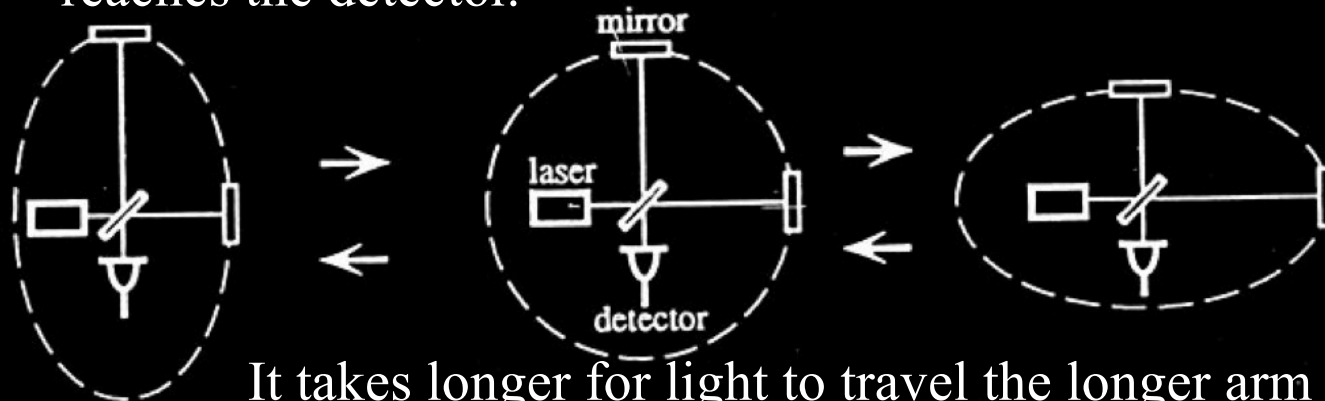


⊙ Gravitational Waves

When the arm lengths are equal, no light reaches the detector.



$$\text{GW amplitude } h = (R_x - R_y) / R$$



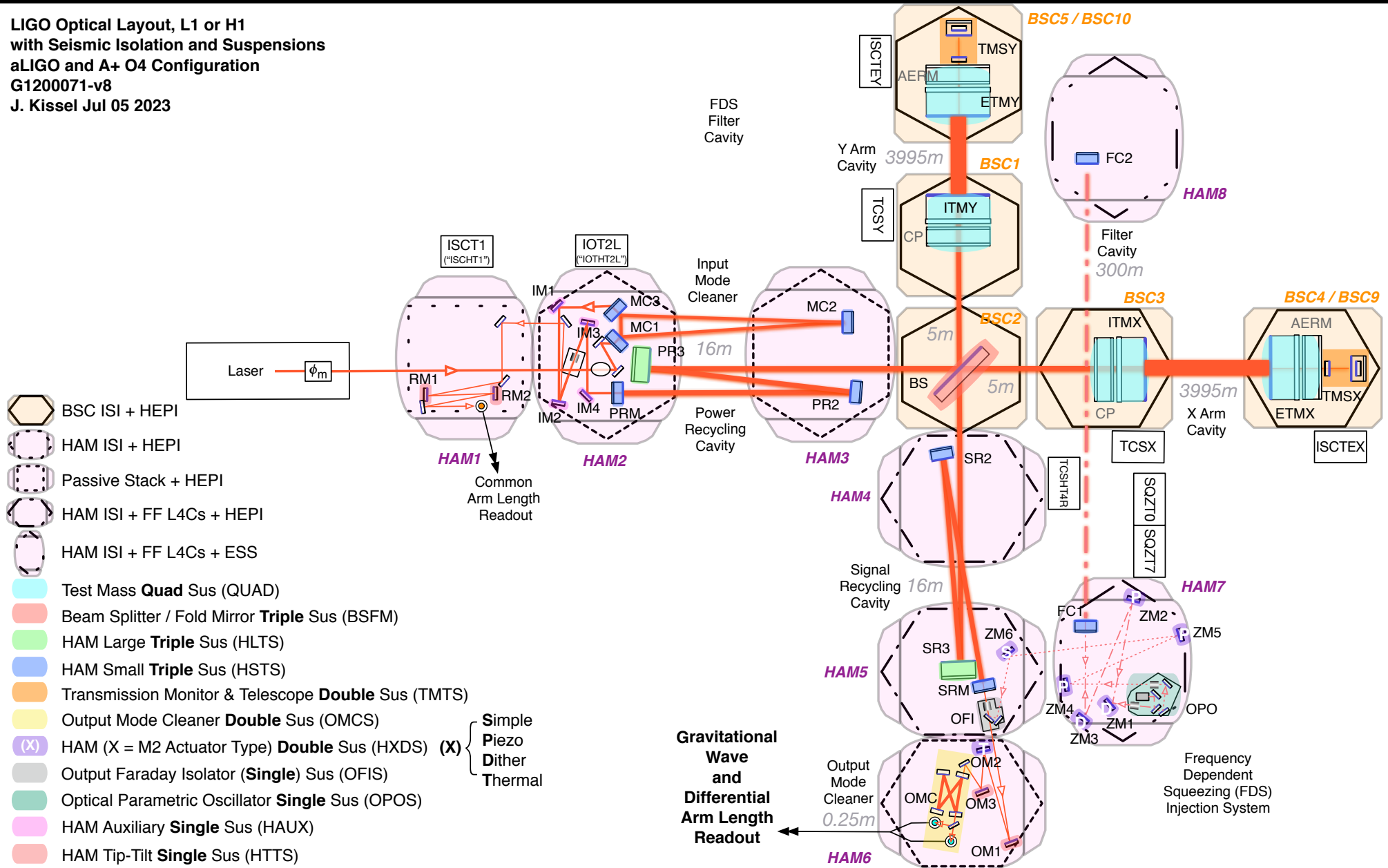
It takes longer for light to travel the longer arm path, which allows light to reach the detector.

Monumental detectors for miniscule signals



The largest gravitational wave ever detected distorted the 4-km arms of LIGO by about 40 billionths of the size of an atom.

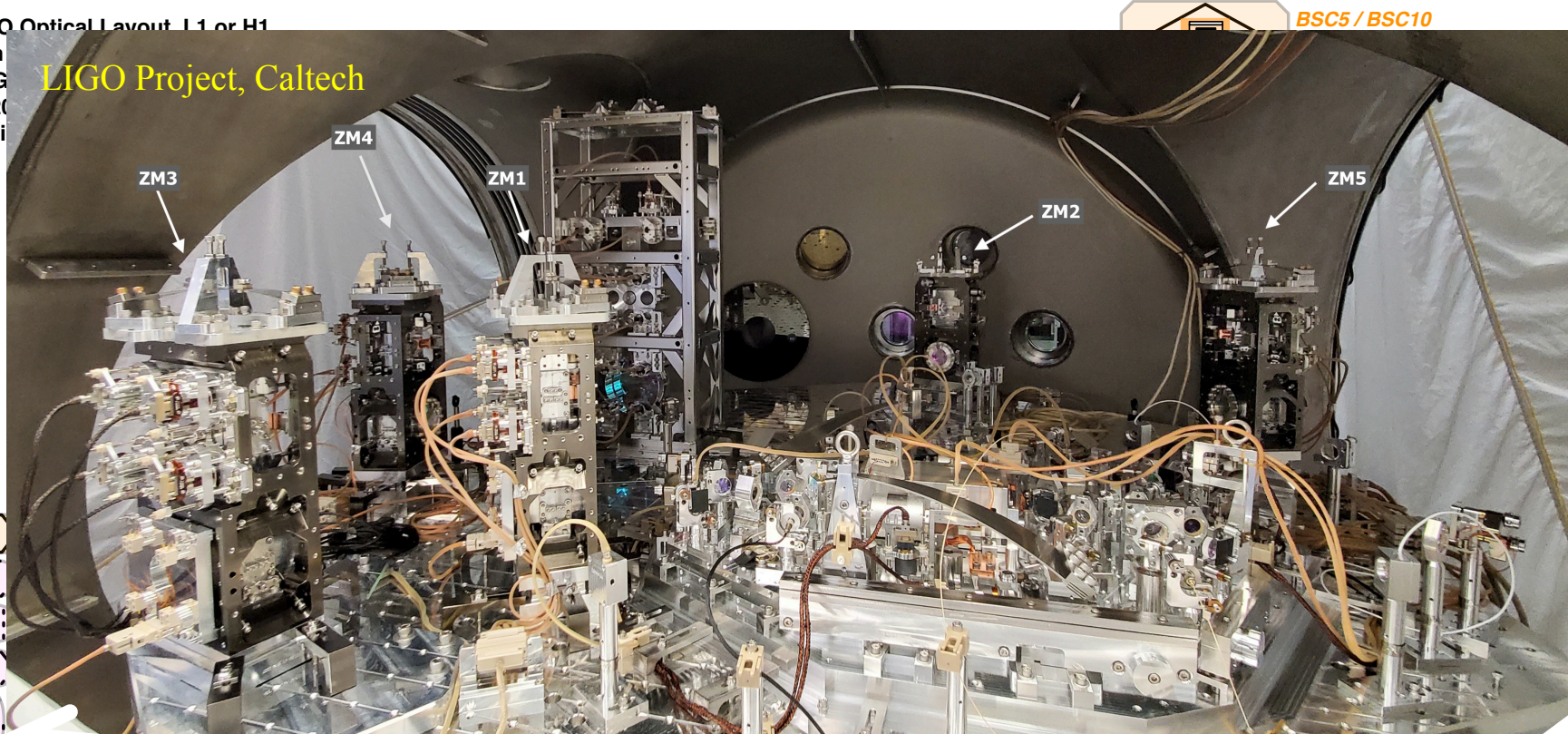
LIGO Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
aLIGO and A+ O4 Configuration
G1200071-v8
J. Kissel Jul 05 2023



Reality is far more complicated: view inside a part of the vacuum squeezing system

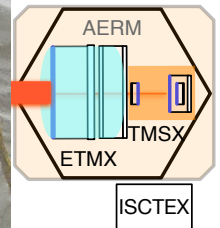
LIGO Optical Layout L1 or H1
with
aLIG
G120
J. Ki

LIGO Project, Caltech

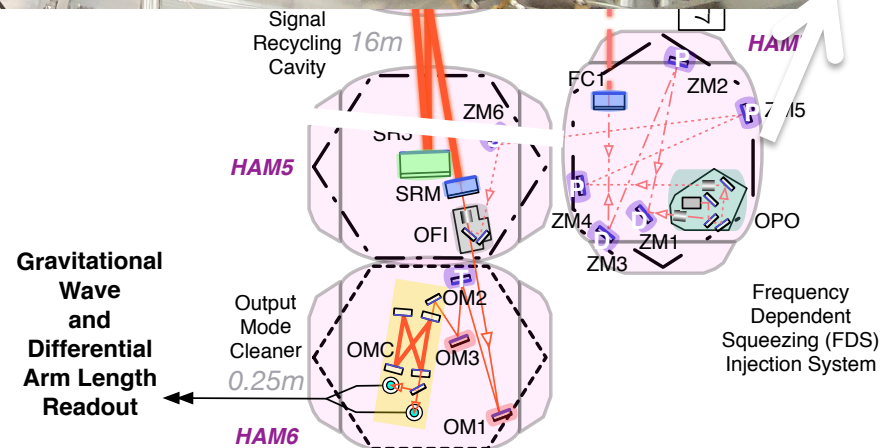


BSC5 / BSC10

BSC4 / BSC9



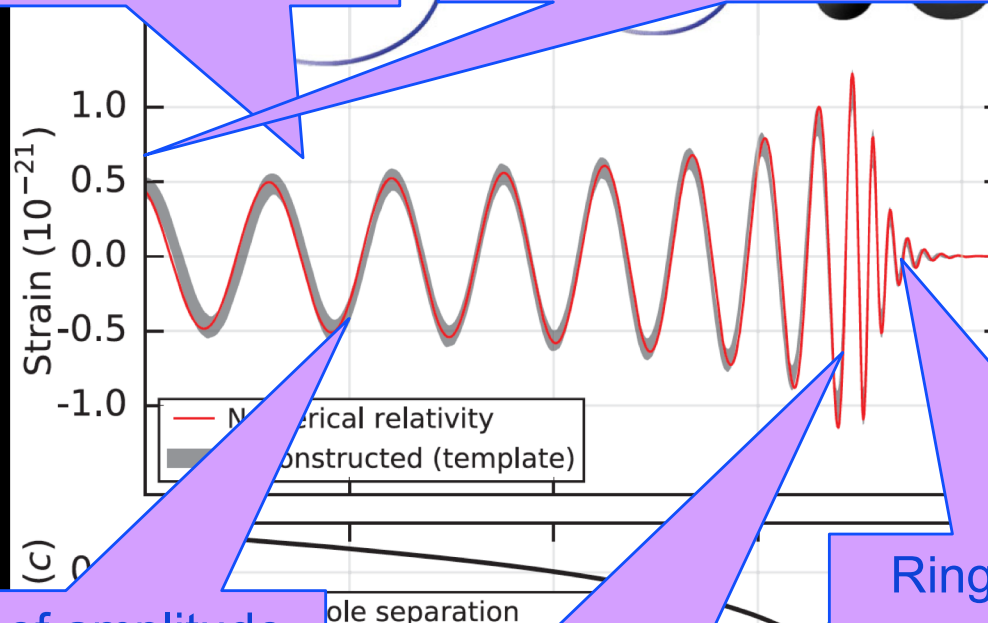
- Tes. Mass **Quad** Sus (QUAD)
- Beam Splitter / Fold Mirror **Triple** Sus (BSFM)
- HAM Large **Triple** Sus (HLTS)
- HAM Small **Triple** Sus (HSTS)
- Transmission Monitor & Telescope **Double** Sus (TMTS)
- Output Mode Cleaner **Double** Sus (OMCS)
- (X) HAM (X = M2 Actuator Type) **Double** Sus (HXDS) (X) } Simple Piezo Dither Thermal
- Output Faraday Isolator (**Single**) Sus (OFIS)
- Optical Parametric Oscillator **Single** Sus (OPOS)
- HAM Auxiliary **Single** Sus (HAUX)
- HAM Tip-Tilt **Single** Sus (HTTS)



What can we learn from a gravitational wave?

Phase evolution gives chirp mass and aligned components of spin

Amplitude scale factor gives luminosity distance (standard siren)



B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

Modulation of amplitude gives nonaligned spin components

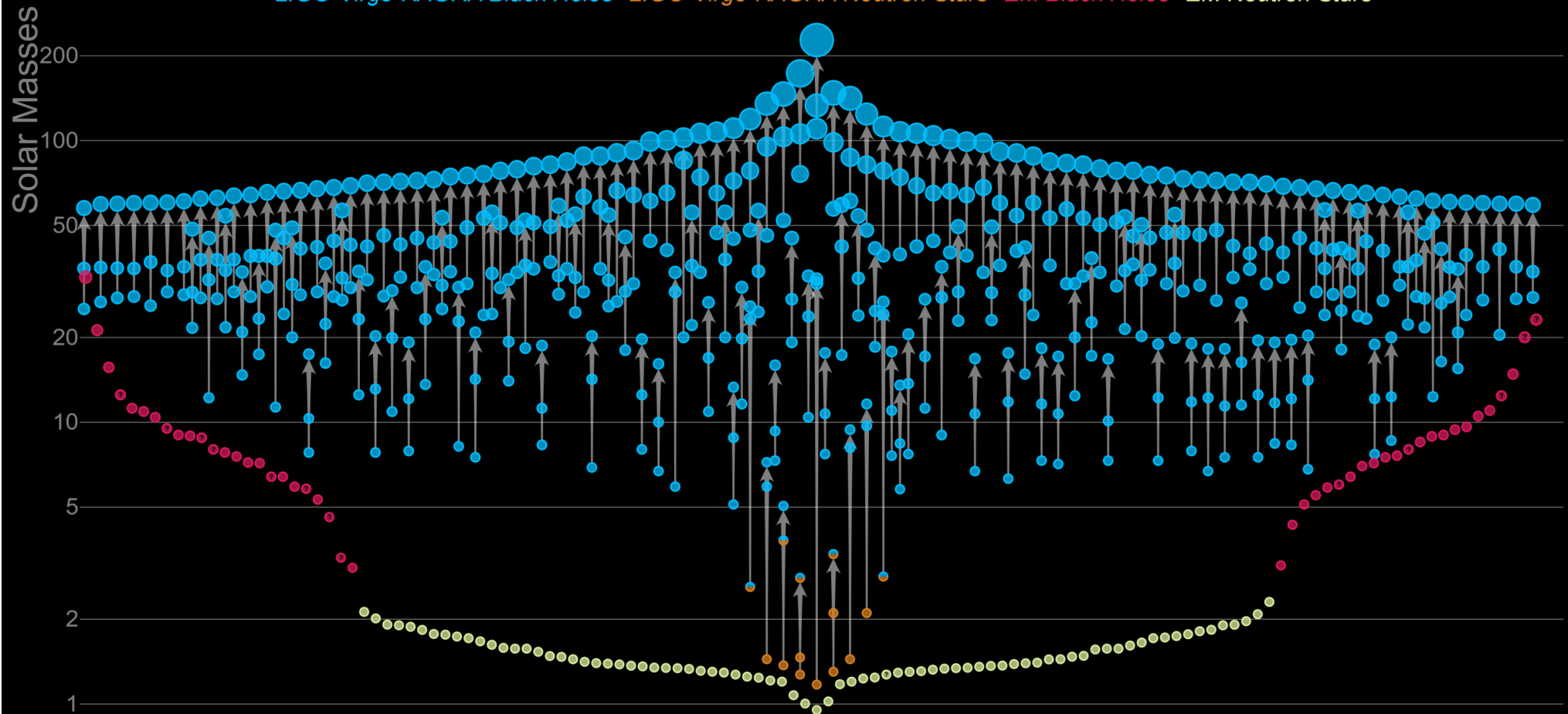
Highest frequency gives sizes of objects just before merger.

Ringdown frequency and Q give mass and spin of final black hole

Black holes and neutron stars are the fossils
of stars

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-G2302235

The New York Times

New England Edition

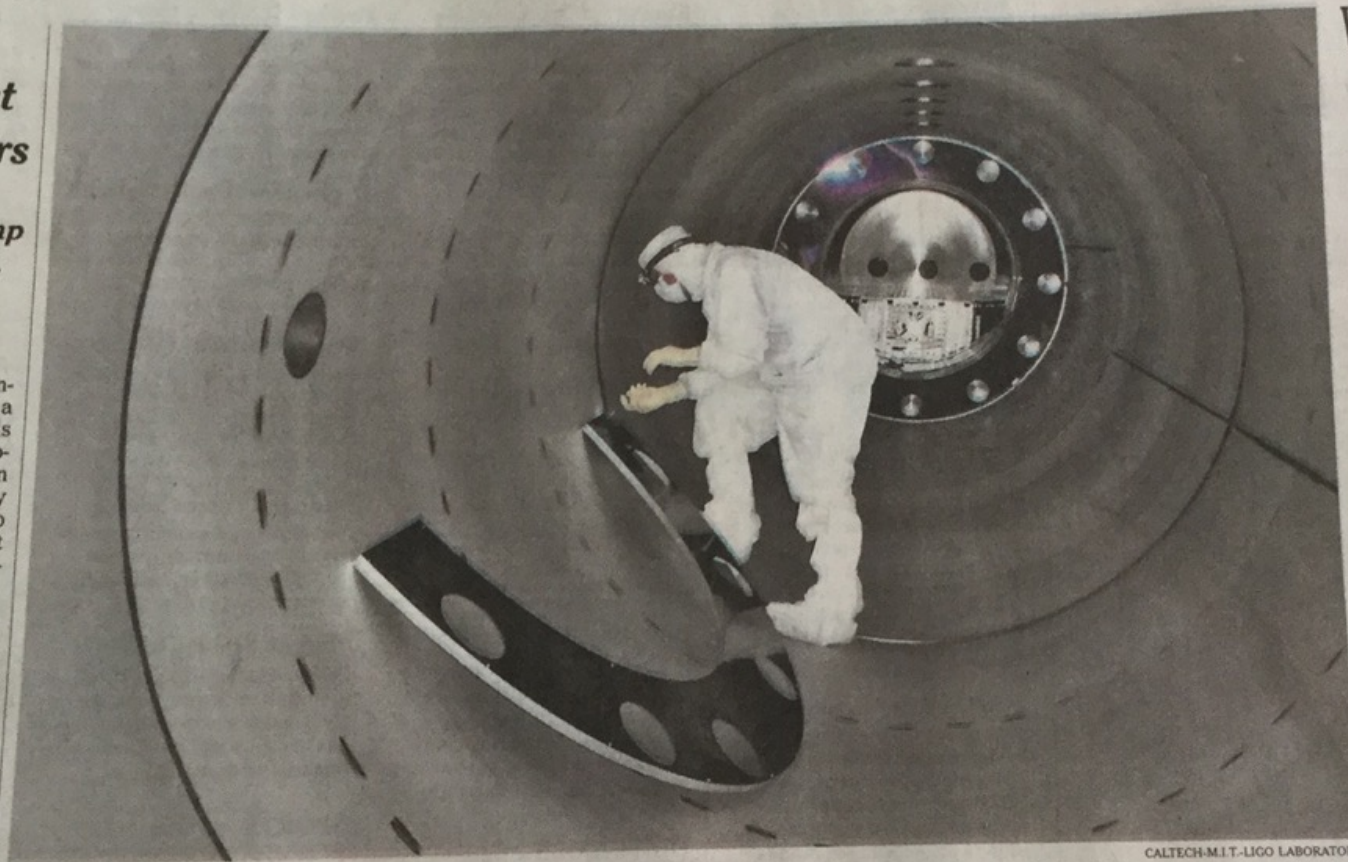
Today, sunshine mixing with some clouds, cold, high 26. Tonight, cloudy, a flurry or heavier squall late, low 17. Tomorrow, windy, frigid, high 18. Weather map, Page A18.

57,140

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FRIDAY, FEBRUARY 12, 2016

\$2.50



CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

Long in Clinton's Corner, Blacks Notice Sanders

By RICHARD FAUSSET

ORANGEBURG, S.C. — When Helen Duley was asked whom

Courted Hard in South Carolina, Loyalists

candidate she barely knew. "It makes me feel good," she said, "that young people are listening to the elderly people." She now said she was an un-

Last Occupier Is Coaxed From Oregon Refuge

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

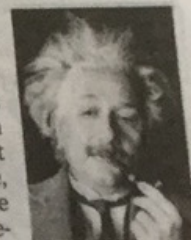
An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of

the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most fore-





Disciplines that depend on gravitational-wave observations



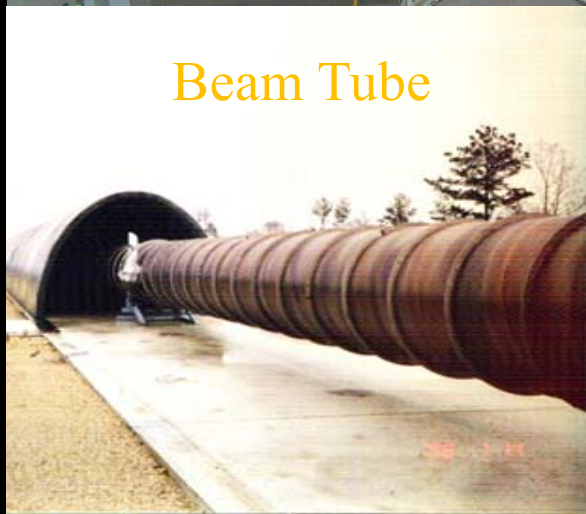
- Astronomy: black holes and neutron stars are the "fossils" of stars, clues to the history of objects in the universe.
- Fundamental physics: nature of the universe, gravitation, linkage to fundamental forces.
- Nuclear physics: neutron star physics; nuclear fluids and solids above the densities in atomic nuclei.
- Precision measurement science and engineering.
- Quantum physics and quantum engineering: LIGO and its sister detectors are macroscopic quantum-limited detectors.
- Observing coordination includes advance communication of observing run start/stop dates that are planned with increasing sensitivity to new EM capabilities coming online.

What does it take to operate a LIGO
observatory?

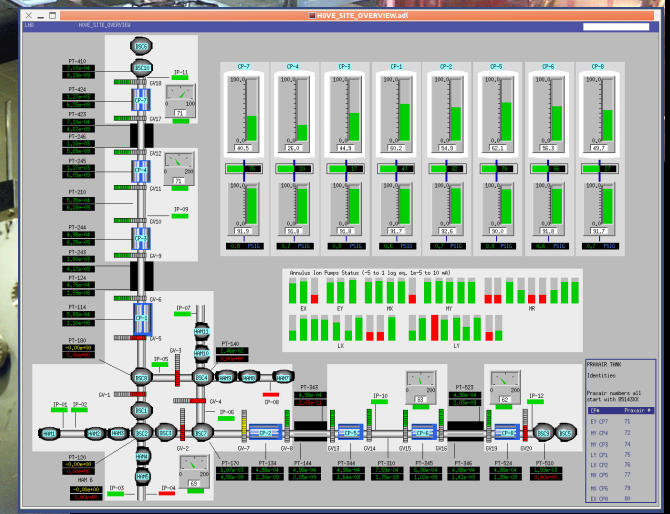
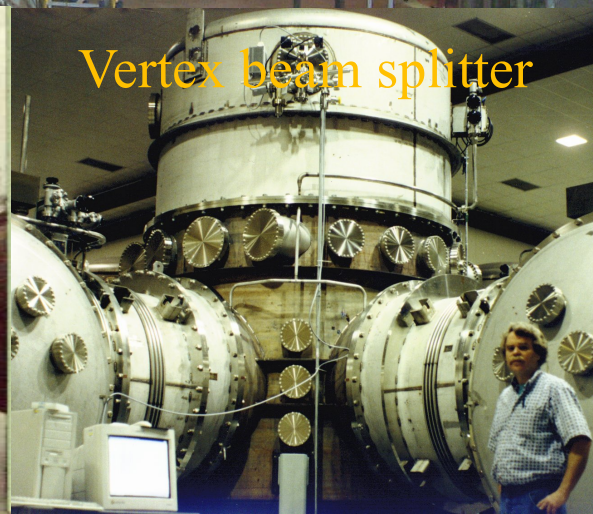
View inside Corner Station



Beam Tube



Vertex beam splitter



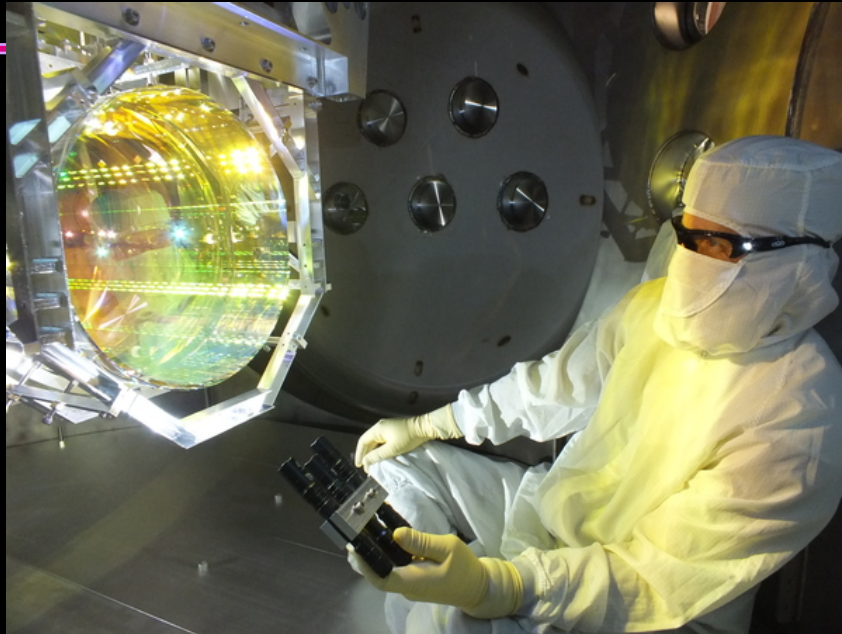
How to win the Nobel Prize.



Caltech/MIT/LIGO Lab

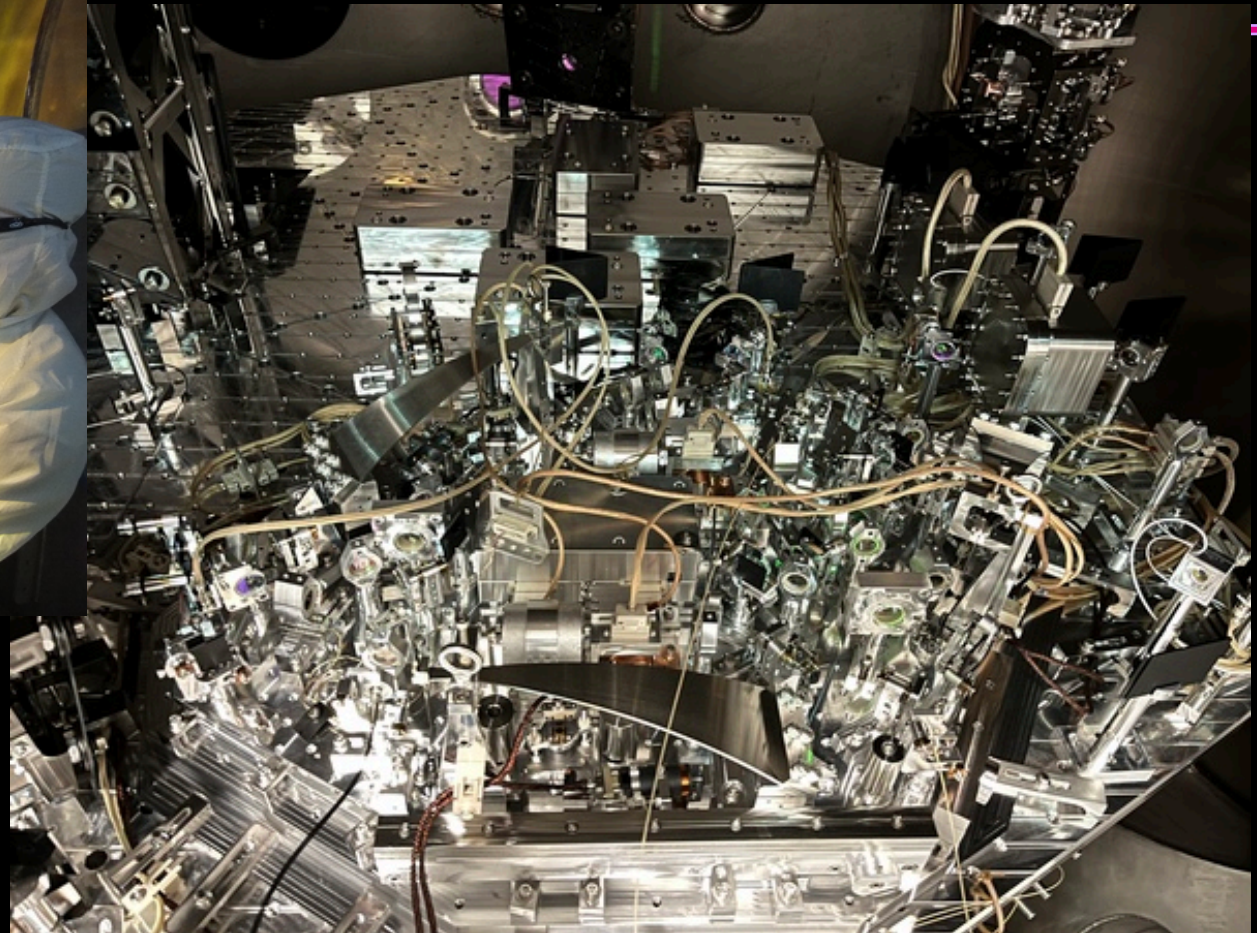
Boilmakers learning about critical role of their work.

Laser Interferometer Gravitational-Wave Detector



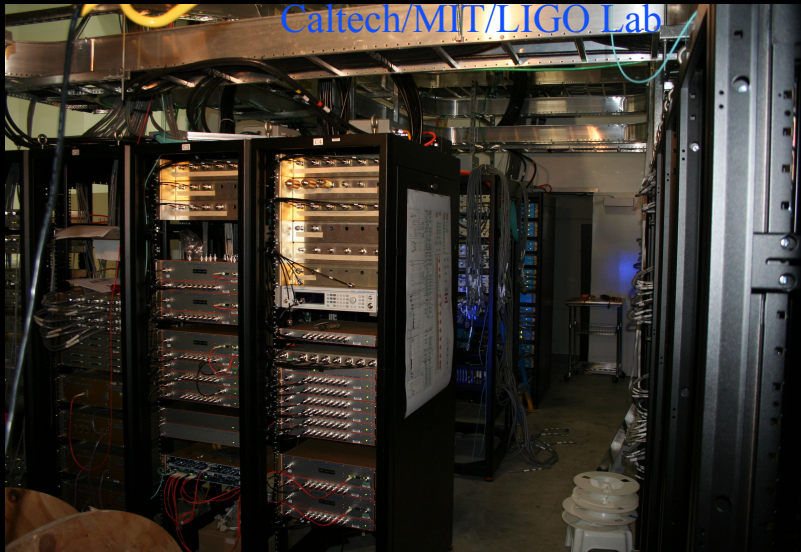
Caltech/MIT/LIGO Lab/(Matt Heintze)

- Powerful lasers
- Mirrors hanging from glass fibers
- Seismic isolation systems



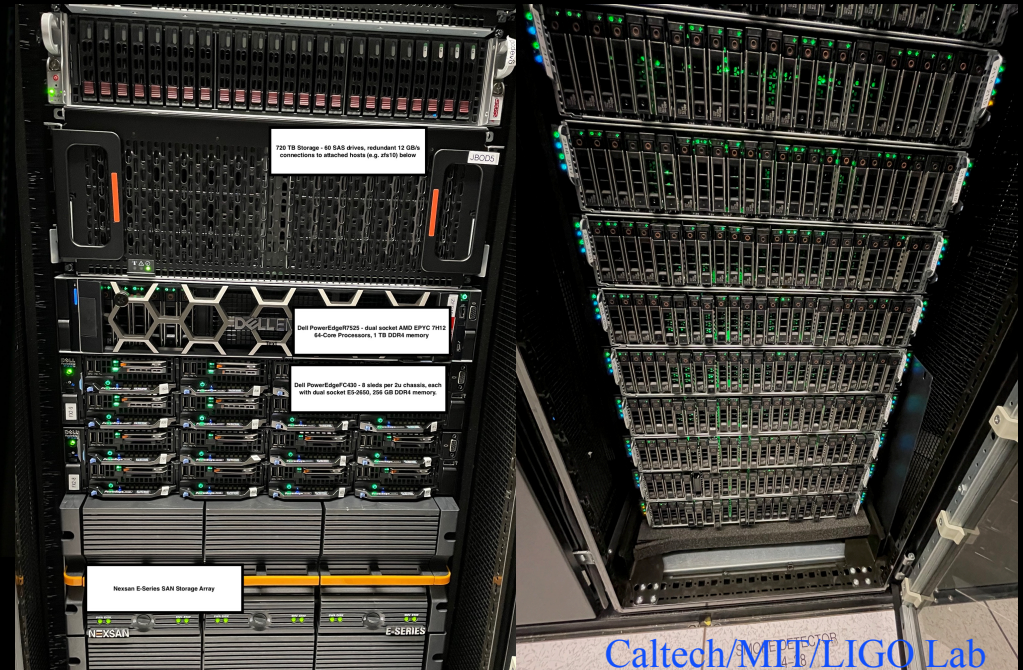
View of the squeezed light source in LIGO's vacuum chamber.
(Image credit: Wenxuan Jia/MIT)

Information Technology



Interferometer Control & Data Acquisition System

- >350 high-performance servo-control loops
- Physics Environmental Monitor (70 fast & 600 slow channels)



Data Archive and Server System

- Data ingestion & archiving
- Data distribution
- Online analysis and alert generation



Working at an Observatory



How to characterize working on LIGO



- One team, many mail codes.
 - » Belonging to a large international team of collaborators, we spend a lot of time communicating with colleagues.
 - » Every job and every person matters!
- LIGO needs strict standards all day, every day
 - » Vacuum tube at an observatory has 50 km of weld seam, but a 1 micron defect can be ruinous (error rate < 1 in 50 billion).
 - » An absorbing spot 10 microns in size on a core optic (error rate of 1 in 1 billion) can limit the range of detectors. Need to reduce this to error rates less 1 in 40 billion.

Observatory staffing is determined by required response times

- On site – ability to respond to issues that compromise observing time or present hazards in minutes to hours.
- On call – ability to respond within an hour.
- Remote – carry on support tasks (e.g., lab-based research, engineering development, procurement, etc.) and can travel to support on-site activities. Labs at Caltech, MIT and other collaborating institutions are in this category.
- Trades – varies by nature of the work. More craft labor, working in teams with scientists and engineers is needed during installation of detector upgrades.

Control-Room Operations



- Control-room coverage for 24x7 during runs and tech support outside runs
- Detector maintenance
- Technical support for construction and installation of detector upgrades

Caltech/MIT/LIGO Lab



Caltech/MIT/LIGO Lab

- Vacuum Operations and Maintenance
- Facilities Operations and Maintenance
- Detector Operations and Maintenance
- Electronics, Control & Data Systems Operations
- Information Technologies

Observatory Science Group

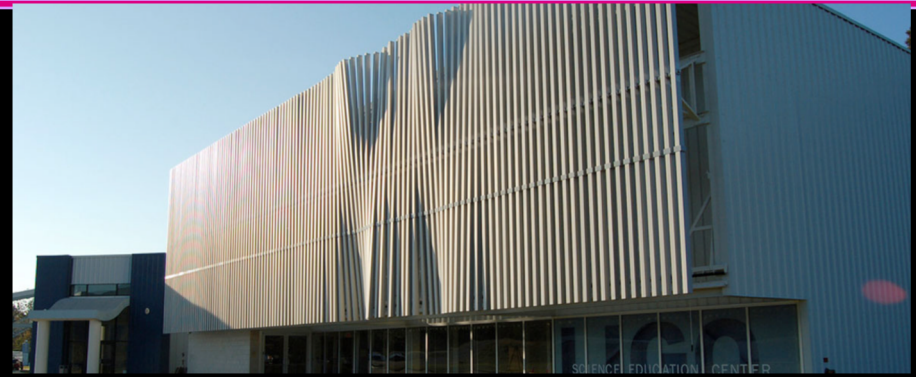


Caltech/MIT/LIGO Lab

- Commissioning
- Detector Characterization
- Detection Support

● Education functions

- » 4-12 Grade Field Trips
- » Monthly Science Saturdays
- » Private Tours
- » Special Public Events
- » Teacher PD
- » Community Events
- » Classroom visits



Caltech/MIT/LIGO Lab



WA State Gov. Jay Inslee curving spacetime

Business Group

- International science creates interesting challenges that need business solutions:
 - » How to create fixed-price contracts for products that have never been delivered?
 - » How to design and build state-of-the-art equipment across international institutions and multiple national funding agencies?
 - » How to manage working to schedules and budgets across national boundaries and time zones.

Perspective

- Gravitational-Wave Astronomy will achieve in a few decades what it has taken Optical Astronomy 400 years to do: reach out to the first era of stars.
- It is rare in human history for the rate of discovery to undergo sustained acceleration by orders of magnitude.
- This will be achieved by international collaborations of experimental scientists, engineers, technicians and craft specialists across many disciplines at many different astronomical and physics facilities.
- Want to ride this new wave?
 - » <https://hr.caltech.edu/careers>
 - » summer internships, google "LIGO SURF"