ACC 2020

Control Challenges for the Laser Interferometer Gravitational-wave Observatory (LIGO)

Dennis Coyne, on behalf of the LIGO Scientific Collaboration
LIGO Laboratory Chief Engineer
California Institute of Technology
Pasadena, CA, USA

Image credit: Aurore Simonnet/Sonoma State University

LIGO

LIGO Scientific Collaboration

LSC NSF

Caltech, Max-Planck-Institut für Gravitationsphysik Albert-Einstein-Institut, American University Washington, DC, Andrews University, Bar-Ilan University, Bard College, Bellevue College, California State University Fullerton, MIT

Christopher Newport University, Colorado State University, Columbia University in the City of New York, Concordia University Wisconsin, Embry-Riddle Aeronautical University, Georgia Tech, NASA Goddard Space Flight Center, Haverford College, Hillsdale College

Hobart & William Smith Colleges, International Institute of Physics, LSU Louisiana State University, Maastricht University, Marquette University Be The Difference., NASA Marshall Space Flight Center, Missouri S&T, Montana State University, Montclair State University

Lomonosov Moscow State University, NCSA, Northwestern, PennState, RIT, Sonoma State University, Science & Technology Facilities Council Rutherford Appleton Laboratory, King's College London

Southern University and Agricultural & Mechanical College, Stanford University, Stony Brook University, Flatiron Institute Center for Computational Astrophysics, University of Portsmouth, University of Birmingham, Cardiff University Prifysgol Caerdydd

Australian National University, Charles Sturt University, Monash University, OzGrav, Swinburne University of Technology, Syracuse University Founded AD 1870, Texas Tech University, Tsinghua University, Polytechnique Montréal, University of the West of Scotland UWS, University of Zurich, University of Glasgow

The University of Adelaide, The University of Melbourne, The University of Western Australia, The University of Arizona, Berkeley University of California, The University of Chicago, The University of Sheffield, GEO 600

UF University of Florida, University of Maryland, University of Michigan, University of Minnesota, University of Oregon, The University of Rhode Island, USC Universidade de Santiago de Compostela, Leibniz Universität Hannover

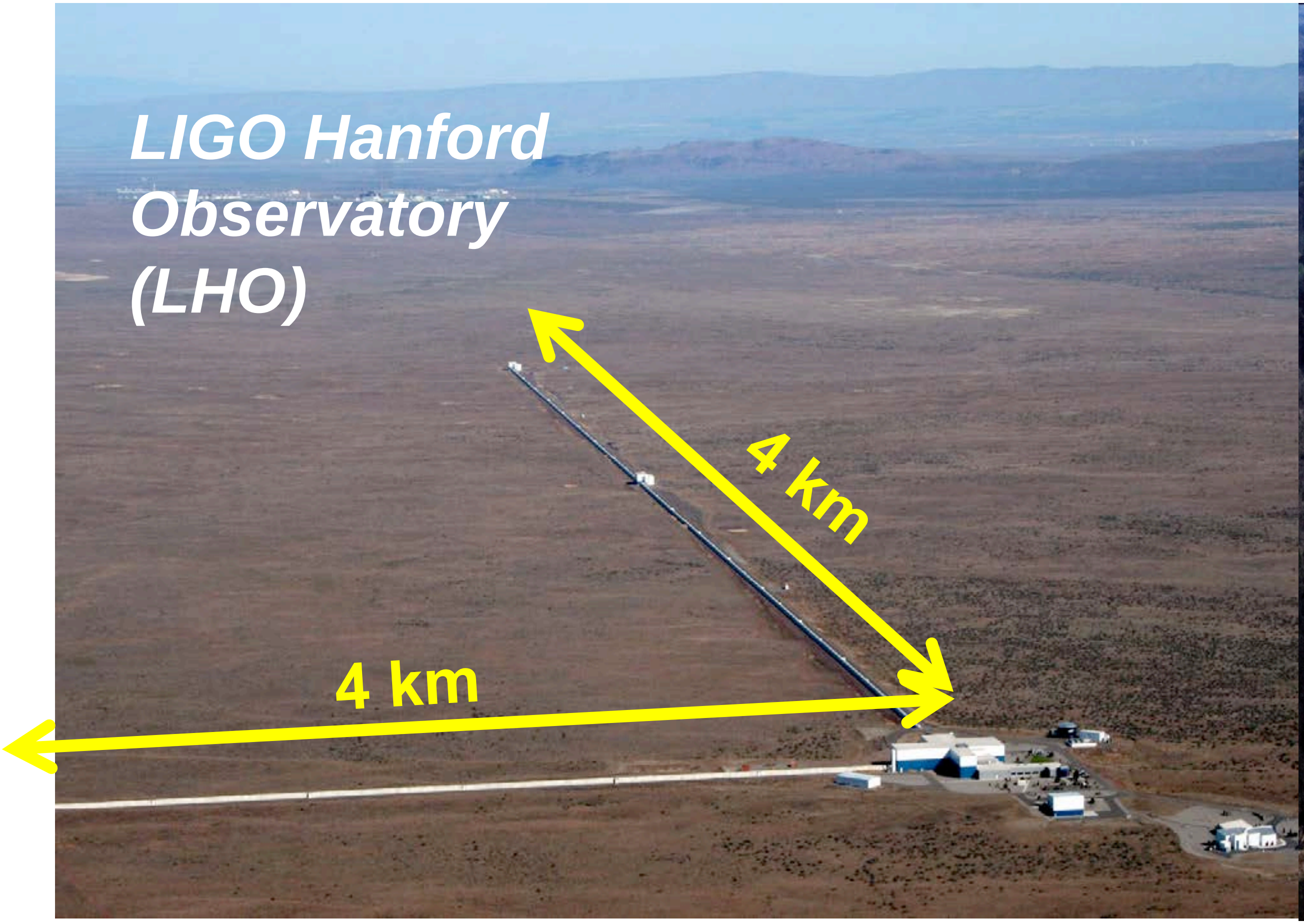
Texas The University of Texas at Austin, UTRGV, UIB Universitat de les Illes Balears, 東京大学 The University of Tokyo, The University of Utah, University of Washington, Bothell, University of Strathclyde Glasgow, University of Cambridge

IISER Kolkata, tifr, ICTS International Centre for Theoretical Sciences, UWM University of Wisconsin Milwaukee, Villanova University, West Virginia University, Universität Hamburg, University of Southampton

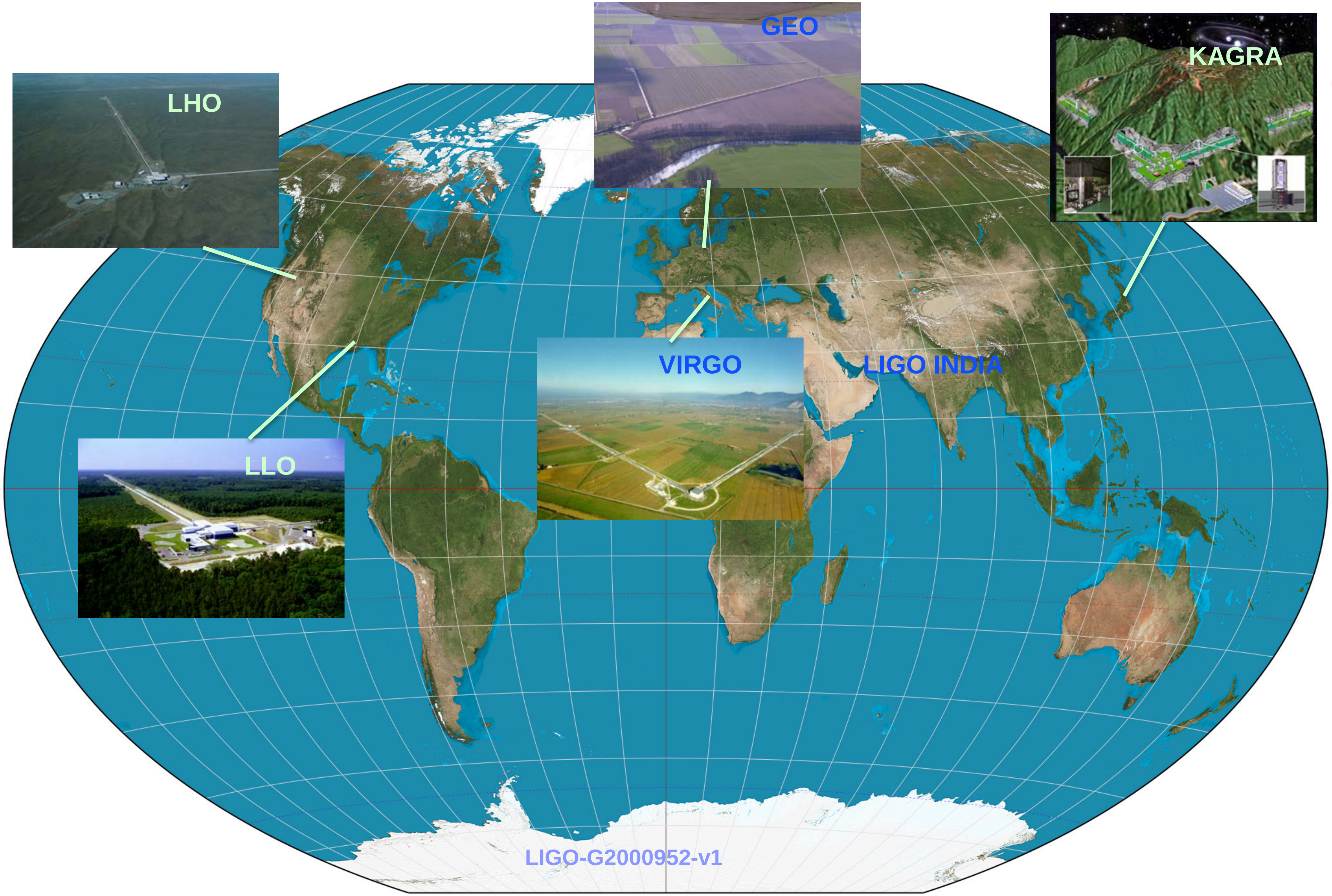
Chennai Mathematical Institute, DCSEM, RRCAT, KISTI 한국과학기술정보연구원, NIMS National Institute for Mathematical Sciences | South Korea, 서울대학교, UNIST, 인제대학교 Inje University

LIGO-India Scientific Collaboration, IISER Pune, IIT Hyderabad, IUCAA, KASI Korea Astronomy and Space Science Institute, 한양대학교 Hanyang University, Korean Gravitational Wave Group

The LIGO Observatories



Building a Global Network



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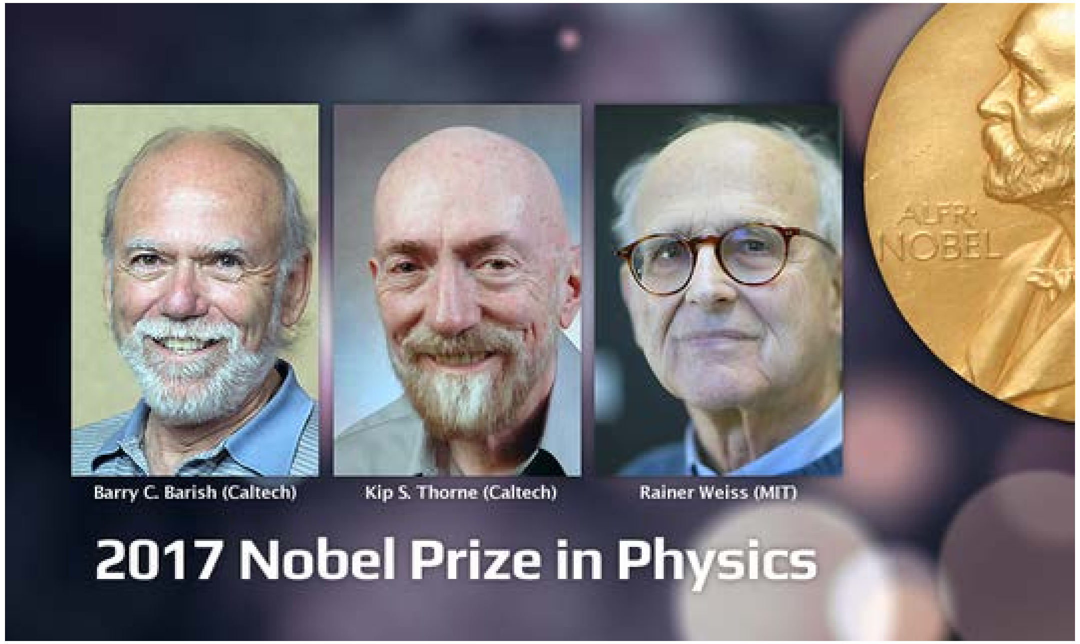
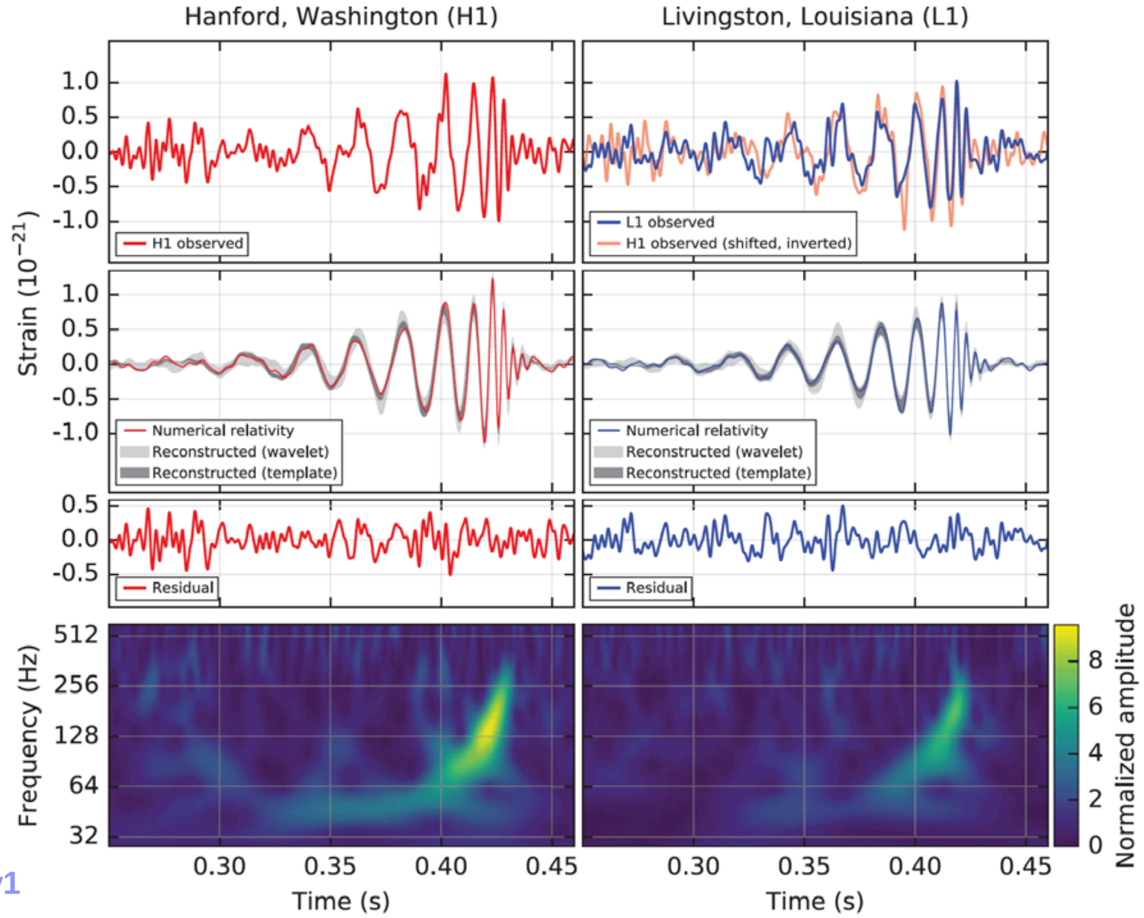
Gravitational Waves

The Birth of Gravitational Wave Astronomy

GW150914: the first detection of a Binary Black Hole (BBH) merger event

- Distance of 1.3 Billion light years
- Initial Black hole masses 36 & 29 Solar masses
- 3 solar masses of energy released
- 50 times brighter than the rest of the universe
- Agrees with Einstein's General Theory of Relativity





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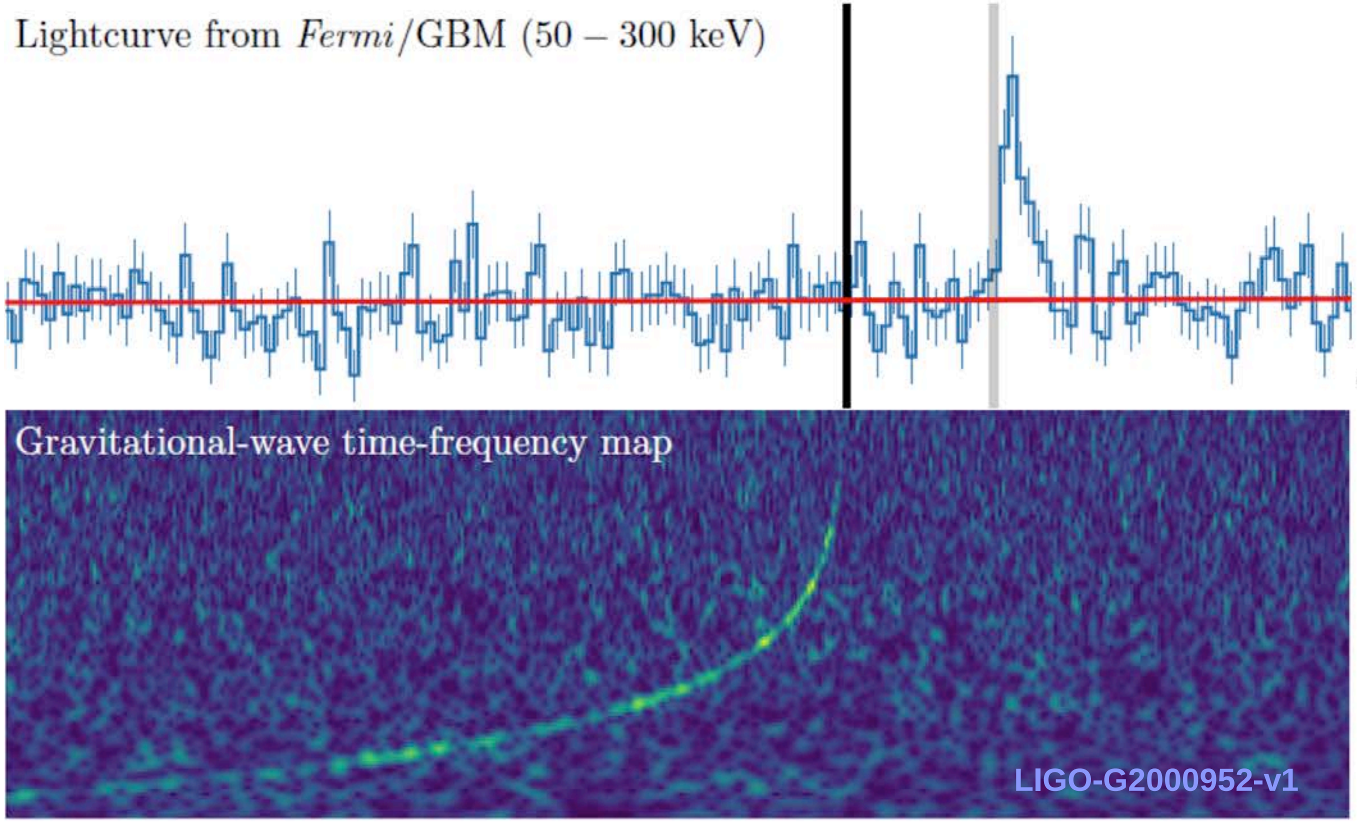
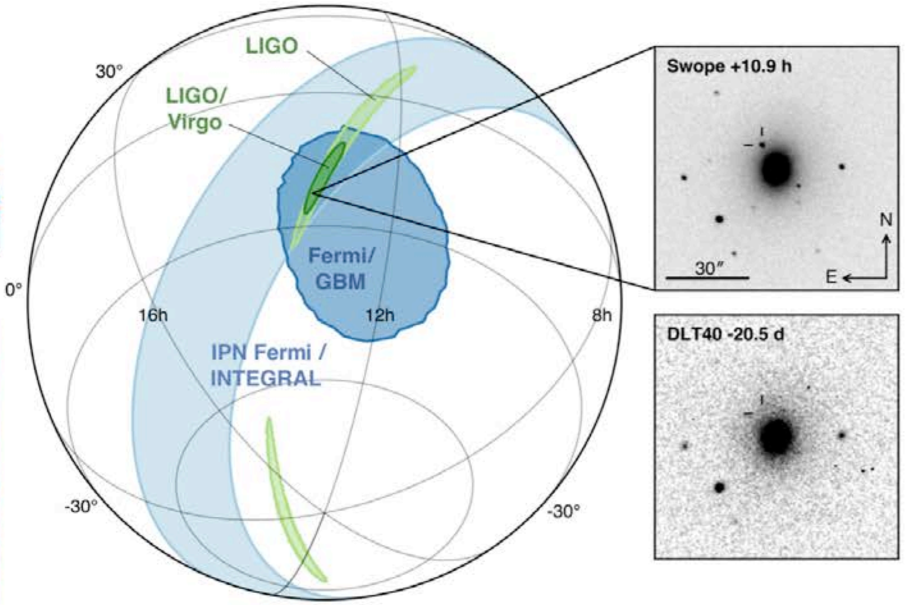
Credit: NASA Goddard Space Flight Center

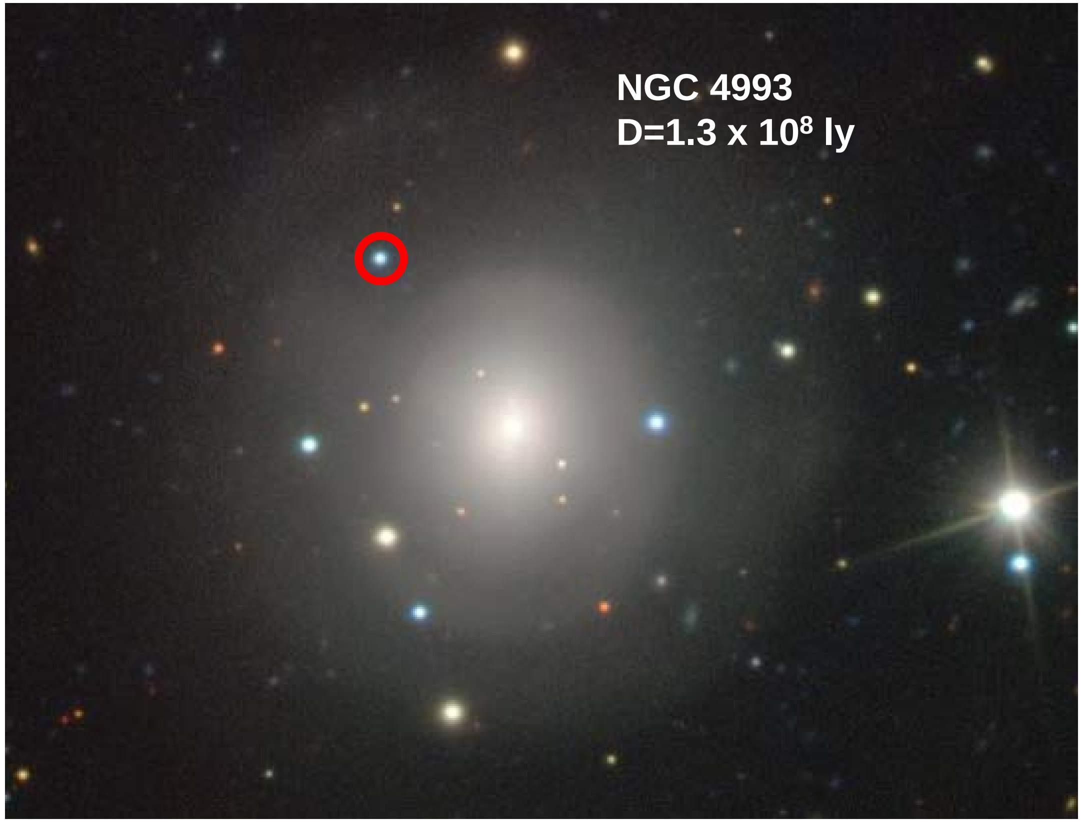
Multi-messenger Astronomy with Gravitational-Waves and Light

GW170817: the first Binary Neutron Star (BNS) merger – a "kilonova"

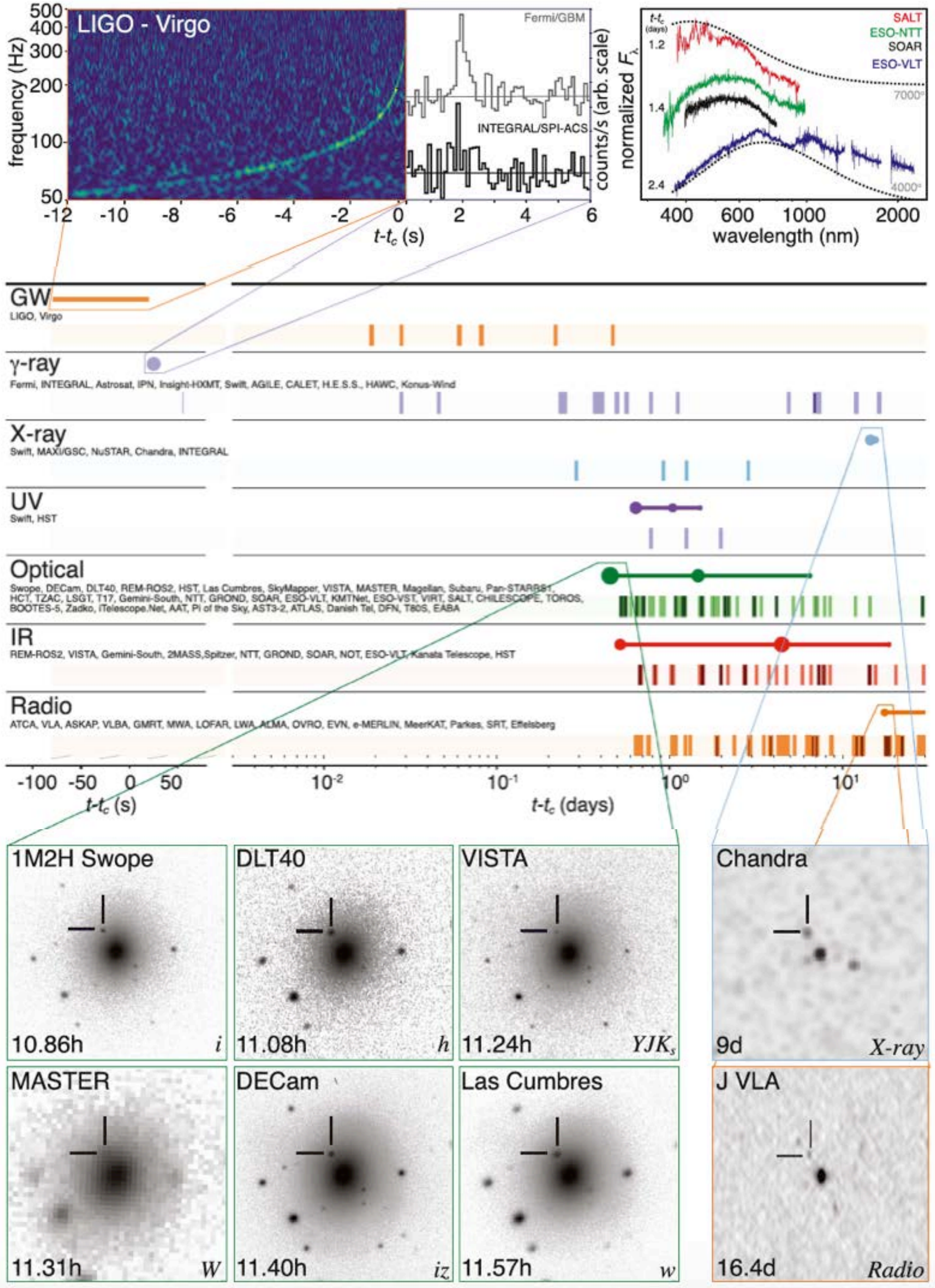




Observations Across the Electromagnetic Spectrum!

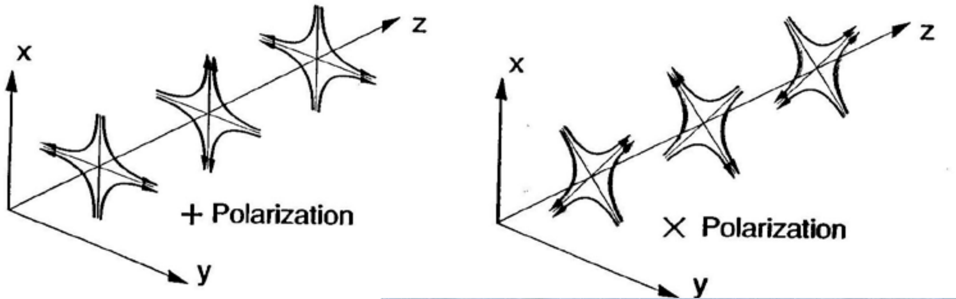


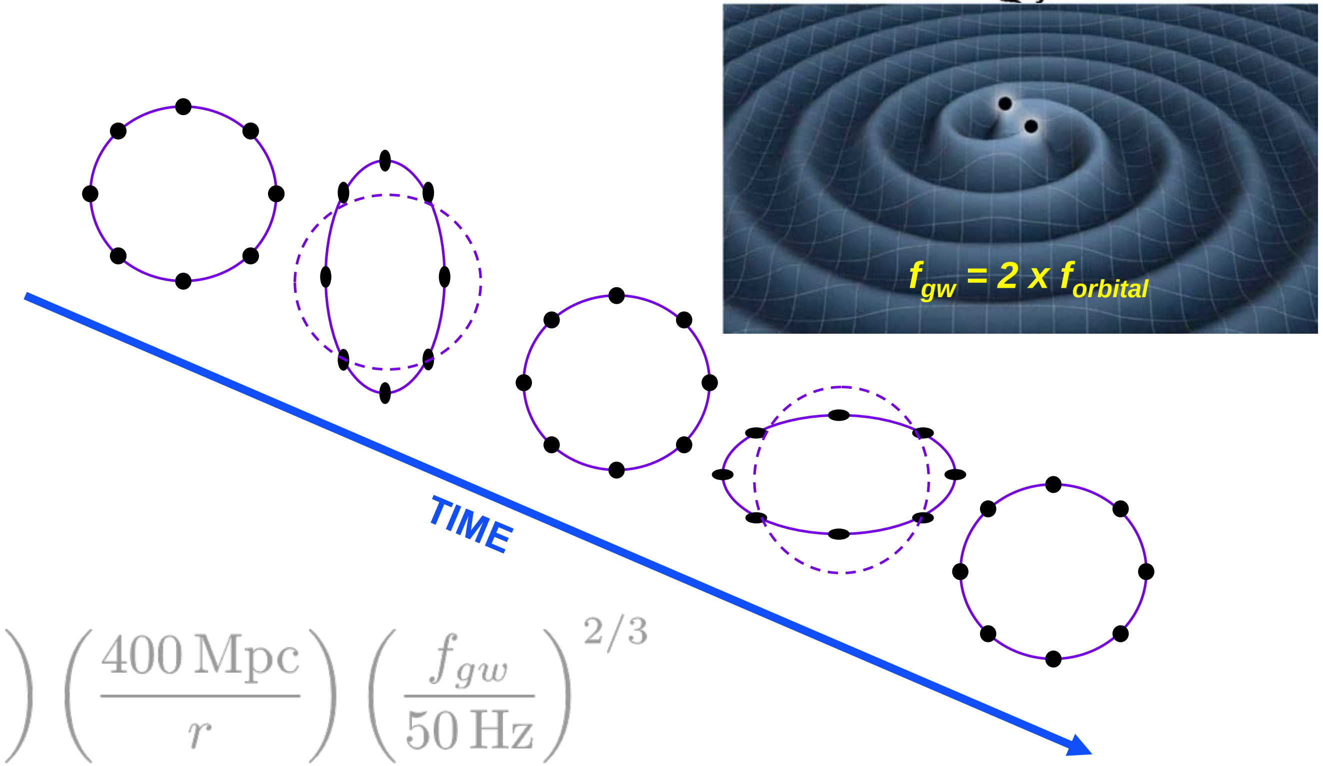
Credit: European Southern Observatory
Very Large Telescope



Transverse Quadrupolar Wave

- GWs are required by Einstein's general relativity (GR)
  - Sources are accelerated masses
  - Propagation velocity is the speed of light, c
  - Lowest order source is a quadrupole
- GWs cause geometry/length fluctuations
  - x and + polarizations
- Dimensionless amplitude strain
  $h = \Delta L/L \sim 10^{-21}$
  - $\sim \frac{atomic\ diameter}{earth-sun\ distance} \approx \frac{1\ Angstrom}{150\ Gm} \approx \frac{proton\ diameter/1000}{1\ km}$





metric perturbation

$$h = \frac{2G}{c^4 r}\ddot{I}$$

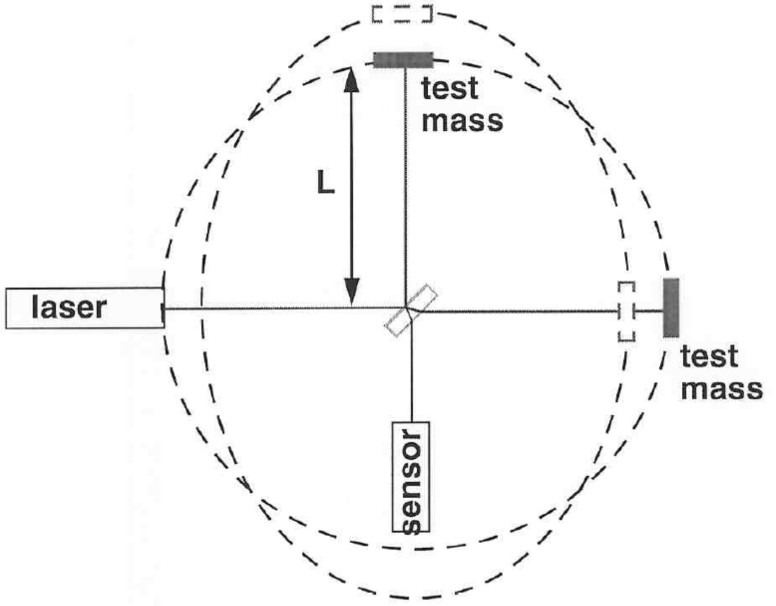
← ***quadrupole moment***

Two masses m in a circular orbit:

$$h = \frac{2Gm}{c^4 r}(2\pi f_{gw})^{2/3} = 1.5 \times 10^{-21}\left(\frac{m}{30M_\odot}\right)\left(\frac{400\,\mathrm{Mpc}}{r}\right)\left(\frac{f_{gw}}{50\,\mathrm{Hz}}\right)^{2/3}$$

Basic Concepts

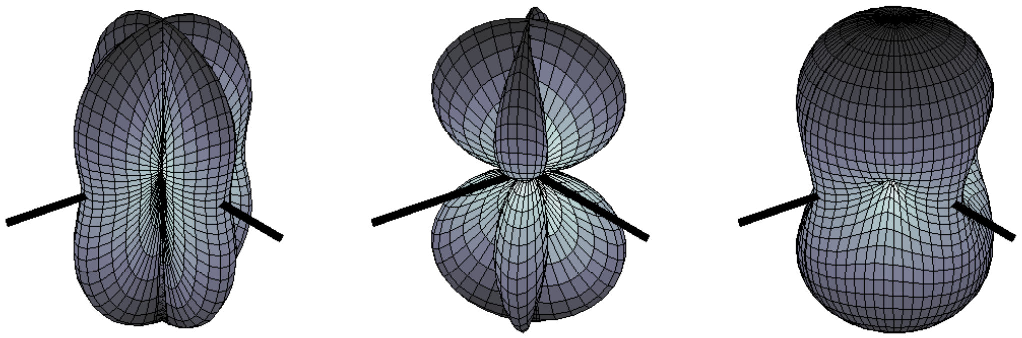
- Optical Interferometery
  - A Michelson interferometer is an ideal transducer for a transverse quadrupolar strain wave
    → two orthogonal arms
    → can measure 0.01 nrad of optical phase
  - Laser frequency fluctuations
    → equal arm lengths
  - Minute strain
    → long arms (~4km as a practical civil engineering limit for earth curvature)
    → Optically resonant cavities amplify the phase shift by ~200x
- Audio frequency measurement
  - Where ground motion is small (and further attenuated by isolators)
- Avoid thermal noise ($k_B T$)
  - Select extremely low mechanical loss materials
  - Measure away from mechanical resonances



‘+’ pol.

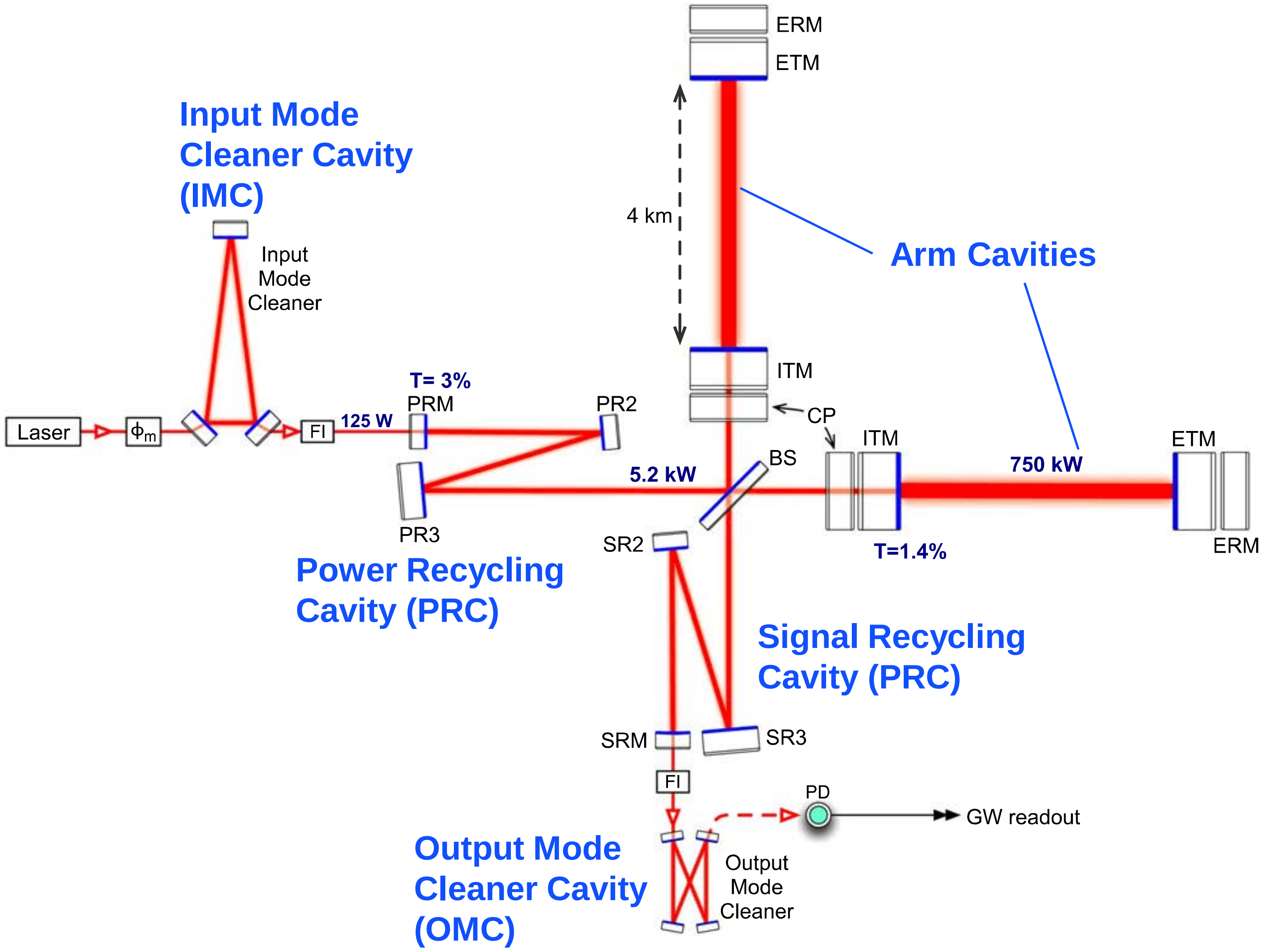
‘x’ pol.

Polarization
-averaged



The Michelson Interferometer as a Receiving Antenna – almost omnidirectional

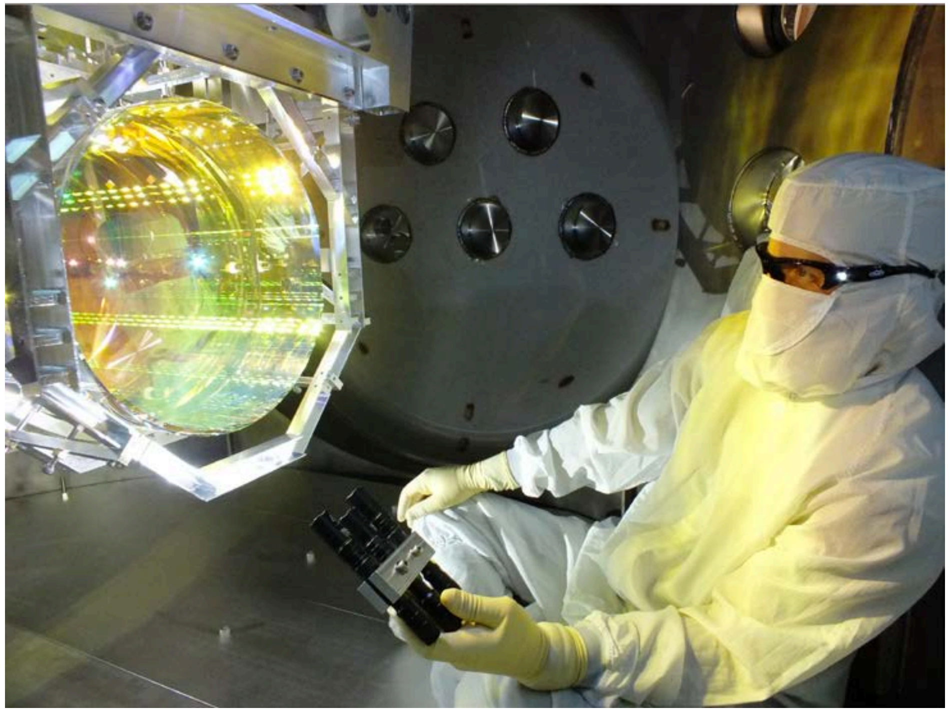
LIGO Laser Interferometry



LIGO-G2000952-v1

Input & End Test Masses (ITM, ETM)

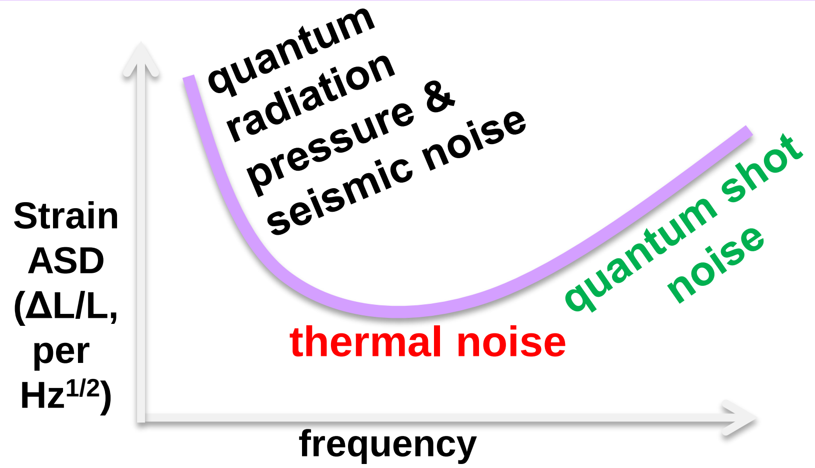
- Ultra-low-loss fused silica
- 34 cm φ x 20 cm thick, 40 kg
- Super-polished + ion beam milling
  - <0.15 nm RMS deviation from sphere
- Mirror coatings:
  - $Ti:Ta_2O_5$ / SiO_2 multi-layers
- A few 10's of ppm total loss
- Absorption < 0.5 ppm:



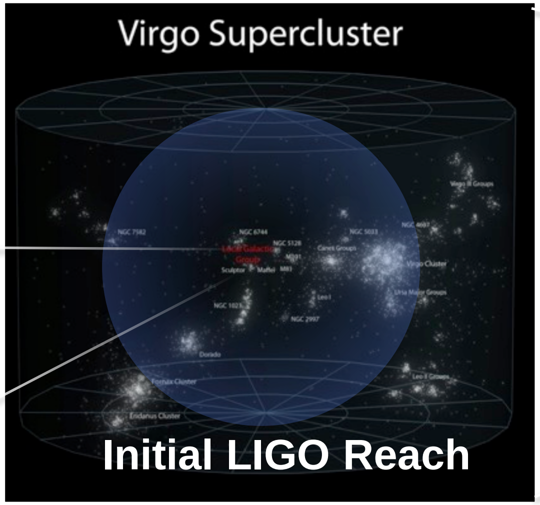
Detection Rate scales as Range Cubed

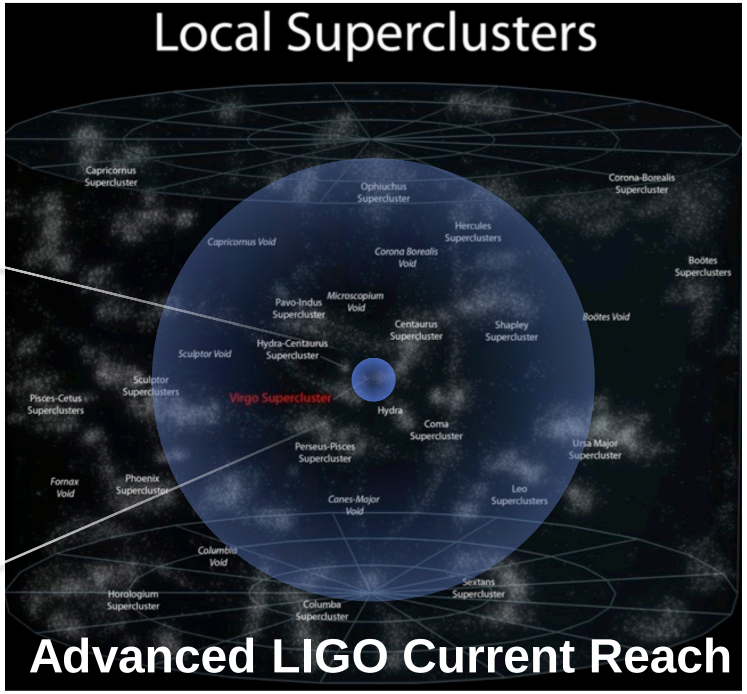
Two common ways of characterizing sensitivity:

1 **Strain Noise Spectrum**
Since interferometers detect GW amplitude, plot amplitude spectral density (ASD) of detector noise (square root of power spectrum), expressed as equivalent GW strain

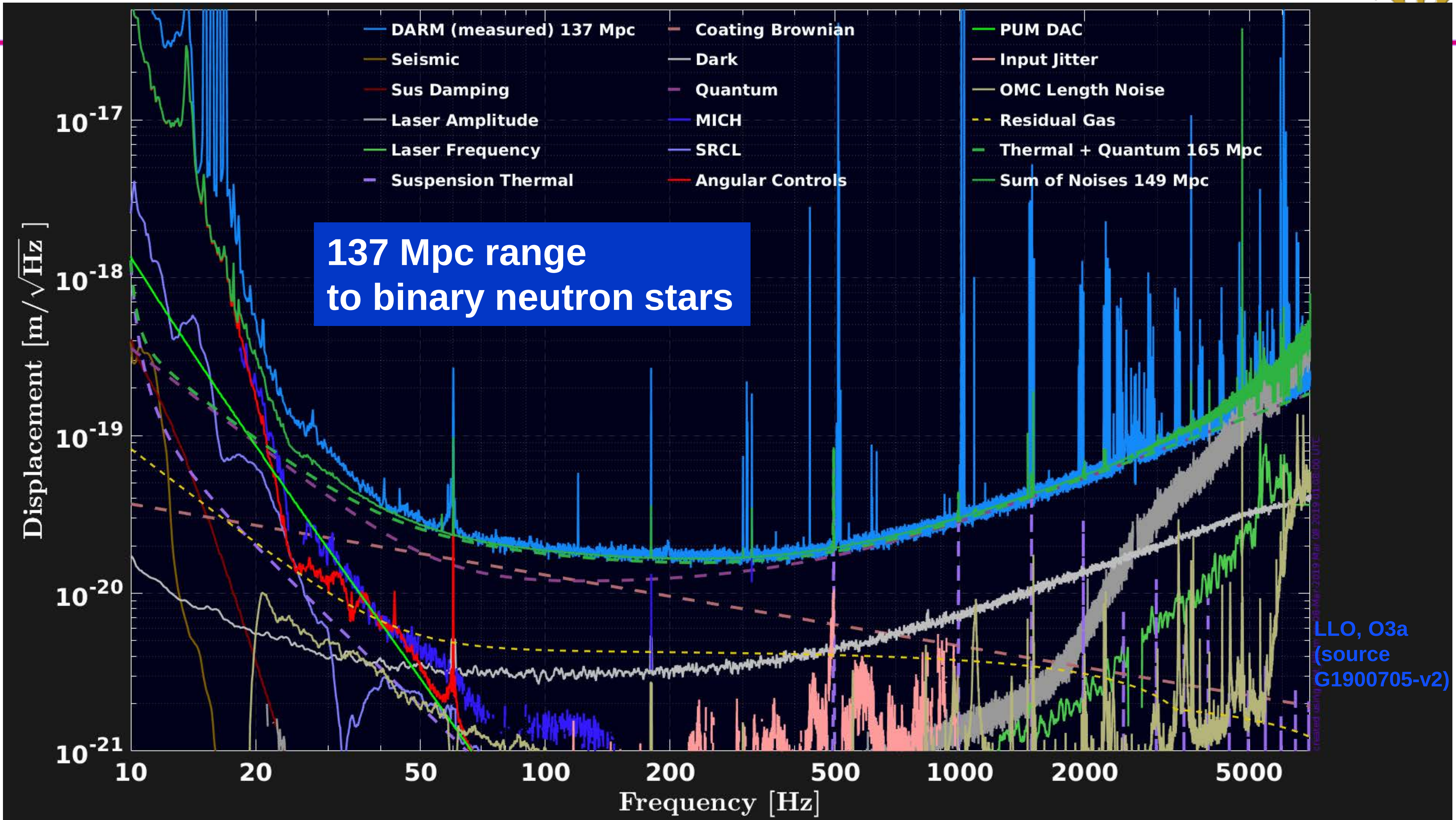


2 **Inspiral Range**
The distance to which the coalescence of a pair of 1.4-solar mass neutron stars can be detected, averaged over direction and orientation





Measured LIGO Noise Budget



LLO, O3a (source G1900705-v2)

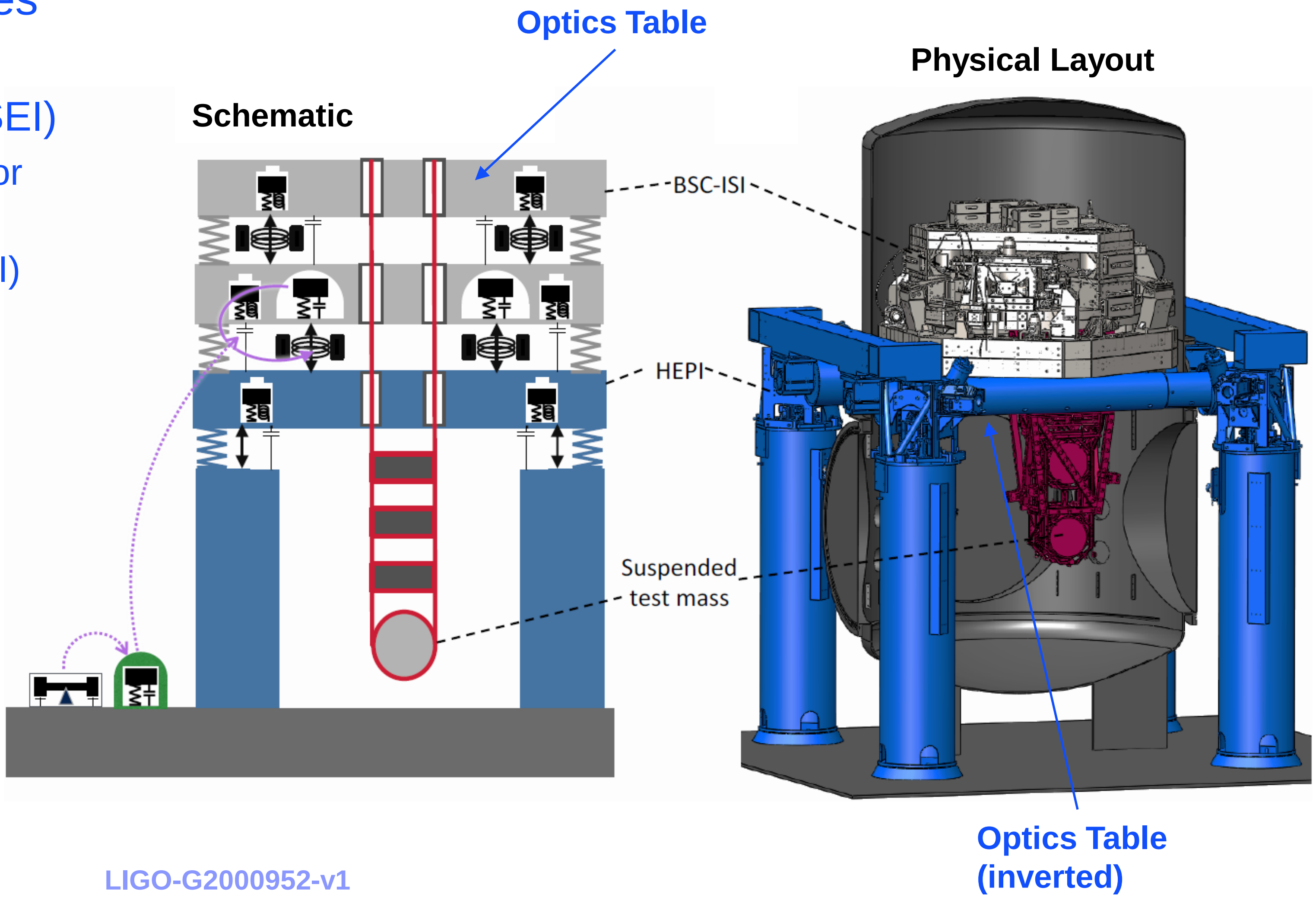
The Principal Control "Plants"

- Seismic Isolation System (SEI)
  - Inertially Isolated platforms for (suspended) optics
- Suspensions (SUS)
  - Single, double, triple & quadruple pendulum suspensions
- Pre-Stabilized Laser (PSL)
  - Frequency, pointing & intensity stabilization
- Interferometer Sensing & Control (ISC)
  - Length
  - Angle
- Auxiliary controls
  - Squeezed vacuum (light) system
  - Thermal compensation system (adaptive optics)
  - Parametric instability control
  - …

View inside the LHO Corner Station

Seismic Isolation & Positioning Systems

- 3 sequential systems, 7 Isolation stages for the Test Mass Optics
  - 3 stages – Seismic isolation system (SEI)
    - 1 stage - Hydraulic External Pre-Isolator (HEPI)
    - 2 stages -Internal Seismic Isolation (ISI)
  - 4 stages - Suspension systems (SUS)



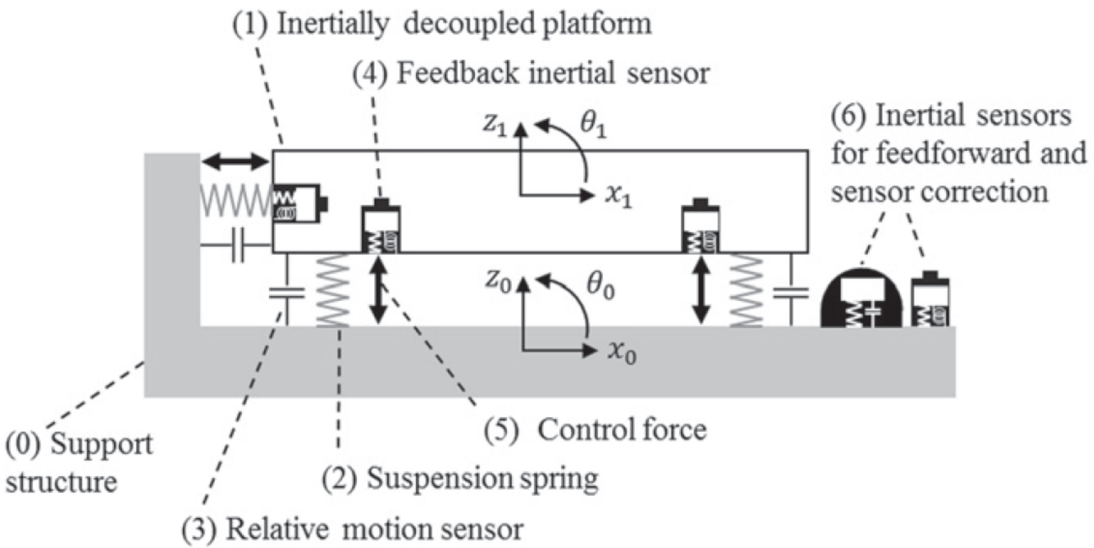
Seismic Isolation

2-stage internal seismic isolation (ISI) system
(test mass optics, large chambers)

1-stage internal seismic isolation (ISI) system
(smaller chambers, input & output optics)

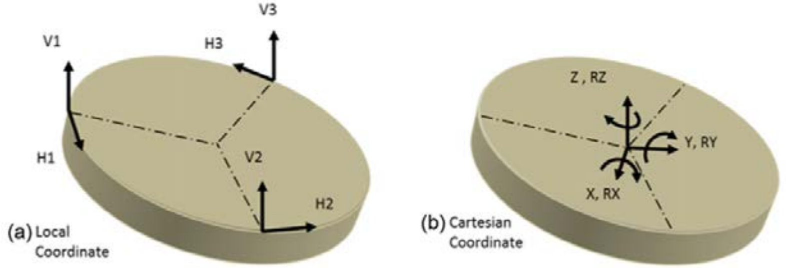
Seismic Isolation Active Control

- 3 stages x 6 dof each = 18 dof per TM chamber
- Hydraulic actuator (outer stage)
- Electromagnetic actuators (inner stages)
- Blended position & velocity sensing
- Sensor correction
  - Ground tilt sensing is used to remove tilt coupling of a collocated ground horizontal seismometer
  - Coherence between the ground and first stage allows the ground seismometer to 'correct' the relative position sensor
- Feed-Forward & Feedback control
- All DOFs are controlled independently in the Cartesian basis



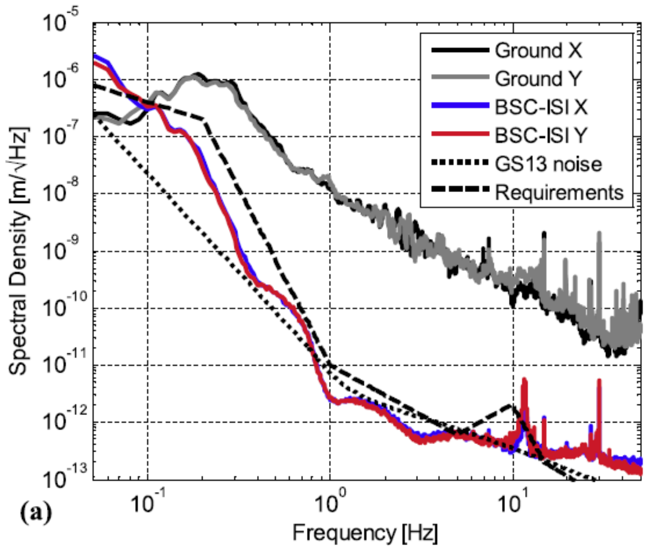
Schematic of each passive/active inertial isolation stage

Coordinate transformation

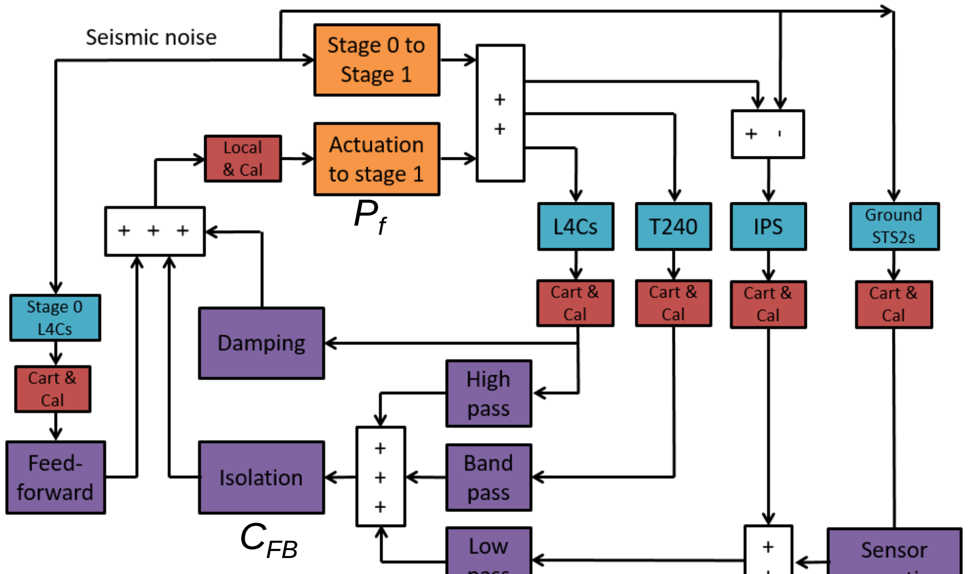


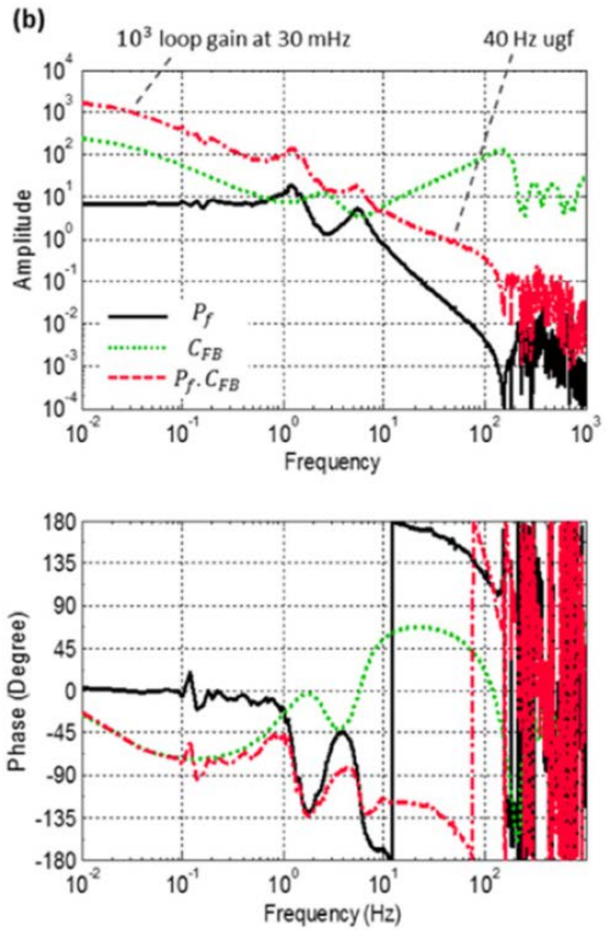
Active Seismic Isolation Control

- Non-stationary disturbances
  (high microseismicity, wind, logging, trains, earthquakes, …)
- Earthquakes
  - warning system is used to put the control system into a more robust state in order to ride out the seismic disturbance without losing optical lock
- Robust error detection to prevent instability induced damage to suspension systems



Typical BSC-ISI isolation performance – horizontal DOF

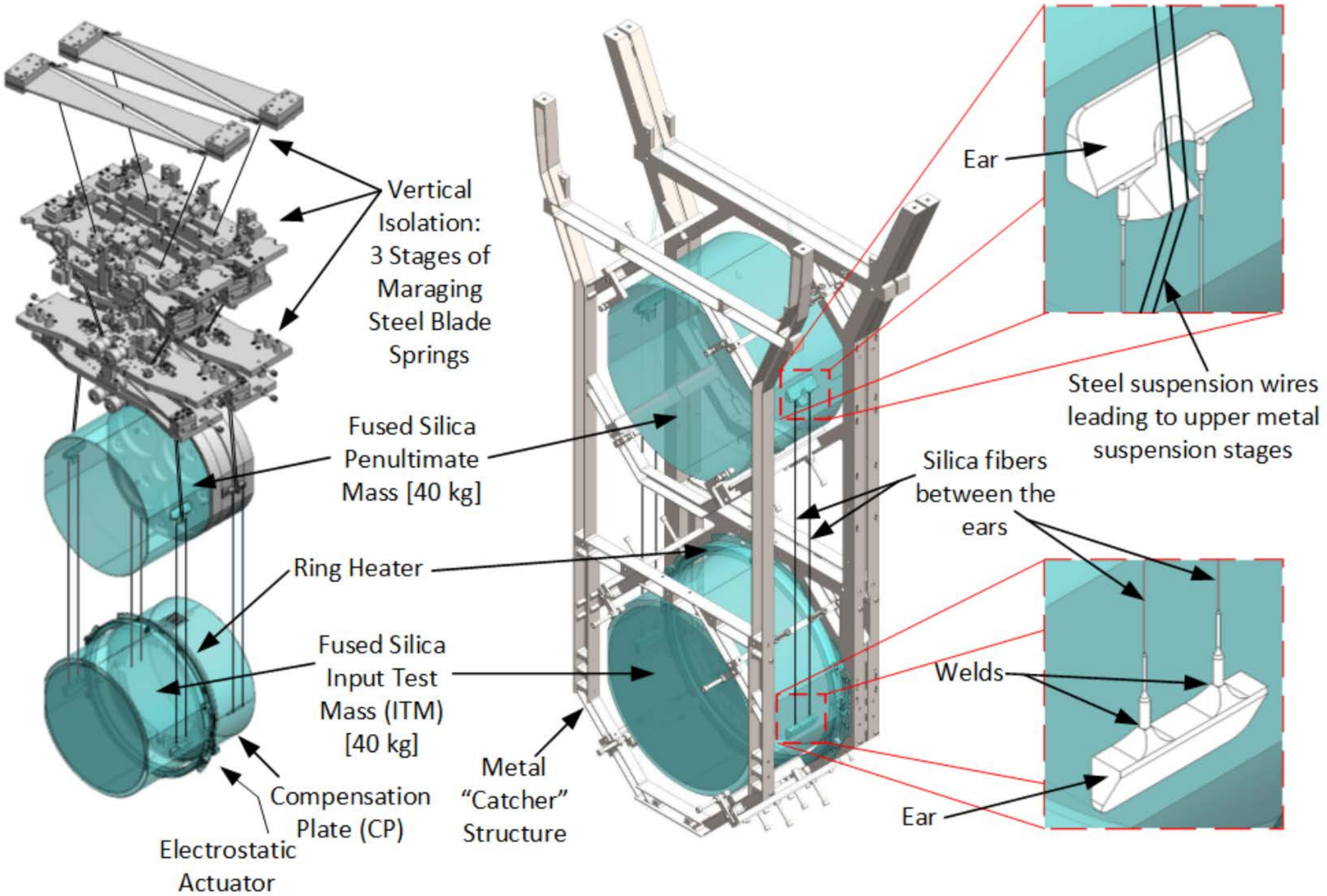




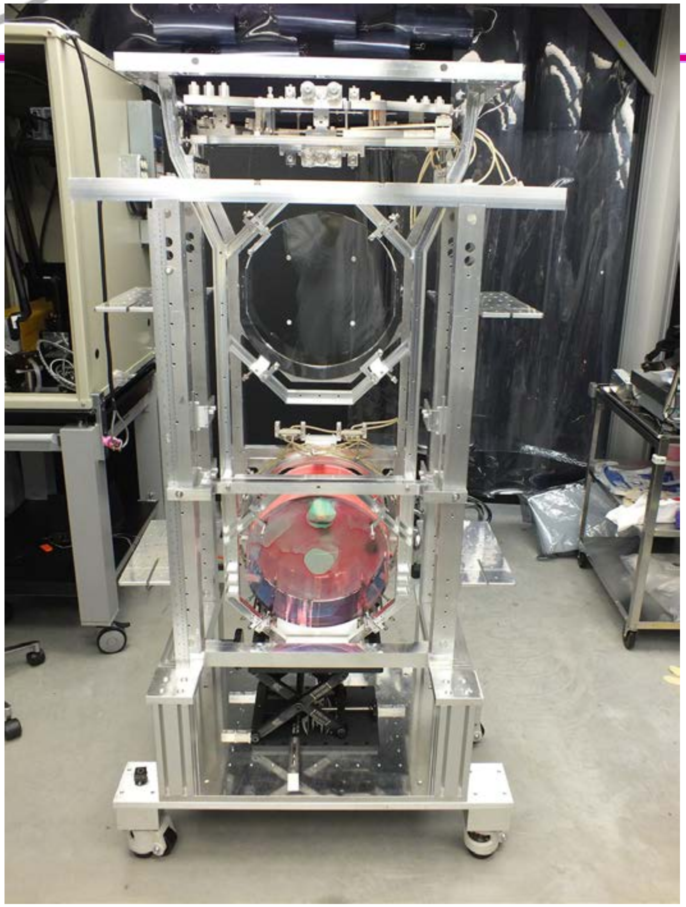
Example BSC-ISI transfer functions

Quadruple Suspension Systems

- Quad Test Mass (TM) suspensions with reaction chain (Contribution from the United Kingdom)
- Observability/controllability of 22 of the 24 pendulum modes from the top stage
  - Silica fiber extensional modes are weakly coupled
- Collocated position sensors & electromagnetic actuators on upper stages
- Electro-static actuation at TM stage
- Damped at low frequency with rapid roll-off to prevent control loop noise injection in-band
- Designed to minimize thermal noise

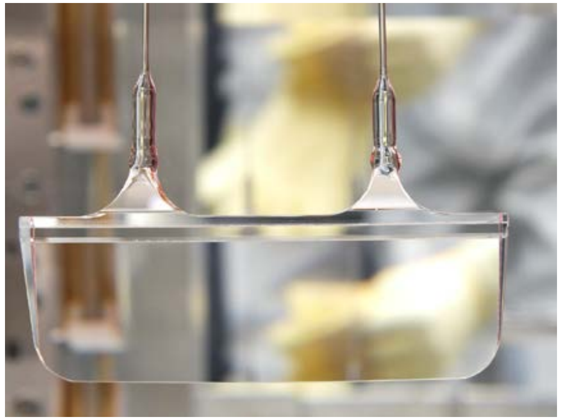


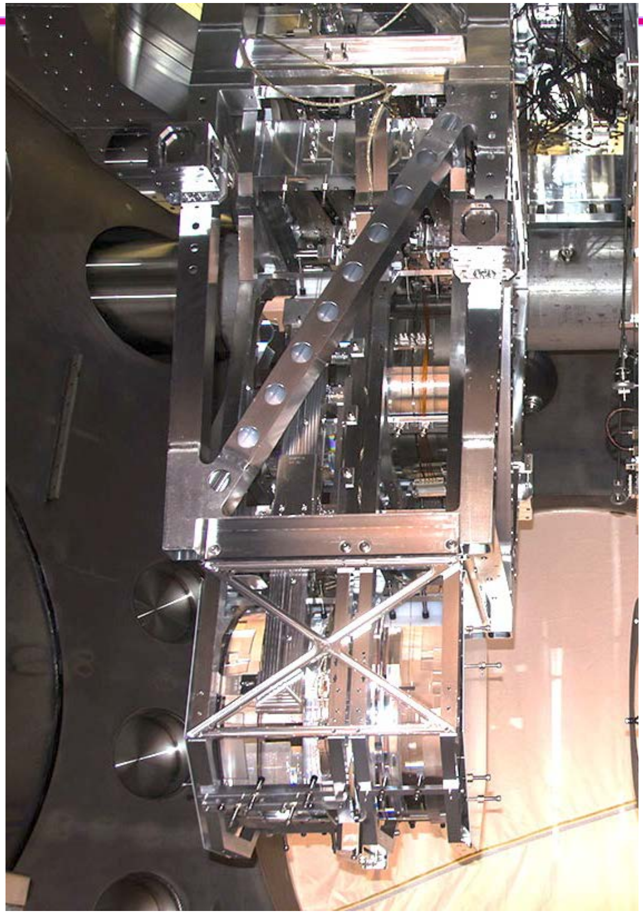
Quadruple Suspension System



Test mass & penultimate mass in assembly fixture

- Silica Ear Sodium Silicate Bonded to Mirror Substrate
- Horn (3 mm) for fiber welding by CO_2 laser
- 0.4 mm x 600 mm long silica fiber

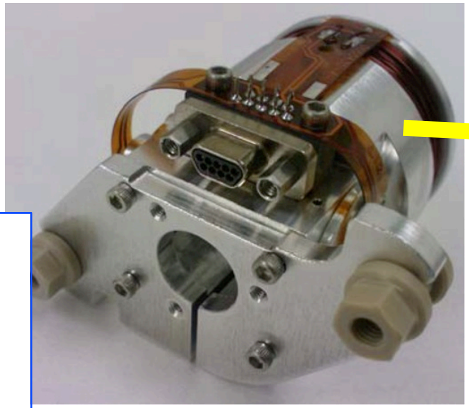


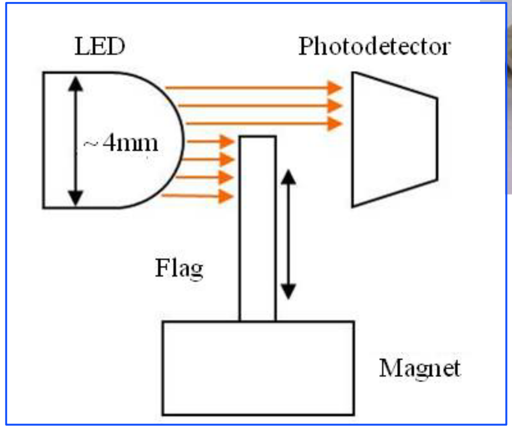


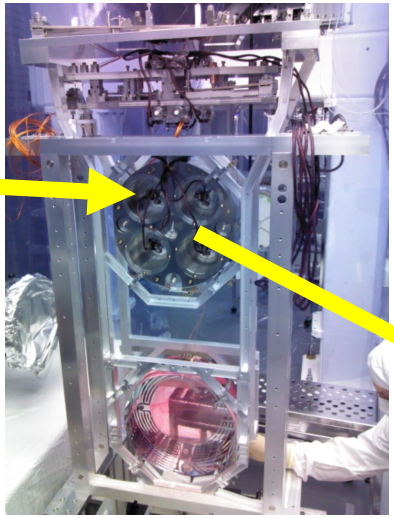
Mounted on actively isolated 3 stage SEI platform (optics table)

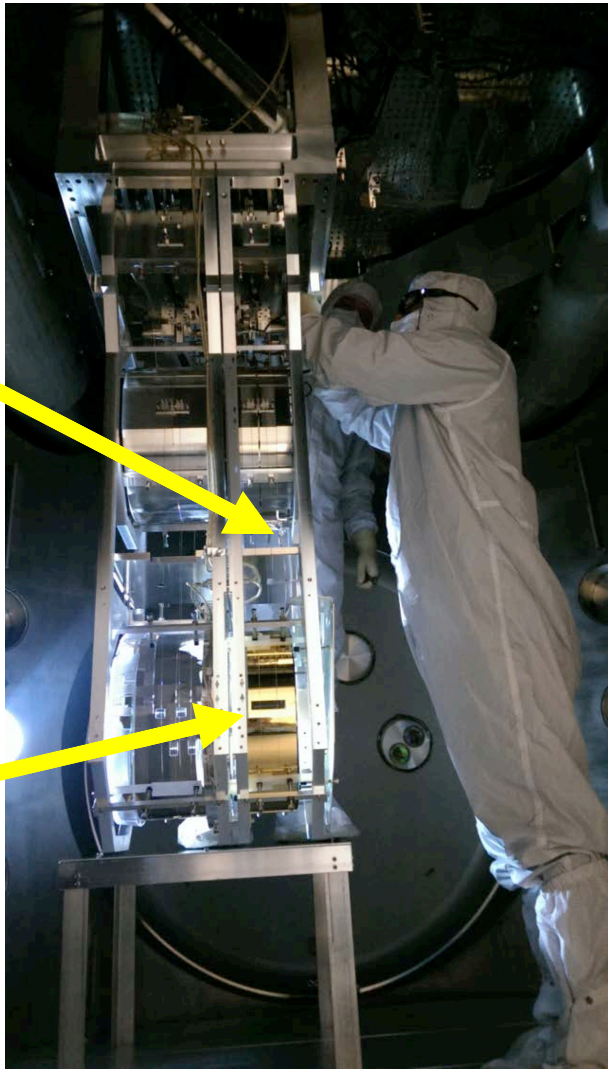
Quadruple Suspension Control

Voice Coil Actuation collocated with shadow sensor – between main chain & reaction chain for upper stages

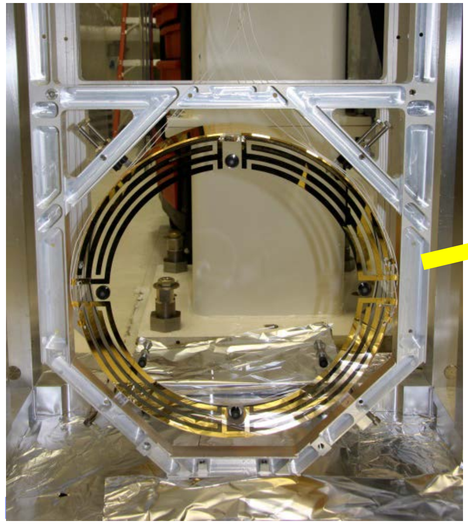






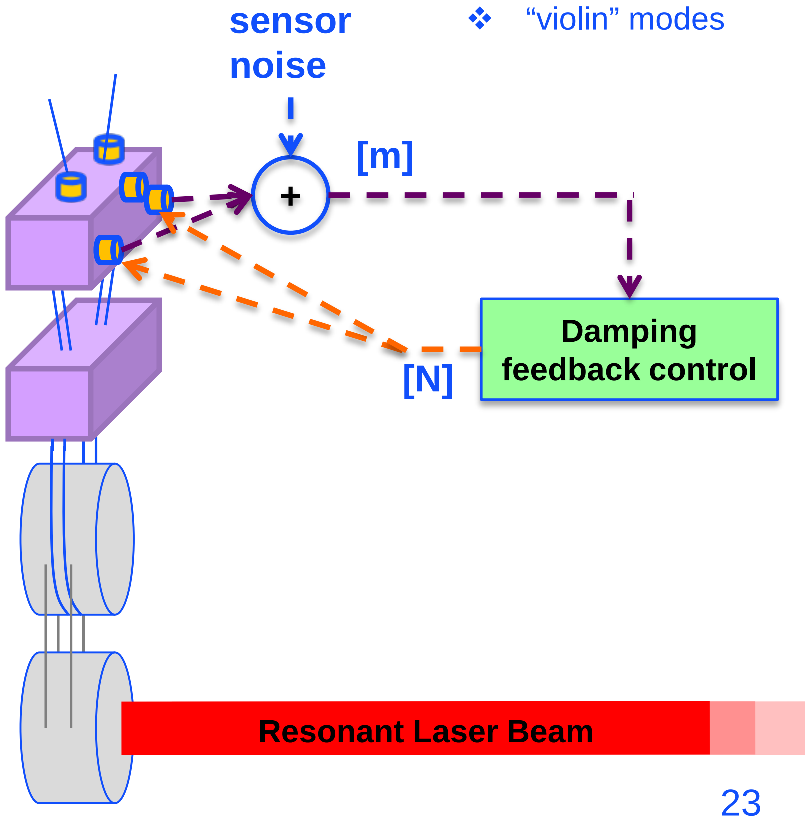


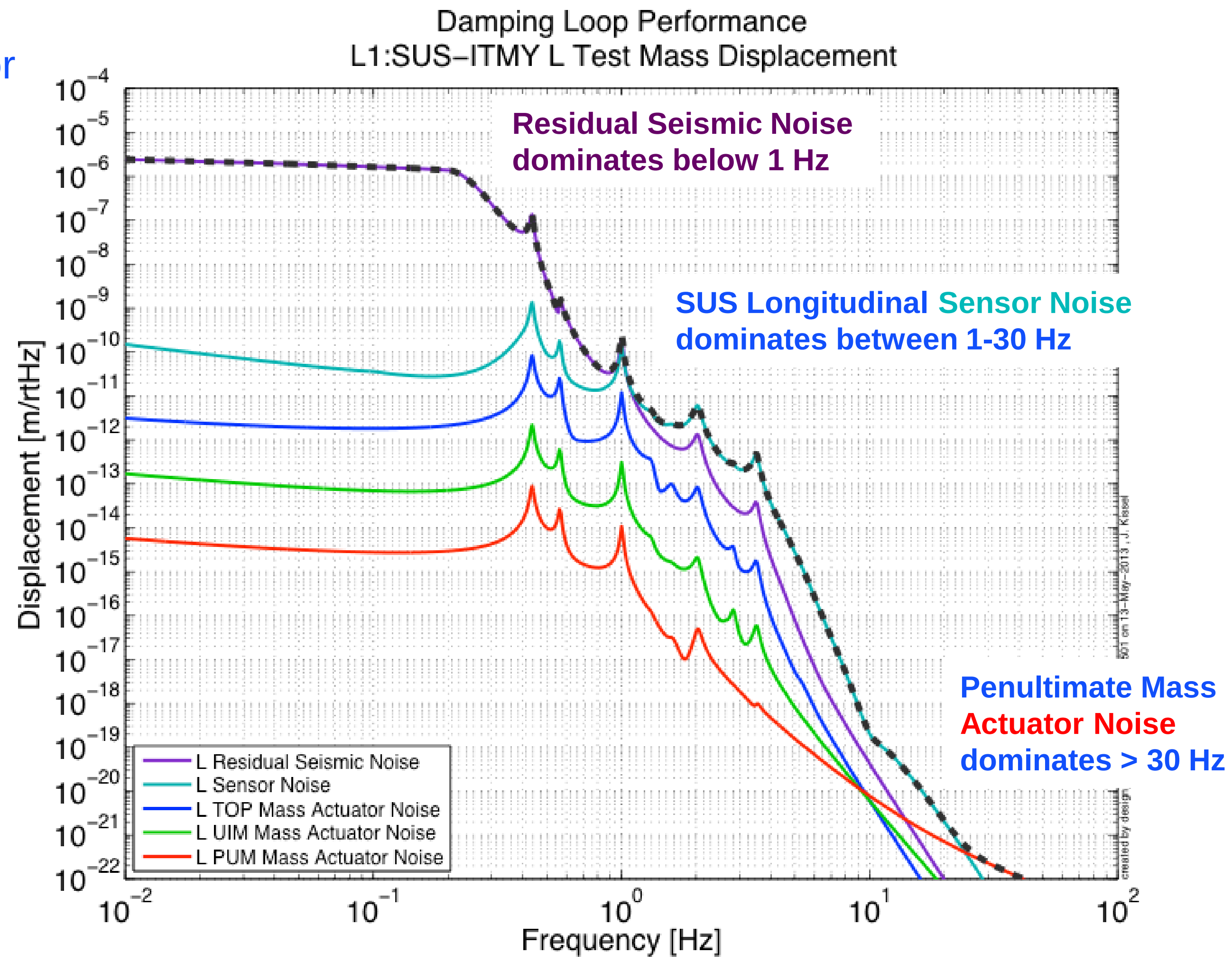
Electrostatic Actuation between Test Mass and Reaction Mass



Suspension Damping Loops

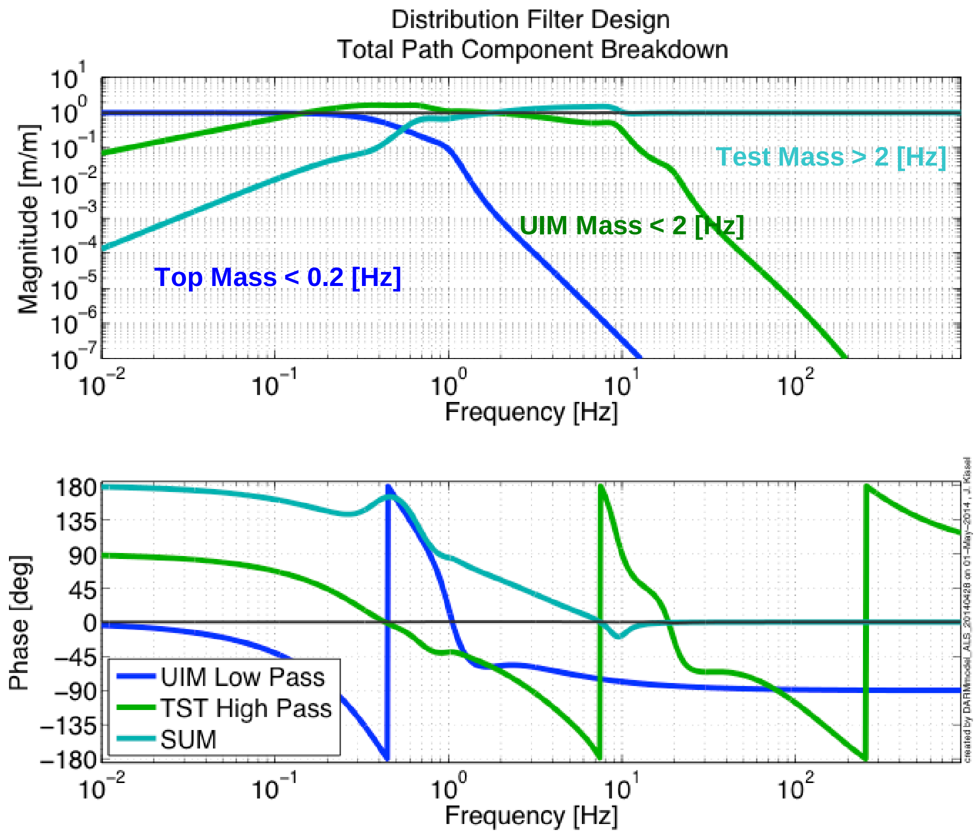
- Local damping control
  - Modal damping
  - Multimode damping
- Passive tuned mass dampers (TMDs) for high Q modes with low controllability
  - vertical bounce modes
  - “violin” modes

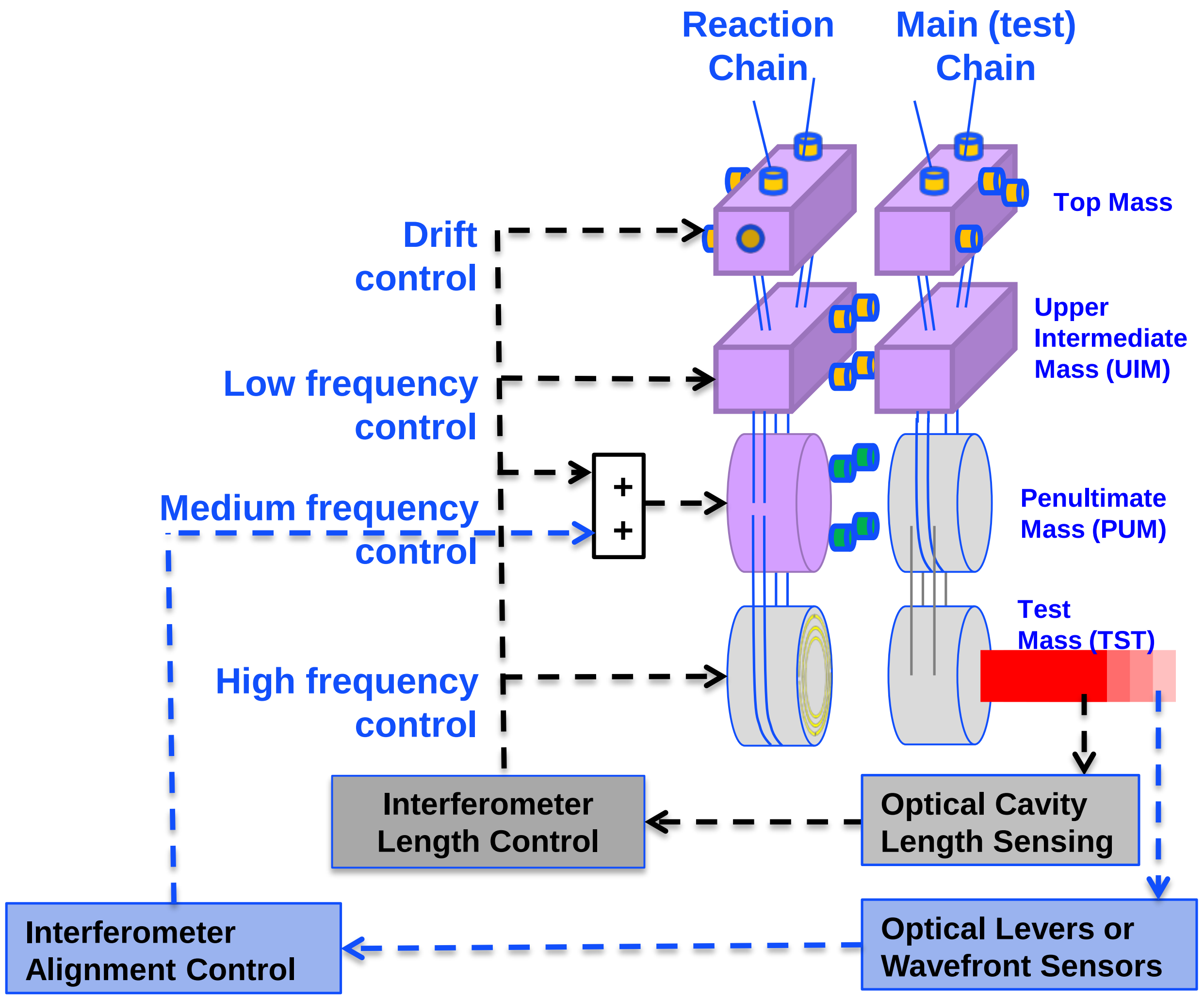




Suspension Optical Cavity Control

- Global hierarchical control

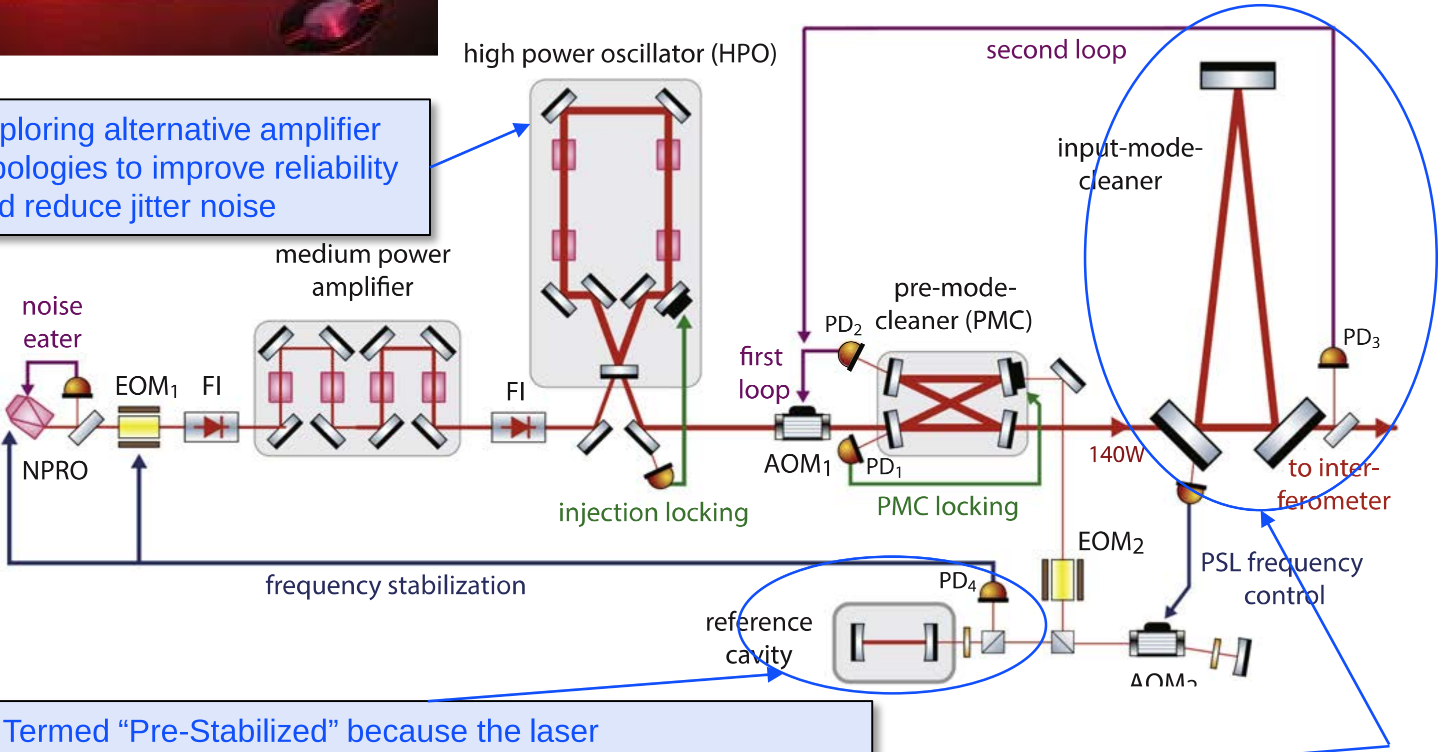




Pre-Stabilized Laser

- Contribution from the Albert Einstein Institute (Germany)
- Nd:YAG Oscillator (1064 nm wavelength)
- Amplifier stages to 200W

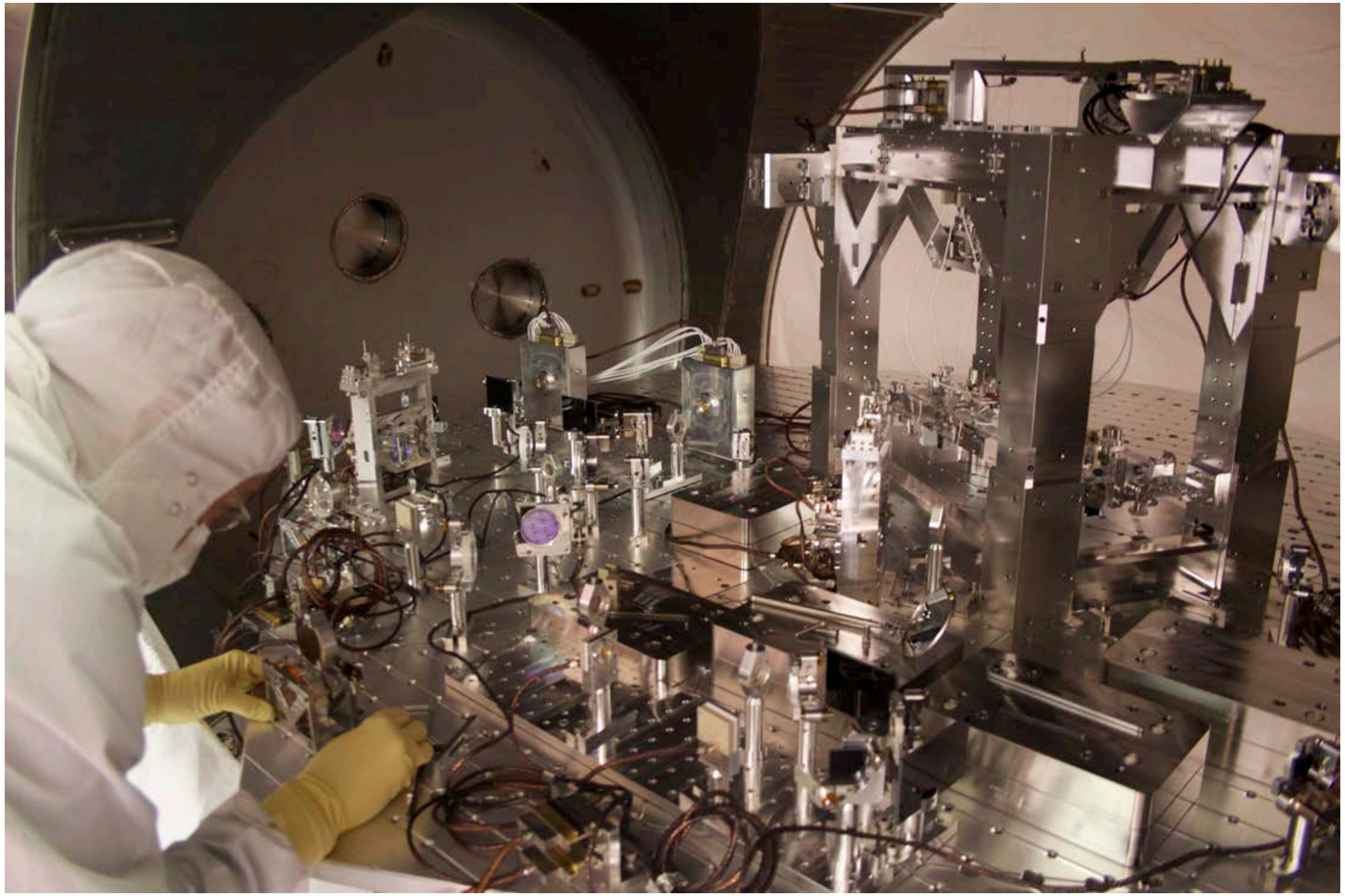
Exploring alternative amplifier topologies to improve reliability and reduce jitter noise



Termed "Pre-Stabilized" because the laser wavelength/frequency is locked sequentially to quieter, in-vacuum cavities & ultimately the Fabry-Perot Arm Cavities (ultimately achieving <1 Hz/√Hz @10 Hz)

Interferometer Sensing & Control (ISC)

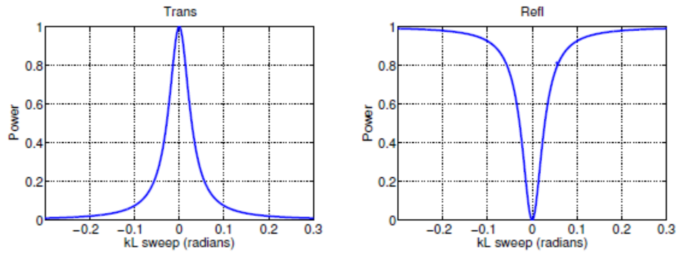
- Control objectives:
  - Bring the interferometer to a low-noise operating state
  - Hold the interferometer at the operating state
  - Provide the Gravitational-Wave (GW) signal

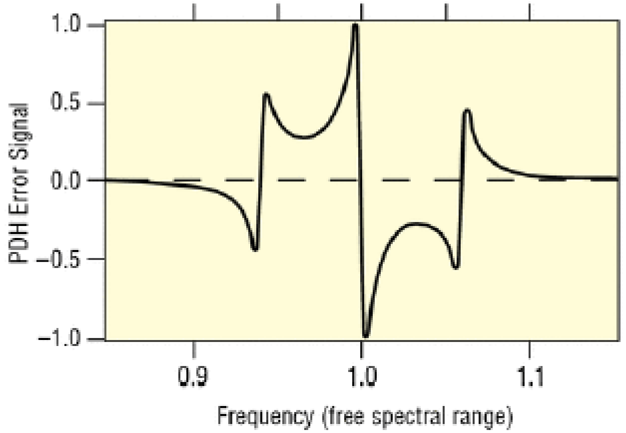


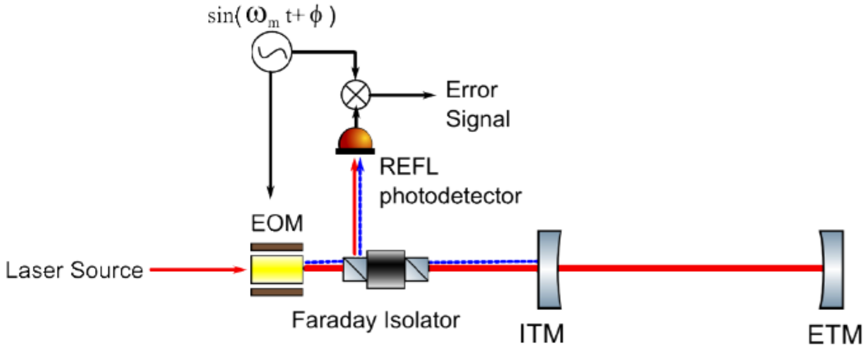
Output Mode Cleaner (OMC)

Optical Cavity Length Sensing & Control Basics

- Consider a single, linear, optical cavity as the mirror separation distance varies
- For ease of control, linearize the signal using the Pound-Drever-Hall (PDH) technique
  - Modulate the main laser (carrier) to obtain sidebands which are anti-resonant in the cavity
  - then demodulate the interference signal at the reflection port at the beat frequency

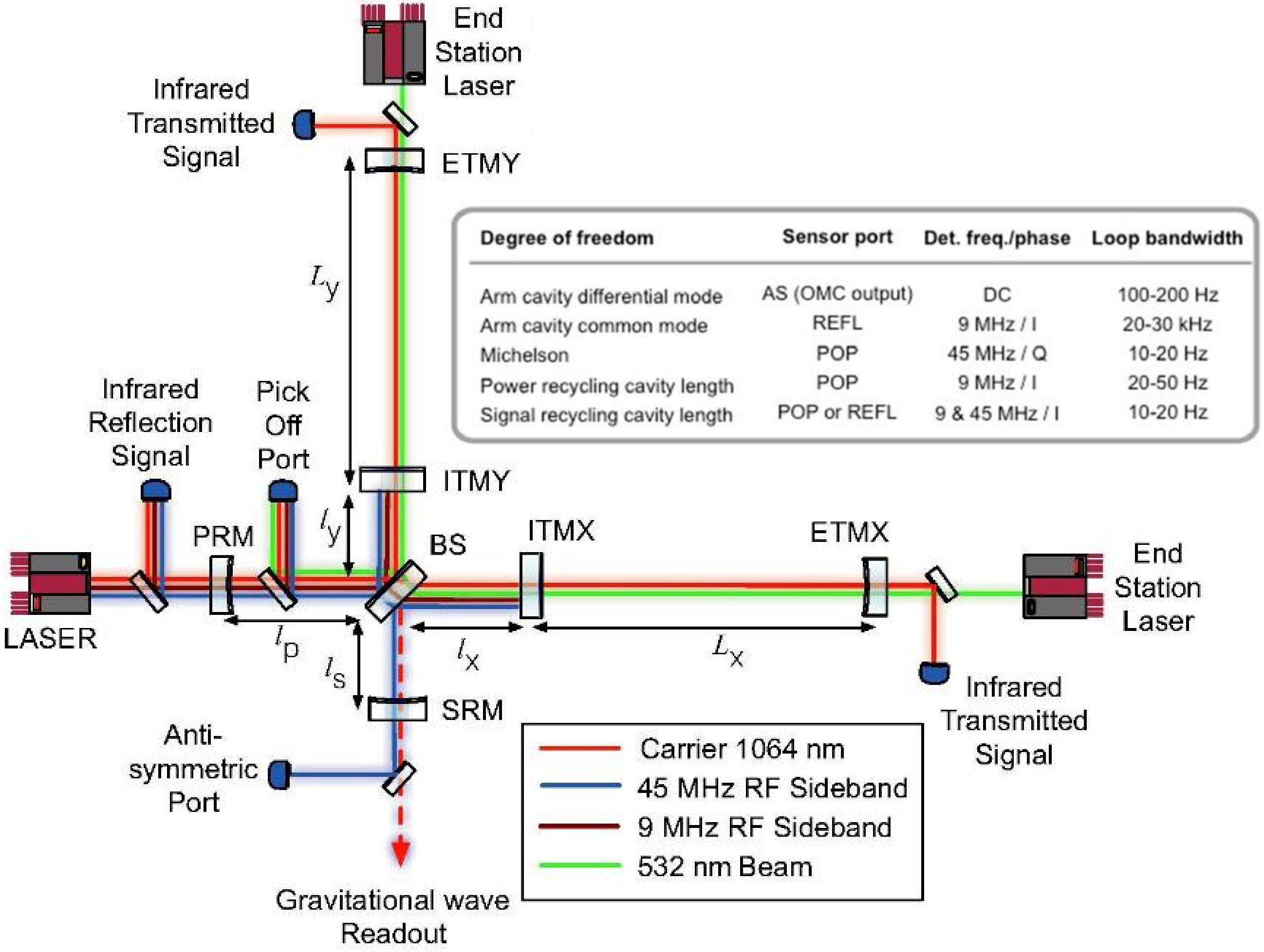






Interferometer Length Sensing

- Length derived from RF demodulated signals
- Five resonant cavity lengths
- Arm Length Stabilization (ALS)
  - Acquire lock with lower finesse at doubled frequency (green wavelength) first



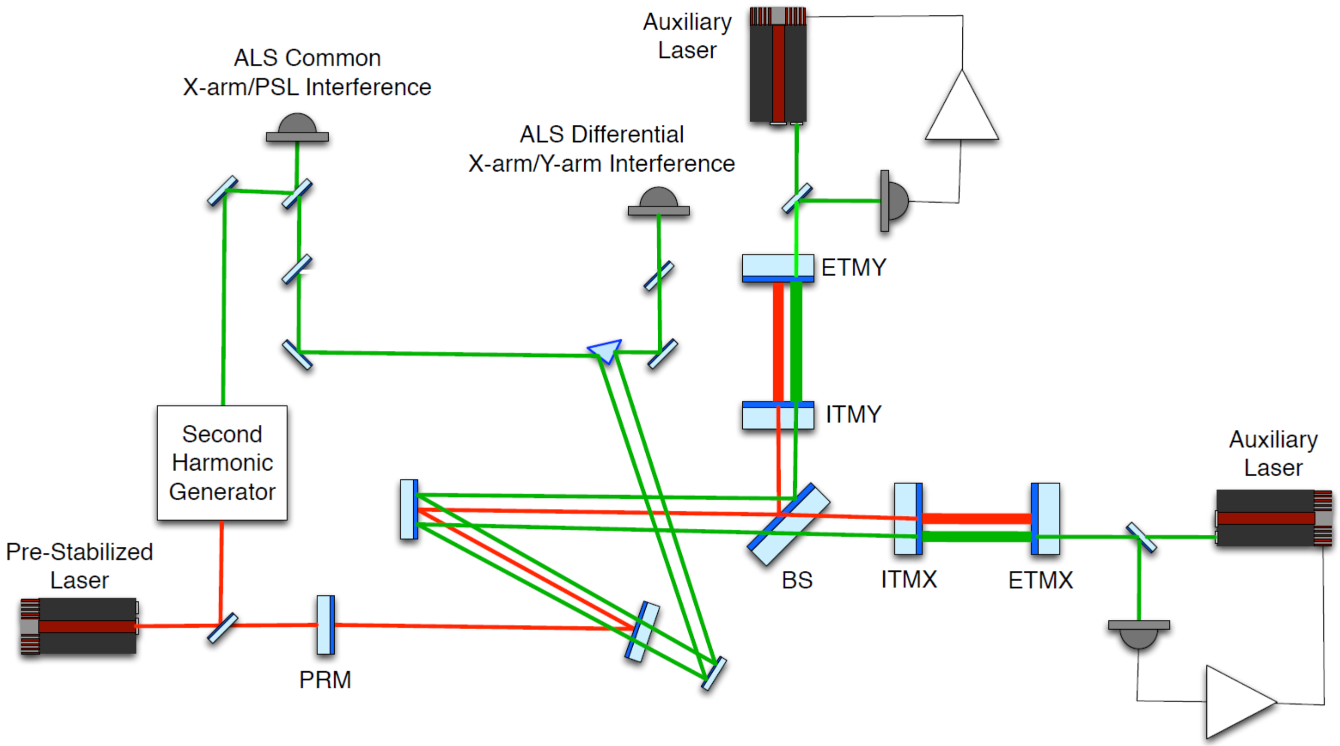
Mode	Definition
Common arm length (CARM)	(Lx+Ly)/2
Differential arm length (DARM)	Lx-Ly
Power recycling cavity length (PRC)	lp+(lx+ly)/2
Signal recycling cavity length (SRC)	ls+(lx+ly)/2
Michelson length (MICH)	lx-ly

Lock Acquisition

- Must guide the interferometer to the operating conditions
  - Multiple, coupled, high finesse optical cavities with narrow linewidth (~1 nm)
- Sequence:

1) Lock arms offset from resonance
   - Maintain both arm cavities at a fixed offset from resonance with a lower finesse green laser beam (532 nm)
   - Reduce RMS motion to within the main beam cavity bandwidth
2) Lock the dual-recycled Michelson degrees of freedom (PRC, SRC, MICH)
   - Demodulation at 3 x f (27 & 135 MHz)
3) Reduce arm offset

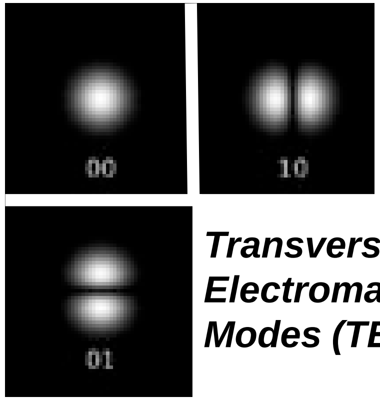
Dual-wavelength locking



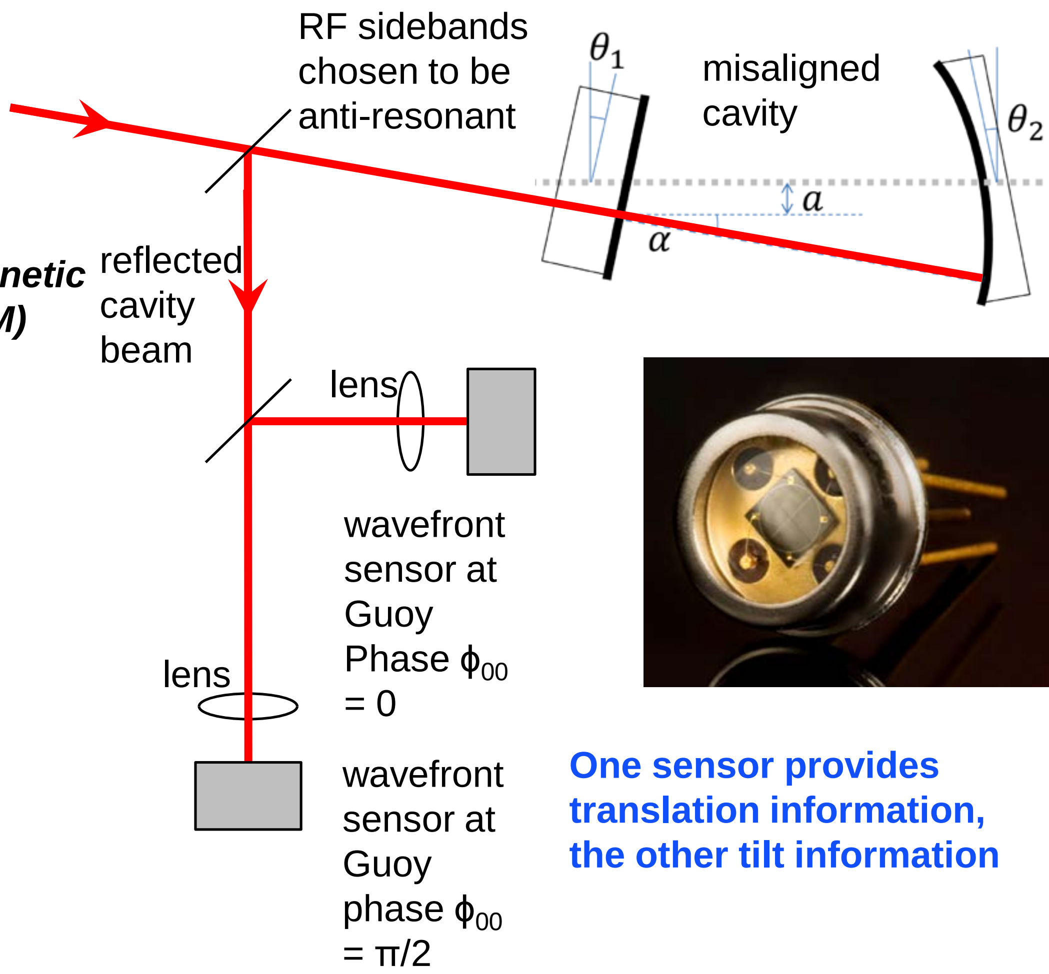
Interferometer Angle Sensing

- Wavefront Sensors
  - The amount of TEM01 and TEM10 indicates how the cavity is misaligned
  - Beat signal between anti-resonant RF sidebands and carrier provide misalignment information
- Optical Levers

Optical Lever Transmitter & Receiver for the Input Test Mass (ITM)



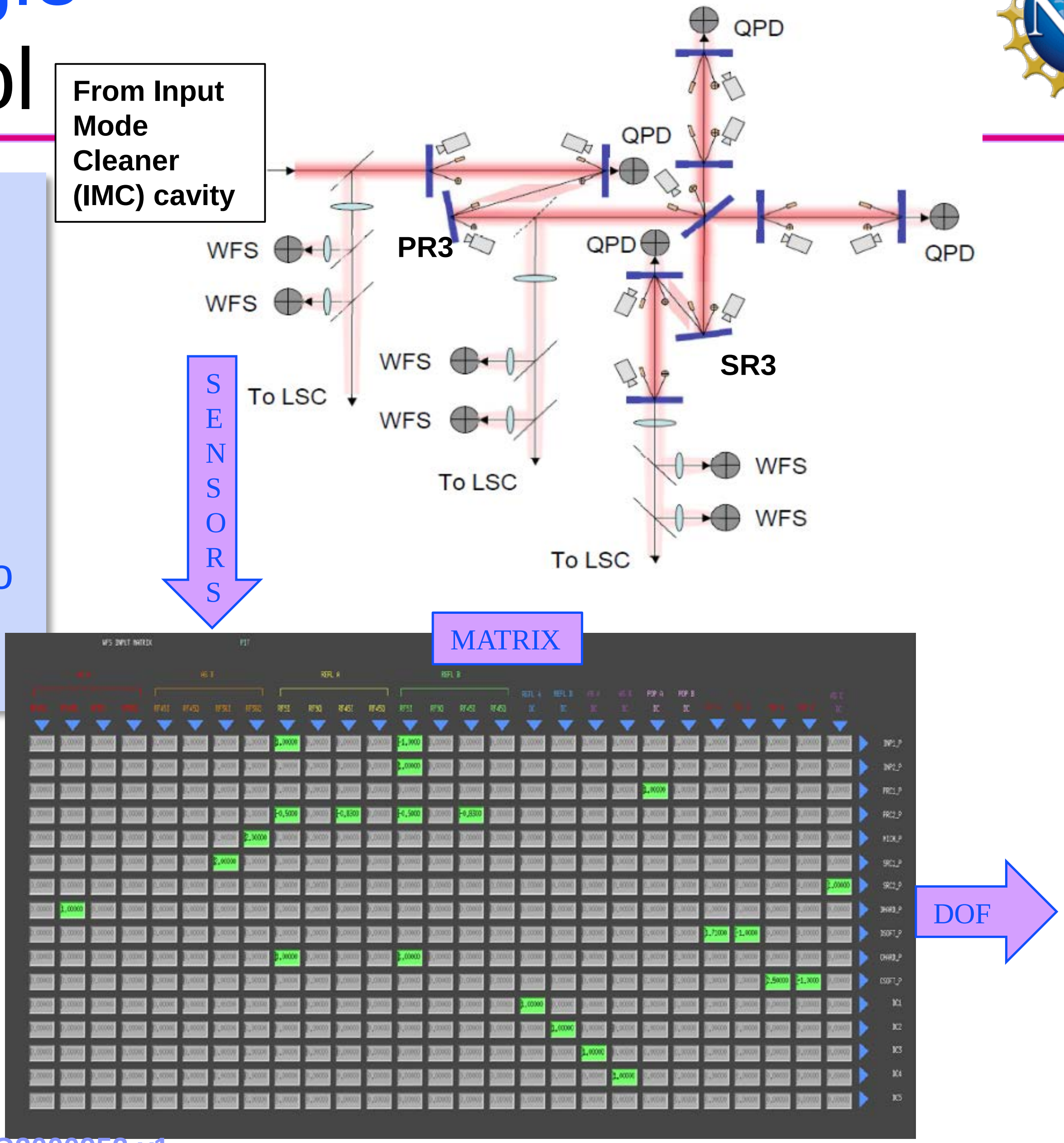
Transverse Electromagnetic Modes (TEM)

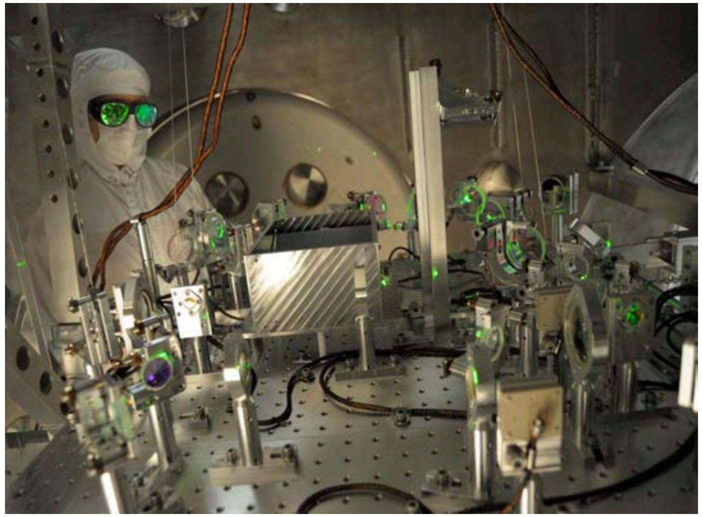


One sensor provides translation information, the other tilt information

Interferometer Angle Sensing & Control

- Require < 1 nrad rms motion of the Test Mass Optics
- Radio frequency (RF) modulation sidebands (MHz) used to sense angular degrees of freedom of optical cavities with Wavefront Sensors (WFS)
- Quadrant Photo-Diodes (QPD) sense laser beam position
- 26 degrees-of-freedom
- Matrix transformation is used to project the sensing to the controlled dofs

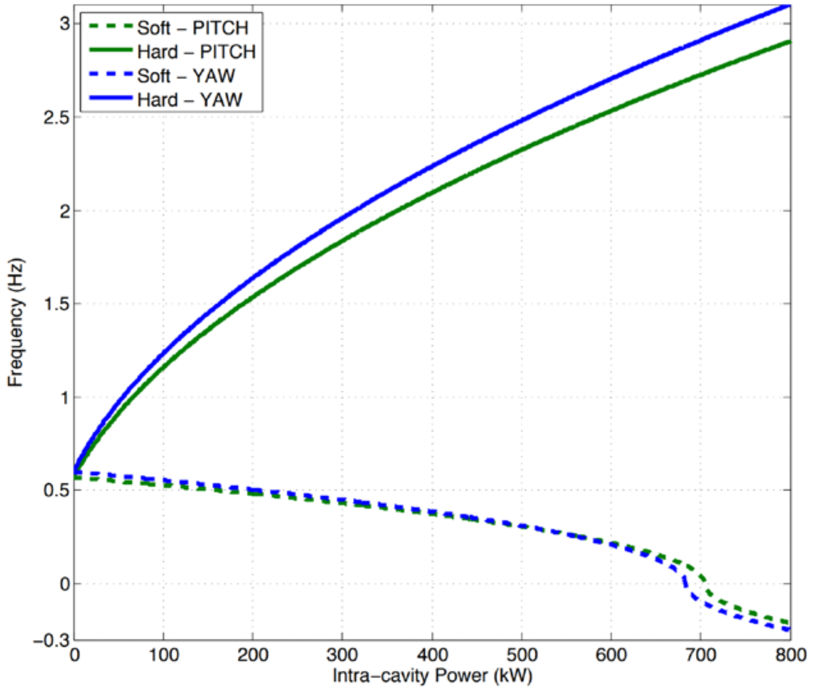


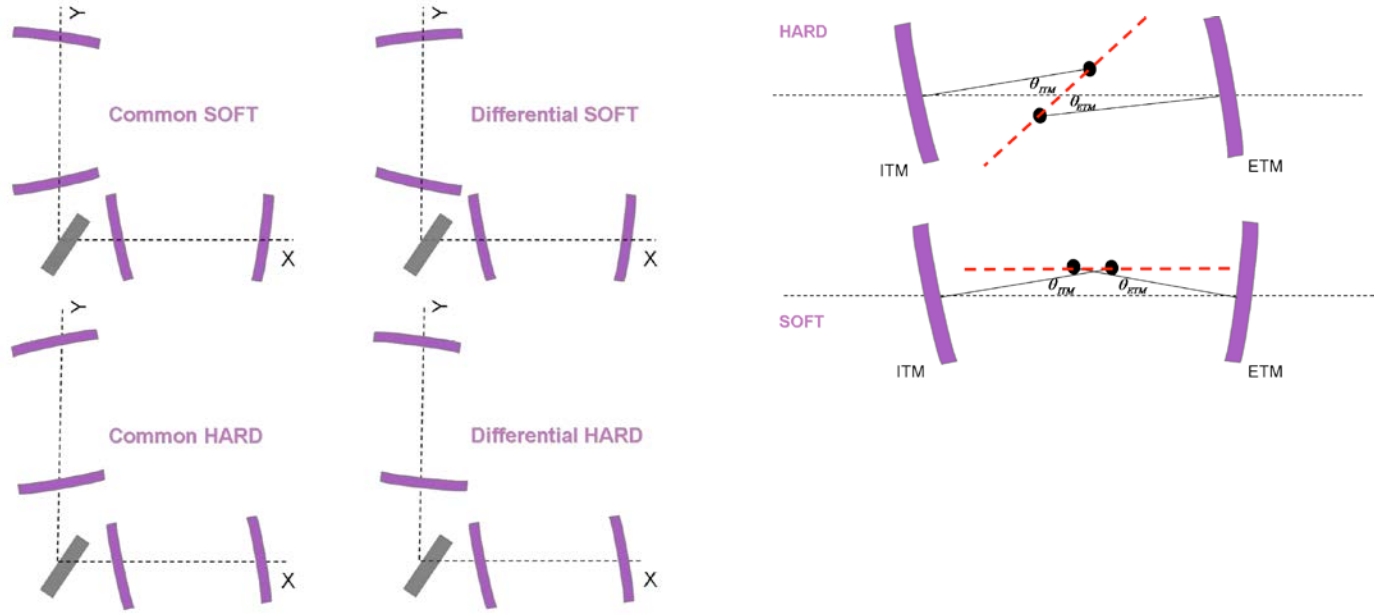


ETM Transsmission Monitor

'Soft' and 'Hard' modes

- Radiation pressure induced torque in the Fabry-Perot arm cavities can exceed the suspension restoring torque
- Radiation pressure effects at high power (>700 kW) cause instability





DOF	Sensor	Freq/Phase	Loop UGF
Differential Hard	WFS AS	45 MHz, Q-phase	1 – few Hz
Common Hard	WFS REFL	9 MHz, I-phase	~1 Hz
Differential Soft	QPD TRX-TRY	DC	~1 Hz
Common Soft	QPD TRX+TRY	DC	~1 Hz
Beamsplitter	WFS AS	36 MHz, Q-phase	~0.1 Hz
Other optics	Various combinations		~0.1 Hz

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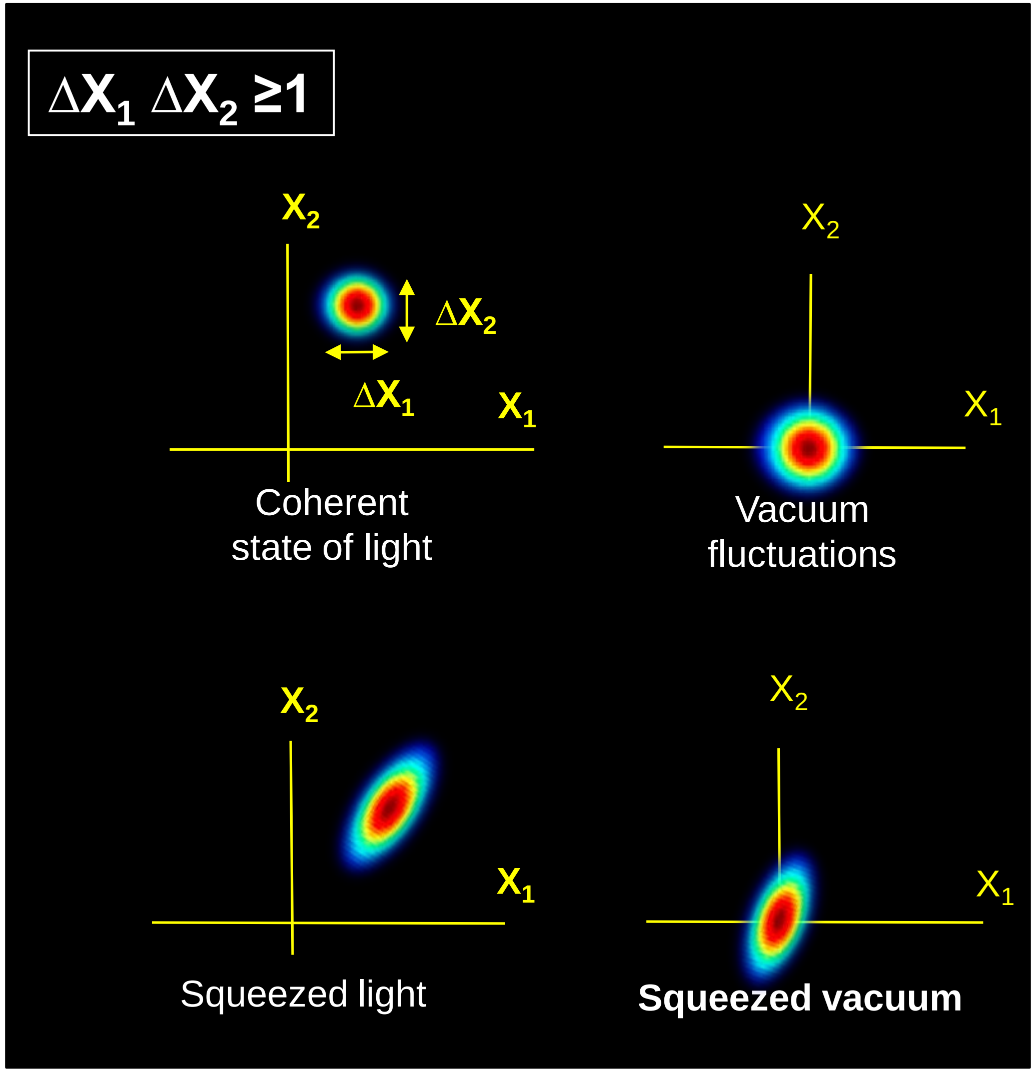
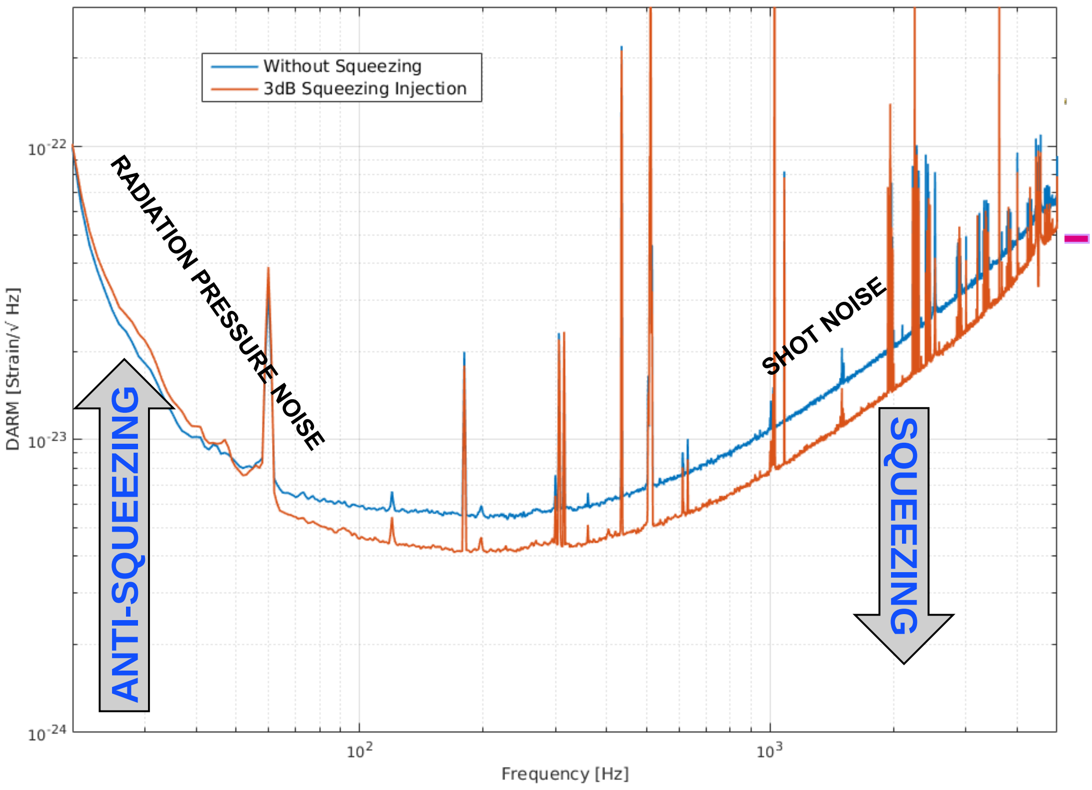
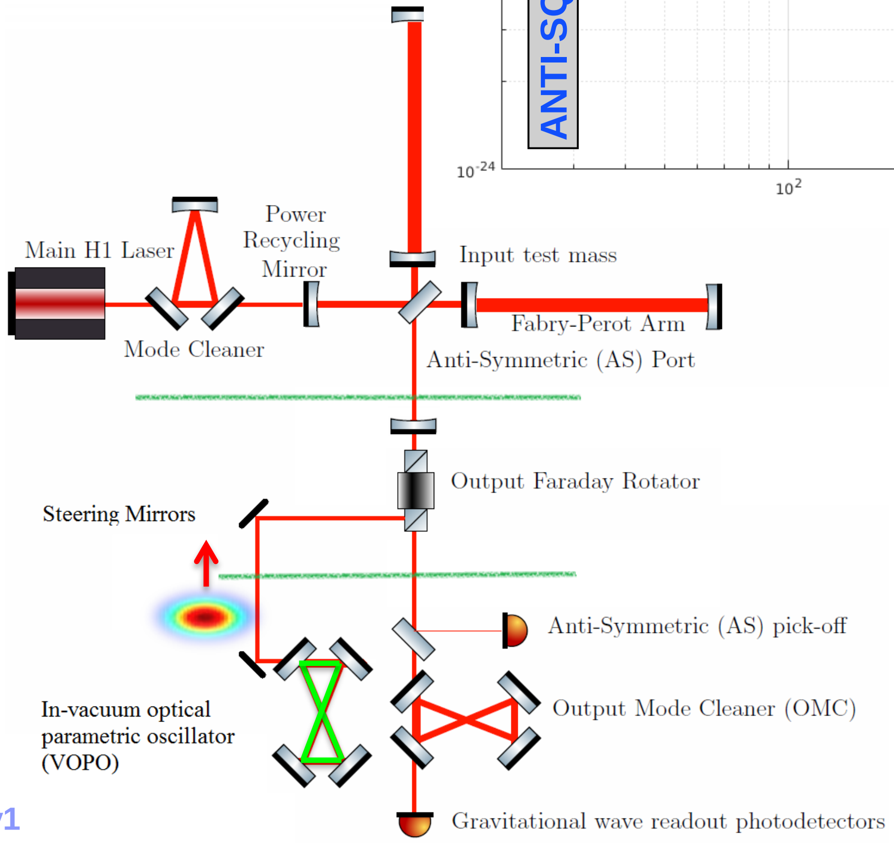
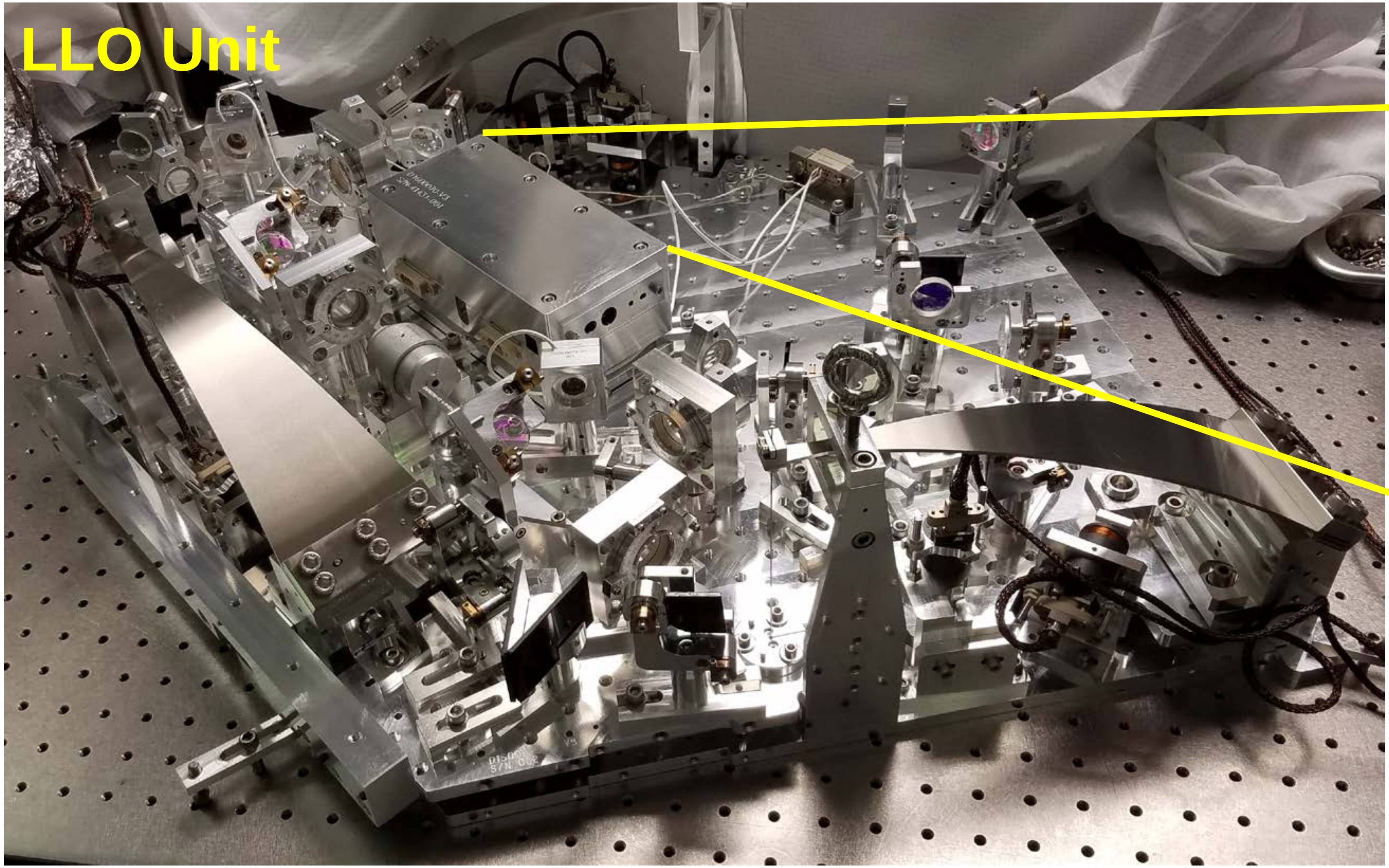
Squeezed Light



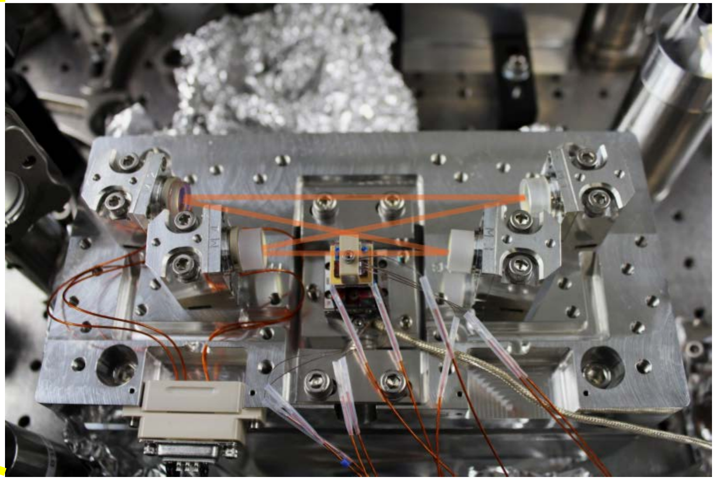




In-Vacuum Squeezed Light Source

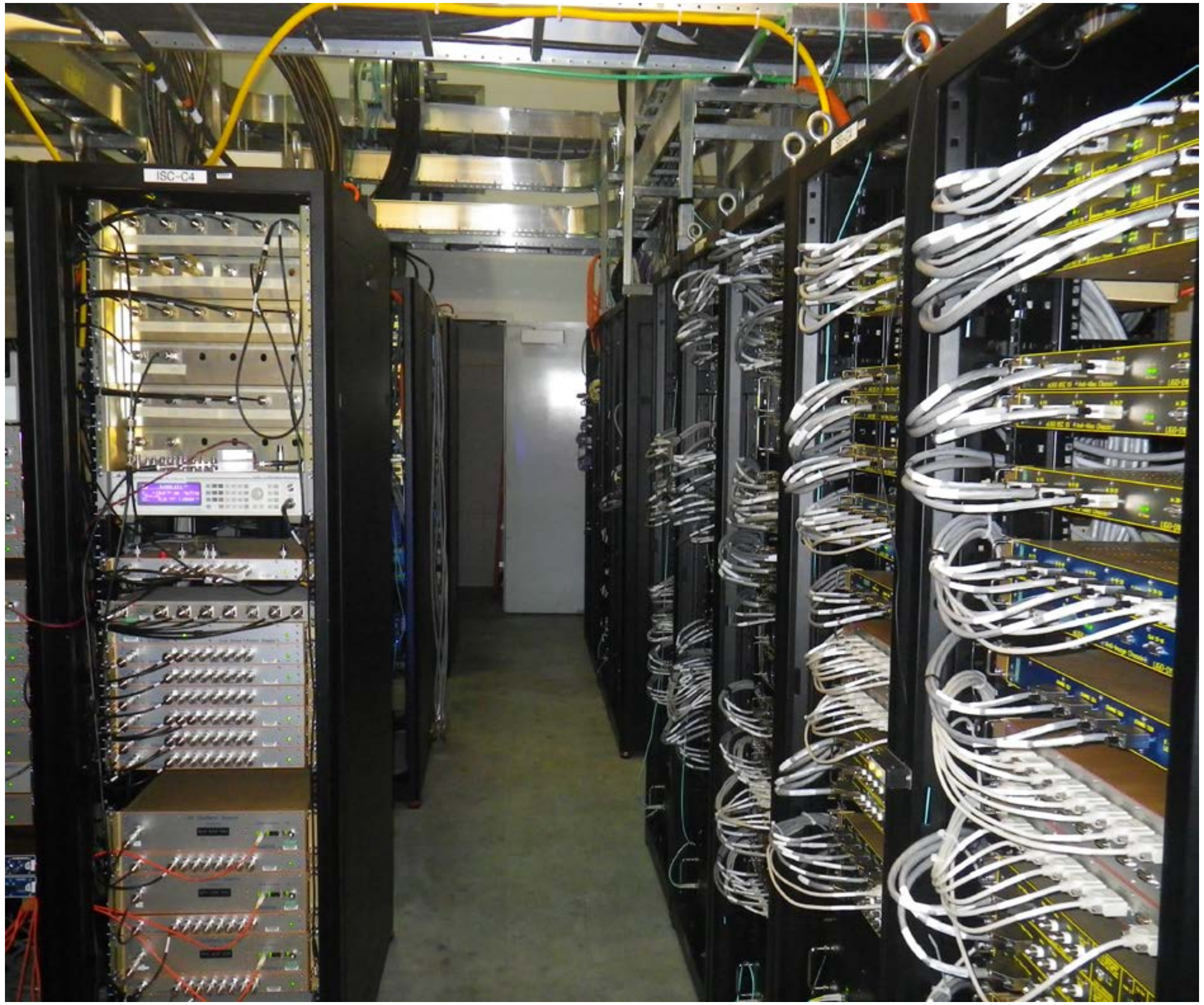


In-Vacuum Optical Parametric Oscillator (OPO)



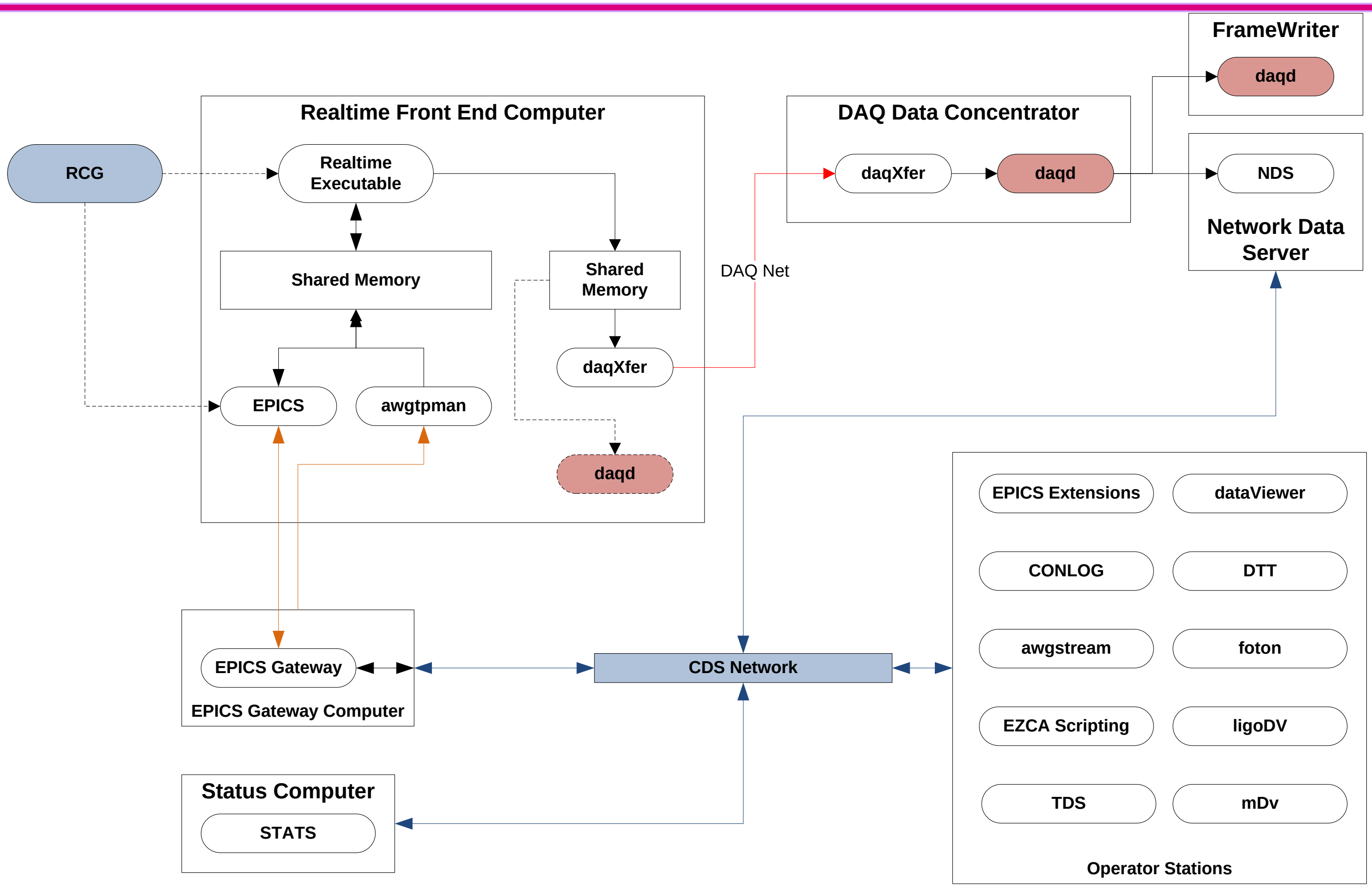
Control & Data System
Hardware Architecture Overview

- Timing derived from GPS
- Front-End Computers
  - Linux real-time OS
  - multi-core, server class
- Fiber-linked PCIe I/O bus with 20-bit ADC/DAC
- Servo loop rates up to 65 kHz
- Synchronous, deterministic operation to within a few microseconds
- “Slow Controls” handled by EtherCAT (Beckhoff) systems



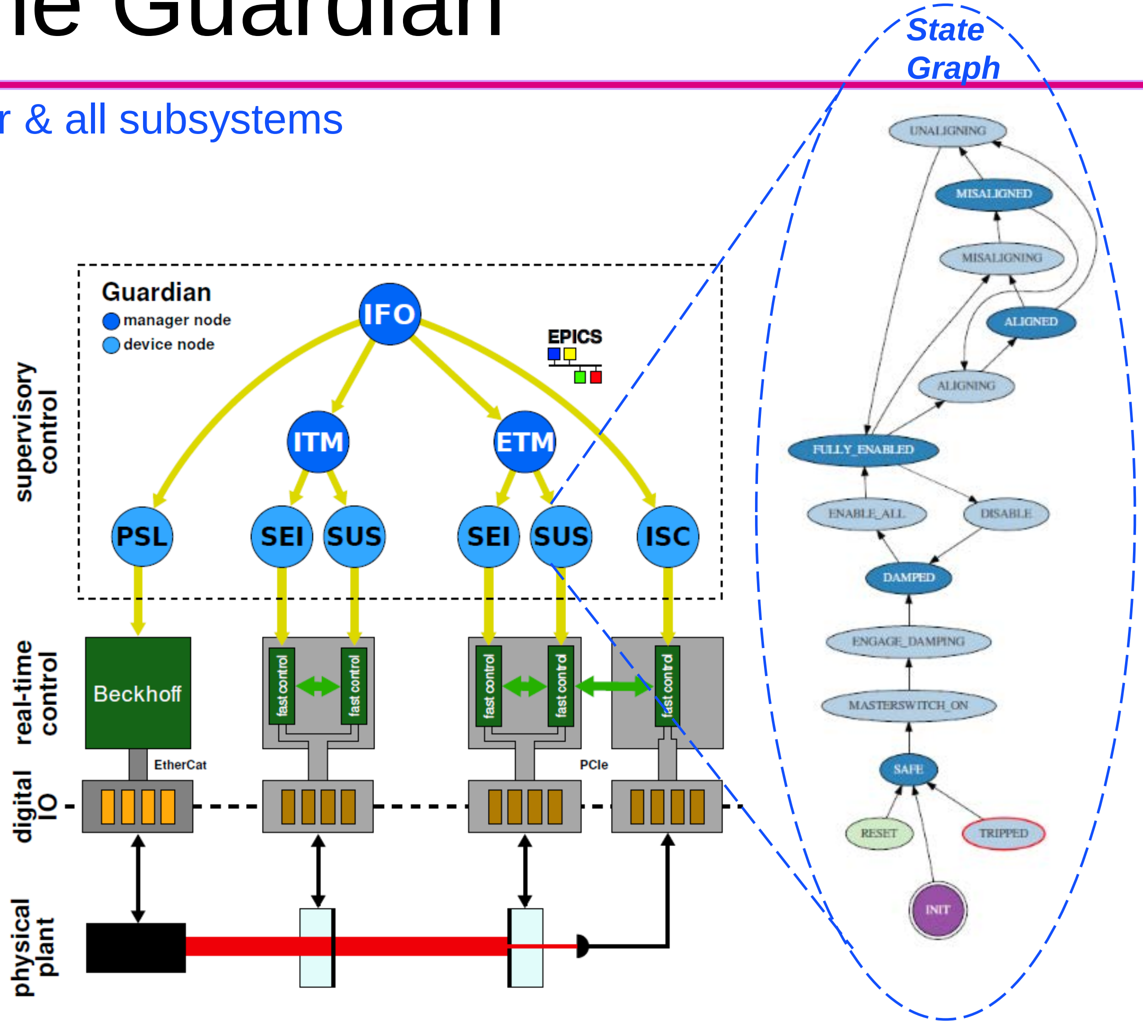
Control & Data System Software Architecture Overview

- Real-Time Code Generator (RCG)
  - Matlab Simulink graphical interface used to sketch control
- EPICS (Experimental Physics and Industrial Control System)
  - Supervisory control
  - Interface for setting ~100k servo system parameters
- Guardian
  - State machine for sequencing



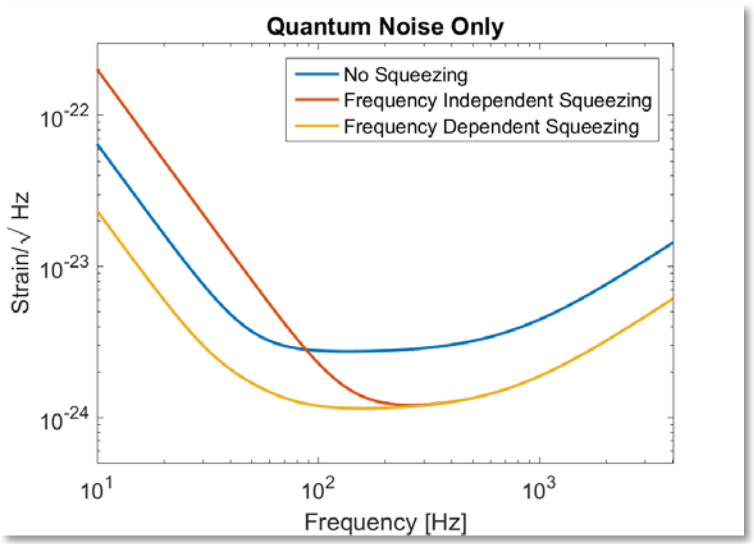
the Guardian

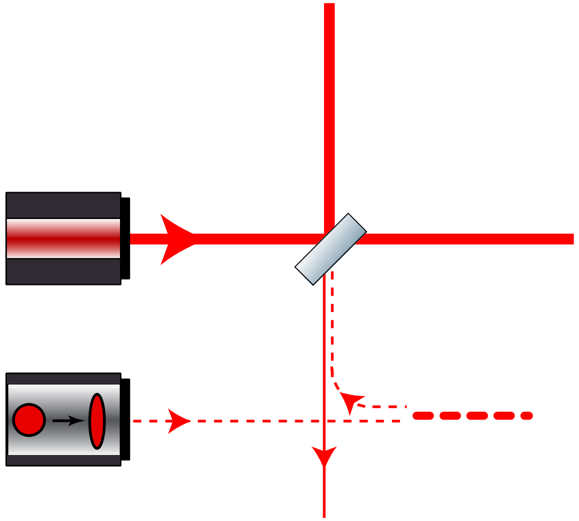
- Robust framework for automation of the interferometer & all subsystems
- Hierarchical, distributed, finite state machine
- Each node executes a state graph for its subsystem
- Supports commissioning & operation modes
- EPICS interface
- Python code

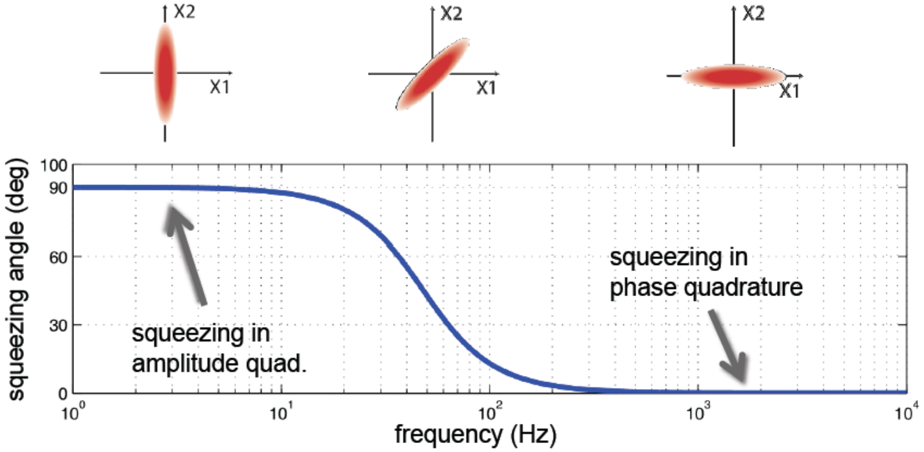


LIGO's Future

- LIGO + Virgo just completed Observing Run O3
  - ~140 MPc BNS range, > 50 events, published catalog soon
- LIGO & Virgo Upgrades leading to Observing Run O4 start in 2022
  - Improved coatings with reduced mechanical loss (lower thermal noise)
  - Frequency dependent squeezing
  - ~190 MPc BNS range
- KAGRA started observing in 2020
- LIGO-India to start observing in ~2025

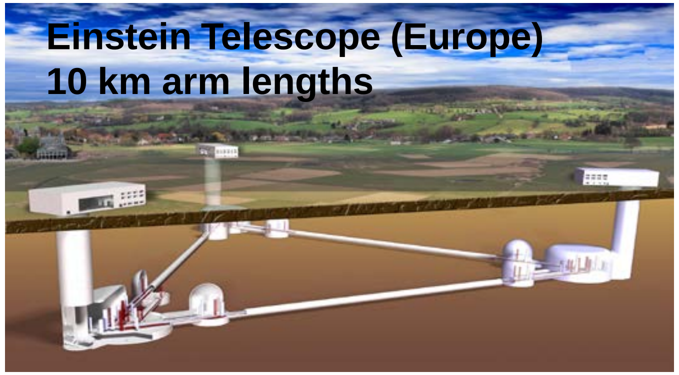


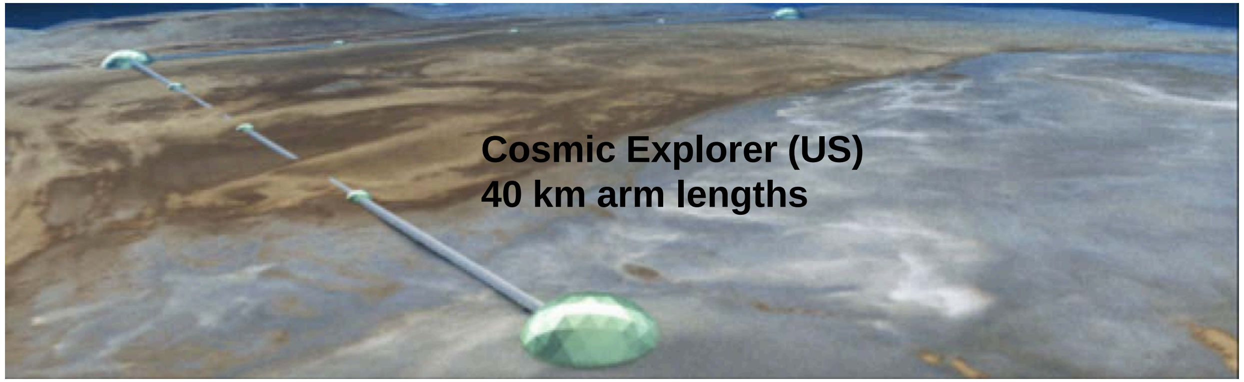


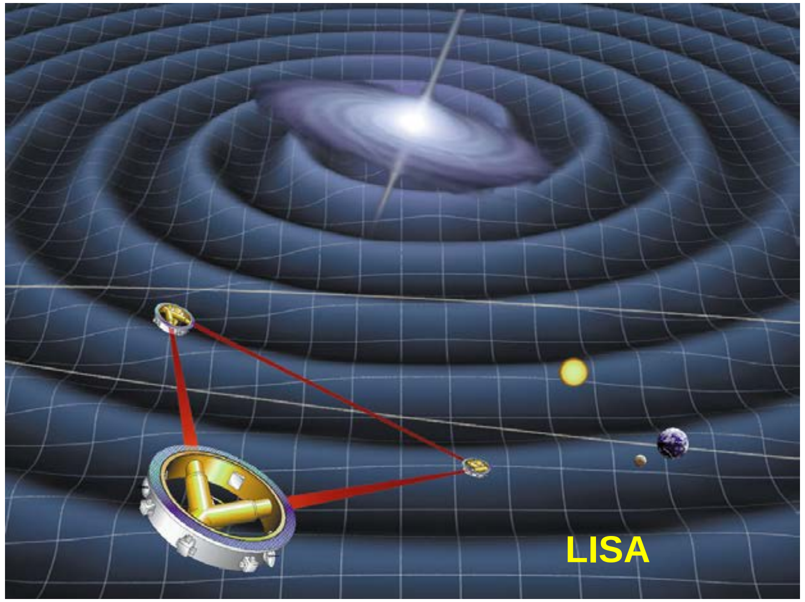


Next (3rd) Generation GW Detectors

- Voyager – at LIGO facilities limit (~10 year timescale)
  - Cryogenic operation (~ 120K)
  - Large (~200 kg) silicon optics
  - 2 micron lasers
- New facilities (~20 year timescale)
  - Cosmic Explorer (US)
    - ~40 km arm lengths
  - Einstein Telescope (Europe)
    - Underground, 10 km arm lengths
- Space Based Detector – LISA
  - NASA & ESA joint effort







Concluding remarks

- Future of Gravitational Wave observation looks promising
- LIGO can benefit from ACC community input/ideas

Short Bibliography & Extra Slides

General instrument overviews:

- J. Aasi, et. al., "Advanced LIGO", Class. and Quantum Grav. 32, (2015) 074001, doi:10.1088/0264-9381/32/7/074001, LIGO-P1400177, http://arxiv.org/abs/1411.4547
- Martynov, D. V., et al., "The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy", Physical Review D 93.11 (2016): 112004. LIGO-P1500260P1500260, doi:0.1103/PhysRevD.93.112004, https://arxiv.org/abs/1604.00439
- F. Matichard, et. al., “An overview of the control layers in LIGO 4km interferometers”, LIGO-P1600104, Proceedings of the ASPE conference 2016, see also keynote presentation LIGO-G1600930

Seismic isolation system (SEI) control overview:

- F. Matichard, et al. "Seismic isolation of Advanced LIGO: Review of strategy, instrumentation and performance", Classical and Quantum Gravity 32.18 (2015): 185003, doi:10.1088/0264-9381/32/18/185003. LIGO-P1200040, http://arxiv.org/abs/1502.06300

Suspension system (SUS) control overview:

- B. Shapiro, et. al., "Modal Damping of a Quadruple Pendulum for Advanced Gravitational Wave Detectors", American Control Conference, Montreal, 2012,DOI: 10.1109/ACC.2012.6315185 , LIGO-P1100102, http://acc2012.a2c2.org/

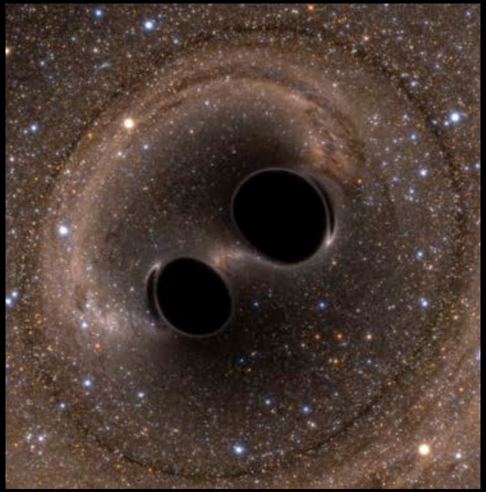
Pre-Stabilized Laser (PSL) control overview:

- P. Kwee, et.al., "Stabilized high-power laser system for the gravitational wave detector advanced LIGO," Opt. Express 20, 10617-10634 (2012), https://doi.org/10.1364/OE.20.010617, LIGO-P

Interferometer Sensing and Control (ISC) overview:

- K. Izumi, D. Sigg, “Advanced LIGO: Length Sensing and Control in a Dual-recycled Interferometric Gravitational-wave Antenna”, LIGO-P1500277, Class. Quantum Grav.34 015001 (2016), https://doi.org/10.1088/0264-9381/34/1/015001
- K. Dooley, et. al., “Angular control of optical cavities in a radiation pressure dominated regime: the Enhanced LIGO case”, LIGO-P1100089, https://arxiv.org/abs/1310.3662, JOSA A, Vol. 30, Issue 12, pp. 2618-2626 (2013), https://doi.org/10.1364/JOSAA.30.002618

Catalog of Possible Astrophysical Gravitational-Wave Sources



Credit: Bohn, Hébert, Throwe, SXS

Coalescing Binary Systems

- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star

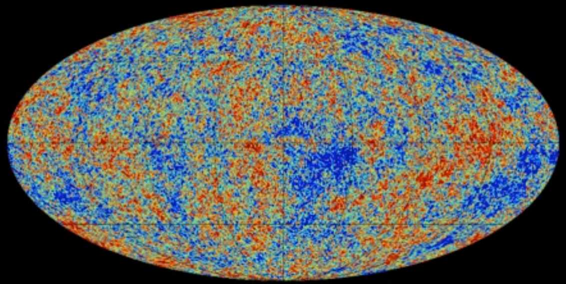
(modeled waveform)

Credit: Chandra X-ray Observatory

Transient 'Burst' Sources

- asymmetric core collapse supernovae
- cosmic strings
- ???

(Unmodeled waveform)

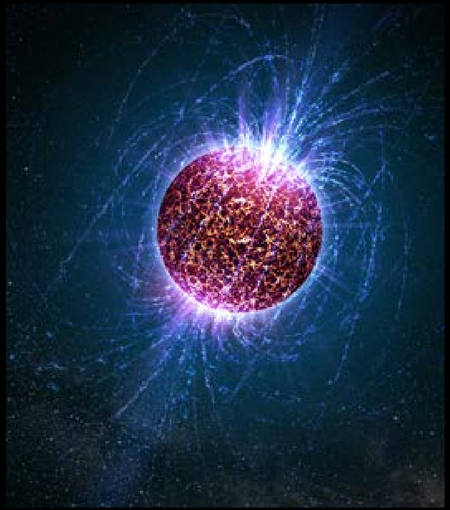


Credit: Planck Collaboration

Stochastic Background

- residue of the Big Bang
- incoherent sum of unresolved 'point' sources

(stochastic, incoherent noise background)



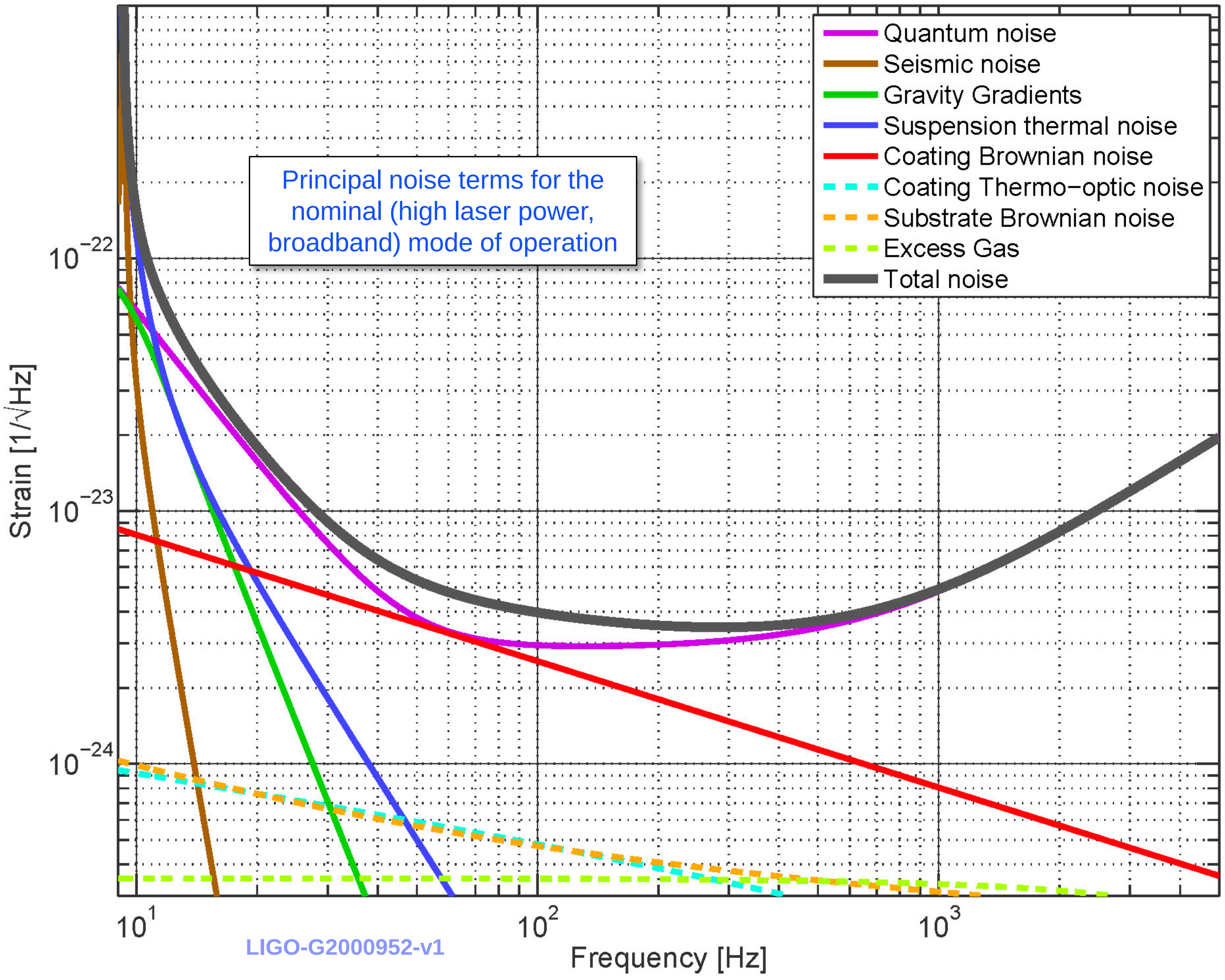
Credit: Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars

(monotone waveform)

Advanced LIGO Design Sensitivity



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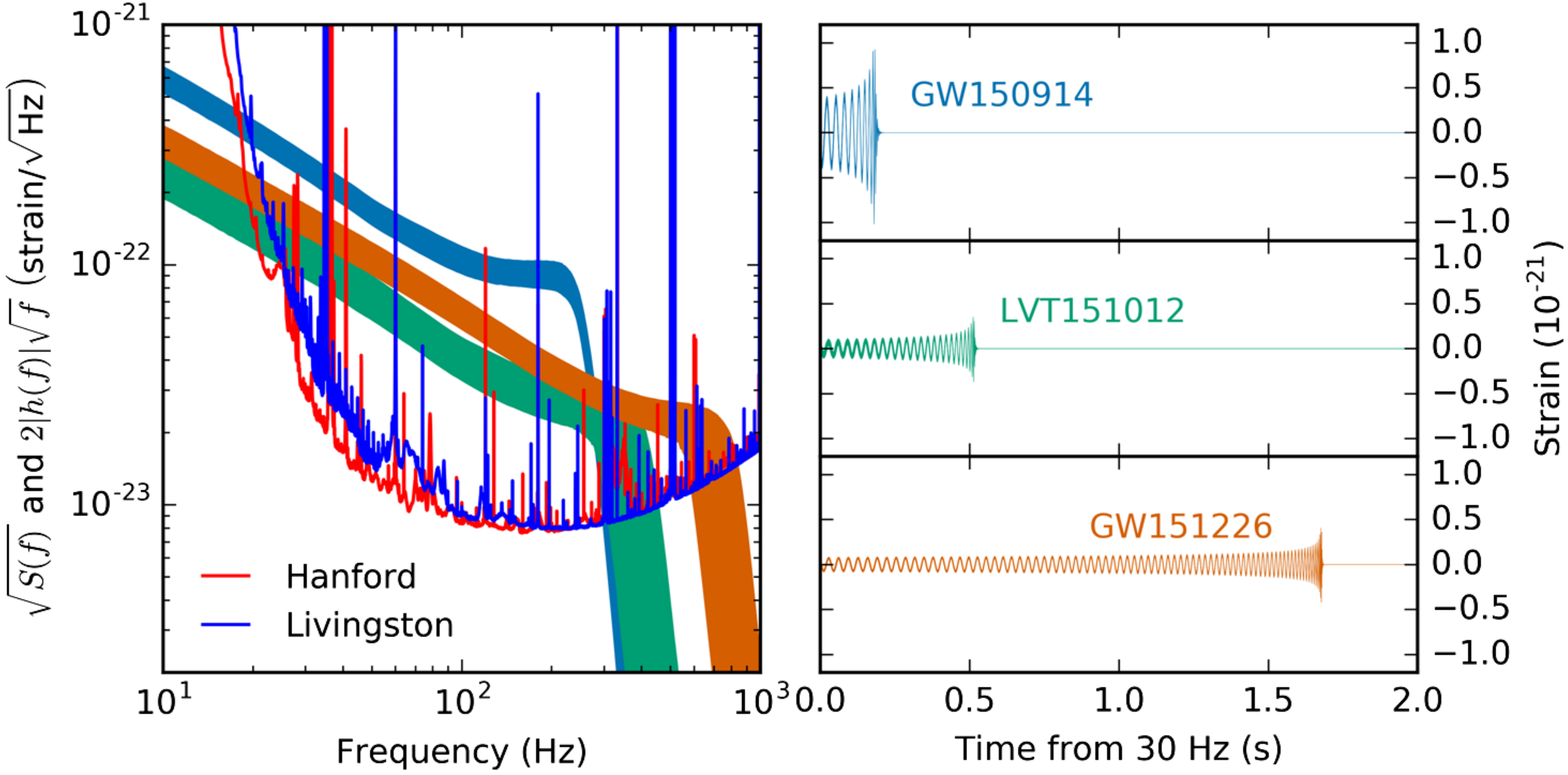
Inspiral Transient "Chirps" Sweep through our Sensing Band

Examples from the first observing run (O1)

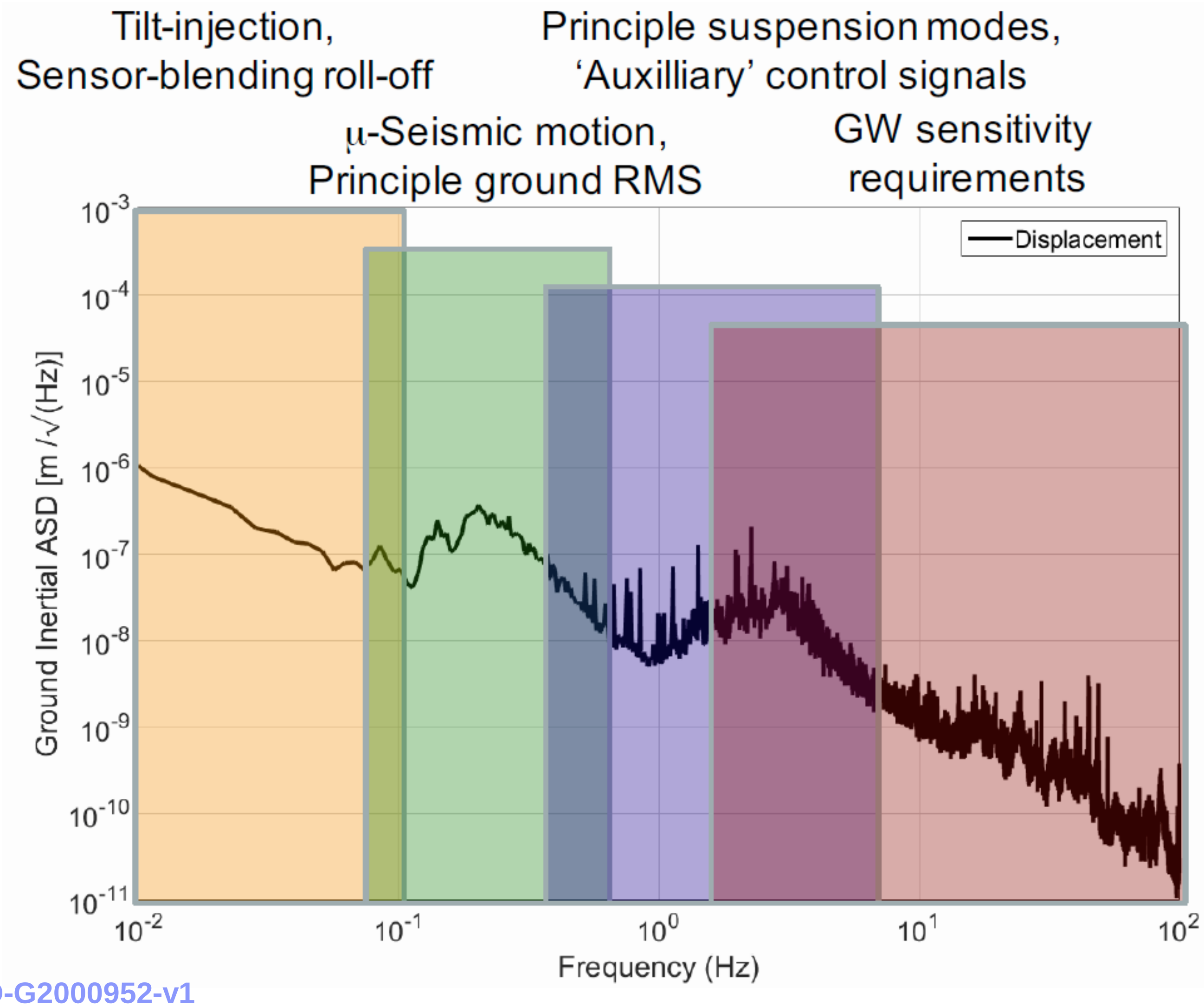


Important seismic frequency region: 10mHz – 100Hz

- Ground Motion at 10 [Hz] ~ 10^{-9} [m/rtHz]

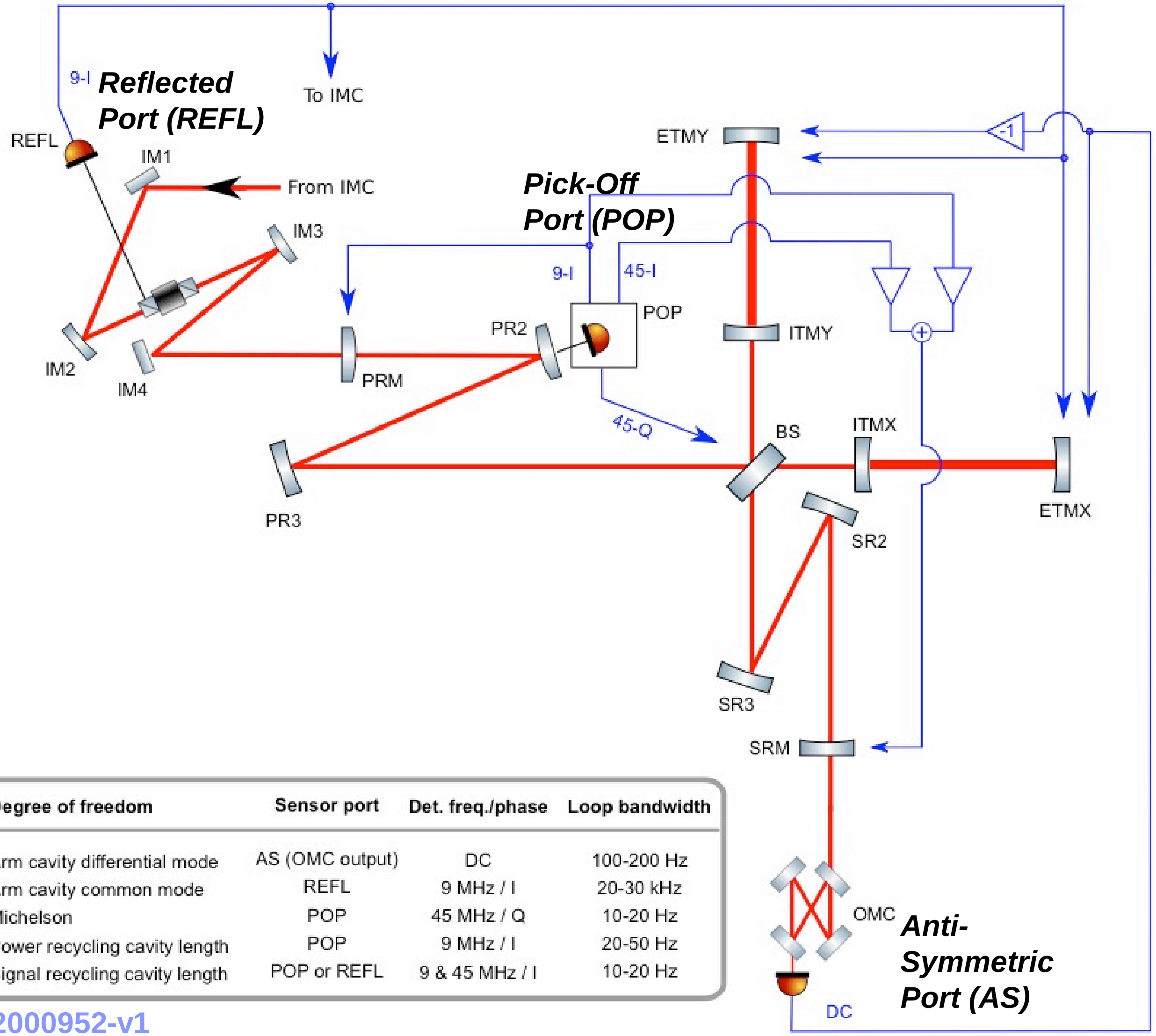
$$\Delta L = h\,L \sim 10^{-19}\,m\,/\,Hz^{1/2}$$

- Need 10 orders of magnitude reduction in seismic motion at 10 Hz



Length Controls

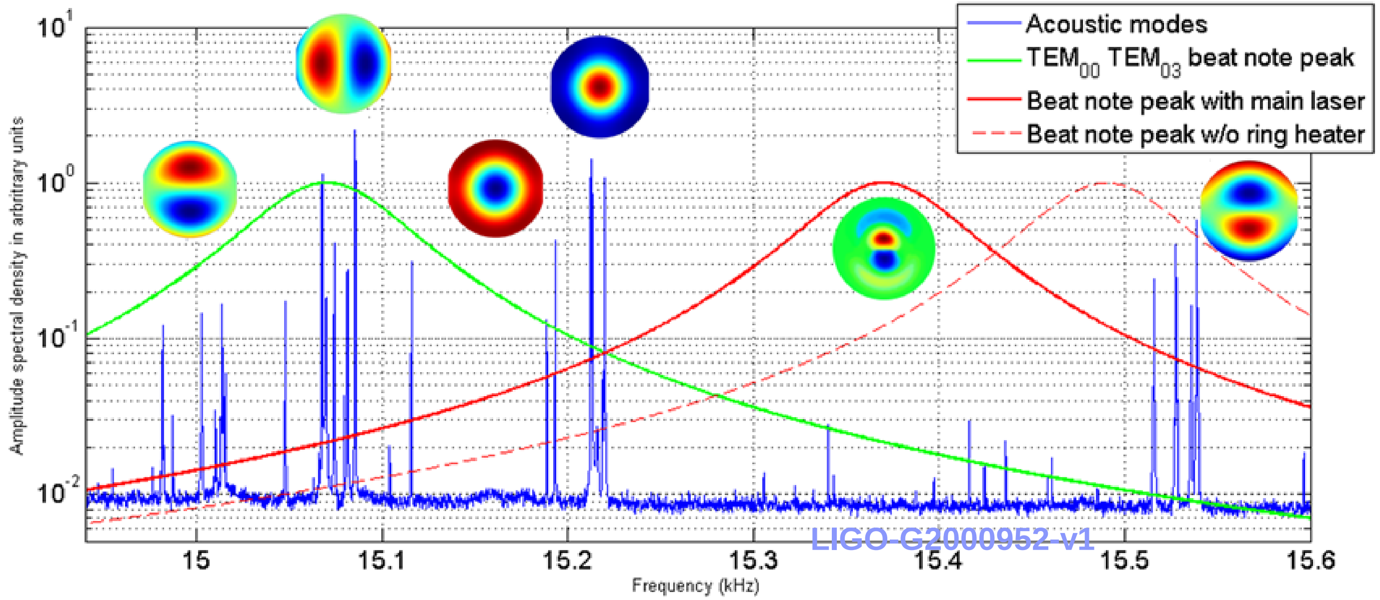
- RF modulation sidebands (9 MHz and 45 MHz)
  - Resonant in recycling cavities, not arm cavities
  - Michelson contains a small Schnupp asymmetry (8 cm) so that RF sideband is transmitted to the antisymmetric port even when carrier is on a dark fringe
  - Demodulated signals used for digital feedback control at 16k samples/sec
  - CARM feedback to the laser frequency is an analog feedback path
- Differential Arm (DARM) signal
  - Accomplished by intentional differential offset of the arm cavities by ~10 pm
    (Homodyne or DC readout technique)



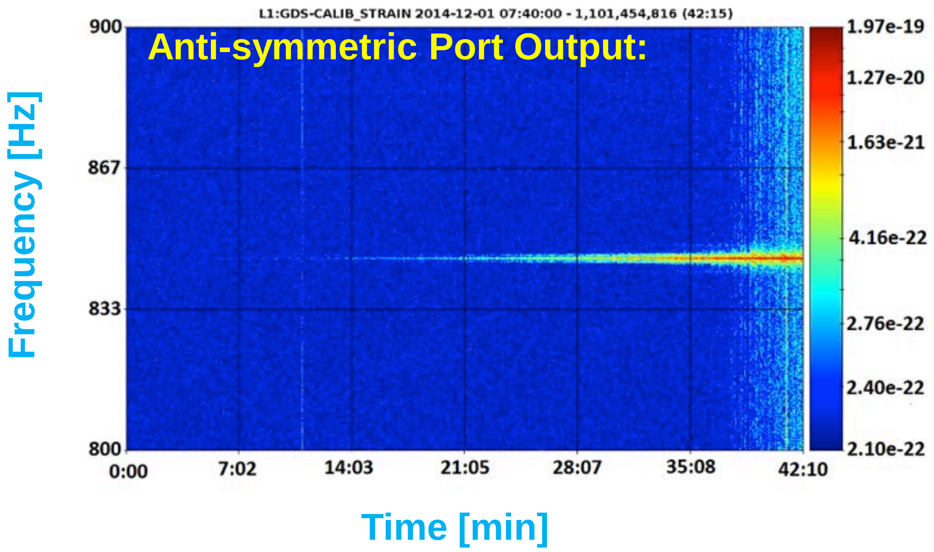
Degree of freedom	Sensor port	Det. freq./phase	Loop bandwidth
Arm cavity differential mode	AS (OMC output)	DC	100-200 Hz
Arm cavity common mode	REFL	9 MHz / I	20-30 kHz
Michelson	POP	45 MHz / Q	10-20 Hz
Power recycling cavity length	POP	9 MHz / I	20-50 Hz
Signal recycling cavity length	POP or REFL	9 & 45 MHz / I	10-20 Hz

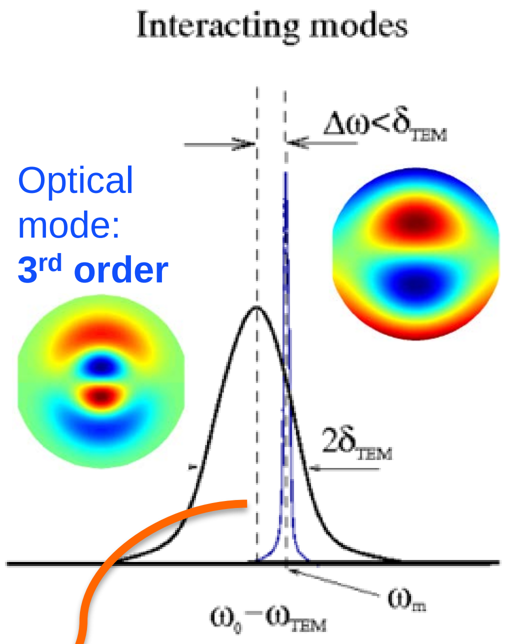
Parametric Instabilities

- Radiation pressure in the Fabry-Perot arm cavities can result in instability
  - Feedback control
- Overlap of high order optical modes & test mass acoustic modes results in Parametric Instabilities
  - Shift off resonance with thermal tuning (ring heaters)
  - Damp with electro-static actuators
  - More recently controlled with passive, broadly tuned, piezoelectric dampers bonded to the test mass optics (without spoiling high mechanical quality factors)

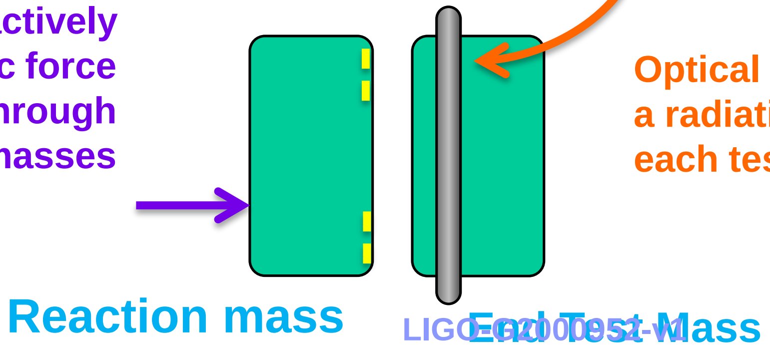


Controlling Parametric Instabilities

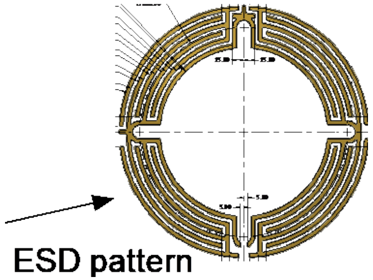




Instabilities can be actively damped with electro-static force feedback applied through reaction masses

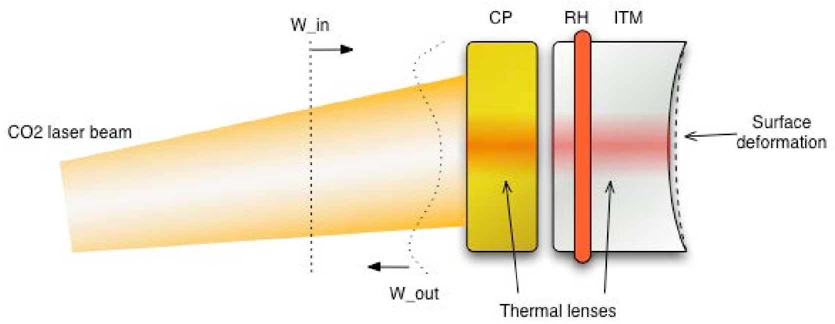


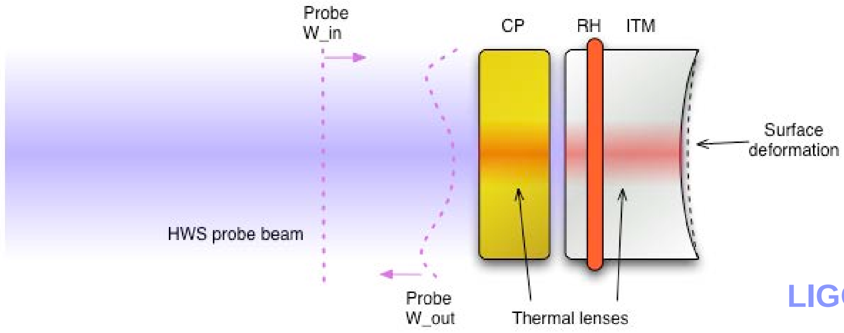
Optical mode can be shifted with a radiative heater that surrounds each test mass

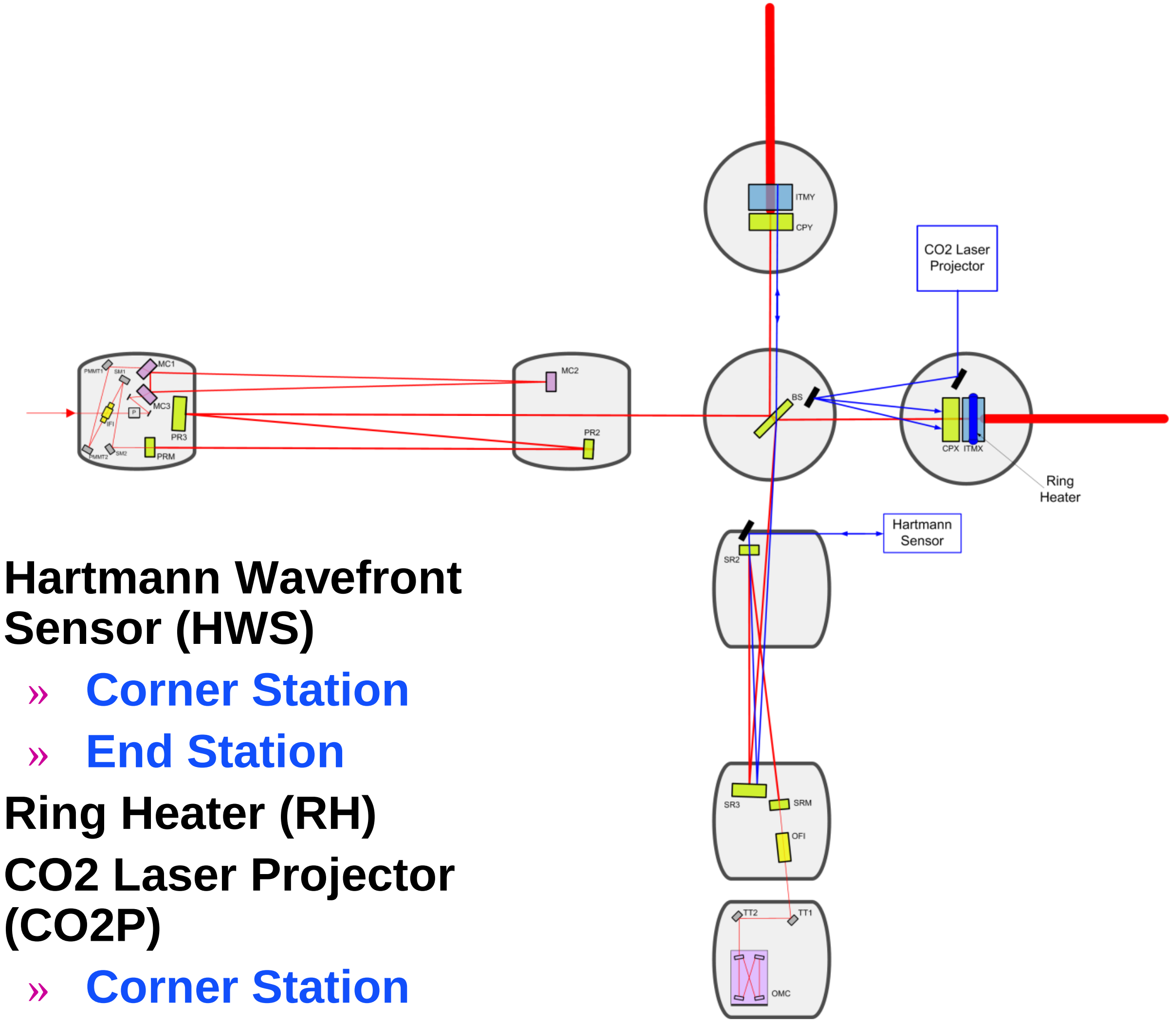


Thermal Compensation System (TCS)

- **Measure & Control thermal lens in the Input Test Mass**
  - Maintain thermal aberrations to within $\lambda/50$
- **Control the Radius Of Curvature (ROC) in the Input & End Test Masses**
  - Provide 35 km ROC range



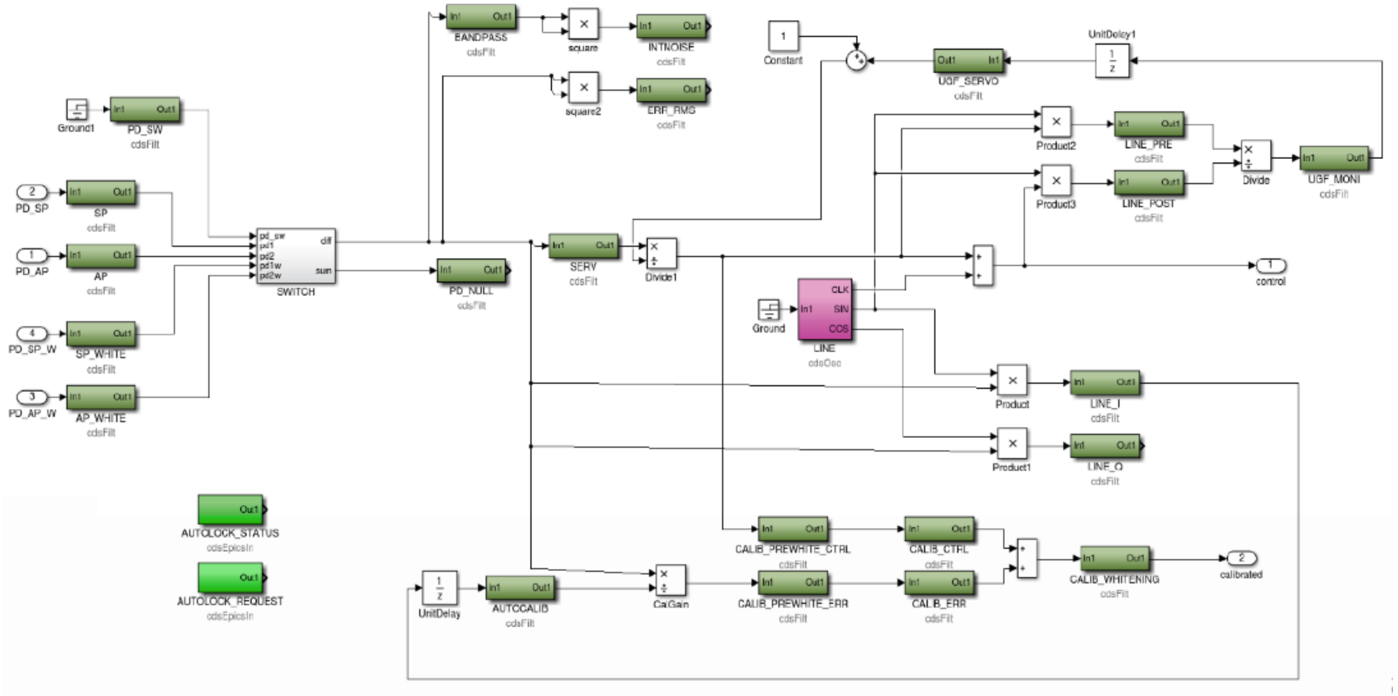




- **Hartmann Wavefront Sensor (HWS)**
  - Corner Station
  - End Station
- **Ring Heater (RH)**
- **CO2 Laser Projector (CO2P)**
  - Corner Station

Real-time digital control

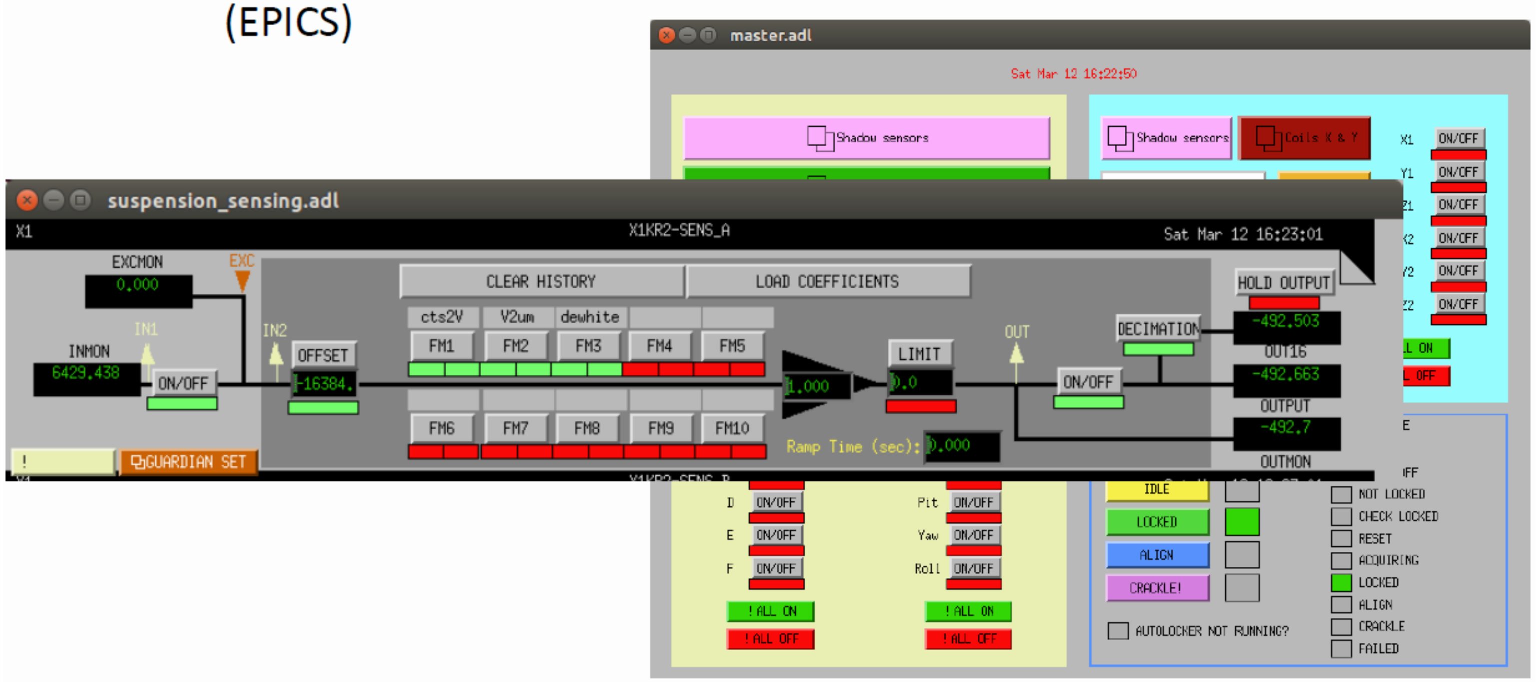
- Matlab/Simulink used as a graphical interface to sketch control system using standard blocks
- Generates real-time code to run on linux front-end machine

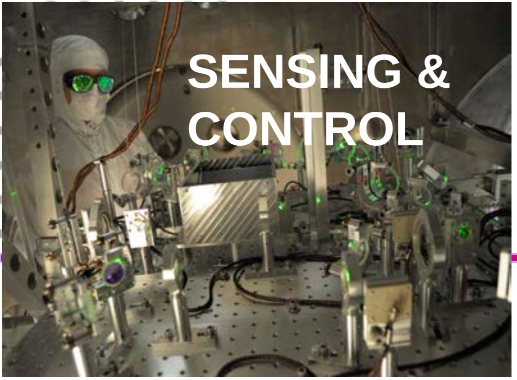


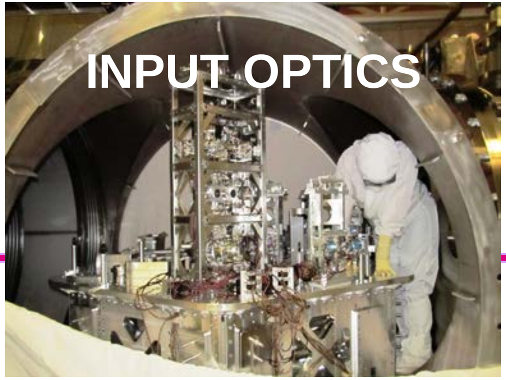
Real-time digital control

- Interface to the front-end, real-time "models" is via EPICS
- Change filters, gains, parameters
- Set Point Definition/Monitor software automates configuration control for the ~100k servo system parameters

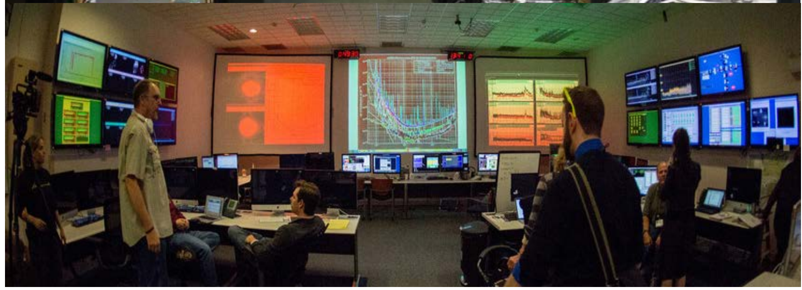
(EPICS)







LIGO ENGINEERING



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