Marco Drago marco.drago@aei.mpg.de via sympa.ligo.org Mon, Sep 14, 2015, 3:54 AM Reply to all

to burst, cbc@ligo.org, The, Calibration, dac, <burst@ligo.org>, <detchar@sympa.ligo.org>, losc-devel, lsc-all@ligo.org

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

The characterization of ground-based gravitational-wave detector data

Marco Cavaglia
Institute of Multi-messenger Astrophysics and Cosmology
Missouri University of Science and Technology

Mathematical and Computational Challenges in the Era of Gravitational Wave Astronomy
SEPTEMBER 13 - DECEMBER 17, 2021

The Meaning of Gravitational-wave Astronomy

~~The characterization of ground-based gravitational-wave detector data~~

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Mathematical and Computational Challenges in the Era of Gravitational Wave Astronomy

SEPTEMBER 13 - DECEMBER 17, 2021

GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run

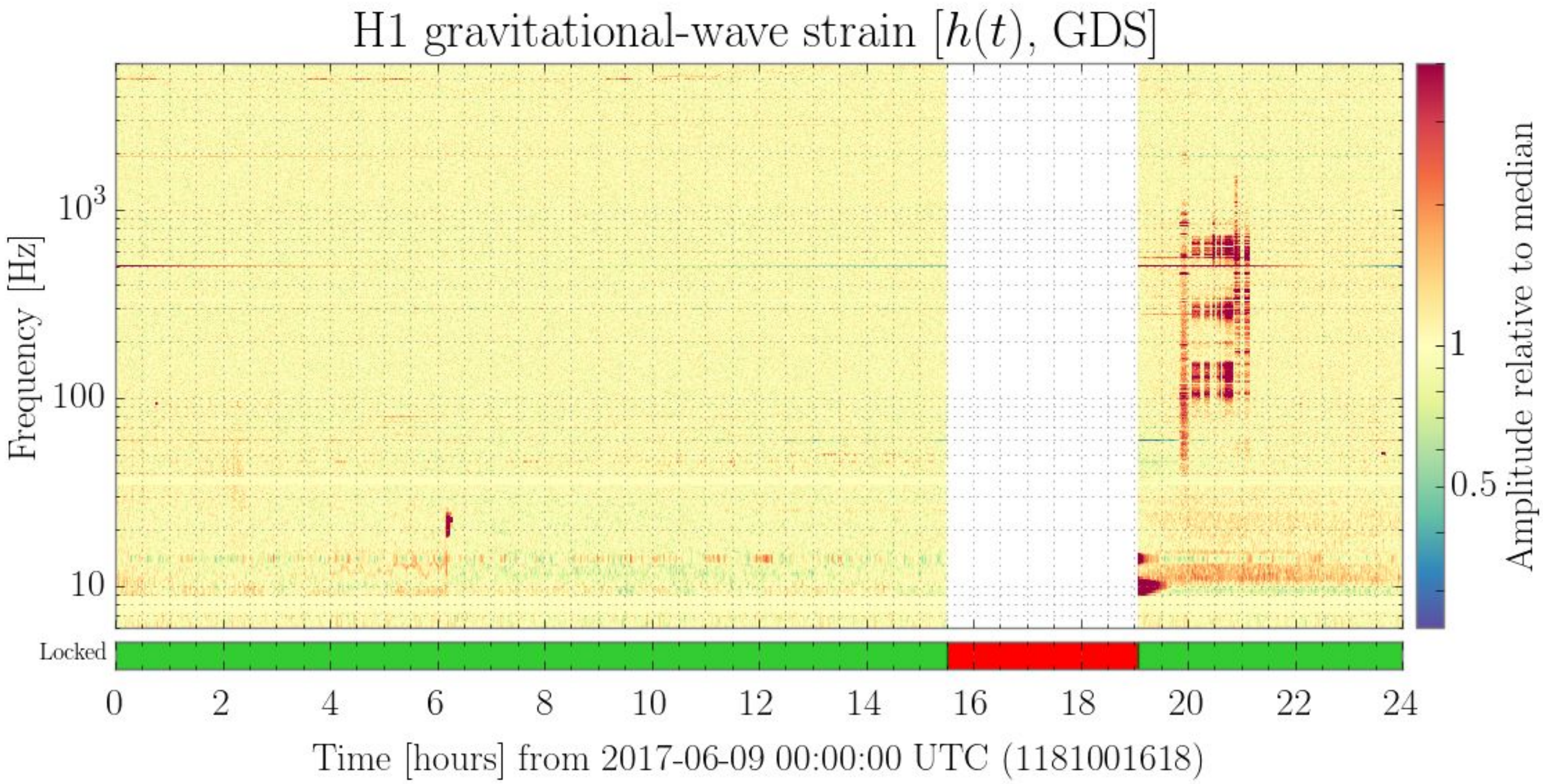
R. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

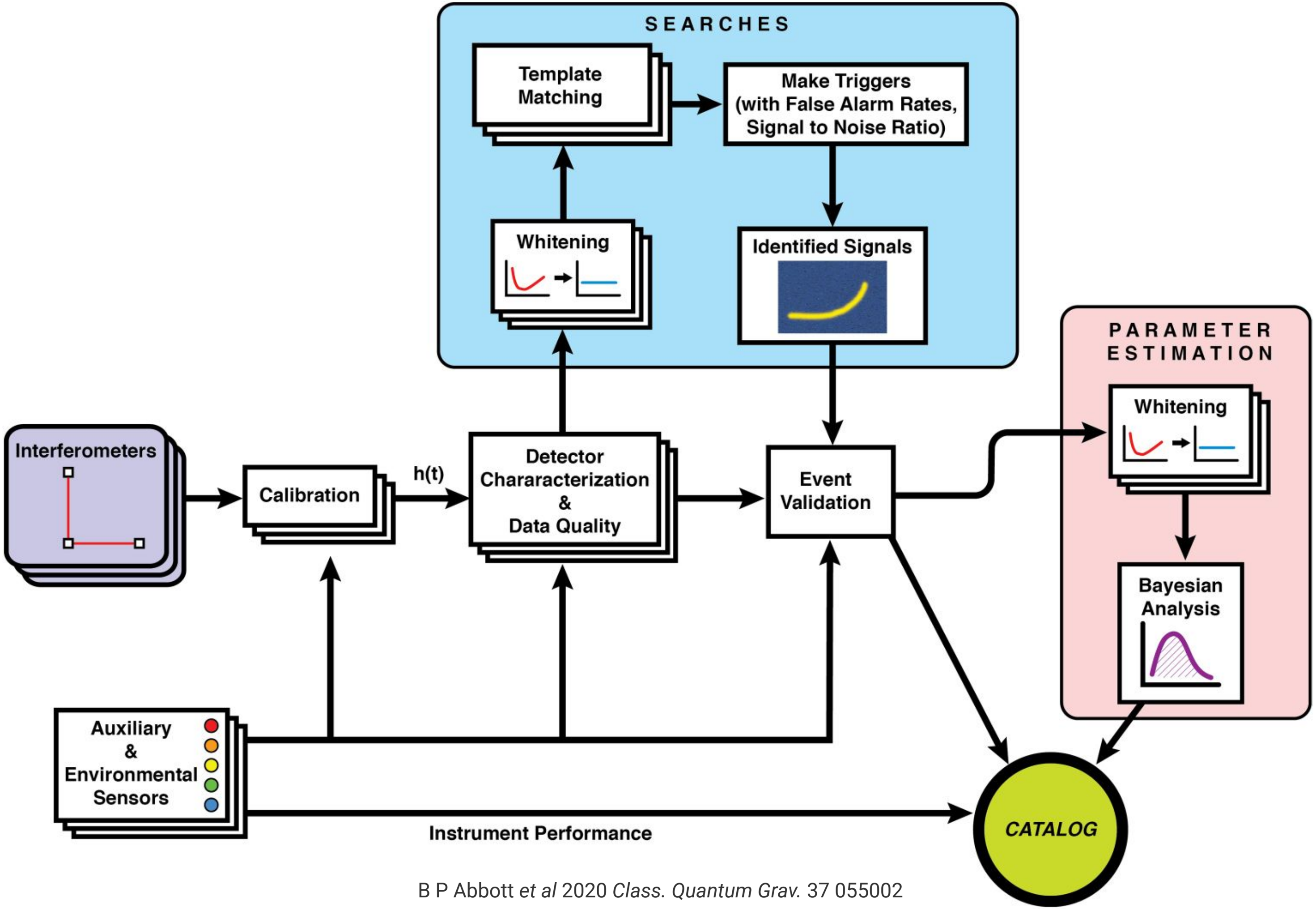
(Received 30 October 2020; revised 23 February 2021; accepted 20 April 2021; published 9 June 2021; corrected 1 September 2021)

We report on gravitational-wave discoveries from compact binary coalescences detected by Advanced LIGO and Advanced Virgo in the first half of the third observing run (O3a) between 1 April 2019 15:00 UTC and 1 October 2019 15:00 UTC. By imposing a false-alarm-rate threshold of two per year in each of the four search pipelines that constitute our search, we present 39 candidate gravitational-wave events. At this threshold, we expect a contamination fraction of less than 10%. Of these, 26 candidate events were reported previously in near-real time through gamma-ray coordinates network notices and circulars; 13 are reported here for the first time. The catalog contains events whose sources are black hole binary mergers up to a redshift of approximately 0.8, as well as events whose components cannot be unambiguously identified as black holes or neutron stars. For the latter group, we are unable to determine the nature based on estimates of the component masses and spins from gravitational-wave data alone. The range of candidate event masses which are unambiguously identified as binary black holes (both objects $\geq 3\ M_\odot$) is increased compared to GWTC-1, with total masses from approximately $14\ M_\odot$ for GW190924_021846 to approximately $150\ M_\odot$ for GW190521. For the first time, this catalog includes binary systems with significantly asymmetric mass ratios, which had not been observed in data taken before April 2019. We also find that 11 of the 39 events detected since April 2019 have positive effective inspiral spins under our default prior (at 90% credibility), while none exhibit negative effective inspiral spin. Given the increased sensitivity of Advanced LIGO and Advanced Virgo, the detection of 39 candidate events in approximately 26 weeks of data (approximately 1.5 per week) is consistent with GWTC-1.

DOI: 10.1103/PhysRevX.11.021053 Subject Areas: Gravitation

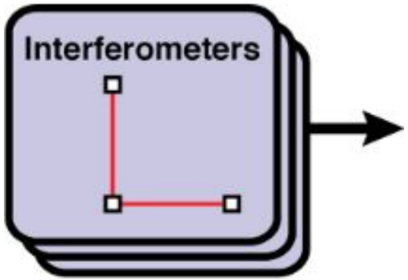


H1 gravitational-wave strain [h(t), GDS]
Frequency [Hz]
10³
100
10
Amplitude relative to median
1
0.5
Locked
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [hours] from 2017-06-09 00:00:00 UTC (1181001618)



B P Abbott *et al* 2020 *Class. Quantum Grav.* 37 055002

Part I: The Miracle of LIGO(*)

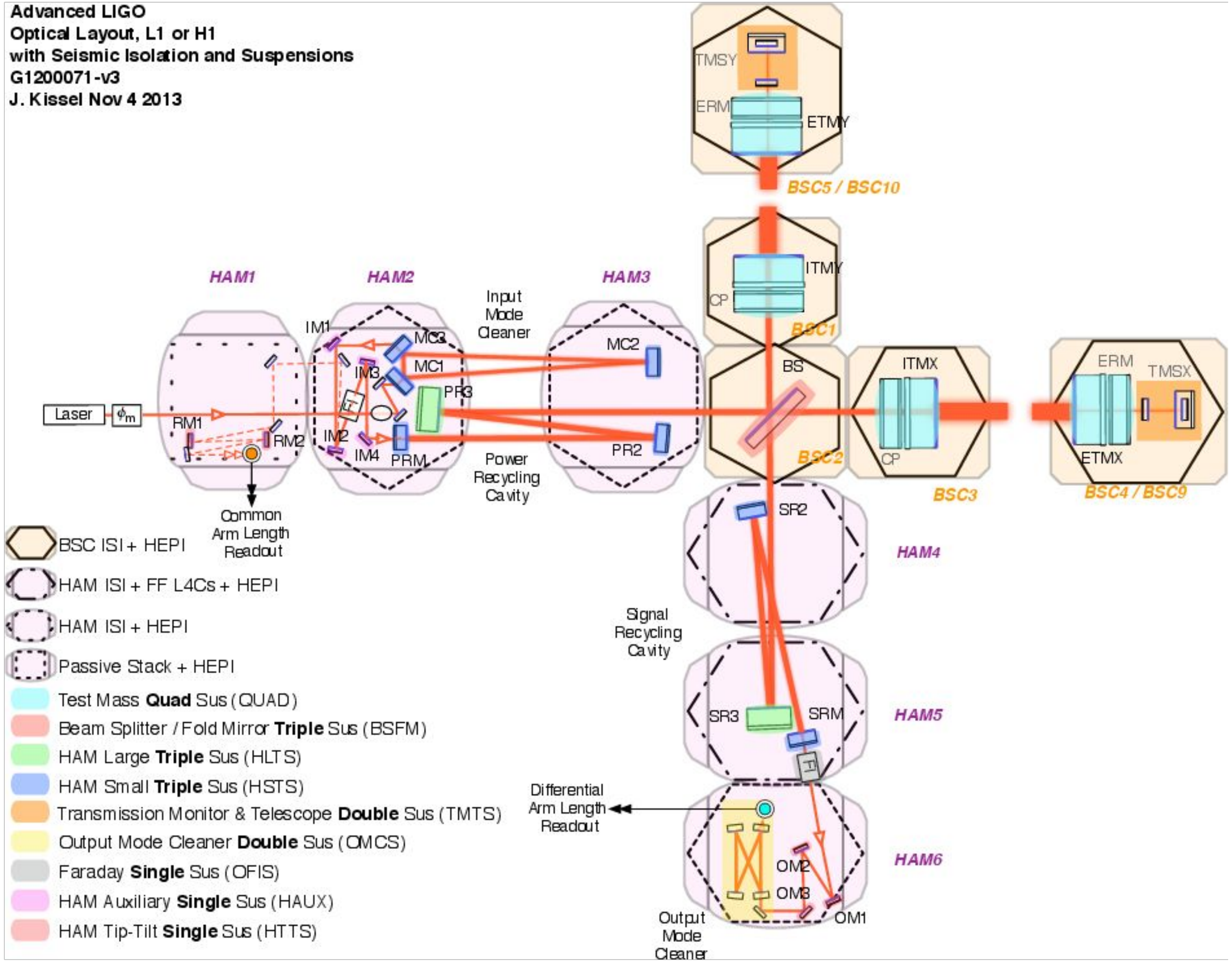


(*)Disclaimer: I will mostly focus on LIGO because I am more familiar with the LIGO detectors than Virgo, but apart from technical differences in the instruments, most of what I will say also applies to Virgo. All astrophysical searches and data quality studies are joint LIGO-Virgo endeavors.

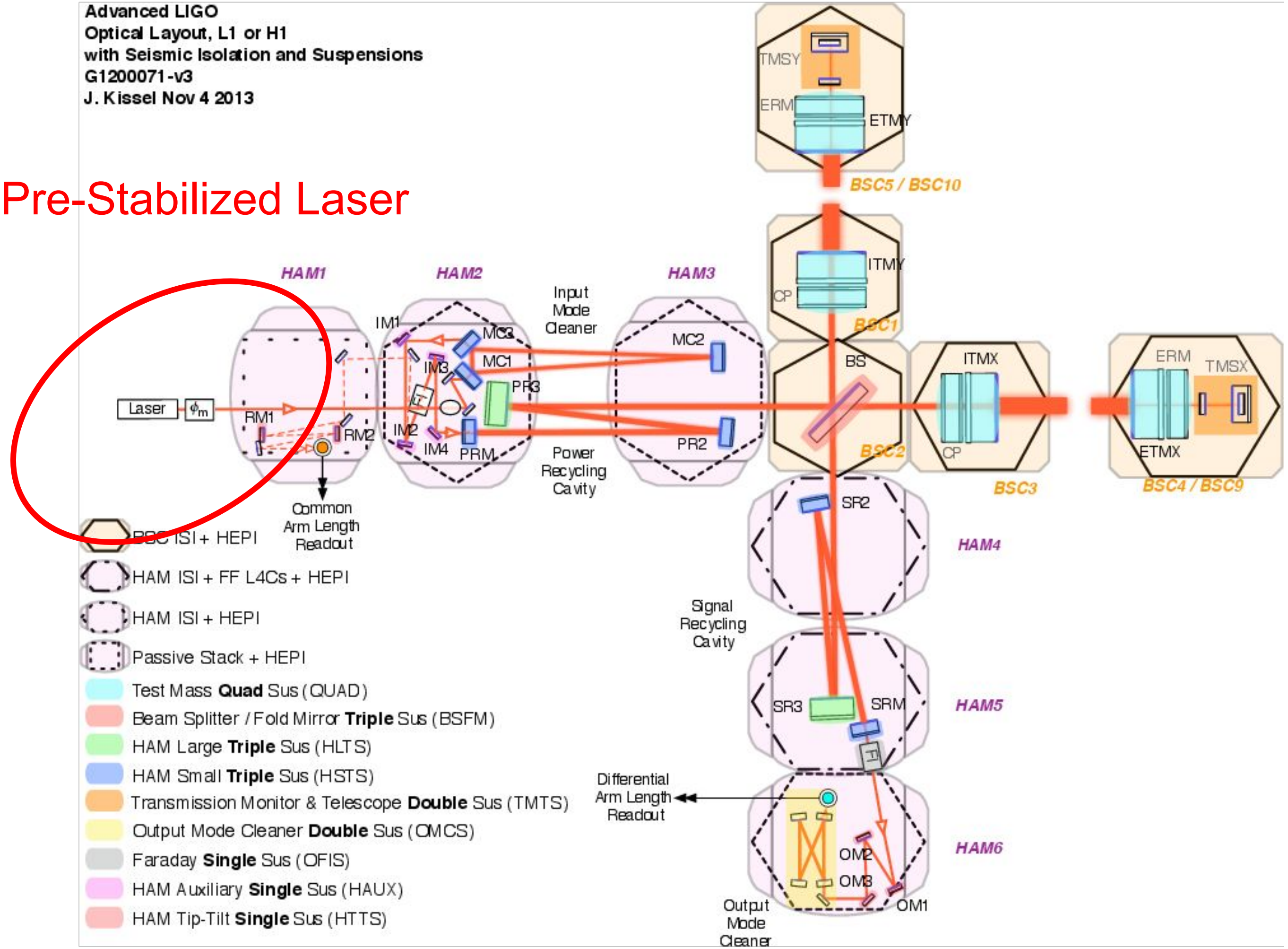
The Animated Tour of LIGO

https://vimeo.com/238065715

K. Staats, L. Cominsky, L. Buono, J. Straus, K. McLin, J. McIver, M. Landry, C. Torrie, E. Sanchez, D. Coyne; Sonoma State Univ NSF 1404215

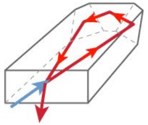

Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013
TMSY
ERM
ETMY
BSC5 / BSC10
ITMY
CP
BSC1
HAM1
HAM2
HAM3
Input Mode Cleaner
IM1
MC3
MC1
MC2
IM3
PR3
Laser
ϕ_m
RM1
RM2
IM2
IM4
PRM
PR2
Power Recycling Cavity
BS
BSC2
ITMX
CP
BSC3
ERM
TMSX
ETMX
BSC4 / BSC9
Common Arm Length Readout
SR2
HAM4
Signal Recycling Cavity
SR3
SRM
HAM5
FI
Differential Arm Length Readout
OM2
OM3
OM1
HAM6
Output Mode Cleaner
BSC ISI + HEPI
HAM ISI + FF L4Cs + HEPI
HAM ISI + HEPI
Passive Stack + HEPI
Test 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)
Faraday **Single** Sus (OFIS)
HAM Auxiliary **Single** Sus (HAUX)
HAM Tip-Tilt **Single** Sus (HTTS)

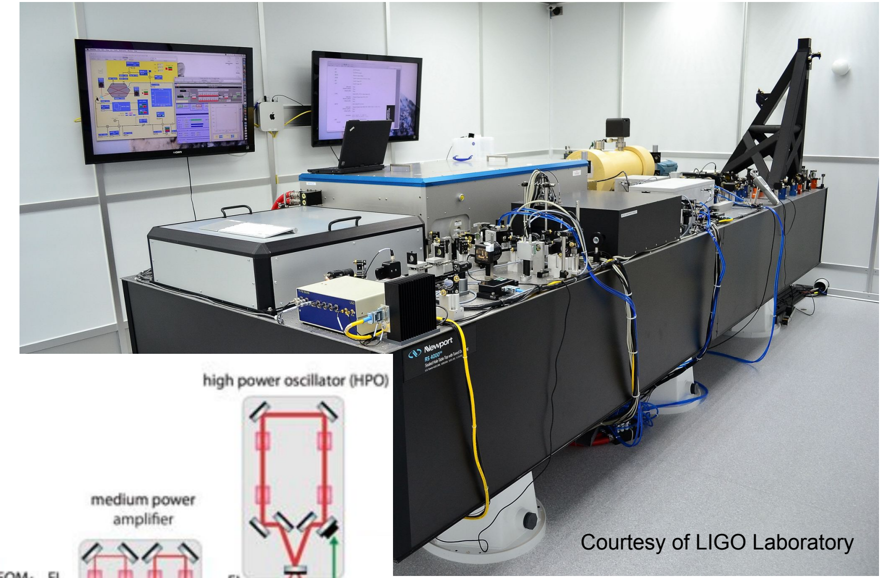
Pre-Stabilized Laser



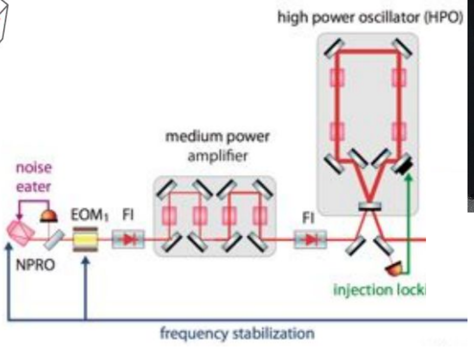
Pre-Stabilized Laser

- Multi-stage 1064 nm Nd:YAG laser that can supply up to 180 W at the laser system output.
- In O3a the LIGO Hanford detector operated with 37 W of input power and the Livingston detector with 40 W.
- The pre-stabilized laser (PSL) system consists of a laser light source and control systems that stabilize it in frequency, beam direction, and intensity.
- Developed and supplied by the Max Planck Albert Einstein Institute in collaboration with Laser Zentrum Hannover e.V.
- Three stages pumped by laser diodes:
  - Non-planar ring-oscillator (NPRO)
  - Medium power amplifier that boosts the NPRO power to 35 W
  - Injection-locked ring oscillator with a maximum output power of about 220 W.



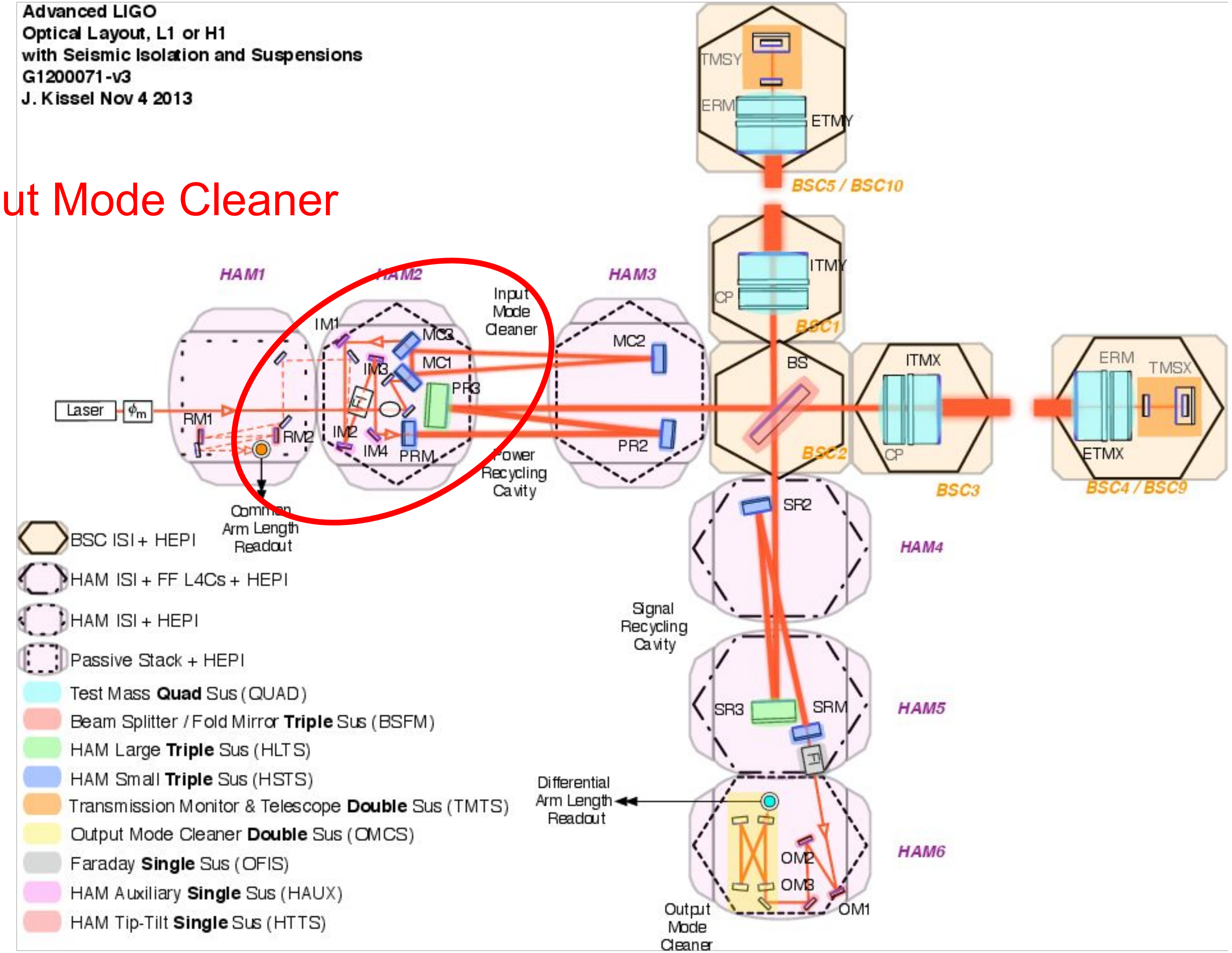


Courtesy of LIGO Laboratory



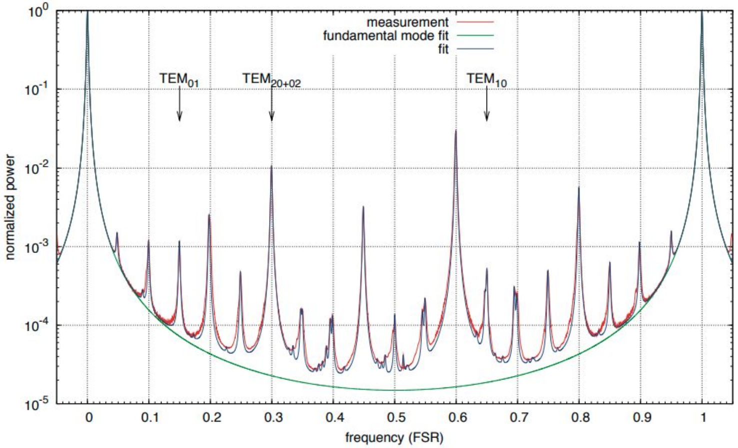
The LIGO Scientific Collaboration (J. Aasi et al), *Advanced LIGO*, Class. Quant. Grav. 32 (2015) 074001
The LIGO Scientific Collaboration and the Virgo Collaboration, *GW150914: The Advanced LIGO Detectors in the Era of First Discoveries*, Phys. Rev. Lett. 116, 131103 (2016)

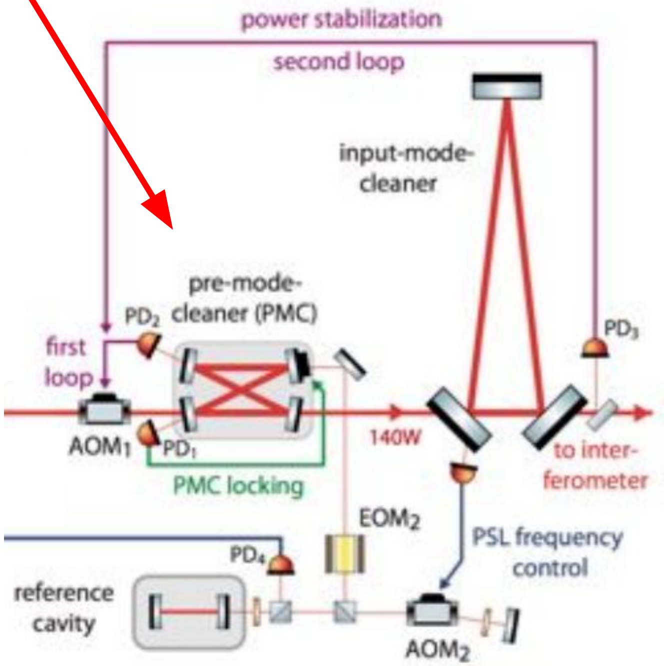
Input Mode Cleaner



Pre-Mode Cleaner

- The source laser is first passed through the pre-mode cleaner (PMC).
- The PMC is a bowtie cavity (2m round trip length) designed to strip higher-order modes from the beam, reduce beam jitter and provide low-pass filtering for RF intensity fluctuations
- Light is then transmitted to the Input Mode Cleaner.





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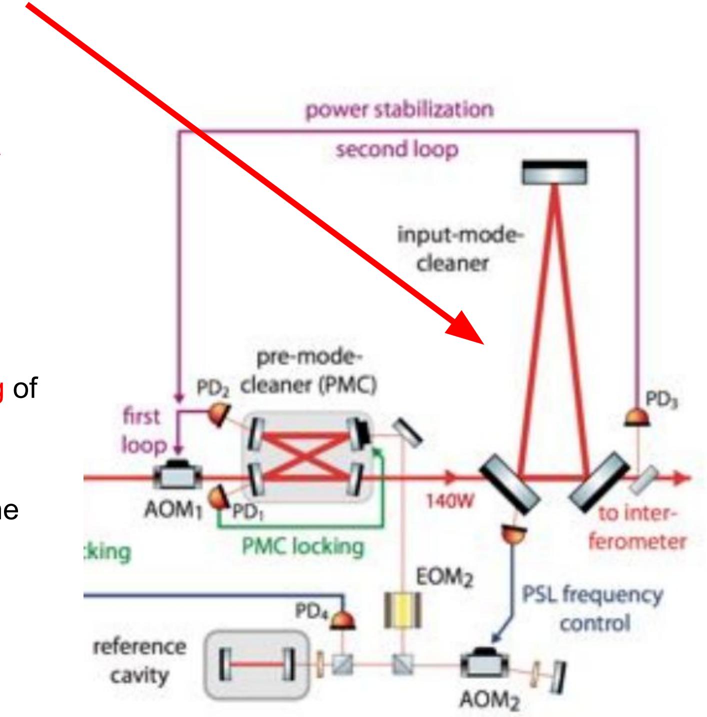
Input Mode Cleaner

- The IMC stabilizes the PSL beam in position and mode content and provides a high-quality laser frequency reference.
- The IMC is a three-mirror ring cavity used in transmission. Each mirror is suspended in a triple pendulum suspension to provide vibration isolation and acceptable thermal noise.
- IMC finesse: 500. Round trip length: 32.9 m. Linewidth: 18 kHz.
- Phase modulation sidebands are used for reflection locking and global sensing of the interferometer (45 MHz) and for sensing of the IMC (24 MHz)
- An in-vacuum Faraday Isolator extracts the beam reflected from the interferometer and prevents this beam from creating parasitic interference in the input chain.
- The IMC output beam is matched to the interferometer mode with a targeted efficiency above 95%.
- This mode matching is accomplished with two curved mirrors, in combination with two flat mirrors used for beam routing. All reflective optics are mounted in single stage suspensions for vibration isolation with actuators for remote steering capability.



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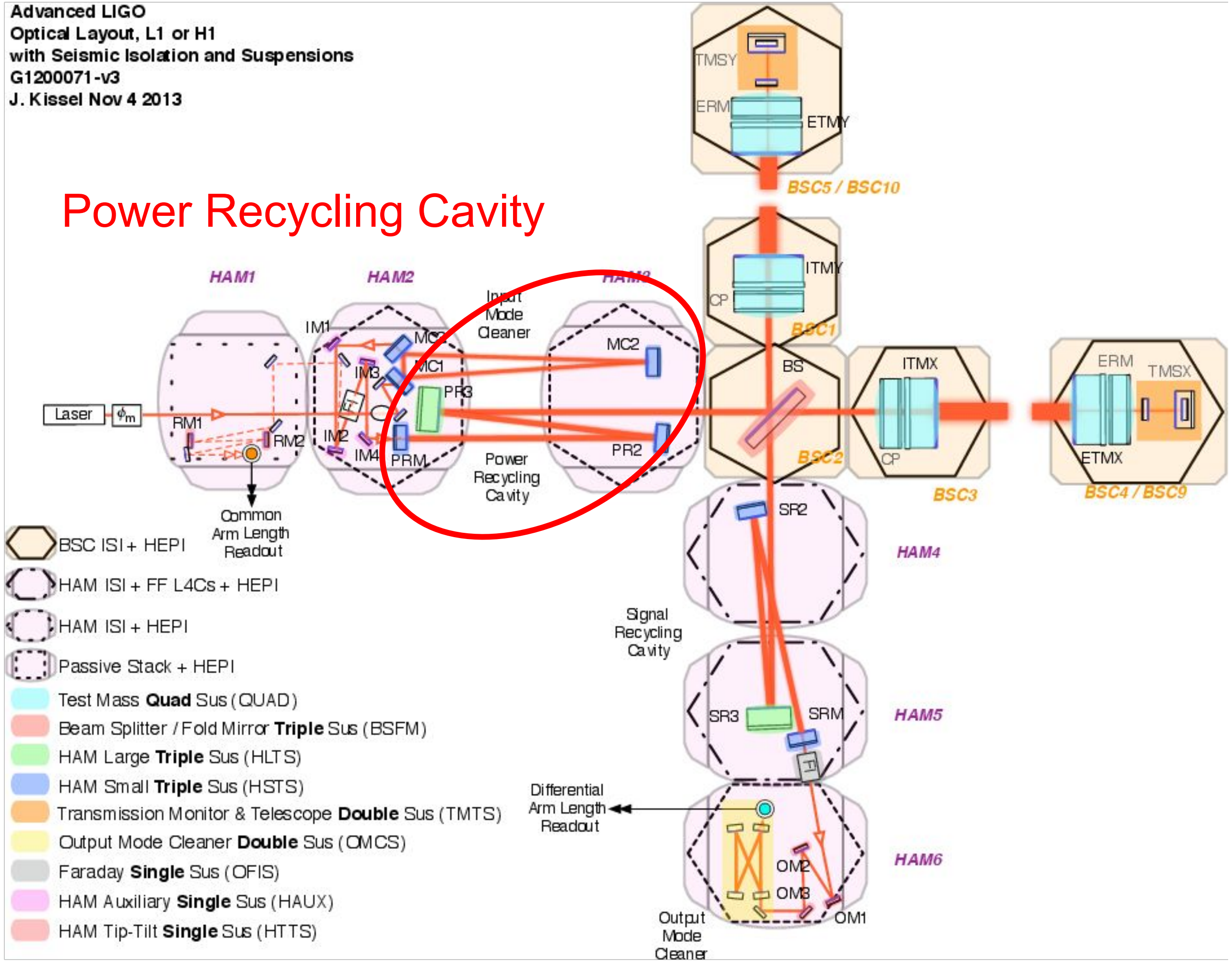
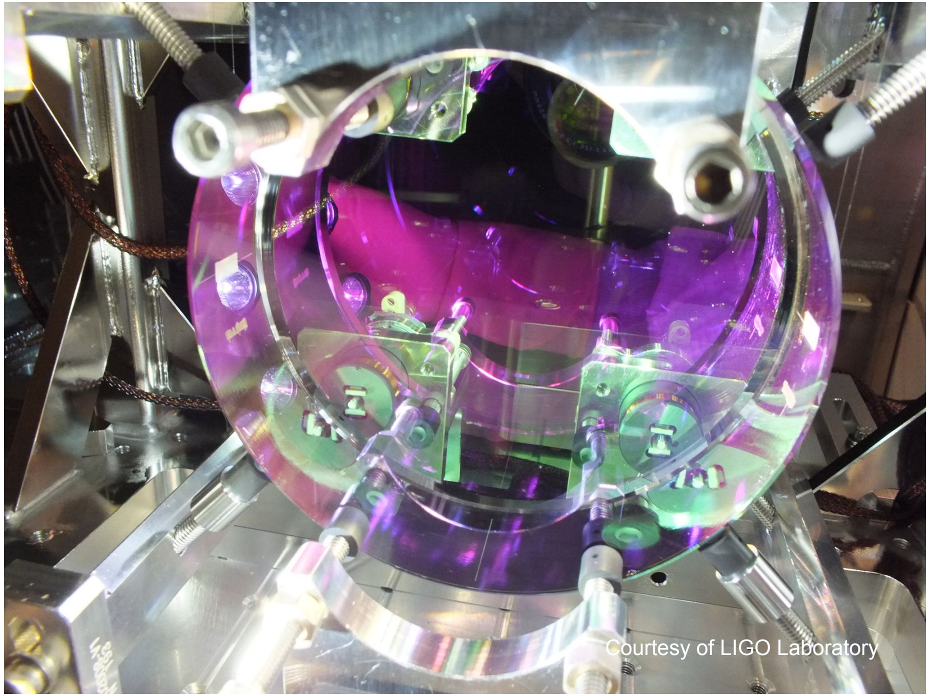
Power Recycling Cavity



Power Recycling Cavity

- The power recycling mirror (PRM) forms a resonant cavity between the laser source and the Michelson to increase the effective laser power.
- Recycling cavity length: 57.6 m.
- Designed to be stable for the fundamental Gaussian mode.
- Mirrors is a curved optic.
- Transforms the beam radius from 5.3 cm at the ITMs to 2.2 mm at the PRM.



Courtesy of LIGO Laboratory

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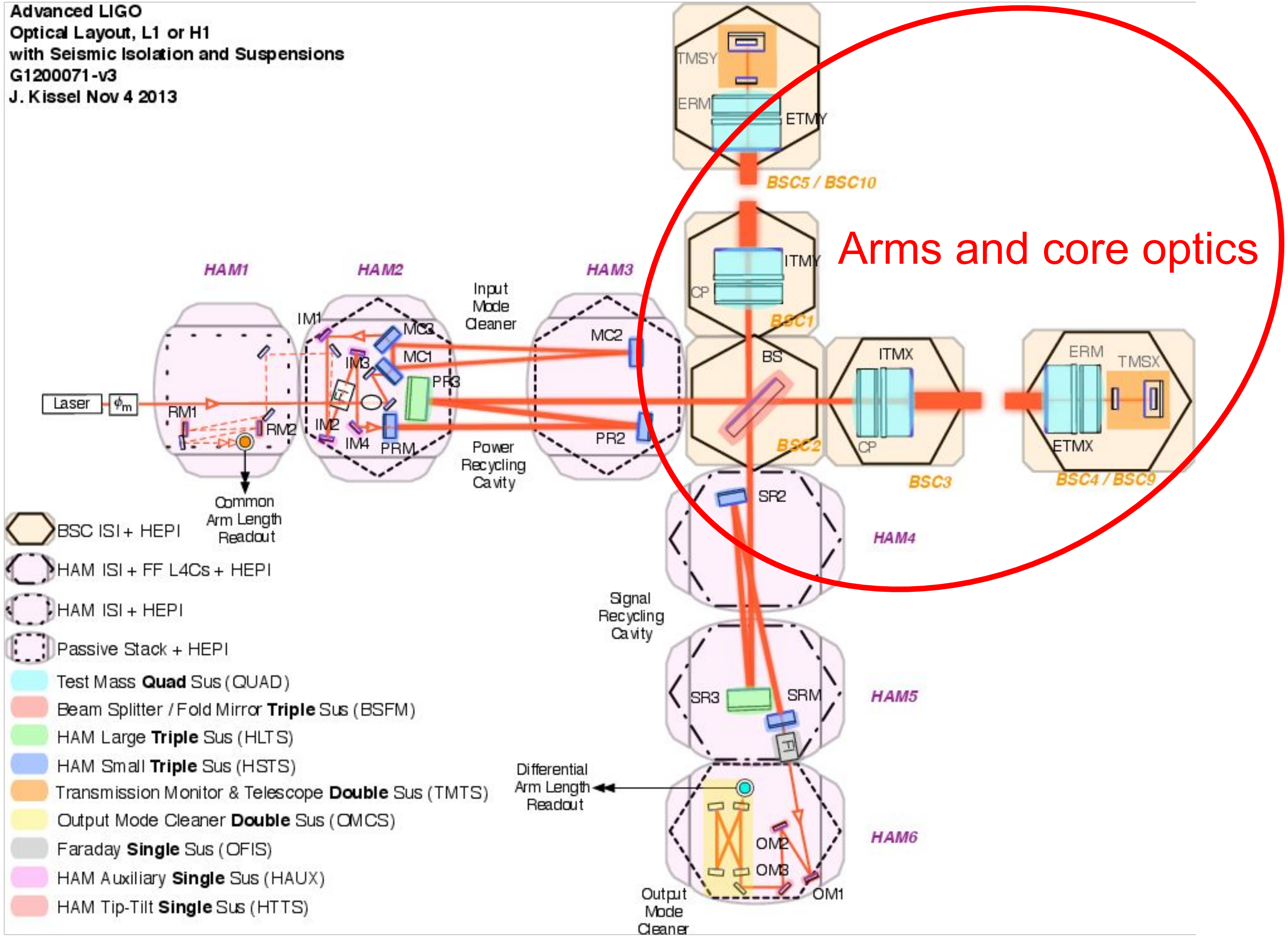
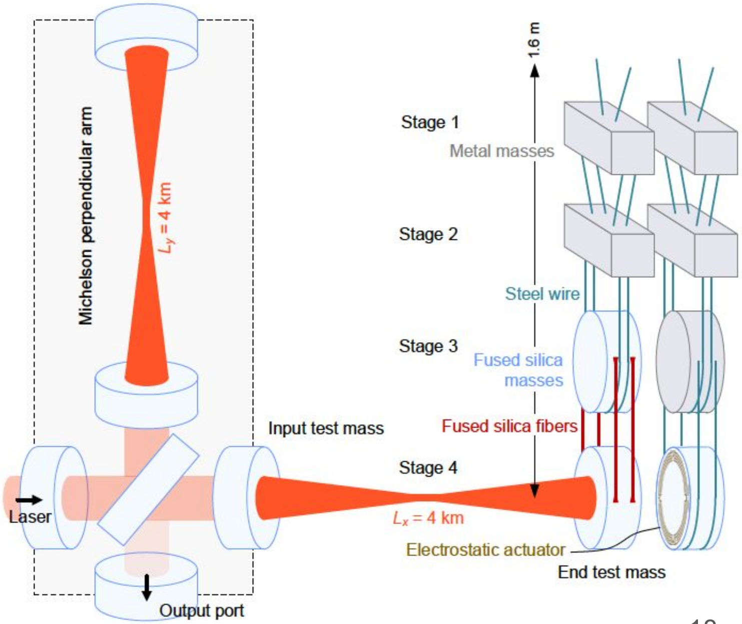


Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013
Arms and core optics
TMSY
ERM
ETMY
BSC5 / BSC10
ITMY
CP
BSC1
BS
BSC2
ITMX
CP
BSC3
ERM
TMSX
ETMX
BSC4 / BSC9
HAM1
HAM2
HAM3
Input Mode Cleaner
IM1
MC3
MC1
IM3
PR3
MC2
Laser
ϕ_m
RM1
RM2
IM2
IM4
PRM
PR2
Power Recycling Cavity
Common Arm Length Readout
SR2
HAM4
Signal Recycling Cavity
SR3
SRM
HAM5
FI
Differential Arm Length Readout
HAM6
OM2
OM3
OM1
Output Mode Cleaner
BSC ISI + HEPI
HAM ISI + FF L4Cs + HEPI
HAM ISI + HEPI
Passive Stack + HEPI
Test 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)
Faraday Single Sus (OFIS)
HAM Auxiliary Single Sus (HAUX)
HAM Tip-Tilt Single Sus (HTTS)

Arm

- A Fabry–Pérot resonator is a linear optical cavity with two highly reflecting mirrors and small transmissivity.
- A circulating optical power is possible for input wave optical frequencies close to one of the resonance frequencies.
- In resonance, the input wave leaking through the input mirror adds constructively to the circulating wave. The input wave reflected at the input mirror is canceled by the field leaking out of the resonator. Effectively no reflection in resonance!
- In anti-resonance, the circulating field is quite weak. Most radiation is reflected at the input mirror. The weak field leaking out of the resonator towards the input source adds constructively to the reflected field.
- The finesse is defined as the free spectral range (i.e., the fundamental mode spacing) divided by the (full width at half-maximum) bandwidth of the resonances. It is a measure for how narrow the resonances are in relation to their frequency distance (high finesse → sharp resonances).
- The finesse is fully determined by the resonator losses and is independent of the resonator length.
- Higher arm finesse leads to lower laser power in the power recycling cavity and reduced coupling from the vertex Michelson d.o.f.
- Lower finesse reduces optical loss and noise in the signal recycling cavity.
- LIGO has an arm cavity finesse of 450 which is a trade-off between these effects.
- LIGO's optical resonator gain is 300.
- LIGO's circulating laser power is ~ few x 100 kW.
- End Test Mass transmission: 5 ppm.
- Input Test Mass transmission: 1.4 %



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Arm

- LIGO's arms are approximately 3994.5 meters in length.
- The dominant noise mechanism in the arms is mechanical loss in the mirror coatings.
- In order to reduce test mass thermal noise, the beam size on the test masses is made as large as possible so that it averages over more of the mirror surface as the displacement thermal noise scales inversely with beam size:

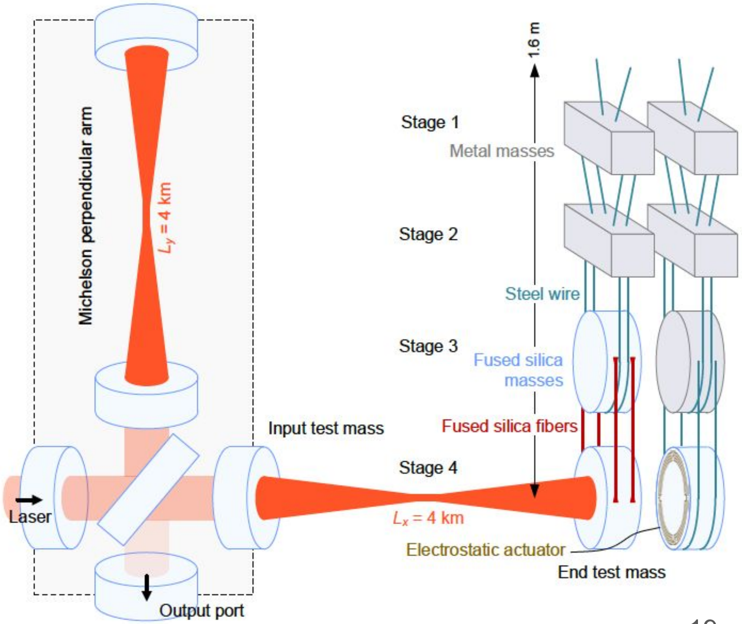
End Test Mass Beam radius ($1/e^2$) = 6.2 cm

- However, lower thermal noise thus comes at the expense of greater sensitivity to angular misalignment.
- LIGO's arm cavities are slightly asymmetrical. The Input Test Masses contribute less to thermal noise because their coatings are half as thick as on the End Test Masses.
- Therefore the beam on the ITMs is a bit smaller to limit aperture losses in the beam splitter and recycling cavities.

Input Test Mass Beam radius ($1/e^2$) = 5.3 cm

- The specified mirror beam sizes are obtained with a near-concentric design:

Mirror radius of curvature: ETM = 1934 m, ITM = 2245 m



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Core optics

- Made with fused silica substrates (Heraeus Suprasil 3001 with ultra-low absorption of < 0.2 ppm/cm at 1064 nm)
- Low level of inhomogeneity and low mechanical loss.
- Coated by the Laboratoire Matériaux Avancés (LMA, Lyon, France)
- Test masses are coated with alternating layers of silicon-dioxide and tantalum pentoxide TaO_5 doped with 25% titanium dioxide to reduce the mechanical loss.
- SiO_2 layers are a little thicker and the $Ti\text{-}TaO_5$ layers are a little thinner than a ¼-wavelength.

	Surface error, central 160 mm diam., power & astigmatism removed, rms		**Radius of curvature spread**
	> 1 mm^{-1}	**1—750 mm^{-1}**	
Specification	< 0.3 nm	< 0.16 nm	-5, +10 m
Actual	0.08—0.23 nm	0.07—0.14 nm	-1.5, +1 m


Courtesy of LIGO Laboratory

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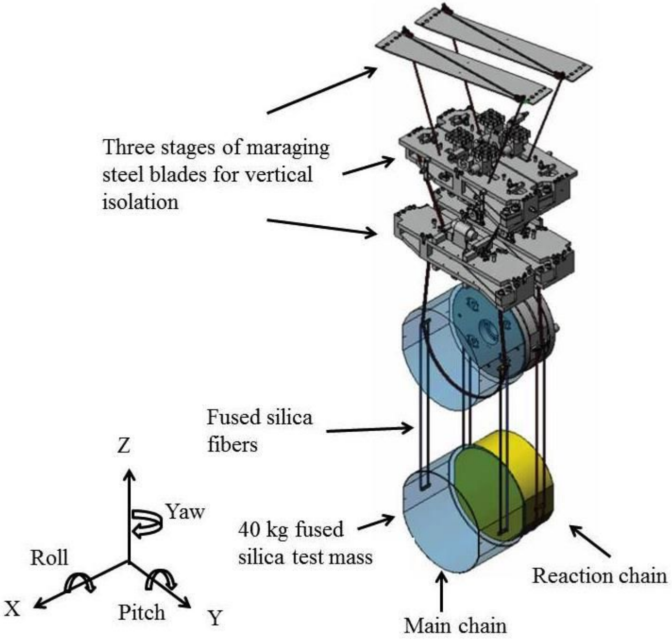
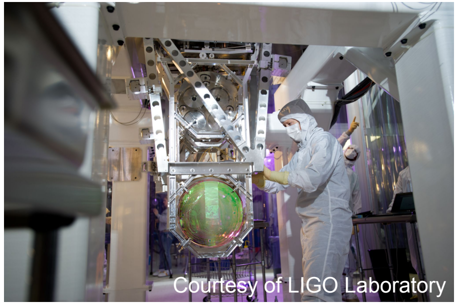
Suspensions

- Quadruple pendula with adjacent chain to provides an isolated set of masses for force reaction.
- Test mass optic is the lowest mass. The bottom mass in the reaction chain is the Compensation Plate optic in the case of an Input Test Mass suspension, and the End Reaction Mass in the case of an End Test Mass suspension.
- A structure surrounds and cages the suspended masses and mounts to the seismically isolated optics table.
- Vibration isolation for the test mass is accomplished with a 4-stage pendulum and 3 stages of cantilevered blade springs, providing isolation in all 6 degrees-of-freedom above approximately 1 Hz.
- For each chain, all the quadruple suspension rigid body modes below 9 Hz can be actively damped from the top stage.
- Force actuation on the upper three masses is accomplished with coil/magnet actuators which enables actuation in pitch, yaw and piston.
- System attenuates the ground motion by 7 orders of magnitude!





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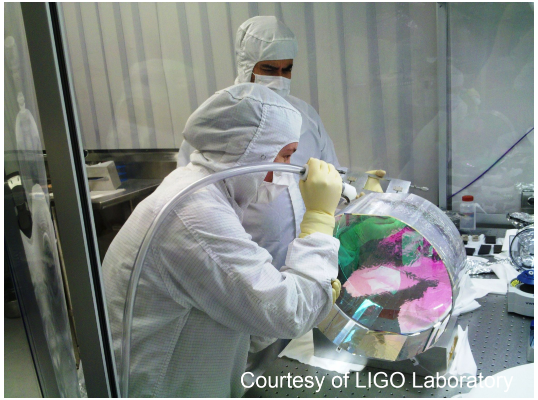
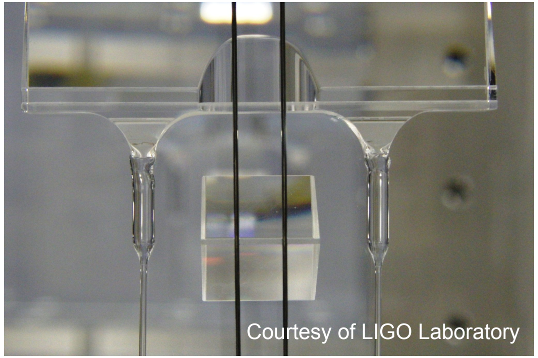
Suspensions

- The test mass and the penultimate mass are a monolithic fused silica assembly.
- Machined fused silica elements ("ears") are hydroxide-catalysis (silicate) bonded to flats polished onto the sides of the TM and penultimate mass.
- Custom drawn fused silica fibres are annealed and welded to the fused silica ears with a CO_2 laser system.
- Fibres is designed to minimize thermal noise (400 μm diameter by 596 mm long with 800 μm diameter by 20 mm long ends) while achieving a low suspension vertical "bounce" mode (9 Hz, below band) and high first violin mode frequency (510 Hz, above the instrument's most sensitive frequency range).
- The other suspension types employ the same basic key principles as the test mass quadruple suspensions, except for using steel wire in the final stage.

Optical Component	vertical isolation stages	pendulum stages	Final stage fiber type	Longitudinal noise requirement @ 10 Hz (m/√Hz)
Test Masses (ITM, ETM)	3	4	Fused silica	1×10^{-19}
Beamsplitter (BS)	2	3	Steel wire	6×10^{-18}
Recycling cavity optics	2	3	Steel wire	1×10^{-17}
Input Mode Cleaner (IMC) optics	2	3	Steel wire	3×10^{-15}
Output Mode Cleaner (OMC) Assy	2	2	Steel wire	1×10^{-13}
ETM Transmission Monitor	2	2	Steel wire	2×10^{-12}
Auxiliary suspensions	1	1	Steel wire	2×10^{-11}


Courtesy of LIGO Laboratory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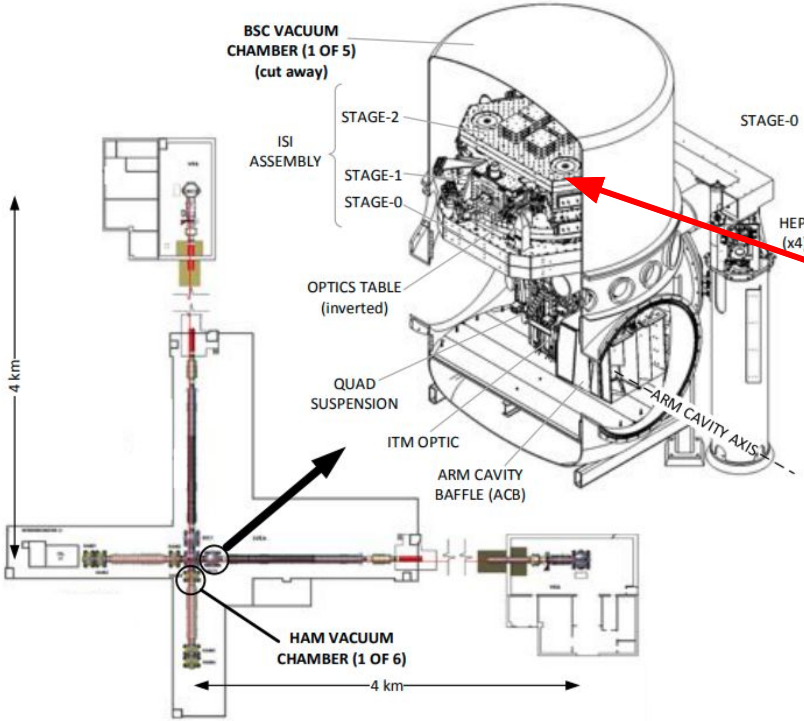
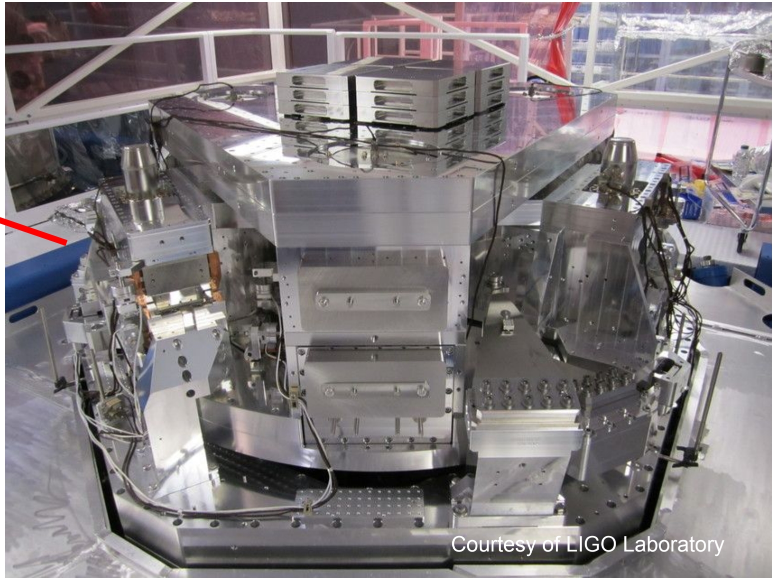
Seismic isolation





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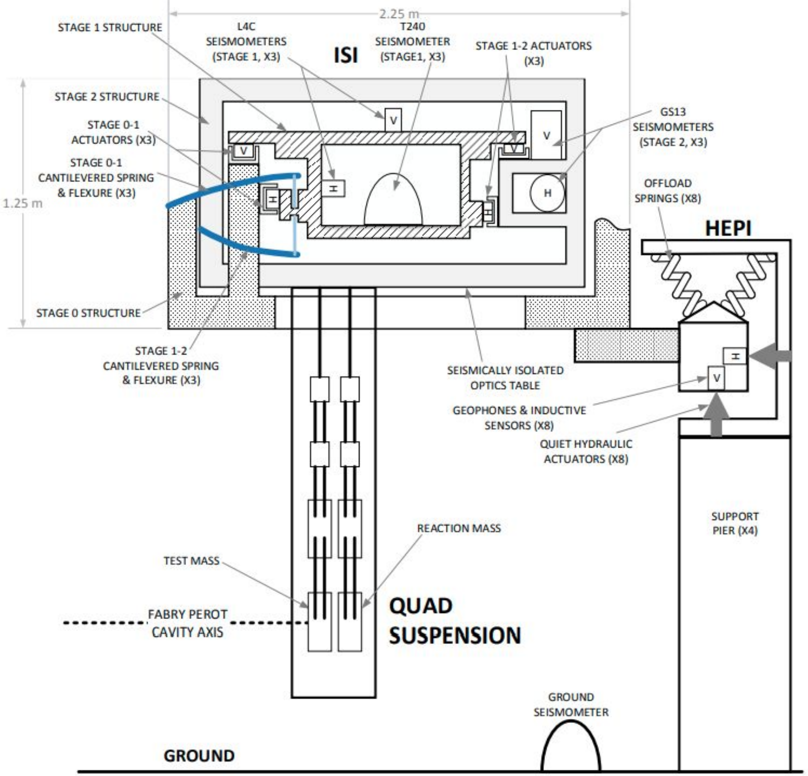
Seismic isolation

- Inverted optics tables (all other interferometer elements are supported by upright optics tables in smaller chambers).
- First stage: Hydraulic External Pre-Isolator system (external to the vacuum system) that supports a total isolated mass of 6400 kg.
- Eight custom designed, laminar flow, quiet hydraulic actuators for low frequency (0.1—10 Hz) active control in 6 degree-of-freedoms.
- Array of geophones and inductive position sensors plus a ground seismometer for feed-forward correction.
- Next three stages: Internal Seismic Isolation system (within the vacuum system).
- Array of different seismometers and geophones and actuators embedded in the system.
- Another three orders of magnitude of isolation noise suppression at low frequencies!



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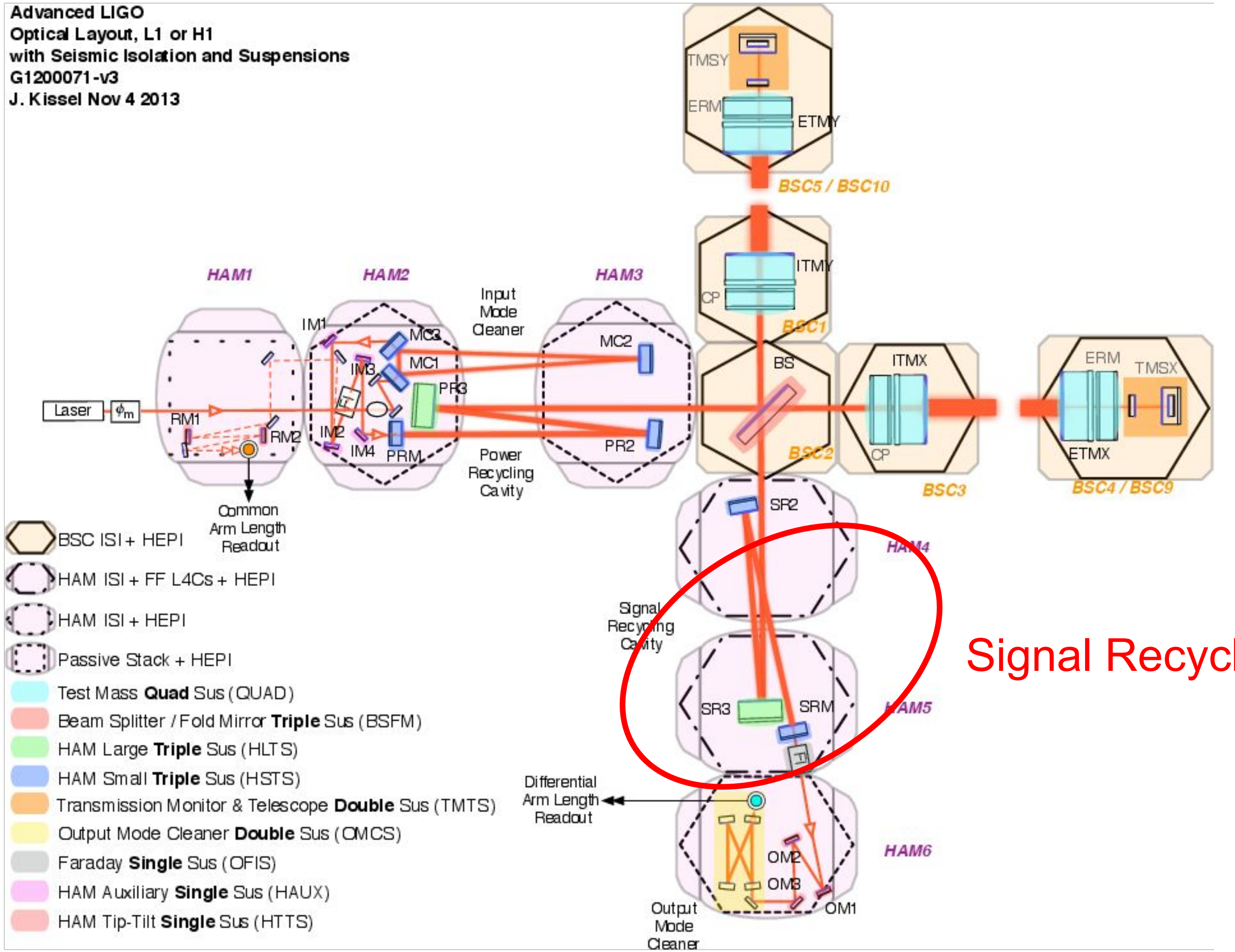
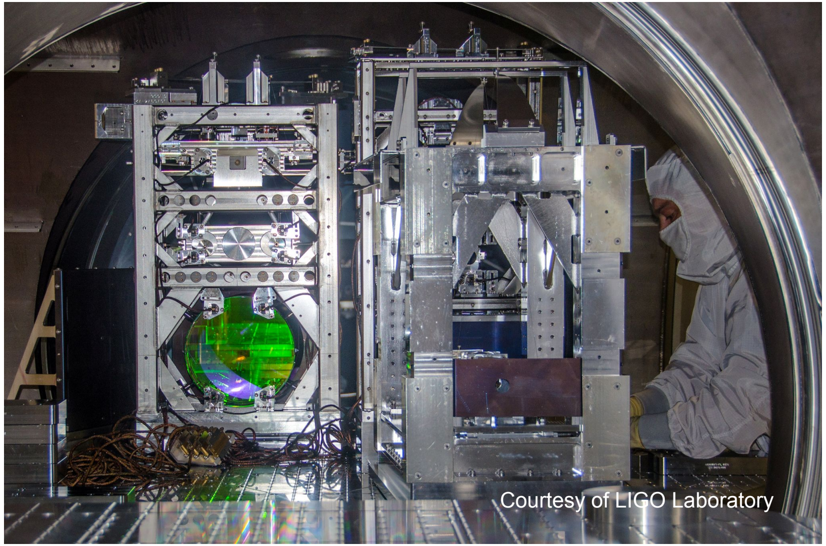


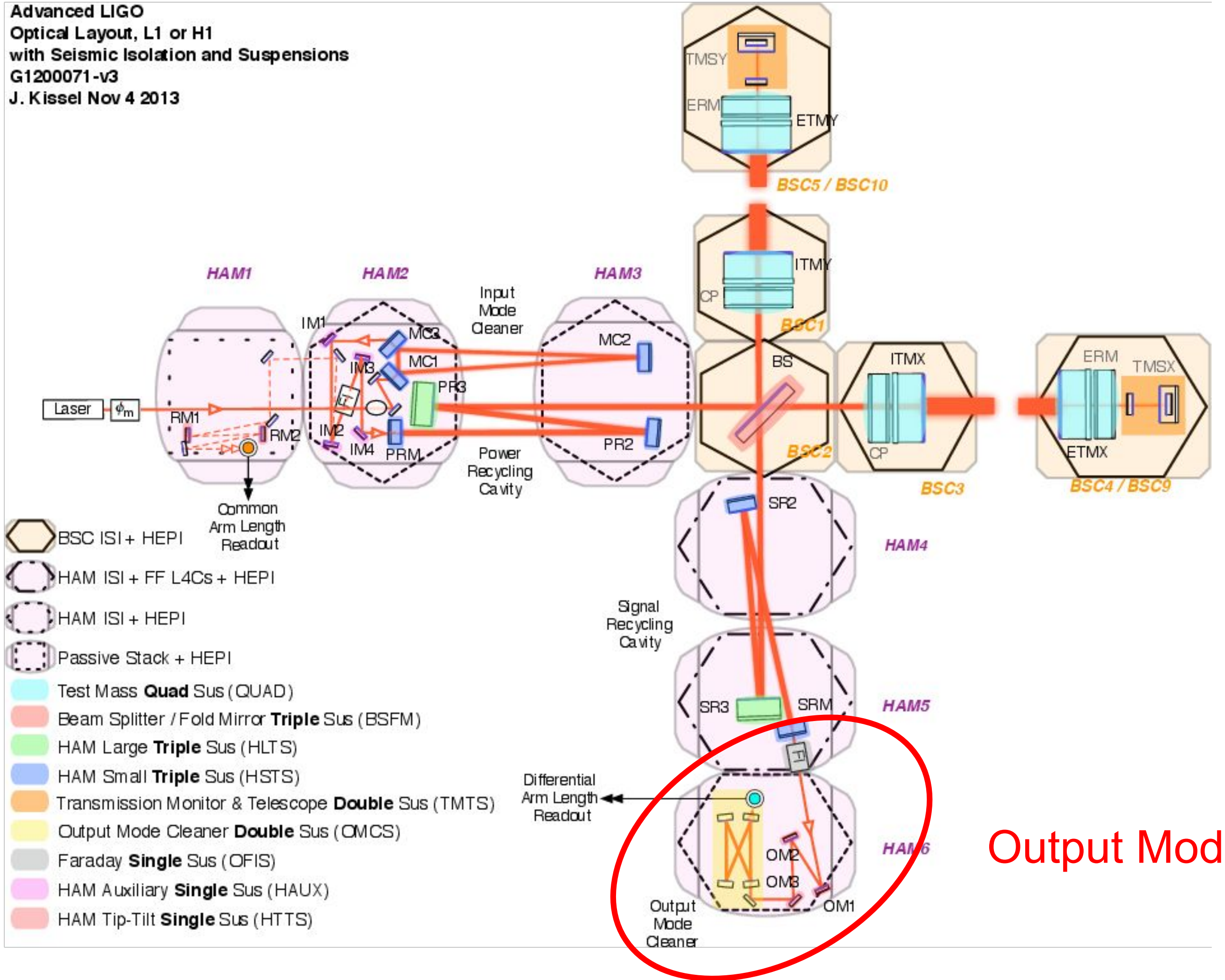
Signal Recycling Cavity

Signal Recycling Cavity

- Signal recycling was added to Advanced LIGO (not present in initial LIGO).
- Similar to the Power Recycling Cavity.
- The signal recycling mirror (SRM) at the anti-symmetric output of the Michelson is used to lower the arm cavity finesse and broaden the detector frequency response.
- Signal recycling can also be used to create a narrowband mode of operation, with enhanced sensitivity at a given frequency (though with higher noise at other frequencies).


Courtesy of LIGO Laboratory

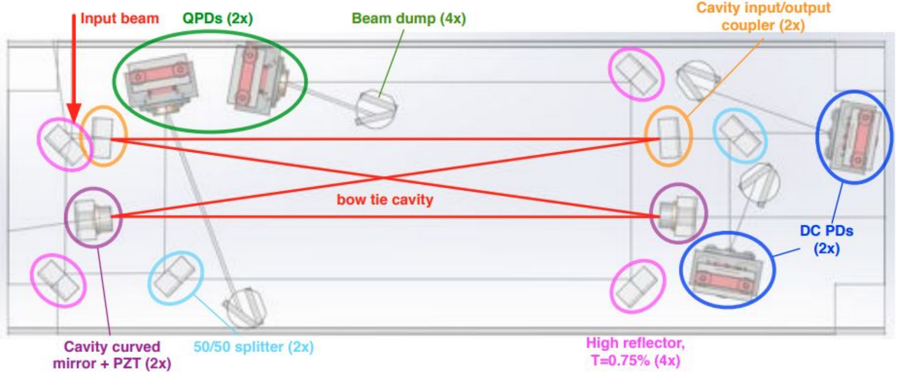
The LIGO Scientific Collaboration (J. Aasi et al), *Advanced LIGO*, Class. Quant. Grav. 32 (2015) 074001
The LIGO Scientific Collaboration and the Virgo Collaboration, *GW150914: The Advanced LIGO Detectors in the Era of First Discoveries,* Phys. Rev. Lett. 116, 131103 (2016)



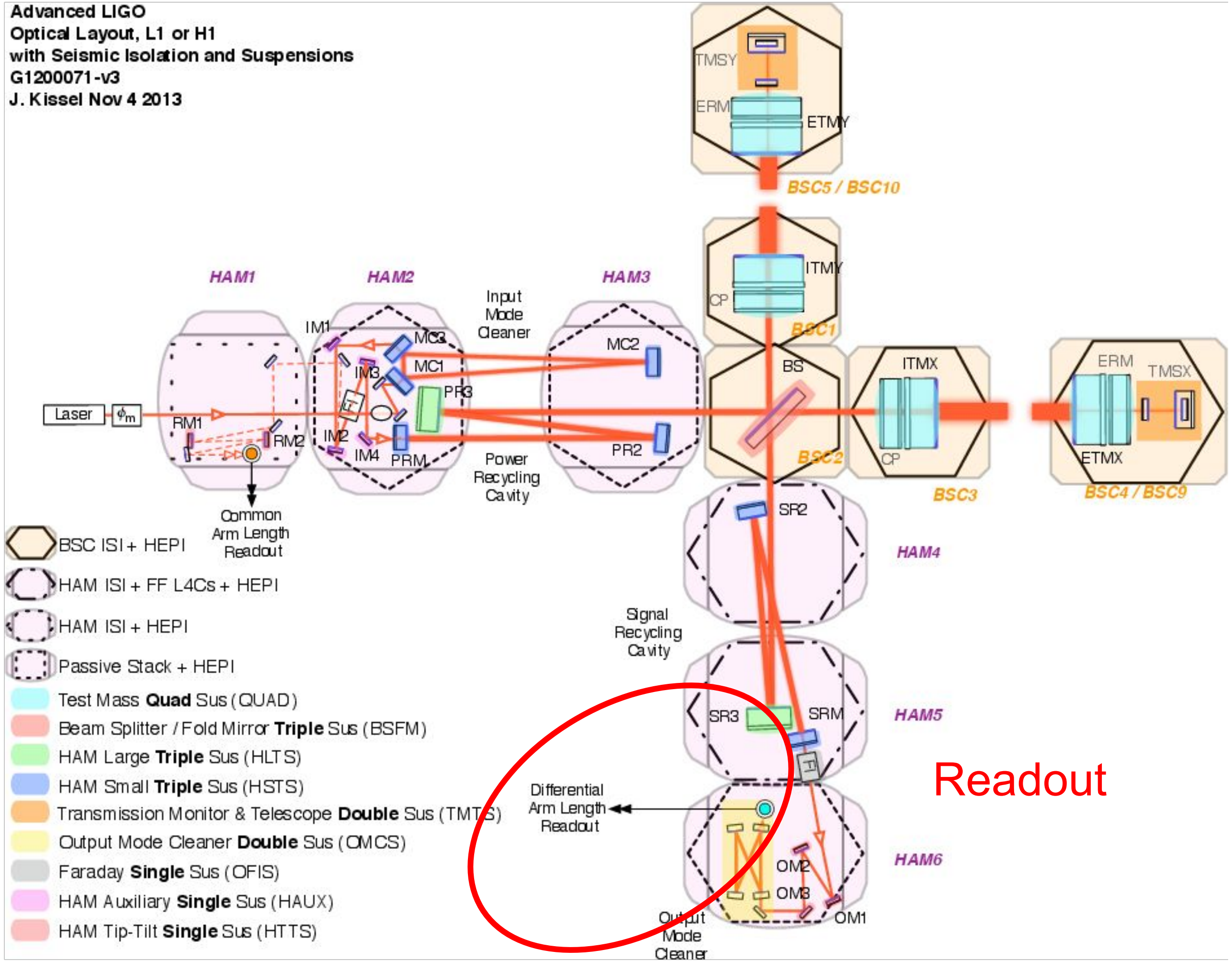
Output Mode Cleaner

Output Mode Cleaner

- The output mode cleaner (OMC) filters out all RF sideband and higher-order spatial mode light at the antisymmetric port, so that the main photodetectors receive only light that carries the gravitational wave signal.
- The OMC is a bowtie cavity with finesse equal to 400 to maintain high transmission efficiency (> 95%).
- Nominal OMC round trip length: 1.13 m.
- All OMC cavity optics and the output photodiodes are bonded to a single breadboard of fused silica to minimize relative motion between the OMC output beam and the diodes.



The LIGO Scientific Collaboration (J. Aasi et al), *Advanced LIGO*, Class. Quant. Grav. 32 (2015) 074001
The LIGO Scientific Collaboration and the Virgo Collaboration, *GW150914: The Advanced LIGO Detectors in the Era of First Discoveries,* Phys. Rev. Lett. 116, 131103 (2016)

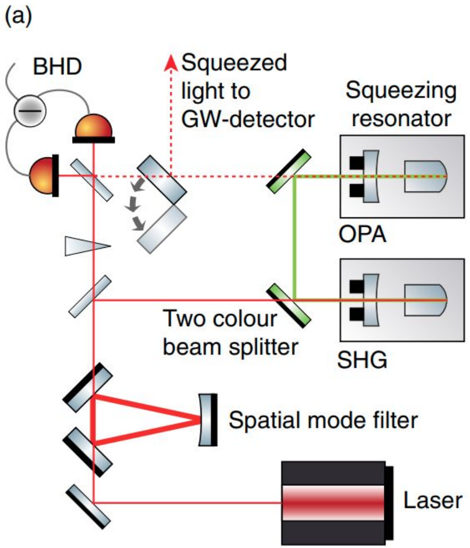


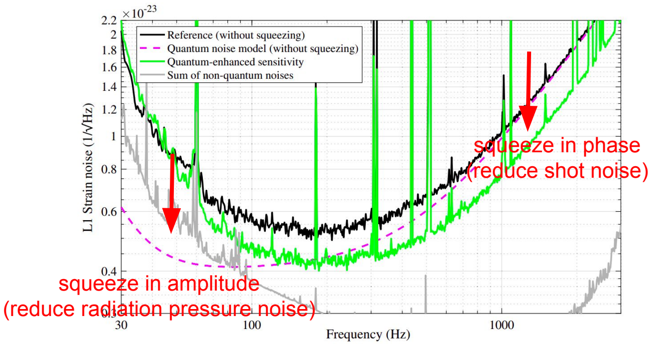
Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013
TMSY
ERM
ETMY
BSC5 / BSC10
ITMY
CP
BSC1
HAM1
HAM2
HAM3
Input
Mode
Cleaner
IM1
MC3
MC1
MC2
IM3
PR3
Laser
RM1
RM2
IM2
IM4
PRM
PR2
Power
Recycling
Cavity
BS
BSC2
ITMX
CP
BSC3
ERM
TMSX
ETMX
BSC4 / BSC9
Common
Arm Length
Readout
SR2
HAM4
Signal
Recycling
Cavity
SR3
SRM
HAM5
Differential
Arm Length
Readout
OM2
OM3
OM1
HAM6
Output
Mode
Cleaner
BSC ISI + HEPI
HAM ISI + FF L4Cs + HEPI
HAM ISI + HEPI
Passive Stack + HEPI
Test 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)
Faraday Single Sus (OFIS)
HAM Auxiliary Single Sus (HAUX)
HAM Tip-Tilt Single Sus (HTTS)

Readout

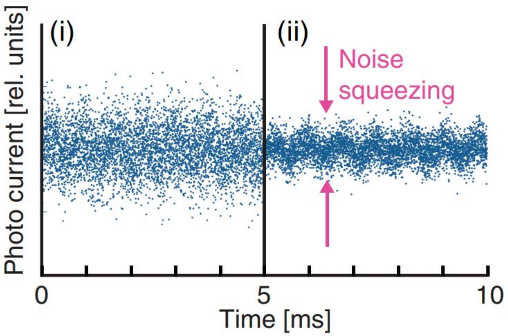
Squeezer and readout

- Accomplished using an output mode cleaner in conjunction with homodyne, or DC detection.
- A local oscillator field is generated by offsetting the arm cavities slightly from their resonance (off the dark fringe).
- The output mode cleaner filters out non-carrier TEM00 modes.
- In-vacuum squeezer was installed for the latest run (O3) at both LIGO sites for quantum noise-reduction (pioneered by GEO600).
- The squeezer pumps a non-linear crystal to create correlated photons that modify the quantum state uncertainty of the light that enters the interferometer.

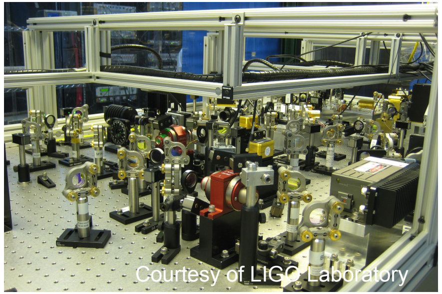




M. Tse et al, Physical Review Letters 123, 23 (2019)

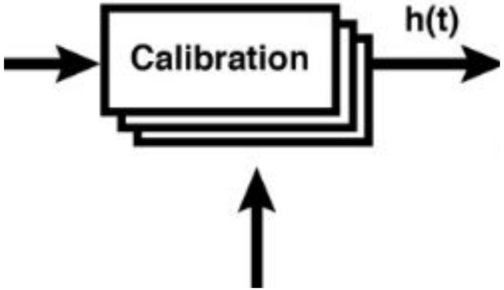


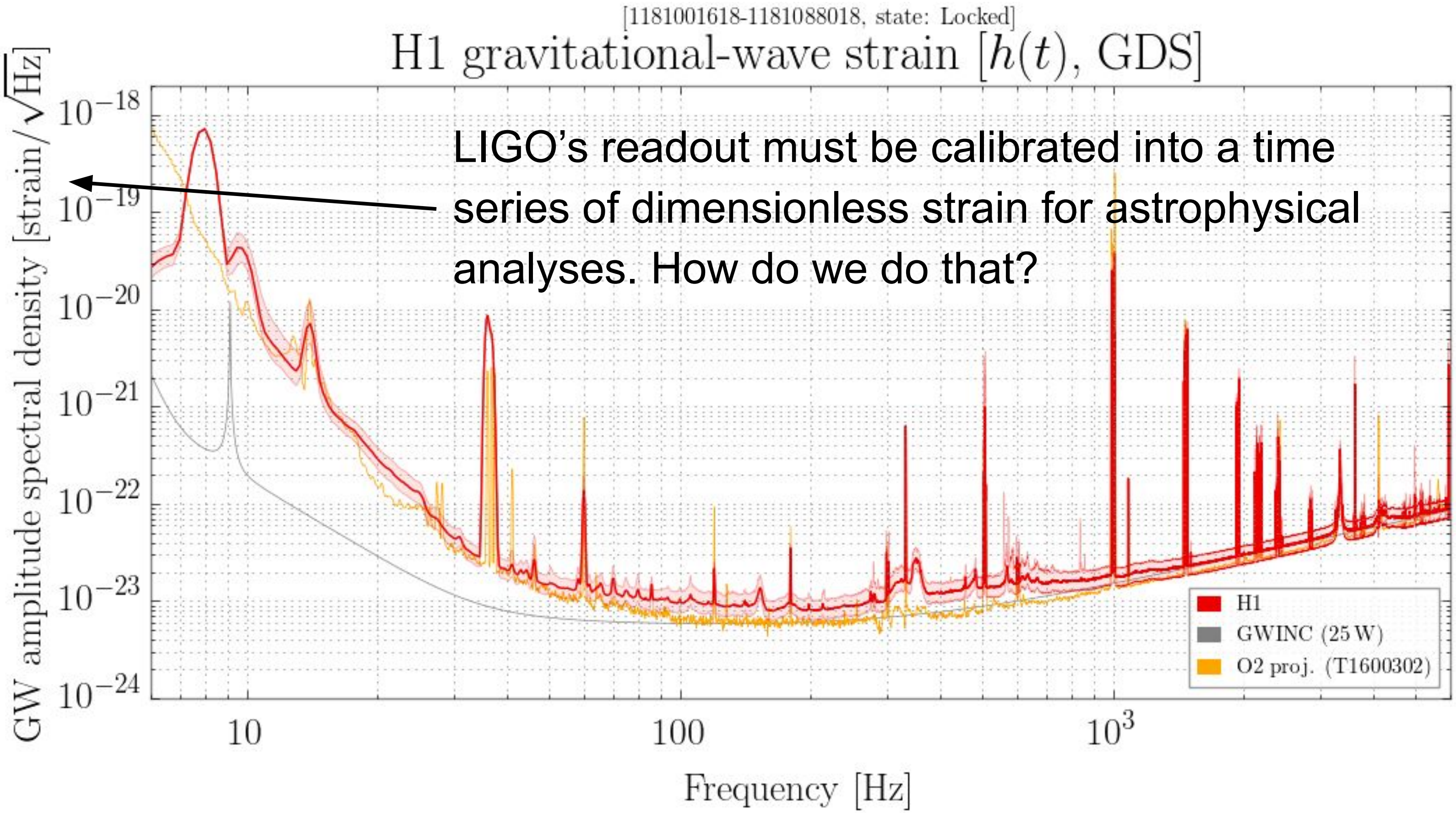
Lisa Barsotti et al 2019 Rep. Prog. Phys. 82 016905



The LIGO Scientific Collaboration (J. Aasi et al), *Advanced LIGO*, Class. Quant. Grav. 32 (2015) 074001
The LIGO Scientific Collaboration and the Virgo Collaboration, *GW150914: The Advanced LIGO Detectors in the Era of First Discoveries*, Phys. Rev. Lett. 116, 131103 (2016)

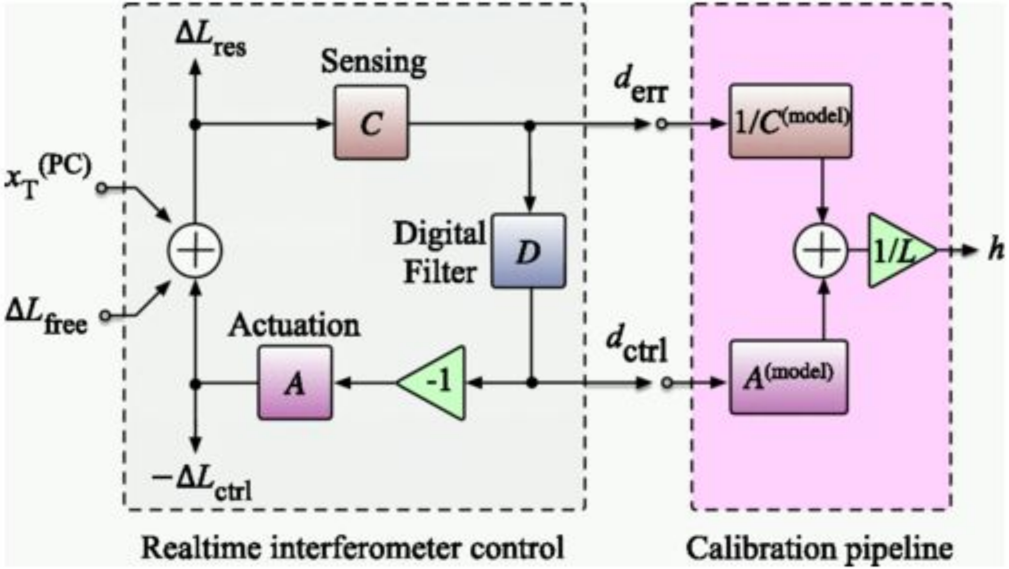
The Miracle of LIGO Part II - Calibration





LIGO's readout must be calibrated into a time series of dimensionless strain for astrophysical analyses. How do we do that?

Interferometer control and calibration



Differential arm length feedback control servo. The sensing function, digital filter function, and actuation function combine to form the open loop transfer function.

The calibration pipeline

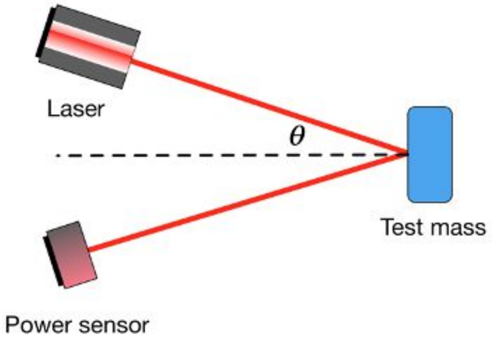
Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914

B. P. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **95**, 062003 – Published 28 March 2017

- Complex valued, frequency dependent data-conditioning filters from models of the feedback control system of the detectors.
- For control system model parameters that are well modeled and vary slowly, filters are applied in near-real time (low latency)
- Other parameters (e.g., poorly compensated changes in electronics configurations, hardware problems…) are corrected a posteriori (offline).
- How do we measure calibration systematic errors?

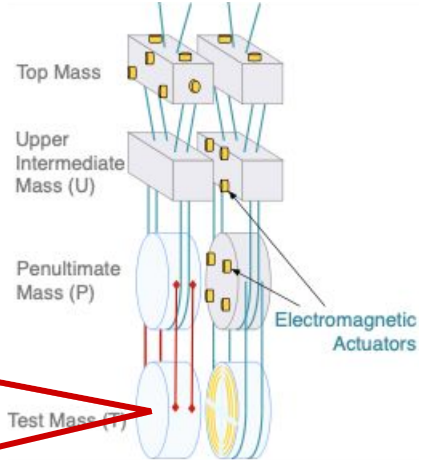
Photon calibrator (Pcal)

Force exerted by a reflecting beam

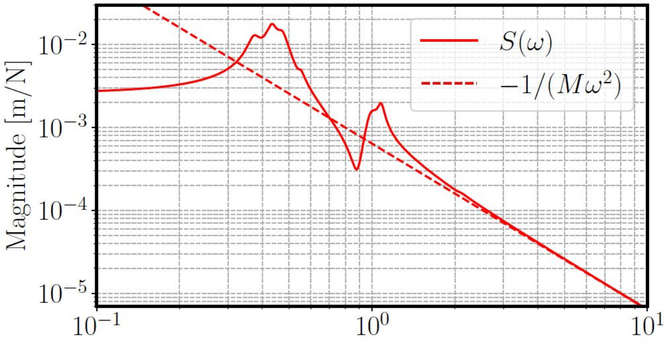


$$F(\omega) = \frac{2cos\theta}{c} P(\omega)$$

Displacement of suspended mass induced by a reflecting beam



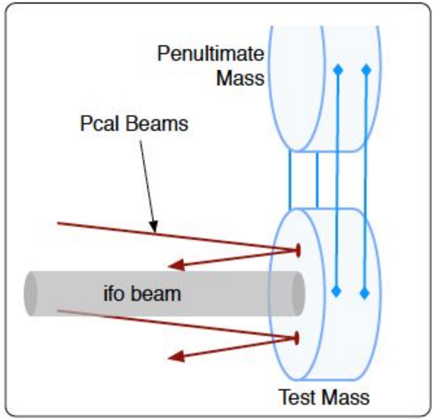
$$x(\omega) \simeq -\frac{F}{m\omega^2}$$

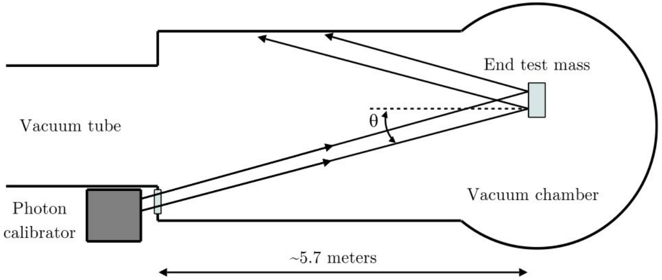


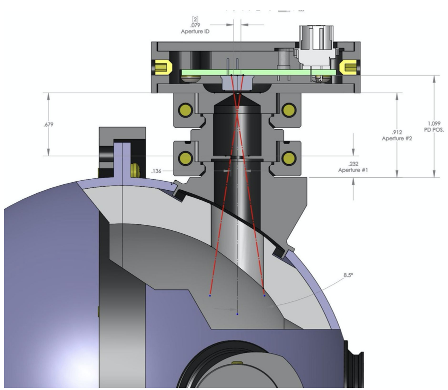
$$x(\omega) = \frac{2cos\theta}{c} P(\omega) \frac{-1}{M\omega^2}$$

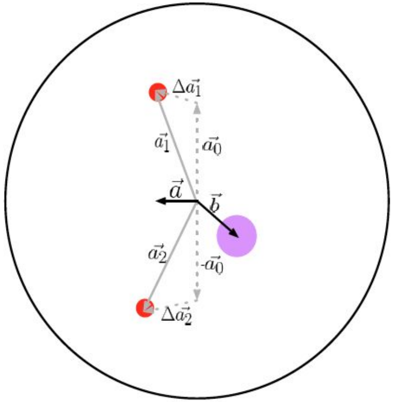
Slide adapted from D. Bhattacharjee and R. Savage - LISC calibration bootcamp - LIGO-G2100654

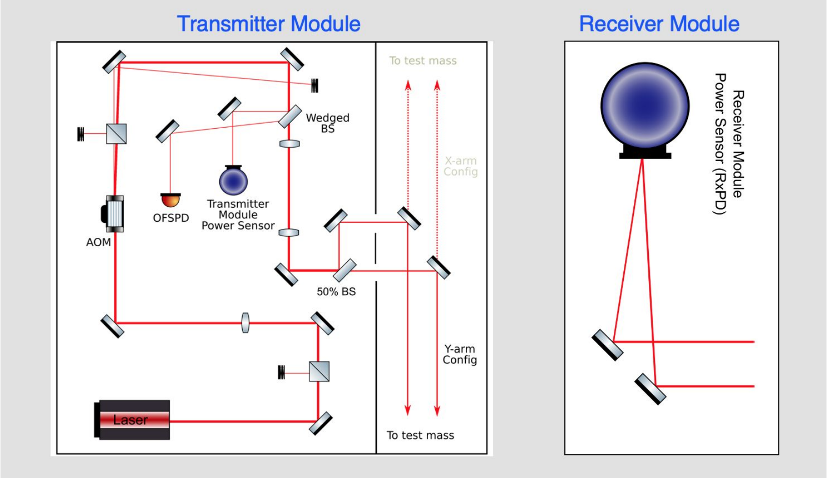
Of course things are not so simple....











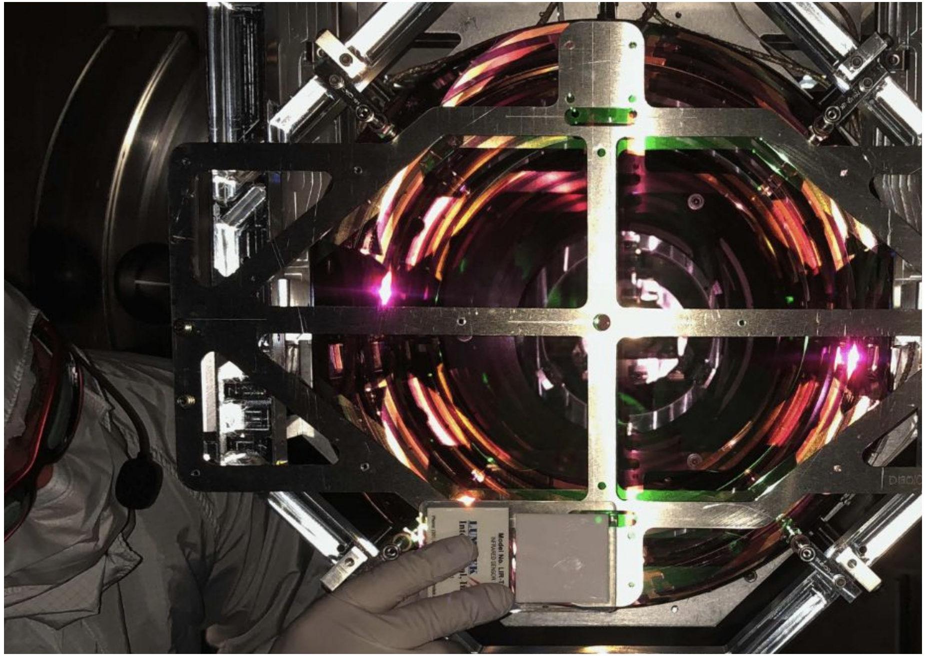
One Power Sensor Gold Standard is calibrated at NIST

One Working Standard is calibrated against the Gold Standard

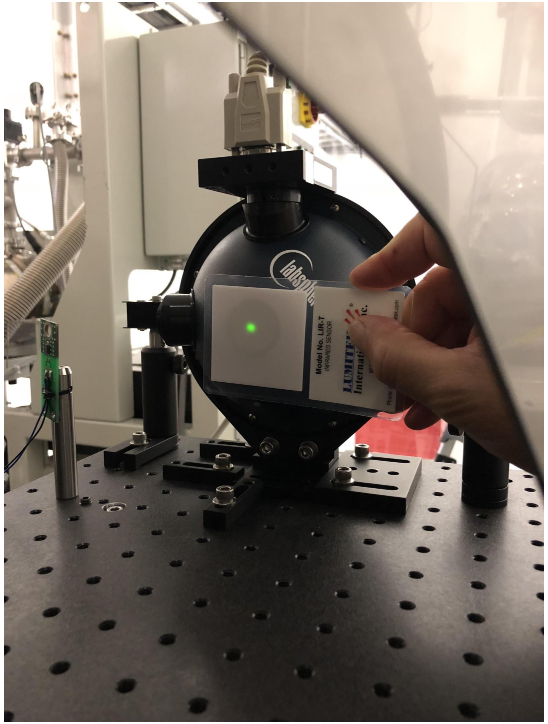
The Pcal power sensors at each end station are calibrated against the Working Standard

Slide adapted from D. Bhattacharjee and R. Savage - LISC calibration bootcamp - LIGO-G2100654

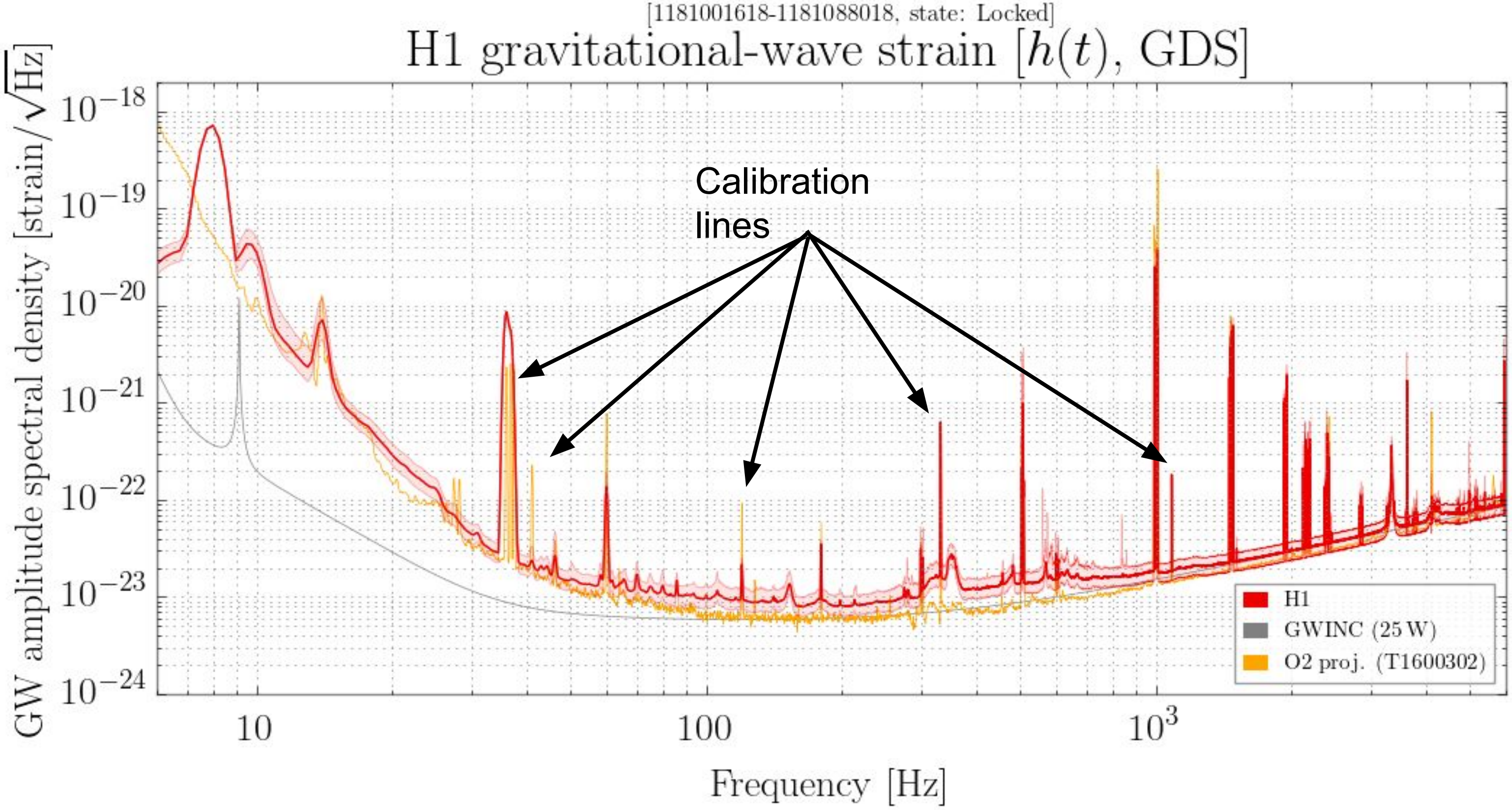
Positioning of Pcal beams on ETM surface



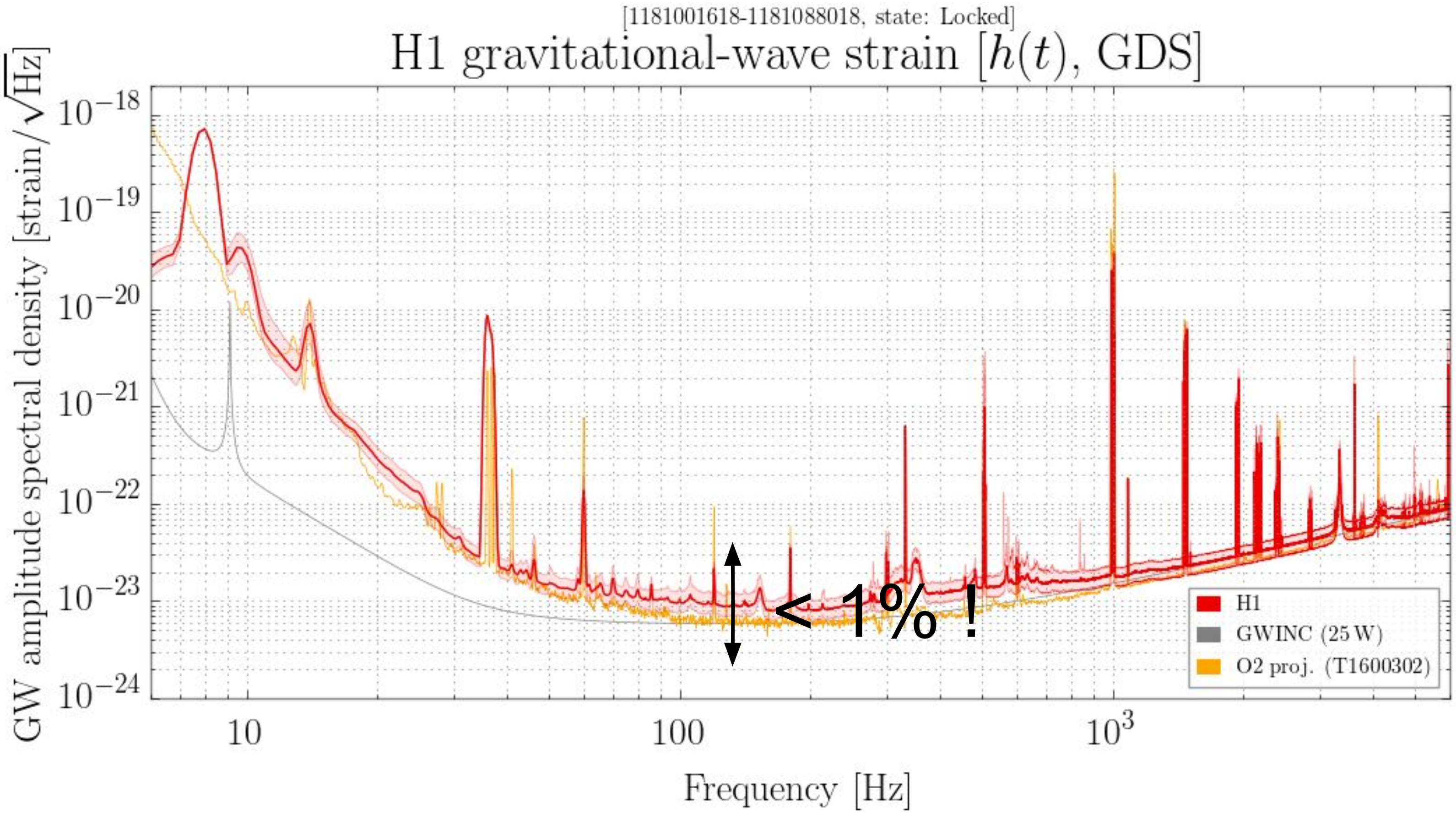
In chamber



At receiver module



- At roughly weekly cadence the detectors are declared out of observation mode and swept-sinusoid and colored-random-noise Pcal excitations are driven above the noise.
- After the observing run has ended estimates of the probability distribution of systematic error for all observation times are created.
- The data stream is then regenerated offline from the optical power variations and control signals.



In the latest Observing Run (O3) it was achieved a sub-one-percent accuracy for fiducial displacement amplitudes!

For more details, see: *D. Bhattacharjee et al., Class. Quantum Grav.* ***38*** *(2021) 015009*

Part II: Data and Detector Learning

LIGO Channel Information System

Home | IFOs | Subsystems | Channels | Tree

Channels

400982 channels found

☑ Current Channels Only

IFO	Subsystem	Channel Name	Data Rate	Units	Acquire	Offset	Slope	Model	Modified
L0	ACM	L0:ACM-DP_ATOB_VOLTS	16	Volts	3	0	1e+0	L0EDCU_ACM	2016-02-23T18:58:01
L0	ACM	L0:ACM-DP_BTOC_VOLTS	16	Volts	3	0	1e+0	L0EDCU_ACM	2016-02-23T18:58:01
L0	ACM	L0:ACM-DP_CTOA_VOLTS	16	Volts	3	0	1e+0	L0EDCU_ACM	2016-02-23T18:58:01
L0	ACM	L0:ACM-DP_LTOL_VOLTS	16	Volts	3	0	1e+0	L0EDCU_ACM	2016-02-23T18:58:01

Over 200,000 channels per detector!

- Sensors continuously monitor the behavior of the detectors and their environment.
- Auxiliary data are used to characterize noise that may negatively impact searches and signal estimation.
- Information is in the form of time series.
- Invalid data due to detector malfunctions, calibration errors, data acquisition are be removed from analyses.
- Flags are created according to different levels of data quality.

Channels

- Naming convention:

  XX:SSS-CCC_CCC_CCC

  site system : subsystem – location/mirror _ signal _ subsignal

  Example:

  L1:SUS-ITMX_ODC_CHANNEL_OUT_DQ

Raw Channel Recorded by Data Acquisition System

Output Filter Bank

Livingston detector

Online Detector Characterization

Suspension

Input Test Mass in the X arm

Channels

- Naming convention:

    XX:SSS-CCC_CCC_CCC

    site system : subsystem – location/mirror _ signal _ subsignal

Can you guess?

    H1:PSL-ODC_CHANNEL_OUT_DQ

Channels

- Naming convention:

  XX:SSS-CCC_CCC_CCC

  site system : subsystem – location/mirror _ signal _ subsignal

Can you guess?

H1:PSL-ODC_CHANNEL_OUT_DQ

Raw Channel Recorded by
Data Acquisition System

Hanford detector

Output Filter Bank

Pre-Stabilized Laser

Online Detector Characterization

Auxiliary channels

- Different data rates (from few Hz to 65536 Hz. Strain is at 16384 Hz).
- Different units.
- Different acquisition systems.
- Safe and unsafe channels.

A full, manual analysis of auxiliary channel data is generally impracticable because of the huge number of instrumental and environmental monitoring sensors. The power of machine learning to handle huge data sets has recently been exploited to analyze auxiliary channel data.

TOPICAL REVIEW • OPEN ACCESS

Enhancing gravitational-wave science with machine learning

Elena Cuoco[1,2,3], Jade Powell[4], Marco Cavaglià[5], Kendall Ackley[6,7], Michał Bejger[8], Chayan Chatterjee[7,9], Michael Coughlin[10,11], Scott Coughlin[12], Paul Easter[6,7], Reed Essick[13]

+ Show full author list

Published 1 December 2020 • © 2020 The Author(s). Published by IOP Publishing Ltd

Machine Learning: Science and Technology, Volume 2, Number 1

Citation Elena Cuoco *et al* 2021 *Mach. Learn.: Sci. Technol.* **2** 011002

See Antonio Marquina's tutorial tomorrow!

DIY

Gravitational Wave Open Science Center

Data Software Online Tools About GWOSC

Auxiliary Channel Three Hour Release

Data Set

A large number of sensors are used to record the state of the LIGO instruments and their enviornment. This data release contains sensor data recorded in around 500 channels at each LIGO site. These data represent three hours of time centered on GW170814 (GPS 1186736512 — 1186747264). Strain data from the same period are available in the O2 Data Release.

Download Data

The data are available as down-sampled HDF5 files [19 GB], or full sample rate GWF files [68 GB]:

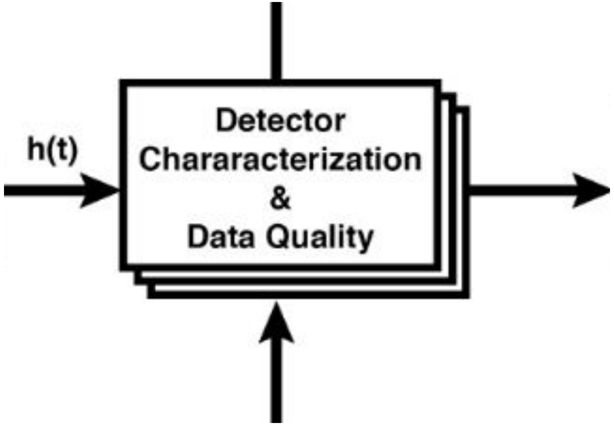
HDF5 Data GWF Data

Data may also be accessed from a network data server (NDS2) using the NDS2 client or GWpy:

```
from gwpy.timeseries import TimeSeries
data = TimeSeries.fetch('L1:LSC-DARM_OUT_DQ', start=1186741850, end=1186741870, host='losc-nds.ligo.org')
```

https://www.gw-openscience.org/auxiliary/GW170814/

Part III: Fighting the Noise



Noise, noise and noise again!

- Fundamental noise sources inherent to the detector's design, e.g.,
    - Quantum sensing noise
    - Suspension thermal noise
    - Mirror coating thermal noise
    - Gravity gradient noise
- Additional noise sources related to the detector's control or environment, e.g.,
    - Feedback control system noise
    - Electronic or mechanical noise
    - Seismic noise
    - Gravity gradient noise
    - Anthropogenic noise
    - Weather
- Most of these noise sources are non-stationary over a range of time scales.
- They typically couple to the detector strain in a nonlinear way.
- Short-lived excess noise is referred as "transient noise" or more colloquially "glitches".
- Persistent excess noise confined to certain frequencies is referred as "spectral lines".

Dealing with stationary noise 101

- Detector noise $\boldsymbol{n}(t_i) = \boldsymbol{n}_i$ *with* distribution $p(\boldsymbol{n})$
- Mean: $\mu = \mathrm{E}[\mathbf{n}]$ Covariance Matrix: $C_{ij} = \mathrm{E}[(n_i - \mu)(n_j - \mu)]$
- Gaussian noise:

$$p(\mathbf{n}) = \frac{1}{\det(2\pi\mathbf{C})^{1/2}} \exp\left[-\frac{1}{2}\sum_{ij}(n_i - \mu)(n_j - \mu)C_{ij}^{-1}\right]$$

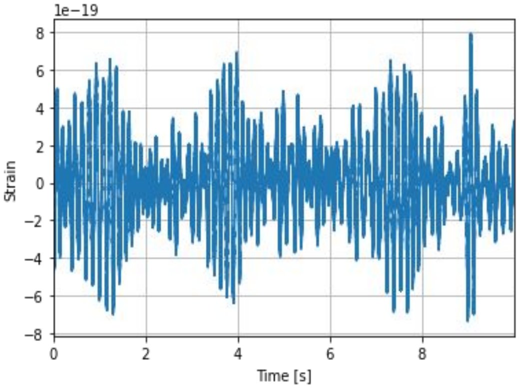
- If the noise is stationary the CM depends only on the lag $\tau = |t_i - t_j|$
- Power Spectral Density: $C_{ij} = \delta_{ij} S_n(f_i)$
- The square root of the PSD is the Amplitude Spectral Density (units of $\mathrm{Hz}^{-1/2}$)
- White noise: $C_{ij} = \delta_{ij}\sigma^2$
- LIGO detector noise is typically not stationary and not Gaussian!

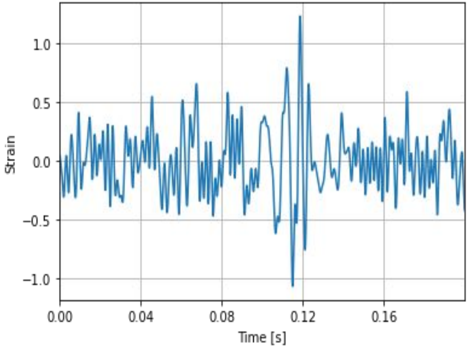
B P Abbott et al 2020 Class. Quantum Grav. 37 055002

Dealing with stationary noise 101

If the detector noise can be considered stationary and Gaussian, in first approximation:

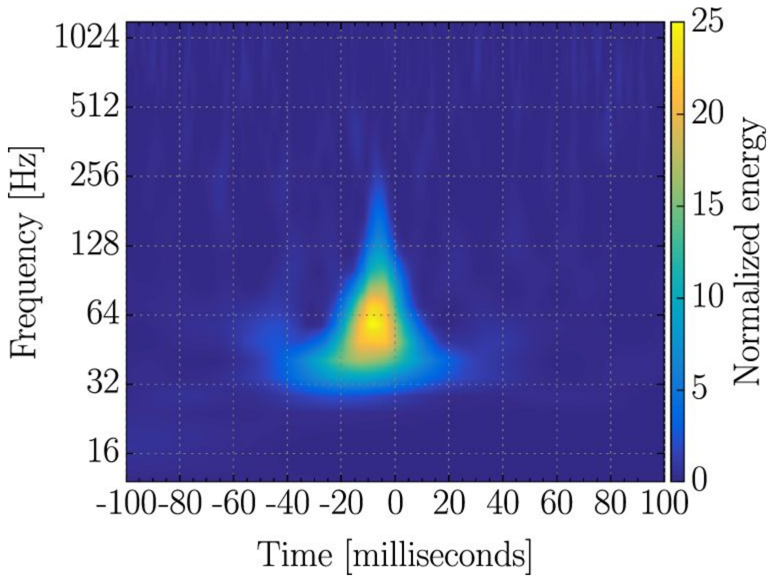
- Fast Fourier transform the data.
- Don't forget to window the data to suppress spectral leakage! Tukey windows is typically better than Hanning or Flattop as it modifies less the signal.
- Whiten the data by dividing the Fourier coefficients by the ASD
- Transform back to time domain
- Bandpass if you wish...





Dealing with non-stationary noise

- But… LIGO data are typically non-stationary and non-Gaussian!
- Spectral lines can impair searches for long-duration signals at those specific frequencies
- Short noise transients may mimic true transient astrophysical signals in individual detectors and increase the search background.
- Glitches with power comparable to detectable signals may occurred at a rate of one per minute.
- Many of them (but not all!) can be associated with transient
  signals in auxiliary “witness” channels.
- How do we deal with them?



B P Abbott *et al* 2016 *Class. Quantum Grav.* 33 134001

Potential sources of short-duration noise transients and their witness channels

- Potential uncorrelated noise between detectors. Examples:
  - Anthropogenic noise. Witnesses: accelerometers, seismometers, microphones.
  - Earthquakes: Witnesses: seismometers installed at the LIGO detectors can easily identify earthquake disturbances.
  - Faults in sensing and control components. Witnesses: Various channels.
  - “Blip transients”. Witnesses: None!
- Potential correlated noise between detectors. Examples:
  - Electromagnetic noise (lightning, solar events, solar-wind driven noise..). Witnesses: radio receivers and magnetometers.
  - Cosmic ray showers. Witness: Cosmic-ray detectors.

PAPER • OPEN ACCESS

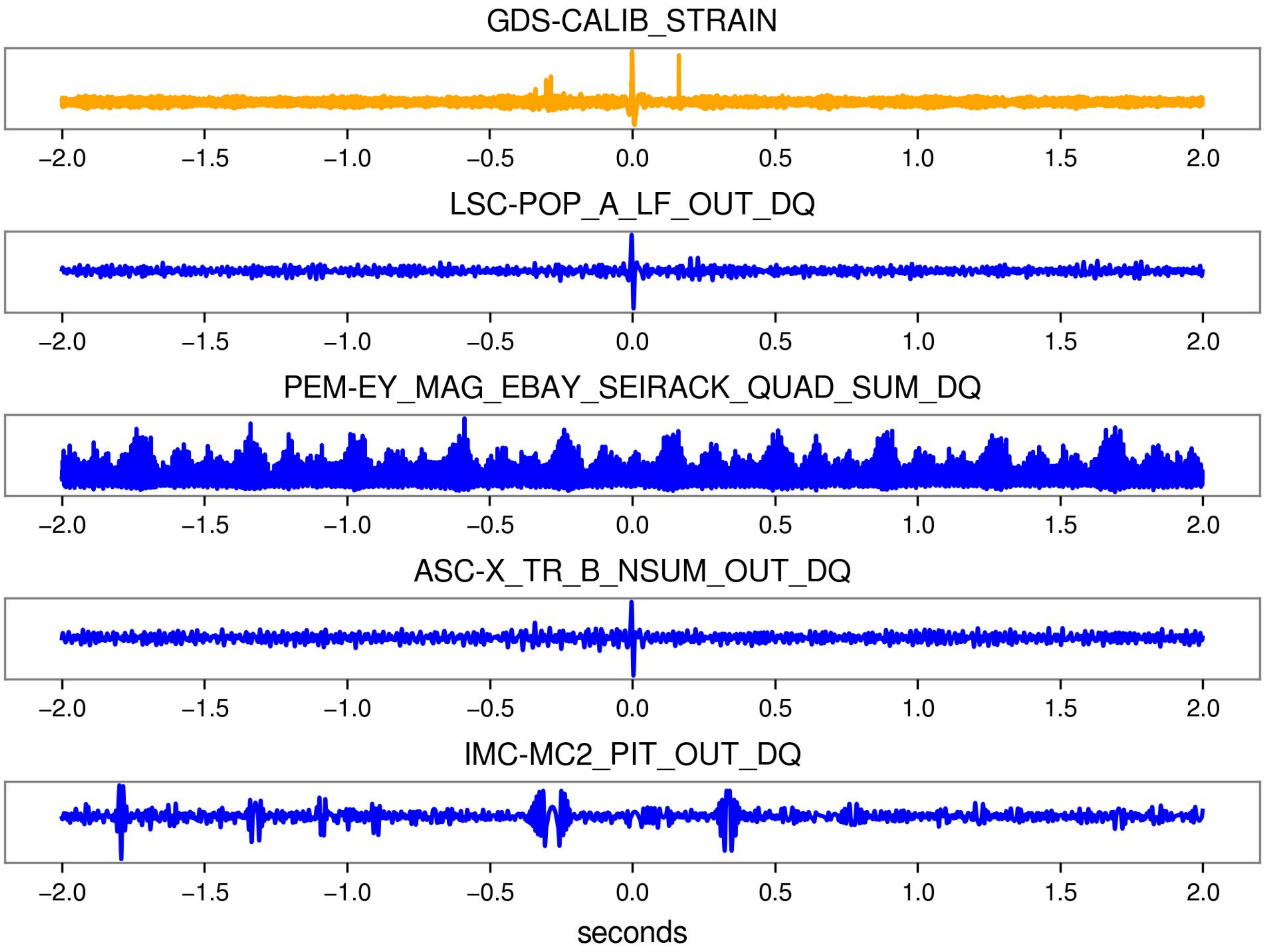
Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914

B P Abbott[1], R Abbott[1], T D Abbott[2], M R Abernathy[1], F Acernese[3,4], K Ackley[5], M Adamo[4,6], C Adams[7], T Adams[8], P Addesso[3] + Show full author list

Published 6 June 2016 • © 2016 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 33, Number 13

Citation B P Abbott *et al* 2016 *Class. Quantum Grav.* **33** 134001


GDS-CALIB_STRAIN
LSC-POP_A_LF_OUT_DQ
PEM-EY_MAG_EBAY_SEIRACK_QUAD_SUM_DQ
ASC-X_TR_B_NSUM_OUT_DQ
IMC-MC2_PIT_OUT_DQ
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
seconds

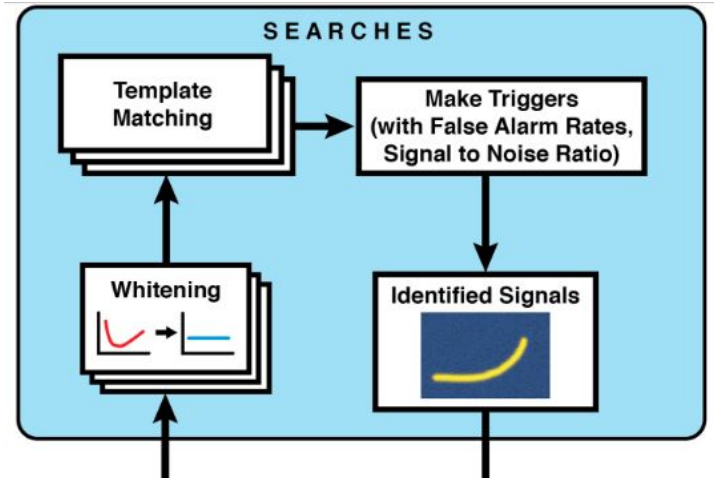
Data quality flags and vetoes

- If mitigating the noise source is not viable, or for data collected prior to a fix, periods of time with significant problems are vetoed. But not all impaired data are thrown away!
- Data quality flags identify periods of data from ~ 1 second to hours associated with known noise couplings.
- Data quality triggers are generated by algorithms through statistical correlations with auxiliary channels.
- Vetoes belong to different categories depending on the severity of the problem or the impact on a search:
    - Category 1 flags indicate times when data should not be analyzed due to a critical issue.
    - Category 2 flags indicate times when noise sources with known physical coupling to $h(t)$ are active.
    - Category 3 flags identify times where the impact is less severe.
- Safety: Likelihood that the veto would accidentally remove a true signal. It is measured using hardware injection tests. If a channel witnesses a number of injected signals greater than expected by chance it is considered unsafe.
- Veto metrics:
    - Efficiency: Fraction of background triggers it removes from a search
    - Deadtime: Fraction of time a particular flag is active.
    - Category 2 vetoes have an efficiency-to-deadtime ratio for high SNR triggers significantly greater than 1 (the value expected for random behavior)

B P Abbott *et al* 2016 *Class. Quantum Grav.* 33 134001

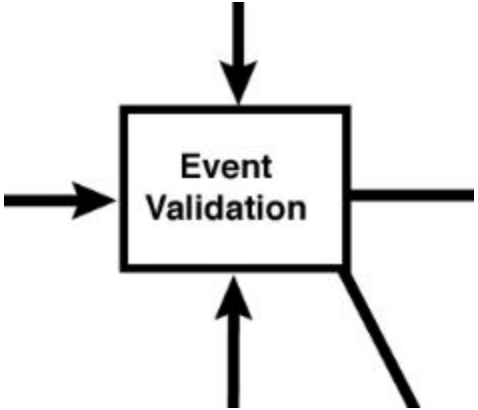
The Middle of the Process

Part IV: Searches



See Pablo Cerdá-Durán’s tutorial tomorrow and Patricia Schmidt’s tutorial and next Tuesday!

Part V: Event validation



Online event validation in the O3 LIGO-Virgo observing run

Superevent Informati[on]	
Superevent ID	S2003[1]1bq
Category	Produc[tion]
Labels	DQOK EM_READY ADVOK EM_Selected EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT PE_READY
t_{start}	1267963150.37
t_0	1267963151.40
t_{end}	1267963152.44
Submitted ▾	2020-03-11 11:59:09 UTC
Links	Data

EM advocate says event is okay.
Added by: Geoffrey Mo
Added: March 11, 2020, 12:15 p.m.

LIGO-Virgo Rapid Response Team

Analyst Comments | Data Quality | Sky Localization | External Coincidence | EM Followup

Analyst Comments

Log Comment

RRT minutes as PDF, updated to include chat text. (S200311bg RRT Minutes.pdf)

— Submitted by Jenne Driggers on March 11, 2020 17:04:24 UTC

Log Comment

RRT minutes: https://docs.google.com/document/d/1TFNX3n7ZfaXmZzTuundu5rYGhmw5pFRhDtM6jcaPuYo/edit

(S200311bg_RRT.mp3)

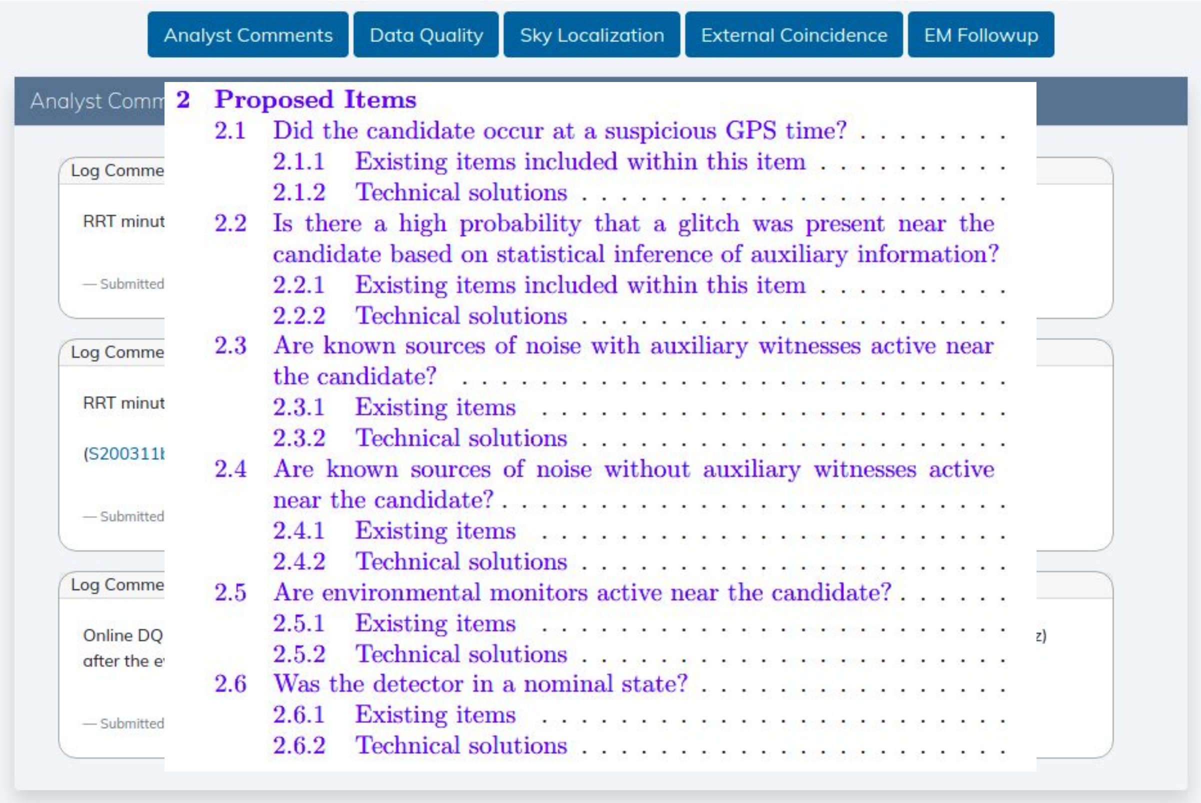
— Submitted by Geoffrey Mo on March 11, 2020 12:34:14 UTC

Log Comment

Online DQ report - H1 and L1 both look clean around the time of the event. There is some slight noise at 1.2s (below 100Hz) after the event at H1 in case anyone uses data after the event time.

— Submitted by Laura Nuttall on March 11, 2020 12:16:24 UTC

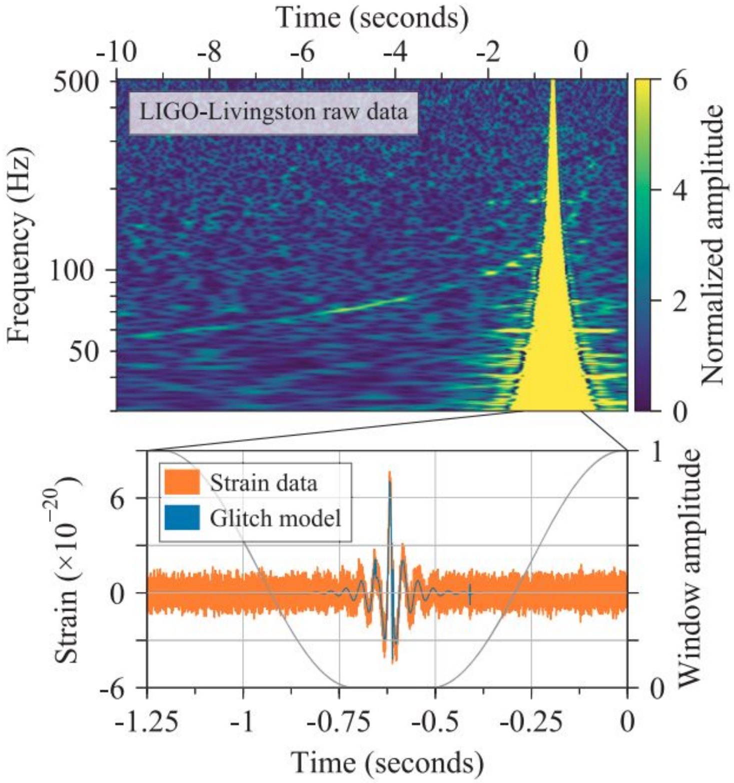
LIGO-Virgo Rapid Response Team



2 Proposed Items

Offline event validation

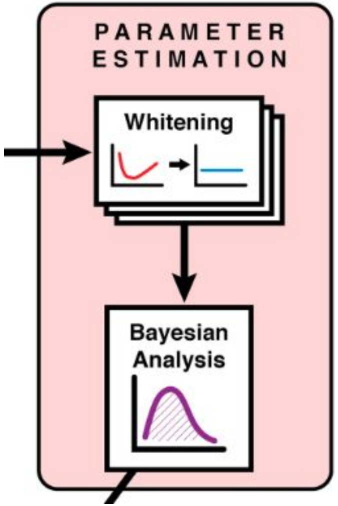
- Additional data quality investigations may be necessary for some gravitational-wave candidates before performing signal parameter estimation, for example glitch modeling and subtraction.
- An example of glitch-subtraction procedure is BayesWave, where the non-Gaussian (incoherent) noise is modeled as a linear combination of wavelets and then subtracted from the data.
- When subtraction is not possible, customized configurations of analysis pipelines are used to exclude the time period or frequency bandwidth impacted by glitches.



N. J. Cornish and T. B. Littenberg, Class. Quant. Grav. 32, 1350124501 (2015).

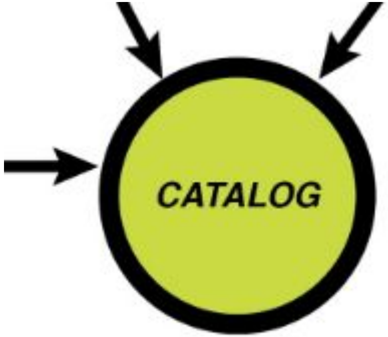
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. 119, 161101

Part VI and VI-B: Parameter Estimation and Bayesian Analysis



See Sylvia Biscoveanu's tutorial next Monday!

Part VII: The Final Product



PHYSICAL REVIEW X **11,** 021053 (2021)

GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run

R. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 30 October 2020; revised 23 February 2021; accepted 20 April 2021; published 9 June 2021; corrected 1 September 2021)

We report on gravitational-wave discoveries from compact binary coalescences detected by Advanced LIGO and Advanced Virgo in the first half of the third observing run (O3a) between 1 April 2019 15:00 UTC and 1 October 2019 15:00 UTC. By imposing a false-alarm-rate threshold of two per year in each of the four search pipelines that constitute our search, we present 39 candidate gravitational-wave events. At this threshold, we expect a contamination fraction of less than 10%. Of these, 26 candidate events were reported previously in near-real time through gamma-ray coordinates network notices and circulars; 13 are reported here for the first time. The catalog contains events whose sources are black hole binary mergers up to a redshift of approximately 0.8, as well as events whose components cannot be unambiguously identified as black holes or neutron stars. For the latter group, we are unable to determine the nature based on estimates of the component masses and spins from gravitational-wave data alone. The range of candidate event masses which are unambiguously identified as binary black holes (both objects $\geq 3\ M_{\odot}$) is increased compared to GWTC-1, with total masses from approximately $14\ M_{\odot}$ for GW190924_021846 to approximately $150\ M_{\odot}$ for GW190521. For the first time, this catalog includes binary systems with significantly asymmetric mass ratios, which had not been observed in data taken before April 2019. We also find that 11 of the 39 events detected since April 2019 have positive effective inspiral spins under our default prior (at 90% credibility), while none exhibit negative effective inspiral spin. Given the increased sensitivity of Advanced LIGO and Advanced Virgo, the detection of 39 candidate events in approximately 26 weeks of data (approximately 1.5 per week) is consistent with GWTC-1.

DOI: 10.1103/PhysRevX.11.021053 Subject Areas: Gravitation

See Salvo Vitale's tutorial next Monday!

The End of the Tutorial

"Try and be nice to people, avoid eating fat, read a good book every now and then, get some walking in, and try and live together in peace and harmony with people of all creeds and nations"

-- Monty Python, The Meaning of Life