Pursuing gravitational waves with Advanced LIGO

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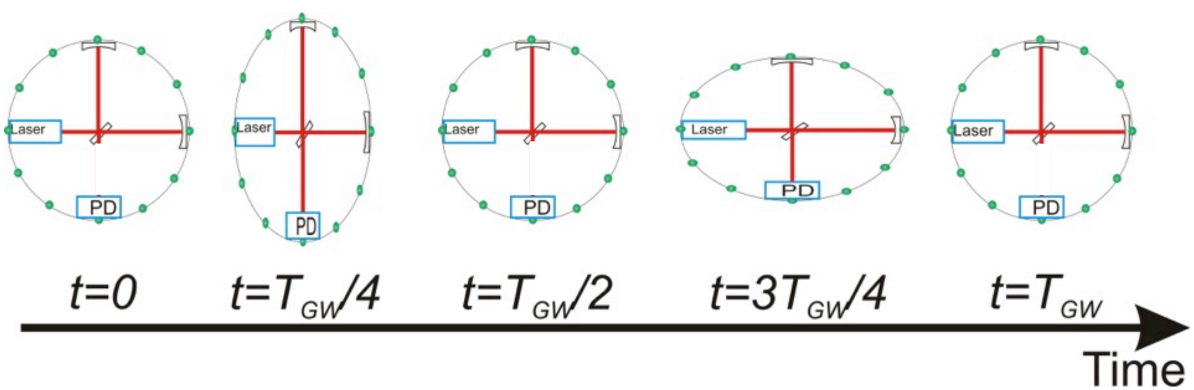
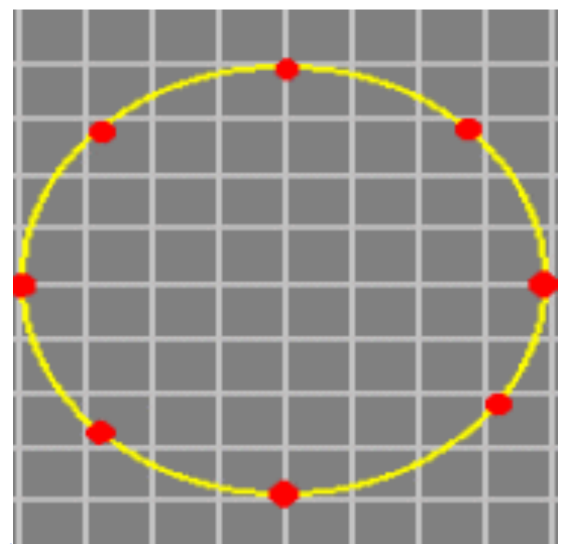
Outline

- Some basics on gravitational waves and astrophysical sources
- LIGO
  - » Two slides on past results
  - » Advanced LIGO status: *installation* and *commissioning*
- The future
  - » Near-term observation scenario
  - » A global network

Gravitational waves

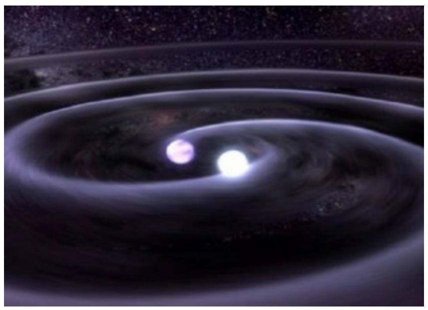
- Predicted by Einstein's theory of gravity, General Relativity, in 1916
- Generated by changing quadrupole moments such as in co-orbiting objects, spinning asymmetric objects
- Interact weakly with matter - even densest systems transparent to gravitational waves
- An entirely new spectrum in which to explore the universe

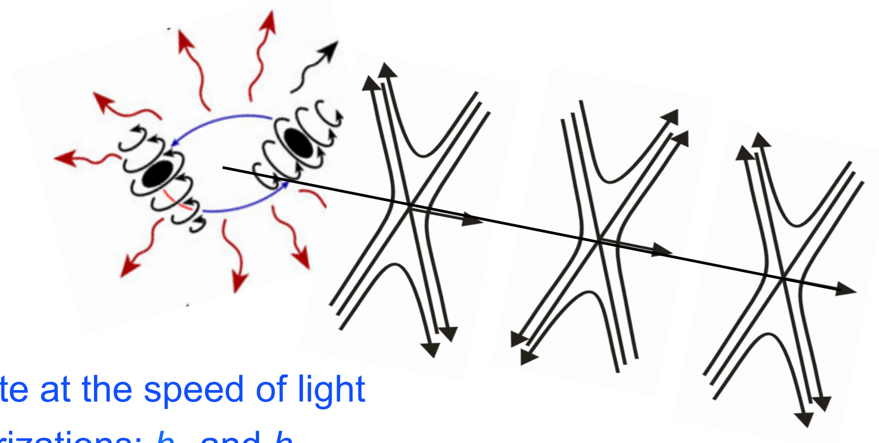




Gravitational waves

- Practically, need astrophysical objects moving near the speed of light

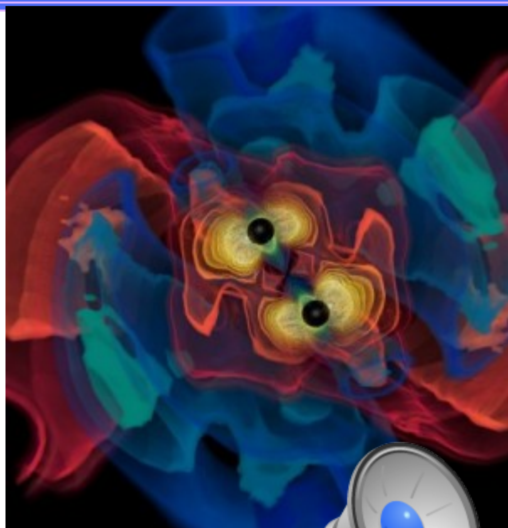




  - According to GR, GWs propagate at the speed of light
  - Quadrupolar radiation; two polarizations: h_+ and h_x
- Physically, gravitational waves are *strains*: $$h = \frac{\Delta L(f)}{L}$$
- Sense of scale: strain from a binary neutron star pair
  - M = 1.4 M⊙, $r = 10^{23}$ m (15 Mpc, Virgo), R = 20 km, f_{orb} = 400 Hz

$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

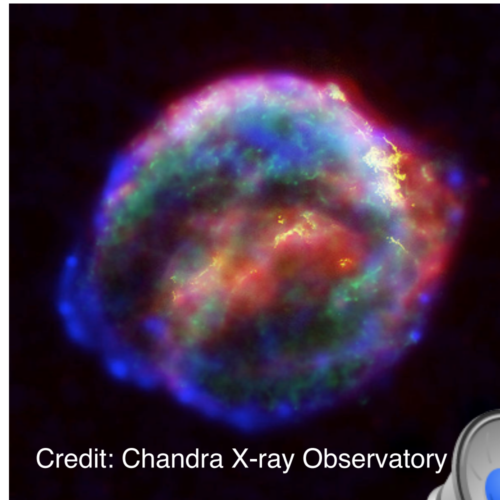
LIGO Astrophysical Sources of Gravitational Waves



Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

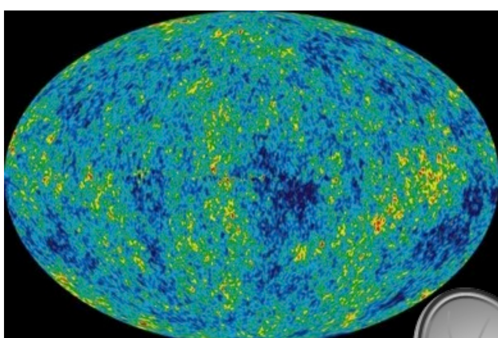
- Strong emitters, well-modeled,
- (effectively) transient



Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

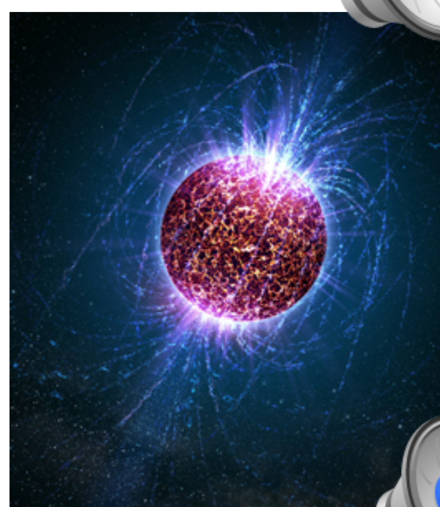
- Weak emitters, not well-modeled ('bursts'), transient
- Also: cosmic strings, SGRs, pulsar glitches



NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang
- Long duration, stochastic background



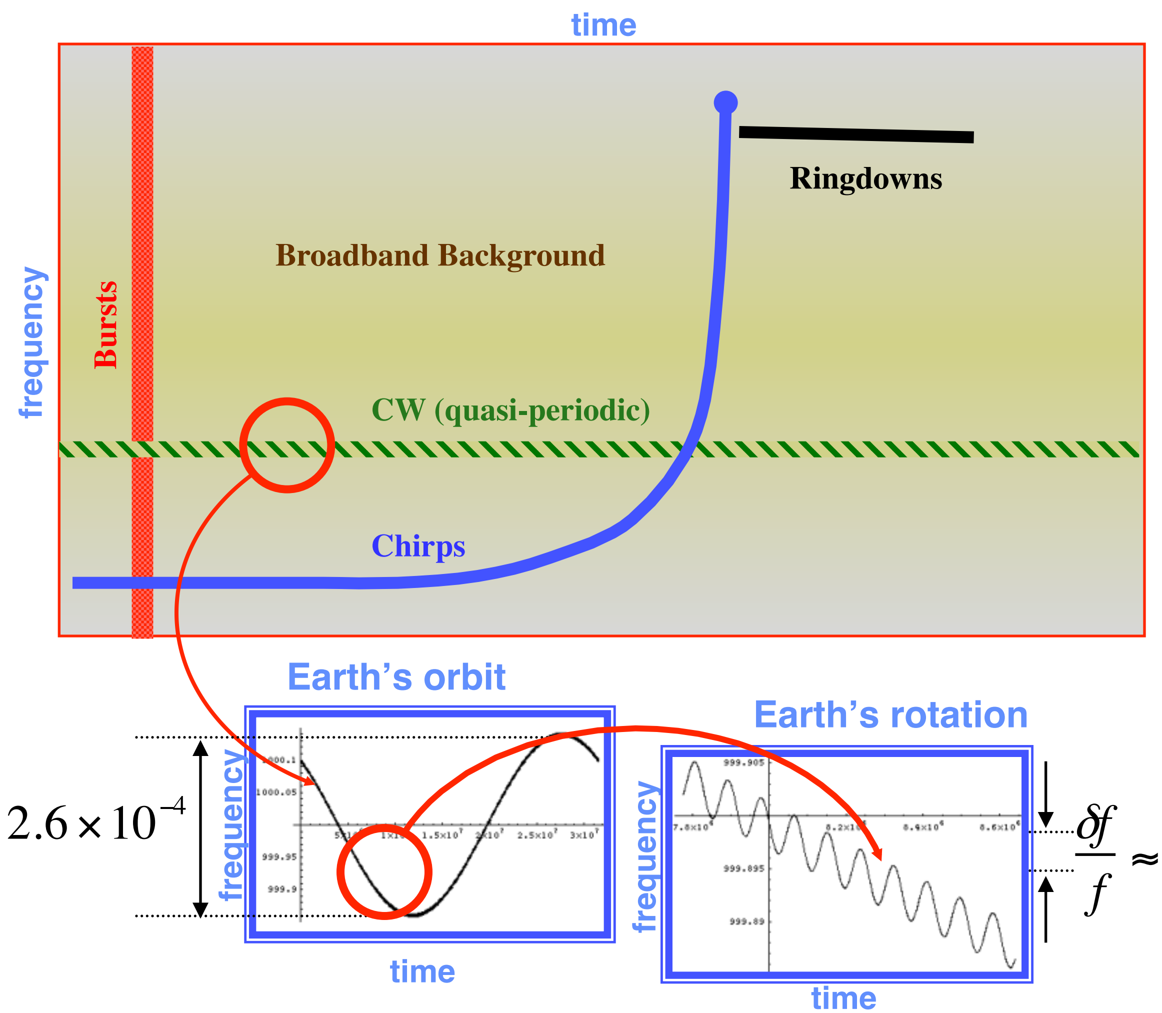
Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform
- Long duration

Audio credit: E. Thrane, CIT

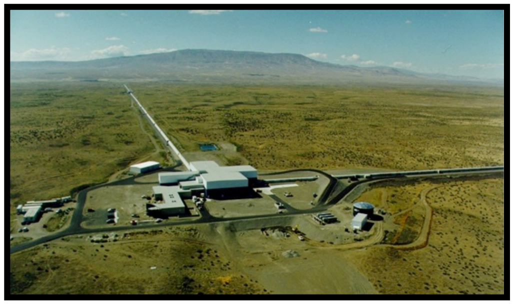
Frequency-Time Characteristics of GW Sources



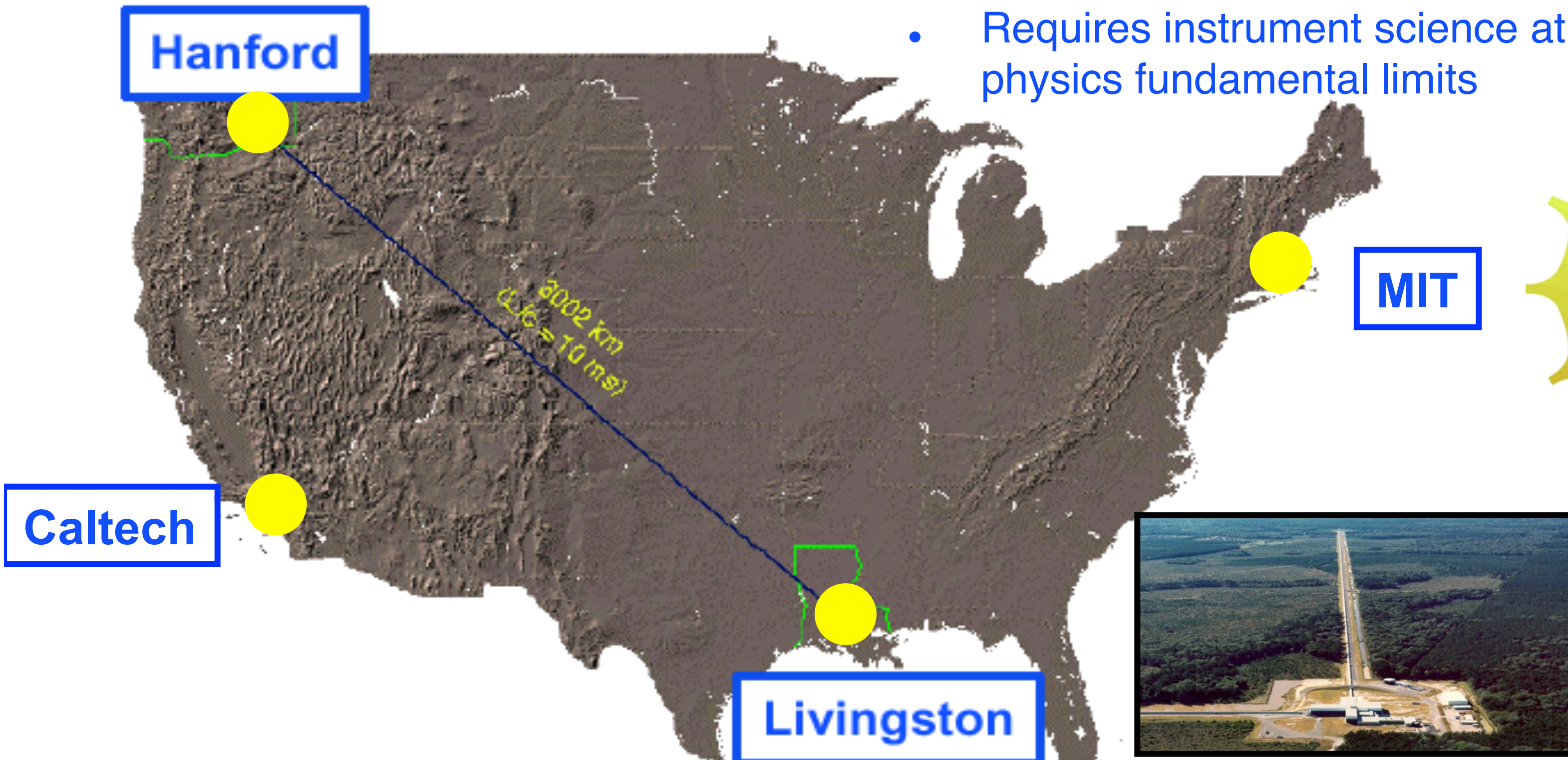
$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

LIGO Laboratory: two Observatories, Caltech and MIT campuses



- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



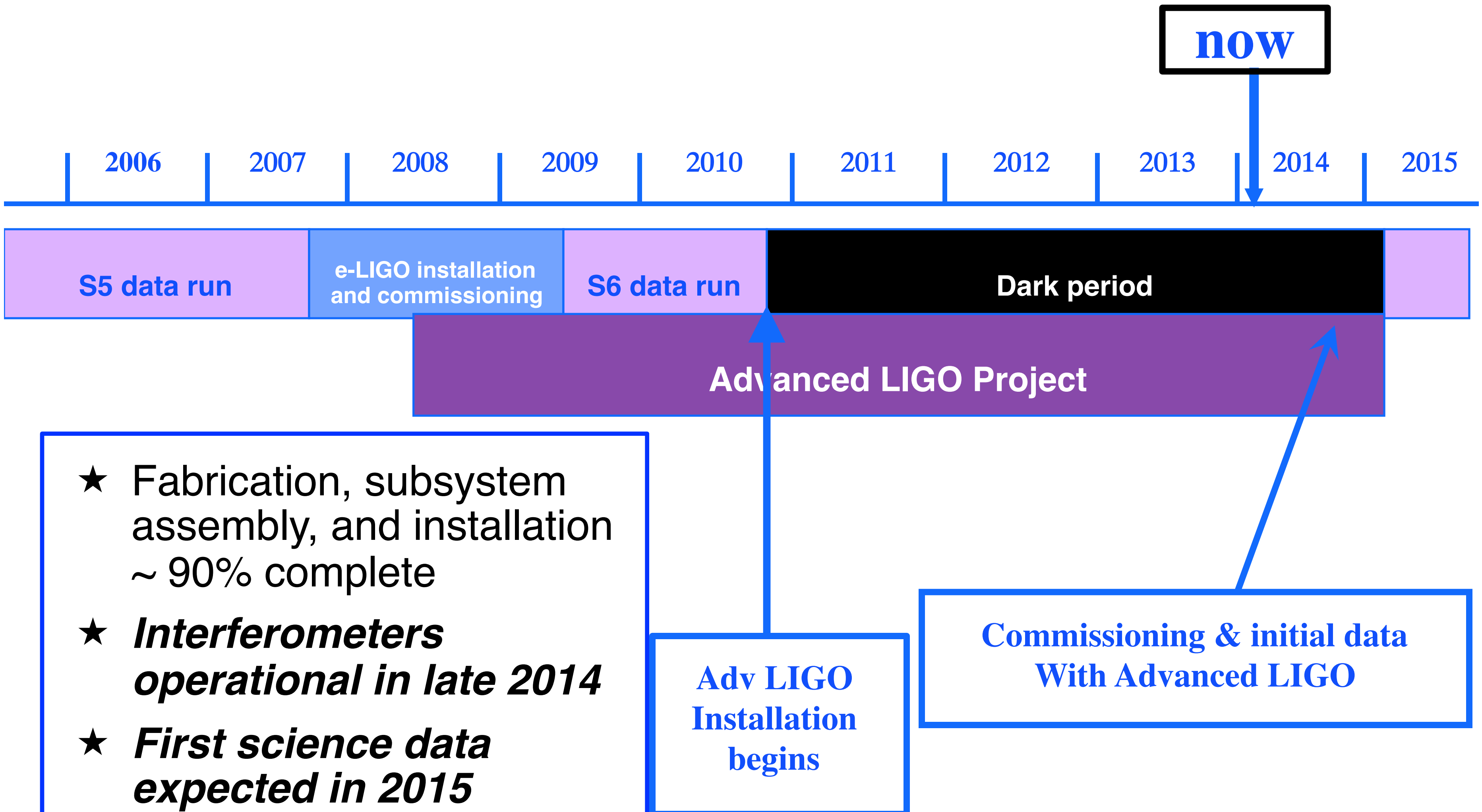
LIGO Scientific Collaboration

- 900+ members, 80+ institutions, 17 countries

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Univ. of Cambridge
- Canadian Institute for Theoretical Astrophysics and Perimeter Institute for Theoretical Physics
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- CSU Fullerton
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd Univ.
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Hanyang University
- Korea Institute of Science and Tech Information
- Leibniz Universität Hannover
- Lund University
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola Univ. of New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- McNeese State University
- Univ. of Melbourne
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Montclair State University
- Moscow State University
- National Astronomical Observatory of Japan
- National Inst. of Mathematical Sciences
- University of New Hamshire
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Pusan National University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- Seoul National University
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- USC - Information Sciences Institute
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Tsinghua University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

LIGO time line



- ★ Fabrication, subsystem assembly, and installation ~ 90% complete
- ★ ***Interferometers operational in late 2014***
- ★ ***First science data expected in 2015***

Publications list at ligo.org

LSC Observational and Instrument Publications

Link to collaboration authored Conference proceedings

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Contact: lsc-pp @ ligo.org

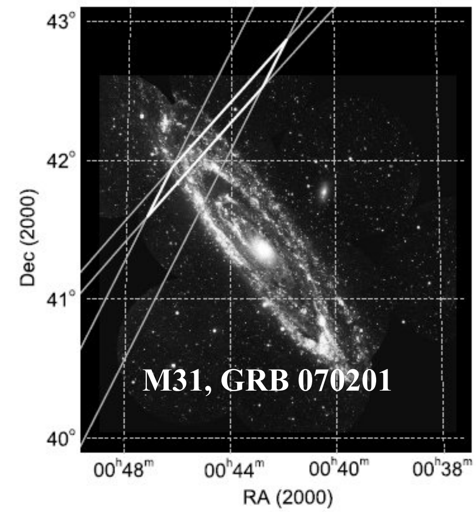
Observational and LSC instrument papers

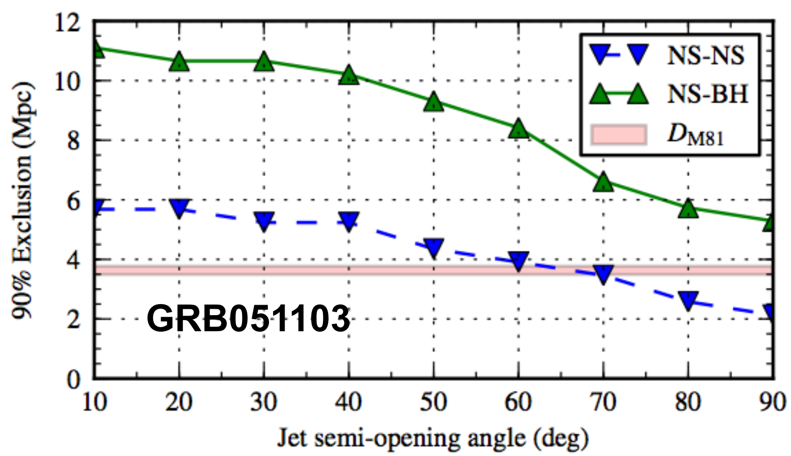
[Papers currently in LSC review]

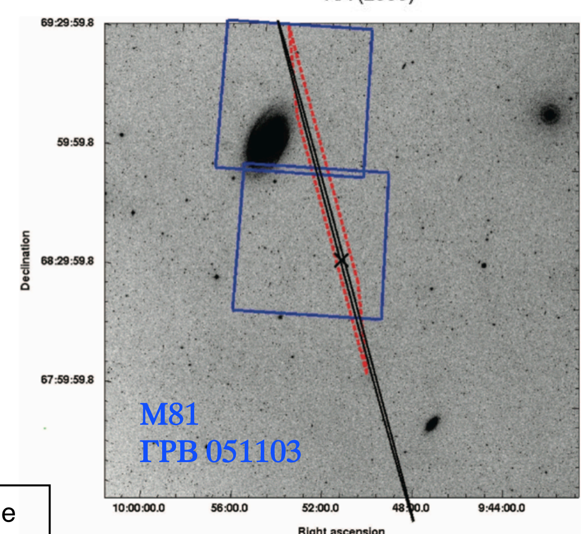
58	VSR2	CW	LSC, Virgo	Astrophys. J. **737** (2011) 93	arXiv:1104.2712	-	*Beating the spin-down limit on gravitational wave emission fr*
59	na	Instrum	LSC	Nature Physics **7** (2011) 962	-	-	*A gravitational wave observatory operating beyond the quantu*
60	S5	Stochastic	LSC, Virgo	Phys. Rev. Lett. **107** (2011) 271102	arXiv:1109.1809	-	*Directional limits on persistent gravitational waves using LIGO*
61	S6/VSR3	CBC/Bursts	LSC, Virgo	Astron Astrophys **539** (2012) A124	arXiv:1109.3498	-	*Implementation and testing of the first prompt search for grav*
62	S5	CW	LSC, Virgo	Phys. Rev. D**85** (2012) 022001	arXiv:1110.0208	-	*All-sky search for periodic gravitational waves in the full S5 L*
63	S6/VSR2-3	CBC	LSC, Virgo	Phys. Rev D**85** (2012) 082002	arXiv:1111.7314	P1100034	*Search for Gravitational Waves from Low Mass Compact Bina*
64	S6/VSR2-3	CBC	LSC, Virgo	non-journal companion to paper 63	arXiv:1203.2674	T1100338	*Sensitivity Achieved by the LIGO and Virgo Gravitational Wa*
65	S6/VSR3	CBC	LSC, Virgo	Astron Astrophys **541** (2012) A155	arXiv:1112.6005	P1100065	*First Low-Latency LIGO+Virgo Search for Binary Inspirals and*
66	S5/VSR1	Stochastic	LSC, Virgo	Phys. Rev. D **85** (2012) 122001	arXiv:1112.5004	P1000128	*Upper limits on a stochastic gravitational-wave background us*
67	pre-S5	Bursts/CBC	LSC	Astrophys. J. **755** (2012) 2	arXiv:1201.4413	P1000097	*Implications for the Origin of GRB 051103 from LIGO Observa*
68	S5/VSR1	Bursts	LSC, Virgo	Phys. Rev. D **85** (2012) 102004	arXiv:1201.5999	P1100068	*Search for Gravitational Waves from Intermediate Mass Bina*
69	S6/VSR2-3	Bursts	LSC, Virgo	Phys. Rev. D **85** (2012) 122007	arXiv:1202.2788	P1100118	*All-sky search for gravitational-wave bursts in the second join*
70	VSR1-3	DetChar	LSC, Virgo	Class. Quantum Grav. 29 (2012) 155002	arXiv:1203.5613	-	*Virgo data characterization and impact on gravitational wave s*
71	S6/VSR2-3	Bursts	LSC, Virgo, Swift	ApJS 203 (2012) 28	arXiv:1205.1124	P1100038	*Swift Follow-Up Observations Of Candidate Gravitational-Wav*
72	S6/VSR2-3	Bursts/CBC	LSC, Virgo, others	Astrophys. J. **760** (2012) 12	arXiv:1205.2216	P1000121	*Search for gravitational waves associated with gamma-ray bu*
73	S5/VSR1	Bursts	LSC, Virgo, ANTARES	JCAP **1306** (2013) 008	arXiv:1205.3018	P1200006	*A first search for coincident gravitational waves and high ener*
74	S5	CW	LSC, Virgo	Phys. Rev. D **87** (2013) 042001	arXiv:1207.7176	P1200026	*Einstein@Home all-sky search for periodic gravitational wave*
75	S6/VSR2-3	CBC	LSC, Virgo	Phys. Rev. D **87** (2013) 022002	arXiv:1209.6533	P1200024	*Search for Gravitational Waves from Binary Black Hole Inspir*
76	na	Instrum	LSC	Nature Photonics **7** (2013) 613	arXiv:1310.0383	P1200041	*Enhanced sensitivity of the LIGO gravitational wave detector*
77	ADE	CBC/Bursts	LSC, Virgo	submitted for publication	arXiv:1304.0670	P1200087	*Prospects for Localization of Gravitational Wave Transients b*
78	S6/VSR2-3	CBC	LSC, Virgo	Phys. Rev. D **88**(2013) 062001	arXiv:1304.1775	P1200021	*Parameter estimation for compact binary coalescence signals*
79	S5/S6	CW	LSC, Virgo	submitted for publication	arXiv:1309.4027	P1200104	*Gravitational-waves from known pulsars: results from the initi*
80	S5	CW	LSC, Virgo	Phys. Rev. D **88**(2013) 102022	arXiv:1309.6221	P1300037	*A directed search for continuous Gravitational Waves from th*
81	S5	Stoch	LSC, Virgo	Phys. Rev. D **88**(2013) 122004	arXiv:1309.6160	P1200093	*Search for long-lived gravitational-wave transients coincident*
82	S6/VSR3	Bursts	LSC, Virgo	submitted for publication	arXiv:1310.2314	P1200171	*First Searches for Optical Counterparts to Gravitational-wave*
83	S6/VSR3	Bursts	LSC, Virgo	submitted for publication	arXiv:1310.2384	P1300093	*Constraints on cosmic (super)strings from the LIGO-Virgo gra*
84	S6/VSR3	CW	LSC, Virgo	submitted for publication	arXiv:1311.2409	P1300071	*Application of a Hough search for continuous gravitational wa*
85	na	CBC/Bursts	LSC, Virgo	submitted for publication	arXiv:1401.0939	P1300199	*The NINJA-2 project: Detecting and characterizing gravitation*

Searches for GWs from known nearby GRB sources

- GRB050311, GRB070201: short GRBs with sky localizations that overlap nearby galaxies
  - » GRB050311 overlap with M81 (3.6 Mpc)
  - » GRB070201 overlap with M31 (770 kpc)
- Binary coalescence in M31 excluded at >99% confidence level
- BNS coalescence in M81 excluded at 98% confidence level





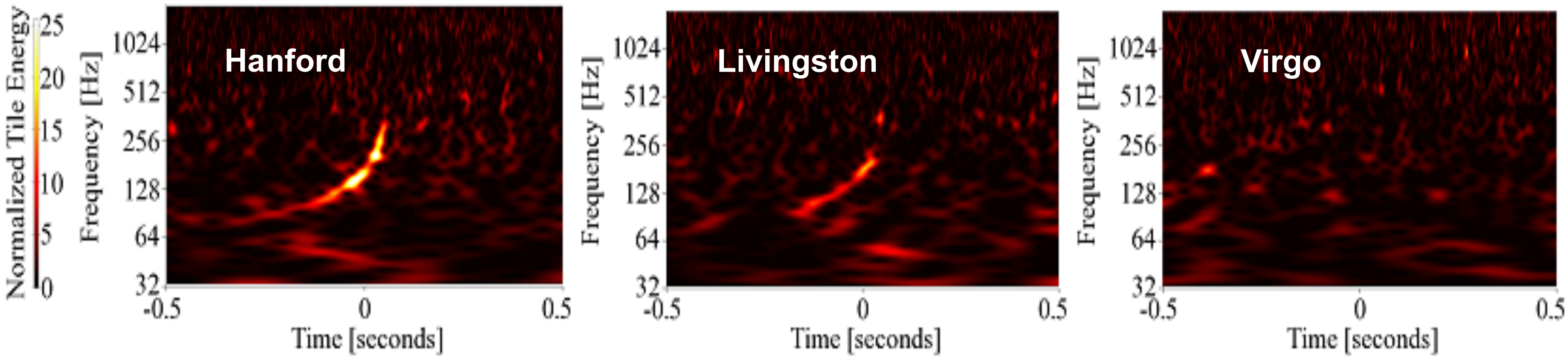


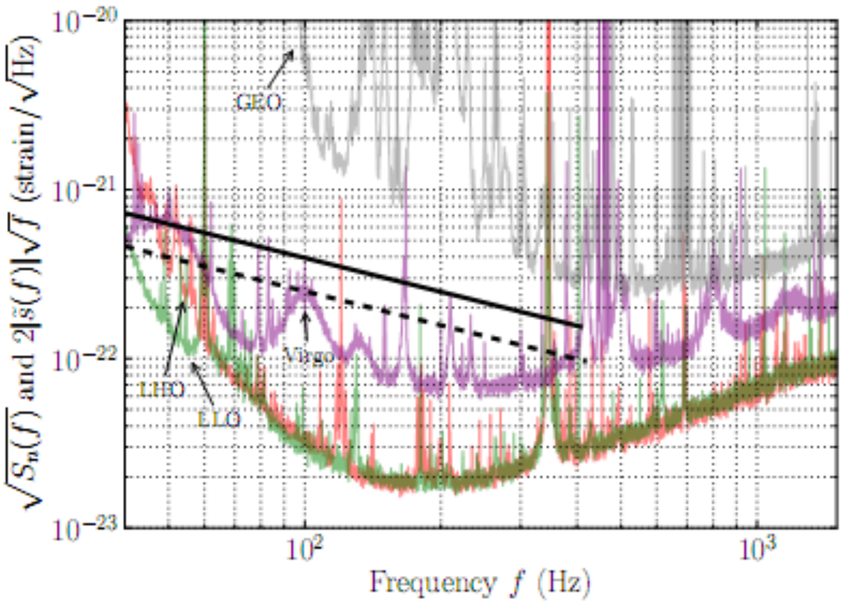
LIGO Scientific Collaboration, K. Hurley, "Implications for the Origin of GRB 070201 from LIGO Observations", Astrophys. J. **681** (2008) 1419

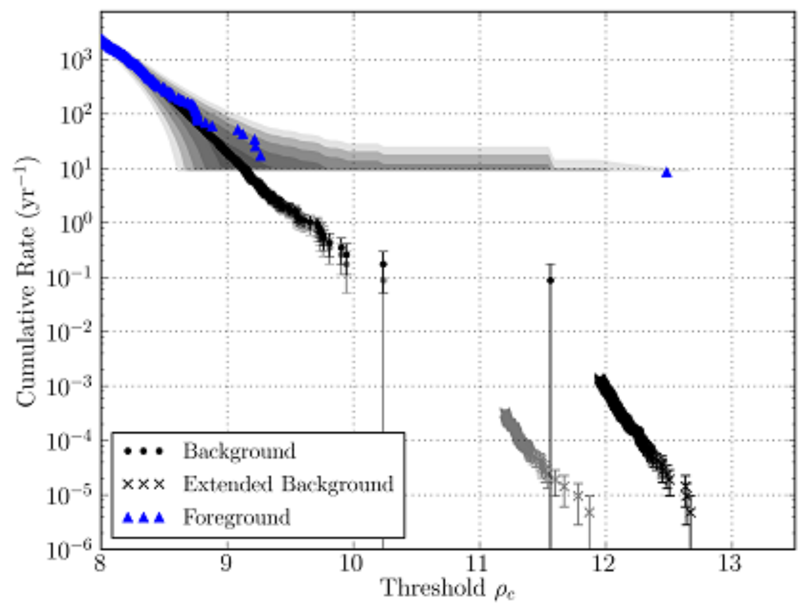
LIGO Scientific Collaboration, "Implications for the Origin of GRB 051103 from LIGO Observations", **Astrophys. J. 755** (2012) 2

'Event' GW100916 – A Blind Injection

http://www.ligo.org/science/GW100916/

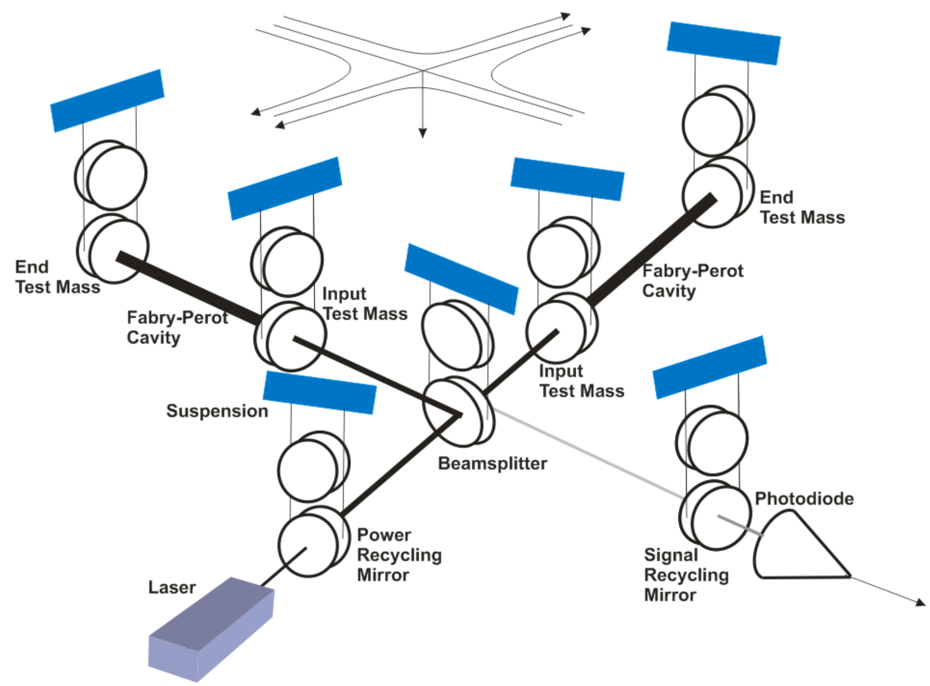


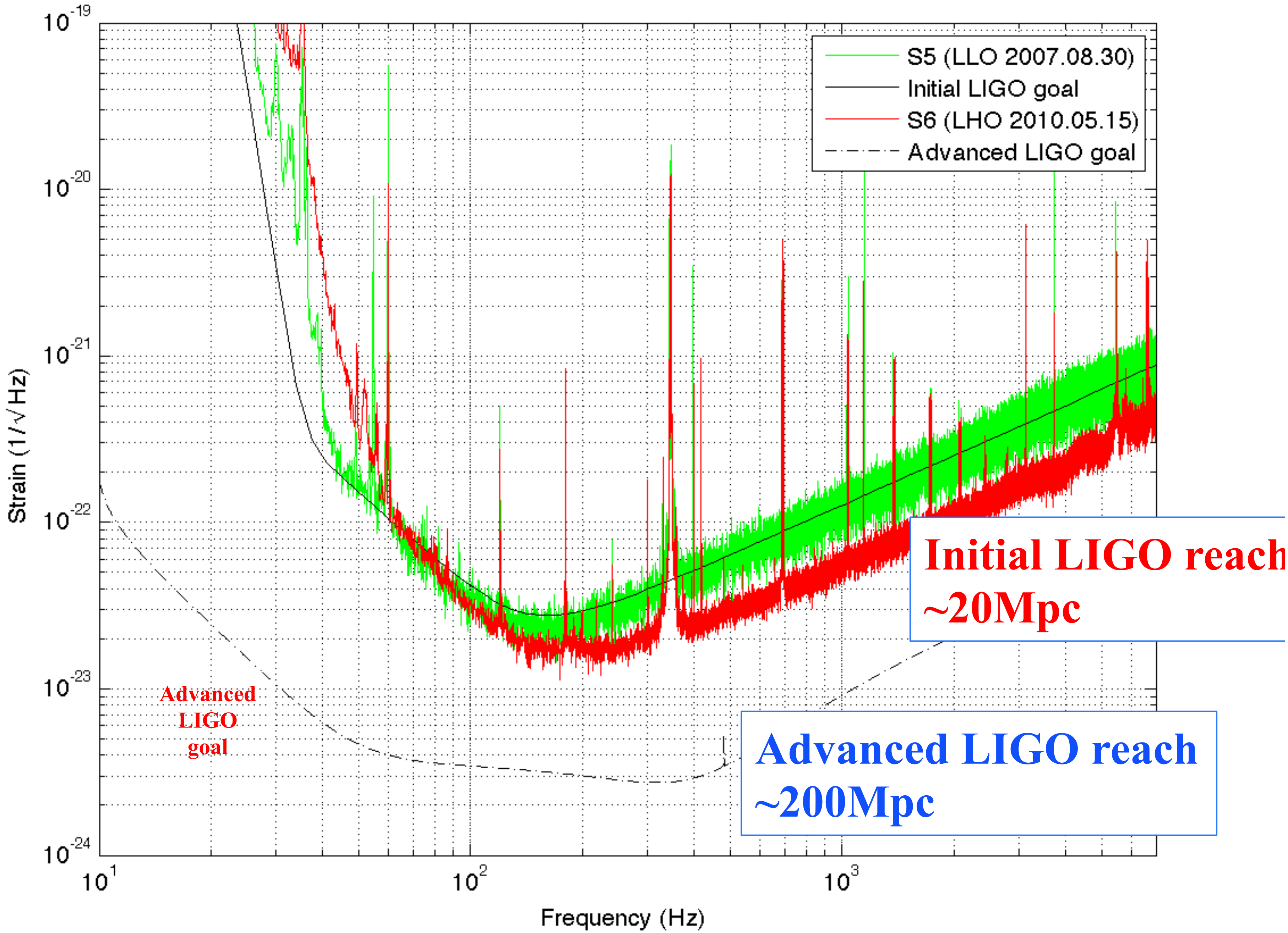




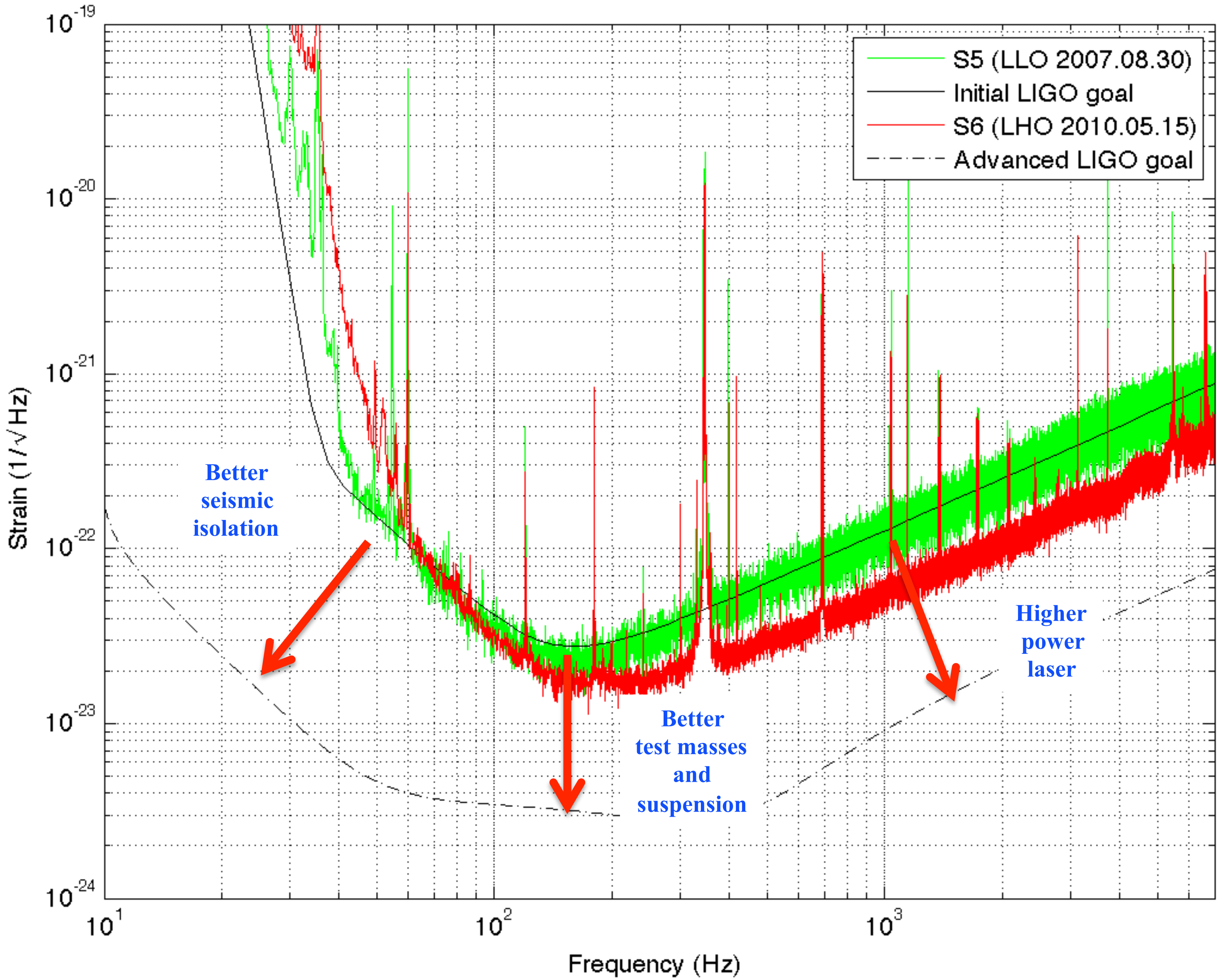
Advanced LIGO

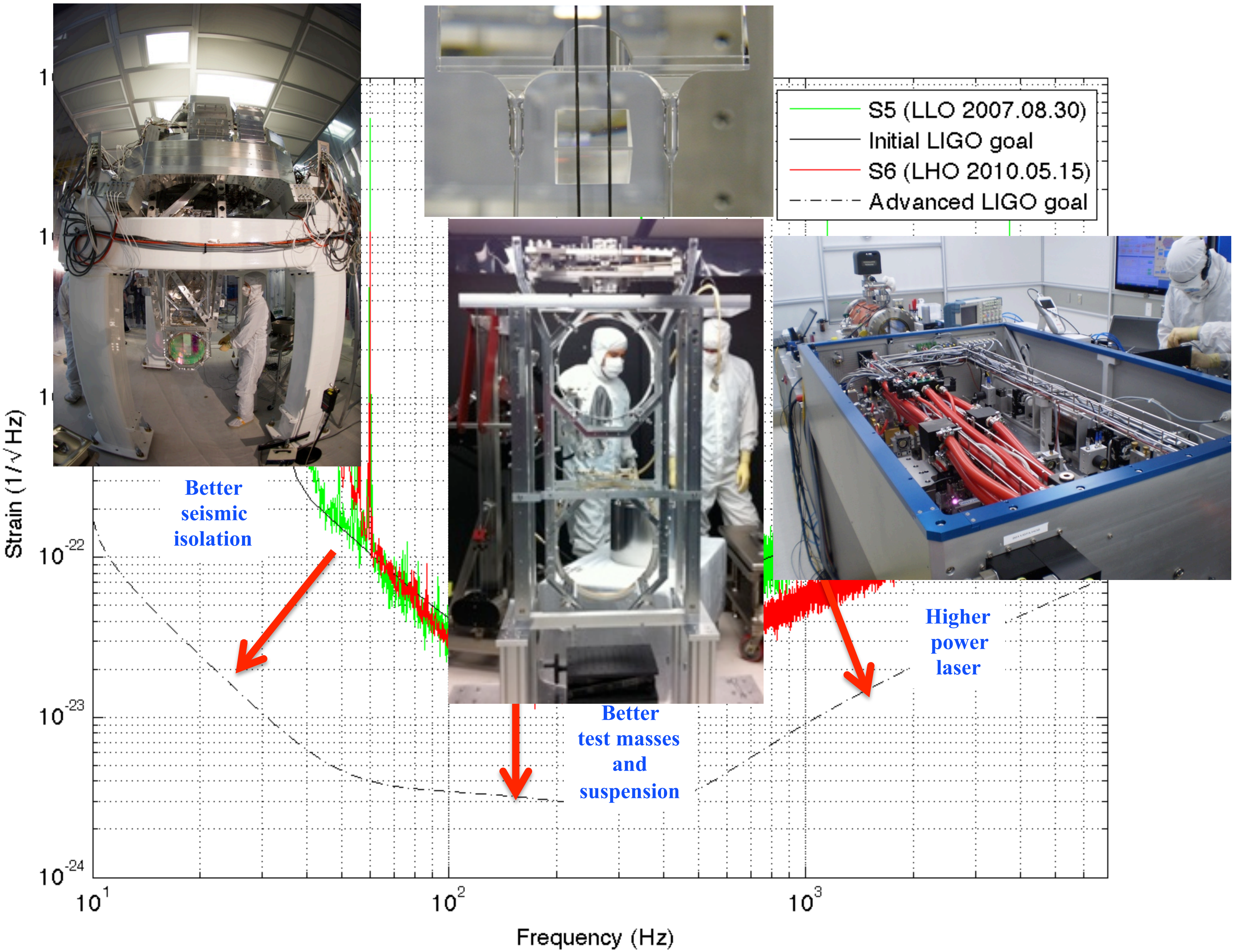
- Power recycled Fabry-Perot Michelson with Signal recycling (increase sensitivity, add tunability)
- Active seismic isolation, quadruple pendulum suspensions (seismic noise wall moves from 40Hz to 10Hz)
- DC readout, Output Mode Cleaner (better use of photons)
- ~20x higher input power (lower shot noise)
- 40 kg test masses (smaller motion due to photon pressure fluctuations)
- Larger test mass surfaces, low-mechanical -loss optical coatings (decreased mid-band thermal noise)
- Fused Silica Suspension (decreased low-frequency thermal noise)





S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3
Advanced LIGO goal
Initial LIGO reach ~20Mpc
Advanced LIGO reach ~200Mpc


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Better seismic isolation
Better test masses and suspension
Higher power laser
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3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10^-22
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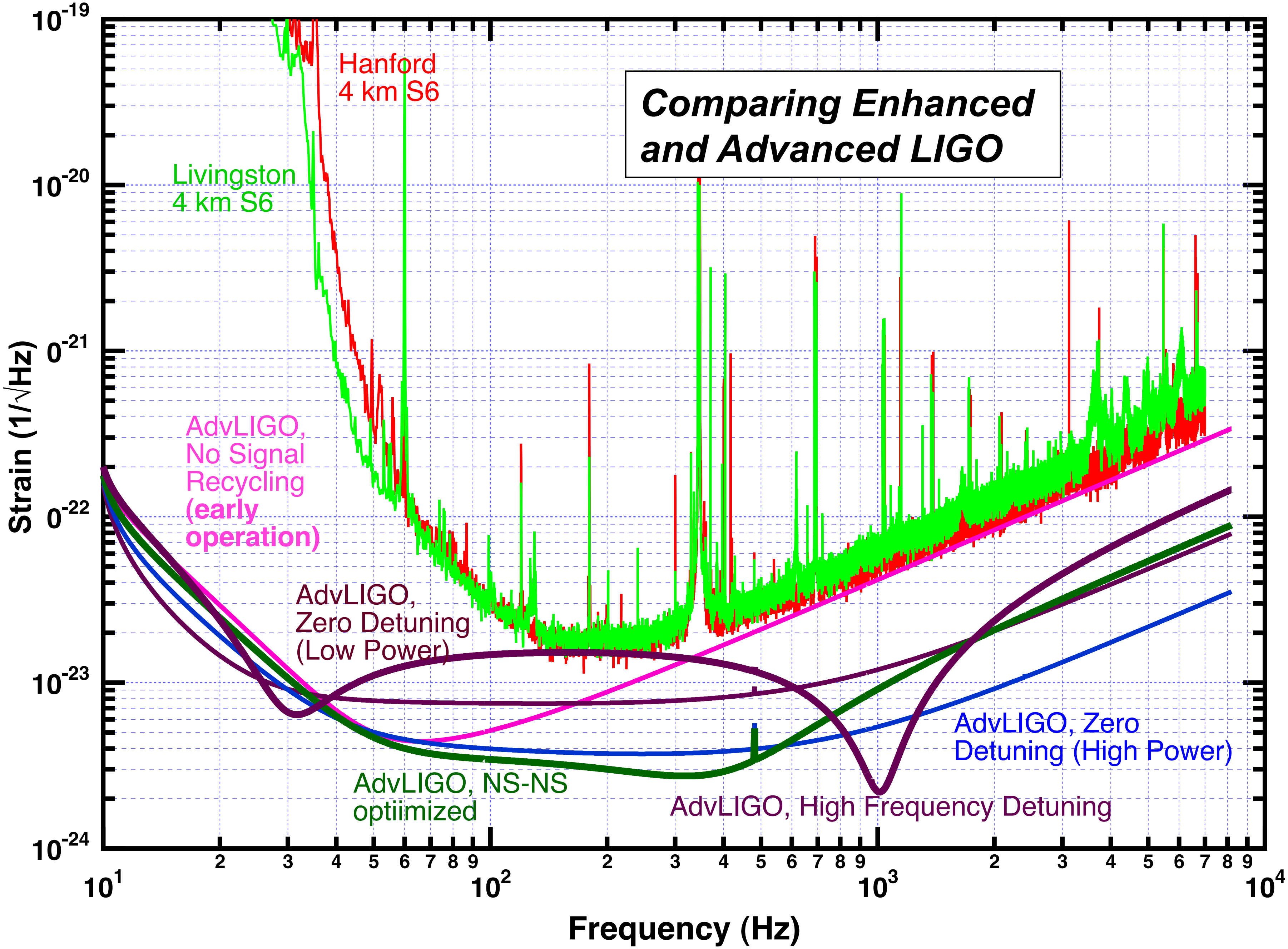
10^2
10^3



Comparing Enhanced and Advanced LIGO
Hanford 4 km S6
Livingston 4 km S6
AdvLIGO, No Signal Recycling (early operation)
AdvLIGO, Zero Detuning (Low Power)
AdvLIGO, NS-NS optiimized
AdvLIGO, High Frequency Detuning
AdvLIGO, Zero Detuning (High Power)
Strain (1/√Hz)
Frequency (Hz)

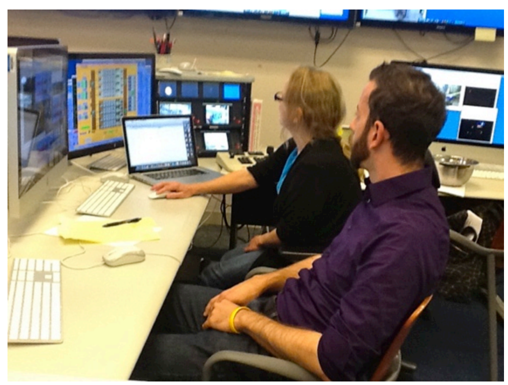
Phases in installation

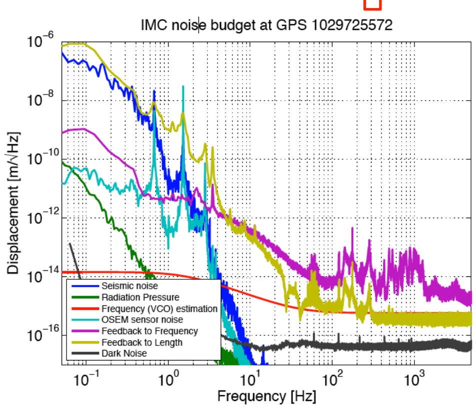
deinstall

modify vacuum

in-chamber clean

install



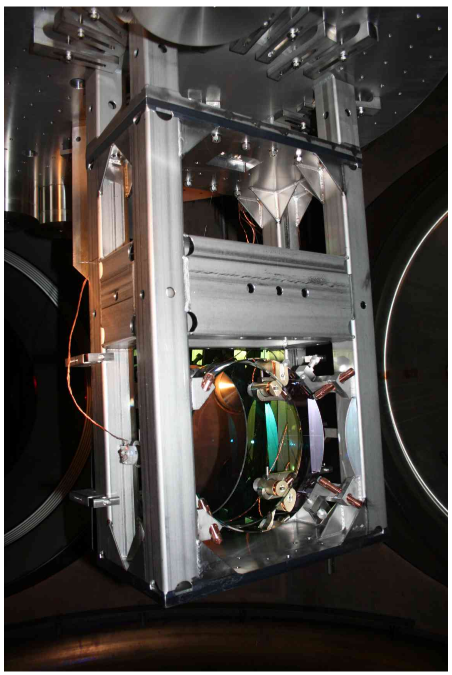


commission

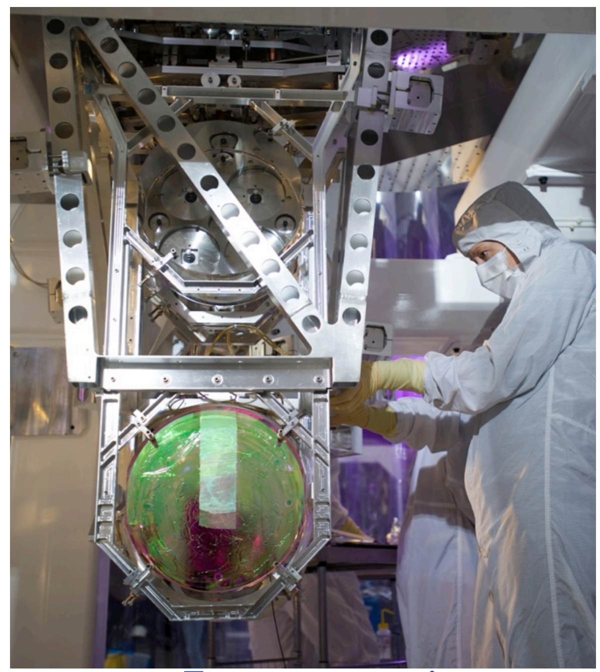
10X more sensitive, >10X harder…

- 14 unique fabricated parts
- 68 fabricated parts total
- 165 total including machined parts and hardware

- 188 unique fabricated parts
- 1569 fabricated parts total
- 3575 total including machined parts and hardware



Test mass suspension From Initial LIGO

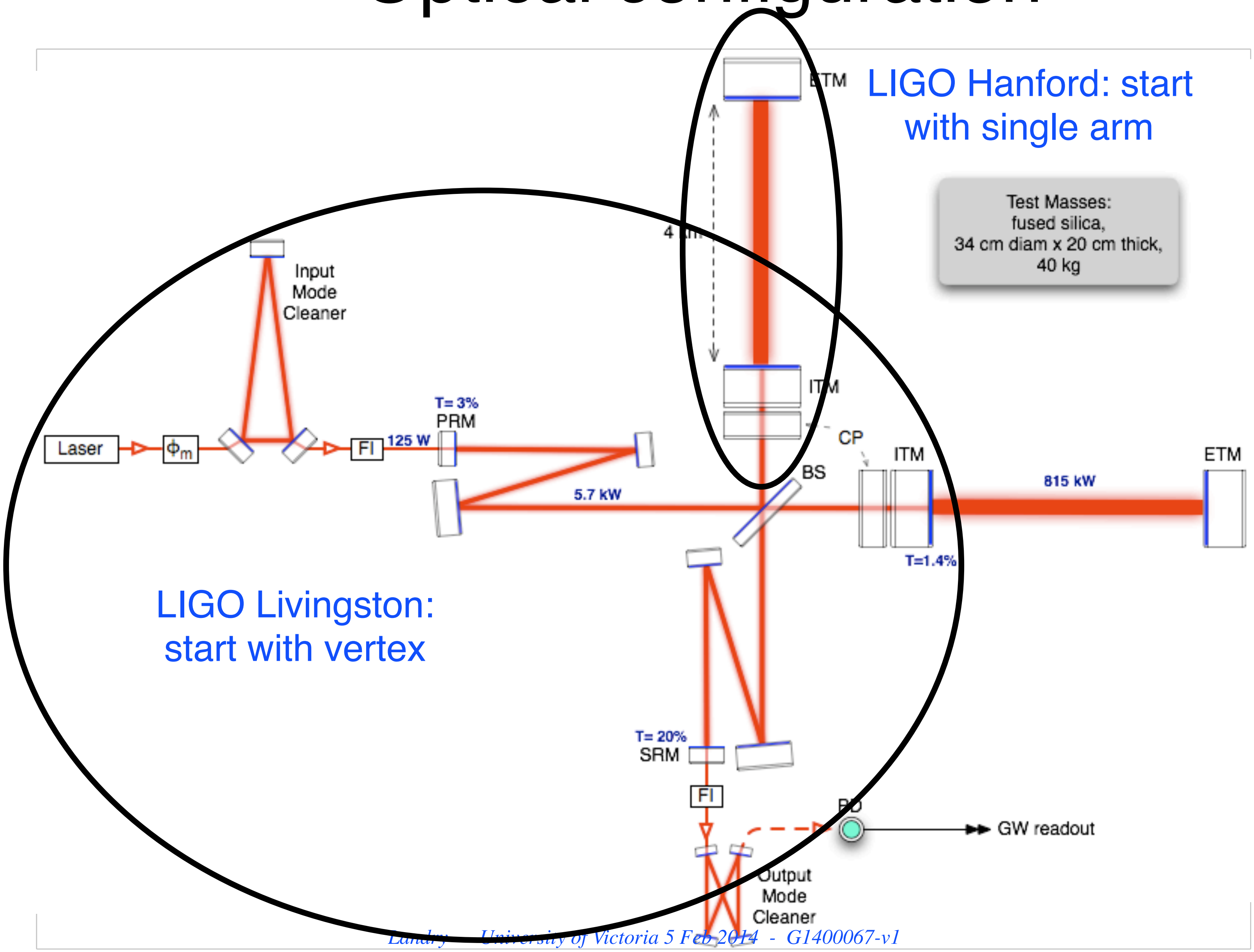


Test mass suspension From Advanced LIGO

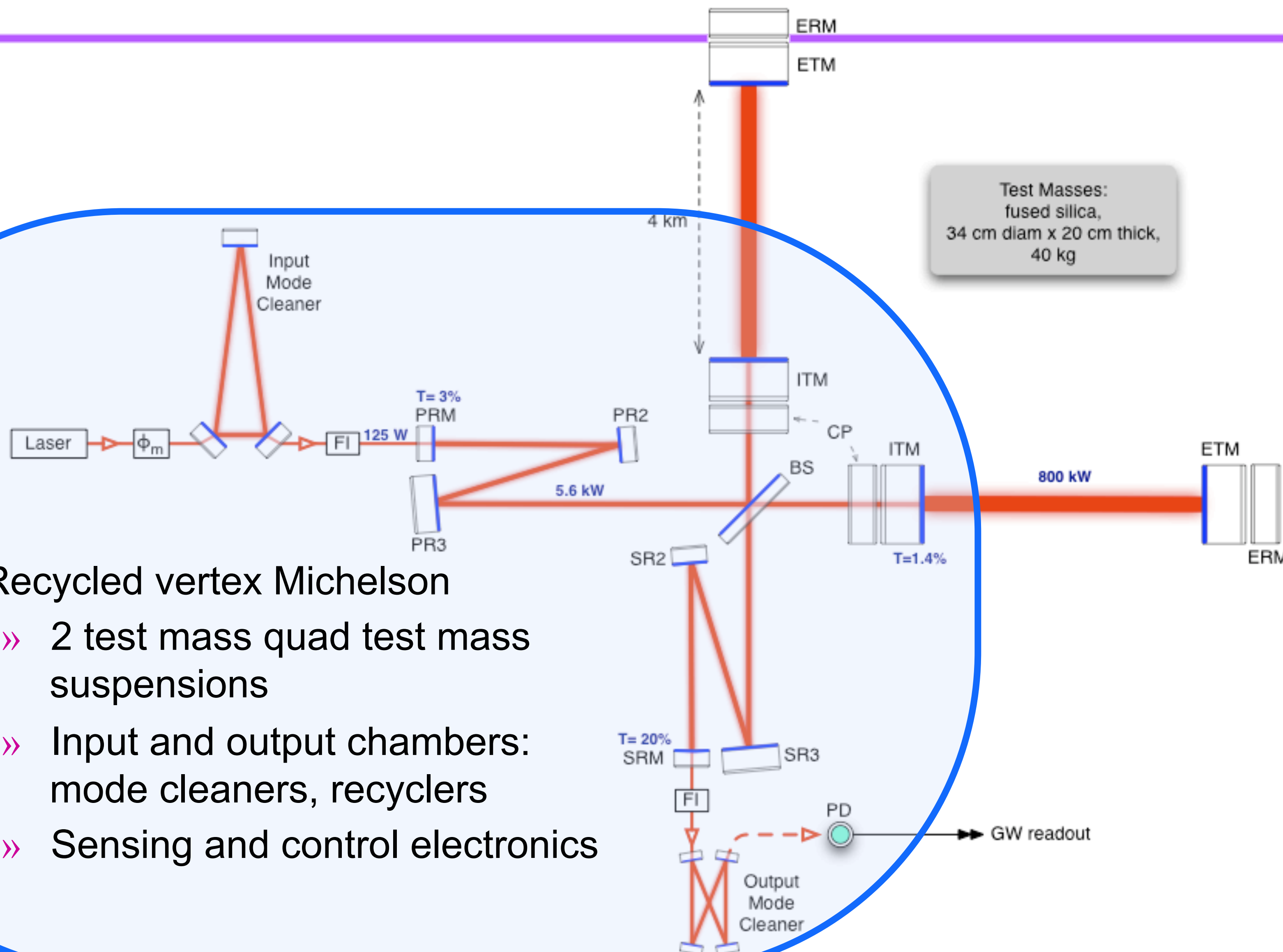
Installation progression

- Advanced LIGO installation start : Oct 20, 2010
- Livingston Observatory was the pathfinder
  - » Natural progression from laser, to input optics, to corner test masses, output and finally, arms
- Hanford Observatory had more complicated path
  - » 4km instrument was frozen for ~6mo, then a squeezed light experiment run for ~1 year
  - » 2km instrument deinstalled
  - » LIGO India evolved
  - » Deinstalled the 4km machine and commenced installation
- Philosophy : get to testing as quickly as possible

Optical configuration

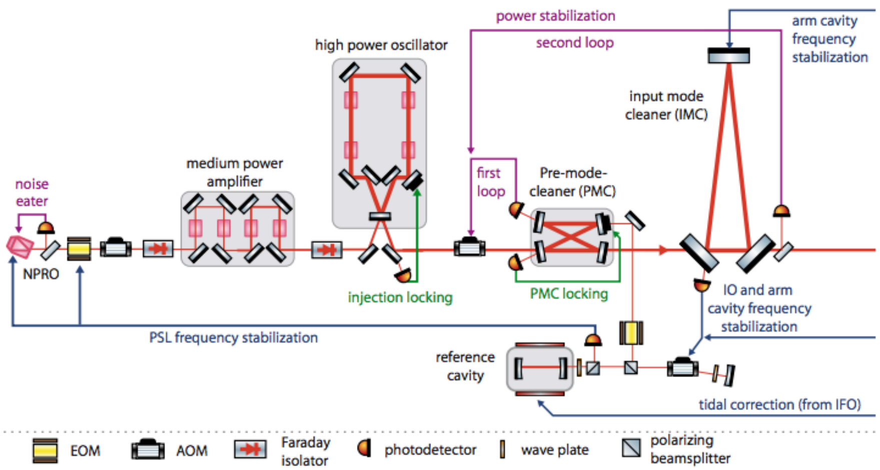


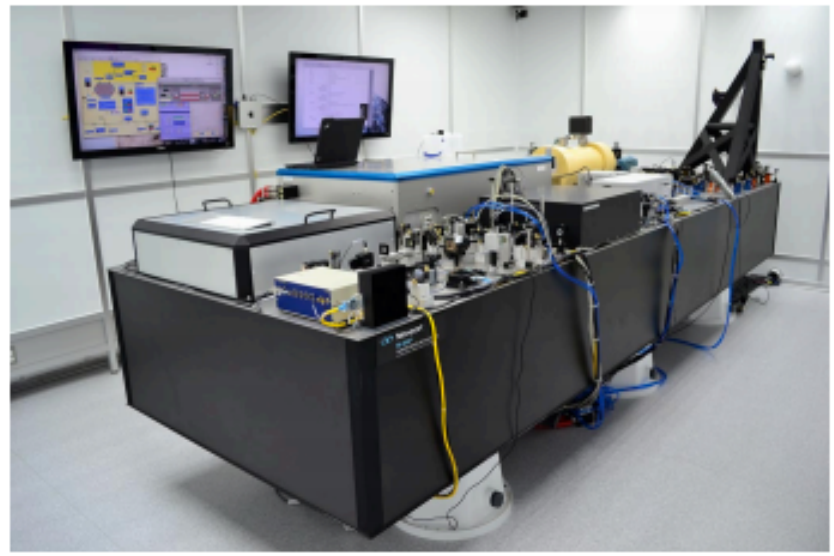
LIGO Livingston Install

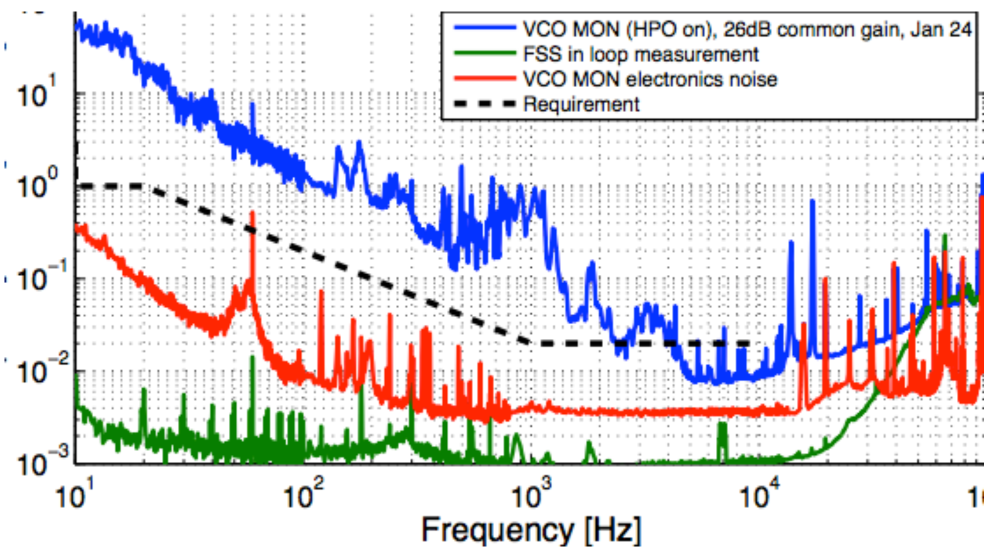


- Recycled vertex Michelson
  - 2 test mass quad test mass suspensions
  - Input and output chambers: mode cleaners, recyclers
  - Sensing and control electronics

Pre-stabilized laser



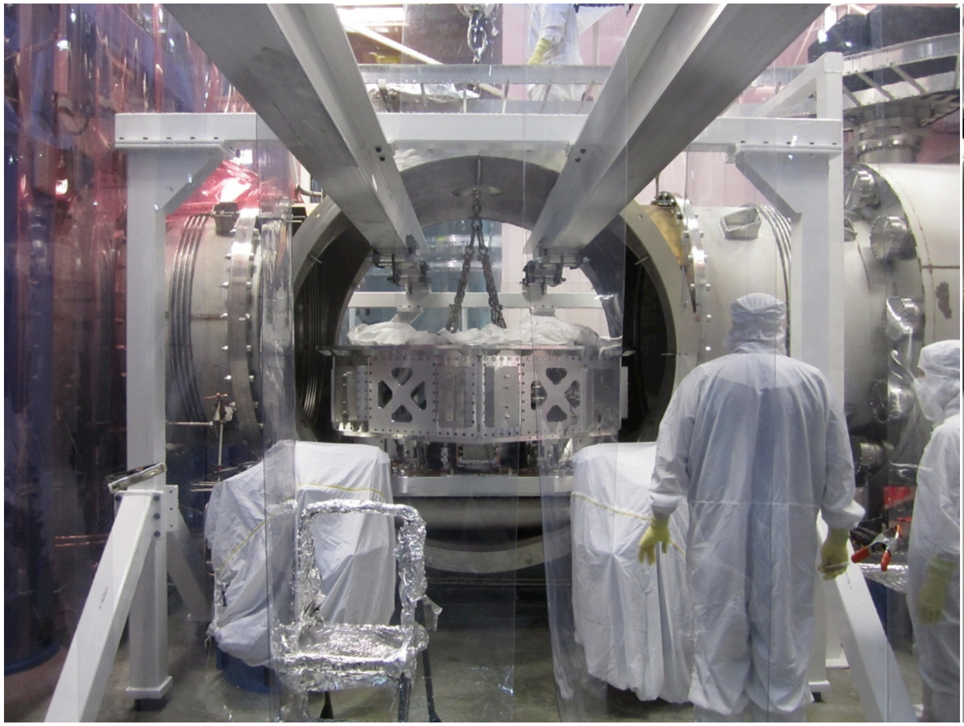


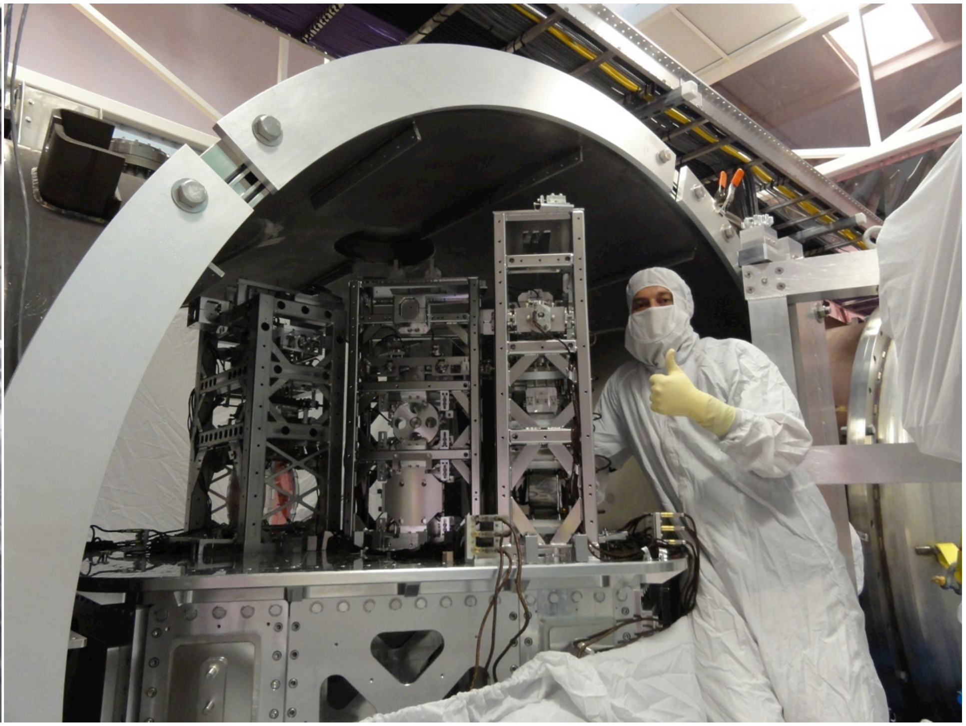


- Frequency noise measured at Livingston
- 3 W input to IMC
- noise between 10 and 100 Hz is already better; expect to meet spec without difficulty

HAM installations

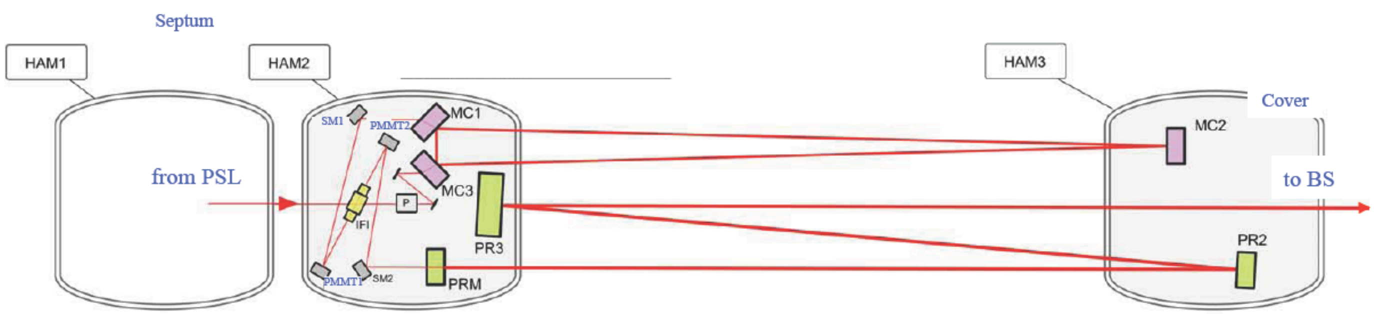
- For LIGO smaller chambers (“HAMs”), we install the seismic isolation platform into the chamber, and then populate it in situ

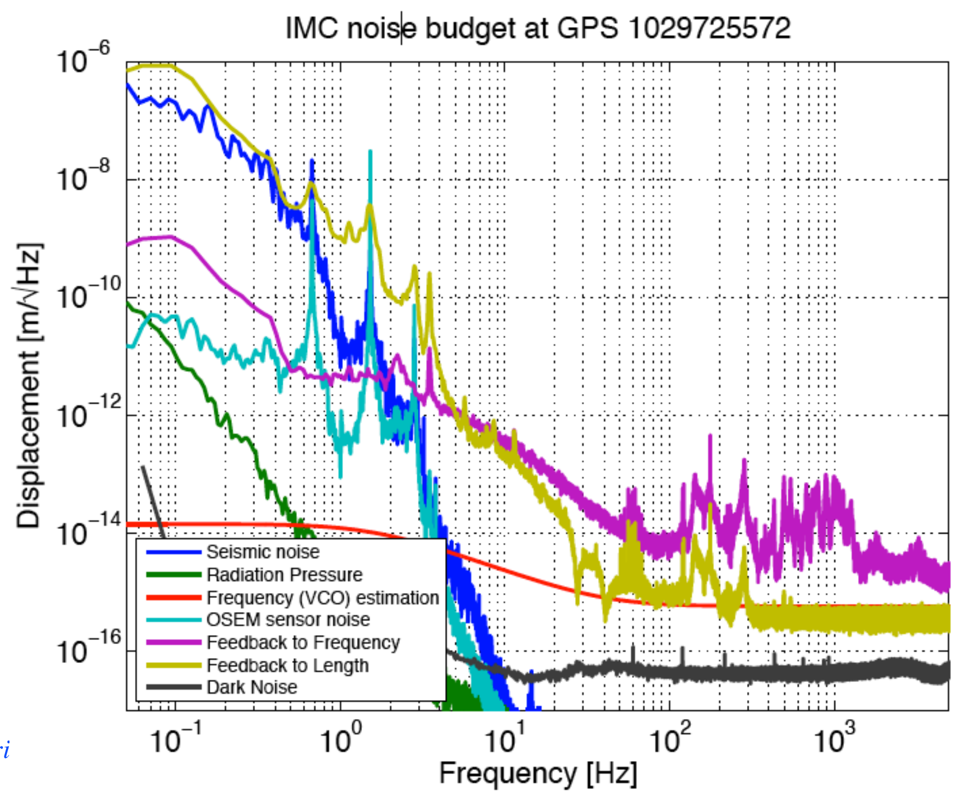




LLO HAM installation

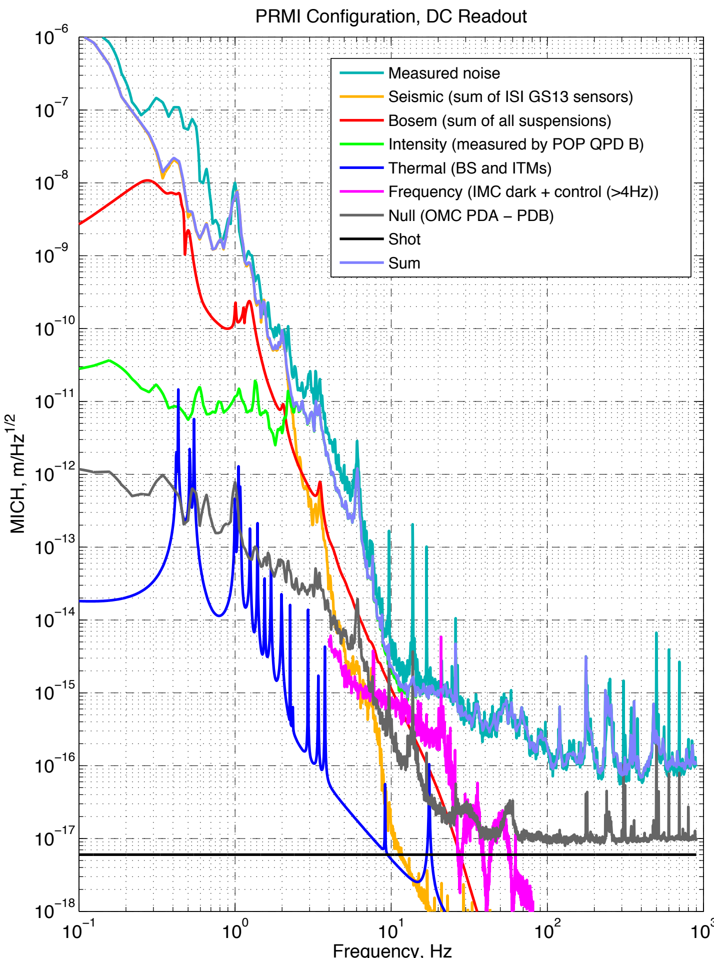
LIGO Livingston input mode cleaner

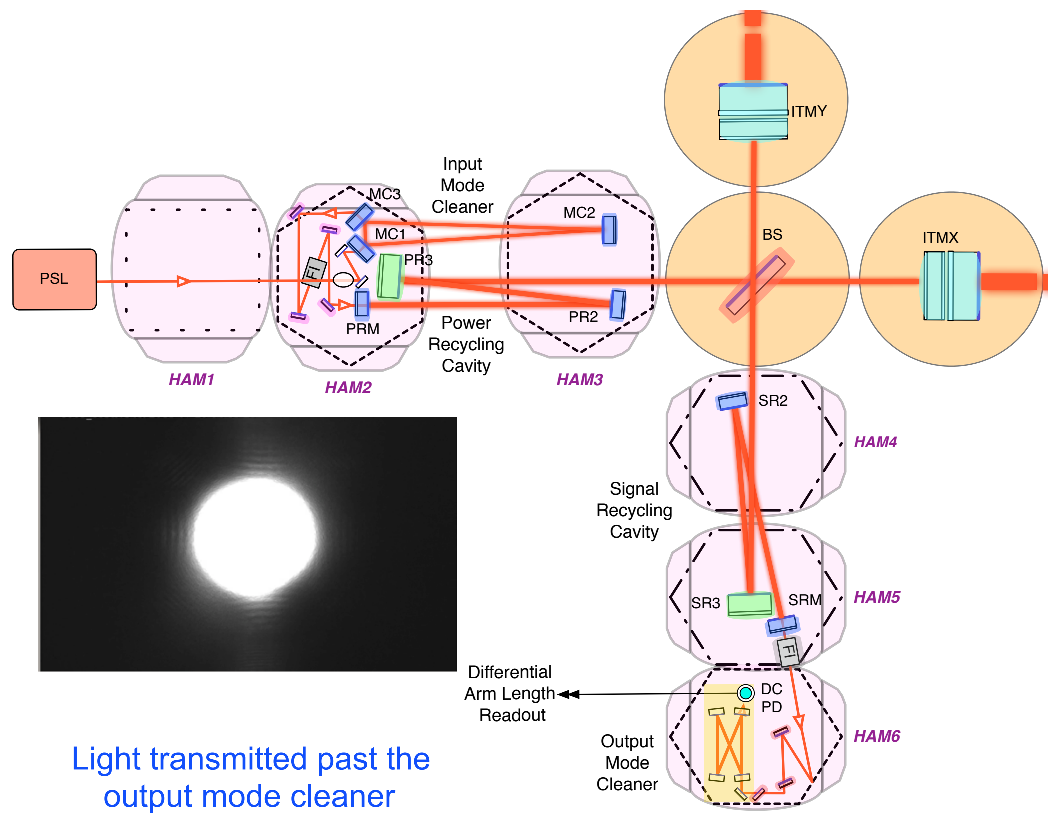




Livingston DRMI

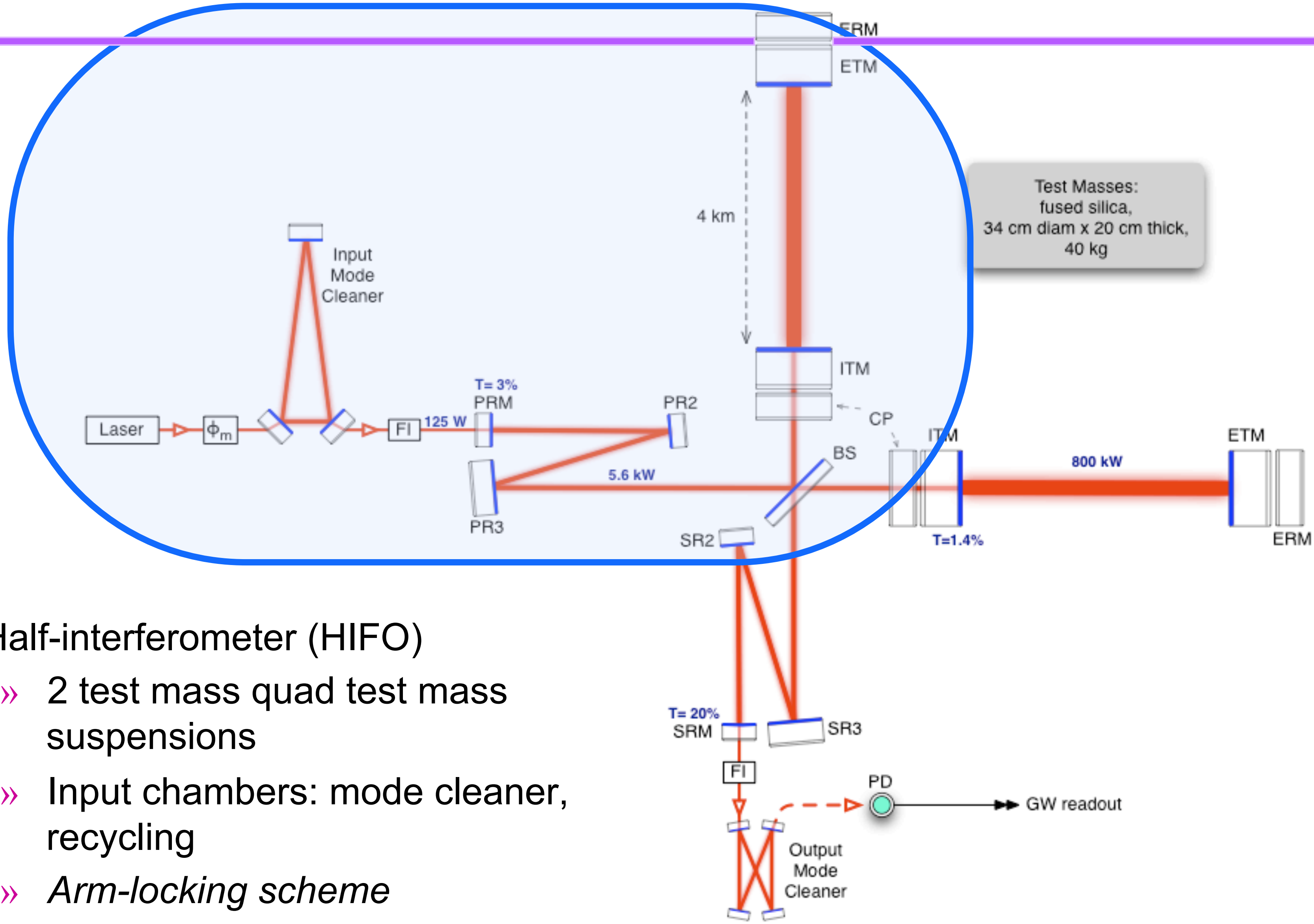
- Dual-recycled Michelson Interferometer ('***DRMI***')
  - » Power recycled Michelson locked on DC readout, calibrated





Light transmitted past the output mode cleaner

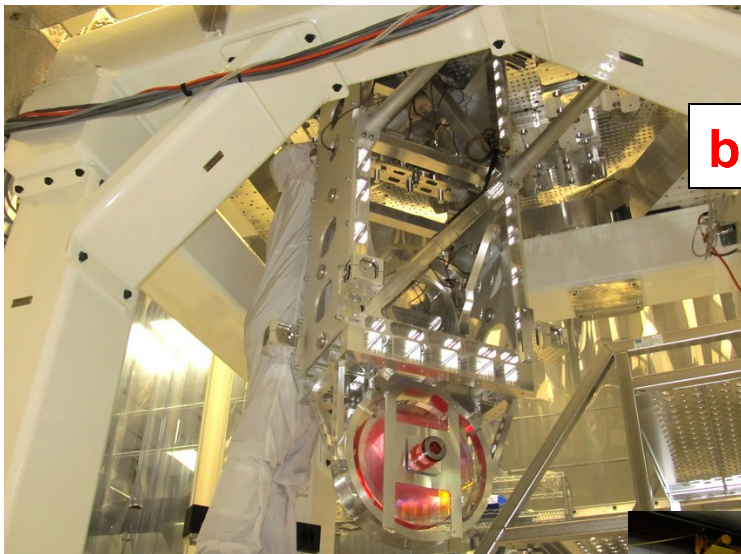
LIGO Hanford Install



- Half-interferometer (HIFO)
  - 2 test mass quad test mass suspensions
  - Input chambers: mode cleaner, recycling
  - *Arm-locking scheme*

BSC installations

- For LIGO large chambers ("BSCs"), we assemble a cartridge in a given hall, and then crane it into the vacuum envelope



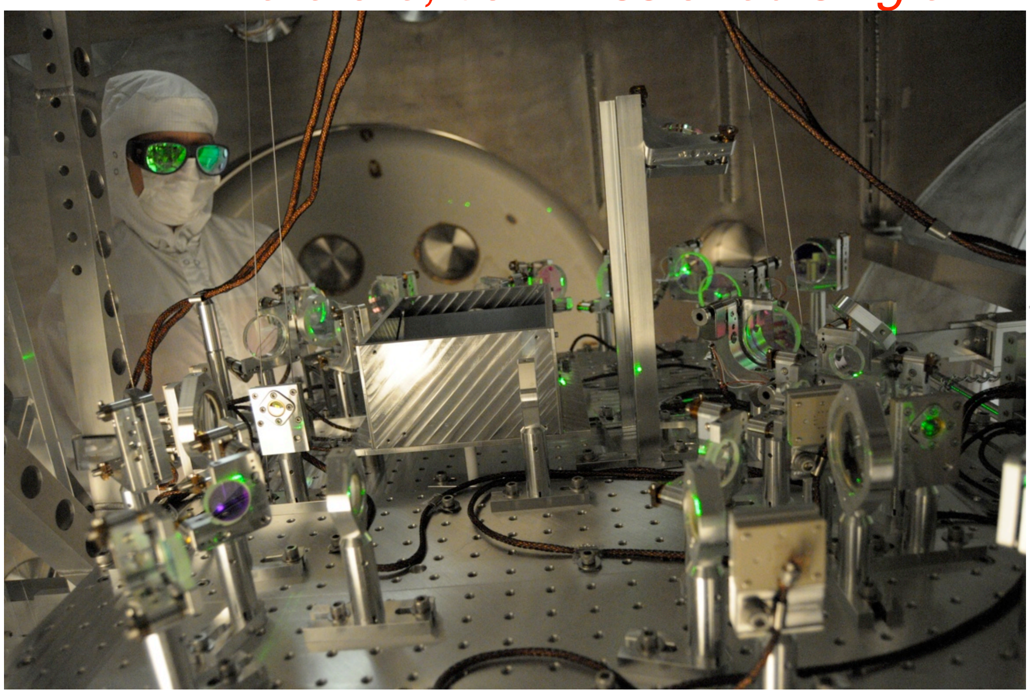
beamsplitter

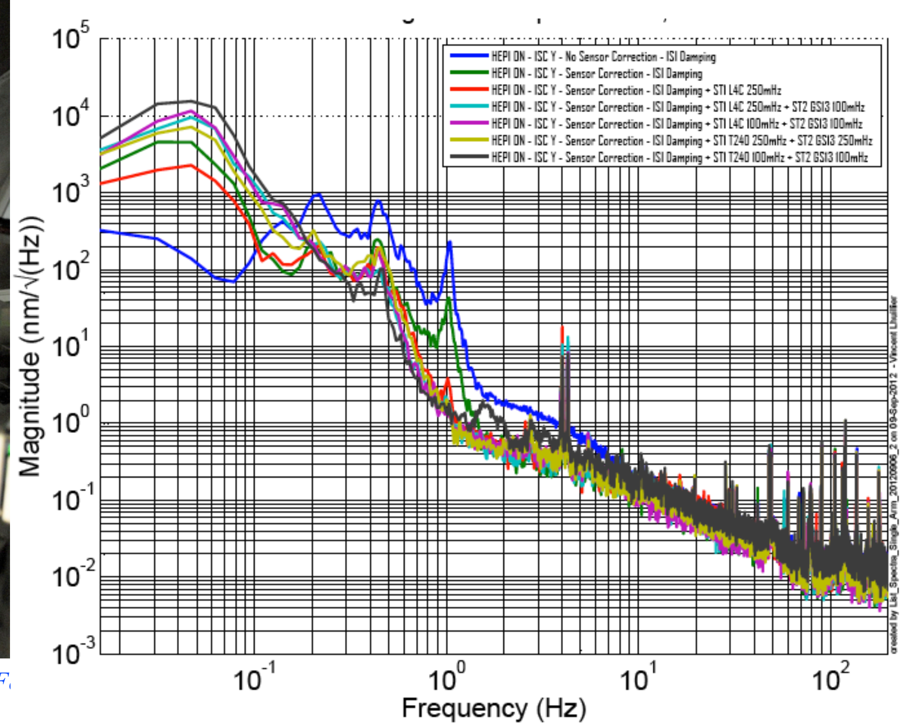
cornerstation Y mirror

End Y mirror

Hanford single-arm integration

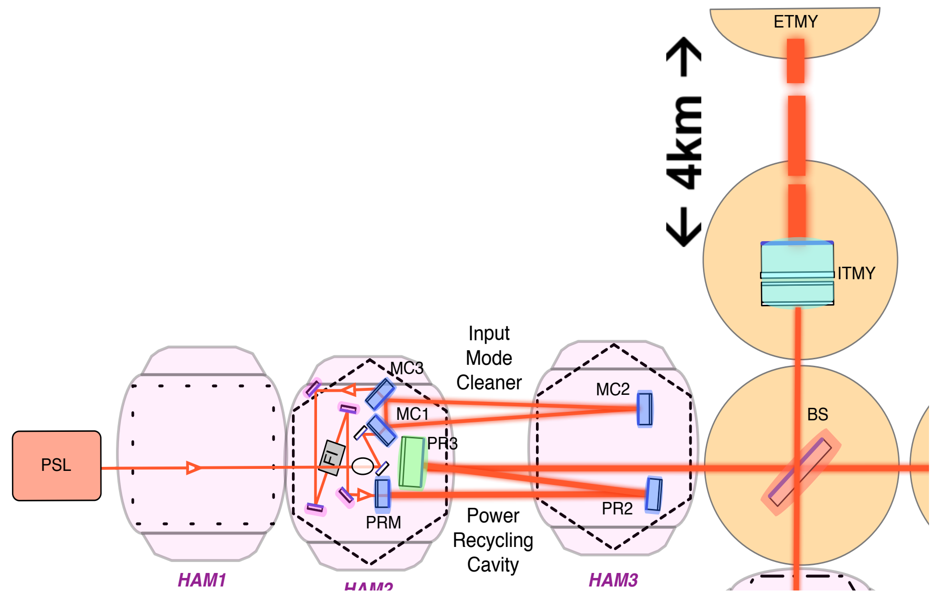
- New lock acquisition strategy developed for Advanced LIGO
  - Arm Length Stabilization system controls each arm cavity, putting them off-resonance
  - The 3 vertex lengths are controlled using robust RF signals
  - Arm cavities are brought into resonance in a controlled fashion
- *Therefore, commissioned single 4km arm*

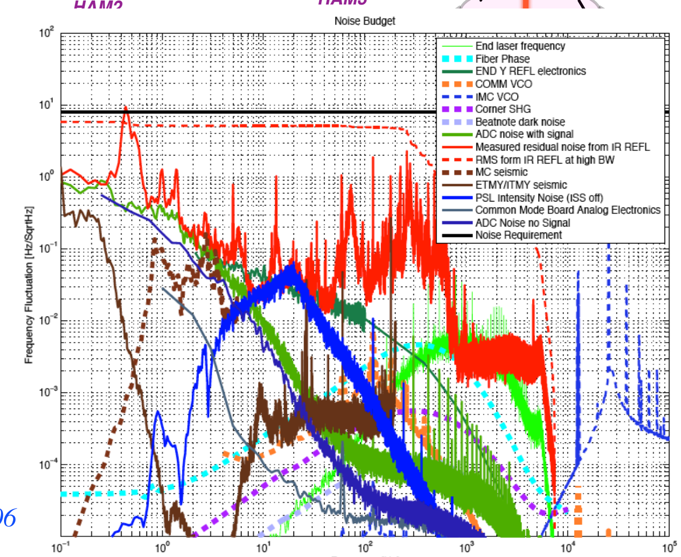




Hanford HIFO-Y

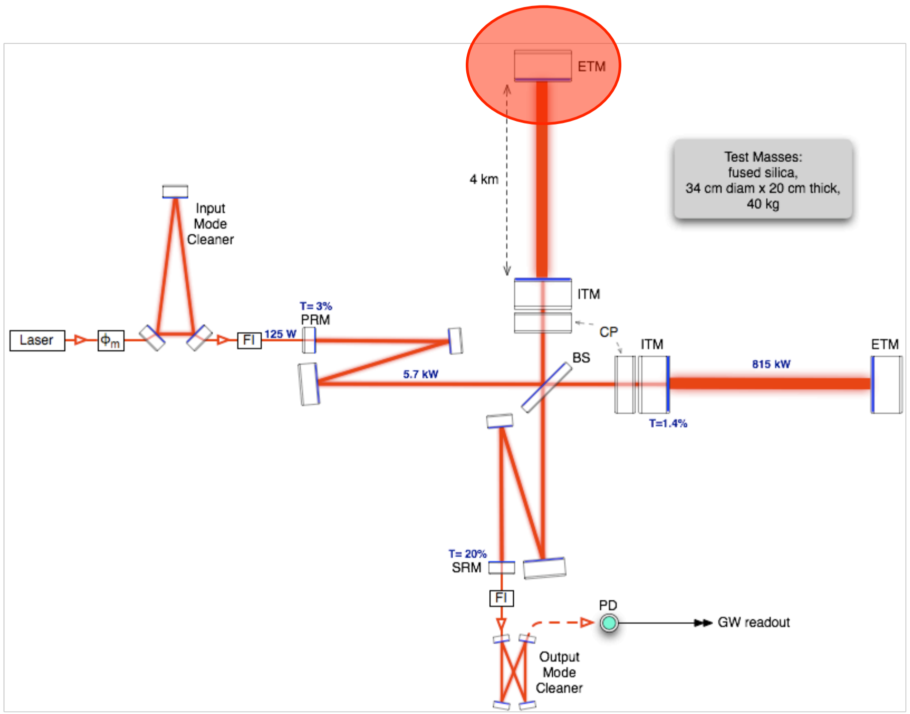
- Half-Interferometer (*'HIFO'*)–Y arm
  - » Green light demonstrated to allow a continuous controlled positioning of cavity
  - » Fluctuations of the HIFO-Y length ~5 Hz RMS (meets noise requirement of 8Hz)
  - » May require acoustic mitigation (in-air periscopes in corner and table motion) and modified suspension control filters for known mechanical modes



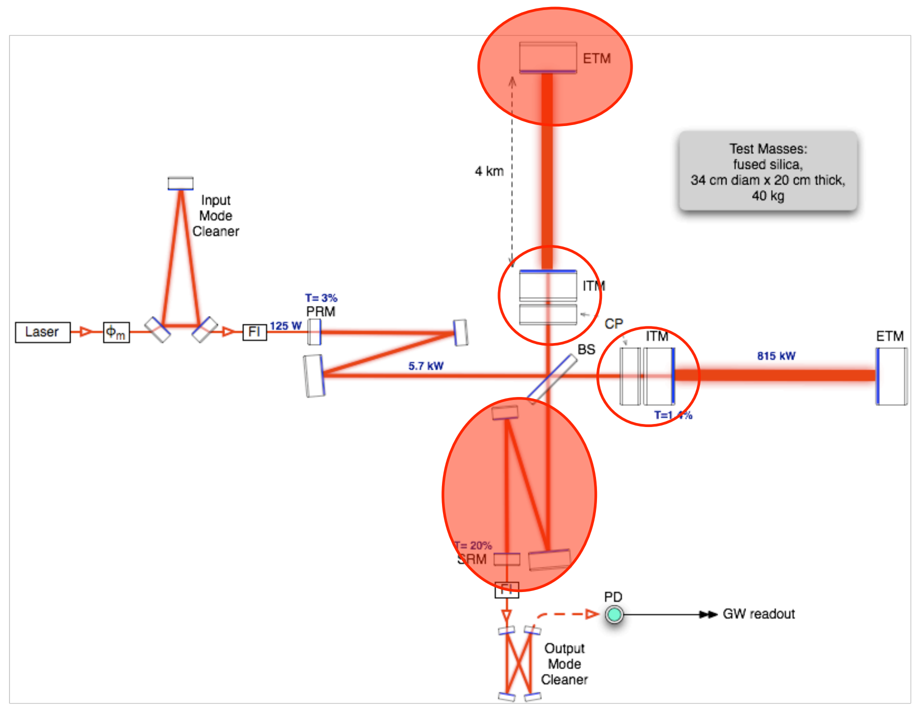


What's left to install?

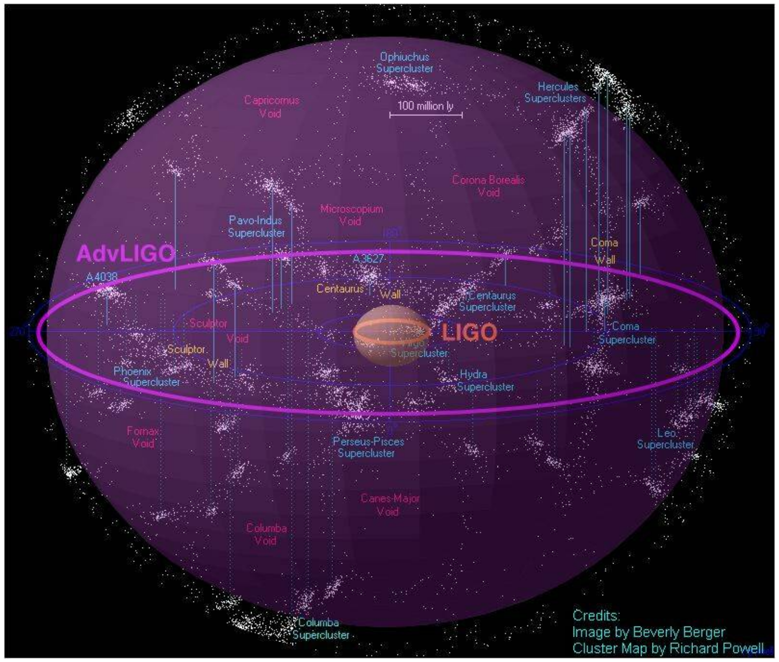
LIGO Livingston



LIGO Hanford



Science



Binary neutron stars

- Initial LIGO reach: 15Mpc; rate ~ 1/50yrs
- Advanced LIGO ~ 200Mpc
- 'Realistic' rate ~ 40 events/yr

Table 5. Detection rates for compact binary coalescence sources.

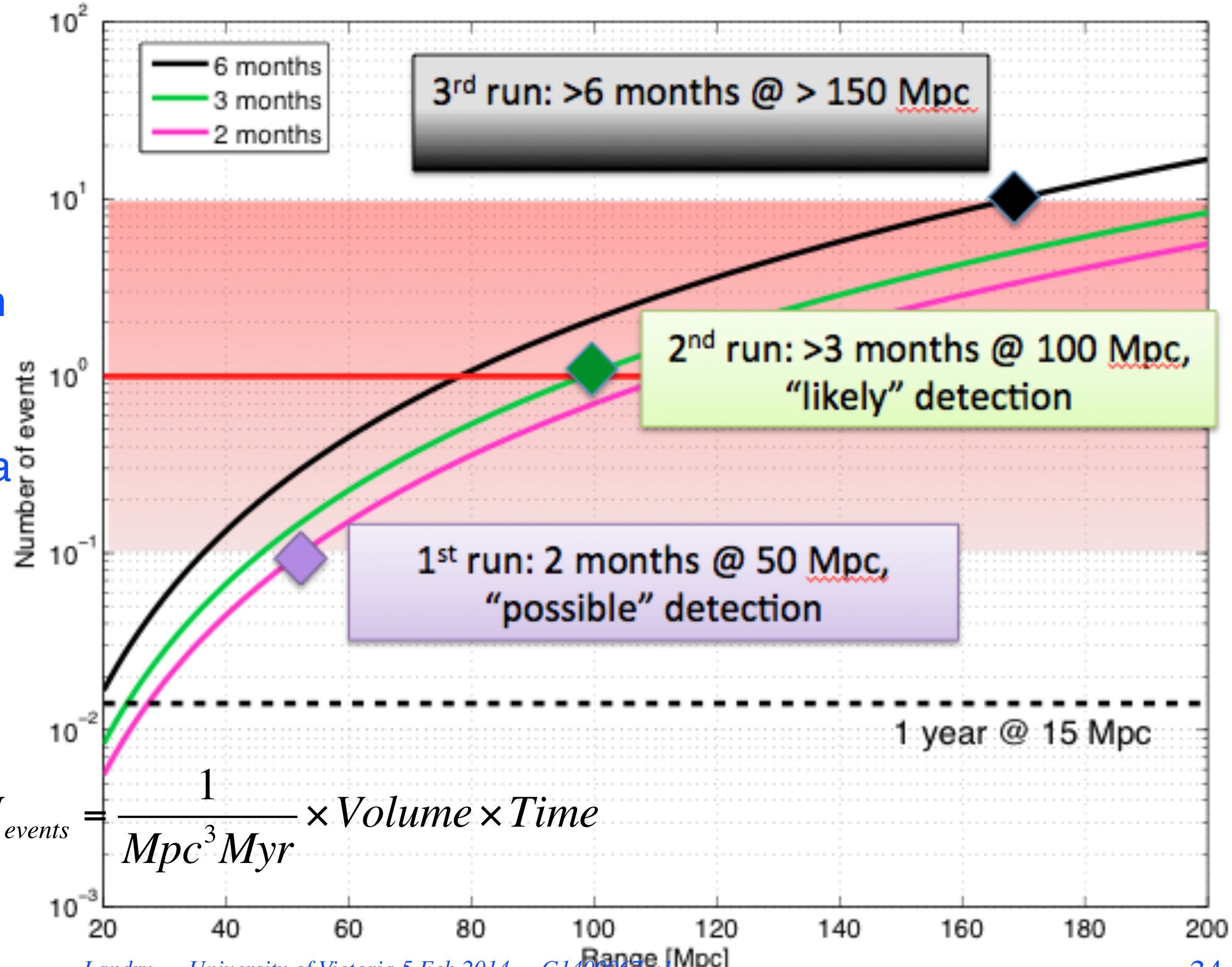
IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Rates paper: Class. Quant. Grav, 27 (2010) 173001

Current guess for sensitivity evolution, observation

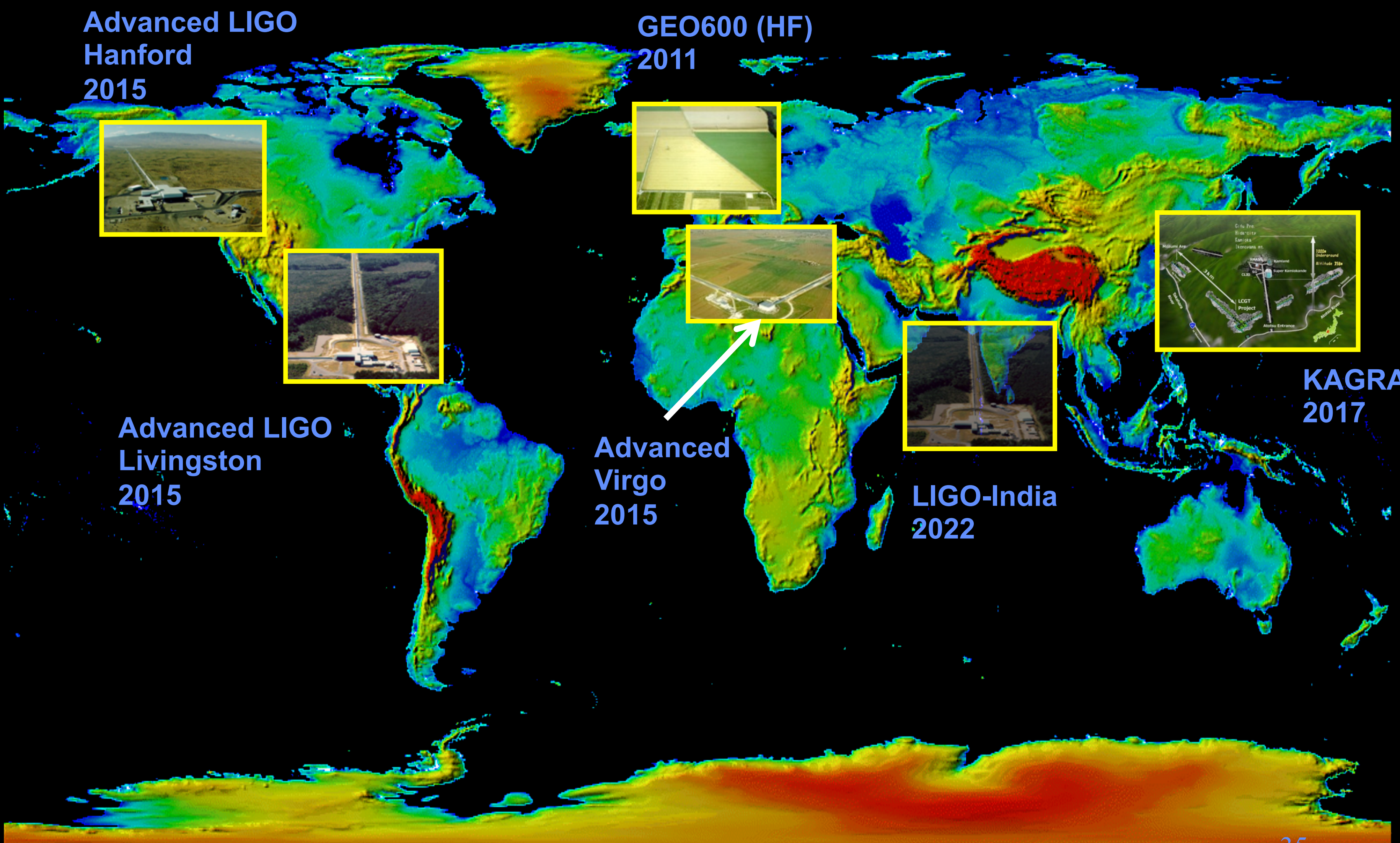
- Vertical scale is the number of binary inspirals detected
- Rates based on population synthesis, realistic but uncertain
- LIGO Scientific Collaboration (LSC) preparing for the data analysis challenge
- Close collaboration with Virgo
- Early detection looks feasible

- arXiv:1304.0670, arXiv:1003.2480



$$N_{events} = \frac{1}{Mpc^3 Myr} \times Volume \times Time$$

The advanced GW detector network: 2015–2025

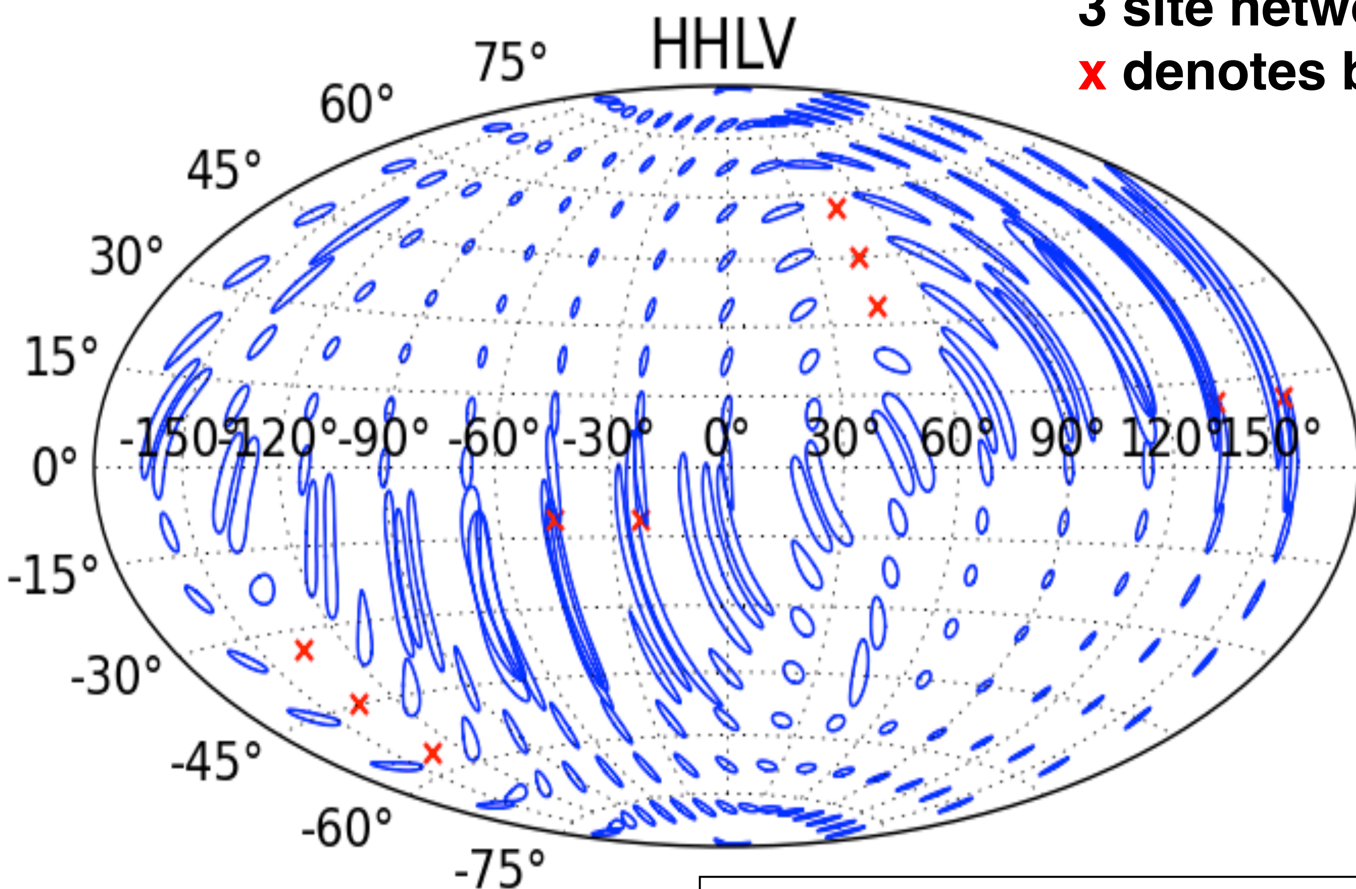


LIGO-India

- International collaboration between US and India to establish a LIGO observatory in India
- LIGO-US provides components for one Advanced LIGO interferometer from the Advanced LIGO project
  - 2^{nd} interferometer originally intended for Hanford
- India provides the infrastructure (site, roads, building, vacuum system), “shipping & handling,” staff for installation & commissioning, operating costs
- Indian funding – India Mega-science Project
  - Total request of ~ $230M to fund construction and operations
- US funding – funding for aLIGO components from NSF
  - Total contribution $140M (includes aLIGO components, designs, documentation)

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

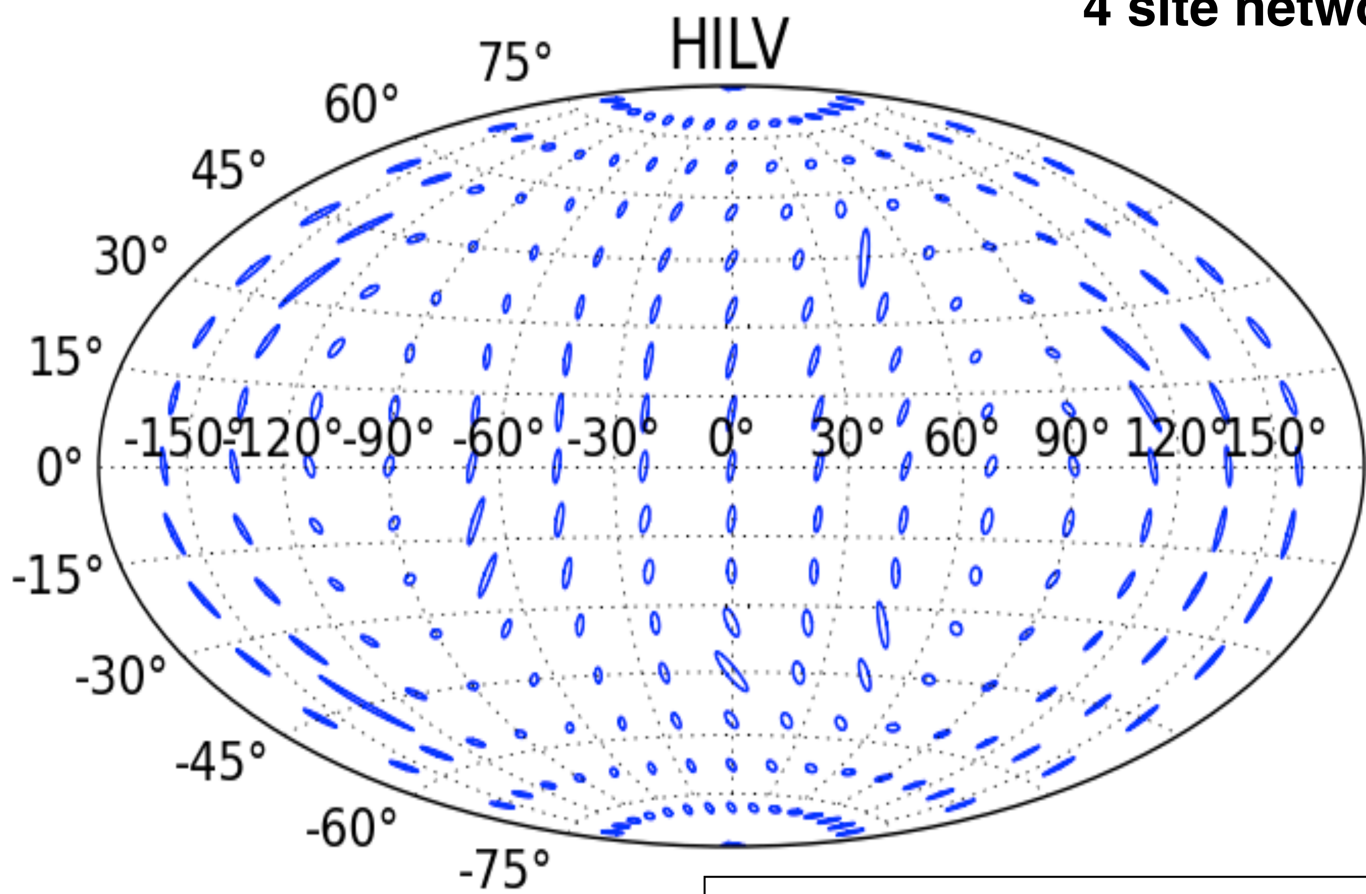
3 site network
x denotes blind spots



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India

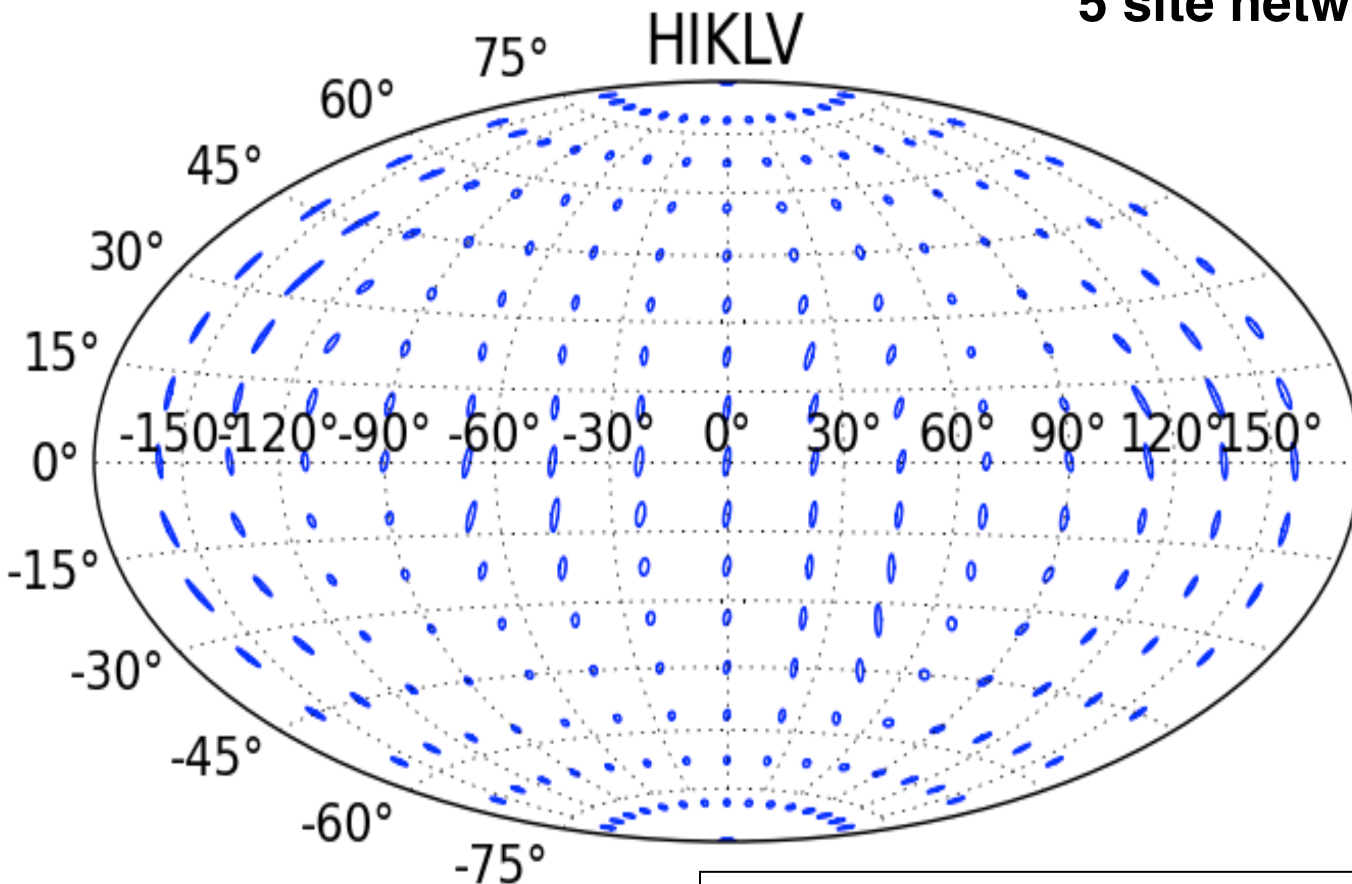
4 site network



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India-KAGRA

5 site network



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

LIGO-India Status

- Status in India:
  - » Funding – through most of a multi-stage approval process; LIGO-India awaiting approval by the Cabinet of the government of India approval and beginning of seed funding for facility design work
  - » Site selection – 4 candidate sites identified and undergoing qualification
  - » Facility and vacuum design – transfer of LIGO-US facility and vacuum designs to LIGO-India team; LIGO-India facility and vacuum requirements established
  - » A LIGO data grid Tier 2 center has been established at IUCAA in Pune
- Status in the US:
  - » -- the National Science Board has given permission to NSF, at its discretion, "to approve the proposed aLIGO Project in scope, enabling plans for the relocation of an advanced detector to India"
- ***Expect LIGO-India to begin operations in 2022***

Enabling multi-messenger astronomy with gravitational waves

- Many GWs sources are likely to radiate in the electromagnetic spectrum
- Multi-messenger astronomy – observation of the same event via different modalities
- GW 'Aperture synthesis'
  - » Crude estimate of angular resolution

$$\theta_{GW} \sim \lambda_{GW} / d \sim \text{few degrees}$$

→ X-ray satellites & wide field telescopes
  - + Image tiling
  - + Galaxy weighting

→ Neutrino observatories

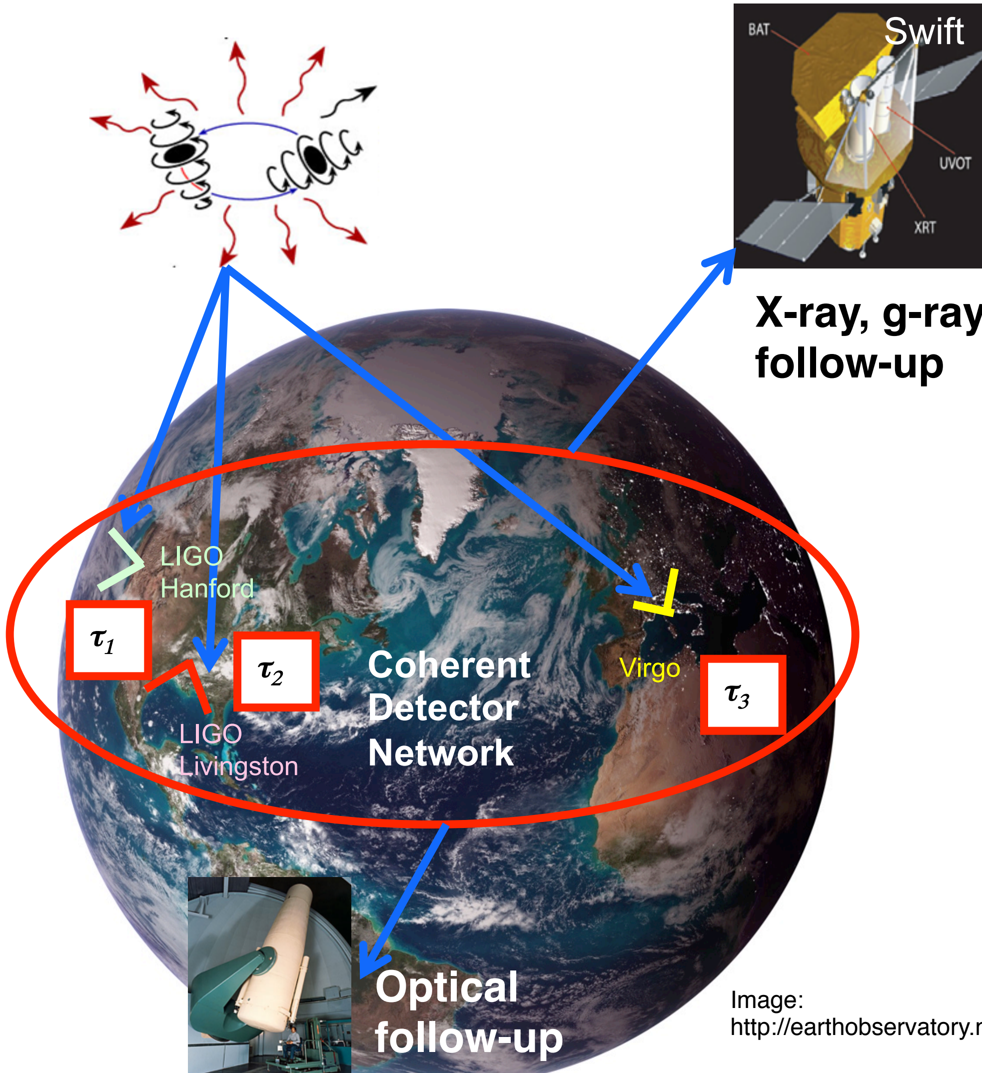


Image: http://earthobservatory.nasa.gov/

Summary

- Advanced LIGO installation is drawing to a close, and rapid progress is being made towards first lock this coming summer
- We expect to make first science run with the second generation detectors in 2015 and 2016, runs which may produce detections
- We will press onward with sensitivity improvements to design sensitivity
- We expect gravitational waves will be detected in the coming few years

Light at the end of a tunnel

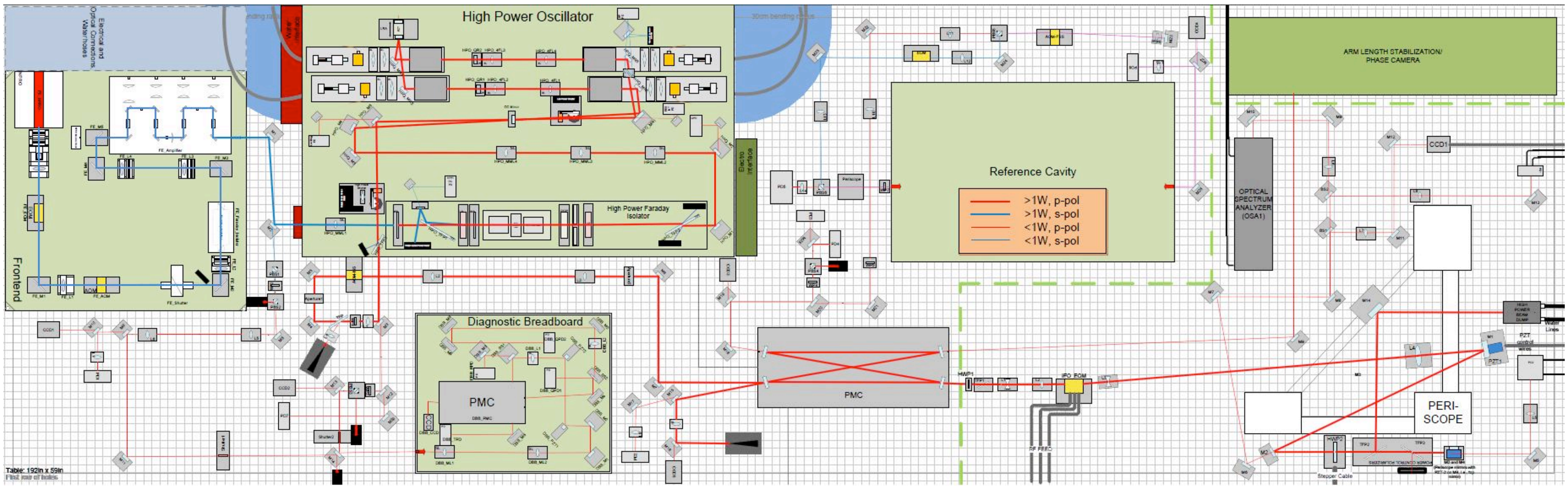
Extra slides

PSL requirements

Property	Value	Comment
Wavelength	1064 nm	Same as initial LIGO
Fundamental Mode Power	≥ 165 W	At the IO interface, in a circular TEM_{00} mode
Higher-order Mode Power	≤ 5 W	
Polarization	horizontal, > 100:1 ratio	At IO interface, polarization parallel to table surface, to ±1 deg
Beam size	550 µm	Beam waist at IO interface
Beam height	4 inches	At IO interface, from table surface
Alignment tolerance	± 2 deg	With respect to the vertical plane defined by the table surface

Table 1. Requirements for the PSL beam, as delivered to the IO subsystem.

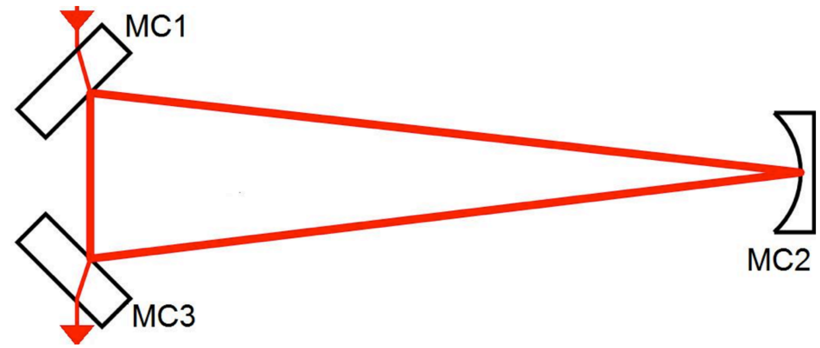
PSL schematic

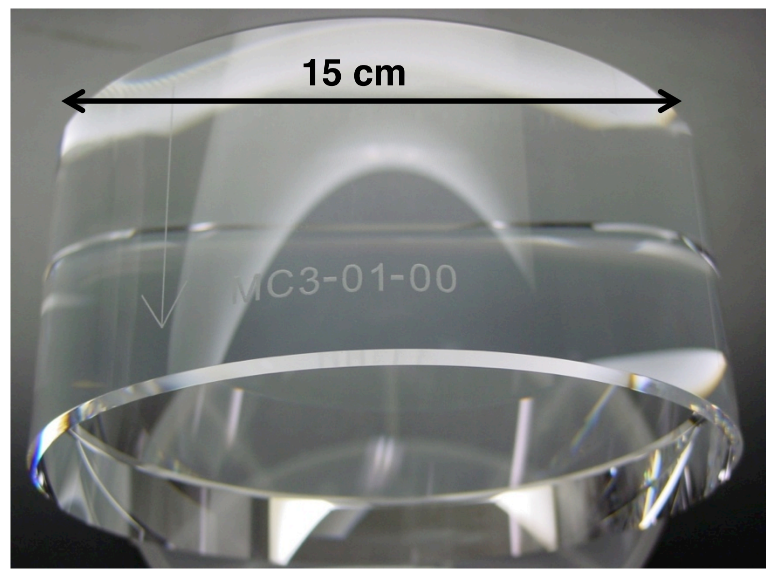


LIGO

Input Mode Cleaner Design

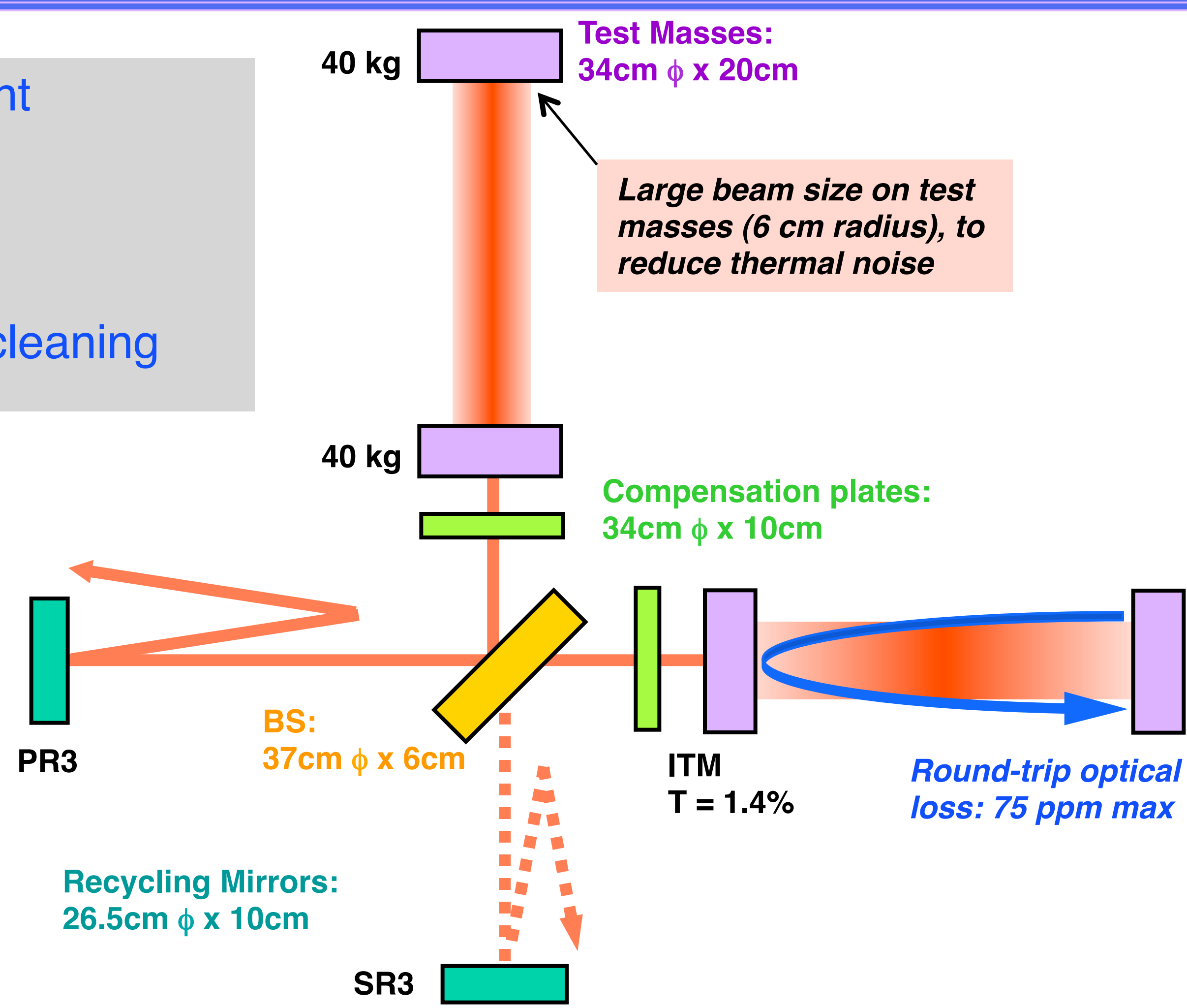
- **Triangular ring cavity**
- ***L/2* = 16.5 m**
- **FSR = 9.1 MHz**
- **Finesse = 520**
- **P_{stored} = 23 kW (@ 165 W input)**
- **MC mirrors suspended from triple suspensions**
- **MC mirrors**
  - » **15 cm diameter x 10 cm thick**
  - » **3 kg: 12x heavier than iLIGO, to limit noise due to radiation pressure**





Core Optics Components

- Substrate procurement
- Substrate polishing
- Dielectric coatings
- Metrology
- Transport, handling, cleaning



All COC are fused silica substrates with ion-beam sputtered dielectric coatings

Test mass (and dummy)

COC Coatings

- Baseline Requirements for Test Mass coatings
  - Low scatter: < 2 ppm
  - Low absorption: < 0.5 ppm
  - Low mechanical loss
    - Several years of LSC R&D resulted in a better coating formula
    - Alternating layers of silica and titanium-doped tantala (25%); gives approx. 40% lower loss than non-doped tantala (20% reduction in thermal noise amplitude)

Rely on IBS coating technology from qualified vendors

- LMA coating designs for the test masses are completed
  - Not a ¼-wave stack design: accommodates arm locking w// green beam & reduces thermal noise

	ETM	ITM
1064 nm	T = 5 ppm	T = 1.4 %
532 nm	T = 5%	T = 1%

- **CSIRO coating designs for other optics nearly complete**
  - **Dielectric coatings also need to accommodate Hartmann sensor probe beam**
  - **Gold coatings for the CP barrel and the electro-static drive pattern on CPs & ERMs**

Test mass parameters

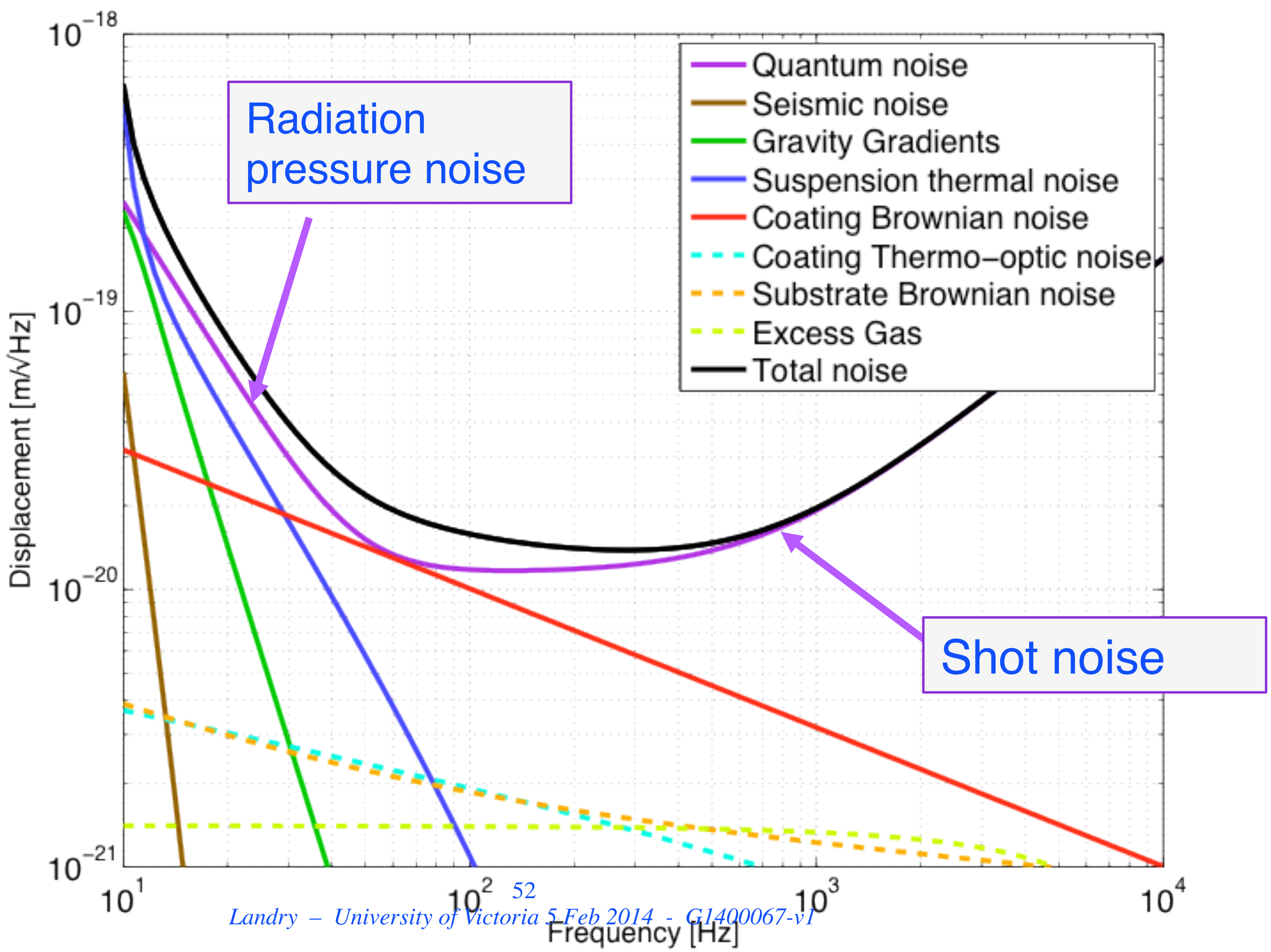
	Baseline requirement.	Expected value
Mass	40 kg	40 kg
Dimensions	340 mm x 200 mm	340 mm x 200 mm
Surface Figure	< 1 nm rms	0.3 nm rms
Microroughness	0.1 nm rms	0.15 nm rms
ITM homogeneity	<10 nm rms	<10 nm rms
ITM/CP bulk absorption	<3 ppm/cm	< 0.2 ppm/cm
Coating absorption	< 0.5 ppm	0.3 ppm
Coating scatter	< 2 ppm	10ppm
Coating mechanical loss	$< 2\times10^{-4}$	1.7×10^{-4}
Arm cavity loss round trip	< 75 ppm	61 + environment

Squeezing

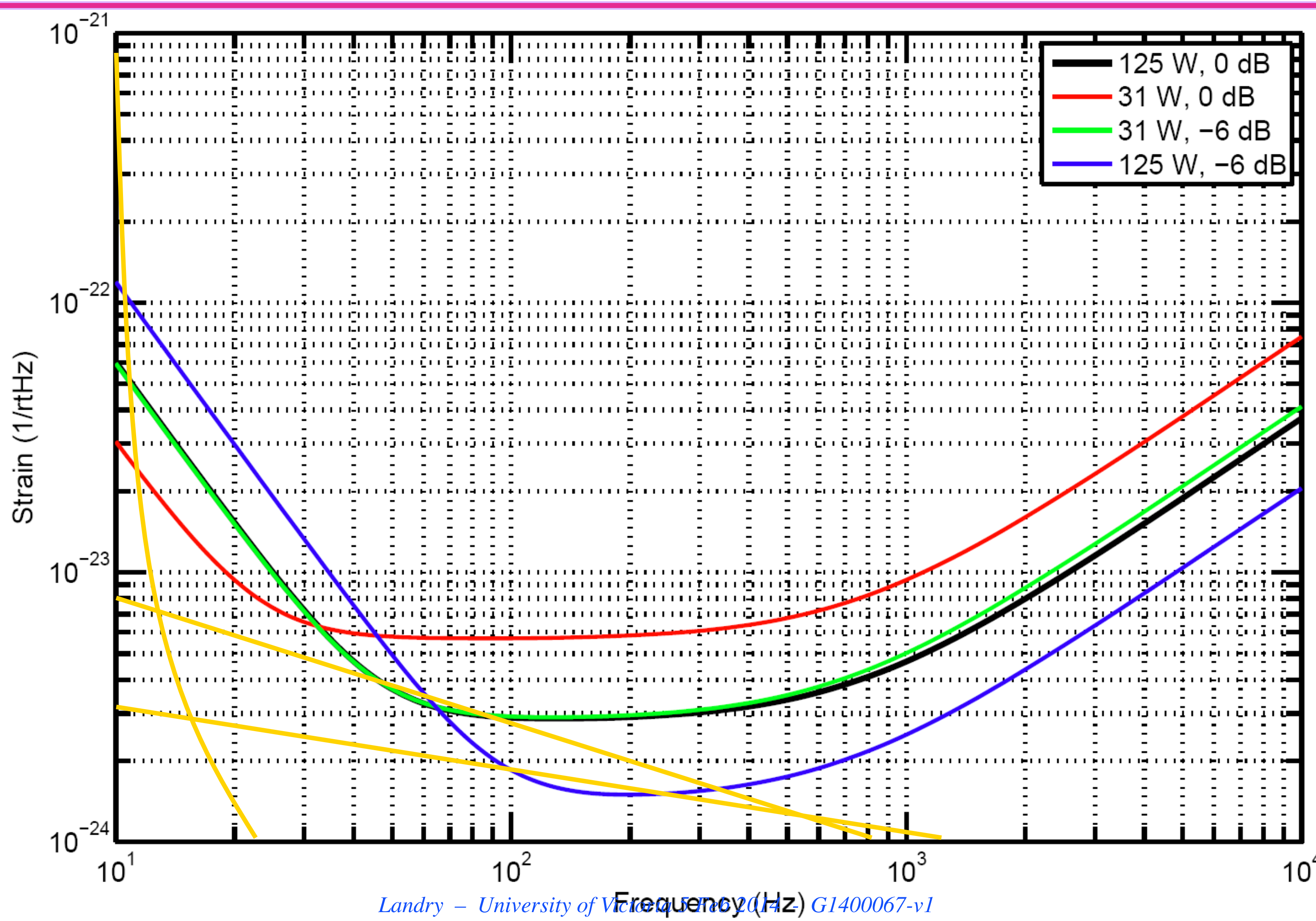
- Shot noise in a Michelson interferometer is due to vacuum fluctuations entering the dark port.
- Quantum noise also produces photon pressure noise.
- Injecting a specially prepared light state with reduced phase noise (relative to vacuum) into the dark port will improve the shot noise sensitivity.
- Similarly, injecting light with reduced amplitude noise will reduce the photon pressure noise.
- Non-linear optical effects can be used to generate a squeezed "vacuum" state.

Noise without squeezing

Projected aLIGO sensitivity at 125W laser power



aLIGO sensitivity with squeezed light



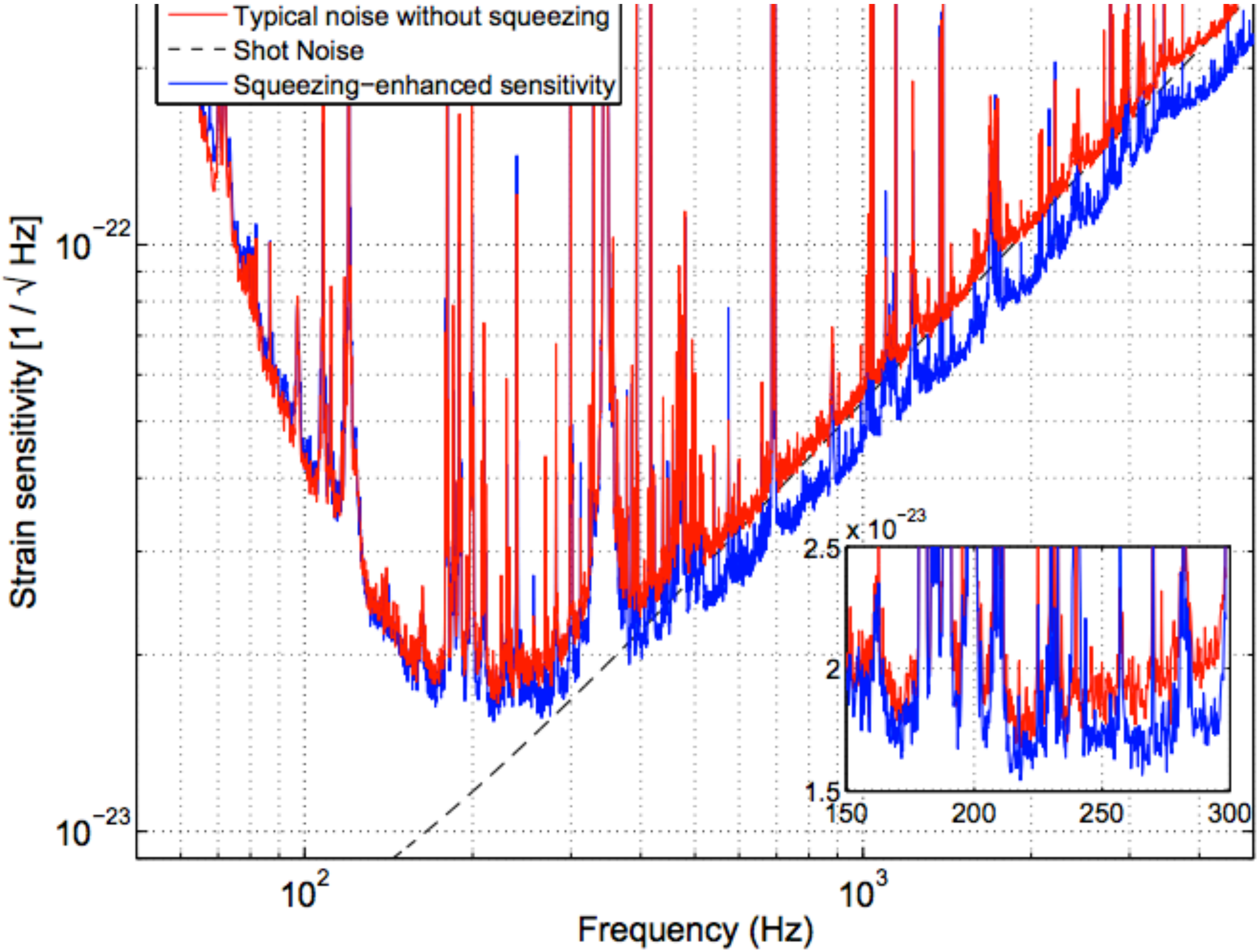


FIG. 2. Strain sensitivity of the H1 detector measured with and without squeezing injection. The improvement is up to 2.15 dB in the shot noise limited frequency band. Several effects cause the sharp lines visible in the spectra: mechanical resonances in the mirror suspensions, resonances of the internal mirror modes, power line harmonics, etc. As the broadband floor of the sensitivity is most relevant for gravitational wave detection, these lines are typically not too harmful. The inset magnifies the frequency region between 150 and 300 Hz, showing that the squeezing enhancement persists down to 150 Hz

Expected data rates

- LIGO will produce, in raw science frames, ~ 10 MB/s ~ 840 TB/day ~ 300 TB/year per IFO.
- For 2 IFOs, with trend and RDS data included, we will generate on the order of 1 Petabyte of data per year total, per copy. (And we'll keep dual copies of all data, with one copy at the observatories and one copy at Caltech.)