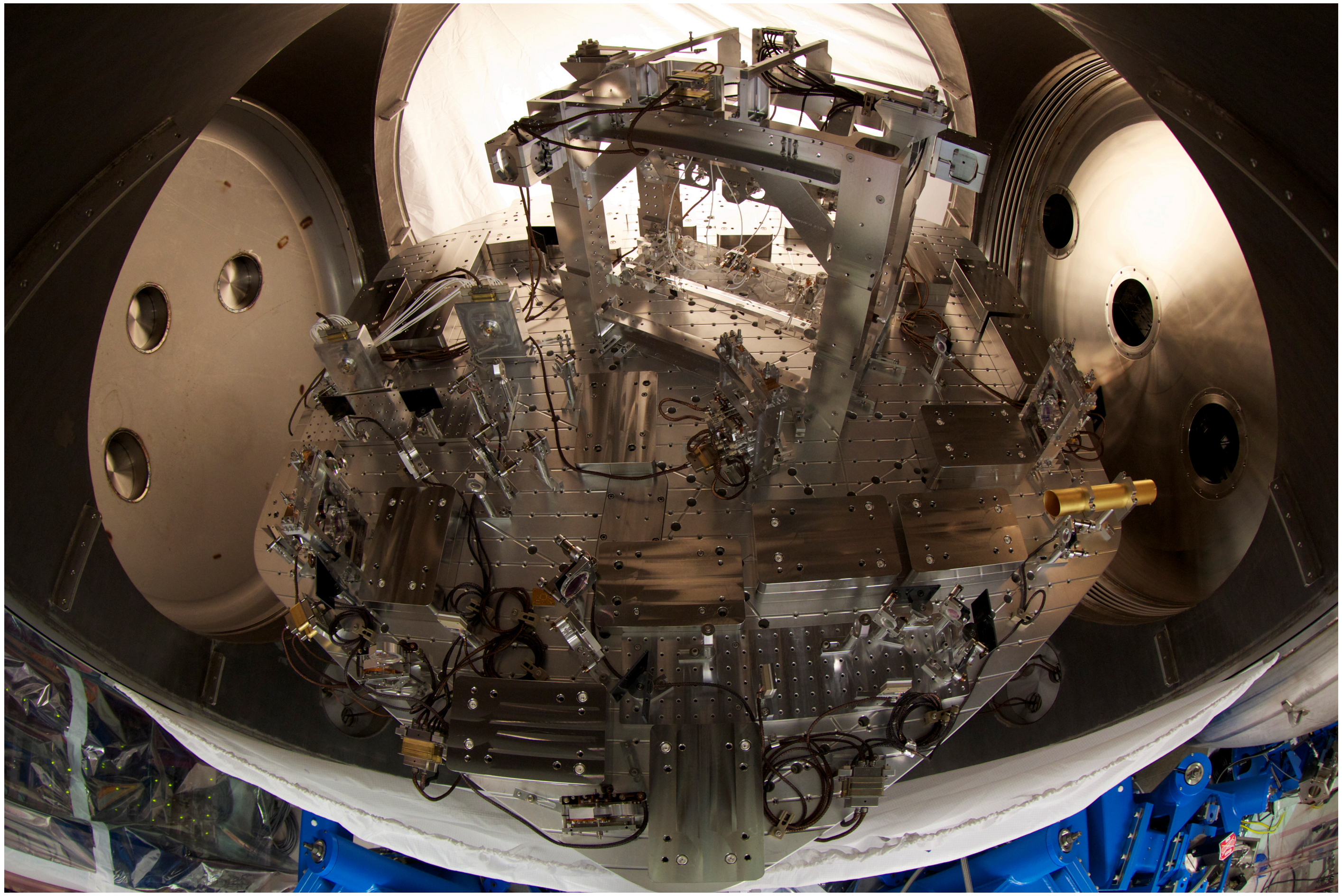
Advanced LIGO status



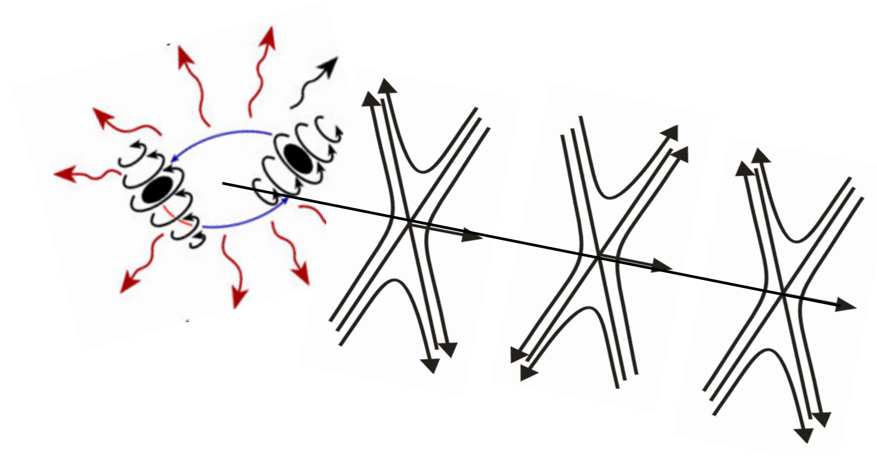
M. Landry
for the LIGO Scientific Collaboration
LIGO Hanford Observatory/Caltech

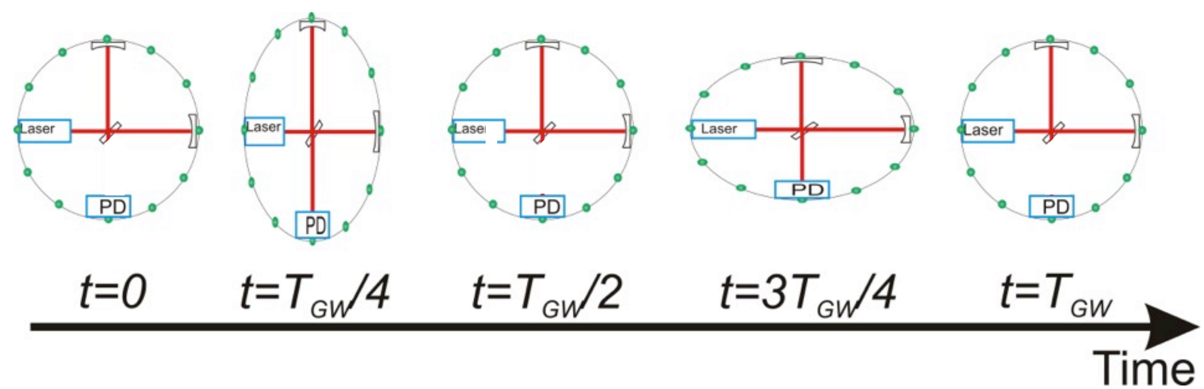
Testing Gravity – SFU Harbour Center
15 Jan 2015
LIGO-G1401333-v1

Gravitational waves

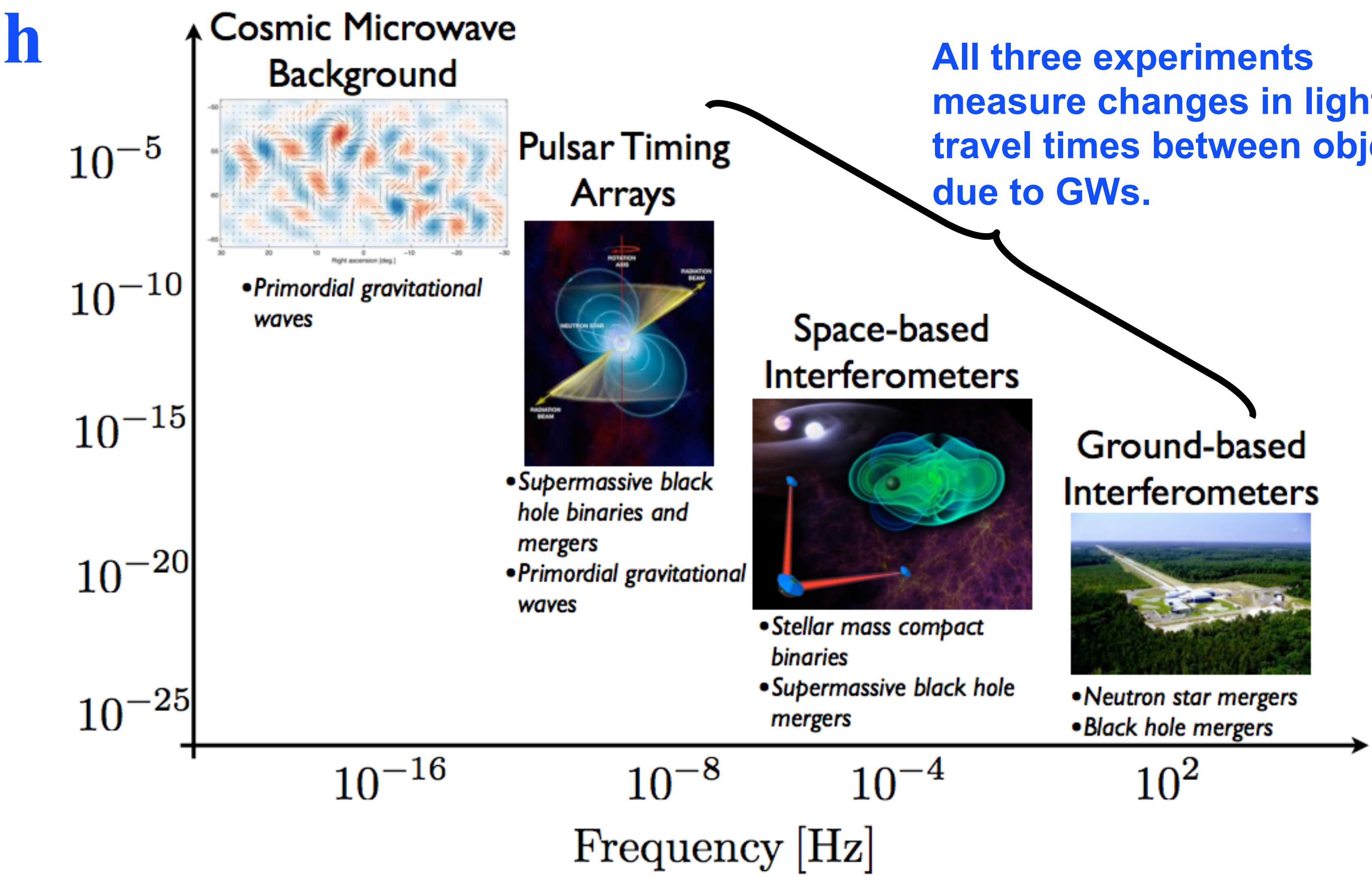
- Predicted in 1916 with General Relativity
- Generated by changing quadrupole moments
- Interact weakly with matter
- An entirely new spectrum in which to explore the universe
- Physically, gravitational waves are *strains:*

$$h = \frac{\Delta L(f)}{L}$$





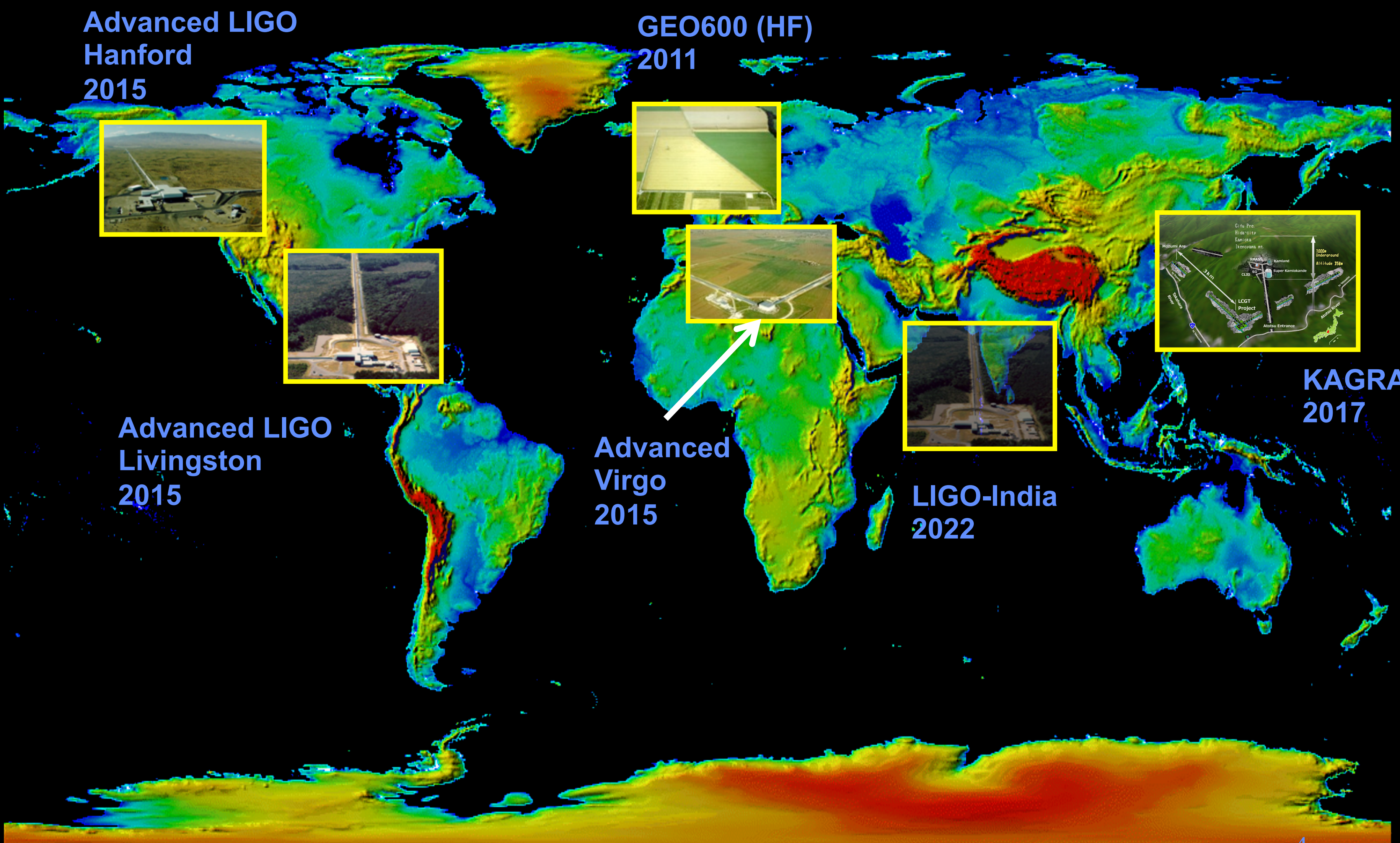
Gravitational wave physics experiments



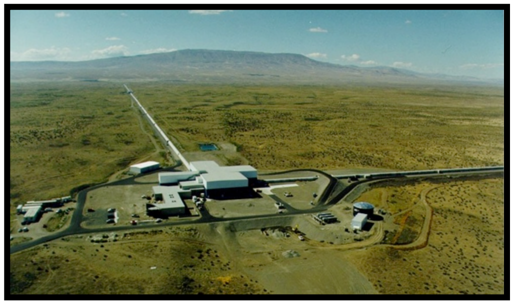
All three experiments measure changes in light travel times between objects due to GWs.

credit: X. Siemens and the NANOGrav Collaboration

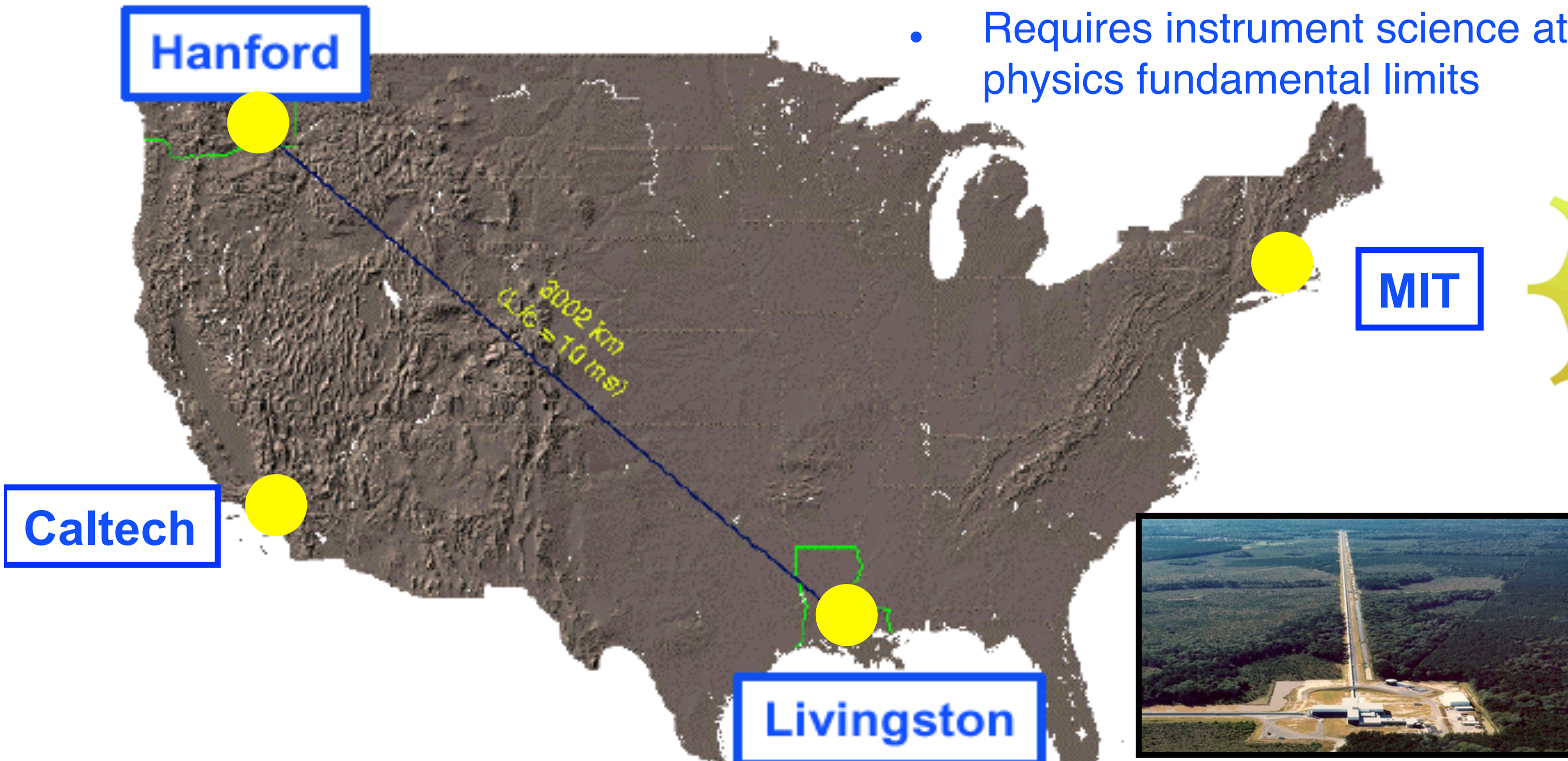
The advanced GW detector network: 2015–2025



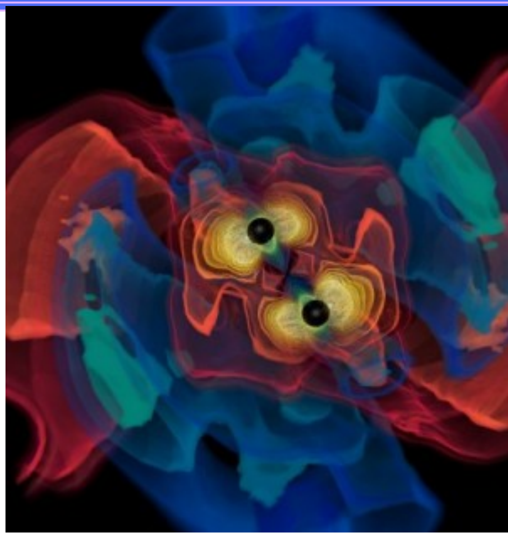
LIGO Laboratory: two Observatories, Caltech and MIT campuses



- 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 Astrophysical Sources of Gravitational Waves

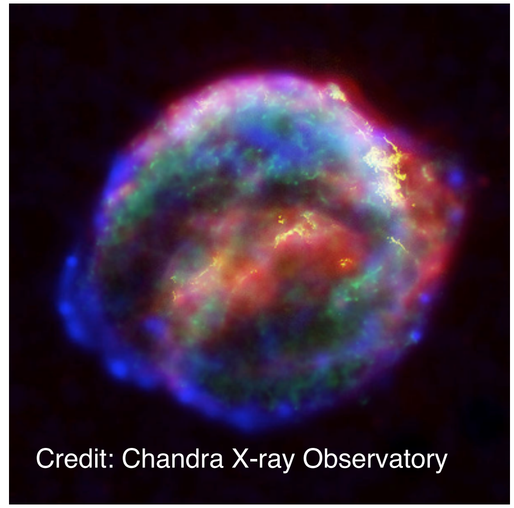


Credit: AEI, CCT, LSU

__Coalescing Compact Binary Systems__: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

- (effectively) transient

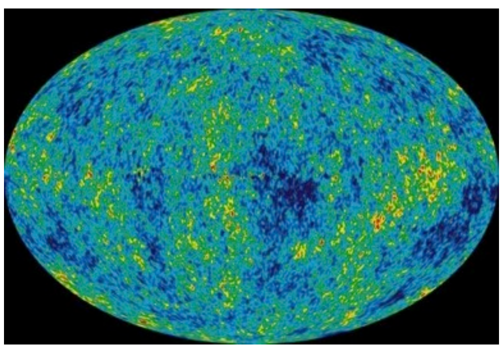


Credit: Chandra X-ray Observatory

__Asymmetric Core Collapse Supernovae__

- Weak emitters, not well-modeled ('bursts'), transient

- Also: cosmic strings, SGRs, pulsar glitches

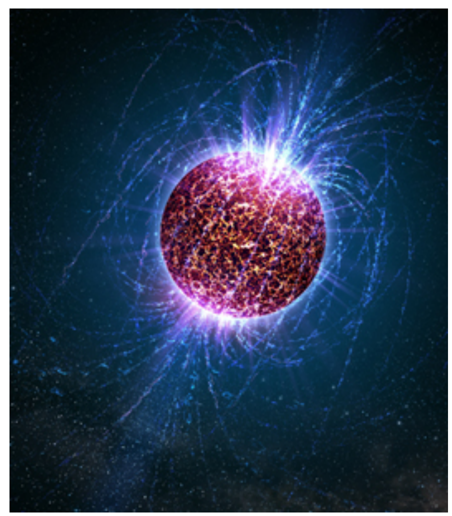


NASA/WMAP Science Team

__Cosmic Gravitational-wave Background__

- Residue of the Big Bang

- Long duration, stochastic background



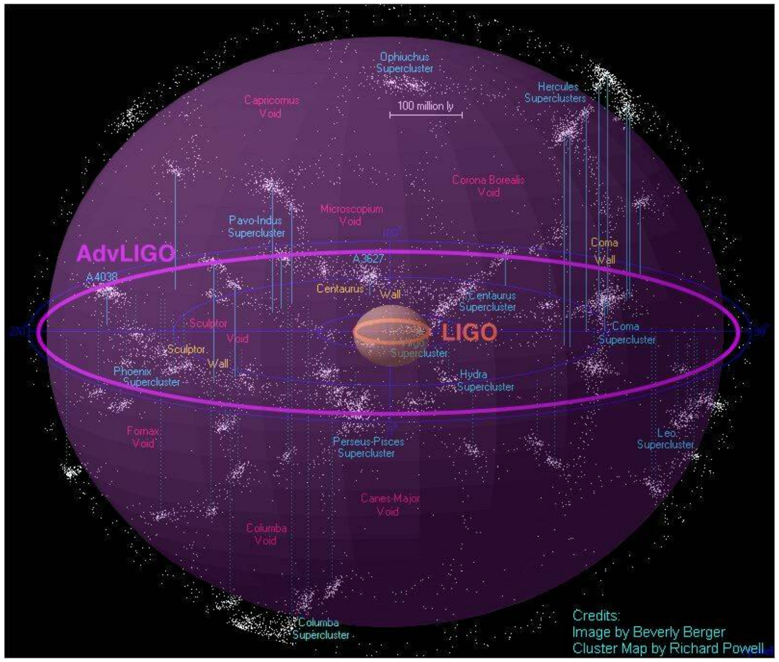
Casey Reed, Penn State

__Spinning neutron stars__

- (nearly) monotonic waveform

- Long duration

Expected event rates



Binary neutron stars

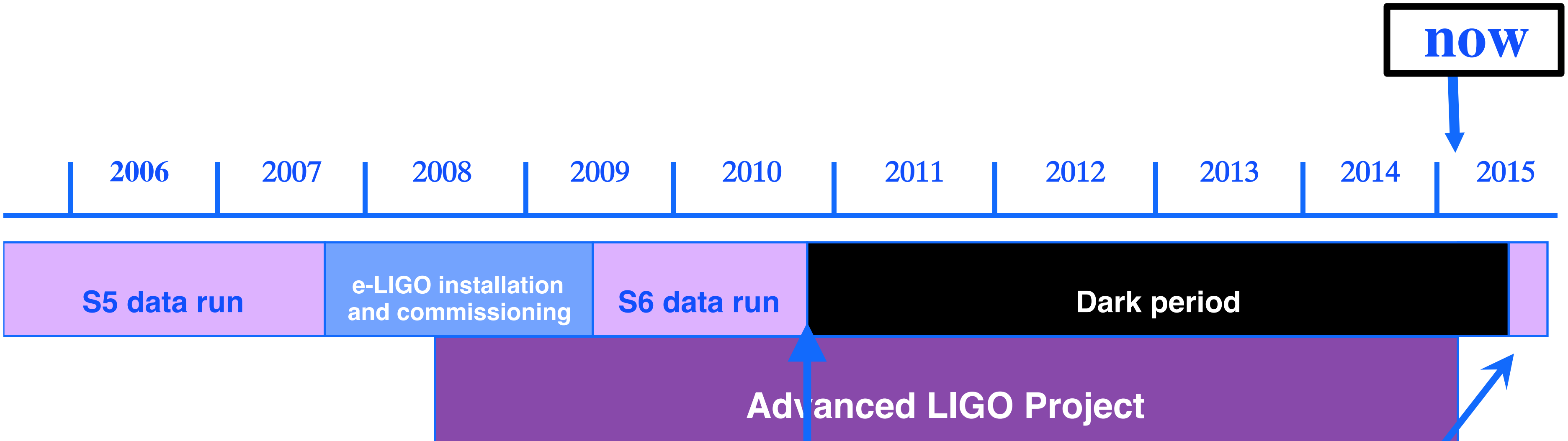
- Initial LIGO reach: 15Mpc; rate ~ 1/50yrs
- Advanced LIGO ~ 200Mpc
- 'Realistic' rate ~ 40 events/yr

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

LIGO time line



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

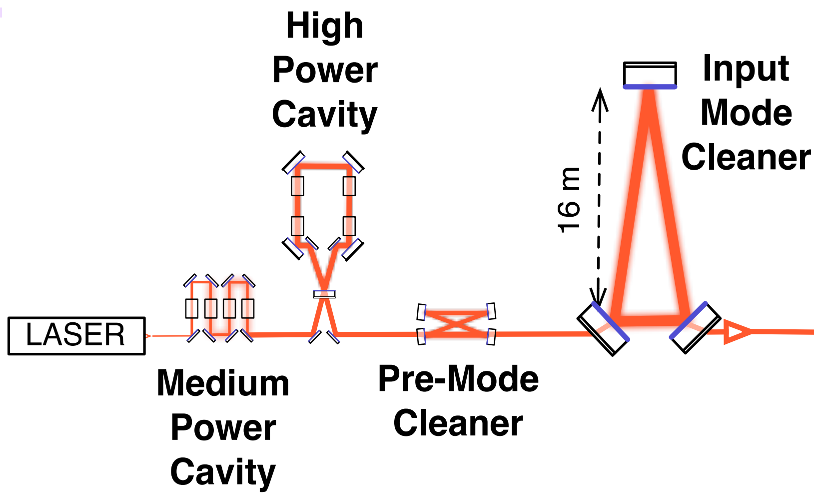
Adv LIGO Installation begins

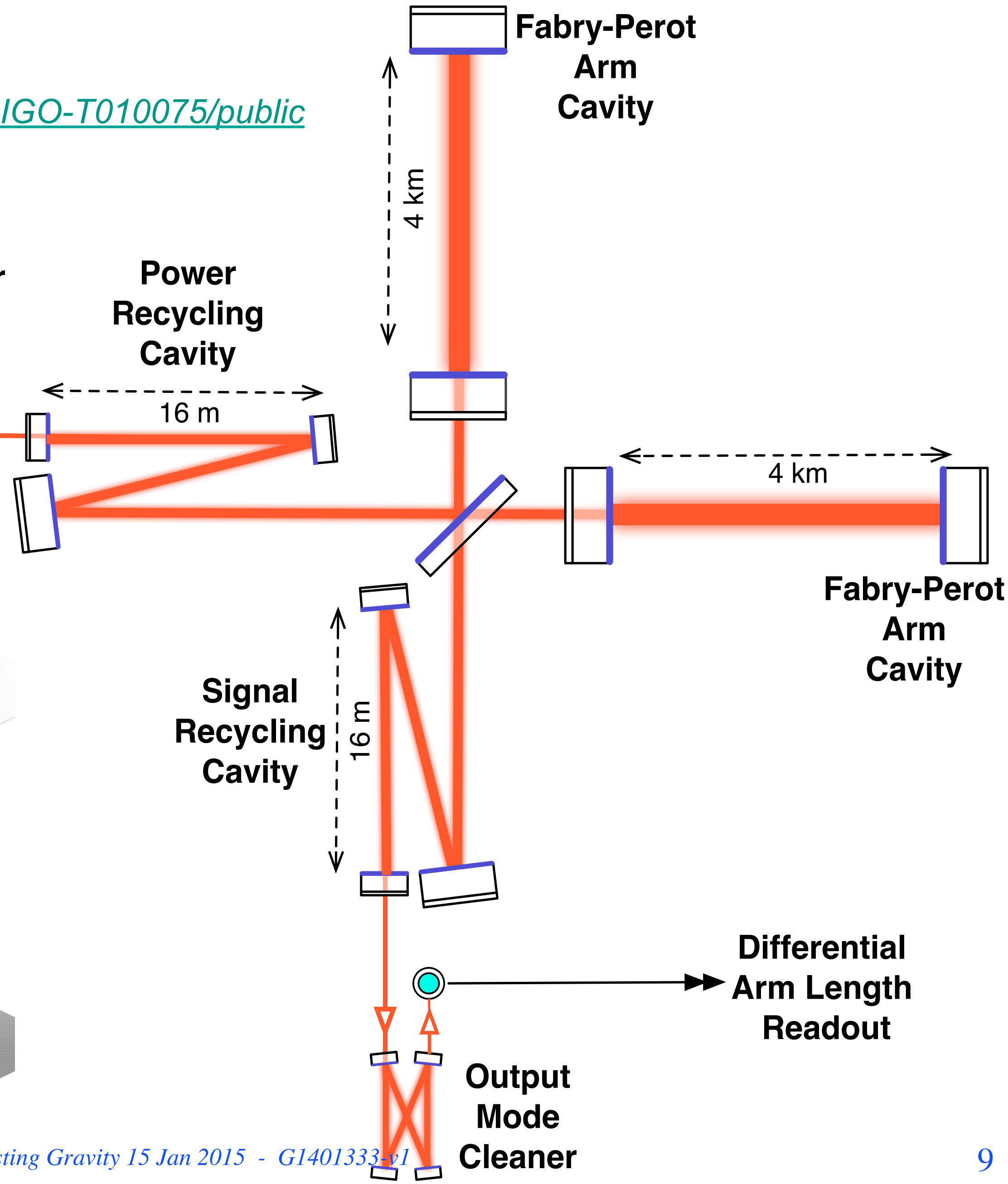
Commissioning & initial data With Advanced LIGO

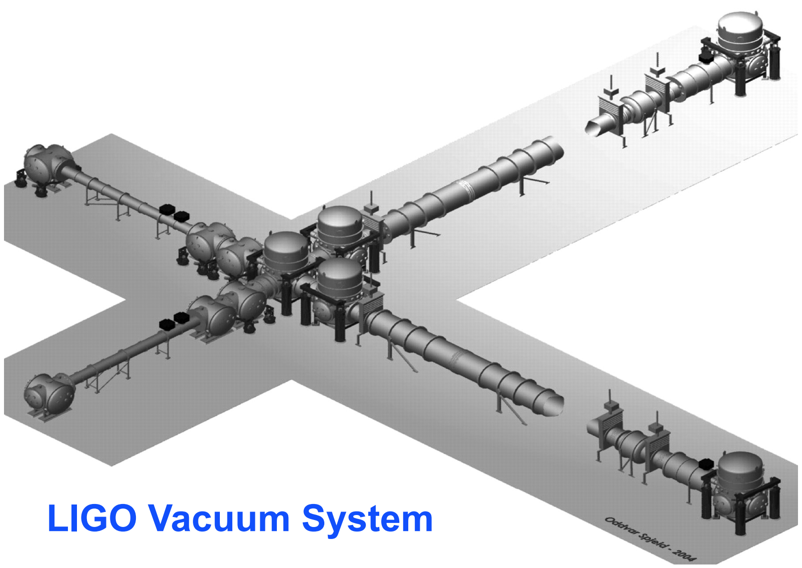
Optical Layout

Harry, G. M., *et al. CQG* 27.8 (2010): 084006.

P. Fritschel, et. al (2010) https://dcc.ligo.org/LIGO-T010075/public



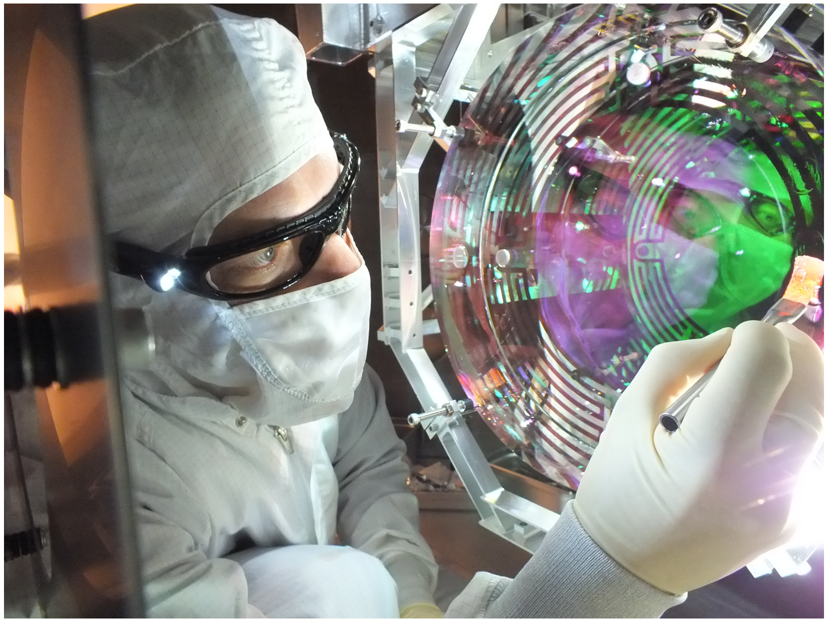




LIGO Vacuum System

Test Masses

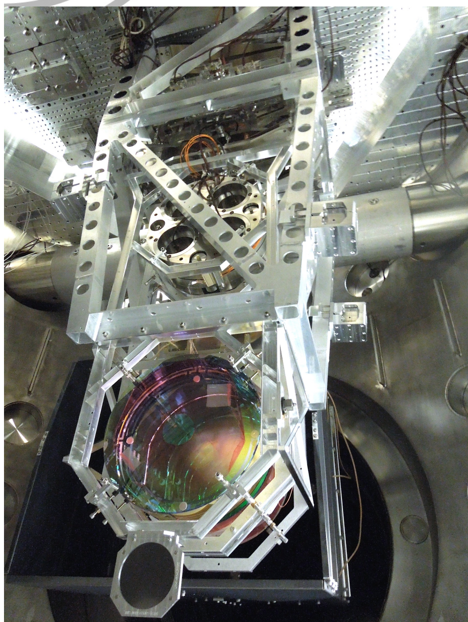
- Heavy Mirrors → Insensitive to photon pressure from high power
- Test mass coating brownian noise dominates strain sensitivity in the most sensitive region (~100 [Hz])
- Larger Mirrors → Increase Spot Size: Average over more surface area



Diameter	**34 cm**
Thickness	**20 cm**
Mass	**40 kg**
$1/e^2$ Beam Size	**5.3-6.2 cm**

Harry, G. M., *et al.* *CQG* 27.8 (2010) 084006

Seismic Isolation

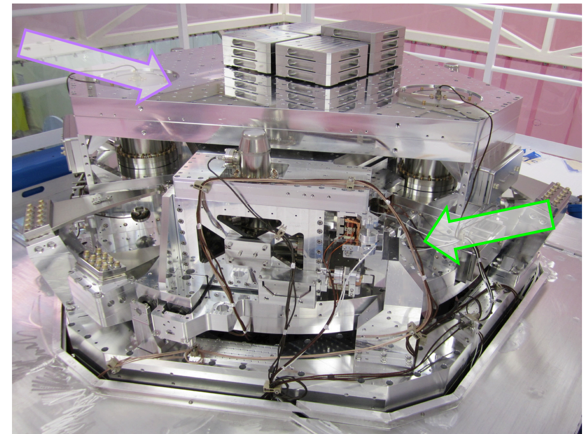


Ground Motion at 10 [Hz] ~ 10^{-9} [m/rtHz]

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

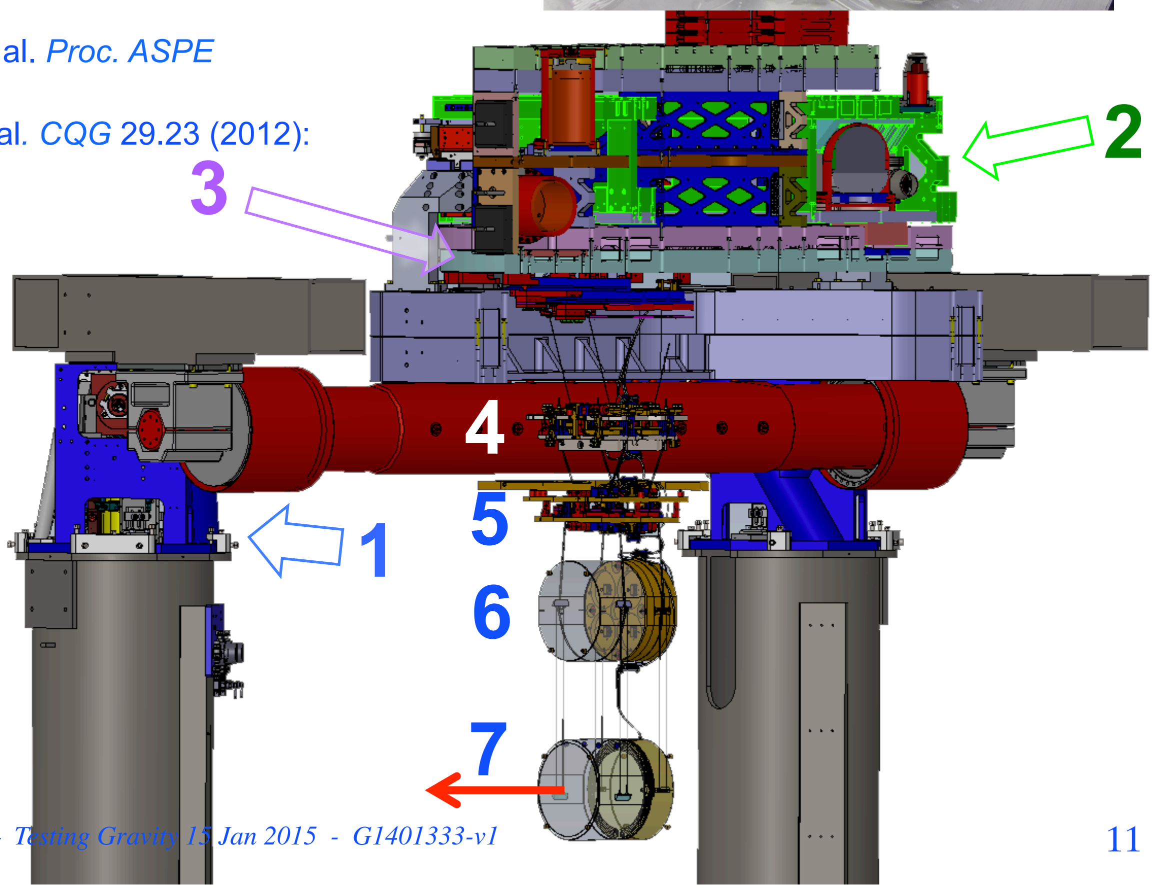
Need 10 orders of magnitude

Test masses are suspended from 7 stages of active and passive vibration isolation

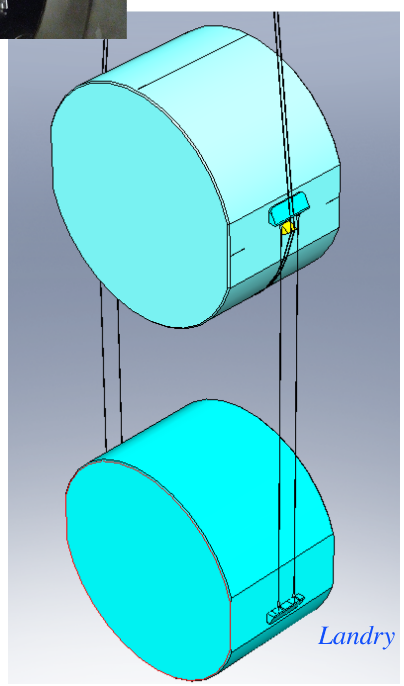


Matichard, F., et al. *Proc. ASPE* (2010)

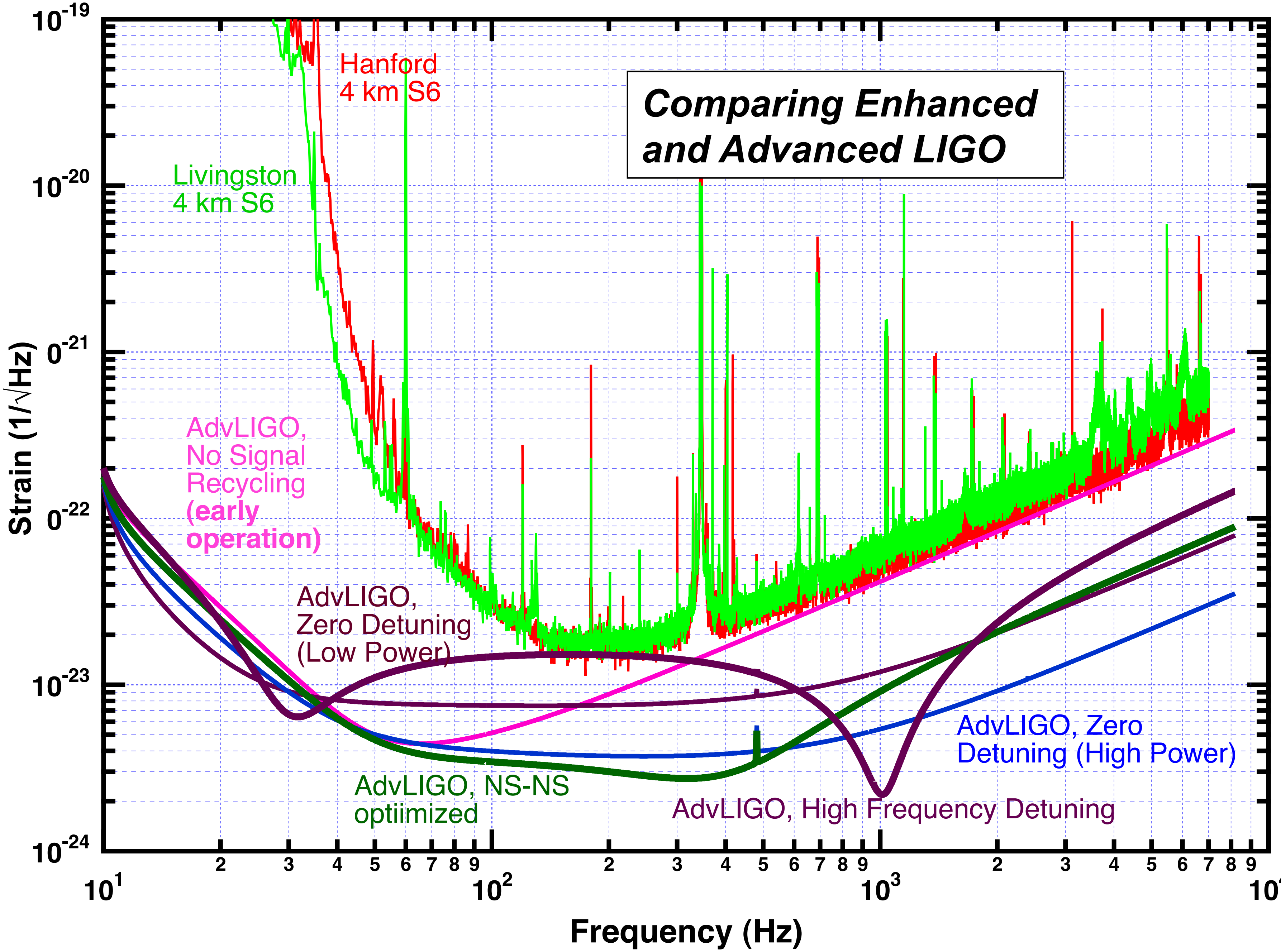
Aston, S. M., et al. *CQG* 29.23 (2012): 235004.



Last two stages are monolithic to improve Brownian noise



Cumming, A. V., et al. *CQG* 29.3 (2012): 035003.

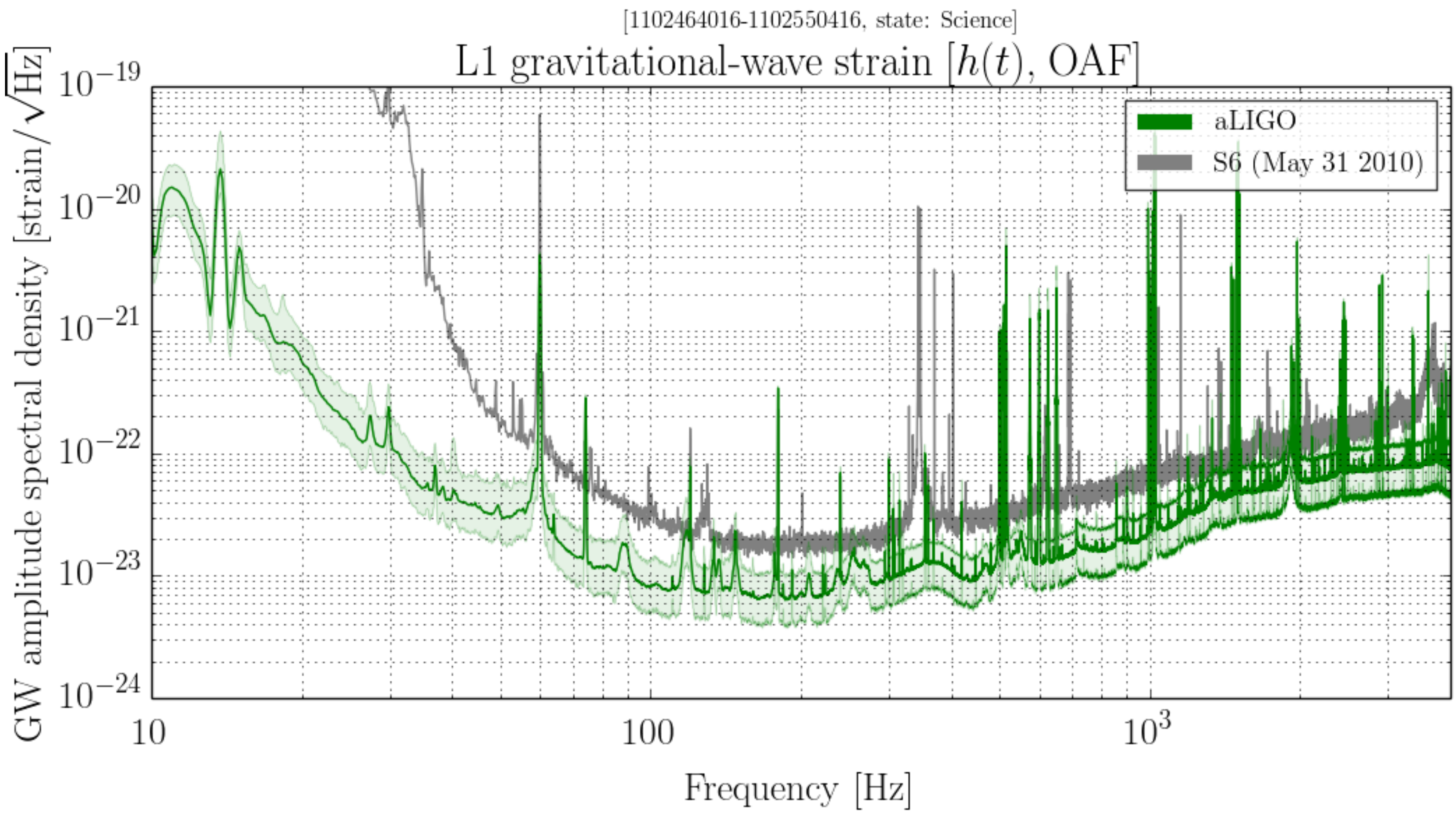


Comparing Enhanced and Advanced LIGO
Hanford 4 km S6
Livingston 4 km S6
AdvLIGO, No Signal Recycling (early operation)
AdvLIGO, Zero Detuning (Low Power)
AdvLIGO, Zero Detuning (High Power)
AdvLIGO, NS-NS optiimized
AdvLIGO, High Frequency Detuning
Strain (1/√Hz)
Frequency (Hz)
10-19
10-20
0-21
0-22
10-23
10-24
10¹
10²
10³
10⁴

Status

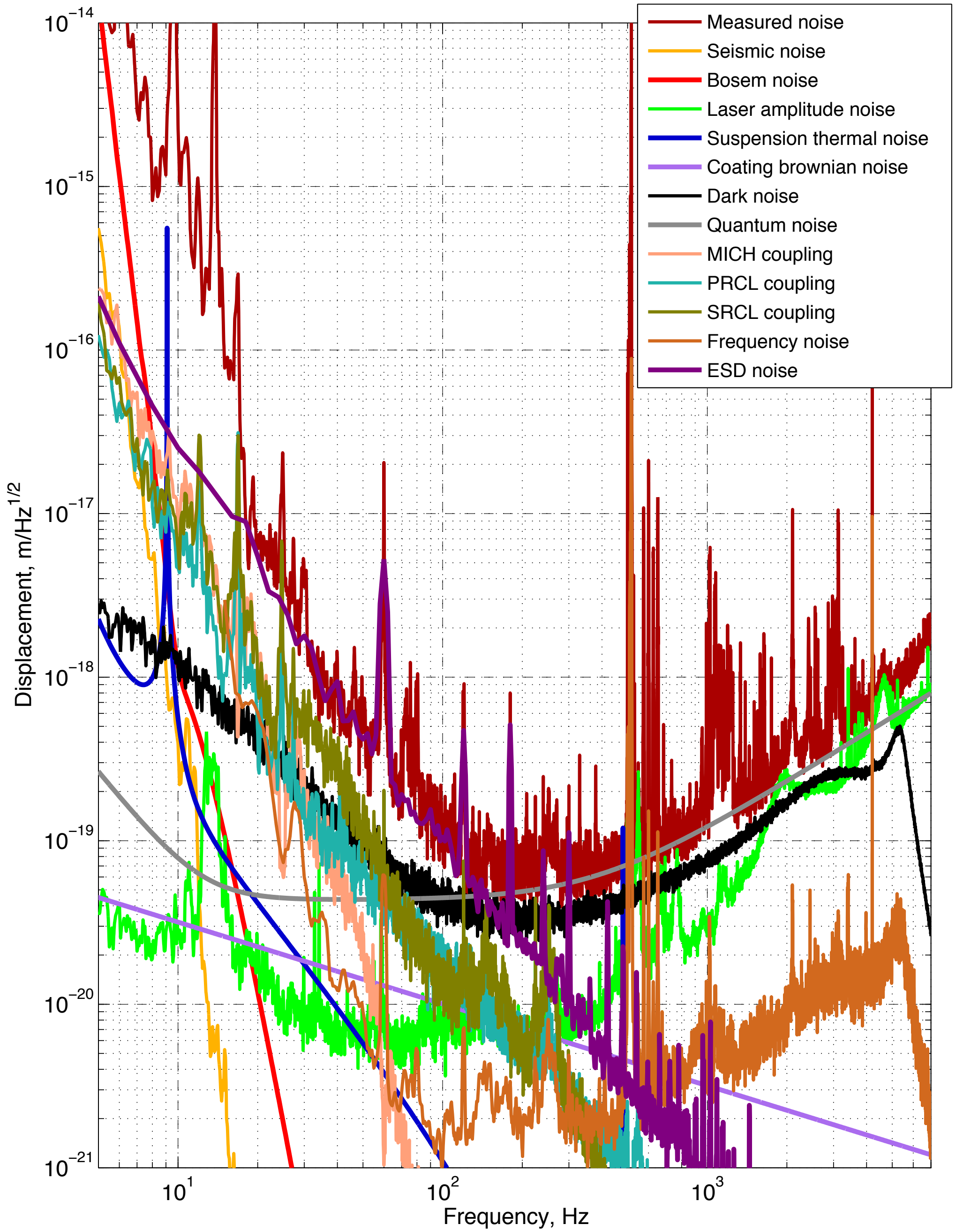
- LLO
  - » Installation complete, interferometer locked (cavities controlled and resonating laser light) on all d.o.f., commissioning underway
  - » Recently completed ER6 engineering run (~1 week), in which the interferometer was locked about 50% of the time, achieved multi-hour locks, and had a maximum inspiral range of 59Mpc
- LHO
  - » Installation complete, interferometer locked on all d.o.f., just embarking on commissioning of the full interferometer
  - » Transferring lessons learned from LLO to LHO
  - » Engineering run ER7 slated for spring 2015

59Mpc lock during ER6



Noise budget for lock at LLO

- ESD: electrostatic drive, the low noise actuator at the test mass
- Many technical noises still dominate these early spectra



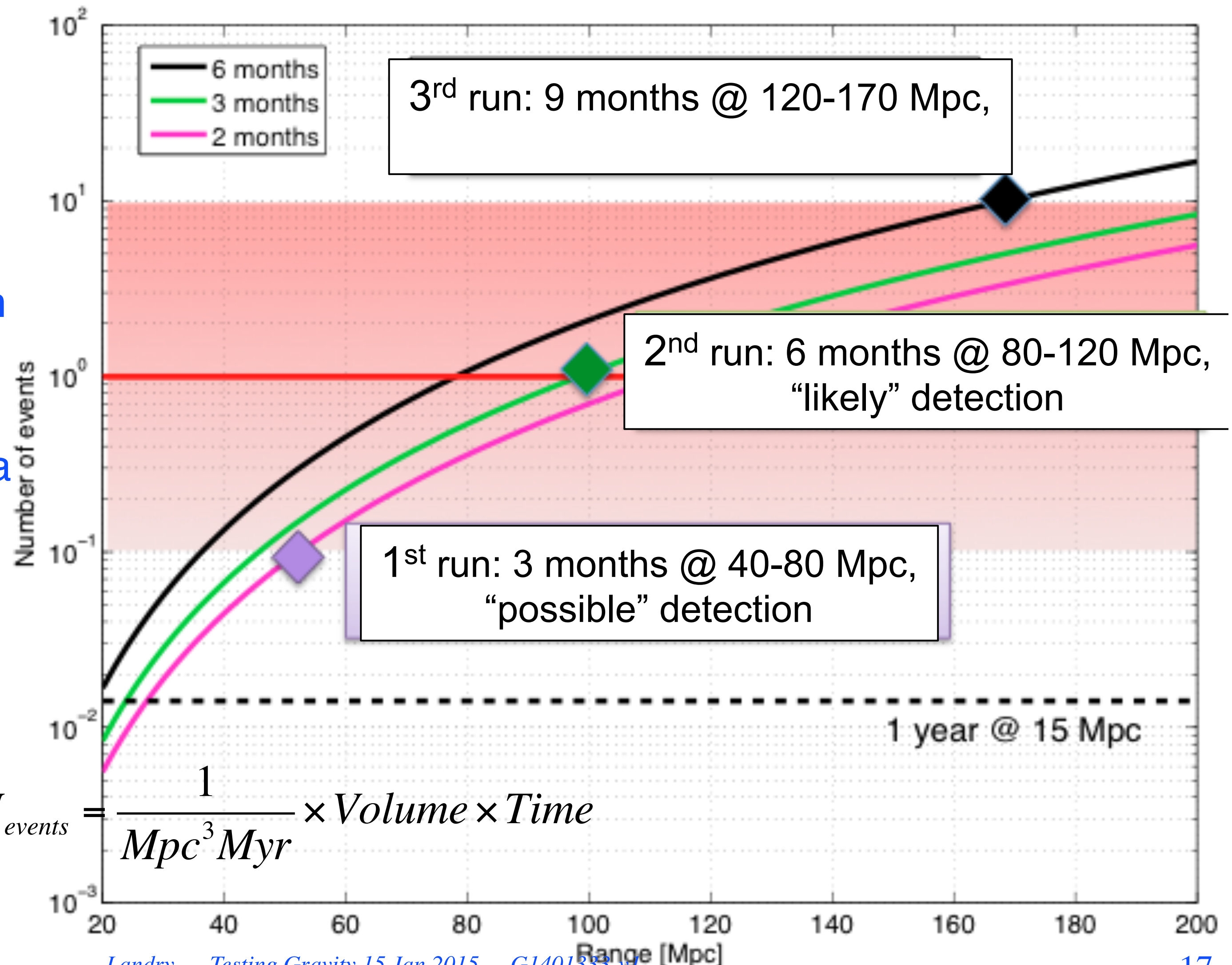
Working through issues

- Leading towards first science run, mitigating issues that impact sensitivity, stability:
  - » Noise excess in electrostatic drive electronics : swap components
  - » Evidence for test mass charging
    - – May be ion pumps
    - – Developed and testing ionizer to eliminate charge
  - » At LHO, some residue on one test mass surface
    - – Excess loss in single arm
    - – Made chamber access to clean optic
  - » At LLO, some evidence for parametric instability at P > 50W
    - – 15.5kHz acoustic mode overlaps with higher order laser mode
    - – Employed thermal compensation system to tune away instability
  - » End test mass (ETM) transmissions for green light too high
    - – Coatings (for green light) do not meet spec
    - – Currently locking robustly at LLO – if problematic in future, may swap out ETMs

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



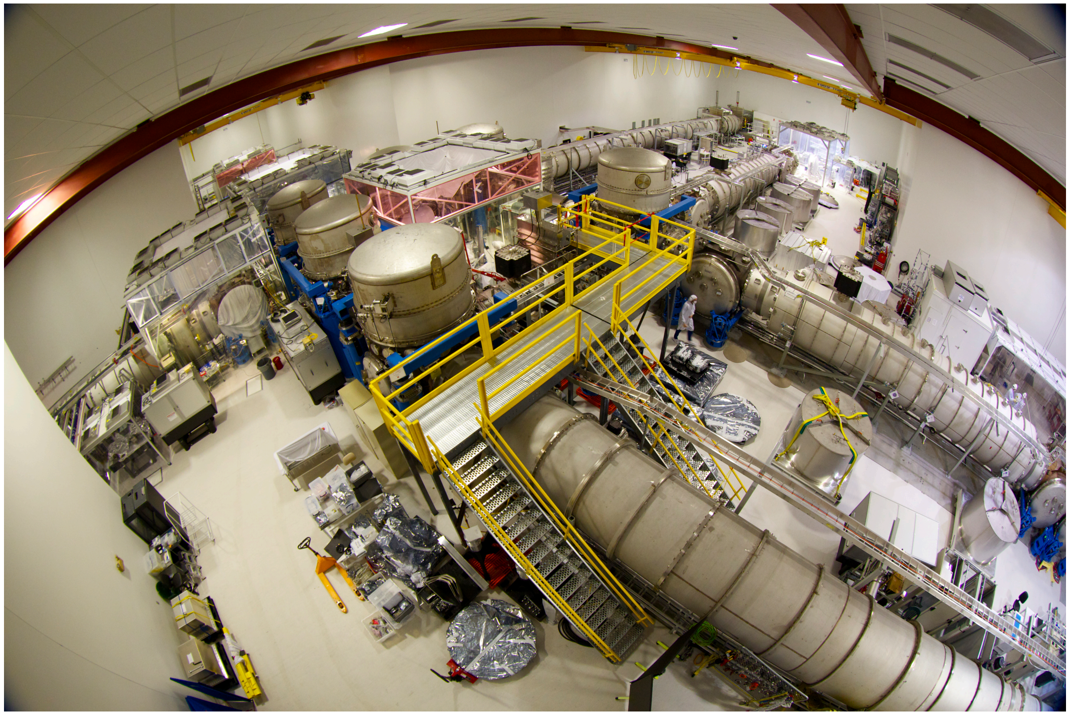
$$N_{events} = \frac{1}{Mpc^3 Myr} \times Volume \times Time$$

LIGO-India

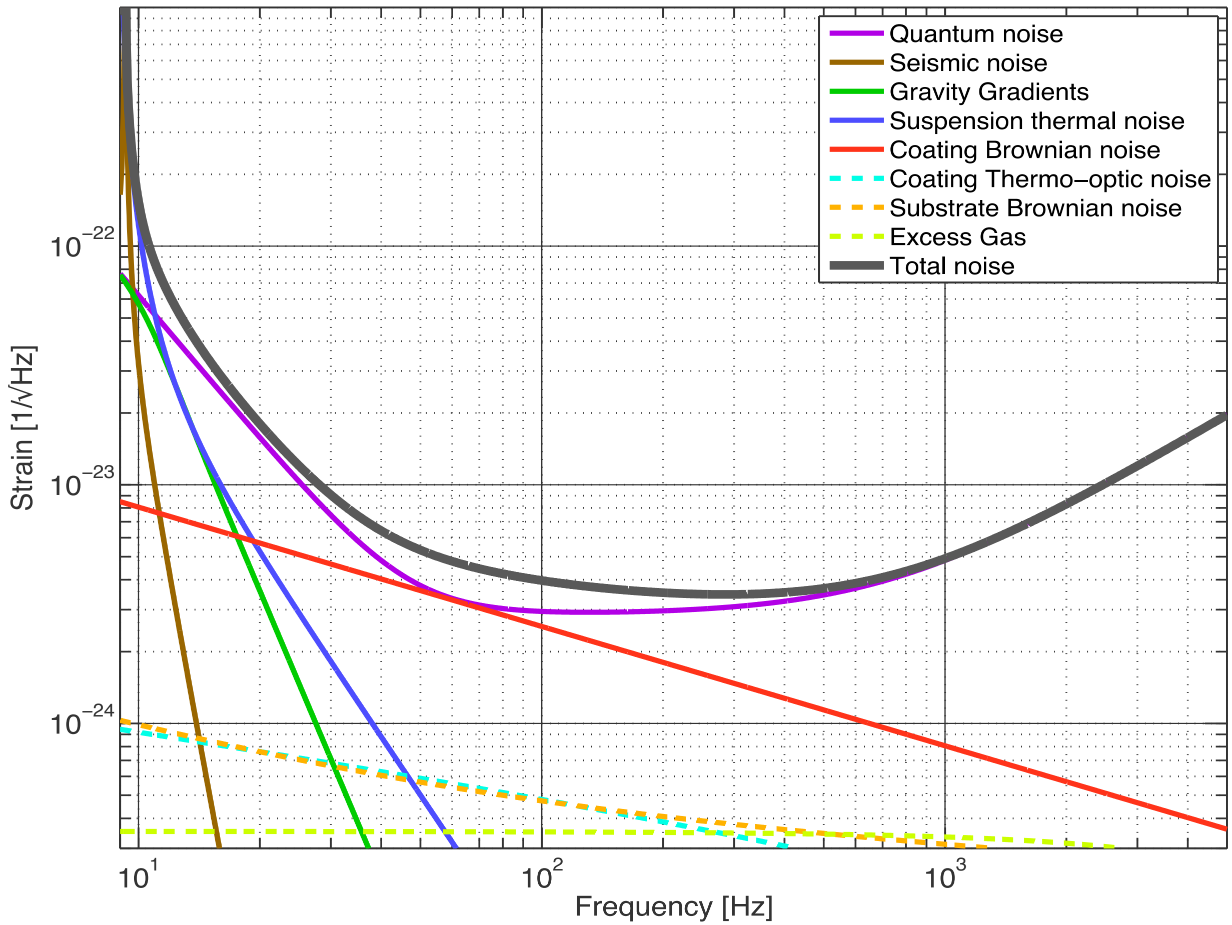
- International collaboration between US and India to establish a LIGO observatory in India
- LIGO-US provides components for one Advanced LIGO interferometer from the Advanced LIGO project
- India provides the infrastructure
- Indian funding – India Mega-science Project (~230M)
- US funding – funding for aLIGO components from NSF
  - » Total contribution $140M (includes aLIGO components, designs, documentation)
- Status in India
  - » Final cabinet approval imminent
  - » Site selection: 4 sites being assessed
- Status in US
  - » National Science Board has given permission to NSF "to approve the proposed aLIGO Project in scope"

Summary

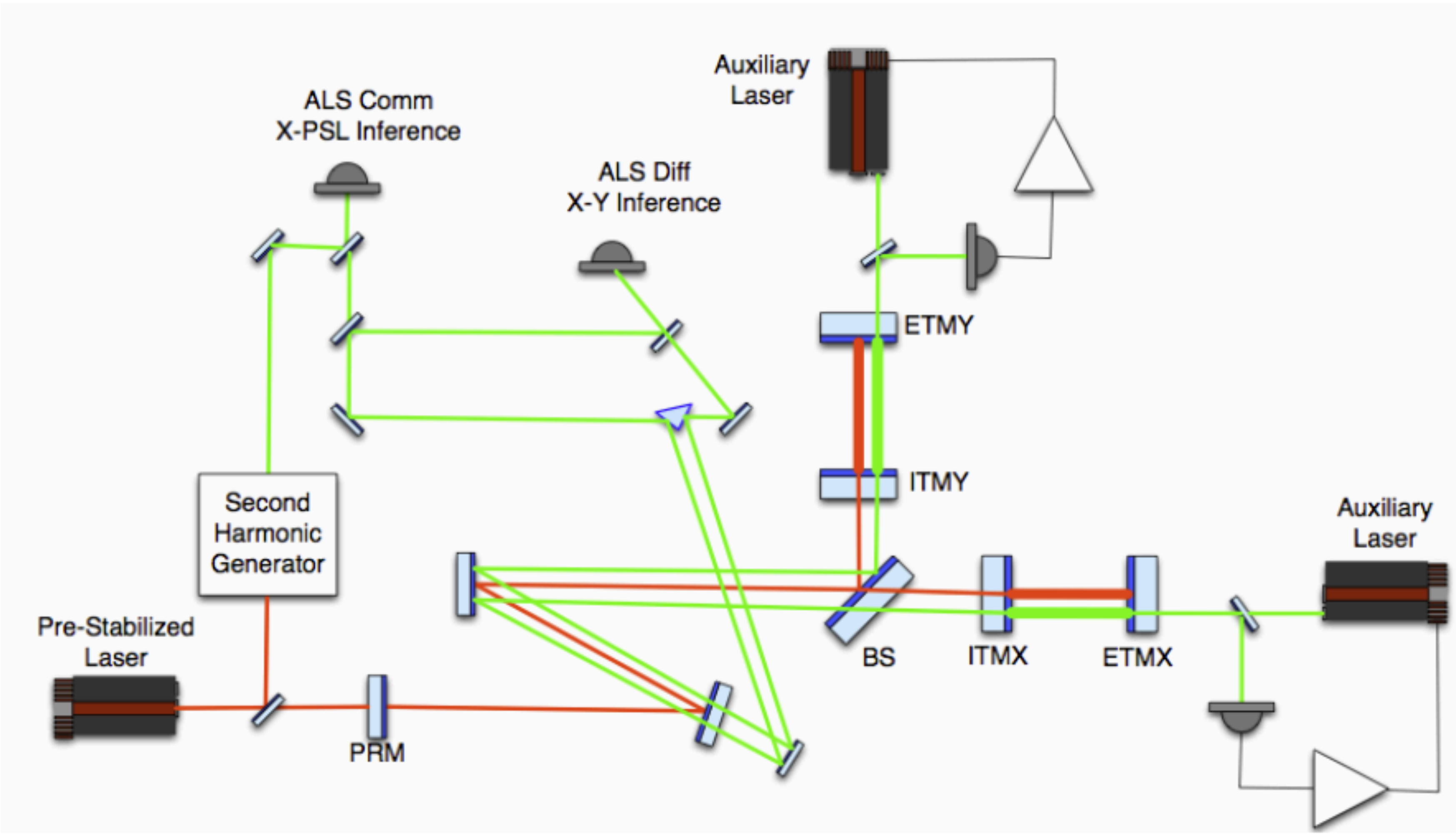
- Advanced LIGO nearly complete as a project: L1 locking at 60Mpc, H1 fully locked but at the outset of noise hunting
- We expect to make first science run with the second generation detectors in 2015 and 2016, runs which may produce detections
- We will press onward with sensitivity improvements to design sensitivity
- We expect gravitational waves will be detected in the coming few years



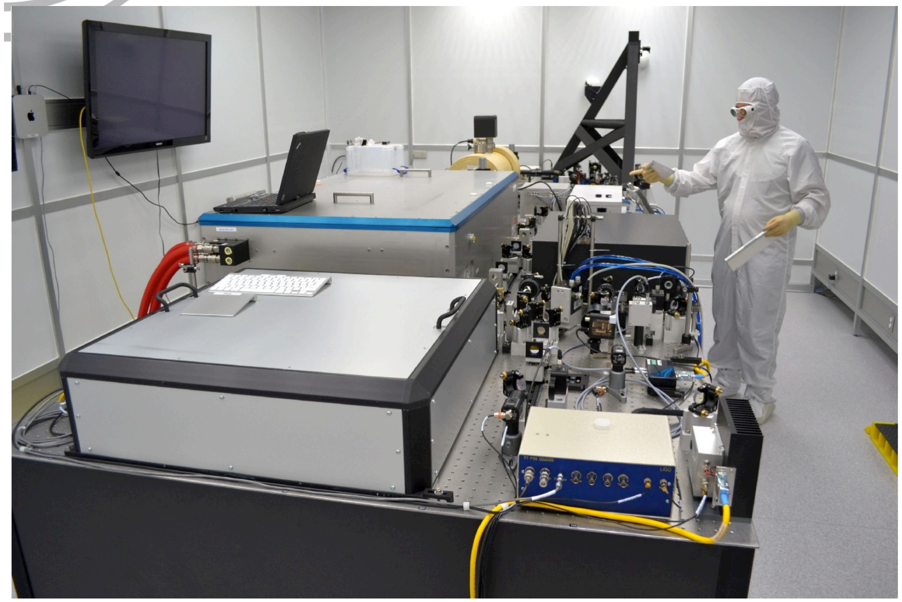
Principal noise terms



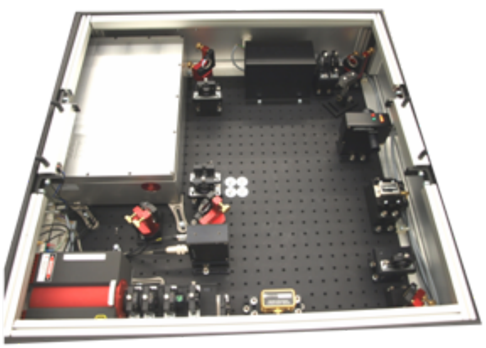
Arm length stabilization

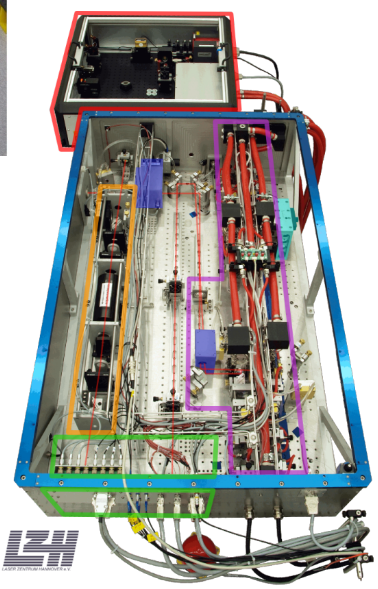


High-power Pre-Stabilized Laser



- Multi-stage, low-noise Nd:YaG, λ=1μm laser
- Power increased by a factor of 5
- Power and frequency noise are better

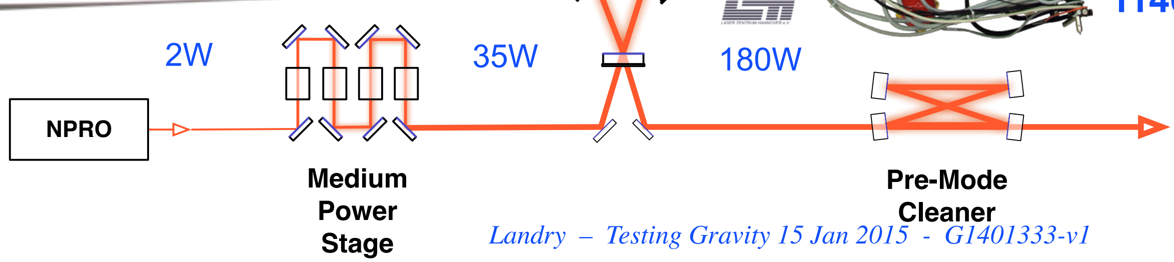




Max Power	**180 W**
Power Noise	**10^{-7} W/Hz$^{-1/2}$**
Frequency Noise	**0.1 Hz/Hz$^{-1/2}$**

(*Noise at 10 Hz)

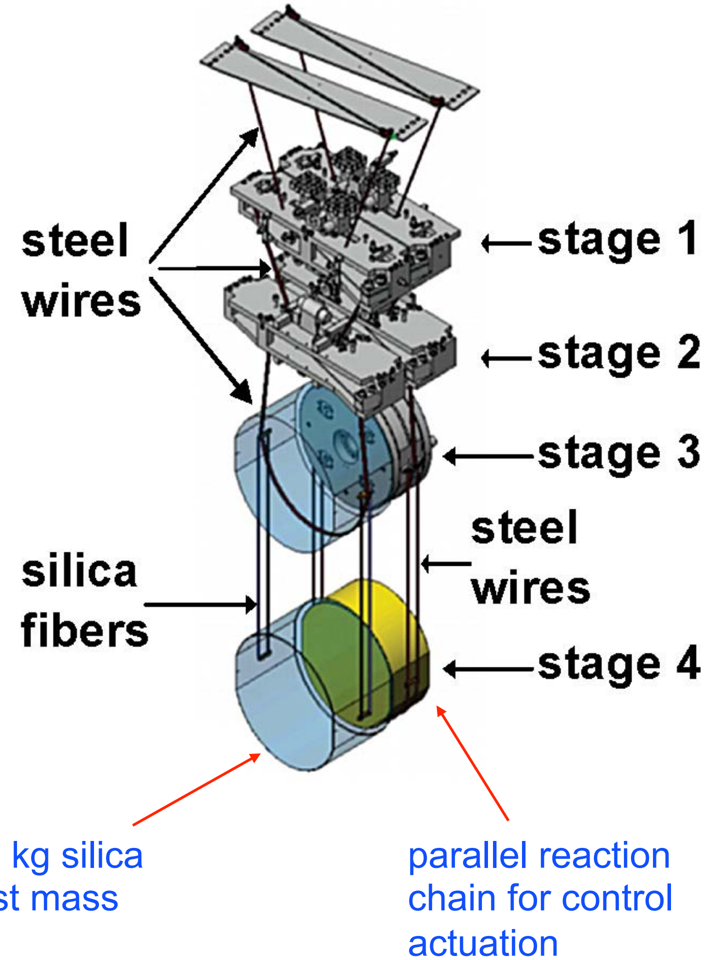
Willke, B., et al. *CQG* 25.11 (2008): 114040.



165W to Interferometer

Test mass suspensions

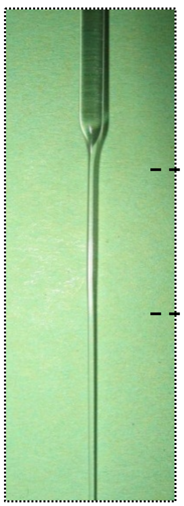
- Thermal noise reduction: monolithic fused silica suspension as final stage - low pendulum thermal noise and preservation of high mirror quality factor
- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades for enhanced vertical isolation
  - » *isolation @ 10Hz: quad ~ 3e-7, c.f. single stage ~ 5e-3*
- Control noise minimisation: apply damping at top mass (for 6 degrees of freedom) and use quiet reaction pendulum for global control actuation in a hierarchical way
  - » Coil/magnet actuation at top 3 stages
  - » electrostatic drive at test mass

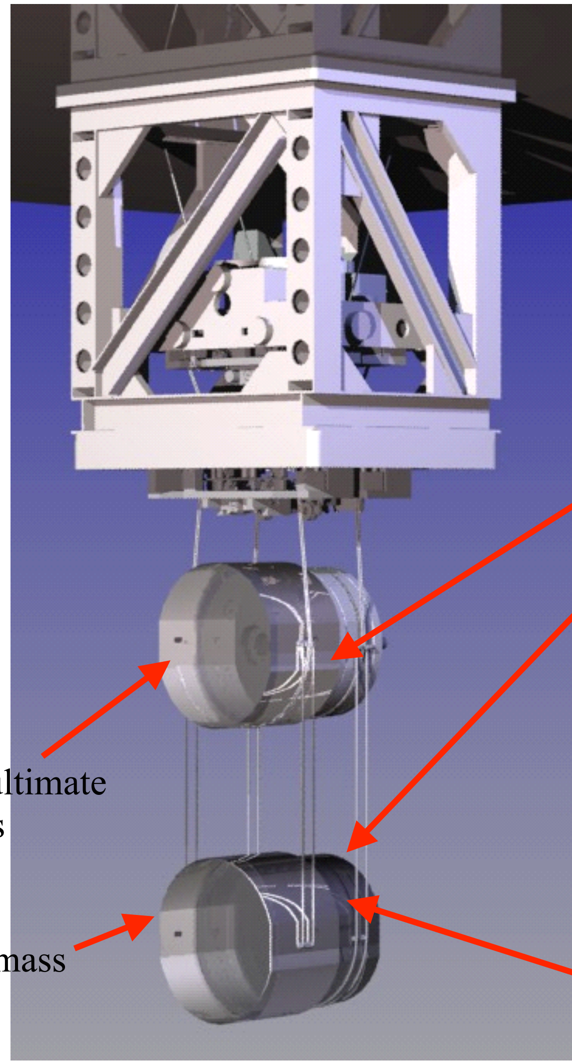


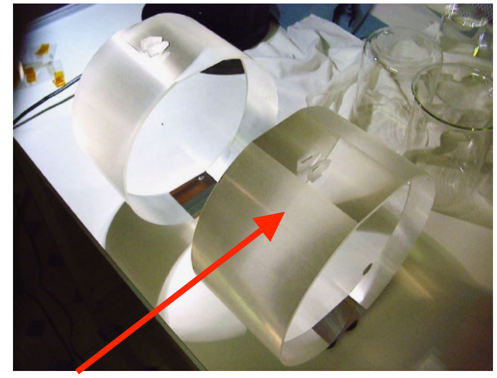
Monolithic stage

Monolithic stage

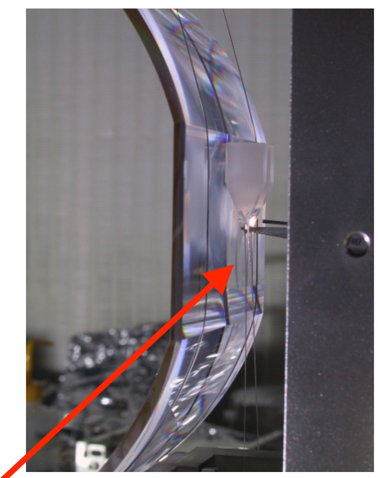
- 40 kg silica test mass suspended from 40 kg penultimate mass, also silica
- Four dumbbell shaped silica fibres (details below)
- Fibres welded to silica ears, bonded to the sides of the silica masses







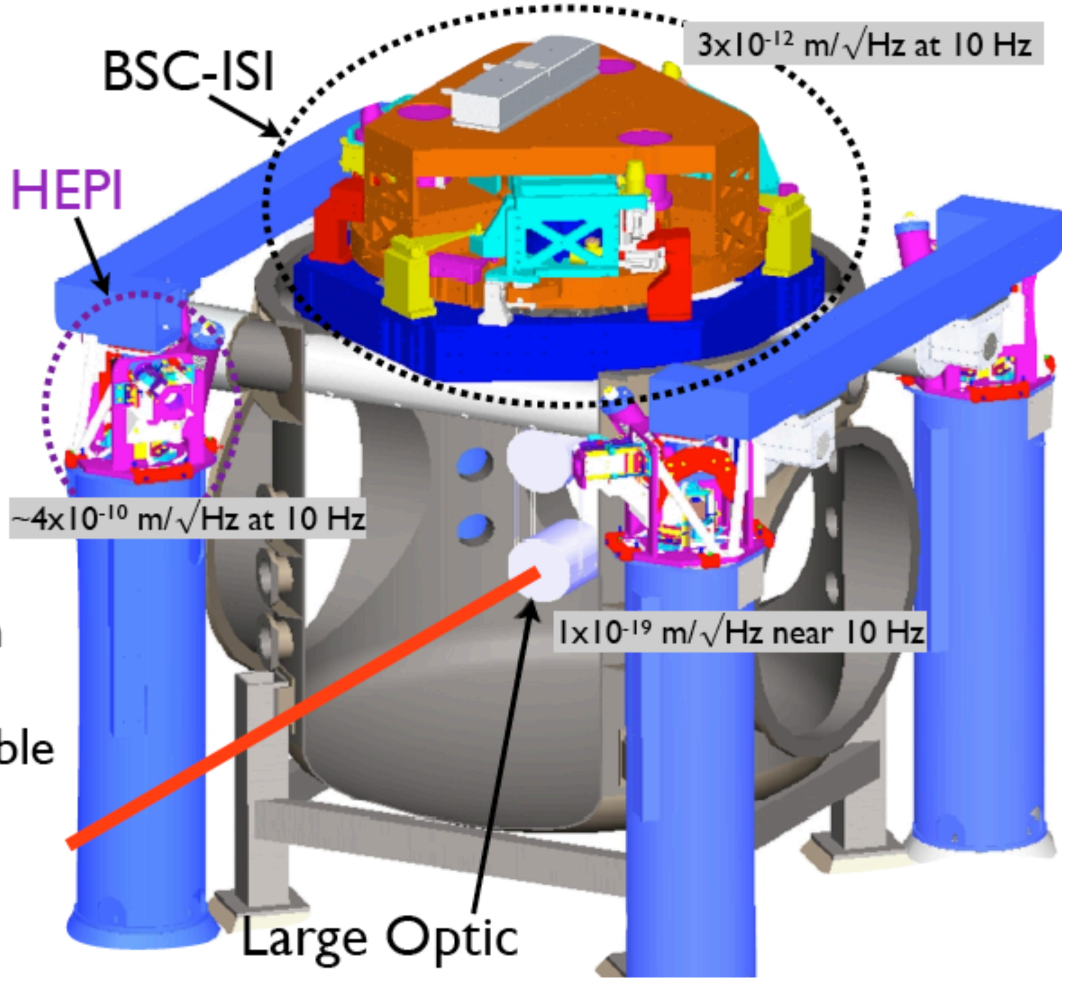
Ears silicate bonded to masses



Silica fibres, length 600 mm diameter 400 μm, welded to silica ears

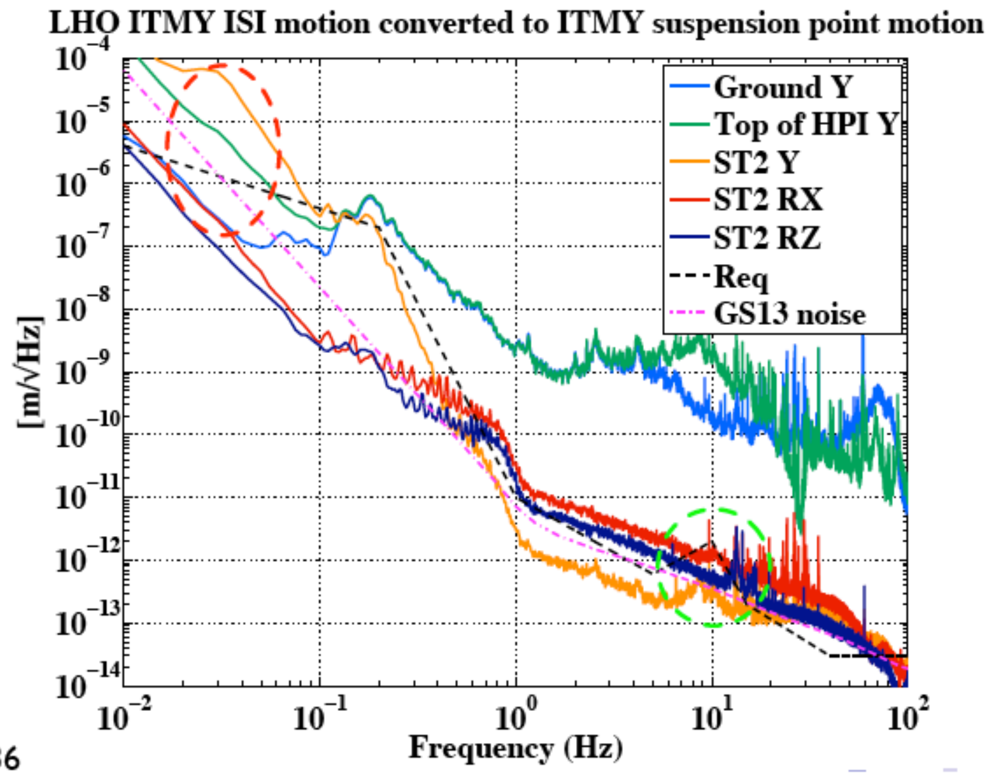
Seismic isolation

- 7 total layers
  - HEPI (1)
  - BSC-ISI (2)
  - Quad SUS (4)
- HEPI: Hydraulic External Pre-Isolator
  large throw,
  isolation below ~5 Hz
- ISI
  Internal Seismic Isolation
  Isolates above ~0.2 Hz
  Quiet, well controlled table
- Quad pendulum
  superior performance
  at 10 Hz and above



Seismic isolation performance

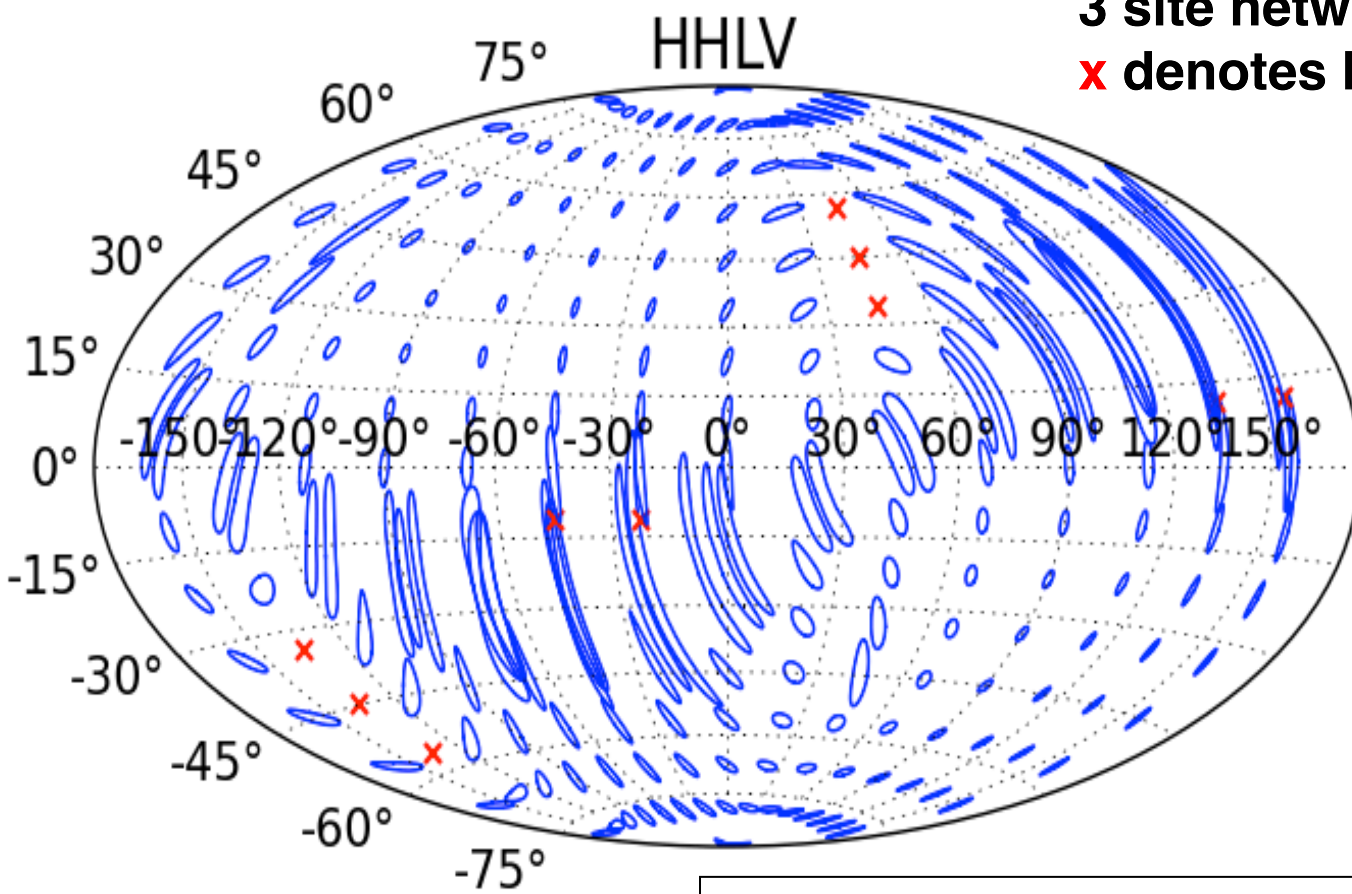
- At LHO the BSC ISI isolation is working at or better than the requirements from 0.1 Hz and up.
- Below 0.1 Hz there is some noise injection which may be removed with better tilt decoupling



R. deRosa, G1300936

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

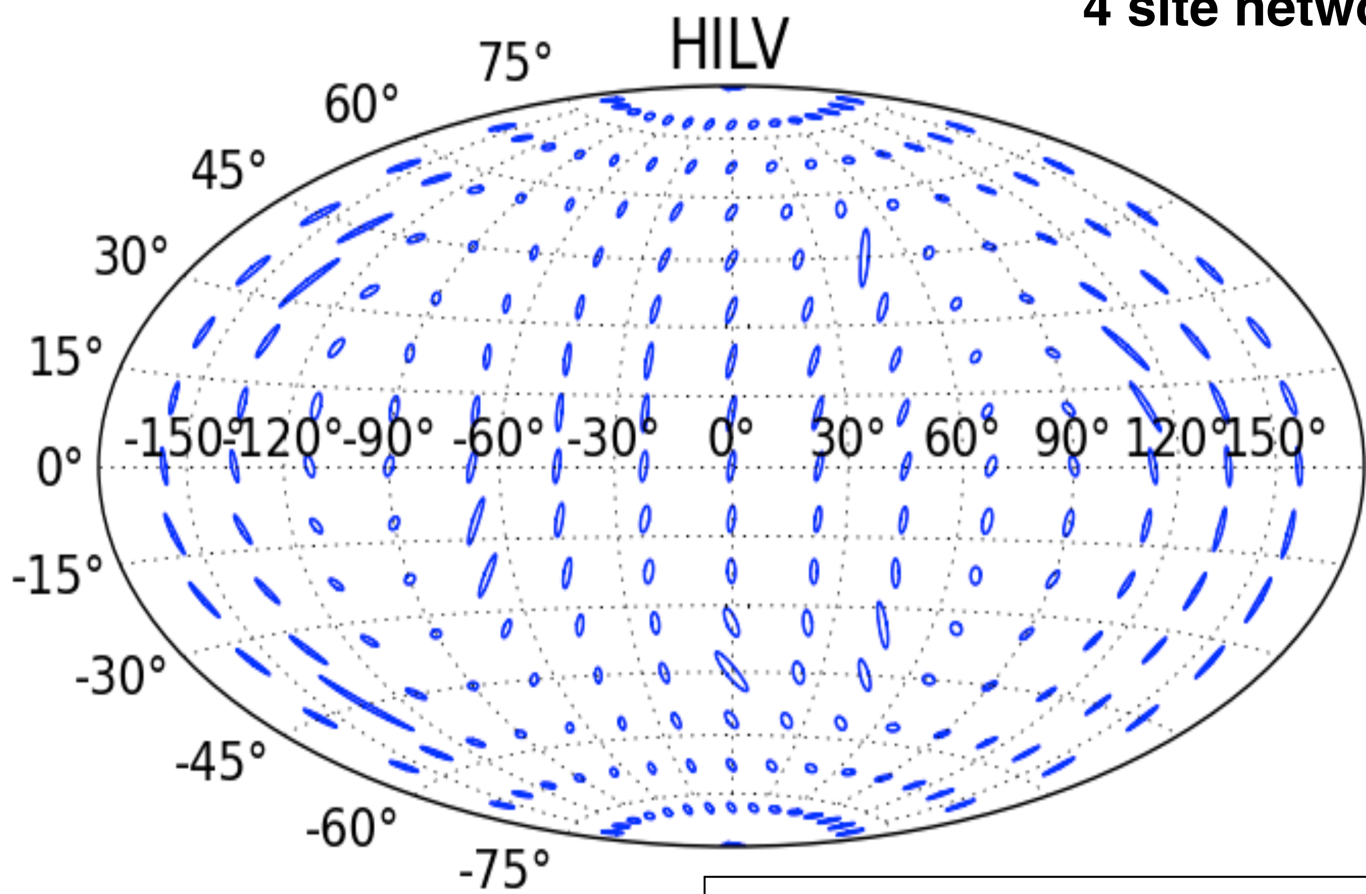
3 site network
x denotes blind spots



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

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

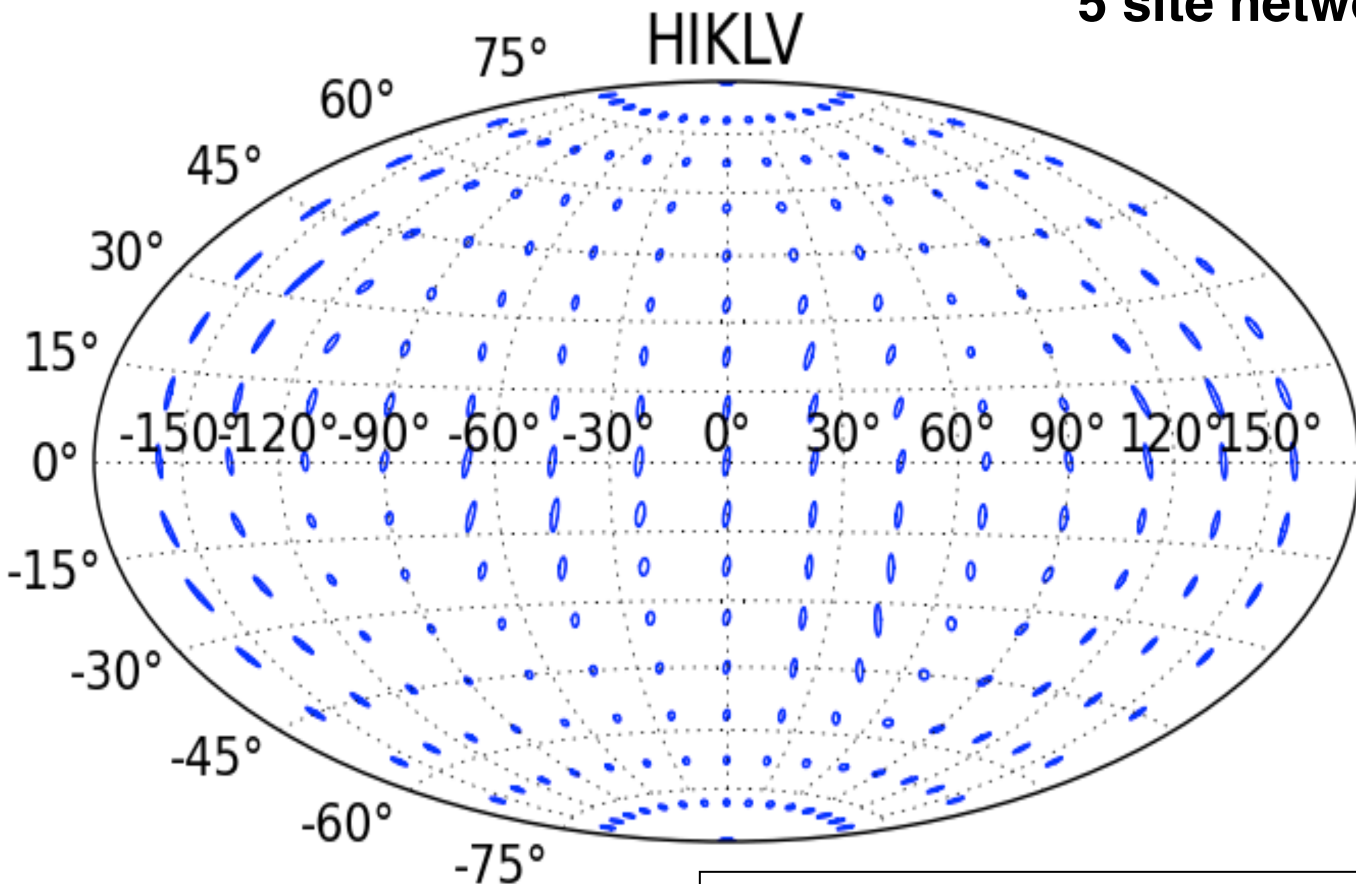
4 site network



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

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

5 site network



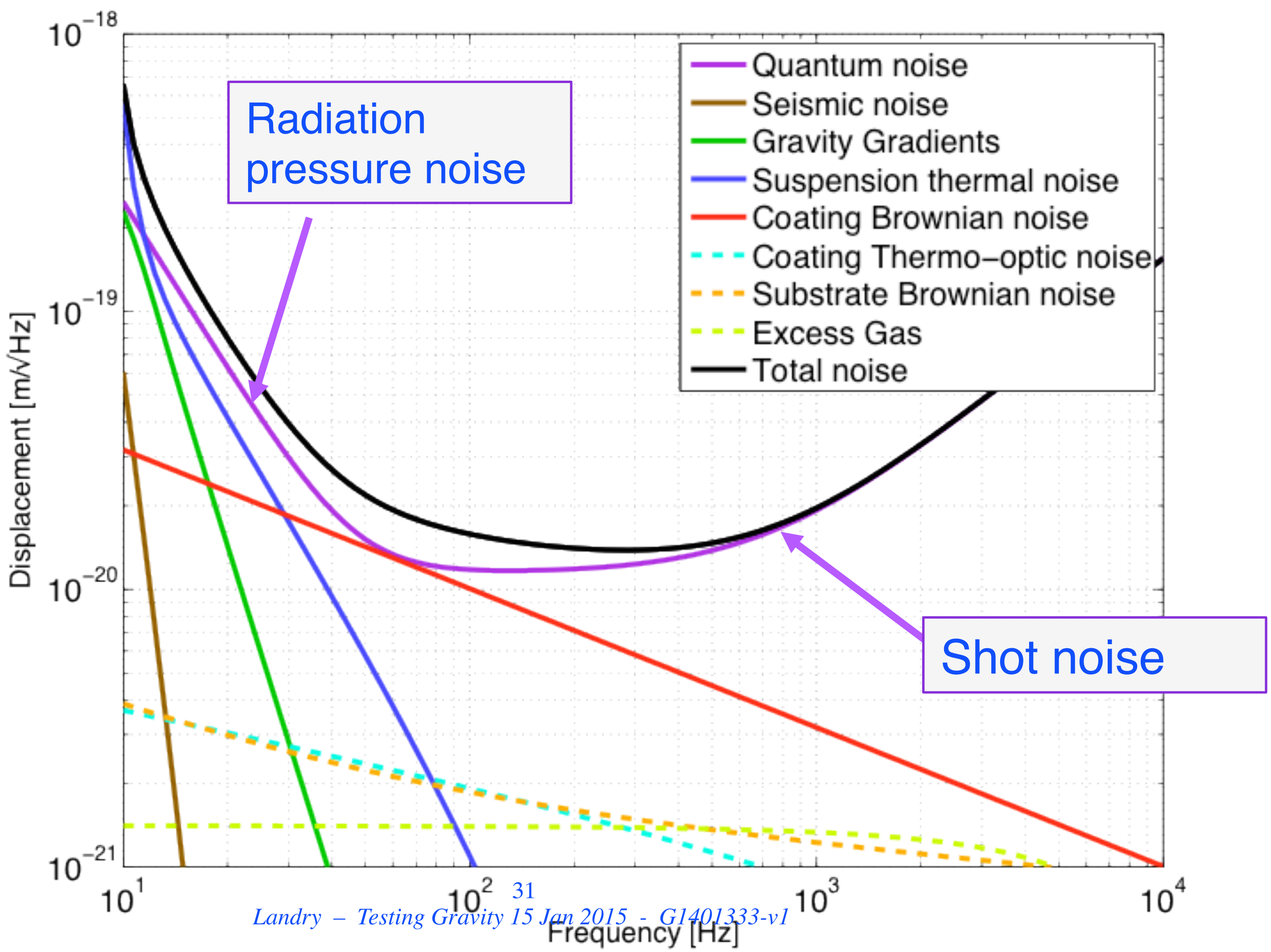
S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Squeezing

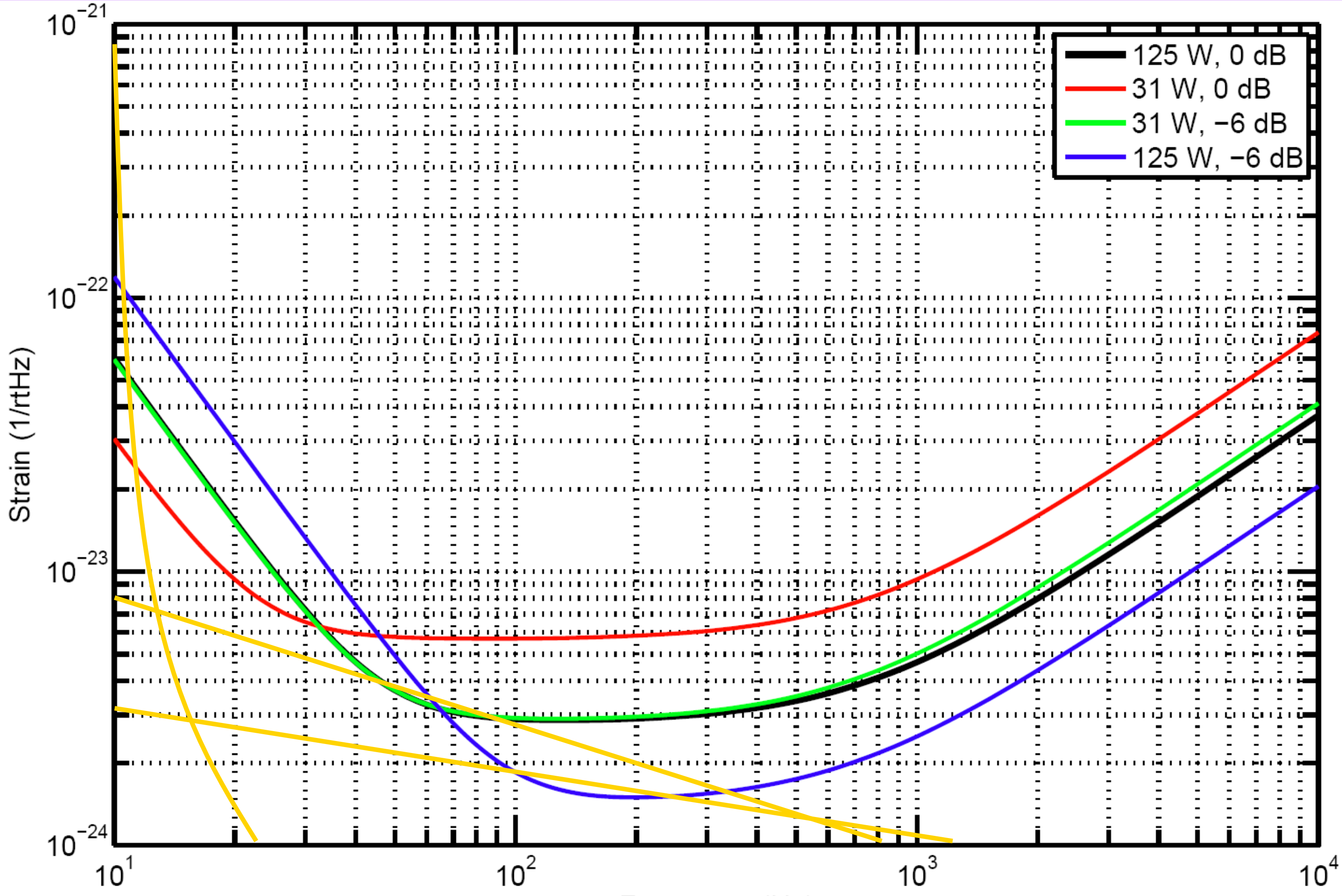
- Shot noise in a Michelson interferometer is due to vacuum fluctuations entering the dark port.
- Quantum noise also produces photon pressure noise.
- Injecting a specially prepared light state with reduced phase noise (relative to vacuum) into the dark port will improve the shot noise sensitivity.
- 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



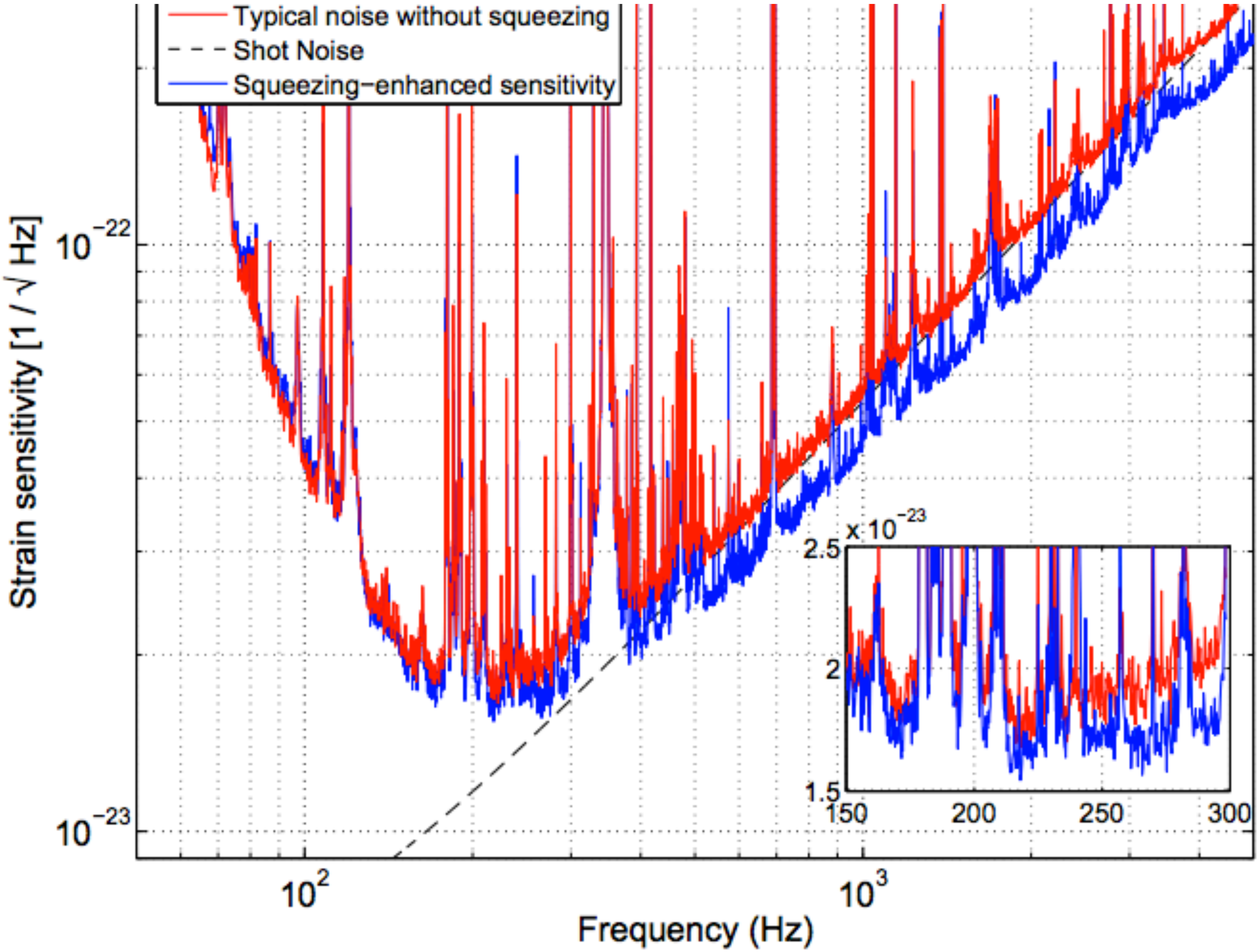


FIG. 2. Strain sensitivity of the H1 detector measured with and without squeezing injection. The improvement is up to 2.15 dB in the shot noise limited frequency band. Several effects cause the sharp lines visible in the spectra: mechanical resonances in the mirror suspensions, resonances of the internal 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