



Status of LIGO and VIRGO towards O3

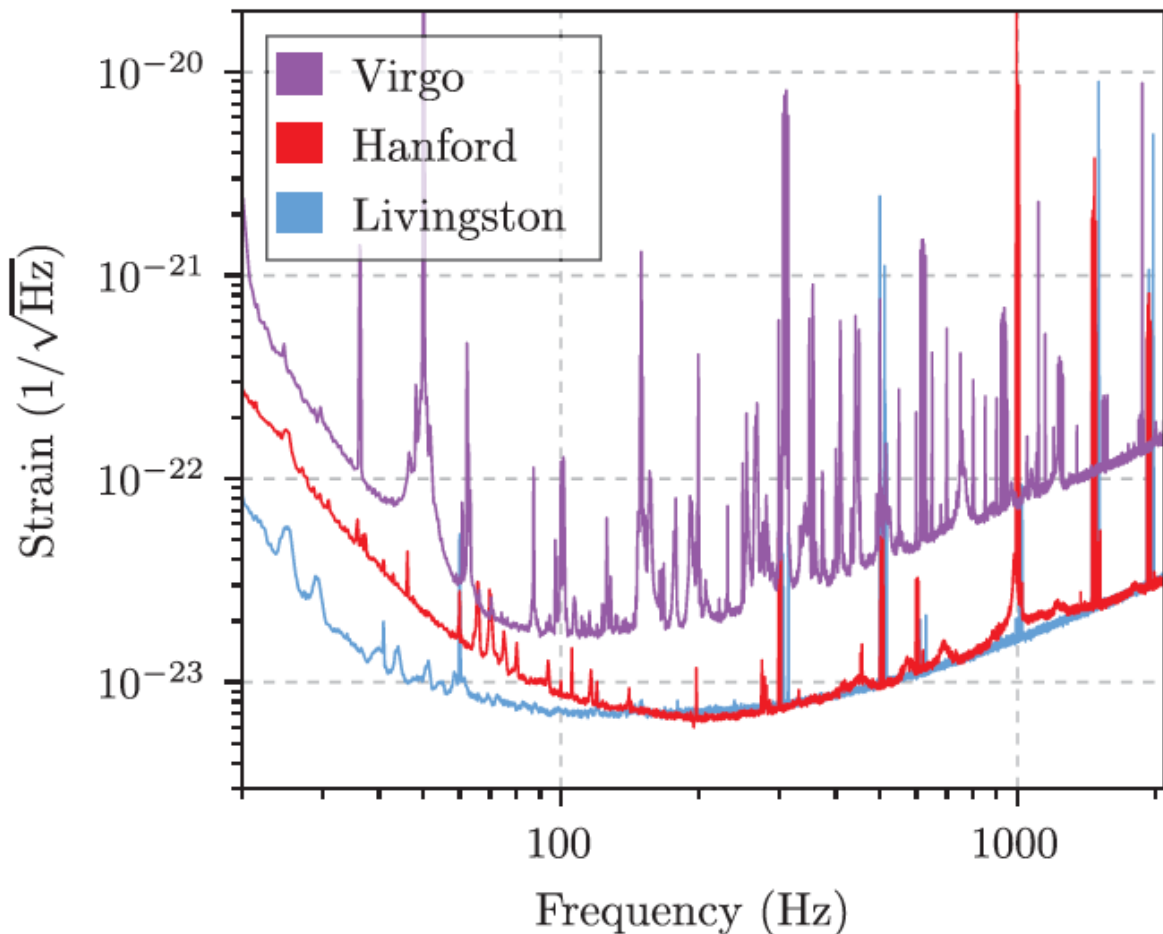
Lisa Barsotti

MIT Kavli Institute – LIGO Laboratory

for the LIGO and VIRGO Collaborations

LIGO-G1800926

LIGO and VIRGO at the end of O2 (August 2017)



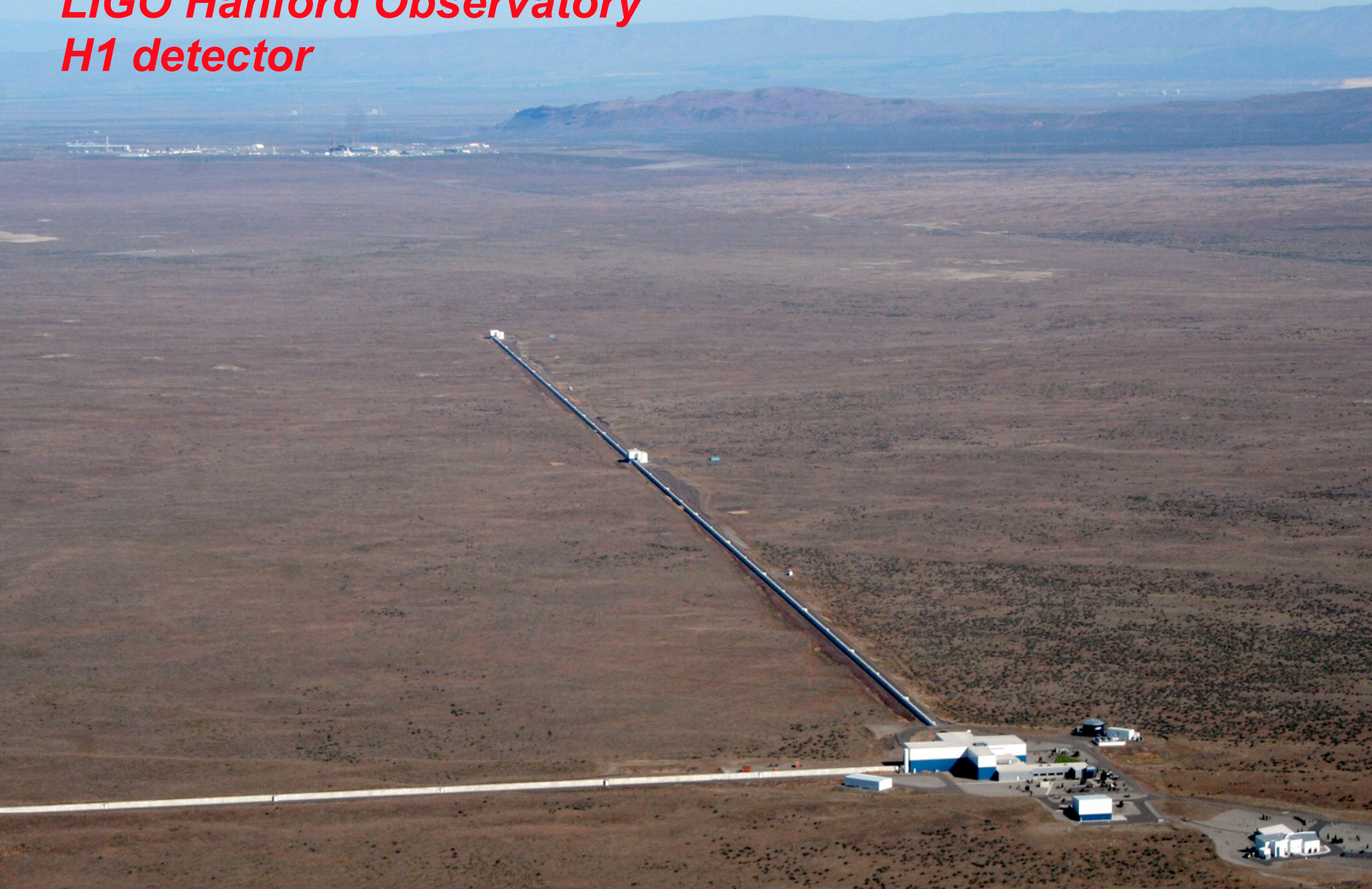
VIRGO: first lock in March 2017, joined O2 in August with 25-30 Mpc BNS (only 5 months of “noise hunting”!)

LIGO-HANFORD: laser noise at high frequency, unknown excess noise at low frequency

LIGO-LIVINGSTON: best sensitivity ever, 100 Mpc BNS

After O2: sequence of installation of new hardware for upgrades and commissioning at all of the three sites

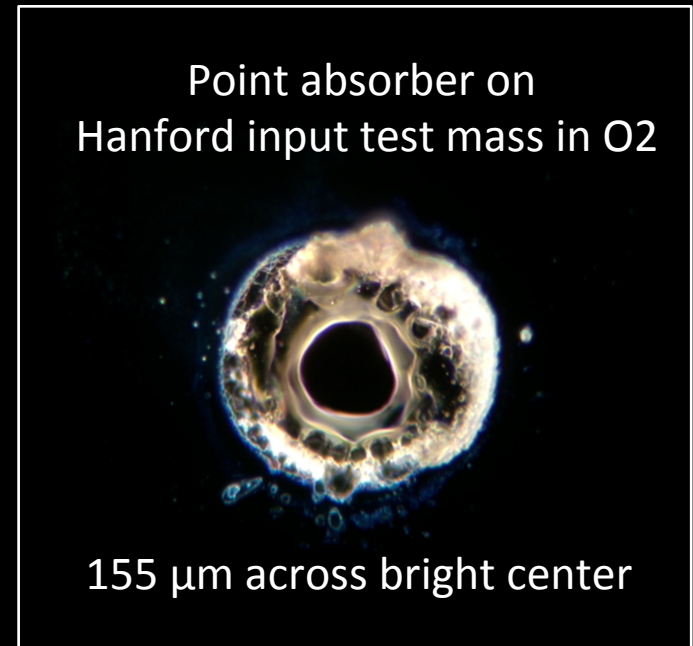
LIGO Hanford Observatory H1 detector



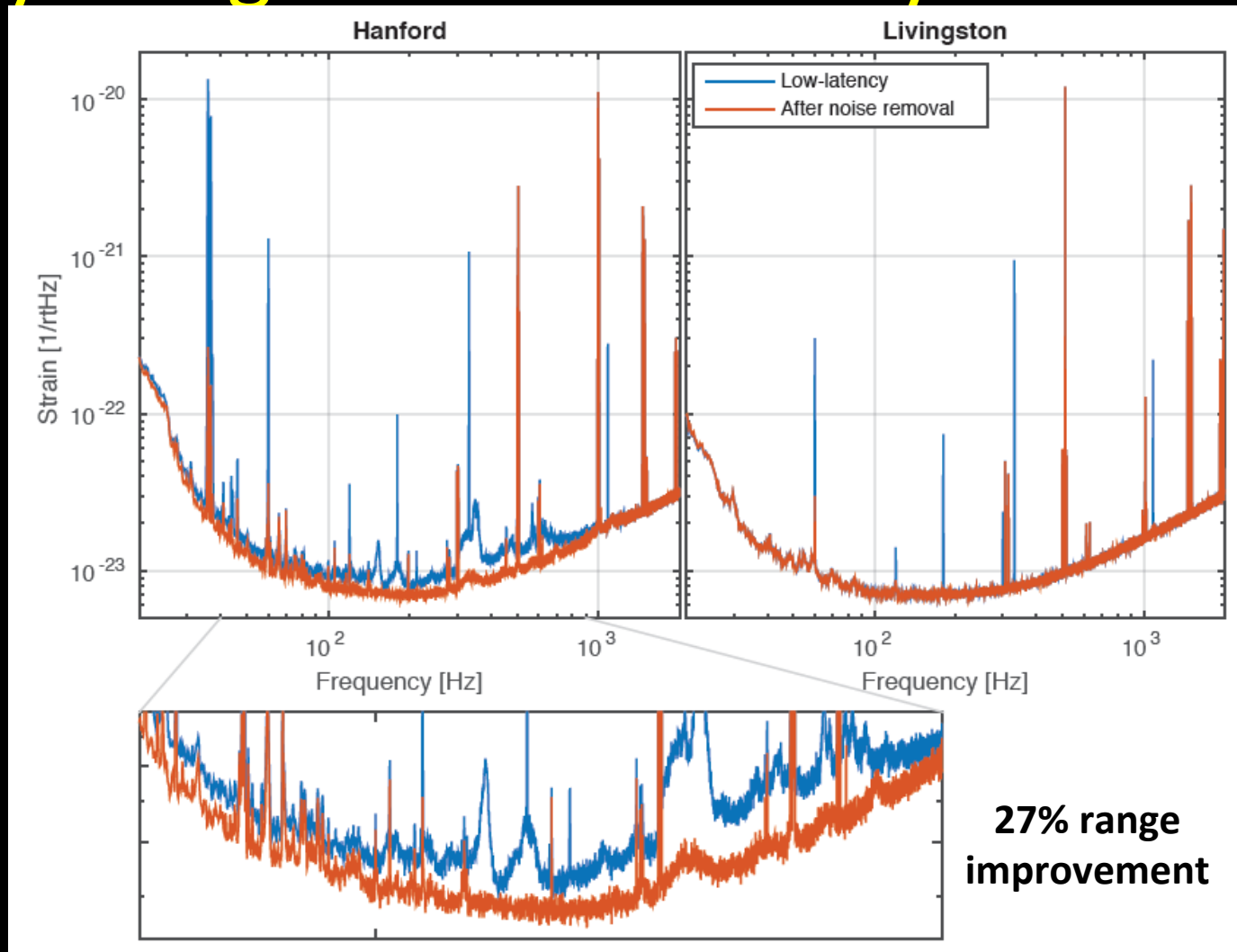
LIGO-HANFORD:

why excess noise at high frequency?

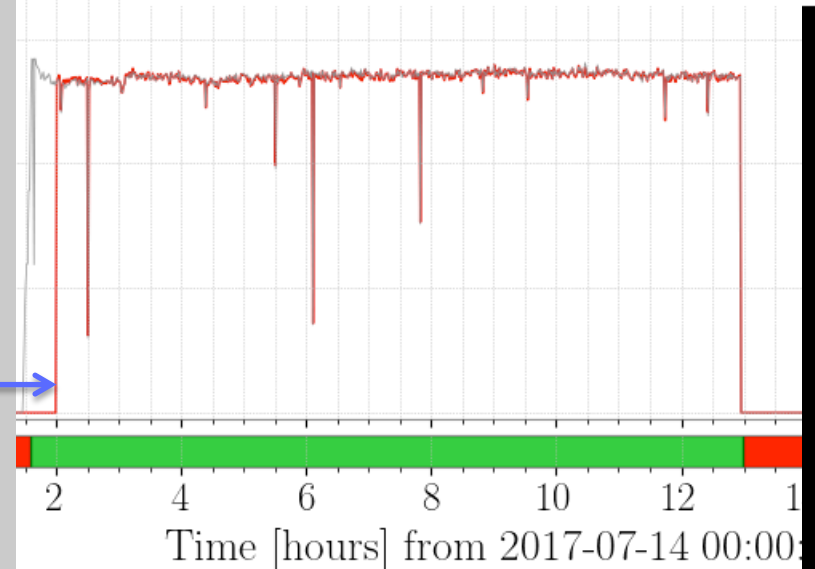
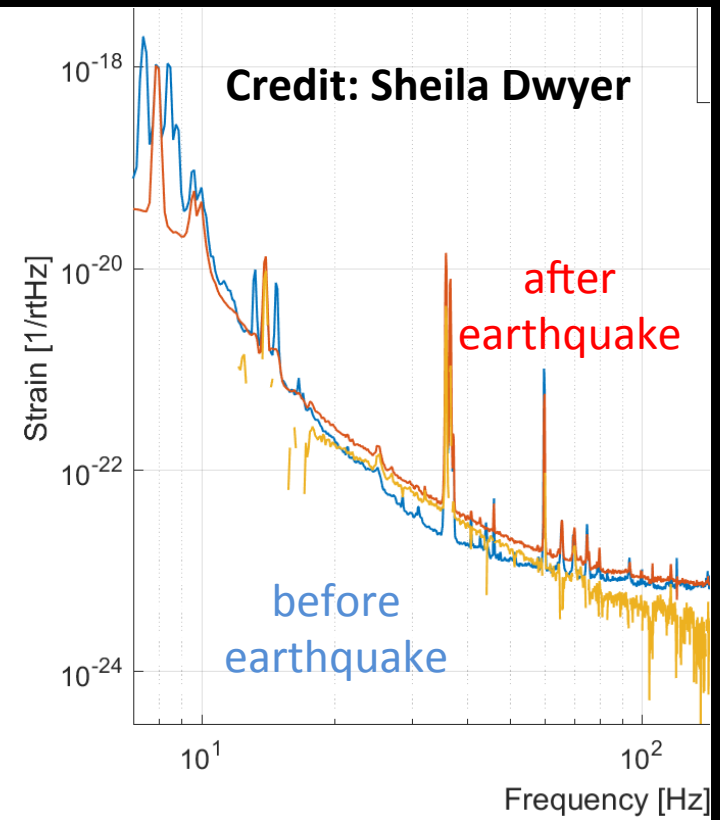
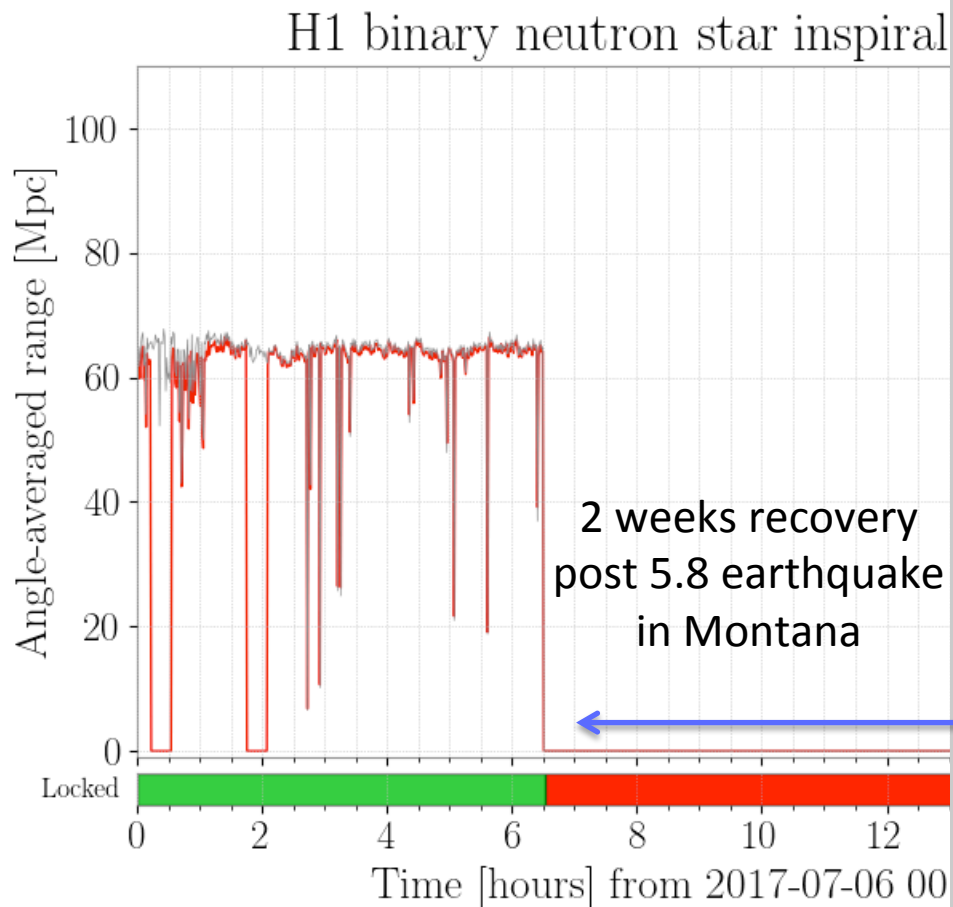
- Leading to O2, Hanford was exploring operation at twice higher power than in O1, using a new high power laser; Livingston was focusing on noise improvements at low frequency
- Two problems observed:
 1. High power laser introduced higher “laser jitter” noise, due to the water flow of cooling system
 2. The coupling of this noise to the interferometer was larger due to a “point absorber” on one of the input test masses



Data “cleaned” in post-processing by using witness auxiliary channels



Not the full story: H1 noise below 100 Hz got worse after earthquake on July 6th, 2017



Hanford - looking toward O3..

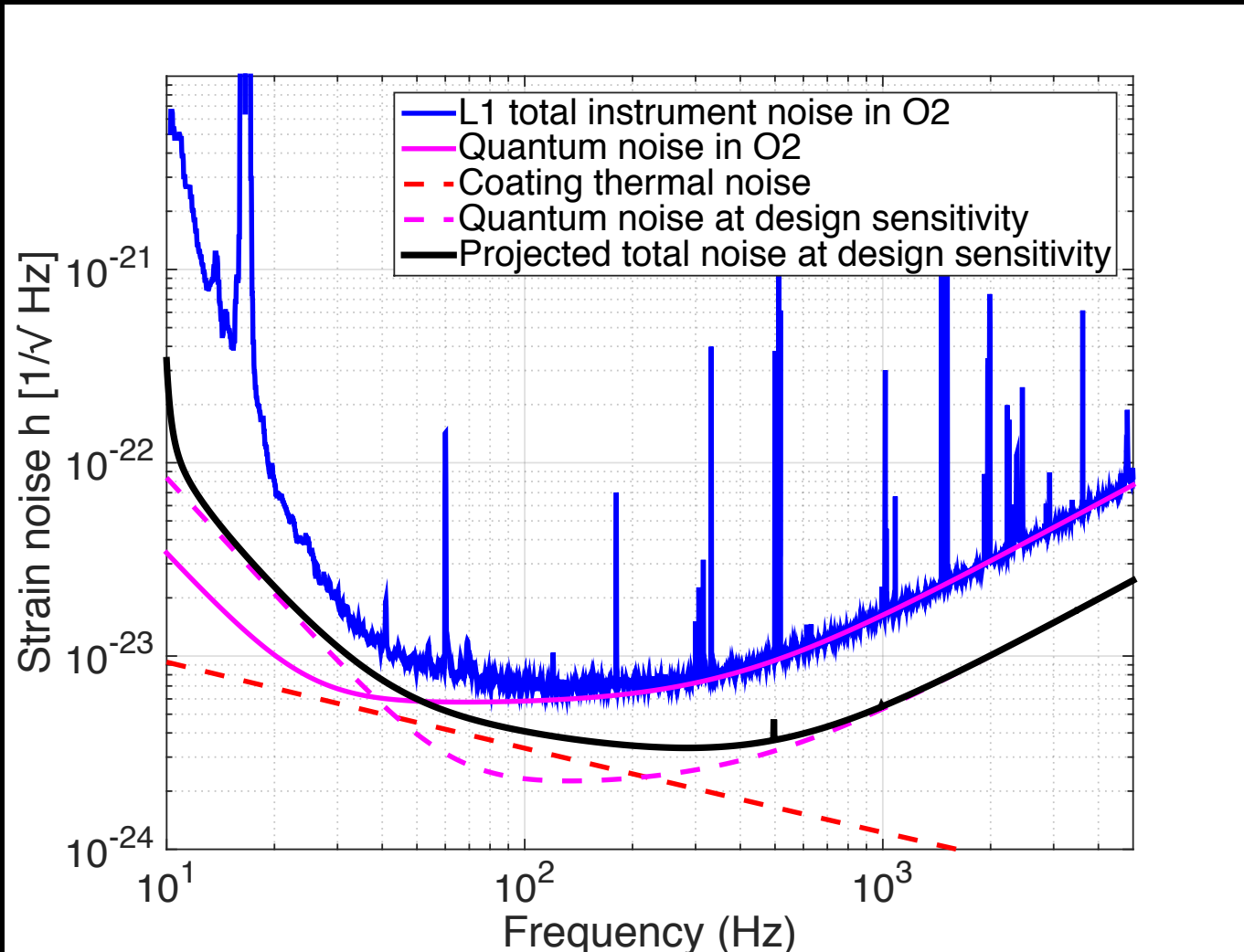
- High power laser replaced at both sites with a less noisy laser; input test mass with point absorber replaced
- ➔ Expectation is that laser jitter noise will be gone in O3
- Low frequency noise identified to be (partially) due to charge (possibly deposited on mirror by hitting earthquake stops during earthquake)
- Optics discharged, noise only partially improved
- New sensor developed to measure electric fields near test masses to identify possibly charge-induced noise mechanisms
- ➔ Finding origin of remaining excess of noise main focus of commissioning activity leading to O3

LIGO Livingston Observatory

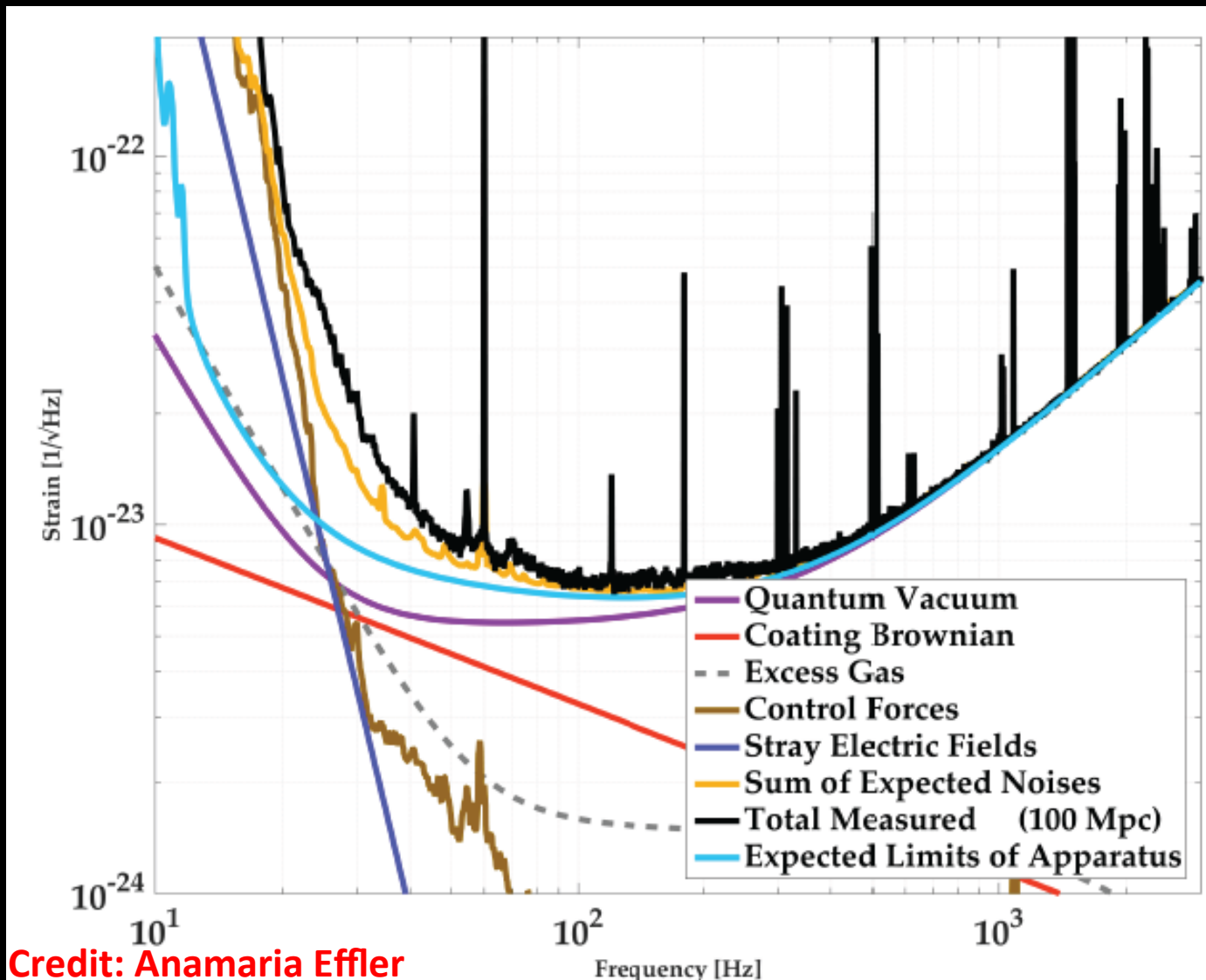
L1 detector



L1 noise in context: better than ever, not yet at design sensitivity

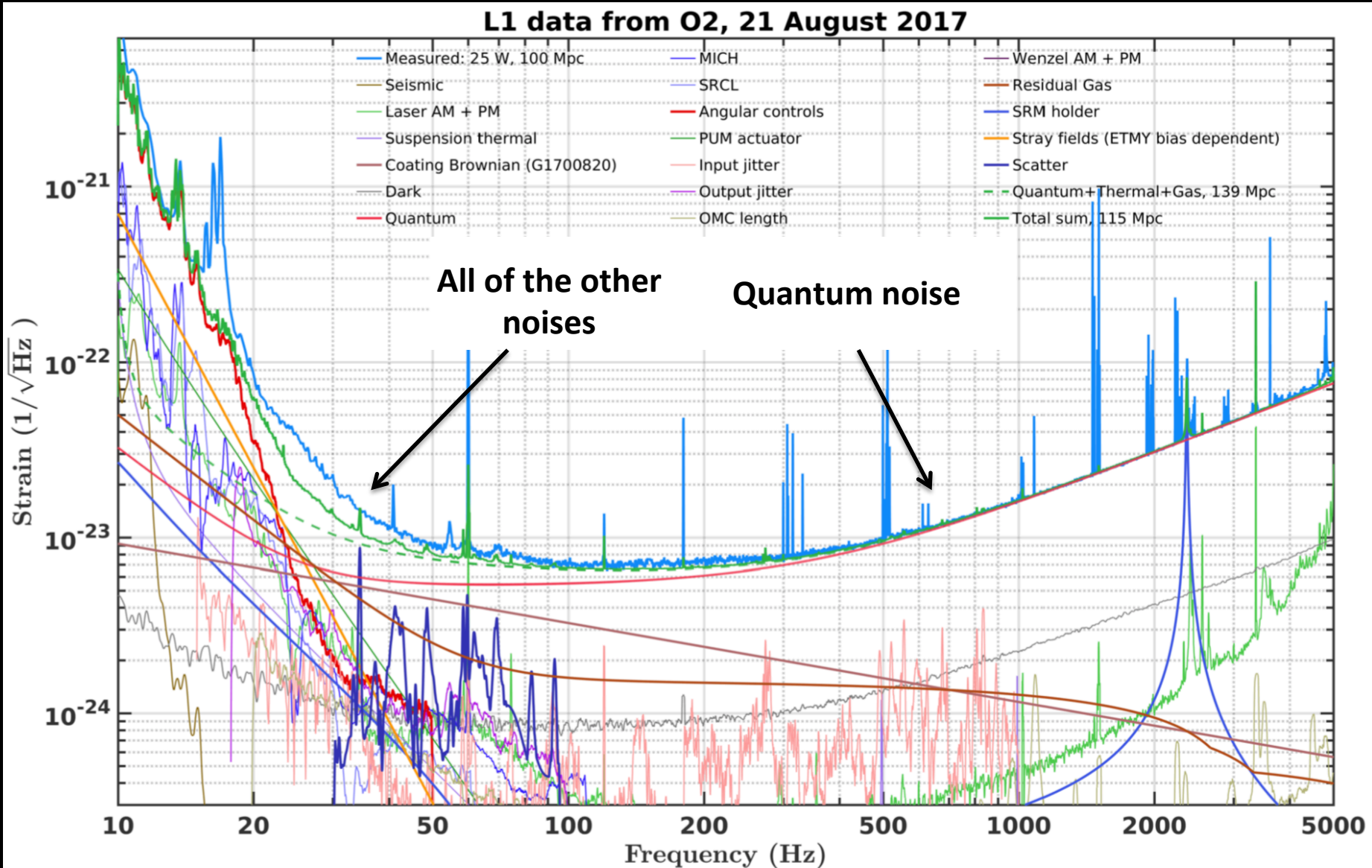


L1 noise budget in O2



Credit: Anamaria Effler

The un-simplified plot..



Credit: Anamaria Effler

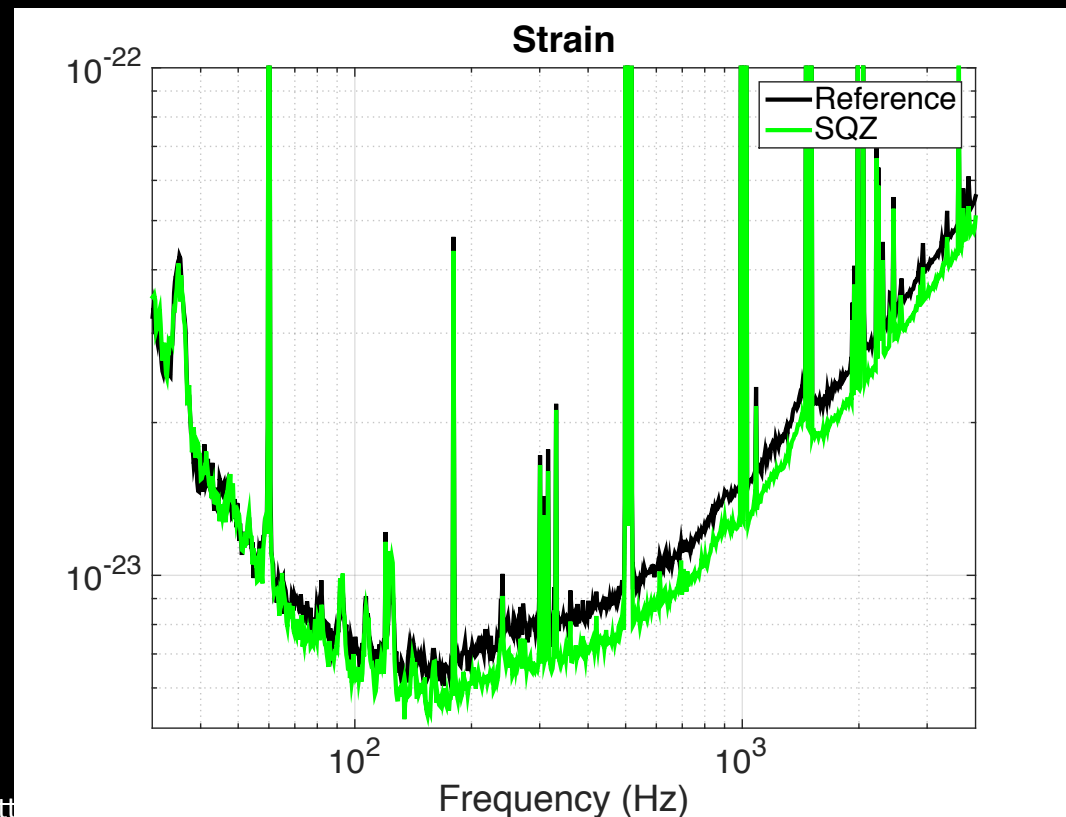
Noise reduction strategy @ both LIGO sites: *high frequency*

- Noise at high frequency is well understood, it is due to quantum shot noise
- It can be reduced with:
 - **higher circulating laser power**
 - **injection of squeezed light**
- Both approaches are particularly difficult when aiming for either a lot of power, or a lot of squeezing
- O3 strategy: do both!
 - a factor of 2 power increase, from 100kW to **200kW** circulating in the arms;
 - **3 dB** of squeezing, equivalent to **40% shot noise** reduction

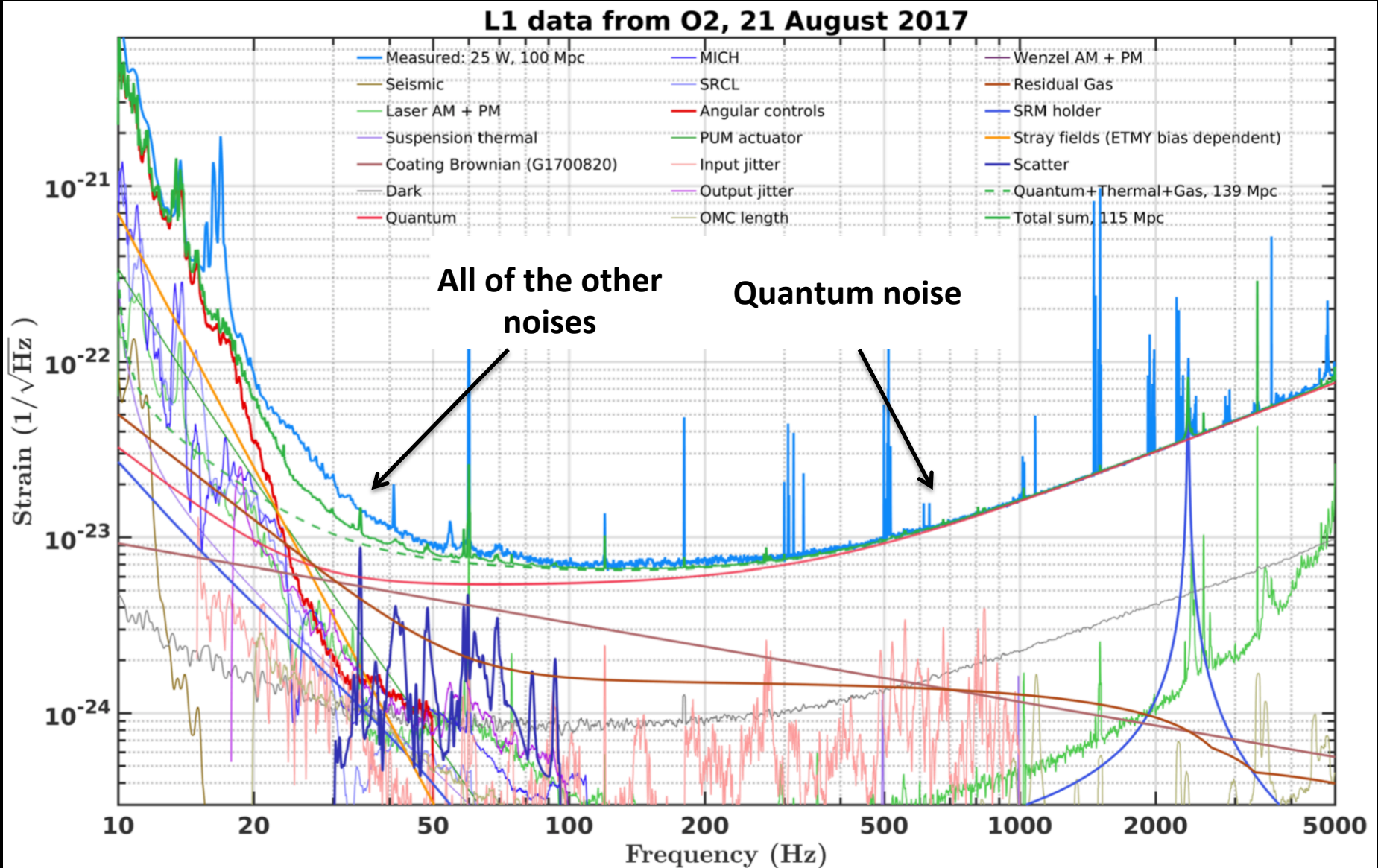
Some good news from early 2018 commissioning window at Livingston

- Interferometer stably operated up to 170 kW
- Strategy developed for dealing with increased complexity in interferometer control: **alignment instabilities, parametric instabilities**
- Also, first opportunity to test the newly installed squeezed light source

Squeezing observed!
15% shot noise reduction at
first attempt,
very encouraging

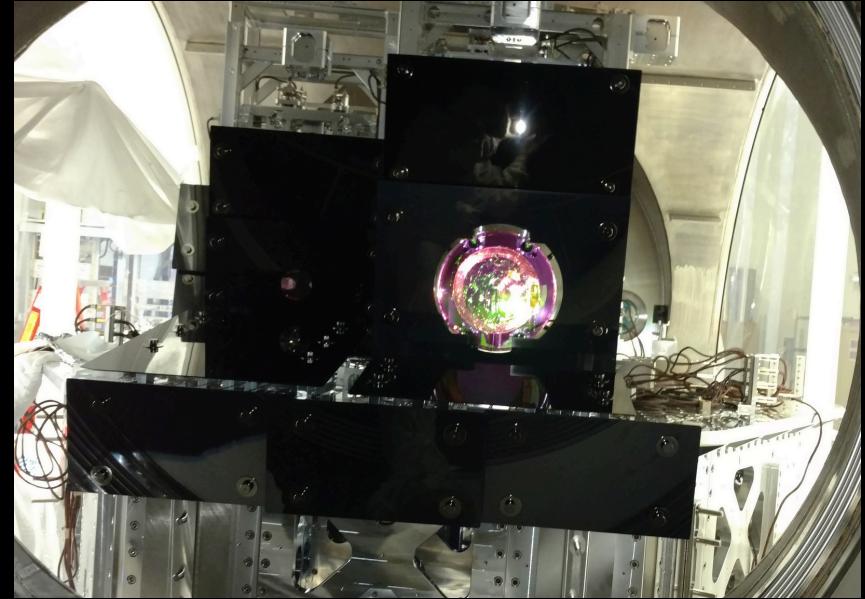
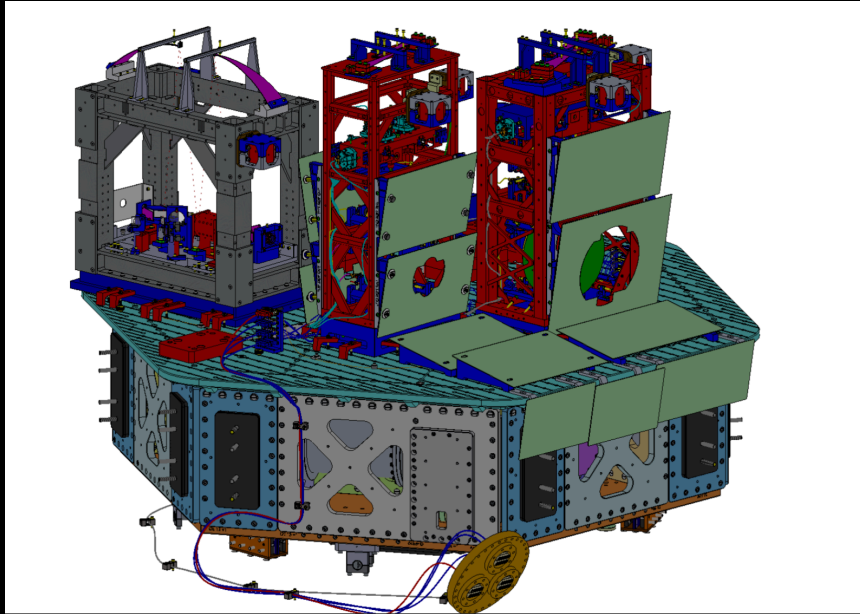


The un-simplified plot..



Credit: Anamaria Effler

One example of scattered light mitigation



BEFORE

AFTER



Barsotti, Sackler Conference 2018

Campaign to add baffles to
(almost) every chamber.

It worked!
Cameras very dark now!

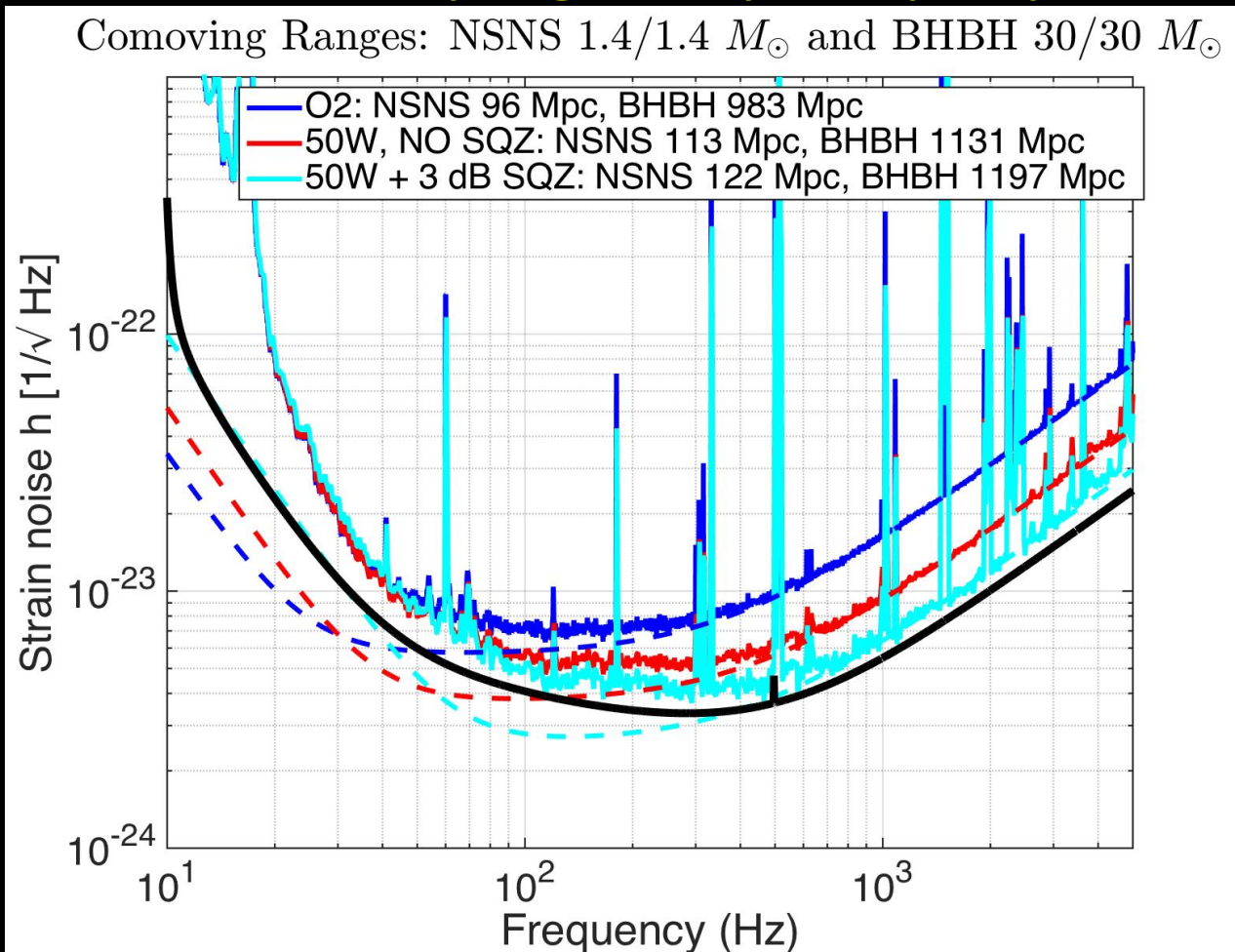
However, not clear impact
in the noise yet.

LIGO status as of today

- Commissioning windows with full interferometer right after O2 at Hanford and in early 2018 at Livingston very informative
- Last major upgrade: end test mass replacement, happening now at both sites
 - Recent fiber breakage during replacement contributed to revised schedule toward O3
- Both LIGO instruments will be in full interferometer configuration again in June/July
 - Approximately 6 months of commissioning estimated to take full advantage of new hardware

LIGO Noise Projections for O3:

Target is to reach at least 120 Mpc – it should be achievable with only high frequency improvement



***European Gravitational Observatory
Virgo detector (near Pisa, Italy)***

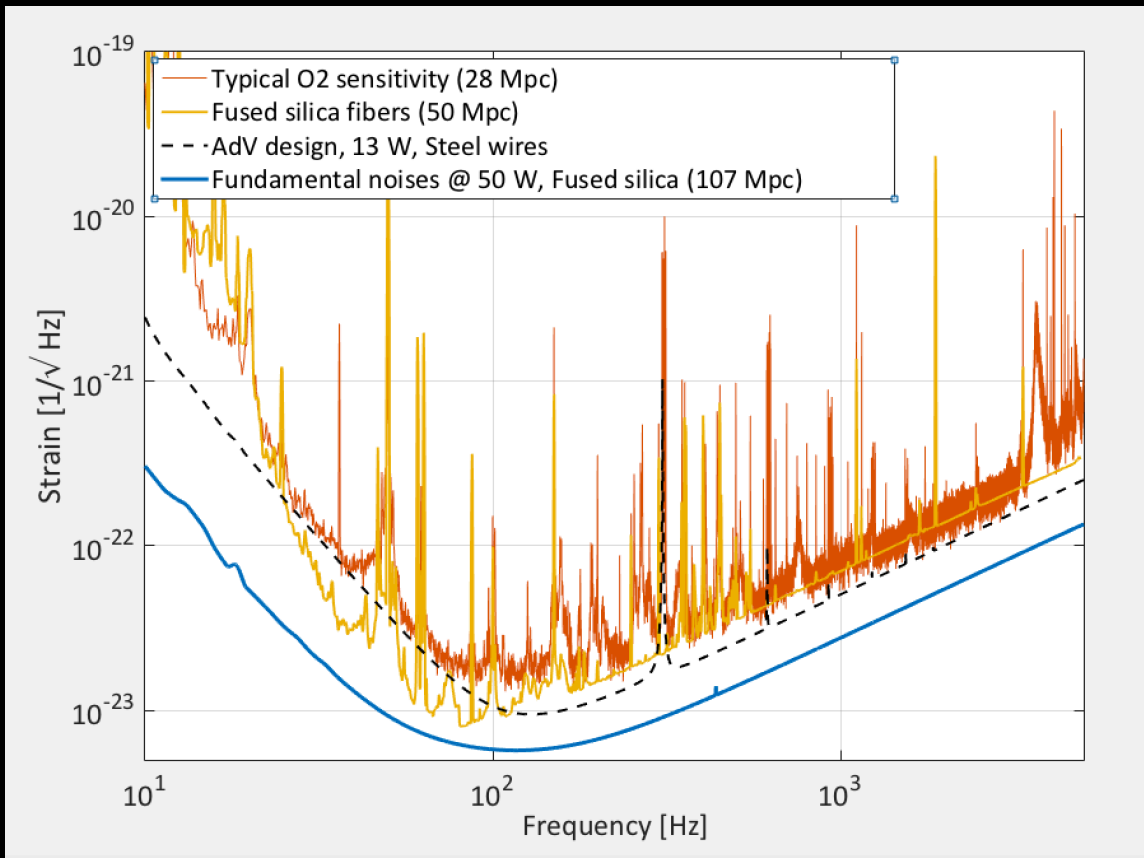


Virgo progress since O2

- Similar strategy as LIGO for high frequency improvements (new laser for high power, squeezing)
- Main noise at low frequency in O2 was due to the presence of metal suspension wires (to temporarily replace failing fused silica fibers)
 - Problem solved, glass fibers installed on all of the test masses, significant improvement expected
- Upgrade phase completed, commissioning recently restarted
 - Interferometer relocked last week!
 - Assessment of noise with fibers imminent
 - Glass fibers will expose other noises below 100 Hz

Virgo Noise Projections for O3

(credit: Alessio Rocchi)

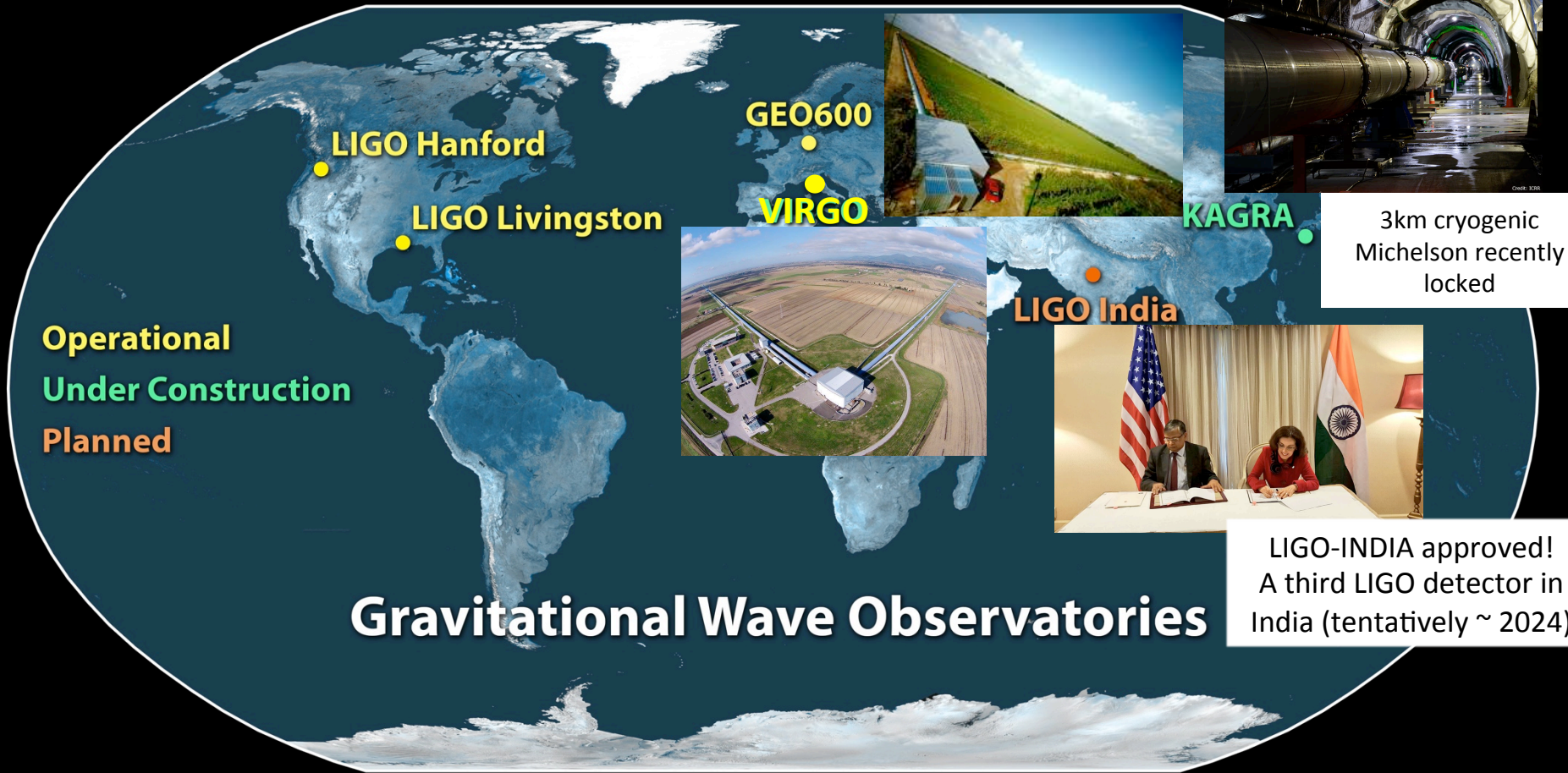


The reduced thermal noise from fused silica fibers will boost the low frequency sensitivity:

projected improvement from 30 Mpc to 50 Mpc

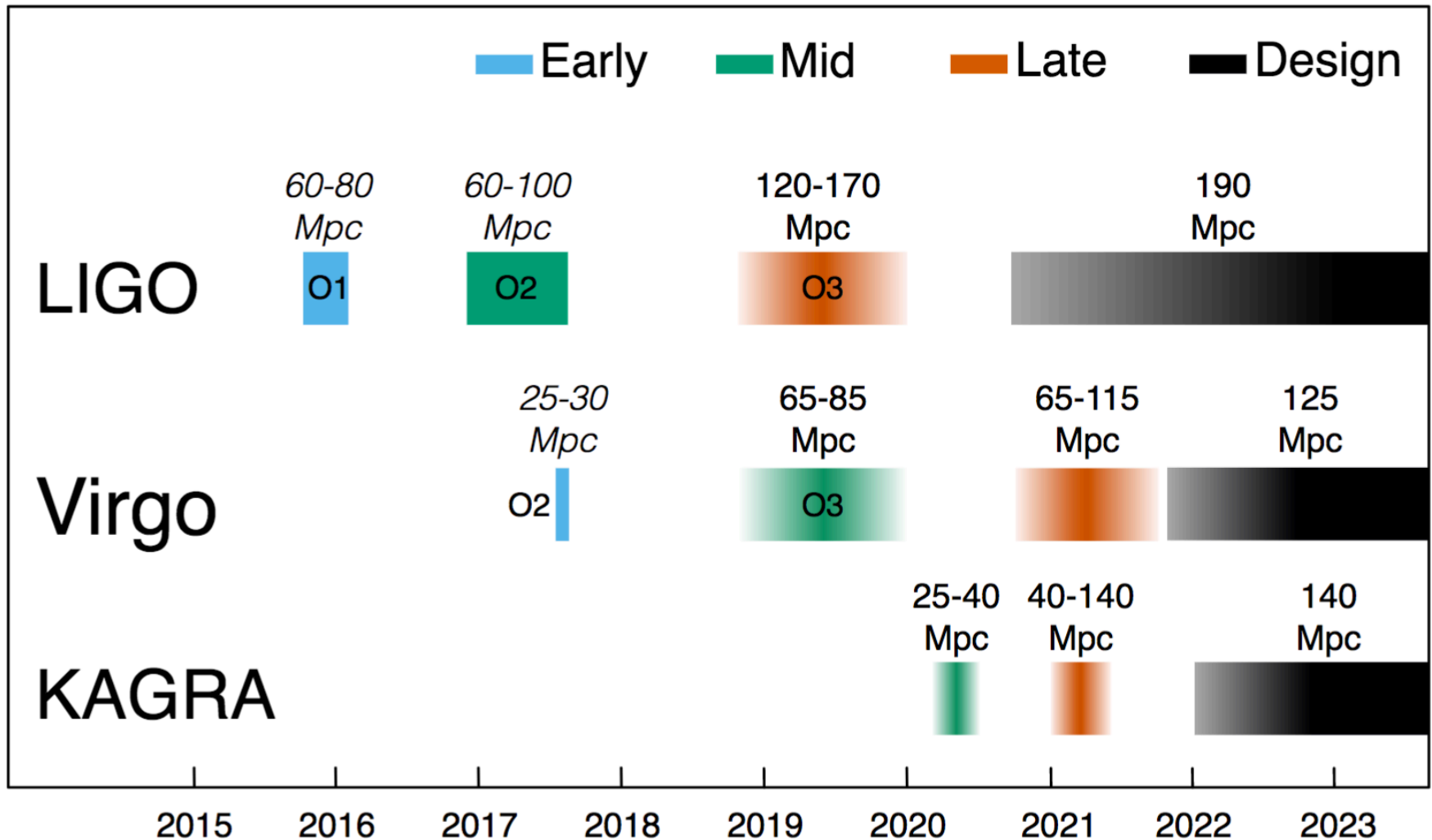
- ➔ Further reduction of known technical noises and higher power/squeezing will improve the sensitivity even further
- ➔ Target is 65-85 Mpc for O3

A world-wide network



LIGO-VIRGO-KAGRA Observing Scenario

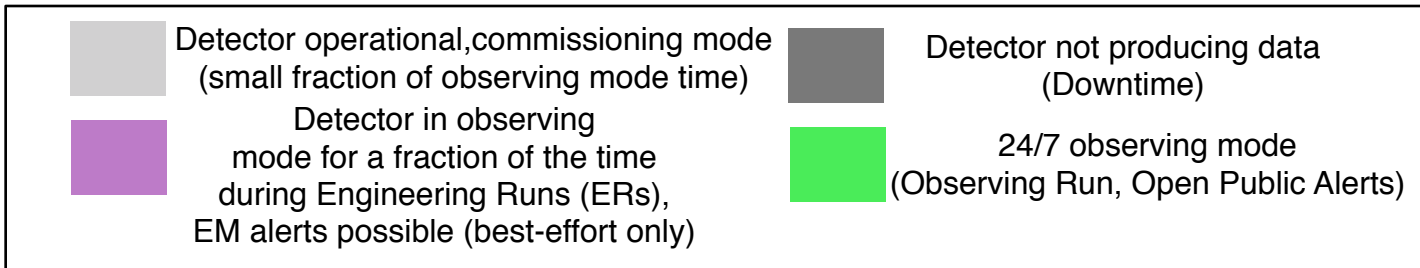
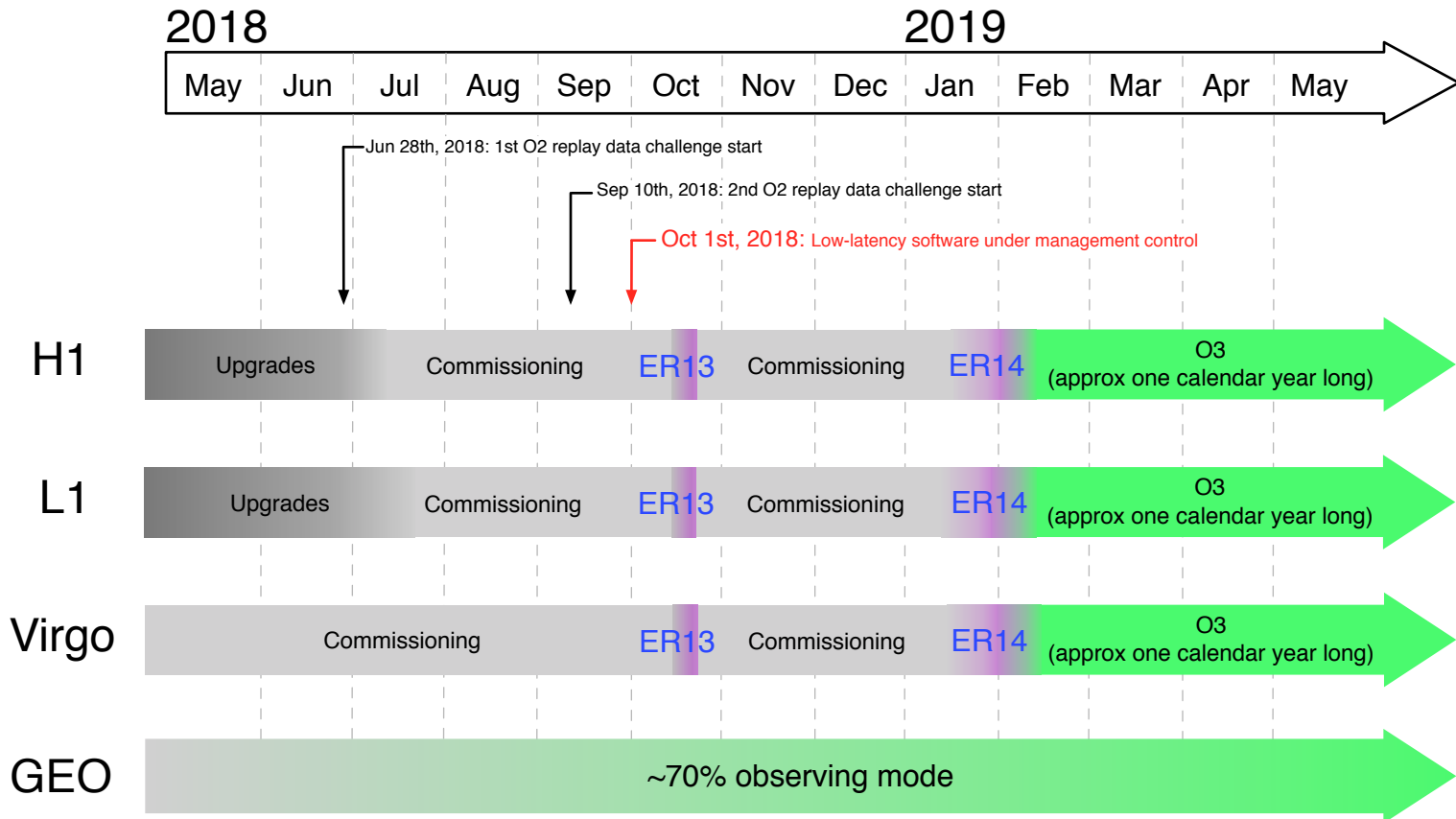
Living Reviews in Relativity



Open Public Alerts in O3

- In O3, LIGO and VIRGO will send alerts autonomously in low latency (~ minutes) and distribute them publically
 - Retractions or confirmations will follow (~ hours)
- System for autonomous alert under development now, major change with respect to system available in O2

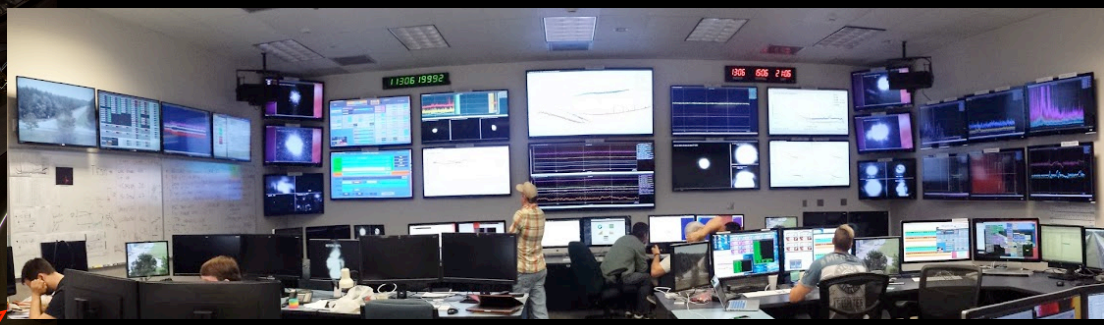
LIGO-VIRGO Joint Run Planning Committee
 Working schedule for O3
 (G1800889-v4)



Conclusions

- Many activities at the LIGO and VIRGO sites to improve the instruments after O2:
 - Promising results in early commissioning phases, but still a lot of work needed to reach sensitivity goals for O3
- Virgo just relocked after successful replacement of suspension fibers of all of the test masses, significant noise improvement expected
- LIGO instruments will be operational again in June/July, followed by approximately six months of commissioning
- Early 2019 start date for O3 is best guess at the moment for reaching sensitivity targets
- ➔ **LIGO and VIRGO will update the community as commissioning progresses**

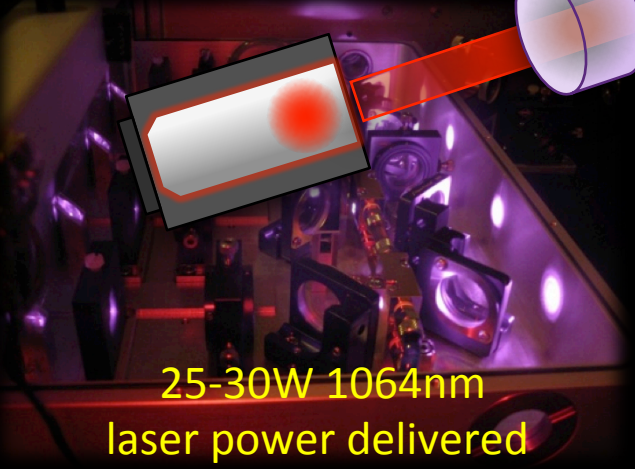
The Advanced LIGO detectors



More than 300 control loops needed to keep the interferometer optimally running

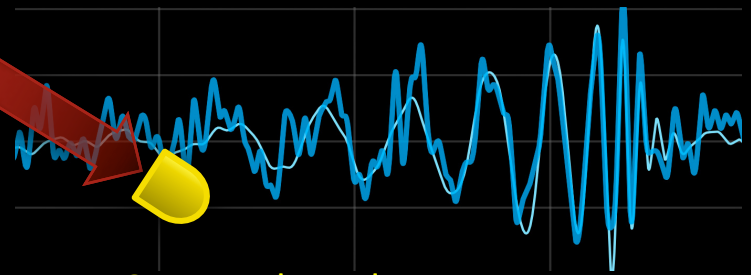
40 kg high quality fused silica mirrors, isolated from the ground

Fabry-Perot cavities in the Michelson arms
~100kW laser power during O2



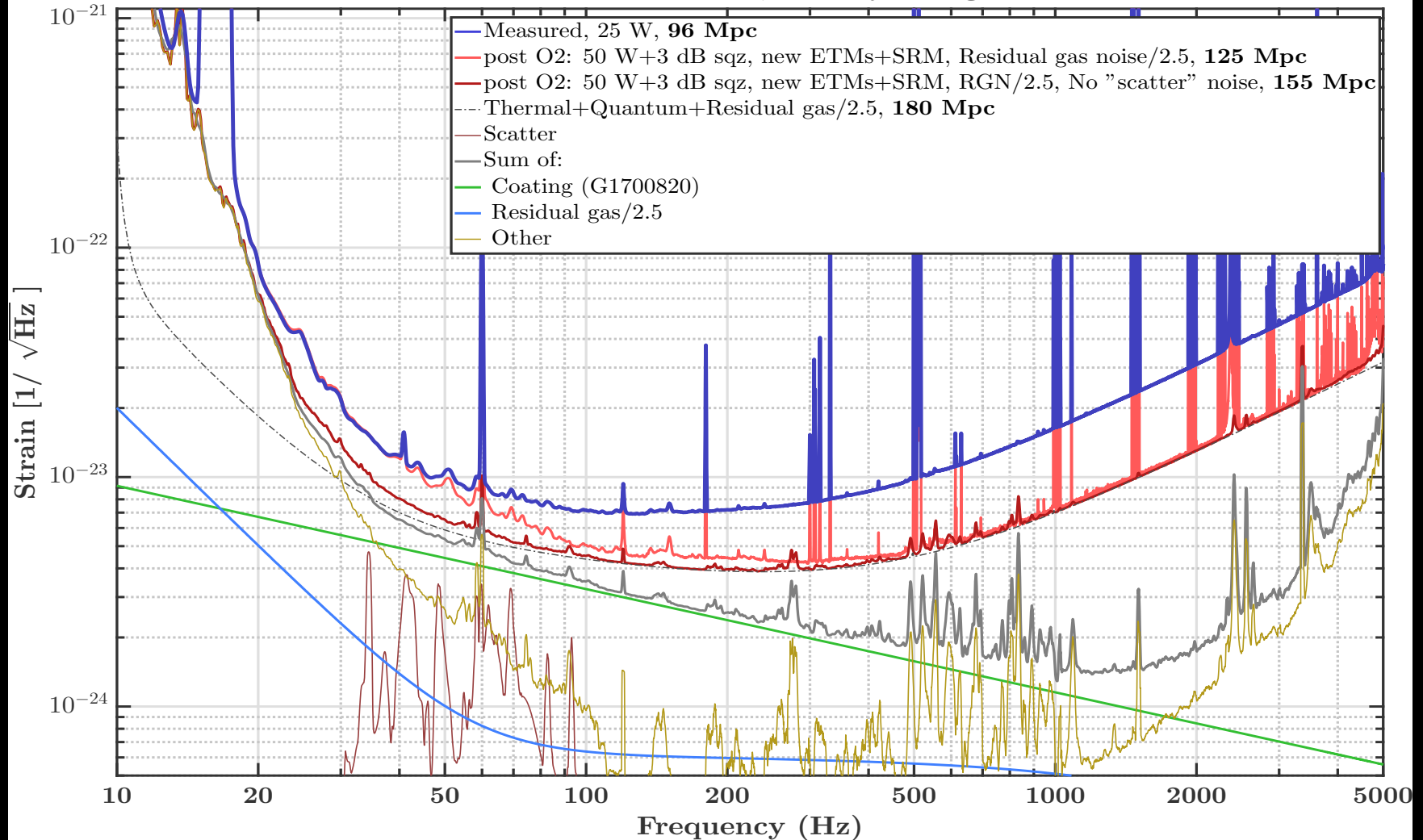
25-30W 1064nm laser power delivered

Output photodetector:
Interferometer noise + gravitational wave signal

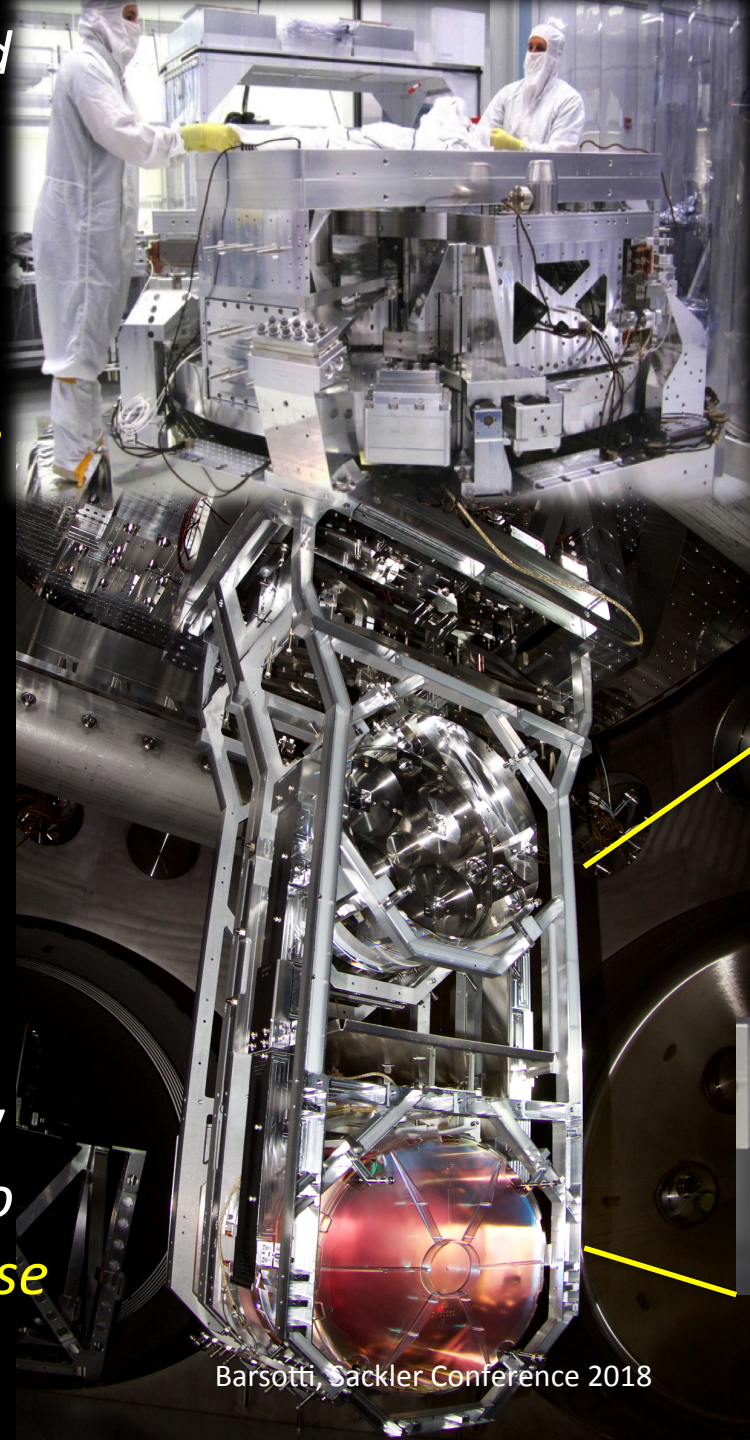


L1 noise projections for O3

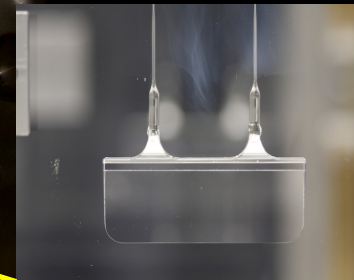
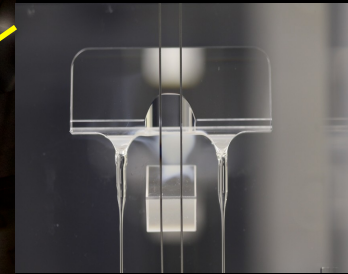
L1 data from end of O2, 27 July - Aug 8 2017



Test mass suspended by a quadruple pendulum, attached to two stages of active isolation to reduce seismic noise

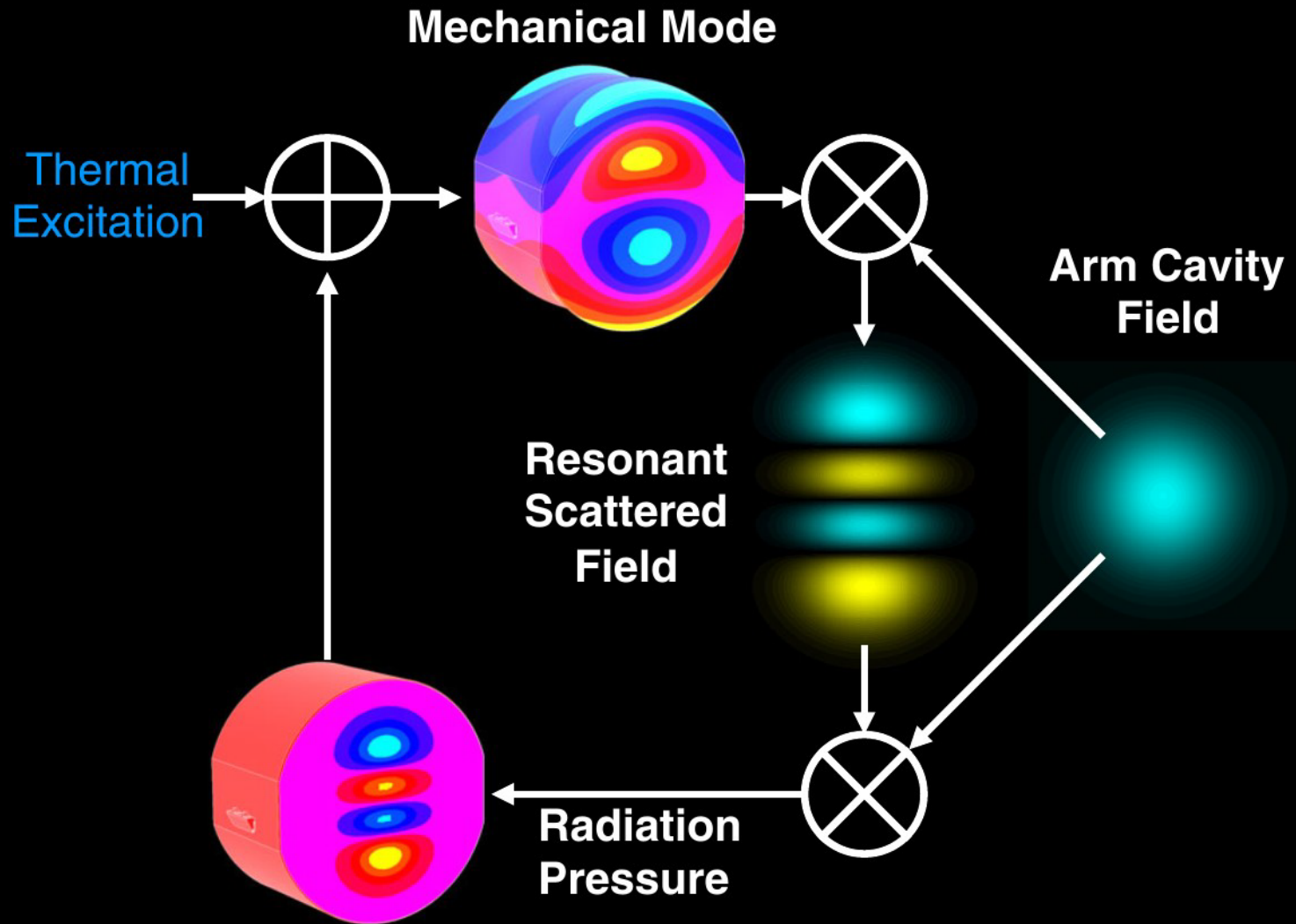


Final stage of test mass suspension all fused silica, very high quality factor, designed to reduce thermal noise



Test masses have dielectric coating material with low mechanical loss to reduce thermal noise

Parametric Instabilities

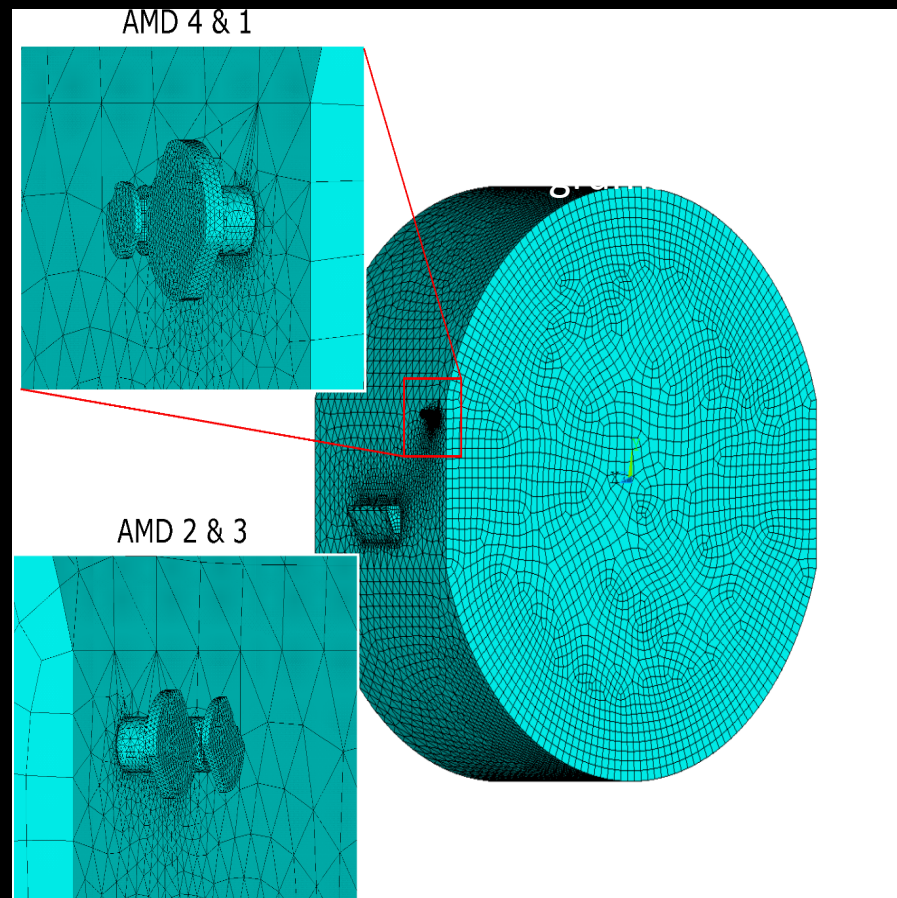
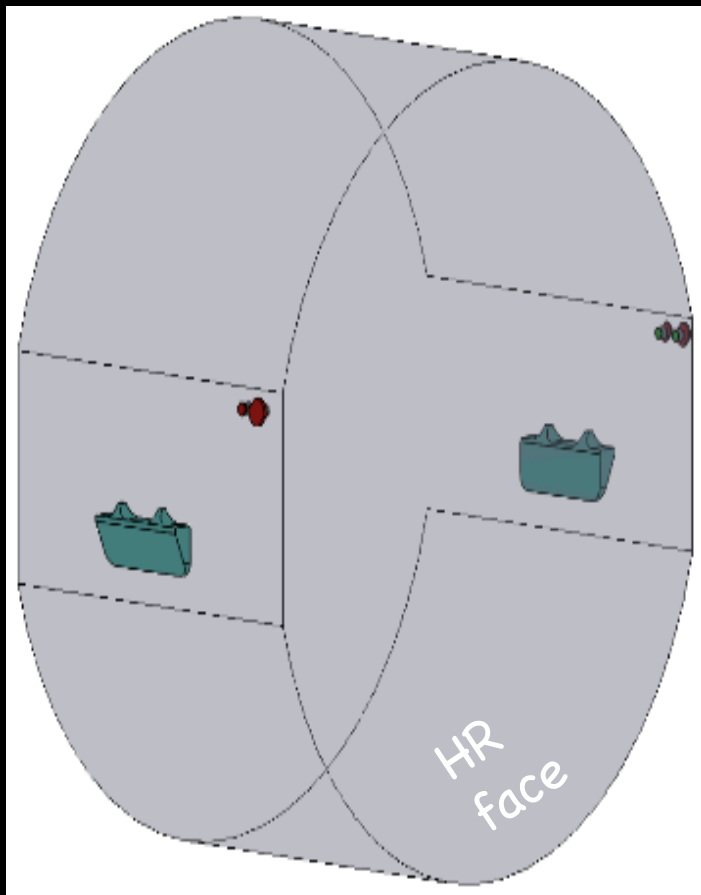


Methods of taming Parametric Instabilities

- ✓ Avoid optical resonances by tuning test mass radii-of-curvature using ring heaters
 - Reduces optical gain of higher order mode
- ✓ Active damping of acoustic modes using test mass electro-static actuators
- Passive damping (Q-reduction) of acoustic modes by applying tuned dampers to the test masses

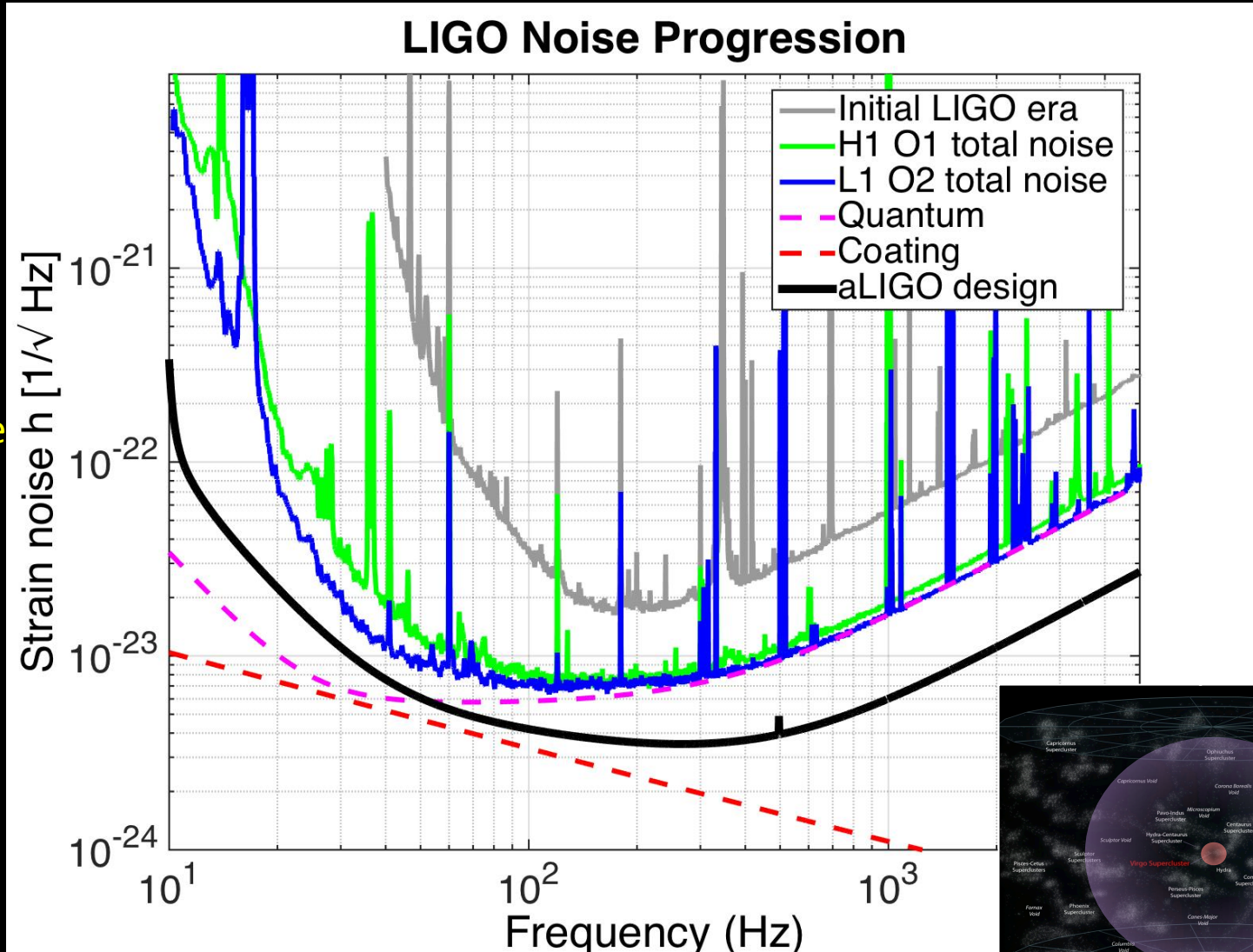
→ **Acoustic Mode Dampers (AMD)**

AMDs bonded to the test mass flats: 2 each side

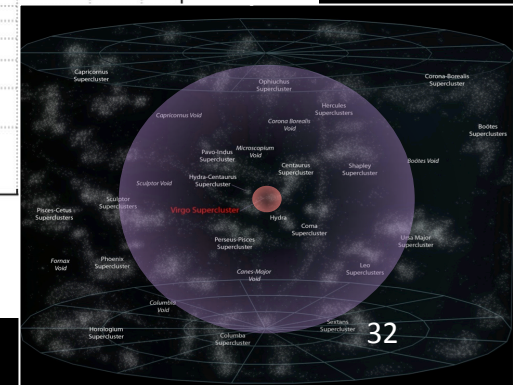


LIGO Noise Progression

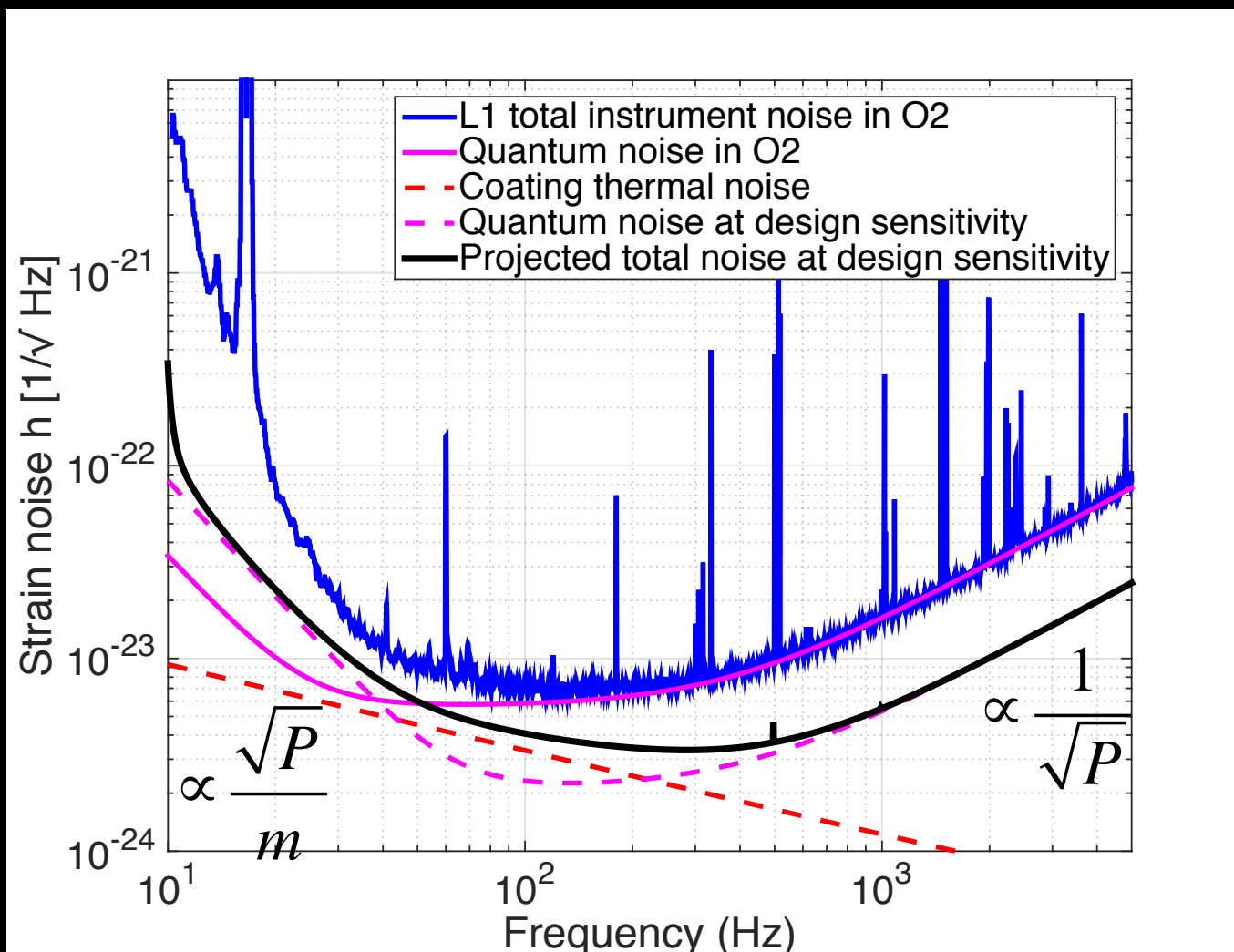
“Strain Noise”
=
Detector noise
expressed as
equivalent
GW strain



Barsotti, Sackler Conference 2018



Another example: shot noise reduction



Radiation
Pressure
Noise

Shot
Noise

P = laser power in the arms

m = mirror mass

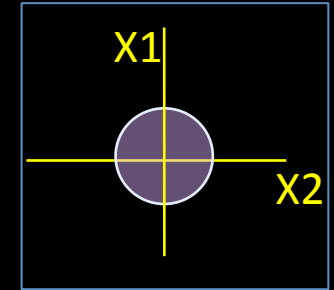
Quantum-mechanical noise in an interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 15 August 1980)

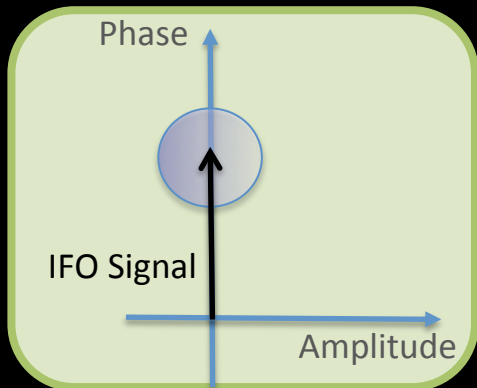
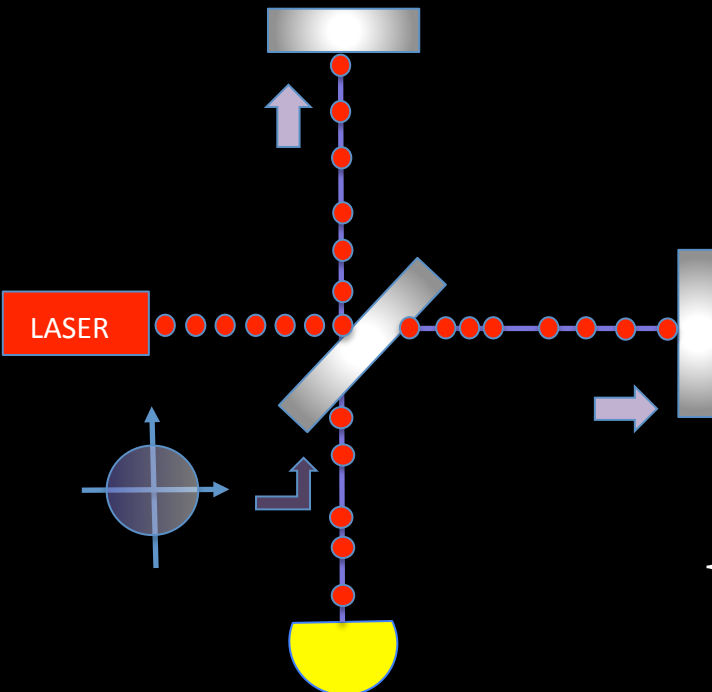
Zero-point energy
(vacuum) fluctuations



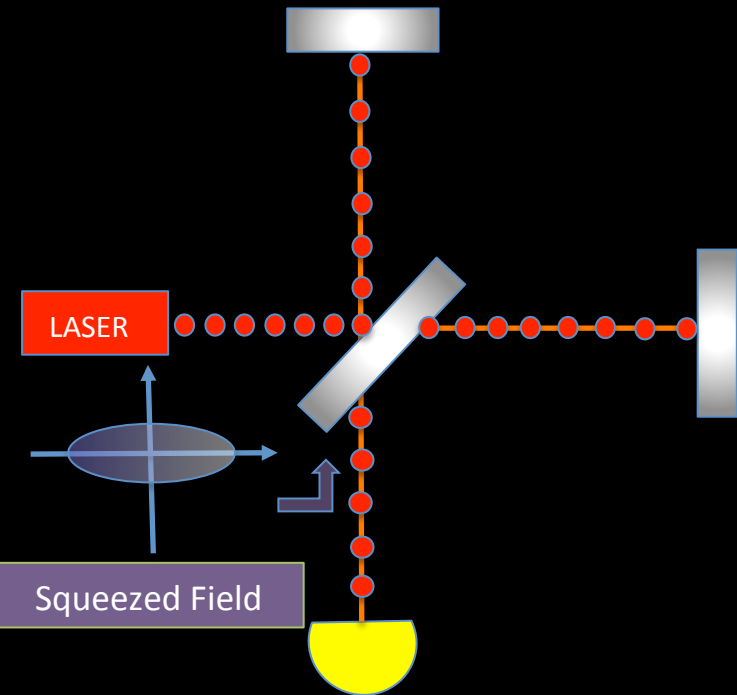
$$\Delta X_1 \Delta X_2 \geq 1$$

- ✧ When average amplitude is zero, the variance remains
- ✧ Heisenberg uncertainty principle, quadratures associated with **amplitude** and **phase**
- ✧ They enter the interferometer from all the open ports of the interferometer, but the ones which matter are the one **entering from the anti-**

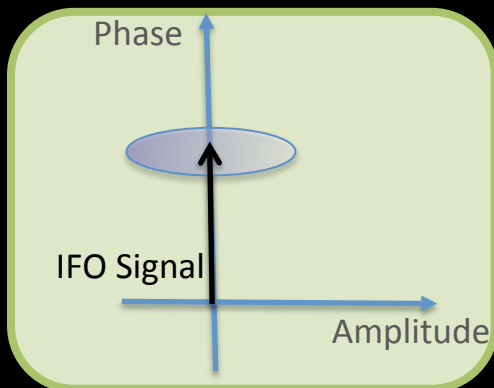
symmetric port



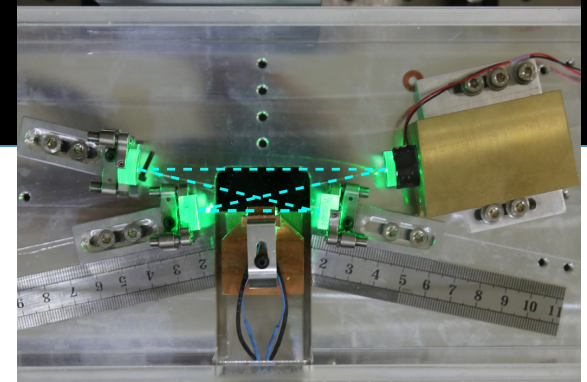
Replace regular vacuum with squeezed vacuum



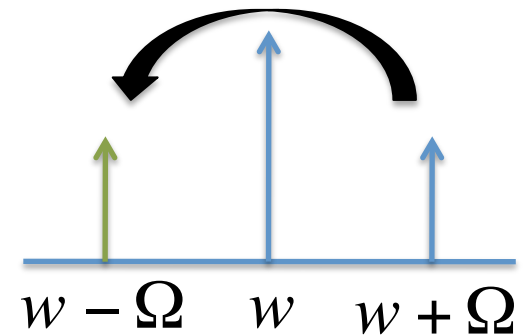
- ✧ Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- ✧ Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- ✧ One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)



How to make squeezed fields

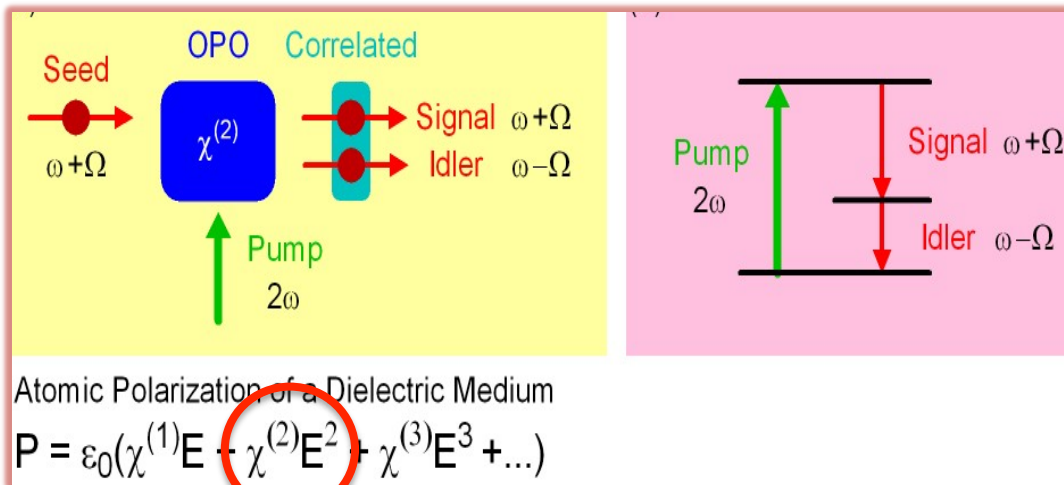


Bow-tie cavity OPO design (ANU)



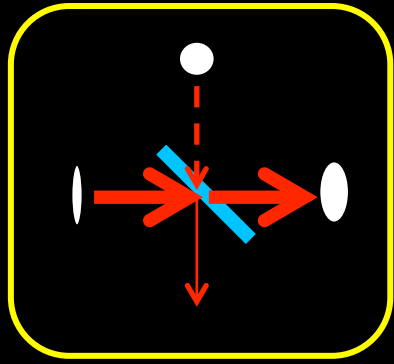
The OPO makes a “copy” of the quantum sideband, and it correlates the sidebands

- ✧ Non linear crystal with a strong second order polarization component, pumped at 2ω
- ✧ Refractive index depends on intensity of light illumination
- ✧ It creates entangled photon pairs by down-conversion

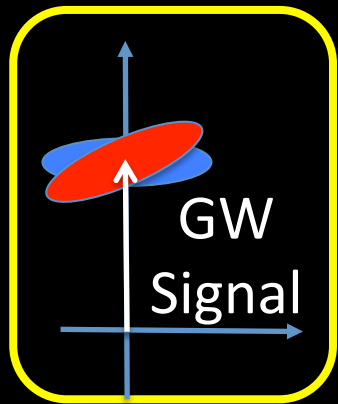


$$P \propto (Ee^{-i2\omega t} + Ee^{-i(\omega+\Omega)t})^2 \Rightarrow Ee^{-i(\omega-\Omega)t}$$

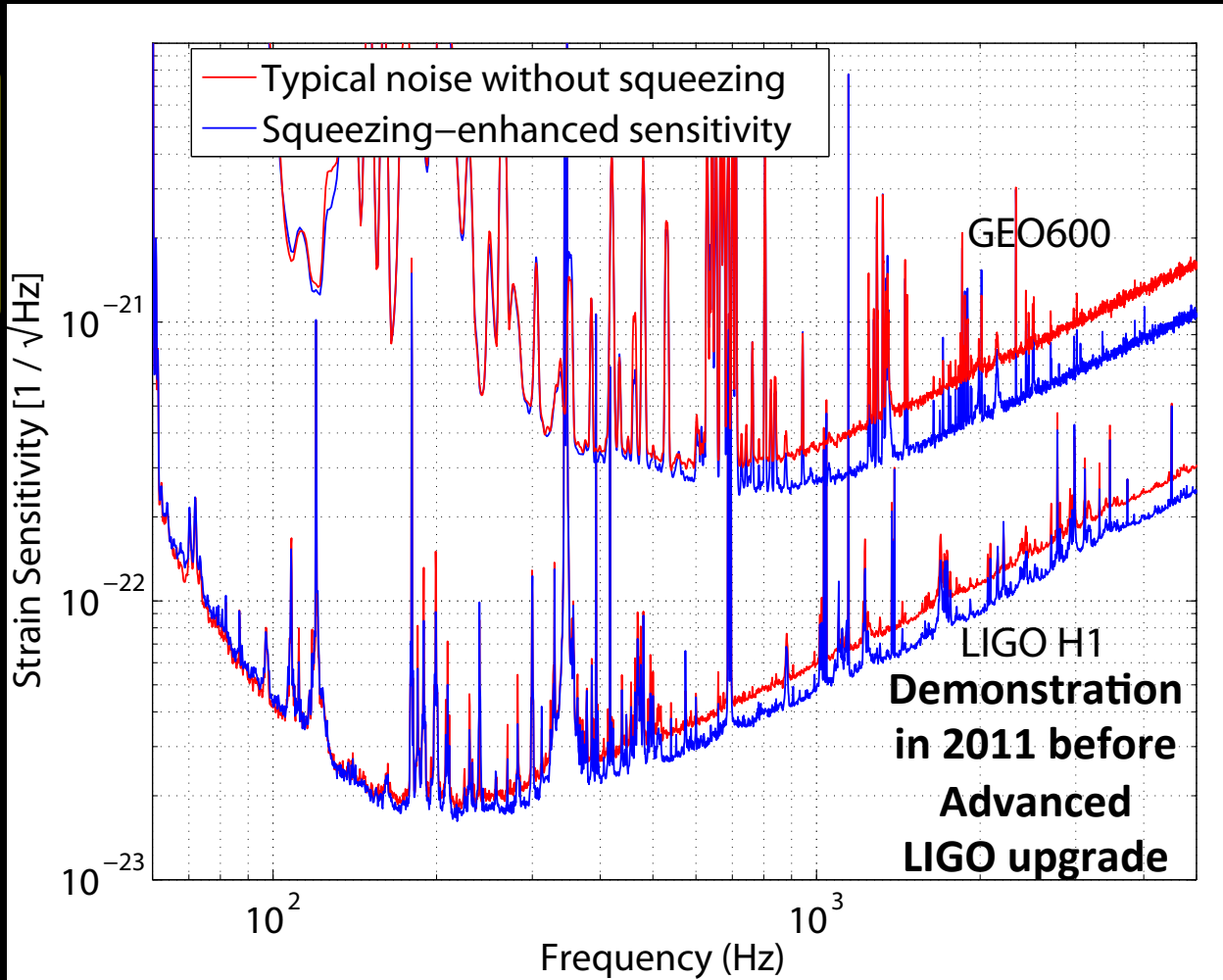
Squeezing enhancement in GEO 600 and LIGO H1



Losses



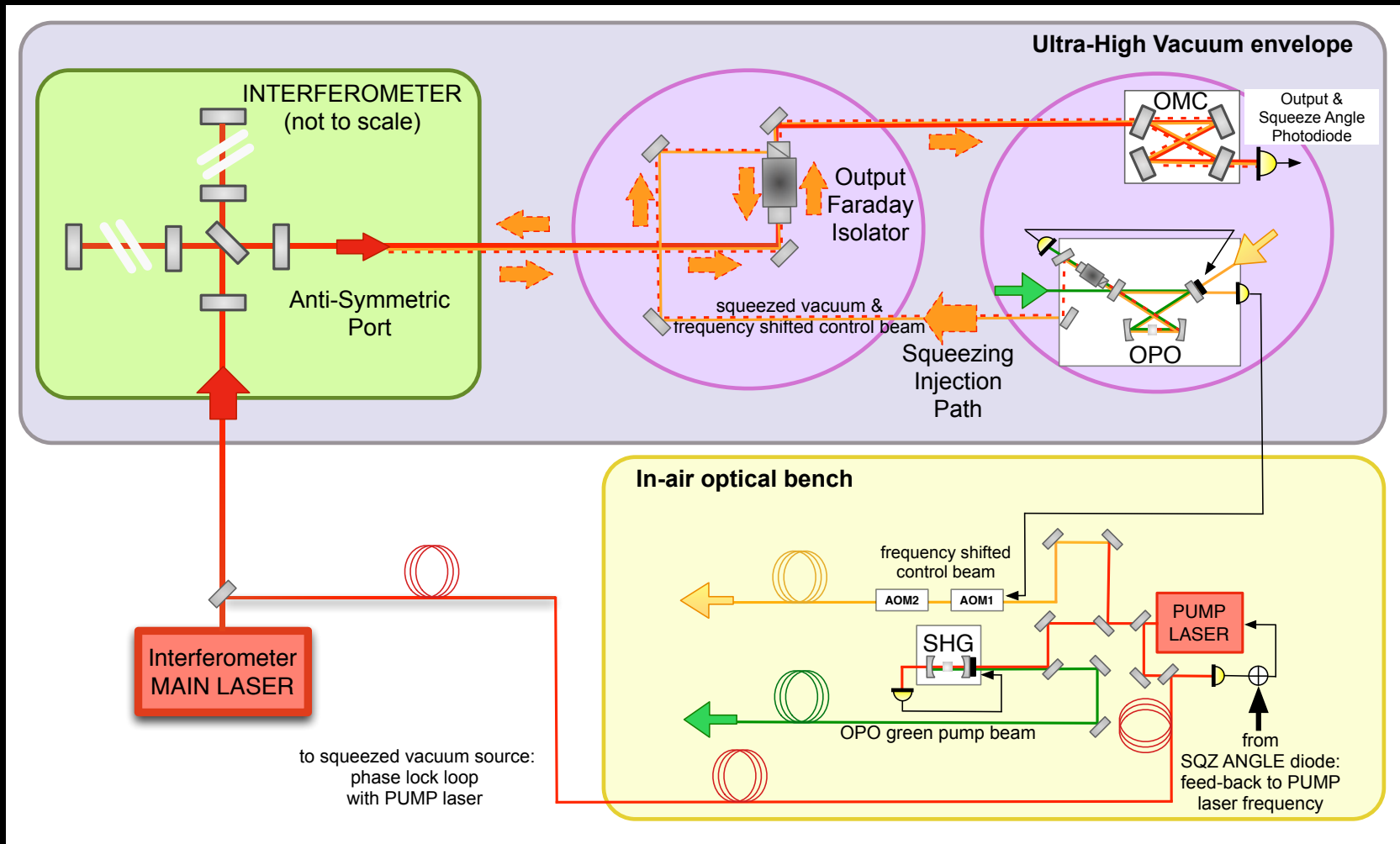
Phase noise



GEO600,
running with
squeezing
since 2009
3.5-4.5 dB

LIGO H1
proof-
of-principle
experiment
2.1 dB

Conceptual layout of squeezing injection in Advanced LIGO



Installation at LLO (November 2017)



TOP VIEW OF THE LLO-HAM6 CHAMBER

