LIGO Status

For the 4th KAGRA International Workshop, Seoul

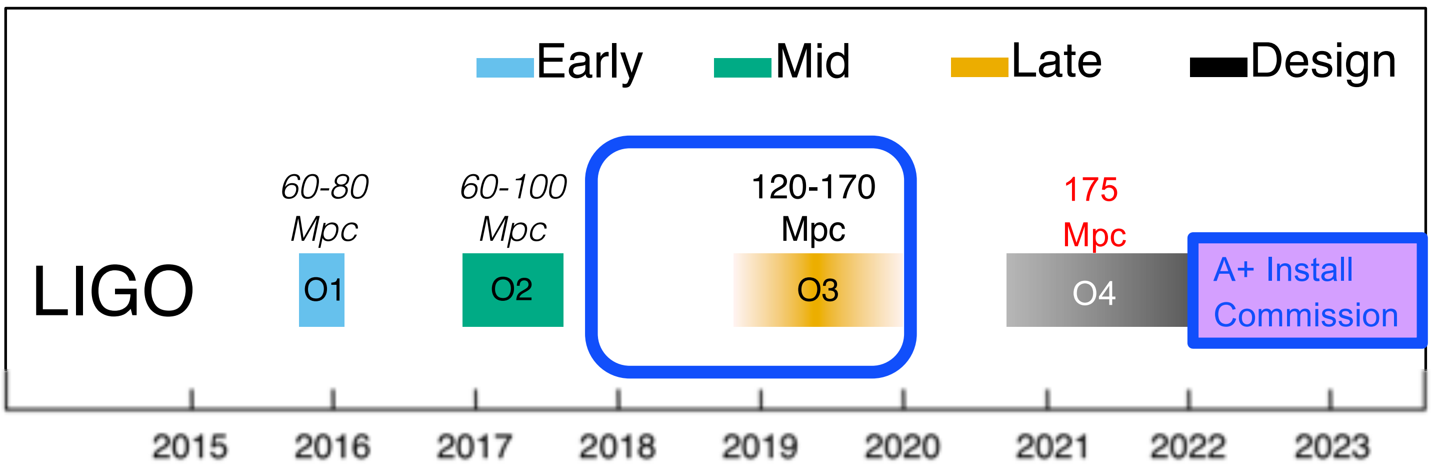
David Shoemaker

Slides Borrowed from Fritschel, Dwyer, Zucker, Raab, Landry, others

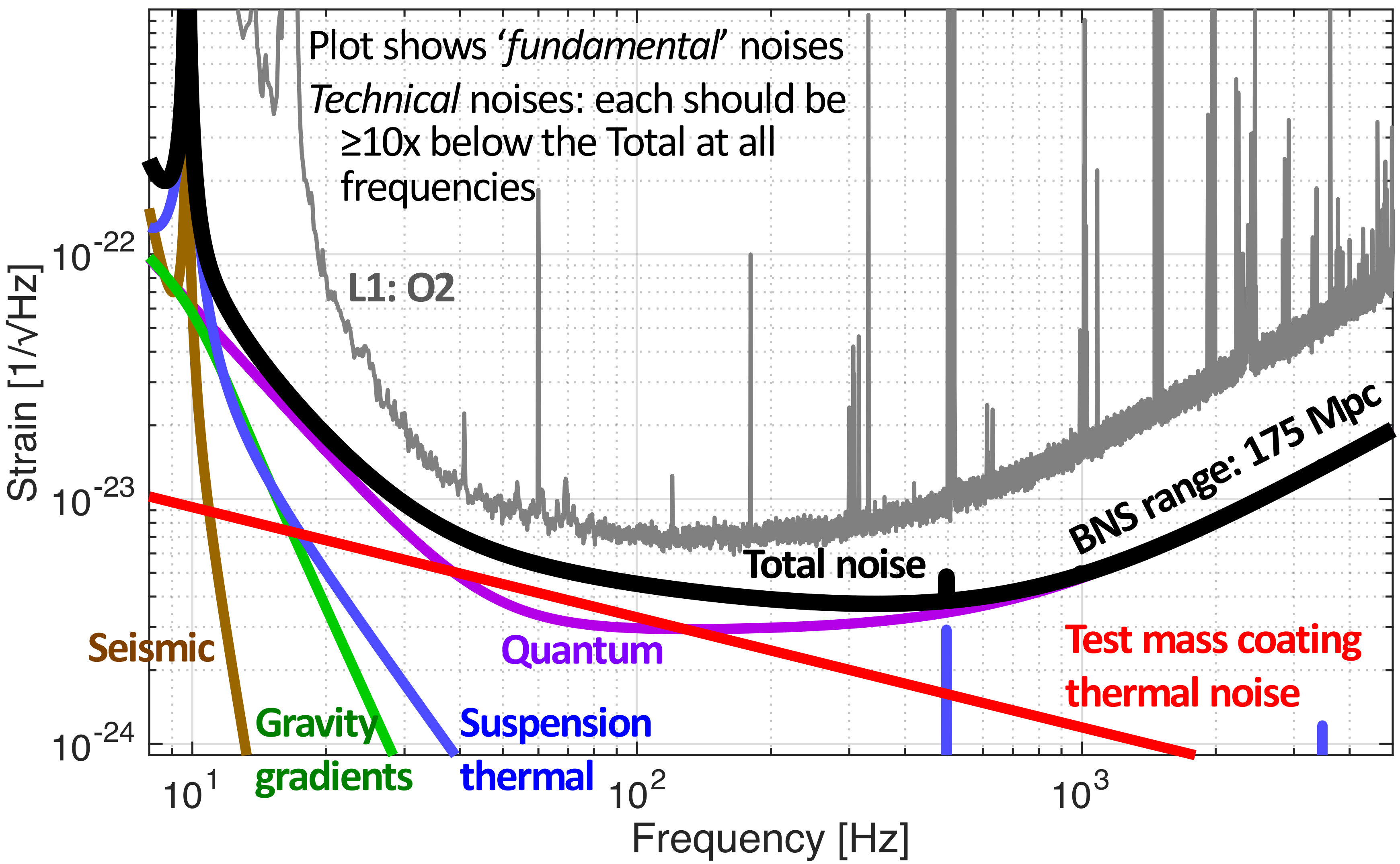
LIGO-G1801329-v1

[Image credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)]

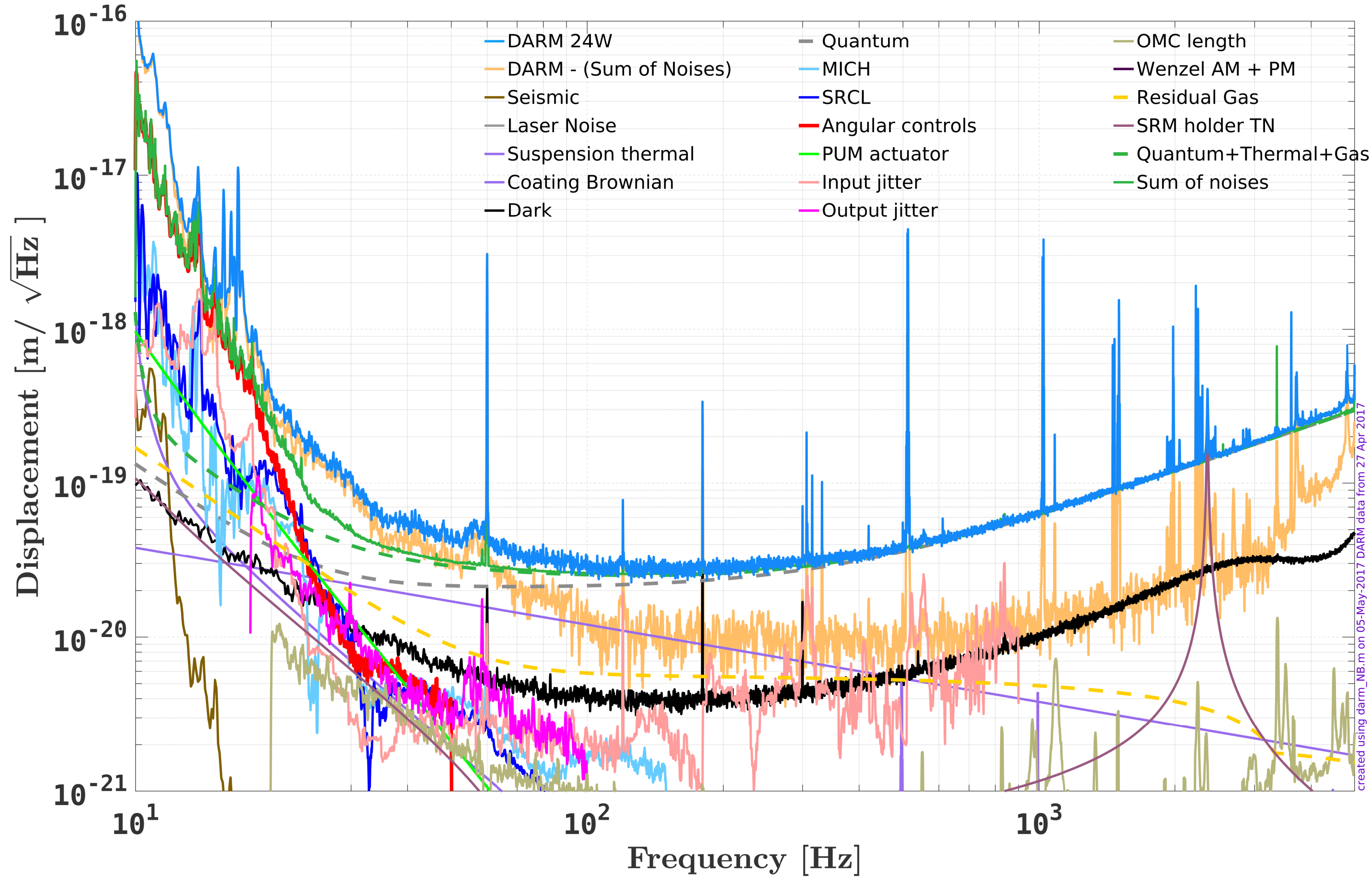
LIGO Roadmap (touched up)



aLIGO Target Design Sensitivity



Noise Budget for LLO detector in O2



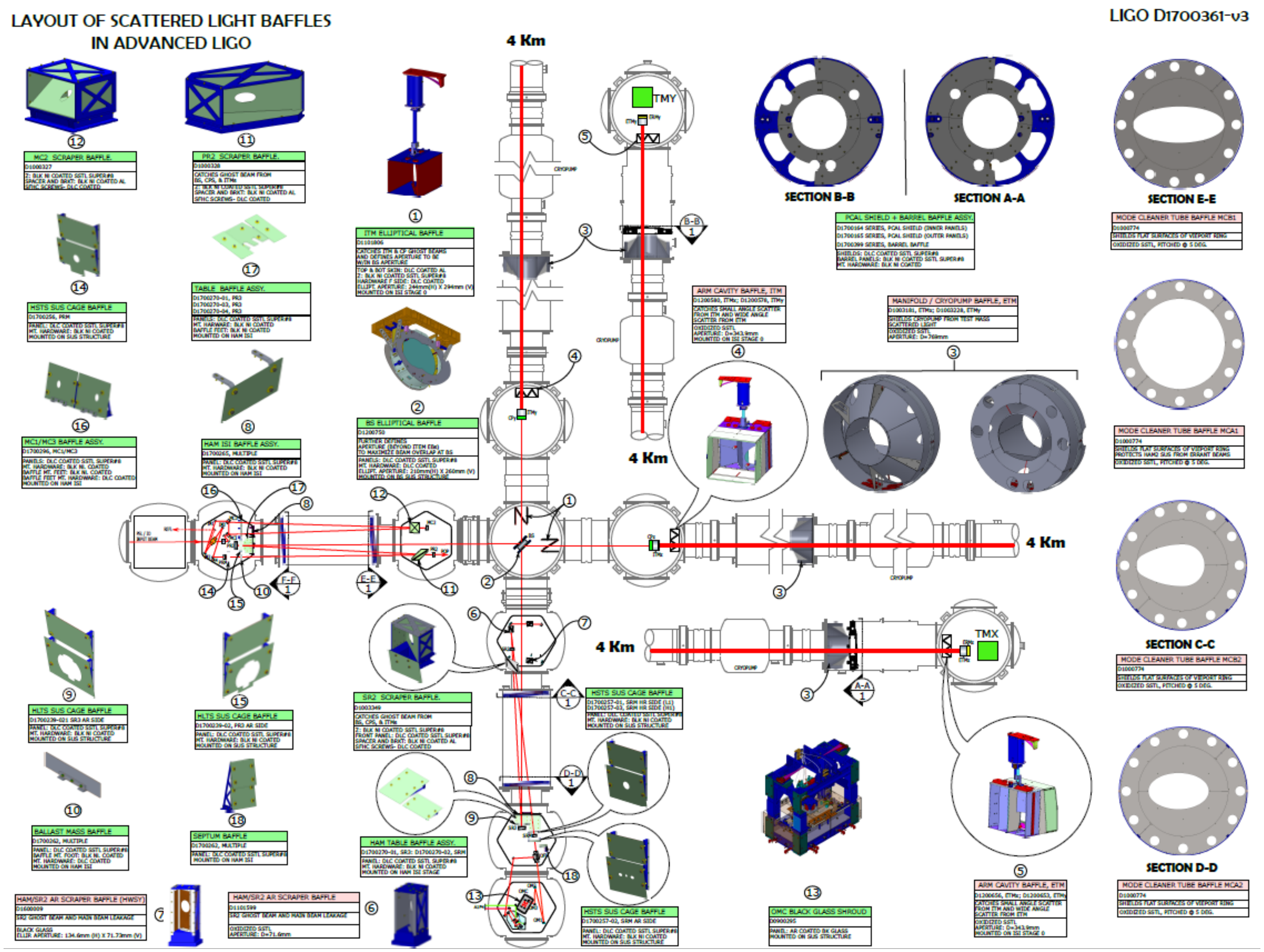
Upgrades & other changes for O3

Upgrade	Motivation	Frequency band impacted
Stray Light improved Control, part A LIGO-D1700361	New & improved light baffles; some testing performed at LLO	50-500 Hz
Monolithic Signal Recycling Mirrors	Original mirrors were temporary, held in a composite structure	3 kHz noise peak; f <100 Hz
neoLASE amplifier for 70 W output LIGO-T1700046	Allows doubling of laser power vs. O2	freqs > 80 Hz
LHO vertex components done pre-O2 at LLO (SR3 heater, ISS upgrades, ISI dampers, TM Bounce/roll dampers, etc.)	LLO was the pathfinder for these components	various & duty cycle
New ITMX on H1 (point absorber on old optic) LIGO-T1700149	Discovered during O2; caused noise problems	freqs > 30 Hz
Squeezed Light Upgrade LIGO-E1600387	Both IFOs have squeezed vacuum injection capability	freqs > 80 Hz
Test Mass Discharge System on all Test Mass chambers LIGO-E1500235	System to neutralize static charge buildup on/near test masses	freqs < 100 Hz
Replace End Test Masses, retrofit annular-End Reaction Masses LIGO-E1500264	Better optical quality ETMs; ERMs have lower residual-gas damping	freqs > 20 Hz

Upgrades & other changes for O3

Upgrade	Motivation	Frequency band impacted
Acoustic Mode Dampers applied to all Test Masses LIGO-E1800071	For parametric instability control; successful results after years of R&D	freqs > 80 Hz
Beam Rotation Sensors for LLO (4 units; built & installed by Univ. of Washington collaborators) LIGO-G1801085	Ground tilt sensing for improved low-frequency isolation (higher duty cycle)	Duty cycle improvement
Signal Recycling Cavity alignment sensing with new 118 MHz modulation LIGO-E1700327	For better sensing of the SRM alignment; required some new electronics & modulator modifications	Duty cycle improvement
Electric Field Sensors: outfit one end-station chamber per IFO LIGO-E1800049	New diagnostic for electric field fluctuations near the test mass	freqs < 100 Hz
Scattered light control for Output Faraday Isolator LIGO-G1800787	Identified in LLO testing as (most likely) the most sensitive remaining area for scattered light noise	30-60 Hz

Baffles for Scattered Light



Stray light control:

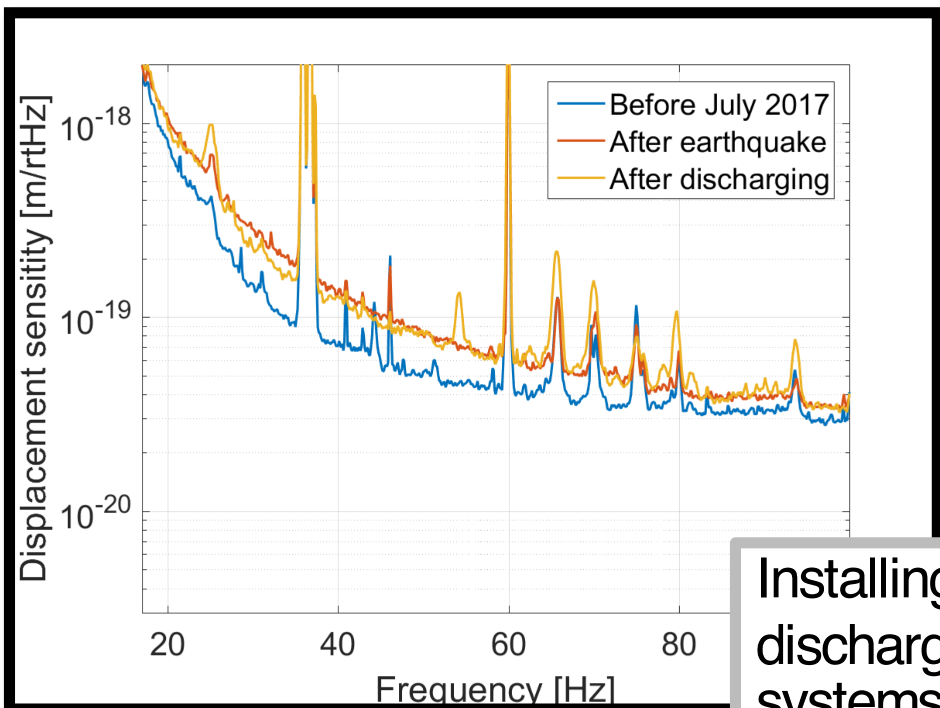
Removing some baffles which caused noise

Adding new baffles

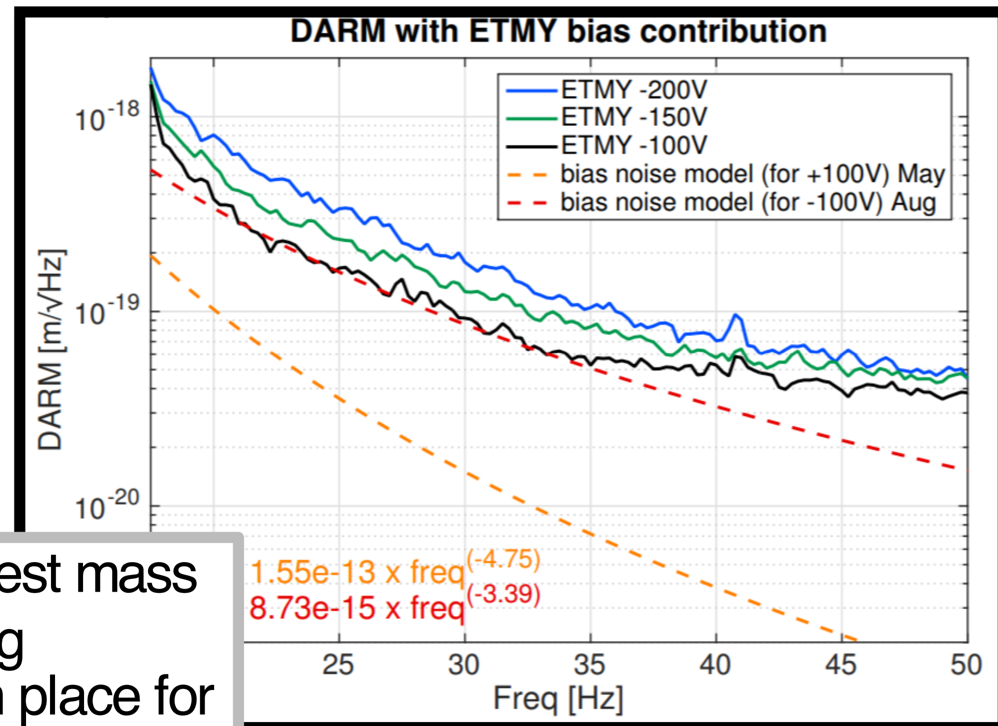
Modifying some baffles

Charge on optics, fluctuating electric fields

Large earthquake added charge to Hanford test masses



Noise dependence on static electric fields around test mass at Livingston



Installing test mass discharging systems in place for all test masses

A Effler G1800748

Electric Field Meters

Sensor for stray electric fields will be installed in one end chamber at each site

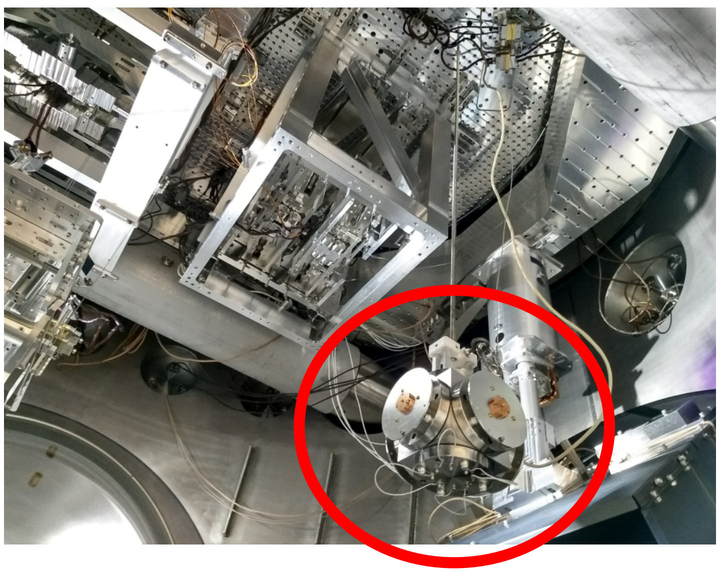
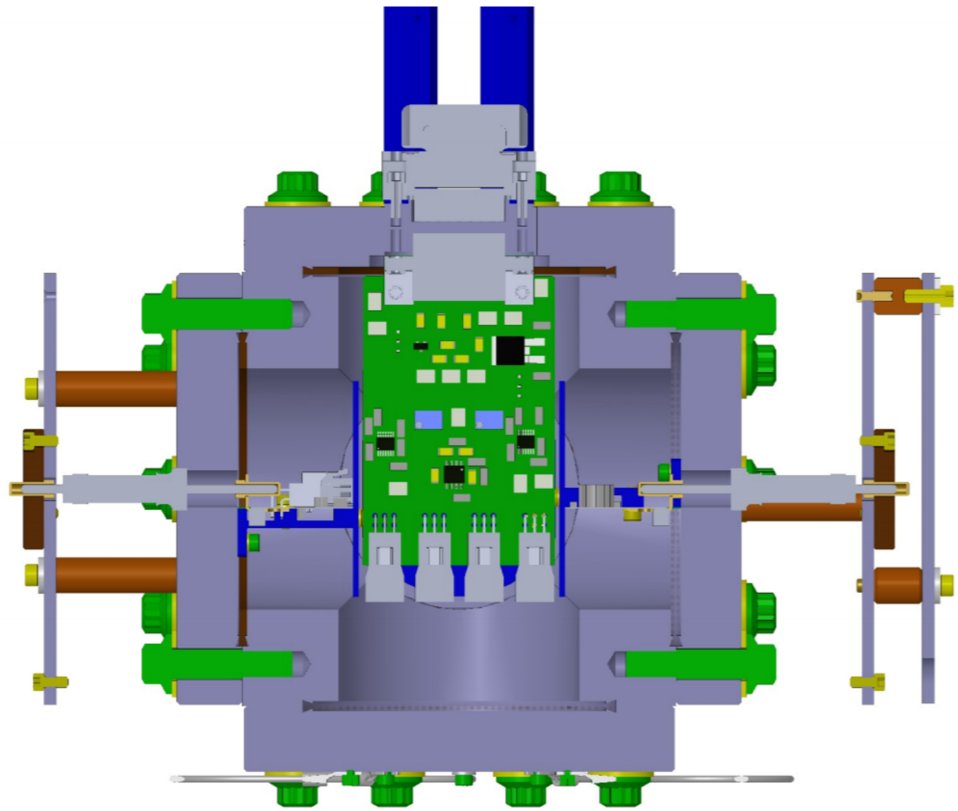


Photo: G Mansell C Cahillane



Design: G1800293

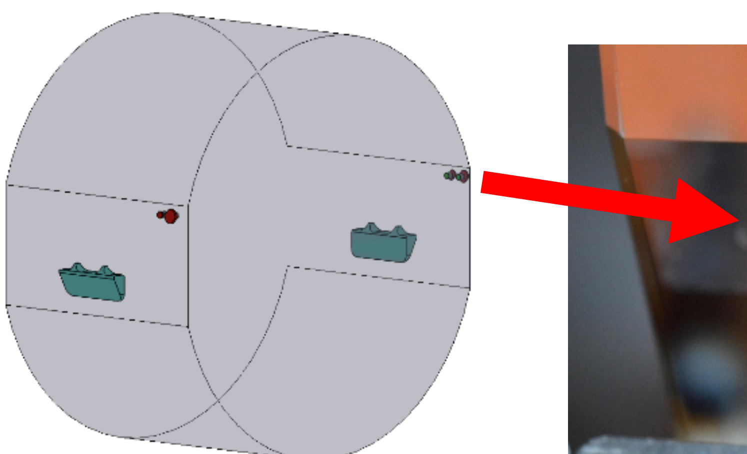
Pre-O3 commissioning: Expect to start in August 2018

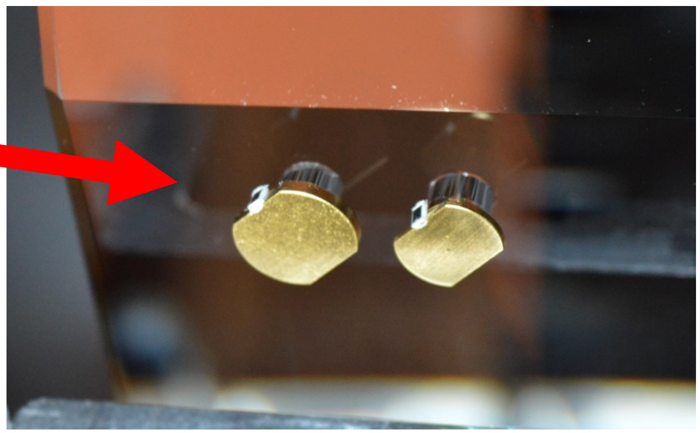
- **Sensitivity**
  - Goal is ≥120 Mpc range for binary neutron star mergers (1.2 Gpc for 30+30 $M_\odot$ black holes)
- **Higher laser power operation**
  - Double the laser O2 power stored in the arm cavities to 200 kW
- **Realize Squeezed light injection**
  - goal of 3 dB of shot noise suppression
- **Iterate on Alignment control**
  - Improved robustness and reduced control noise coupling
- **Optics, cavities, wavefronts**
  - characterization of new optics & optimization of thermal compensation
- **Environmental couplings**
- **Duty cycle improvements**

High Power Operations

Establish operations at high interferometer power

- Goal: 200 kW arm power → 50W input laser power
- New laser amplifier: Characterization of jitter etc.
- Alignment control design to compensate for power induced instabilities
- Thermal compensation
  - Optimization for mode-matching, noise couplings
- Parametric Instability control
  - Opto-mechanical feedback between the test mass acoustic modes & the arm cavity optical modes can lead to instability
  - For O3, all test masses will have Acoustic Mode Dampers to mitigate PIs





Small tuned dampers: Resistively-shunted PZT + reaction mass, bonded to sides of TM

New test mass Optics

- Anomalous absorption spot found on one Hanford input test mass (~10 microns dia.)
- May have been responsible for increased jitter coupling
- This test mass has now been replaced
- Also: correcting wrong 532 nm transmission (locking), reduced coating planetary ripple

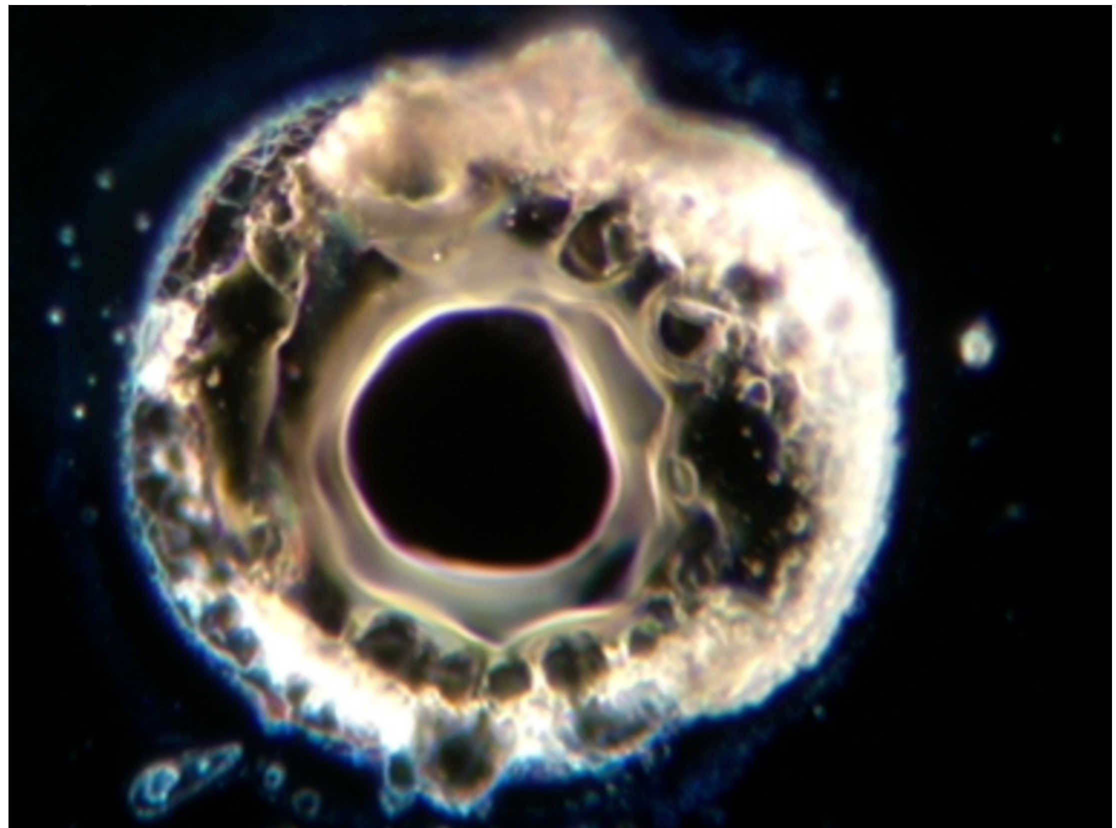
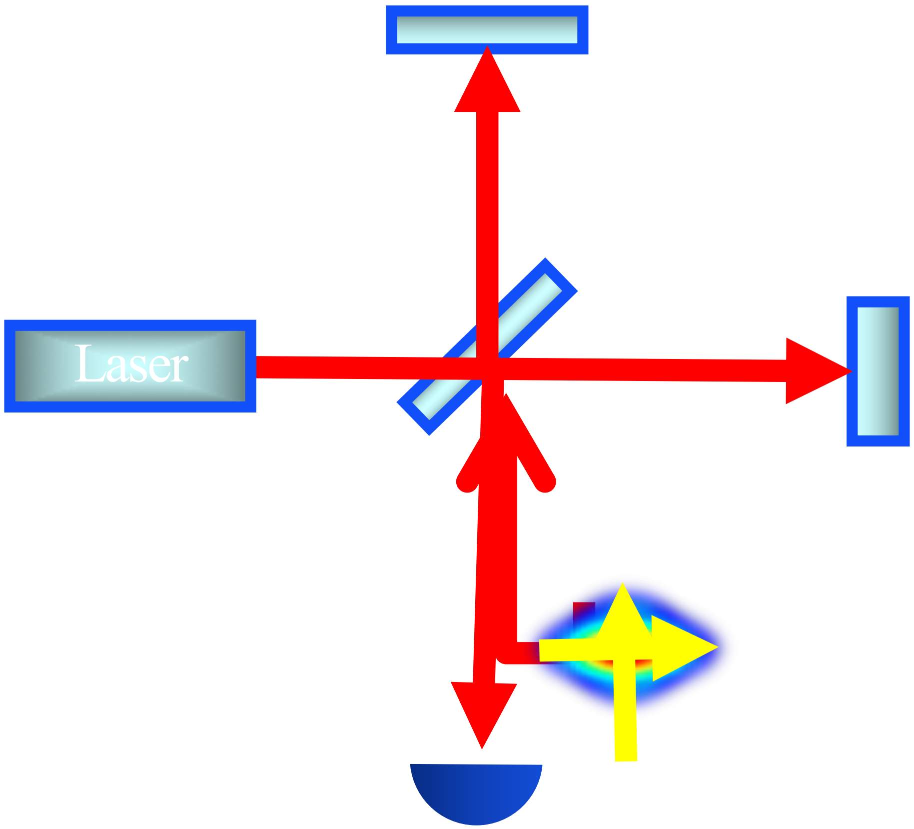


Photo: G Billingsley

Frequency independent Squeezing for O3



Squeezers now installed at both sites

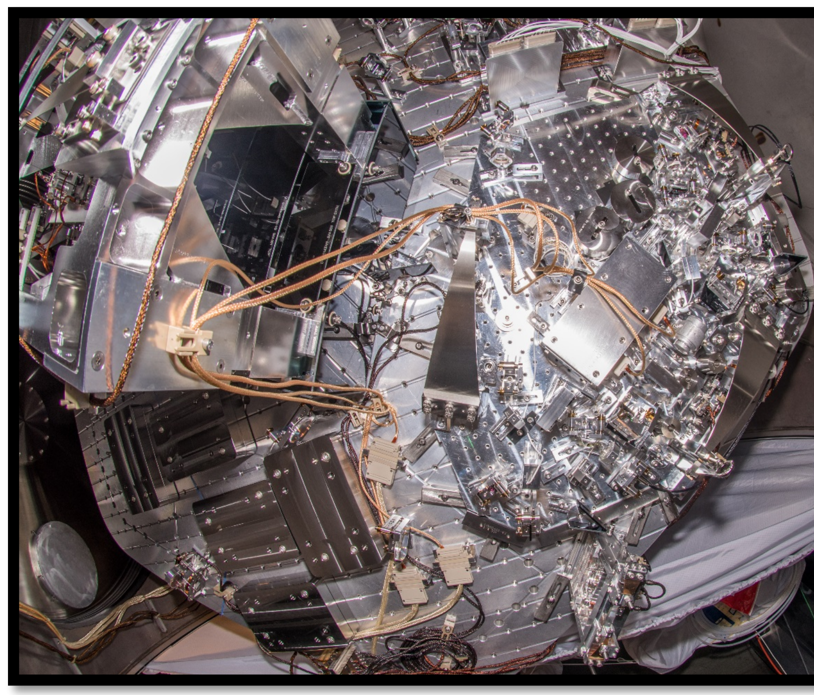
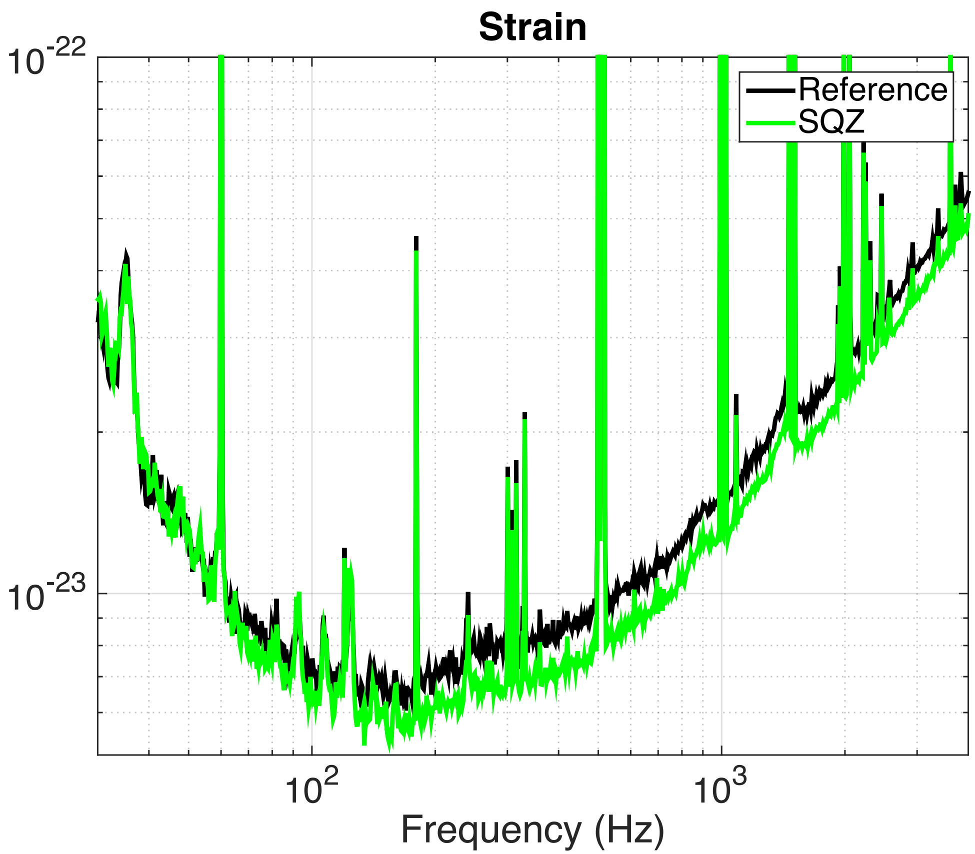


Photo: M Tse

Squeezing preliminary results

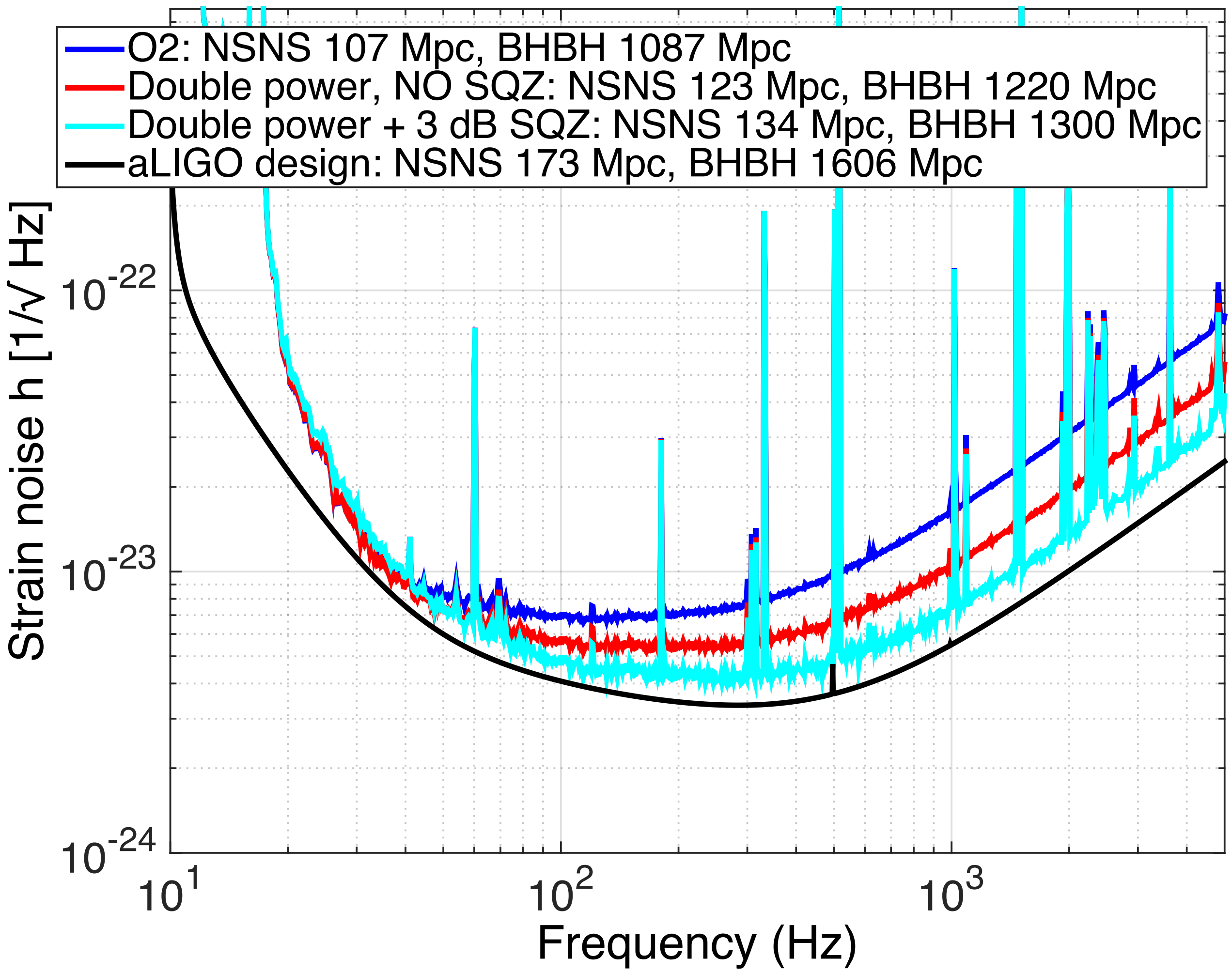


- Early results from Livingston
- Around 1 dB of squeezing measured
- No harm done!
- Goal is to 3dB of squeezing (40% shot noise reduction)

Plot: L Barsotti

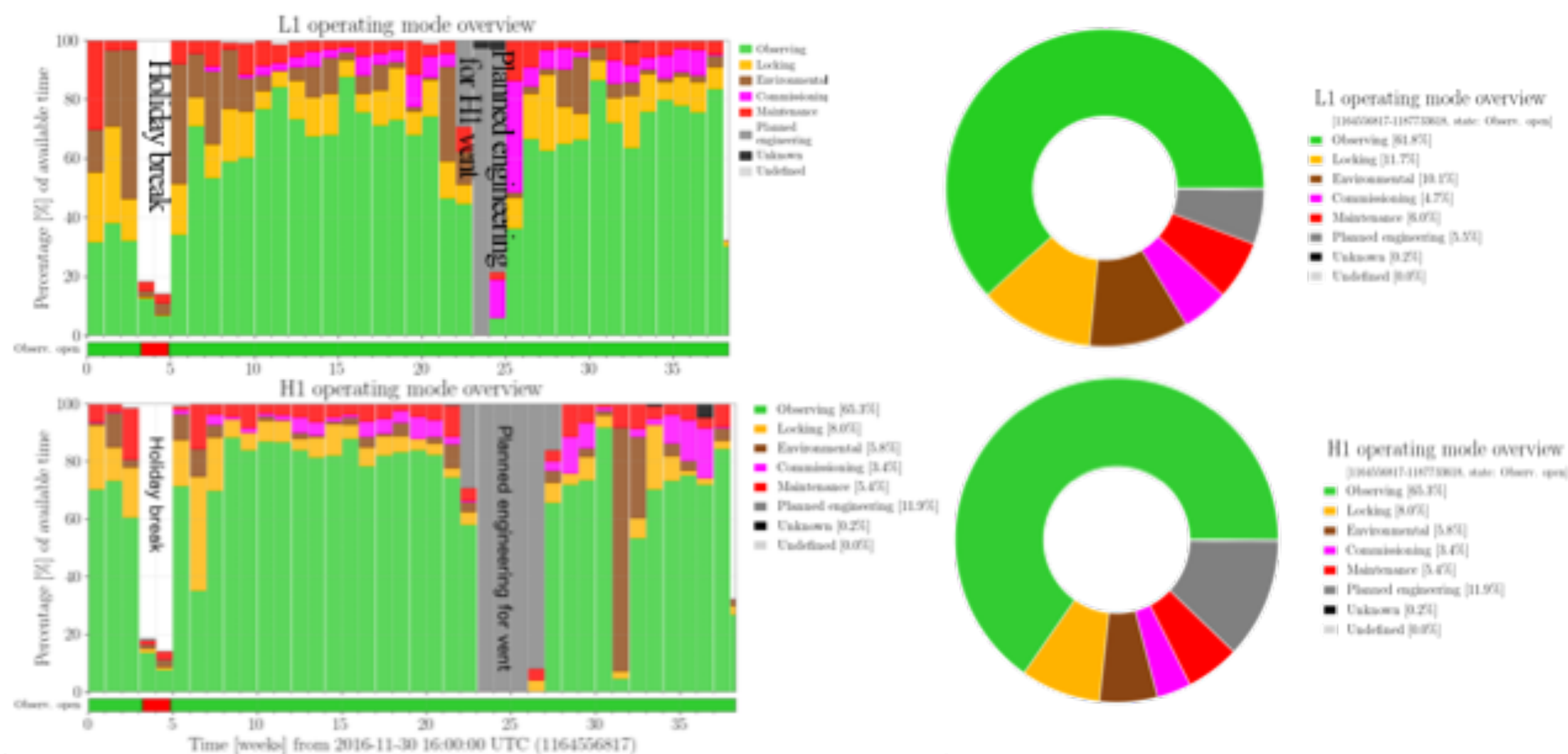
Target sensitivity for O3

Projections made by starting with the **L1 sensitivity in O2**, and
Reducing technical noise by 1.5x, Increasing laser power, injecting squeezing



Detector duty factor

- Observation run overall uptime of 70% for individual detectors, and 50% H1-L1 double-coincidence.
- Suppresses events; could miss a unique event (supernova)



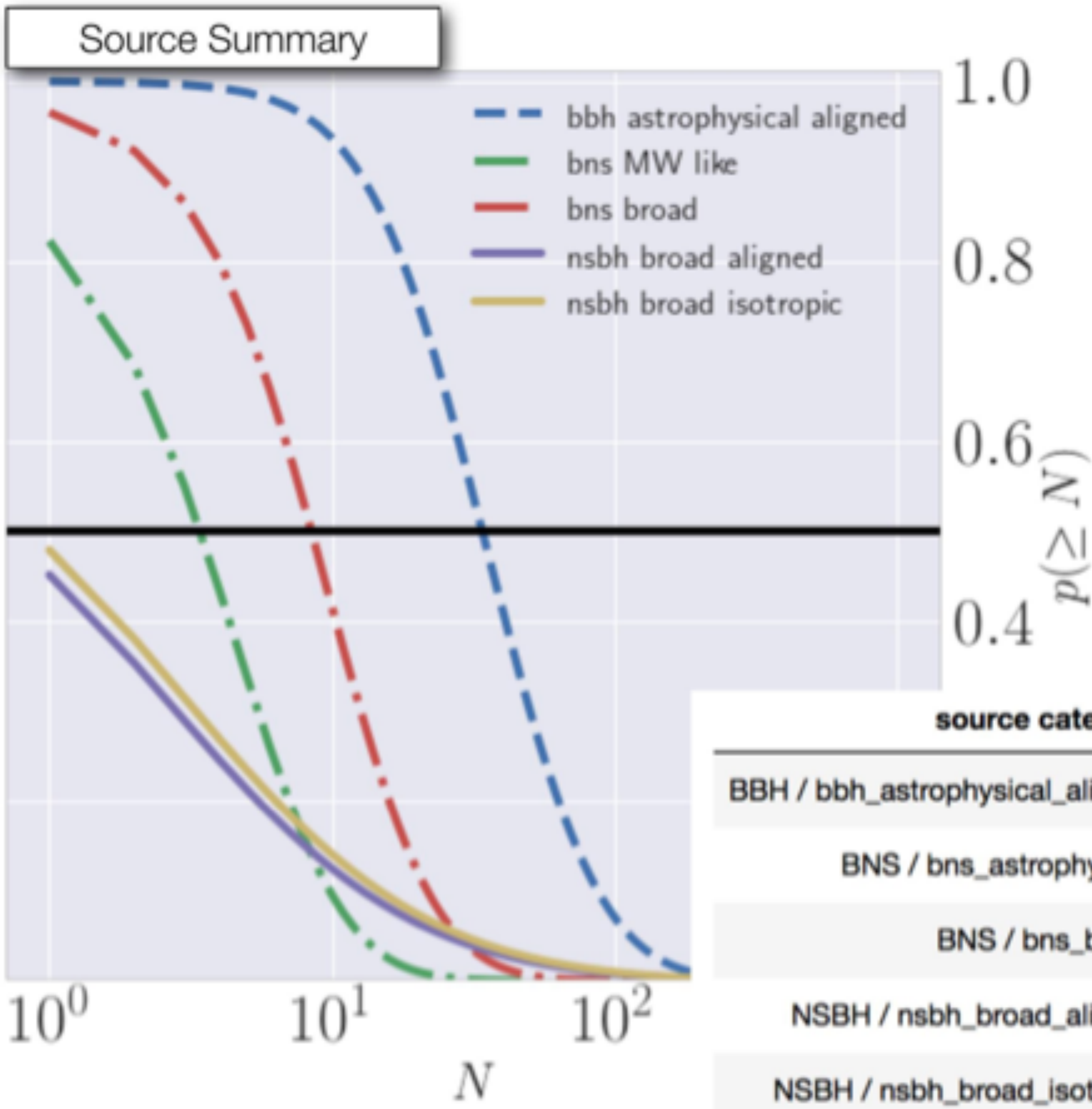
Improvements to robustness/duty cycle

- **Passive dampers** for suspension modes to reduce time spent in active damping
  - Bounce & roll mode dampers being propagated to H1 (successfully deployed on L1 prior to O2)
  - Investigating designs for dampers for the violin modes, for possible O4 implementation
- Improve ability to **hold lock during low-level earthquakes**
  - Modify controls in advance of EQ arrival
- Shorten time required for **lock acquisition**
  - New ETMs: arm cavities will now have current, higher green finesse to benefit Arm Length Stabilization
  - R&D ongoing on machine learning to speed up certain steps
- Improve ability to lock in times of **high wind** and **high microseism**
  - Beam rotation sensors, to deal with low-frequency tilts, now deployed at both observatories

Once O3 is running, ~February 2019

- Fundamental change for O3: Open Public Alerts for Triggers
  - No more standard EM follow-up MOUs or private GCN alerts!
  - LIGO/Virgo to release public alerts for **all event candidates for which we have reasonable confidence**
    - For binary mergers: one false-alarm-rate threshold, aiming for 90% purity overall (in practice, lower purity for neutron star binary candidates— i.e., pursue them more aggressively)
    - More restrictive threshold for unmodeled GW burst candidates
    - We can "promote" a weaker GW candidate if it is coincident with a GRB, core-collapse supernova, etc.
  - We'll provide basically the **same information as in O2**: significance, time, binary type classification, sky position and distance 3D map
    - Considering adding some more information to aid prioritization
  - We'll provide **automatic *preliminary* alerts** before human vetting
- See https://www.ligo.org/scientists/GWEMalerts.php for more info

Rates in O3



There are caveats, but the general picture is:

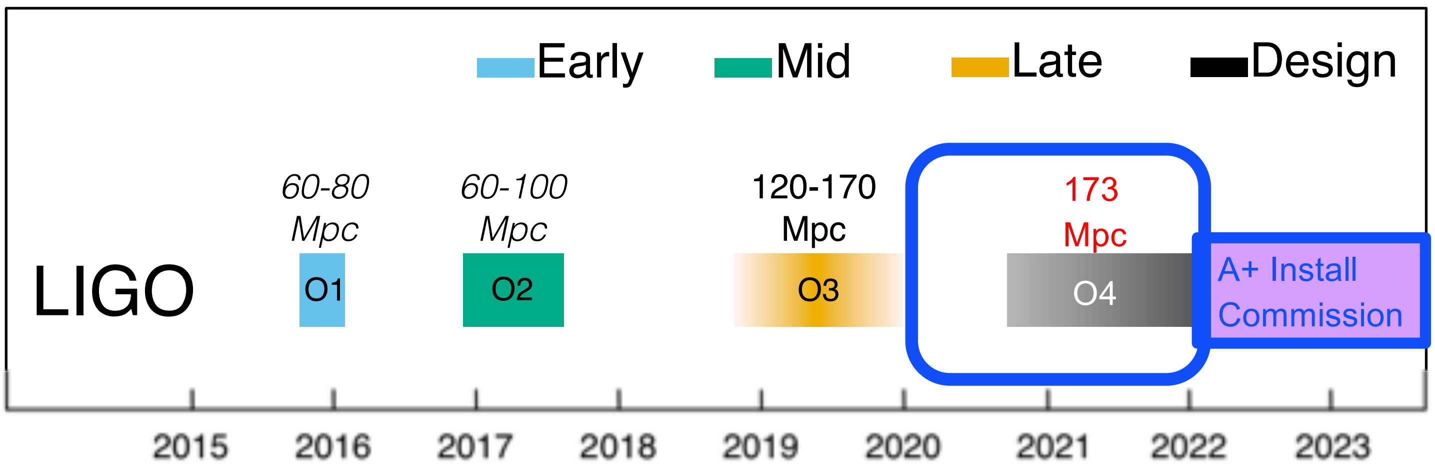
BBH: at least a few per month, maybe more

BNS: 1–10, possibly up to ~1 per month

NSBH: Could detect one or more during O3, but uncertain. We'll see!

source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	34^{+79}_{-25}
BNS / bns_astrophysical	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	5.0×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

LIGO Roadmap (touched up)

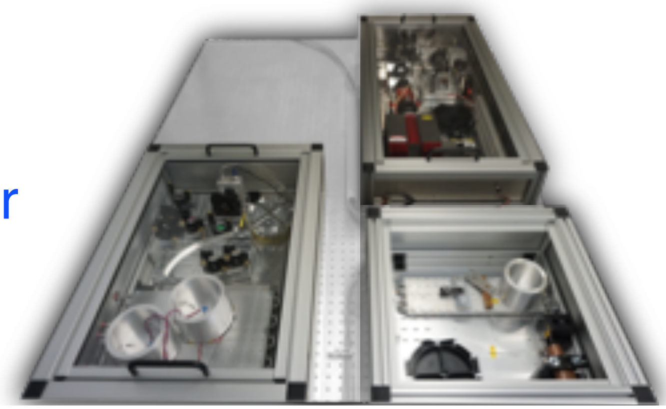


Detector upgrades for O4

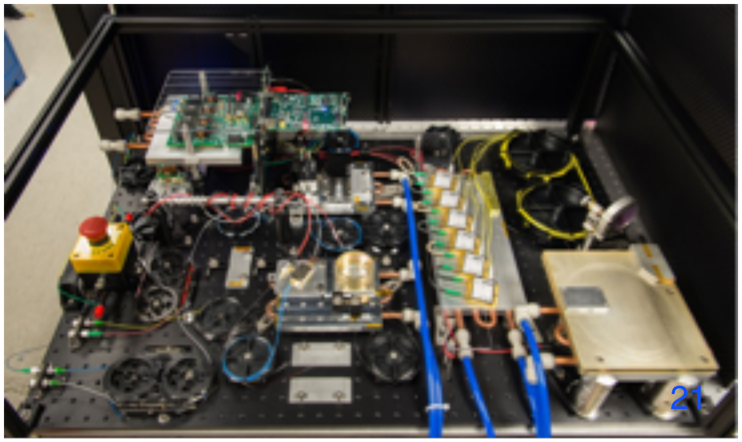
New Higher Power Laser

- 200 W at the laser source → 600-700 kW in the arms
- Will evaluate several options:
  - Custom 200 W fiber amplifier
  - Coherent beam combining of multiple amplifiers
  - Original high power oscillators
- Plan on down-selecting between these options in early 2019, to be ready with new lasers in early 2020 (right after O3)

LZH fiber amplifier



MIT-Lincoln Labs fiber amplifier



Detector upgrades for O4

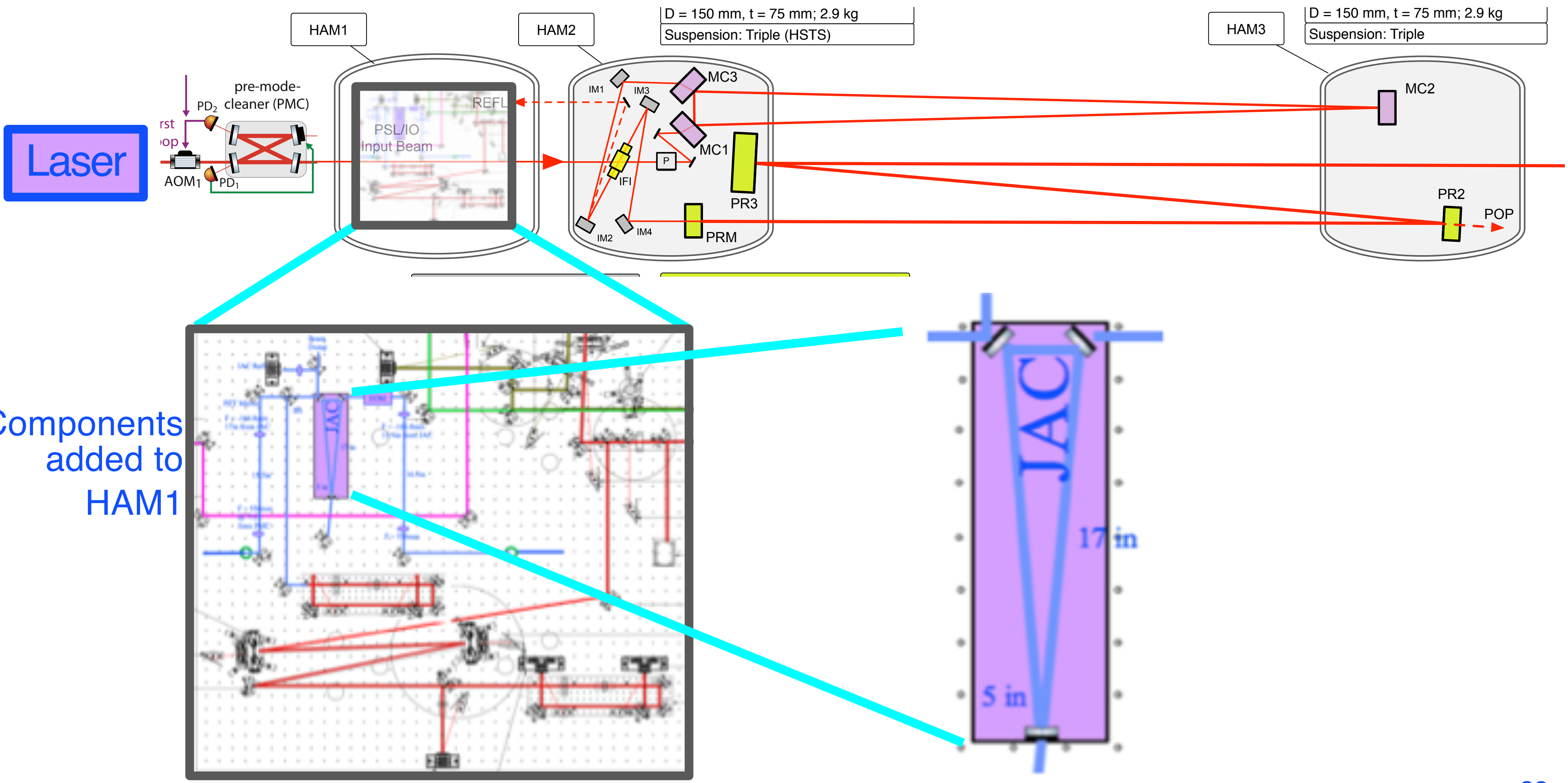
Jitter Attenuation Cavity

- Noise due to input beam pointing fluctuations
  - (Input beam jitter) x (differential arm misalignment)
  - Original requirements on both of these factors are proving difficult to achieve
  - Projected to limit aLIGO target design sensitivity in the 200-1000 Hz band
- Noise due to input beam higher order fluctuations
  - (Input beam size fluctuations) x (differential lensing in the arms)
  - Not considered in the original design; difficult to tightly control the differential lensing
- An additional mode-filtering cavity would address both of these noise issues
  - LIGO-T1700542, Jitter attenuation cavity preliminary design

Detector upgrades for O4

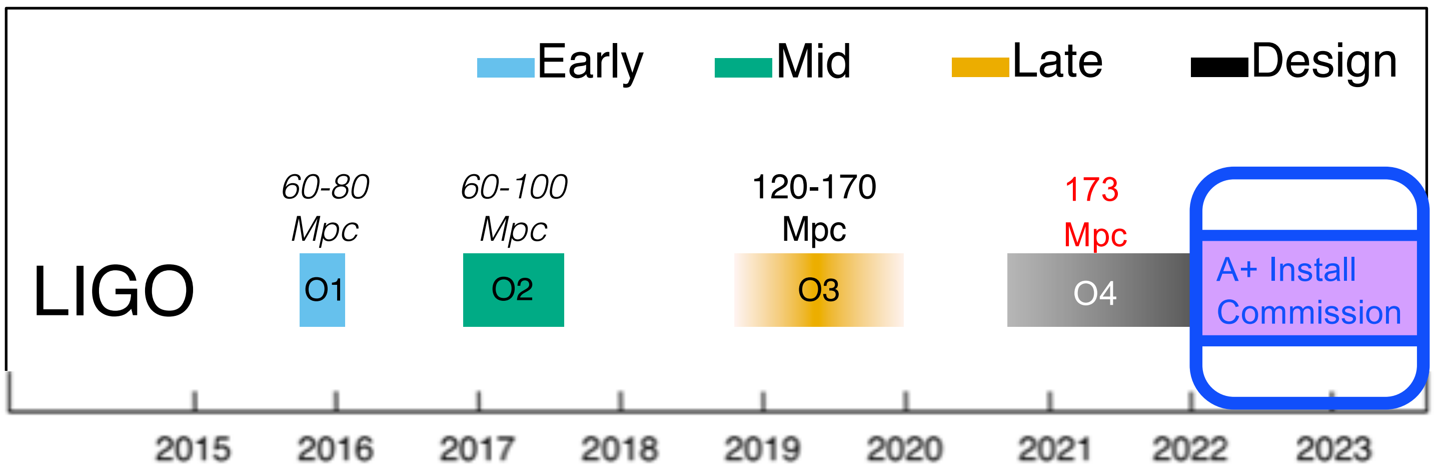
Jitter Attenuation Cavity

JAC documentation:
LIGO-E1700002



Components added to HAM1

LIGO Roadmap (touched up)



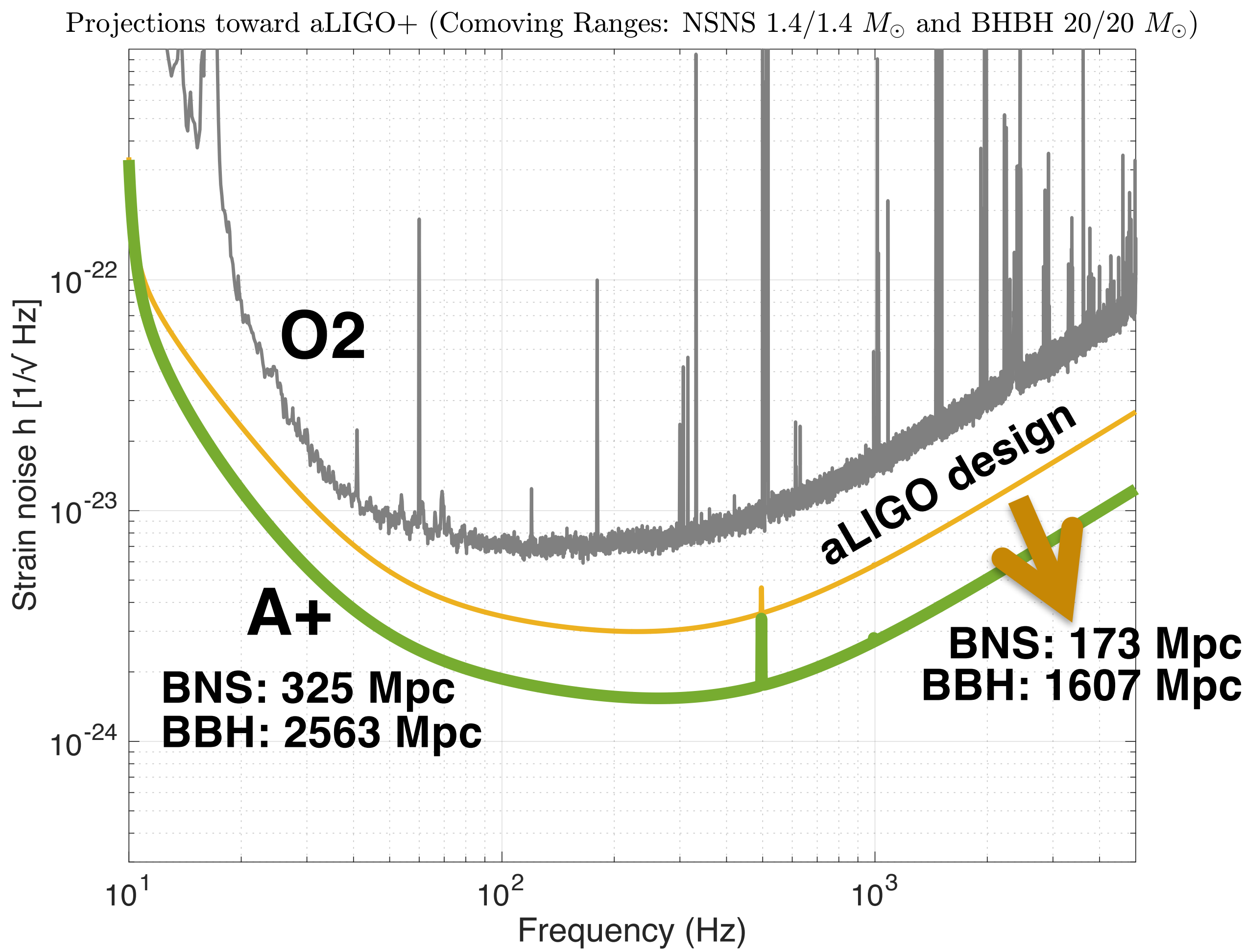
A+ elevator pitch

- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment, and moderate risk
- Target: factor of 1.7* increase in range over aLIGO
  - ➔ About a factor of 4-7 greater CBC event rate
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Stepping stone to 3G detector technology
- Can be observing within 6 years (mid- 2024)
- “Scientific breakeven” within 1/2 year of operation
- Incremental cost: *a small increment on aLIGO*

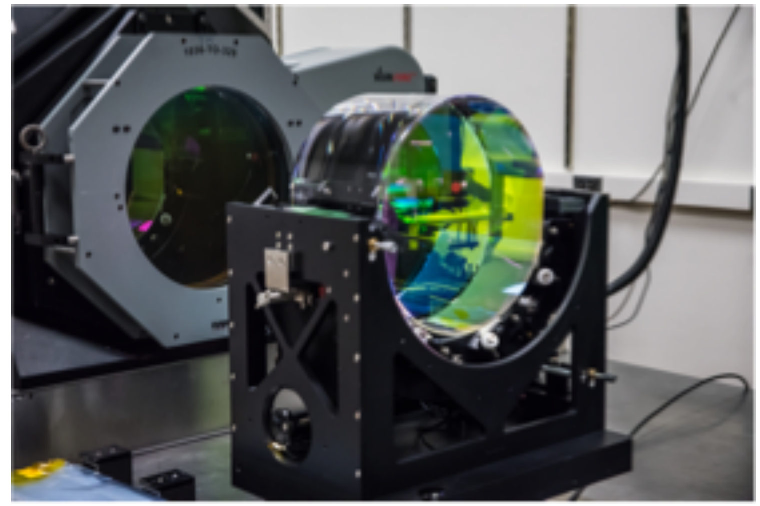
*BBH 30/30 $M_\odot$: 1.6x
*BNS 1.4/1.4 $M_\odot$: 1.9x

A+: a mid-scale upgrade to Advanced LIGO

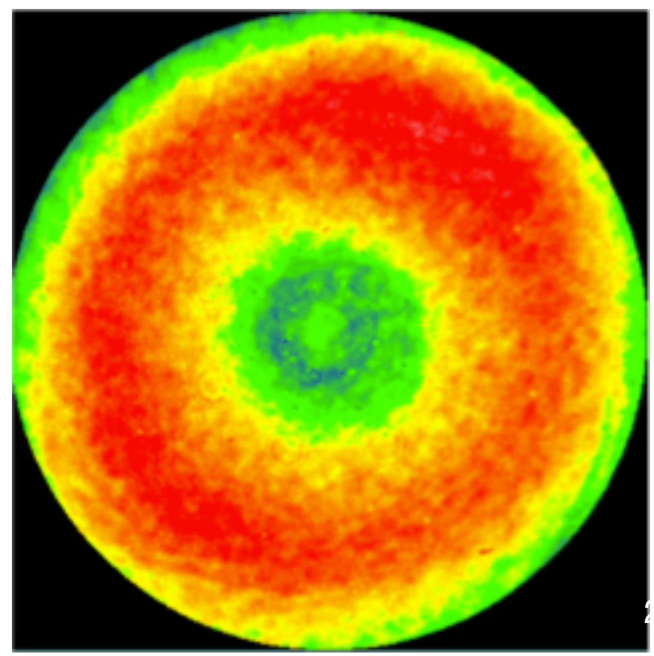
- Reduced quantum noise
  - Improved optical losses
  - Improved readout
  - Frequency-Dependent Squeezing
- Reduced thermal noise
  - Improved mirror coatings
- Observing by mid-2024



Improved Mirror Coatings for A+



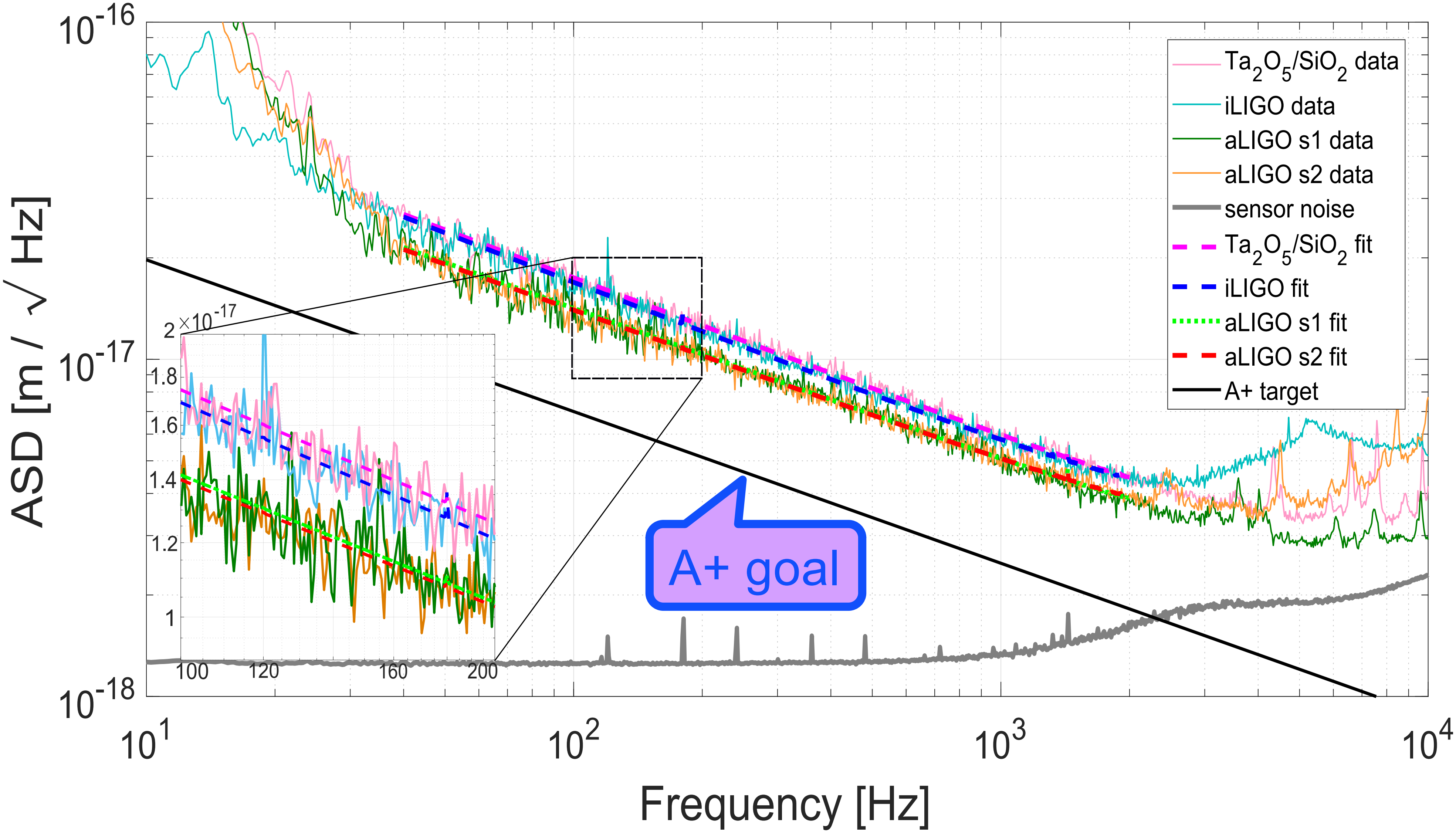
- TARGET: Elastic loss angle $\phi < 9 \times 10^{-5}$
  - (aLIGO $\phi = 3.6 \times 10^{-4}$)
- Current R&D on small samples
- UK, Europe and US Center for Coatings Research initiative to select best low-loss coating design in about 2 years
- A+ Coating Pathfinder program will spin up industrial vendor(s) and qualify full-aperture coatings for production
- In parallel, new and existing spare aLIGO optics will be polished
- Metrology, QA, lab infrastructure, tooling, procedures all same as aLIGO & reused
- Replacement core optics delivered for final phase of A+ installation (mid-FY23)



aLIGO ETM figure map
6.5 ÅRMS over central 160 mm Φ
(LIGO Lab/G. Billingsley)

A+ Coatings

Gras & Evans, P1700448



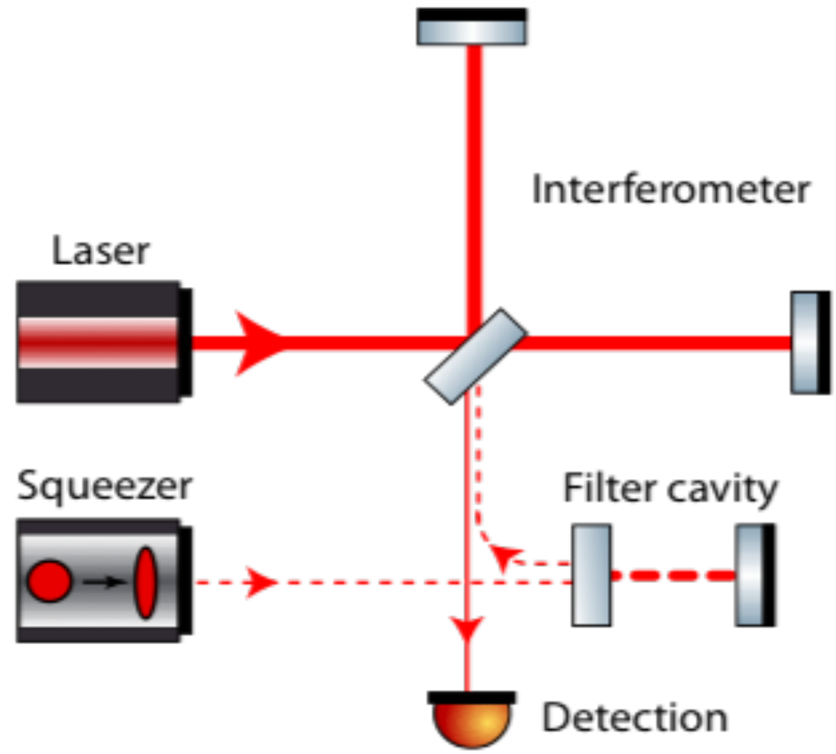
Frequency-Dependent Squeezing

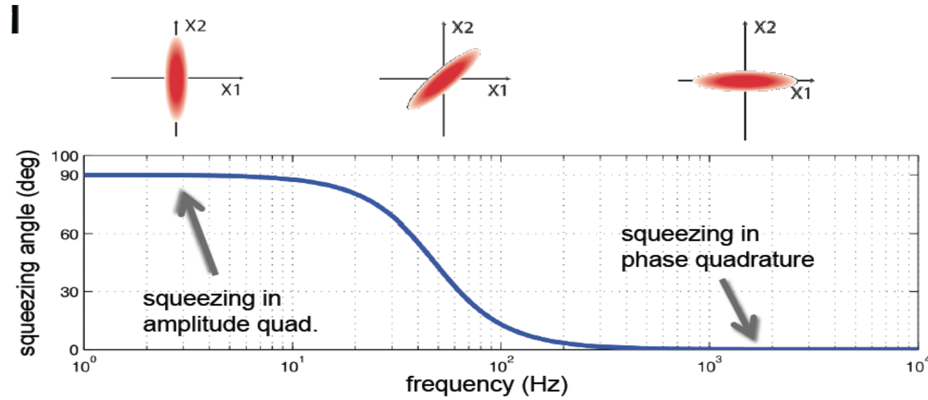
- Optical "filter cavity" (FC)
- Rotates squeezing phase; improve radiation pressure at LF *and* phase noise at HF
- Low-loss, high finesse cavity with bandwidth ~100 Hz
- Sensitive to optical losses, scattering and mirror motion

→ Requires *seismic isolation and quiet mirror suspension*

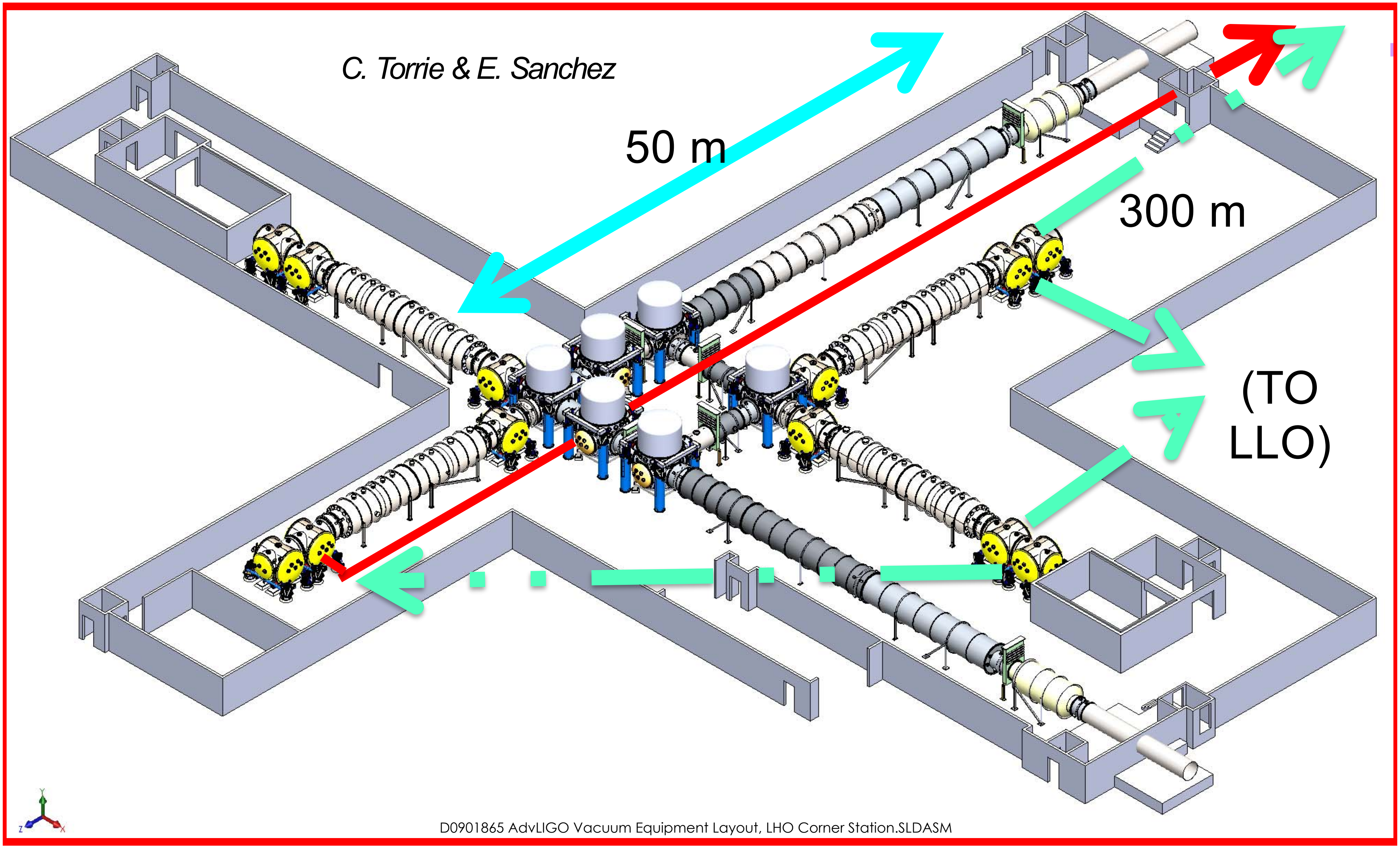
→ Requires *high-quality FC mirrors*

→ **Requires** $\boldsymbol{L_{FC}}$ **~ 300 m**

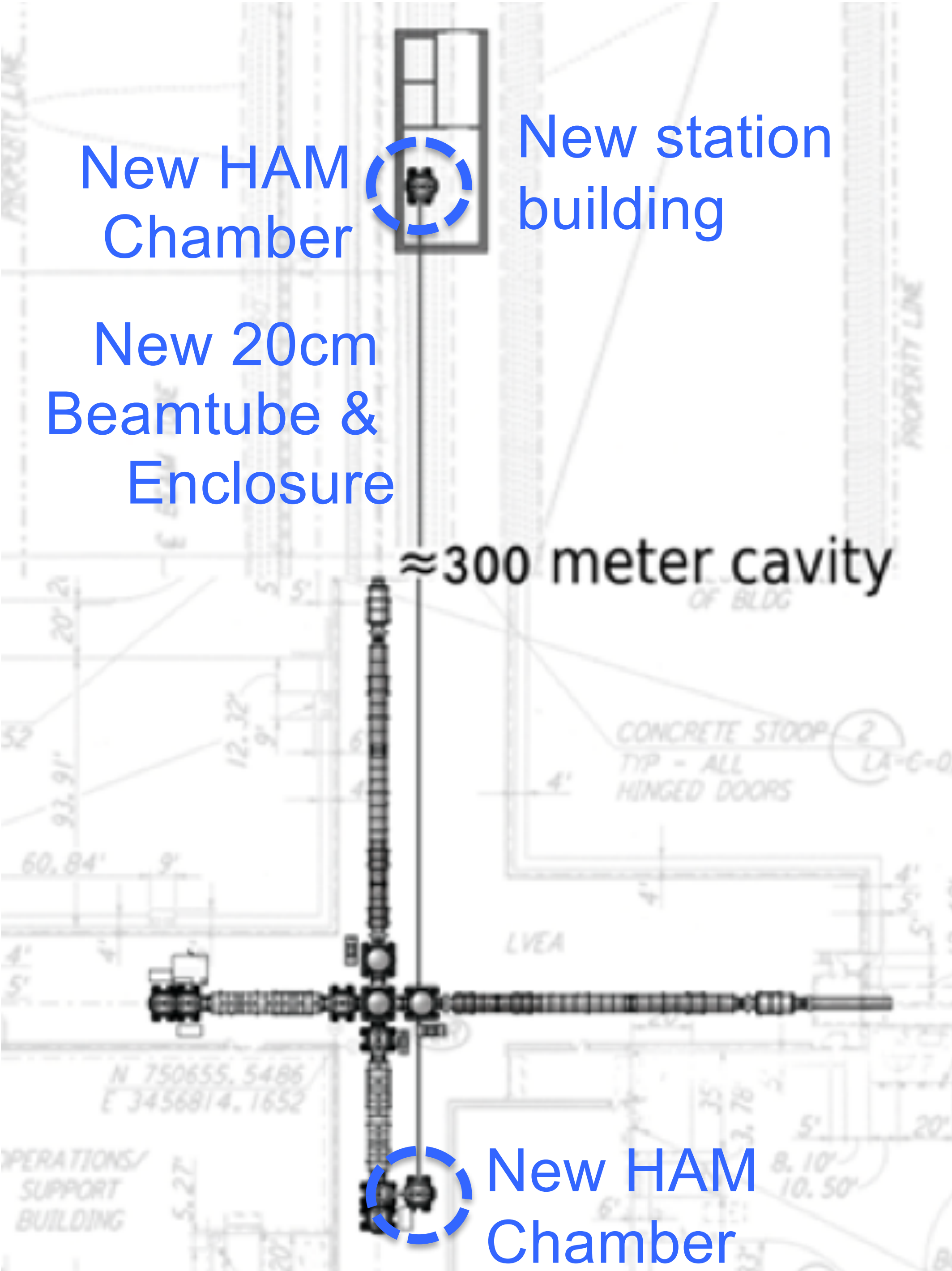




Filter cavity vacuum system and facility modifications



A+ FILTER CAVITY BEAMLINE



C. Torrie, E. Sanchez , G. Billingsley
M1800040

A+ Program/Funding Update

- Preliminary Construction Proposal submitted March 2018
  - NSF (lead)
  - STFC (UK) planning partnering in support; ARC also helping
- Peer review convened 5/10 with UK participation
  - Rigorous and *extremely positive* panel report returned to NSF
- **A+ RECOMMENDED FOR CONSTRUCTION**
- Accelerated start date: **October 2018**
  - Late-2022 construction completion unchanged
    - paced by mirror coating development and observing obligations
- Highly construction-efficient award funding profile

LIGO-India

- Concept: Put the ‘spare’ aLIGO detector in a new southern Observatory
- NSF contributes detector; India contributes Observatory
- A greater number of detector facilities around the world improves:
  - Sky localization
  - Polarization information
  - Network robustness/duty-factor; at 75% uptime,
    - P(triple detection, 3 detector network) = 42%
    - P(triple+ detection, 4 detector network) = 74%
    - P(triple+ detection, 5 detector network) = 90%
- Status:
  - Site acquisition nearly complete
  - Initial funding (~10%) being used for site, preparing engineering
- Instrument is planned to be upgraded to A+ technology
- **Expect fully-commissioned observation to start in 2025**

Summary

- Preparations for O3 are challenging
  - Instrument installation and commissioning
  - Collaboration preparations for anticipated detection rates also challenging! But that's another talk…
- Future development of the instrument, and field, looks bright
- **Eager for KAGRA to join O3!**