LIGO Evolutions

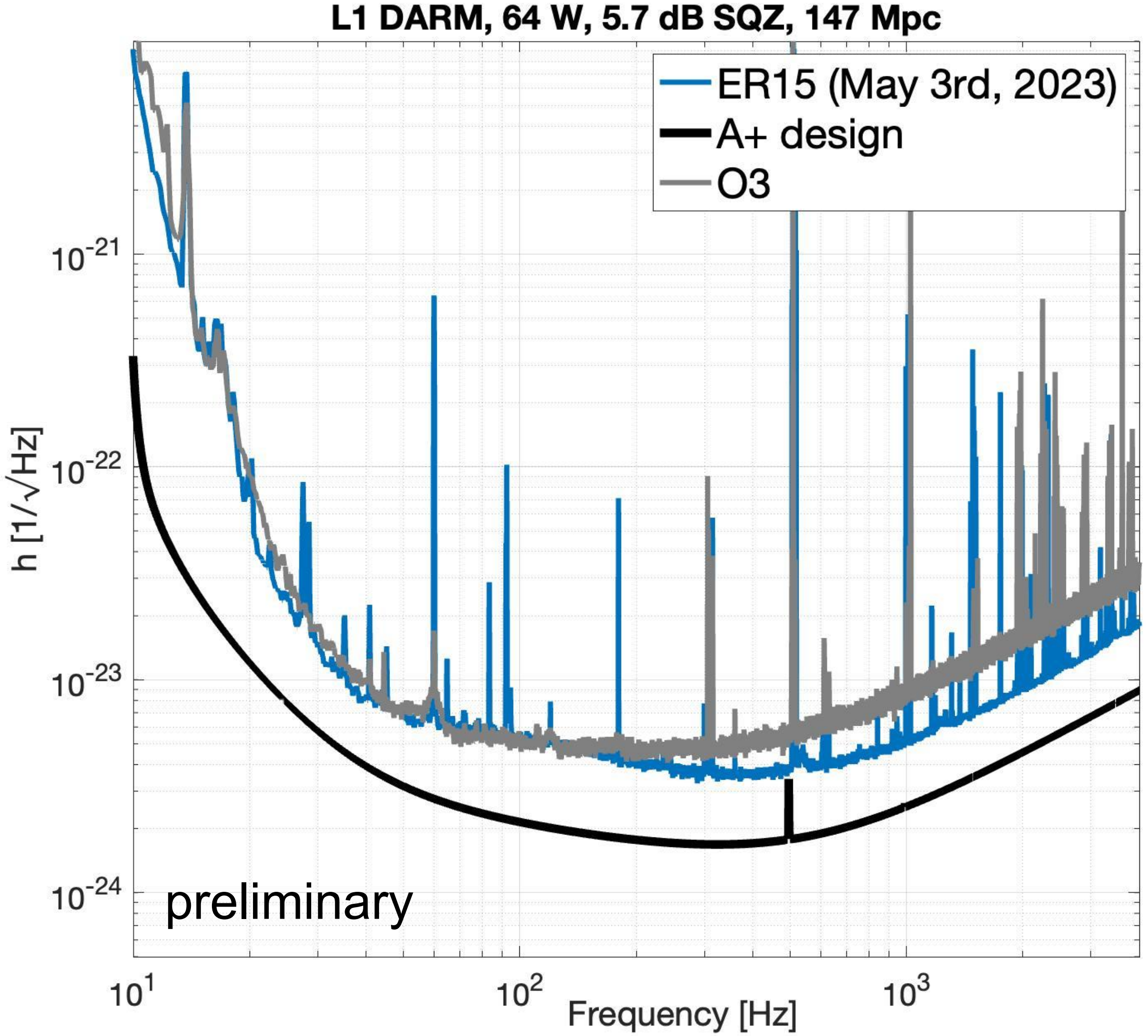
Lisa Barsotti (MIT)

LIGO-G2300963

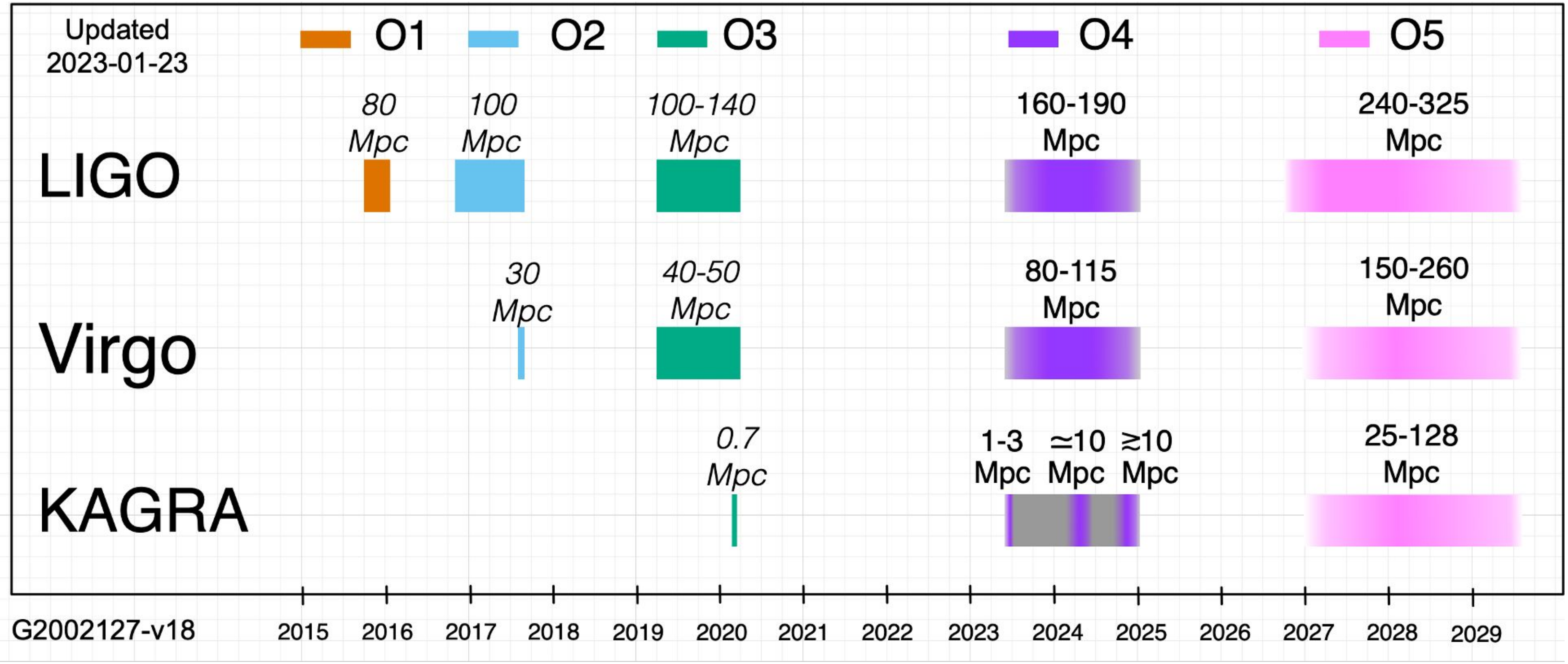
ET Symposium, Cagliari

May 11th, 2023

O4 (close to) best sensitivity



LVK Timeline towards O5



LSC Post-O5 study

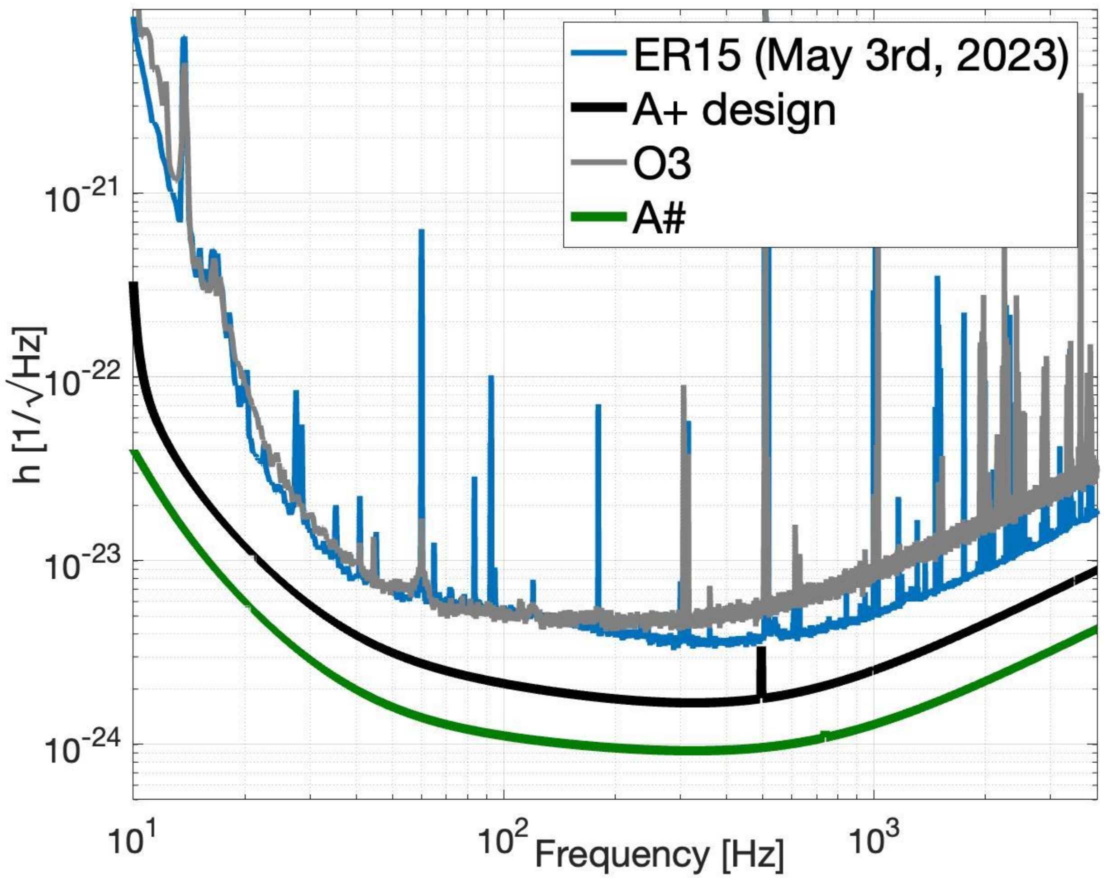
- LSC “post-O5” Report (LIGO-T2200287) recommends pursuing a collection of upgrades known as **A#** (“*A sharp*”)

- A# design: 1 um laser wavelength, room temperature, fused silica masses
  - Stepping stone toward **Cosmic Explorer** and **ET HF**

- Mainly 4 new components:
  - Larger Test Masses (40 → 100 kg) with improved suspensions
  - Seismic isolation improvements
  - Higher levels of laser power and squeezing
    - 1.5MW arm power (x2 A+ design, x4 current)
    - 10 dB squeezing (up to 6 dB current)
  - Reduced coating thermal noise
    - x2 below A+ design; A+ design not yet achieved

A# Sensitivity Goal

A♯ versus A+: Low frequencies: close to a factor of 2 reduction
- Larger test mass for lower radiation pressure
- Higher stress fibers to reduce thermal noise
- Improved seismic isolation to reduce excess control noise



A♯ versus A+: Mid frequencies: close to a factor of 2, limited by coating thermal noise
- Improve coating thermal noise below A+ level

A♯ versus A+: High frequencies: factor of 2 reduction
- Higher laser power
- Improved thermal effect compensation
- Improved squeezed light injection, lower optical loss

Adapted from Gabriele Vajente

Technical Risks of A#

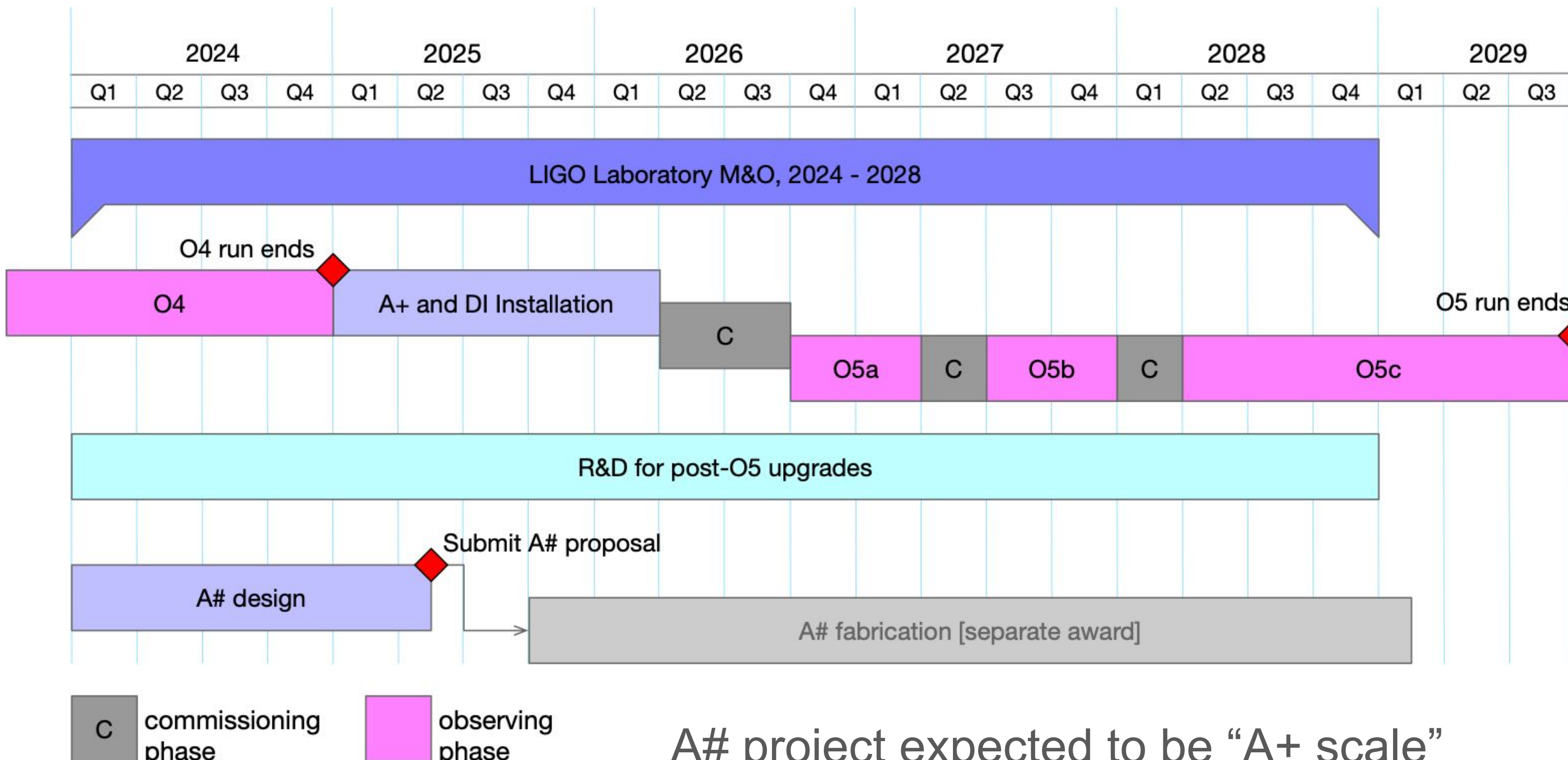
- Inability to operate at the power level of 1.5 MW in the arms
  - Thermal distortions in the test masses – can we really get rid of point absorbers?
  - Parametric instabilities
  - Control problems associated with radiation pressure should be mitigated by larger test masses

- Insufficient compensation of thermal distortions at 1.5 MW
  - Resulting optical loss would limit squeezing (particularly at high frequencies)

- No improvements in coating thermal noise
  - AlGaAs doesn’t work out: has excess noise, or can’t fund the large-scale development
  - No improvements in amorphous material mechanical loss

- Inability to identify & mitigate low-frequency technical/mystery noises

Timeframe for A# development

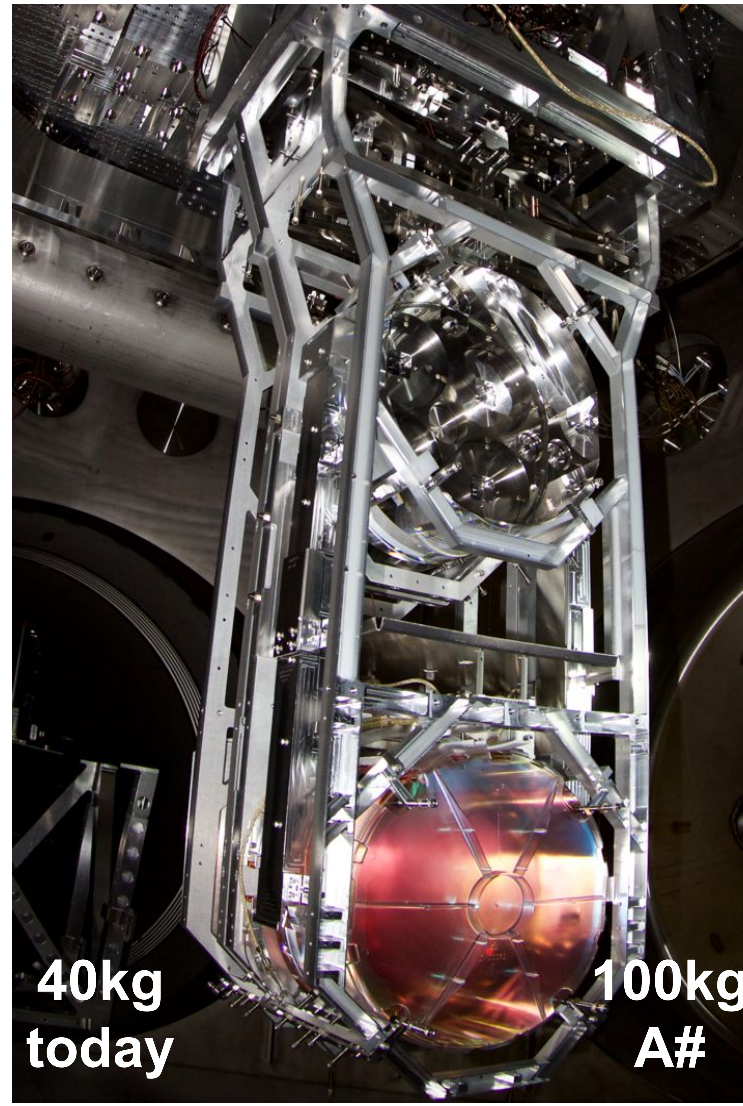


A# project expected to be "A+ scale"

Detailed costing not yet done

New Suspension: LSC group for concept design

- Several changes **required** to support a heavier test mass
- Opportunity to incorporate **lessons learned**:
  - Suspension controllability, mass distribution, ..
- New LSC "Heavy SUS" group
  - Main goal: conceptual design of new suspension
  - Chaired by Brian Lantz (Stanford)
  - Several groups with interest and expertise, well attended workshop at MIT last March



High Power: Thermal Studies

LSC study group:
Caltech, UC Riverside, Adelaide, MIT

Existing Thermal Compensation System (TCS) might not be sufficient for reaching A# 1.5 MW arm power target

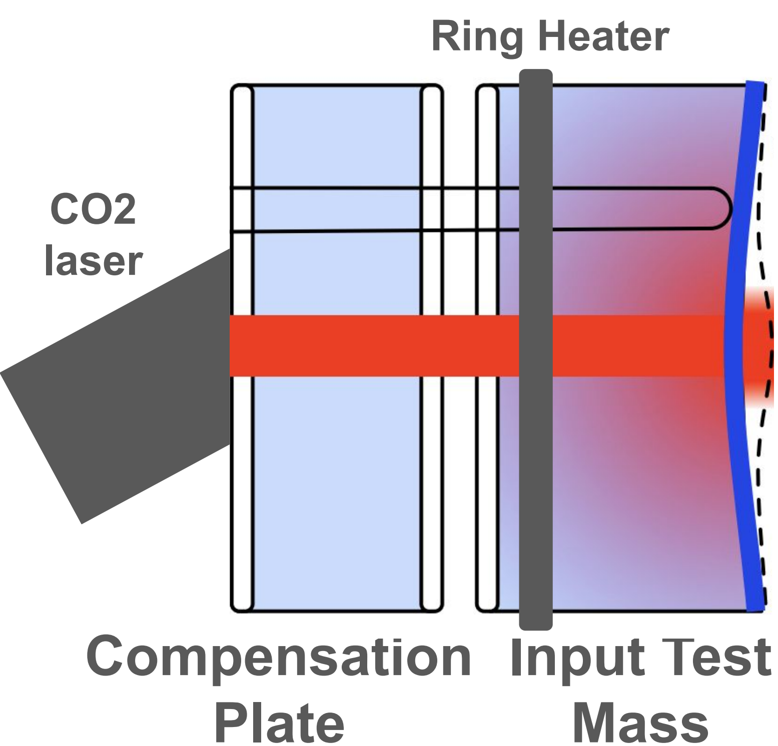
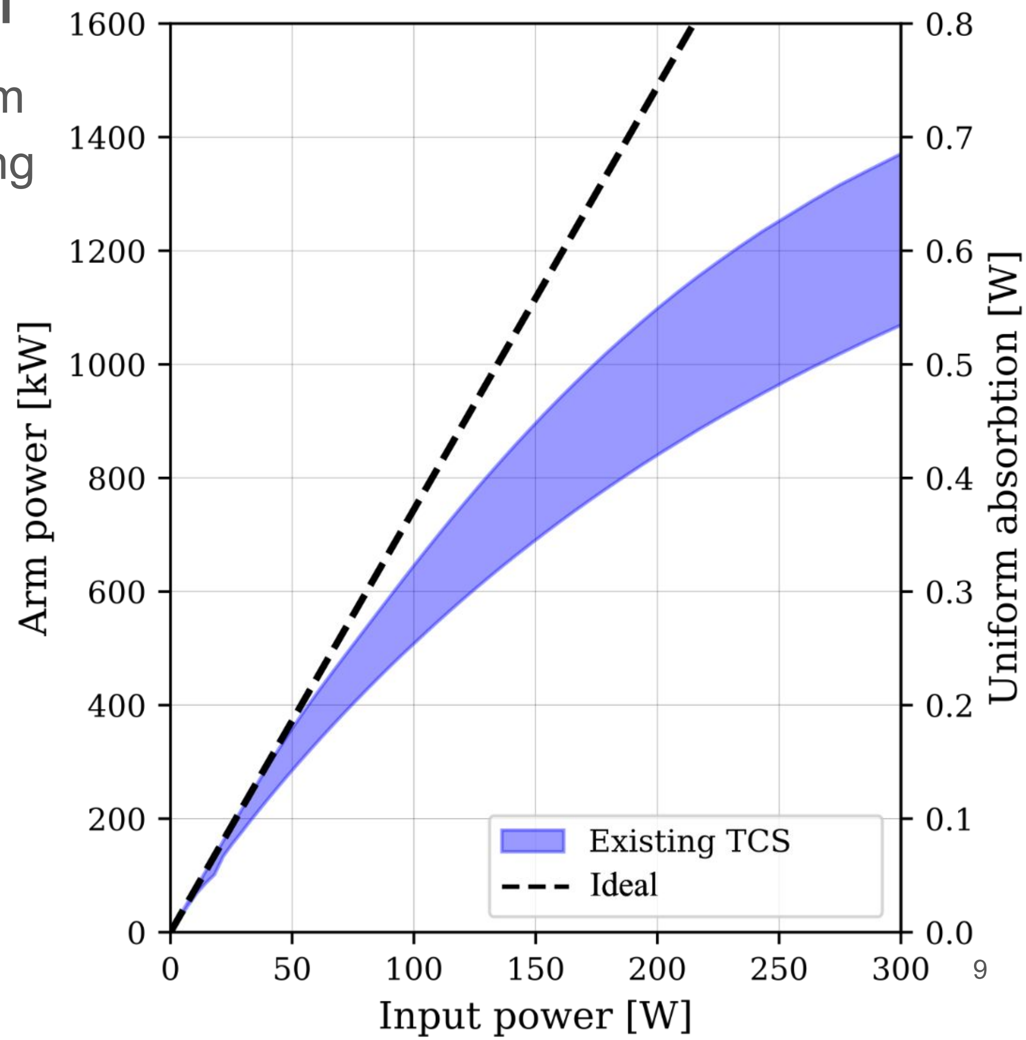


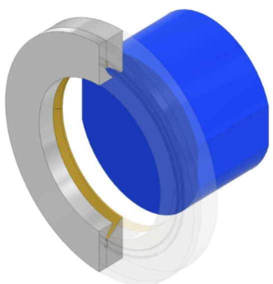
Image credit: Huy Tuong Cao (UC Riverside)



High Power: Additional Actuators

On-going R&D: UC Riverside, Caltech

New actuator to improve existing thermal compensation system



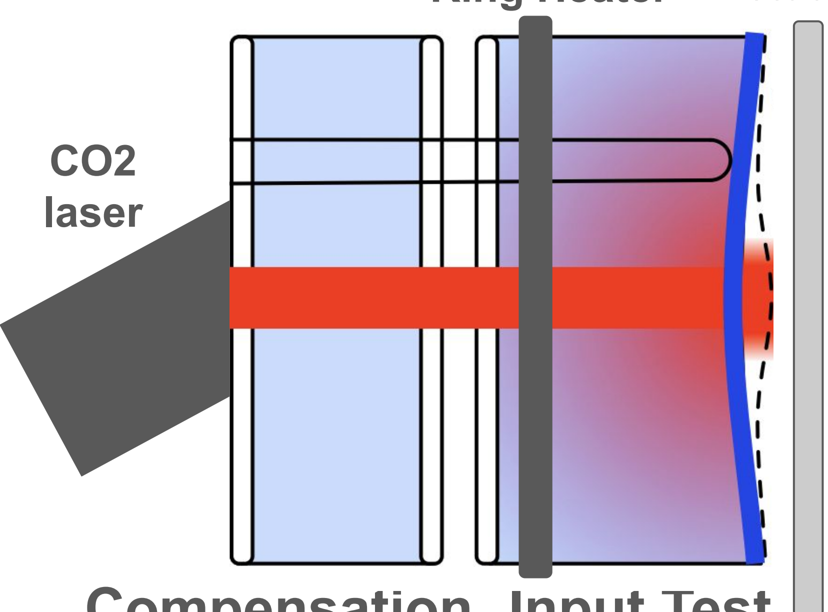
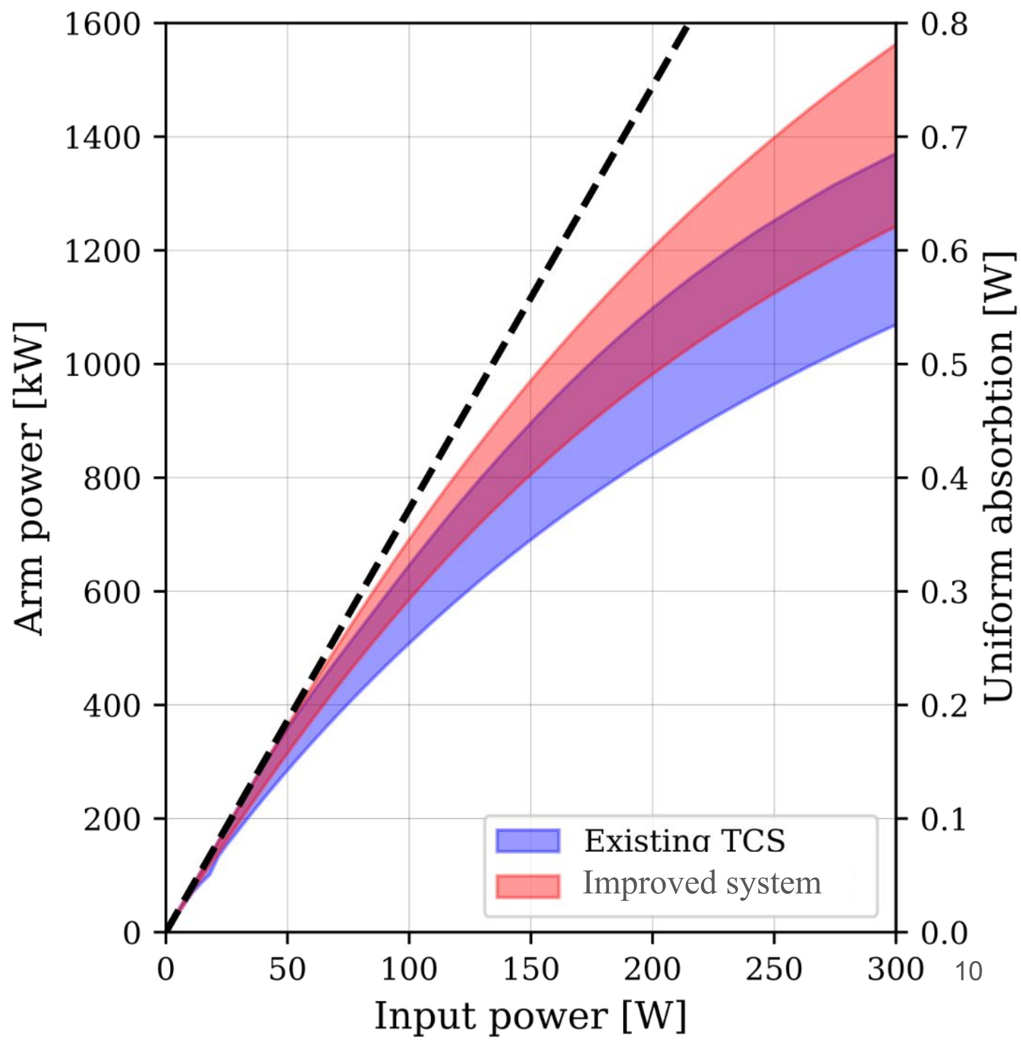
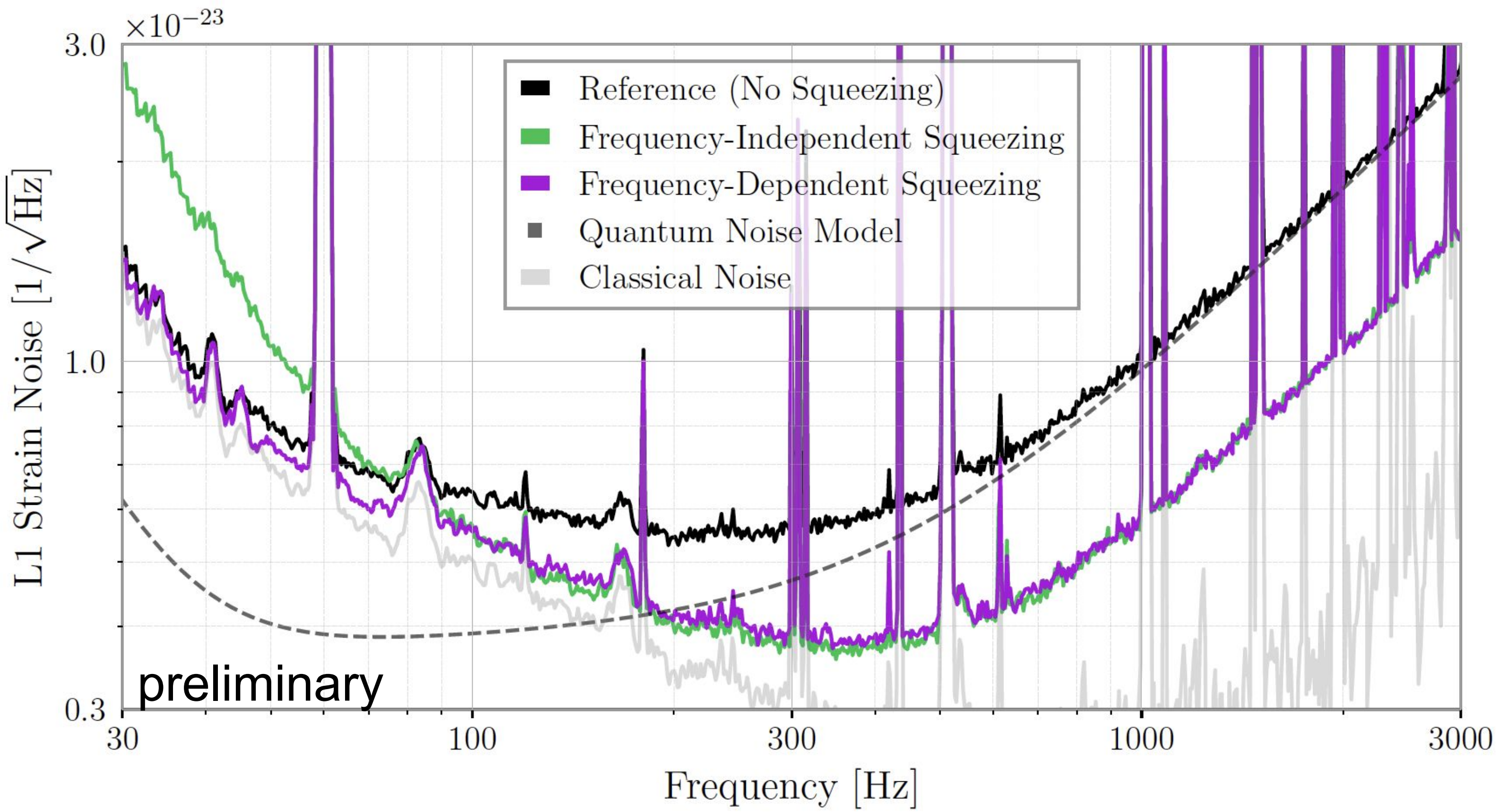


Image credit: Huy Tuong Cao (UC Riverside)



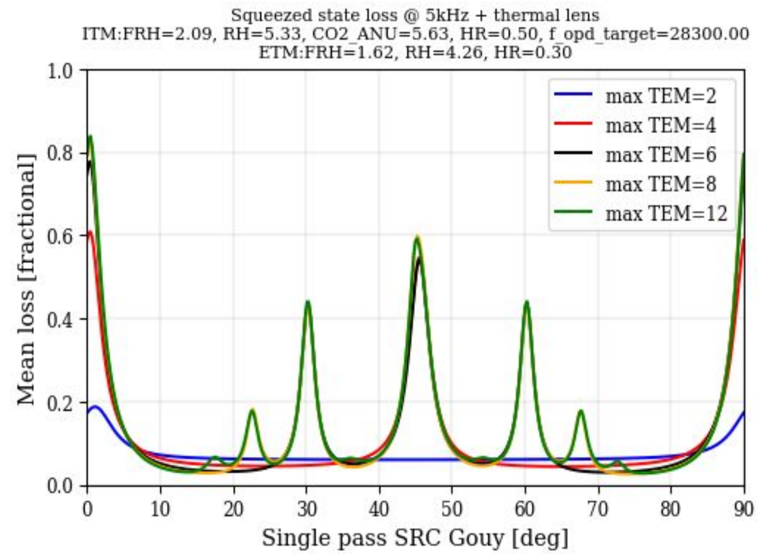
Squeezing in O4

- Frequency-dependent squeezing implemented at both sites
- Up tp 6 dB measured at high frequency at LLO, 4.5 dB at LHO



Squeezing for A#: the 10 dB challenge

- Ready to react to the lessons learned operating with frequency-dependent squeezing
- Thermal compensation R&D important for enabling high levels of squeezing
    - Improved mode-matching sensing/actuators
    - Improved thermal compensation system
- Detector improvement
    - low-loss optical elements
    - SRC re-design?



Coating Development

- Baseline for A# is a factor of 2 reduction (in amplitude) of coating thermal noise over A+ (a factor of 4 reduction with respect to Advanced LIGO)
- A# curve based on AlGaAs coatings, but improvement could come from amorphous coatings
  - AlGaAs proven low thermal noise in small samples
  - “Scaling-up” to large sizes challenging (=expensive)
  - We are interested in collaborating to make AlGaAs coatings an option for GW detectors

Other News: LIGO India funded!

Cabinet nod to set up Laser Interferometer Gravitational-Wave Observatory

$320M

PTI | Updated: April 06, 2023 22:32 IST

New Delhi, Apr 6 (PTI) The Union Cabinet on Thursday gave its nod to a project to construct and set up a Laser Interferometer Gravitational Wave Observatory- India (LIGO-India) at an estimated cost of Rs 2,600 crore which is likely to be completed by 2030.

The Message

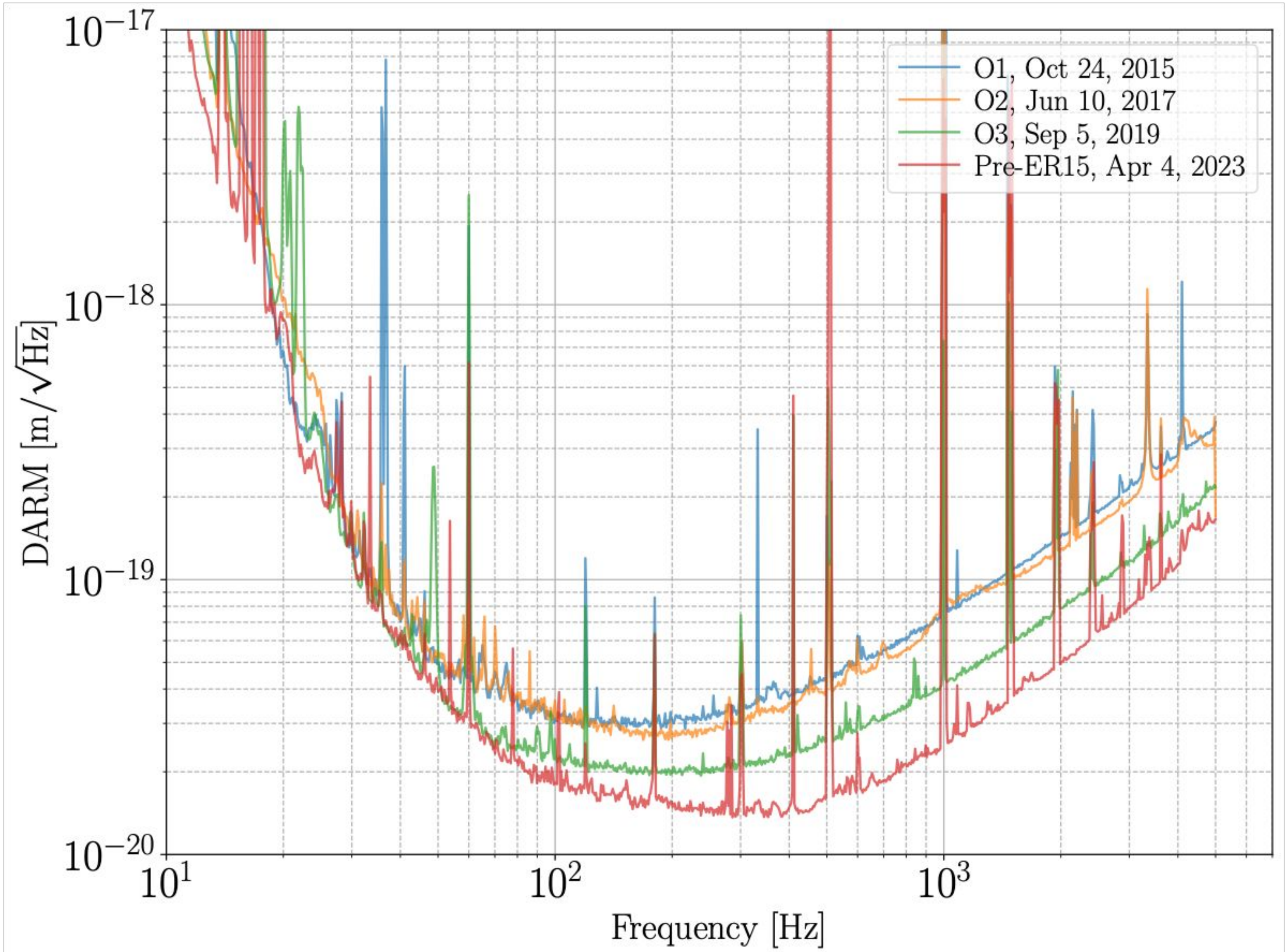
- A# is being pursued as “post-O5” upgrade
    - LIGO Lab cooperative agreement with NSF for next 5 years includes R&D for A#
    - Funds for A# upgrade requires dedicated funds; proposal to be submitted “early 2025”, accurate costing to be done (expected to be “A+ scale”)
- A#, as Virgo_nEXT, is a stepping stone towards Cosmic Explorer and ET-HF
    - Common R&D on challenges with high power (thermal compensation, controls), coating development, suspension design, high levels of squeezing

1 um, fused silica @ room temperature

	Arm power	Test Mass Weight	Coating Target	Squeezing
A#	**1.5 MW**	**100 kg**	Best available (target x4 better than adv)	**10 dB**
Virgo_nEXT	**1.5 MW**	**105 kg**	Best available	**10.5 dB**
ET_HF	**3 MW**	**200 kg**	Best available (X2.7 better than adv)	**10 dB**
Cosmic Explorer	**1.5 MW**	**320 kg**	Best available (X2 better than adv)	**10 dB**

Spare slides

H1 Sensitivity Progression



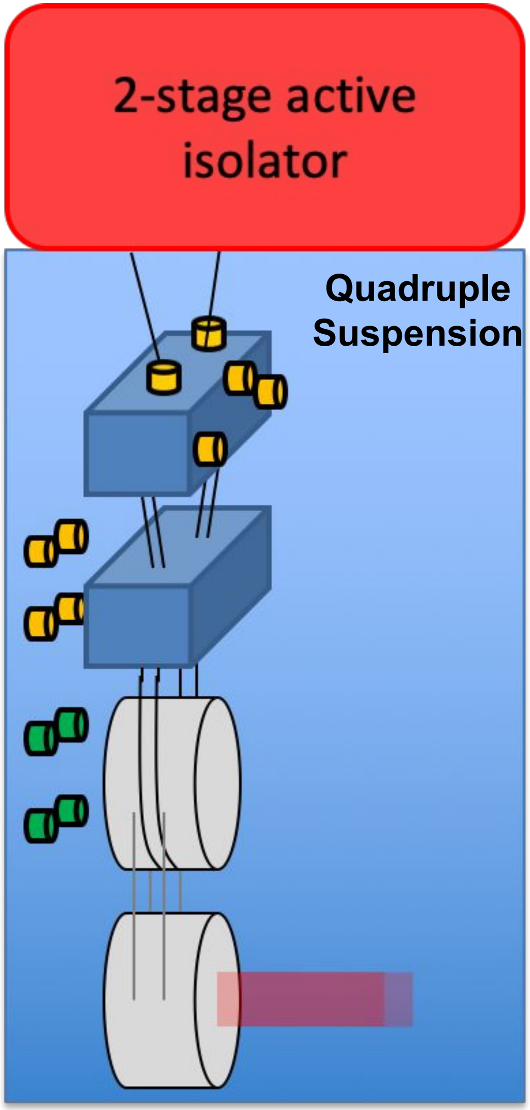
Courtesy of Georgia Mansell

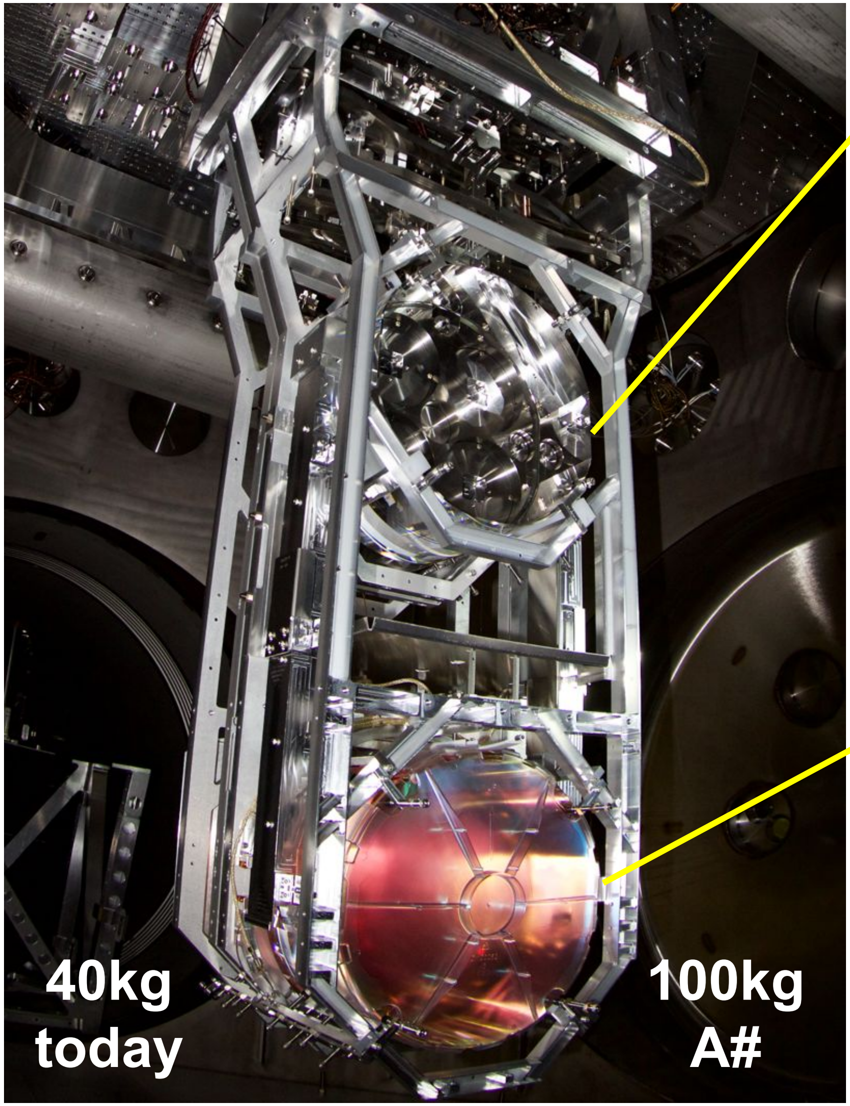
A# Science Goals

- $A^{\#}$ baseline design will boost the annual detection rate by a factor of ~5 for BNS and ~3 for BBH
  - Could observe O(10s) of BBH with sizeable higher-order modes per year
- $A^{\#}$ could measure H_0 with BBH to percent-level precision within a few months of observation time
- All $A^{\#}$ designs will more than double the pre-merger alert time for BNS
  - Significantly enhances prospects for joint GW+EM observations
- $A^{\#}$ will provide tighter EOS constraints with many BNS detections over a wide range of masses
- All $A^{\#}$ designs guarantee a detection of the stochastic GW background from binary mergers
- All $A^{\#}$ designs enlarge the discovery space
  - By doubling the supernova detection range
  - By providing access to the post-merger of BNS

Courtesy of Patricia Schmidt

New Suspension: Overview



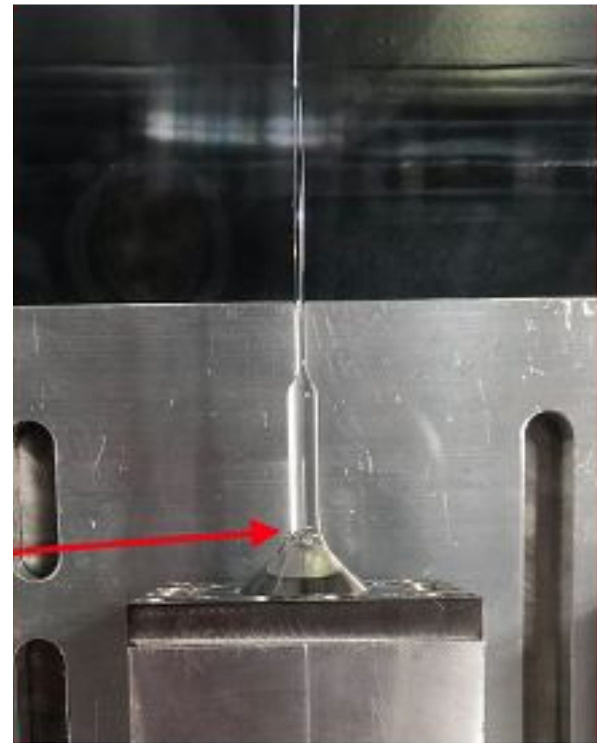


Fused silica fibers

A# goal: 1.6 GPa stress (twice current stress)

New Suspension:
high stress fused silica fibers (required upgrade)

- Glasgow’s group has several decades of expertise in fiber technology
- R&D for future detectors on going
- **A# 1.6 GPa stress goal within reach**
  - 160 kg mass prototype built with fibers @ 1.2 GPa stress, 3 years in air
  - on-going measurements on fibers @ 1.6 GPa stress in vacuum
- For future detectors:
  - 200 kg prototype in 2023
  - plans to demonstrate 400 kg in 2-3 years



Large-scale Monolithic Fused-Silica Mirror Suspension for Third-Generation Gravitational-Wave Detectors

A. V. Cumming,* R. Jones, G. D. Hammond, J. Hough, I. W. Martin, and S. Rowan
SUPA (Scottish Universities Physics Alliance), Institute for Gravitational Research, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom

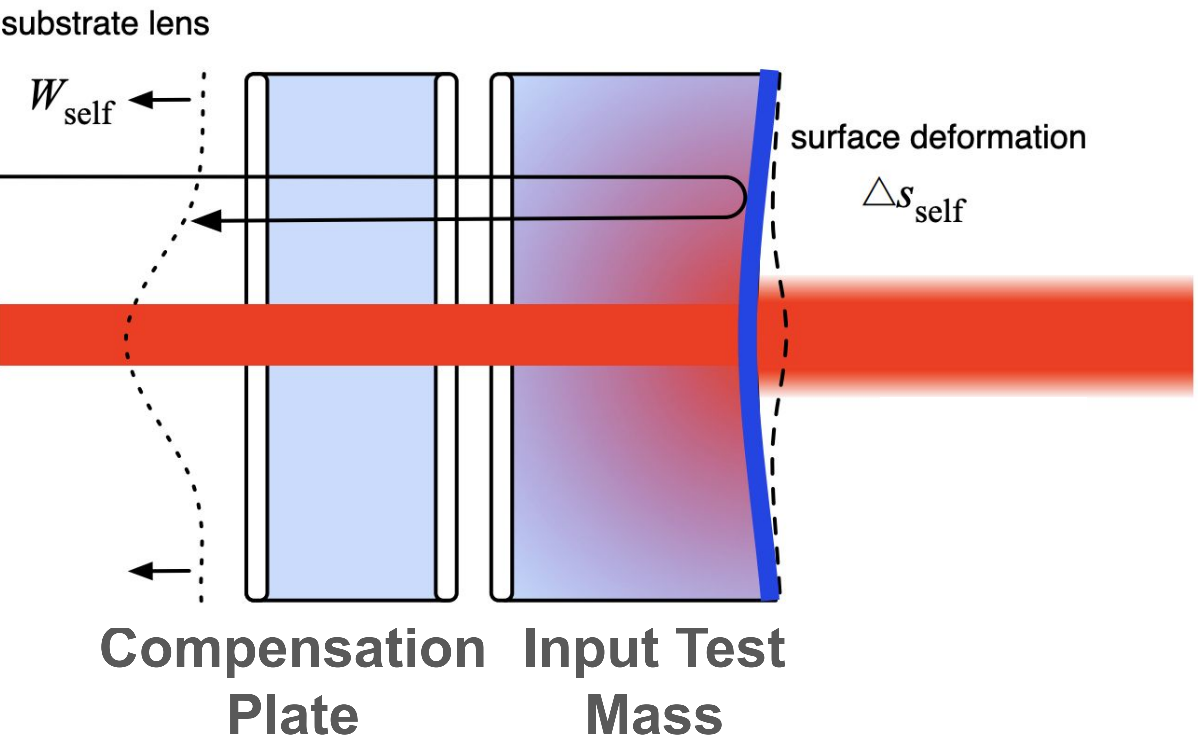
PHYSICAL REVIEW APPLIED **17,** 024044 (2022)

Credit: Giles Hammond (Glasgow University)

High Power: Background

Laser power absorbed by the optic creates wave-front distortion

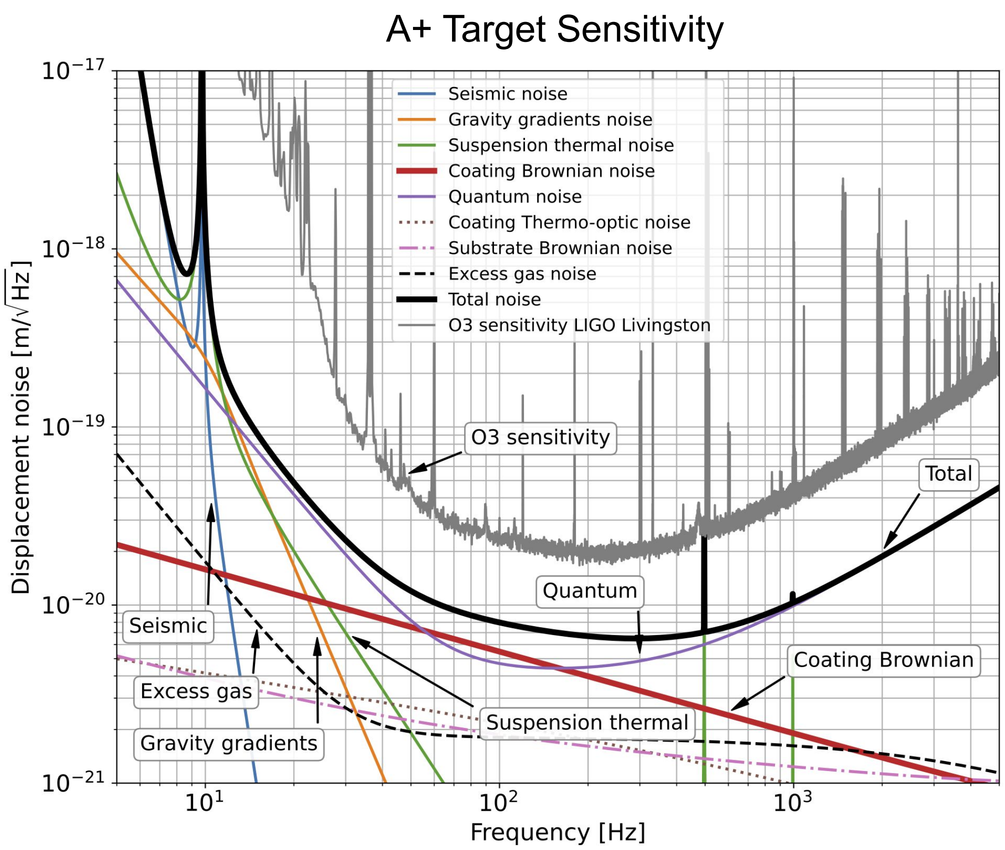
- Thermo-elastic surface deformation
- Thermal-gradient in the optic



Arm Cavity Power

200 kW (O3)
400 kW (O4)
750 kW (A+)
1.5 MW (A# post-O5)

Main R&D Lines



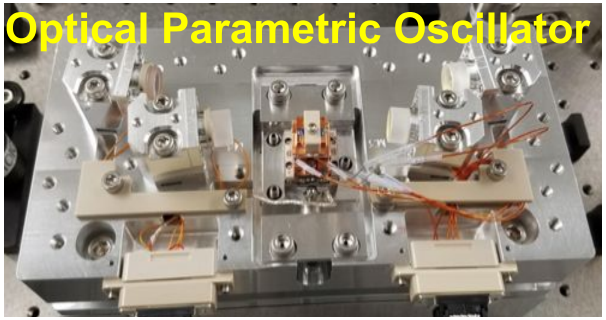
Low frequency (10-50 Hz):
- Suspensions
- Seismic noise
- Feedback control noise
- Scattered light

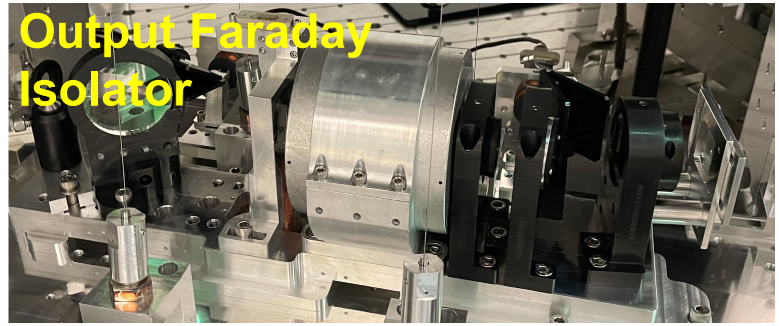
Middle frequency (50-300 Hz):
- Quantum noise
- Coating thermal noise

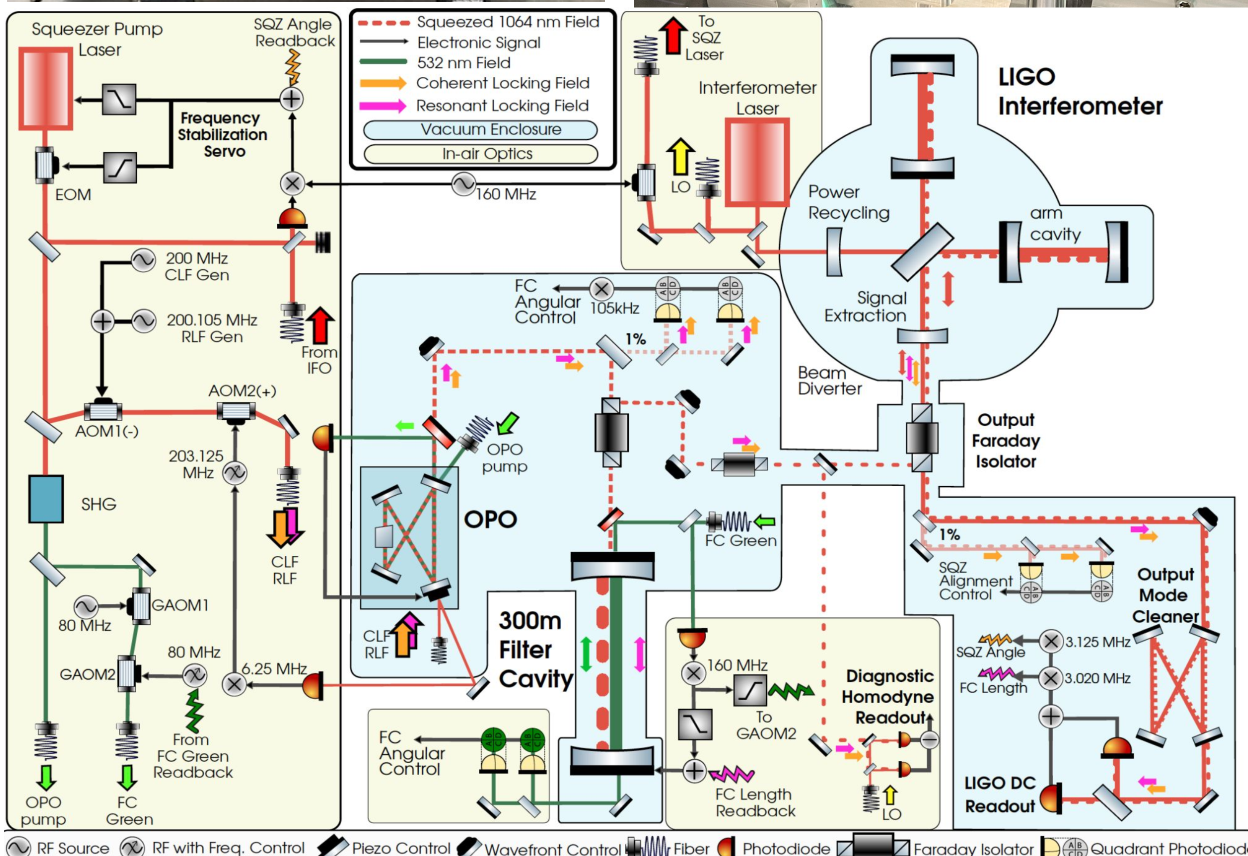
High frequency (>300 Hz):
- Quantum noise
- Higher power operation

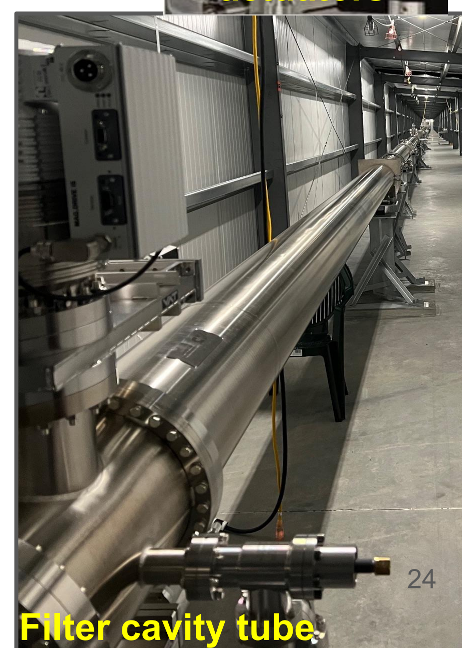
Duty cycle and robustness:
- Control systems

Squeezing: O4 Optical Layout









Squeezing: Vision for LIGO

2 dB(1.2) 2011

3 dB(1.4) O3

4.5 dB(1.7) O4

6 dB (2) O5

8 dB (2.5)

10 dB (3.2) A#

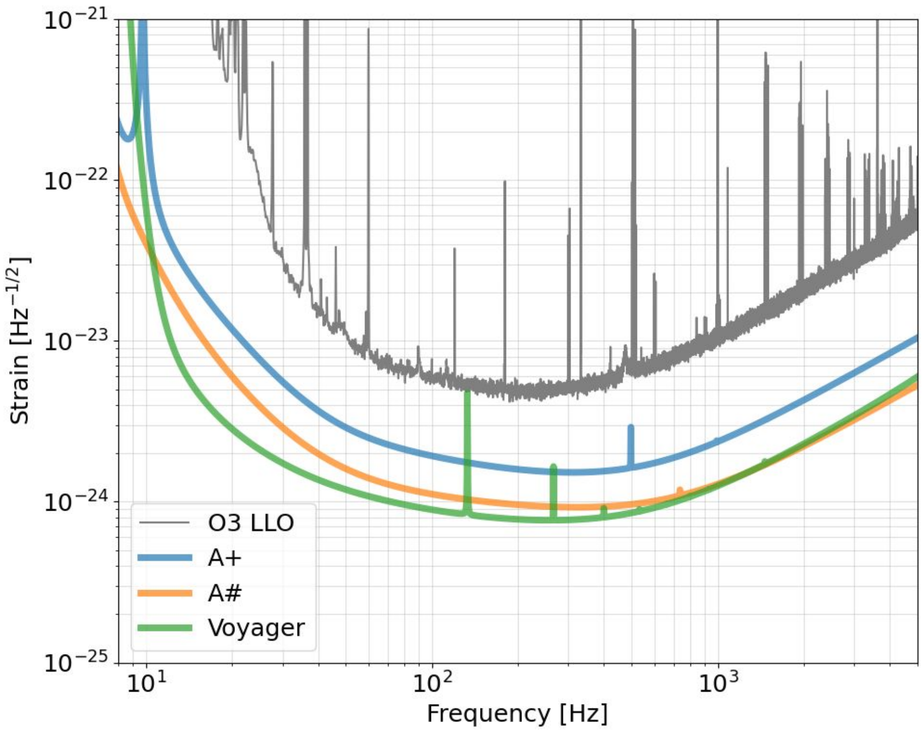
Good news! 6 dB already achieved at LLO!!

It is difficult to get high levels of squeezing in large scale interferometers:

- Optical loss
- Mode-mismatch
- Phase noise
- Misalignment
- Thermal effects
- Control noises
- ….

- **O3:** first deployment of squeezing
- **O4:** filter cavity upgrade ("no harm at low frequency"), low-loss hardware
- **O5:** optimization of the filter cavity for low frequency quantum enhancement, fine tuning
- **post-O5:** new hardware as informed by O4/O5, optimization

Voyager R&D



Voyager largely re-uses the existing Advanced LIGO infrastructure: vacuum systems, controls, seismic isolation, suspensions, and all of the interferometer sensing and control infrastructure. 200kg crystalline silicon test masses, operated at 123K. The laser wavelength is 2μm, with 4MW of power in each arm cavity. Frequency-dependent squeezing is employed at a level of 10 dB of effective squeezing

Class. Quantum Grav. **37** 165003

- The LIGO laboratory vision for the post-O5 upgrade is A#, also a stepping stone toward Cosmic Explorer and third generation detectors
- The LIGO laboratory does not plan to extensively support Voyager related research
- A small fraction of R&D funds and personnel will be devoted to supporting key demonstration of silicon test masses and coatings; most of the development is based on external funds
- Those R&D tasks are well aligned with the laboratory expertise
- Risk reduction toward improving the detector performance beyond A+