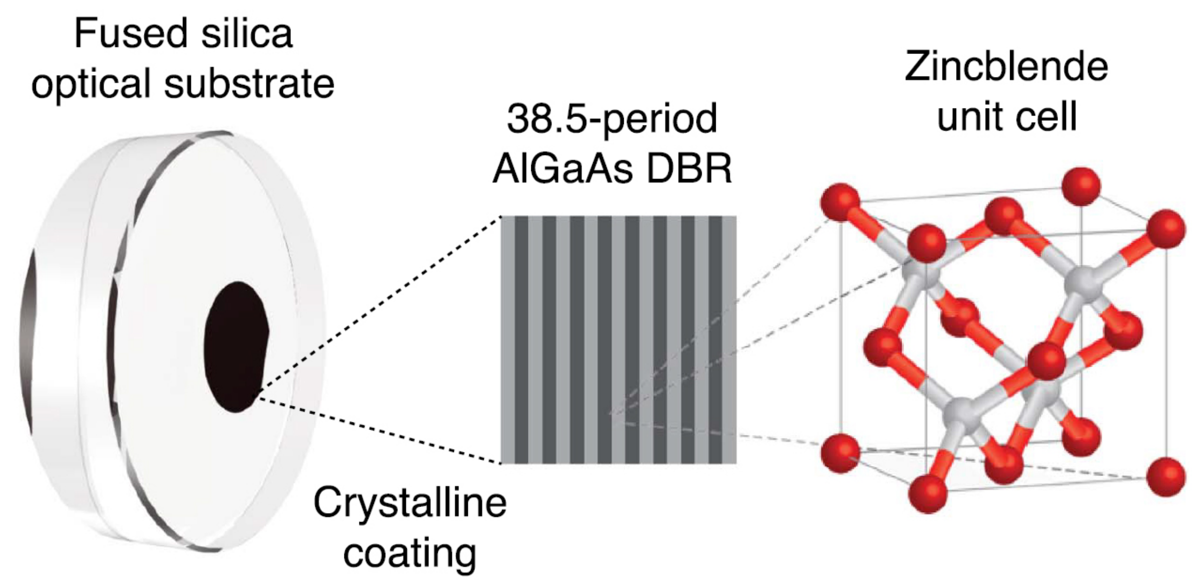
Post-O5 LIGO with Crystalline Coatings

Gravitational Wave Advanced Detector Workshop • 17–21 May 2021 • LIGO-G2101071

Crystalline GaAs/AlGaAs Coatings • Overview

- The crystal is grown via Molecular Beam Epitaxy (MBE) on a single-crystal GaAs wafer.
- Alternating the Al alloy composition forms a Bragg reflector from layers of $Al_{0.92}Ga_{0.08}As$ ($n = 2.89$) and GaAs ($n = 3.30$)
- Wafer is etched away. Coating is transferred and bonded to substrate.
- Material is bandgap limited to $\lambda > 870\,\mathrm{nm}$
- Bragg reflectors can be made for $\lambda \approx 0.9 - 12$ μm. Specific mirrors produced at 1, 1.5, 2, 3.3, 3.8, 4, 4.5 μm



Crystalline GaAs/AlGaAs Coatings • Optical Properties

- Scatter now typically < 5 ppm
  - ≈ 3-4 ppm [Gleckl, Fullerton]
  - ≈ 6-9 ppm [Marchio]
- Absorption typically < 1 ppm
  - < 1 ppm [Marchio, et al.]
  - ≈ 0.6-0.7 ppm at 1064 nm [Cole, 2016]
- Uniformity
  - < 2 nm/5 cm [Koch 2019]
- Laser Damage Threshold
  - > 64 MW/cm^2 [Koch 2019]
- Finesse: ≈ 500,000 at 1397 nm
  - ≈ 500,000 at 1397 nm [Thorlabs]
  - > 600,000 at 1550 nm

Amy Gleckl, *et al*., https://dcc.ligo.org/LIGO-G2000376

Marchiò, M. *et al*. Optical performance of large-area crystalline coatings. *Optics Express* **26**, 6114 (2018).

Garrett D. Cole, *et al*., "High-performance near- and mid-infrared crystalline coatings," Optica 3, 647-656 (2016)

Koch, P. *et al*. Thickness uniformity measurements and damage threshold tests of large-area GaAs/AlGaAs crystalline coatings for precision interferometry. *Opt Express* **27**, 36731 (2019).

Crystalline GaAs/AlGaAs Coatings • Mechanical Properties

Elasticity Matrix (Cubic Crystal — Voigt Notation)

$$\begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

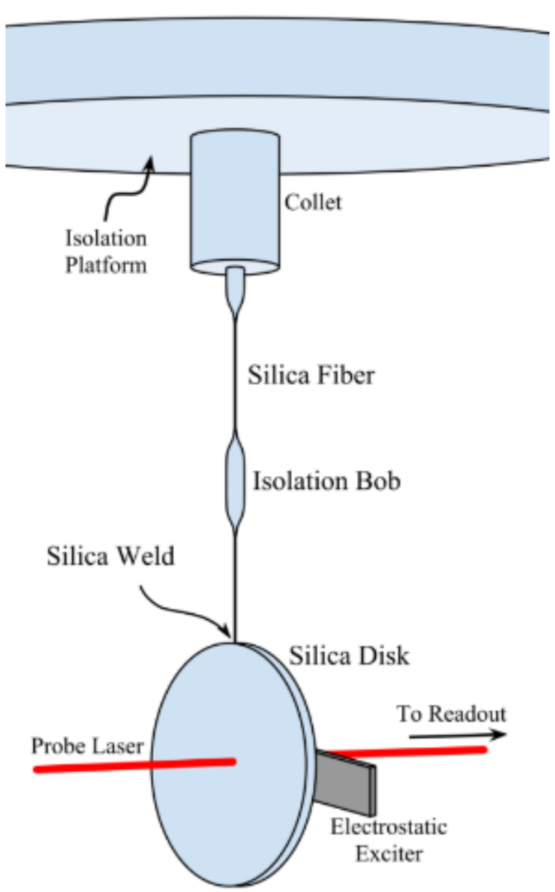
Real Elastic Constants

$$C_{11} = 118 \text{ GPa}$$
$$C_{12} = 55.9 \text{ GPa}$$
$$C_{44} = 58.2 \text{ GPa}$$

3 Loss Angles

ϕ_{11}, ϕ_{12} } Bulk

ϕ_{44} Shear

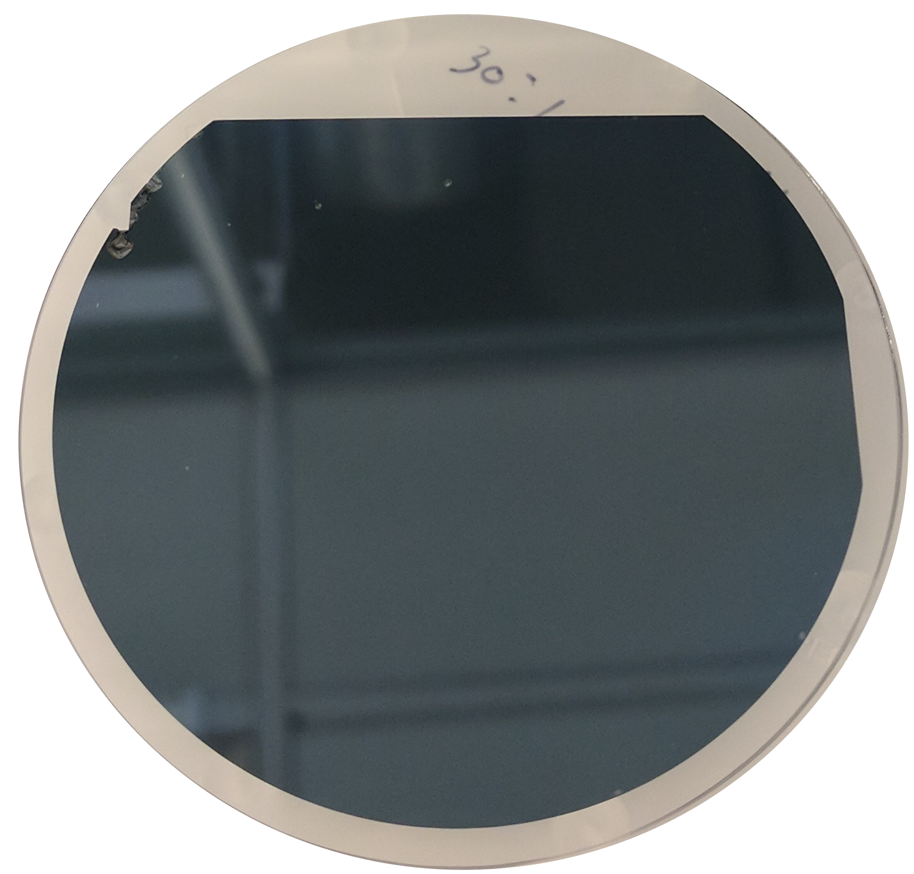


Mechanical Ringdown

75 mm x 1 mm FS disks

$$\phi_{44} < 1 \times 10^{-6}$$
$$\phi_{11} < 2.3 \times 10^{-4}$$
$$\phi_{12} < 5.2 \times 10^{-4}$$

Bulk loss dominated by thermoelastic loss



Coating Thermal Noise for Crystalline GaAs/AlGaAs

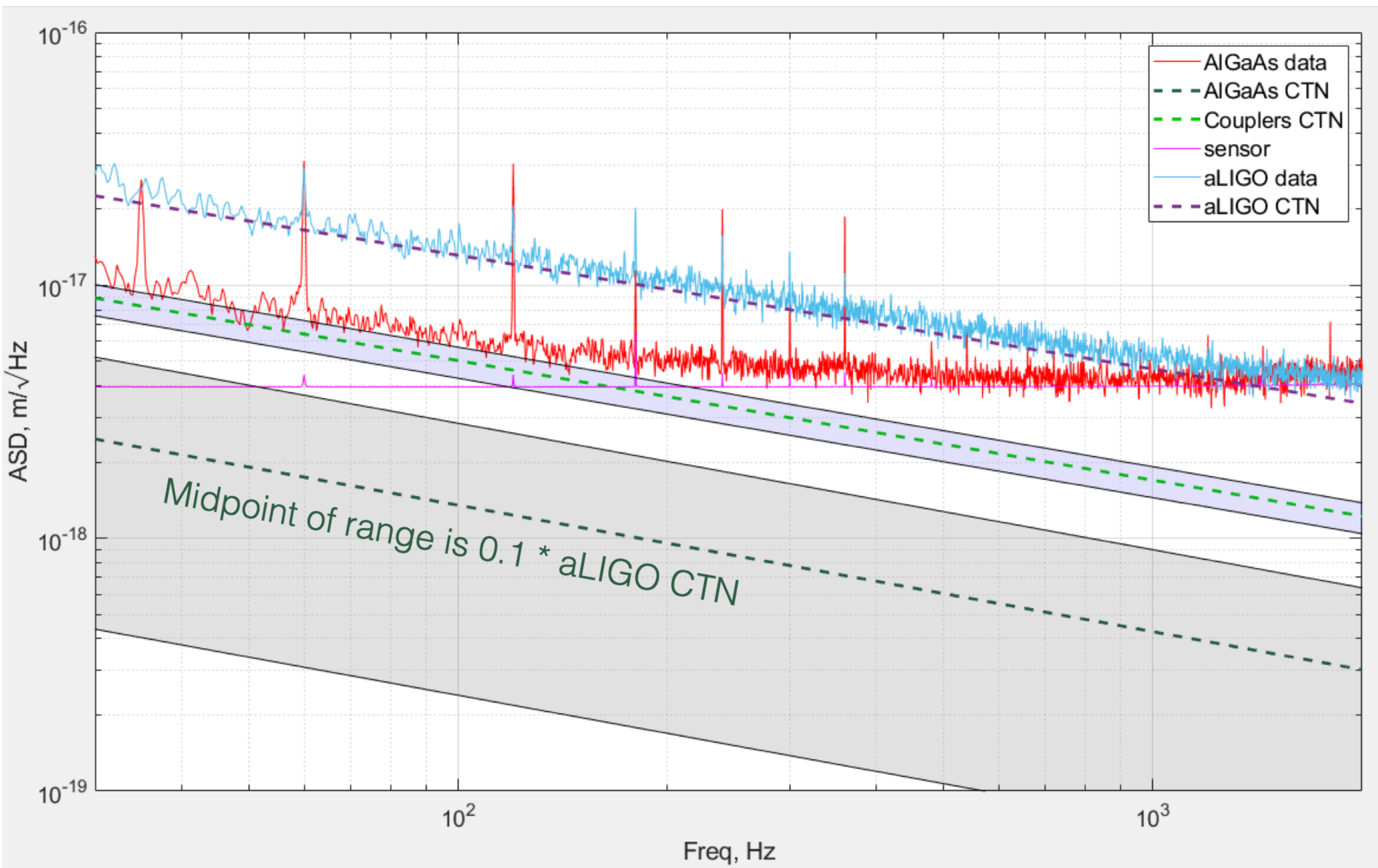
- CTN measured by Nick Demos, Slawek Gras, & Matt Evans @ MIT*
- Coating layer design optimized by Rana Adhikari to minimize Thermo-optic noise**.

- Measured noise dominated by cavity end mirrors (couplers)
- Upper limit for Crystalline mirror CTN is **5x lower than Adv. LIGO**

- Data mean ⇒ Crystalline mirror CTN is **10x lower than Adv. LIGO**

* LIGO-G2001592

** Coherent Cancellation of Photothermal Noise in AlGaAs Bragg Mirrors, LIGO-P1500054



Graph borrowed with permission from Nick Demos, et al. LIGO-G2001592

The Challenges of Crystalline GaAs/AlGaAs Coatings

- Scaling & Cost
- New Locking Scheme
- Birefringence & Noise
- Surface Quality, Uniformity, and Defect Density
- Electro-Optic Noise

Image modified without permission

Image Credit: LIGO Laboratory, MIT/Caltech

Scaling Crystalline Coatings: 30 cm

- **Freiberger Compound Materials:**
  - 30 cm GaAs wafers
  - 2.6 years: Grow, Cut, Etch, Polish
  - 8.2 M€ = $9.94M
  - Selectable orientation: (100) default
  - Substrates ≈ $1k each

- **IQE, North Carolina:** MBE coating facility
  - ≈ 20 Production systems
  - 8 hour MBE growth time per coating
  - A few weeks to grow all HR coatings
  - Growth of 20 cm coatings to test larger profile while 30 cm boule grown
  - $300k/month rent of MBE chamber
  - $3.6 M to grow and process coatings

Bonding Crystalline Coatings: 30 cm

EVG: Bonding the coatings

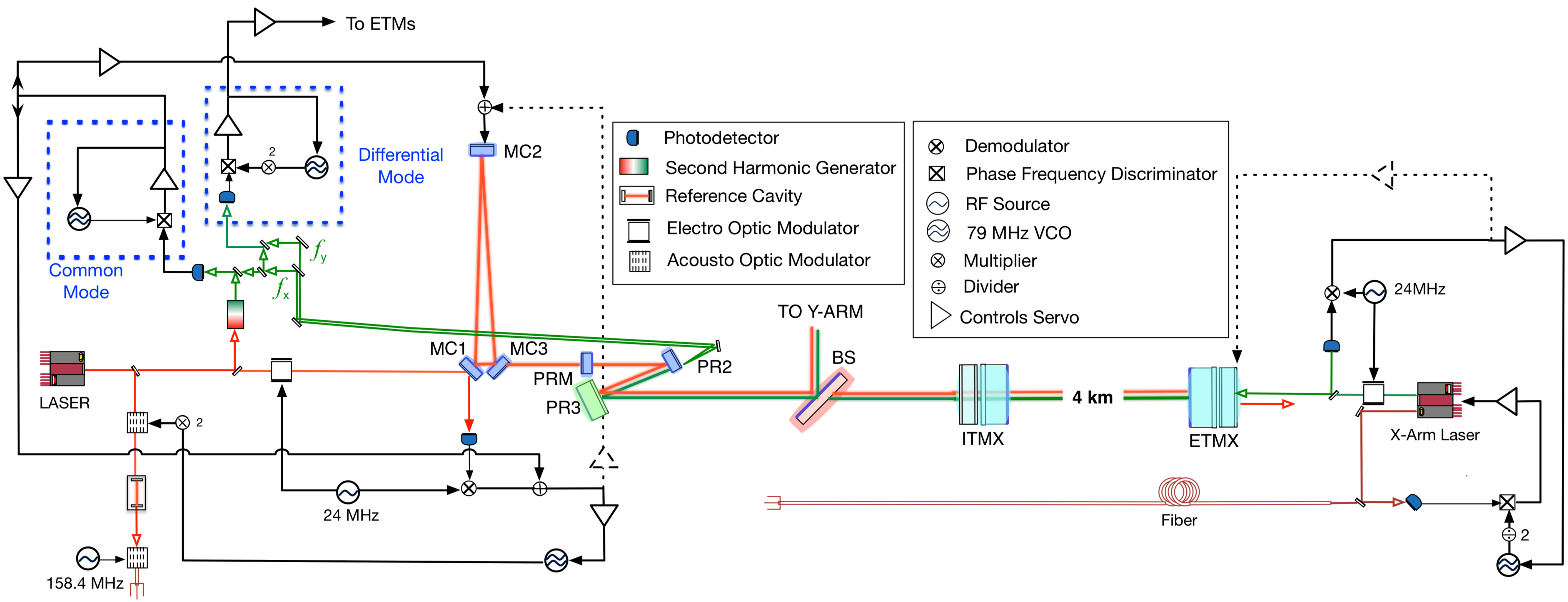
- Produces robotic bonding machines for the semiconductor industry
- Up to 45 cm bonds
- Promises zero bond defects
- History of high quality, SOI bonds
- Quoted $4.7M for a 30 cm bonding machine for test mass.
- LIGO must provide polished, cleaned test masses.
- Thorlabs provides coating
- 13 month delivery time

Development: Timeline & Budget

Timeline	Activity	Cost
First Year	1. Design and order of GaAs crystal wafer (Freiberger) 2. Order AlGaAs mirrors for prototype detector (Hannover) 3. Continuing noise studies (Syracuse, American, MIT)	$1.6 M
Second Year	1. Growth and measurement of gallium arsenide crystal (Freiberger) 2. Begin AlGaAs coating bonder construction (EVG) 3. Install AlGaAs mirrors in prototype (Hannover) 4. Continuing noise studies (Syracuse, American, MIT, Caltech, CSU Fullerton)	$6.6M
Third Year	1. Gallium arsenide substrate etching and metrology (Freiberger) 2. Bonder delivery (EVG) 3. Prototype detector operation (Hannover) 4. Continuing noise studies (Syracuse, American, Stanford)	$5.2M
Fourth Year	1. Single gallium arsenide wafer deliver (Freiberger) 2. AlGaAs epitaxy on GaAs wafer (ThorLabs) 3. Continuing noise studies (Syracuse, American, Caltech)	$4.8M

Current Green-Light Arm Length Stabilization System

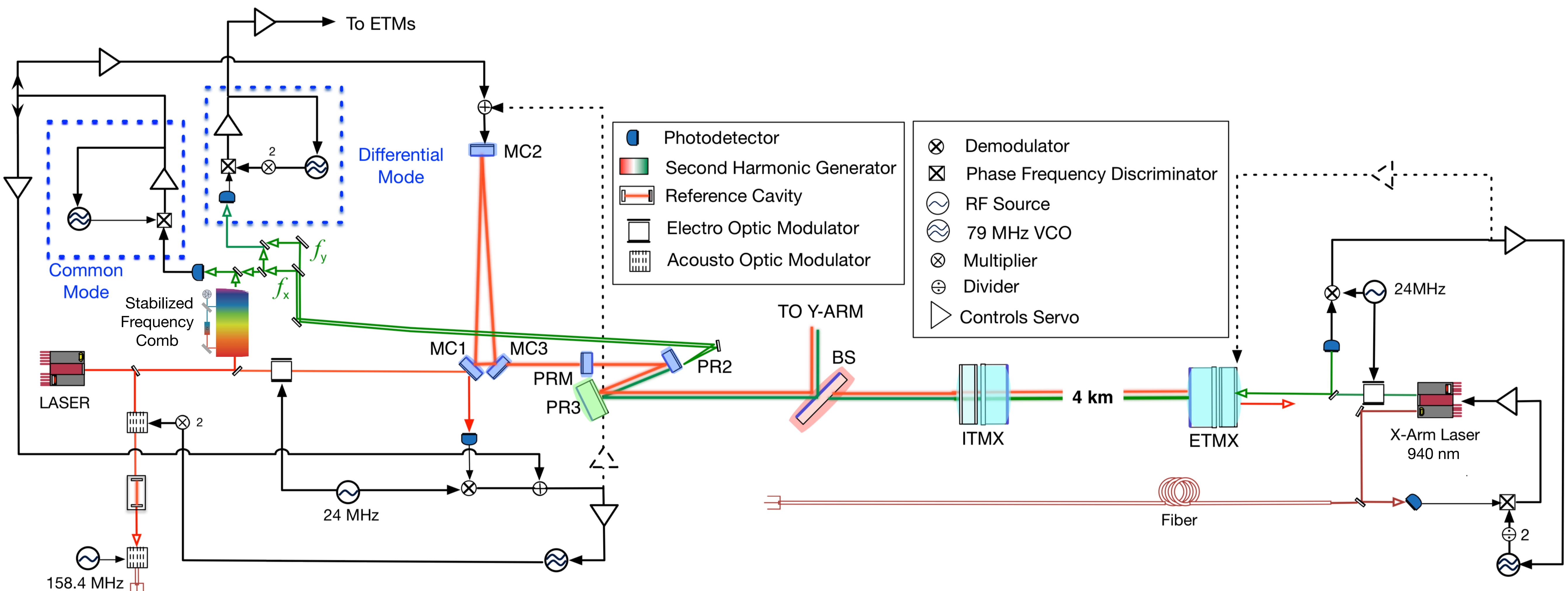
- Green, frequency-doubled beam (532 nm) is injected through each ETM.
- Each arm separately locked via PDH.
- Differential X-Y transmission signal then adjusted to 0 offset frequency
- Finally ETMs adjusted to lock main beam (1064 nm)



Graphic borrowed from A. Staley LIGO-G1400946

Proposed 940-nm Arm Length Stabilization System

- In each end station, a stabilized Optical Frequency Comb (OFC)[1,2] is used to phase-lock a 940-nm laser to the main 1064-nm beam, and replaced the 532-nm beam.
- The coatings are manufactured to accommodate a low-finesse 940-nm beam cavity as well as high reflectivity at 1064 nm.
- The transmitted X-Y beams are referenced, via a stabilized OFC, to the main beam
- The locking procedure is otherwise the same.



Graphic adapted from A. Staley LIGO-G1400946

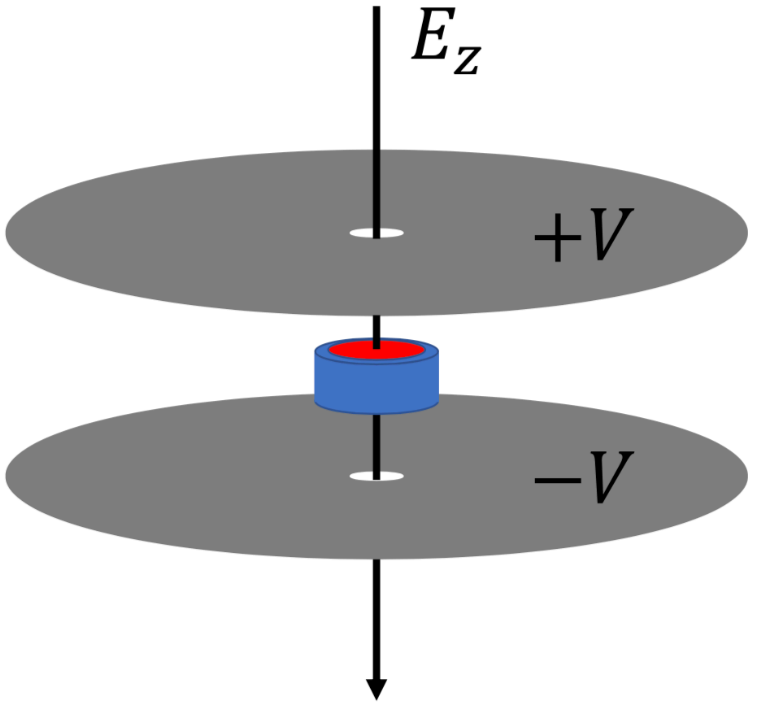
1. T Fortier, E Baumann, "20 years of developments in optical frequency comb technology and applications", https://doi.org/10.1038/s42005-019-0249-y
2. Cole, G. D., Zhang, W., Martin, M. J., Ye, J. & Aspelmeyer, M. Tenfold reduction of Brownian noise in high-reflectivity optical coatings. Nature Photonics 7, 644–650 (2013).

Birefringence

- Birefringence arises from differential strain between GaAs/AlGaAs layers.
- $\Delta f \approx 4 - 5\ \mathrm{MHz}$ between polarizations.
- High-Finesse, low-noise cavities, like clock cavities, use a single polarization.
- Investigations by A. & E. Gretarsson (expt) and M. Fejer (theory) to asses possible noise from strain-induced birefringence.
    - Thermally induced strain from beam heating
    - Mechanically induced strain from suspension

Electro-Optic Noise

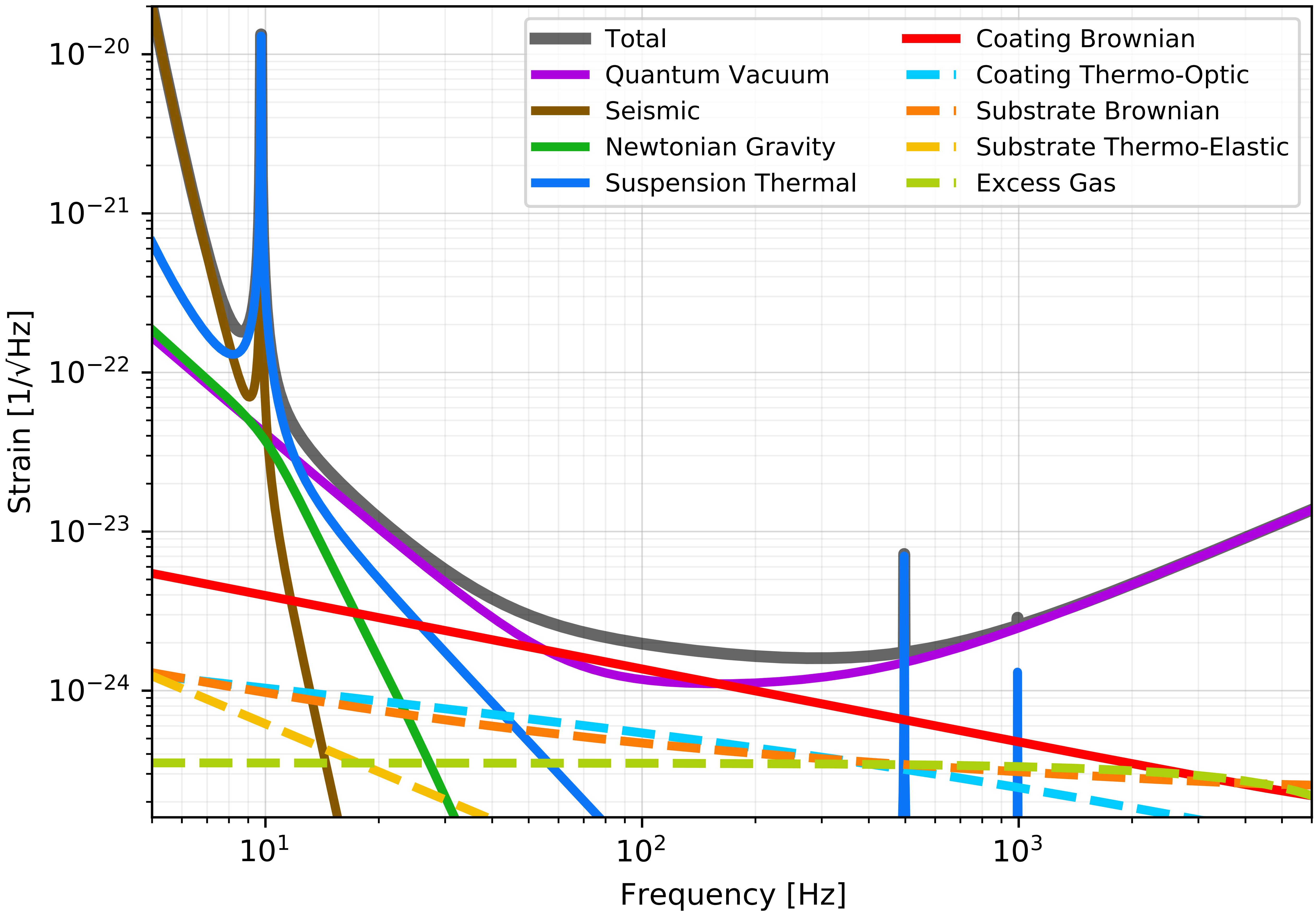
- Electro-optic noise arises from electric-field-induced changes in index, $\frac{\mathrm{d}n\left(f\right)}{\mathrm{d}E}$
- Thesis experiment by Daniel Vander-Hyde, Syracuse, to measure cavity noise induced by oscillating E-field on cavity mirror.

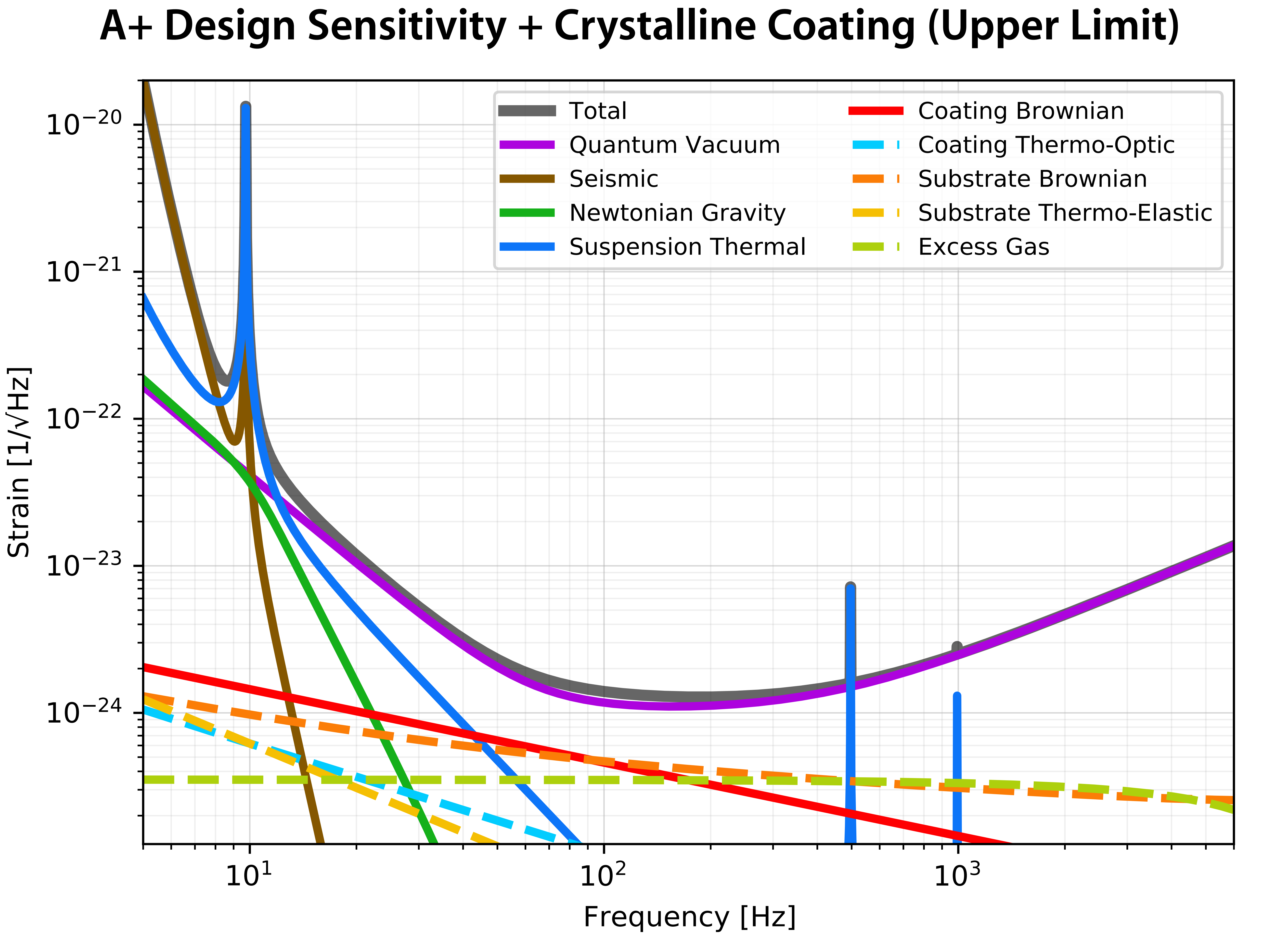


Surface Quality and Uniformity

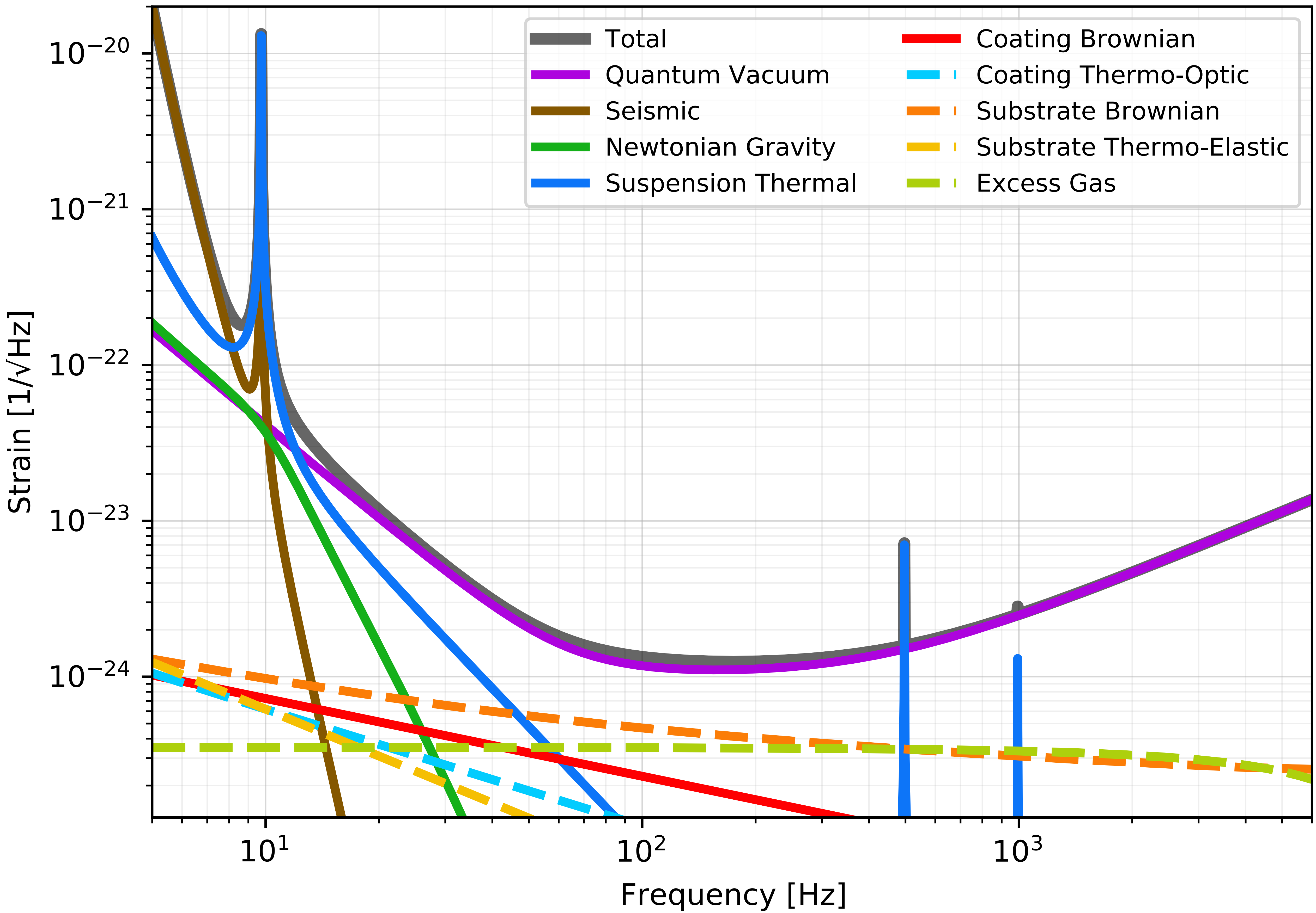
- Crystalline GaAs/AlGaAs coatings currently available up to 20 cm ∅.
- Test to begin this summer on surface quality and uniformity for 10 cm ∅ samples.
- Funding sought for tests on 20 cm ∅ samples to be completed in the next year.
- Measurements on scatter and absorption at defect sites to follow surface characterization.

A+ Design Sensitivity

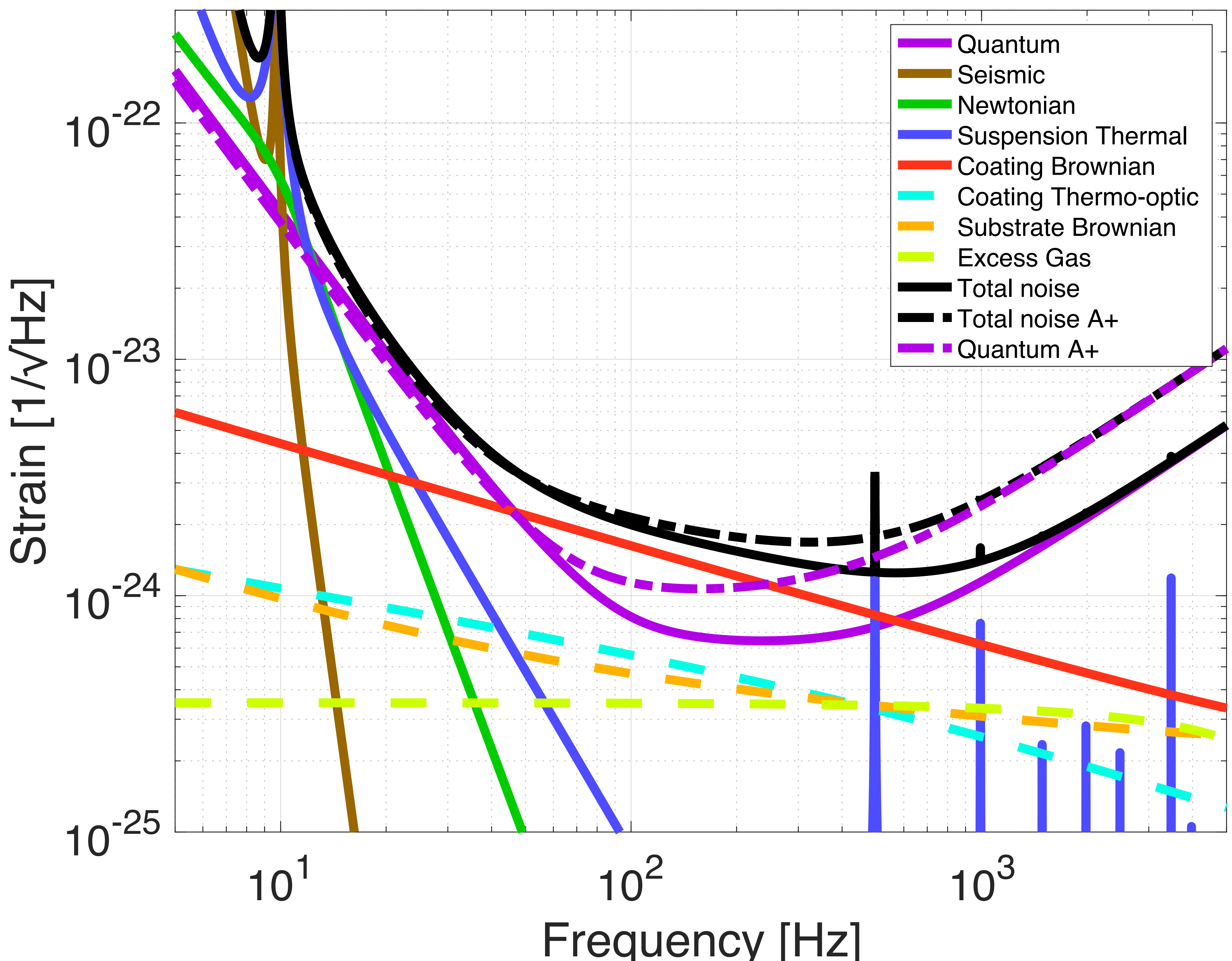



A+ Design Sensitivity + Crystalline Coating (Upper Limit)
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermo-Elastic
Excess Gas
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{1}
10^{2}
10^{3}
Frequency [Hz]

A+ Design Sensitivity + Crystal Coating (Mean Value)

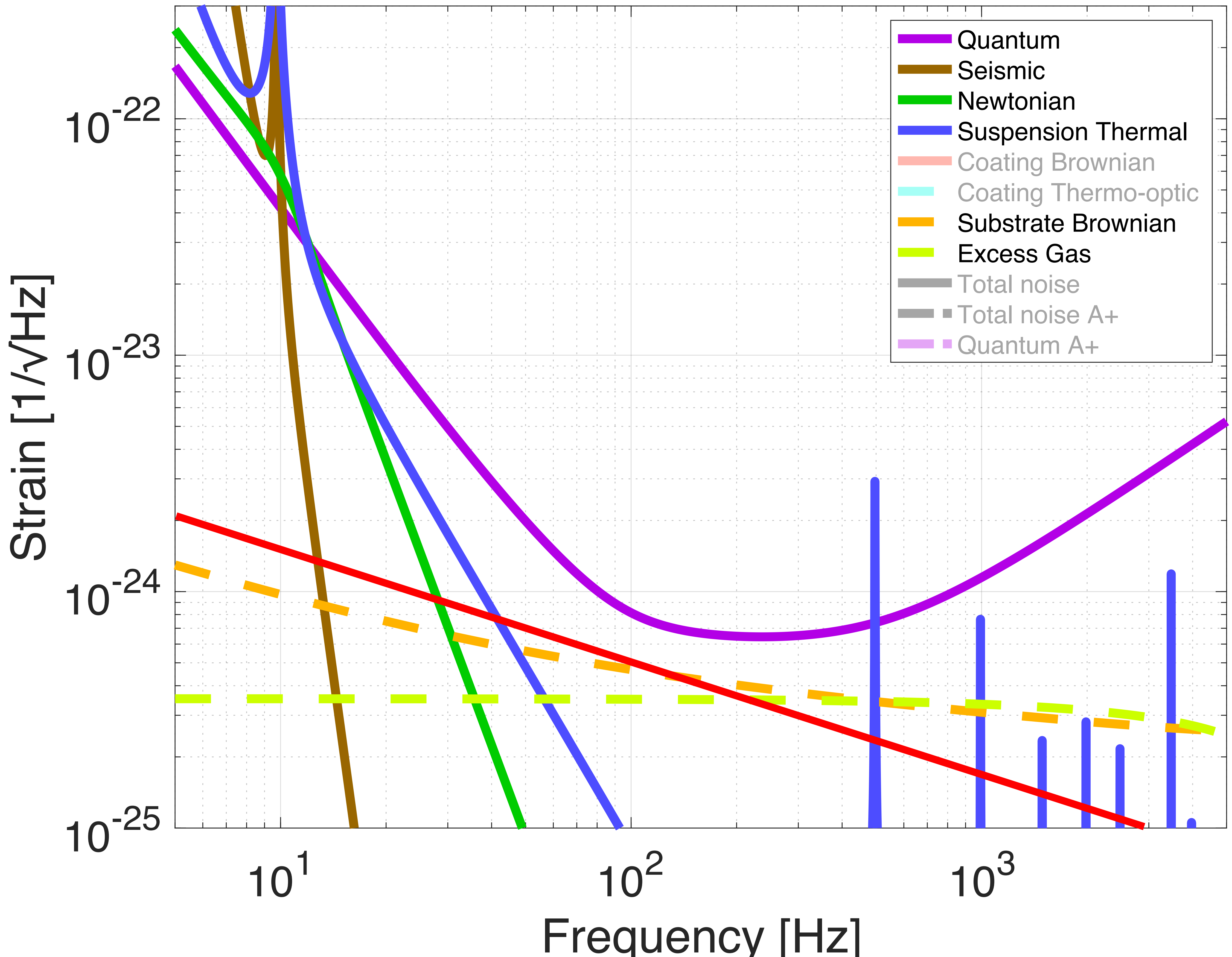


Post-O5 Design: 250 W input,10dB Squeezing, A+ CTN



Post-O5 Quantum Noise estimate provided by Lisa Barsotti

Post-O5: 250 W in, 10dB Squeezing, Crystal coatings (upper limit)



Post-O5 Quantum Noise estimate provided by Lisa Barsotti

Next Steps…

Stage 1:

- Characterize surface quality for 10- & 20-cm coatings
- Raise $20M for 30-cm development, and
- Continue research on E-O noise, Birefringence noise, …

Stage 2:

- Retooling and Boule growth for 30-cm wafers,
- With exclusive chamber use, optimize process to minimize absorption, scatter, & defects,
- Order bonding machine
- Continue research on E-O noise, Birefringence noise, …

Stage 3:

- Grow and bond 30-cm mirrors,
- Test that mirrors meet LIGO spec's, and
- Enjoy a more sensitive detector.

Summary

**Thermo-optically optimized,
crystalline GaAs/AlGaAs mirror coatings:**

- Extremely low optical losses,
- CTN 5-10x lower than aLIGO coatings, and
- Allows RT Post-O5 upgrade with impressive sensitivity gains.

After 20 years of coatings research …
Future LIGO need not be limited by CTN.

We need ≈ $22M and a few years to make this reality.