Substrate-transferred GaAs/AlGaAs crystalline coatings for future gravitational wave detectors

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INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **19** (2002) 897–917 PII: S0264-9381(02)31215-2

"It was 20 years ago today ..."

Thermal noise in interferometric gravitational wave detectors due to dielectric optical coatings

Gregory M Harry[1,2], Andri M Gretarsson[2], Peter R Saulson[2], Scott E Kittelberger[2], Steven D Penn[2], William J Startin[2], Sheila Rowan[3], Martin M Fejer[3], D R M Crooks[4], Gianpietro Cagnoli[4], Jim Hough[4] and Norio Nakagawa[5]

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"The Long and Winding Road…"

"The Long and Winding Road..."

PHYSICAL REVIEW D VOLUME 57, NUMBER 2 15 JANUARY 1998

Internal thermal noise in the LIGO test masses: A direct approach

Yu. Levin
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 July 1997; published 22 December 1997)

The internal thermal noise in LIGO's test masses is analyzed by a new technique, a direct application of the fluctuation-dissipation theorem to LIGO's readout observable, $x(t)$=(longitudinal position of test-mass face, weighted by laser beam's Gaussian profile). Previous analyses, which relied on a normal-mode decomposition of the test-mass motion, were valid only if the dissipation is uniformly distributed over the test-mass interior, and they converged reliably to a final answer only when the beam size was a non-negligible fraction of the test-mass cross section. This paper's direct analysis, by contrast, can handle inhomogeneous dissipation and arbitrary beam sizes. In the domain of validity of the previous analysis, the two methods give the same answer for $S_x(f)$, the spectral density of thermal noise, to within expected accuracy. The new analysis predicts that thermal noise due to dissipation concentrated in the test mass's front face (e.g., due to mirror coating) scales as $1/r_0^2$, by contrast with homogeneous dissipation, which scales as $1/r_0$ (r_0 is the beam radius); so surface dissipation could become significant for small beam sizes. [S0556-2821(97)05524-0]

PACS number(s): 04.80.Nn, 05.40.+j

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INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **20** (2003) 2917–2928 PII: S0264-9381(03)59947-6

Mechanical loss in tantala/silica dielectric mirror coatings

Steven D Penn[1,6], Peter H Sneddon[2], Helena Armandula[3], Joseph C Betzwieser[4], Gianpietro Cagnoli[2], Jordan Camp[3,7], D R M Crooks[2], Martin M Fejer[5], Andri M Gretarsson[1,8], Gregory M Harry[4], Jim Hough[2], Scott E Kittelberger[1], Michael J Mortonson[4], Roger Route[5], Sheila Rowan[5] and Christophoros C Vassiliou[4]

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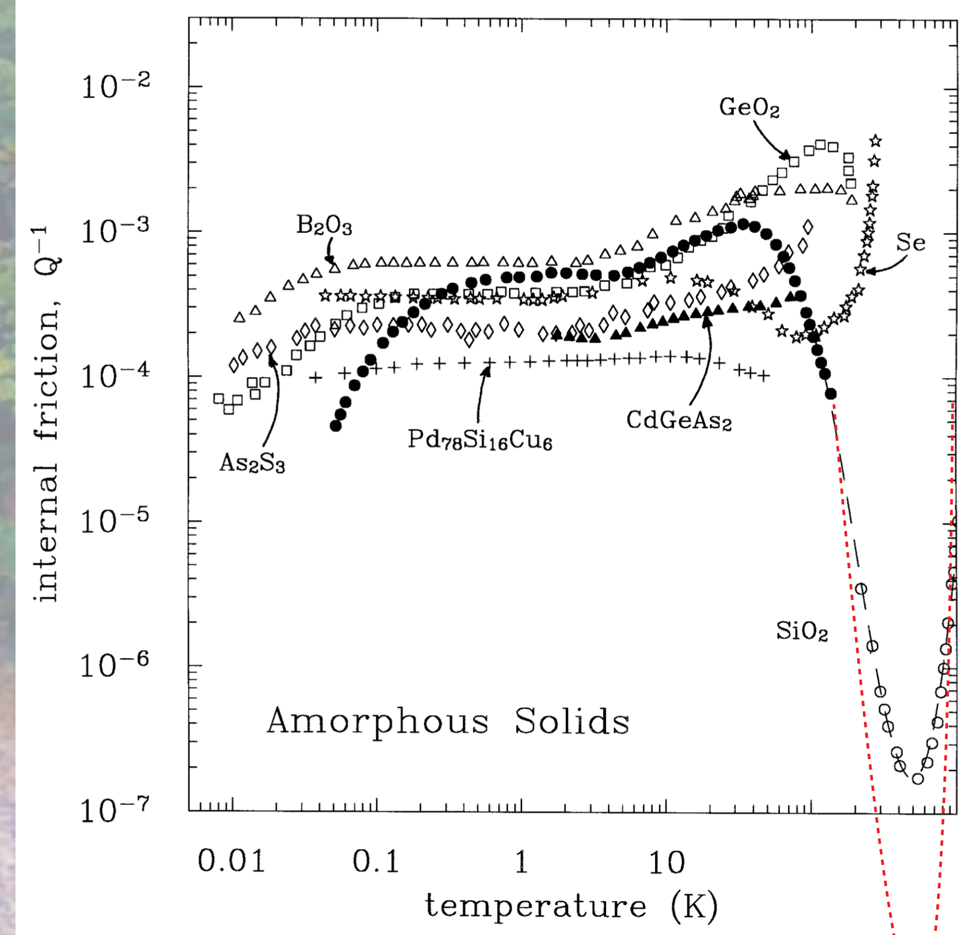

K. Topp and D. Cahill, *Zeitschrift für Physik B Condensed Matter*, **101**, #2, pp. 235–245, 1996.

$\phi = 2 \times 10^{-9}$

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Harry, G. M. et al., *Classical and Quantum Gravity* **19**, 897 (2002).
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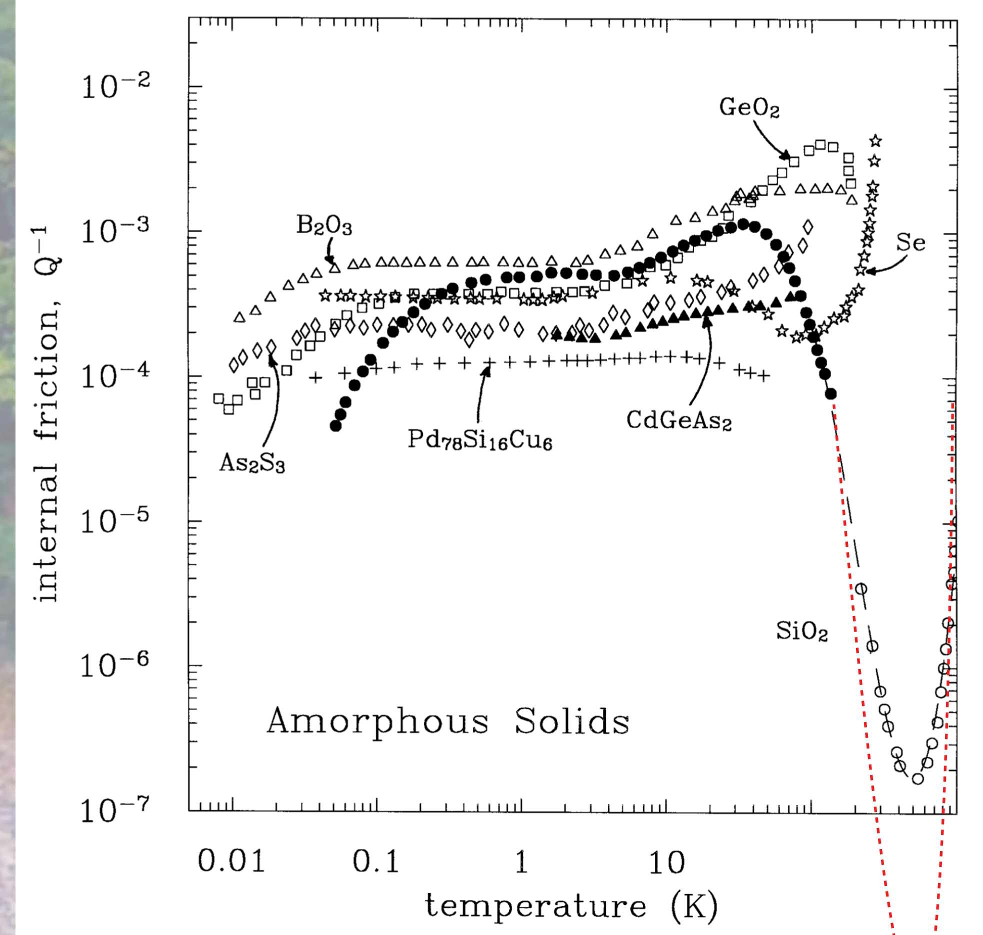
Cole, G. D., et al.. *Nature Photonics* **7**, 644–650 (2013).



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$\phi = 2 \times 10^{-9}$

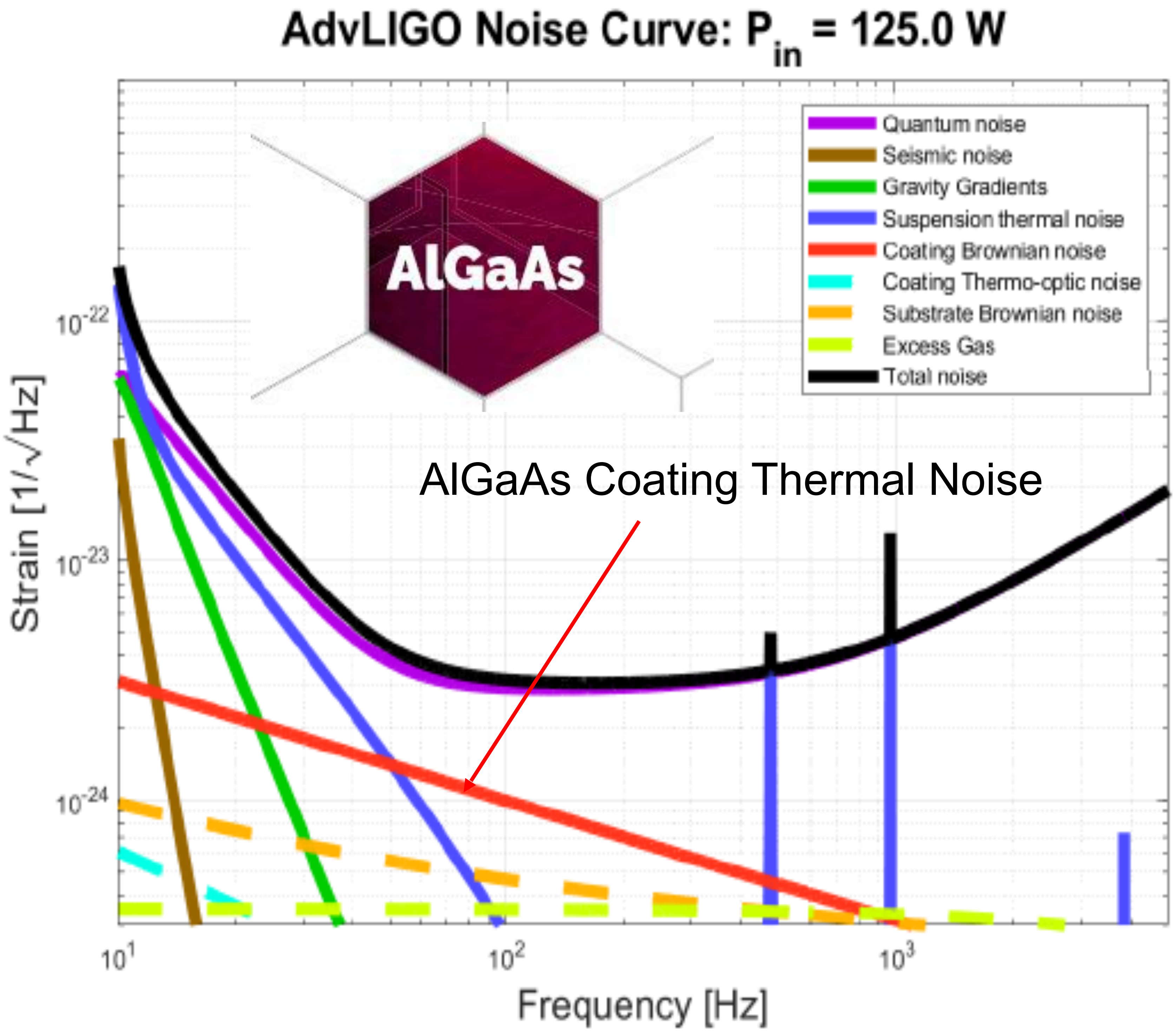
ARTICLES nature photonics
PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NPHOTON.2013.174

Tenfold reduction of Brownian noise in high-reflectivity optical coatings

Garrett D. Cole[1,2†*], Wei Zhang[3†], Michael J. Martin[3], Jun Ye[3*] and Markus Aspelmeyer[1*]

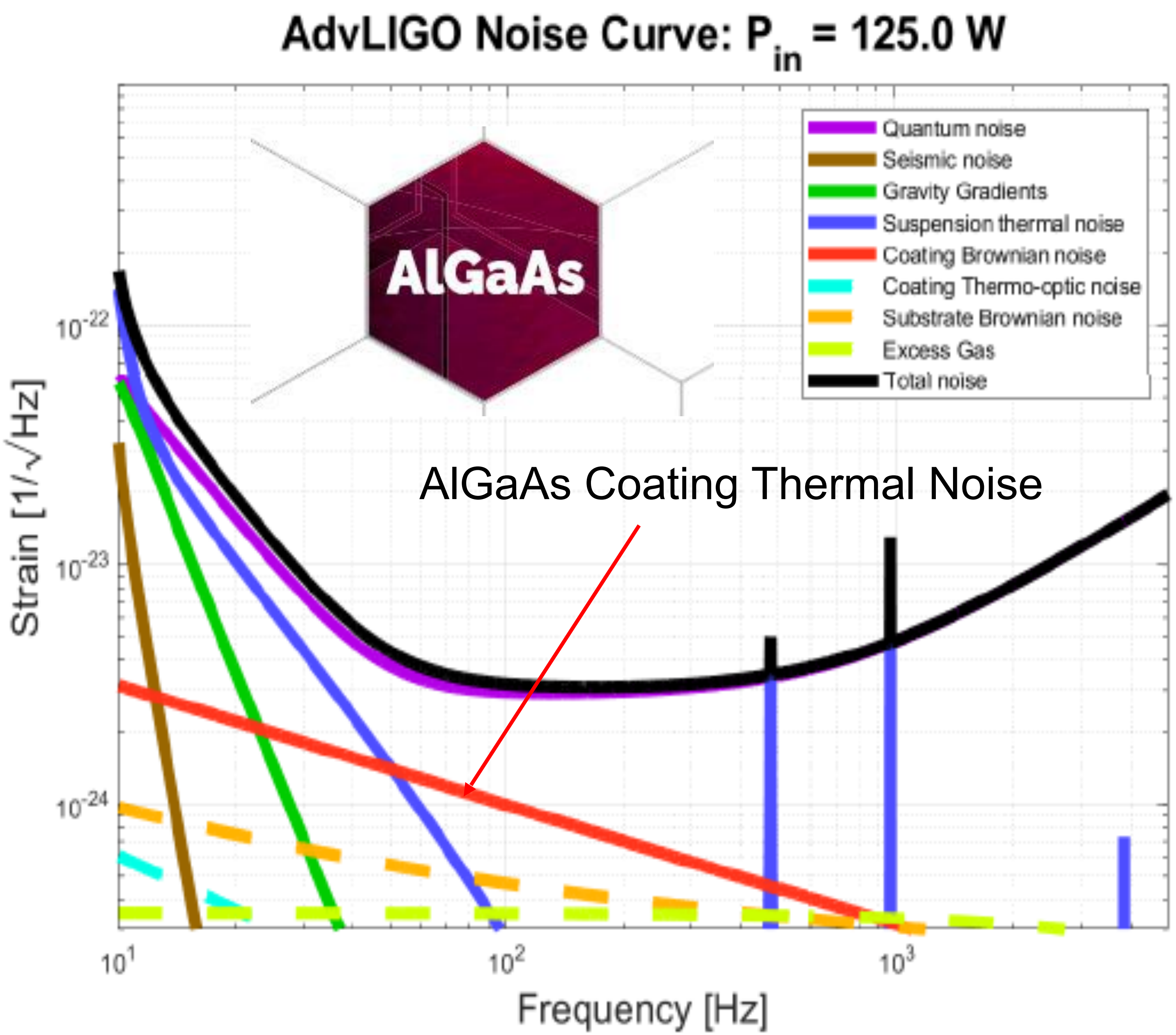
Thermally induced fluctuations impose a fundamental limit on precision measurement. In optical interferometry, the current bounds of stability and sensitivity are dictated by the excess mechanical damping of the high-reflectivity coatings that comprise the cavity end mirrors. Over the last decade, the dissipation of these amorphous multilayer reflectors has at best been reduced by a factor of two. Here, we demonstrate a new paradigm in optical coating technology based on direct-bonded monocrystalline multilayers, which exhibit both intrinsically low mechanical loss and high optical quality. Employing these 'crystalline coatings' as end mirrors in a Fabry–Pérot cavity, we obtain a finesse of 150,000. More importantly, at room temperature, we observe a thermally limited noise floor consistent with a tenfold reduction in mechanical damping when compared with the best dielectric multilayers. These results pave the way for the next generation of ultra-sensitive interferometers, as well as for new levels of laser stability.

The Promise of GaAs/AlGaAs Coatings



The Promise of GaAs/AlGaAs Coatings

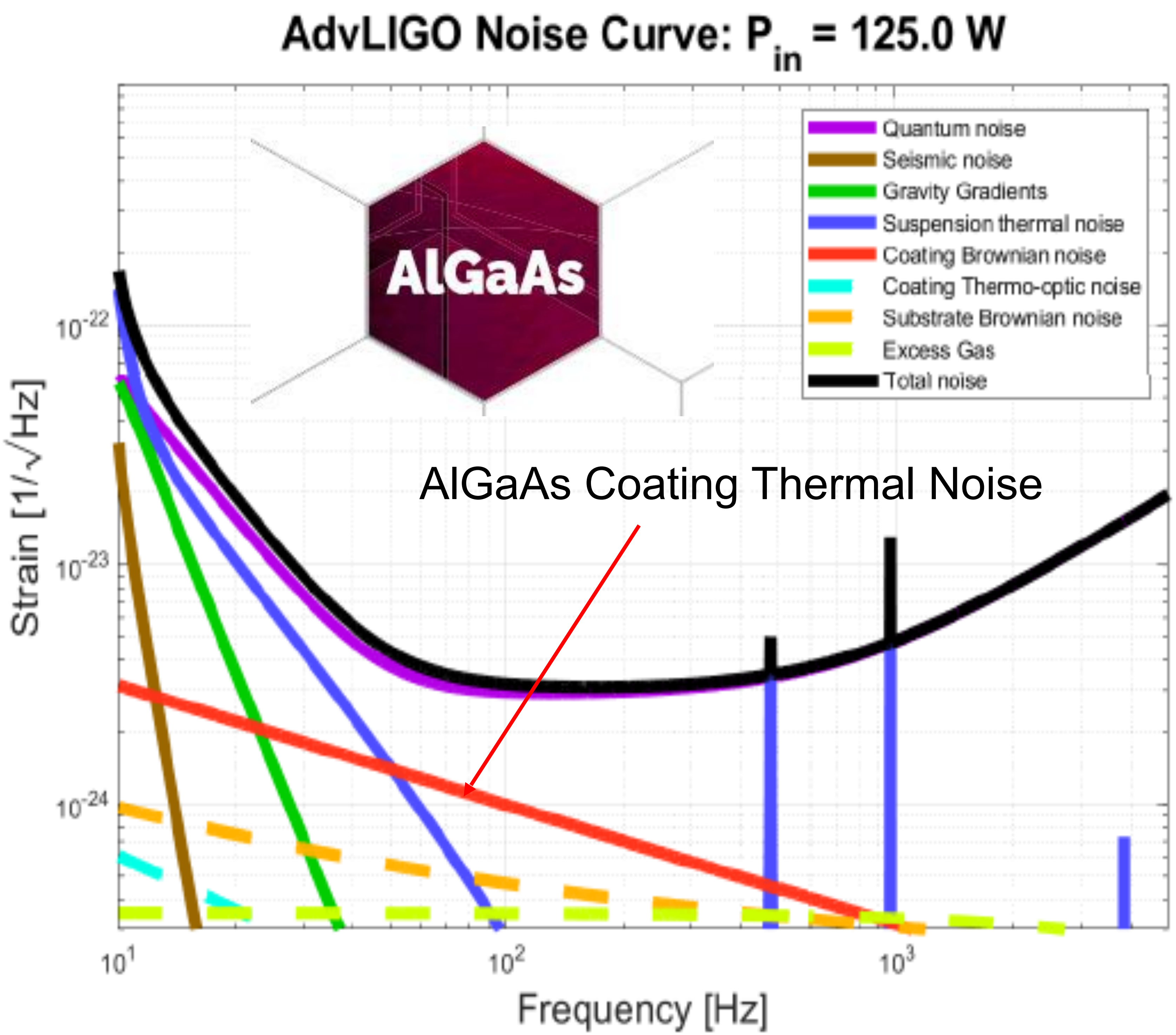
Meets optical specs



The Promise of GaAs/AlGaAs Coatings

Meets optical specs

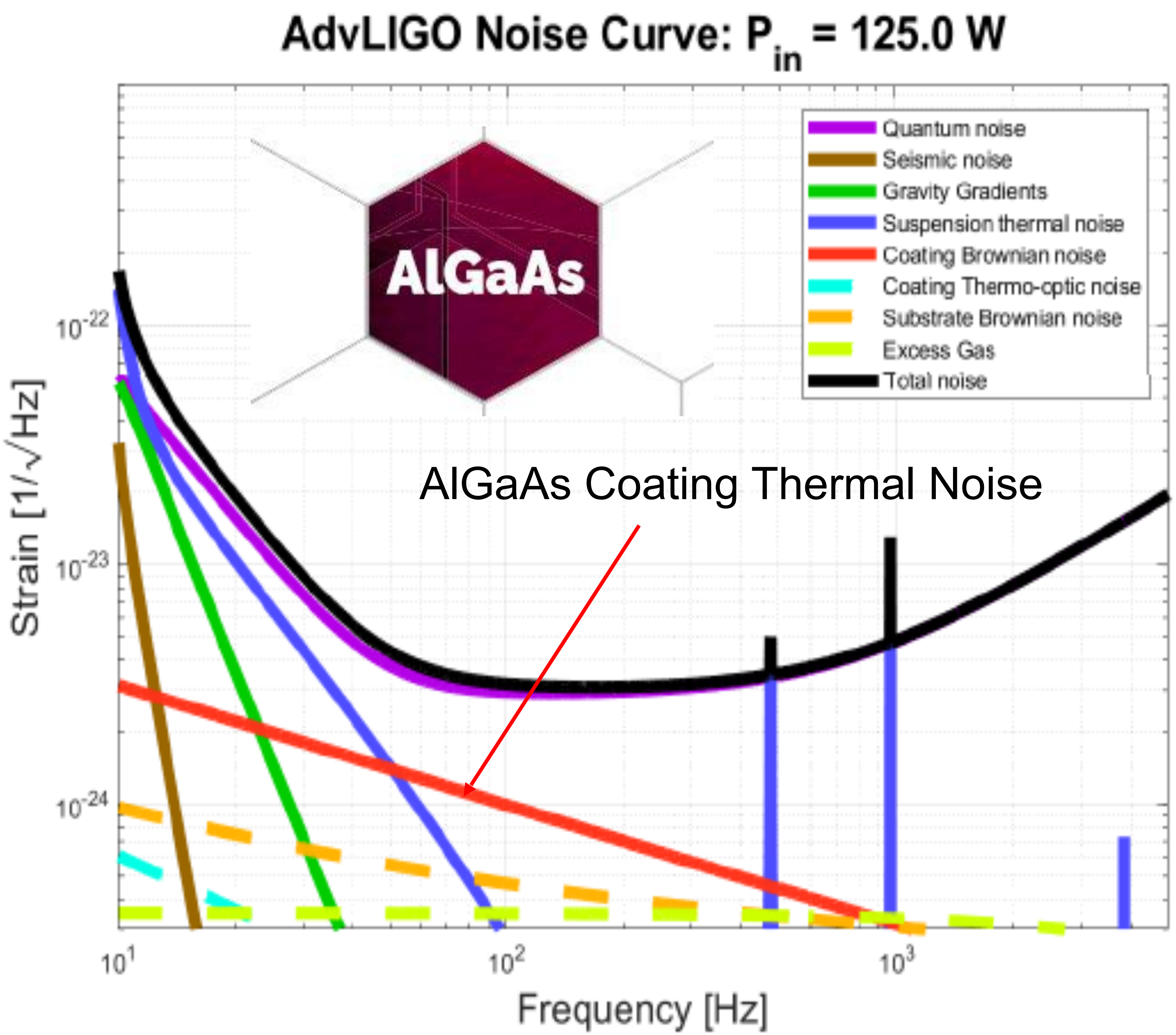
Coating thermal not limiting

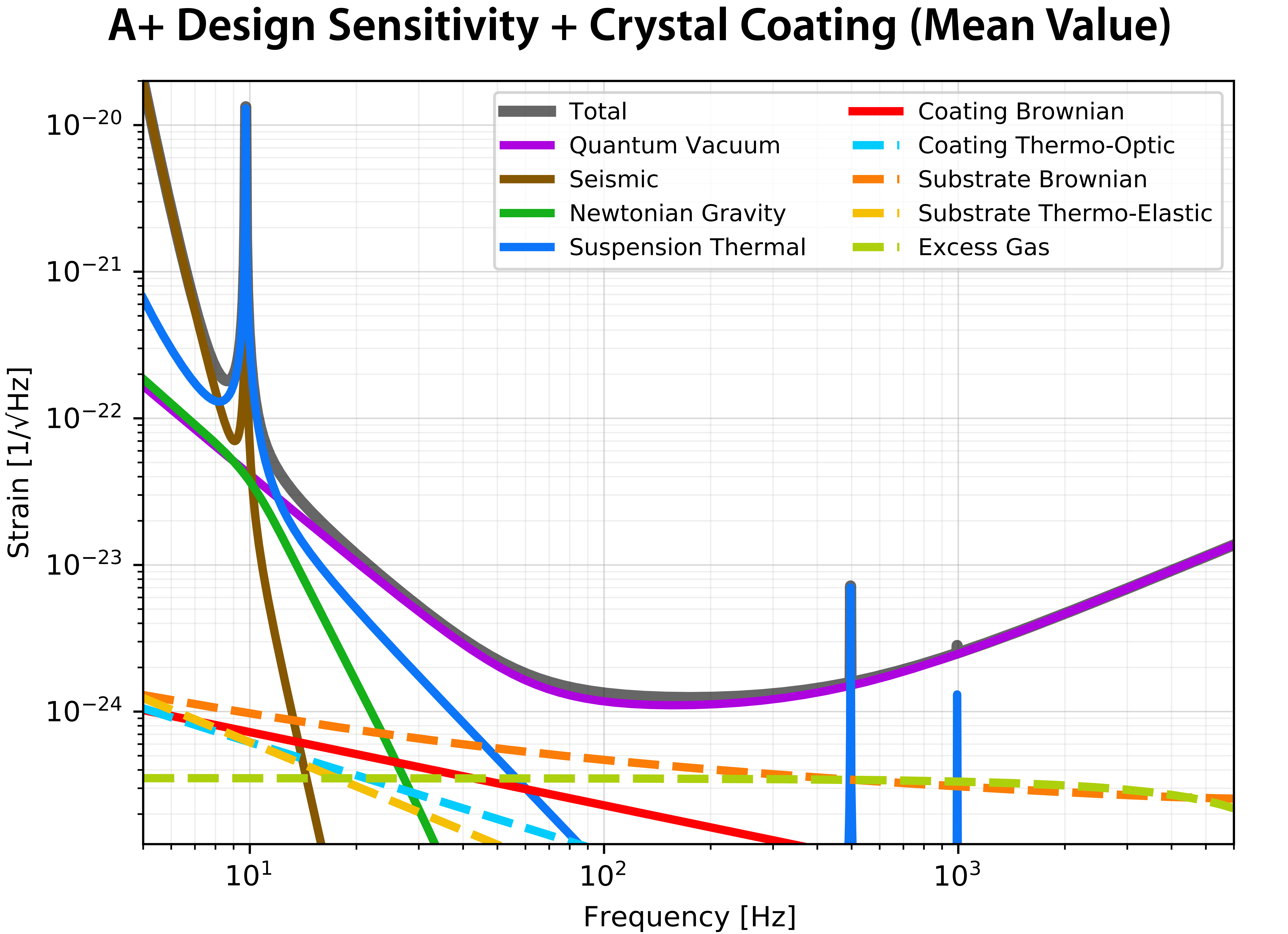


The Promise of GaAs/AlGaAs Coatings

Meets optical specs

Coating thermal not limiting for any current or planned detector




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

Crystalline GaAs/AlGaAs Coatings • Overview

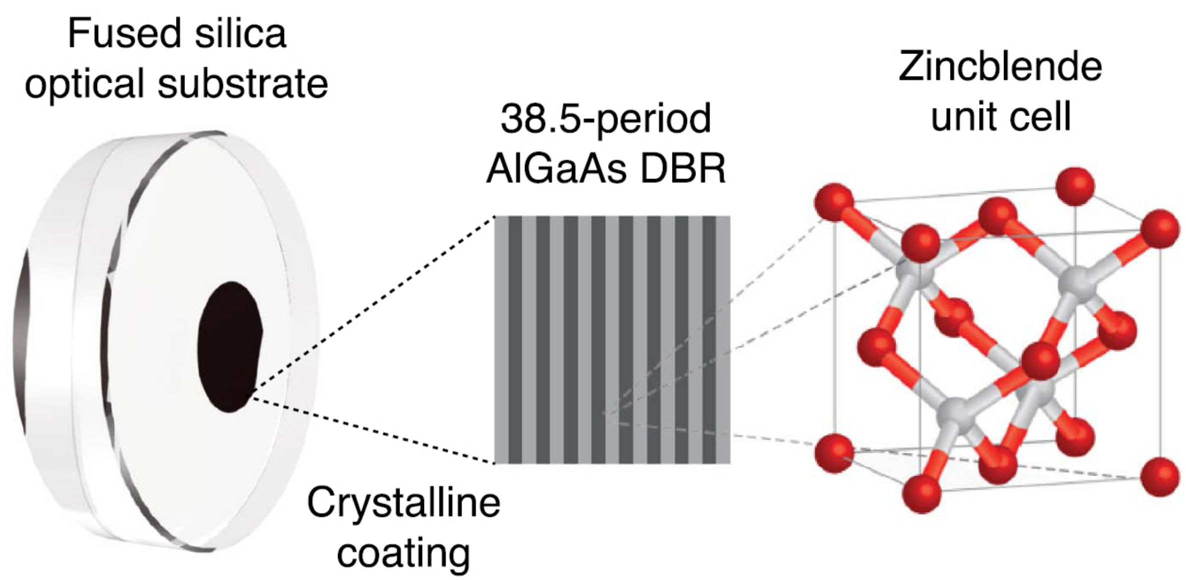
- The crystal is grown via Molecular Beam Epitaxy (MBE) on a single-crystal GaAs wafer.

- 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

$C_{11} = 118$ GPa

$C_{12} = 55.9$ GPa

$C_{44} = 58.2$ GPa

3 Loss Angles

ϕ_{11}, ϕ_{12} } Bulk

ϕ_{44} Shear

Mechanical Ringdown

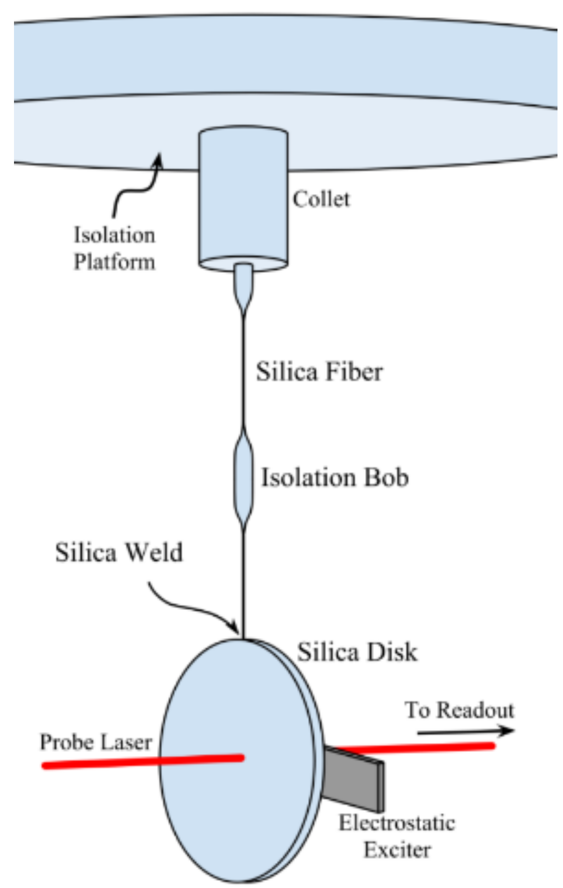
75 mm x 1 mm FS disks

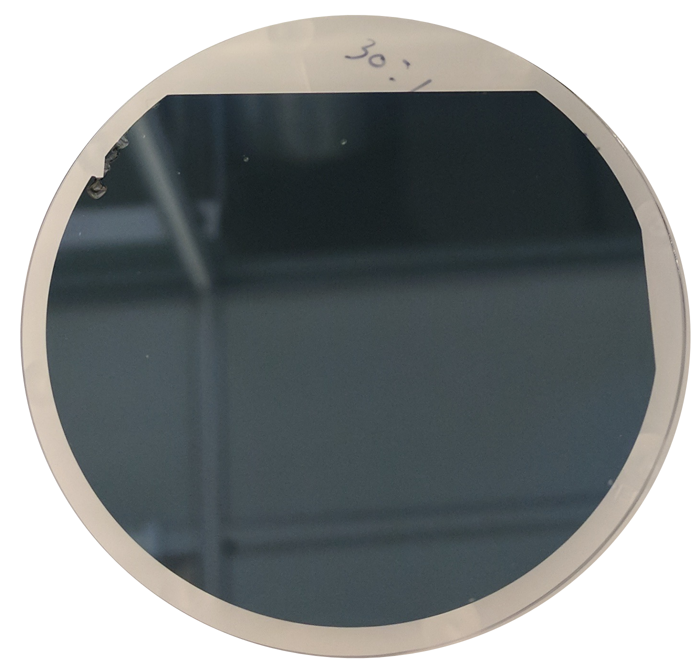
$\phi_{44} < 1 \times 10^{-6}$

$\phi_{11} < 2.3 \times 10^{-4}$

$\phi_{12} < 5.2 \times 10^{-4}$

Bulk loss dominated by thermoelastic loss





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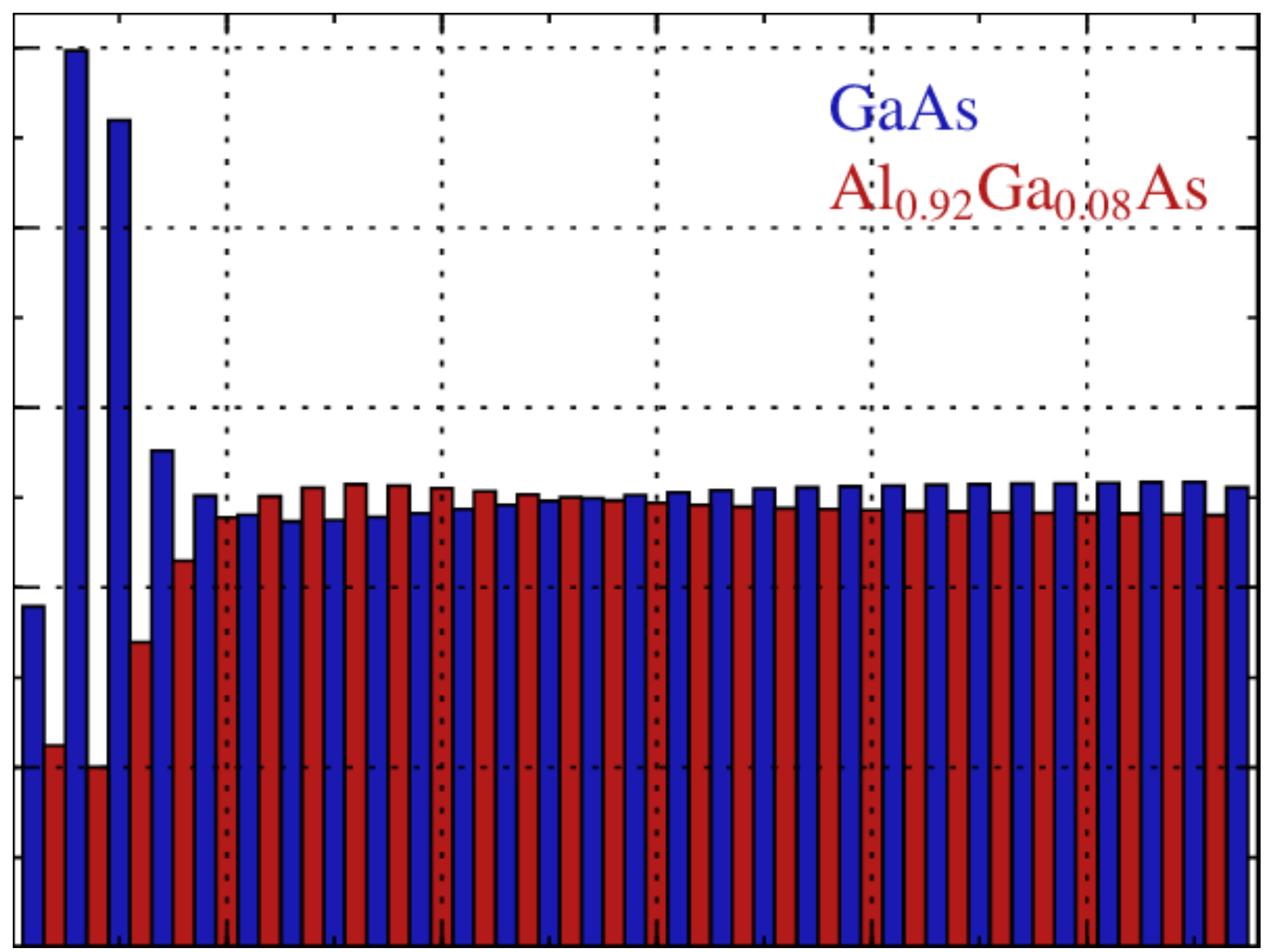
ThermoOptic Optimization

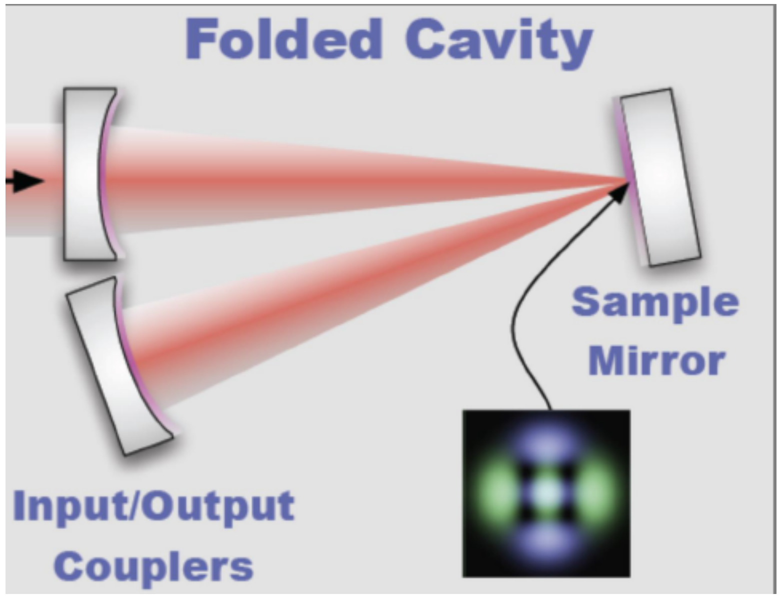
Tara C. et al Metrologia **53** (2016) 860

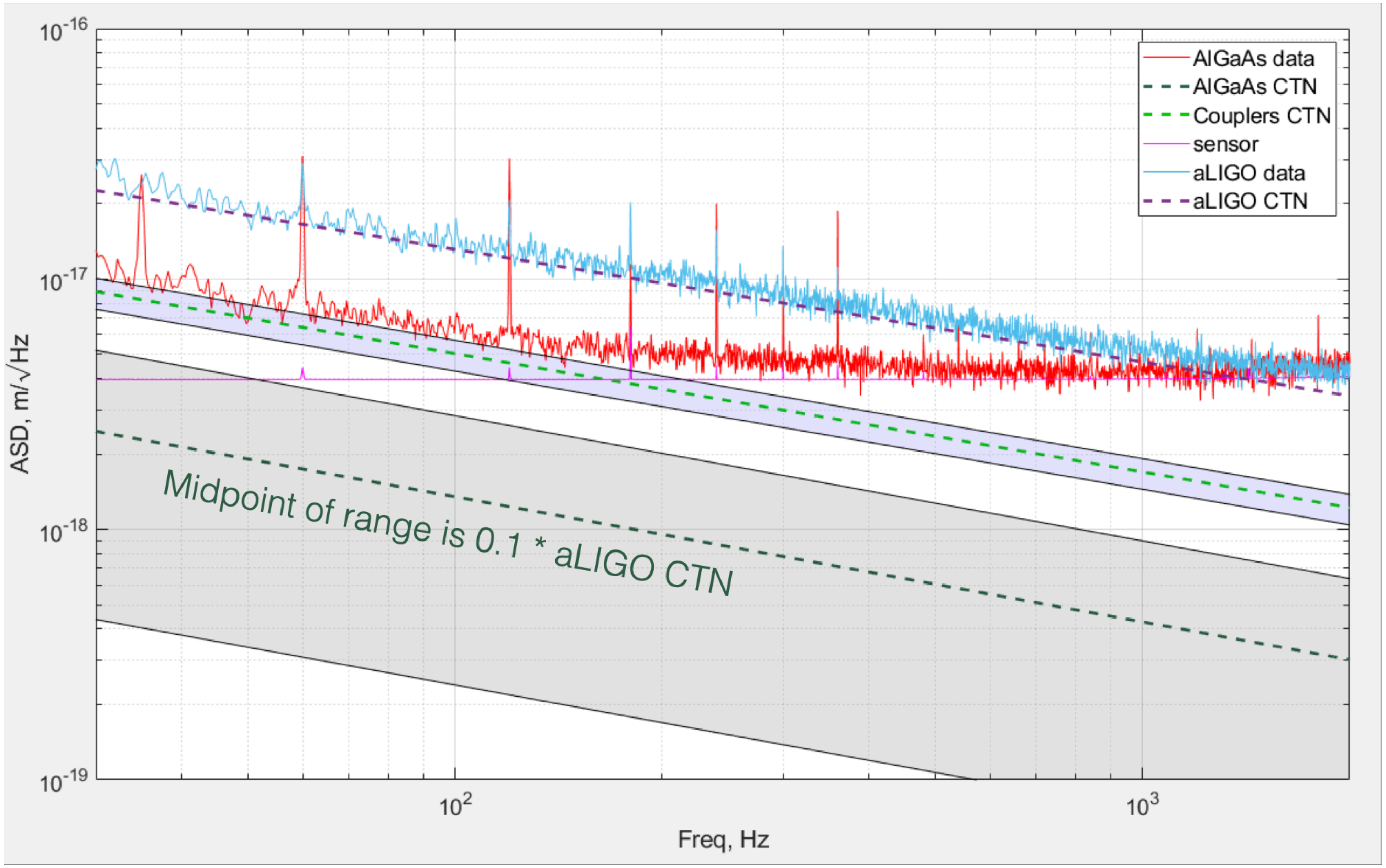


Rana Adhikari, "Coherent Cancellation of Photothermal Noise in AlGaAs Bragg Mirrors", LIGO-P1500054

CTN Measurements

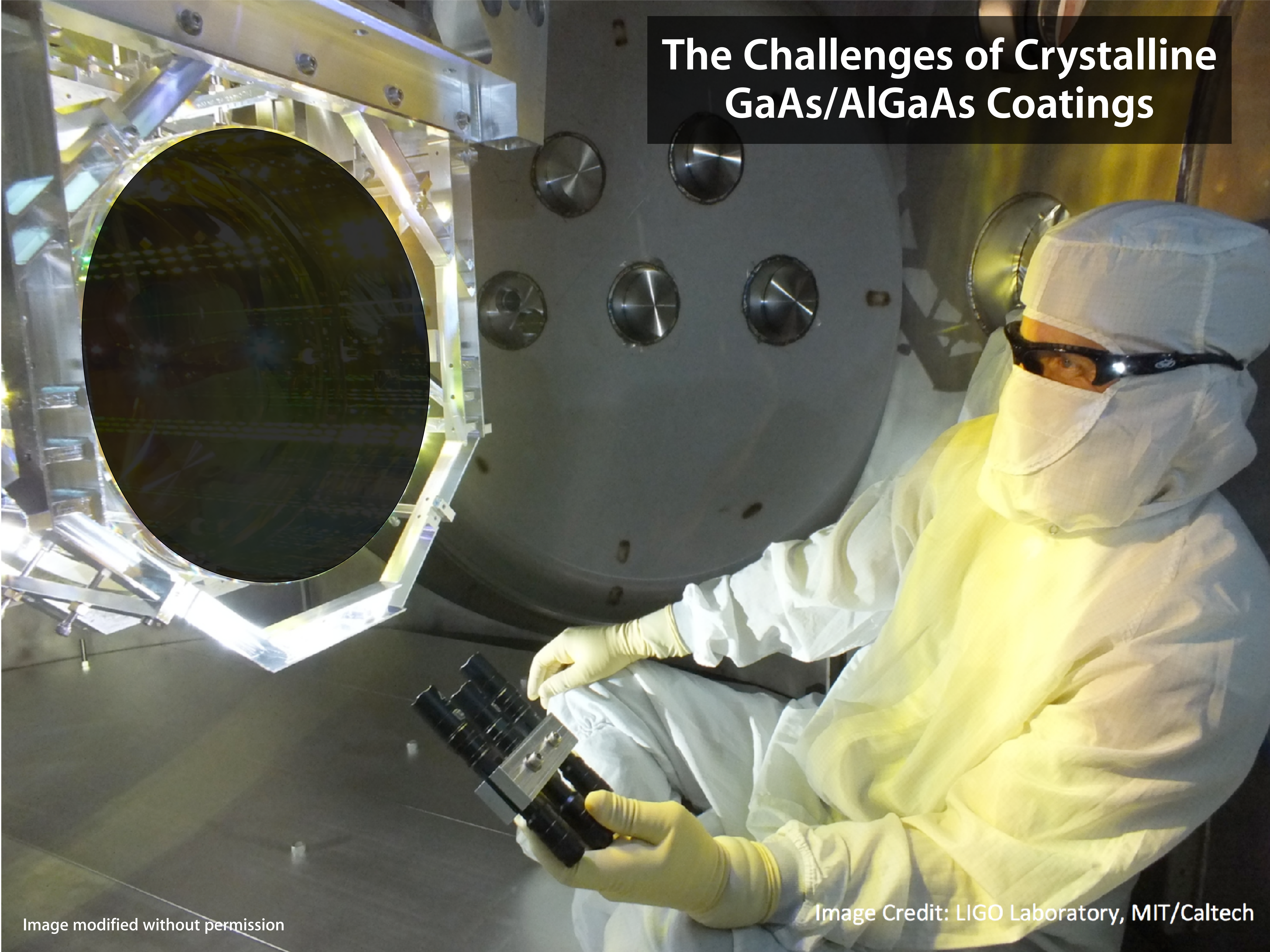
- Measured by Nick Demos, Slawek Gras, & Matt Evans (LIGO-G2001592)
- Noise dominated by cavity end mirrors (couplers)
- Upper limit CTN is **5x lower than Adv. LIGO**
- Mean CTN is **10x lower than Adv. LIGO**





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

The Challenges of Crystalline GaAs/AlGaAs Coatings



The Challenges of Crystalline GaAs/AlGaAs Coatings

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

Option 1: Scale Coatings to 30 cm

★ **Freiberger Compound Materials:**

- 30 cm GaAs wafers
- 2.6 years: Grow, Cut, Etch, Polish
- 8.2 M€ = $9.94M

★ **IQE, NC:** MBE coating facility

- Retooling to 30 cm = $300k
- $300k/month rent of MBE chamber
- $4 M to grow and process coatings

★ **EV Group:** Robotic Bonder

- $5M for bonder for 30 cm coating
- 12-16 month delivery time

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Option 1: 3–5 years, ≈$20M

Option 2: 20 cm coatings and Shrink the beam.

★ **Beam Reduction:** (6 cm ⟶ 3.8 cm)

- Coating Reduction: 30 cm ⟶ 19 cm
- GaAs wafers available now

★ **IQE, NC:** MBE coating facility

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- 12 test mass coatings ≈ $2.8 - 3 M total

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- Will bond 20 cm coatings
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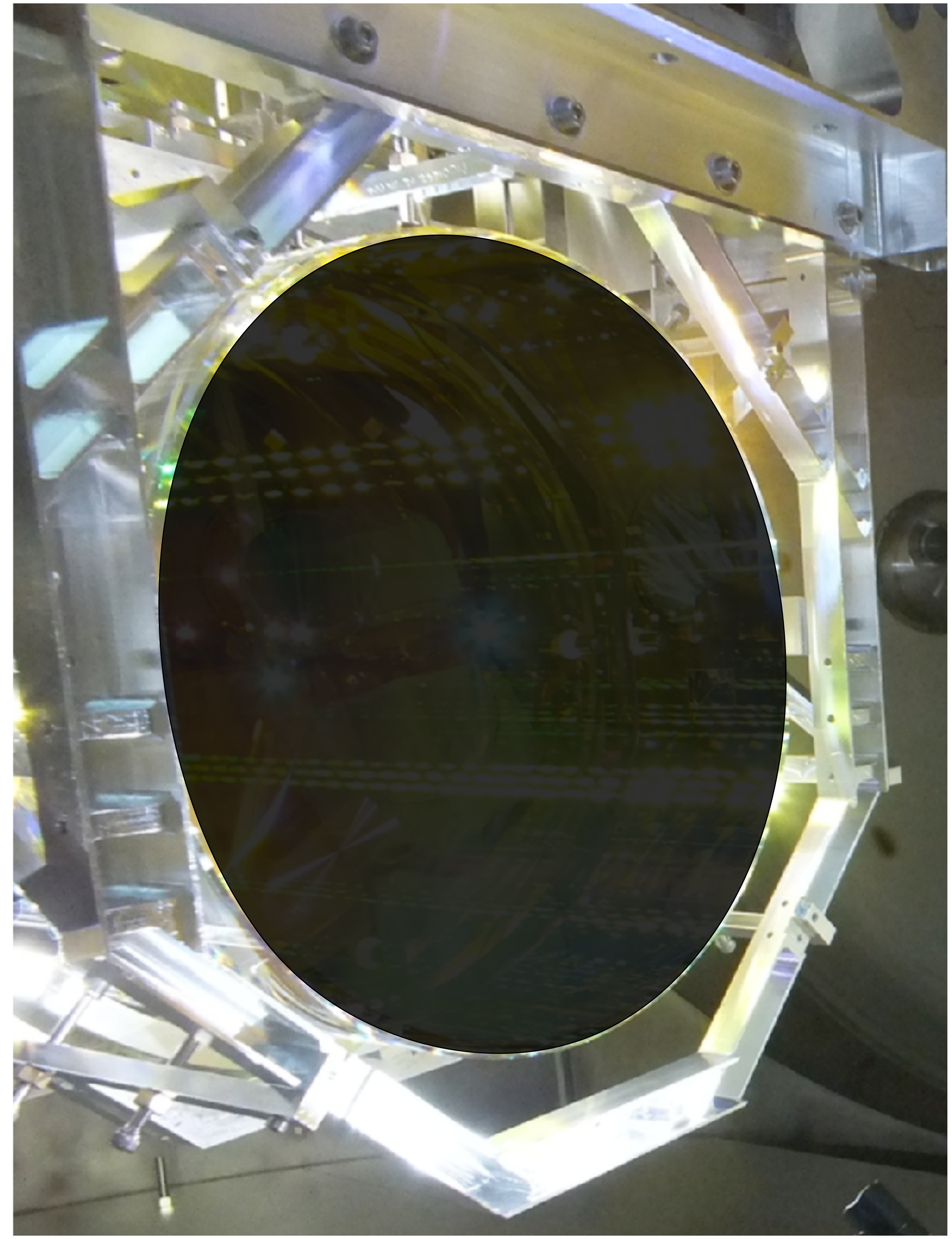

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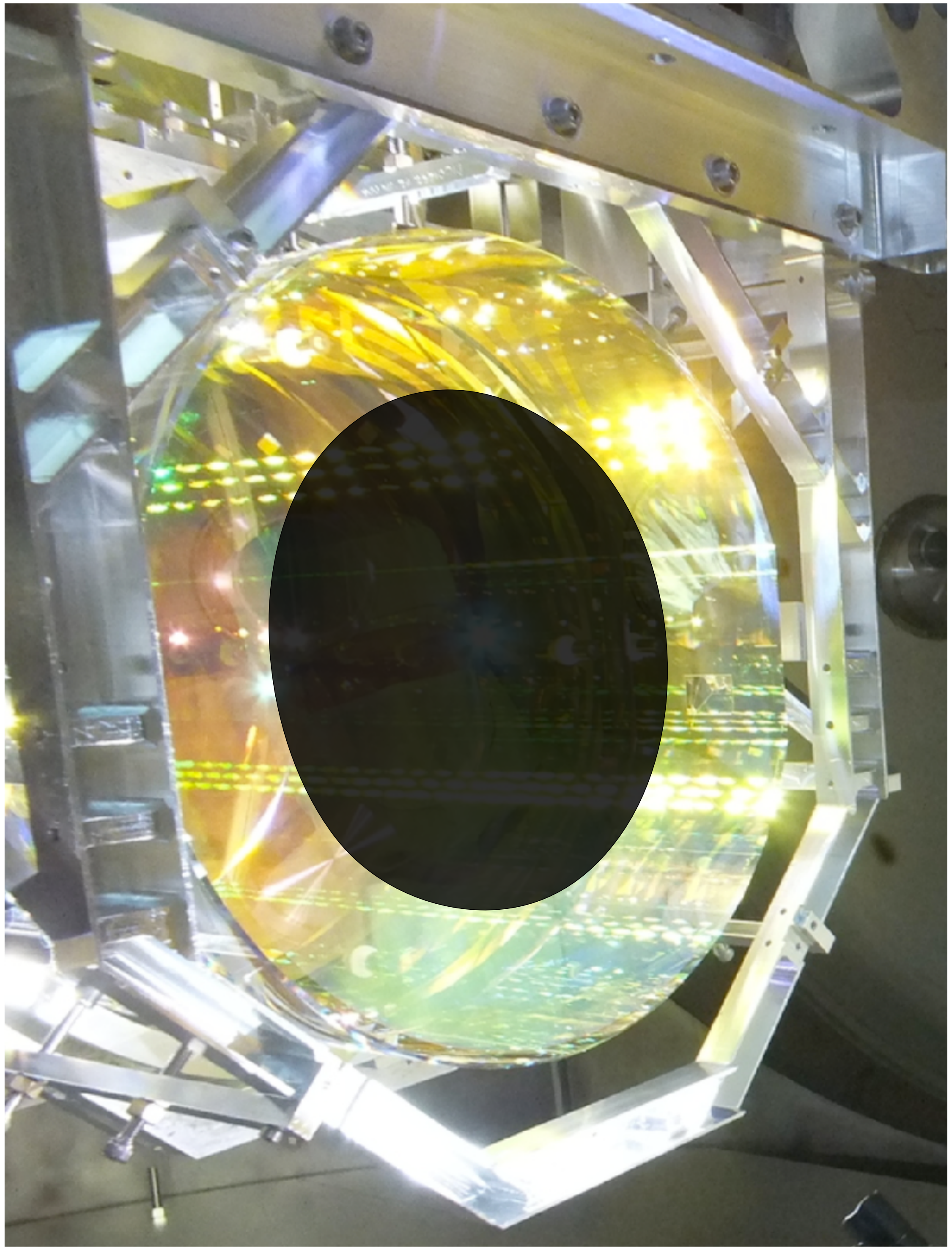

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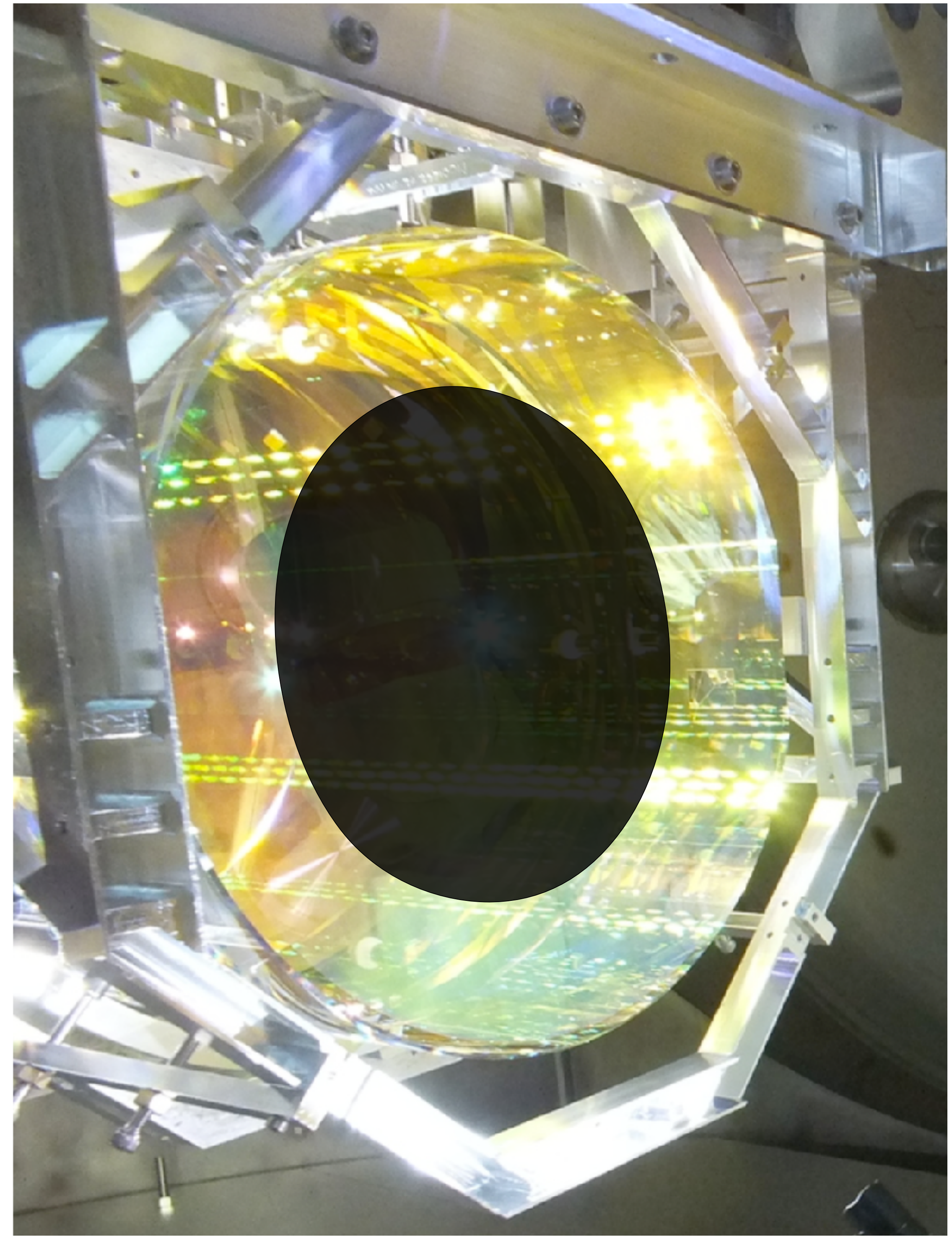
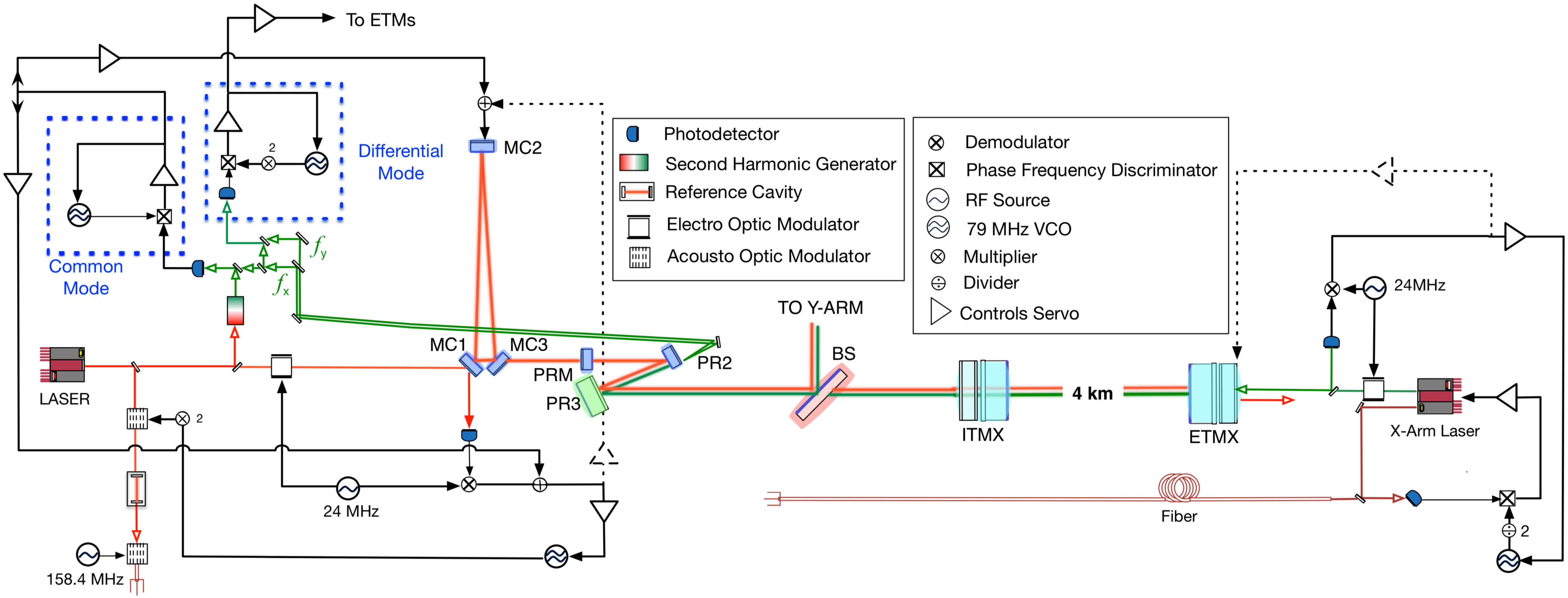


Option 2: 1.5–2.5 years, ≈$10M

Current Green-Light Arm Length Stabilization System

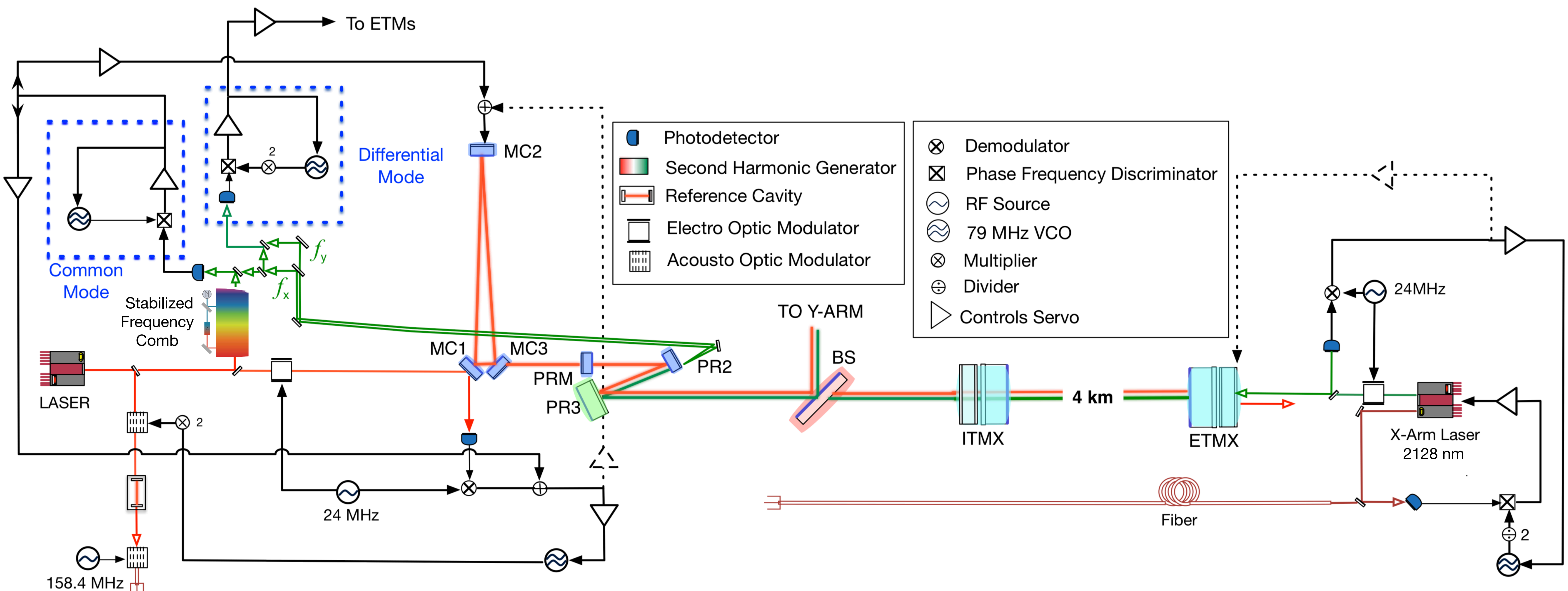
- Green, frequency-doubled beam (532 nm) is injected through each ETM.
- Each arm separately locked via PDH.
- Differential X-Y transmission signal then adjusted to 0 offset frequency
- Finally ETMs adjusted to lock main beam (1064 nm)



Graphic borrowed from A. Staley LIGO-G1400946

Proposed 2128-nm Arm Length Stabilization System

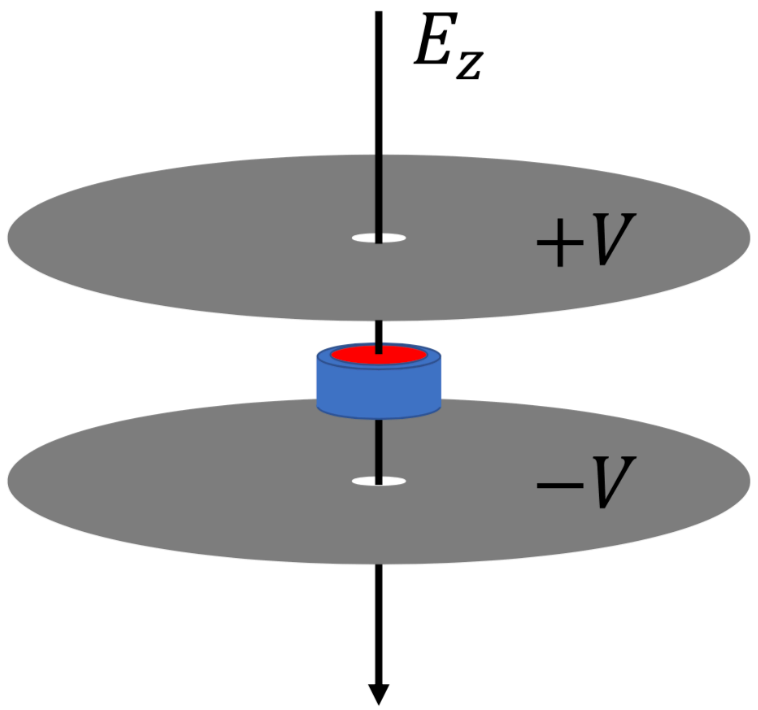
- In each end station, a stabilized Optical Frequency Comb (OFC)[1,2] is used to phase-lock a 2128-nm laser to the main 1064-nm beam, and replaced the 532-nm beam.
- The coatings are manufactured to accommodate a low-finesse 2128-nm beam cavity as well as high reflectivity at 1064 nm.
- The transmitted 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).

Electro-Optic Noise (see talk by Satoshi Tanioka)



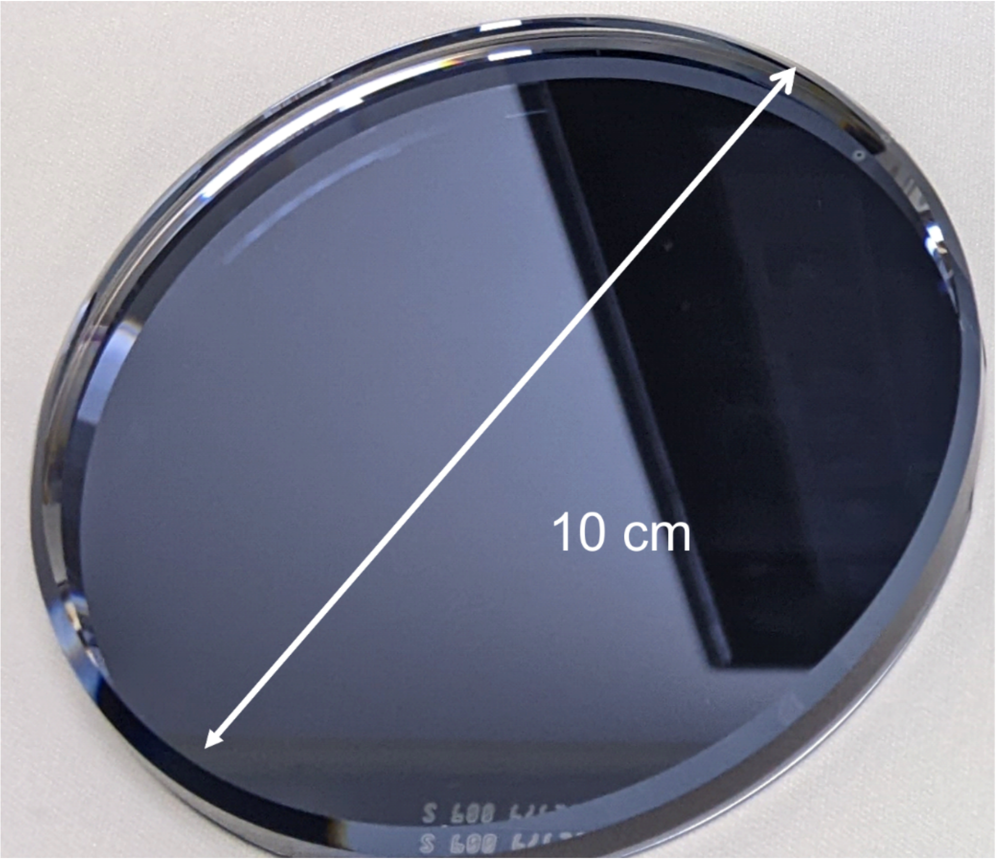
- Electro-optic noise arises from electric-field-induced changes in index, $\frac{\mathrm{d}n\left(f\right)}{\mathrm{d}E}$
- Thesis experiment by Daniel Vander-Hyde, Syracuse, to measure cavity noise induced by oscillating E-field on cavity mirror.

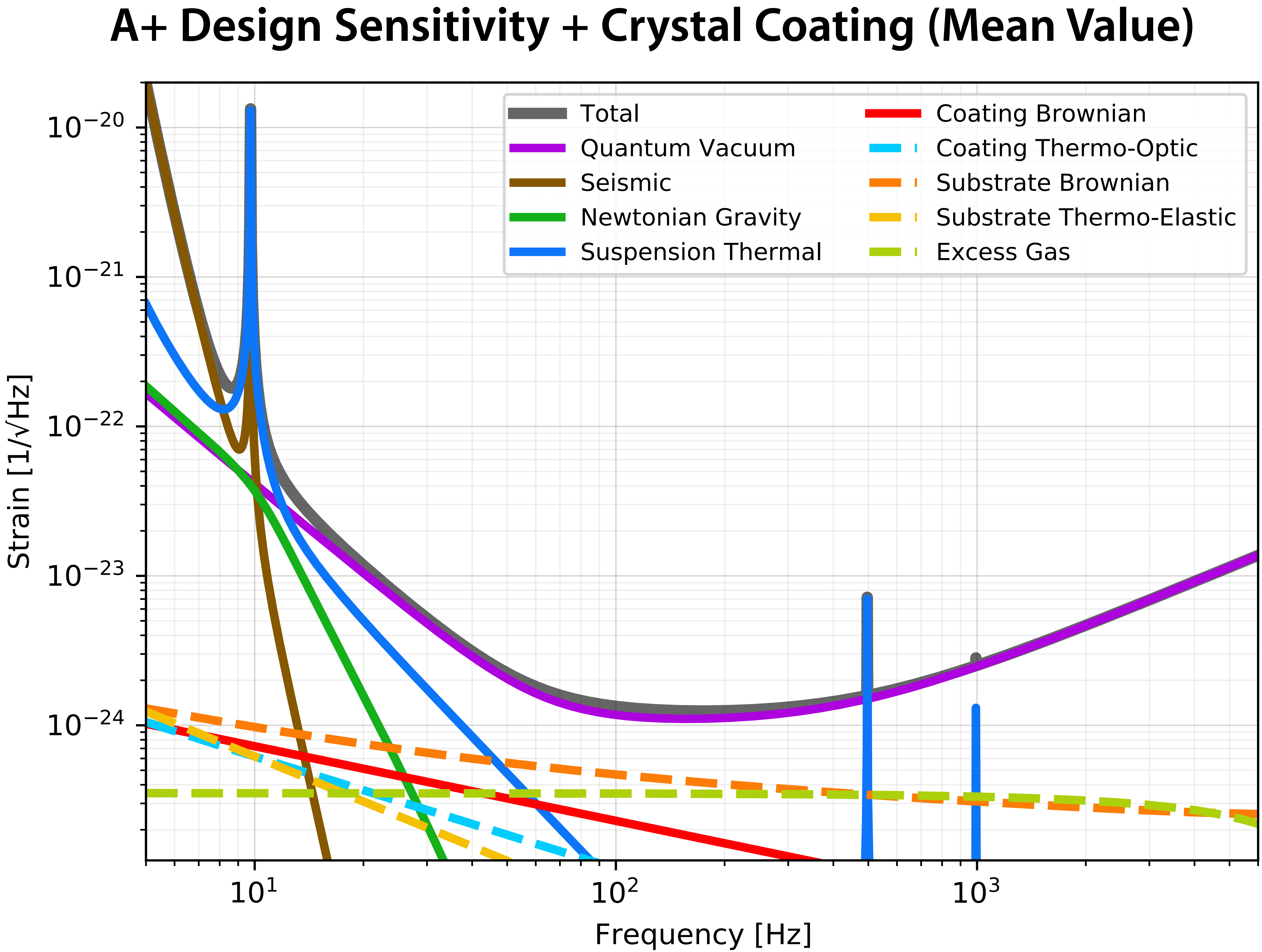
Birefringence

- 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

Surface Quality and Uniformity

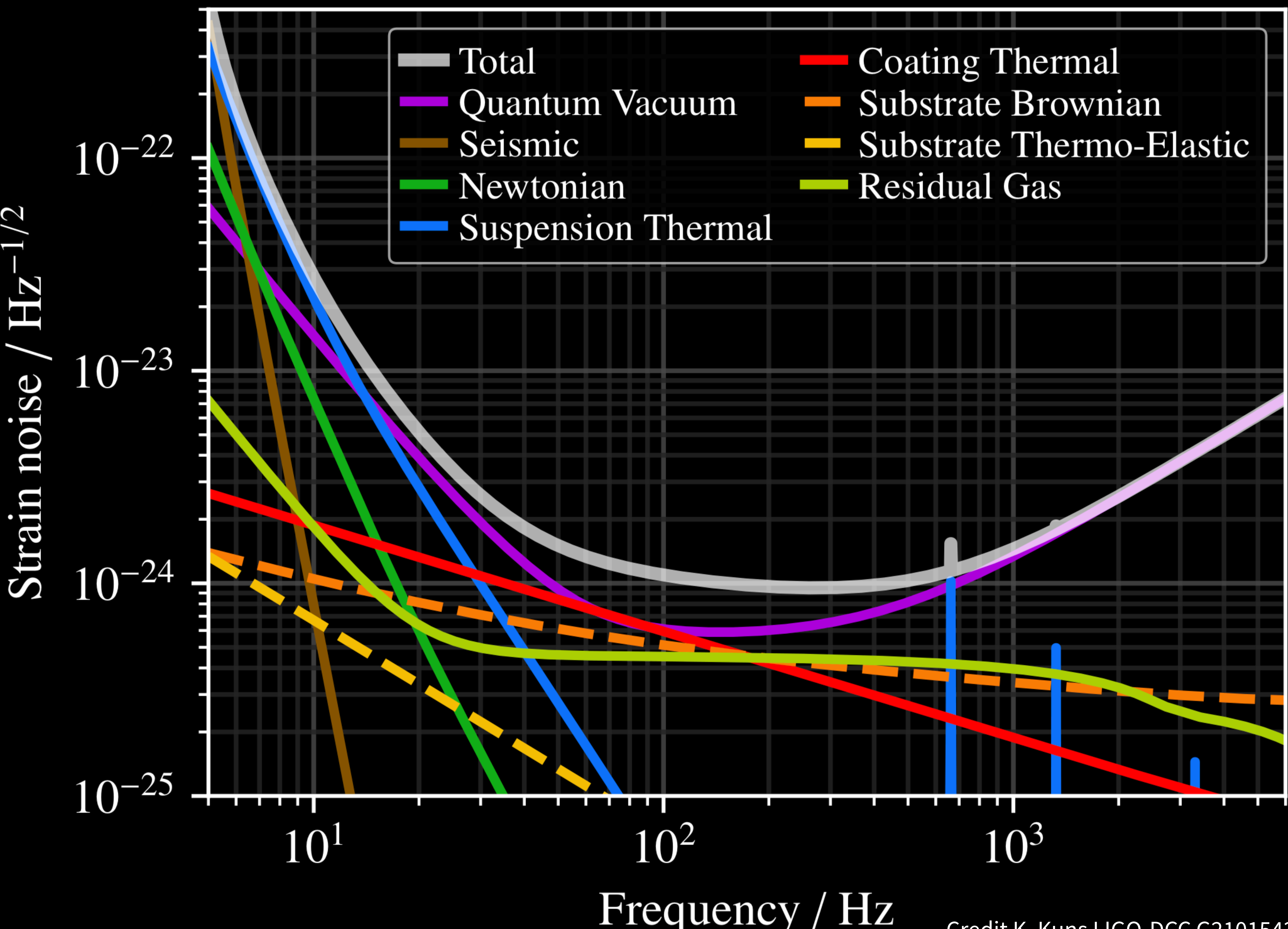
- Tests in progress on surface quality and uniformity for 10 cm ∅ samples.
- 20 cm substrates at Caltech. Funding sought for 20 cm ∅ coatings. (≈$260k)
- Scatter and absorption measurements follow surface characterization.





A+ Design Sensitivity + Crystal Coating (Mean Value)
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]

“Conservative” A++ with AlGaAs Coatings



Credit K. Kuns LIGO-DCC G2101543

Summary

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

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

For 30 cm coatings: ≈ \$22M & 3-5 years.

For 20 cm coatings: ≈ \$10M & 3 years.

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

Indian Lake, New York

Extra Slides

Next Steps…

Stage 1: (***…in progress…***)

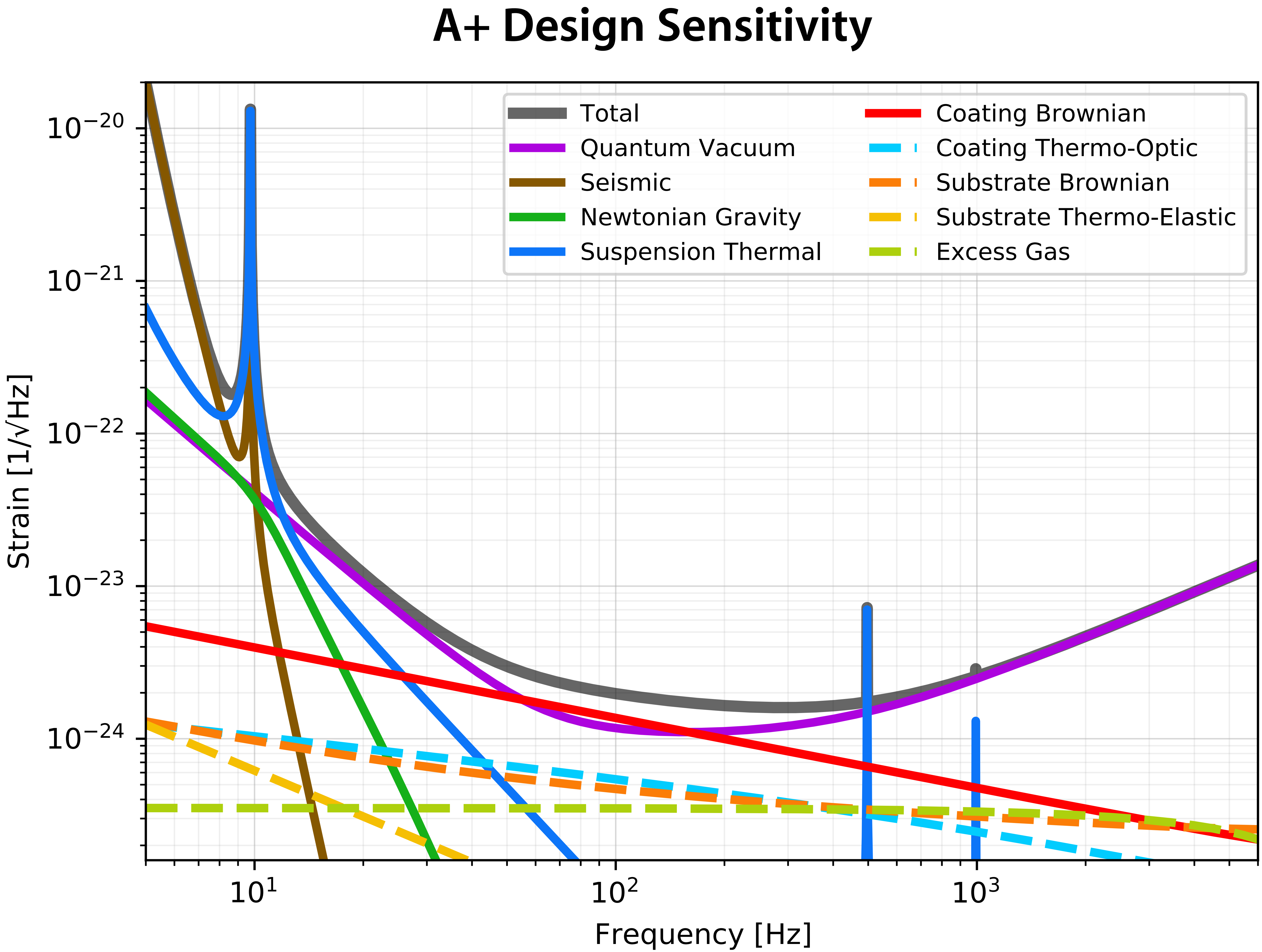
- Characterize surface quality for 10- & 20-cm coatings
- Raise $20M for 30-cm development, and
- Continue research on E-O noise, Birefringence noise, …

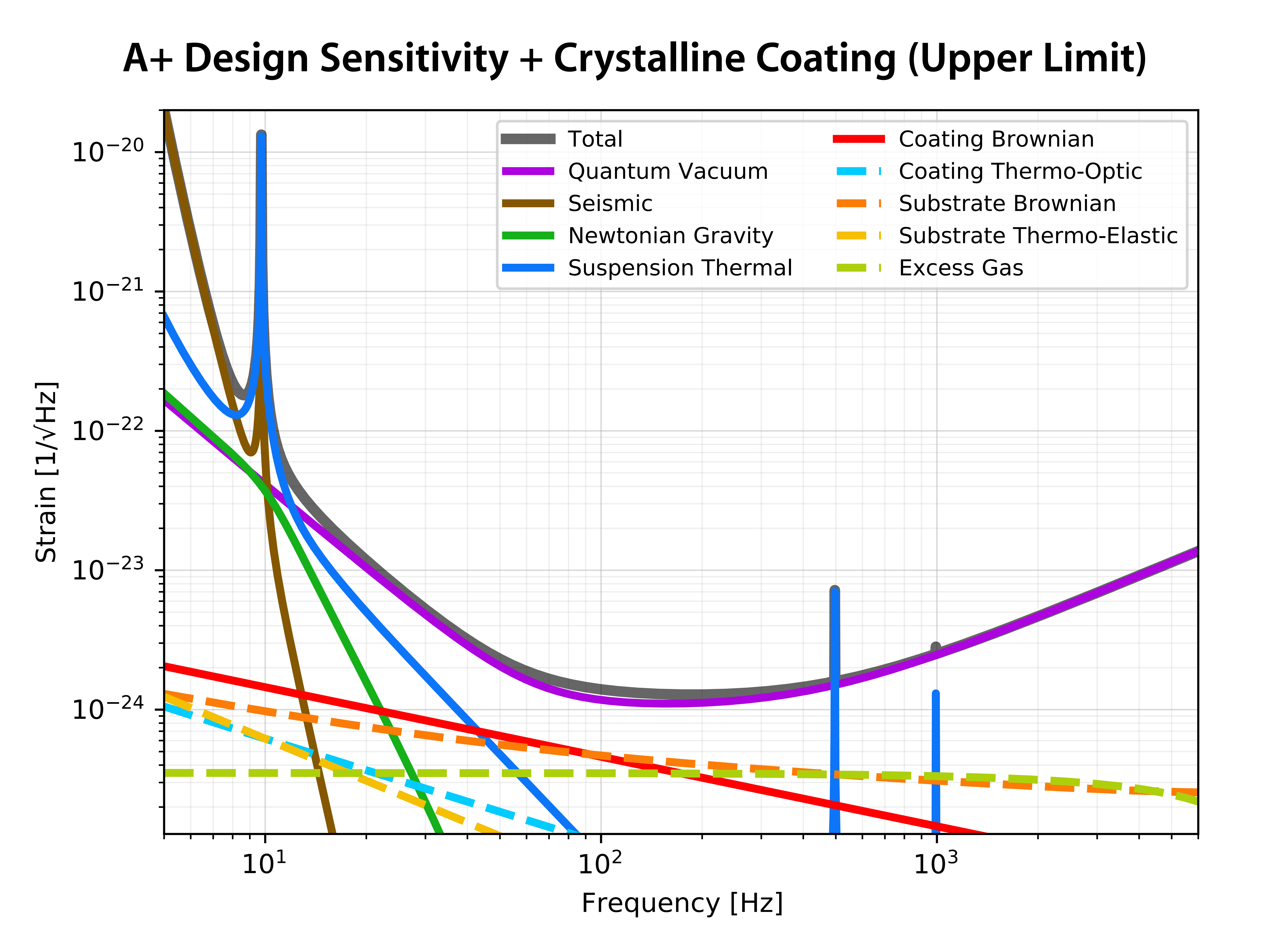
Stage 2:

- 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:

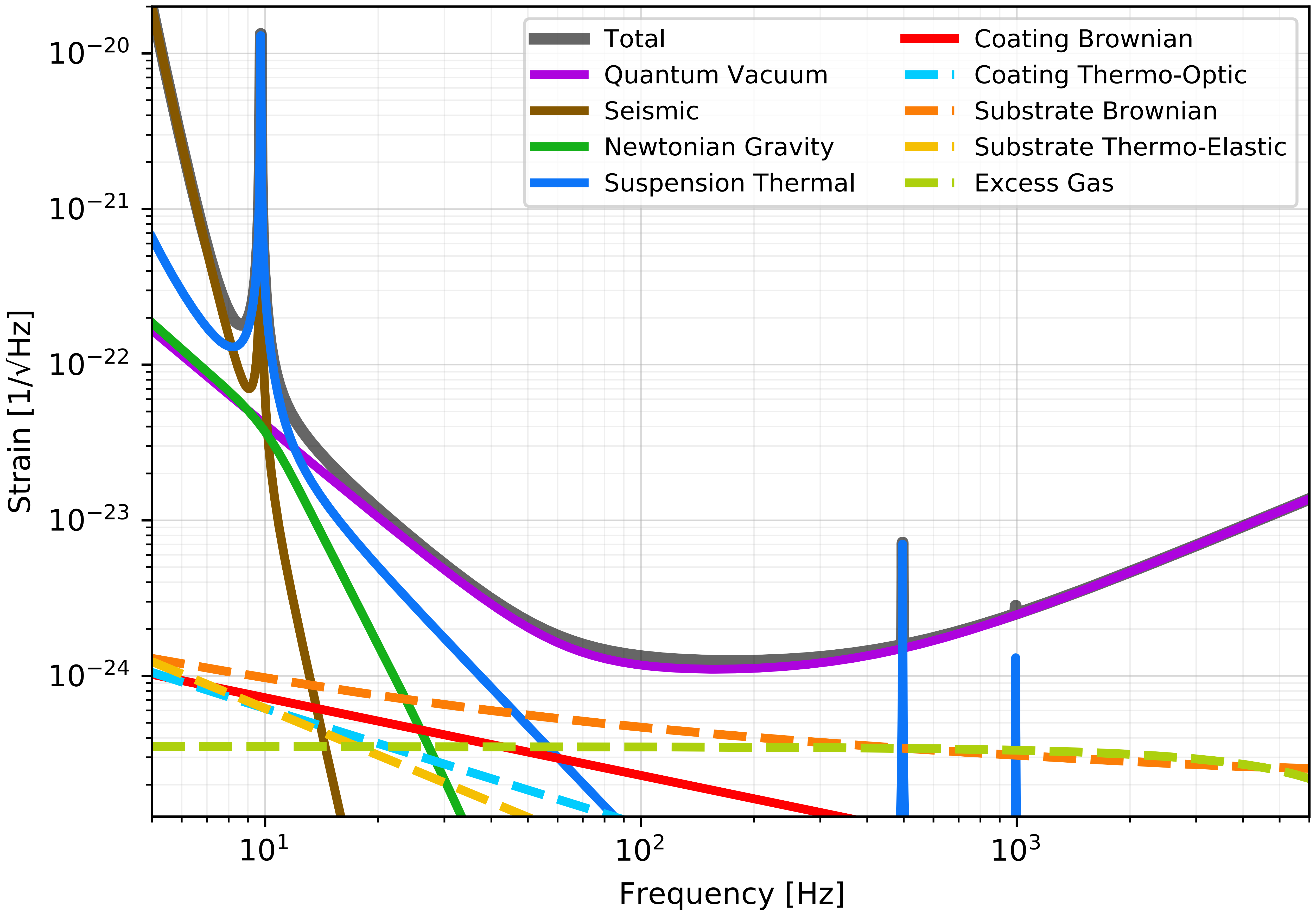
- Grow and bond 30-cm mirrors,
- Test that mirrors meet LIGO spec's, and
- Enjoy a more sensitive detector.


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

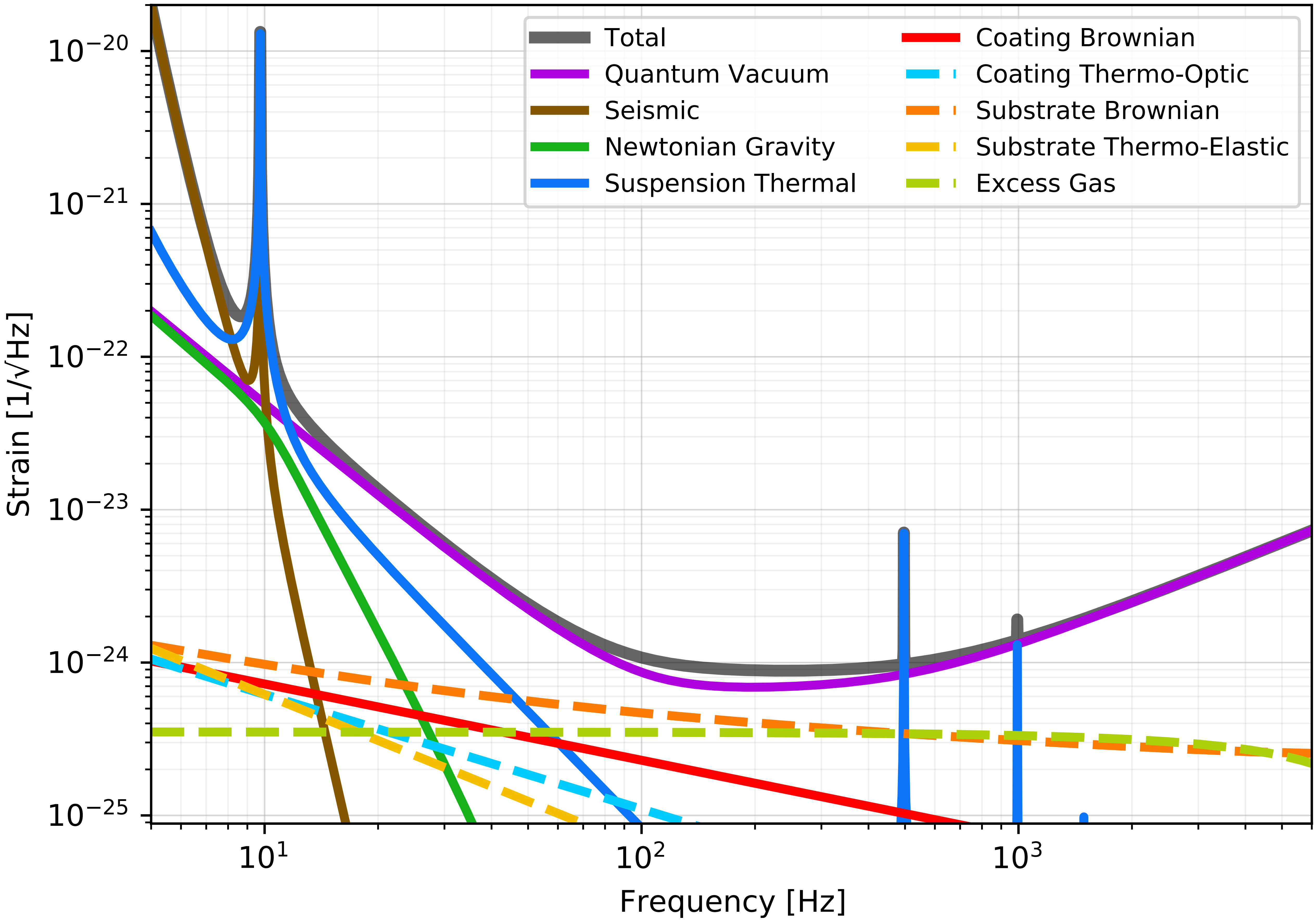


A+ Design Sensitivity + Crystalline Coating (Upper Limit)
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermo-Elastic
Excess Gas
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{1}
10^{2}
10^{3}
Frequency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

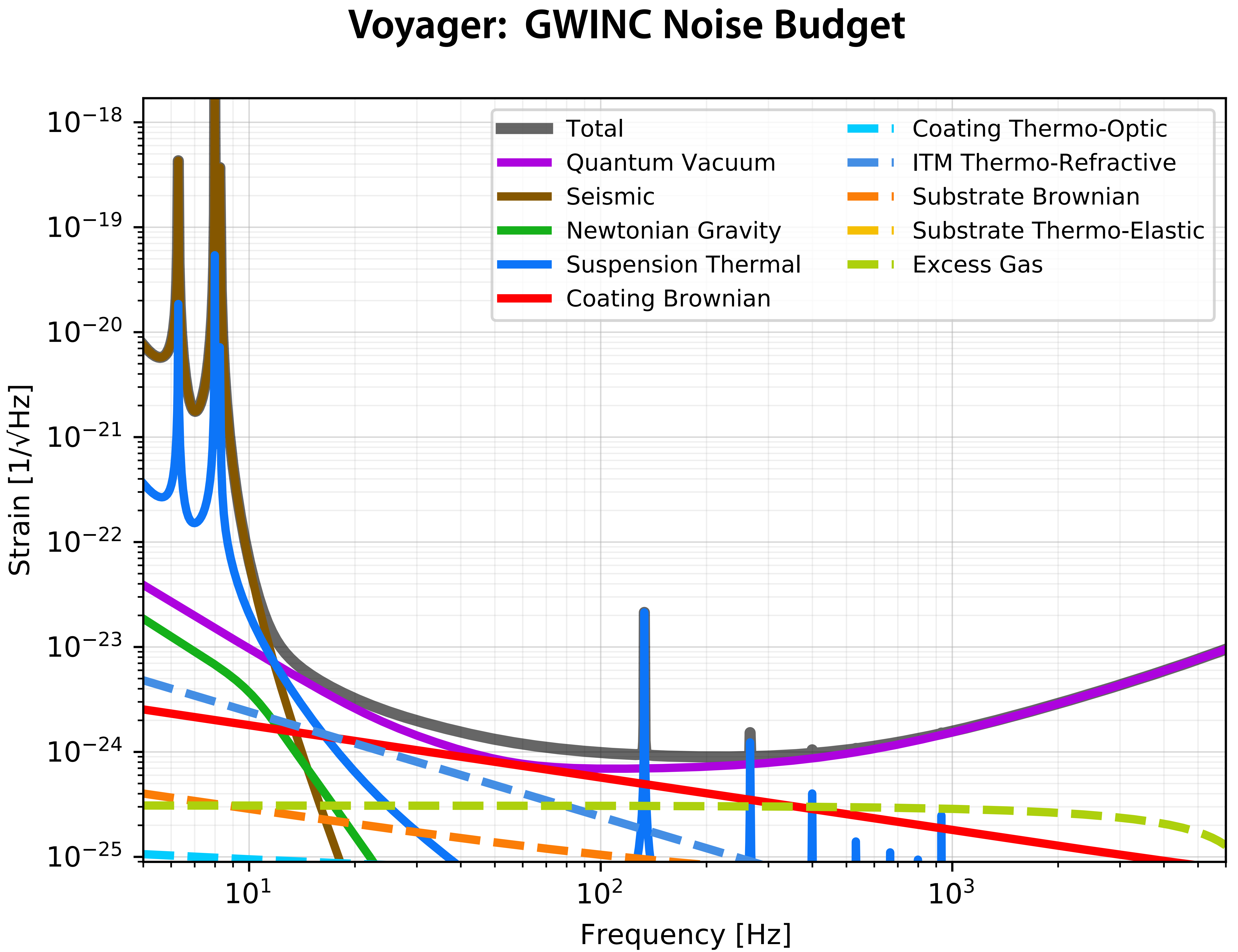
A+ Design Sensitivity + Crystal Coating (Mean Value)



Post-O5: 250 W in,10dB Squeezing, Crystal coatings (mean value)

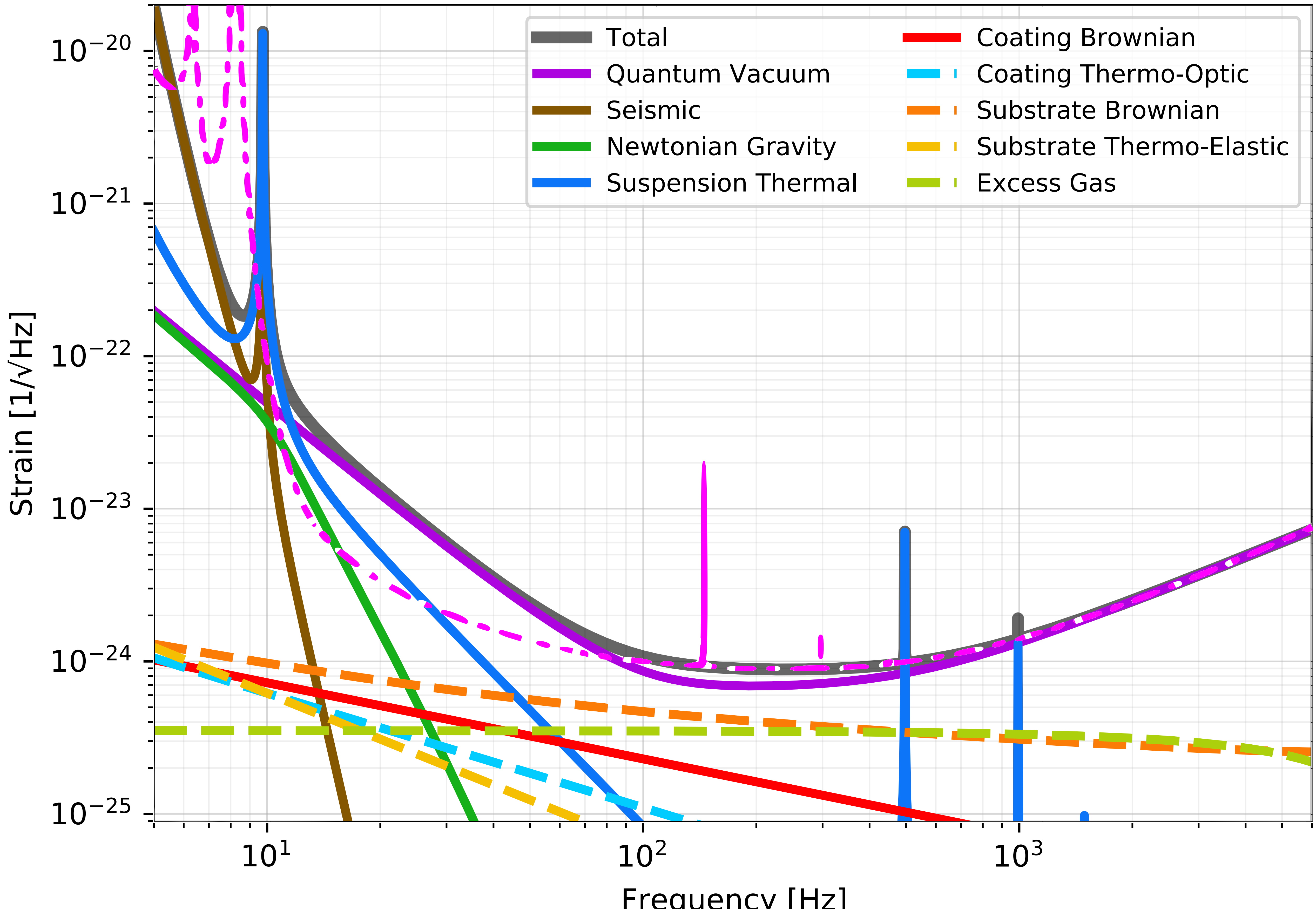


Post-O5 Quantum Noise Parameters provided by Lisa Barsotti



Voyager: GWINC Noise Budget
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
ITM Thermo-Refractive
Substrate Brownian
Substrate Thermo-Elastic
Excess Gas
Strain [1/√Hz]
Frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}

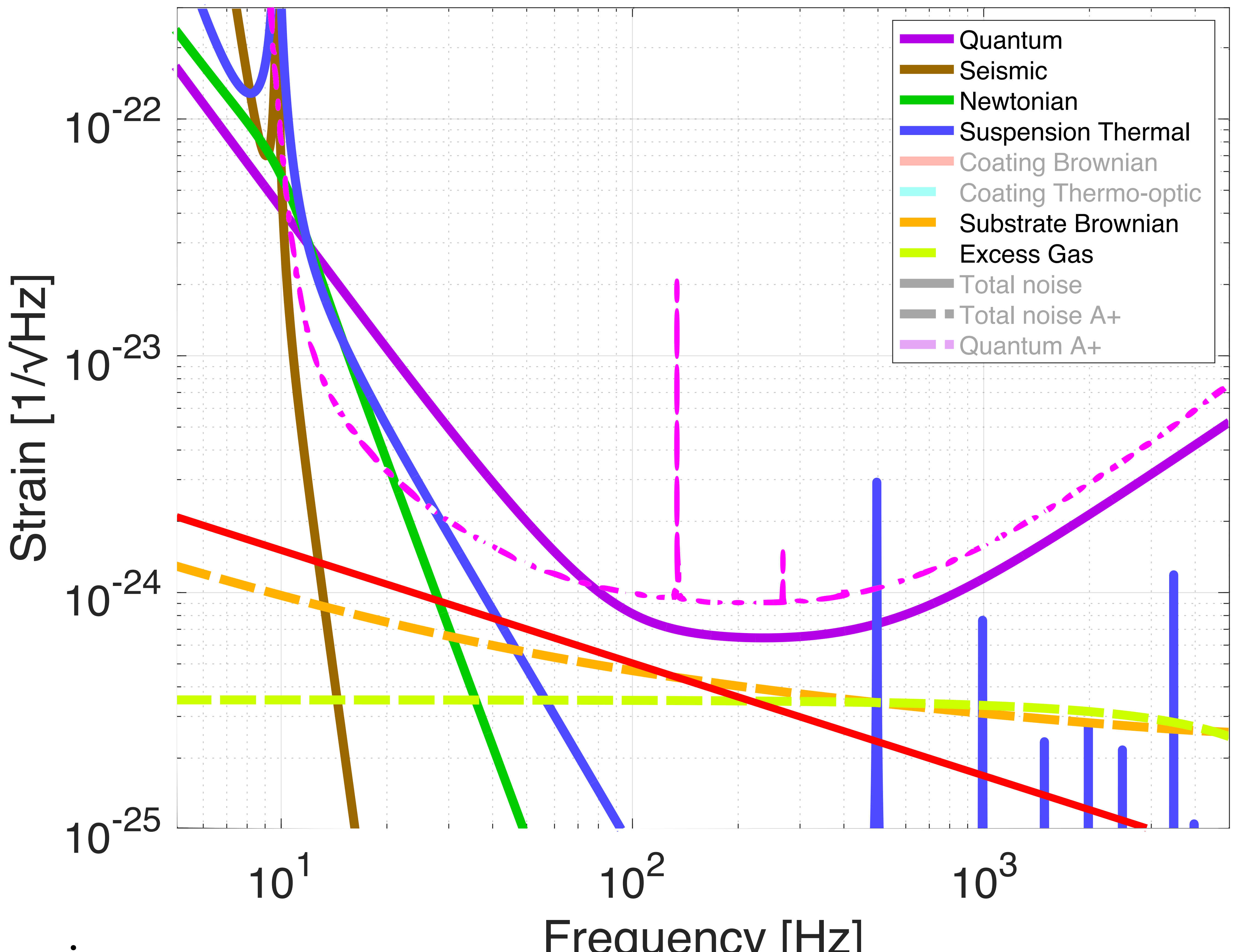
Post-O5: 250 W in, 10dB Squeezing, Crystal coatings (mean CTN) vs. Voyager



My version

Post-O5 Quantum Noise Parameters provided by Lisa Barsotti

Post-O5: 250 W in,10dB Squeezing, Crystal coatings (mean CTN) vs. Voyager



Lisa's version

Post-O5 Quantum Noise Calculation provided by Lisa Barsotti

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

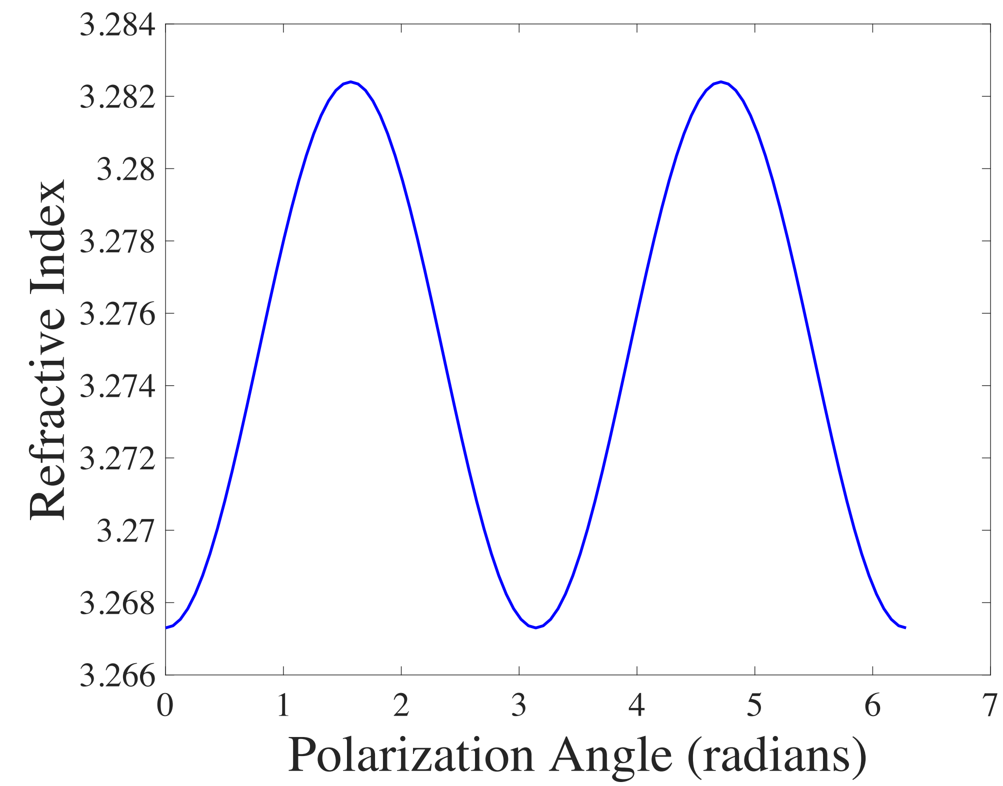
- Produces robotic bonding machines for the semiconductor industry
- Up to 45 cm bonds
- Promises zero bond defects
- History of high quality, SOI bonds
- Quoted \$4.7M for a 30 cm bonding machine for test mass.
- LIGO must provide polished, cleaned test masses.
- Thorlabs provides coating
- 13 month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

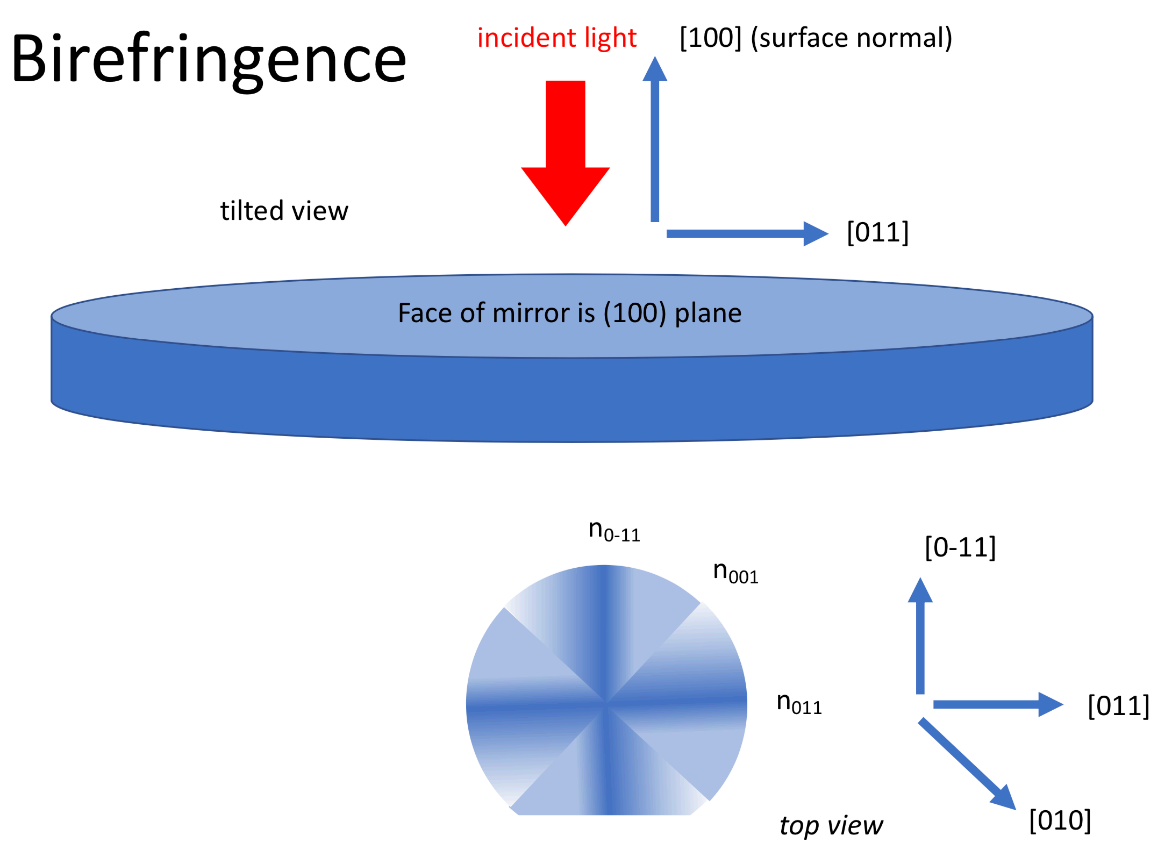
Development: Timeline & Budget

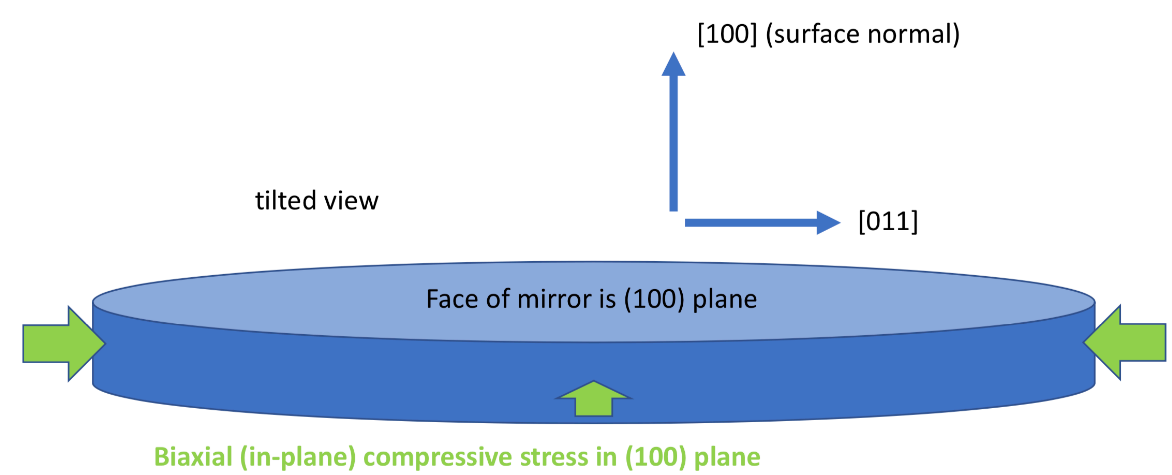
Timeline	Activity	Cost
First Year	1. Design and order of GaAs crystal wafer (Freiberger) 2. Order AlGaAs mirrors for prototype detector (Hannover) 3. Continuing noise studies (Syracuse, American, MIT)	$1.6 M
Second Year	1. Growth and measurement of gallium arsenide crystal (Freiberger) 2. Begin AlGaAs 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

Birefringence

In-plane compressive strains have been shown to induce birefringence in AlGaAs. Strain induced birefringence is common in many materials, including silica. A 1% strain has been shown to induce a 0.2% fluctuation in the index with angle.







Biaxial [in-plane] compressive stress in (100) plane

ElectroOptic Noise

Thesis experiment of Danny Vander-Hyde

- Longitudinal E field measurements performed at 10752 Hz
  - Preliminary results match prediction
  - Next measurement is a frequency sweep from 300–5000 Hz
- Transverse E field measurements pending

Normal E-field injection (basic construction)

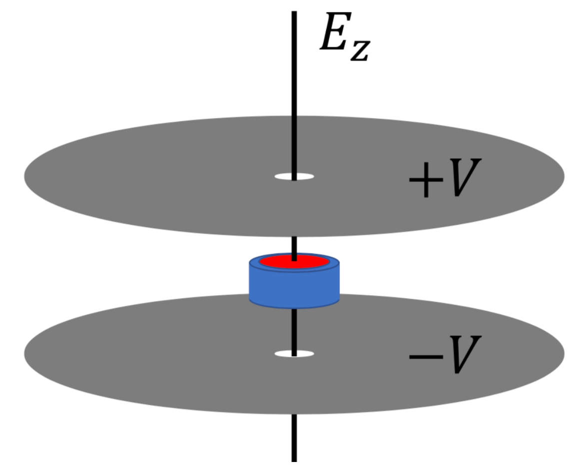
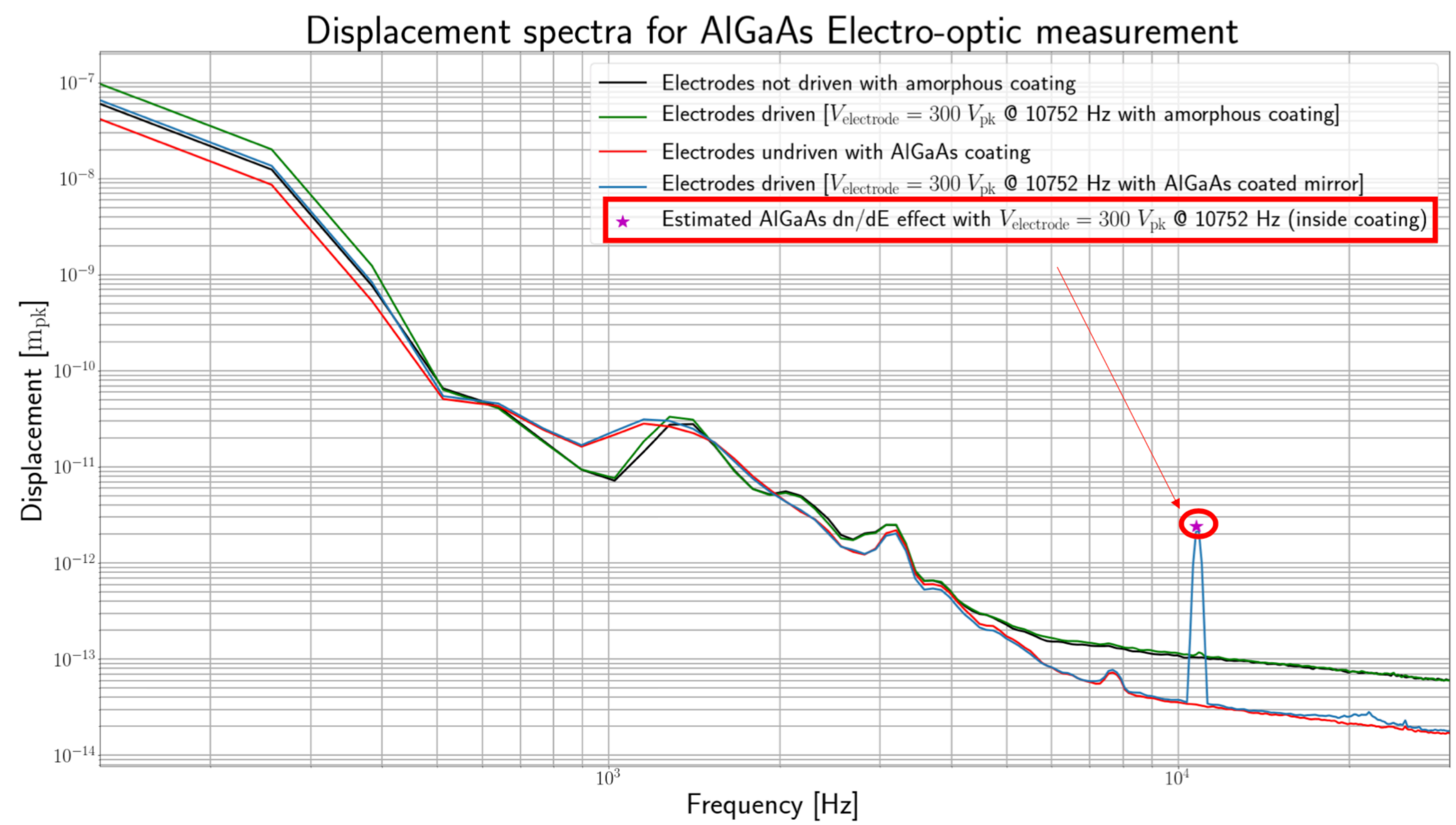
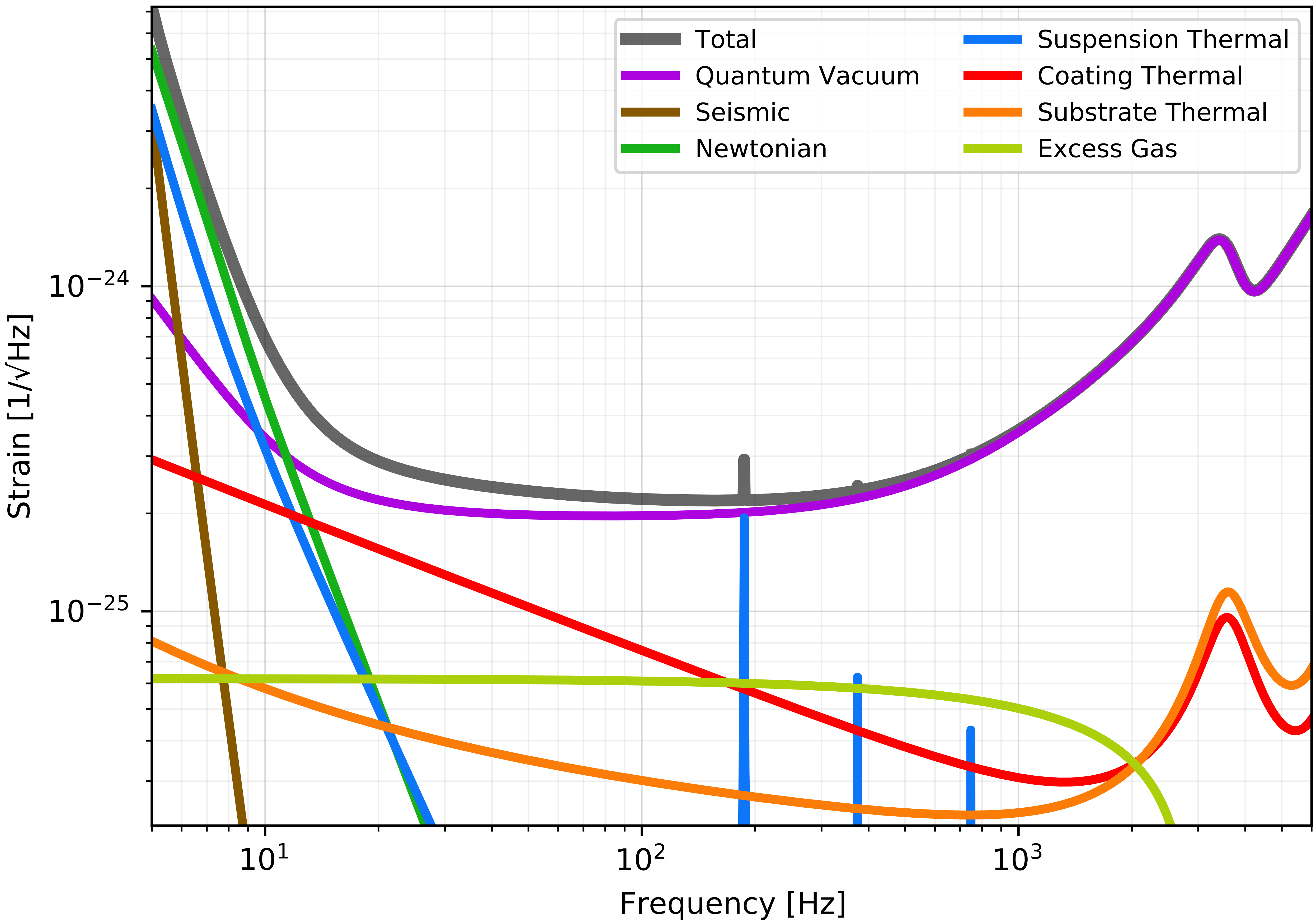


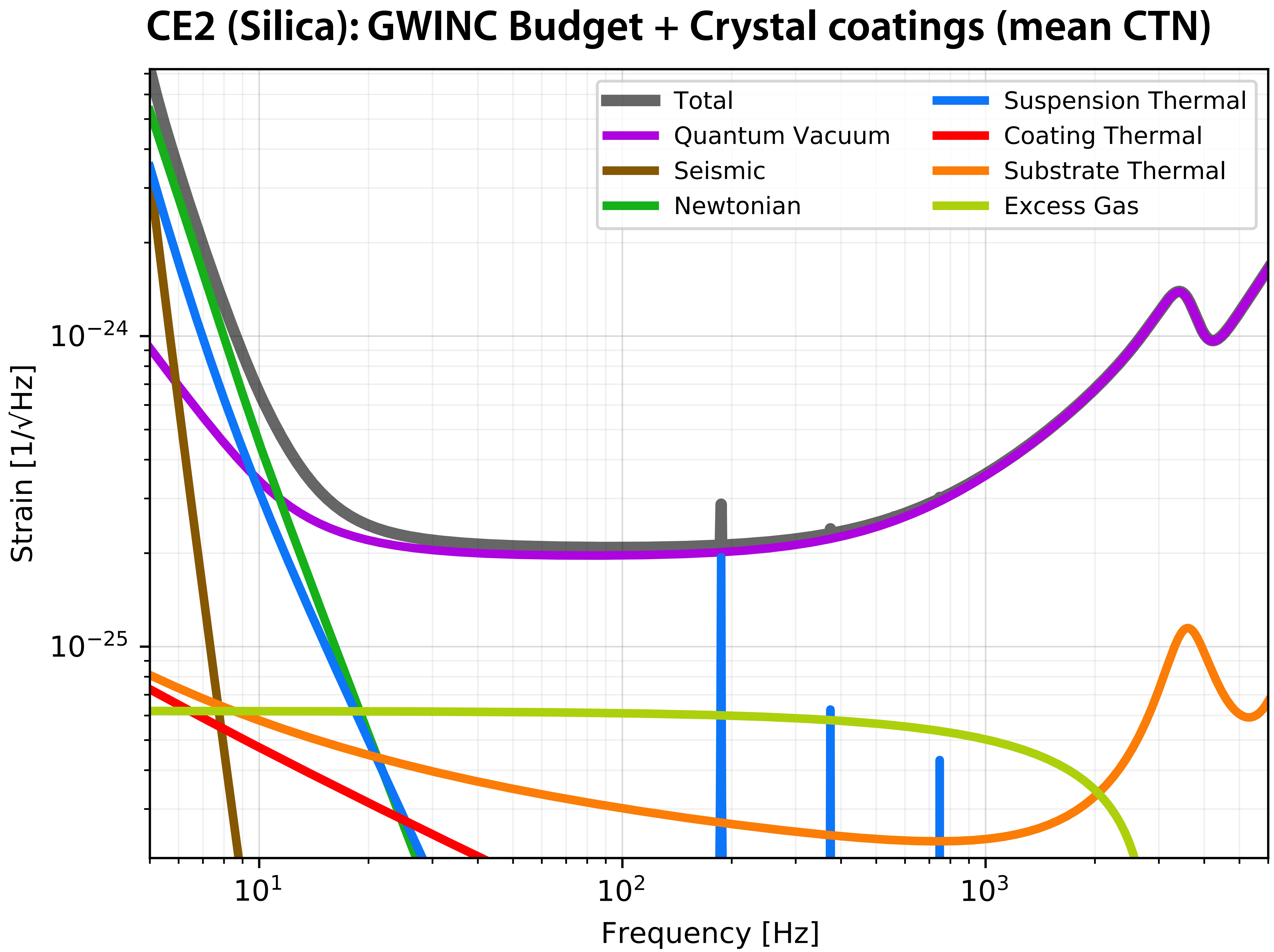
Figure elements do not reflect realistic scaling

Single frequency measurement



CE2 (Silica): GWINC Noise Budget




CE2 (Silica): GWINC Budget + Crystal coatings (mean CTN)
Total
Quantum Vacuum
Seismic
Newtonian
Suspension Thermal
Coating Thermal
Substrate Thermal
Excess Gas
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}
Frequency [Hz]
Strain [1/√Hz]

Cantilever Thermal Noise

$\phi_{11} = 8 \times 10^{-5}$

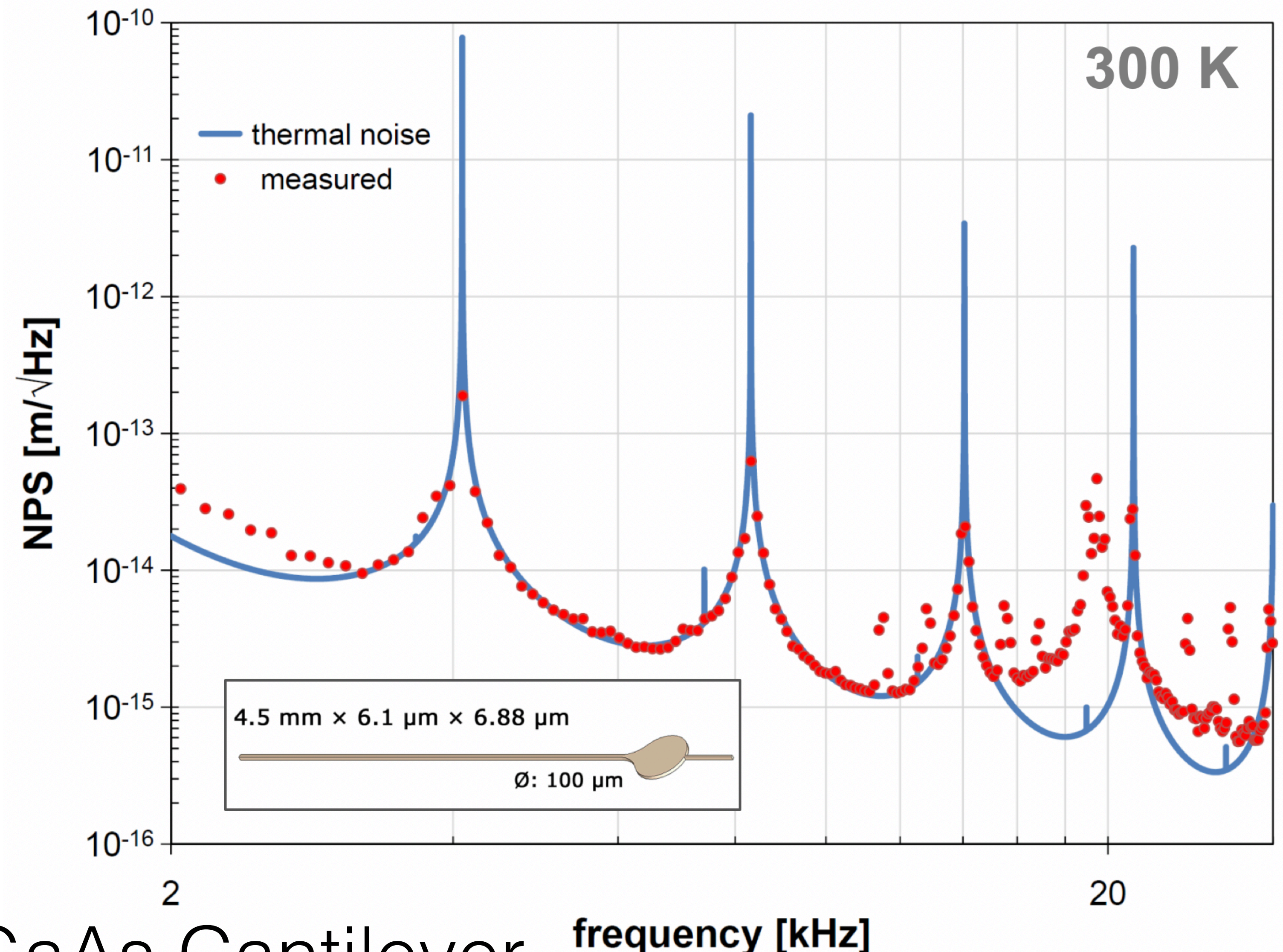
$\phi_{12} = 8 \times 10^{-5}$

$\phi_{44} = 5 \times 10^{-7}$

40.5-period GaAs/ AlGaAs stack. Total thickness of 6.88 um (4.5-mm long × 6-µm wide × 6.8-µm

Room Temperature Thermal Noise

Shannon Sankar, Thomas Corbitt, and Nergis Mavalvala @ MIT



Q: 40k
F: 20k
P_{ext}: 5 µW

AlGaAs Cantilever