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IGR SUPA

Cryogenics for Future Gravitational Wave Detectors

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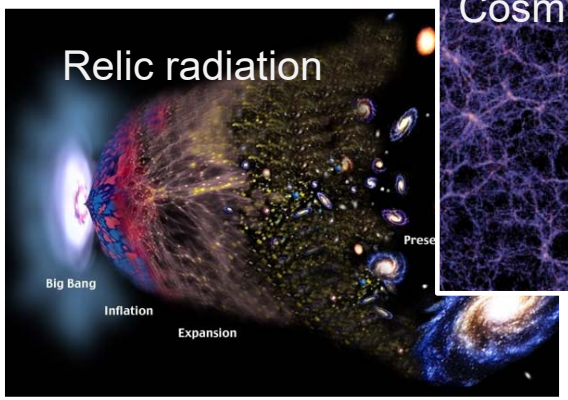
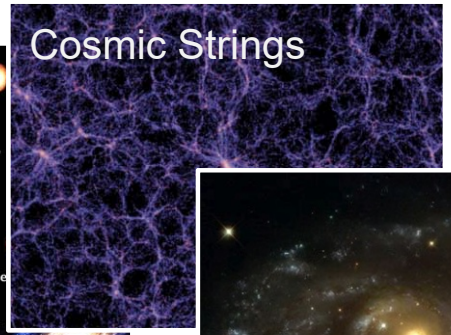
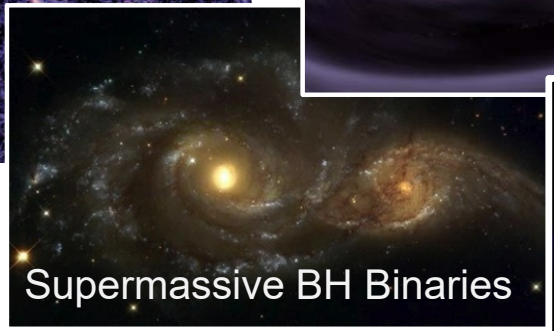
Overview

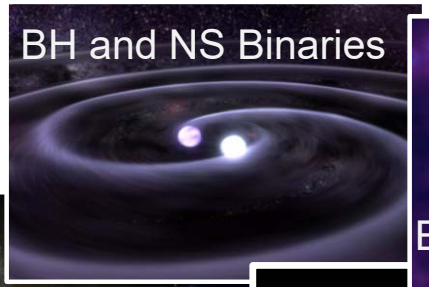
- GW astronomy and the current network of detectors
- Why cryogenic
- Cryogenic R&D
  - Bulk material
  - Suspension thermal noise
  - Coating thermal noise
  - Seismic noise/Baffling/Cooling
- Summary

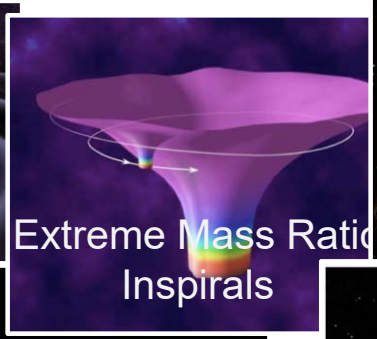
The Gravitational Wave Spectrum

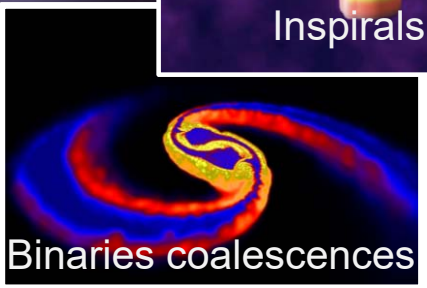


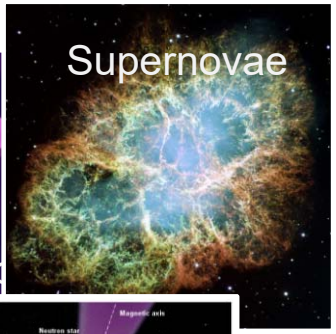


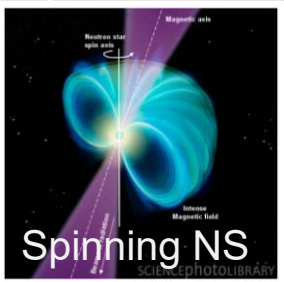












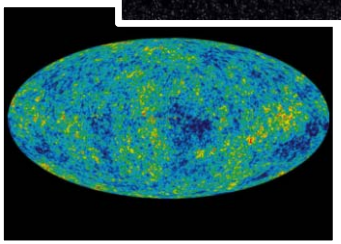
10^{-16} Hz 10^{-9} Hz 10^{-4} Hz 10^{0} Hz 10^{3} Hz

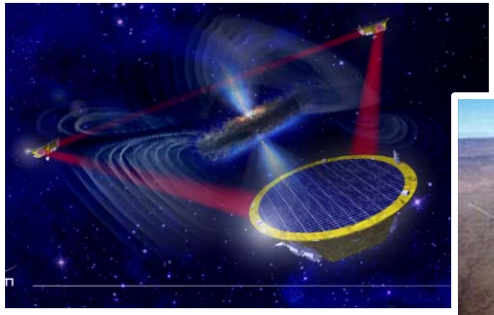
Inflation Probe

Pulsar timing

ace detectors

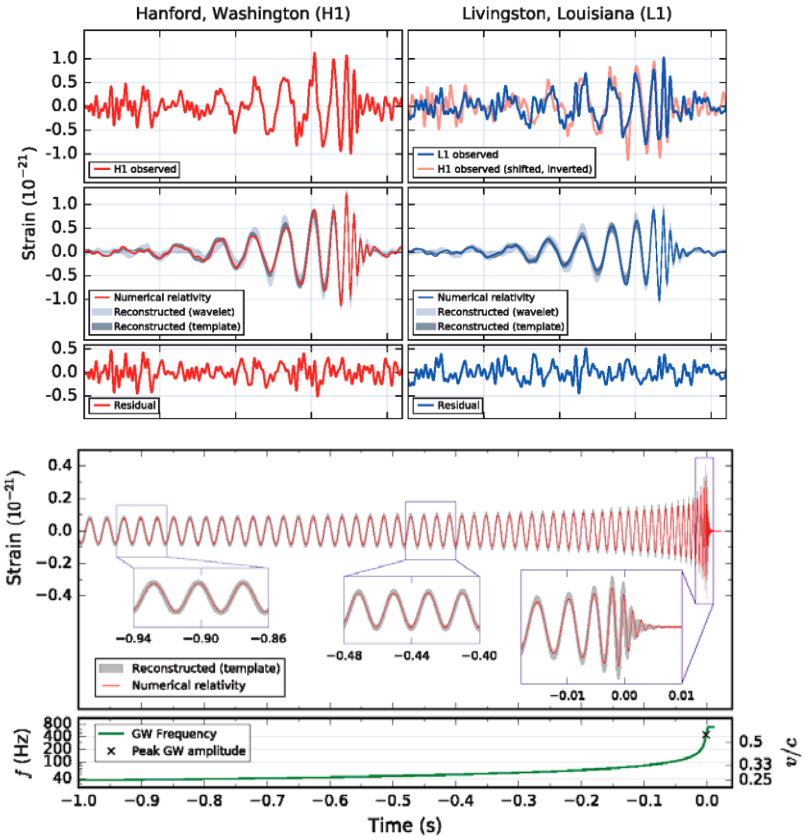
Ground based





- Adapted from M. Evans (LIGO G1300662-v4)

First Detections



Phys. Rev. Lett. 116, 061102, 2016
Phys. Rev. Lett. 116, 241103, 2016

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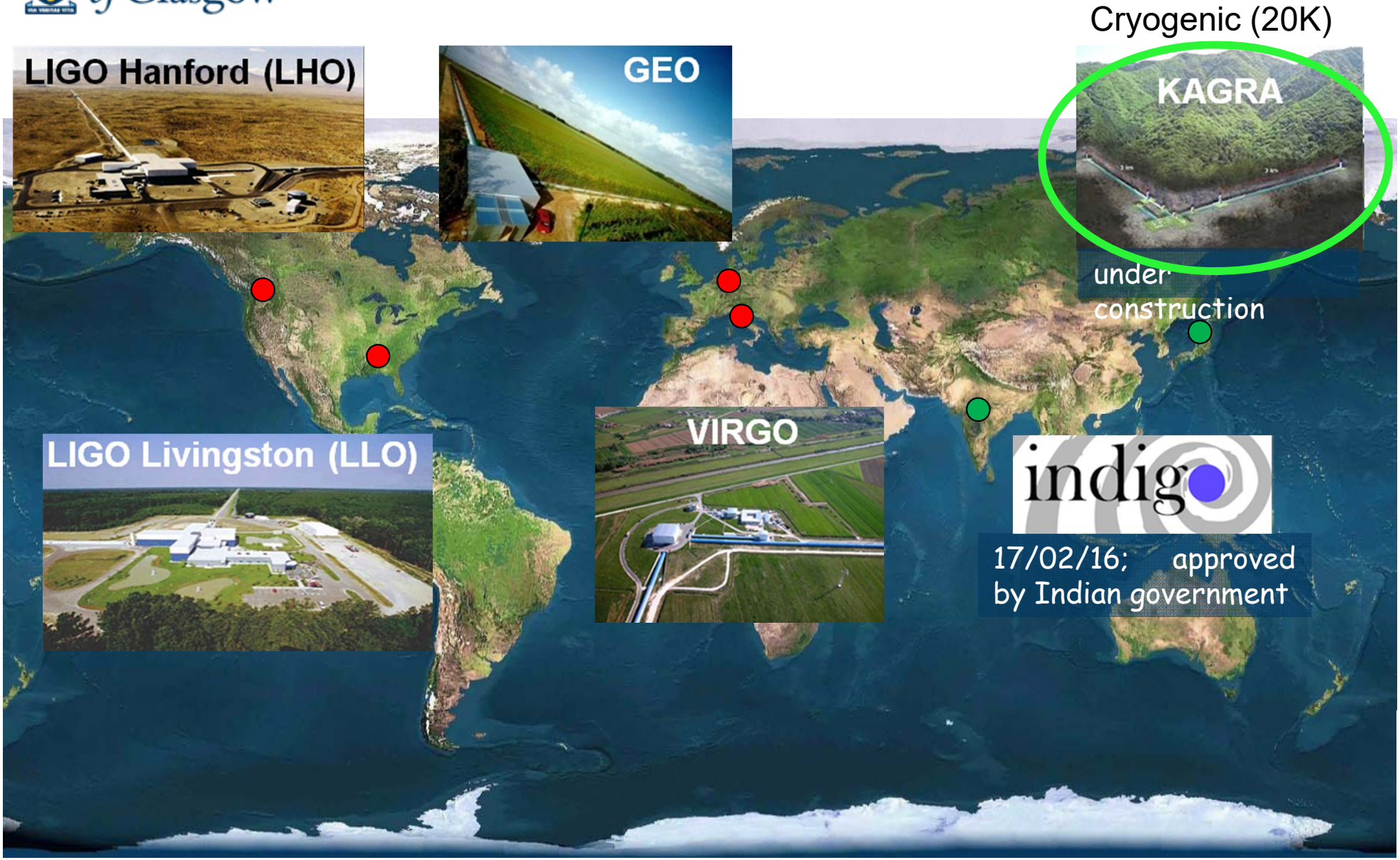
International Network



- A network is required to localise the source position
- 2G detectors have opened the window, 3G will give a rich astrophysical output

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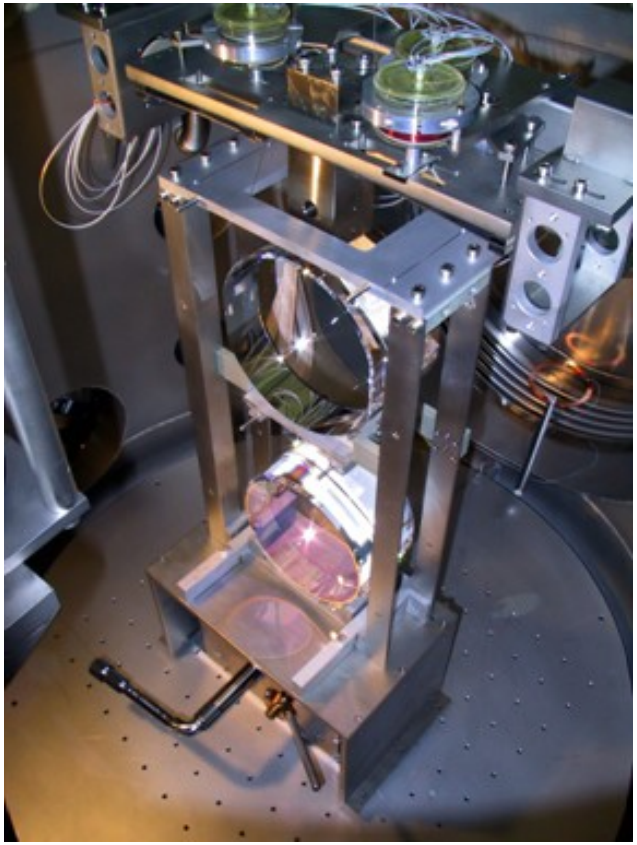
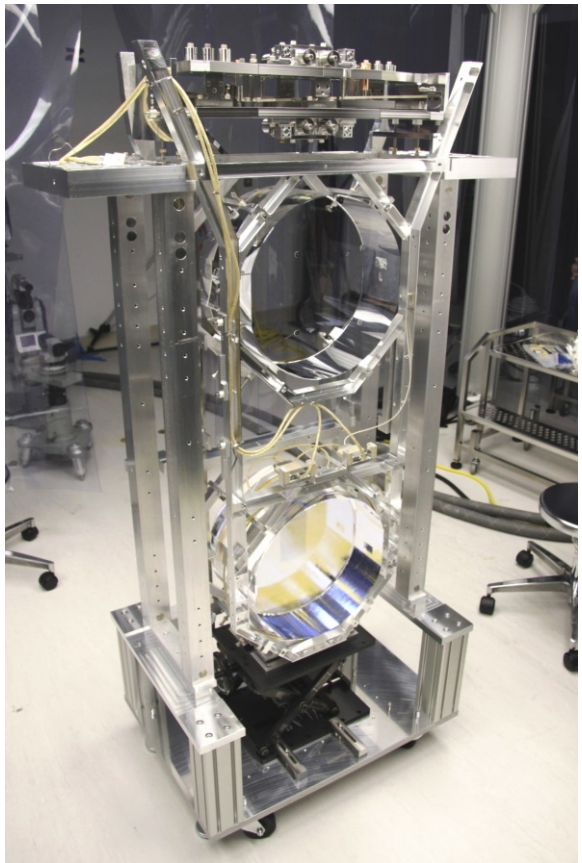
R&D Timeline

- Small scale R&D → prototypes → detectors
- Technology typically takes ≥10 years from design to implementation
- Monolithic suspensions & signal recycling pioneered in GEO-600 → upscaled to aLIGO





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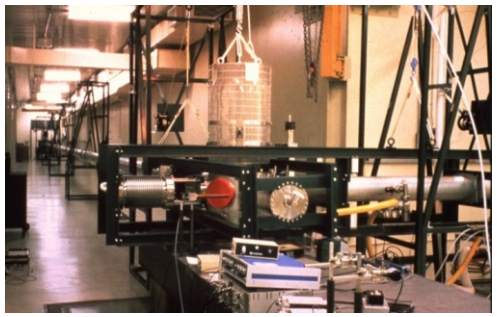
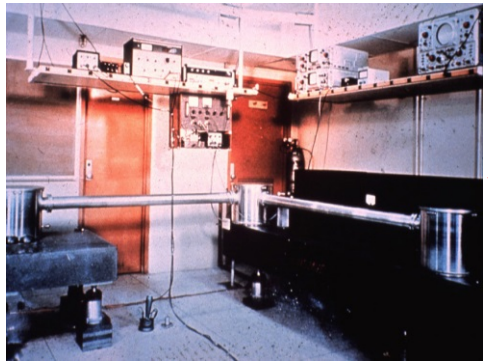
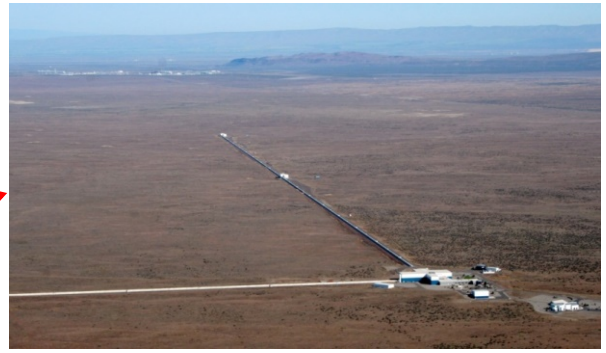


Prototypes (80s-current)

GEO 600/HF (90s-current)

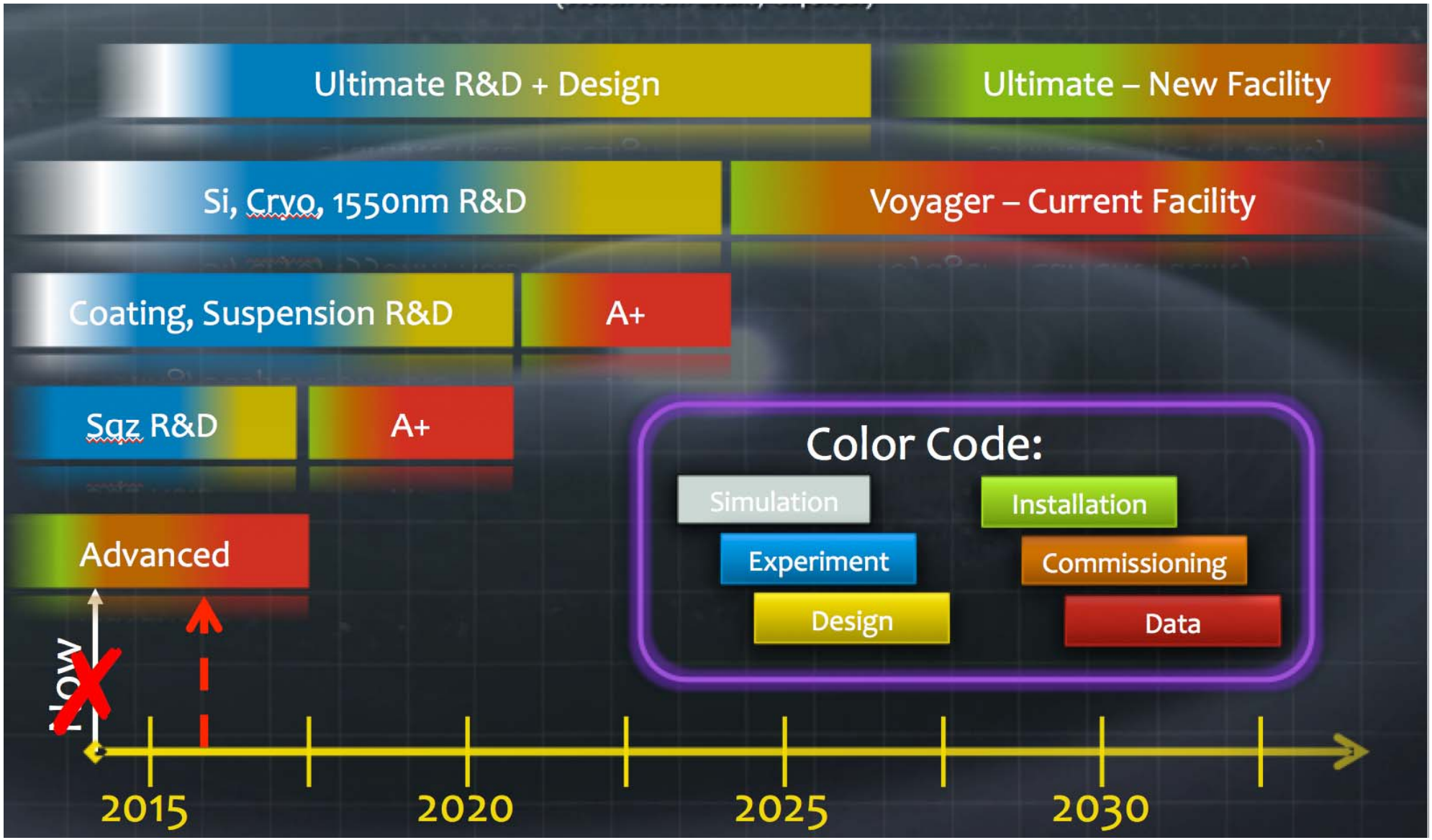


R&D (70s-80s)



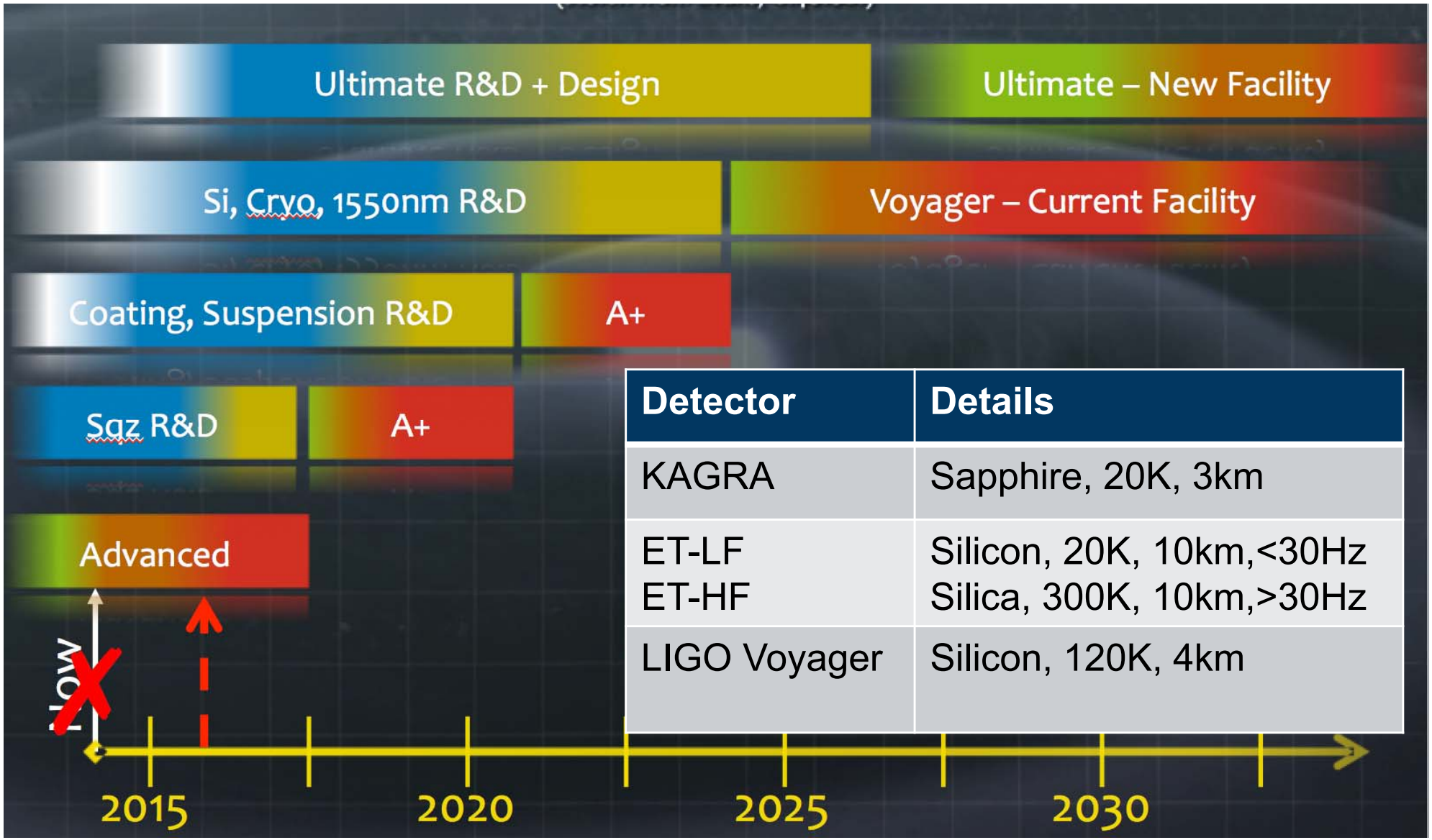
LIGO/aLIGO (90s-current)

Current/Future Outlook (aLIGO)



Evans (G1401081), Shoemaker (G1600194-v1)

Current/Future Outlook (Globally)



Detector	Details
KAGRA	Sapphire, 20K, 3km
ET-LF ET-HF	Silicon, 20K, 10km,<30Hz Silica, 300K, 10km,>30Hz
LIGO Voyager	Silicon, 120K, 4km

Evans (G1401081), Shoemaker (G1600194-v1)

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Why Cryogenic?

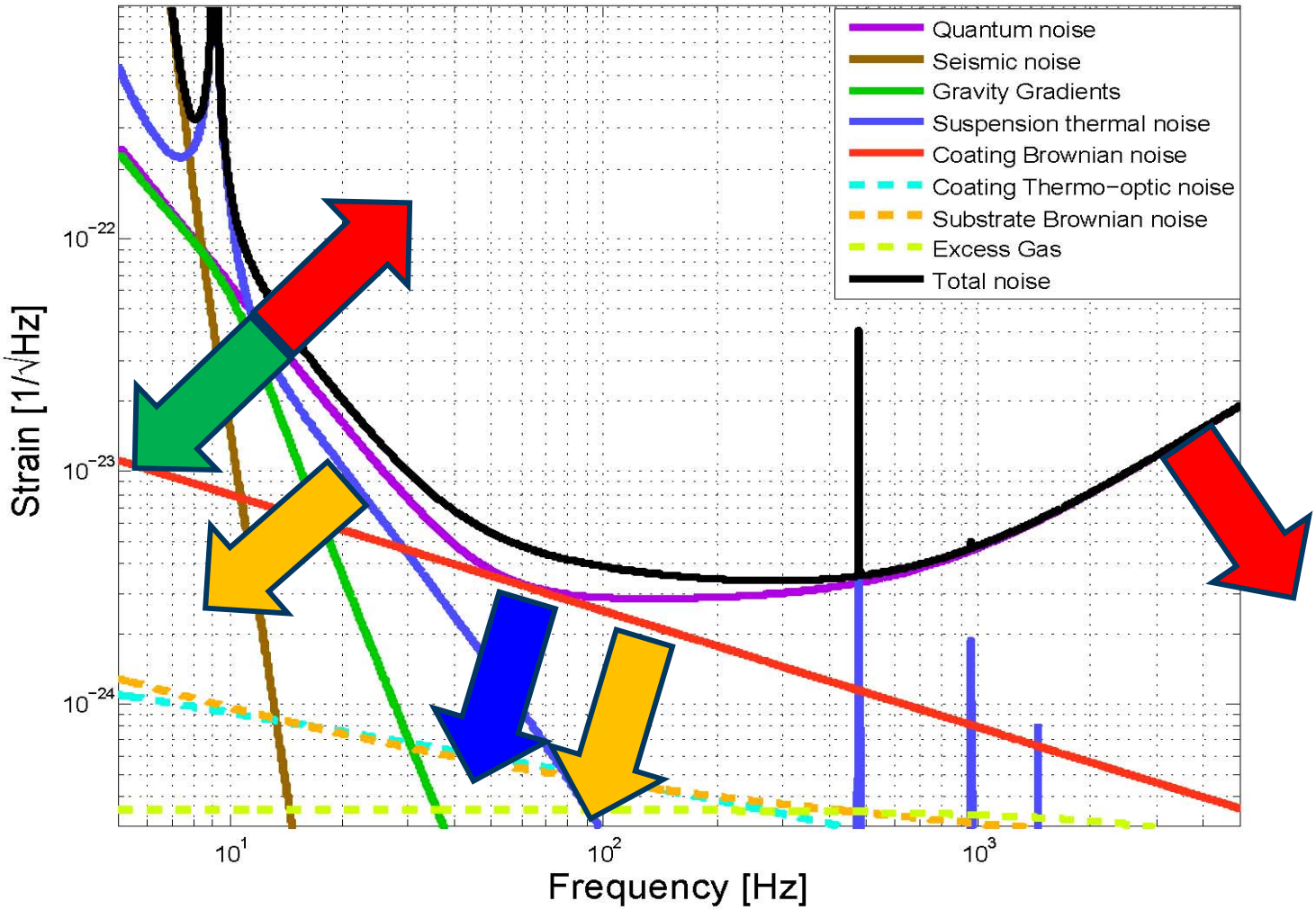
- aLIGO design sensitivity

Higher laser power

Heavier masses

Larger beam

Cryogenic



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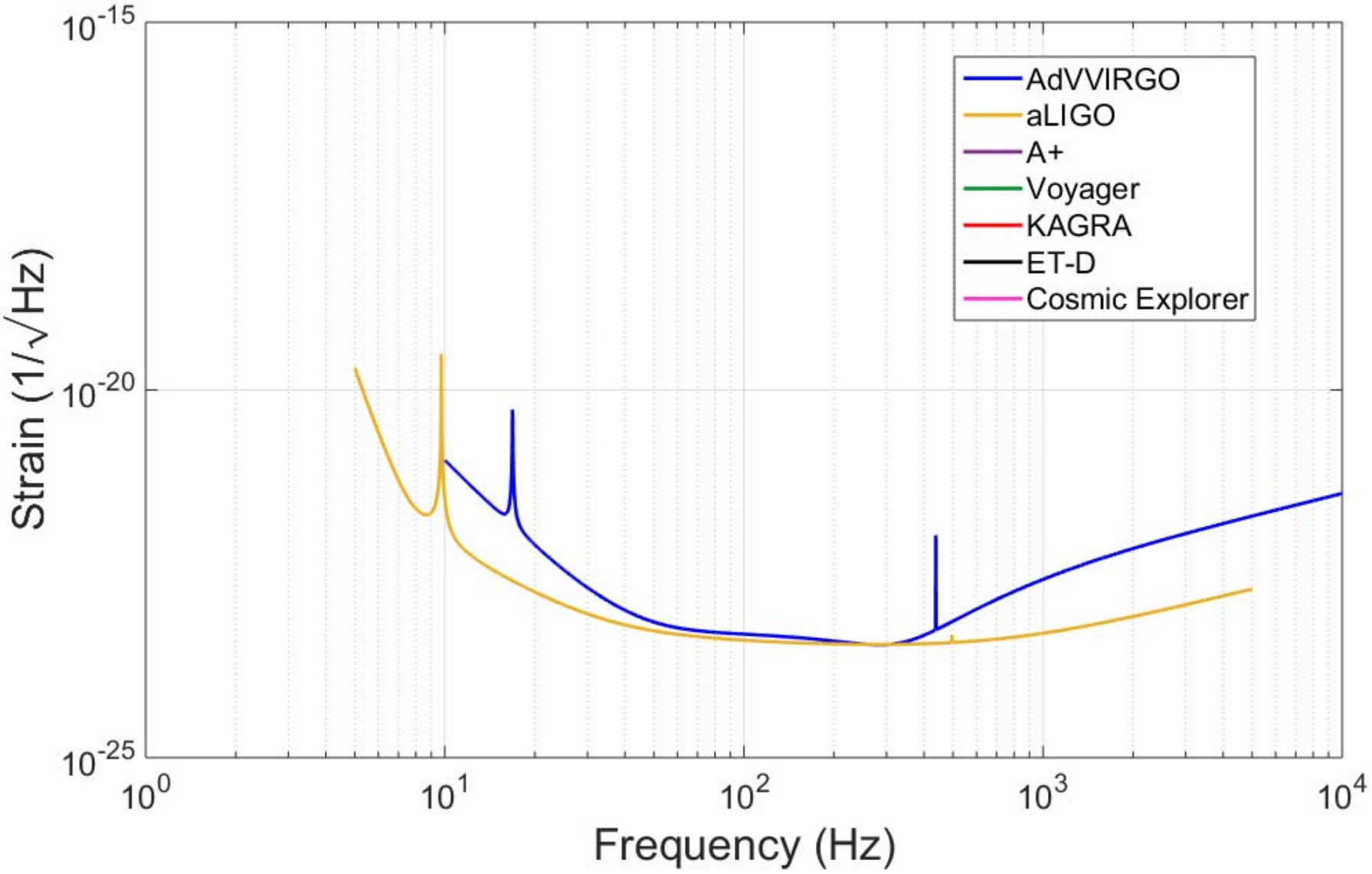
Sensitivity Comparison



M. Evans, T1500293-v8

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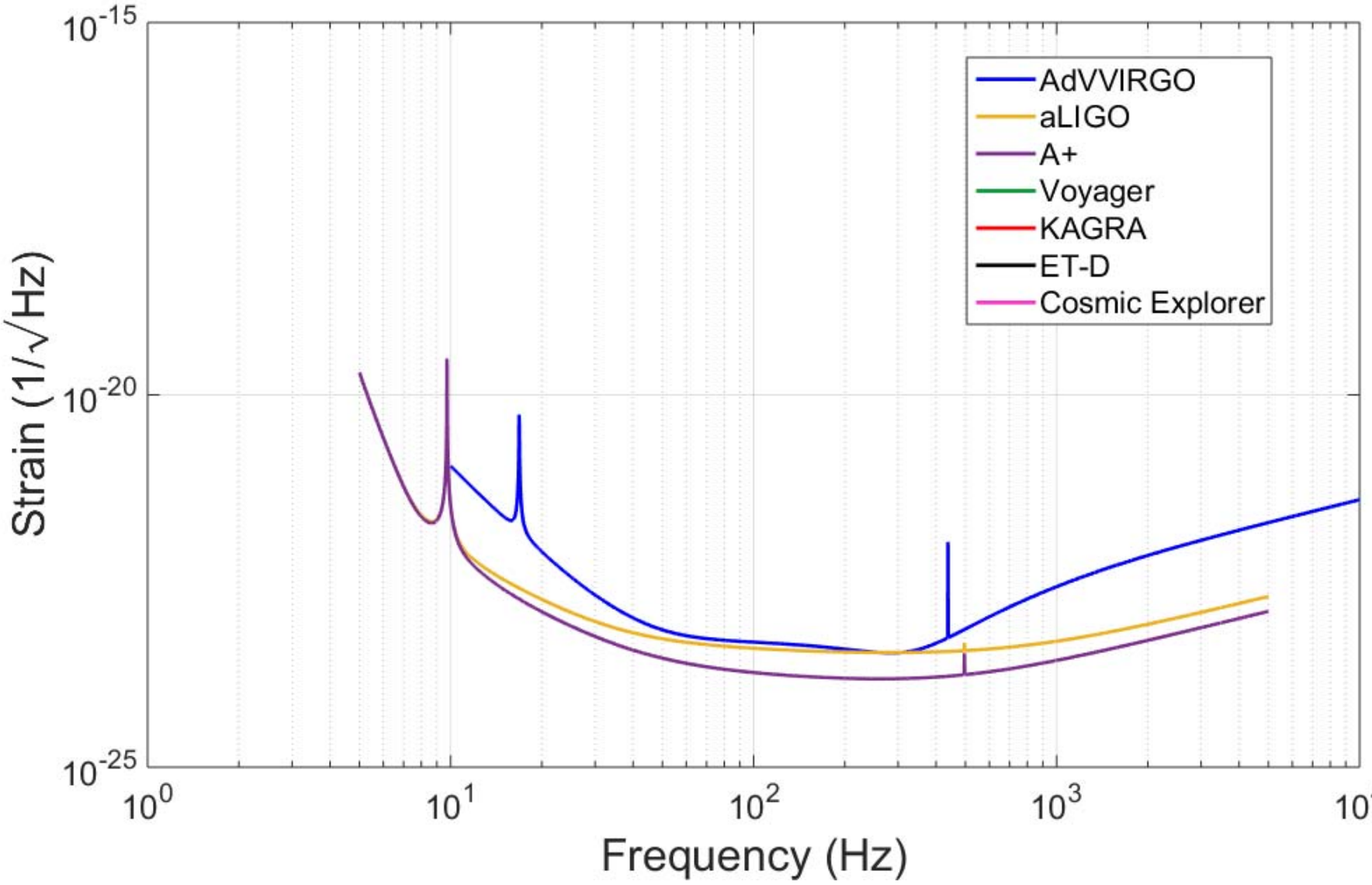
Sensitivity Comparison



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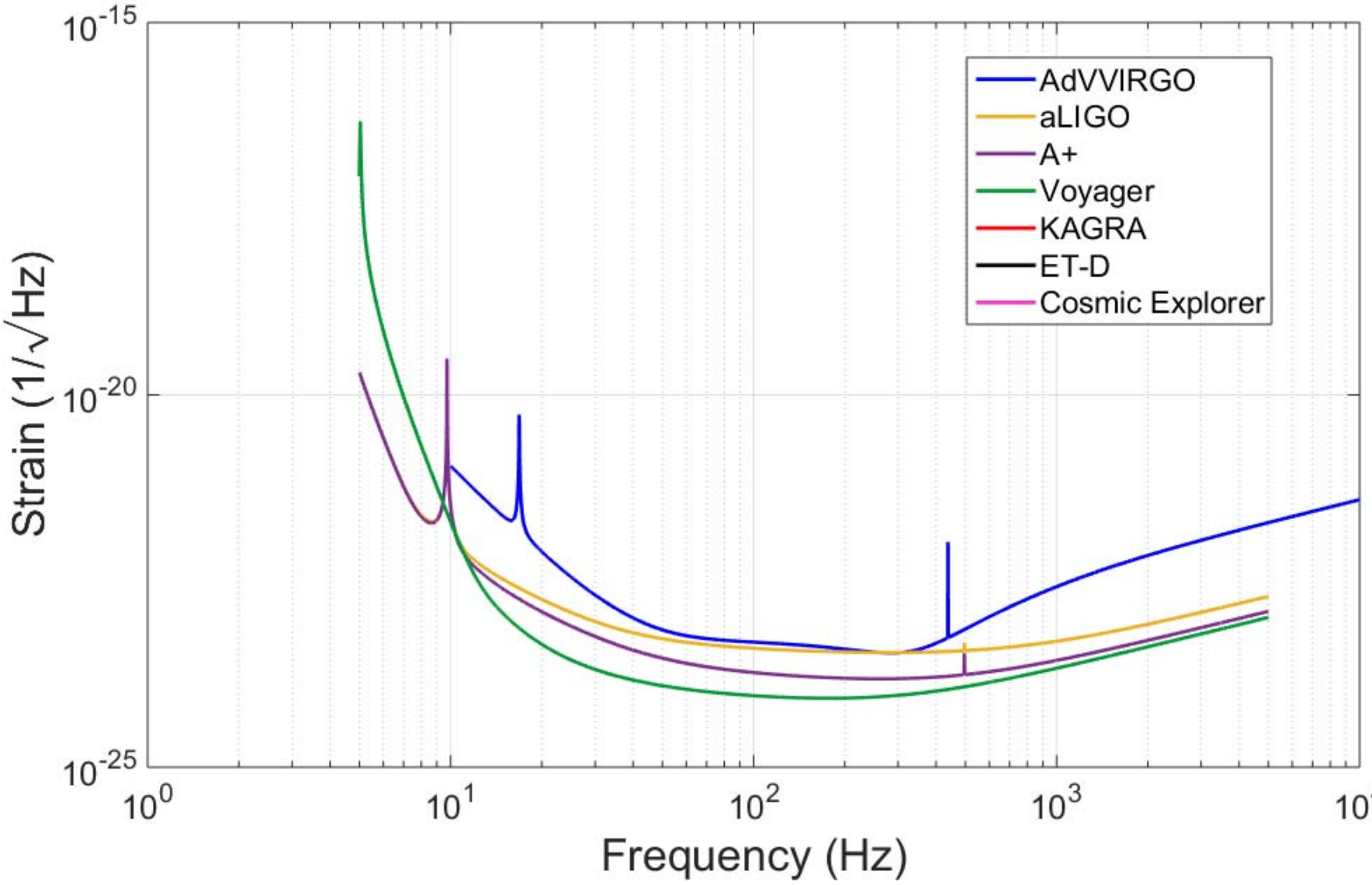

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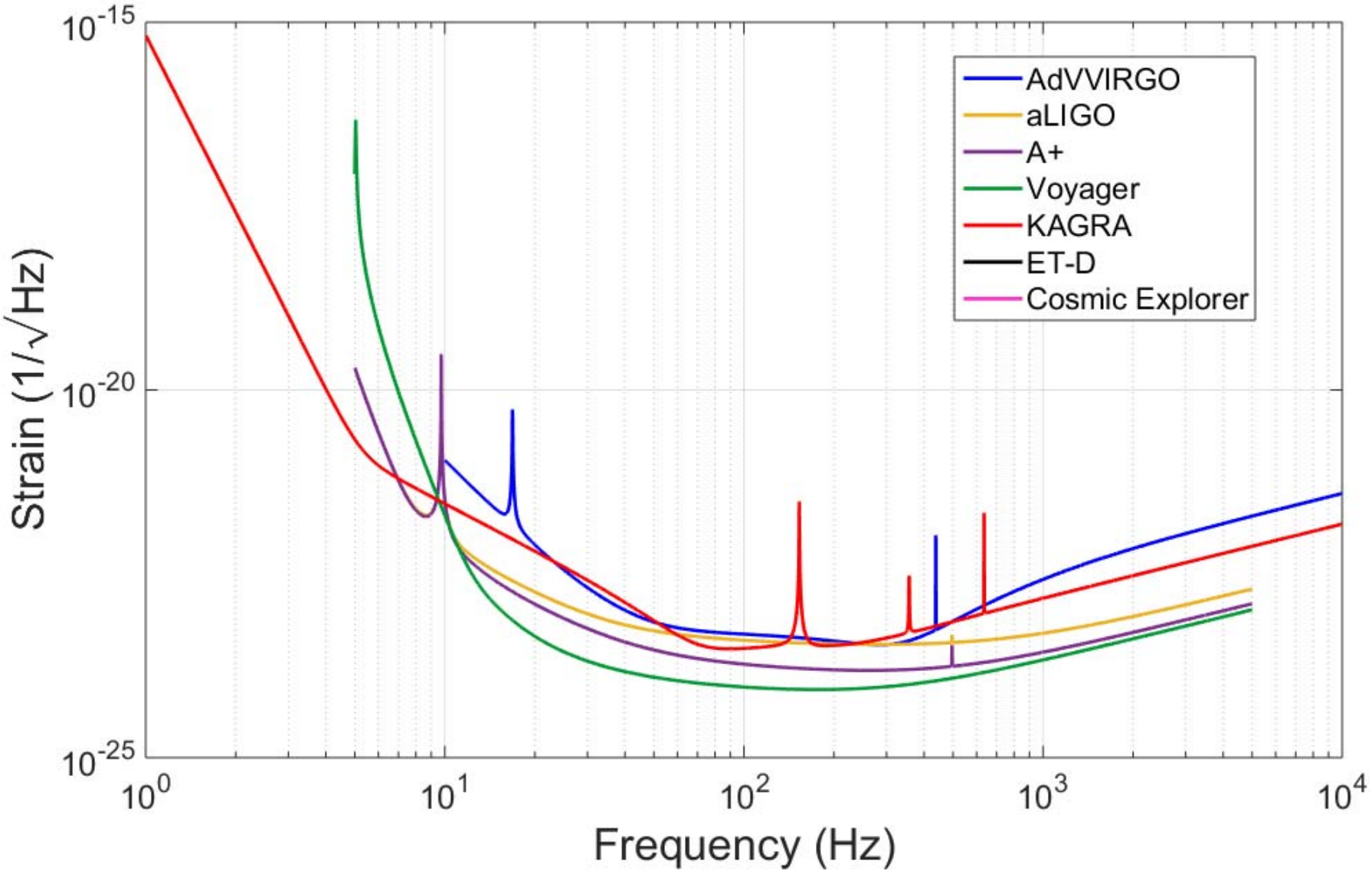

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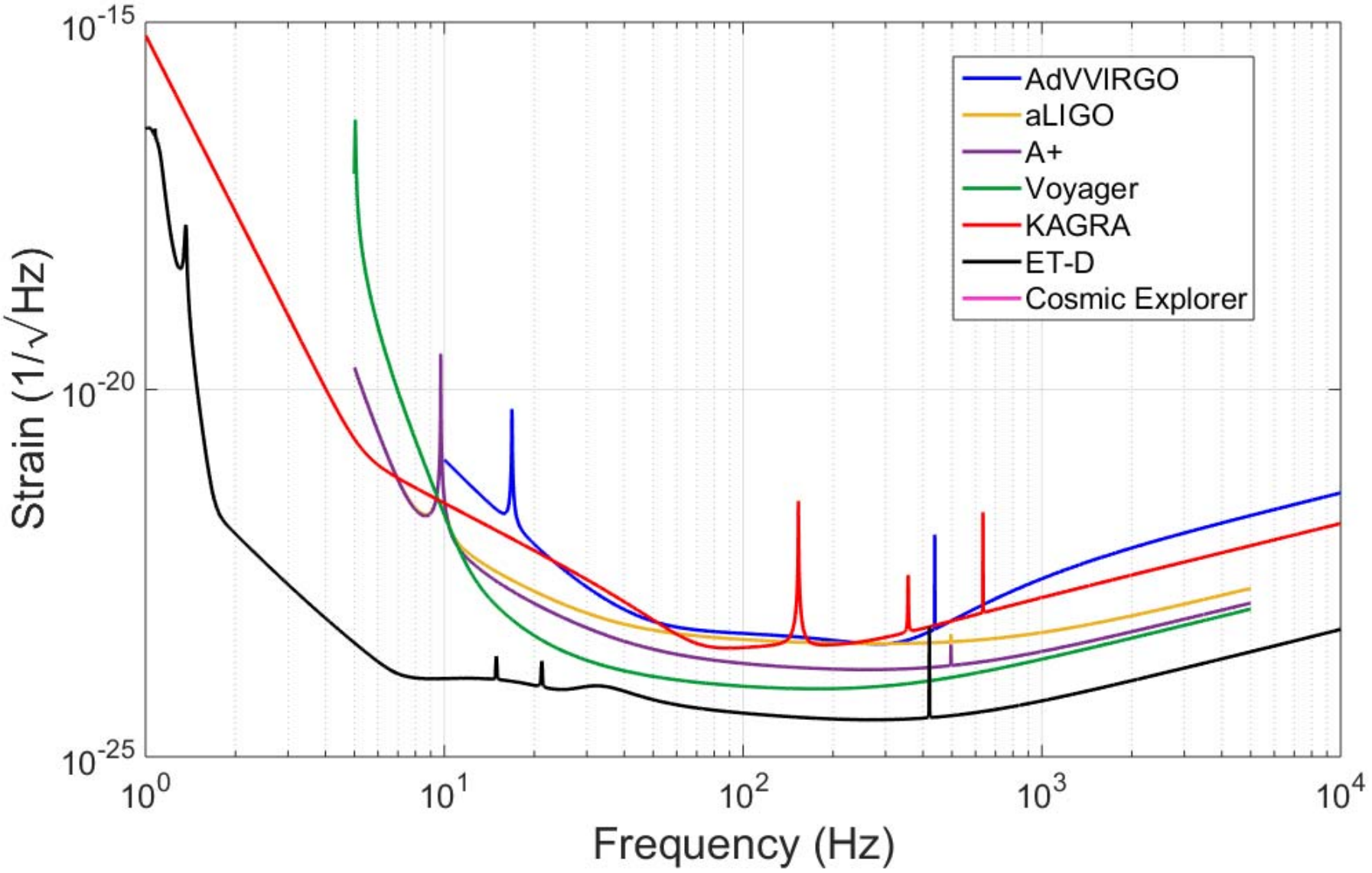

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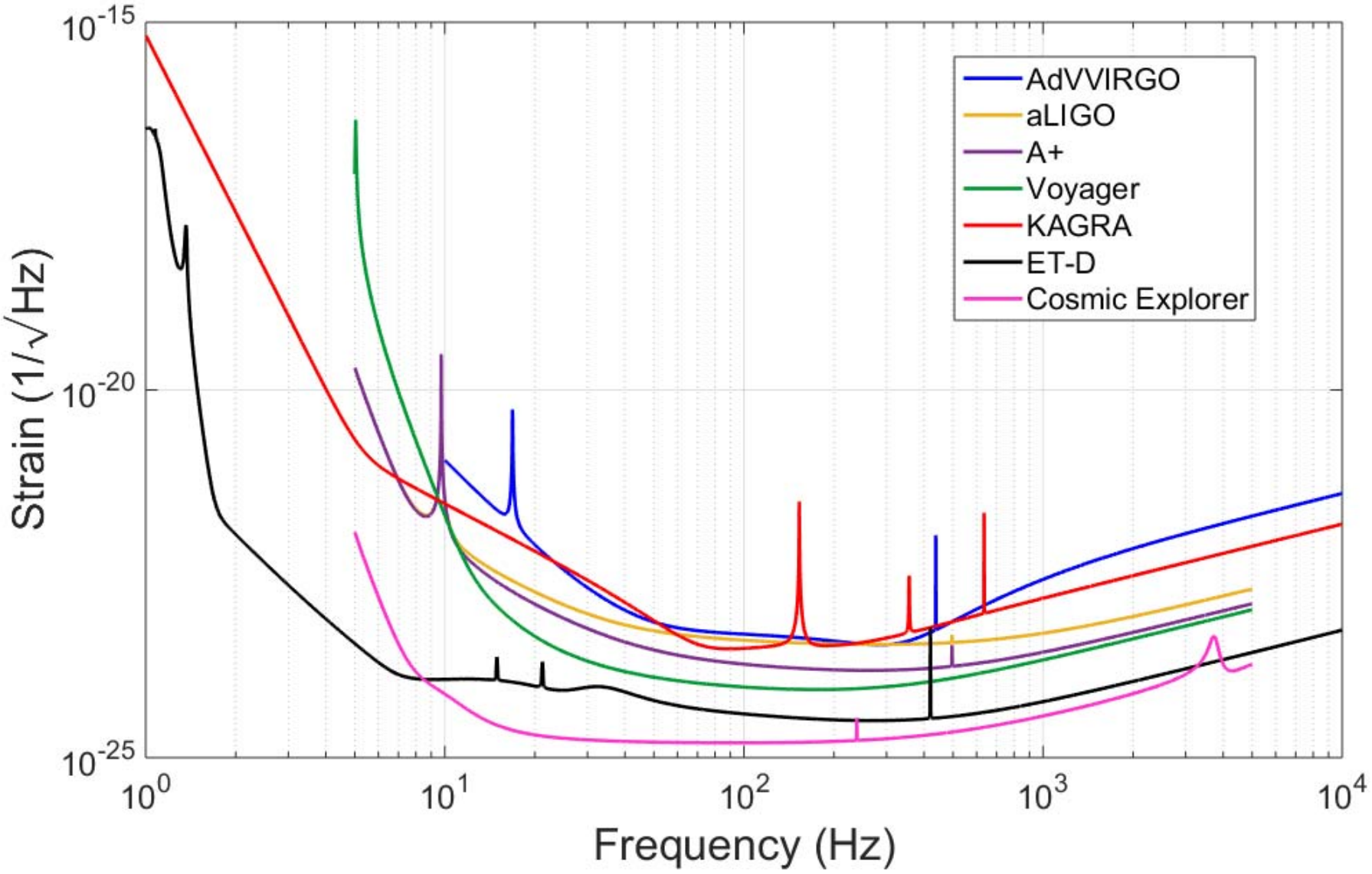
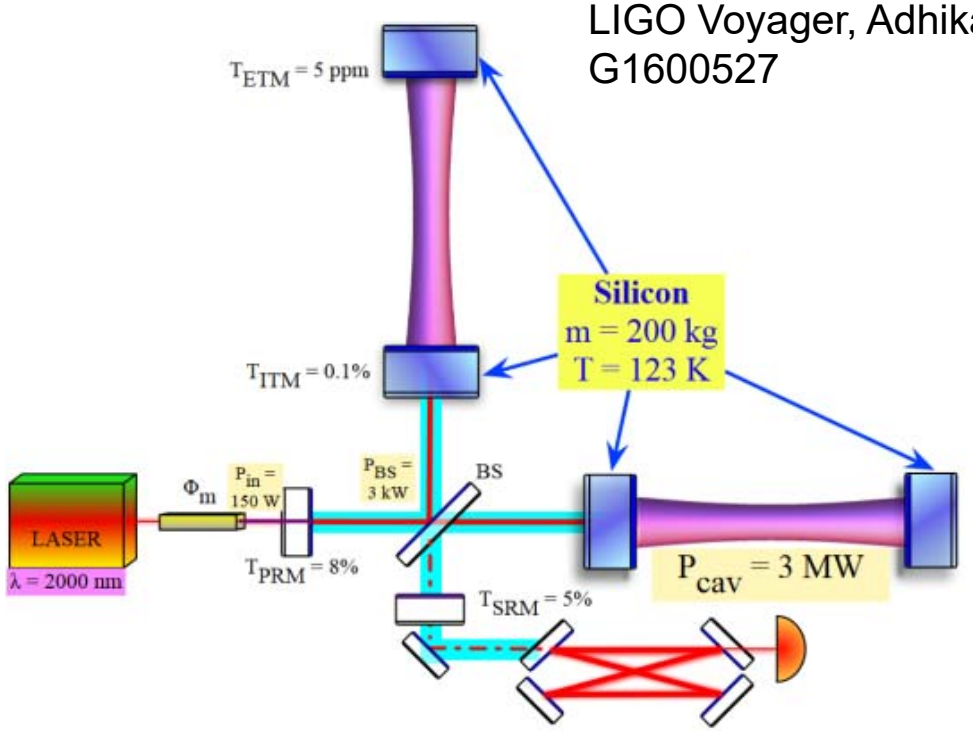
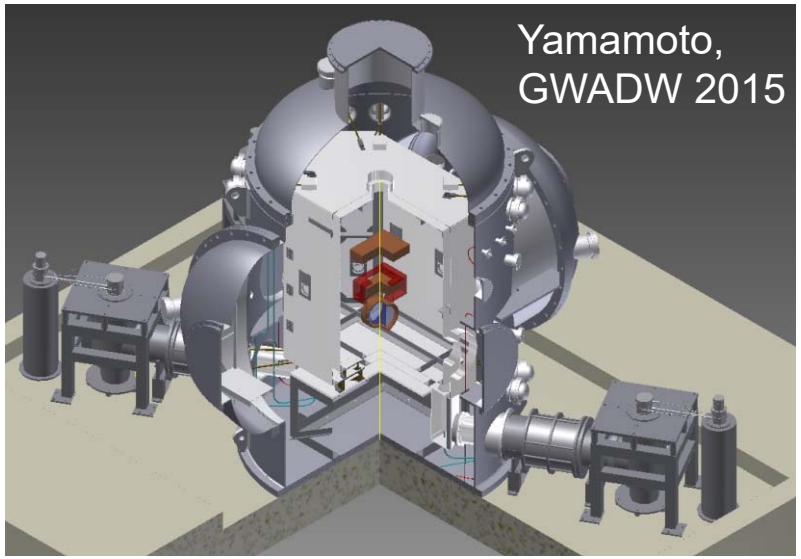
Sensitivity Comparison

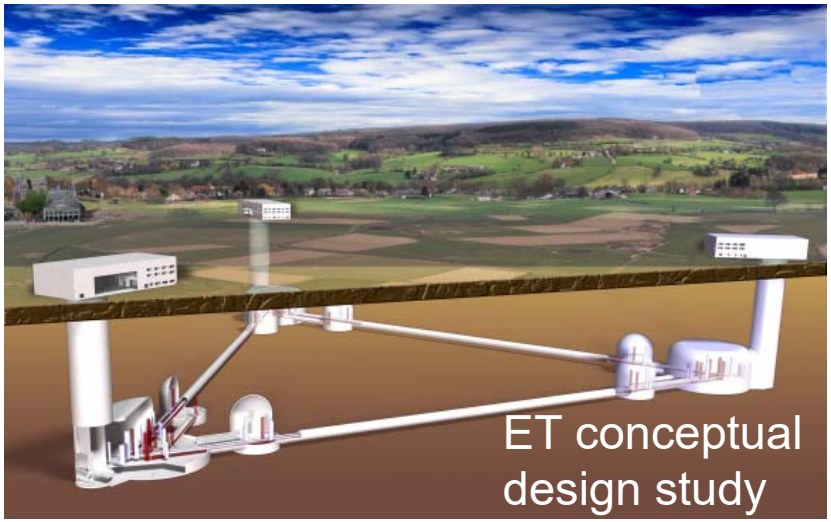


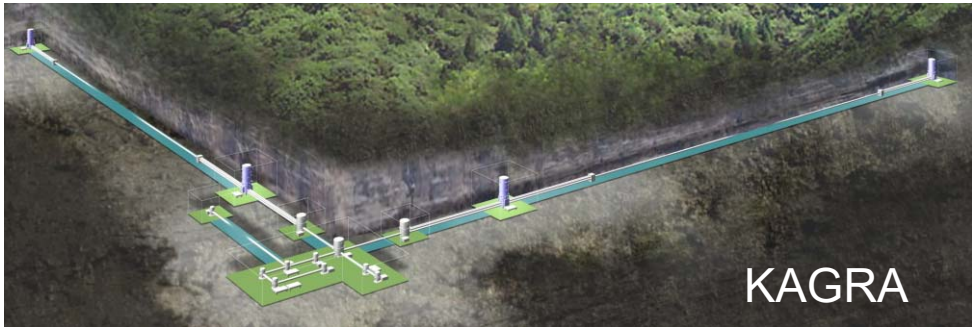
M. Evans, T1500293-v8

Detector Overview





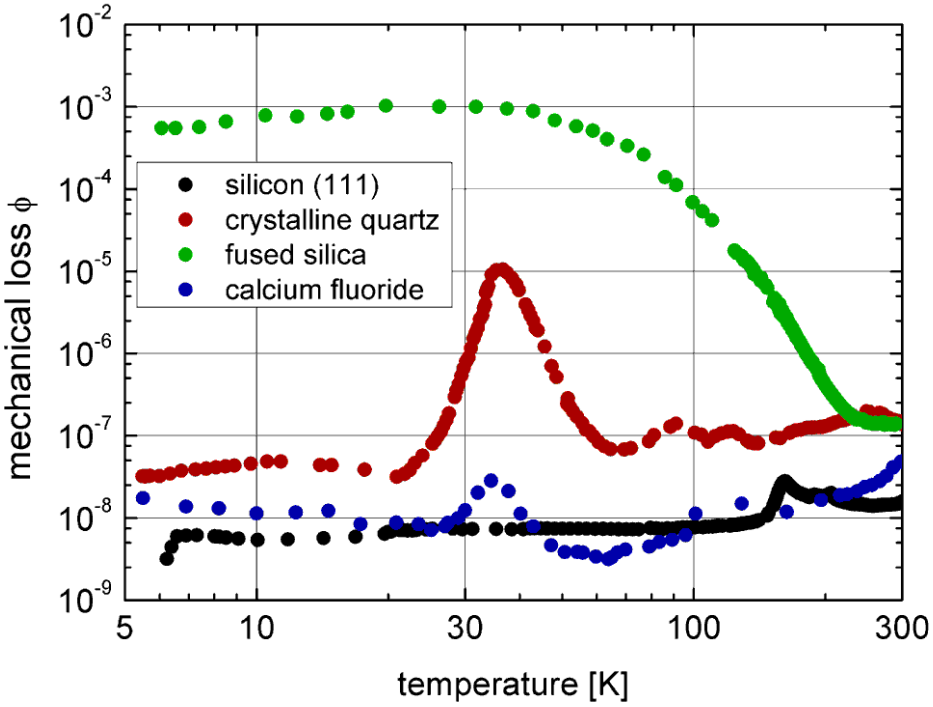




Cryogenic Properties

- Crystalline materials exhibit high thermal conductivity and low mechanical loss

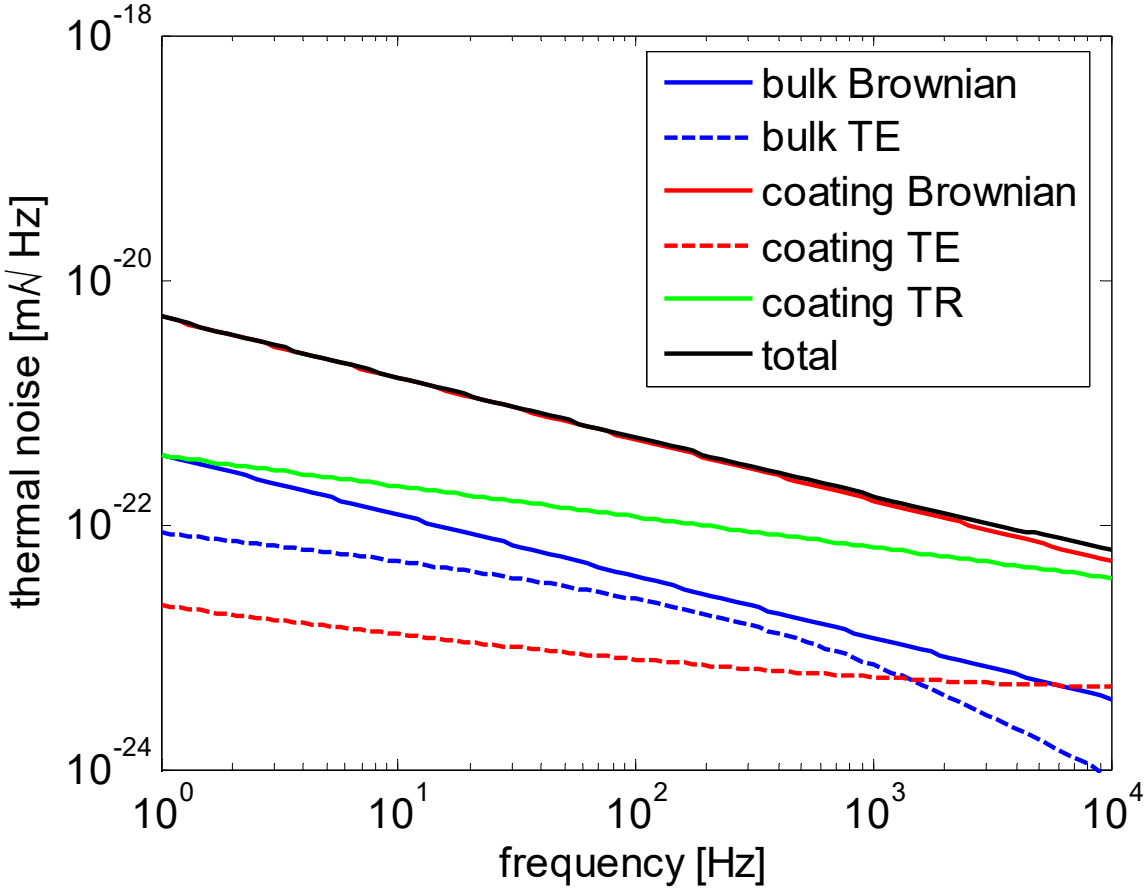
- Trade-off in circulated power and heat extraction techniques:
  - > 100K radiative cooling
  - < 20K conduction cooling)

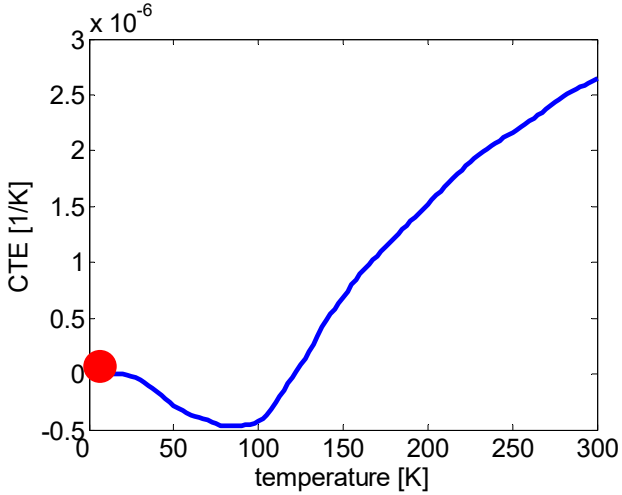


Property	Sapphire	Silicon
mechanical loss		
mechanical strength	Good, for pristine material	Good, for pristine material
optical material	1064nm, 40ppm/cm	≥1550nm*, <5 ppm/cm for mCz**
thermal conductivity	≈3kW/mK @ 20K	≈5kW/mK @ 20K
Polishing	Hard material	
size availability	23kg possible	semiconductor industry/purity

- See talk in C3 by Volker Quetschke on laser development for silicon
- ** Bell, T1600169

Thermal Noise Estimate





5 K

Bulk thermoelastic: Braginsky, Phys. Lett. A, 264, 1999

Coating thermoelastic: Liu, Thorne, Phys. Rev. D, 62, 2000

Bulk Brownian: Braginsky et al, Phys. Lett. A, 312, 2003, Fejer et al., Phys. Rev. D, 70, 2004

Coating Brownian: Harry et al., Class. Quant. Grav, 19, 2002

Coating thermorefractive: Braginsky, Phys. Lett. A, 71, 2000

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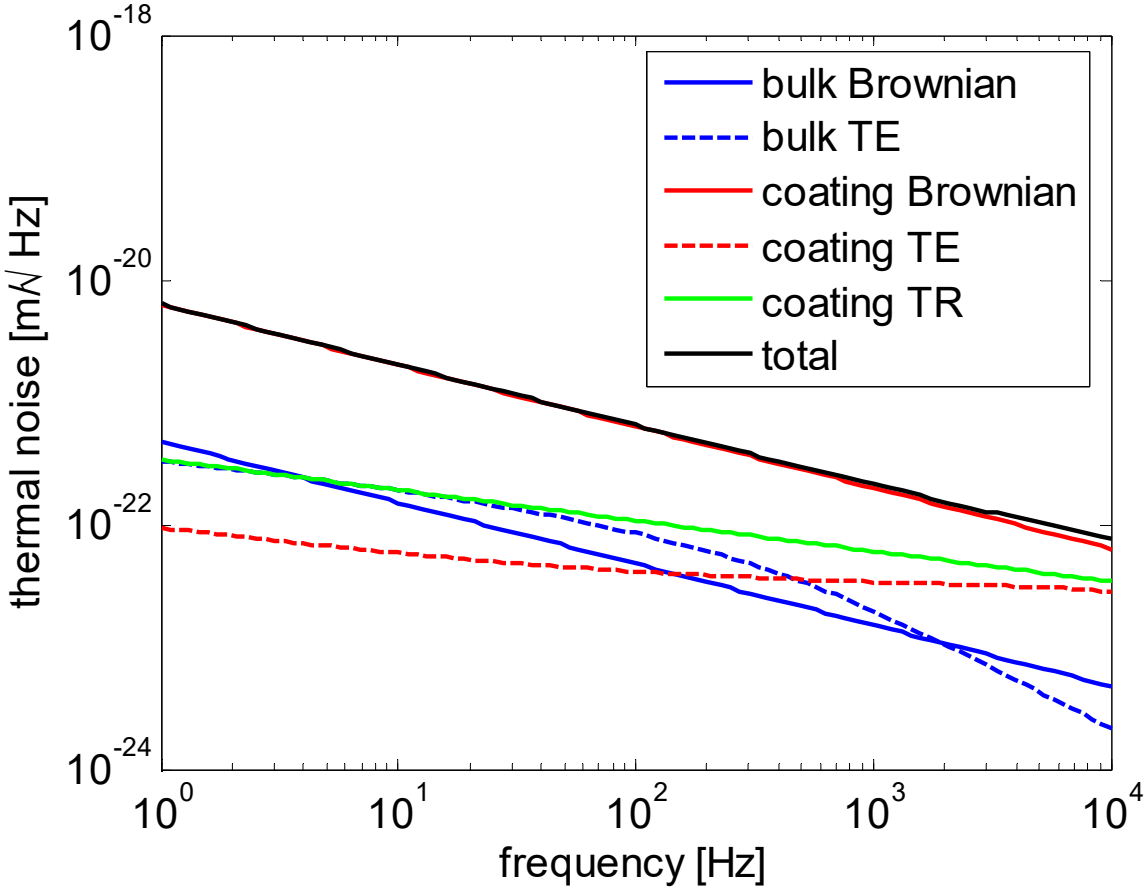
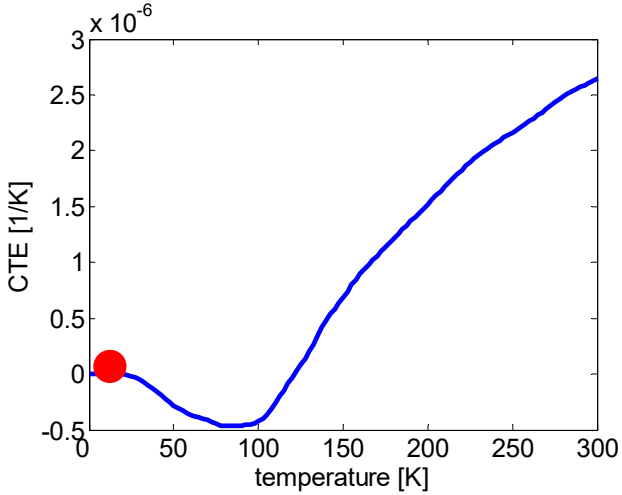
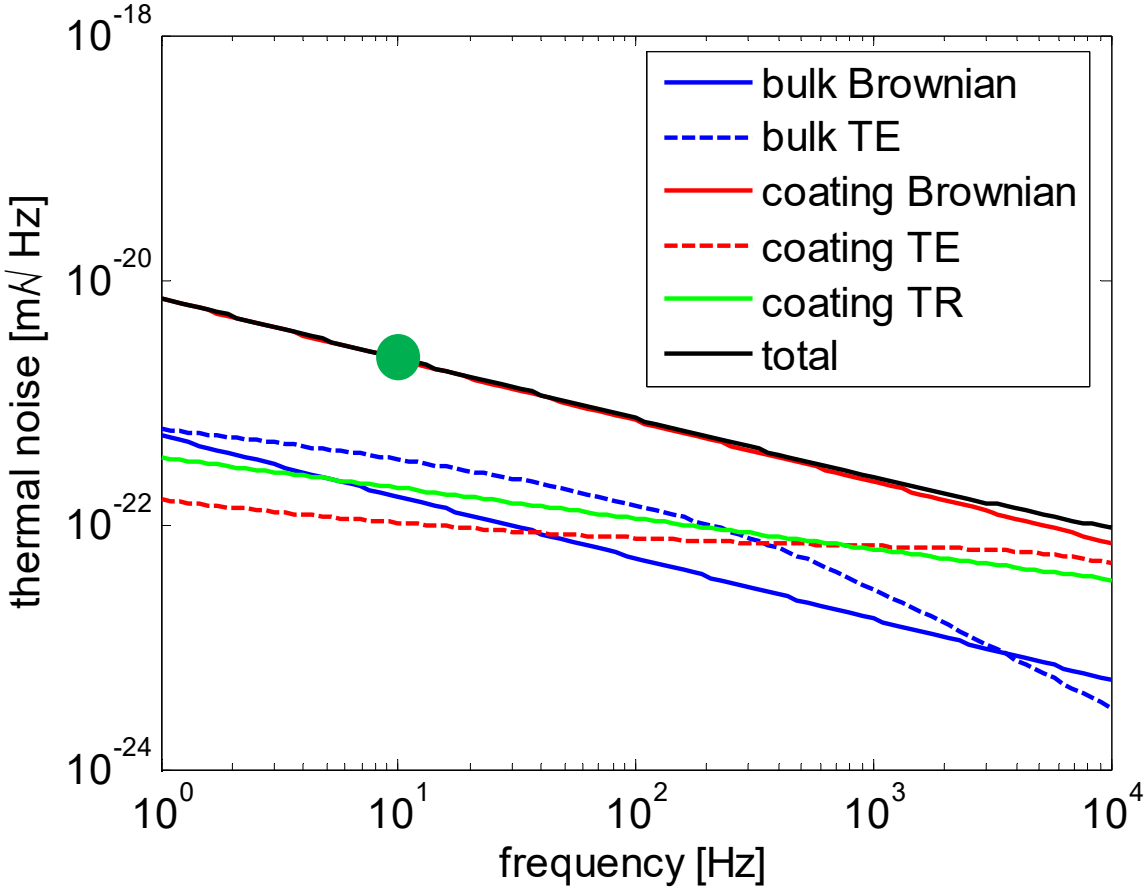
Thermal Noise Estimate

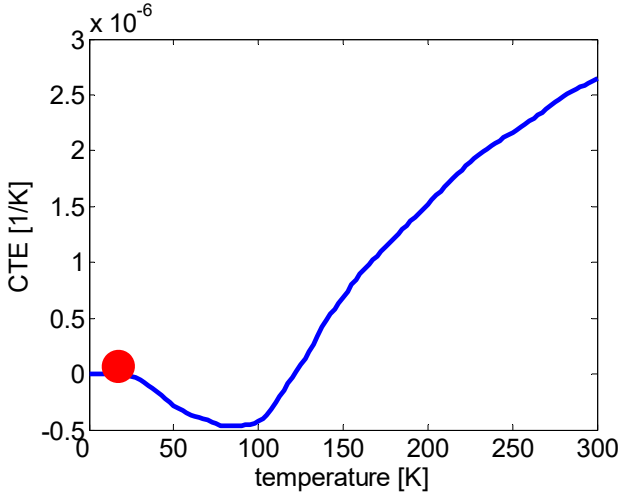




8 K

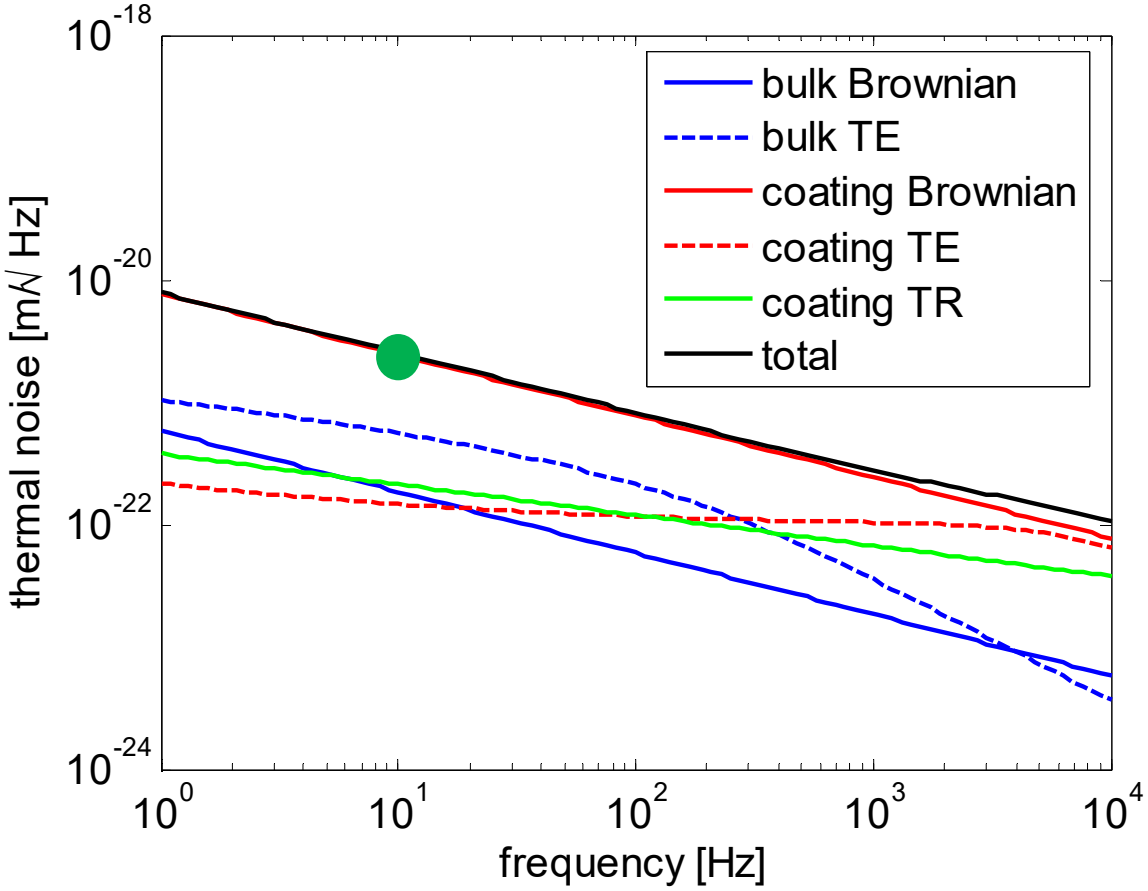
Thermal Noise Estimate

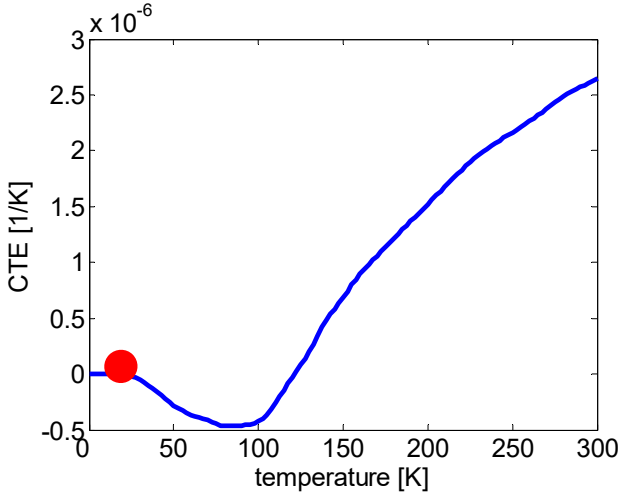




10 K

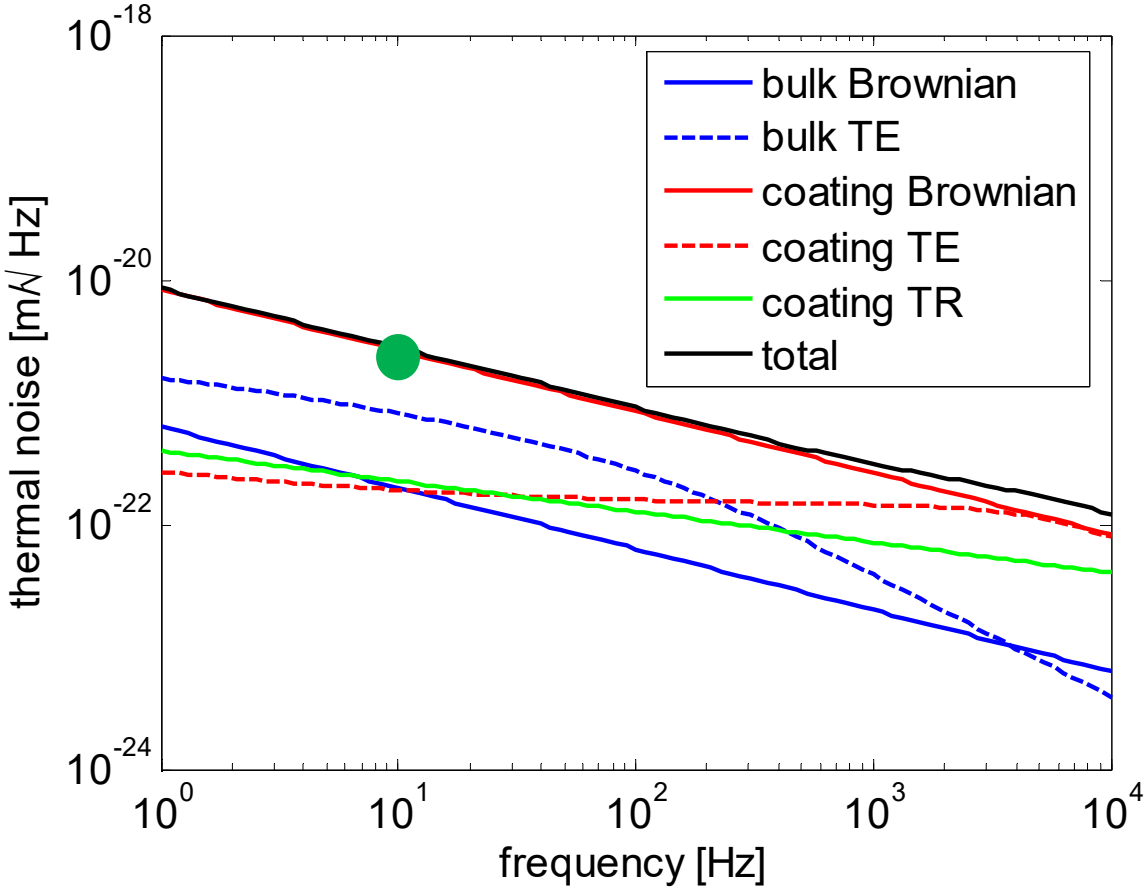
Thermal Noise Estimate

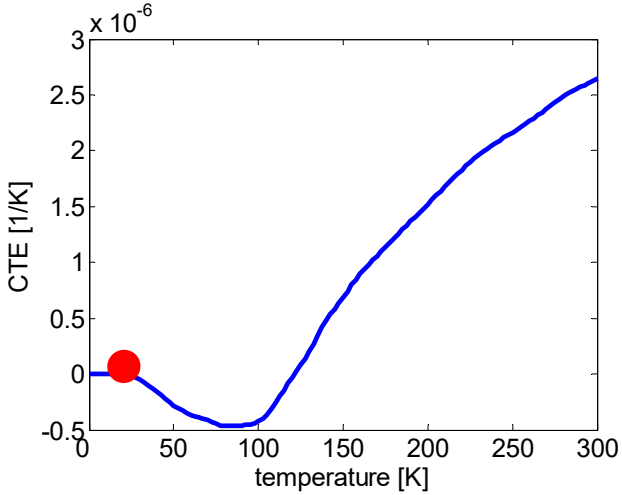




12 K

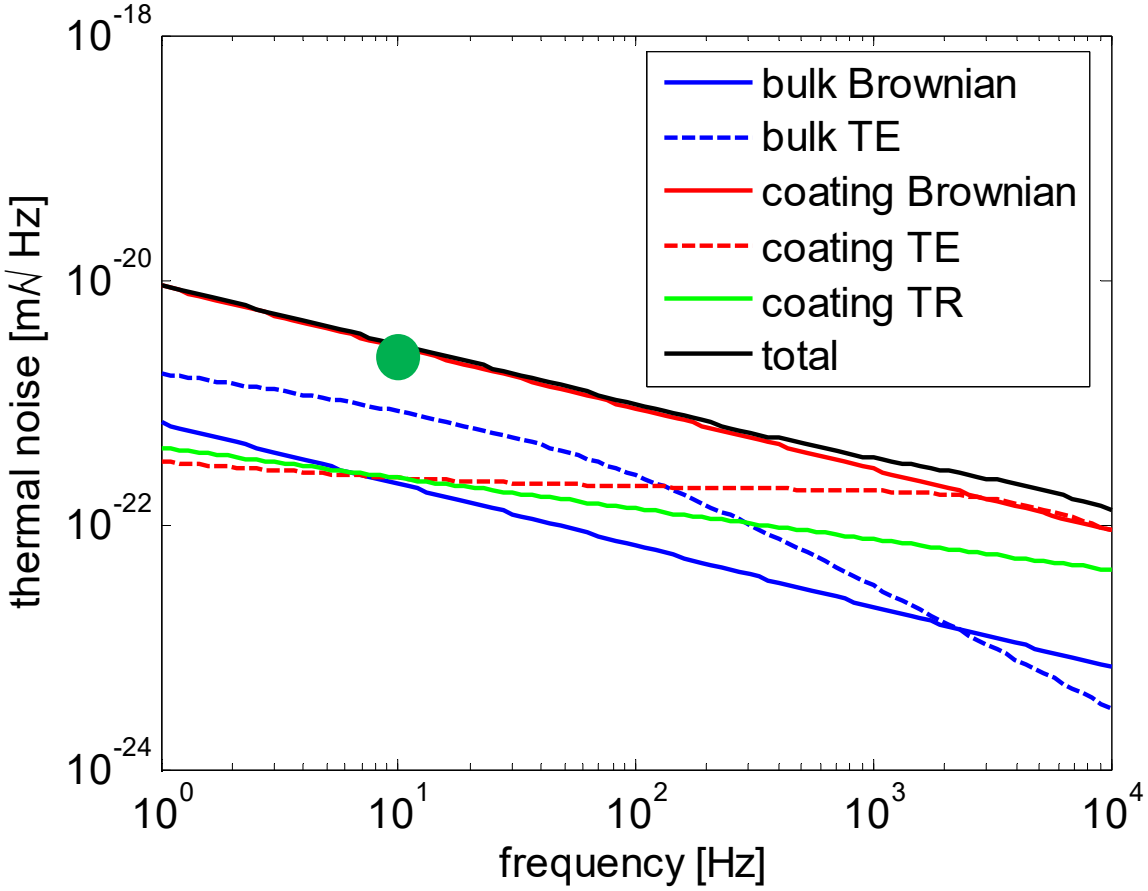
Thermal Noise Estimate

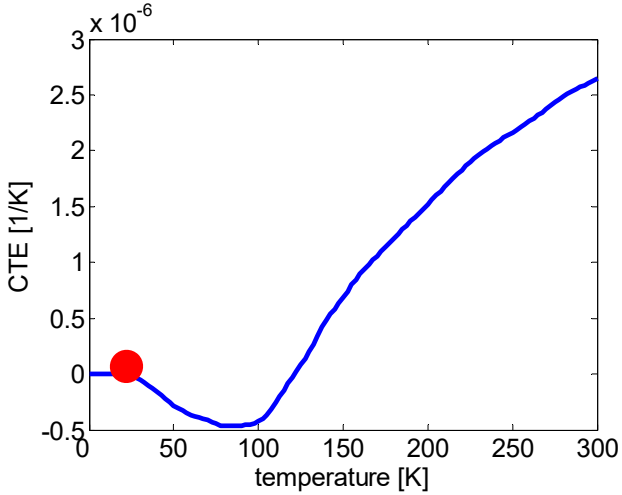




14 K

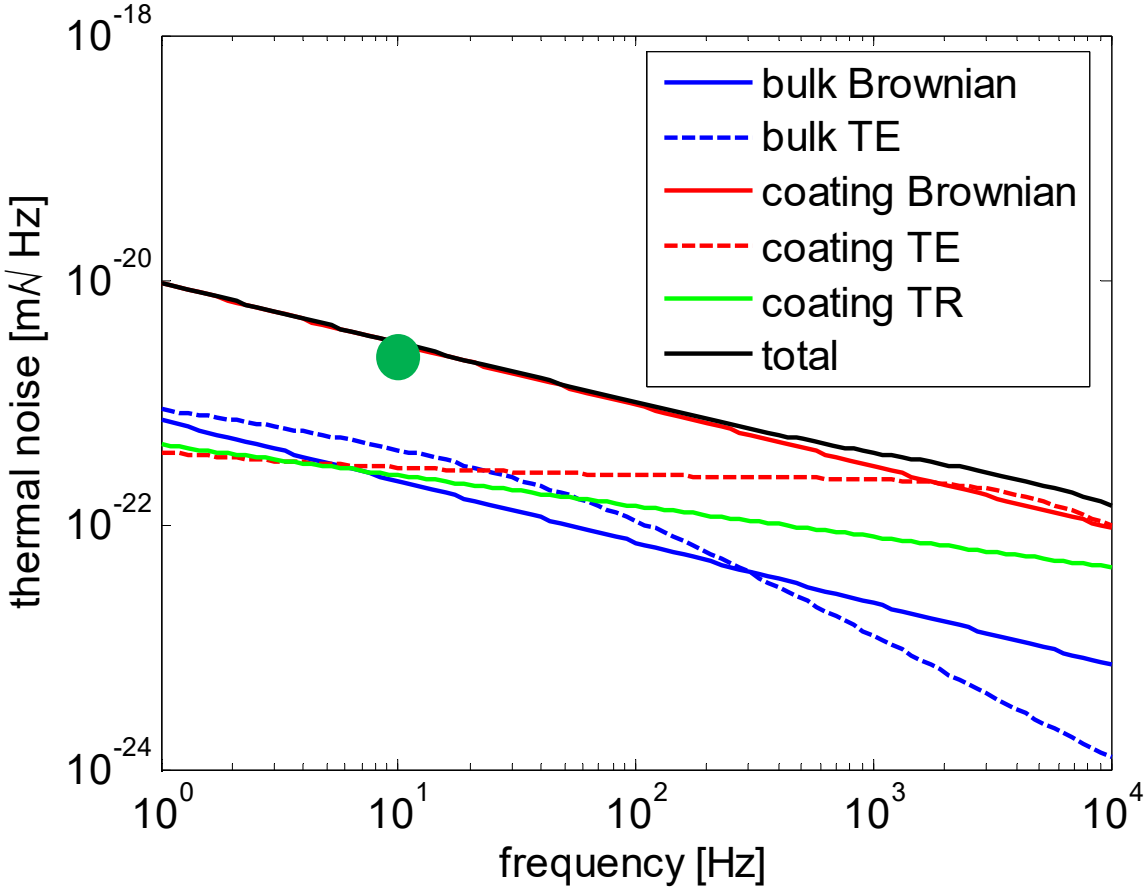
Thermal Noise Estimate

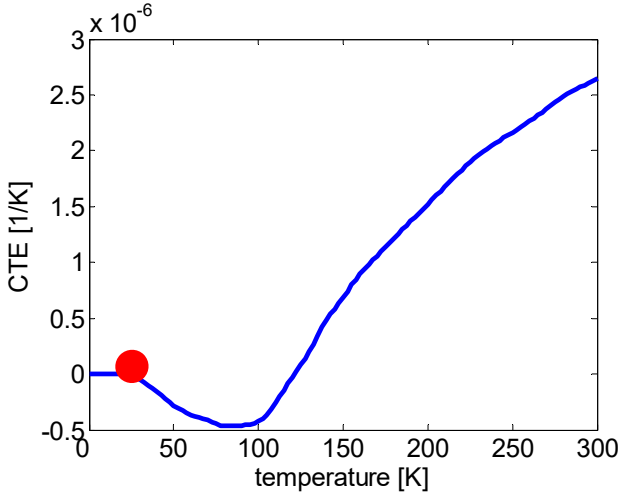




16 K

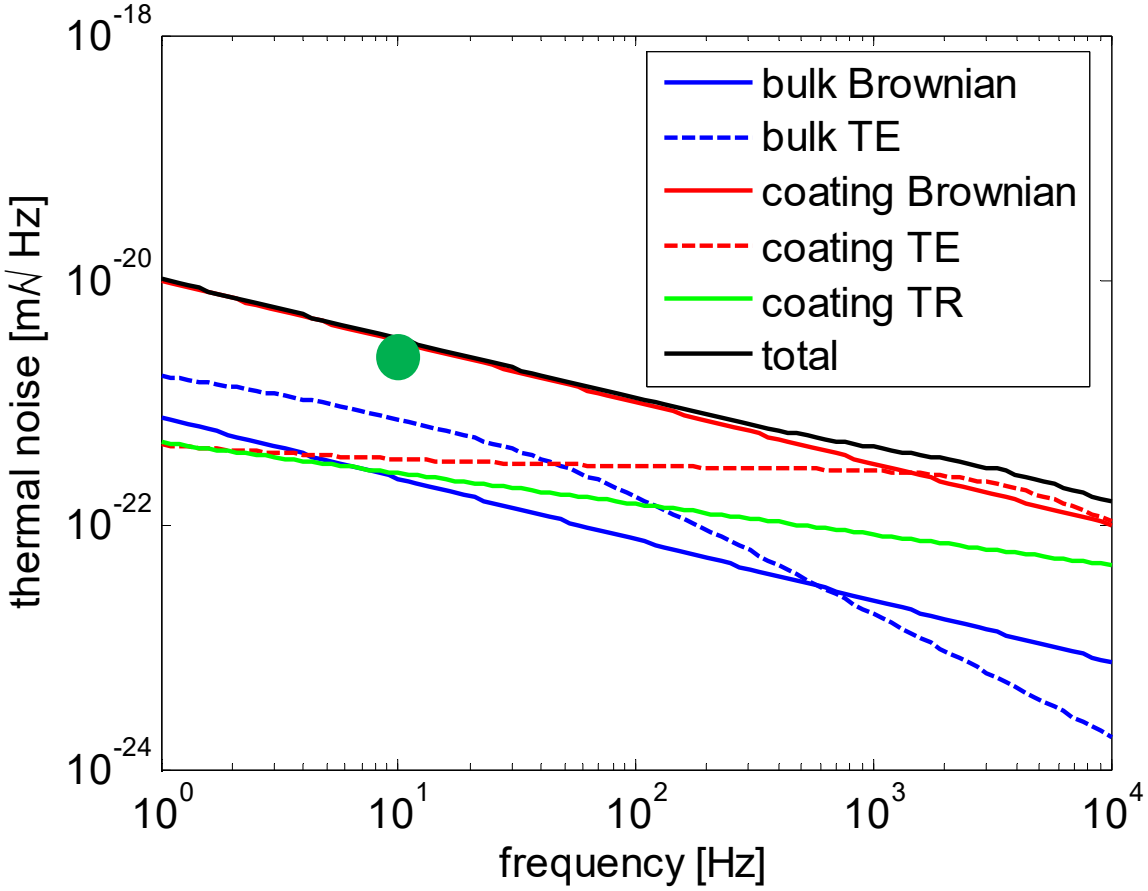
Thermal Noise Estimate

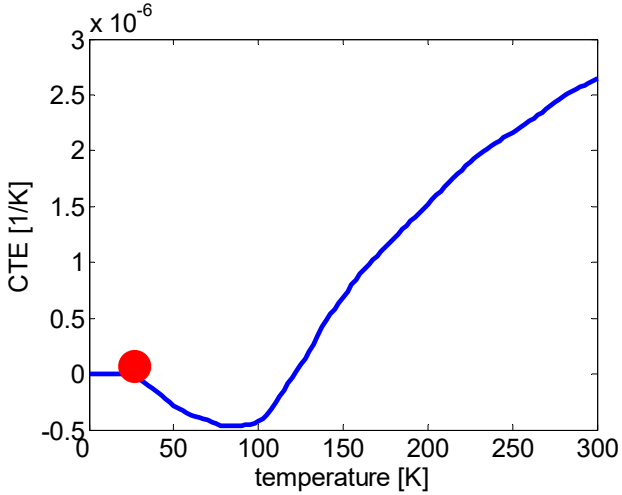




18 K

Thermal Noise Estimate





20 K

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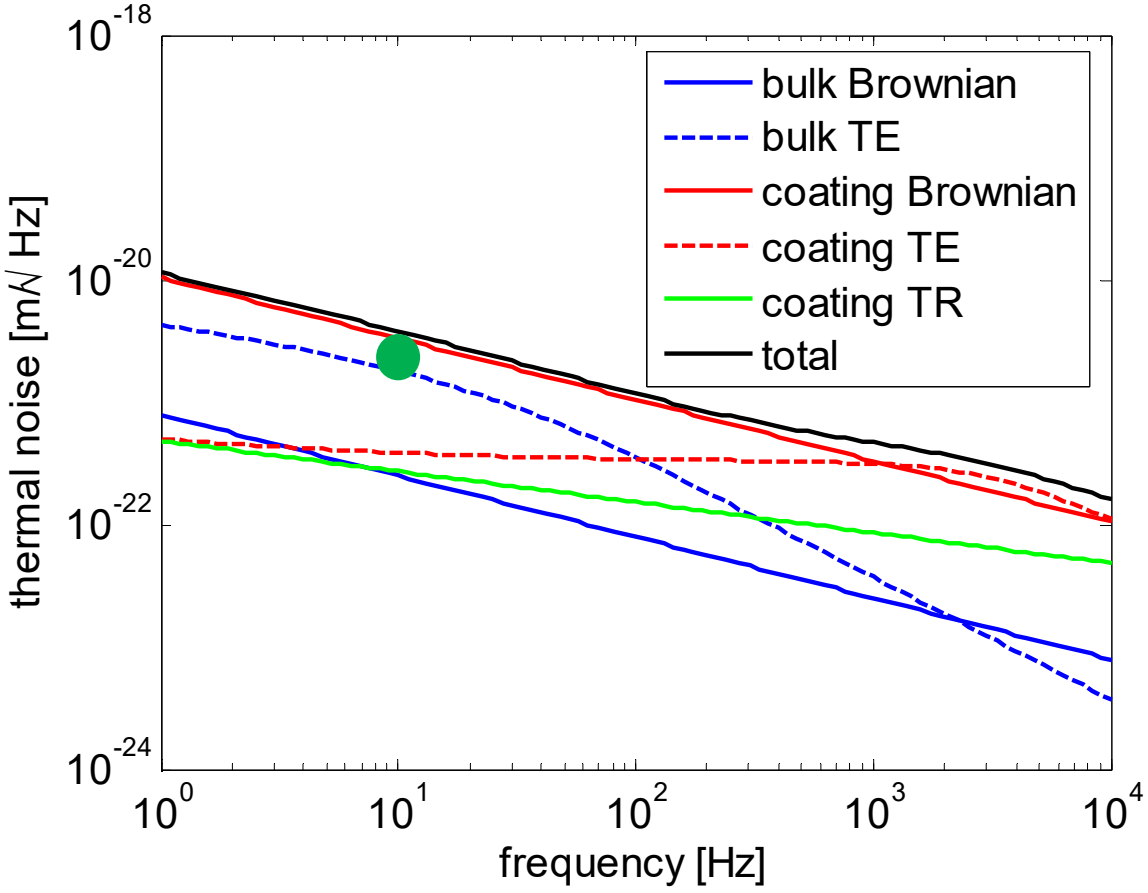
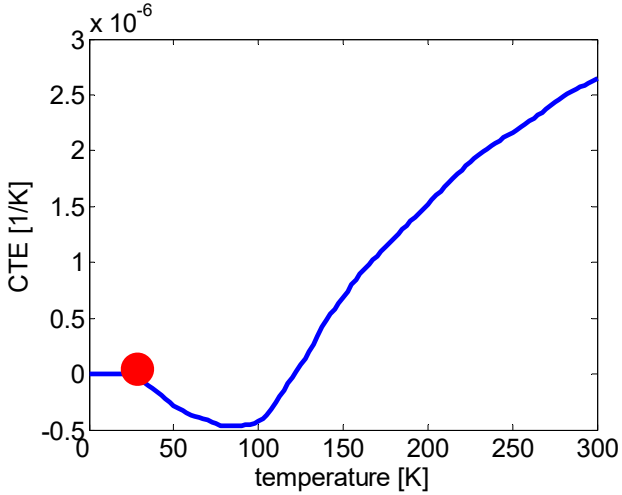
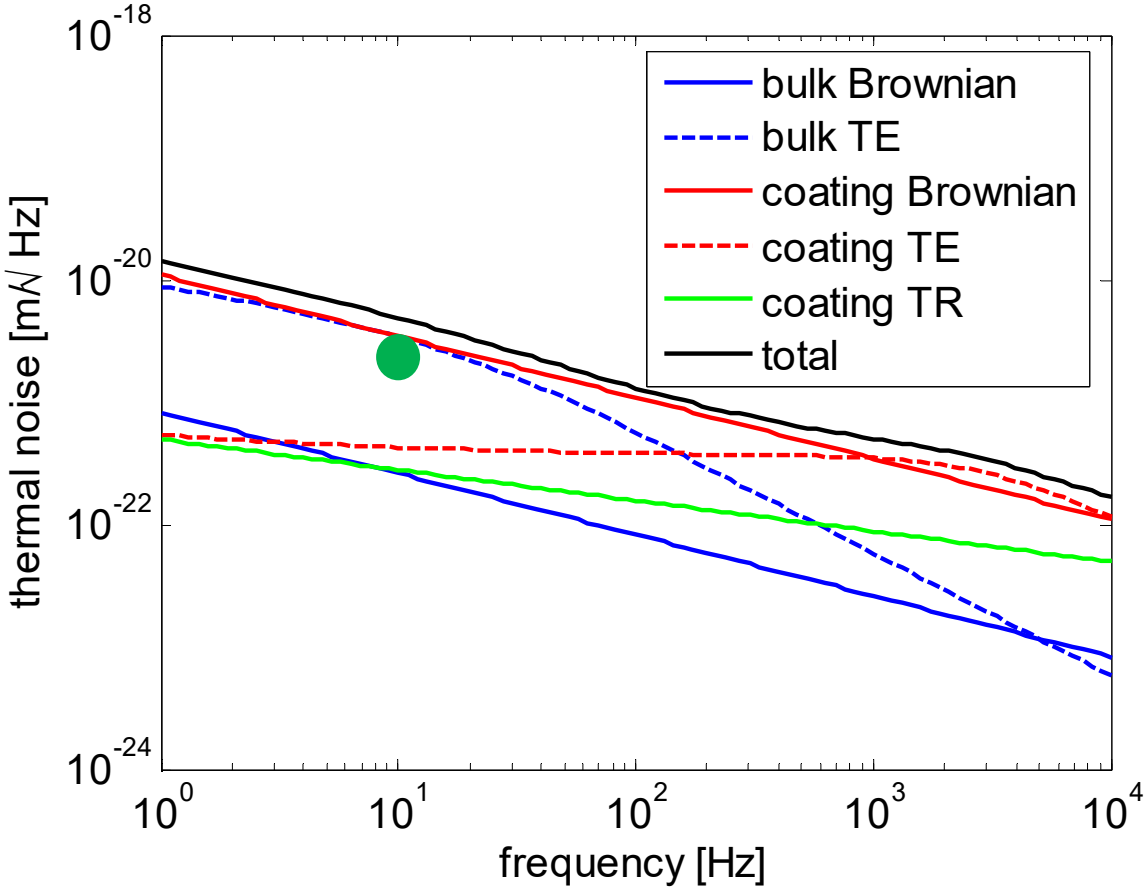
Thermal Noise Estimate

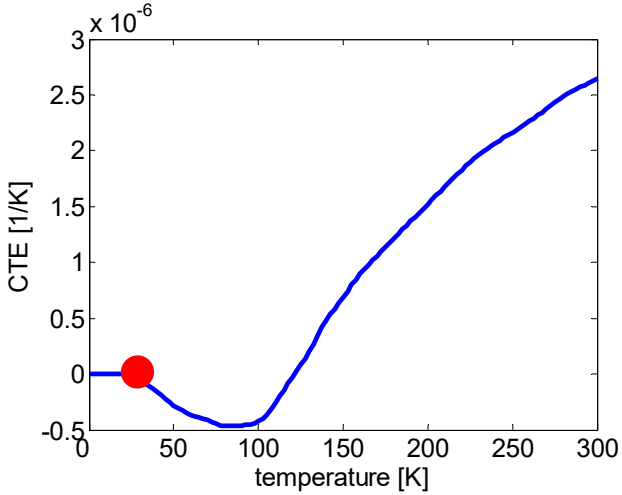




22 K

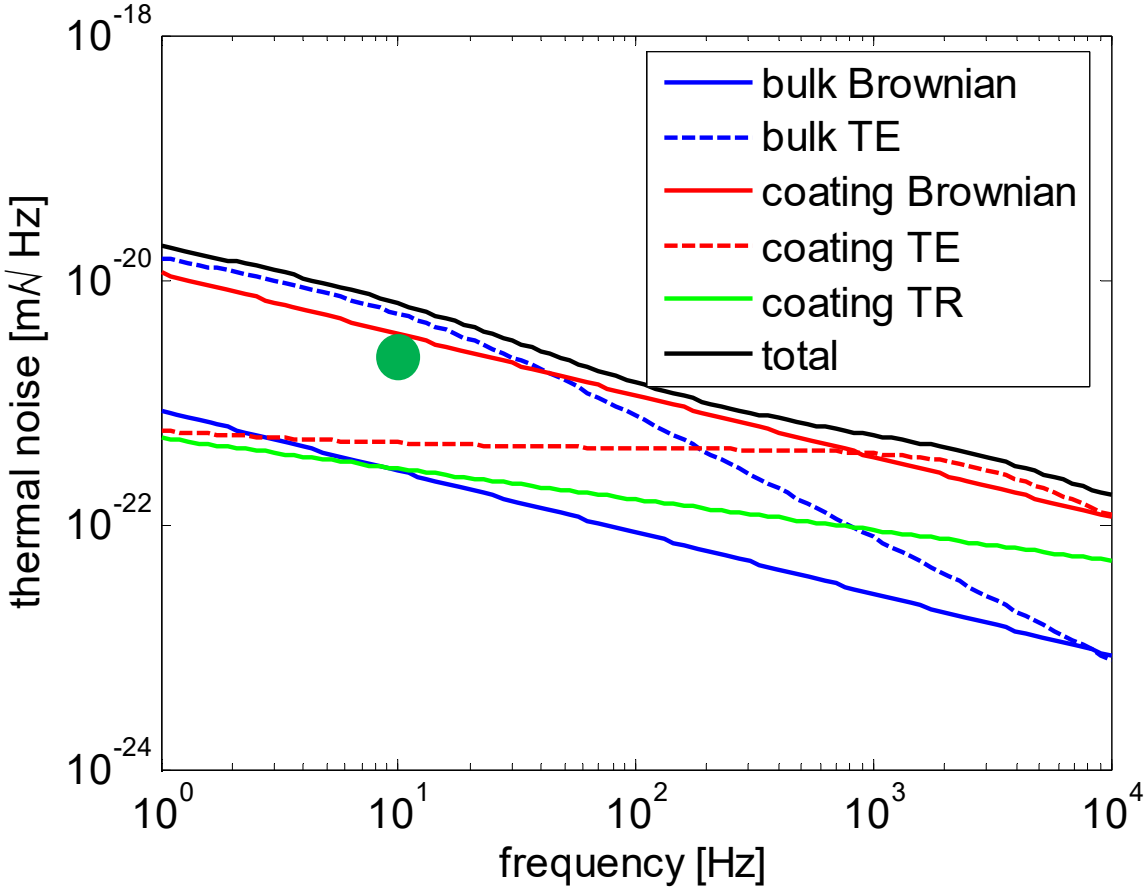
Thermal Noise Estimate

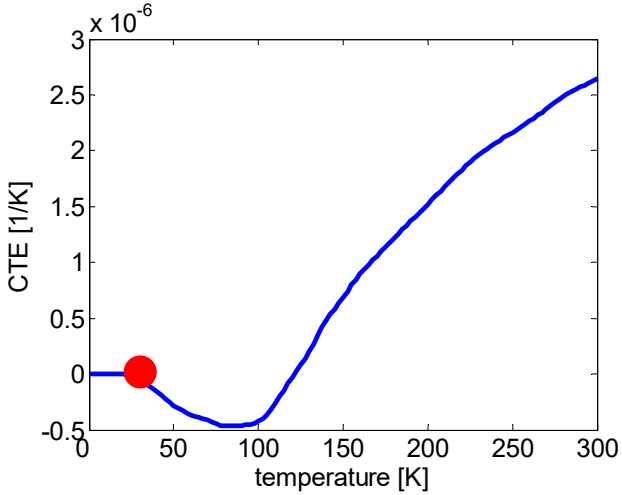




24 K

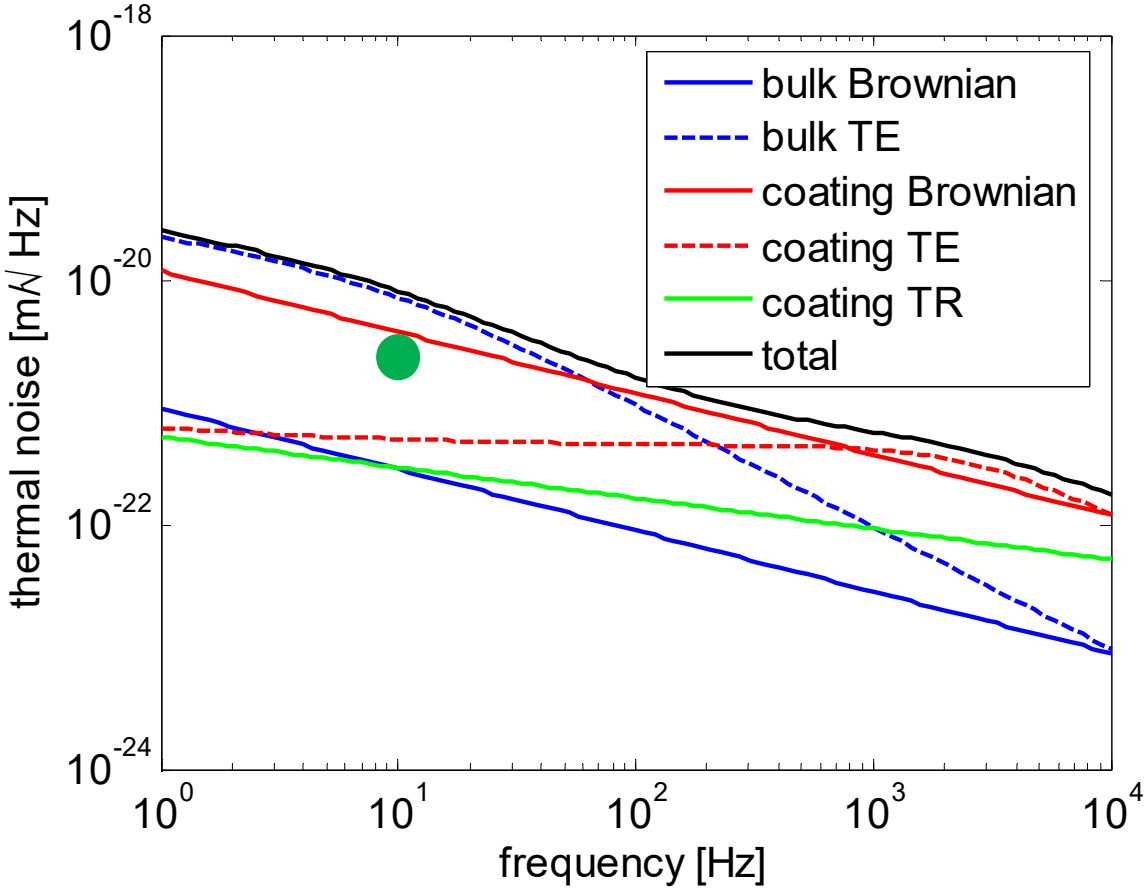
Thermal Noise Estimate

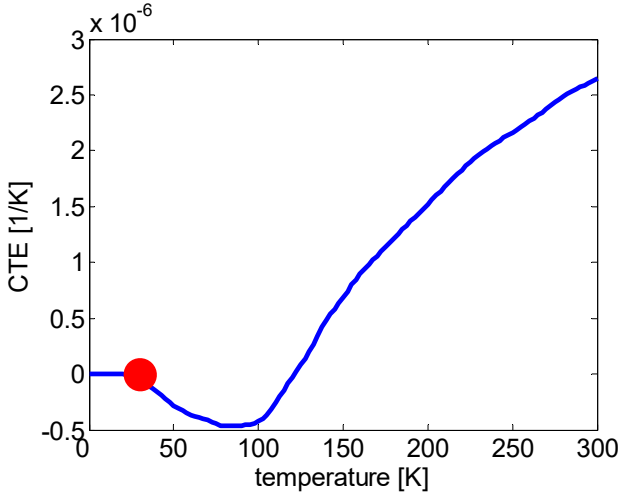




26 K

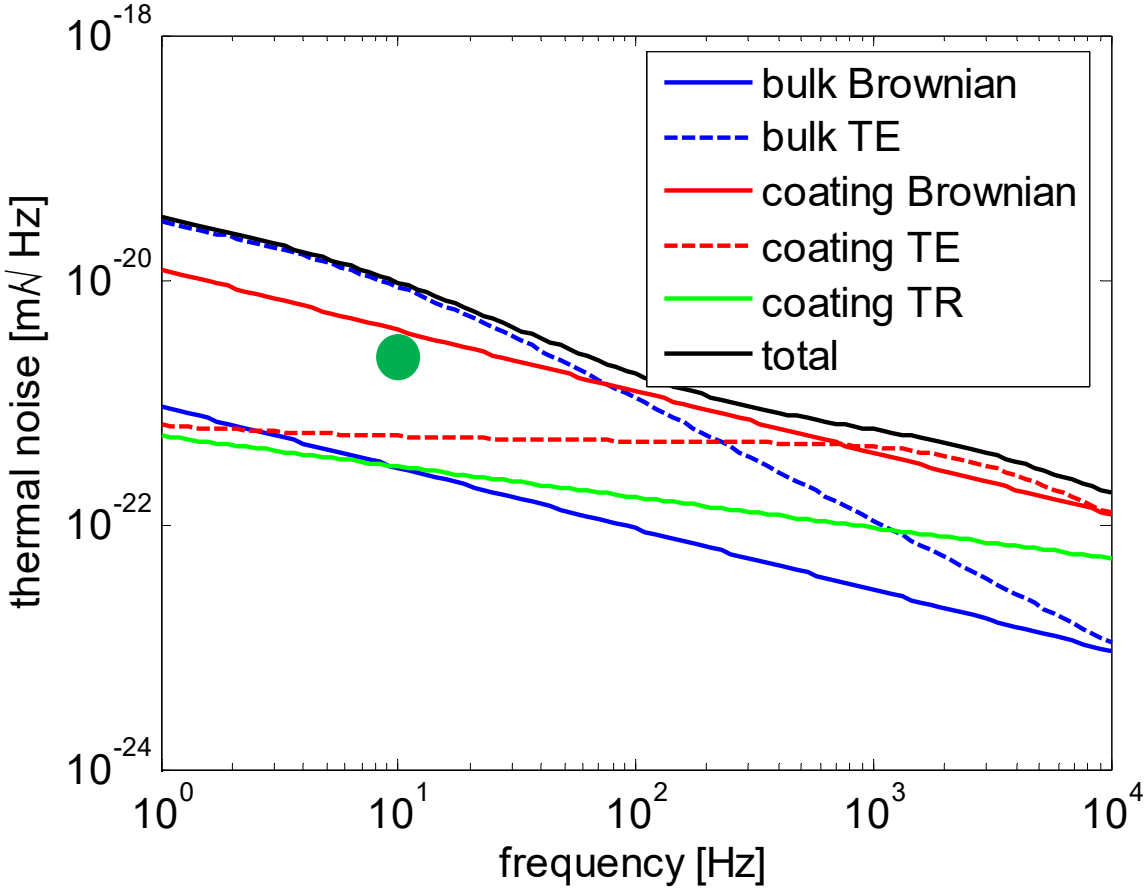
Thermal Noise Estimate

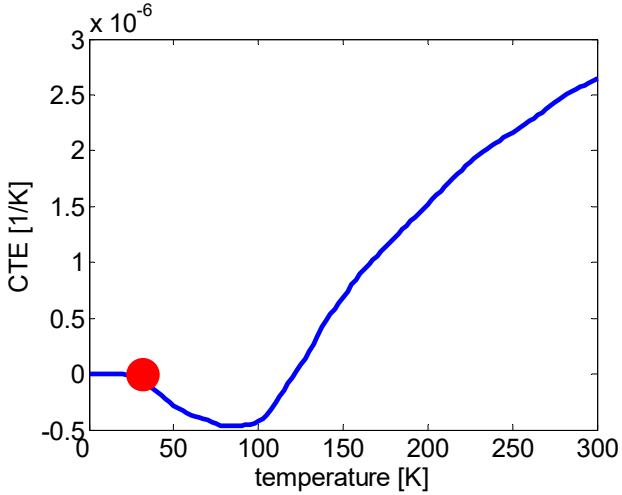




28 K

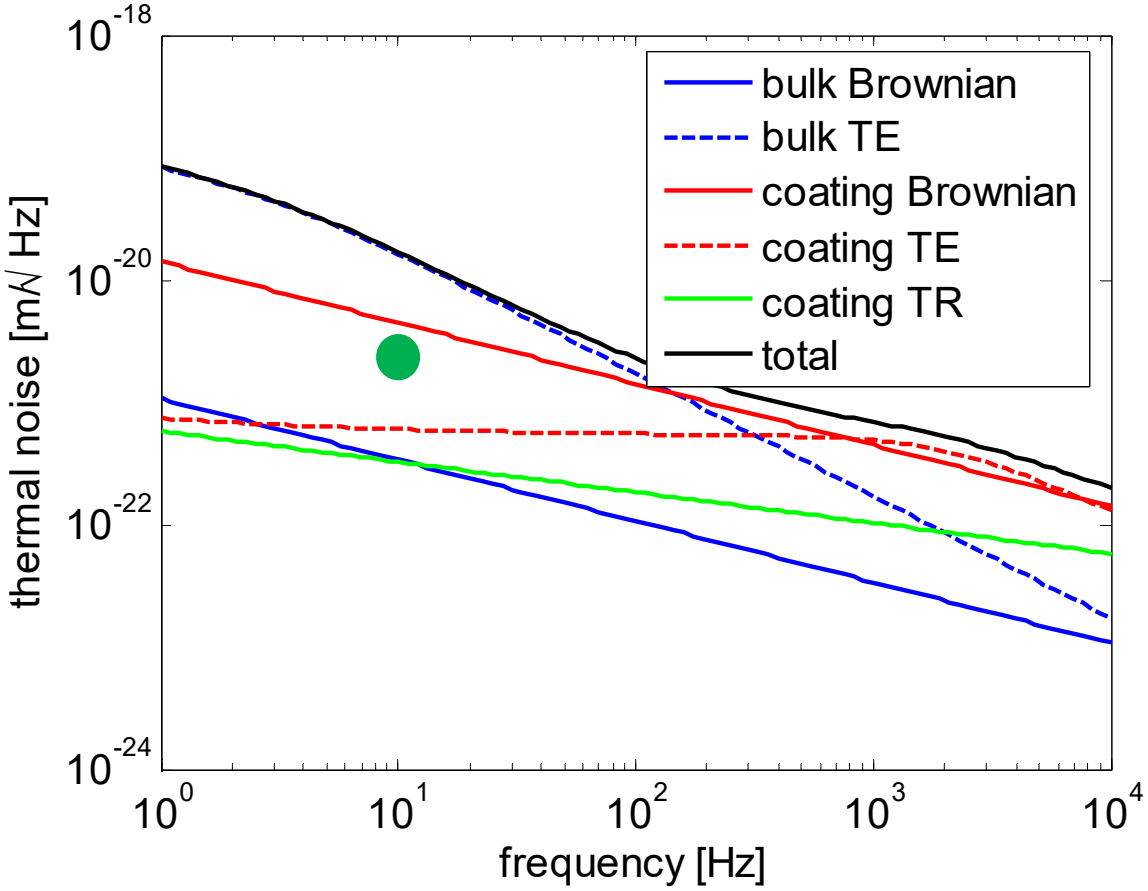
Thermal Noise Estimate

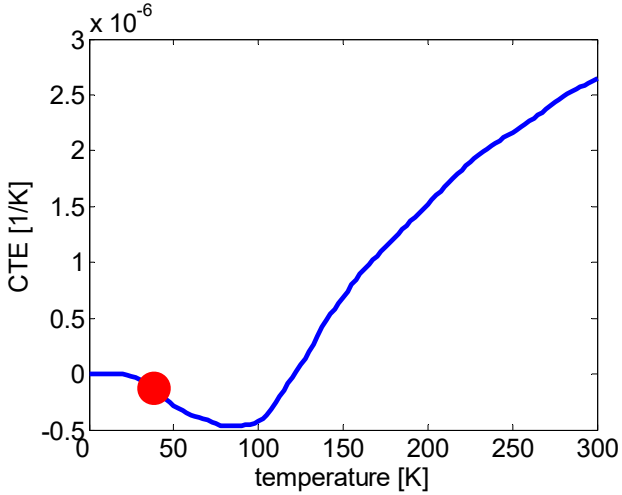




30 K

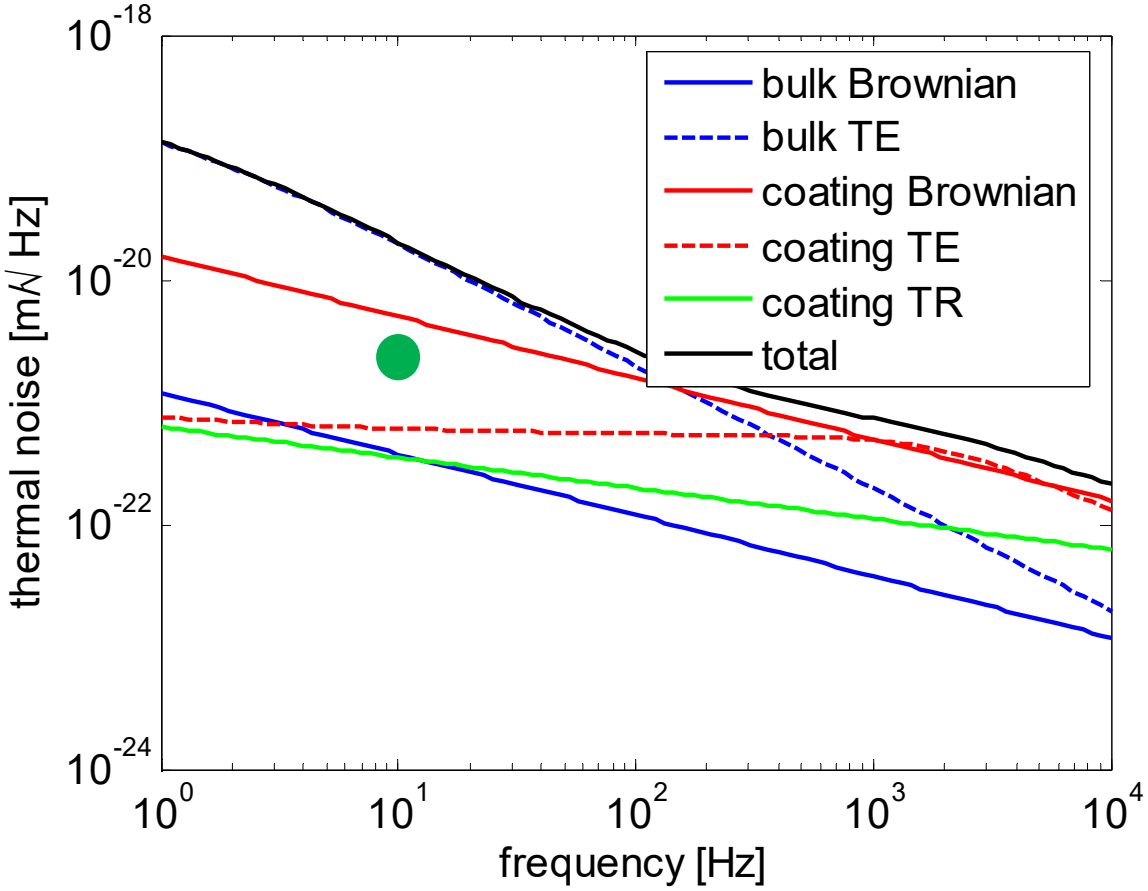
Thermal Noise Estimate

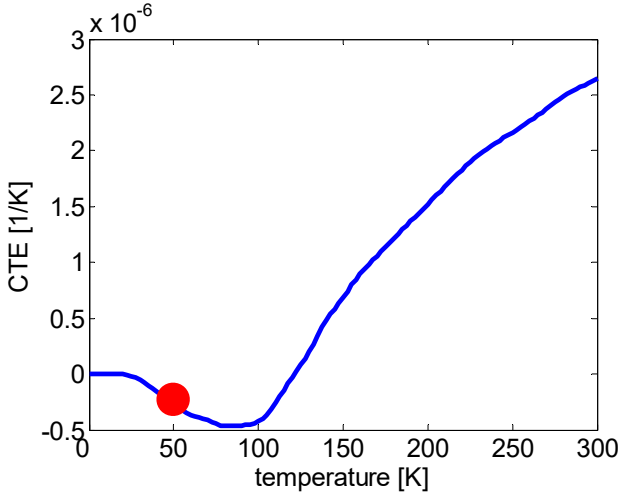




40 K

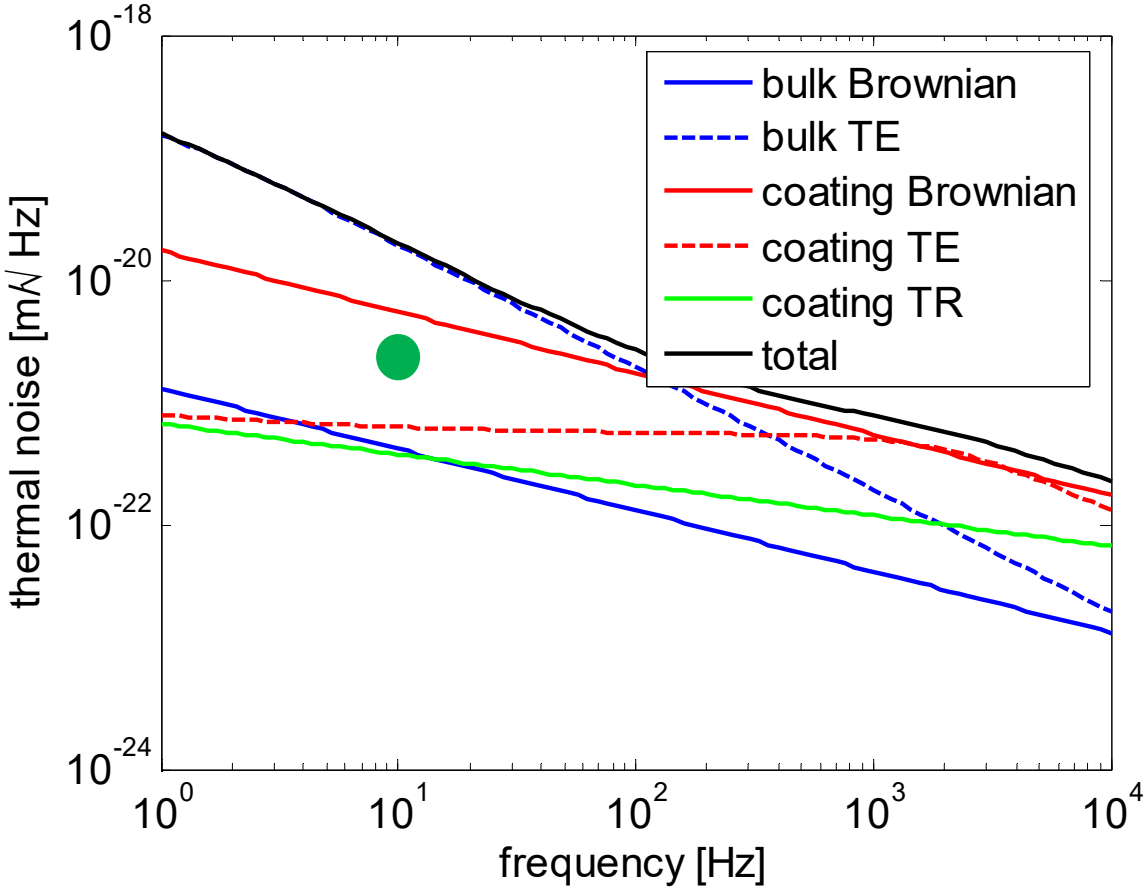
Thermal Noise Estimate

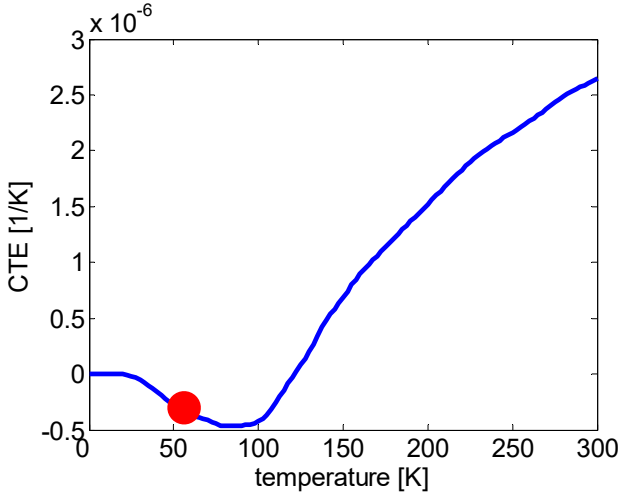




50 K

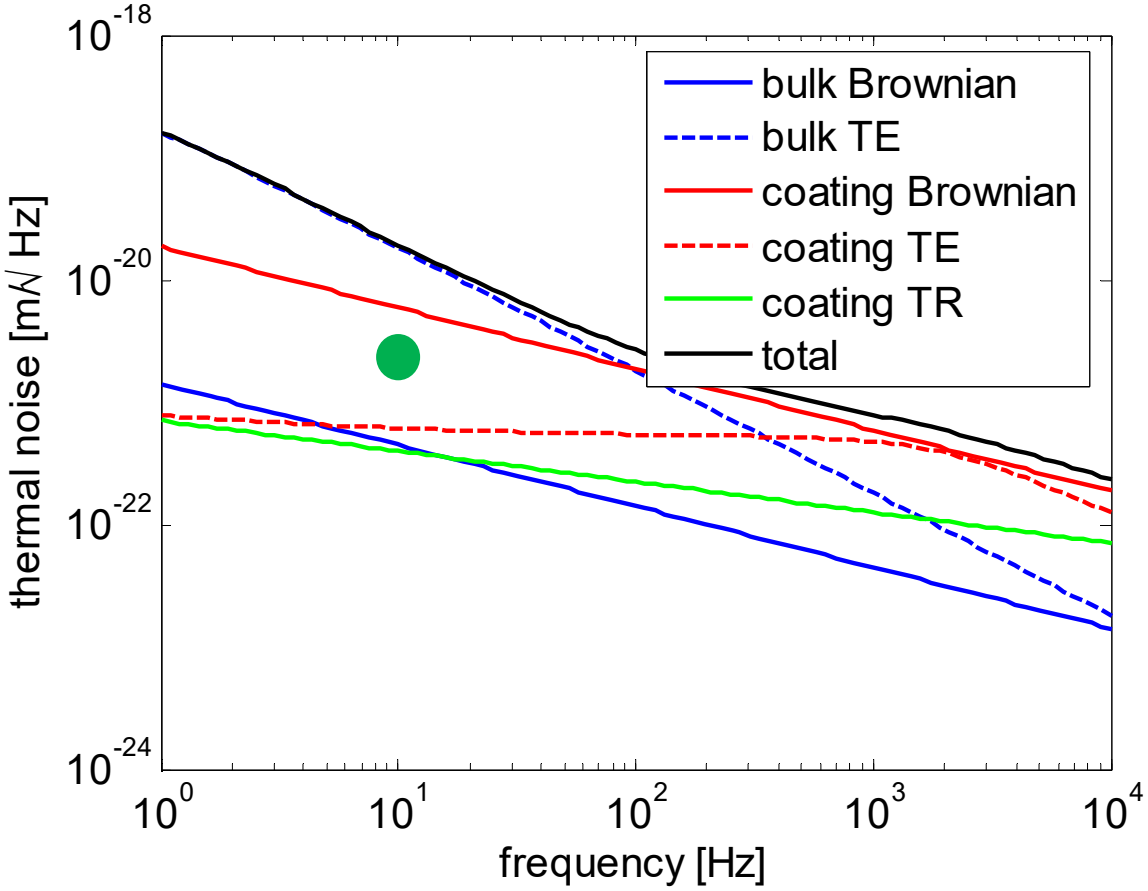
Thermal Noise Estimate

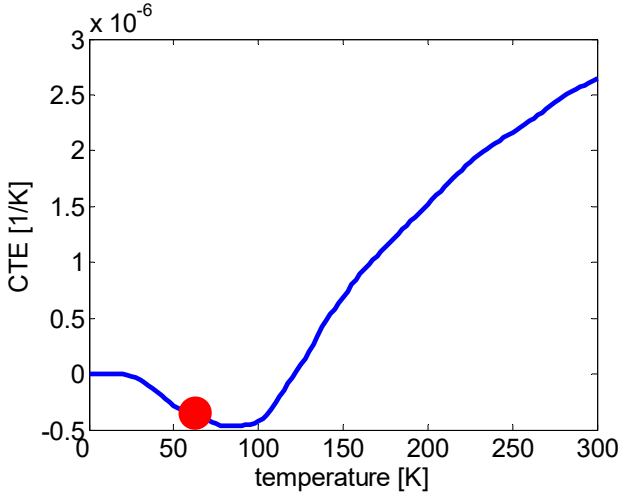




60 K

Thermal Noise Estimate

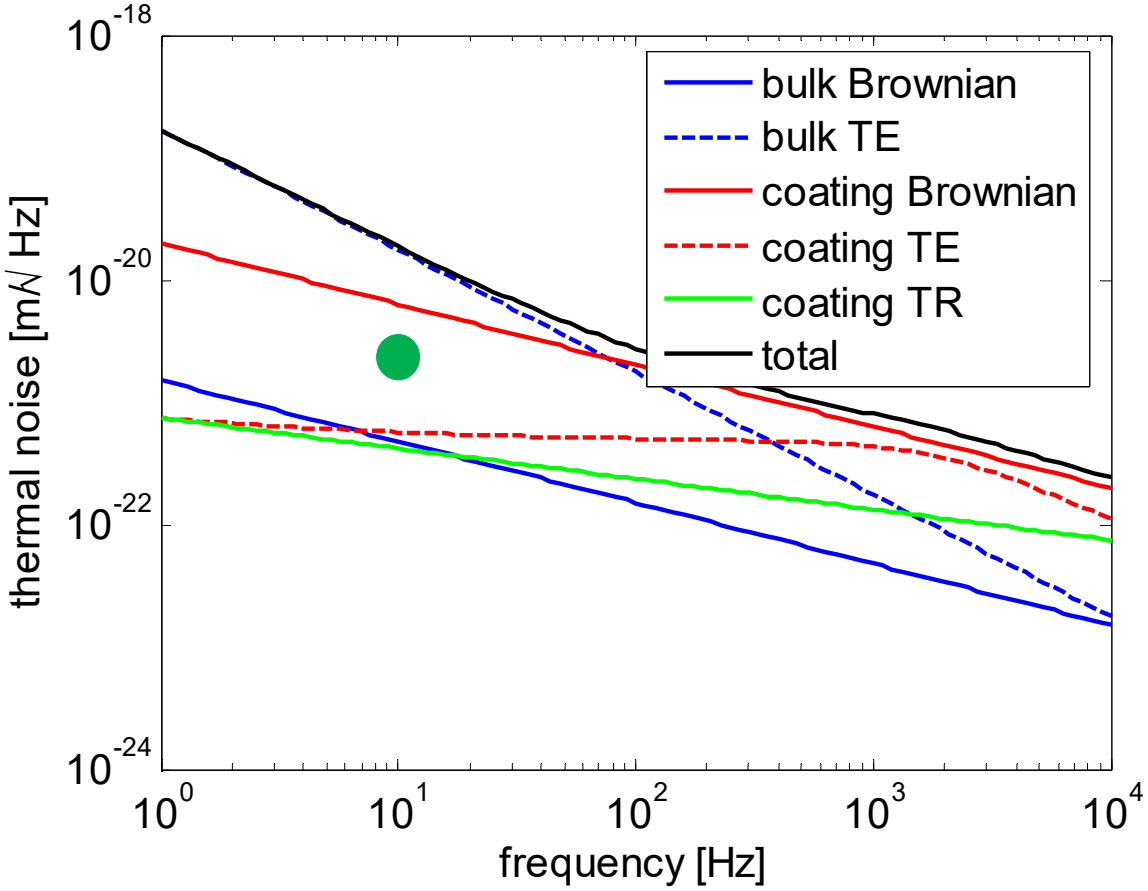


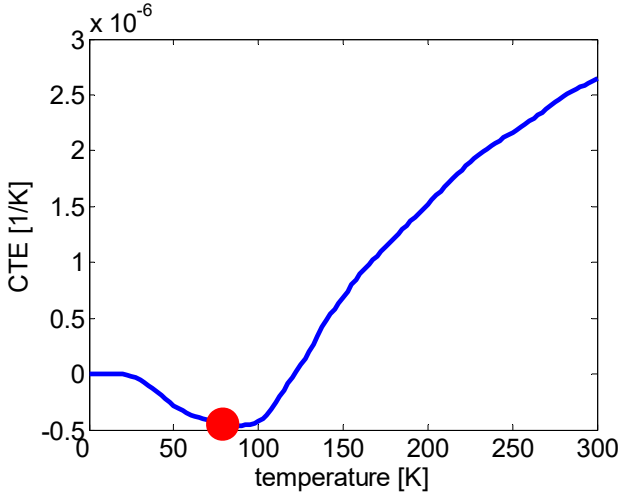


70 K

University of Glasgow

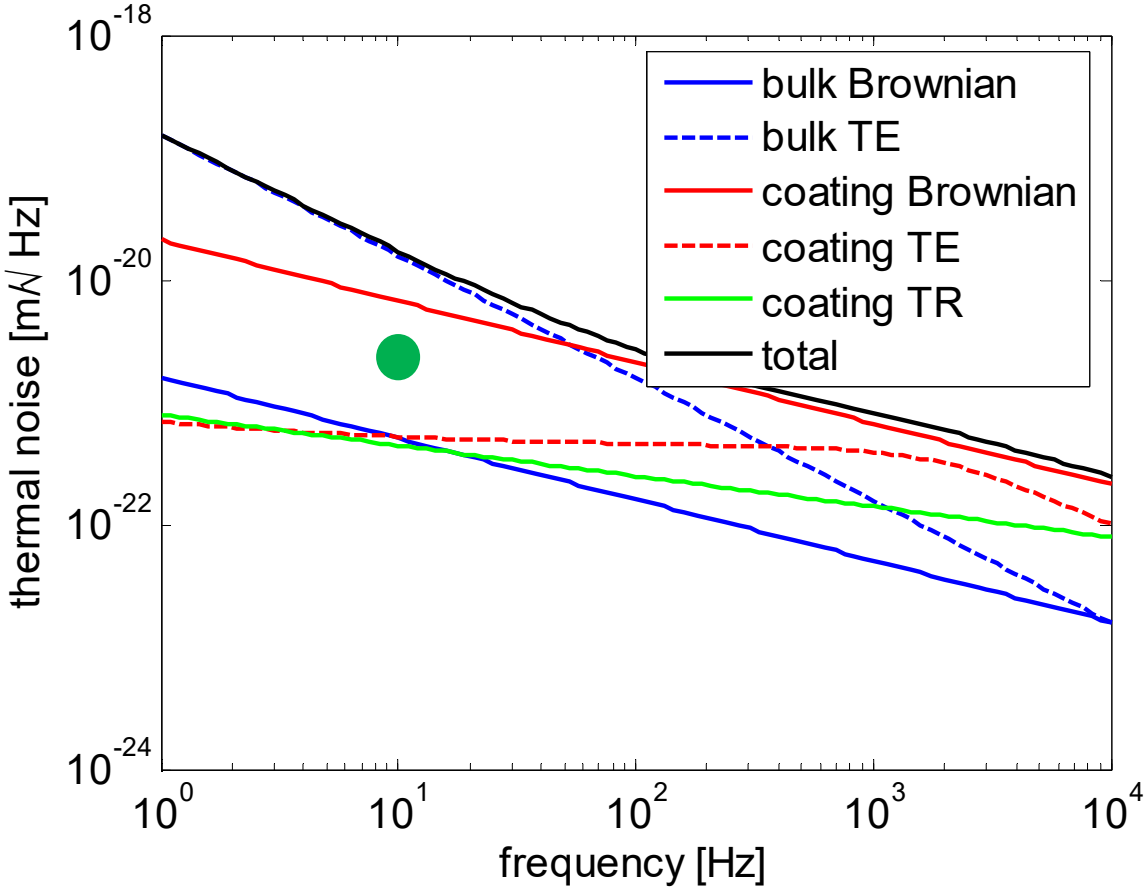
Thermal Noise Estimate

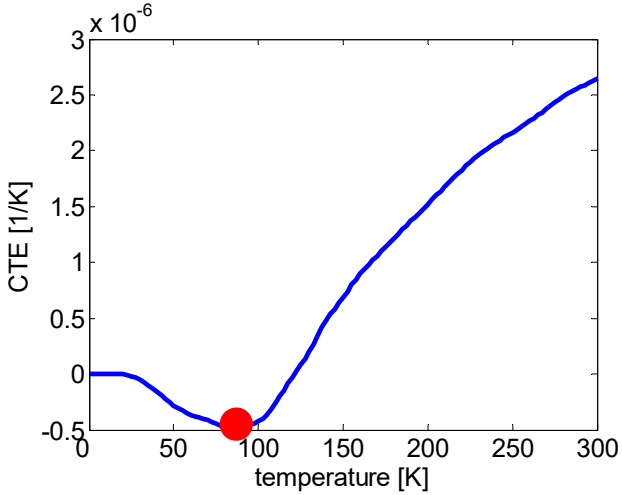


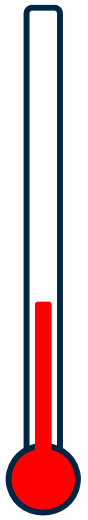


80 K

Thermal Noise Estimate

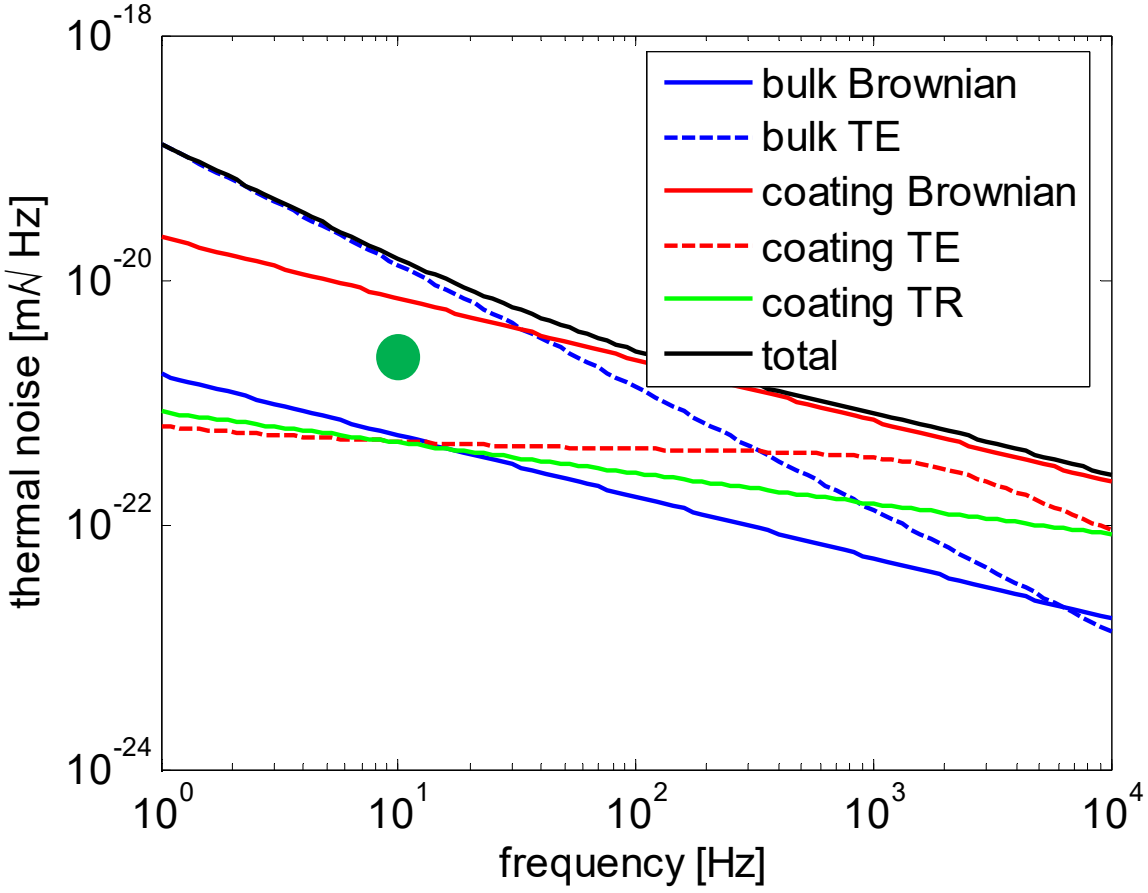


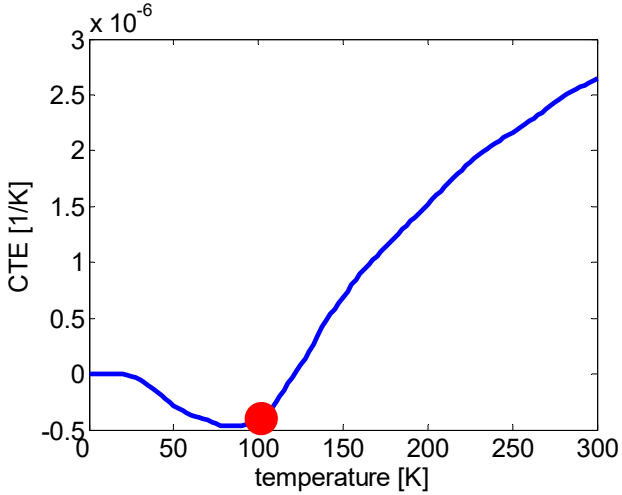


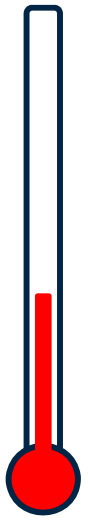


90 K

Thermal Noise Estimate

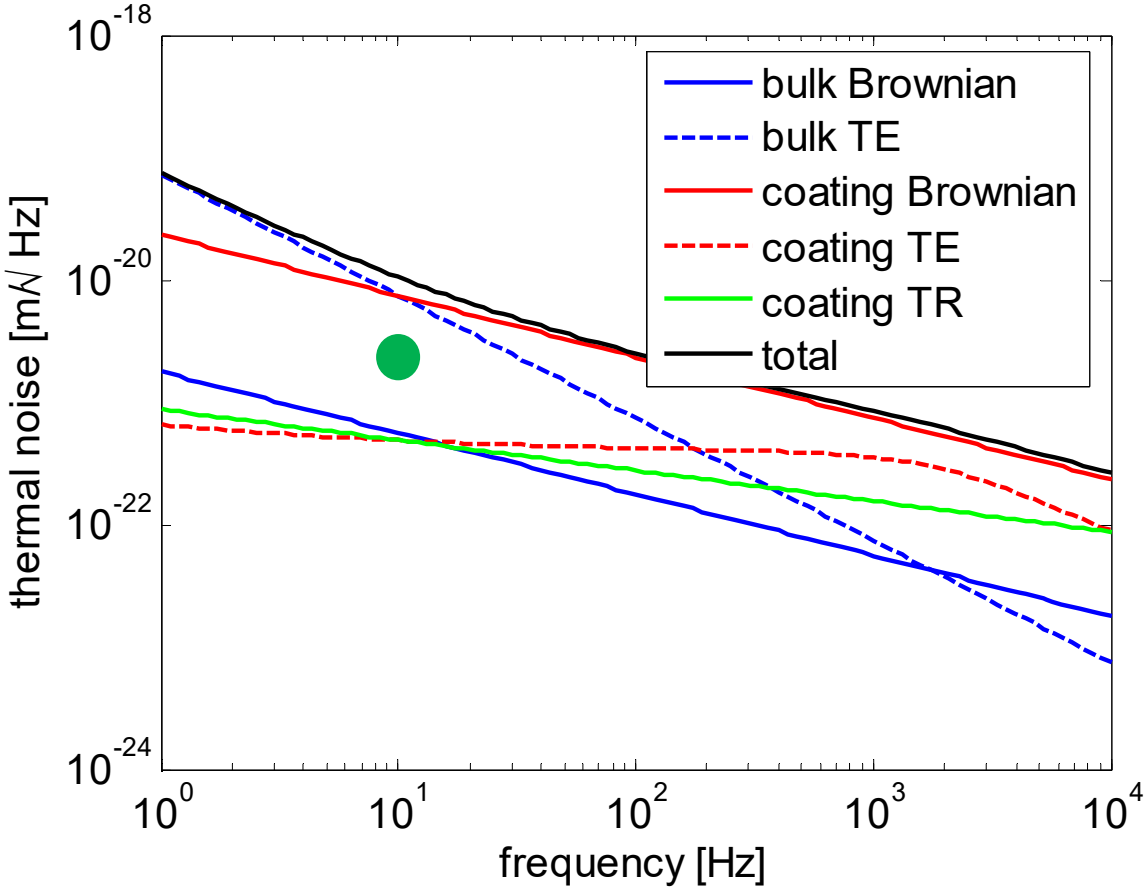


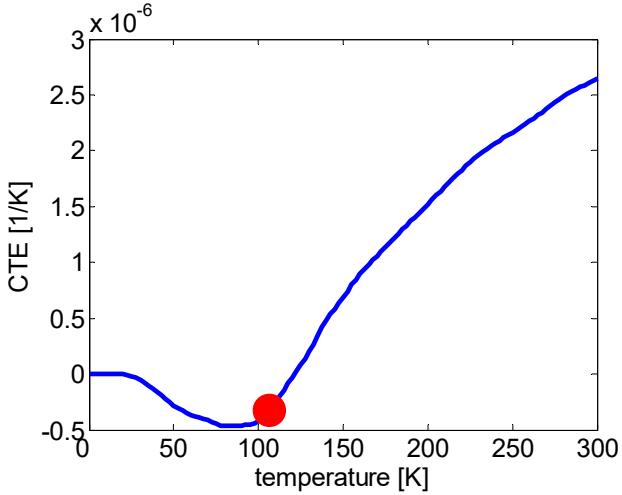


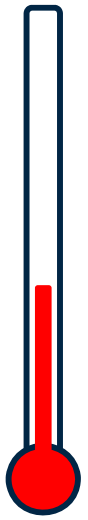


100 K

Thermal Noise Estimate

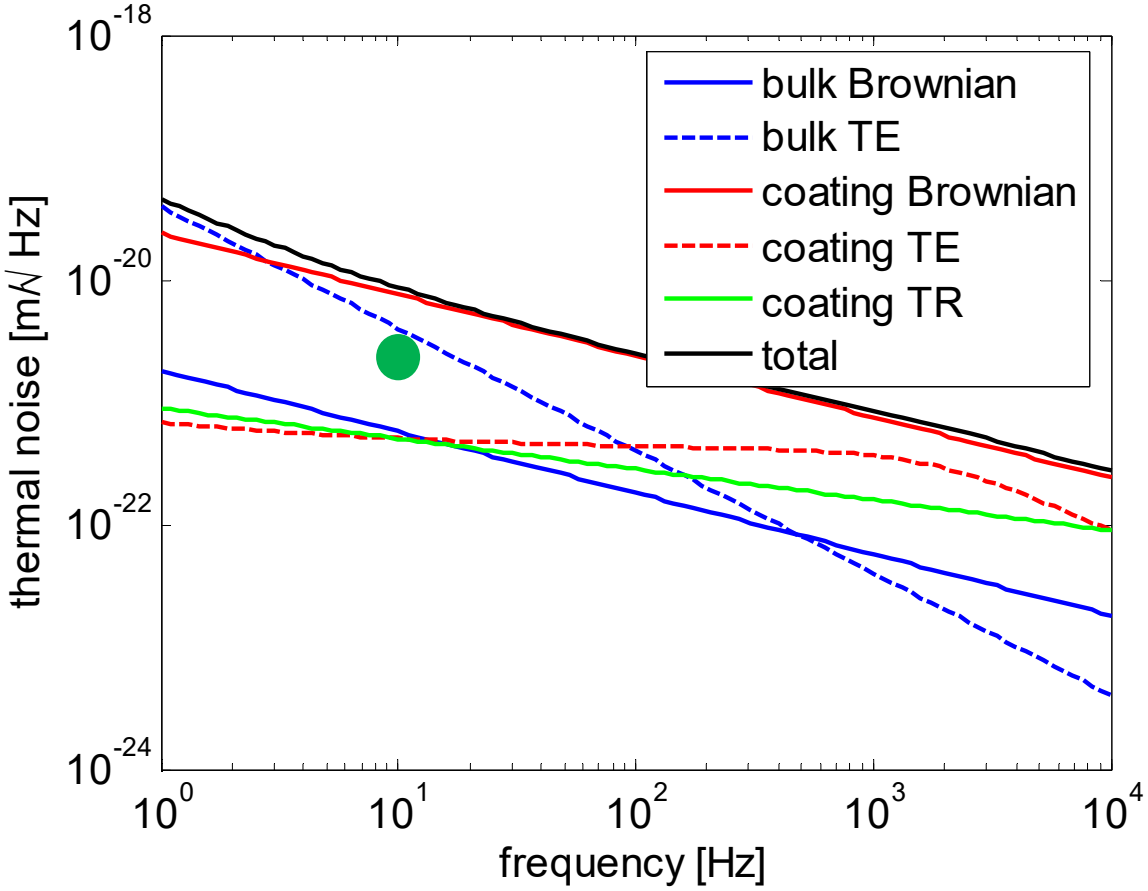


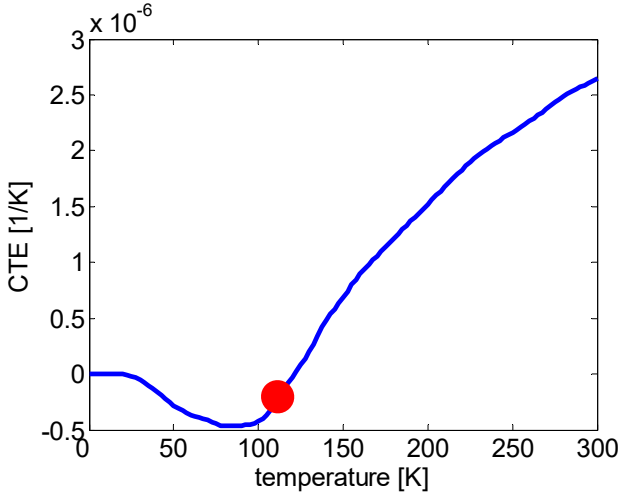


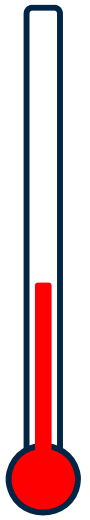


110 K

Thermal Noise Estimate

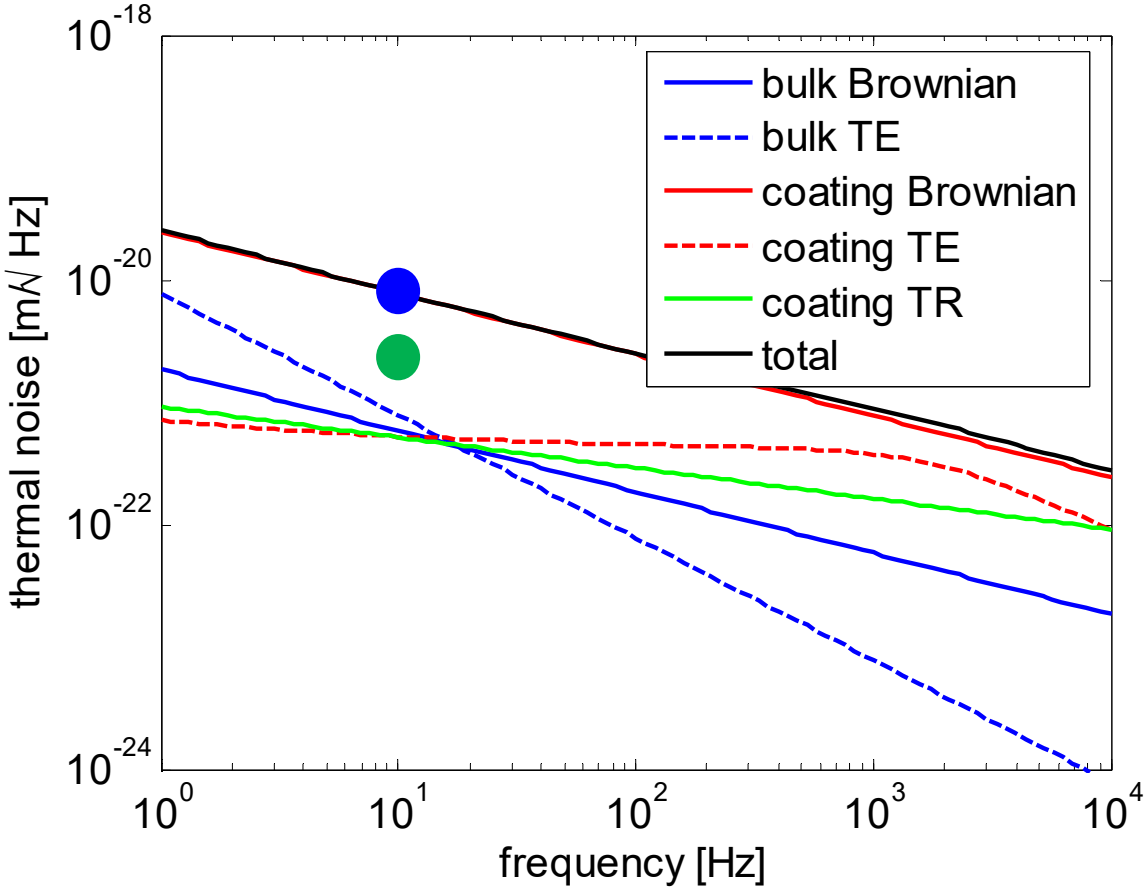


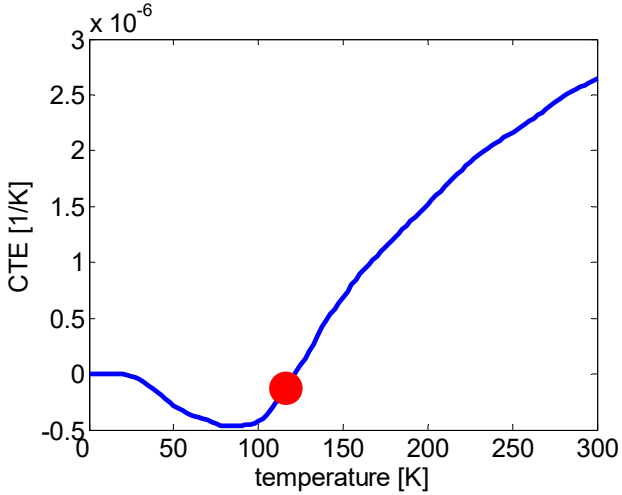


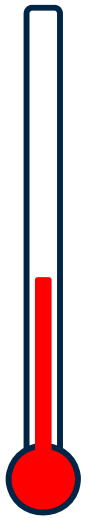


115 K

Thermal Noise Estimate

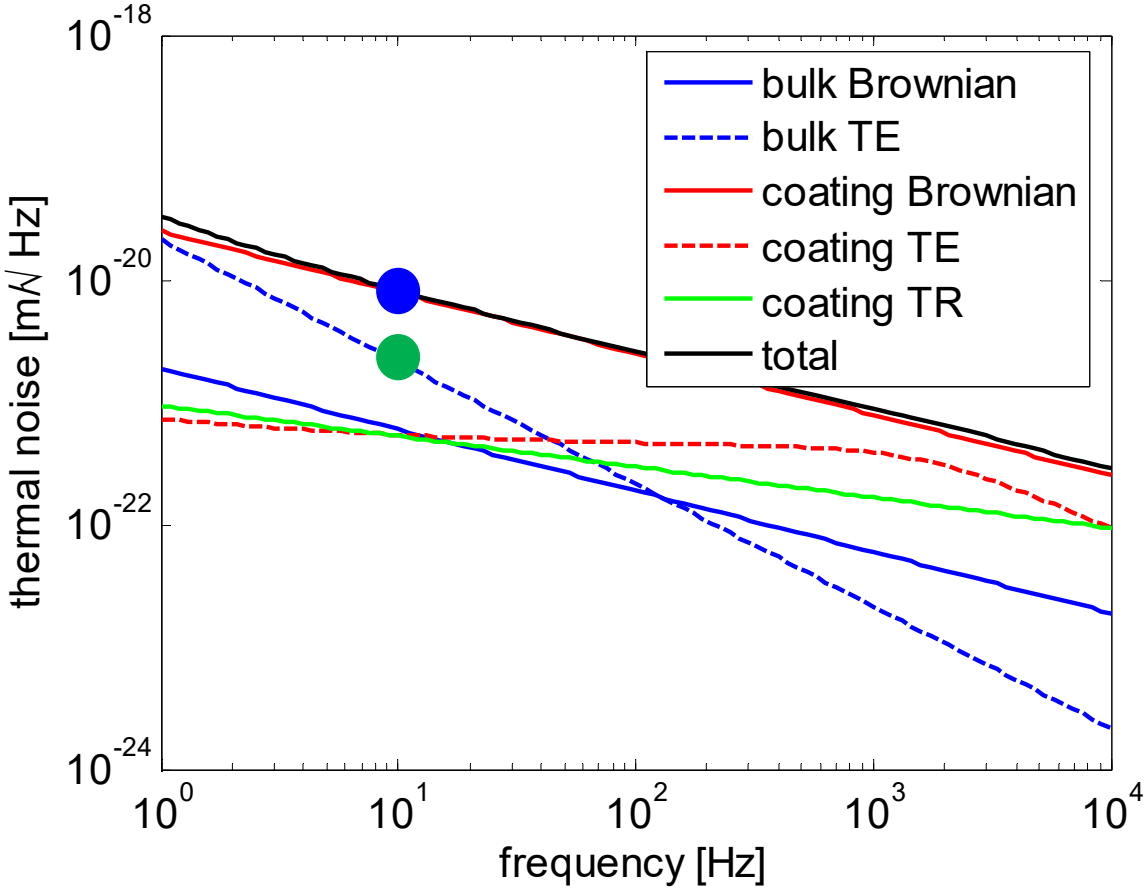


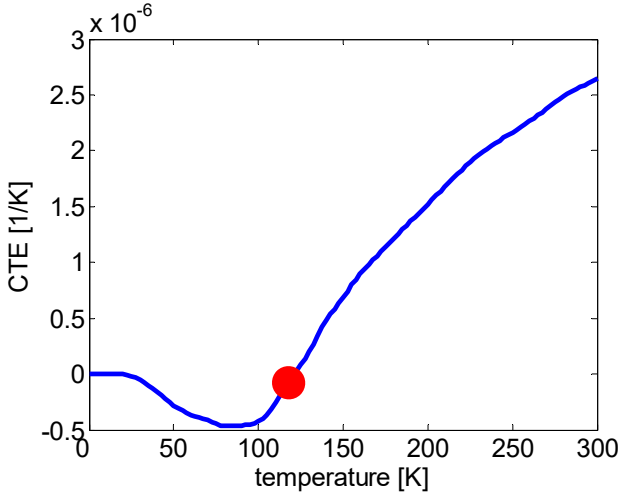




120 K

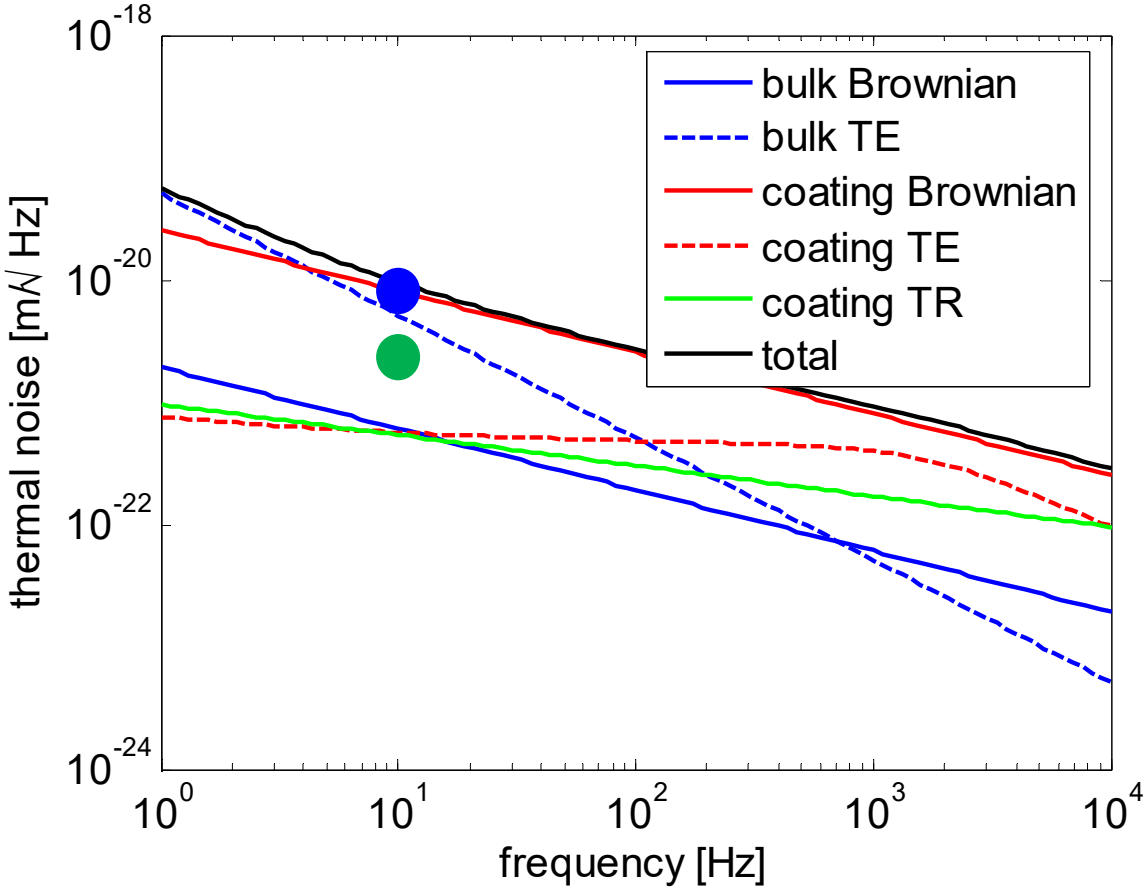
Thermal Noise Estimate

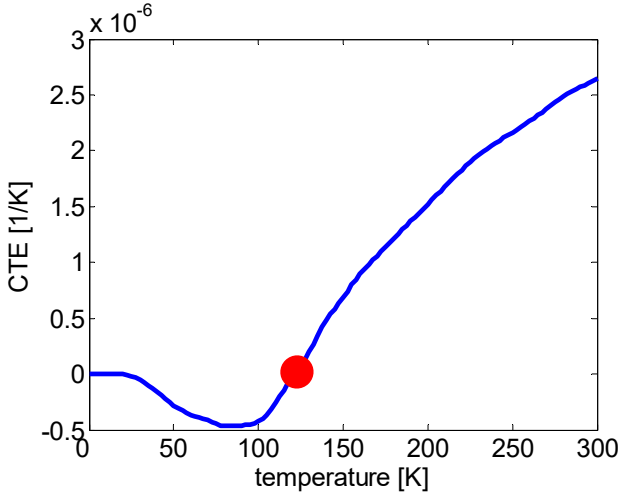




125 K

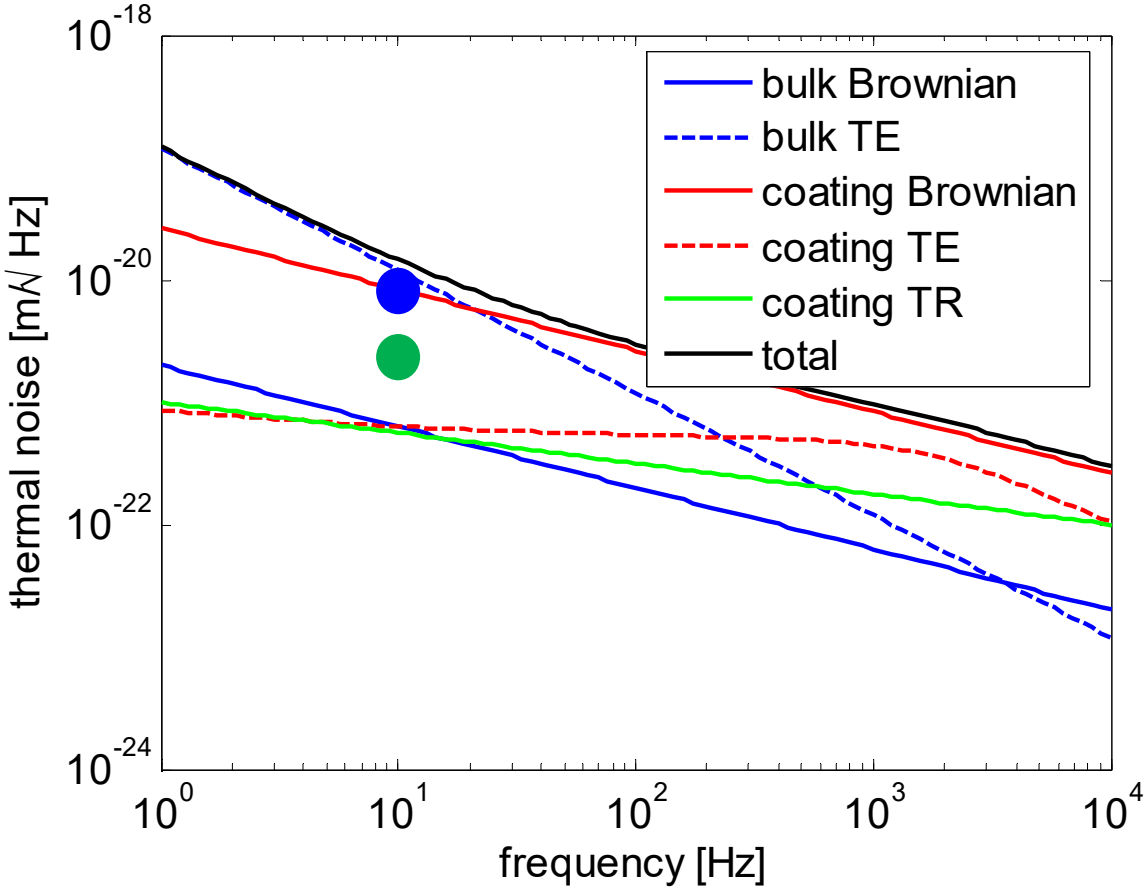
Thermal Noise Estimate

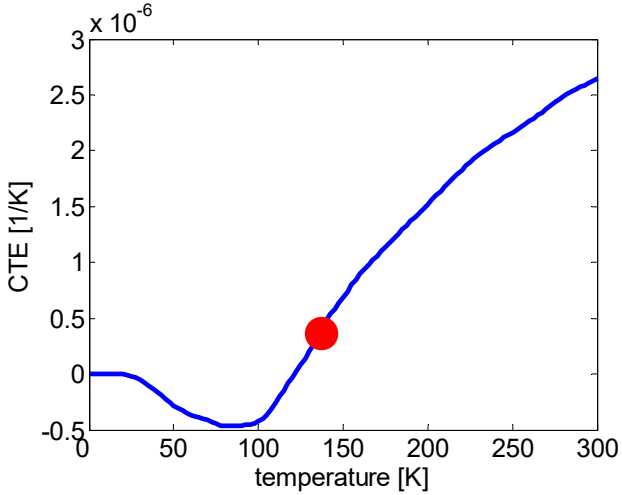




130 K

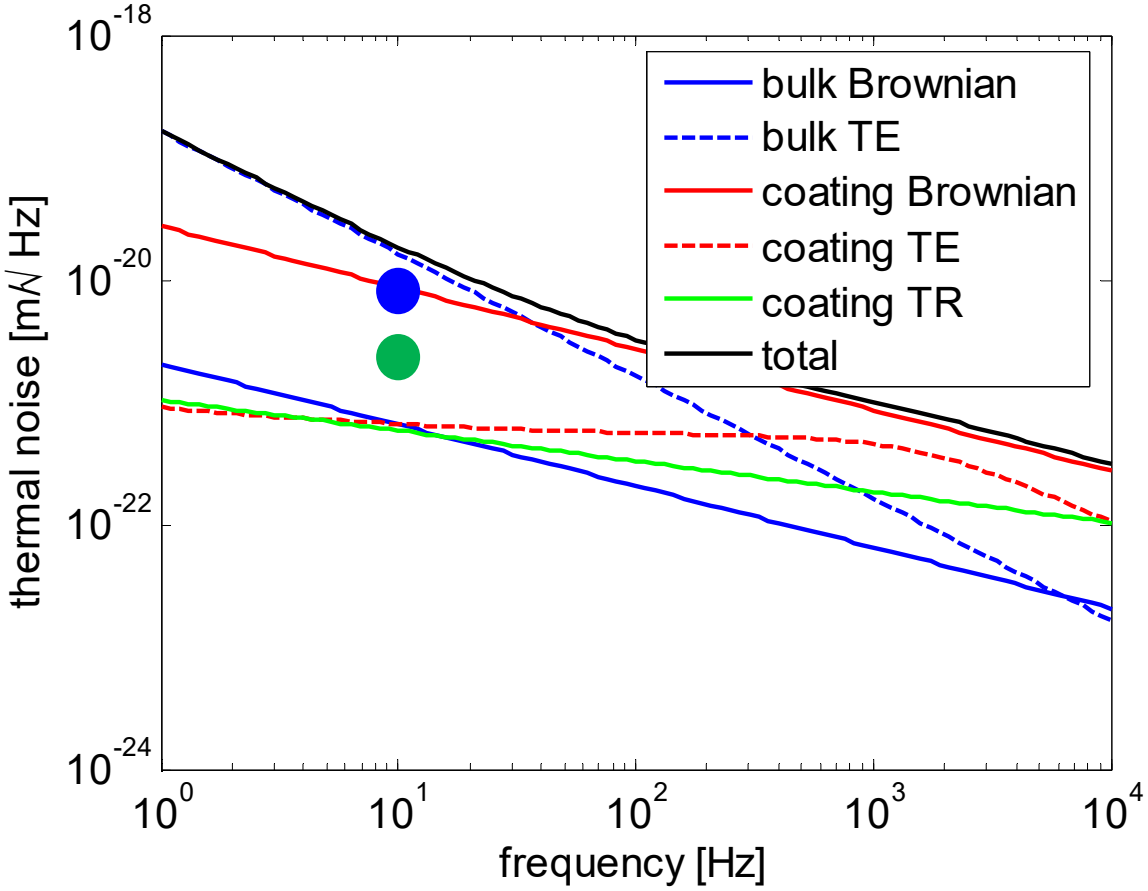
Thermal Noise Estimate

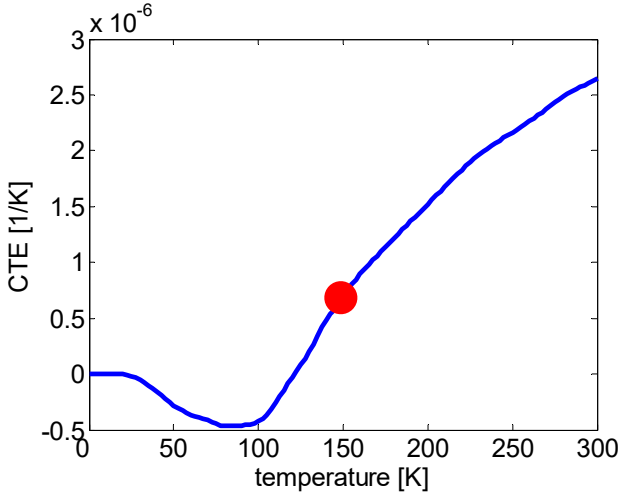




140 K

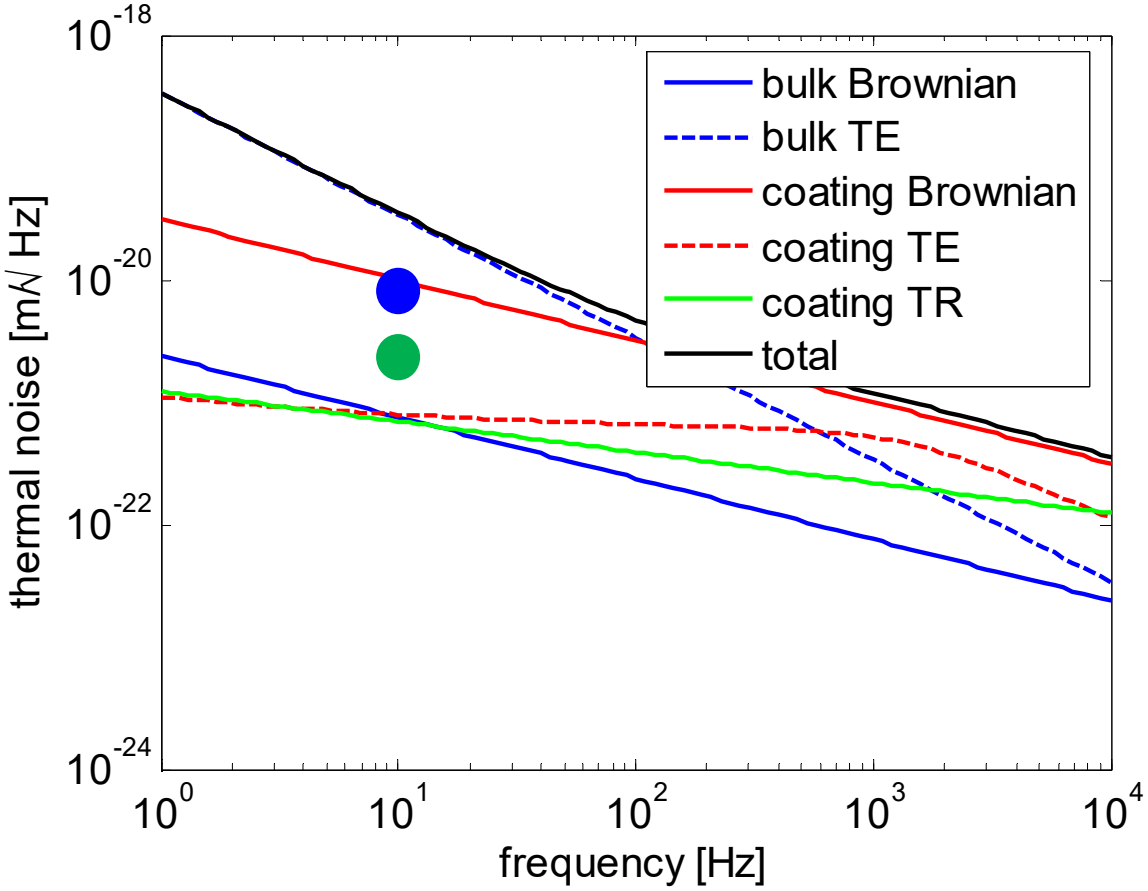
Thermal Noise Estimate

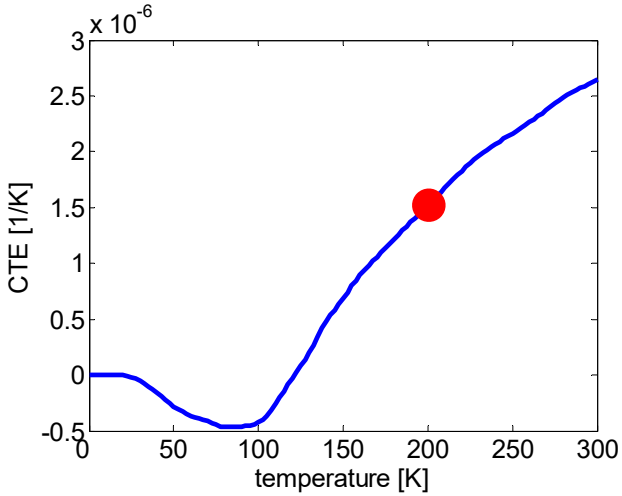




150 K

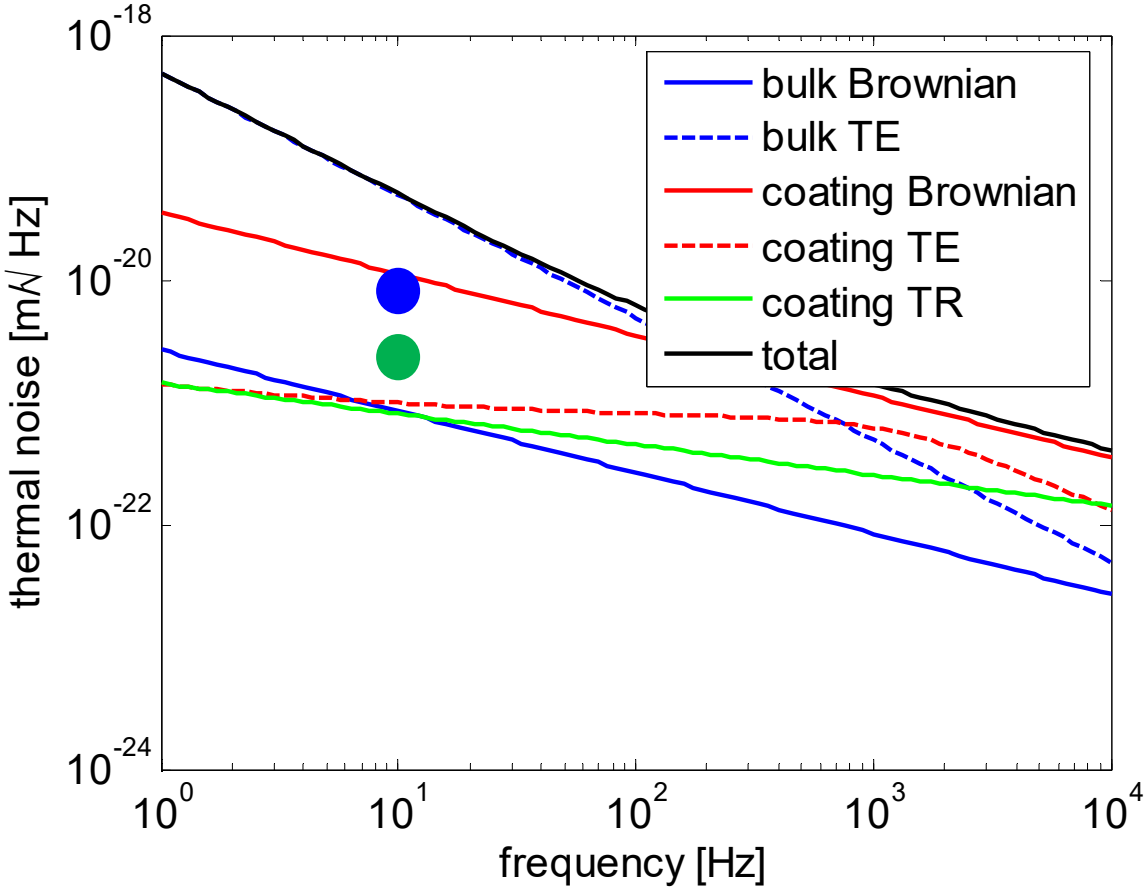
Thermal Noise Estimate

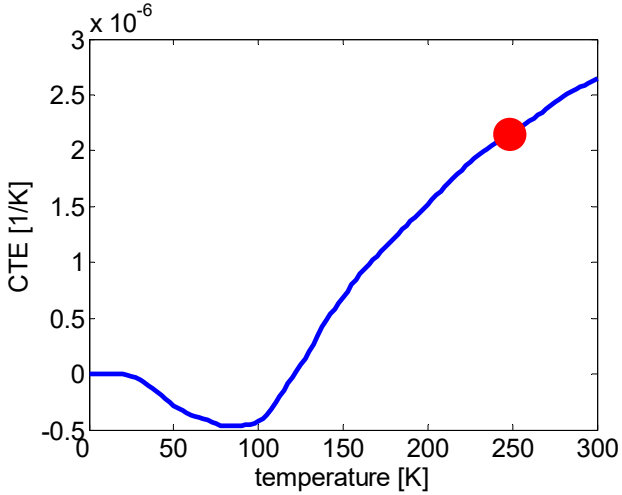




200 K

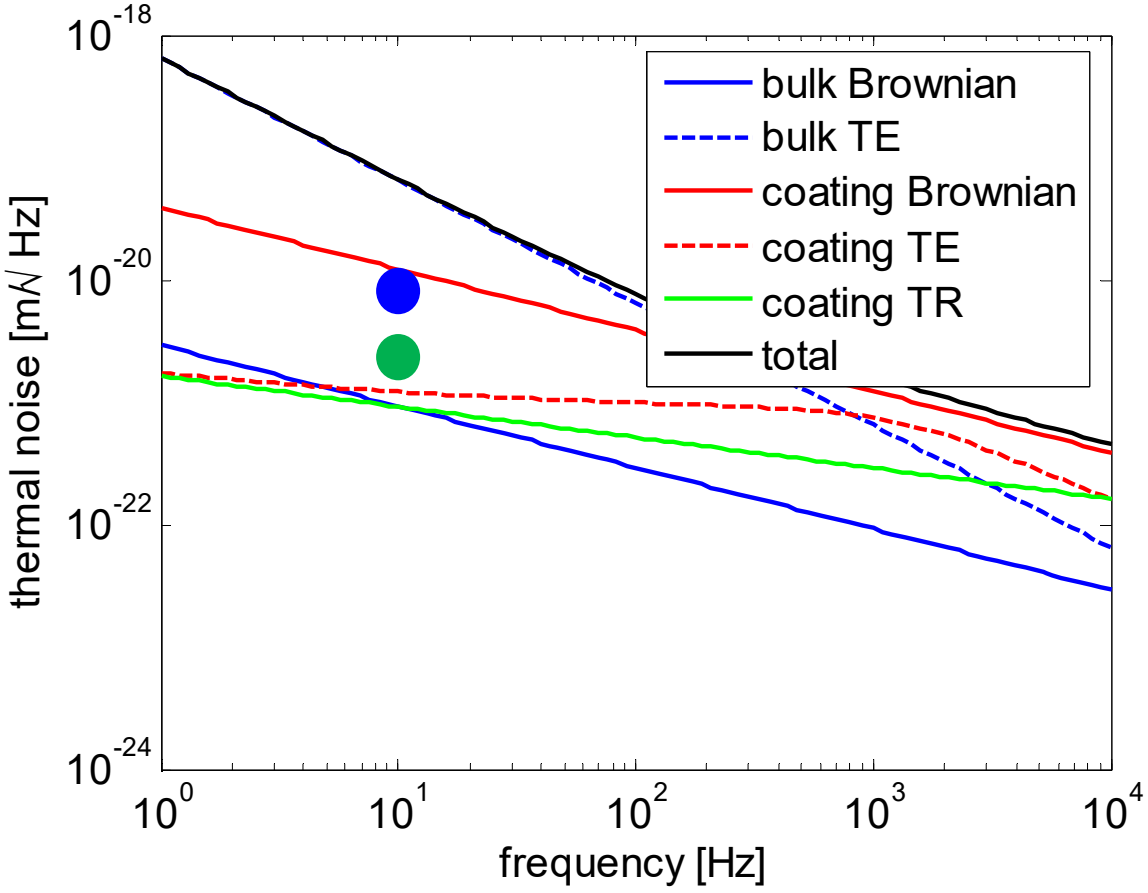
Thermal Noise Estimate

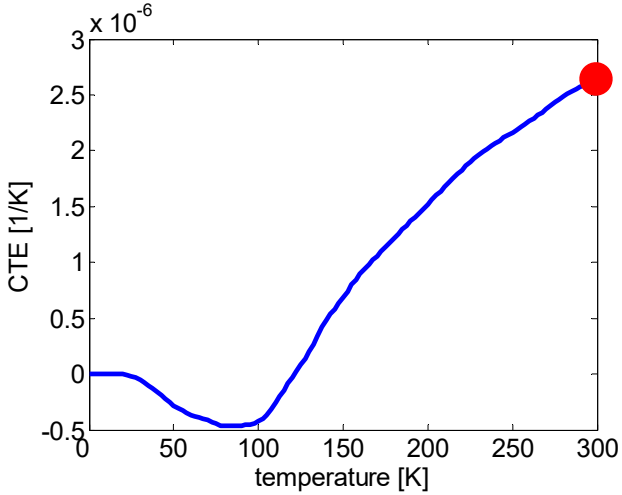




250 K

Thermal Noise Estimate



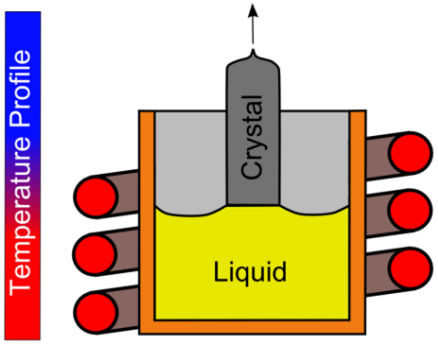


300 K

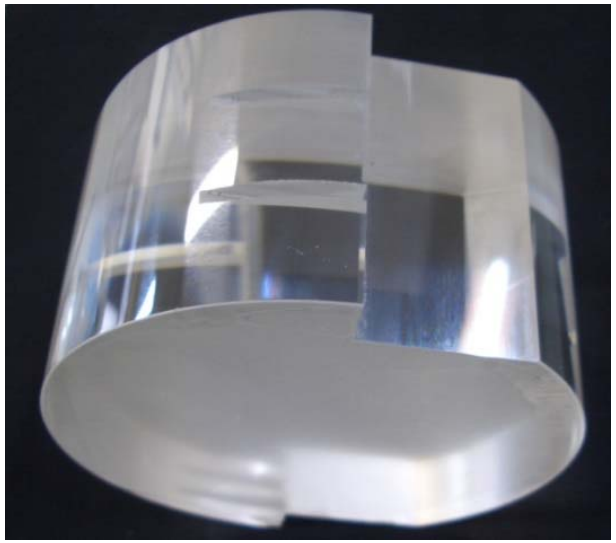
Good operating points: T<20K, T=120K

Bulk Material

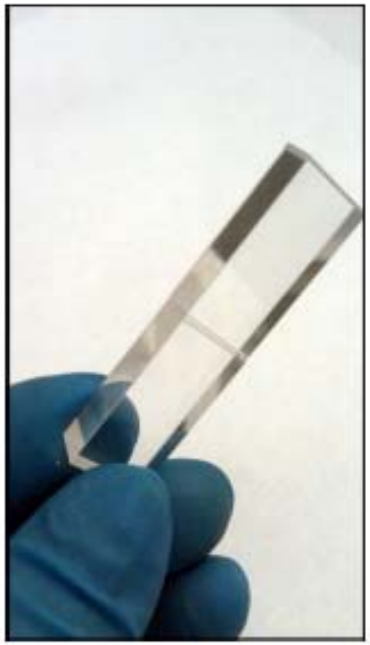
- **Silicon**
- Silicon boules available in large sizes up to 45cm (Czochralski process >20cm).
- Magnetic Czochralski (mCz) offers opportunity to reduce absorption to ppm/cm by reducing impurities from crucible



- **Sapphire**
- KAGRA working with Shinkosha to develop KAGRA sapphire test masses (measurement of optical absorption currently underway)
- KAGRA sapphire c-axis: ϕ22cm$\times$15cm (23kg)

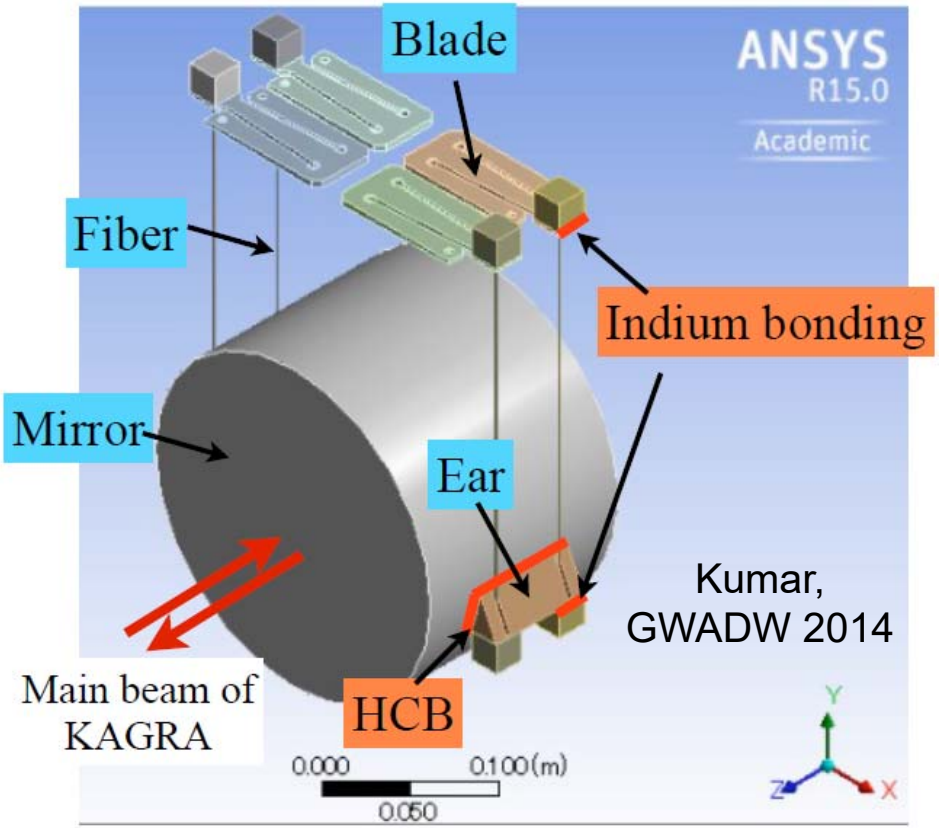


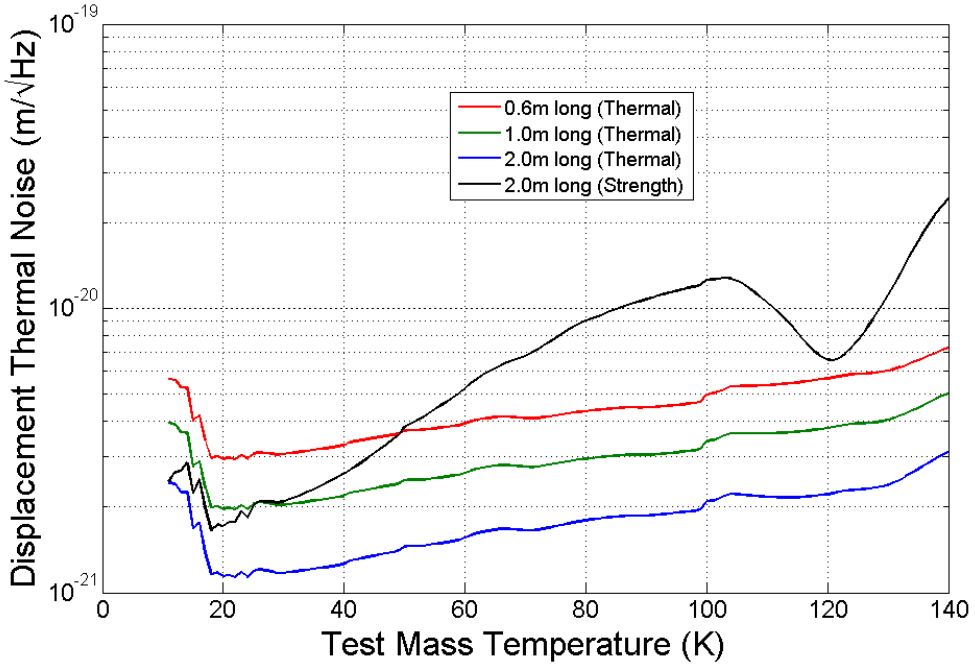
Yamamoto, 2013 ET meeting



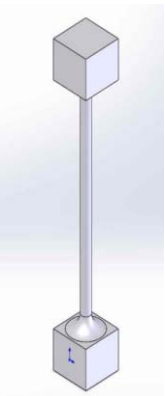
Cryogenic Suspensions

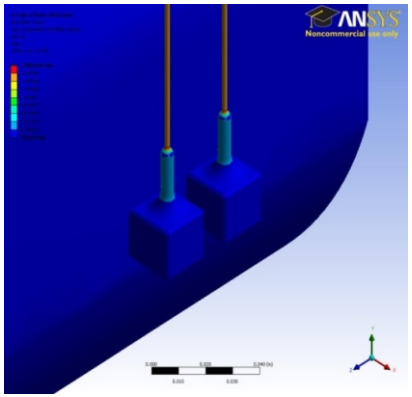
- Cryogenic upgrades offer potential improvements in strain sensitivity of >20.





- Need techniques to:
  - produce suspension fibres in silicon/sapphire
  - joint crystalline materials
  - assemble suspensions in a robust way, with techniques for replacement of fibres





Suspension Fabrication

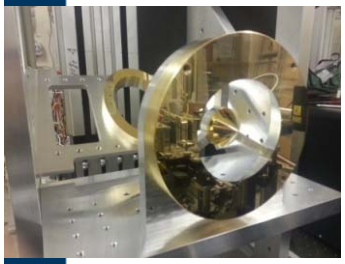
- Two possible construction methods for suspension elements:

(i) Laser heated pedestal growth (ii) mechanical machining/polishing

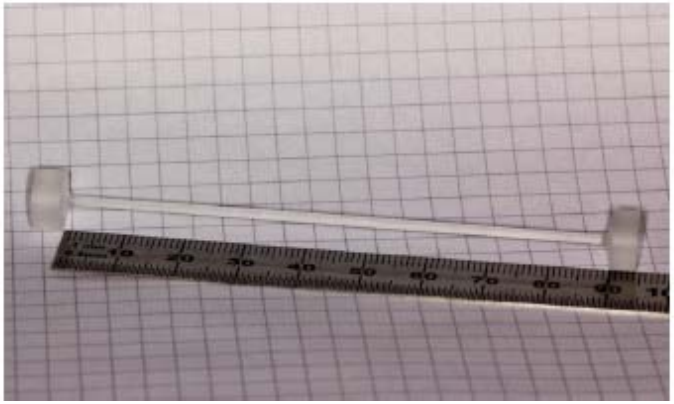
Glasgow

- 120K operation (LIGO Voyager): radiative cooling => fibre can be sized according to tensile strength (300MPa)
- 20K operation: fibre extract heat from absorbed power => fibre size is a combination of strength/heat extraction

Glasgow



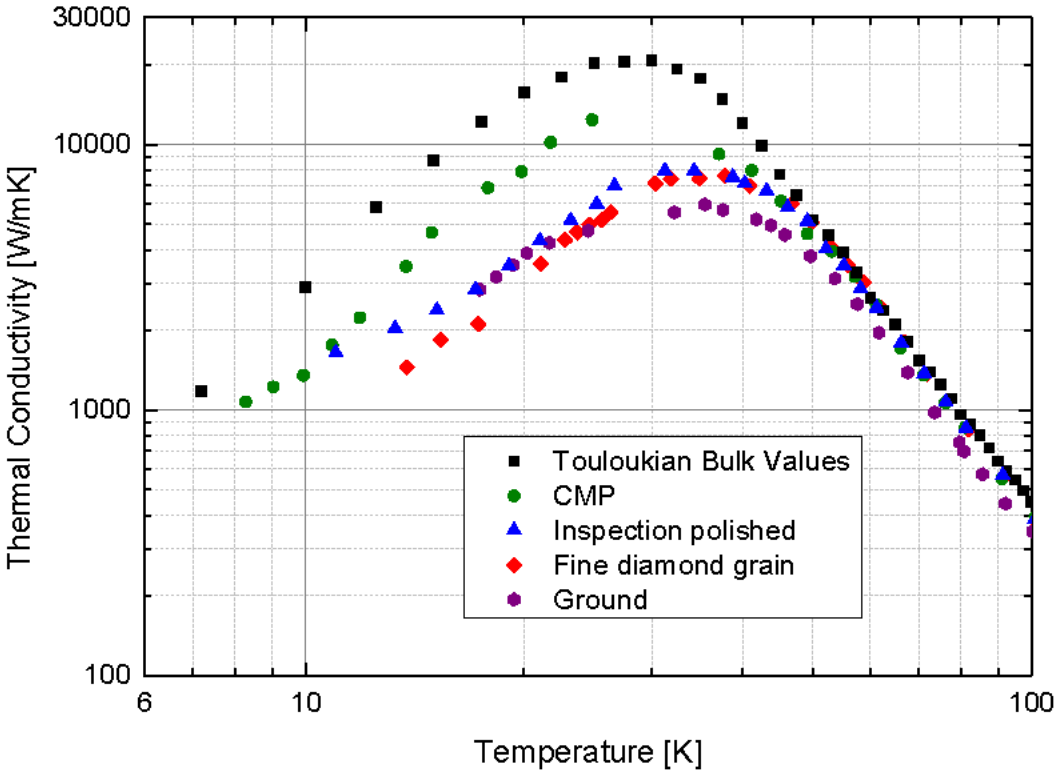
Buric et al., Proc. of SPIE Vol. 9852



Yamamoto, 2013 ET meeting

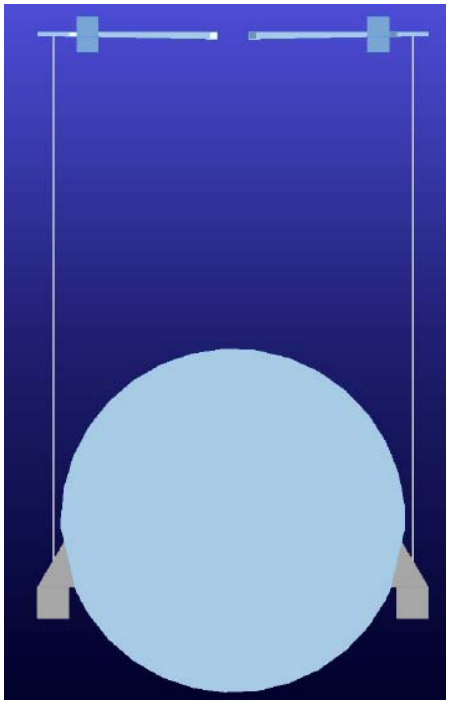
Suspension Components

- Thick suspension fibres (ϕ1.8mm) will requires final stage springs to lower the bounce and roll modes



- Thermal conductivity of a KAGRA suspension fibre (Nawrodt, 4th ELITES meeting)

springs



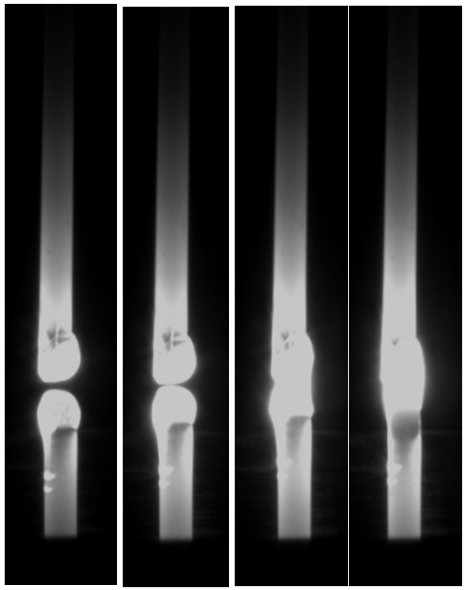
fibres

ears/test mass

- Prototype KAGRA springs (Kumar, GWADW 2014)

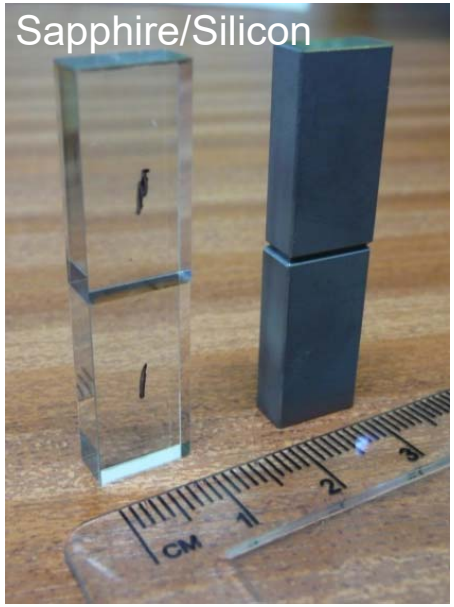
Bonding Research

- A combination of techniques will ensure the availability of quasi-monolithic suspensions: hydroxy-catalysis/metal bonding/direct heating. This will enable
  - robust suspension deployment
  - ability to replace fibres
- Strength testing/thermal conductivity tests are ongoing to prove technologies in KAGRA

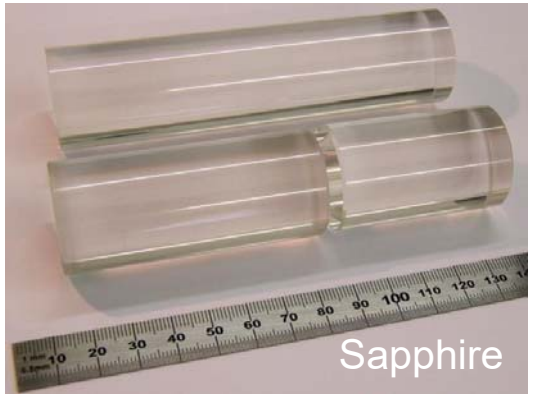


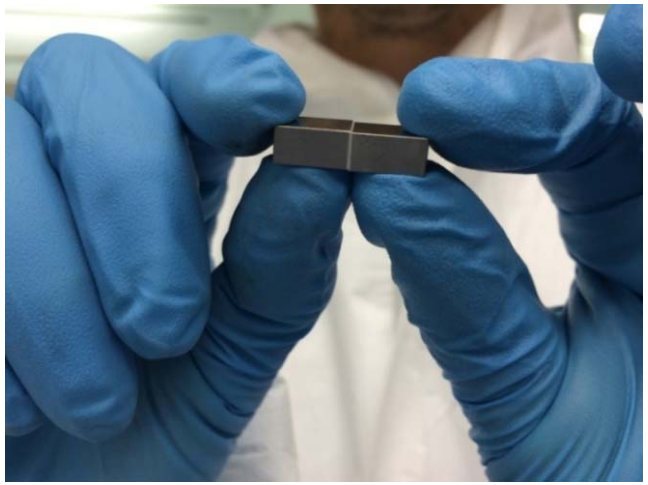
Joining sapphire

Indium bonding



Glasgow R&D



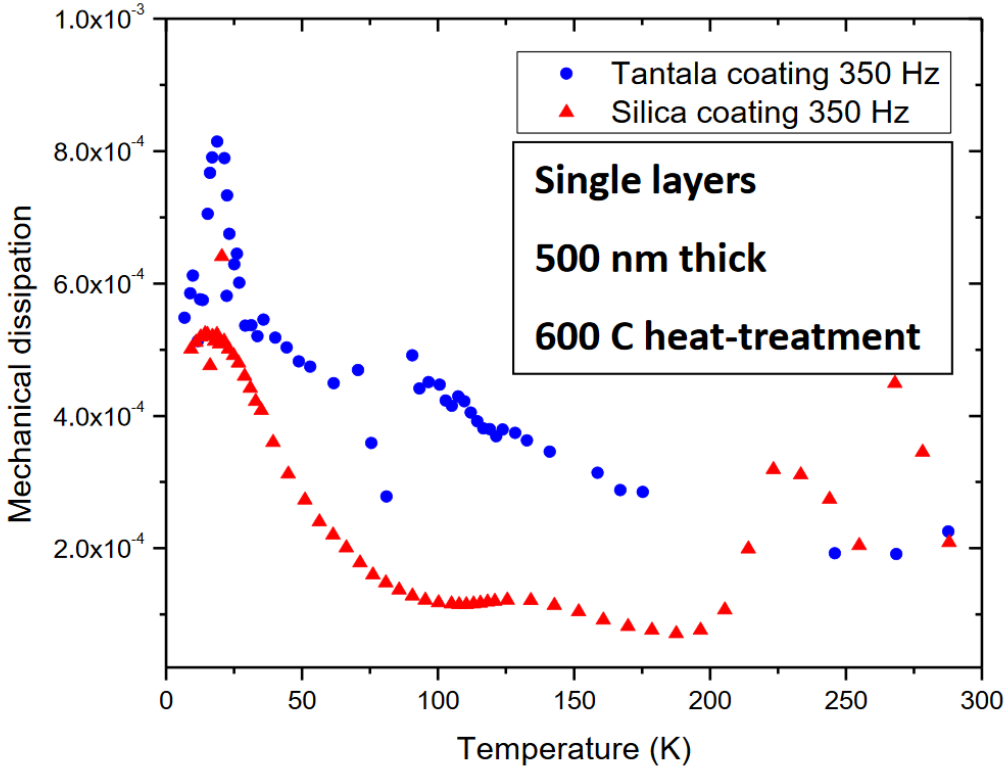


Coating Research

- IBS coatings are the technology currently employed in the room temperature advanced detectors
- Improving coating thermal noise for 3rd generation detectors will require a combination of techniques such as larger beams and improved materials (low absorption and mechanical loss)
- IBS coatings show a dissipation peak at low temperatures (but still gain from product of loss × temperature)

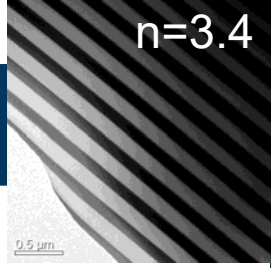
$$S_X \propto \phi_{coating} \times T$$

- The KAGRA baseline is IBS coatings of titania doped tantala and silica

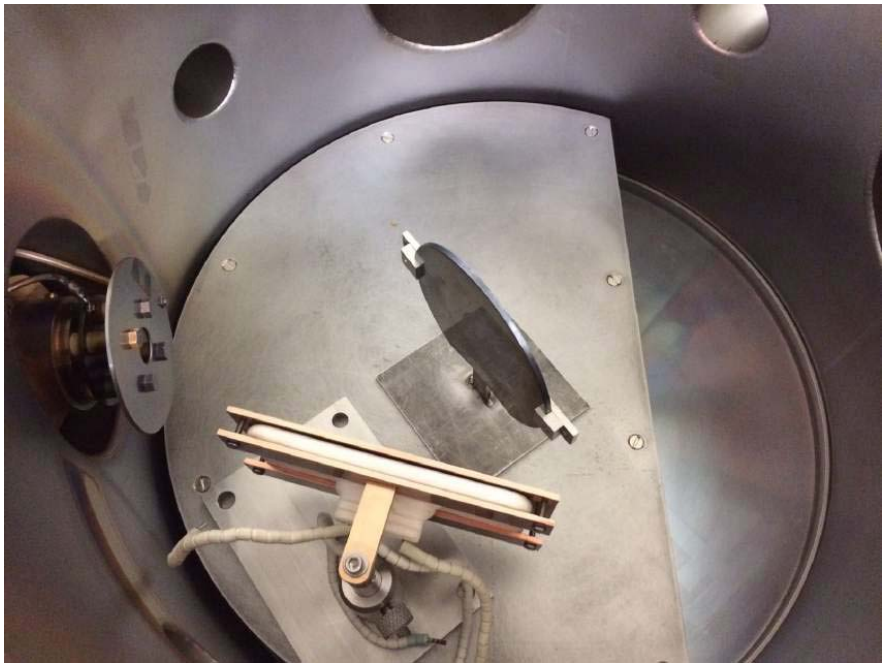


Martin et al, Class. Quant. Grav., 27, 2010,
Martin et al, Class. Quant. Grav., 31, 2014,

Amorphous Silicon

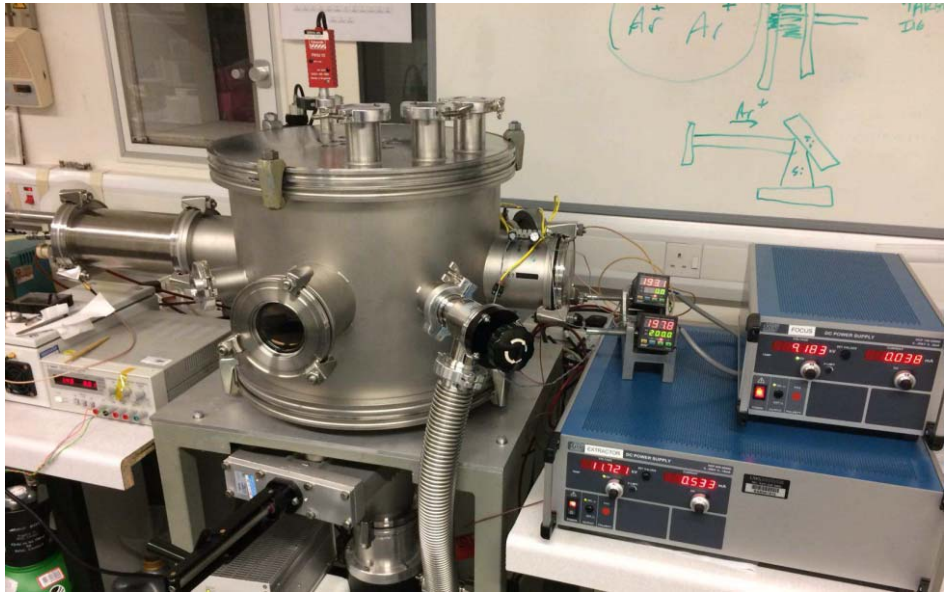


- Recent results from University of the West of Scotland/University of Glasgow now suggest it is possible to reduce optical absorption in IBS aSi coatings, whilst maintaining low ϕ.



- Amorphous silicon has a high refractive index contrast => reduce # stack layers
- The microwave cavity is filament free and low maintenance

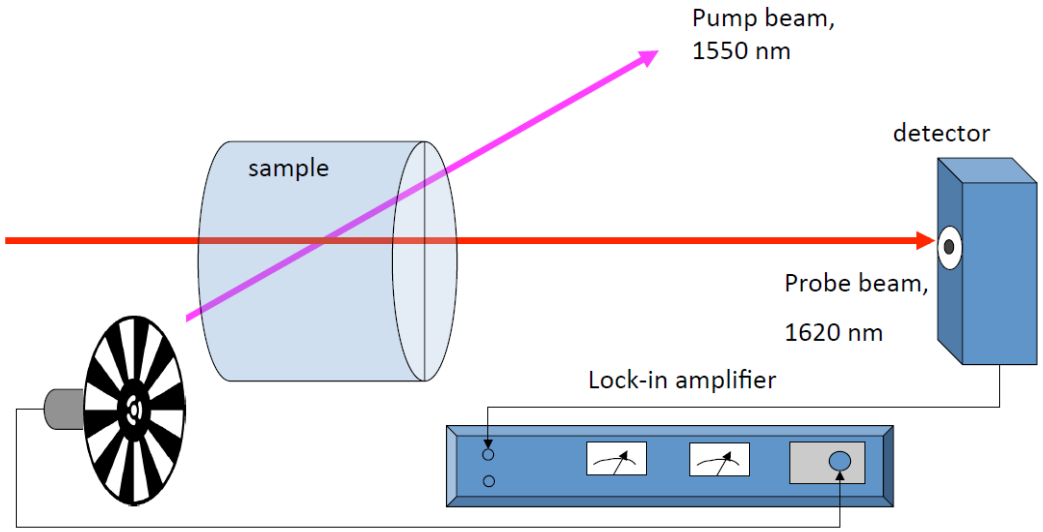
$$S_{Br,C} \approx \frac{2k_B T}{\pi^{3/2} f} \frac{t_{eff}\phi_{eff}}{w^2 Y}$$



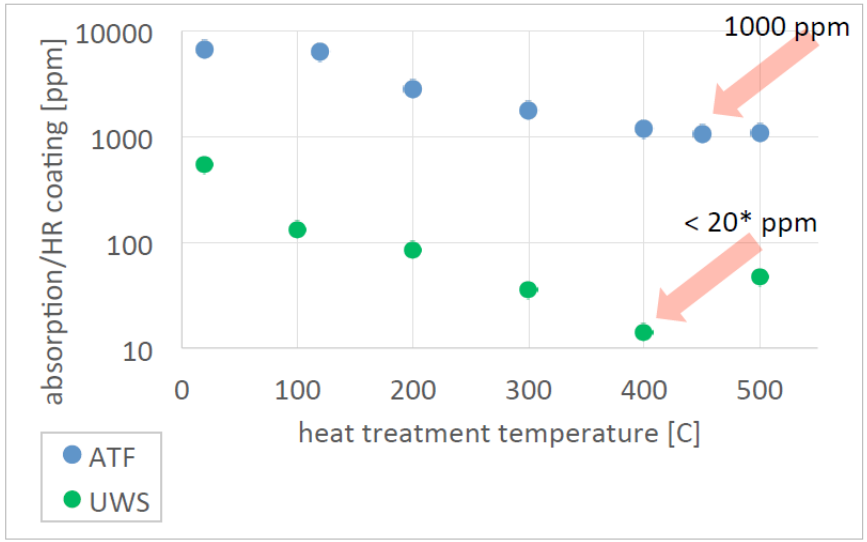
Reid, 2016 GWADW meeting

Amorphous Silicon

- Absorption measured at 1550nm with the pump-probe method



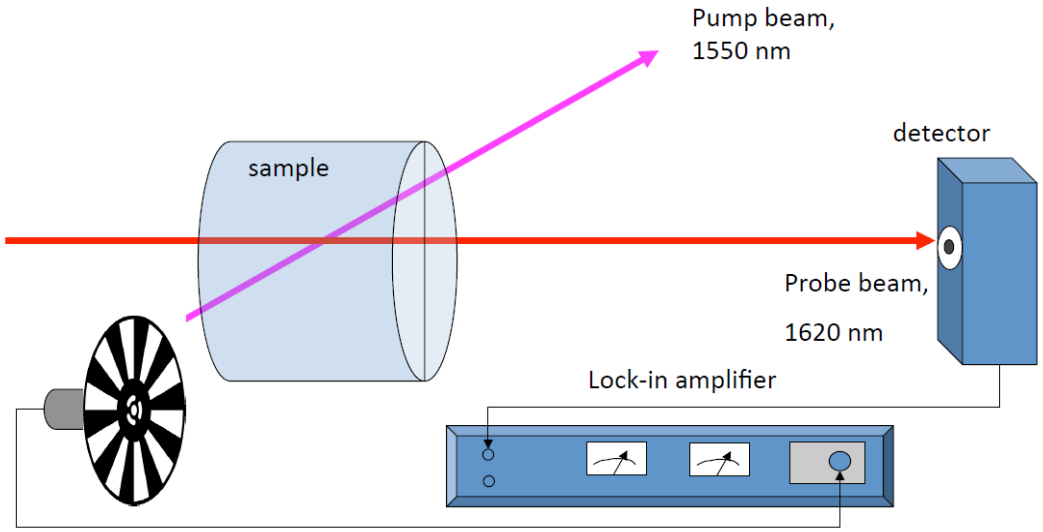
- 1550 nm absorption significantly lower than for other commercial coatings
- Refractive index ~3.4 from transmission measurements



Reid, 2016 GWADW meeting

Hybrid Coatings

- Absorption measured at 1550nm with the pump-probe method



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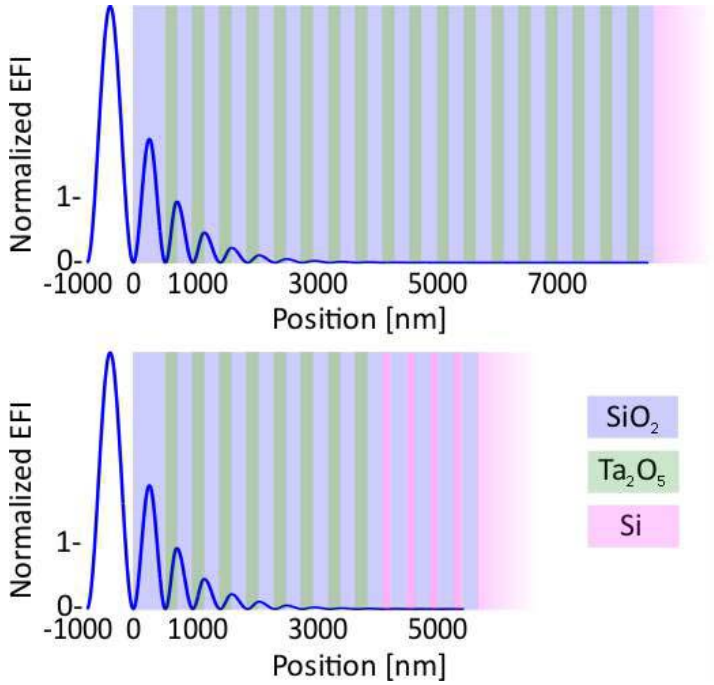


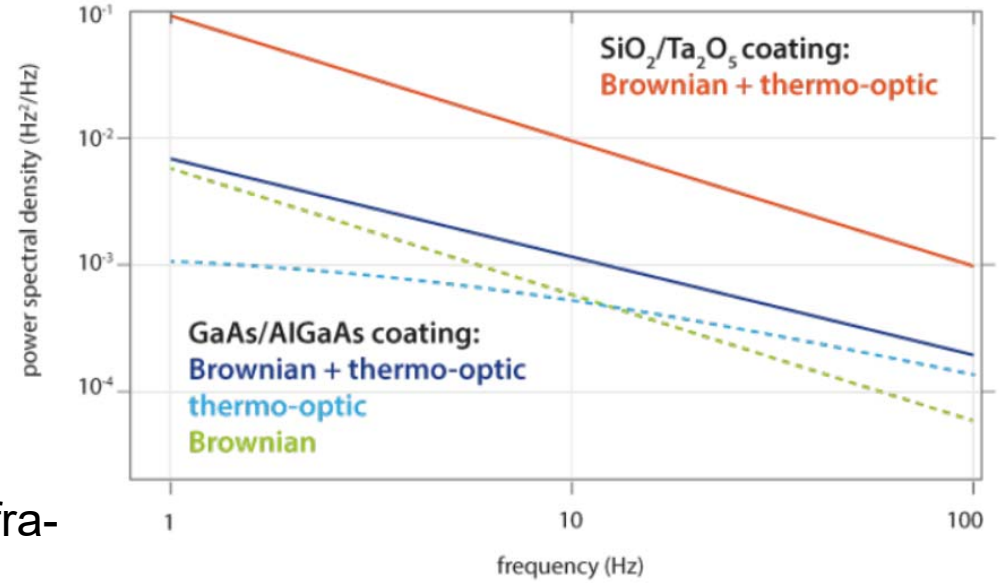
- Thermal noise improvement

	120K	20K
ITM	-21%	-20%
ETM	-38%	-36%
Total	-32%	-31%

Reid, 2016 GWADW meeting

Crystalline Coatings

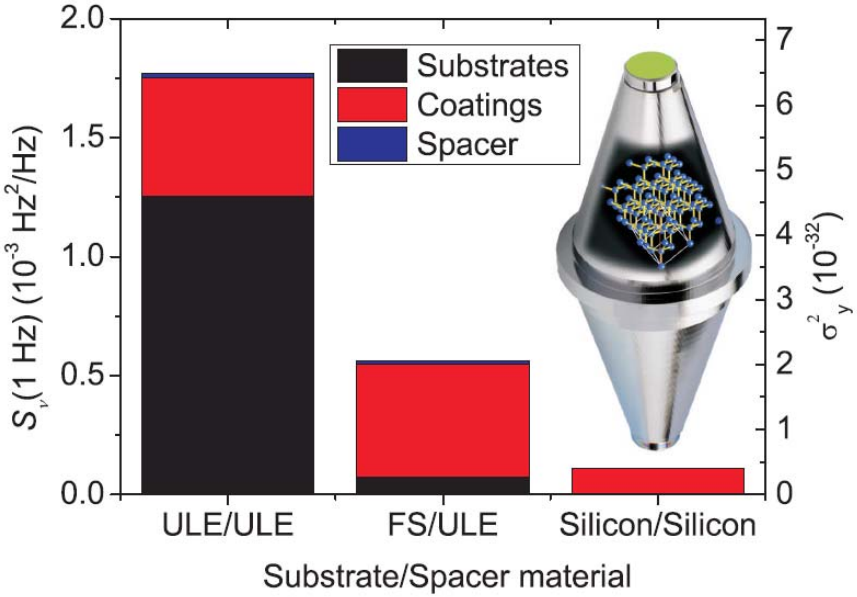
- Significant interest in crystalline coatings
- Two interesting candidates
  - AlGaAs multilayer with varying Al content for index contrast
  - AlGaP: lattice matched to silicon



- Sub ppm absorption at visible and near infra-red wavelength
- Need to show the scalability of the technology to larger optics (e.g. AEI 100g mirrors) and curved surfaces
- Cryogenic cycling

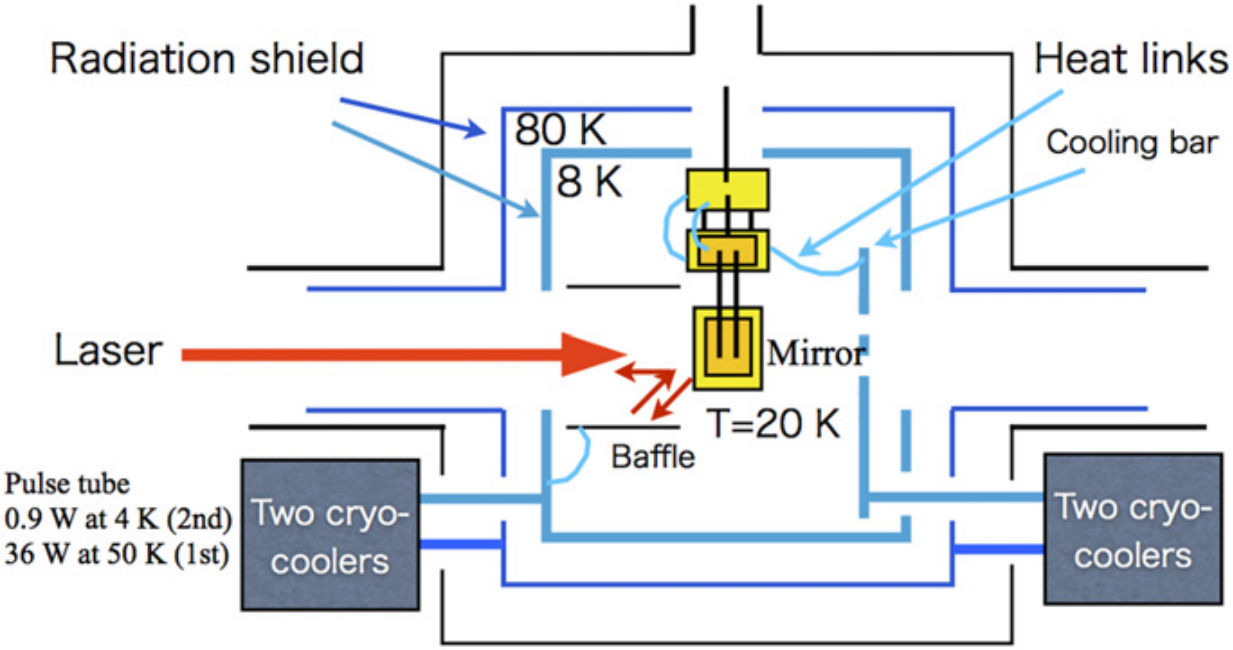
Cole, 2016
GWADW meeting

- 10x improvement in performance of AlGaAs at room temperature



Seismic Noise/Baffling

- Suspensions already incorporate several layers of isolation (active/passive) to lower seismic noise
- It is also essential to ensure that noise associated with cooling is not a limit



KAGRA heat load

KAGRA cryostat

Chen, Class. Quantum Grav. 31 (2014) 224001

Yamamoto, 2013 ET meeting

Seismic Noise/Baffling

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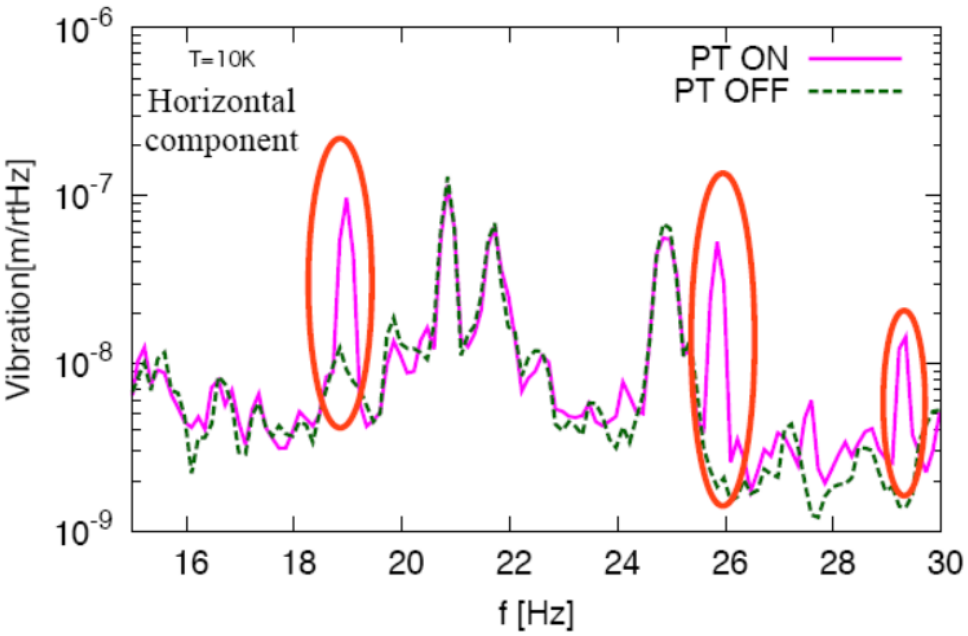
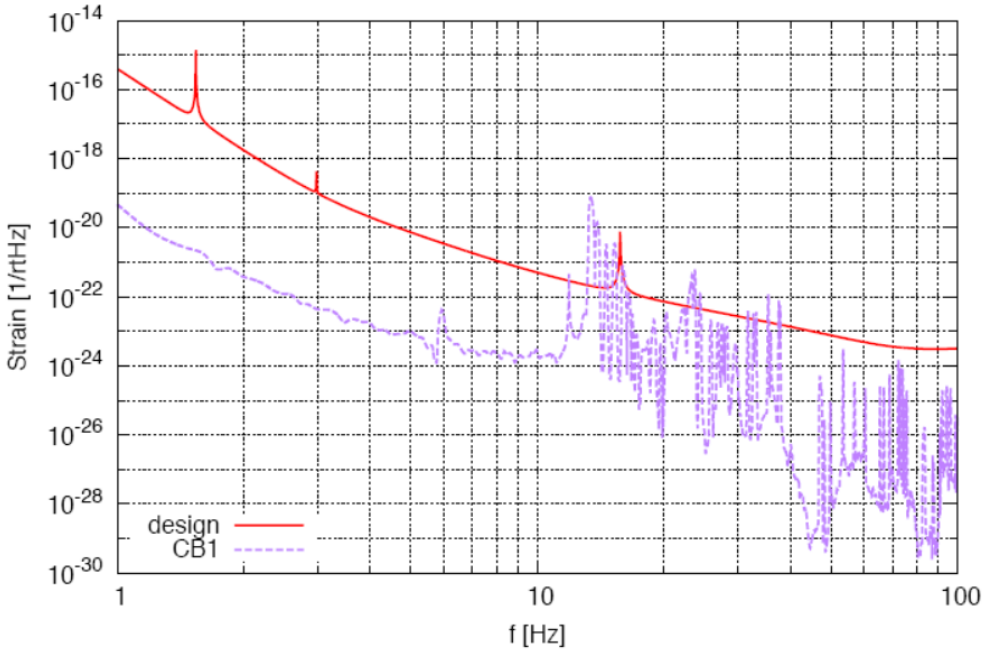


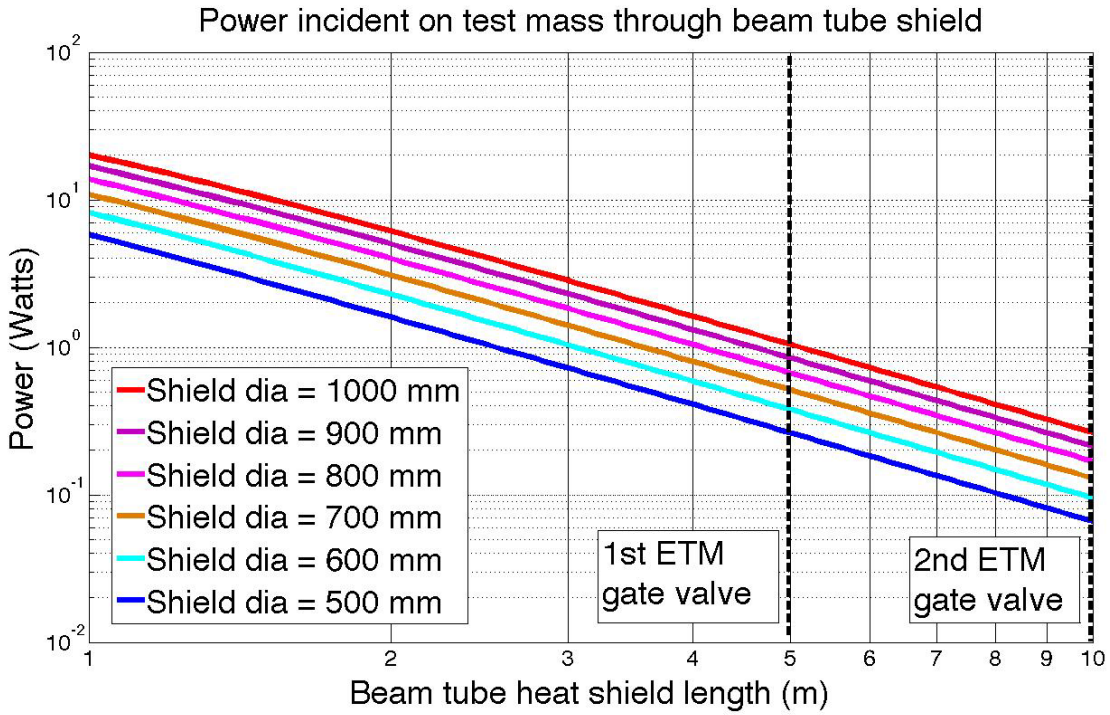


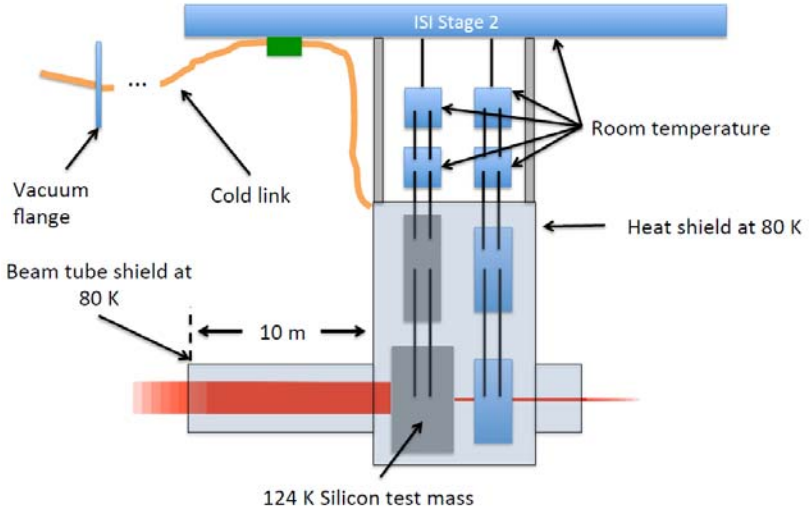
- Some excess noise around 20Hz =>utilise additional vertical isolation

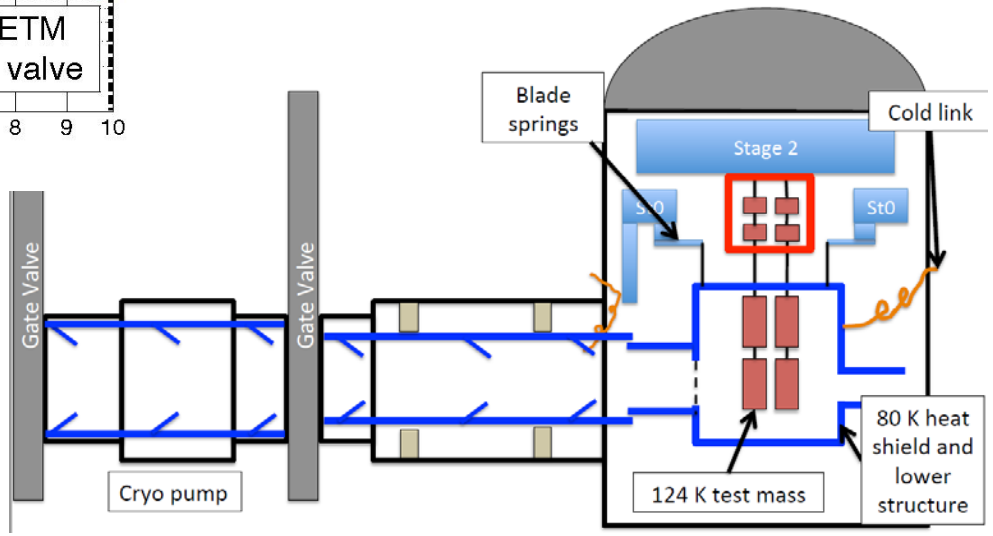
Yamamoto, 2013 ET meeting
Chen, Class. Quantum Grav. 31 (2014) 224001

Seismic Noise/Baffling

- Need radiation shields into the tubes to reduce 300K radiative heating of the test mass



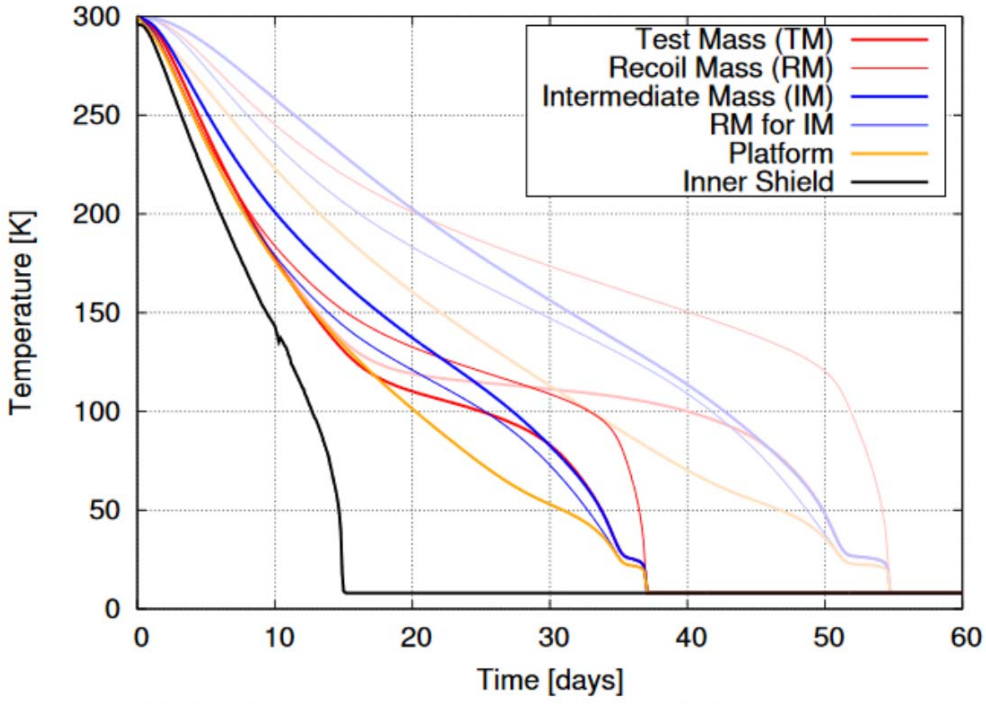




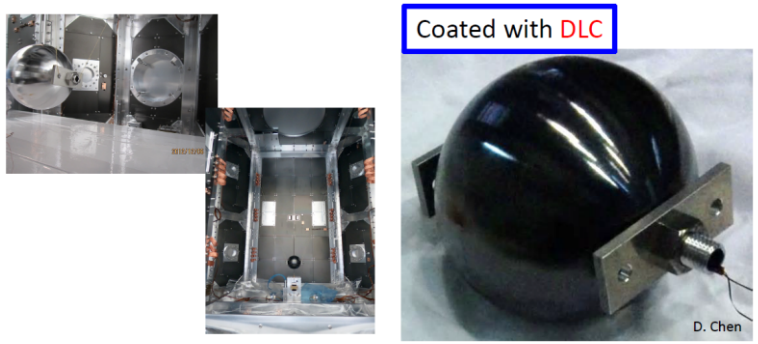
LIGO Voyager (Shapiro, G1500246)

Cooling Time

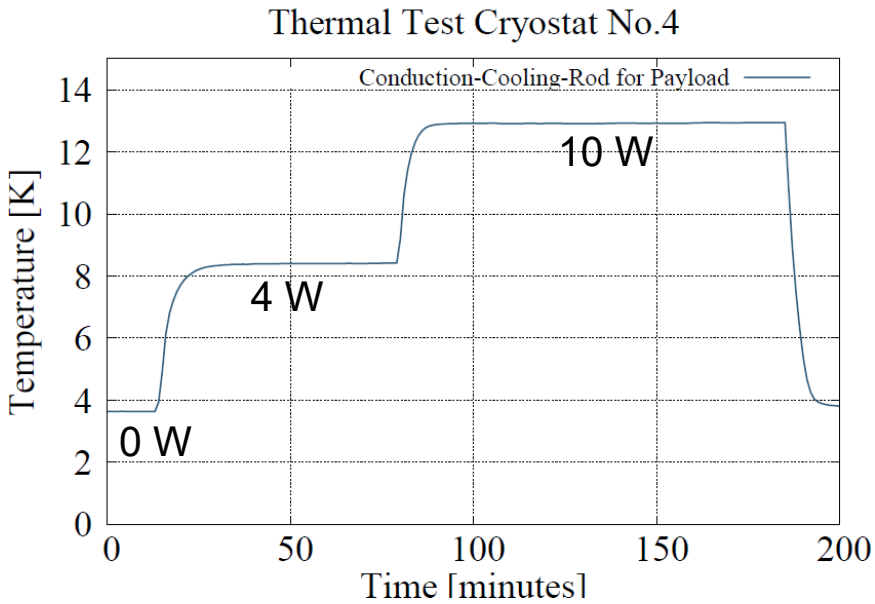
- The cooling time is an important parameter when considering commissioning/fixing items in the vacuum system



Thick: DLC coating; Thin: no DLC coating



- KAGRA cooling test
- Consideration of exchange gas/sorption pump could reduce these times



- KAGRA heat load test (design requires T<8K for 1W absorbed power)

Yamamoto, 2013 ET meeting

University of Glasgow

Summary

- There is significant R&D ongoing to prove the techniques necessary for 3rd generation techniques including cryogenic interferometry
- Typically the design timelines is around 10 years from conceptual design to implementation
- For bulk material the challenge is large masses with high purity. The semiconductor industry is useful for driving silicon R&D.
- Substrate absorption is an important driver
- Need laser development at transmissive wavelengths of silicon (1550nm-2μm)
- Cryogenic suspensions offer an order of magnitude improvement over aLIGO. Fabrication/bonding techniques are ongoing areas of R&D
- There are several exciting opportunities for improved coatings at low temperature including aSi, crystalline coatings and hybrid coatings
- Cooling remains a challenge, although exchange gas will reduce timescales