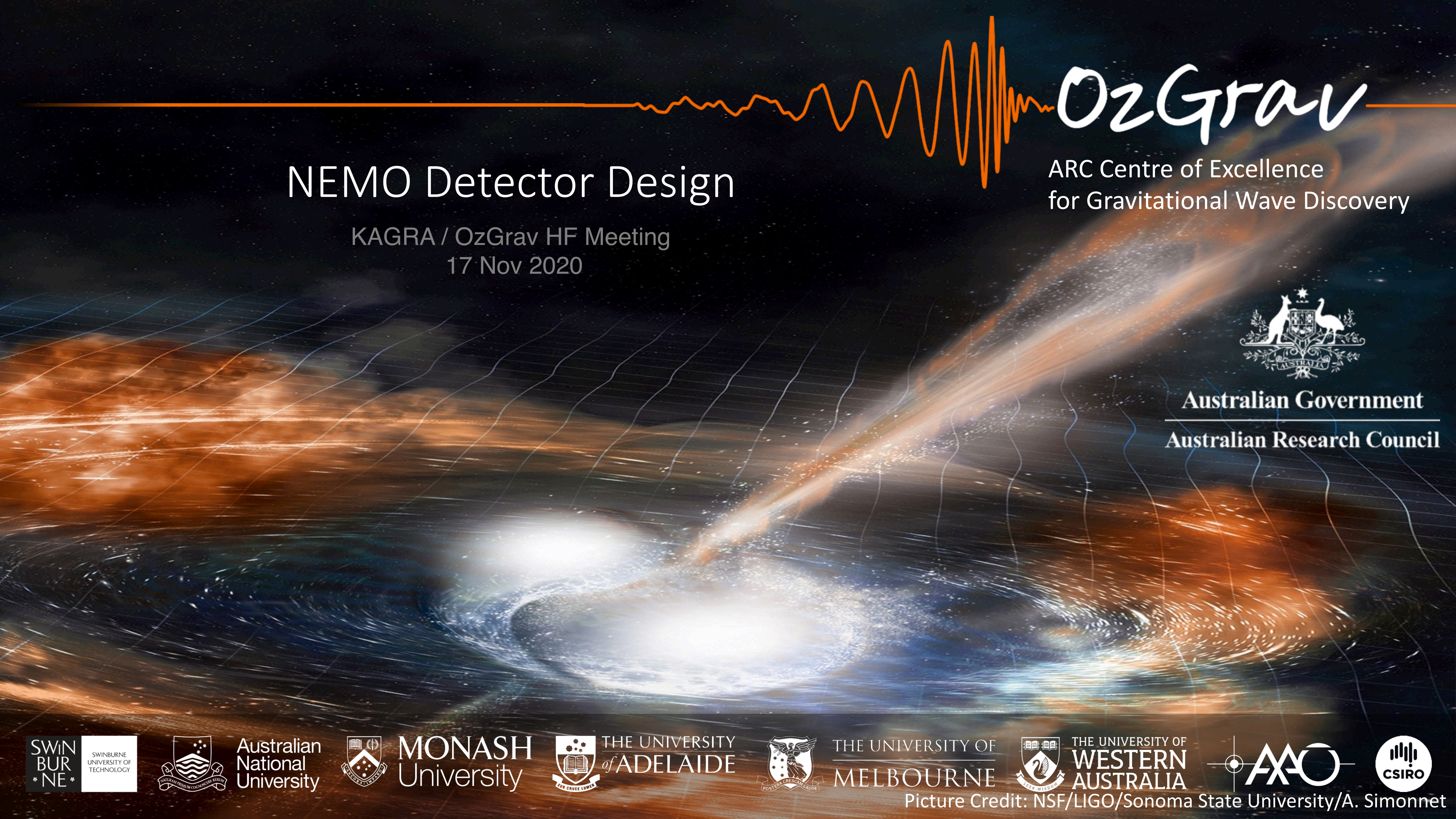

OzGrav

ARC Centre of Excellence
for Gravitational Wave Discovery

NEMO Detector Design

KAGRA / OzGrav HF Meeting
17 Nov 2020

Australian Government
Australian Research Council

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THE UNIVERSITY OF MELBOURNE
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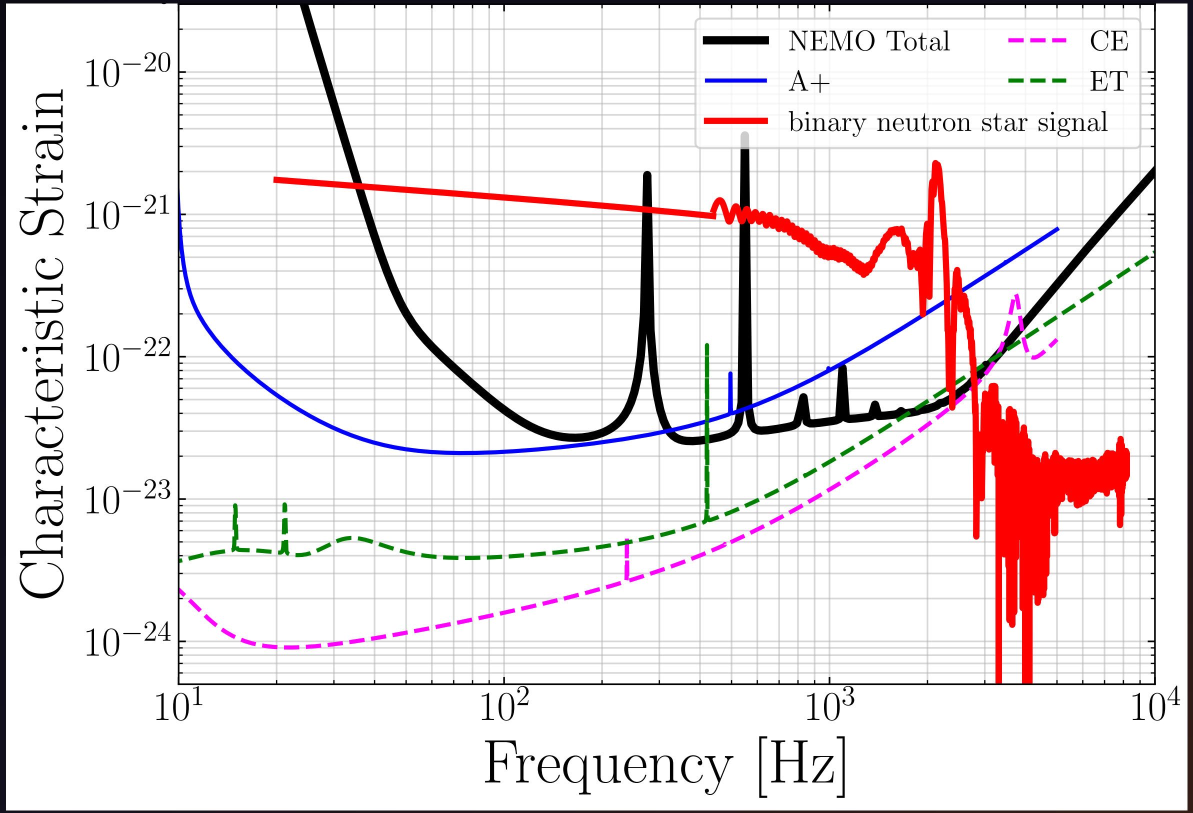
Picture Credit: NSF/LIGO/Sonoma State University/A. Simonnet

NEMO: Neutron-Star Extreme Matter Observatory

Basic Idea

- ‘High-frequency detector’
  - Target band: 1-3 kHz
  - Target level: 10^{-24} $\mathrm{Hz}^{-1/2}$
- Neglect noise requirements <1 kHz
- ‘Use 2nd and 2.5th generation tech’
- Science case + design paper recently published: Ackley, K. et al, *Publications of the Astronomical Society of Australia, 37*, E047, doi:10.1017/pasa.2020.39
- Technology enabler for 3G



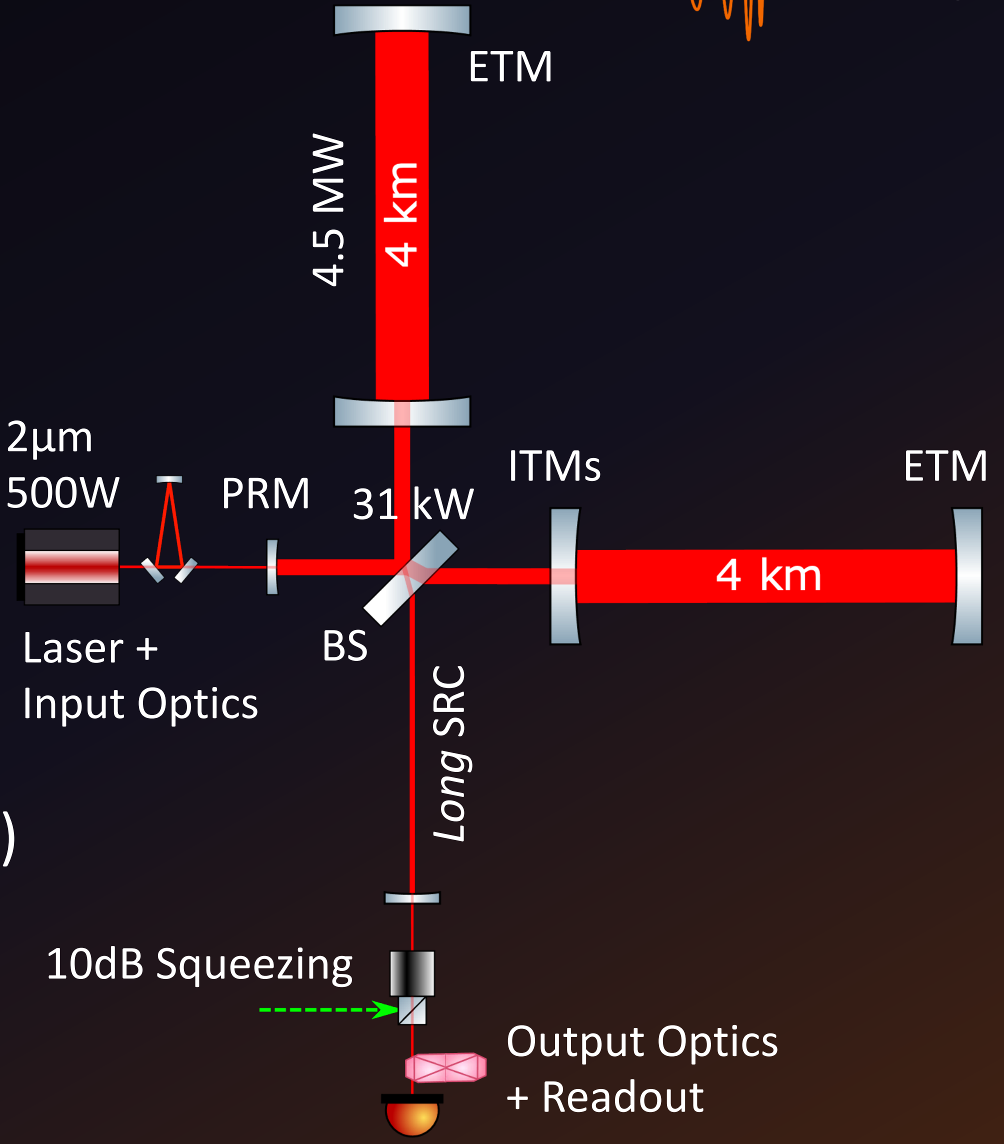
Baseline Design

Original High-Level Design Choices

- 4 km armlength
- Silicon test masses
- 2µm carrier wavelength
- 500 W input power
- 5 MW target arm power
- 10 dB squeezing

Central Tasks

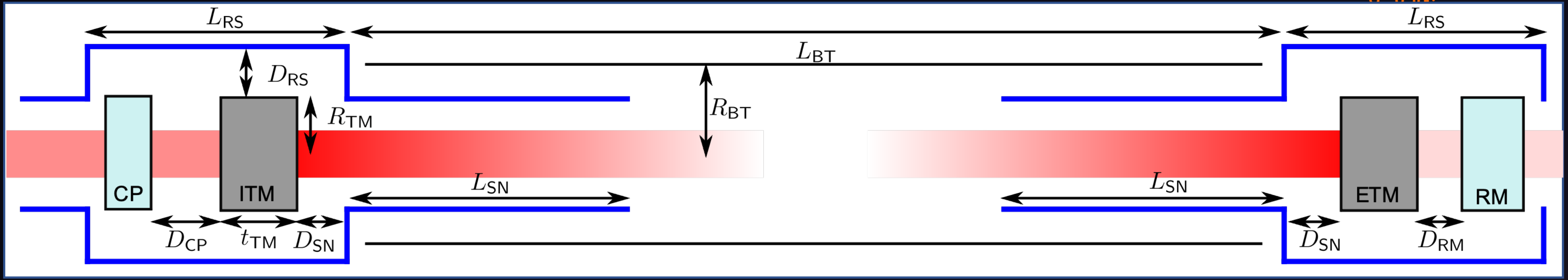
- Optical response (ARM, PRC, SRC design)
- Thermal budget and thermal noise
- Parametric instabilities
- Site selection



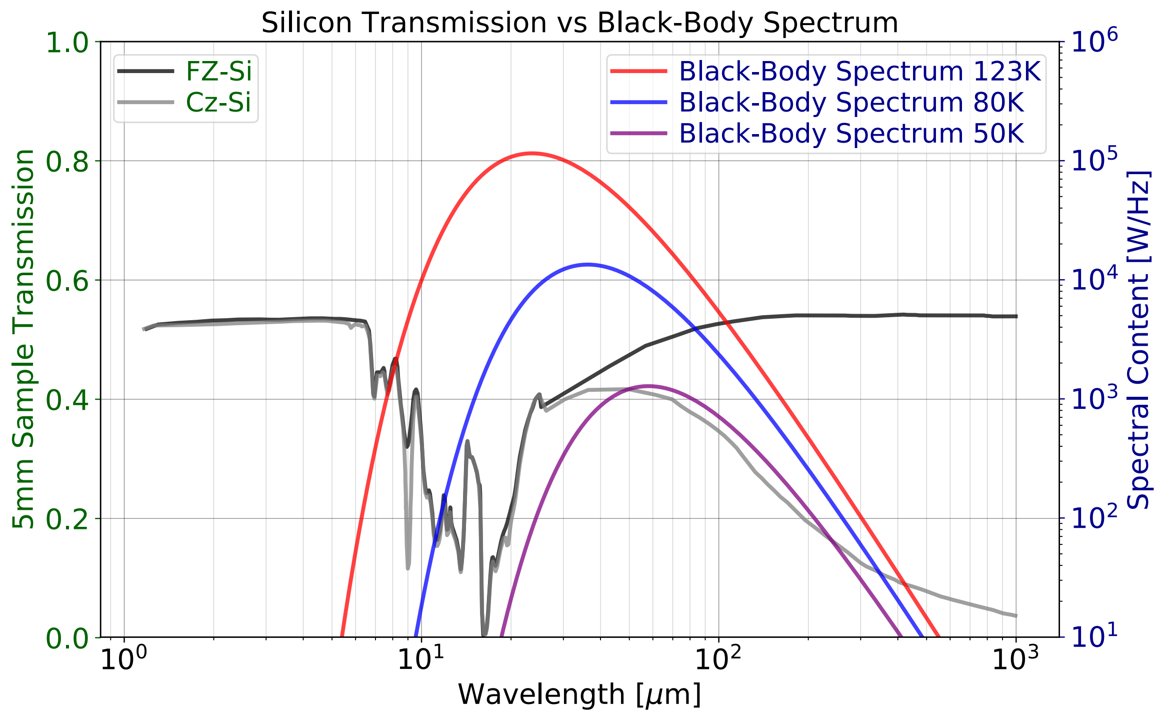
The Test Mass

- Floatzone (FZ, ø20cm max) vs magnetic Czochralski (mCz, ø45cm max) silicon
- Fundamental absorption limit still unclear; inhomogeneity could be big issue
- NEMO design assumes mCz with 10 ppm/cm at 2µm (chosen for several reasons)
  - 1-2 ppm/cm observed in FZ
  - 1 ppm HR coating absorption
- Heating per unit length (P_{PRC}= 31kW) > cooling per unit length from TM barrel
- Compromise: 20cm thickness
  - Rad. Pressure; Parametric Instability; Cooling
  - Total mass: 74.1 kg
- Heat loads – ETM: 4.5W, ITM: 10.7 W
  - Too much to operate < 20 K
  - How can we extract this from the TMs?

Thermal Budget



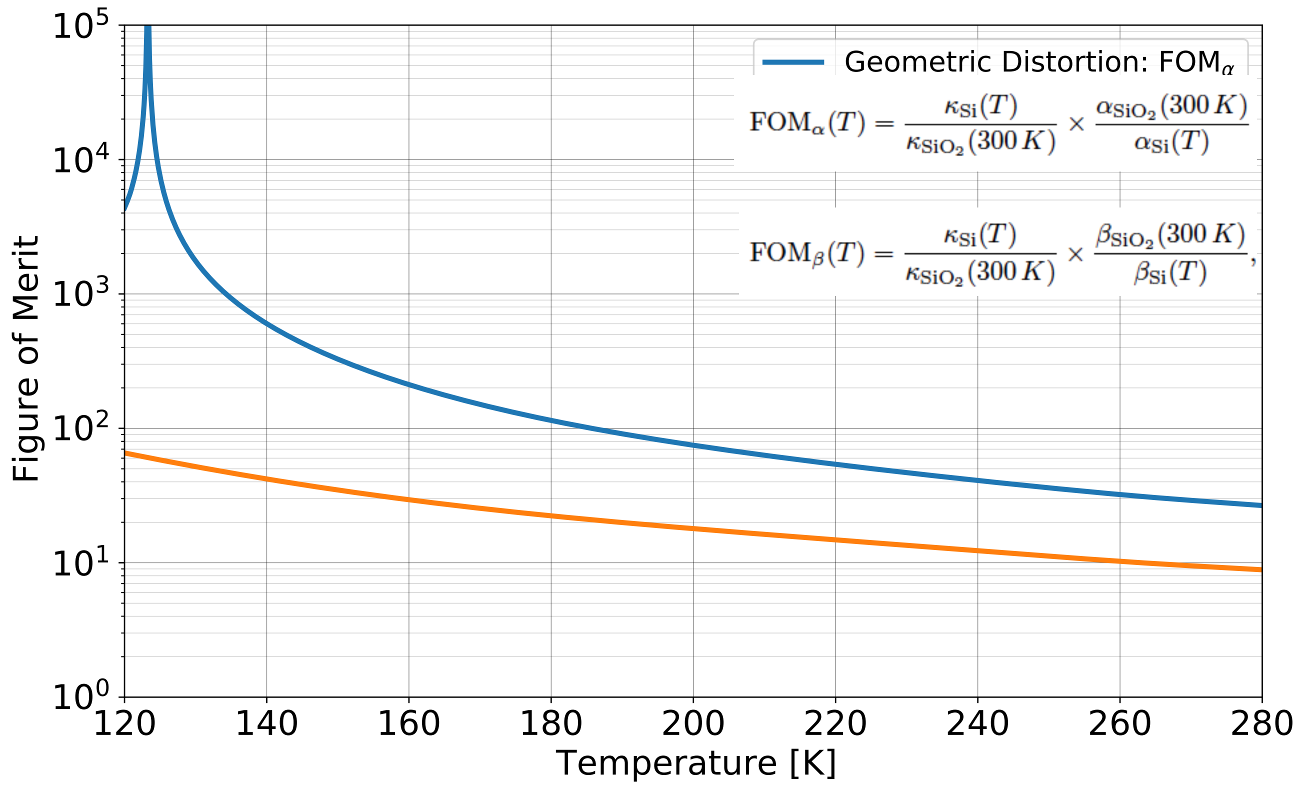
- TM black-body emission at 123 K: 7.8 W not enough! (ETM: 4.5W, ITM: 10.7 W)
- Hybrid (radiative + conductive) cooling?
  - Requires complex suspension design
  - Results in large number of violin modes
- Simplified analytical thermal model
  - Possible to remove about 6 W radiatively
  - Optical properties at thermal wavelengths?
- HF-approach tolerant to thermal noise
- Increase ITM temperature to 150 K ?



Wavefront Aberration Figures of Merit

- Point absorber scattering suppressed by FOM$_\alpha$
- Surface deformation from bulk heating also suppressed by FOM$_\alpha$
- ITM thermal lensing 'suppressed' FOM$_\beta$ - but more heat absorbed!
- Best case scenario: 160 ppm round-trip loss (optimal suppression with TCS)
- Not impossible!

$$S(T) = 40\,\mathrm{ppm}\left(\frac{1.4\,\mathrm{Wm^{-1}K^{-1}}}{\kappa_{\mathrm{Si}}(T)}\right)^2 \times \times \left(\frac{\beta_{\mathrm{Si}}(T)}{10\,\mathrm{ppm/K}}\right)^2 \left(\frac{1\,\mu\mathrm{m}}{\lambda}\right)^2 \left(\frac{P_{\mathrm{abs}}}{1\,\mathrm{mW}}\right)^2$$



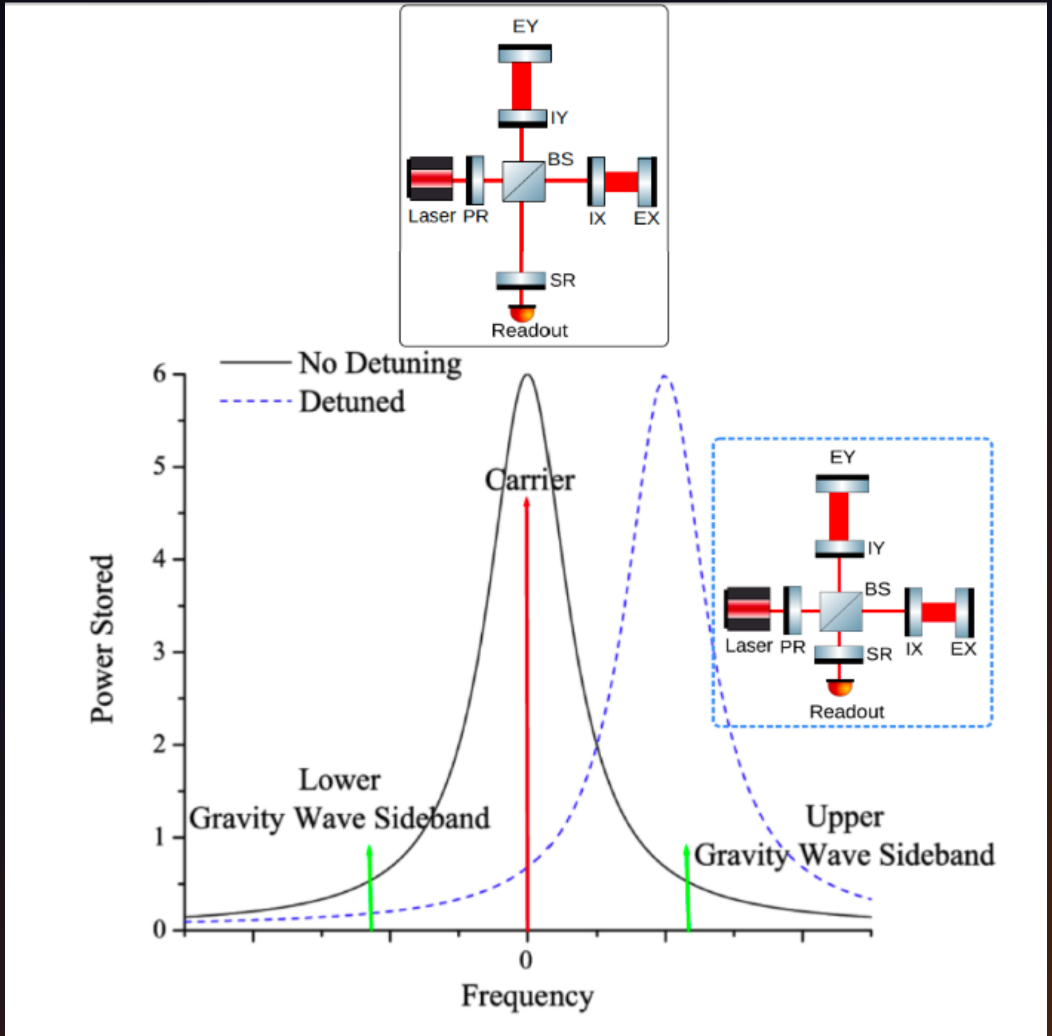
$$\mathrm{FOM}_\alpha(T) = \frac{\kappa_{\mathrm{Si}}(T)}{\kappa_{\mathrm{SiO_2}}(300\,K)} \times \frac{\alpha_{\mathrm{SiO_2}}(300\,K)}{\alpha_{\mathrm{Si}}(T)}$$

$$\mathrm{FOM}_\beta(T) = \frac{\kappa_{\mathrm{Si}}(T)}{\kappa_{\mathrm{SiO_2}}(300\,K)} \times \frac{\beta_{\mathrm{SiO_2}}(300\,K)}{\beta_{\mathrm{Si}}(T)},$$

Quantum noise manipulation

Long SRC :

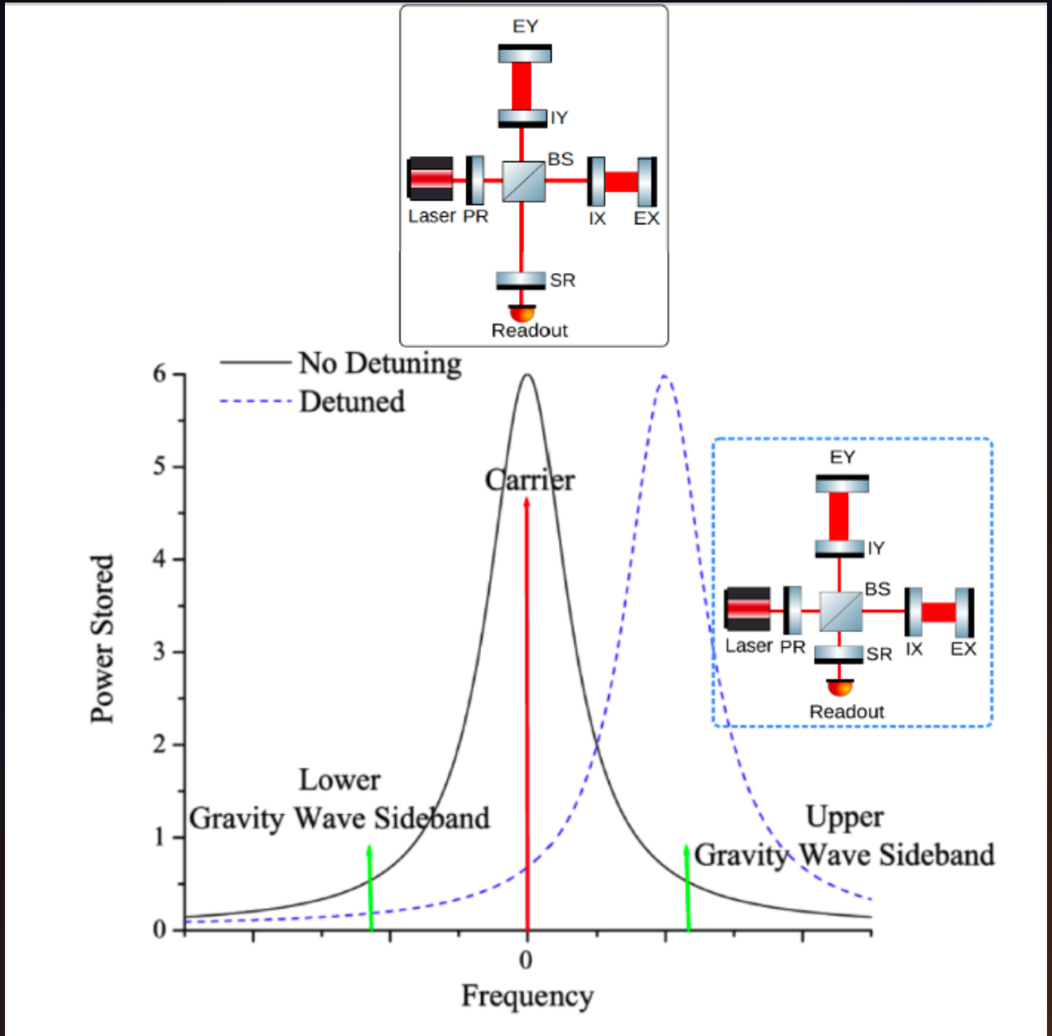
- Upper and lower signal sidebands equally enhanced
- Phase picked up by GW sidebands in the SRC cannot be ignored
- Analogous to a DRMI interferometer with two signal recycling cavities



Slide Credit: V. Adya

Long Signal Recycling Cavities

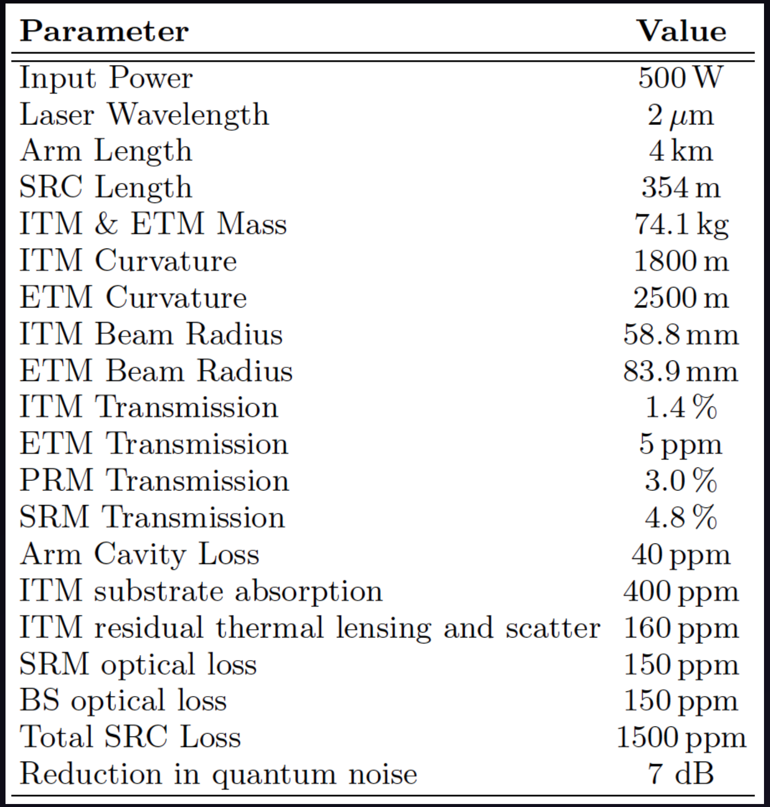
- Advantages : Control potentially easier, requires no filter cavity to improve sensitivity around coupled cavity pole
- Robust to losses inside the interferometer: loss per m value relaxed
- Disadvantage: Un-demonstrated (Twin signal recycling control for DRMI, proven concept)



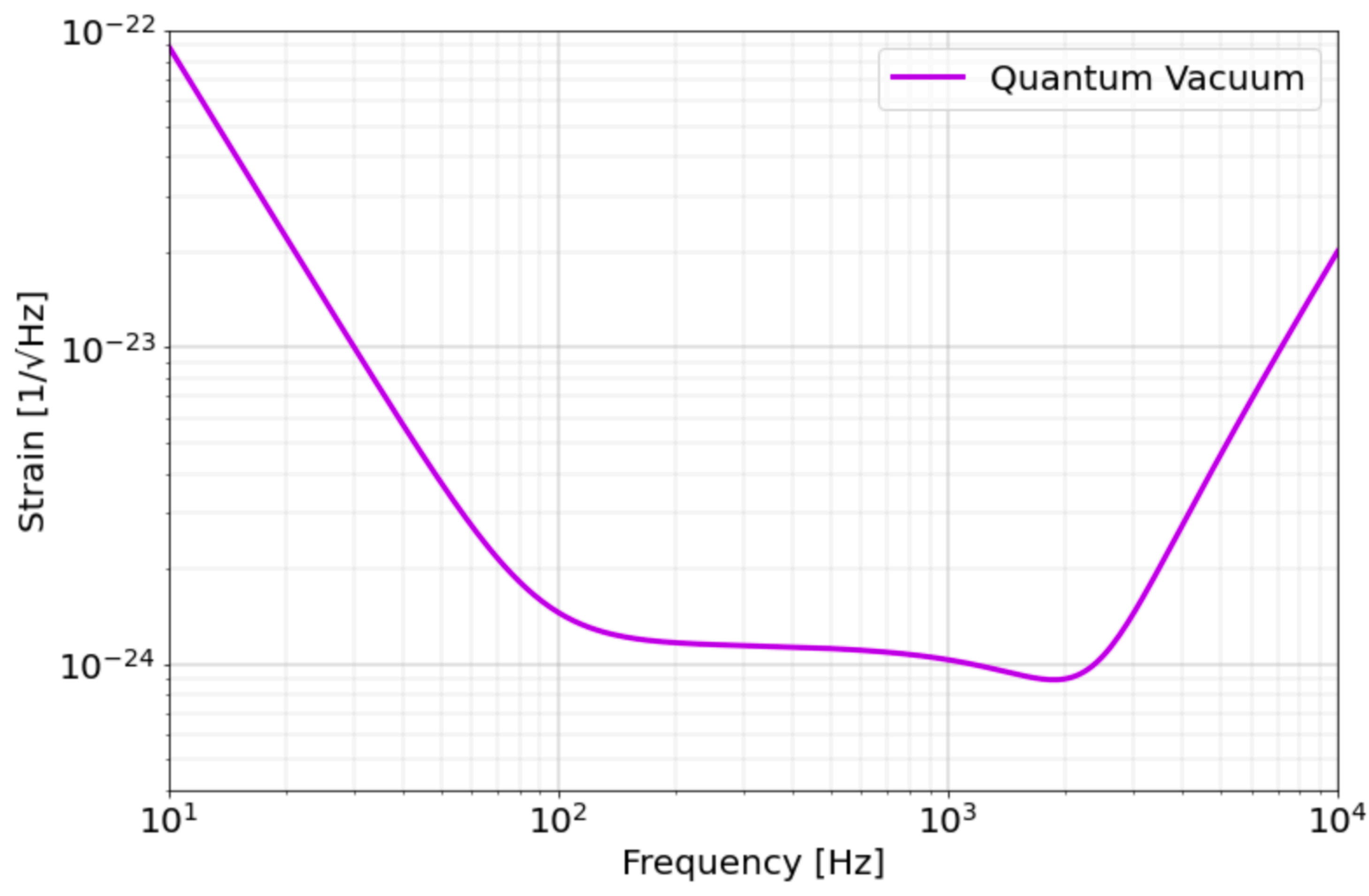
Slide Credit: V. Adya

NEMO Quantum Noise

Radiation pressure noise is out of band; no squeezed state rotation necessary!



Parameter	Value
Input Power	500 W
Laser Wavelength	2 μm
Arm Length	4 km
SRC Length	354 m
ITM & ETM Mass	74.1 kg
ITM Curvature	1800 m
ETM Curvature	2500 m
ITM Beam Radius	58.8 mm
ETM Beam Radius	83.9 mm
ITM Transmission	1.4 %
ETM Transmission	5 ppm
PRM Transmission	3.0 %
SRM Transmission	4.8 %
Arm Cavity Loss	40 ppm
ITM substrate absorption	400 ppm
ITM residual thermal lensing and scatter	160 ppm
SRM optical loss	150 ppm
BS optical loss	150 ppm
Total SRC Loss	1500 ppm
Reduction in quantum noise	7 dB



Coatings

- Voyager candidate: a-Si/SiO_2
- Crystalline AlGaAs coatings

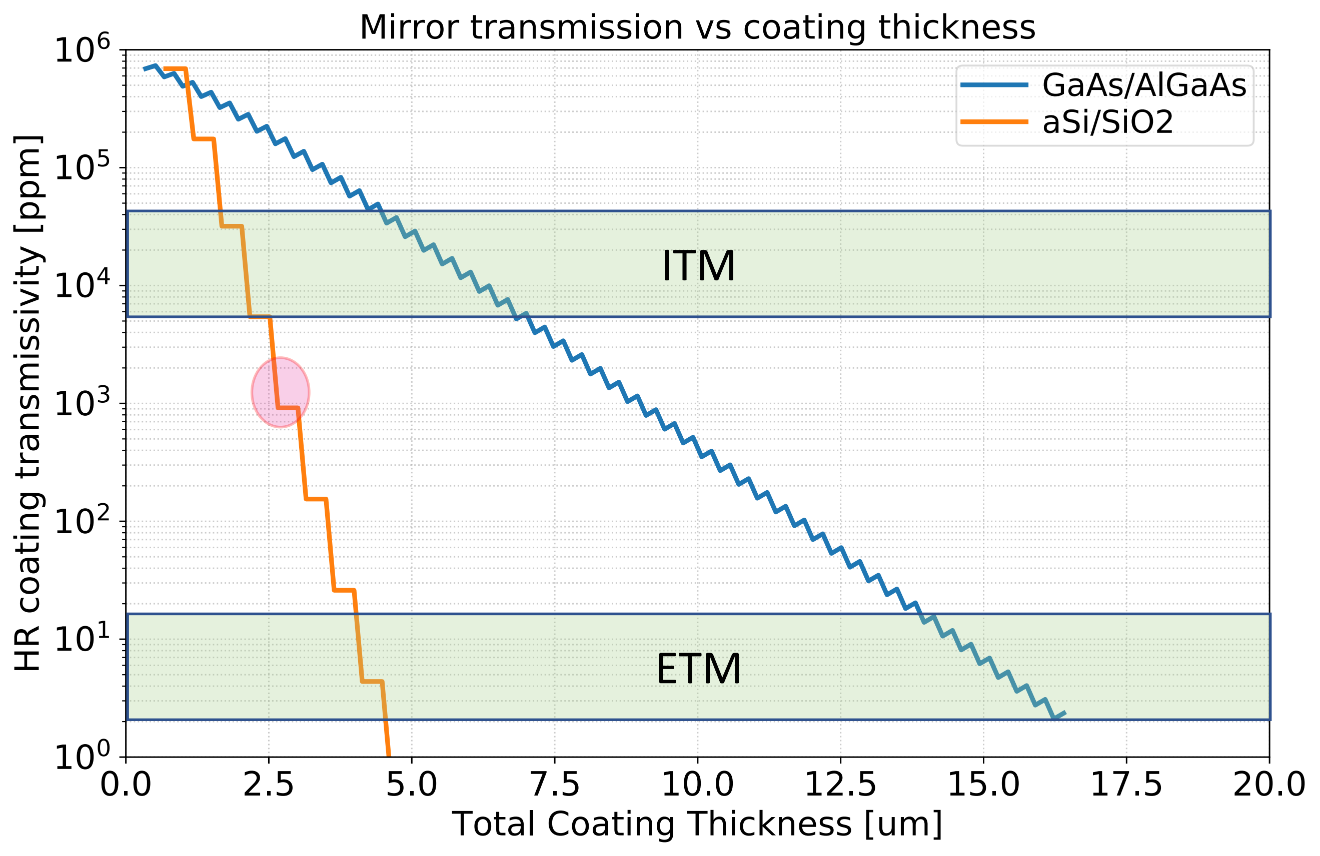
NEMO choice: low absorption, low loss

- Any A+ coating (must work with 2µm)
- Adv. LIGO tantala/silica as fallback option

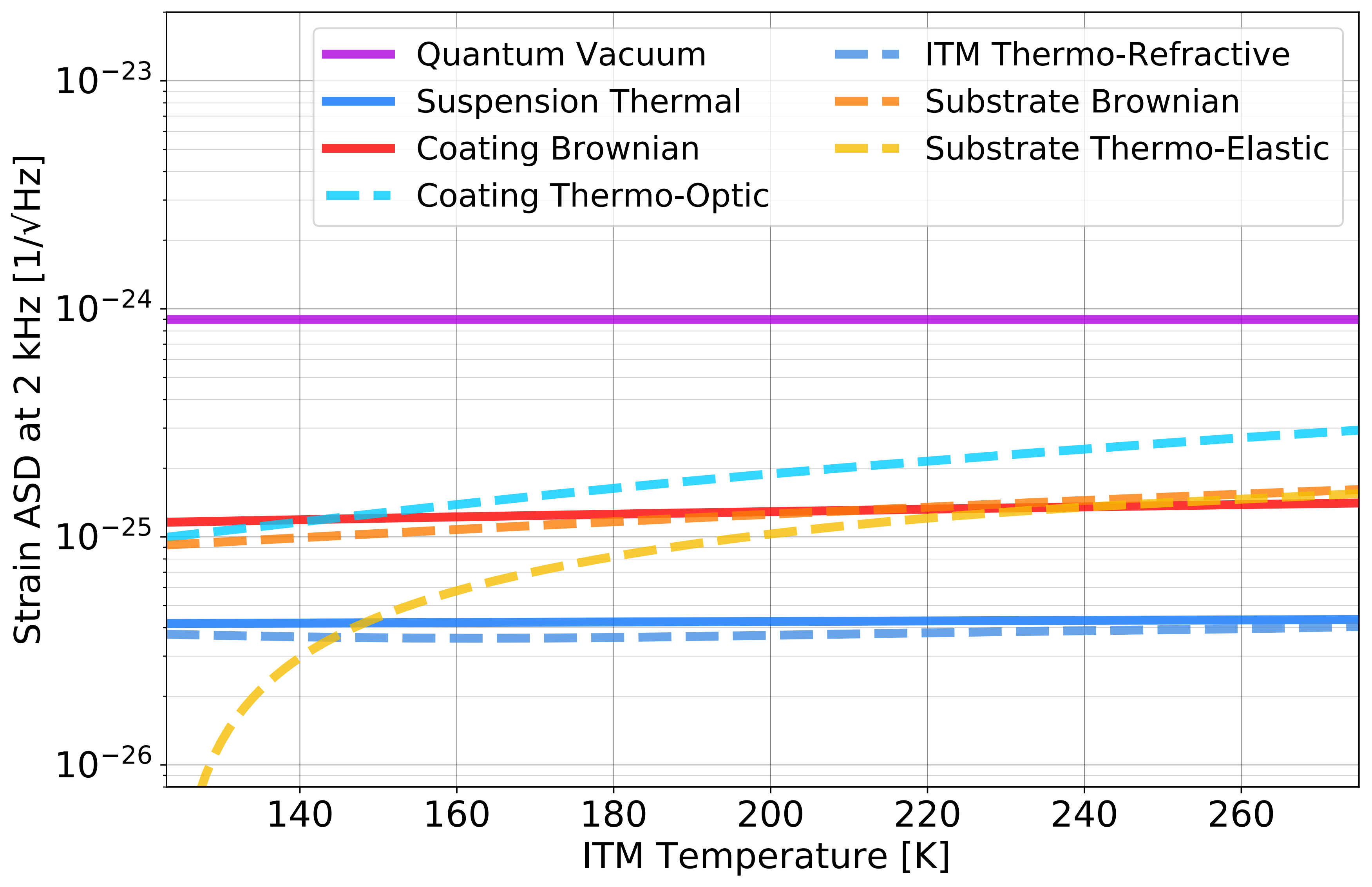
	a-Si	SiO_2	GaAs	$Al_{0.92}GaAs_{0.08}$
Mech. Loss	3×10^{-5}	1×10^{-4}	2×10^{-5}	2×10^{-5}
Absorption	Current best ~20 ppm (1550nm)		0.5 ppm possible?	
Thermal Exp.	$< 5 \times 10^{-9}\ K^{-1}$	$5.1 \times 10^{-7}\ K^{-1}$	$5.39 \times 10^{-6}\ K^{-1}$	$5.36 \times 10^{-6}\ K^{-1}$
Thermo-Optic	$1.4 \times 10^{-4}\ K^{-1}$	$8 \times 10^{-6}\ K^{-1}$	$2.04 \times 10^{-4}\ K^{-1}$	$1.83 \times 10^{-4}\ K^{-1}$
Refractive index	3.5	1.4	3.307	2.891
Thermal Cond.	$1\ Wm^{-1}K^{-1}$	$1.38\ Wm^{-1}K^{-1}$	$140\ Wm^{-1}K^{-1}$	$261\ Wm^{-1}K^{-1}$
Heat Capacity	$7.78 \times 10^{5}\ Jm^{-3}K^{-1}$	$1.64 \times 10^{6}\ Jm^{-3}K^{-1}$	$4.48 \times 10^{6}\ Jm^{-3}K^{-1}$	$3.82 \times 10^{6}\ Jm^{-3}K^{-1}$
Young's Mod.	80 GPa	72 GPa	85.3 GPa	83.6 GPa
Poisson Ratio	0.22	0.17	0.31	0.38

GaAs/AlGaAs Coatings

- Compatible with 2µm wavelength, but small refractive index step: very thick coatings!
- Chosen for low optical absorption: crucial for high power detector
- Ø45cm coatings far from demonstrated, but partial coverage may also be okay
- If low absorption in a-Si can be achieved, it would probably be the better choice

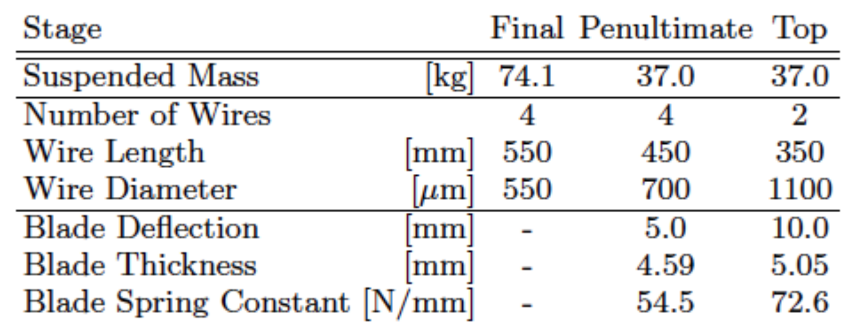


Thermal Noise vs ITM Temperature

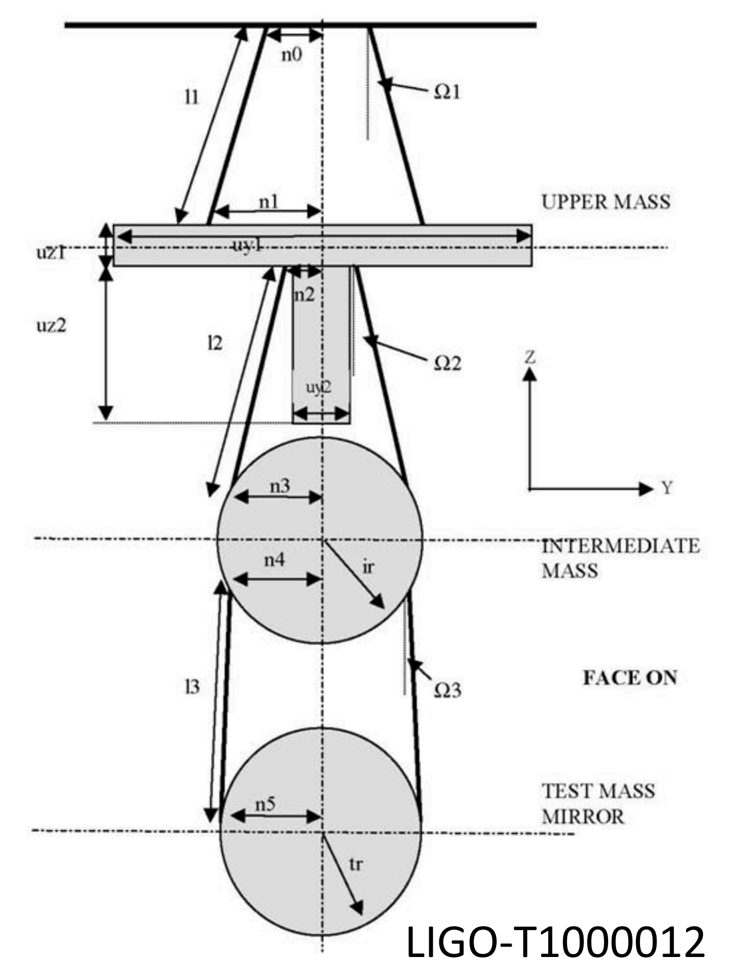


Suspensions

- Architecture (active damping or mostly passive)? – LIGO Triple Suspensions
- Cold or warm PUM? – Warm
- Spring Blades on last stage? – No
- Suspension materials – piano wire + maraging steel)



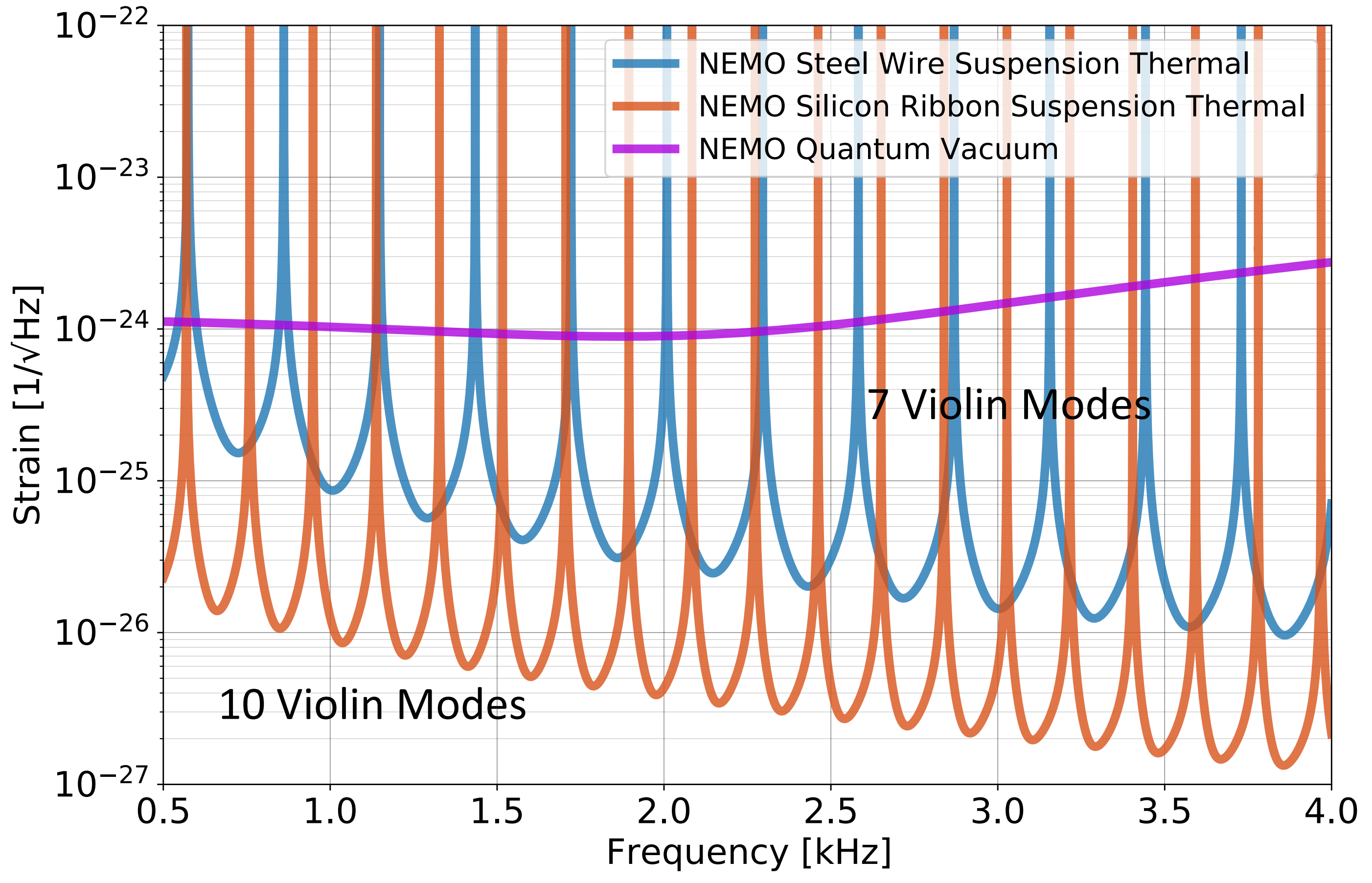
Stage		Final	Penultimate	Top
Suspended Mass	[kg]	74.1	37.0	37.0
Number of Wires		4	4	2
Wire Length	[mm]	550	450	350
Wire Diameter	[μm]	550	700	1100
Blade Deflection	[mm]	-	5.0	10.0
Blade Thickness	[mm]	-	4.59	5.05
Blade Spring Constant	[N/mm]	-	54.5	72.6



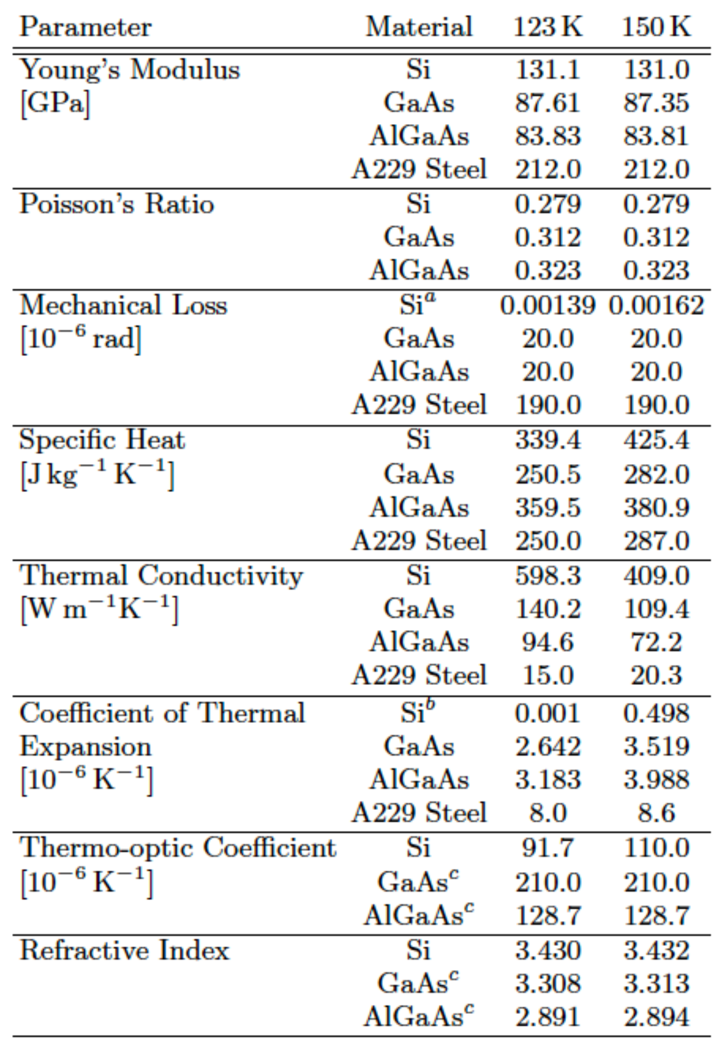
LIGO-T1000012

Why not go monolithic?

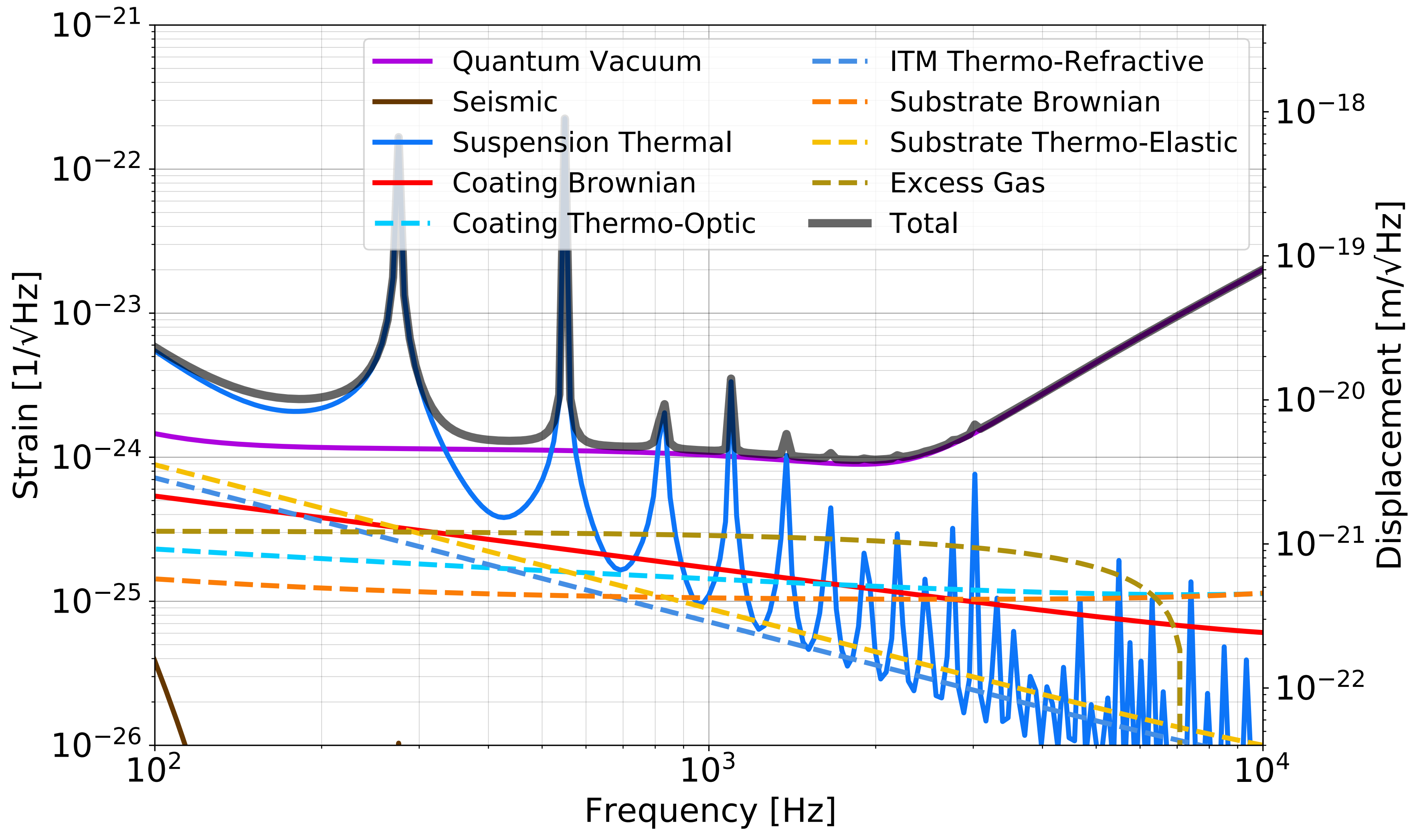
- Silicon ribbons (100 MPa) vs ASTM A229 piano wire (750 MPa)
- Mechanical loss of piano wire is diluted by thickness
- Ribbon aspect ratio 10:1
- Violin modes between 1-3 kHz:
  10 (Si) vs 7 (A229) (degeneracy!)
- 'Lost' bandwidth above QN:
  7Hz (Si) vs 61Hz (A229)
- Steel wire is 'mature tech'
- Thermoelastic loss in silicon near warm PUM



Full Noise Budget (150K ITM)

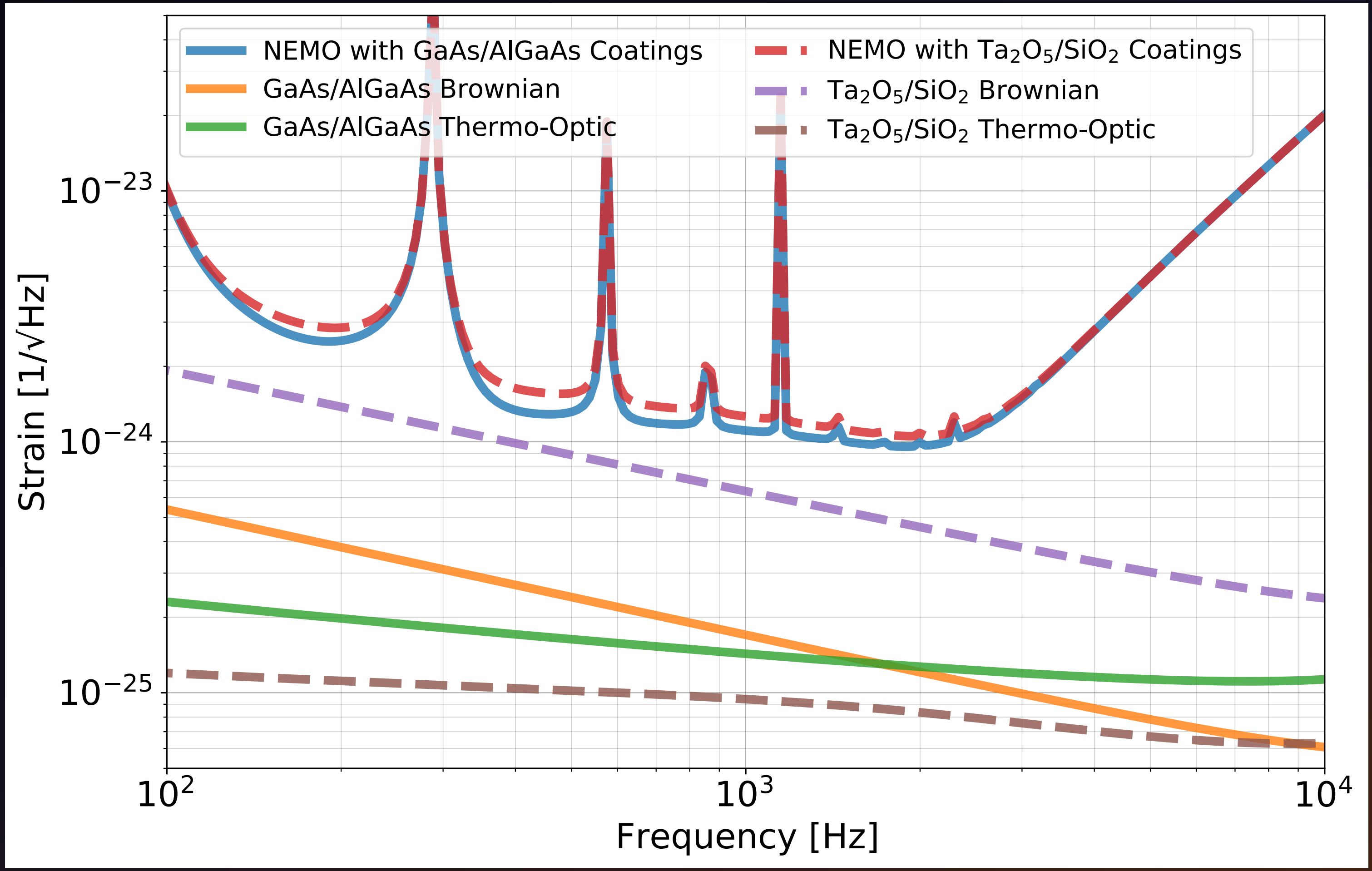


Parameter	Material	123 K	150 K
Young's Modulus [GPa]	Si	131.1	131.0
	GaAs	87.61	87.35
	AlGaAs	83.83	83.81
	A229 Steel	212.0	212.0
Poisson's Ratio	Si	0.279	0.279
	GaAs	0.312	0.312
	AlGaAs	0.323	0.323
Mechanical Loss [10^{-6} rad]	Si^a	0.00139	0.00162
	GaAs	20.0	20.0
	AlGaAs	20.0	20.0
	A229 Steel	190.0	190.0
Specific Heat [J kg^{-1} K^{-1}]	Si	339.4	425.4
	GaAs	250.5	282.0
	AlGaAs	359.5	380.9
	A229 Steel	250.0	287.0
Thermal Conductivity [W m^{-1}K^{-1}]	Si	598.3	409.0
	GaAs	140.2	109.4
	AlGaAs	94.6	72.2
	A229 Steel	15.0	20.3
Coefficient of Thermal Expansion [10^{-6} K^{-1}]	Si^b	0.001	0.498
	GaAs	2.642	3.519
	AlGaAs	3.183	3.988
	A229 Steel	8.0	8.6
Thermo-optic Coefficient [10^{-6} K^{-1}]	Si	91.7	110.0
	GaAs^c	210.0	210.0
	AlGaAs^c	128.7	128.7
Refractive Index	Si	3.430	3.432
	GaAs^c	3.308	3.313
	AlGaAs^c	2.891	2.894



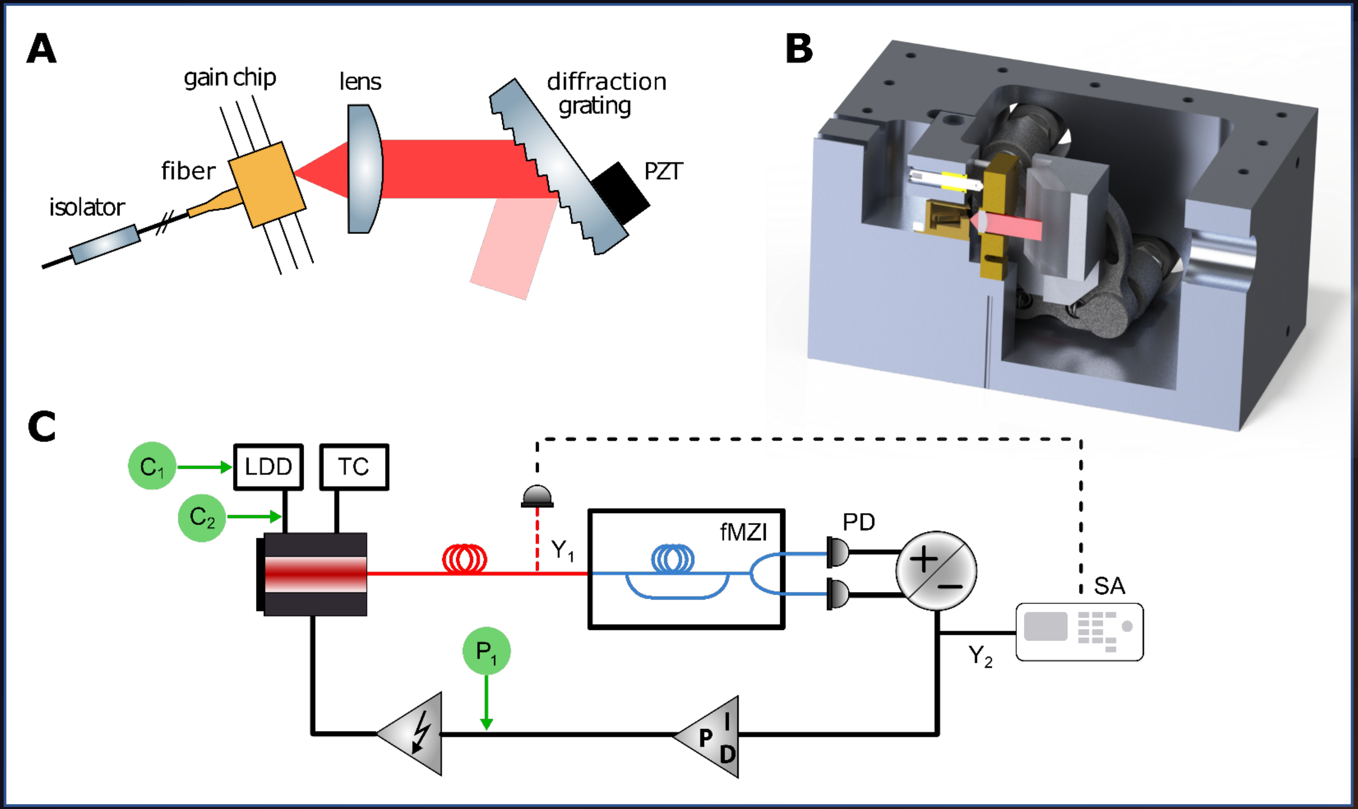
Tantala/silica coatings: fallback alternative

- Thermal noise from tantala/silica coatings *moderate* at kHz freqs
- Profits from cryo temps and larger beams
- Longer wavelength makes coatings thicker
- Increase in detector noise is about 15% at 2kHz



Laser Sources

- Requirement : 500 W At 2 µm
- 200 W at 1.06 µm level with near required linewidth demonstrated by MIT LIGO\Lincoln Labs and AEI/LZH in Fiber laser systems
- 500 W with required linewidth not yet demonstrated but Thulium-doped fiber lasers : promising
- External Cavity Diode Lasers at 2 µm : promising



Slide credit : Sebastian Ng, D.Kapasi
2 µm ECDL reference : https://www.osapublishing.org/oe/abstract.cfm?uri=oe-28-3-3280

Search for reference sites

- Possible scenario: Build NEMO and CE-south at the same site (speculative).
- Focus on potential sites for a CE-south detector as it has tighter constraints.

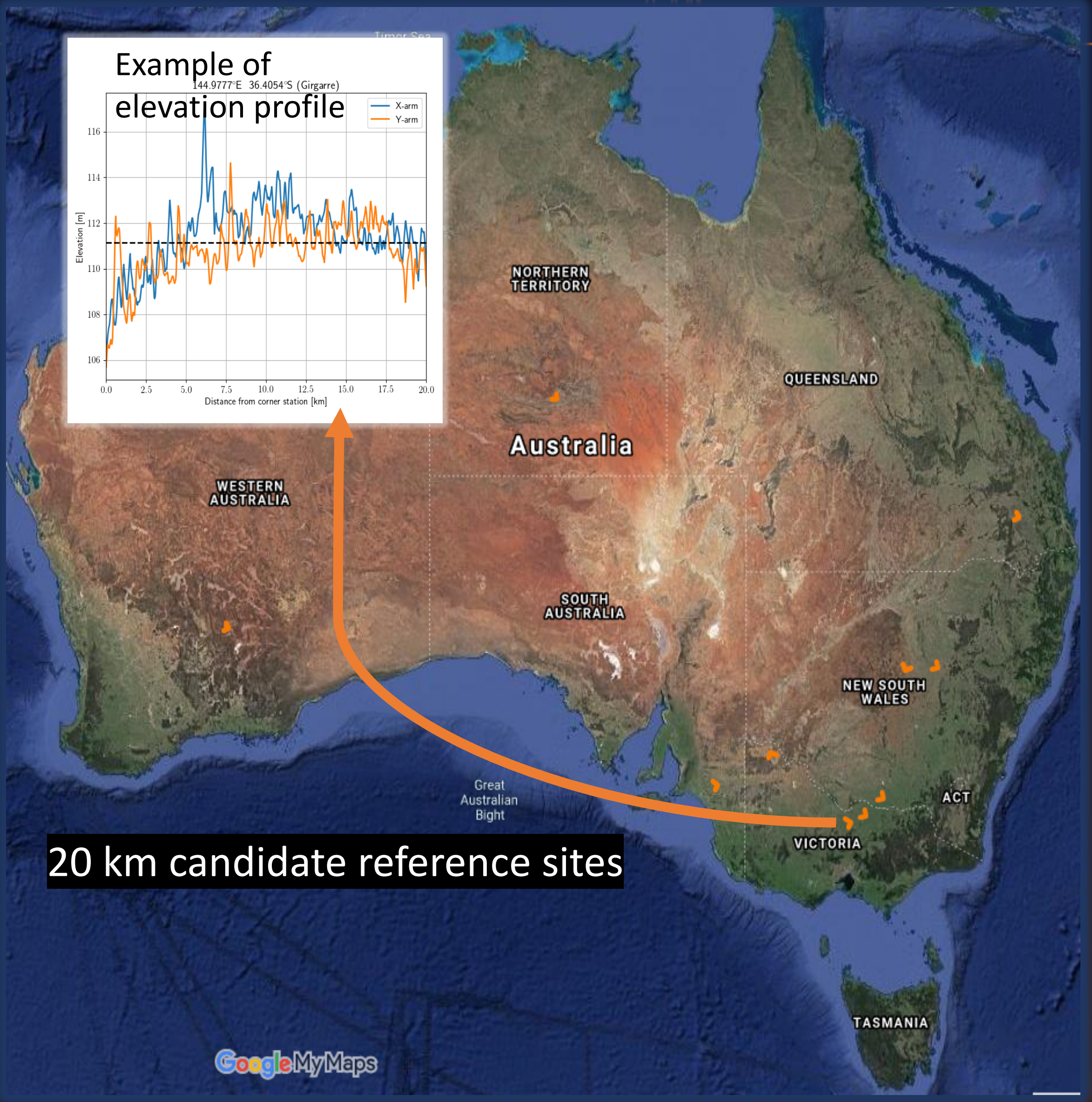
Identifying 20 km and 40 km reference sites based on:

- Volume of earth to cut and fill
- Proximity to cities, towns, and airports

And gathering information on:

- Seismic noise
- Geology
- Soil composition
- Land ownership, usage and status
- Proximity to existing infrastructure (electricity, water, sewage, roads)
- Risks (earthquakes, floods, storms, fires, future sea levels)

Slide credit : D.Toyra



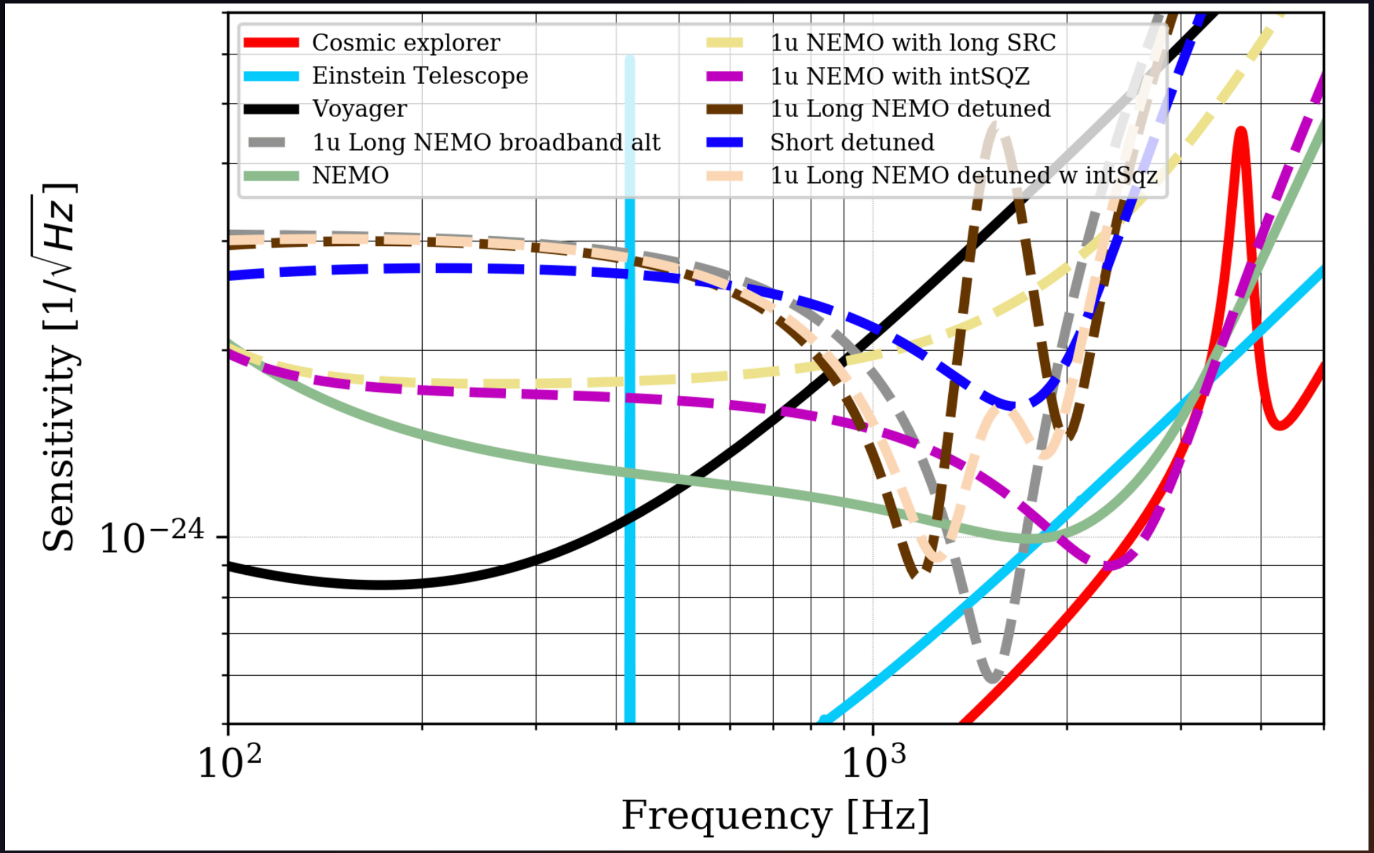
Example of elevation profile

20 km candidate reference sites

But nothing is set in stone…

Quantum Noise Tuning Options

- What are the options to achieve a quantum noise limited design with 1µm/2µm?
  - Long signal recycling (NEMO)
  - Detuned signal recycling
  - Long detuned signal recycling
  - Internal squeezing
  - A combination of all/some of the above
- In the era of 3G detectors, could convert existing detector to HF-concept



Slide Credit: V. Adya

Critically Revisit & Review Design Choices

- Science case remains intact for location of HF detector outside Australia
- (Very) initial plan was 2 km long arms (construction cost), eventually became 4 km
  - Optimisation for 3km possible; some thermal noise penalty (margin may prove sufficient)
  - Quantum noise scales inversely with square root of length
- Can we use FZ silicon? For ITM only?
  - Decrease beam size on ITM? What about cavity loss & PI
  - Are compound test masses a possibility?
- Laser wavelength: Keep 2 µm or go back to 1.55 µm?
  - Photodetector and camera technology more mature / affordable
  - Same sensitivity with less laser power
  - Thinner coatings; but looks like higher absorption in Si
- Best suspension approach; how to enhance TM surface emissivity
- Alternatively: What can we achieve with a 1 µm detector?
  - Can we use silica; should we think about sapphire? If so, what temperature?
- Coating material?
- Important issue: Beamsplitter material

A Team effort!

Image: Carl Knox, OzGrav Swinburne

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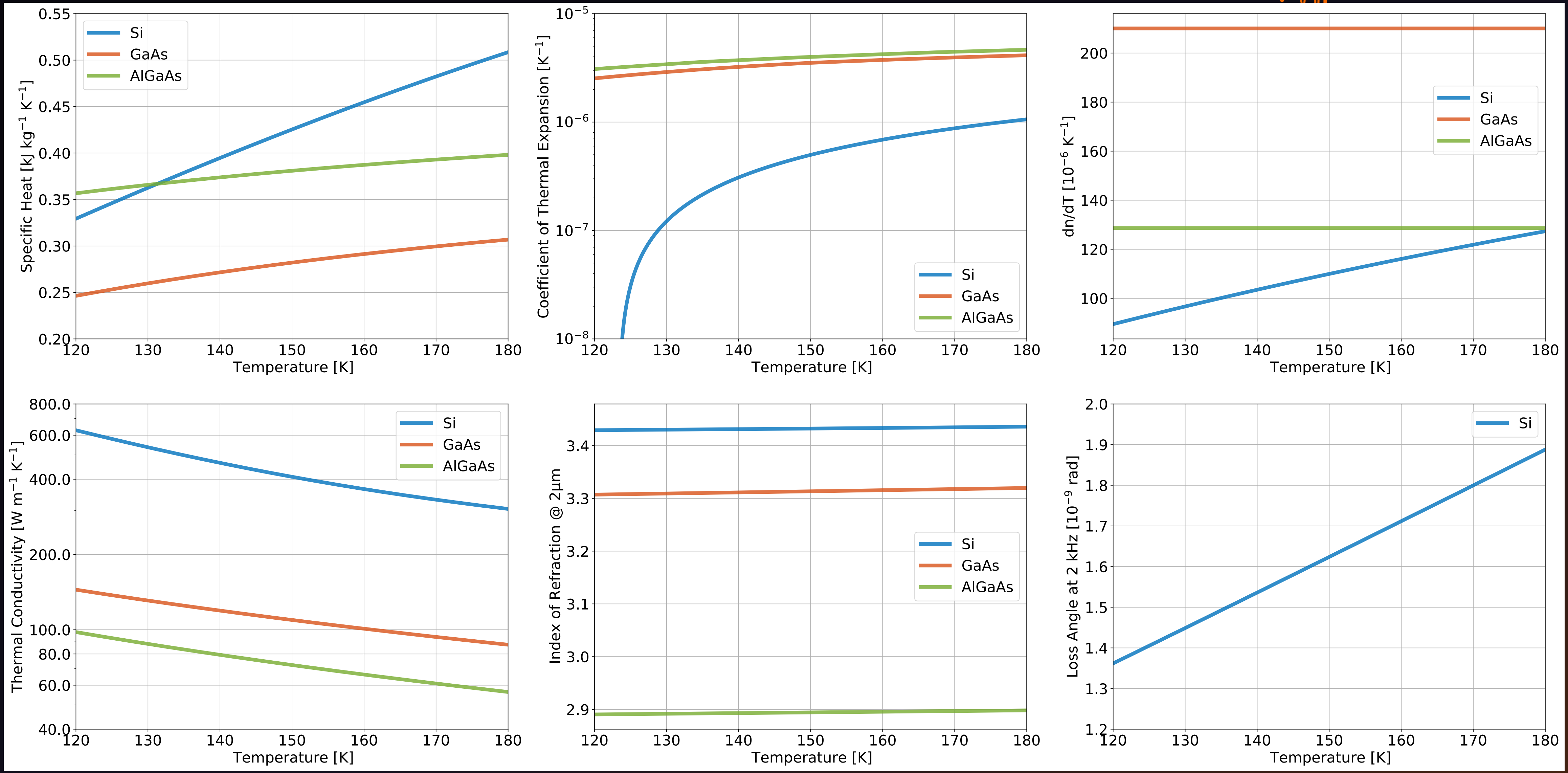
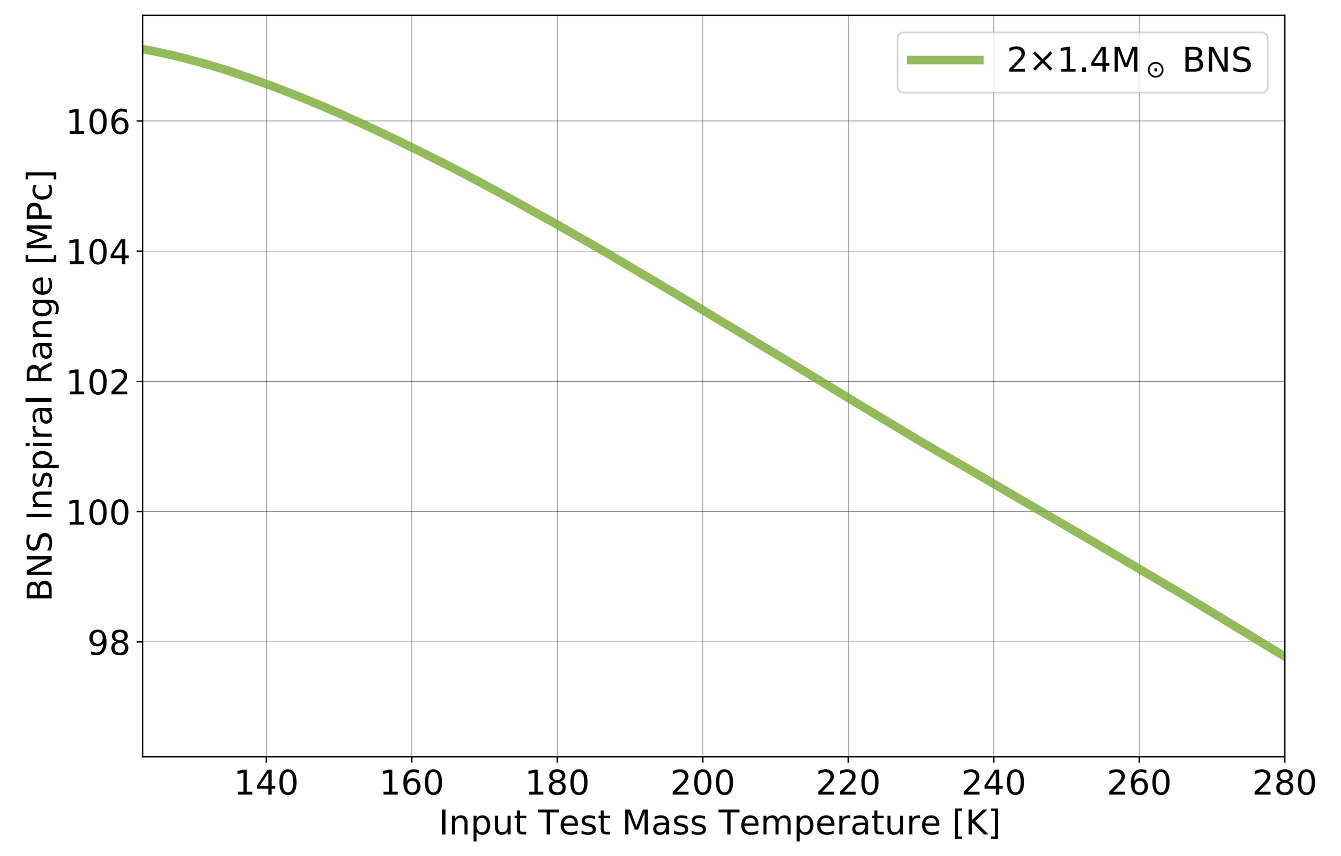
Material Parameter Temp. Dependence



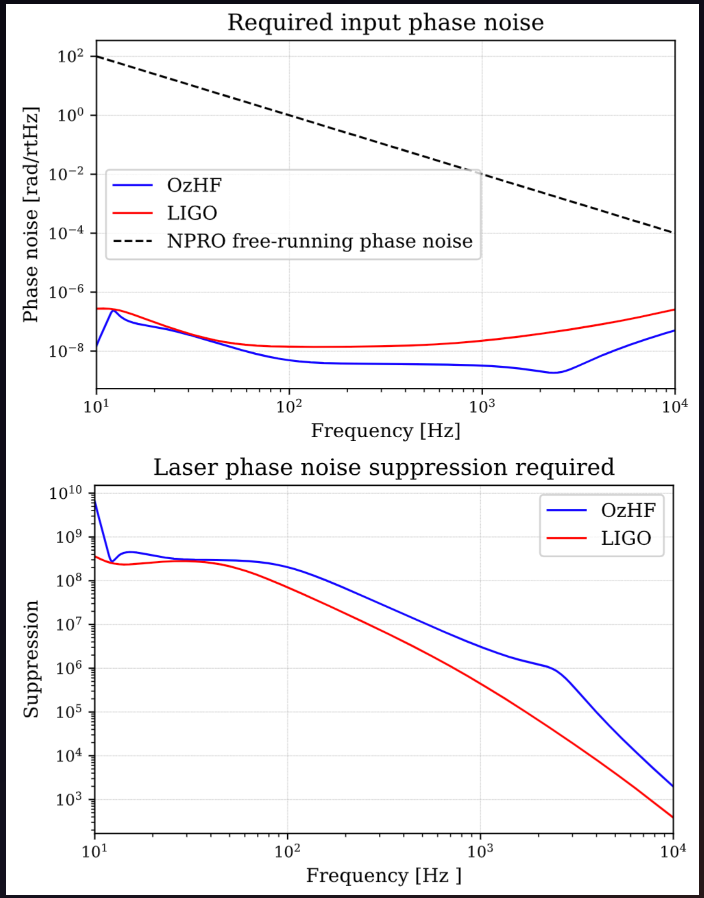
NEMO Inspiral Range vs ITM Temperature

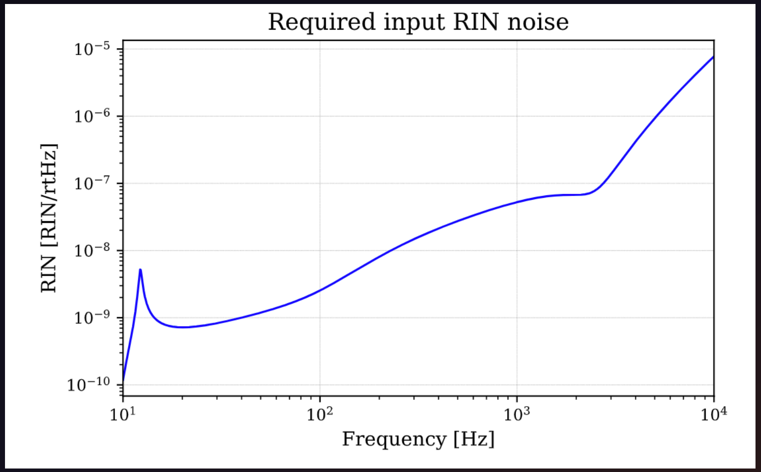
- TaylorF2 BNS waveform
- Inspiral range estimated based only on signal content >1kHz, NEMO only
- In terms of thermal noise, could operate at higher temps with only small sensitivity penalty
- Does not take into account thermal lensing; SRC loss



RIN and frequency noise

- RIN/Phase noise requirement at PRC input in GW band
    - 1% power imbalance in arm
    - Safety factor of 10 below
    - ~10pm DC offset
    - Plane wave model
- Requirement around 2kHz:
    - Require RIN of 10^{-7}
    - Require Phase noise of ~3×10^{-9}
    - Or would need 10^{6} suppression of NPRO noise
- Concern: Higher frequency/RIN noise coupling seen in LIGO than simple model would predict at higher frequencies.
    - Could potentially be attributable to thermal effects which would be significantly less of an issue with cryo IFO





Requirements here are to beat QN limited sensitivity at GW frequencies, haven't considered requirements in control band yet.

Slide Credit: V. Adya

Some more details

- Tilt modes (15 Hz) can be controlled with a bandwidth without injecting control noise into the sensitivity regime of interest
- Parametric instabilities due to 4.5 MW in the arm currently being modelled – potentially controllable in NEMO with AMDs and careful consideration

Slide Credit: V. Adya