NEMO, the concept of a high frequency gravitational wave detector

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ARC Centre of Excellence for Gravitational Wave Discovery

Overview

- NEMO : Neutron star Extreme Matter Observatory : technology enabler for 3G
- Key design parameters
  - Science case driven sensitivity
  - Signal Recycling Cavity design
  - Suspensions and thermal noise
- NEMO : tunability with variable SRM reflectivity
- Conclusions

NEMO paper : doi:10.1017/pasa.2020.39 (published in *Publications of the Astronomical Society of Australia*)

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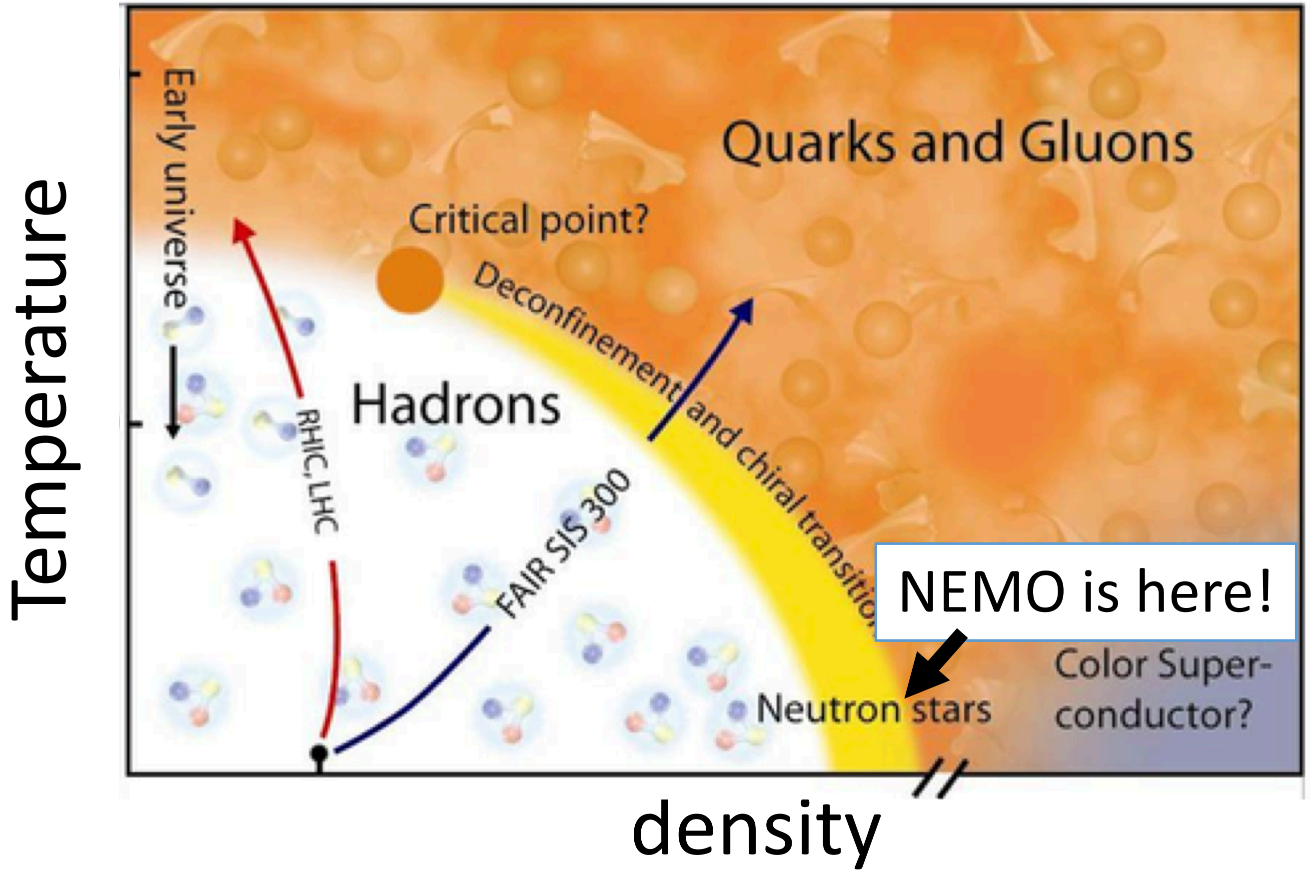
NEMO : The Science

"kHz gravitational wave detectors are way to access stellar particle colliders!"

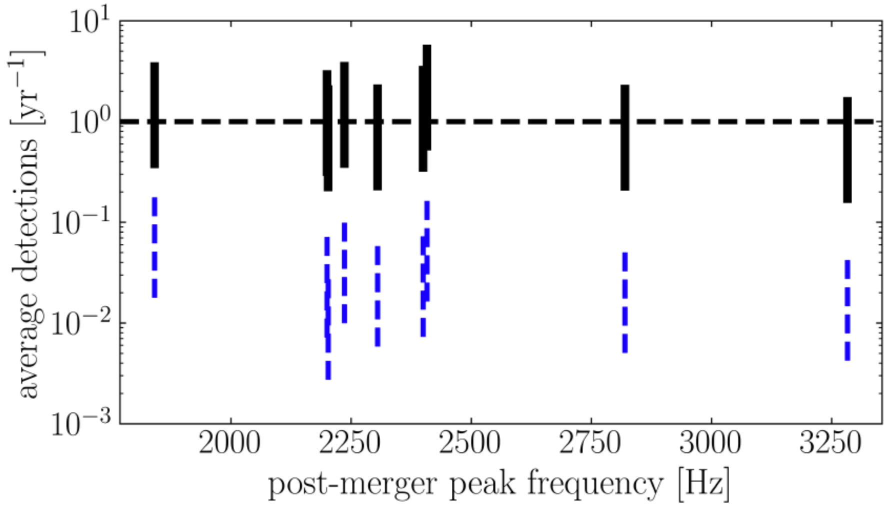


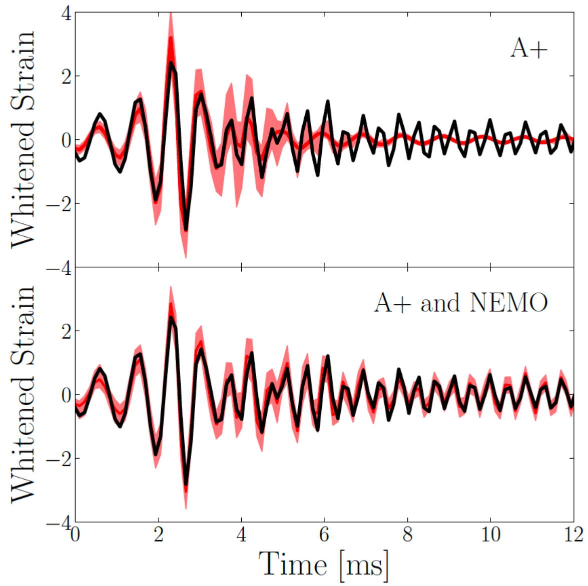
Reference : arXiv:1102.5531

NEMO paper : doi:10.1017/pasa.2020.39
(published in PASA)

NEMO : The Science

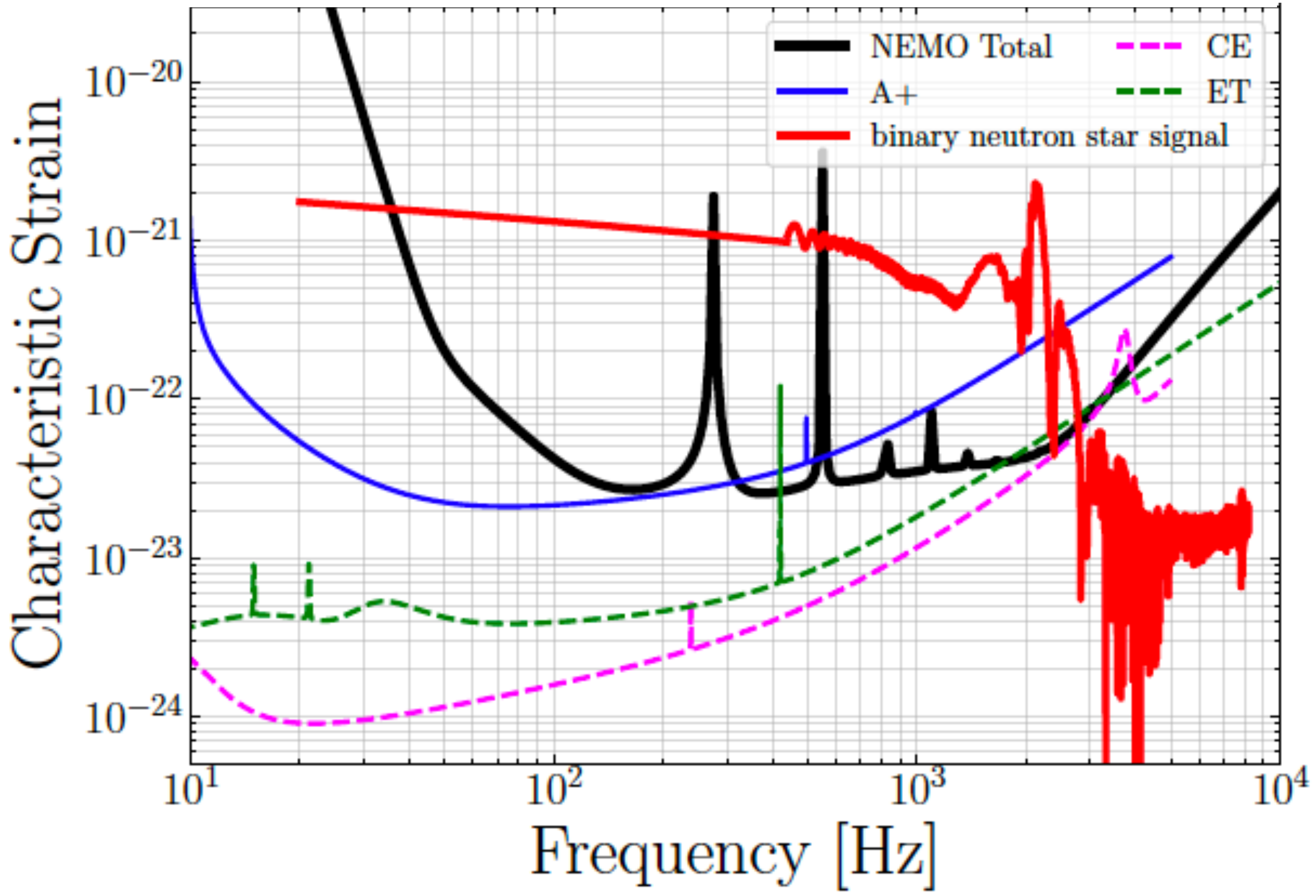
- Average number of post merger events detected with with NEMO increased to 1 – a few per year
- Increased sensitivity at kHz places significant constraints on EoS
- Potential to measure phase transitions in hot remnants : deconfined quarks, other exotica





Reference : NEMO paper

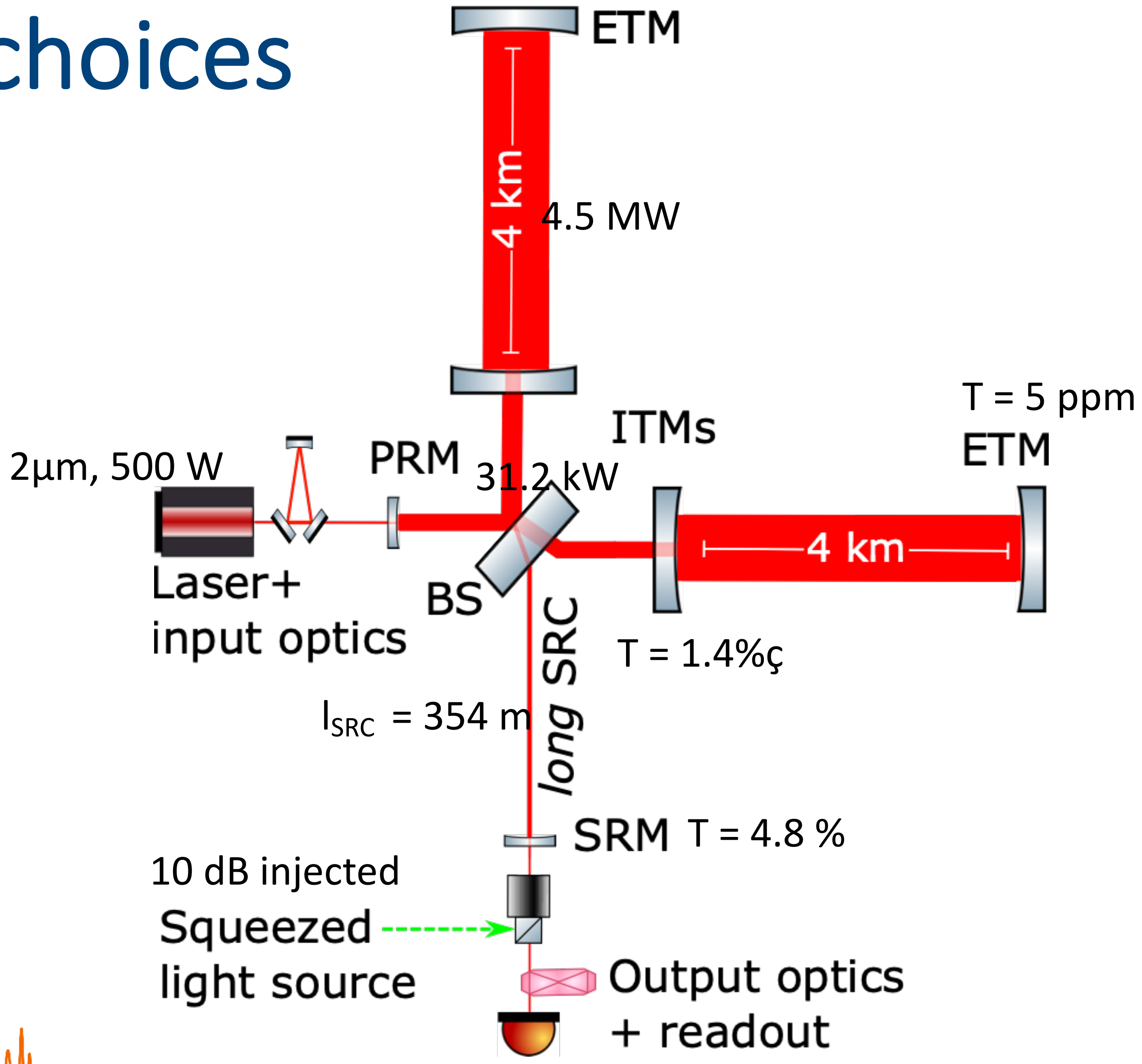
Design Sensitivity



Reference : NEMO paper

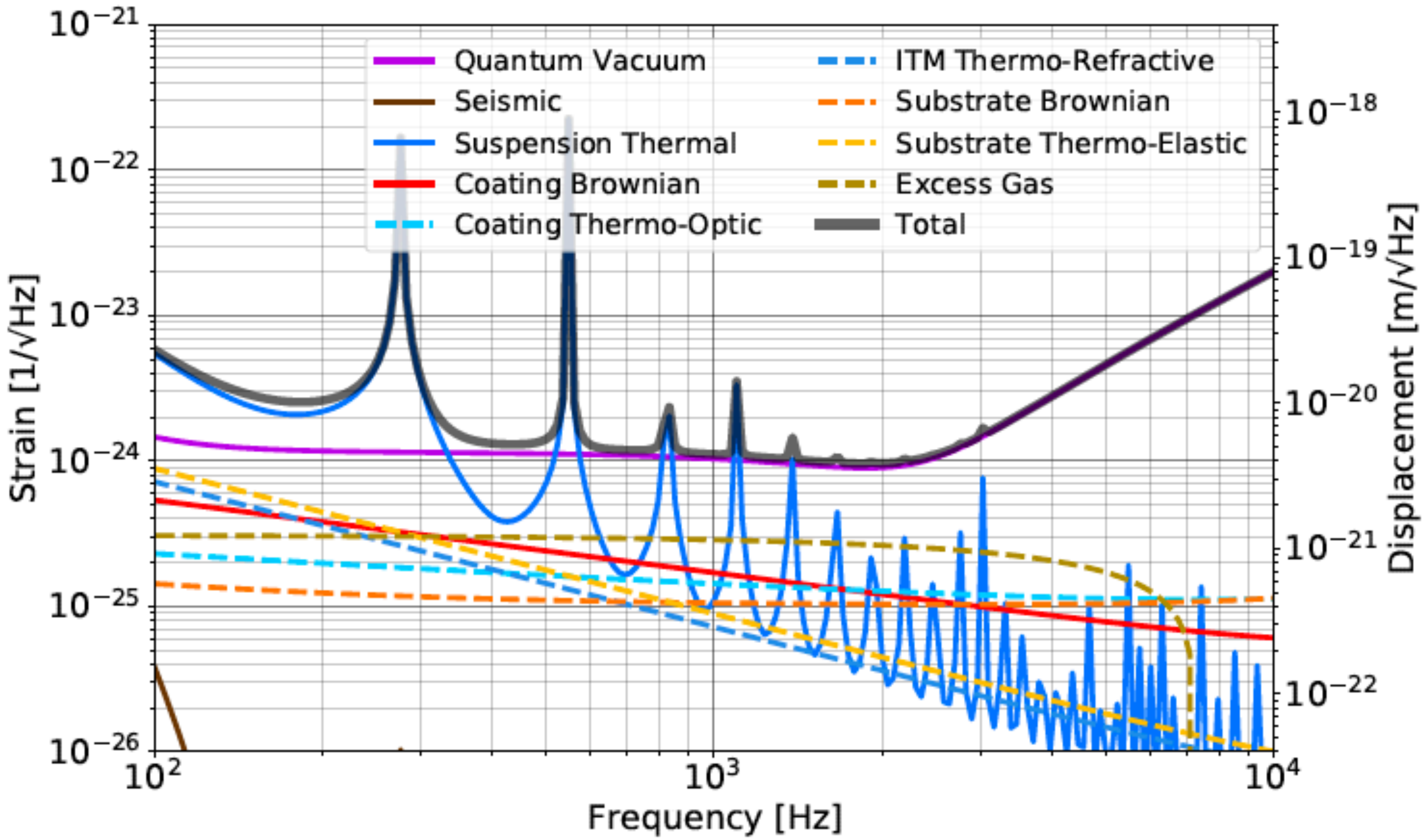
NEMO current design choices

- Test mass weight = 74.1 kg
- Test mass coating : AlGaAs/GaAs*
- ITM = 150 K, ETM = 123 K
- ROC_{ITM} = 1800 m; ROC_{ETM} = 2500 m
- Suspension material : steel*
- Test mass cooling method : radiative



Picture modified from : J. V. van Heijningen, NEMO paper

NEMO instrument noise budget

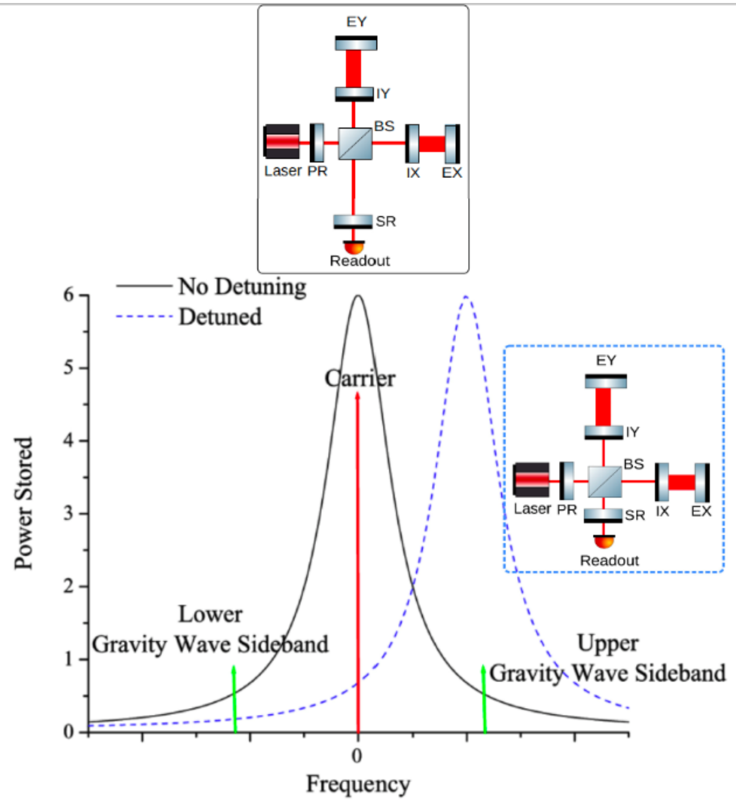


Reference : NEMO paper

Quantum noise manipulation

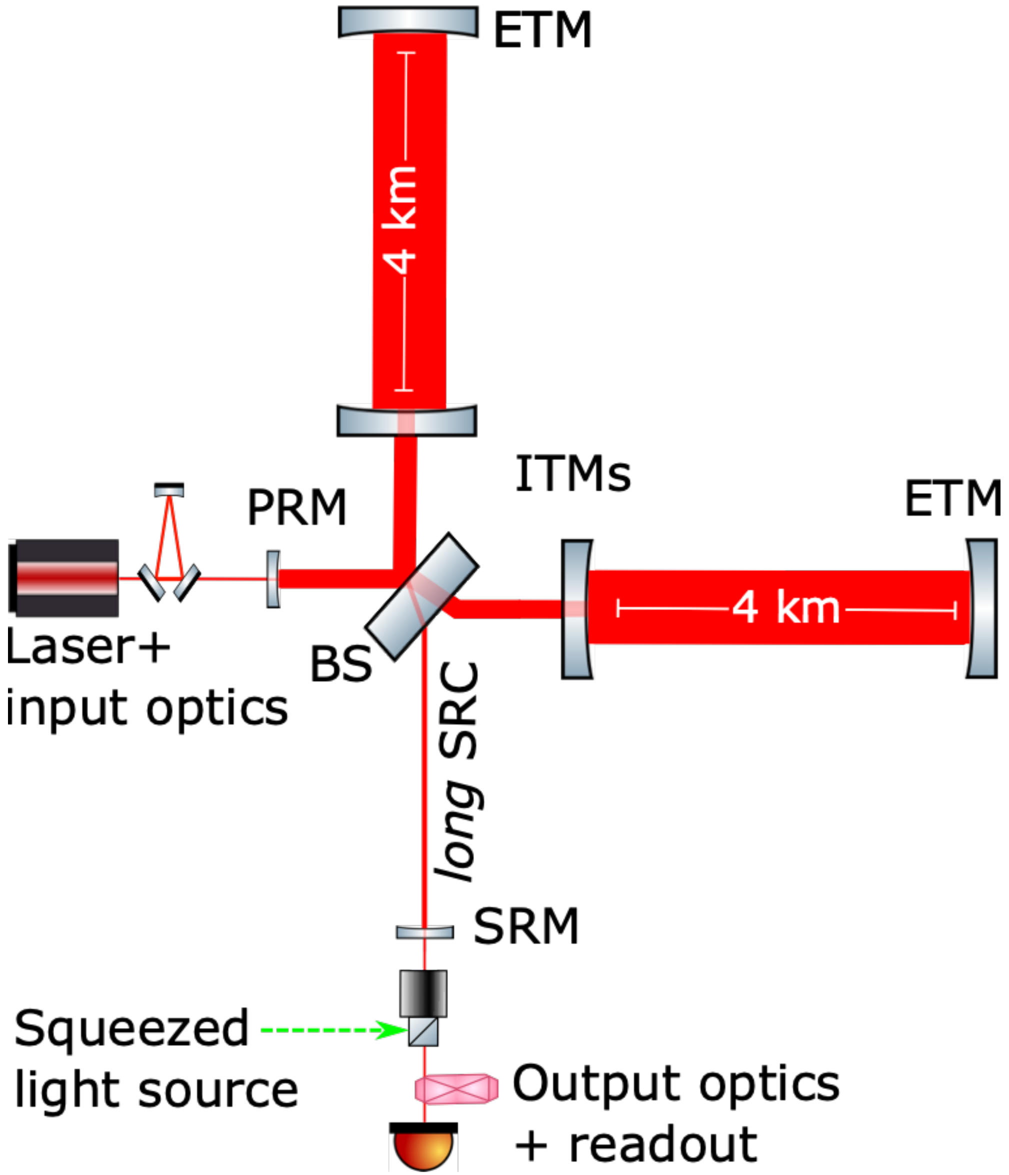
Long SRC :

- 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



Long Signal Recycling Cavities

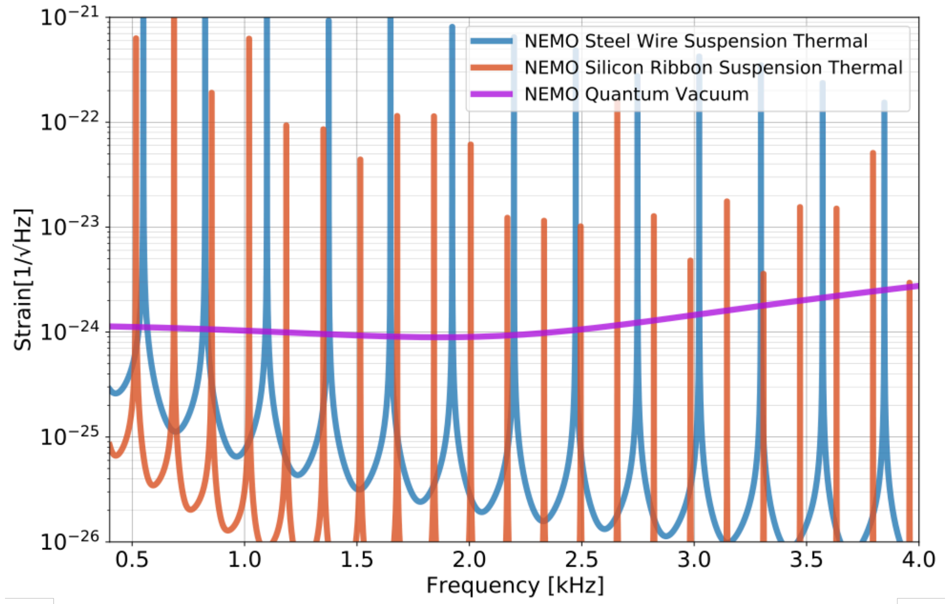
- Advantages : Control potentially easier, requires no filter cavity to improve sensitivity around coupled cavity pole
- Robust to losses inside the interferometer: loss per m value relaxed
- Disadvantage: Un-demonstrated (Twin signal recycling control for DRMI, proven concept)

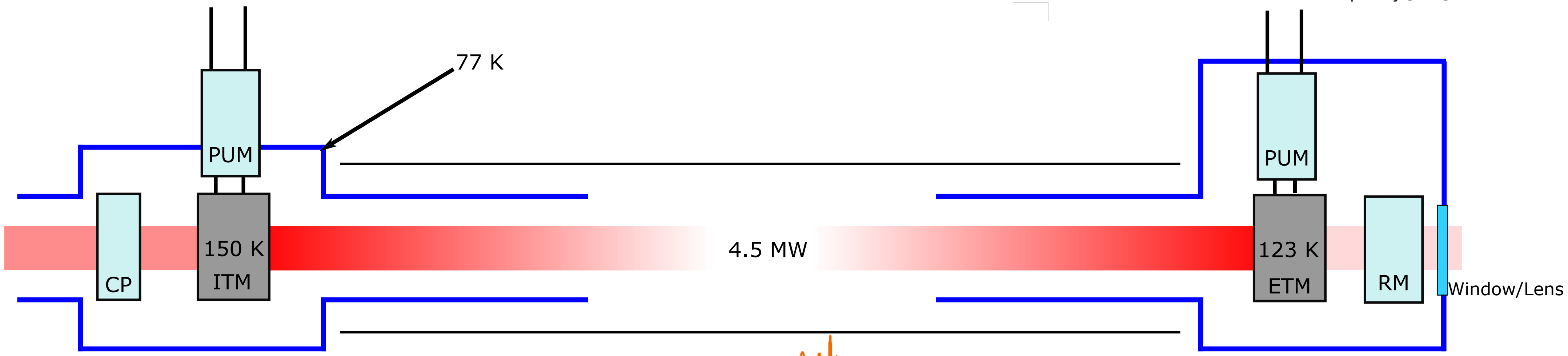


Picture reference : Phys. Rev. D 102, 122003

Suspensions and thermal noise considerations

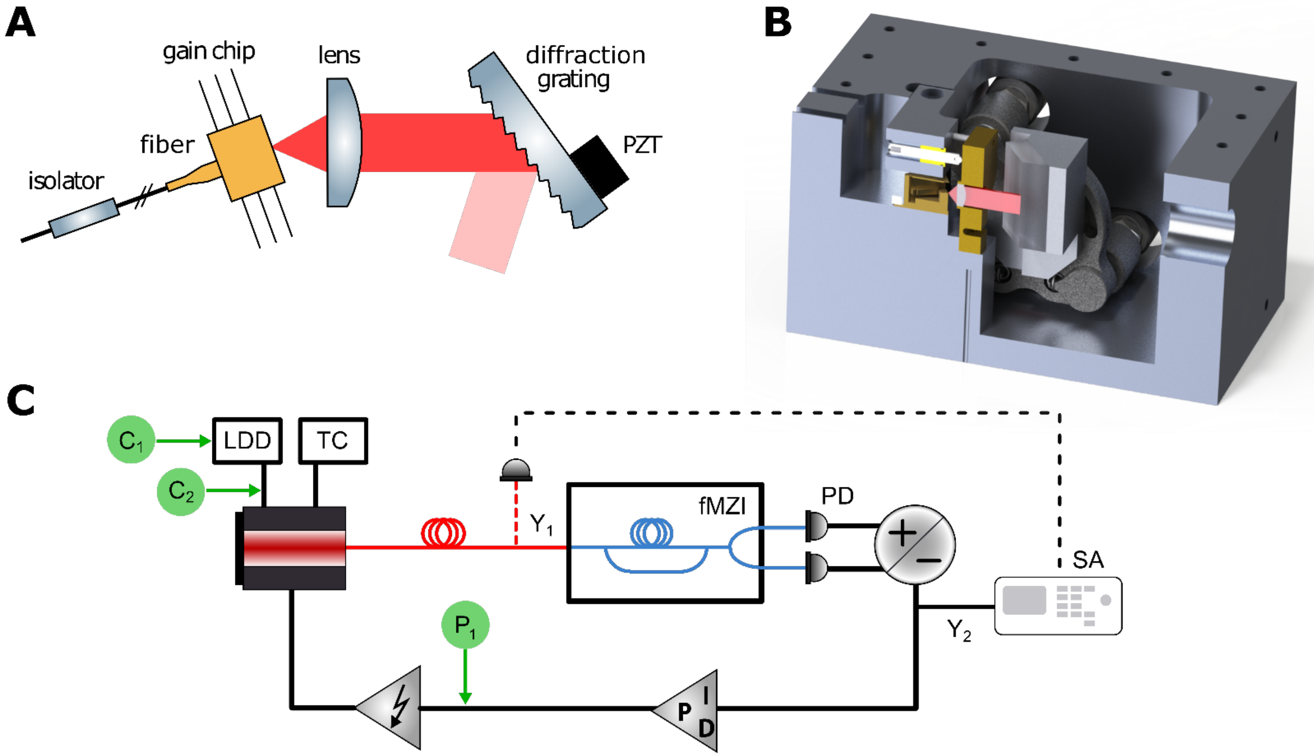
- Simpler 3-stage horizontal and vertical vibration isolation system, thin steel wire suspensions
- Radiative cooling only
  - 45 cm diameter , 20 cm thick mirrors --> mass 74.1 kg
  - 4.5 MW in the arms; 10.7 W absorption in the ITMs
  - 150 K result of trade offs





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

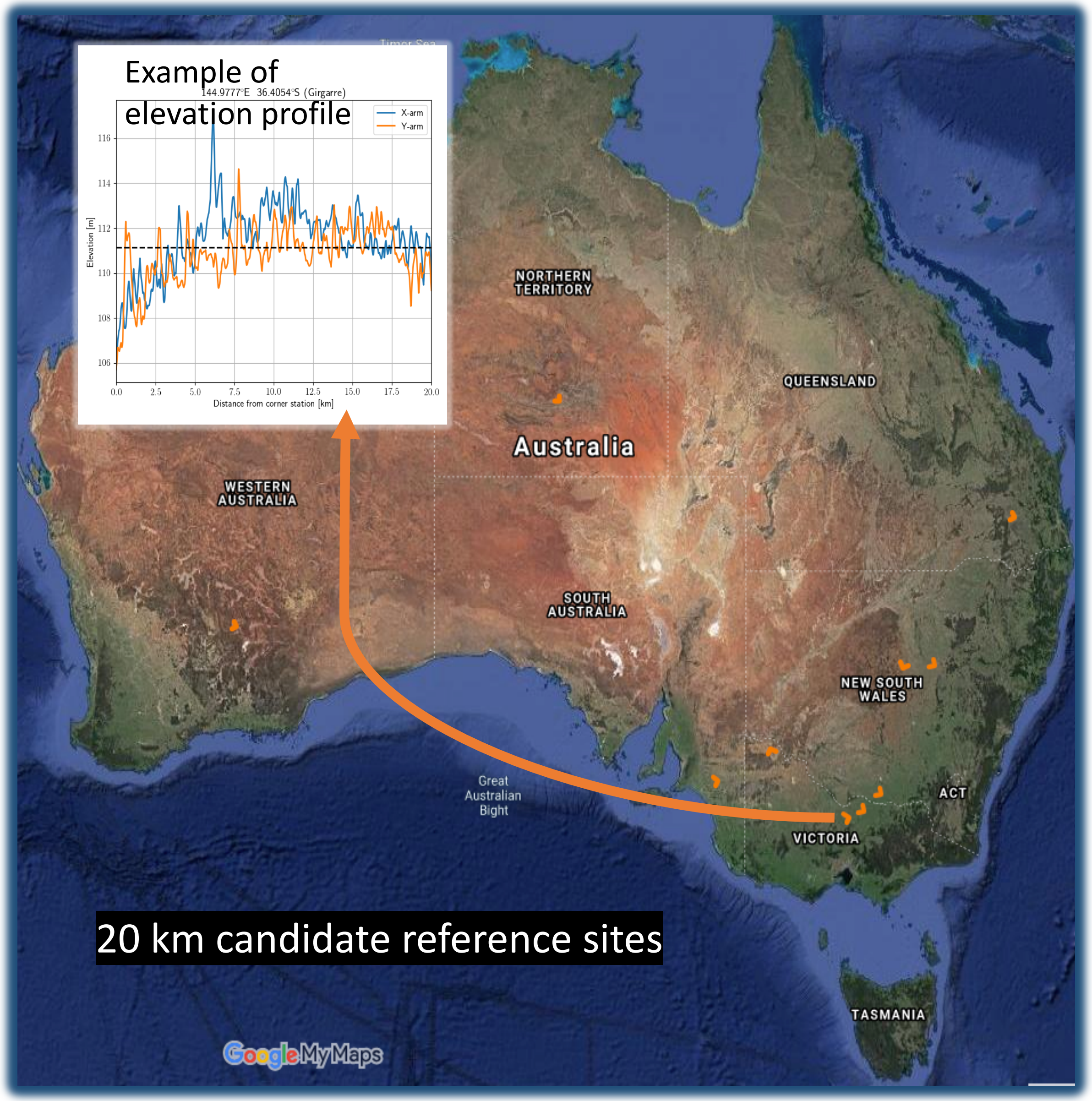


Slide credit : Sebastian Ng, D.Kapasi

2 µm ECDL reference : https://www.osapublishing.org/oe/abstract.cfm?uri=oe-28-3-3280

Search for reference sites

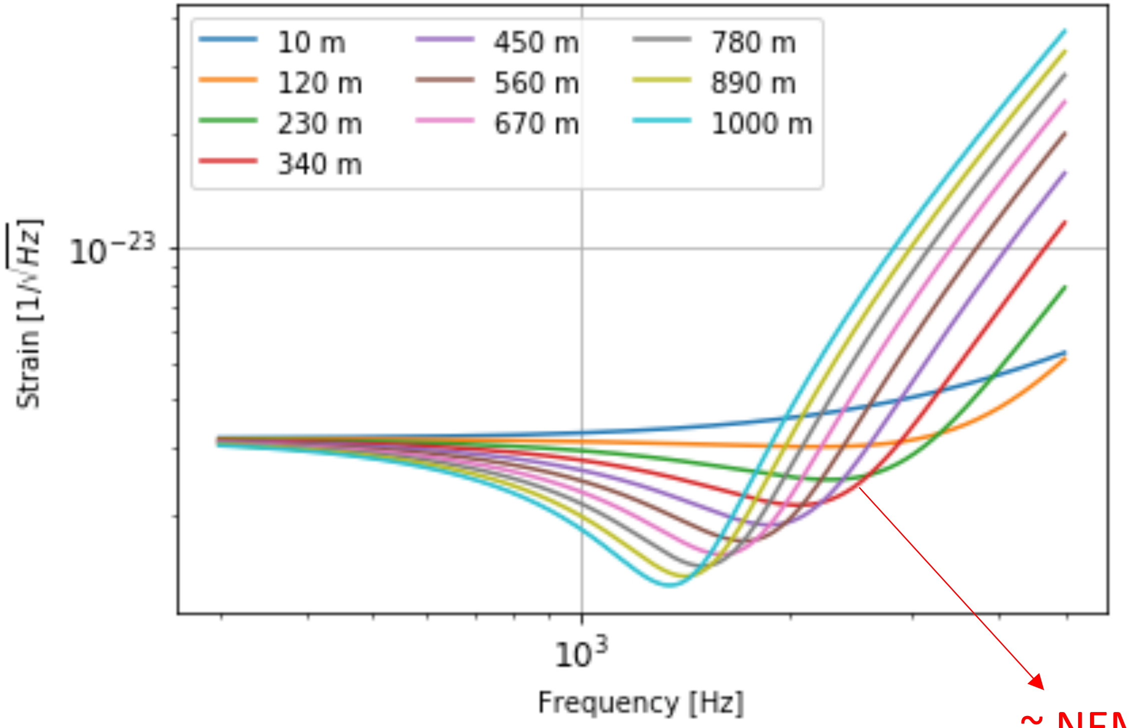
See talk by Bram Slagmolen for details



Tunabililty of NEMO

- How tunable is NEMO** ?
- Assuming no ‘dynamic tuning’
- Parameters to could be varied :
  - SRC length : macroscopic and microscopic
  - SRC reflectivity
- Coupled cavity pole depends on
  - T _ITM
  - L_SRC , L_ARM
- Bandwidth of coupled cavity
  - L_SRC and T_SRM

No squeezing included here either!



~ NEMO

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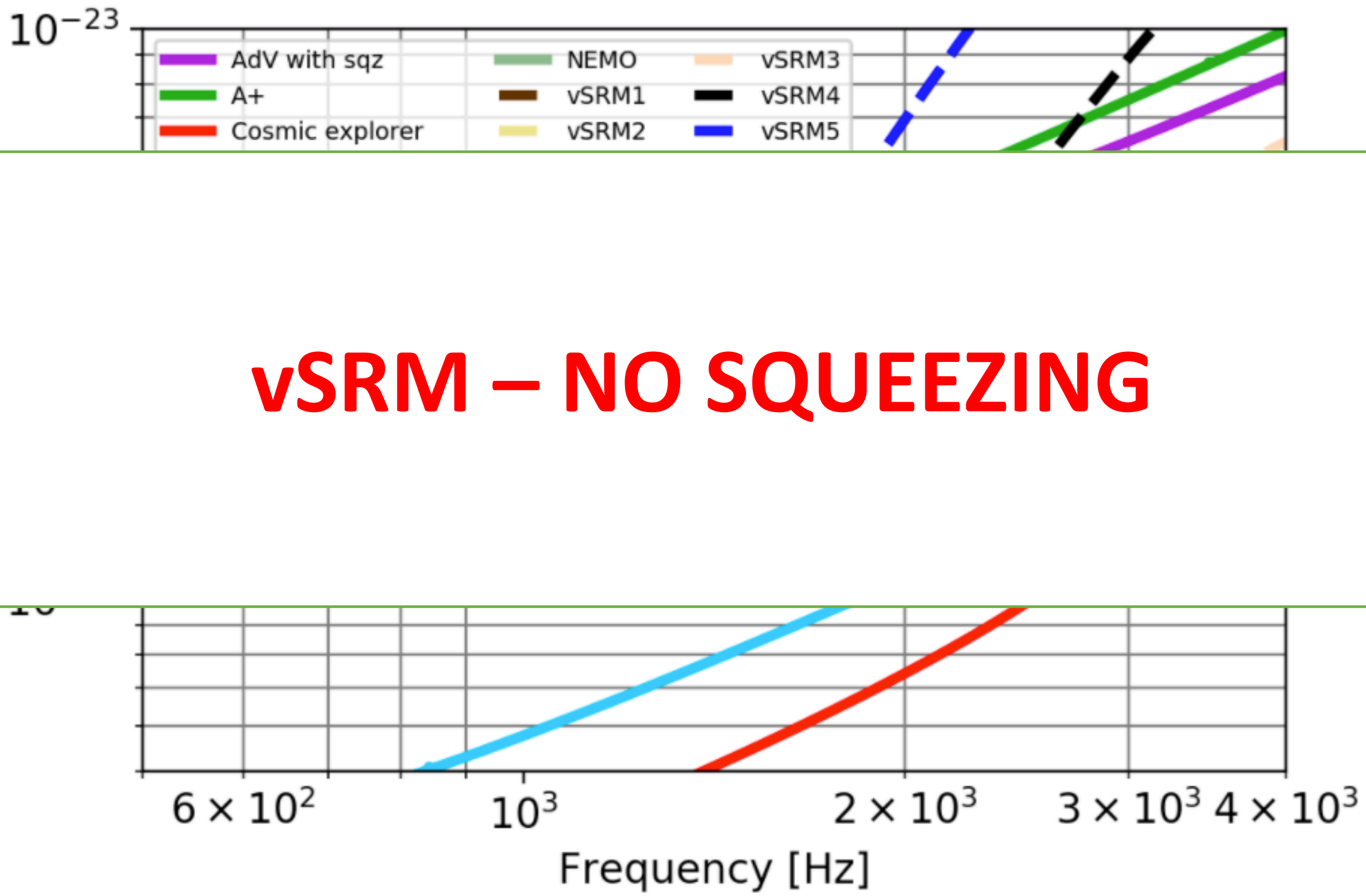
** Current NEMO design not limited by SRC losses

Results of tunings*

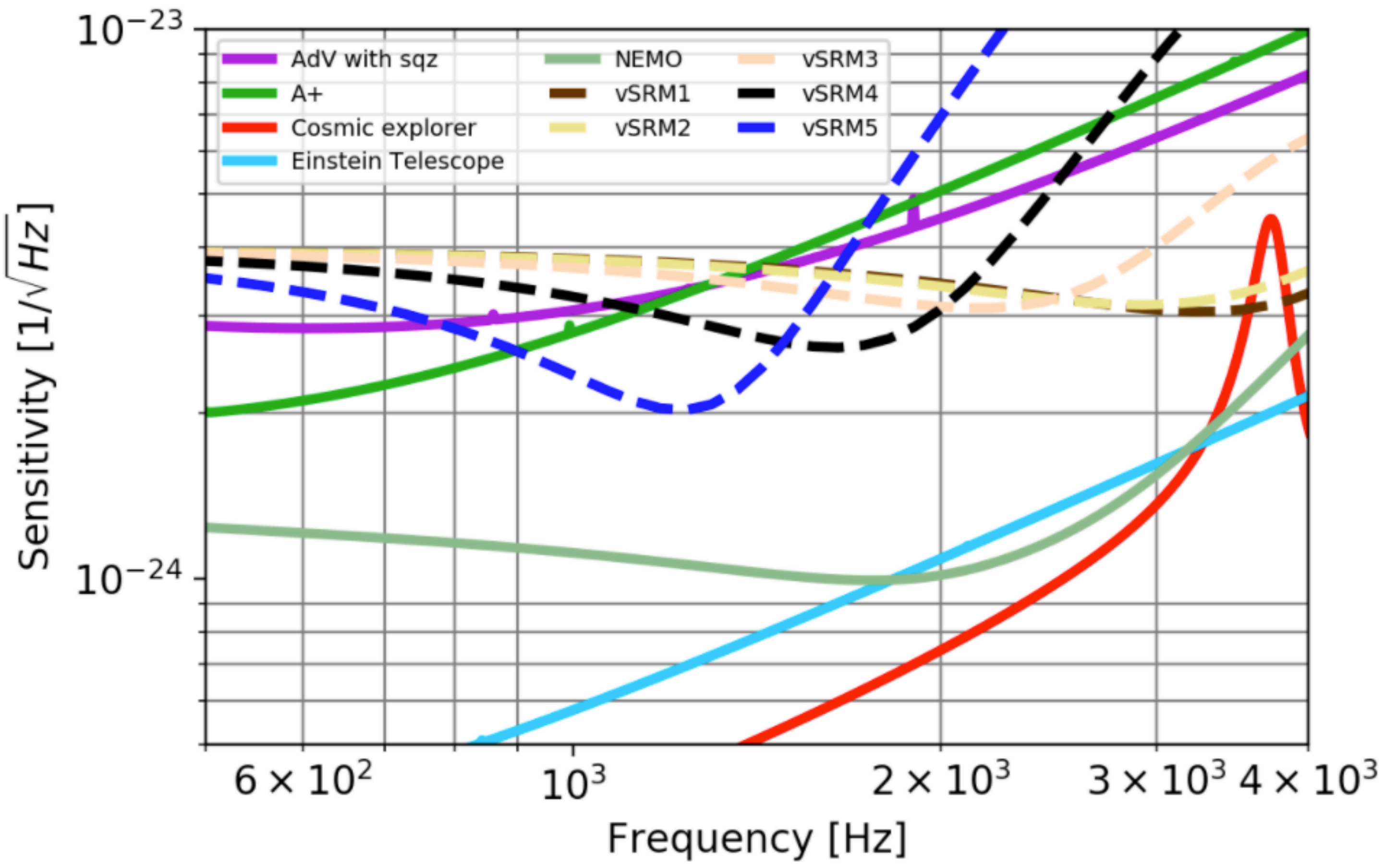


vSRM – NO SQUEEZING

Reference for some curves : T1500293-v13

* Statutory warning : Preliminary modelling

Results of tunings*



Reference for some curves : T1500293-v13

Variable reflectivity concept :

- LIGO : G050524
- Glenn de Vine, Daniel A. Shaddock, and David E. McClelland, "Experimental demonstration of variable-reflectivity signal recycling for interferometric gravitational-wave detectors," Opt. Lett. 27, 1507-1509 (2002)
- A 7 dB reduction by squeezing here would drop these curves by a factor 2.5

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* Statutory warning : Preliminary modelling

Building NEMO

- NEMO : strain of ≈ 10^{-24} 1/√Hz between 1-3 kHz
- Focus : post merger remnant of BNS
- Part of a global network of detectors operating in late 2020s-2030s
- 4 km NEMO infrastructure could potentially host Cosmic Explorer South
- To do : Assess feasibility of squeezing with variable reflectivity

A happy heterogenous network of interferometers
PC : Pixar

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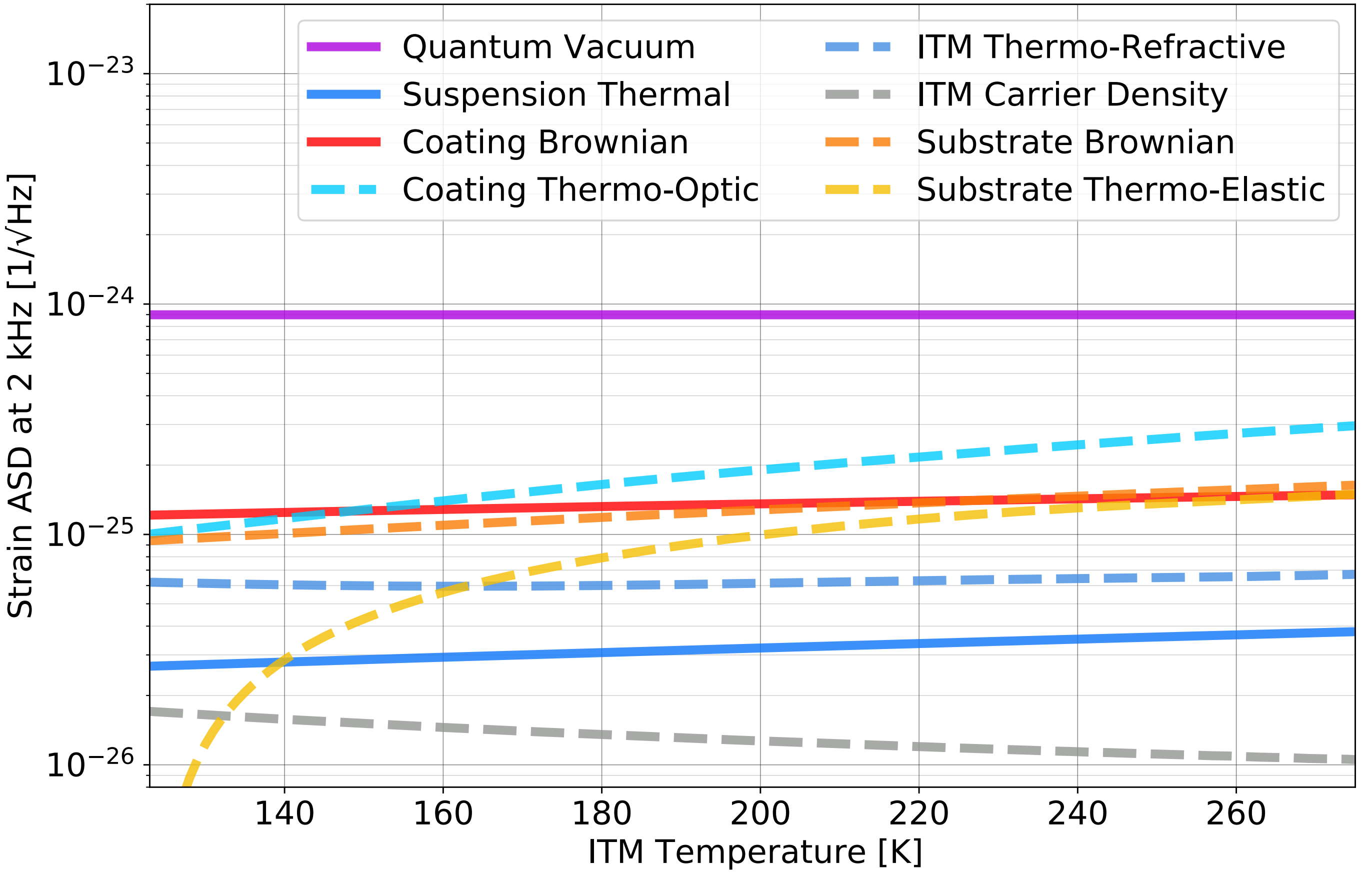
Questions / comments ?

Back up slides

Why can we do this?

- Only interested in high frequencies and suspension and coating thermal noise are not dominant at 2 kHz
- Not very beneficial for a broadband detector



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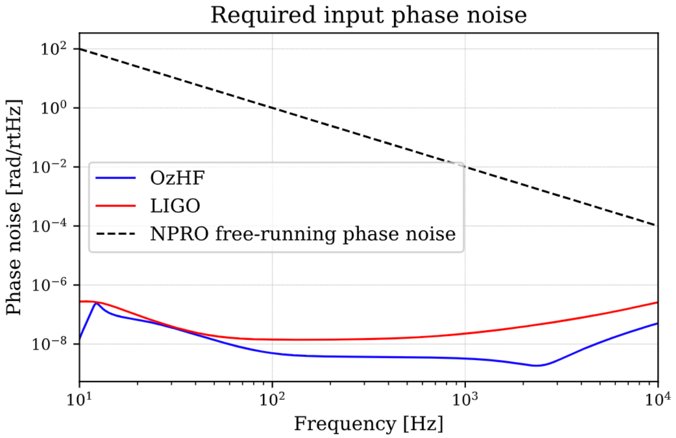
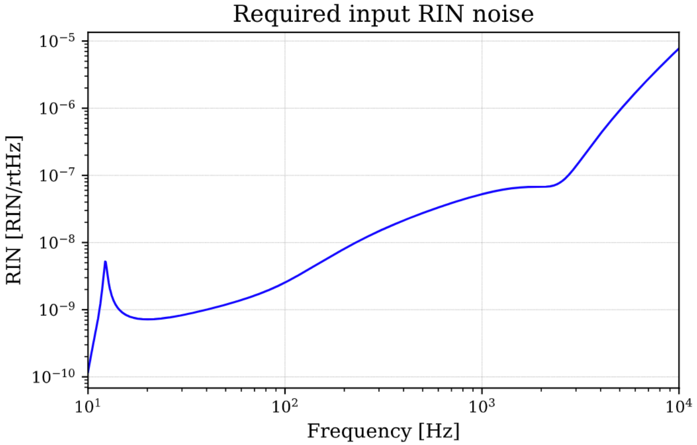
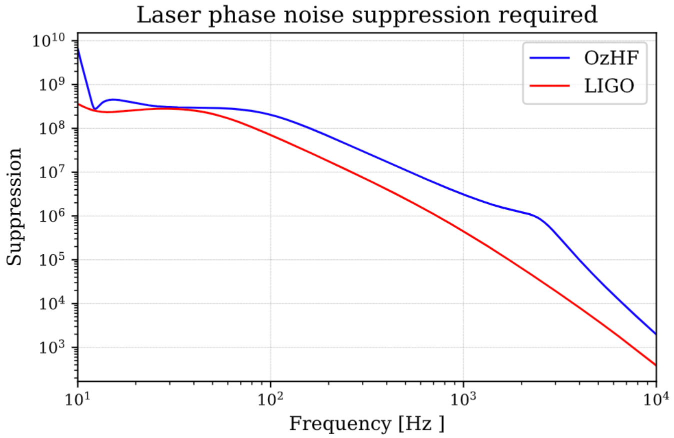
Slide credit : J. V. van Heijningen, J.Eichholz, DCC : P2000243

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

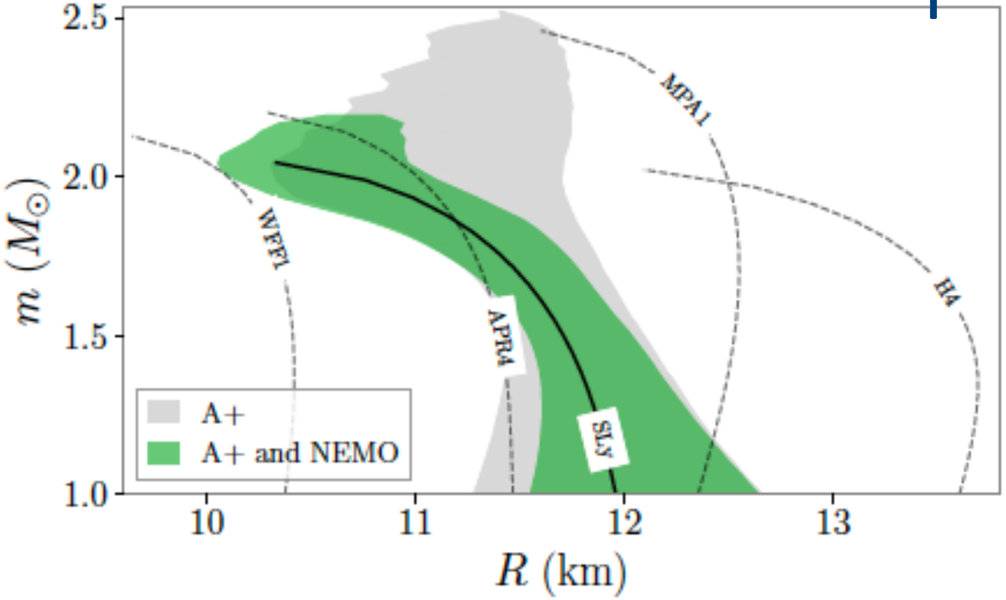






Requirements here are to beat QN limited sensitivity at GW frequencies, haven't considered requirements in control band yet.

Additional numbers and plots



Arm Cavity Loss	40 ppm
ITM substrate absorption	400 ppm
ITM residual thermal lensing and scatter	180 ppm
SRM optical loss	150 ppm
BS optical loss	150 ppm
Total SRC Loss	1500 ppm
Reduction in quantum noise	7 dB

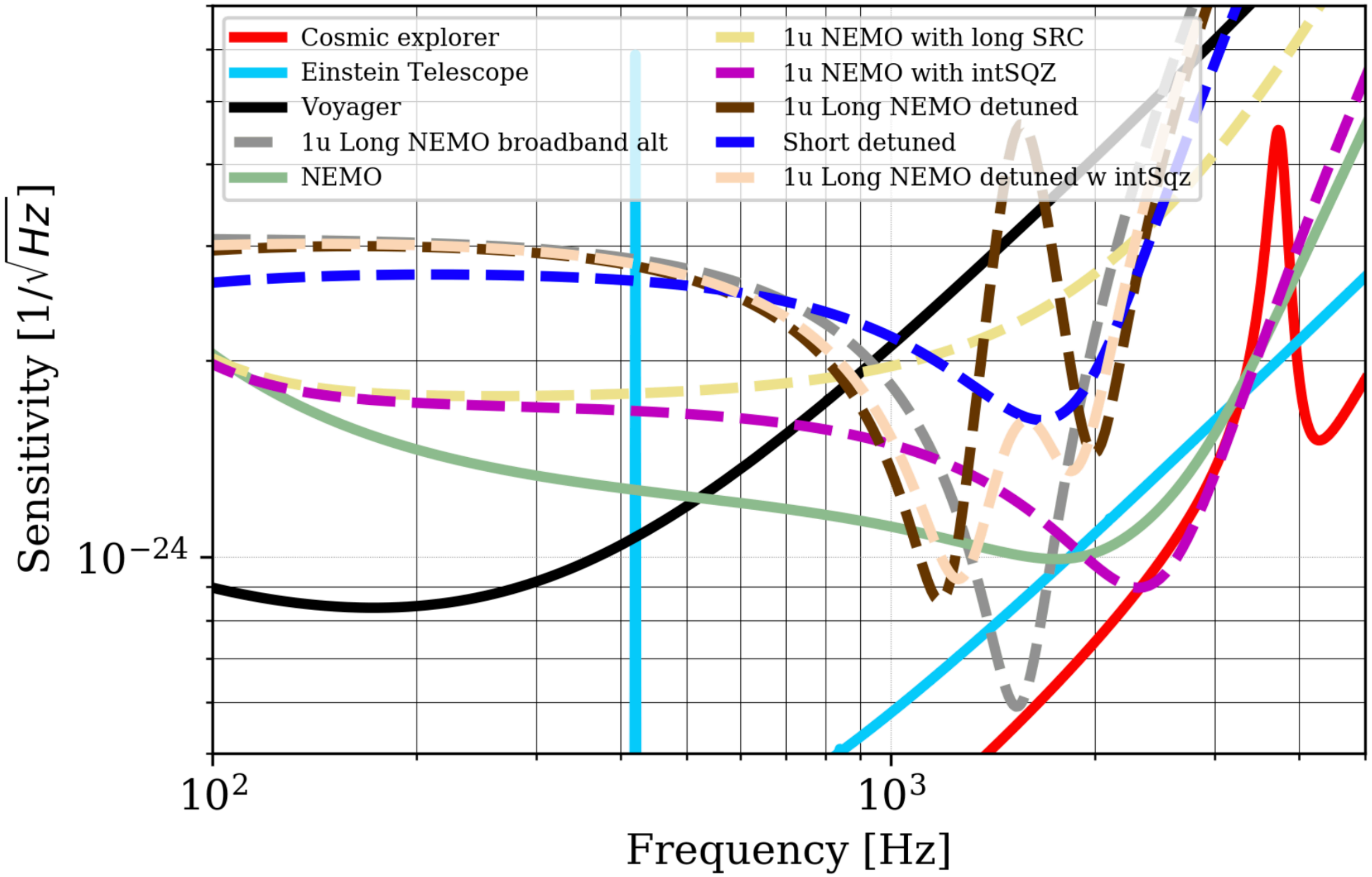
TABLE I: NEMO optical parameters used in the calculation of the noise traces featured in Fig. 2. The round trip losses due to absorption, scatter, surface roughness and mode-mismatch are shown separately for the ITMs, BS and SRM.

Parameter	Value
Laser Wavelength	2 μm
Laser Power	500 W
Arm Length	4 km
Signal Recycling Cavity Length	354 m
Power Recycling Mirror Transmission	3%
Input Test Mass (ITM) Transmission	1.4%
End Test Mass (ETM) Transmission	5 ppm
Signal Recycling Mirror Transmission	4.8%
Power on Beamsplitter	31.2 kW
Arm Circulating Power	4.5 MW
Injected Squeezing level	10 dB
Test Mass Material	Silicon
ITM Temperature	150 K
ETM Temperature	123 K
Test Mass Coating	AlGaAs/GaAs
Test Mass Diameter	45 cm
Test Mass Thickness	20 cm
Test Mass Weight	74.1 kg
ITM Radius of Curvature	1800 m
ETM Radius of Curvature	2500 m
Beam Radius on ITM	57.9 mm
Beam Radius on ETM	83.9 mm
Suspension Fiber Length	0.55 m
Suspension Fiber Material	Steel
Suspension Fibers per Test Mass	4
Test Mass Cooling Method	Radiative
Interferometer Configuration	Dual Recycled with Fabry Perot Arms

Additional 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

Additional plots



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