KAGRA-OzGrav: Collaboration Opportunities for a kHz-Band Gravitational-Wave Detector

Johannes Eichholz for the OzGrav Community

ANU CENTRE FOR GRAVITATIONAL ASTROPHYSICS

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Swinburne University of Technology · Australian National University · Monash University · AAO · The University of Western Australia · The University of Adelaide · The University of Melbourne · CSIRO · Australian Government Australian Research Council

KAGRA/OzGrav HF Meeting Nov 17 2020

- Half-day workshop about potential collaboration towards high-frequency GW detector
  - OzGrav: Science case & HF detector design
  - KAGRA: Facility status & future plans
- KAGRA/Japanese Contribution to HF Detector in Australia?
- Australian contribution to & involvement in a KAGRA-HF?
- Outcome: both are interesting pathways & should be explored!

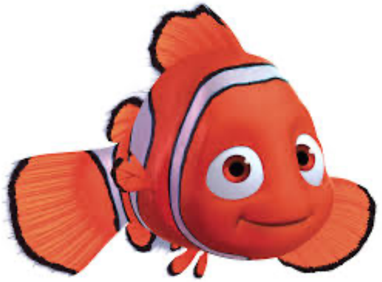
HF Detector Science & Design: NEMO Concept

- NEMO Design Concept: Neutron star Extreme Matter Observatory
- Technology enabler for 3G
- Science case driven sensitivity

From Wikipedia:

Captain Nemo (/ˈniːmoʊ/, later identified as an East Indian, **Prince Dakkar**) is a fictional character created by the French novelist Jules Verne (1828–1905).

Nemo is a mysterious figure. Though originally of unknown nationality, he is later described as the son of an East Indian raja. A scientific visionary, he roams the depths of the seas in his submarine, the *Nautilus*, which was assembled from parts manufactured in several different countries, then shipped to a cover address. The



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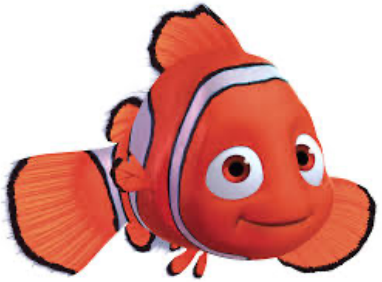
HF Detector Science & Design: NEMO Concept

Key Design Topics:

- Bandwidth tuning
- High power
- Squeezing
- Thermal noise
- Parametric instabilities
- Site selection

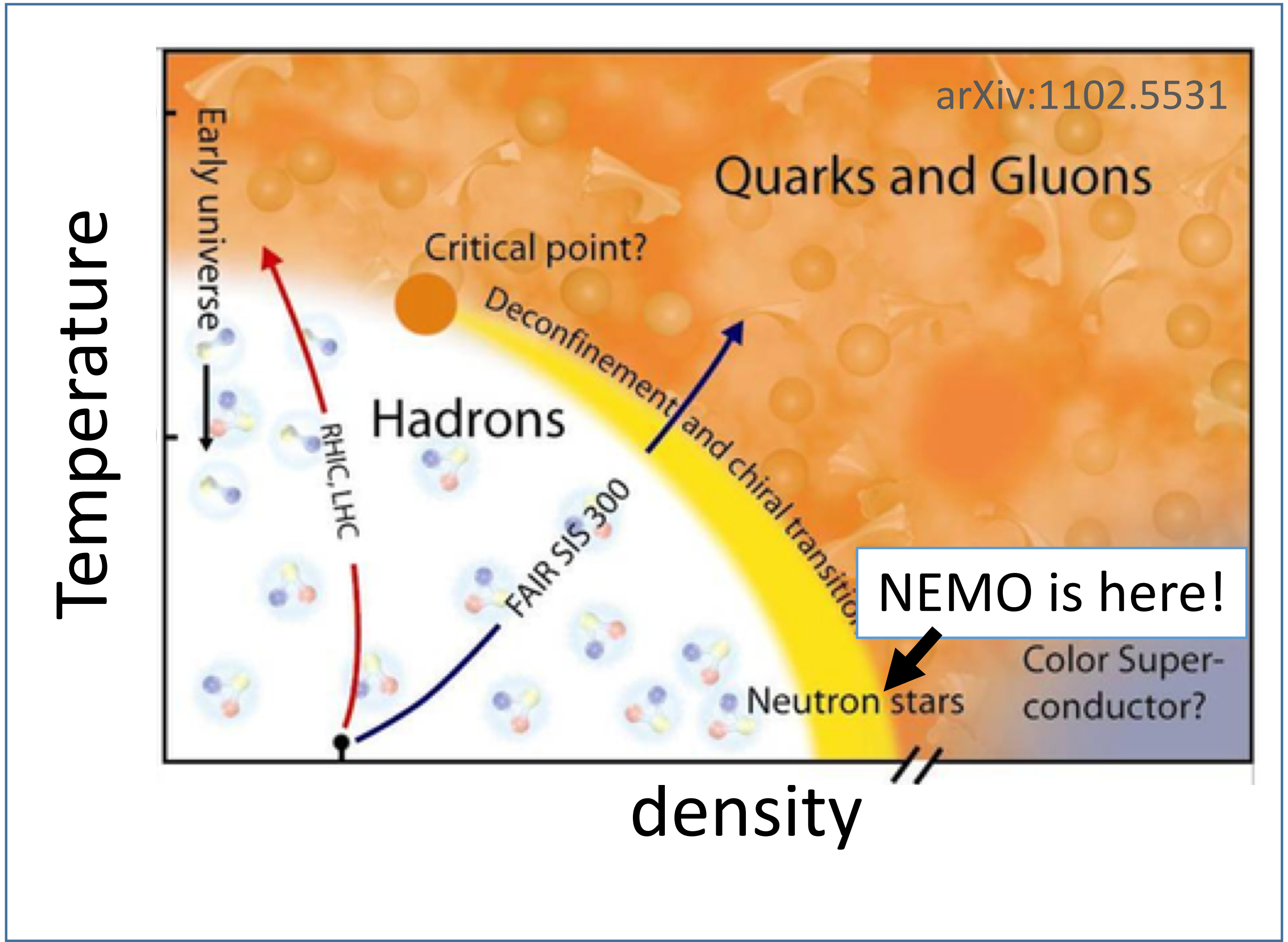


Publications:

- Main NEMO paper (science case & overview):
  - Ackley et al., *Publications of the Astronomical Society of Australia, 37*, E047 (2020)
- Suspensions, High-Power, Thermal Noise:
  - Eichholz et al., Phys. Rev. D 102, 122003 (2020)
- SRC design, squeezing & beyond:
  - Adya et al., Class. Quantum Grav. 37 07LT02 (2020)
- In preparation:
  - Parametric instablities
  - Detailed scenarios & advanced science case

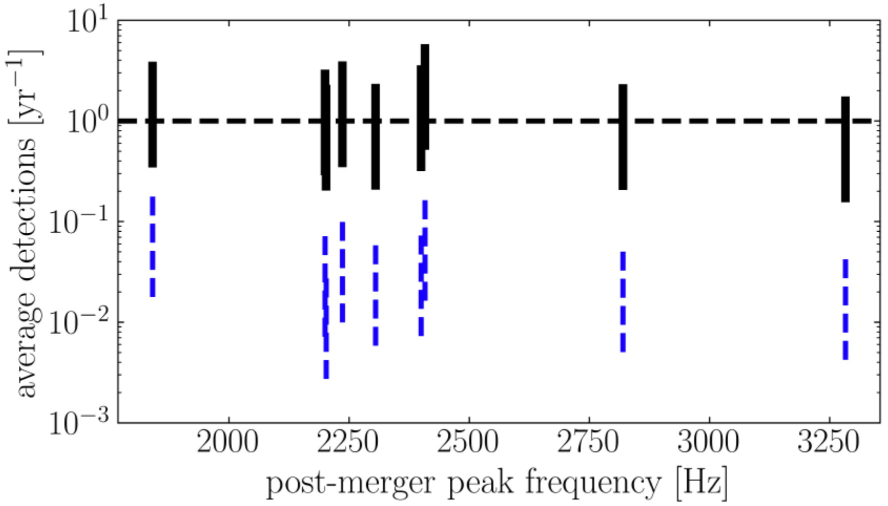
NEMO: The Science

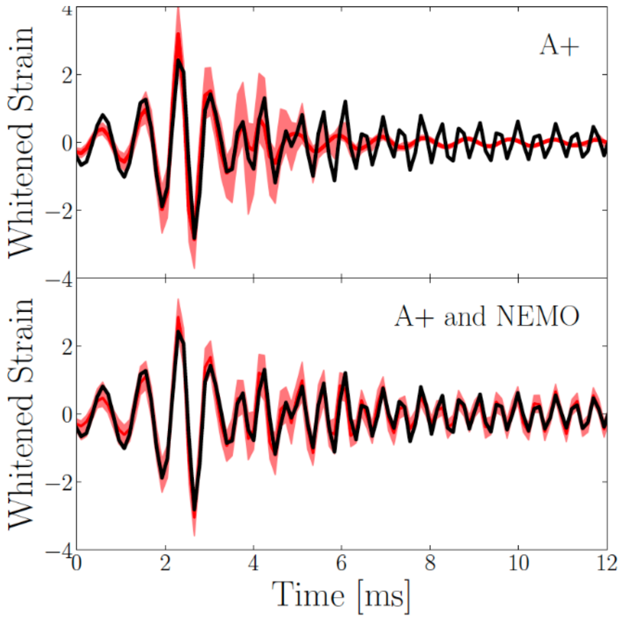
"High Frequency Detectors are Matter Machines"



NEMO: The Science

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





Source: NEMO Paper

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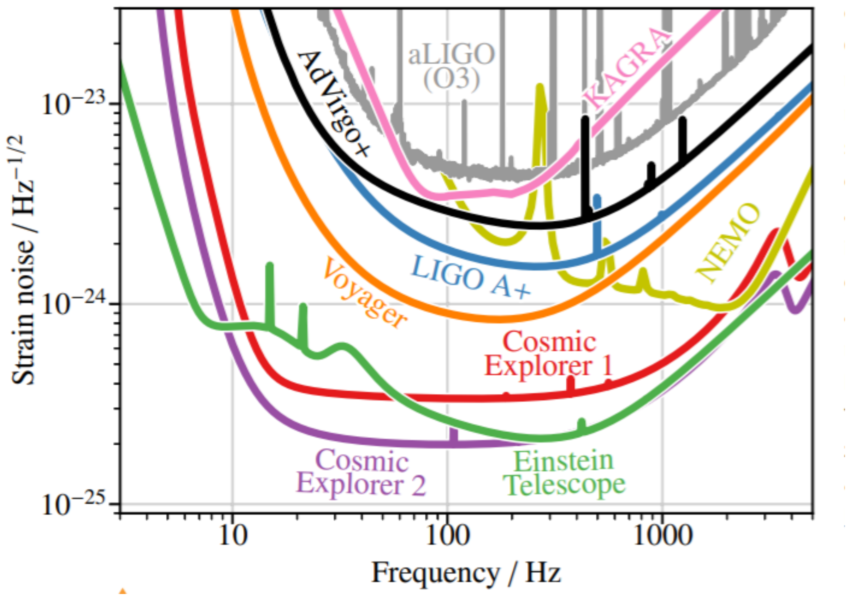
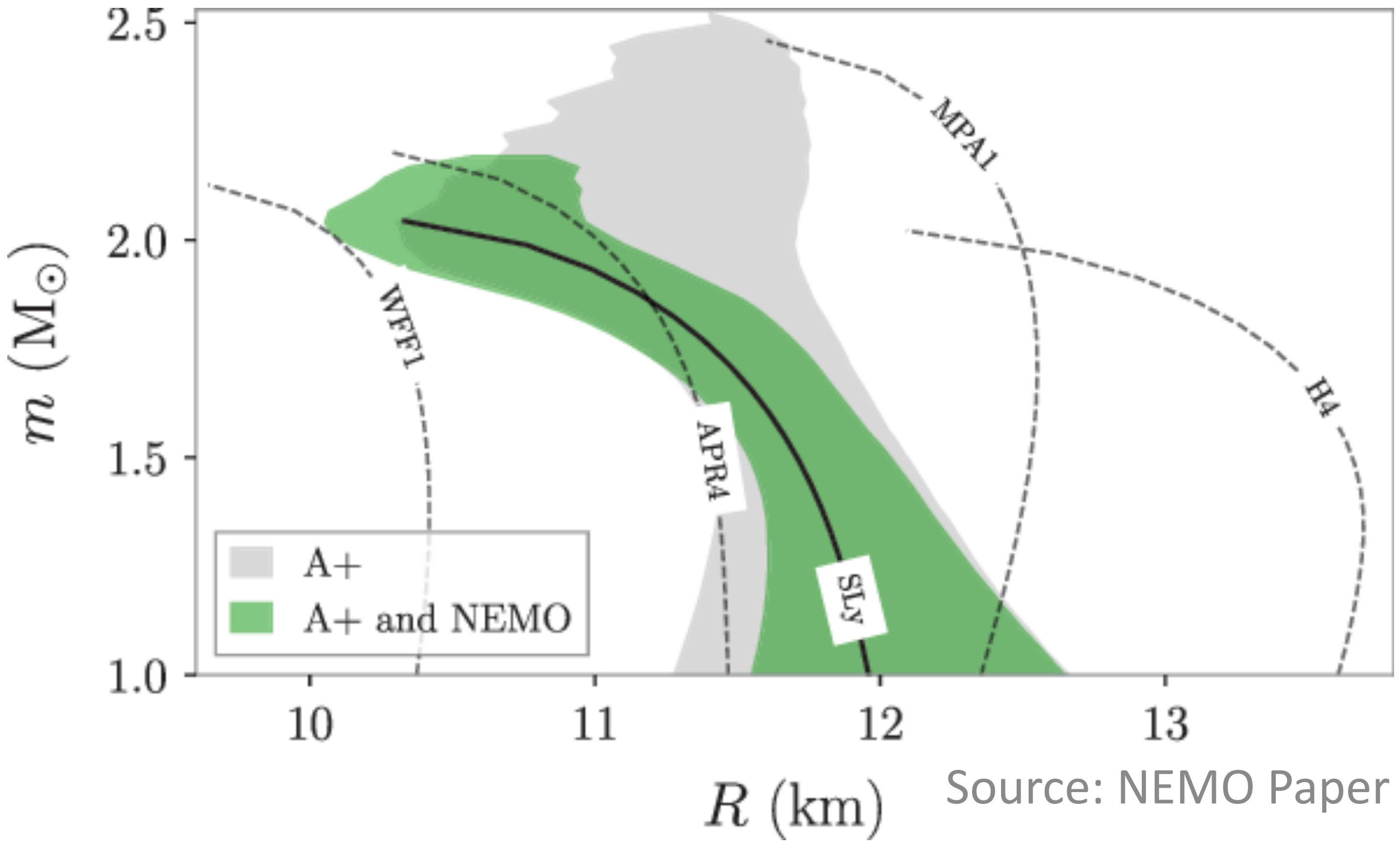
NEMO: The Science

- Discriminate between different equations of state
- Significant improvement over A+ only

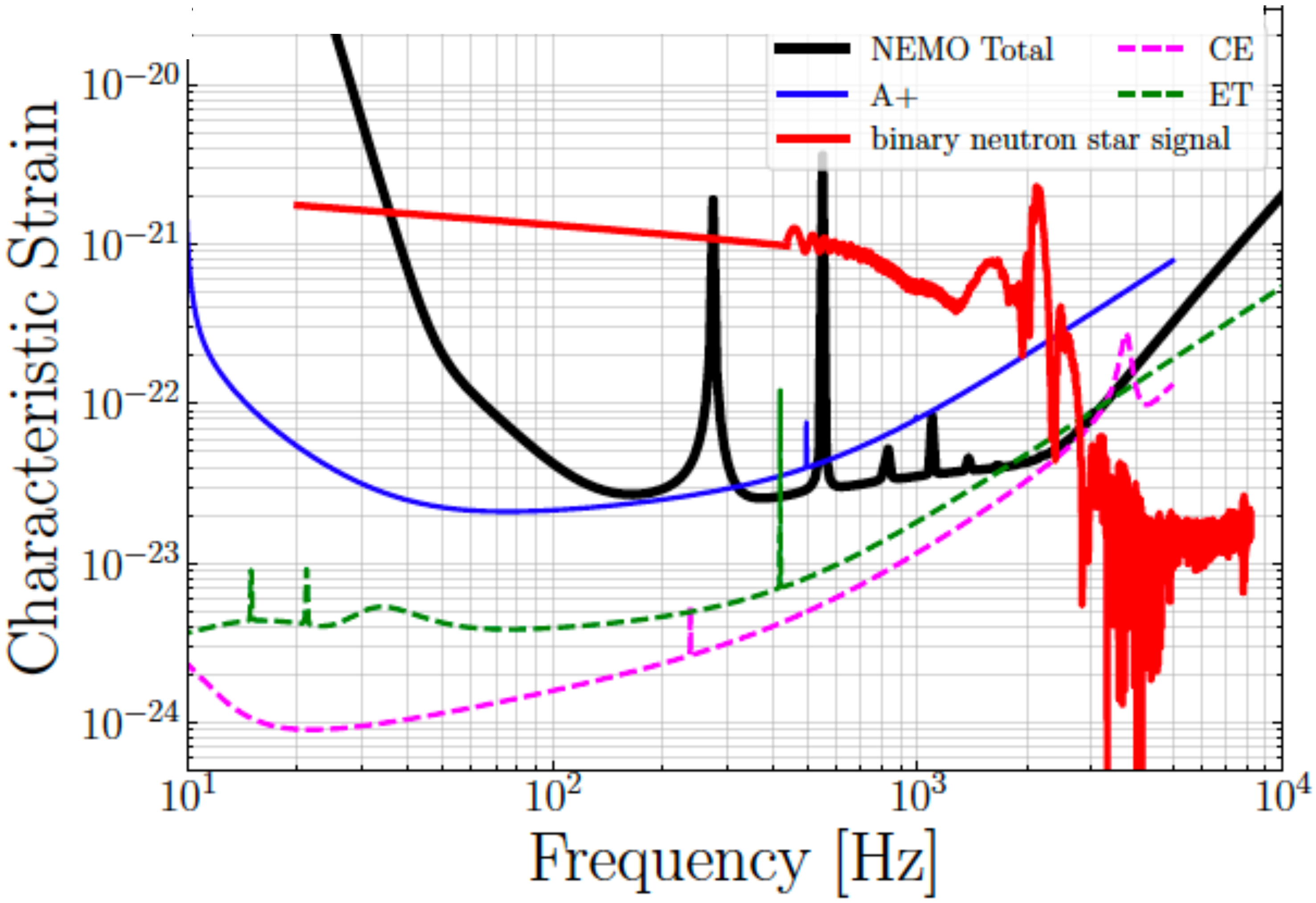




Source: NEMO Paper

Slide credit : Paul Lasky

Design Sensitivity



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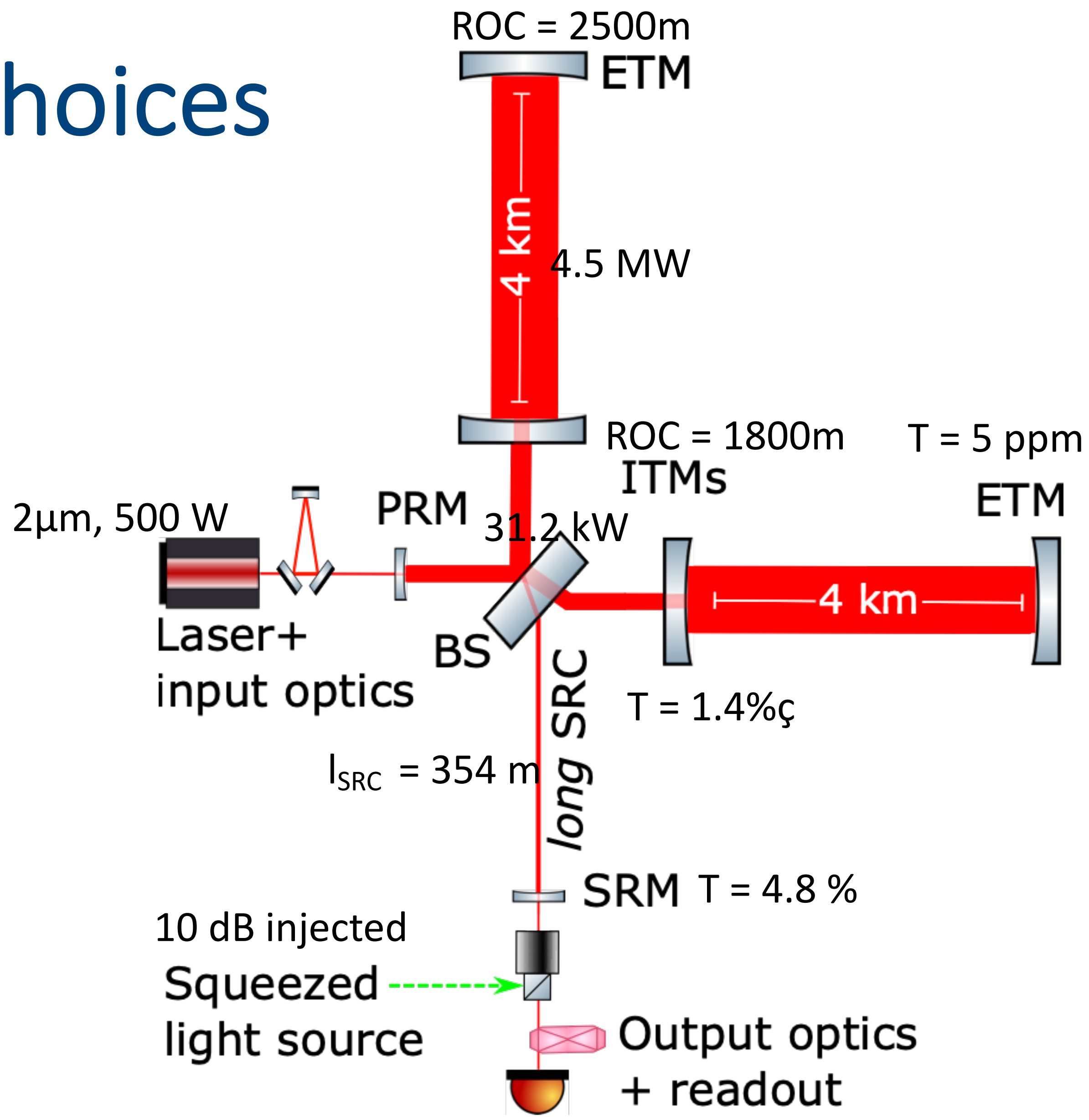
Source: NEMO paper

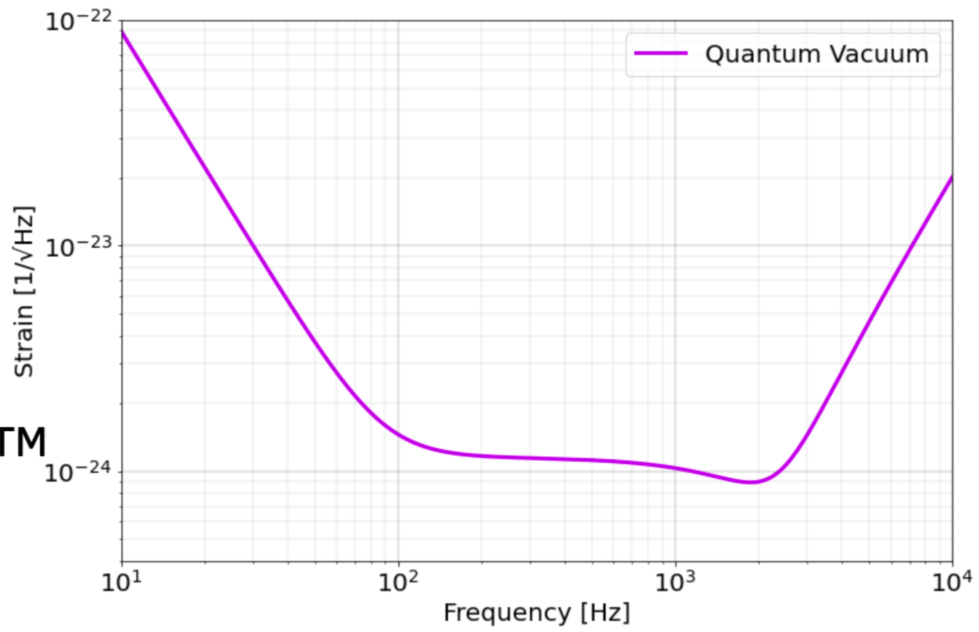
NEMO: Current Design Choices

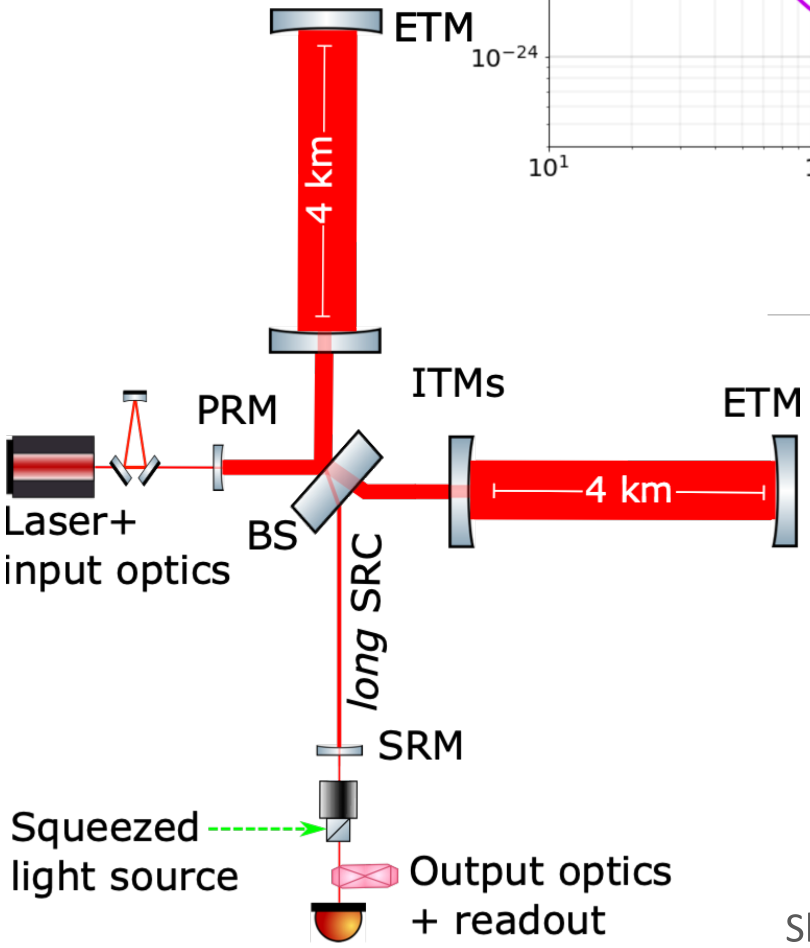
- Silicon test masses, 45cm X 20cm
  - Radiatively cooled
  - Mass: 74 kg
- 2µm carrier, 500W
- Steel wire suspensions
  - For simplicity
- Coating: AlGaAs/GaAs
  - Low absorption
- Temperatures: ITM 150K, ETM 123K
  - Satisfy thermal budget

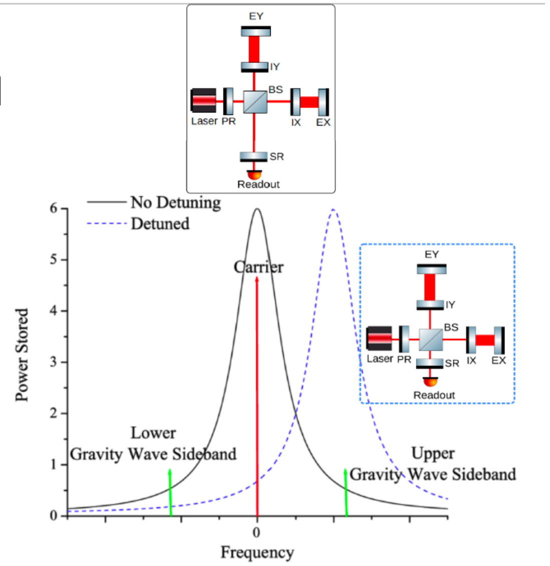


Long Signal Recycling Cavity

- Phase picked up by GW sidebands in the SRC cannot be ignored
- Analogous to a DRMI interferometer with two signal recycling cavities
- Robust to losses inside the inter-ferometer: loss per m value relaxed
- Advantage: Control potentially easier, requires no filter cavity to improve sensitivity around coupled cavity pole
- Disadvantage: Un-demonstrated (Twin signal recycling control for DRMI, proven concept)

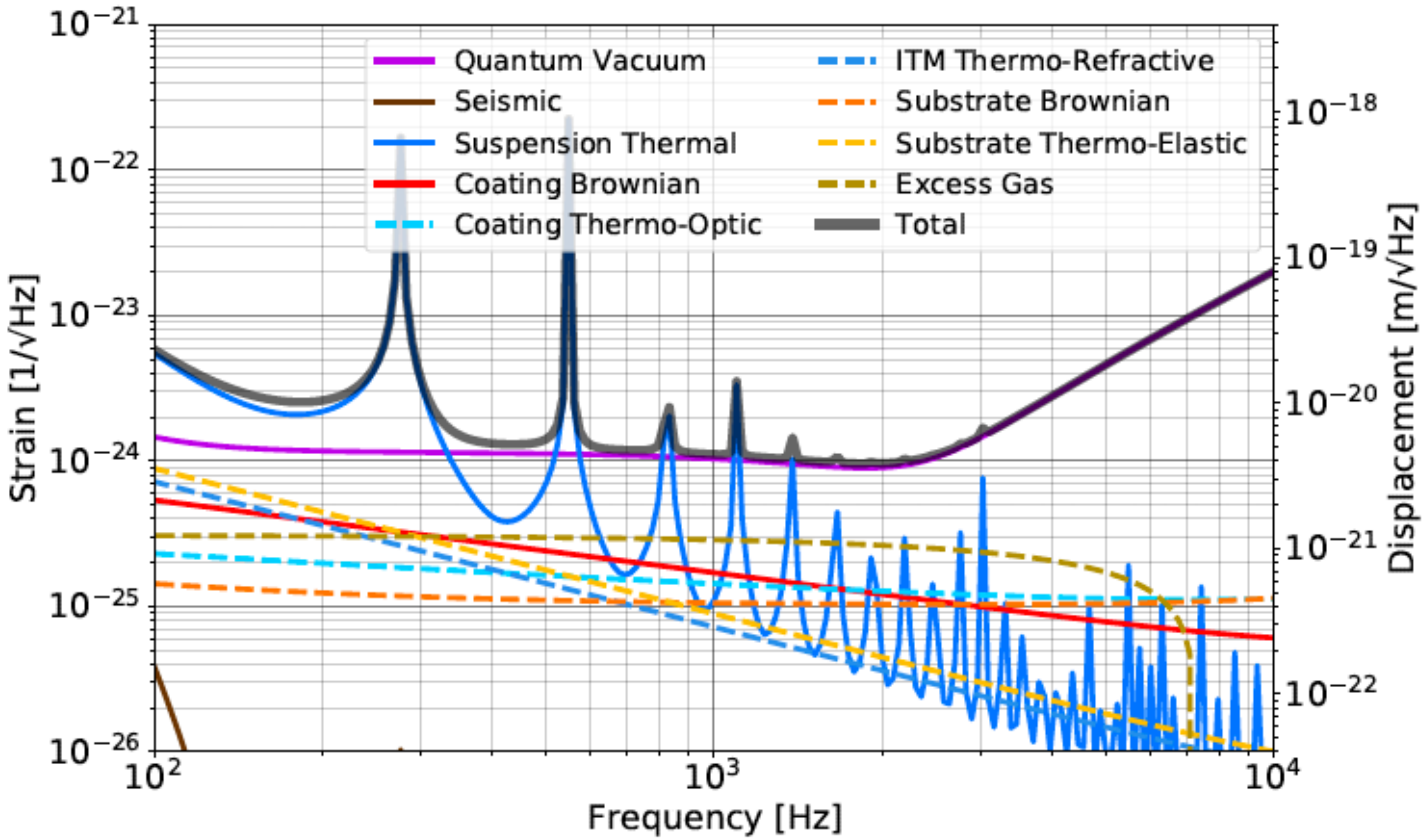






Slide credit: V. Adya

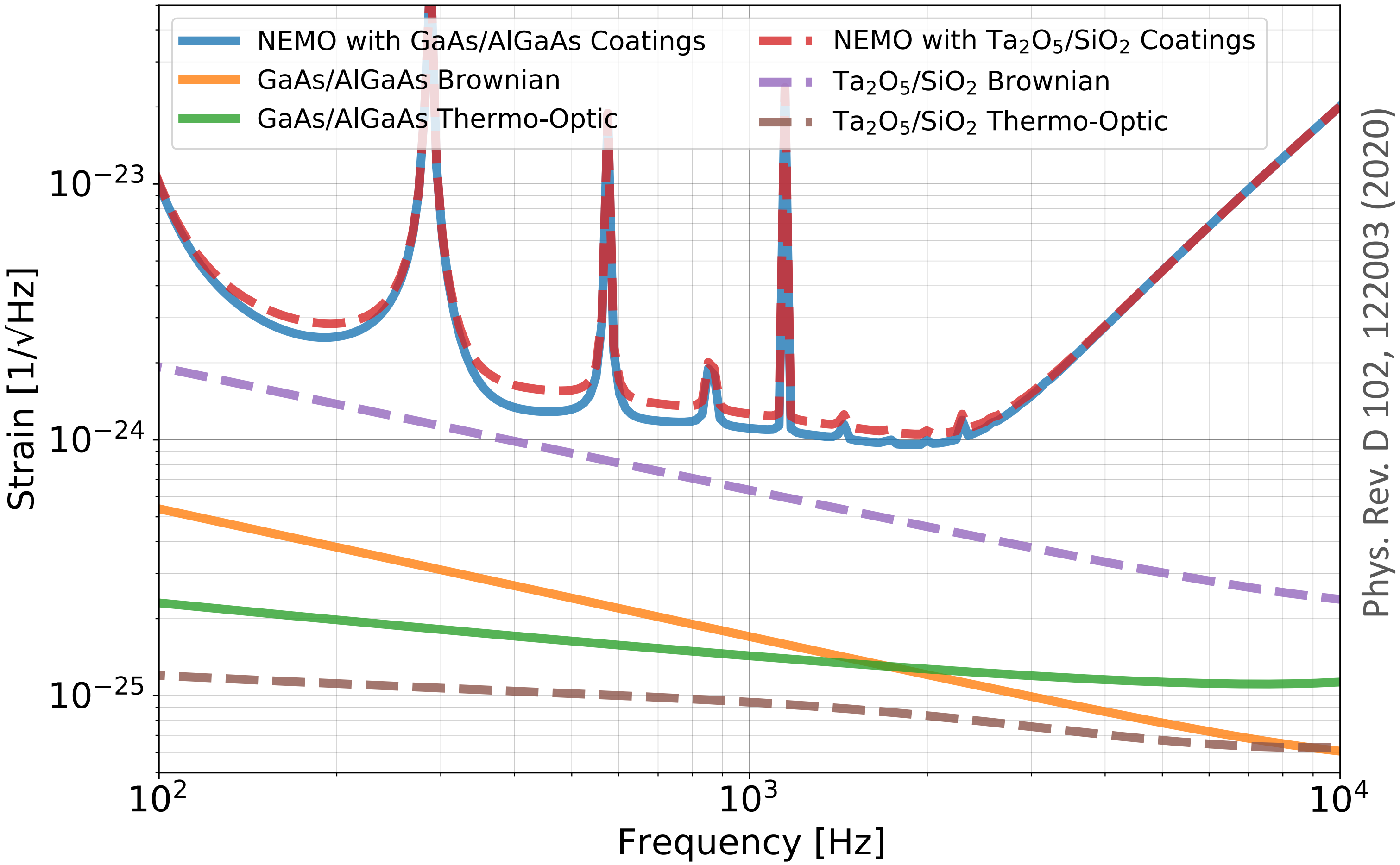
NEMO: Instrument Noise Budget



Reference : NEMO paper

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



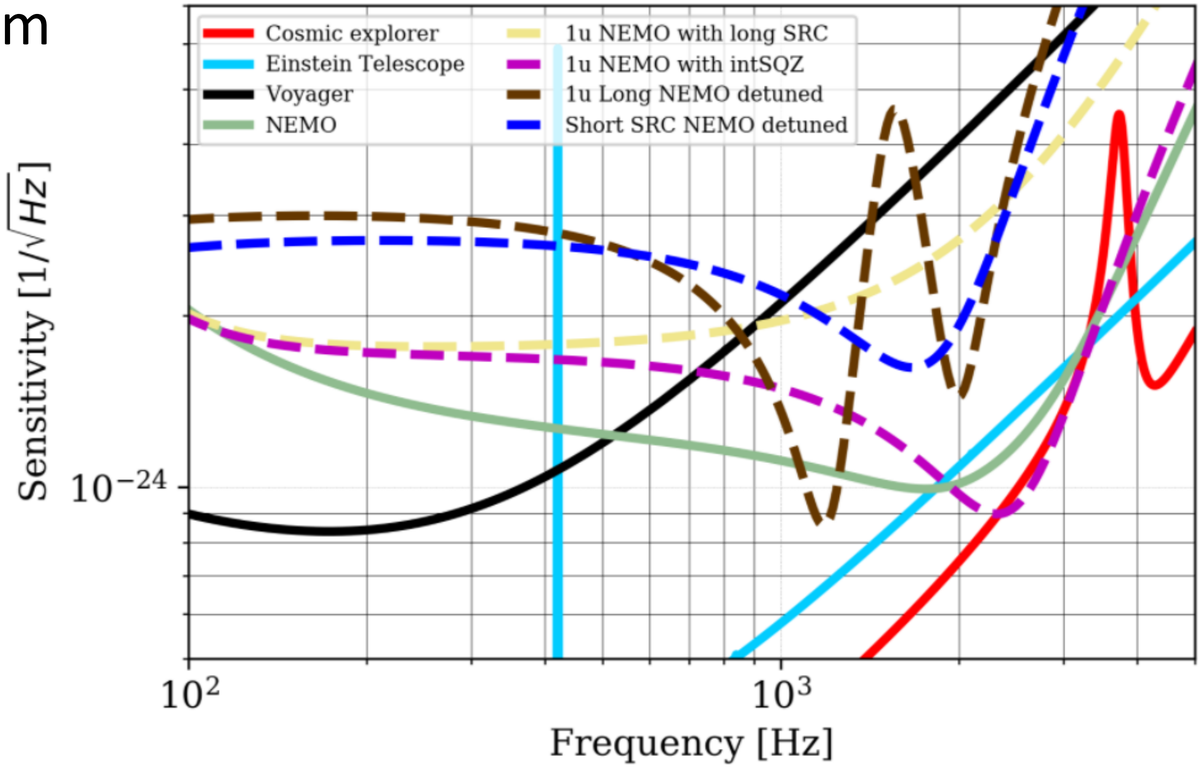
Phys. Rev. D 102, 122003 (2020)

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
- Quantum Tuning
  - Stick with long signal recycling cavity?
  - Detuned signal recycling (long?)
  - Can we use internal squeezing?
- 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: beam splitter material

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

* Statutory warning : Preliminary modelling

KAGRA/OzGrav HF Summary

- Science case-driven target:
  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
- Preliminary design: possible
- New infrastructure in Australia could potentially host Cosmic Explorer South
- Using existing infrastructure would allow network contribution much sooner
- Workshop outcome:
  Joint working group to explore options


“Finding Nemole” by RSboo220, found on deviantart.com

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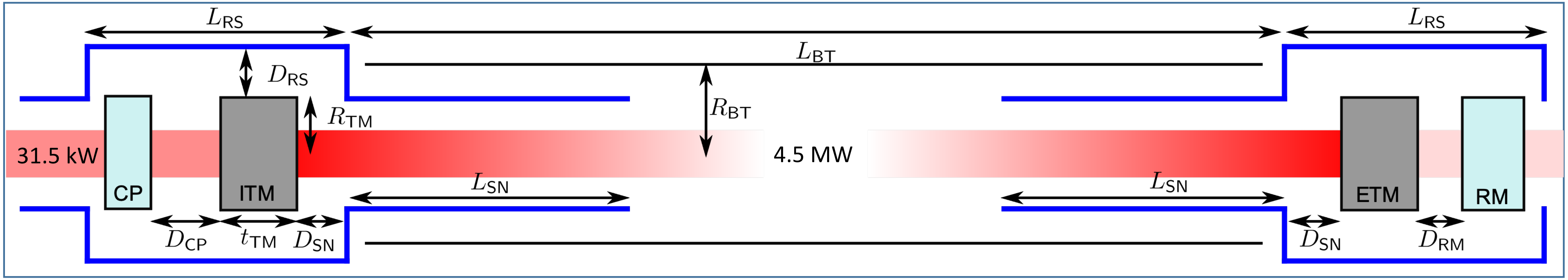
Questions / comments ?

Backup Slides

High Power Thermal Budget



- TM black-body emission at 123 K: 7.8 W
- Estimated real cooling rate at 123 K: 6 W not enough! (ETM heating: 4.5 W, ITM heating: 10.7 W)
- But: HF-approach tolerant to thermal noise
- Increase ITM temperature to 150 K!

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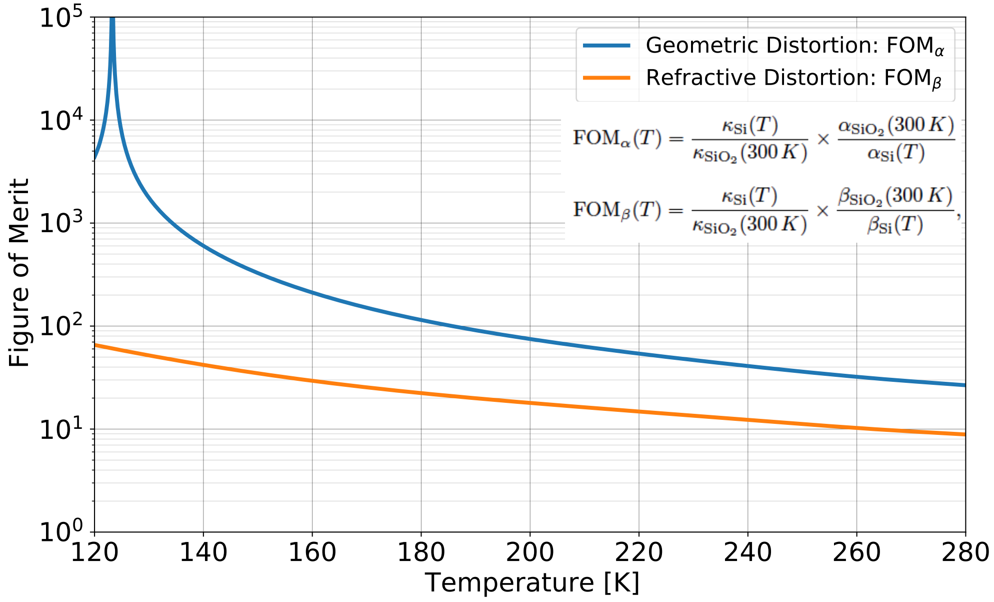
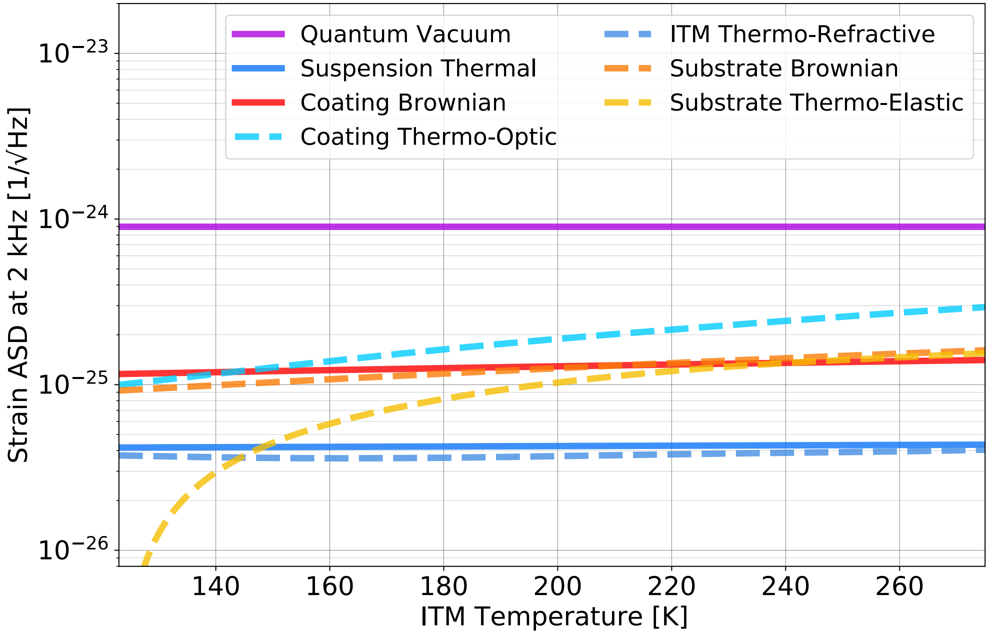
Elevated ITM Temperature Implications

- Point absorber scattering suppressed by FOM_α
- Surface deformation from bulk heating also suppressed by FOM_α
- ITM thermal lensing 'suppressed' FOM_β - but more heat absorbed!
- Best case scenario: 160 ppm round-trip loss
- Thermal noise increase not significant





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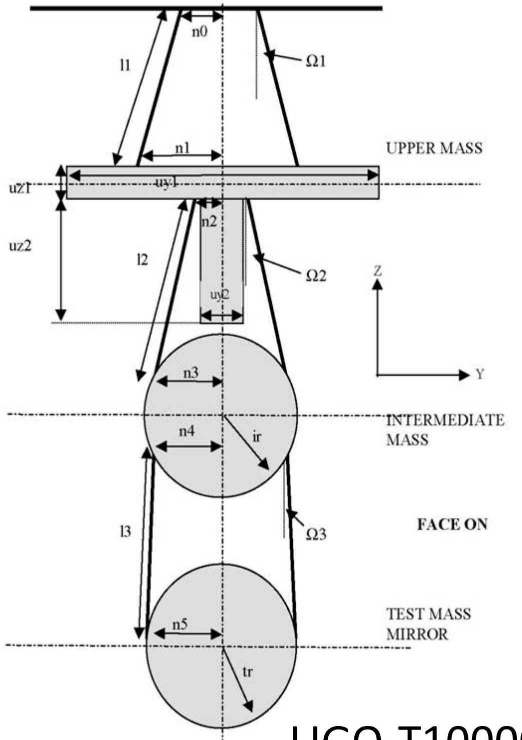
Steel Suspensions

- Minimal pre-isolation
- 3-stage horizontal, 2-stage vertical vibration isolation system
- Steel has high tensile strength such that large diameter wires are not needed
- Silicon ribbons would have better noise, but are more difficult to build



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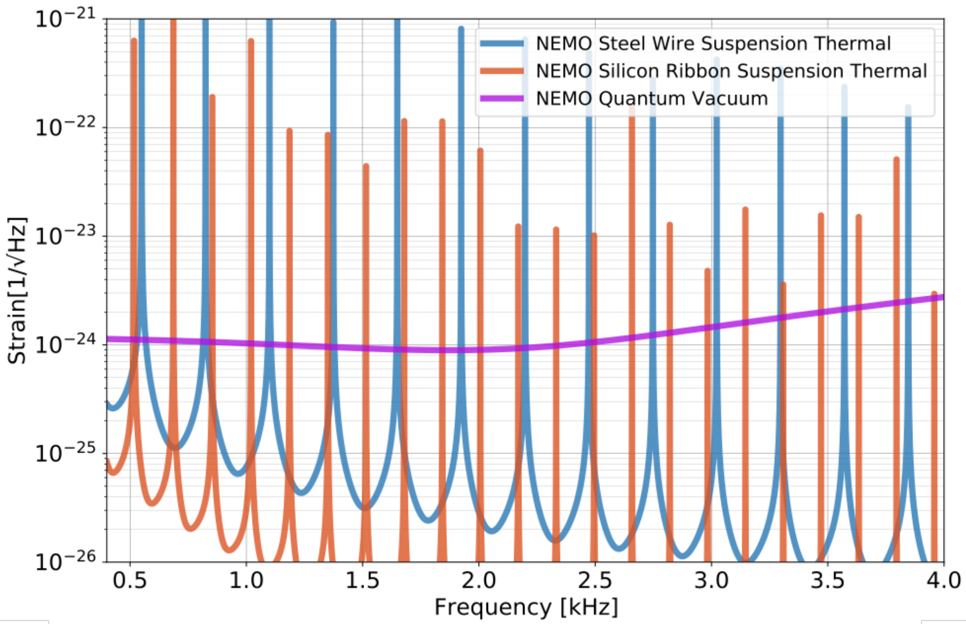

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Search for reference sites

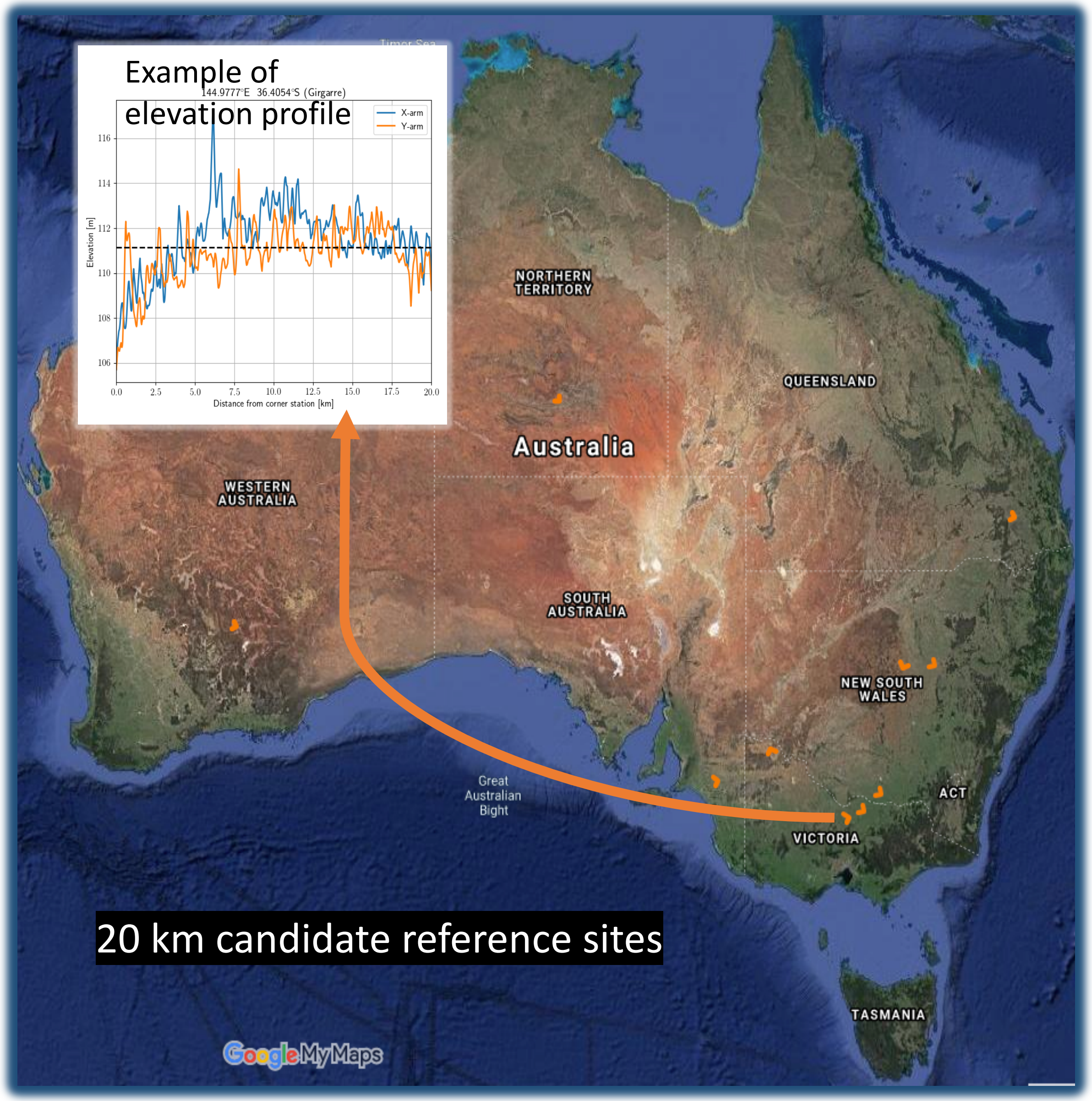
- Only applicable for scenarios where NEMO is transformed into CE-south at the same site (this is hypothetical).
- Focus on potential sites for a CE-south detector as it has far tighter constraints.

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

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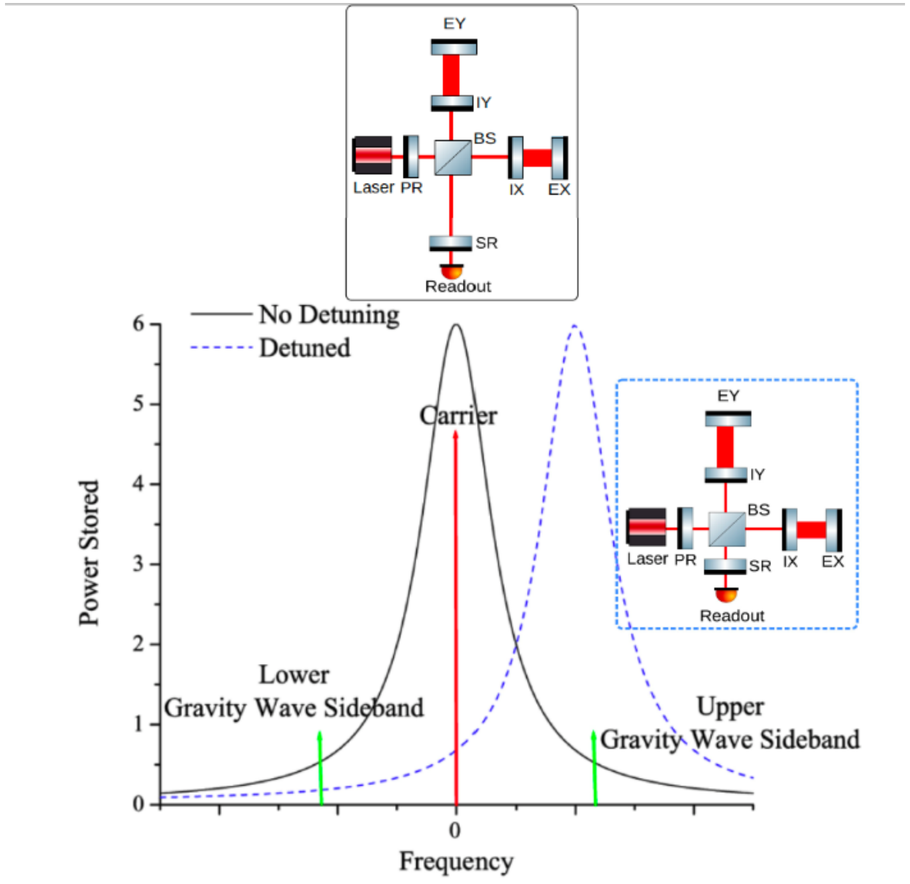
Quantum noise manipulation

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



Additional numbers

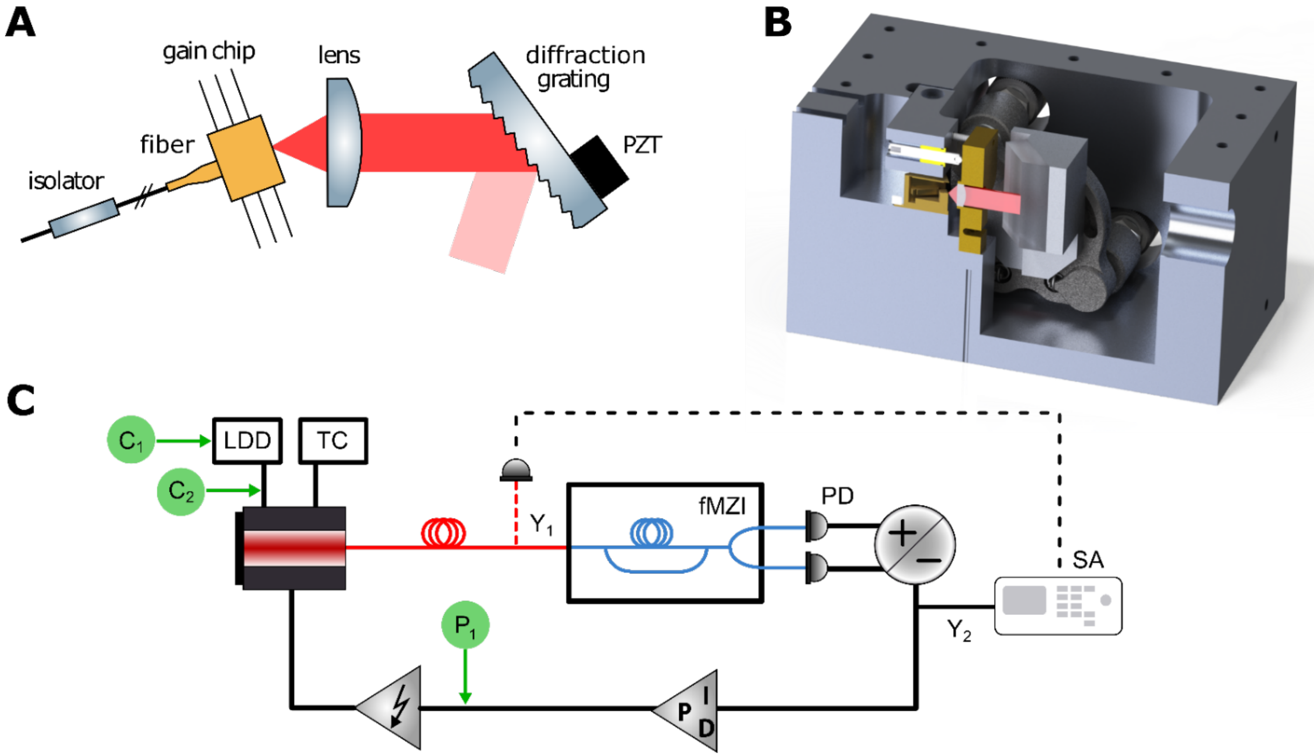
Arm Cavity Loss	40 ppm
ITM substrate absorption	400 ppm
ITM residual thermal lensing and scatter	180 ppm
SRM optical loss	150 ppm
BS optical loss	150 ppm
Total SRC Loss	1500 ppm
Reduction in quantum noise	7 dB

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

Laser Sources

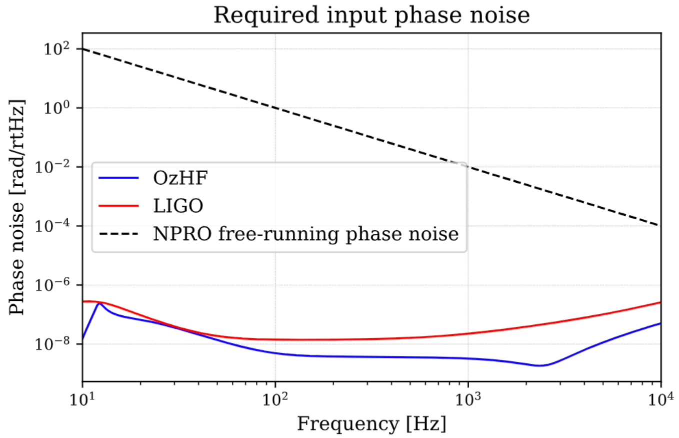
- Requirement : 500 W At 2 µm
- 200 W at 1.06 µm level with near required linewidth demonstrated by MIT LIGO\Lincoln Labs and AEI/LZH in Fiber laser systems
- 500 W with required linewidth not yet demonstrated but Thulium-doped fiber lasers : promising
- External Cavity Diode Lasers at 2 µm : promising

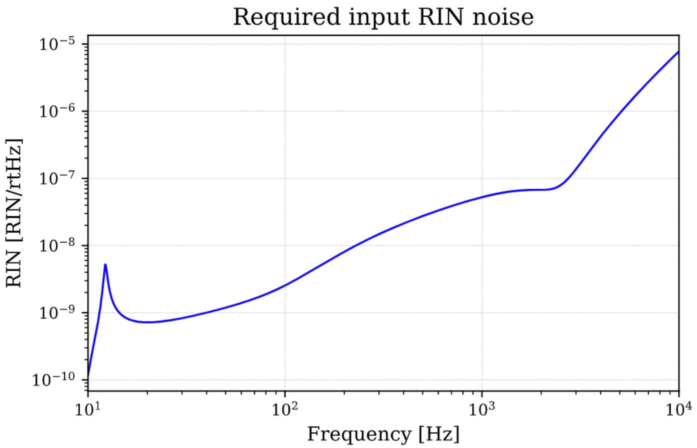


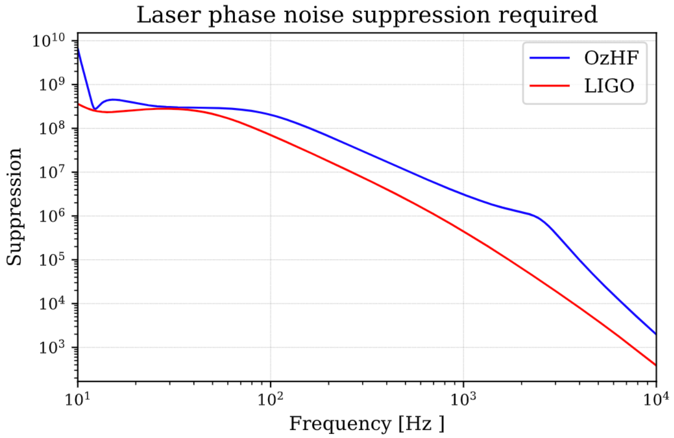
Slide credit : Sebastian Ng, D.Kapasi
2 µm ECDL reference : https://www.osapublishing.org/oe/abstract.cfm?uri=oe-28-3-3280

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.

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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