ET noise budget (2 x L shape)

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Observatory design & noise budaegt WP
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https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

Contents:

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   Quantum noise
   Seismic noise
   Newtonian noise (Common for HF and LF)
   Substrate Brownian noise Substrate thermo-elastic noise
   Coating Brownian noise Coating Thermo-optic noise
   Excess noise
   Suspension thermal noise

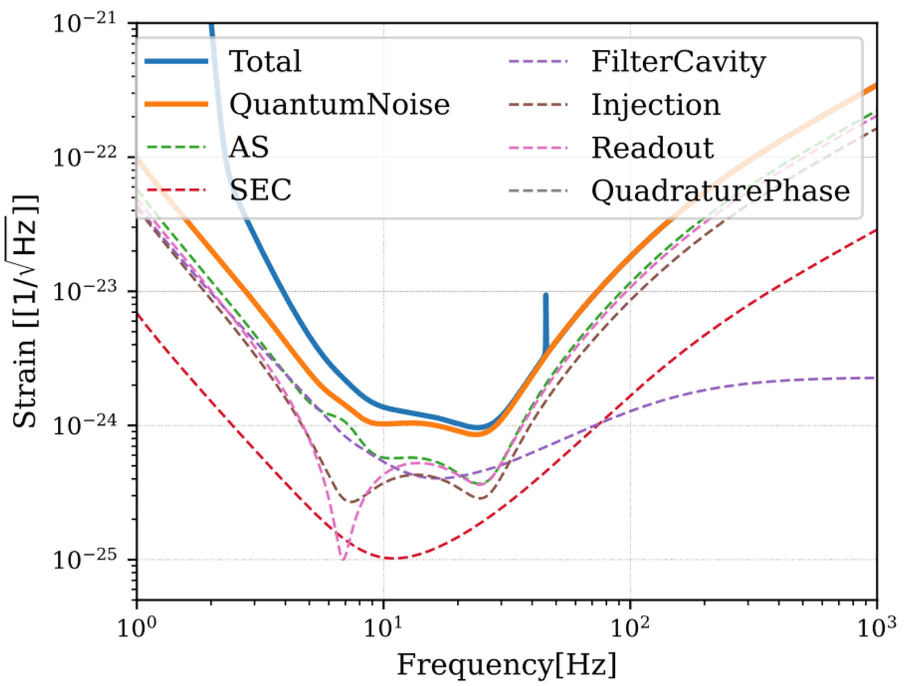
2. Other lengths

ET LF

10km ET LF

Arm length L [km]	10
Laser wavelength λ [nm]	1550
Arm circulating power P_c, [kW]	18
ITM transmissivity, T_{ITM}	0.007
Arm round-trip loss, [ppm]	80
SRM transmissivity, T_{SRM}	0.2
SRC detuning, φ_{SRC} [rad]	0.6
SRC round-trip loss, [ppm]	1000
PD readout loss, [%]	3
Squeezing	
Injected squeezing, r_{dB} [dB]	15
Injection loss, [%]	2
FC1: Length, [km] Transmissivity, Ti Detuning [Hz],	1 1.27e-4 -6.88
Round-trip loss [ppm]	11
FC2: Length, [km] Transmissivity, Ti Detuning [Hz]	1 4.8e-4 25.3
Round-trip loss [ppm]	11

Quantum noise



10km ET LF

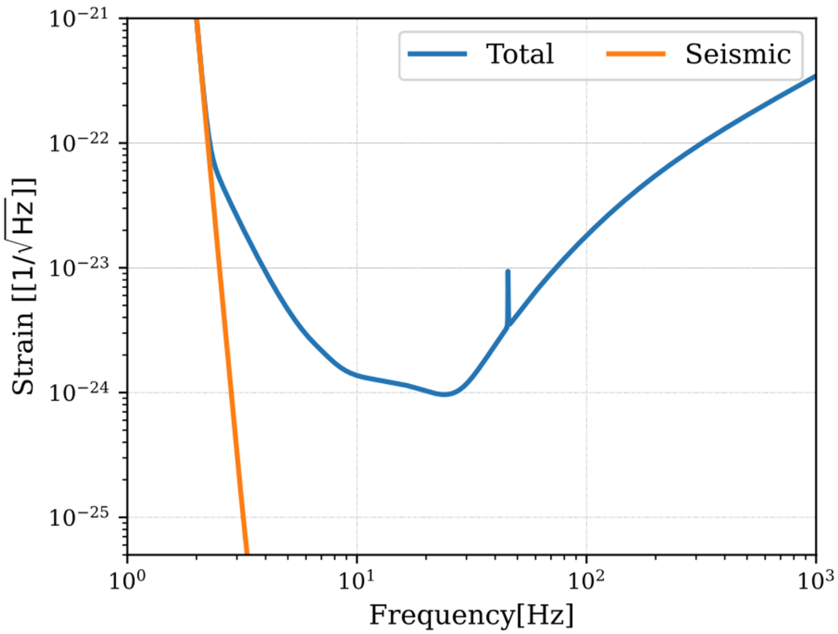
Seismic noise:

Seismic noise is from the coupling of rayleigh wave and body waves through 17m seismic isolation structure in three degrees of freedom (horizontal-horizontal, vertical-to-horizontal, tilt-horizontal)

Bodywaves: 5 times peterson's LNM

Rayleigh waves: Logarithmic average of LNM and HNM.

Suspension TF: Data vector from Lucia Trozzo.



Reference: Rev. Sci. Instrum. 91, 094504 (2020);
https://doi.org/10.1063/5.0018414

10km ET LF

Newtonian noise:

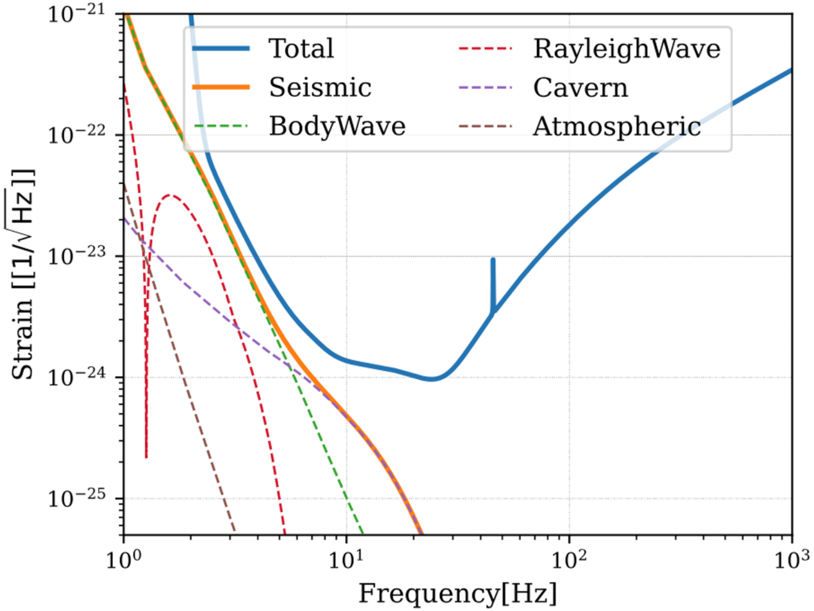
Newtonian noise is modelled as the combination of contribution from Seismic waves (Body waves, Rayleigh waves), Atmospheric noise and Cavern noise. A factor of 3 reduction.

The formulas and acoustic spectrum assumptions are from

Reference: Rev. Sci. Instrum. 91, 094504 (2020); https://doi.org/10.1063/5.0018414

Relevant facility parameters:

300m depth, 15m cavern radius.

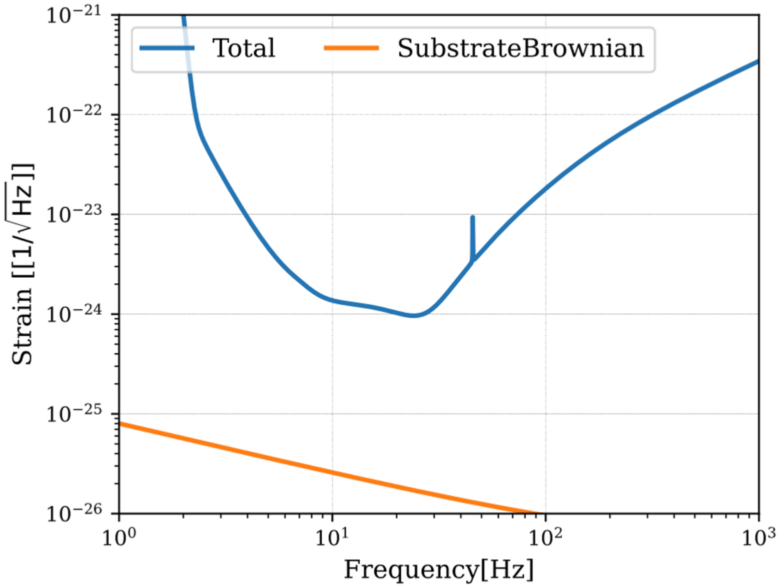


10km ET LF

Substrate Brownian noise:

10k temperature

Material	Silicon
Temperature, [K]	10 K
Young's modulus [Pa]	1.62e11
Poisson's ratio	0.22
Mechanical loss angle	$3e\text{-}13 \cdot f^1$
Mirror Diameter	45cm
Mirror thickness	57cm
Beam size	9cm



Reference:

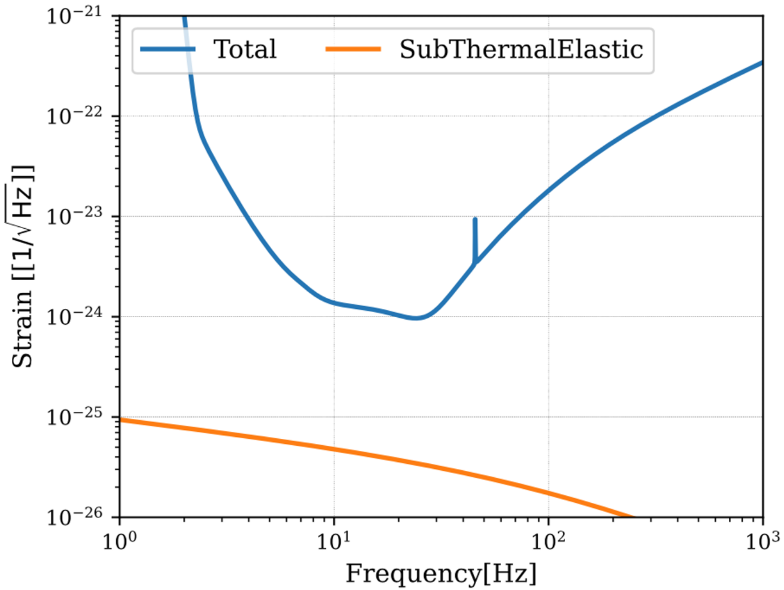
Measured loss ~3e-9 at 10K and at 14kHz. R. Nawrodt *et al.* 2008 J. Phys.: Conf. Ser. **122** 012008

Frequency dependence of the loss: Lam, C. C., & Douglass, D. H. (1981)

10km ET LF

Substrate thermoelastic noise:

Material	Silicon
Specific heat [J·kg^{-1}·K^{-1}]	0.276
Thermal conductivity [W·m^{-1}·K^{-1}]	1000
Thermal expansion coeff [K^{-1}]	4.8e-10
Temperature, [K]	10 K
Mirror Diameter	45 cm
Mirror thickness	57 cm

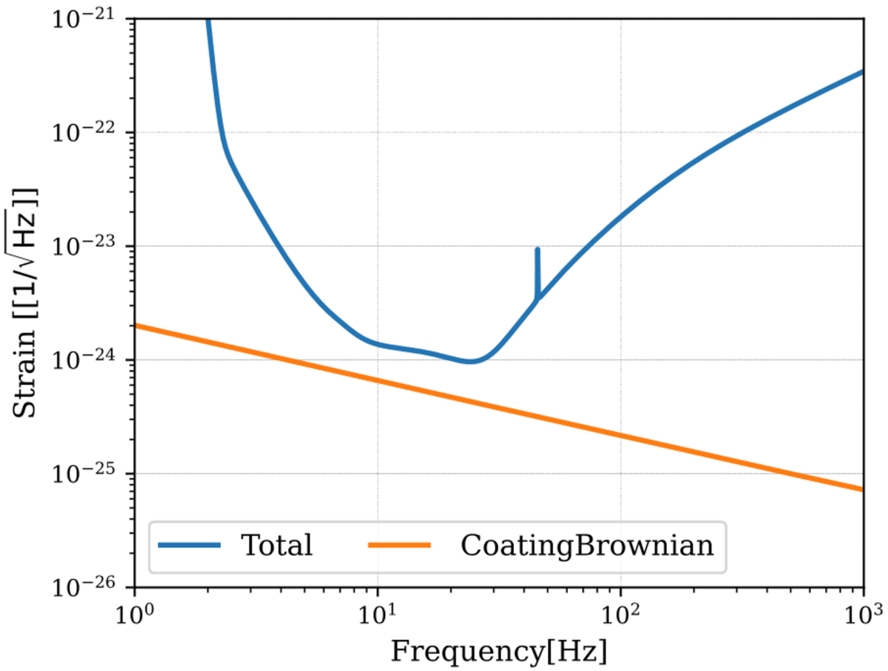


10km ET LF

Coating Brownian noise

Material	Tantala/Silica
Young’s modulus [Pa]	123e9/72e9
Poisson’s ratio	0.28/0.17
Mechanical loss angle	7e-4/5e-4
Temperature, [K]	10 K
Mirror Diameter	45cm
Mirror thickness	57cm

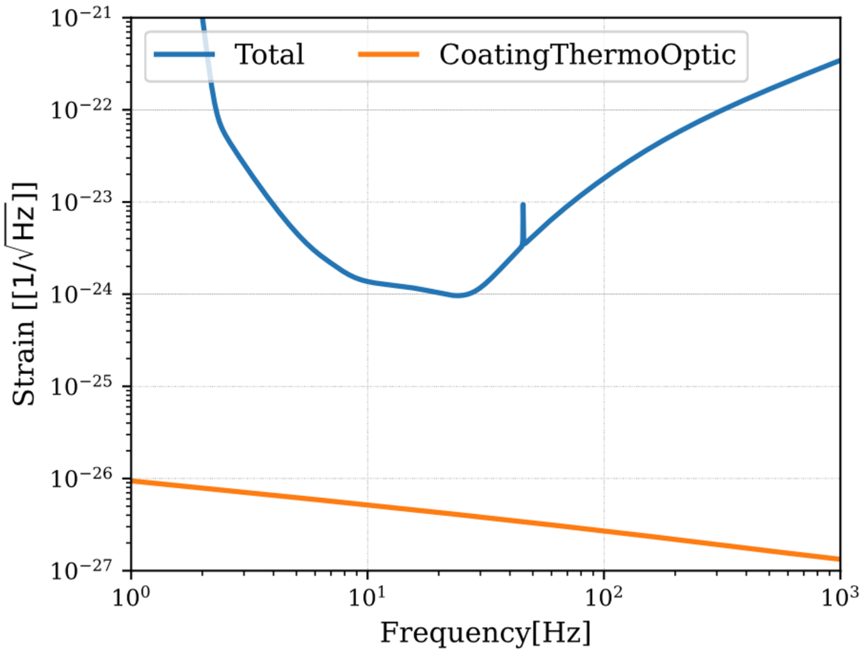
The goal is to include the multi-material coating in https://doi.org/10.1103/PhysRevLett.122.231102, which is currently out of the capability of official GWINC.



10km ET LF

Coating Thermo-optic noise

Material	Tantala/Silica
Thermal expansion coeff [K^{-1}]	3.6e-6/5.1e-7
dn/dT [K^{-1}]	1.4e-5/8e-6
Thermal Diffusivity [m^2/s]	33/1.38



Note: needs check

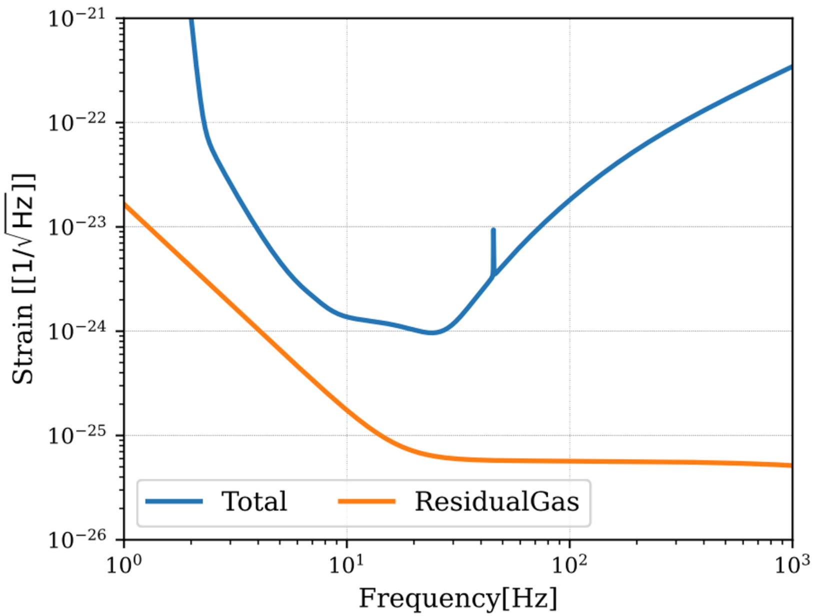
10km ET LF

Excess noise:

The excess noise consists of phase noise and damping noise.

We assume 5e-8 H2. (we expect H2 pressure to be 2e-8 but also some more molecules, like H20, N2, HC(250) etc).

Damping noise is modelled based on Cavalleri's paper: https://doi.org/10.1016/j.physleta.2010.06.041



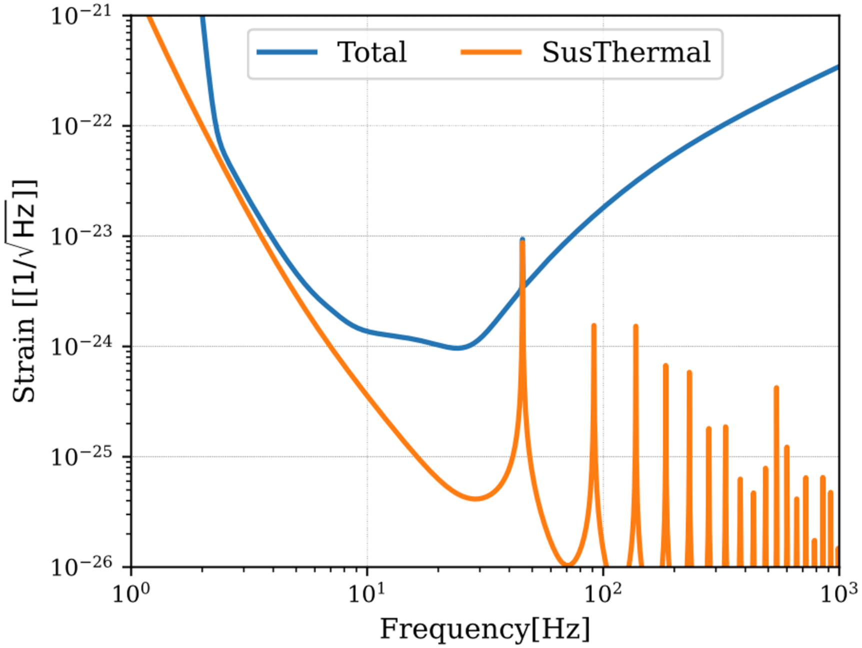
Note : Both different molecules and gas damping noise are bulid-in features in pyGWINC now, we will update in near future

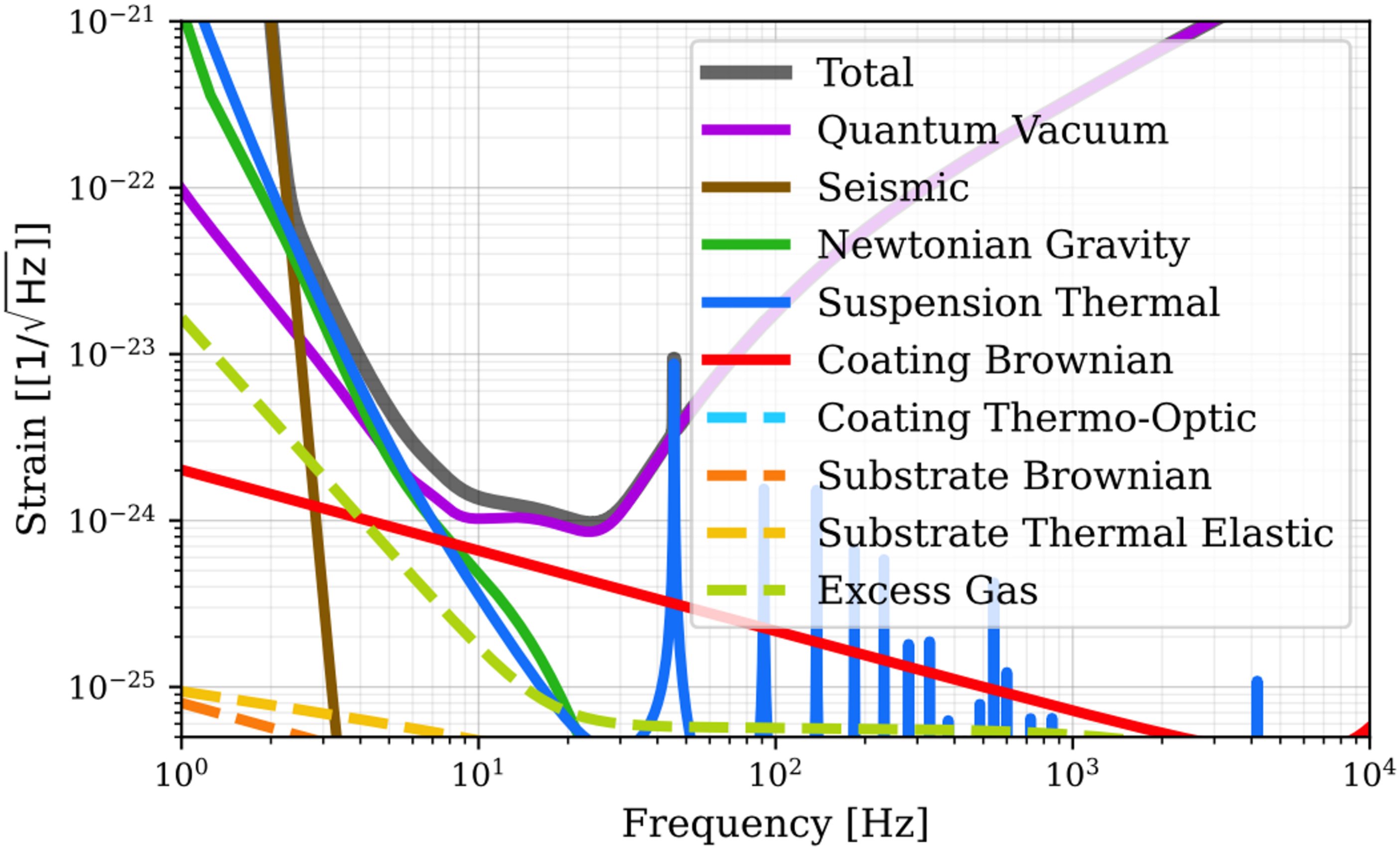
10km ET LF

Suspension thermal noise:

This part is **not accurate** in current noise budget. We adapted the model from Virgo matGWINC, however, we are still investigating the parameters and awaiting for the code to match the ET-D 2011 noise curve.

The material parameters in the model on git are room temperature silica for mirror fiber and Maraging Steel Marionette fiber. We've only noticed this mistake recently and still updating the code.





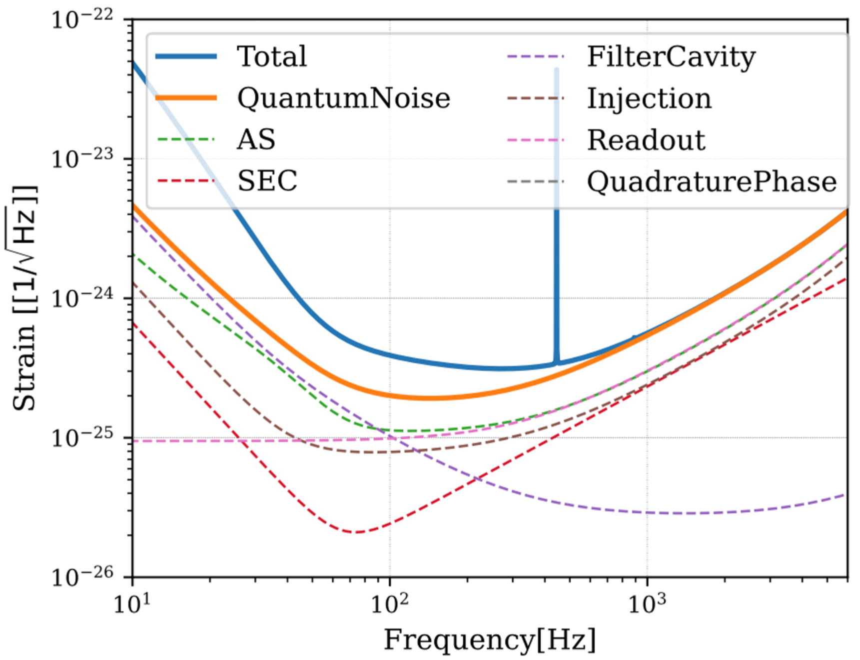
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermal Elastic
Excess Gas
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain $[1/\sqrt{\mathrm{Hz}}]$
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

ET HF

10km ET HF

Arm length L [km]	10
Laser wavelength λ [nm]	1064
Arm circulating power P_c, [kW]	3091
ITM transmissivity, T_{ITM}	0.007
Arm round-trip loss, [ppm]	80
SRM transmissivity, T_{SRM}	0.1
SRC detuning, φ_{SRC} [rad]	0.0
SRC round-trip loss, [ppm]	500
PD readout loss, [%]	3
Squeezing	
Injected squeezing, r_{dB} [dB]	15
Injection loss, [%]	2
FC1: Length, [km] Transmissivity, Ti Detuning [Hz],	0.300 7.7e-4 -30.48
Round-trip loss [ppm]	60

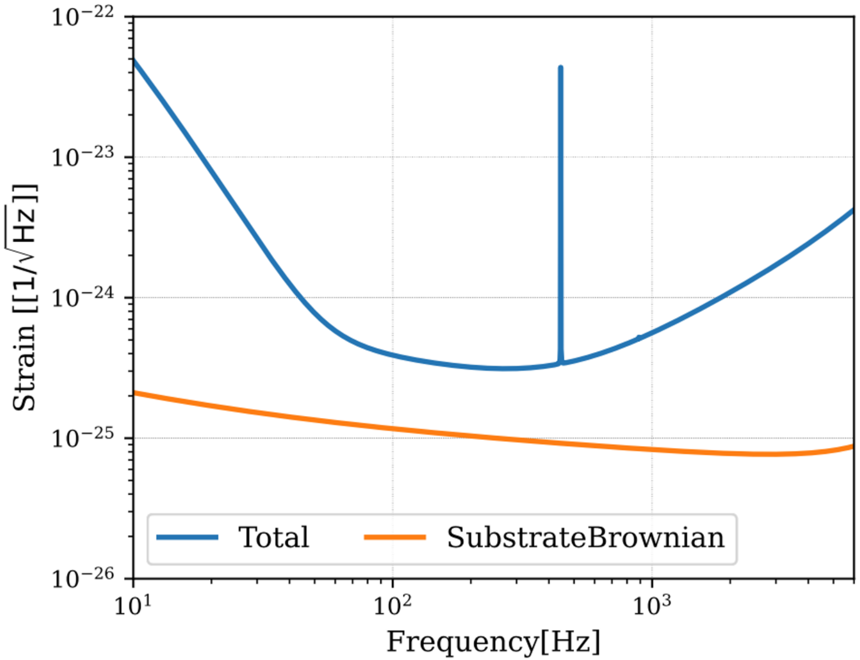
Quantum noise



10km ET HF

Substrate Brownian noise:

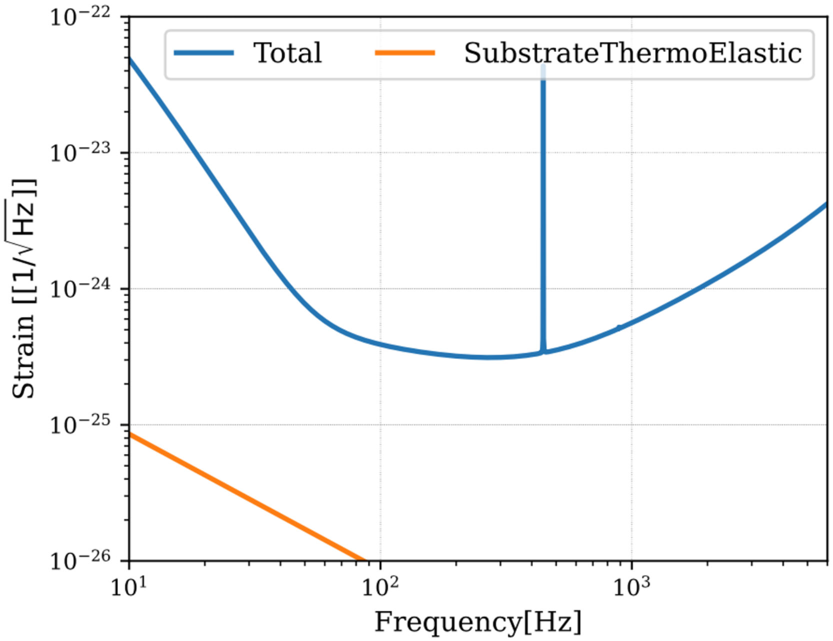
Material	Silica
Temperature, [K]	290 K
Young's modulus [Pa]	7.27e10
Poisson's ratio	0.167
Mechanical loss angle	7.6e-12·$f^{0.77}$
Mirror Diameter	62cm
Mirror thickness	30cm
Beam size	12cm



10km ET HF

Substrate thermoelastic noise:

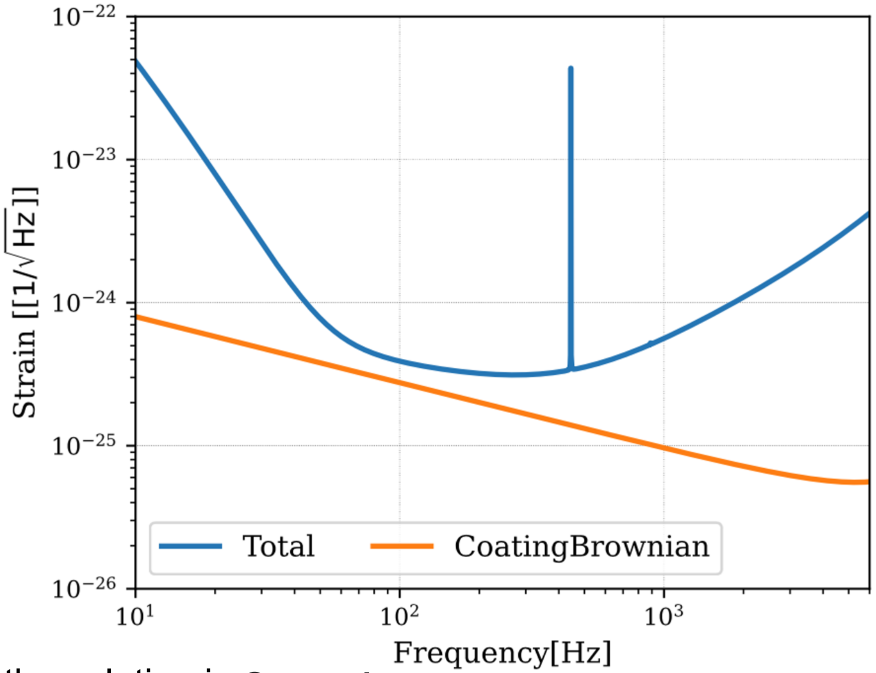
Material	Silicon
Temperature, [K]	290 K
Specific heat [J·kg^{-1}·K^{-1}]	739
Thermal conductivity [W·m^{-1}·K^{-1}]	1.38
Thermal expansion coeff [K^{-1}]	3.9e-7
Mirror Diameter	62 cm
Mirror thickness	30 cm



10km ET HF

Coating Brownian noise

Material	Tantala?/Silica
Temperature, [K]	290 K
Young's modulus [Pa]	120e9/70e9
Poisson's ratio	0.29/0.19
Mechanical loss angle	9e-5/1.25e-4
Mirror Diameter	62cm
Mirror thickness	30cm
Beam size	12cm

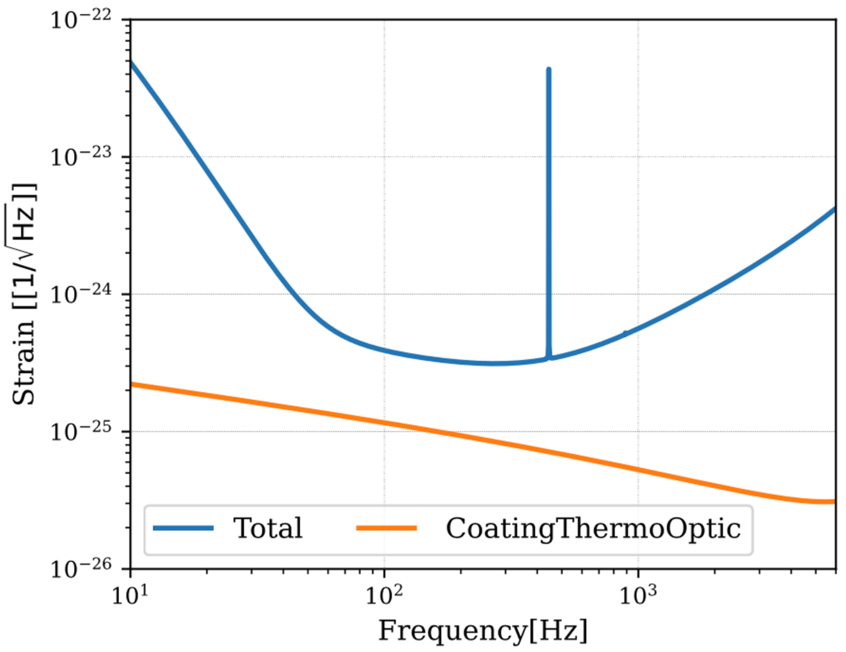


Note: The mechanical loss is assumed A+ coating, the solution is **Germanium dioxide,** https://doi.org/10.1103/PhysRevLett.127.071101 , we have not update the exact parameters of GeO2 for ET.

10km ET HF

Coating Thermo-optic noise

Material	Tantala?/Silica
Thermal expansion coeff [K^{-1}]	3.6e-6/5.1e-7
dn/dT [K^{-1}]	1.4e-5/8e-6
Thermal Diffusivity [m^2/s]	33/1.38



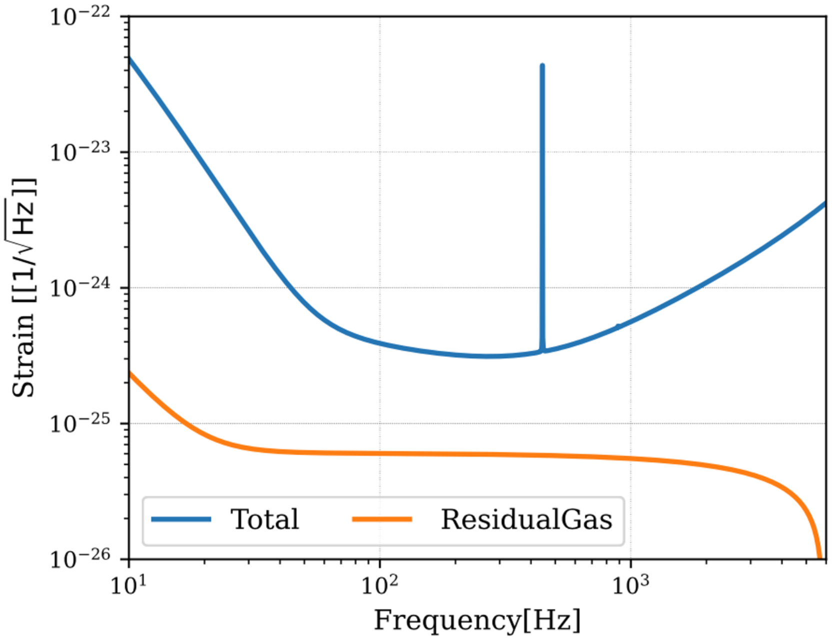
10km ET HF

Excess noise:

The excess noise consists of phase noise and damping noise.

We assume 5e-8 H2. (we expect H2 less than this pressure but some more molecules, like H20, HC(250) etc).

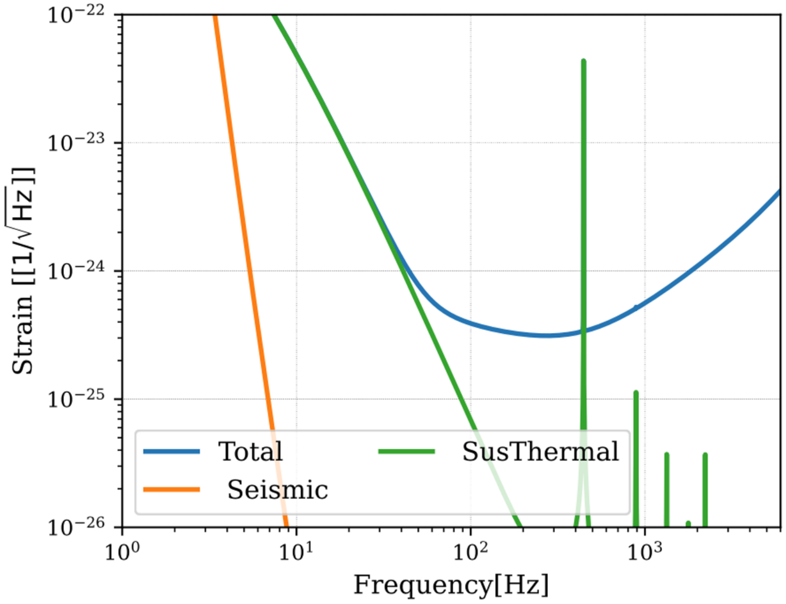
Damping noise is modelled based on Cavalleri's paper:
https://doi.org/10.1016/j.physleta.2010.06.041

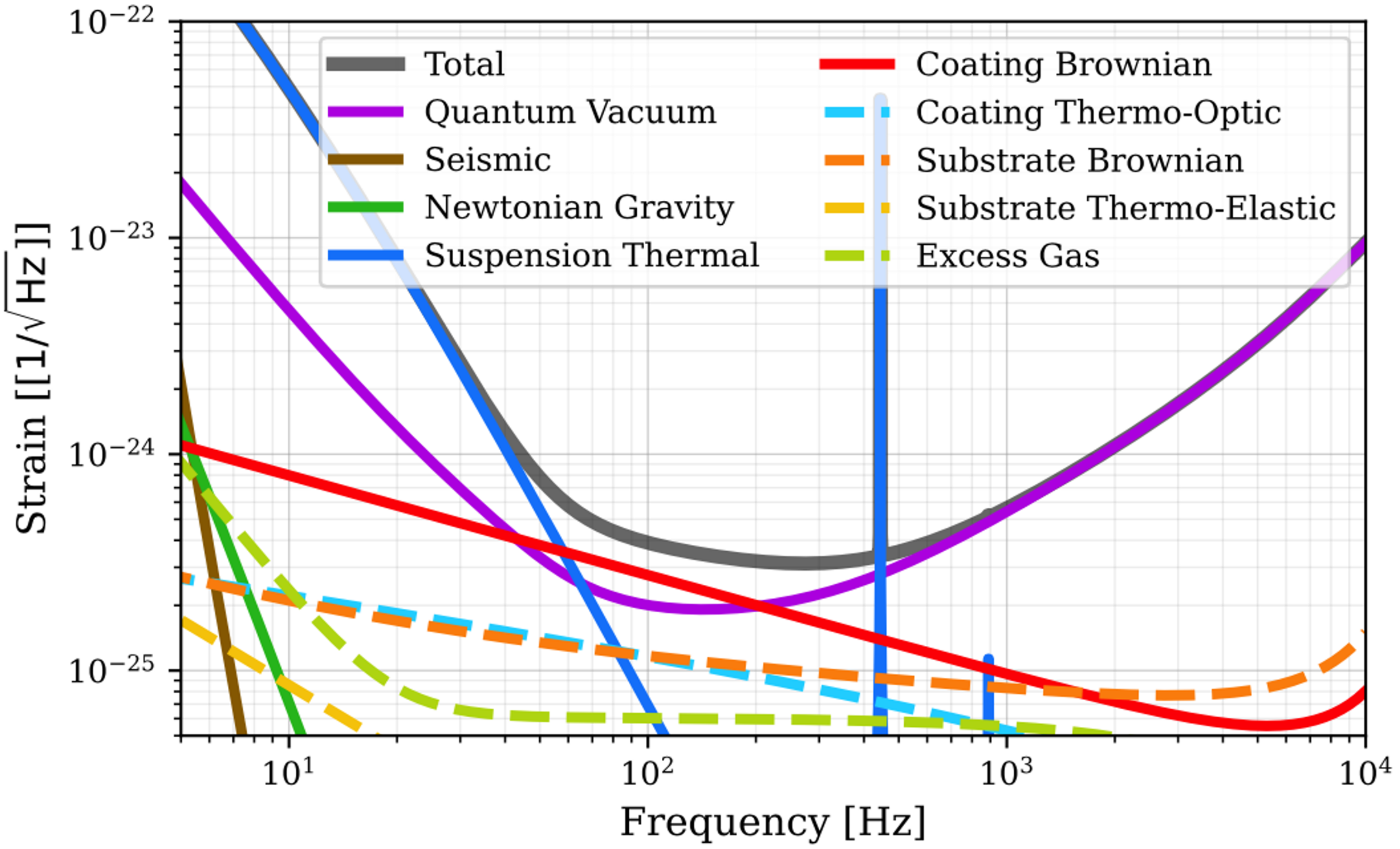


10km ET HF

Seismic & Suspension thermal noise:

The two parts are **not very accurate** in current noise budget. The seismic waves are not assumed and suspension TF are not as accurate as LF, but extracted automatically from GWINC. The suspension thermal noise is also under investigation.





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^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}
10^{4}

Other lengths

One set of parameter choice (Reference)

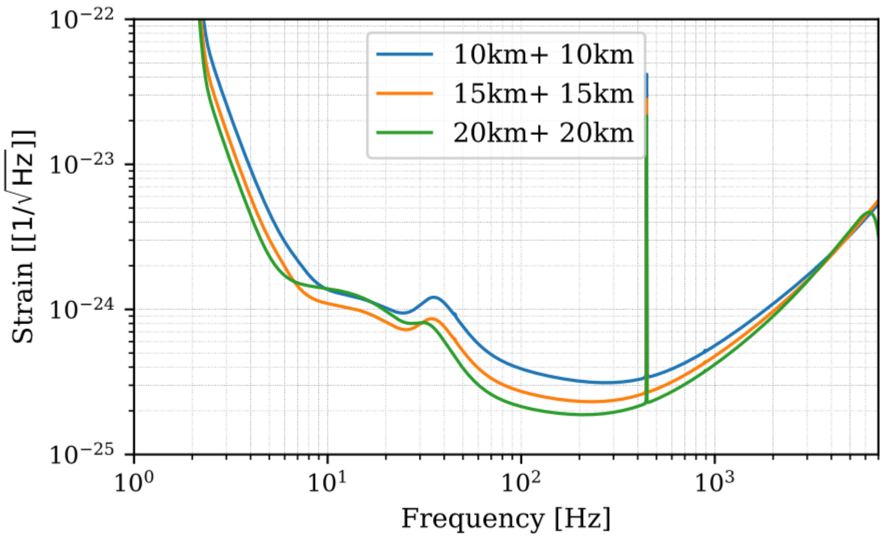
ETHF (1064 nm, 200kg)	10km	15km	20km
Bandwidth	320Hz	310Hz	325Hz
SRM transmissivity	0.1	0.07	0.05
Beam size	12cm (g=0.94)	12cm (g=0.88)	12cm (g=0.78)
Mirror diameter	62cm	62cm	62cm

ETLF (1550 nm, 200kg)	10km	15km	20km
Bandwidth	150Hz	150Hz	150Hz
SRM transmissivity	0.2	0.135	0.105
Detuned frequency	25Hz	25Hz	25Hz
Detuned phase	0.6	0.4	0.3
Beam size	9cm (g=0.63)	9cm (g=0.17)	10cm (g=0.06), 40ppm clipping loss
Mirror diameter	45cm	45cm	45cm

Shot noise $\propto L^{-1/2}$
Radiation pressure noise $\propto L^{-3/2}$
Displacement noise $\sim \propto L^{-1}$

Reference

Except for longer arms, suspension vertical coupling increase,
mirror thermal noise also slightly effected by different mirror Geometry.



20km LF either suffers high clipping loss or unstable arm cavity.

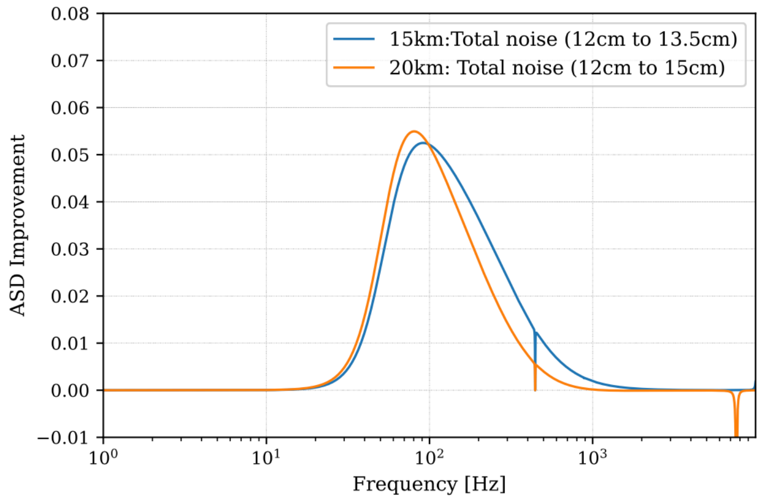
Assuming the input power same, only 10kw arm power left).

20km LF is not desired with 45cm mirror.

ET HF

Alternative choice: Larger beam size

ETHF (1064 nm, 200kg)	10km	15km	20km
Beam size	12cm	13.5cm	15cm
Mirror diameter	62cm	68cm	75cm
Thickness	30cm	25cm	21cm

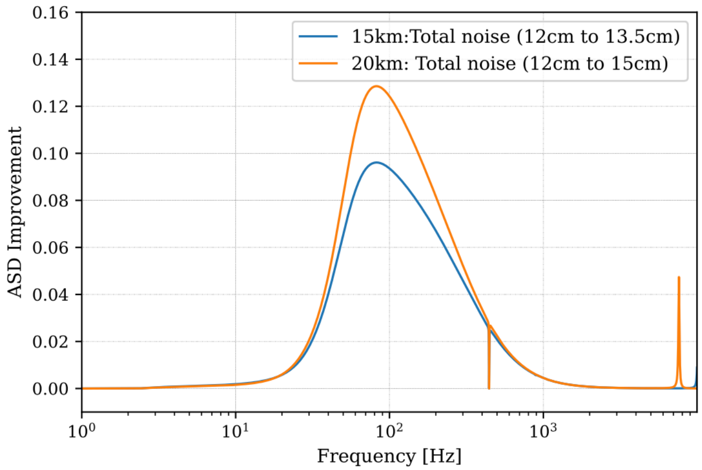


Worse aspect ratio!

Not good for mirror thermal noise, too.

Alternative choice: Larger beam size& 320kg mirror

ETHF (1064 nm, 320kg)	10km	15km	20km
Beam size	12cm	13.5cm	15cm
Mirror diameter	62cm	68cm	75cm
Thickness	48cm	40cm	33cm



15km case corresponds to optimal aspect ratio

Assuming the suspension thermal noise and TF the same.

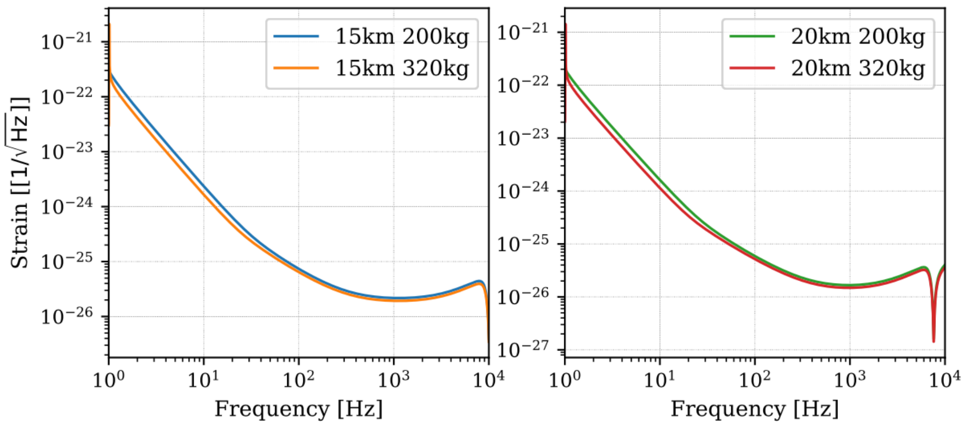
Larger mirror gives ~10% sensitivity improvement.

Longer arm prefers heavier mirror.

Alternative choice: Larger beam size& 320kg mirror

ETHF (1064 nm, 320kg)	10km	15km	20km
Beam size	12cm	13.5cm	15cm
Mirror diameter	62cm	68cm	75cm
Thickness	48cm	40cm	33cm

Can the filter cavity requirement be relaxed?



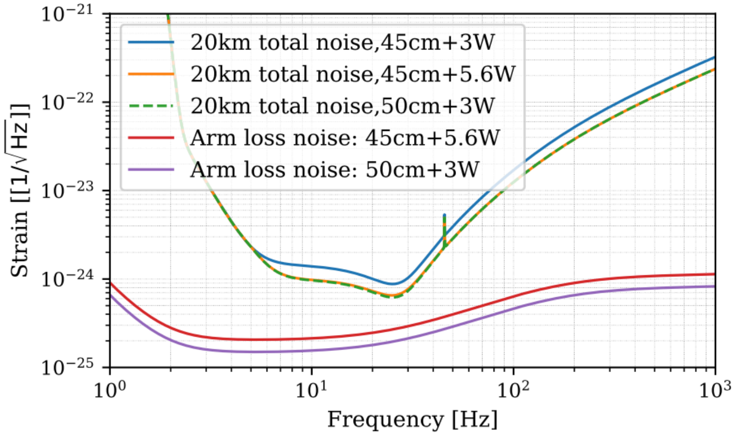
Filter cavity loss contamination is very slightly reduced.

Other impacts except on noises?

ET LF

Alternative choice: Larger mirror for 20km/ higher input power

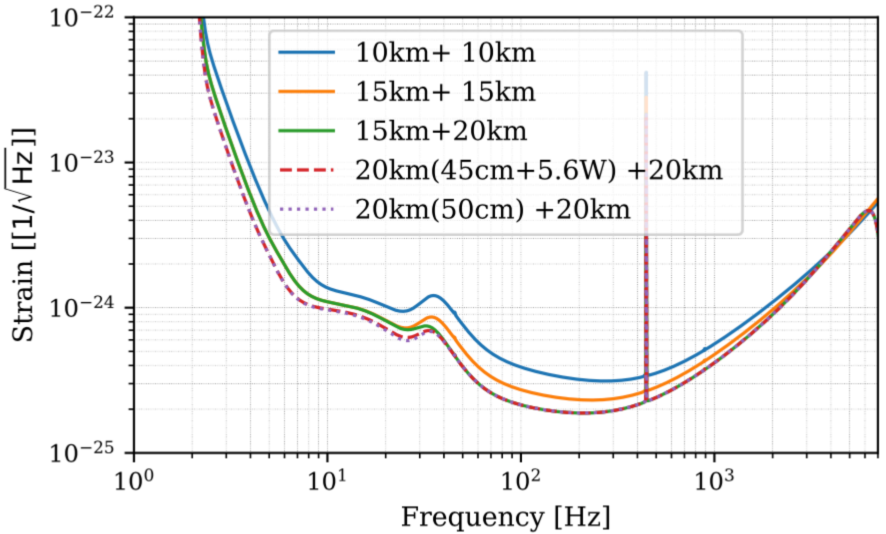
ETLF (1550nm)	20km(211kg)	20km(260kg)
Beam size	10cm (g=0.06), 40ppm clipping loss	10cm (g=0.06)
Mirror diameter	45cm	50cm
Thickness	57cm	57cm

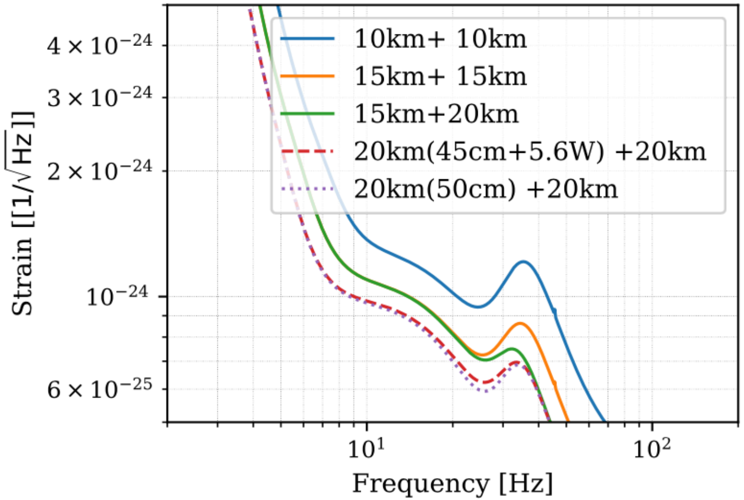


Arm cavity less important contribution is less important in the total noise.

ETHF+LF

Overall sensitivity estimation





Note:
The HF and LF suspension thermal noises are not meant to be the final version.

290k LF

Here we assume LF suspension at room temperature for both 290k LF and single HF.
We assume silica mirror and 12cm beam size for 290k LF, which is the case of HF.

10km