Noise budget

vs

Wavelength

Observatory design & Noise budget working package

ET wavelength workshop

2021.09.16

Wavelength impact

Direct:

Quantum noise
- Shot noise $\propto \lambda$
- Radiation pressure noise $\propto 1/\lambda$
- Optical losses

Indirect:

Substrate material
- Substrate Brownian noise
- Substrate Thermoelastic noise

Coating material

Residual gas noise: Cavity Geometry

Quantum noise

Assumption:

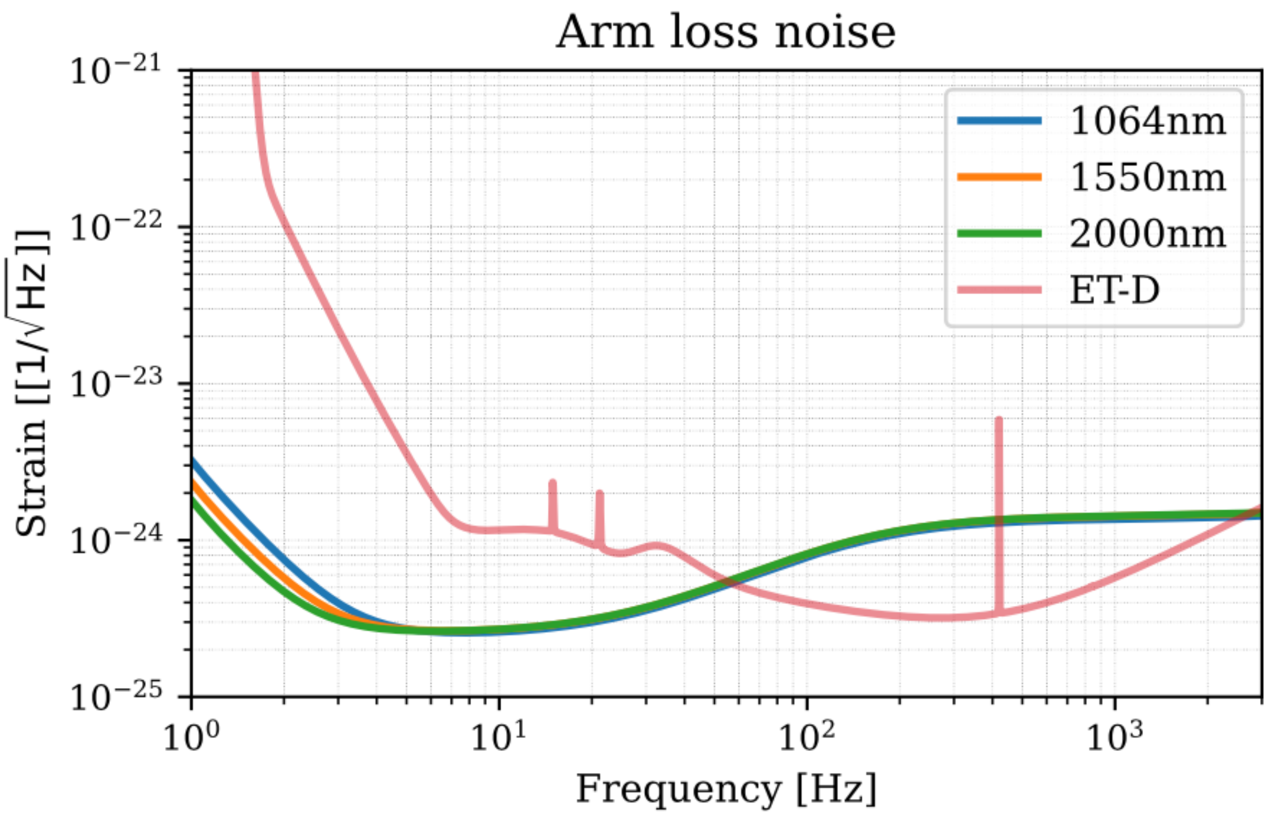
- Arm power 18kW for three cases.
- Test mass 200kg for three cases.
- 15dB injection Squeezing for three cases.
- 10km long filter cavity for three cases.
- Optical losses:

	Arm m RT L	Filter Cav RT L	PD E
1064nm	75ppm	150ppm	0.97
1550nm	55ppm	75ppm	0.97
2000nm	40ppm	45ppm	0.92

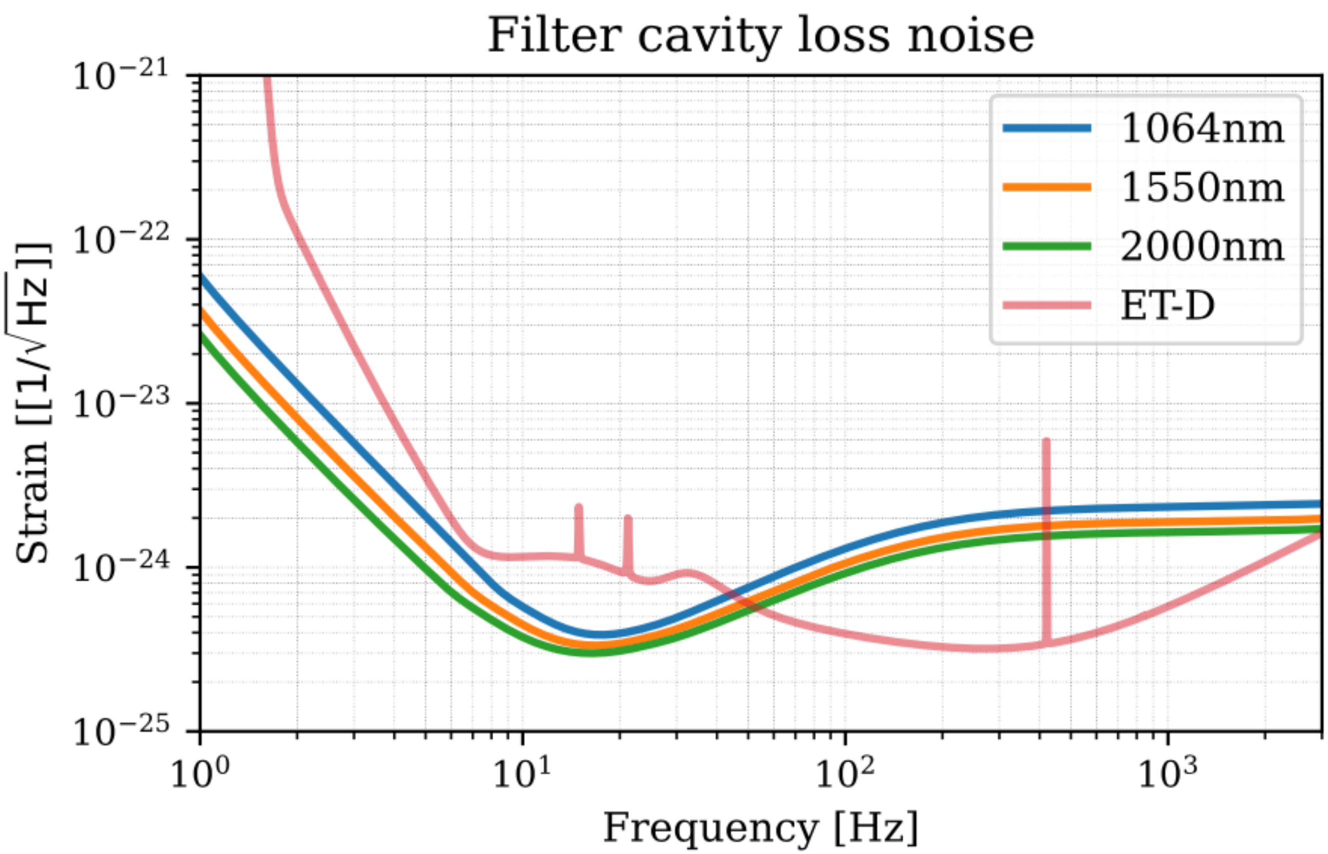
Light scattering

$$\mathcal{L} = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

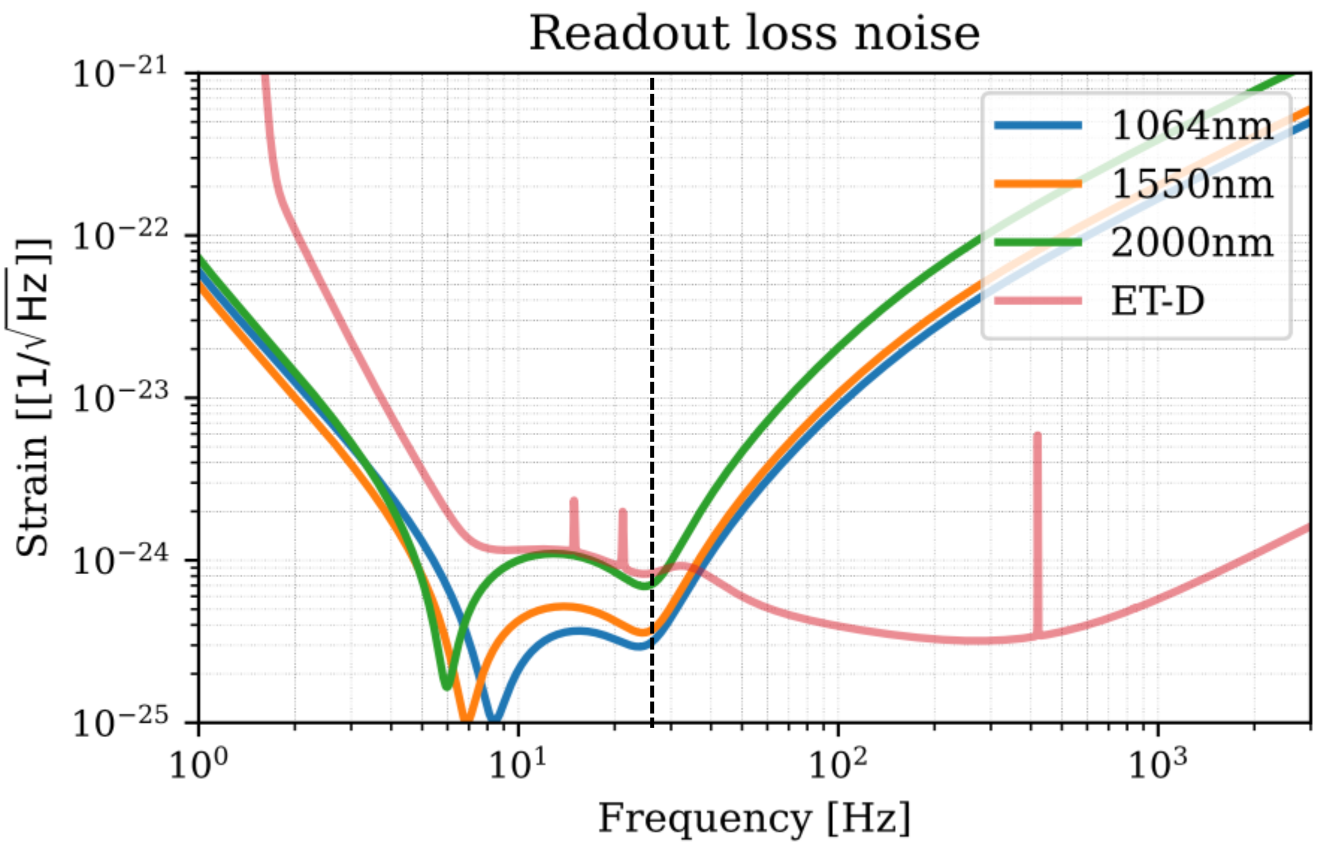
10 ppm loss per mirror for arm cavity is added as a margin for losses from absorption, clipping, etc.
PD efficiency imperfection is for readout loss.



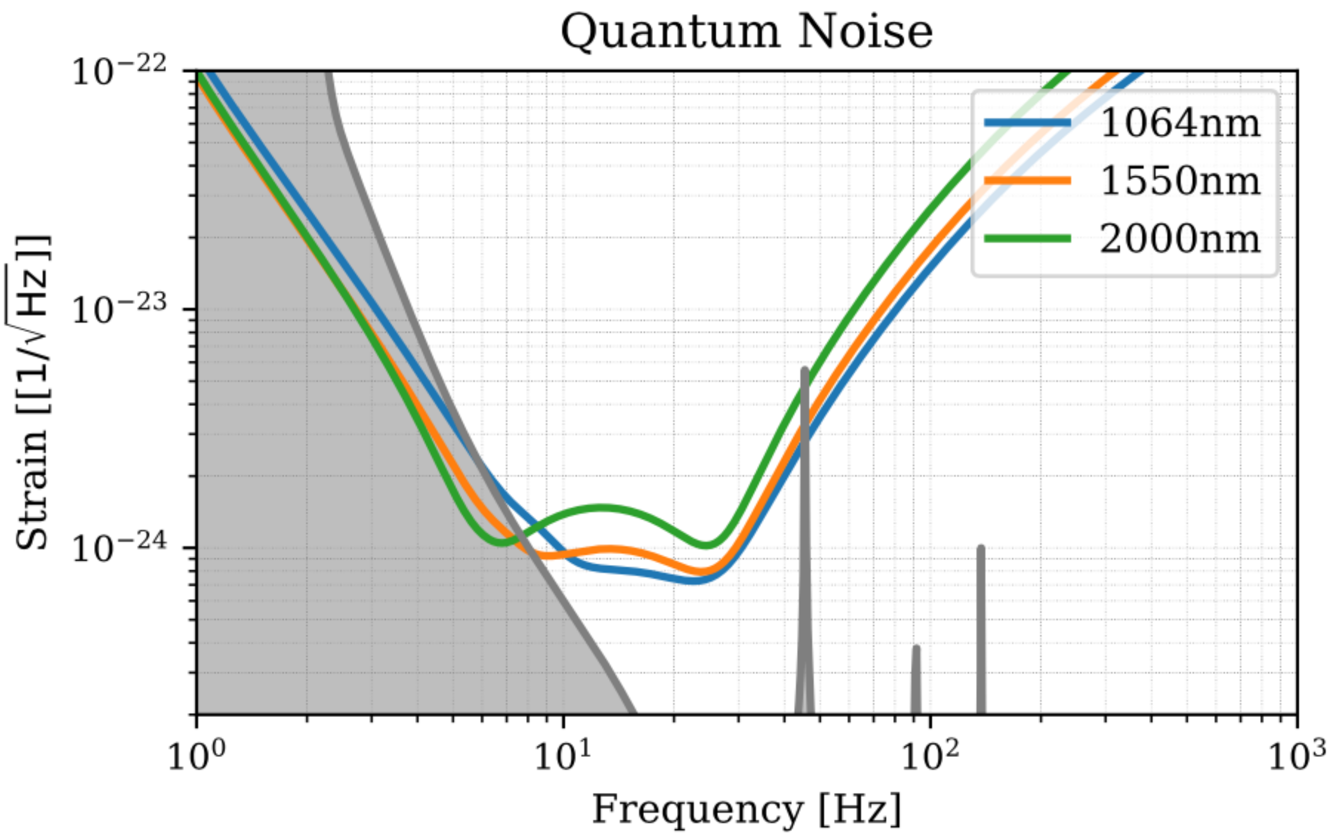
The overlap of high frequency shot noise comes from the compensation between loss coefficient and scaling $1/\lambda$.



Longer wavelength gives lower loss.



The SRC is detuned to give identical optical resonant frequency. 92% PD efficiency is assumed for 2000nm.



The sum of seismic, Newtonian and suspension thermal noise@10K is set to be the low frequency barrier.

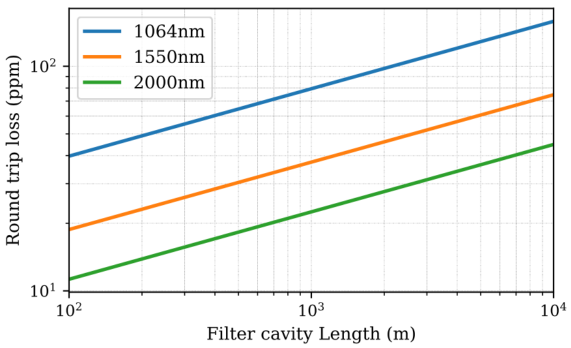
Quantum noise

1km filter cavity length

Assumption:

- Arm power 18kW for three cases.
- Test mass 200kg for three cases.
- 15dB injection Squeezing for three cases.
- **1km** long filter cavity for three cases.
- Optical losses:

M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao. Phys. Rev. D **88**, 022002



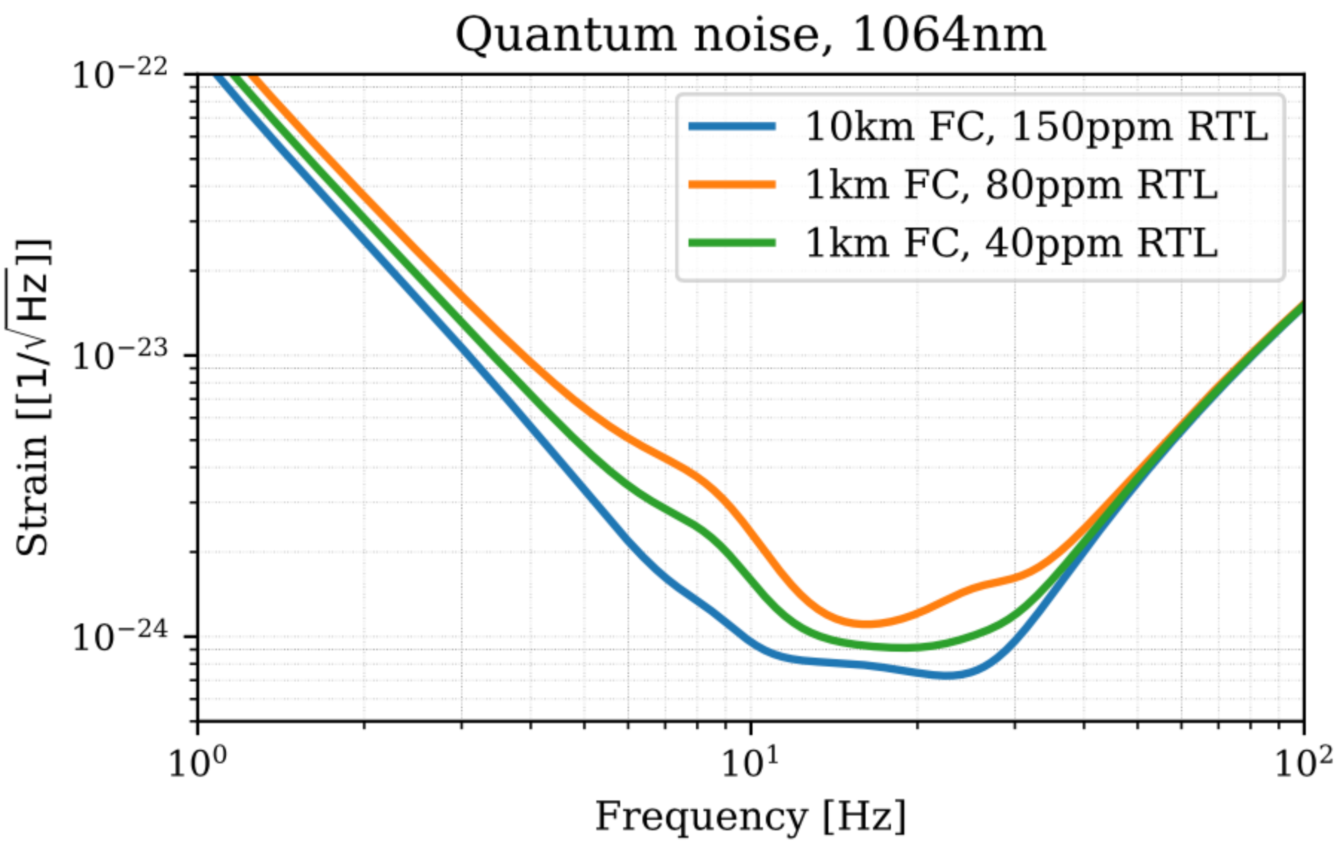
	Arm m RT L	**Filter Cav RT L**	**PD E**
1064nm	75ppm	**80ppm/40ppm**	0.97
1550nm	55ppm	**40ppm/20ppm**	0.97
2000nm	40ppm	**23ppm/12ppm**	0.92

Light scattering

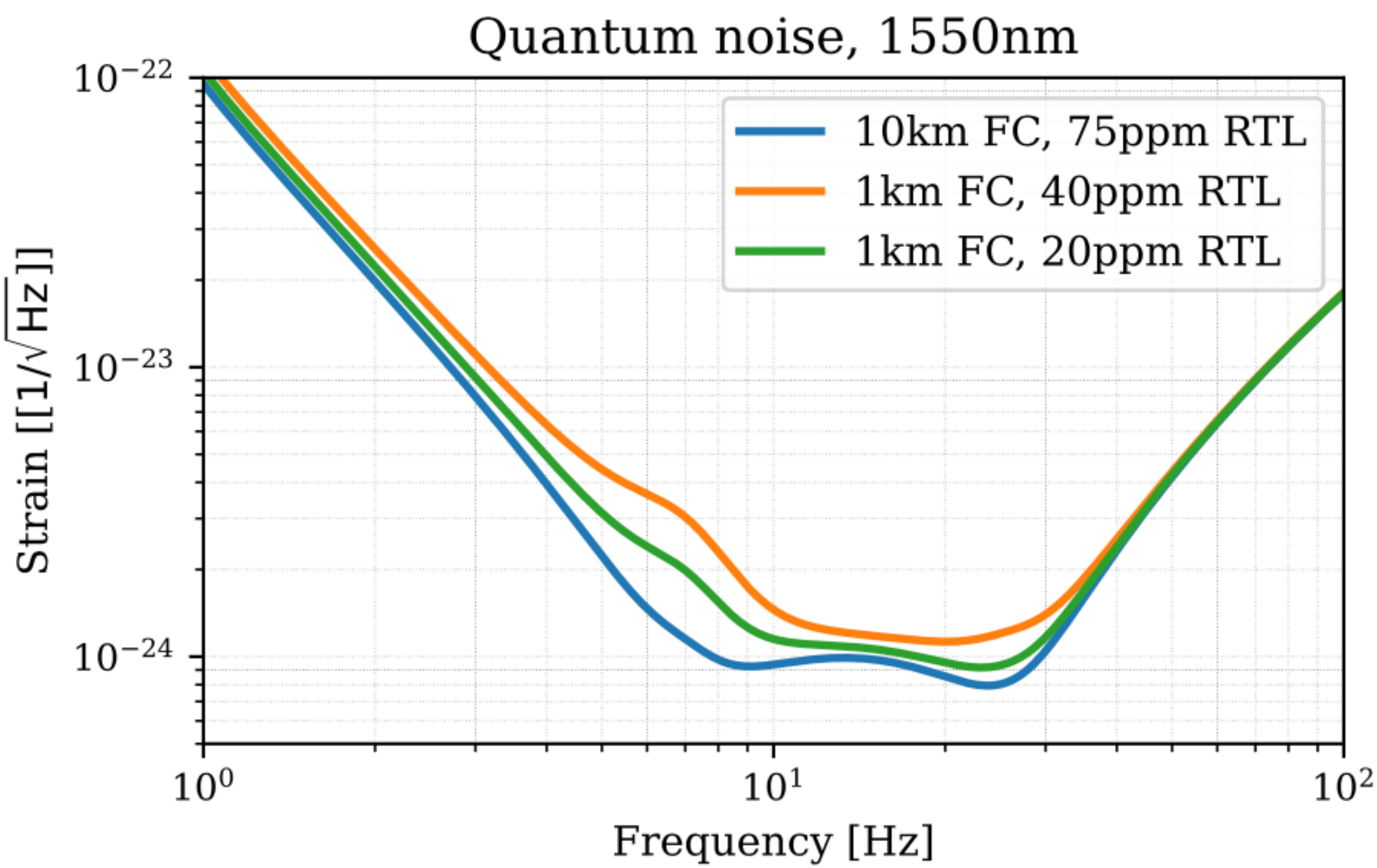
$$\mathcal{L} = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

10 ppm loss per mirror for arm cavity is added as a margin for losses from absorption, clipping, etc.
PD efficiency imperfection is for readout loss.

1064nm

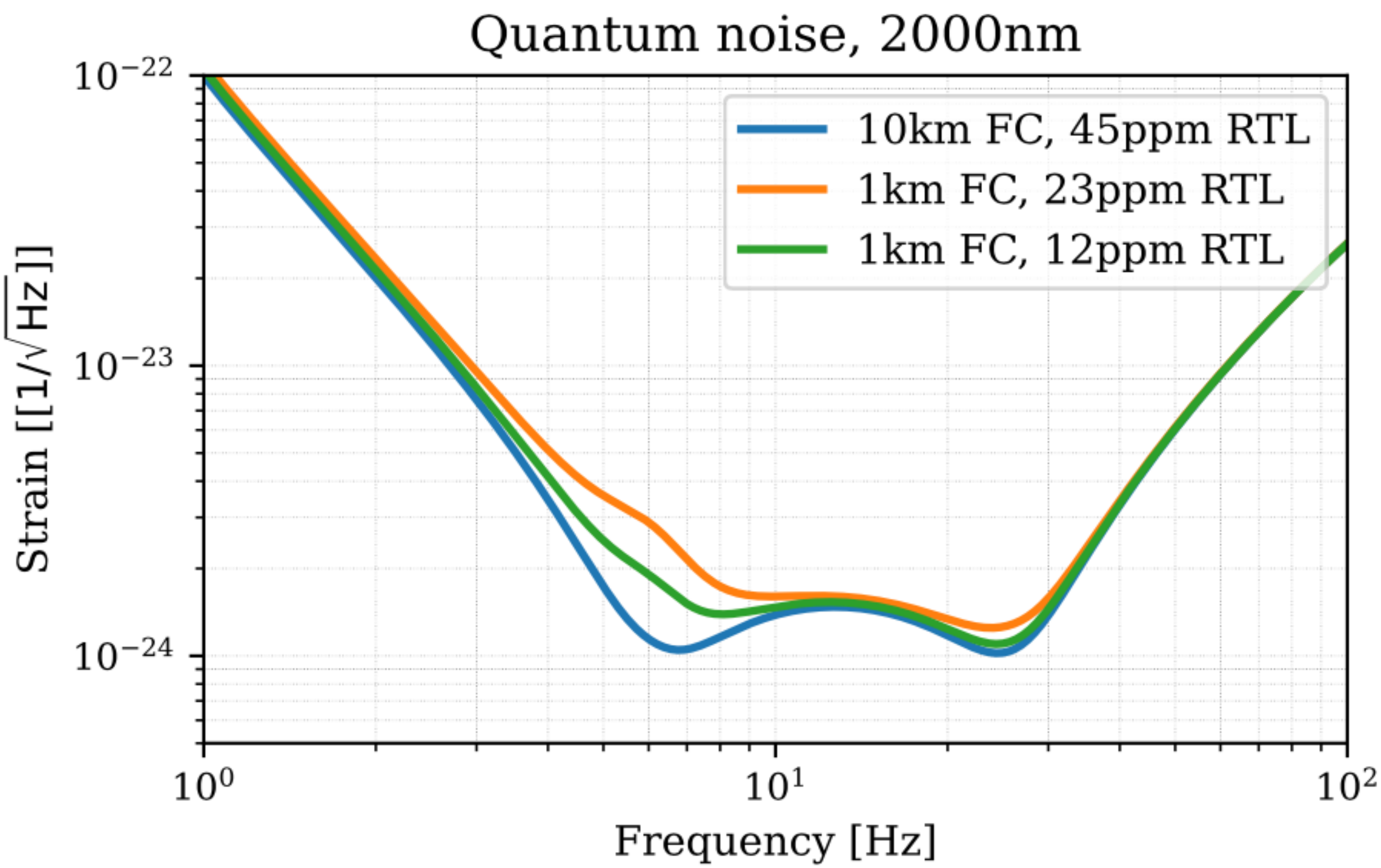

Quantum noise, 1064nm
10km FC, 150ppm RTL
1km FC, 80ppm RTL
1km FC, 40ppm RTL
Strain [[1/√Hz]]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}

1550nm



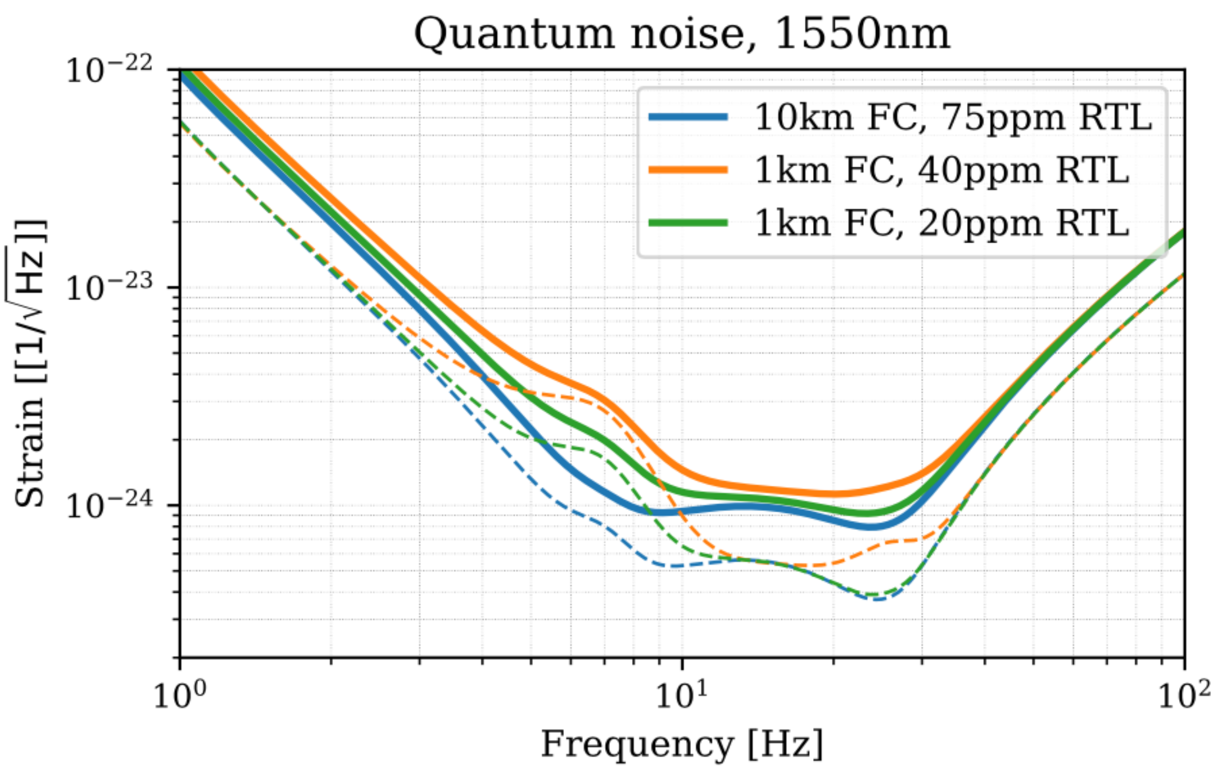
Quantum noise, 1550nm
Strain [[1/√Hz]]
10−22
10−23
10−24
10km FC, 75ppm RTL
1km FC, 40ppm RTL
1km FC, 20ppm RTL
10⁰
10¹
10²
Frequency [Hz]

2000nm



Quantum noise, 2000nm
10^{-22}
10^{-23}
10^{-24}
Strain [[1/√Hz]]
10^{0}
10^{1}
10^{2}
Frequency [Hz]
10km FC, 45ppm RTL
1km FC, 23ppm RTL
1km FC, 12ppm RTL

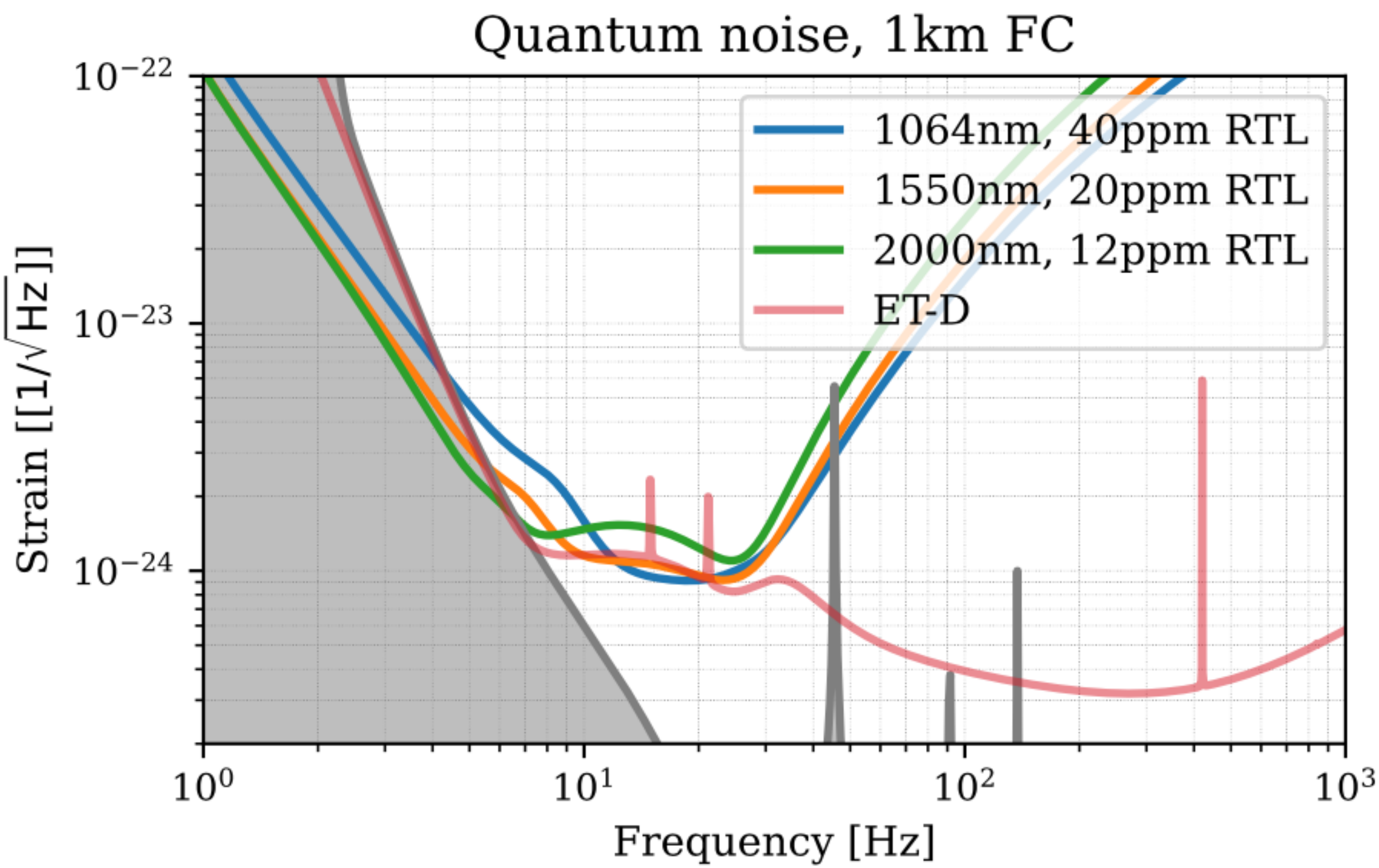
1550nm



Linear analytical model not appropriate?

Dashed lines are the noises from dark port inherent vacuum.

Filter cavity T: 128ppm, 480ppm.   L/T ratio is high.


Quantum noise, 1km FC
10^{-22}
10^{-23}
10^{-24}
Strain [[$1/\sqrt{\text{Hz}}$]]
1064nm, 40ppm RTL
1550nm, 20ppm RTL
2000nm, 12ppm RTL
ET-D
10^{0}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

Quantum noise

Higher power for 2000nm

Assumption:

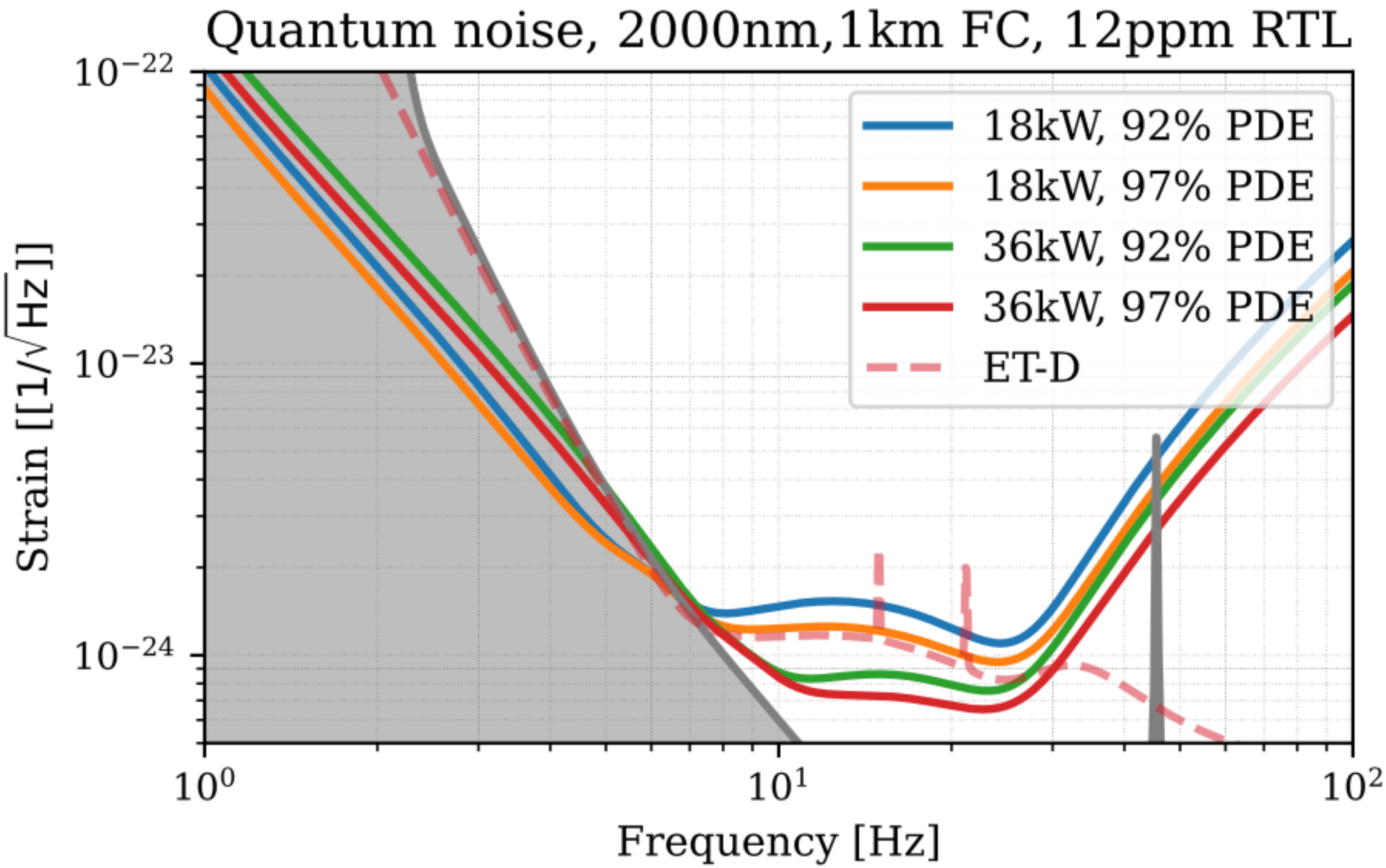
- Arm power 18kW for 1064nm/1550nm, **36kW for 2000nm**.
- Test mass 200kg for three cases.
- 15dB injection Squeezing for three cases.
- **1km** long filter cavity for three cases.
- Optical losses:

	Arm m RT L	Filter Cav RT L	PD E
1064nm	75ppm	**40ppm**	0.97
1550nm	55ppm	**20ppm**	0.97
2000nm	40ppm	**12ppm**	**0.92/ 0.97**

Light scattering

$$\mathcal{L} = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

10 ppm loss per mirror for arm cavity is added as a margin for losses from absorption, clipping, etc.



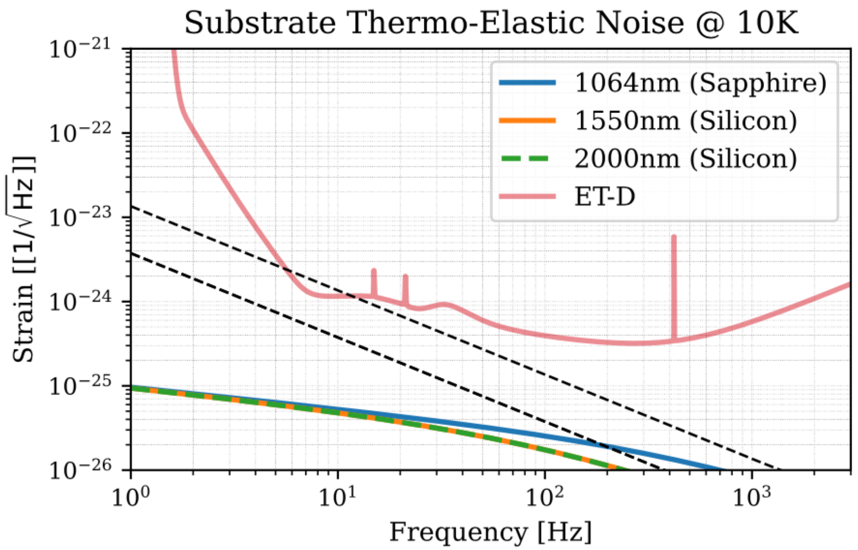
Quantum noise, 2000nm,1km FC, 12ppm RTL
10^{-22}
10^{-23}
10^{-24}
Strain [[1/√Hz]]
10^{0}
10^{1}
10^{2}
Frequency [Hz]
18kW, 92% PDE
18kW, 97% PDE
36kW, 92% PDE
36kW, 97% PDE
ET-D

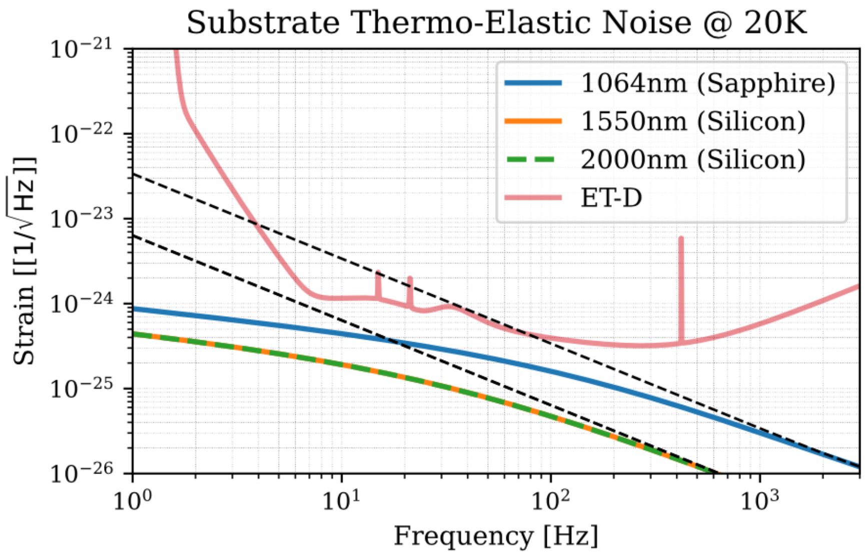
Summary:

- Compatibility of detuning and frequency dependent squeezing requires more detailed study.
- Longer wavelength is more preferred from the first glance.

Substrate Thermoelastic noise

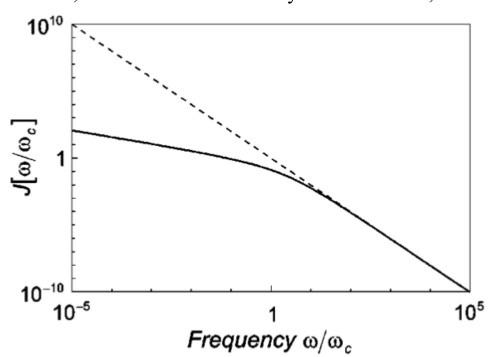
Updated in pyGwinc of ET!





	Silicon (10K)	Silicon (20K)	Sapphire (10K)	Sapphire (20K)	Silica (300K)
K_s(W/m/K)	1000	3000	2900	4300	1.38
α_s(1/K)	4.8e-10	2.9e-9	5.3e-10	4.6e-9	3.8e-7
C_s(J/kg/K)	0.276	3.41	0.085	0.72	739

Kenji Numata, Masaki Ando, Kazuhiro Yamamoto, Shigemi Otsuka, and Kimio Tsubono. Phys. Rev. Lett. **91**, 260602



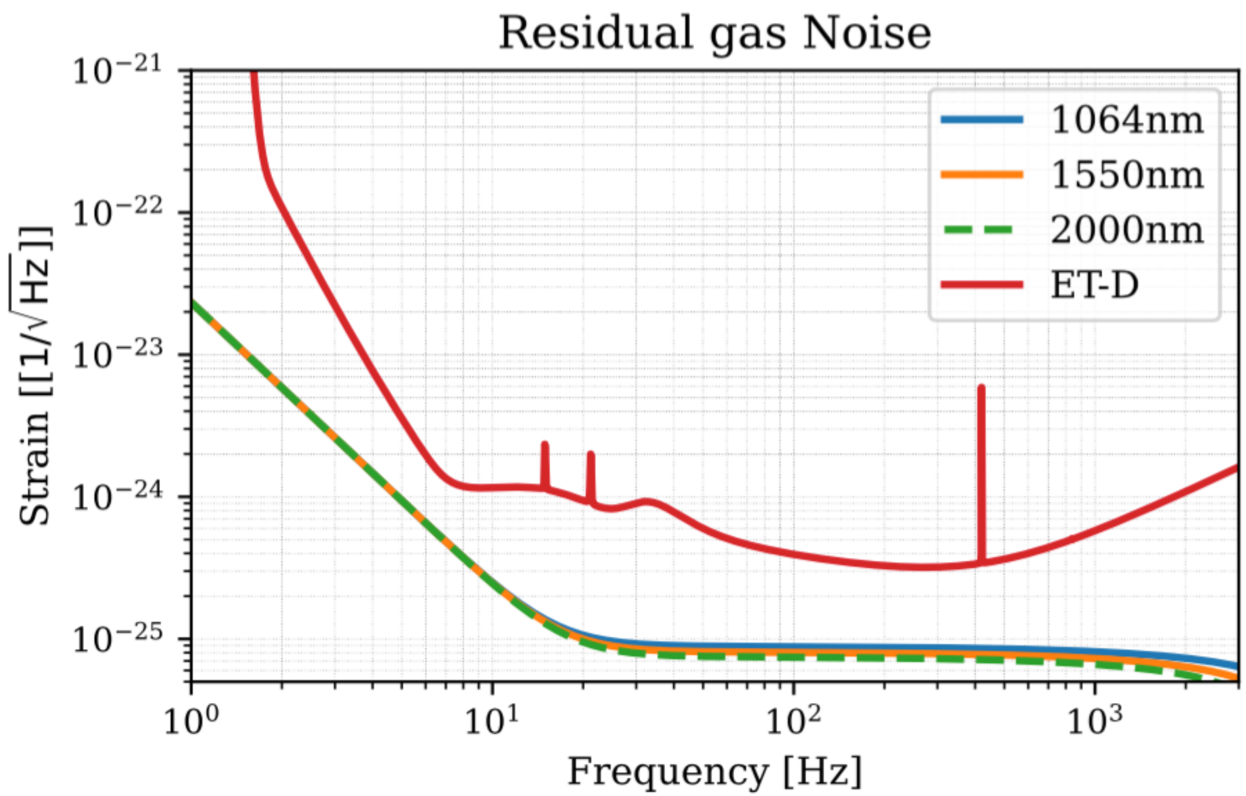
Corner frequency becomes higher at low temperature.

Summary:

- The updated thermal elastic noise model is included in ET pyGwinc, https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

- Both sapphire and silicon satisfy the noise requirement in principle at 10k and 20k.

Residual gas noise



Assumption:

- 1e-7Pa hydrogen
- the same beam size on test masses (different cavity g factor)

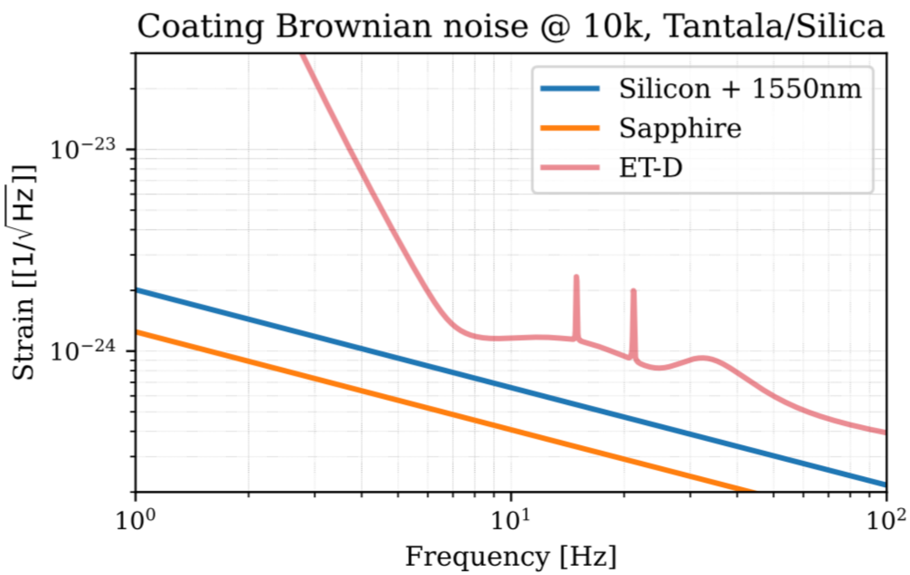
Summary:

- The wavelength impact to residual gas noise is trivial.

Coating thermal noise

In Current model, we are assuming Tantala/Silica coating with 8/17 quarter-wave bilayers for ITM and ETM.

Assuming the cavity g factor of HF for LF, the CTN can be improved by a factor of 1.6.



	Tantala	Silica
Loss	7e-4	5e-4

Mirror	Silicon	Sapphire (1064nm)	Sapphire (1550nm)
Diameter	45cm	60cm	72.5cm
Thickness	57cm	19cm	13cm

The wavelength impact on beam size and coating thickness get compensated.

Sapphire mirror diameter for 2000nm will be too large.