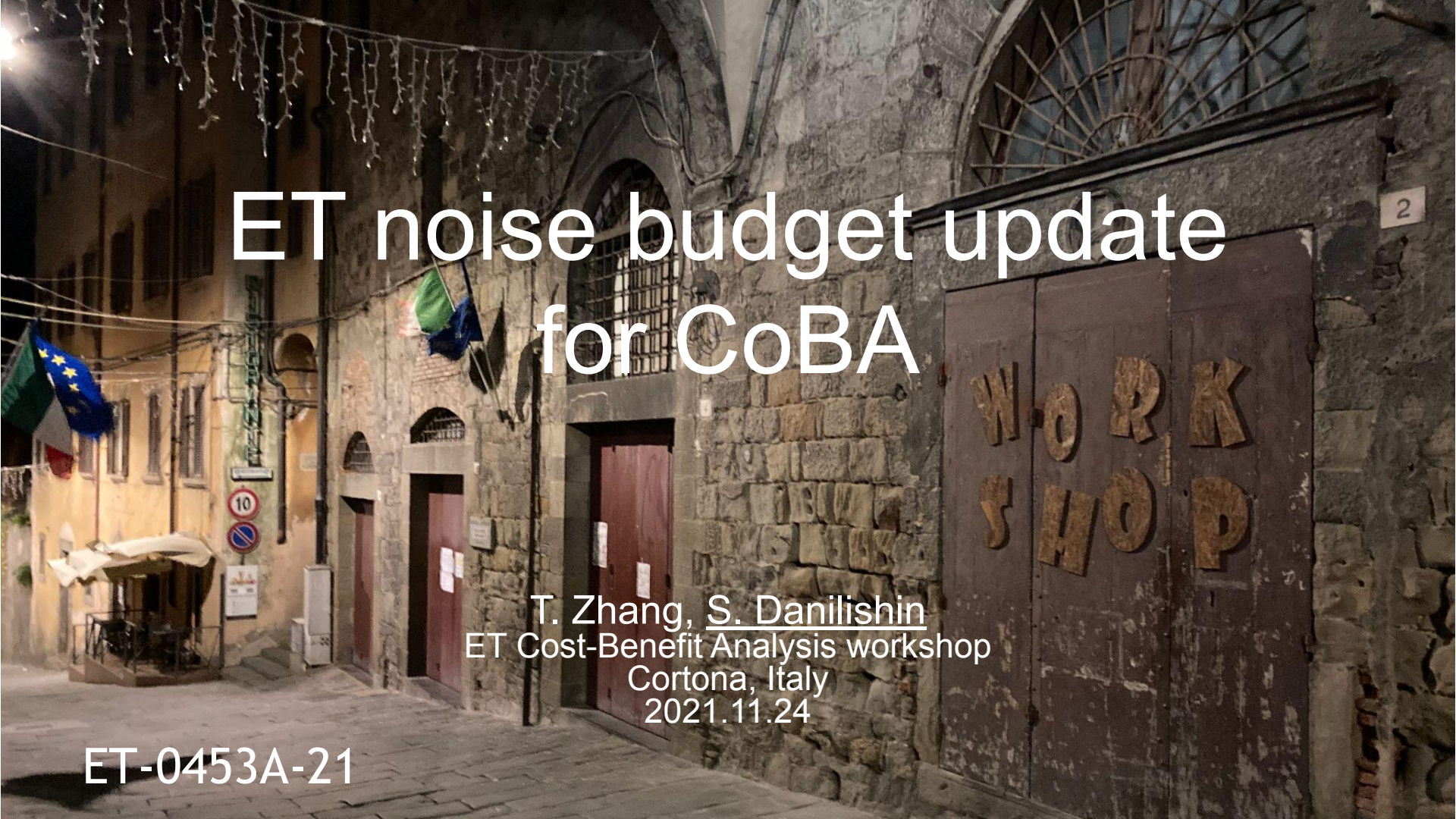


ET noise budget update for CoBA

T. Zhang, S. Danilishin

ET Cost-Benefit Analysis workshop
Cortona, Italy
2021.11.24

ET-0453A-21

Contents:

Updates on ET Noise Budget since October 28th, 2021

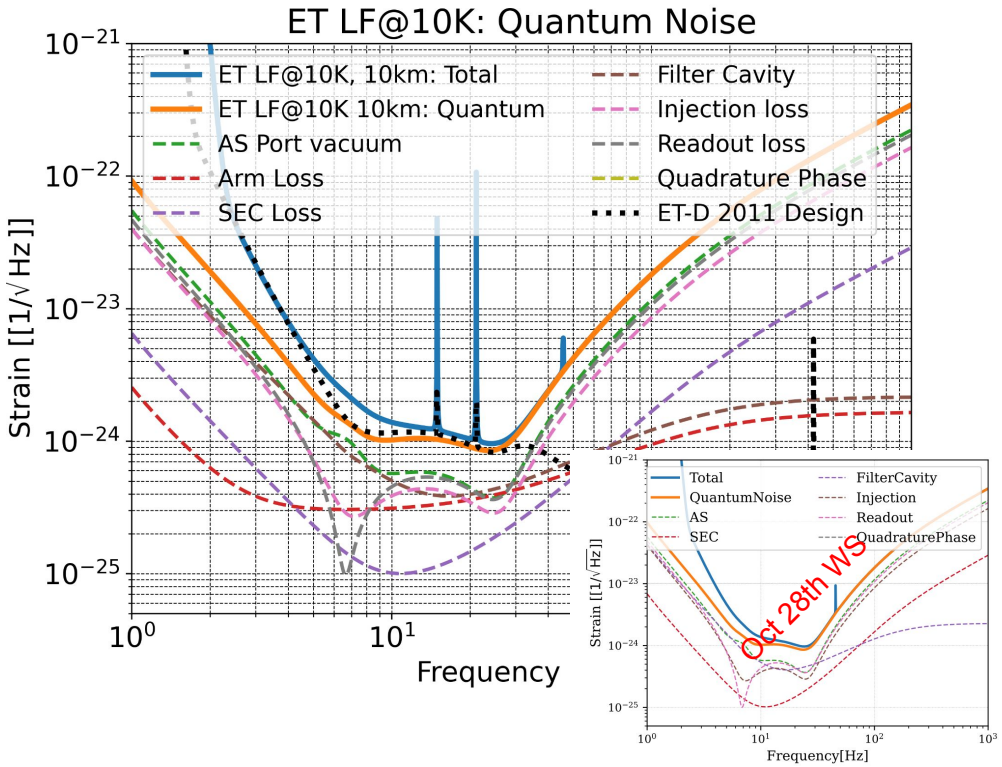
- Suspension TN model updated with the great help of P. Puppo ⇒ **now in pyGWINC**: triple branched pendulum model with violin modes, parameter files used for 2011 ET Design Study
- Active discussions in Optics division on the LF coating options (google document) ⇒
  - Silica-Tantala coating@10K not ideal, but can be used for the time being (Optics Division)
  - Implementation of multimaterial coating code is in progress (S. Steinlechner)
- Room-temperature ET LF variant studied (J. Harms)
- 'Official' (with quotes!) sensitivity curves for CoBA generated and shared with OSB. Generated 10km/15km/20km variants for 2 temperature scenarios: LF@10K and LF@290K.

  Curves and the notebook that generates them are publicly available here:
  https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget/-/tree/master/CoBA/CoBA_sensitivity_curves
  and here (notebook): https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget/-/blob/master/OtherArmLength_CoBA.ipynb

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 loss per mirror, [ppm]	37.5
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

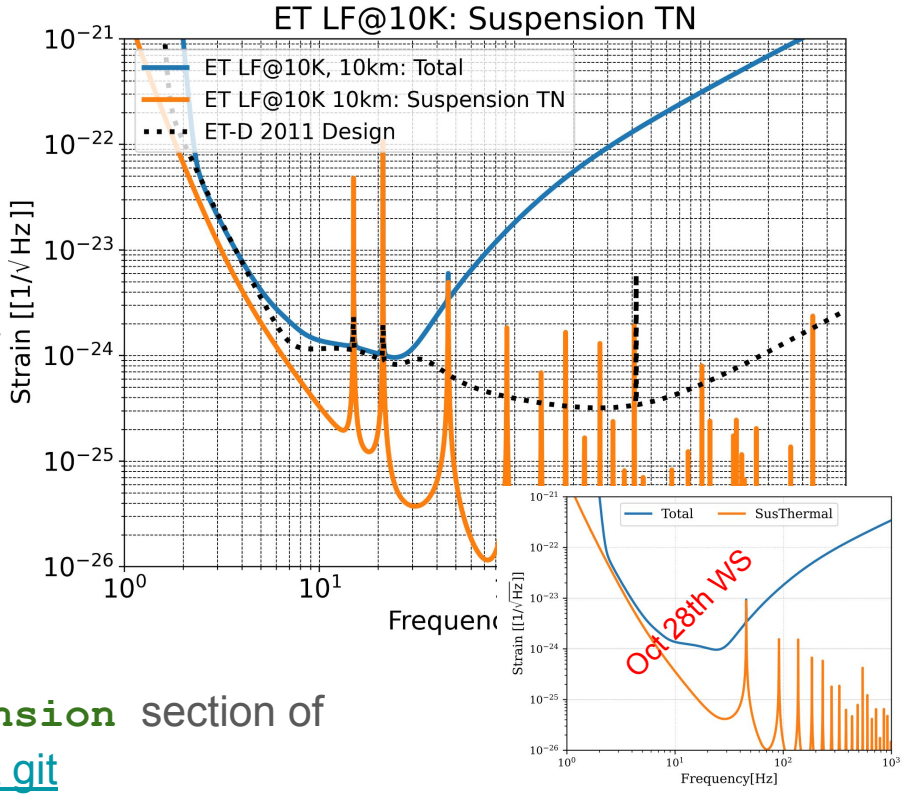


Check relevant parameters in the **`Laser`**, **`Optics`** and **`Squeezer`** sections of **`ETLF/ifo.yaml`** file on ET-NoiseBudget git

10km ET LF

Suspension thermal noise

- Code and parameters obtained from P. Puppo to reproduce the ***triple branched pendulum suspension*** used for the ET Design Study 2011 noise curves;
- Violin modes contribution included;
- Current design for **LF** uses ***branched pendulum model*** with ***silicon*** as material for ***TM*** and ***RM*** suspensions, and ***titanium*** as material for ***marionetta*** suspension;
- Material Database is currently being created on ET-ISB Wiki jointly by Suspension and Optics divisions. We wait for final parameters to put in the model.



Check relevant parameters in the **`Suspension`** section of **`ETLF/ifo.yaml`** file on ET-NoiseBudget git

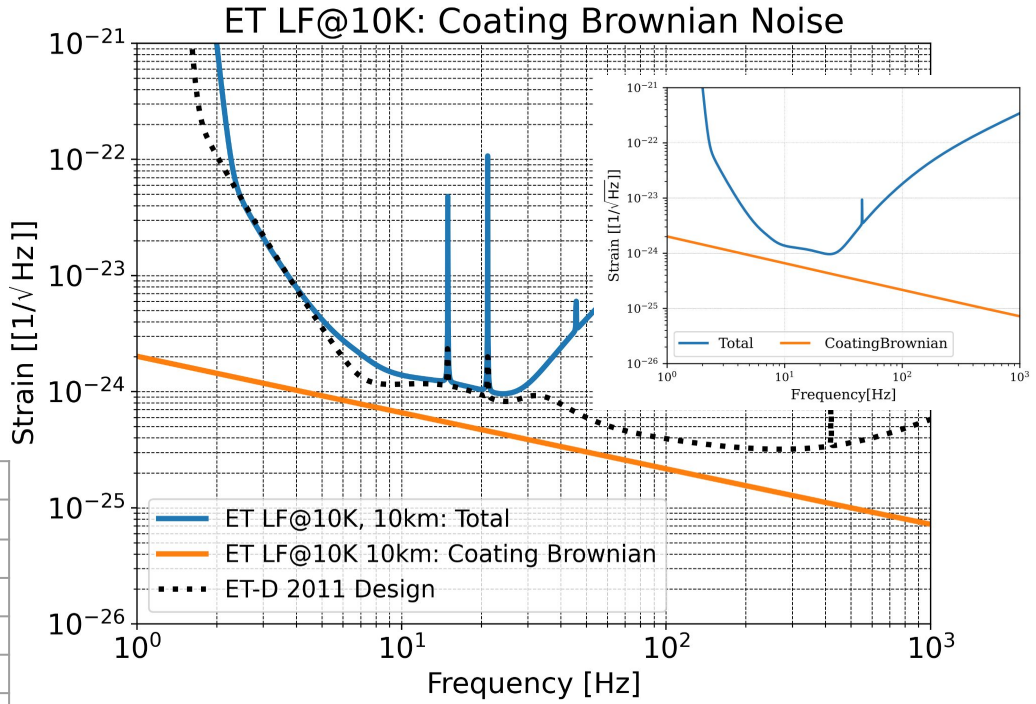
10km ET LF

No changes after 28th Oct.

- SiO_2/Ta_2O_5@10K coating is still used in the model (Optics Division doc)
- Material Database is currently being created on ET-ISB Wiki jointly by Suspension and Optics divisions. We wait for final parameters to put in the model.
- 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. **Work in progress (S. Steinlechner)**

Material (high/low)	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

Coating Brownian noise



Check relevant parameters in the **`Materials.Coating`** section of **`ETLF/ifo.yaml`** file on ET-NoiseBudget git

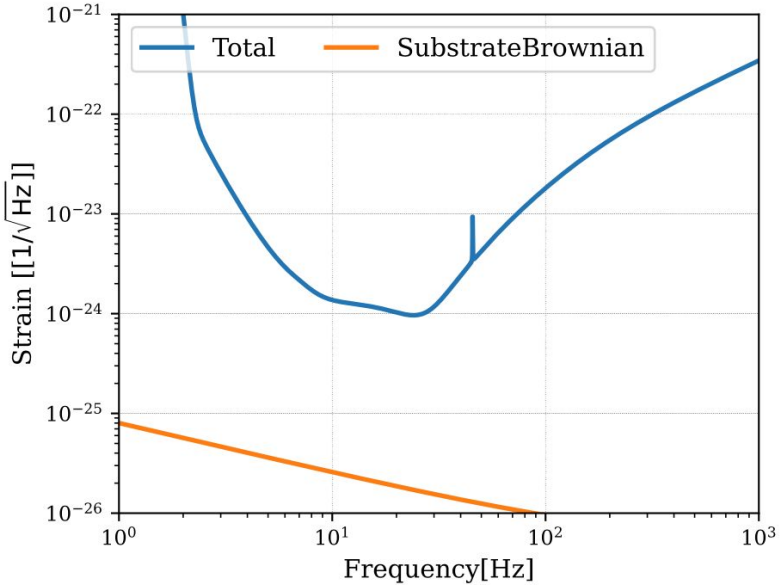
10km ET LF

Substrate Brownian noise

No changes after 28th Oct.

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

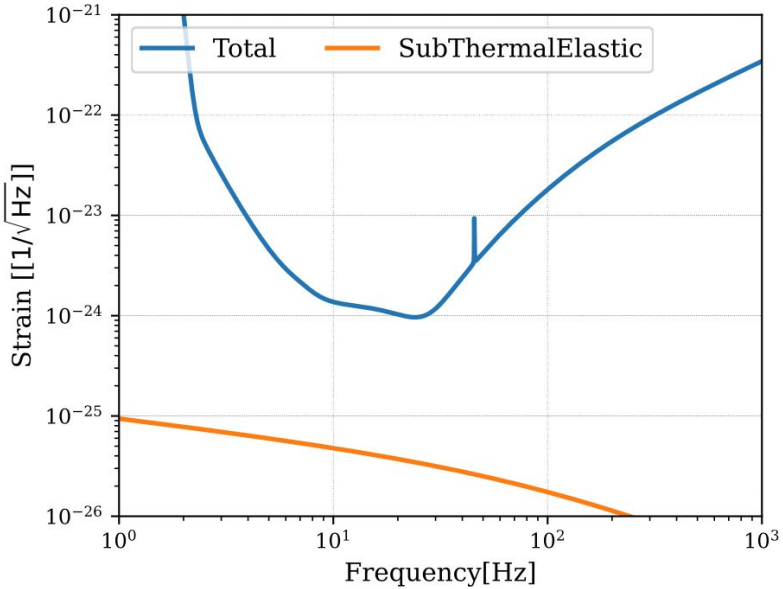
Frequency dependence of the loss: Lam, C. C., & Douglass, D. H. (1981)

10km ET LF

Substrate thermoelastic noise:

No changes after 28th Oct.

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



Check relevant parameters in the **`Materials.Substrate`** section of **`ETLF/ifo.yaml`** file on [ET-NoiseBudget git]

10km ET LF

Seismic noise: No changes after 28th Oct.

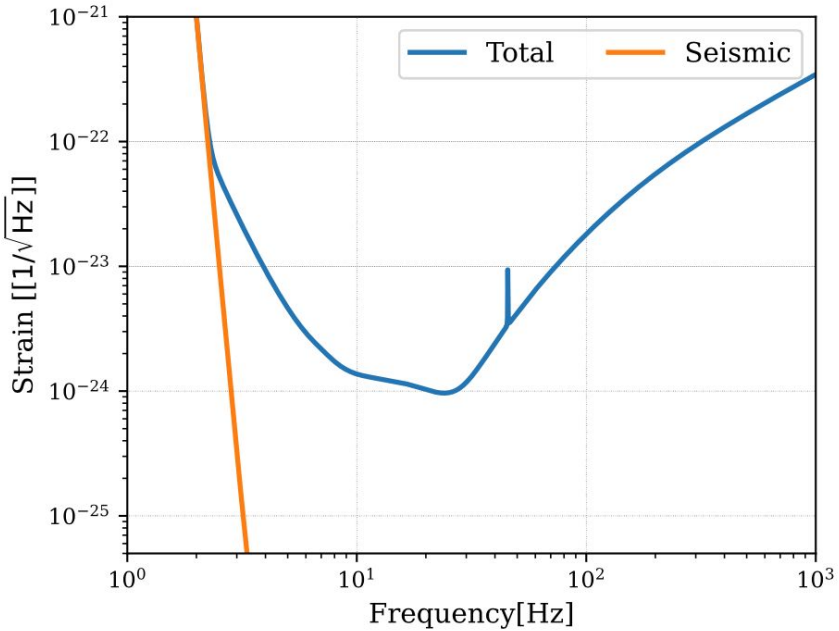
Seismic noise is from the coupling of rayleigh waves and body waves through 17m seismic isolation structure in three degrees of freedom (horizontal-horizontal, vertical-to-horizontal, tilt-horizontal)

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



Check relevant parameters in the **`Seismic`** section of **`ETLF/ifo.yaml`** file on ET-NoiseBudget git

10km ET LF

Newtonian noise: No changes after 28th Oct.

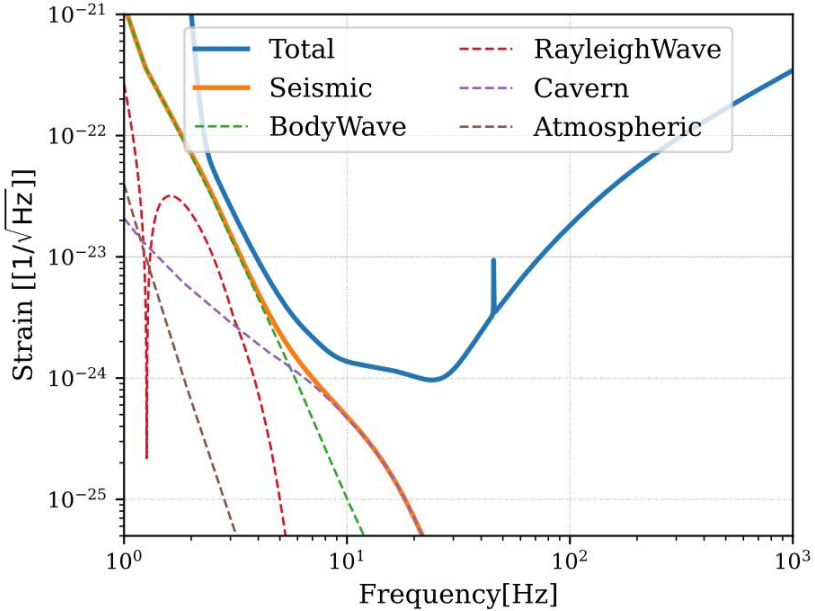
Newtonian noise is modelled as a combination of contribution from Seismic waves (Body waves, Rayleigh waves), Atmospheric noise and Cavern noise.

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.



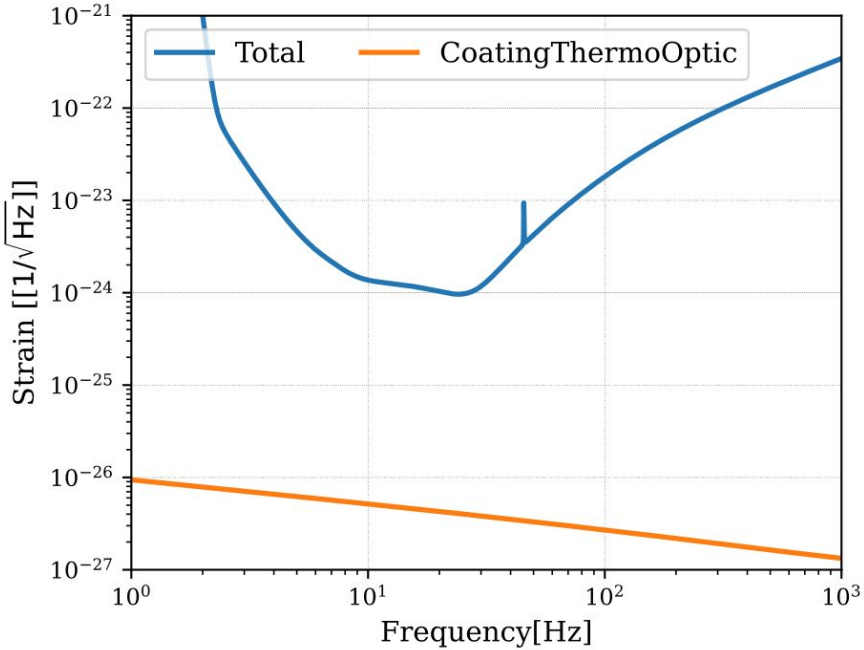
Check relevant parameters in the **`Seismic`** section of **`ETLF/ifo.yaml`** file on ET-NoiseBudget git

10km ET LF

Coating Thermo-optic noise

No changes after 28th Oct.

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

Check relevant parameters in the **`Materials.Coating`** section of **`ETLF/ifo.yaml`** file on [ET-NoiseBudget git]

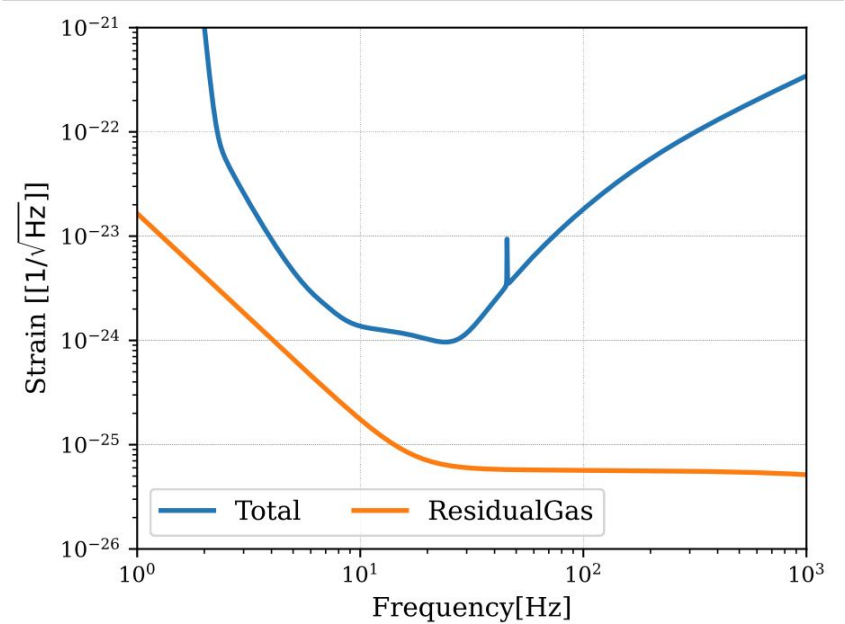
10km ET LF

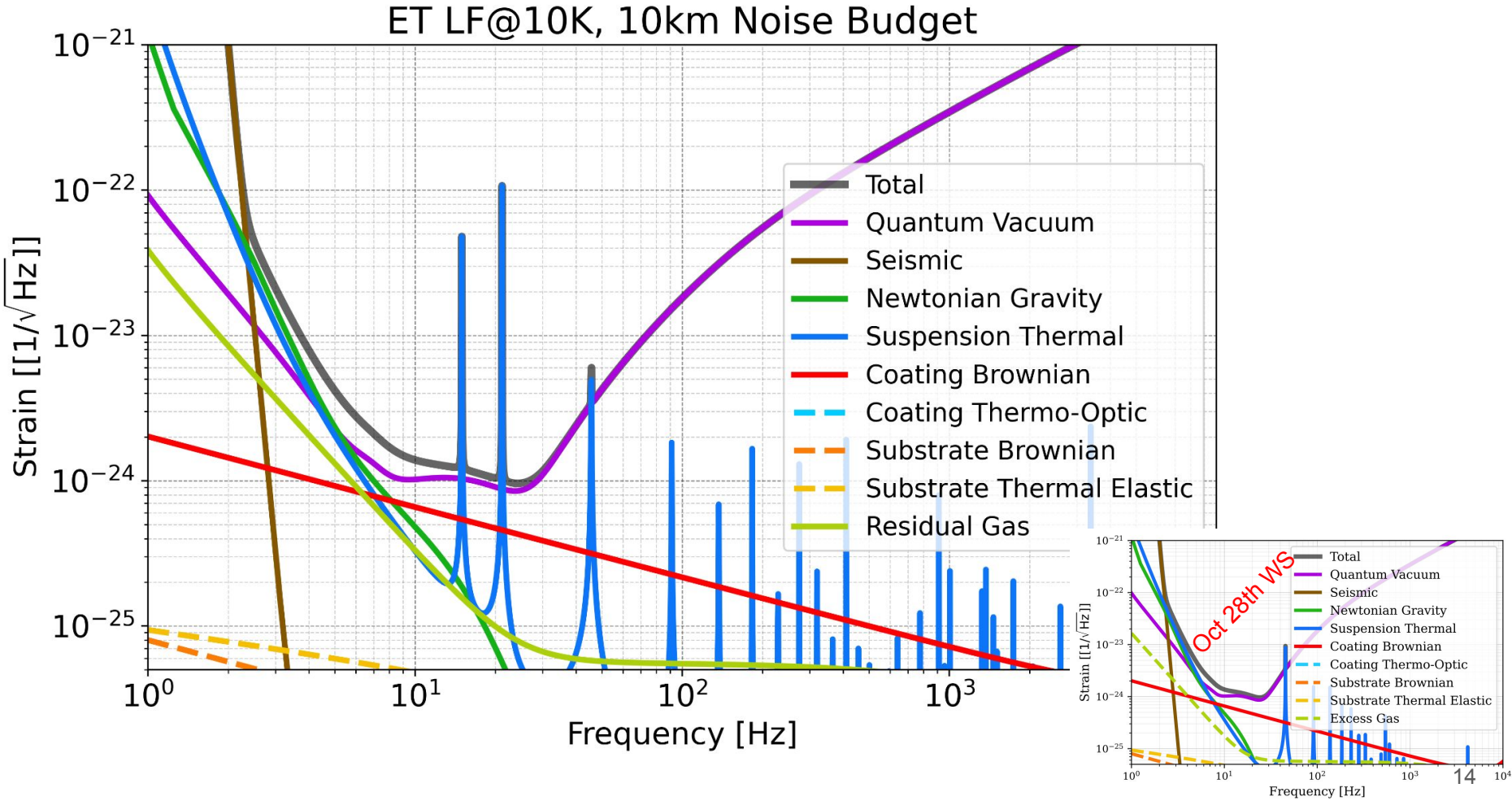
Excess noise:

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

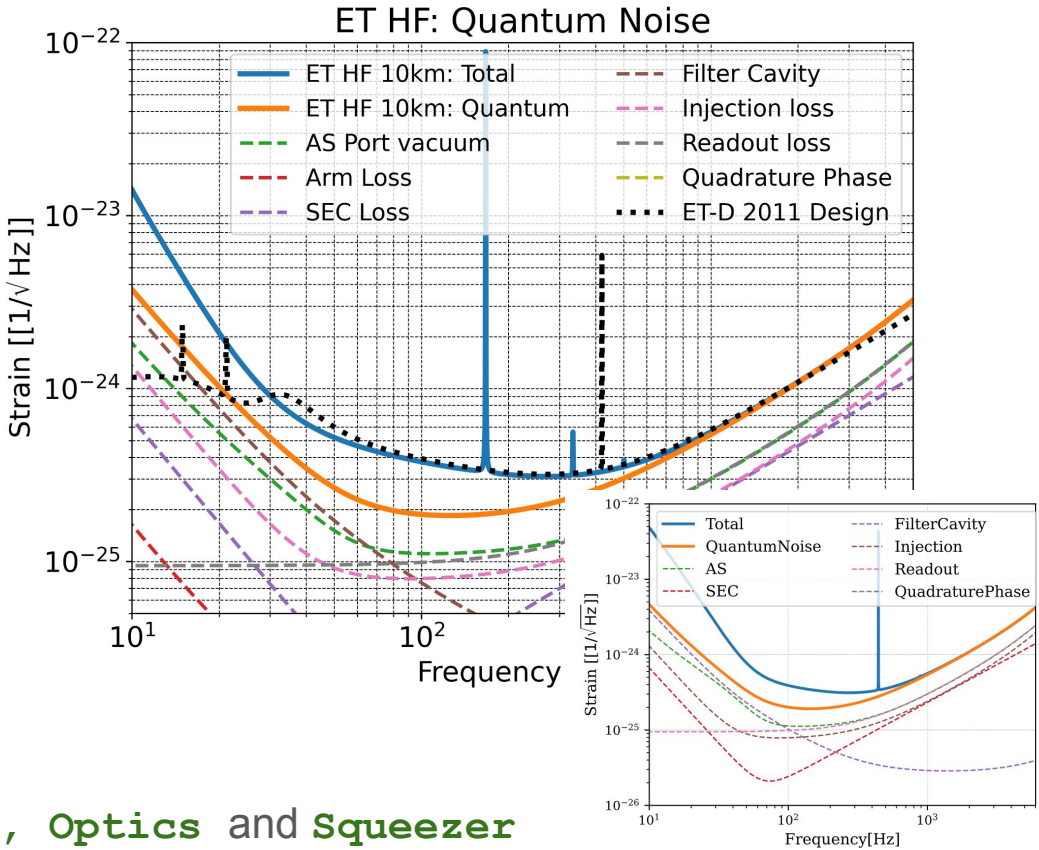



ET LF@10K, 10km Noise Budget
Strain [[1/√Hz]]
Frequency [Hz]
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermal Elastic
Residual Gas
Oct 28th WS
Excess Gas

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 loss per mirror, [ppm]	37.5
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]	55

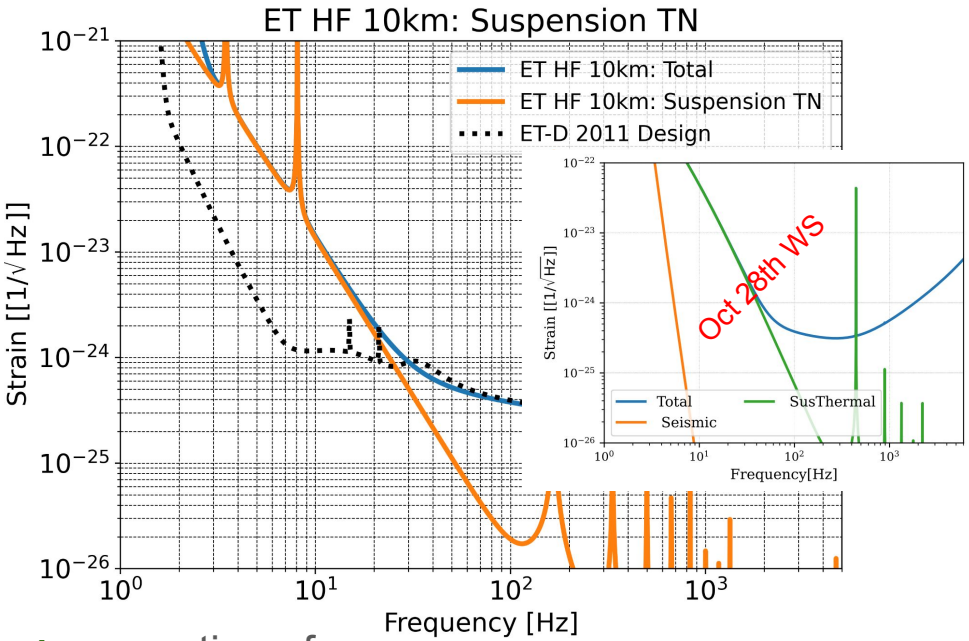


Check relevant parameters in the **`Laser, Optics`** and **`Squeezer`** sections of **`ETHF/ifo.yaml`** file on [ET-NoiseBudget git]

10km ET HF

Suspension thermal noise

- Code and parameters obtained from P. Puppo to reproduce the ***triple branched pendulum suspension*** used for the ET Design Study 2011 noise curves;
- Violin modes contribution included;
- Current design for **HF** uses ***branched pendulum model*** with ***silica*** as material for ***TM***, ***C85 steel*** for ***RM*** suspensions, and ***maraging steel*** as material for ***marionetta*** suspension
- Material Database is currently being created on ET-ISB Wiki jointly by Suspension and Optics divisions. We wait for final parameters to put in the model.



Check relevant parameters in the **`Suspension`** section of **`ETHF/ifo.yaml`** file on ET-NoiseBudget git

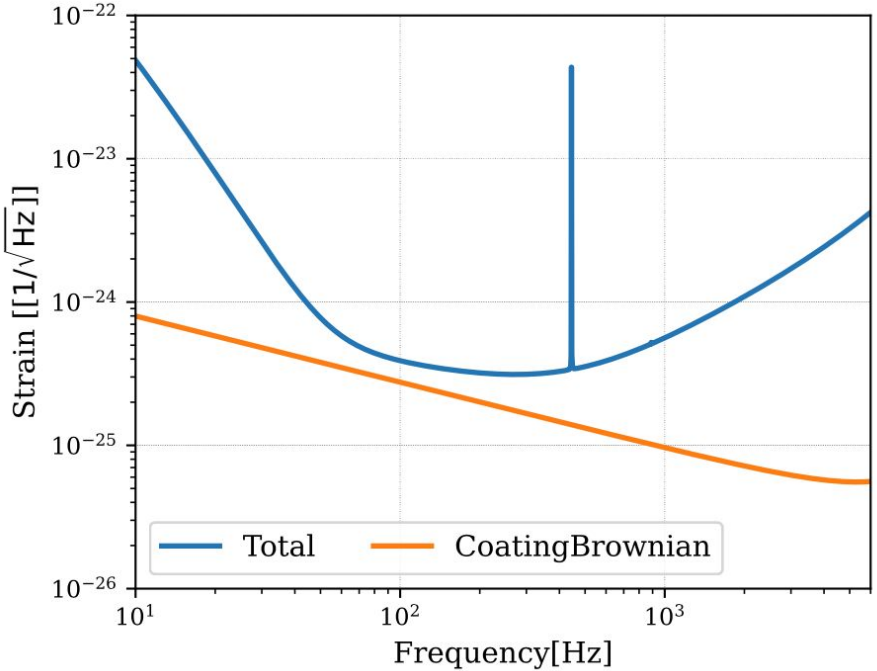
10km ET HF

Coating Brownian noise

No changes after 28th Oct.

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.



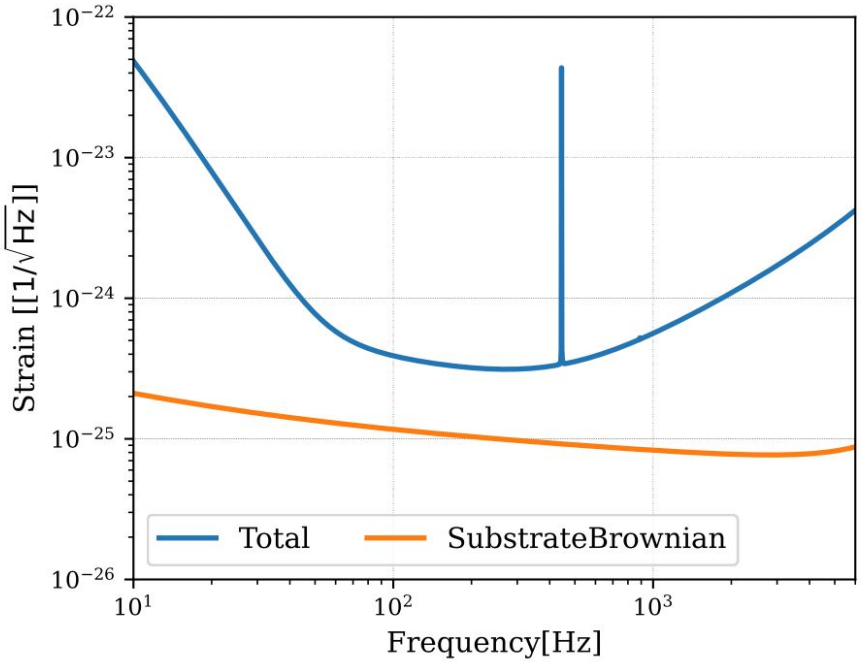
Check relevant parameters in the `Materials.Coating` section of `ETHF/ifo.yaml` file on ET-NoiseBudget git

10km ET HF

Substrate Brownian noise:

No changes after 28th Oct.

Material	Silica
Temperature, [K]	290 K
Young's modulus [Pa]	7.27e10
Poisson's ratio	0.167
Mechanical loss angle	$7.6e\text{-}12 \cdot f^{0.77}$
Mirror Diameter [cm]	62 cm
Mirror thickness [sm]	30 cm
Beam size [cm]	9 cm



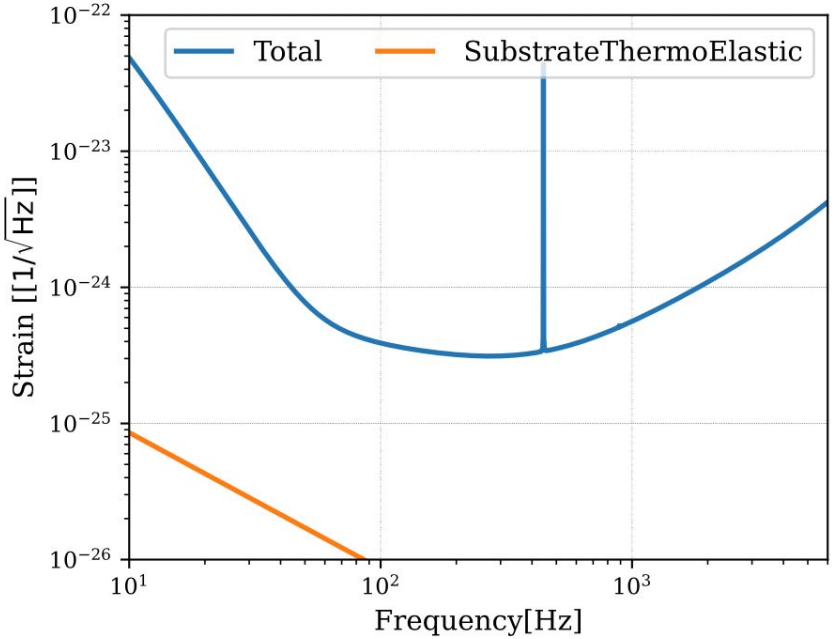
Check relevant parameters in the **`Materials.Substrate`** section of **`ETHF/ifo.yaml`** file on ET-NoiseBudget git

10km ET HF

Substrate thermoelastic noise:

No changes after 28th Oct.

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



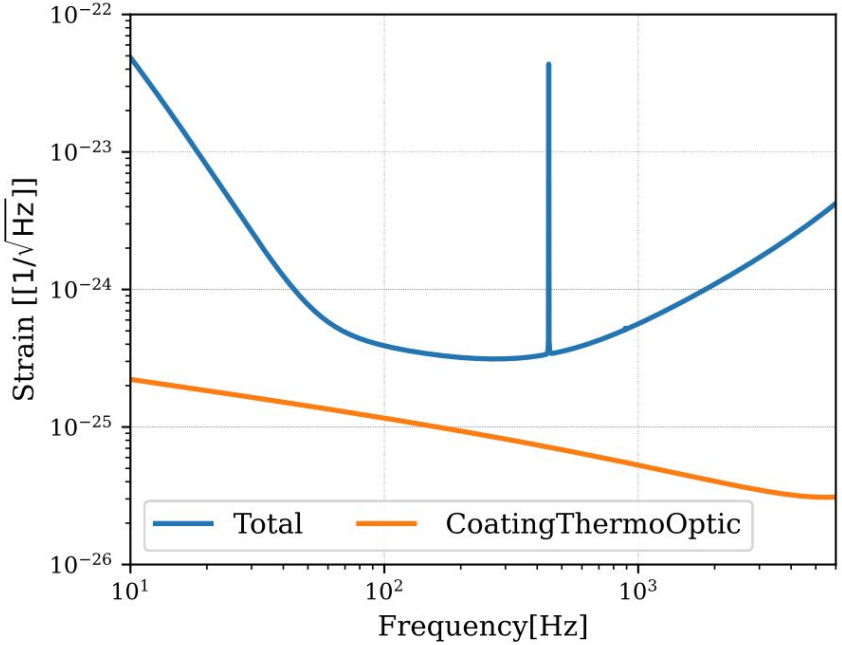
Check relevant parameters in the **`Materials.Substrate`** section of **`ETHF/ifo.yaml`** file on ET-NoiseBudget git

10km ET HF

Coating Thermo-optic noise

No changes after 28th Oct.

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



Check relevant parameters in the **`Materials.Coating`** section of **`ETHF/ifo.yaml`** file on ET-NoiseBudget git

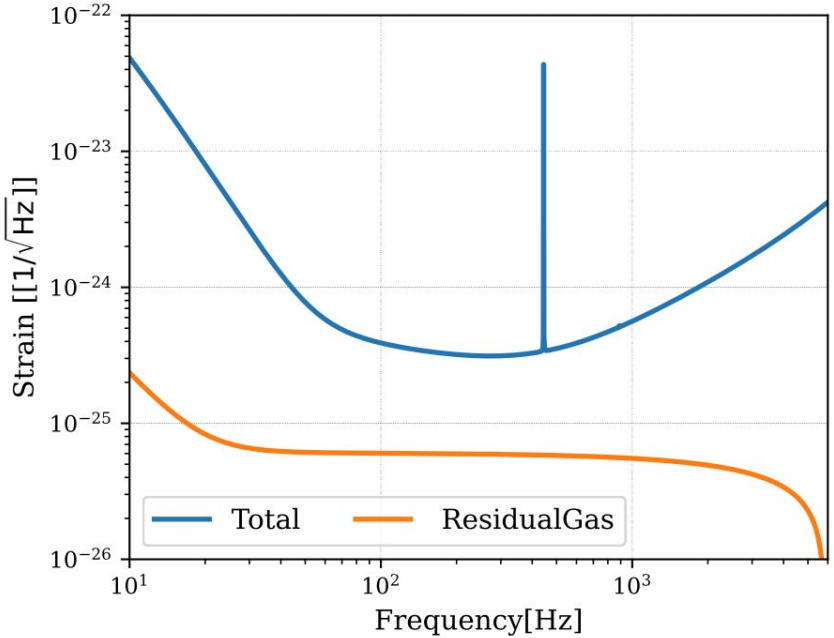
10km ET HF

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).

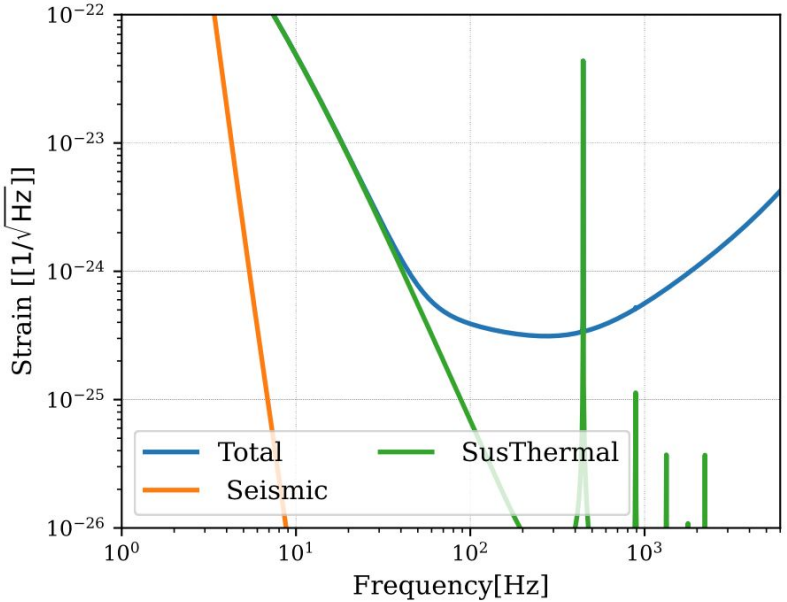
Damping noise is modelled based on Cavalleri's paper: https://doi.org/10.1016/j.physleta.2010.06.041

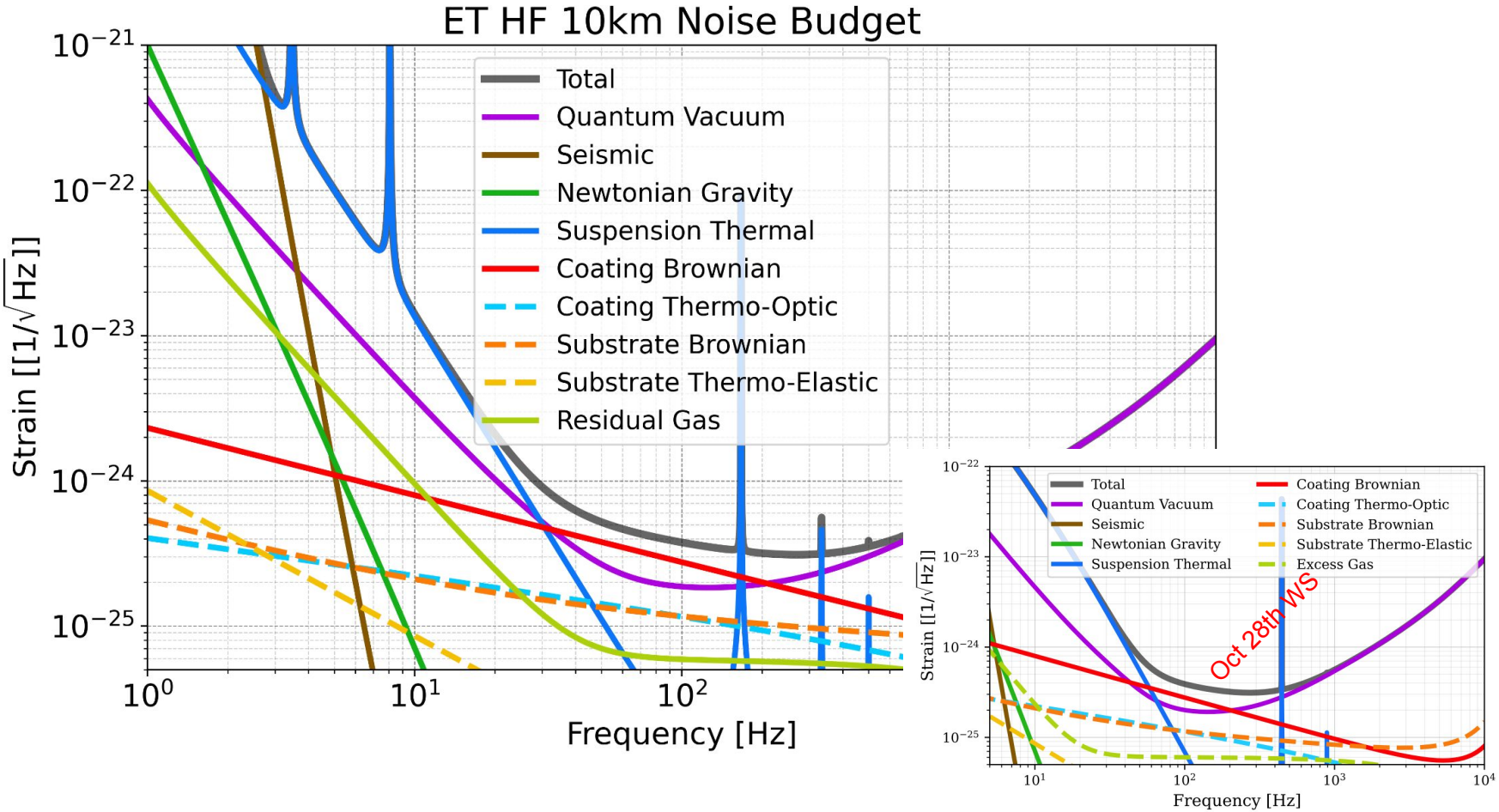


10km ET HF

Seismic 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.



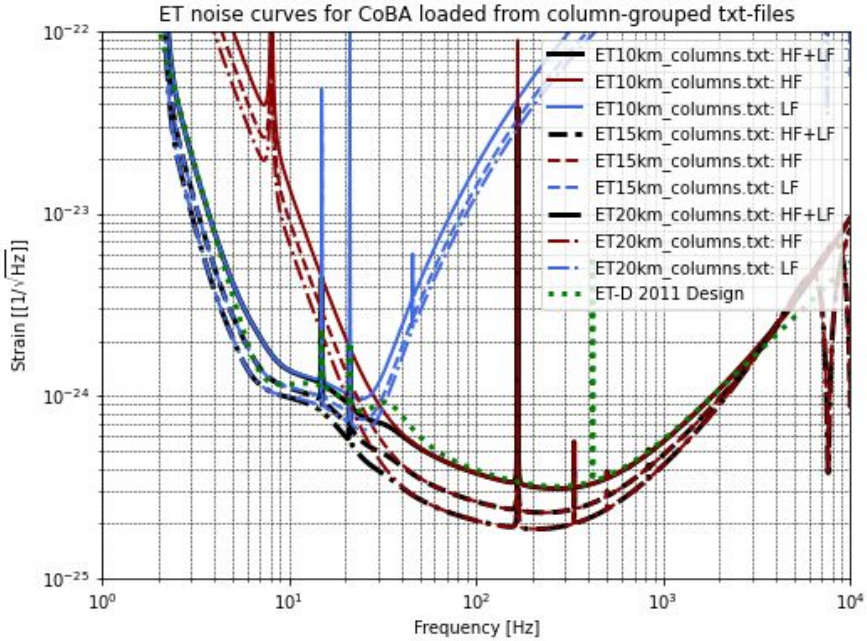

ET HF 10km Noise Budget
Total
Quantum Vacuum
Seismic
Newtonian Gravity
Suspension Thermal
Coating Brownian
Coating Thermo-Optic
Substrate Brownian
Substrate Thermo-Elastic
Residual Gas
Strain [[1/√Hz]]
Frequency [Hz]
Oct 28th WS
Excess Gas

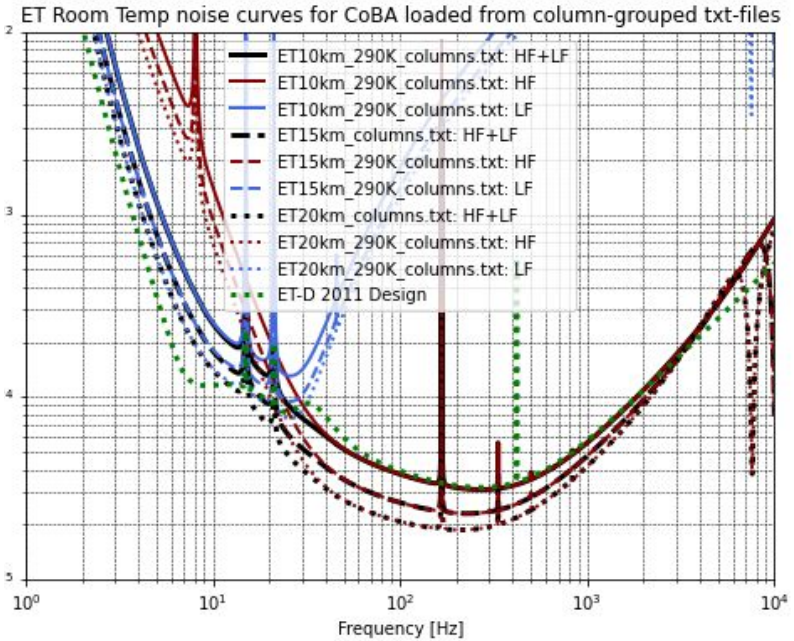
Other lengths

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

Arm lengths (l): 10km | 15km | 20km (cryo vs. room T)

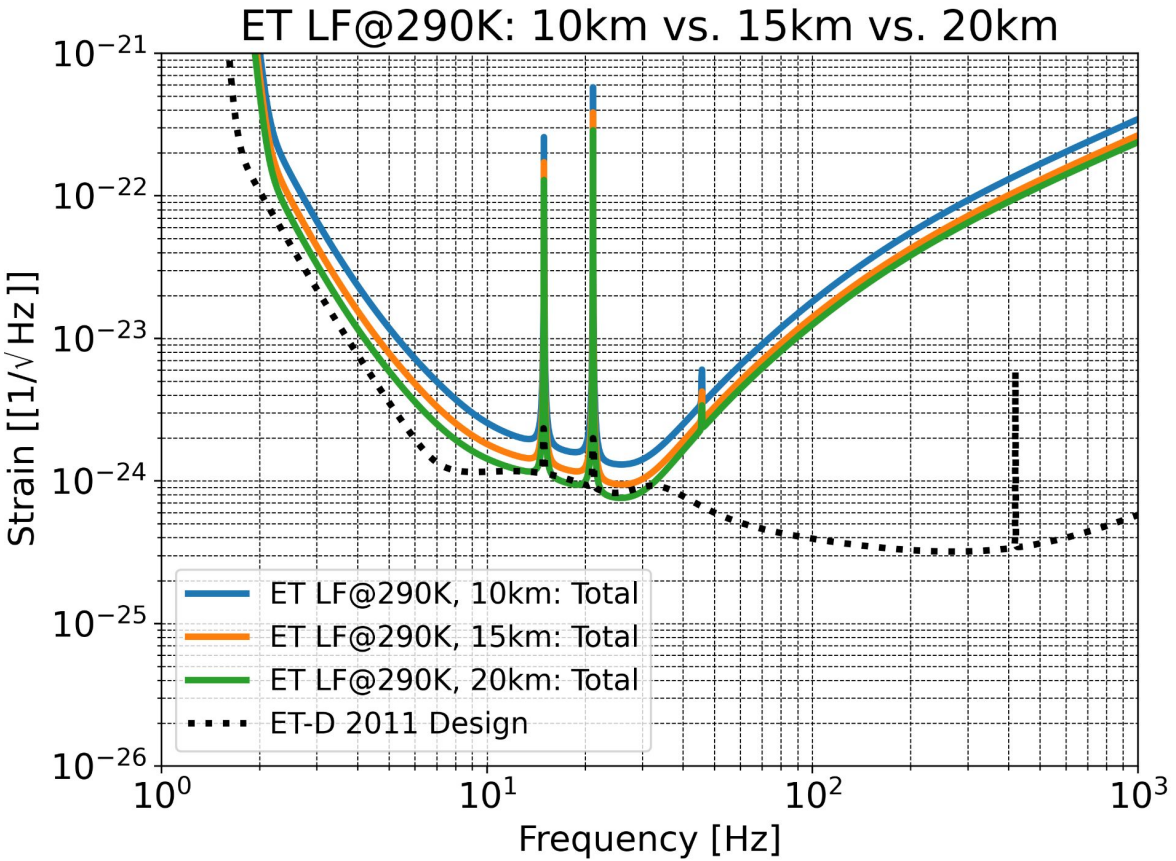


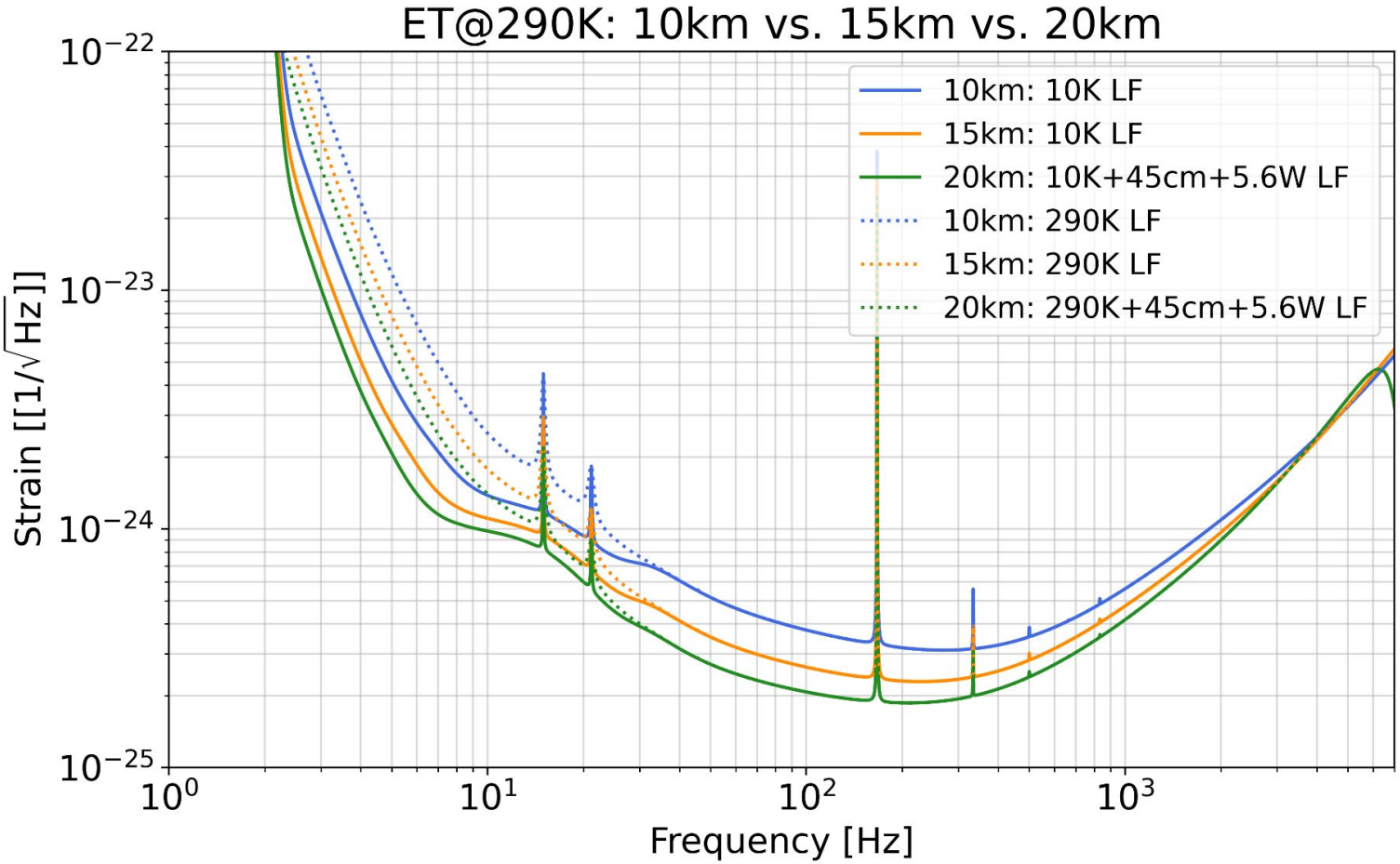


Room-temperature ET LF

Room-temperature ET

- Analysis done by J.Harms
- Parameters from **Materials** section of `ETHF/ifo.yaml` transplanted to **Materials** section of `ETLF/ifo.yaml`




ET@290K: 10km vs. 15km vs. 20km
10km: 10K LF
15km: 10K LF
20km: 10K+45cm+5.6W LF
10km: 290K LF
15km: 290K LF
20km: 290K+45cm+5.6W LF
Strain [[1/√Hz]]
Frequency [Hz]
10^-22
10^-23
10^-24
10^-25
10^0
10^1
10^2
10^3