ET-0007A-23

Conceptual Design and Noise Budget of Einstein Telescope

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XIII Einstein Telescope Symposium

09 May, 2023

Goal :

- Produce a new *official current sensitivity curve of ET*.
- Recover/revise ET D
- A chance to reconsider the design

Materials :

- The GWINC model is available at https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget
- The document is at https://www.overleaf.com/read/qjrcqmyvhrkv

Next steps:

- Check the document, add your opinion on git/overleaf, and add references missing.
- Launch the new sensitivity.

Contents of the document

Current version of the document is available on overleaf: https://www.overleaf.com/1612765838ncdtppyrntrc

Conceptual design and noise budget of Einstein Telescope

ET-0007B-23

Teng Zhang, Stefan Danilishin and many others to be added

Issue: 1

Date: May 6, 2023

General Description of ET

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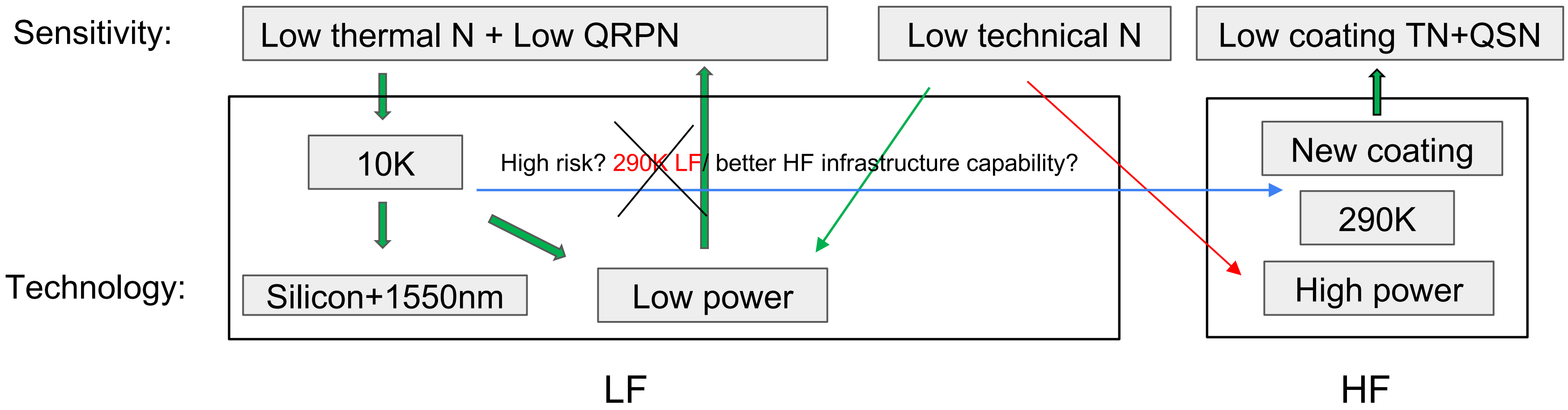
- Key features of ET design

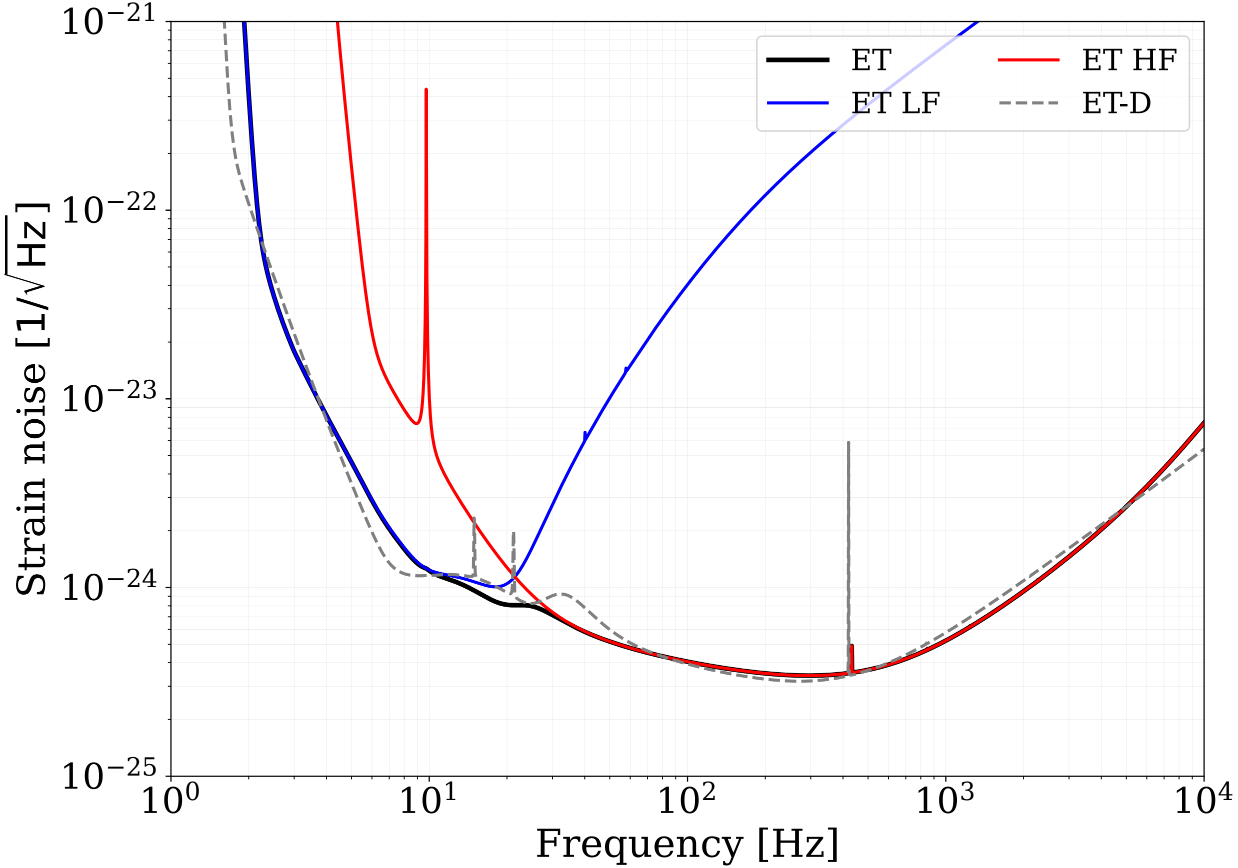
  Underground & Xylophone

- Why we have such designs?
- Underground: Much lower seismic N and seismic NN, namely low infrastructure limit at low frequencies.
- Xylophone: Sensitivity driven? Technology driven? *Risk driven*?



Contents of the document

ET sensitivity



General Description of ET

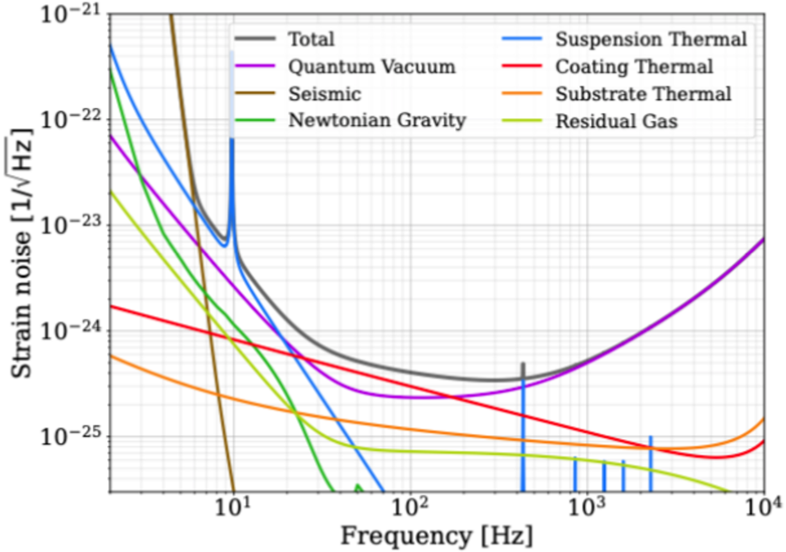


Figure 1: Strain noise budget of the HF detector. Noise traces shown in this figure correspond to a single interferometer with an intersection angle of 90 degrees ("L" shape).

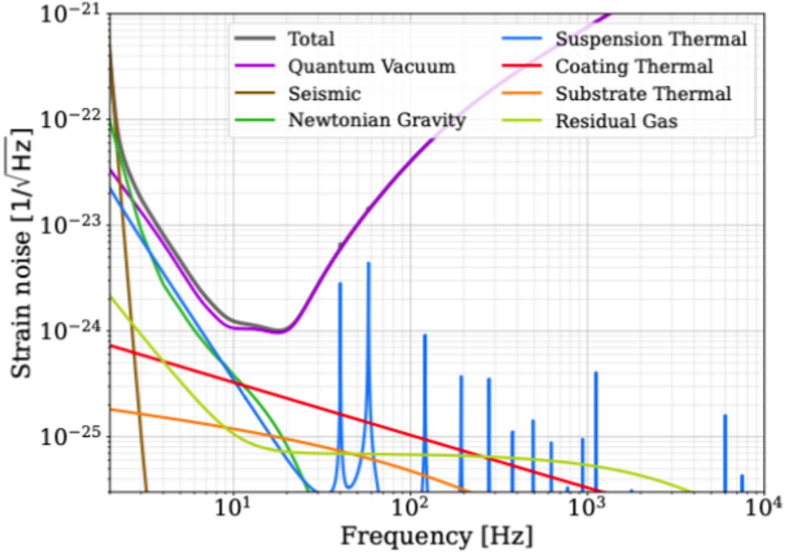


Figure 2: Strain noise budget of the LF detector. Noise traces shown in this figure correspond to a single interferometer with an intersection angle of 90 degrees ("L" shape).

The infrastructure noise of ET

- Seismic noise
  - TFs for seismic isolation for LF (currently the 17m version) and HF (Not designed, extracted from ET-D?)
  - 90th percentile of borehole data from Sos Enattos site is used for ET sensitivity curve

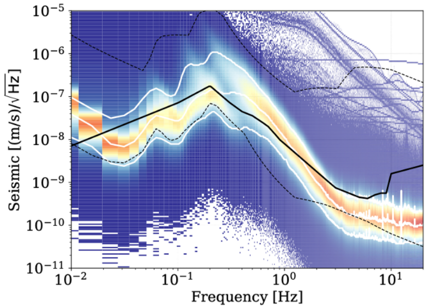


Figure 4: Histogram of horizontal/ vertical ground motion measured in the P2 borehole at 264m depth at Sos Enattos site in Sardinia (data from October 1, 2021 to December 31, 2021). The white lines indicate the 10th/50th/90th percentiles. The solid black line indicates the Rayleigh wave at the surface. The dashed curves represent the Peterson's Low-noise Model and high-noise model.

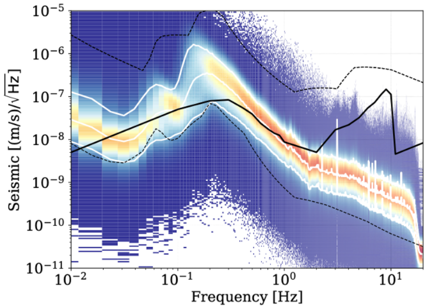


Figure 5: Histogram of horizontal/ vertical ground motion measured in the Terziet borehole at 250 m depth at EMR site (data from September 30, 2019 to September 14, 2020). The white lines indicate the 10th/50th/90th percentiles. The solid black line indicates the Rayleigh wave at the surface. The dashed curves represent the Peterson's Low-noise Model and high-noise model.

- Seismic noise is modeled by specifying the coupling in three degrees of freedom, horizontal, vertical, and tilt direction.

- For simplicity, the ground tilt and horizontal and vertical displacements are assumed to be uncorrelated. Different test mass is uncorrelated.

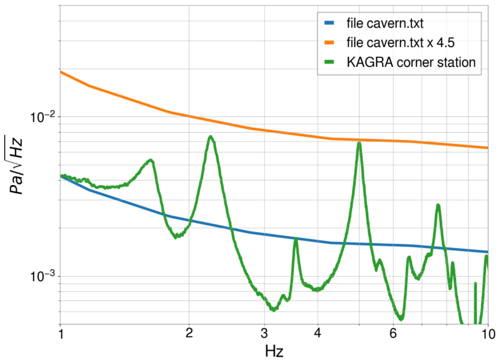
The infrastructure noise of ET

- Newtonian noise
  - Included projections for body waves, Rayleigh waves, cavern acoustic, and atmospheric disturbances
  - A factor of 3 suppression factor (amplitude) is assumed for ETLF

$$S^h_{\rm bw}(f) = \left(\frac{4}{3}\pi G\rho_{0,\rm ug}\right)^2 (3p+1) S_{\rm bw}(\xi_x; f)\,\frac{4}{L^2(2\pi f)^4}$$

We assume ⅓ compressional wave in power spectral density.

Cavern acoustic spectrum assumes the median level of Kagra, which level spectrum should we use?)



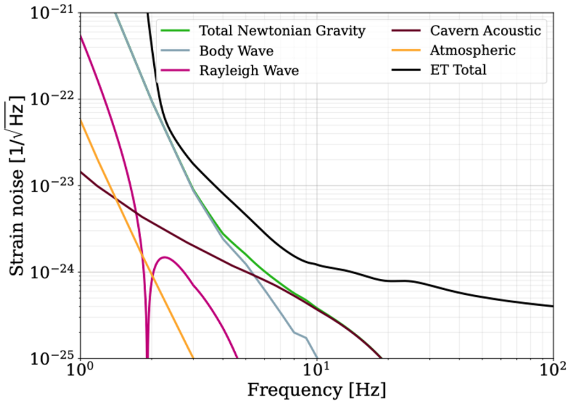


Figure 6: Newtonian noise budget of LF detector with seismic waves data from Sardinia site. A factor of 3 mitigation of amplitude noise is included.

The infrastructure noise of ET

- Residual gas noise
  - Both the scattering noise component and the gas damping component of the residual gas noise are included in the noise budget.
  - LF chamber pressure: 3e-8 Pa, HF chamber pressure: 3e-7 Pa
  - LF tube pressure: 1.5e-8 Pa, HF tube pressure: 1.5e-8 Pa

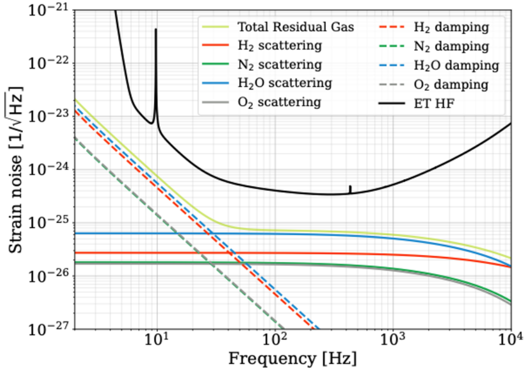


Figure 8: Residual gas noise budget of HF detector.

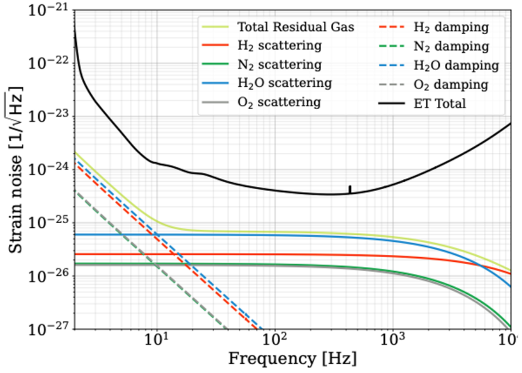


Figure 9: Residual gas noise budget of LF detector.

Table 1: Infrastructure parameters of ET detectors.

Parameter	**Units**	**HF detector**	**LF detector**
Detector depth	m	250	250
Cavern diameter	m	25	25
Arms length	km	10	10
Residual H_2 parameters			
Beamtube pressure	Pa	1×10^{-8}	1×10^{-8}
ChamberPressure	Pa	2×10^{-7}	2×10^{-8}
Mass	kg	3.35×10^{-27}	3.35×10^{-27}
Polarizability	m^3	7.87×10^{-31}	7.87×10^{-31}
Residual N_2 parameters			
Beamtube pressure	Pa	2.5×10^{-10}	2.5×10^{-10}
ChamberPressure	Pa	5×10^{-9}	5×10^{-10}
Mass	kg	4.65×10^{-26}	4.65×10^{-26}
Polarizability	m^3	1.71×10^{-30}	1.71×10^{-30}
Residual H_2O parameters			
Beamtube pressure	Pa	5×10^{-9}	5×10^{-9}
ChamberPressure	Pa	1×10^{-7}	1×10^{-8}
Mass	kg	2.99×10^{-26}	2.99×10^{-26}
Polarizability	m^3	1.5×10^{-30}	1.5×10^{-30}
Residual O_2 parameters			
Beamtube pressure	Pa	2.5×10^{-10}	2.5×10^{-10}
ChamberPressure	Pa	5×10^{-9}	5×10^{-10}
Mass	kg	5.31×10^{-26}	5.31×10^{-26}
Polarizability	m^3	1.56×10^{-30}	1.56×10^{-30}

Quantum noise

- ❖ No mismatch included yet

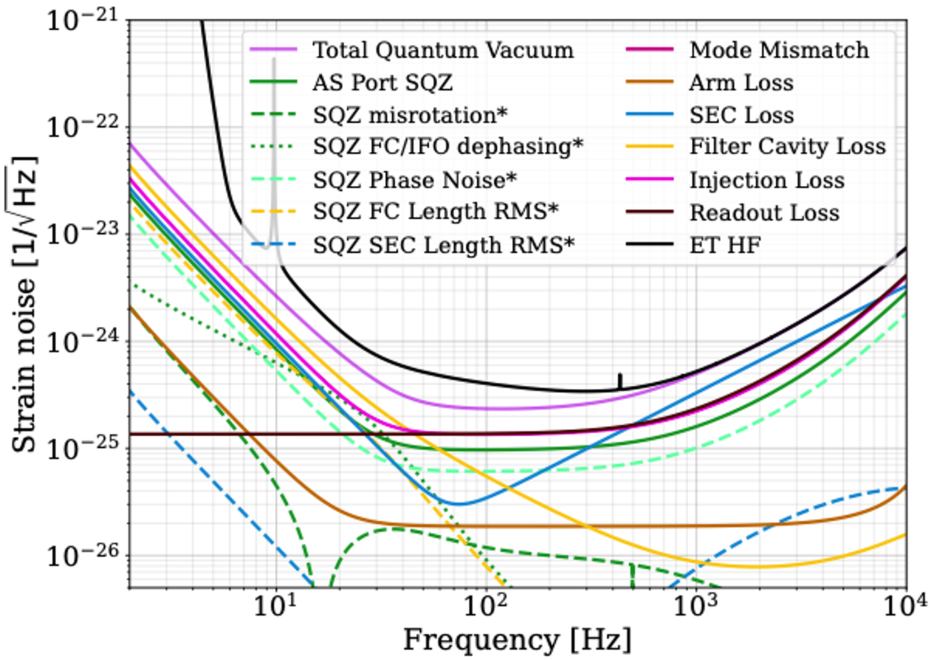


Table 2: Parameters for quantum noise model of ET detectors.

Parameter	Units	HF Detector	LF Detector
Interferometer configuration	Tuned dual-recycled Fabry-Perot-Michelson		
Laser wavelength	nm	1064	1550
Laser power	W	500.0	1.7
Arms length	km	10	10
Arms circulating power	kW	3000	18
ITM transmissivity	%	0.7	0.7
Arm finesse		888	888
Arm half-bandwidth	Hz	8.3	8.3
Power recycling cavity (SEC)			
SEM transmissivity	%	0.045	0.026
Signal extraction cavity (SEC)			
SEM transmissivity	%	5.0	20
SEC tunephase	rad	0.0	0.75
SEC length	m	100	100
Squeezing injection			
Squeezing type	Frequency-dependent squeezing		
Injected squeezing	dB	18	10
Injected squeezing angle	rad	0.00	0.3
Filter cavity length	m	1000	1000/1000
Filter cavity input transmissivity	ppm	1773	357.1/ 138
Filter cavity half-bandwidth	Hz	21.16	4.26/1.65
Filter cavity detuning	Hz	-21.15	19.51/-7.65
Readout loss			
Photodetector Inefficiency	%	1	1
Faraday isolator	%	1	1
Output mode cleaner	%	1	1
Internal loss of interferometer			
ETM transmissivity	ppm	5.0	5
Arm Loss per mirror	ppm	37.5	20
Arm round trip loss	ppm	80	45
SEC loss	ppm	1000.0	1000
Squeezing injection loss			
OPA cavity	%	1.0	1
Faraday isolators	%	2	3
FC end mirror transmittance	ppm	5	5
FC round-trip loss	ppm	45	20
Phase noise			
Squeezer phase noise RMS	rad	10e-3	10e-3
Local oscillator angle noise RMS	rad	10e-3	10e-3
Filter cavity length RMS	pm	1	1/1
SEC length RMS	pm	1	1

SEC length is chosen to be 100m, giving potential to explore couple-cavity resonance @ 2kHz.

Quantum noise

❖ No mismatch included yet

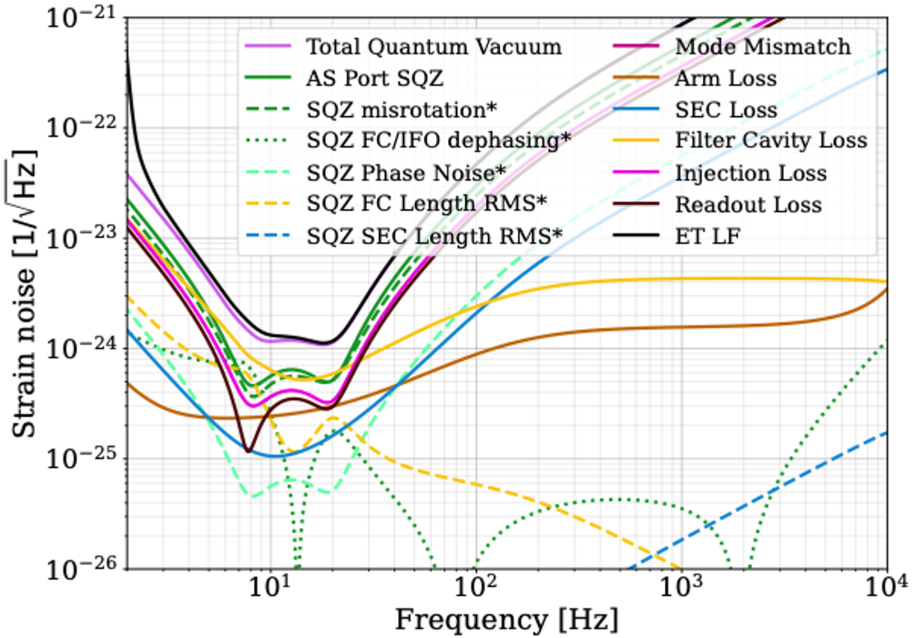
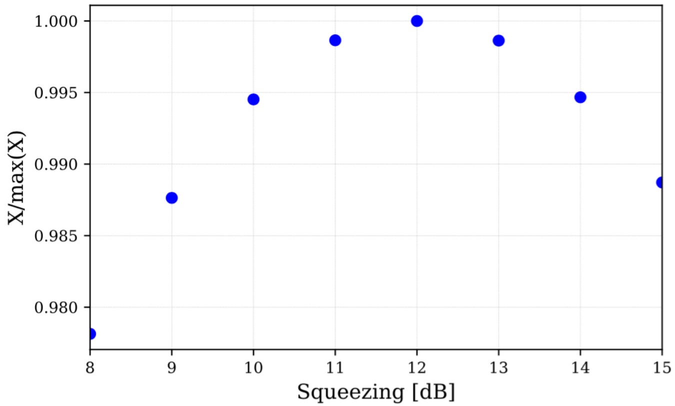


Figure 11: Quantum noise budget of LF detector.

Parameter optimisation

➢ Figure of merit:

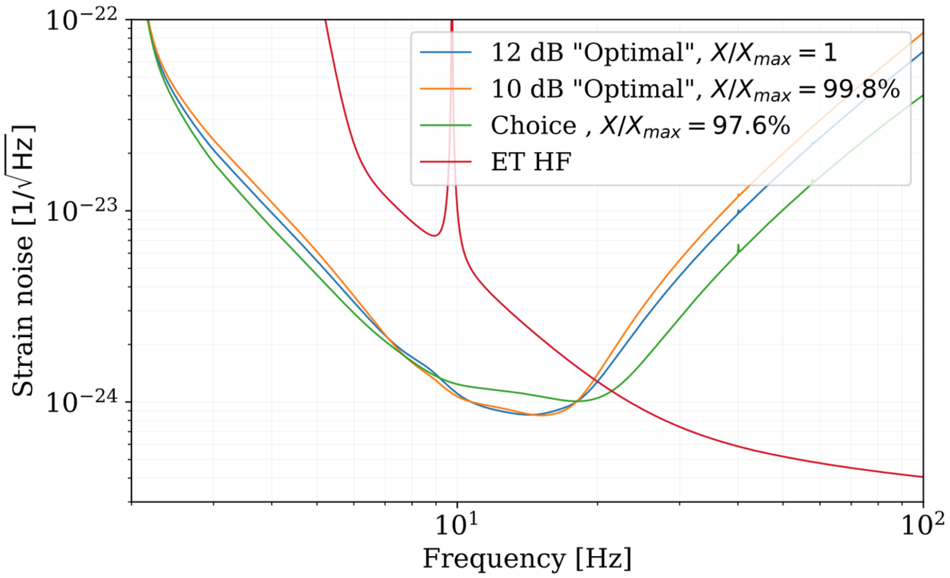
$$X = \sqrt{\int_{f_{min}}^{f_{max}} \frac{f^{-7/3}}{S_h} df}$$



Squeezing is maginely helpful and can make it worse.

Quantum noise

- Do we need to fine-tune and choose the “optimal squeezing” and “optimal parameter”?



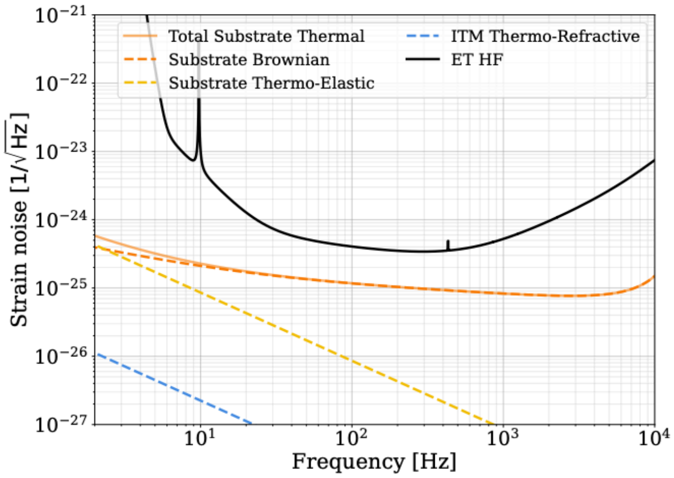
- ➔ 12 dB optimal: 'Ti': 2.05e-4 ,'Ti': 1.08e-4
- ➔ 10 dB optimal: 'Ti': 1.71e-4, 'Ti': 9.18e-5
- ➔ 10 dB, choice :'Ti': 1.38e-4, 'Ti': 3.57e-4

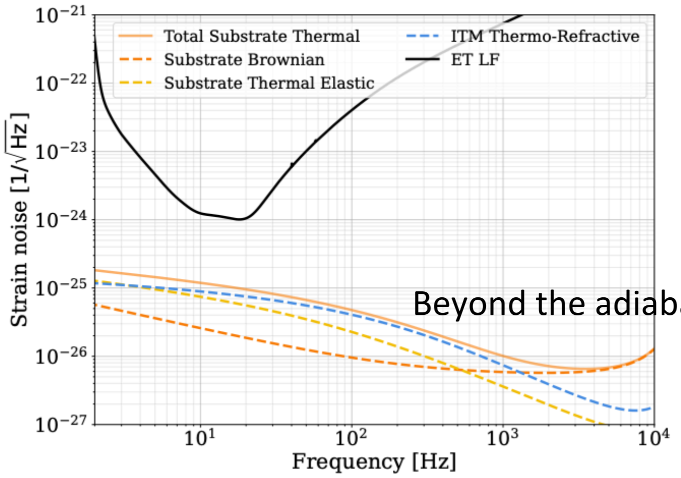
We may **not** need to adopt the “optimal” choice, because

1. Technical difficulties.
2. It relays on artificially estimated imperfections.
3. The figure of merit is almost valid for the BNS horizon. ET emphasizes on LF and larger masses.

Thermal noise of the test masses

- ❖ Substrate thermal noise
  - ➢ Three main contributors: Brownian thermal noise, Thermo-Elastic noise and ITM Thermo-Refractive noise are included in the estimate.
  - ➢ ETHF uses fused silica test masses of 62cm x 30cm and 200kg
  - ➢ ETLF uses silicon test masses of 45cm x 57cm and 211kg (production limited)





Beyond the adiabatic approximation

Thermal noise of the test masses

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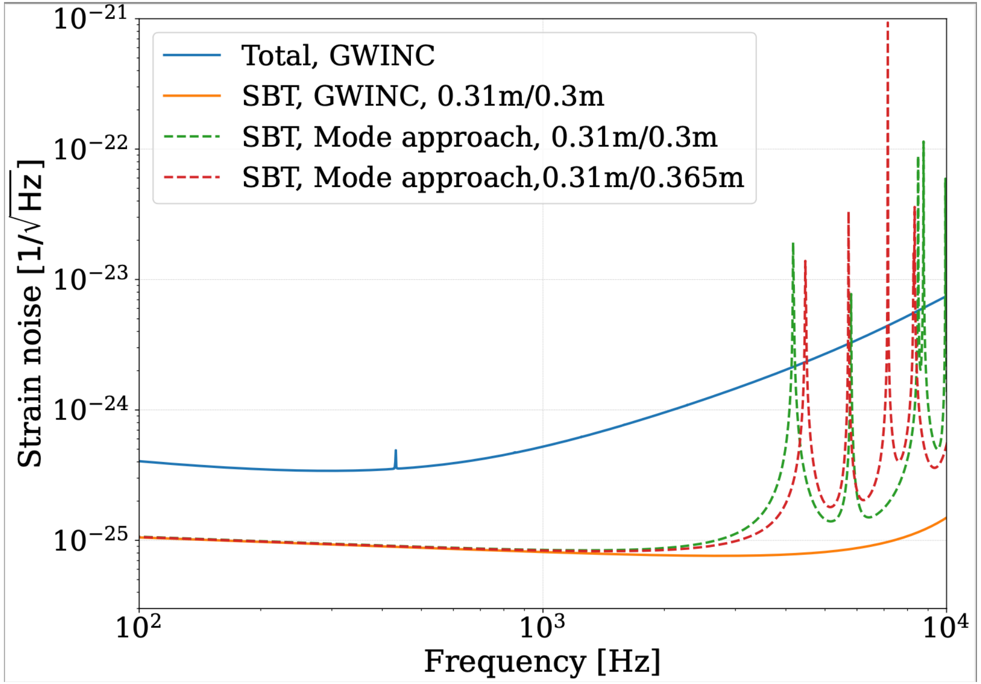
- Substrate thermal noise
  - ETHF uses fused silica test masses of 62cm x 30cm and 200kg.
  - With such large scale mirror, the bulk mode will enter the detection band.



The mode expansion simulation is made with "CYPRES". https://www.sciencedirect.com/science/article/abs/pii/037596019400983V

The mirror geometry is a topic TBC, not only for the thermal noise but also for the parametric instability.

Thermal noise of the test masses

Table 3: Parameters of test masses of ET detectors.

Parameter	Units	HF Detector	LF Detector
General optical parameters of TM			
Mirror radius	cm	31.0	22.5
Mirror thickness	cm	30.0	57
Laser beam radius	cm	12.0	9
TM Temperature	K	290.0	10
Substrate parameters			
Substrate material		Silica	Silicon
Substrate density	kg/m^3	2200.0	2331
Young's modulus	Pa	7.3×10^{10}	1.6×10^{11}
Poisson's ratio	1	0.2	0.2
Specific heat	J/(kg·K)	739	0.276
Thermal conductivity	W/(m·K)	1.4	1000
Thermal expansion coefficient	1/K	3.9×10^{-7}	4.8×10^{-10}
Refractive index	1	1.4	3.5
Thermorefractive coefficient, dn/dT	[1/K]	8.5×10^{-6}	5×10^{-7}
Loss angle		$7.6 \times 10^{-12} \times f^{0.77}$	$3 \times 10^{-13} \times f$

Thermal noise of the test masses

- Coating thermal noise
  - Two main contributors: Coating Brownian and Coating Thermo-Optic
  - ETHF coating applies traditional Ta2O5/SiO2 pair with 4 times lower mechanical loss than aLIGO/aVirgo coatings.
  - ETLF applies the use multi-material coating design with two top bi-layers of Ta2O5/SiO2 (with low optical absorption) and the rest of the stack of a-Si/SiO2:HfO2 bi-layers (with low mechanical loss)

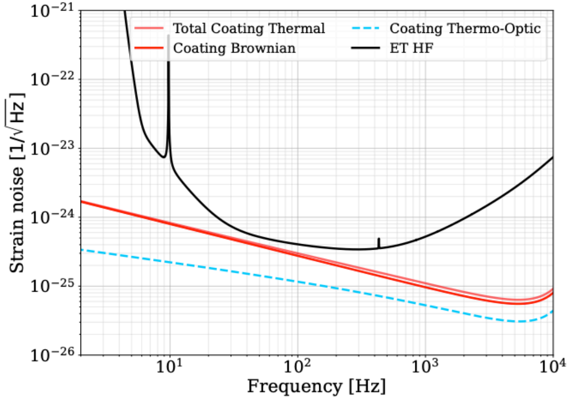


Figure 14: Coating thermal noise budget of HF detector.

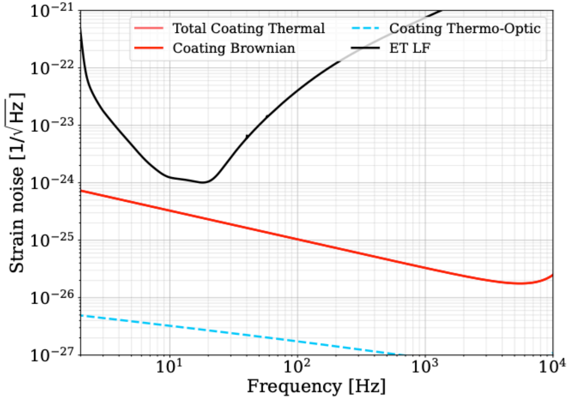


Figure 15: Coating thermal noise budget of LF detector.

Thermal noise of the test masses

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Table 4: Parameters of coatings of ET HF detector.

Parameter	Units	HF Detector
ITM coating bi-layers		8
ETM coating bi-layers		17
High-n layers material		TBD
Each layer thickness	Wavelength	0.25
Young's modulus	Pa	1.2×10^{11}
Poisson's ratio	1	0.29
Volumetric heat capacity	J/(m^3·K)	2.1×10^{6}
Thermal conductivity	W/(m·K)	33.0
Thermal expansion coefficient	1/K	3.6×10^{-6}
Refractive index		2.09
Thermorefractive coefficient	1/K	1.4×10^{-5}
Loss angle	1	$9.0 \times 10^{-5} \times f^{0.10}$
Low-n layers material		TBD
Layer optical thickness	Wavelength	0.25
Young's modulus	Pa	7.0×10^{10}
Poisson's ratio	1	0.19
Volumetric heat capacity	J/(m^3·K)	1.6×10^{6}
Thermal conductivity	W/(m·K)	1.4
Thermal expansion coefficient	1/K	5.1×10^{-7}
Refractive index	1	1.45
Thermorefractive coefficient	1/K	8.0×10^{-6}
Loss angle	1	$1.2 \times 10^{-5} \times f^{0.00}$

Thermal noise of the test masses

Table 6: Parameters of coatings of ET LF detector.

Parameter	Units	LF Detector
Layer material		Ta_2O_5
Young's modulus	Pa	1.4×10^{11}
Poisson's ratio	1	0.28
Specific heat	J/(kg·K)	2.1×10^{6}
Thermal expansion coefficient	1/K	3.6×10^{-6}
Thermorefractive coefficient, dn/dT	1/K	1.4×10^{-5}
Thermal conductivity	W/(m·K)	33.00
Refractive index	1	2.05
Loss angle	1	5.0×10^{-4}
Layer material		SiO_2
Young's modulus	Pa	7.2×10^{10}
Poisson's ratio	1	0.17
Specific heat	J/(kg·K)	1.6×10^{6}
Thermal expansion coefficient	1/K	5.1×10^{-7}
Thermorefractive coefficient, dn/dT	1/K	8.0×10^{-6}
Thermal conductivity	W/(m·K)	1.38
Refractive index	1	1.44
Loss angle	1	8.5×10^{-4}
Layer material		$SiO_2 : HfO_2$
Young's modulus	Pa	1.8×10^{11}
Poisson's ratio	1	0.20
Specific heat	J/(kg·K)	1.6×10^{6}
Thermal expansion coefficient	1/K	5.1×10^{-7}
Thermorefractive coefficient, dn/dT	1/K	8.0×10^{-6}
Thermal conductivity	W/(m·K)	1.38
Refractive index	1	1.91
Loss angle	1	3.8×10^{-4}
Layer material		a-Si
Young's modulus	Pa	1.5×10^{11}
Poisson's ratio	1	0.20
Specific heat	J/(kg·K)	2.1×10^{6}
Thermal expansion coefficient	1/K	3.6×10^{-6}
Thermorefractive coefficient, dn/dT	1/K	1.4×10^{-5}
Thermal conductivity	W/(m·K)	33.00
Refractive index	1	3.48
Loss angle	1	1.7×10^{-5}

Suspension thermal noise

- Suspension TN is calculated for the payload stage, which is following the Virgo design of *double pendulum*
- Two main contributors: Brownian noise from the bulk and surface loss of the wires and Thermo-Elastic noise
- **ETHF:**
  - Tapered fused silica suspension fiber of length 0.7m (5cm+0.6m+5cm) for test mass (Not studied by the collaboration?), 0.6m *cylindrical* for marionette stage.
  - Tapered fiber profile for cancellation of thermo-elastic noise
  - Stress on each fiber is 770 MPa, a factor of 6 safety margin vs. breaking stress
- **ETLF:**
  - Aplies silicon *cylindrical rods* of length 1.2m for suspending the test mass and of length 1m for the marionette
  - Temperature gradients are not accounted for in the current model. Uniform 10K temperature along the suspension rods is assumed
  - Maximal stress on each fiber is 35 MPa, a factor of 6 safety margin vs. breaking stress (200-300 Pa. (In ISB workshop, we discussed the safety margin)

Suspension thermal noise

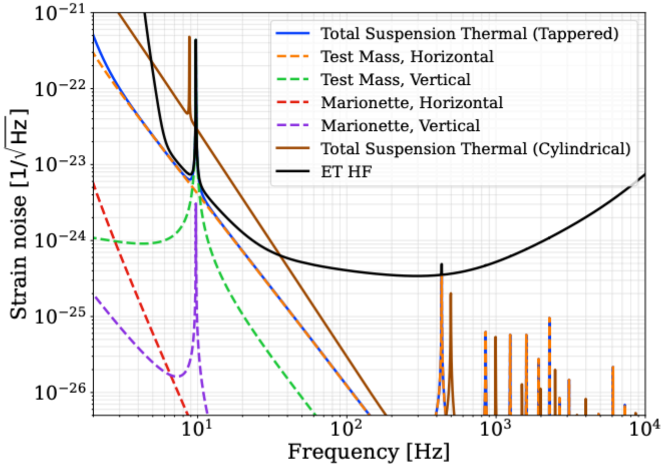

Figure 16: Suspension thermal noise budget of HF detector.

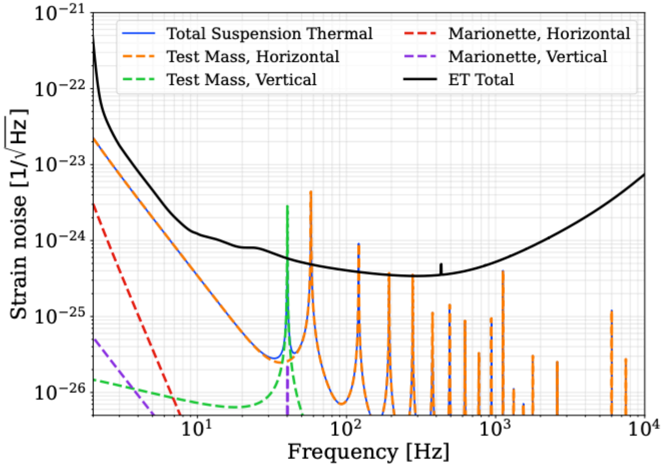

Figure 17: Suspension thermal noise budget of LF detector.

	Temperature	Bulk loss	Surface loss	Elastic loss	Break stress
Silica	290K	4.1e-10	6.5e-12m	Cancelled	~4.2Gpa
Silicon	10-18K	1e-9	0.5e-12m	Low TEC	200-300MPa

Suspension thermal noise

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Table 7: Parameters of suspension payload of HF detector.

Parameter	**Units**	**HF Detector**
Payload Design	Double pendulum (marionette + test mass)	
Temperature	K	290.0
SiO_2 parameters at 290K		
Density	kg/m^3	2.2×10^3
Heat capacity	J/(kg·K)	772
Thermal conductivity	W/(m·K)	1.38
Young's modulus	Pa	7.20×10^{10}
Thermal expansion coefficient	1/K	3.9×10^{-7}
Thermo-elastic coefficient, dY/dT/Y	1/K	1.52×10^{-4}
Mechanical loss angle	1	4.1×10^{-10}
Dissipation depth	mm	15
Test mass stage parameters		
Mass	kg	200
Fiber Material	SiO_2	
Number of wires	1	4
Fiber stress	MPa	770
Fiber Shape	Tapperd	
Head length	mm	50
Middle length	m	0.6
End length	mm	50
Head diameter	mm	1.8
Middle diameter	mm	0.9
End diameter	mm	1.8
Marionette stage parameters		
Mass	kg	200
Fiber Material	SiO_2	
Number of wires	1	1
Fiber stress	MPa	740
Fiber Shape	Cylindrical	
Fiber length	m	0.6
Fiber diameter	mm	2.6

Suspension thermal noise

Table 8: Parameters of suspension payload of LF detector.

Parameter	Units	LF Detector
Payload Design	Double pendulum (marionette + test mass)	
Temperature	K	10
Silicon parameters at 10 K		
Density	kg/m^3	2.3×10^3
Heat capacity	J/(kg·K)	0.276
Thermal conductivity	W/(m·K)	2110
Young's modulus	Pa	1.32×10^{11}
Thermal expansion coefficient	1/K	8.1×10^{-10}
Thermo-elastic coefficient, dY/dT/Y	1/K	?
Mechanical loss angle	1	1.0×10^{-9}
Dissipation depth	mm	0.5
Test mass stage parameters		
Mass	kg	211
Fiber material	Silicon	
Fiber shape	Cylindrical	
Number of fibers	1	4
Fiber stress	Mpa	34
Fiber length	m	1.2
Fiber diameter	mm	4.4
Marionette stage parameters		
Mass	M kg	211
Fiber Material	Silicon	
Fiber shape	Cylindrical	
Number of fibers	1	1
Fiber stress	Mpa	35
Fiber length	m	1.0
Fiber diameter	mm	12.4

Summary of changes/improvements from ET D

- ➢ Include loss and phase noise budget in quantum noise modeling
- ➢ Apply suspension thermal noise model and payload design.
- ➢ Detailed budget of Seismic N and NN based on the measurement at sites.
- ➢ Include gas-damping noise.
- ➢ Optimized power recycling cavity gain.

ET HF

- ❖ Improved suspension thermal noise (from tapped fiber geometry)
- ❖ Update SEC length from 30m to 100m, to be more realistic and allows to explore sensitivity @2kHz only by replacing SEM.
- ❖ Increase the FC length from 300m to 1km, in order to benefit at the LF-HF joint frequency.

ET LF

- ❖ Optical parameters update following HF sensitivity update.
- ❖ FC length from 10km to 1km (cost driven)
- ❖ Mirror thermoelastic & refractive noise are modeled beyond adiabatic approximation.
- ❖ Update the coating to multi material design.

Further potential improvements

1. LF FC from 1km to 10km.

2. Carven acoustic NN can be a factor of 3 lower.

3. Implement fiber stress, a factor of 3 safe margin vs. the break stress for LF suspension. (Assumed in https://apps.et-gw.eu/tds/?content=3&r=18267)

Sensitivity & horizon