ET noise budget

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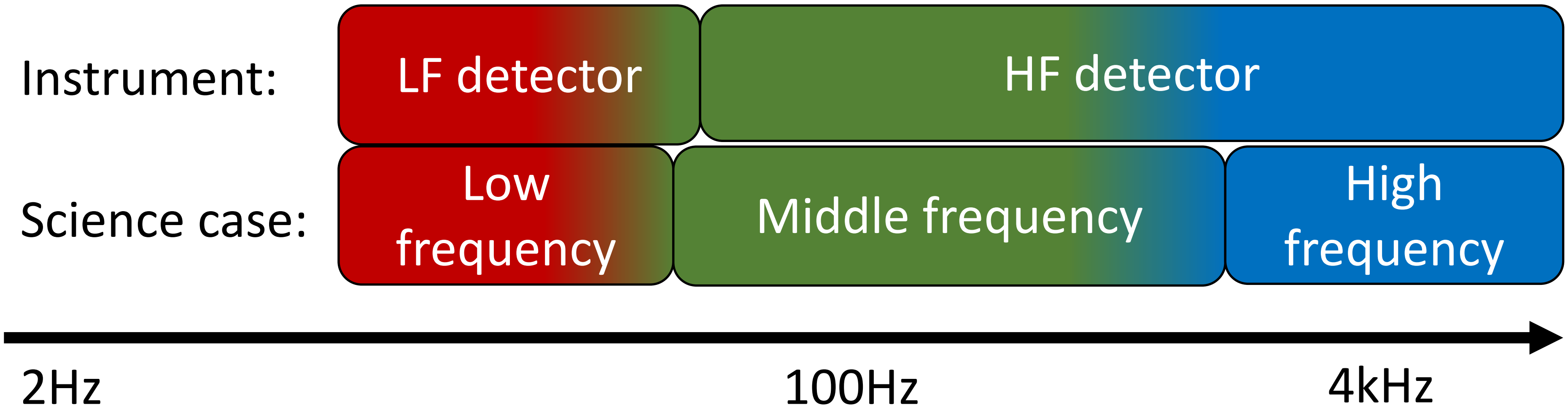
ISB workshop, 2022.10.18

Contents



Noise surces:

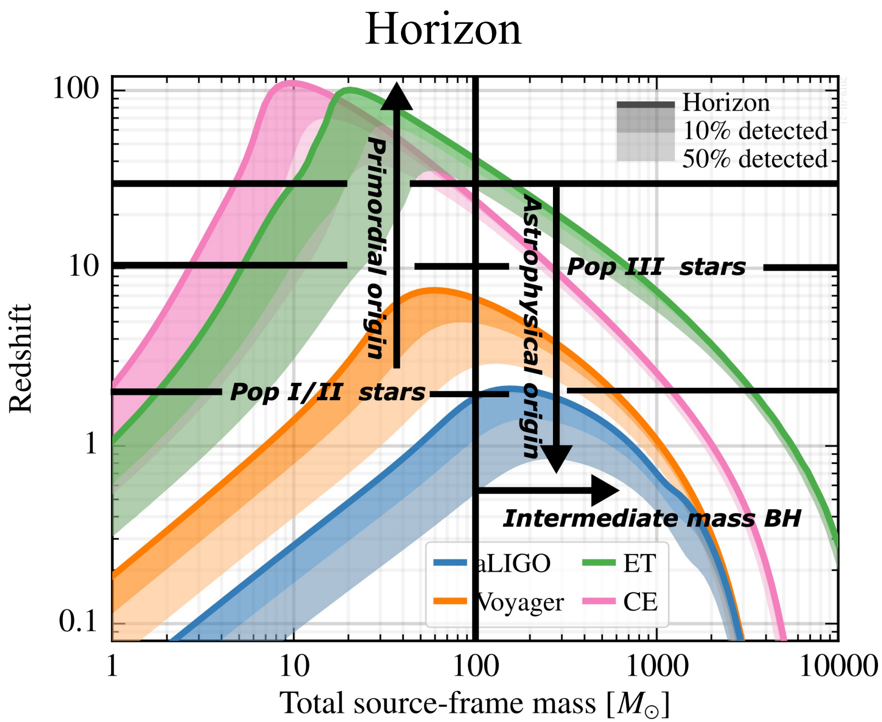
Seismic,
Newtonian,
Residual gas, } Infrastructure

Suspension thermal,
Mirror thermal: coating & substrate, } Material

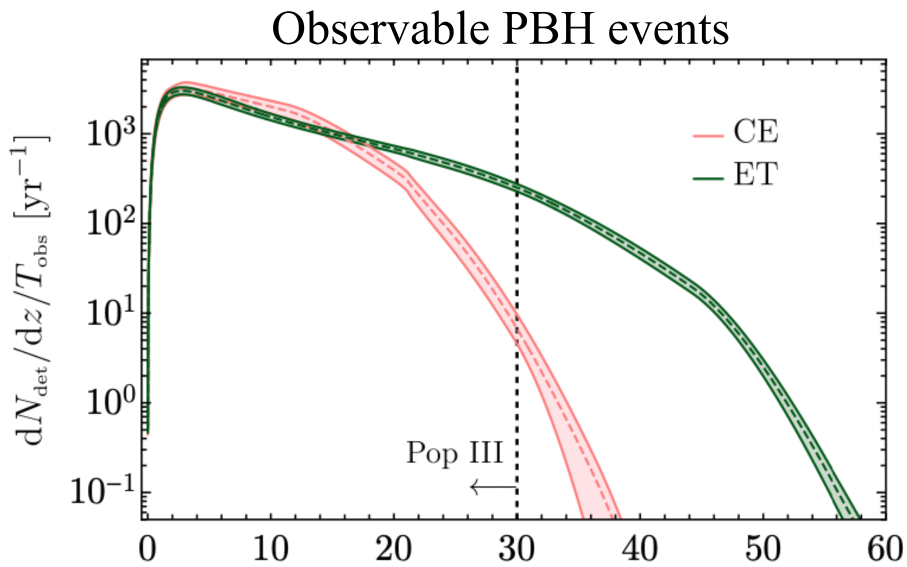
Quantum. } Laser/interferometry

LF detector

Low frequency science



Evan D Hall and Matthew Evans 2019 *Class. Quantum Grav.* **36** 225002
further edited by T. Zhang



$$N_{\rm det}^{\rm ET}(z > 30) = 1315^{+305}_{-168}\ /{\rm yr}.$$

$$N_{\rm det}^{\rm CE}(z > 30) = 12^{+22}_{-11}\ /{\rm yr}.$$

Note this is with CE1 sensitivity!

V. De Luca *et al* JCAP05(2021)003

Intermediate mass BH:

1. Astrophysical BBH evolution from the first stars.
2. BBH from primordial original, dark matter.
3. Seed black hole, formation of supermassive BH in the centre galaxy.

Low frequency sensitivity

The desirable low frequency design sensitivity benefits from:

Cryogenic temperature
- Suspension thermal noise
- Mirror thermal noise

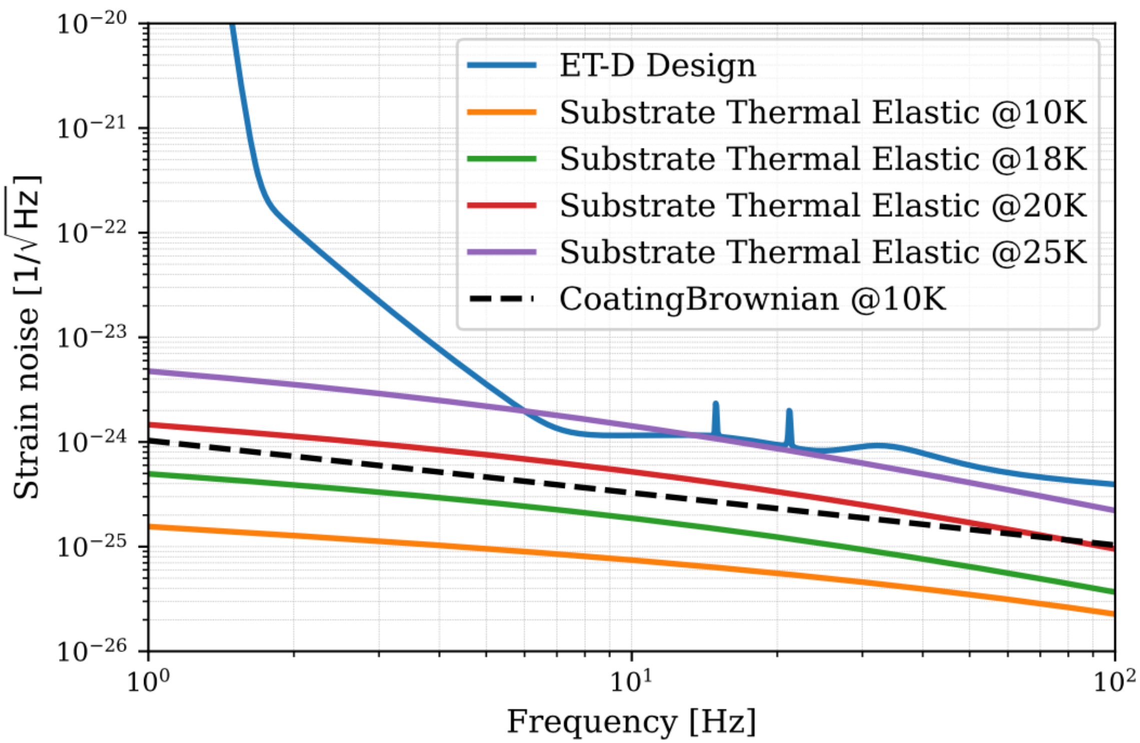
Underground
- Surface-wave Newtonian noise
- Atmosphric Newtonian noise

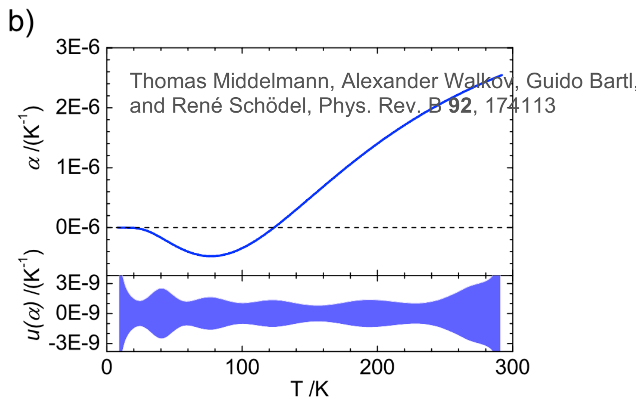
Detuned SEC
- Quantum radiation pressure noise

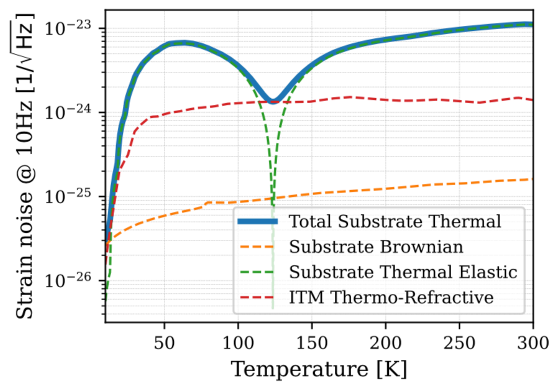
Substrate thermo-elastic noise

Q: What is the targeted cryogenic temperature ? 10K/20K/30K?

A: For mirror thermal noise, the cryogenic temperature is largely constrained by the silicon substrate thermal elastic noise. <u>The temperature should not be higher than 18K!</u>

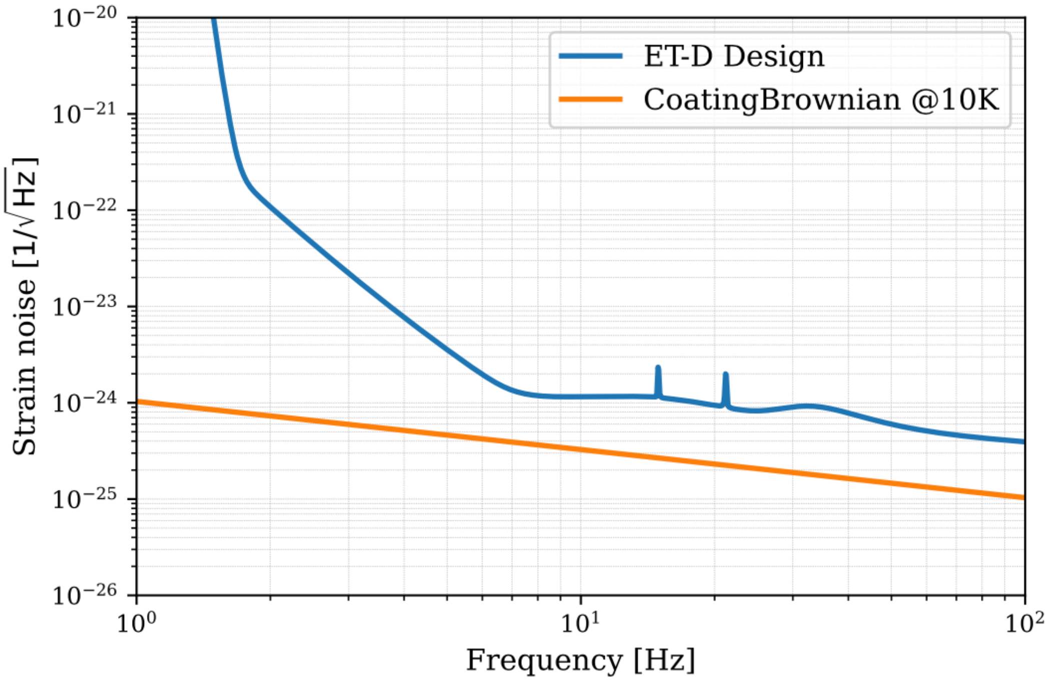






Coating thermal noise

Coating choice: 4 materials



To be updated:
*The coating design is at **10K**, however, the suspension heat extraction gives result of ~**20K**.*

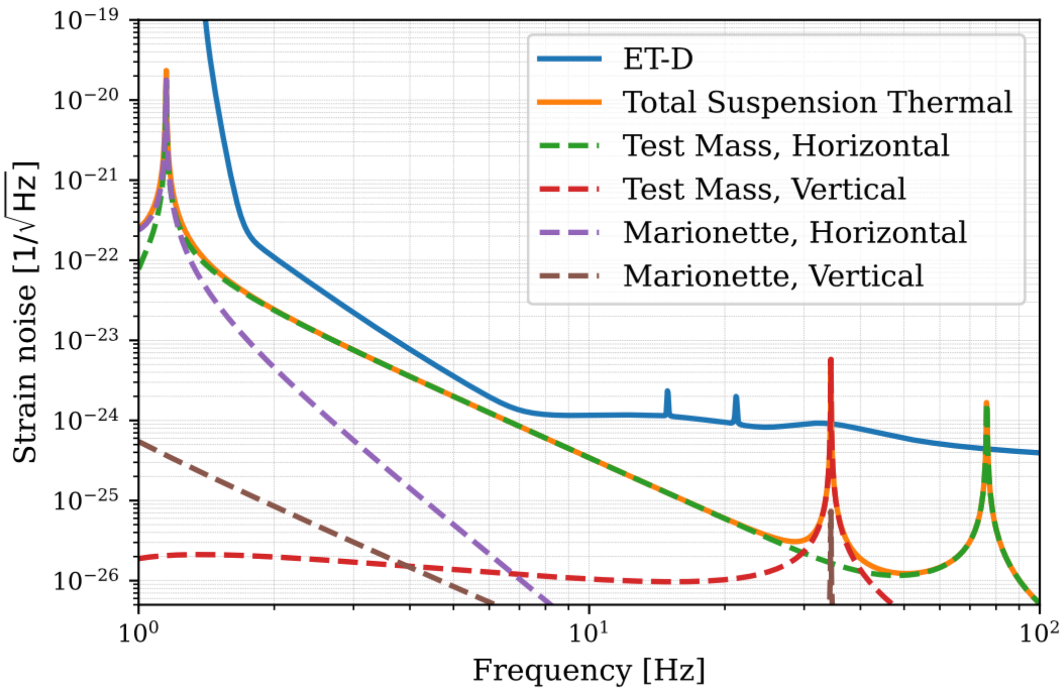
Wavelength 1550nm
Beam size: 9cm
Silicon mirror diamater: 45cm.

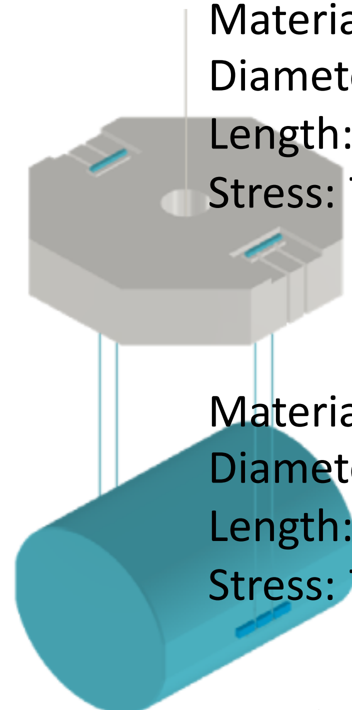
Kieran Craig, etal. Phys. Rev. Lett. **122**, 231102 – Published 13 June 2019

Case	Bilayers ETM (ITM)	Transmission ETM (ITM) (ppm)	Heat treatment (°C)	CTN ETM (ITM) ($\times 10^{-21}$ m/$\sqrt{\text{Hz}}$)	CTN_D	α_{HR} (ppm)
(a)	$18\,(7) \times SiO_2/Ta_2O_5$	4 (8500)	600	4.0 (2.4)	6.6	0.6
(b)	$10\,(4) \times SiO_2{:}HfO_2/a\text{-}Si$	2 (9000)	400	1.4 (0.9)	2.4	11.9
(c)	$2 \times SiO_2/Ta_2O_5 + 10\,(4) \times SiO_2{:}HfO_2/a\text{-}Si$	4.4 (6000)	400	1.9 (1.6)	3.5	3.4
ET-LF requirement [13]		5 (7000)			≈3.6	≤ 5

Suspension thermal noise

The LF suspension thermal noise is modelled at 20K, I put **18K** in the noise budget as the least senario.





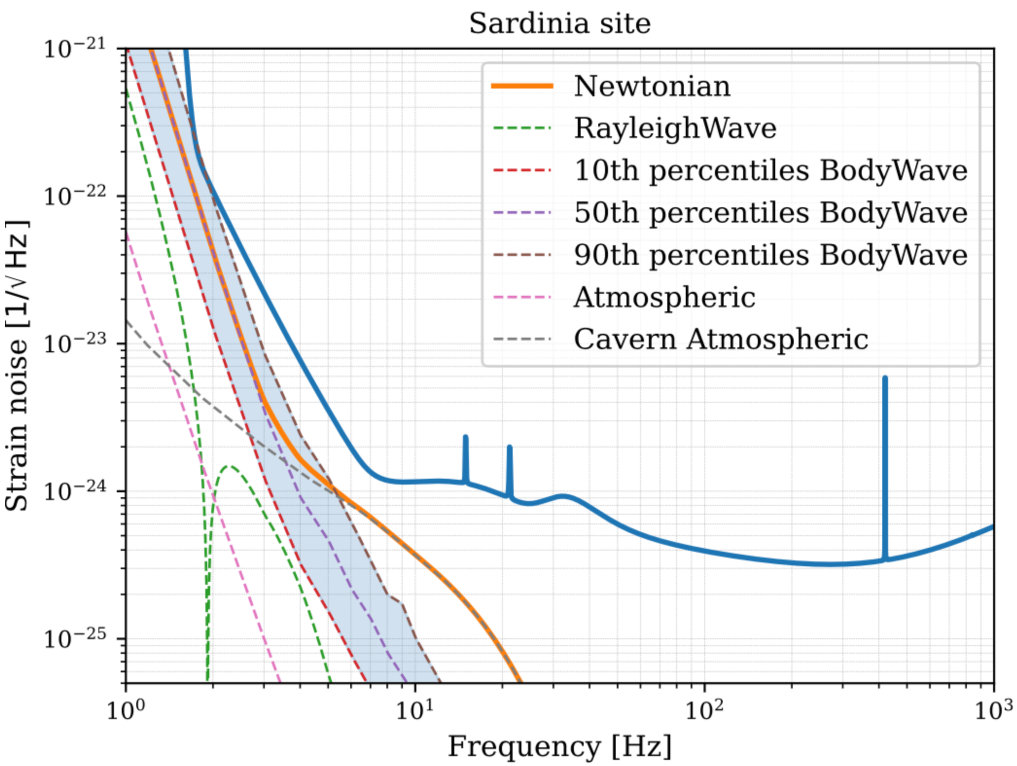
Material: Silicon
Diameter: 7mm
Length: 1m
Stress: 70Mpa (safe factor 3)

Material: Silicon
Diameter: 3mm
Length: 1.2m
Stress: 70Mpa (safe factor 3)

More details in ET-0235A-22, ET-0230A-22

Newtonian noise

Underground



<u>What's the infrastructure model we should use here?</u>

Depth: 250m.
Cavern radius is set 12.5m?.

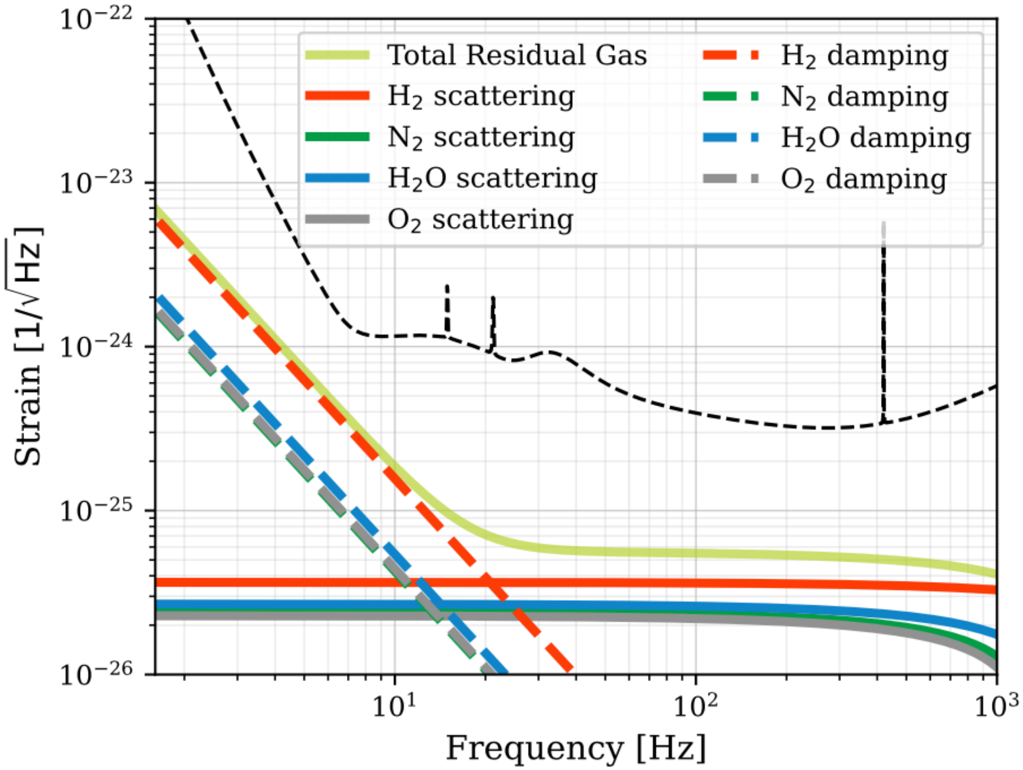
Here we assume a factor 3 cancellation for seismic NN and for acoustic NN.

In the body wave NN, it assumes equal contribution from cavern walls displacement and compression of rock (assuming 1/3 compressional waves).

Eq (7) in Rev. Sci. Instrum. ***91****, 094504 (2020)*

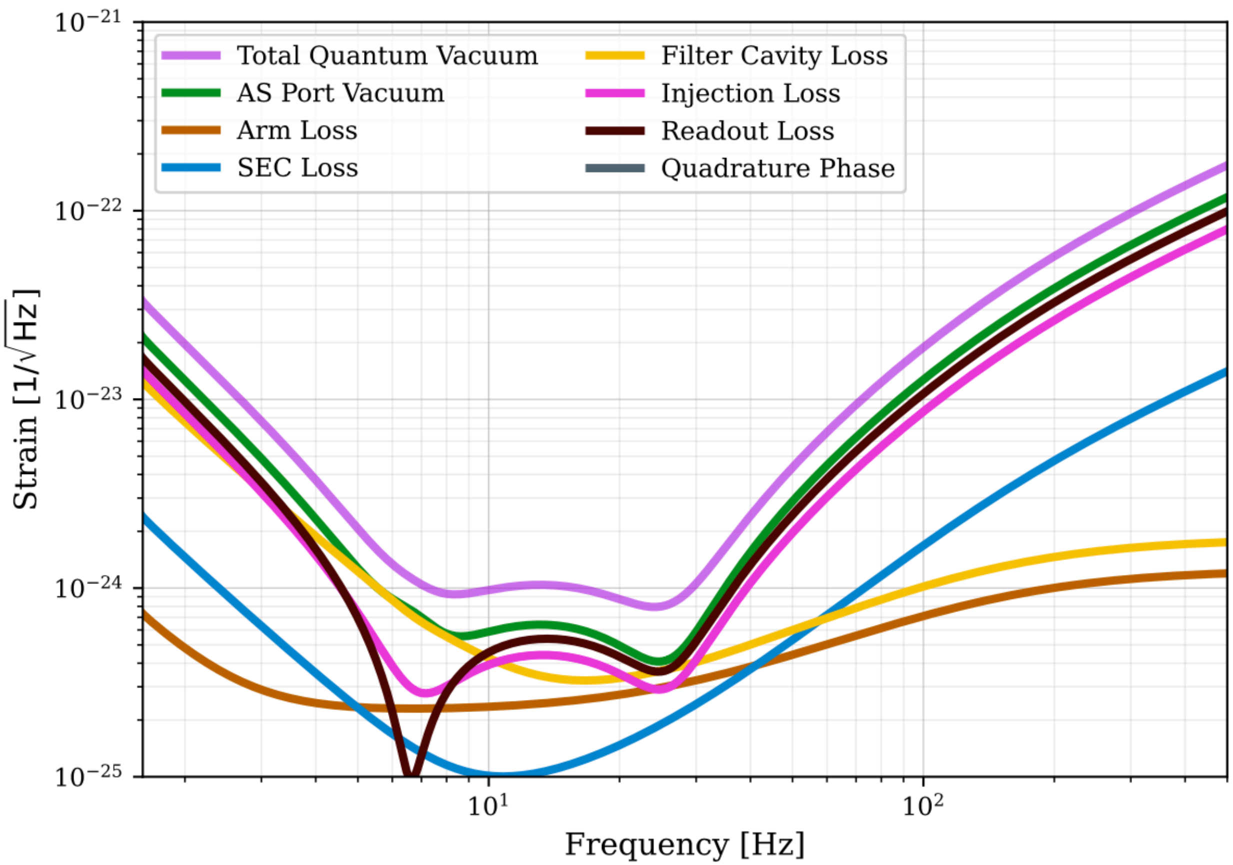
Gas damping noise

Note that in suspenison thermal noise model, we set viscous Q as larger as 1e20 to eliminate such effect.




```
H2:
  BeamtubePressure: 2.0e-8
  ChamberPressure: 5.0e-8
  mass: 3.35e-27
  polarizability: 7.87e-31
N2:
  BeamtubePressure: 5.0e-10
  ChamberPressure: 1.0e-9
  mass: 4.65e-26
  polarizability: 1.71e-30
H2O:
  BeamtubePressure: 1.0e-9
  ChamberPressure: 2.0e-9
  mass: 2.99e-26
  polarizability: 1.50e-30
O2:
  BeamtubePressure: 5e-10
  ChamberPressure: 1.0e-9
  mass: 5.31e-26
  polarizability: 1.56e-30
```

Quantum noise



Parameters	
Wavelength	1550nm
Arm power	18kW
ITM/ETM T	7000/5 ppm
SEC tuning	0.6rad
SEC T	0.2
FCL length	>=5km
FC RT loss	>=30ppm
FC EM T	5ppm
Input Sqz	14dB
Input loss	2%
Readout loss	3%
SEC loss	1000ppm
Arm RT loss	40ppm

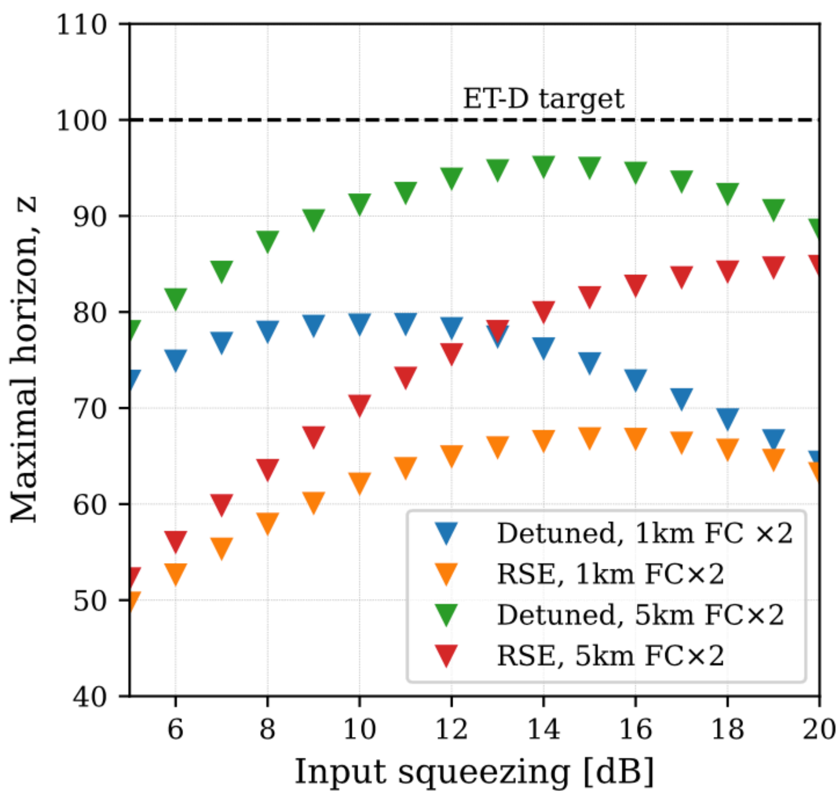
Quantum noise optimisation

ET-D
FC: 10km

ESFRI
FC: 1km

Now
FC:>5km

Detuned SEC



Except loss of squeezing, detuend SEC is especially sensitive to the anti-squeezing induced from dephasing (originating from FC loss & phase noise).

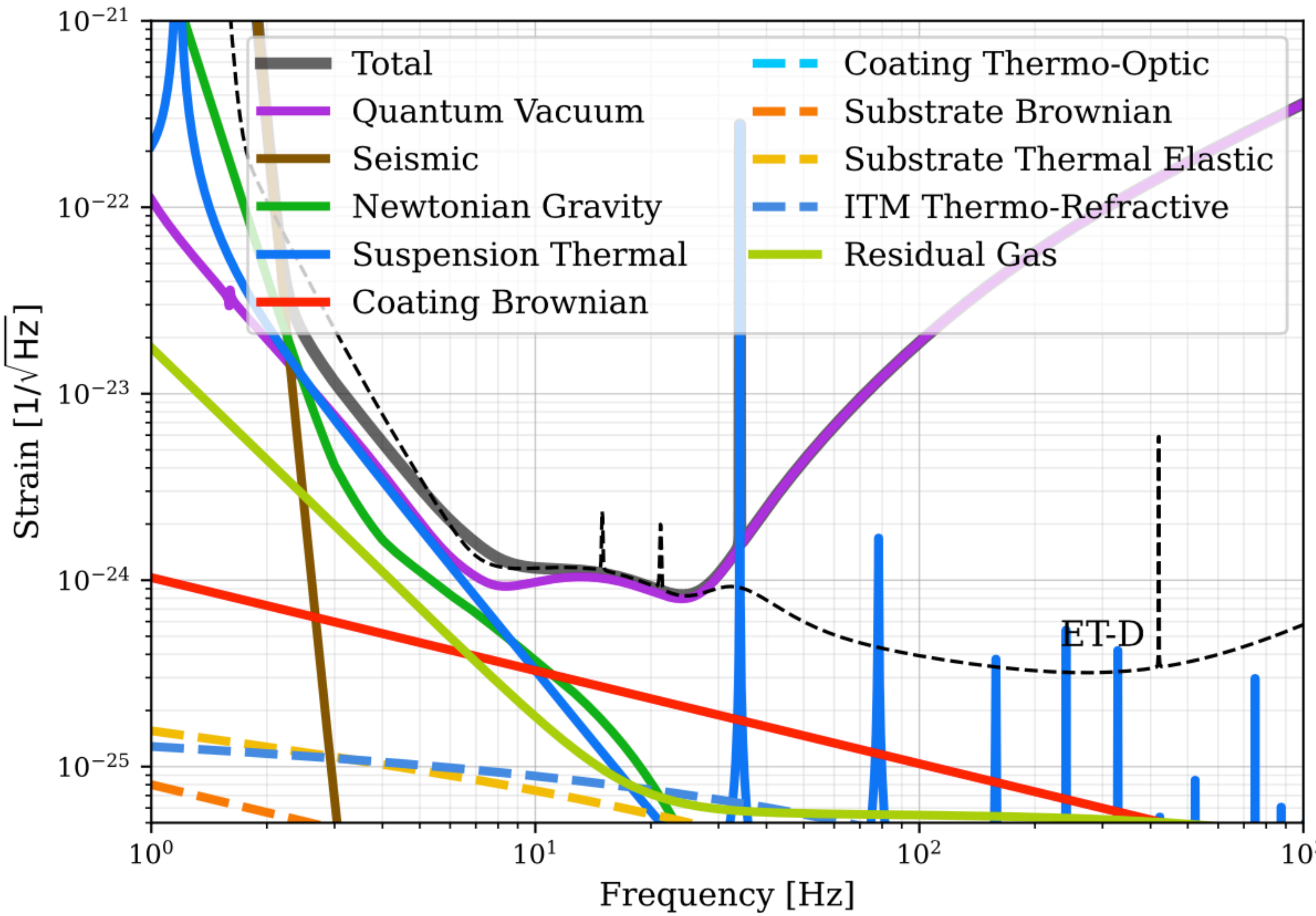
$$S_{\pm} \equiv (1 - \Xi'(\Omega))e^{\pm 2r} + \Xi'(\Omega)e^{\mp 2r}$$

$$\sqrt{\Xi(\Omega)} \approx \Lambda_{\rm fc}/T_{\rm fc}$$

Consider only FC loss effect here for the lower bound estimation.

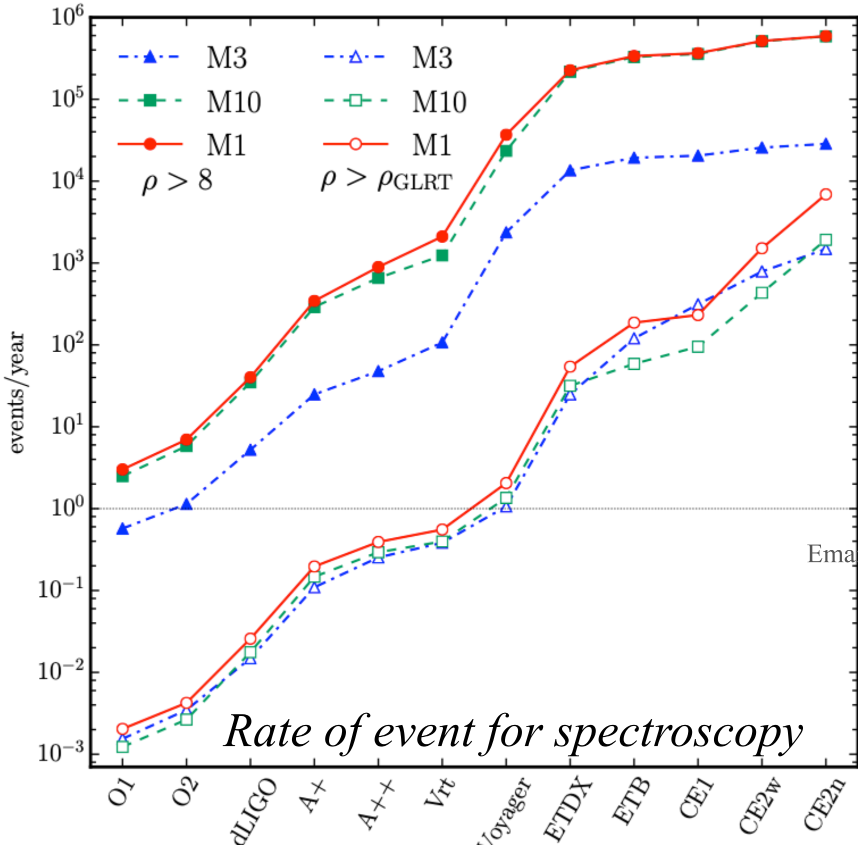
To be updated:
Inclued also the FC phase noise.

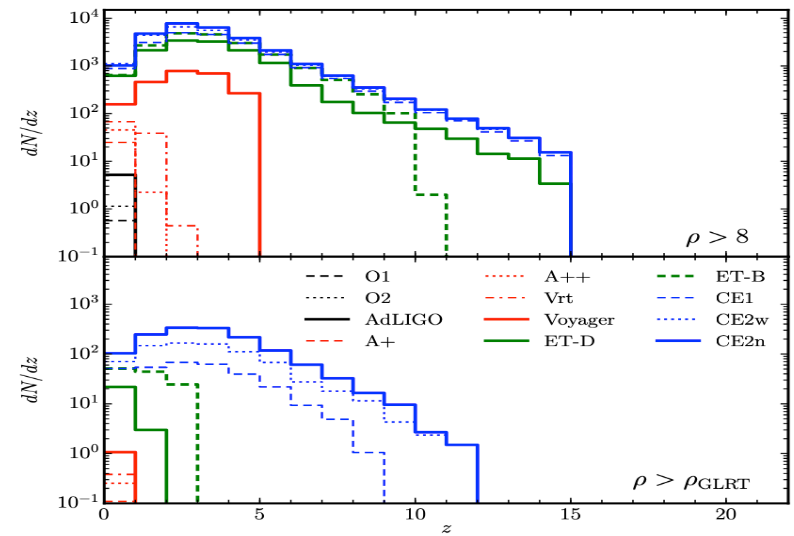
ET-LF noise budget



HF detector

Middle frequency science





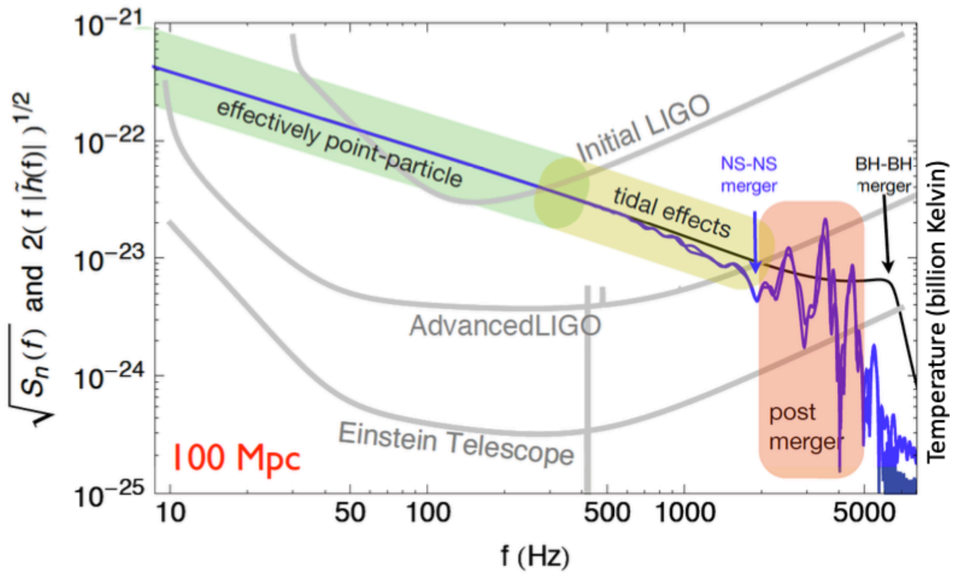
Emanuele Berti, etal. Phys. Rev. Lett. **117**, 101102 – Published 2 September 2016

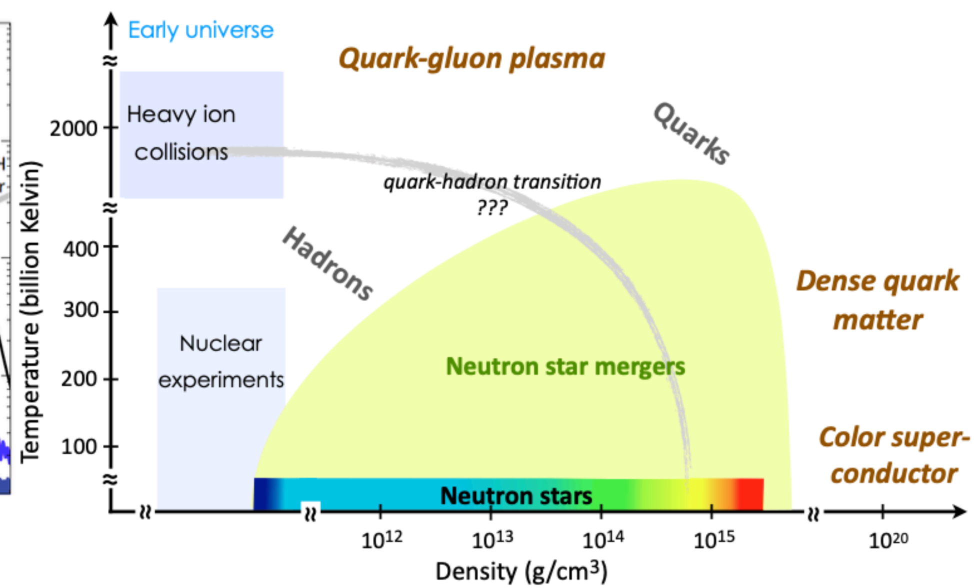
With SNR threshold that allows to resolve either 33 or 44 mode, a single ET allow to reach z~2, only CE can reach z~10 with has better sensitivty at hundread Hz.

BBH ringdown signal:

1. Test GR in strong gravity, Spectroscopy.
2. Exotic compacts, quantum gravity.

High frequency science





BNS signals:

1. Dense matter physics: from pre-merger to post-merger.
2. Post-merger remnant, Gamma-Ray burst Engine
3. Heavy elements, chemical evolution.

Middle and high frequency sensitivity

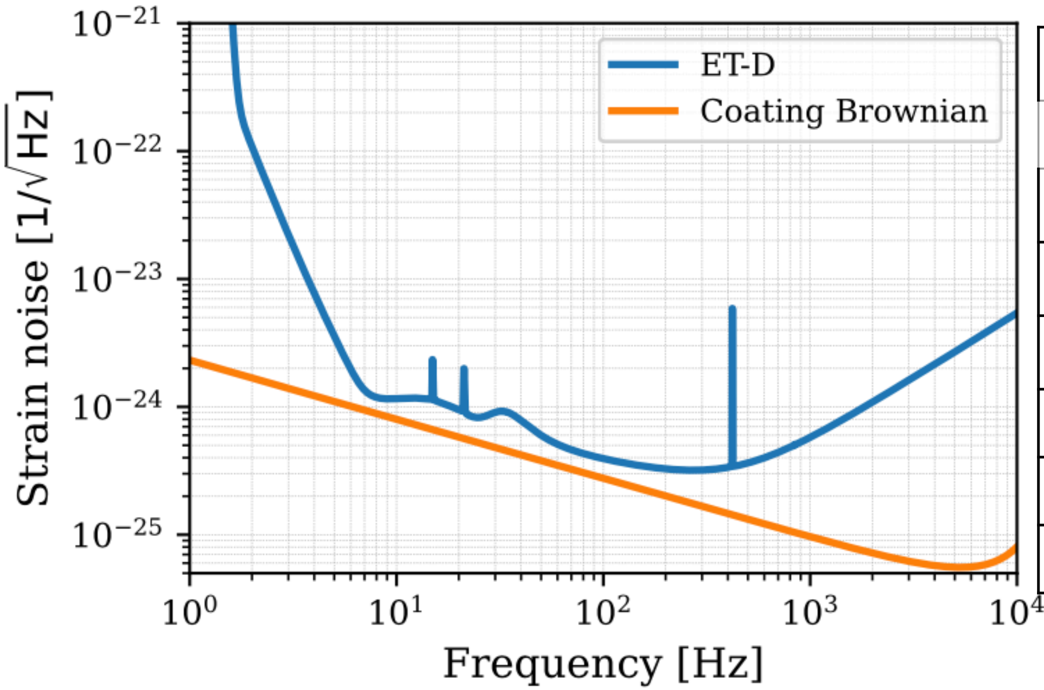
The HF detector uses room temperature techology.

Optics
- Coating thermal noise

High power
- Quantum shot noise/signal response

Suspension thermal noise defines the low frequency boundary of HF detector.

Coating thermal noise



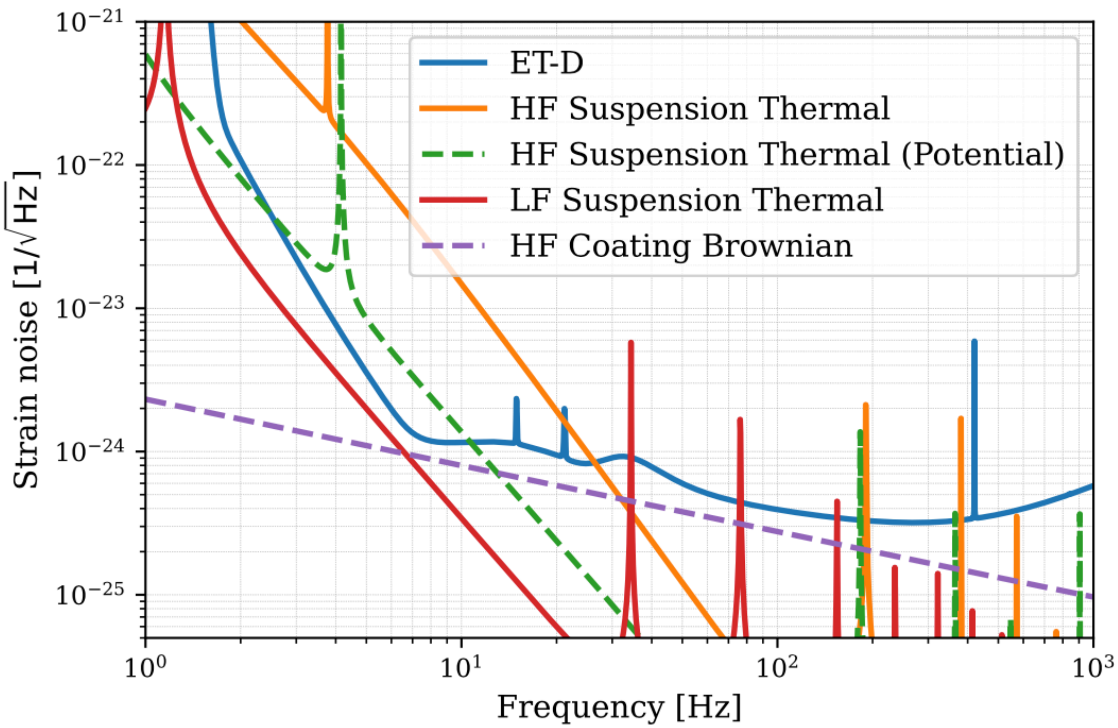
Material	?/?
Temperature, [K]	290 K
Young's modulus [Pa]	120e9/70e9
Poisson's ratio	0.29/0.19
Mechanical loss angle	9e-5/1.25e-5
Mirror Diameter [cm]	62
Mirror thickness [cm]	30
Beam size [cm]	12

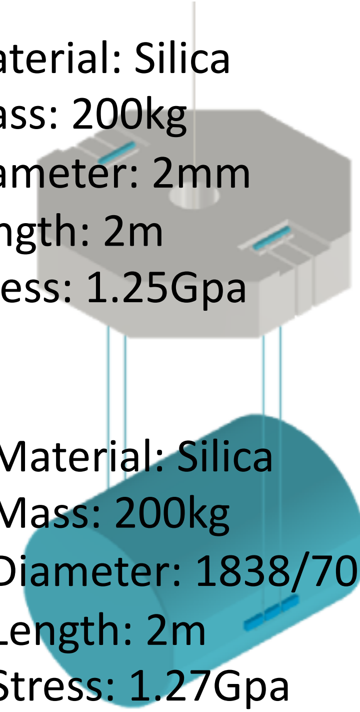
We assume a factor of 2 improvement of the thermal noise ASD of Ta2O5/SiO2 bi-layer coatings and the exact potential material are to be decided.

The absoption here is also important for reaching high power.

Suspension thermal noise

What's the design of HF detector suspension?



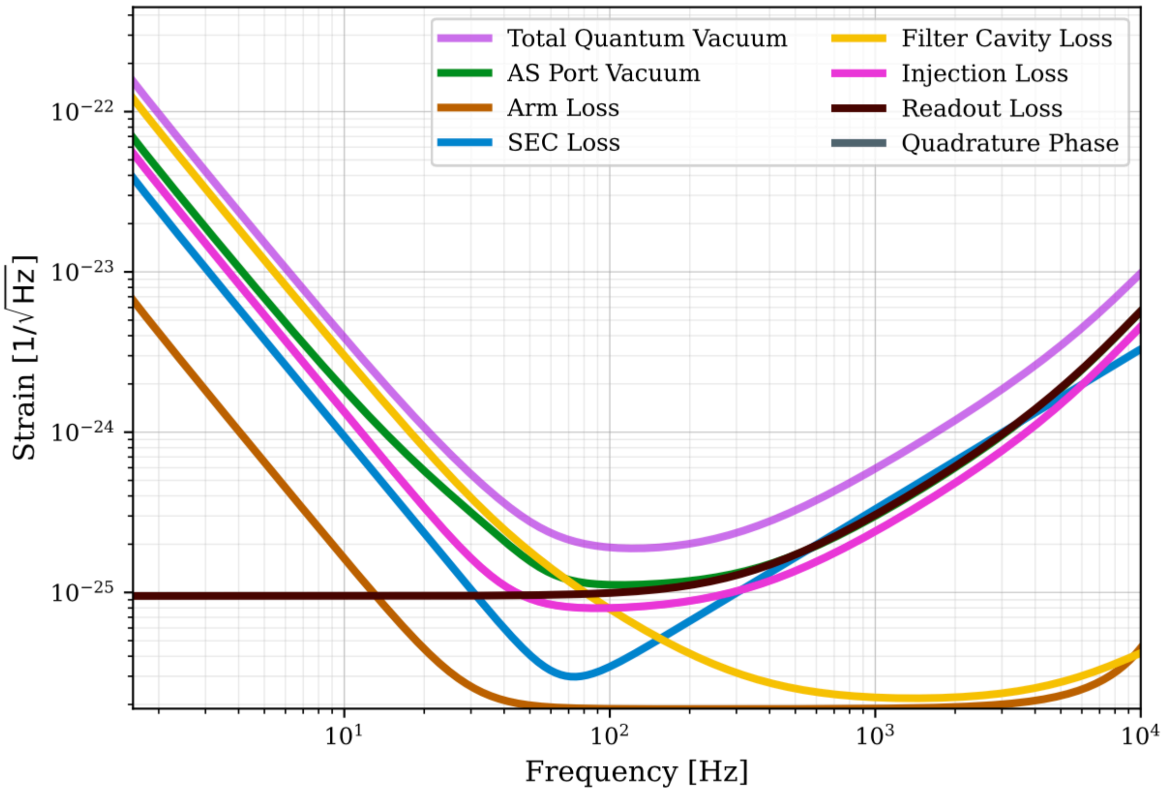


Material: Silica
Mass: 200kg
Diameter: 2mm
Length: 2m
Stress: 1.25Gpa

Material: Silica
Mass: 200kg
Diameter: 1838/700/1838um
Length: 2m
Stress: 1.27Gpa

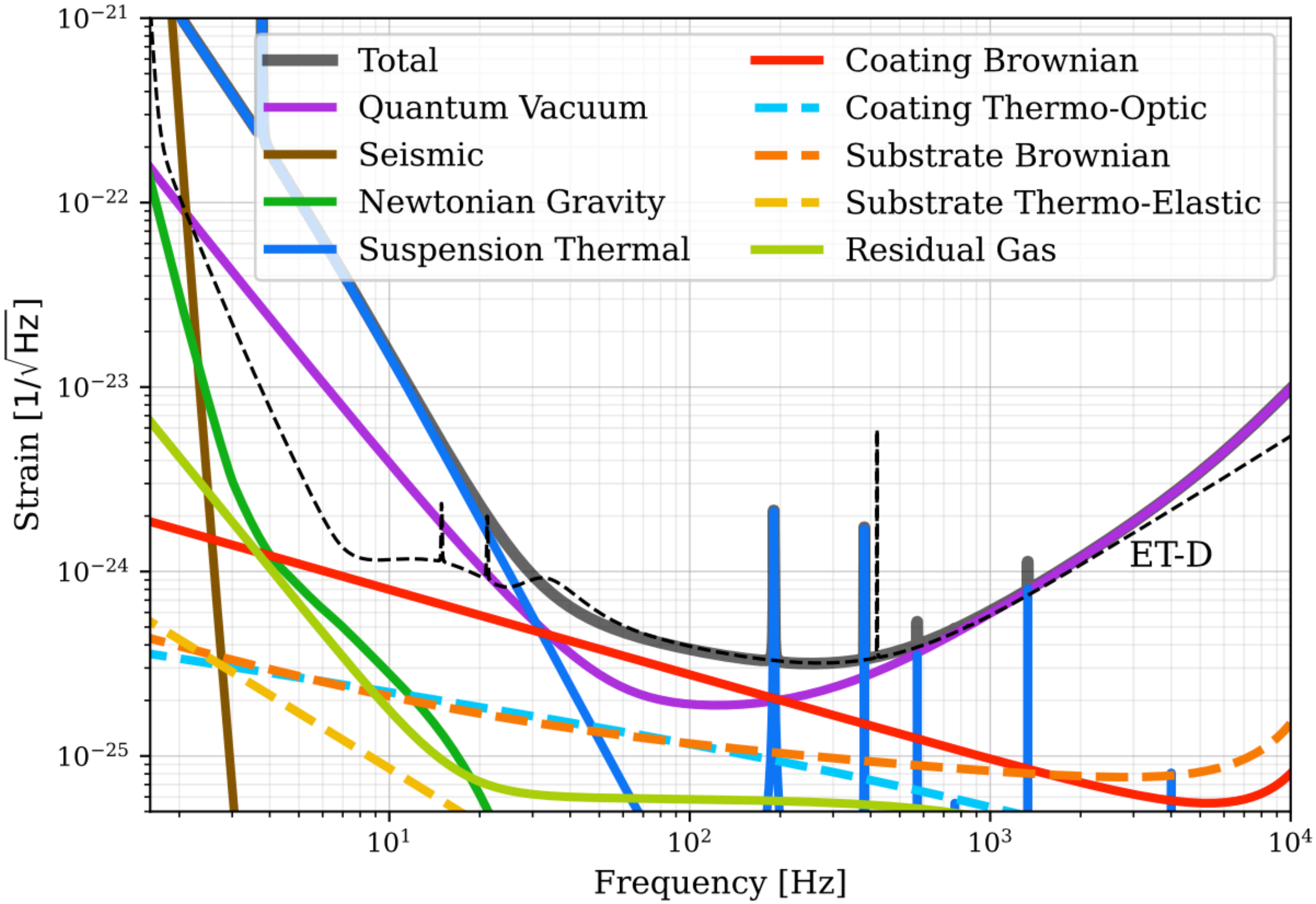
	Temperature	Bulk loss	Surface loss	Elastic loss	Break stress
Silica	290K	4.1e-10	6.5e-12m	Cancelled	~4.2Gpa
Silicon	10-18K	1e-9	0.5e-12m	Low TEC	200-300MPa

Quantum noise



Parameters	
Wavelength	1064nm
Arm power	3MW
ITM/ETM T	7000/5 ppm
SEC tuning	0rad
SEC T	0.1
SEC length	200m
FCL length	300m
FC RT loss	30ppm
FC EM T	5ppm
Input Sqz	15dB
Input loss	2%
Readout loss	3%
SEC loss	1000ppm
Arm RT loss	75ppm

ET-HF noise budget



Here we still keep the suspension thermal noise at ET-D level.

Potential topics for parallel sessions (Thu)

The low frequency detector

1. Improve the accuracy of current noise budget

(1): NN crosschecks + effects of caverns

(2): Temperature consistence for coating and suspension.

(3): FC cavity length, including FC phase noise.

(4): HOM mode effect on QN.

2. Development of strategy/hierarchy of global detector/sensitivity optimization

So far only pockets of optimization: e.g. ET-LF mirror temperature vs STN.

At some point we need global optimization of e.g. ET-LF mirror temperature vs STN vs CTN (multi-material coatings) vs heat extraction (couples again to suspension thermal noise) vs beam size on mirror. Document of such joint effort was suggested, https://www.overleaf.com/read/qjrcqmyvhrkv .

On another level, the mirror size will then have an impact on vacuum tube diameter and then the cavern radius and then effect the NN. In terms of hardware, it may then have impact on tower positions and/or pumping position distances along the tube and so on and so on ….

How to best approach this? Probably not something we can do during this workshop, but would be good to start the discussion how to approach such optimizations.

The high frequency detector

Should we consider a phase 1 design for HF detector operation, before the readiness of LF detector technology? If Yes! What is the strategy?

Starting from political/strategic discussion to science discussion? What is our strategy to trade-off design decisions for ET1 (first detectors in ET infrastructure) vs flexibility and potential of improvements for the 40 years after ET1?

A: Go for best possible room temperature technologies?

1. Update the low frequency barrier: Lower STN (can be a factor 10 lower than current design level with LF idea) and design the seismic isolation.
2. Having larger test mass?
3. Broaden the HF interferometer bandwidth:
   (1) lower the QRPN to fill the gap between the QN and the new STN
   (2) balance the CTN and the QSN at medium frequencies (~100Hz.)
   (3) explore ways to improve HF sensitivity at ~kHz.
   Q1: How can we estimate the signal recycling cavity loss?. Can we budget them and estimate promising loss for the future?
   Q2: Is there sweet spot for arm cavity finesse to balance a) the ITM/BS thermal distortion (inversely proportional to arm finesse), and b) the transfer function from loss to noise?
   O3: Other considerations for determining the core optics parameters?
4. Other ideas?

B: Go for the economical design.

what flexibility we should consider for future potentials?

Thank you for you attention!