Cryogenic aspects in future Gravitational Wave Experiments

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Overview

- aim: overview of the cryogenic plans of the design study for the Einstein Telescope

- content:
  - Gavity waves and their detection with an interferometer
  - sensitivity curve and implications for the setup
  - thermal noise of optical components as limitation
  - cryogenic approaches to operate at low temperatures

- summary

Gravity waves and their detection

What are gravitational waves?

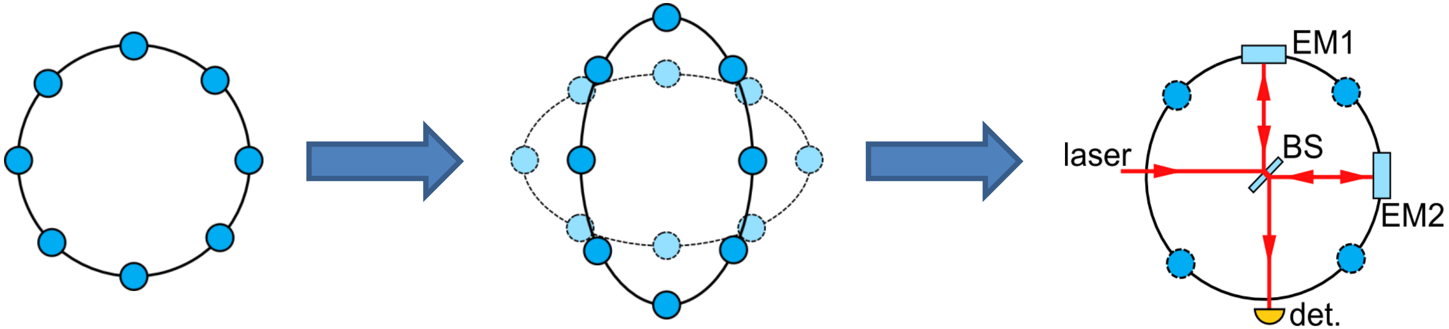
- gravitational waves are ripples in the curvature of spacetime predicted by Einstein in 1916
- possible sources: e.g. binary systems of neutron stars, black holes,…

How to detect these waves?

ring of free falling test masses

deformation due to an incident gravitational wave

replace test masses by end mirrors of an interferometer

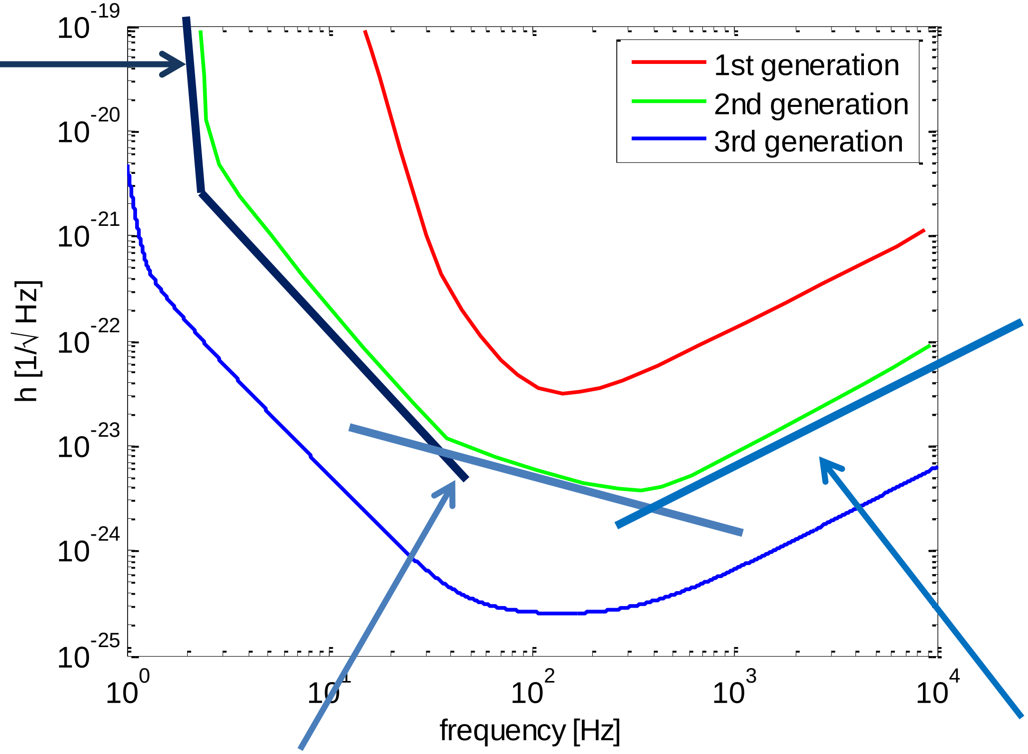


Sensitiviy of current and future generations of detectors

- initial aim: sensitivity enhancement of about an order of magnitude in all of the frequency range form 1 Hz to 10 kHz

seismic
suspension
radiation pressure

larger mass



higher laser power

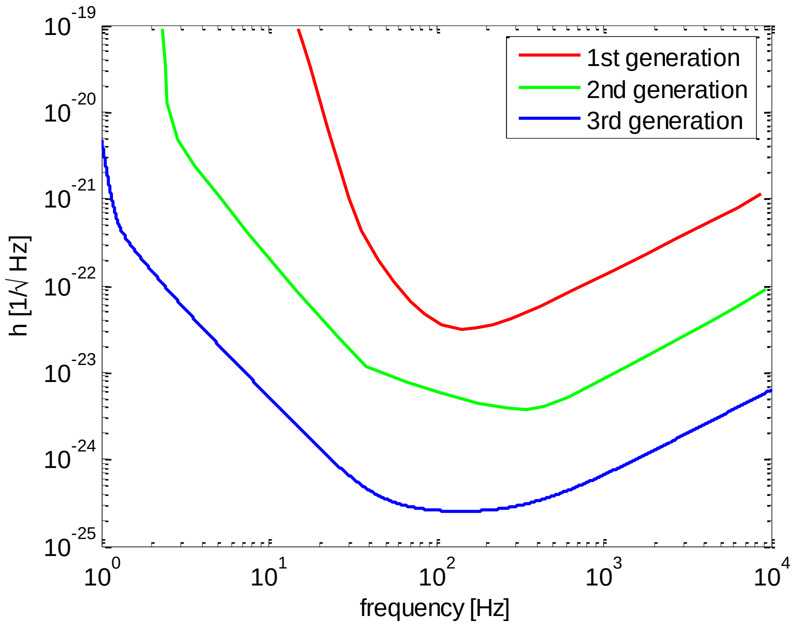
larger beam dia.
low temperatures

photon shot noise

mirror thermal noise

Laser power vs. Cryogenics

To achive that goal all currently available techniques need to be pushed to the limits and even beyond



cryogenic temperatures beneficial

↔

CONFLICT?

high laser power beneficial

The ET-LF and ET-HF Xylophone concept

- two cavities with high power lasers
  - 1064 nm for ET-HF (approx. 500 W)

    ET-HF → 3 MW circulating in cavity

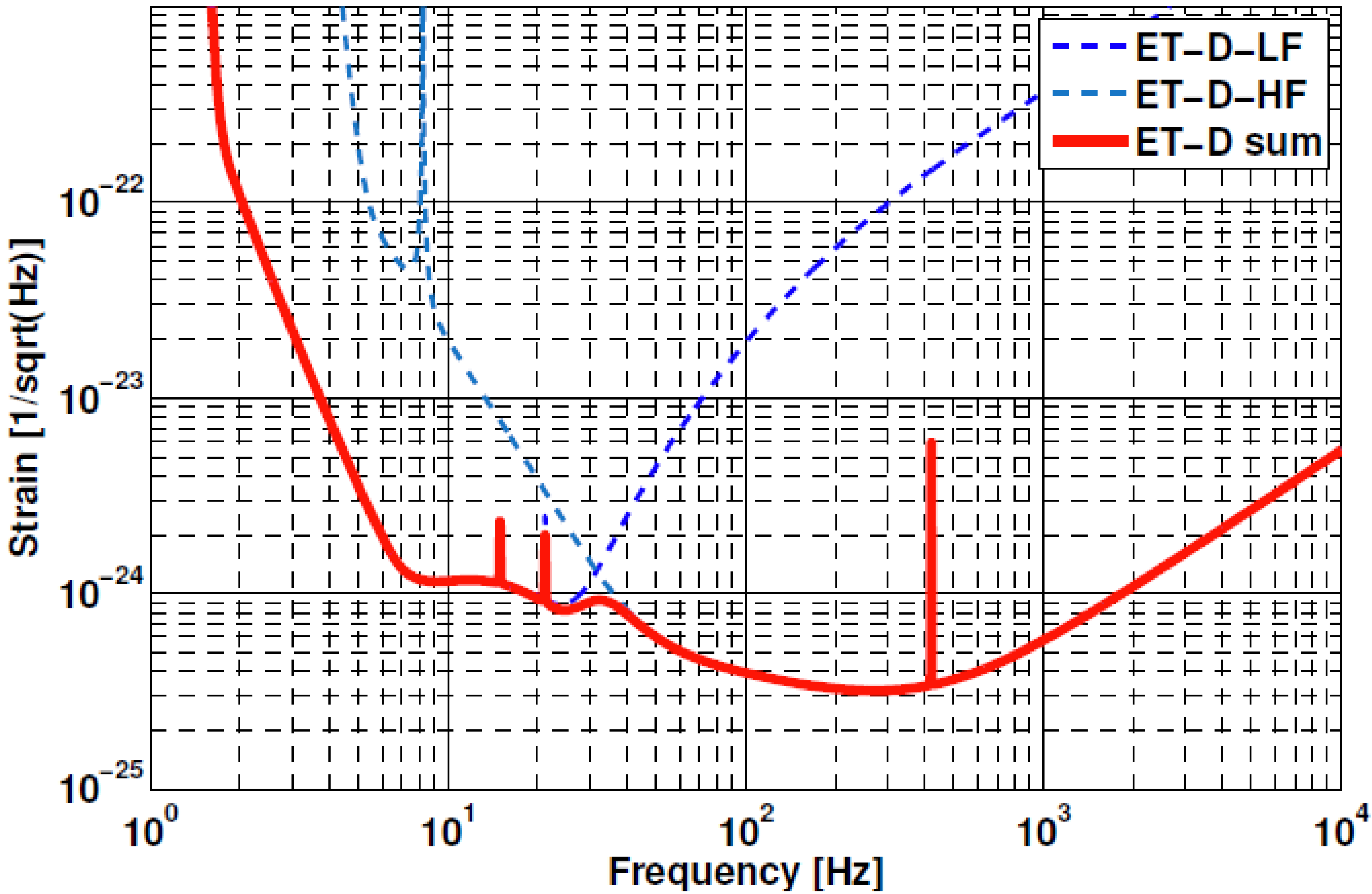
  - 1550 nm for ET-LF (approx. 3 W)

    ET-LF → 18 kW circulating in cavity

    ET-LF mirror mass 211 kg (supress rad. pressure noise)

    (compare to ~ 40 kg in advanced detectors)

Optical layout – Xylophone concept



[S. Hild et al., CQG 27 (2010), ET note ET-0135B-10]

The two main origins of thermal noise

Thermo-elastic noise:

α=0 possible for some materials, e.g. silicon (@ 18 and 125 K)

$$S_{TE}^{ITM}(f,T) = \frac{4k_B T^2 \alpha^2 (1+\sigma)^2 \kappa}{\pi^{5/2} \rho^2 C^2 f^2 w^3}$$

[Braginsky 1999]

Brownian thermal noise:

$$S_X^{ITM}(f,T) = \frac{2k_B T}{\pi^{3/2} f} \times \frac{1-\sigma^2}{w Y} \times \phi_{substrate}(f,T)$$

[Liu, Thorne 2000]

⇒ temperature | beam diameter | material

First conclusions

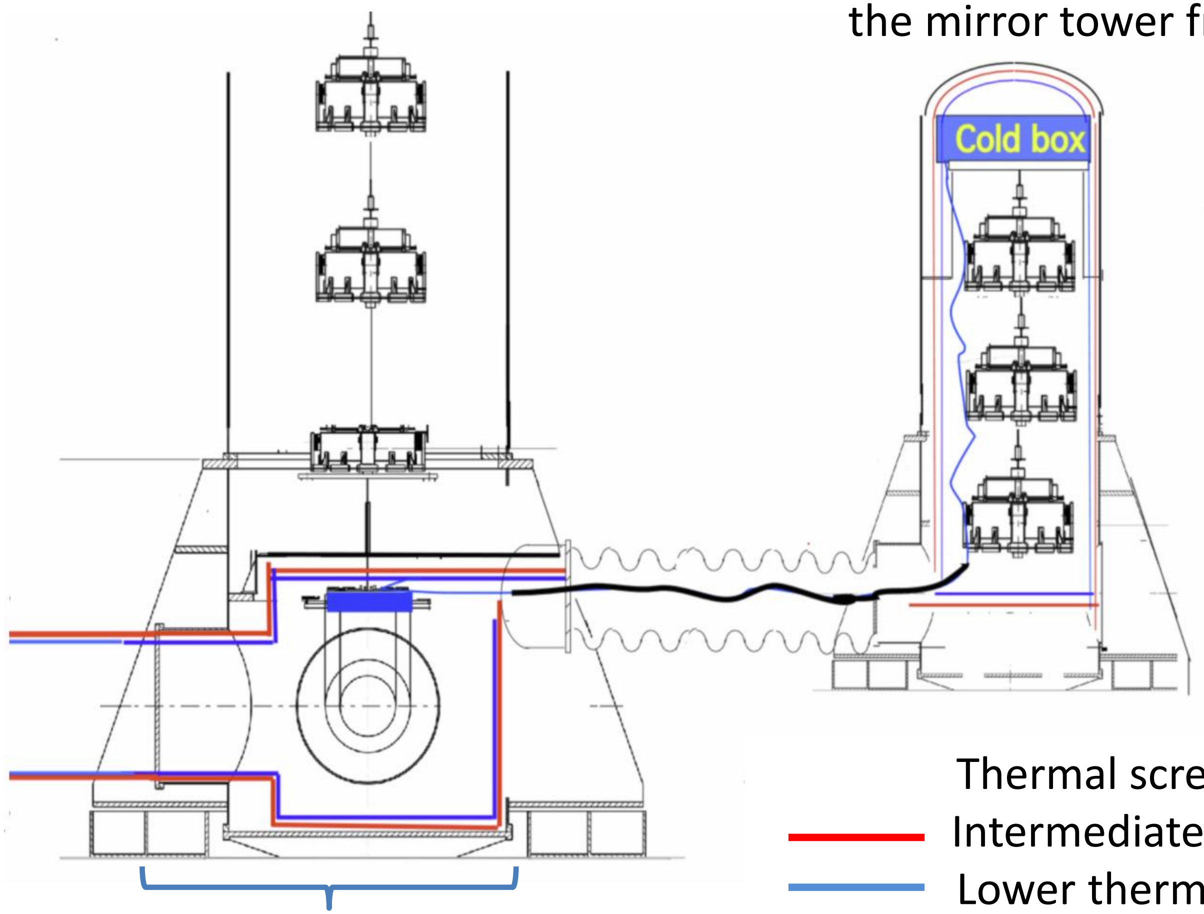
- reduction of thermal noise by:
  - cryogenics
  - large beams
  - new materials

DFG SFB TR7

Cryogenic design for ET-LF

mirror tower (height ≈ 20m) with cryostat at basement

ancillary tower with separate cryostat (containing suspension stages) to decouple the mirror tower from unavoidable vibrations



Thermal screens:

Intermediate thermal shield @ ≈ 80 K

Lower thermal shield @ ≈ 4 K

Sealable volume for adding pure He gas for fast cool down

Cryogenic design for ET-LF

- extraction of heat from the mirrors via the suspension fibres (silicon) attached to the marionette (@ 5K)
- ancillary tower hosting the cold box
- connection of both towers by a thermal link (Al or Cu offer up to 2kW/m/K)
- use of 75 respectively 25 layers of aluminized mylar around thermal shields

(Almost) total heat budget:

- ≈ 20mW from laser absorption (1ppm of 18kW in ET-LF)
- radiation from the warm vacuum tube to the mirror surface

Boltzmann equation: $\frac{\dot{Q}}{A_1} = \sigma F_e F_{1-2}(T_2^4 - T_1^4)$

A_1…mirror surface, σ…Boltzmann constant, F_e…emissivity, F_{1-2}…geometric confg. factor, T…temperature

$\frac{\dot{Q}}{A} \approx 460\ W/m^2$ Problem!!!!

Cryogenic design for ET-LF

Solution:

- reduction of the emissivity factor (appropriate material choice or coating)
- implementation of cryotraps to reduce the geometric configuration factor

→ optimization of F_e and the cryotrap length necessary!!!

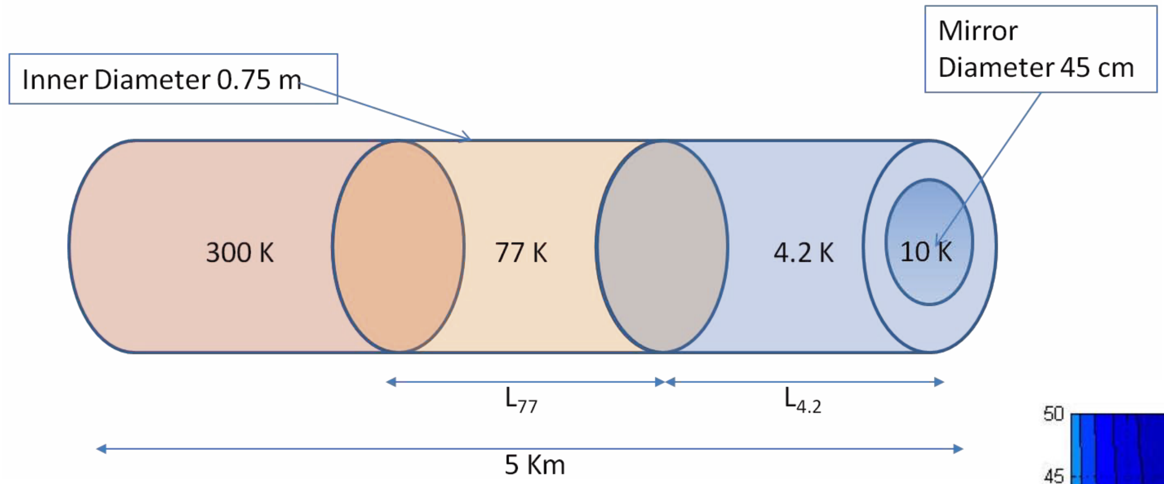
heat extraction via suspensionwires:

$$\dot{Q} = \frac{4A_w}{L} k(T_{mirror} - T_{marionette})$$

A_w…suspension cross section (Ø 3mm), L…fibre length (2m), k…thermal conductivity (≈1.4kW/m/K), T…temperature

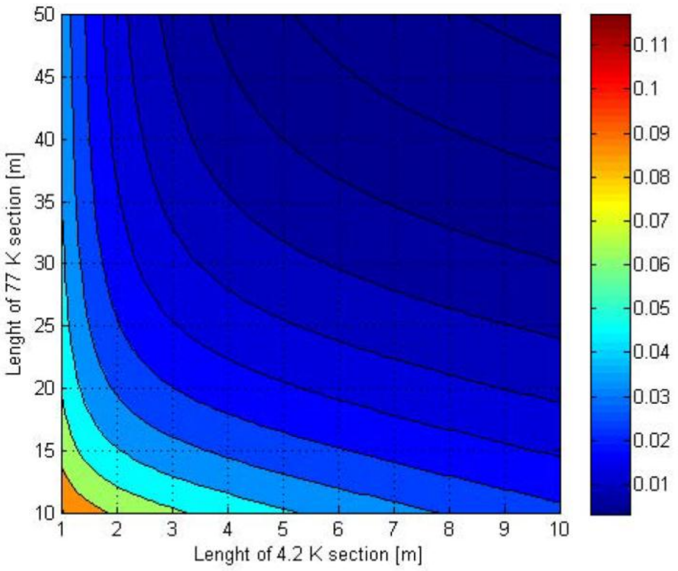
$\dot{Q}$ ≈ 100mW while not exceeding 10K at the mirror

Cryogenic design for ET-LF



If $L_{4.2K} \approx 10$m and $L_{77K} \approx 50$m the direct heat from the cryotrap is ≈ 3mW!!!

Problem solved!!!



Cryogenic cooling concepts

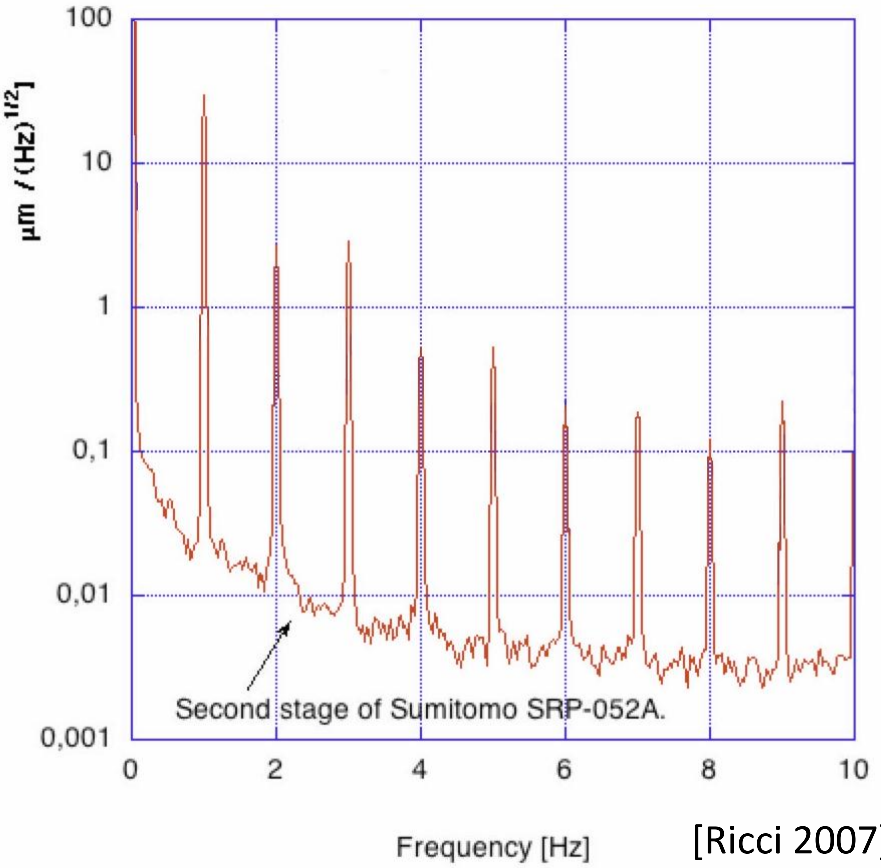
#1 – battery of pulse tube cryocoolers

- Up to 10 PTs needed for cryotraps
- active vibration compensation necessary (see fig. 29µm/√Hz @ 1Hz)
- noisy compressor operation @ ≈ 53db(A)

In favor:
- high duty cycle
- limited manpower needed

Against:
- High level of vibration
- High electric power consumption in the underground environment

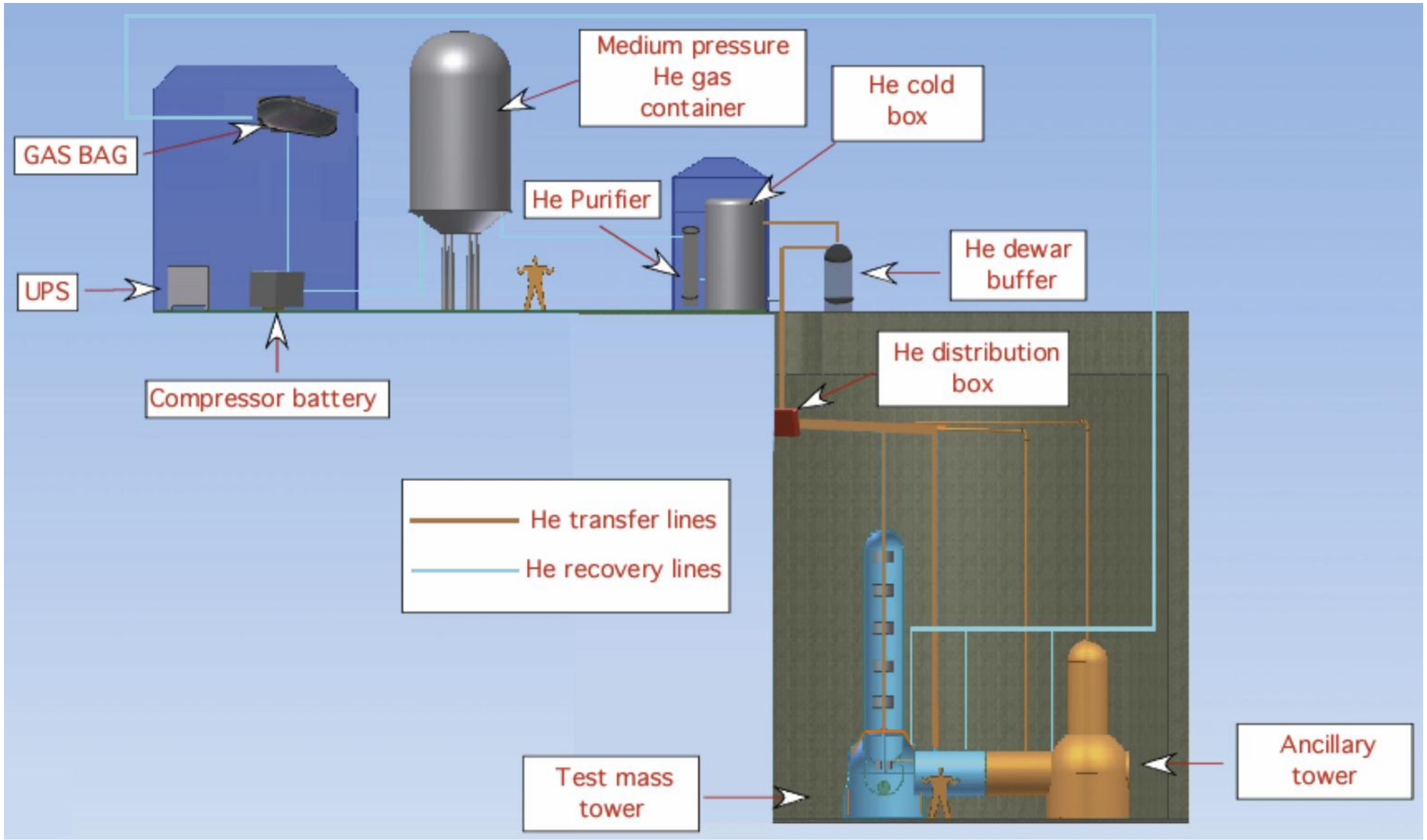
vibration spectrum



[Ricci 2007]

Cryogenic cooling concepts

#2 – classic approach of liquid helium



Proved industrial technologies and already used in projects like the LHC (CERN cryoplant)

Cryogenic cooling concepts

Future developments in lowering the temperature with He II

Advantages:

- even more effectiv way of heat extraction from mirrors by:
  - high thermal conductivity
  - high heat capacity
  - extremly low viscosity (@ the λ-point)

Summary

- Cryogenics needed for further reduction of the thermal noise level in current detectors
- Combination of a high power (3 MW) interferometer @ room temperature and a low power (18 kW) interferometer @ 10 K
- Cooling of the lower parts (mirror + marionette) of ET-LF in the mirror tower
- Cryotraps in front of the mirror important for reduction of thermal load
- Two cooling concepts available (PT and liquid He)