Studies on Cryogenics and Vacuum for the Einstein Telescope Detector

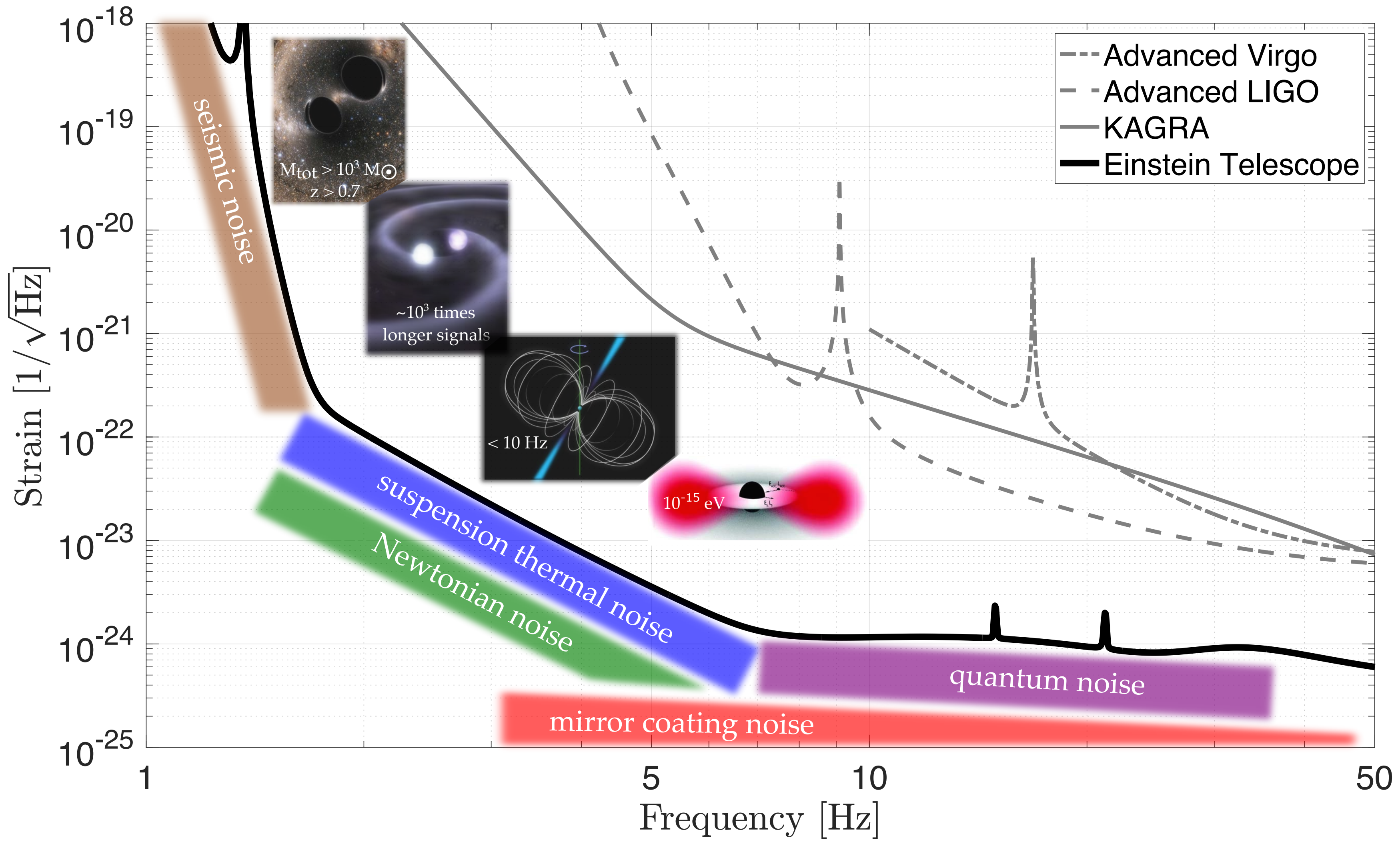
Steffen Grohmann – On behalf of ET-ISB Division IV: Vacuum and Cryogenics
GWADW 2023, La Biodola, Elba, May 21-27, 2023

Outline

- Recap: Necessity of cryogenic ET-LF
- Baseline design of cryogenic payloads for ET-LF
- Conceptual cryostat design
- Mitigation of adsorption on mirrors
- Cryogenic infrastructure concept
- Roadmap to TDR
- R&D facilities

Necessity of cryogenic ET-LF

- **Comparison of low-frequency sensitivities**
  - Adv. Virgo / Adv. LIGO (2G): $f_{\mathrm{min}} = 10\,\mathrm{Hz}$
  - KAGRA (2.5G): $f_{\mathrm{min}} = 5\,\mathrm{Hz}$
  - ET (3G): $f_{\mathrm{min}} = 3\,\mathrm{Hz}$ $\longrightarrow$ 5 Hz sensitivity $\times\,10^{-3}$!



Source: S. D. Pace et al.: Research Facilities for Europe's Next Generation Gravitational-Wave Detector Einstein Telescope. Galaxies 10 (3), 65, doi: 10.3390/galaxies10030065 (2022)

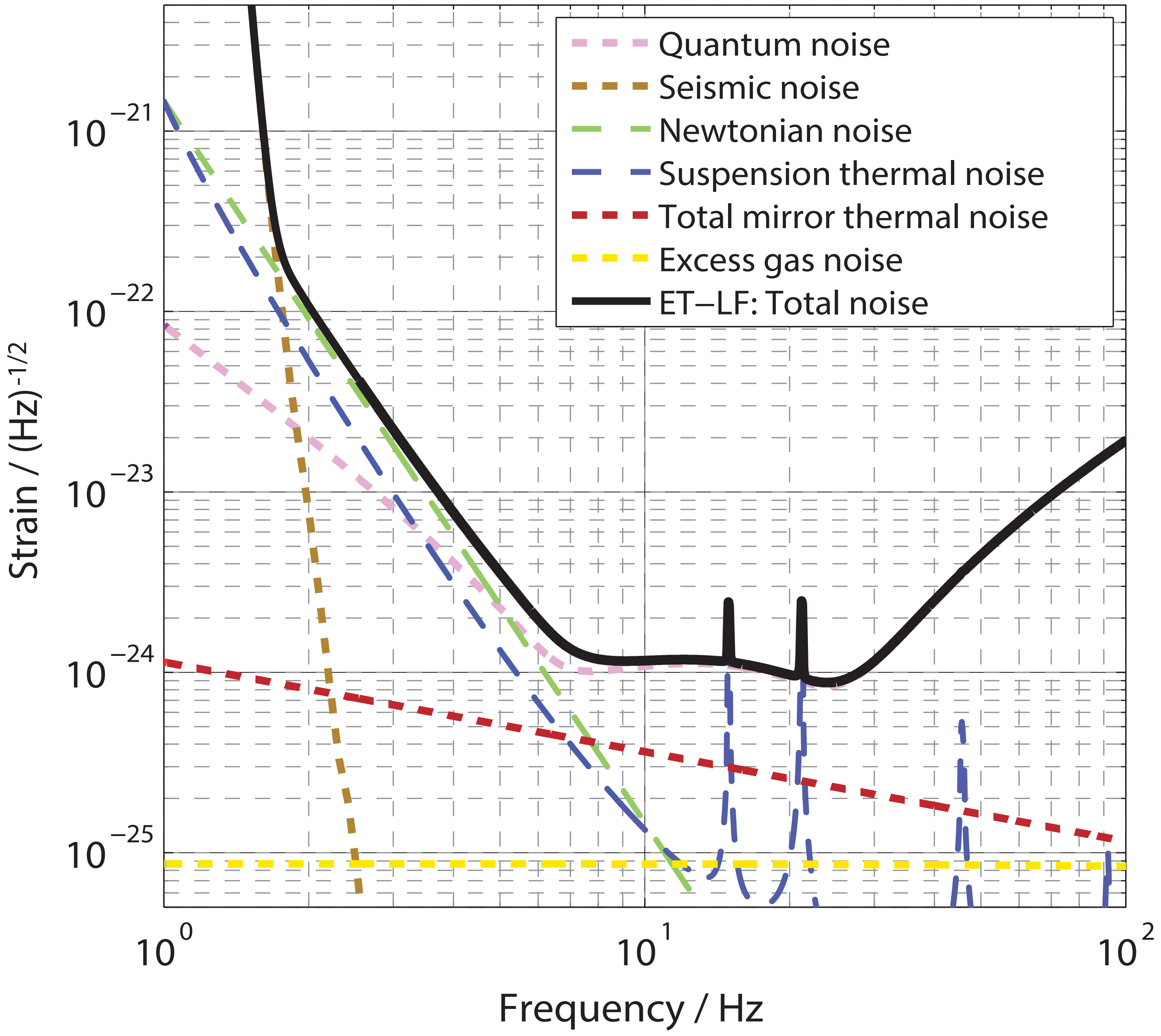
From: M. Maggiore et al.: Science with the Einstein Telescope: a comparison of different designs. arXiv:2303.15923 [gr-qc] (2023)

The low-frequency sensitivity is crucial for exploiting the full scientific potential of ET, in particular with regard to:

- the observation of binary neutron stars (BNS), staying long time in the bandwidth,
- pre-merger detection to probe the central engine of gamma ray bursts (GRB), particularly to understand the jet composition, the particle acceleration mechanism, the radiation and energy dissipation mechanisms,
- detecting a large number of kilonovae counterparts,
- detecting primordial black holes (PBH) at redshifts $z > 30$, and
- detecting intermediate massive back holes (IMBH) in the range of $10^2 - 10^4\,M_\odot$.

Feasibility of cryogenic payloads for ET-LF

ET-D sensitivity curve



Assumptions

- ET Conceptual Design Study (2011)
- Design Report Update (2020)

	Marionette	Recoil mass	Mirror
Mass (kg)	422	211	211
Suspension length (m)	2	2	2
Suspension diameter (mm)	3	3	3
Suspension material (-)	Ti6Al4V	Silicon	Silicon
Loss angle (-)	1×10^{-5}	1×10^{-8}	1×10^{-8}
Temperature (K)	2	10	10

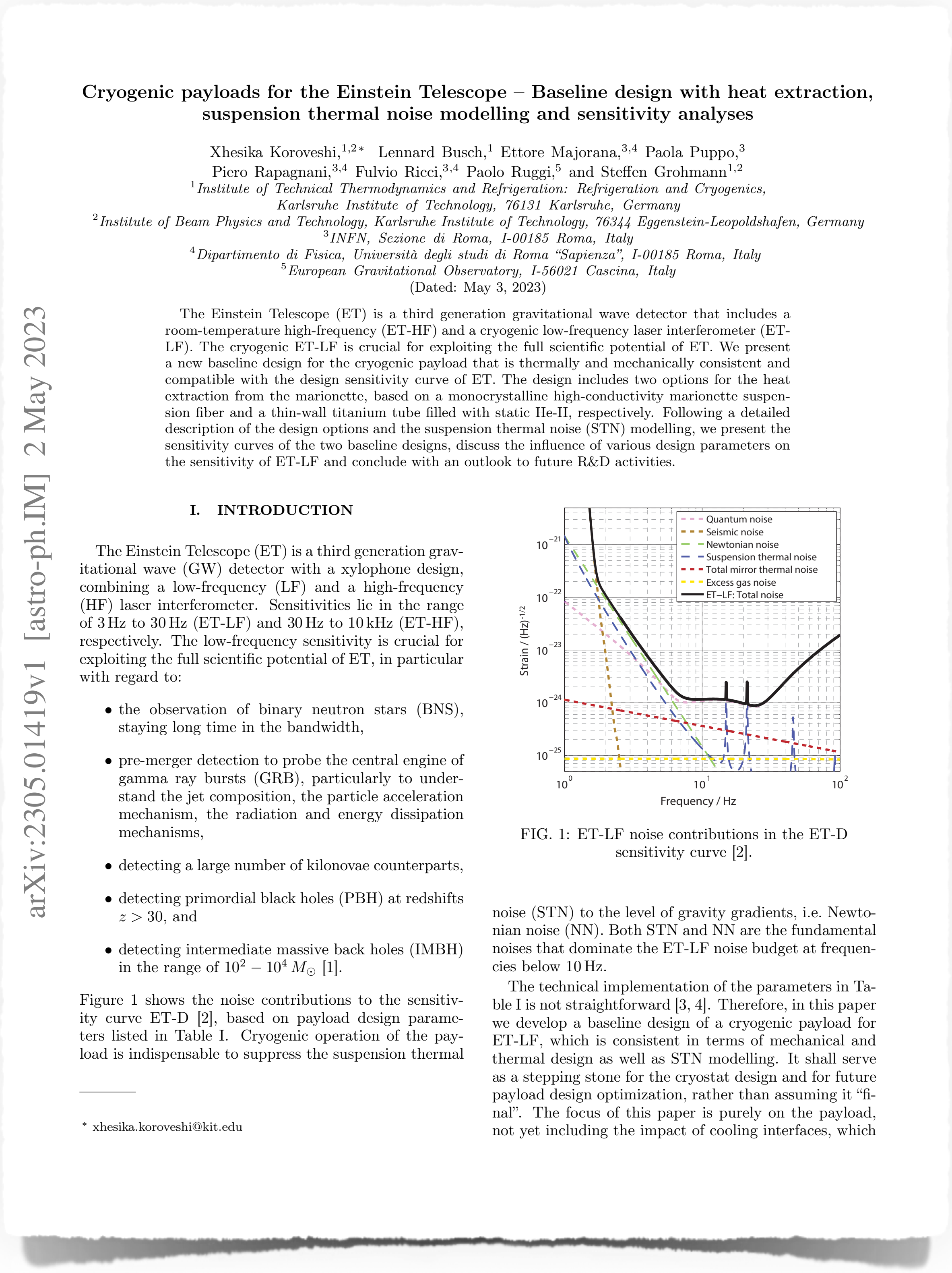
- Technical implementation not straightforward

- **Baseline design study** carried out by ET-ISB Divisions I and IV

Baseline design of ET-LF cryogenic payloads

New reference paper

- Link: https://arxiv.org/abs/2305.01419



arXiv:2305.01419v1 [astro-ph.IM] 2 May 2023

Cryogenic payloads for the Einstein Telescope – Baseline design with heat extraction, suspension thermal noise modelling and sensitivity analyses

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(Dated: May 3, 2023)

The Einstein Telescope (ET) is a third generation gravitational wave detector that includes a room-temperature high-frequency (ET-HF) and a cryogenic low-frequency laser interferometer (ET-LF). The cryogenic ET-LF is crucial for exploiting the full scientific potential of ET. We present a new baseline design for the cryogenic payload that is thermally and mechanically consistent and compatible with the design sensitivity curve of ET. The design includes two options for the heat extraction from the marionette, based on a monocrystalline high-conductivity marionette suspension fiber and a thin-wall titanium tube filled with static He-II, respectively. Following a detailed description of the design options and the suspension thermal noise (STN) modelling, we present the sensitivity curves of the two baseline designs, discuss the influence of various design parameters on the sensitivity of ET-LF and conclude with an outlook to future R&D activities.

I. INTRODUCTION

The Einstein Telescope (ET) is a third generation gravitational wave (GW) detector with a xylophone design, combining a low-frequency (LF) and a high-frequency (HF) laser interferometer. Sensitivities lie in the range of 3 Hz to 30 Hz (ET-LF) and 30 Hz to 10 kHz (ET-HF), respectively. The low-frequency sensitivity is crucial for exploiting the full scientific potential of ET, in particular with regard to:

- the observation of binary neutron stars (BNS), staying long time in the bandwidth,
- pre-merger detection to probe the central engine of gamma ray bursts (GRB), particularly to understand the jet composition, the particle acceleration mechanism, the radiation and energy dissipation mechanisms,
- detecting a large number of kilonovae counterparts,
- detecting primordial black holes (PBH) at redshifts $z > 30$, and
- detecting intermediate massive back holes (IMBH) in the range of $10^2 - 10^4\, M_\odot$ [1].

Figure 1 shows the noise contributions to the sensitivity curve ET-D [2], based on payload design parameters listed in Table I. Cryogenic operation of the payload is indispensable to suppress the suspension thermal noise (STN) to the level of gravity gradients, i.e. Newtonian noise (NN). Both STN and NN are the fundamental noises that dominate the ET-LF noise budget at frequencies below 10 Hz.

FIG. 1: ET-LF noise contributions in the ET-D sensitivity curve [2].

The technical implementation of the parameters in Table I is not straightforward [3, 4]. Therefore, in this paper we develop a baseline design of a cryogenic payload for ET-LF, which is consistent in terms of mechanical and thermal design as well as STN modelling. It shall serve as a stepping stone for the cryostat design and for future payload design optimization, rather than assuming it "final". The focus of this paper is purely on the payload, not yet including the impact of cooling interfaces, which

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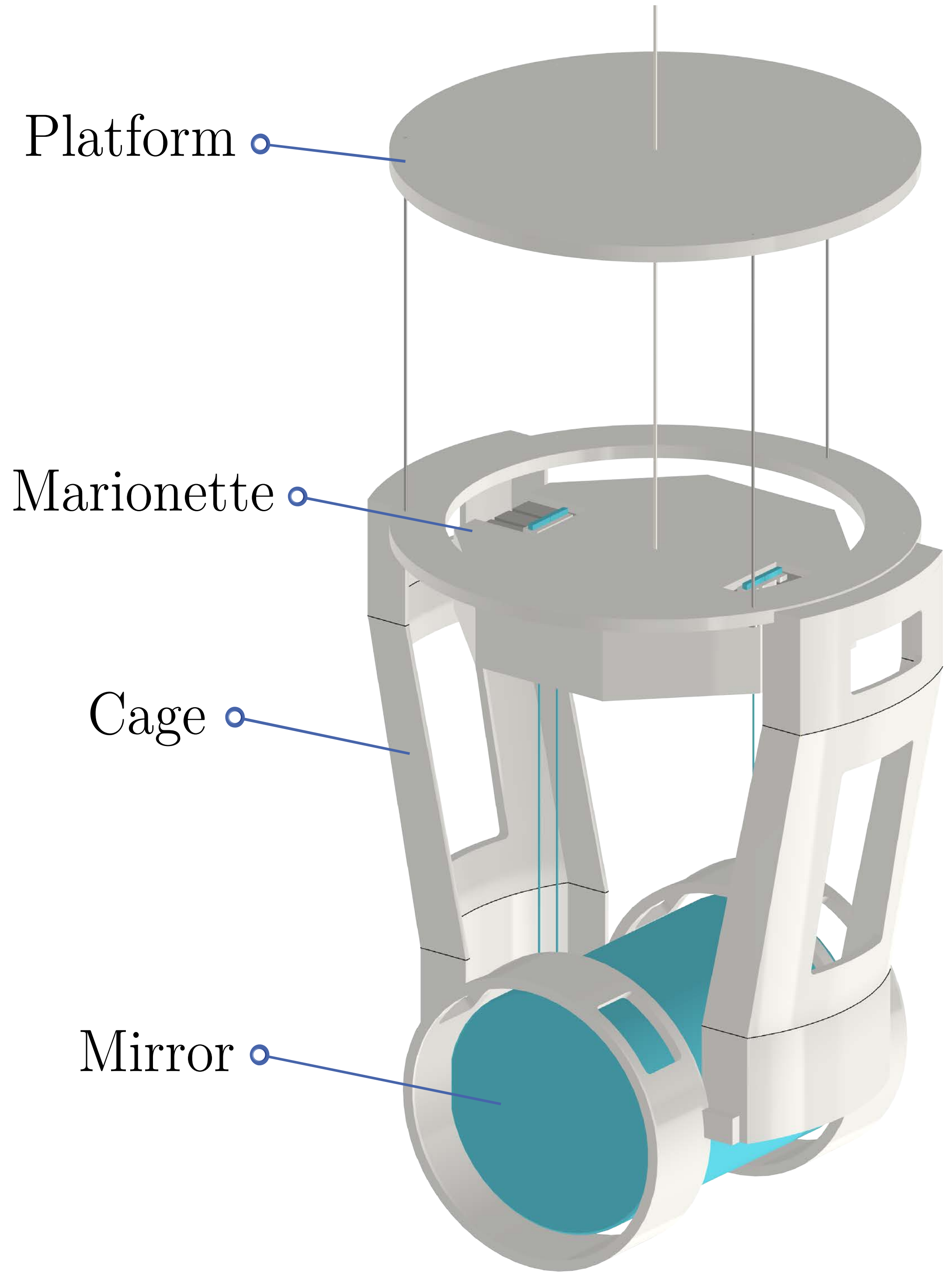
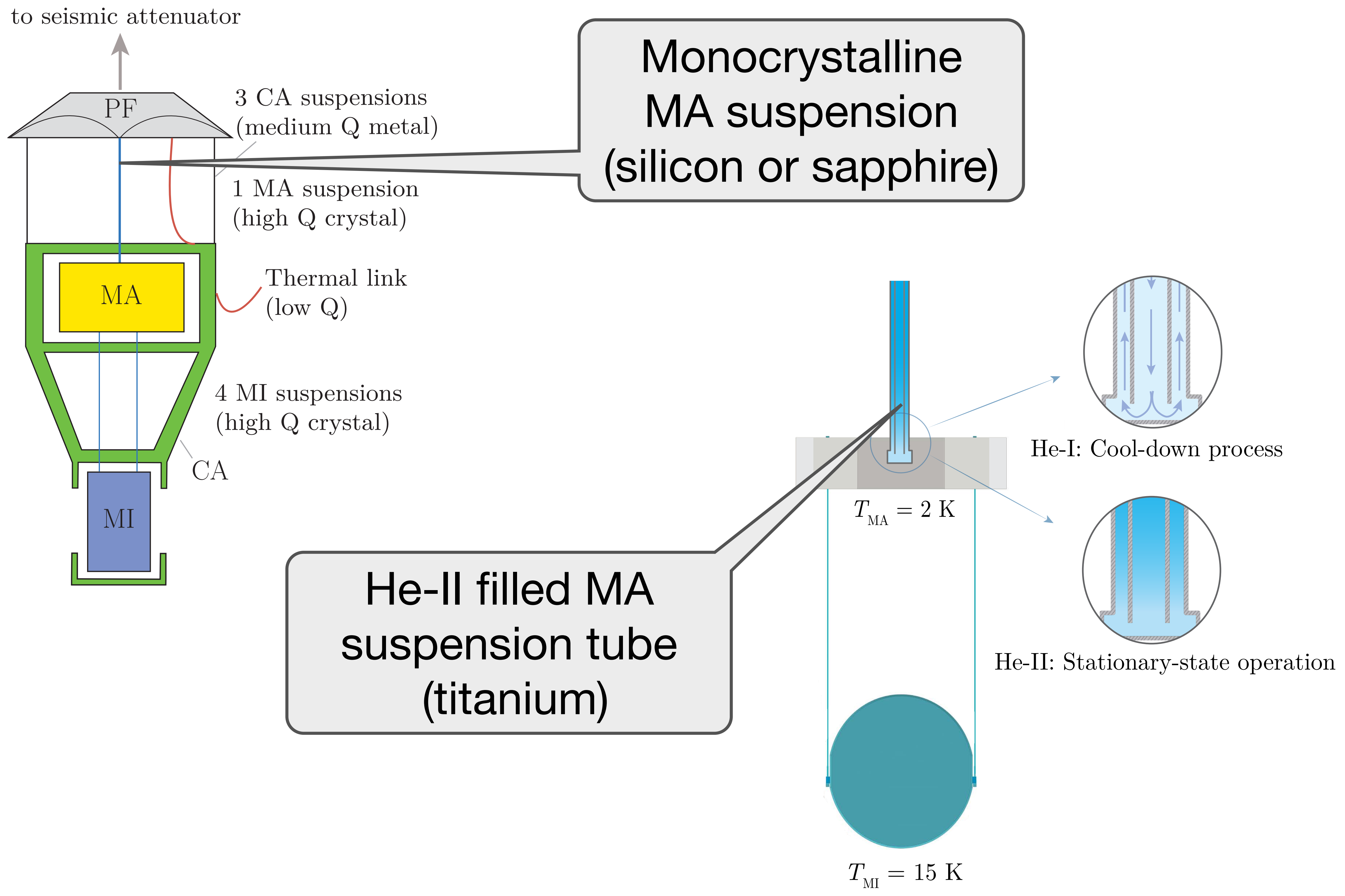


Objectives

- **Consistent** design study in terms of
  - **Mechanical** design
  - **Thermal** design
  - **STN** modelling
- Compete description of the **STN model**, including collection of available material data
- **Stepping stone** for future design optimisation(s)
- Reference for **cryostat design** (dimensions)

Baseline design of ET-LF cryogenic payloads

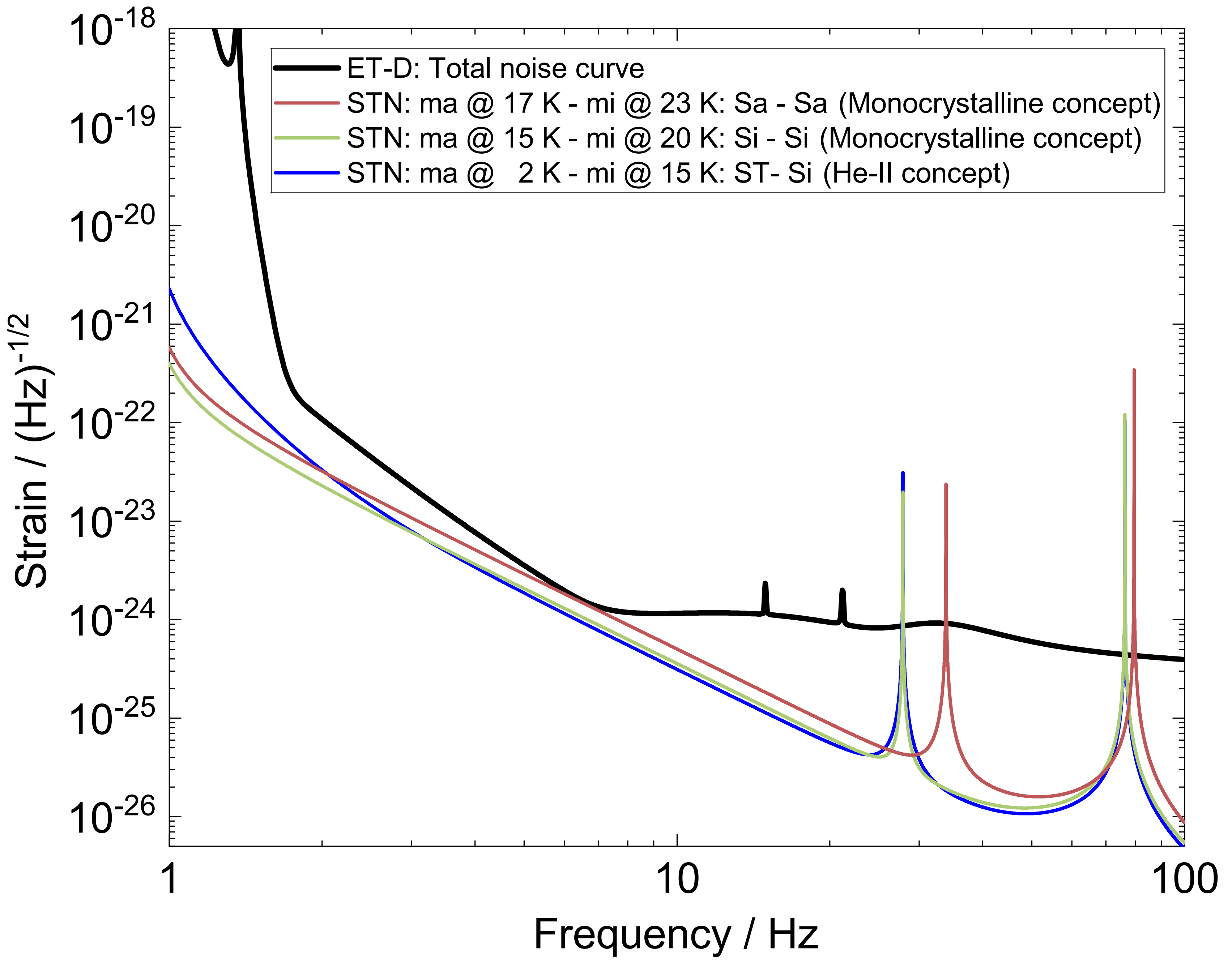
Two options for the heat extraction



- Cooling interfaces **not yet** part of the study!

Sensitivity (STN)

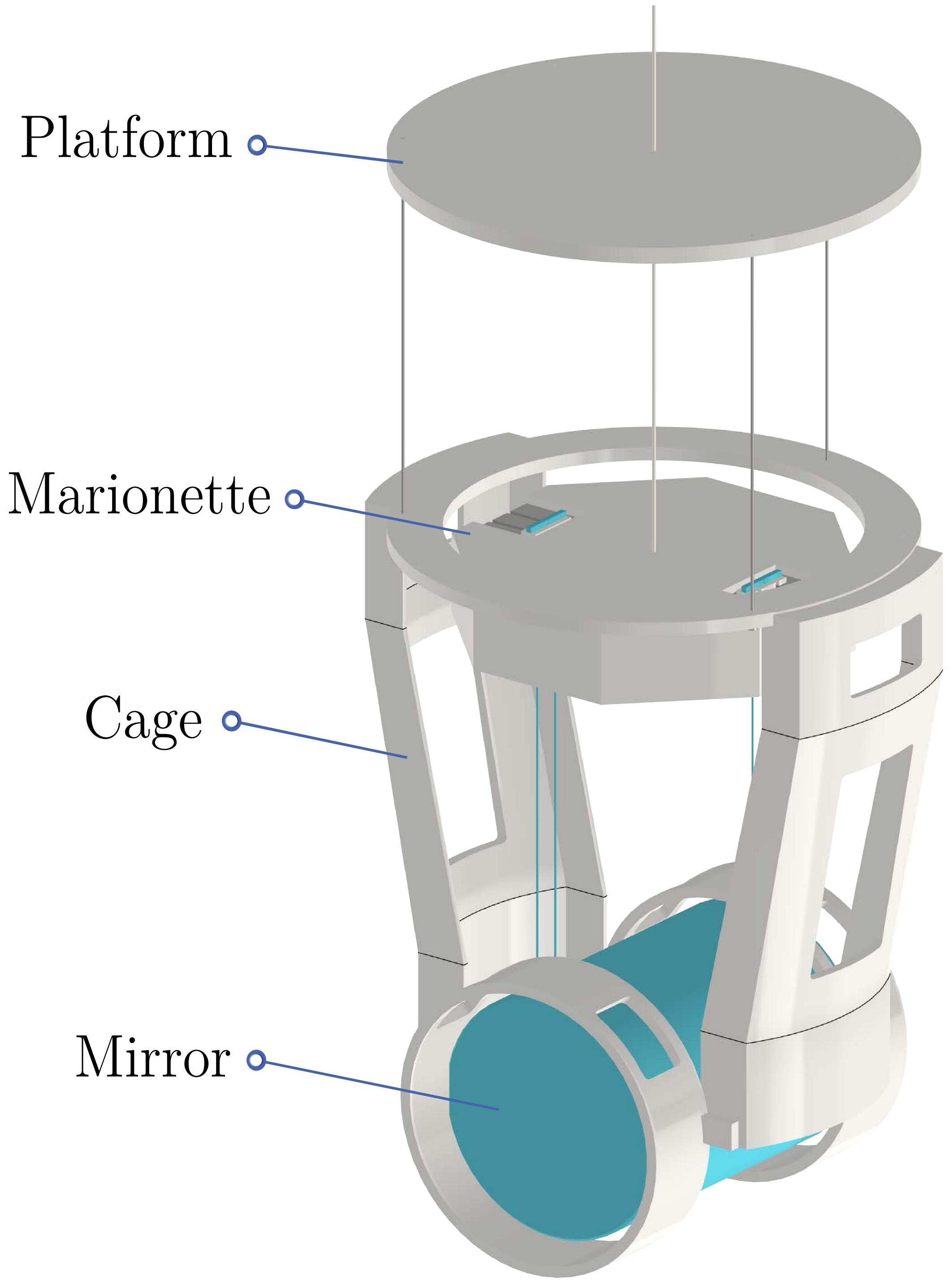
- Both concepts fulfil the requirements of the ET-D curve



Conceptual design of ET-LF cryostat

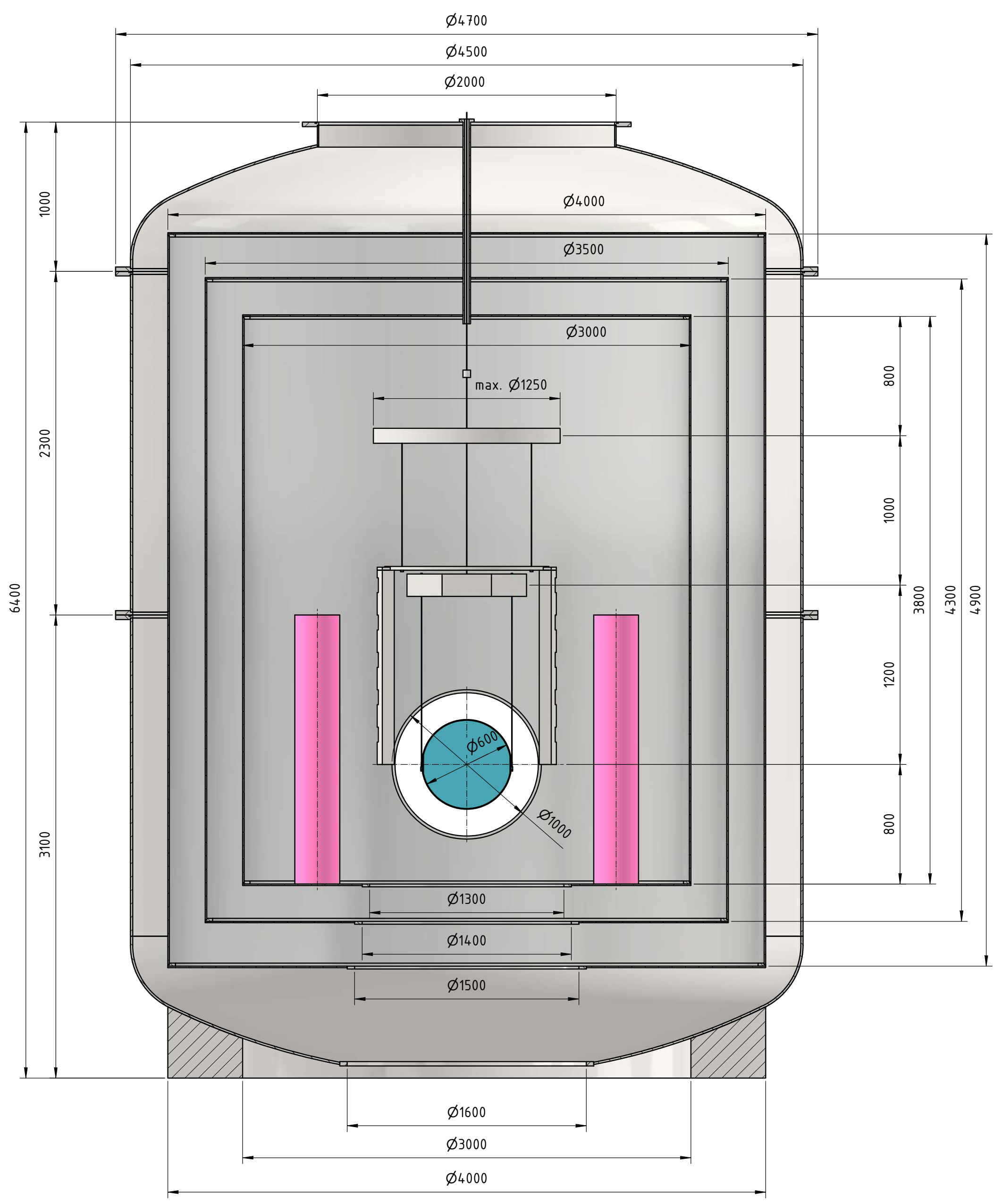
Baseline payload design

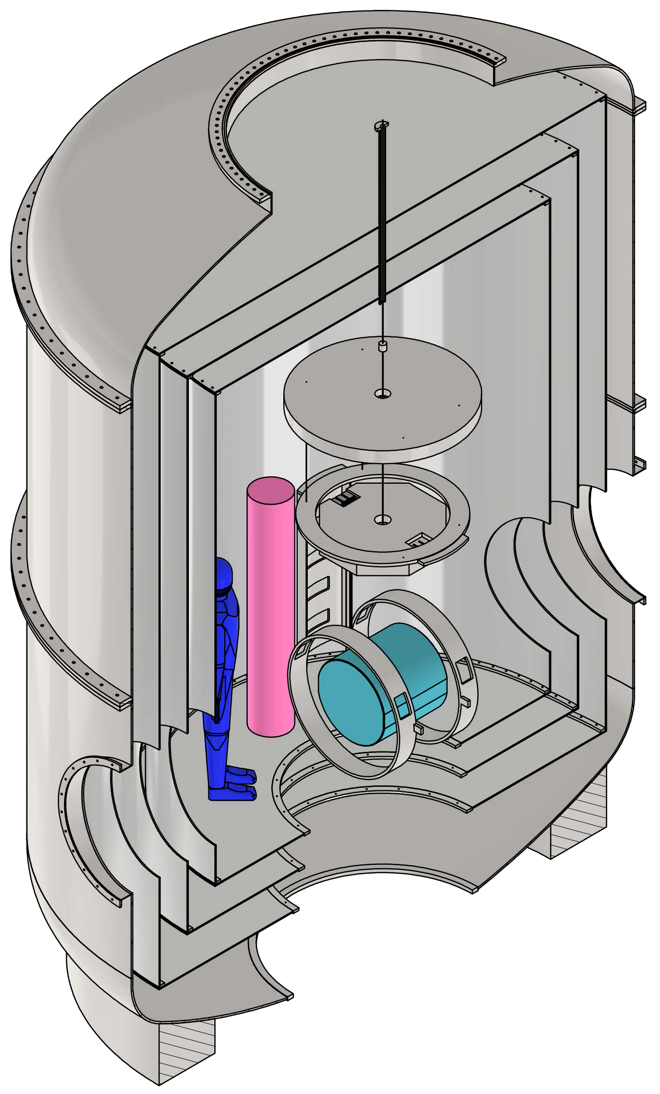
- Details: https://arxiv.org/abs/2305.01419



Conceptual cryostat design

- Details: ET-0272A-22
  https://apps.et-gw.eu/tds/ql/?c=16460





Mitigation of adsorption on mirrors

Cryogenic operation in KAGRA

3.2.3. Recent Results on Cryogenics

Cooling mirrors for reducing thermal noise are a unique feature of KAGRA, adding certain difficulties related to cryogenics. One of them is molecular adsorption on the cryogenic mirror surface, which causes variations in the reflectivity of the mirrors and laser absorption in the molecular layers [41]. Because molecular layers of a few micrometers cause significant changes in the sensitivity of KAGRA, the mirrors need to be frequently warmed to desorb the molecules from the mirror surface. For this purpose, new heaters for the desorption of molecules were newly installed on the IM stage of the cryogenic payload to mitigate the downtime of observation. Owing to these new heaters, the downtime of the desorption process is expected to reduce from several weeks to a few days.

Source: H. Abe et al.: The Current Status and Future Prospects of KAGRA, the Large-Scale Cryogenic Gravitational Wave Telescope Built in the Kamioka Underground. Galaxies 10, 63, doi: 10.3390/galaxies10030063 (2022)

Paper of frost mitigation strategies

Source: L. Spallino et al.: Cryogenic vacuum considerations for future gravitational wave detectors. Phys. Rev. D 104, p. 062001, doi: 10.1103/PhysRevD.104.062001 (2021)

PHYSICAL REVIEW D **104,** 062001 (2021)

Cryogenic vacuum considerations for future gravitational wave detectors

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In recent years, gravitational wave observatories have conquered the world science scene due to their unprecedented capability to observe astrophysical signals. Those first observations opened up multi-messenger astronomy and called for a tremendous R&D effort to improve the sensitivity of future detectors. One of the many issues to be solved, not to affect the desired sensitivity, is the noise induced by the use of room temperature mirrors, especially for the low-frequency detection range. The use of cryogenic mirrors to reduce such a noise source has been individuated as a viable solution to obtain the desired sensitivity at low frequency. Cryogenically cooled mirrors, routinely operating at 10 K, present a number of extraordinary challenges, one being the cryogenic vacuum system hosting the cold mirrors. Gases composing the residual vacuum will tend to cryosorb and build a contaminant ice layer ("frost") on the mirror surface. Depending on such ice layer thickness, various unwanted detrimental effects may occur affecting mirror performances. This paper analyzes the consequences of hosting a cryogenically cooled mirror in a vacuum system and sets new limits for an acceptable operating pressure to avoid frost formation in a given period of continuous data taking. Since ice formation can be reduced but not avoided, we analyze potential mitigation methods to cure such a phenomenon. Thermal and nonthermal methods are analyzed and compared. Electron stimulated desorption is also considered as an alternative method to desorb the ice layer on mirrors. Finally, we briefly discuss further studies needed to validate the various methods with special care on their effects on the mirror perfection and optical properties.

DOI: 10.1103/PhysRevD.104.062001

I. INTRODUCTION

From the first detection of gravitational waves (GWs) in 2015 [1], the interferometry detection method has been established as an extremely powerful tool to significantly enrich multimessenger astrophysics for years to come. In the ongoing and future research, it is of paramount importance to reduce undesired noise that can limit the sensitivity of gravitational interferometers and, hence, their physical reach. Higher sensitivities are indeed foreseen to be essential to reveal the nature of GWs [2], the evolution of black holes [3], and the Hubble constant. Among other noise sources, coating thermal noise (CTN) is one of the limiting factors in the presently operational interferometers. All the advanced observatories will reach their design sensitivity if CTN is under control and opportunely mitigated [4–6]. CTN is intrinsic to mirrors, and its amplitude spectral density, to which a gravitational wave detector is sensitive, is proportional to $\sqrt{T}$. For this reason, cooling the mirrors is a very promising way to reduce CTN and, therefore, to improve sensitivity [7], especially in the low-frequency range. This approach is already foreseen at the Japanese KAGRA detector [8–10], which is currently under commissioning, for the low-frequency detector of the planned Einstein Telescope (ET LF) [11–13] and for the American Cosmic Explorer [14]. Cooling and running a suspended mirror of up to 200 kg at temperatures as low as 10 K presents a number of extraordinary technological challenges that will attract an enormous research and development effort in the coming years. Among other issues, a cryogenically cooled mirror will inevitably undergo the formation of a contaminant cryosorbed layer that could seriously affect mirror optical performances. Indeed, as reported in Refs. [15–17], the cryocooled mirrors at the KAGRA GW detector undergo a decrease in reflectivity due to ice growth. Its formation is induced by molecules both residual in the mirror vessel and moving from the warm laser beam transfer line. In those works, the authors assume water molecules as the dominant source of

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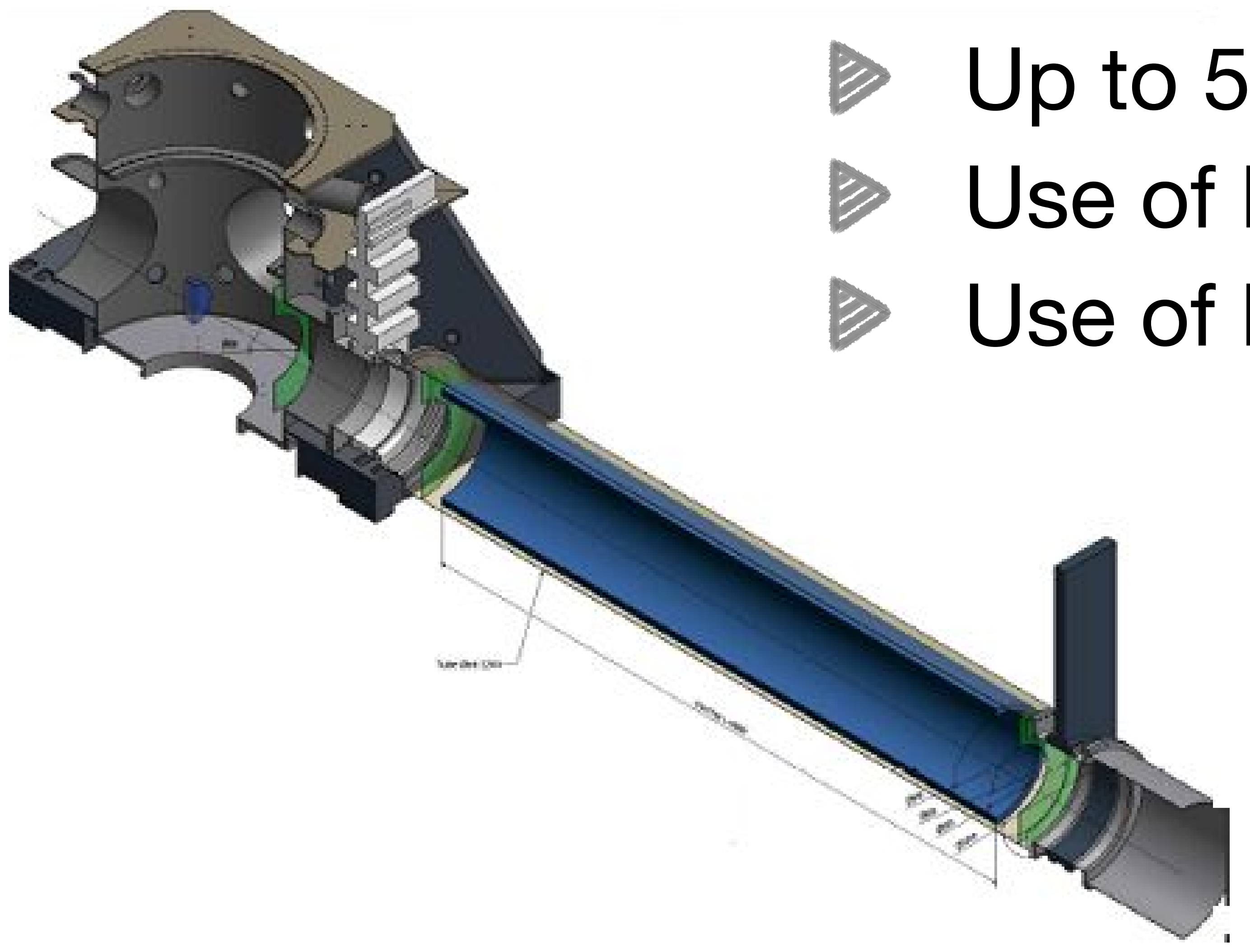
Cryopump development for ET-LF

- Original concept
  - ET Conceptual Design Study (2011)
  - Design Report Update (2020)



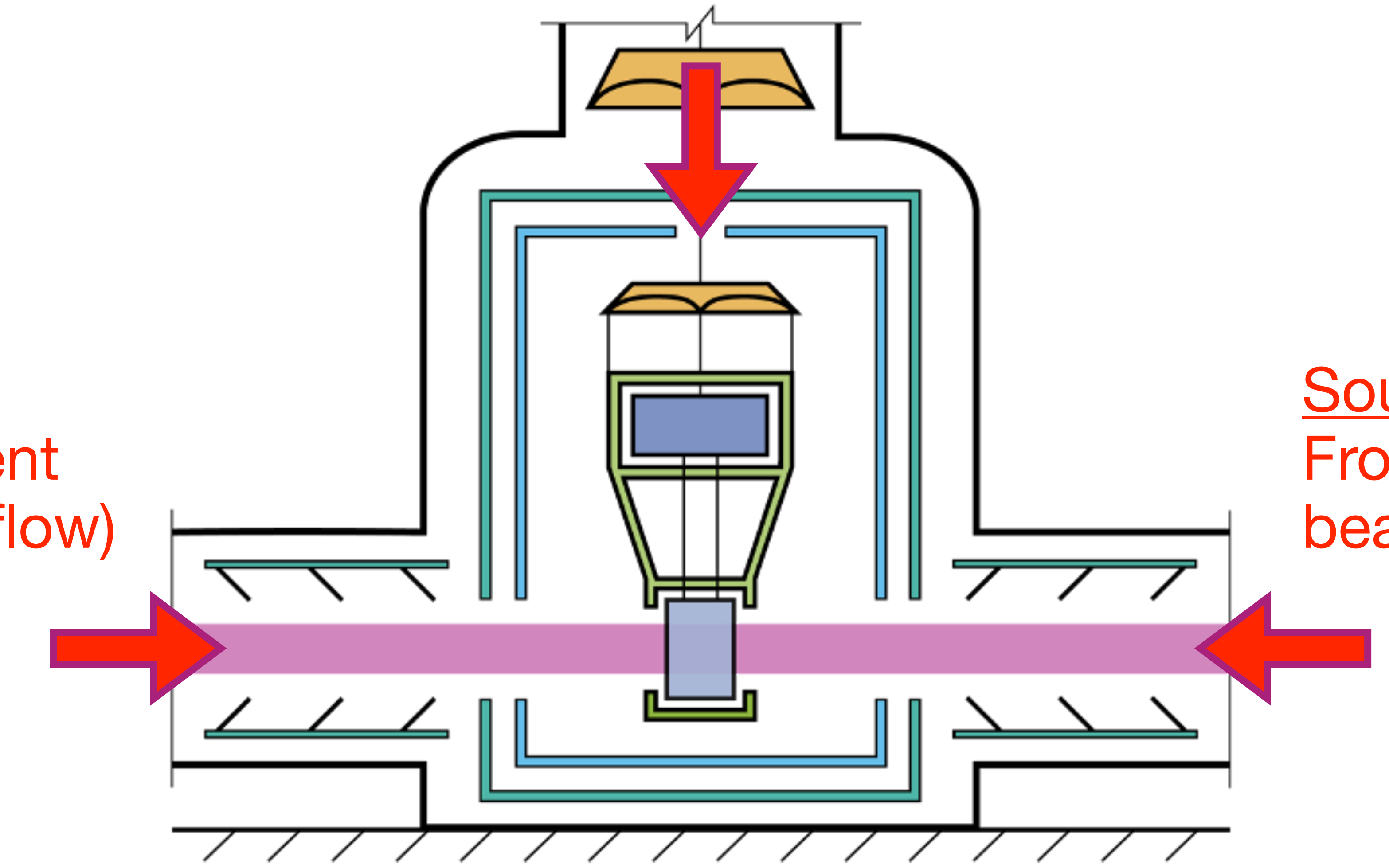
- Up to 50 m long
- Use of LN2
- Use of LHe

Source: ET science team: Einstein gravitational wave Telescope conceptual design study. https://apps.et-gw.eu/tds/ql/?c=7954 (2011)

- Vacuum modelling and cryopump development at KIT
  - TPMC modelling with all gas sources and simplified geometry
  - KIT in-house code ProVac3D

Source 2: From upper part of suspension tower

Source 3: From adjacent tower (high flow)



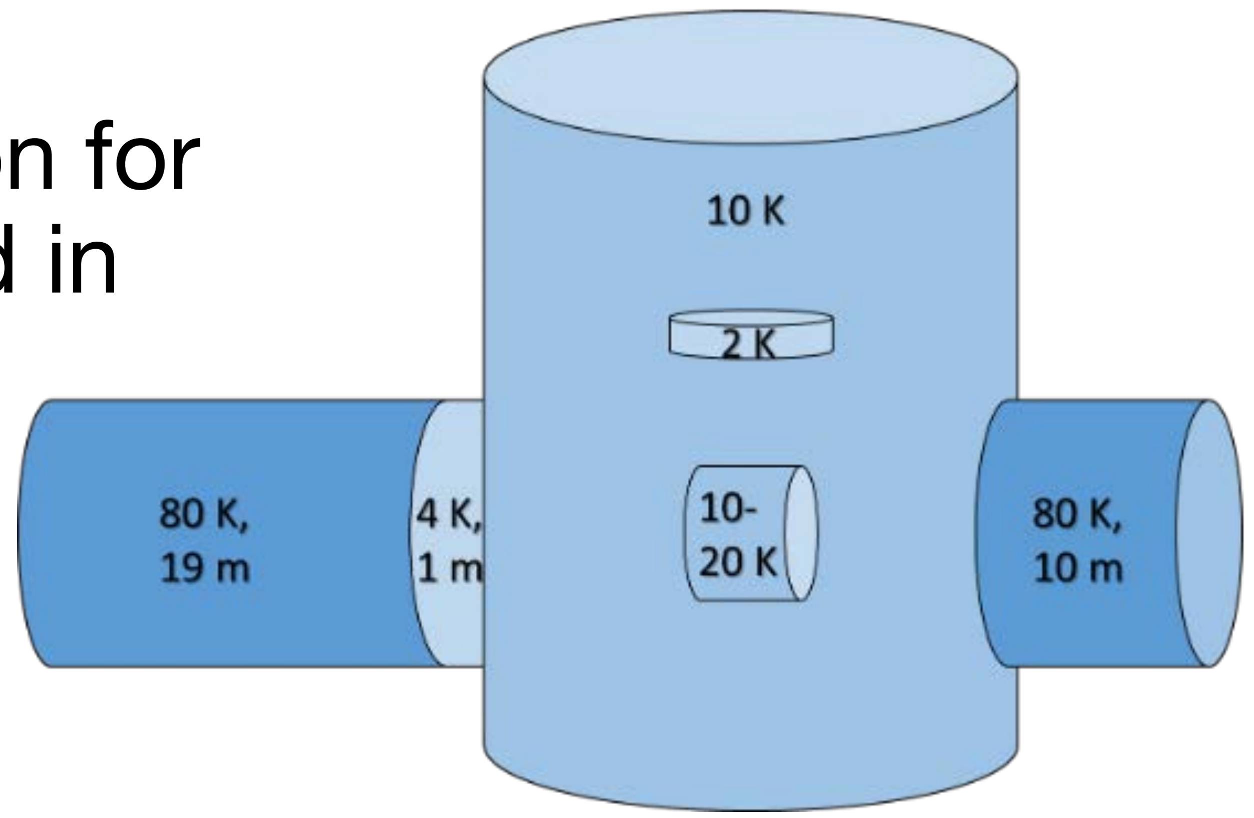
Source 1: From 10 km beam pipe

More details: See presentation by Katharina Battes

Preliminary results of tower vacuum modelling

Modelling results

- **Source 1:**
  Cryopump at 80 K for water trapping sufficient
- **Source 2:**
  Conductance minimisation plus (cryo)pumping in upper tower needed to reduce flow
- **Source 3:**
  Cryopump section for hydrogen needed in addition to main water pumping section



Source: S. Hanke, K. Battes, X. Luo and C. Day: Cryopumps at the extremities of the beampipes: design and performance. Beampipes for Gravitational Wave Telescopes 2023, CERN, March 2023, https://indico.cern.ch/event/1208957/

Main conclusions

- **Pressures** around mirror
  - Hydrogen: $p_{\mathrm{H2}} \approx 3 \times 10^{-13}\,\mathrm{mbar}$
  - Water: $p_{\mathrm{H2O}} \approx 1 \times 10^{-14}\,\mathrm{mbar}$
- **Water ice** build-up **~2 years for 1 ML**
- Pumping of **water** at 80 K
- Pumping of **hydrogen**
  - 10 K with adsorbent
  - 3.8 K with metallic surface
  - **Helium cooling** needed for H2 cryopumps

Adsorption can be mitigated by appropriate cryopump R&D

Intermediate conclusions

1) **Cryogenic payloads** compatible with ET-D are **technically feasible** ✅

2) **Particle adsorption** on cryogenic mirrors **can be mitigated** ✅

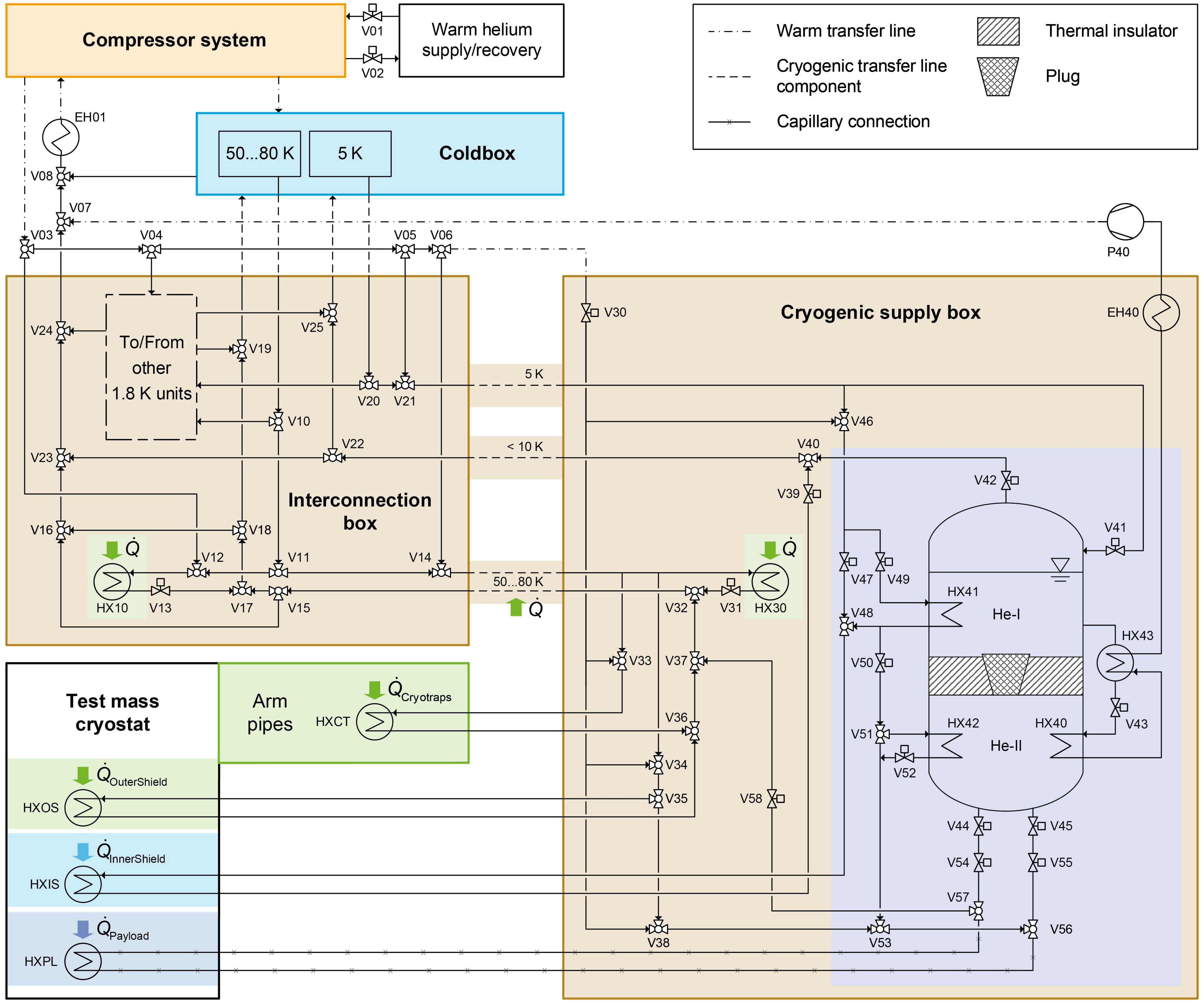
3) Work on **technical solutions** for

- Cryopump design
- Cryostat design
- Cryogenic infrastructure design
- Cooling integration in the payloads
- …

| **Important for ET infrastructure** (Cryopump design, Cryostat design, Cryogenic infrastructure design)

| Detector R&D (Cooling integration in the payloads)

Cryogenic infrastructure concept



- No underground LN_2 (safety)
- One He refrigerator at each vertex
  - (Remote) surface compressors
  - Underground coldbox
  - Interconnection box to several cryogenic supply boxes (1 for each tower/cryostat)
    - Up to c. 500 m long transfer lines
  - 1-phase cooling H_2O cryopumps/outer shields
  - 1-phase cooling H_2 cryopumps/inner shields
  - Optional He-II payload cooling/inner shield

Reference:
L. Busch, S. Grohmann: Conceptual Layout of a Helium Cooling System for the Einstein Telescope. Procs. CEC/ICMC 2021, doi: 10.1088/1757-899x/1240/1/012095.

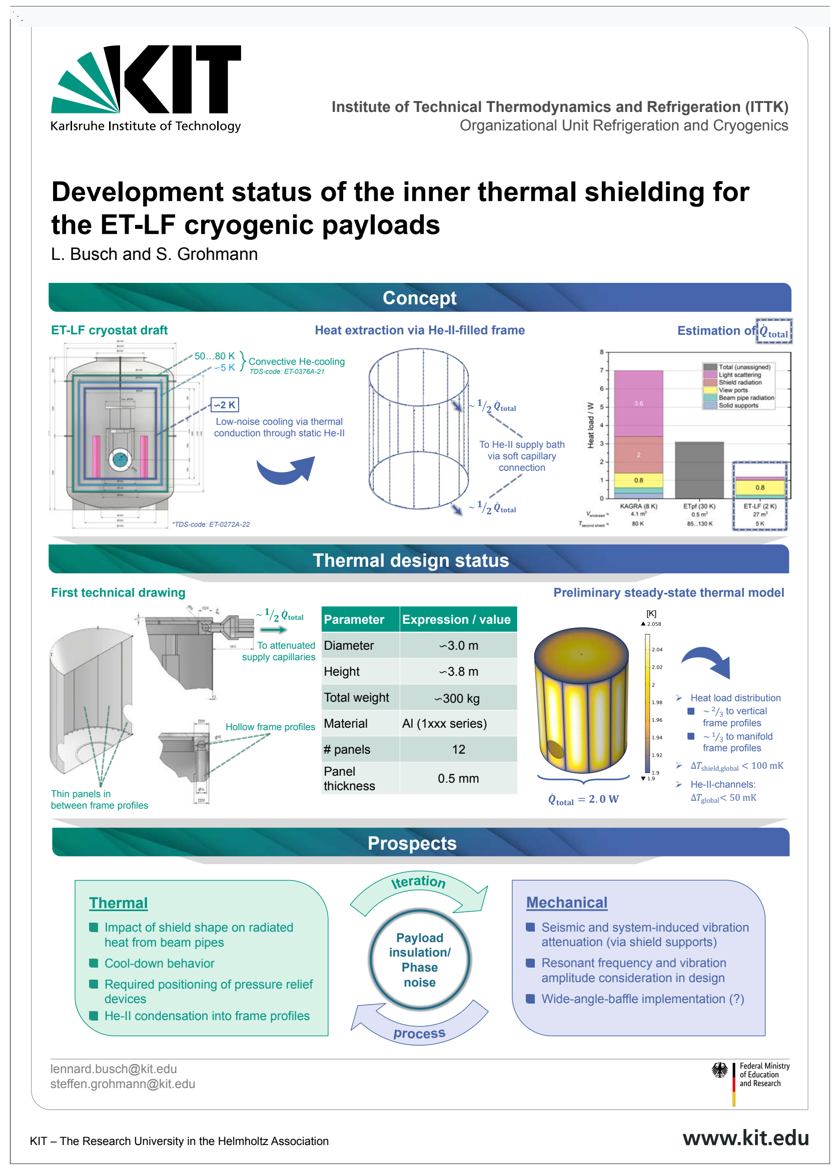
Required cooling capacities

Consumers at 80 K
- **Cryopumps for water** (10…20 m)
- Other thermal shields (use of **MLI open**…)
- Shielding of transfer lines and cryostats

Consumers at 5 K
- **Cryopumps for hydrogen**
- Cryogenic supply boxes
- Inner thermal shields

Poster
Lennard Busch

Consumers at 2 K
- Cryogenic payloads (0.5 W each) ✅
- Inner thermal shields (2 W each) ✅



Present status

We need **results** from tower vacuum simulations and cryopump design (i.e. the **main consumers**) to determine **the size** of the cryogenic infrastructure

Roadmap to ET TDR

Cryogenic requirements of main consumers

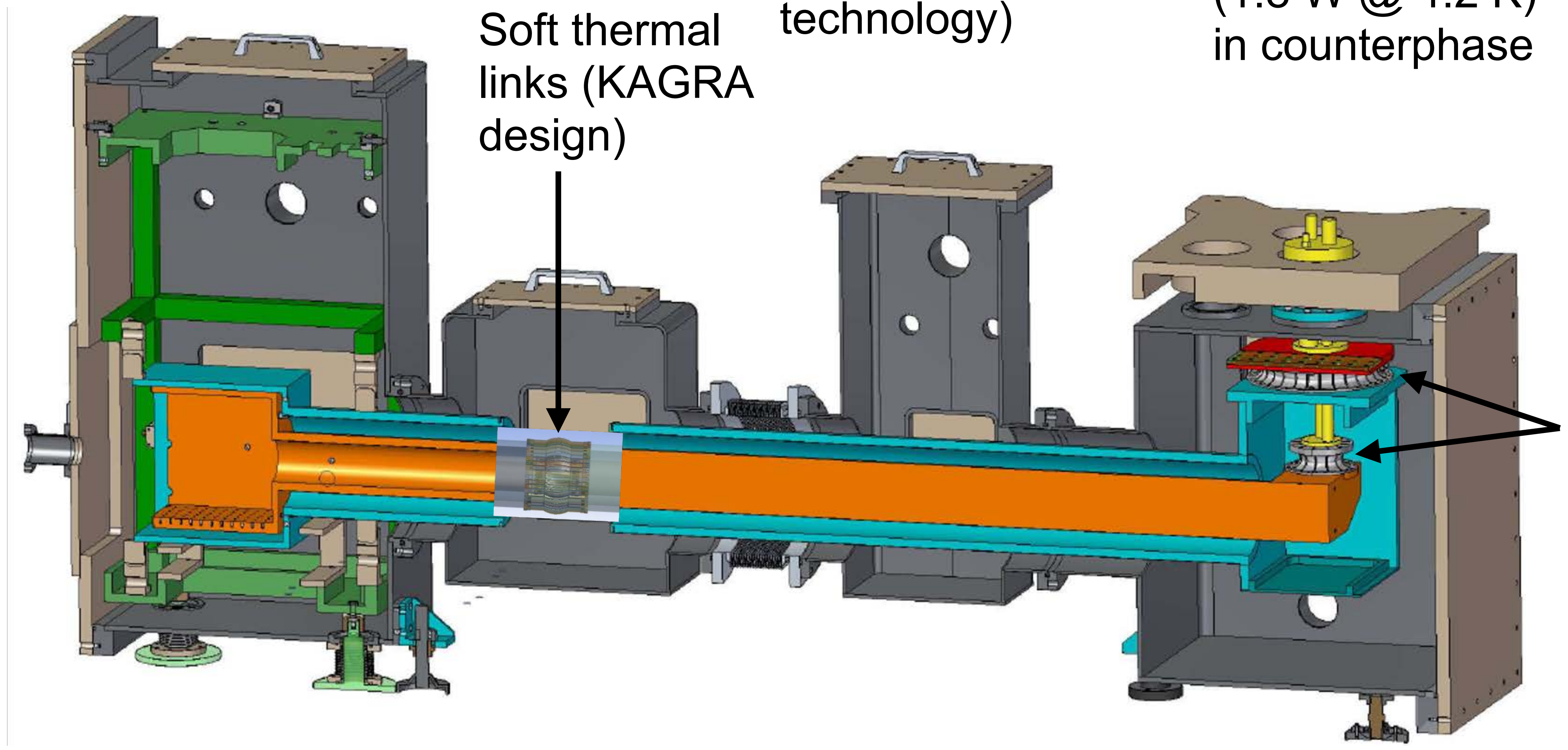
Cryoplant design study **with industry**

Budget determination for TDR

R&D FACILITIES (OVERVIEW)

R&D facilities – ARC (Rome)

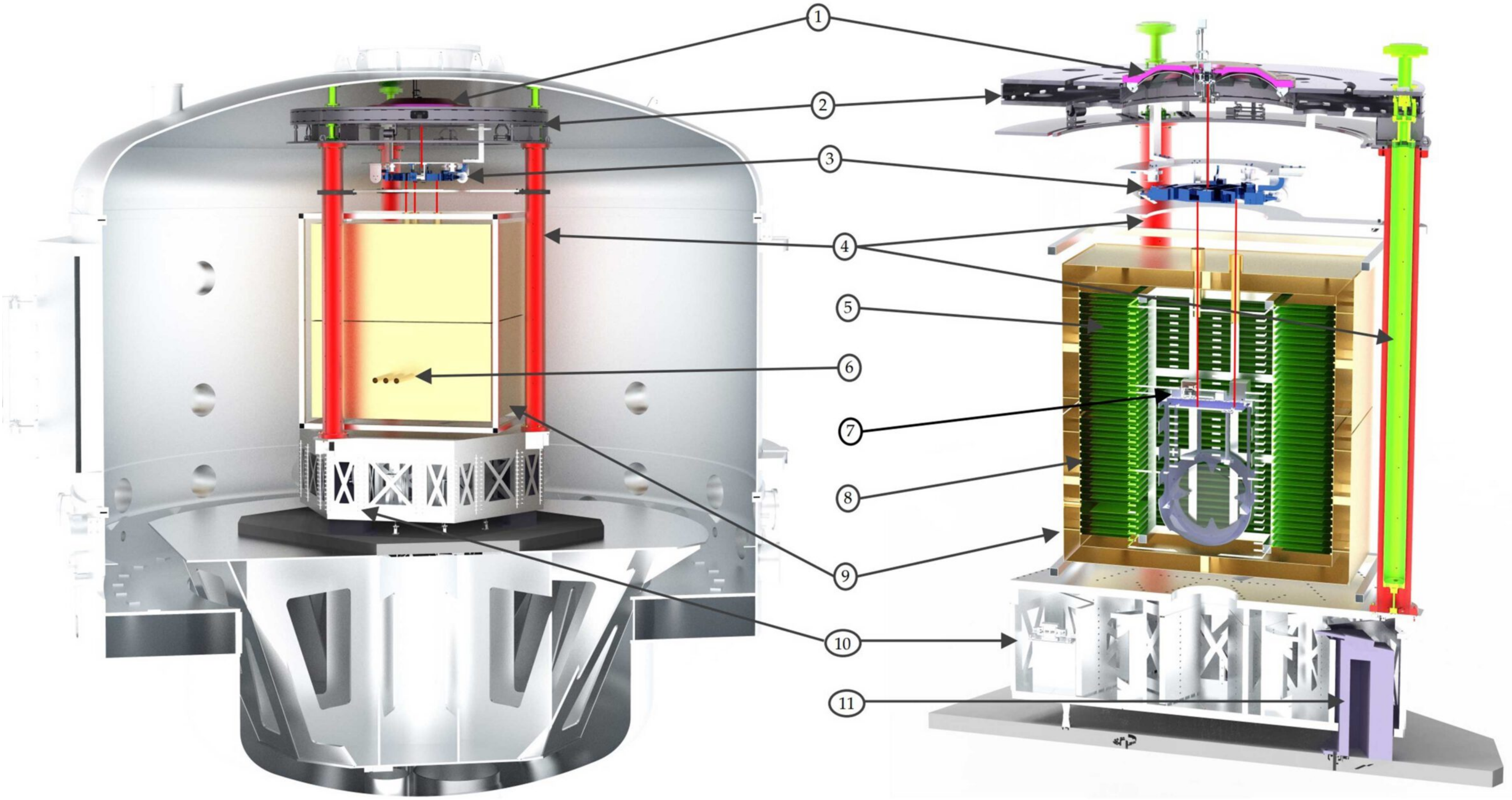
- Objective: Development of complete ET-LF payloads
  Contact: https://www.phys.uniroma1.it/fisica/en/arc_amaldi_research_center



More details: See presentation by Valentina Mangano and Marco Ricci

R&D facilities – E-Test (Liège)

- Objective: R&D on optics, cryogenics and seismic isolation
  Contact: https://www.etest-emr.eu/activities/prototype-2/



More details: See presentation by A. Sider

R&D facilities – ETpathfinder (Maastricht)

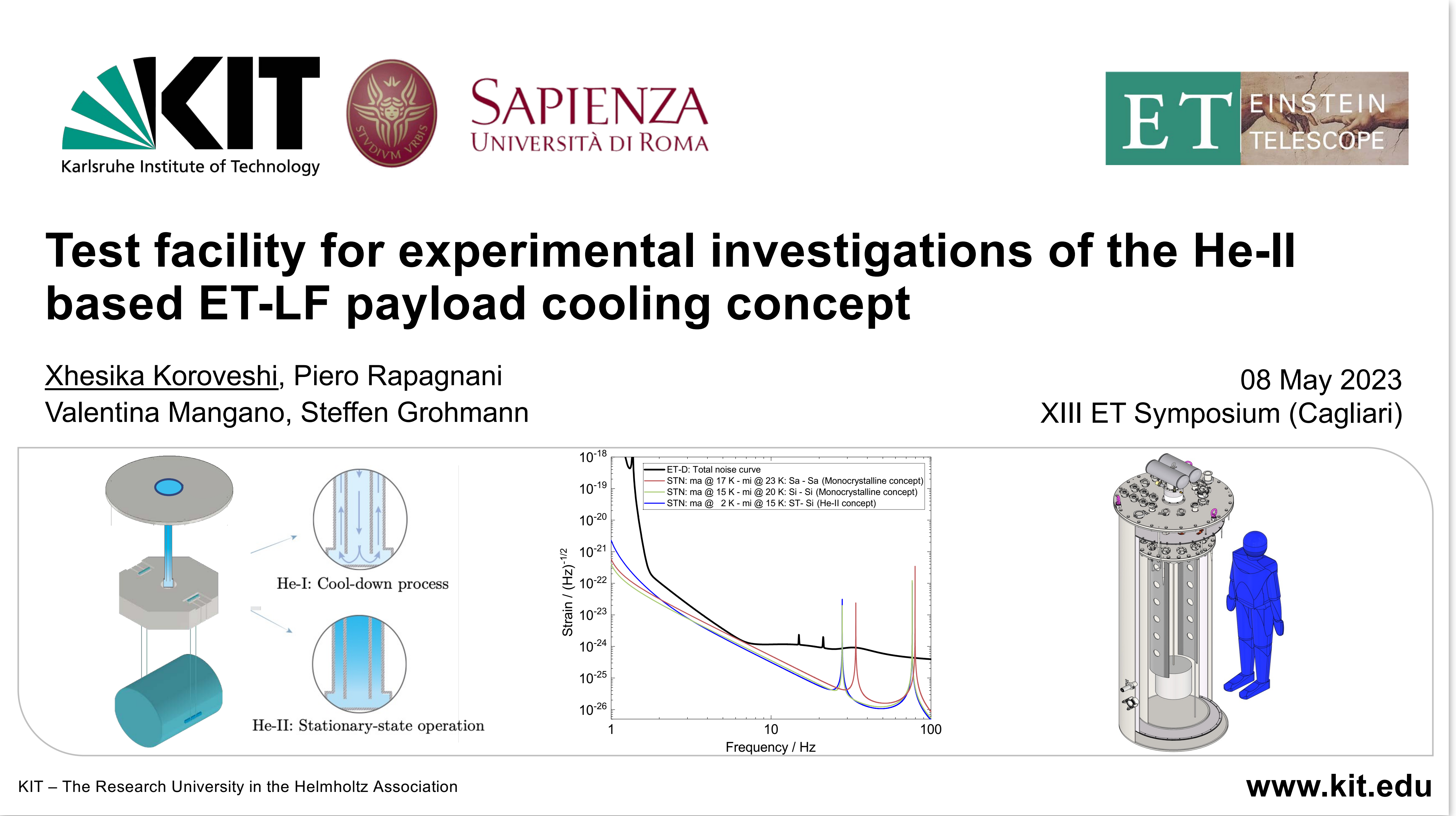
- Objective: Testing of full ET-LF interferometer configurations
  Contact: https://www.maastrichtuniversity.nl/etpathfinder

More details: See presentation by Sebastian Steinlechner

R&D facilities – KIT (Karlsruhe)

- **New proposal**: Development of He-II technology towards **TRL4**
  Contact: https://kkt.ttk.kit.edu/

Poster
Xhesika Koroveshi



Thank you for your attention!

Source: ET Design Report Update (2020)