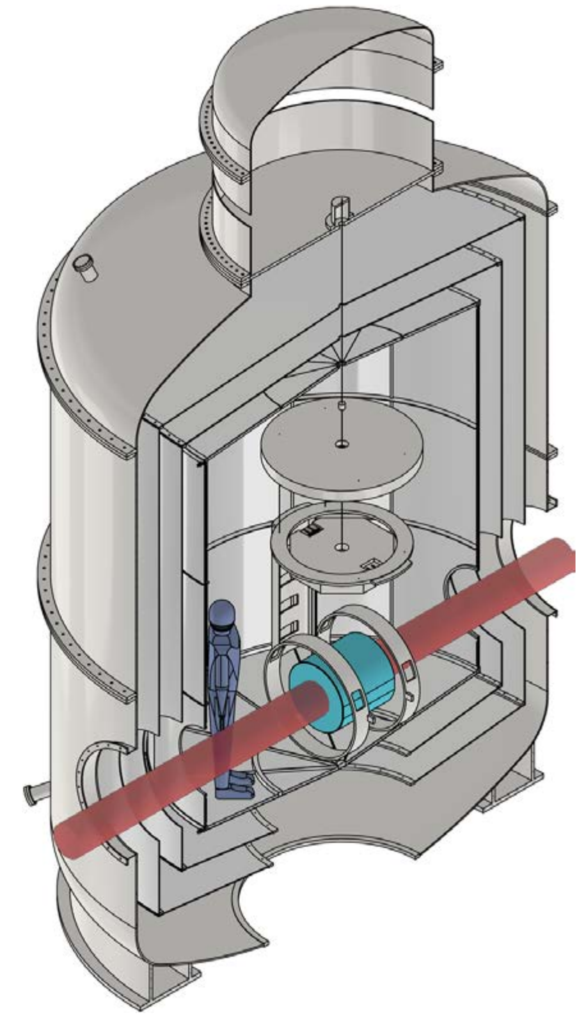
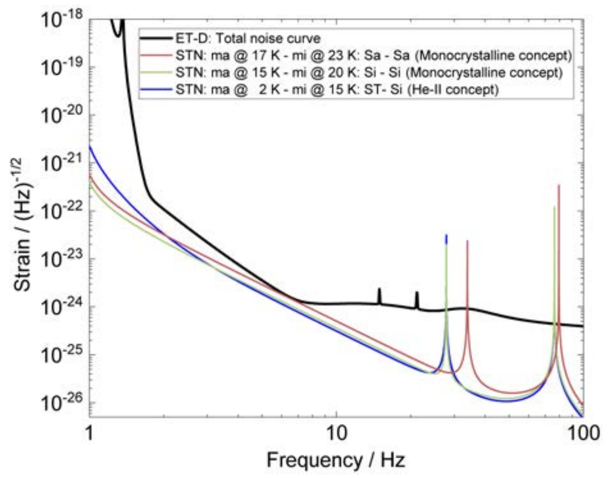
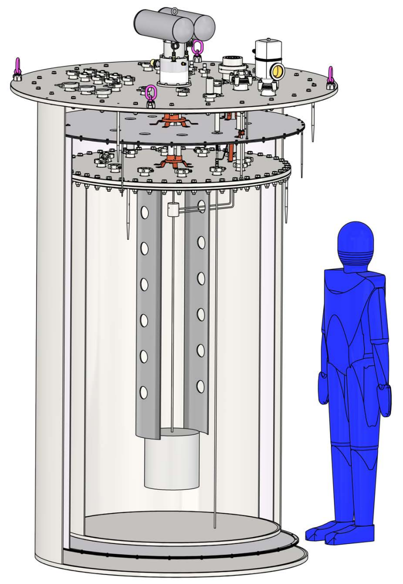
ET – Status of R&D activities at KIT

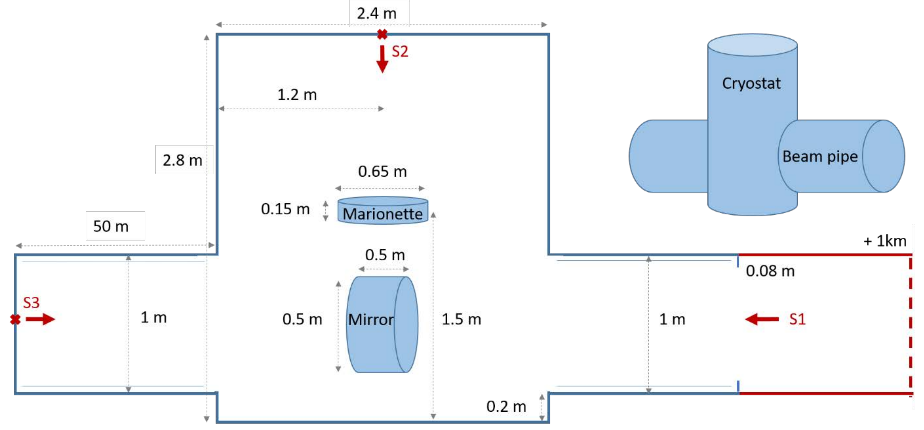
Steffen Grohmann – On behalf of the KIT ET Research Unit

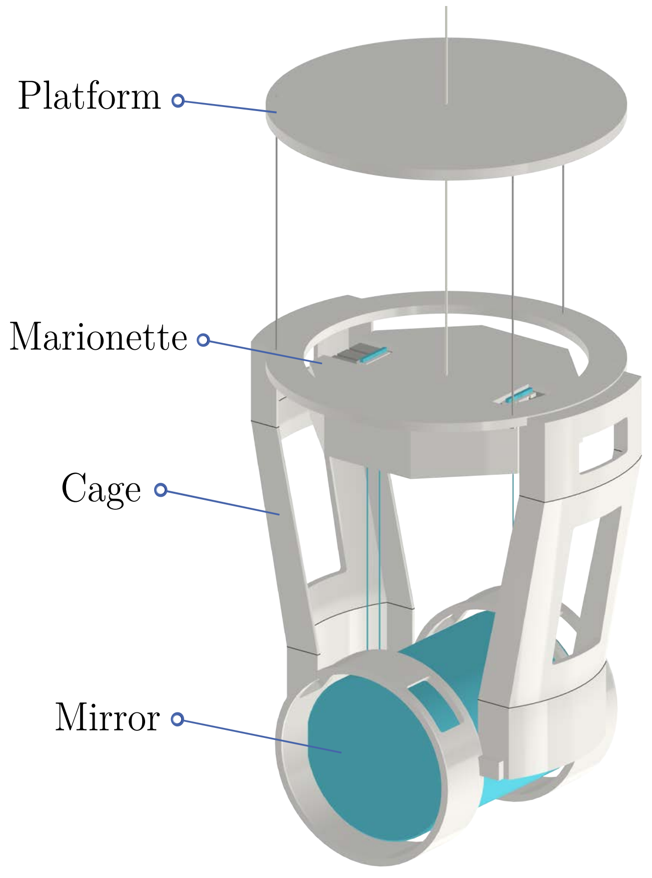
3rd DMLab Meeting, Karlsruhe, November 16-17, 2023

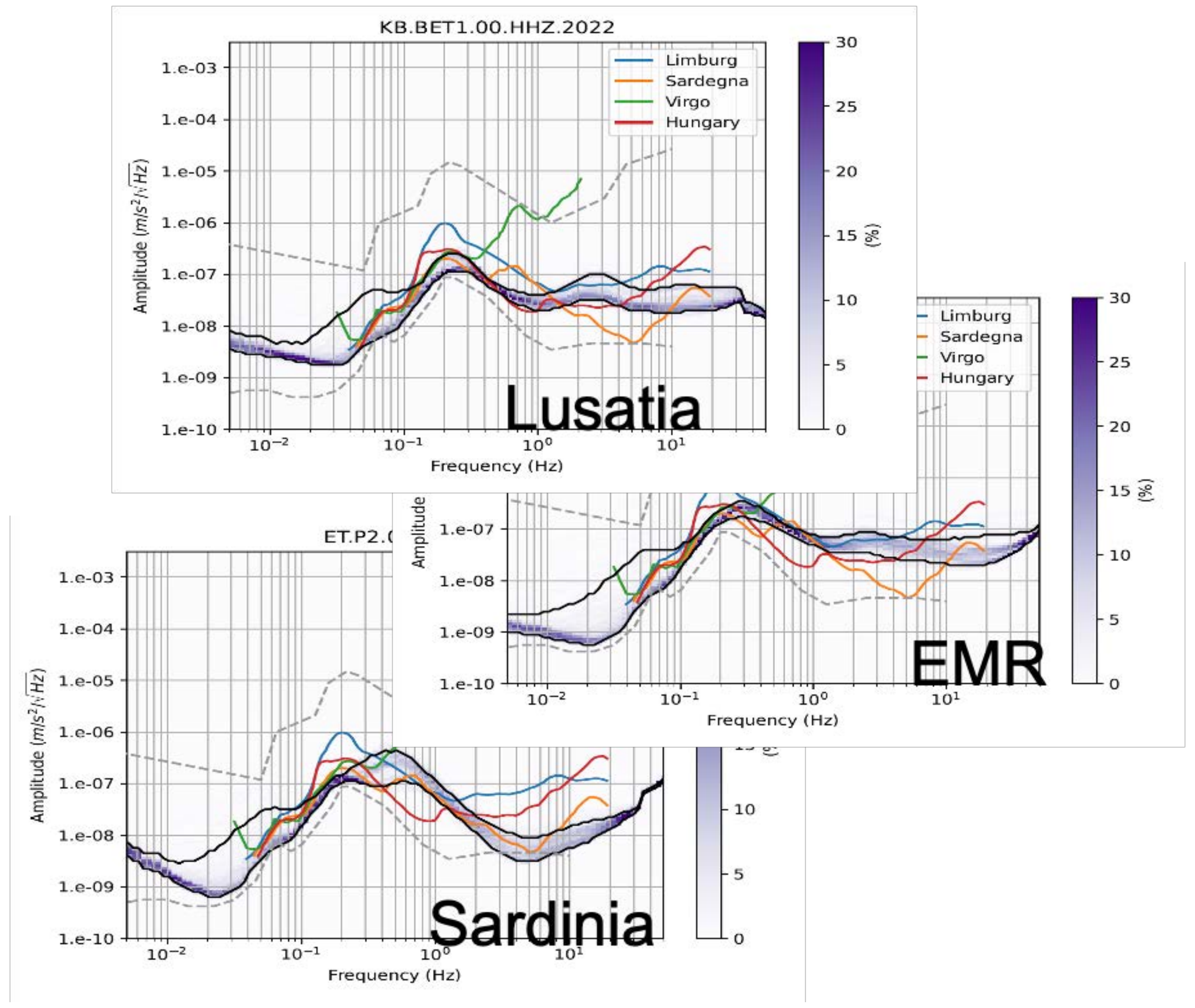


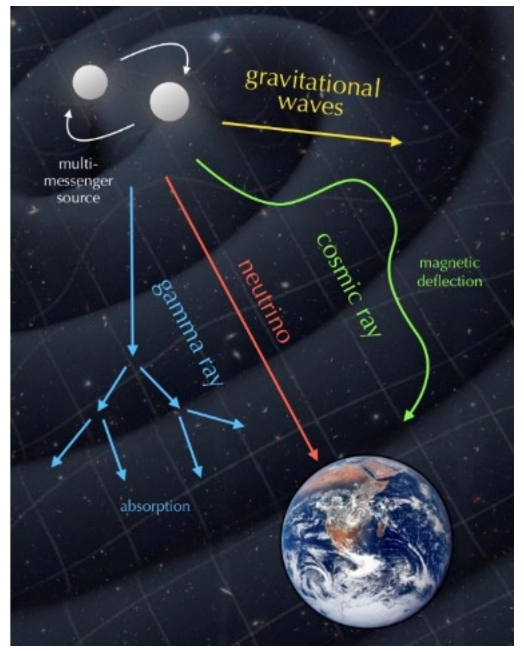




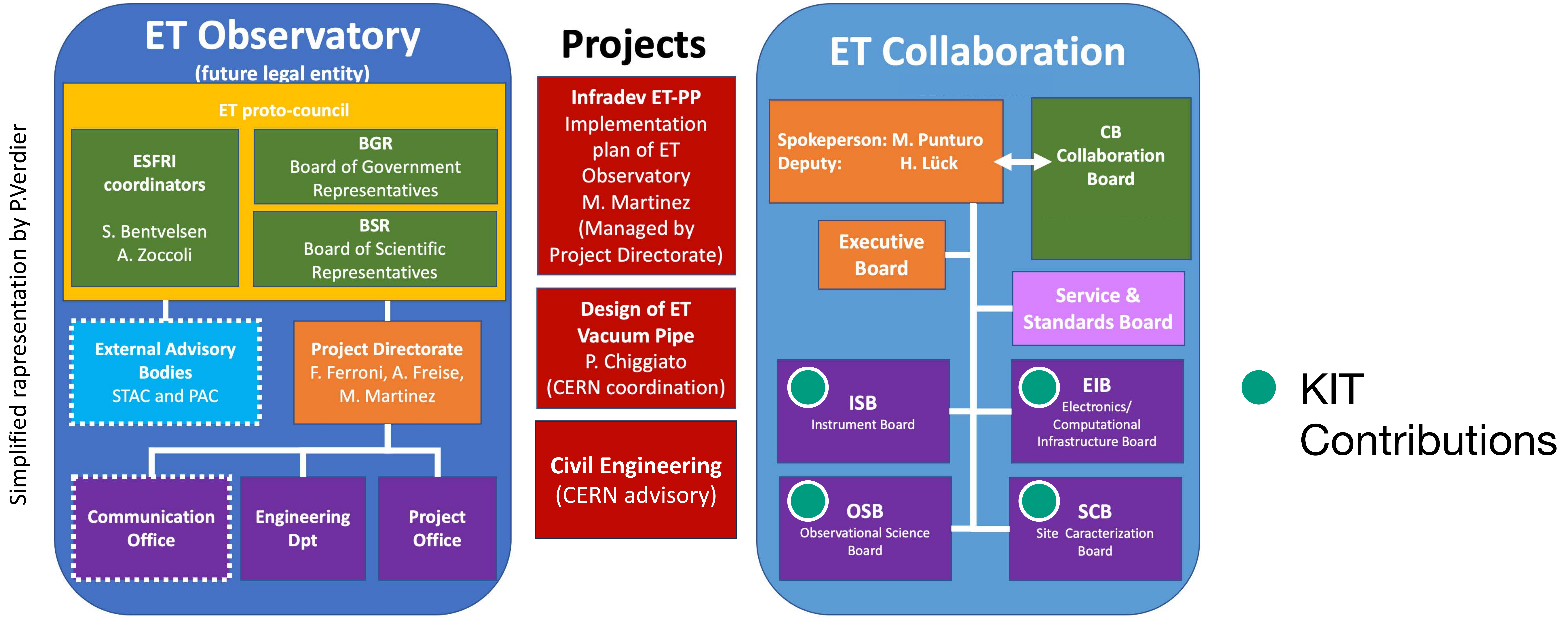






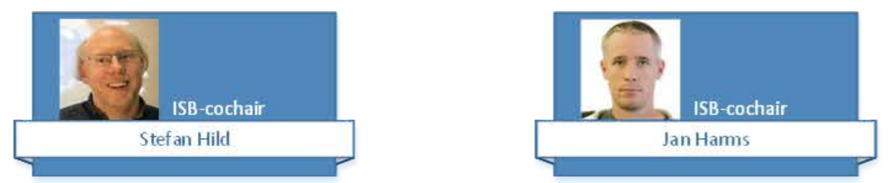


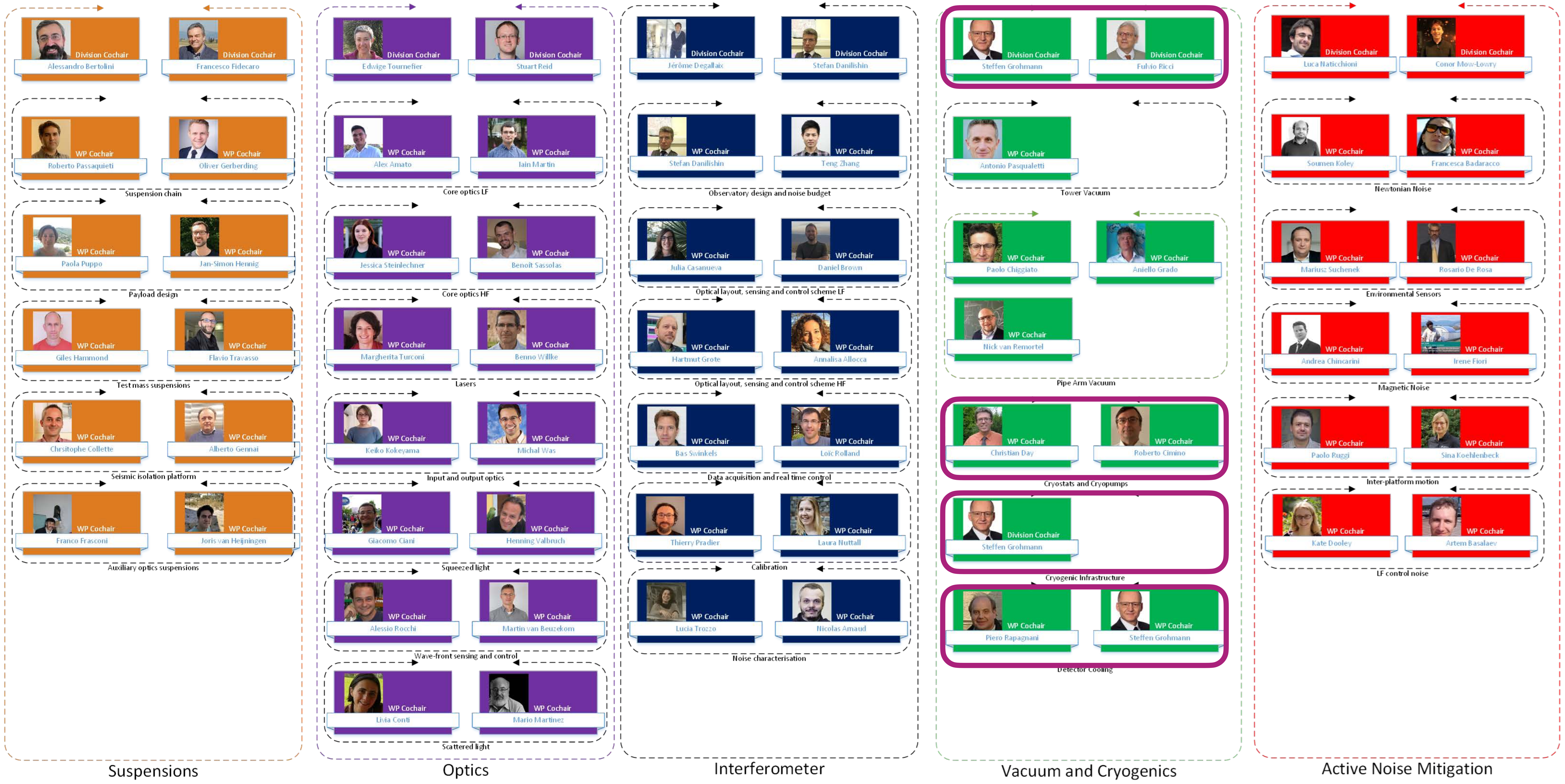
Current organisation of ET



CONTRIBUTIONS TO THE ISB

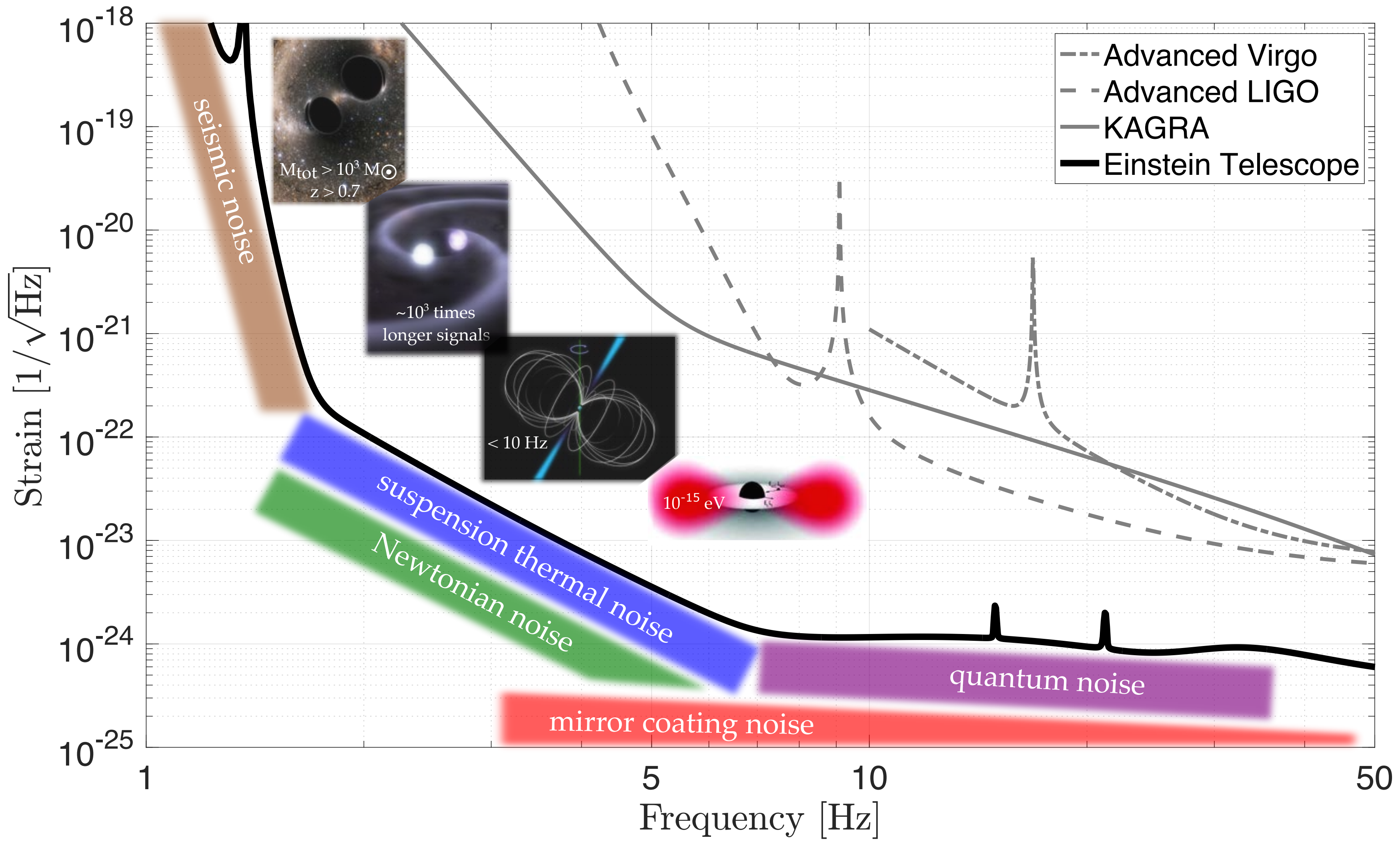
ISB organigram





Necessity of cryogenic ET-LF

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

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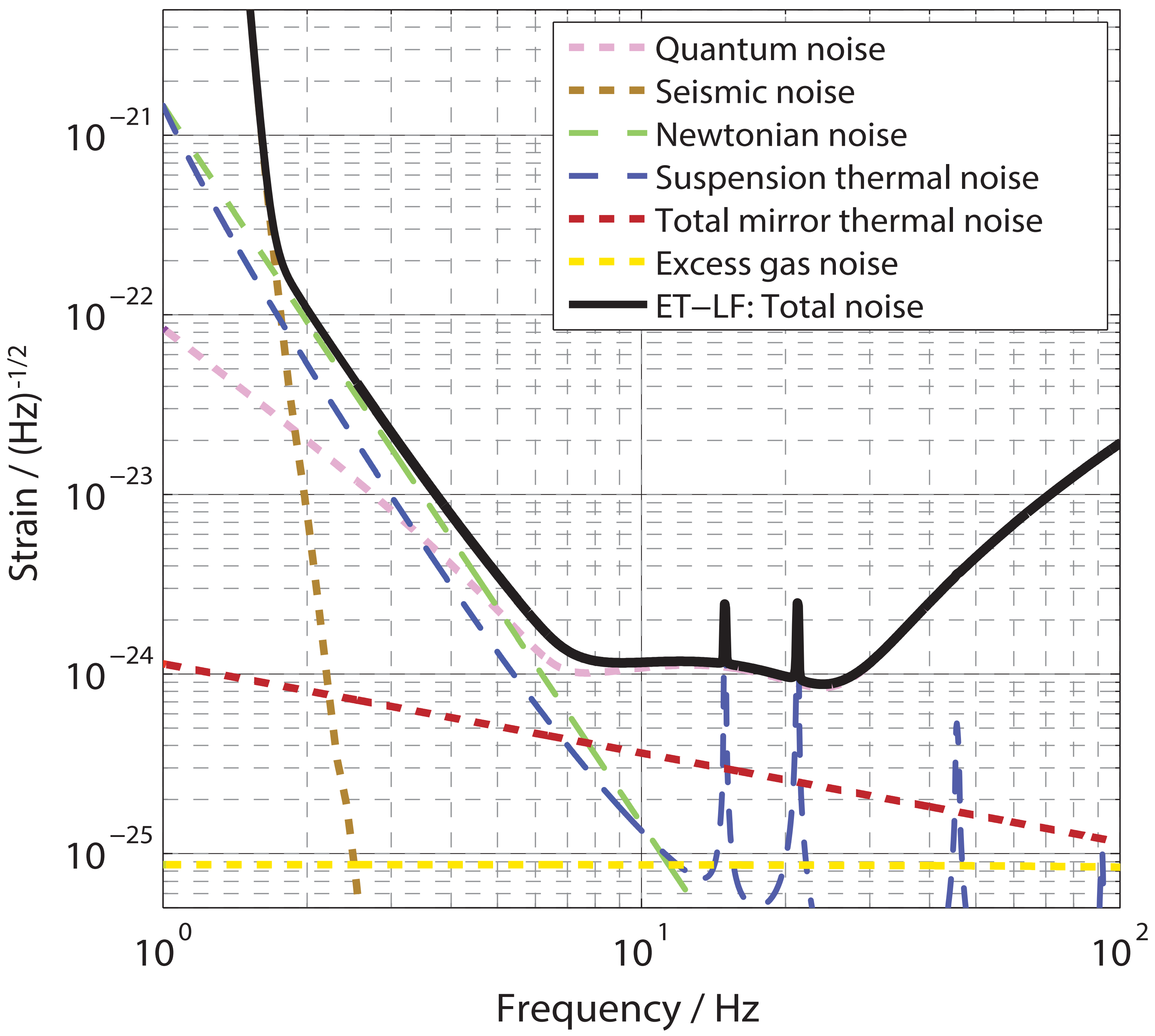
ET-D sensitivity curve



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

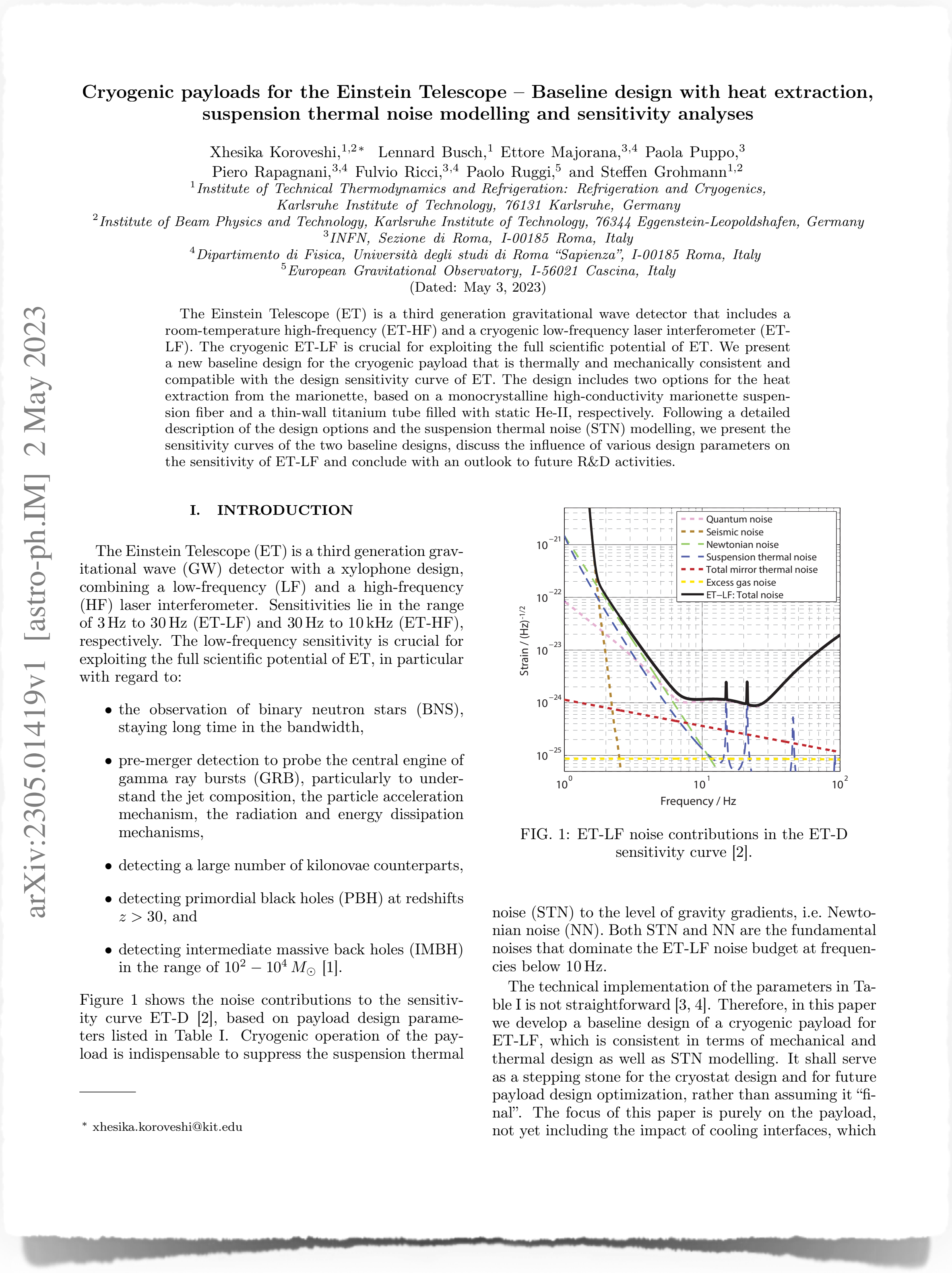
- **Baseline design study** carried out by ET-ISB Divisions I and IV

Baseline design of ET-LF cryogenic payloads

Karlsruhe Institute of Technology

Reference Paper [1]

[1] Koroveshi X, Busch L, Majorana E, Puppo P, Rapagnani P, Ricci F, Ruggi P, Grohmann S, 2023, accepted in Phys.Rev. D https://arxiv.org/abs/2305.01419



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

Xhesika Koroveshi,[1,2*] Lennard Busch,[1] Ettore Majorana,[3,4] Paola Puppo,[3] Piero Rapagnani,[3,4] Fulvio Ricci,[3,4] Paolo Ruggi,[5] and Steffen Grohmann[1,2]

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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.

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

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

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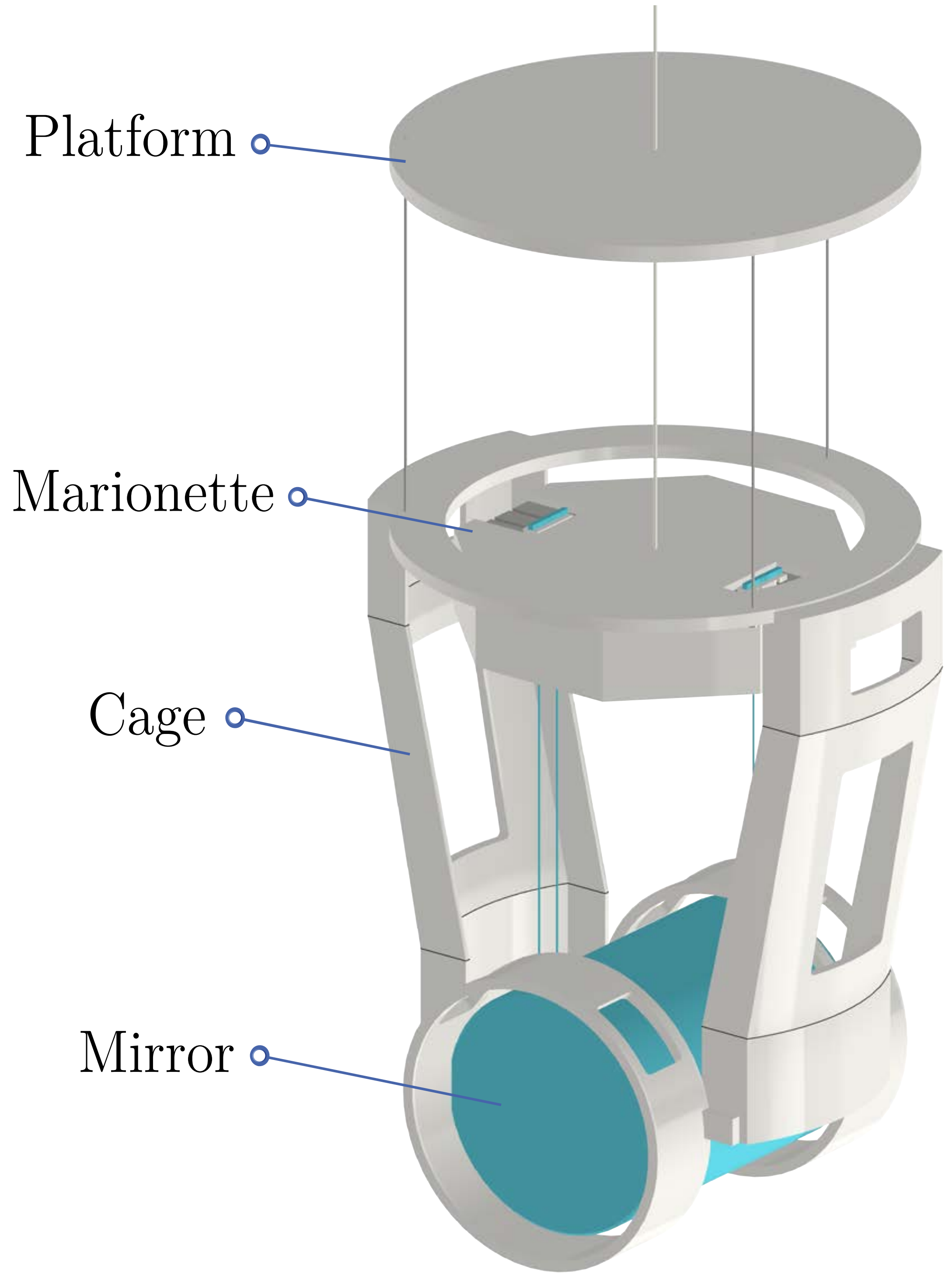

Objectives

- **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 [1]

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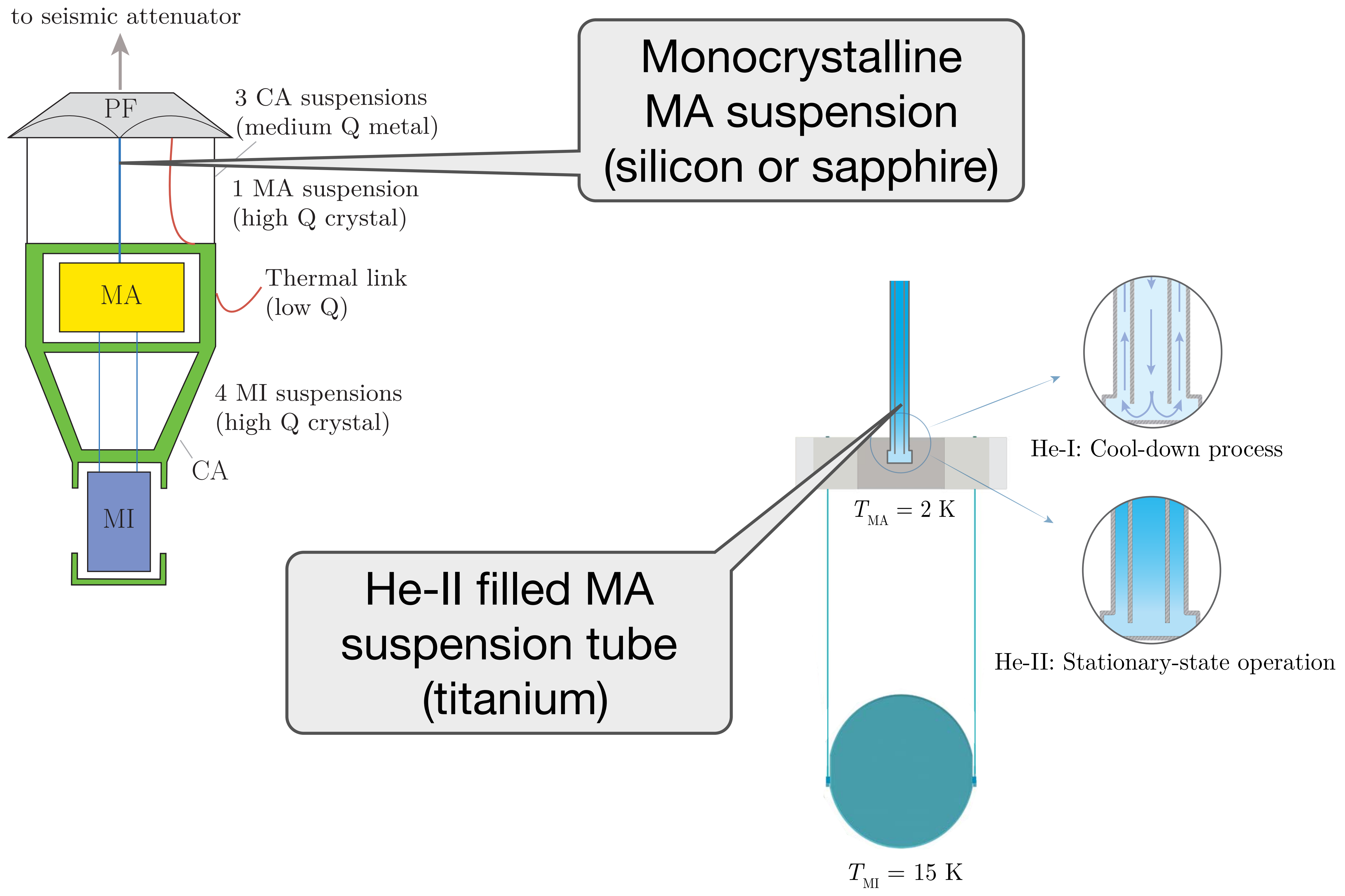
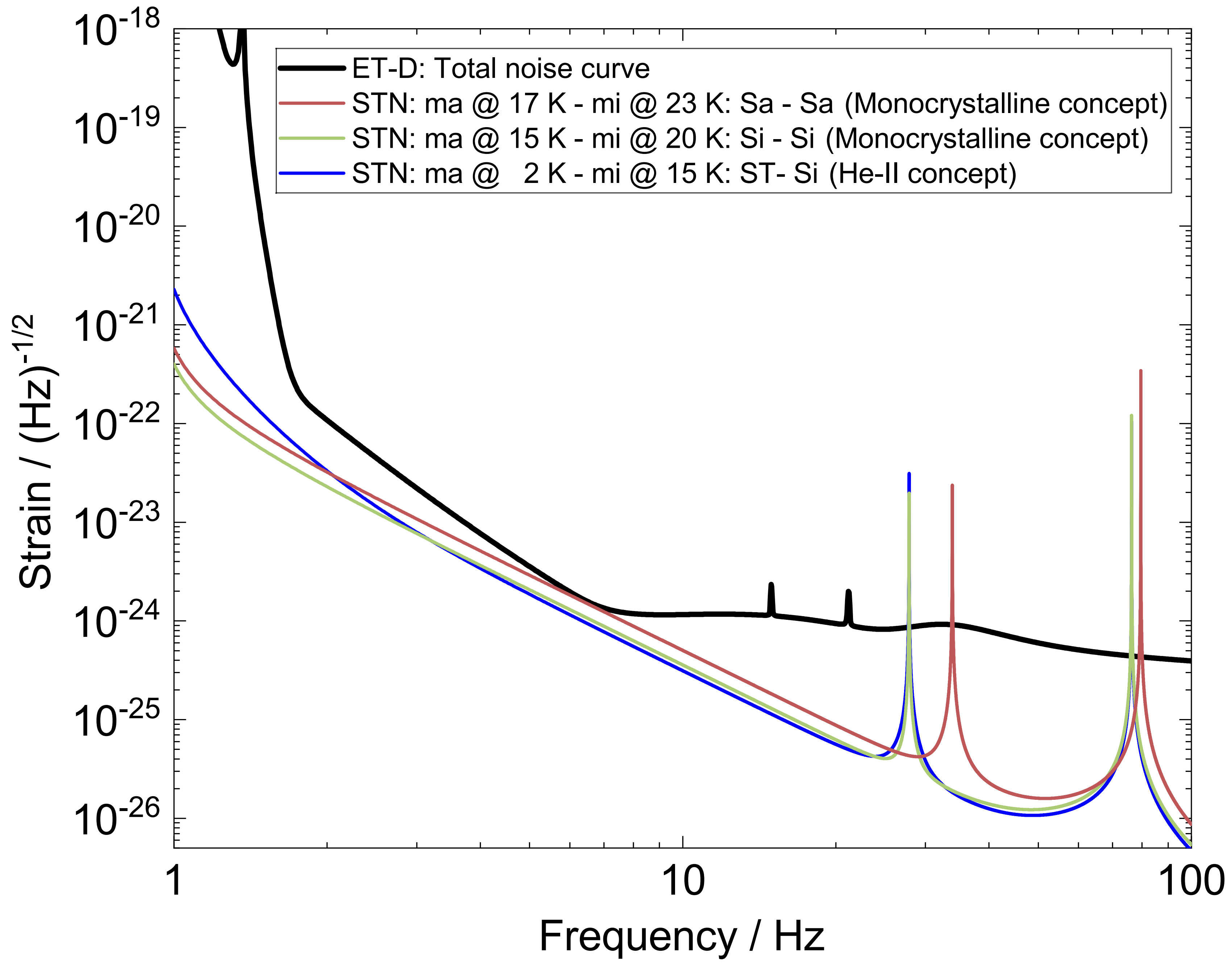
Two options for the heat extraction



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

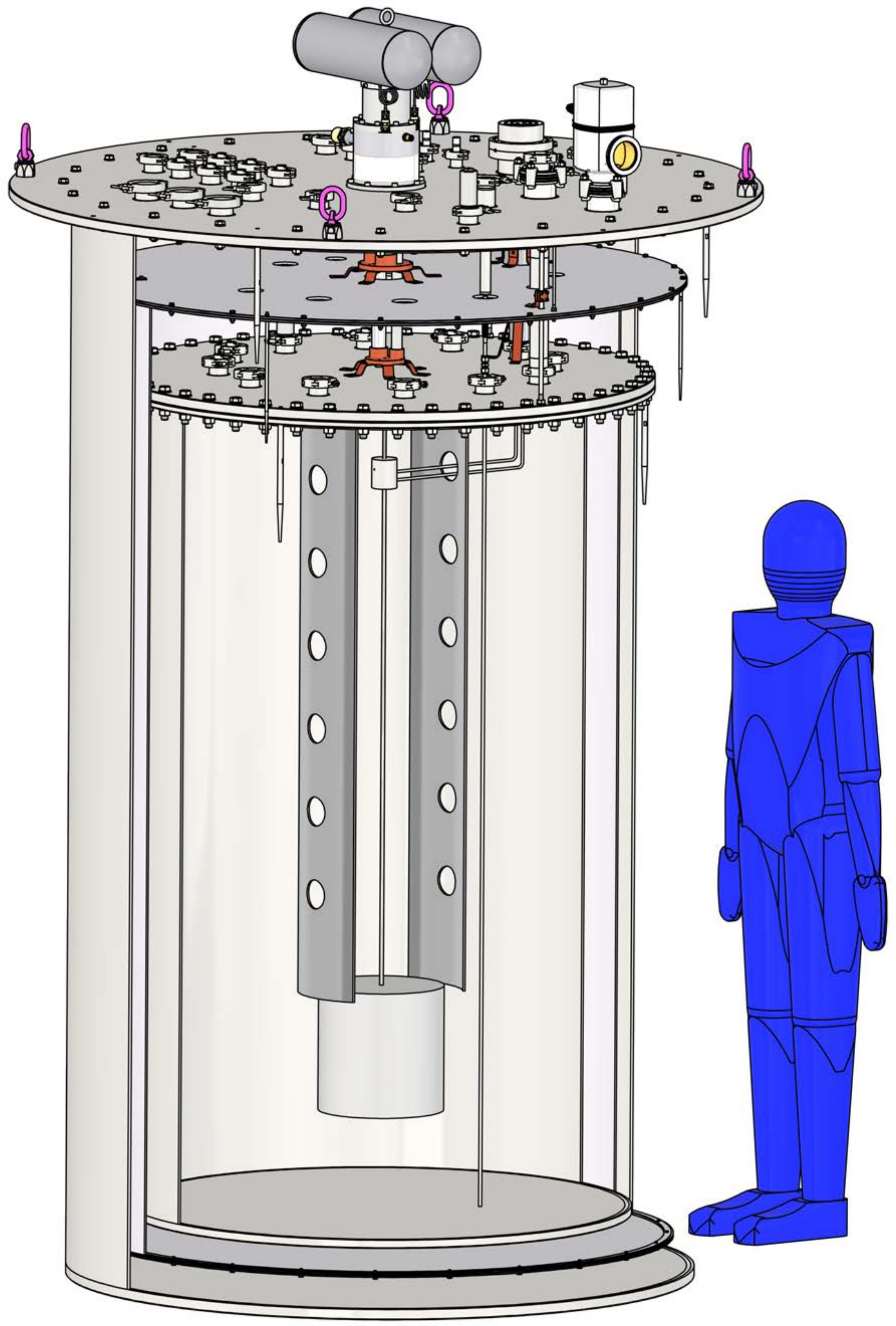
Sensitivity (STN)

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

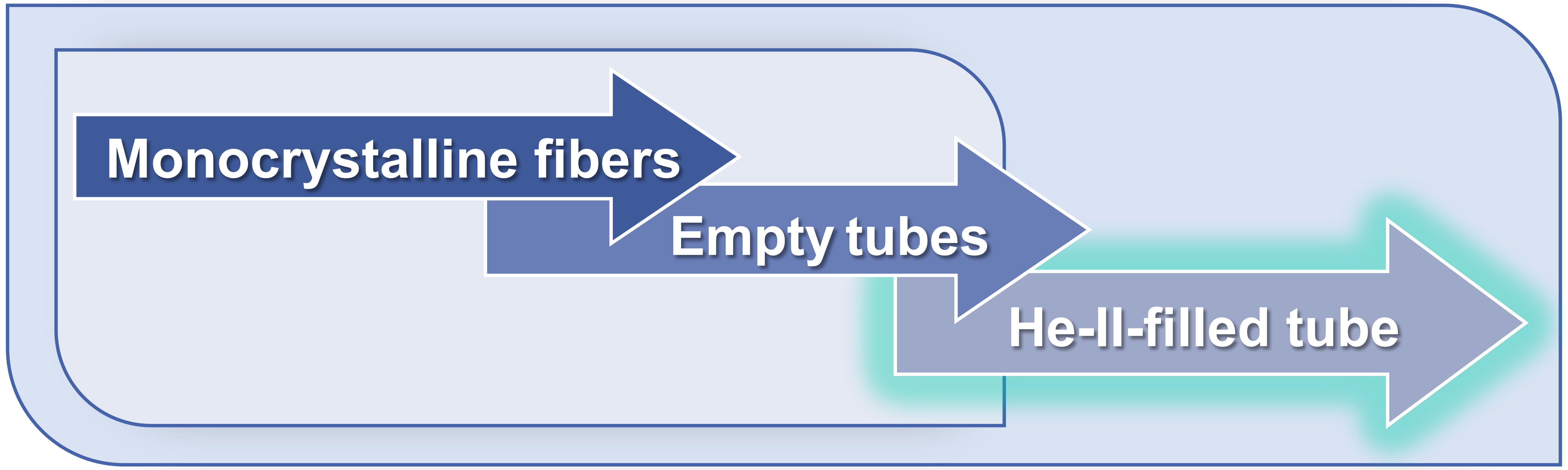


Xhesika Koroveshi, TTK
(S. Grohmann)

Investigation of He-II in cryogenic suspensions [2]



- **Test facility for investigating:**
  - Full-size suspension fibres and tubes
  - Loss mechanisms in He-II filled suspension tubes
  - Experimental proof of concept for He-II based ET-LF payload cooling [1]

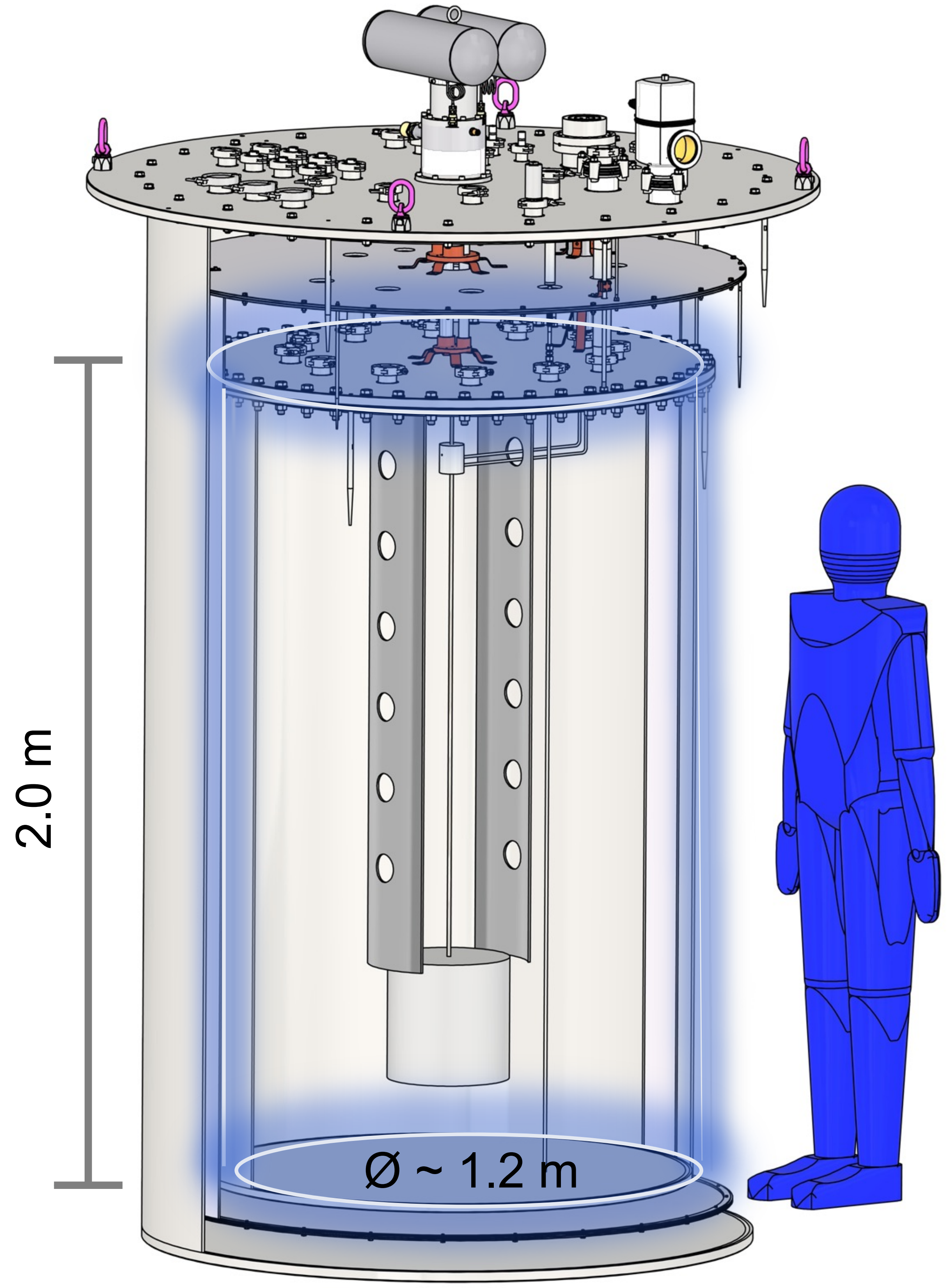


[2] Koroveshi X, Rapagnani P, Mangano V , Stamm M, Grohmann S, 2023, IOP Conf. Ser.: Mater. Sci. Eng. submitted

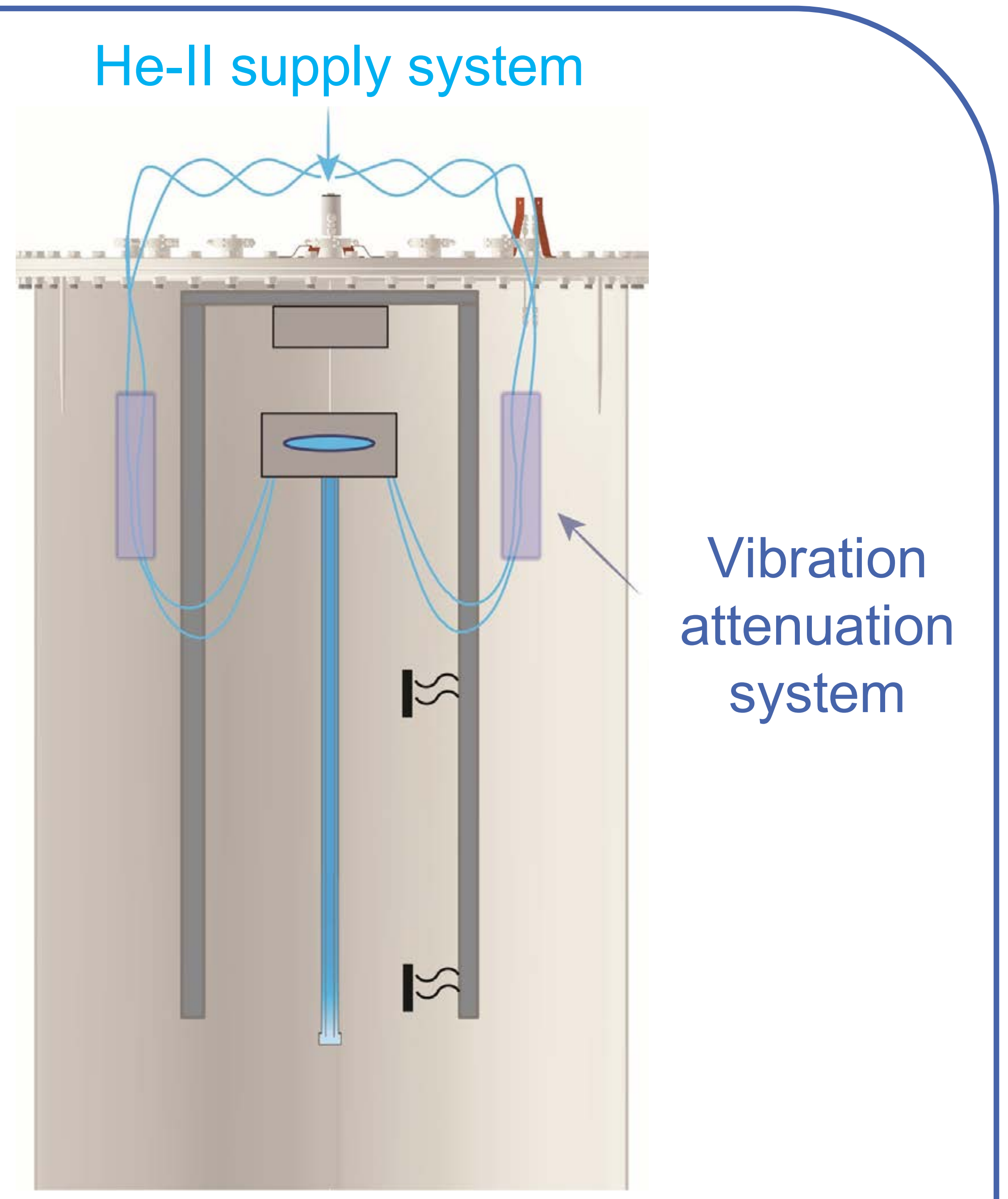
Cryogenic payload suspension studies [2]

Xhesika Koroveshi, TTK
(S. Grohmann)

Phase 1:
He-II free campaigns



Know-how transfer



Phase 2:
He-II filled tube campaigns

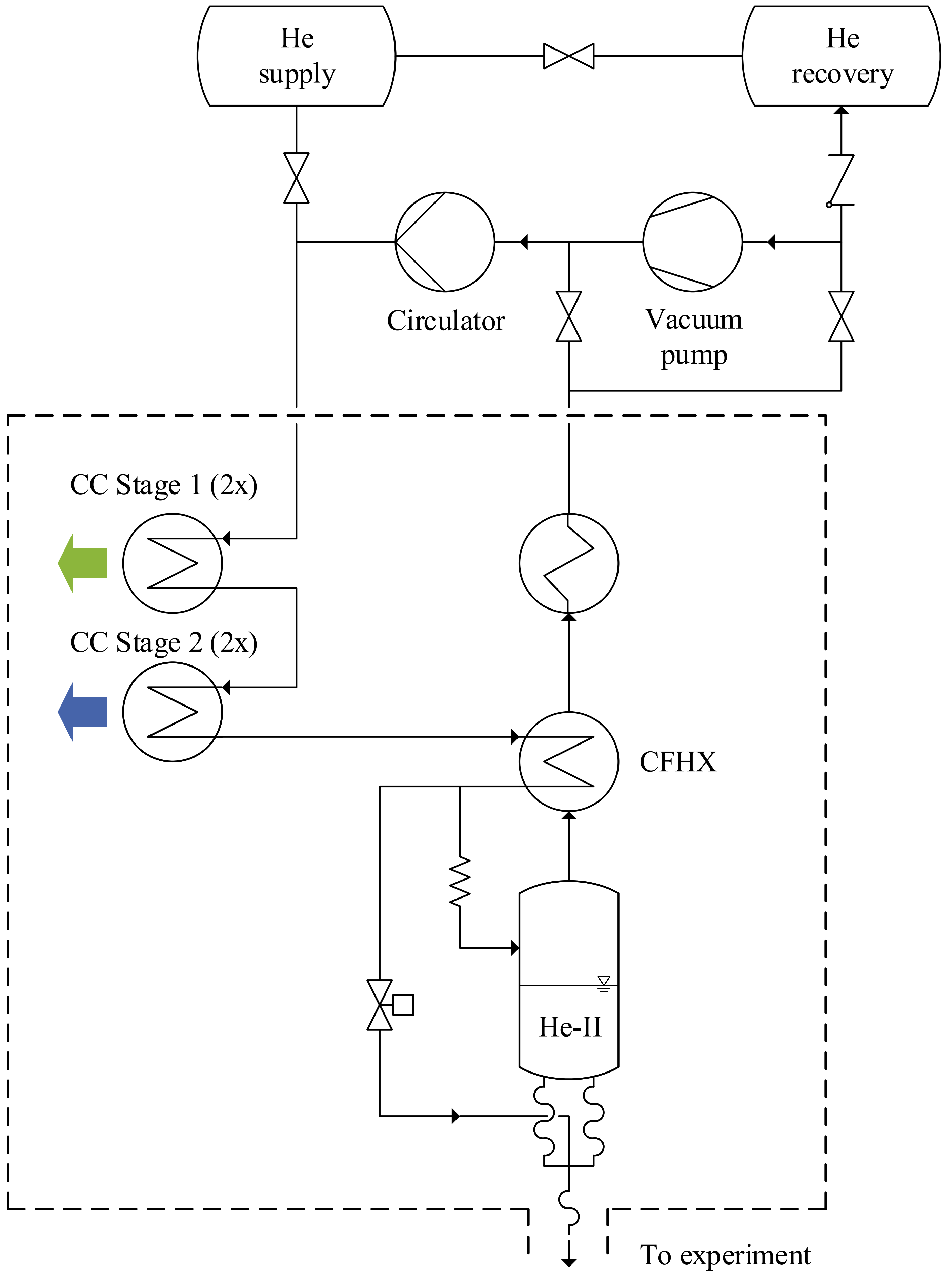
Cooperation partners

Development of lab-scale He-II supply

Lennard Busch, TTK
(S. Grohmann)

Karlsruhe Institute of Technology

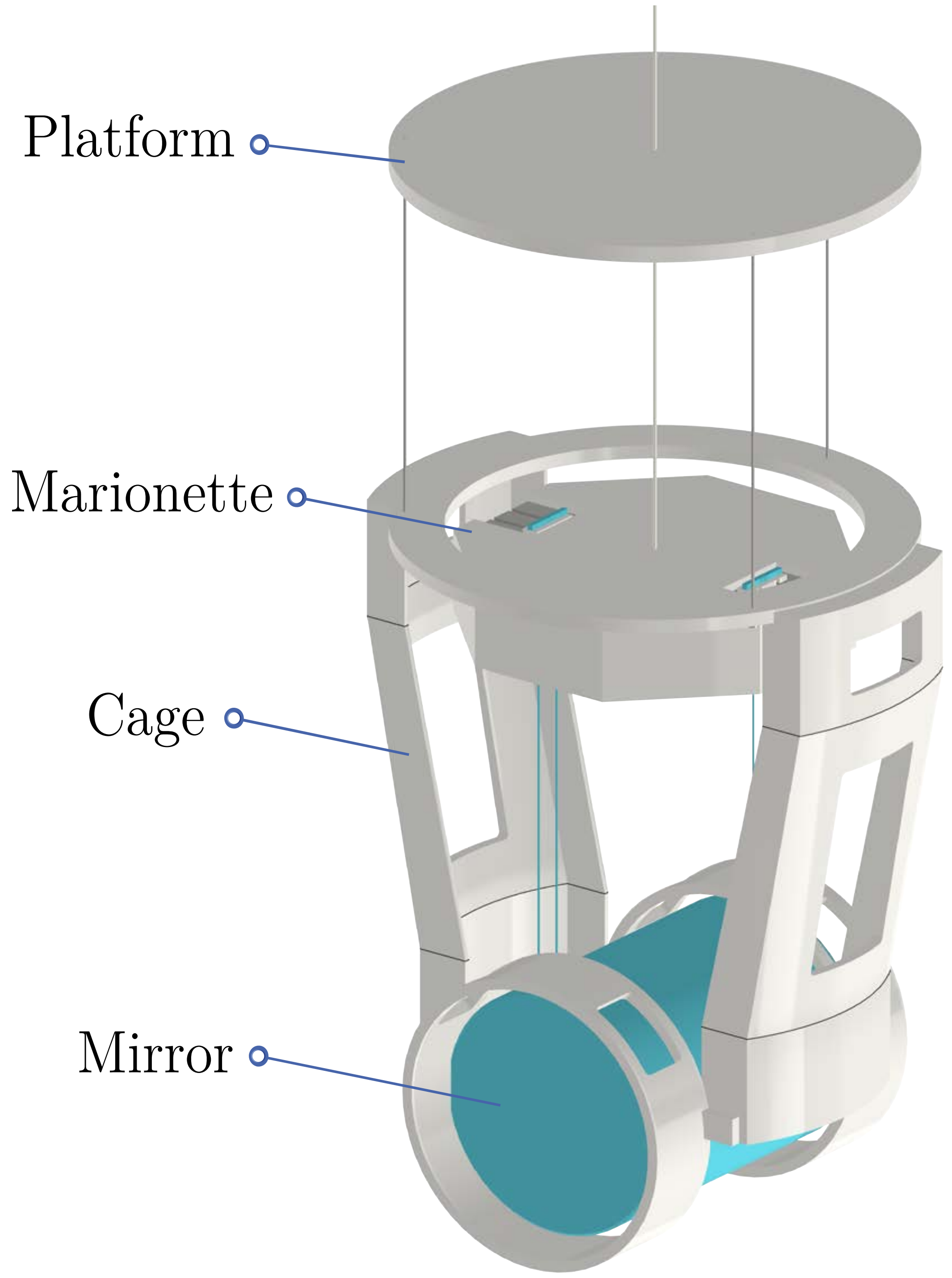
- Cooling capacity $\dot{Q}_{\mathrm{nominal}} \approx x \cdot 100\,\mathrm{mW}$
- Cooling cycle based on
  - Cryocoolers
  - Circulator
  - Vacuum pump
- He-I flow for cooldown
- Static He-II bath maintenance for steady-state experiment operation
- Mechanical isolation of experimental apparatus



Conceptual design of ET-LF cryostat

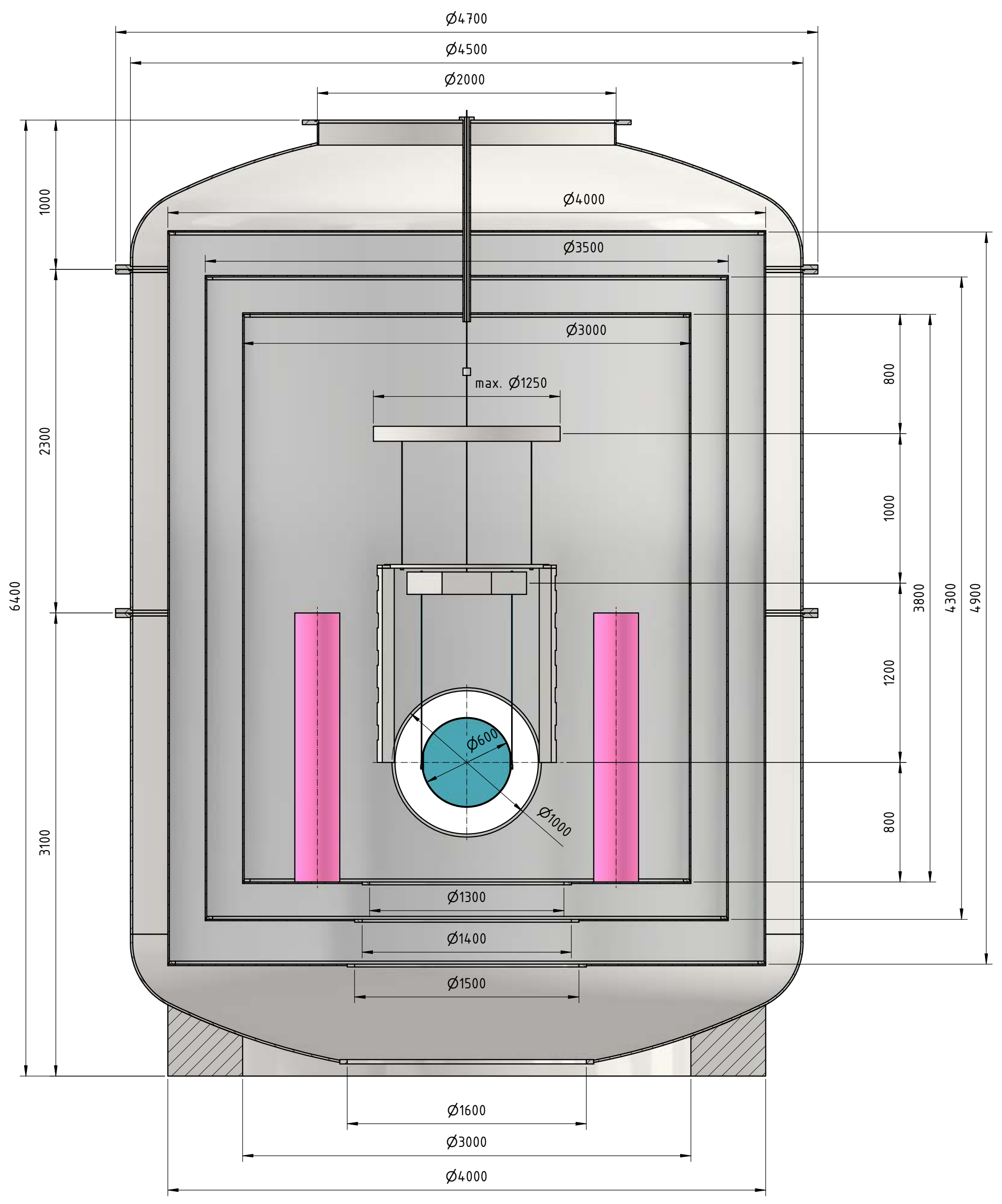
Baseline payload design

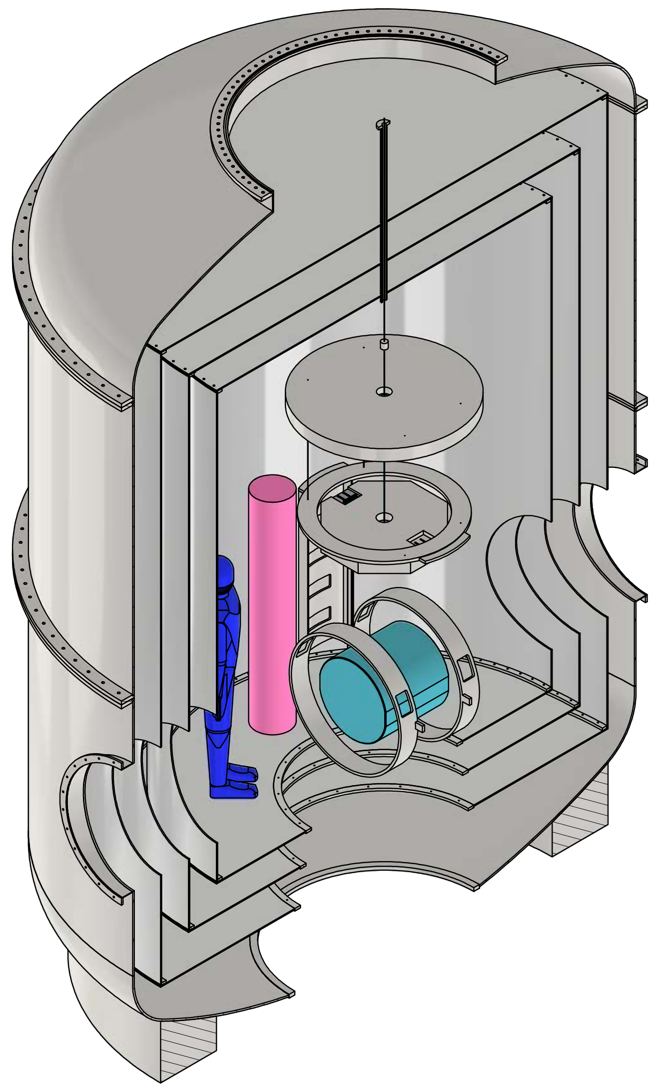
- Details: https://arxiv.org/abs/2305.01419



Conceptual cryostat design

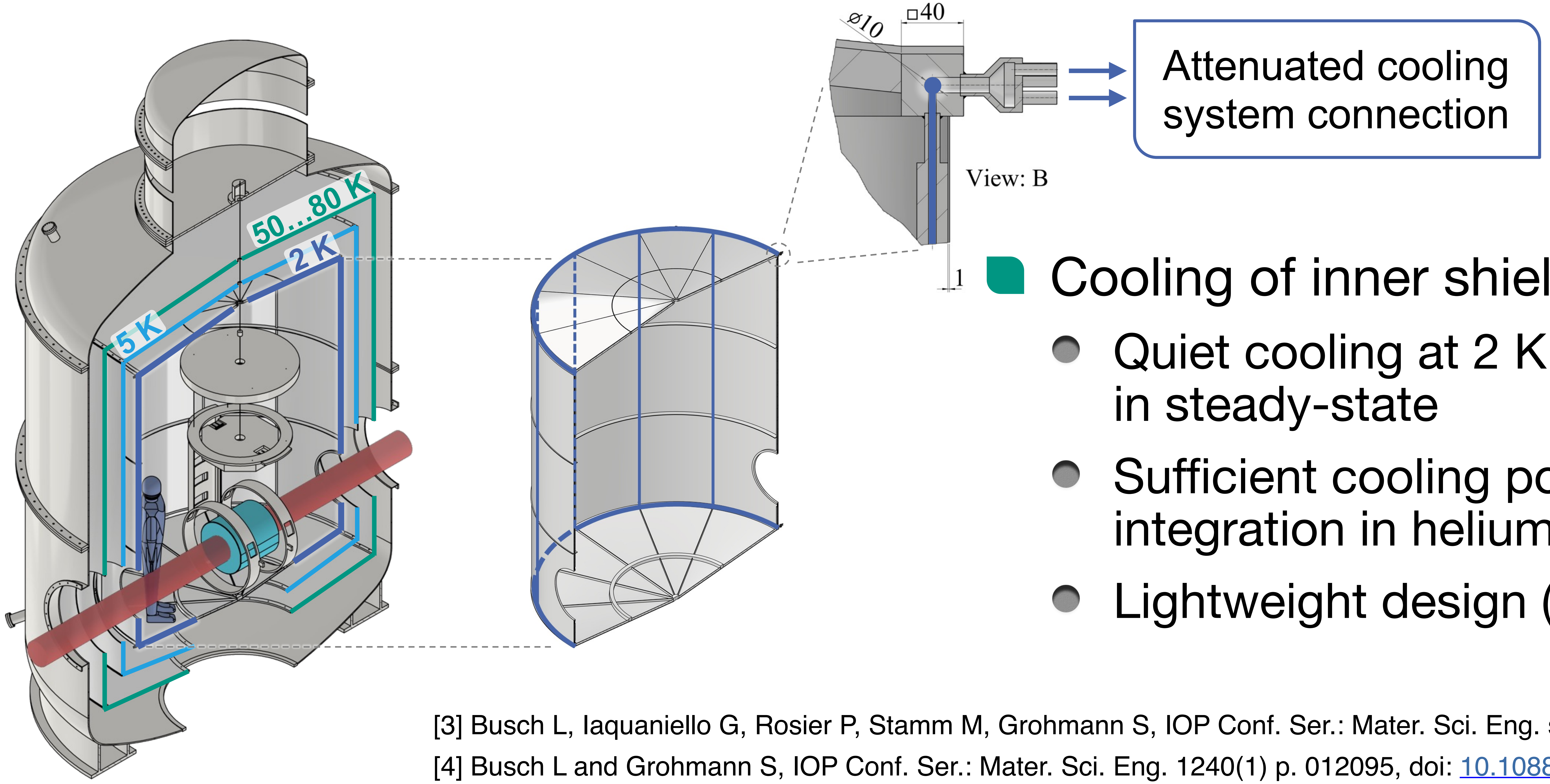
- Details: ET-0272A-22
  https://apps.et-gw.eu/tds/ql/?c=16460





Lennard Busch, TTK
(S. Grohmann)

ET-LF cryostat thermal shielding concept [3]



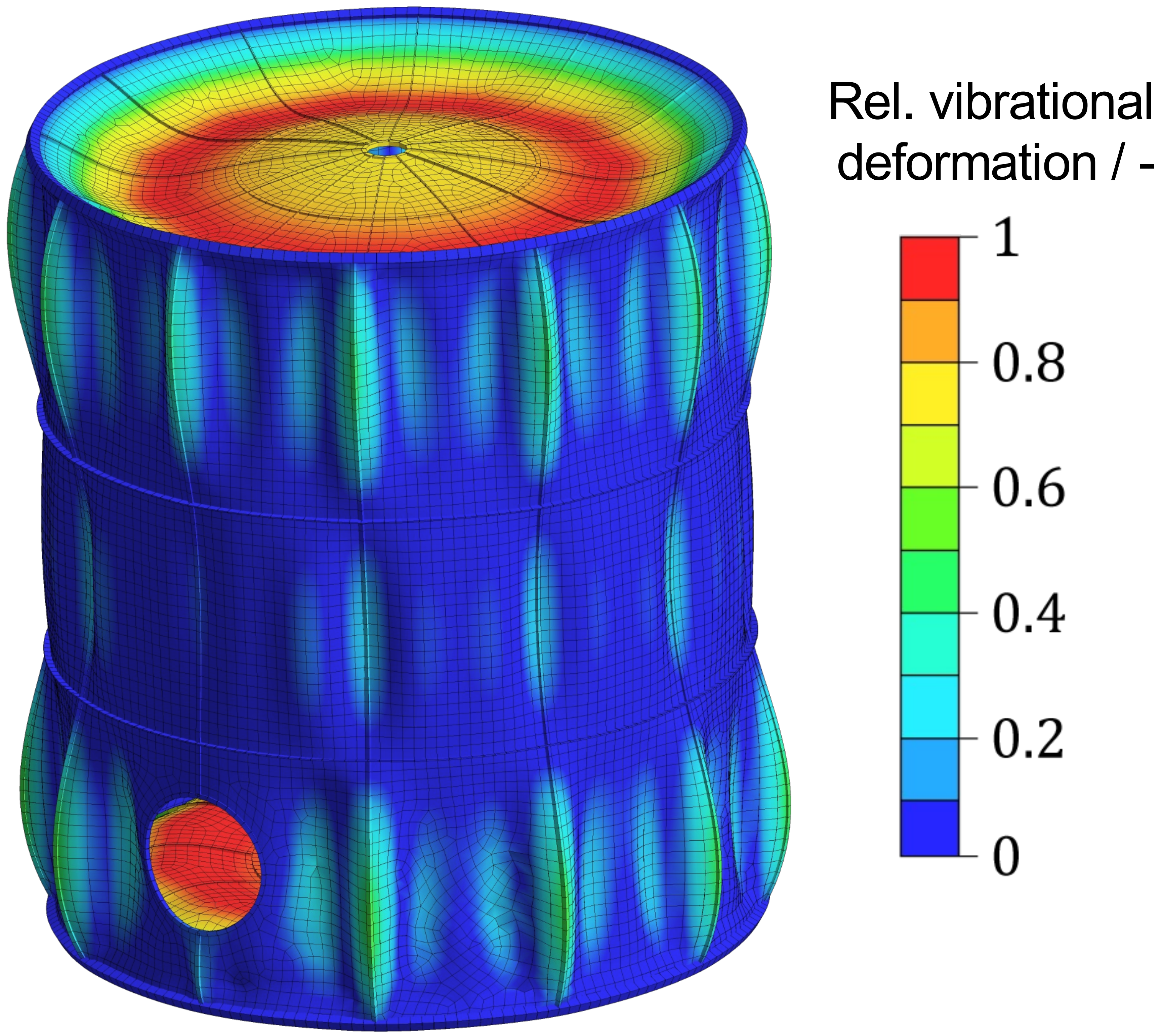
- Cooling of inner shield with **He-II**:
  - Quiet cooling at 2 K via conduction in steady-state
  - Sufficient cooling power provision by integration in helium infrastructure [4]
  - Lightweight design (c. 450 kg)

[3] Busch L, Iaquaniello G, Rosier P, Stamm M, Grohmann S, IOP Conf. Ser.: Mater. Sci. Eng. submitted (2024)
[4] Busch L and Grohmann S, IOP Conf. Ser.: Mater. Sci. Eng. 1240(1) p. 012095, doi: 10.1088/1757-899x/1240/1/012095 (2022)

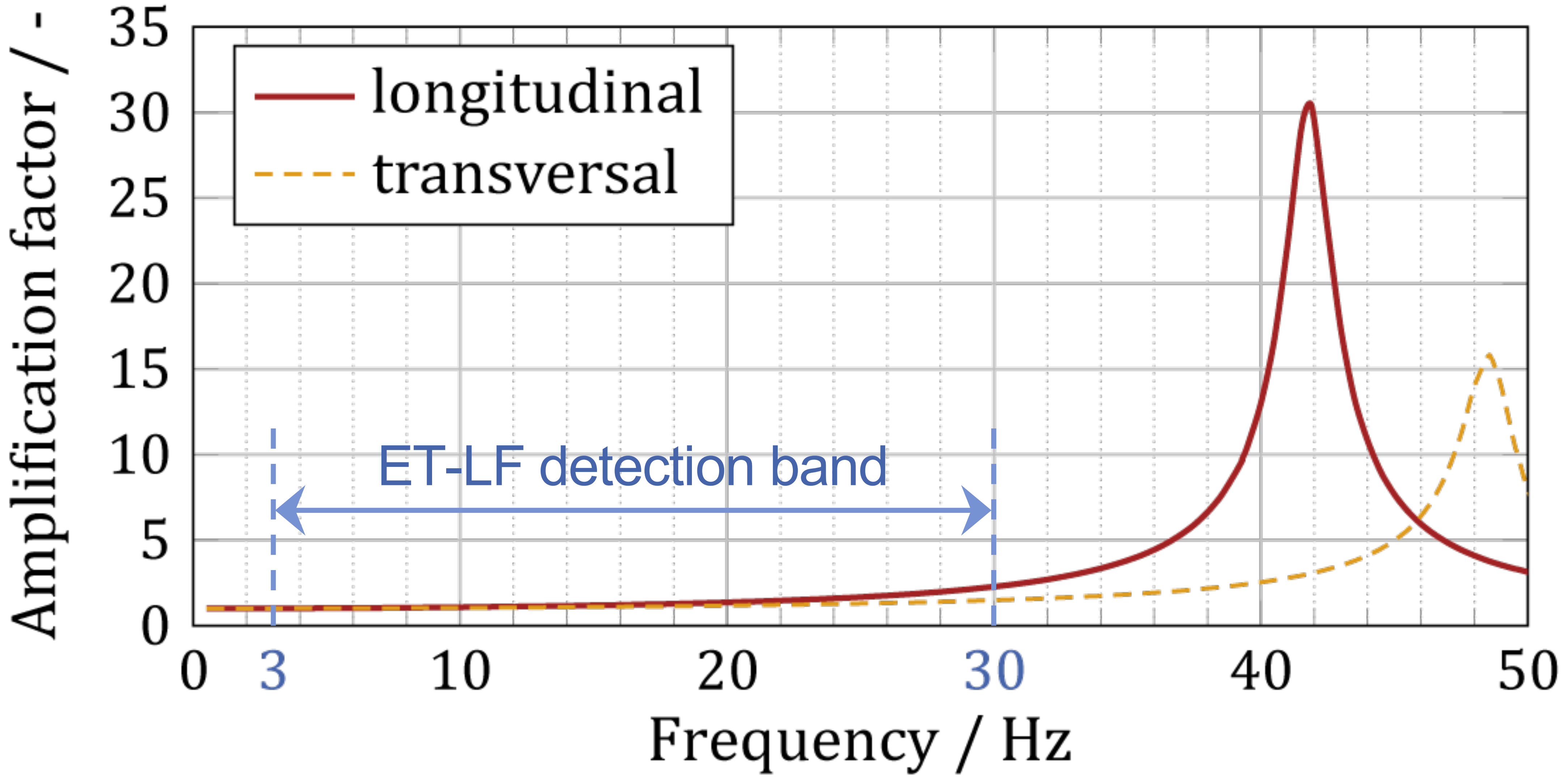
G. Iaquaniello IJCLab
(Ph. Rosier)

Modal and harmonic response analysis [3]

Free modal analysis results



Harmonic response results



- ✓ First resonant modes:
  c. 42 Hz (longitudinal), c. 48 Hz (transversal)
- ✓ Below 30 Hz: very low amplification factors achieveable

Mitigation of adsorption on mirrors

Karlsruhe Institute of Technology

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.

[5] 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 [6]

[6] 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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[2] *European Gravitational Observatory (EGO), 56021 Cascina (Pisa), Italy*
[3] *Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344, Eggenstein-Leopoldshafen, Germany*
[4] *Dipartimento di Fisica, Universitá degli Studi di Roma "La Sapienza," Roma, Italy*

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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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2470-0010/2021/104(6)/062001(12) 062001-1

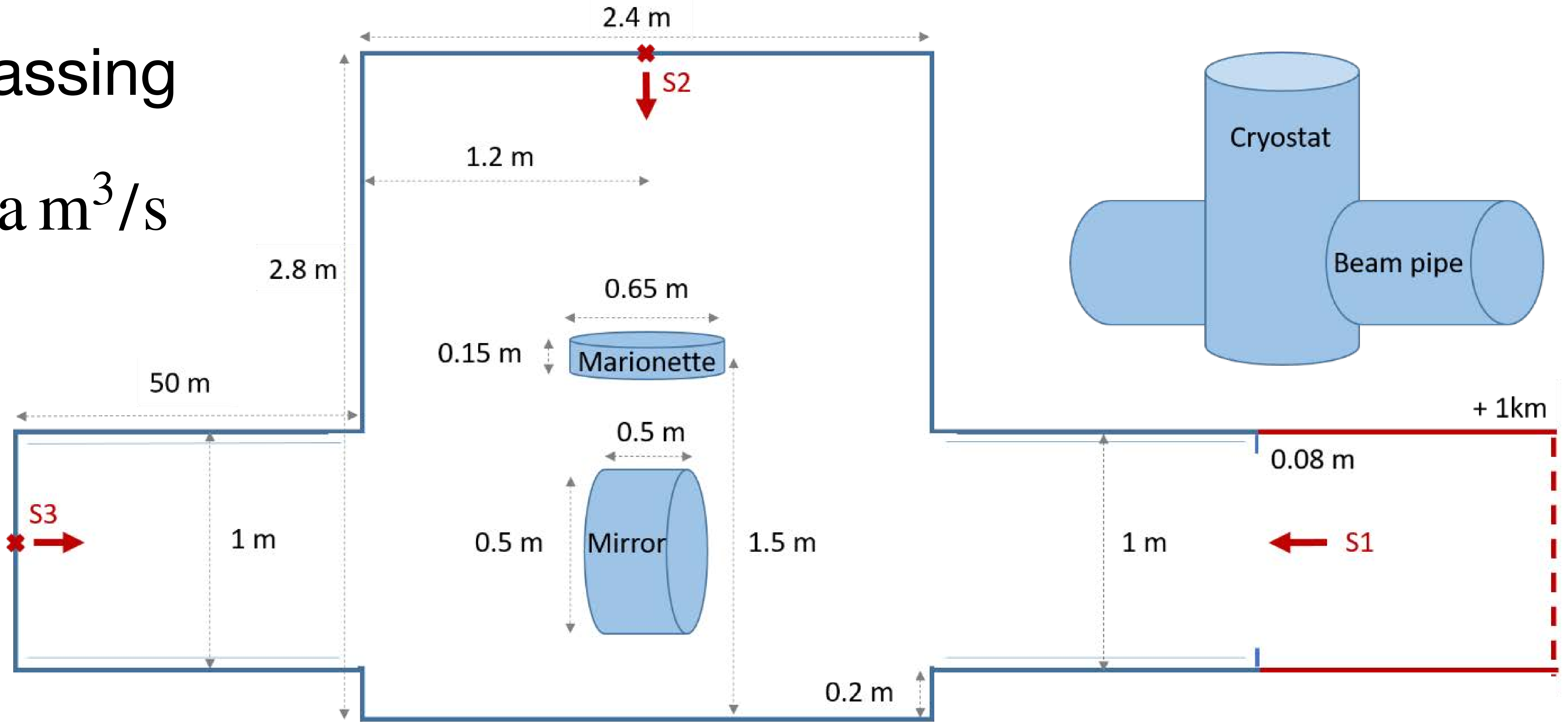
Stefan Hanke, ITEP
(Ch. Day)

Vacuum simulation towards cryopump concept [7]

- Complete model of ET-LF cryogenic mirror environment established
- Simulated with in-house TPMC code ProVac3D
- Simulation of both H_2O and H_2
- Cryostat with 10-20 K mirror

[7] S. Hanke et al., Cryopump concept development for the cryogenic mirror region of the Einstein Telescope – the future gravitational wave observatory, IOP Conf. Ser.: Mater. Sci. Eng. submitted (2024), https://apps.et-gw.eu/tds/ql/?c=16853

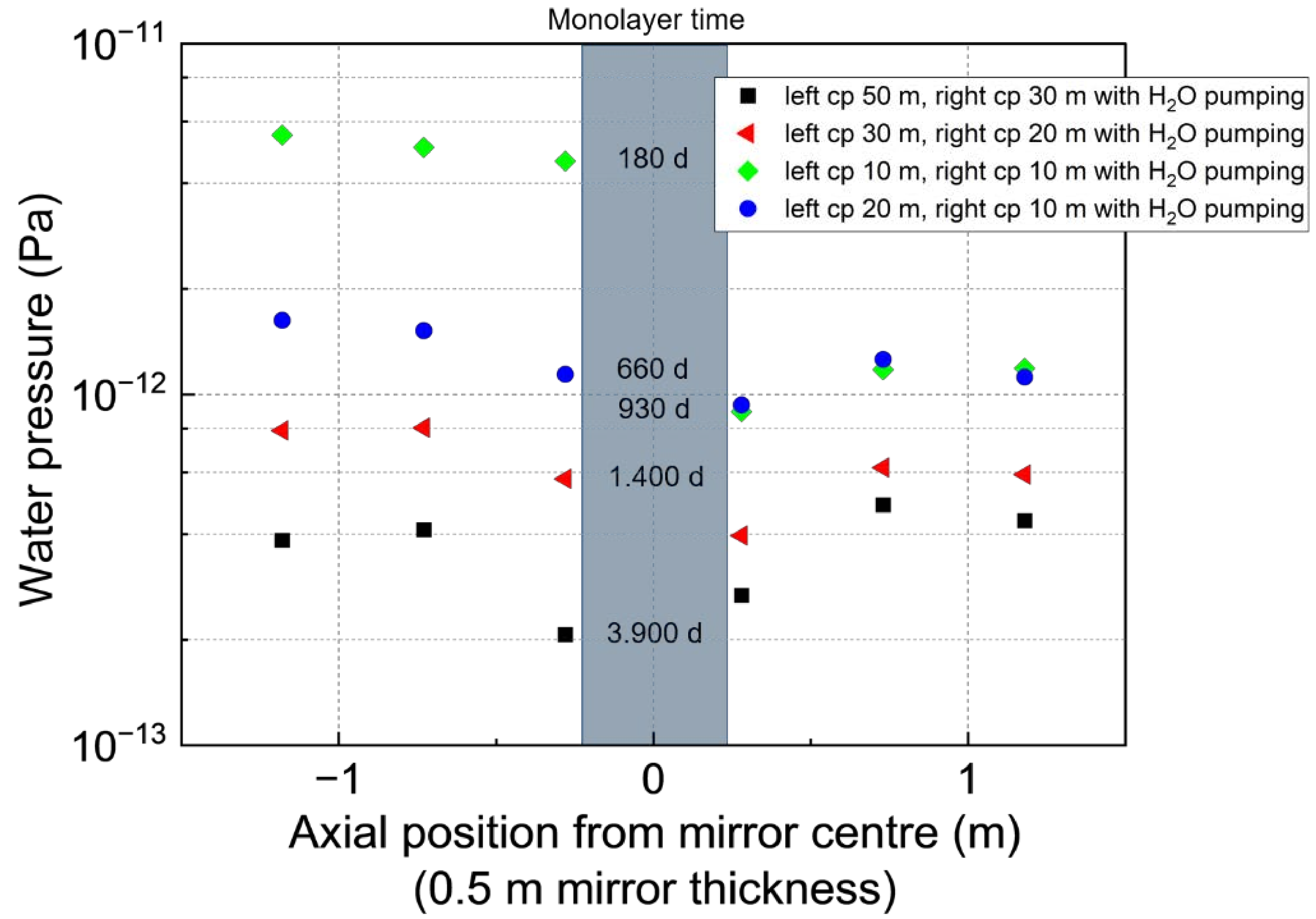
- S1: Source from $1\,\mathrm{km}$ beam pipe outgassing
- S2: Upper tower source with $2 \cdot 10^{-9}\,\mathrm{Pa\,m^3/s}$ for H_2 and H_2O each (requires special conductance minimisation)
- S3: Adjacent tower being main source with 10^{-7} and $10^{-6}\,\mathrm{Pa\,m^3/s}$ for H_2 and H_2O, respectively



Results for frost formation rate on mirror [7]

Stefan Hanke, ITEP
(Ch. Day)

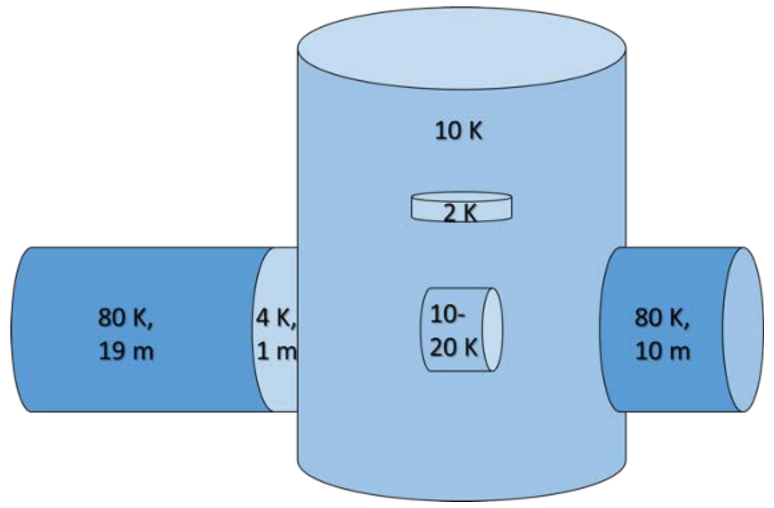
- Vacuum requirements **AND** frost formation on mirror are design drivers
- Simulation of water adsorption based on water pressure is achieved with different cryopump concepts
- **Results:**
  - Frost formation rate drives pump design
  - Rate corresponding to $\tau \approx 2\,\mathrm{a}$ build-up time for one monolayer of water ice seems sufficient (maximum allowable deposition rate)



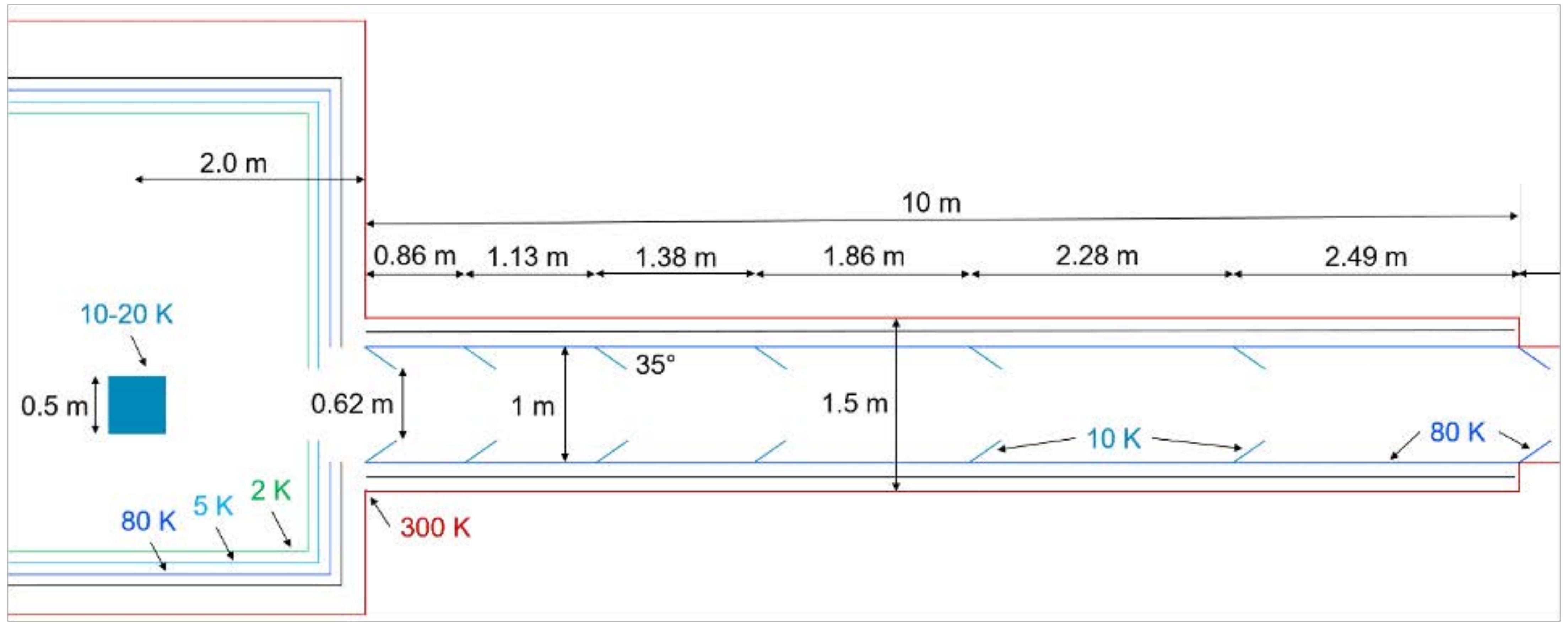
Resulting cryopump concept [7]

Stefan Hanke, ITEP
(Ch. Day)

- **Cryopumps** for heavy gases (H_2O & co) at 80 K, and for H_2 at 3.7 K
- Separation of long **beam pipe** sufficient with 10 m at 80 K cryopump
- **Adjacent tower** side needs 20 m at 80 K **plus** 1 m at 3.7 K cryopumps



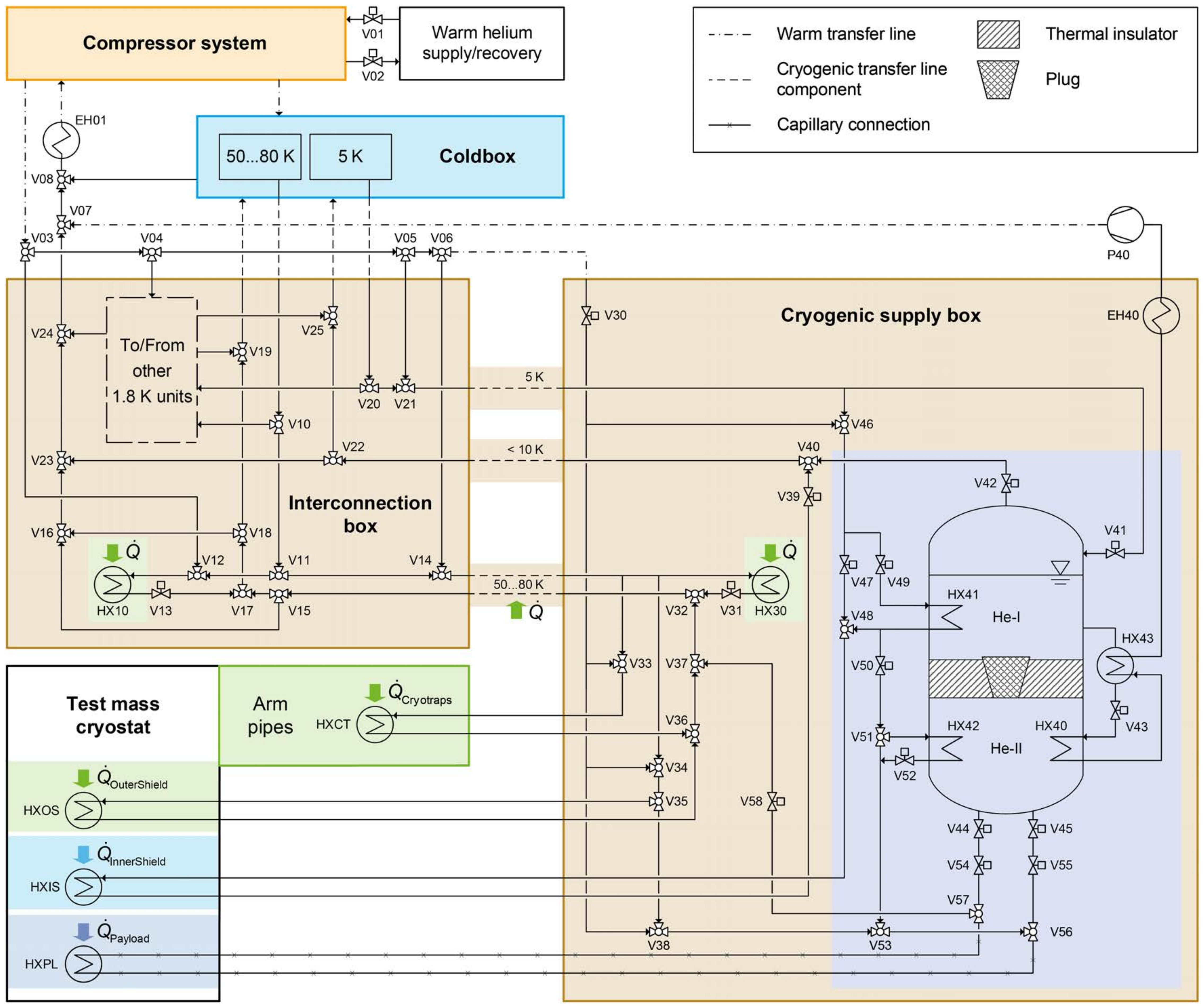
- **Ongoing work**
  - Thermal optimisation for **mirror thermal budget** with 10 K baffles in 80 K cryopumps needed to screen mirror from 80 K radiation
  - Simulation of heat loads to estimate the overall **cryogenic demands** of the cryopumps, needed to scale the cryogenic infrastructure concept
    - Cryopumps are the largest cryogenic consumers in ET



Cryogenic infrastructure concept [4]

Lennard Busch, TTK
(S. Grohmann)

Karlsruhe Institute of Technology



- 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 for 80 K cryopumps/ outer shields
  - 1-phase cooling for 10 K baffles, 5 K inner shields and 3.7 K cryopumps
  - He-II payload cooling/inner shield

Required cooling capacities

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- He-I consumers at 80 K
  - **Cryopumps for water** (10…20 m)
  - Other thermal shields (use of MLI open…)
  - Shielding of transfer lines and cryostats
- He-I consumers at 3.7 to 10 K
  - **Cryopumps for hydrogen**
  - **Baffles** in the 80 K cryopumps
  - Cryogenic supply boxes
  - Inner thermal shields
- He-II consumers at <2 K
  - Cryogenic payloads (0.5 W each) ✅
  - Inner thermal shields (2 W each) ✅

- **Present status**
  - We need **results** from the cryopump design (i.e. the **main consumers**) to determine **the size** of the cryogenic infrastructure
- **Next steps**
  - **Industry design studies** for cryoplants, cryogenic distribution system and cryogenic supply boxes

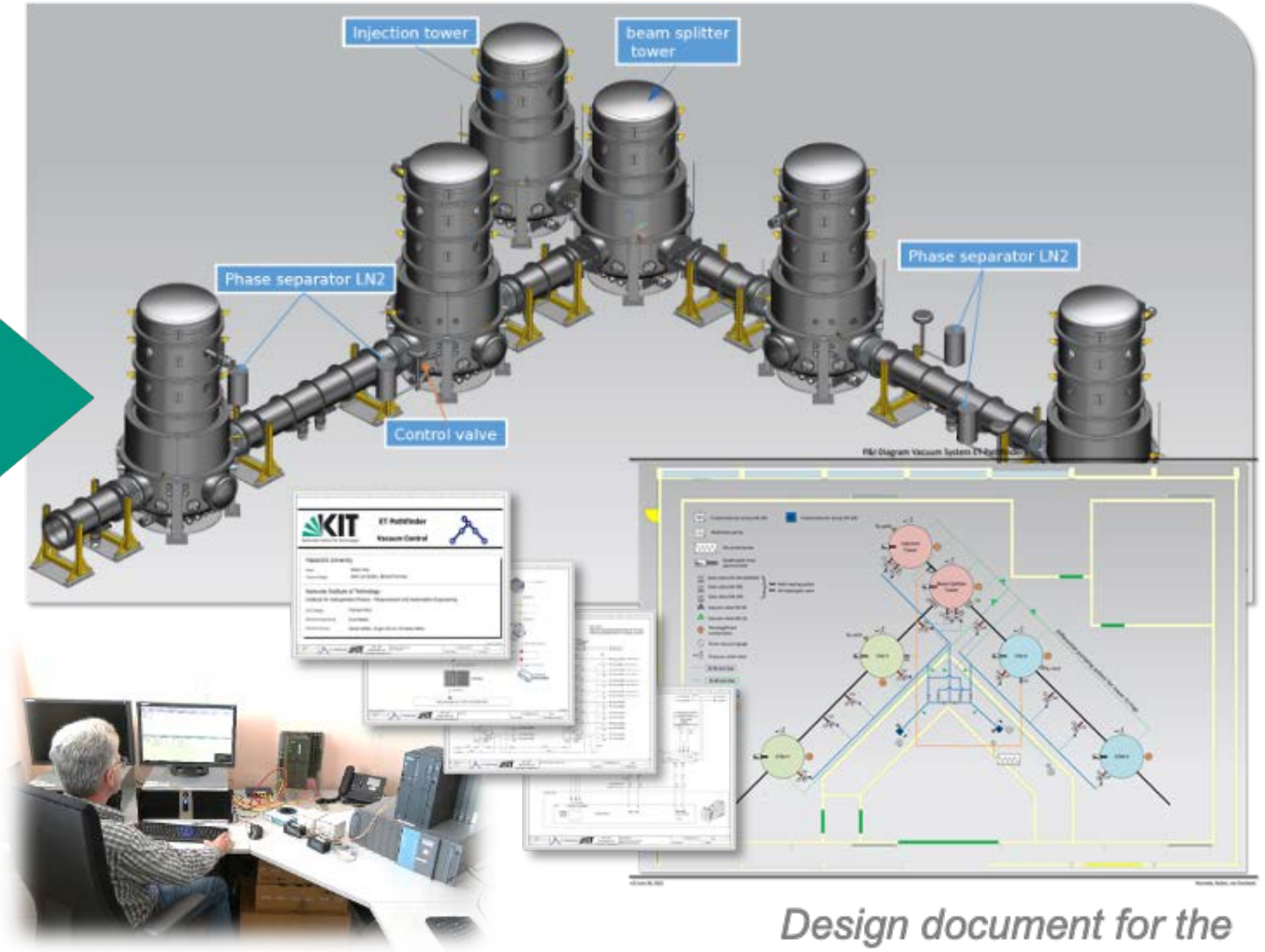
KIT at ETpathfinder

Thomas Thümmler, Joachim Wolf, Thomas Höhn, IAP
(A. Haungs, R. Engel)

Karlsruhe Institute of Technology

Present task

- Provide experience from design, building, and operation of the KATRIN vacuum system ($10^{-11}\,\mathrm{mbar}$ in $< 1200\,\mathrm{m}^3$ vessel)
- Design of the ET-PF vacuum control system based on Siemens PCS7
- Work out interlock list for safe operation



Vacuum control setup at KIT

Design document for the ET-PF vacuum control system

Future activities

- Contribute to the commissioning and operation of the system
- Utilise ET-PF as test facility for cryogenic designs developed at KIT

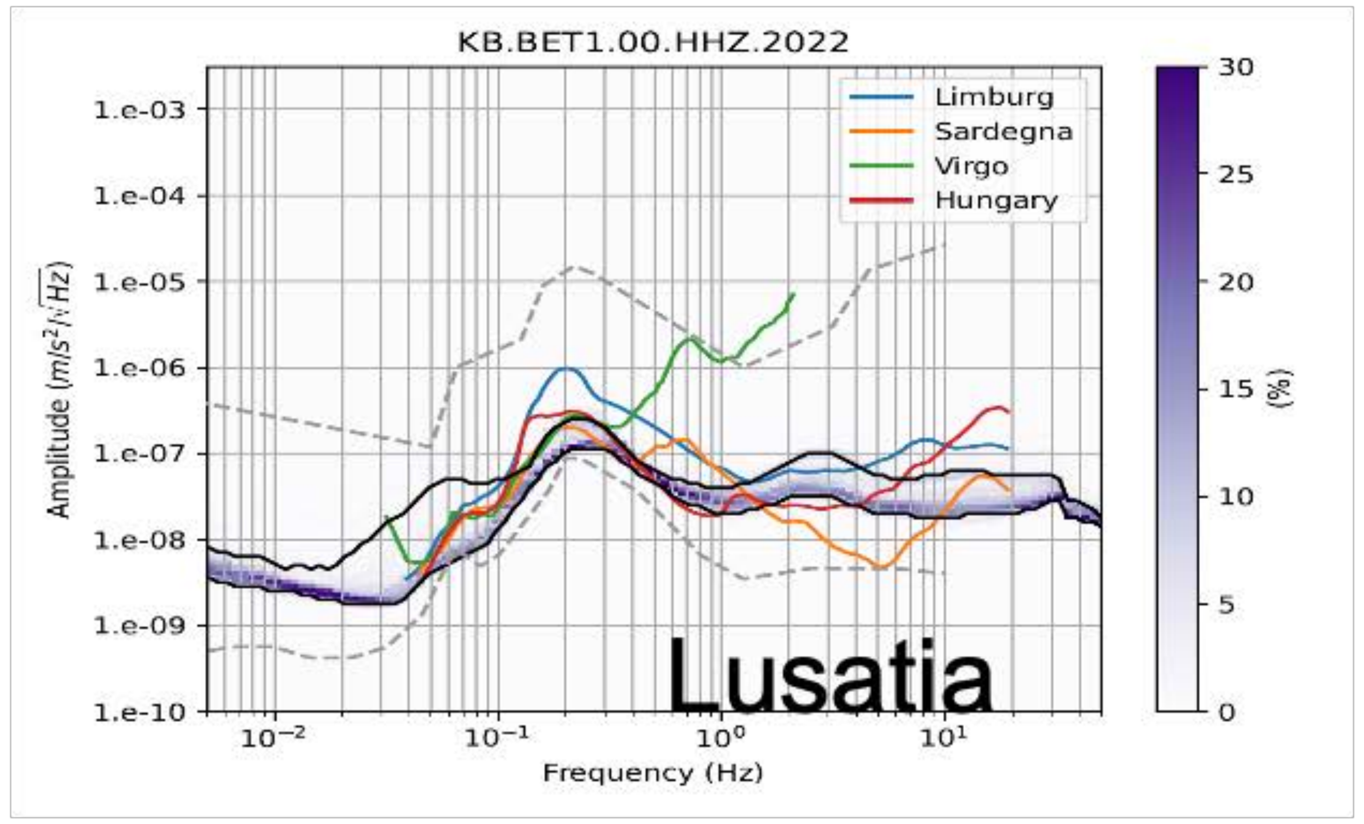
CONTRIBUTIONS TO THE SCB

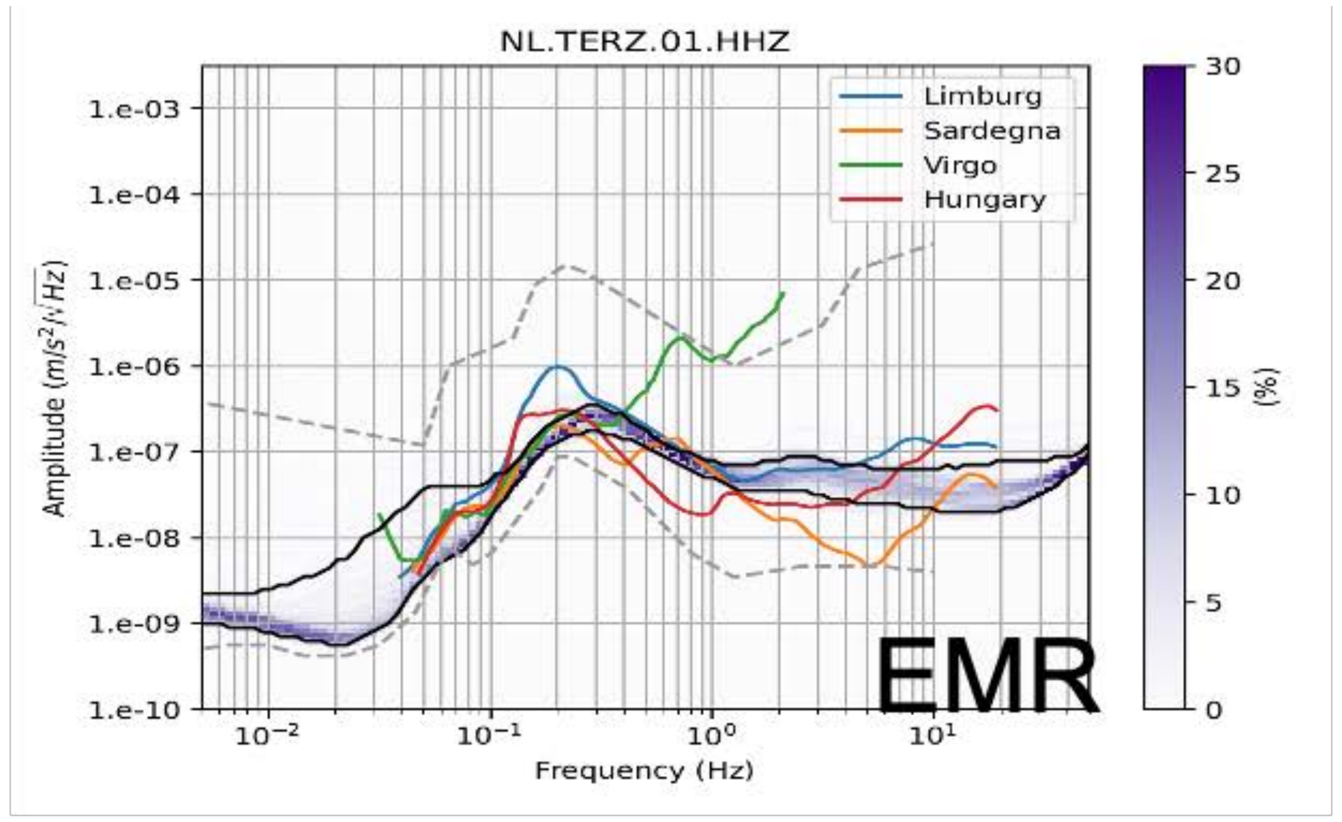
Seismic noise at ET sites

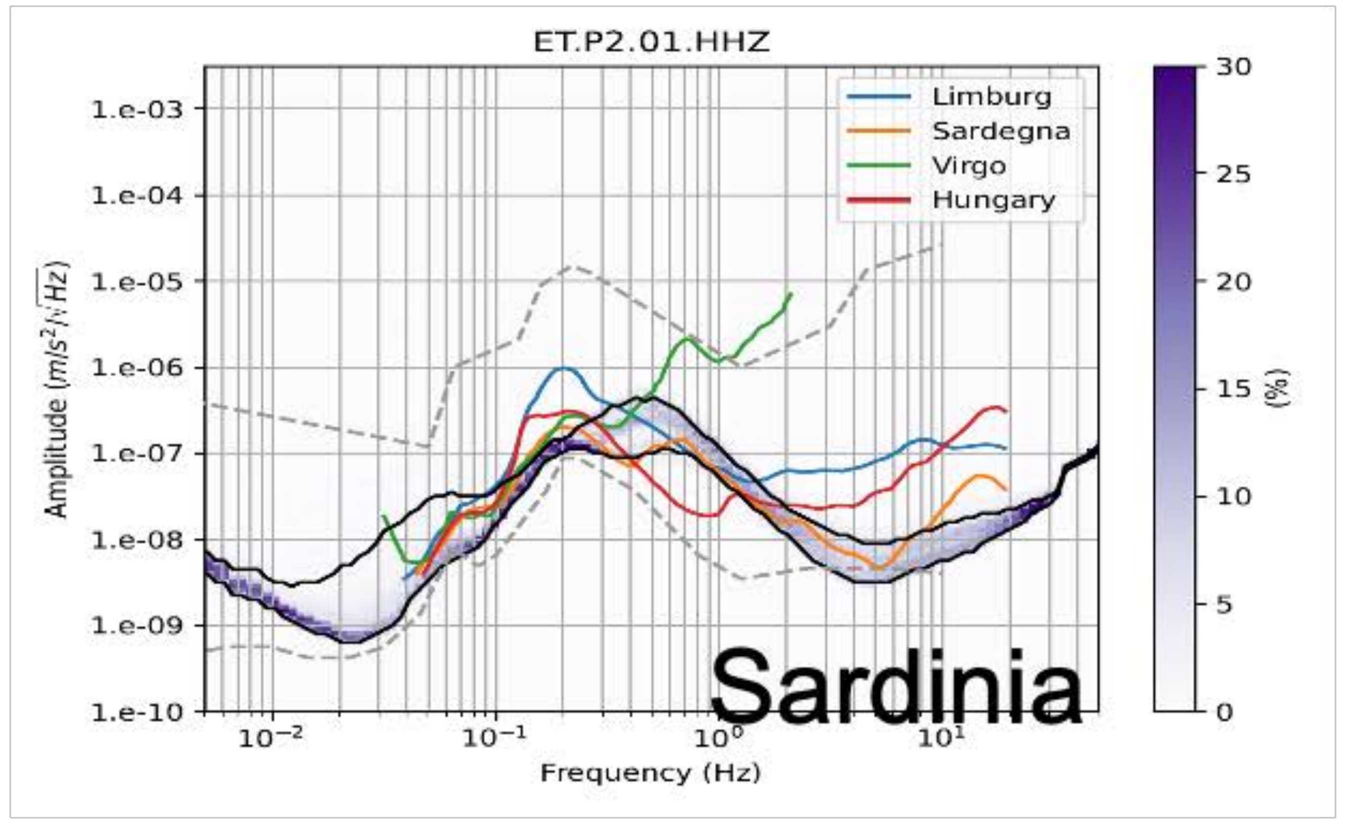
Andreas Rietbrock, GPI

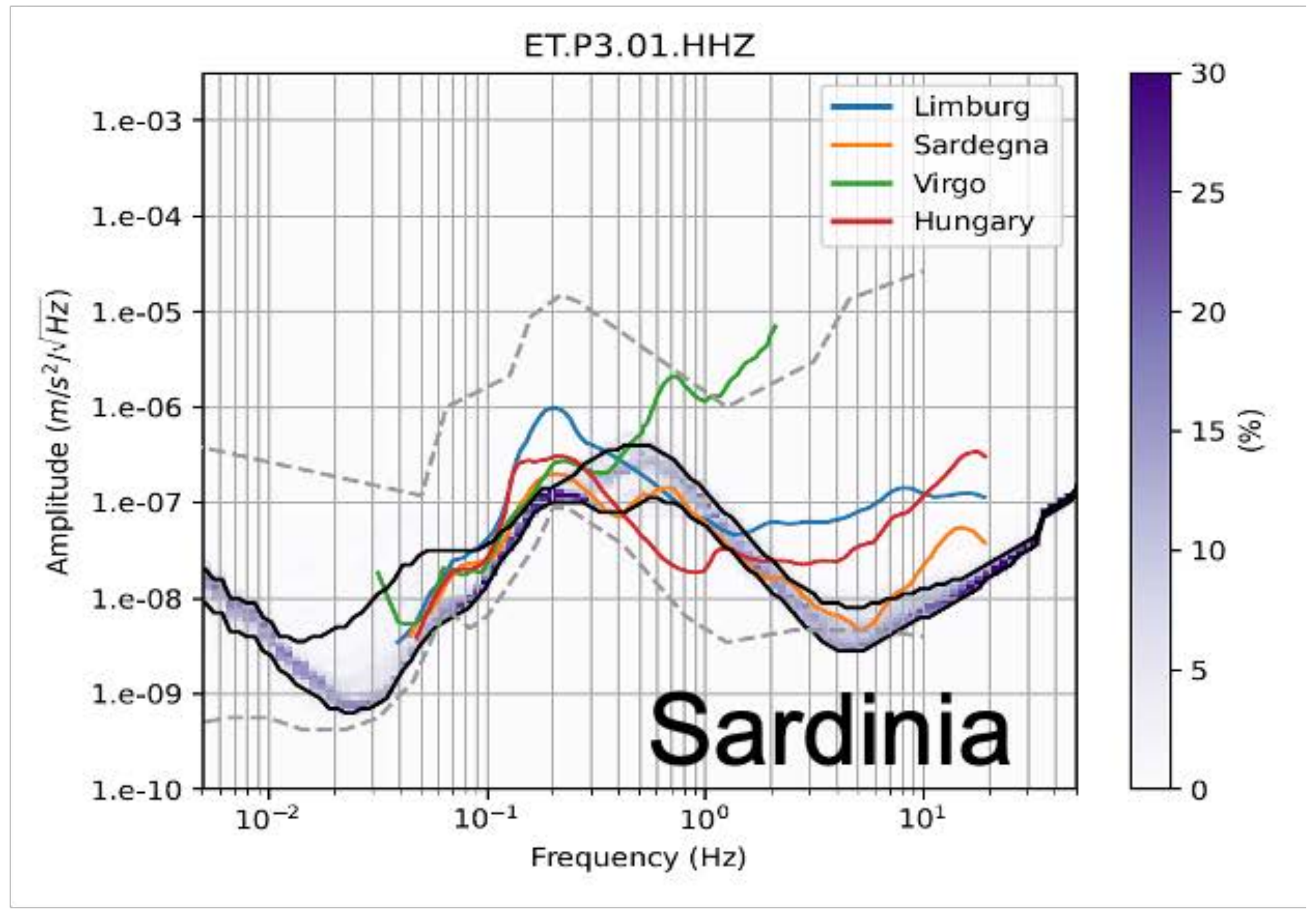
Karlsruhe Institute of Technology

- Coordination and evaluation of seismic noise at ET sites







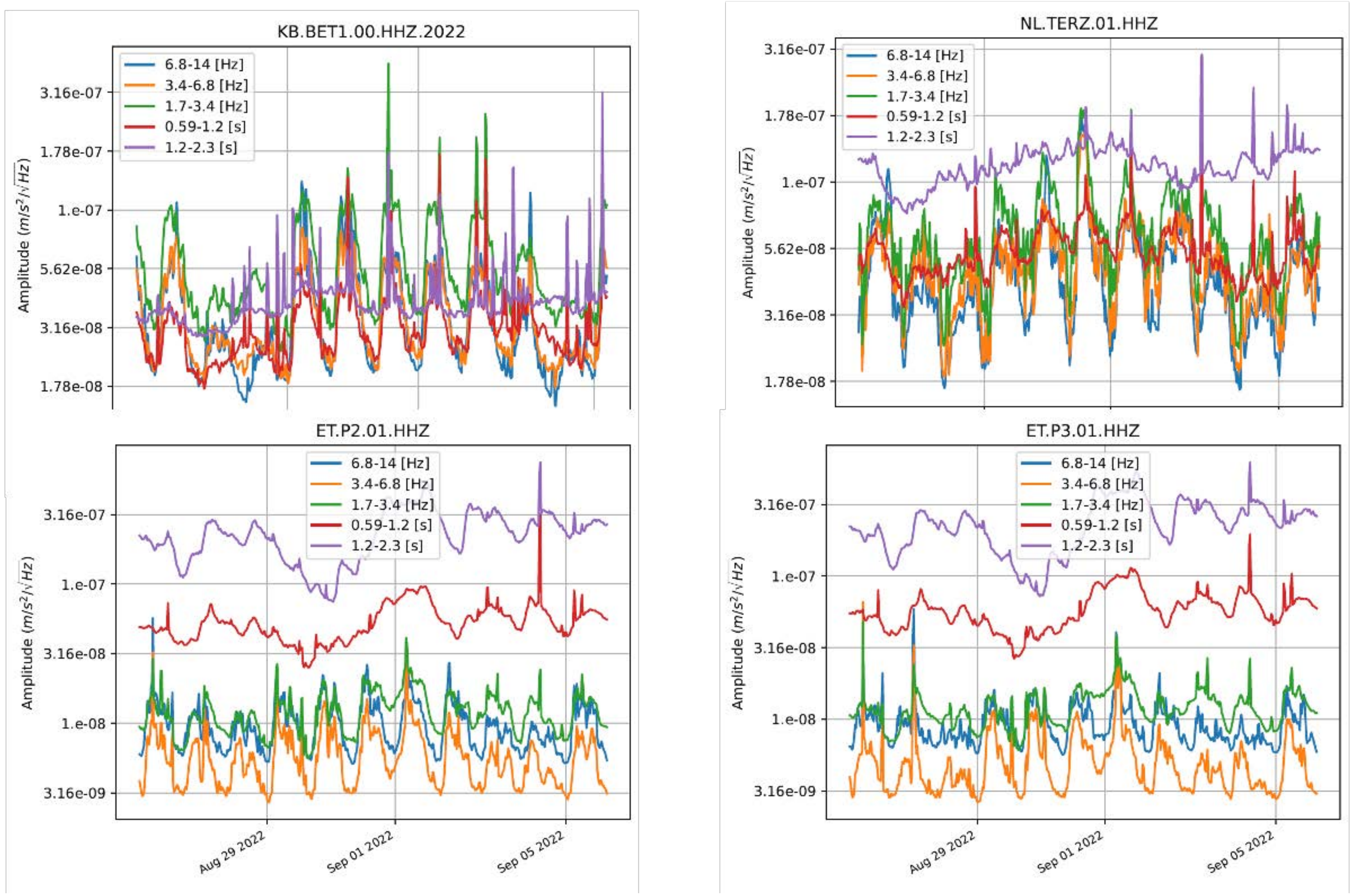


Andreas Rietbrock, GPI

Karlsruhe Institute of Technology

Temporal distribution at distinct frequencies

- Day to night amplitude change
- Strong influence of cultural noise sources
- Long term comparison for one year is currently carried out



Current findings

Andreas Rietbrock, GPI

Karlsruhe Institute of Technology

- All candidate sites reach a noise level below $10^{-7}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$
- Sardinia shows the lowest noise values between $2-14\,\mathrm{Hz}$, however, an increase towards lower and higher frequencies is observed
- EMS and Lusatia show a clear dependence on cultural noise
  - Day-night, weekdays-weekends
- All sites are excellent seismological stations and that means there will be roughly one earthquake recorded above the noise level
  - ET has to be designed for it
- Better understanding of noise suppression in underground laboratories needs full characterisation of the incoming wave fields / noise sources
- Full analysis of the longterm characteristic at the sites is currently under way

CONTRIBUTIONS TO THE OSB

Activity in the ET OSB-MM

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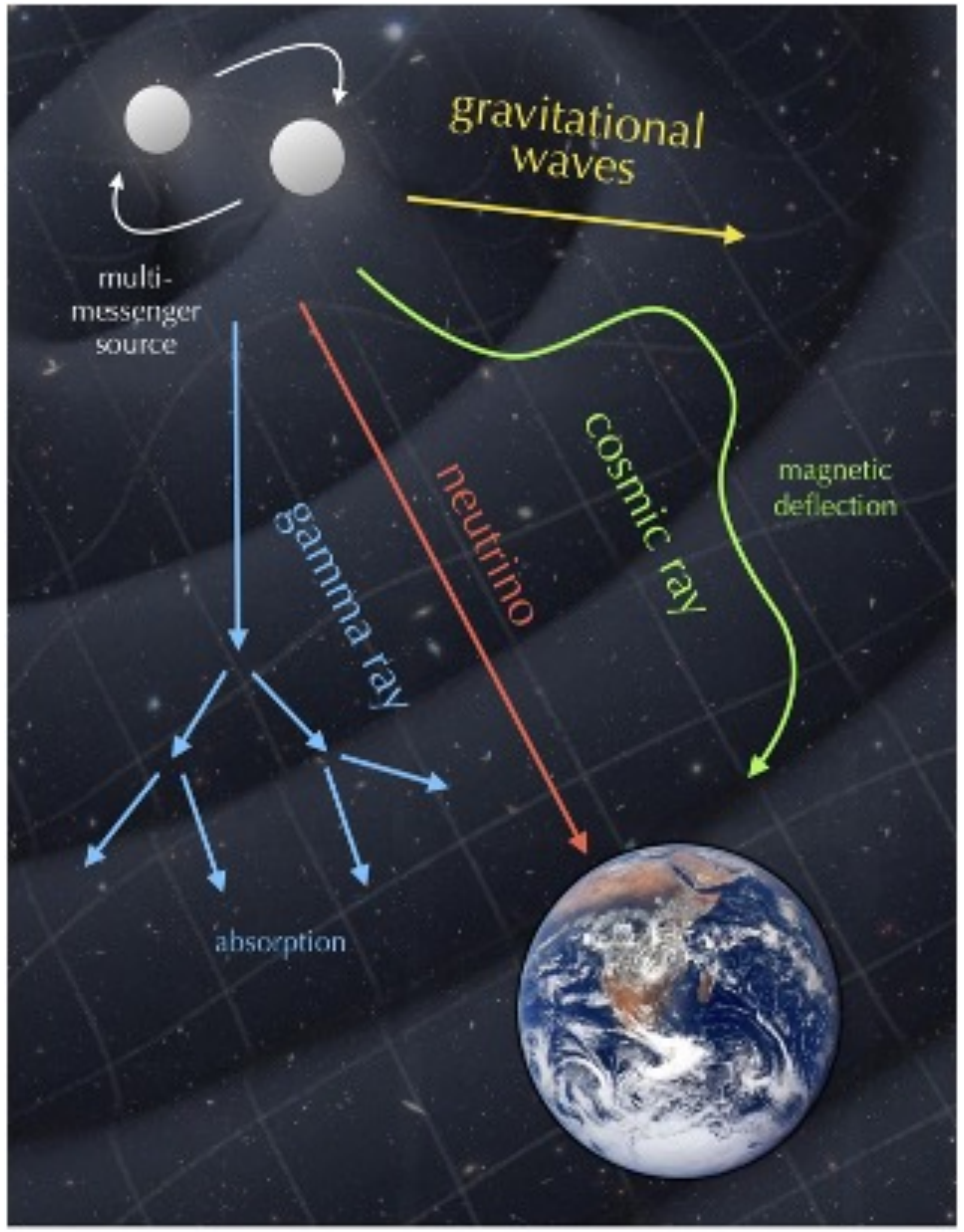
- With multi-messenger studies, we access maximum information that we get from nature to unveil the unknowns of the Universe
- Two main questions….
  - How does the current understanding about GW event detection threshold from LVK translate for the case of ET?
    - Looking for IceCube neutrino counterparts to 'sub-threshold' LVK candidates
  - Joint detection probability in the era ET and next generation neutrino detectors
    - Work being done on the prediction of GW + EM detection probability, specifically the Neutrino + GW probabilities



CONTRIBUTIONS TO THE EIB

Activity in the ET EIB-Div1

Software, frameworks, and data challenge support

Steffen Hahn, IAP
(A. Haungs, R. Engel)

Rewrite of Mock Data Challenge (MDC) code

Why is a rewrite beneficial?

- ``Historically grown" C-code
- One file, no modularisation
- Variation of reuses and side-effects
- Polluted repository (big files...)

Rewrite

What is the plan?

- Modernise codebase: C -> C++23
- Update/grade for collaborative use
- Add validation tests/more checks
- Use as an example for code quality

Current status

- Modularised most of the code
- All original features implemented
- Output (mostly) validated

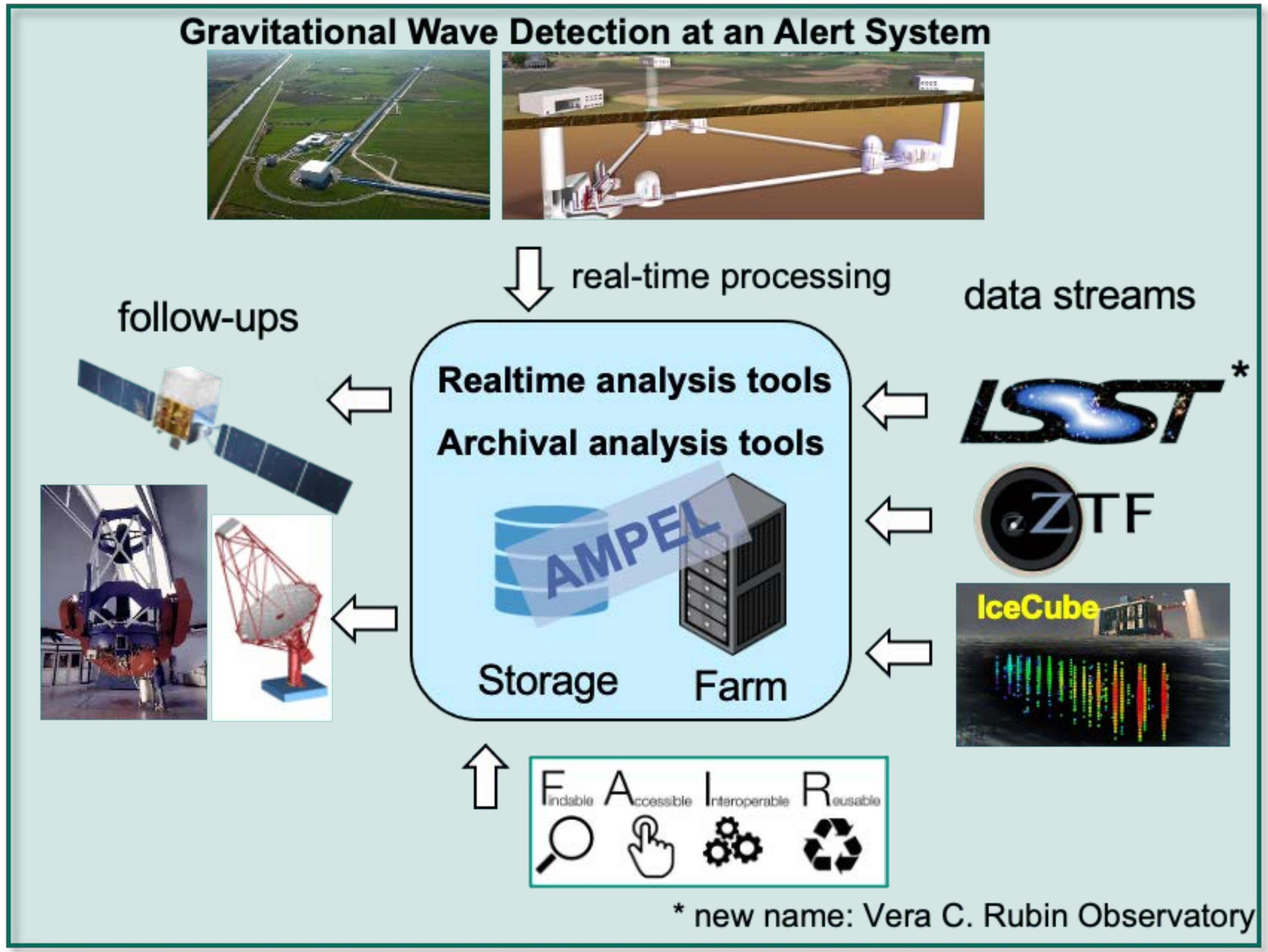
Improve

Next steps

- Clean up debugging code
- Add (real) validation checks
- Add documentation

Realtime Multi-Messenger Astro-(particle-)physics

- Multi-messenger **follow-up studies** of GW events (alert systems)
- Enhancement of **environmental monitoring system** at Virgo and ET
- GW observations as part of a MM astroparticle physics **data center**
  - Based on expertise and competences available at Helmholtz and IN2P3
  - Close cooperations with CTA, IceCube and Pierre Auger groups
  - Preparatory work by AMPEL group [8]



[8] J.Nordin et al., Astron.Astrophys. 631 (2019) A147 e-Print:1904.05922

Source: ET Design Report Update (2020)