ET-LF Vacuum and Cryogenics Requirements

S. Grohmann – On behalf of ET-ISB Division IV: Vacuum & Cryogenics

ET Cost-Benefit Analysis (CoBA) full immersion workshop, Cortona, 21-24 November 2021

Outline

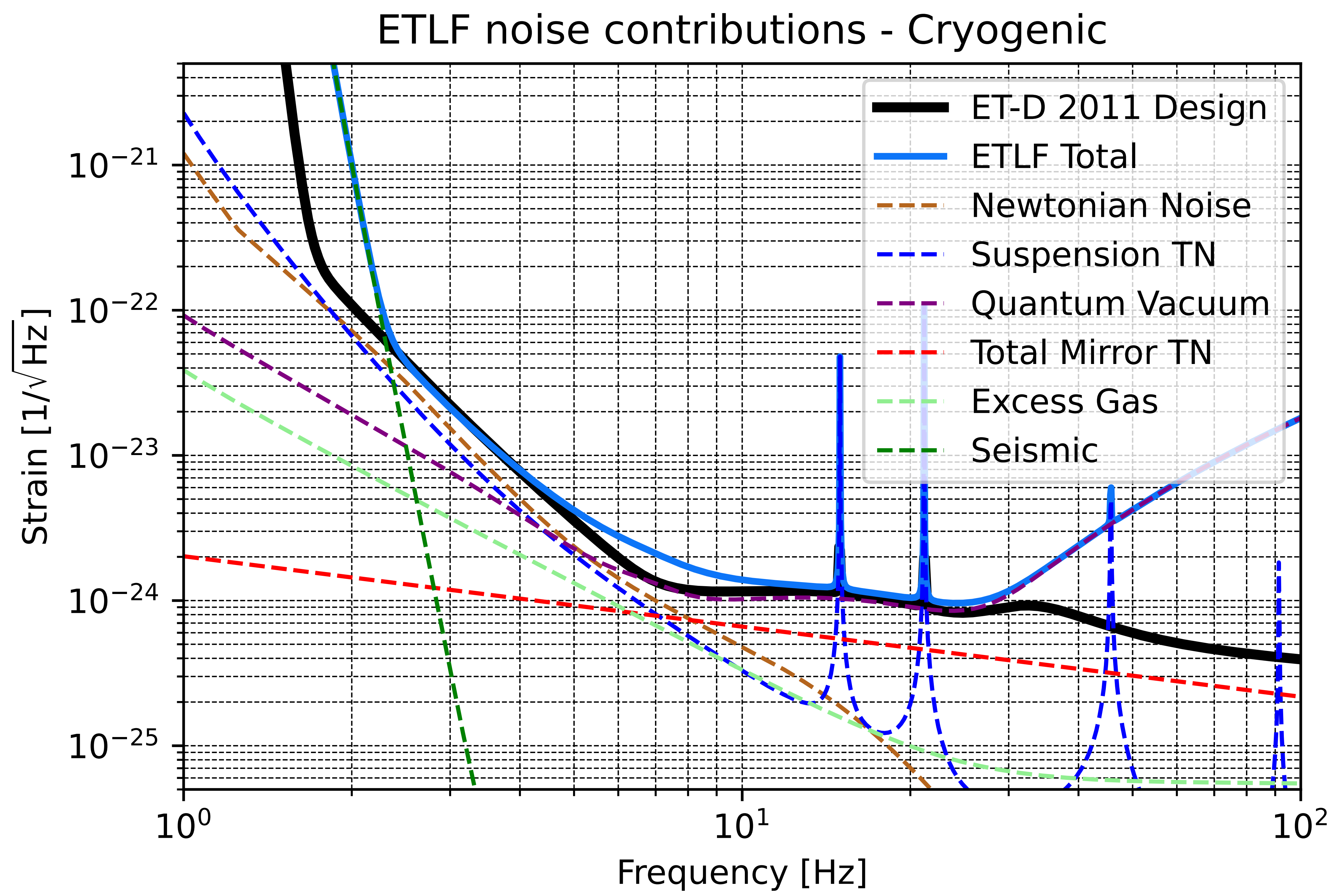
- Motivation for cryogenic ET-LF
- Vacuum requirements for cryogenic payload operation
- Cryogenic design and operating scenarios
- Summary

MOTIVATION FOR CRYOGENIC ET-LF

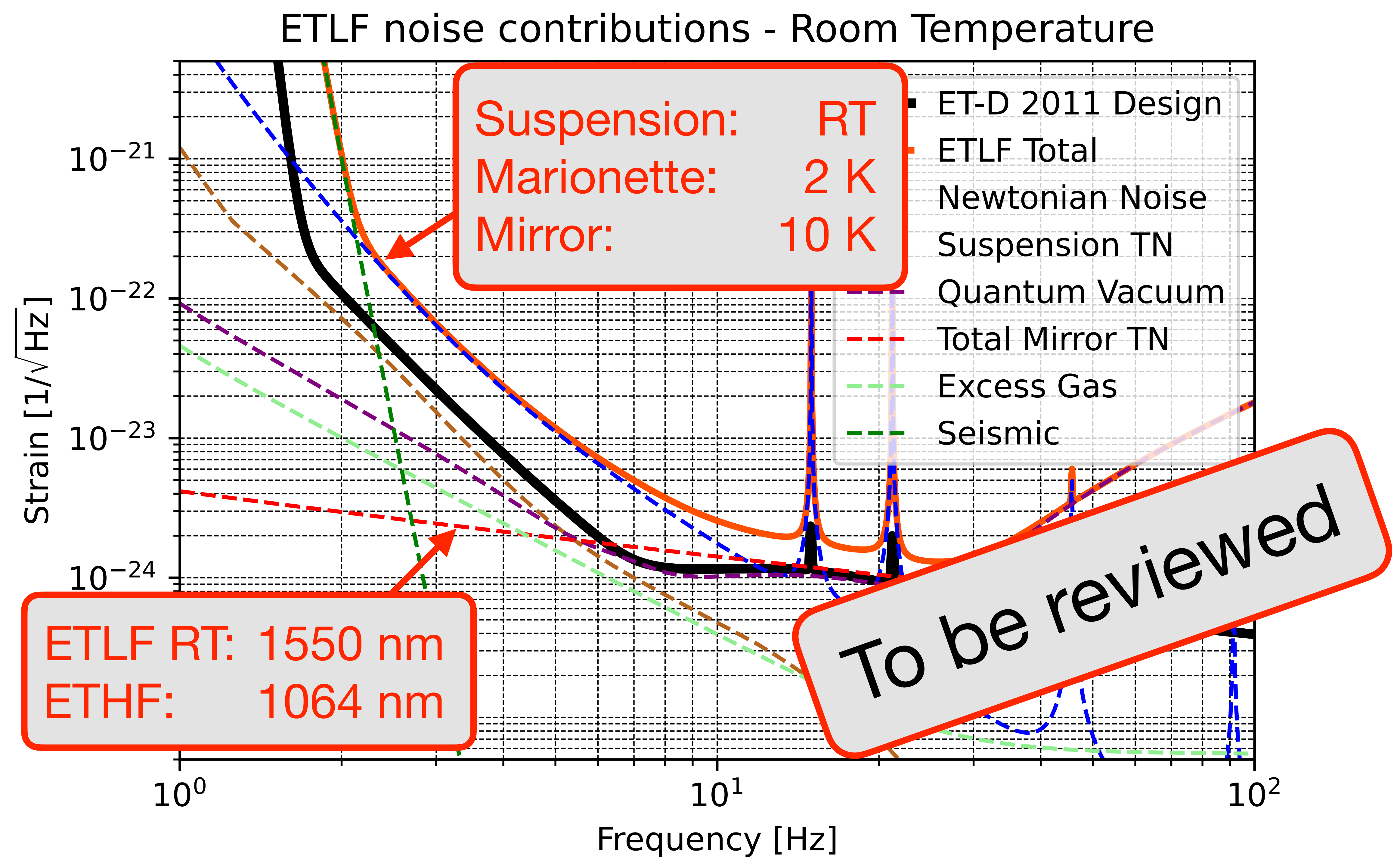
Contributed by Xhesika Koroveshi

Noise contributions in ET-LF sensitivity

Cryogenic ET-LF



Room-temperature ET-LF



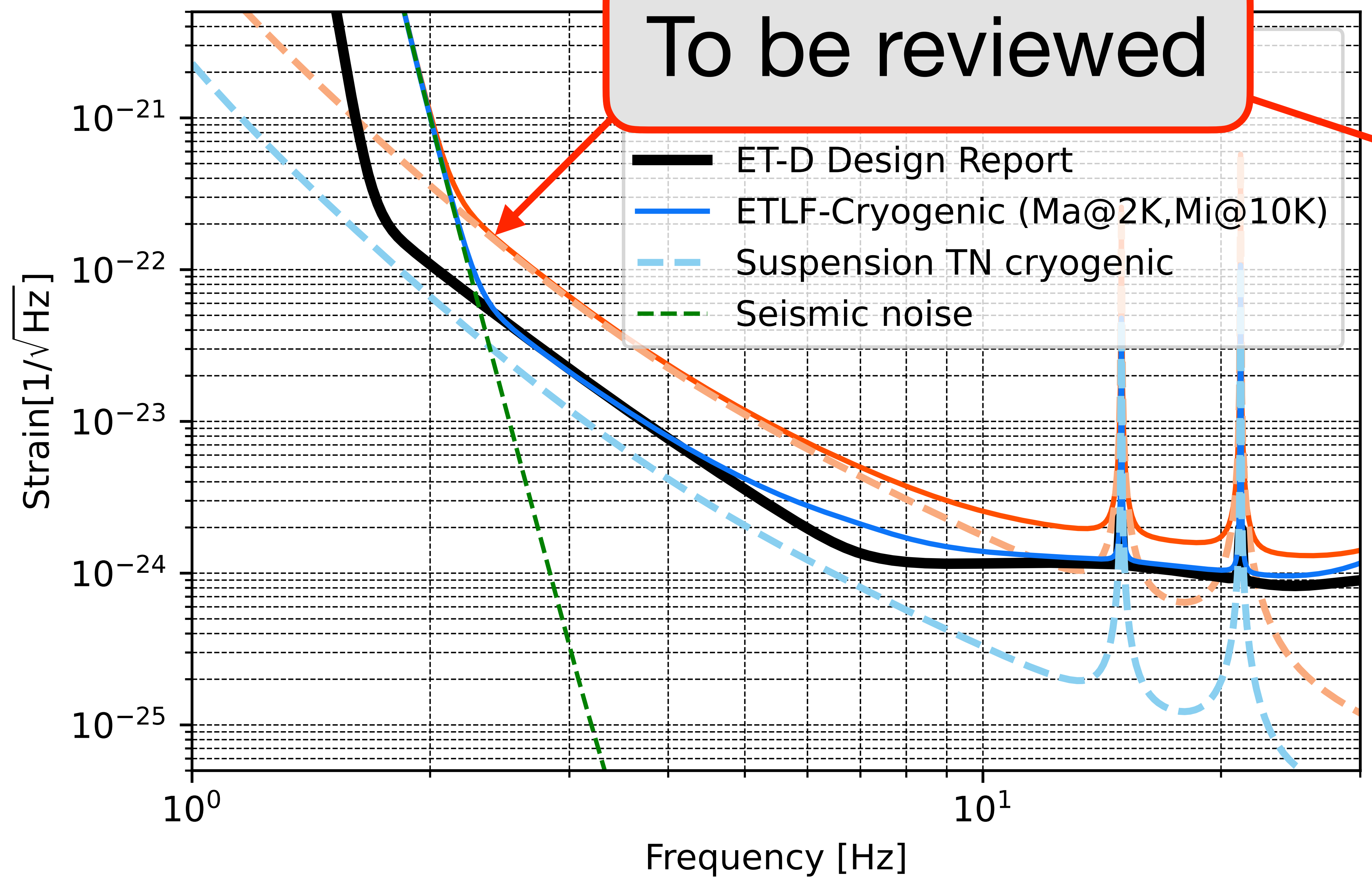
Figures based on ET-Noise Budget Gitlab - PyGwinc Code (18.11.2021) - https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

Contributed by Xhesika Koroveshi

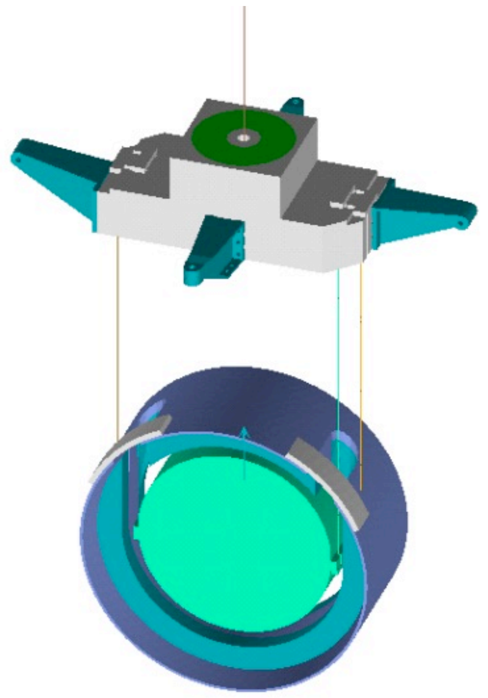
ET-LF suspension thermal noise

- ET-LF noise limits: Cryogenic vs. room-temperature (RT) operation

To be reviewed



	Marionetta	Recoil Mass	Mirror
Masses for ETDLF (kg)	422	211	211
Wire Diameter (mm)	5	3	3
Wire length (m)	2	2	2
Wire Material	Ti6Al4V	Silicon	Silicon
Loss Angle	10^{-5}	10^{-8}	10^{-8}
Temperature (K)	2	10	10



ET-Noise Budget Gitlab - PyGwinc Code (18.11.2021)
Figure Payload: ET Design Report Update (2020)

- RT payload **reduces sensitivity by factor 5** over entire ET-LF frequency band!
- **Seismic noise limit below 3 Hz** compared to the ET Design Report

Figure based on ET-Noise Budget Gitlab - PyGwinc Code (18.11.2021) - https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

VACUUM REQUIREMENTS FOR CRYOGENIC PAYLOAD OPERATION

Contributed by Roberto Cimino and Christian Day

ET-LF vacuum requirements

- Detailed discussion of ET-LF vacuum requirements in reference below
  - Main conclusions in subsequent slides

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

Cryogenic vacuum considerations for future gravitational wave detectors

L. Spallino,[1,*] M. Angelucci,[1] A. Pasqualetti,[2] K. Battes,[3] C. Day,[3]
S. Grohmann,[3] E. Majorana,[4] F. Ricci,[4] and R. Cimino[1,†]
[1]*LNF-INFN, Via E.Fermi 40, 00044 Frascati (Rome), Italy*
[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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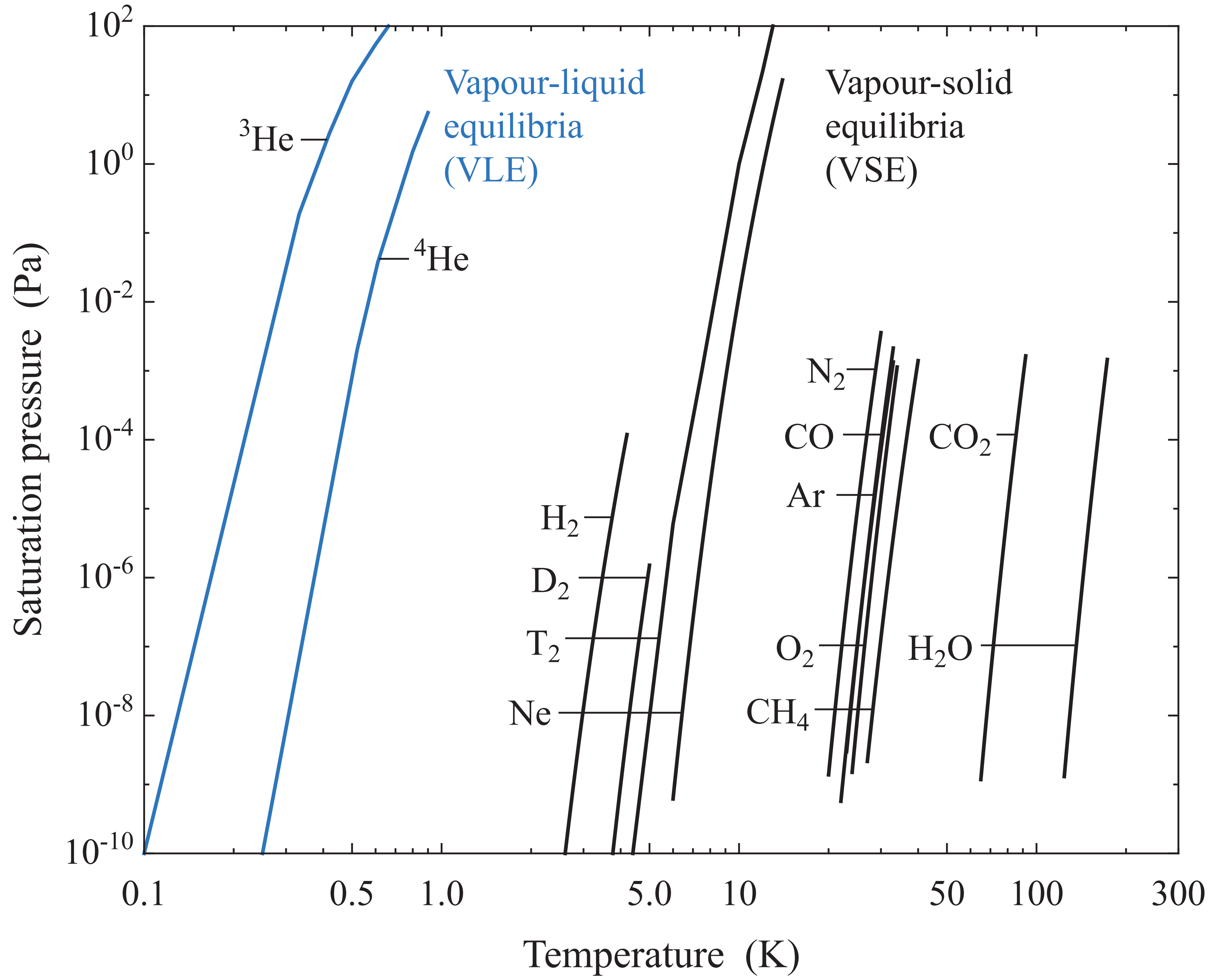
Contributed by Roberto Cimino and Christian Day

Residual gas adsorption on cold surfaces

- Cryosorption depends on
  - Surface temperature
  - Gas partial pressures
- Evaluation requires consideration of
  - Thermal transpiration correction, i.e. $p_{\mathrm{RT}} \neq p_{\mathrm{LT}}$
  - Vacuum history

Saturated vapour pressure curves



For $T \approx 10\,\mathrm{K}$ and $p < 10^{-10}\,\mathrm{mbar}$, the most common residual gas species in a UHV chamber (except H_2 and He) will be adsorbed, forming a **molecular ice ("frost") layer** on the surface

Contributed by Roberto Cimino and Christian Day

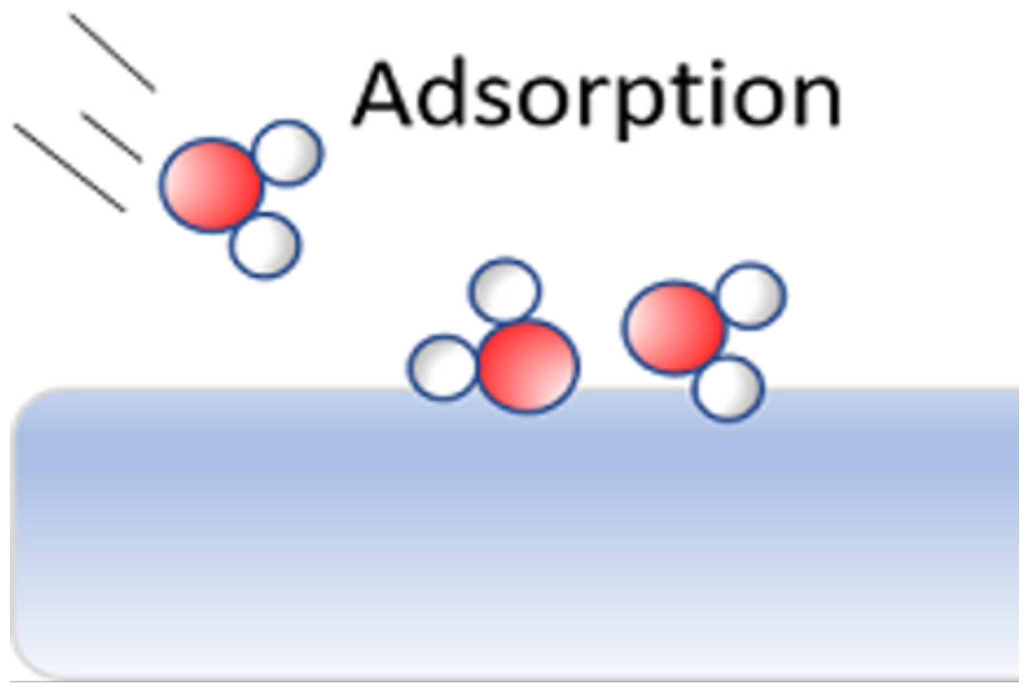
Residual gas adsorption on cold surfaces

- The right evaluation of gas pressure allows to give reliable estimates of ice layer thickness forming on the cold surface

Langmuir (L) unit:

$1\,\mathrm{L} = 1 \times 10^{-6}\,\mathrm{mbar} \cdot \mathrm{s}$

- gas exposure of a surface (or dosage)



For sticking coefficient $S_c = 1$:

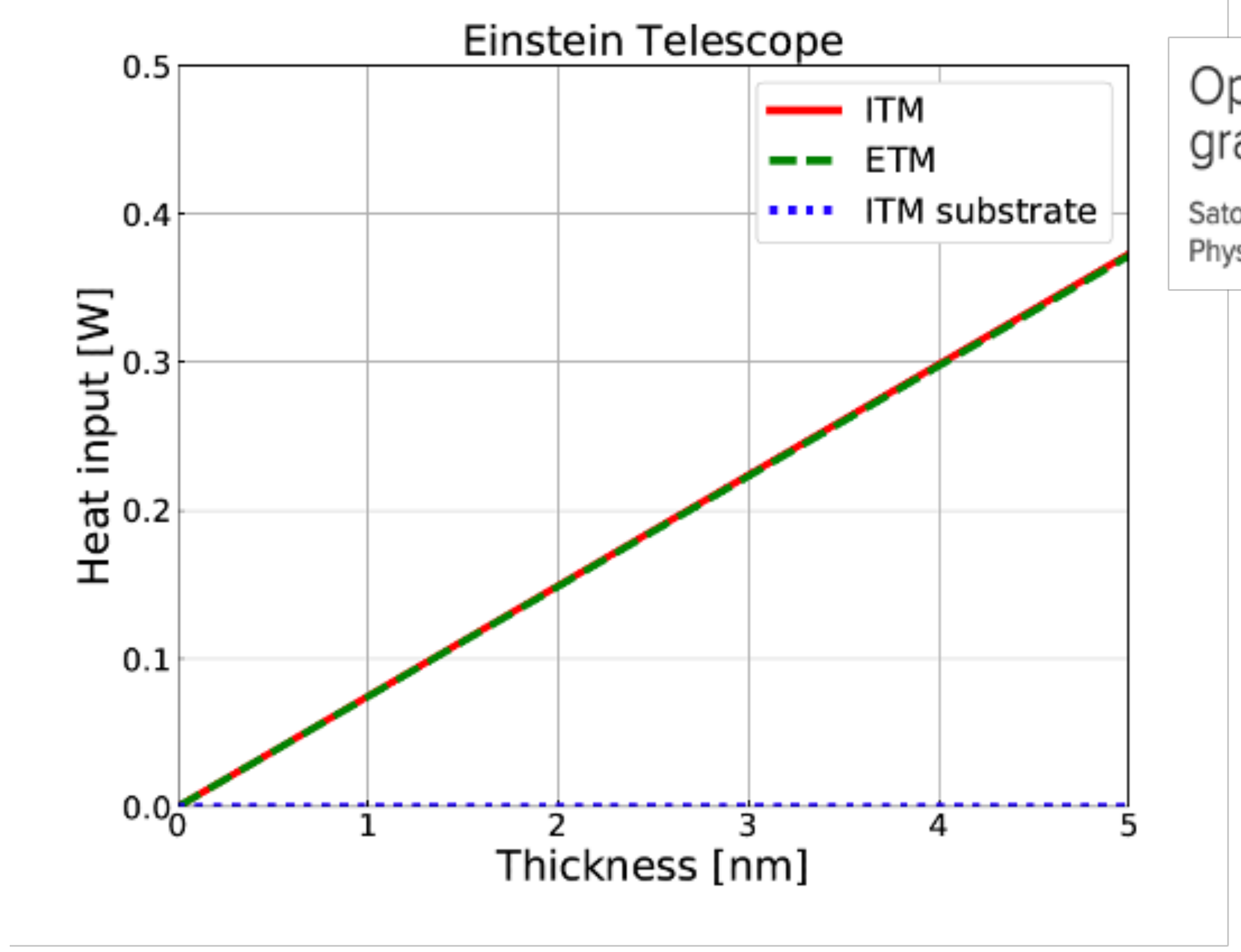
- 1 L ~ 1 monolayer (ML) cryosorbed
- For H_2O: 1 ML ~ 0.3 nm

- In $1 \times 10^{-10}\,\mathrm{mbar}$, it takes 10.000 s (~ 3h) to build up one ML

Contributed by Roberto Cimino and Christian Day

Cryogenic vacuum issues on GWD optics

- From KAGRA experience, simulations indicate:
  - Reflectivity gets affected, already after 100 nm of H_2O ice
  - ET maximum thermal budget $(0.1 - 1.0\,\mathrm{W})$ is expected to be exceeded already after $\approx 1 - 10\,\mathrm{nm}$ of H_2O ice !!!



Optical loss study of molecular layer for a cryogenic interferometric gravitational-wave detector

Satoshi Tanioka, Kunihiko Hasegawa, and Yoichi Aso

Phys. Rev. D **102**, 022009 – Published 27 July 2020

$$1 - 10\,\mathrm{nm}\,\mathrm{H_2O} \rightarrow 3 - 30\,\mathrm{L}$$

Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes

Kunihiko Hasegawa,[1,*] Tomotada Akutsu,[2] Nobuhiro Kimura,[3,4] Yoshio Saito,[1] Toshikazu Suzuki,[1,3] Takayuki Tomaru,[3,4] Ayako Ueda,[3] and Shinji Miyoki[1,†]

[1]*Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[2]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[3]*High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[4]*The Graduate University for Advanced Studies, Tsukuba, Ibaraki 305-0801, Japan*

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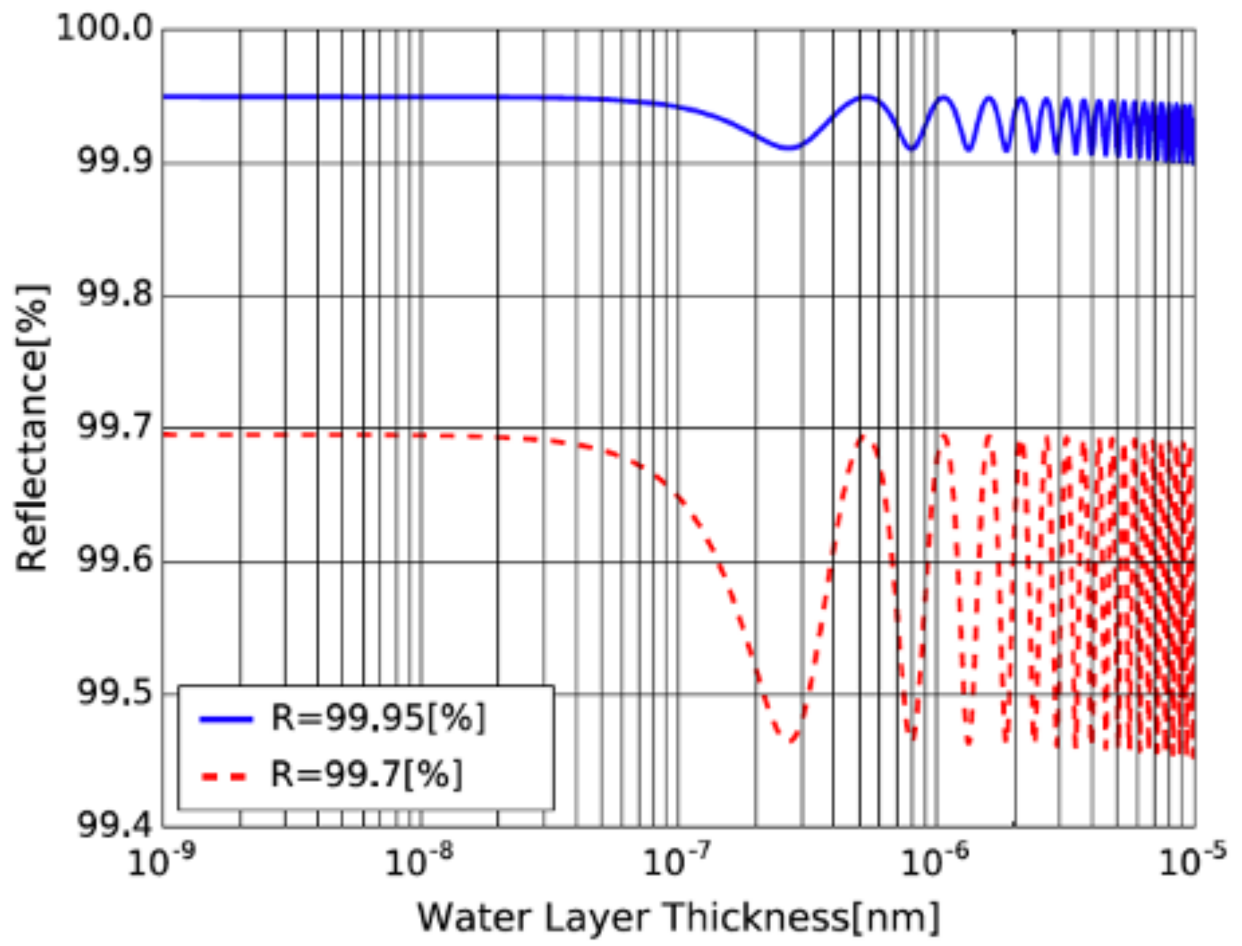


If $p_{H_2O} \approx 1 \times 10^{-10}\,\mathrm{mbar} \rightarrow$ it takes $\left(10^4 \times (3 - 30)\,\mathrm{s}\right) = (9 - 90)\,\mathrm{h}$ to start observing detrimental effects!!!

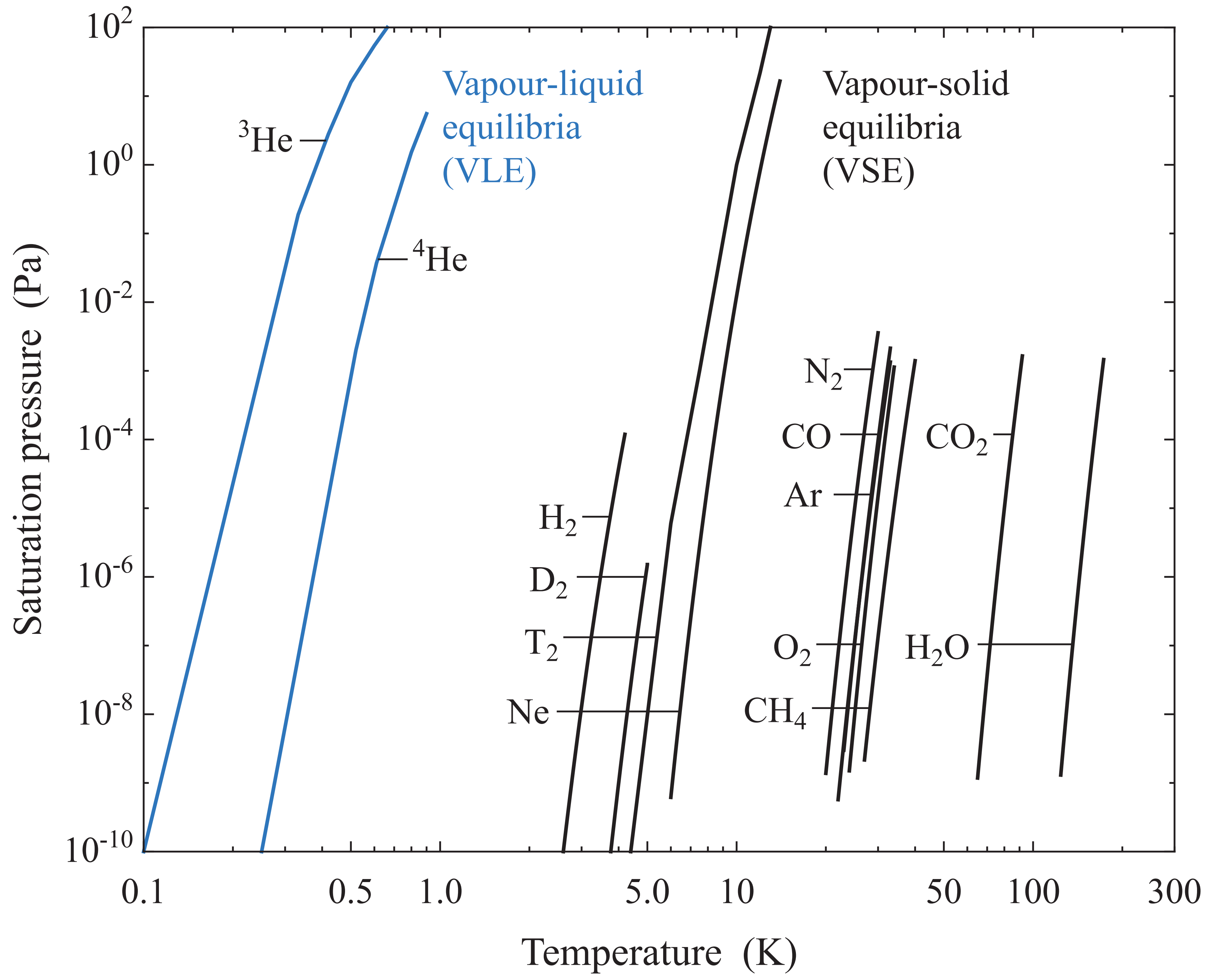
Contributed by Roberto Cimino and Christian Day

Limits for base operating vacuum in ET-LF towers

- Considering **1 W** maximum thermal budget
  - Cooling limit with this margin already anticipated in cryogenic design studies

If $p_{H_2O} = 1 \times 10^{-12}$ mbar → it takes 11.000 h to form 12 nm

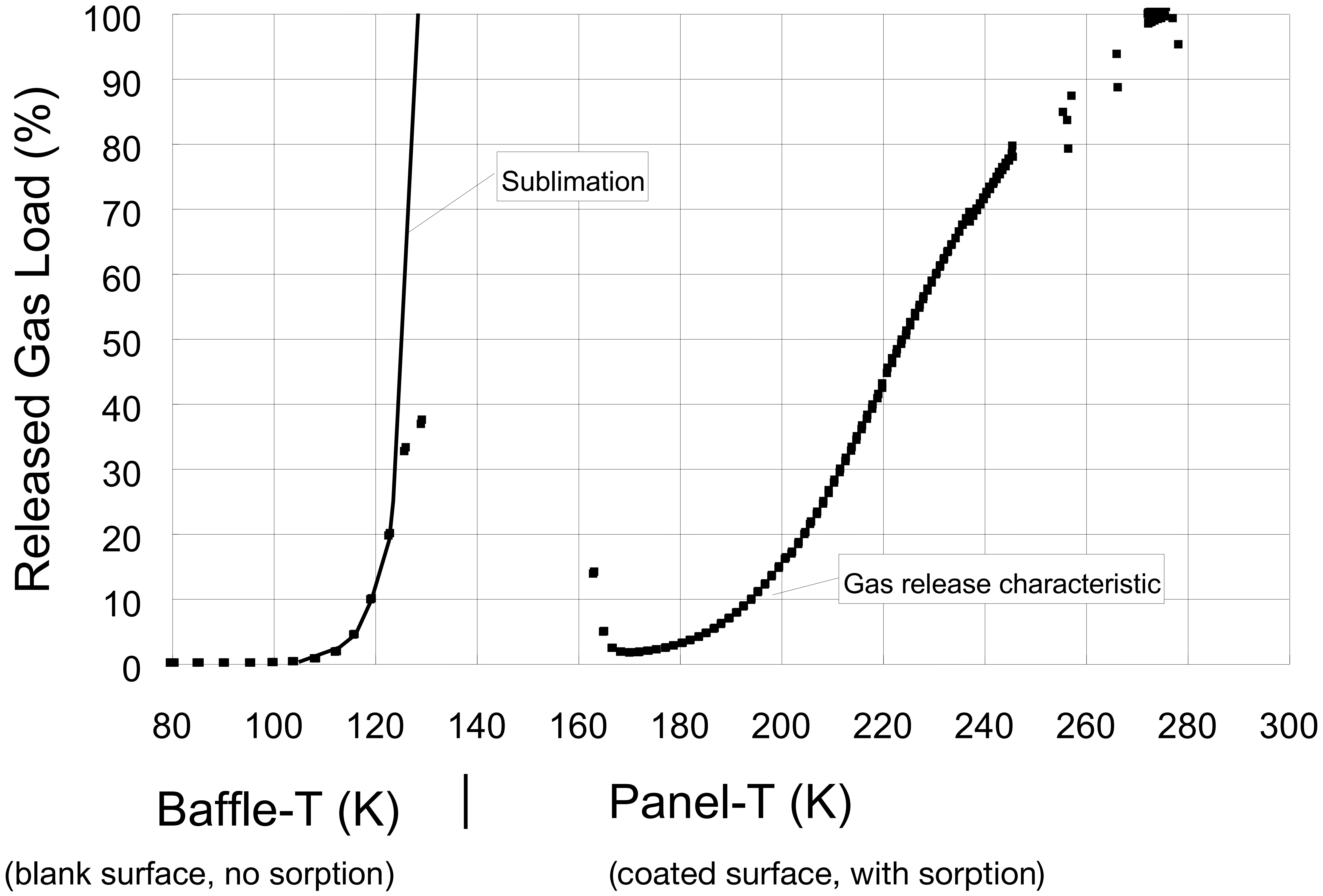
A full year of operation!



  - This reasoning applies to all gases (CO, CO_2, N_2, etc.) that have desorption temperatures higher than 10 K

How does cryoadsorption compare against desublimation?

Contributed by Christian Day

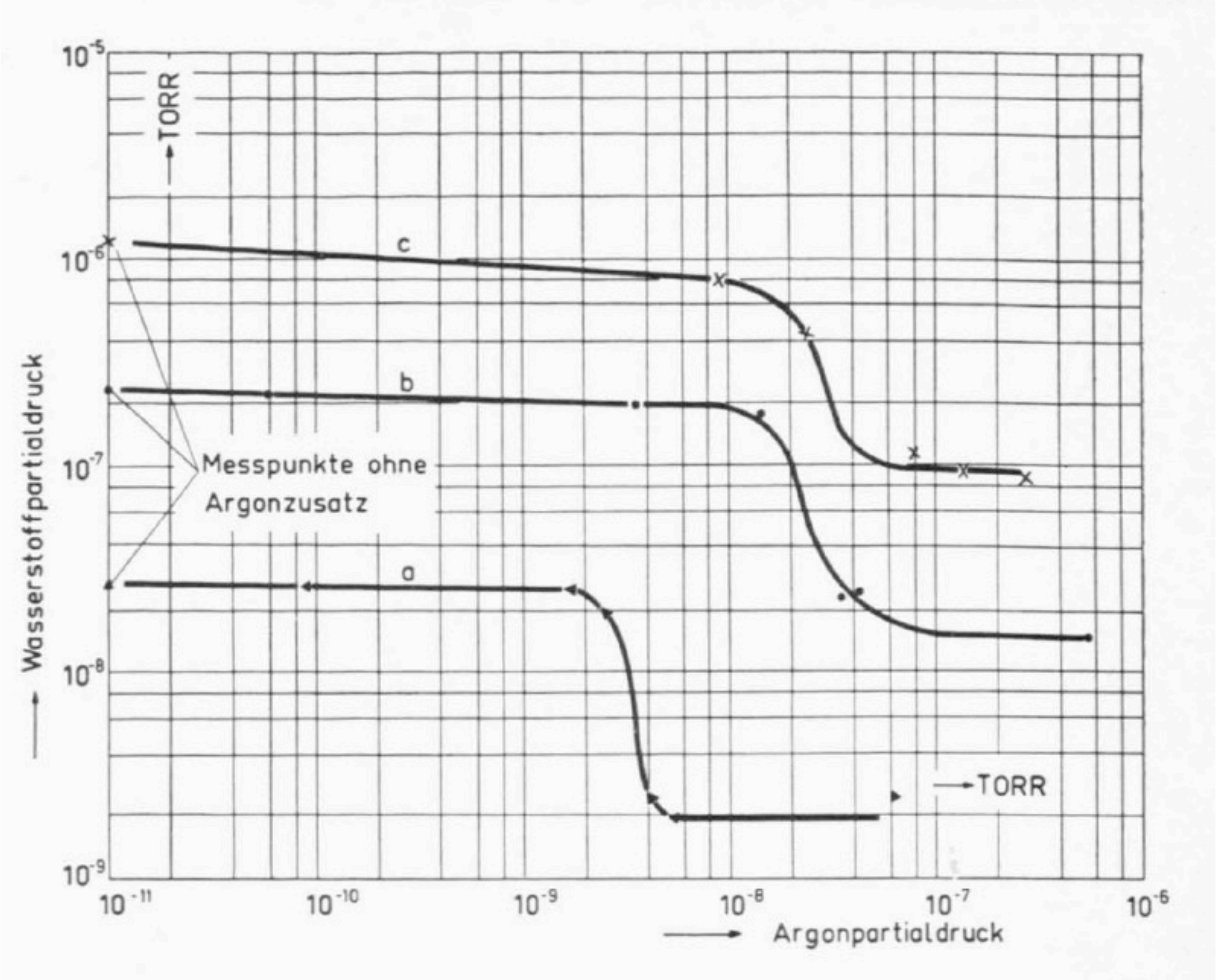


Example from CO_2 (water data to be investigated, but they follow a similar pattern):

- The plot shows particle release when heating a cryobaffle with an amount of pre-condensed gas: Particles are going from solid to gas when the heating meets the saturation temperature, get re-adsorbed if a sorbent is present, and are then re-released from there only at significantly higher temperatures
- In other words:
  If the sorbent is well chosen, adsorption works always at higher temperatures than for desublimation

How does cryotrapping compare against cryoadsorption ?

Contributed by Christian Day



The plot shows the achieved end pressure in a vacuum system *(´ohne Argonzusatz´)*, and how this pressure further decreases if a surface is installed that has condensed Ar on it

- Very similar patterns may be expected for water

Ongoing, triggered by molecular dynamics: Effects of surface functionalization

Contributed by Christian Day

- There is very interesting R&D ongoing that studies the influence of surface adsorption at different **surface functionalizations** and correlate it with the parameters in the Cercignani-Lampis scattering law

- With some of this bundle of measures, although they have not yet been applied for situations as in ET, **the partial pressure requirements of ET-LF can probably be achieved**, if an accompanying R&D programme is installed

Contributed by Roberto Cimino and Christian Day

Limits for base operating vacuum in ET-LF towers

- Is it feasible?

$$p_{H_2O} = 1 \times 10^{-12}\,\text{mbar}$$

- Use of cryo-panels around the mirror (inner shield)
- Careful cool-down strategy (mirror to be cooled last)
- Efficient warm-up/cool-down (already in the design phase)
- Use of porous materials on cryo-panels to enhance adsorption over condensation and increase pumping speed and efficiency around the mirror
- Other mitigations schemes?

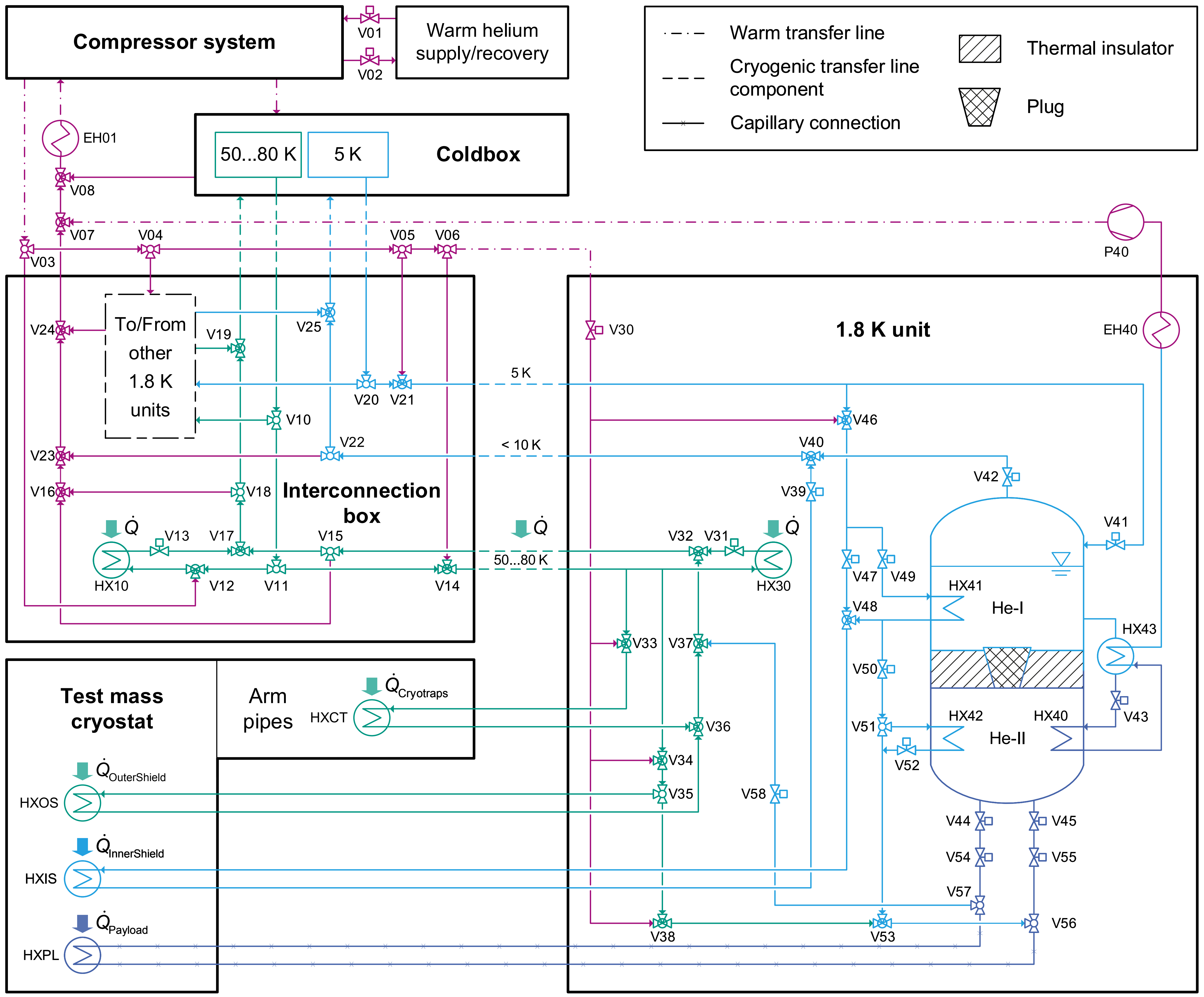
Challenging, requiring R&D, **BUT** it is indeed **FEASIBLE**!

CRYOGENIC DESIGN AND OPERATING SCENARIOS

The need of cryogenics in ET

- Cryogenic infrastructure concept
  - **One He cooling plant** in each vertex
  - Cooling power for **cryotraps**, **thermal shields** and **cryogenic detectors** at three different temperature levels
  - Surface compressors
  - Underground coldbox
  - Cryogenic transfer system to towers

Reference in TDS:
https://apps.et-gw.eu/tds/?content=3&r=17648



The need of cryogenics in ET

EINSTEIN TELESCOPE

- Overview of cryogenic load estimates (per tower)

ET-LF **and** ET-HF

ET-LF **and** ET-HF

Component	Temperature level / K	Cooling power / W
Arm pipe cryotraps	50...80	$x \ldots 10^4$
Outer thermal shield	50...80	$x \ldots 10^3$
Inner thermal shield	5	$x \ldots 10^2$
Payload heat sink	2	$x \ldots 10^0$

$T \leq 20\,\mathrm{K}$ possibly needed

Determines cryogenic infrastructure design!

Small influence on overall cost

Yet, there is **scientific interest** on the **feasibility of a cryogenic payload**

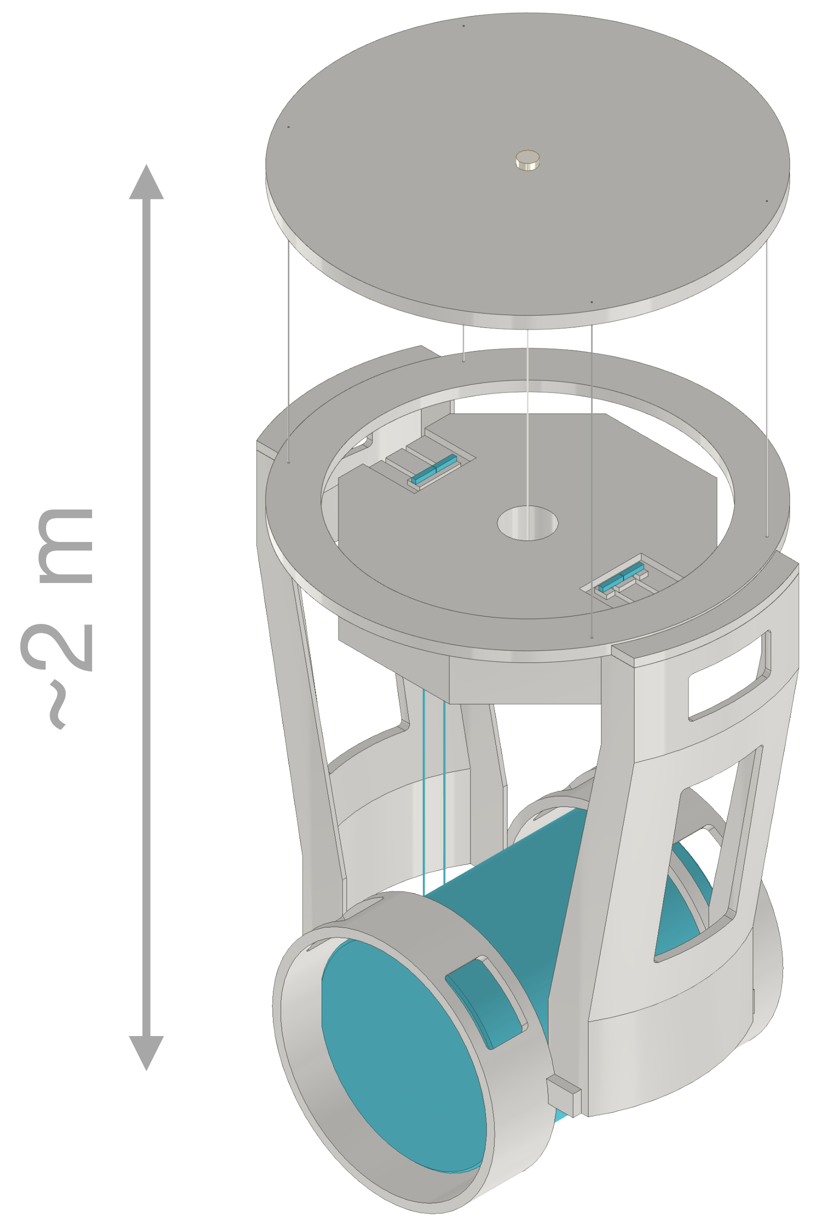
Reference in TDS: https://apps.et-gw.eu/tds/?content=3&r=17648

Contributed by Lennard Busch

Cool-down studies of a cryogenic payload

ET EINSTEIN TELESCOPE

Payload geometry and materials

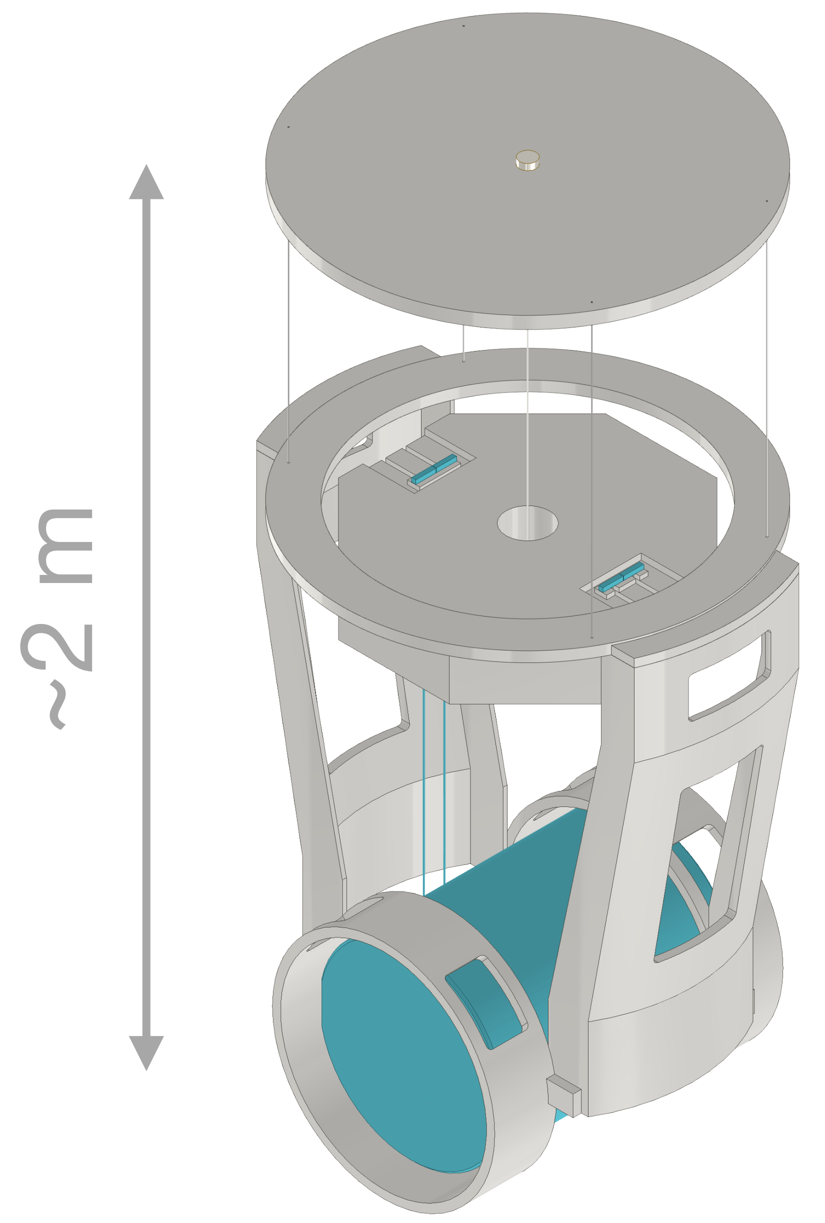


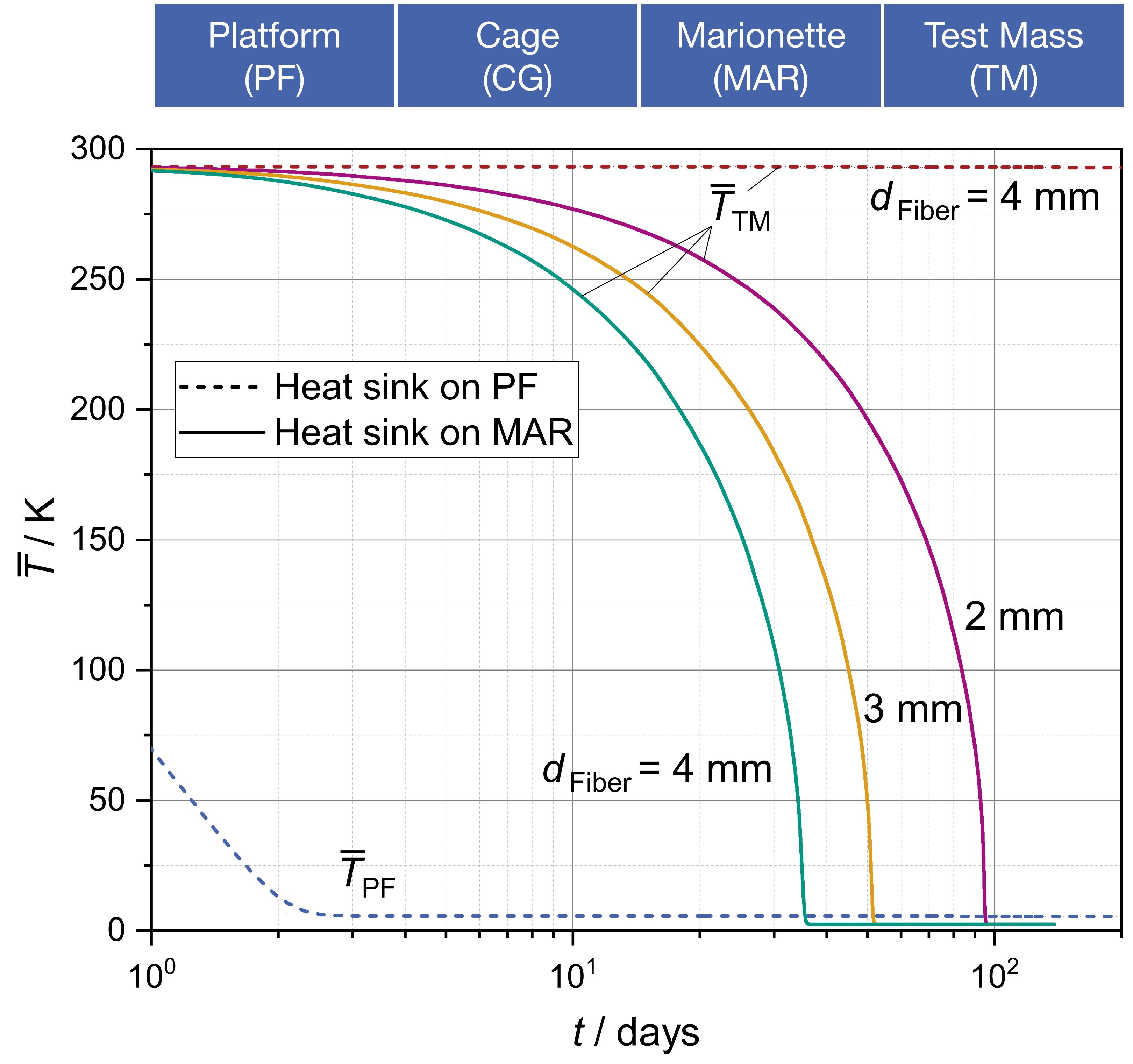
		Platform (PF)	Cage (CG)	Marionette (MAR)	Test Mass (TM)
Bulk mass	Dimensions	∅ 900x30	∅ ~1000 h ≈ 1300	∅ ~700 h = 150	∅ 450 s = 570
	Material	Stainless 316L			Si
Suspensions	Dimensions	N/A	4x ∅ 3 L = 700	1x ∅ 3 L = 780	4x ∅ **2…4** L ≈ 1000
	Material	N/A	Stainless 316L	Ti6Al4V	Si

Contributed by Lennard Busch

Cool-down studies of a cryogenic payload

Results of **solid conduction only**



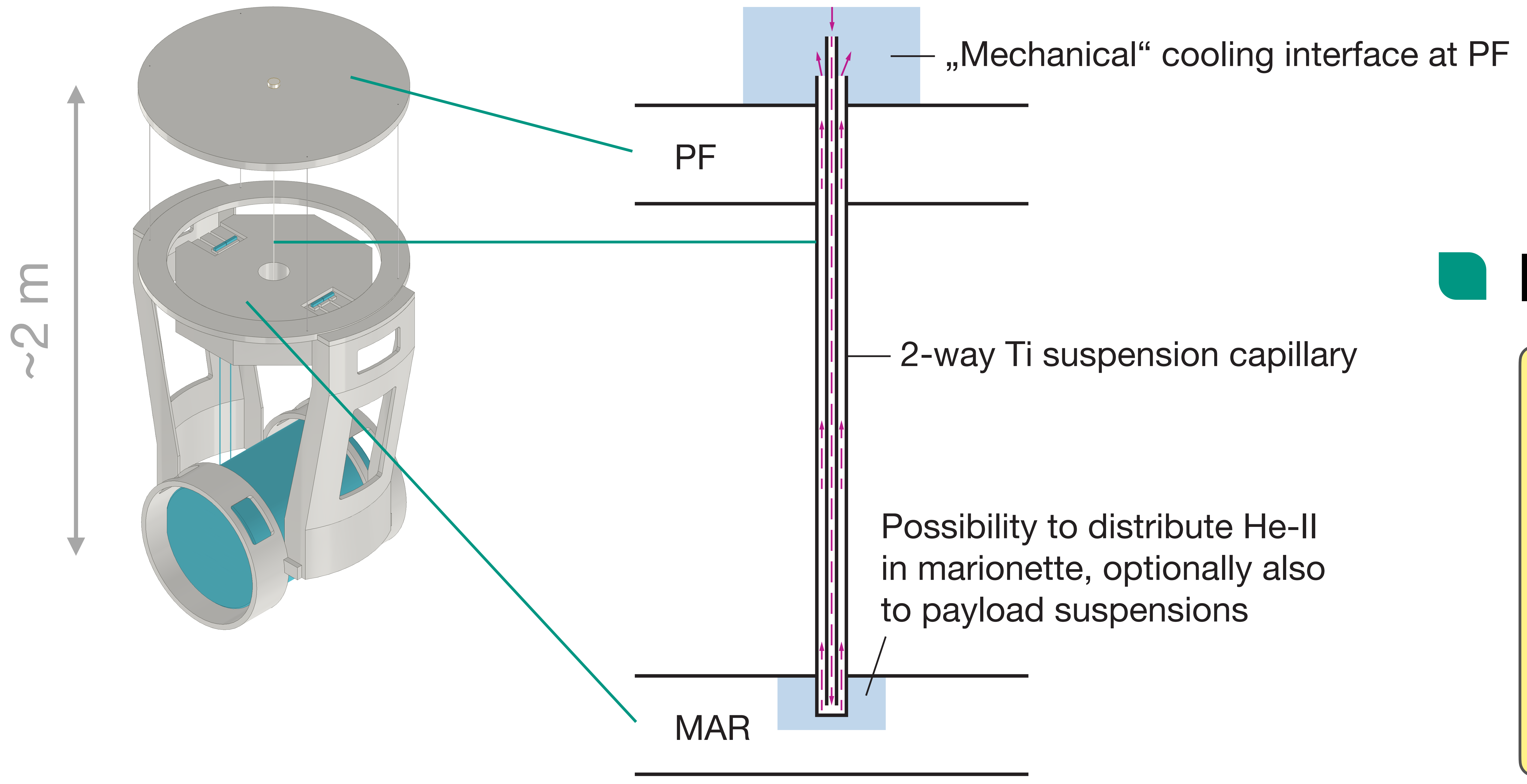


Conclusions

- A cooling interface implemented on the **platform (PF)** is **completely ineffective**
- The cooling interface **must** be implemented on the **marionette (MAR)**
- Depending on the suspension fiber diameter, the cool-down by **pure solid conduction** would take **~1-3 months**

Cooling system interface – design option

- Possibility to implement **ultra-low-noise cooling** on the **marionette**



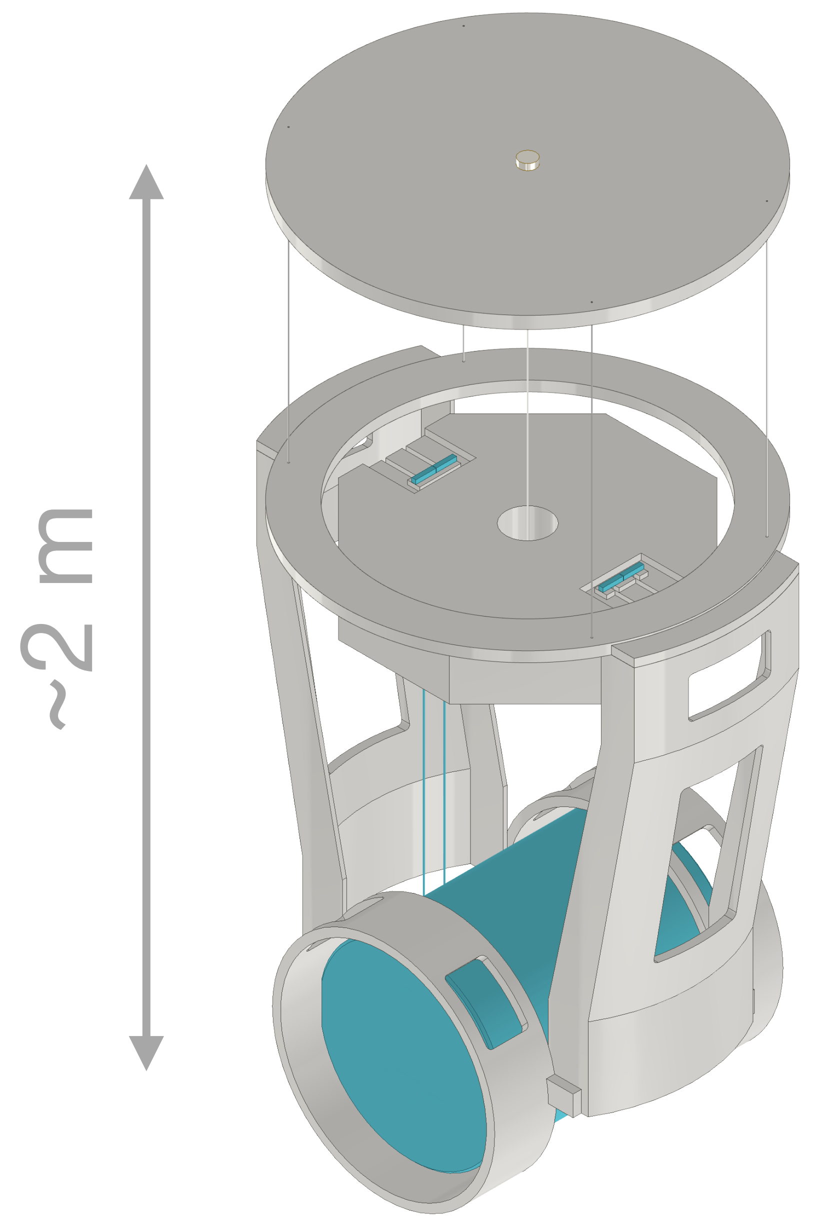
Design features

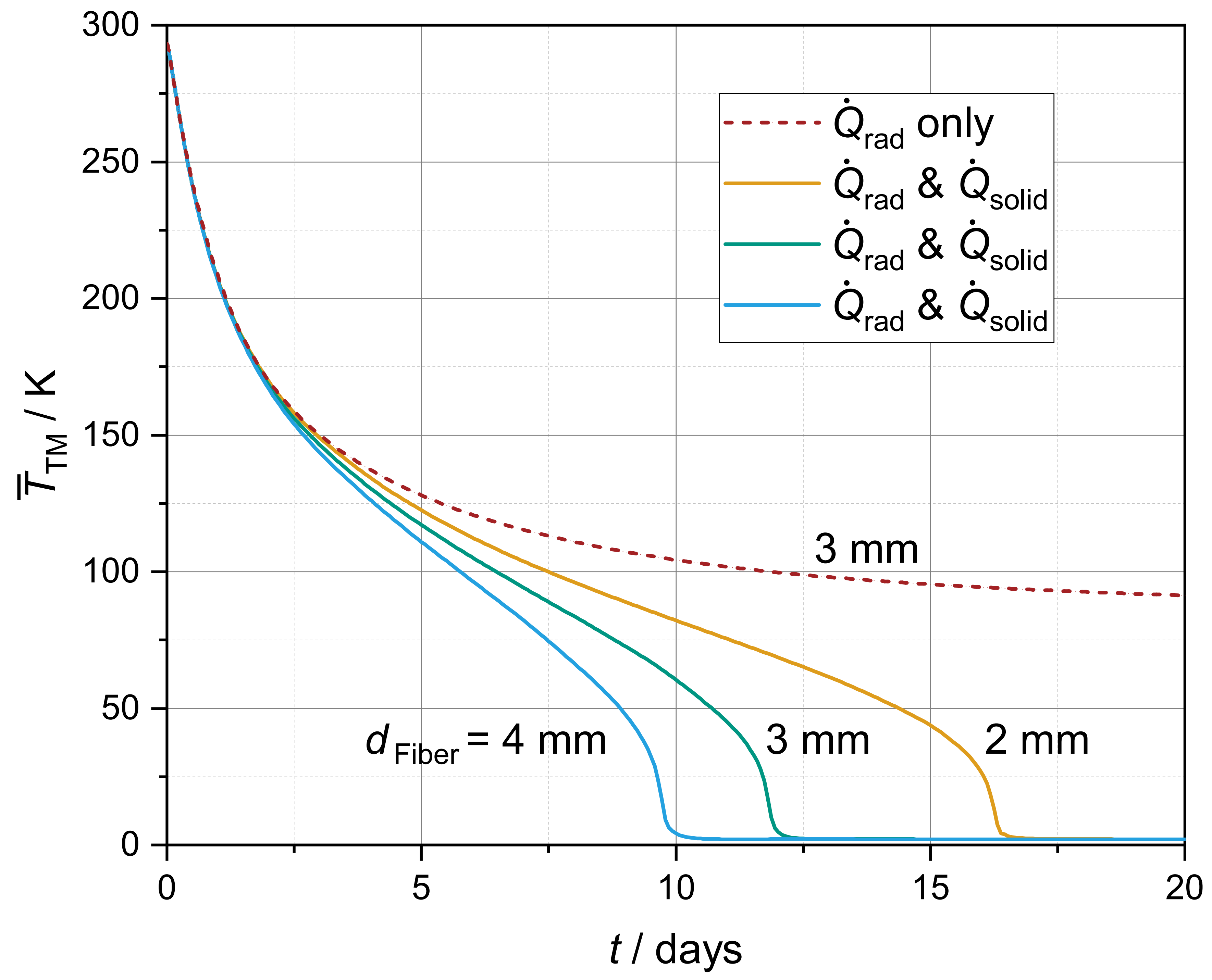
- Double-walled Ti capillary suspension for **counter-flow cool-down** with super-critical He-I
- **He-II** cooling by **steady-state conduction** in standard operation (no macroscopic flow)

Contributed by Lennard Busch

Cool-down studies of a cryogenic payload

Solid conduction + thermal radiation





Applied emissivity values

Material	ε(*T*) / -
316L (PF, MAR, CG)	~0.02…0.06
Ti6Al4V (MAR Susp.)	0.1
Si (TM & -Susp.)	~0.12…0.75 [1]

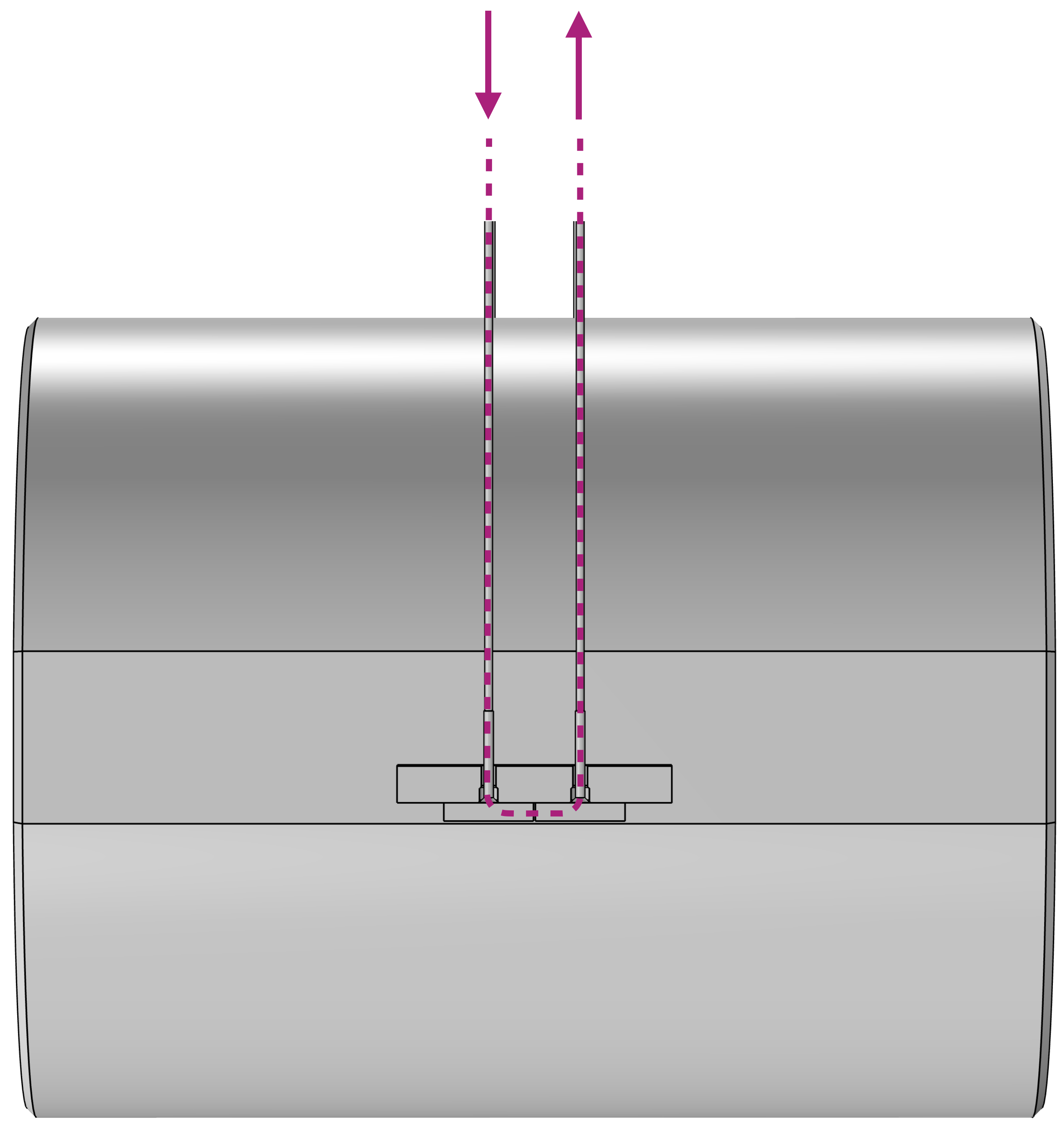
[1] Constancio et al. 2020
Silicon emissivity as a function of temperature

Conclusions

- Cooling by **thermal radiation only** is **ineffective**
- **Reduction** of conductive **cool-down time** by thermal radiation by **~factor 3**
- Sufficiently fast, i.e. **no need** for **contact gas cooling**

Option with He-II in hollow suspensions

- Possibility of **even faster mirror cooling**
  - Cool-down and warm-up: Controlled **super-critical He-I flow** through hollow suspensions at temperatures of 300 K ↔ 3 K
  - Steady-state operation: Hollow suspensions filled with **superfluid He-II** → **ultra-low-noise** cooling by steady-state heat conduction in the superfluid He-II **(no macroscopic flow)**
  - In this case, the **suspension** and **mirror temperatures** are close to 2 K



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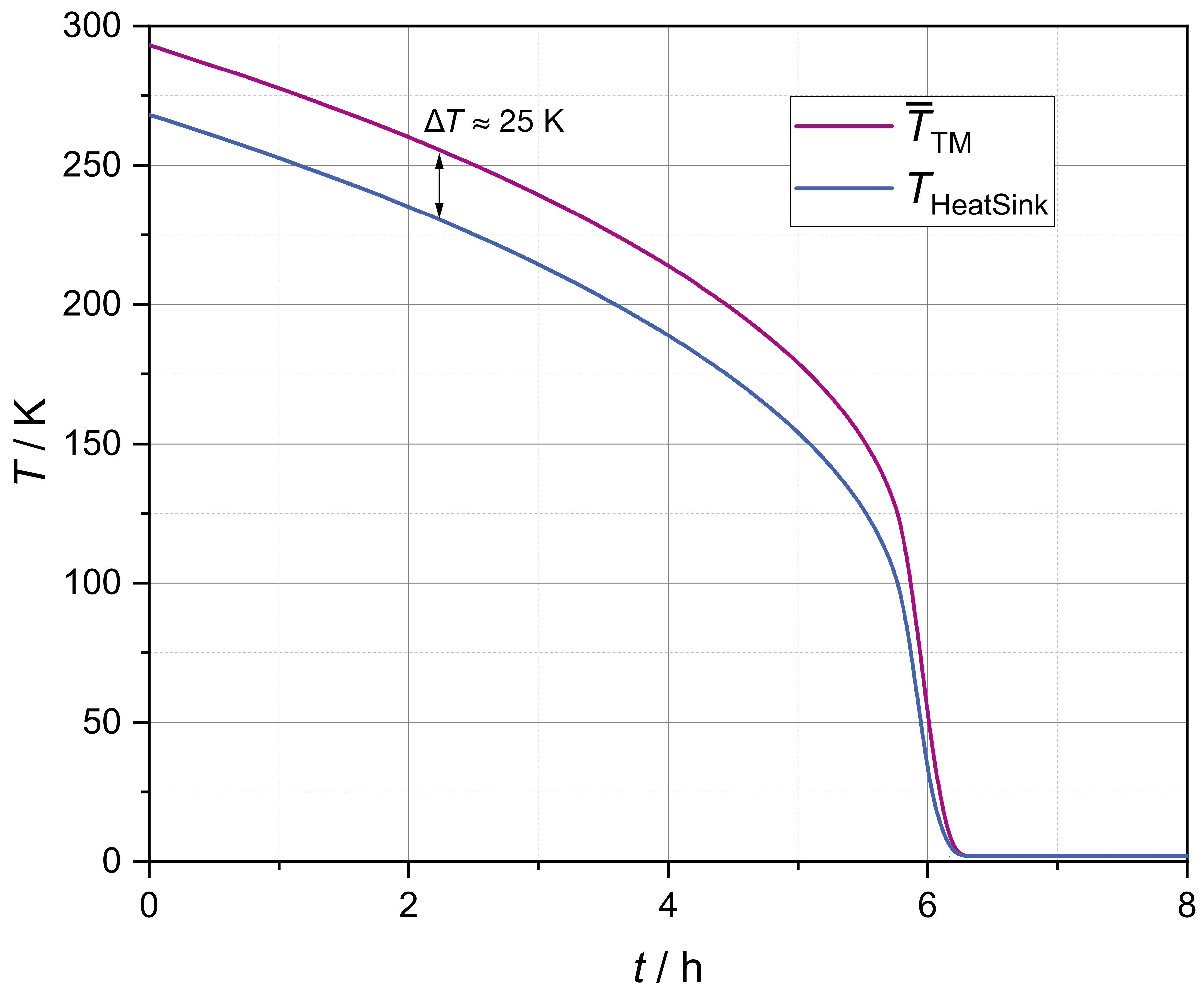
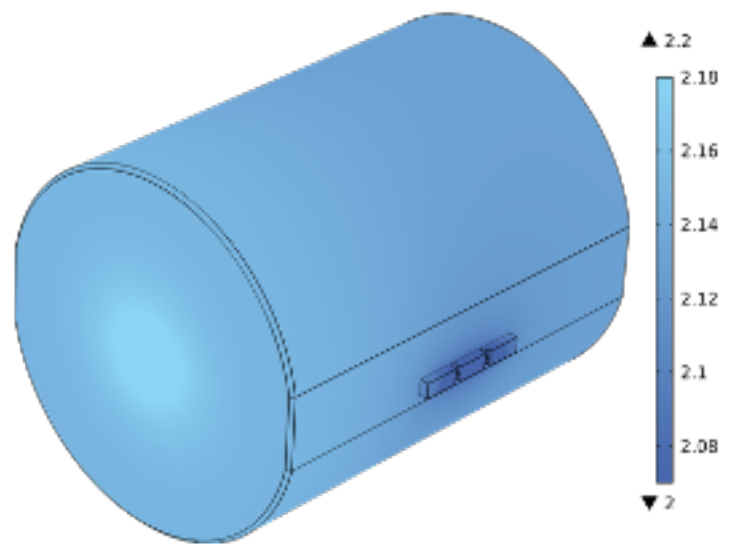
Option with He-II in hollow suspensions

- Achievable **cool-down** and **warm-up** cycles with **hollow suspensions**





Conclusions

- **Very short thermal cycles** of **a few hours** may be achieved
- Option for **surface regeneration** of cryosorbed gas layers on **hour time scales**

SUMMARY

Summary

1) The ET-LF sensitivity is strongly influenced by **suspension thermal noise**. **Cryogenic operation is required** to achieve the design sensitivity of ET.

2) The **water partial pressure** around a cryogenic payload must be on the level of $p_{H_2O} \leq 10^{-11} \ldots \leq 10^{-12}\,\mathrm{mbar}$ to limit frost formation on the surface. This level appears to be **achievable** with an appropriate R&D programme.

3) A **cryogenic infrastructure** is required to fulfil the **vacuum requirements** in **ET-LF** and **ET-HF!** Those **cryopumps** (cryotraps and inner/outer shields) **determine the dimensions, cost and installation schedule** of the cryogenic infrastructure.

4) **Ultra-low-noise cryogenic payload cooling is feasible**, absorbing heat loads up to 1 W from the payload. The impact on the cryogenic infrastructure is small.


Thank you for your attention!