Cryogenics for the Einstein Telescope (ET)

Steffen Grohmann
On behalf of the ET Instrument Science Board, Vacuum & Cryogenics Division

International Cryogenic Engineering Conference

Geneva, July 22–26, 2024

Outline

I. Overview on the Einstein Telescope (ET)

II. Vacuum and Cryogenic Infrastructure

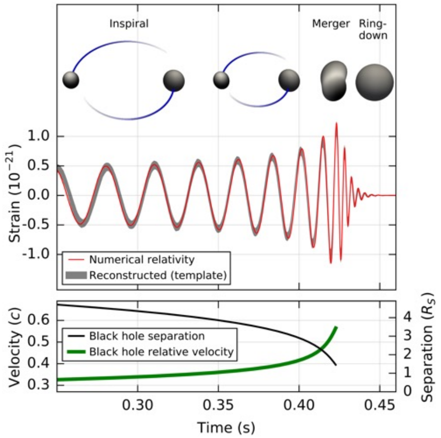
III. Cryogenic Detector Cooling Developments

I. EINSTEIN TELESCOPE

Brief history of gravitational waves (GW)

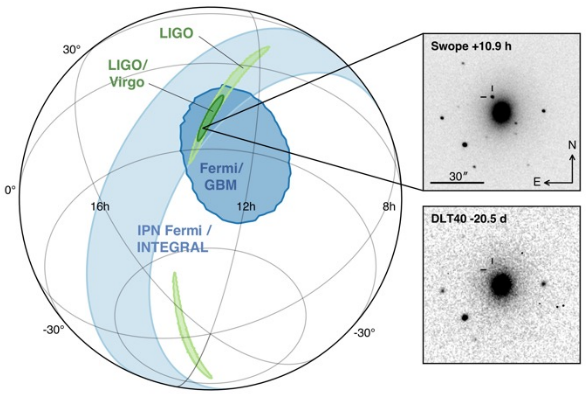
- 1916 **Postulation** of gravitational waves by Albert Einstein
- 2015 **First** direct GW **detection**
- 2017 **Synchronous detection** at LIGO (US) and VIRGO (Pisa, IT)

GW150915 PRL 116, 061102 (2016)

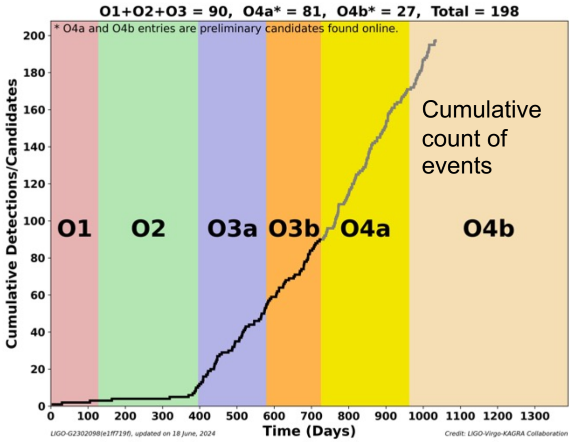


Source: B. P. Abbott et al. Phys. Rev. Lett. 116, 061102, doi 10.1103/PhysRevLett.116.061102

GW170817 + GRB170817A + AT 2017gfo



Source: B. P. Abbott et al 2017 ApJL 848 L12, doi: 10.3847/2041-8213/aa91c9



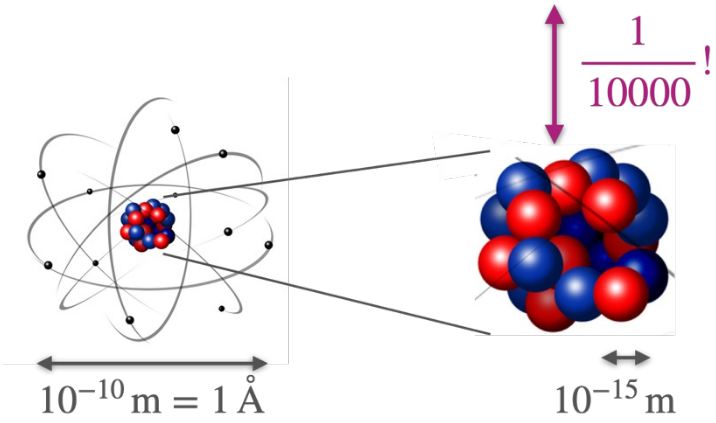
Source: https://dcc.ligo.org/LIGO-G2302098-v15/public

- 2017 **Nobel prize in physics** for R. Weiss, B. Barish, K. Thorne (**GW detection**)
- 2020 **Nobel prize in physics** for R. Penrose, R. Genzel, A. Ghez (**Black holes**)

GW detection principle

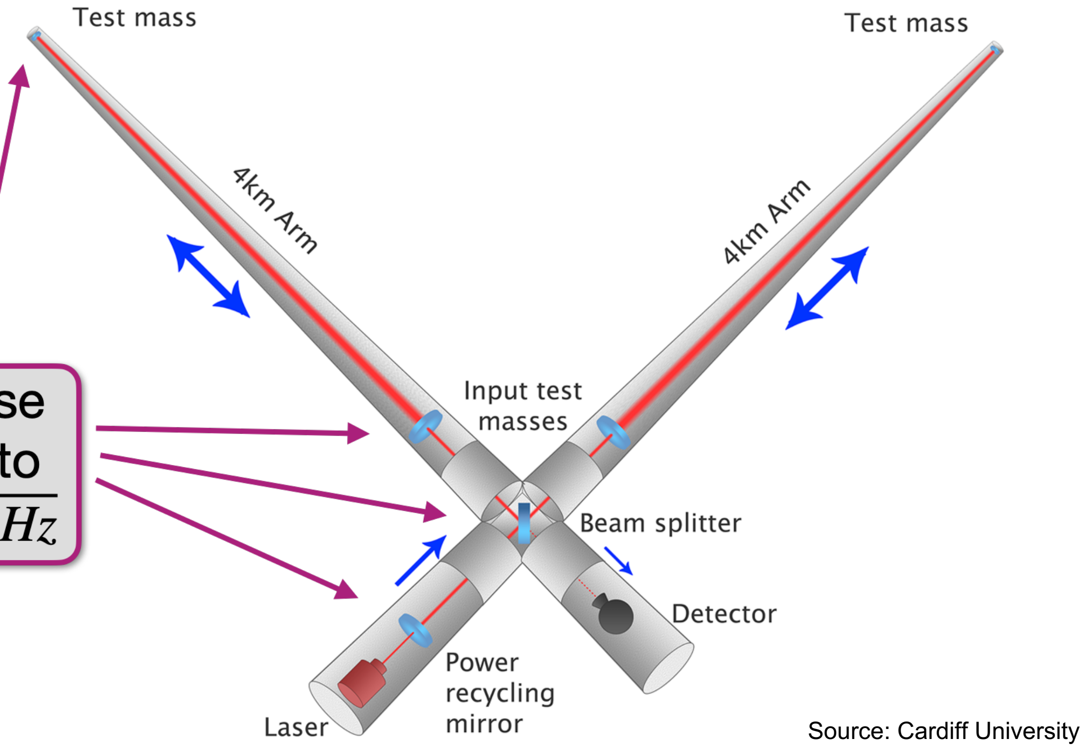
Check

- Michelson interferometer
  - Laser through beam splitter
  - Reflection at end mirrors (test masses)
  - Extinction at identical arm lengths
  - Signal due to GW length deformation
  - Sensitivity needed: $\Delta \boldsymbol{L} \approx \mathbf{10^{-19}\ m}$



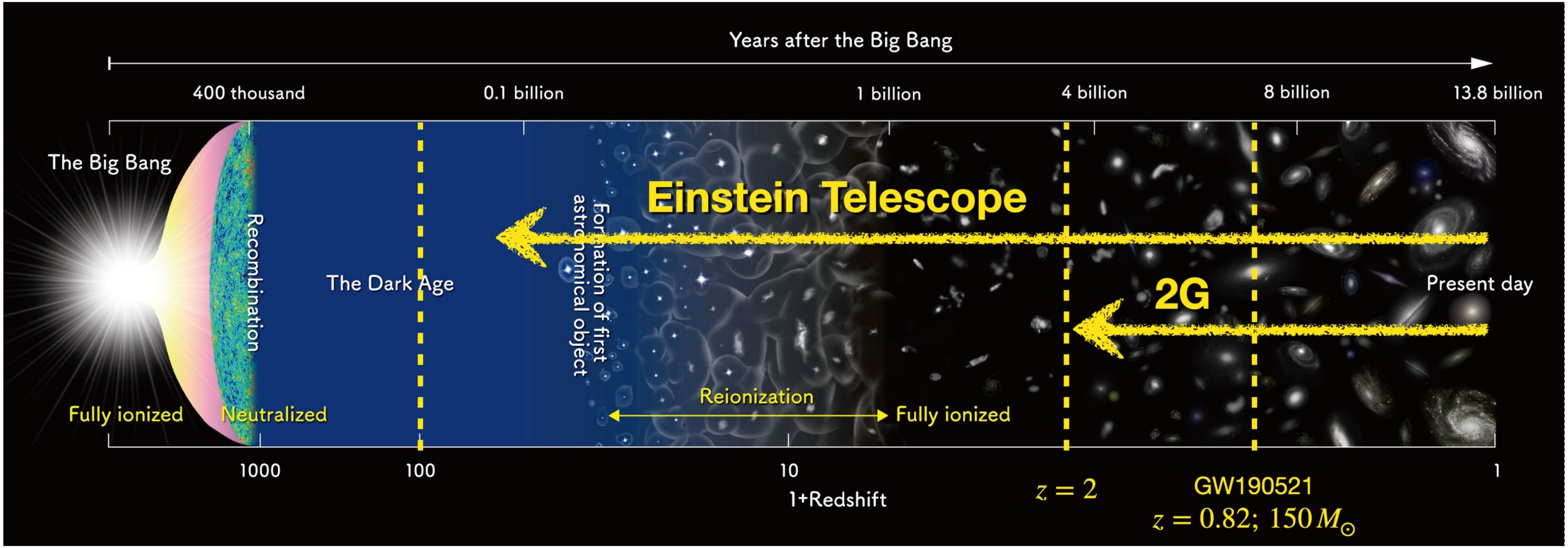
Extreme noise attenuation to $\sim 10^{-20}\,\mathrm{m}/\sqrt{Hz}$

LIGO layout



Source: Cardiff University

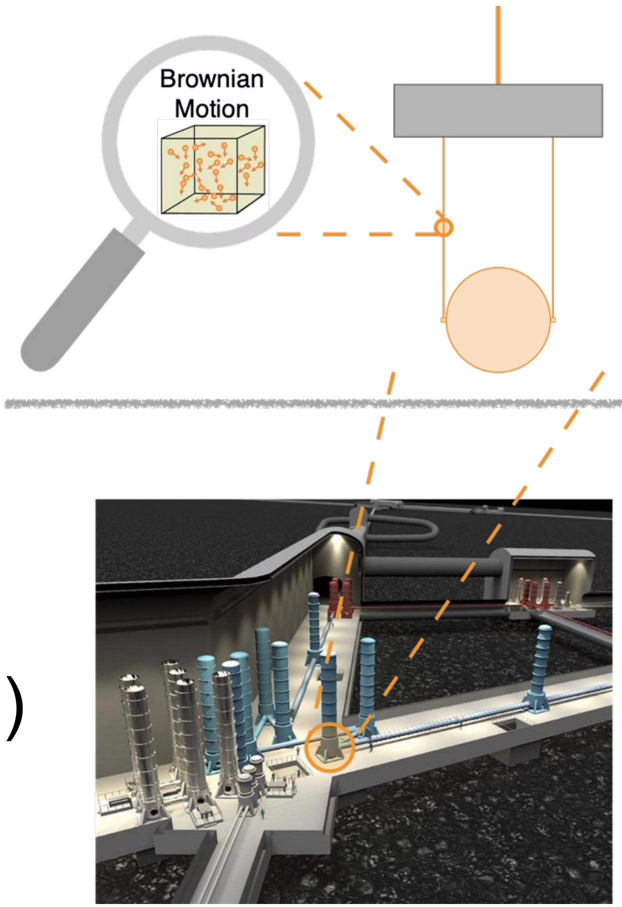
Detection horizon for black hole binaries



Credit: ALMA Collaboration

Challenge: Create the QUIETEST Place on Earth

LIGO / Virgo (2G)



ET (3G)

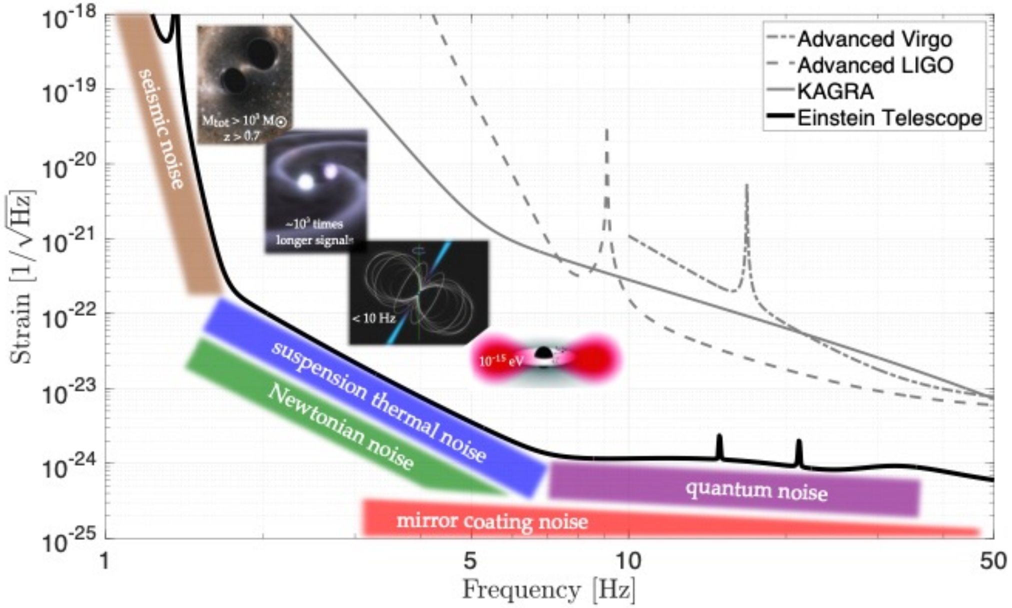
Cryogenic operation is a **new key technology** to limit the suspension thermal noise (STN) at low frequency (ET-LF)

- ➢ $T = 10 \ldots 20\ \mathrm{K}$

Importance of the cryogenic ET-LF

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

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

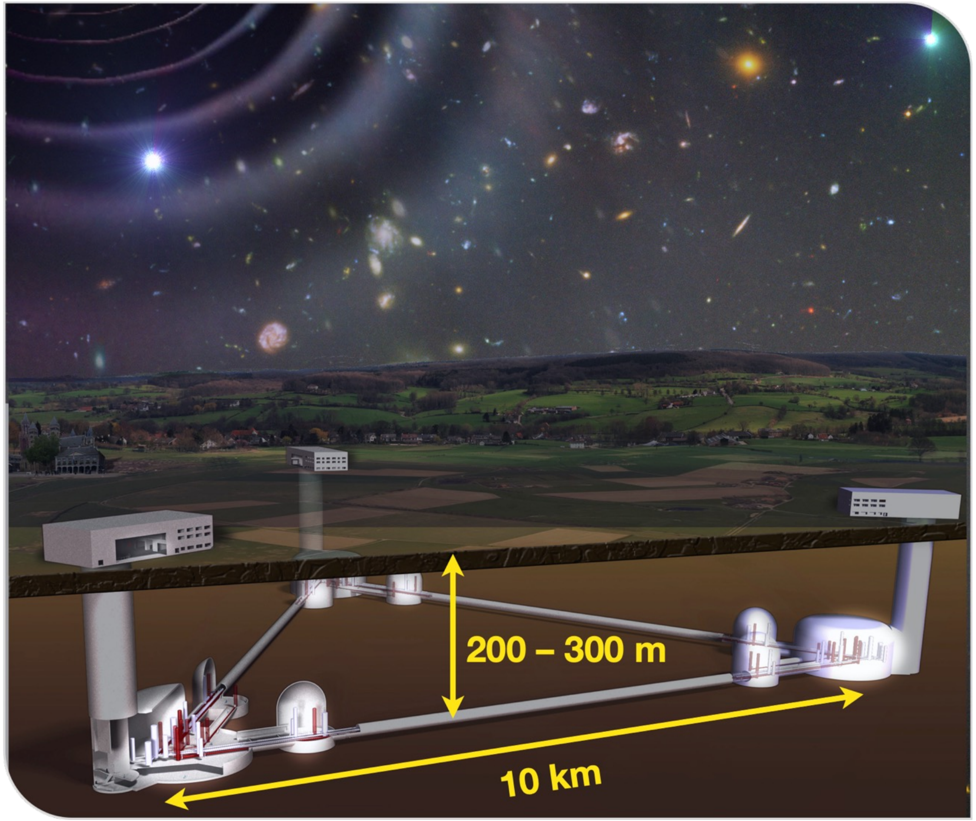


Source: S. D. Pace et al.: Research Facilities for Europe's Next Generation Gravitational-Wave Detector Einstein Telescope. Galaxies 10 (3), 65, doi: 10.3390/galaxies10030065 (2022)

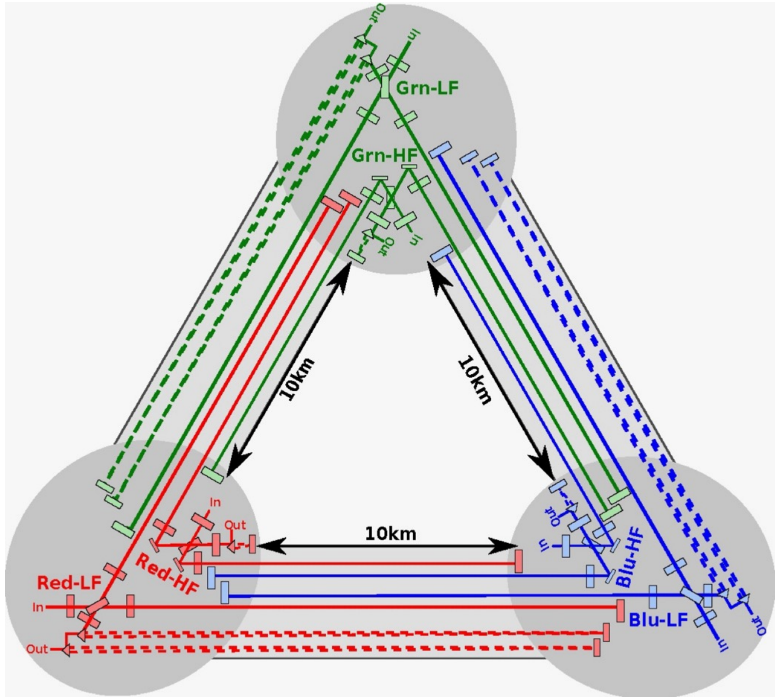
The low-frequency sensitivity is crucial for exploiting the full scientific potential of ET, in particular with regard to:

- 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 $10^2 - 10^4\,M_{\odot}$.

Layout(s) of the Einstein Telescope



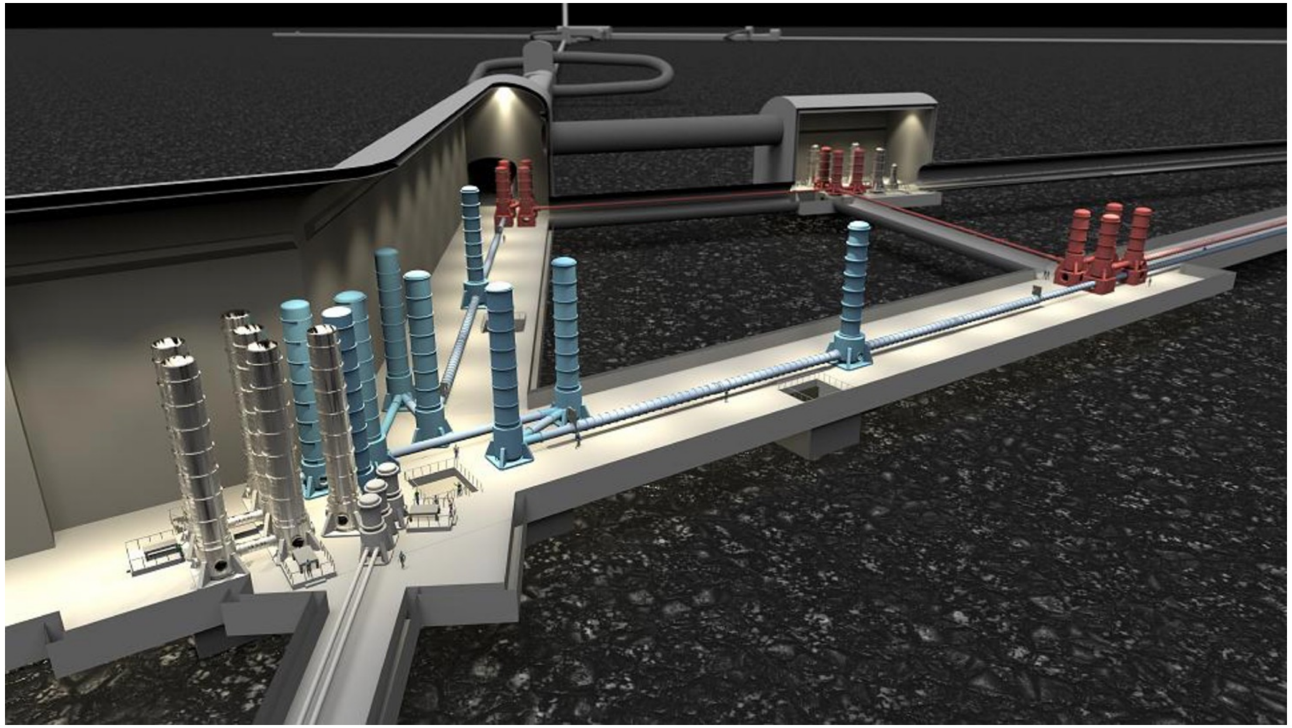
Xylophone design of ET



Source: ET Conceptual Design Study (2011)

- Alternatively, a 15 km double-L solution is under investigation

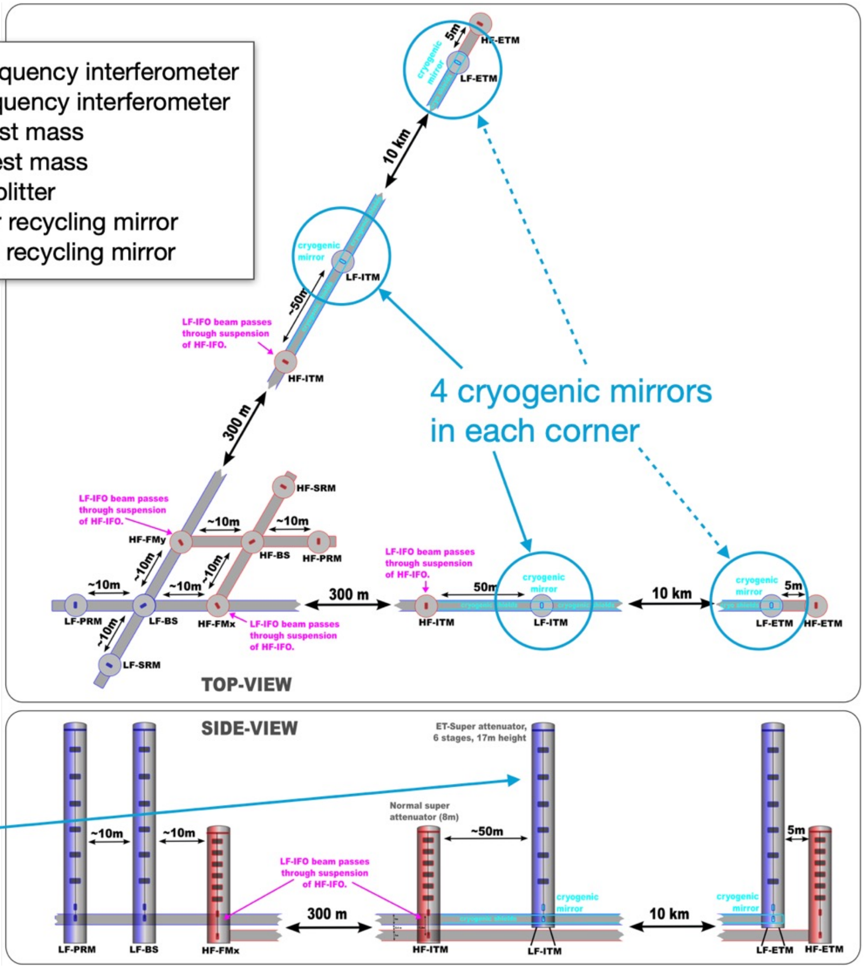
Views of underground installation



Source: ET Design Report Update (2020)

Source: ET Conceptual Design Study (2011)

HF: High-frequency interferometer
LF: Low-frequency interferometer
ETM: End test mass
ITM: Input test mass
BS: Beam splitter
PRM: Power recycling mirror
SRM: Signal recycling mirror



4 cryogenic mirrors in each corner

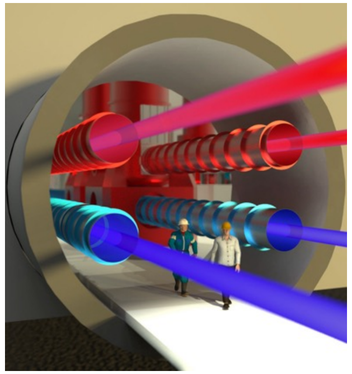
Up to 17 m high super-attenuators

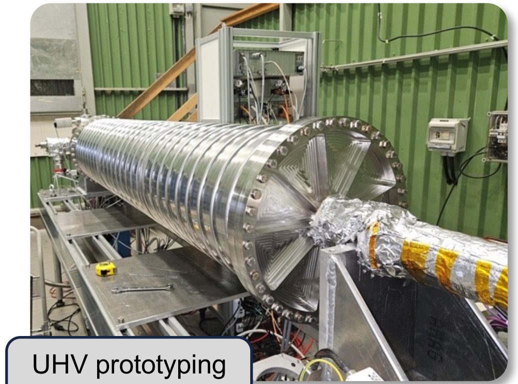
II. VACUUM AND CRYOGENIC INFRASTRUCTRE

Beam pipe vacuum system

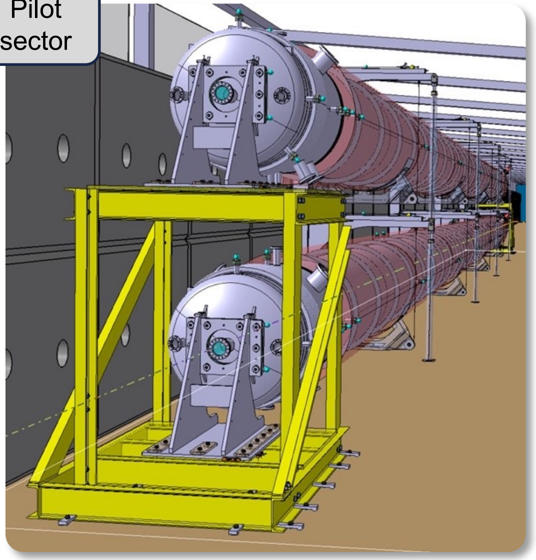
- **10 km long** beam pipes of **1 m diameter**
  - $p_{\mathrm{H_2}} \leq 10^{-8}\,\mathrm{Pa}$, $p_{\mathrm{H_2O,others}} \leq 10^{-9}\,\mathrm{Pa}$
- Development lead by **CERN**
  - Frame: MOA CERN-INFN-NIKHEF
  - Coordinator: Paolo Chiggiato
  - Collaboration: INFN, Nikhef, IFAE, U. of Ghent, U. Antwerp, U. Aachen + industry partners
  - Overview: [2023 Beampipes Workshop]
- Development of a **pilot sector**
  - Installation Q4 2024

Source: https://www.einsteintelescope.nl/en/mediakit/

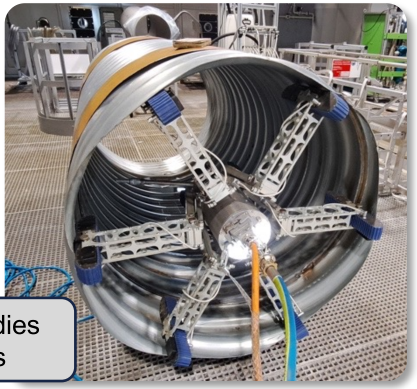




UHV prototyping and testing



Pilot sector

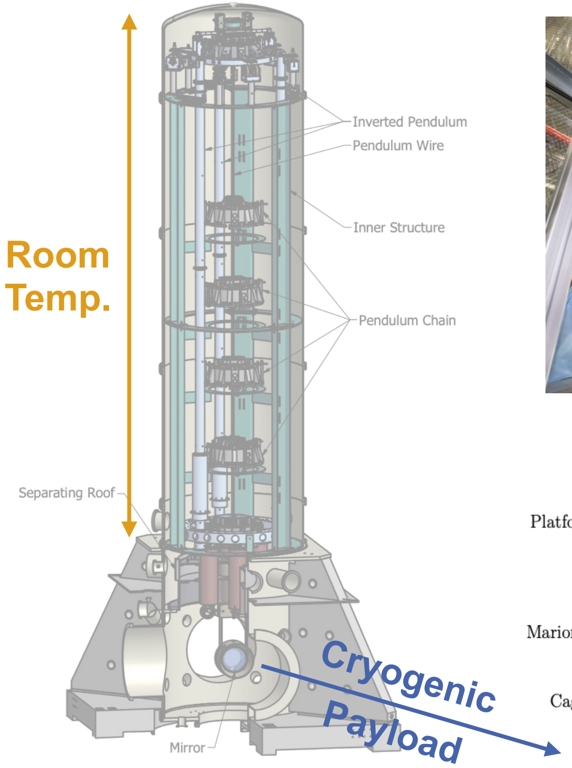


Cleaning studies with robots

Gratitude: Paolo Chiggiato, Carlo Scarcia

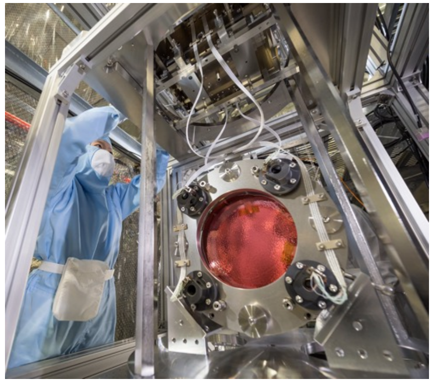
ET-LF TM tower and cryostat layout

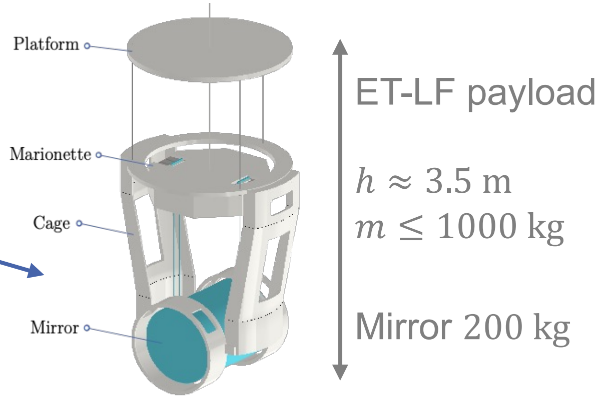
Tower layout



Source: ET Design Report Update (2020)

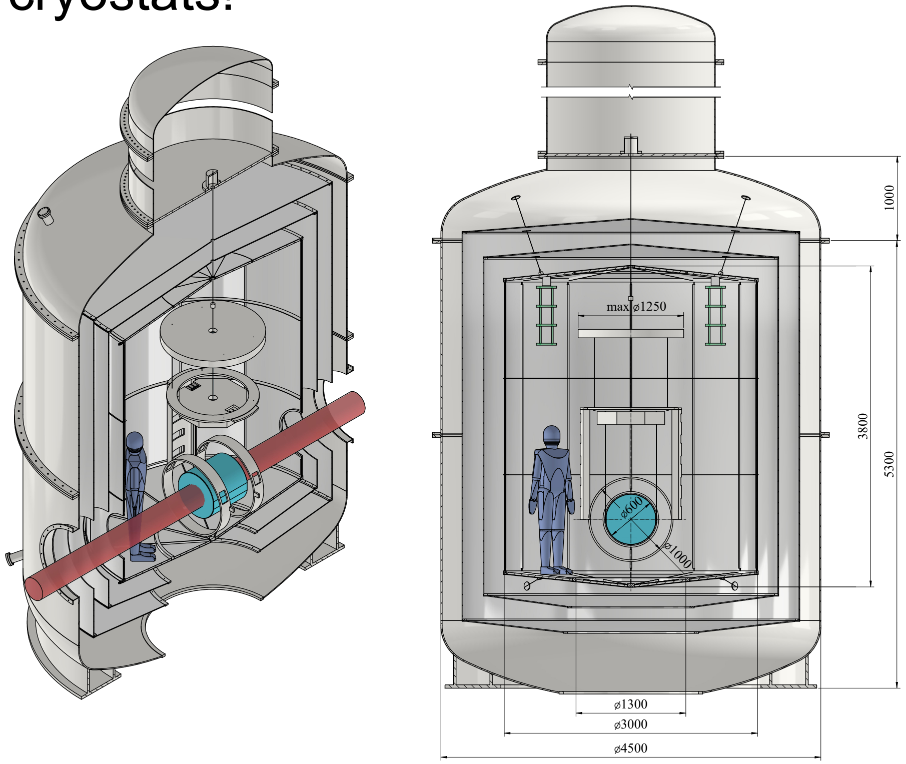
KAGRA mirror (23 kg)
https://www.nao.ac.jp/





Conceptual cryostat layout

- Challenge: **Human access** inside cryostats!



ET-LF cryostat vacuum concept

Poster presentation

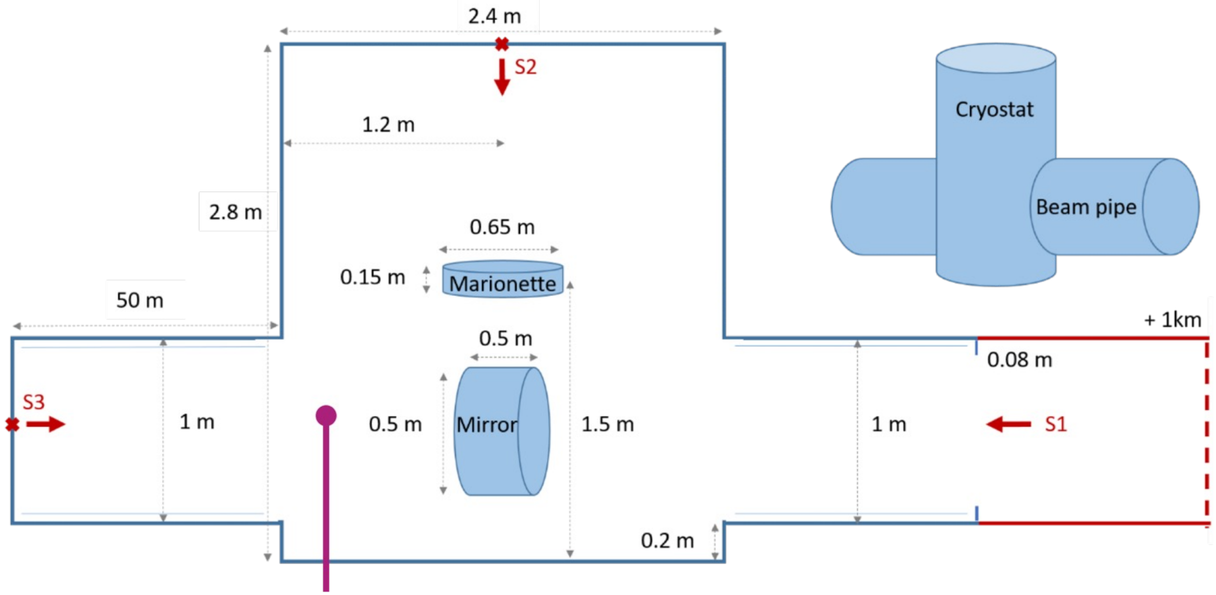
[X. Luo, S. Hanke, Ch. Day: Monte Carlo simulation of the thermal radiation heat load to the cryogenic mirror and vacuum system of the Einstein Telescope]

Warm tower components not bakeable
$p_{\text{warm tower}} \approx 10^2\, p_{\text{cryostat}}$
Flow restriction by adaptive orifice around suspension wire

Adjacent tower at $l \approx 50\,\mathrm{m}$

Very high gas loads of H_2 and H_2O

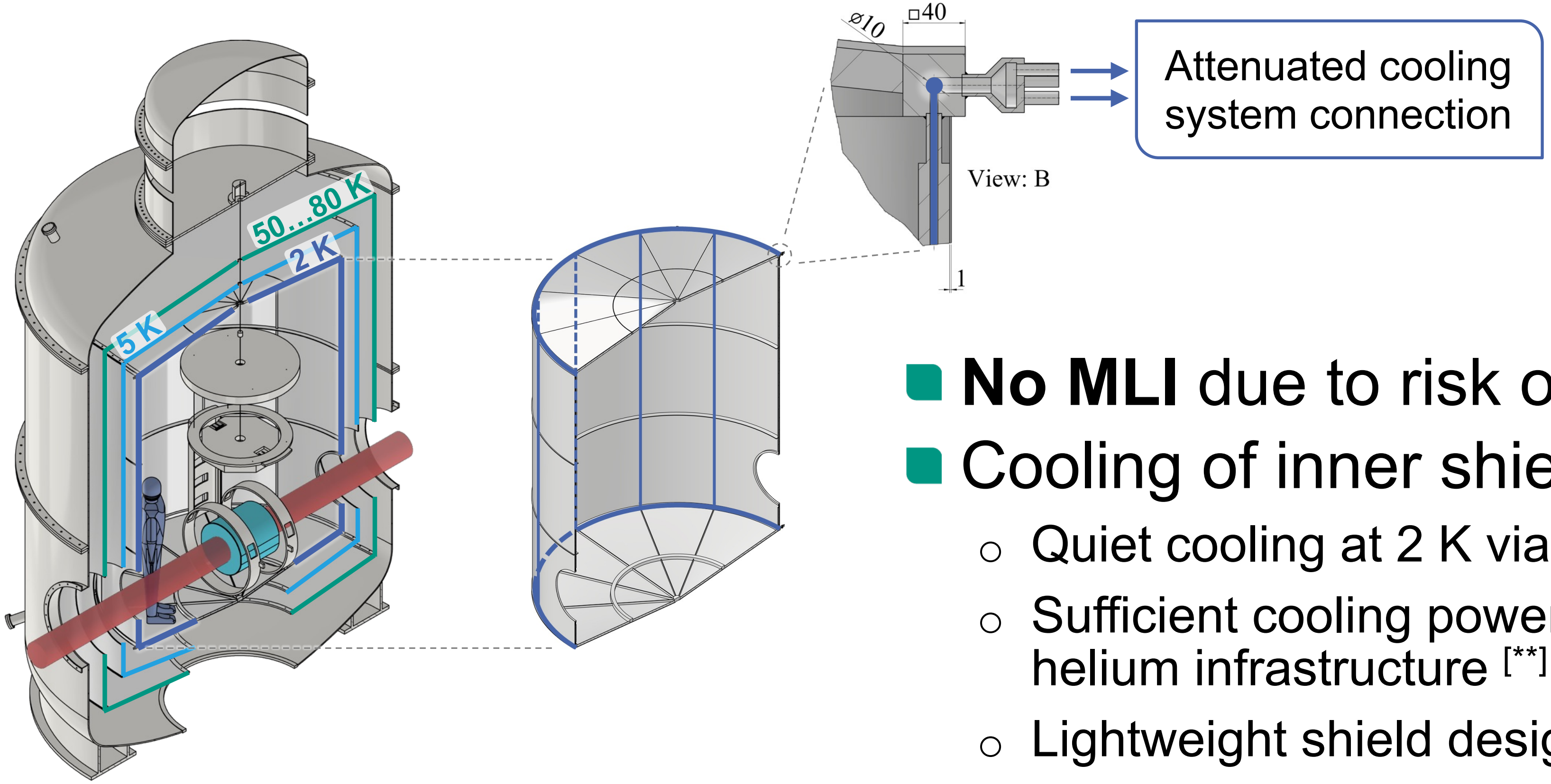
$20\,\mathrm{m}$ cryopump at $80\,\mathrm{K}$ plus $1\,\mathrm{m}$ cryopump at $3.7\,\mathrm{K}$



Separation of the $10\,\mathrm{km}$ beam pipe by $10\,\mathrm{m}$ cryopump at $80\,\mathrm{K}$

Driving design parameter: Water pressure $p_{H_2O} \approx 10^{-12}\,\mathrm{Pa}$ to extend monolayer build-up to $\tau > 1\,\mathrm{a}$

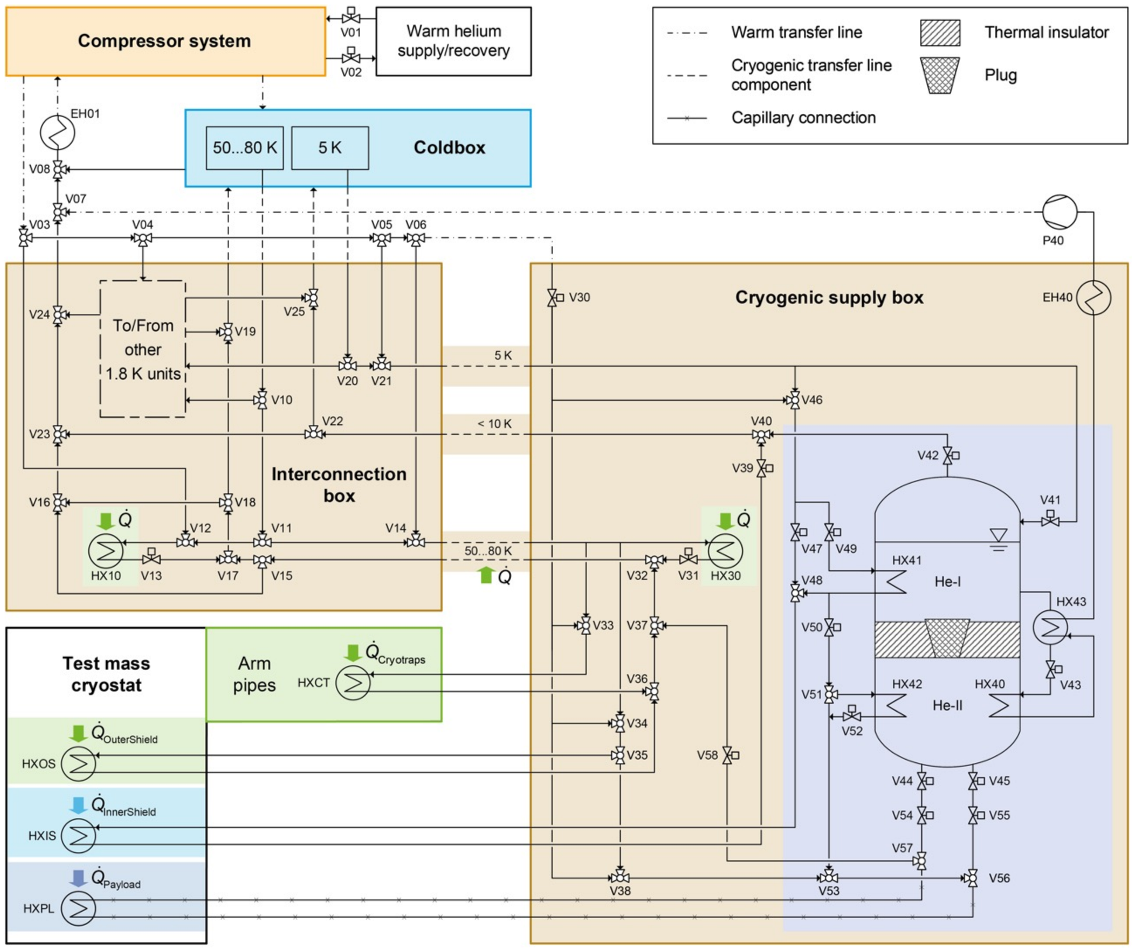
Cryostat thermal shielding concept [*]



- **No MLI** due to risk of pollution
- Cooling of inner shield with **static He-II**
  - Quiet cooling at 2 K via static He-II heat conduction
  - Sufficient cooling power provision by integration in helium infrastructure [**]
  - Lightweight shield design (c. 450 kg)

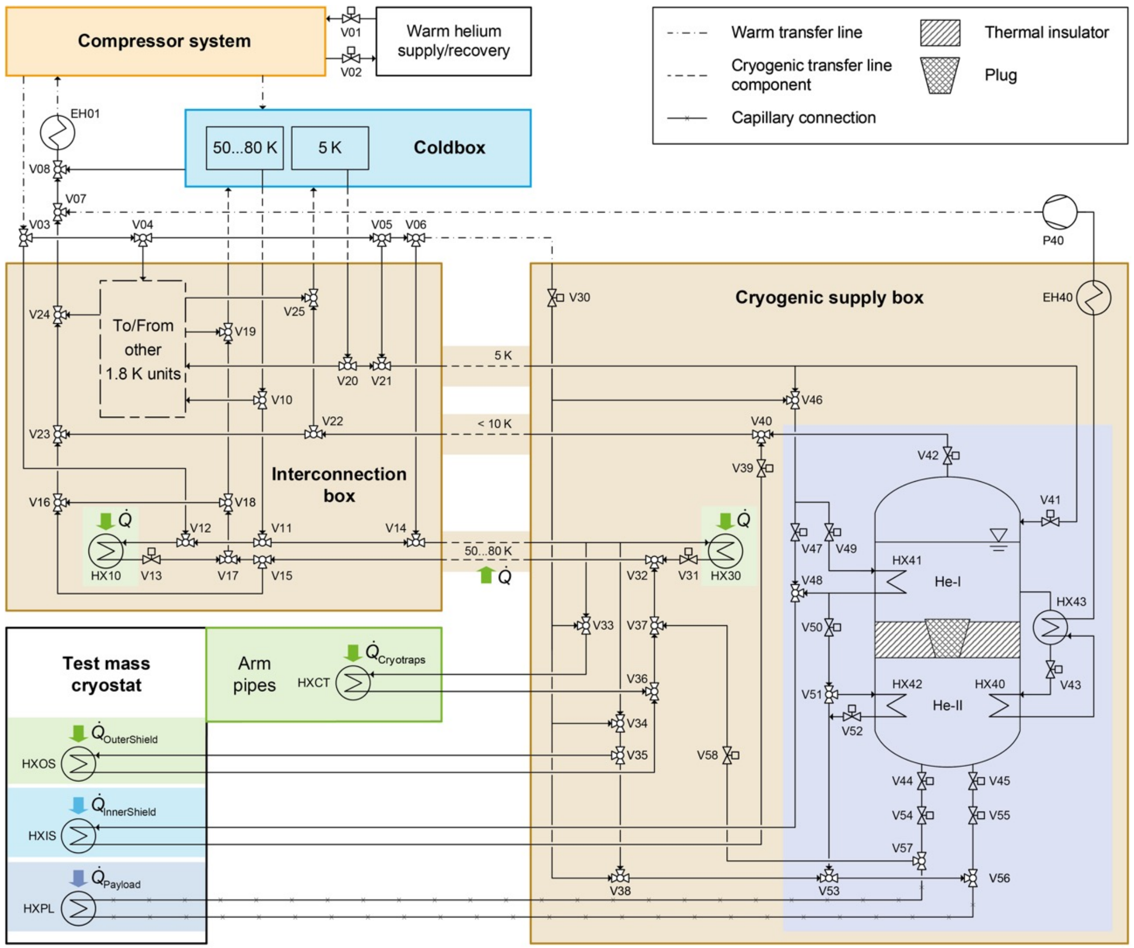
[*] Busch L, Iaquaniello G, Rosier P, Stamm M, Grohmann S, IOP Conf. Ser.: Mater. Sci. Eng. 1301(1), p. 012013, doi: 10.1088/1757-899X/1301/1/012013 (2024)
[**] Busch L and Grohmann S, IOP Conf. Ser.: Mater. Sci. Eng. 1240(1) p. 012095, doi: 10.1088/1757-899x/1240/1/012095 (2022)

Cryogenic infrastructure concept [**]

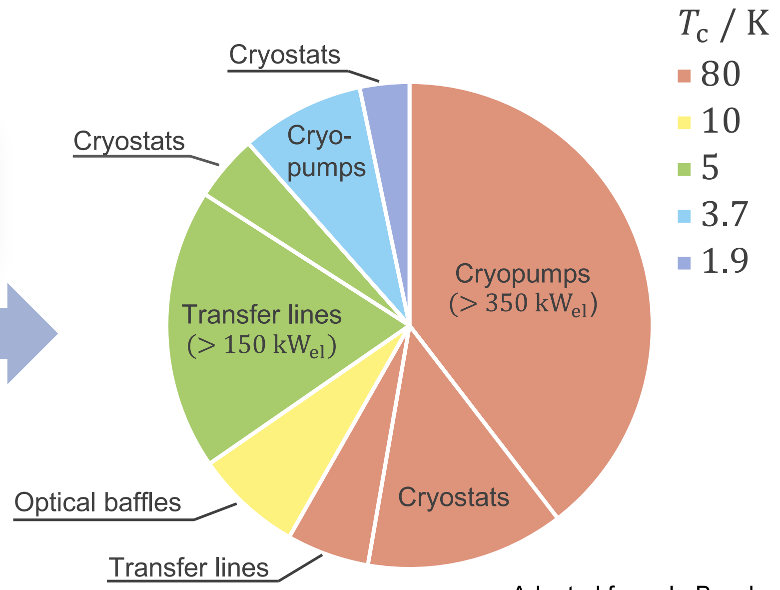


- No underground LN_2 (safety)
- One He refrigerator at each vertex
  - (Remote) surface compressors
  - Underground coldbox
  - Interconnection box to several cryogenic supply boxes (1 for each tower/cryostat)
    - Up to c. 500 m long transfer lines
  - 1-phase cooling for 80 K cryopumps/outer shields
  - 1-phase cooling for 10 K baffles, 5 K inner shields and 3.7 K cryopumps
  - He-II payload cooling/inner shield

Cryogenic infrastructure concept [**]



Vertex-cryoplant input power approximation



Adapted from: L. Busch, “Helium-based cryogenic infra-structure and payload cooling concepts for the Einstein Telescope”, Dissertation (in preparation)

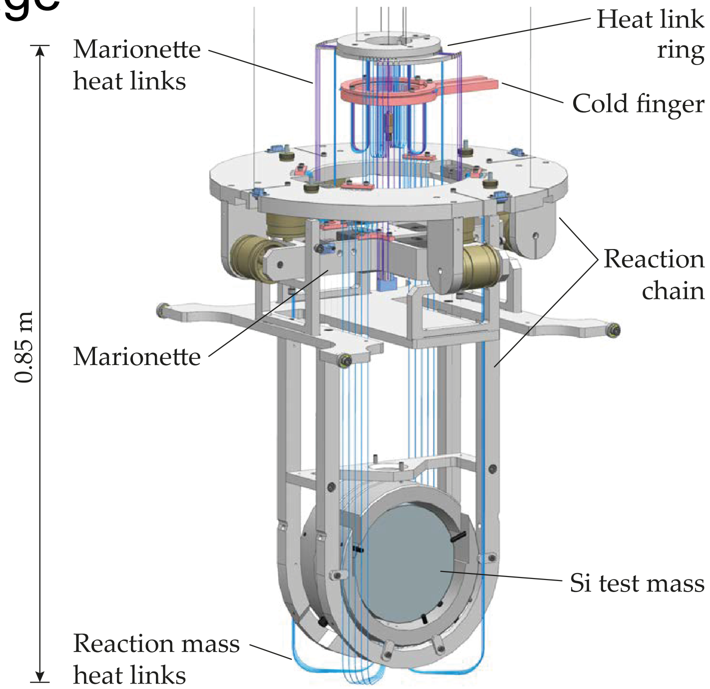
- ET-wide steady-state: $\sum \sim \mathbf{3 \times 1\ MW_{el}}$

- **Additional cryopumps** presently under investigation

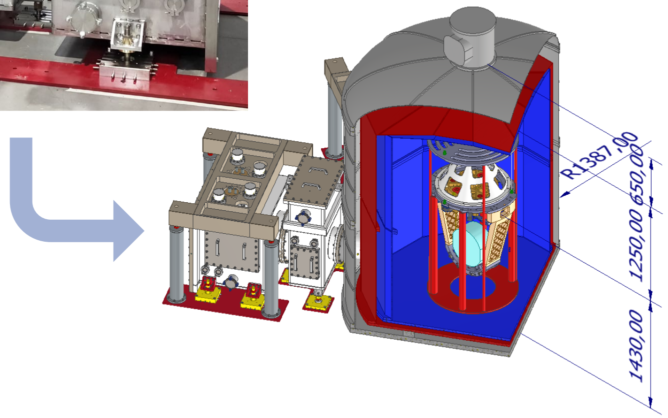
III. CRYOGENIC DETECTOR COOLING DEVELOPMENTS

Payload cooling R&D using cryocoolers

- ETpathfinder cryogenic payload
  - 2.3 kg mirror
  - **Sorption cooler** with multi-stage pre-cooling
  - „Jelly-fish“ heat link design with 32 Al6N wires of ∅ 0.15 mm



- Prototype devt. at ARC Rome
  - 75 % scale **cryogenic payload** and **cryostat** development
  - Cooling by **PT cryocoolers** (KAGRA concept)



Payload cooling R&D using thermal radiation

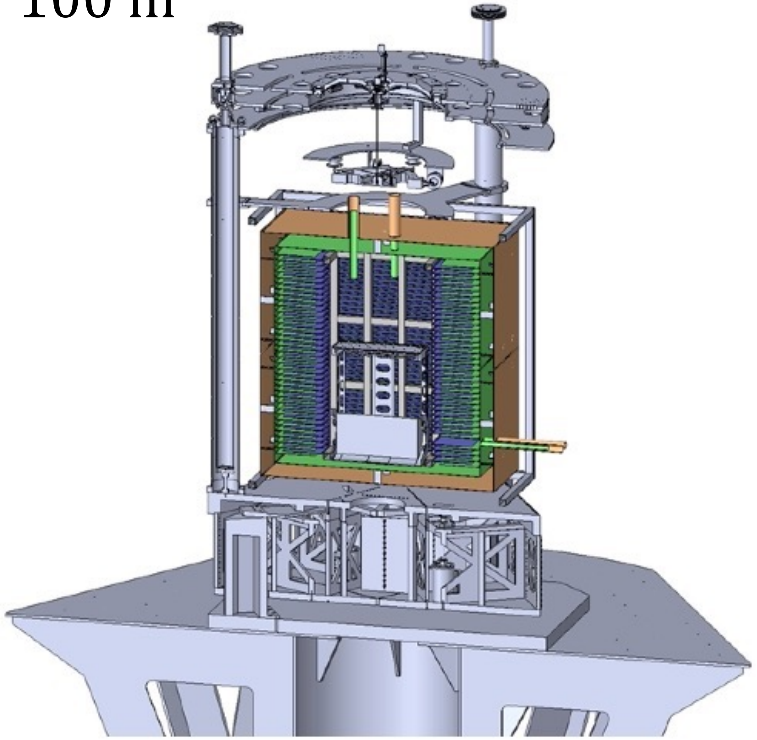
- Radiation cooling studies in E-TEST
  - **Challenge:** T^4 dependence of the heat flux $\dot{q}_{\mathrm{rad}}$, i.e. $\dot{q}_{\mathrm{rad},T<100\mathrm{K}} \rightarrow 0$
  - **Concept:** Increase of payload surface from $\approx 2\ \mathrm{m}^2$ to $\approx 100\ \mathrm{m}^2$
  - **Potential issues:**
    - Cool-down time and final payload temperature
    - Suspension and noise contribution of the enhanced surface
    - XHV compatibility
    - Payload integration and accessibility
    - Payload balancing and control


E–TEST prototype

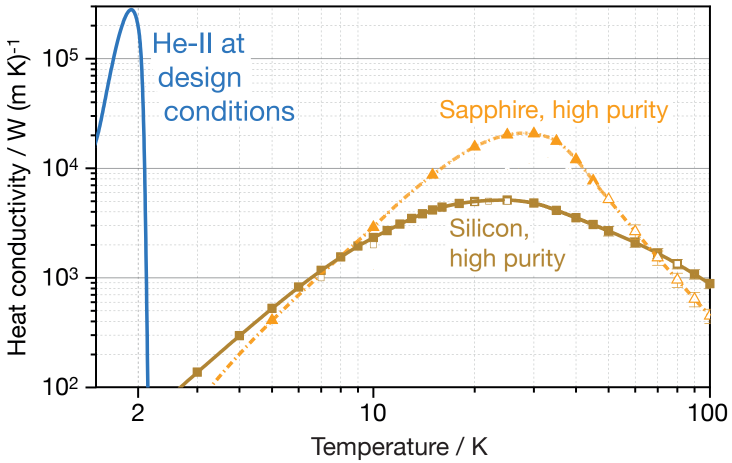
DESIGN REPORT

The E–TEST Prototype Team*

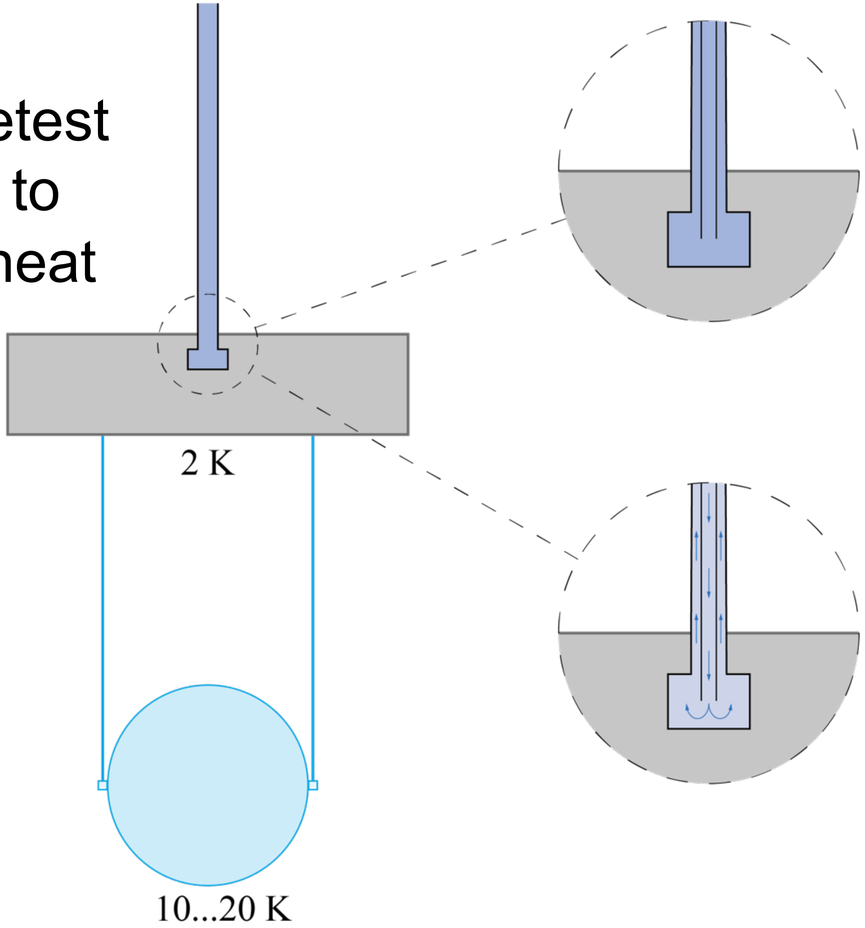
*Nikhef, Maastricht University, Katholieke Universiteit Leuven, Université Catholique de Louvain, Hasselt University, Vrije Universiteit Brussel, Fraunhofer Institute for Laser Technology, RWTH Aachen, Liege Université.



Payload cooling with superfluid helium (He-II)



He-II:
The quietest medium to absorb heat



Steady-state:
Static He-II

Cool-down:
He-I counter-flow

Theoretical proof of He-II concept

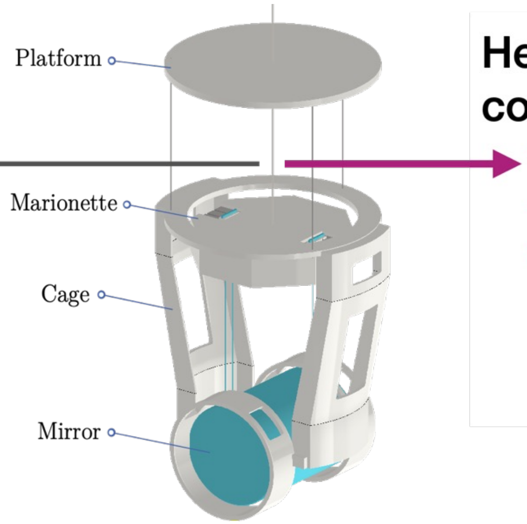
Baseline design of ET-LF payload

- First consistent **thermal**, **mechanical** and **STN** modeling
- Study of two cooling options

Reference: Koroveshi X, Busch L, Majorana E, Puppo P, Rapagnani P, Ricci F, Ruggi P, Grohmann S, Phys.Rev. D (2023), DOI: 10.1103/PhysRevD.108.123009

Conventional concept

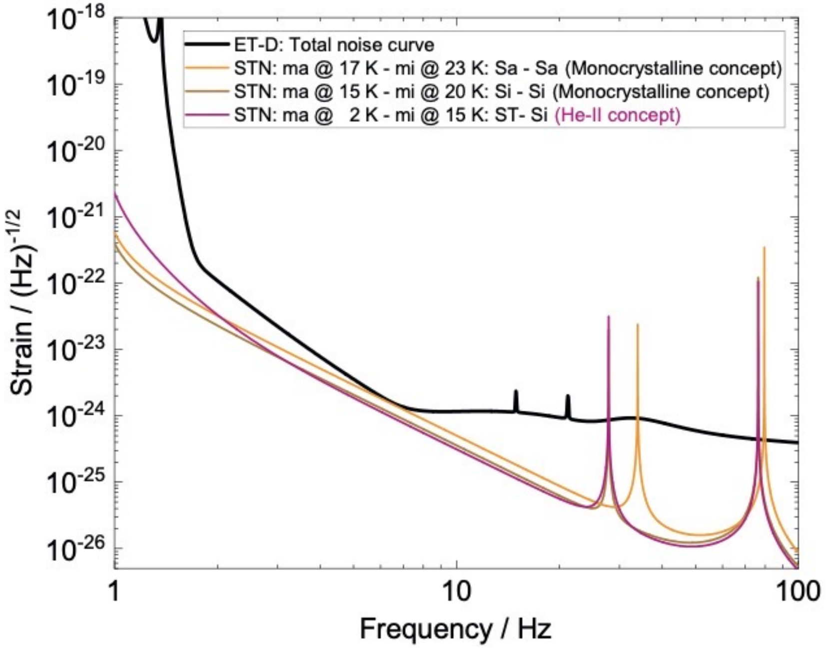
- Monocrystalline rod
- 6N Al heat links attached to cage and platform



He-II concept

Titanium tube filled with static He-II

Results of STN modeling



- 2 K Ti tube is feasible, but how does the He-II contribute to the STN?
- ➢ **Experimental investigation** needed!

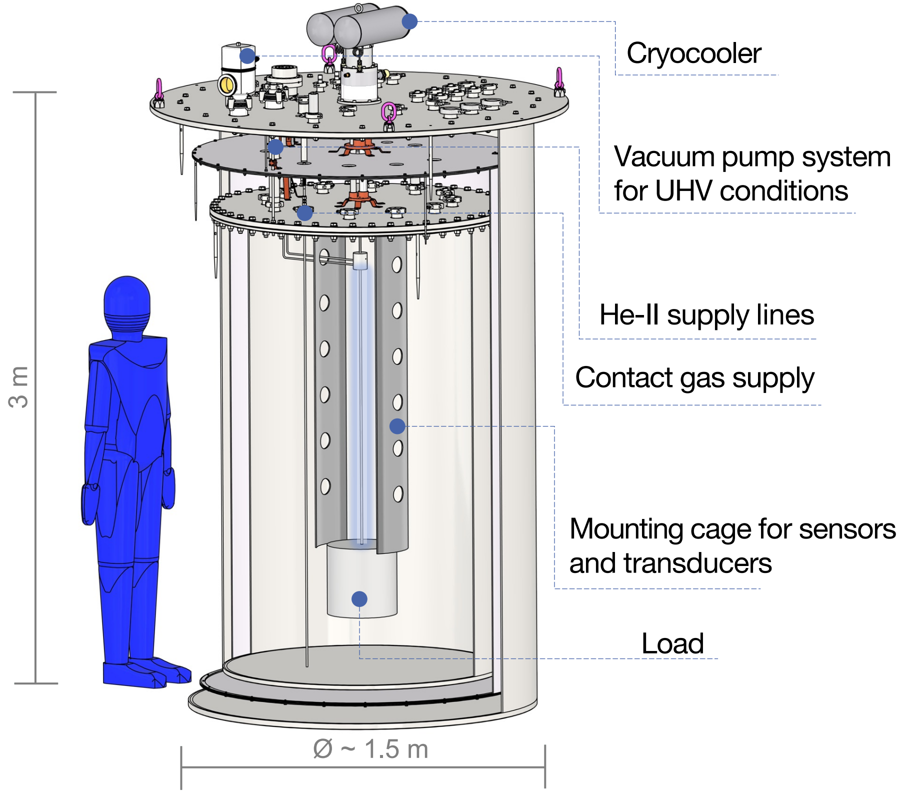
ERC AdG GRAVITHELIUM

Funded by the European Union

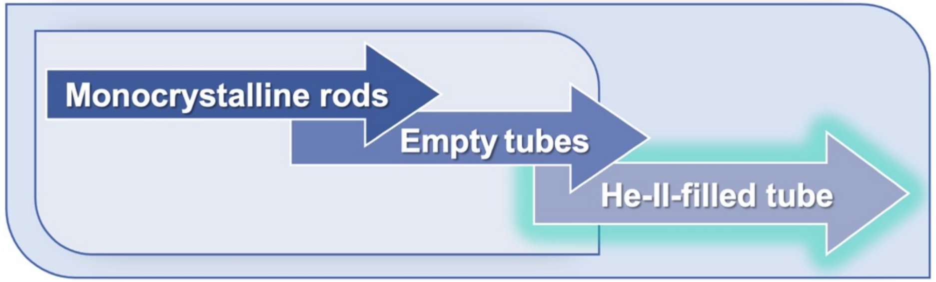
European Research Council
Established by the European Commission

GRAVITHELIUM
Gravitational Wave Detectors
Cooled with Superfluid **Helium**

Objective: **Proof of** He-II payload cooling **concept**



- Test facility for **full-size suspension fibers** and **tubes**
- Low-noise **lab-scale He-II supply** system
- Investigation of **loss contributions** in suspensions by ring-down method, so-called Q **measurements**
  - **Poster presentation:** Xhesika Koroveshi et al.: Status of cryostat design for cryogenic payload suspension studies for the Einstein Telescope




Thank you for your attention!