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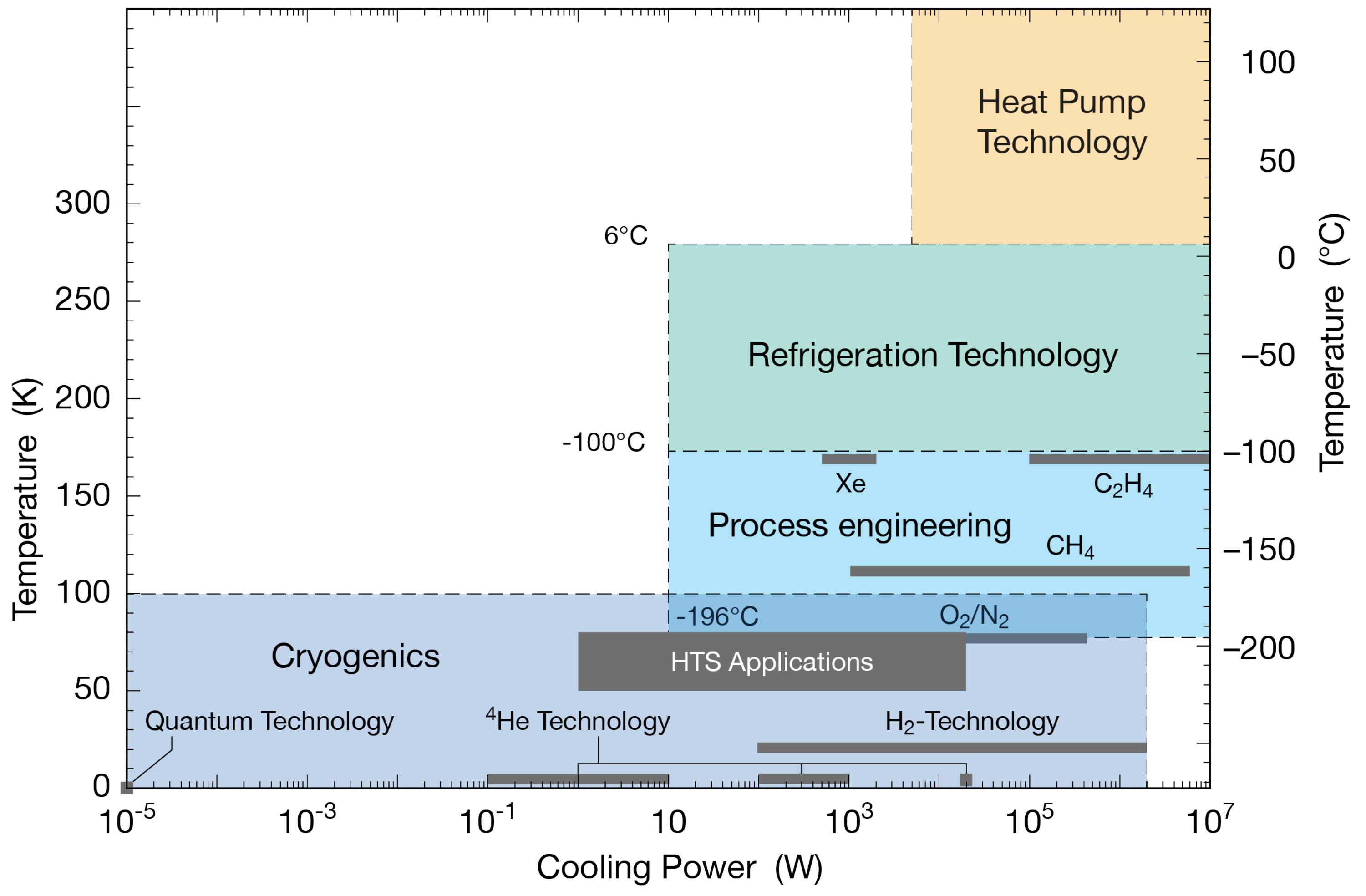
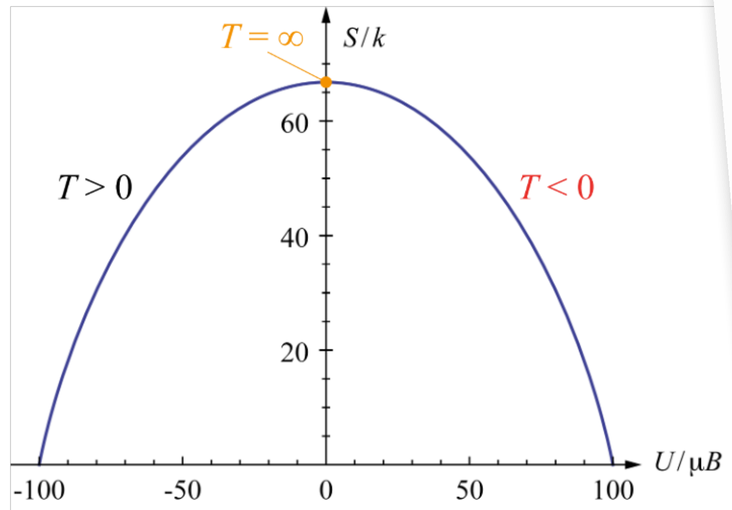
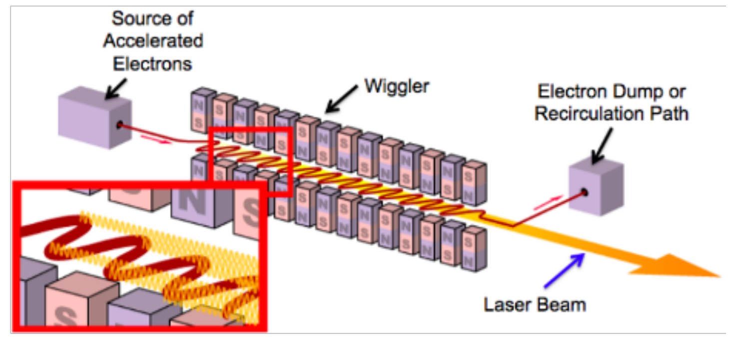
Cryogenics in Particle, Astroparticle and Nuclear Physics

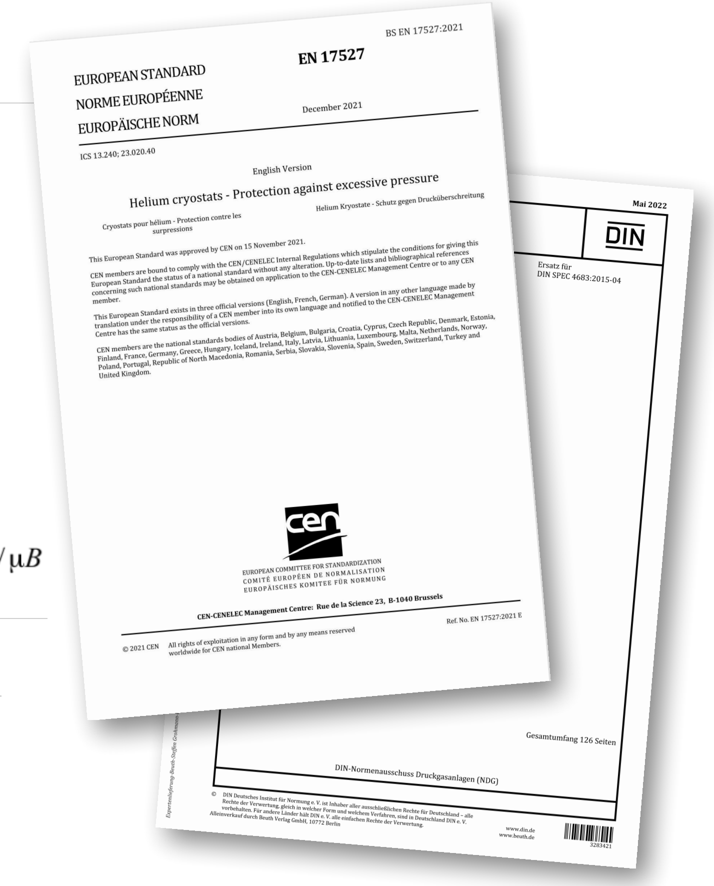
2nd Joint ECFA-NuPECC-APPEC Symposium, JENAS 2022, Madrid, 3-6 May 2022

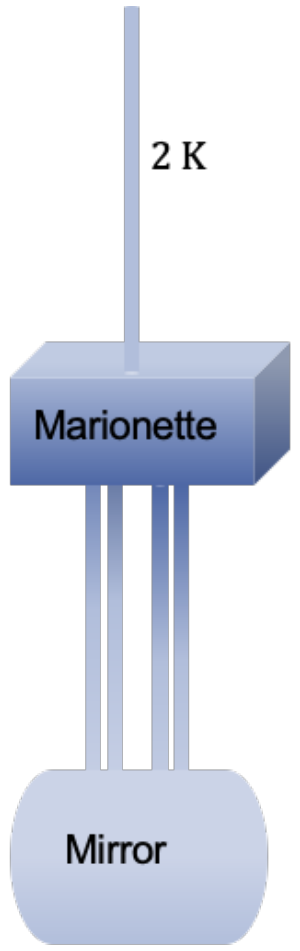
Steffen Grohmann

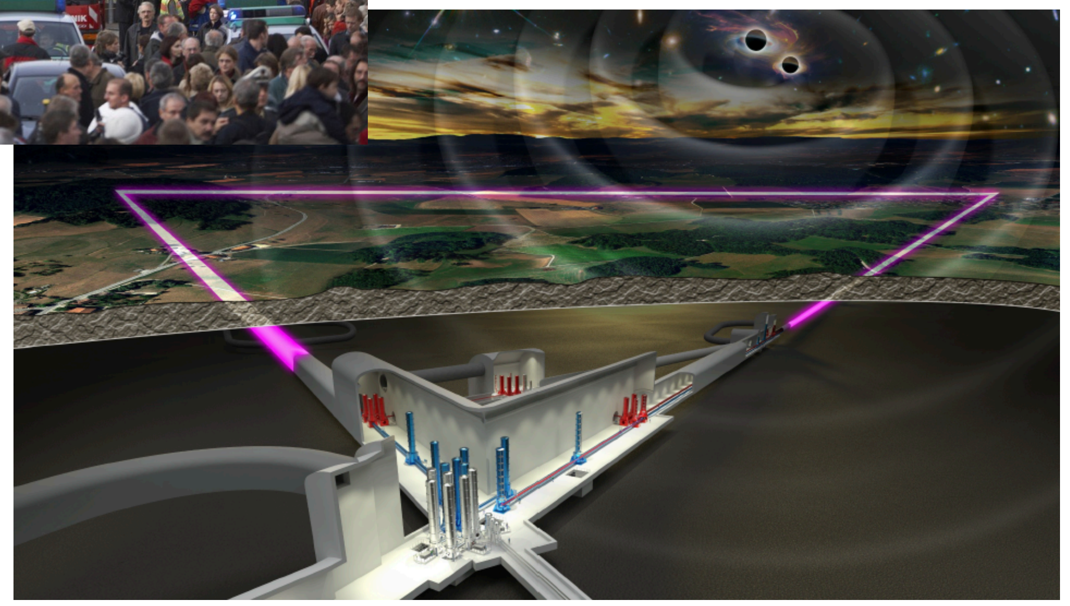








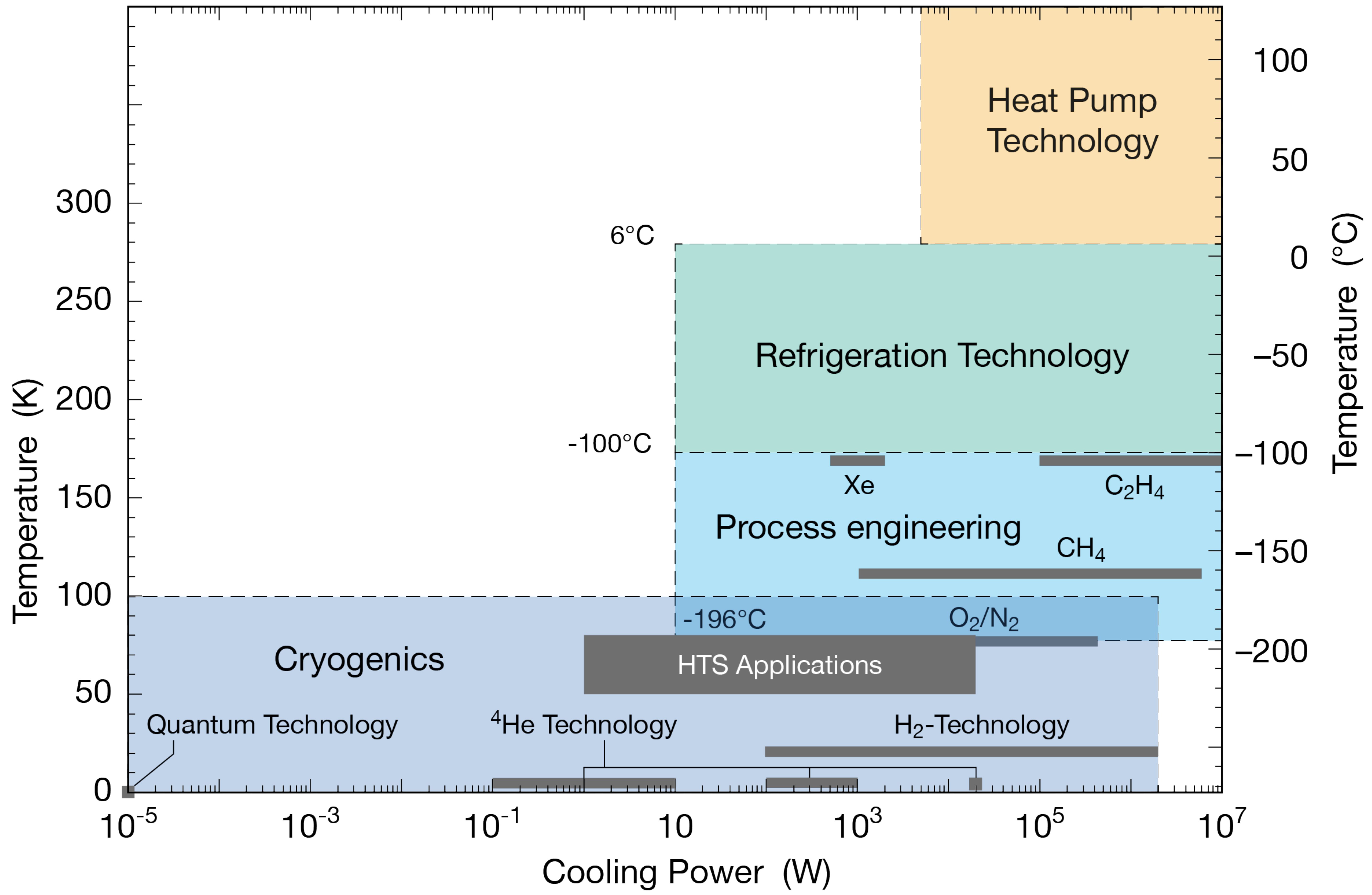




Outline

- Introduction
- Temperature concepts in physics
- Cryogenic cooling technology
- Cryogenic system developments
- Synergies

Introduction – application spectrum



- Refrigeration and cryogenics comprises all „left-handed“ (↺) thermodynamic cycles and processes

Cryogenics in Particle, Astroparticle and Nuclear Physics

TEMPERATURE CONCEPTS IN PHYSICS

Temperature scales

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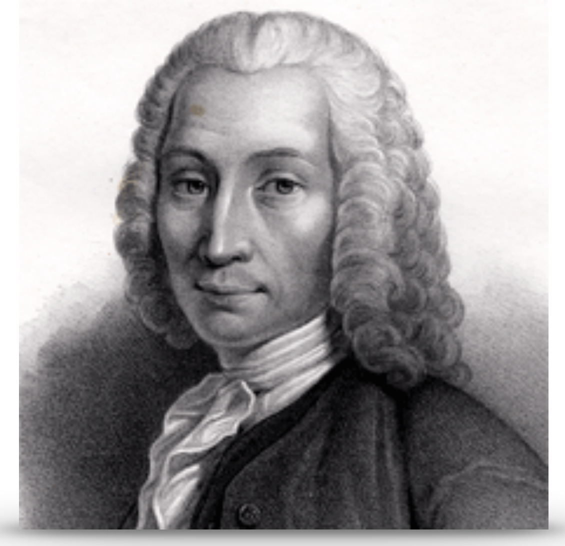
Celsius scale (empiric)

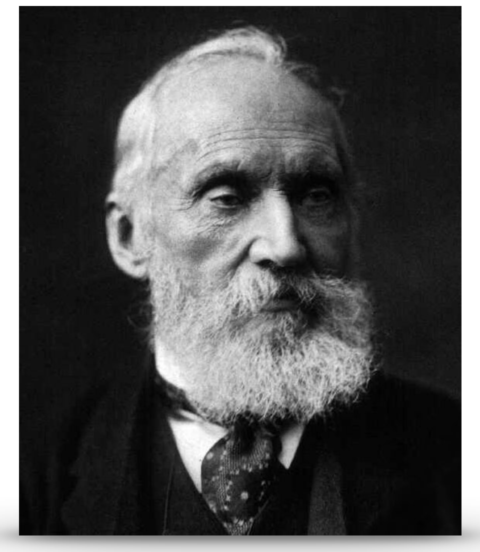
- Take 2 convenient temps. (e.g. T_{tr} and T_{nb} of water)
- Assign arbitrary numbers (e.g. 0 and 100)



Anders Celsius
Source: https://www.uu.se/

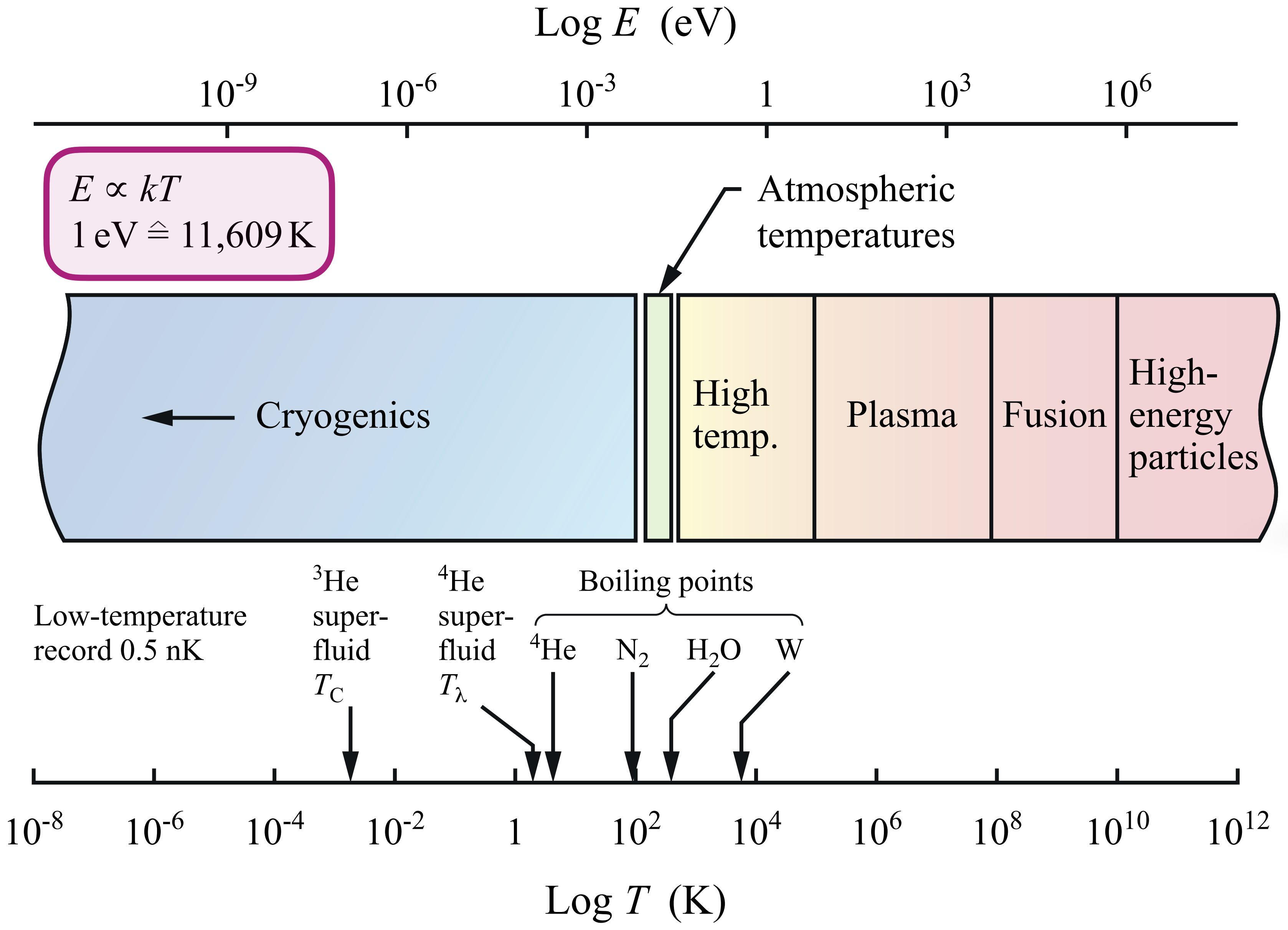
Kelvin scale (semi-empiric)

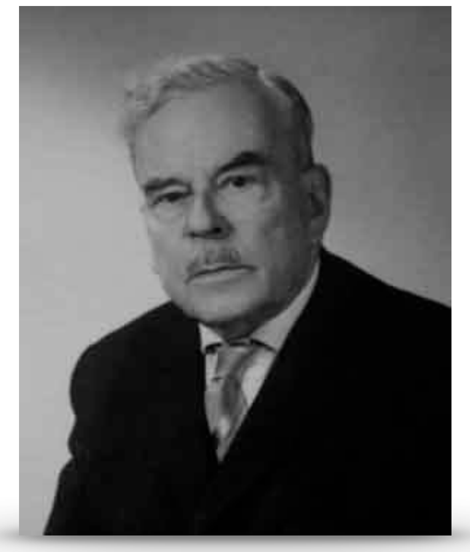
- Take the pressure of a gas at constant V
- Extrapolate to low temperatures (ideal gas law)
- Pressure goes to zero at -273.15 °C = 0 K



Sir William Thomson
Source: https://en.wikipedia.org/

Logarithmic scale





Rudolf Plank
Source: ITTK Library

262 R. Plank: Die logarithmische Temperaturskala Forschung 4. Bd. / Heft 6

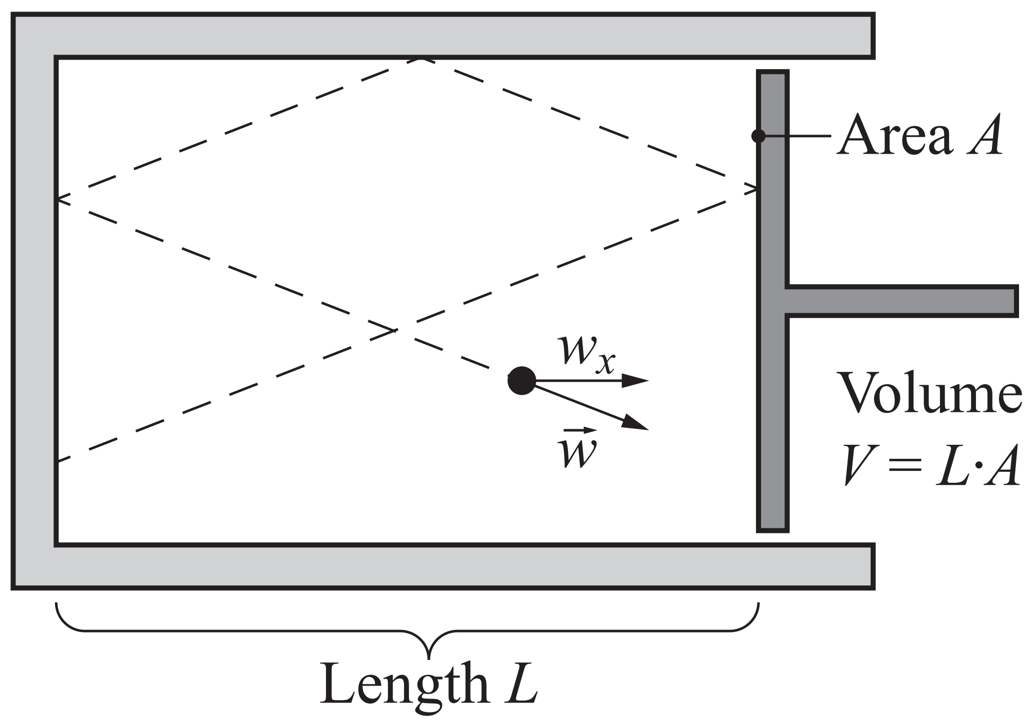
Die logarithmische Temperaturskala

Von R. PLANK VDI, Karlsruhe

1. Die Annäherung an den absoluten Nullpunkt der Temperaturskala — 2. Die logarithmische Temperaturskala — 3. Kalorische Zustandsgrößen für ideale Gase — 4. Der Carnotsche Kreisprozeß — 5. Allgemeine Ausdrücke für Entropie, Enthalpie und spezifische Wärme — 6. Das Sättigungsgebiet — 7. Zusammenfassung.

Physical interpretations of temperature (1/2)

Classical interpretation from kinetic theory



(1) Start from cylinder with just one gas molecule

- Velocity $\vec{w}$, horizontal component w_x
- Elastic collisions with smooth walls

(2) Relate pressure with kinetic energy

- $\overline{p} = \frac{\overline{F}_{x,Piston}}{A} = \frac{-\overline{F}_{x,Molecule}}{A} = -\frac{m\frac{\Delta w_x}{\Delta\tau}}{A} = \ldots = \frac{m\,\overline{w_x^2}}{V}$

> Newton's 3rd law: $\vec{F}_{A\to B} = -\vec{F}_{B\to A}$
> Newton's 2nd law: $\vec{F} = m\,\vec{a}$

(3) Large number N of molecules with random positions and directions

- Large N yields continuous p and $\sum_{i=1}^{n} w_{i,x}^2 = N\,\overline{w_x^2}$ → $p\,V = N\,m\,\overline{w_x^2}$

(4) Applying the ideal gas law $p\,V = N\,k\,T$

- $k\,T = m\,\overline{w_x^2}$ or $\frac{1}{2}k\,T = \overline{\frac{1}{2}m\,w_x^2}$ ☞ $E_{trans} = \overline{\frac{1}{2}m\,w^2} = \frac{1}{2}m\left(\overline{w_x^2} + \overline{w_y^2} + \overline{w_z^2}\right) = \frac{3}{2}k\,T$

Two issues:

- Particles considered as non-interacting point masses
- Both T and p related to kinetic energy

Physical interpretations of temperature (2/2)

Theoretical definition from statistical mechanics

- $\frac{1}{T} \equiv \left(\frac{\partial S}{\partial U} \right)_{V,N}$ with $S = S(U, V, N)$

  ▷ *Intensive state properties* from partial derivatives of entropy in terms of its *extensive state variables*

- Possibility of **negative absolute temperatures** in systems of limited total energy
  - First experiments and concept by E.M. Purcell, R.V. Pound (1951)
  - Proof that negative temperatures are real by P. Hakonen, O.V. Lounasmaa (1994)
  - Stable negative temperatures for motional degrees of freedom by S. Braun et al. (2013)

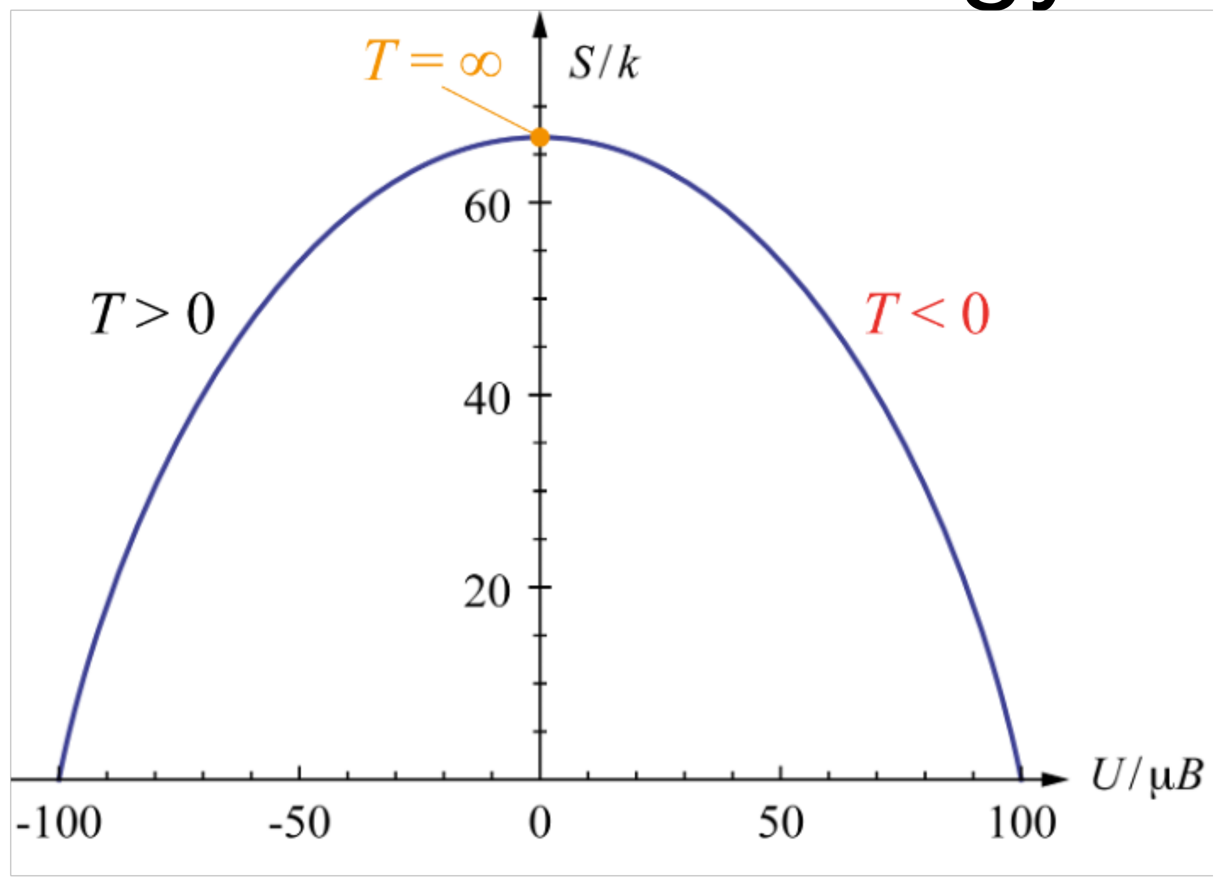

ScienceNews
MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

Hottest temperature ever measured is a negative one

Ultracold gas sets record on the kelvin scale

BY ANDREW GRANT 10:38PM, JANUARY 4, 2013

Magazine issue: February 9, 2013



Understanding temperature

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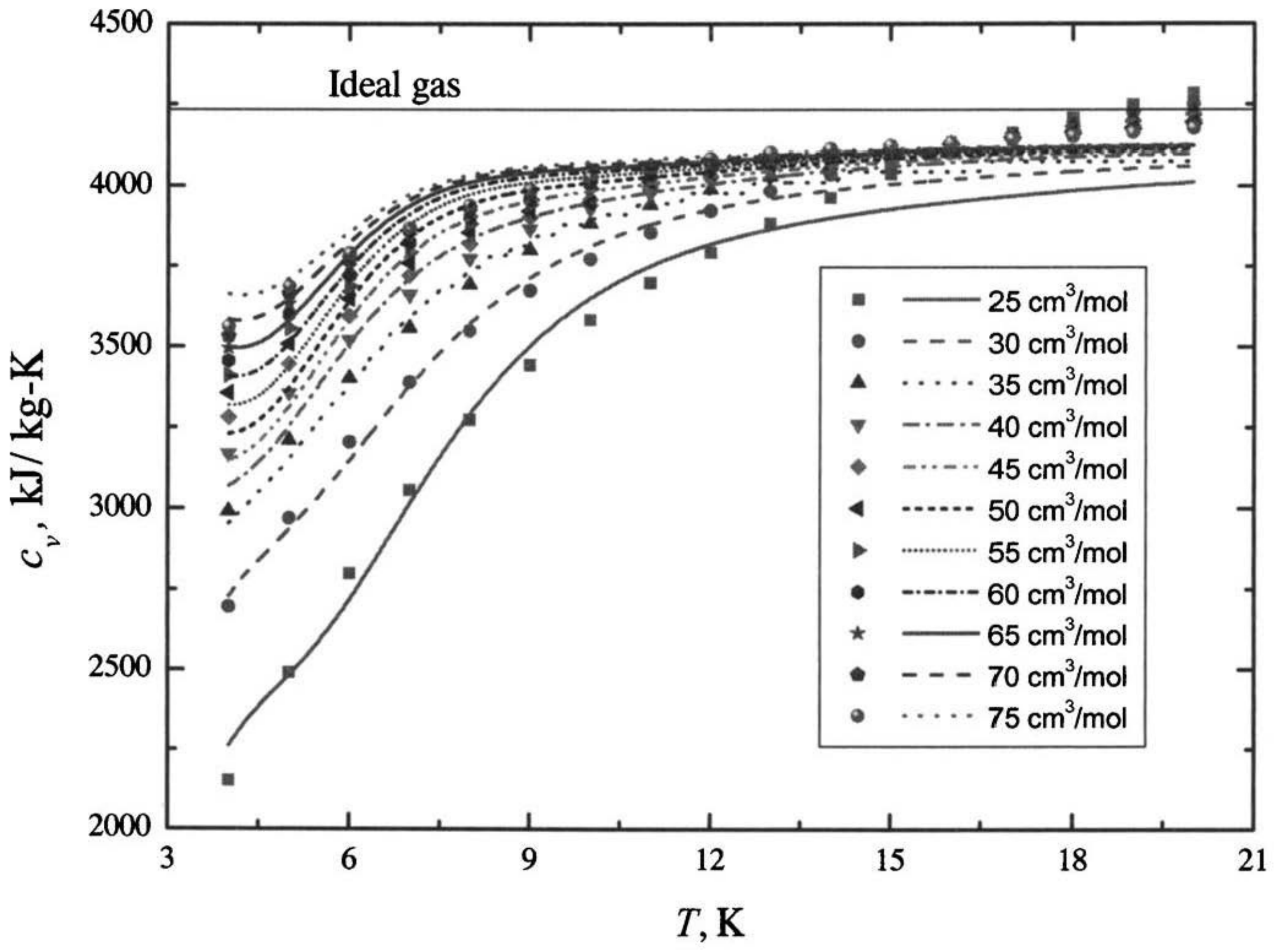
- The classical relation of T with kinetic energy and the **Equipartition Theorem** $\overline{U} = N_\mathrm{A} f \frac{1}{2} kT$ cannot explain negative absolute temperatures!
- Moreover, kinetic theory yields $\overline{C}_\mathrm{v} = \frac{\partial \overline{U}}{\partial T} = \mathrm{const.}$, which is incompatible with the **Third Law of Thermodynamics** requiring $\overline{C}_\mathrm{v} \to 0$ at $T \to 0$
  - Specific heat of ^{3}He in the gas region



Source: Huang, Y. et al.: **Debye equation of state** for fluid helium-3 (2006), https://doi.org/10.1063/1.2217010

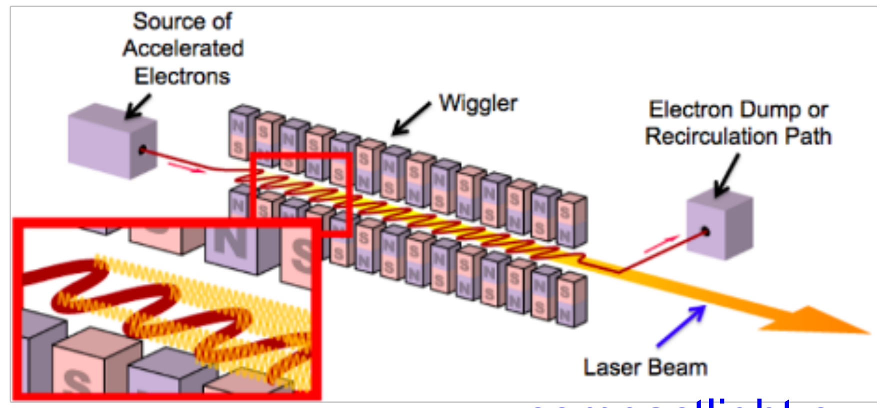
- $\overline{C}_\mathrm{v}$ starts falling below $\frac{3}{2}\overline{R}$ at $T \approx 20\,\mathrm{K}$
- This is **4 orders of magnitude** above the lambda point of ^{3}He at $T_\lambda = 2.6\,\mathrm{mK}$, i.e. **no quantum effects!**

Particles move in **particle-wave functions** (not in straight lines), even in an ideal gas!

Cryogenics in Particle, Astroparticle and Nuclear Physics

CRYOGENIC COOLING TECHNOLOGY

Cooling study for Compact



www.compactlight.eu

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- Conceptual design study for **next-generation hard X-ray FEL facility**
- Beamline consisting of **16 cryomodules** containing sc. magnets
- Cryogenic cooling requirements: 3500 W @ 77 K plus 70 W @ 4.2 K

- **Option A – Multiple cryocoolers**
  - Largest cryocooler: 2.7 W @ 4.2 K (PT425, Cryomech)

- **Option B – LHe plant**
  - Smallest cryoplant: 100 W @ 4.2 K (LR70, Linde Kryotechnik)

www.cryomech.com

Not *„cryogen-free"*

Not *„mechanical cooling"*

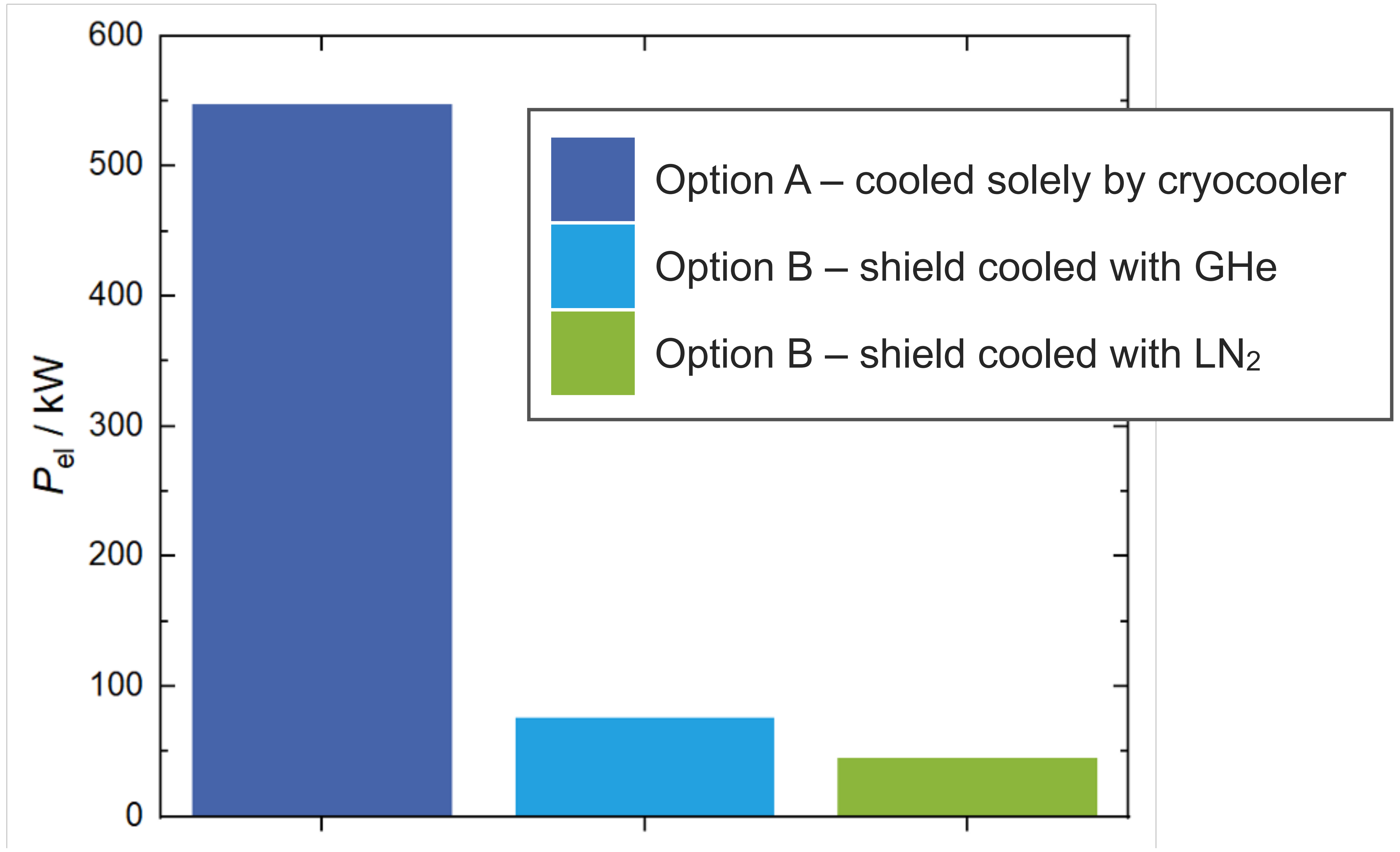
The **working fluid** is the **key player** in any thermodynamic process !!

www.linde-kryotechnik.ch

Compact cooling system comparison

- **Option A:**
  - At least 3 cryocoolers (2 W @ 4.2 K) needed per cryomodule
  - **48 cryocoolers** per beamline
  - **Investment** cost of about **2.4 M€**
- **Option B:**
  - **Smallest LHe-plant** by Linde (LR70) sufficient
  - Cooling of shield with LN_2 or GHe
  - **Investment** cost of about **2.1 M€**

- **Power consumption**

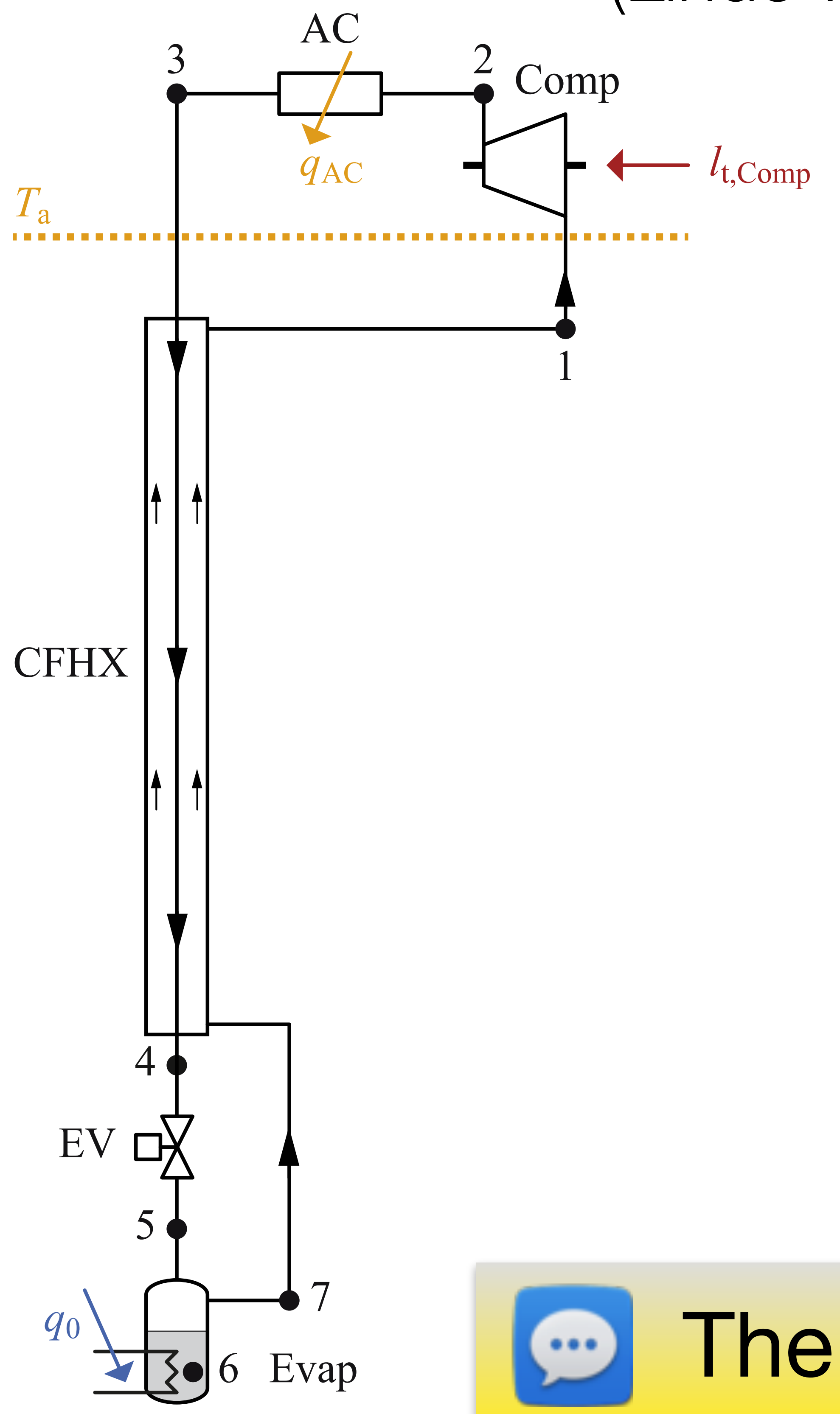


Investment cost almost identical, **power consumption/operating cost** is **crucial!**

Cryogenic development potentials

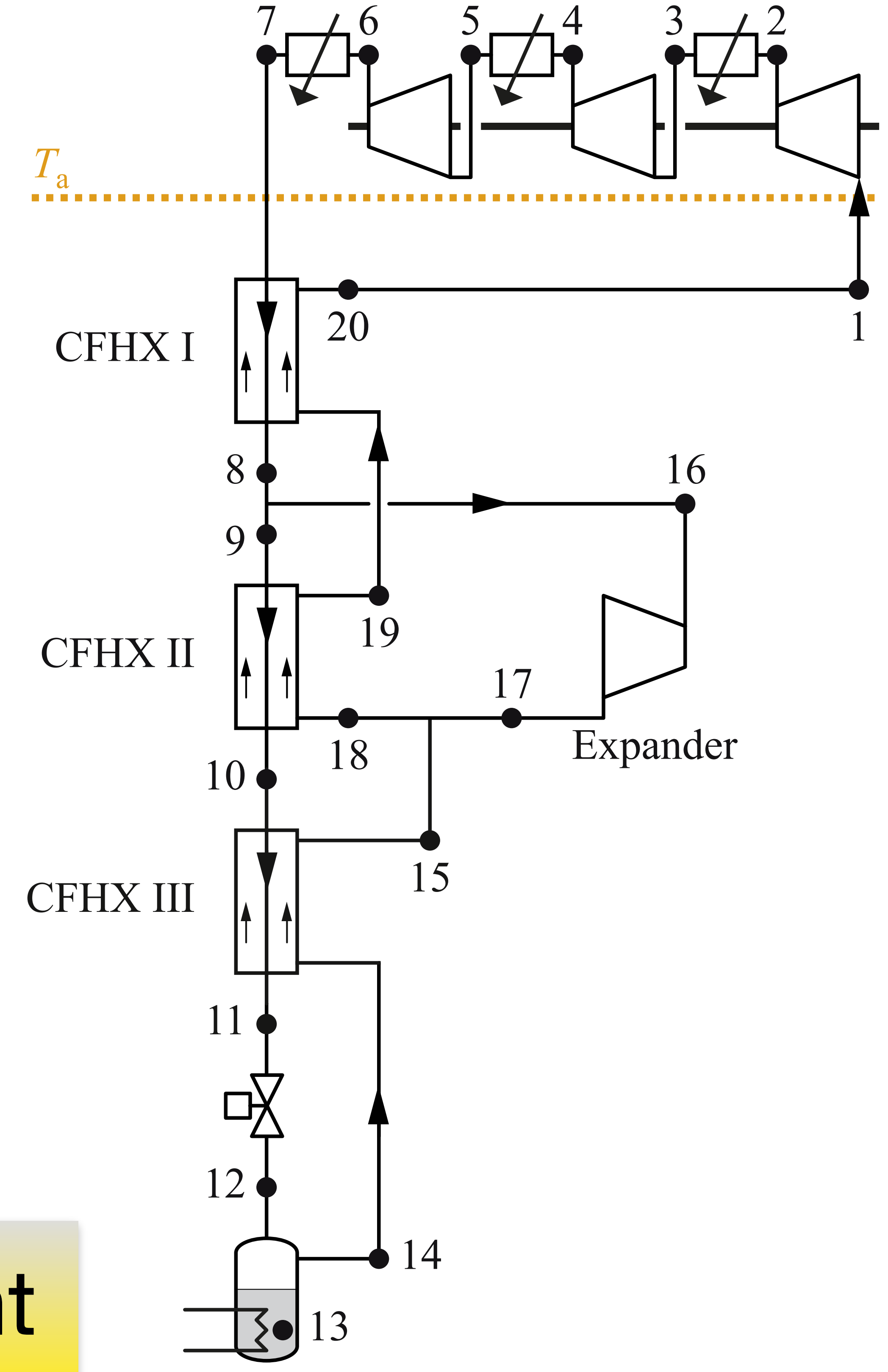
Simplest cryogenic cycle

(Linde-Hampson cycle)



Improved cryogenic cycle

(Claude cycle)



Options for efficiency increase

Higher efficiency by using **refrigerant mixtures** (MRC)	Higher efficiency by **increased system complexity**
„Molecular Engineering" Negligible cost Scalable	Cold expander Number of HX ↑ Control ↑ Investment cost ↑

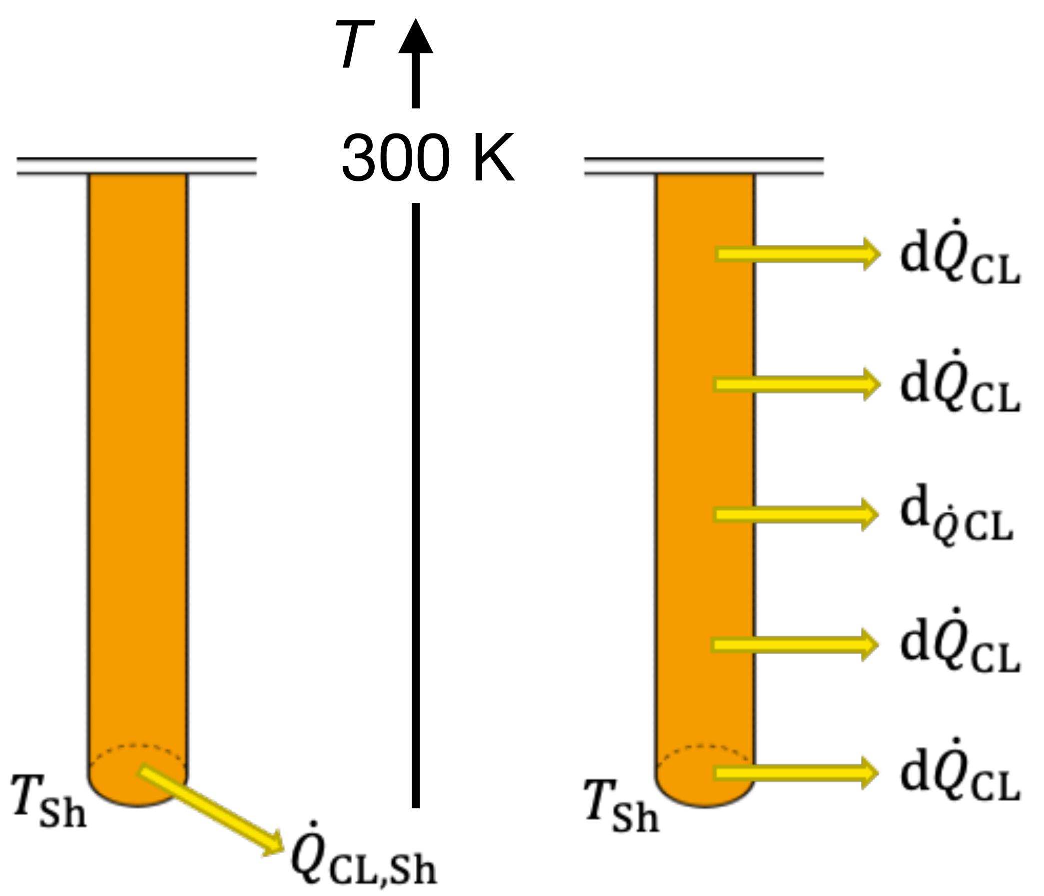
The only path for a **substantial** technology improvement

Cryogenics in Particle, Astroparticle and Nuclear Physics

CRYOGENIC SYSTEM DEVELOPMENTS

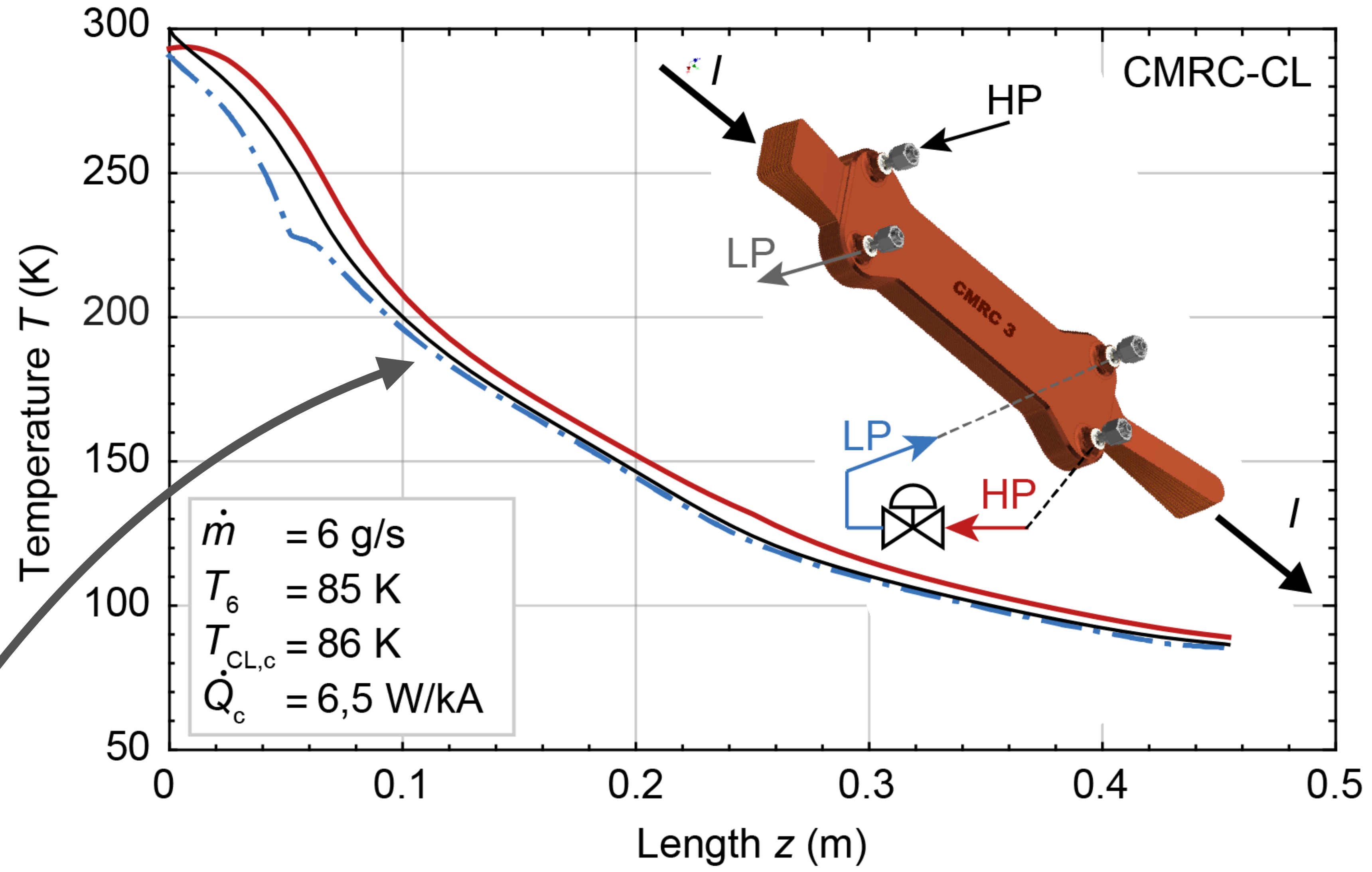
Current lead development for sc. applications

- Micro-structured current leads cooled with cryogenic mixed-refrigerant cycles (CMRC-MSCL)



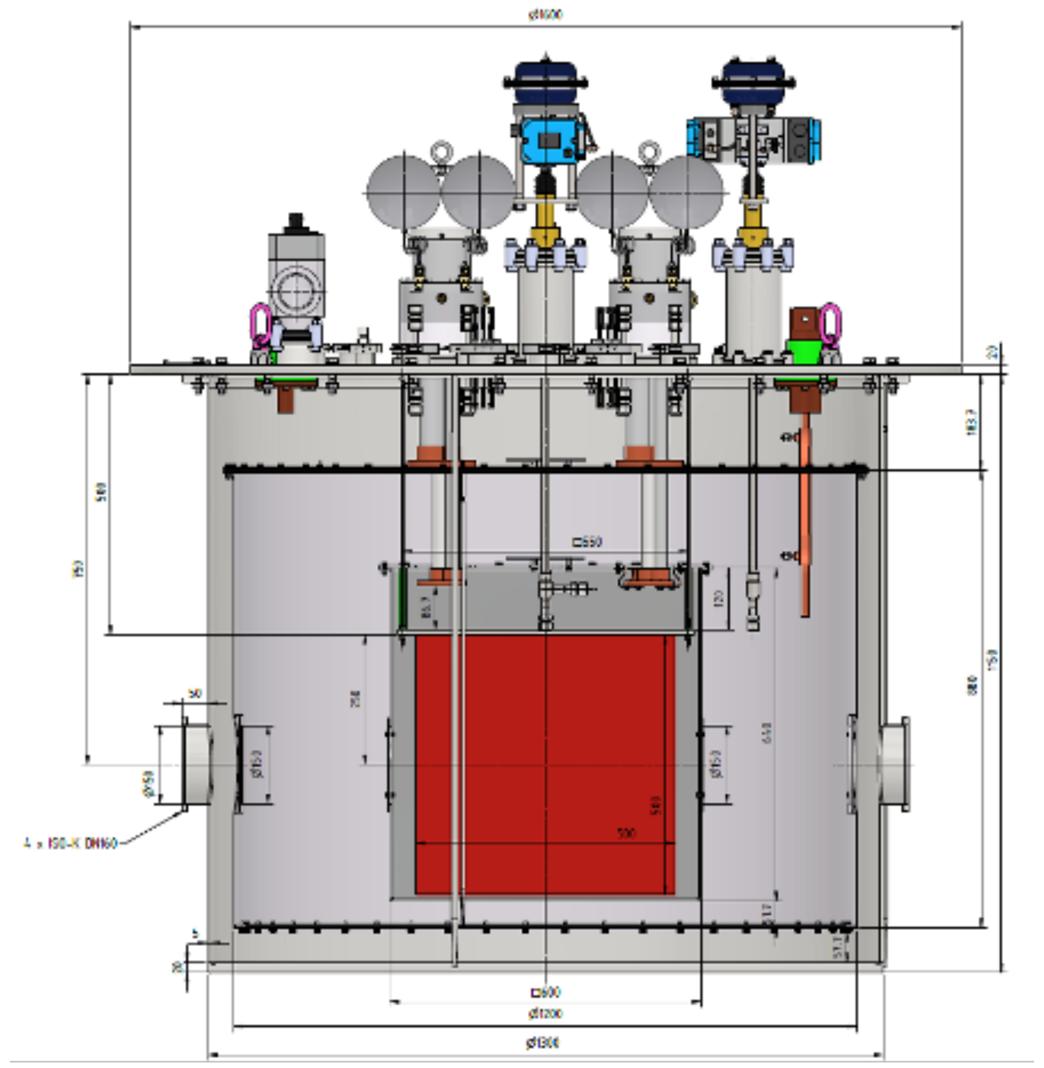
- Simplest
- Least efficient

- Most efficient
- Adapt fluid mixture properties
- Provide large HX surface

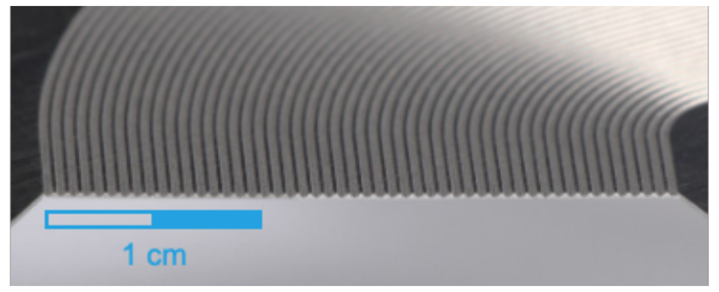


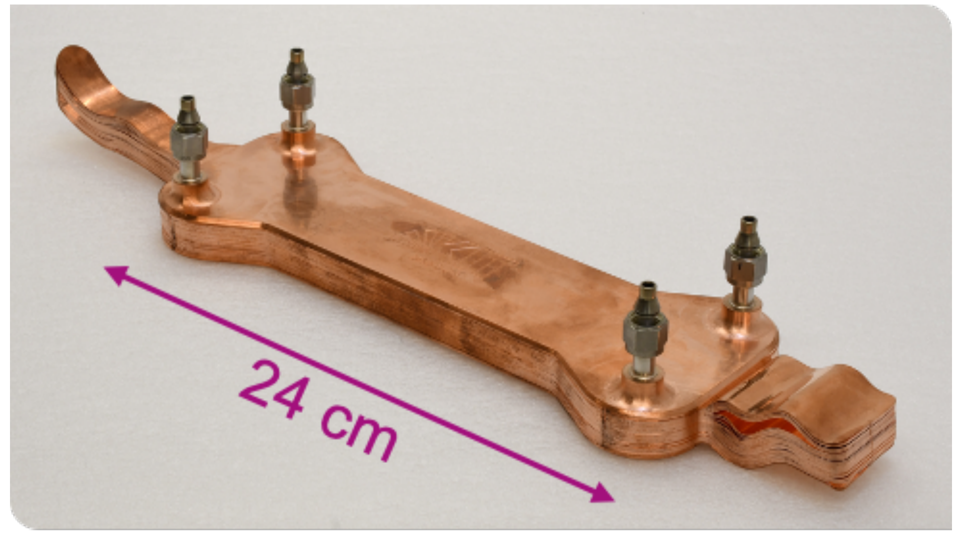
Source: Shabagin, E.: Development of a CMRC cooled 10 kA current lead for HTS applications. DOI: 10.5445/IR/1000144514

COMPASS Test Stand (→ 10 kA)

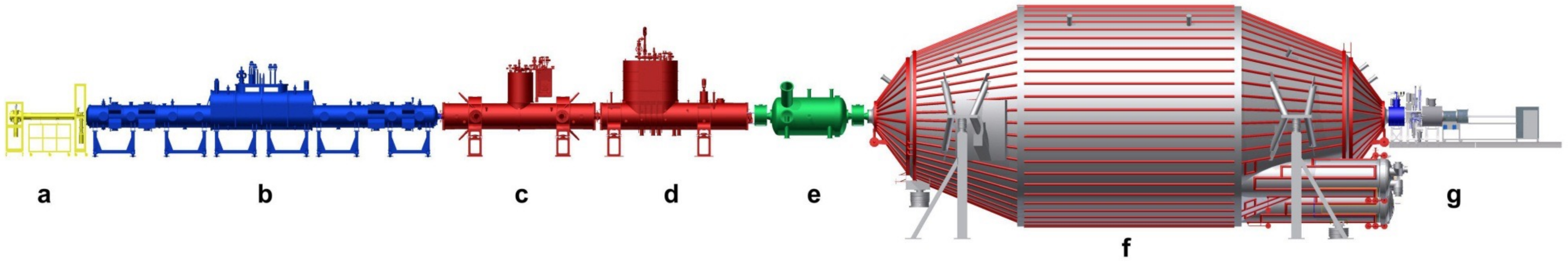


Reduction of power consumption to about 1/3!

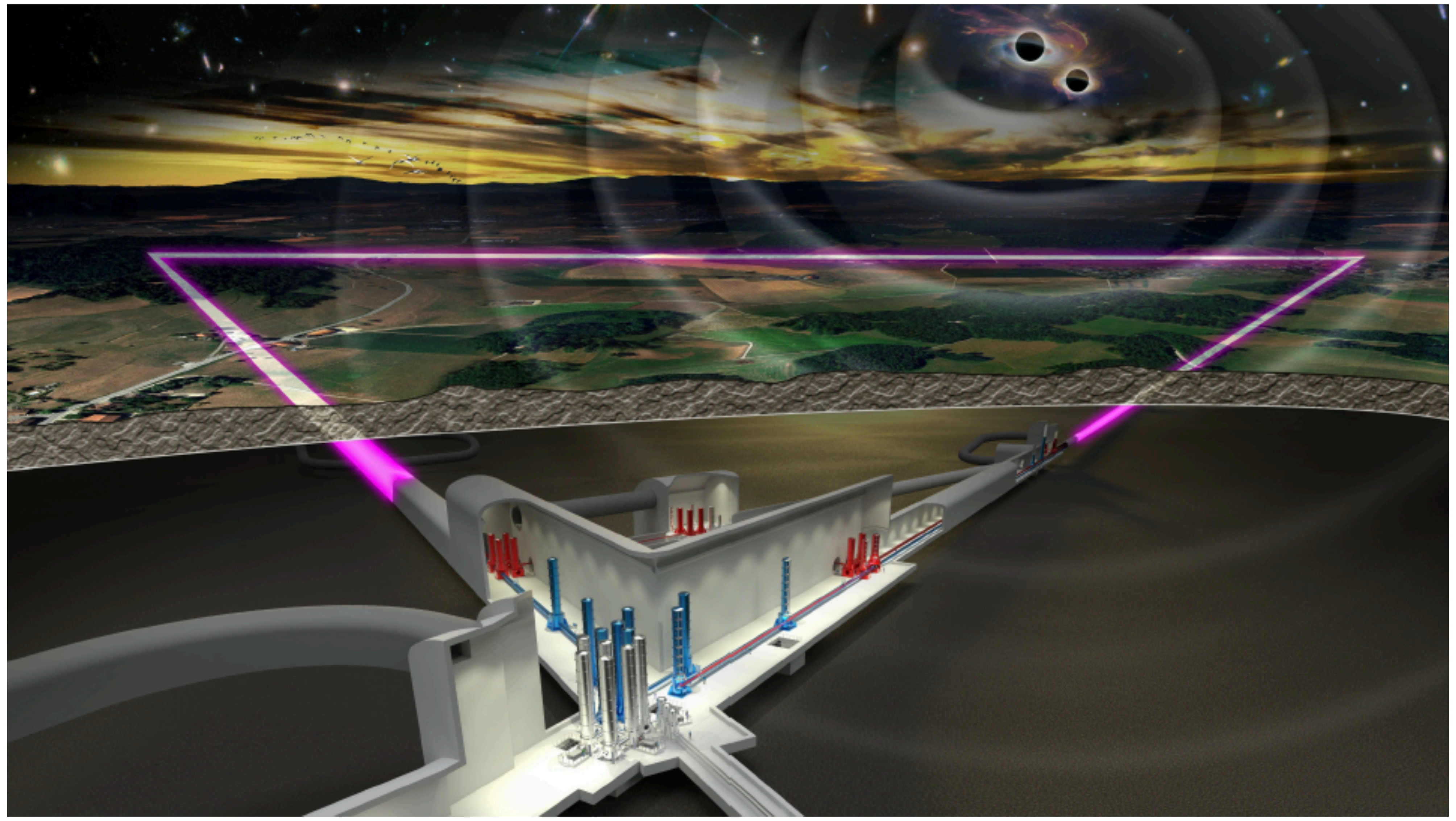




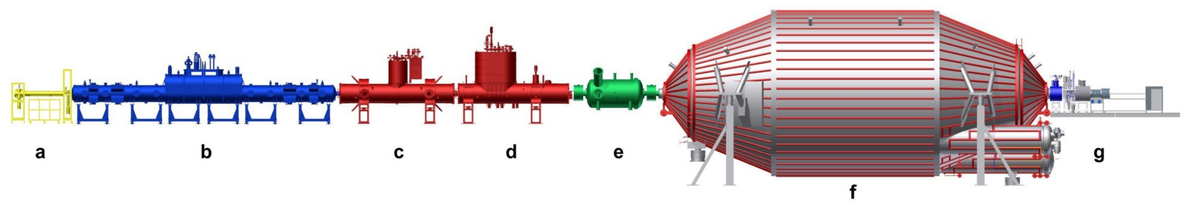
2 Examples – Cryogenics in large-scale experiments



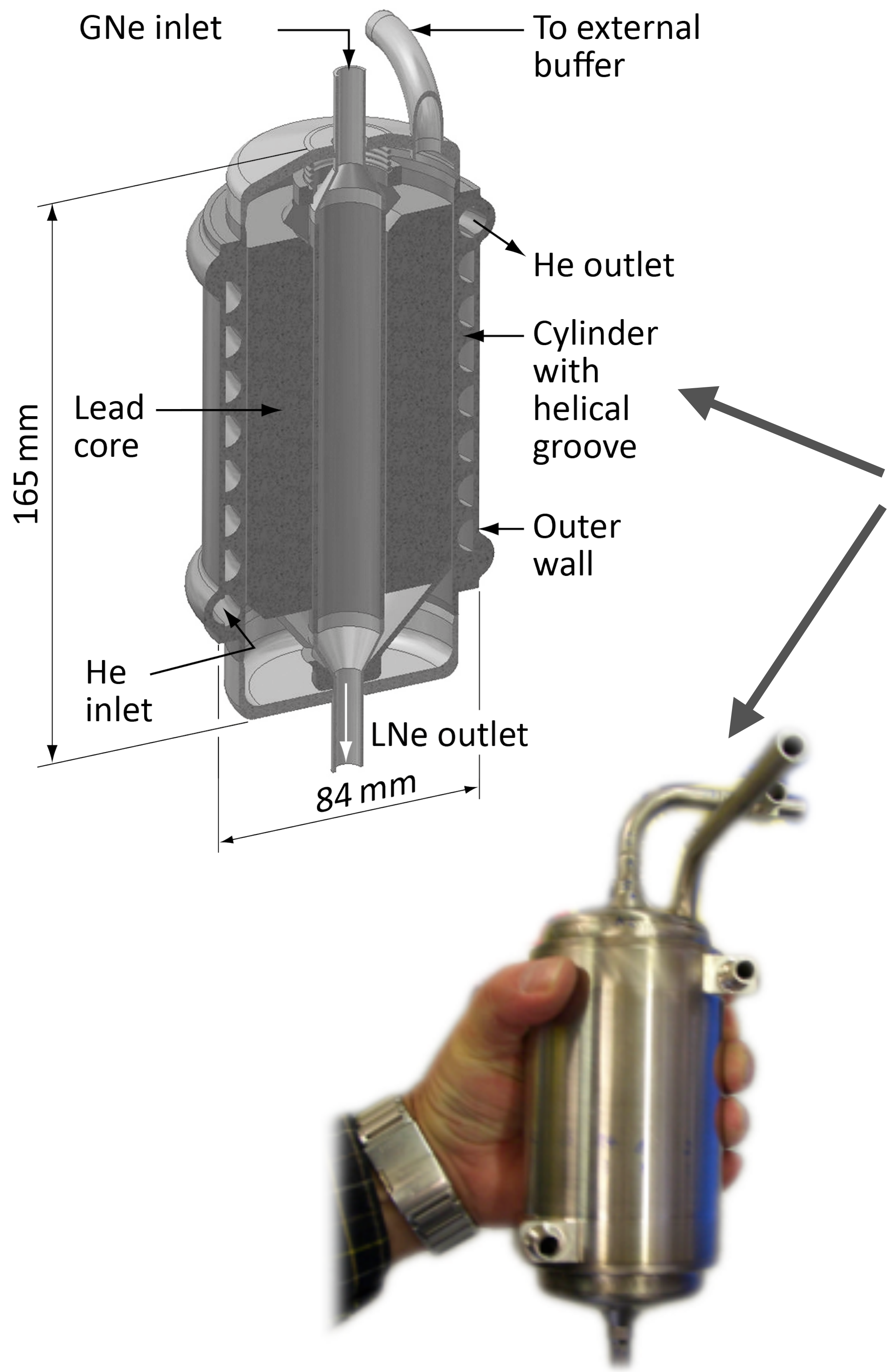
- **Einstein Telescope**

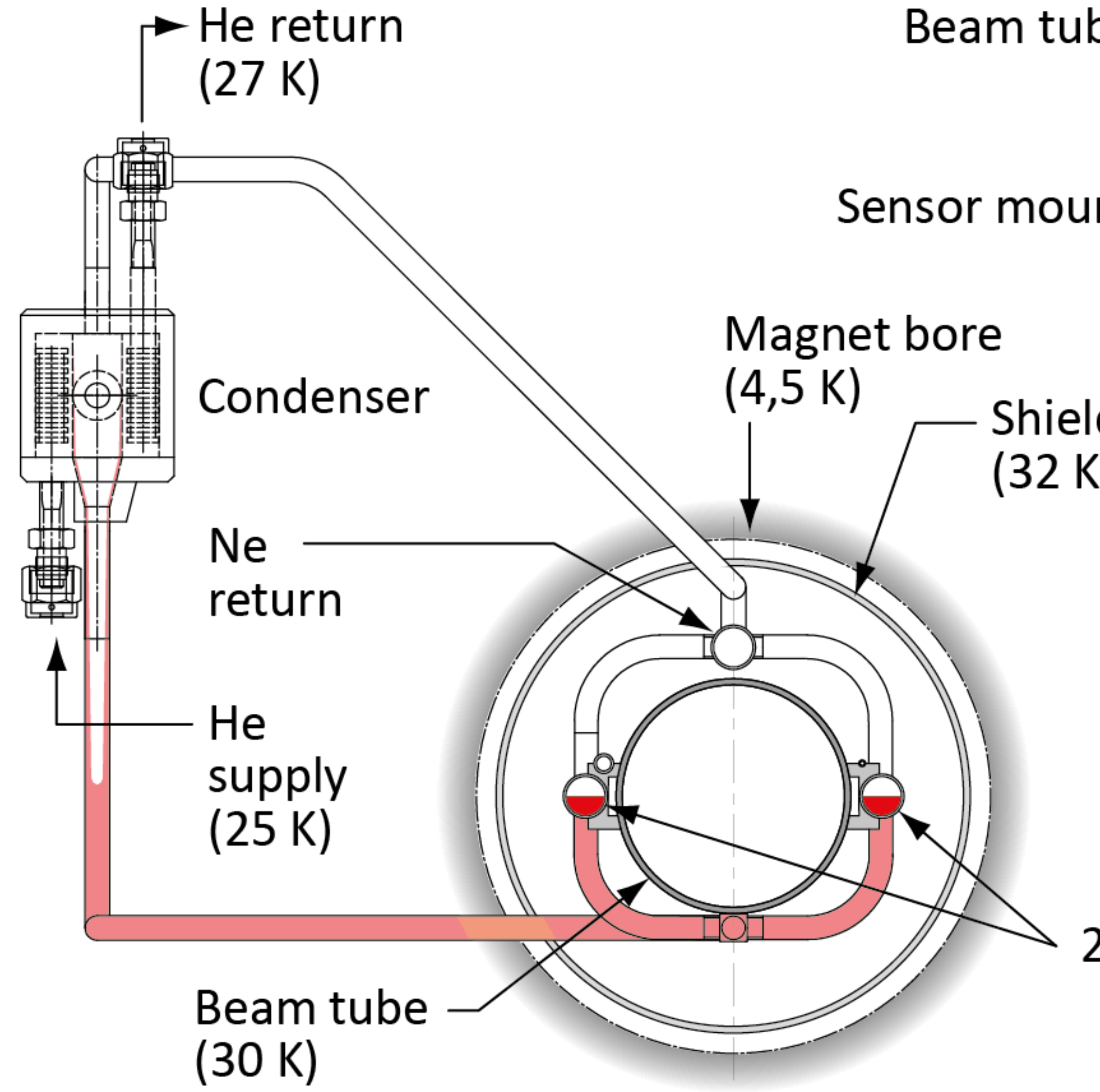


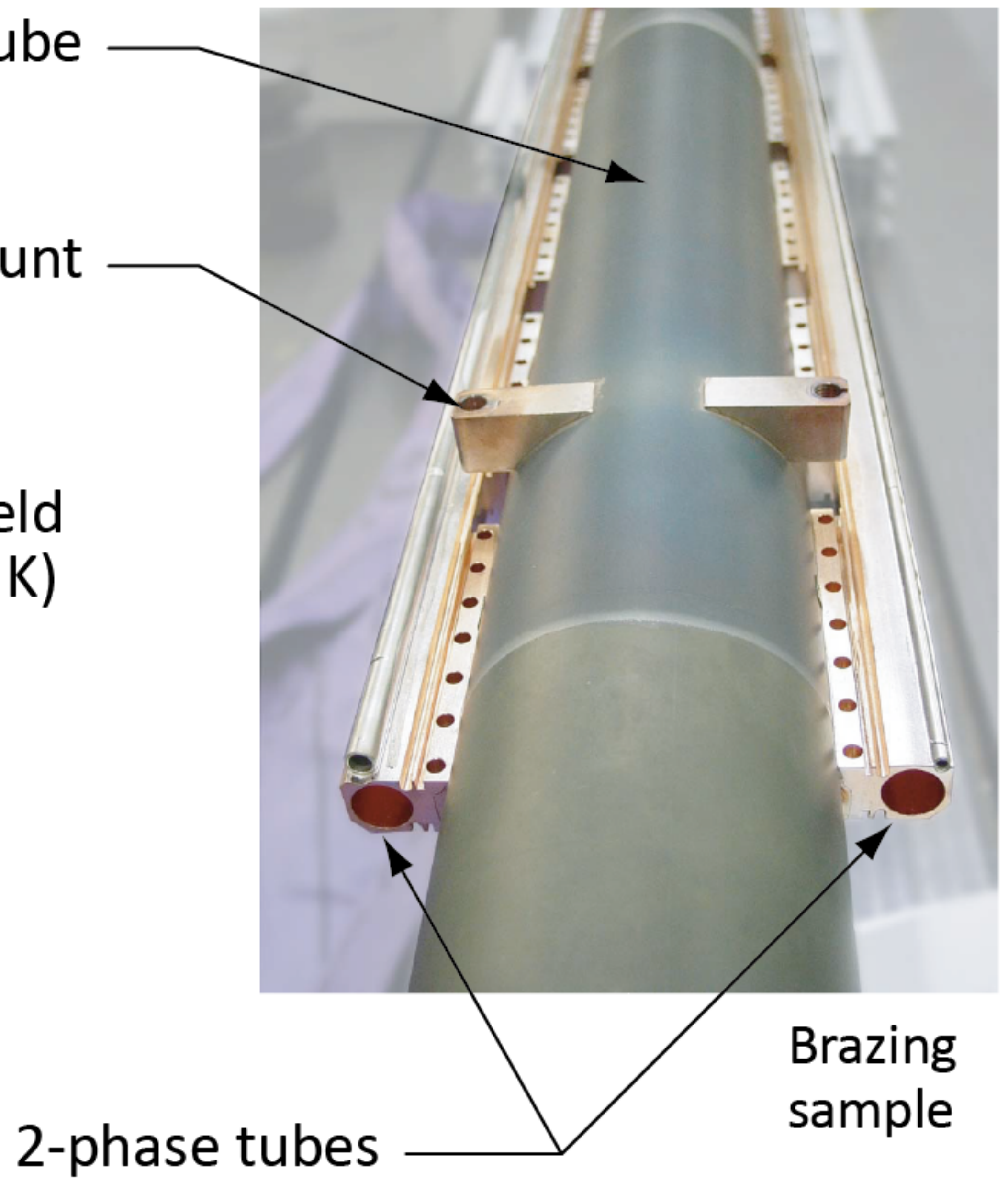
Cooling of the tritium source in KATRIN



- Neutrino mass measurement with 0.2 eV sensitivity requires **extremely stable source**



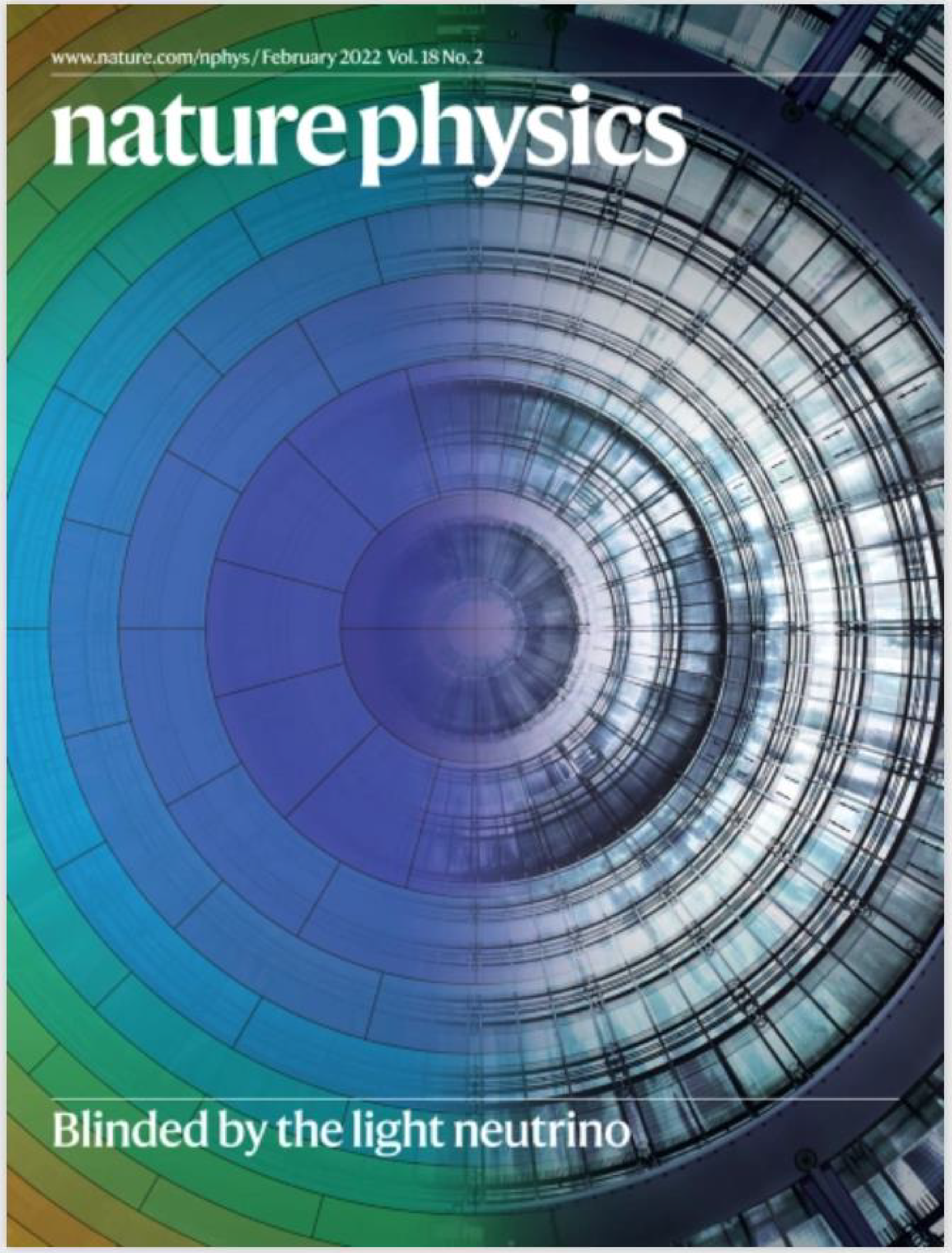




- 90% of systematics in KATRIN have their origin in the tritium source
  - Temperature stability of $5 \times 10^{-5}\,\mathrm{h}^{-1}$ @ $30\,\mathrm{K}$

Understand requirements and solutions in complex system developments

KATRIN Highlight – Nature Physics



ARTICLES
https://doi.org/10.1038/s41567-021-01463-1
nature physics
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OPEN

Direct neutrino-mass measurement with sub-electronvolt sensitivity

The KATRIN Collaboration*

Since the discovery of neutrino oscillations, we know that neutrinos have non-zero mass. However, the absolute neutrino-mass scale remains unknown. Here we report the upper limits on effective electron anti-neutrino mass, m_ν, from the second physics run of the Karlsruhe Tritium Neutrino experiment. In this experiment, m_ν is probed via a high-precision measurement of the tritium β-decay spectrum close to its endpoint. This method is independent of any cosmological model and does not rely on assumptions whether the neutrino is a Dirac or Majorana particle. By increasing the source activity and reducing the background with respect to the first physics campaign, we reached a sensitivity on m_ν of 0.7 eV c^{-2} at a 90% confidence level (CL). The best fit to the spectral data yields $m_\nu^2 = (0.26 \pm 0.34)$ eV^2 c^{-4}, resulting in an upper limit of $m_\nu < 0.9$ eV c^{-2} at 90% CL. By combining this result with the first neutrino-mass campaign, we find an upper limit of $m_\nu < 0.8$ eV c^{-2} at 90% CL.

The discovery of neutrino flavour oscillations[1,2] proves that neutrinos must have a mass, unlike originally assumed in the standard model of particle physics. Neutrino oscillation experiments have shown that the weakly interacting neutrino flavour eigenstates ν_f, where $f \in \{e, \mu, \tau\}$ for electron, muon and tau-neutrino, are admixtures of the three neutrino-mass eigenstates ν_i with mass eigenvalues $m_i j \in \{1, 2, 3\}$. Although neutrino oscillation experiments can probe the differences of squared neutrino-mass eigenvalues Δm_{ij}^2, the absolute neutrino-mass scale remains one of the most pressing open questions in the fields of nuclear, particle and astroparticle physics today. In this paper, we report a measurement of the effective electron anti-neutrino mass defined as $m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$, where U_{ei} are elements of the Pontecorvo–Maki–Nakagawa–Sakata matrix that describes the mixing of neutrino states.

The neutrino masses are at least five orders of magnitude smaller than the mass of any other fermion of the standard model, which may point to a different underlying mass-creation mechanism[3]. The determination of the neutrino mass would, thus, shed light on the fundamental open question of the origin of particle masses. Despite the smallness of their masses, neutrinos play a crucial role in the evolution of large-scale structures of our cosmos due to their high abundance in the Universe[4,5]. A direct measurement of the neutrino mass could, hence, provide a key input to cosmological structure formation models. In this respect, cosmological observations themselves provide a stringent limit on the sum of neutrino masses of $\sum m_i < 0.12$ eV (95% confidence level (CL))[6,7] (here we use the convention $c = 1$ for the speed of light). However, these limits strongly rely on the underlying cosmological assumptions[8,9]. An independent measurement of neutrino mass could help in breaking the parameter degeneracies of cosmological models. A powerful way to probe this neutrino property in the laboratory is via a search for neutrinoless double-beta (double-β) decay. In contrast to m_ν, the effective mass in double-β decay is given by $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$. This neutrino-mass interpretation is only valid under the assumption that neutrinos are their own anti-particle (Majorana particle) and that light neutrinos mediate the decay. The current most stringent limits derived from different isotopes are $m_{\beta\beta} < 79$–180 meV (^{76}Ge) (ref. [10]), $m_{\beta\beta} < 75$–350 meV (^{130}Te) (ref. [11]) and $m_{\beta\beta} < 61$–165 meV (^{136}Xe) (ref. [12]), and the spread is related to uncertainties in the model-dependent nuclear matrix element calculation.

The most direct way to assess the neutrino mass is via the kinematics of single-β decays or electron capture processes. This method is independent of any cosmological model and of the mass nature of the neutrino, that is, it may be a lepton of the Majorana or Dirac type. The neutrino masses m_i lead to a reduction in the maximum observed energy of the decay and a small spectral-shape distortion close to the kinematic endpoint of the β-decay spectrum. In the quasi-degenerate mass regime, where $m_i > 0.2$ eV, the mass splittings are negligible with respect to masses m_i, and the observable value can be approximated as $m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$ (refs. [13,14]).

The Karlsruhe Tritium Neutrino (KATRIN) experiment[15,16] exploits the single-β decay of molecular tritium as

$$T_2 \rightarrow {}^3HeT^+ + e^- + \bar{\nu}_e \quad (1)$$

and currently provides the best neutrino-mass sensitivity in the field of direct neutrino-mass measurements with its first published limit of $m_\nu < 1.1$ eV (90% CL)[17,18]. KATRIN is designed to determine the neutrino mass with a sensitivity of close to 0.2 eV (90% CL) in a total measurement time of 1,000 days (ref. [15]). Another class of experiments is based on the electron capture of ^{163}Ho, where the decay energy is measured with micro-calorimeters[19,20]. Note that electron capture experiments based on ^{163}Ho measure the mass of the neutrino ν and β^- experiments based on tritium measure that of the anti-neutrino $\bar{\nu}$. New ideas exist to extend the sensitivity of tritium-based neutrino-mass experiments beyond the KATRIN design sensitivity by new technologies, such as cyclotron radiation emission spectroscopy and the development of atomic tritium sources[21,22].

In this work, we present the second neutrino-mass result of KATRIN, reaching an unprecedented sub-electronvolt sensitivity and limit in m_ν from a direct measurement.

The KATRIN experiment

The design requirements to detect the small signature of a neutrino mass in the last few electron-volts of the β-decay spectrum are a high tritium activity (1×10^{11} Bq), a low background rate ($\lesssim 0.1$ counts

*A list of authors and their affiliations appears online only.

Online attention

- 163 tweeters
- 1 Redditors
- 13 Mendeley
- 66 news outlets
- 10 blogs
- 3 Wikipedia page

First ever sub-eV limit by direct neutrino mass experiment

KATRIN Highlight – Nature Physics

- **distribution of fitted m_ν^2 and E_0 values**

  - best-fit ν-mass:

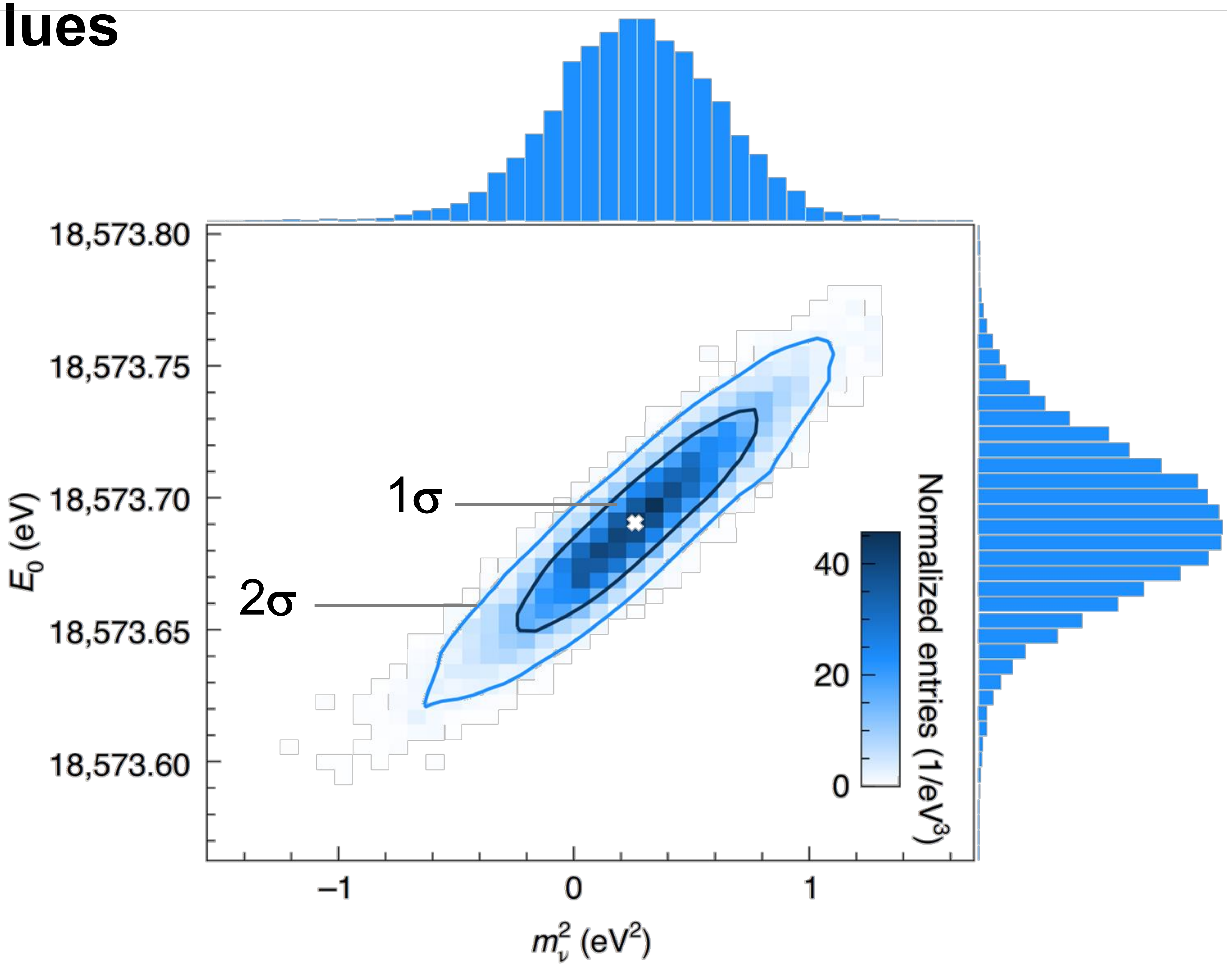
$$m_\nu^2 = (0.26 \pm 0.34)\ eV^2$$

$$E_0 = (18{,}573.69 \pm 0.03)\ eV$$

combined result KNM1 & KNM2:

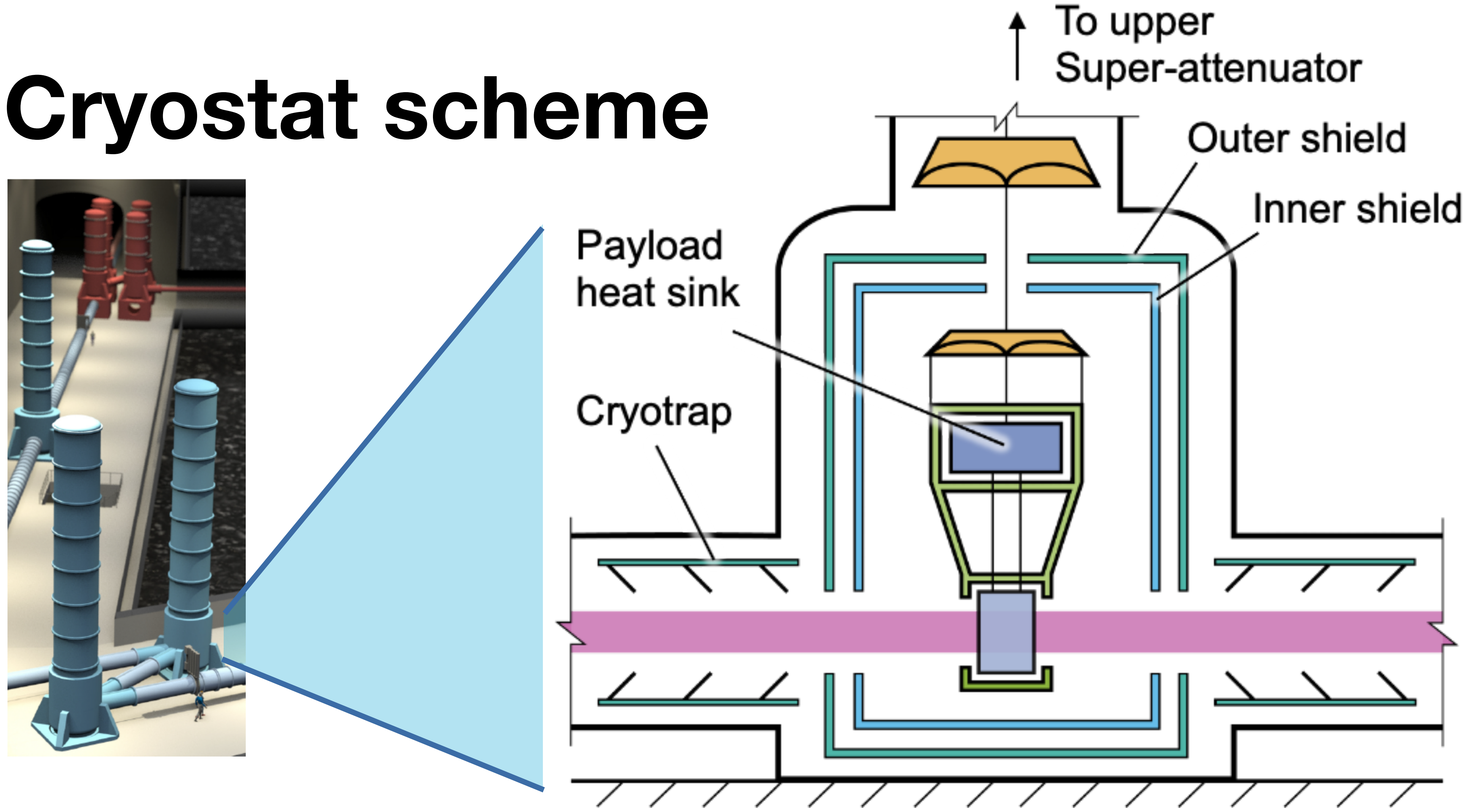
$$m(\nu) < 0.8\ eV\ (90\%) C.L.$$

  - only 7% of expected final data-set



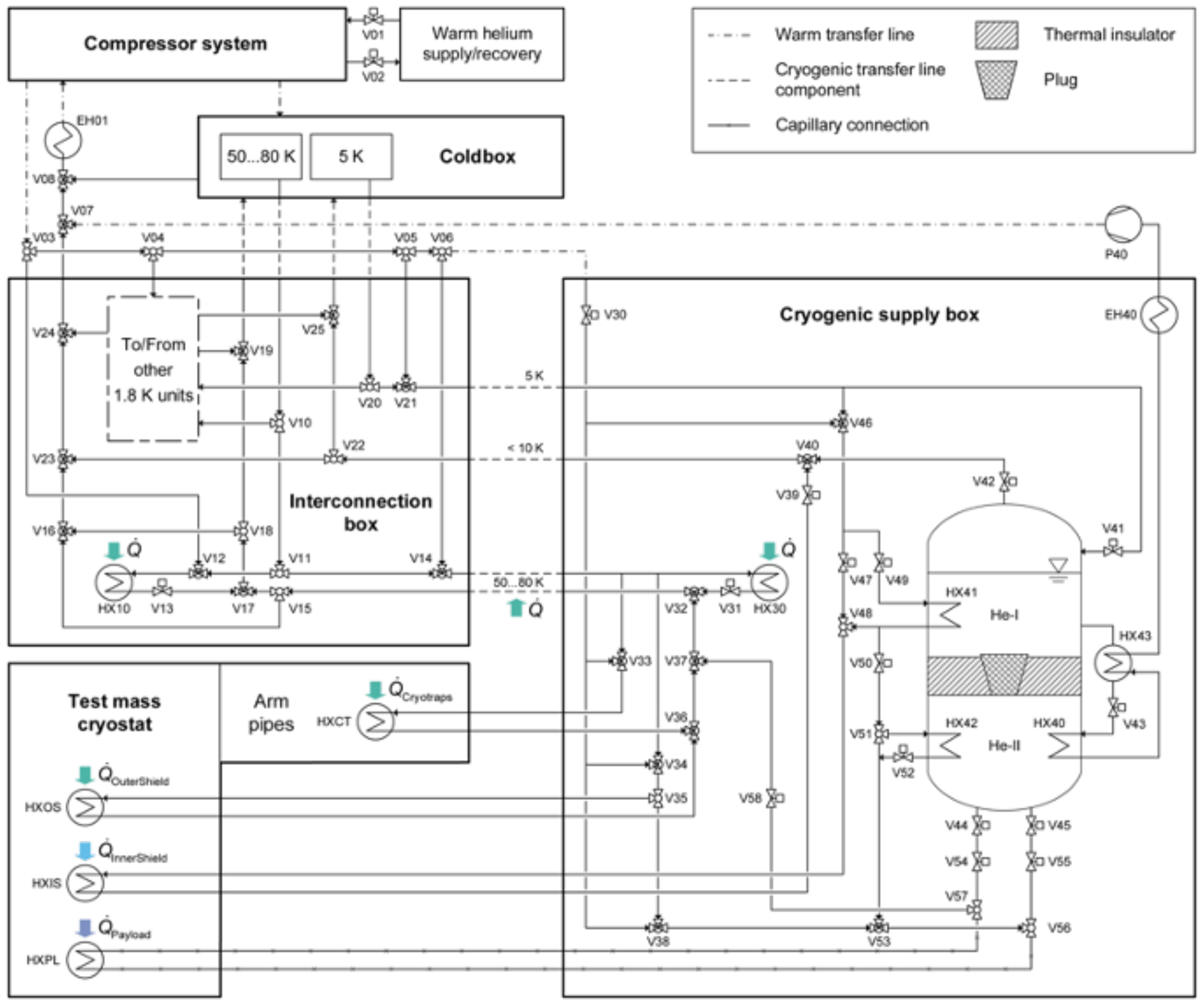
Einstein Telescope: Cryogenic infrastructure

Cryostat scheme



Part(s)	Temp. level	Est. cooling power
Outer thermal shield & cryotraps	5…80 K	x…10^4 W
Inner thermal shields	5 K	x…10^2 W
Payload heat sink	2 K	x…1 W

Conceptual process flow diagram



Source: Busch, L.; Grohmann, S.: Conceptual Layout of a Helium Cooling System for the Einstein Telescope. Adv. Cryo. Eng., Procs. Cryo. Eng. Conf. (CEC) 2021, Accepted.

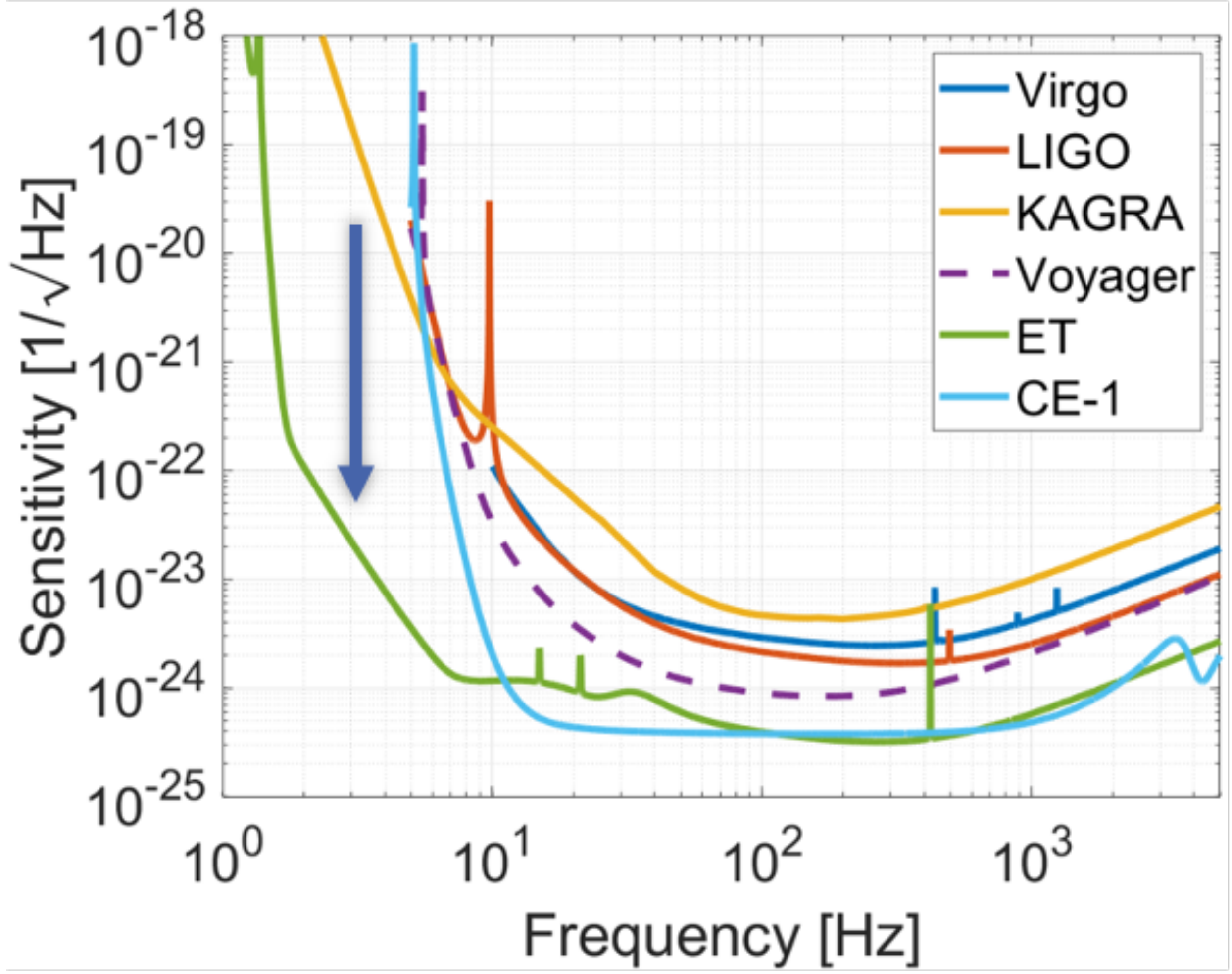
Cryogenics and **cryo-vacuum** are **key technologies** for ET-LF

Einstein Telescope: Cryogenic ET-LF

Karlsruhe Institute of Technology

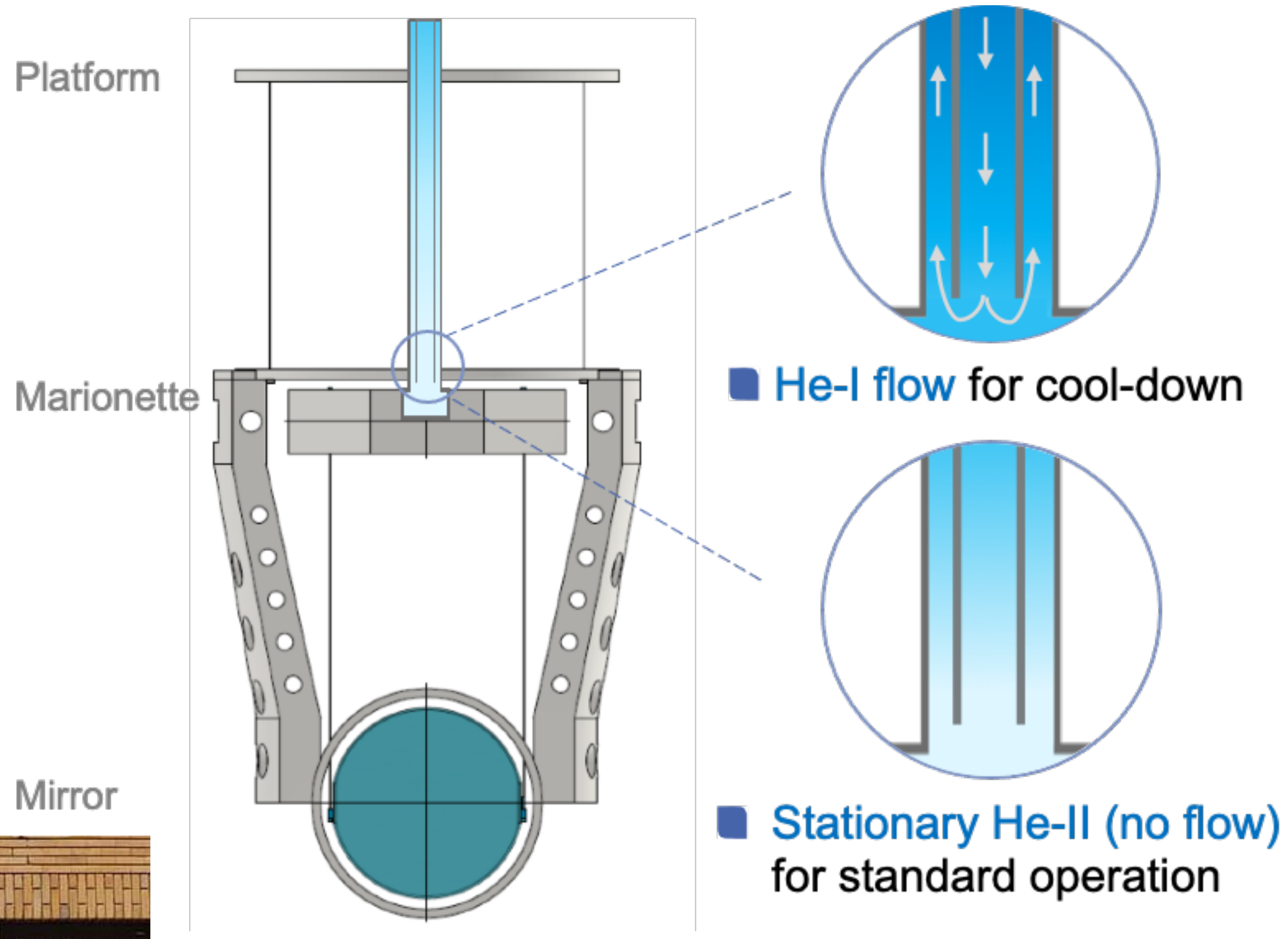
ET-LF interferometer (3…30 Hz)

- Sensitivity improvement $\Delta S < 10^{-3}\,@\,3\,\mathrm{Hz}$ compared to 2.5G detector (KAGRA)
- Laser power 18 kW
- **Cryogenic optics @ $T = 10 \ldots 20\,\mathrm{K}$ essential**

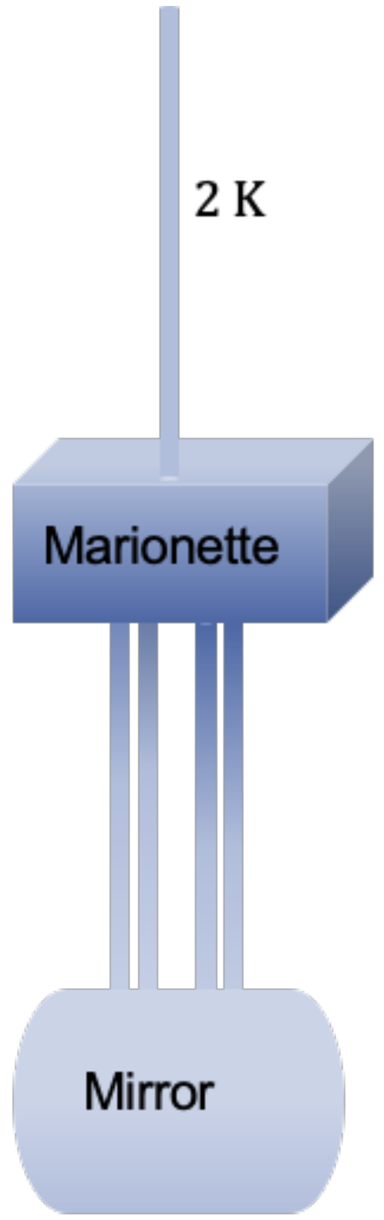


ET Cryogenics Meeting
Rome, April 27-28, 2022

Concept of superfluid He-II capillary suspension



Most important
Suspension
Thermal Noise
(STN)



Feasible in terms of STN
Impact of He-II yet unknown
New direction of R&D

Cryogenics in Particle, Astroparticle and Nuclear Physics

SYNERGIES

European Standardisation

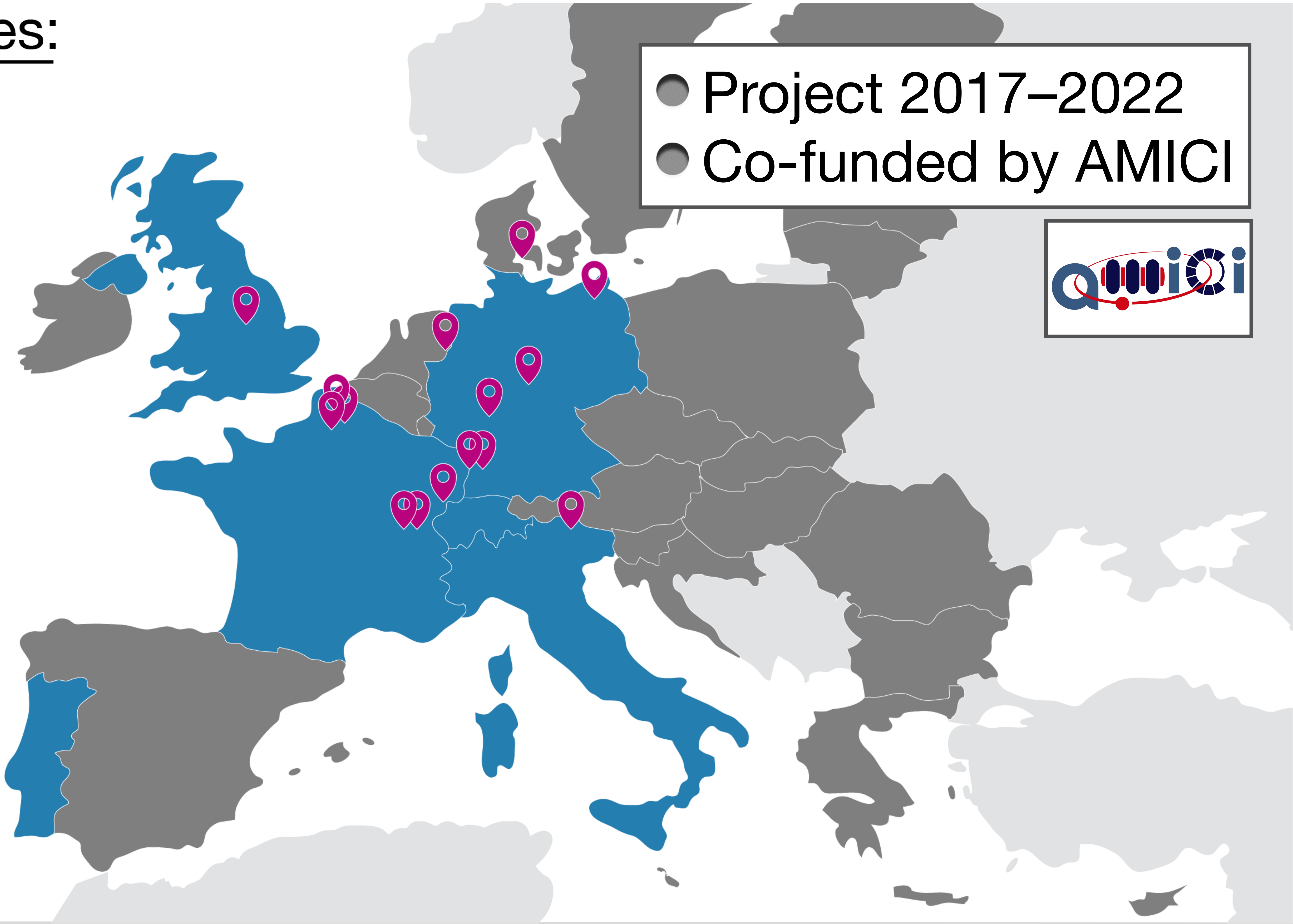
Helium cryostats – Protection against excessive pressure

- National Standardisation Bodies:

DIN, afnor GROUPE, bsi., UNI ENTE ITALIANO DI NORMAZIONE, Instituto Português da Qualidade, SNV

- Organizations:

Air Liquide creative oxygen, BILFINGER, cea, CERN, HEROSE, INFN, KIT Karlsruhe Institute of Technology, The Linde Group Linde, PAUL SCHERRER INSTITUT PSI, Science & Technology Facilities Council



New European Standard EN 17527

- Helium cryostats → **complex** and **individual design solutions**
  - Small design margins, cutting-edge performance
  - Common solutions cannot be standardised
  - Standardisation **of the way** towards a safe design
- Contents
  - …
  - Risk assessment
  - Protection concepts
  - Dimensioning of pressure relief devices
  - …
  - Operation

First **International Standard** on safety of helium cryostats **now available**


Thank you for your attention!