Karlsruhe Institute of Technology

Cryogenic Developments towards the Einstein Telescope (ET)

Steffen Grohmann

European Cryogenics Days, November 3–4, 2021


Source: Design Report Update 2020 for the Einstein Telescope. ET Steering Committee Editorial Team, September 2020

Outline

- The Einstein Telescope (ET)
  - History of gravitational waves (GW)
  - Scientific goals of 3G GW detectors – ET
  - GW detection principle
  - ET design and technologies
- Cryogenic developments towards ET
  - Vacuum requirements and challenges
  - Test facilities and detector cooling developments
  - Cryogenic infrastructure concept
- Organisation / participation

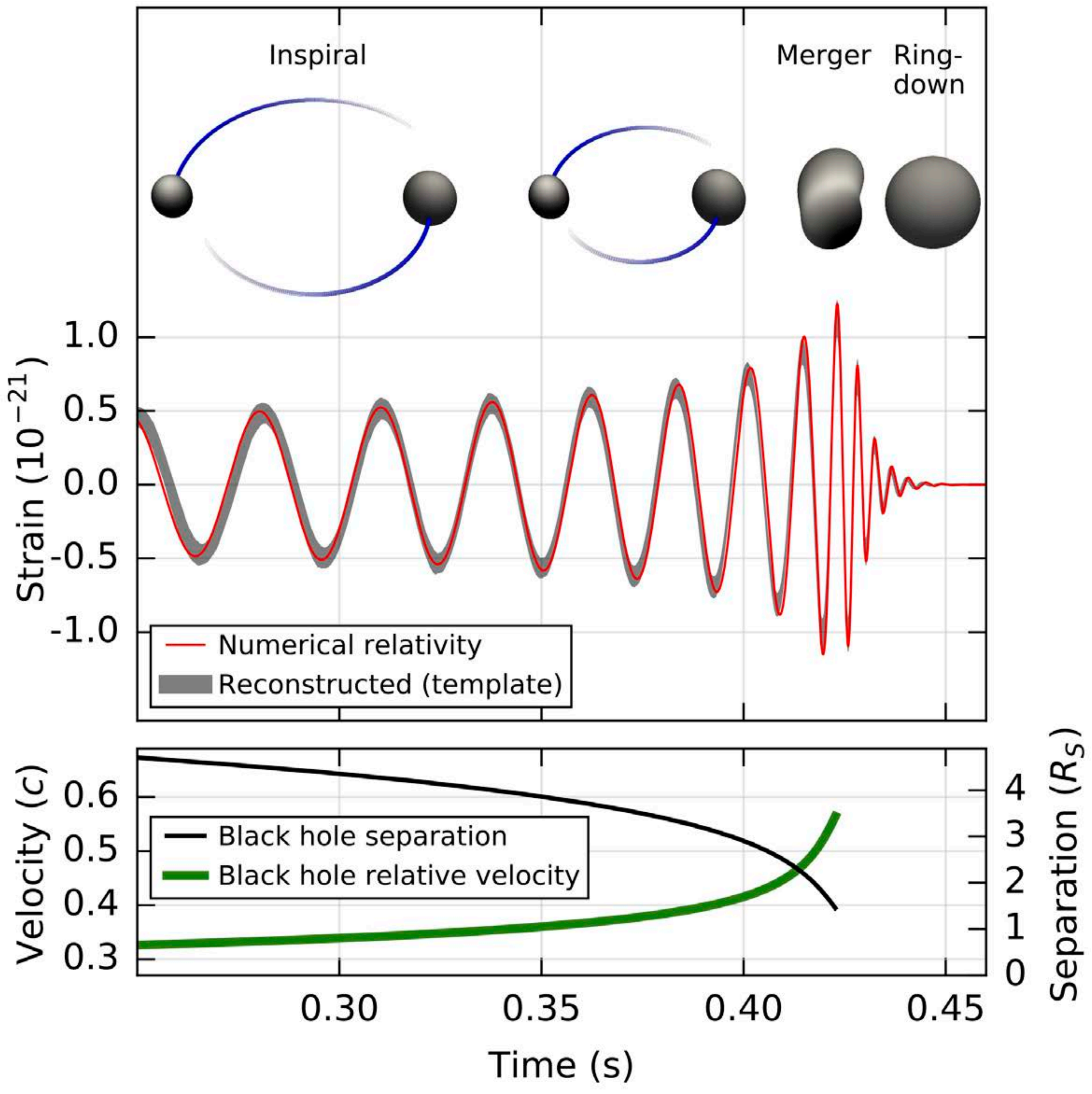
THE EINSTEIN TELESCOPE (ET)

History of gravitational waves (GW)

- 1916 **Postulation** of gravitational waves by Albert Einstein
- 2015 **First** direct GW **detection**
  - LIGO, Hanford/Livingston, US
  - Possible after major upgrade 1G → 2G GW detectors

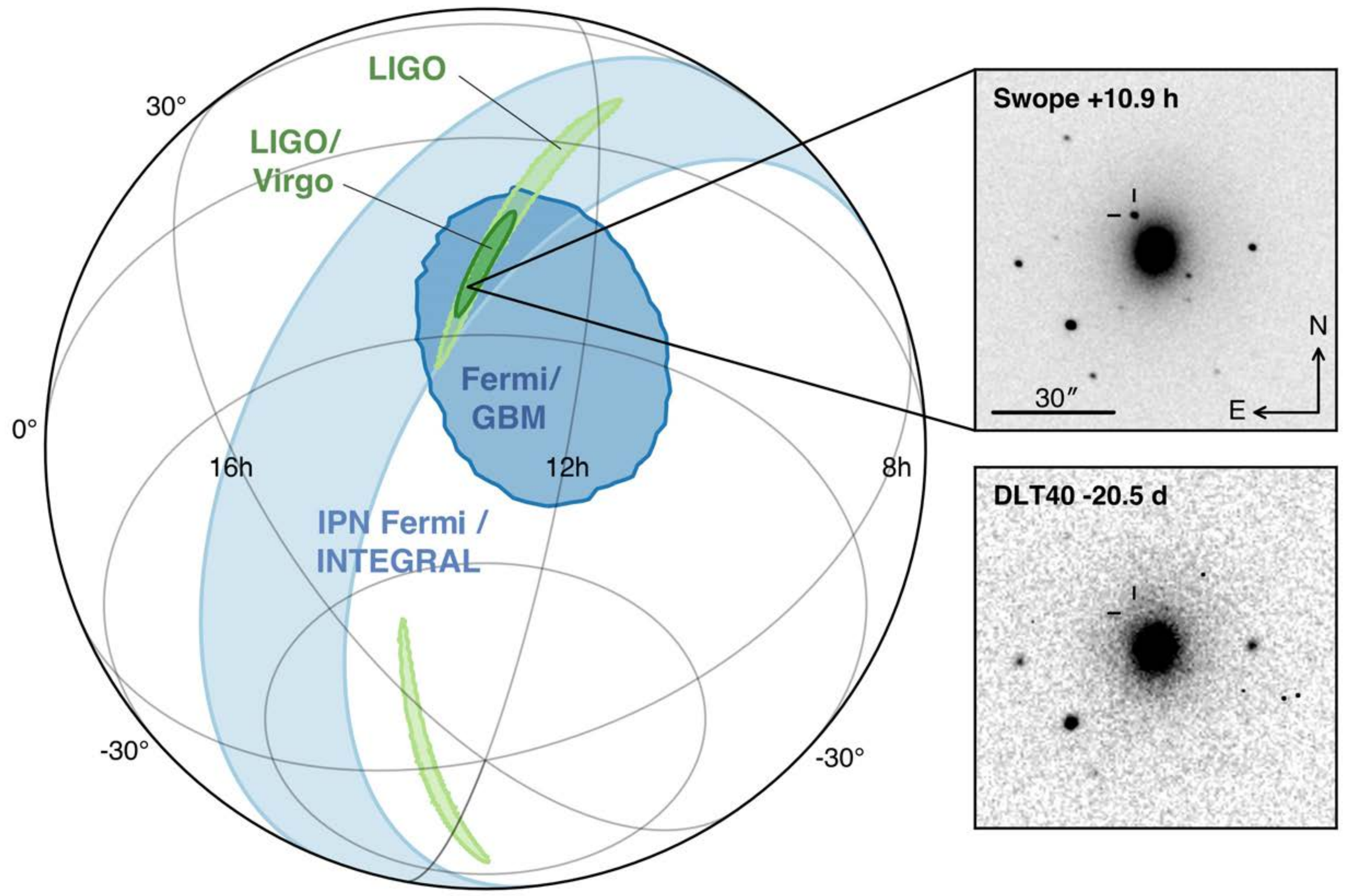
  - Merger of 2 black holes $(29\,M_\odot + 36\,M_\odot) \rightarrow 62\,M_\odot$
  - Radiation of $3\,M_\odot$ in $\tau < 1\,\mathrm{s}$
  - Energy $E_{\mathrm{rad}} \approx 50 \times \Phi$ of all stars in the universe
  - Signal reaching earth after 1.3×10^9 years
  - **Experimental proof** of **black hole** existence

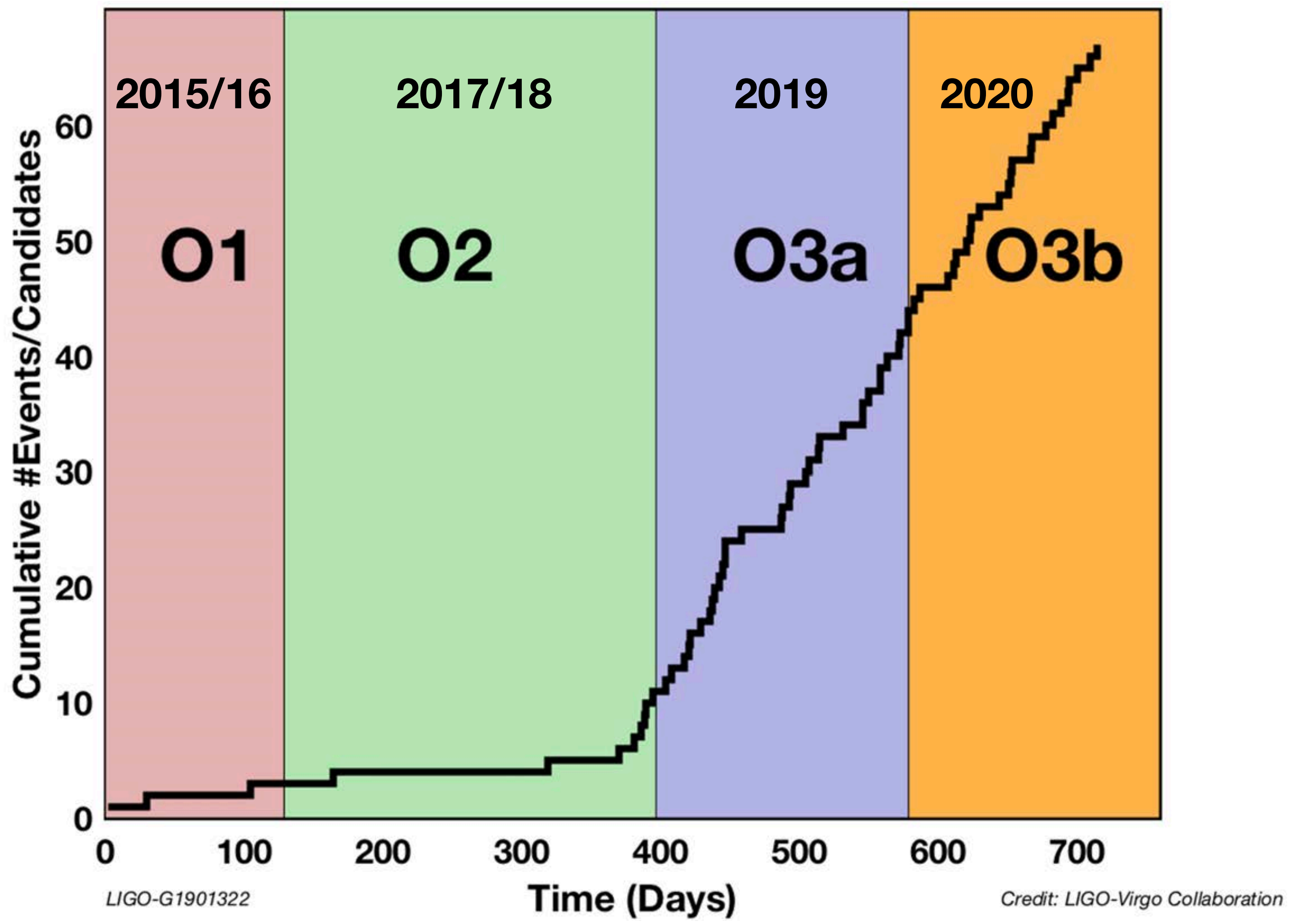
GW150915 PRL 116, 061102 (2016)



History of gravitational waves (GW)

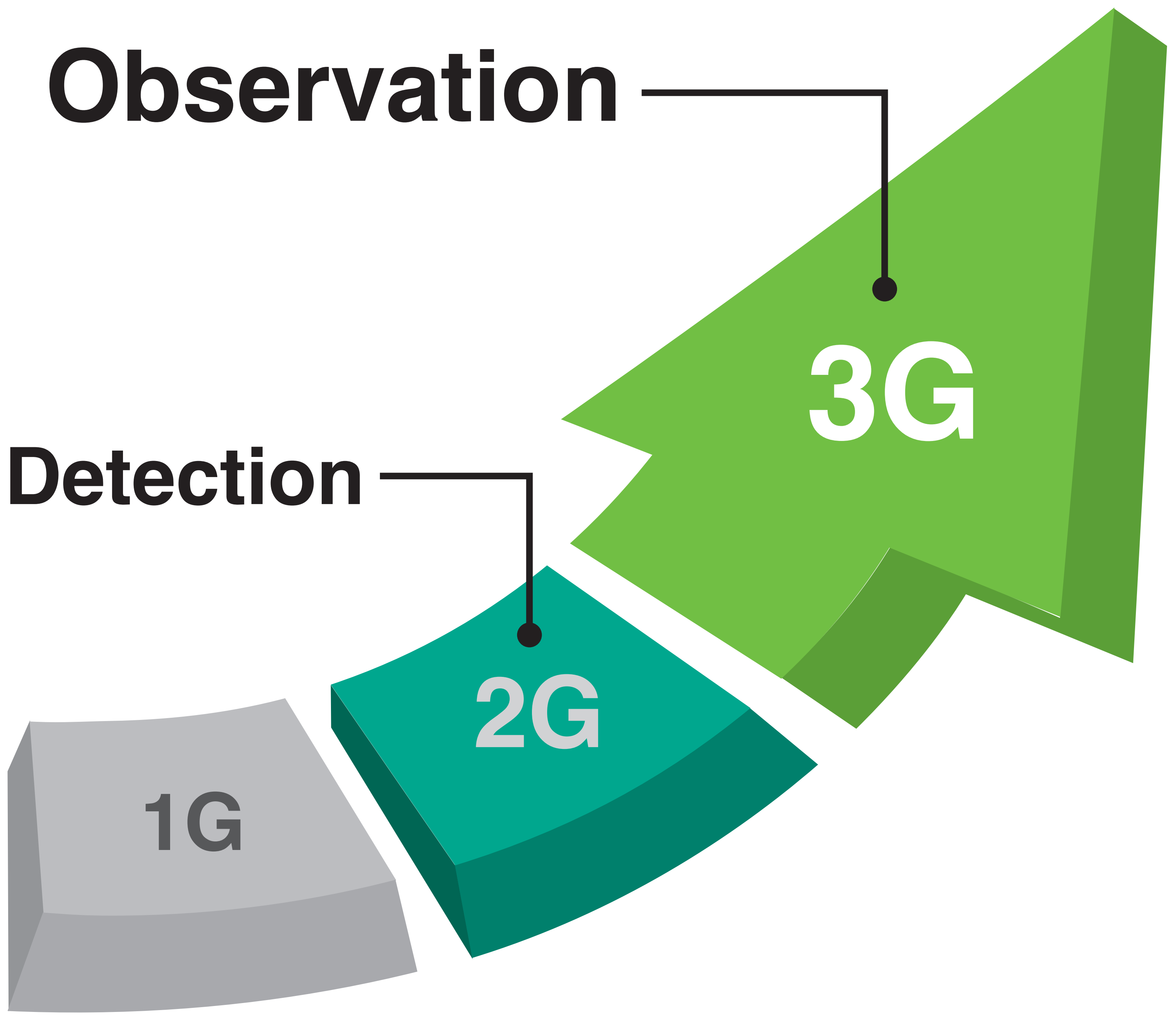
- 2017 **Synchronous detection** at LIGO (US) and VIRGO (Pisa, IT)



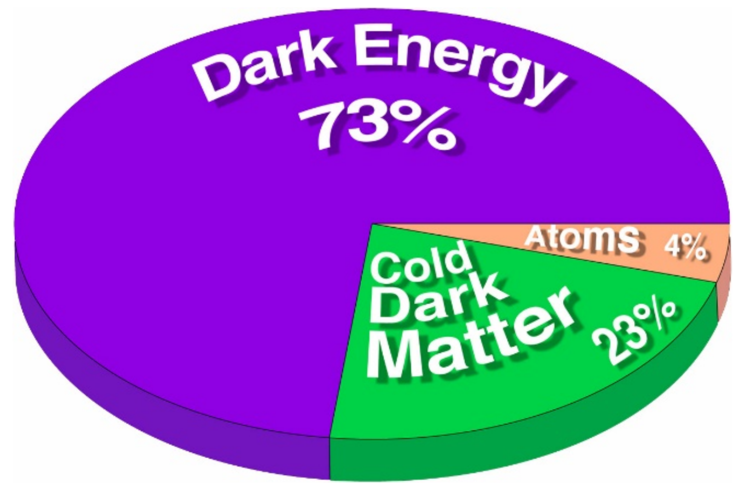


- 2017 **Nobel prize** in physics for *R. Weiss*, *B. Barish*, *K. Thorne* **(GW detection)**
- 2020 **Nobel prize** in physics for *R. Penrose*, *R. Genzel*, *A. Ghez* **(Black holes)**

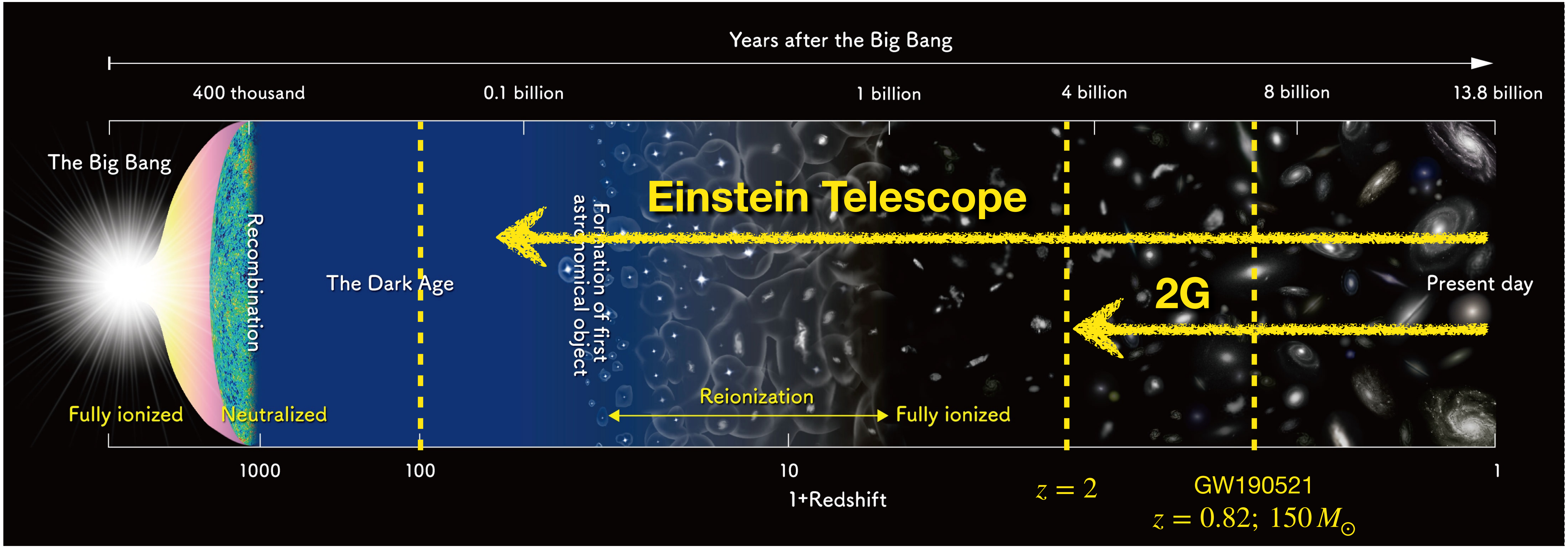
Scientific goals of 3G GW detectors



- **Binary black hole coalescences** up to cosmological distances
  - Redshift $z \leq 20$ at rates $10^5 - 10^6$ per year
- Extend the region of **black hole masses**
- Coalescence of **binary neutron stars**
  - Redshift $z \simeq 2 - 3$ at rates 6×10^4 per year
- Measurement of the **Hubble constant** H_0
- Study the high-energy universe through **multi-messenger physics**
- Test several **dark matter candidates**
- Explore the nature of **dark energy**



Detection horizon for black hole binaries

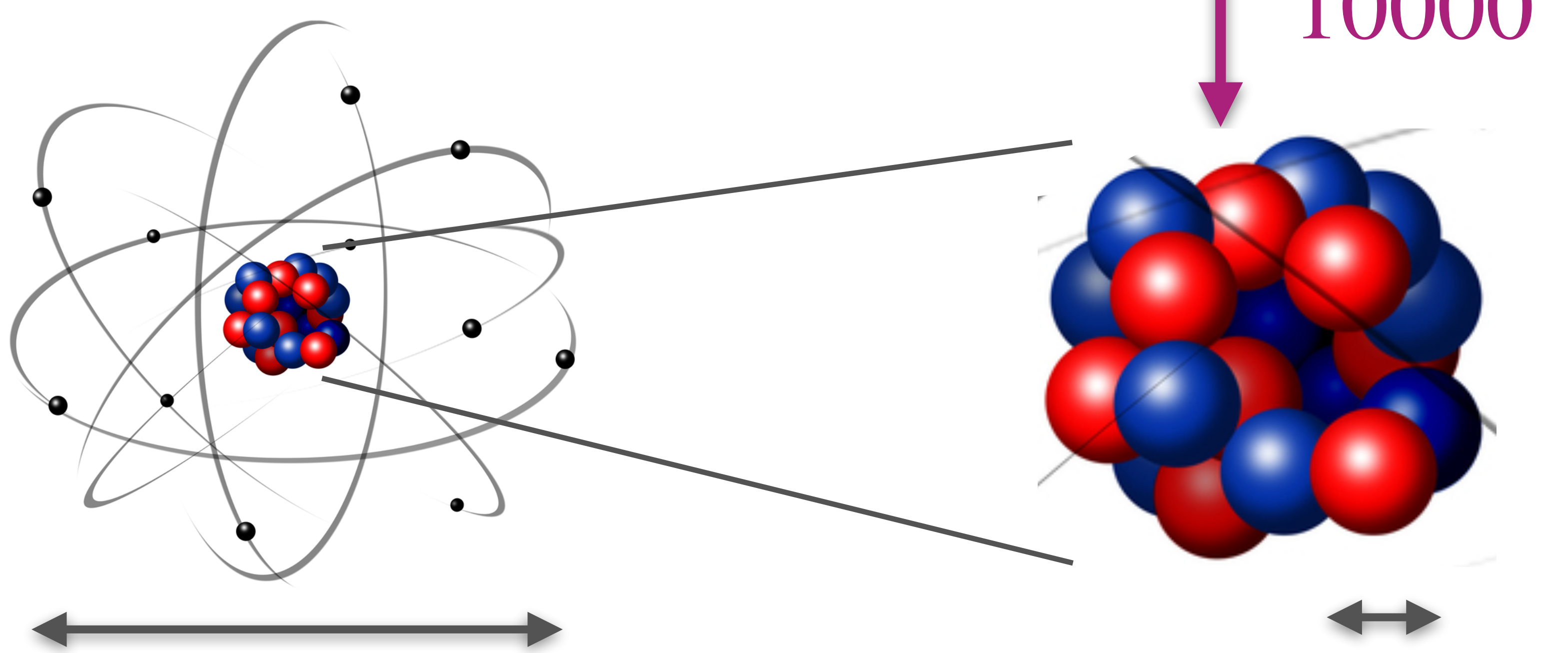


Credit: ALMA Collaboration

GW detection principle

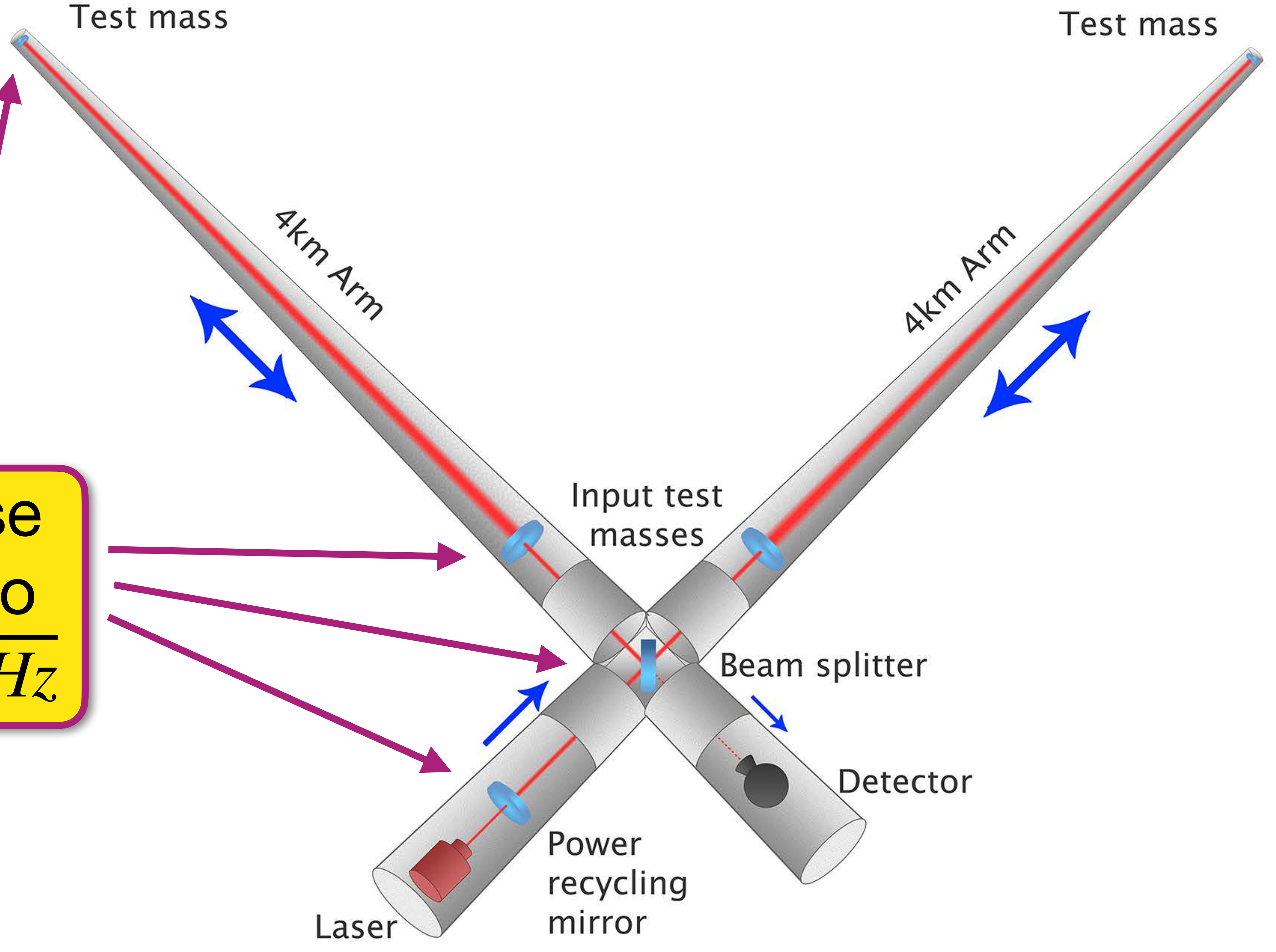
- Michelson interferometer
  - Laser through beam splitter
  - Reflection at end mirrors (test masses)
  - Extinction at identical arm lengths
  - Signal due to GW length deformation
  - LIGO/VIRGO wavelength $0.8 \times 10^{-6}\,\mathrm{m}$
  - **Sensitivity** $\Delta L = 4 \times 10^{-19}\,\mathrm{m}$

$\frac{1}{10000}$!



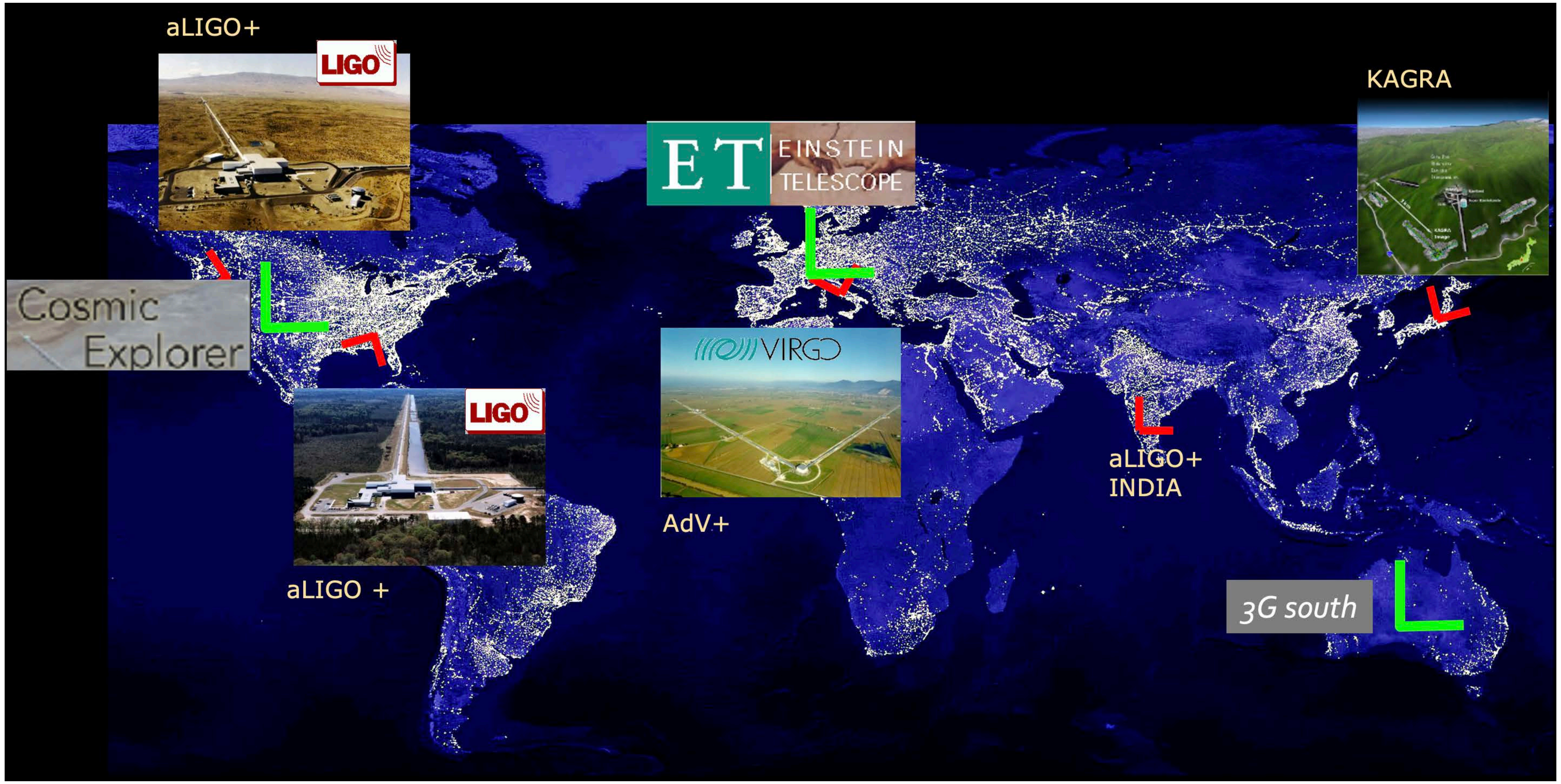
Extreme noise attenuation to $\sim 10^{-20}\,\mathrm{m}/\sqrt{Hz}$

LIGO layout



Source: Cardiff University

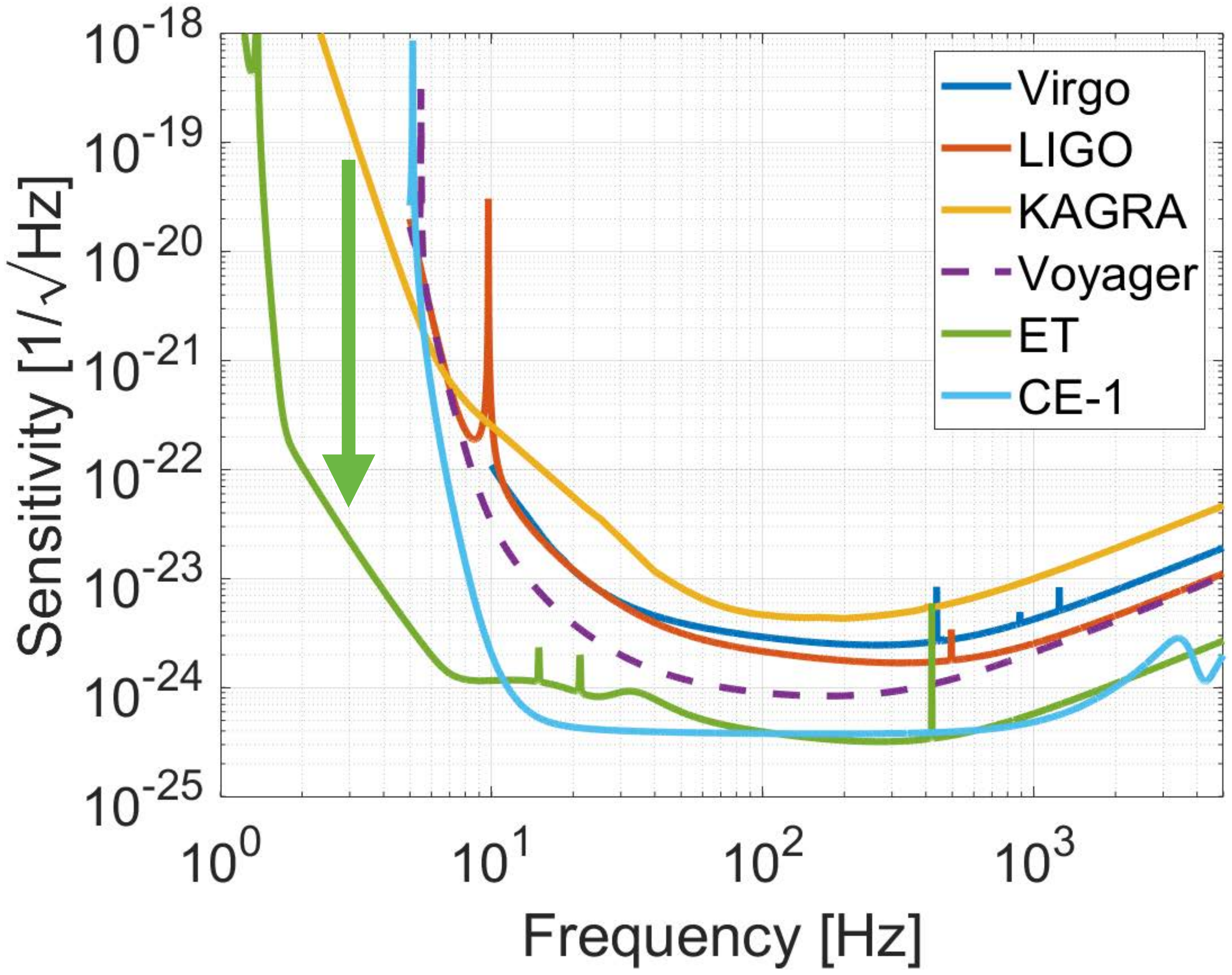
2G and planned 3G GW network (2035+)



1) ET **ramp-up phase**
   - Significant benefits from 2G network to localise events
2) ET design has **good localisation capability**
   - 2G increases the number of well localised events
3) ET will **significantly benefit** from **3G network**
   - 2G contributions will become negligible

Sensitivity goals of ET

- ET **scientific goals** achievement requires significant **sensitivity improvements**
- **ET-HF** interferometer $\left(30\,\mathrm{Hz}\ldots10\,\mathrm{kHz}\right)$
  - Sensitivity improvement $\Delta S \leq 10^{-1}$
  - Laser power $\sim 3\,\mathrm{MW}$
  - Room-temperature optics
- **ET-LF** interferometer $(3\ldots30\,\mathrm{Hz})$
  - Sensitivity improvement $\Delta S < 10^{-3}$ @ $3\,\mathrm{Hz}$!!
  - Laser power $\sim 18\,\mathrm{kW}$
  - Cryogenic optics at $T \sim 10\ldots20\,\mathrm{K}$

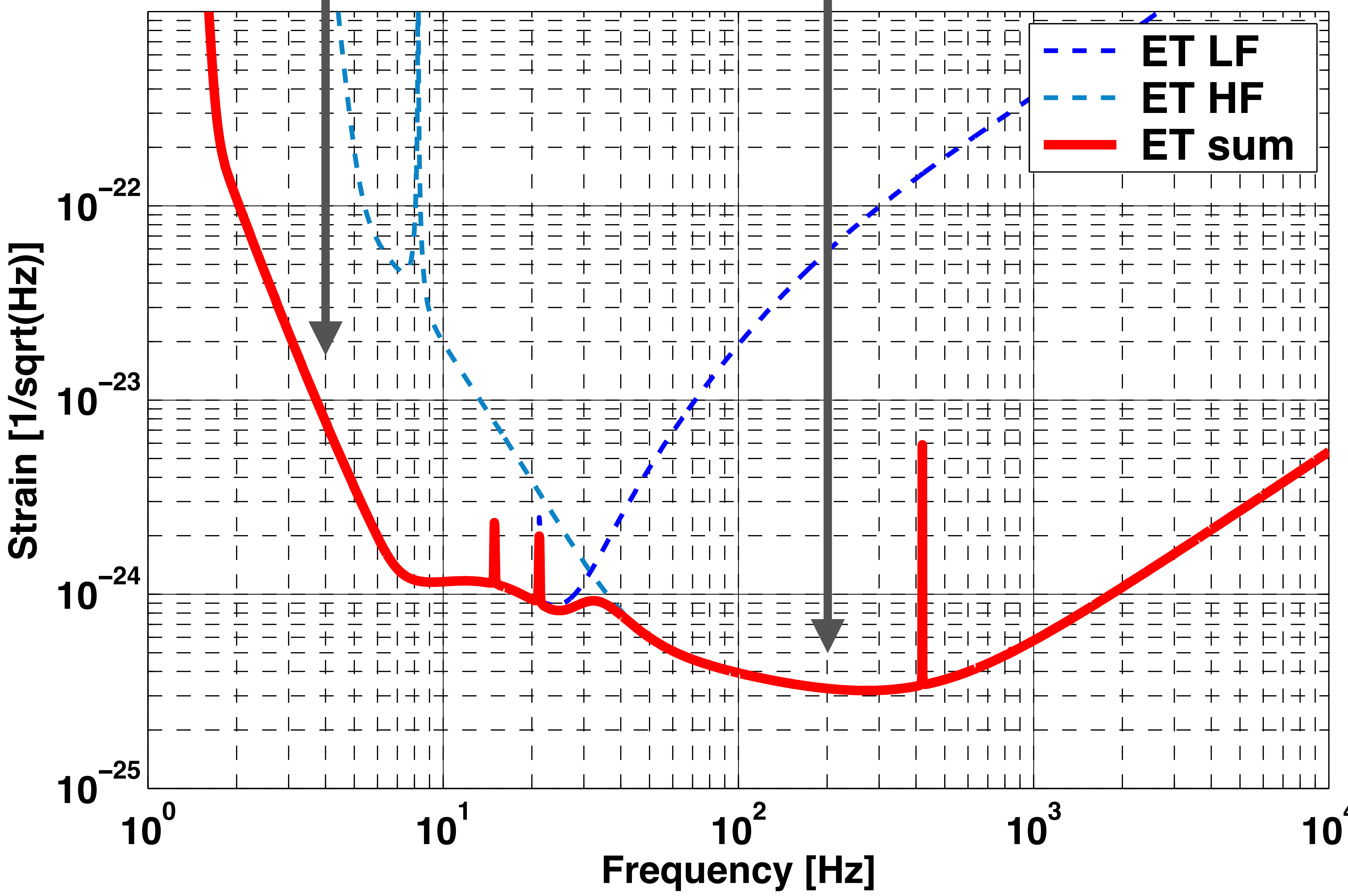


Technologies for ET sensitivity achievements

- ET-LF interferometer
- ET-HF interferometer

New **key technologies** in **cryogenics** and **cryo-vacuum**

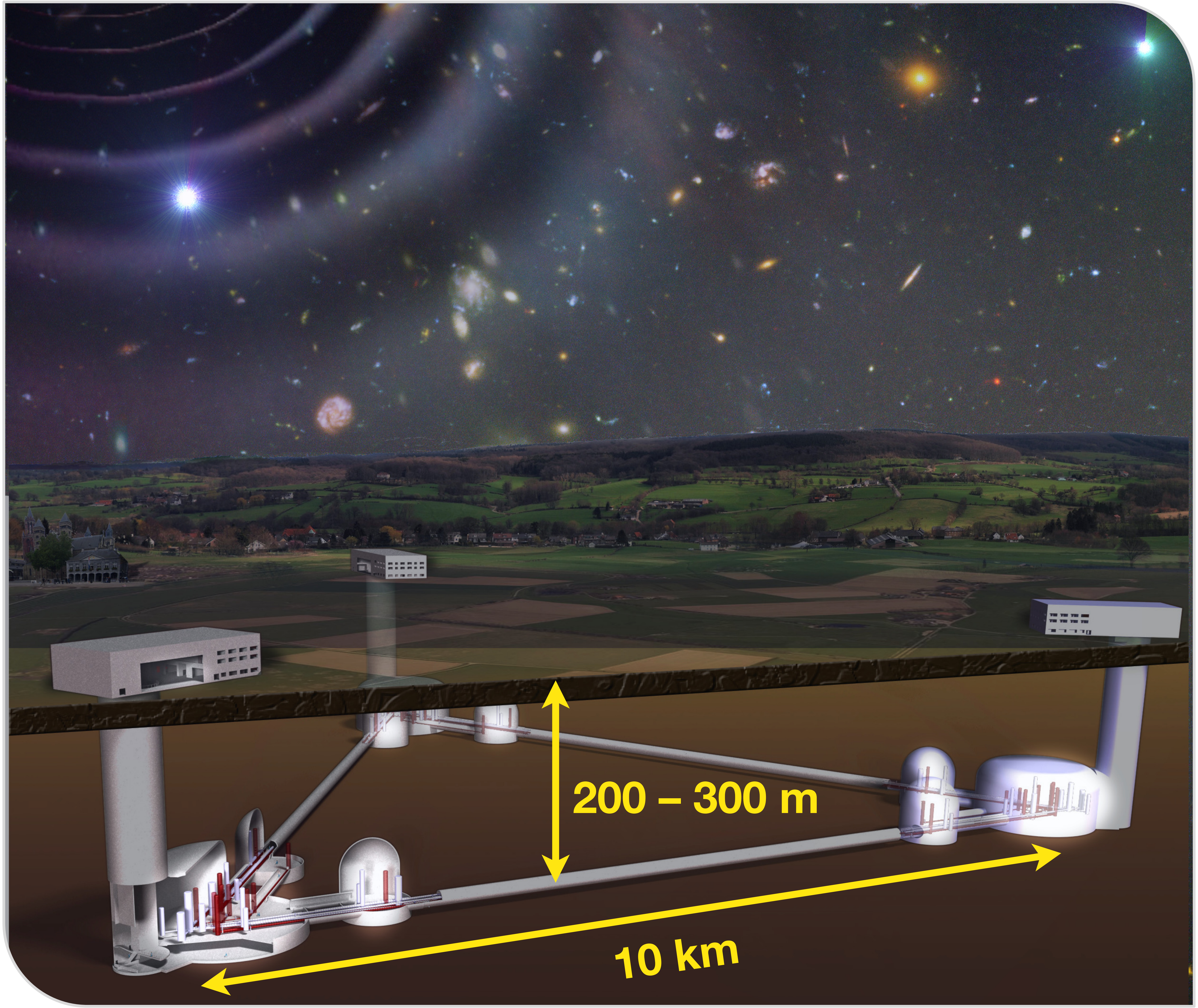
- Extreme ultra-low-noise cooling requirements
- Complex thermal noise behaviour
- New thermal shielding and cryopumping requirements



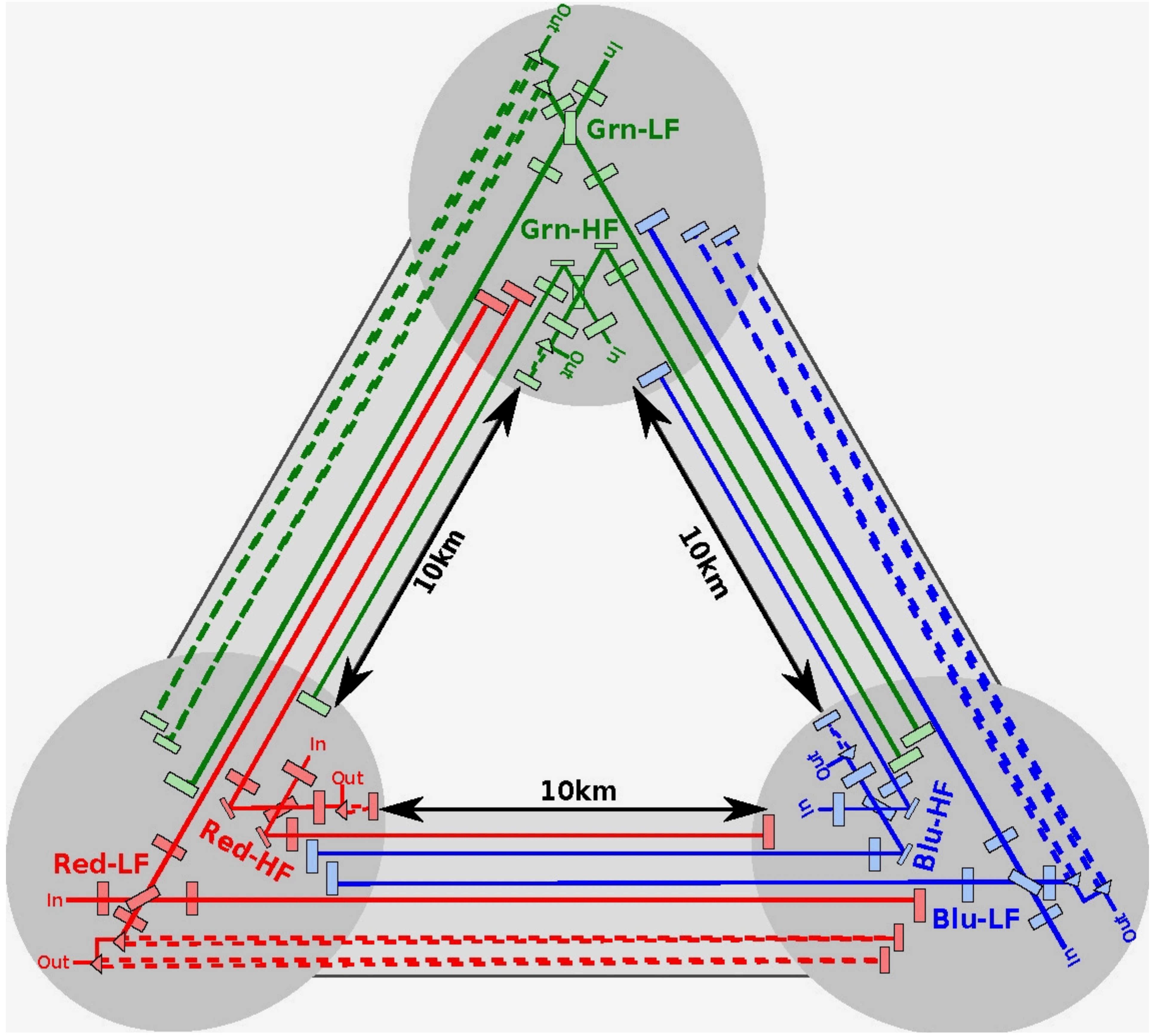
Advancement of 2G technologies

- Underground installation
- Longer pipe arms $(4 \rightarrow 10\,\mathrm{km})$
- Larger laser power
- Heavier test masses $(20 \rightarrow 200\,\mathrm{kg})$
- …

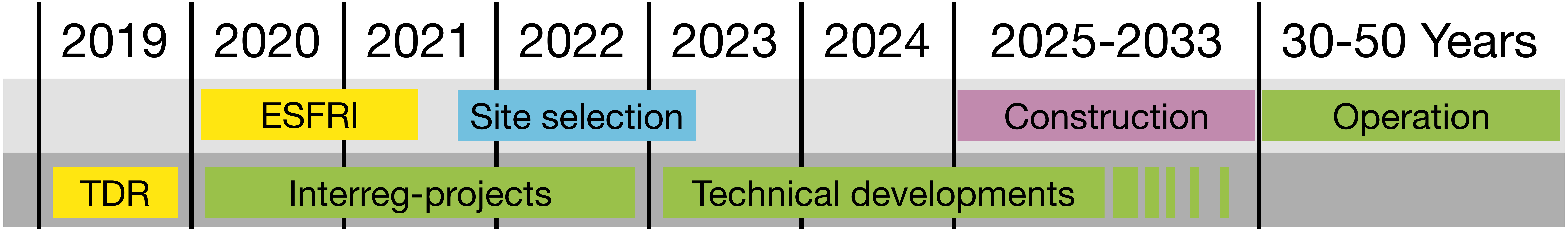
Layout of the Einstein Telescope (3G)

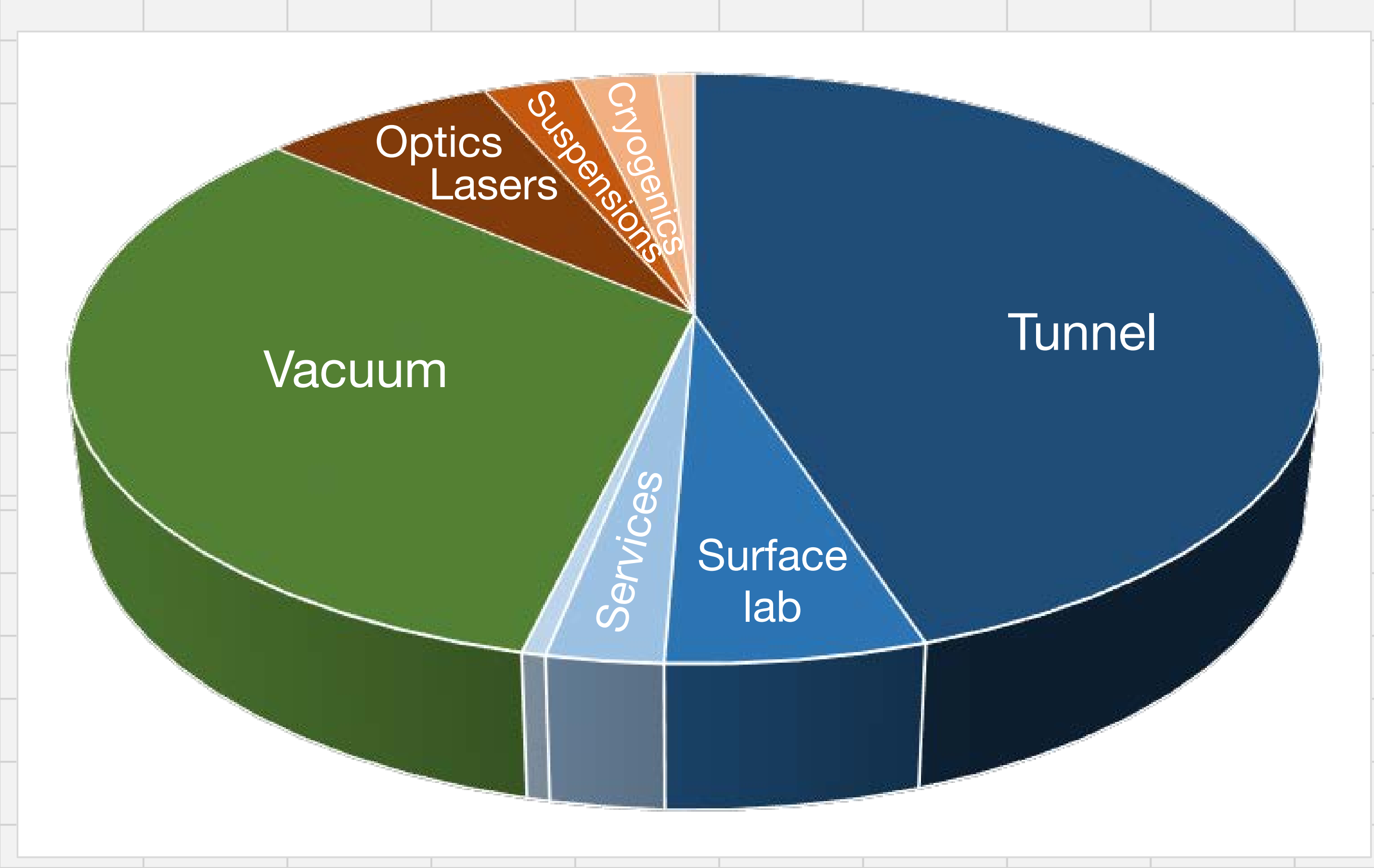


Xylophone design of ET



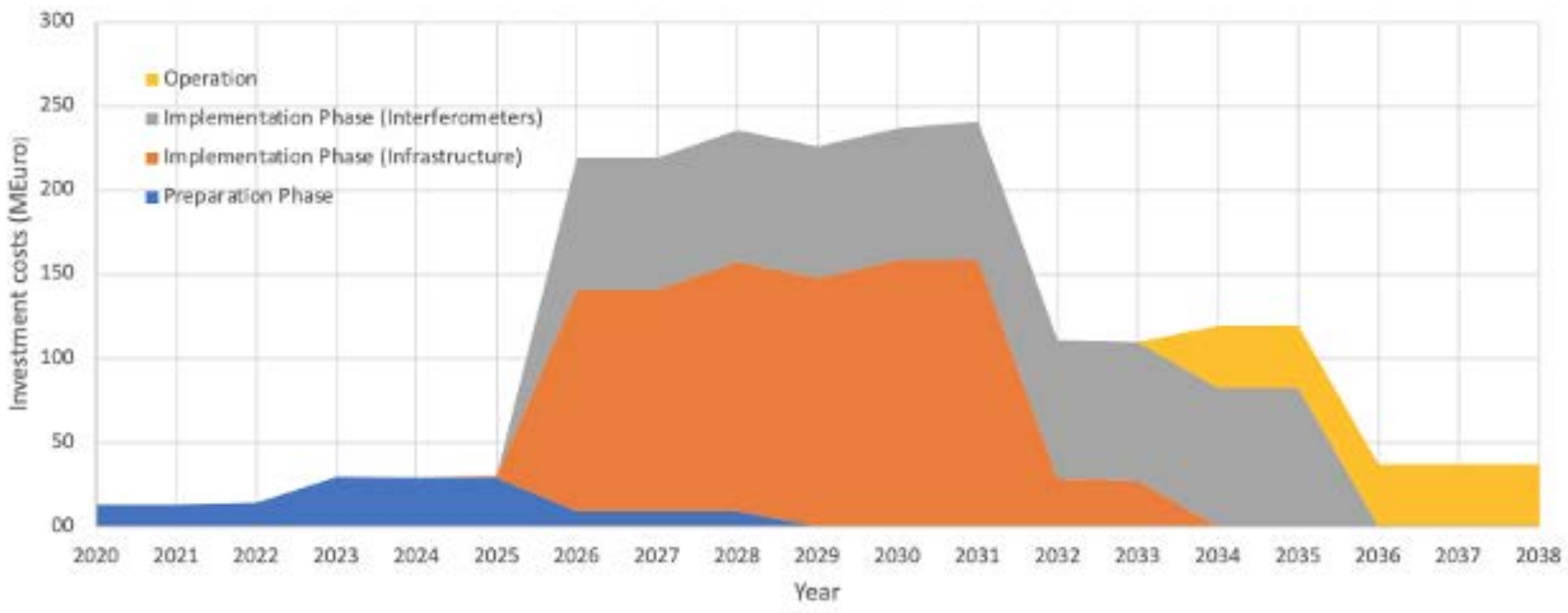
Time scale and cost (from ESFRI proposal)





	Full	Start
Tunnel	781 M€	781 M€
Surface Lab	98 M€	98 M€
Underground Services	44 M€	44 M€
Direction	9 M€	9 M€
	932 M€	**932 M€**
Vacuum Systems	566 M€	189 M€
	566 M€	**189 M€**
Optics & Lasers	125 M€	42 M€
Suspensions	48 M€	16 M€
Cryogenics	45 M€	15 M€
Installation	20 M€	7 M€
	238 M€	**79 M€**
	1.74	**1.20**

Mrd. €



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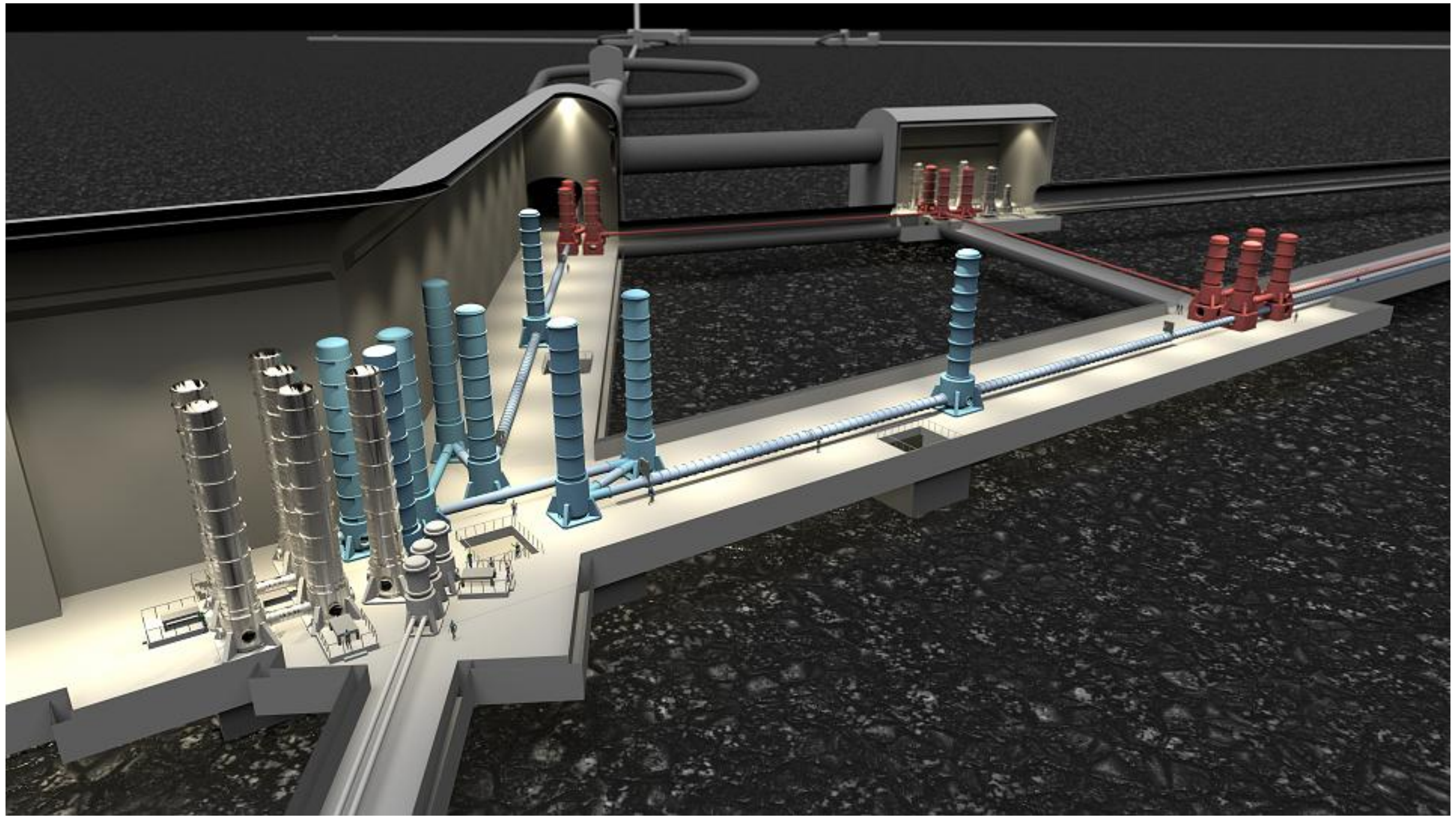

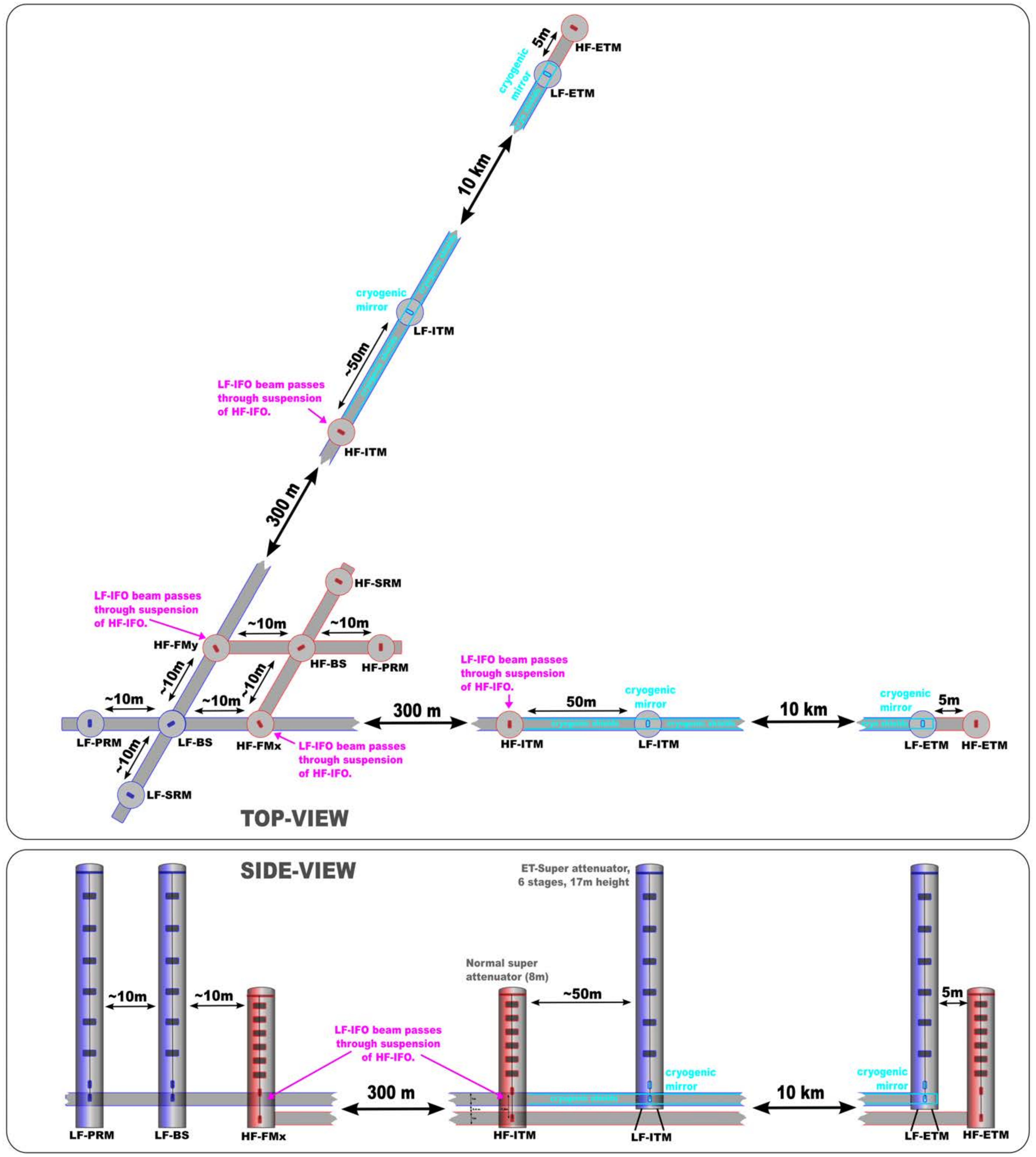

CRYOGENIC DEVELOPMENTS TOWARDS ET

Overall vacuum requirements

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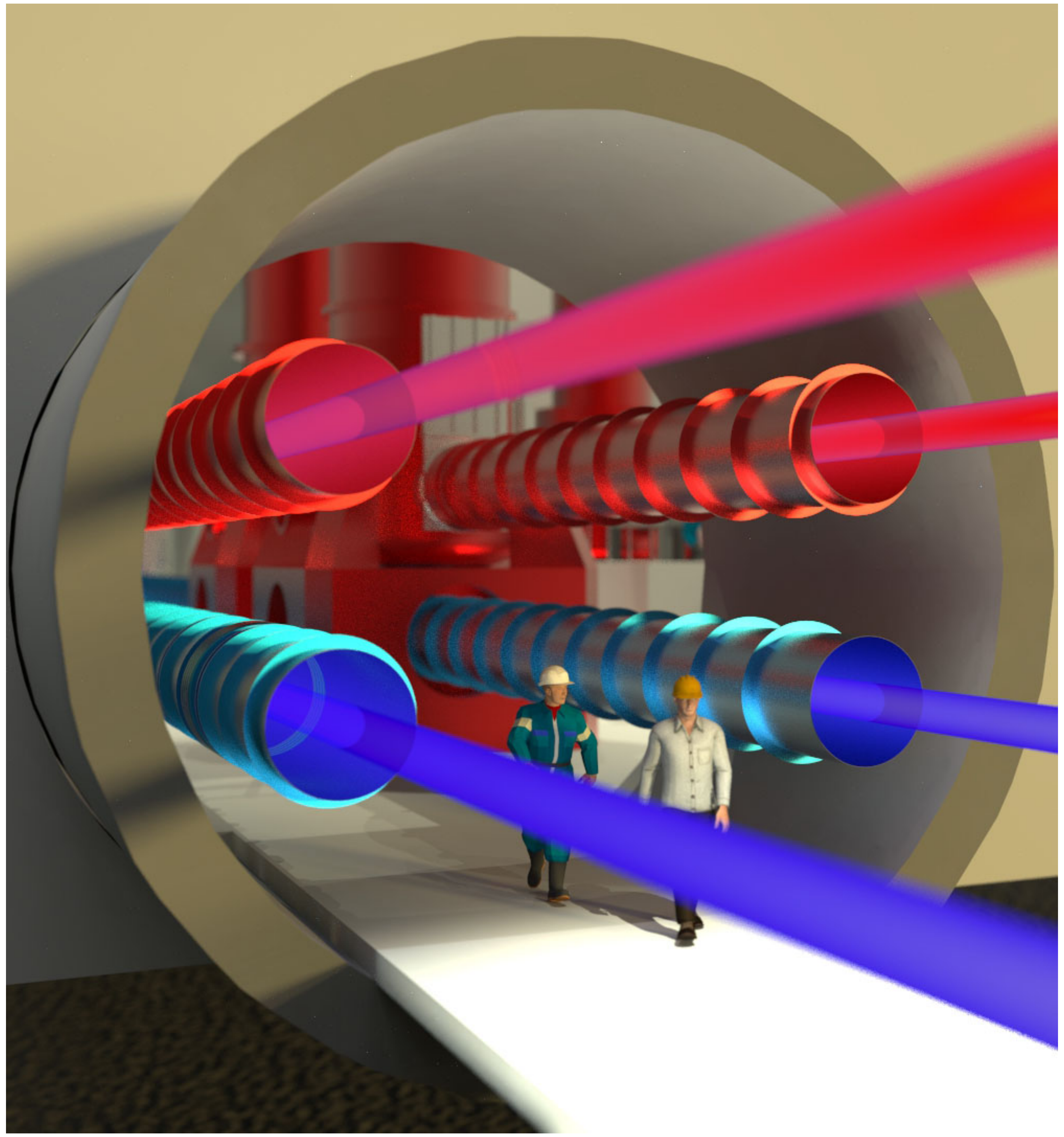
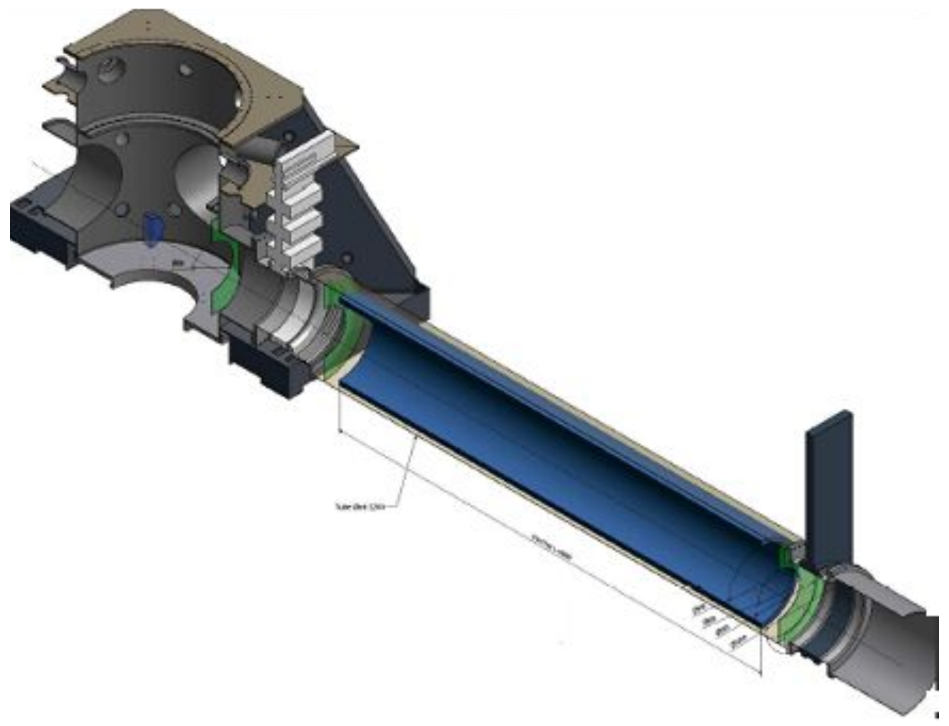
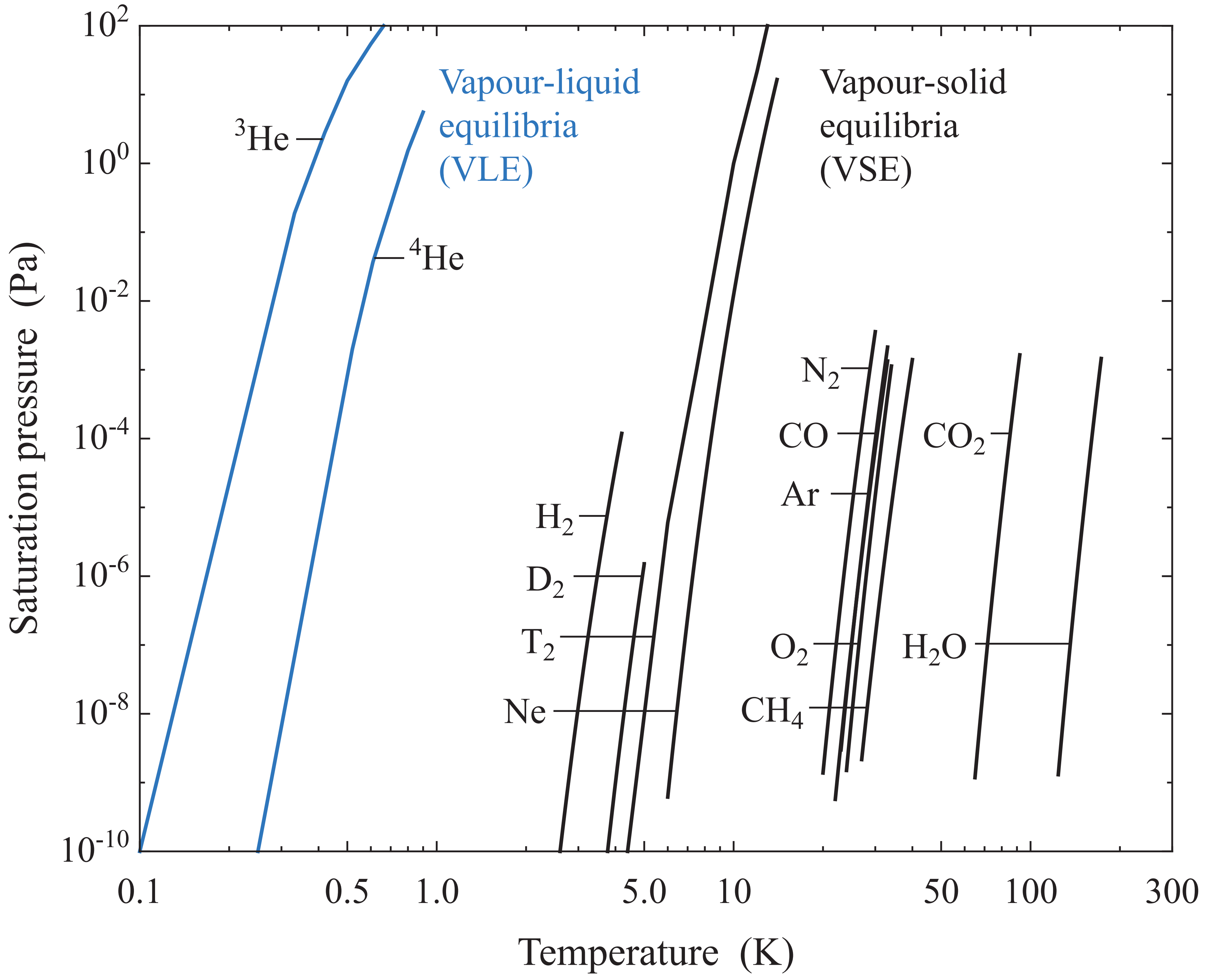
- **Arm pipe vacuum** of $p < 10^{-10}\,\mathrm{mbar}$ required at room-temperature in order to limit phase noise
  - Very challenging requirements
  - Need for sophisticated and reliable **bake-out** procedures and/or **coating developments**
  - Trade-off between **investment vs. operation**, i.e **outgassing** of SST / mild steel vs. **pumping** effort
  - Large cost impact
- Extremely low $p_\mathrm{i} < 10^{-14}\,\mathrm{mbar}$ of organic components
  - No use of **MLI**
  - **Differential pumping** between upper parts and final stages of super-attenuators due to material incompatibilities



Cryogenic vacuum requirements

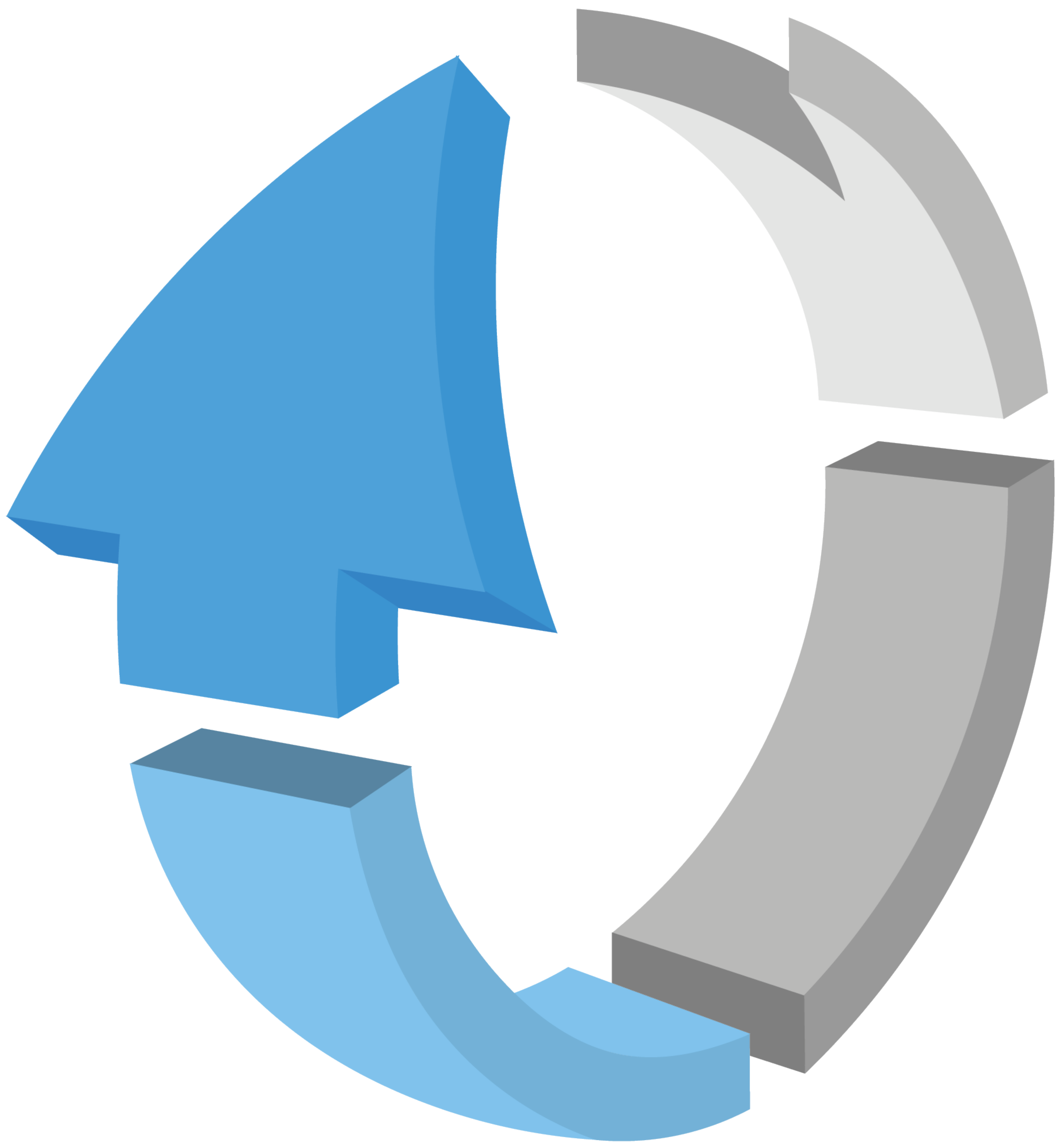
- Limitation of **particle flux from arm pipes to detectors (ET-LF** and ET-HF)
  - Up to **50 m long cryotraps** operated at (**20**)50–80 K
- **Adlayers on cryogenic mirror surfaces**
  - **Adsorption** of residual gas molecules on cryogenic mirror surfaces **cannot be avoided** completely
  - Partial pressure of $p_{H_2O} < 10^{-11}\,\mathrm{mbar}$ needed in the cryostats to **limit frost layer formation** on the optics
  - Concept: Cryogenic shielding at $T_{Shield} < T_{Optics}$
  - Development of **desorption strategies**





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

Cryo-vacuum R&D subjects for ET



Design of shielding systems
- Cryotraps, inner and outer thermal shields
- Geometries, temperatures, surface emissivities...
- Cooling scenarios

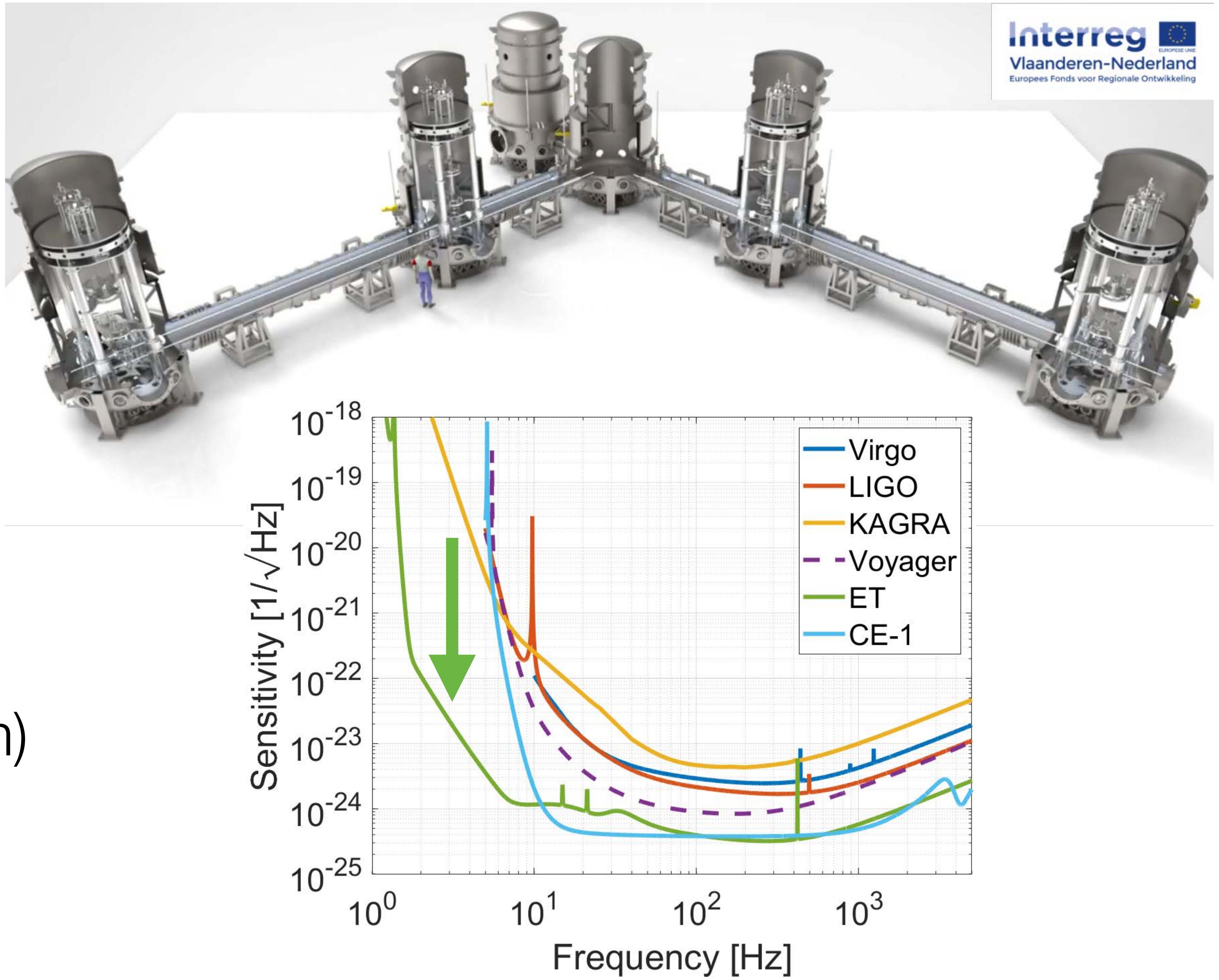
Gas background simulations
- Gas loads from arm pipes with warm/cold transition
- Gas loads from cryostat walls and upper tower

Frost mitigation strategies
- Passive methods (base pressure)
- Active methods (thermal and non-thermal)

Experimental verification
- Materials and procedures (outgassing)
- System performance tests (test cryostats)

ETpathfinder @ University of Maastricht

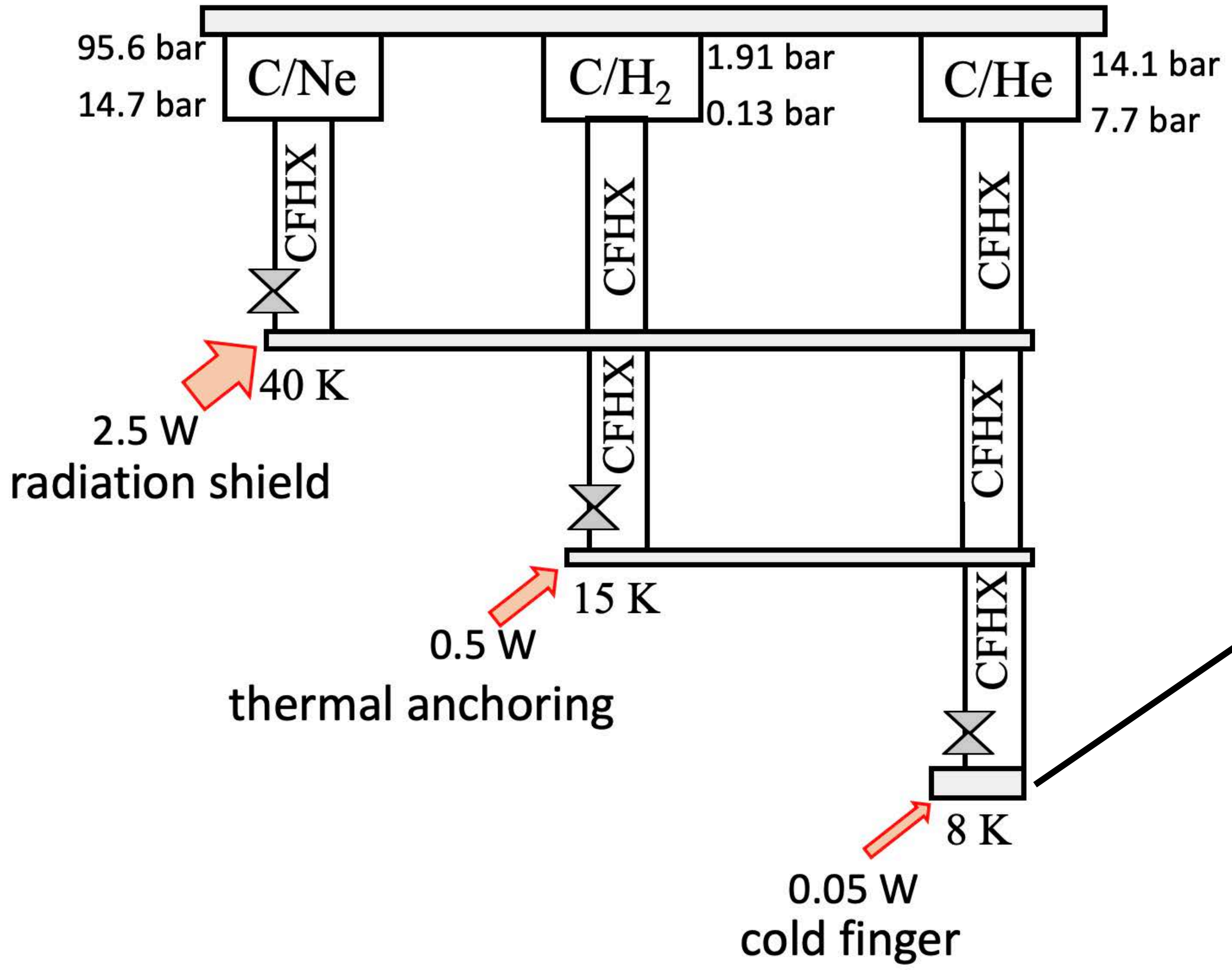
- Most of the spectacular science of ET is based on the ET-LF sensitivity improvement
  - Full-interferometer setup
- Key technology aspects
  - Silicon mirrors
  - **Cryogenics**
  - **Water/ice management**
  - Mirror coatings
  - „New“ wavelengths (1550 and 2090 nm)
- Open for experts to join
  - www.etpathfinder.eu

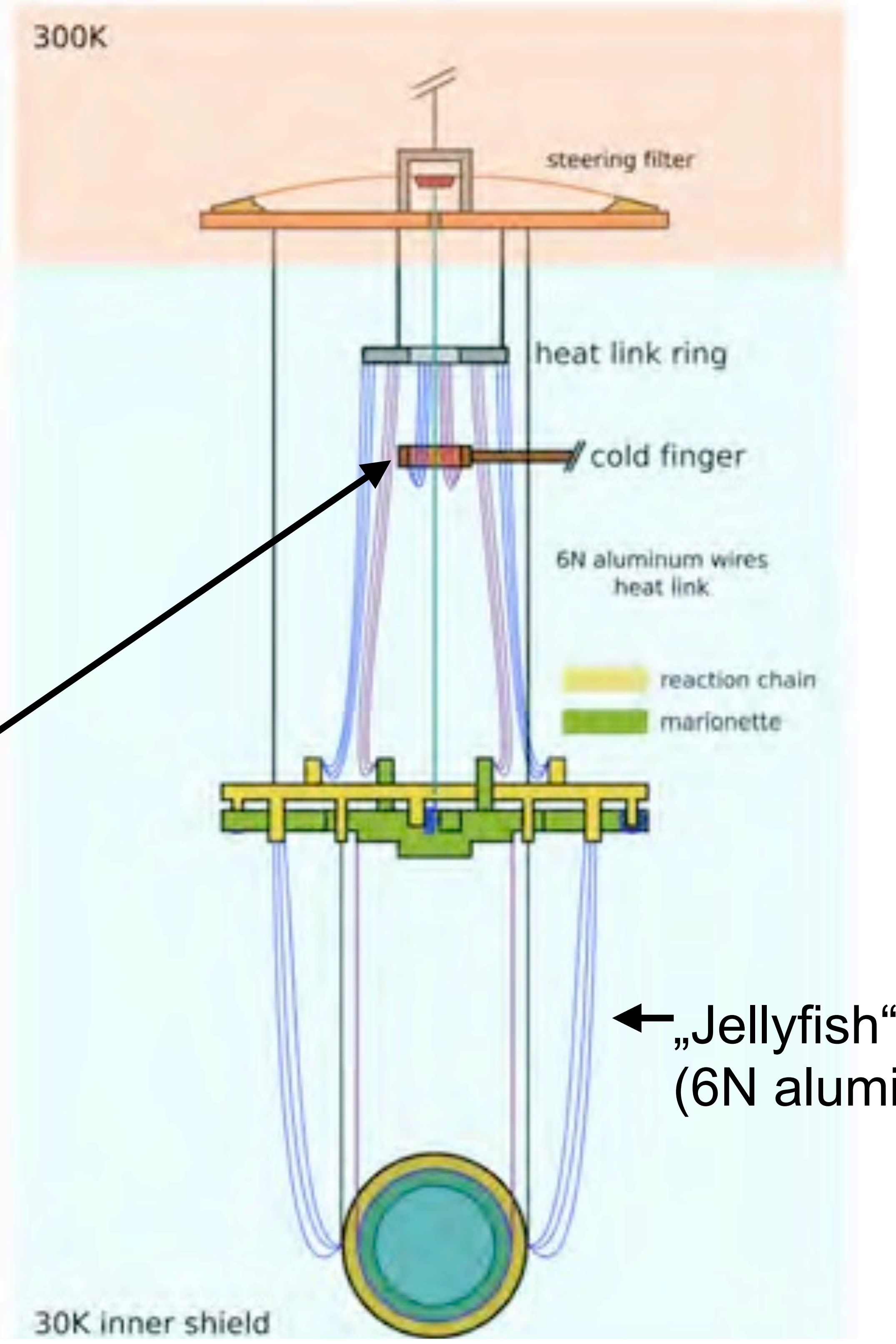


ETpathfinder – Cooler chain and cryogenics

- Sorption cooler development @ **University of Twente**

T heat sink	Ne	H_2	He	Total
70 K	12 cells 184 W	5 cells 87 W	6 cells 65 W	23 cells 35 liter 336 W

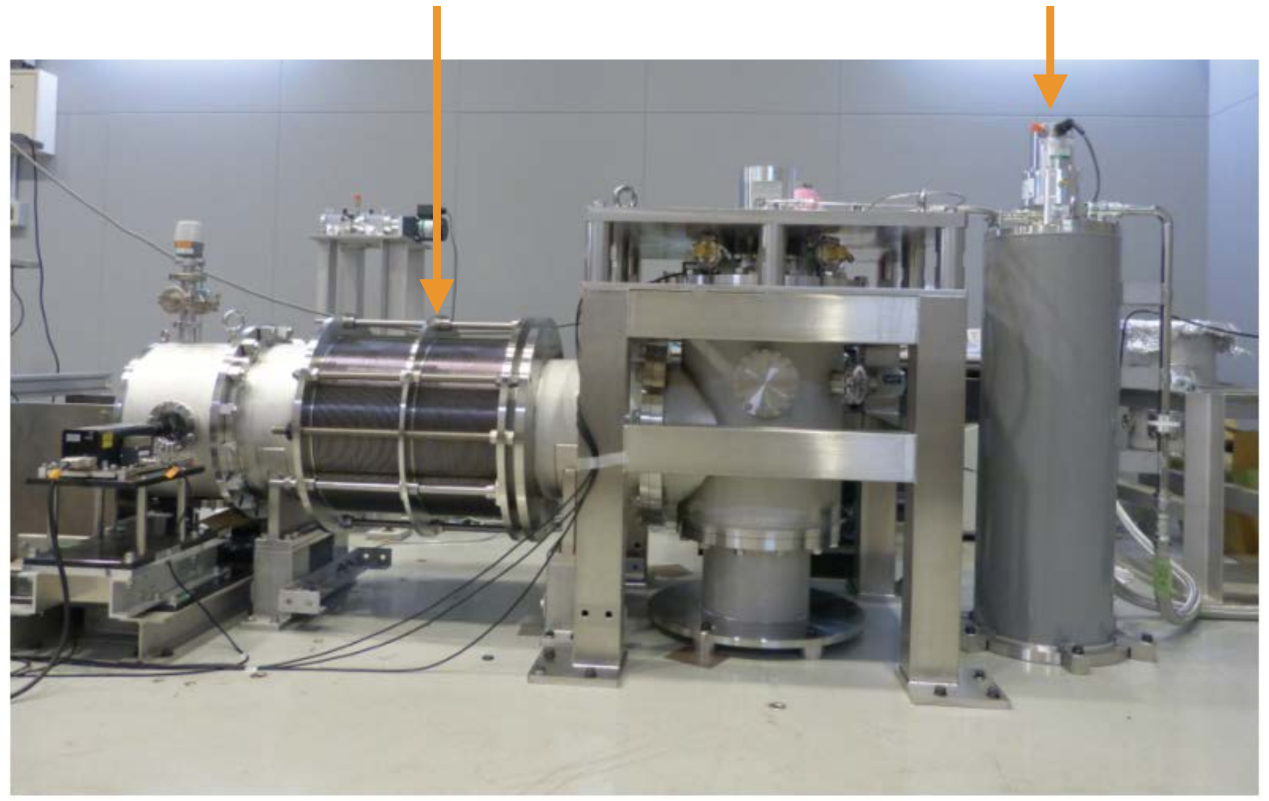




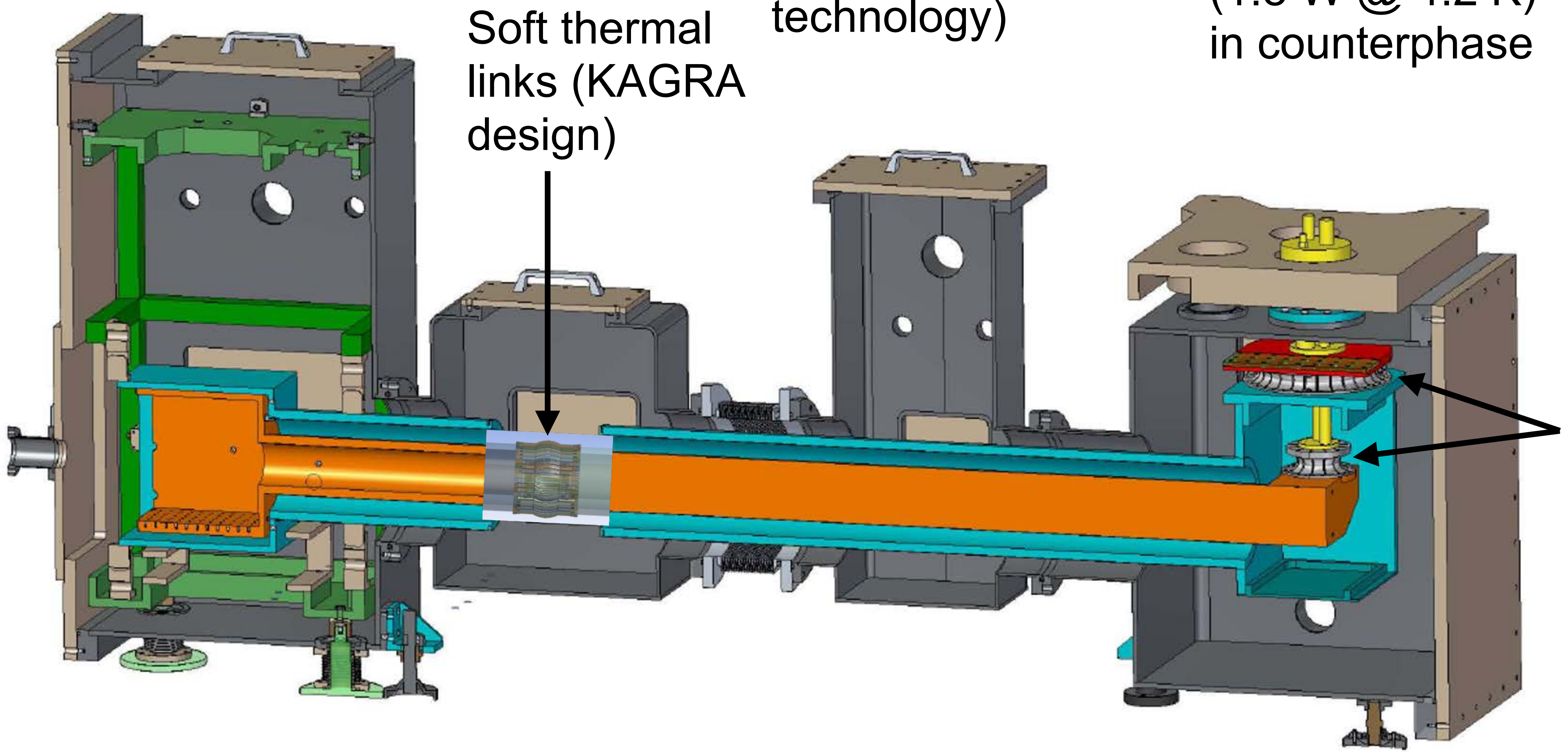
„Jellyfish“ heat links (6N aluminum)

ET-LF detector cooling with PT cryocoolers

- **Rome «La Sapienza» University** and **INFN Rome** Group has a 50 years tradition in cryogenics in GW detection
- **PT cooling station prototype** for ET mirror suspension test cryostat
  - Ongoing design
  - Construction / assembly 2022

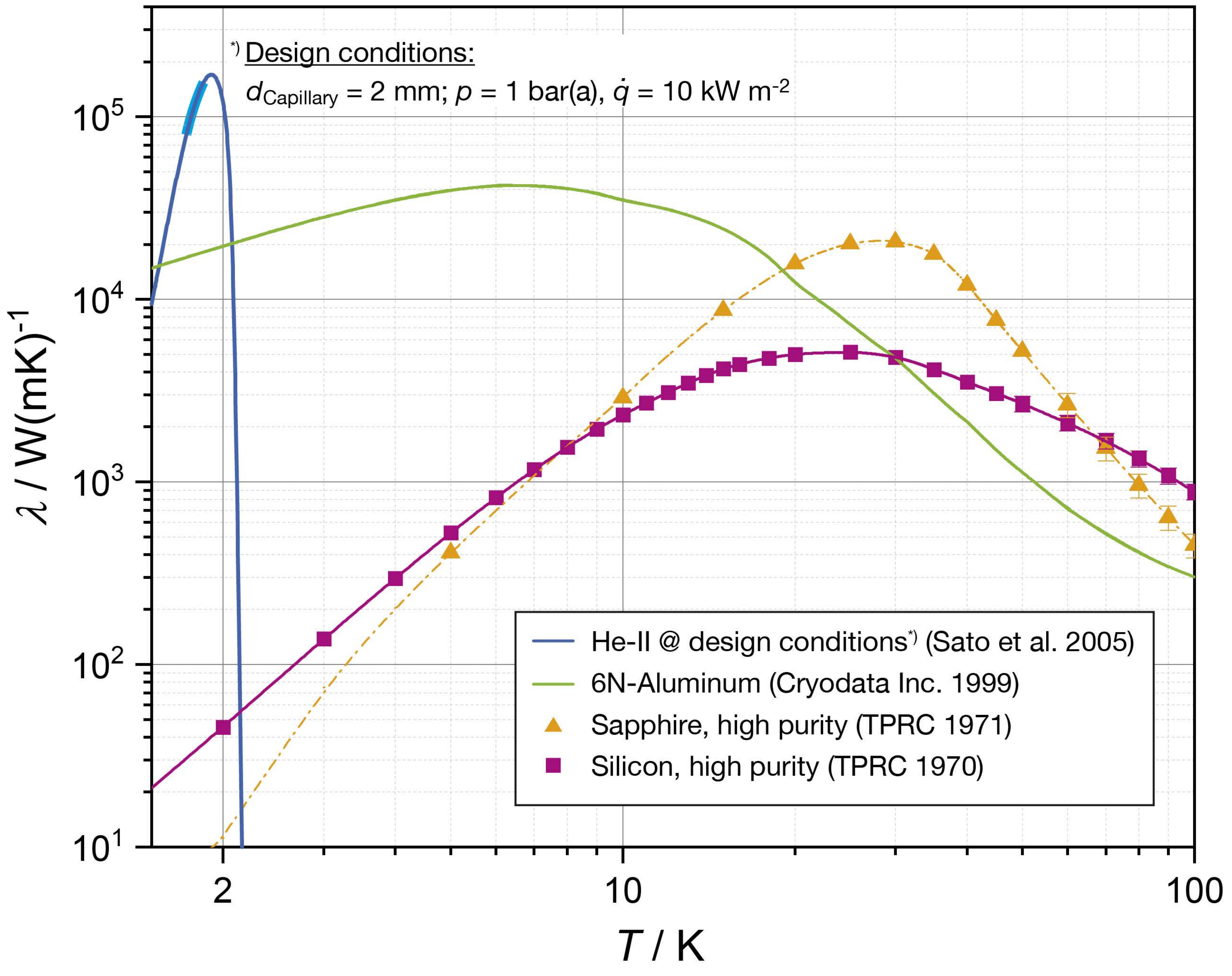


KAGRA design



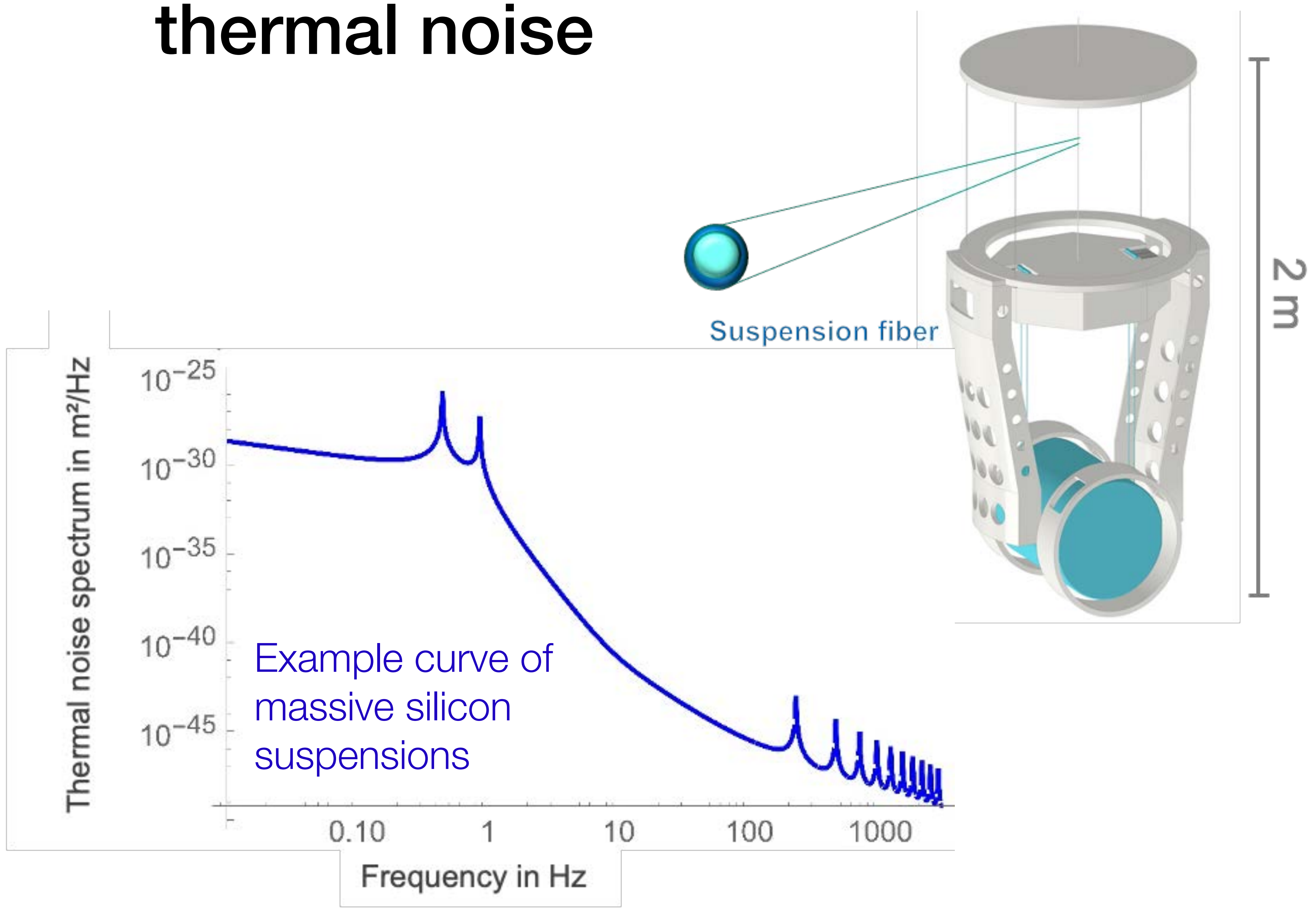
He-based detector cooling concept

- Motivation for **He-II detector cooling**
  - Large heat conductivity of the quantum fluid **He-II** by **steady-state heat conduction**
  - No macroscopic flow
  - No massive thermal links
  - **Ultra-low noise cooling development @ KIT**
- He-II implementation concept
  - Parallel capillaries between supply box and payload heat exchanger
    - $\lambda_{\mathrm{HeII}} = f(d, p, \dot{q})$
    - $L \approx 10\,\mathrm{m}$

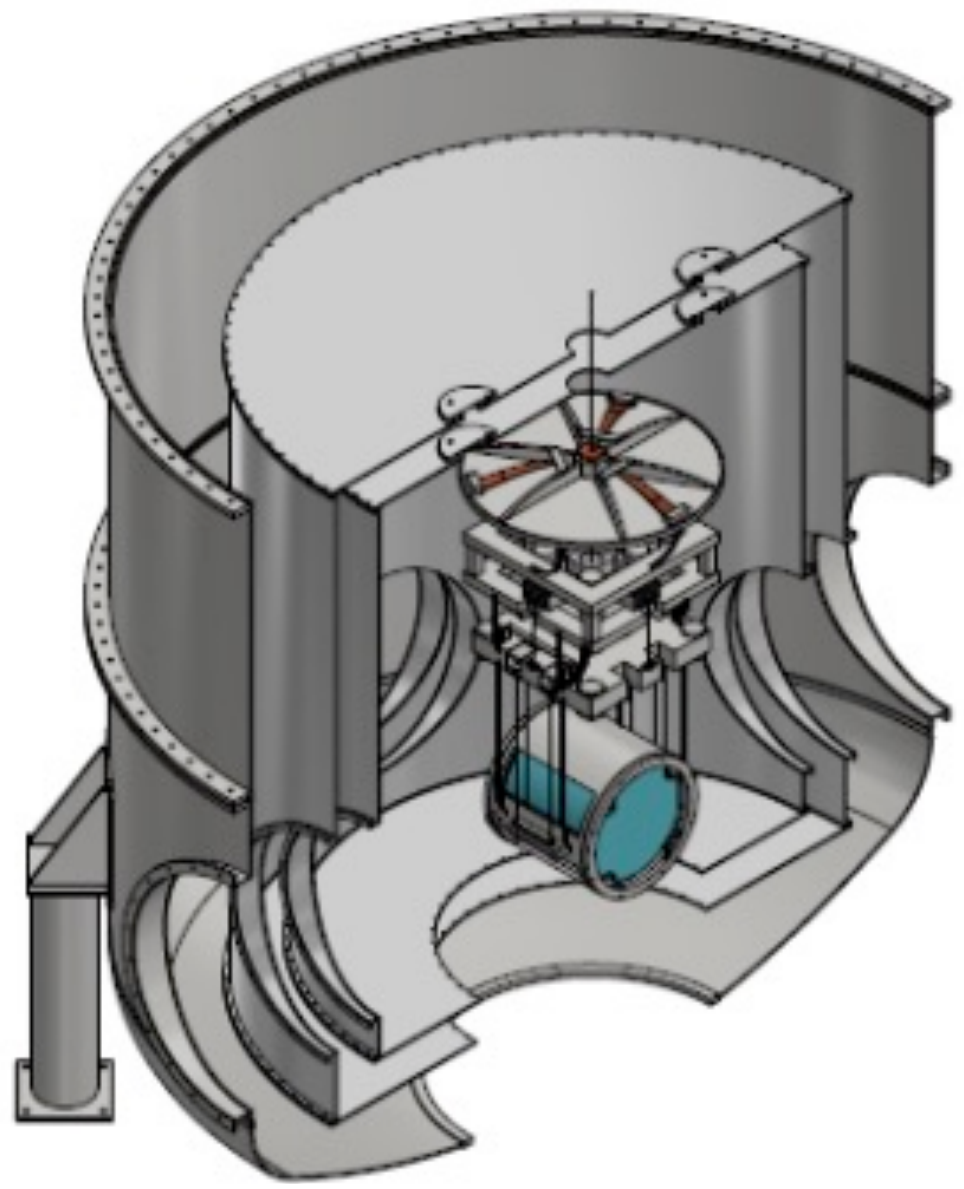


He-based detector cooling concept

- Detector cooling through **He-II filled hollow suspension fibres**
  - Theoretical modelling of **suspension thermal noise**

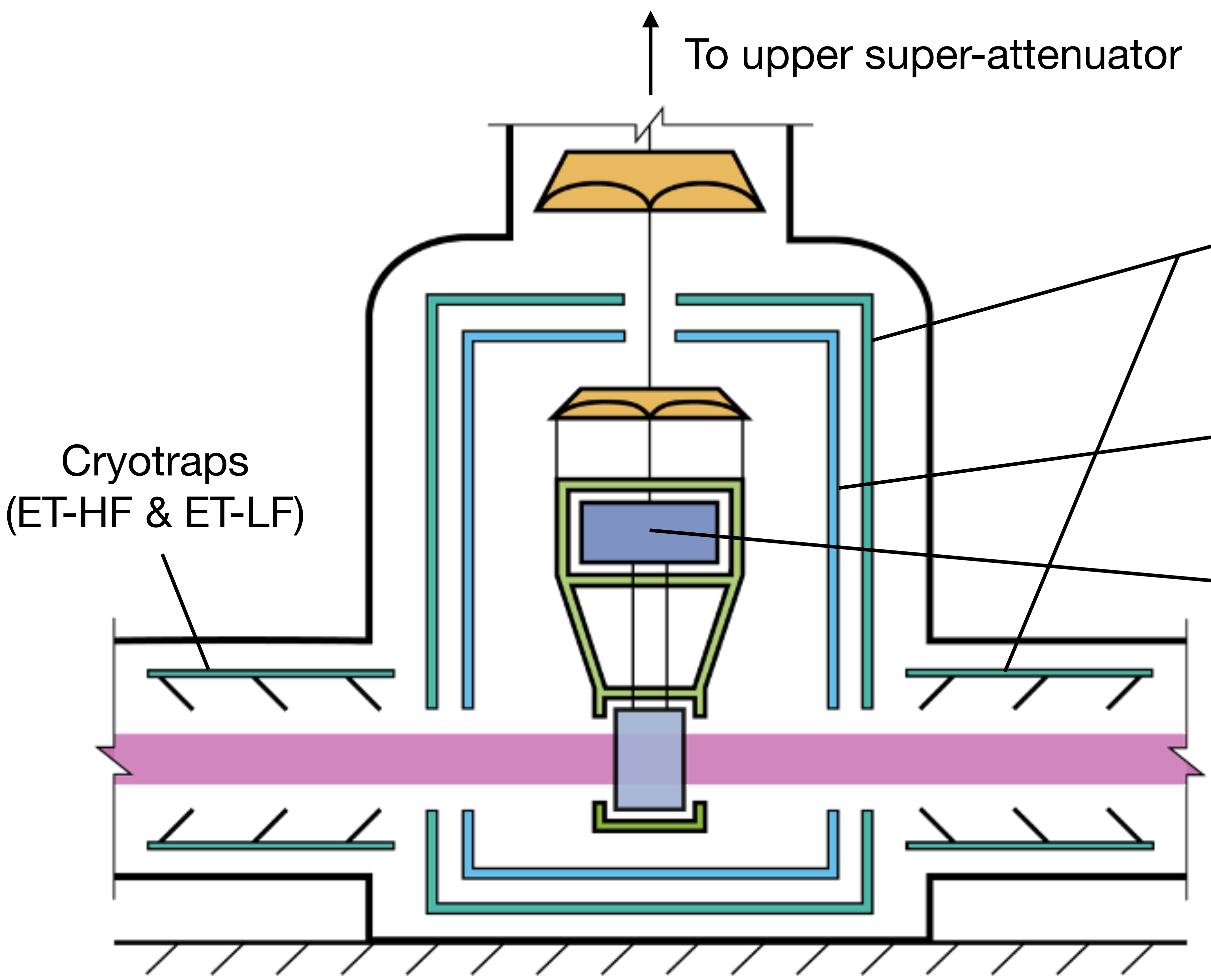


- Concept for **He-based test cryostat**
  - Single-phase He cooling of **cryotraps** and **thermal shields**
  - **He-II cooling** of payload heat sink and possibly payload suspensions



Summary of cryogenic requirements per tower

- ET-LF cryostat scheme

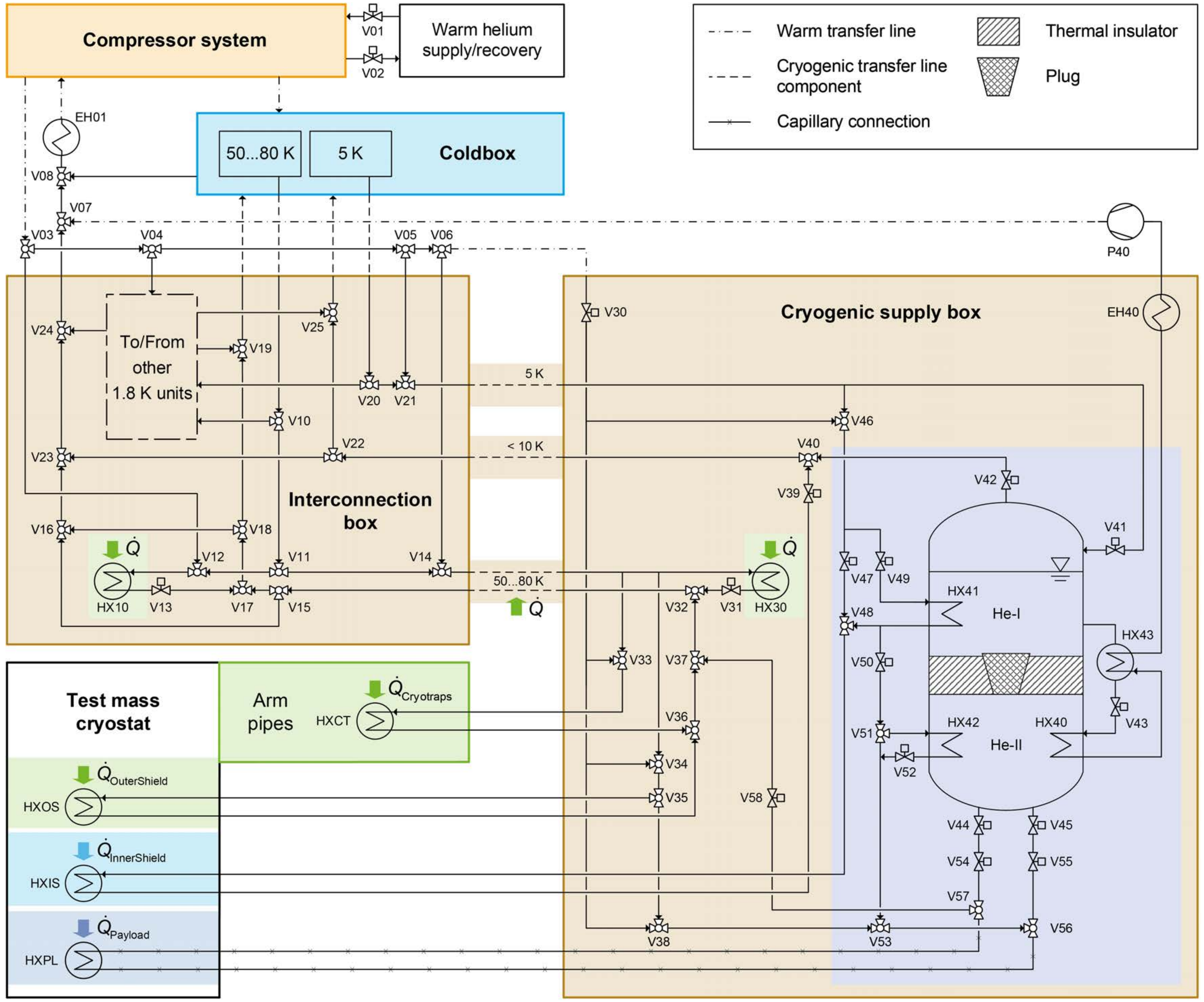


Components	ET-HF	ET-LF	Temperature level	Estimated cooling power
Outer thermal shields and cryotraps	X	X	(20) 50…80 K	x…10^4 W
Inner thermal shields		X	5 K	x…10^2 W
Payload heat sinks		X	2…10 K *)	x…1 W

*) Depending on detector cooling option

> No use of MLI due to vacuum constraints!

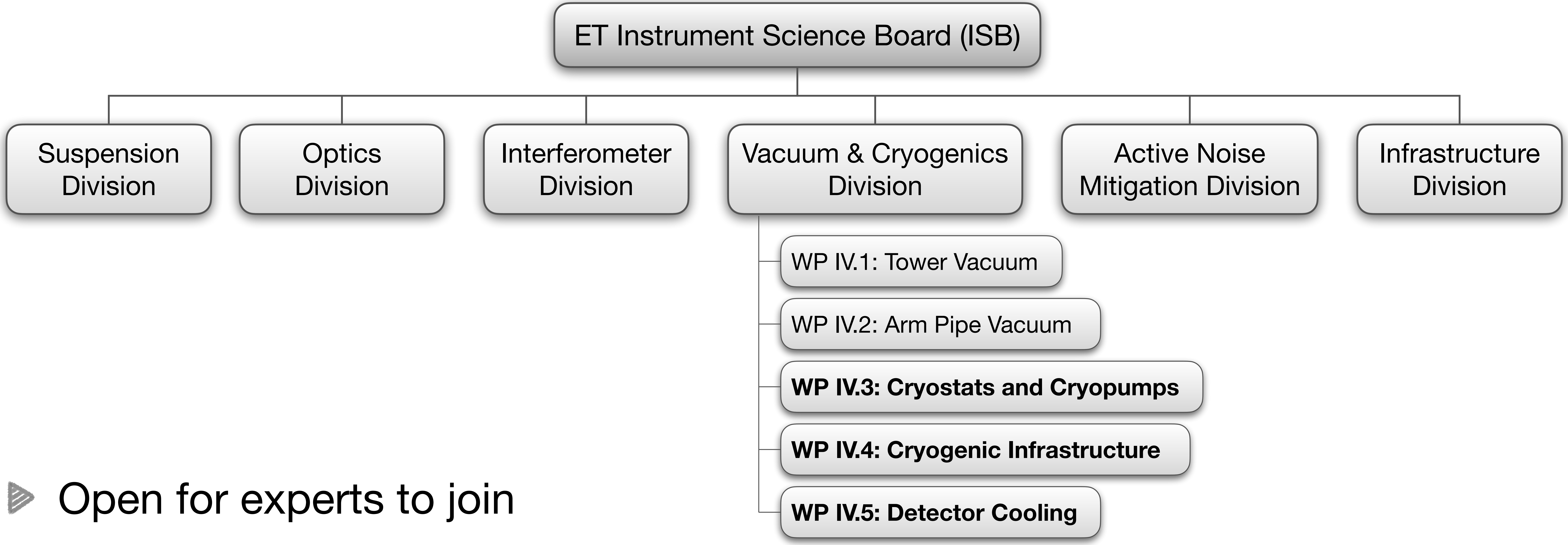
Cryogenic infrastructure concept



- 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 of cryotraps / outer shields
  - 1-phase cooling of inner shields
  - Optional He-II detector cooling

Reference:
L. Busch, S. Grohmann: Conceptual Layout of a Helium Cooling System for the Einstein Telescope. Procs. CEC/ICMC 2021. To be published.

Coordination in the ET Instrument Science Board



- Open for experts to join
- **Et-isb-vac-cryo** mailing list:
  - Register at https://mail.ego-gw.it/mailman/listinfo/et-isb-vac-cryo


Thank you for your attention!