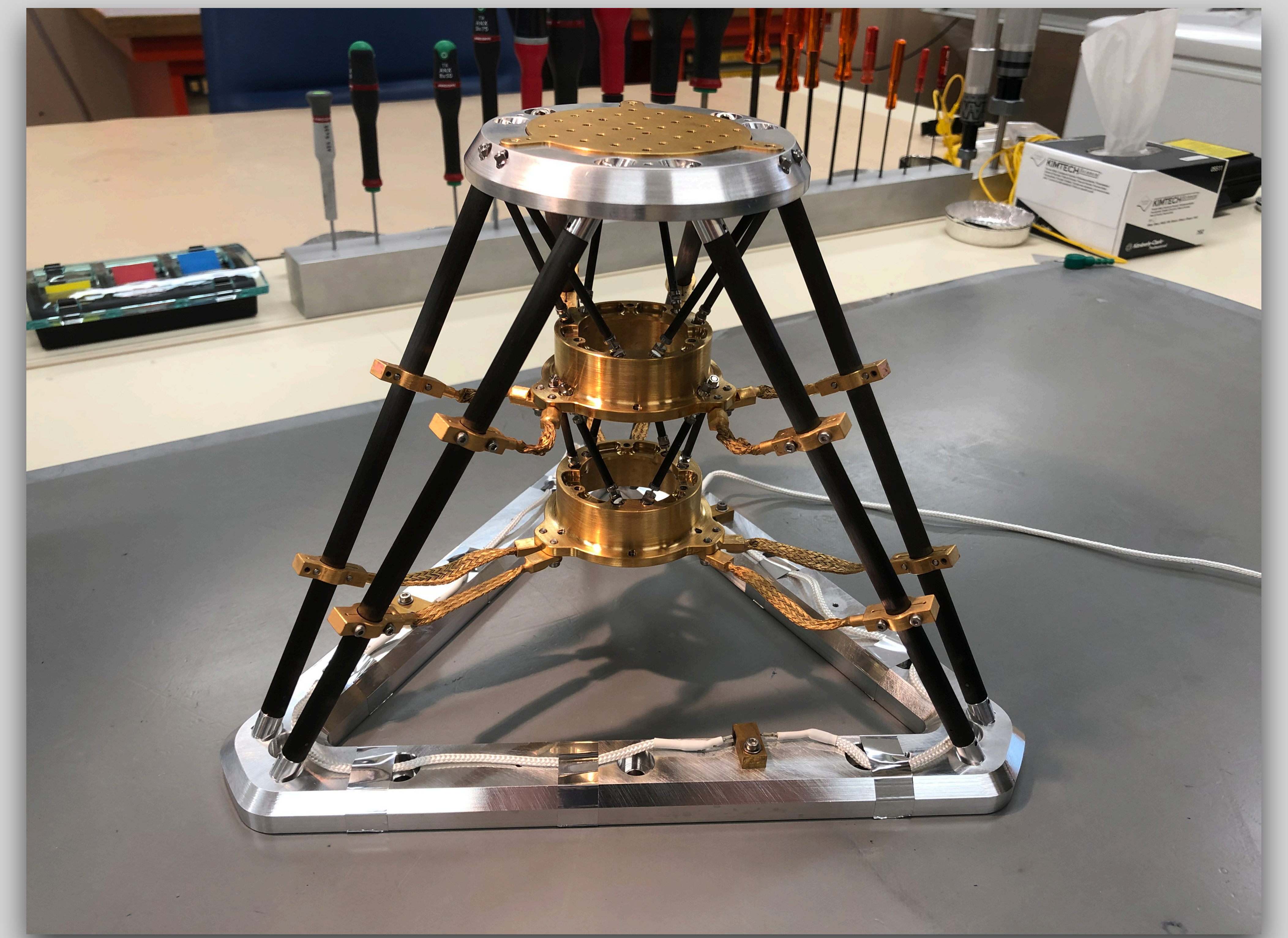
Colloque national CMB-France #6

December 18, 2024



Developing a Closed-Cycle Dilution Refrigerator for future CMB space missions

Focus on the Structural & Thermal Model

Valentin SAUVAGE

Institut d'**A**strophysique **S**patiale, ORSAY, FRANCE

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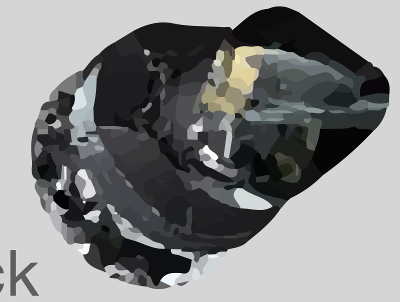
Context

Increase the sensitivity

CMB (anisotropies , E-modes, spectrum, …)


COBE


WMAP


Planck

Relikt-1
COBE
WMAP
Planck

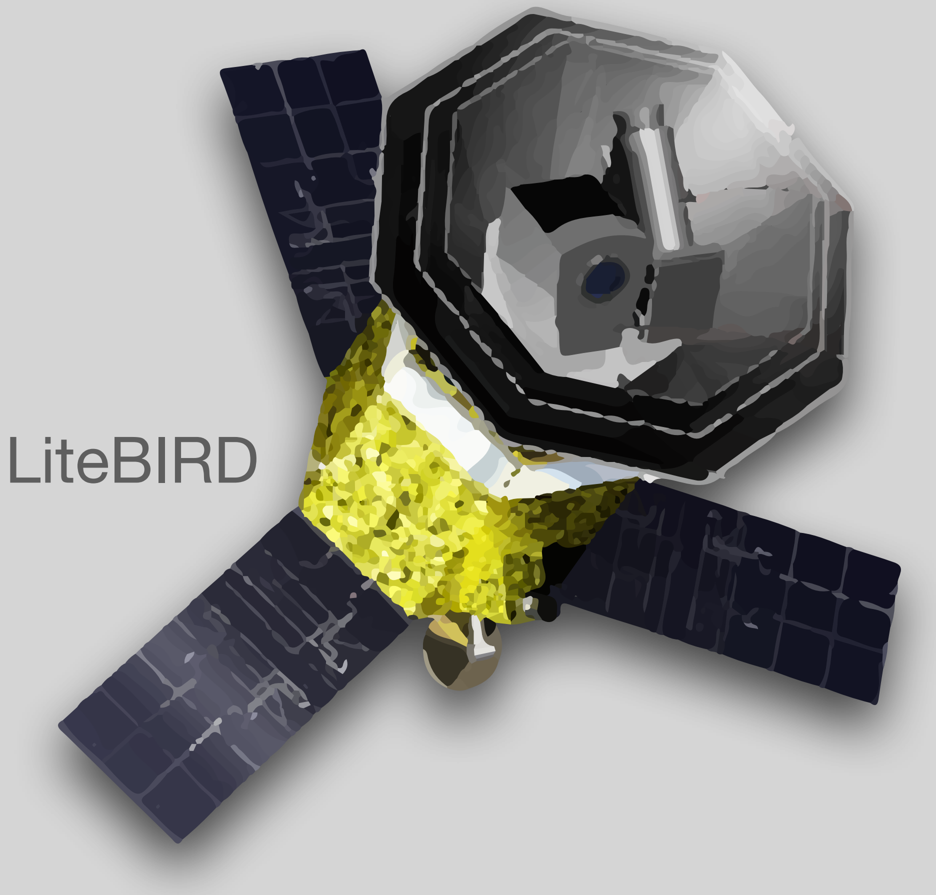
- **More detectors**
- **Less noises**
- **Longer observation time**

=

- **Continuous 100 mK for a longer time**
- **More cooling power**

Existing cryogenic sub-Kelvin system not suitable anymore

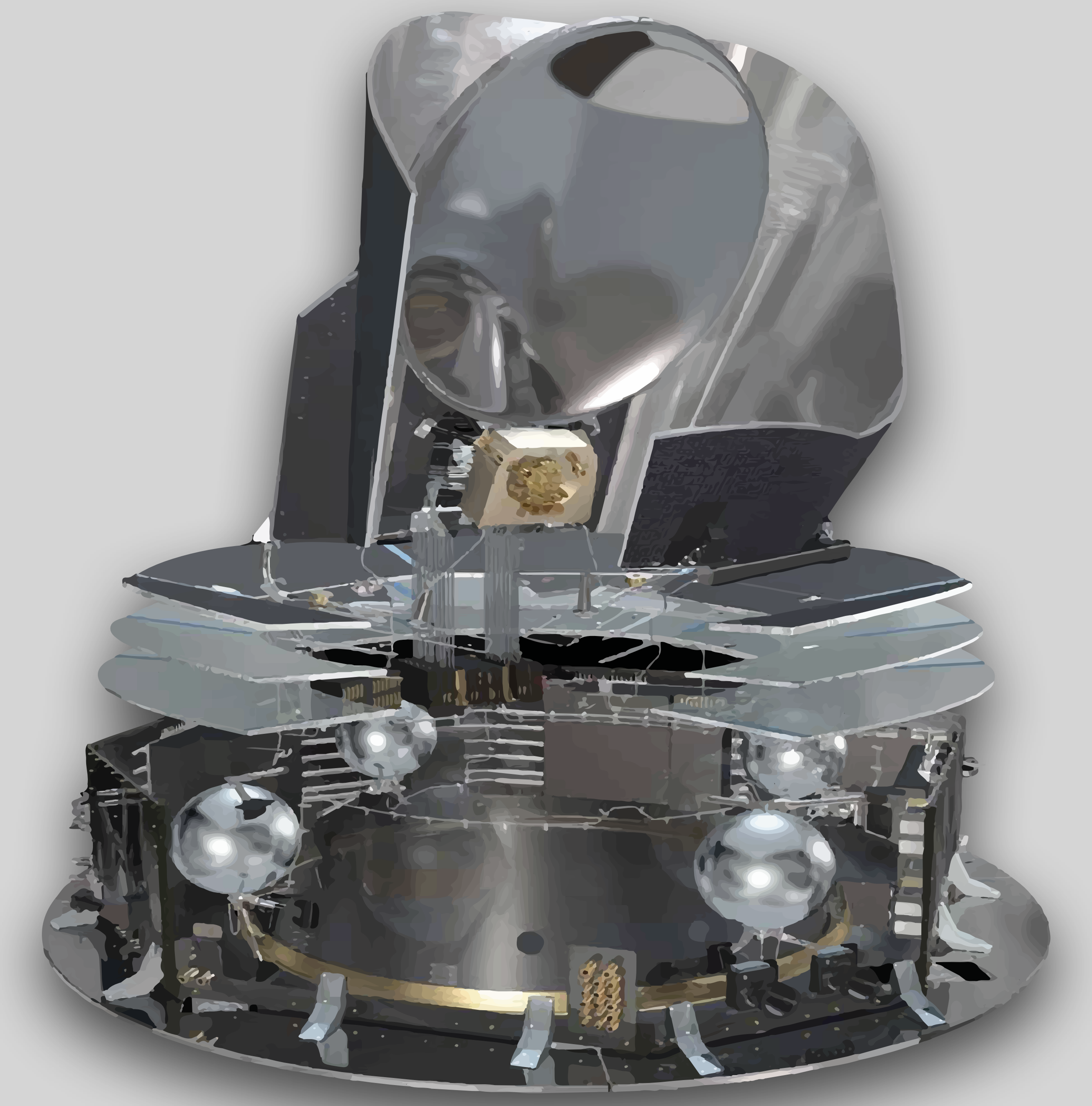
CMB B-modes
CMB spectral distortions


LiteBIRD

LiteBIRD
PRISTINE
FOSSIL

REJECTED ONGOING ENDED

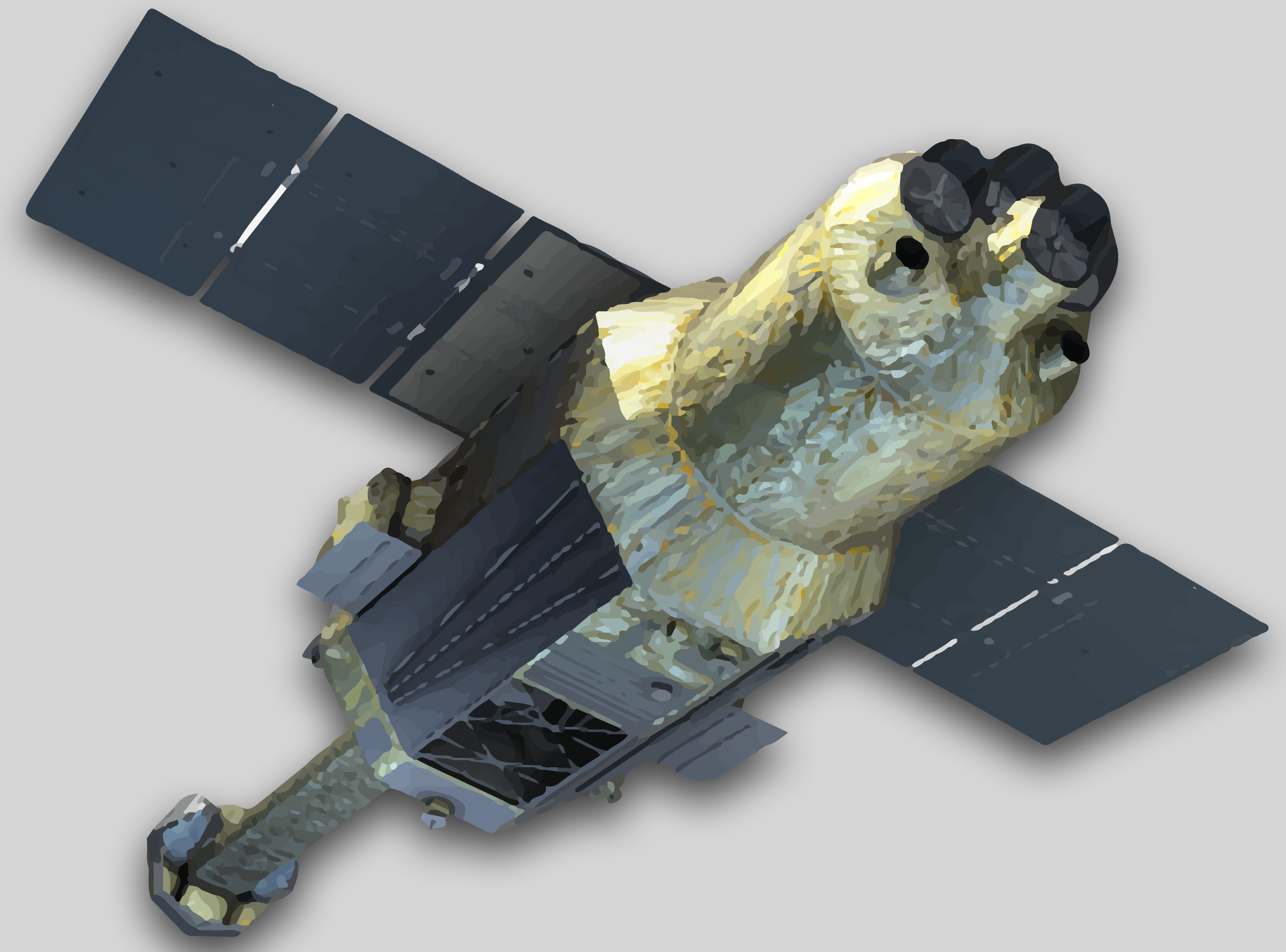
State of the art : the existing solutions



Planck Space Telescope [1]

100 mK

Open-**C**ycle **D**ilution **R**efrigerator



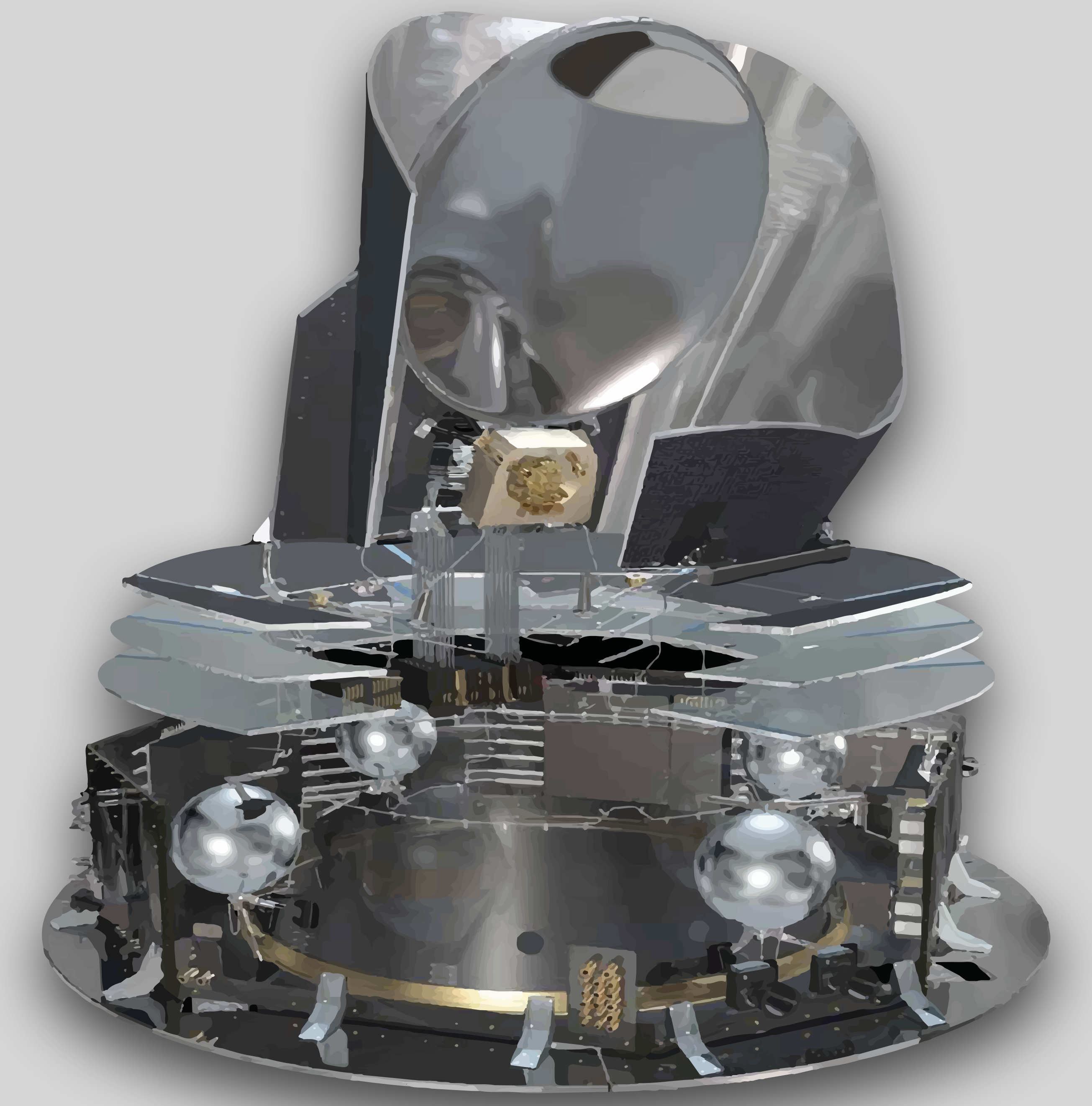
Suzaku Space Telescope [2], Hitomi Space Telescope [3], XRISM Space Telescope [4]

50 mK

Adiabatic **D**emagnetization **R**efrigerator

[1] Triqueneaux *et al.* [2006]
[2] Kelley *et al.* [2006]
[3] Shirron *et al.* [2016]
[4] Ezoe *et al.* [2019]

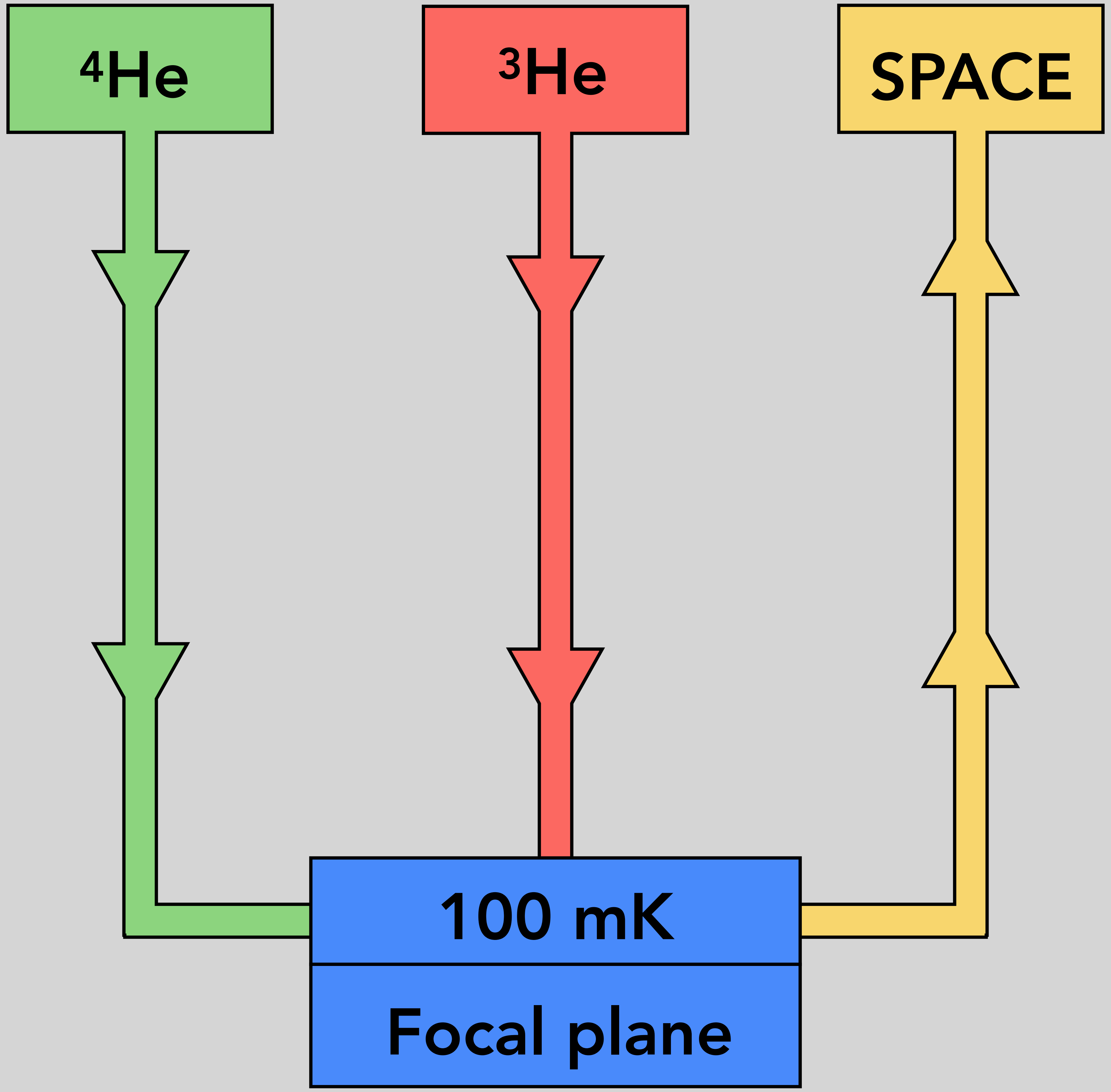
The Open-Cycle Dilution Refrigerator



Planck Space Telescope [1]

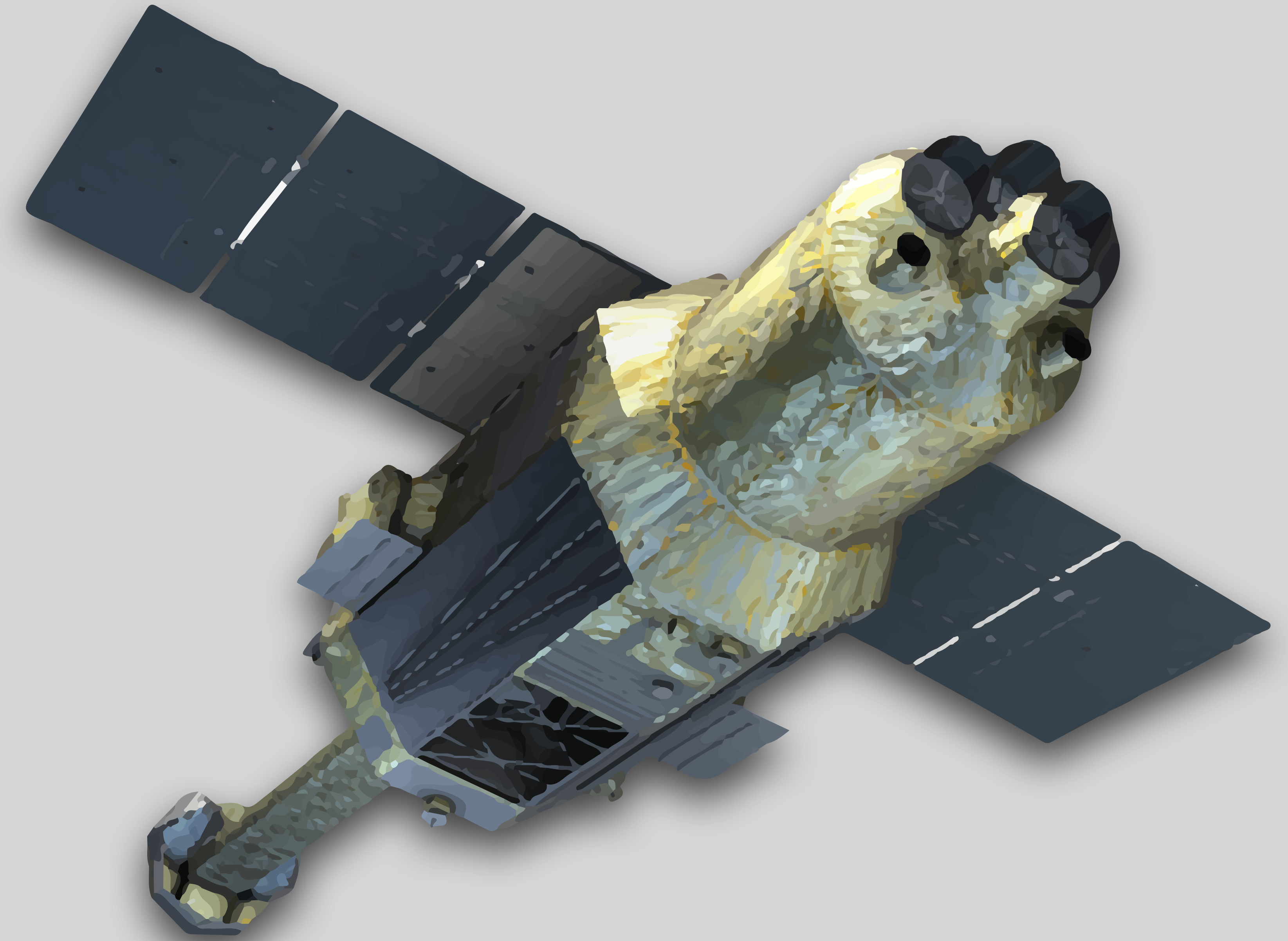
100 mK

Open-Cycle Dilution Refrigerator



[1] Triqueneaux *et al.* [2006]

The Adiabatic Demagnetization Refrigerator

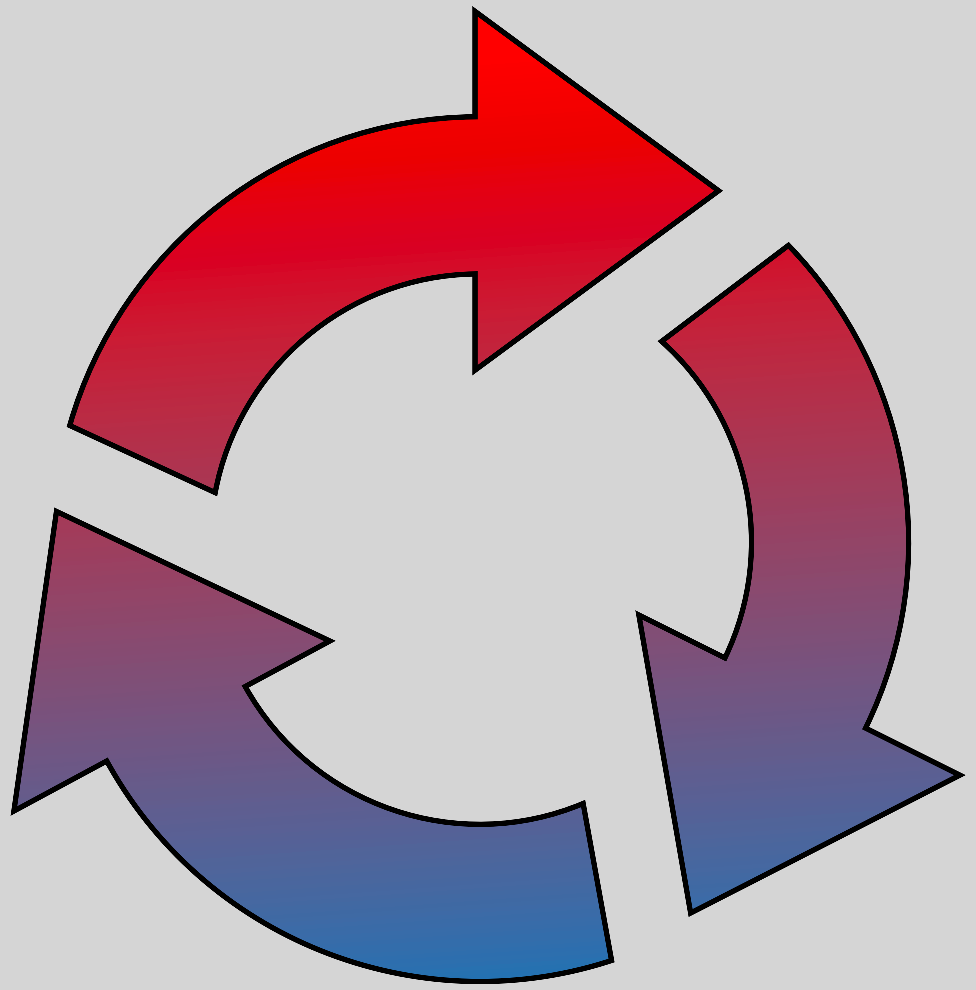


Suzaku Space Telescope [1], Hitomi Space Telescope [2], XRISM Space Telescope [3]

50 mK

Adiabatic Demagnetization Refrigerator

A magnetic field is applied to a paramagnetic material



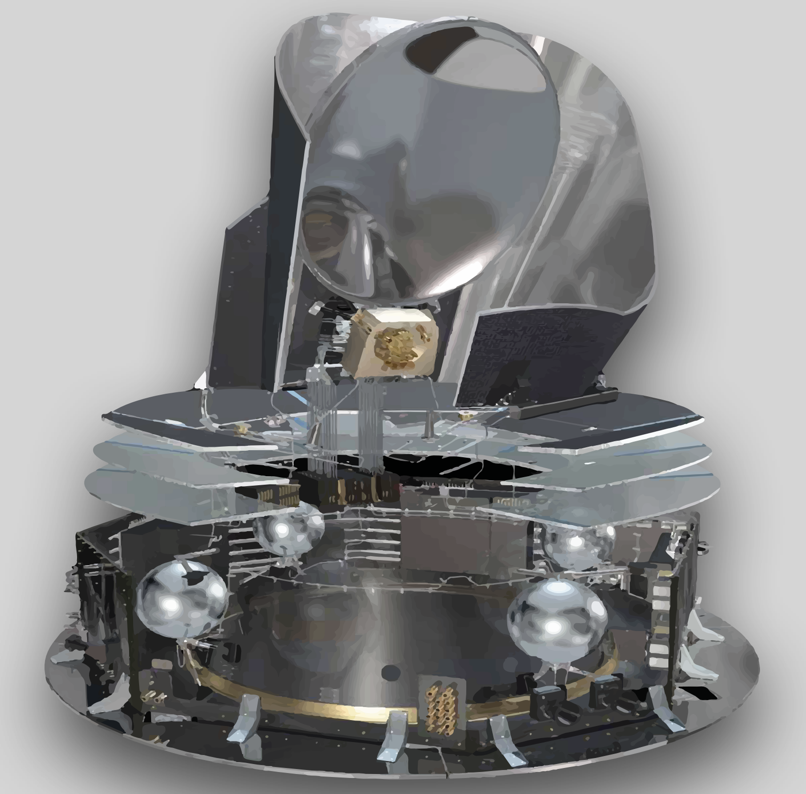
The magnetic field is slowly reduced

[1] Kelley *et al.* [2006]
[2] Shirron *et al.* [2016]
[3] Ezoe *et al.* [2019]

State of the art : the existing solutions

	Open **C**ycle **D**ilution **R**efrigerator	**A**diabatic **D**emagnetization **R**efrigerator
Provides 100 mK		
Continuous temperature		
Operates indefinitely		
TRL 5 or more		

The limitations of the OCDR

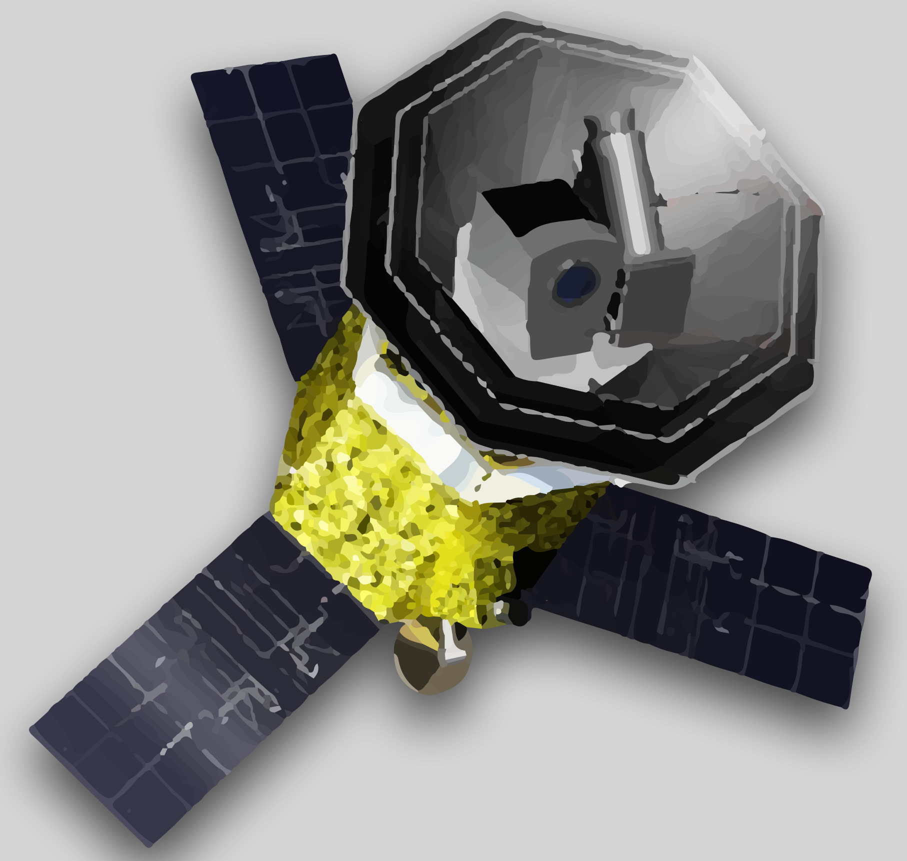


Planck Space Telescope

Operation time: **2.5 years**
Cooling power at 100 mK: **0.2 µW**

^3He: 12 000 liters STP

^4He: 36 000 liters STP



LiteBIRD Space Telescope

Operation time: **3 years**
Cooling power at 100 mK: **2 µW**

^3He: 63 000 liters STP

^4He: 234 000 liters STP

Necessity of a closed-cycle that requires much less heliums

State of the art : the future solutions

	Open Cycle Dilution Refrigerator	Closed Cycle Dilution Refrigerator	Adiabatic Demagnetization Refrigerator	Continuous Adiabatic Demagnetization Refrigerator
Provides 100 mK				
Continuous temperature				
Operates indefinitely				
TRL 5 or more				
		Martin *et al.* [2009]		Duval *et al.* [2020]
				LiteBIRD baseline

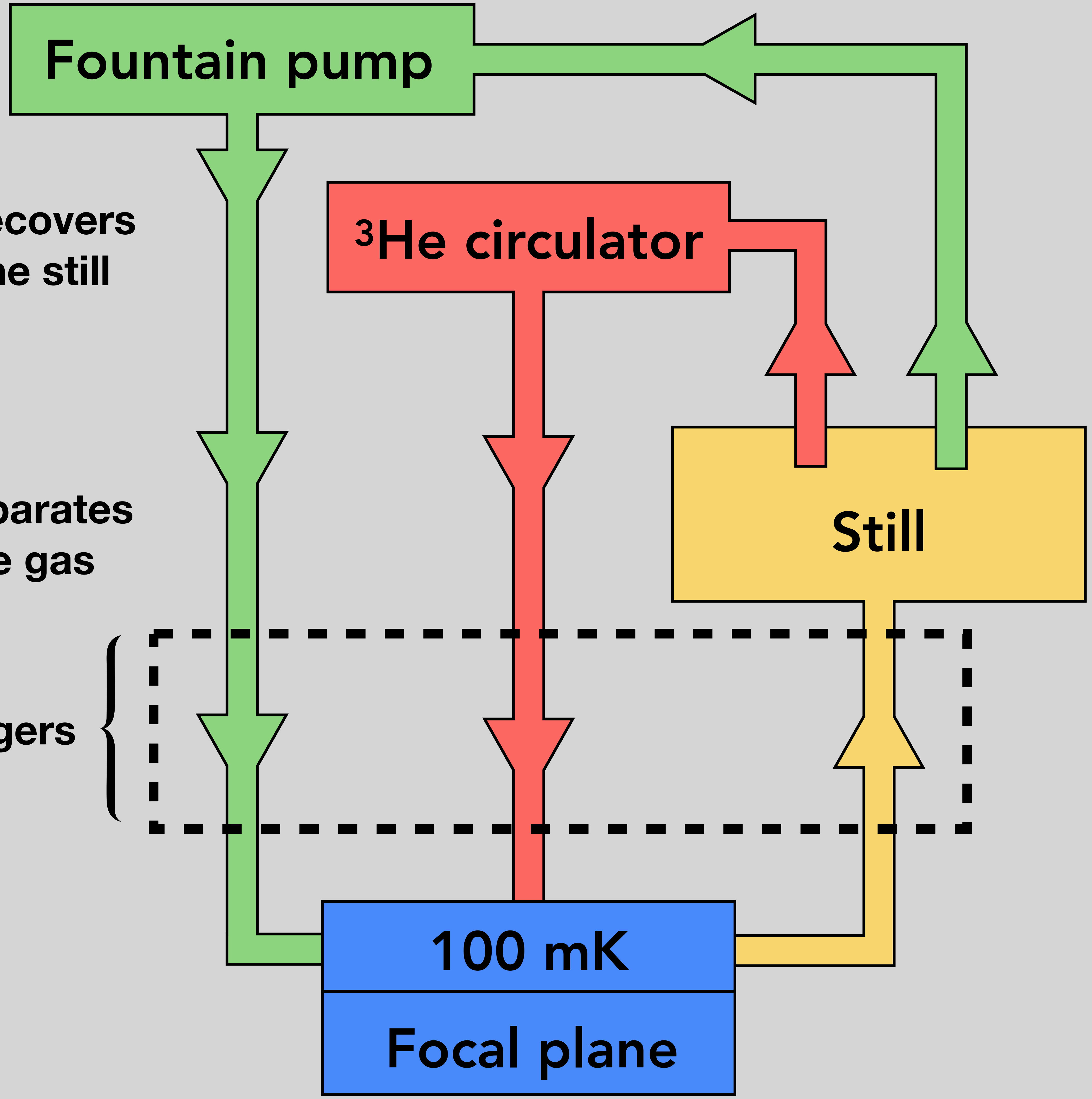
From OCDR to CCDR

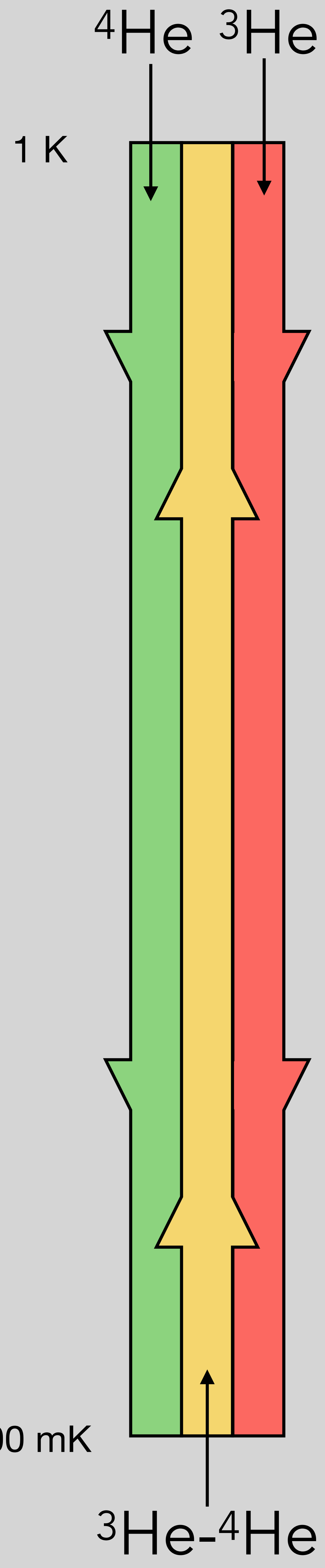
Fountain pump recovers the superfluid ^4He from the still

^3He circulator recovers the ^3He from the still

Porous material separates the liquid from the gas

CounterFlow Heat eXchangers





What about the space CCDR?

✓

Isotope separation works [1]
Requirement in term of cooling power [2]
8 µW @ 100 mK, 1 µW @ 50 mK
Operation in negative gravity achieved [3]

Development of a
Demonstrator **M**odel for Athena X-iFU
by Vermeulen *et al.* (Institut Néel)

TRL 4
Component and/or breadboard
functional verification
in a laboratory environment

→

Structural and **T**hermal **M**odel [4]
....

Development of an
Engineering **M**odel in progress

TRL 5
Component and/or breadboard
critical function verification
in a relevant environment

[1] Martin thesis [2009]
[2] Chaudhry *et al.* [2012]
[3] Volpe thesis [2014]
[4] Sauvage *et al.* [2022], Sauvage thesis [2023]

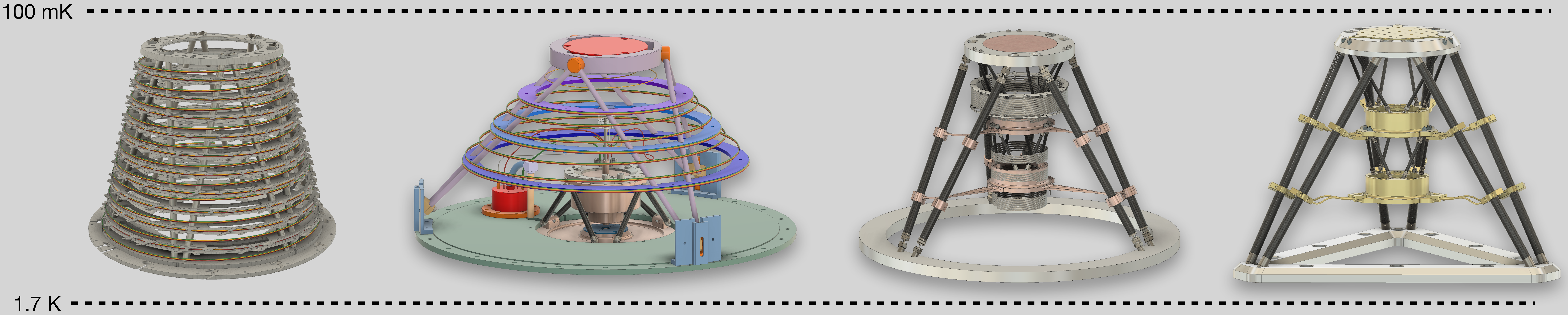
The Structural and Thermal Model

Thermal aspects:

- Hosts the ^3He-^4He dilution providing 2 μW of cooling power at 100 mK
- A heat sink at 1.7 K

Mechanical aspects:

- Supports a focal plane of 750 g on top of it
- Supports the vibrations of the launch (under 100 g), pushing the first mode above 140 Hz
- Limited size and mass (35 cm diameter, 25 cm height, 6 kg without the ^3He circulator)
- Holds the various sub-systems (capillaries, still, …)



Support of the Planck HFI dilution | DM of Athena X-iFU (Institut Néel) | First design by IAS | Last design by IAS

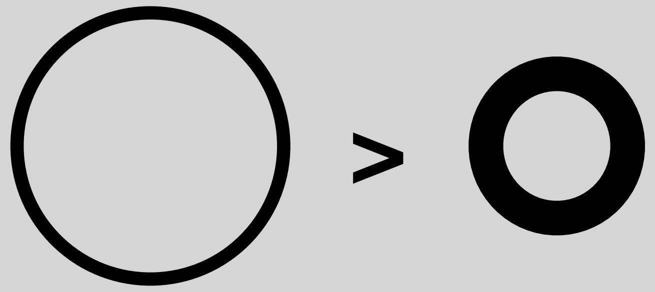
The struts

Purpose:
- **Thermal insulation** of the 100 mK stage from the 1.7 K stage
- Strong enough to **withstand launch vibrations**

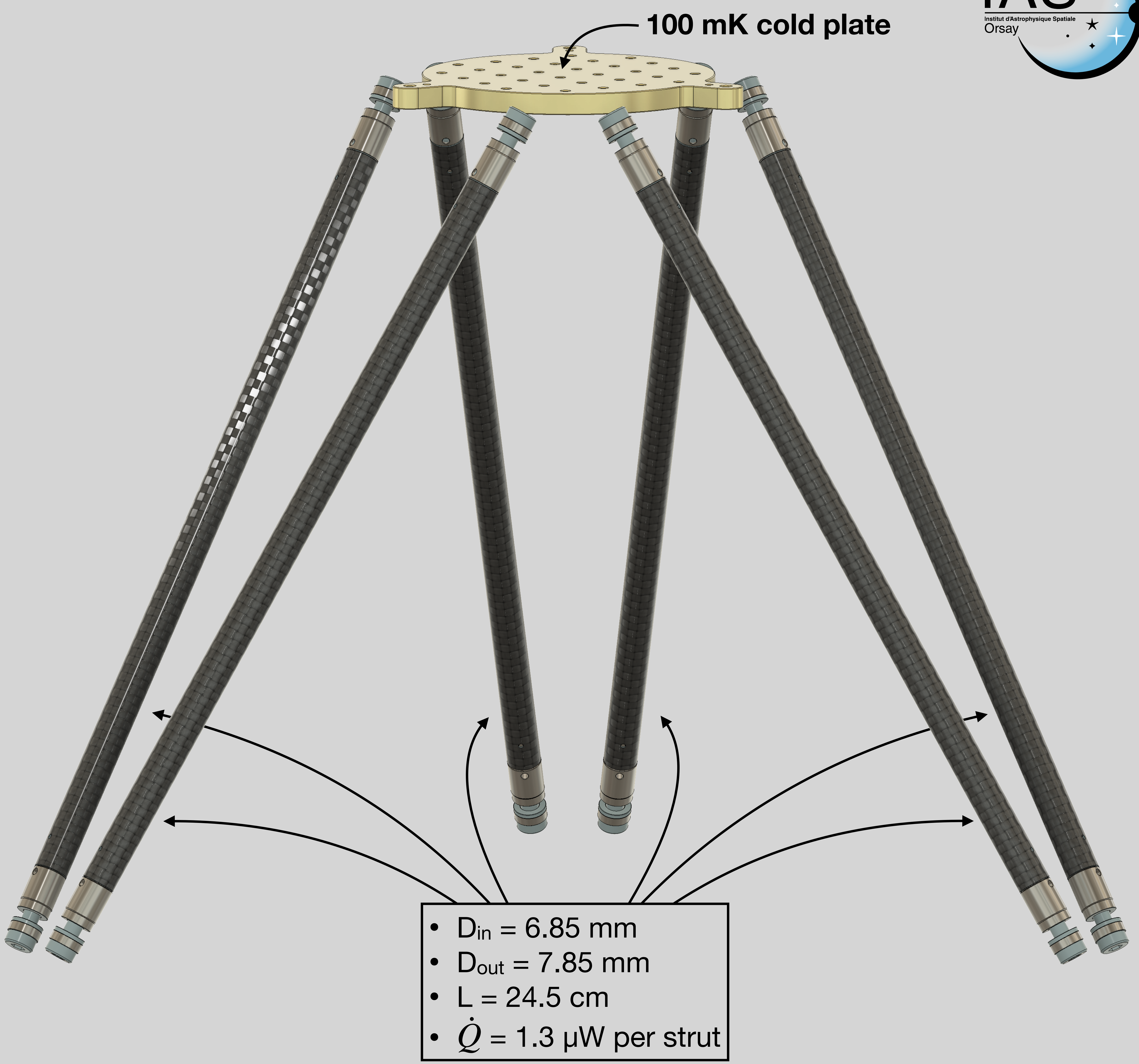
Mechanical requirements:
- First vibration mode > 140 Hz (good stiffness)
- Choice of an isostatic structure

Thermal requirements: $\dot{Q} = \frac{S}{L} \int_{T_1}^{T_2} \kappa(T)dT$

Strut sizing:
- Fixed length (limited by the requirements)
- Maximise IgZ/A (moment of inertia by surface area)



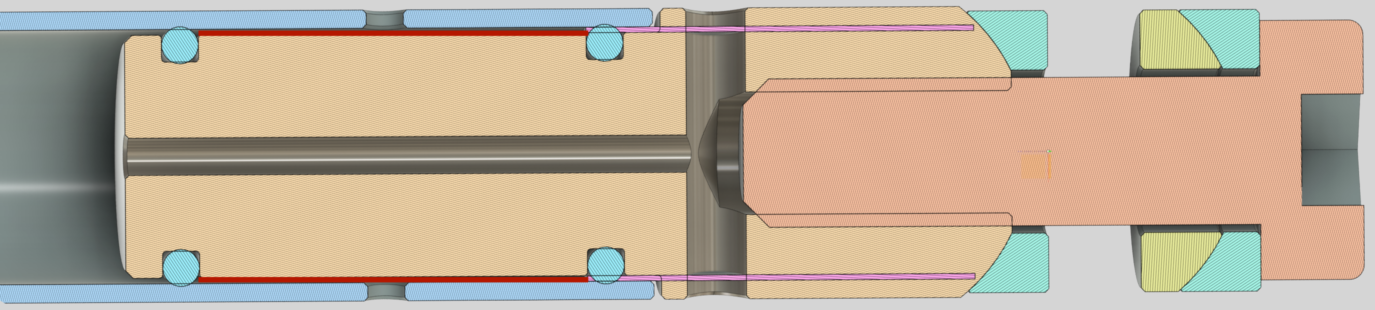
Carbon **F**iber **R**einforced **P**olymer
- Low thermal conductivity
- High resistance on tension/compression
- Lightweight

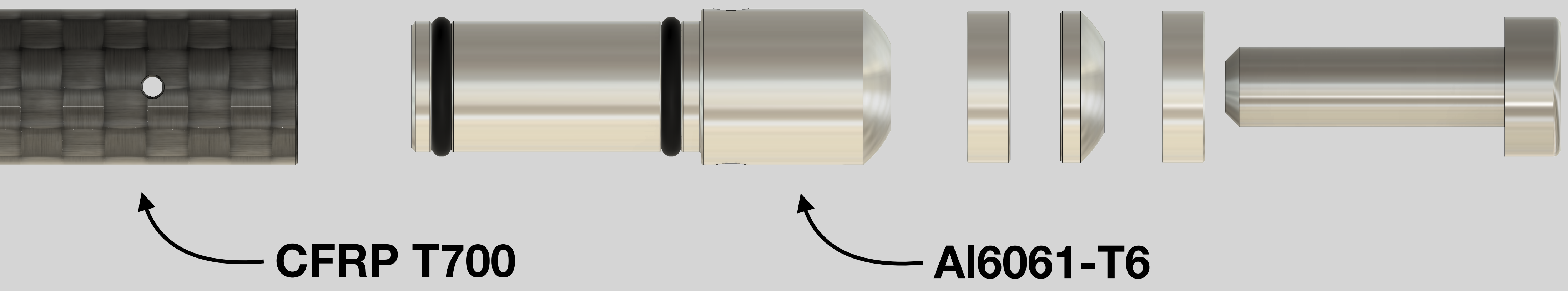


TOTAL: 7.8 μW from 1.7 K to 100 mK

The end fittings

- Avoid mounting stresses (no bending)
- Once tightened, it behaves like a fixed connection



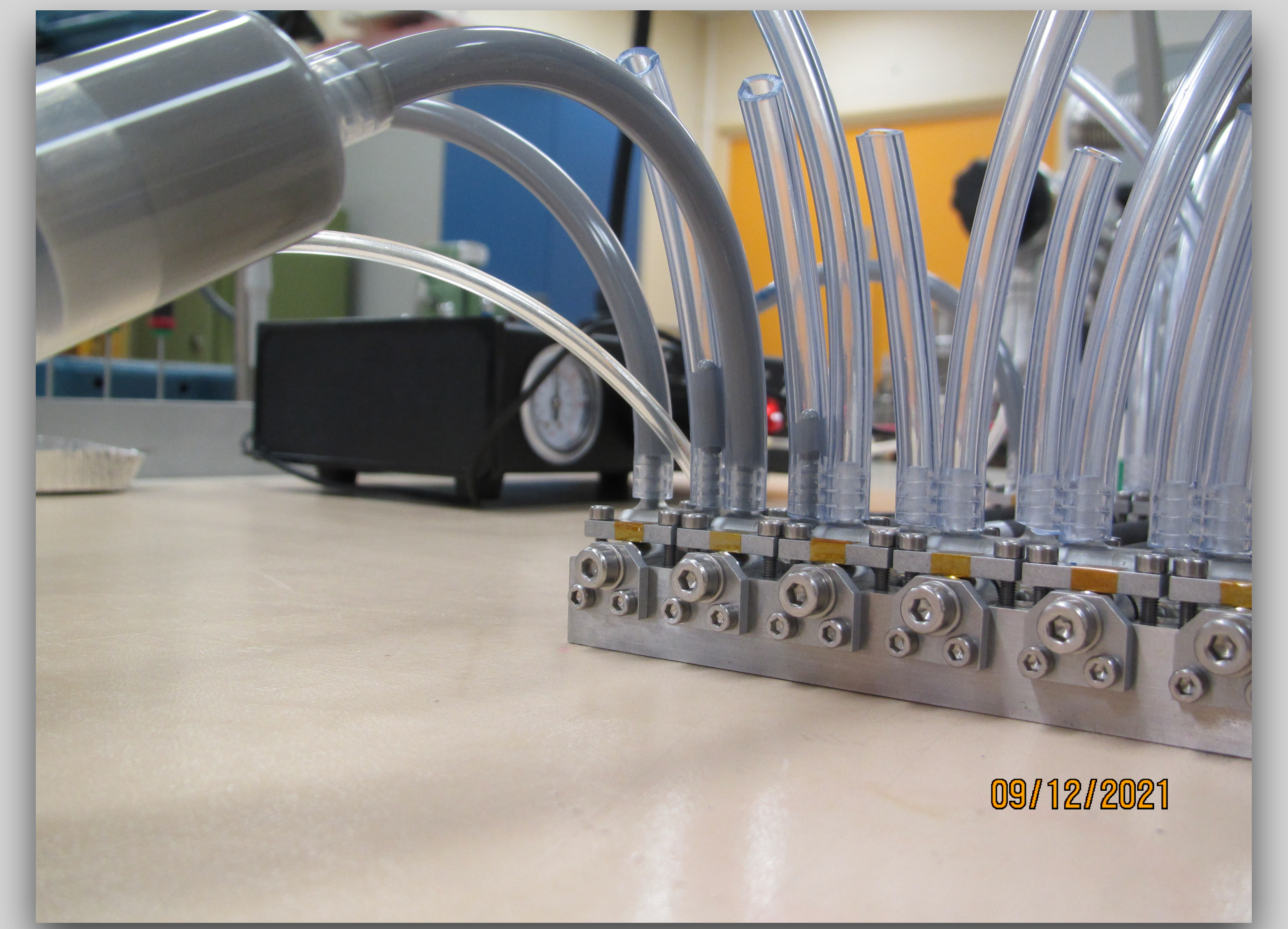


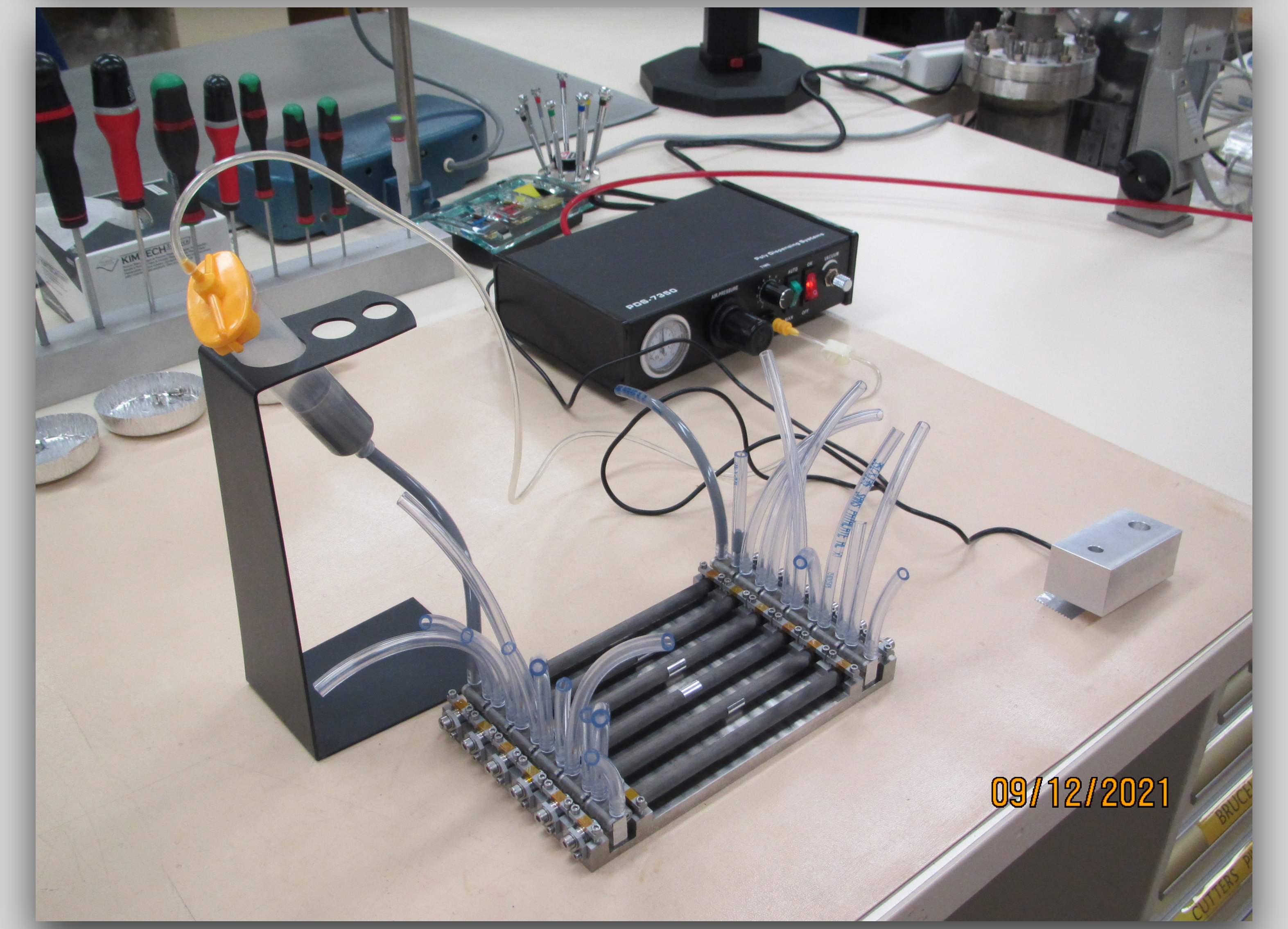
End fittings have to be glued to CFRP (no data of the glue characteristics available at low temperature)

Inheritance of Planck: **the glue have to work on compression to avoid breakage**

Differential contraction tested a 77 K:

- CFRP contracts more than aluminium
- The end fittings are glued inside the CFRP tubes (Hysol 9395)



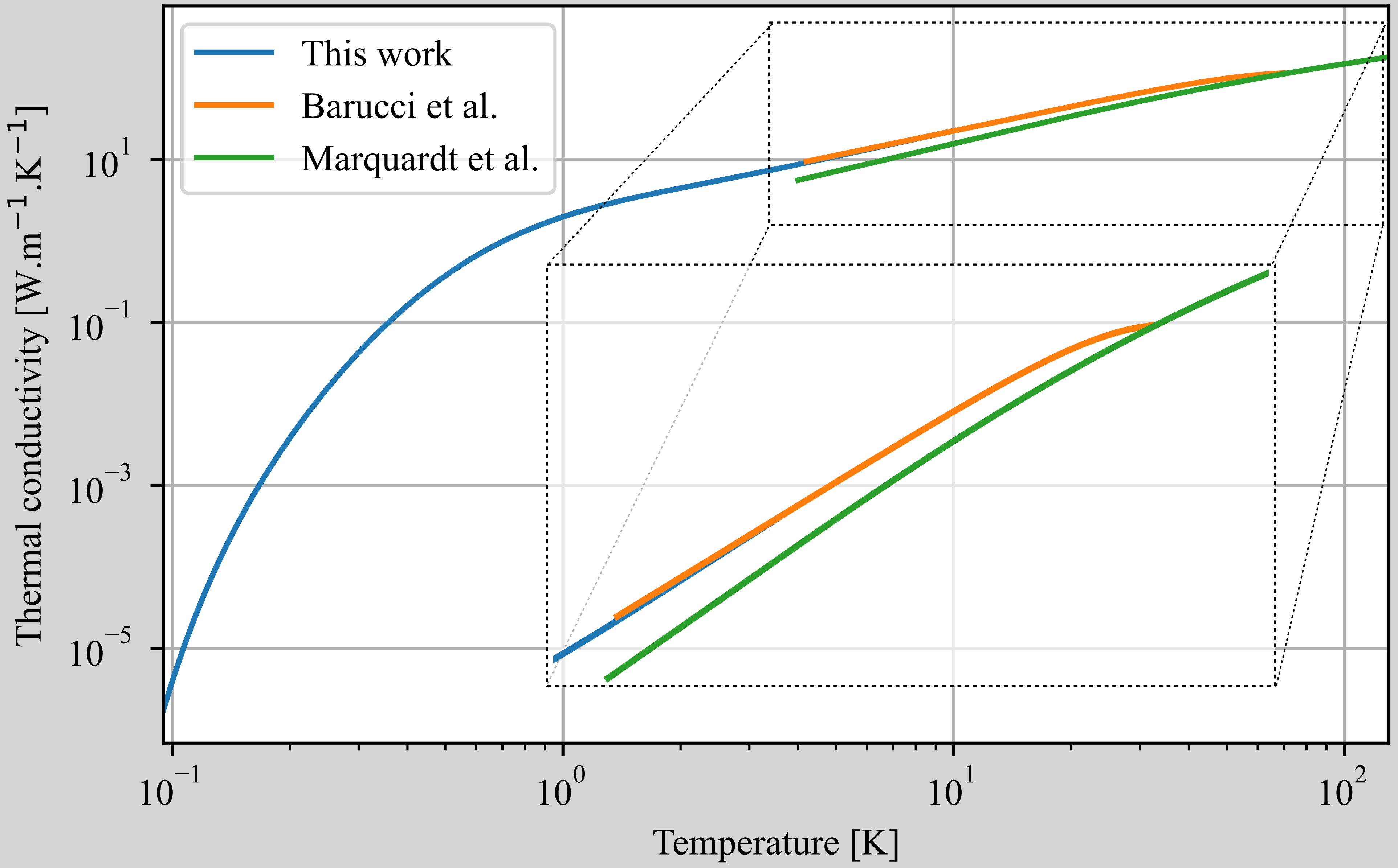


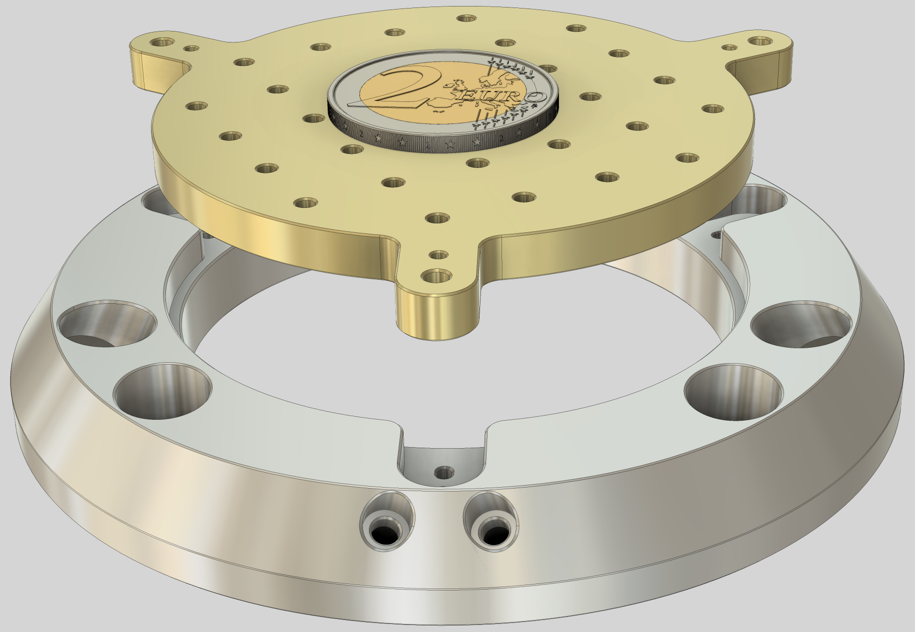
Hysol 9395 is pressure-injected to avoid air bubbles

The thermal interfaces

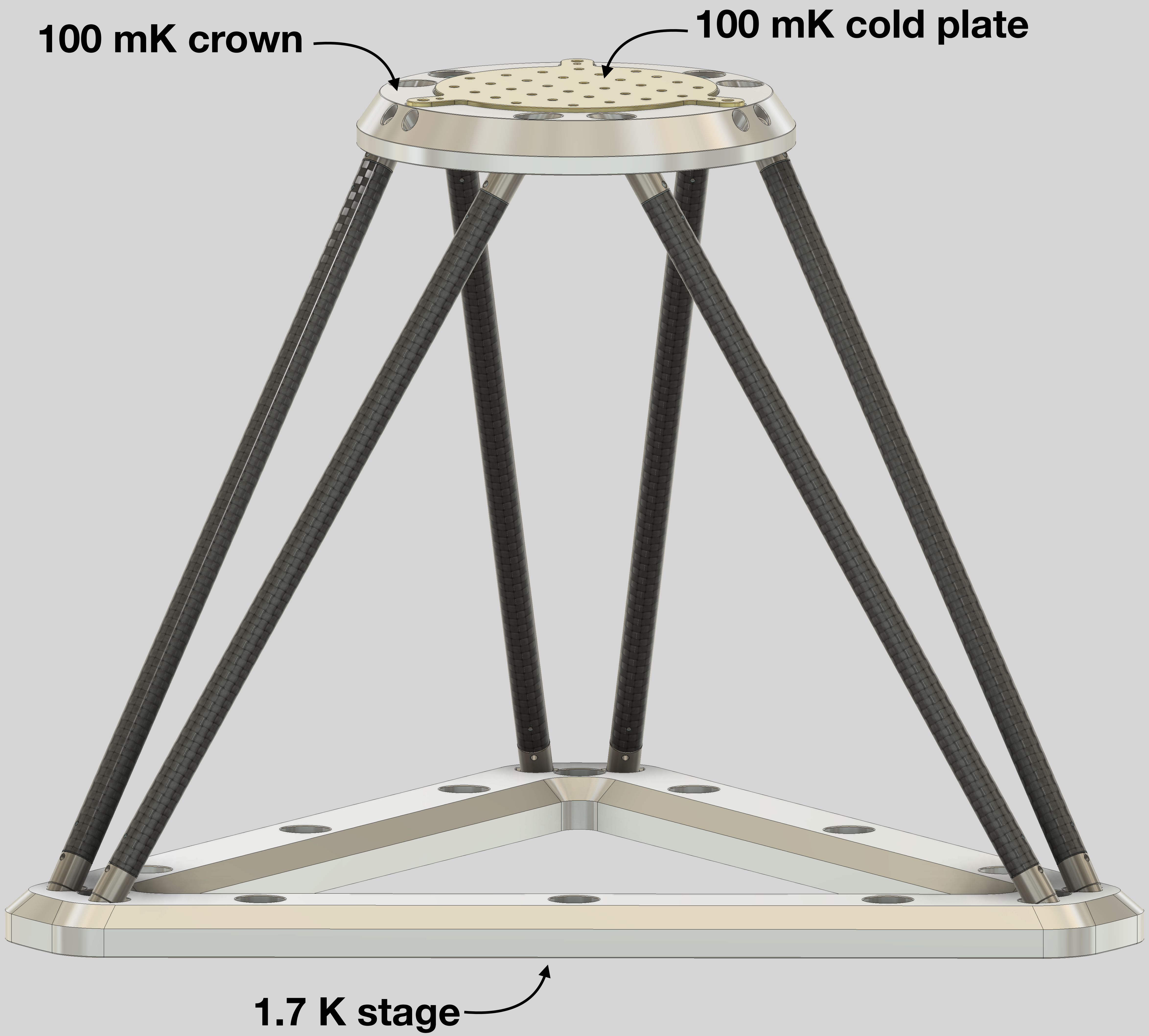
Same thermal contraction to avoid differential deformations

Choice of Al6061-T6:
- Light and machinable
- Thermal isolation of the 100 mK cold plate (4×10^{-6} $W.m^{-1}.K^{-1}$)
- Good thermal coupling at 1.7 K (4 $W.m^{-1}.K^{-1}$)



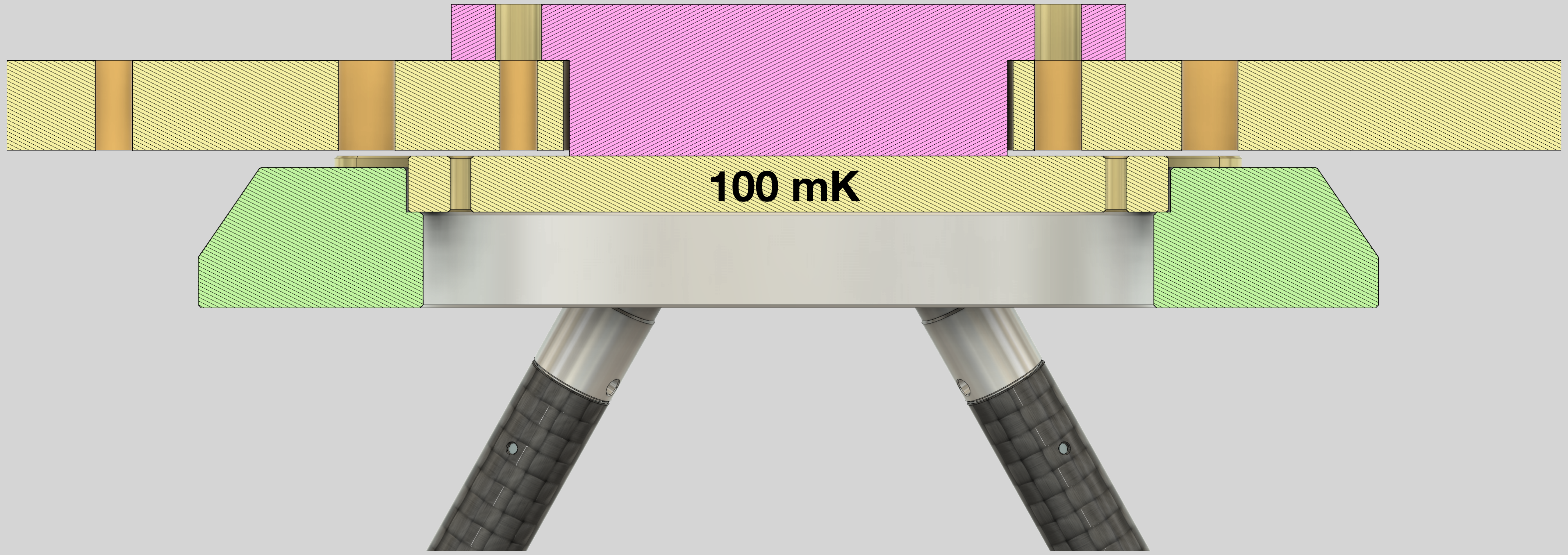


Small surface contact area

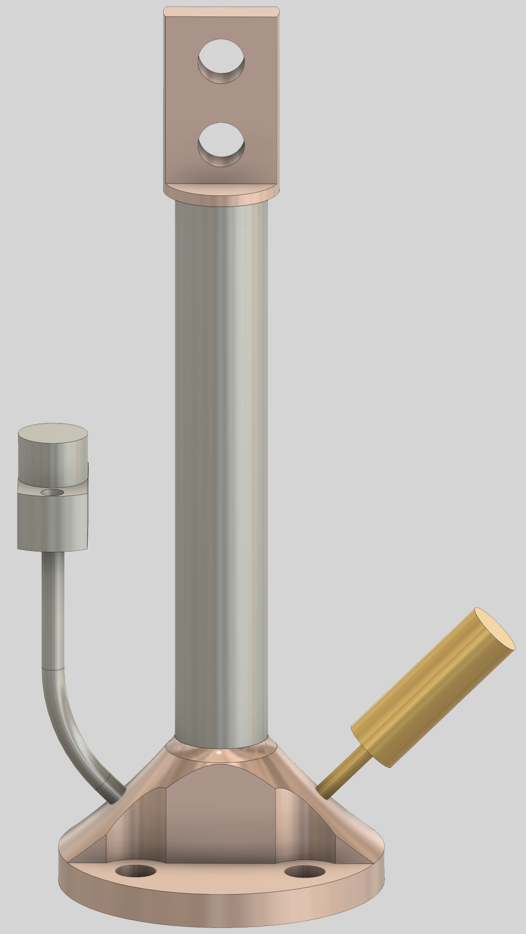


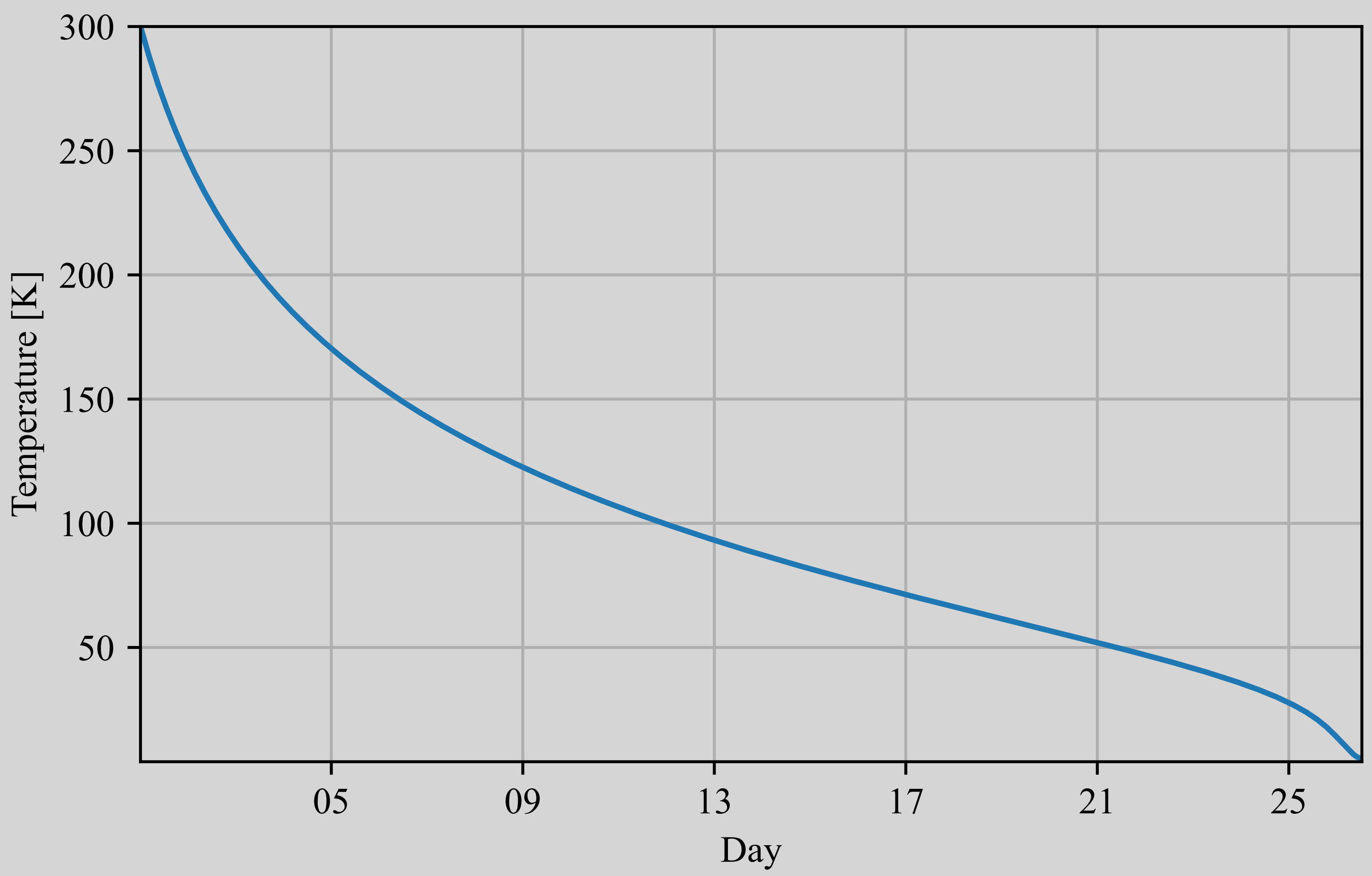
The Structural and Thermal Model

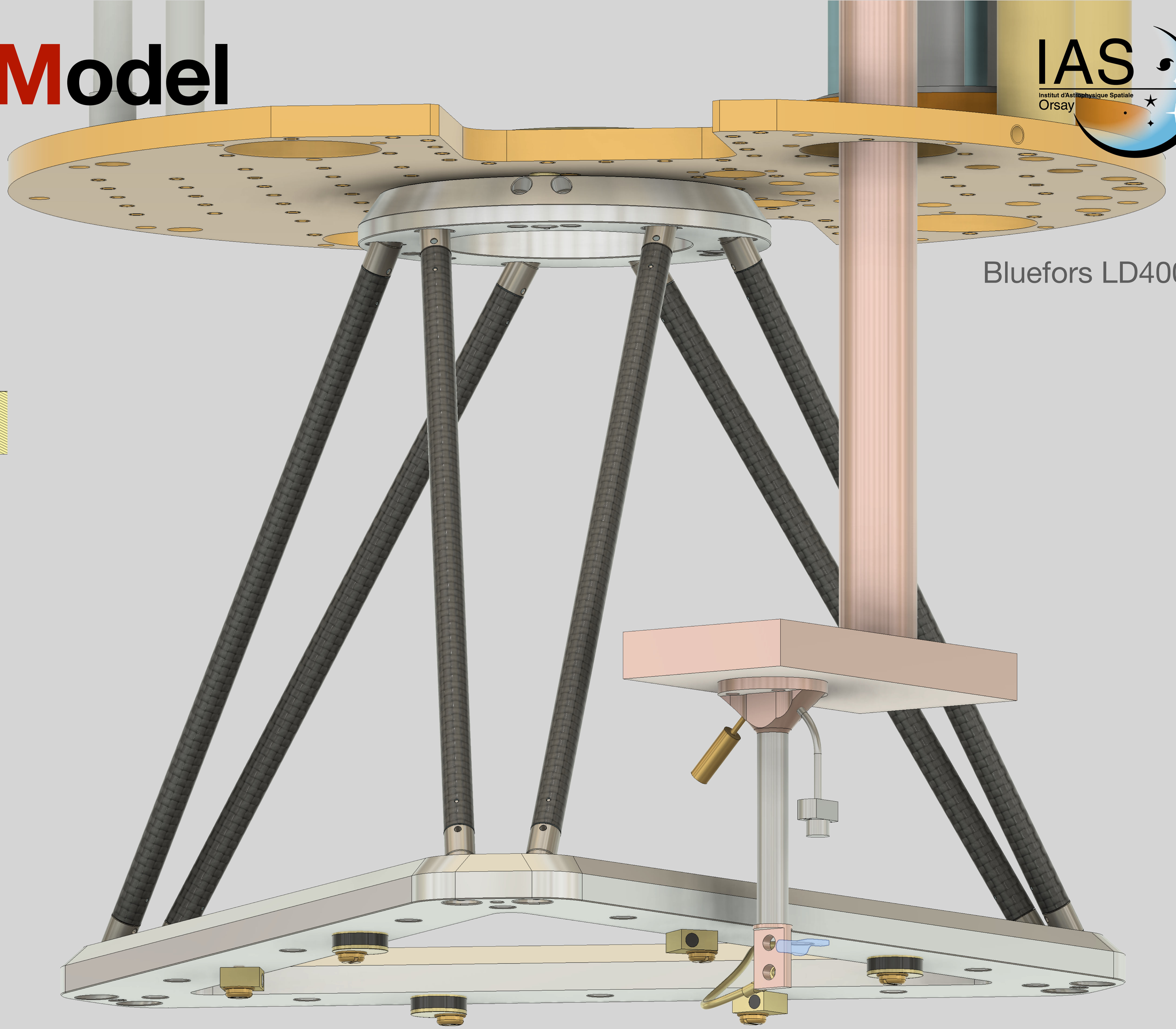
Only the STM cold plate was steady at 100 mK.
The 100 mK was produced by the cryostat.



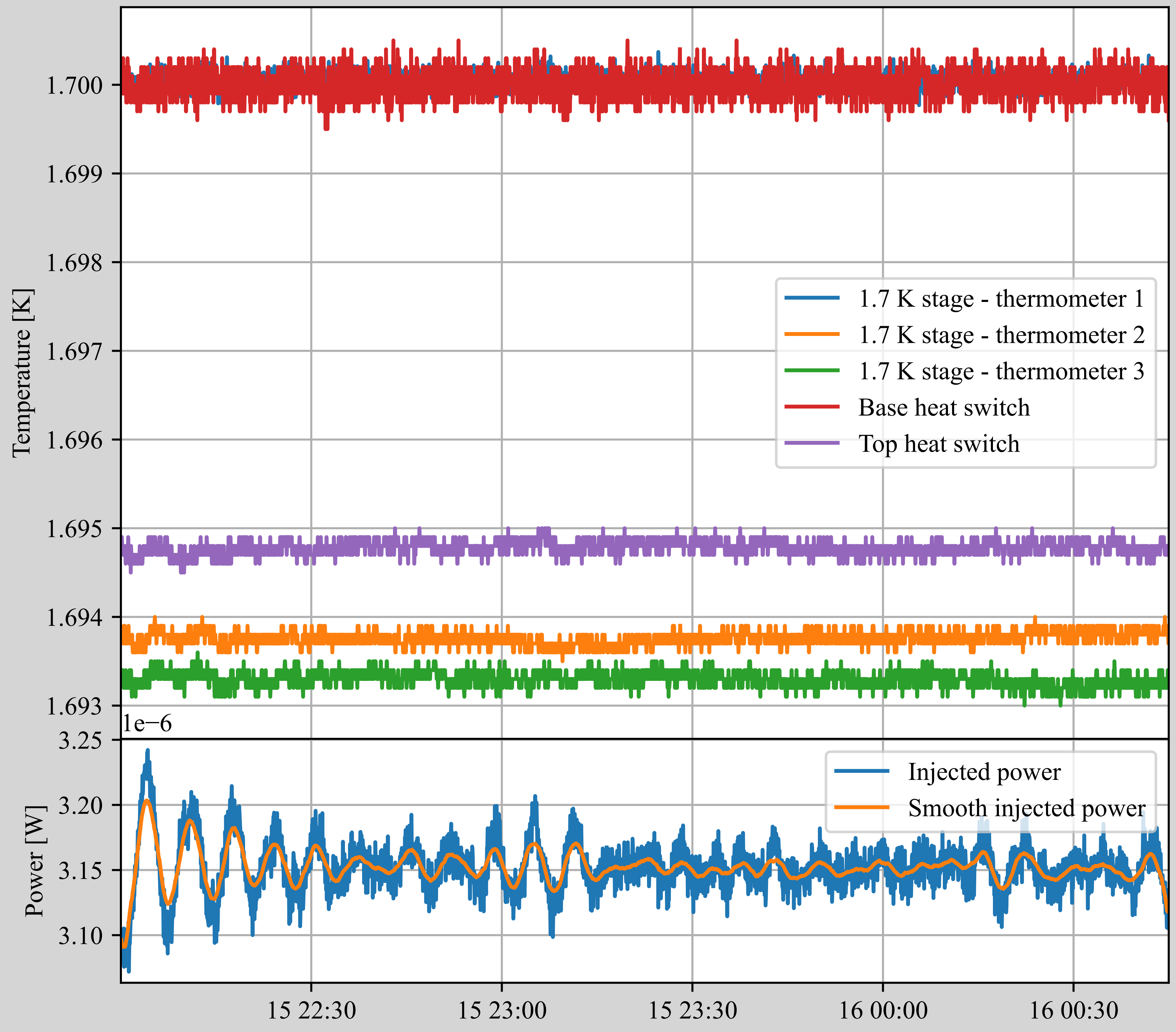
A gas gap heat switch helped cooling down the 1.7 K stage.

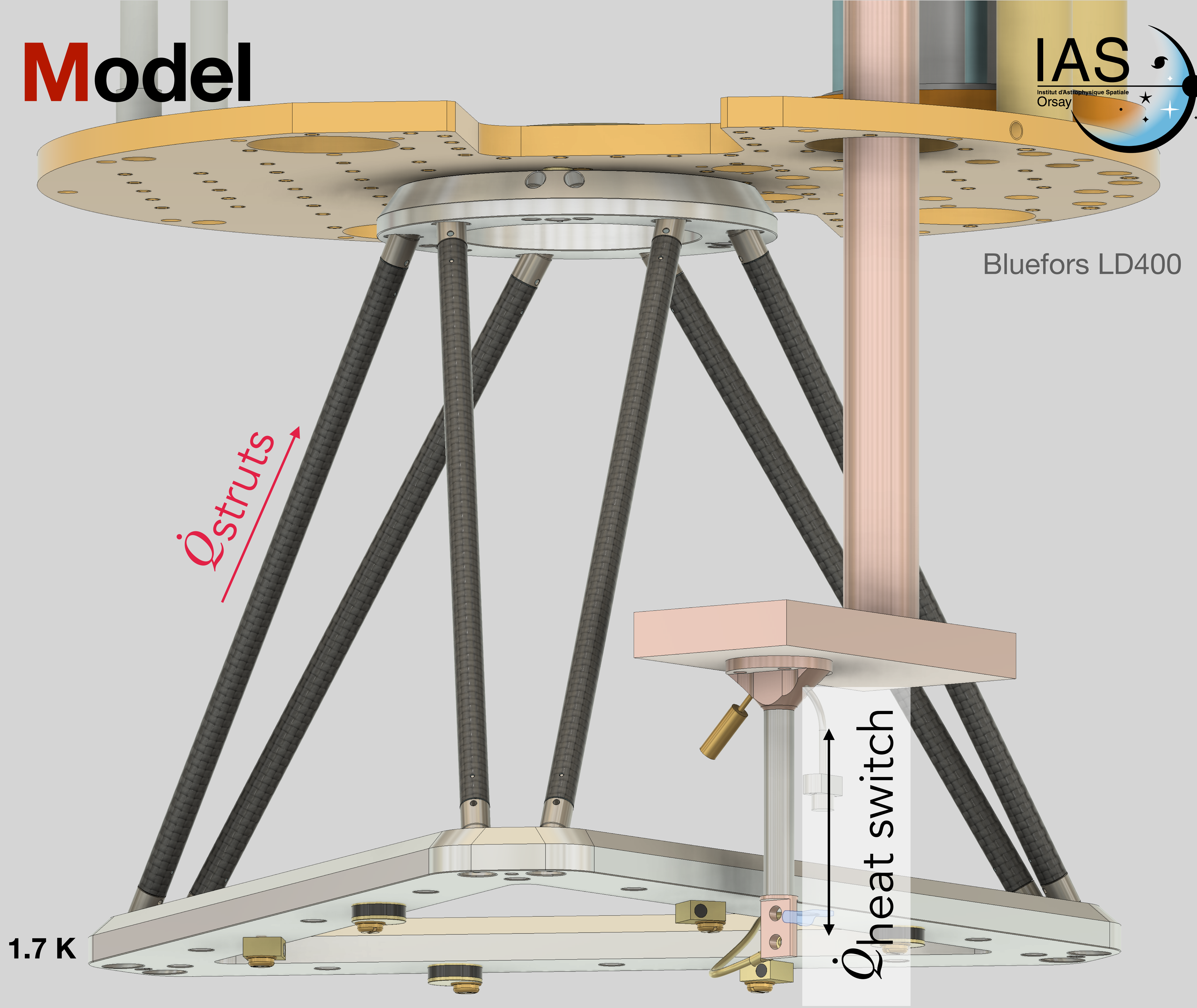






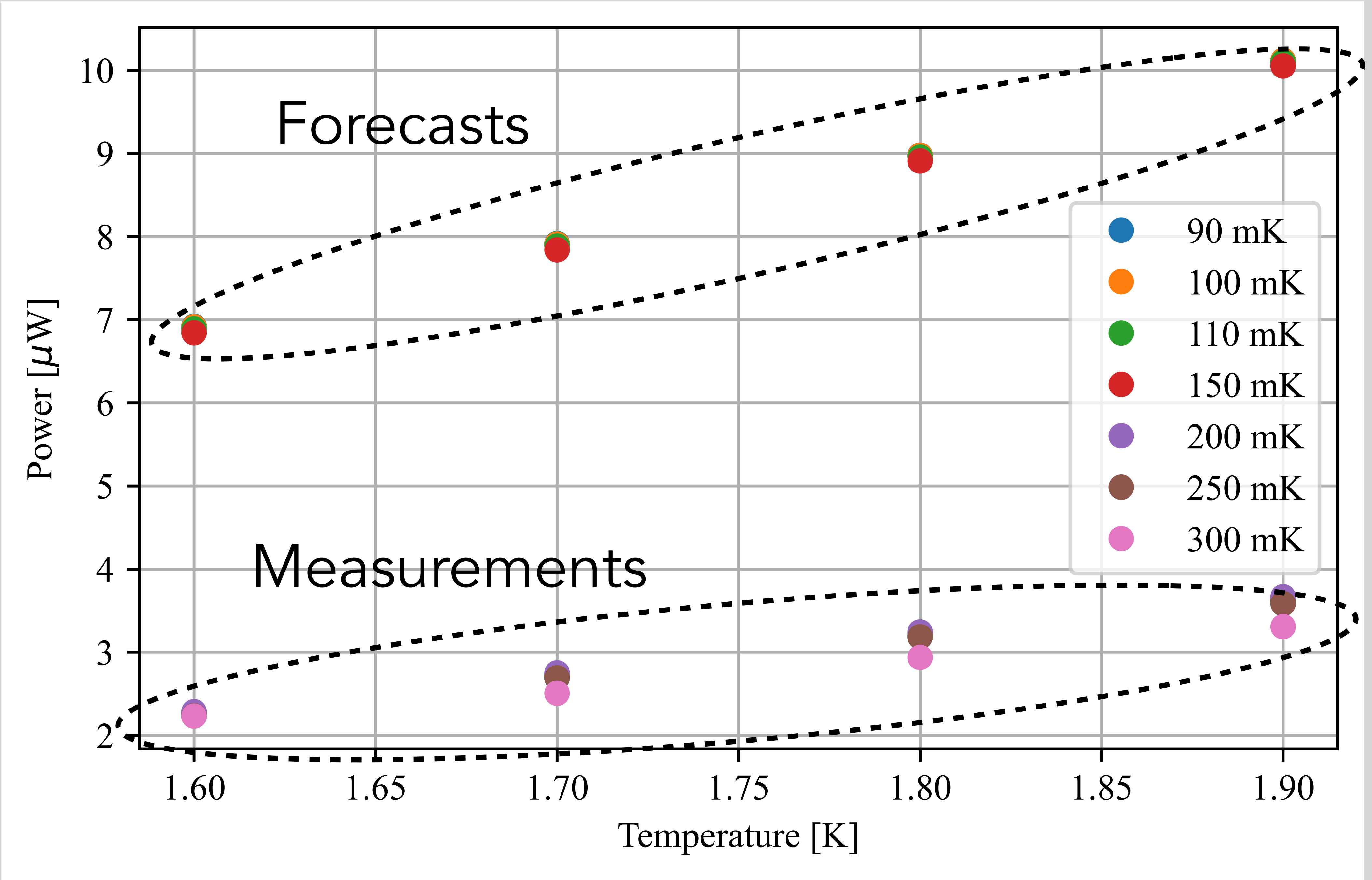
The Structural and Thermal Model

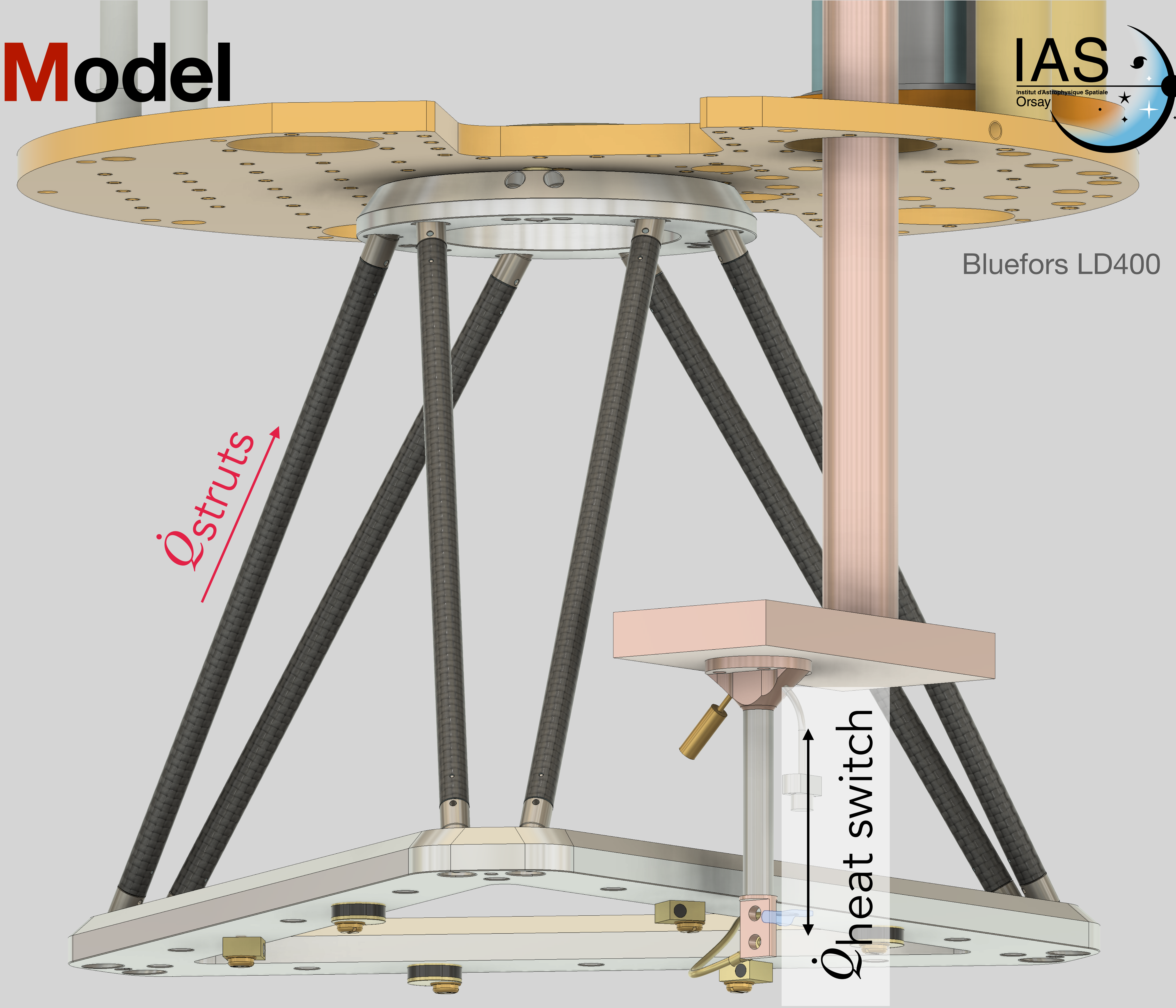




$$\dot{Q}_{injected} = \dot{Q}_{struts} - \dot{Q}_{wires} \pm \dot{Q}_{heat\ switch}$$

The Structural and Thermal Model



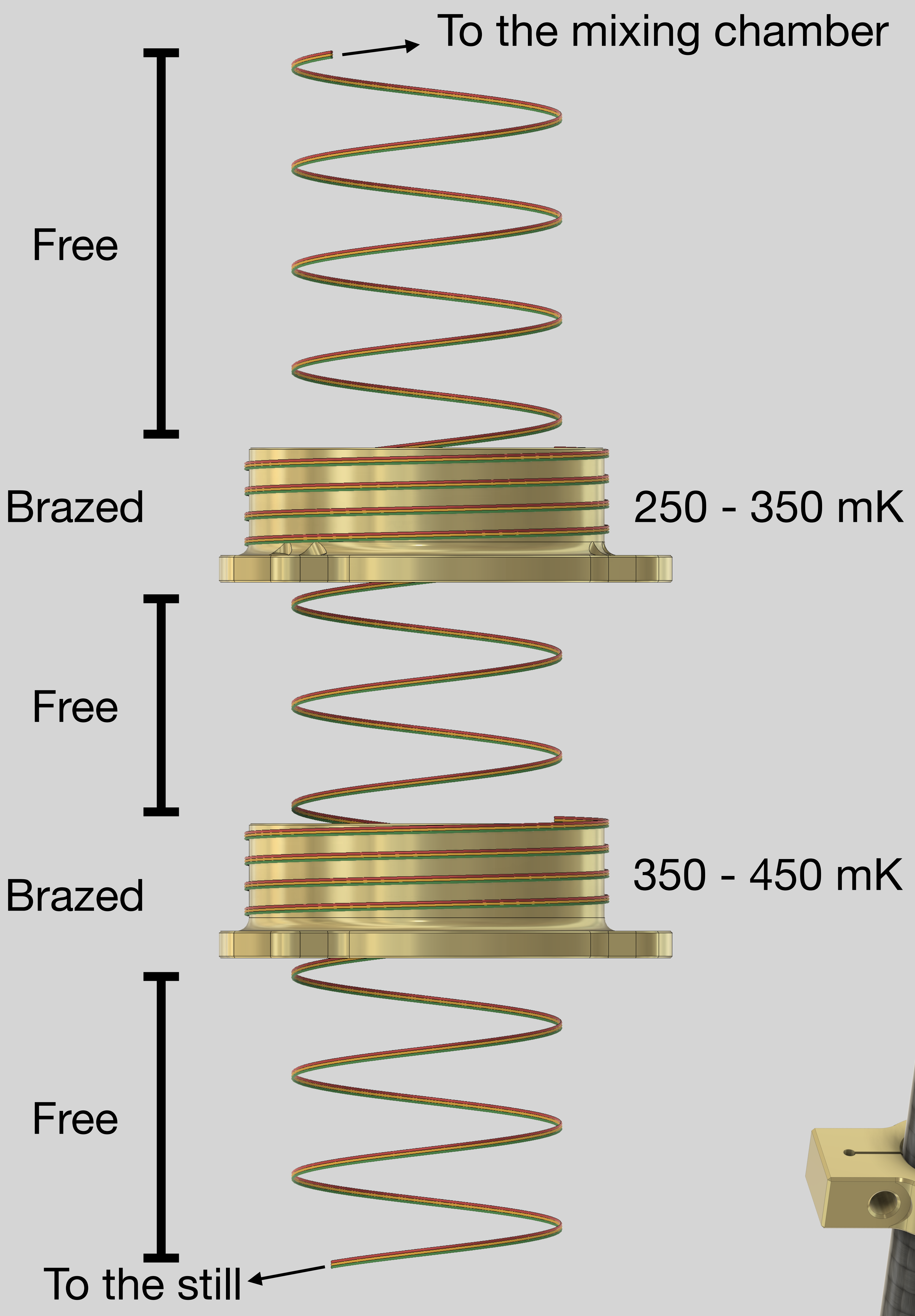


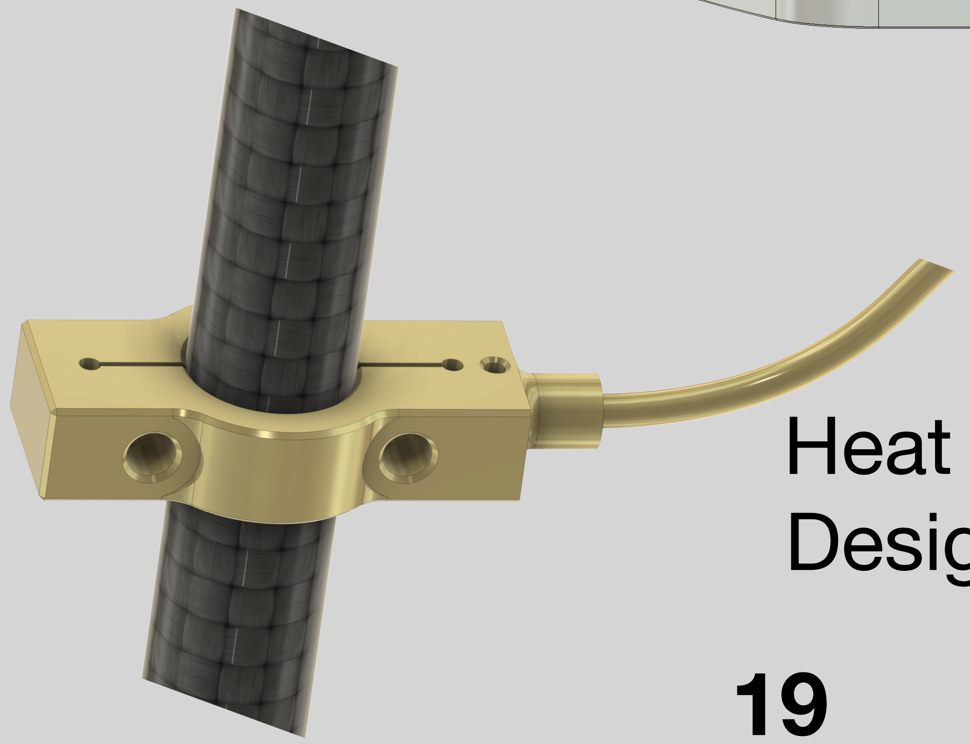
From 1.7 K to 100 mK
- Predicted: 7.8 μW
- Measured: 2.7 μW

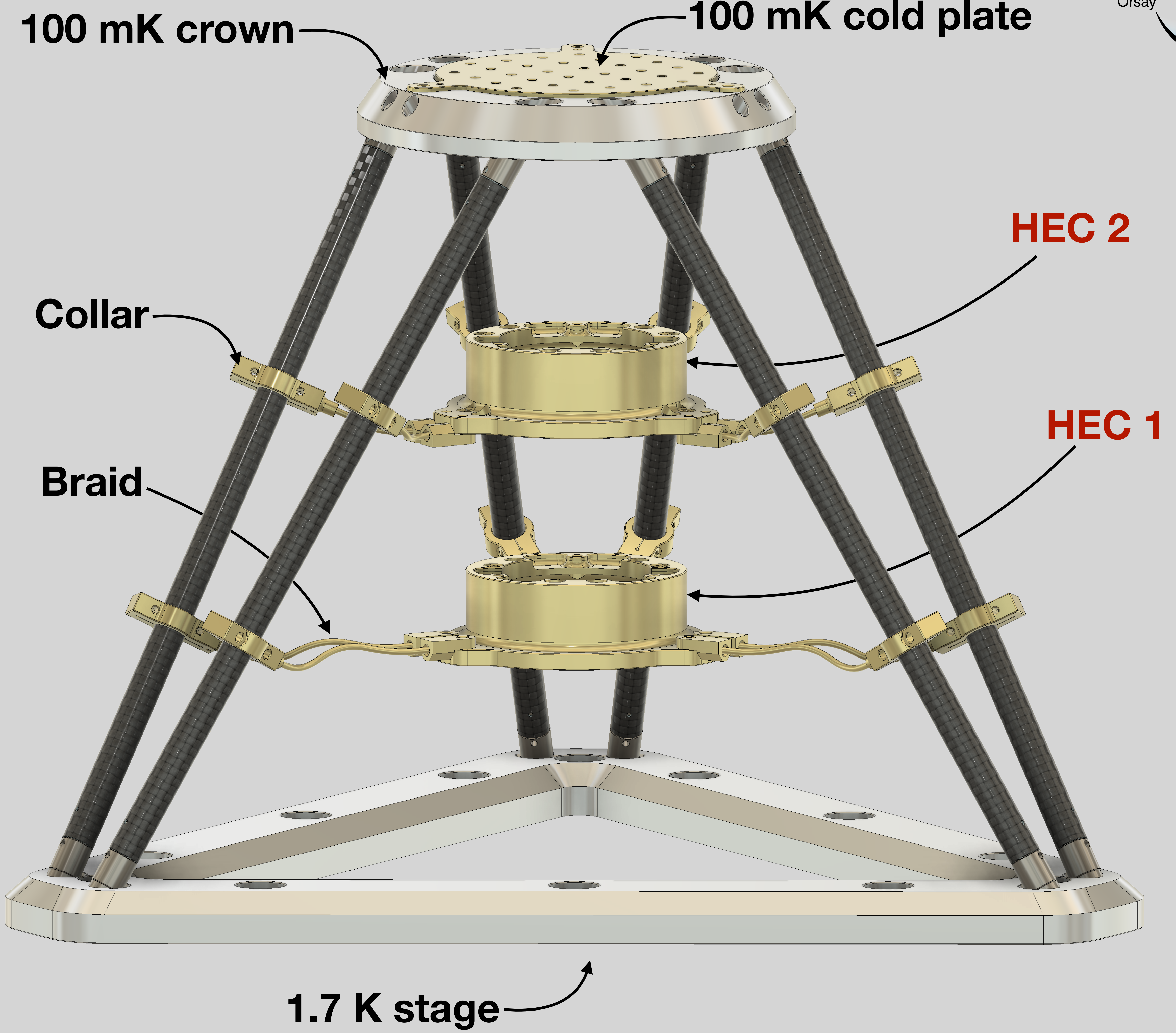
Thank you Kapitza resistance!

We can do better! **Addition of intermediate stages to intercept heat**

The Heat Exchanger Crowns





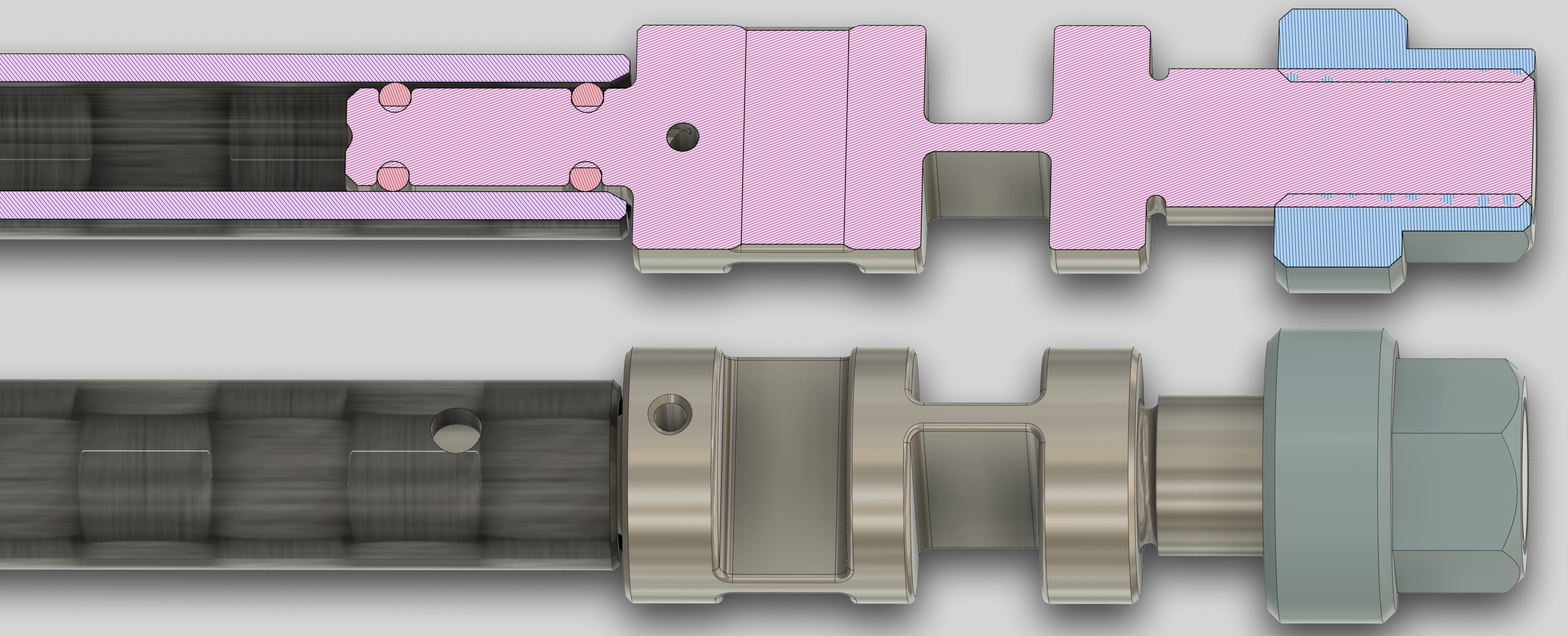


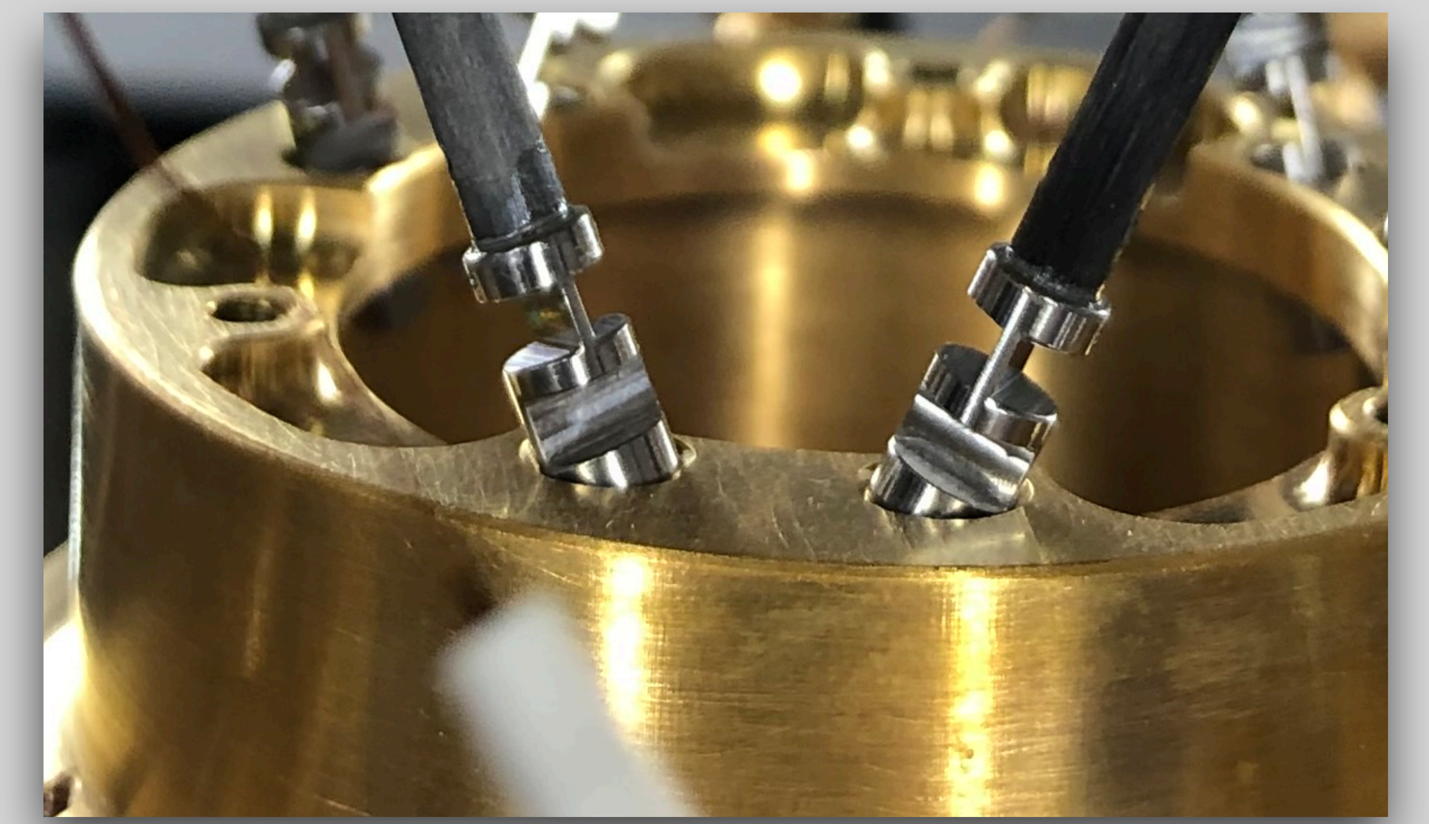
Heat interceptor collars
Designed to be repositioned

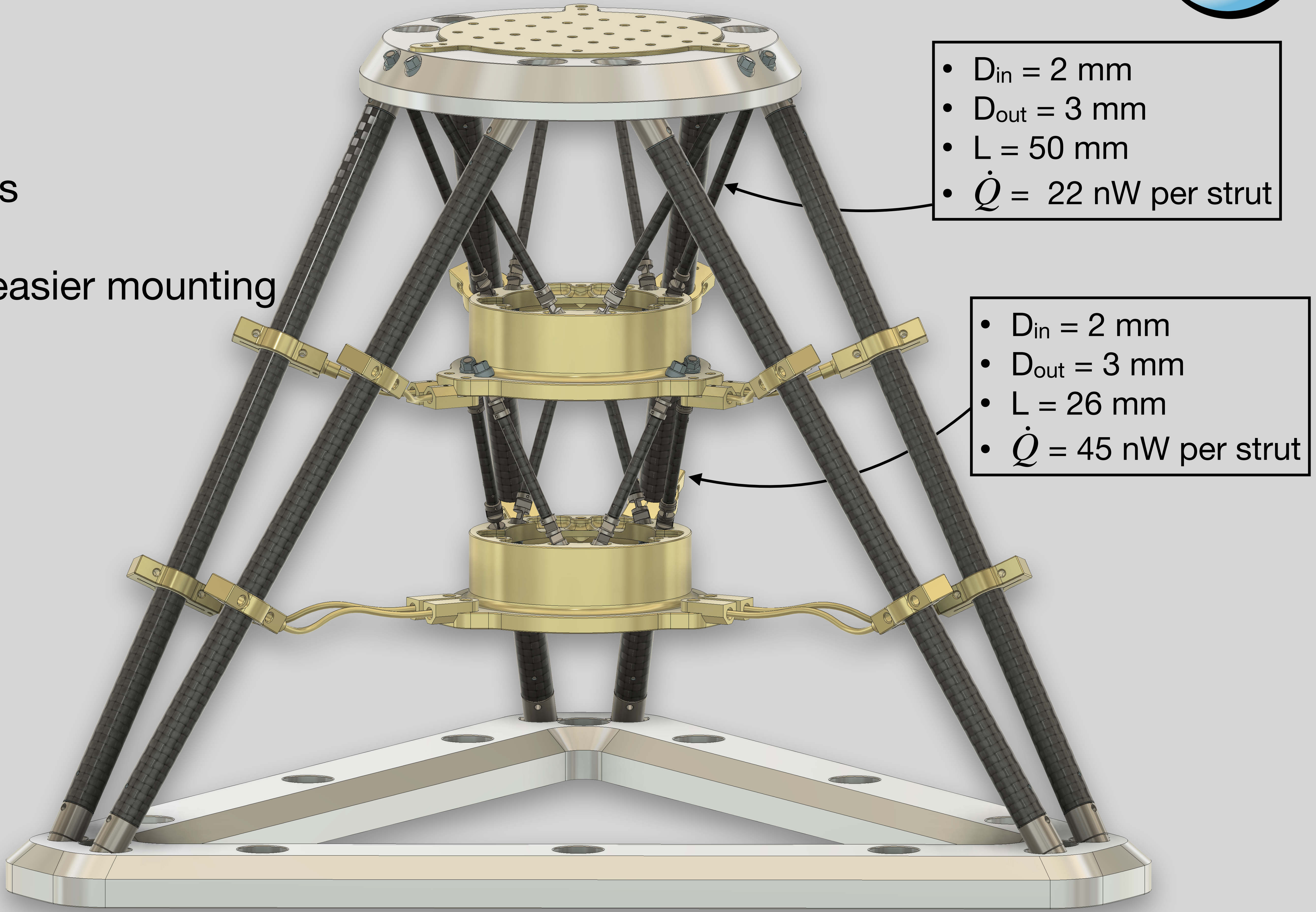
HECs will be used to thermalize the electronic harnesses

The small struts

- No structural function
- Flexible blades used as end fittings to have isostatic hexapodes
- Fewer parts than in Planck's design (used for main struts) —> easier mounting

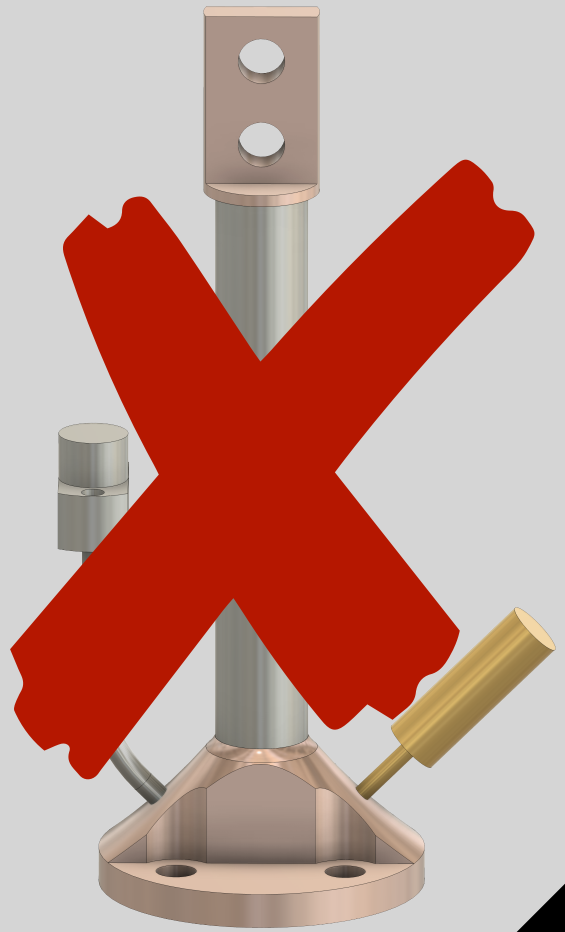




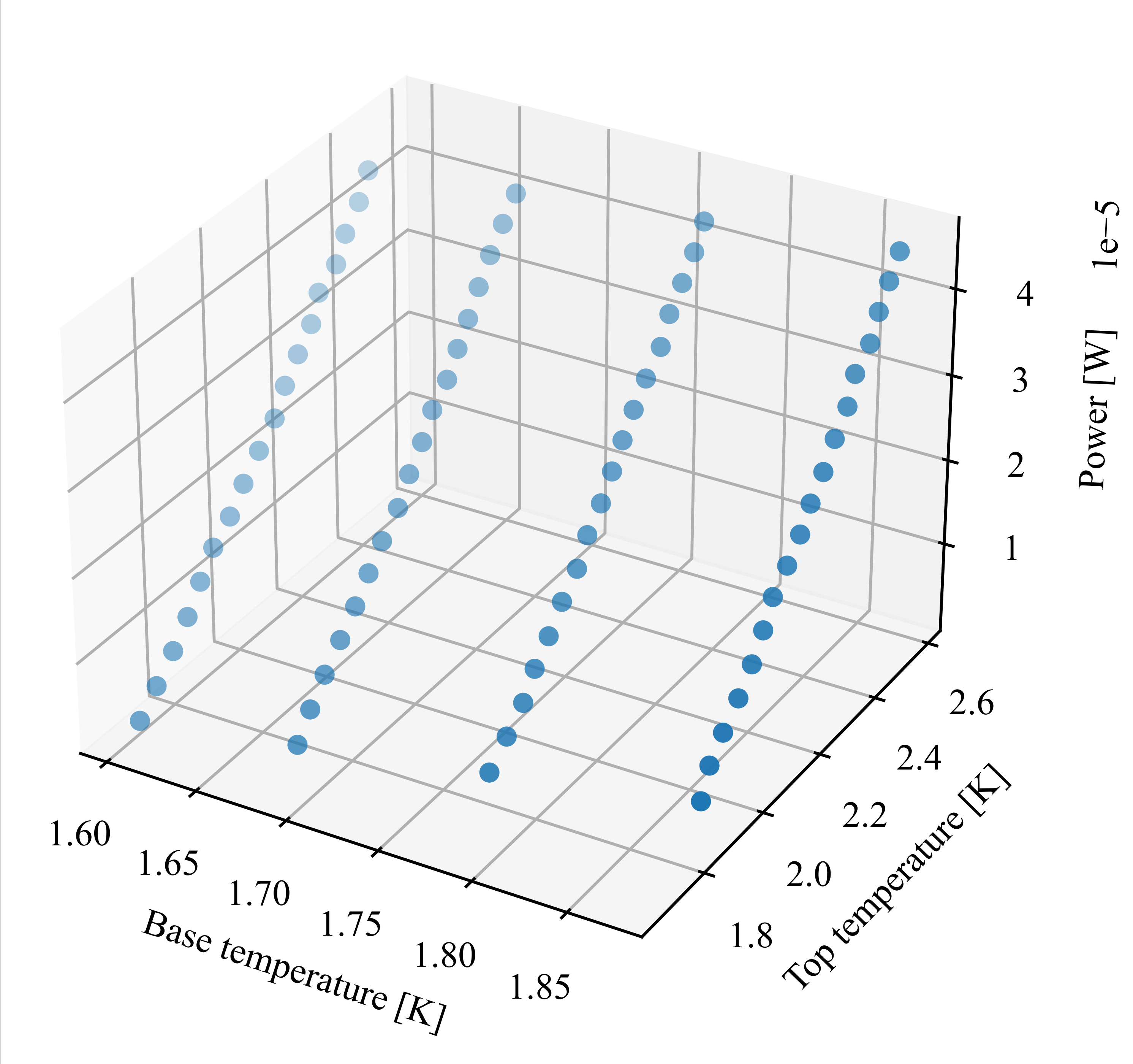


The Structural and Thermal Model

Reduced STM, from 1.7 K to 100 mK
- Predicted: 7.8 µW
- Measured: 2.7 µW

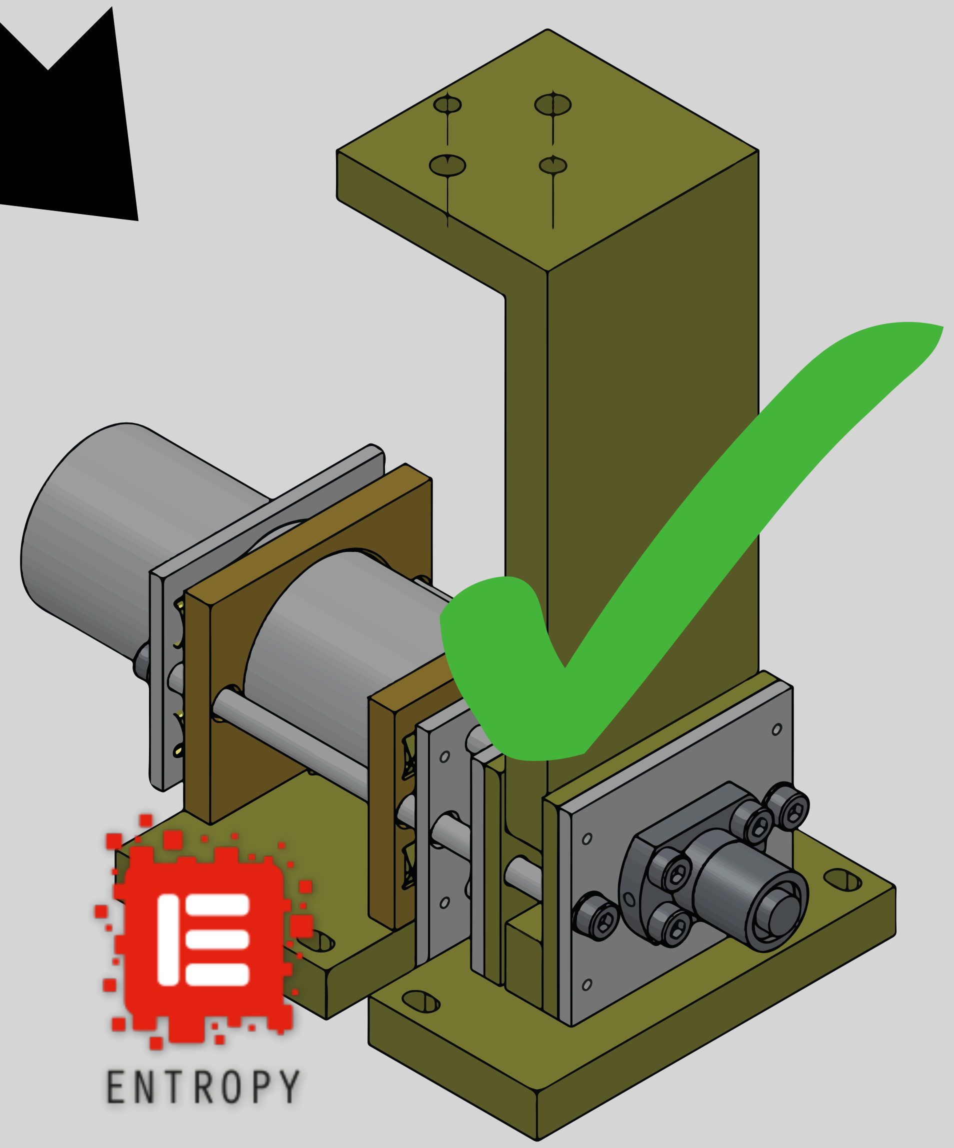


$\dot{Q} \neq 0$



Full STM, from 1.7 K to 100 mK
- Predicted: 0.63 µW
- Measured: .. µW

$\dot{Q} = 0$



What’s next ?

Next step (next January)

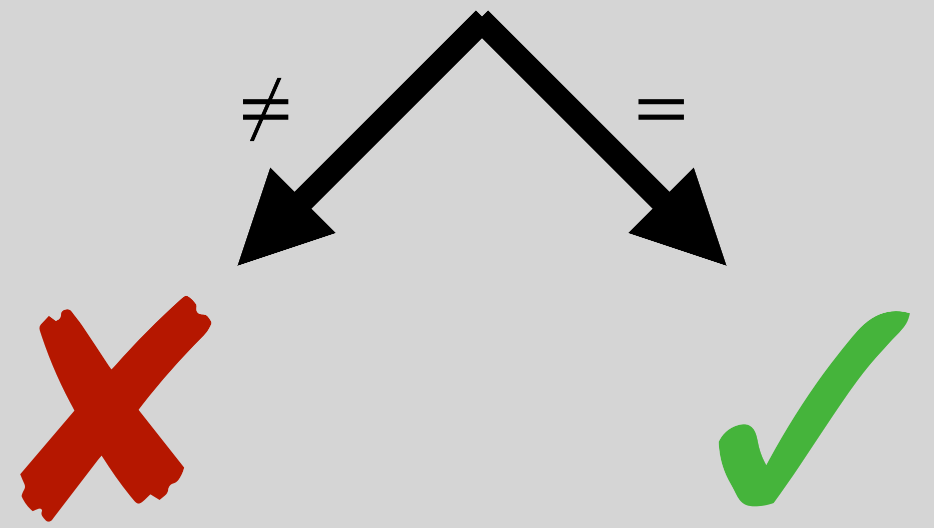
Determination of the STM thermal performances

↓

Vibration tests of the STM

↓

Recheck the STM thermal performances



Design and integration

Finalise the design
to hold the free capillaries

Integration of the sub-systems
(mixing chamber, capillaries, still, fountain pump, …)

Planning

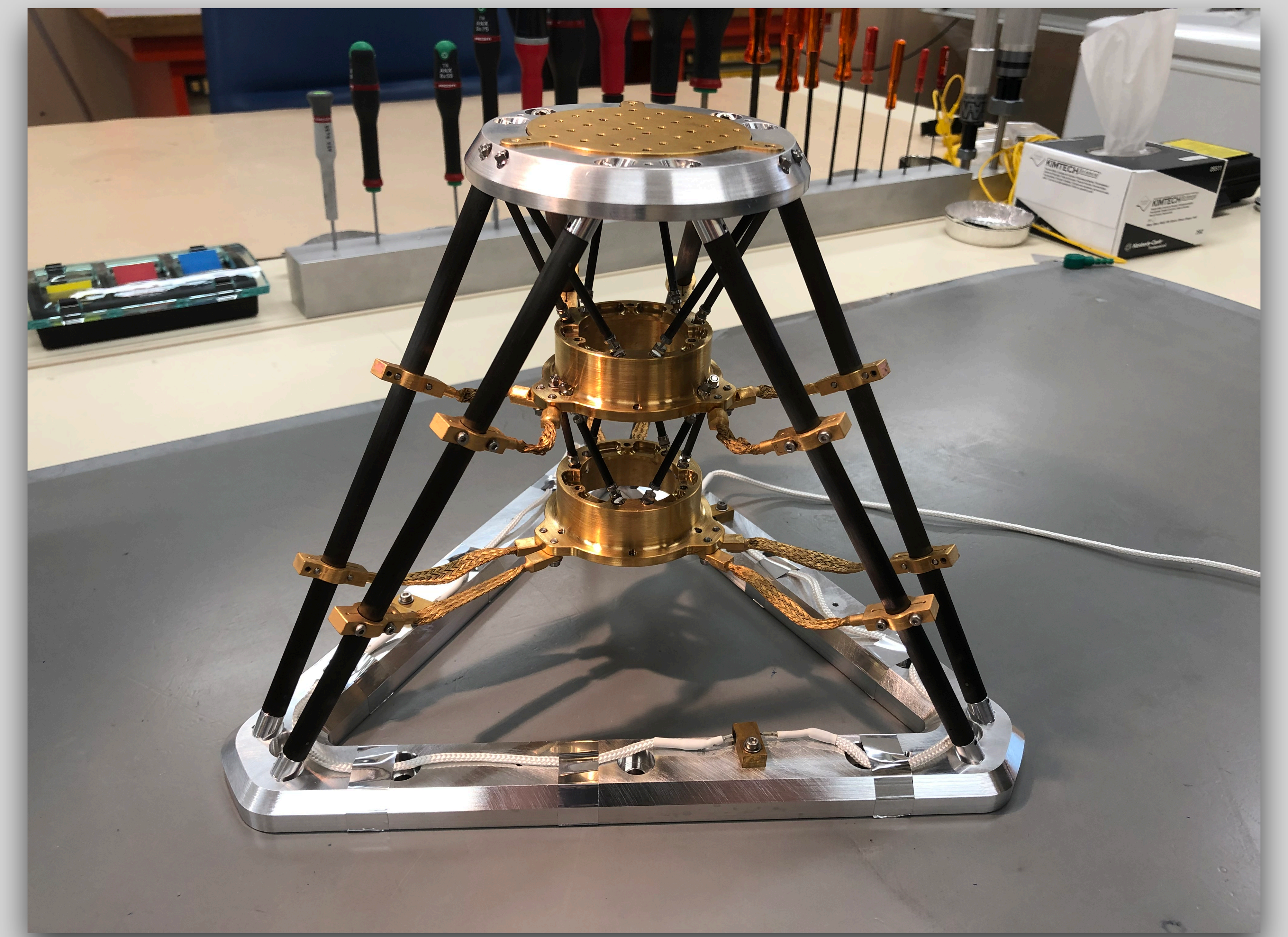
May 2025: Validated STM
December 2025: First still prototype
June 2026: Final still version
End of 2026: First EM of the CCDR

Take home messages

- Accommodate future CMB missions requirements (e.g. LiteBIRD) but not only. CCDR could provides:
  - A continuous 100 mK (or 50 mK to be demonstrated)
  - A large cooling power (8 µW at 100 mK and 1 µW at 50 mK)
  - A compact and light system (^{3}He circulator excluded)
  - A support for the focal plane
  - A thermalization for electronic harnesses
  - Compatible with any detector technology (e.g. no magnetic field)

- IAS is pushing the CCDR to TRL 5.

- We provide also properties on various materials

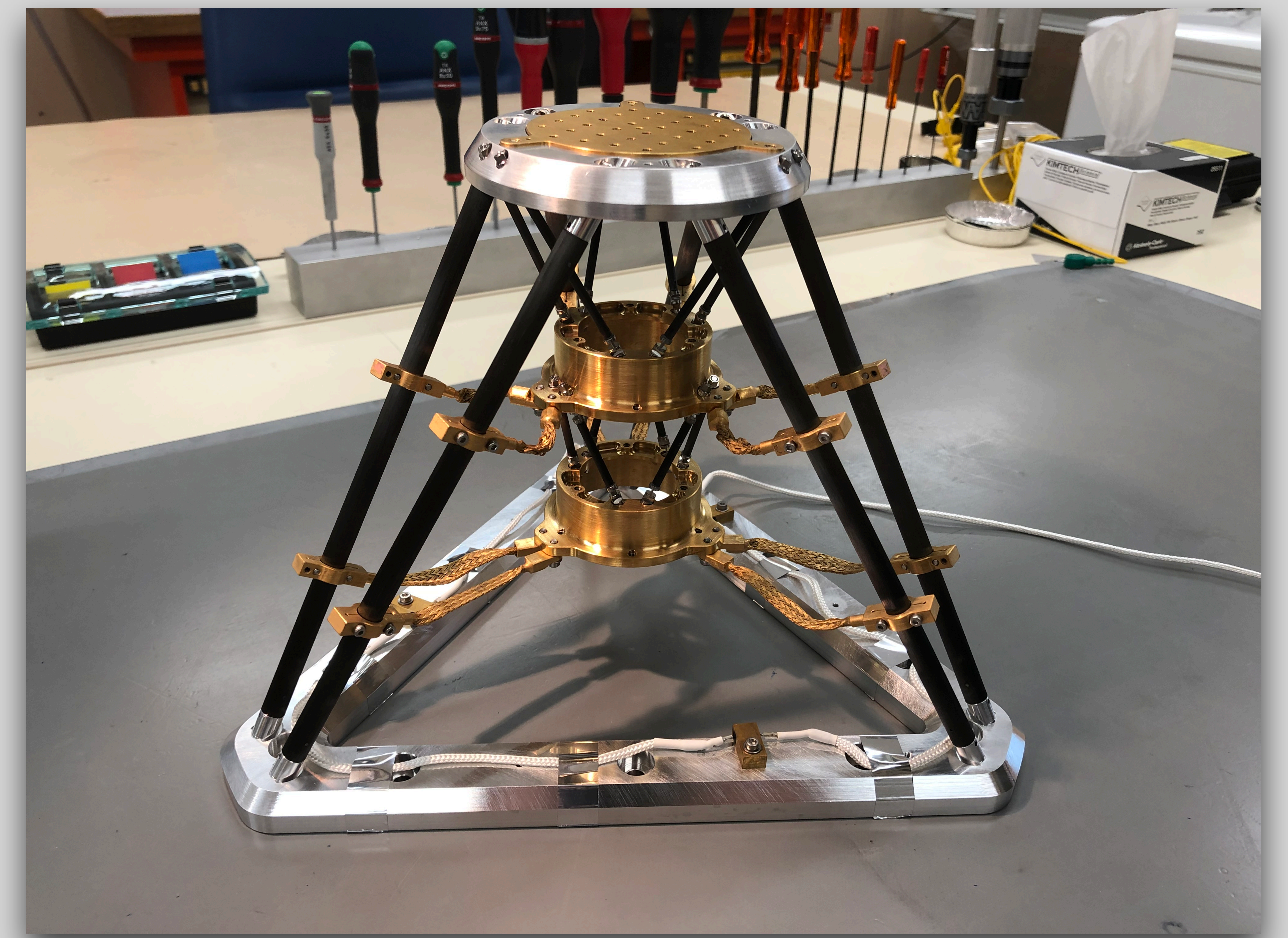


See you next time

- Cryogenics in April 25'
- Low Temperature Detectors in June 25'
- Whenever you want at IAS

Colloque national CMB-France #6

December 18, 2024



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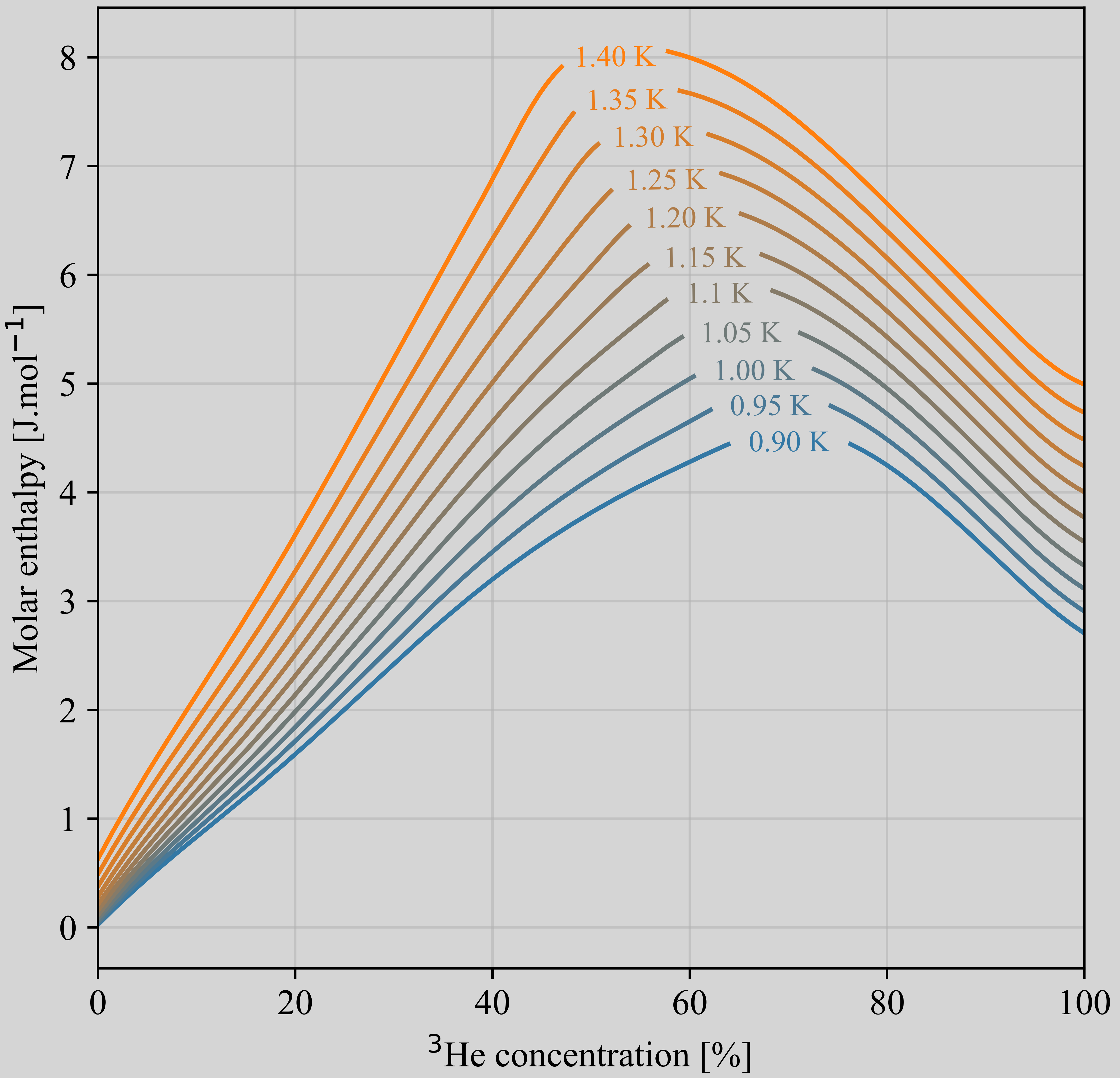
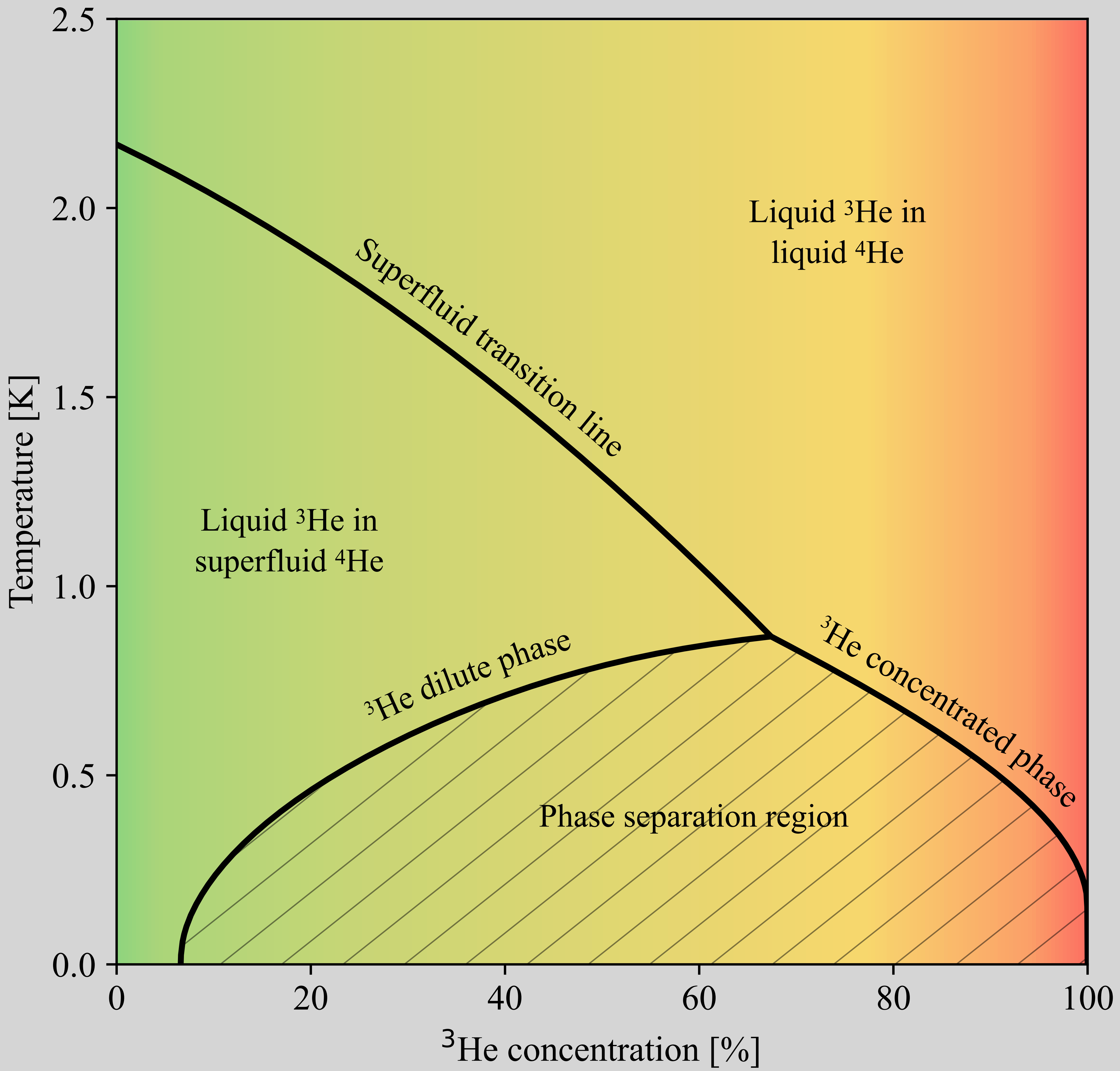
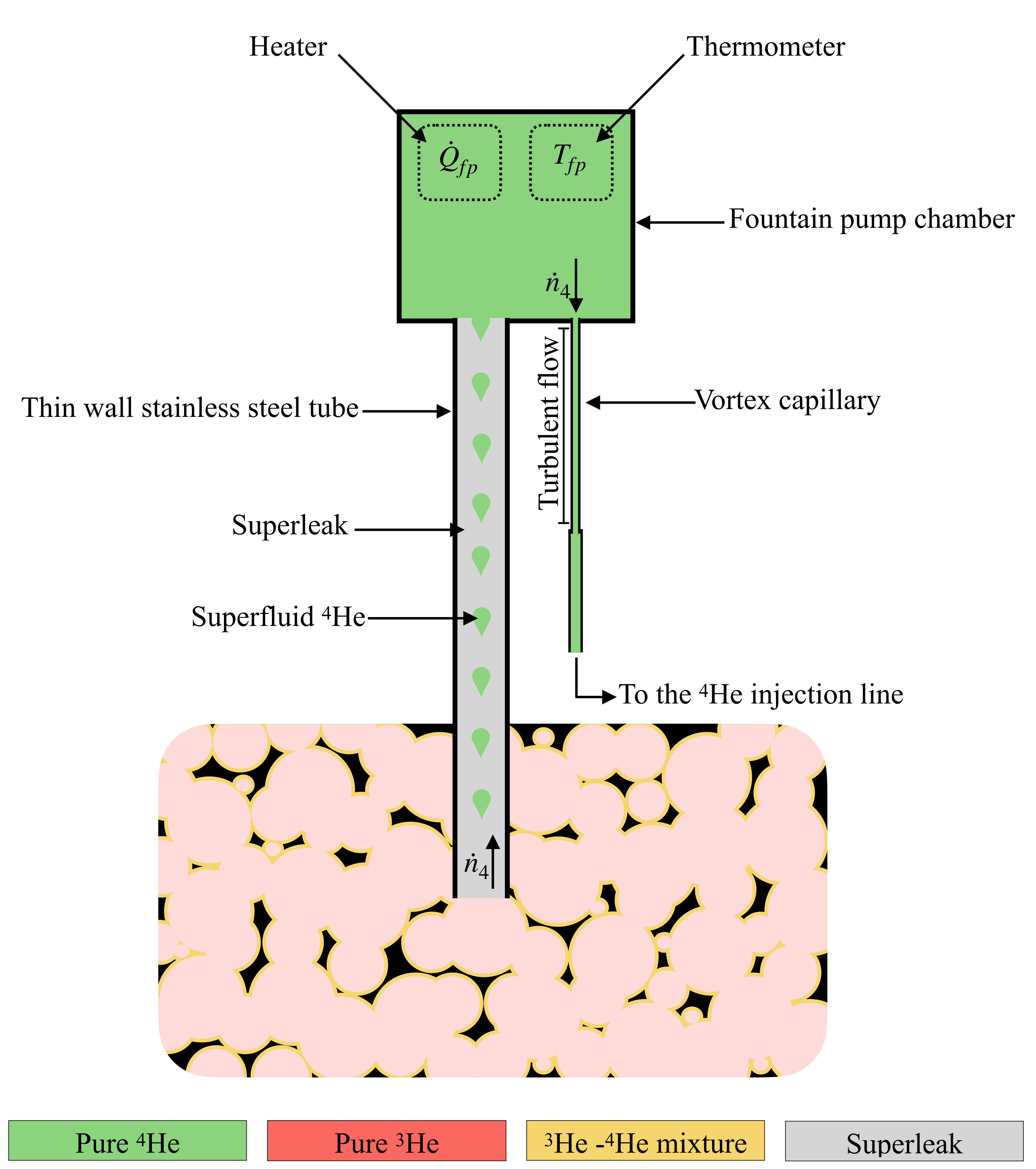
The state of the art

Principe of the dilution





Principe of the fountain pump



Principe of the fountain pump