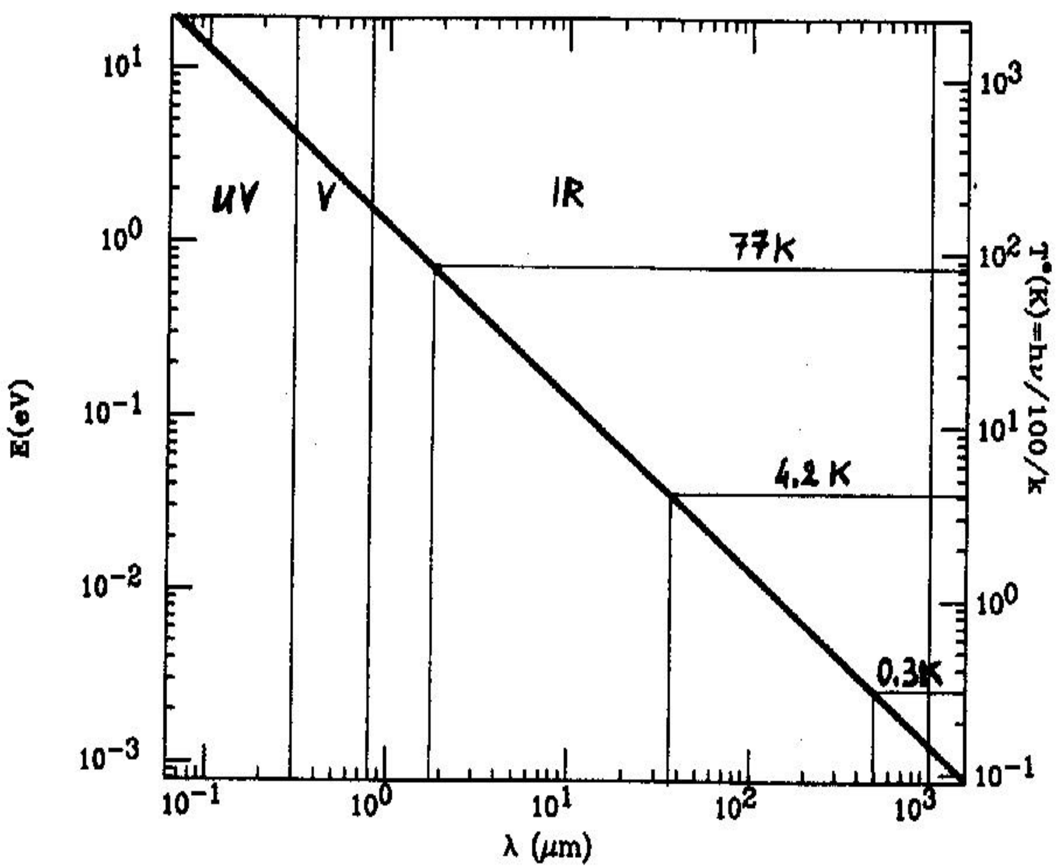
Space Cryogenics – Why ?

- Cryogenics is needed to take full advantage of space-based astronomical observations.
- Space-based astronomical observations are needed to avoid the effects of the atmosphere: limited transmission or/and high emission, depending on the wavelength of interest.
- Ultra sensitive photon detectors need very low temperatures for their operation (Cryogenics) but also very low background (Space+Cryogenics)

Detector Noise

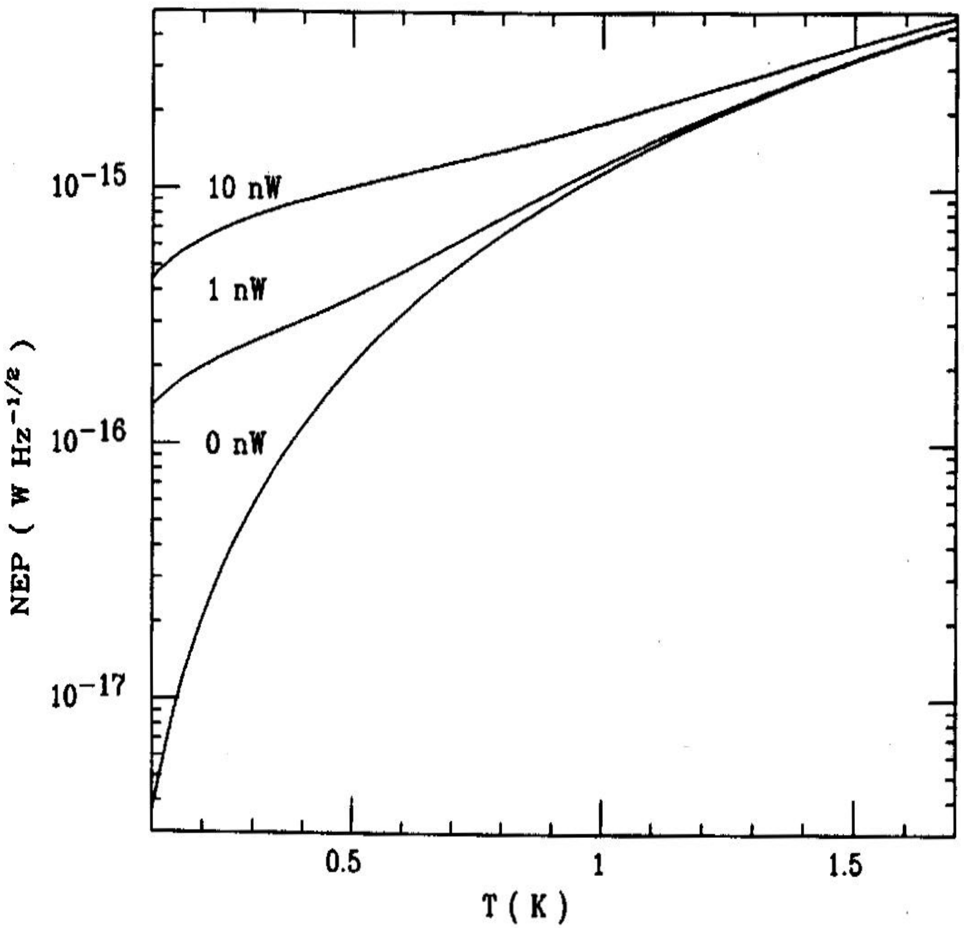


- Plot of the temperature where

$$kT = \frac{1}{100} h\nu$$

- At this temperature thermal noise is low enough that single photons can be detected.

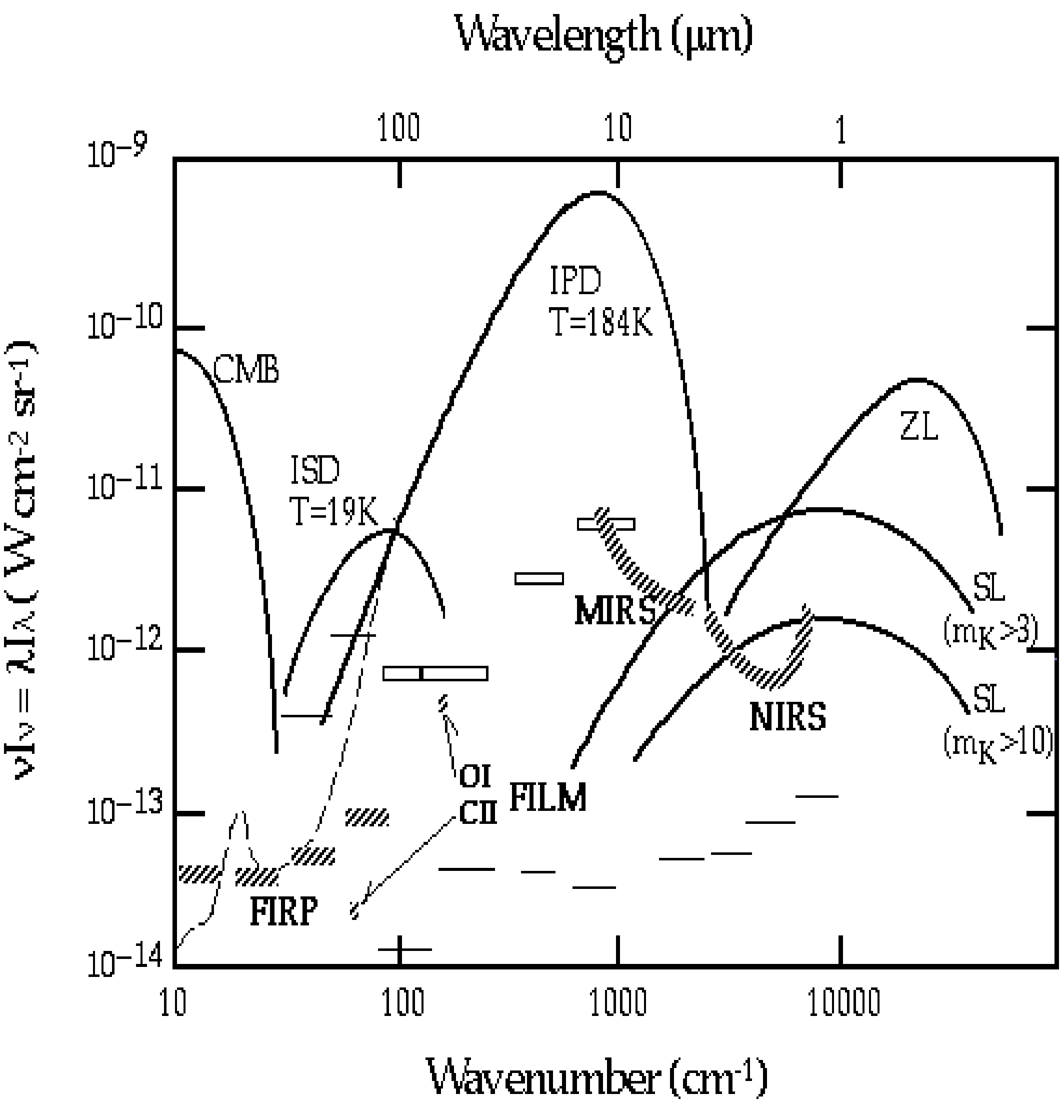
Example: Bolometer Noise



- The combination of
  - Johnson Noise
  - Temperature Noise
  - Photon noise

  is the total fundamental noise of a bolometer.
- It can be minimized by reducing the physical temperature of the detector.
- However, the radiative background (nW in the fig.) must be reduced as well.
- Need for low background

Radiative Background in space

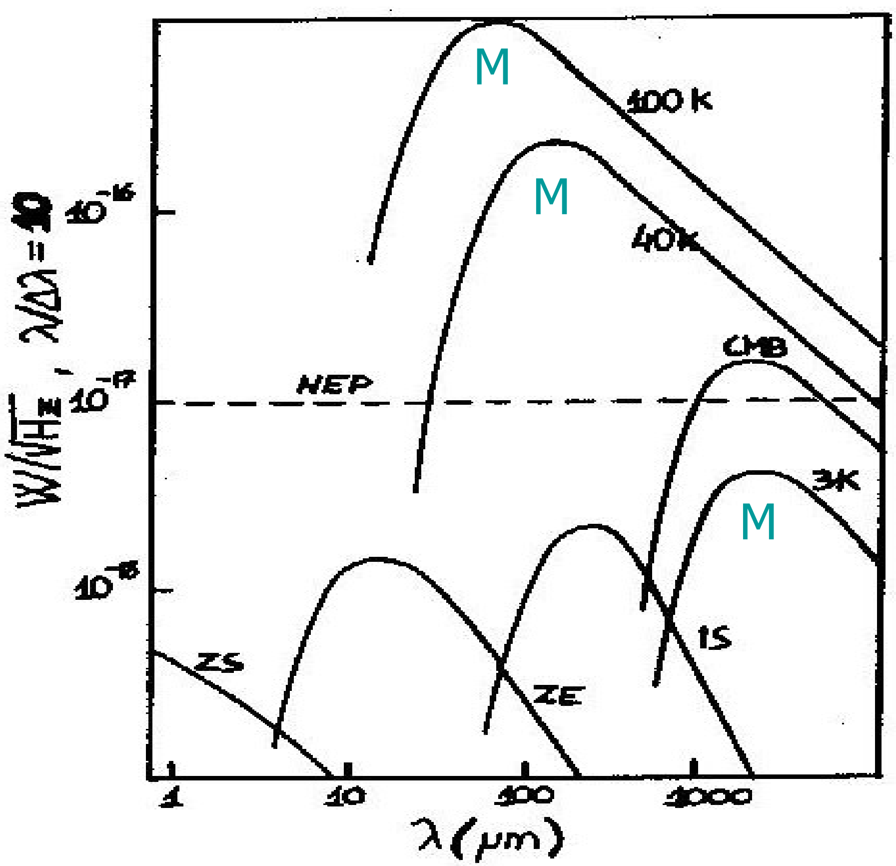


- Zodiacal dust (scattered)
- Zodiacal dust (thermal)
- Interstellar dust
- CMB

Instrument background and related photon noise must be reduced below astrophysical backgrounds

Photon Noise

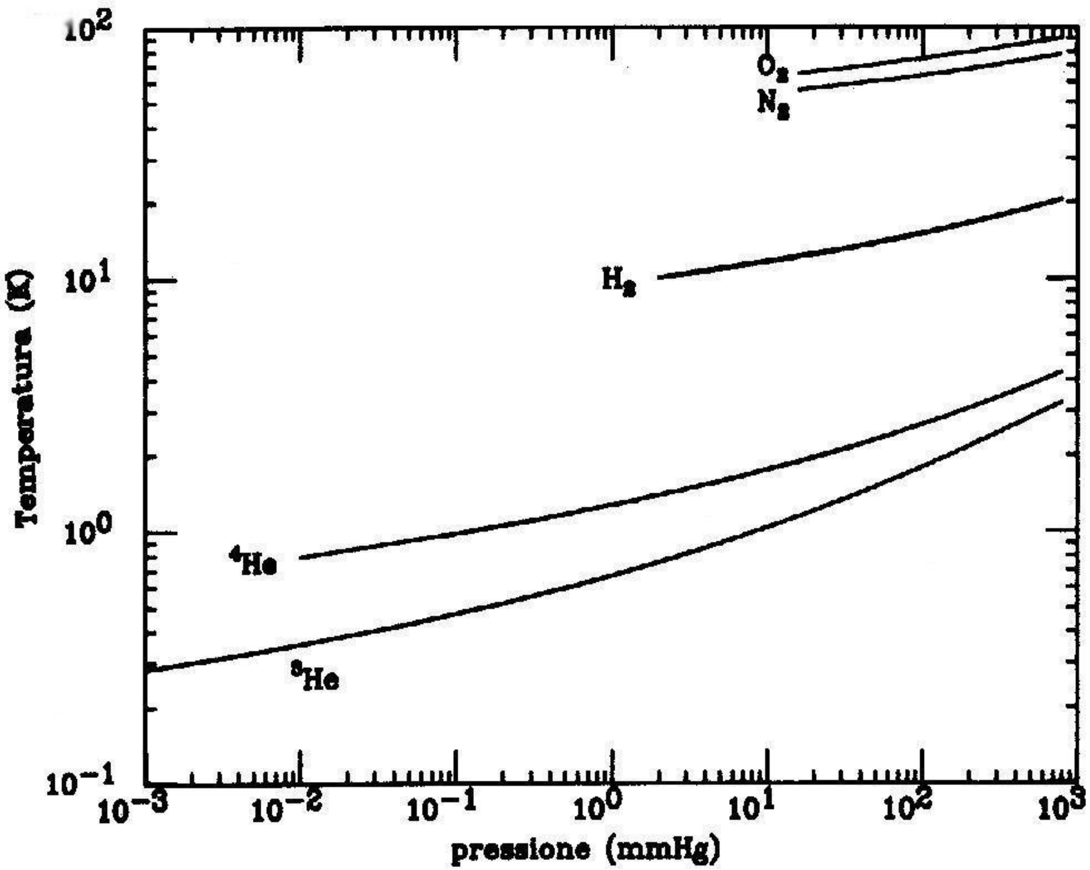
$$W_W = NEP = \sqrt{\frac{4k^5}{c^2h^3}}\sqrt{A\Omega}\sqrt{T^5\int_{x_1}^{x_2}\varepsilon\frac{x^4\left(e^x-1+\varepsilon\right)}{\left(e^x-1\right)^2}dx}$$



- Photon noise spectra for the thermal emission of a mirror M (5% emissivity) at different temperatures: 100 K, 40 K, 3 K.
- This is compared to the photon noise for the astrophysical background (lower curves)
- The best IR detectors have NEP of the order of or lower than 10^{-17} W/\sqrt{Hz}, (dashed line). To achieve this noise level, detectors must be cooled.
- If the mirror is not cold, at many wavelengths in the IR/FIR the natural sensitivity limit cannot be achieved.

Cryogens

^3He	3.2->0.3 K	24.5 j/g
^4He	4.2->1.0 K	21 j/g
H_2	20 -> 10 K	452 j/g
N_2	77 -> 60 K	199 j/g
O_2	90 -> 65 K	213 j/g

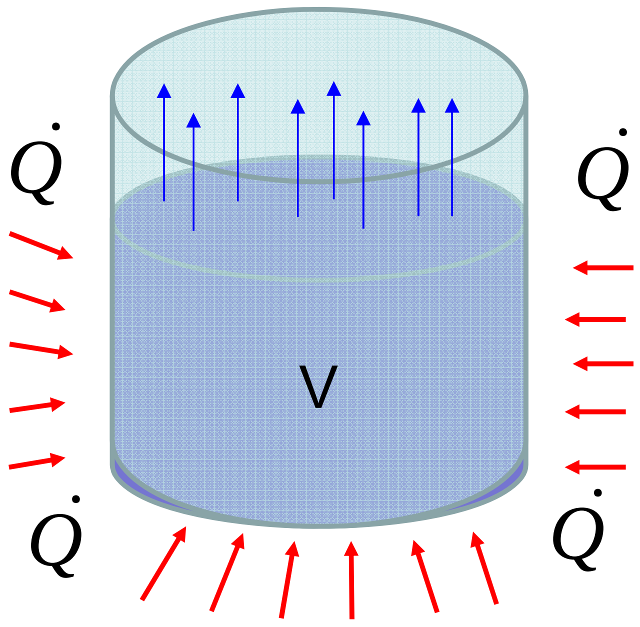


Boiling point (STP -> pumped)

Latent Heat at STP

Cryostats

- A cryostat is a container for a cryogen.
- The cryogen, in liquid form, slowly evaporates, keeping its container at its boiling point as long as the last drop evaporates.
- A good cryostat is engineered to reduce as much as possible the heat load on the cryogen. In this way the cryogen evaporation rate is reduced and the hold time t is maximized.



$$t = \frac{VH}{\dot{Q}}$$

$$\dot{Q} = \dot{Q}_{rad} + \dot{Q}_{cond} + \dot{Q}_{conv}$$

V = volume of liquid (lit)
H = specific latent heat (J/lit)
Q = heat load (W)

Orders of magnitude:

$$\frac{V}{t} = \frac{\dot{Q}}{H}$$

- Heat load on liquid nitrogen (77K) can be of the order of 10W
- Heat load on liquid helium (4.2K) can be of the order of 10W
- Heat load on liquid 3-He (0.3K) can be of the order of 10mW

^{4}He cryostat example : the BOOMERanG dewar

- Universita' La Sapienza, Dipartimento di Fisica
  P. de Bernardis, S. Masi, F. Piacentini,
  A. Raccanelli, D. Sforna.
- ENEA - Frascati
  E. Aquilini, P. Cardoni, L. Martinis,
  F. Scaramuzzi.

- S. Masi et al., Cryogenics, 1998, **38**, 319
- S. Masi et al., Cryogenics, 1999, **39**, 217

A Long Duration Cryostat for the BOOMERanG payload - 1

Specifications: the BOOMERanG cryostat must ….

- Cool a large focal plane @ 0.285K for 15 days
- Cool the reimaging optics and the Lyot stop @ 1.6K
- Work with minimum background from the optical window
- Be lightweight and heavy-duty for balloon operation
- Work in the stratospheric environment:
  P=3 mbar, T=-60^{o}C …+30^{o}C

A Long Duration Cryostat for the BOOMERanG payload - 2

Solutions:

- Superinsulation + nitrogen tank
- Helium tank + vapor cooled shield
- Kevlar cord suspension system
- Aluminum (6061) construction for tanks
- Connect stainless steel fill/vent tubes using explosion weld joints
- Large volume single shot ^{3}He fridge
- Twin thin polypropilene window (ϕ 60mm)

BOOMERANG Cryostat

Liquid Nitrogen tank:

T=77 K

65 liters of liquid N_2

Holding time: 16 days

Liquid Helium tank:

T=1.6 K

60 liters of liquid ^4He ⇒ 30 liters at low pressure

50 liters of experimental volume

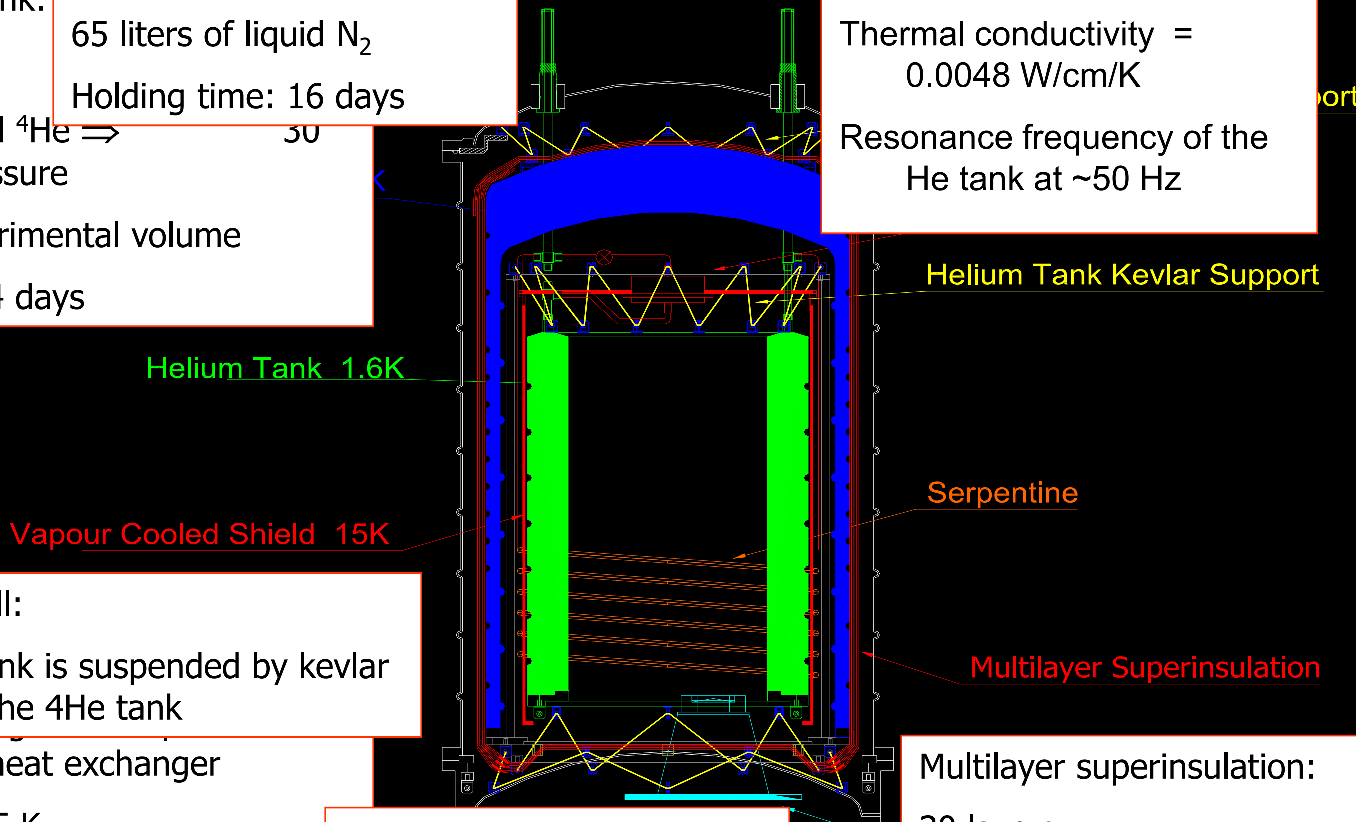
Holding time: 14 days

Kevlar suspension system:

Rope diameter = 1.65 mm

Thermal conductivity = 0.0048 W/cm/K

Resonance frequency of the He tank at ~50 Hz



Outer shell:

The N2 tank is suspended by kevlar ropes as the 4He tank

the heat exchanger

T=15 K

Window:

Thickness = 50 μm

Material: polypropylene

Multilayer superinsulation:

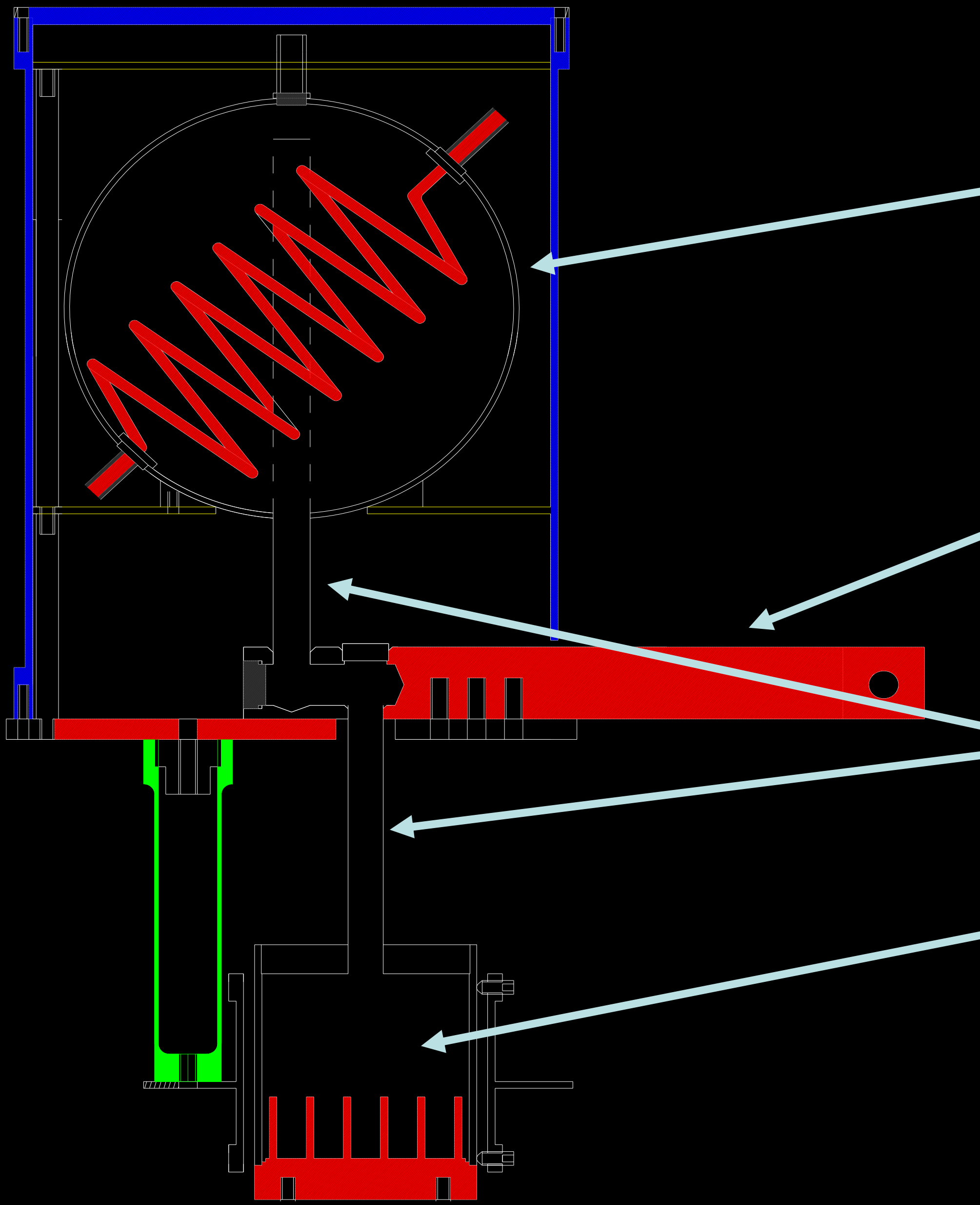
30 layers

Thermal input = 1 W/m^2

S. Masi et al. **Cryogenics**, 39, 217-224, 1999

S. Masi et al. **Cryogenics**, 38, 319-324, 1998

The Fridge



Cryopump

It works with charcoal carbon grains

It adsorbs when T < 12 K (mechanical thermal switch)

It desorbs when T > 20 K (heater)

Condensation point

Thermally connected to the ^{4}He bath with 2 gold plated high purity copper rods

Pumping tubes

Thin wall stainless steel tubes

Liquid ^{3}He evaporator

T = 0.280 K

Volume = 130 cm^3

34 STP liters of ^{3}He gas

Holding time: 14 days

OLIMPO cryostat

•The dewar has been developed in Rome

•The idea is to thermally isolate through layers interposing between 300K and 0.3K in order to reduce heat load.

Requirements:

1) Duration: at least 2 weeks

2) Sufficently strong to resist to external sollicitations

3) High stability of the focal plane of the instrument and the cold optics

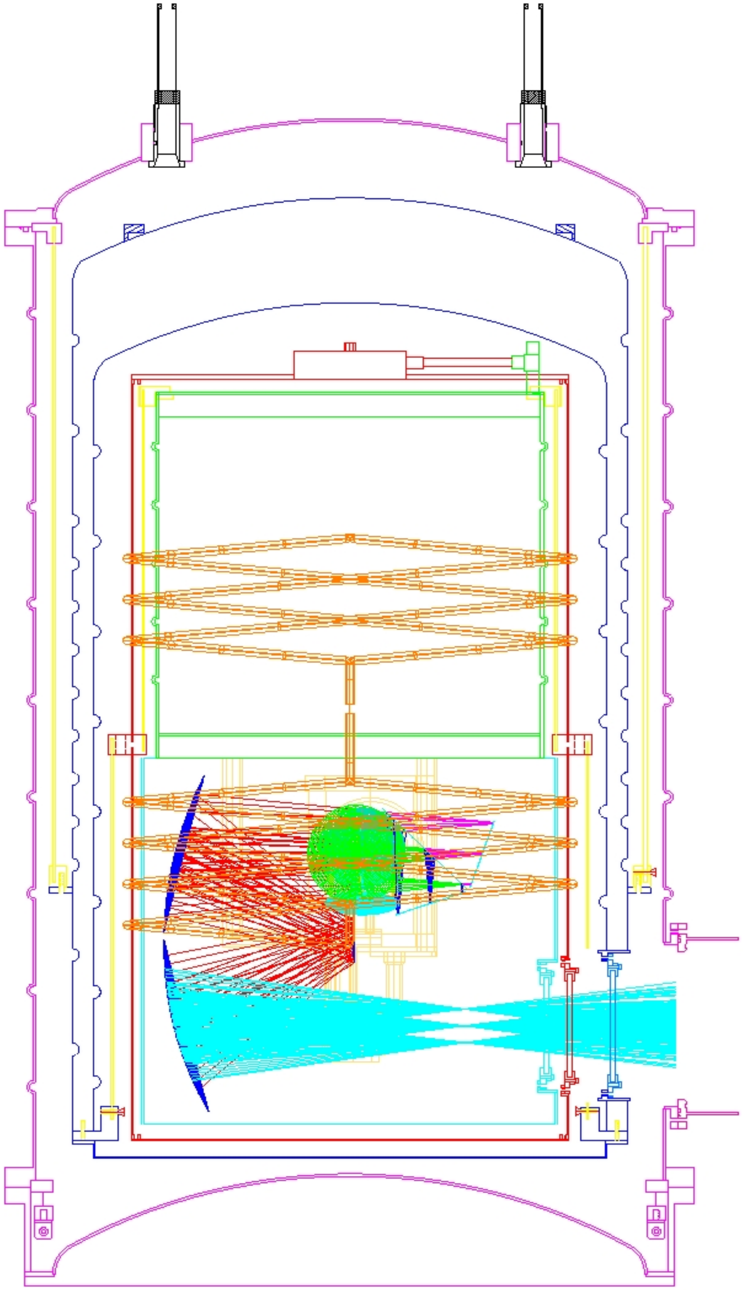
(respectively at 0.3K and 2K, with drifts <0.1mK/h [Masi S., 1998])

4) The optical chamber containing the cold optics should be completely accessible from the outside, for alligments and tests

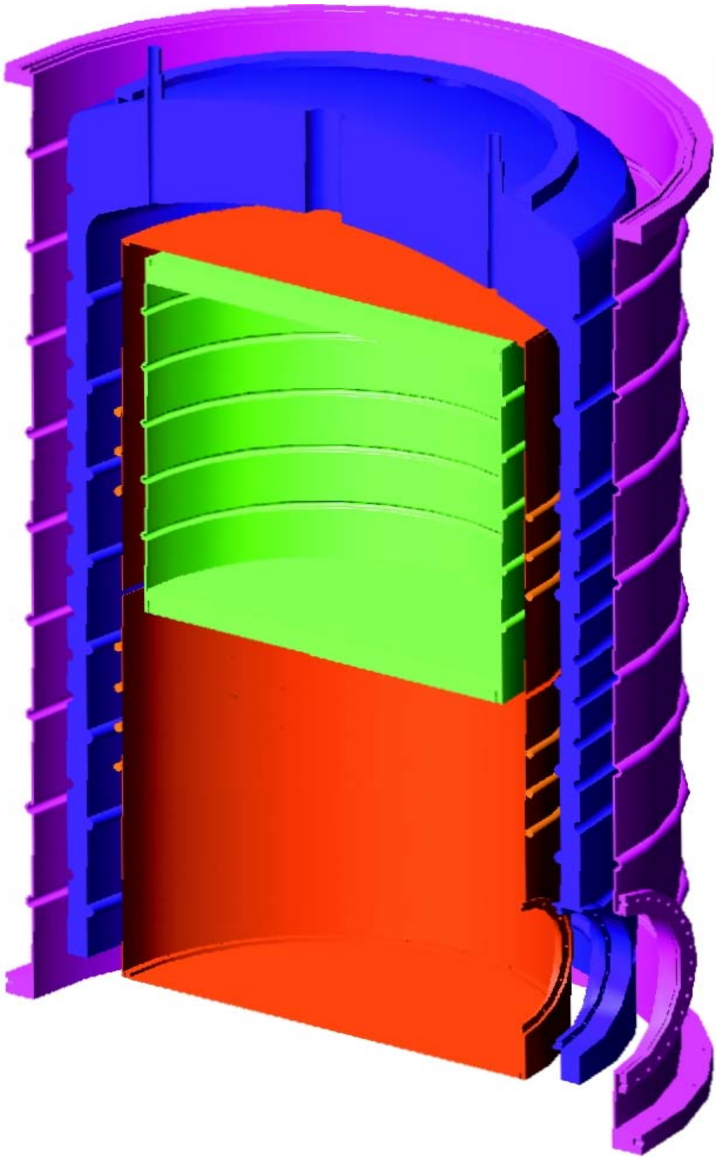
5) It has to operate automatically for many days

OLIMPO Cryostat

- Detailed sketch of the cryostat
- It's possible to distinguish thermal layers aimed to drastically reduce the heat load on the cold part



OLIMPO Cryostat



- **External shell:**

  aluminum vessel that contains all components.

  It's the first shield against radiative load and allows the evacuation of the inner volume, reducing the convective load on the inner layers.

- **Nitrogen tank:**

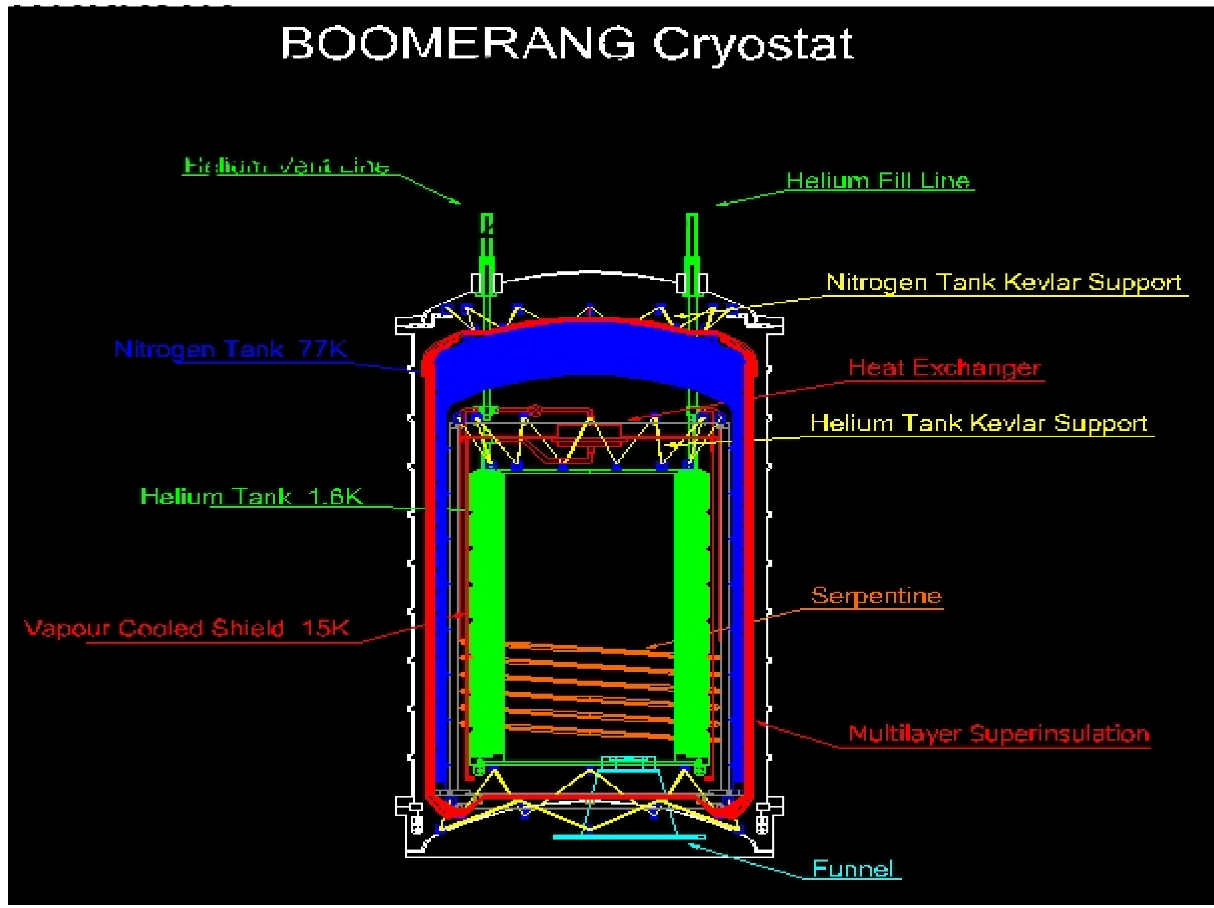
  bell shape, ~65 liters.

  Latent heat of evaporation: L=199 J/g (p=1atm, T=77K): significant thermal load absorbed by the evaporation of a limited amount of liquid.

- **Optical chamber** available for the optics: diameter of 450mm and height of 450mm

Comparison with BOOMERanG

- OLIMPO is a Cassegrain telescope: a lateral window is needed
- OLIMPO scan strategy: cross-elevation. The cryostat is skewed for all the flight: the inner structure has to be steady despite it's subject to a transversal sollicitation

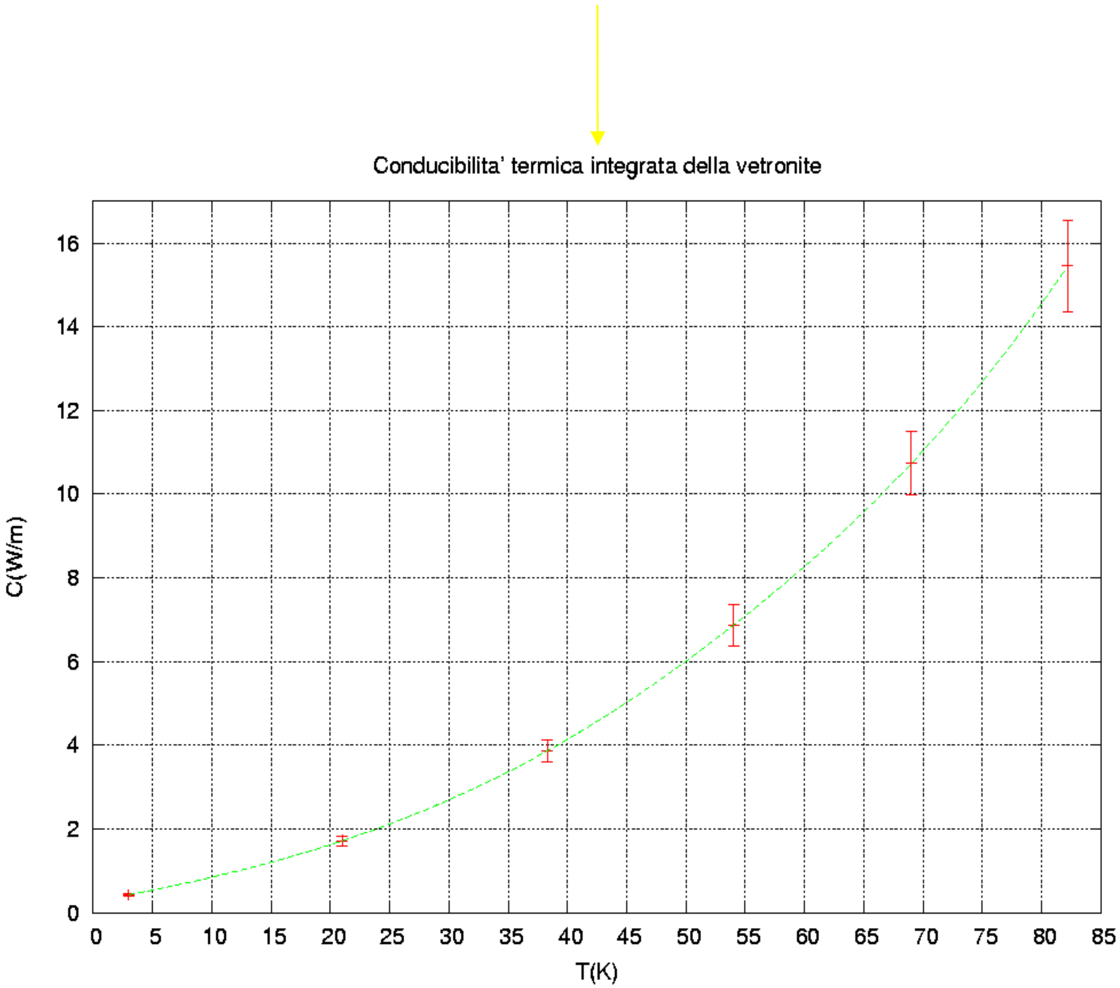


- Conclusion: kevlar is not the right solution! Test done on geometry BOOM-like: the inner tank shift is of ~2mm after few days of transversal load (the hanging part of the cryostat has weight of ~200 kg)

Fiberglass

- The inner components are supported by tubes made of fiberglass
- Fiberglass has the property to have a low thermal conductivity; moreover, it's rather solid, comparable to aluminum
- Fiberglass is a composite material obtained by fibre of glass and epoxy resin: depending on the detail and structure, remarkable variations on thermal conductivity can occur

Measurements of thermal conductivity



SUPERINSULATION

Composed of *n* layers made of *mylar* film,
covered by aluminum on one face in order to reduce emissivity and trasparency, and by insulator on the other side to avoid thermal contact between consecutive layers.

Radiative load:

$$\dot{Q}_{rad} = \sigma \frac{\varepsilon}{2} A_1 (T_2^4 - T_1^4).$$

$\varepsilon = \varepsilon(\lambda, T)$ surface emissivity (=1 for black body)

With *n* layers of superinsulation it's reduced of a factor (n+1):

$$\dot{Q}_{rad} = \left(\frac{1}{n+1}\right)\left(\frac{\varepsilon}{2}\right)\sigma \cdot A(T_{n+1}^4 - T_0^4)$$

SUPERINSULATION: test

$$\dot{Q} = \frac{LV}{t} \longrightarrow m = \frac{\dot{Q}}{L} = \frac{V}{t}$$

Linear fit on thermalized data $\longrightarrow$ angular coefficient m $\longrightarrow$ $\dot{Q}$

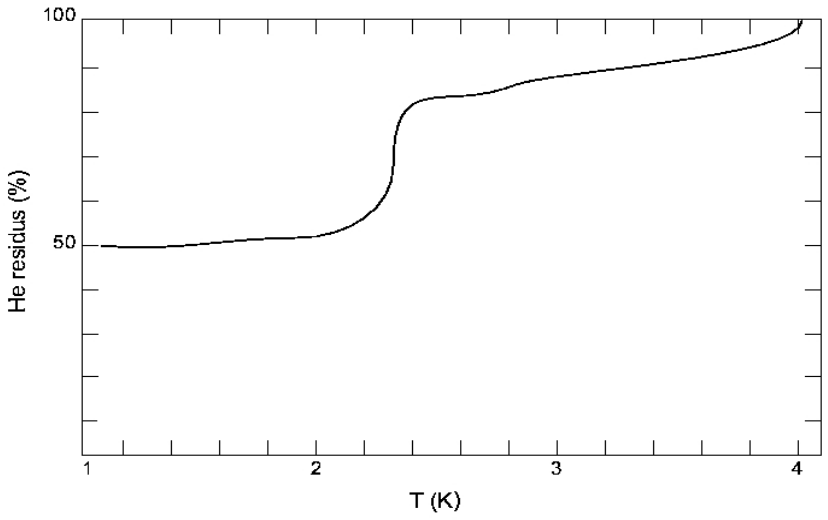
$\longrightarrow$ 30 layers of superinsulation ($\bar{Q} \simeq 8W$)

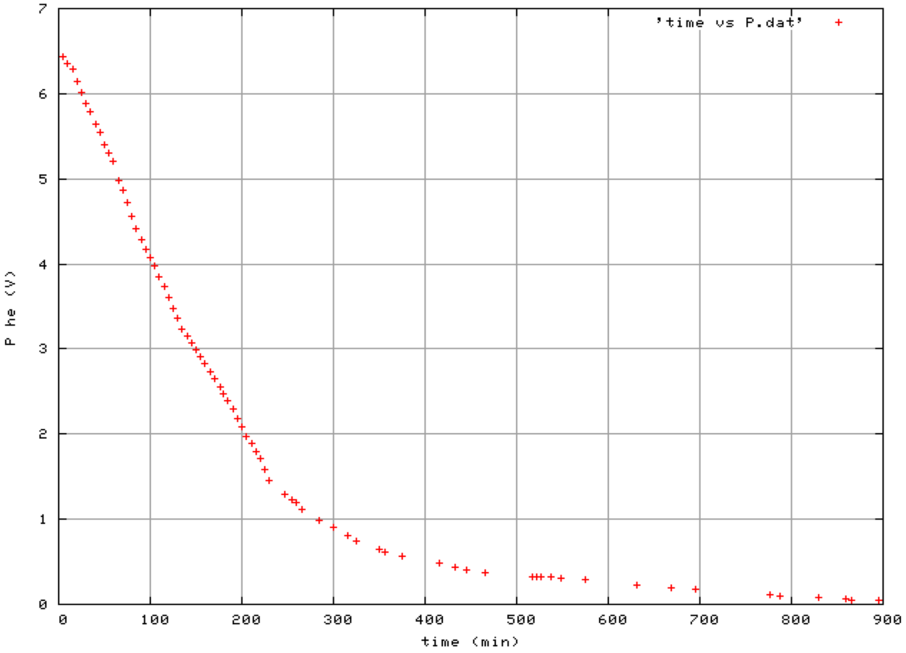
Tank ^4He

A way to reduce the temperature of a cryogenic liquid under the STP boiling point : reducing the pressure on it -> vapour gas cools down rest of the liquid [Conte,1970]

T(^4He): 4.2K down to ~ 2K

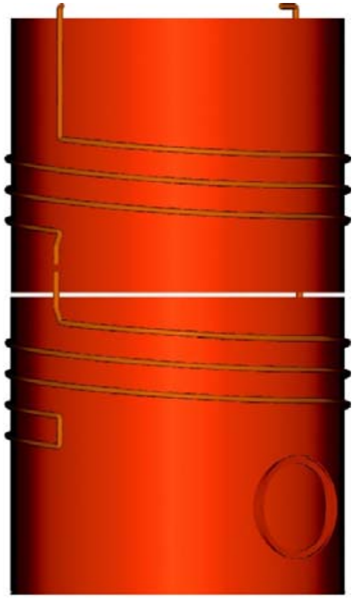
For ^4He, an important part of liquid is consumed during evaporation (~50%)

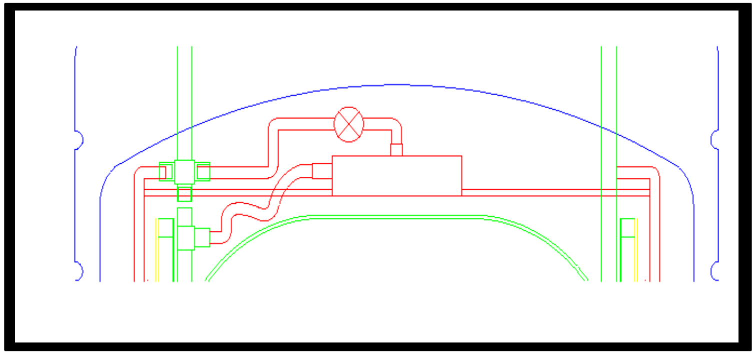




^{4}He vapour shield

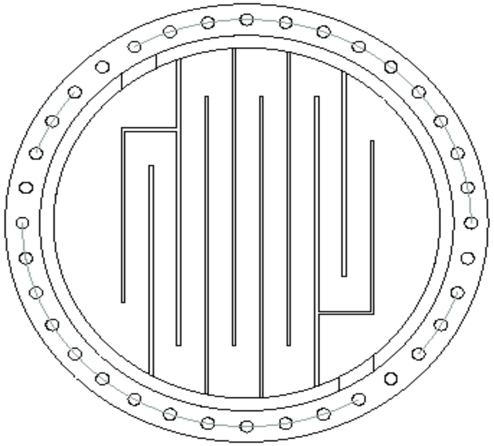
This stage makes lower radiative load on ^{4}He: vapour of boiling liquid passes through a serpentine welded on a copper shield placed between the two tanks -> vapour can absorb heat from the shield and its temperature achieves (20-40)K depending on the efficiency of the heat echange between shield and vapour (eff=1 if $T_{shield}=T_{vapour}$).





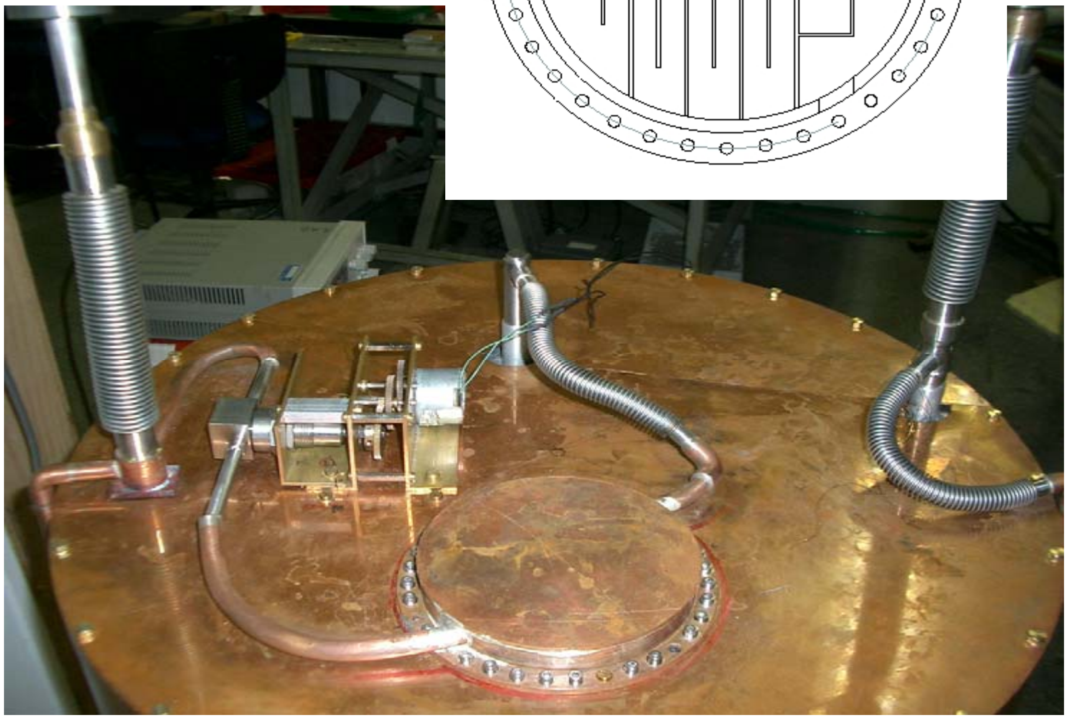
Heat exchanger

A large impedance of the serpentine can generate pressure oscillations during operation of pumping on ^4He



Heat exchanger in parallel to serpentine.

Motorized valve regulates flux of evaporating gas.



The window

- Radiation penetrates in the cryostat and reaches cold optics through a vacuum window
- Material: UHMWPE (Ultra High Molecular Weight PolyEthilene)
- In order to remove interference due to inner reflections, anti-reflection coating is applied
- The dimension (d=130mm) is set by the configuration of cold optics and by the beam size
- Thickness: 4mm

Cold wiring:

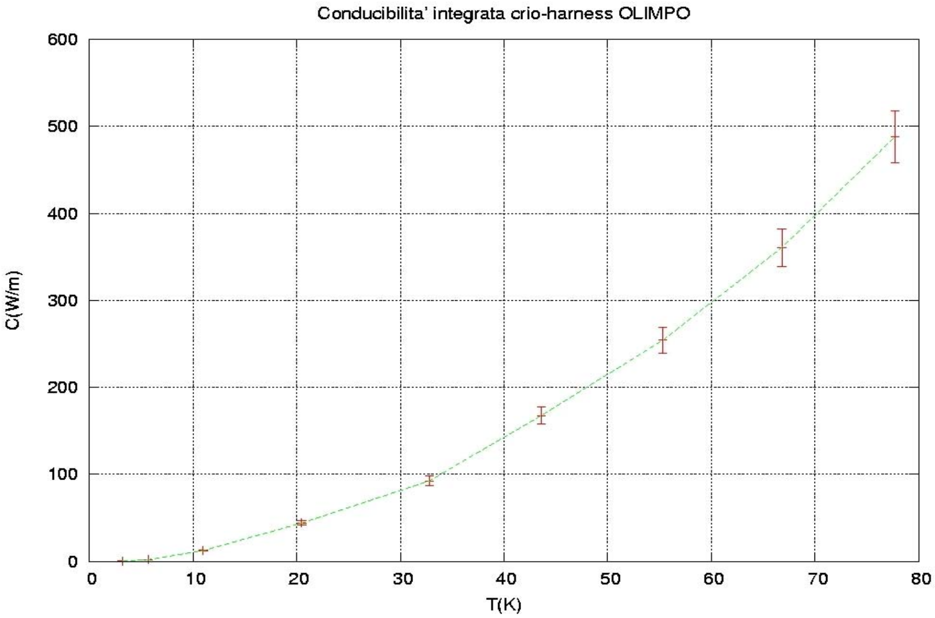
(D.Yvon)

300K-77K Cryoharness prototype

Thermal shock at 77 K

OLIMPO Cryoharness 1

Measurements of thermal conductivity



From numerical simulations for OLIMPO cryostat:

Efficiency	T_{Shield}(K)	Days
0.1	46.0	8
0.2	41.0	10
0.3	37.0	12
0.4	35.0	13
0.5	33.0	14
0.6	31.0	16
0.7	29.0	17
0.8	28.0	18
0.9	27.0	19
1.0	26.0	20

Data of the He cooldown:

after pumping on He bath

⇕

~ 2 weeks

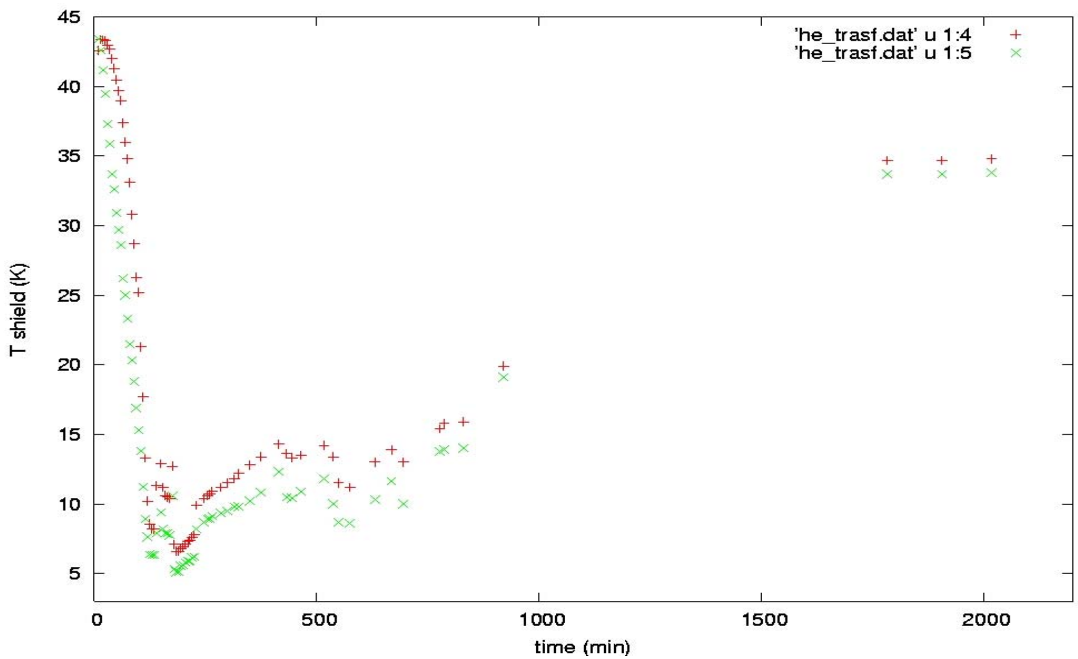
HELIUM BOILOFF

Date	Time	Date Time	# HE	HE gas (l)	HE gas(l/hour)	LHE (l/h)	LHE (l)	Life (days)	Already	Total
10/11/07	00:00	10/11/07 00:00	623033	0			0			
10/11/07	00:05	10/11/07 00:05	623046	13	156	0.206	0.02	**8.11**	0.00	**8.11**
10/11/07	00:15	10/11/07 00:15	623072	39	156	0.206	0.05	**8.1**	0.01	**8.11**
10/11/07	00:30	10/11/07 00:30	623107	74	140	0.184	0.1	**9.01**	0.02	**9.03**
10/11/07	00:55	10/11/07 00:55	623154	121	112.8	0.149	0.16	**11.17**	0.04	**11.21**
10/11/07	08:37	10/11/07 08:37	623741	708	76.23	0.100	0.93	**16.21**	0.36	**16.57**
10/11/07	10:00	10/11/07 10:00	623841	808	72.29	0.095	1.06	**17.03**	0.42	**17.45**
10/11/07	12:55	10/11/07 12:55	624069	1036	78.17	0.103	1.36	**15.63**	0.54	**16.17**
10/11/07	15:18	10/11/07 15:18	624206	1173	57.48	0.076	1.55	**21.16**	0.64	**21.79**
10/11/07	15:55	10/11/07 15:55	624237	1204	50.27	0.066	1.59	[illegible]	0.66	**24.83**
10/11/07	16:59	10/11/07 16:59	624327	1294	84.38	0.111	1.7	**14.35**	0.71	**15.06**
10/11/07	17:21	10/11/07 17:21	624354	1321	73.64	0.097	1.74	**16.43**	.72	**17.15**
10/11/07	17:59	10/11/07 17:59	624403	1370	77.37	0.102	1.81	**15.61**	.75	**16.36**
10/11/07	18:48	10/11/07 18:48	624468	1435	79.59	0.105	1.89	**15.14**	.78	**15.93**
10/11/07	19:13	10/11/07 19:13	624498	1465	72	0.095	1.93	**16.72**	.80	**17.52**
10/11/07	22:55	10/11/07 22:55	624789	1756	78.65	0.104	2.31	**15.15**	0.95	**16.11**

T_{shield} ~ 33K

⇕

~ 2 weeks



Pilot cryostat

Duration: ~ 2 days

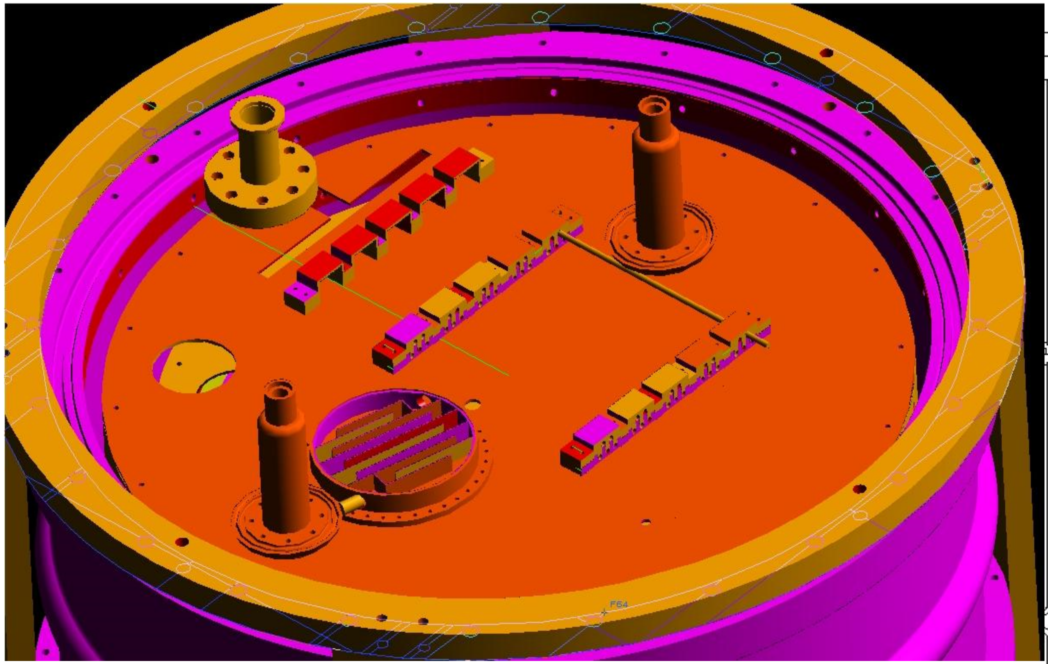
Optical chamber available for the optics: diameter of 400mm and height of 580mm

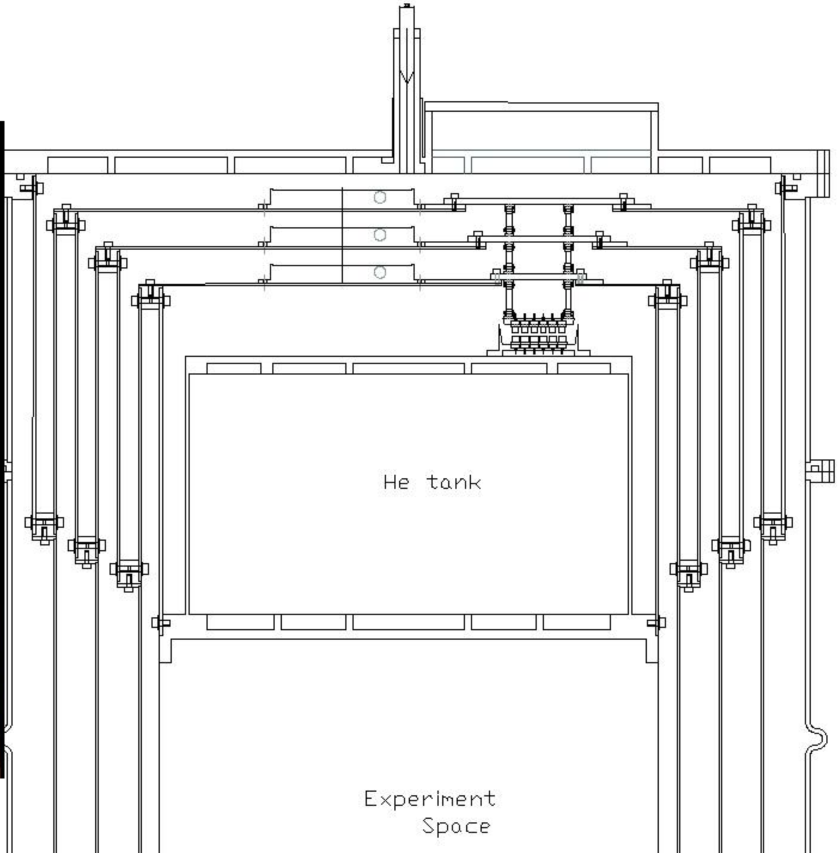
Weight: 120 Kg (much less than OLIMPO, that is ~200Kg, because in Pilot there isn't N_2 liquid)

In order to be light and compact: instead to use N_2-cooled shield -> three He-Vapour Cooled Shields, each surrounded by a superinsulation jacket of 20-30 layers. This is the standard solution for space cryostats like the ones used in COBE, ISO, IRTS, SPITZER.

Pilot cryostat

The temperatures of the 3 shields are expected to be around 30, 65 and 150 K with efficiency of the heat exchangers of about 70%.





From numerical simulations for Pilot Cryostat:

T shields ~ 38, 70, 140 K
with efficiency of 70%

It corresponds to life of ~ 4 days

What changes when working in space?

- OLIMPO Cryostat successfully works:

simulations done before construction have had a positive feedback from test on the dewar with both nitrogen and helium liquid.

- Pilot cryostat tested in Paris, and flown from Timmins, Canada. 24 hours flight, cryostat OK.

- Future missions will benefit of this know-how: in particular LSPE, which is a validation of one of the possible satellite missions for CMB B-modes; also these technologies were useful to design the cryogenics system of Sagace, an ASI satellite to measure S-Z effect.

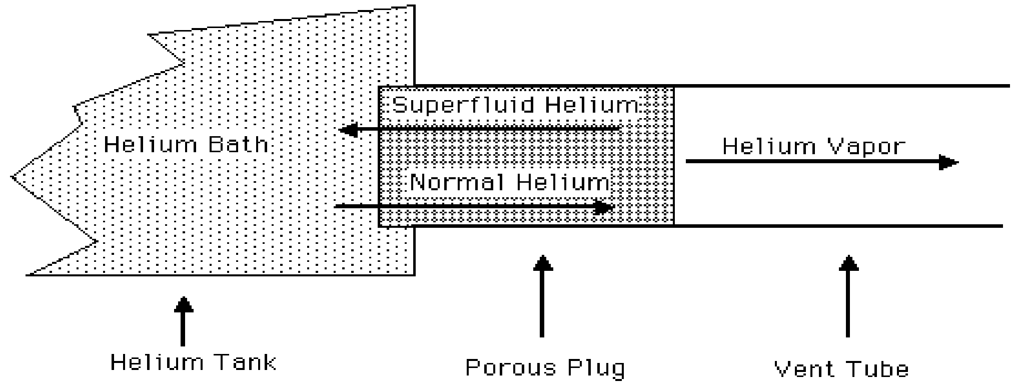
Cryostats for space

- There are two main difficulties to design a cryostat to be used in space:
  - The absence of gravity makes difficult to keep the liquid in good thermal contact with its container, and to keep it inside its container while pumping on it.
  - The very high acceleration at the launch of the rocket requires very strong support structures. This increases the conductive heat load on the cryogen, reducing the hold time.
- The first problem has been solved only in the 80s with the development of the porous plug.
- The second one has been solved by careful design of straps and struts, and, in extreme cases, with the use of supports to be removed after launch.

The Porous Plug

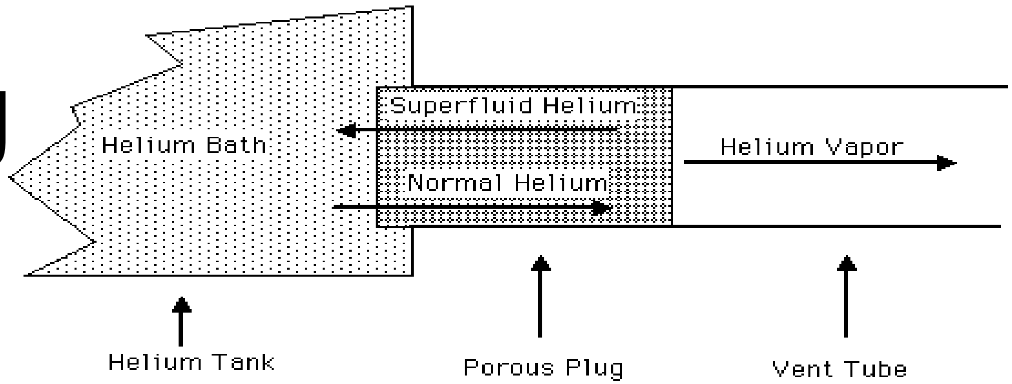
- In a He dewar, the helium vapor must be allowed to escape - if it's held in the dewar, high pressure will build up.
- How can we let the vapor escape while making sure the liquid stays in the dewar?
- On the ground that's easy: the liquid sits in the bottom of the tank, so we put the vent on the top of the tank.
- In «zero gravity», however, there is no top or bottom. We still have to put vents in the tank, but in the vents we install porous plugs.

The Porous Plug



- The vent plugs have pores that are large enough that both the normal and superfluid components of helium can flow through.
- When the liquid helium reaches the outside surface of the plug, that is, the surface exposed to the vacuum of space, it evaporates. As it evaporates it cools.
- To the "cool" helium on the outside surface of the plug, the "warm" helium inside the dewar now looks like a hot spot.
- Since superfluid helium flows from cold towards warm, the superfluid at the outer surface of the plug flows back into the dewar.

The Porous Plug

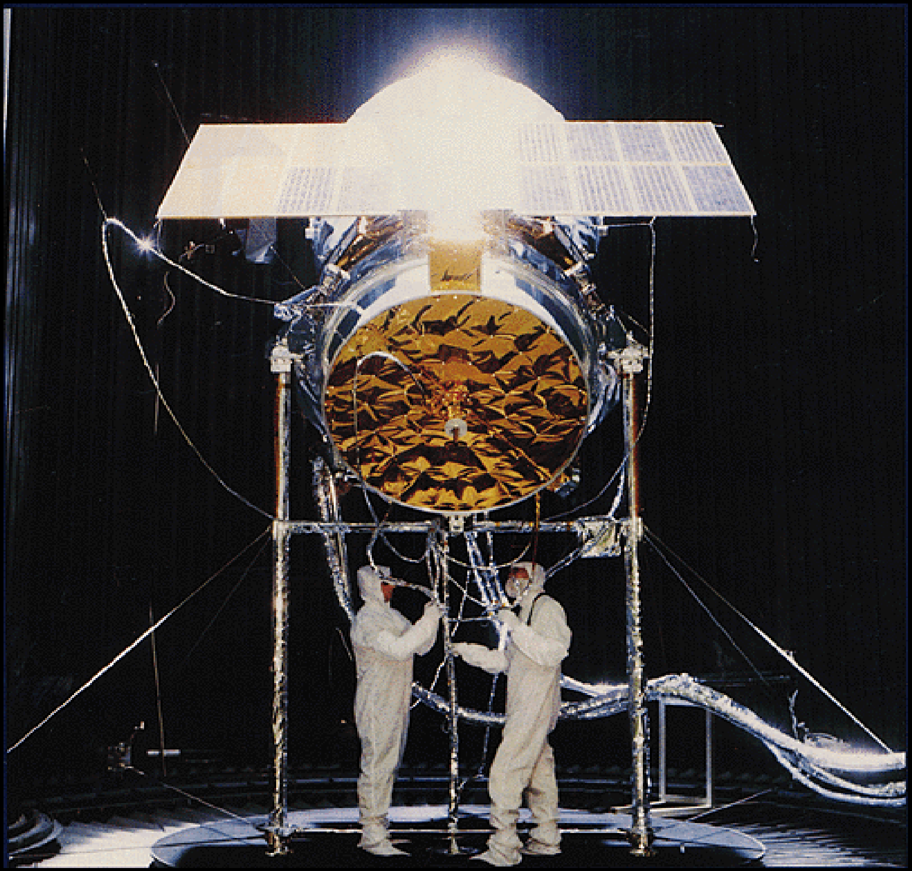


- As superfluid leaves the outer surface of the plug, normal helium at the outer surface converts to superfluid helium to keep the mixture appropriate to the temperature.
- Thus, there is a combination fluid flowing from the inside to the outside of the plug, fluid evaporating and escaping, and fluid flowing back into the dewar.
- If the porous plug is designed correctly, the cooling caused by evaporation at the plug will hold the dewar at the desired temperature.

Space Cryogenics: Important steps/examples

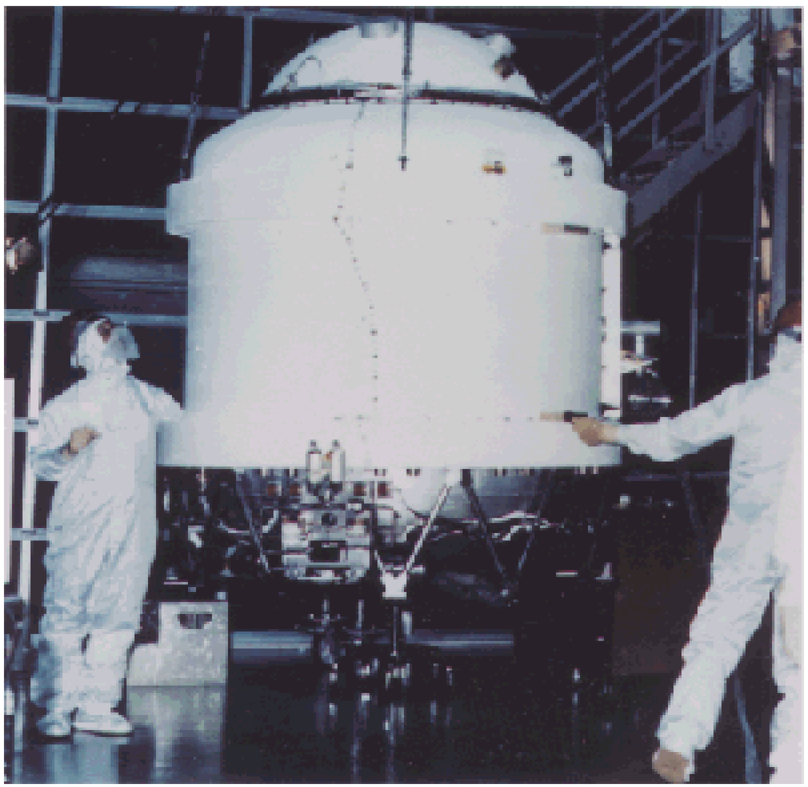
- IRAS – 1983 – IR 10-100 μm - telescope and detectors cooled with superfluid liquid Helium – Porous Plug – 11 months operation, 1.8 K
- COBE – 1989 – 0.1/4mm - 11 months - similar dewar
- ISO – 1995/8 – 1-200 μm - similar dewar – 2000 liters, 28 months of operation
- Sorption Cooler (10K) flown on the Space Shuttle (BETSCE 1995)
- Stirling Mechanical Cooler (65K) flown on the Shuttle (STS-63 1995)
- IRTS, 1-800 μm, 1995, 0.3K ^{3}He fridge, 28 days
- XQC suborbital rocket, 1996, 0.06K ADR (few minutes)
- MAXIMA balloon: 0.1K ADR; ARCHEOPS balloon: 0.1K dilution fridge, about 1 day of operation
- The SPITZER IR telescope and detectors cryogenic system (He dewar + passive radiator cooling)
- Herschel (2009): large He cryostat.
- Planck (2009): dry cryostat with dilution fridge,

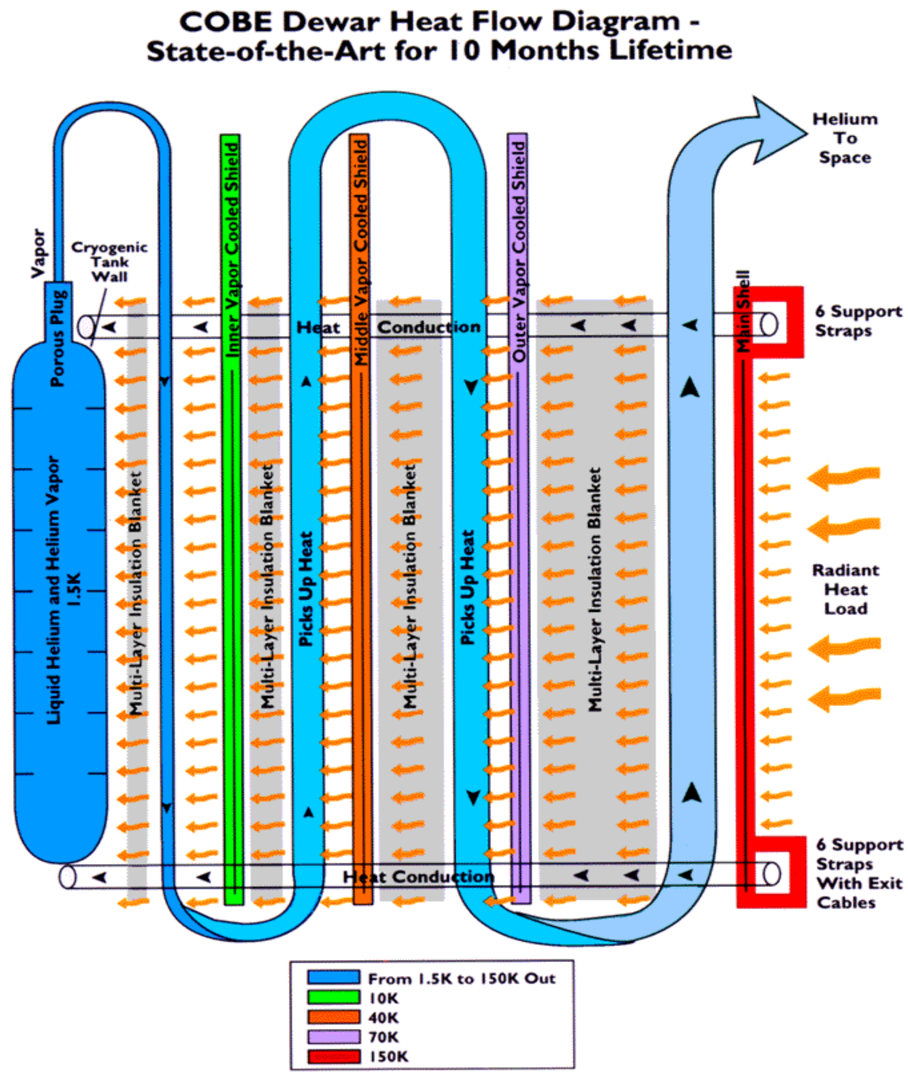
InfraRed Astronomical Satellite (1983/4) ESA



- IRAS was a spacecraft with a 60 cm telescope mounted in a liquid helium cooled cryostat.
- The mirrors were made of beryllium and cooled to 4 K.
- The focal plane assembly was located at the Cassegrain focus of the telescope and was cooled to about 3K.

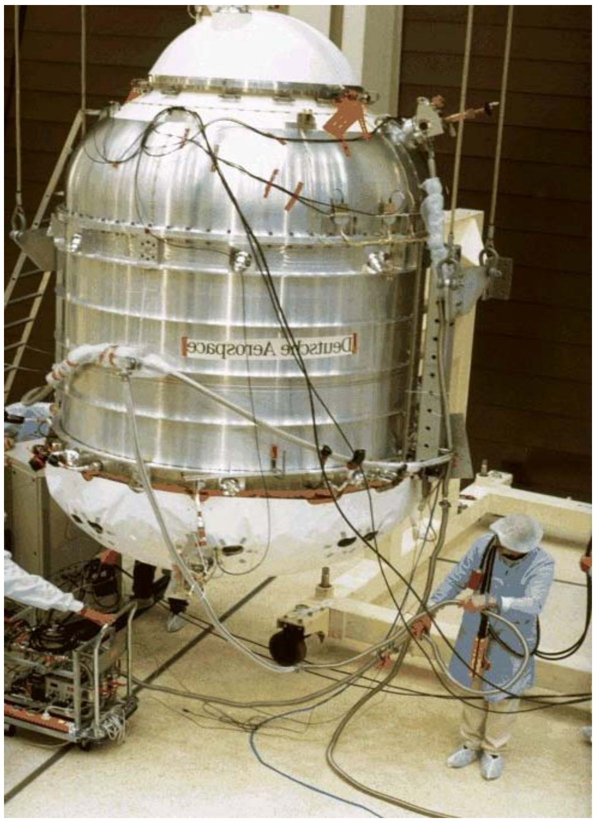
COBE



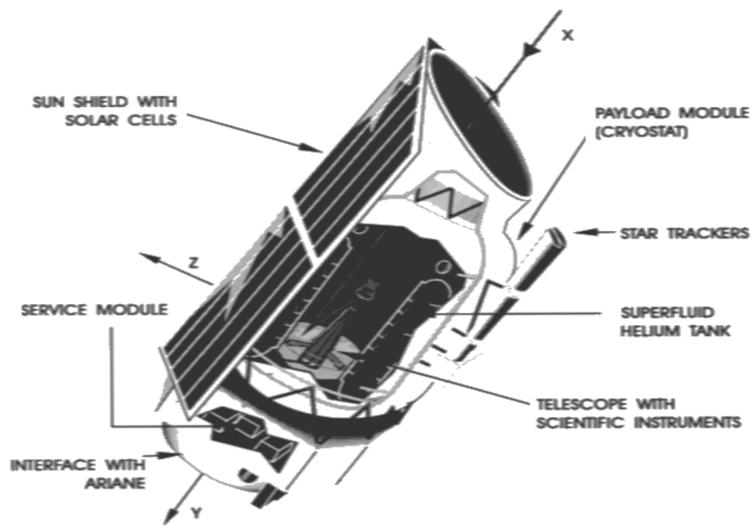

COBE Dewar Heat Flow Diagram -
State-of-the-Art for 10 Months Lifetime
Helium To Space
Vapor
Cryogenic Tank Wall
Porous Plug
Inner Vapor Cooled Shield
Middle Vapor Cooled Shield
Outer Vapor Cooled Shield
Main Shell
Heat Conduction
6 Support Straps
Liquid Helium and Helium Vapor 1.5K
Multi-Layer Insulation Blanket
Multi-Layer Insulation Blanket
Picks Up Heat
Multi-Layer Insulation Blanket
Picks Up Heat
Multi-Layer Insulation Blanket
Radiant Heat Load
Heat Conduction
6 Support Straps With Exit Cables
From 1.5K to 150K Out
10K
40K
70K
150K

ISO (ESA, Nov.1995-Apr.1998)

http://www.iso.vilspa.esa.es/ , http://sci.esa.int/iso/



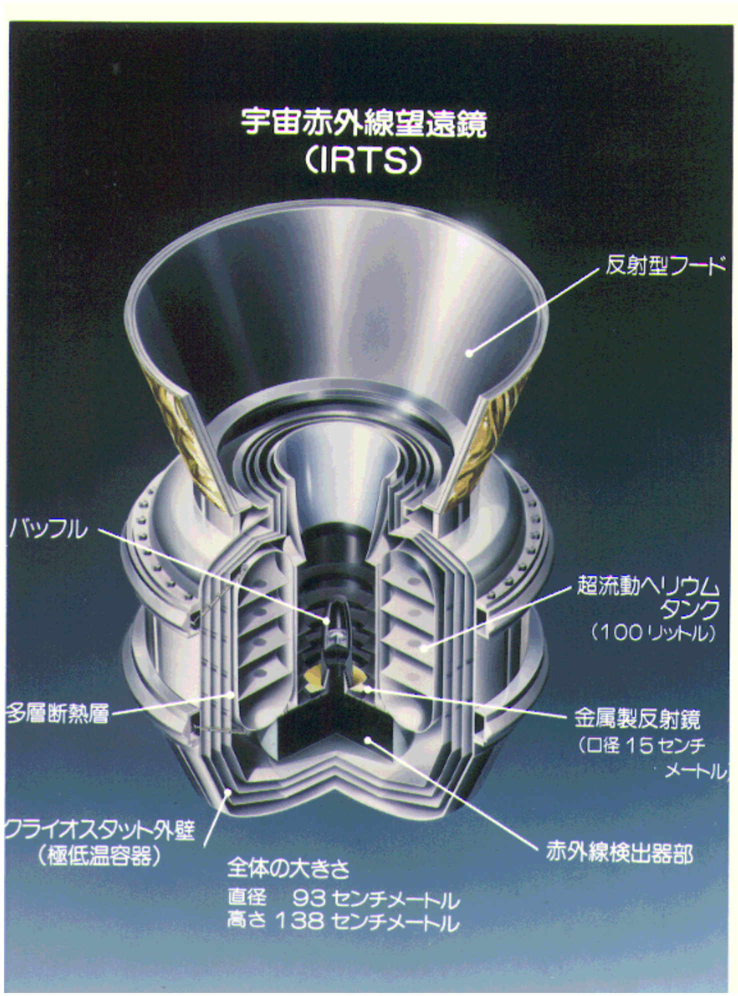
- 2200 liters of superfluid He
- 28 months of operation, cooling a 60 cm IR telescope and thousands of detectors



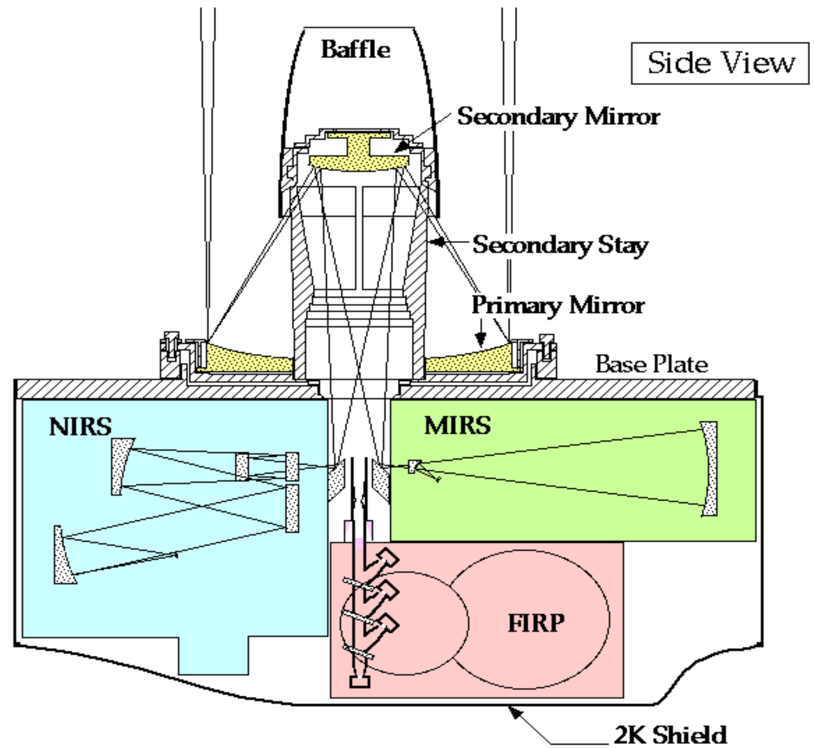
ISO (Nov.1995-Apr.1998)

- At its launch in November 1995, ISO carried a supply of 2200 litres of superfluid helium. Slow venting of the helium into space maintained the low temperature of the optical system. The forecast lifetime for liquid He was 18 months.
- The lifetime in orbit was 28 months !
- How did ISO achieve its extended life? Three months came from a prudent safety margin in the engineering calculations of the rate of loss of helium. Two months were the result of favourable circumstances in the launch campaign at Kourou in French Guiana. During a technical check of the Ariane 44P launcher, ISO's engineers seized the chance to recharge the helium, and the quick launch that followed meant that the outer parts of the cryogenic system of the spacecraft had little time to warm up in Kourou's tropical climate. Finally, the daily loss of helium turned out to be 17% less than expected, at the lower end of a range of possibilities considered by the engineers. That gave ISO an estimated five months of additional life

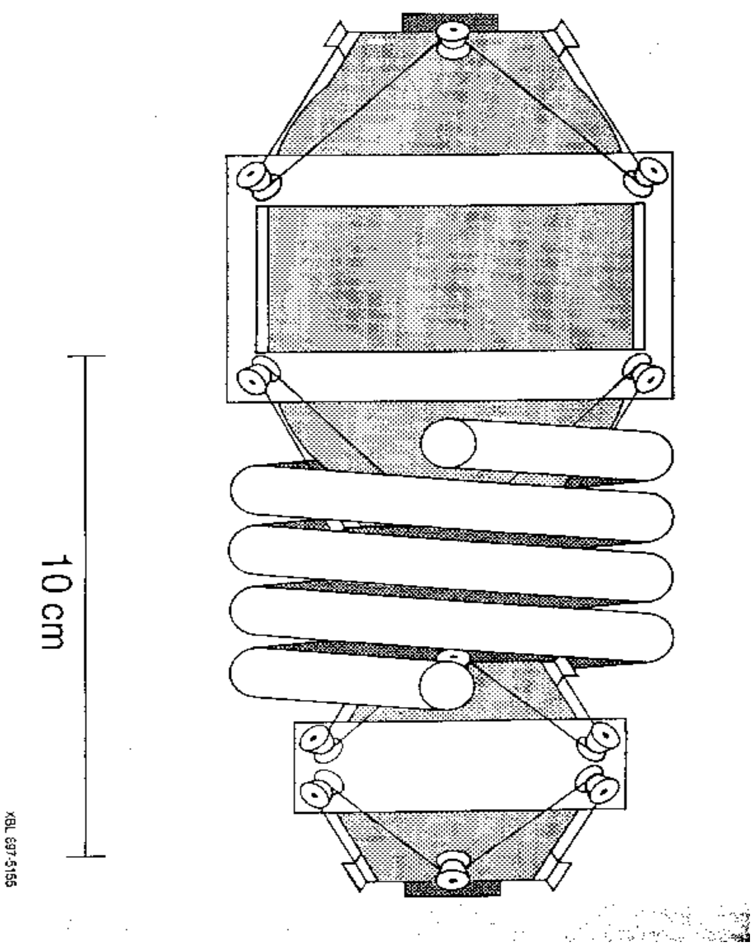
IRTS – Infrared Telescope in Space – ISAS 1995



- Superfluid He dewar
- First ^{3}He refrigerator in space, 0.3K to cool FIR bolometers



First ^{3}He fridge in space (IRTS, 15 days)



- Basic components:
- Evaporator with sintered copper sponge
- Charcoal Cryopump
- Gas Heat switches

(Duband et al. Cryogenics, **30**, 263, 1990)

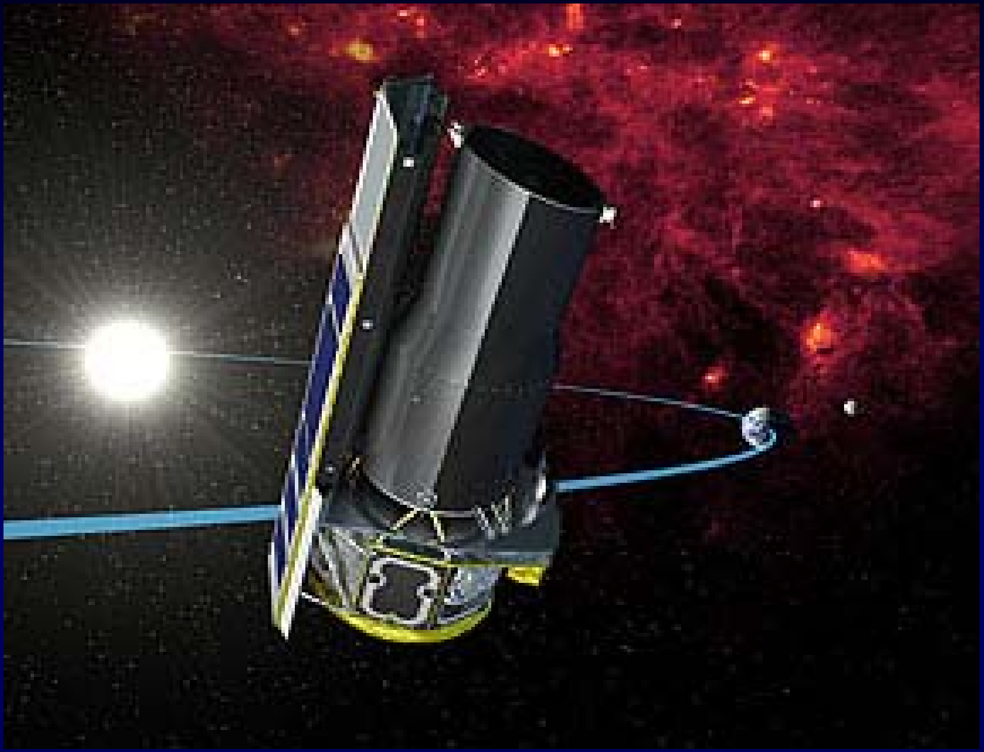
ARCHEOPS : 0.1K dilution fridge on a stratospheric balloon (41Km)

http://www-crtbt.polycnrs-gre.fr/archeops/Egeneral.html

- CRTBT dilution fridge (A. Benoit and S.Pujol. Cryogenics 34, 421, 1994): dilution of ^3He and ^4He microbubbles
- Large entrance He cryostat

Herschel - ESA

Spitzer



The **Spitzer Space Telescope** was launched into space by a Delta rocket from Cape Canaveral, Florida on 25 August 2003. Liquid helium was exhausted on may 15th 2009. Spitzer obtained images and spectra radiated by objects in space at wavelengths between 3 and 180 microns. Consisting of a 0.85-meter telescope and three cryogenically-cooled science instruments, Spitzer is the largest infrared telescope ever launched into space. Most of this infrared radiation is blocked by the earth's atmosphere and cannot be observed from the ground.

SPITZER (SIRTF)

The telescope must be protected from the heat of the Sun and the infrared radiation from the Earth.

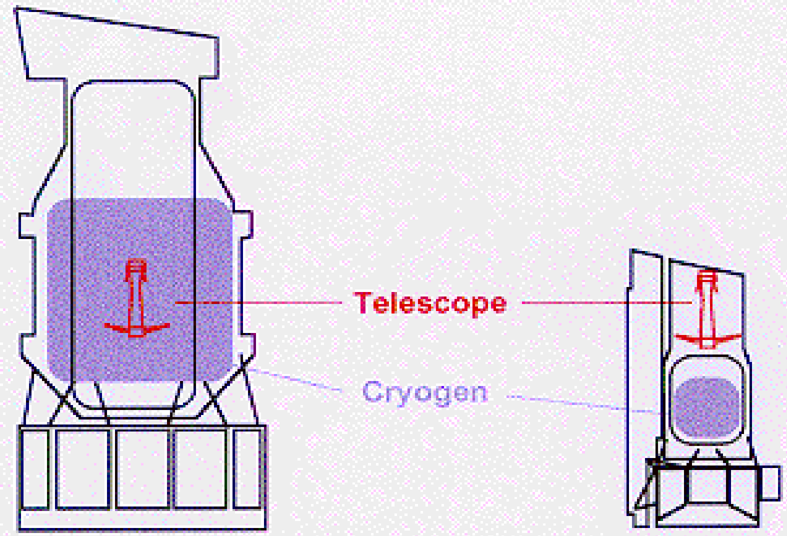
To do this, Spitzer carries a solar shield and has been launched into an Earth-trailing solar orbit.

This unique orbit places Spitzer far enough away from the Earth to allow the telescope to cool rapidy without having to carry large amounts of cryogen (coolant).

This innovative approach, and the radiative cooling of the telescope, have significantly reduced the cost of the mission.

SIRTF Launch Architecture

Old Design | New Design



Cold	Architecture	Warm
5700 kg	Launch Mass	950 kg
3800 liters	Cryogen Volume	360 liters
5 years	Lifetime	5 years
$2.2 B	Development Cost	$0.45 B

General References

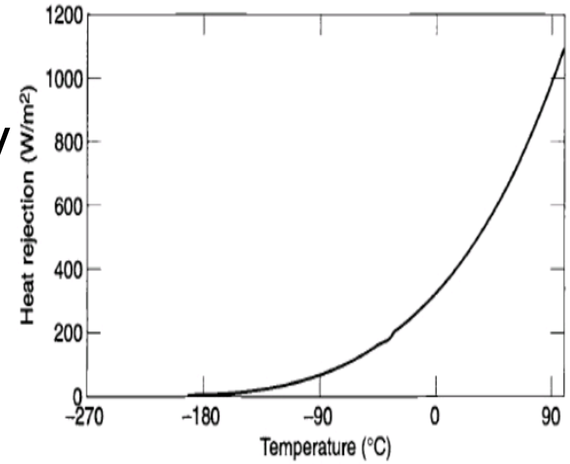
- White GK, Meeson PJ. Experimental techniques in low-temperature physics. Clarendon Press. 2002. 4th edition.
- Lounasmaa OV. Experimental principles and methods below 1K. Academic press. 1974.
- Collaudin B, Rando N. Cryogenics in space: a review of the missions and of the technologies. Cryogenics, 40. 2000. pp797-819.
- Planck ESA site: http://sci.esa.int/planck/45498-cooling-system/?fbodylongid=2124

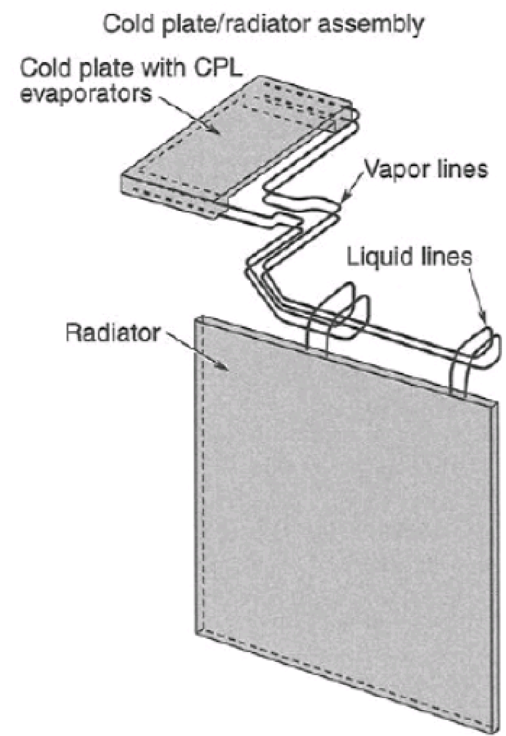
Dry cryostats

- 6 years of operation of Spitzer represent the record for wet cryostats (cryostats with liquid He).
- This required 360 liters of LHe, and 237 kg of cold mass to cool a 0.85 cm diameter telescope to 5.5K.
- For much larger telescopes, the mass and quantity of LHe to obtain similar performance would be prohibitive.
- The current trend in space cryogenics is to avoid large liquid He reservoirs, and use
  - passive (radiation) cooling plus
  - mechanical cryocoolers instead.
- This allows for longer operation times (up to 10 years, and above)
- and reduces the mass of the system.

passive (radiation) coolers

- A panel with 1 m^2 of blackbody surface initially at 300K emits about 400W towards deep space. As a result, it quickly cools down.
- The panels must be protected from solar radiation to work, or be a blackbody at long wavelengths (~10 μm, where most of the thermal emission happens) and a mirror at visible wavelengths (~0.5 μm, where most of the sunlight absorption happens).
- When the panel cools down, its emission is reduced as T^4, so the cooling power of passive radiators reduces quickly at low temperatures.
- A set of radiating panels can cool a telescope at 40K in the best multi-layer configuration.





passive (radiation) coolers

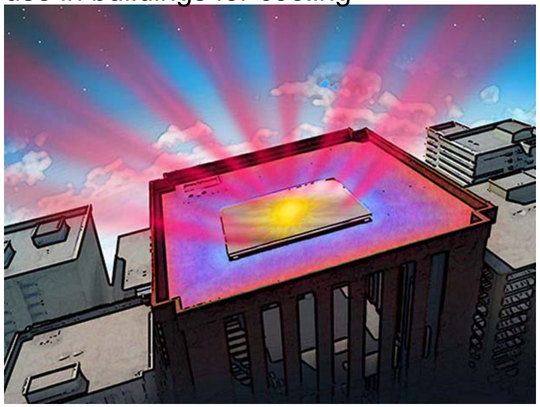
Advantages:

- No moving parts
- low mass
- degradation only due to surface deteriorating with time

Disadvantages:

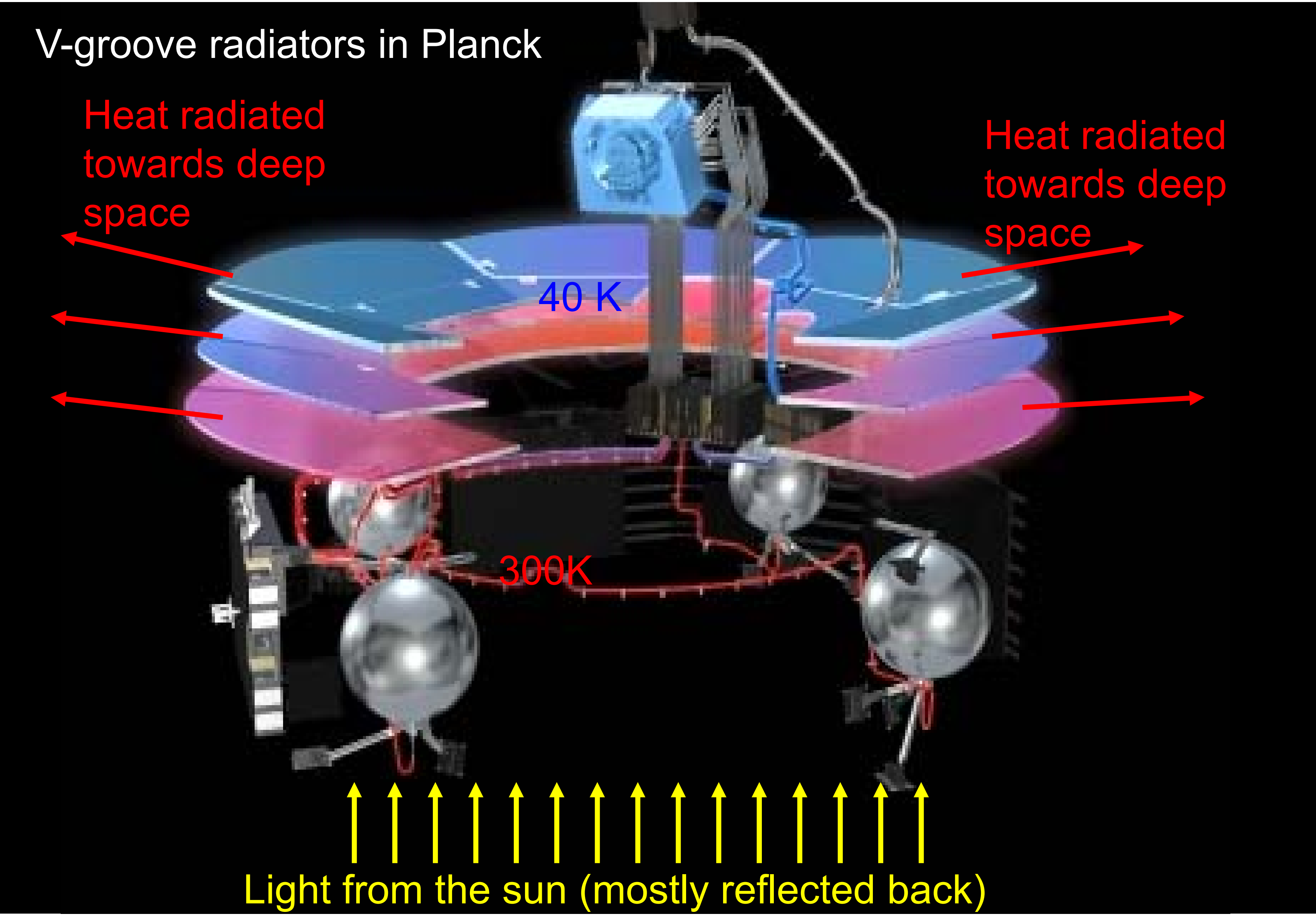
- Connection to warm components in the satellite through heat pipes, added weight, risk of fluid freezing in low T worst case
- Requires crytical design and careful material study required
- Limited heat load at low temperatures: mW at 70K
- Used normally in multiple stages (at least three), complex design in V-grooves

use in buildings for cooling



Raman et al. Nature 515, 540–544 (27/11/2014)

Planck satellite with V-grooves (see next slide)


V-groove radiators in Planck
Heat radiated towards deep space
Heat radiated towards deep space
40 K
300K
Light from the sun (mostly reflected back)

Active Cryocoolers

- Passive radiative coolers cannot withstand large heat loads at low temperature. To reach temperatures below 40K they must be complemented by active systems.

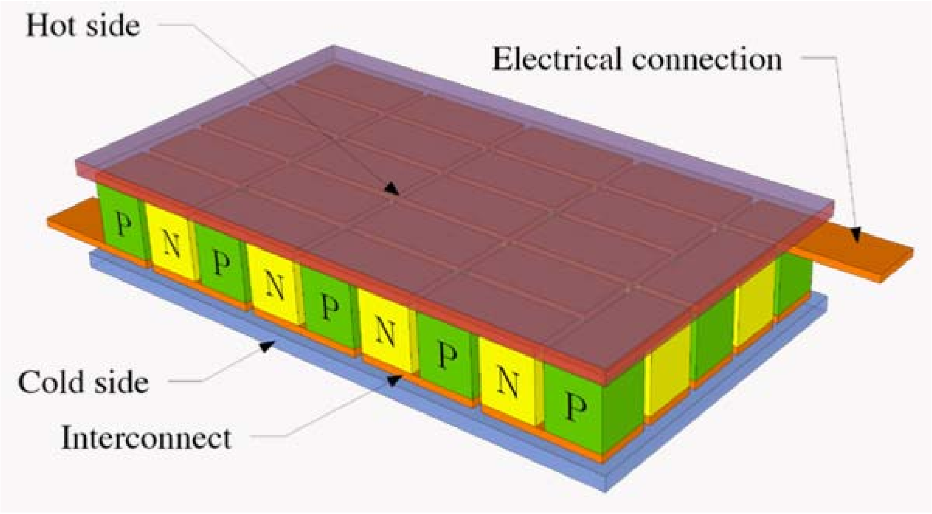
- Coolers requiring input power to work, are called cryocoolers.

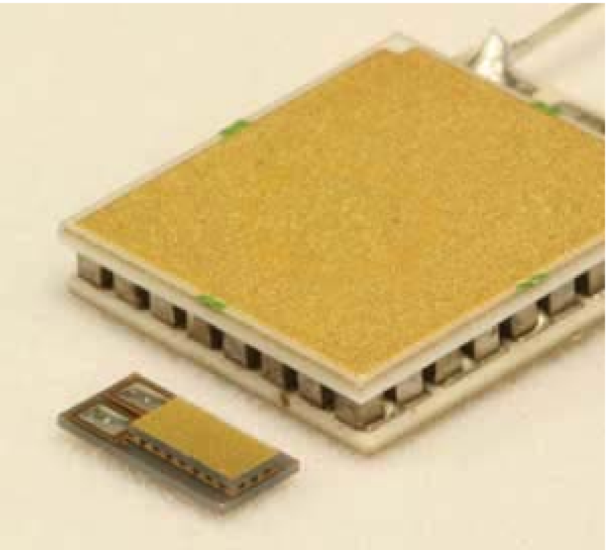
- They use closed thermodynamic cycles to achieve and mantain a device or system at lower (cold end) temperature, at the expense of electrical power.

- The first long-life cryocoolers successfully used in space were Stirling-cycle cryocoolers (grease lubricated), in 1978, to cool 2 gamma ray detectors

Peltier Effect cooler

- Solid state Peltier effect coolers or thermo-electric converters, used on a routine basis in space to achieve T above 170 K (e.g. freezers on the ISS).
- These devices work on the same principle as the Seebeck effect, in reverse: creation of a temperature difference between two dissimilar metals by application of a current.
- Similar to those used in CCD cameras at the telescopes.





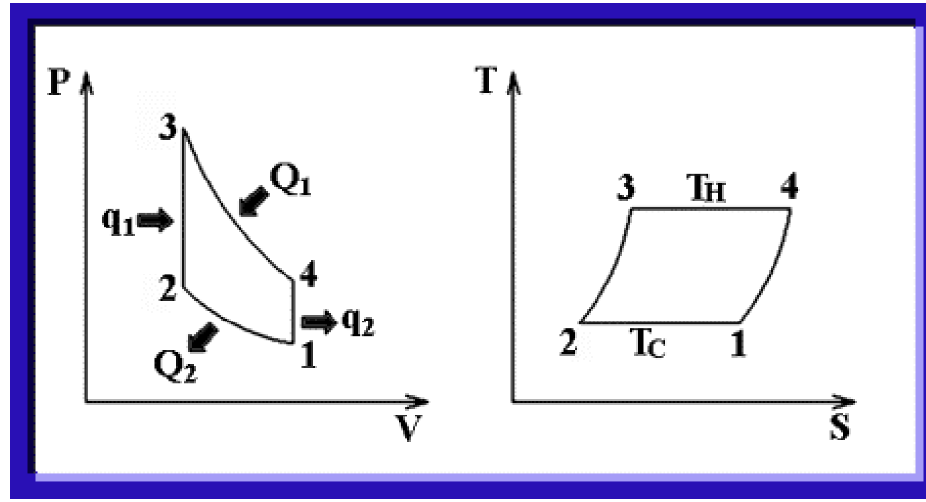
http://spinoff.nasa.gov/Spinoff2009/ip_4.html

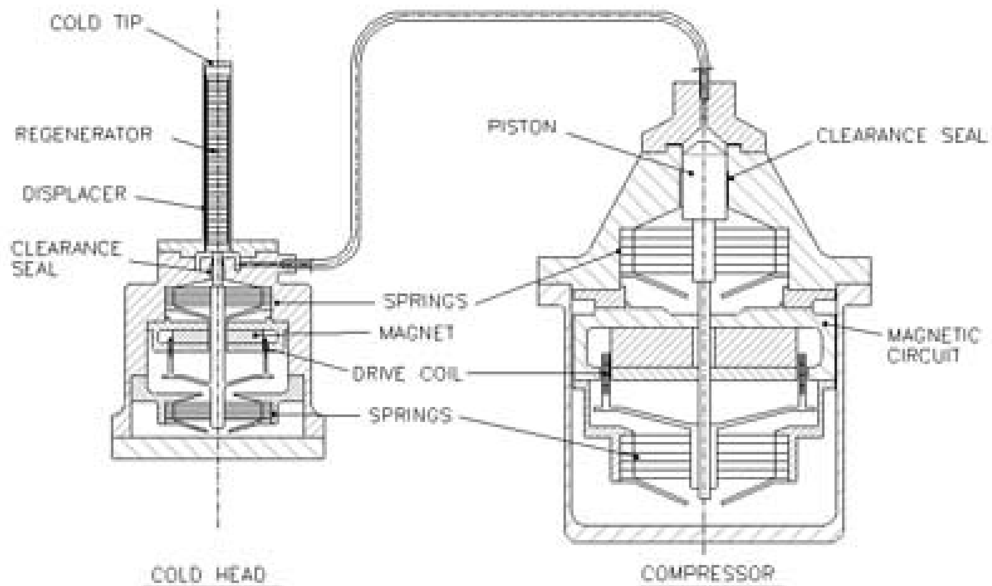
Optical Cooling

- *In recent years this principle has been developed and deemonstrated. Anti- Stokes fluorescence in Ytterbium doped Zirconium Fluoride used to provide vibration free solid state cooling. Not yet ready for space application, but under intense study*

Stirling cycle

- Working gas undergoes a process with 2 constant volume and 2 isothermal phases
- They use a compressor pump and a displacer unit with a regenerative heat exchanger (regenerator).
- Recently two stage devices have been developed, extending the lower temperature of single stages from (60-80) K to (15-30)K

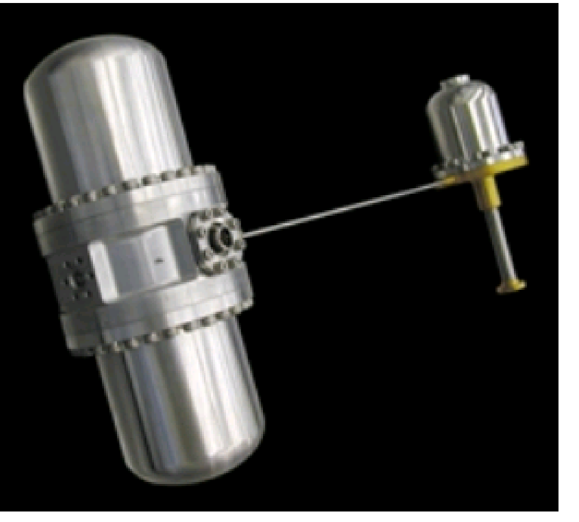




http://www.eng.ox.ac.uk/cryogenics/research/cryocoolers-for-space-applications

FS1ST: Single-stage Stirling Cooler

The FS1ST is a space qualified single-stage Stirling cooler that is compact, long lifetime and high efficiency . It is suitable for detector cooling, thermal shield cooling, etc.



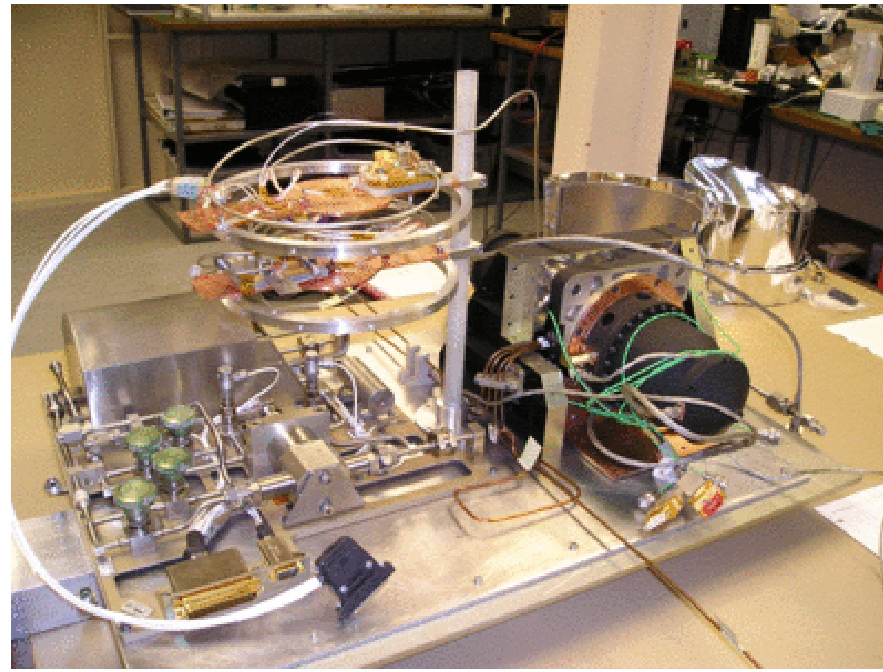
Specifications (Drive electronicsisexcluded)

Cooling Power	1.5W at 70K with 50W input
Life time	>50,000hrs(verified with ground test)
Input Power	<60W
Mass	4.1kg
Heritage	SUZAKU(ASTRO-E2) 2005/07 ~ Operating 5 years in orbit (as of 2010/08)
	KAGUYA(SELENE)2007/09~2009/06
	Akatsuki(PLANET-C)2010/05 ~

http://www.shi.co.jp/quantum/eng/product/space/FS1ST.html

Joule-Thomson

- They use the J-T effect: a gas is forced to pass through a thermally isolated porous plug or throttle valve by a mechanical compressor unit, and this causes an isoenthalpic cooling process.
- This is an irreversible process, with a corresponding low efficiency. The efficiency of Joule-Thomson coolers is lower than that of Stirling and Pulse Tube coolers, so Joule-Thomson coolers are used to extend the cooling range of those coolers down to 4 K.
- The various Joule-Thomson coolers used in space can be classified by the compressor technology employed.



- Very reliable and simple, with low electrical and mechanical noise levels.
- A J-T stage driven by a valved linear compressor has been used on Planck

LB2ST: Double-stage Stirling Cooler

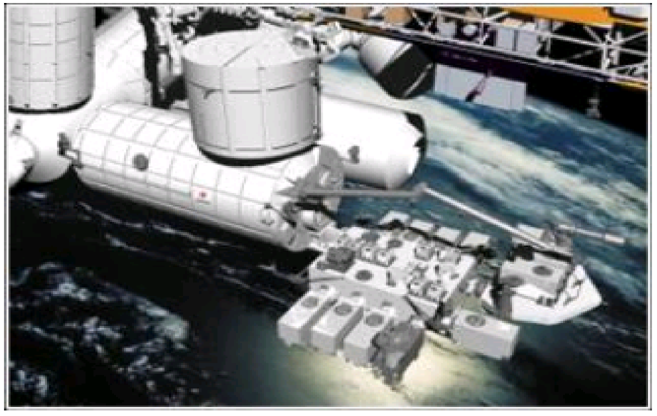
The LB2ST is a space qualified double-stage Stirling cooler. This cooler can be used for detector cooling,thermal shield cooling and pre-cooling for JT circuit cooler. Special mechanism(patent) is used to achieve long lifetime. This cooler is adopted to ASTRO-H/SXS to be launcehed in 2014.

Specifications(Drive electronics is excluded)

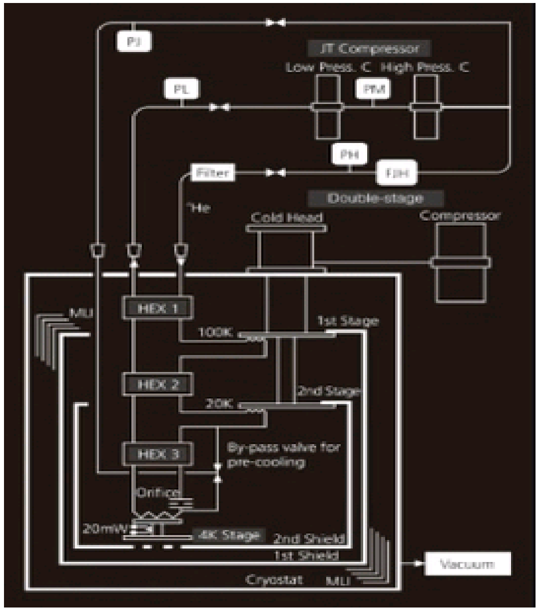
Cooling Power	0.2W at 20K/ 1W at 100K
Life time	>3years
Input Power	<90W
Mass	<9.5kg
Heritage	AKARI(ASTRO-F) 2006/02 ~ Operating 4.5years in orbit (as of 2010/08)
	ISS/Kibo(JEM)/SMILES(JAXA)2009 /09 ~

Mechanical Cooler below 4.5K

4K-class cooler is combination of a JT cooler and a double-stage Stirling Cooler. The JT cooler consists of JT compressors, heat exchangers and JT orifice. 4K-class cooler is adopted to ASTRO-H/SXS to be launched in 2014.



ISS/Kibo(JEM)/SMILES(Courtesy of JAXA)



Specifications

Items	4K-class Cooler (^4He)	1K-class Cooler (^3He)
Cooling Capacity	20mW at 4.5K	10mW at 1.7K
JT Cooler		
Power comsumption	≤50W	≤80W
Double-stage Stirling Cooler		
Cooling Capacity	200mW at 20K,1W at 100K	80mW at15K,1W at 100K
Power comsumption	≤90W	≤90W
Heritage	ISS/Kibo(JEM)/SMILES 2009/09 ~ in orbit	Labo test of the bread board adopted to SPICA

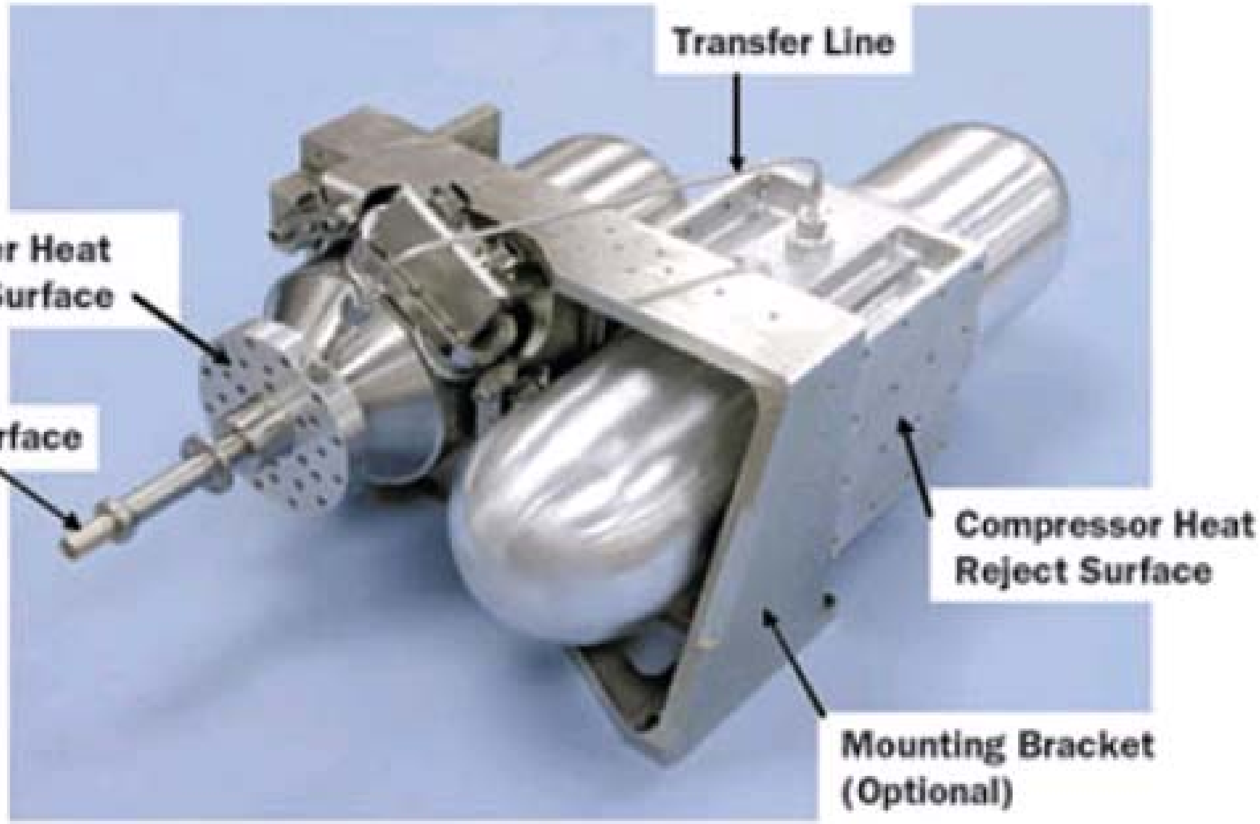
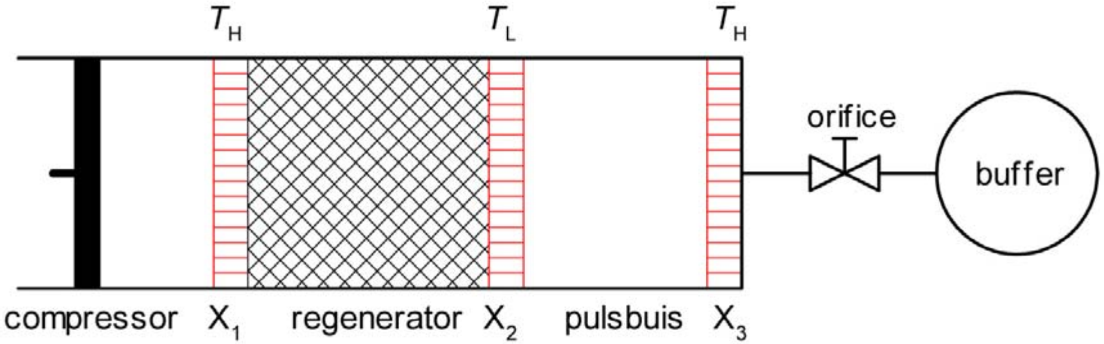


Figure 2. Raytheon Stirling One-Stage (RS1) Cryocooler. Key integration features noted. Produces nominally 4 W refrigeration at 60 K for about 120 W input power. Mass ~ 13 kg. Total packaging volume is 51 cm x 28 cm x 20 cm.

- The pulse tube works by transporting heat against a temperature gradient, through enthalpy transfer into the pulse tube from the regenerator and out of the pulse tube through the orifice at the hot end of the pulse tube. Basic system:

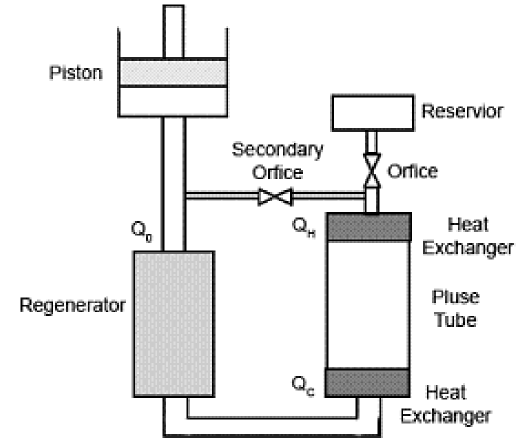
Pulse Tube



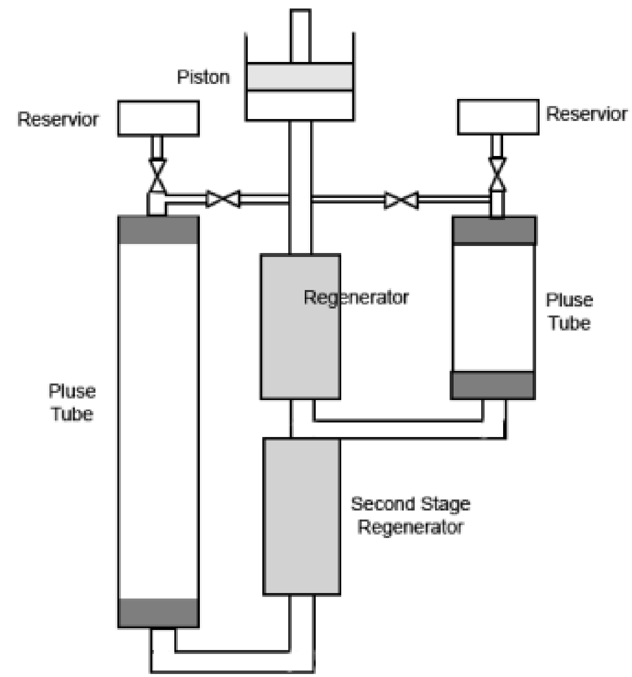
- The compressor produces a periodic pressure in the system, so the gas moves from left to right and back.
- When the gas from the compressor space moves to the right enters the regenerator (a porous medium) with temperature TH and leaves the regenerator at the cold end with temperature TL, hence heat is transferred into the regenerator material. On its return the heat stored within the regenerator is transferred back into the gas.
- In X3 the gas enters the orifice during the high pressure phase, and goes back in the pulse tube through the orifice when the pressure is low. So removes heat from the tube.
- In X2 similarily the gas removes heat, cooling X2 at TL.

Pulse Tube

- Advantages:
  - no moving mechanical parts at cold
  - efficiency similar to Stirling cryocoolers
  - high reliability
  - low mechanical vibrations
  - small magnetic interferences
- Single-stage pulse tubes reach 70K, with cooling power of tens of W
- Double-stage pulse tubes reach 3K, with cooling power of the order of 1W.
- Power required : of the order of a few kW.
- Space-qualified pulse-tube coolers recently available



Single stage PT



Two-stages parallel PT

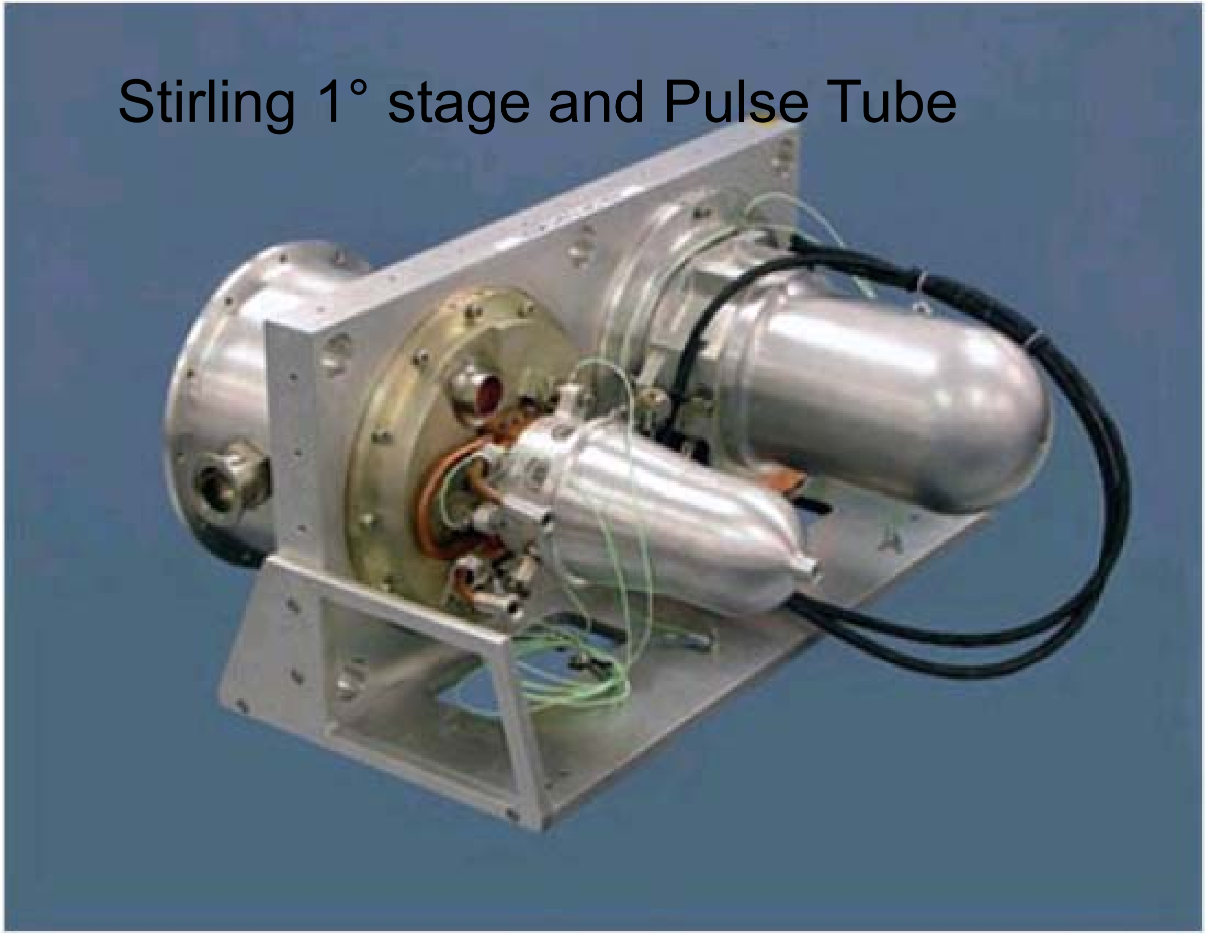
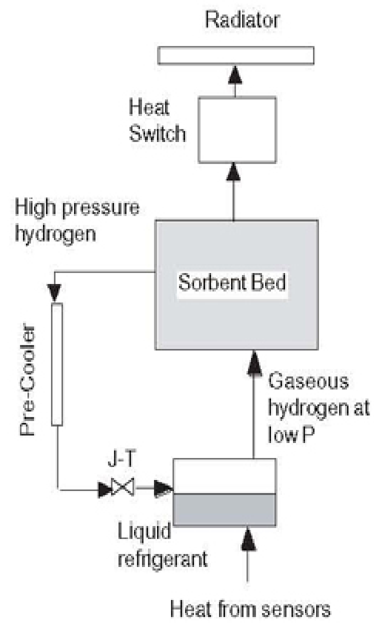
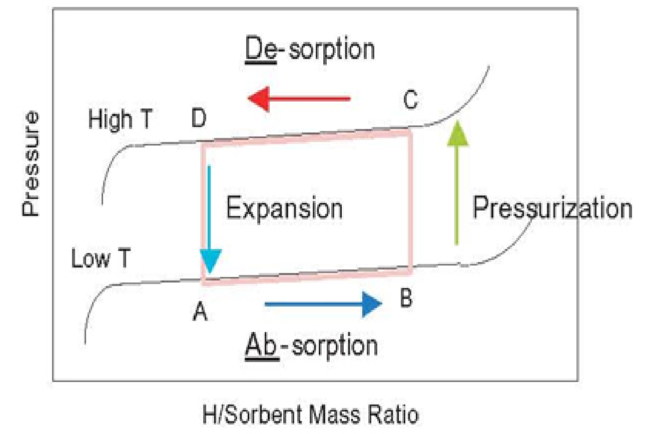


Figure 3. Raytheon Stirling / Pulse Tube Two-Stage (RSP2) Cryocooler. Produces 2.6 W at 35 K and over 16 W at 85 K simultaneously for 500 W input power (compared to the 120 W design shown in Figure 2). This is exemplary of the present trend in space cryocoolers towards higher capacities to meet the demands of large and more capable space IR sensors. This is a nominally 22 kg cooler with overall package size of 56 cm x 46 cm x 20 cm.

Sorption cooler

- Like J-T with a thermo-chemical process to provide gas compression.
- No moving parts, completely vibration-free
- Powdered sorbent materials (e.g. metal hydrides), are electrically heated and cooled to pressurize, circulate, and adsorb a working fluid such as hydrogen.
- Efficiency is low, but can be increased by using mixed working gases.
- Was used on Planck for the 20K stage.

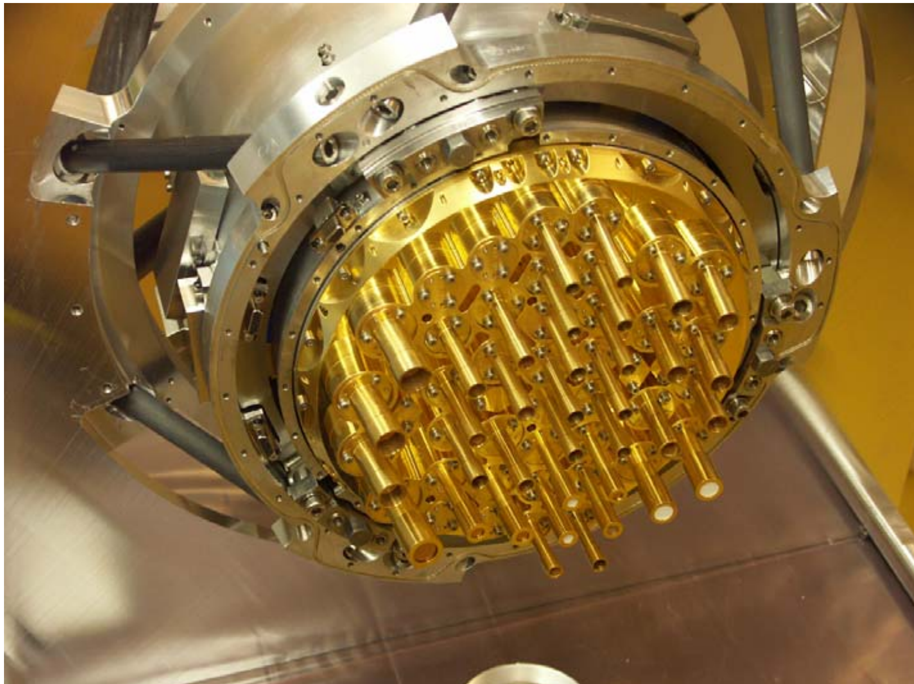


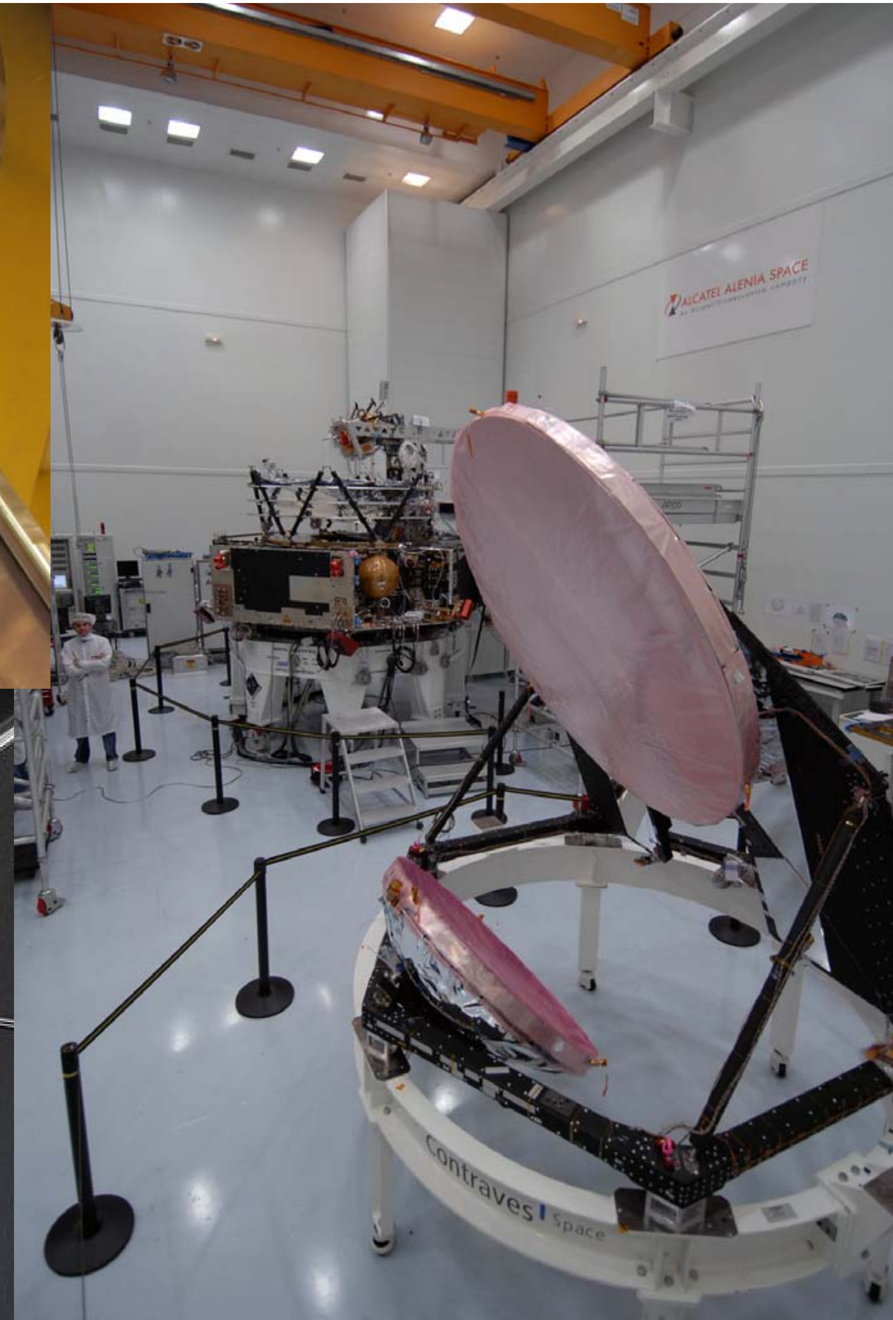


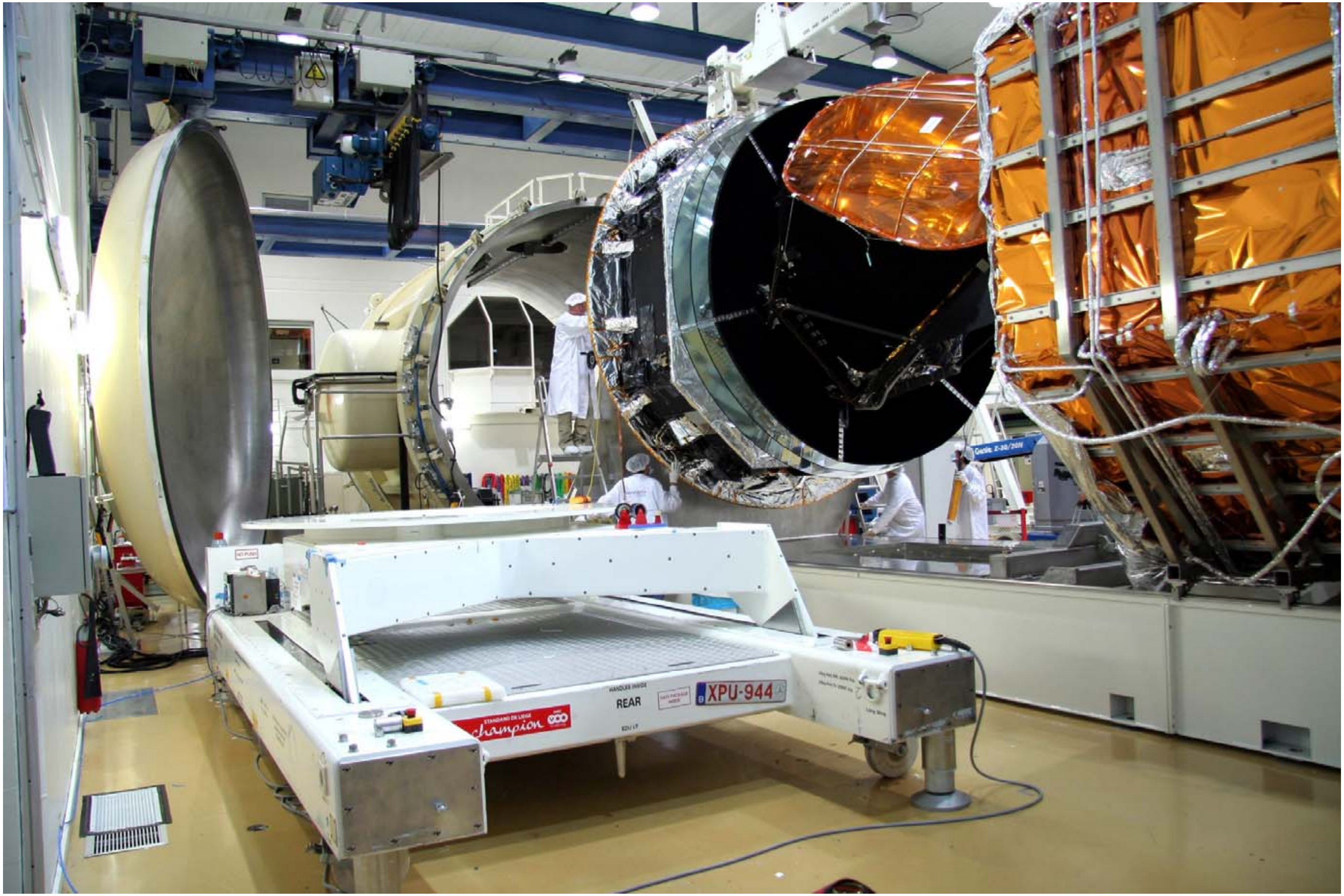
The sorption cooler consists of a compressor and an expander (the cold end). The sorption compressor (SCC) absorbs gas at low pressure and releases (desorbs) gas at high pressure after being heated. It is therefore a thermal compressor. By sequencing several sorbent compressor elements, a continuous flow of high-pressure refrigerant is provided.

- **Planck** is a satellite launched in the lagrangian point L2 of the Earth-Sun system, 1.5Mkm away from the Earth, beyond the moon orbit.
- From this advantage location it mapped the Universe with unprecedented sensitivity and resolution in the range 20-800 GHz

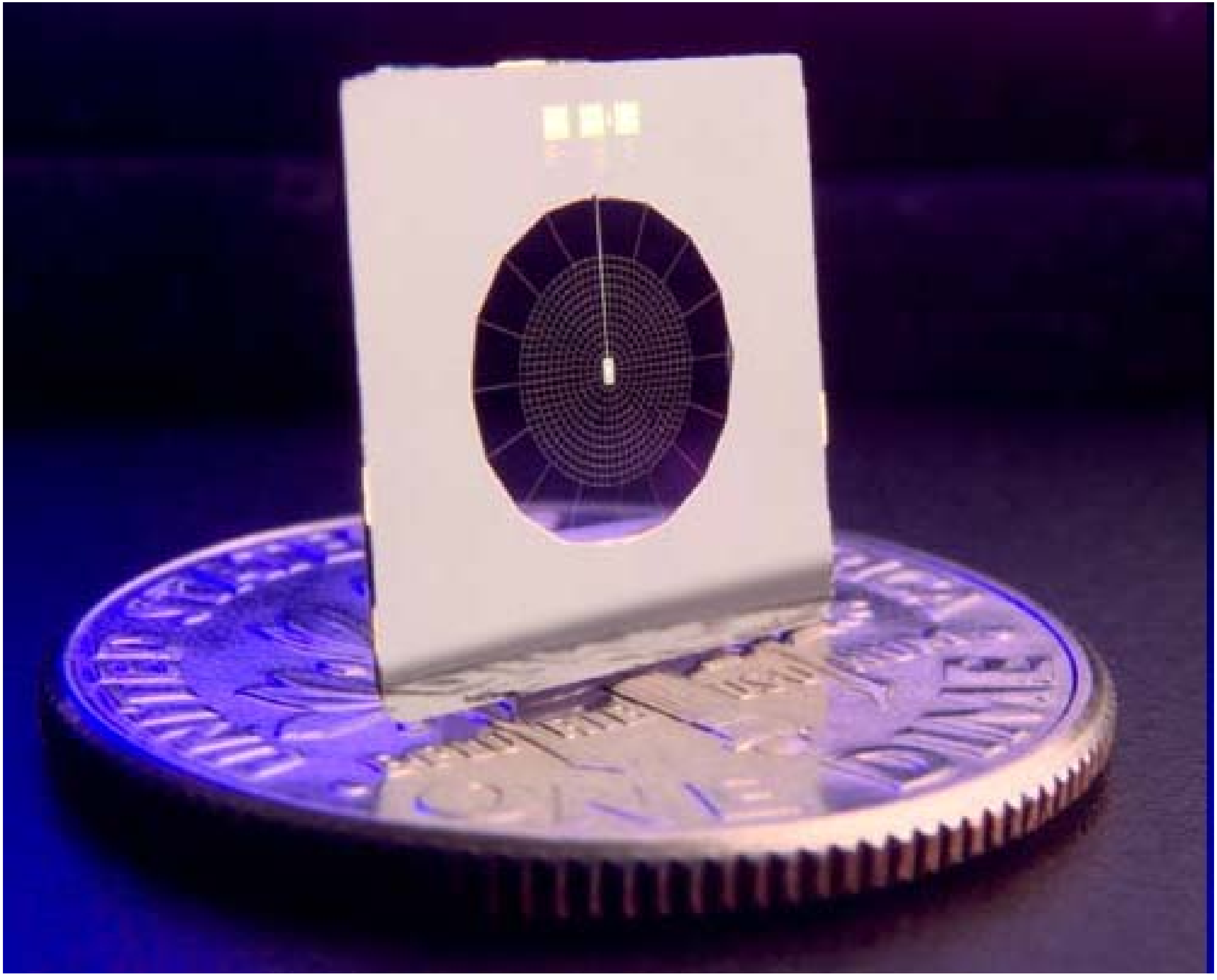
Telescopio fuori asse, diametro specchio principale 1.8 m

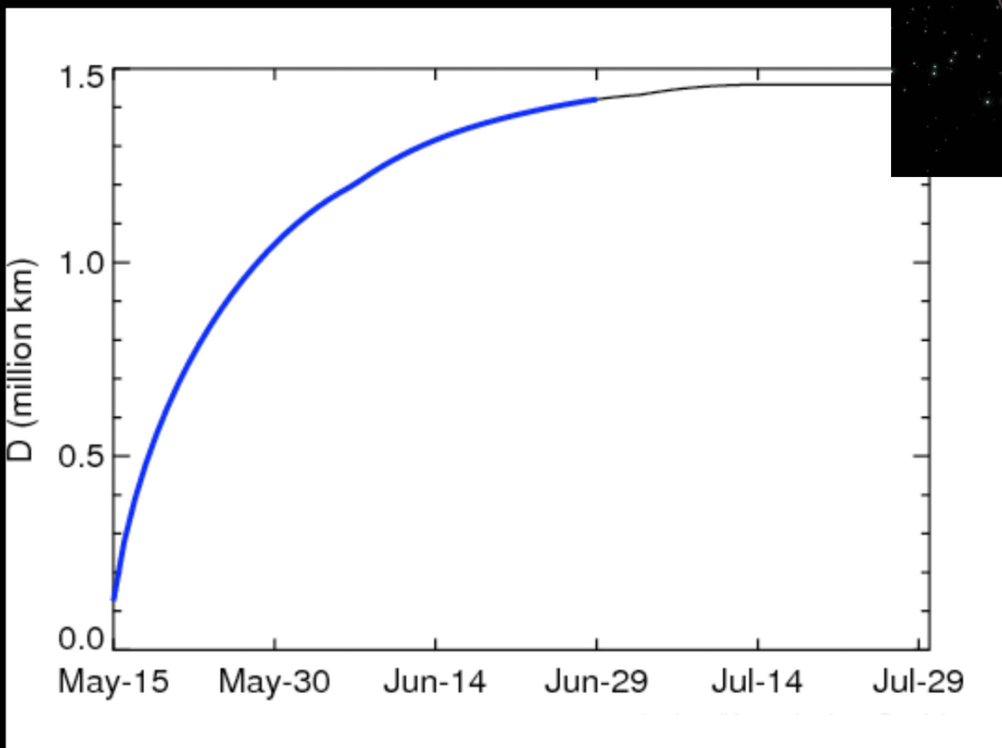


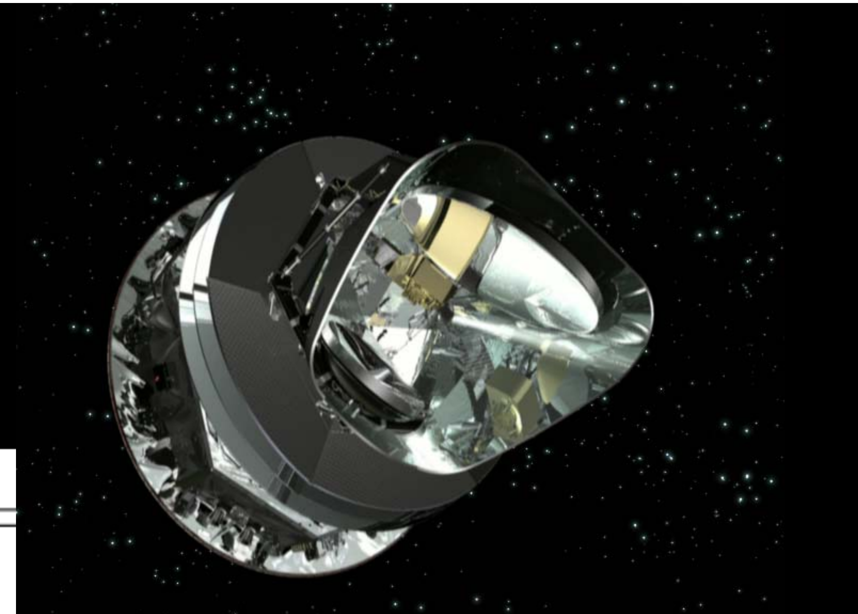

ALCATEL ALENIA SPACE
Contraves Space

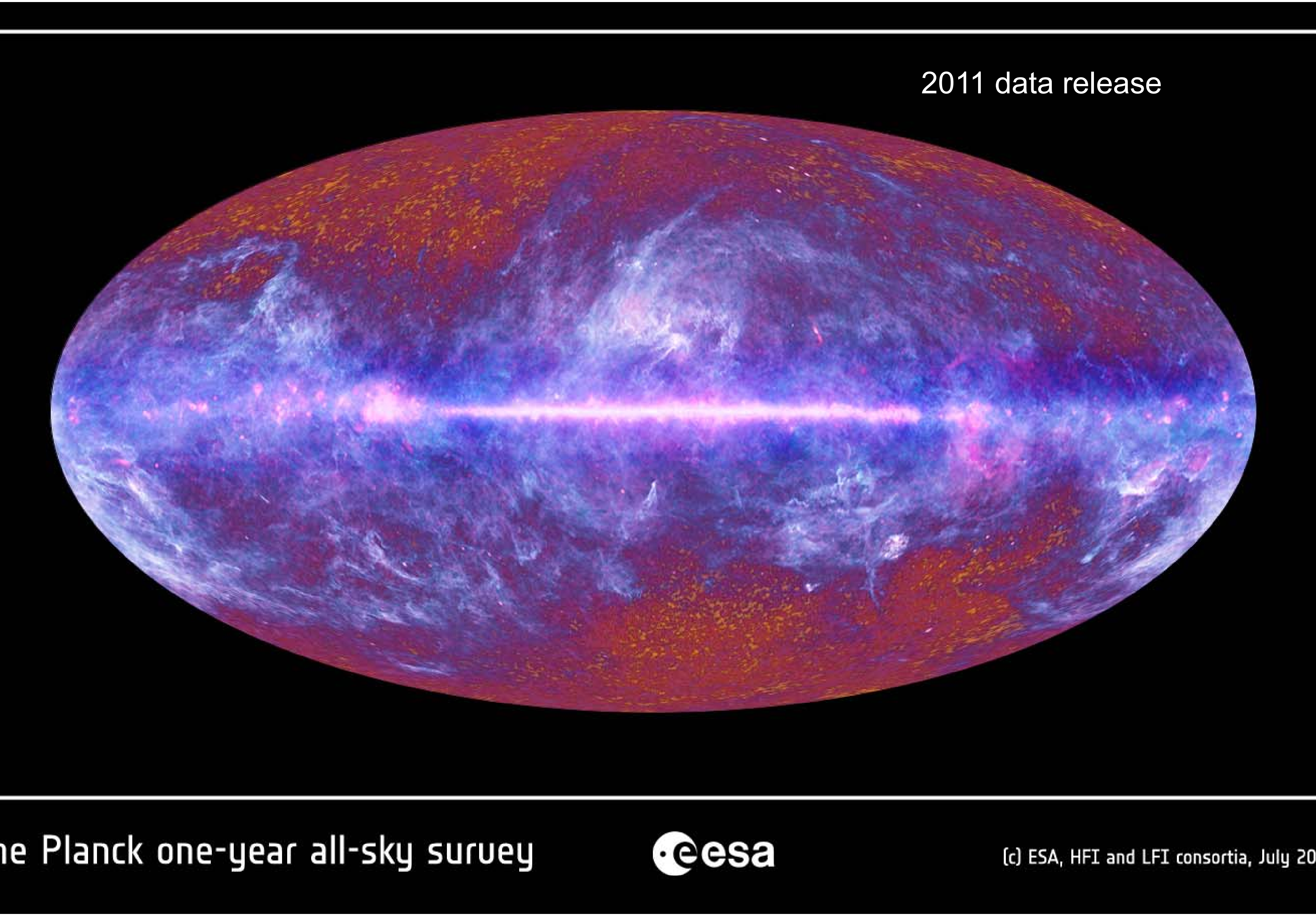


REAR
XPU-944
champion



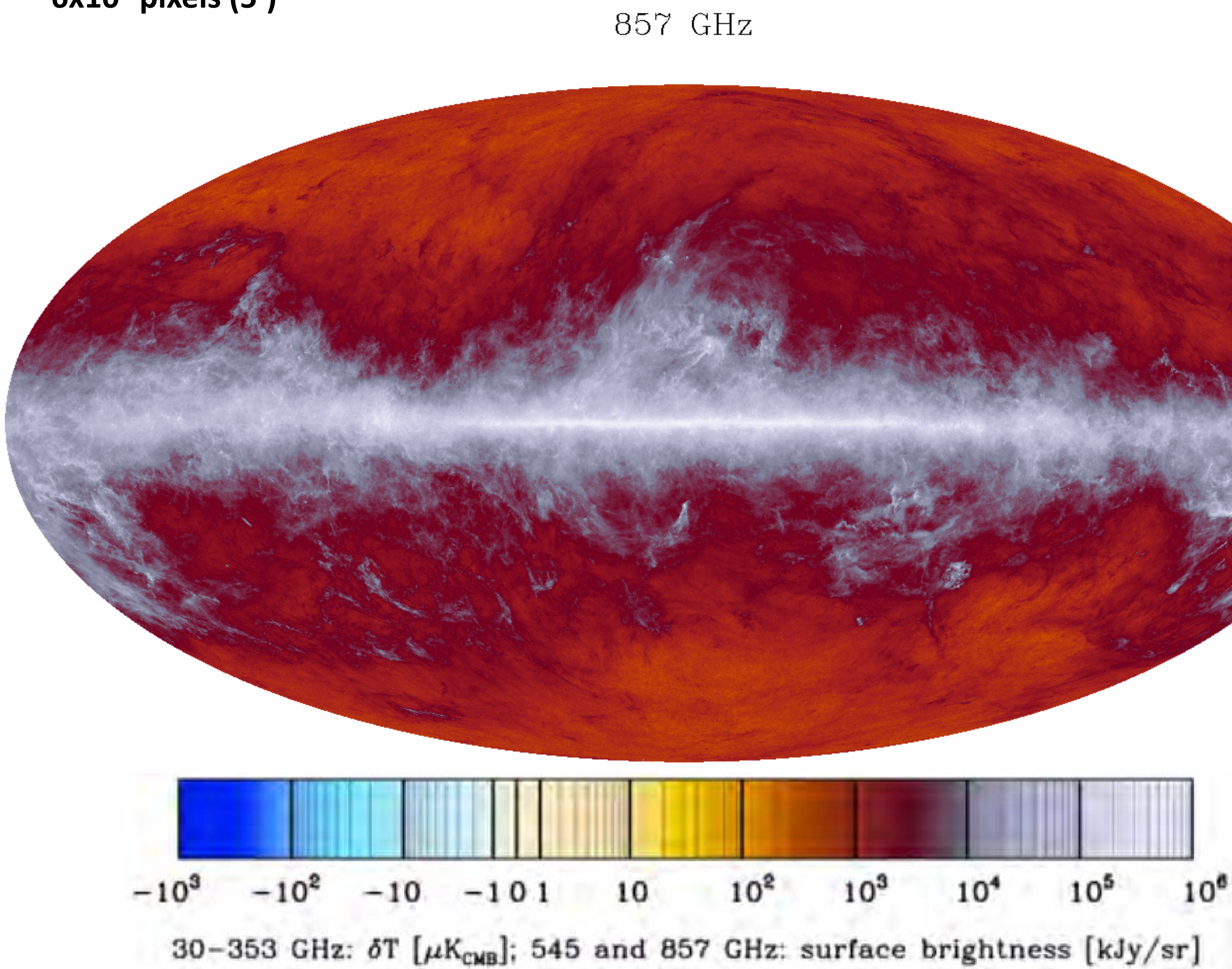

D (million km)
1.5
1.0
0.5
0.0
May-15
May-30
Jun-14
Jun-29
Jul-14
Jul-29




2011 data release
he Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 20

$6x10^6$ pixels (5')

Planck Legacy Maps



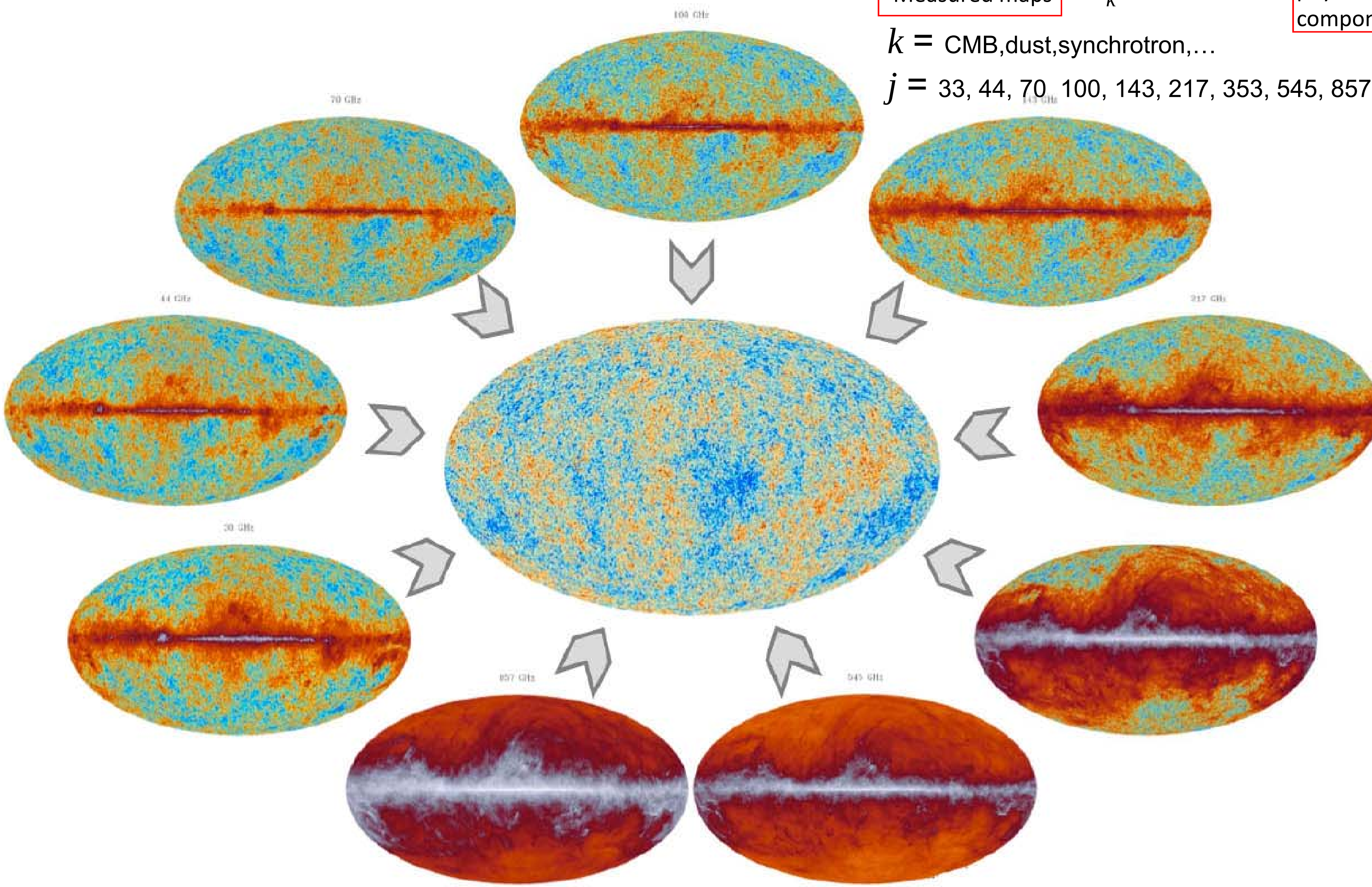
components separation

$$\Delta T(\nu_j, \ell, b) = \sum_k a_k(\nu_j, \ell, b) C_k(\ell, b)$$

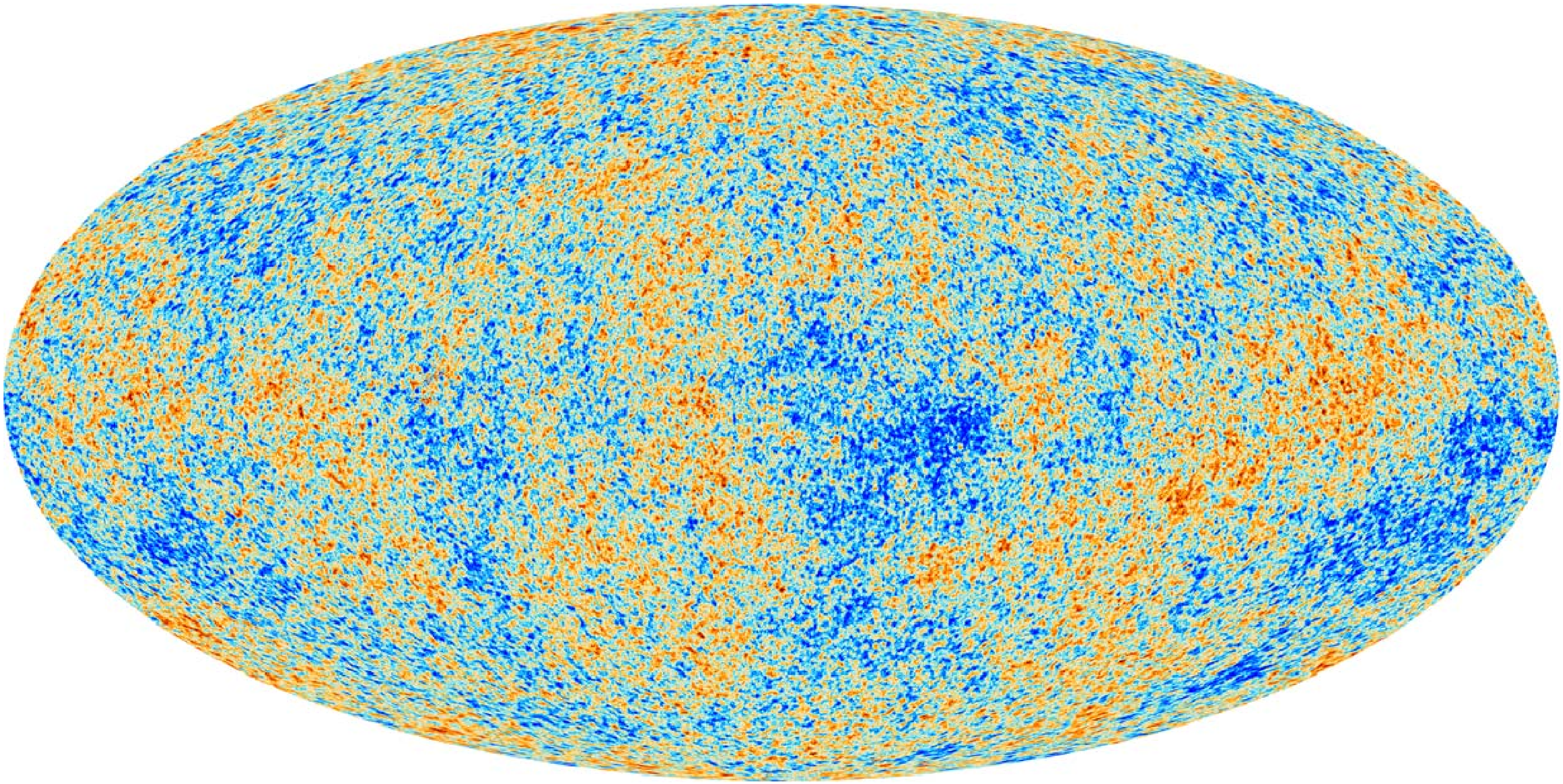
Measured maps — physical components

k = CMB,dust,synchrotron,…

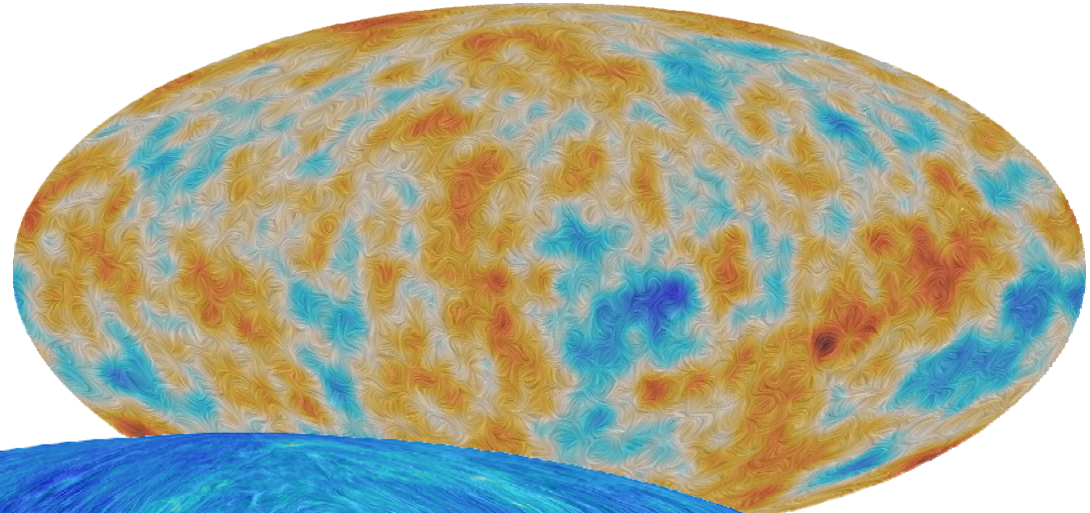
j = 33, 44, 70, 100, 143, 217, 353, 545, 857 GHz

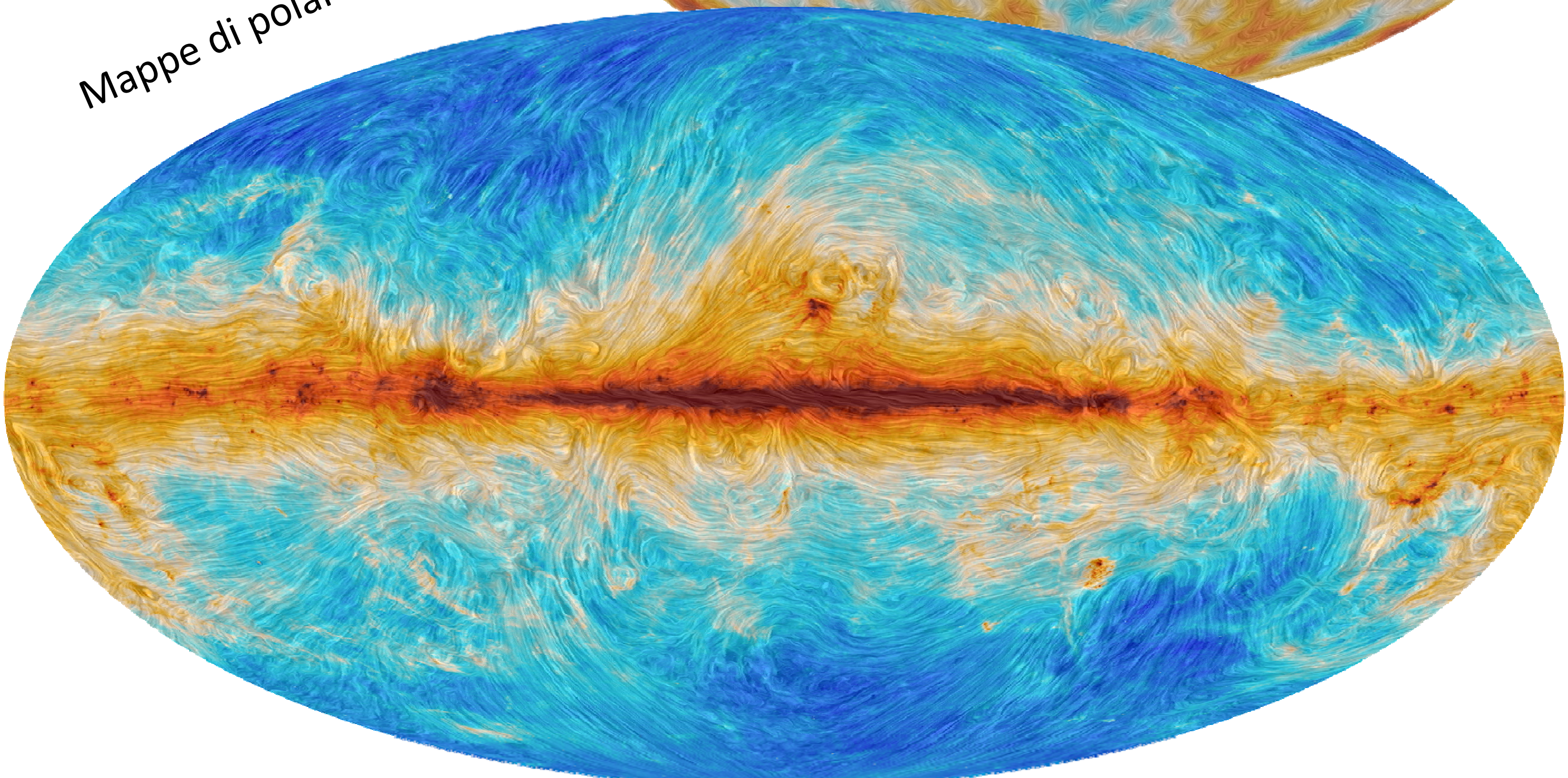


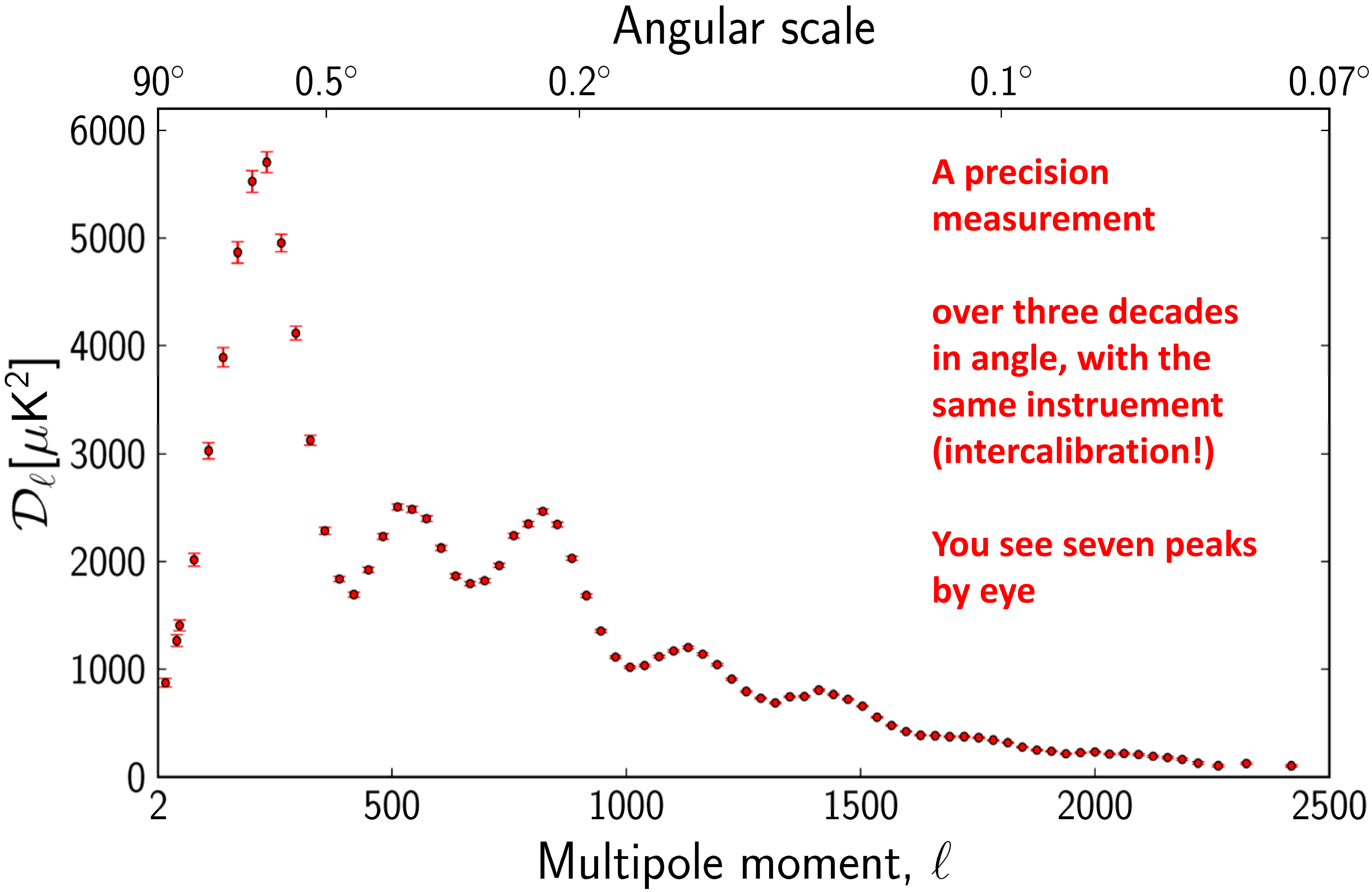
The CMB component



Mappe di polarizzazione



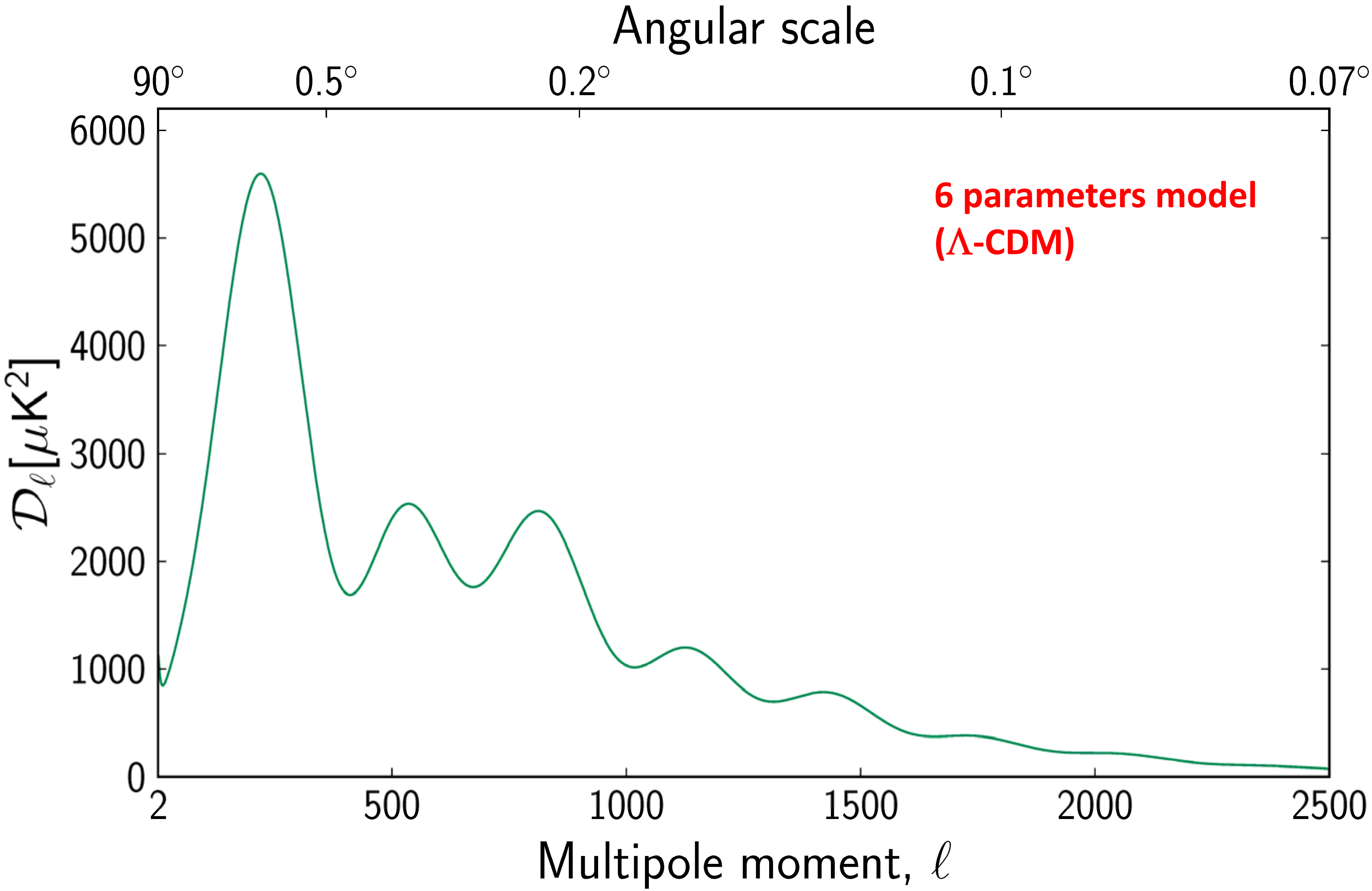


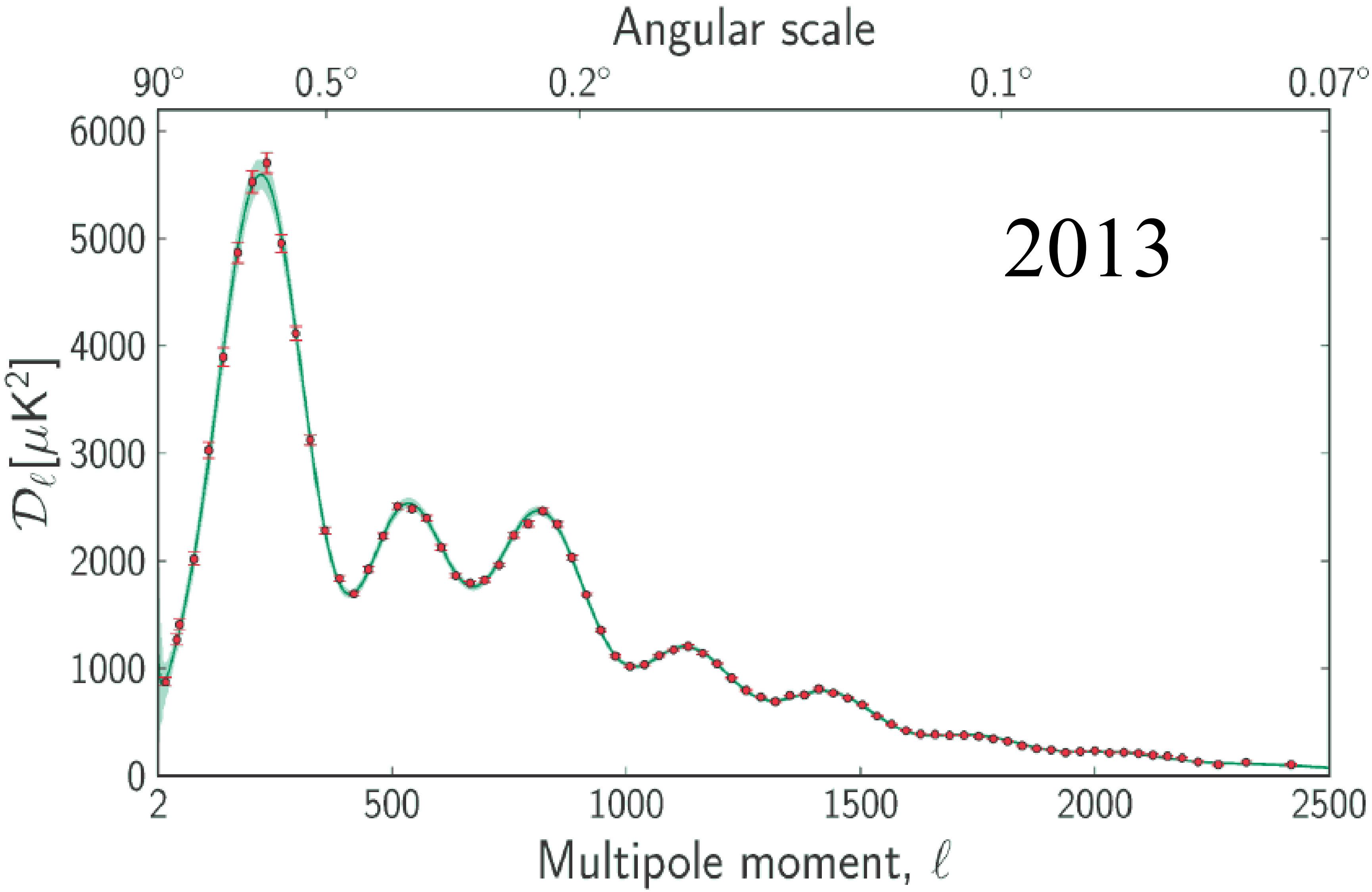


A precision measurement

over three decades in angle, with the same instruement (intercalibration!)

You see seven peaks by eye


Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
6 parameters model
(Λ-CDM)
2
500
1000
1500
2000
2500
Multipole moment, ℓ



Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2013
2
500
1000
1500
2000
2500
Multipole moment, ℓ

Planck Cryo-chain

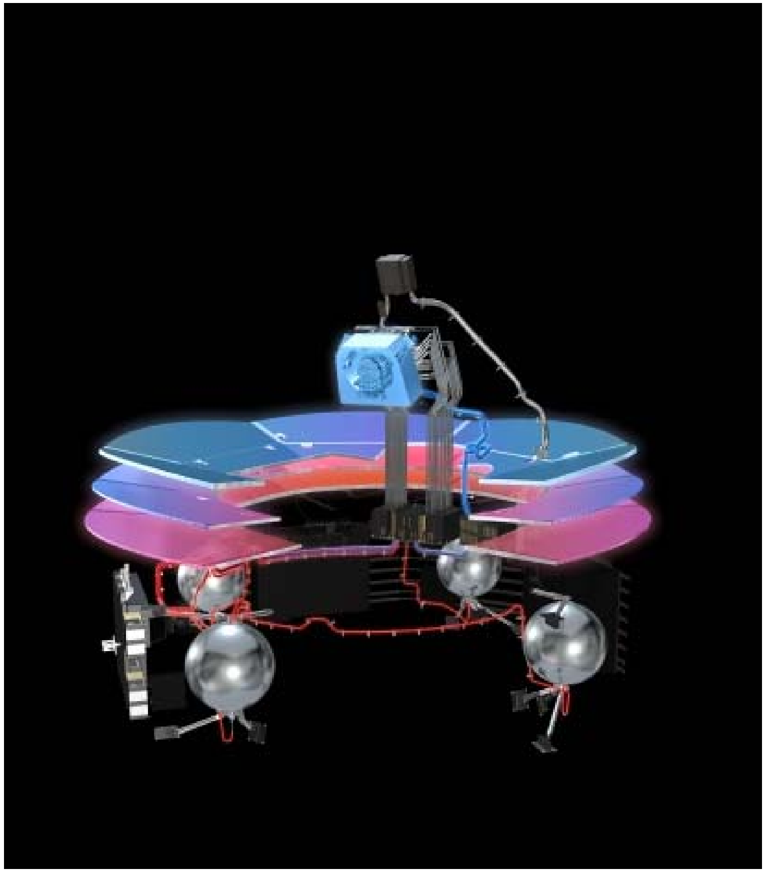
- LFI and HFI instruments share a part of the cryogenic chain for the satellite mission
- Optimal performance point for the LFI radiometers is at about 20 K, temperature reached through a combination of passive cooling to about 50 K (V grooves shields) and active cooling using H2 sorption cooler
- HFI bolometers are cooled to 100 mK through a combination of passive cooling (radiator down to 50 K), the 20 K sorption cooler, a 4.5 K mechanical J-T cooler and a Benoit open cycle helium dilution cooler

Planck 0.1 K cooler

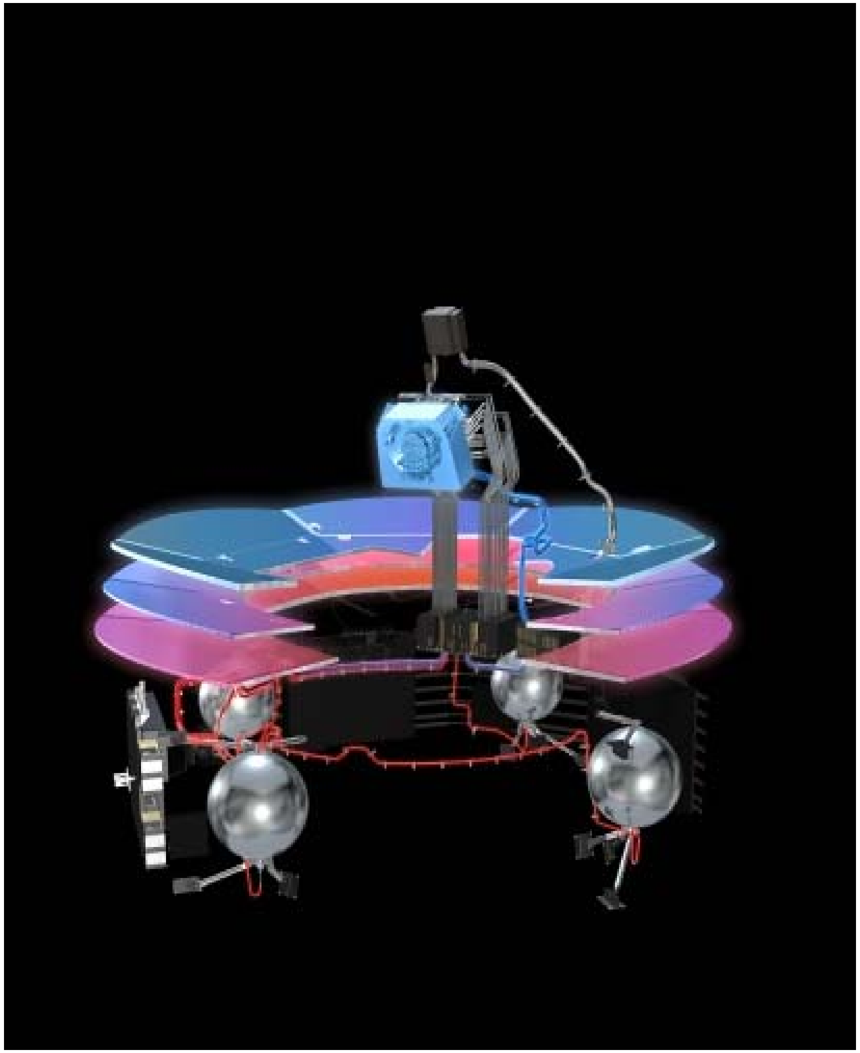
Active cooling system on board the Planck spacecraft, with the components of the 0.1 K cooler highlighted. Also the three V-grooves of the passive cooling system are coloured, representing their progressively lower temperature from bottom to top.

The 0.1 K cooler is the final, and coldest, stage of the active cryogenic cooling chain.

It is a dilution cooler that cools the HFI detectors to 0.1 K.



Planck Cryo-chain

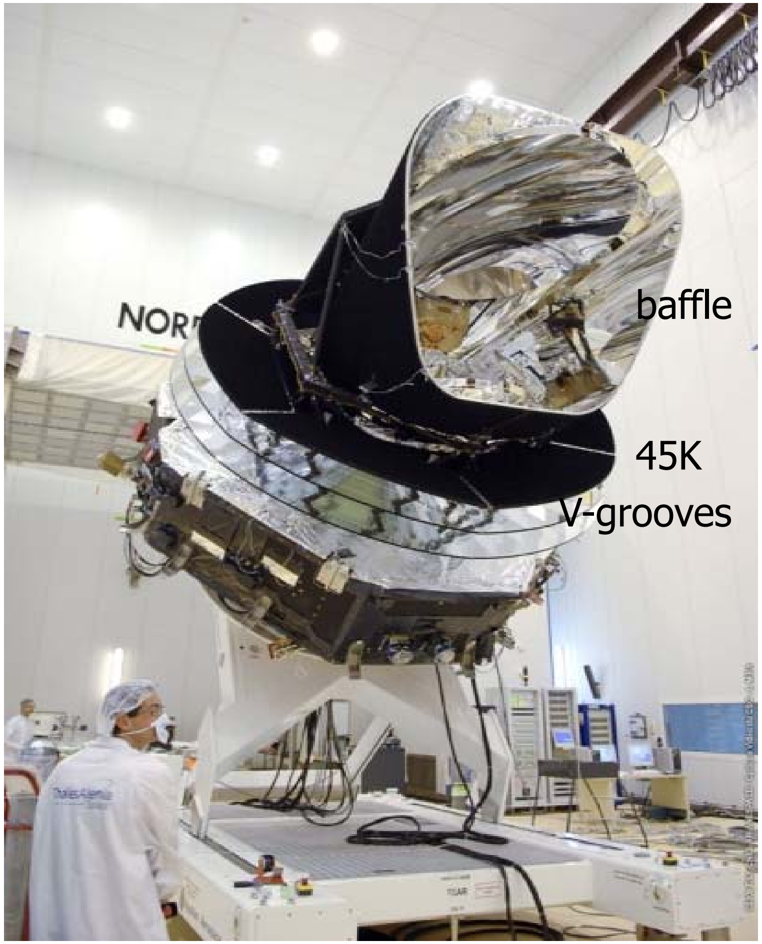


3 high pressure tanks filled with ^4He and 1 high pressure tank filled with ^3He are housed in the service module (four highlighted silver spheres). From each tank a pipe runs to the flow regulation control unit (at lower left). From here the helium isotope gases flow separately towards the HFI focal plane unit (FPU) (in the middle of the blue highlighted focal plane).

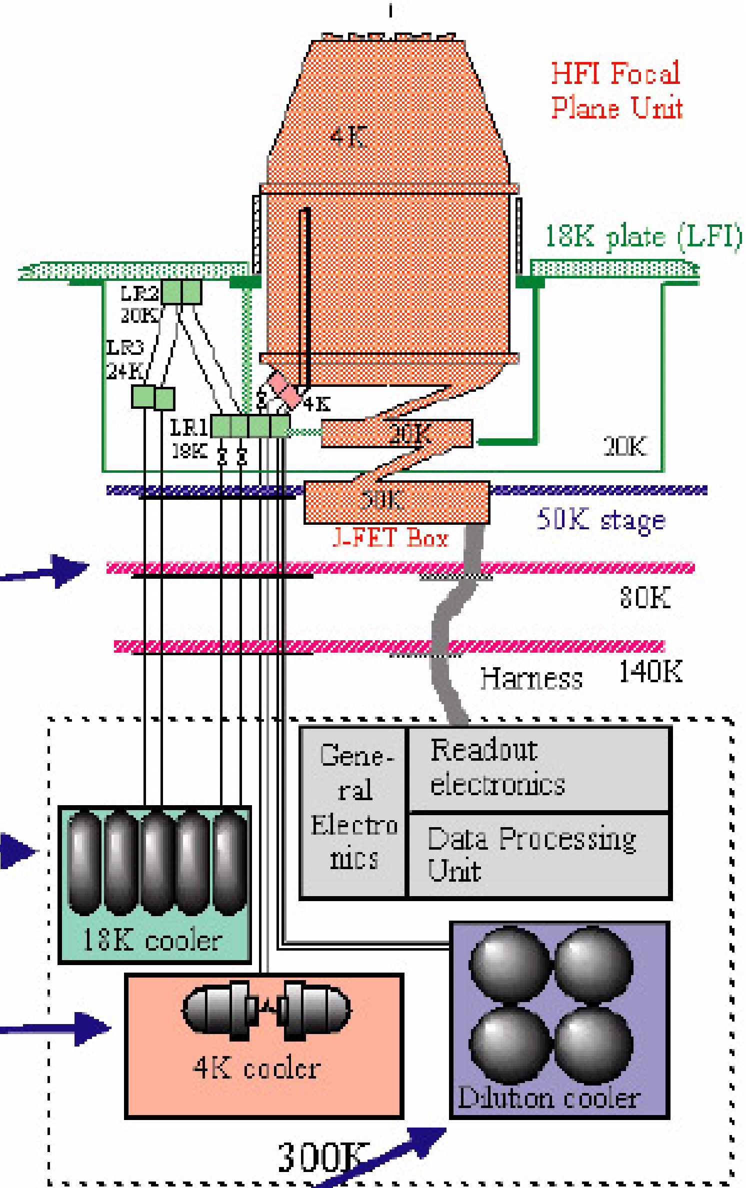
Along the way the gases progressively cool down through heat exchangers with the spacecraft's three V-grooves and with the 18K and 4K stages of the active cooling system. Within the HFI FPU the ^3He and ^4He are mixed, after which a thermo-dynamical process causes the mixture to cool and the detectors reach 0.1 K.

Planck Satellite

(http://sci.esa.int/planck/45498-cooling-system/?fbodylongid=2124)



Cooling system

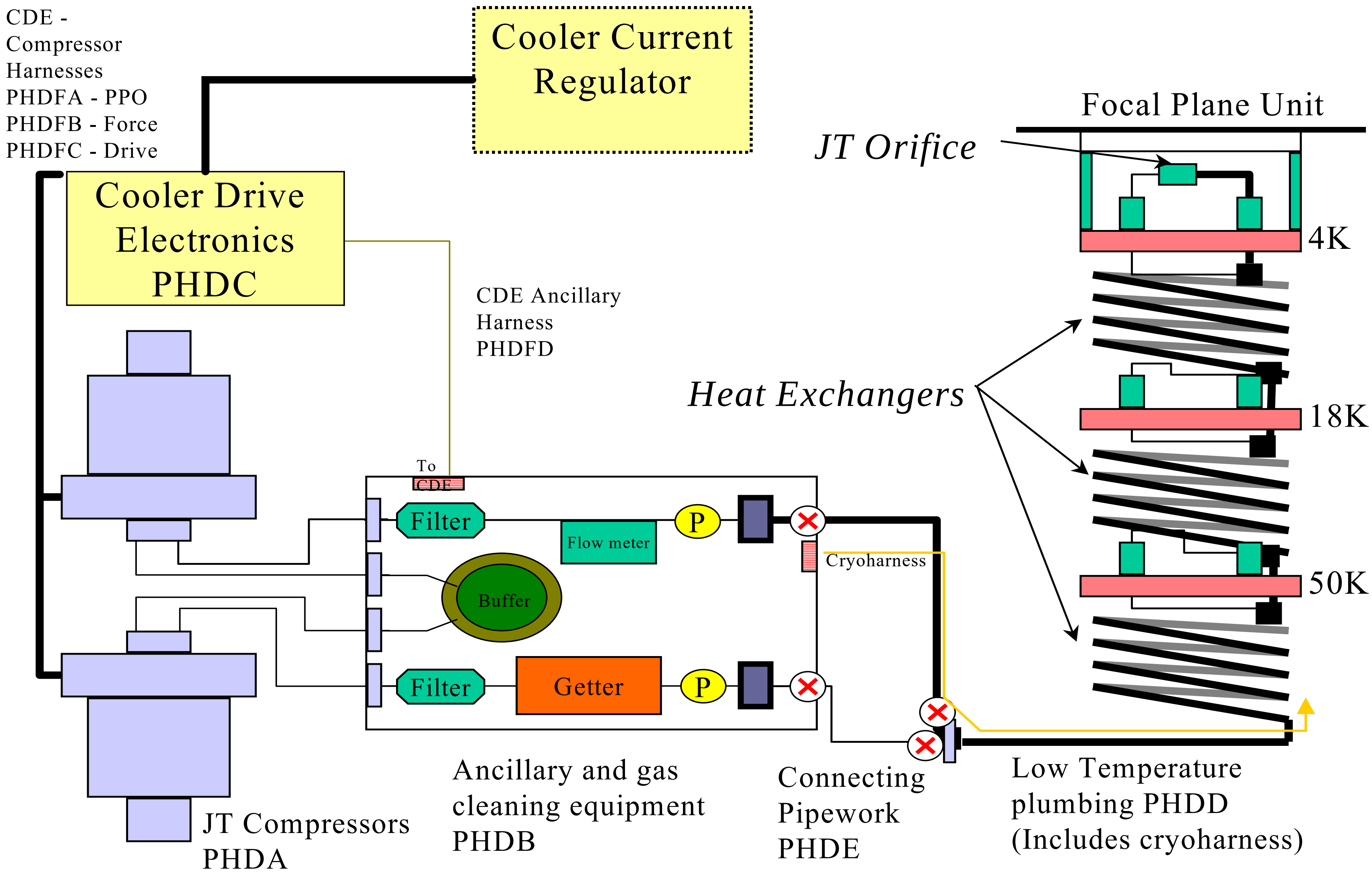


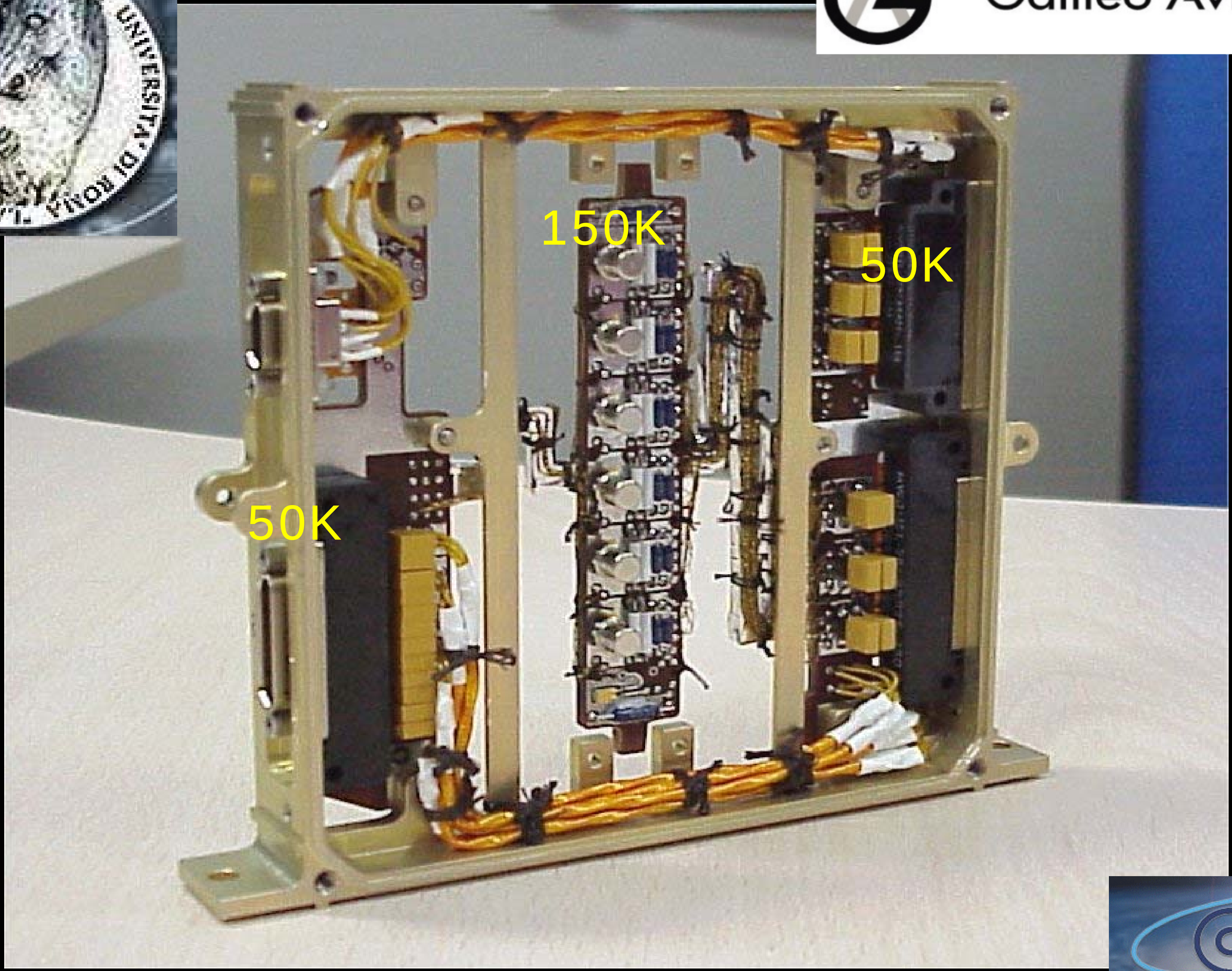
V-groove radiators (to 60 K)

20 K H_2 sorption coolers (JPL)

4 K Stirling cooler (RAL/MMS)

0.1 K $^3He/^4He$ dilution cooler (CRTBT)


CDE - Compressor Harnesses
PHDFA - PPO
PHDFB - Force
PHDFC - Drive
Cooler Current Regulator
Cooler Drive Electronics PHDC
CDE Ancillary Harness PHDFD
To CDE
Filter
Flow meter
P
Buffer
Filter
Getter
P
Cryoharness
JT Orifice
Focal Plane Unit
4K
18K
50K
Heat Exchangers
JT Compressors PHDA
Ancillary and gas cleaning equipment PHDB
Connecting Pipework PHDE
Low Temperature plumbing PHDD (Includes cryoharness)



The JFET BOX: 72 diff. Channels, < 200mW @ 50K, 3nV/sqrt(Hz)

CRYOGENICS for SAGACE

S. Masi

Dipartimento di Fisica, La Sapienza, Roma

Purposes

- The cryostat in SAGACE serves two purposes:

a) reduce the emission of the optical components in the interferometer (mirrors, filters, beamsplitters, baffles, lyot-stop etc.) at temperatures of a **few K**. In this way the dominating radiative background in addition to the CMB itself is the emission of the primary and secondary mirrors. Adding other mirrors at 70K would increase the radiative background, limiting significantly the performance of the instrument. The size of the interferometer is **0.7*0.6*0.5 m^3** (TBC). The cryostat should be large enough to accommodate this volume inside its cold section.

b) cool the cryogenic detector arrays and readout front-end at the operation temperature (**0.3K** for the TES detector arrays and a few K for the readout SQUIDs). Given the radiative background of the 70K mirrors and the relative wide bands of the FTS, there is no need to cool down the detectors below 0.3K.

Basic configuration

- the SAGACE cryostat configuration should be optimized to:

a) reduce the heat load on the cryogens to achieve a hold time as long as possible (baseline **2 years**), given the radiative environment and the required strength and stiffness of the support system (straps).

b) have an **optical entrance** large enough to allow the full throughput of the optical system. This optical entrance should be closed at ground to withstand atmospheric pressure. This is achieved using of an **openable cover** for the window, which can also be used as a **safety shutter** in case the telescope observes the earth or the sun.

c) Be relatively lightweight (**M<250 kg**), and able to withstand the **acceleration at launch** and the **atmospheric pressure** for all the tests at ground.

Heritage (year 2008!)

- Space cryogenics is now a well developed science.
- Several cryostats using cryogenic liquids have been flown: astronomy missions like
  - IRAS
  - ISO
  - COBE
  - IRTS
  - Spitzer
- Earth observation and military missions have been flown with active cryogenerators (77K) to cool IR detectors.
- Next year the **Planck** satellite will carry a very ambitious active cryogenerator, comprising of a 0.1K dilution fridge. The active cryogenerator has been developed by RAL under ESA contract, while the dilution fridge has been developed by CRTBT (Grenoble) and fabricated by Air Liquide under ESA contract.
- Similarly, the **Herschel** satellite will also fly next year, carrying a large LHe tank and a ^{3}He fridge similar to the one flown on IRTS.

Heritage and Options

- The first choice is Active cryocooler vs Passive Cryostat with cryo fluids.
- In the case of SAGACE there are several considerations favoring **a passive solution with cryogenic fluids**:
  - Absence of mechanical compressor and of the related vibrations and electromagnetic interference
  - Lower power budget
  - Lower total cost of the system
  - Availability of the design expertise and fabrication technology in Italy, and in particular within the SAGACE collaboration: no need for extensive R&D.
- For all these reasons, we have considered from the very beginning :
  - a **liquid helium cryostat** to provide a base temperature of about 2K for the interferometer
  - a **3He system** to provide the lower temperature (0.28K) for the detector arrays.
  - These subsystems have been already developed by the Rome group for several stratospheric balloon missions (Palumbo et al. 1994, Masi et al. 1998, 1999, 2006).

Main Features of LHe Cryostat

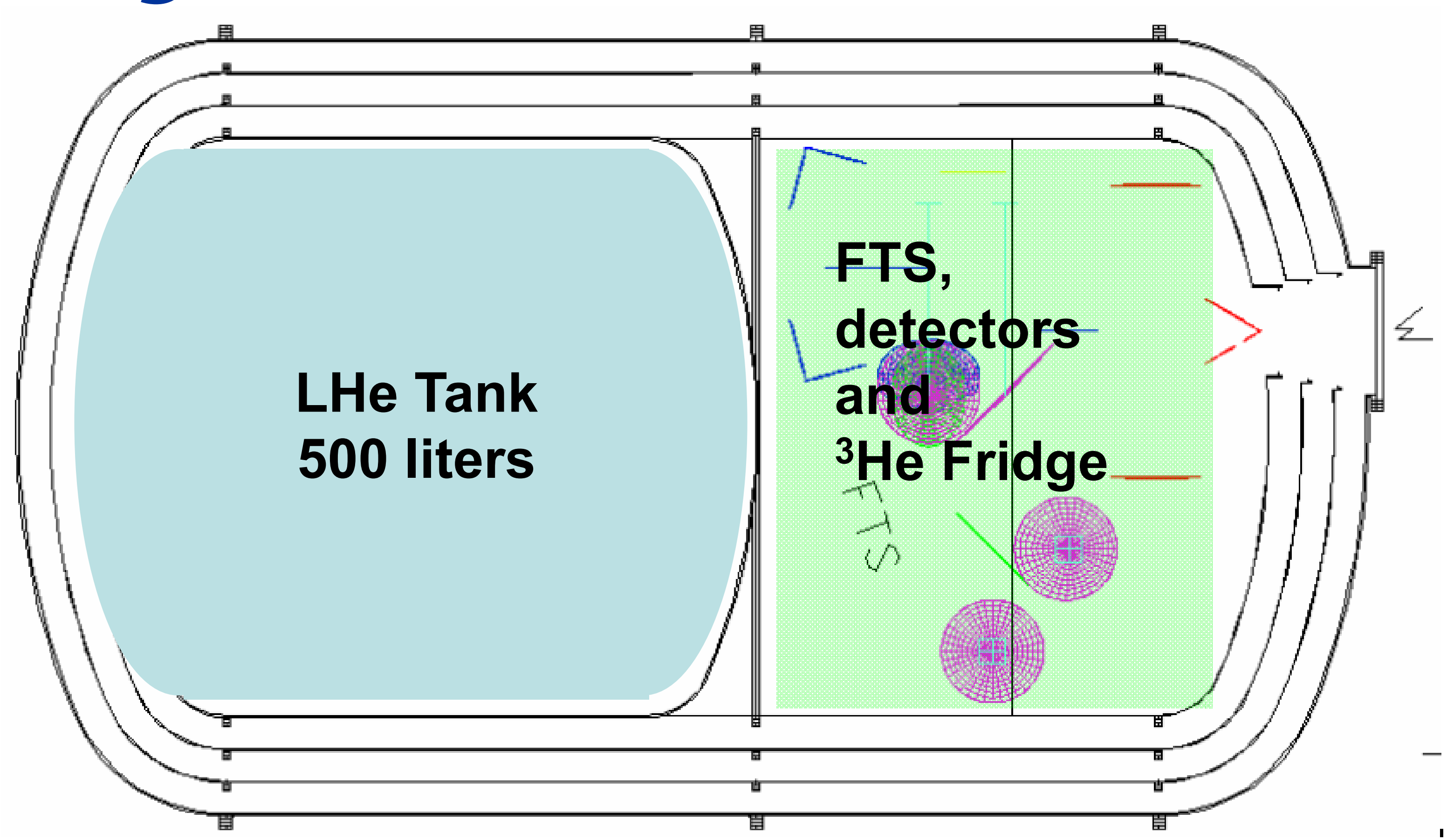
The main features of the SAGACE liquid He cryostat are:

1. A large LHe tank (500 to 700 Liters)
2. supported by straps or **struts**; possibly supports removable after launch (electromechanical latches or shape memory alloys)
3. Surrounded by **vapor cooled shields** and aluminised mylar multi layer insulation (MLI)
4. LHe confined inside the He tank by means of a **porous plug** in the vent port
5. A fill port sealed after refilling, by means of a **cryogenic valve** remotely actuated
6. **Superfluid transfer** to fully exploit all the LHe
7. A number of accurate **thermometers**

LHe Cryostat: first calculation

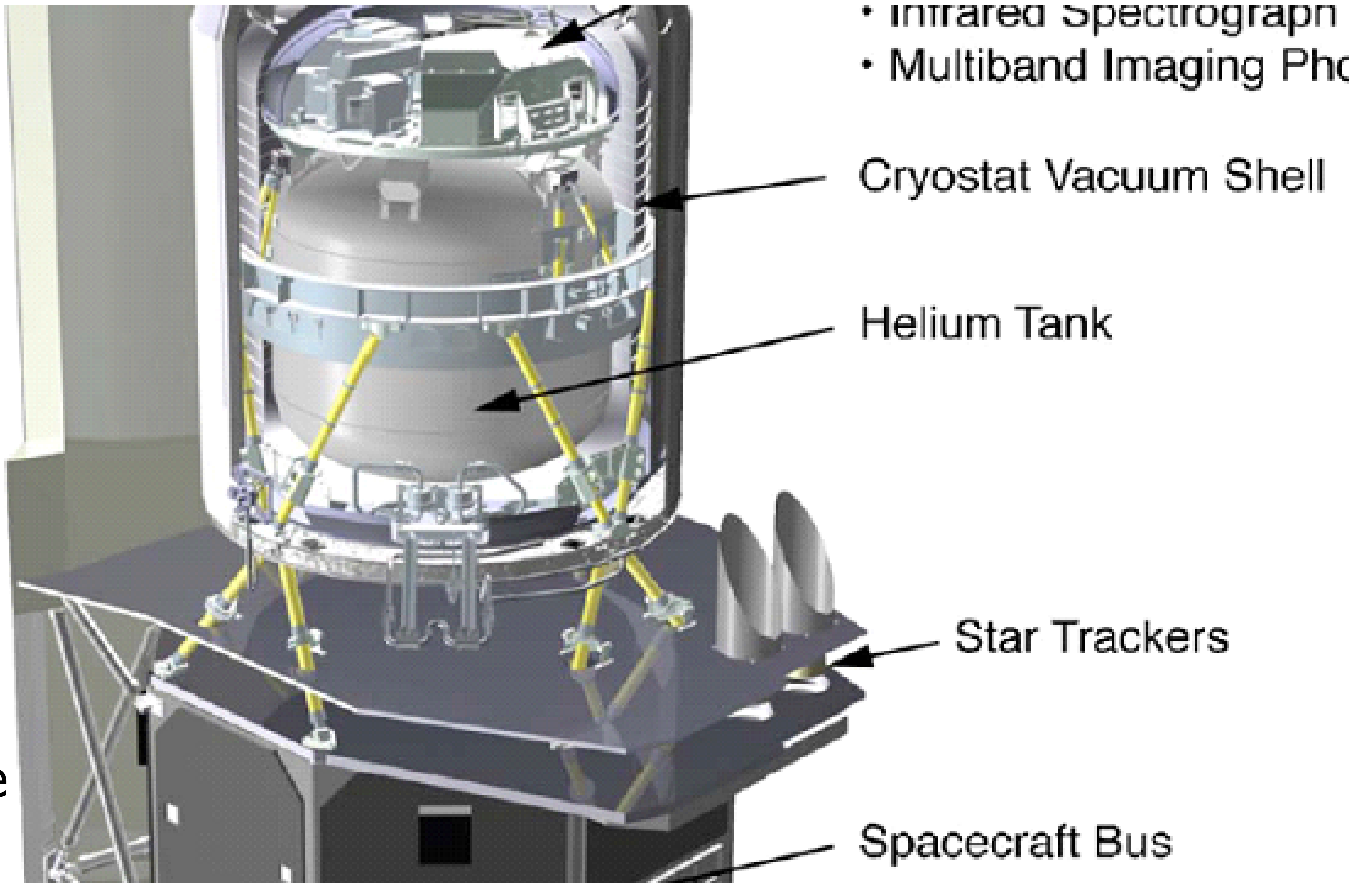
	A	B	C	D	E
1	======= SAGACE MAIN DEWAR – He tank ====================				
2	latent heat of Liquid Helium (2.2 K)			2890.8	J/liter
3	--				
4	**LIQUID HE TANK**				
5	cylinder height			90	cm
6	cylinder diameter			90	cm
7	cylinder surface			38170	cm2
8	emissivity			0.05	
9	temperature			2.2	K
10	volume form factor			0.9	
11	volume of the helium tank			515.30	liters
12	usable He volume			**515.30**	**liters**
13	assuming superfluid transfer				
14	**HE VAPORS SHIELD**				
15	cylinder height			100	cm
16	cylinder diameter			95	cm
17	screen surface			44022	cm2
18	emissivity			0.05	
19	temperature			20	K
20	Form and emissivity factor			0.0256	
21	RADIATION HEAT LOAD ON HE			**0.001**	**W**
22	**SUPPORT struts**				
23	number of supports			6	
24	length			20	cm
25	diameter			1.5	cm
26	thickness			0.1	cm
27	K(40 – 2.2)			0.08	W/cm
28	heat load on He			**0.011**	**W**
29	**CABLING HEAT LOAD**			**0.005**	**W**
30	**EXTRA load (mechanisms, cycles,**			**0.005**	**W**
31	**total heat load on He**			**0.022**	**W**
32	**He hold time**			**776.71**	days =
33				**2.13**	**years**

LHe Cryostat: basic design



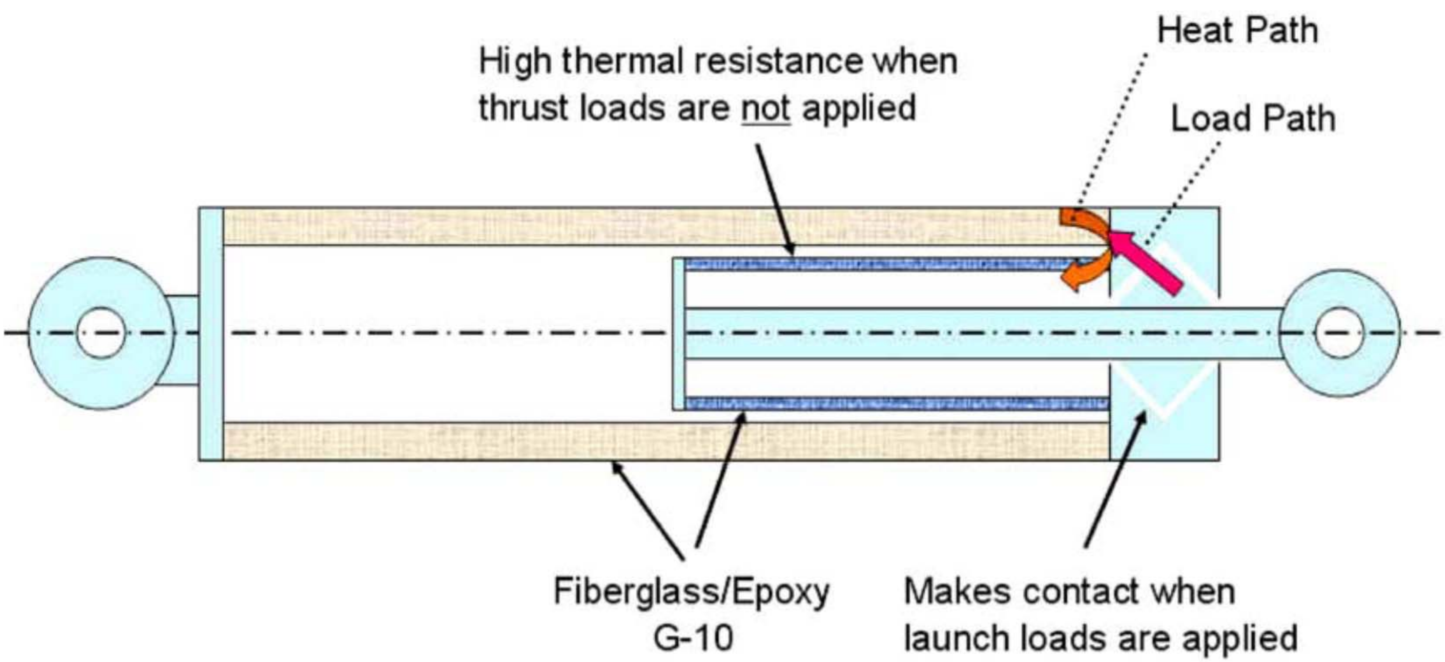
Support system

- Reference configuration:
- Gamma Alumina/Epoxy struts as in Spitzer
- (yellow in fig.)
- These struts can be manufactured by SCI (Structural Composite Industries) following our design.



Passive Orbital Disconnect Struts

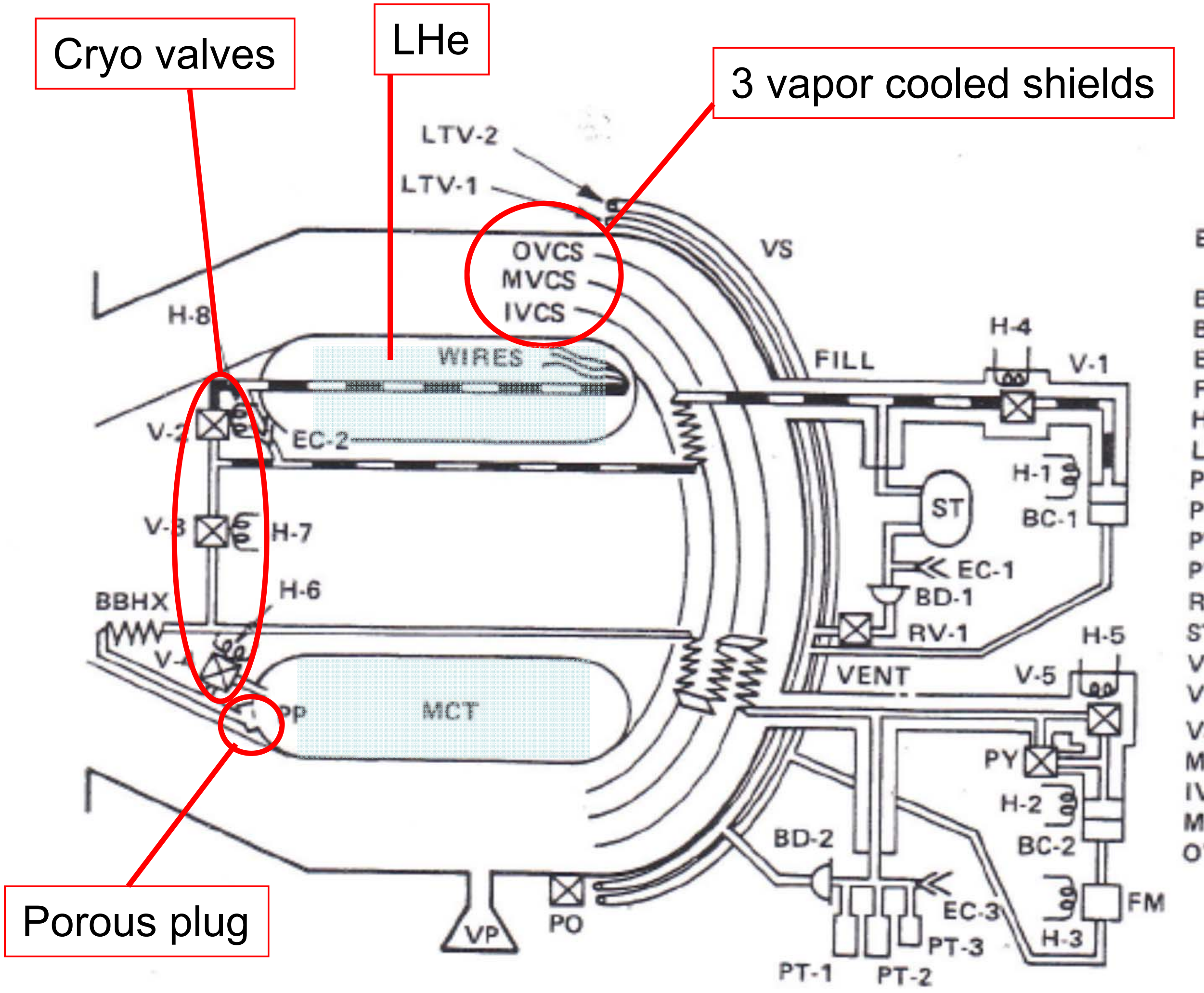
Passive Orbital Disconnect Struts (PODS)



High stiffness when loads are applied.
Low stiffness on-orbit.

LHe Cryostat: basic plumbing

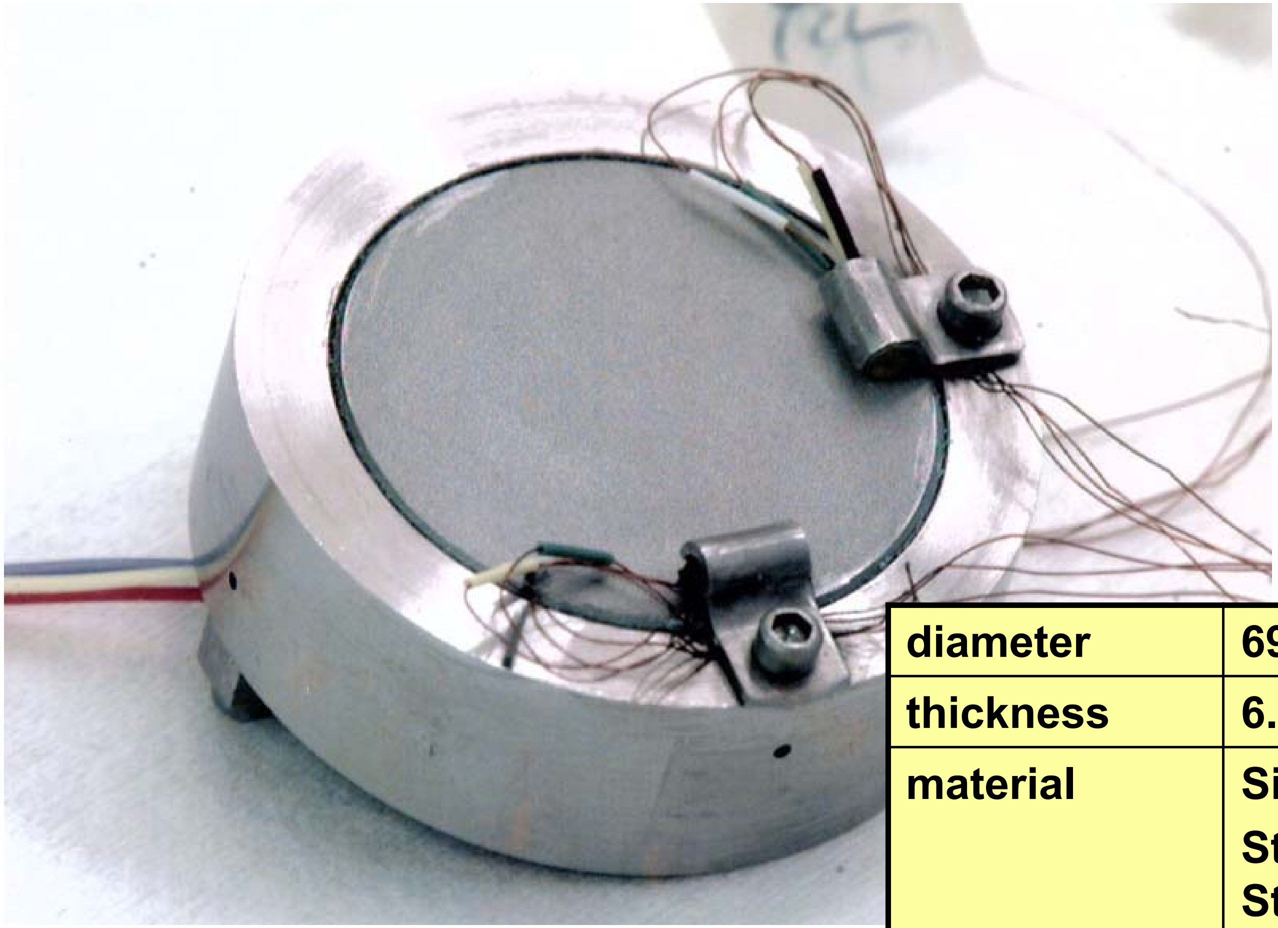
- Reference configuration:
- IRAS/ISO/COBE cryostats with cryogenic valve and porous plug



Porous Plug

- A porous plug is needed to separate contain the liquid inside the cryostat while pumping on the vapors.
- The porous plug works if and only if there is a thermal gradient across it, with cold outside.
- In normal conditions this is mantained by the evaporation of He on the outer surface
- If the outer side is warmer than the inner side, and there is LHe on the outer side, the so-called Castle's catastrophe happens: the fountain effect pushes quickly all the LHe outside the cryostat !
- Accurate thermometry, heaters and valves strategically placed are needed to avoid this.

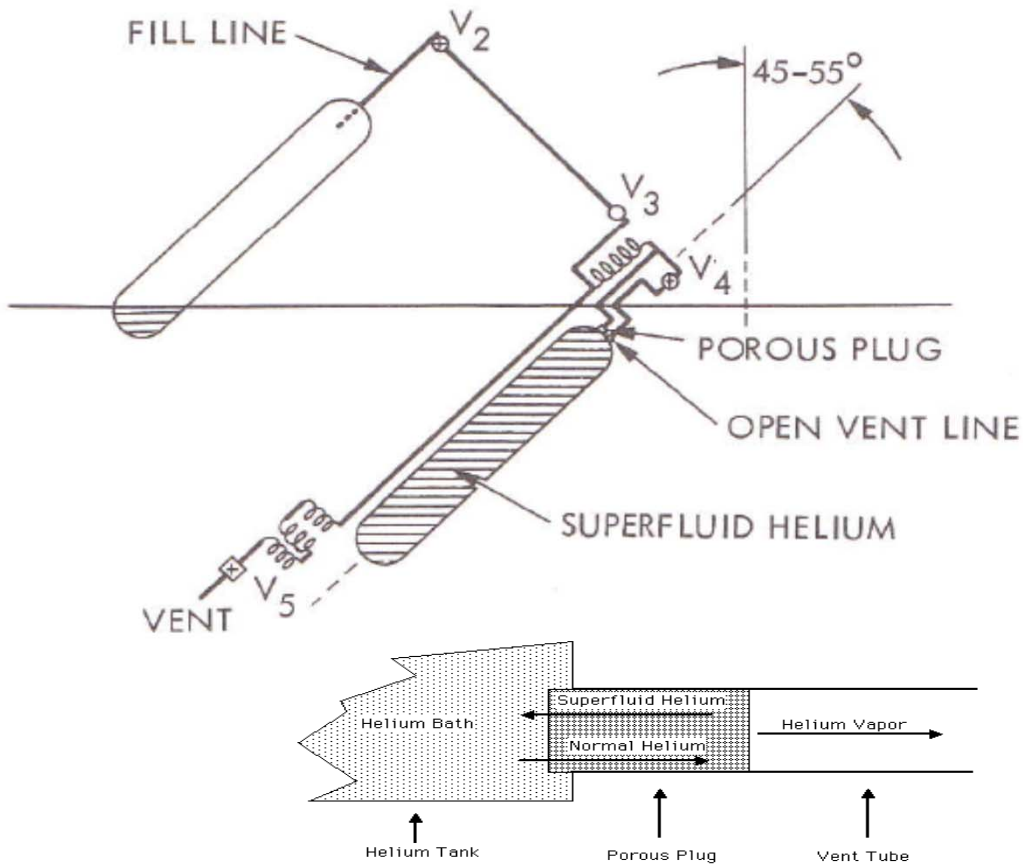
Porous Plug



diameter	69 mm
thickness	6.35 mm
material	Sintered Stainless Steel
permeability	3.8×10^{-10} cm^2

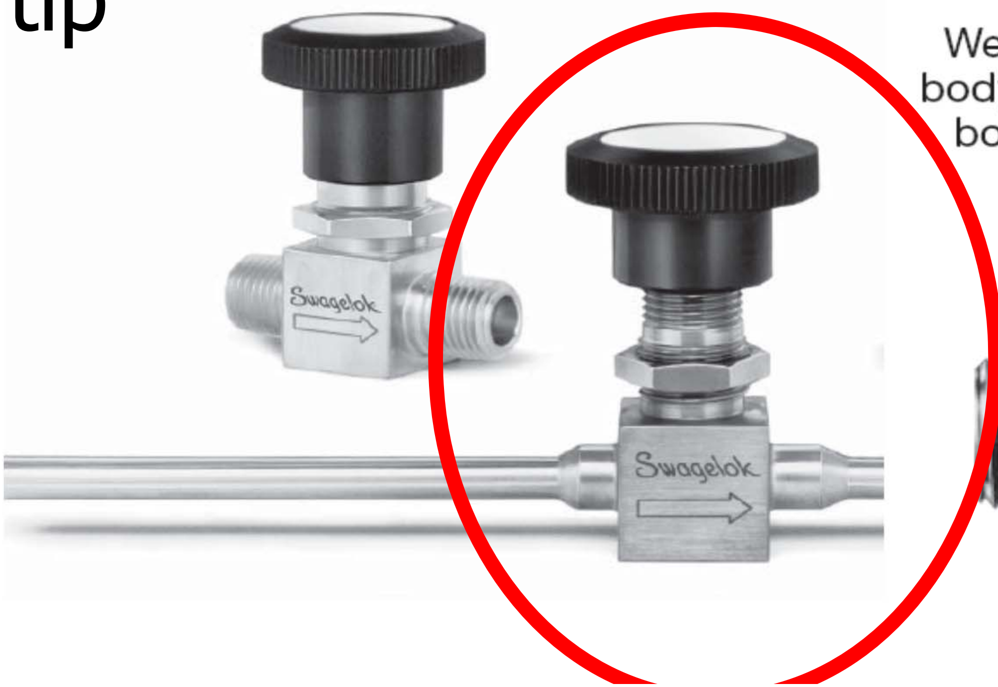
Porous Plug

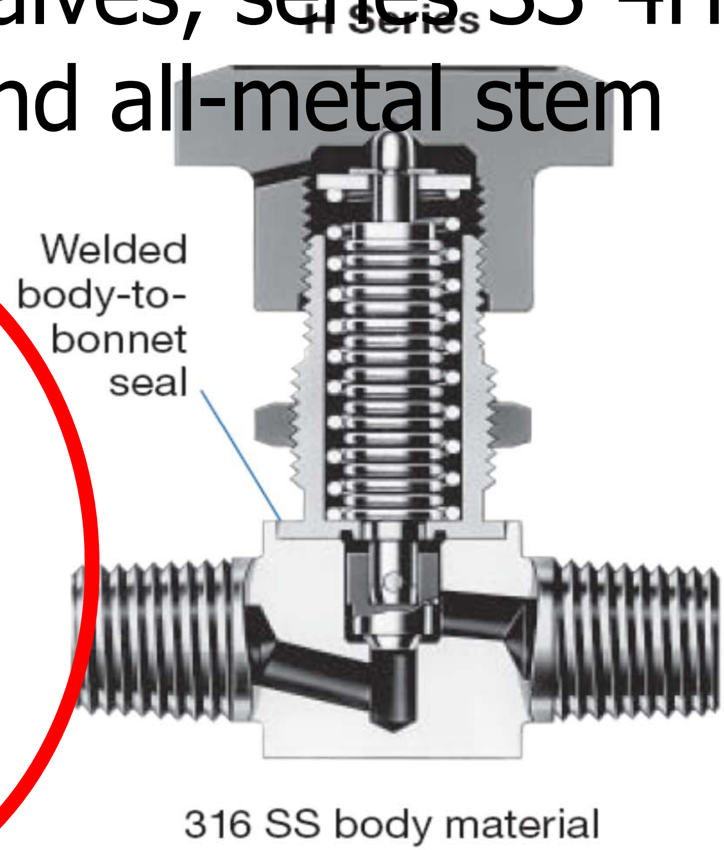
- Two sources of porous plugs have been identified, and samples have been shipped to carry out qualification tests with the custom system shown in fig.
- The detailed design of the test setup is being completed.



Cryo Valves

- We have successfully used, immersed in LHe, NUPRO bellows valves, series SS-4H , with welded bellow and all-metal stem tip





He3 Cooler

- Used in addition to other coolers to achieve T<1K with closed cycle sorption coolers (T>250 mK) and dilution refrigerators T>50 mK. The first one used in SPIRE and PACS on Herschel while the second one used in Planck

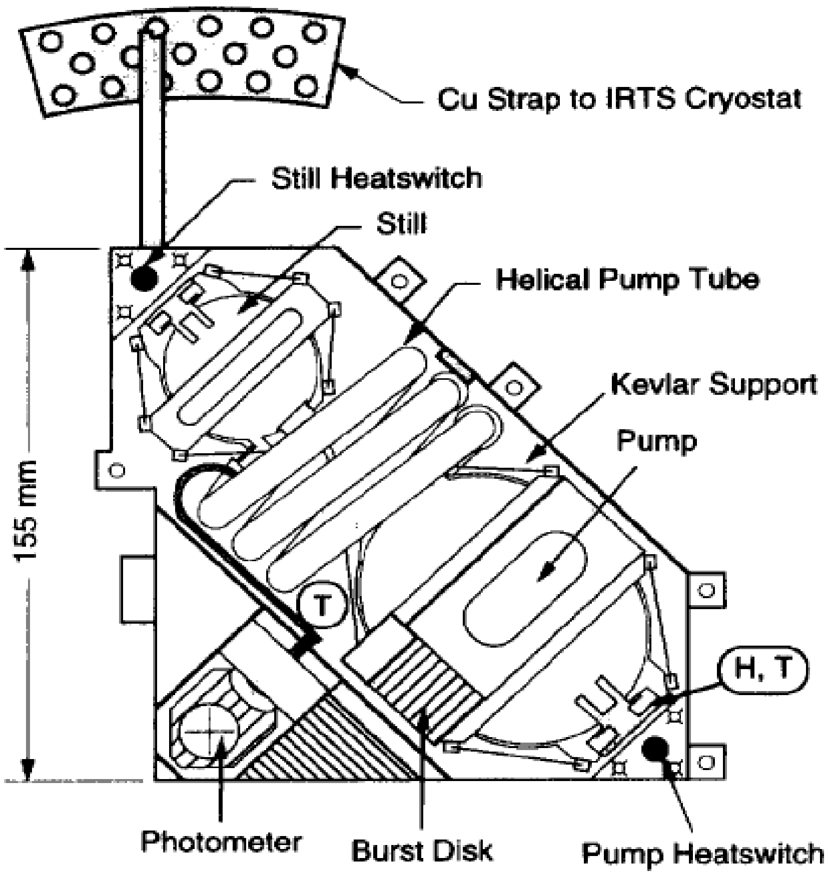
^3He fridge

Already flown example: IRTS (’90s)

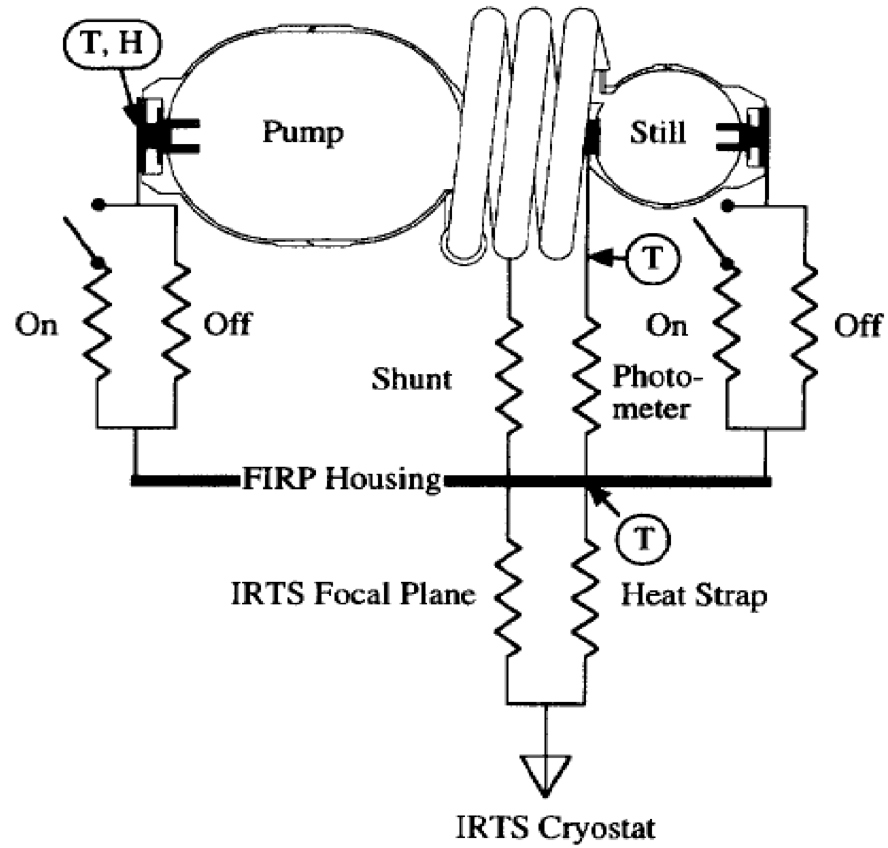
Problems to analyze :

- sponge to keep 3He
- Heat switches
- support system for evaporator and cryopump

^{3}He fridge

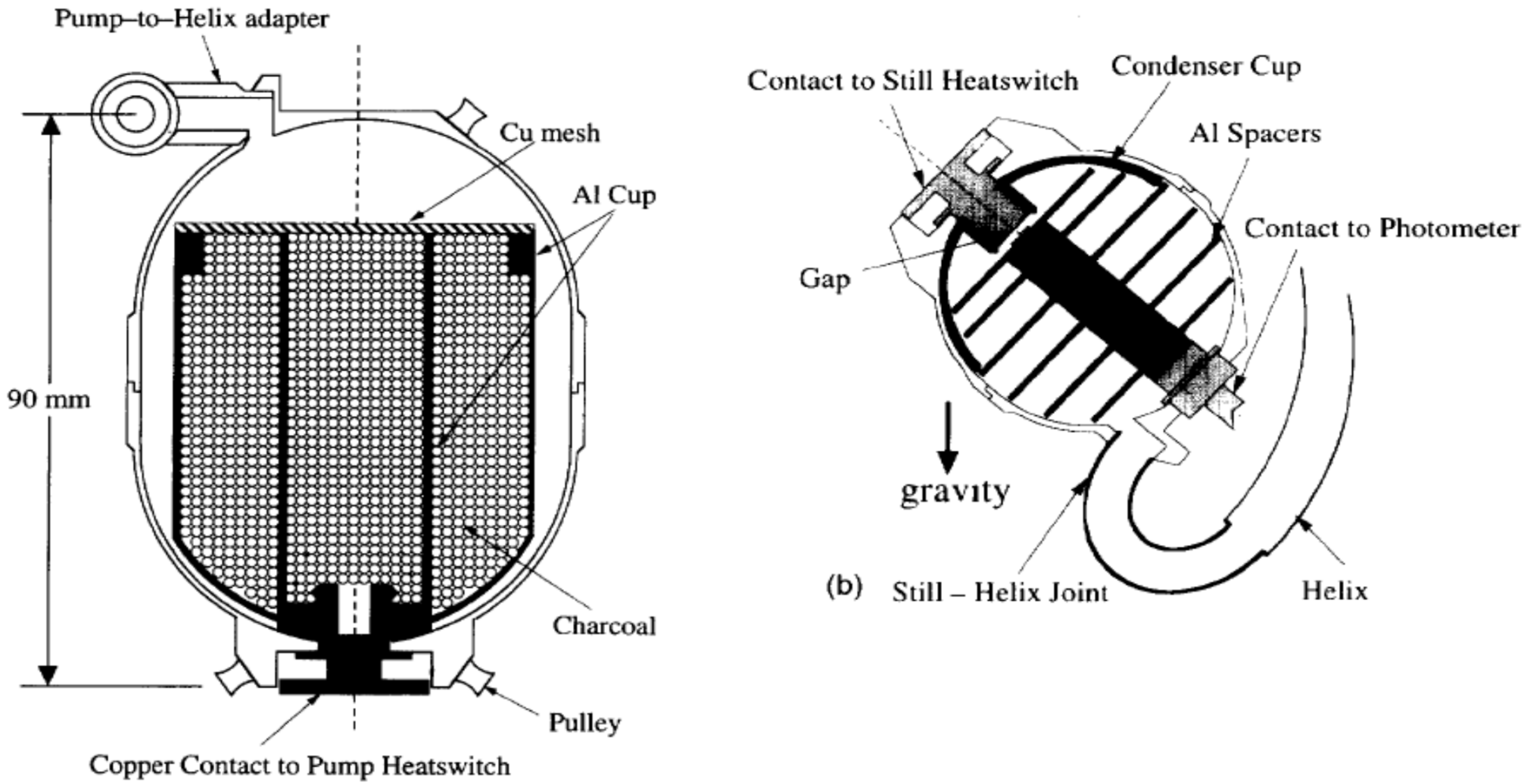


Cu Strap to IRTS Cryostat
Still Heatswitch
Still
Helical Pump Tube
Kevlar Support
Pump
155 mm
T
H, T
Photometer
Burst Disk
Pump Heatswitch



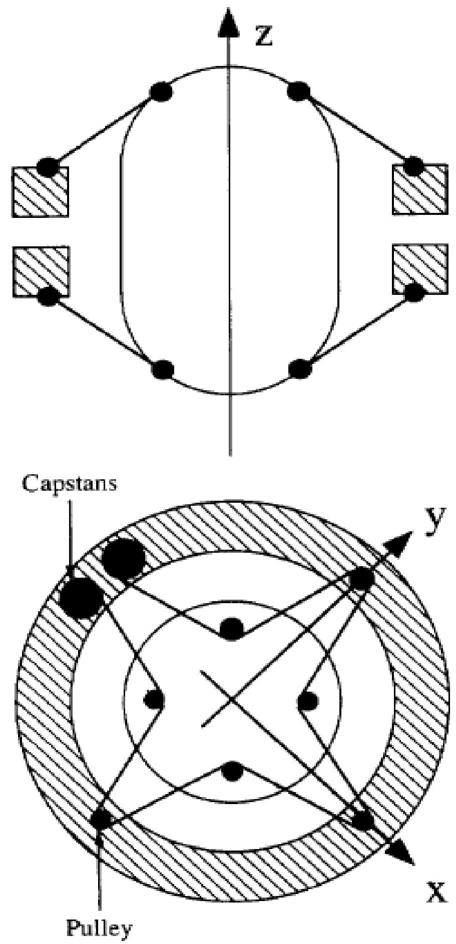
T, H
Pump
Still
T
On
Off
On
Off
Shunt
Photo-
meter
FIRP Housing
T
IRTS Focal Plane
Heat Strap
IRTS Cryostat

^{3}He fridge


Pump–to–Helix adapter
Cu mesh
Al Cup
90 mm
Charcoal
Pulley
Copper Contact to Pump Heatswitch
Contact to Still Heatswitch
Condenser Cup
Al Spacers
Contact to Photometer
Gap
gravity
(b)
Still – Helix Joint
Helix

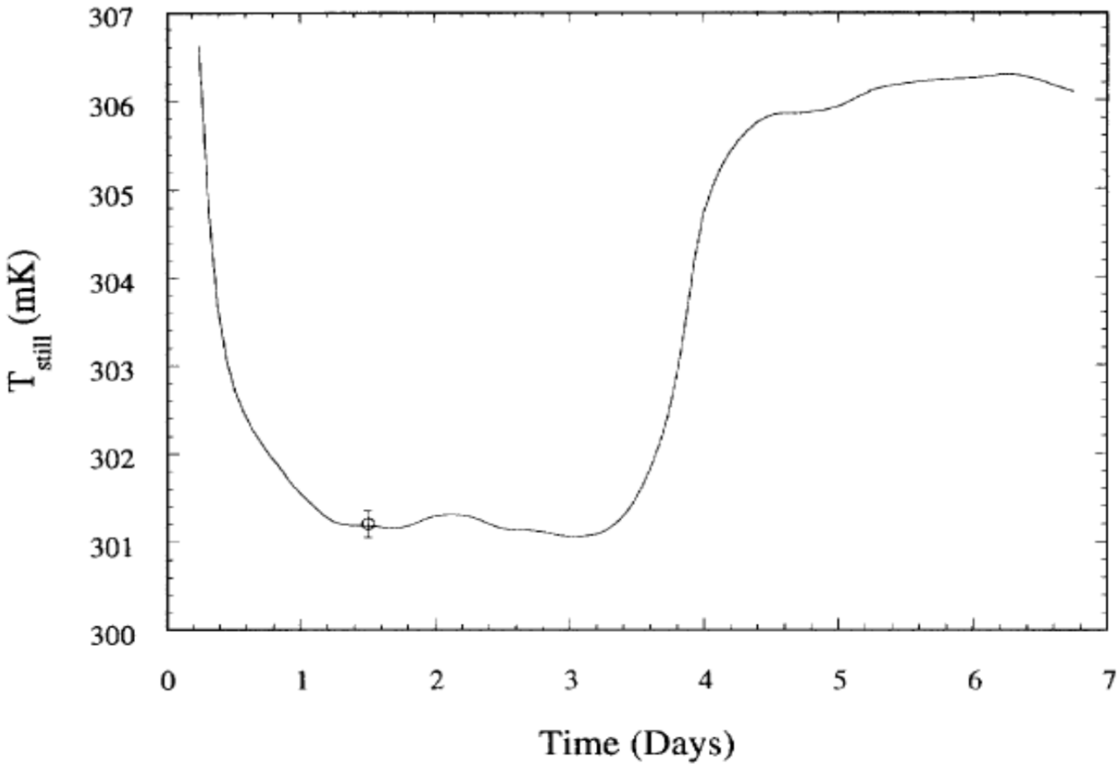
^3He fridge

- Support system based on Kevlar cords
- Constrains all 6 degrees of freedom with negligible heat load.
- We have used kevlar in BOOMERanG already



^3He fridge

IRTS
In-flight performance (1 cycle of 3 shown)



^{3}He fridge

Next to go: SPIRE on Herschel

Upgrade of the IRTS

Titanium alloy fabrication

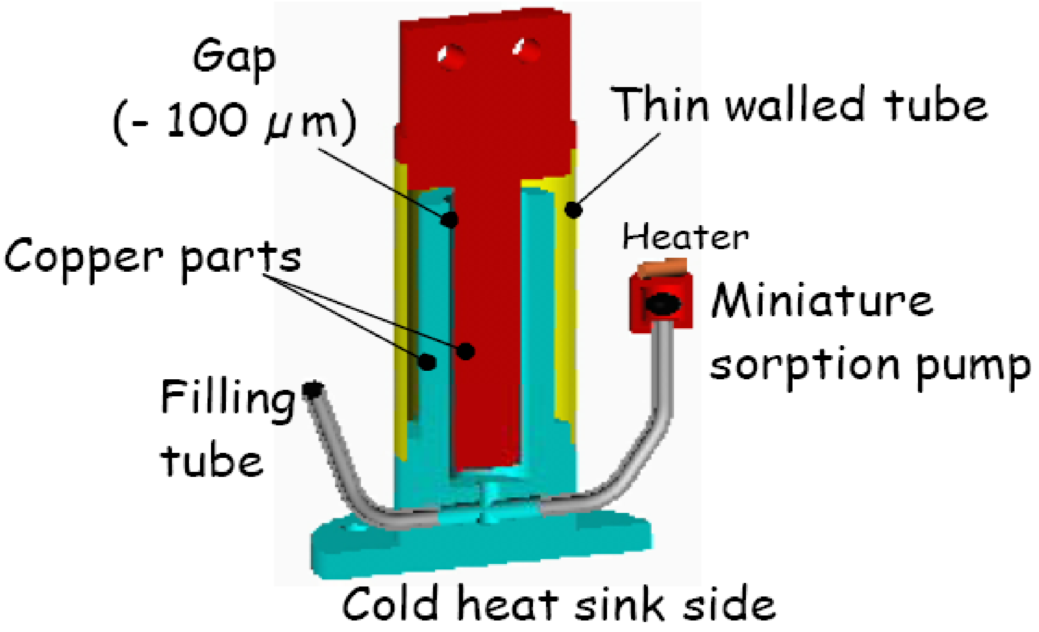
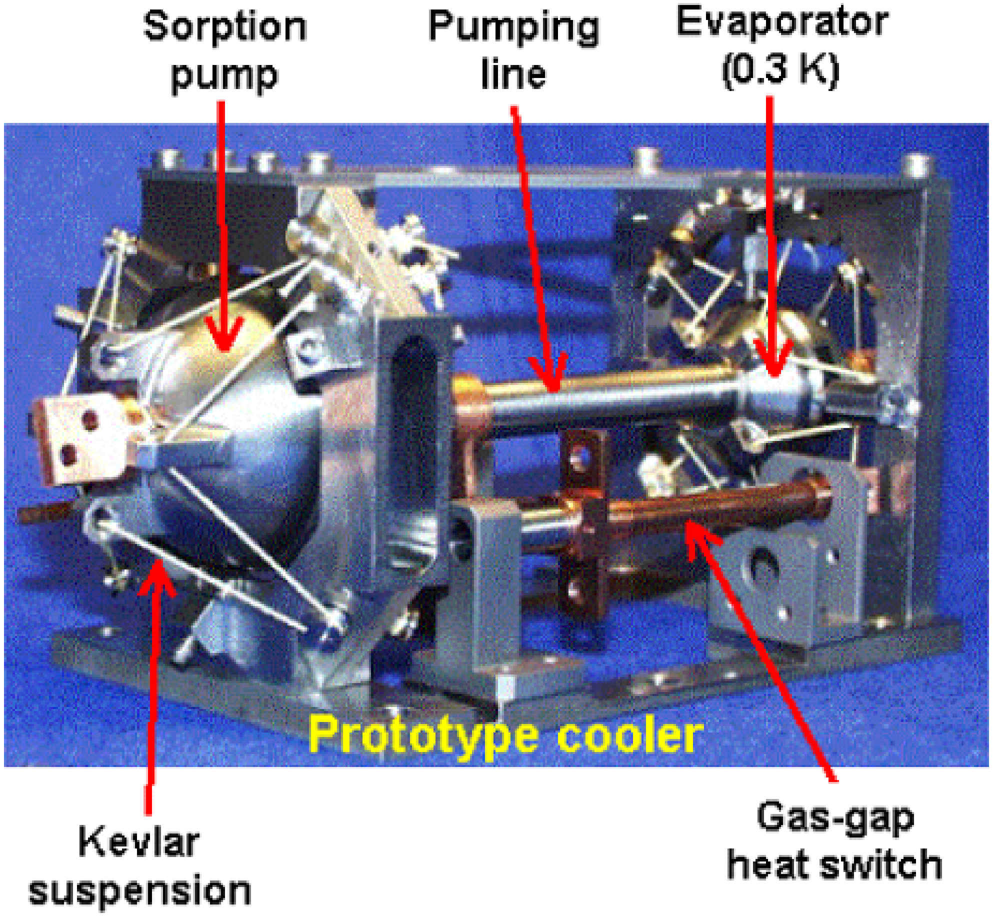


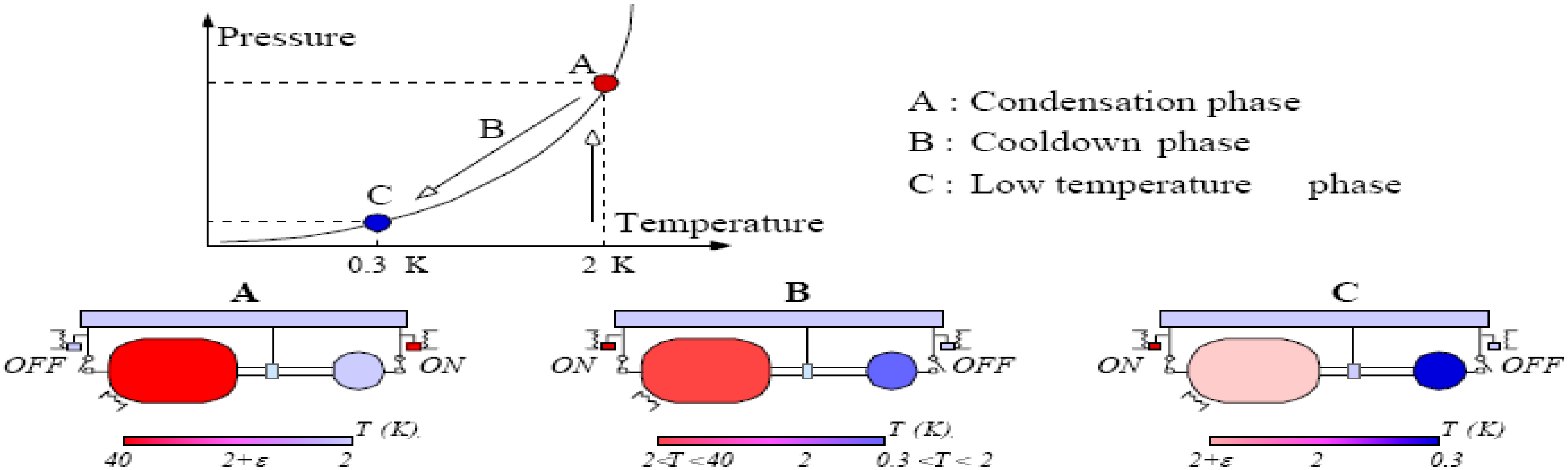
Figure 4-56 - Schematic representation of the gas gap heat switch.

^{3}He fridge


Sorption pump
Pumping line
Evaporator (0.3 K)
Prototype cooler
Kevlar suspension
Gas-gap heat switch

^{3}He fridge

- Operations sequenced electronically (cryopump and switches micro CP actuated by ohmic heaters)



Control {
Thermal Gradient: Gas gap heat switch
Cooler internal pressure: Sorption pump
Liquid position: Confinement by capillary action (evaporator)

Figure 4-57 - Operation of the 3He cooler during recycle, (A and B) and normal operation (C).

^{3}He fridge

- We have made several ^{3}He fridges for balloons (ARGO, BOOMERanG, OLIMPO), but never one for a satellite.
- Differences:
  - Heat switches (to test against gravity and after vibration)
  - 100g support system (to design)
  - Sponge to contain ^{3}He by means of surface tension (to test against gravity !!!)
- We are focussing our attention to these elements before passing to the detailed design in the forthcoming activities.

^{3}He fridge

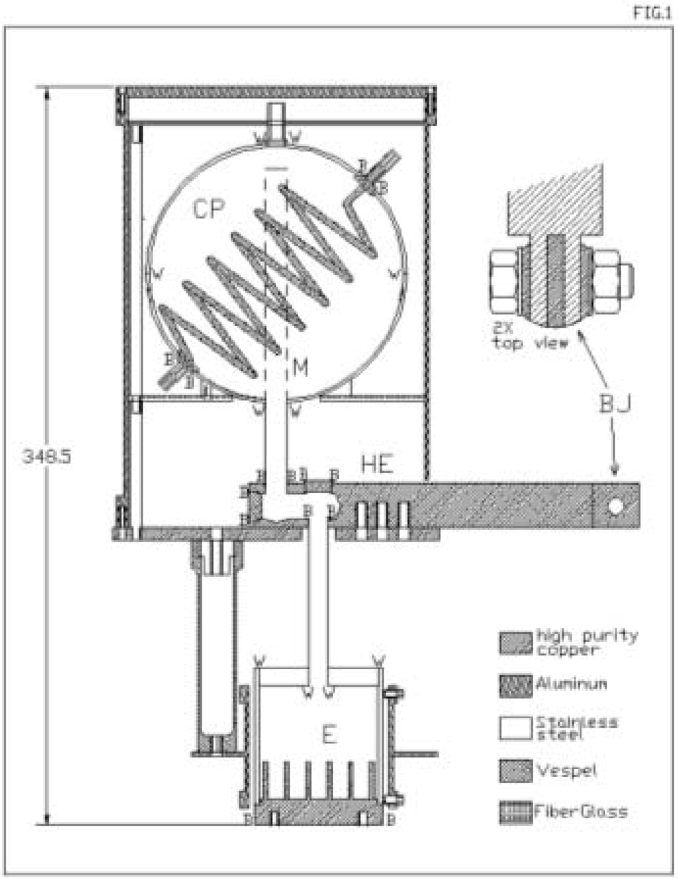
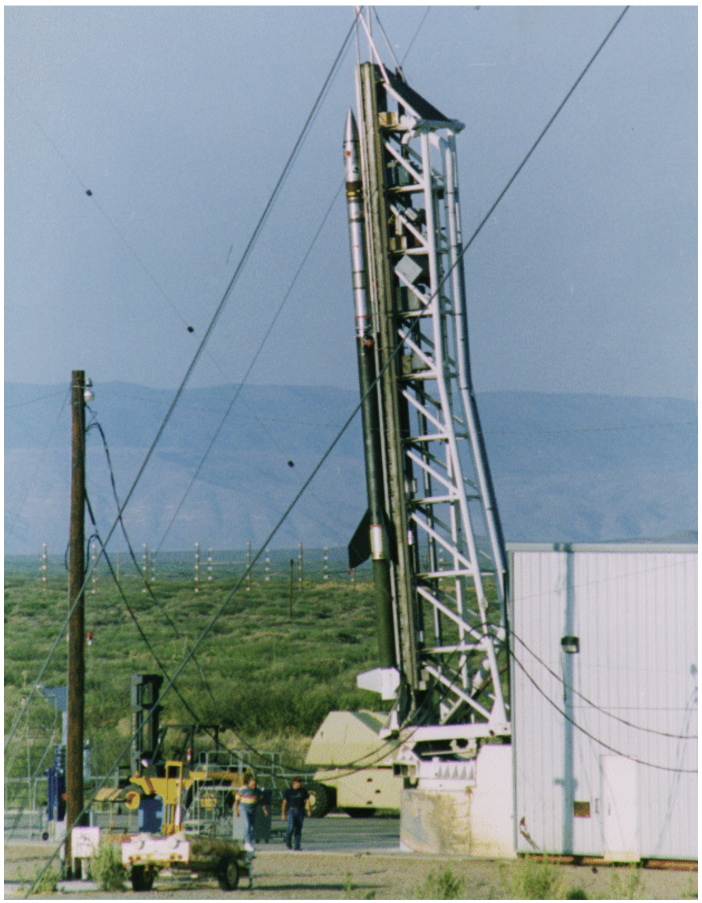


FIG.1
CP
M
HE
BJ
2X
top view
348.5
E
high purity copper
Aluminum
Stainless steel
Vespel
FiberGlass

Adiabatic Demagnetization

- ADR used on ground for many years to get to millikelvin temperatures after a first stage pre cooling system. The process uses the magneto-caloric effect with a paramagnetic salt. Currently under development for use in space

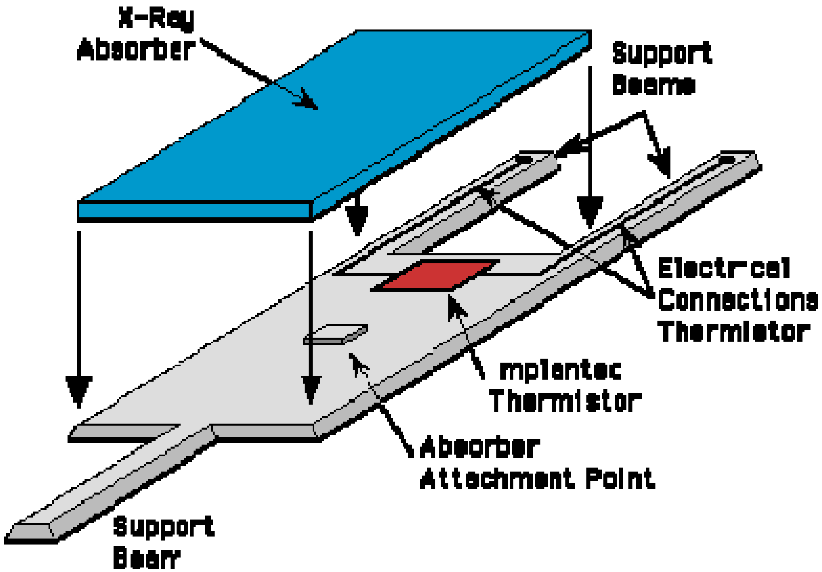
XQC rocket: 1996
X-ray Quantum Calorimeter

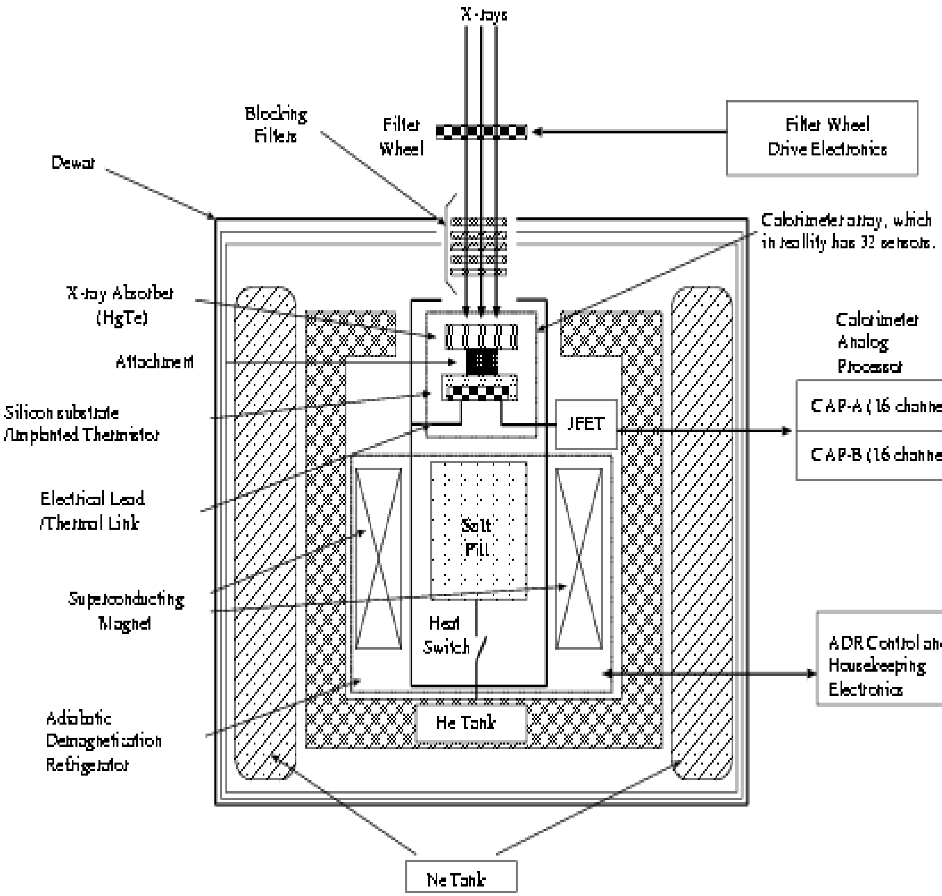


- Soft x-ray spectrometer
- 36 pixel microcalorimeter array cooled by an adiabatic demagnetization refrigerator at 60 mK.
- 12 eV resolution!.
- observing time of 240 seconds during the sounding rocket flight
- Testbed for forthcoming XRS and HTXS, ASTRO-H, ATHENA instruments

A microcalorimeter @ 60 mK

http://astroe.gsfc.nasa.gov/docs/astroe/xrs_inst.html

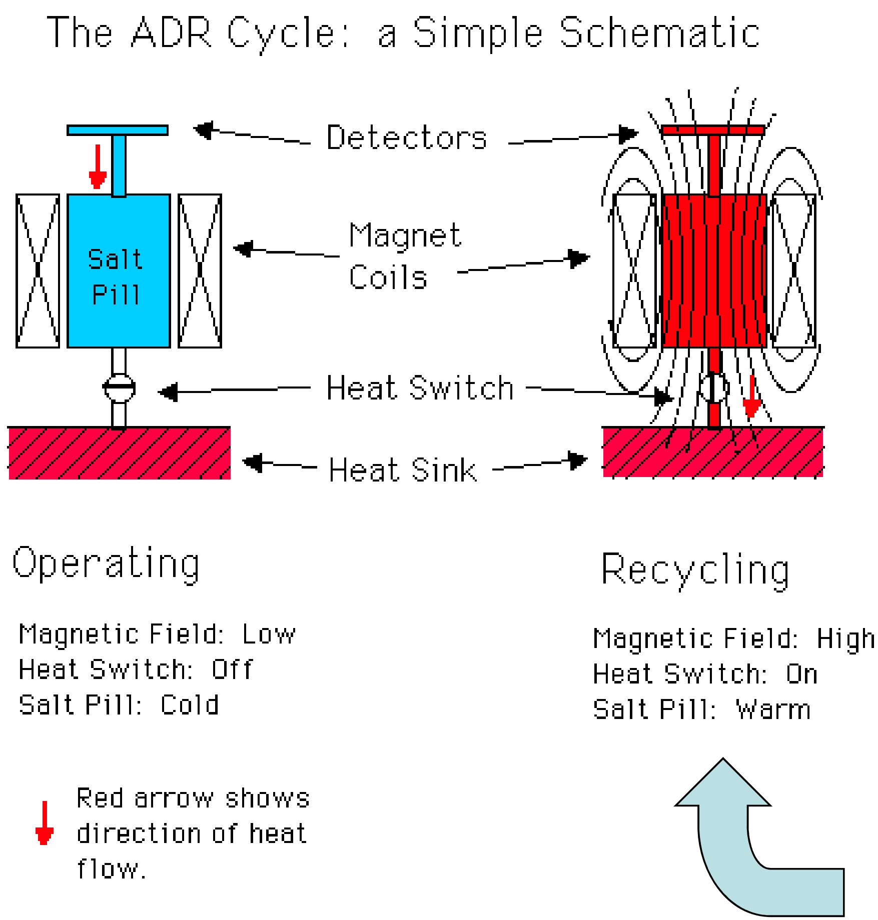




ADR

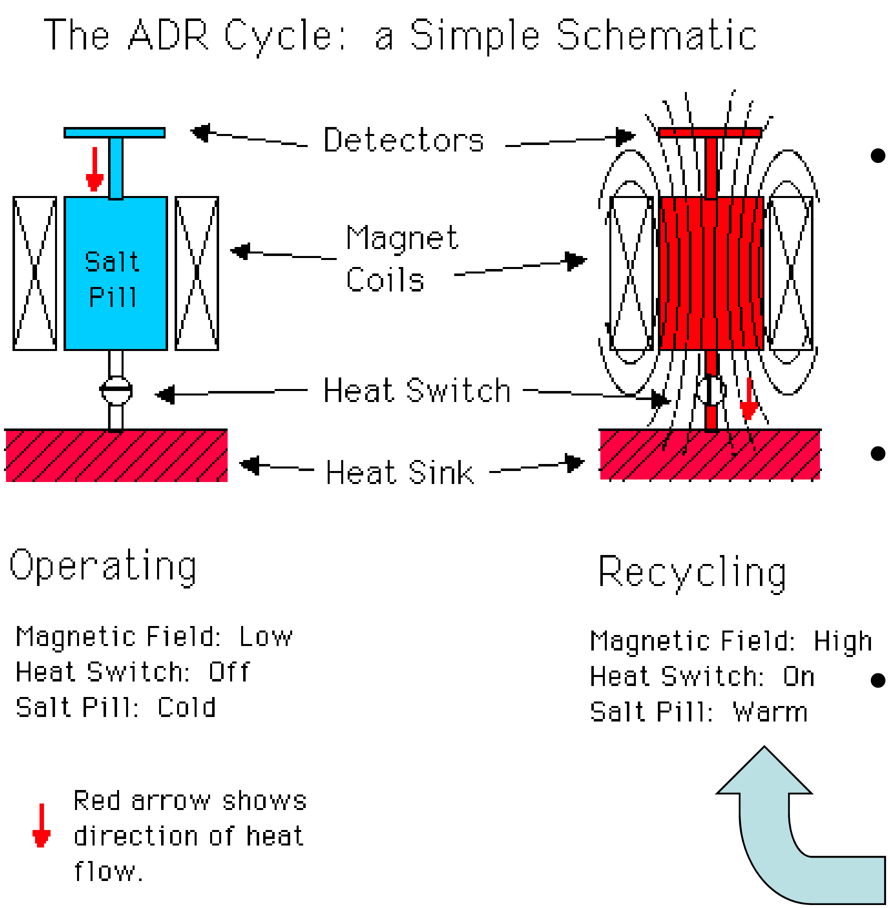
- Evaporation cryostats use a liquid which evaporates as it absorbs heat, then condenses elsewhere in the circuit as it dumps heat.
- The Adiabatic Demagnetization Refrigerator (ADR) stores heat in the disorder of magnetic moments of the molecules in a paramagnetic substance. The magnetic moment arises from the angular momentum of the electrons in the molecule.
- The ADR is a cyclic cooling system. It alternates between two states:

ADR



- The first step is to connect the paramegnetic salt to a low temperature heat sink, and increase the magnetic field using a superconducting magnet.
- With a strong enough applied field, virtually all the magnetic moments are forced into alignment with the field, and kept at the temperature of the thermostat (Heat Sink, normally ^{4}He at 2K)

ADR



- Then the heat switch is opened, and the magnetic field is reduced
- The salt is de-magnetized in adiabatic conditions, since the heat switch is open.
- As a result, the magnetic moments absorb thermal energy as they move out of alignment with the field.
- In absorbing the thermal energy, the magnetic moments cool the paramagnetic substance.
- In other words, as the field drops, the entropy of random thermal vibrations is transformed into the entropy of random magnetic moment alignment.

Entropy of a paramagnetic salt

- Spin-1/2 salt:

$$S = Nk_B \ln\left[2\cosh\left(\frac{\mu_B B}{k_B T}\right)\right] - \frac{N\mu_B B}{T}\tanh\left(\frac{\mu_B B}{k_B T}\right)$$

- Entropy depends of the ratio B/T .
- If B is decreases in adiabatic conditions, to keep Entropy constant, T must decrease as well, so that the ration B/T is constant.
- So

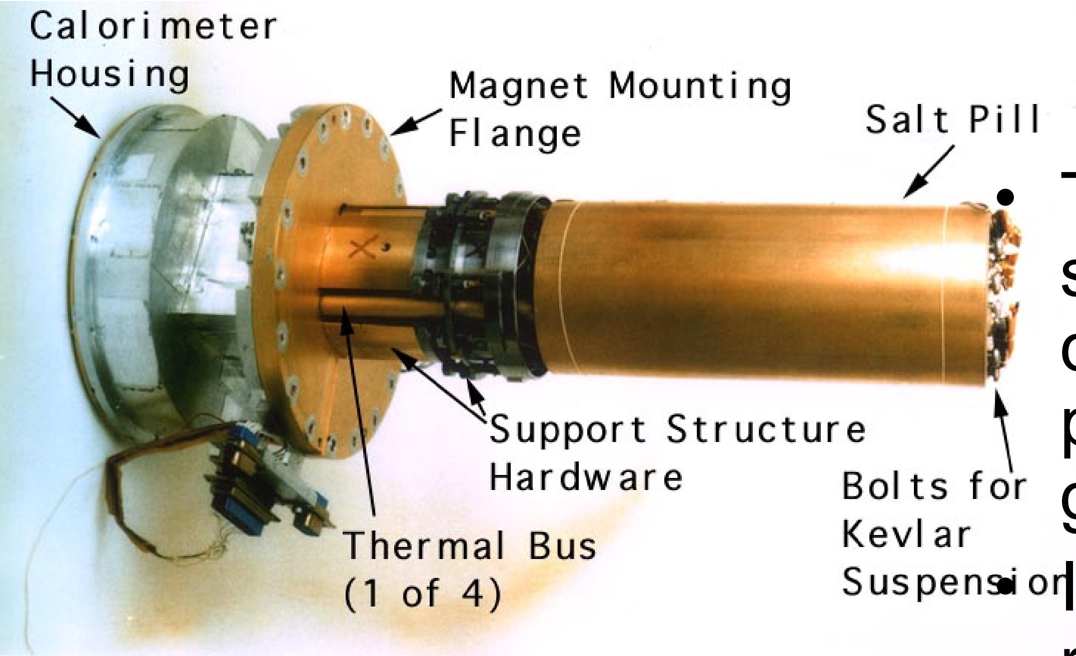
$$\left.\frac{B}{T}\right|_{\text{end of adiabatic demagnetiz ation}} = \left.\frac{B}{T}\right|_{\text{start of adiabatic demagnetiz ation}}$$

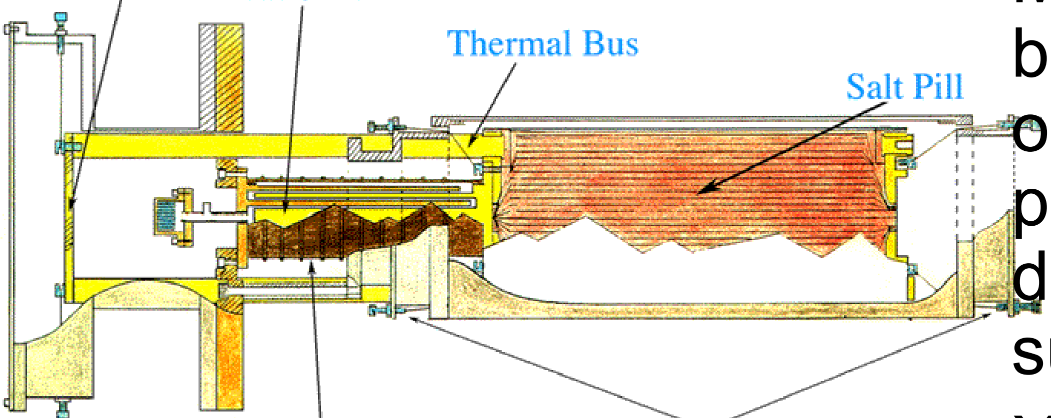
- There is a minimum B, due to the spontaneous alignment of spins, so there is a minimum T

ADR parts

- **Salt Pill**: a block of paramagnetic substance. For example, the XRS ADR uses Ferric Ammonium Alum (FAA, also called Ferric Ammonium Sulfate.) However, chemicals other than salts have been proposed, such as Gadolinium Gallium Garnate (GGG.)
- **Magnet**: The magnet provides the magnetic field that controls the flow of entropy and energy into and out of the molecular magnetic moments.
- **Thermal Sink**: The thermal sink is where the heat is dumped after it leaves the salt pill. In the XRS ADR, the thermal sink is a bath of liquid helium coolant. For other ADR's, the thermal sink could be some other cryogen, or even another cooler.
- **Heat Switch:** allows the salt pill to make or break contact with the thermal sink.

XRS ADR





- The ADR is appealing for space operations, since it does not have moving parts and does not require gravity for operation.
- It has been used for the rocket XQC and for the MAXIMA experiment on a balloon. Never flown in outer space, however, probably due to the quench danger in the superconducting magnet.
- XRS will be on the astro-EII satellite.