Enabling Technology Development
Space Cryogenics

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on behalf of the Italian CMB community

Overview

- Space cryogenics: introduction
- European space cryogenic trends for next future
- CMB oriented key technologies in cryogenics
- Italian status on space cryo
- Italian expertise in CMB related cryo and possible contributions
- Ideas to be (more) competitive
- Conclusions

Space Cryogenics: introduction

- **Cryogenics** in **space** is used for Earth and science obs and space exploration:
  - detectors/focal planes cooling (both direct or as precooling)
  - propulsion
  - SC magnets cooling (fund physics or shielding for next exploration missions)
  - sample collect and conservation (spacelabs)
- Ground vs space cryo: differences are mainly related to some tech solutions and limitations typical of space platforms
  - fluid confinement in μ-g, lifetime (no maintenance), vibrations, low power consumption vs max heat lift (-> high efficiency), mass and size limitations
  - in general space cryo systems must be **custom made** (no off-the-shelf solution)
- Liquid or solid cryogen dewars were the choice in the early phases until the 80's - 90's (COBE), now are less popular (Herschel)
- In the 70's **Stirling coolers** generated a first revolution, then the break-through was the **Oxford type cooler** (early 90's)
- Since the 90's and including the missions under development right now ~50 instruments required/are requiring cryocoolers. In the 1990 – 2025 period a total of **~110 flight coolers** worldwide
- What is going to be the next break-through (if any)?

Credits for input: T. Tirolien (ESA-ESTEC)

European status and trend for next future 1/2

European Space Cryogenic Workshop organized by ESA every odd year.

Last workshop (Dec 2015) indicated the trend on research and enabling technologies to be pursued in the mid/long term future

Earth Observation (Earth Explorer–Earth Watch), end of a cycle, ready for the next

- Cooling below 77K: no large/complex thermal/cryo mission before 2030 but potential peak of demand in the 30's (e.g. MTG): lowest T in the **40-50K** range (European IR MCT detectors), **tens of mW** heat lift, long lifetime in the **8-10 years** range, **μ-vibrations** will be the **main concern**, more than ever, as ~**100mN** in all axis in all harmonics are required
- Cooling above 77K: 120 – 170K T range of special interest, Ws of heat lift. Trend is to go to **cheaper, scaled** and **reliable** coolers or combined passive/active solutions. Smaller missions (of opportunity) shall avoid mech coolers unless small, efficient, cheap, reliable, low vibes

Cryogenics for ***scientific missions***, current Cosmic Vision plan:

- 3 selected missions need cryogenics (**ATHENA**, JUICE, Euclid)
- 2 missions to be selected (ARIEL)
- ATHENA, ambitious cryogenic mission with **complex cryochain** (at Planck level)
  - Cryochain to 50 mK for X-IFU (baseline: PT@15K, ^{3}He JT @ 2K, ^{3}He sorption, ADR)
  - Potential needs of ~ 200 – 250K HP or LHP for WFI

European status and trend for next future 2/2

Evolution of the scientific missions need for next future

- Exploit **L2** orbit efficient **passive cooling**: 60-180K range is less critical (Euclid – FPA@~95K)
- Specific cooling requirements (**mission dependent**) e.g.:
  - Cryochains down to 50 mK (e.g. SPICA, ATHENA)
  - Vibration Free cooling to 6K (e.g. Darwin)
  - Remote Deployable Cooling (e.g. JWST)
  - Ne cooler JT cold-end with mechanical Planck-like compressor (ARIEL)

Potential issues that might (will?) come up:

- Cooled Mirror below 10K (NGCryoIRTel): 6-10K Cooler, heat transportation below 10K?
- **Continuous 50 mK cooling** (post Planck mission):
  - Closed-cyle dilution refrigerator
  - 50 mK heat switch

Space Exploration:

- Sample conservation: miniaturized, power limited, and (usually) lifetime limited experiments will look for efficient, not expensive, light coolers
- Zero Boil Off architecture for ambitious Human Exploration Missions: needs to be prepared, even though there is no mission identified before 2035

Telecomm:

- Cryogenically Cooled LNAs might be used for secondary applications: T>77K, lifetime > 15 y, miniaturized coolers

Credits for input: T. Tirolien (ESA-ESTEC)

Sorption coolers

Summary of future trend **keywords**: high heat-lift, low input power, low exported μ–vibrations, reduced (or scalable) dimensions -> **sorption coolers**

Sorption coolers have **many advantages** over mechanical refrigerators:

- no moving parts, compression/decompression only by heating/cooling chemi/physi-sorption
- high reliability and long-life
- virtually vibration-free end electromagnetic interference (EMI)
- readily scaled to match a wide range of cooling loads by simply adding/removing (increasing/decreasing) compressor modules (beds)
- cold end T is defined by gas selection

Two types of compression and two expansion principles:

- oxides/oxygen, hydrogen/hydrides (**chemi**-sorption) and charcoal (or Zeolite/aerogel)/noble gases (**physi**-sorption) compressors
- cooling occurs by gas condensation below boiling point and isenthalpic expansion or by JT expansion
- JT cooling allows remote location of cold end from warm end (flexibility in integration)

Sorption cooler cascades can cover wide ranges of low temperature (RT → sub-K)

CMB oriented key technologies/expertise

Potential key systems and techs for next CMB missions/experiments

- Active cooling **below 1K**
  - ^3He sorption coolers, $^3He/^4He$ sorption coolers, ADR, **CCDR**
- Active cooling **above 1K**
  - 2 - 4 K range: 2K ^3He JT, 4K ^4He JT, PT's as pre-coolers for sub-K refrigerators
  - 60 - 4 K range: H_2 sorption JT, Ne sorption JT, PT in particular for the 15 - 30 K range dedicated to coherent HEMT-based receivers
- Sorption cooler cryochains (from Room T → to sub-K)
- Passive cooling (radiators, VGrooves)
- Temperature control stages (active/passive)
- High conductance thermal links, heat switches (sub-K or higher)
- Payload thermal/cryo architecture and design
- Cryochain system engineering
- AIV & qualification

Italy and space cryogenics

Research in cryogenics with potential interest for space applications:

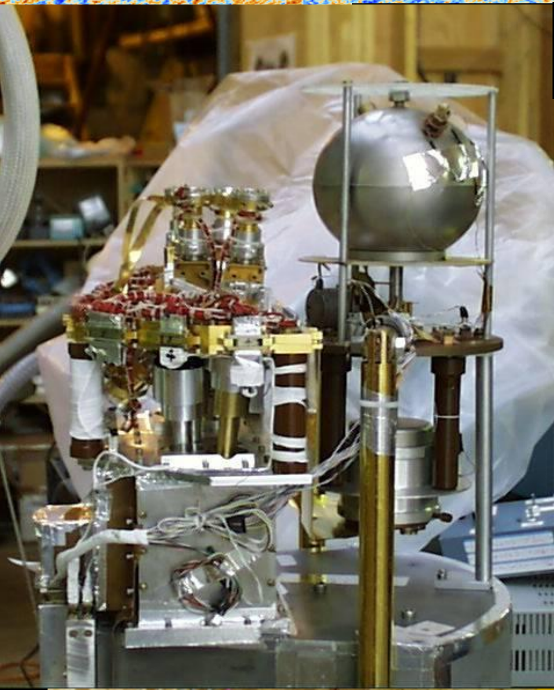
- INFN (SC magnets, detectors, accelerator cryostats, GW antennas, space cryostats)
  - LN Legnaro, LN Frascati, LN Gran Sasso, LN Sud, TIFPA Tn
- CNR (condensed matter, materials study)
- Universities (dept. of physics, engineering): fund physics, cosmology, applications
  - Uni MiB → Cryo lab for particle physycs
  - Uni Pisa → Optical cooling (ground and space cryo)
- INAF (detectors/focal planes cooling, cryostats, space missions thermal design)

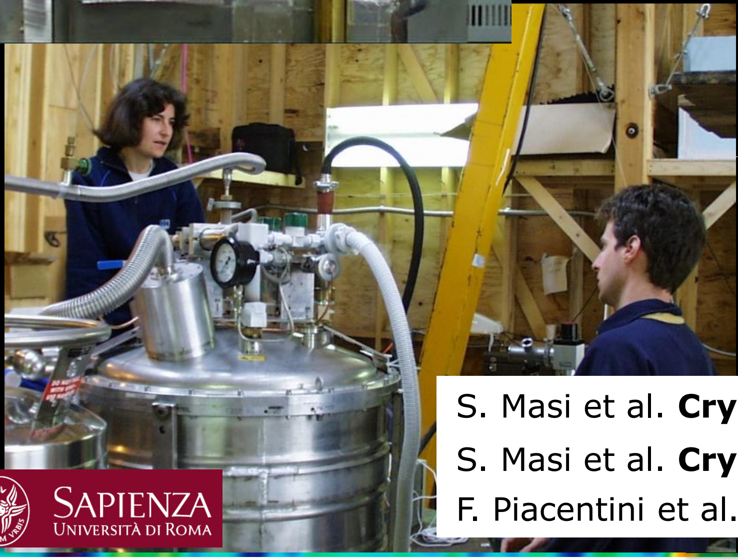
Top level expertise **scattered** among institutes and often closed within the specific applications

Today italian space cryogenic research, in general, is not as competitive as should be at international level, despite the excellence of the heritage/expertise

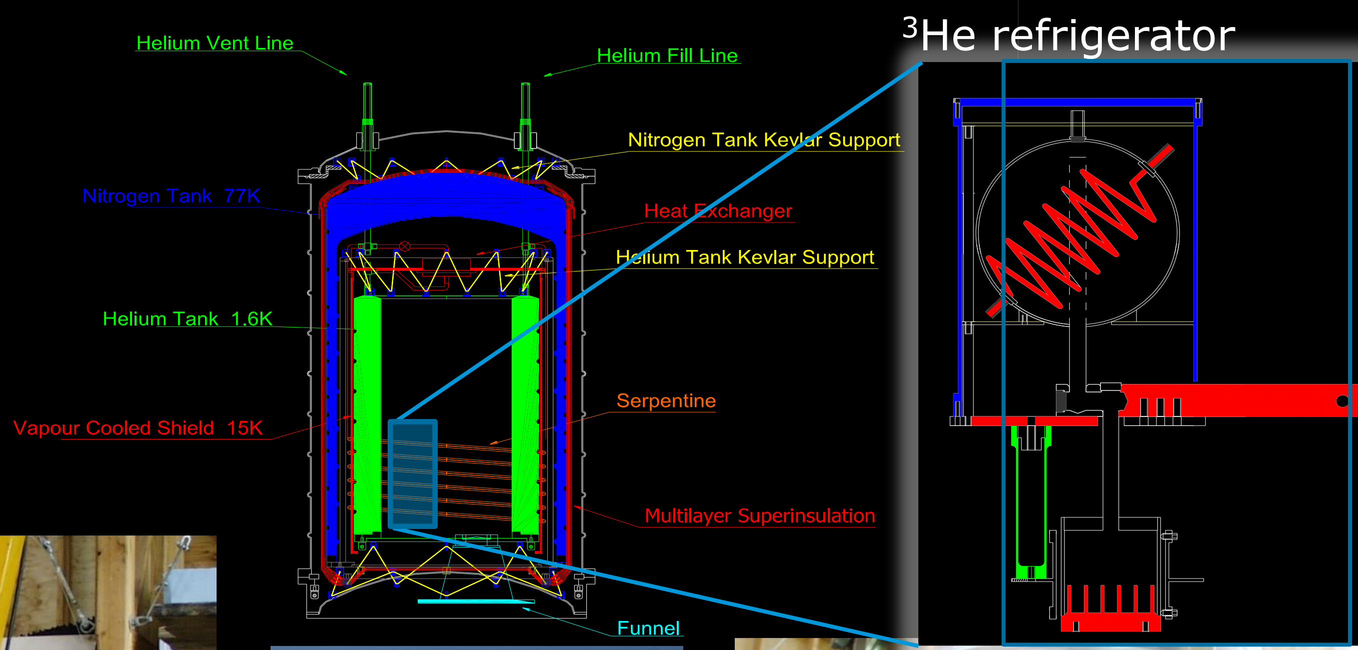
In Italy cryogenics is still studied and exercised as a tool, an application, a need for the core science of the research groups. No specific educational paths, cryogenics is learned "on the field" and "hands-on": experimental approach

Wet cryostats for stratospheric balloons from the Sapienza group (Roma)





BOOMERanG: liquid ^4He + liquid N_2 main cryostat



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

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

F. Piacentini et al. **Ap.J.Suppl.**, 138, 315-336, 2002

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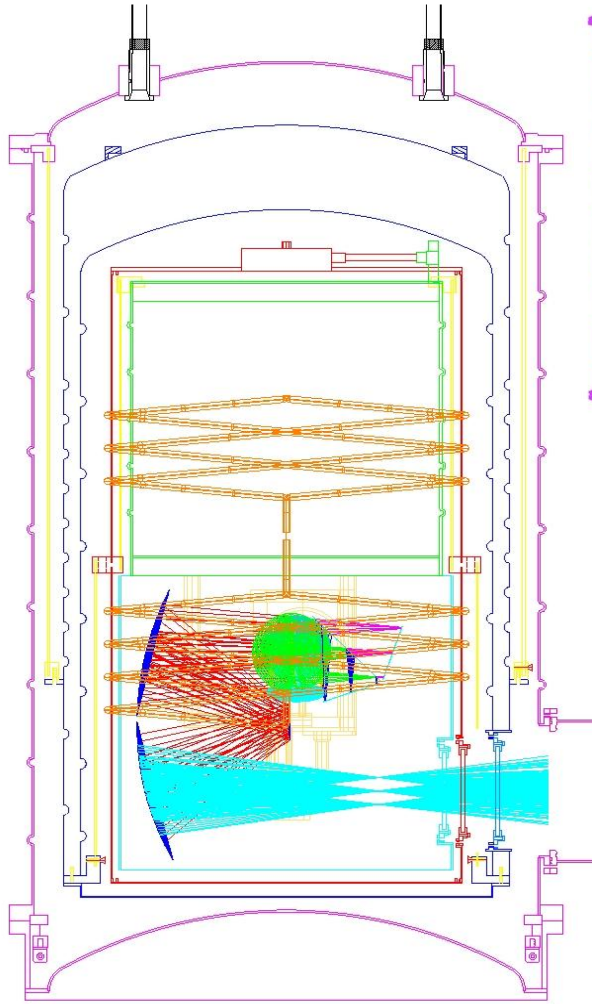
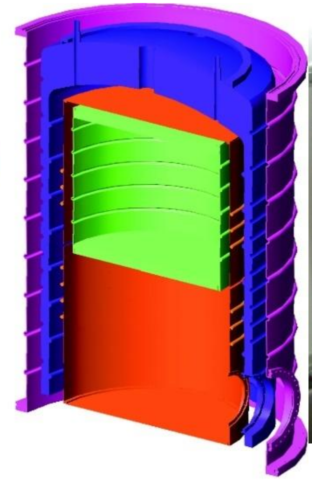
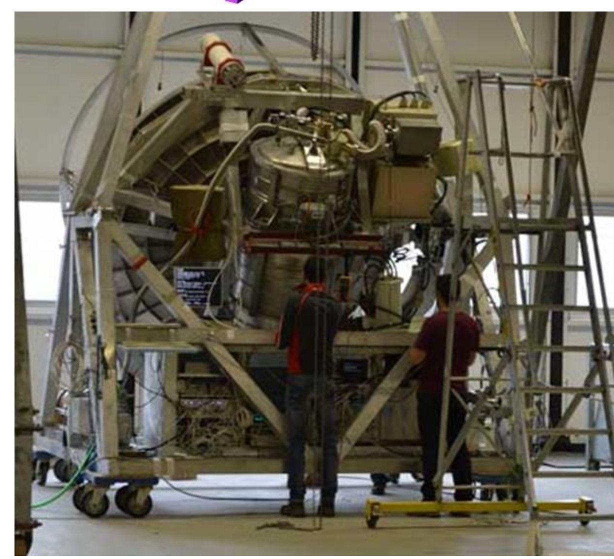
Wet cryostats for stratospheric balloons from the Sapienza group (Roma)

OLIMPO: liquid ^4He + liquid N_2 main cryostat + ^3He refrigerator







http://oberon.roma1.infn.it/olimpo

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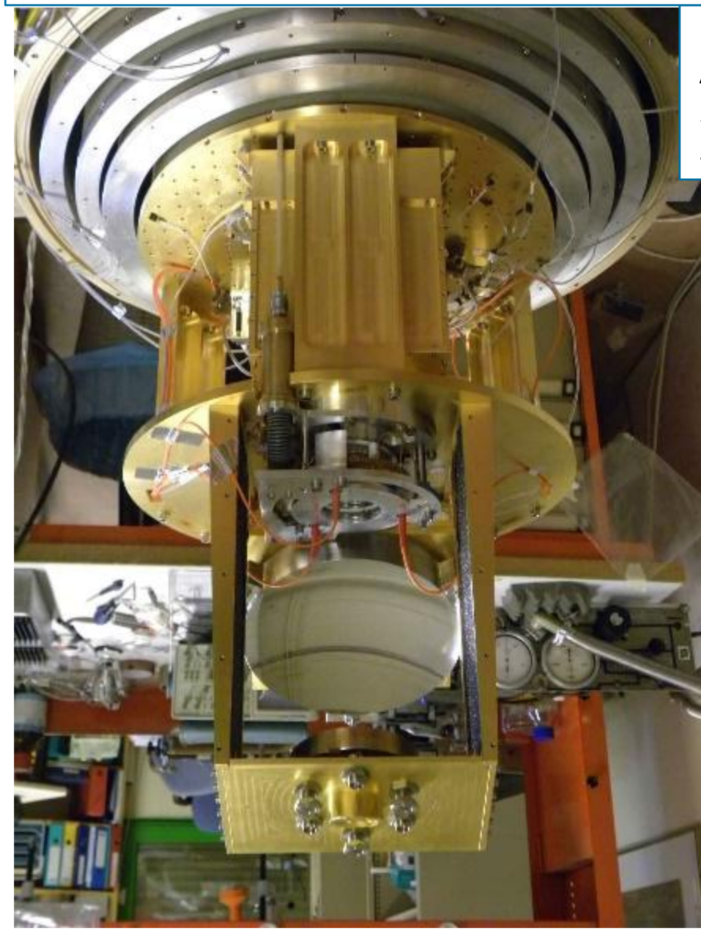
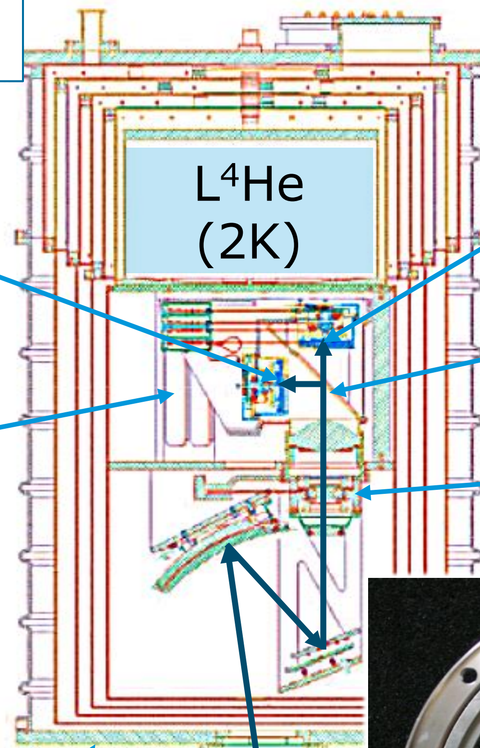
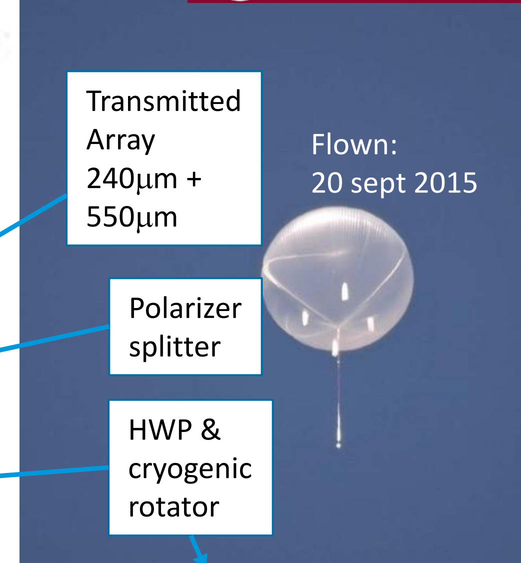
Wet cryostats for stratospheric balloons from the Sapienza group (Roma) .. and cryomechanisms

PILOT (CNES): liquid ^{4}He + VCS main cryostat + ^{3}He refrigerator





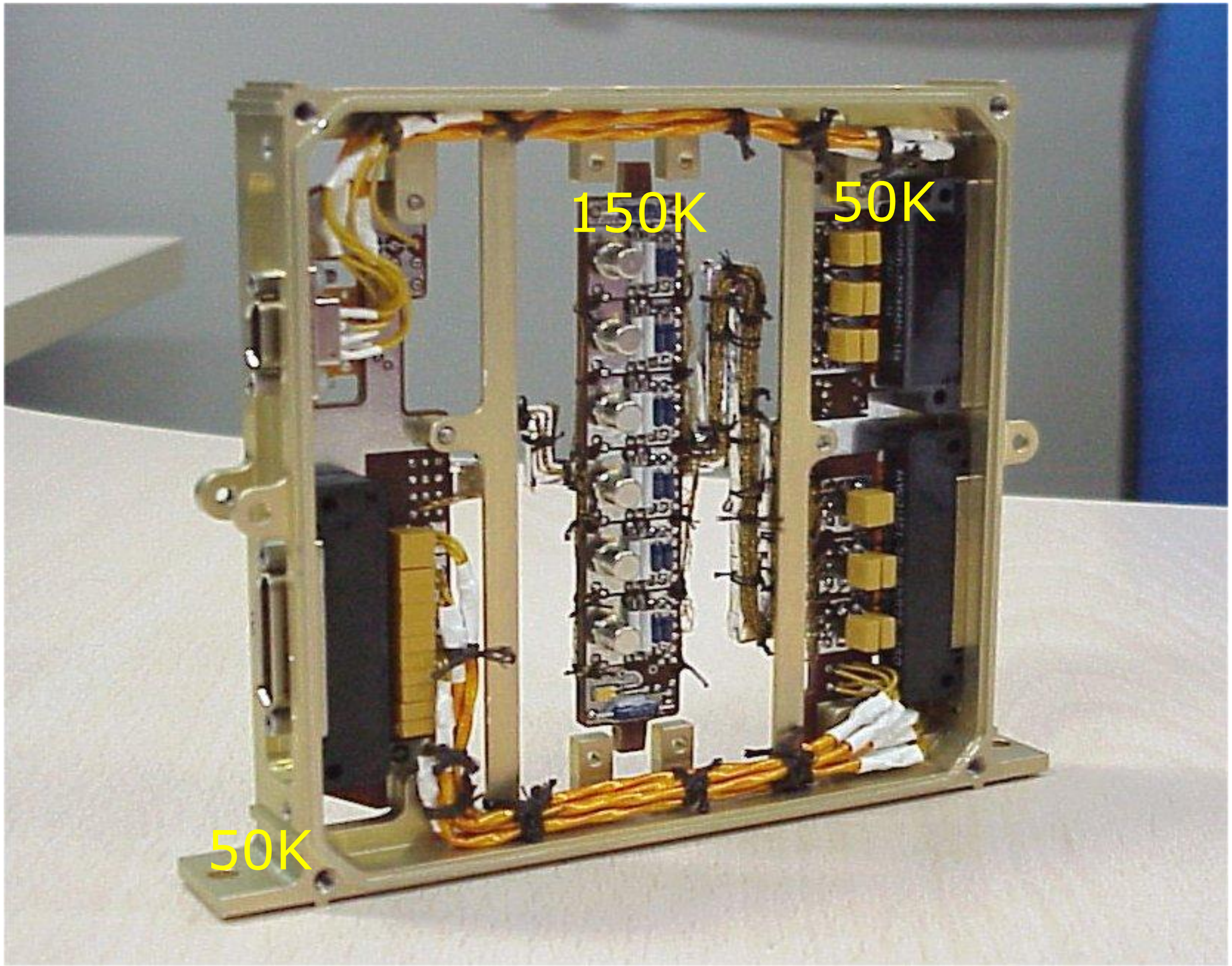


PILOT (CNES): Cryogenic HWP rotator

Salatino+ A&A **528** A138 (2011)

www.spaceflight.esa.int/pac-symposium2009/proceedings/papers/s7_6engel.pdf

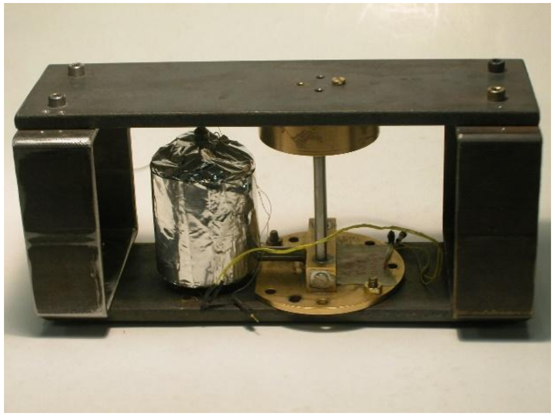
Cryogenic preamplifiers for Planck-HFI



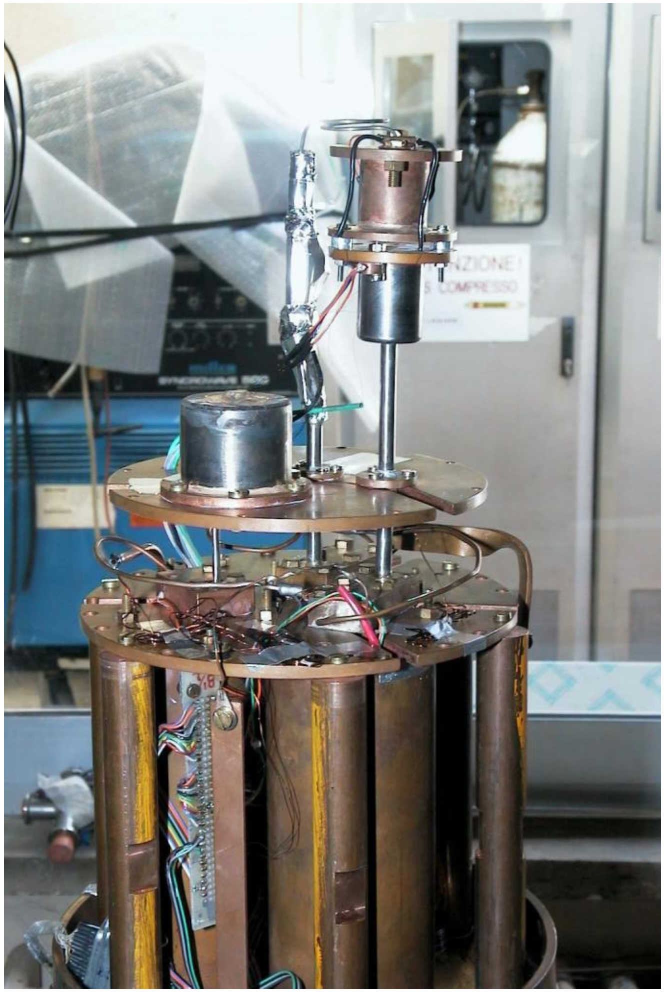
- Cryogenic preamplifiers for Planck-HFI - 72 diff. Channels, < 200mW @ 50K, 3nV/sqrt(Hz)
- see D. Brienza et al., WOLTE-7 - ESA-WPP-264, pg. 283-288, (2006)

Uni Roma Tre OASI Group (Roma)

- Cryostats for cosmological instruments in the mm-wave
  - e.g. OASI, APACHE96, COCHISE
- ^{3}He sorption refrigerators with innovative solutions
  - One patent
  - Several upgrades
- ^{3}He/^{4}He two-stage sorption refrigerators
- Dilution refrigerator

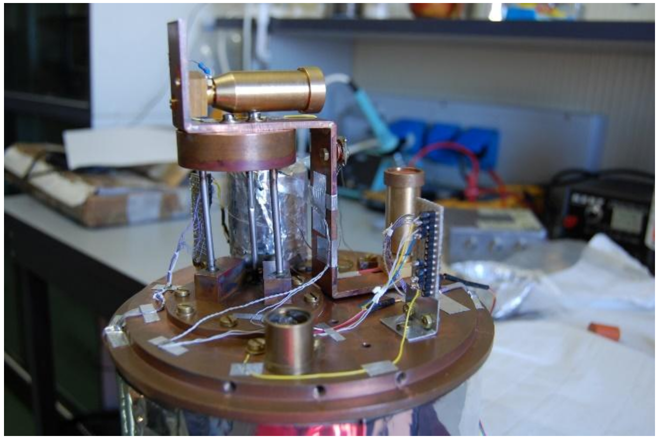


Dall'Oglio, G., L. Martinis, G. Morgante, and L. Pizzo
An improved ^{3}He refrigerator, Cryogenics, 37, 63, 1997



Low noise dilution refrigerator
ENEA Report RT/2002/60/FUS

Uni Roma Tre OASI Group (Roma)



Single stage ^{3}He improved sorption refri
Patent CNR RM93A000728, 1993
Dall'Oglio G., et al., Cryogenics , 37, 63, 1997

Two-stage ^{3}He/^{4}He sorption refrigerator
Dall'Oglio, G., et al., Cryogenics, 31, 61, 1991
Dall'Oglio, G., et al., Cryogenics, 33, 213, 1993

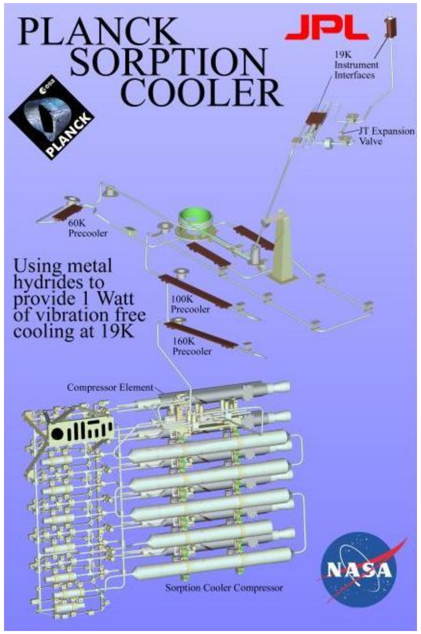
A new generation of ^{3}He refrigerators
Graziani, A., et al., Cryogenics, 43, 659, 2003

Referee response:
«…The interest in the submitted paper lies in the presentation of a cooler which not does require initial pumping on the main 4He bath. This was claimed not possible for many years and such a technology should deserve a publication in Cryogenics…»

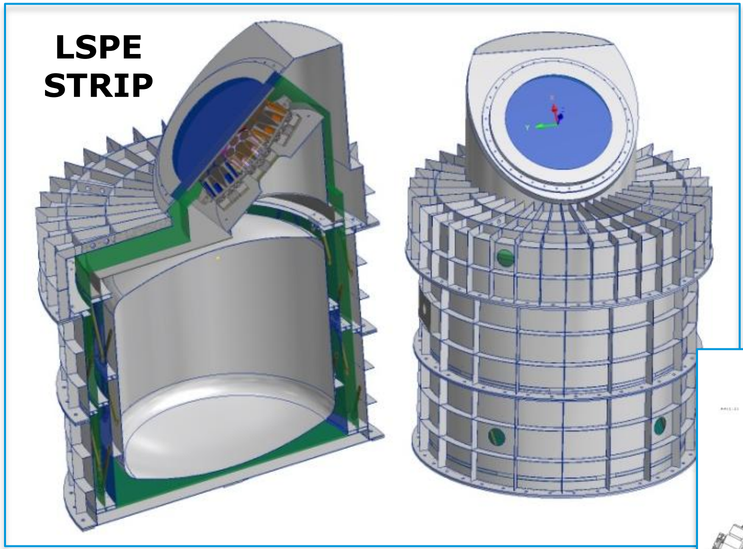
A multipurpose 3He refrigerator
L. Pizzo, et al., Cryogenics, 46, 10, 2006

INAF – IASF Bologna

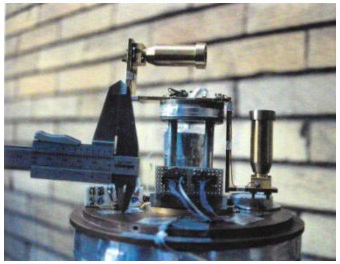
- Nearly 20 years expertise in sorption coolers and space cryochains
  - H_2 Planck chemi-sorption cooler
  - $^3He/^4He$ physi-sorption one/two stage refrigerators (in collaboration with RomaTre group)
- Cryostat design and implementation (e.g. LSPE-STRIP, FAMU)



Bhandari, P., et al. Astroph.l Letters and Comm., 37, 227, 2000
J. Borders, G. Morgante, et al., Cryogenics, 44, Is. 6-8, 2004
Morgante, G., et al., Exp. Cosmology at mm Wavelengths, 616, 298, 2002
Morgante, G., et al. Journal of Instrumentation, 4, 2016, 2009
Prina, M., et al., Low-heat input cryogenic temperature control with recuperative heat-exchanger in a JT cryocooler, Cryogenics, 44, 595, 2004

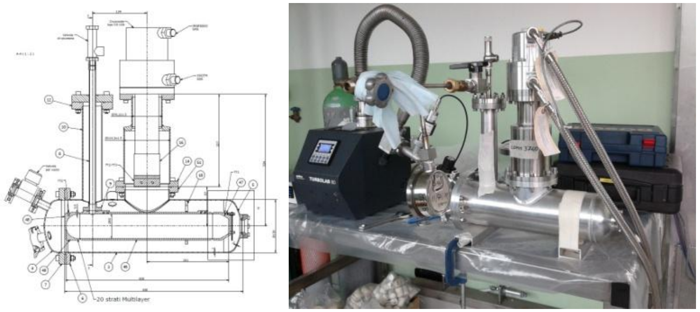


Bersanelli, M., et al., Proc. SPIE, vol. 8442, 84467C (2012)



^{3}He sorption refrigerator for balloon flight cryostat

Dall'Oglio, G., L. Martinis, G. Morgante, and L. Pizzo
An improved 3He refrigerator, Cryogenics, 37, 63, 1997



FAMU cryostat

Adamczak, A., et al., FAMU: Characterization of Beam Line, Target and Detectors for the HFS Measurement of Muonic Hydrogen Ground Level, in preparation for JINST

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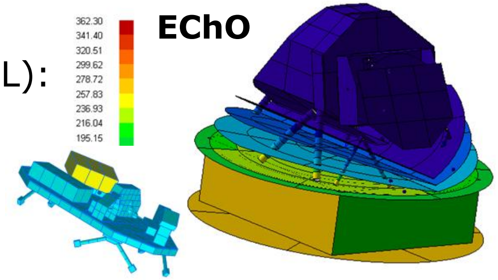
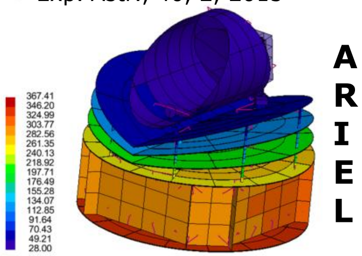
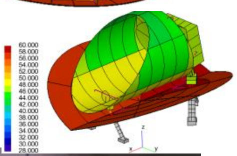
- Passive cooling: radiators, VGrooves (Planck, EChO, ARIEL)
- Cryochain architecture, design and system engineering (Planck, EChO, ARIEL): e.g. **Planck Cryo-chain Operations, Planck/PSO/2007-017, Is. 3.0, 5/5/2009**
- PLM thermal/cryo architecture and design (Planck, Euclid, EChO, ARIEL)
  – Planck early results. II. The thermal performance of Planck, A.A. 536, A2, 2011
- Thermal simulations and modeling
- Temperature control stages (active/passive) (Planck, Euclid, EChO, ARIEL, LSPE, FAMU)
- High conductance thermal links (braids, collaboration with CNR to find possible applications of graphene & carbon-based nanomaterials is in progress)
- AIV & qualification (three major facilities for balloon/space instrumentation or cryogenic system verification)



G. Morgante, L. Terenzi, et al., Exp. Astr., 40, 2, 2015

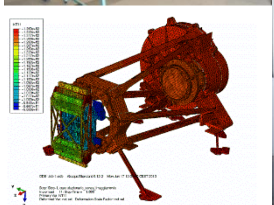




Morgante G, et al., *Euclid NISP thermal control design*, Proc. SPIE, vol. 8442, 844234 (2012)

Terenzi, L., et al., *Cryogenic environment and performance for testing the Planck radiometers J INST,* 4, 2009

Terenzi, L., et al., *Thermal stability in precision cosmology experiments: the Planck LFI case*, Nucl. Instr and Meth. in Phys. Research, A, 520, 2004



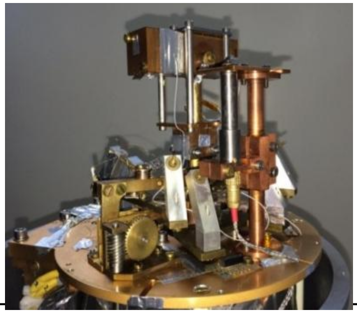
Euclid-NISP TMM

Large TV facility, 6 m3 vol, 1 mbar, +100C / -35C for balloon instr.

Test facilities at INAF - IAPS Roma

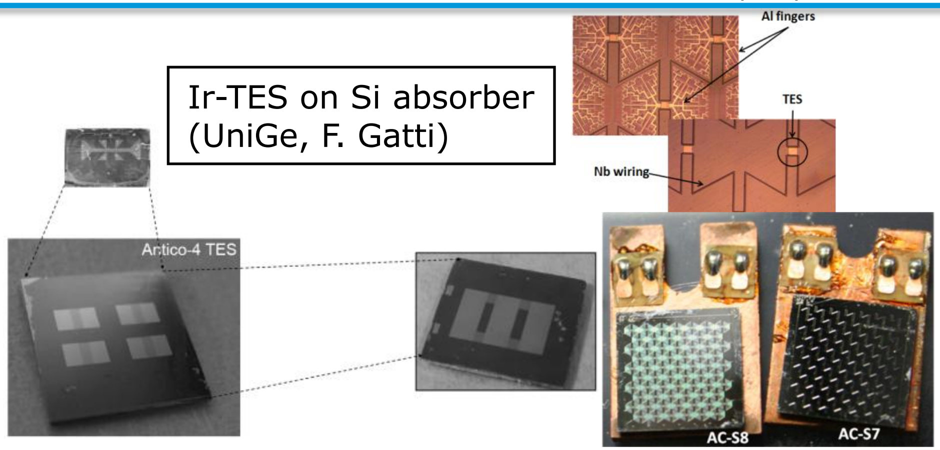
TES detectors & cryogenic electronics testing

Macculi, C., et al., J Low Temp Phys, on-line, Jan 2016
Macculi, C., Piro, L., et al., J Low Temp Phys, 176, 2014



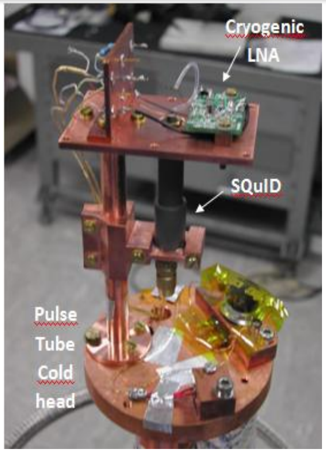
PT + ADR (< 50 mK, Vericold) for detectors test in shielded cage

Ir-TES on Si absorber (UniGe, F. Gatti)



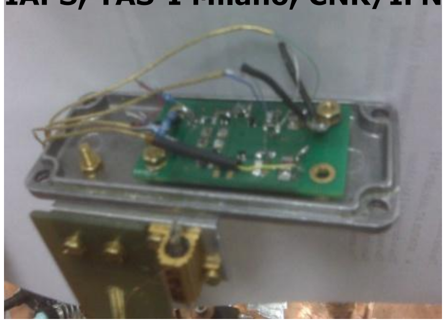
Pulse tube (~2.4 K) for cryo electronics test

DL-FLL (4K-300K) TES array readout



SPICA cryogenic LNA (135 K)

IAPS, TAS-I Milano, CNR/IFN



Dry system constituted by Pulse Tube + Dilution Refrigerator (400 uW@0.1K) to be acquired, for the integration activities of the cryogenic anticoincidence detector models (CryoAC) for the ATHENA X-IFU (L. Piro Co-Pi ship).

Italian possible contribution to next CMB missions

Key systems and techs for next CMB missions/experiments

- Active cooling below 1K
  - ^{3}He sorption coolers, ^{3}He/^{4}He sorption coolers, CCDR, ADR
- Active cooling above 1K
  - 2 - 4 K range: 2K ^{3}He JT (sorption?), **4K ^{4}He JT (sorption)**, PT's as pre-coolers for sub-K refri
  - 60 - 4 K range: H_2 sorption JT, Ne sorption JT, PT in particular for the 20 - 30 K range dedicated to coherent HEMT-based receivers
  - Wet cryostats (for balloon-borne experiments)
- Sorption cooler cryochains (Room T → sub-K)
- Passive cooling (radiators, VGrooves)
- Temperature control stages (active/passive)
- High conductance thermal links, heat switches (sub-K or higher)
- Cryochain system engineering
- Payload thermal/cryo architecture and design
- AIV & qualification

The italian CMB related cryogenic community has the expertise to design of a whole cryochain from Room T down to 300 mK fully based on sorption cooling (with passive precooling)

Possible ideas to improve italian competitiveness

- **Education**: low temperature physics courses/degrees. Students with specific knowledge, more skilled researchers, solid scientific basis in low T physics
- Expertise at excellence level is scattered → need to find condensation states:
  - cryo teams **knowledge sharing**: **national workshop**, **discussion fora**
  - **dedicated institutes** (e.g. France, UK)?
  - **national labs** (across Institutes)?
- Synergies with **industry** in R&D, permeation of expertise/personnel (Fr, Nl, UK)
- Technological development projects
  - we need national support to grow at international level and access to competitive grants: **ideas** and **prototypes** development can help Italian teams to compete for ESA CTP Emits, GSTP, TRP's or EC grants
  - dedicated technological development projects, aimed **to specific technologies**
  - **balloon experiments** (such as LSPE and Olimpo)
    - fundamental **pathfinders** towards scientific results and tech developments that can lead to future space missions **but**
    - can have more **limited allocations** than satellites and cannot always work as demonstrators for all technologies (typically based on wet cryostats)
  - from this point of view **ground projects** can offer more margins to work with innovative cryo systems

Conclusions

- Cryogenics is, and will be for the next decades, fundamental to both EO and Scientific space missions (with particular interest for CMB related experiments)
- Italian CMB community has a top level heritage/expertise in
  - **wet cryostats** → leading role in next balloon-borne experiments
  - **sorption coolers**, really attractive systems for many space applications, including CMB missions → it's worth to invest resources in this direction (building on Planck heritage)
- We need to increase our capabilities of competing at international level in the general space cryogenics application field:
  - **knowledge sharing** and collaborations at national level
  - invest resources in
    - CMB experiments from **balloon-borne platform** and **ground** → critical to science and to prepare the next generation experiments/missions
    - dedicated **tech development programs**: aimed to demonstrators and prototyping
- Improve collaboration & find synergies with **industrial partners** (tech projects)

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Contributions from:
- G31 Uni RM1 La Sapienza
- Gruppo OASI Uni RM3
- INAF – IAPS RM (C. Macculi)
- ESA - ESTEC