Thermometry in cryogenics

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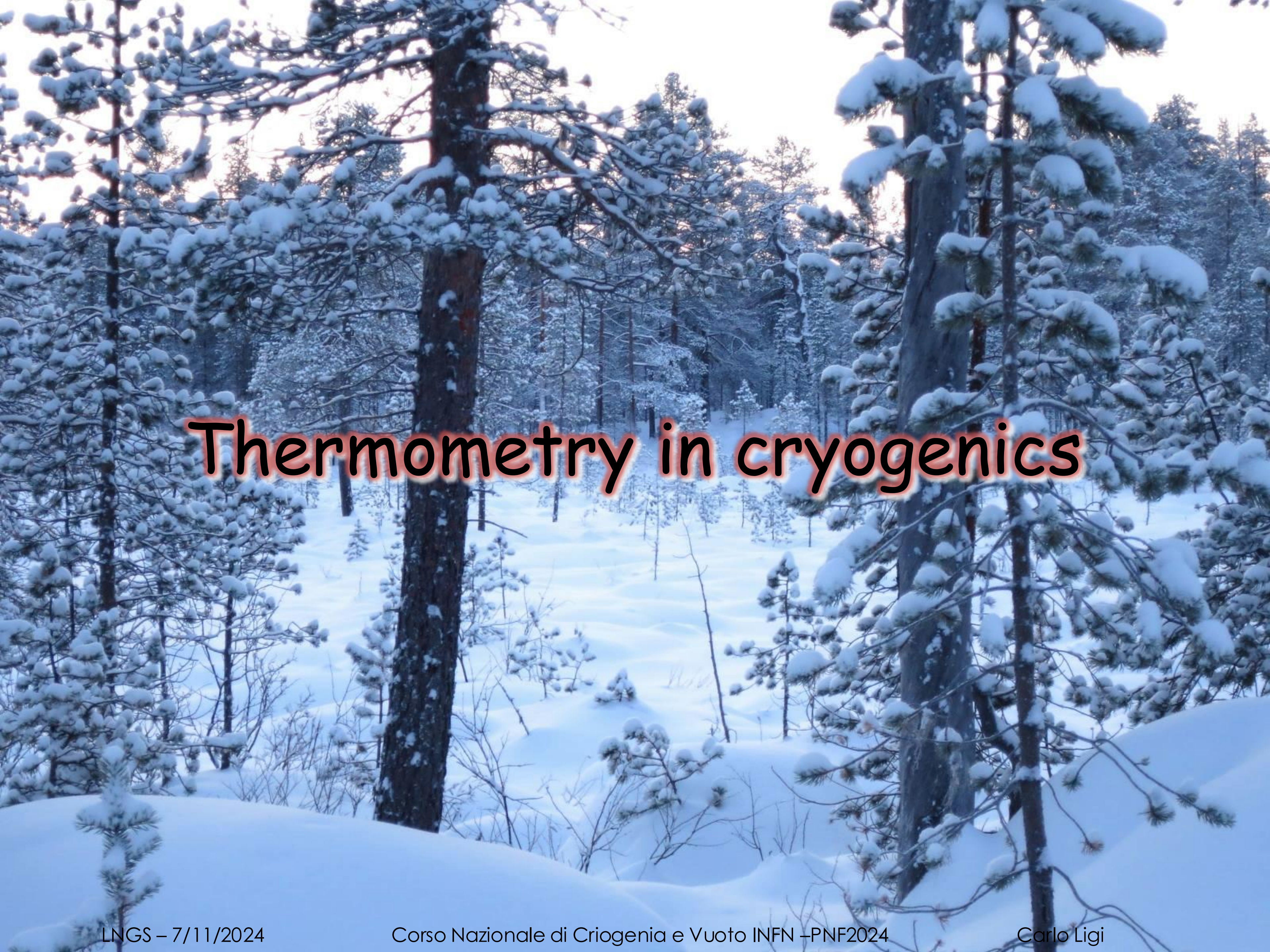
Refrigeration at T < 4 K

Carlo Ligi INFN-LNF



Thermometry in cryogenics

Thermometry in cryogenics

from mK to ambient temperature

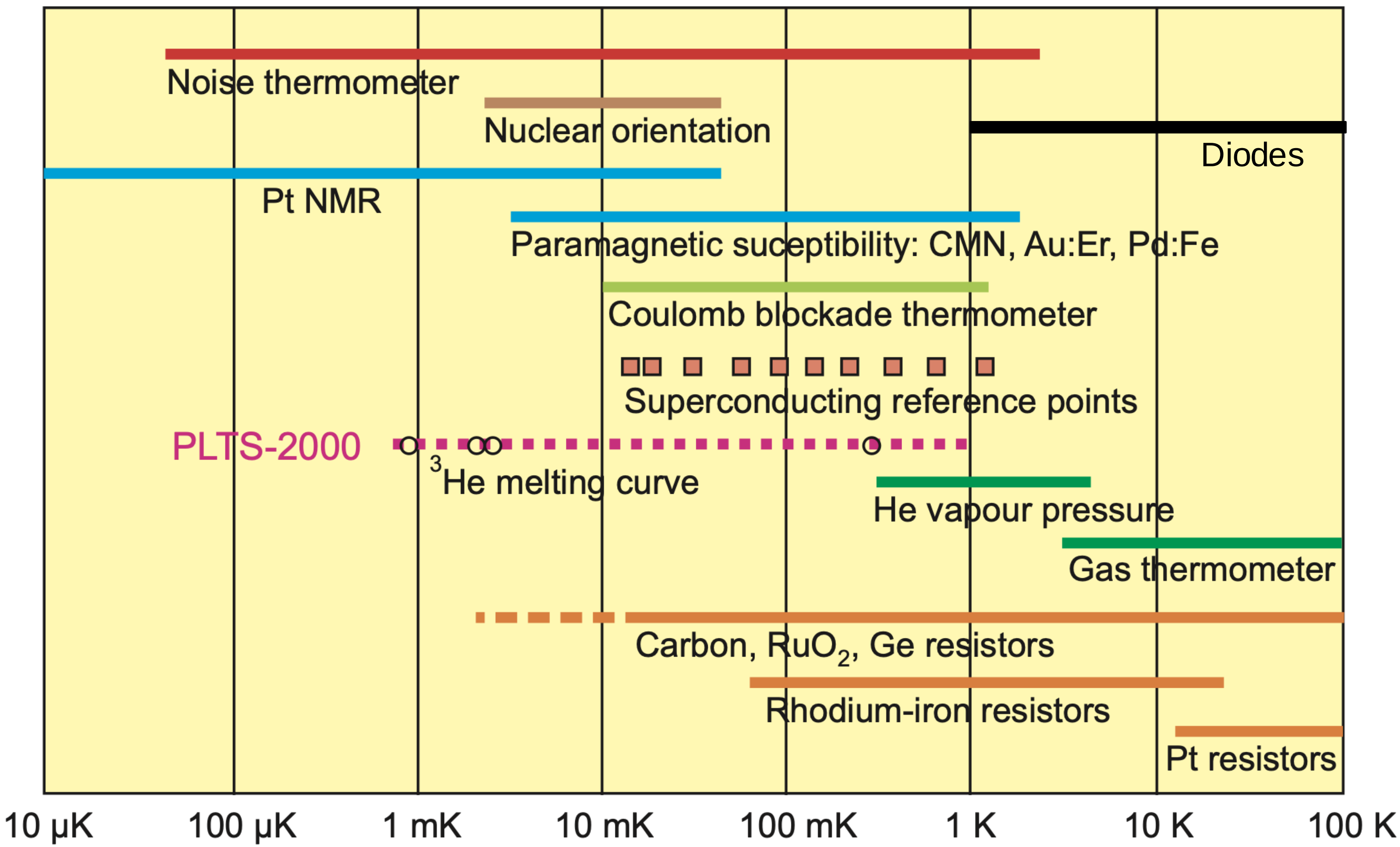
Measure of *f (T)* (mainly electrical measurement)
Plethora of different types of thermometers
All characterized by a measurement *RANGE*

PRIMARY THERMOMETERS
T has a functional dependence from the measured value and all the parameters are known
** No calibration required **
Example:
gas thermometers
noise thermometers
fixed point thermometers
(boiling point, freezing point, triple point, superconducting transition…)
acoustic thermometers

SECONDARY THERMOMETERS
T has a functional dependence from the measured value but one or more parameter are unknown
**Calibration required **
Example:
carbon resistors
Platinum resistors
RhuteniumOxide resistors
Germanium resistors
Cernox resistors
Silicon diodes
CMN

Thermometry in cryogenics

from mK to ambient temperature

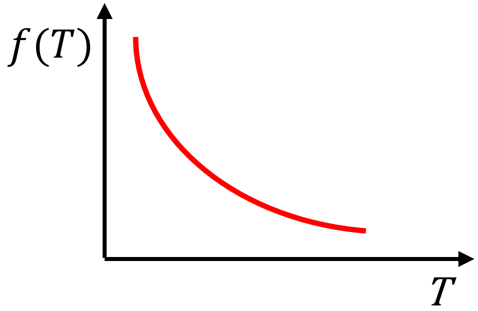


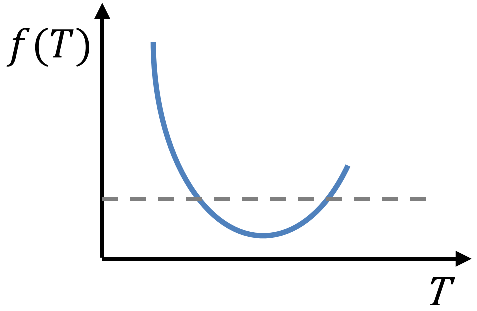
Thermometry in cryogenics

from mK to ambient temperature

Thermometers properties

- measurement range
- sensitivity (how much it change with temperature)
- relaxation time (how quickly it follow a change in temperature)
- needed power to read out it (that can generate dissipation and self heating)
- ease of reading (the way in which we can measure the temperature)
- stability over lifetime (both respect to thermal cycling and long term stability)
- sensitivity to external conditions (magnetic field, RF interference, vibration)
- *MONOTONIC* dependence from T of the measured value in all the considered range





Thermometry in cryogenics

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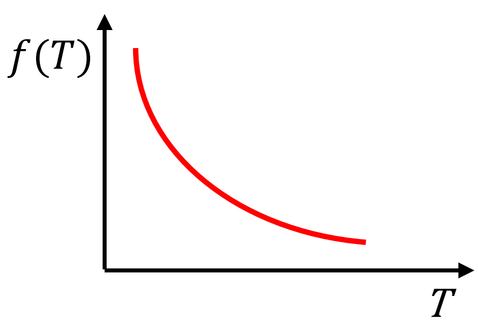
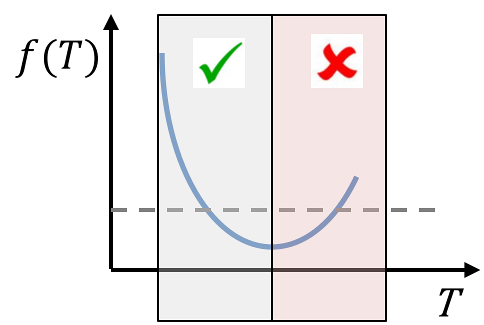
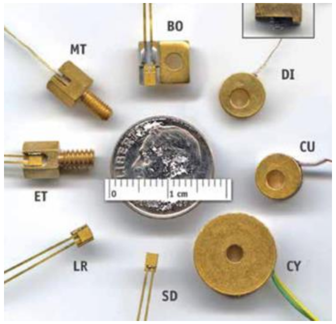




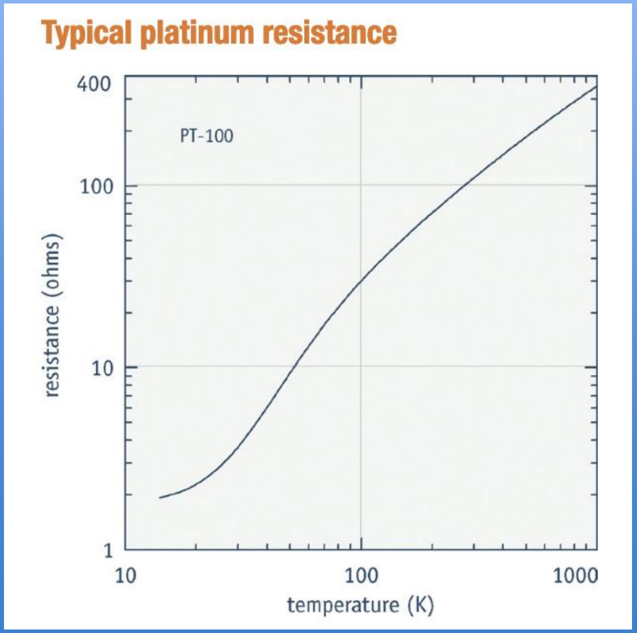


Resistors

0.01 < T < 300 K

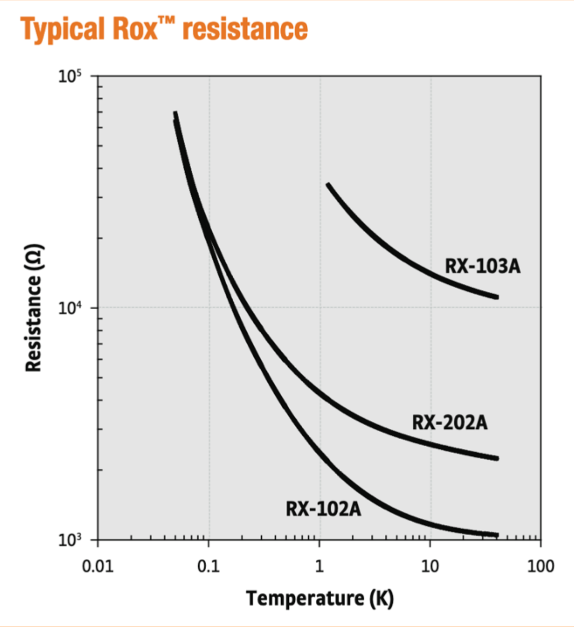
POSITIVE TEMPERATURE COEFFICIENT
(metallic resistors)

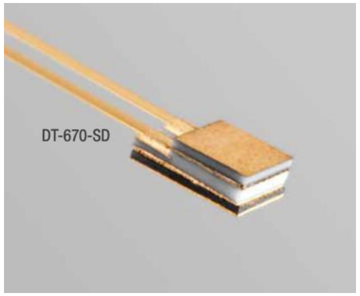
Example:
Platinum (20-300 K)
Rhodium-Iron (1 – 500 K)



NEGATIVE TEMPERATURE COEFFICIENT
(semiconductors)

Example:
Germanium (0.05 – 100 K)
RhuteniumOxide (0.01 – 40 K)
Cernox (0.1 – 300 K)





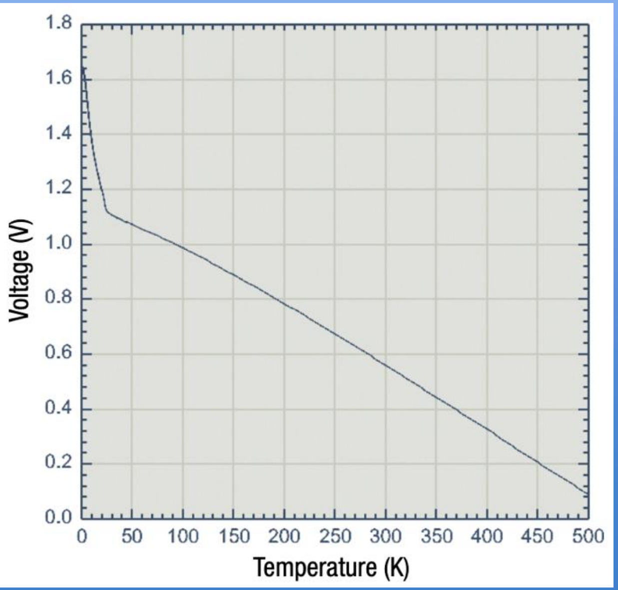
Diodes / CMN

JUNCTION DIODES

(voltage drop across a *p-n* junction)

Excitation: typ. 10 μA

Range: 1.4 – 500 K

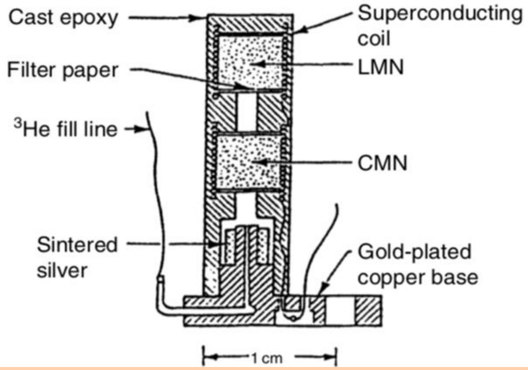


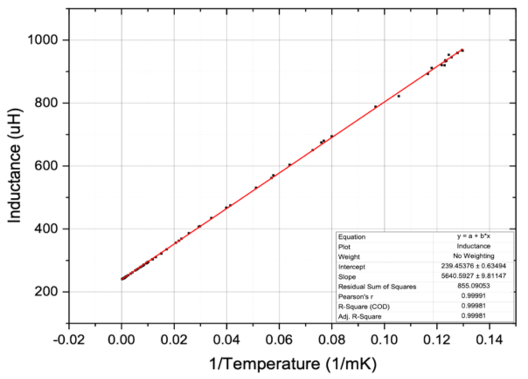
***CMN** (cerium magnesium nitrate)*

(Paramagnetic salt thermometers)

L ~ 1/T dependence

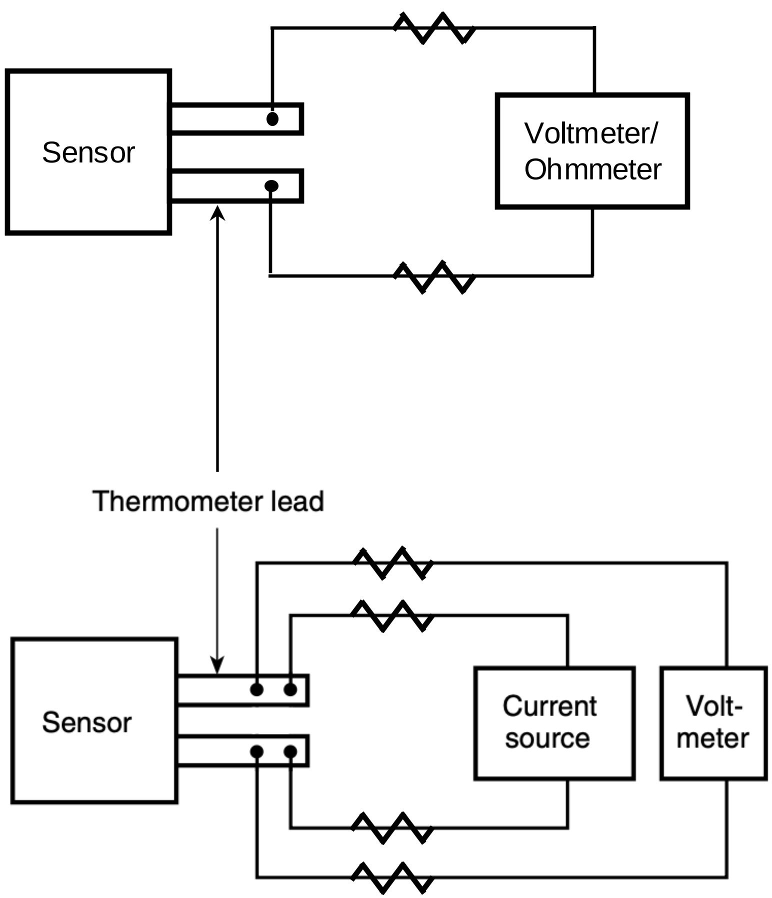
Range: 0.001 – 2 K





T measurement instrumentation

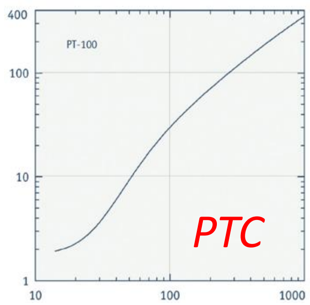
(resistors, diodes, inductance…)

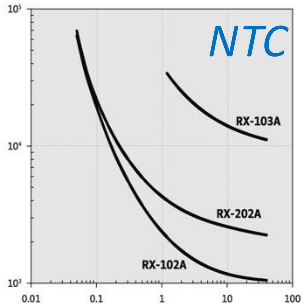


2-lead measurement

4-lead measurement

T measurement instrumentation
(resistors, diodes, inductance...)



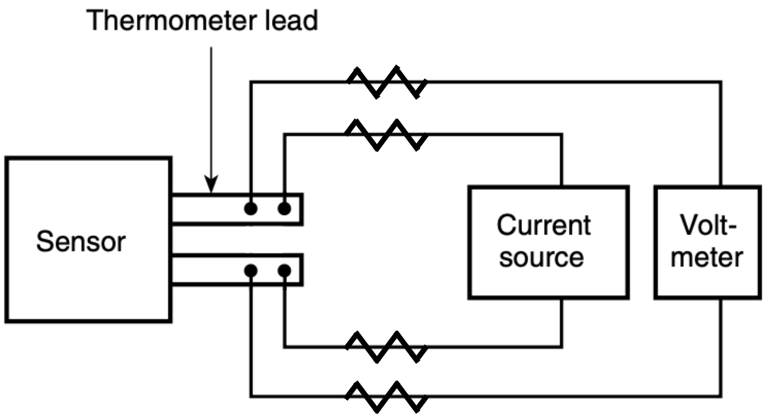


PTC resistors → constant CURRENT meas.

$$power = I^2 \cdot R$$

NTC resistors → constant VOLTAGE meas.

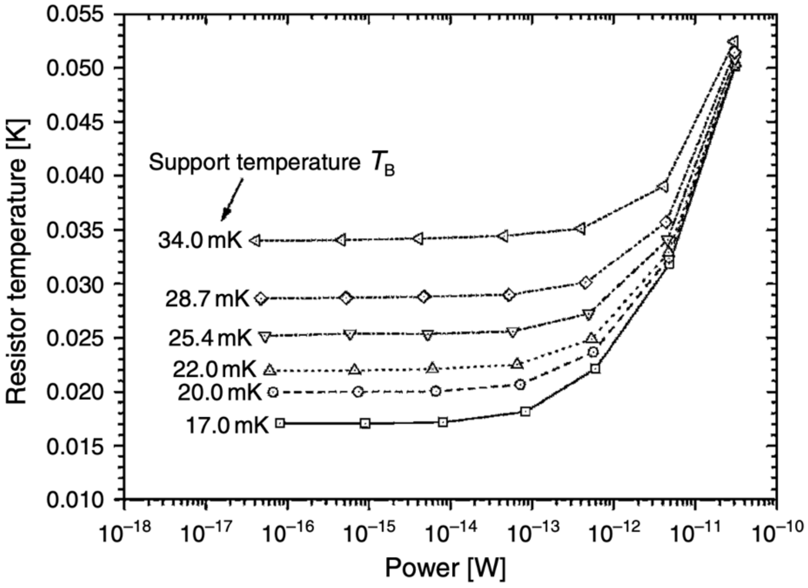
$$power = V^2/R$$



4-lead measurement

T measurement instrumentation
(resistors, diodes, inductance…)

How much electrical power we can send to a resistor to read it?
There is always a thermal contact between a thermometer and the sample which is connected to → the dissipated power to the thermometer itself can become a problem at very low temperature.
For example, a power of 5×10^{-12} W dissipated to a thermometer connected to a sample at 20 mK, can produce a self-heating of 12 mK.

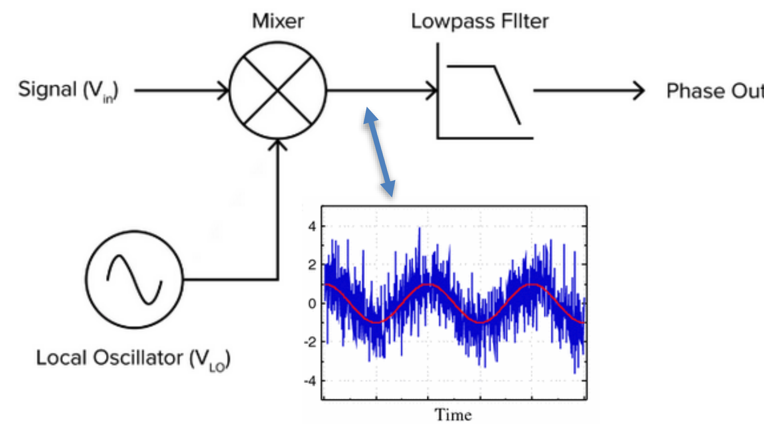


Overheating of an RuO_2 thermometer as a function of temperature for six different support temperatures.

T measurement instrumentation

(resistors, diodes, inductance…)

To minimize noise and detect very low signals →
AC measurement with a LOCK-IN resistance bridge

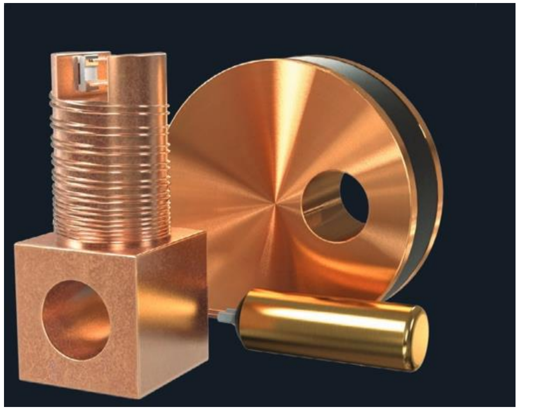


excitation current/voltage

calibration curve

direct T reading

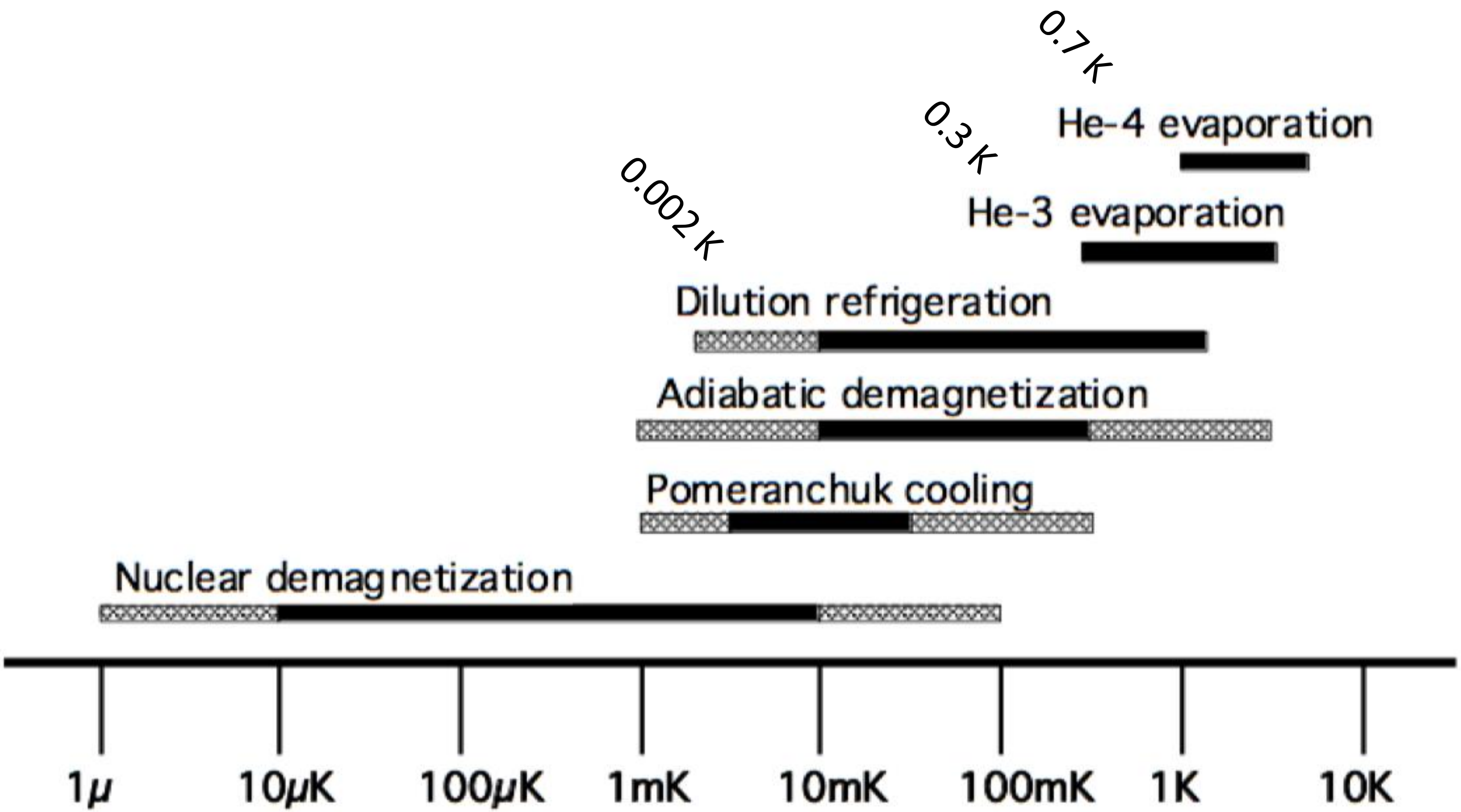
common issues in T measurement



- *self heating in resistors*
- *poor thermal contact*
- *wiring (heating from the wires, poor thermal/electrical isolation…)*
- *wrong positioning of the thermometer*
- *magnetic fields / RF power*

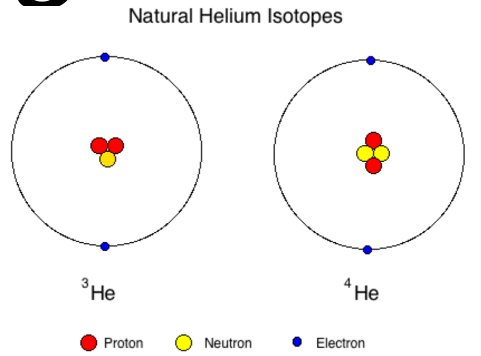
Refrigeration at T < 4 K

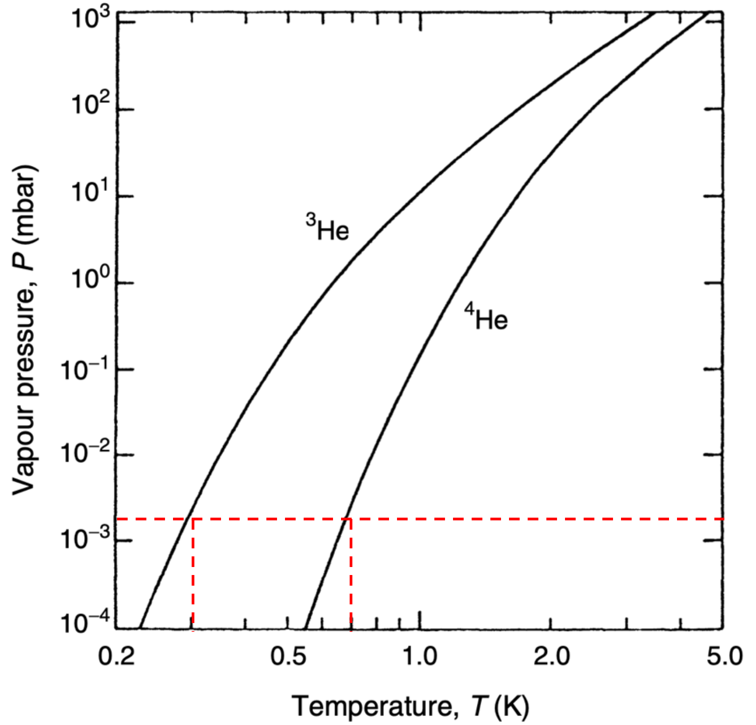
Cryogenics in the Kelvin range



Cryogenics below 1 K
^{4}He and ^{3}He evap. refrigerators

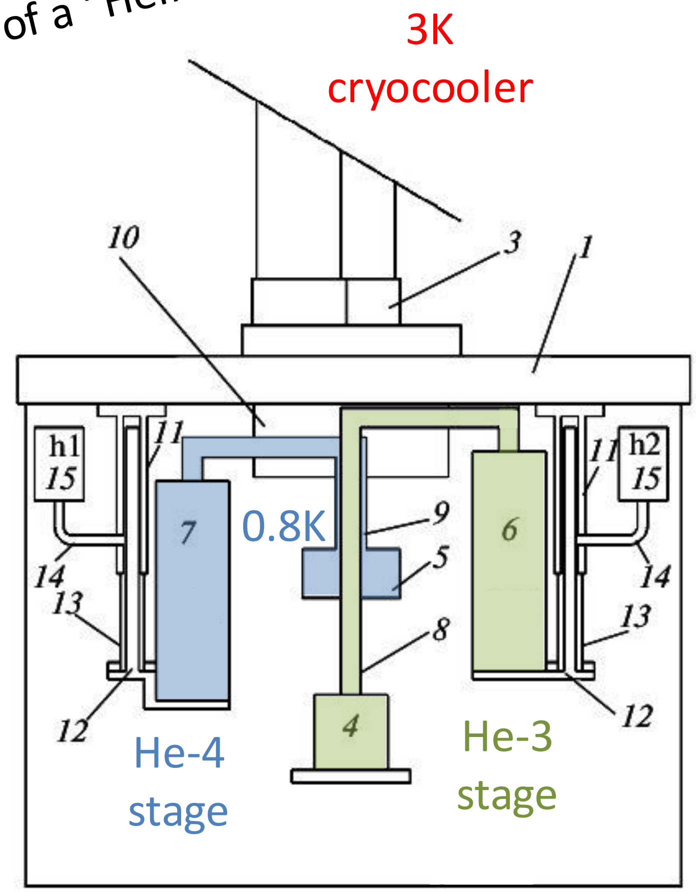
- ^{4}He is extracted from natural gas by distillation, adsorption and other methods
- ^{3}He is produced from the radioactive decay of tritium, bombarding lithium-6 with neutrons in a nuclear reactor
- Evaporation of liquid allows stable T
- How to? Liquefy some gas and reduce the pressure over the bath
- ^{4}He evaporation → down to 0.7 K
- ^{3}He evaporation → down to 0.3 K
    - *^{4}He gas cost: 30 €/m^3 STP*
    - *^{3}He gas cost: **1-2 million €/m^3 STP***





Cryogenics below 1 K

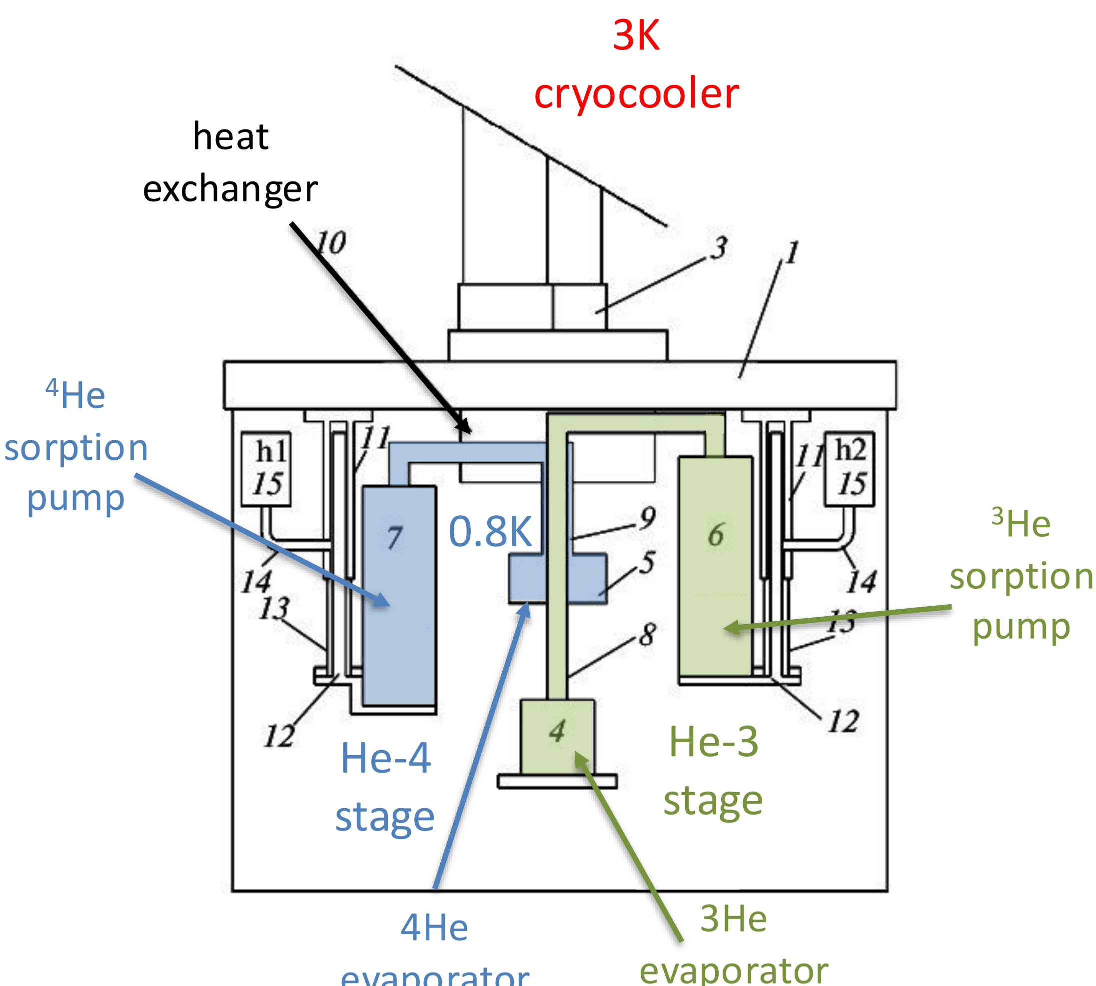
Scheme of a “Helium-seven” fridge



^{3}He closed-cycle refrigerator

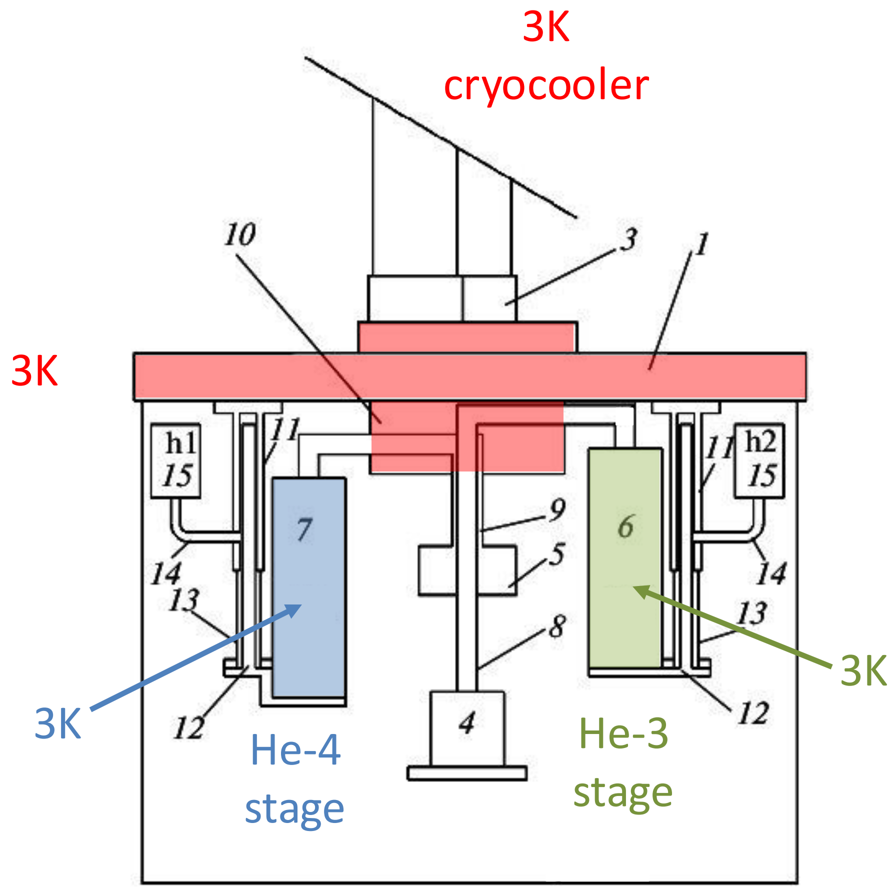
(but ^{4}He too…)

Cryogenics below 1 K



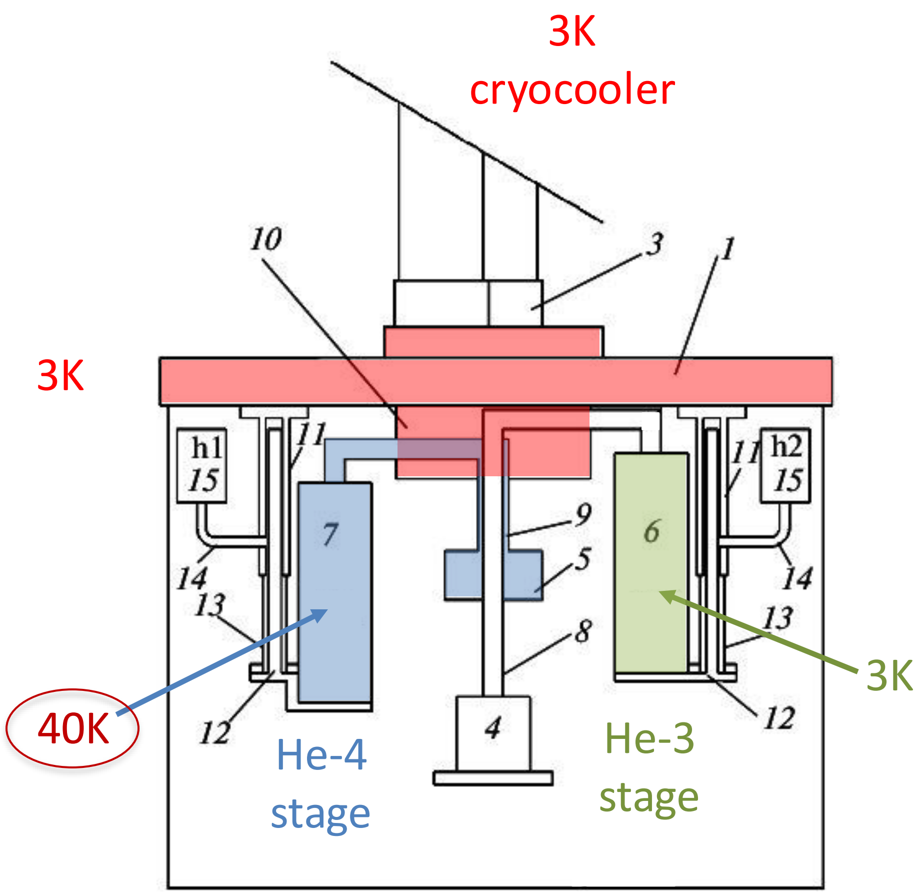
- The fridges are composed by an evaporator connected to a sorption pump full of active charcoal
- Both ^{3}He and ^{4}He stages are charged with gas at ambient T and sealed
- Precooled with a 3-4 K source (cryocooler or liquid Helium)

Cryogenics below 1 K



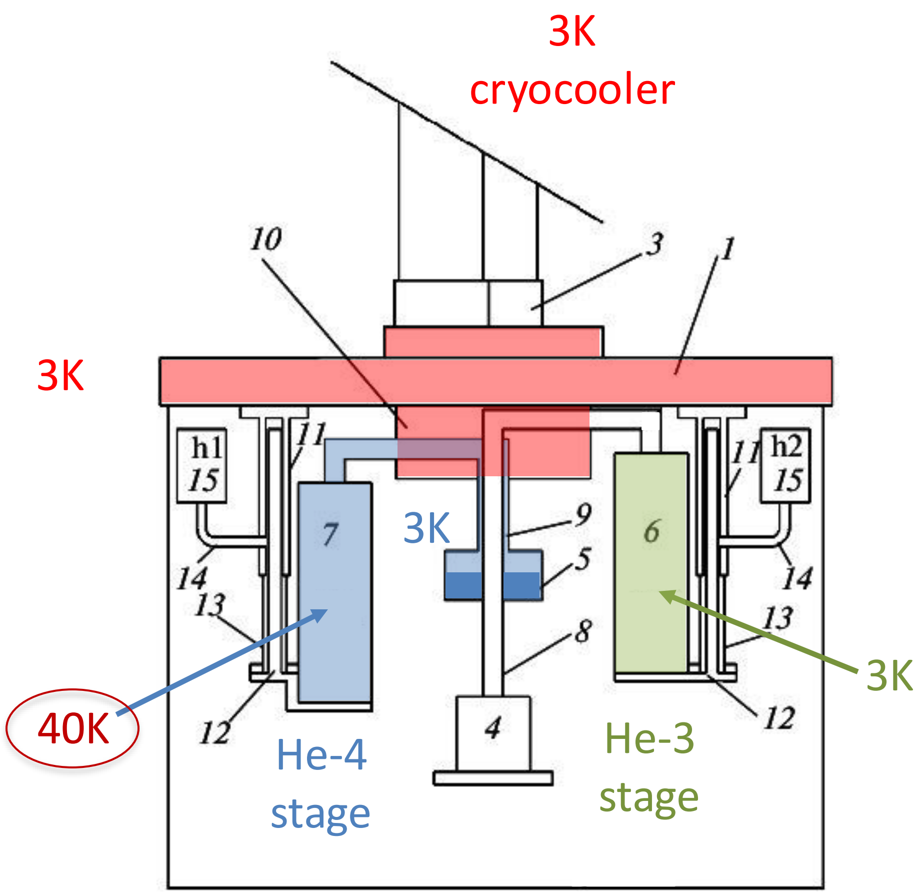
- The ^{3}He and ^{4}He refrigeration process start with the absorption of the gases into the sorption pumps

Cryogenics below 1 K



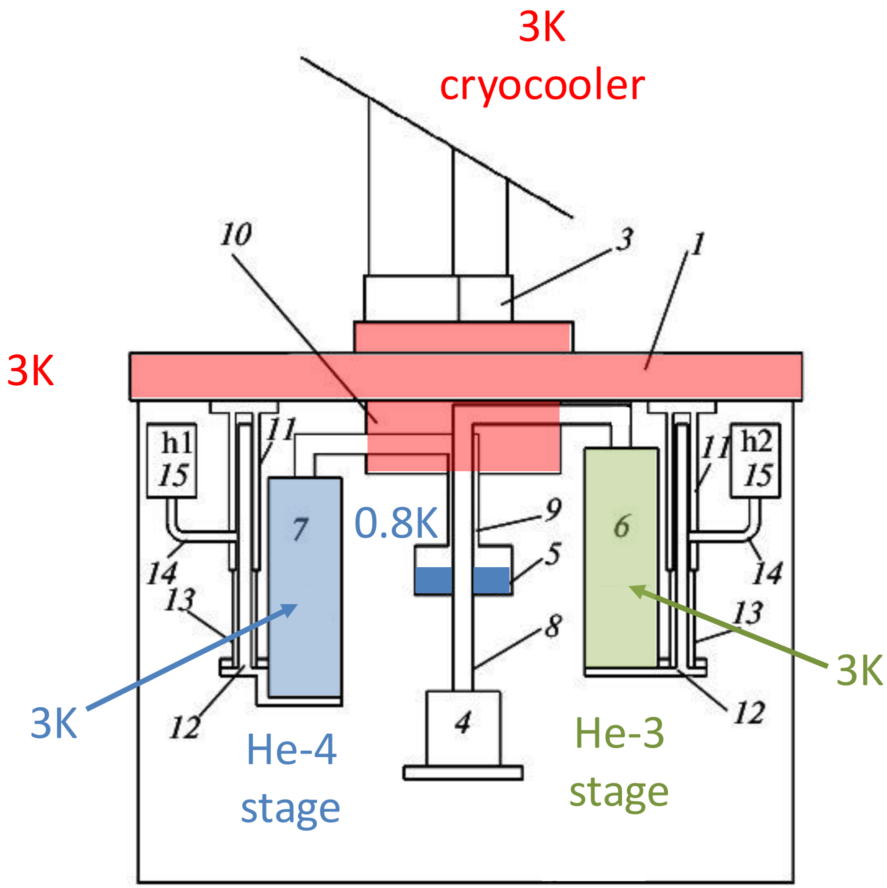
- Then, the ^4He sorption pump are heated to 40 K, so the gas is desorbed and go in the tube, is cooled down by the cryocooler via the heat exchanger and condense inside the evaporator

Cryogenics below 1 K



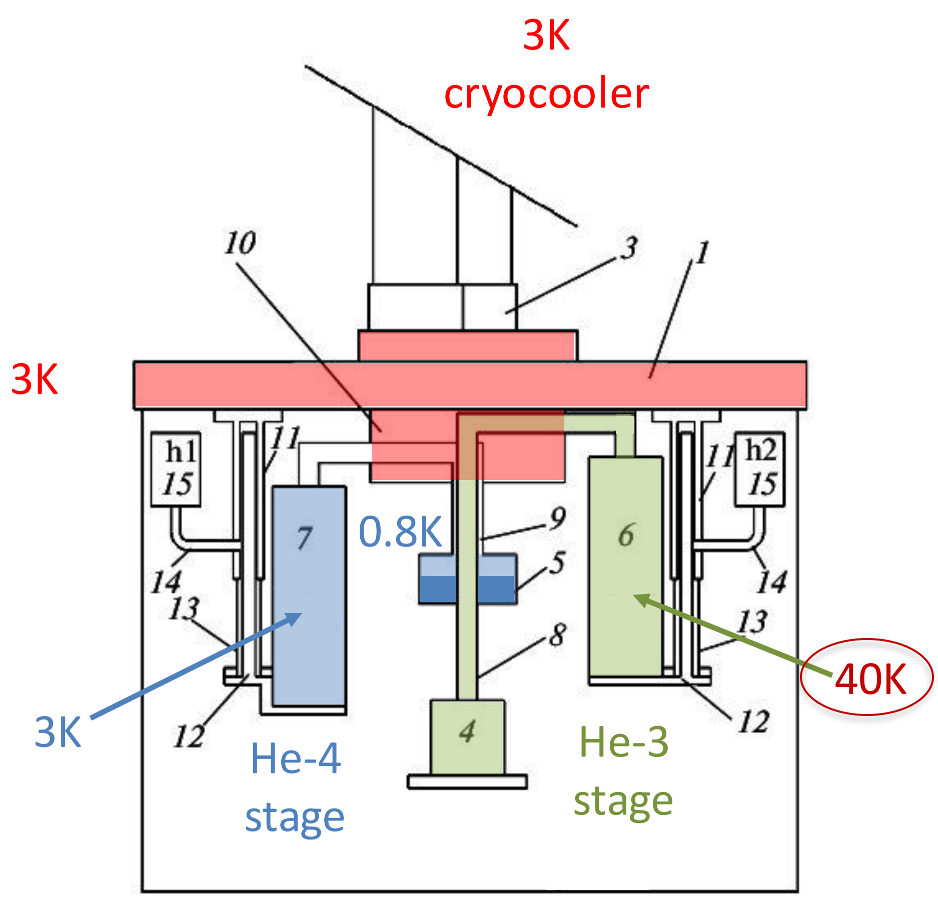
- After a while, some liquid ^{4}He fills the evaporator

Cryogenics below 1 K



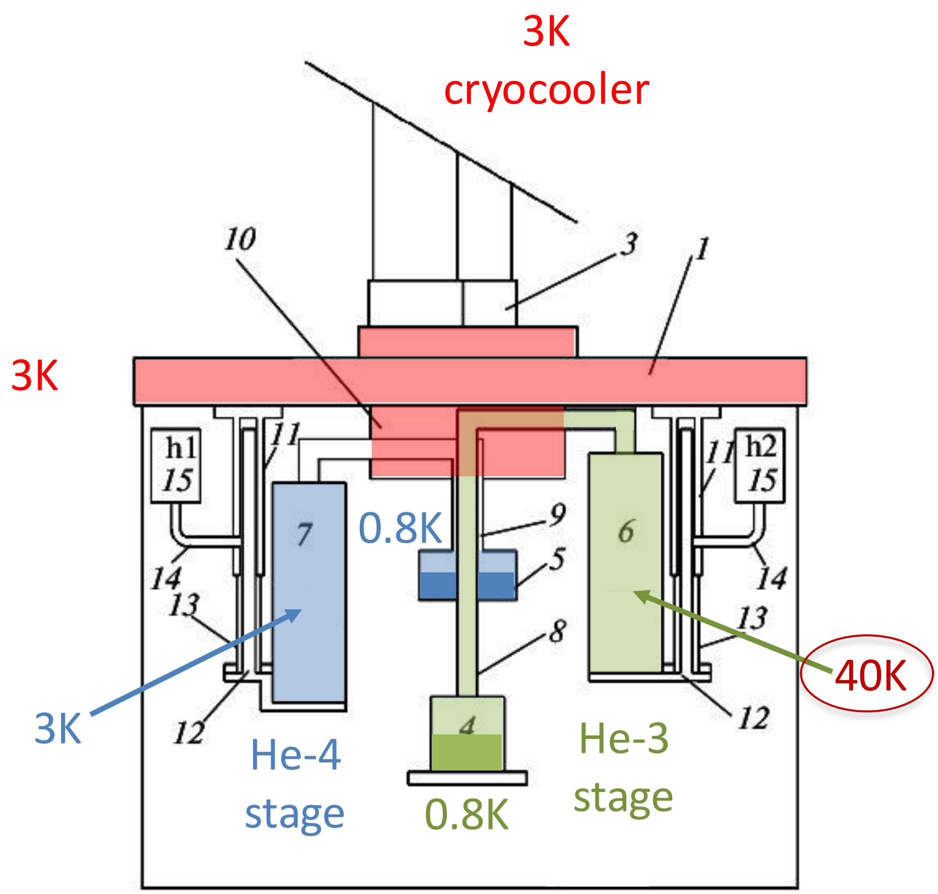
- Then, we stop to heat the sorption pump, so it will return to about 3 K, restarting to pump on the vapour ^{4}He. This will drop down the pressure on the liquid bath, lowering its temperature. Tipically T reach 0.8 K

Cryogenics below 1 K



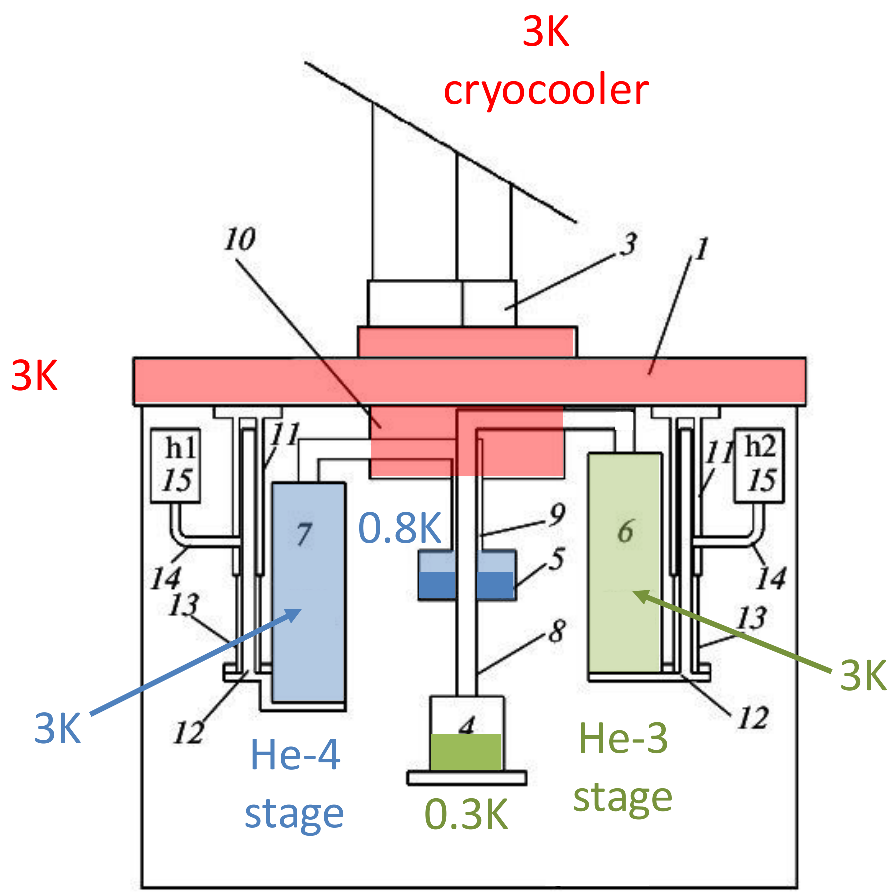
- Now, we can repeat the same cycle on the ^{3}He stage, starting to heat the pump

Cryogenics below 1 K



- The ^{3}He gas will be cooled firstly at 3 K and then at 0.8 K, in thermal contact with the ^{4}He evaporator, condensing inside the ^{3}He evaporator.

Cryogenics below 1 K



- Stopping heating the ^{3}He sorption pump will cool it at 3 K, causing the pressure drop over the ^{3}He bath. In this way it reaches about 0.3 K

Superfluidity

^4He below a certain T shows a singular behavior. We call it ***SUPERFLUIDITY*** in analogy with the superconductivity effect

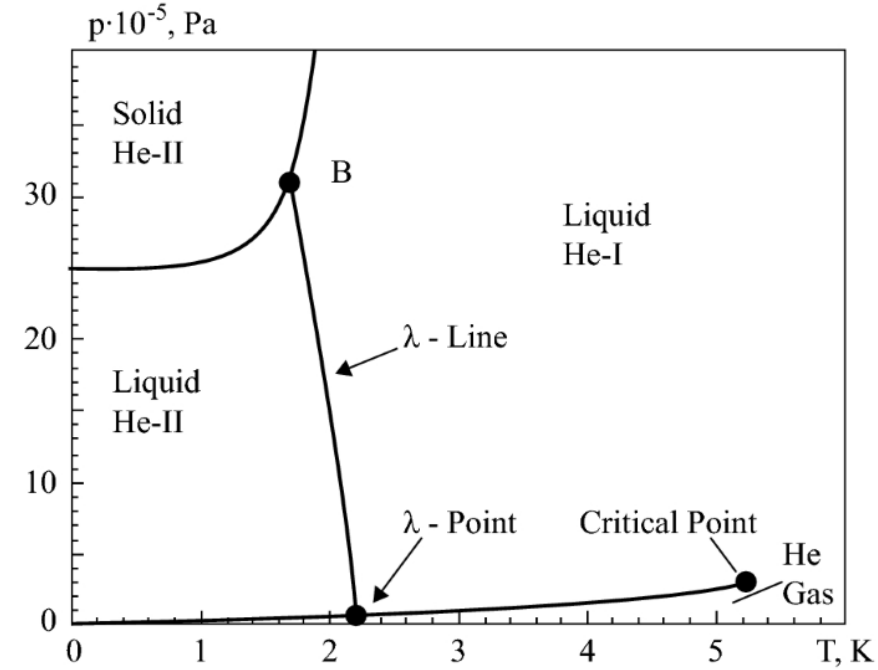
ONLY ^4He AND ^3He shows this effect

The fluid in this condition shows ***NO viscosity, zero entropy, very high heat conduction***

Superfluidity in ^3He and ^4He shows similar behavior, but its physical origin its different. ^4He is a BOSON (spin zero) while ^3He is a FERMION (spin ½)

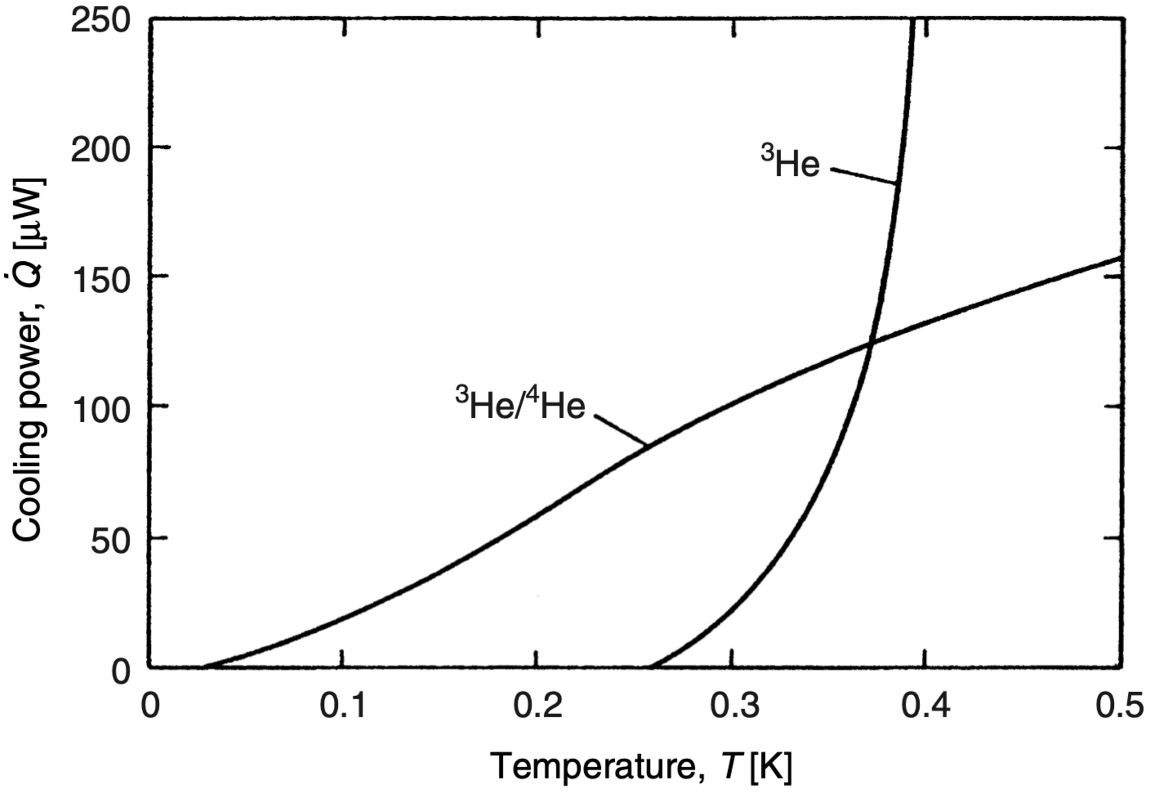
^4He become superfluid at about 2.17 K, while ^3He make the transition at few mK

Typical effect is the ability of superfliud helium to climb the walls of its container



Cryogenics below 300 mK

What below 300 mK???



Cryogenics below 300 mK

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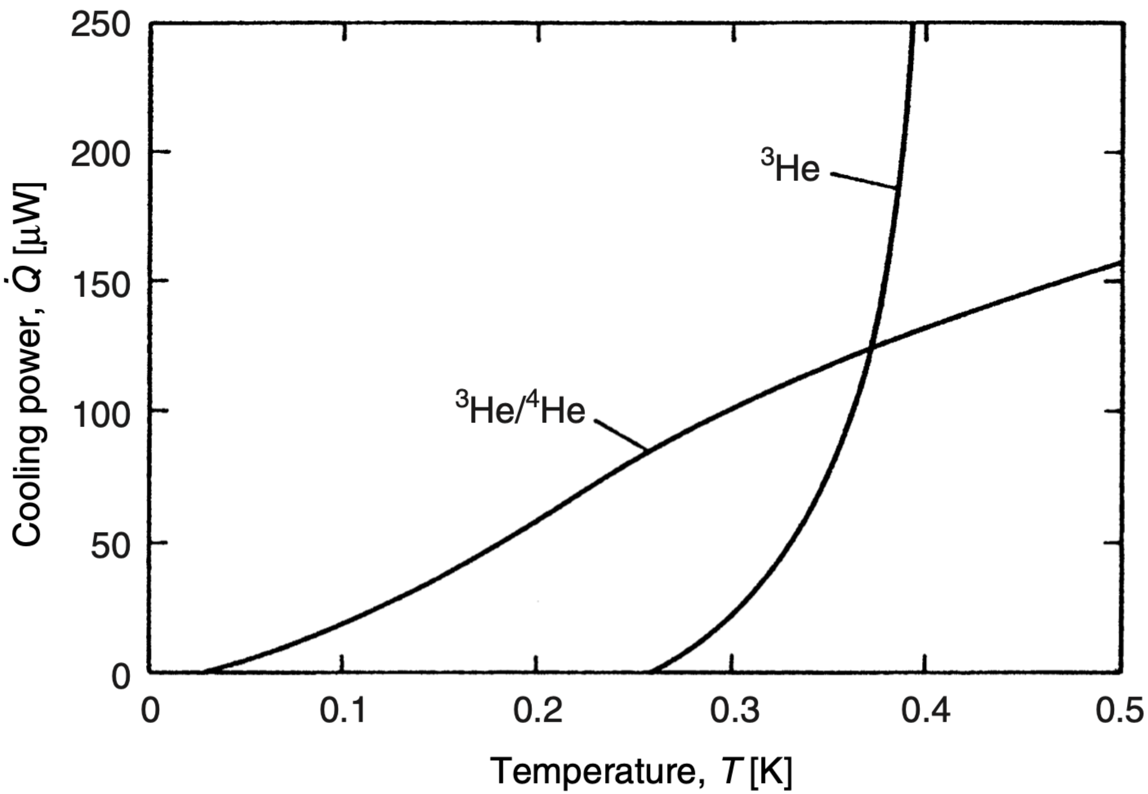


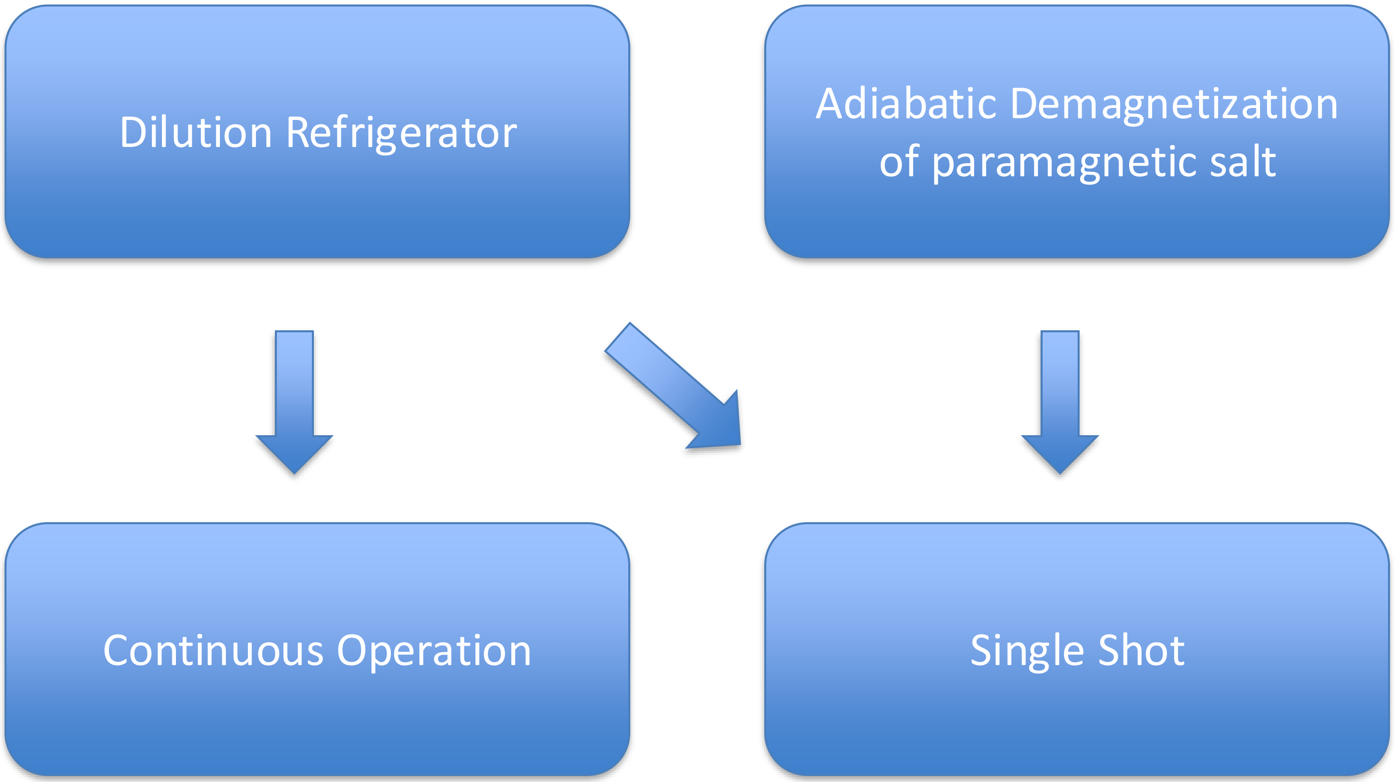
^{3}He / ^{4}He DILUTION REFRIGERATION

Cryogenics below 300 mK

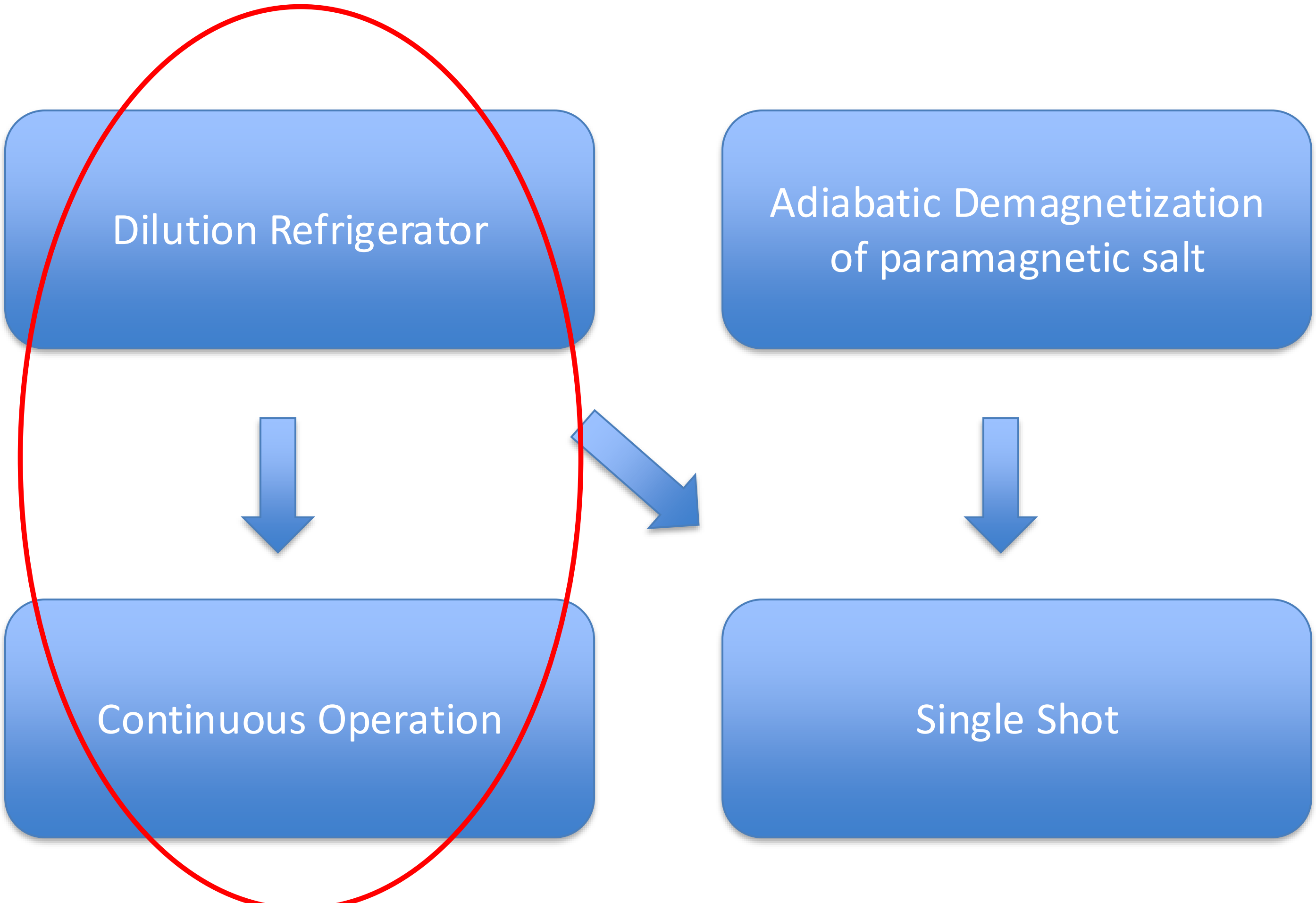
Dilution Refrigerator

Adiabatic Demagnetization of paramagnetic salt

Cryogenics below 300 mK



Cryogenics below 300 mK



Only way to CONTINUOUSLY cool below 300 mK

Dilution Refrigerators

1951 : Principle suggested by London

1965 : First prototypes at Leiden

1968 : 5.5 mK (continuous mode)

1972 : 3 mK (single cycle)

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Osmotic Pressure of He^3 in Liquid He^4, with Proposals for a Refrigerator to Work below 1°K

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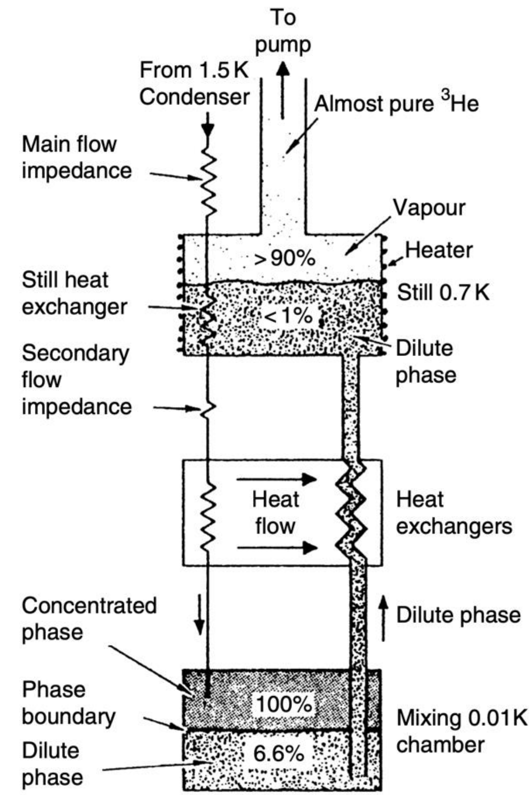
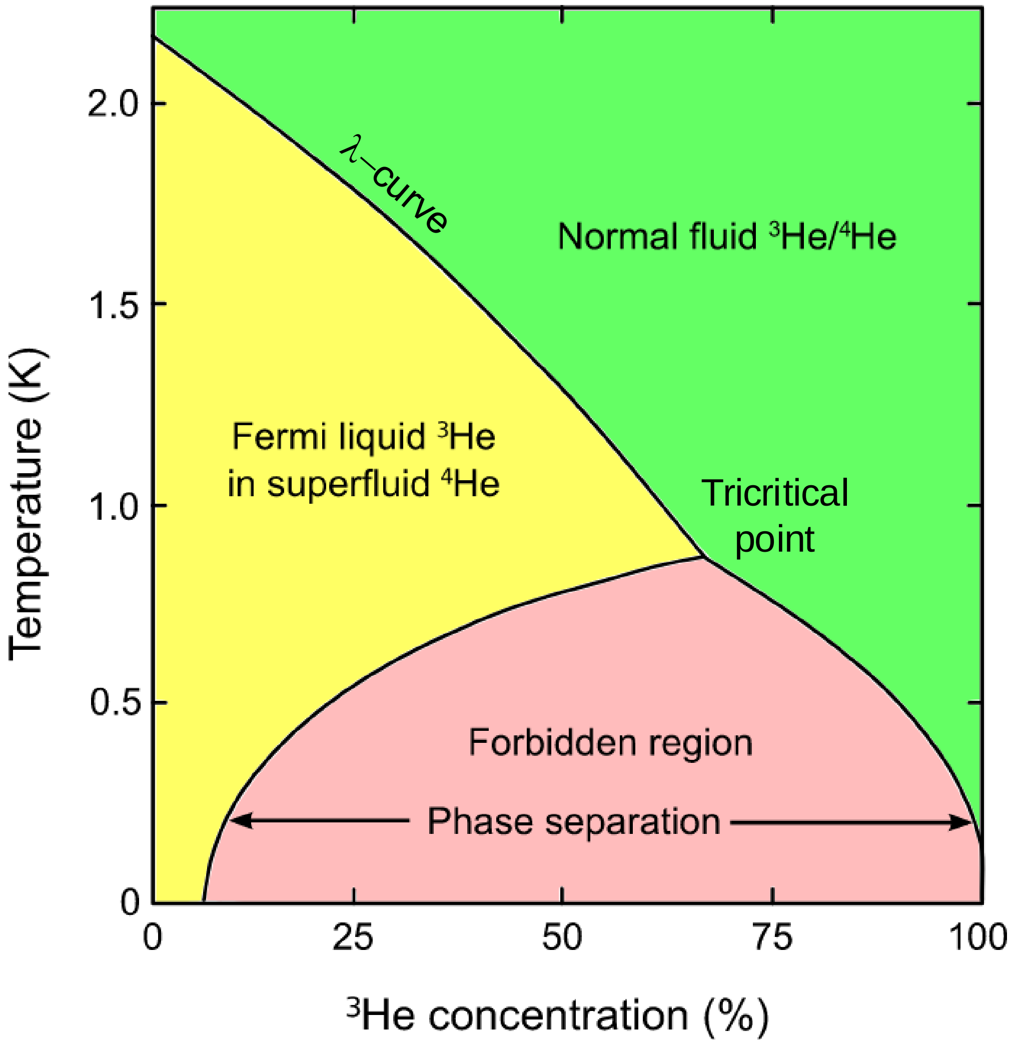
Atomic Energy Research Establishment, Harwell, England
and
Eric Mendoza
Physical Laboratories, University of Manchester, Manchester, England

(Received September 21, 1961; revised manuscript received May 14, 1962)



$^3He/^4He$ Mixture



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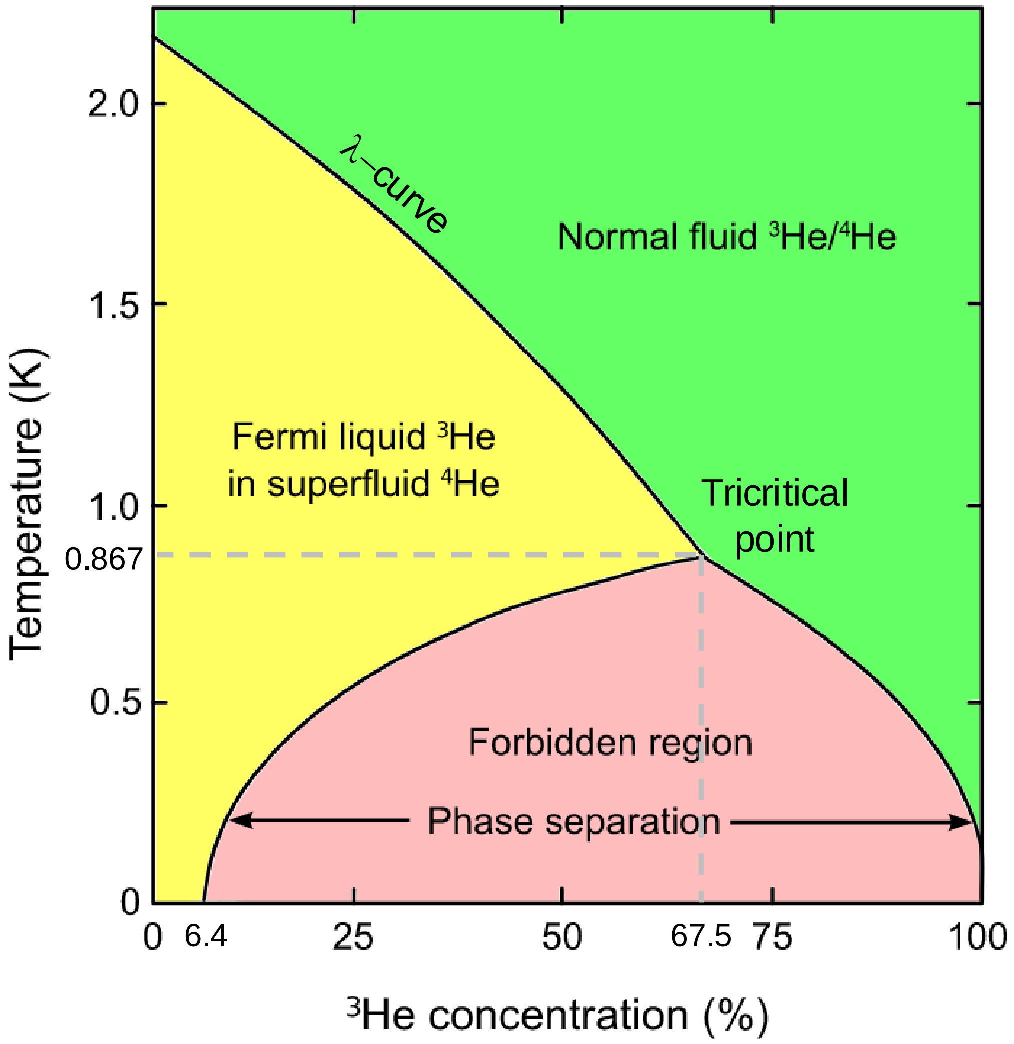

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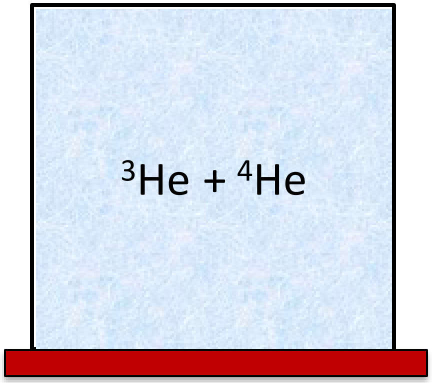
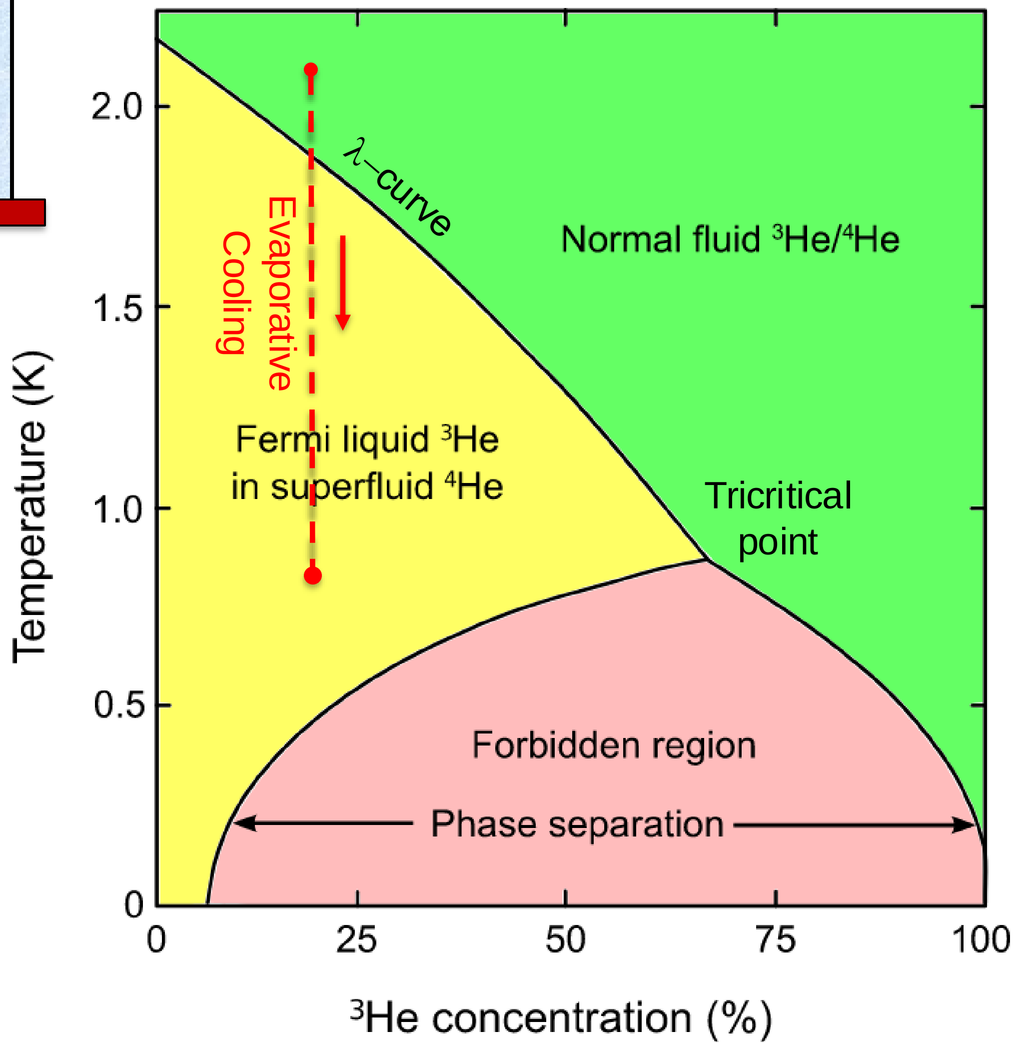
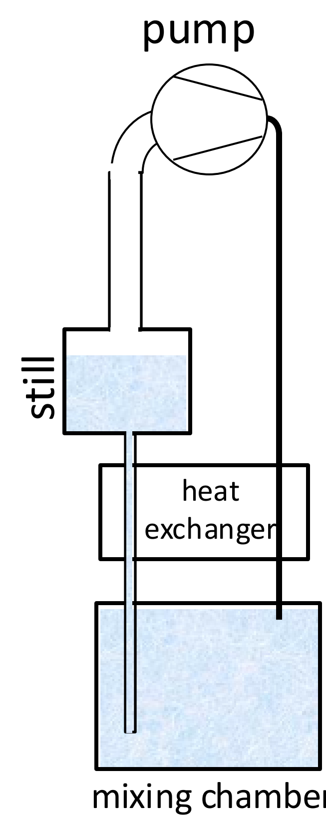
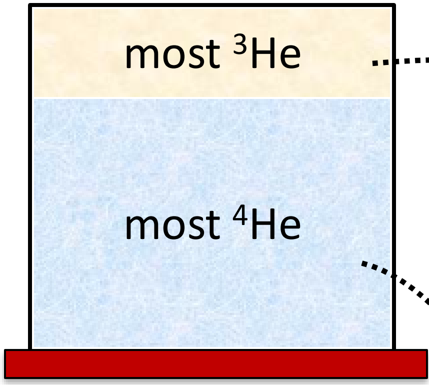
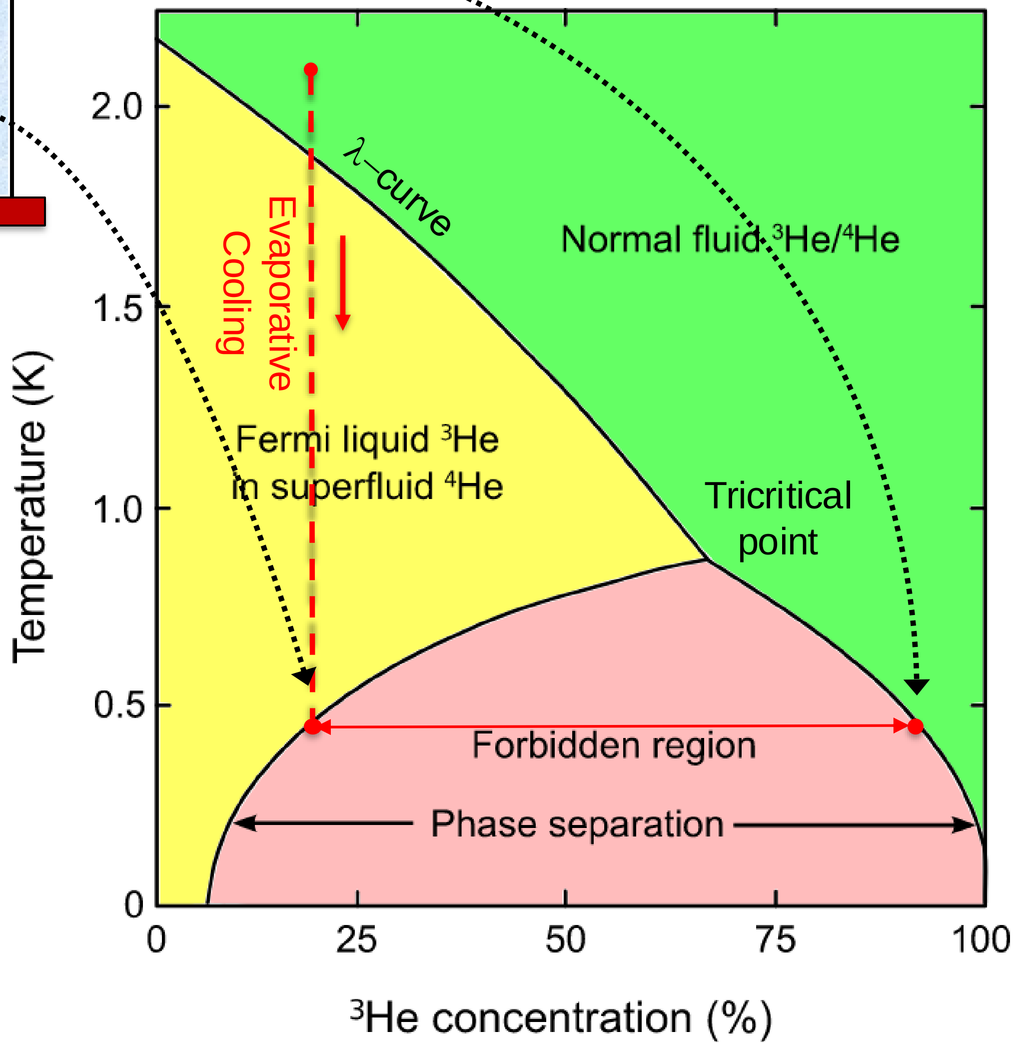


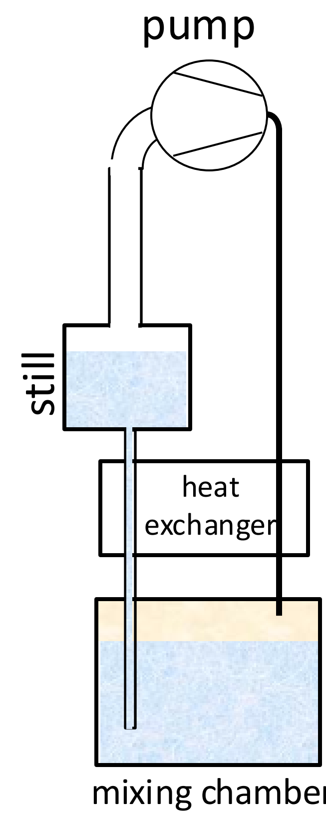




^{3}He/^{4}He Mixture







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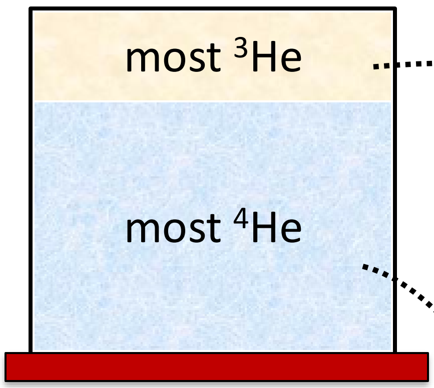
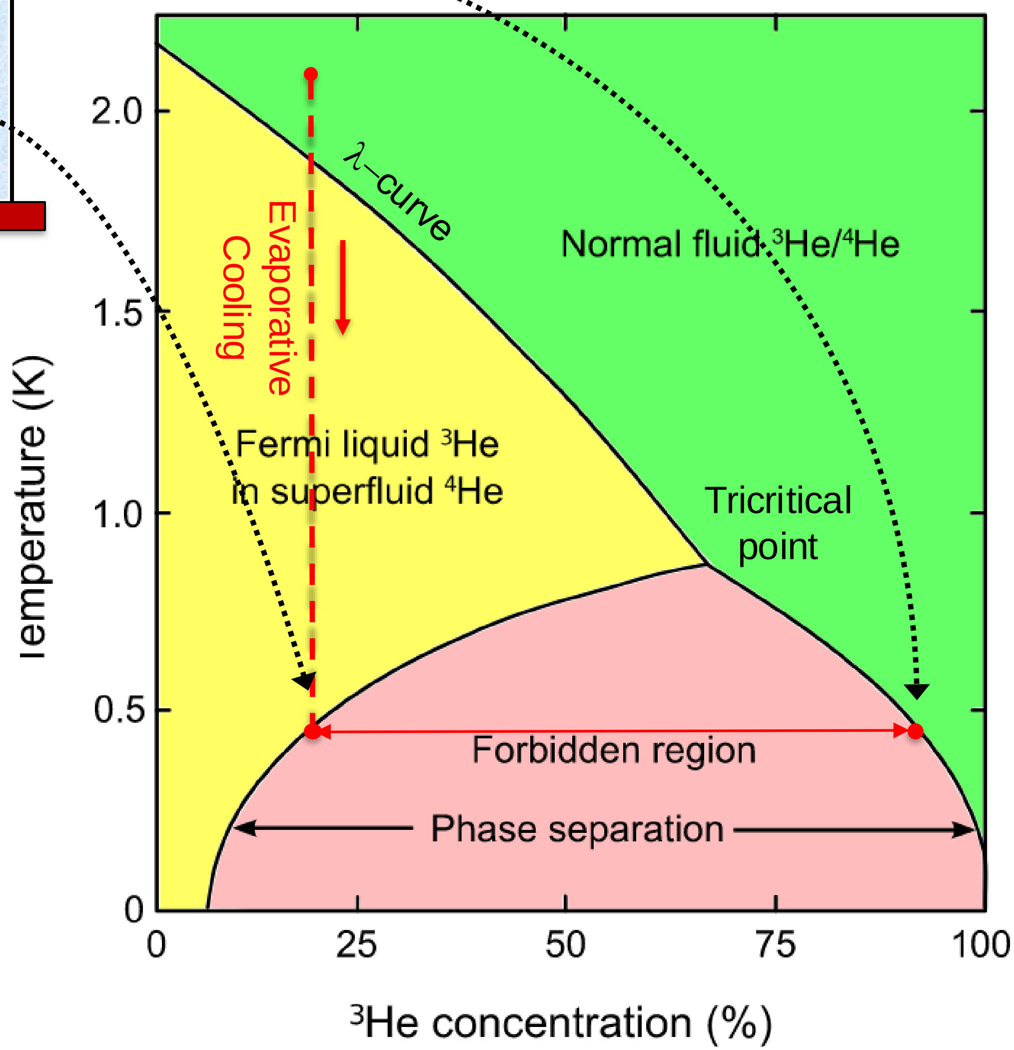
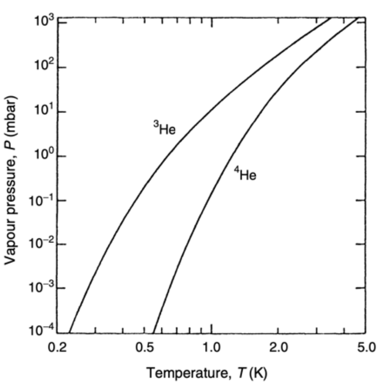
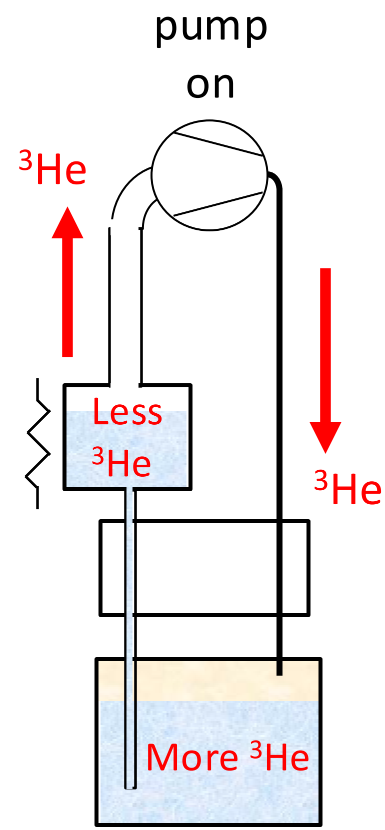
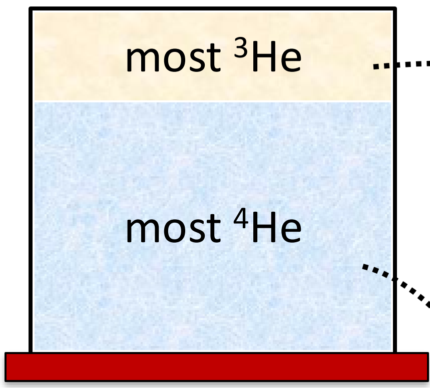


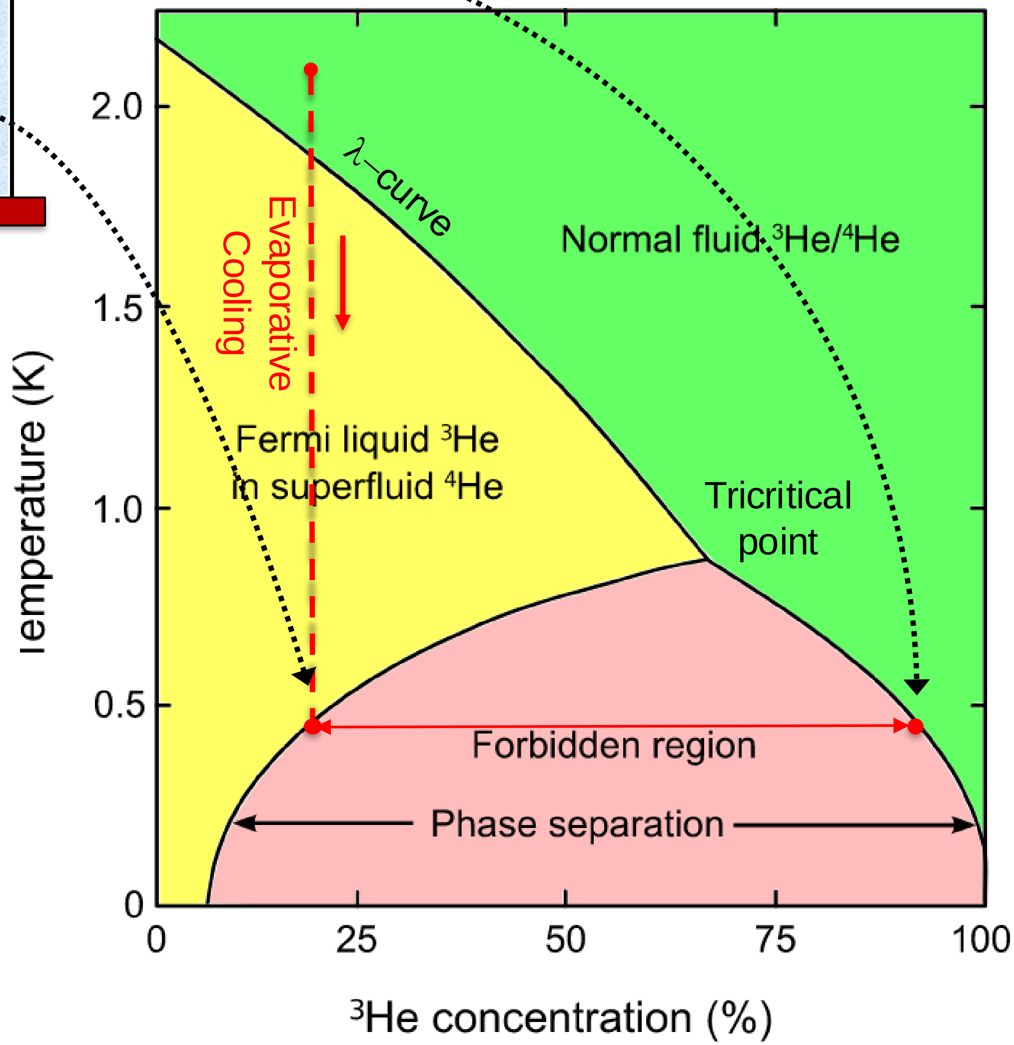


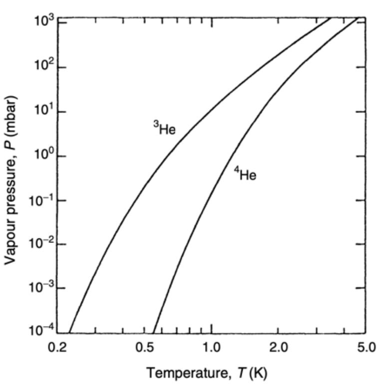


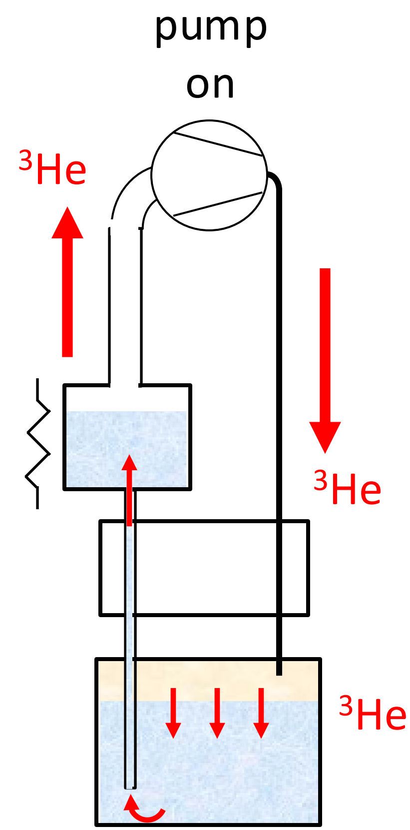


$^3He/^4He$ Mixture

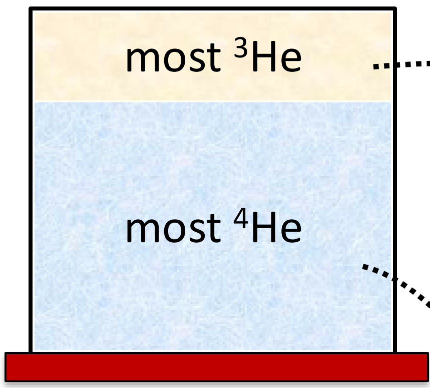


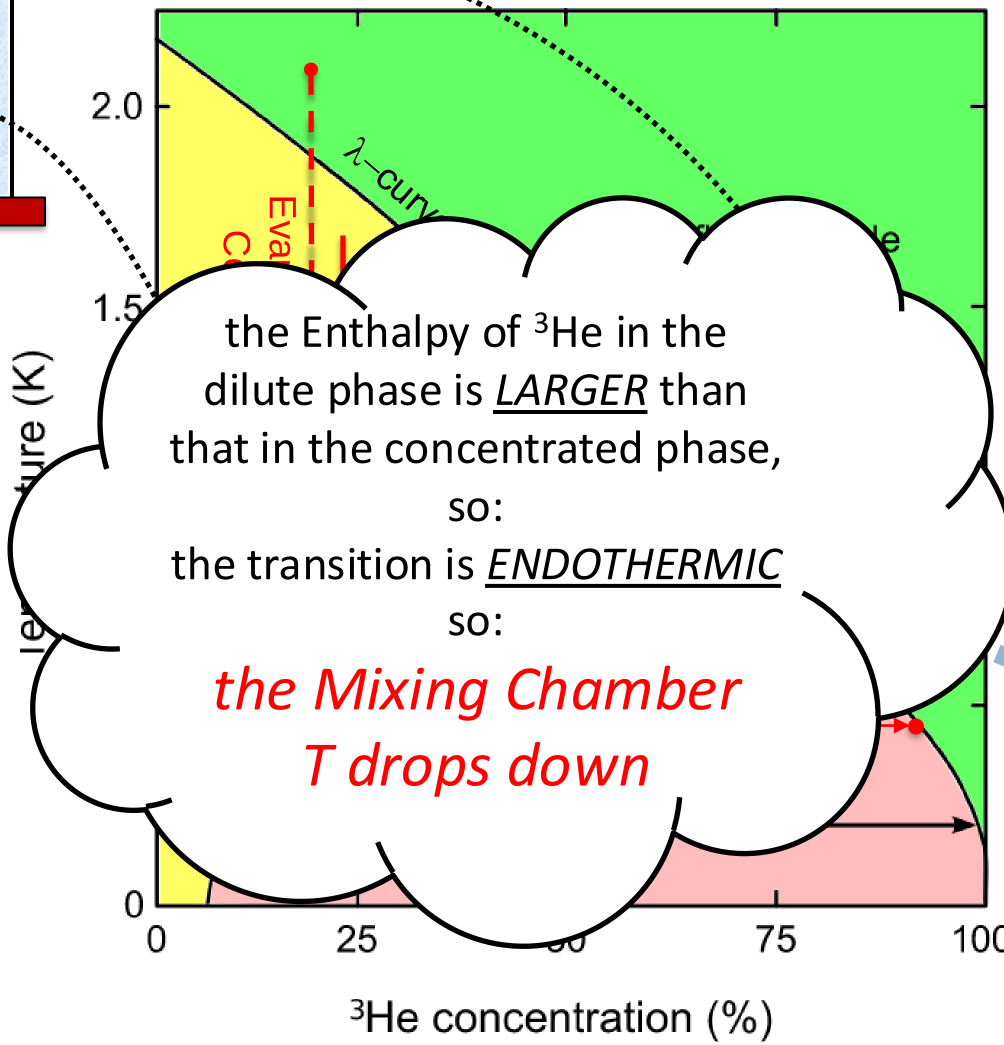






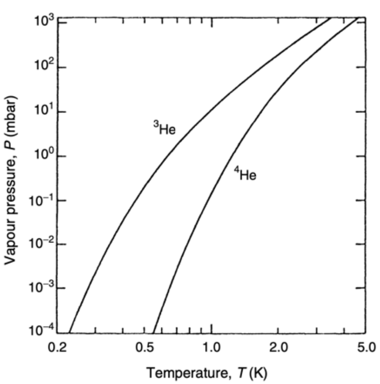
^{3}He/^{4}He Mixture

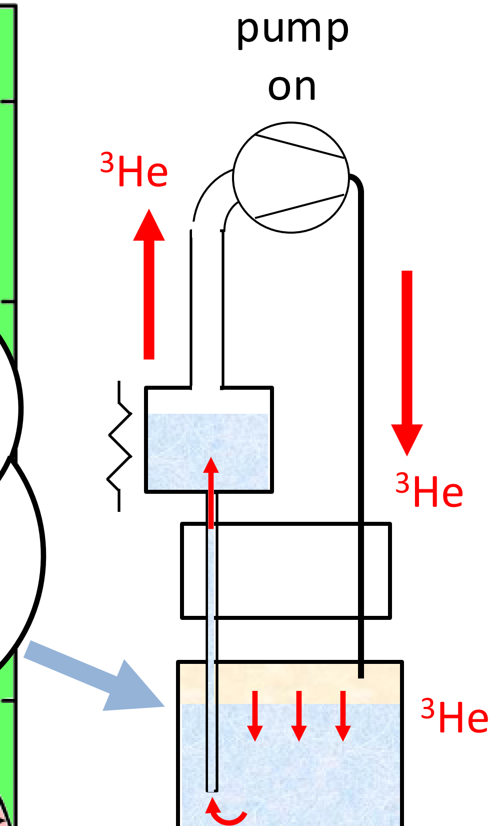




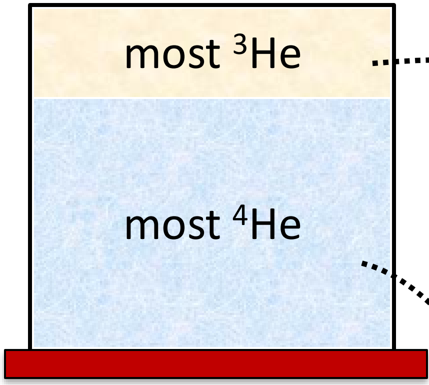
the Enthalpy of ^{3}He in the dilute phase is *LARGER* than that in the concentrated phase,
so:
the transition is *ENDOTHERMIC*
so:

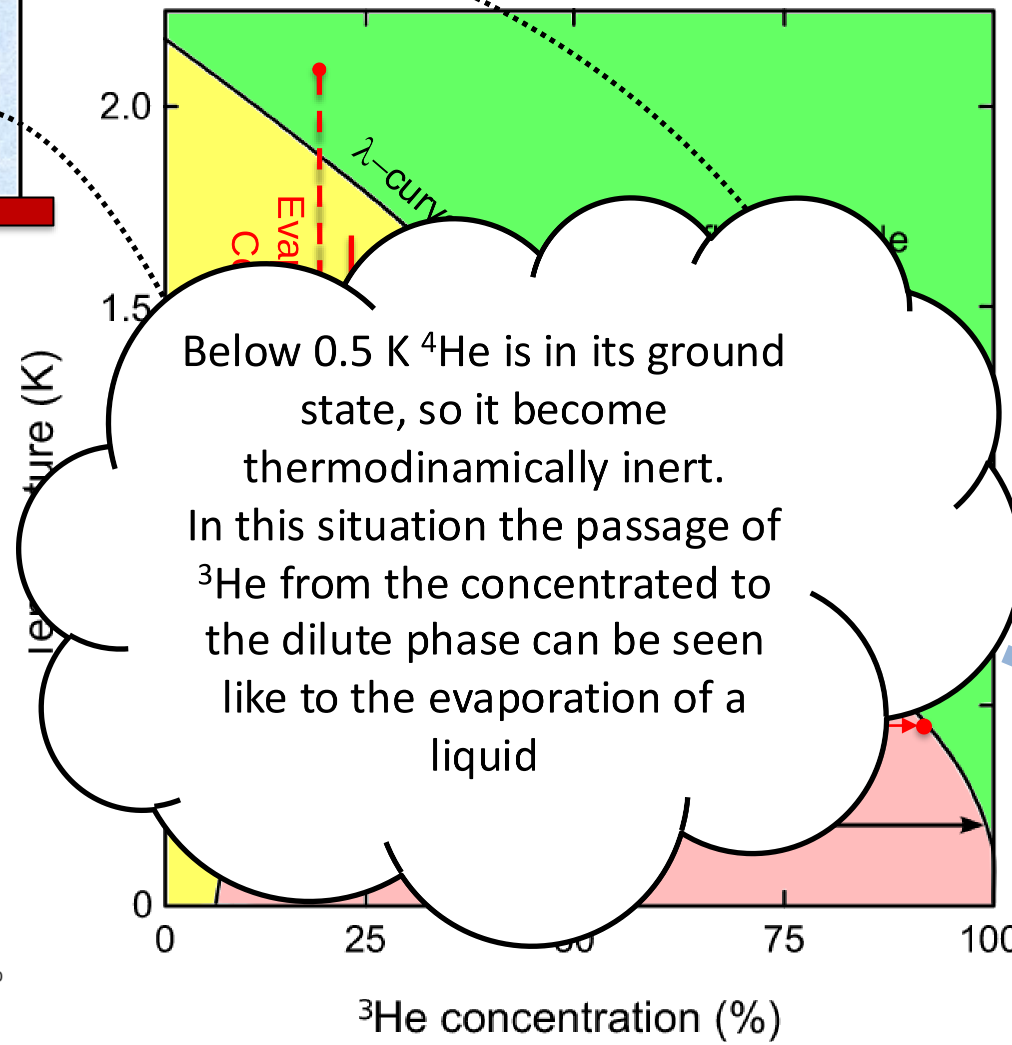
the Mixing Chamber T drops down



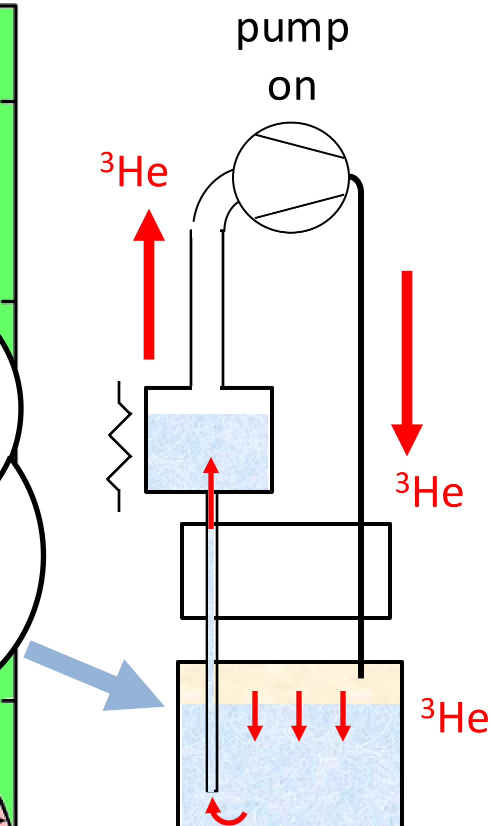


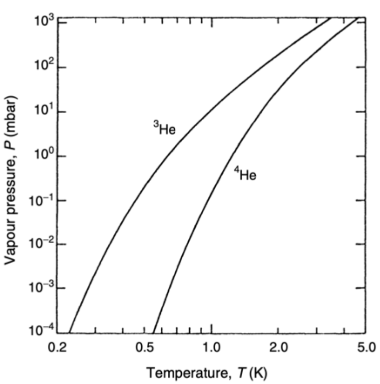
^{3}He/^{4}He Mixture



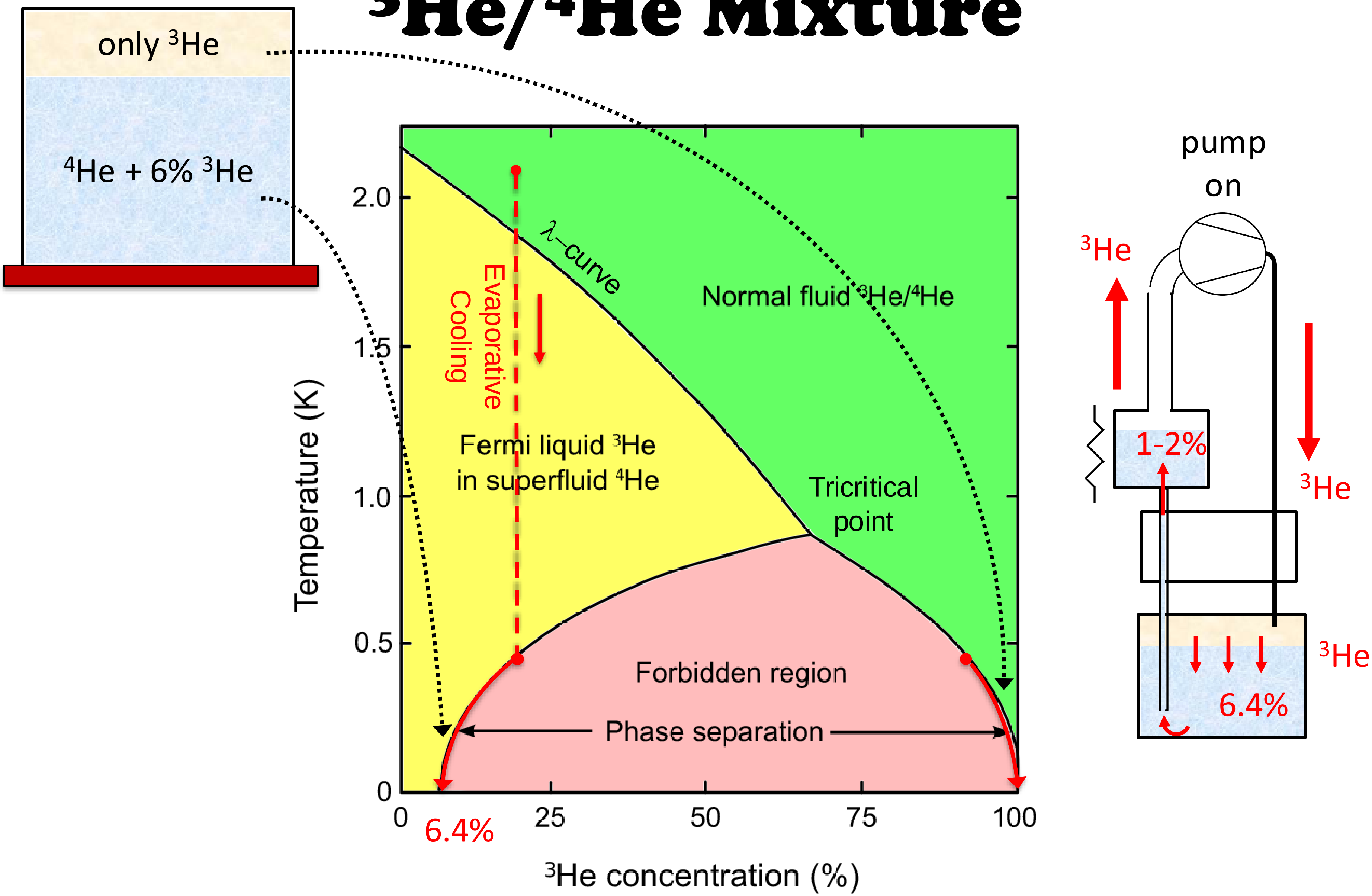


Below 0.5 K ^{4}He is in its ground state, so it become thermodinamically inert.
In this situation the passage of ^{3}He from the concentrated to the dilute phase can be seen like to the evaporation of a liquid





$^3He/^4He$ Mixture

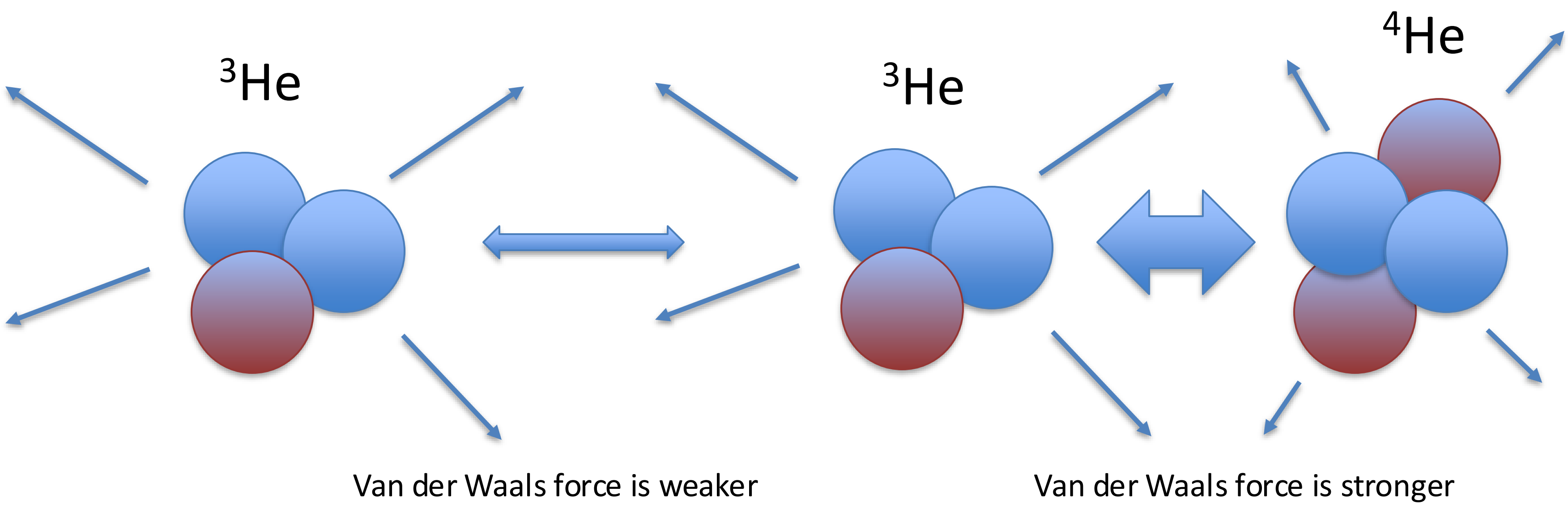


$^3He/^4He$ Mixture

^4He is a **boson** with nuclear spin zero → *below 0.5 K is in its QM ground state, e.g. no phonons/rotons excited, the liquid is thermally and hydrodynamically inert (may be described as a mechanical vacuum)*

^3He is a **fermion** with nuclear spin 1/2 → Heat capacity and entropy $\propto T$

Why ^3He concentration do not tend to zero for $T \rightarrow 0$?

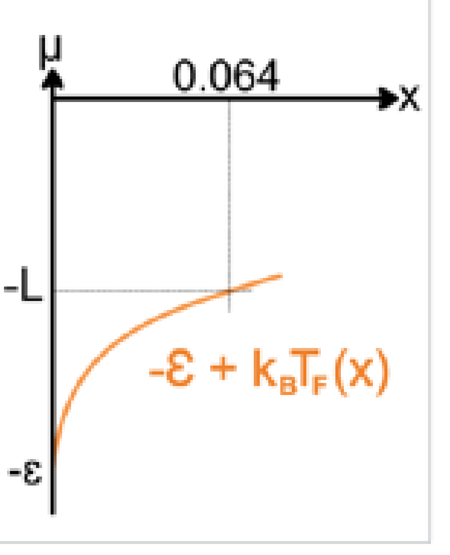


^{3}He/^{4}He Mixture

Why 6.4% ??

To understand why the finite solubility is 6.4%, we need to look in more detail at the binding energy.

- Consider the chemical potential μ of ^{3}He in ^{4}He and let's say the binding energy of a single ^{3}He atom in ^{4}He is ε
- The binding energy of ^{3}He in ^{3}He is equal to the latent heat of evaporation of pure ^{3}He, L, so ε must be greater than L
- The first two ^{3}He atoms will occupy the lowest energy state – ε with anti-parallel spins
- Additional ^{3}He atoms have to obey the Pauli Exclusion principle and therefore occupy increasingly higher energy states
- At a concentration of 6.4%, the chemical potential equals that of a ^{3}He atom in pure ^{3}He.

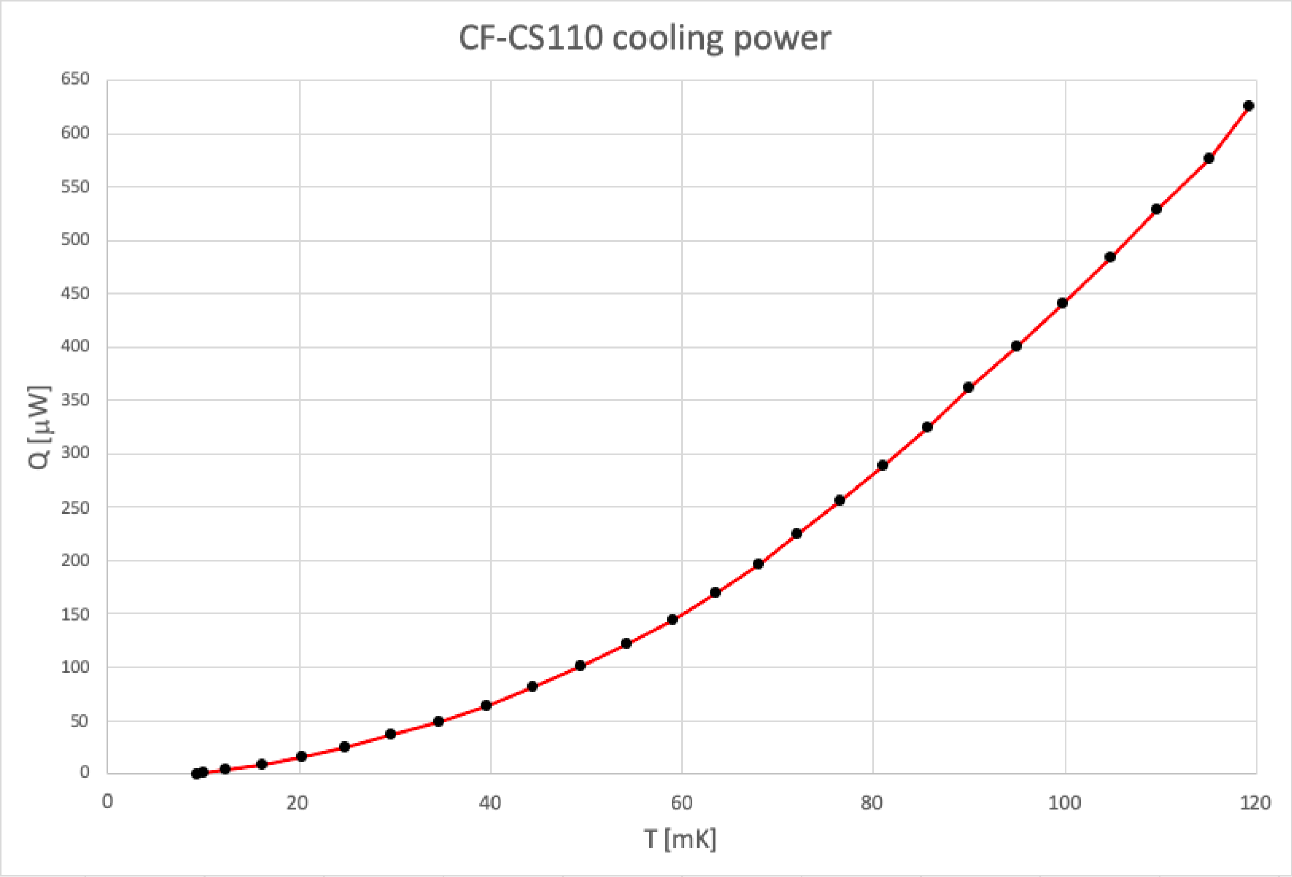


DRs can in principle goes down to absolute zero. Practical reasons limits T base to about 2 mK (due to the increase of both ^{3}He viscosity and thermal conductance)

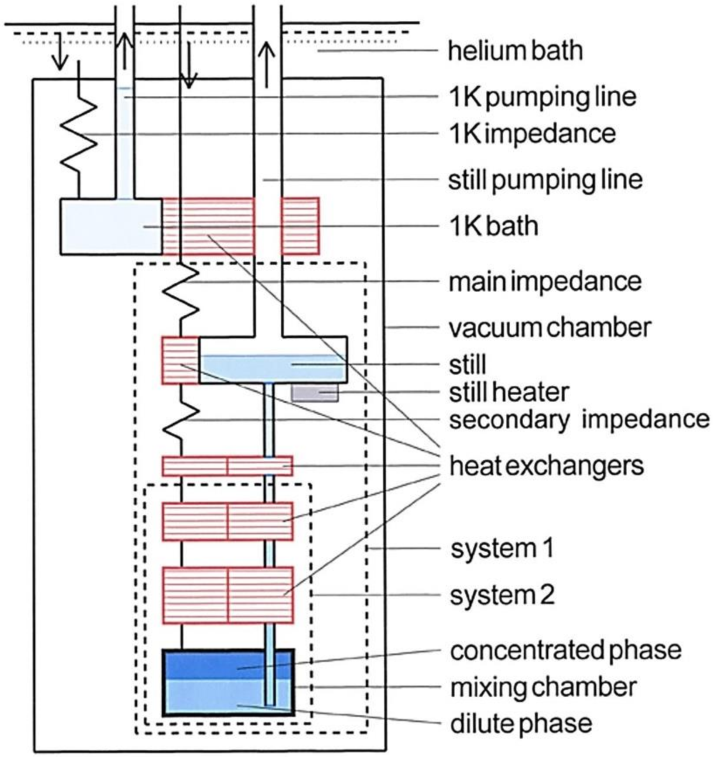
$^3He/^4He$ Mixture

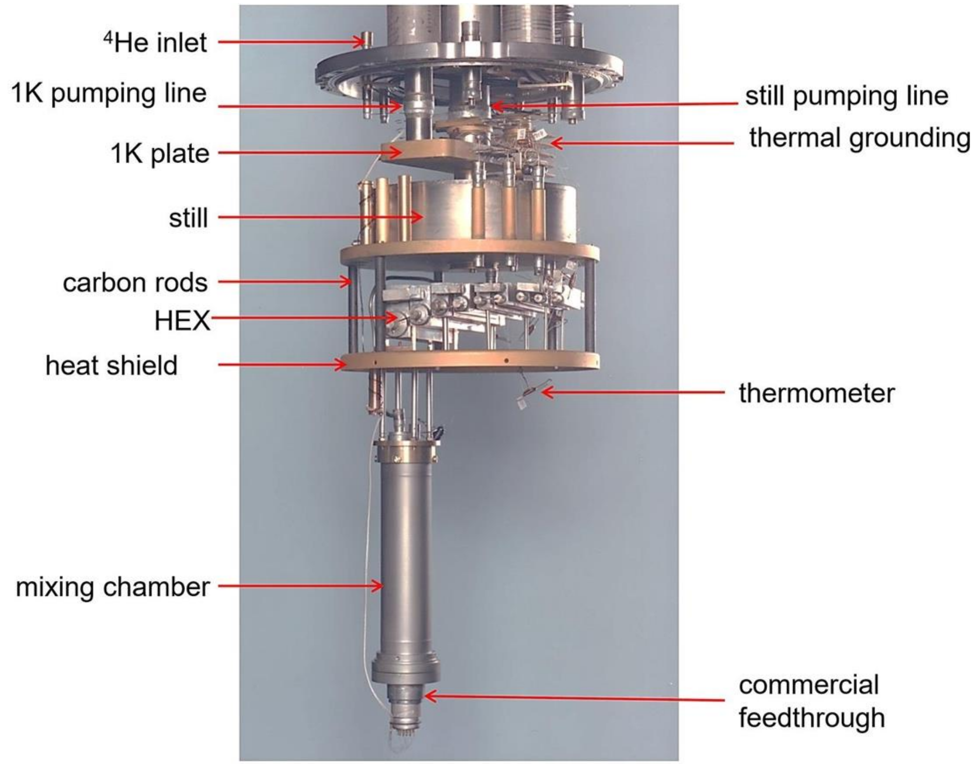
DRs Cooling power is $\propto \dot{n}\, T^2$

($\dot{n}$ is the mixture flow rate)



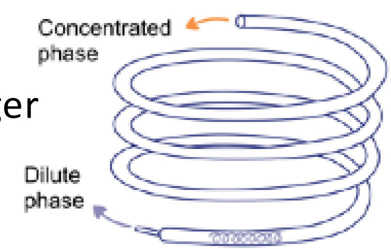
Real dilution refrigerators

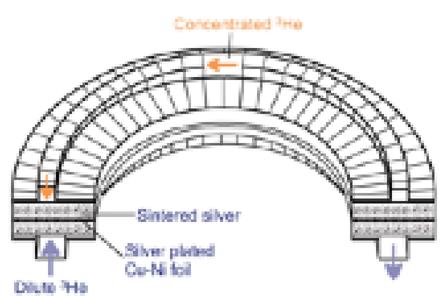




continuous heat exchanger

higher temperatures



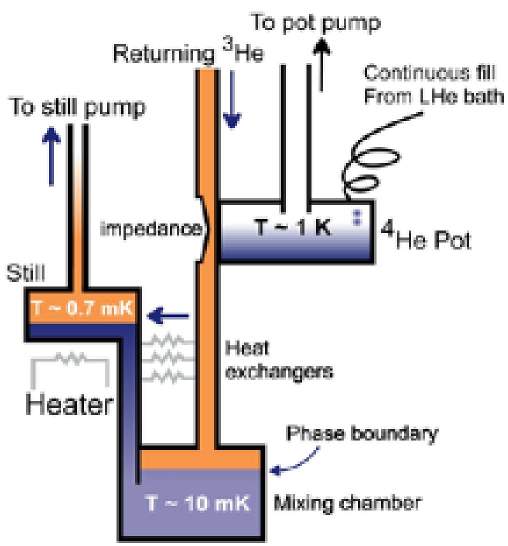


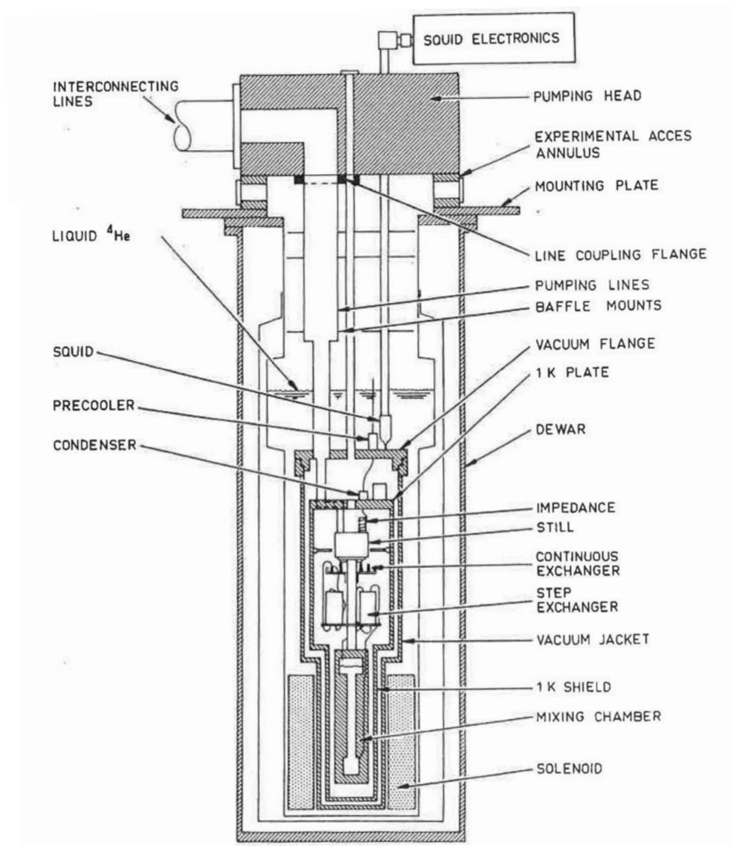
sintered heat exchanger

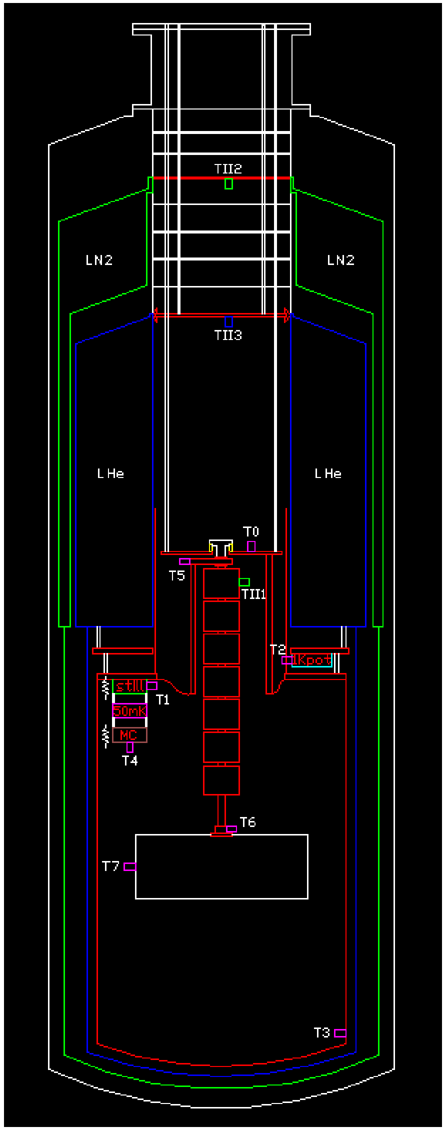
lower temperatures

Cryostats for dilution refrigerator

- DRs needs a precooling at T about 3-4 K
- <u>wet cryostats (Liquid Helium + Liquid Nitrogen)</u>
- dry cryostats (Cryocoolers / Pulse Tubes *[less vibrations]*)







Cryostats for dilution refrigerator

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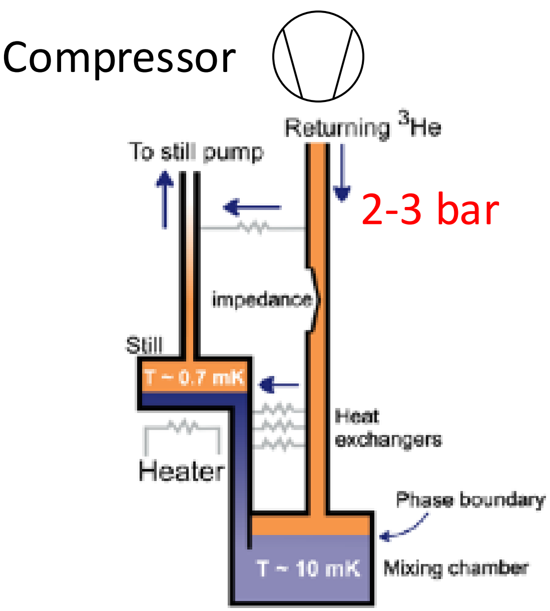

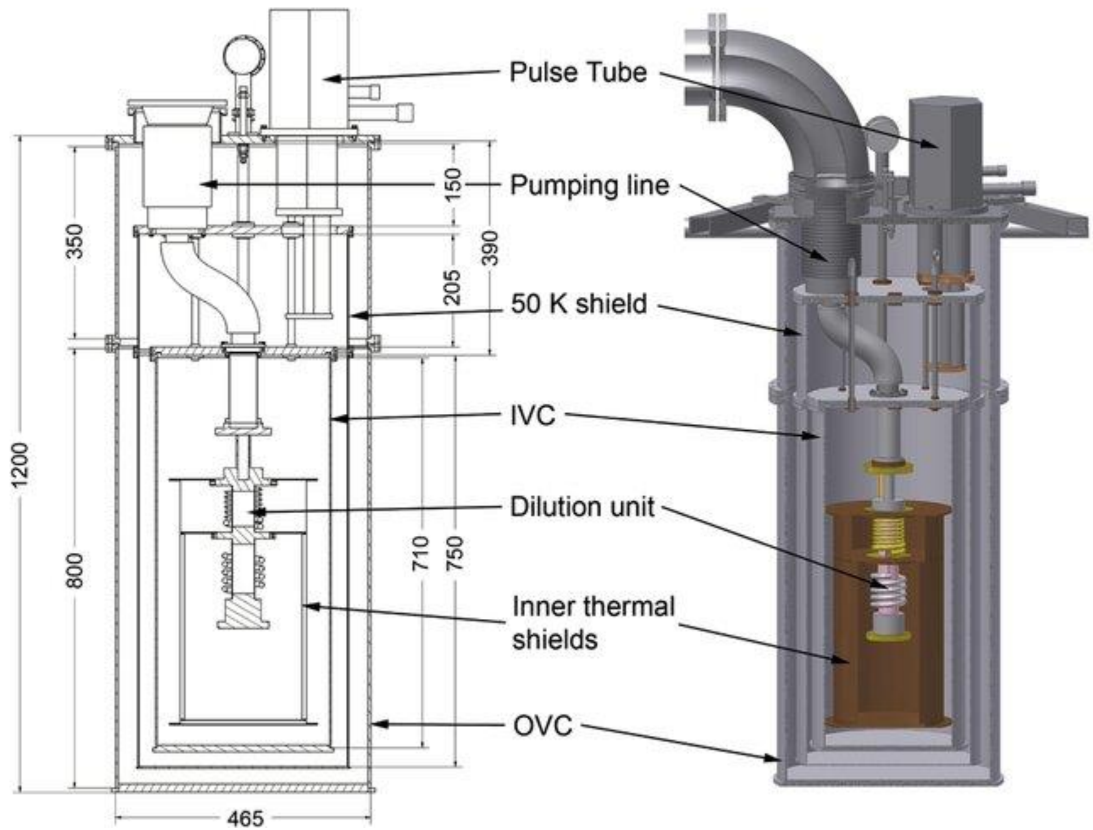

Cryostats for dilution refrigerator

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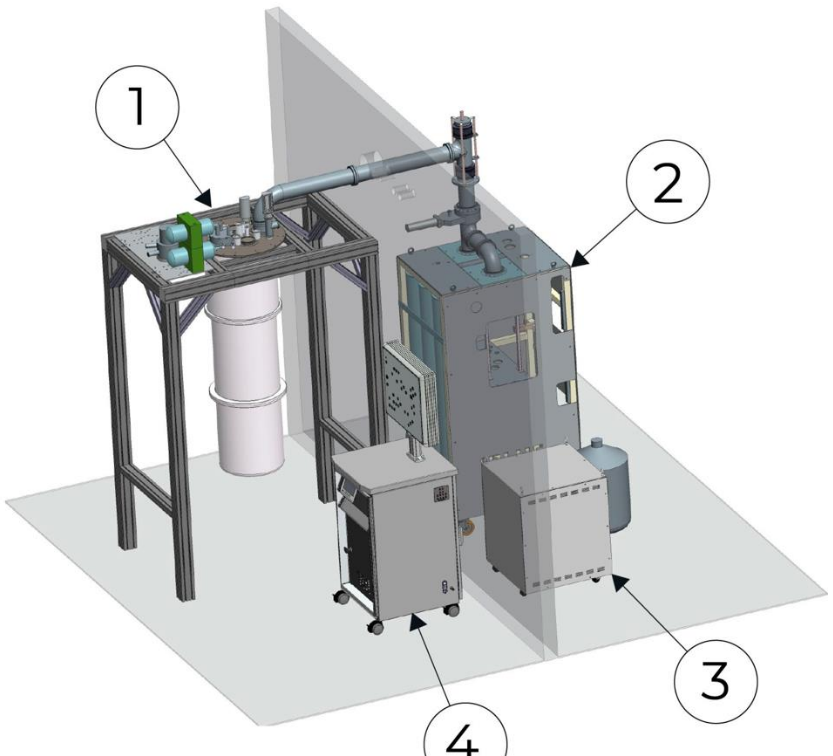


mK refrigeration applications

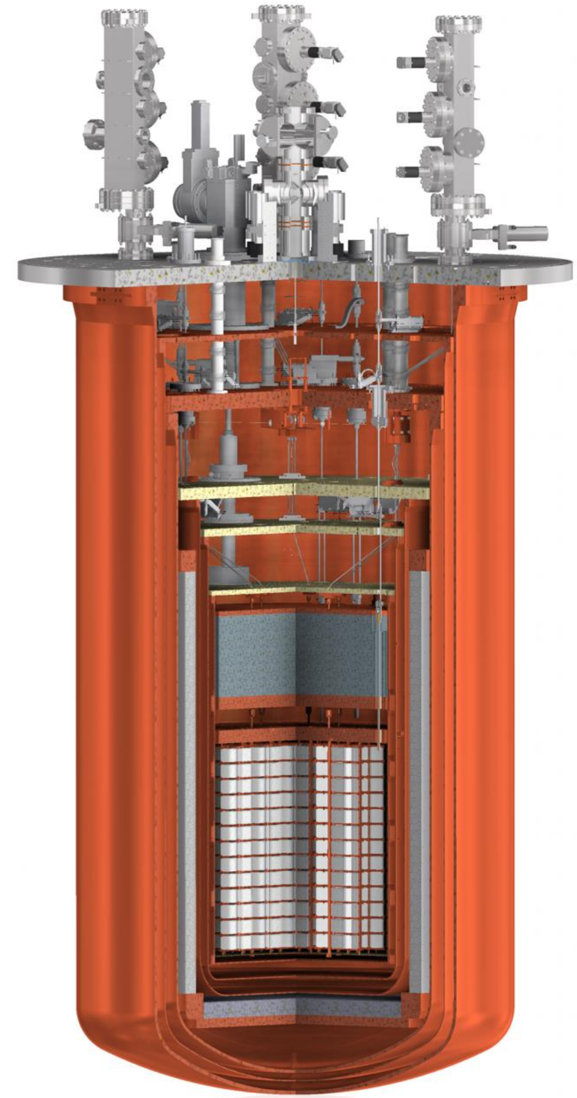
- *scientific research (thermal noise reduction)*
  - *dark matter search, condensed matter physics, Bose/Einstein condensate, degenerate Fermi gas …*
- *superconductivity, superfluidity*
- *semiconductors, graphene*
- *nanotechnology*
- *quantum electronics*
- *quantum computing*

Nobel Prize in physics 1996 to
D.M. Lee, D.D. Osheroff and R.C. Richardson
for their discovery of
"superfluidity in helium-3"

Nobel Prize in physics 1998 to
Robert B. Laughlin, H.L. Störmer and D.C. Tsui
for their discovery of
"a new form of quantum fluid with fractionally charged excitations"

The biggest DR: CUORE
(Cryogenic Underground Observatory for Rare Events)

- The biggest DR are here at LNGS!
- The CUORE cryostat cools more than 1 ton of material at 10 mK since 2018
- 988 TeO_2 cubic crystals
- 1.5 mW @ 120 mK cooling power
- DR made by Leiden Cryogenics



The Coldest Cubic Meter in the Known Universe

Jonathan L. Ouellet
*University of California, Berkeley**
(Dated: August 27, 2018)

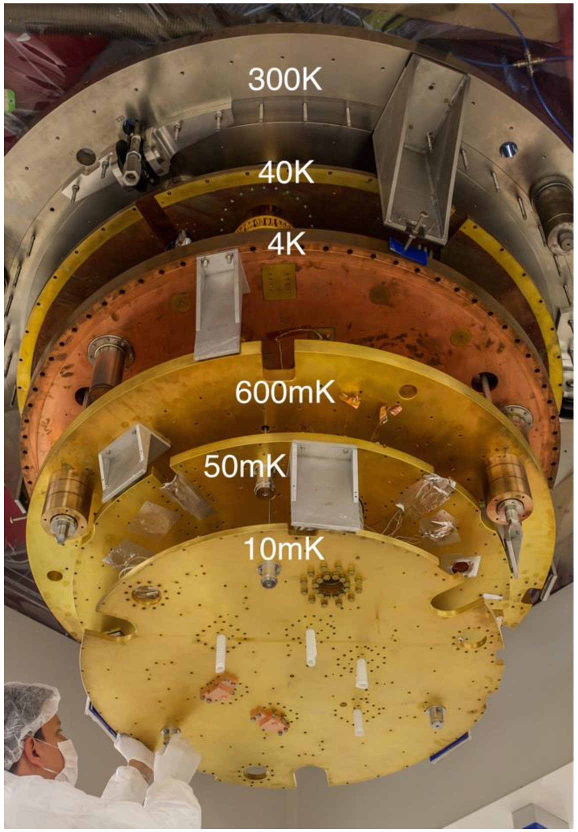
The biggest DR: CUORE
(Cryogenic Underground Observatory for Rare Events)

- No company available to design the CUORE cryostat, so it has been designed by the collaboration: design took 3 years, commissioning took other 4 years

- Dilution goal: to cool 1 ton at 7 mK

L.Taffarello (INFN- Padova): " We need a machine as powerful as the Challenger and as performing as the F12"

- Measured cooling power @ 10 mK: 3 microW



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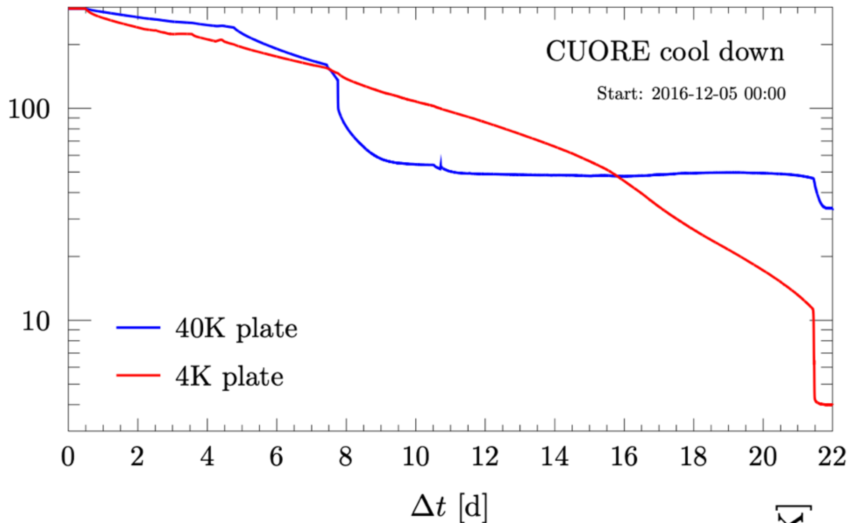
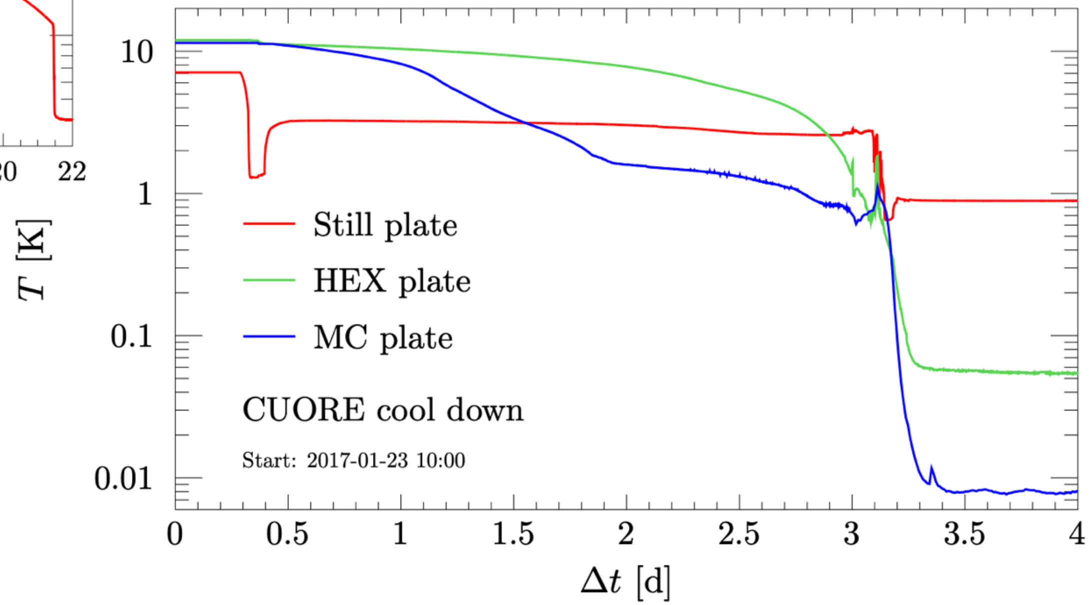
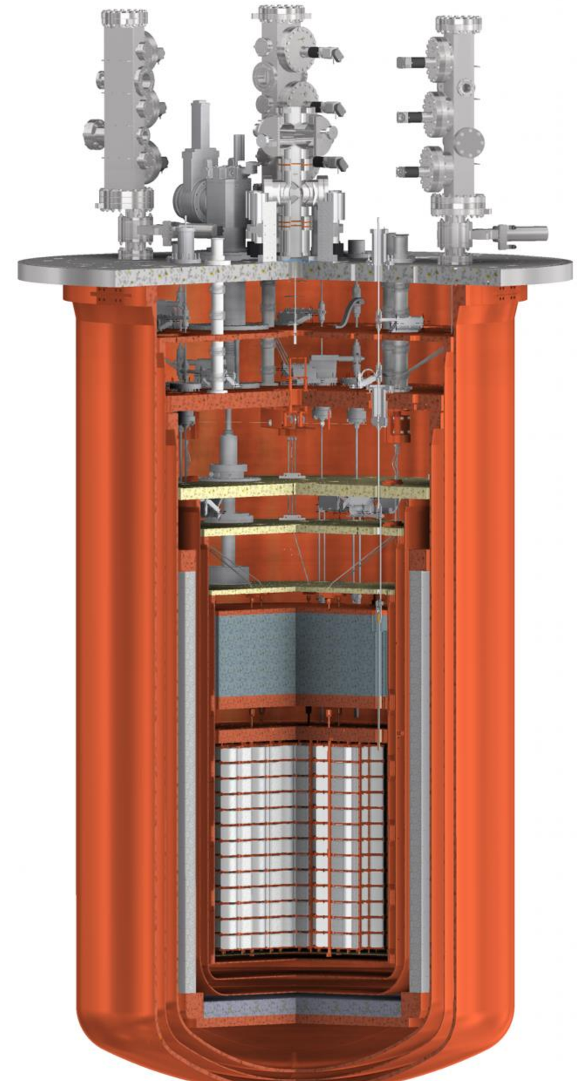




The biggest DR: CUORE
(Cryogenic Underground Observatory for Rare Events)

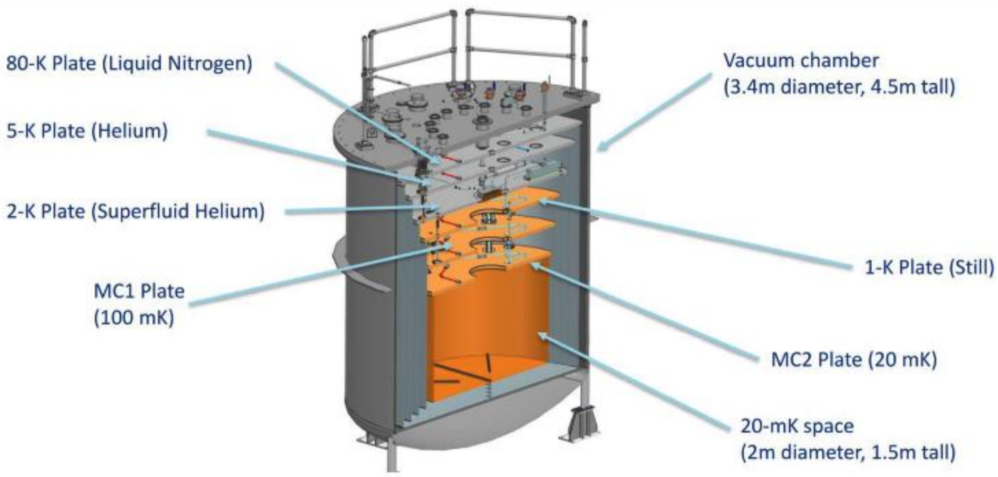
38077 In un esperimento condotto nel 2014 ai laboratori dell'Istituto nazionale di fisica nucleare del Gran Sasso, una struttura di rame del volume di un metro cubo è stata portata alla temperatura di –273,144 °C, vicinissima allo zero assoluto (che corrisponde a –273,15 °C).



The future challenges

clusters of niobium alloy-based SC RF cavities combined with two-dimensional SC qubits acting as three-dimensional quantum processor elements

Colossus mK Platform at Fermilab (Courtesy of Matthew Hollister, Fermilab)



- 2-meter diameter cold plate @the 20-mK stage
- 20-mK cold volume is 5 cubic meters, enclosed by a Cu thermal shield
- Internal structure consists of 6 progressively colder plates with thermal shields

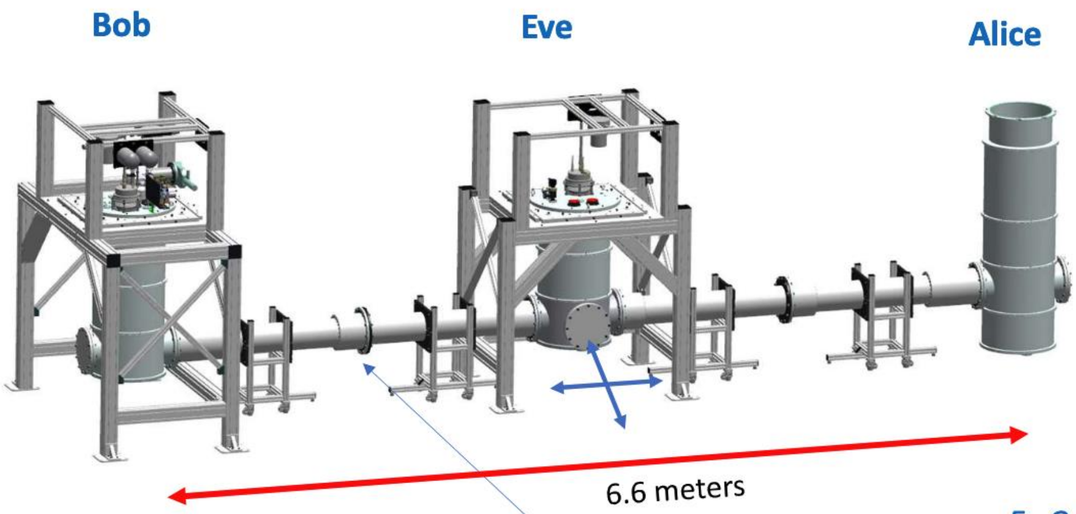
- Dilution cooling at the bottom plate is provided by up to 10 dilutions “cores” each providing up to 20-50 mW @ 20 mK at the MC2 layer
- Total cooling power ~ 200-500 mW @20mk

courtesy of Ziad Melhem (Oxford Quantum Solutions Ltd.)

The future challenges

Q-LAN for Quantum Communications & Computing Scale up

- New innovations required Q Computing/Communications/Sensing
  - Quantum local area network (Q-LAN) - Cryogenic link between two dilution refrigerators Enabling clustering of multiple fridges for large number of Qubits



Achieved ~35 mK (Specifications <100 mK)

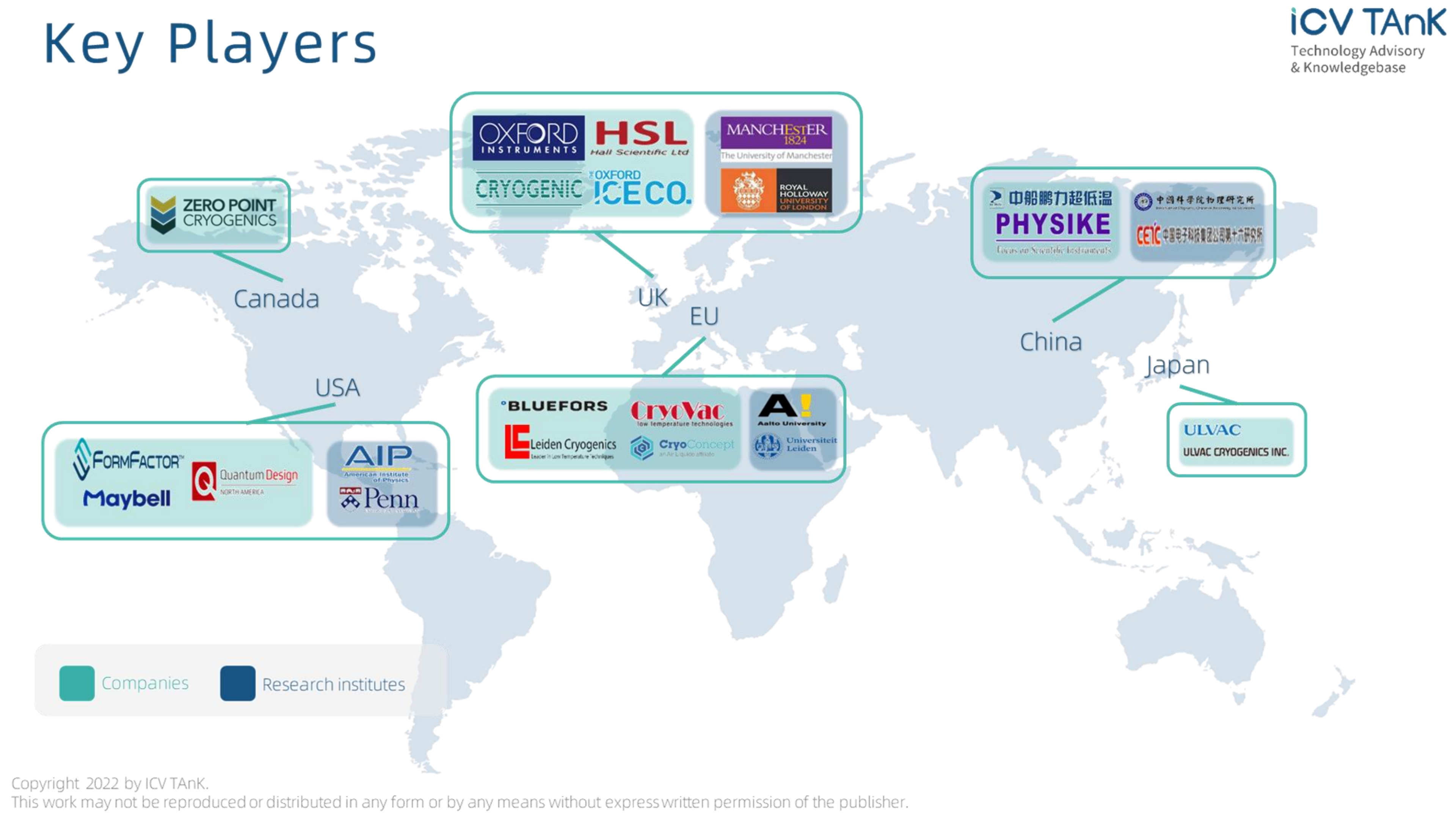
Eu Quantum Flagship Project led by WMI with Ziad Melhem Coordinating Oxford Instruments development of the CryoLink in QMiCS (Oct 2018- Jan 2021)

courtesy of Ziad Melhem (Oxford Quantum Solutions Ltd.)

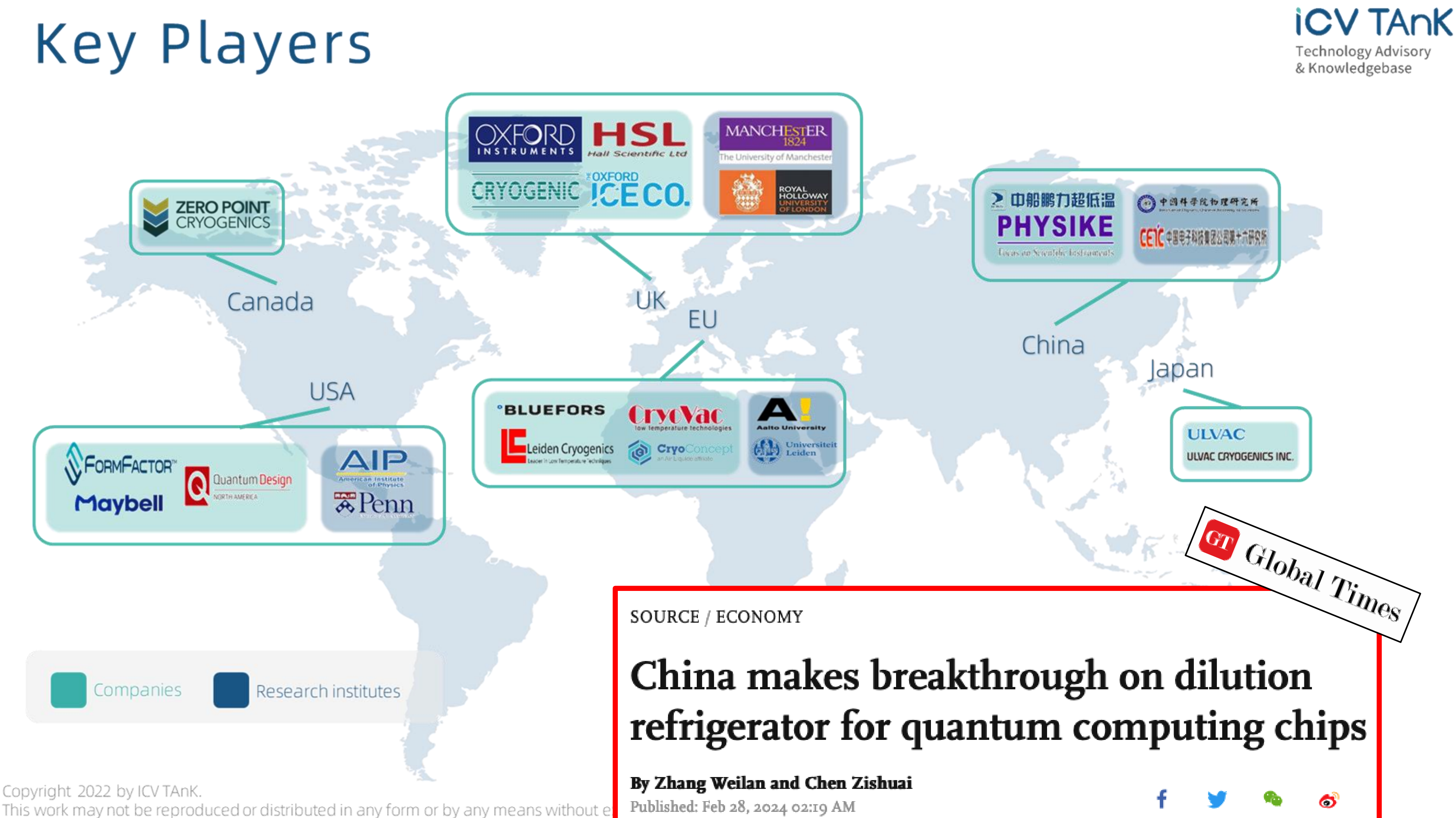
companies selling DRs

- **BLUEFORS** (FI) - bluefors.com
- **OXFORD** (UK) - nanoscience.oxinst.com
- **LEIDEN CRYOGENICS** (NL) - leidencryogenics.nl
- **CRYOCONCEPT** (AIR LIQUIDE - FR) - cryoconcept.com
- **FORM FACTOR** (ex JANIS - USA) - formfactor.com
- **ICE OXFORD** (UK) - iceoxford.com
- **ZERO POINT CRYOGENICS** (CA) - zpcryo.com
- **MAYBELL** (USA) - maybellquantum.com
- **ENTROPY** (DE) - entropy-cryogenics.com
- **QINU** (DE) - qinu.de
- **PHYSIKE** (CN) - physike.com
- **ORIGIN QUANTUM** (CN) - qcloud.originqc.com.cn
- …

companies selling DRs



companies selling DRs



GT Global Times

SOURCE / ECONOMY

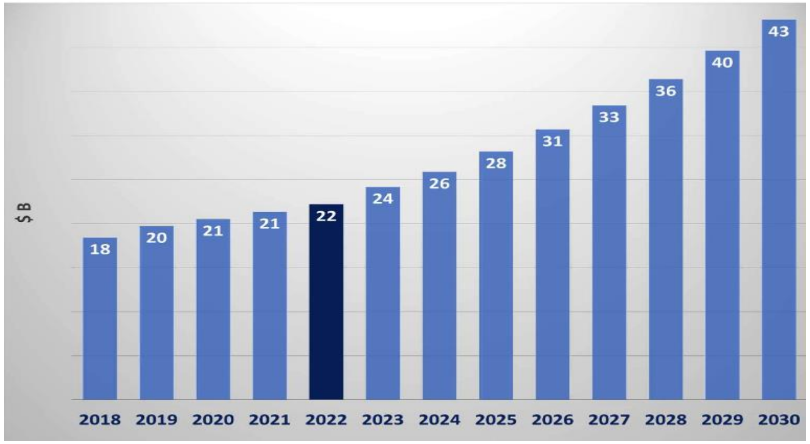
China makes breakthrough on dilution refrigerator for quantum computing chips

By Zhang Weilan and Chen Zishuai

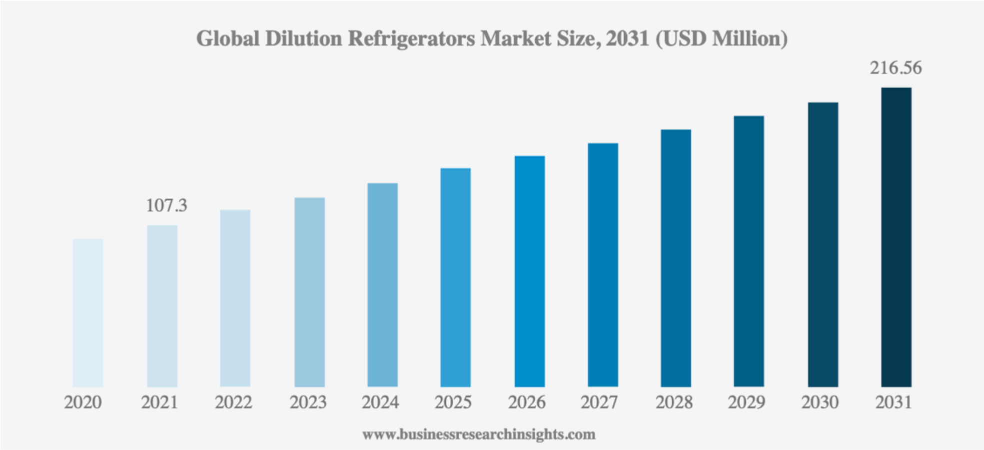
Published: Feb 28, 2024 02:19 AM

Cryo & DRs worldwide market

Estimated cryogenic equipment market growth



DRs market size



References

- F. Pobell – *Matter and Methods at Low Temperatures*
- O.V. Lounasmaa – *Experimental Principles and Methods Below 1 K (Dilution refr.)*
- G. Frossati – *Low Temperature Techniques*
- G. Ventura/L. Risegari – *The Art of Cryogenics*
- J.W. Ekin – *Experimental Techniques For Low Temperature Measurements*
- *LakeShore catalog Appendices (Thermometry)*