

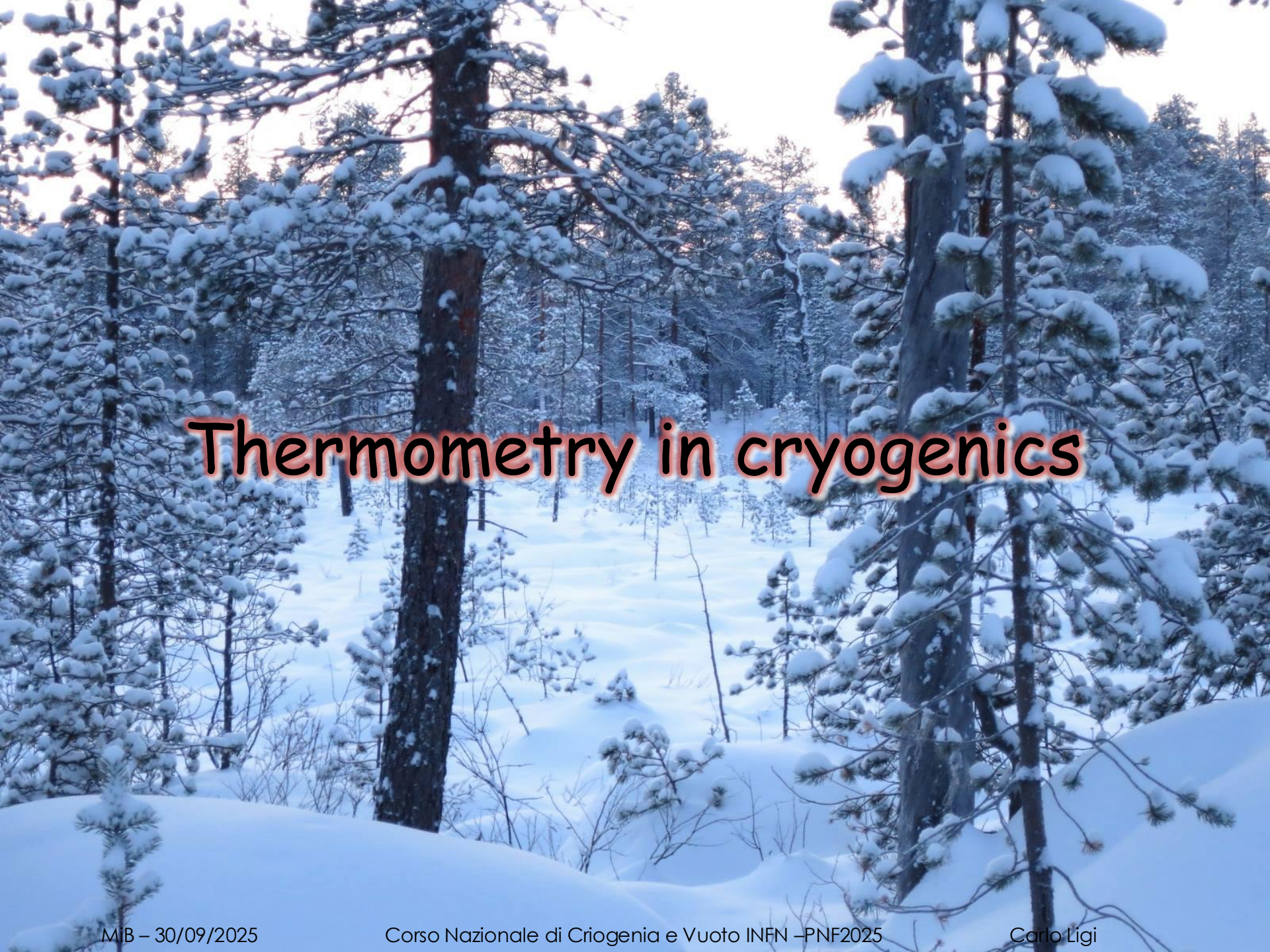
Thermometry in cryogenics

+++++

Refrigeration at $T < 4\text{ K}$



Carlo Ligi INFN-LNF



Thermometry in cryogenics

Thermometry in cryogenics

from ambient temperature down to mK

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
acoustic thermometers
fixed point thermometers
(*phase transition*: boiling point,
freezing point, triple point,
superconducting transition...)

SECONDARY THERMOMETERS

T has a functional dependence from the measured value but one or more parameter are unknown

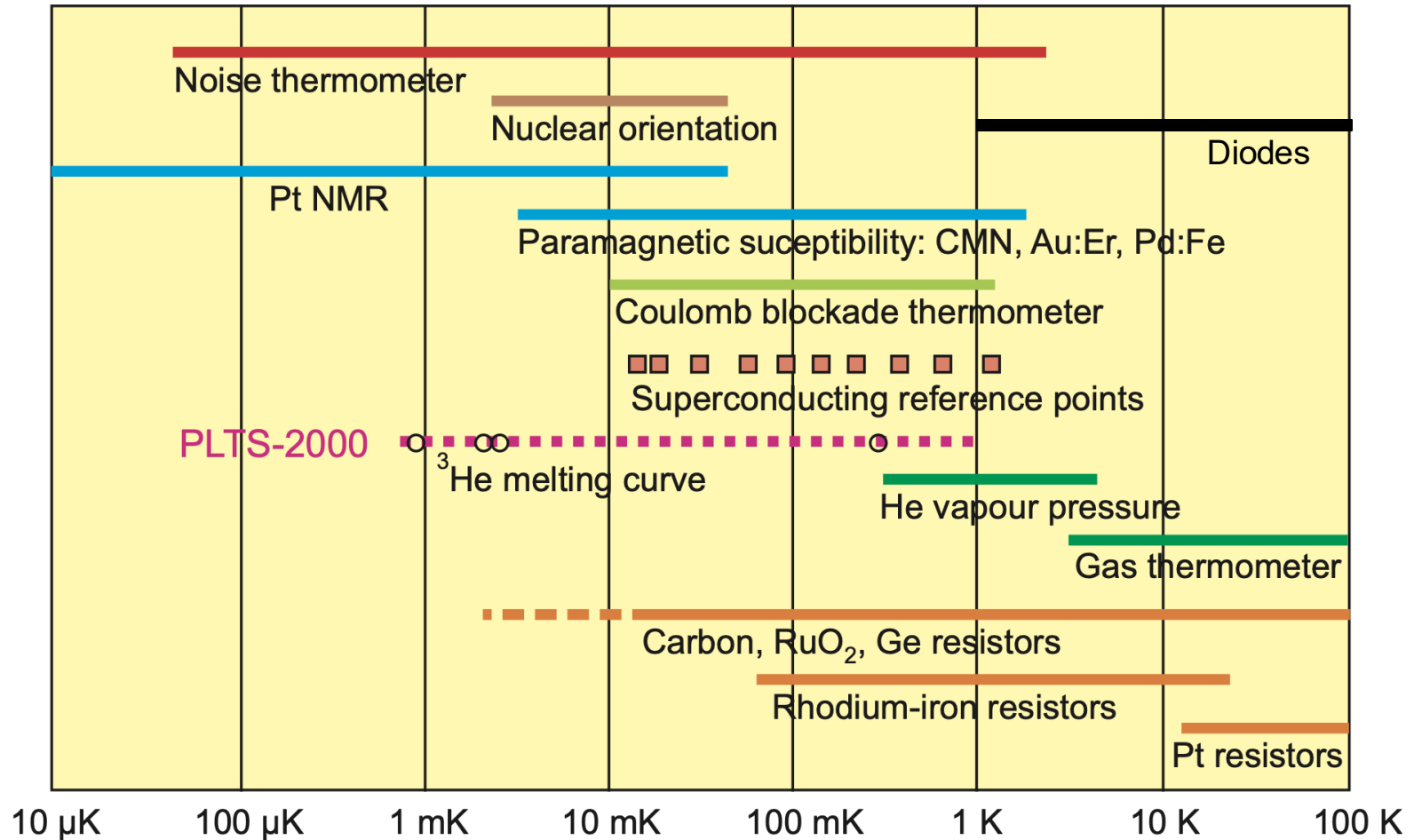
**** Calibration required ****

Example:

carbon resistors
Platinum resistors
RhuteniumOxide resistors
Germanium resistors
Cernox resistors
Silicon diodes
CMN

Thermometry in cryogenics

from mK to ambient temperature

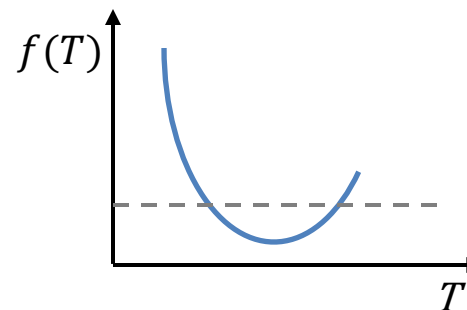
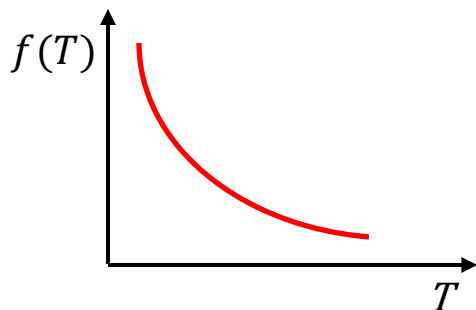


Thermometry in cryogenics

from mK to ambient temperature

Thermometer properties

- **measurement range** ($T(\min) \rightarrow T(\max)$)
- **sensitivity** (how much its signal changes with temperature)
- **relaxation time** (how quickly it follows a change in temperature)
- **necessary power** to read it out (*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

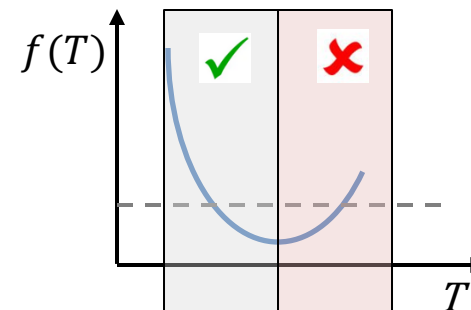
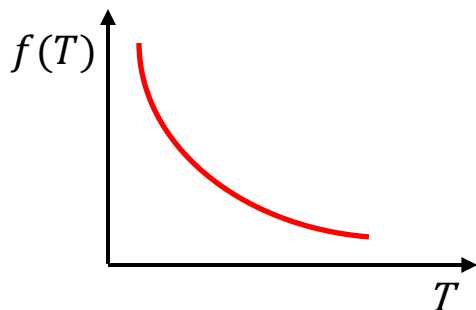


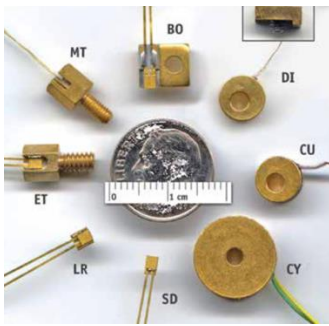
Thermometry in cryogenics

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Resistors

$$0.01 < T < 300 \text{ K}$$

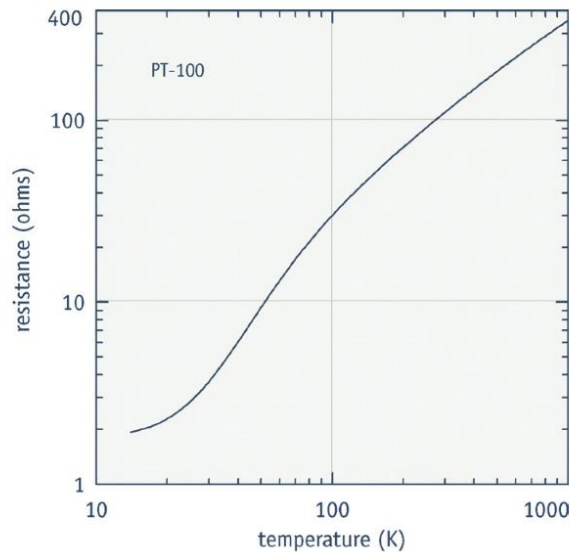


POSITIVE TEMPERATURE COEFFICIENT
(metallic resistors)

Example:

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

Typical platinum resistance

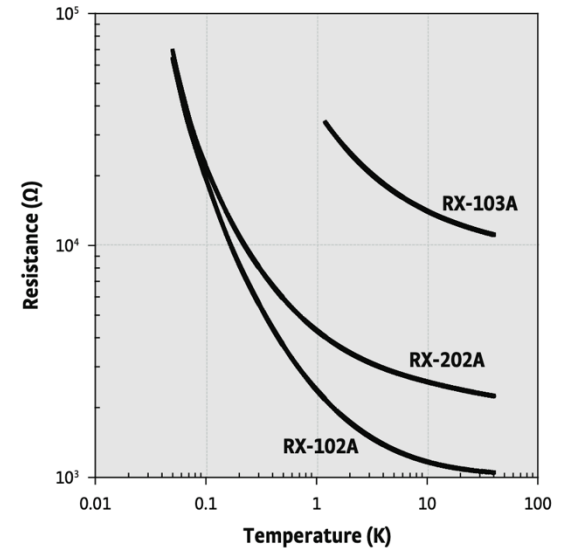


NEGATIVE TEMPERATURE COEFFICIENT
(semiconductors)

Example:

Germanium (0.05 – 100 K)
RhutheniumOxide (0.01 – 40 K)
Cernox (0.1 – 300 K)

Typical Rox™ resistance





Diodes / CMN

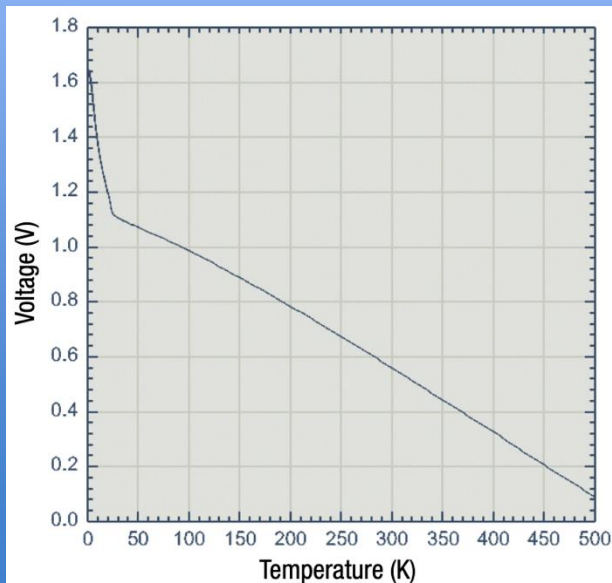


JUNCTION DIODES

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

Excitation: typ. 10 μA

Range: 1.4 – 500 K

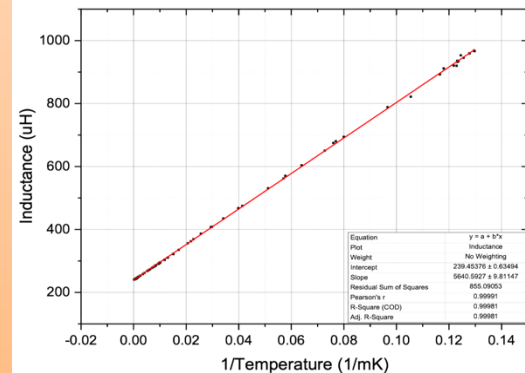
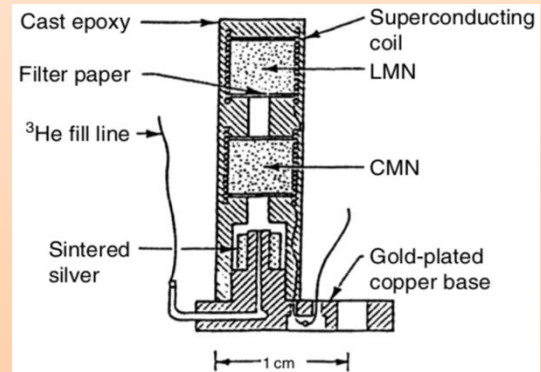


CMN (cerium magnesium nitrate)

(Paramagnetic salt thermometers)

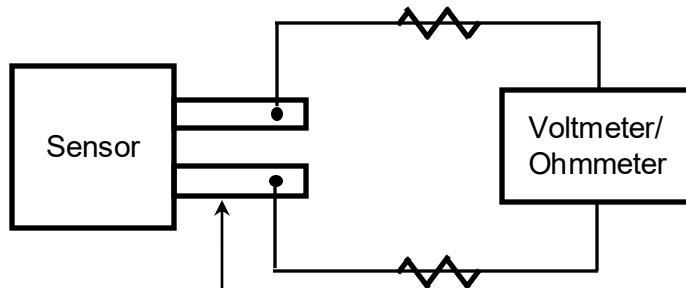
$L \sim 1/T$ dependence

Range: 0.001 – 2 K



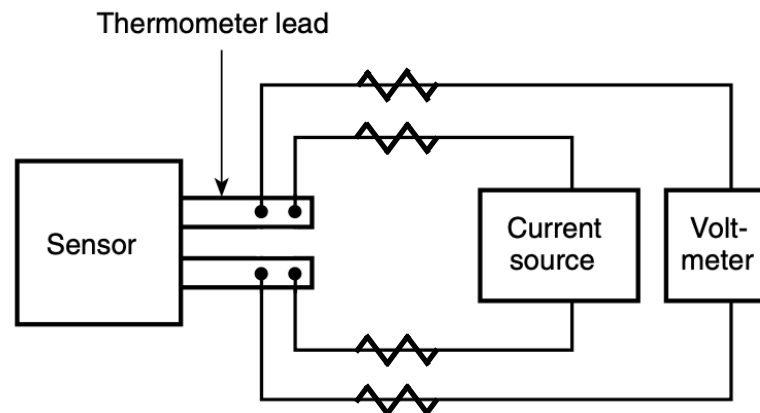
T measurement instrumentation

(resistors, diodes, inductance...)



2-lead measurement

$\rightarrow R_{\text{measured}} = R(\text{sensor}) + R(\text{wires})$



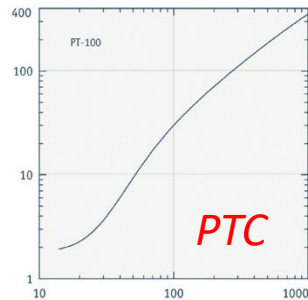
4-lead measurement

$\rightarrow R_{\text{measured}} = R(\text{sensor})$
($R(\text{wires})$ contribution is cancelled)

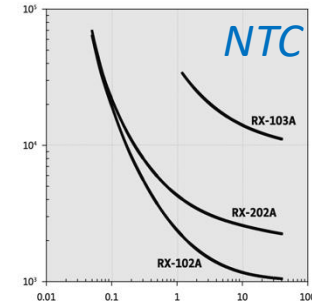
T measurement instrumentation

(resistors, diodes, inductance...)

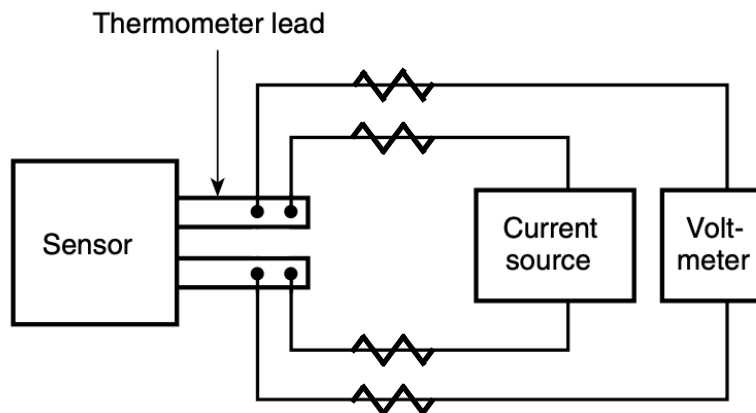
4-lead measurement



Positive Temperature Coefficient resistors
 → *constant CURRENT measurement*
dissipated power = $I^2 \cdot R$



Negative Temperature Coefficient resistors
 → *constant VOLTAGE measurement*
dissipated power = V^2 / R



SELF HEATING
is the effect of T raise inside a thermometer due to the power dissipated by the current passage in the resistor

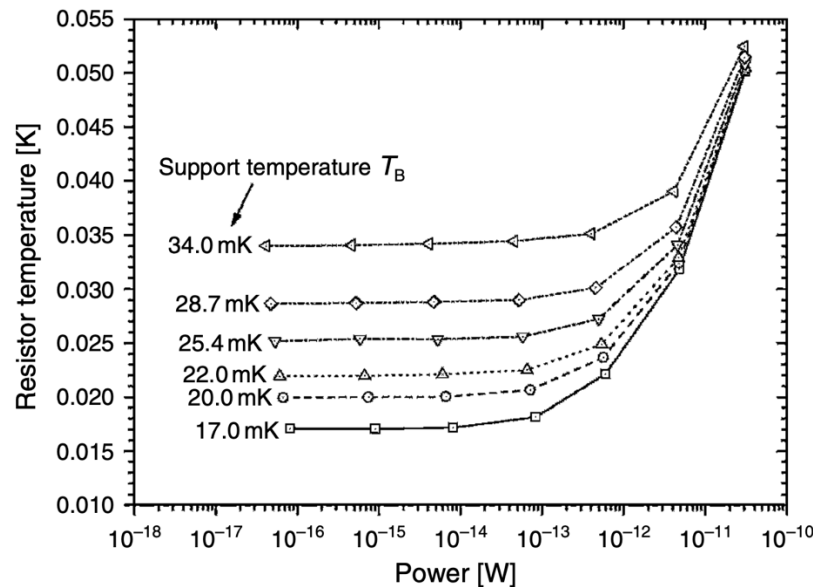
T measurement instrumentation

(resistors, diodes, inductance...)

How much electrical power we can send to a resistor to read it?

*There is always a thermal resistance 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**.*

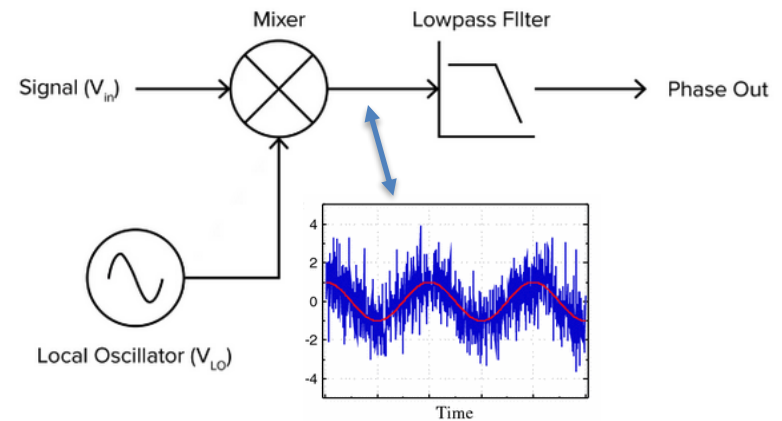


Overheating of an RuO_2 thermometer as a function of temperature for six different support temperatures.

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

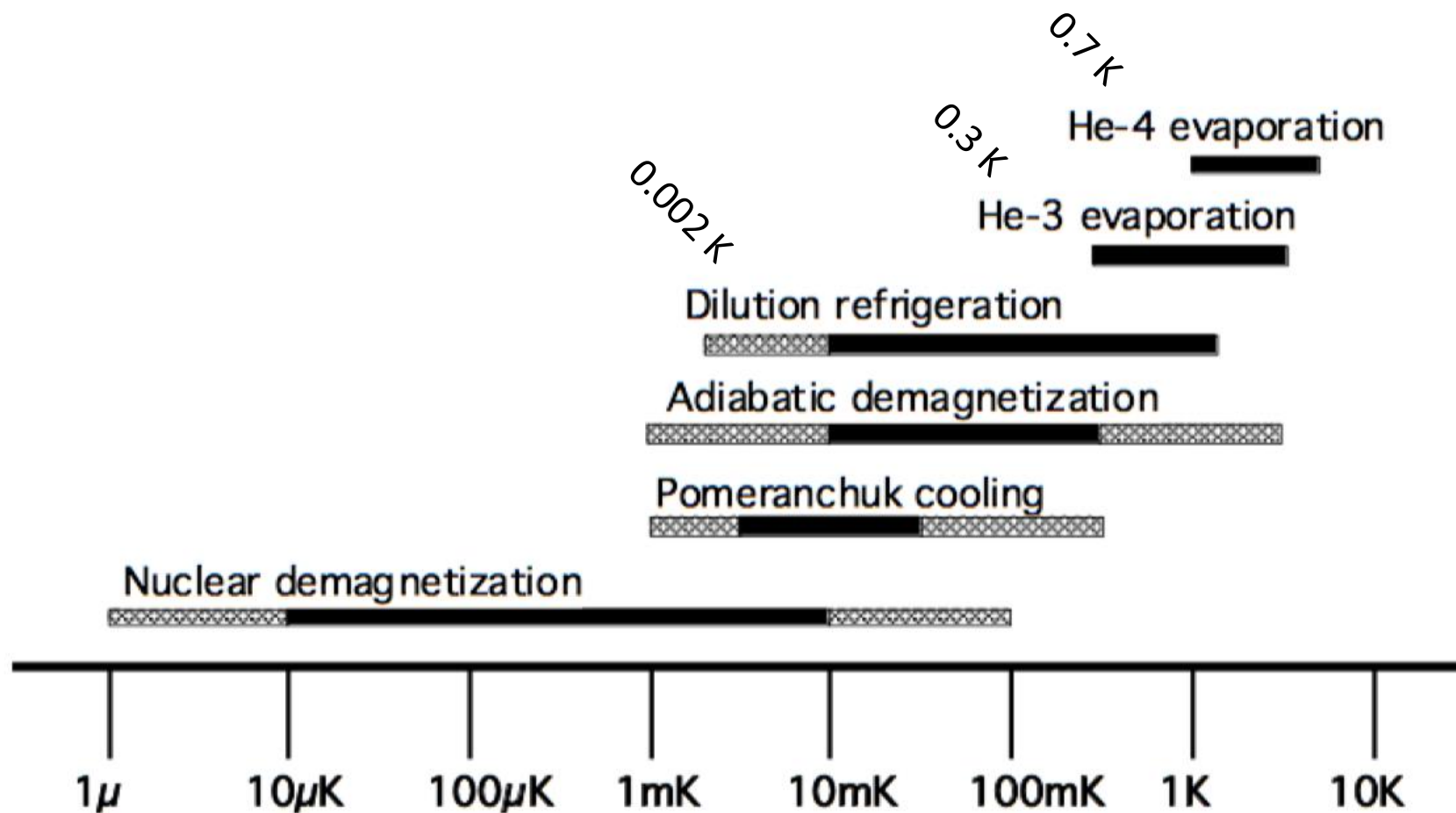
- *self heating in resistors*
- *poor thermal contact*
- *wiring (heating from the wires, poor thermal/electrical isolation...)*
- *wrong positioning of the thermometer*
- *magnetic fields / RF power*





Refrigeration at $T < 4\text{ K}$

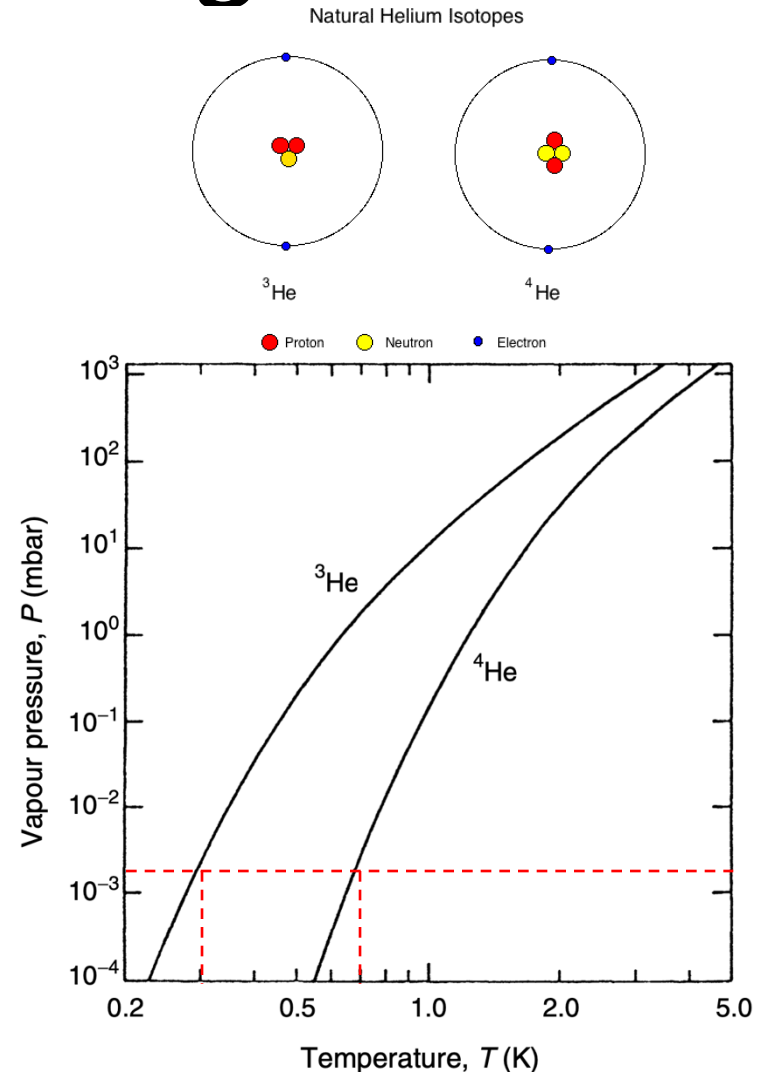
Cryogenics in the Kelvin range



Cryogenics below 1 K

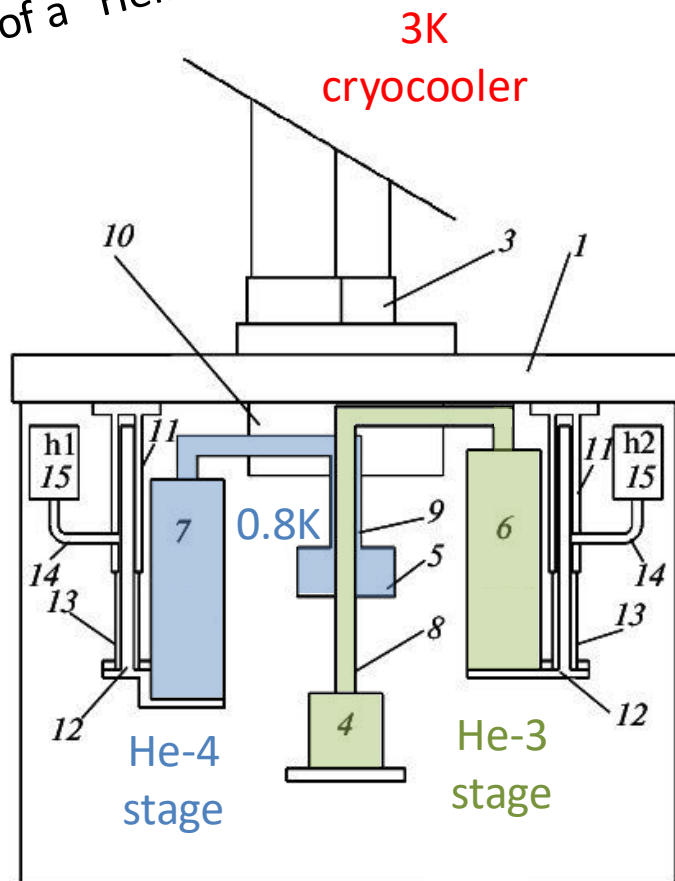
^4He and ^3He evap. refrigerators

- ^4He is 5 ppm in atmosphere, so it is extracted from natural gas by distillation, adsorption and other methods
- ^3He 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 lower T? Liquefy some gas and reduce the pressure over the bath
- ^4He evaporation $\rightarrow$ down to 0.7 K
- ^3He evaporation $\rightarrow$ down to 0.3 K
 - ^4He gas cost: 30 €/m³ STP
 - ^3He gas cost: 3 million €/m³ STP



Cryogenics below 1 K

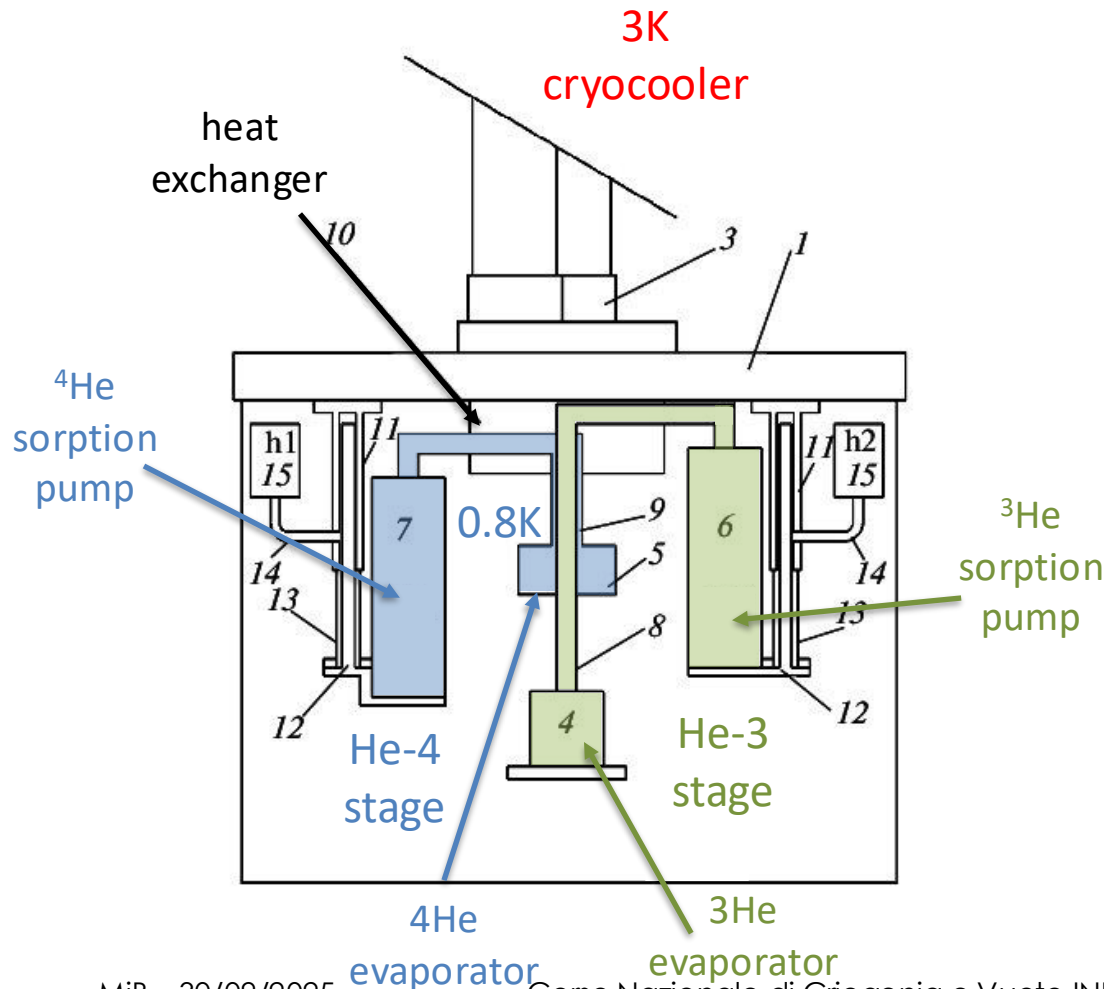
Scheme of a “Helium-seven” fridge



^3He closed-cycle refrigerator

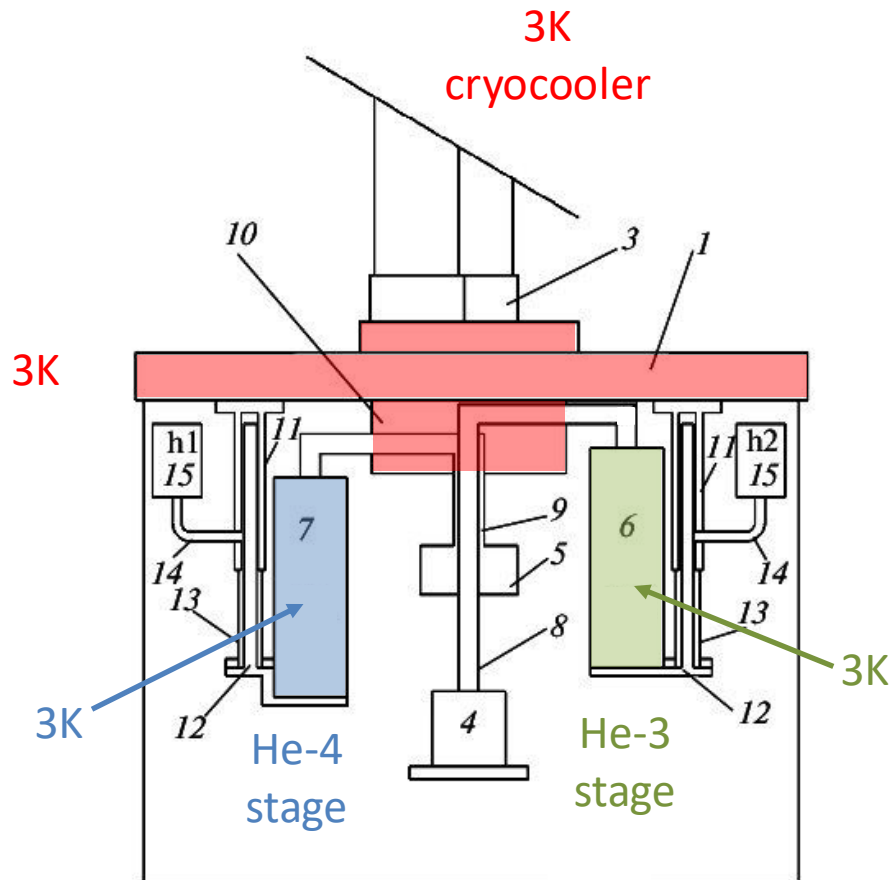


Cryogenics below 1 K



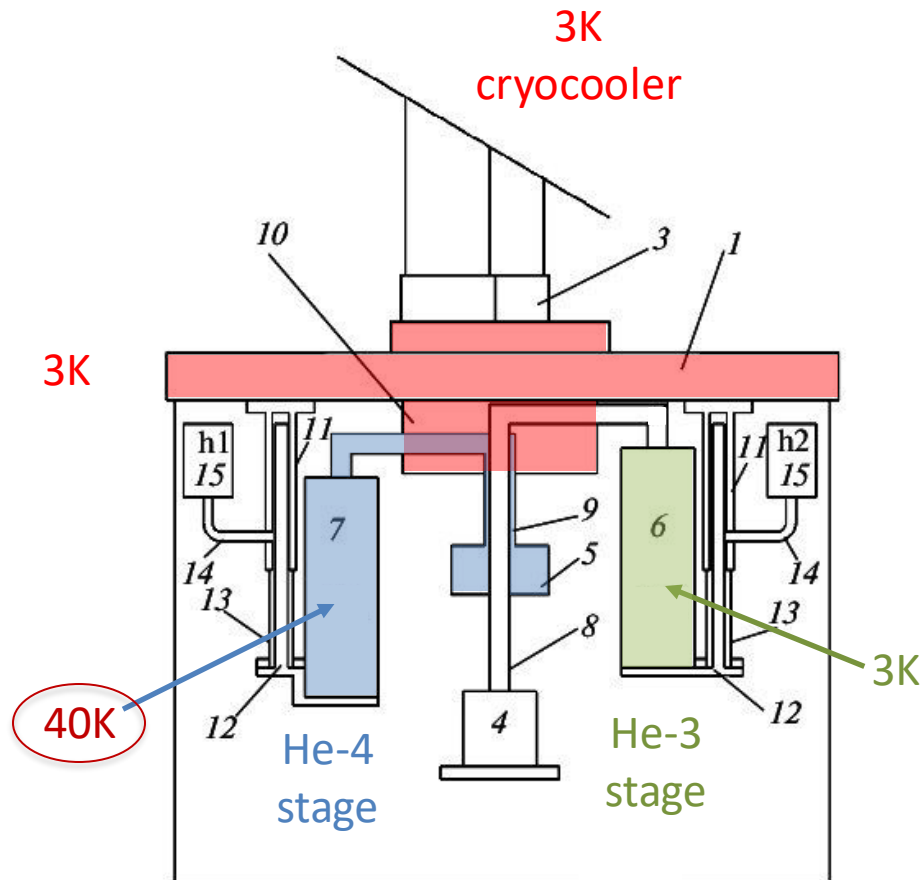
- The fridges are composed by an evaporator connected to a sorption pump full of active charcoal
- Both ^3He and ^4He stages are charged with gas at ambient T and sealed
- Precooled with a 3-4 K source (cryocooler or liquid Helium)

Cryogenics below 1 K



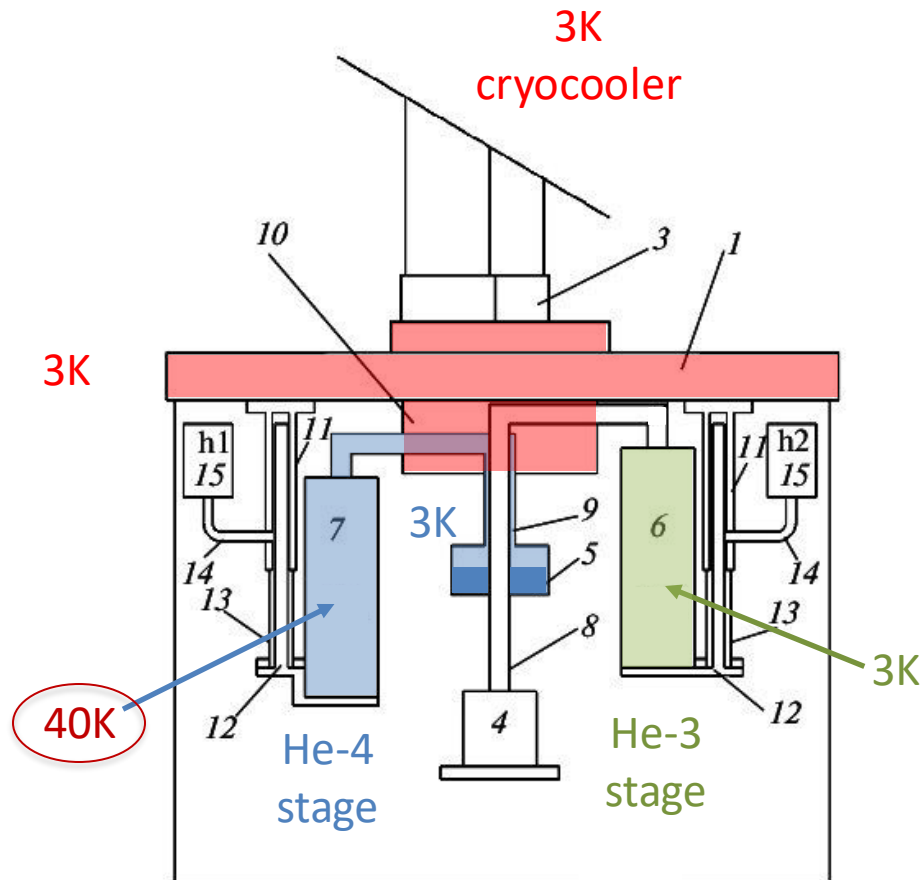
- The ^3He and ^4He refrigeration process start with the absorption of the gases into the sorption pumps

Cryogenics below 1 K



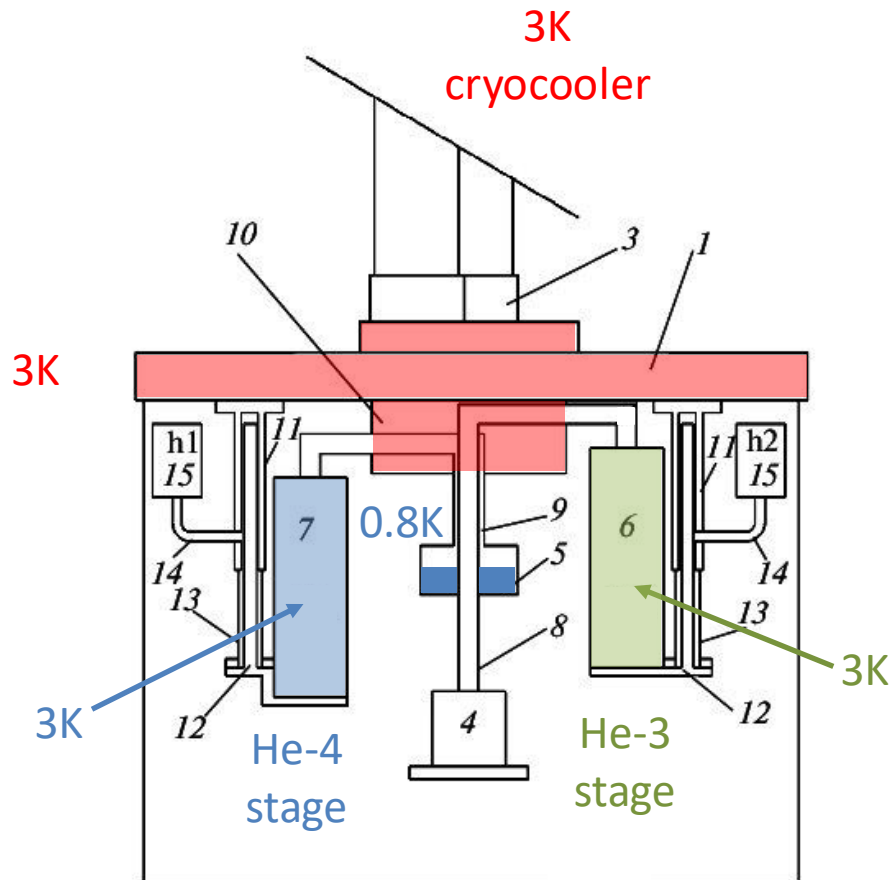
- Then, the ^4He sorption pump are heated to 40 K, so the gas is desorbed and go in the tube, is cooled down by the cryocooler via the heat exchanger and condense inside the evaporator

Cryogenics below 1 K



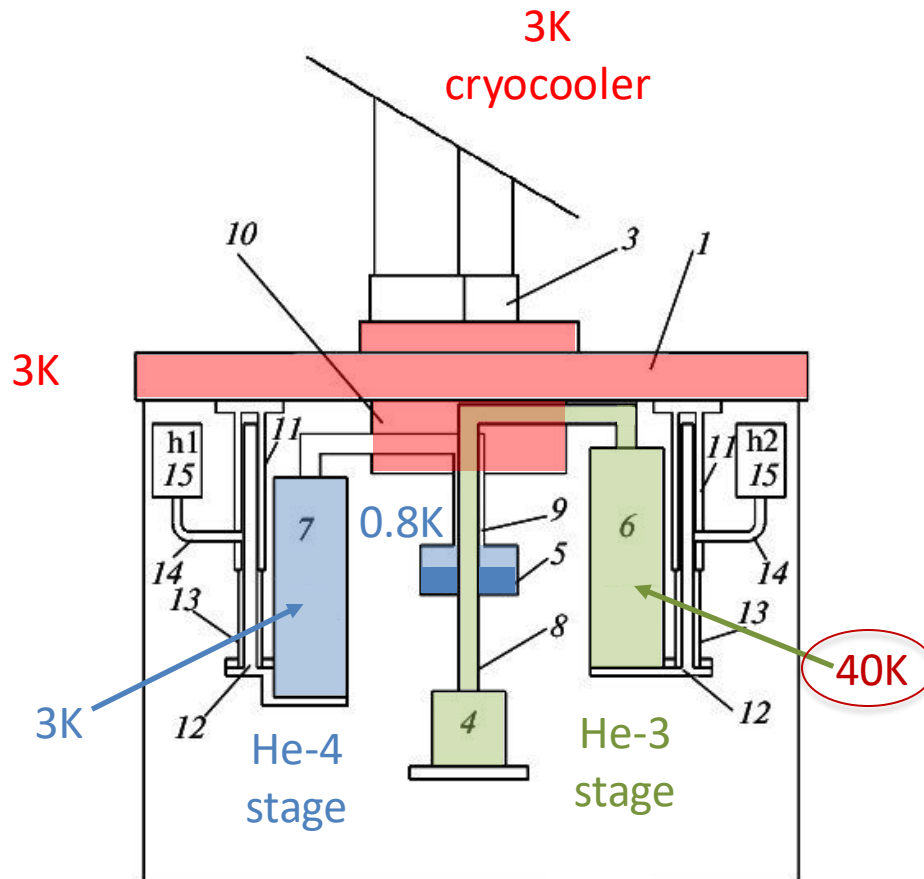
- After a while, some liquid ^4He fills the evaporator

Cryogenics below 1 K



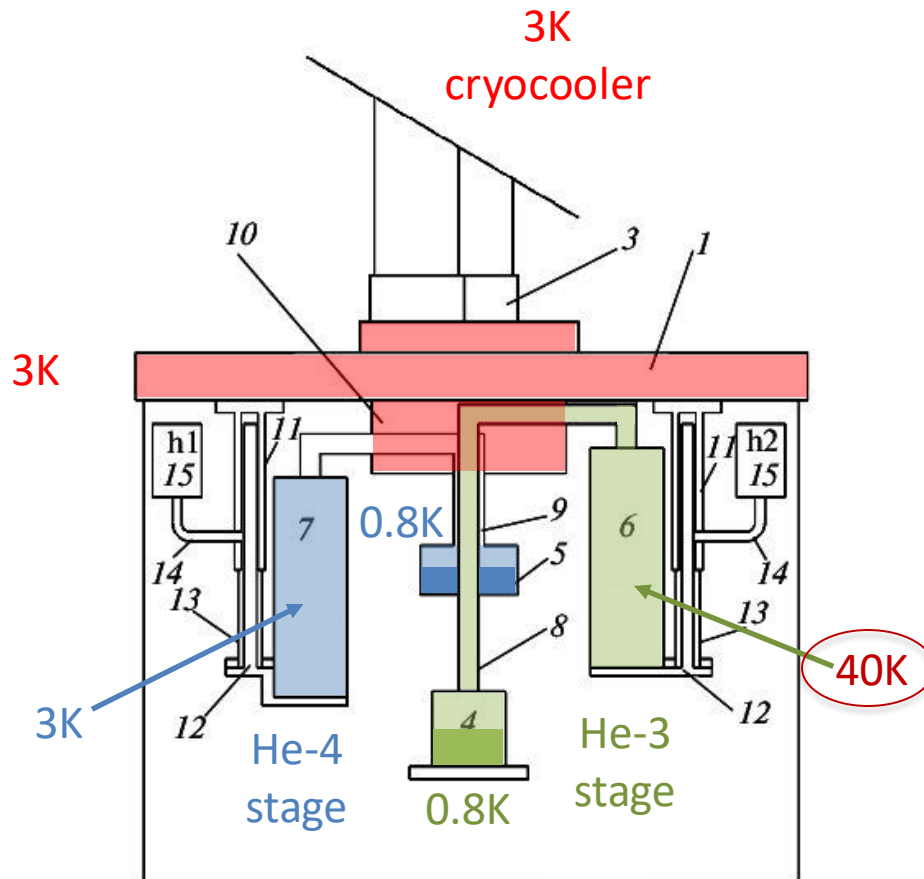
- Then, we stop to heat the sorption pump, so it will return to about 3 K, restarting to pump on the vapour ^4He . This will drop down the pressure on the liquid bath, lowering its temperature. Typically T reach 0.8 K

Cryogenics below 1 K



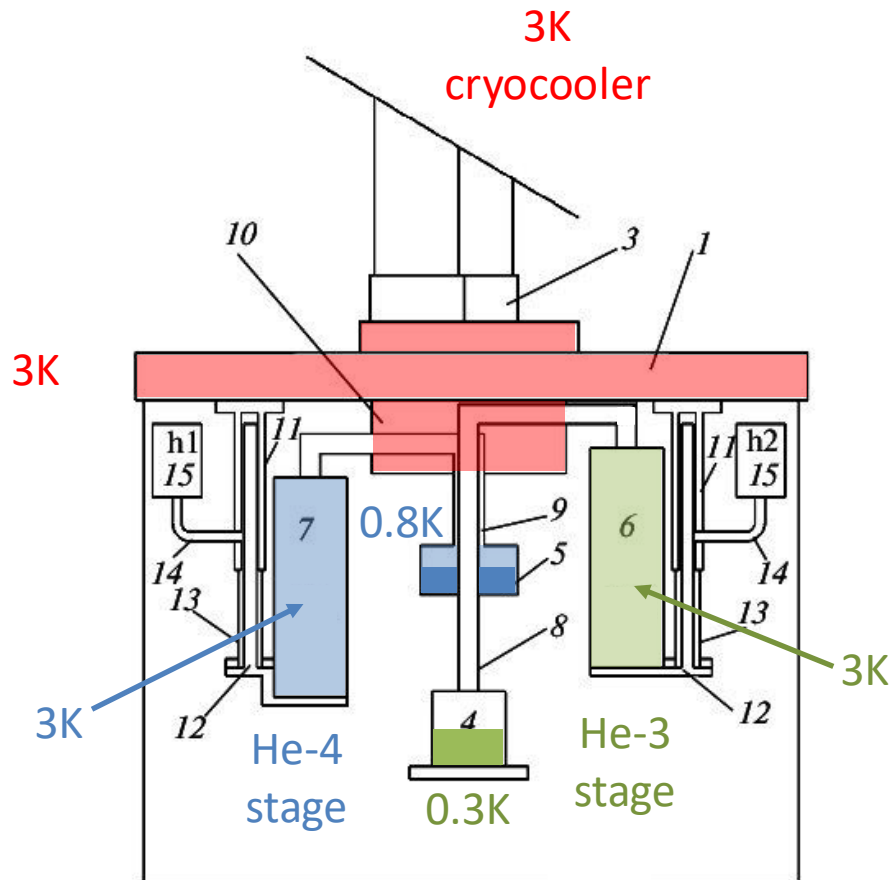
- Now, we can repeat the same cycle on the ^3He stage, starting to heat the pump

Cryogenics below 1 K



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

Cryogenics below 1 K



- Stopping heating the ^3He sorption pump will cool it at 3 K, causing the pressure drop over the ^3He 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

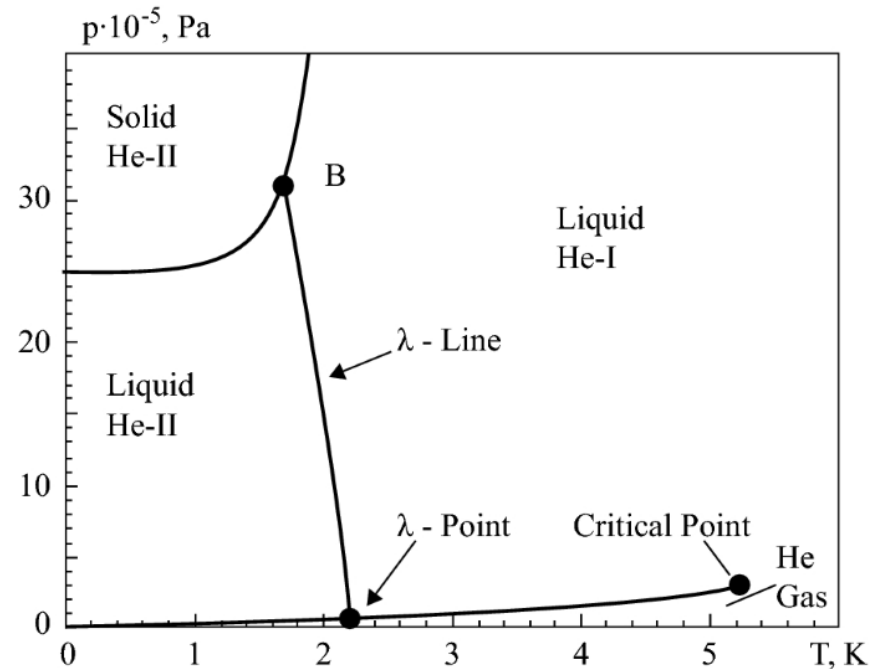
ONLY ^4He AND ^3He shows this effect

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 is different. ^4He is a BOSON (spin zero) while ^3He is a FERMION (spin $\frac{1}{2}$)

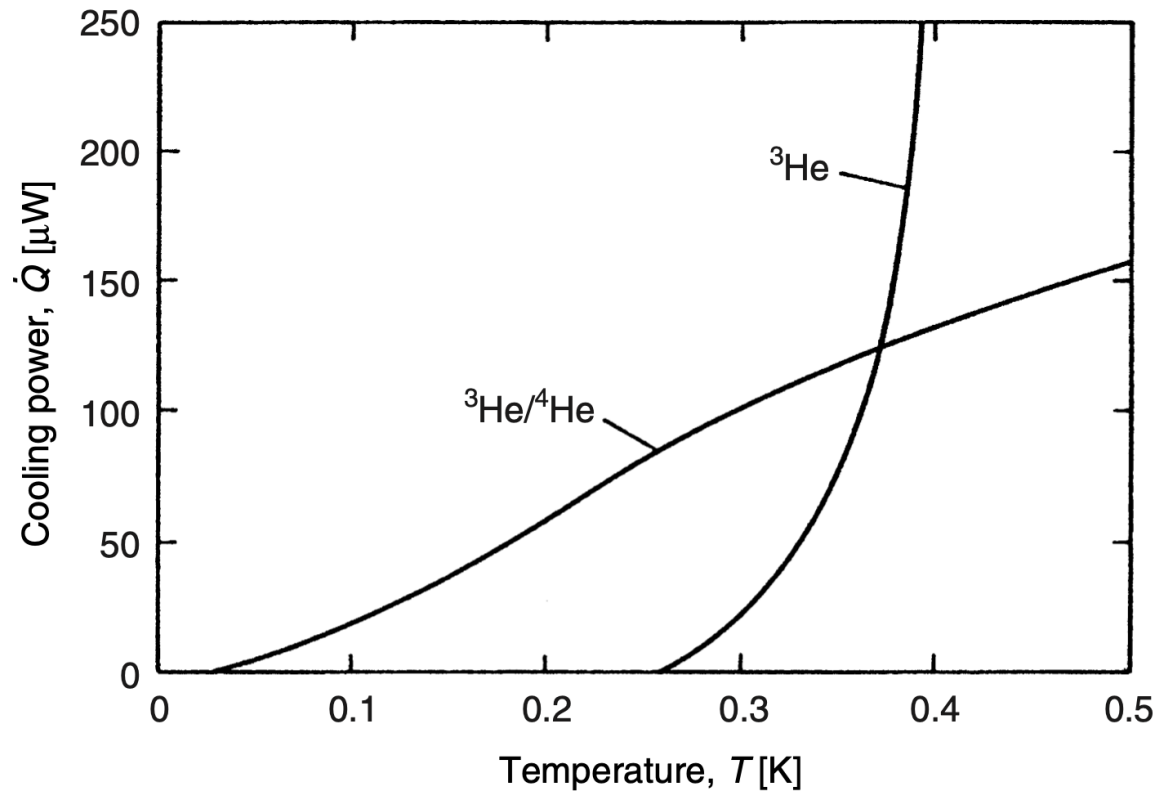
^4He becomes superfluid at about 2.17 K, while ^3He makes the transition at a few mK

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



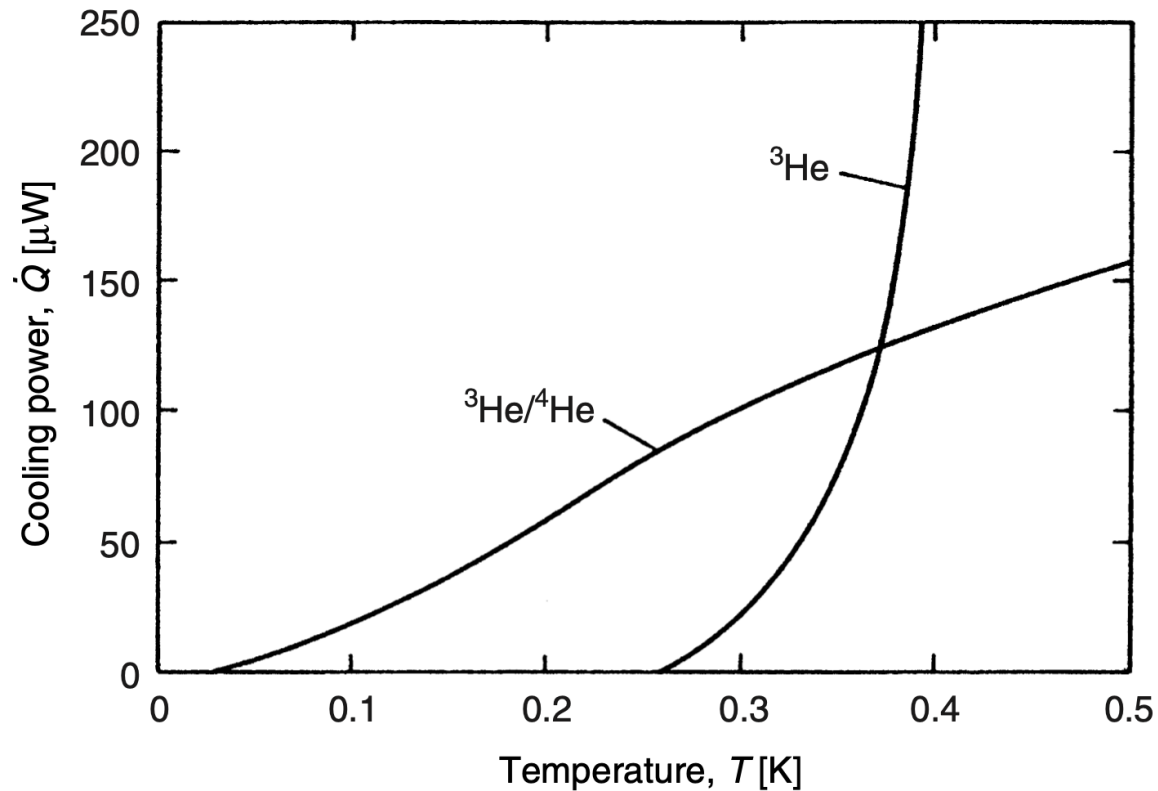
Cryogenics below 300 mK

What below 300 mK???



Cryogenics below 300 mK

What below 300 mK???



${}^3\text{He} / {}^4\text{He}$ DILUTION REFRIGERATION

Cryogenics below 300 mK

Dilution Refrigerator

Adiabatic Demagnetization
of paramagnetic salt

Cryogenics below 300 mK

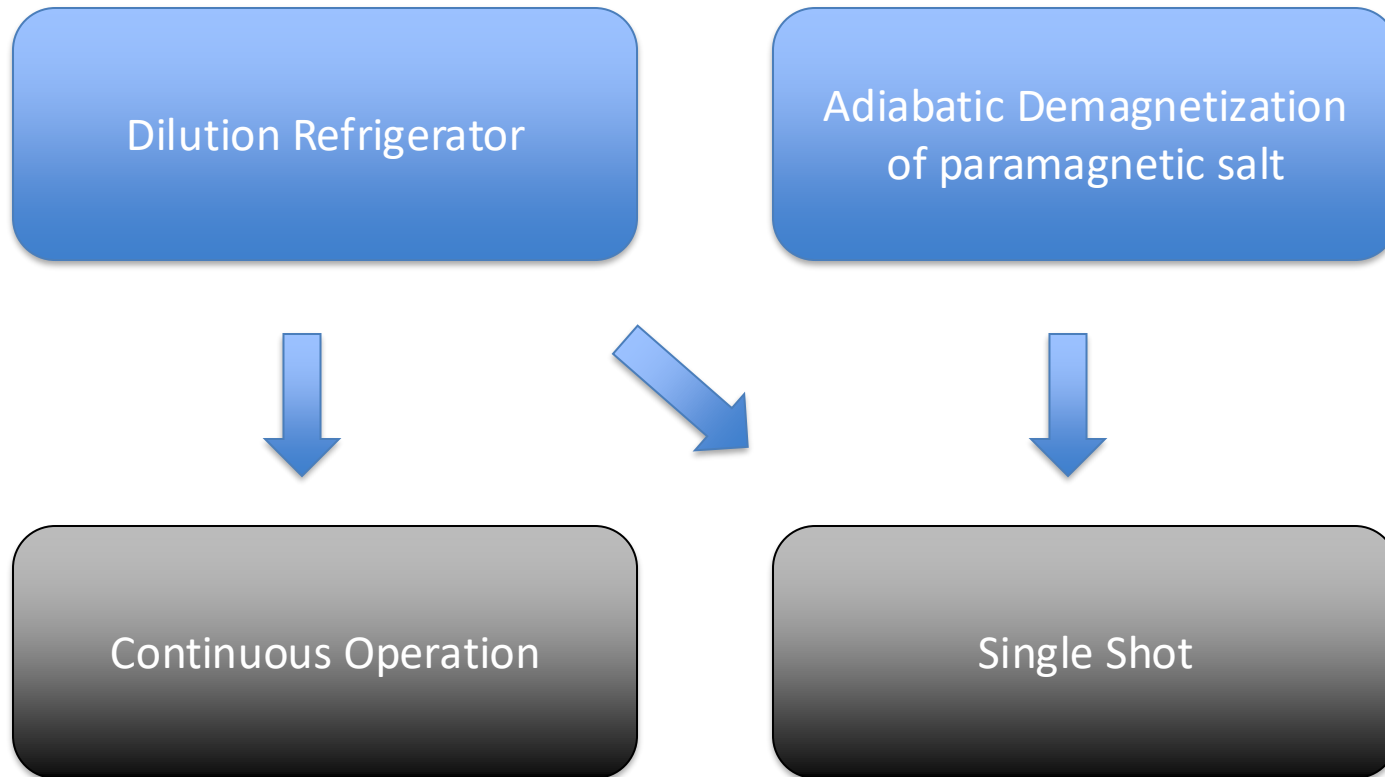
Dilution Refrigerator

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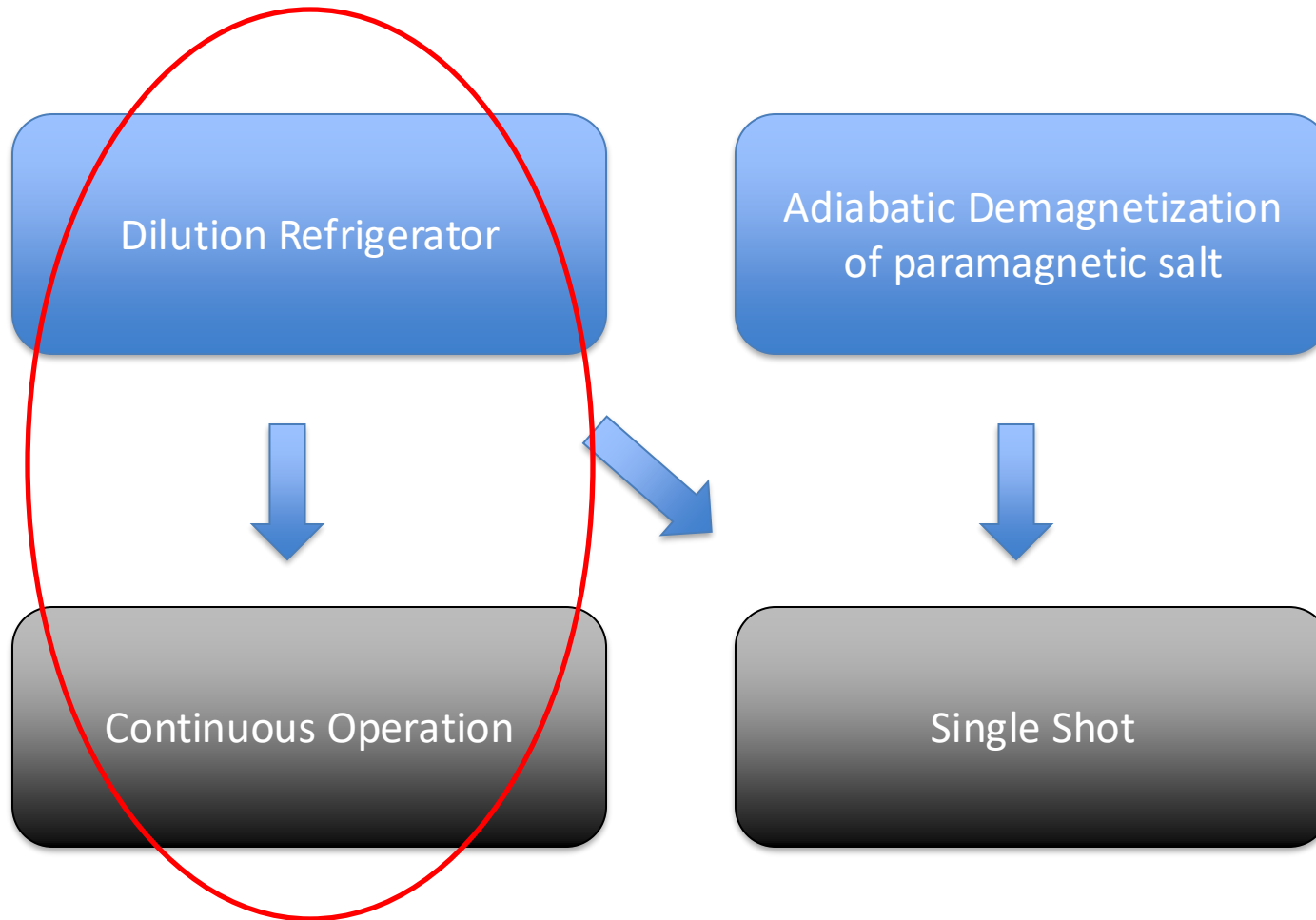
Continuous Operation

Single Shot

Cryogenics below 300 mK



Cryogenics below 300 mK



This is the only way to CONTINUOUSLY cool below 300 mK

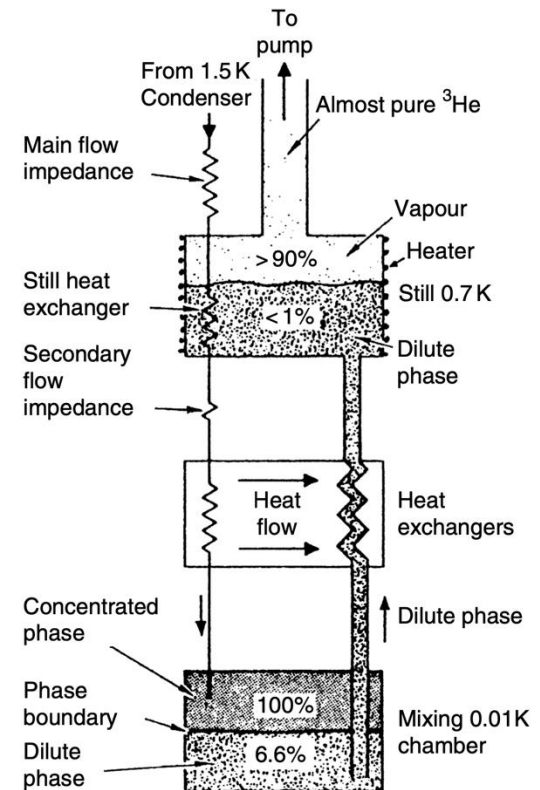
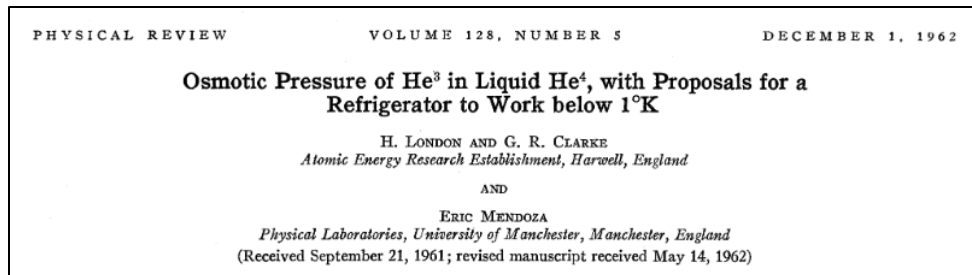
Dilution Refrigerators

1951 : Principle suggested by London

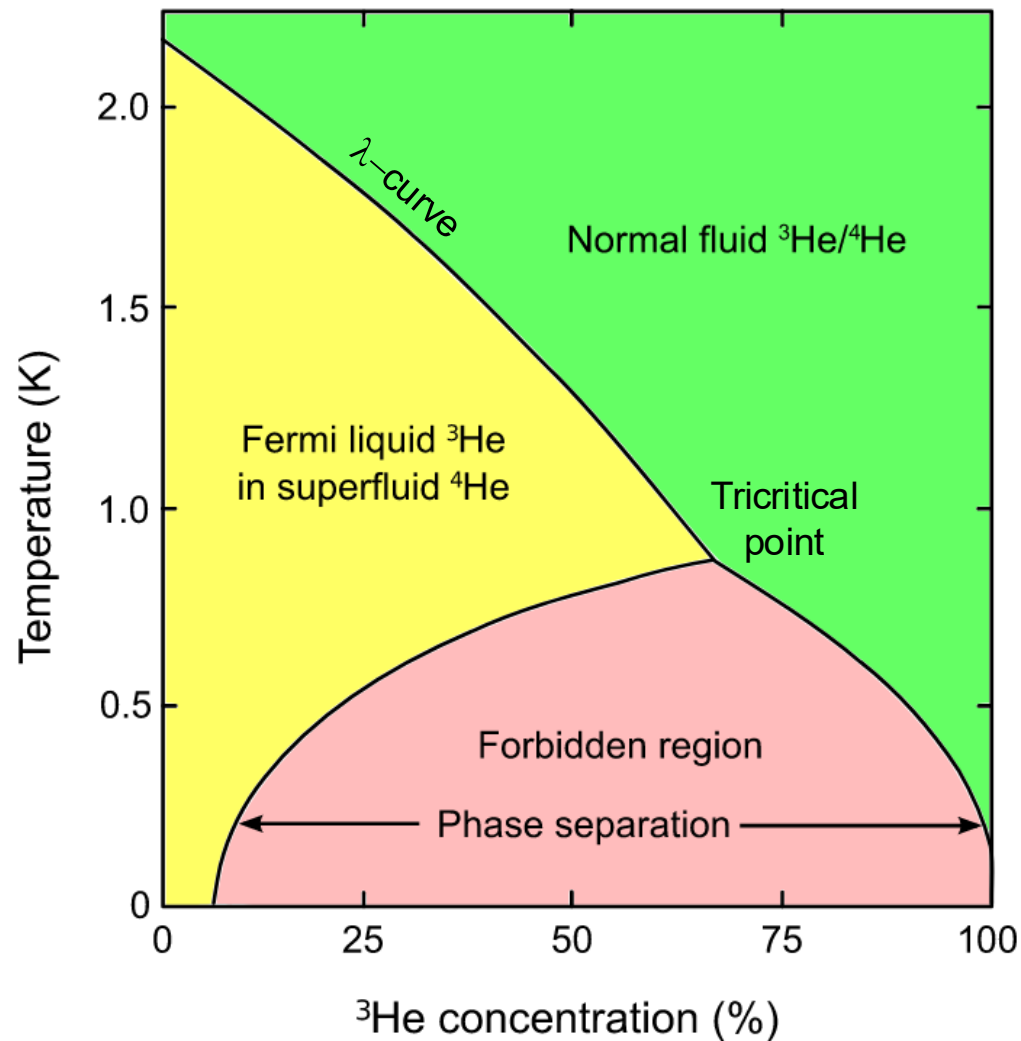
1965 : First prototypes at Leiden

1968 : 5.5 mK (continuous mode)

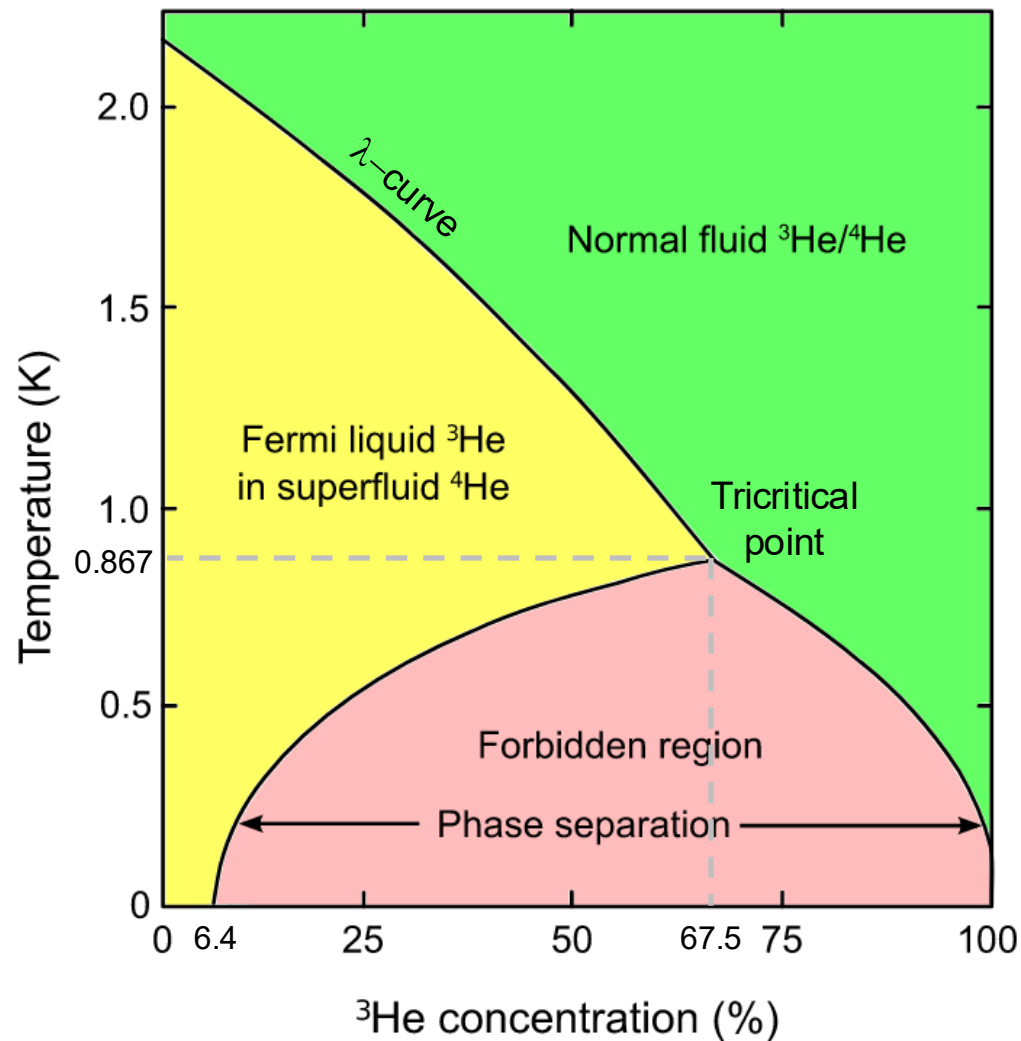
1972 : 3 mK (single cycle)



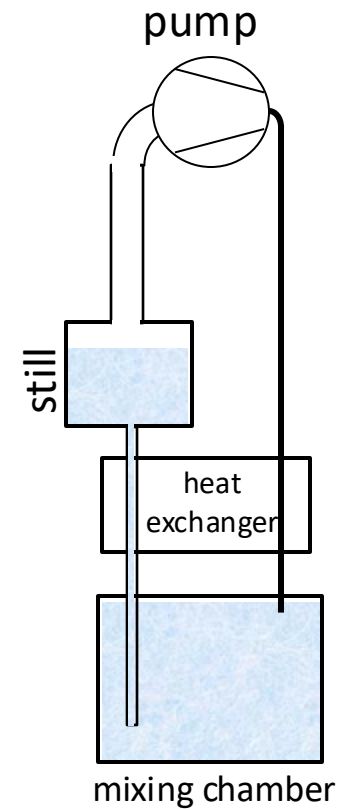
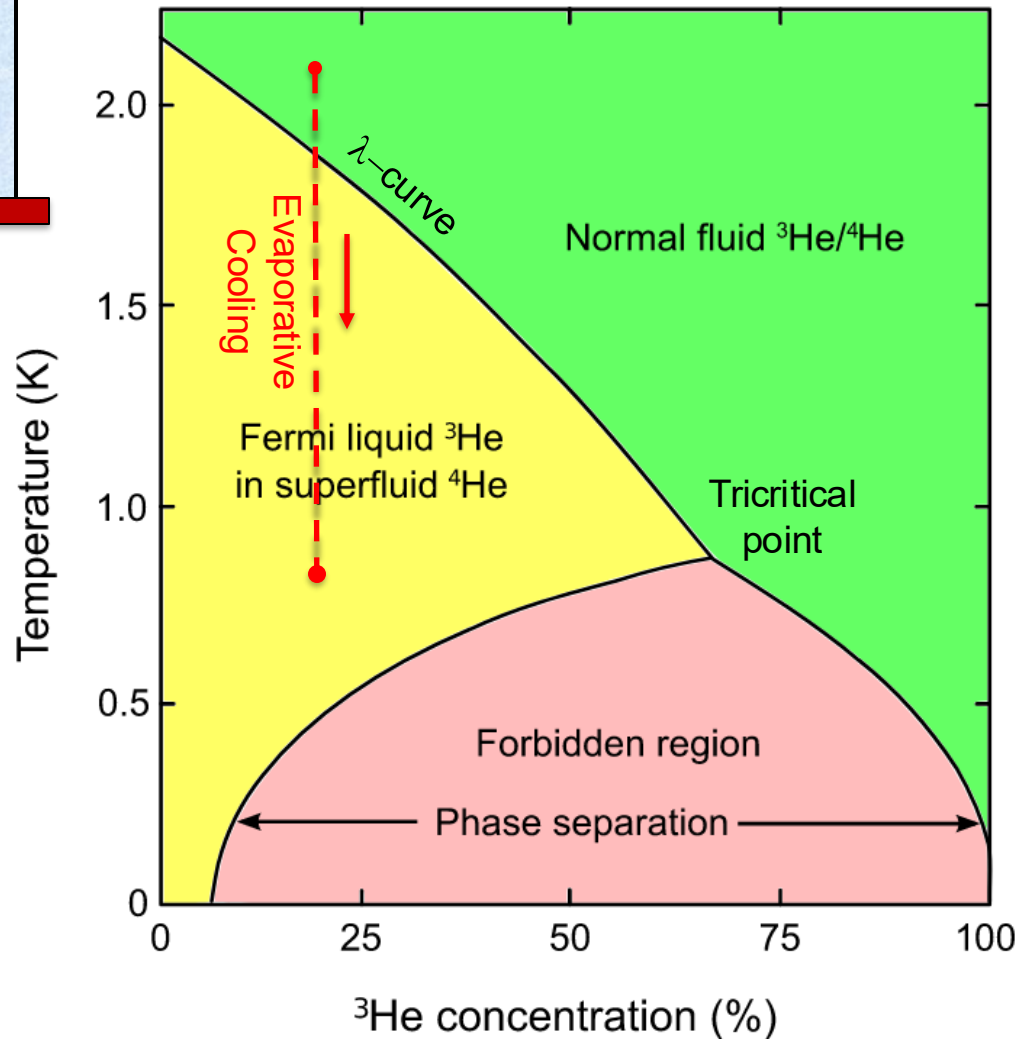
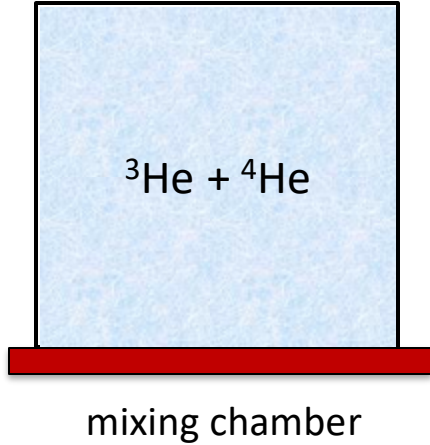
$^3\text{He}/^4\text{He}$ Mixture



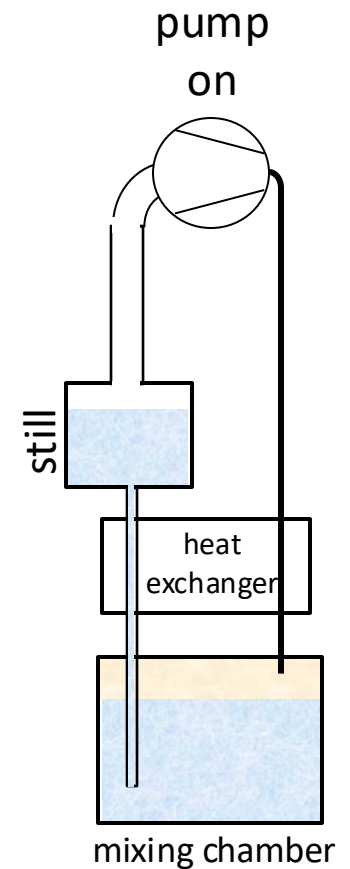
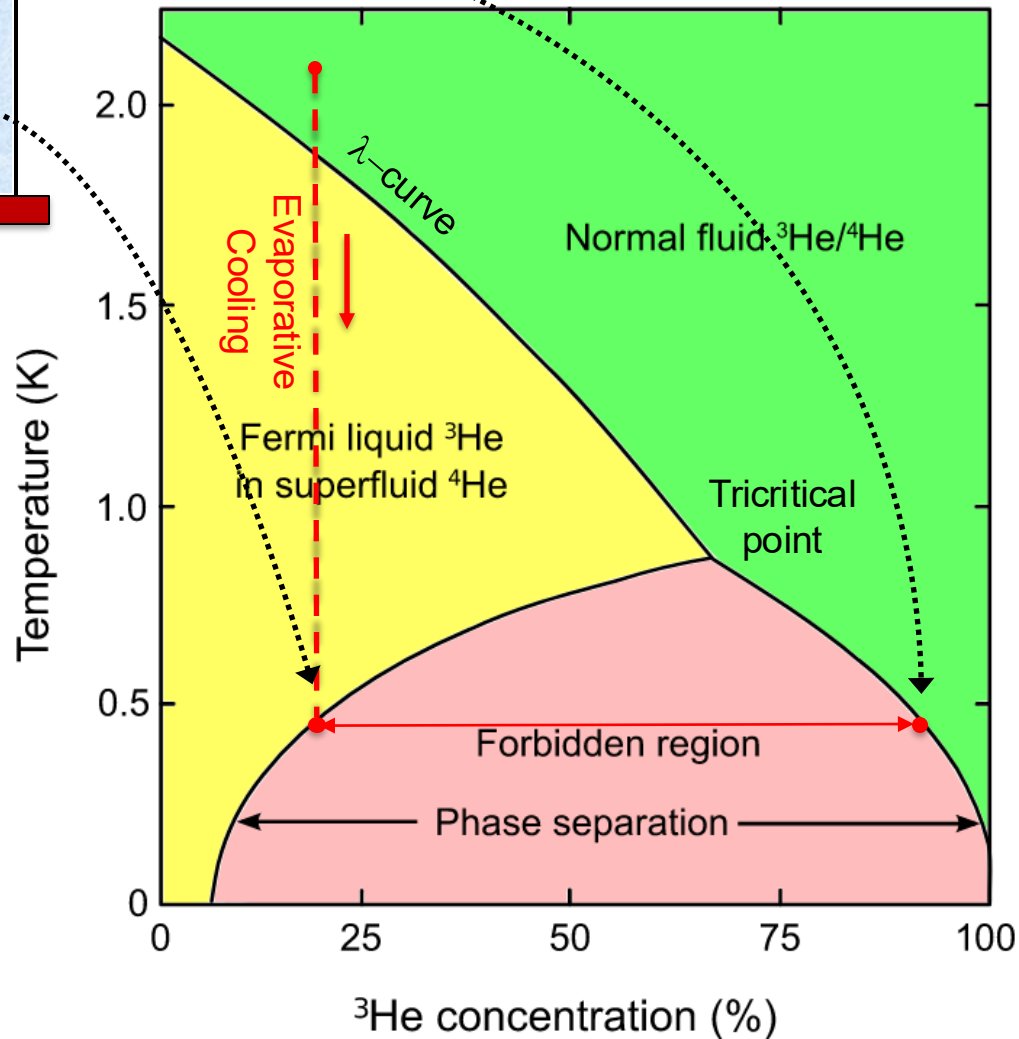
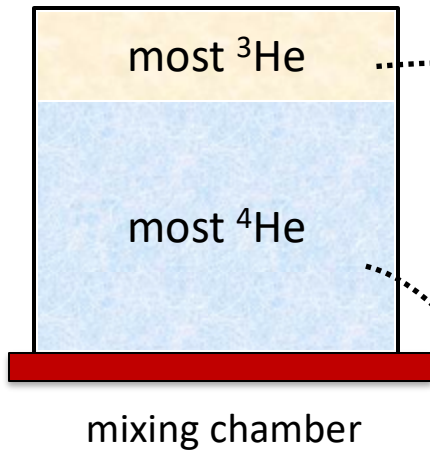
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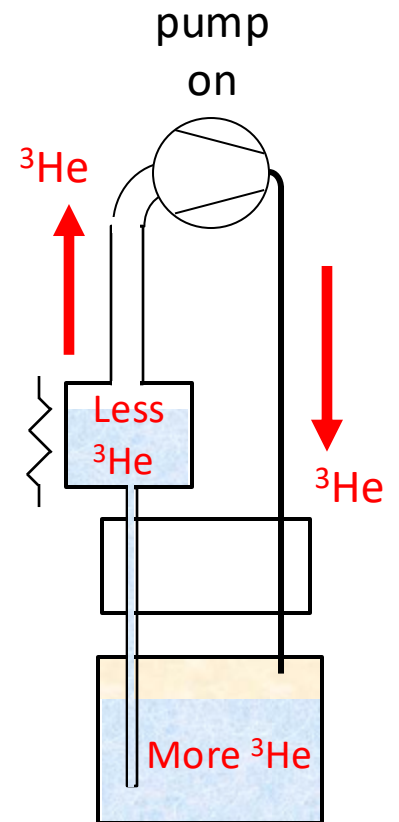
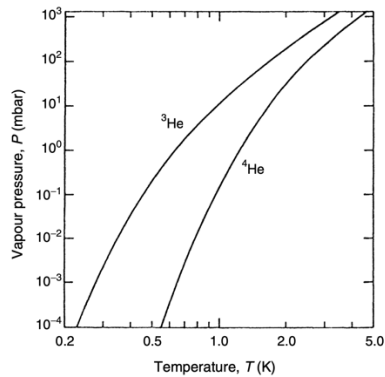
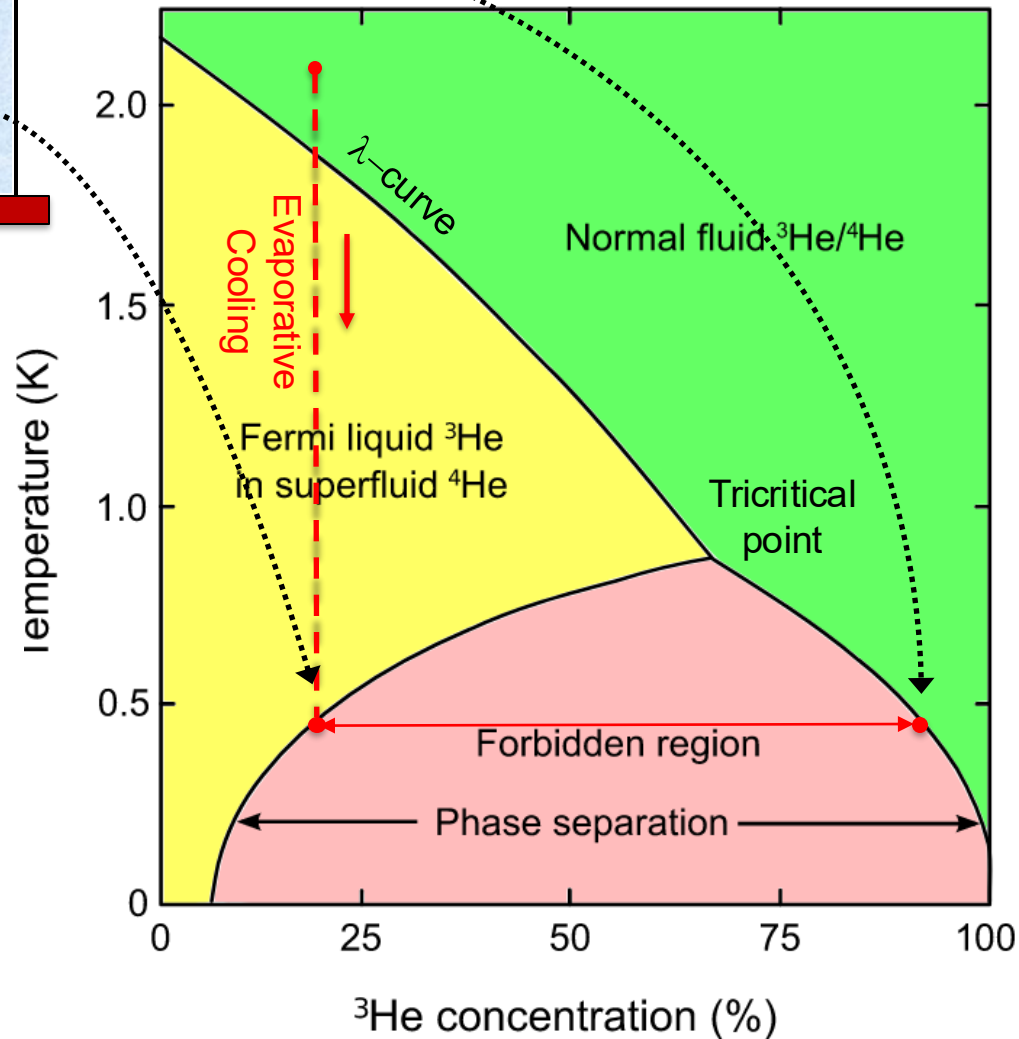
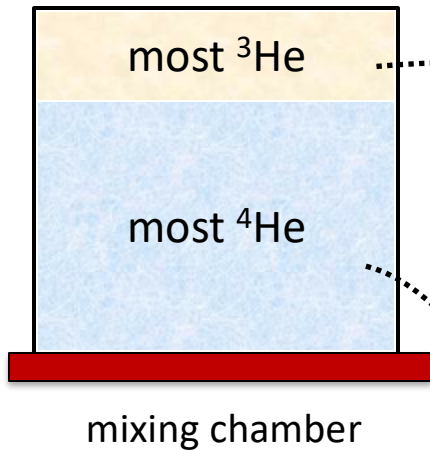
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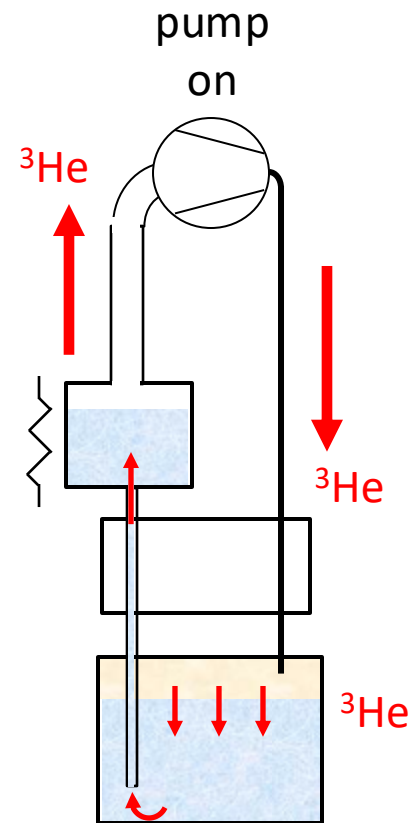
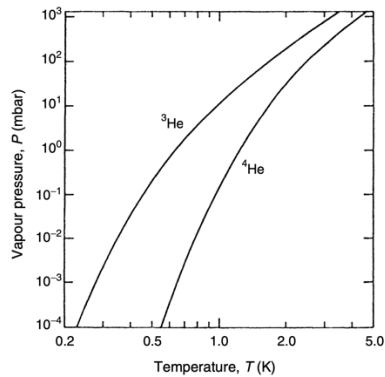
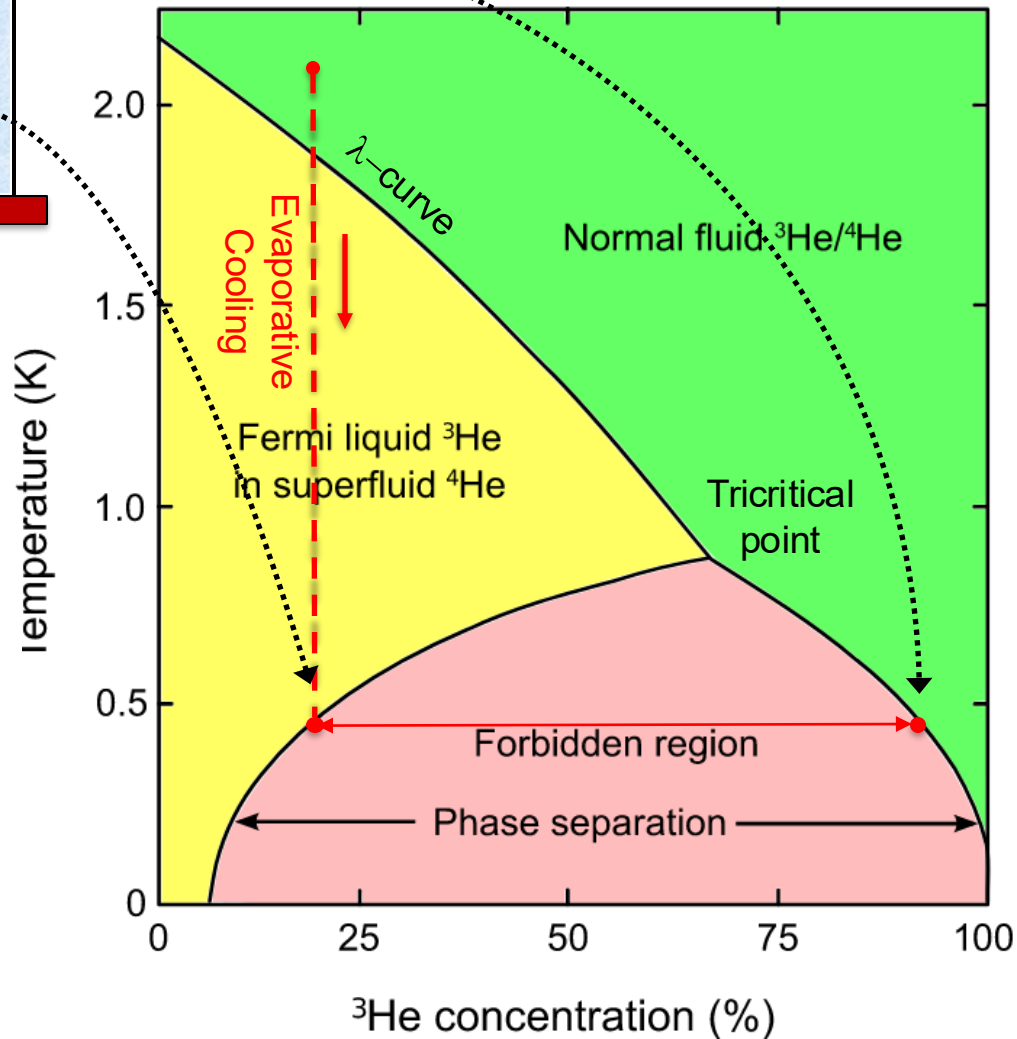
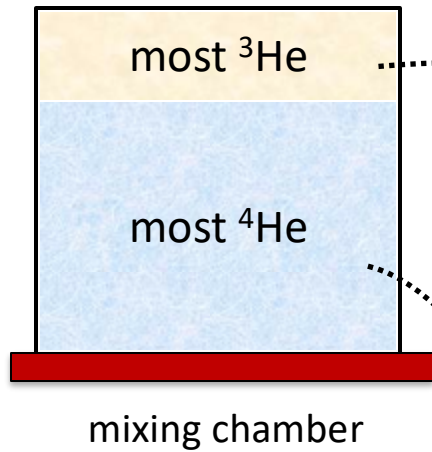
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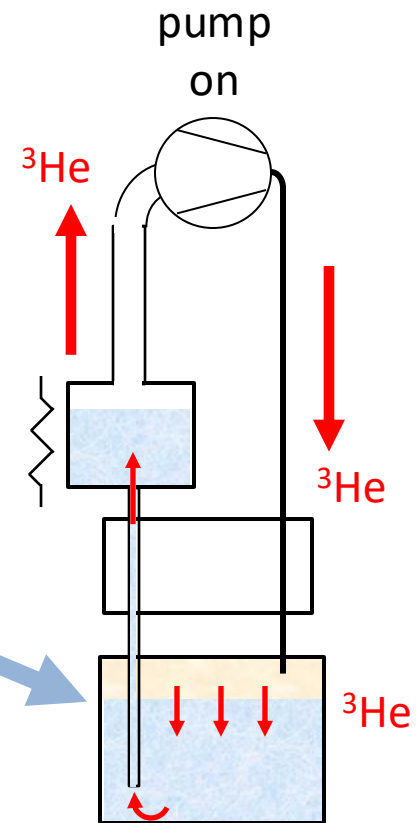
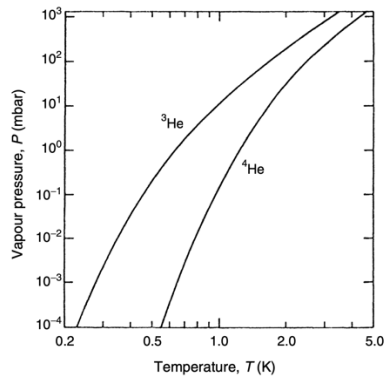
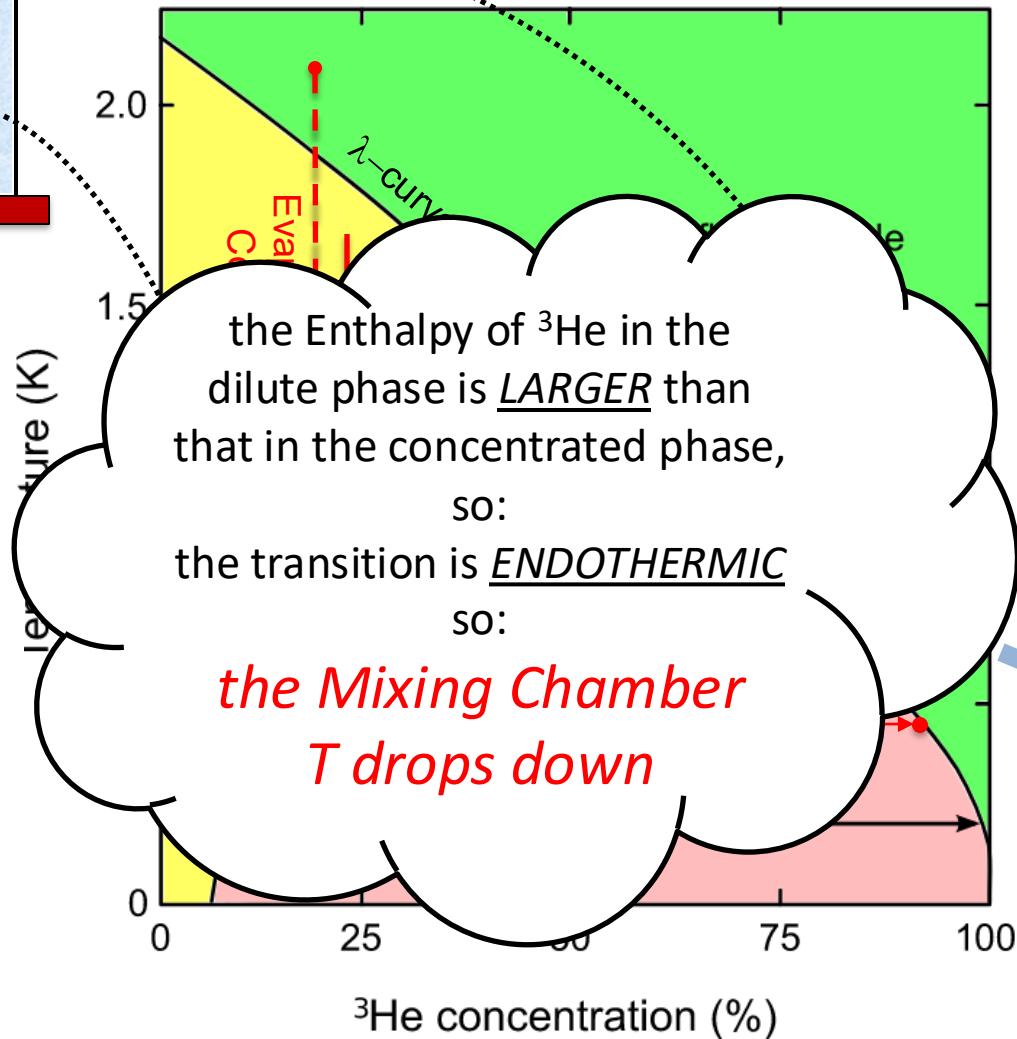
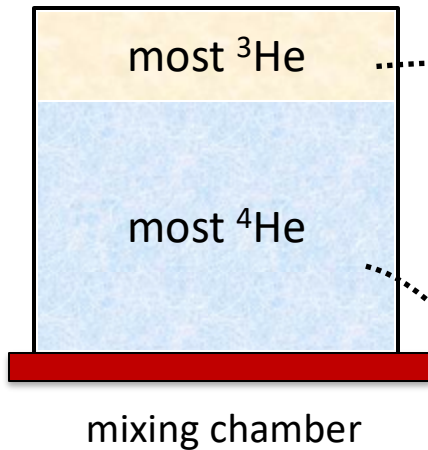
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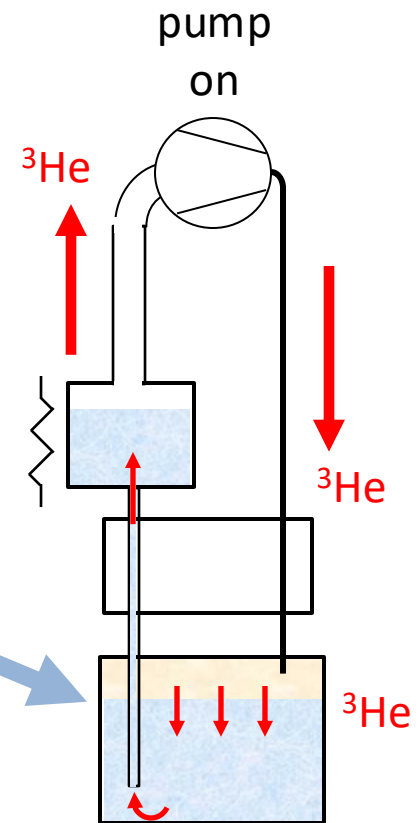
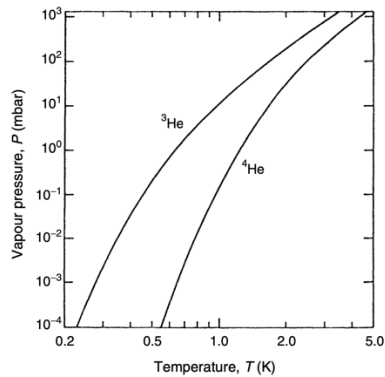
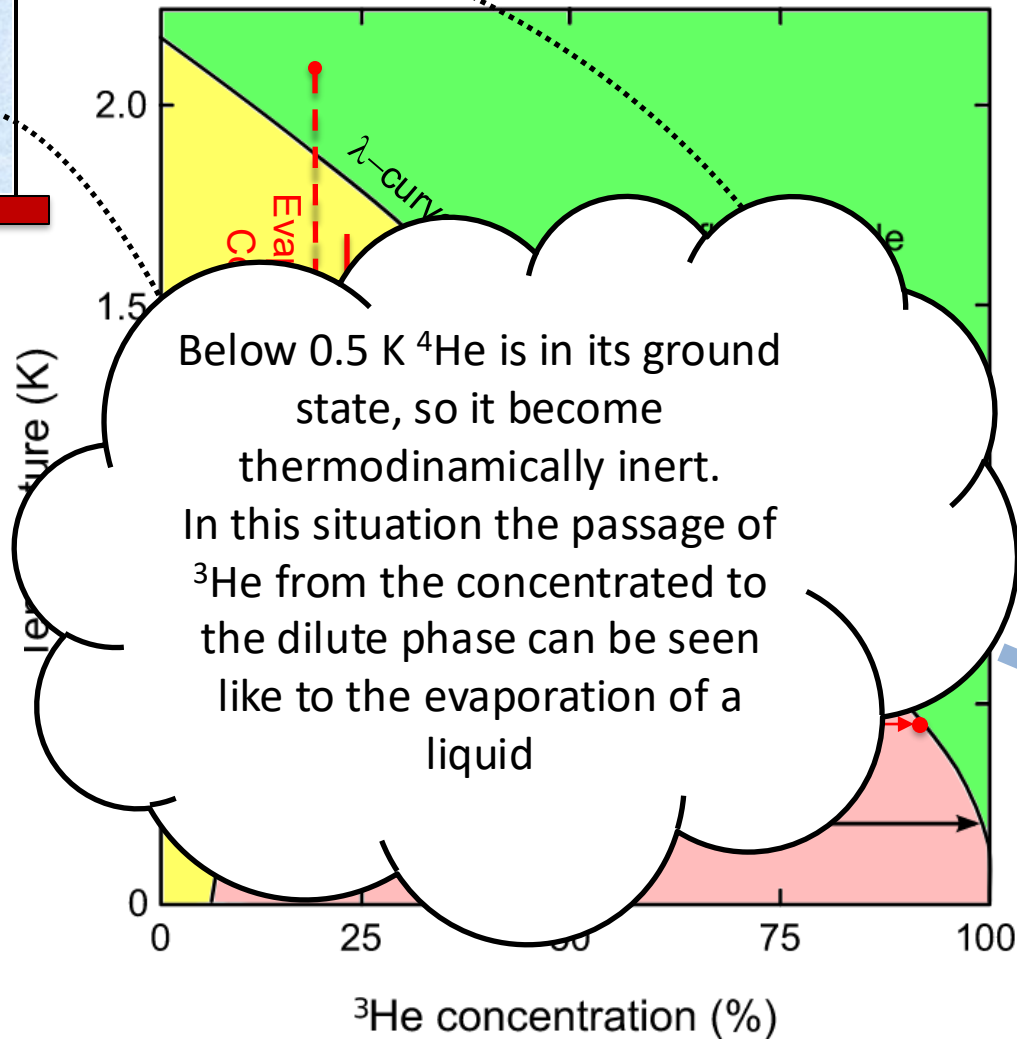
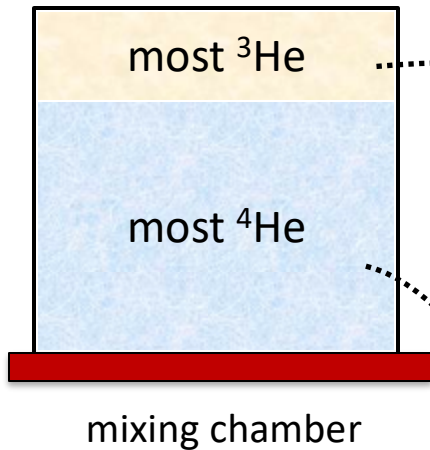
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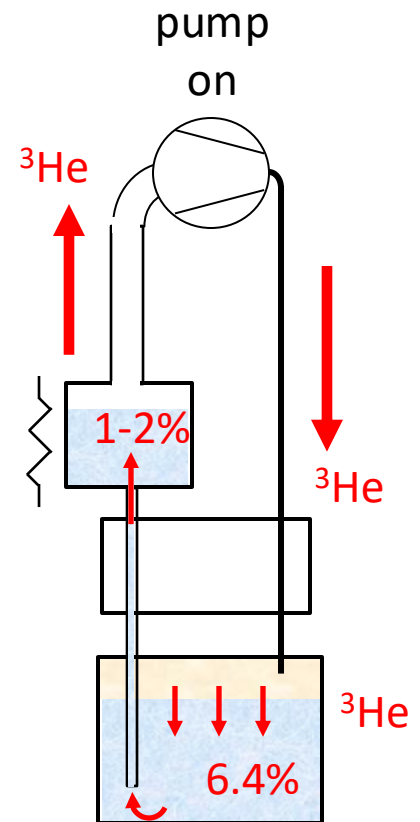
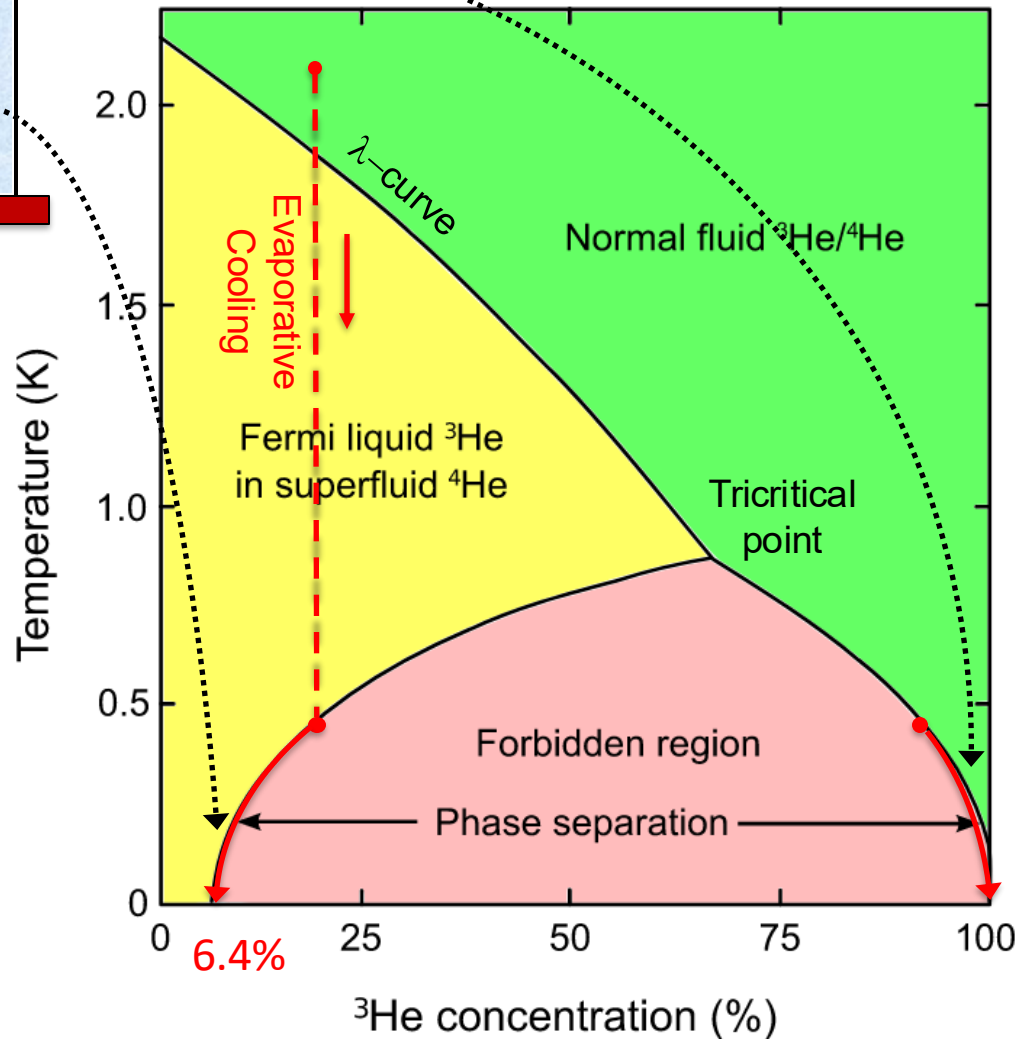
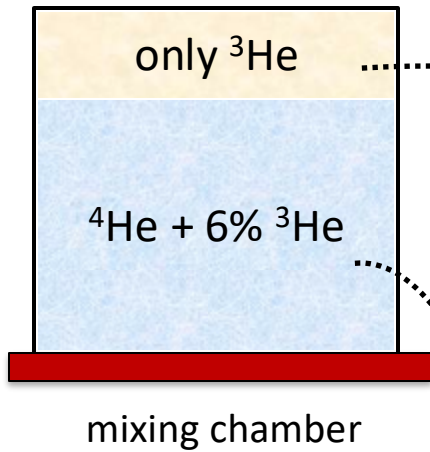
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$^3\text{He}/^4\text{He}$ Mixture



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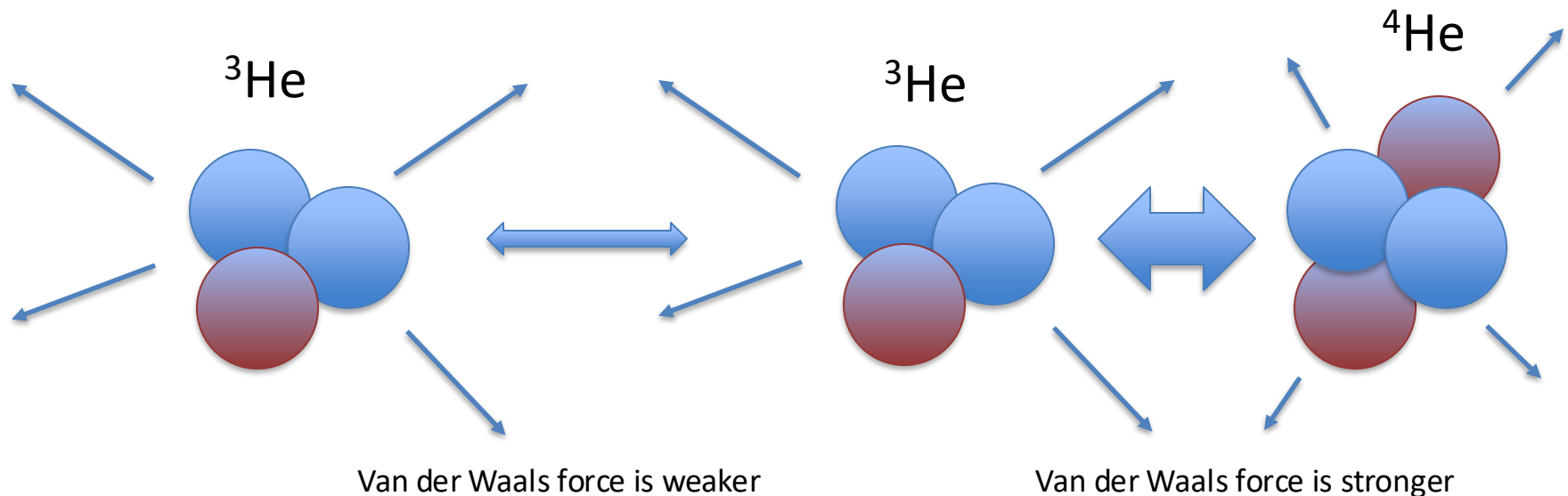


$^3\text{He}/^4\text{He}$ Mixture

^4He is a **boson** with nuclear spin zero $\rightarrow$ 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 $\rightarrow$ Heat capacity and entropy $\propto T$

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

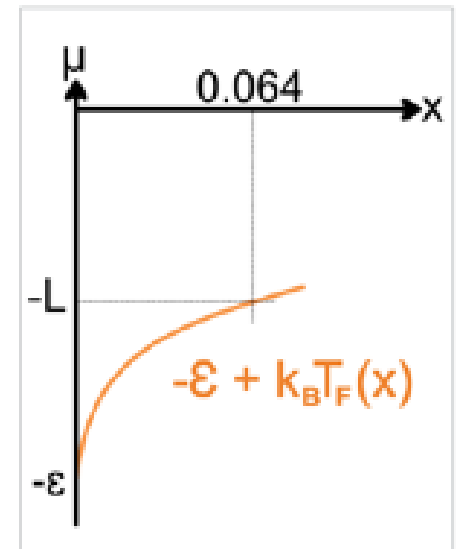


$^3\text{He}/^4\text{He}$ Mixture

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 ^3He in ^4He and let's say that the binding energy of a single ^3He atom in ^4He is ε
- The binding energy of ^3He in ^3He is equal to the latent heat of evaporation of pure ^3He , L , so ε must be greater than L
- The first two ^3He atoms will occupy the lowest energy state $-\varepsilon$ with anti-parallel spins
- Additional ^3He 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 ^3He atom in pure ^3He .

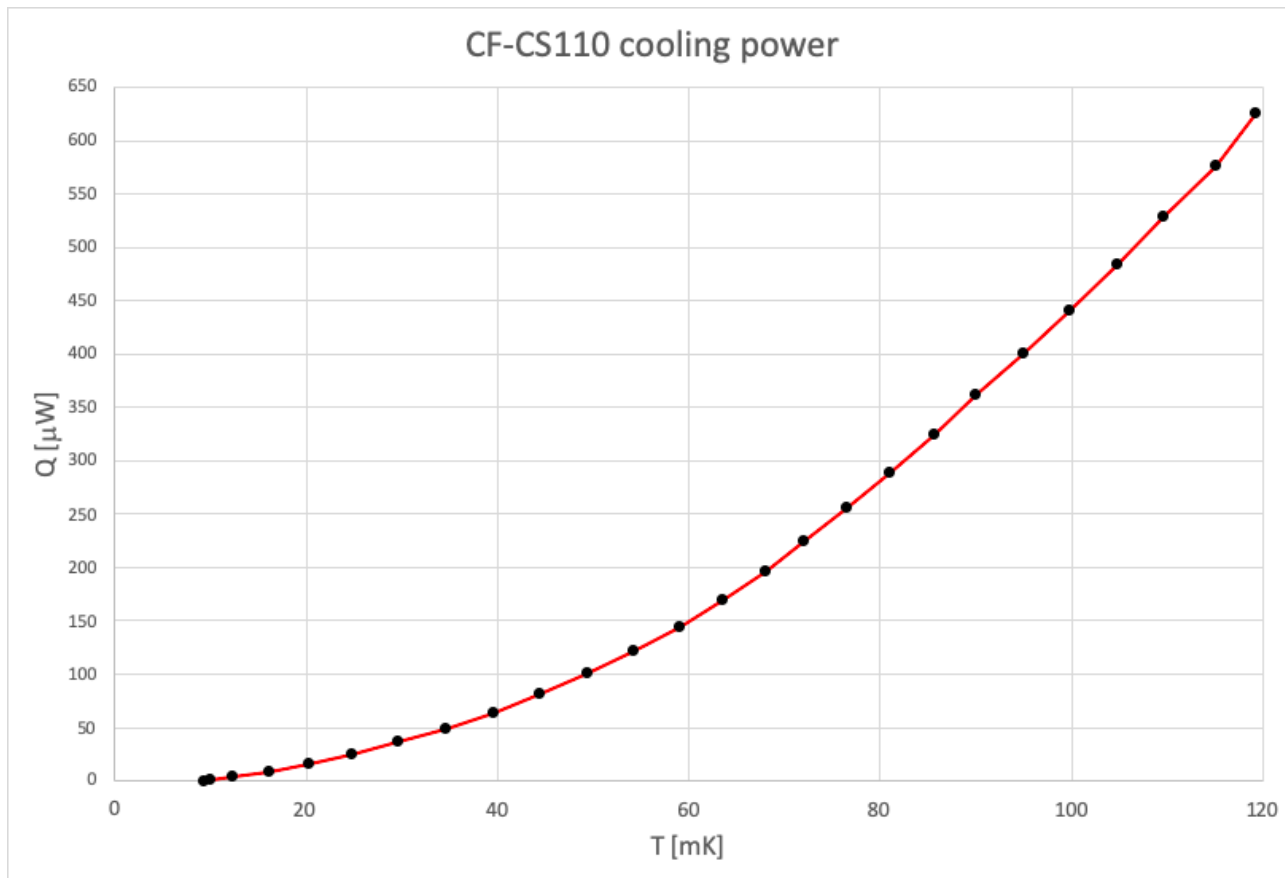


DRs can in principle go down to absolute zero. Practical reasons limit T base to about 2 mK (due to the increase of both ^3He viscosity and thermal conductance)

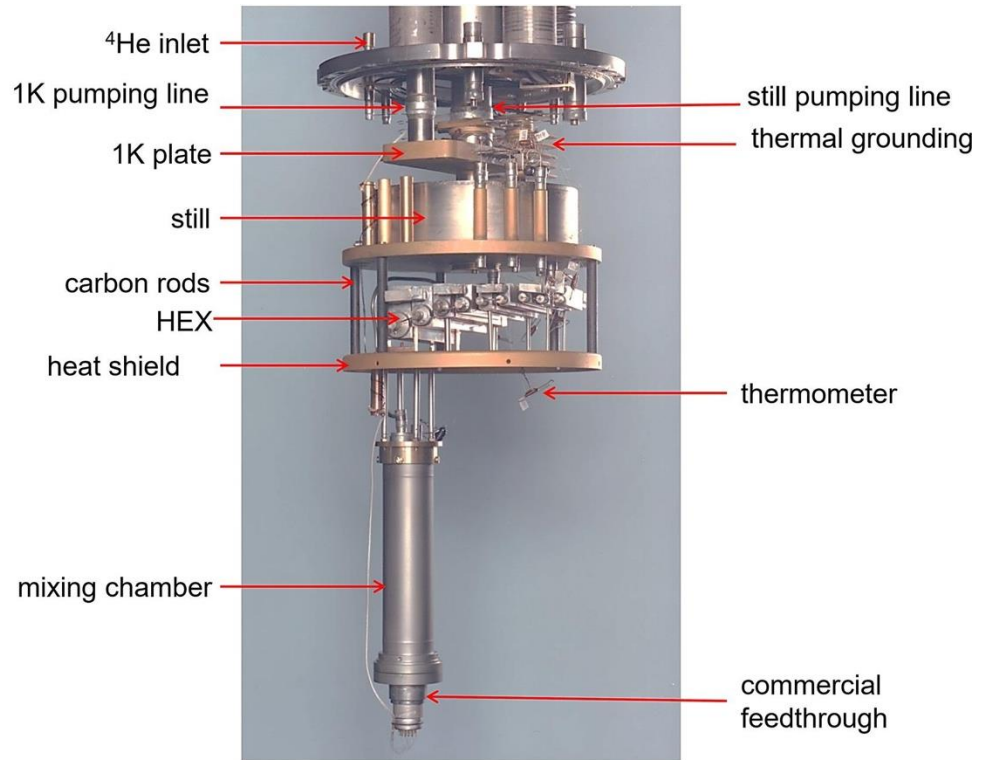
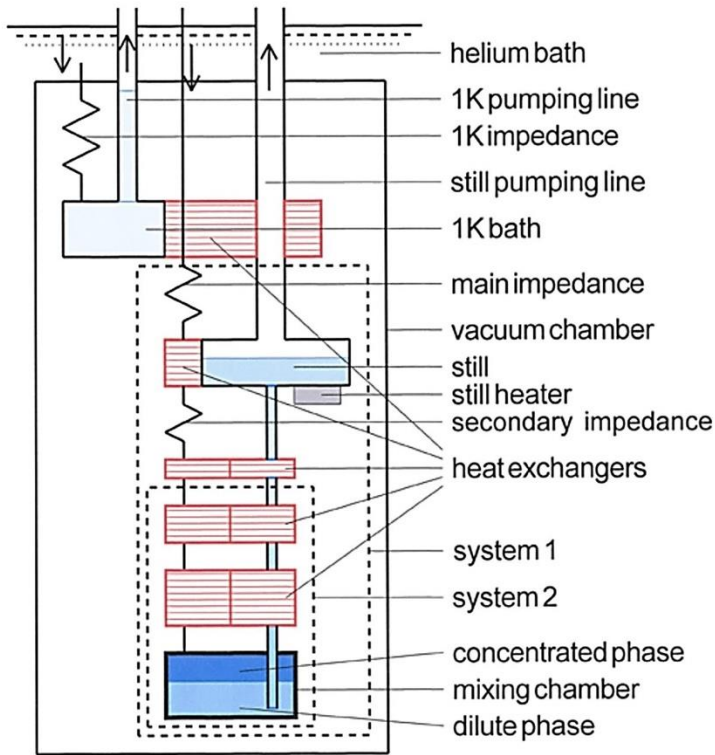
$^3\text{He}/^4\text{He}$ Mixture

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

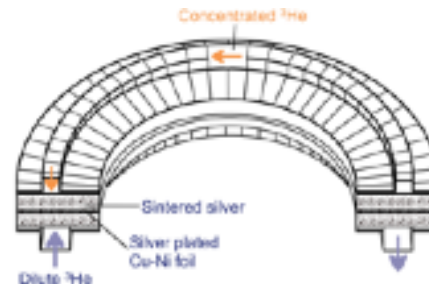
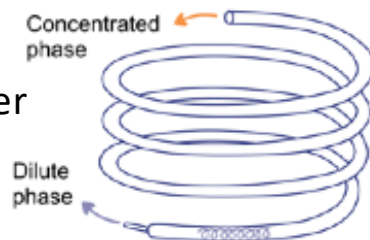
($\dot{n}$ is the mixture flow rate)



Real dilution refrigerators



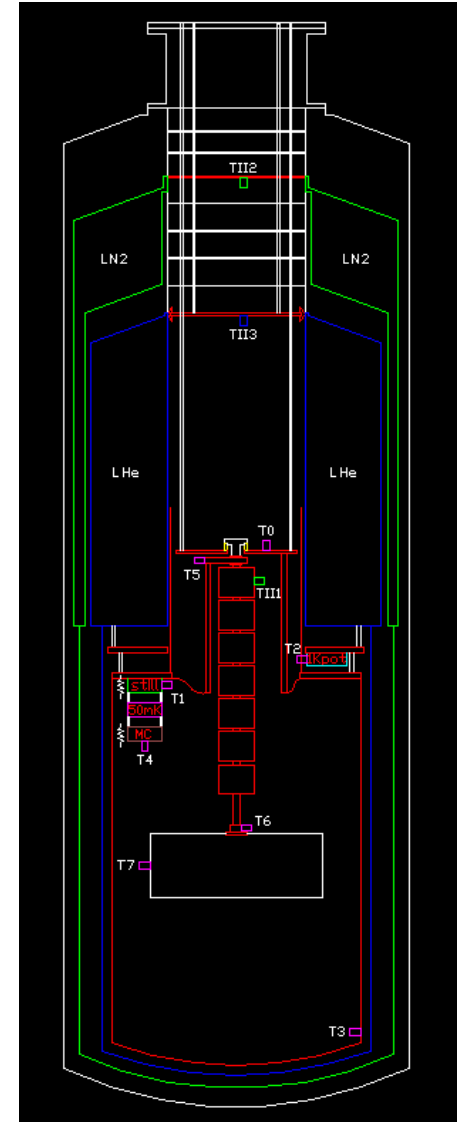
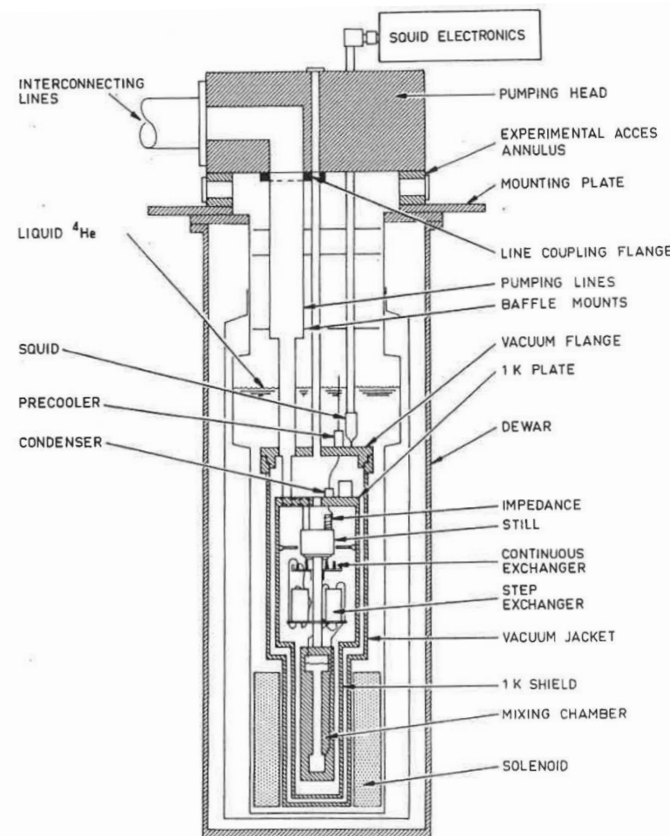
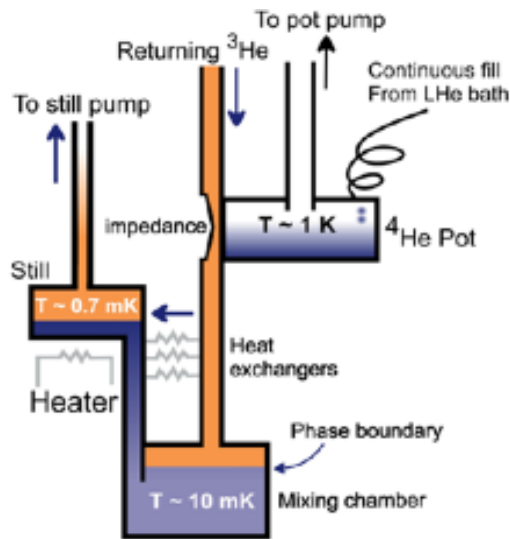
continuous heat exchanger
higher temperatures



sintered heat exchanger
lower temperatures

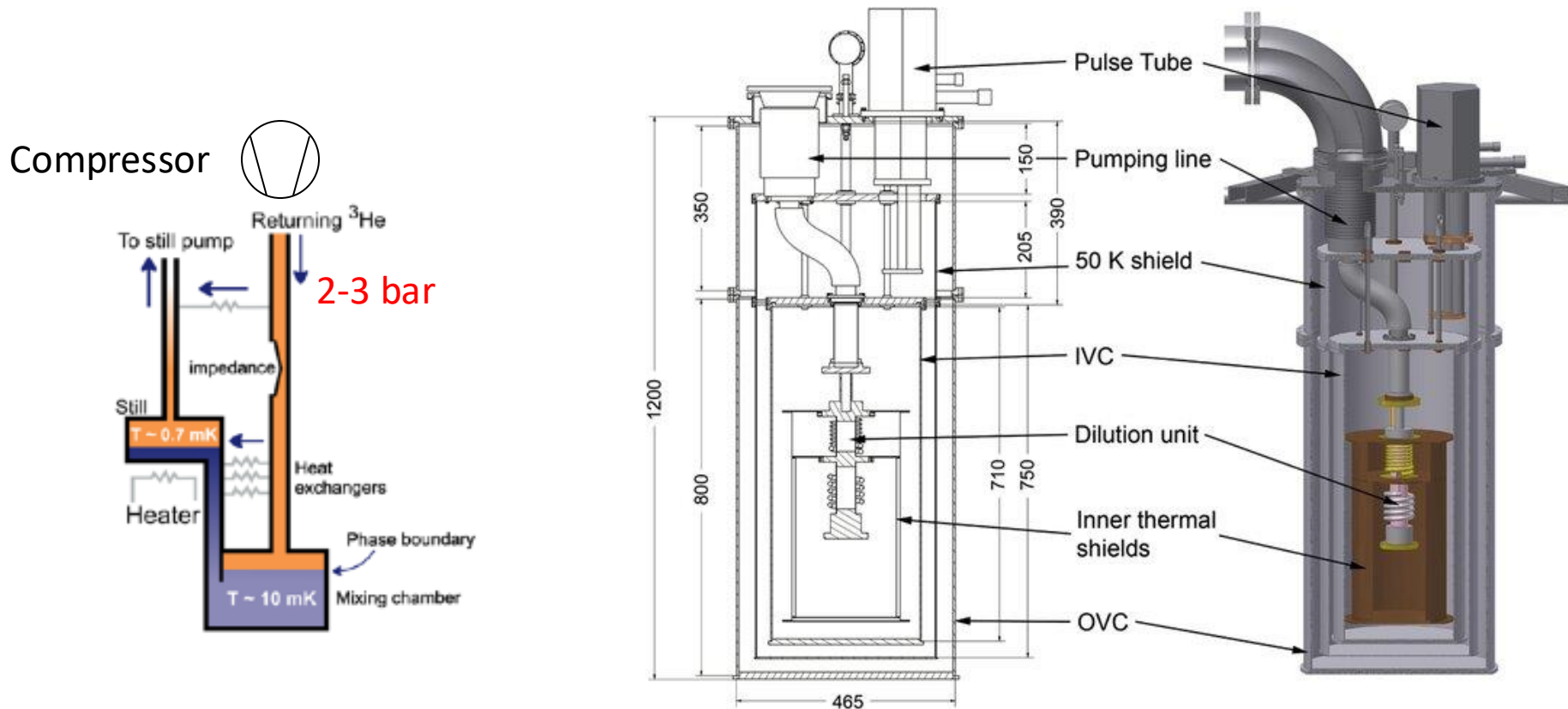
Cryostats for dilution refrigerator

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



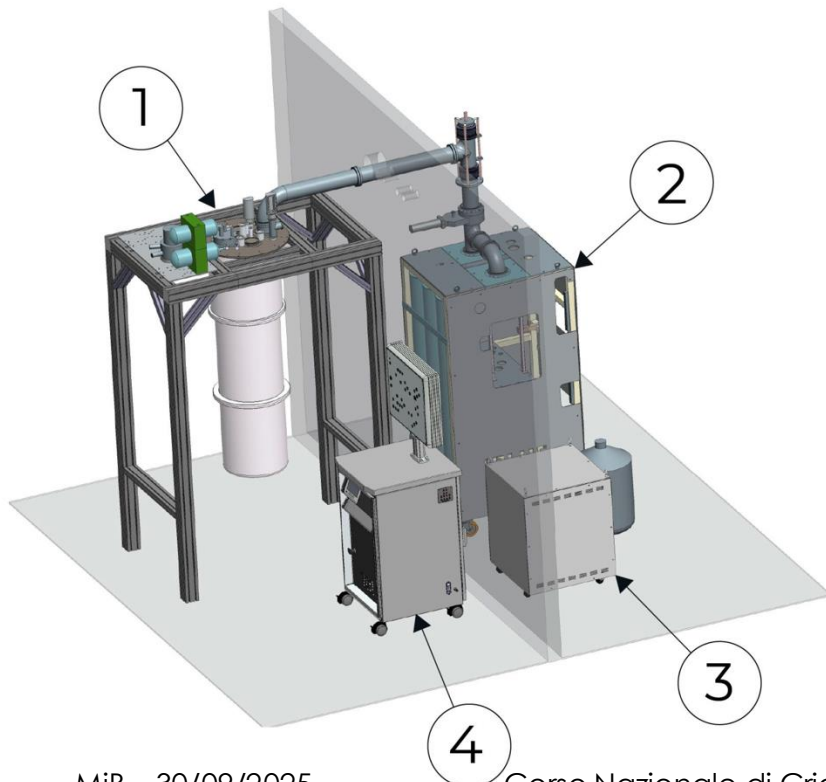
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mK refrigeration applications

- *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"*

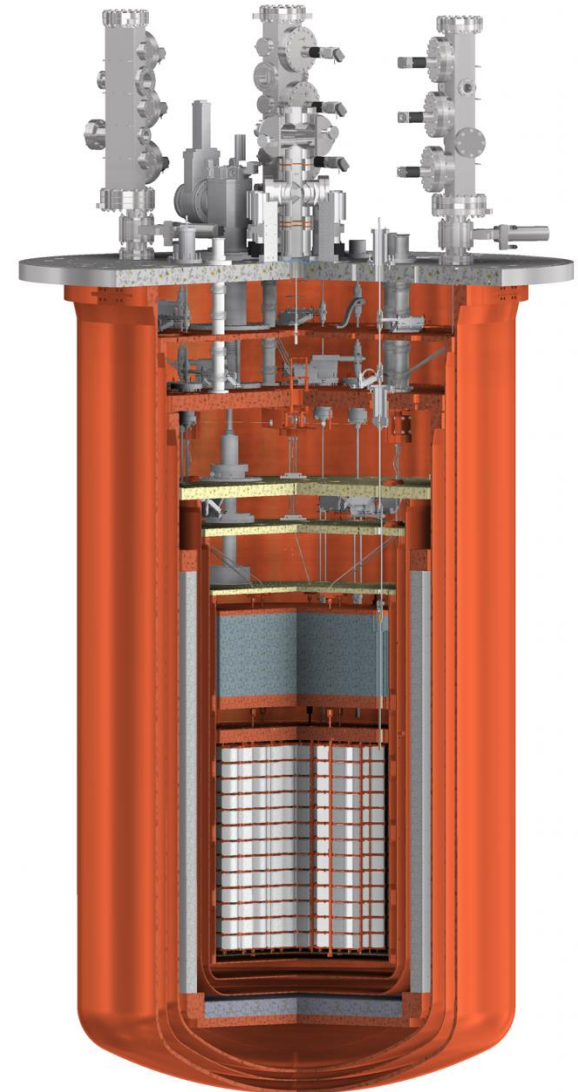
The biggest DR: CUORE

(Cryogenic Underground Observatory for Rare Events)

- The biggest DR are in Italy, at INFN-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

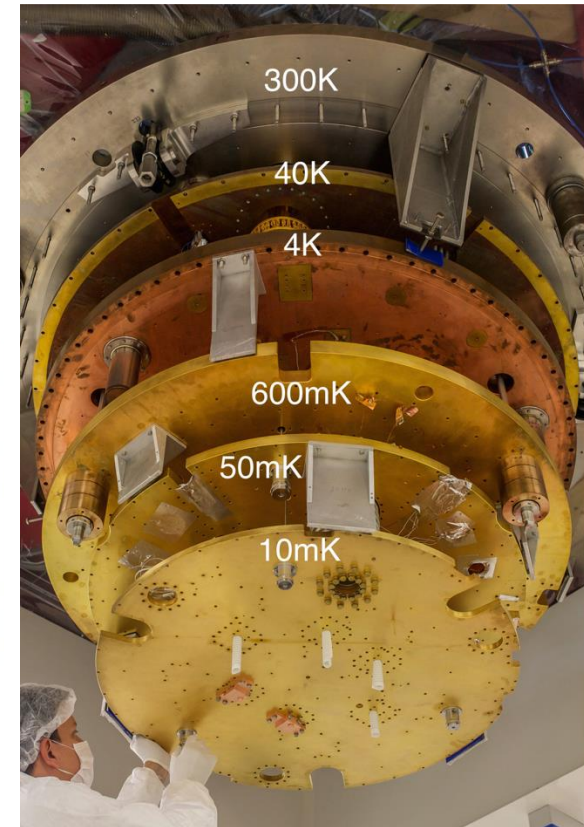
(Cryogenic Underground Observatory for Rare Events)

- 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**



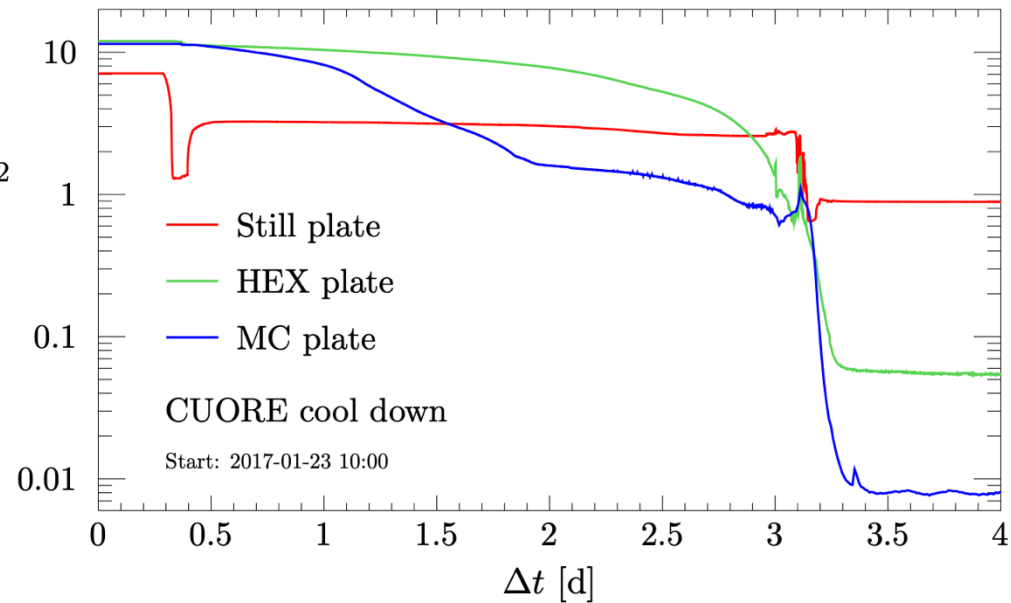
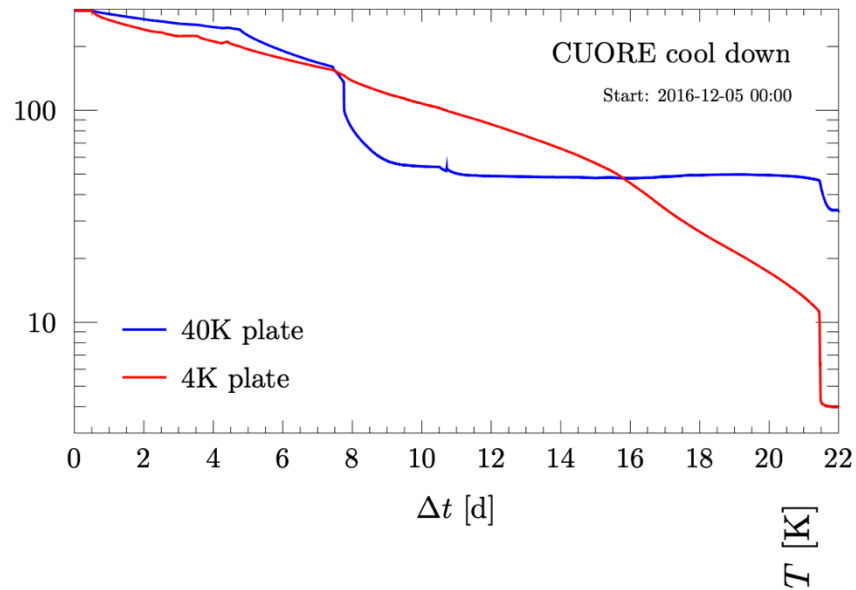
L.Taffarello (INFN- Padova): " We need a machine as powerful as the Challenger and as performing as the F12"

- Measured cooling power @ 10 mK: 3 microW



The biggest DR: CUORE

(Cryogenic Underground Observatory for Rare Events)

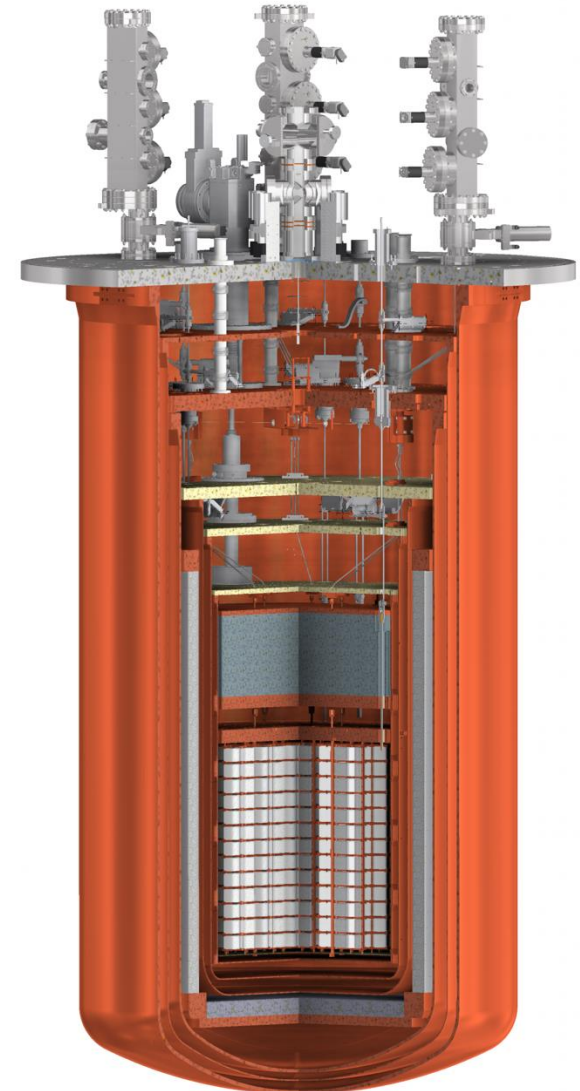


The biggest DR: CUORE

(Cryogenic Underground Observatory for Rare Events)



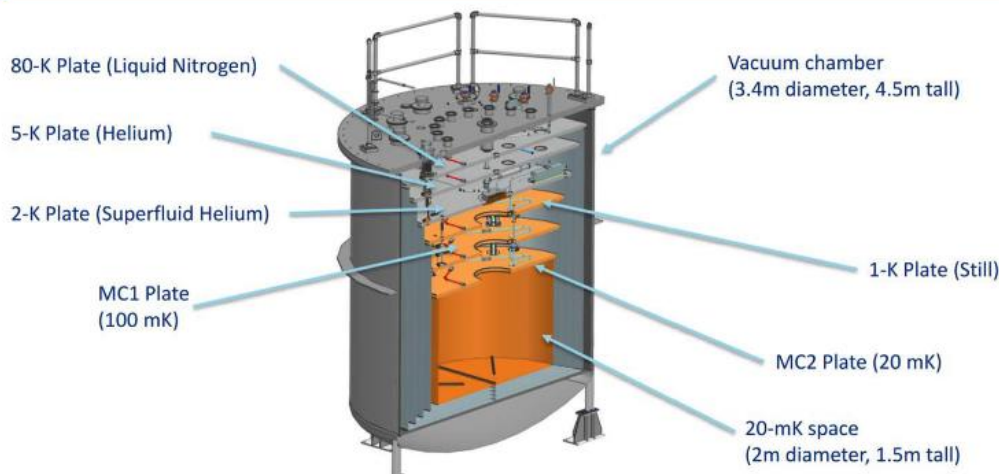
38077 In un esperimento condotto nel 2014 ai laboratori dell'Istituto nazionale di fisica nucleare del Gran Sasso, una struttura di rame del volume di un metro cubo è stata portata alla temperatura di $-273,144\text{ }^{\circ}\text{C}$, vicinissima allo zero assoluto (che corrisponde a $-273,15\text{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



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



An Update on the Colossus mK Platform at Fermilab

Matthew Hollister, Ram Dhuley, Christopher James and Grzegorz Talkowski
Fermi National Accelerator Laboratory
CEC/CMC 2023

J40-1A-02
FERMILAB-DIS-23-056-0001

Still 0.6K ~ 0.7K

Continuous heat exchanger 0.05K ~ 0.07K

Intermediate cold plate 0.04K ~ 0.05K

Silver heat exchanger 0.02K ~ 0.03K

Mixing chamber 0.01K or lower

Image: Janis Research Company

- 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

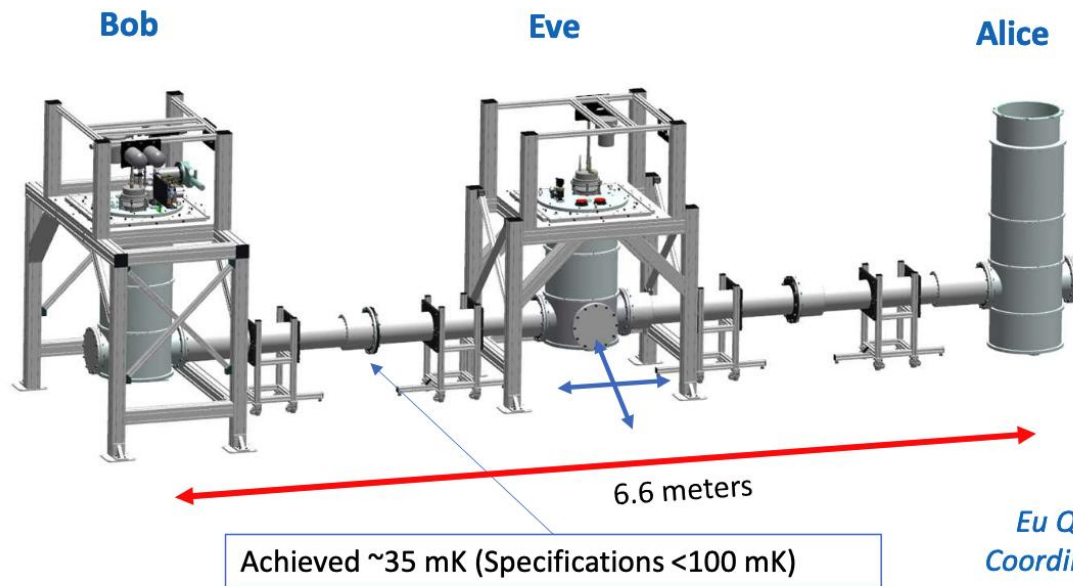
Q-LAN for Quantum Communications & Computing Scale up



- 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



*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

Key Players

ICV TANK
Technology Advisory
& Knowledgebase



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companies selling DRs

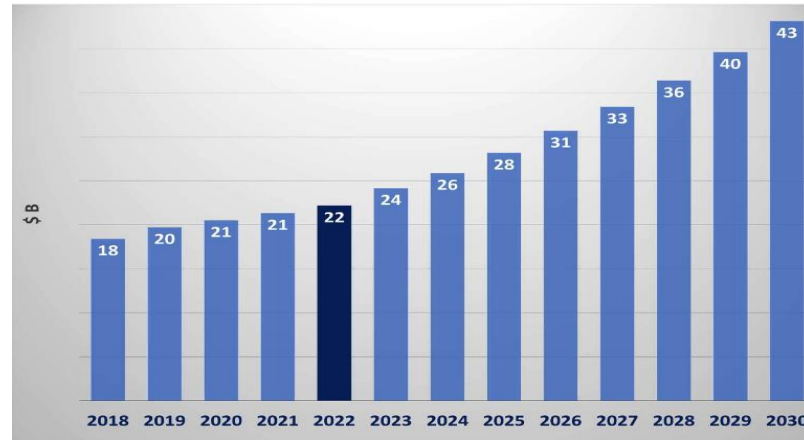
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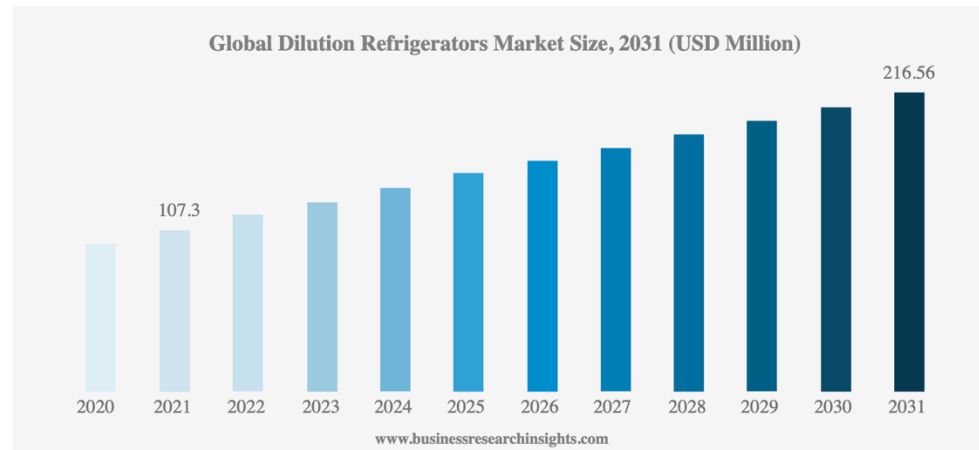


Cryo & DRs worldwide market

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)*



Thank you!