# Introduction to Cryogenics

## Neutron LifeCycle

## Talk 3


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ORNL is managed by UT-Battelle
for the US Department of Energy

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OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR

# Condensation during winter:

## Ideal Gas Equation:

$$P\,V = m\,R\,T$$

P = Pressure

V = Volume

m = Mass

R = Real Gas Constant

T = Temperature

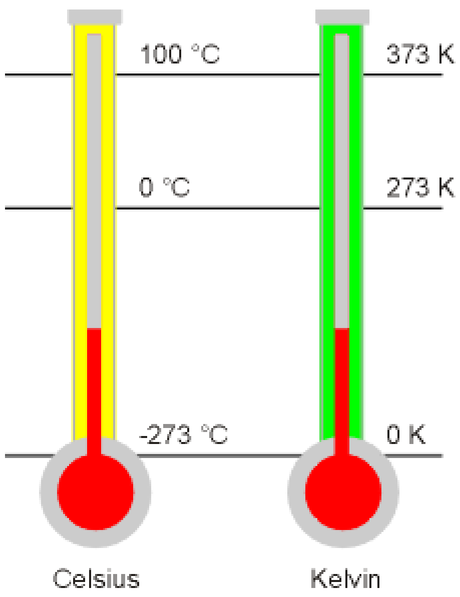
V, m and R = Constant

$$P \,\alpha\, T$$

# Contents of this talk:

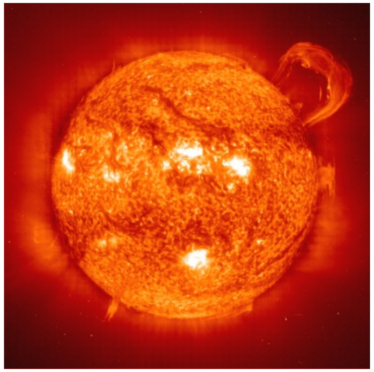
- Introduction
- Cryogen free closed cycle refrigerator (CCR)
- Variable temperature insert (VTI)
- Helium-3 system (3He)
- ‘Wet’ dilution refrigerator (DR)
- ‘Dry’ dilution refrigerator (DR)
- Some typical failure modes

# What do we mean by Ultra Low Temperature (ULT)?




<1 K is called ULT

**Sun~** 6,000 K



**X 20**

**Room temp ~** 300K

**X 30,000**

**D/R system~10mk**

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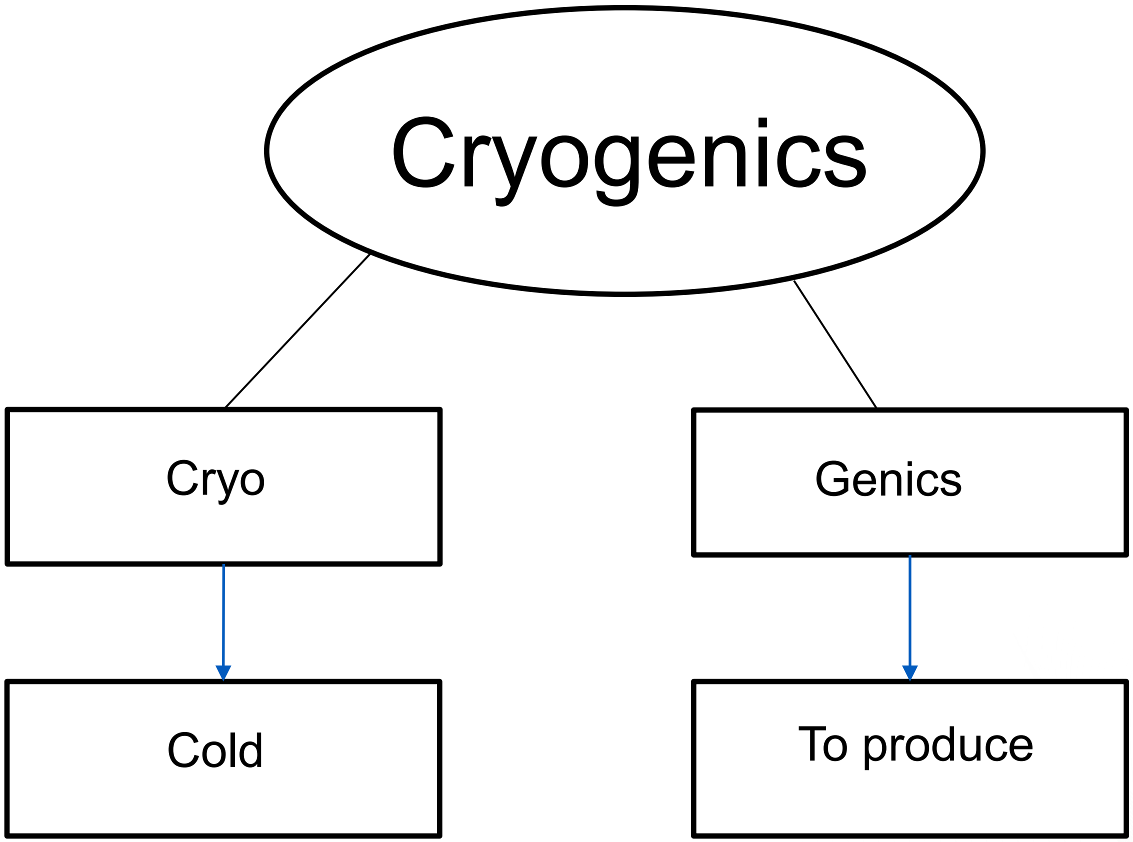
# ‘How do we get there?’

# Let starts with Basics:



# How do we get there to 10mK?

Cryogenics

4.2K

Cryostat

**Liquid Helium Or CCR**
Superconducting Magnet

1.5K

Pumped LHe4

**Variable Temperature Insert**

0.3K (300mK)

Pumped LHe3

**3He insert**

0.01K (10mK)

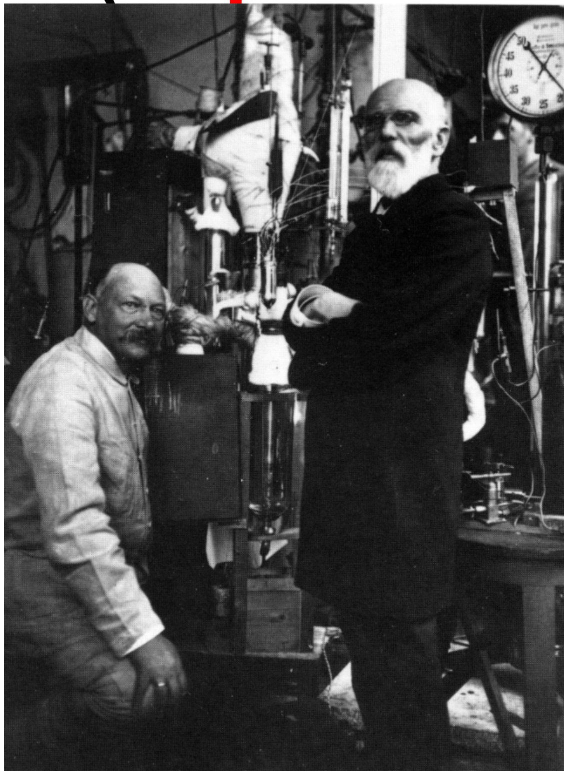
Pumped LHe3+LHe4 Mixture

**Dilution Refrigerator**

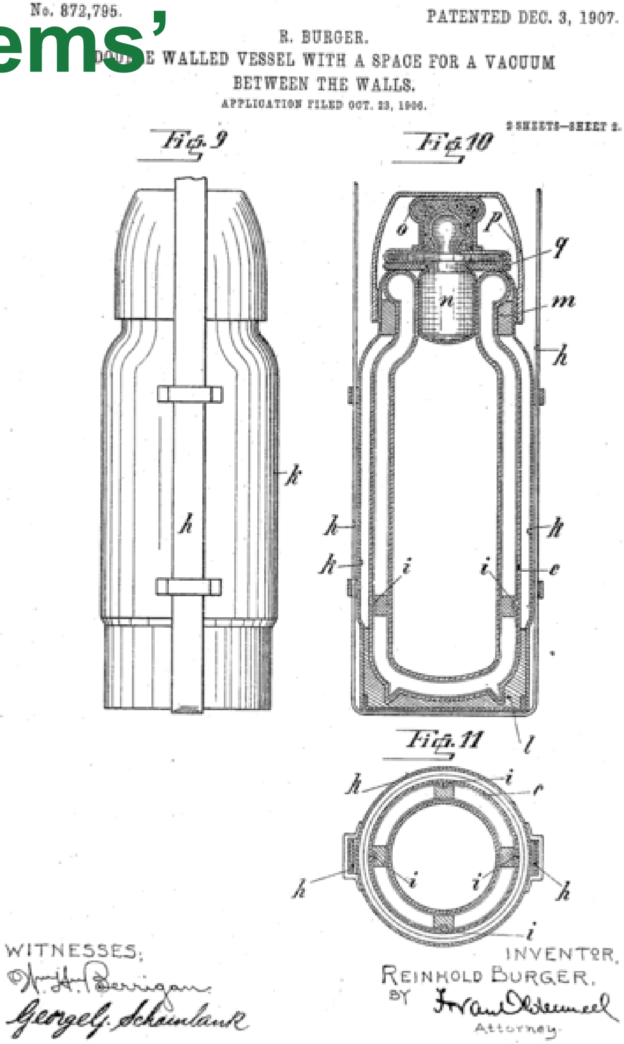
**ULT**

# First step for ULT: need 4K
# 2 Ways to achieve 4K

## First method – Wet Systems’ (Liquid helium)



Heike Kamerlingh Onnes (left) and Johannes Diderik van der Waals in 1908 in the Leiden physics laboratory, in front of the apparatus used later to condense helium. (Source: [Museum Boerhaave, Leiden](Museum Boerhaave, Leiden))



# Dramatic events in Leiden

~106 Years ago

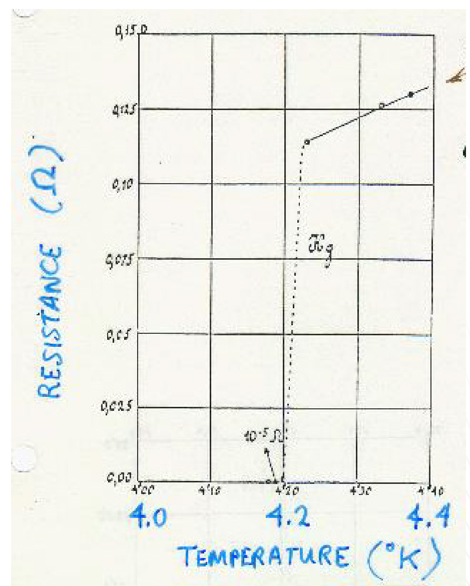
H. Kamerlingh Onnes

appointed to a chair of physics in Leiden aged 29

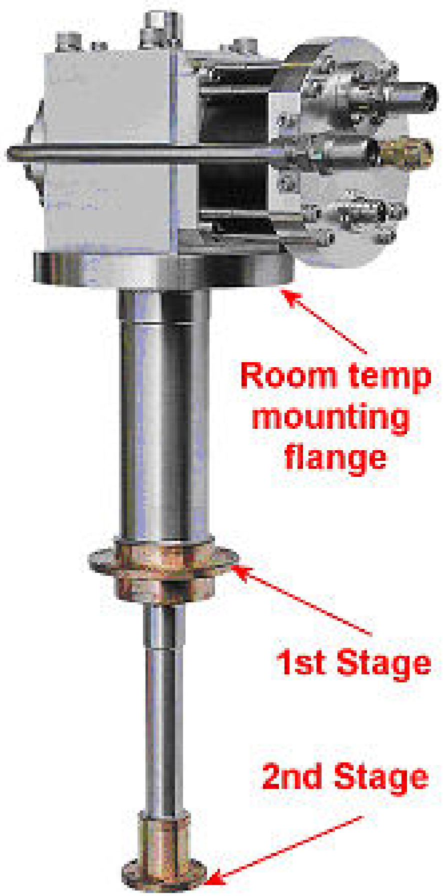
experimentalist, engineer and organisational genius

| | |
|---|---|
| 1884 | Constructed a cascade liquefaction plant for oxygen, nitrogen and air |
| 1906 | Liquefied hydrogen |
| 1908 | First liquefaction of helium |
| 1911 | Discovered superconductivity (in mercury) |

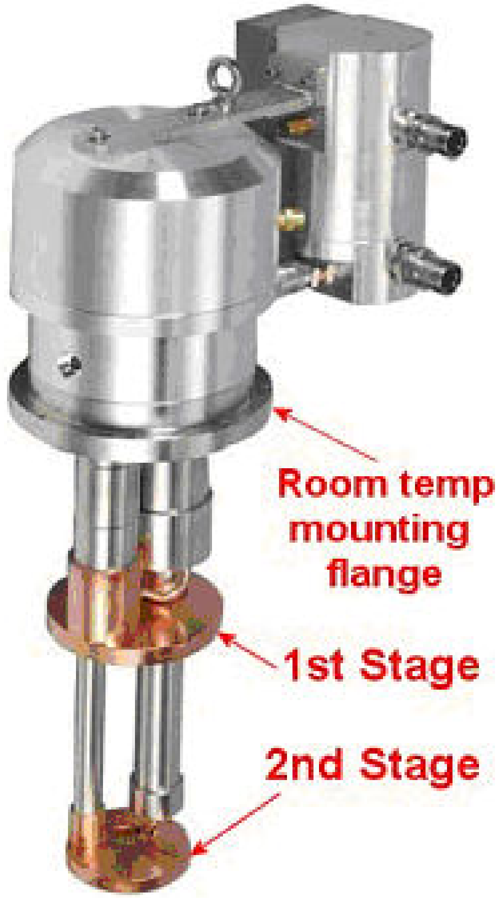
Received the Nobel Prize for his studies of the properties of matter at low temperatures



# 2nd method for 4K - 'Dry systems'



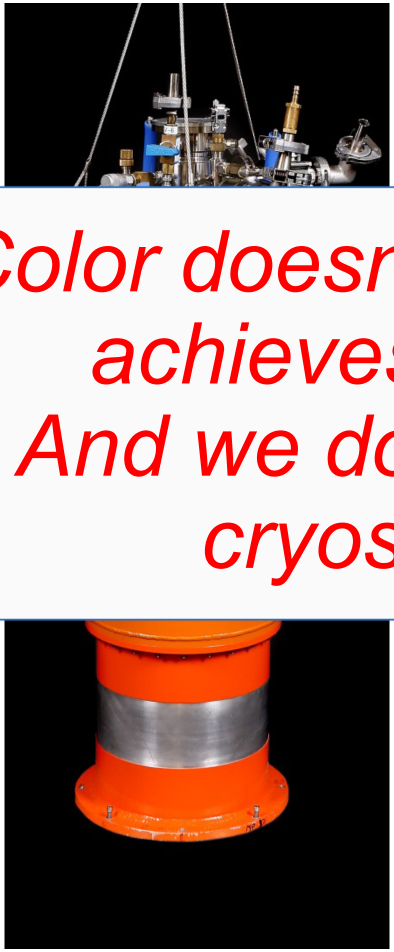

GM Cold Head

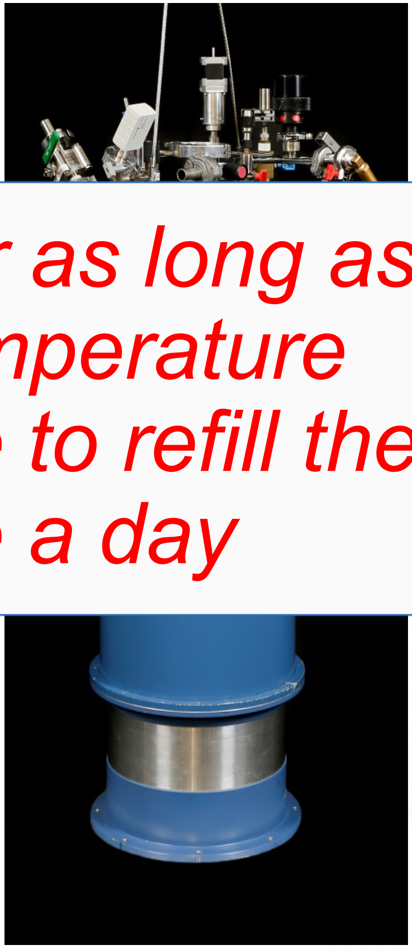



PTR Cold Head

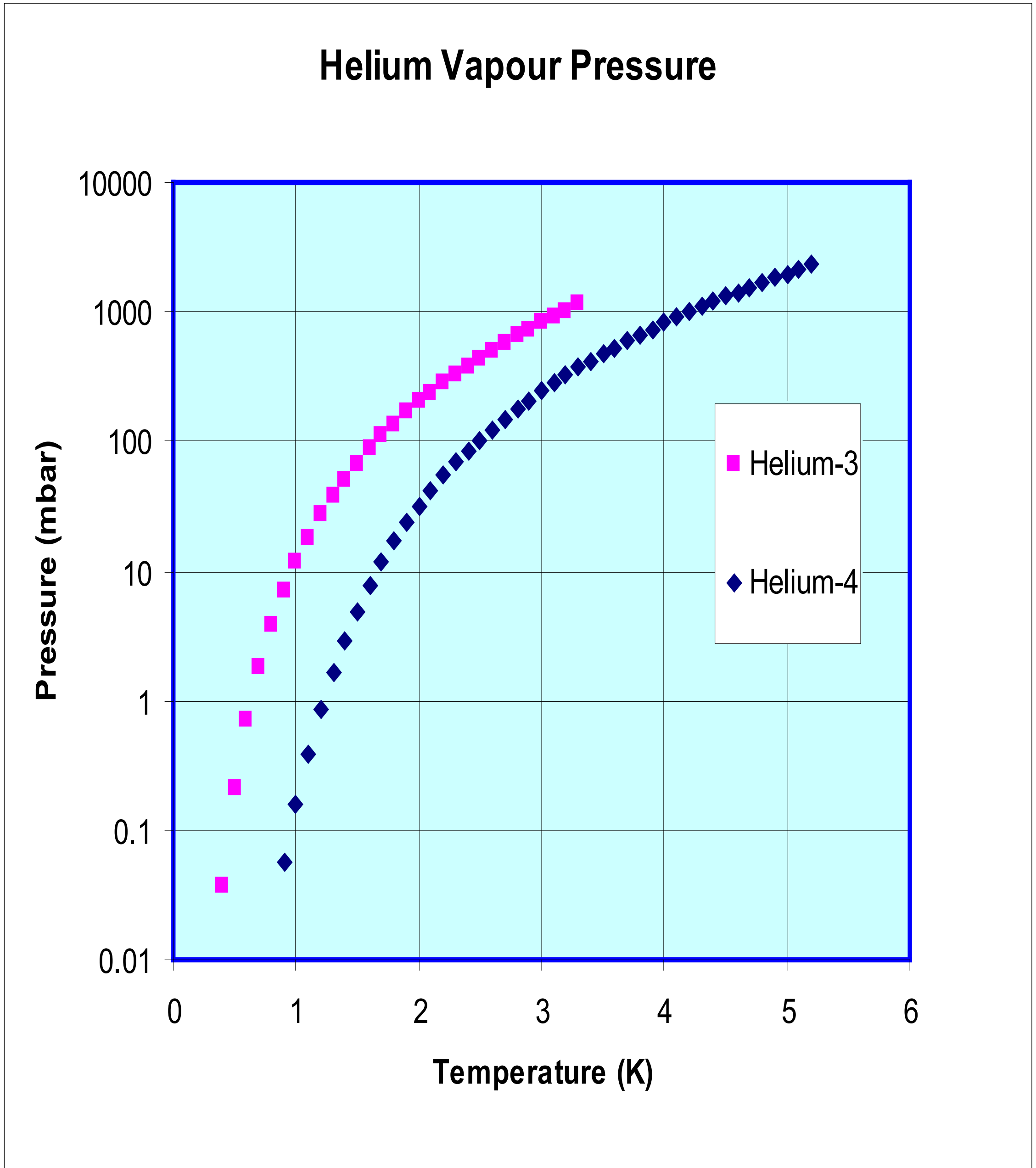
# Second Step for ULT:

- Requires 1.5 K environment:





*Color doesn't matter as long as it achieves low temperature*
*And we don't have to refill the cryostat twice a day*



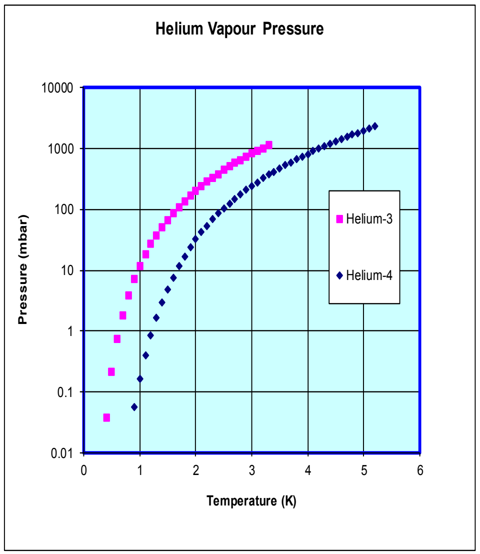

$P\,V = m\,R\,T$

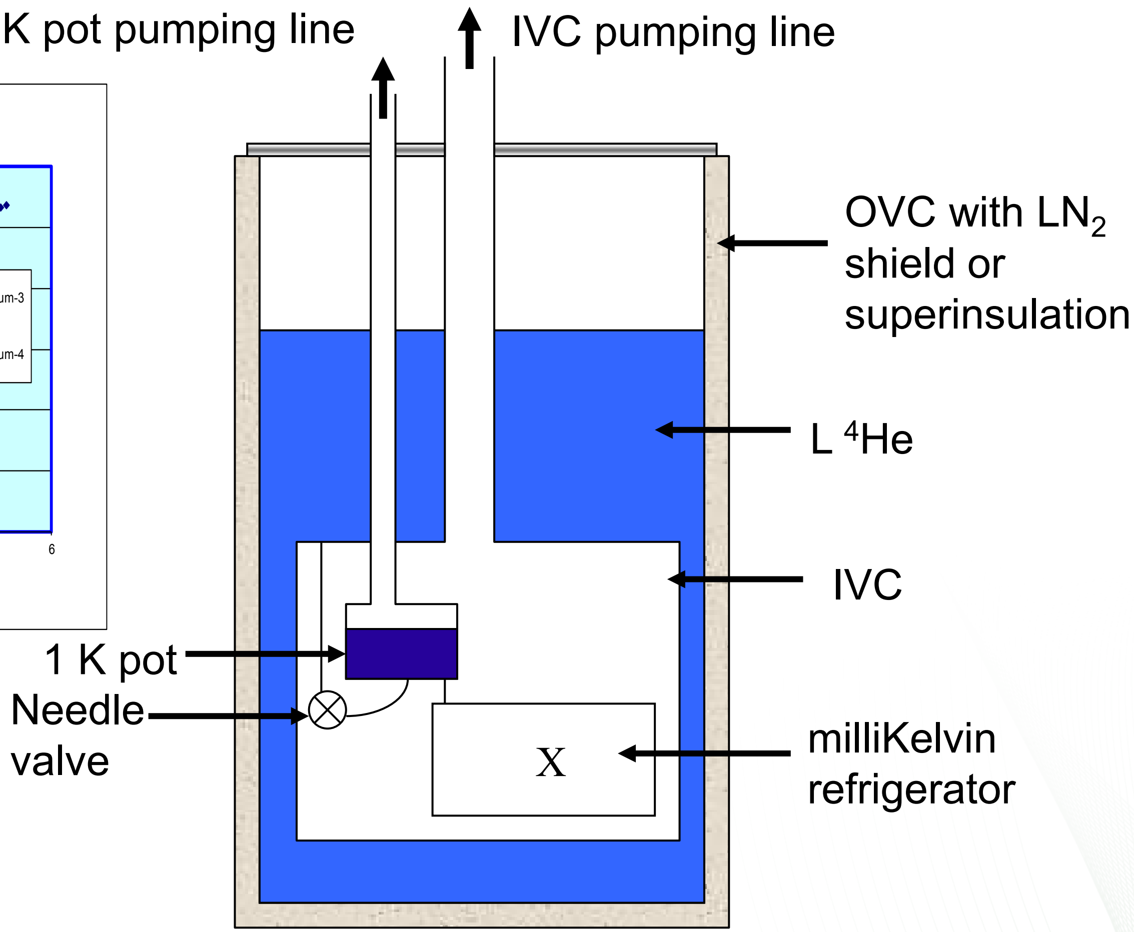
P = Pressure
V = Volume
m = Mass
R = Real Gas Constant
T = Temperature

V, m and R = Constant

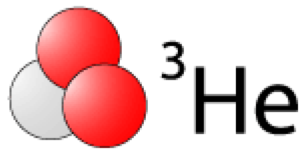
$P \propto T$

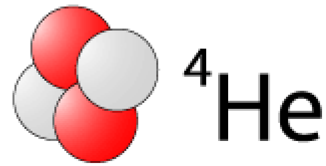
# $2^{nd}$ Step -1K pot (VTI) ~1.5K



# Now we need Helium-3 or mixture of Helium-3 and Helium-4 gas to go to lower temperatures




Helium has two stable isotopes 4He and 3He

- At room temperature, both isotopes are chemically identical and difficult to distinguish from one another.
- 4He-It is usually extracted from natural gas wells, predominantly in Qatar, US, Algeria and Russia
- 3He is incredibly rare.
  - It is only in the last 50 years that significant quantities of 3He have become available to allow experiments to be performed.
  - 3He is a bi-product of nuclear processing

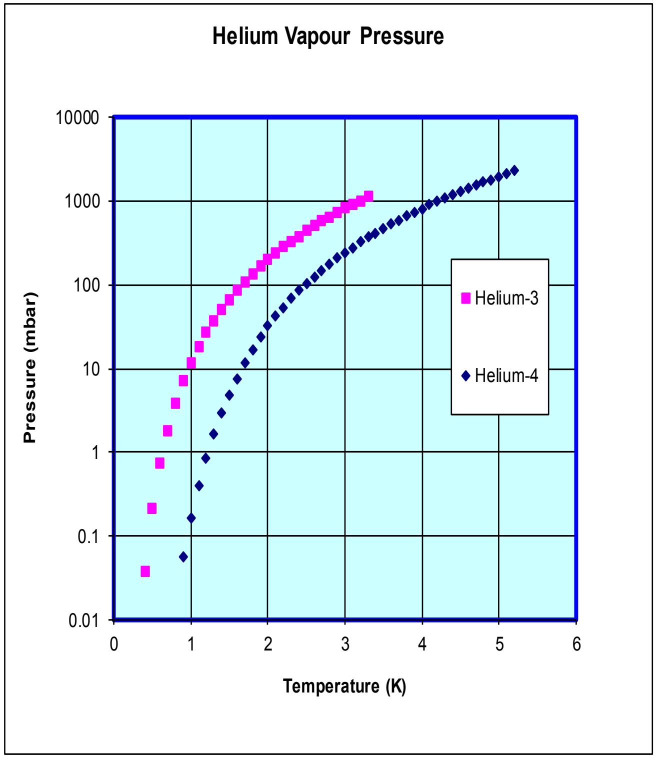
# Helium-3 Systems:

Base Temperature **<300mK**

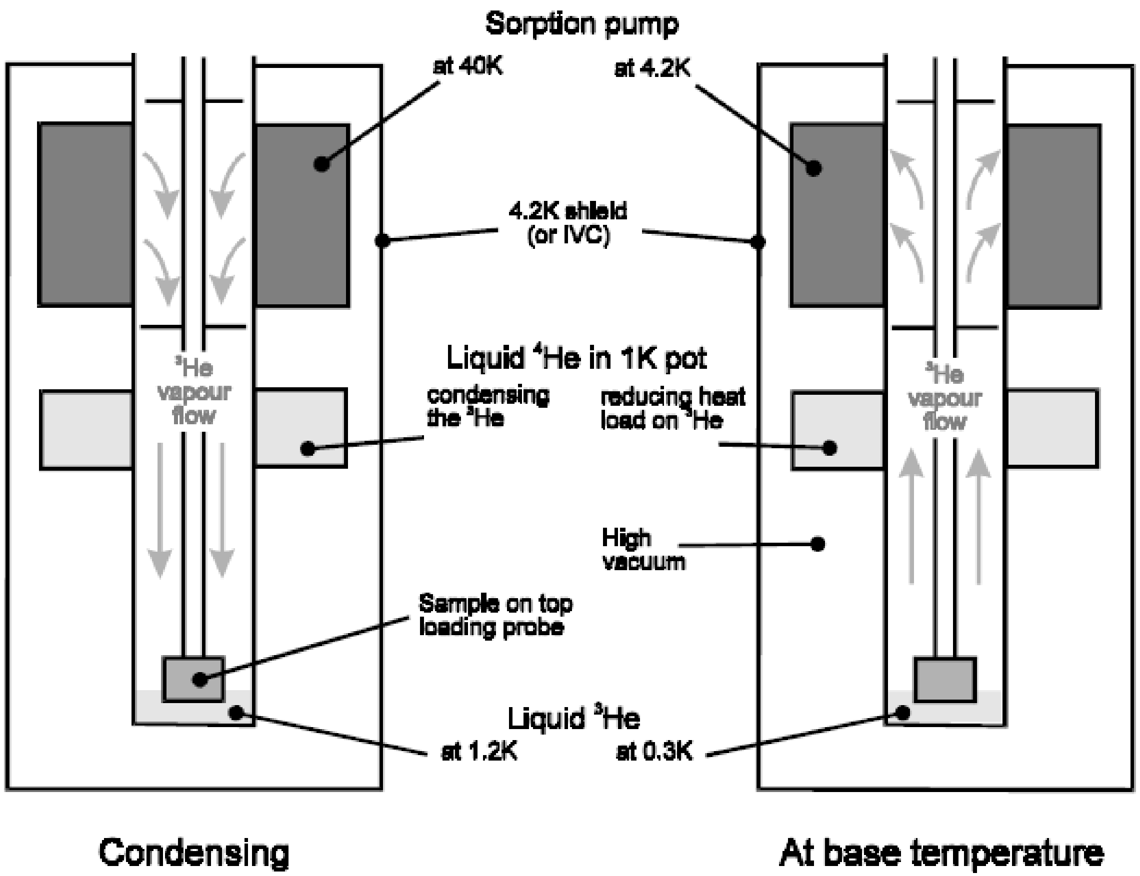
**Activated Carbon** has extremely high absorption capabilities at low temperatures~ 0.5lt of helium per gram of charcoal

**Single Shot System**: By cycling the Carbon between 1K and 40K an absorption and desorption cycle can be generated

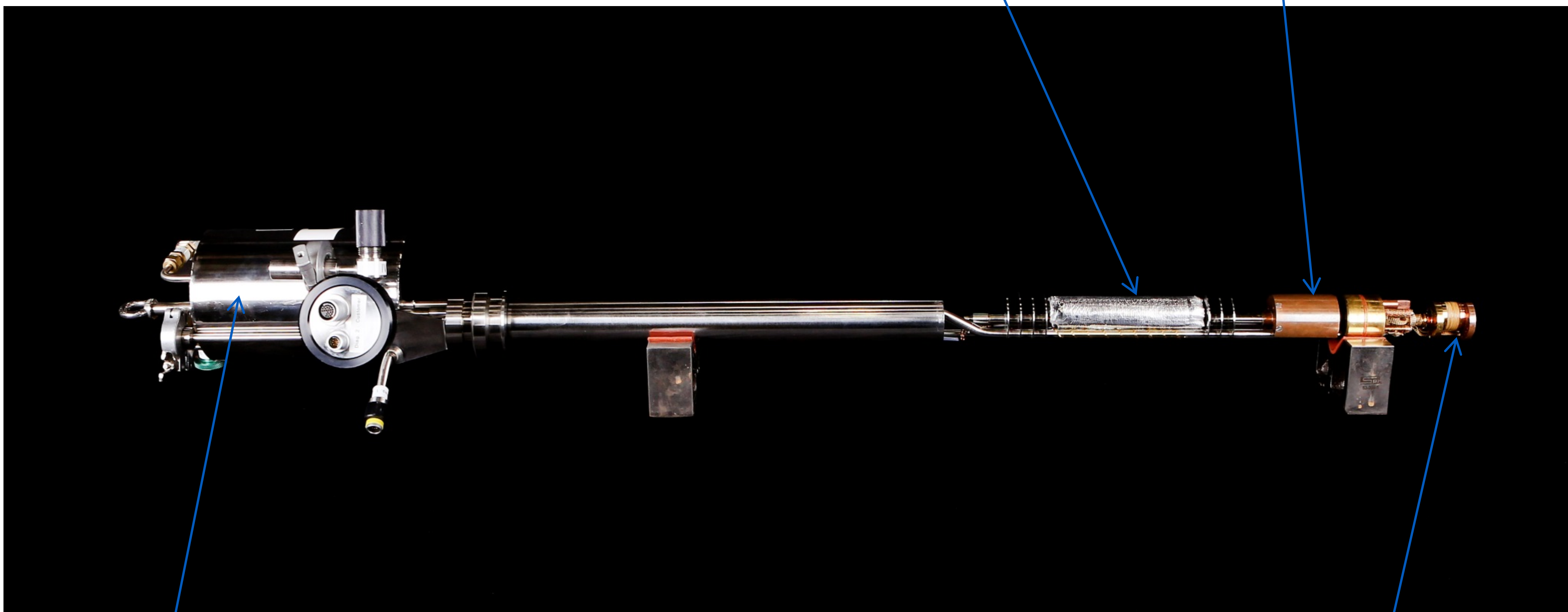
During the absorption cycle the effective pumping speed and ultimate base pressure on the 3He far **exceeds** that achievable by external pumping means

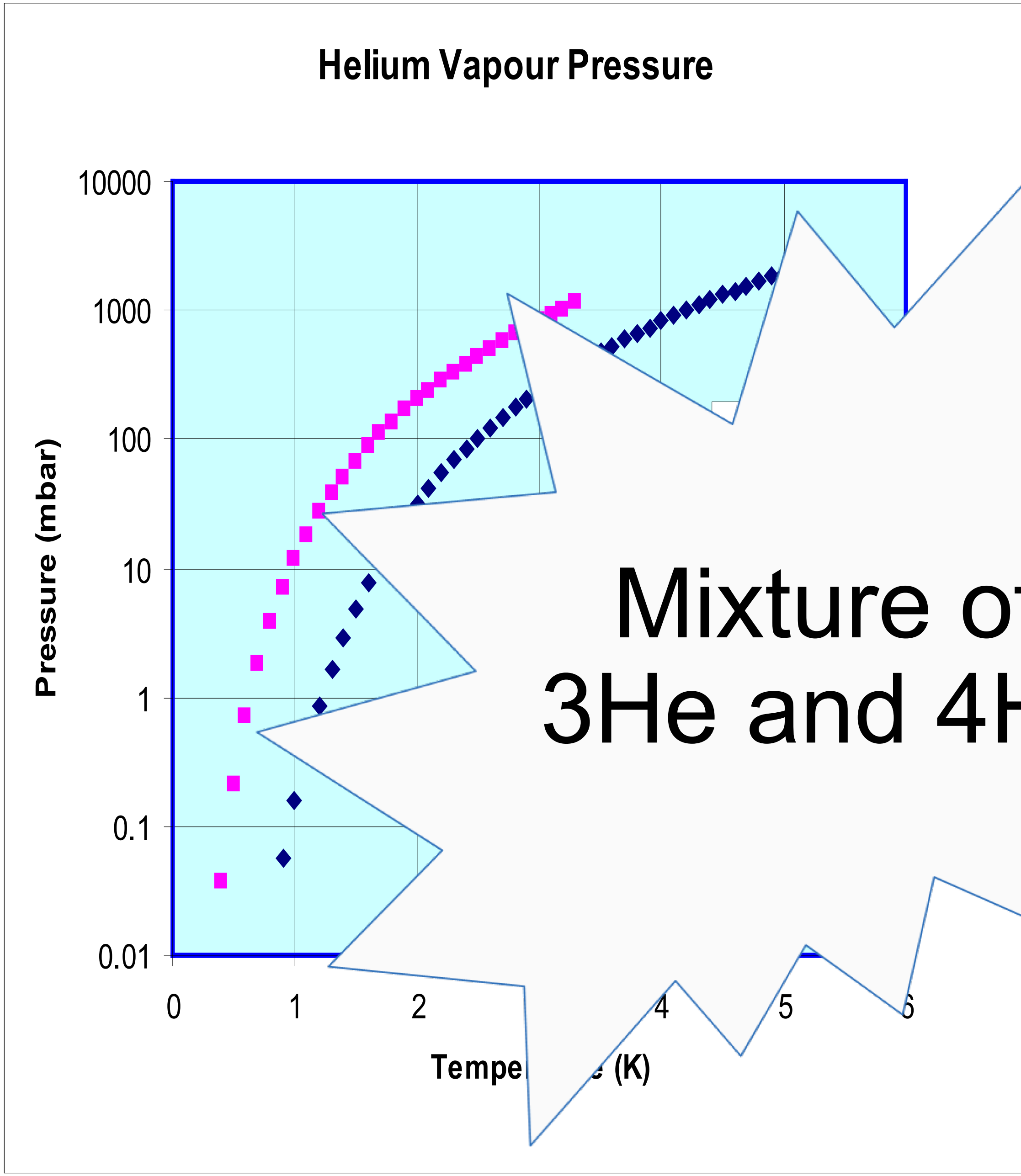



# Principle of Operation of Helium-3 System:



# Helium-3 insert – in real life






# Mixture of 3He and 4He

V = m R T

essure

= Volume

Mass

Real Gas Constant

= Temperature

V, m nd R = Constant

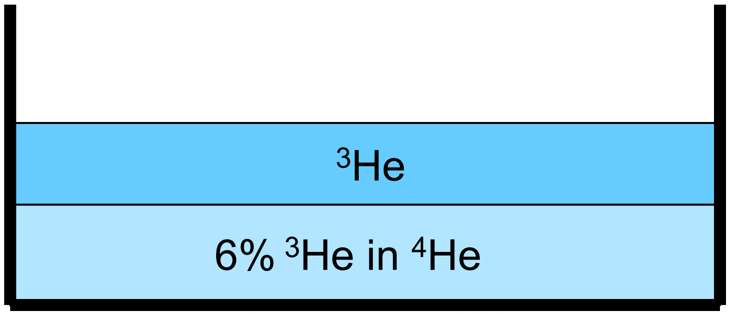
P α T

# Dilution Refrigerator Systems:

# Properties of $^3$He & $^4$He – phase separation

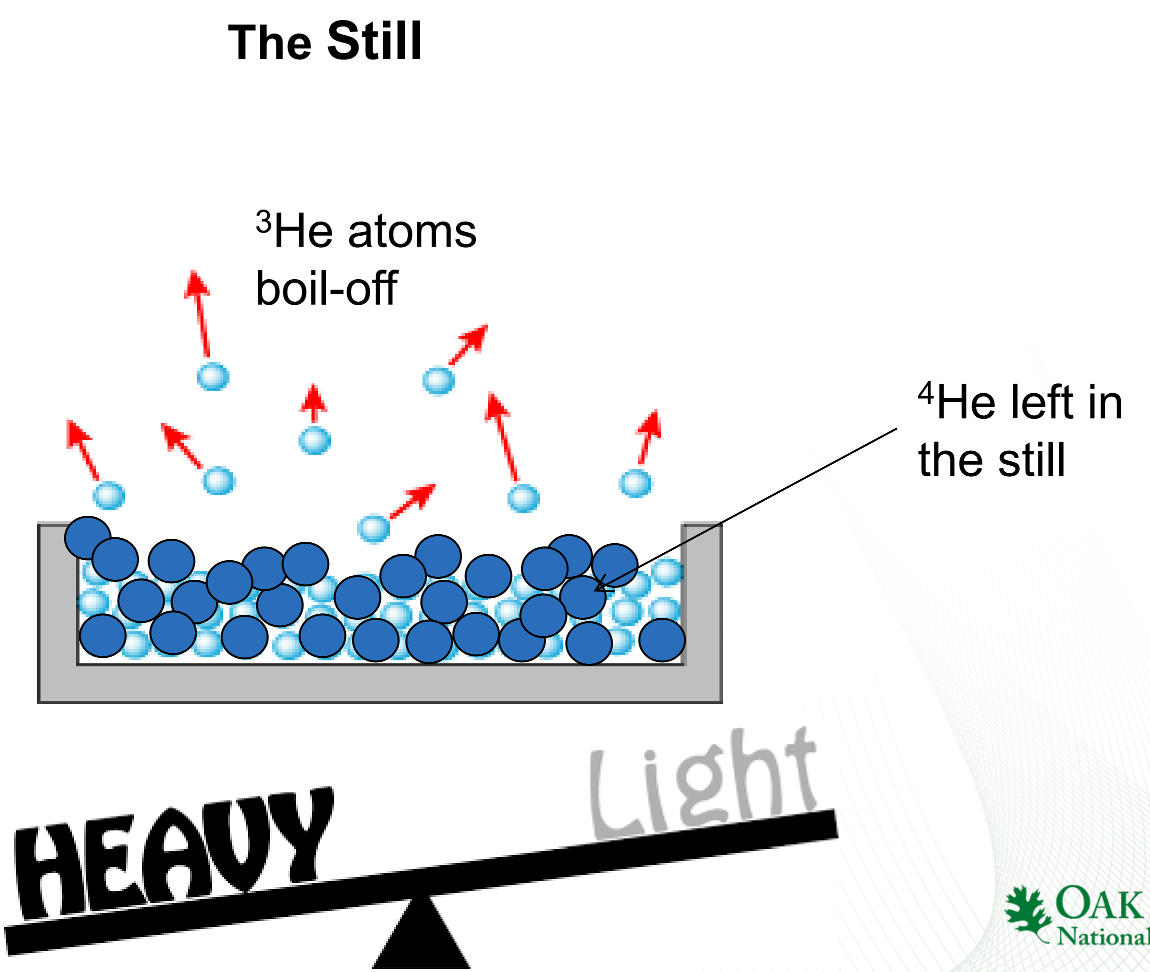
- Mix 3He and 4He at room temperature
- As the temperature drops below 0.87Kelvin, 3He separates out of the mixture
- Gravity pulls the heavier fluid to the bottom of our container, while the lighter pure helium-3 floats on the top
- The phase boundary exists
- ***This effect occurs in the mixing chamber***

**The mixing chamber**



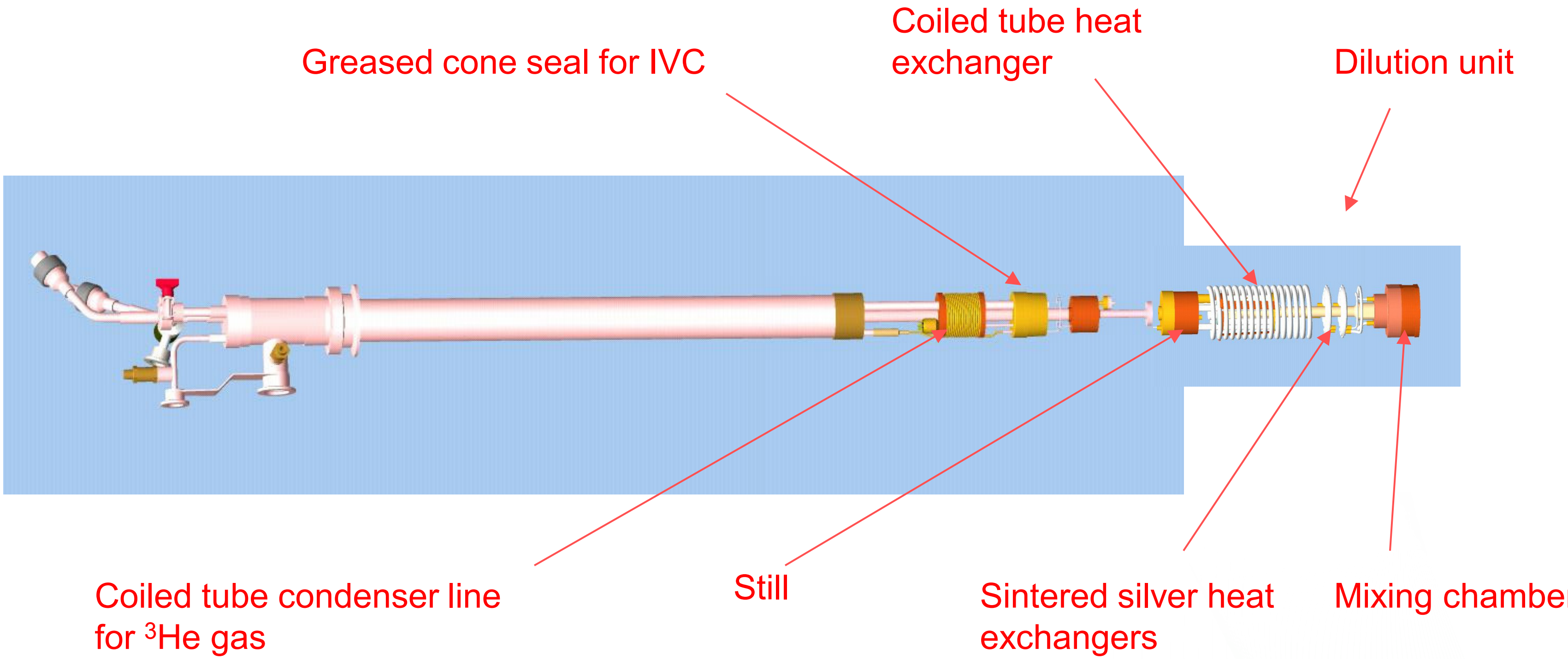
# Properties of $^3He$ & $^4He$ cont. – boiling in the still

If you heat a mixture of $^3He$ & $^4He$ atoms the lighter $^3He$ atoms boil-off leaving the heavier $^4He$ atoms behind



# Dilution Refrigerator – in real life known as KelvinoxVT

**Outer diameter < 50 mm to suit 50 mm diameter VTI**

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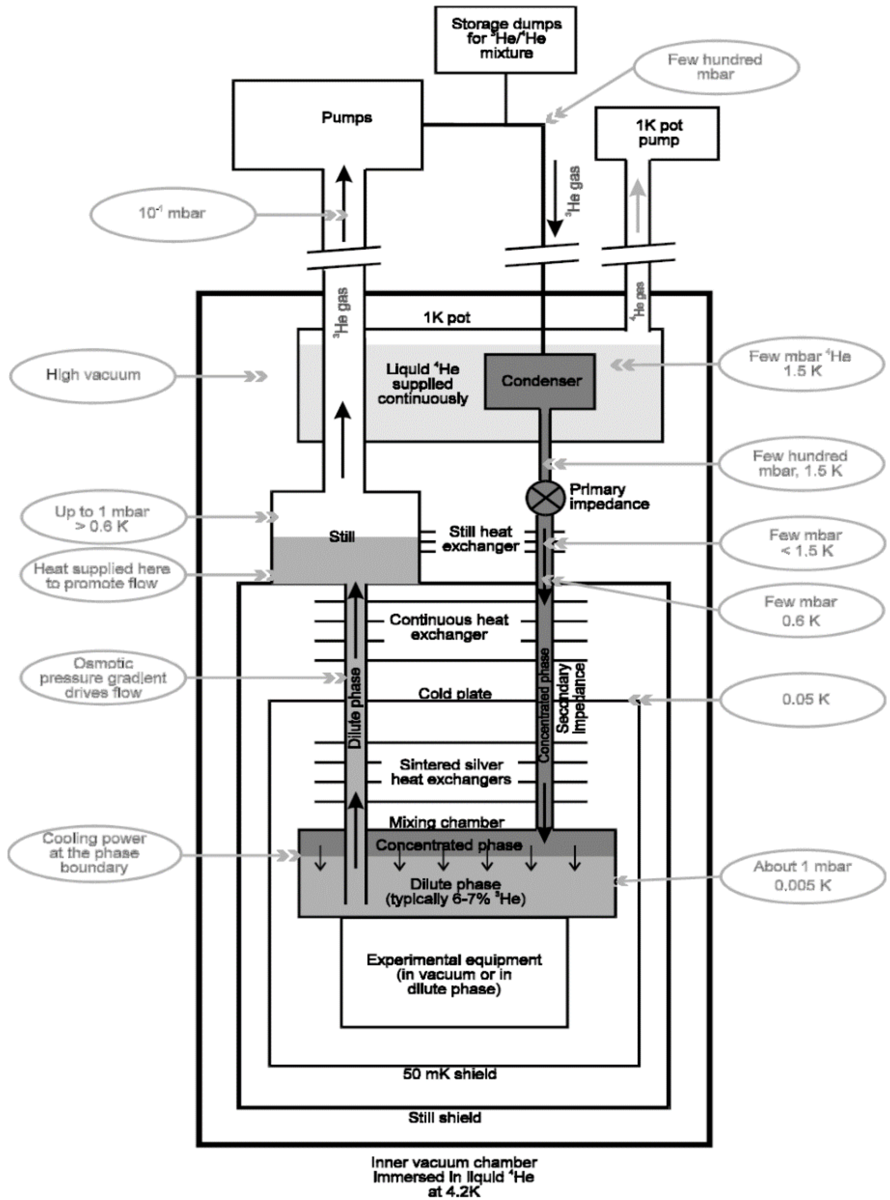
# Helium-3 circulation path

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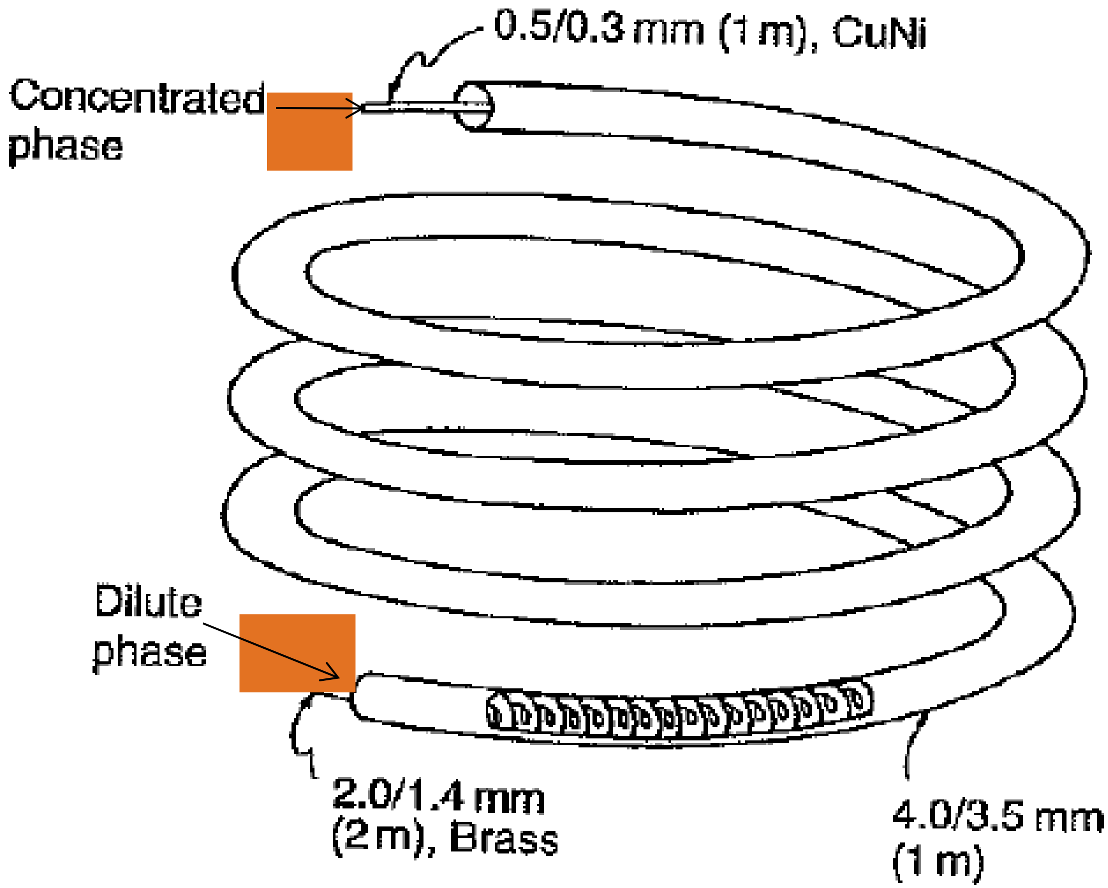
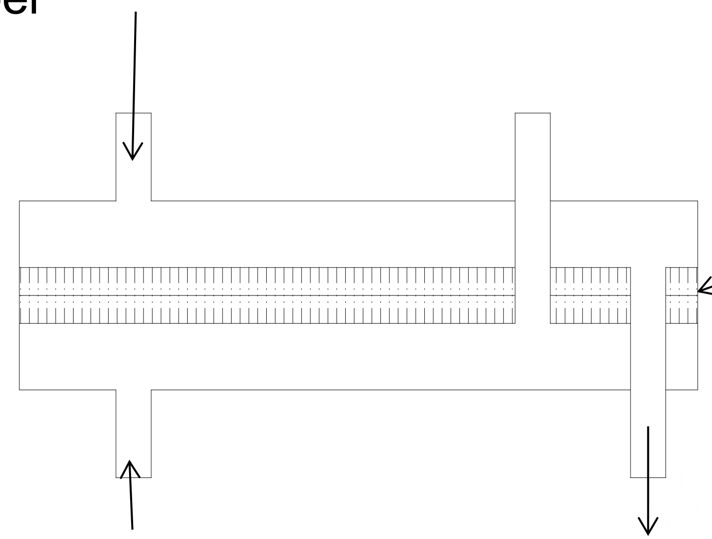
# Coil Heat exchanger



# Silver Heat exchangers

Warmer Helium-3 returning into system on route to mixing chamber

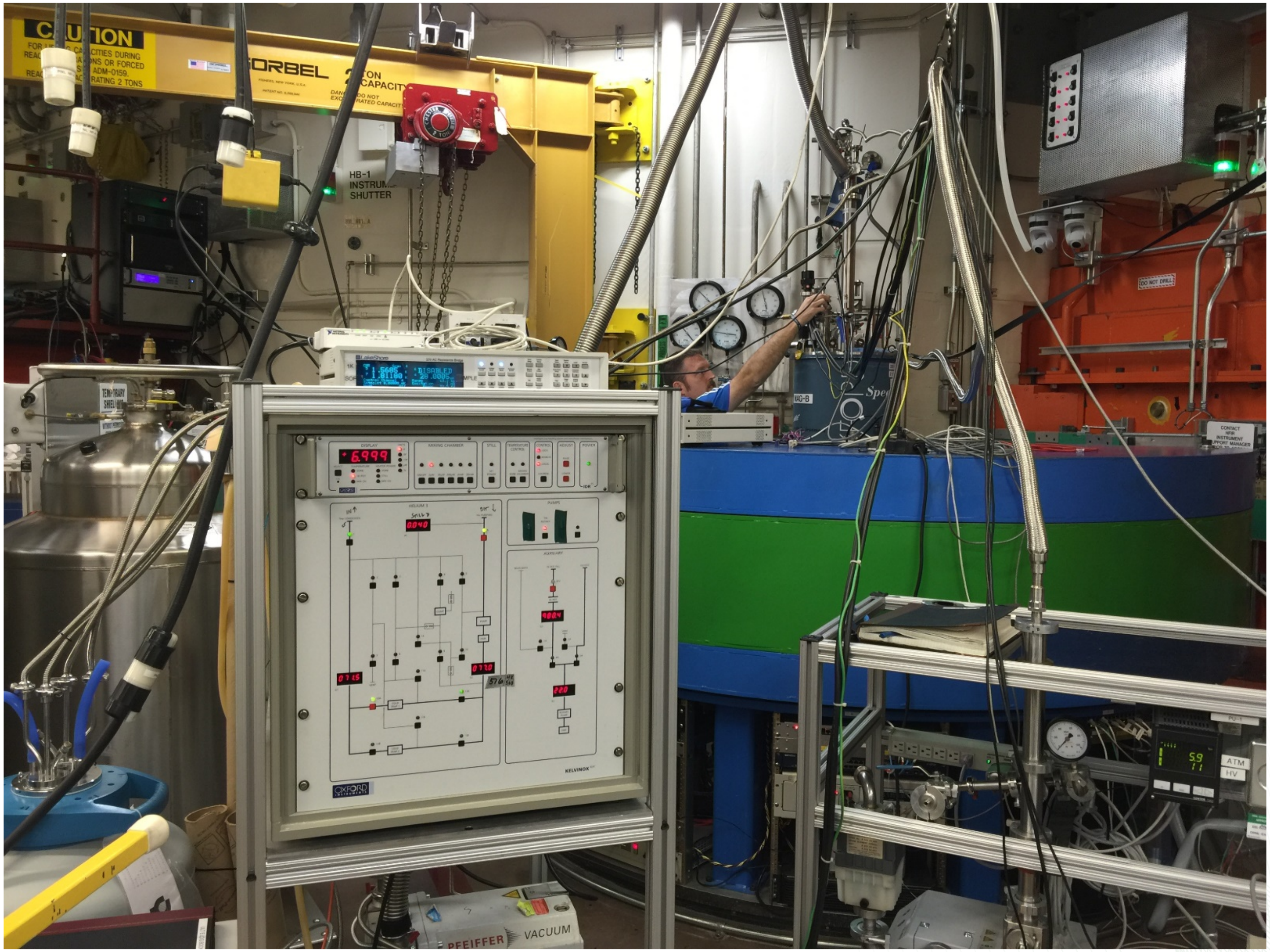


Silver sinter both sides of foil

'Colder' Helium-3 from mixing chamber on route to the still

Cooled Helium-3 on route to mixing chamber

# DR Experiment at HB2A

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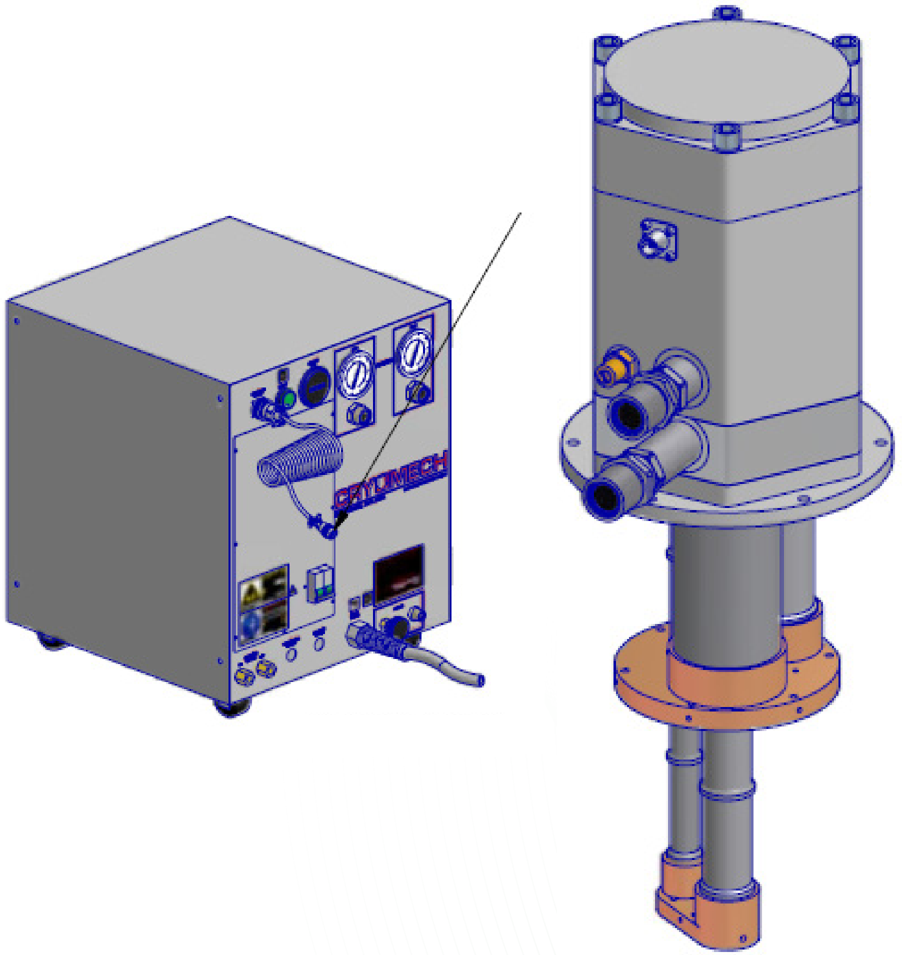
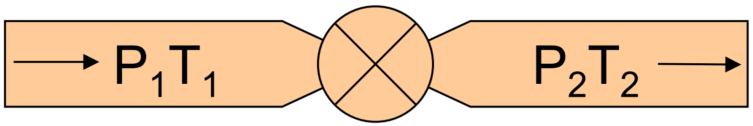
# ‘Dry’ Dilution Refrigerator

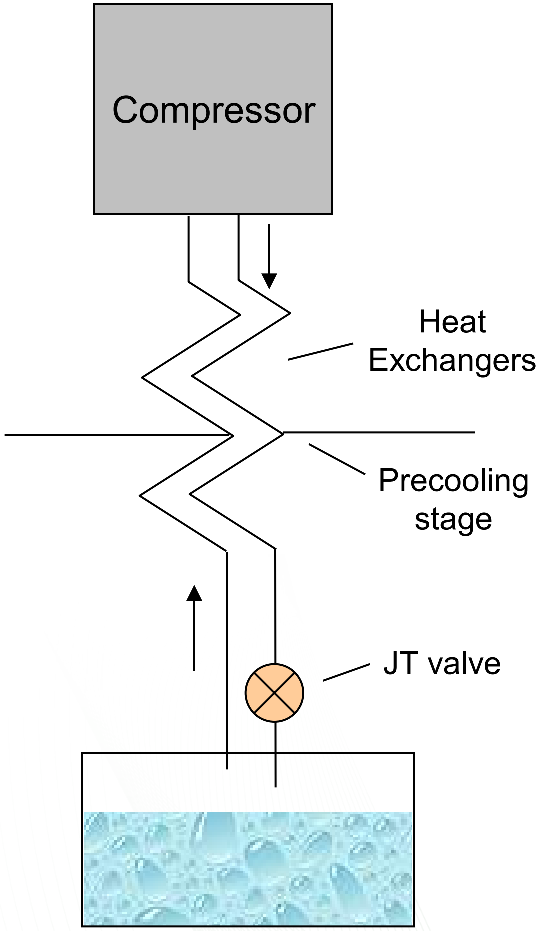
Supplier uses a pulse tube cooler to achieve a starting temperature of 4Kelvin or below



# Condensing Helium-3 at 4K



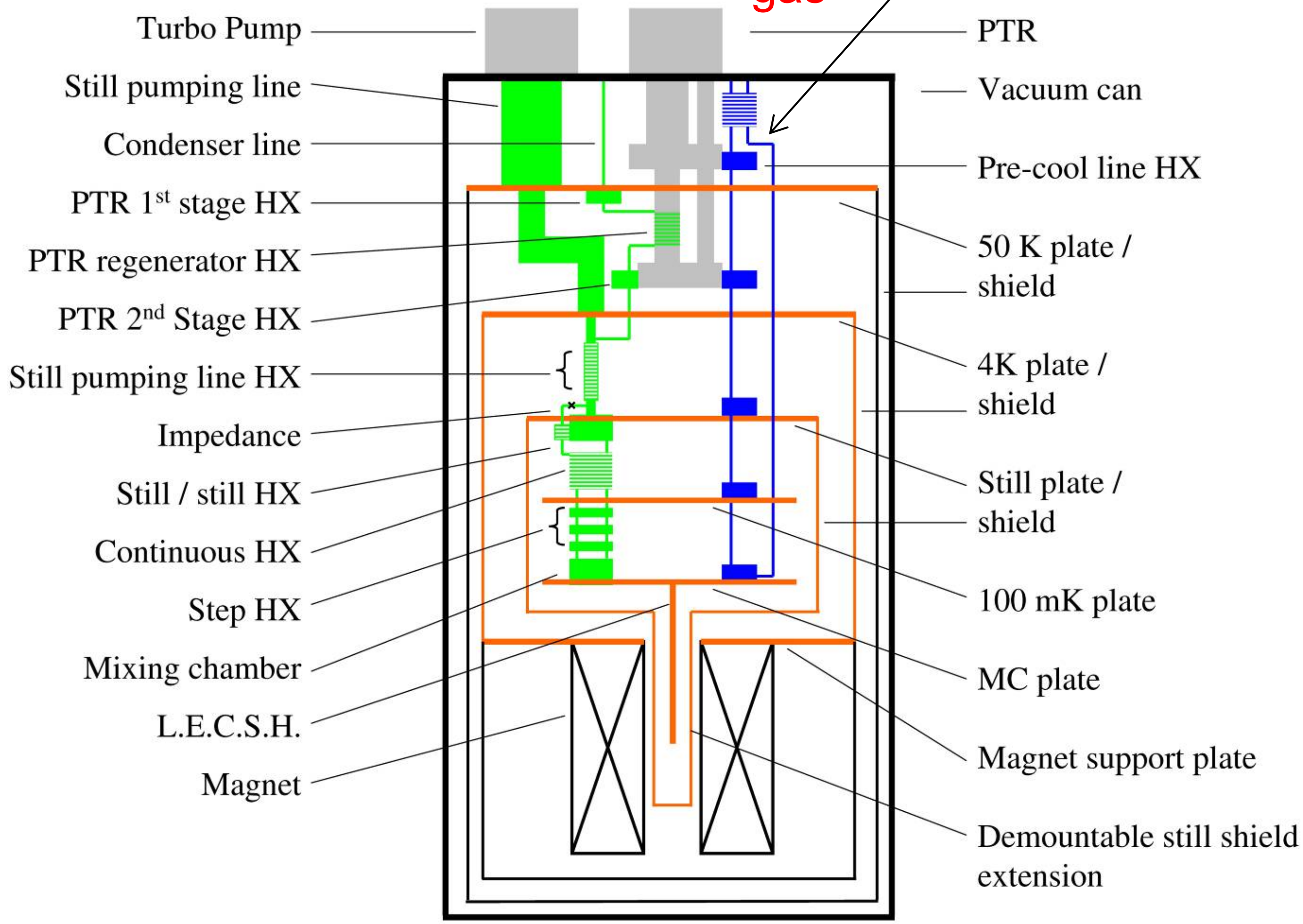

- The Joule Thomson valve is a simple device that cools gas through a nozzle due to expansion from high pressure to low pressure gas.




A simplified liquefier

# The Dry Dil Fridge concept

Special pre-cool line to cool unit dilution unit to 4K without exchange gas

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# Cryogen-free dilution refrigerators

## The Triton cryogen-free dilution refrigerator

No liquid cryogens

Base temperature <10 mK

Cooling power 400 uW at 100 mK

Temperature control possible > 30 K

240 mm diameter mixing chamber plate

Open structure for easy experimental access

Fully automated cool down from room temperature in **< 24 hours**

Courtesy: Oxford Instruments

# What can possibly go wrong?

1. IVC Leaks through cone seal

Helium is superfluid, ‘tiny’ holes on atomic scale will pass helium & destroy cryostat vacuum

2. Heat Load from radiation or touch

Holes in shields pass 46mW/cm$^2$, so holes as small as ~1mm$^2$ can impact performance – cover all the radiation holes with Al tape

3. Blockages

Contamination in tubes or air leaks can cause blockages in cold traps

4. Bolted connections/thermal contact

There are lots of bolted connections on ULT systems PTR, shields, mixing chamber ,all need securing.

# Useful Books

- **G.K.White and P.J.Meeson**:
  - *Experimental Techniques in Low Temperature Physics*
  - (Oxford University Press 2002)
- **F.Pobell**:
  - *Matter and Methods at Low Temperatures*
  - (Springer, 1996)
- **R.C.Richardson and E.N.Smith**:
  - *Experimental Techniques in Condensed Matter Physics at Low Temperatures*
  - (Addison-Wesley, 1988)
- **D.S.Betts**:
  - *Refrigeration and Thermometry Below 1 K*
  - (Sussex University Press, 1976)
- **O.V.Lounasmaa**:
  - *Experimental Principles and Methods Below 1 K*
  - (Academic Press, 1974)

# Questions?