To Low Temperatures and Beyond

Lab Tutorial
May 24th, 2019

MJ Carballido, Zumbühl Group

Intro

Miguel: “HELP! I’m anxious about something random!”

Kris: “Well, first you’ve got to chill…”

Tim: “… and then you need to keep your cool.”

Outline

- Our goal is to extract heat with a heat pump …
- … by using a coolant …
- … inside a thermally isolated vessel to avoid warming up.

Outline

Working principles of our different refrigerators

- Our goal is to extract heat with a heat pump …
- … by using a coolant … → Requirements and Properties
- … inside a thermally isolated vessel to avoid warming up.

Managing heat flow

Cryofluids

Important characteristics:

Boiling point T_b, the latent heat of evaporation L and Enthalpy H.

Ideal candidates: Helium and Nitrogen

He's almost point-like nature and weak interaction (No dipole moments, only Van der Waals int.) make it the closest to an ideal gas. N_2 is cheap, good for precooling.

	^4He	^3He	N_2
L ($kJ\ l^{-1}$)	2.56	0.48	161
T_b (K)	4.21	3.19	77.2
H ($kJ\ l^{-1}$)	200 *	-	64 **

* : between 4.2K - 300K

** : between 77.2K - 300K

Cryofluids

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cryoliquid	temperature change [K]	Al	SS	Cu
N_2	300 → 77	1.0 (0.63)	0.53 (0.33)	0.46 (0.28)
^{4}He	77 → 4.2	3.2 (0.20)	1.4 (0.10)	2.2 (0.16)
^{4}He	300 → 4.2	66 (1.6)	34 (0.8)	32 (0.8)

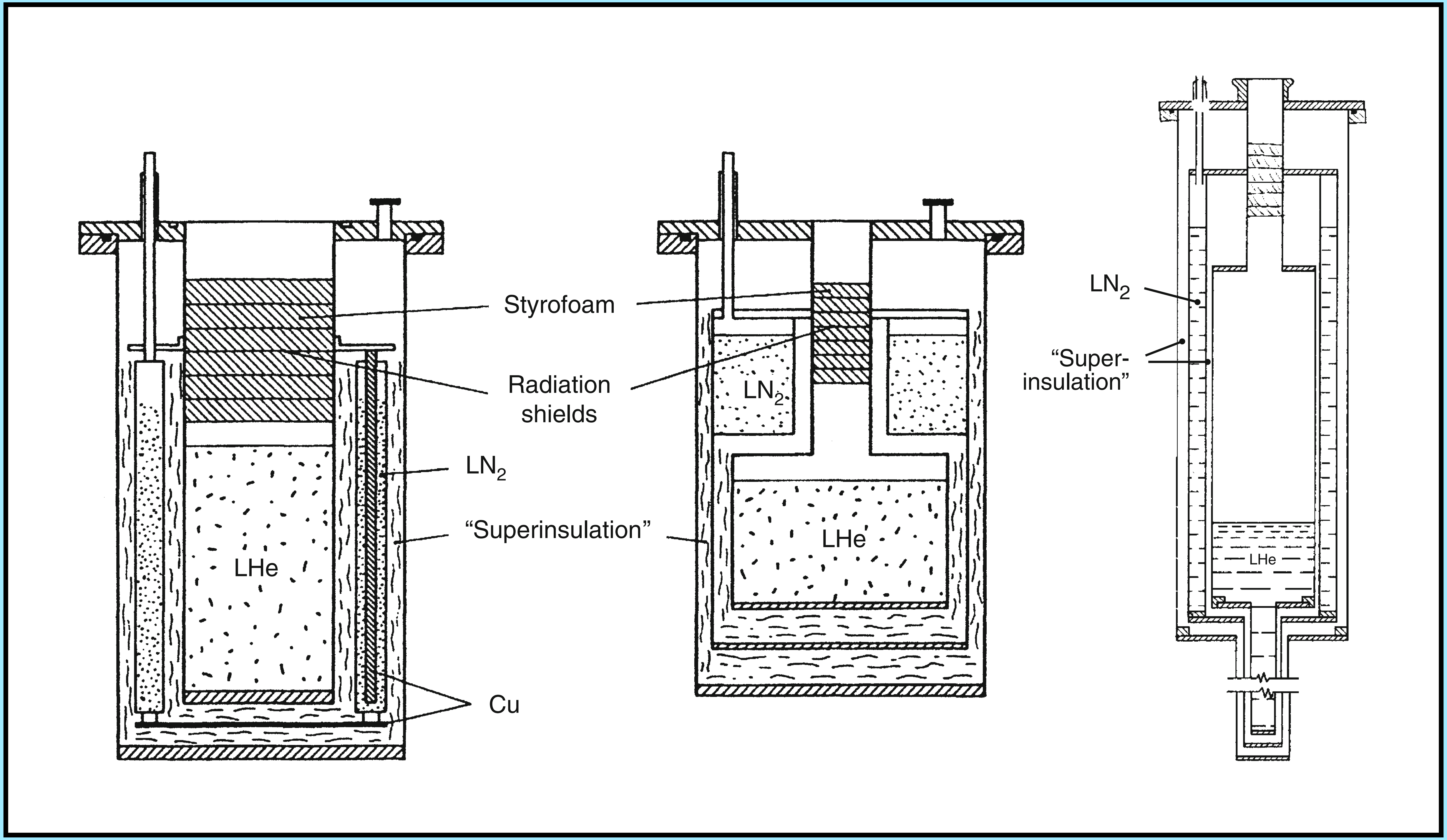
F. Pobell, 2007

Dewars

[…] the Scottish scientist James Dewar […] had to improve the storage vessels for cryogenic liquids. […] He eventually arrived at the double-walled vacuum isolation vessel, now commonly called a “dewar”.

The dewar in its simplest form is nothing but the double walled flasks which are used to keep coffee warm on a camping trip.

Dewars



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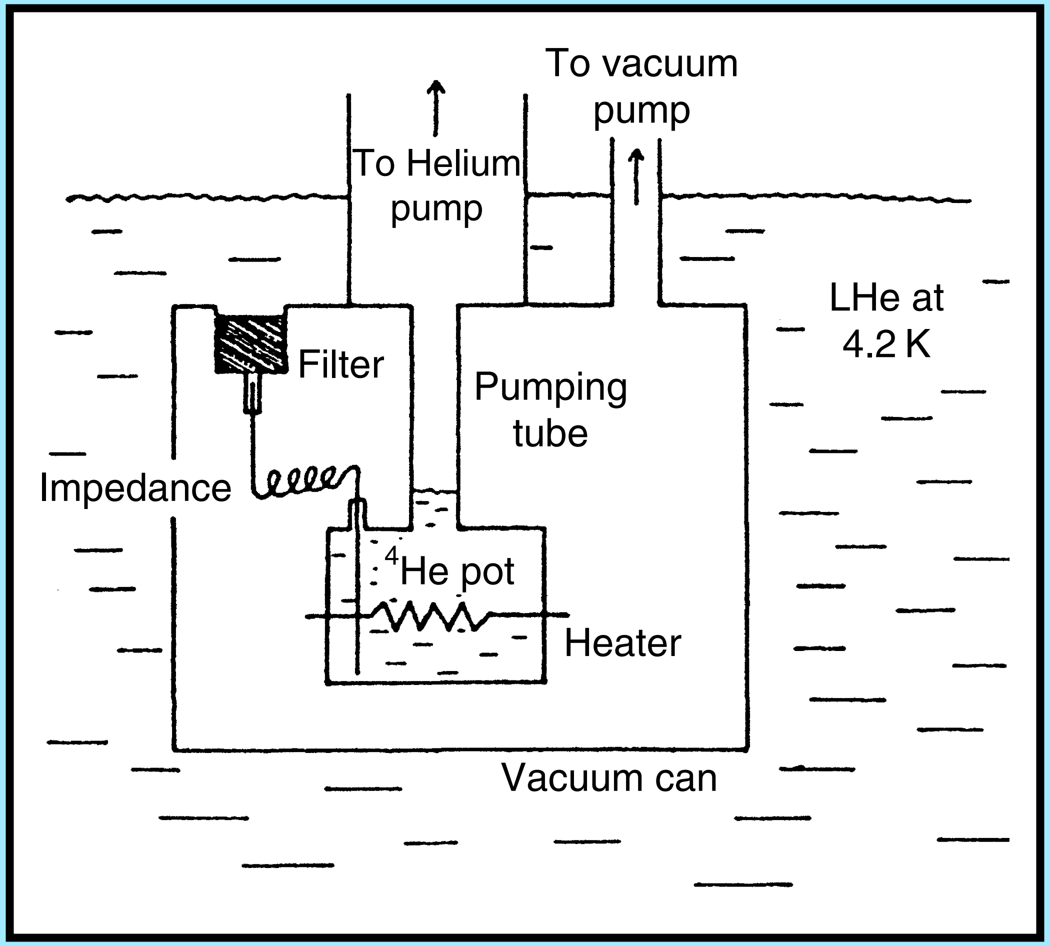
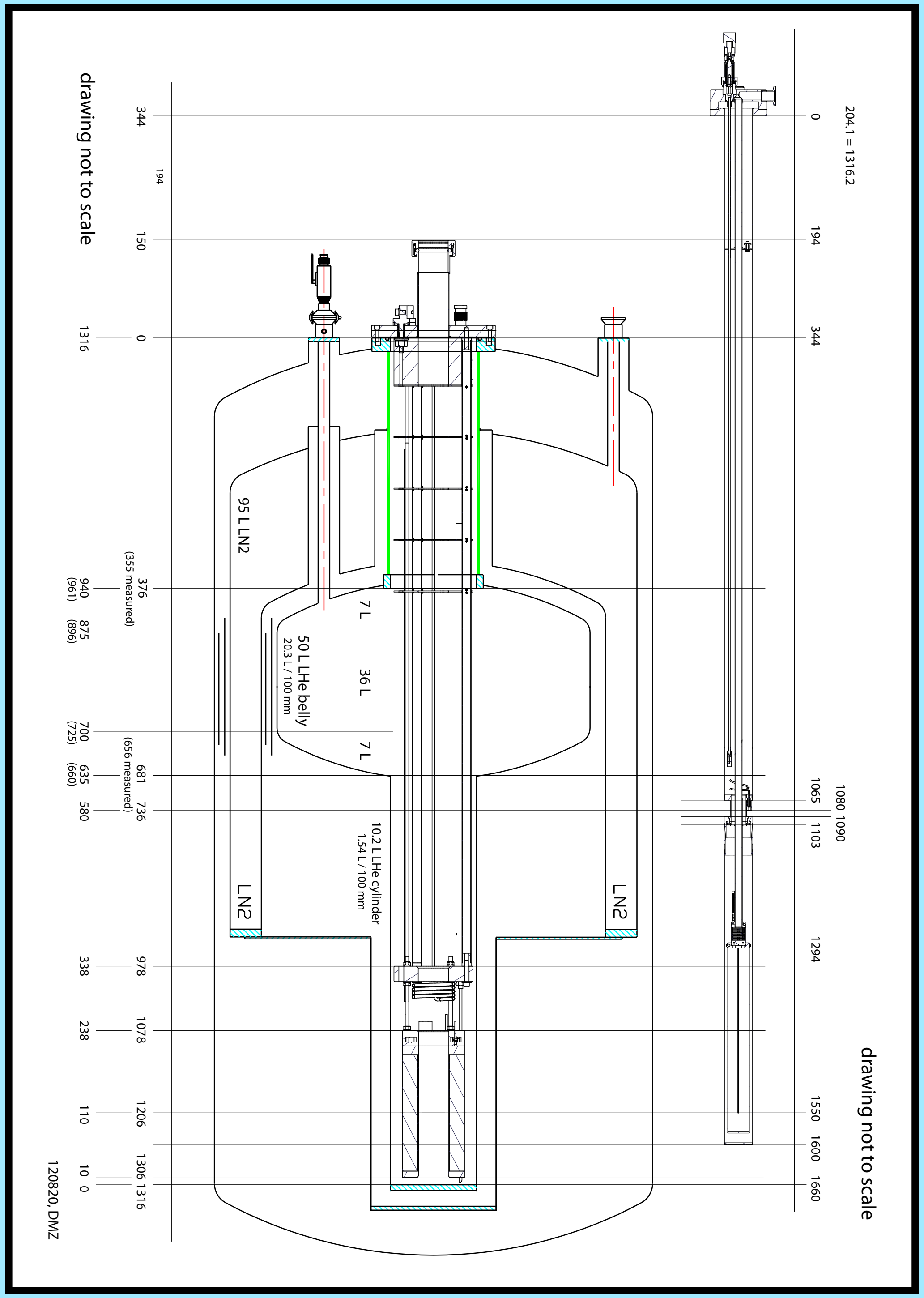
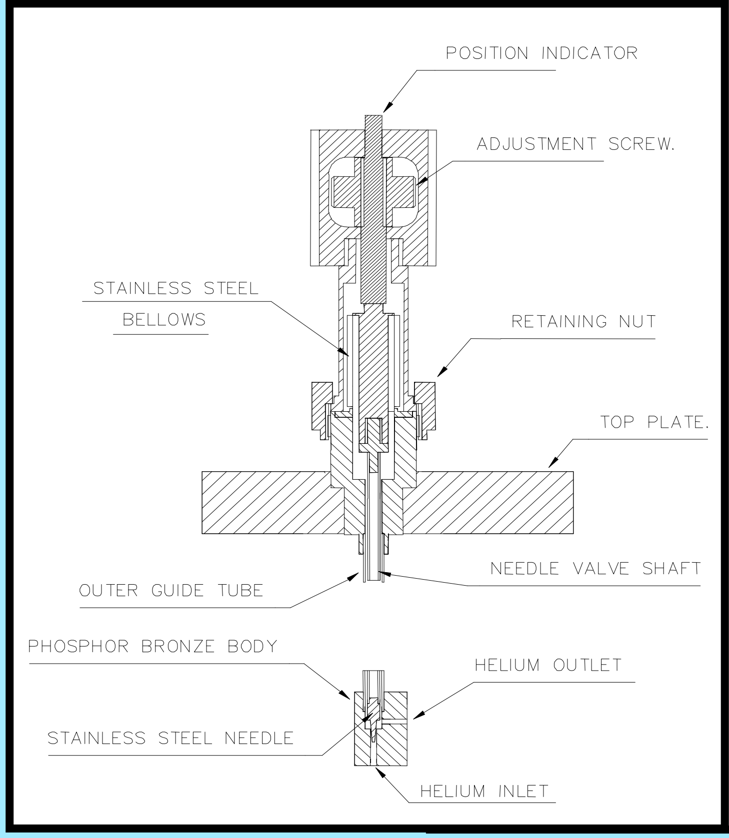
The VTI

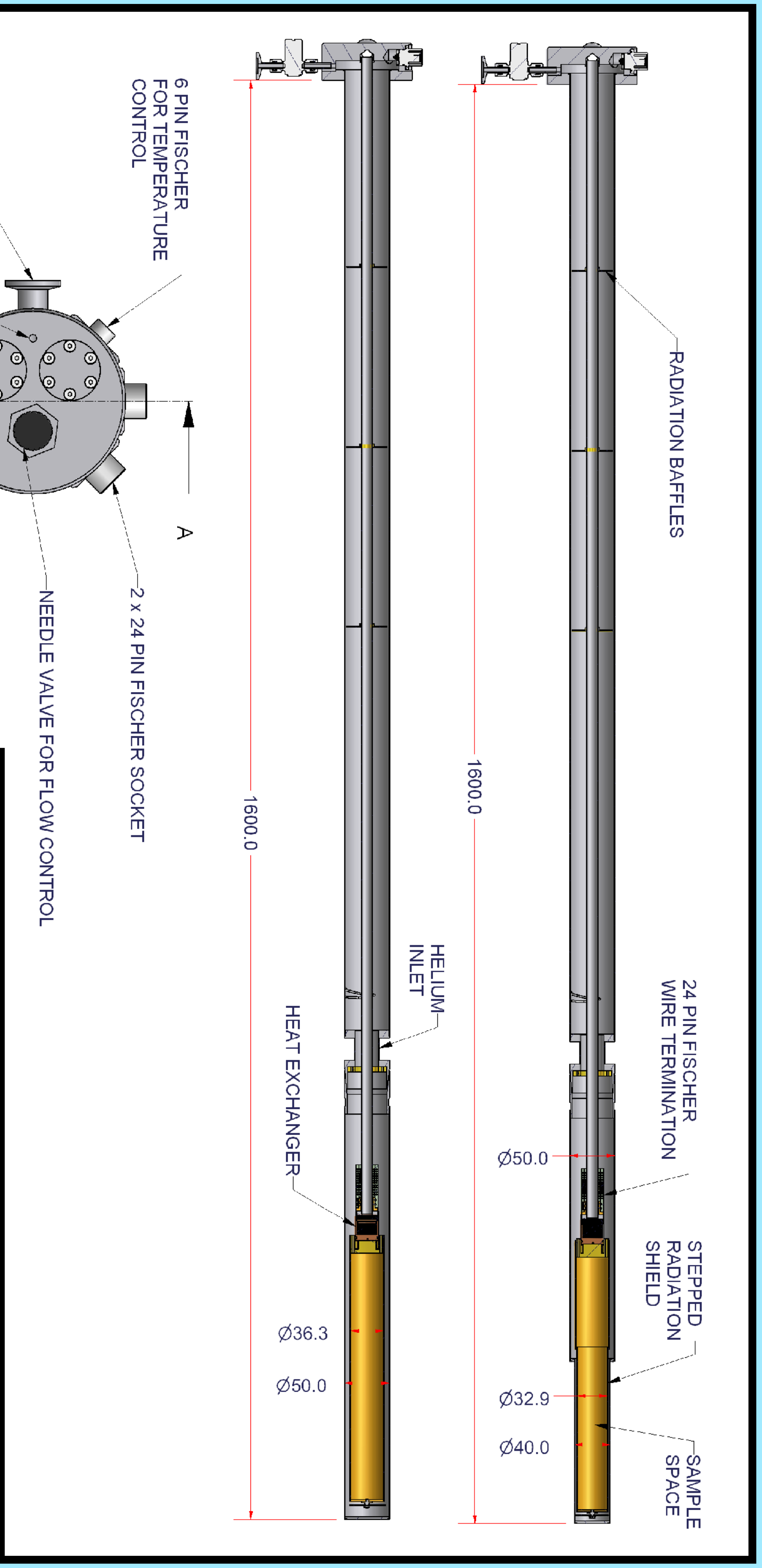
To go from T_b = 4.2 K to 1.3 K, we must pump on the vapour above the L^4He bath. This would require evaporating approx. 40% of the L^4He volume. Hence it makes sense to pump on a smaller volume —> 1-K pot



The VTI







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Overall

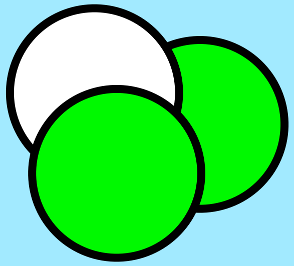
- Flexible temperature regime
- Quick operation
- Limited by BP of L^{4}He (when pumping) to around 2 K
- Can run “indefinitely”

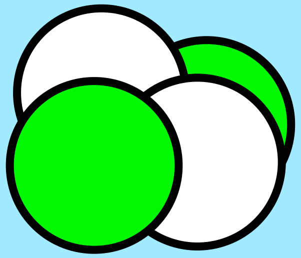
^{3}He-^{4}He Dilution Refrigerators

Exploiting the mixing entropy for cooling to the milikelvin regime

“Quantum Liquids”

Further special characteristics of ^{3}He and ^{4}He:

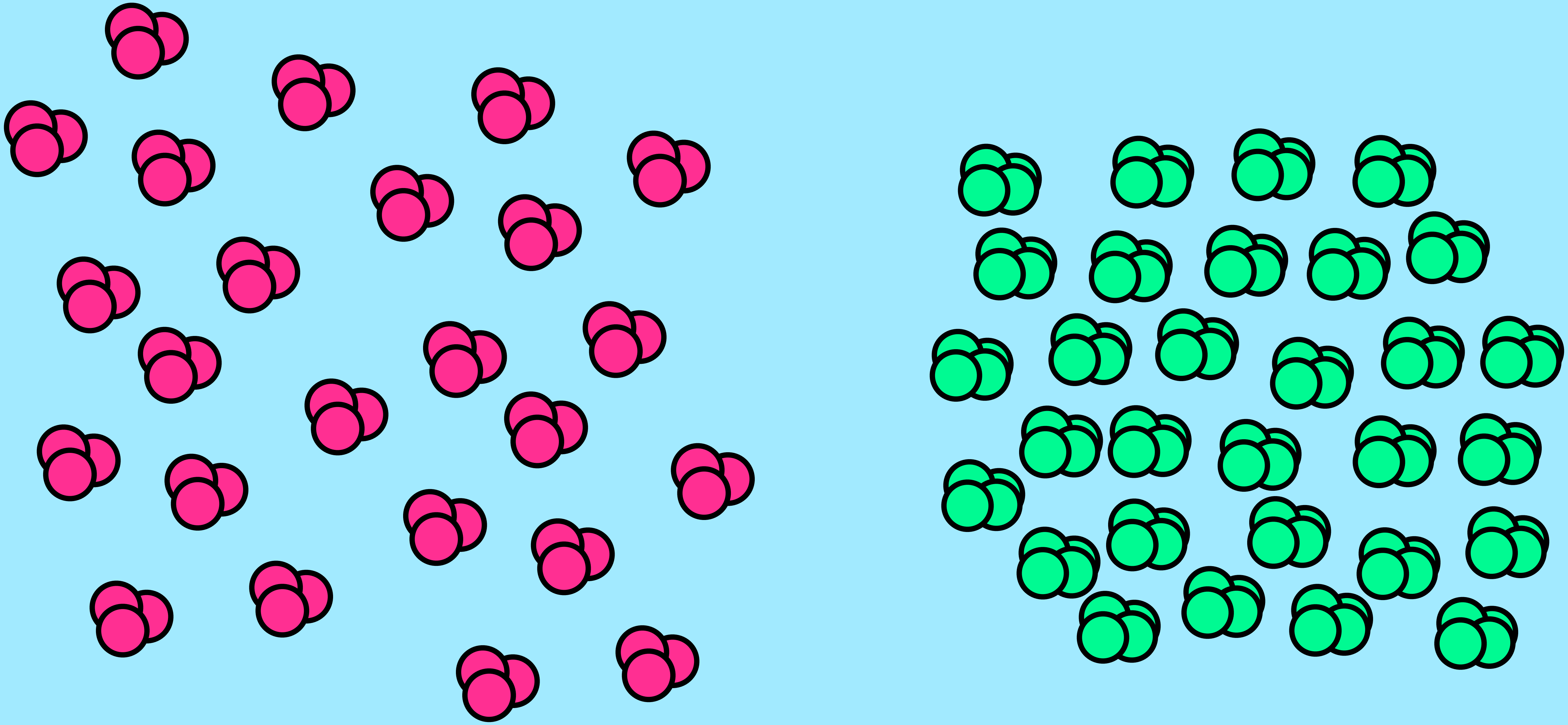




Fermion I = 1/2	Boson I = 0
Obeys PEP	E-B condensation
Superfluid @ 2.5 mK	Superfluid @ 2.2 K
Low ZPE	Lower ZPE

Mixtures

Consider the case of mixing L^3He and L^4He near $T = 0$ K:



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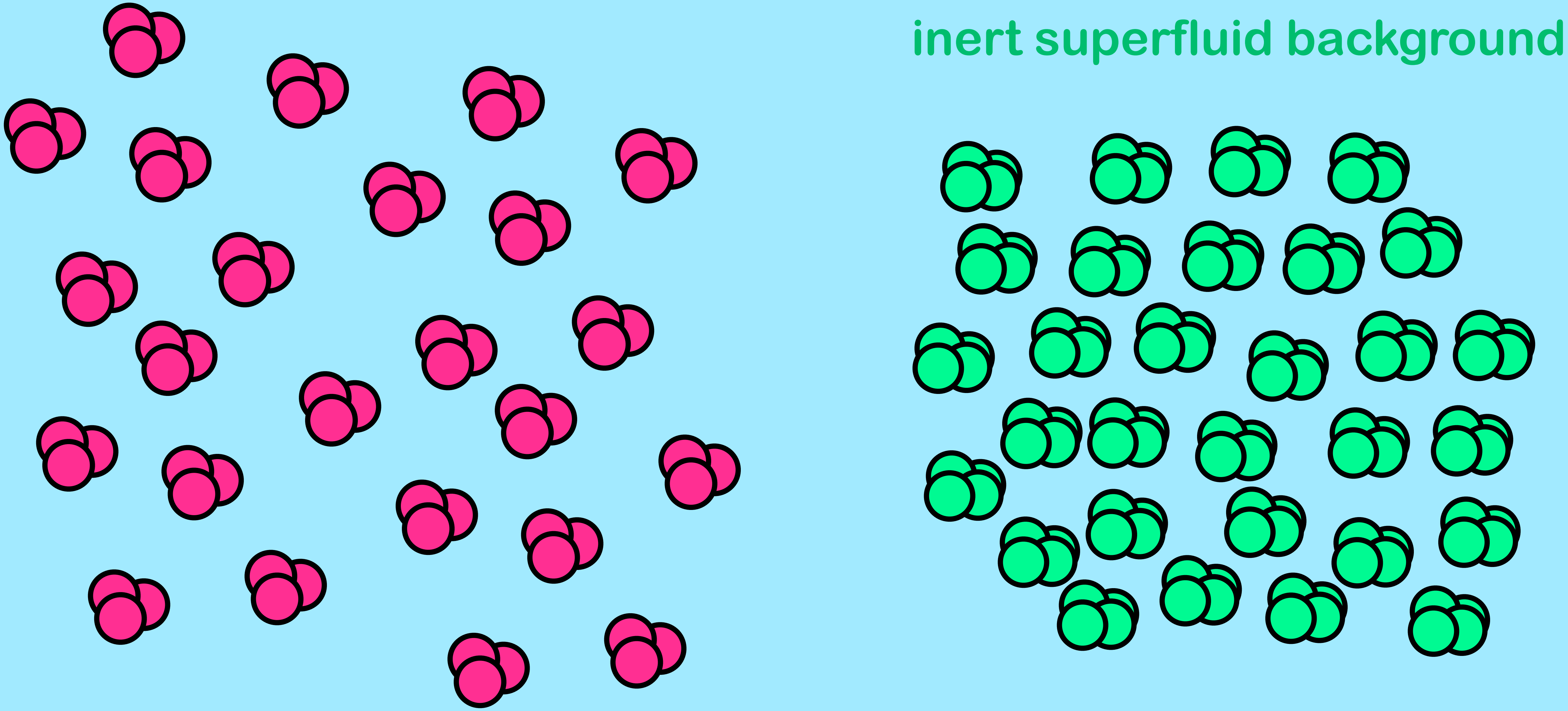
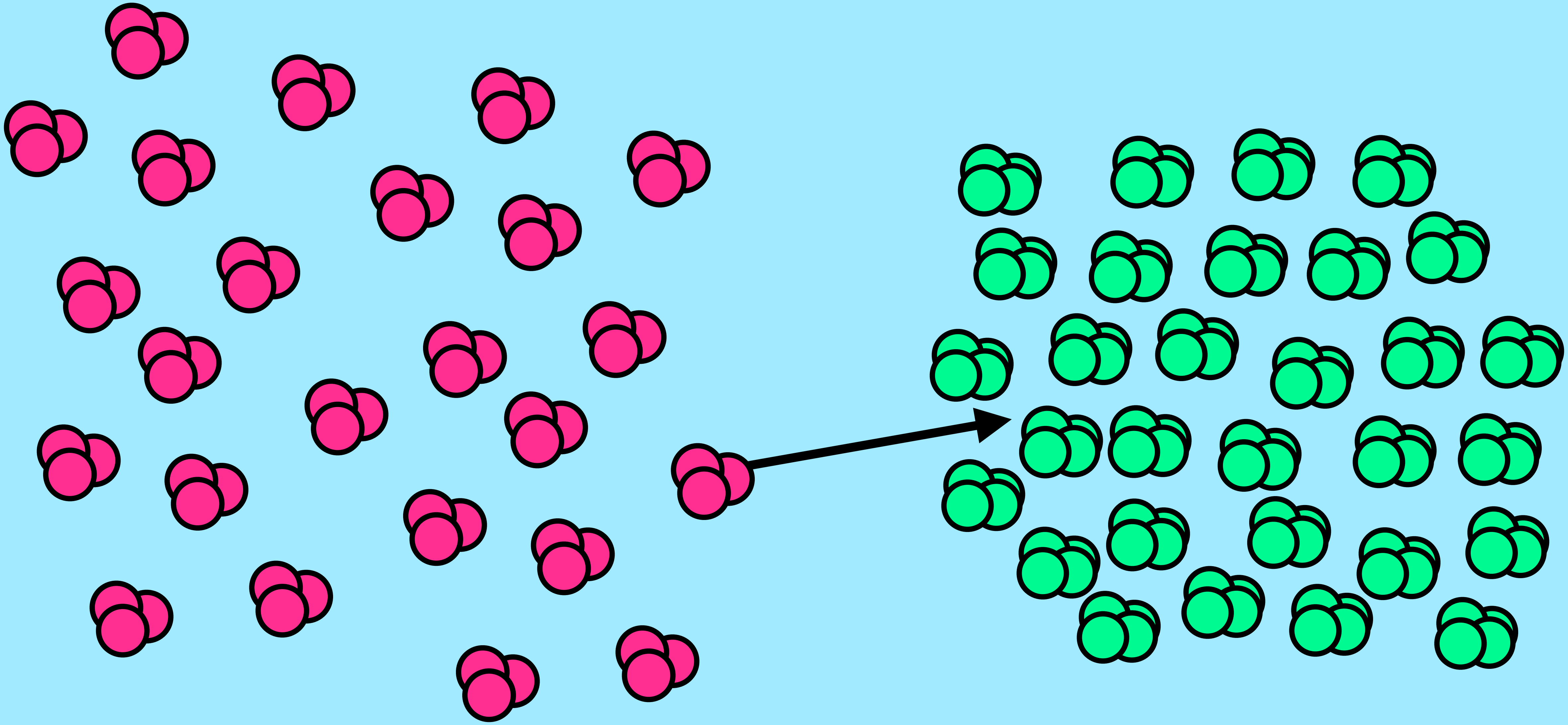


Mixtures

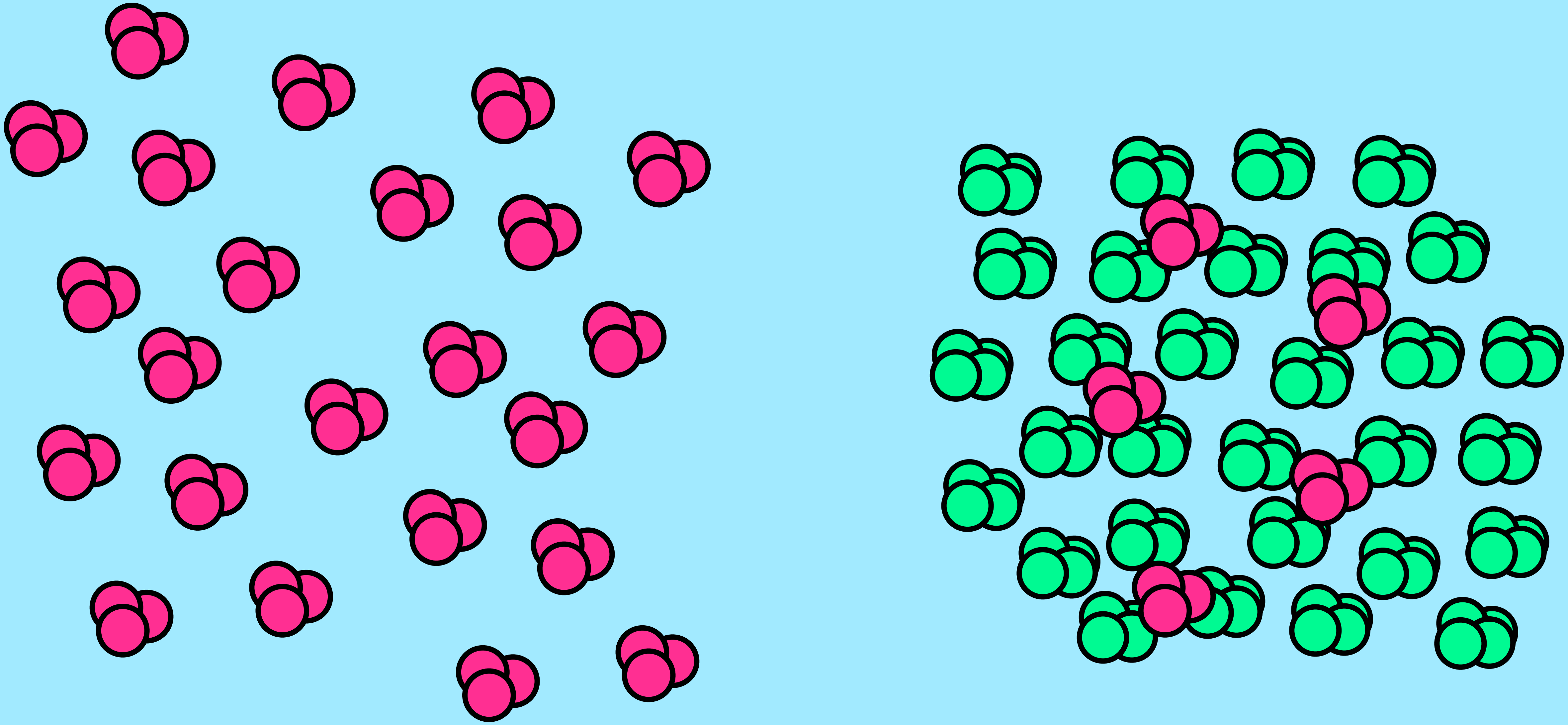
$\mu_{3,c} / N_0 = - L_3 / N_0$ $>$ $\mu_{3,d} / N_0 = - \varepsilon_{3,d}$

because of difference in ZPE



Mixtures

$\mu_{3,d} / N_0 = - \varepsilon_{3,d}(0)$



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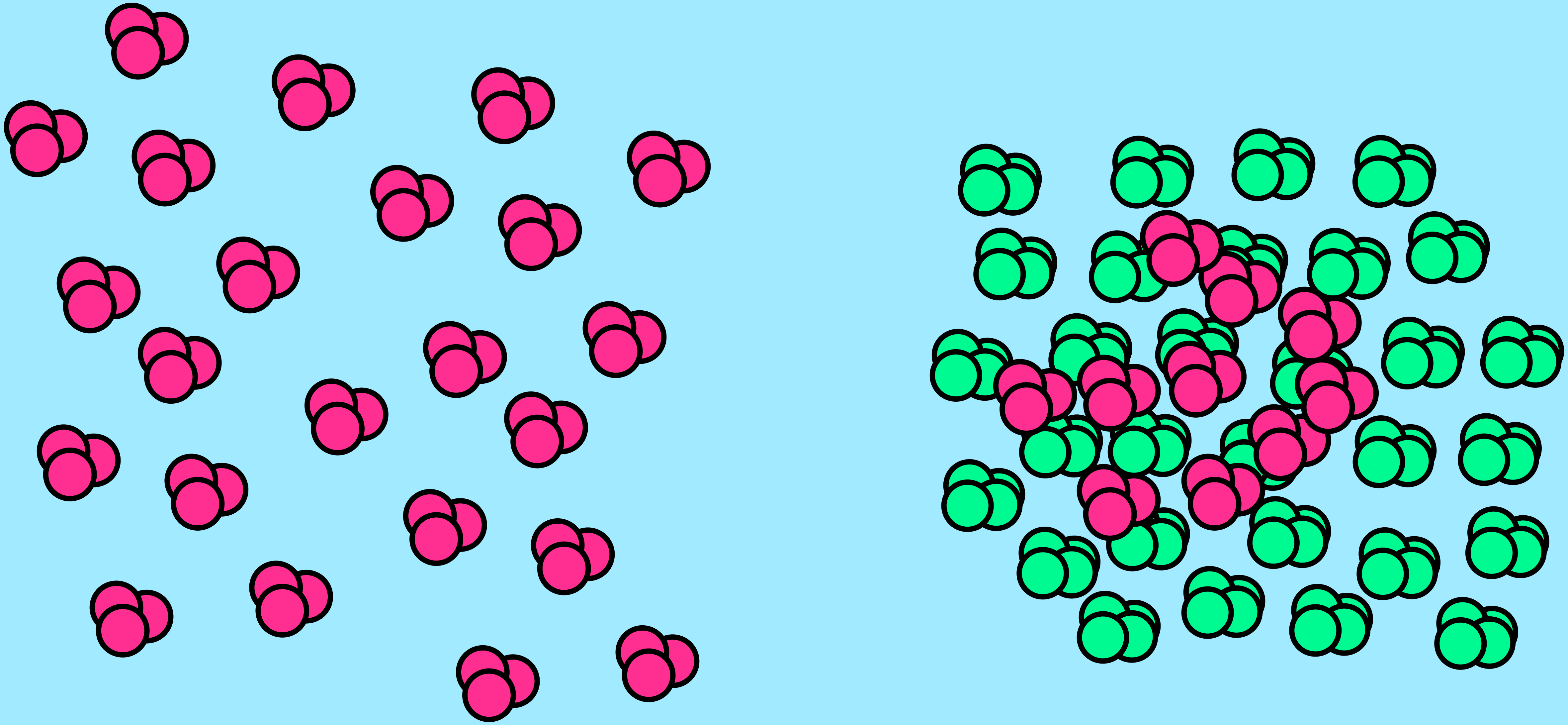
Mixtures

$$\mu_{3,d} / N_0 = - \varepsilon_{3,d}(0)$$

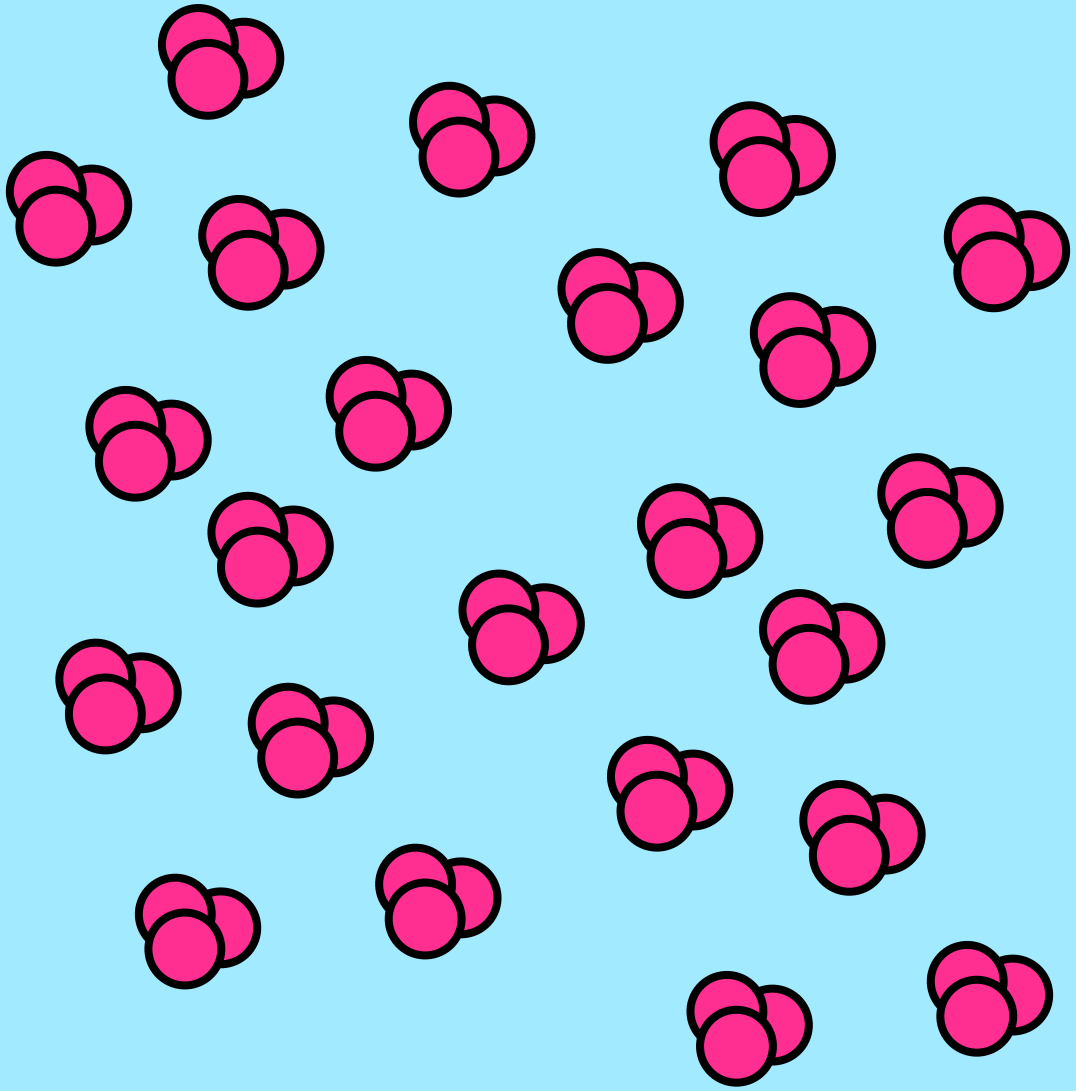
$$- \varepsilon_{3,d}(x) < - \varepsilon_{3,d}(0)$$

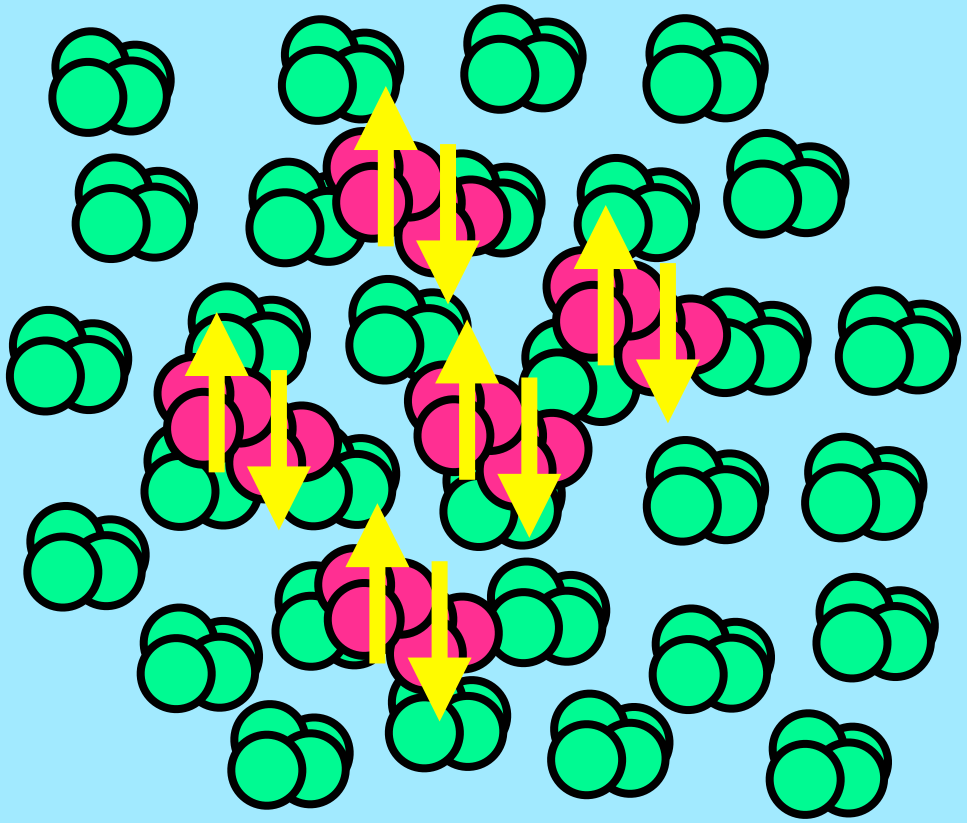


Mixtures

$$-\varepsilon_{3,d}(x) < -\varepsilon_{3,d}(0)$$

$$\mu_{3,d} / N_0\,(x) = -\varepsilon_{3,d}(x) + k_B\, T_F(x)$$

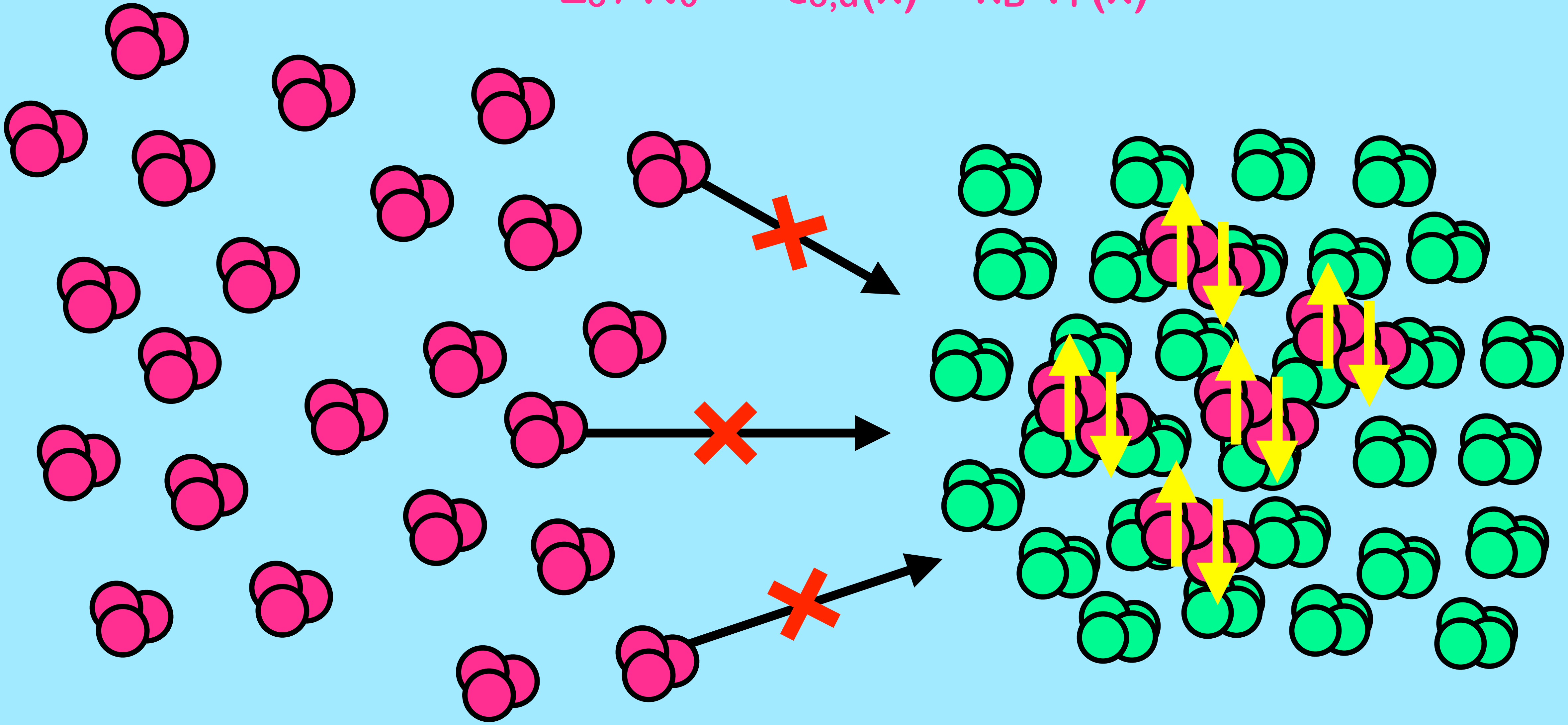




Mixtures

Limiting concentration x = 6.6 %

$$- L_3 / N_0 = - \varepsilon_{3,d}(x) + k_B T_F(x)$$



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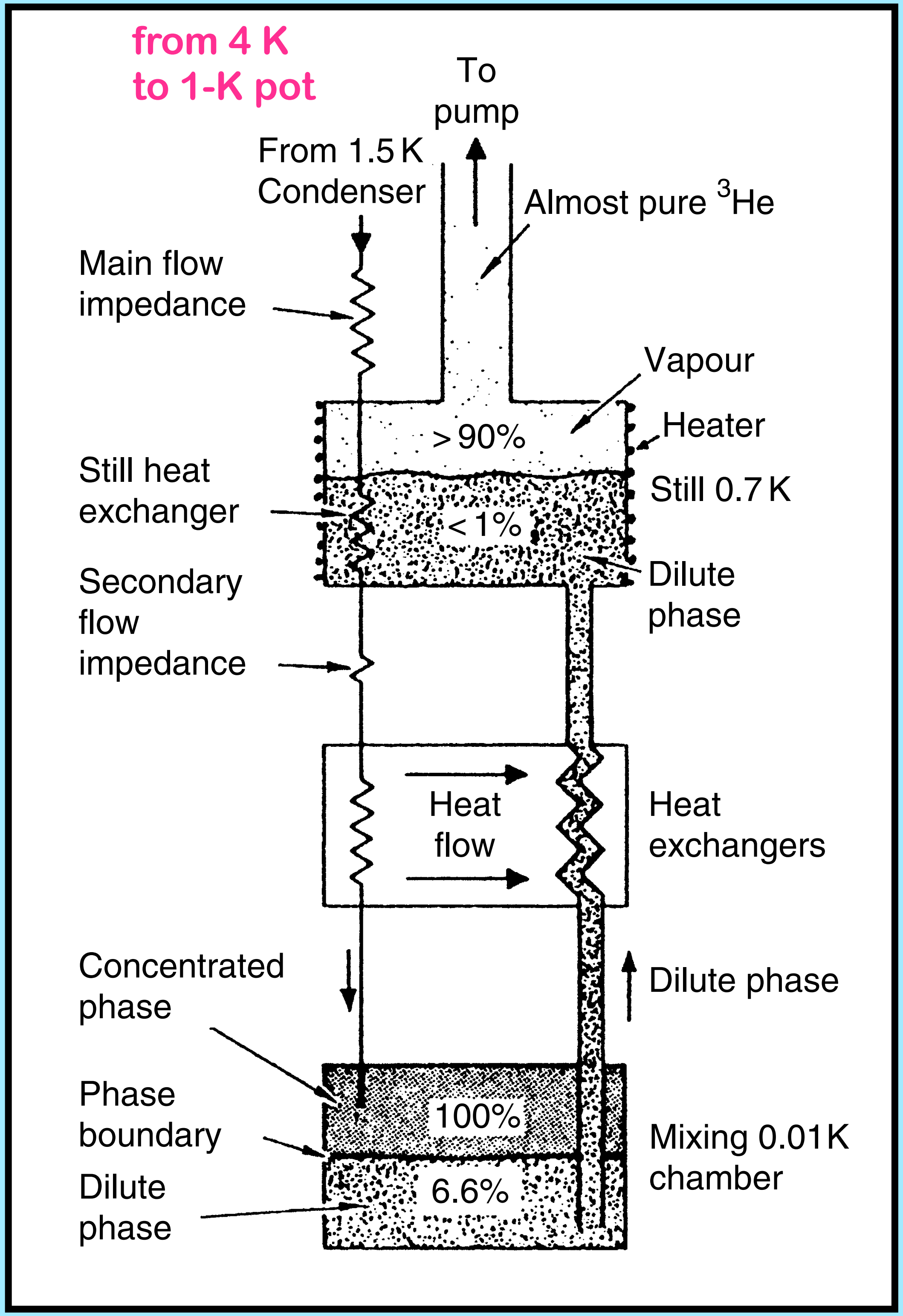
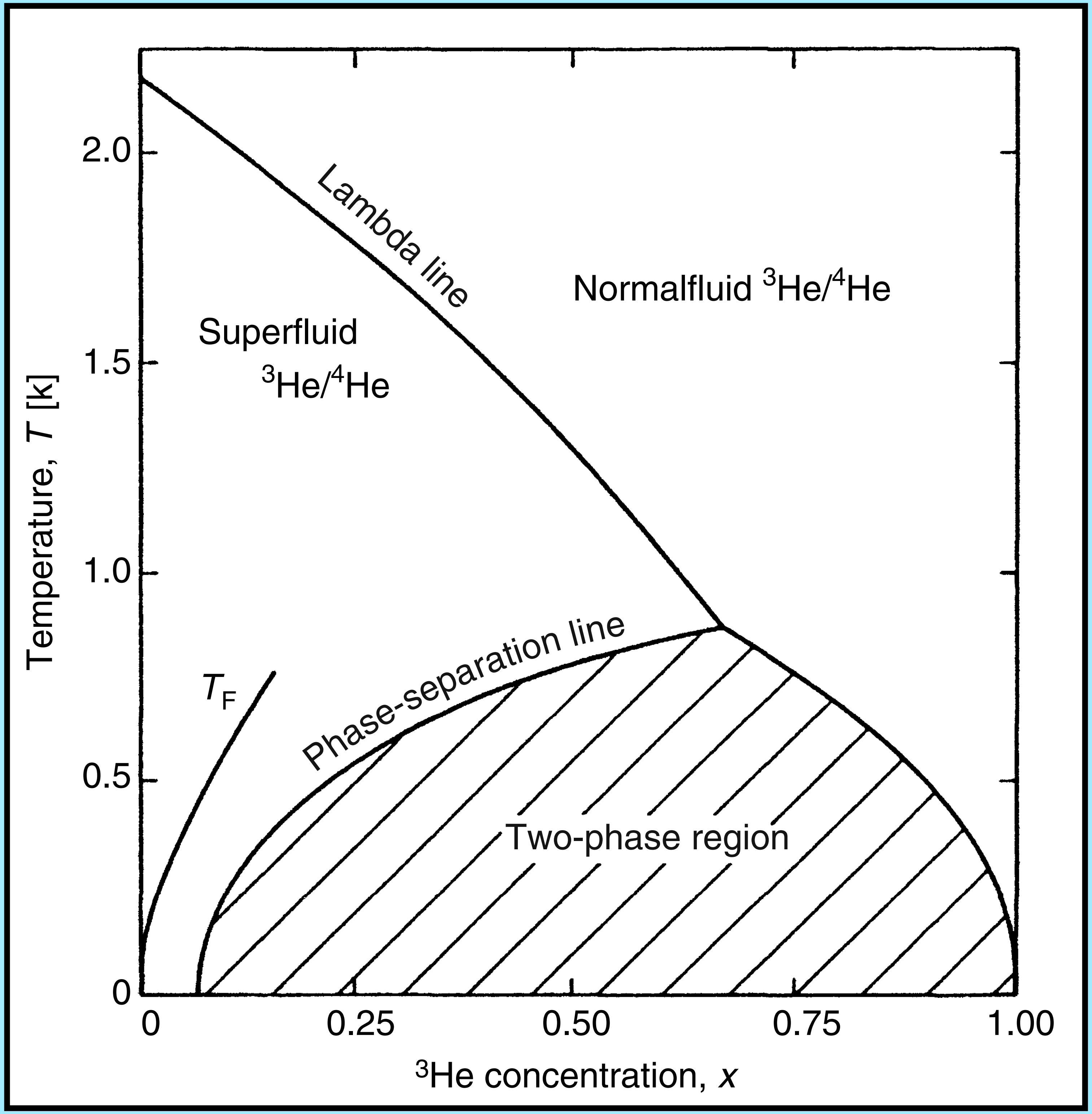
Dilution Refrigerators





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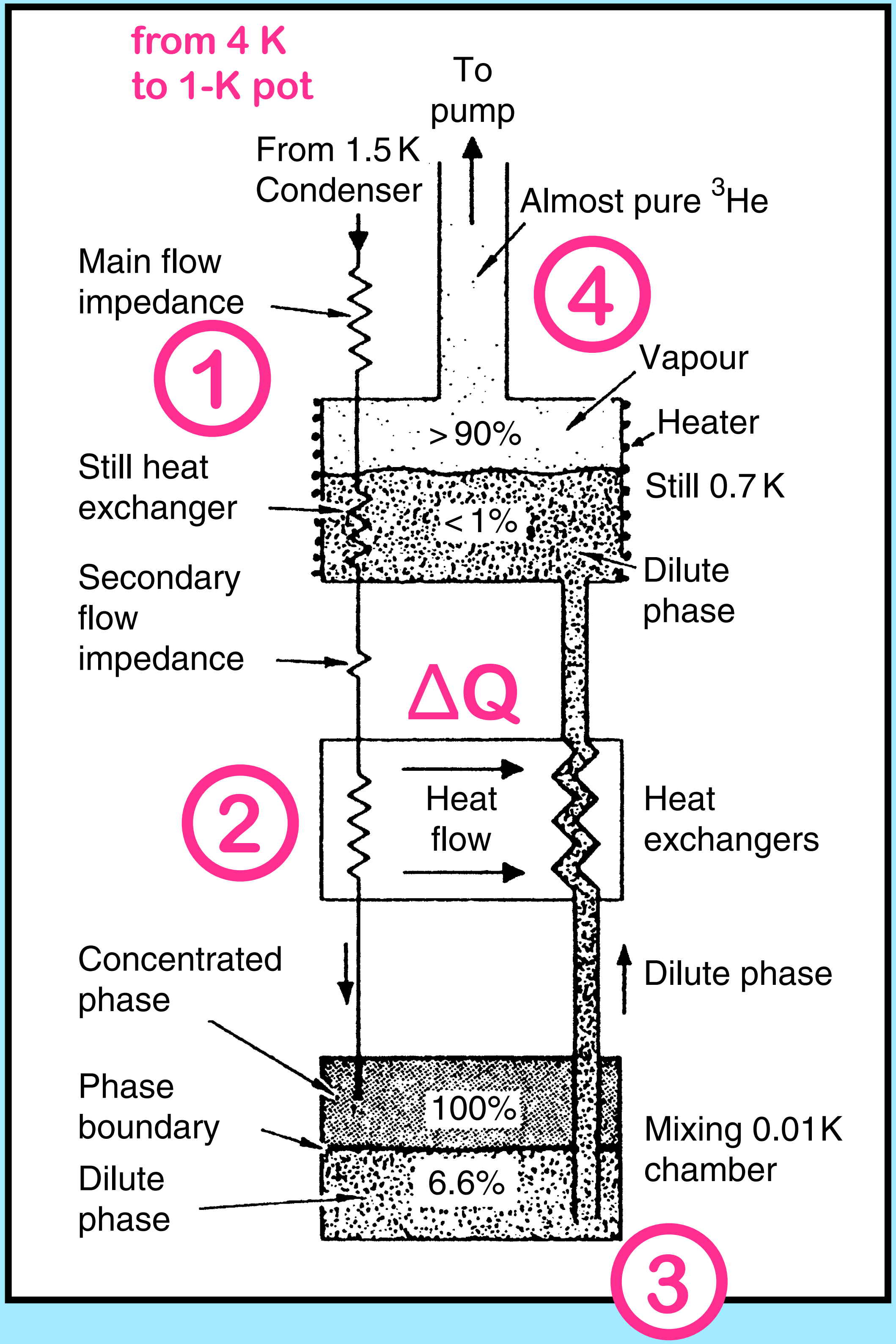
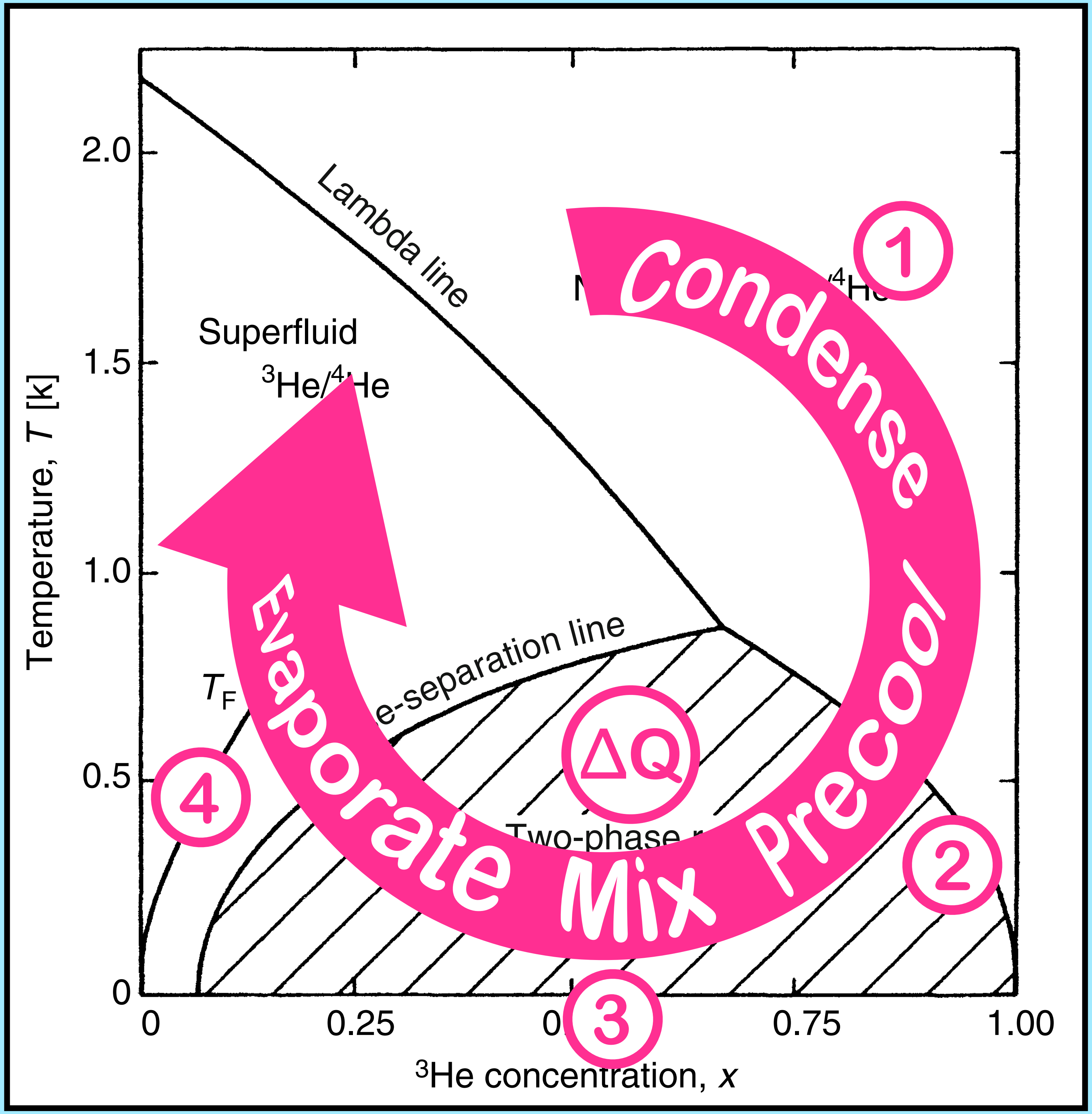
Dilution Refrigerators





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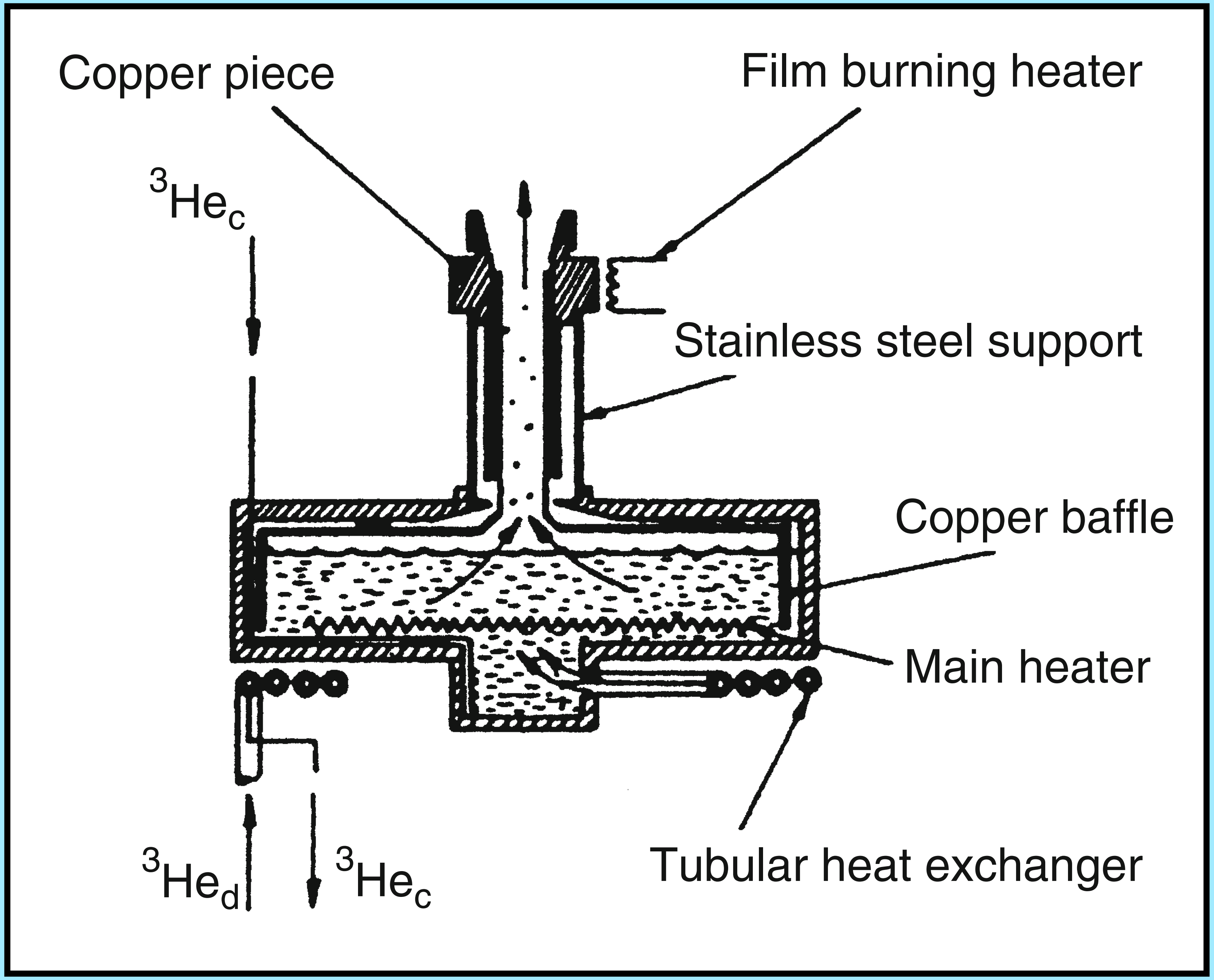
Still

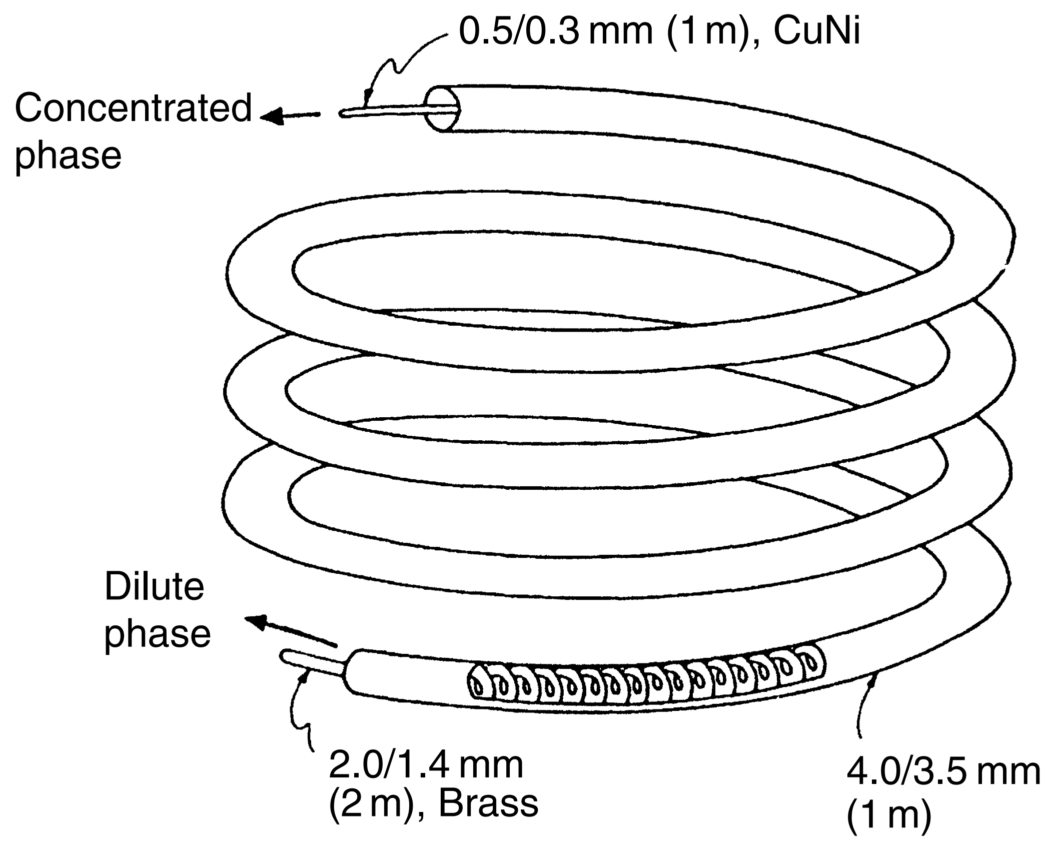


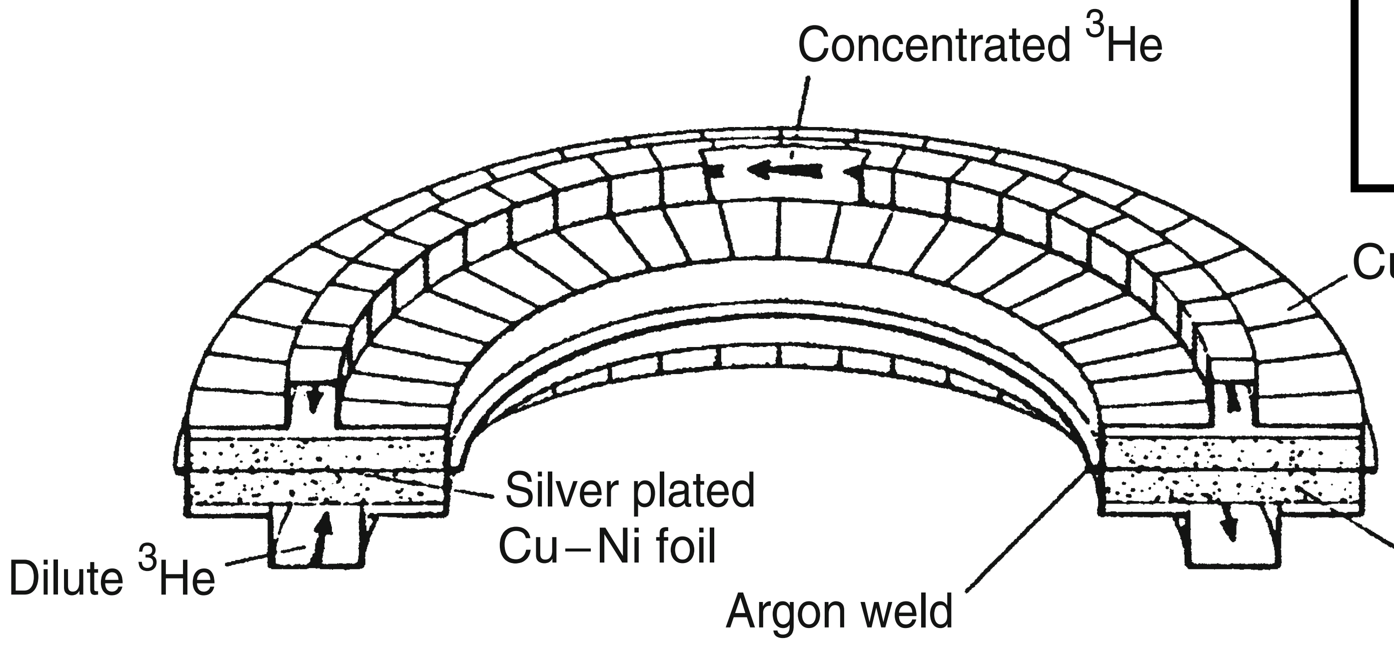
- When evaporating ^{3}He out of the dilute phase, we want to avoid taking along some superfluid ^{4}He
- Breaking superfluid film with strategically placed heaters or sharp edges
- Measure fluid level with the still-capacitor
- Heating the still can improve the flow rate of the circulation if needed

F. Pobell, 2007

Heat Exchangers

- **Heat exchangers are essential for precooling**
- **Heat transfer between fluid and solid mediated by phonons. Problem: Kapitza resistance Solution: Large contact areas**

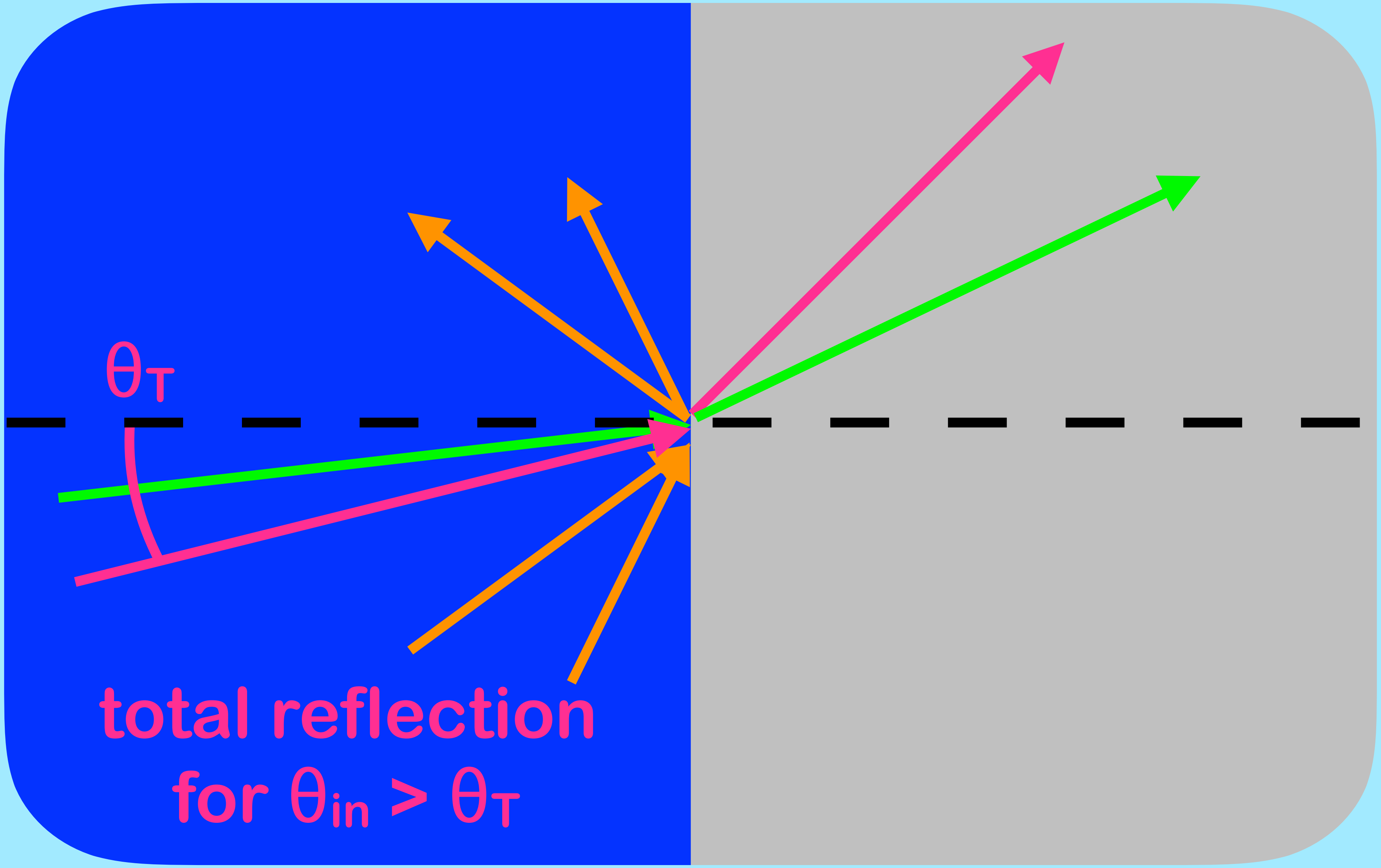




Kapitza Resistance

accoustic mismatch

$v_{LHe} << v_{Ag}$



total reflection
for $\theta_{in} > \theta_T$

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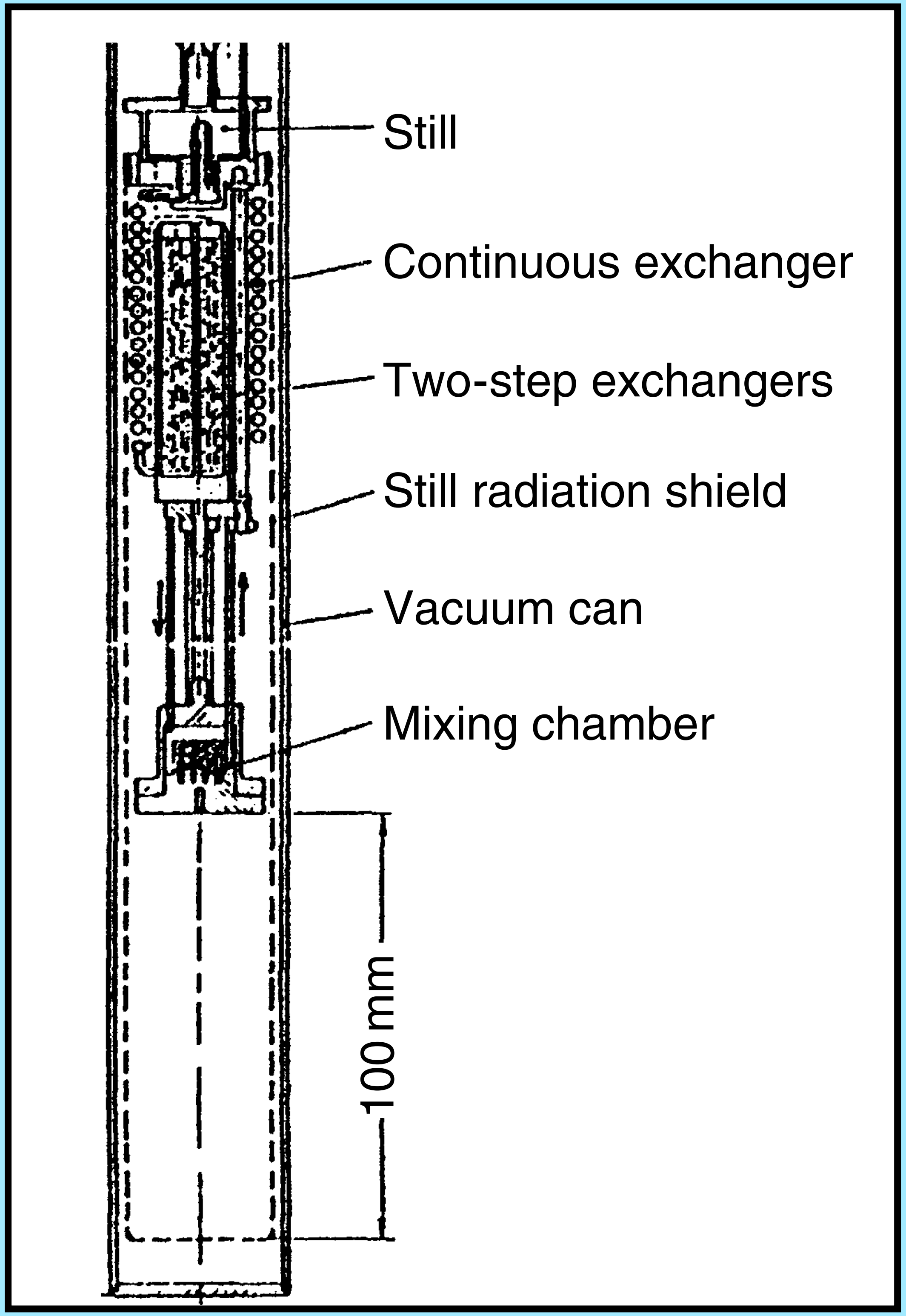
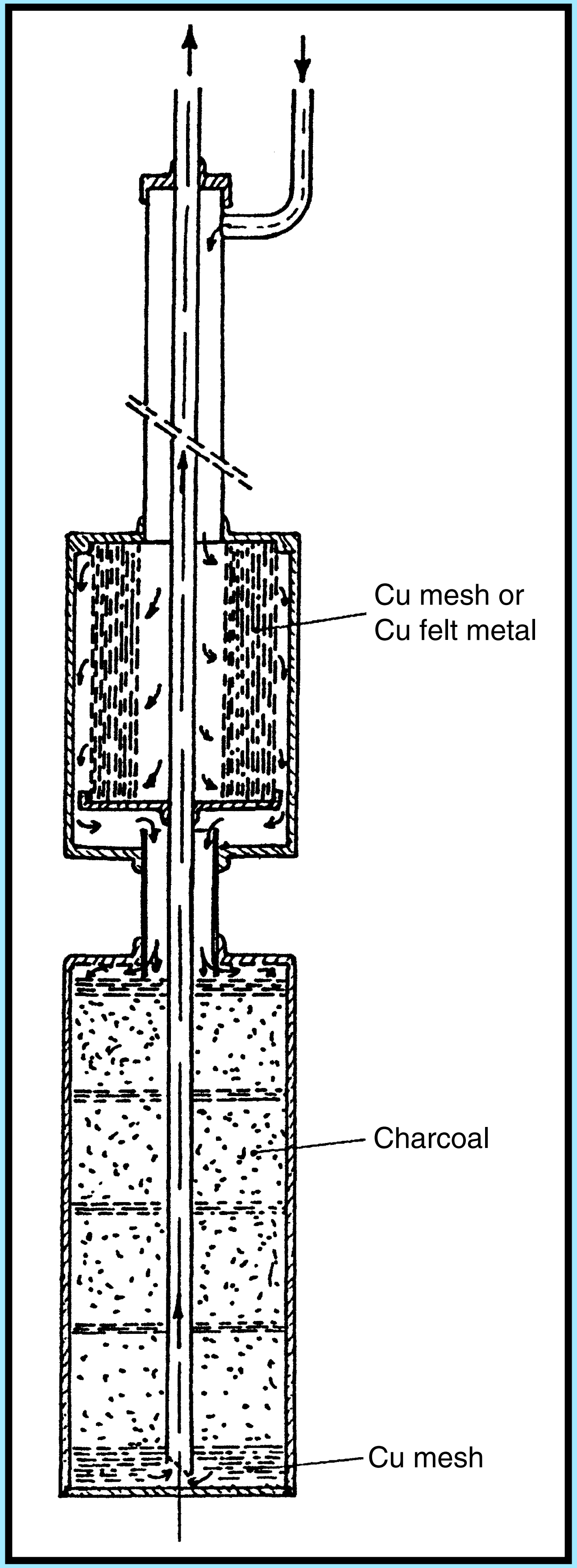
Insert


Still
Continuous exchanger
Two-step exchangers
Still radiation shield
Vacuum can
Mixing chamber
100 mm

Trap

To efficiently filter oil residue from the pumps, water or other contaminants, a filter consisting of metallic meshes, felts and porous charcoal “sponges” is used, which submerged inside LN_2.



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Capt. Ackbar, Battle of Endor, Return of the Jedi, 1983

Magnets

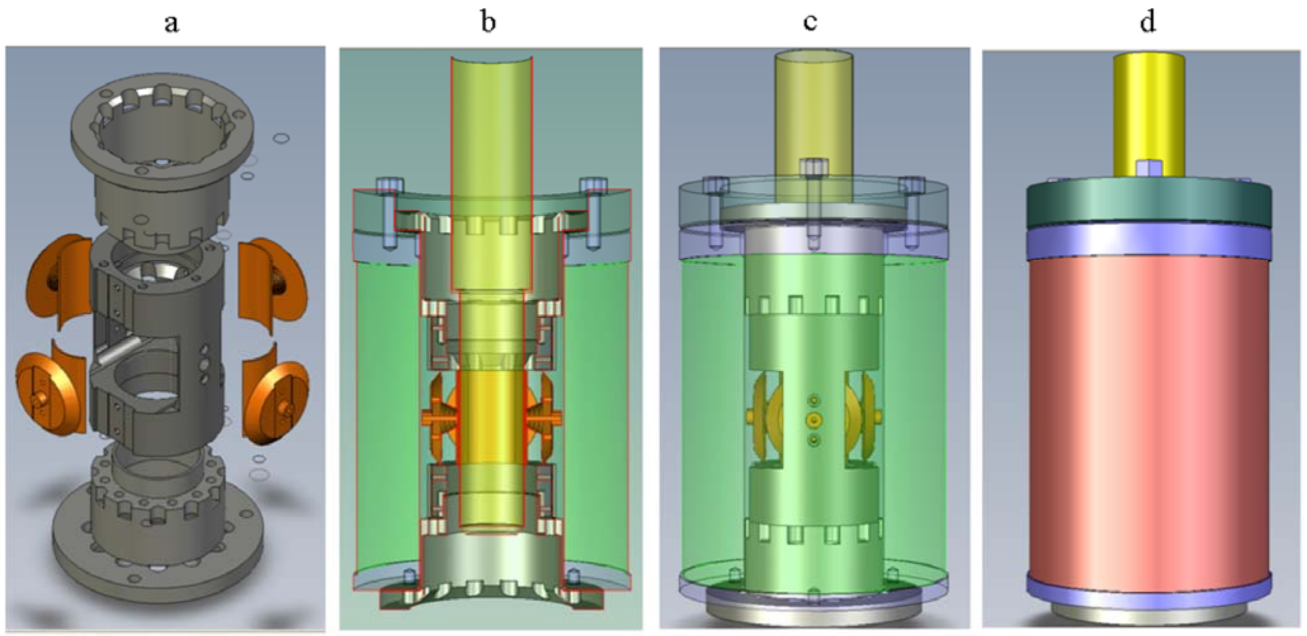
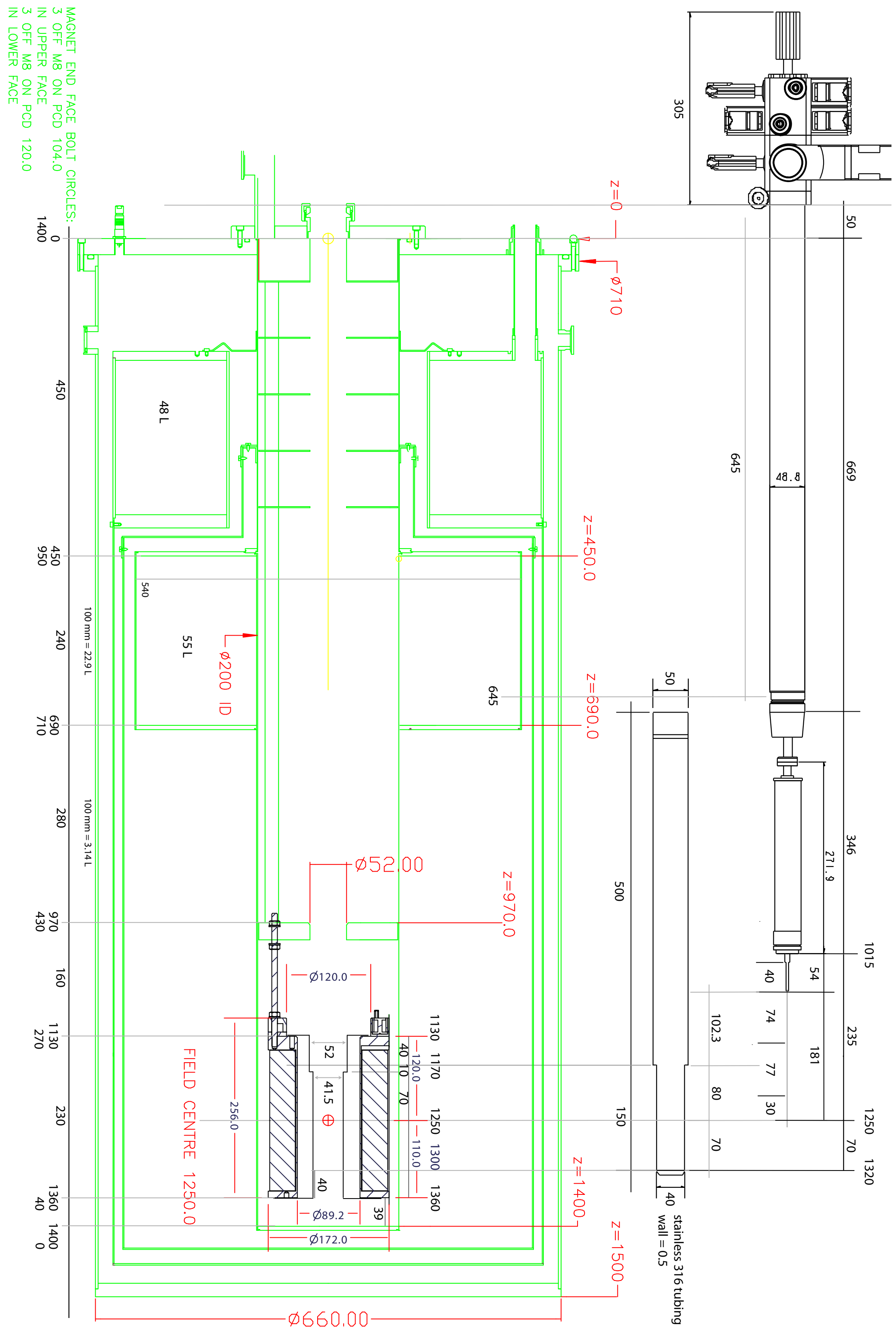
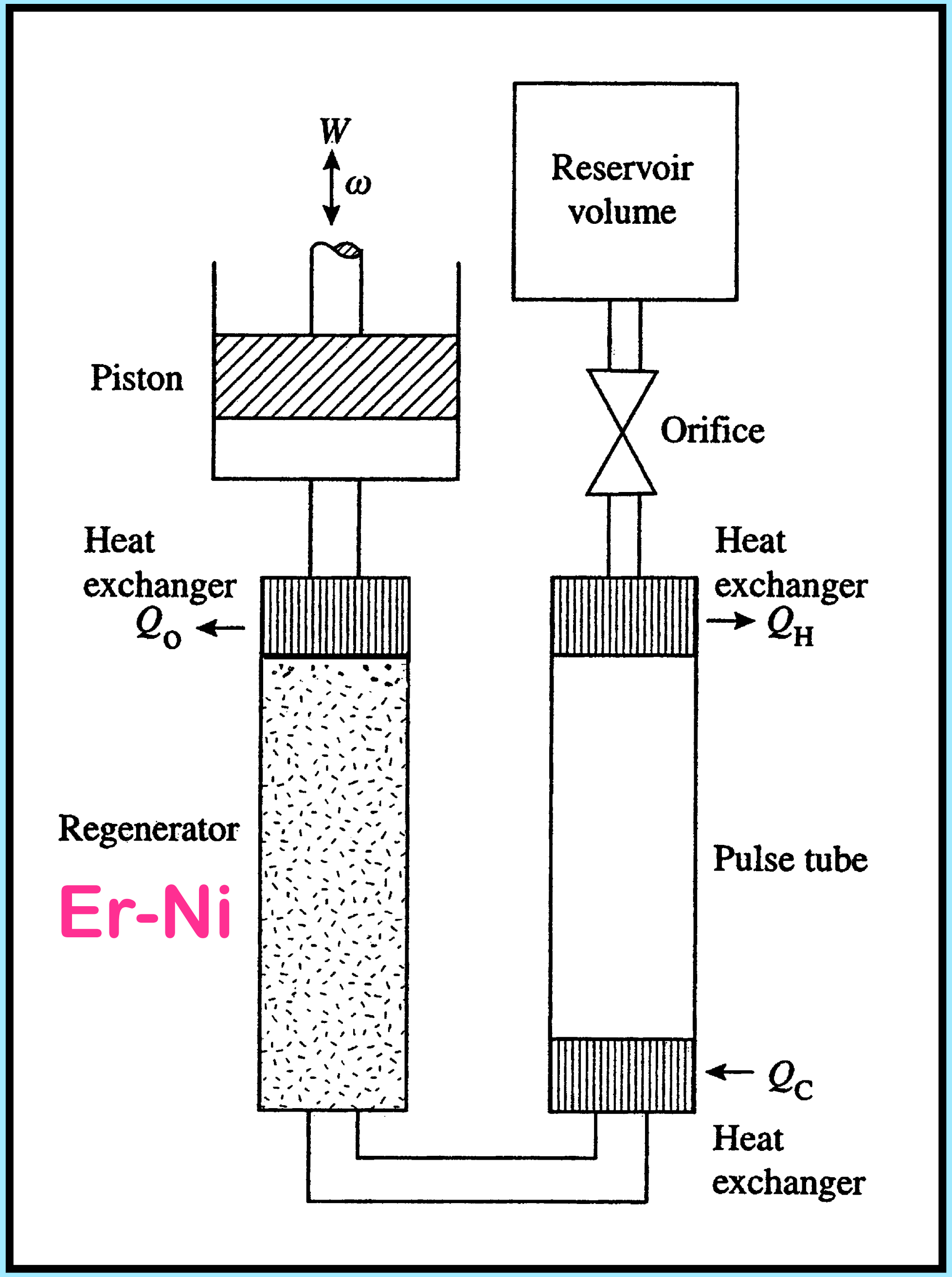


Figure 8: a) the disassembled cage with the upper flange, the cage, the lower flange and the four spools. b,c,d) assembled cage and mounted into the solenoid. yellow: IVC, green/red: solenoid



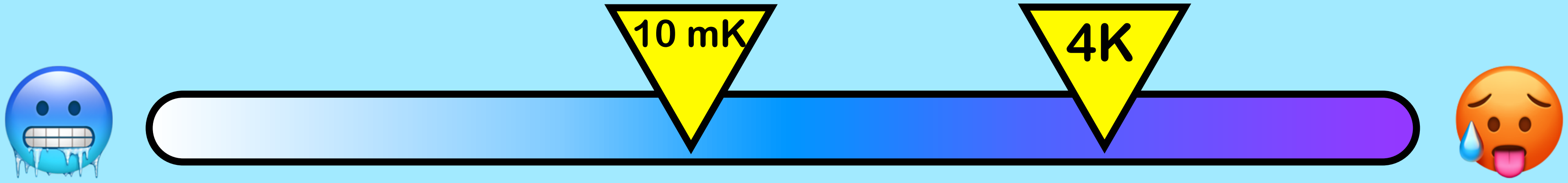
Pulsetube



- Alternative to the 1K pot
- No need for He transfers
- Might induce undesired vibrations
- (Some people might go crazy from the “psst, psst psst” - noise)

Overall

- Flexible temperature regime down to mK
- More cumbersome operation
- Limited by the viscosity/viscous heating of L^{3}He to approx. 10 mK
- Can run “indefinitelt”



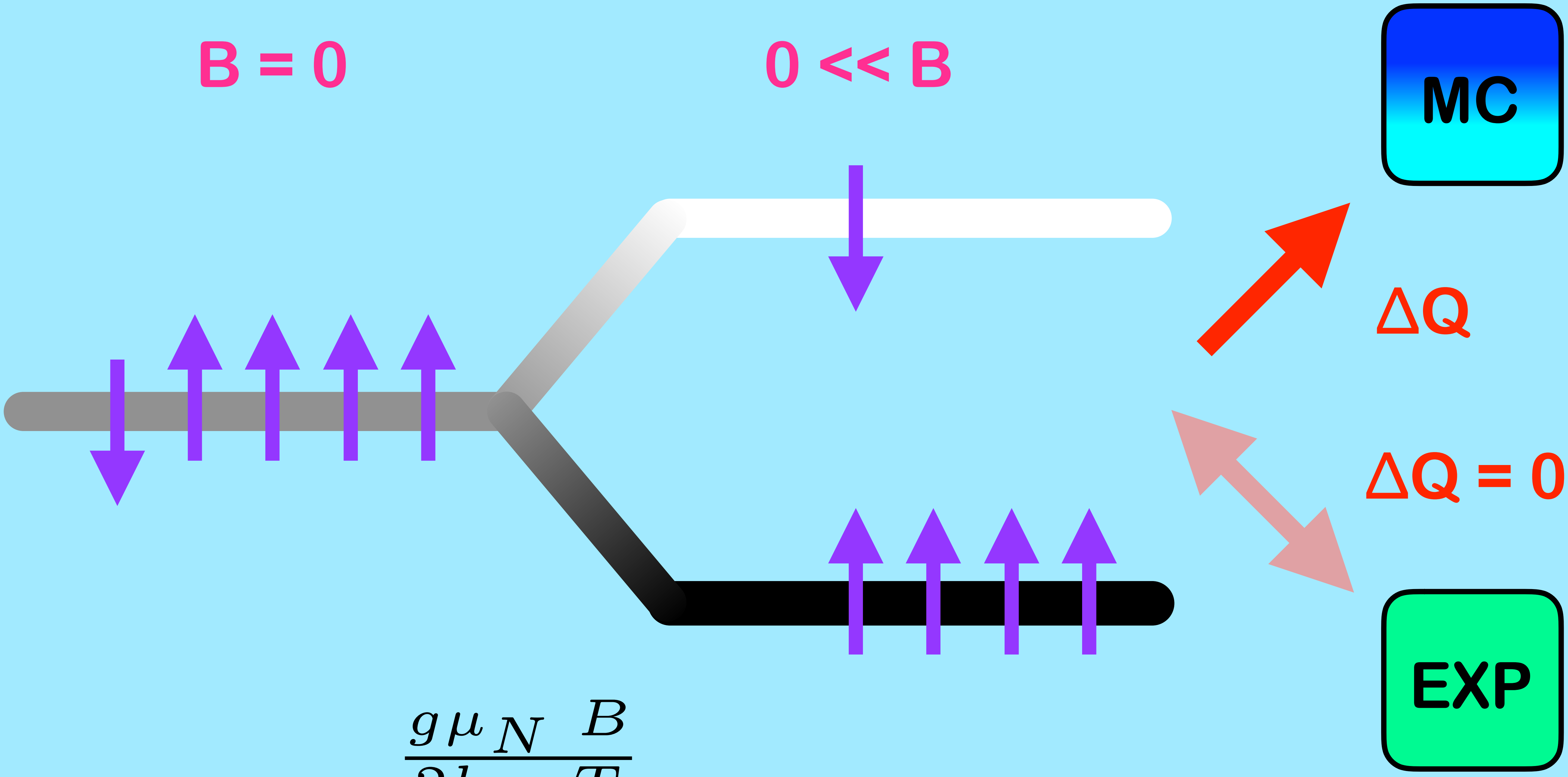
Adiabatic Nuclear Demagnetization

$$T_{ord} \propto \frac{\mu^2}{r^3}$$

good materials:
- Cu with nuclear spin 3/2
- Paramagnetic Salts

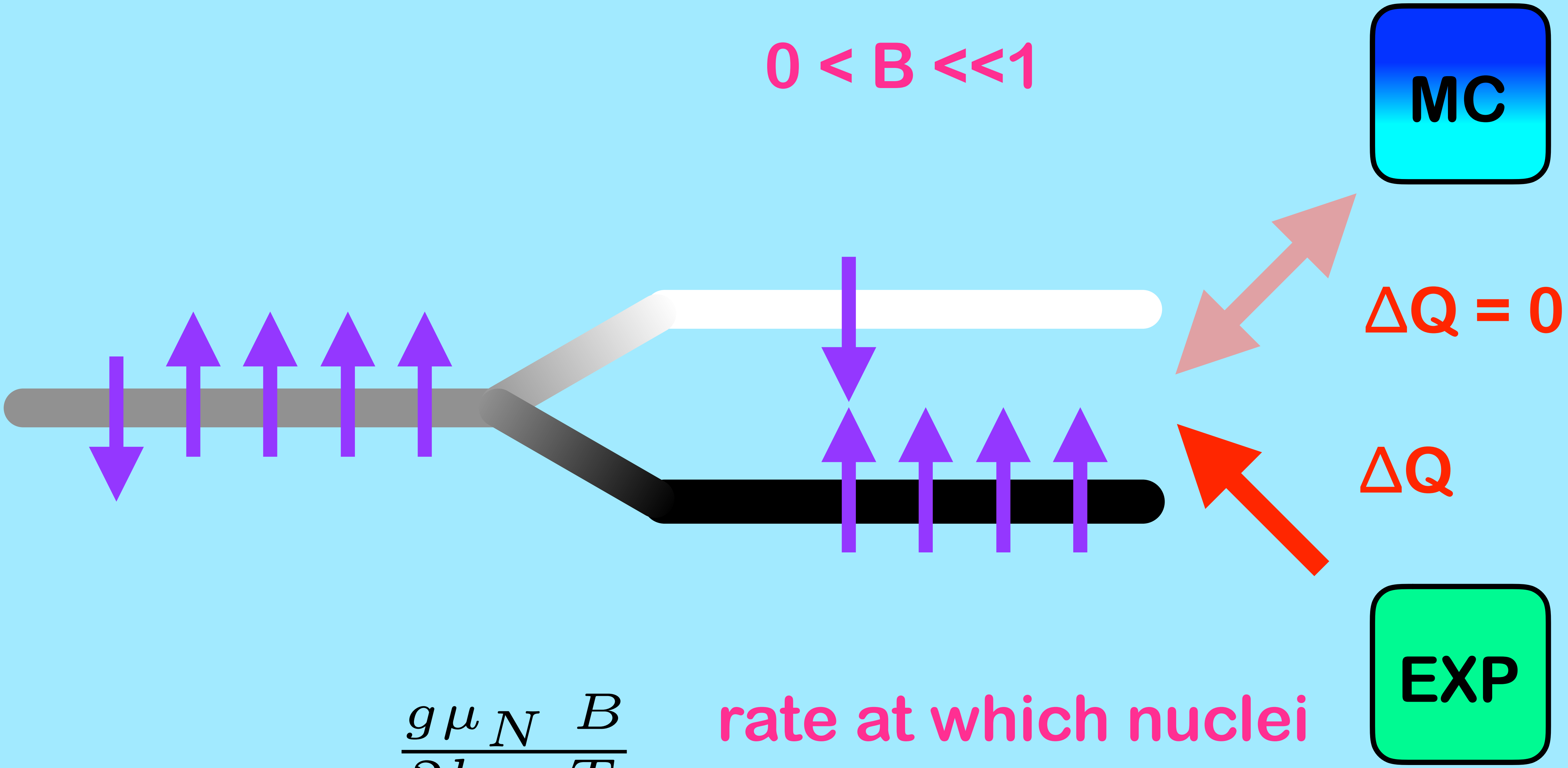
bad idea:
- Metals

Scheme



nucl. pol. $\propto e^{\frac{g\mu_N B}{2k_B T}}$

Scheme

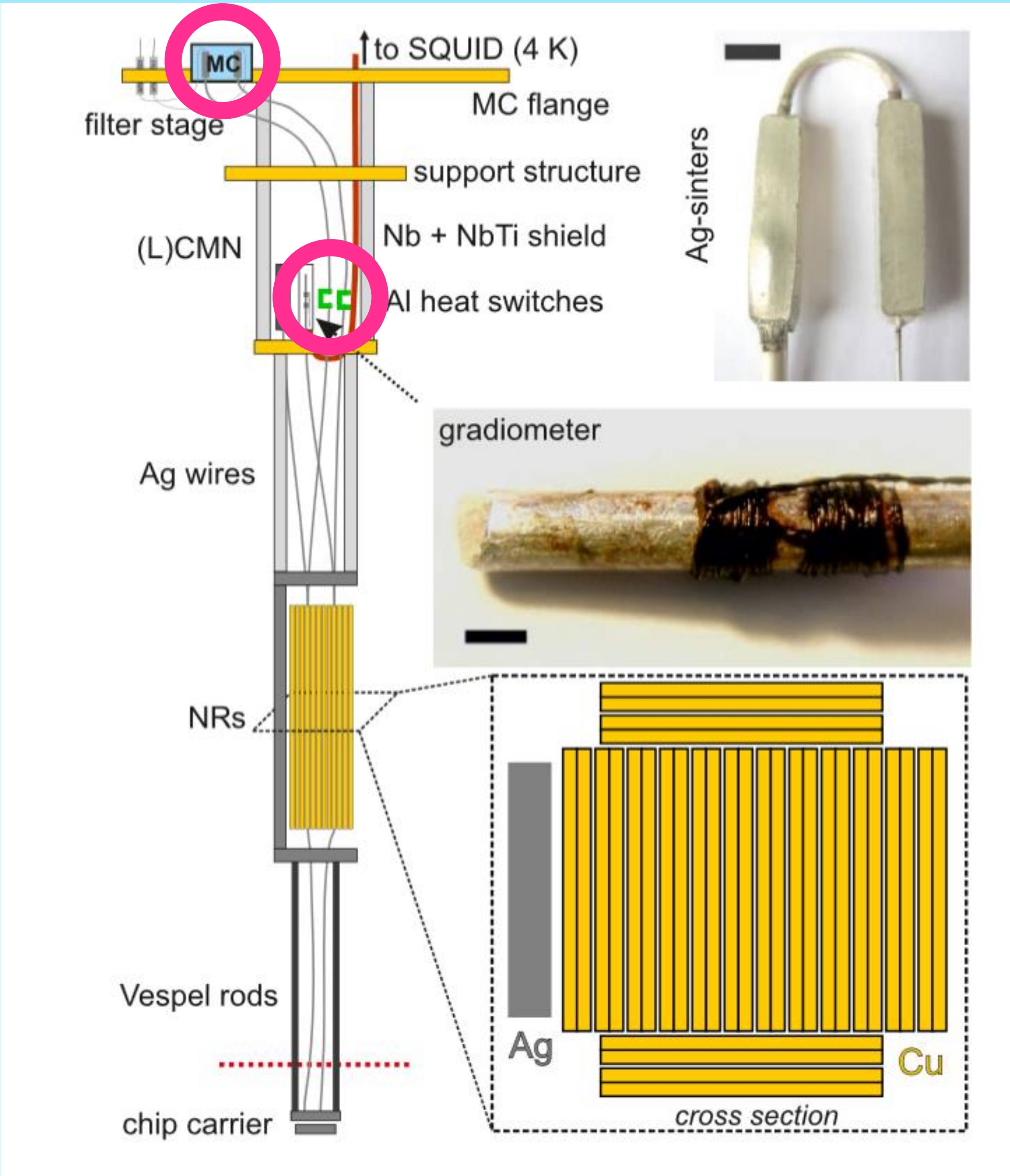


nucl. pol. $\propto e^{\frac{g\mu_N B}{2k_B T}}$

rate at which nuclei equilibrate with e⁻

$$\tau_1 = \frac{\kappa}{T_{\rm e,lat}}$$ (Korringa Law)

Setup



- We require a large surface area at the interface between Ag lines LHe, due to the Kapitza resistance
- The Al heat switches are interrupted/opened by switching on/off a small B-field, allowing to toggle between the Al's superconducting (therm. insulating) and normal (therm. conducting) state

C. Scheller, 2019

Overall

- Opens the door to the µK regime
- Takes a while to cool down
- Limited by the applicable magnetic fields
- Can not run “indefinitely”

Thanks

A. Cooling Power $\dot{Q}$

- **Pumped-on liquid bath where $\dot{n} \propto P_{\mathrm{vap}}(T)$ particles / t are evaporated**

$$\dot{Q} \propto L P_{\mathrm{vap}} \propto \mathrm{e}^{-1/\mathrm{T}}$$

- **Dilution refrigeration process of ^{3}He-^{4}He (x : concentration of the ^{3}He dilute phase)**

$$\dot{Q} \propto x \, \Delta H \propto T^2$$

- **Adiabatic nuclear demagnetization**

$$\dot{Q} \propto \left(\frac{T_{\mathrm{e}}}{T_{\mathrm{n}}} - 1 \right) B_{\mathrm{f}}^2$$