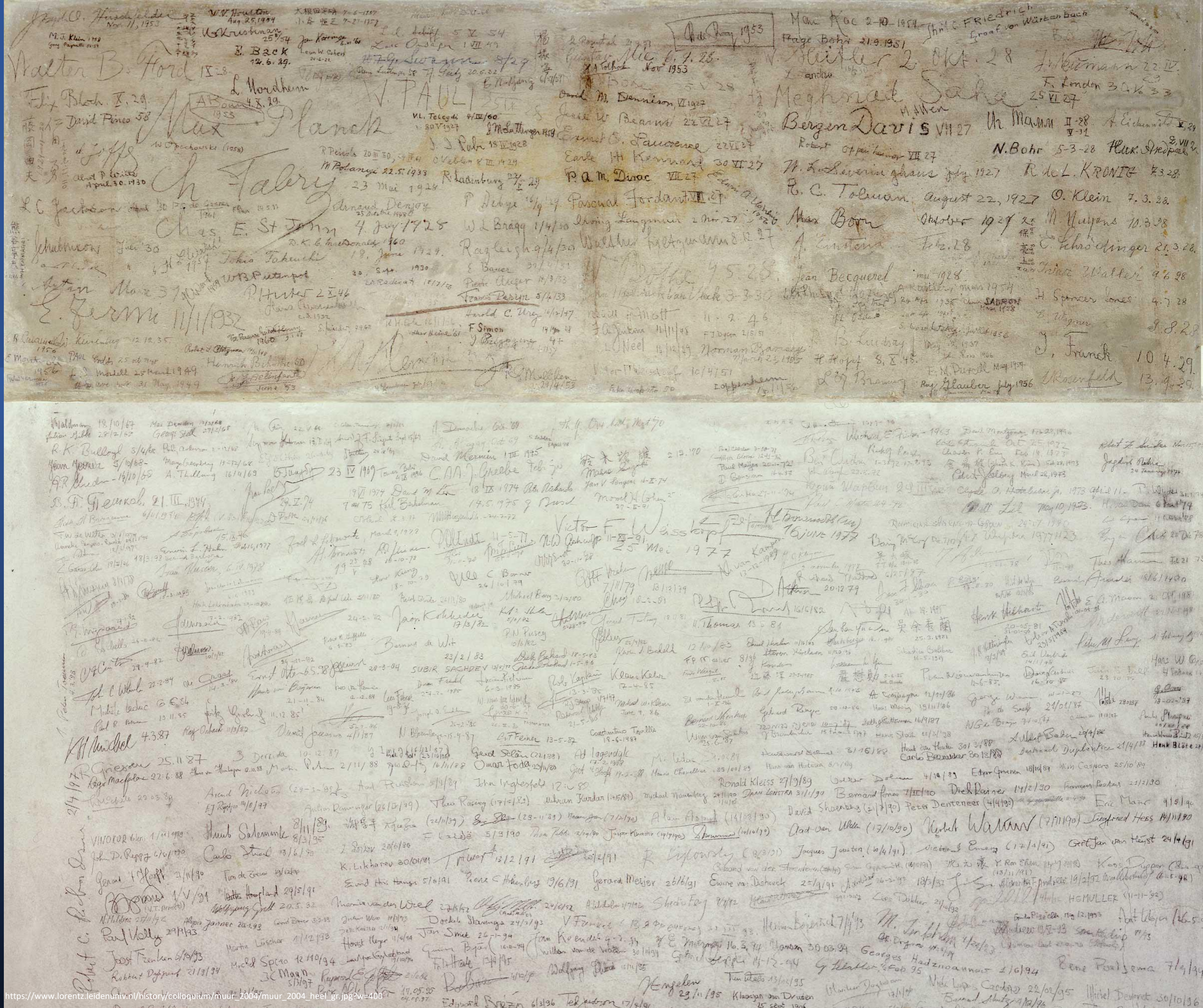
Reaching low temperatures

Lukas Berger

2021

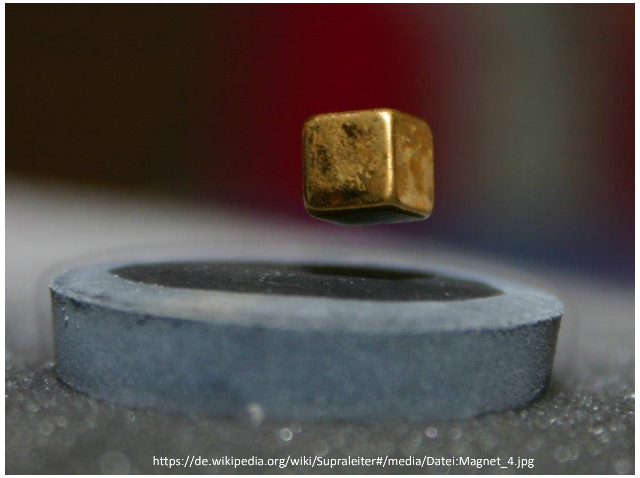


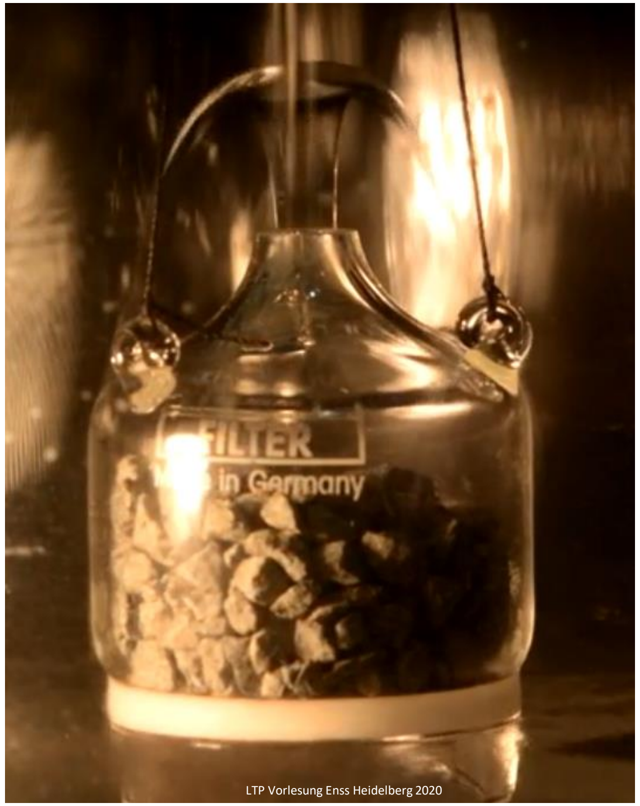
https://www.lorentz.leidenuniv.nl/history/colloquium/muur_2004/muur_2004_heel_gr.jpg?w=400

Table of Content

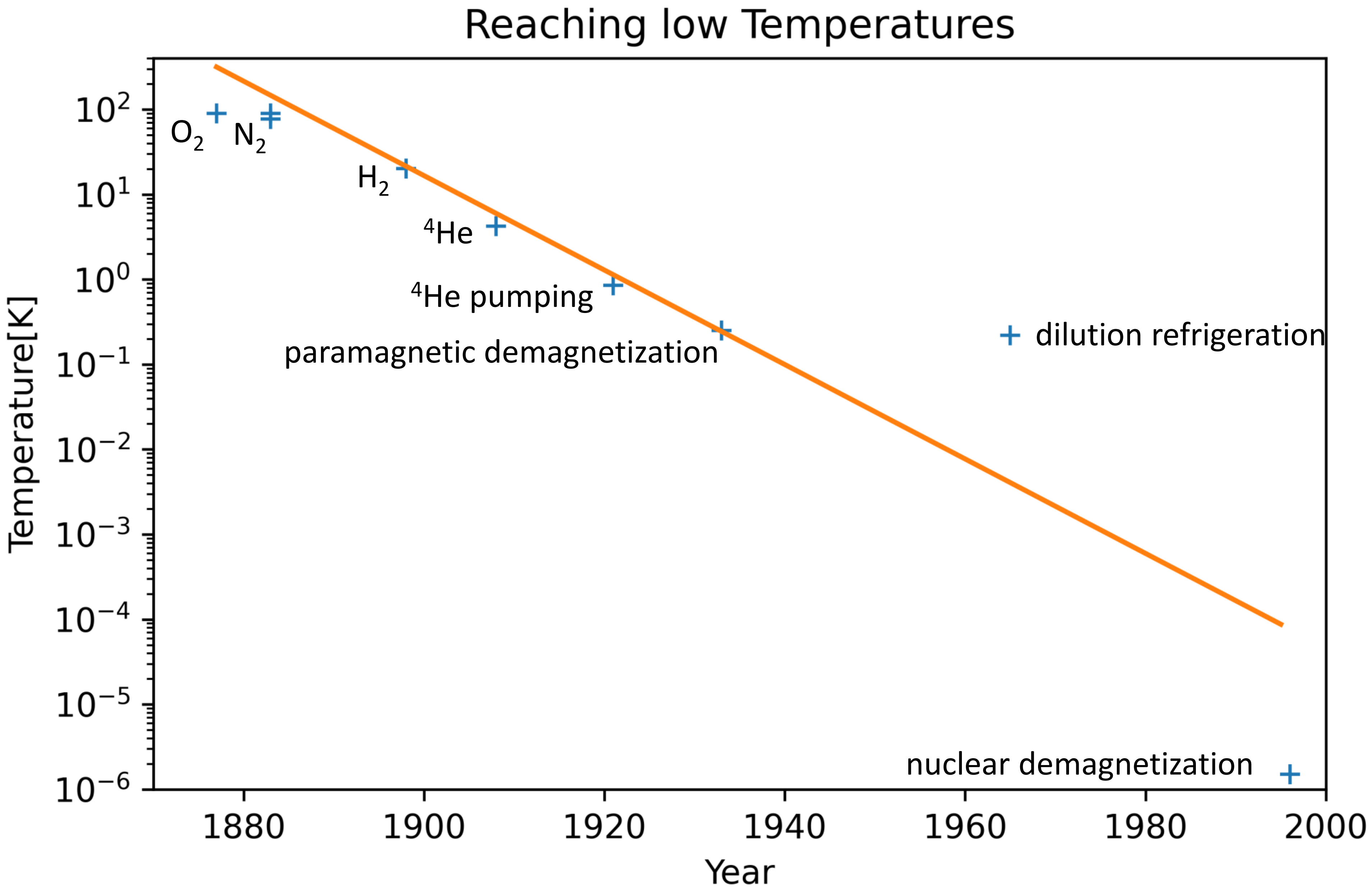
Why low temperatures

- Low noise measurements
- Different timescales
- Freezing out degrees of freedom
- Superconductivity
- Superfluidity


https://de.wikipedia.org/wiki/Supraleiter#/media/Datei:Magnet_4.jpg



LTP Vorlesung Enss Heidelberg 2020

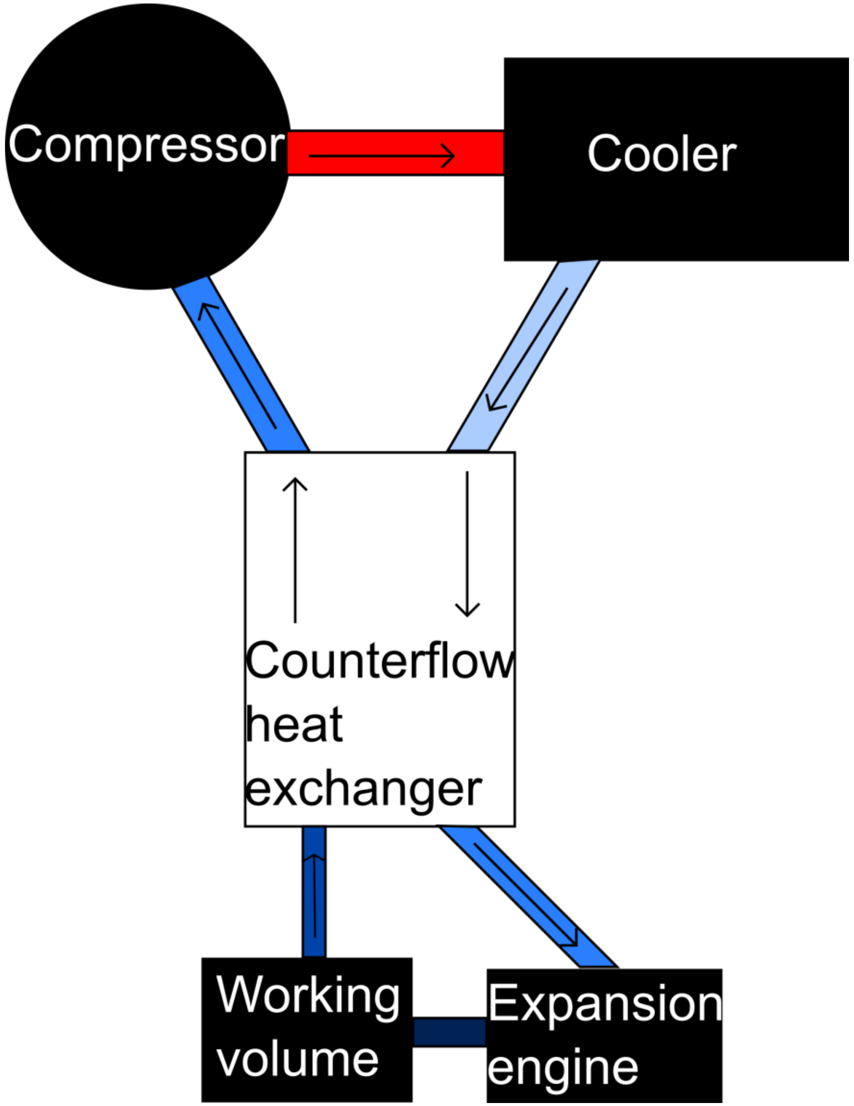

Reaching low Temperatures
Temperature[K]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
O_2
N_2
H_2
^{4}He
^{4}He pumping
paramagnetic demagnetization
dilution refrigeration
nuclear demagnetization
1880
1900
1920
1940
1960
1980
2000
Year

Expansion engines

- Compressing at room temperature
- Approximately adiabatic process
- Cooling gas has to be above critical temperature

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{(\kappa-1)/\kappa}$$

$$\kappa = C_p/C_V$$

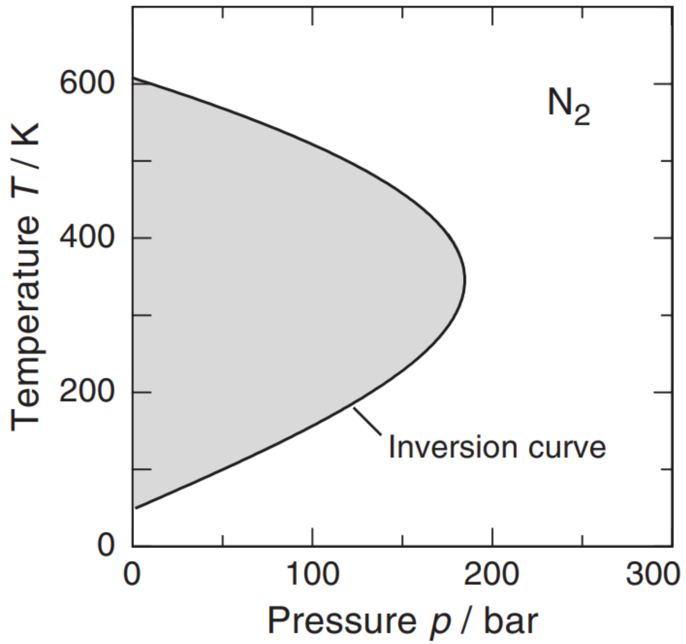


Substance	T_b/K	T_c/K	p_c/bar	ΔH/kJ mol^{-1}	T_{inv}/K
CO_2	195	304	73.84	25.2	(2050)
CH_4	112	191	45.99	8.18	(1290)
O_2	90.2	154.6	50.43	6.82	762
N_2	77.4	126.0	33.99	5.57	625
H_2	20.3	32.9	12.84	0.90	203
^4He	4.21	5.19	2.29	0.082	43.2
^3He	3.19	3.32	1.16	0.025	(23)

Low temperature physics Enss Hunklinger

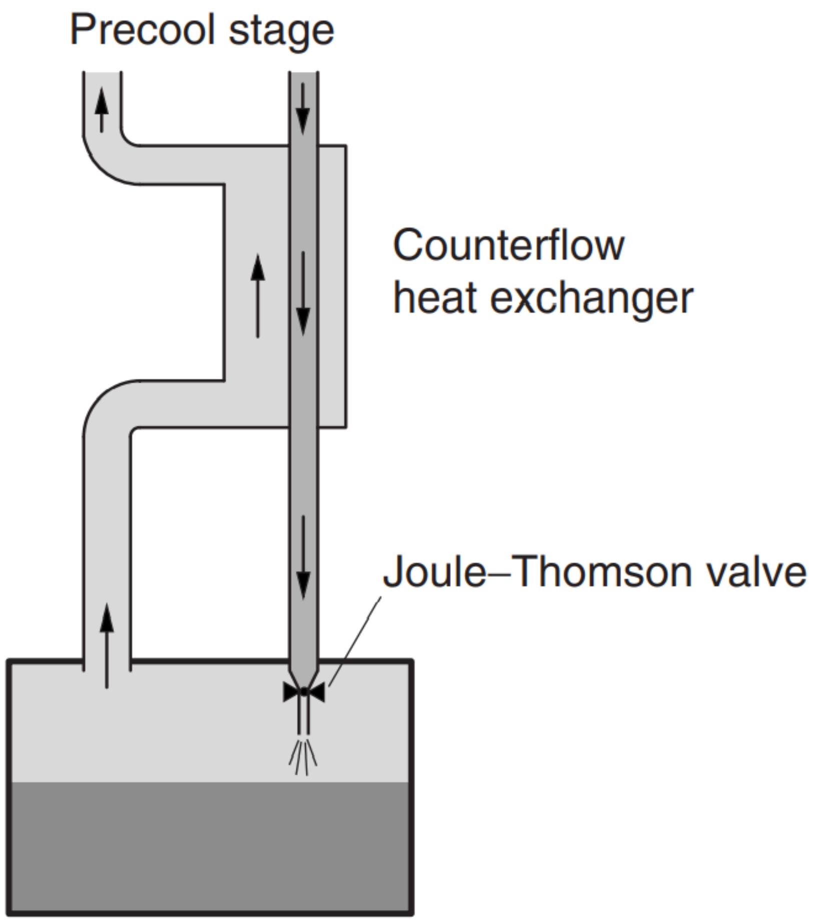
Joule-Thomson Expansion

- Gas performs work against internal forces
- no temperature reduction with ideal gases
- Isenthalp pressure reduction
- Heating or cooling
- Joule-Thomson-coefficient



Low temperature physics: Enss; Hunklinger

$$\mu_{\mathrm{JT}} = \left(\frac{\partial T}{\partial p} \right)_H$$

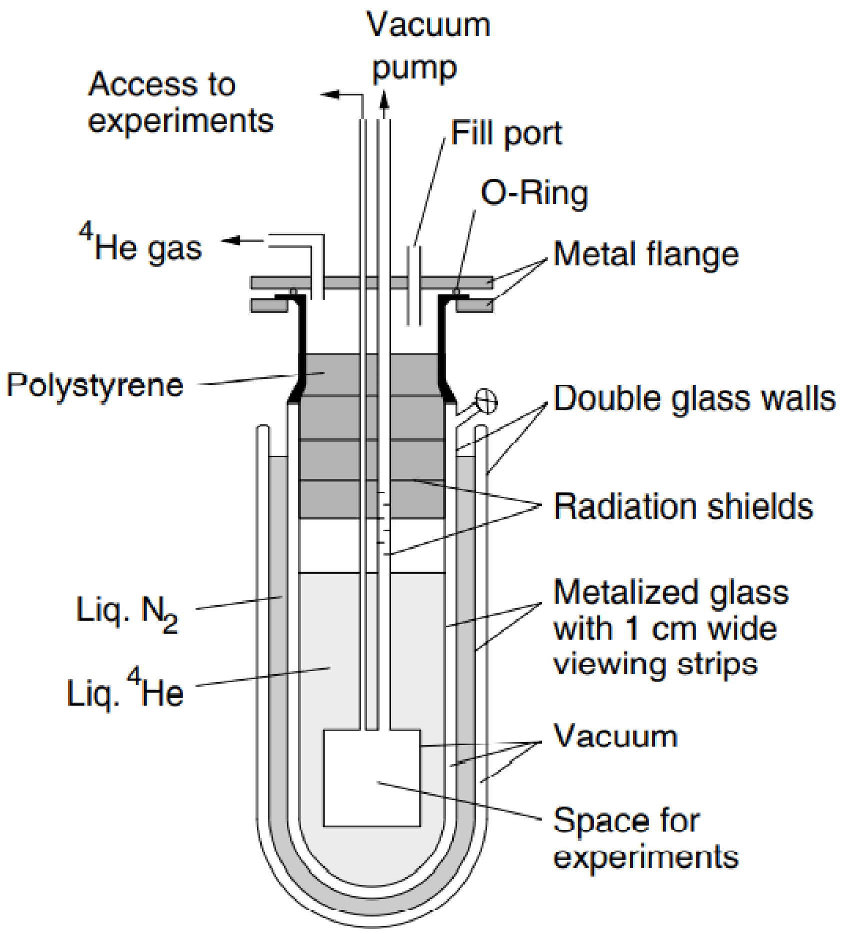


Low temperature physics: Enss; Hunklinger

(Helium-)Bath Cryostats

- Vacuum-isolated glass vessels (Dewar vessels) (down to 4.2 K)
- Can be pumped to reach lower temperatures

  → Evaporation Cryostats (down to 1.3 K)
- High consumption of Helium (40%)



Low temperature physics: Enss; Hunklinger

Clausius-Clapeyron

$$\frac{\mathrm{d}p}{\mathrm{d}T} = \frac{L}{\Delta V\, T}$$

$$\Delta V = V_g - V_\ell \approx V_g$$

$$\frac{\mathrm{d}p}{\mathrm{d}T} = \frac{L}{R T^2}\, p$$

$$p(T) = p_0\, \mathrm{e}^{-L/RT}$$

$$\dot{Q} \propto p \propto \mathrm{e}^{-L/RT}$$

^4He vs. ^3He

^4He:

- Boson(I=0)
- Liquid at T=0 (and normal p)
- He-I, normalfluid
- He-II, superfluid
- Boilingtemperature: 4.21
- Density at boiling point: 0.055 g/cm^3

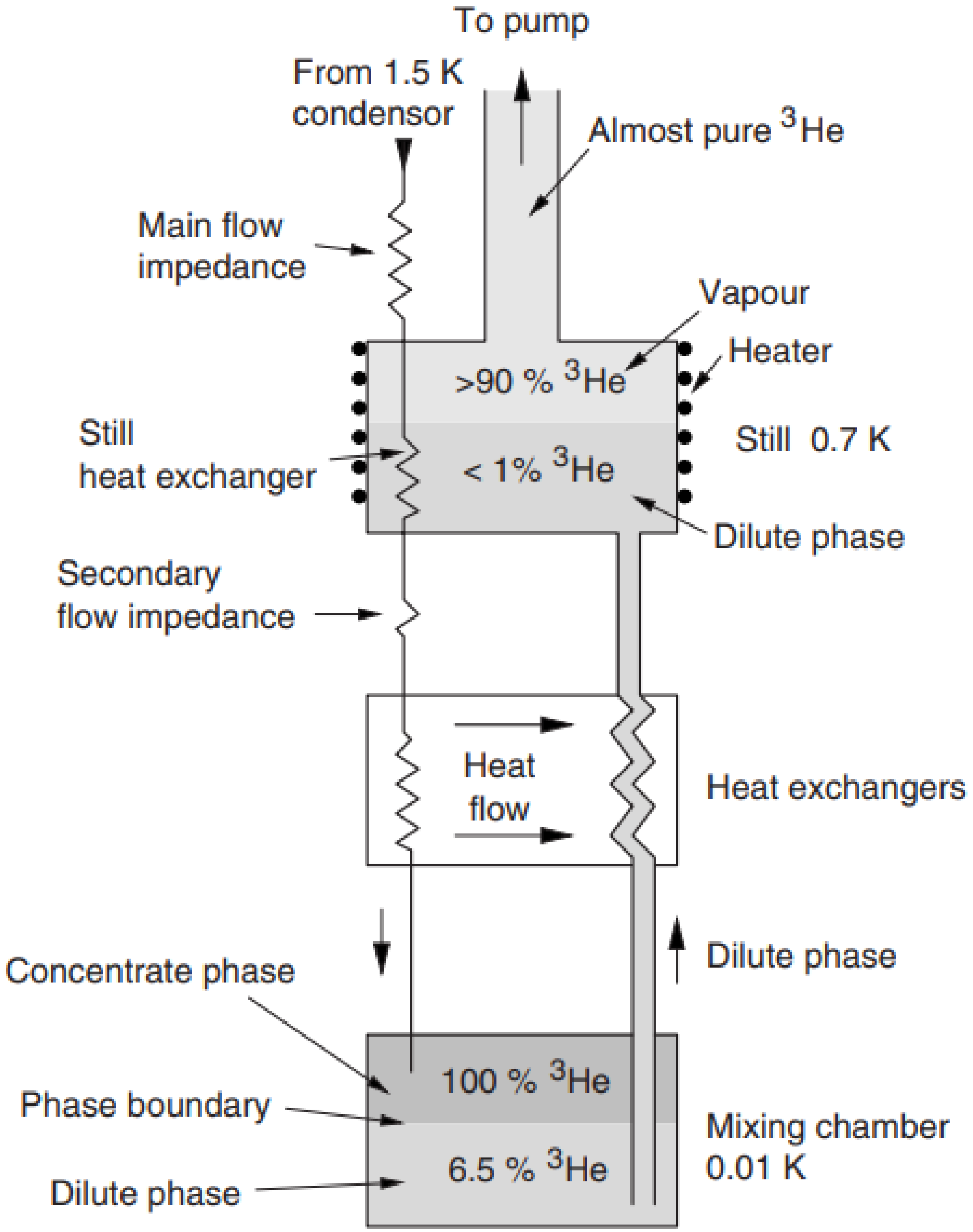
^3He:

- Fermion(I=1/2)
- Liquid at T=0 (and normal p)
- He-N, normalfluid
- He-A, He-A1, He-B, superfluid
- Boilingtemperature: 3.19
- Density at boiling point: 0.145 g/cm^3

Dilution Refrigeration

- Kinetic Energy of ^{3}He rises with density of ^{3}He (Fermi-statistics)
- effective binding energy is reduced
- At 6.5% ^{3}He in ^{4}He binding energy vanishes (T→0)
- Phase separation in ^{4}He/^{3}He-mixtures (0.86K)
- A light ^{3}He-rich phase and a heavy mixed phase
- ^{3}He has lower entropy in the ^{3}He-rich phase

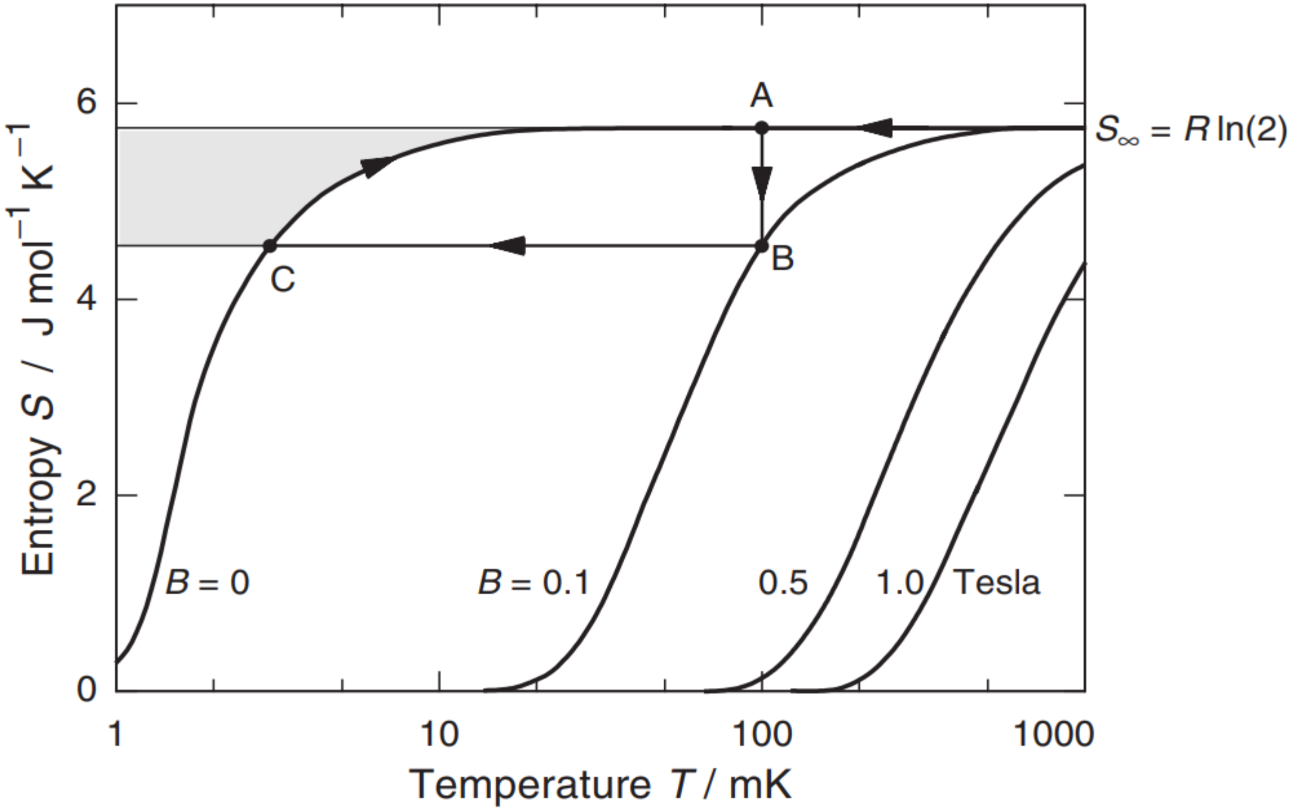
$$\Delta Q = T\Delta S = aT^2$$
$$a = -84\,\mathrm{J\,K^{-2}}$$



Low temperature physics: Enss; Hunklinger

Magnetic refrigeration

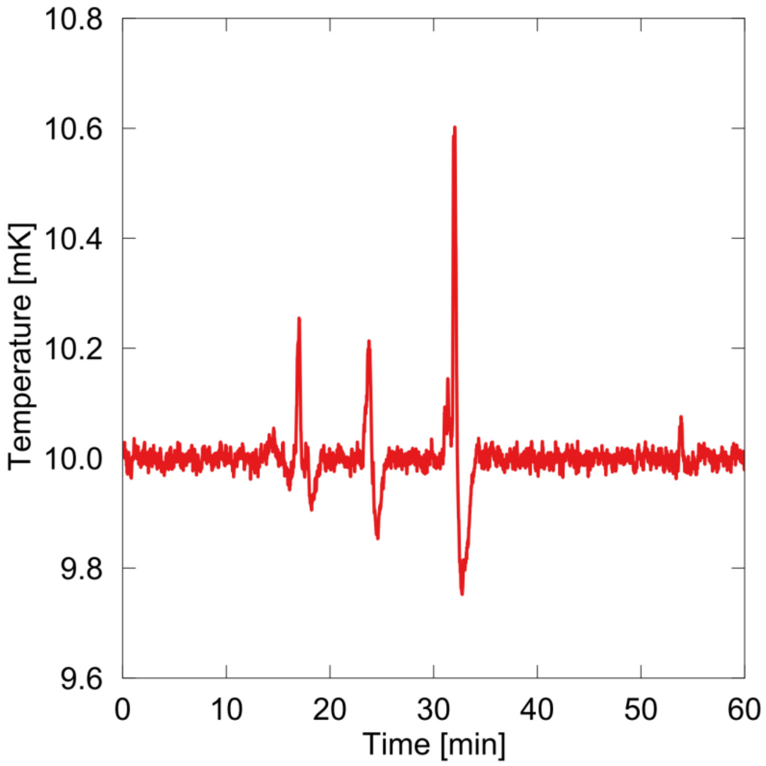
- spin entropy is magnetic field dependent
- Cooled magnetization
- Adiabatic demagnetization
- Isomagnetic entropic transfer



Low temperature physics: Enss; Hunklinger

Technical Problems magnetic refrigeration

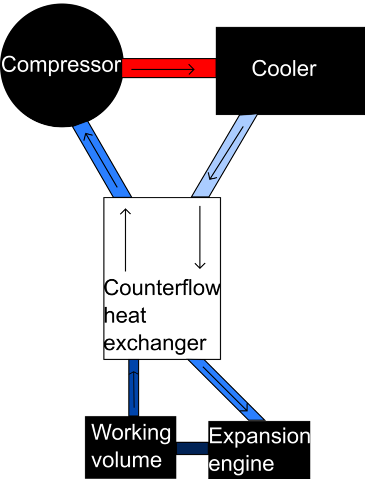
- Nuclear spin
- Heat switch (superconducting)
- Thermally isolated for long time
- T<100 µK, a leak has to be smaller than 10^{-9} W
  - (eg. 2×10^{-6} W for a typical watch)
- Vibrations (eddy currents in magnetic field)
- Cosmic rays (10^{-11} W)



Jan Blickberndt

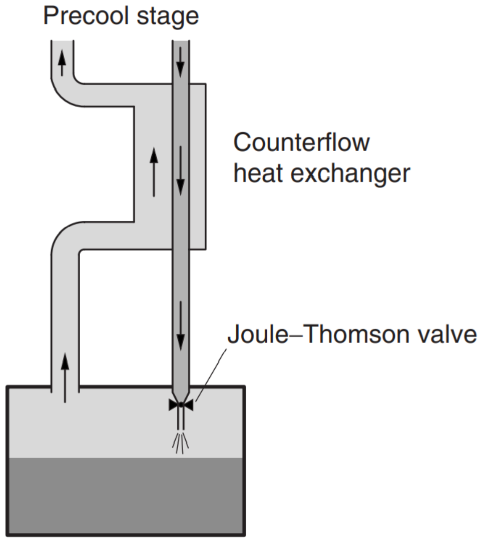
Summary

Expansion Engine



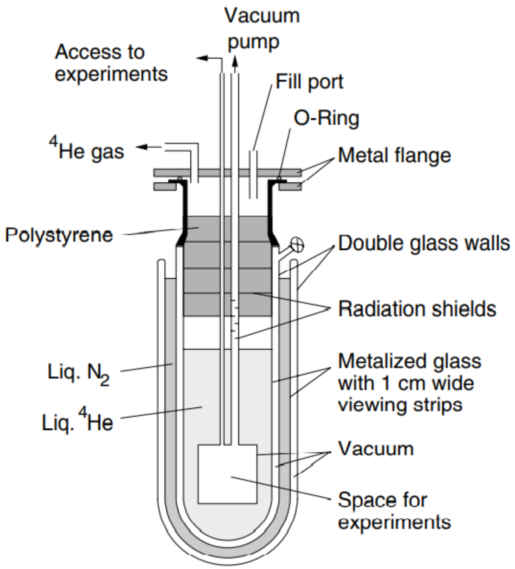
T>5.19K

Joule-Thomson Expansion



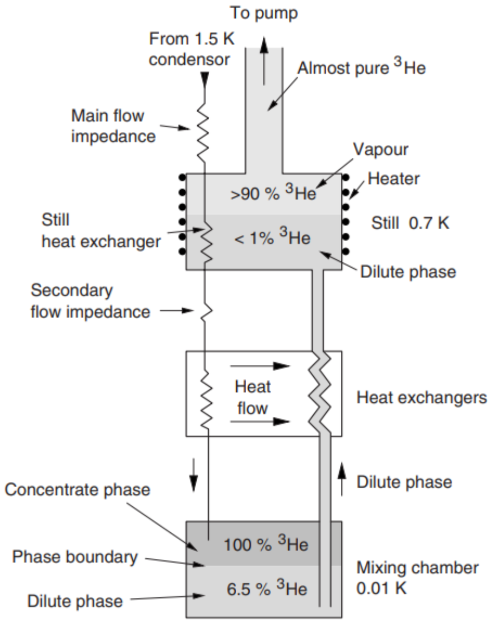
T≈4.2K

(Helium-)Bath Cryostats



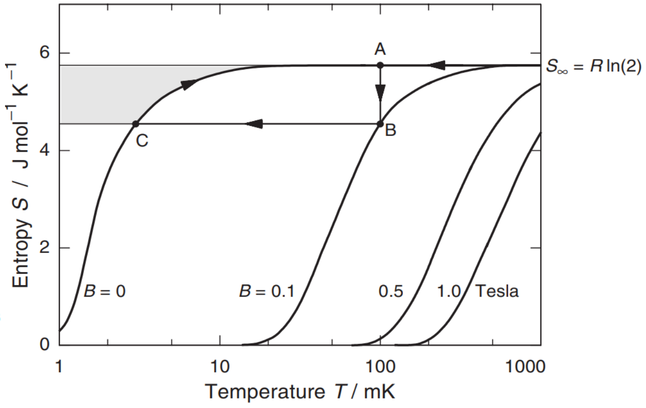
T≈1K

Dilution Refrigeration



T≈0.01K

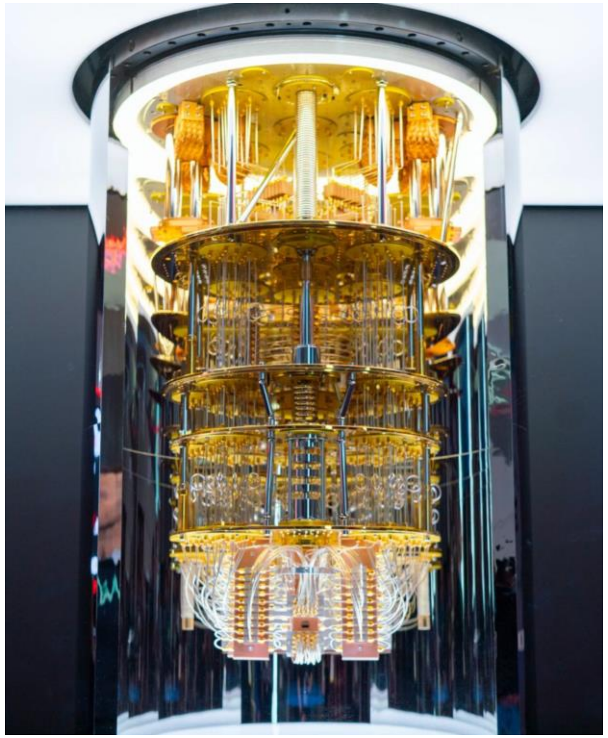
Magnetic refrigeration



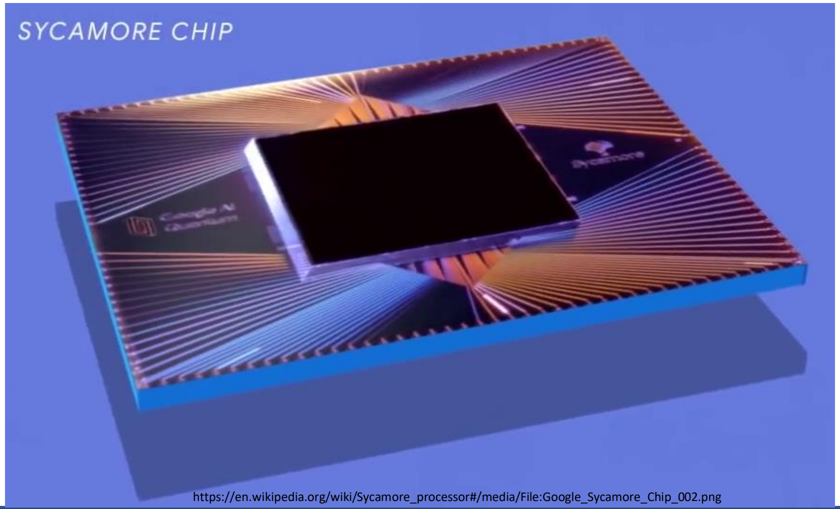
T≈10^{-6}K

Where is it used now?

- Quantum processors
- Josephson-junctions
  →Superconducting
- Dilution Refrigeration



https://cdn.prod.www.spiegel.de/images/00e7eacb-ae92-4b00-90aa-303d03558082_w1600_r1.499250374812593б_fpx52.67_fpy44.98.jpg



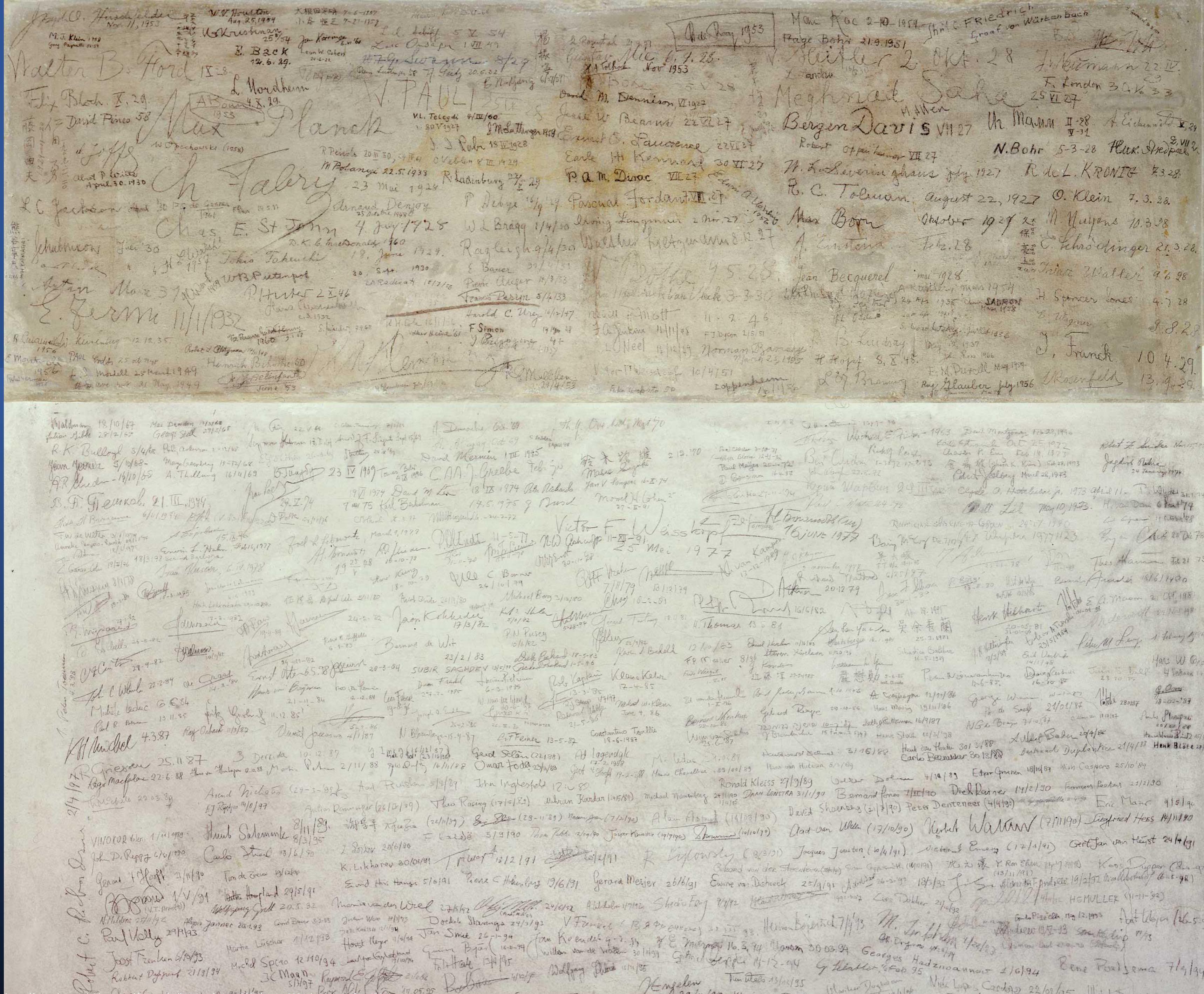
https://en.wikipedia.org/wiki/Sycamore_processor#/media/File:Google_Sycamore_Chip_002.png

Citations

- Enss, Hunklinger: Low-Temperature Physics, 2005
- Pobell: Matter and Methods at Low Temperatures, 2007
- Lecture: Enss, Reiser: Low temperature physics Heidelberg, 2020
- Lecture: Klingeler: Condensed Matter Physics Heidelberg, 2021
- Frossati, G. Experimental techniques: Methods for cooling below 300 mK. *J Low Temp Phys* **87,** 595–633 , 1992

Thank you for the attention

Questions?



https://www.lorentz.leidenuniv.nl/history/colloquium/muur_2004/muur_2004_heel_gr.jpg?w=400

Lukas Berger