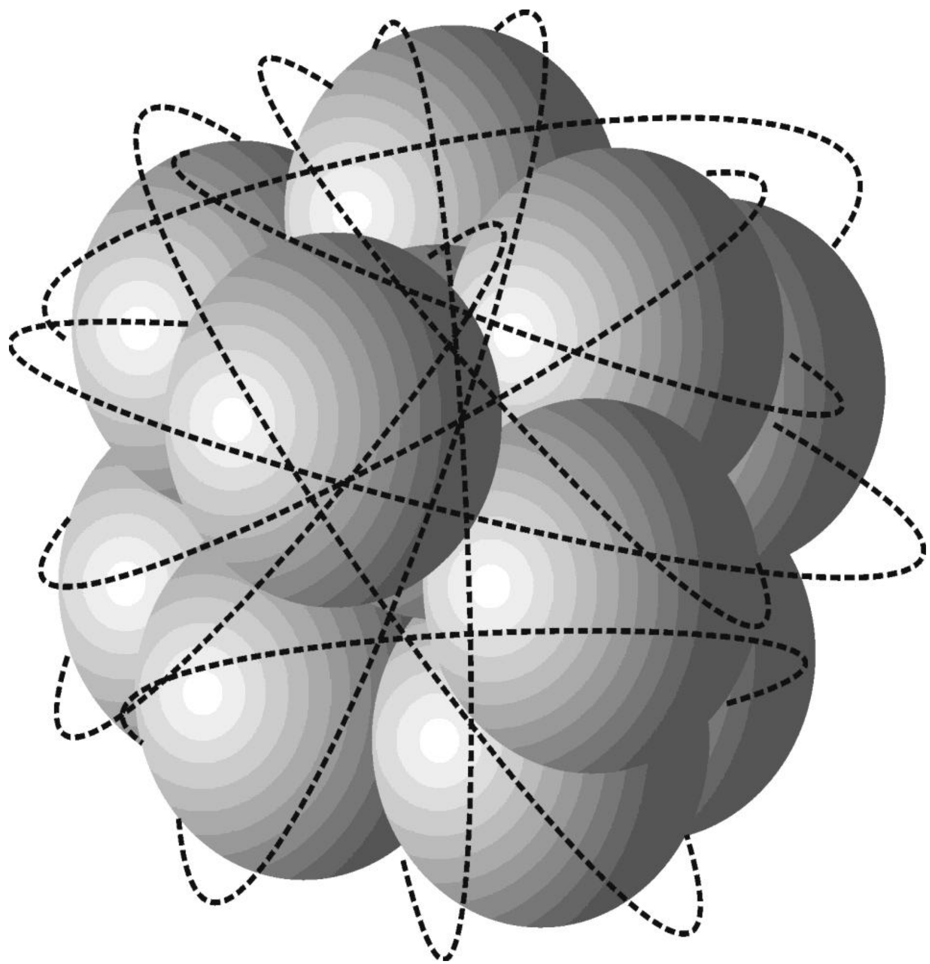
lecture 20.10.2011
we had in the last week:

- introduction into atomic physics, relevance
- introduction into cluster physics

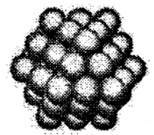
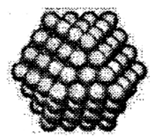
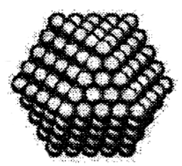
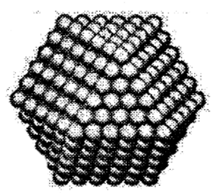
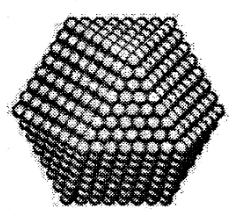
today:

- few more remarks on cluster physics
- atomic physics: history
- Doppler-free spectroscopy
- preparation of atomic beams

A cluster of simple metal atoms can be considered as a metallic quantum dot. In the corresponding bulk materials the electrons need much more space.



size-dependence

Full-shell Clusters		Total Number of Atoms	Surface Atoms (%)
1. Shell		13	92
2 Shells		55	76
3 Shells		147	63
4 Shells		309	52
5 Shells		561	45
7 Shells		1415	35

Electronic shell structure of metal clusters

example: Al_N
3 electrons per atom

5s (2)	330	Al_{110}
4d (10)	328	
3g (18)	318	Al_{106}
2i (26)	300	Al_{100}
1k (34)	274	Al_{91}^-
4p (6)	240	Al_{80}
3f (14)	234	Al_{78}
2h (22)	220	Al_{73}^-
1j (30)	198	Al_{66}
4s (2)	168	Al_{56}
3d (10)	166	Al_{55}^-
2g (18)	156	Al_{52}
1i (26)	138	Al_{46}
3p (6)	112	Al_{37}^-
2f (14)	106	Al_{35}^-
1h (22)	92	
3s (2)	70	Al_{23}^-
2d (10)	68	
1g (18)	58	Al_{19}^-
2p (6)	40	Al_{13}^-
1f (14)	34	Al_{11}^-
2s (2)	20	
1d (10)	18	
1p (6)	8	
1s (2)	2	

FIG. 1. Spherical shell closings and the corresponding closed shell neutral and negative clusters of trivalent Al. The number in the parentheses after each shell index indicates the occupation number, $2(2l + 1)$.

will be derived later in this lecture

electronic levels revealed by photoelectron spectroscopy

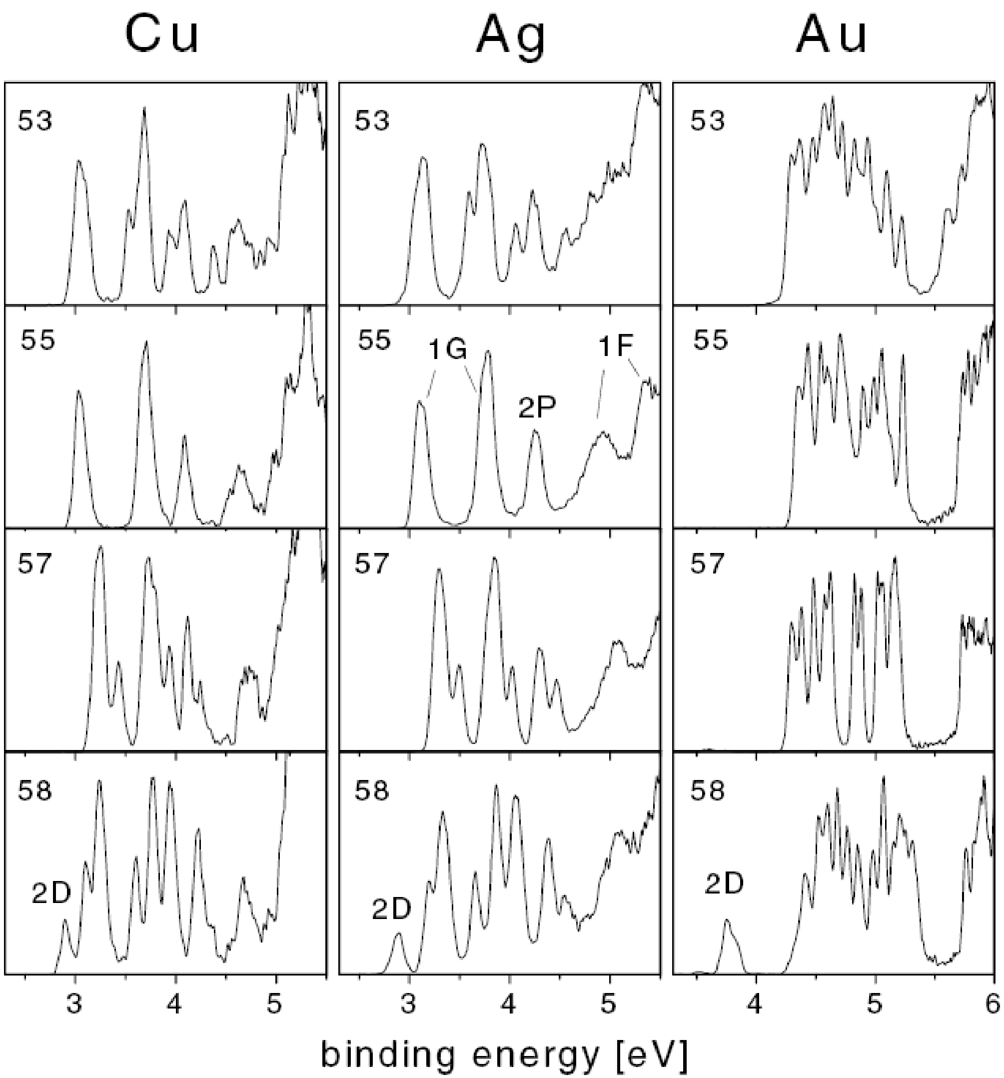
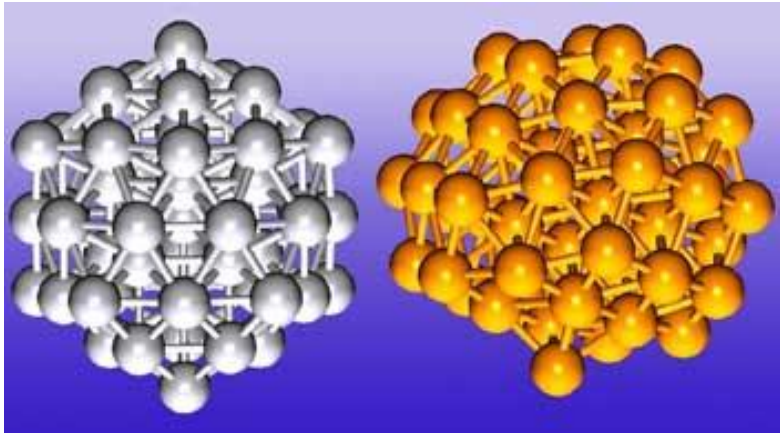


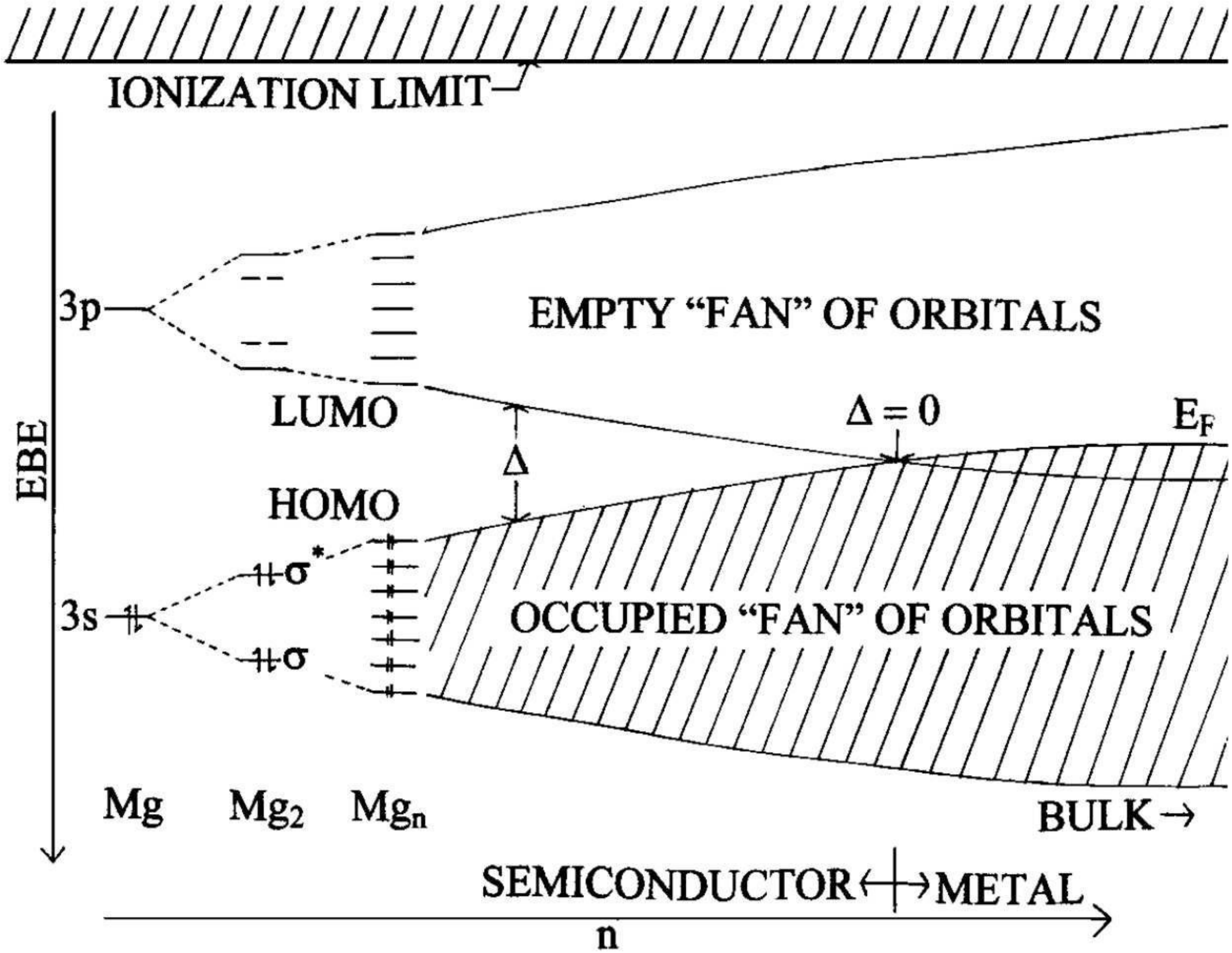
FIG. 1. Photoelectron spectra of Cu_n^-, Ag_n^-, and Au_n^- (n = 53, 55, 57, 58) obtained at a photon energy of 6.42 eV.



Hakkinenet al., PRL 93 093401(2004)

Physical nature of clusters may change with size

Example: *Electronic states in Magnesium from the atom to bulk. Metallic behaviour stets in when the full s-band starts to overlap with the empty p-band*

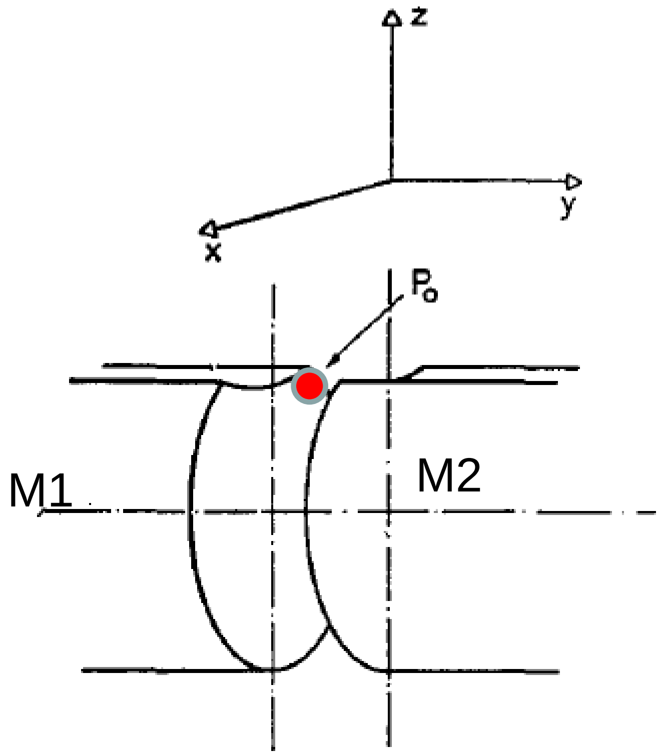


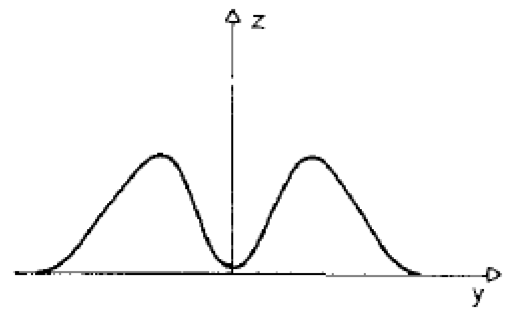
atomic physics - the beginning

- Leuklipp 440 v Chr, Demokrit 460-370 v Chr
  ατομοσ   'completely undivisible' (gänzlich unteilbar).
  idea: outside the atom emty space
- Epikur 341-271 v Chr: atom -- gravity (Schwere)
- later the idea of 'atom' has been forgotten for centuries
- for the church the reinvention of the atom has been too materialistic; in 1348 Nicolas von Antrecourt had to retract (widerrufen) his ideas on the atomic nature
- break-through from the 17th century on mainly by chemists (weighing, reactants and products)
- 19. Jht. Clausius, Maxwell, Boltzmann: p, T, specific result from atomic cillisions

historical key experiments still important today

another Millikan experiment: magnetic levitation spectrometer





trapping potential along y

measure the oscillation period and amplitude

►deduce the charge state with extremely high precision

Morpurgo et al., Nucl. Inst. Meth. 79 (1970) 95

modern Millikan experiment **with magnetic levitation**

Electric Neutrality of Matter

G. Gallinaro, M. Marinelli, and G. Morpurgo
Istituto di Fisica, Università di Genova, Genova, Italy, and Istituto Nazionale di Fisica Nucleare— Sezione di Genova, Italy
(Received 18 April 1977)

With the use of a new feedback levitation electrometer (with an increase in sensitivity by 10^3 in comparison to our previous graphite experiments) iron objects of mass $\sim 2\times10^{-4}$ g have been explored for fractionally charged quarks and/or a possible electron-proton charge difference. Upper limits found were $N(\text{quarks})/N(\text{nucleons}) < 3\times10^{-21}$ and $(Q_p - |Q_e|)/Q_p < 10^{-21}$. The present "sensitivity" is $\sim 10^7$ times that of the original Millikan experiment.

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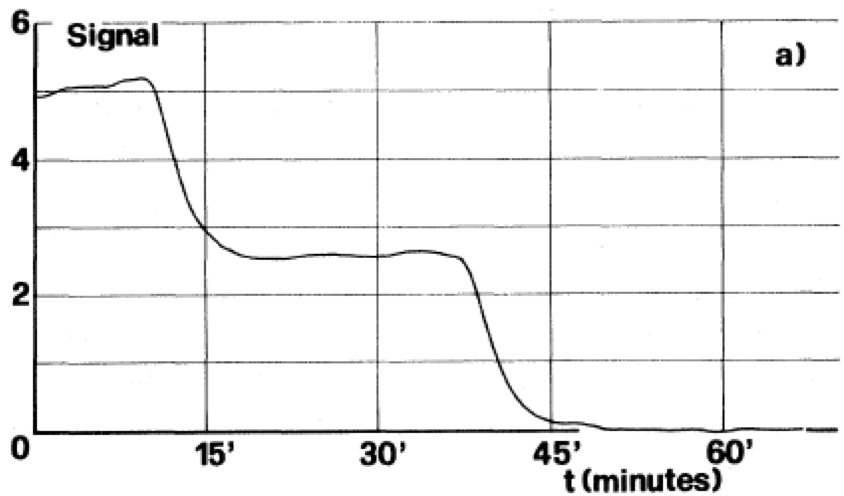
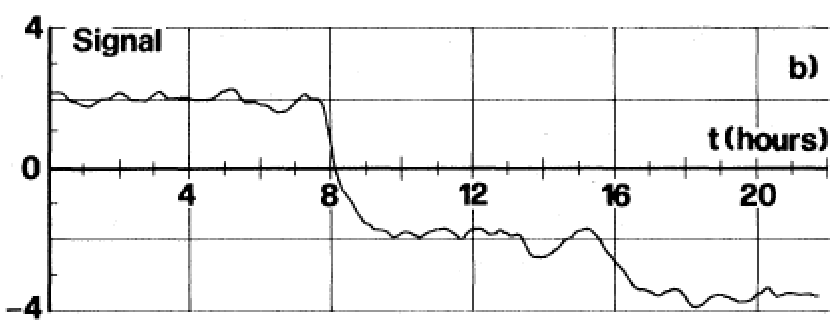


a) changes in the charge of a steel sphere with $3.3\text{x}10^{-5}$ g
Residual charge smaller than 1/40 e

b) rotating cylinder with $2.5 \text{ x } 10^{-4}$ g.
Charge changes from +1 to -1 and -2



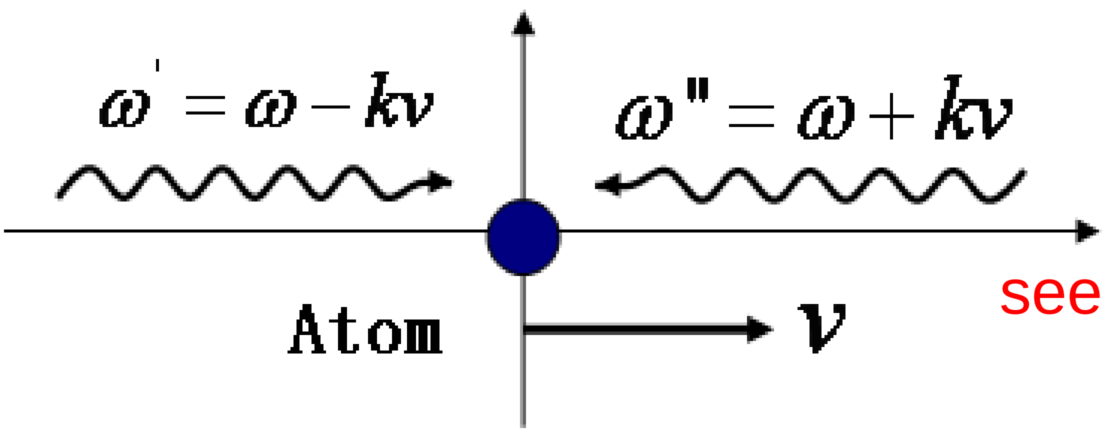
conclusions:
- upper limit N(quarks)/N(Nucleons) smaller than $3\text{x}10^{-21}$
- $(Q_p-Q_e)/Q_p$ smaller than 10^{-21}
- sensitivity 10^7 times Millikan

Basics of atom (and molecular) spectroscopy - how to overcome effects of motion and collisions

one aim: to do undisturbed spectroscopy to learn, e.g., about line widths (lecture by Prof. Bauer)

- **Doppler-reduced spectroscopy**

- **supersonic atom beams**

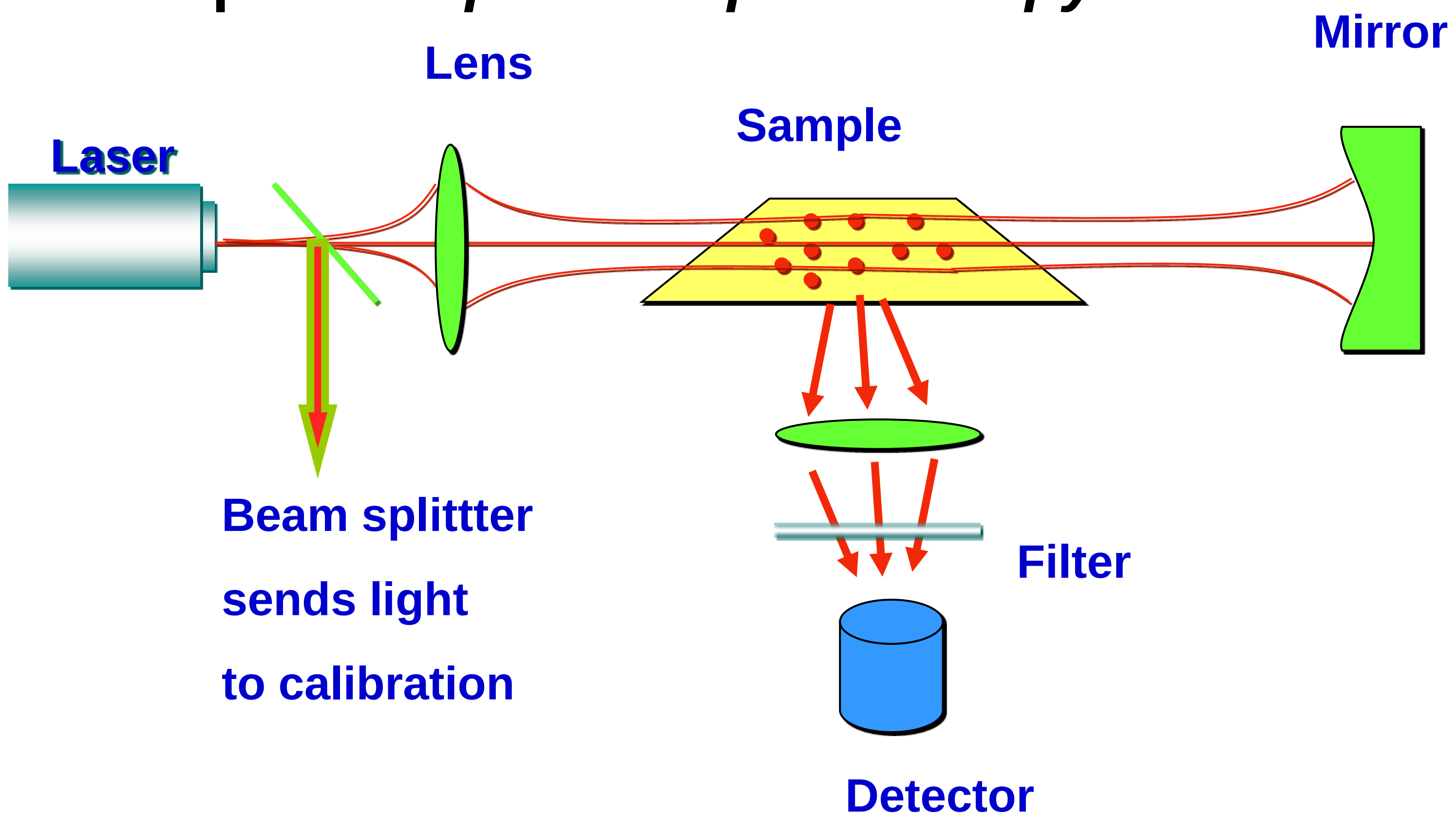


see blackboard

In the laboratory frame: angular frequency **ω**.

In a reference frame of an atom moving with a speed **v**: angular frequencies ω' or ω''.

solution 1: Doppler-free spectroscopy
for example *Two-photon spectroscopy*

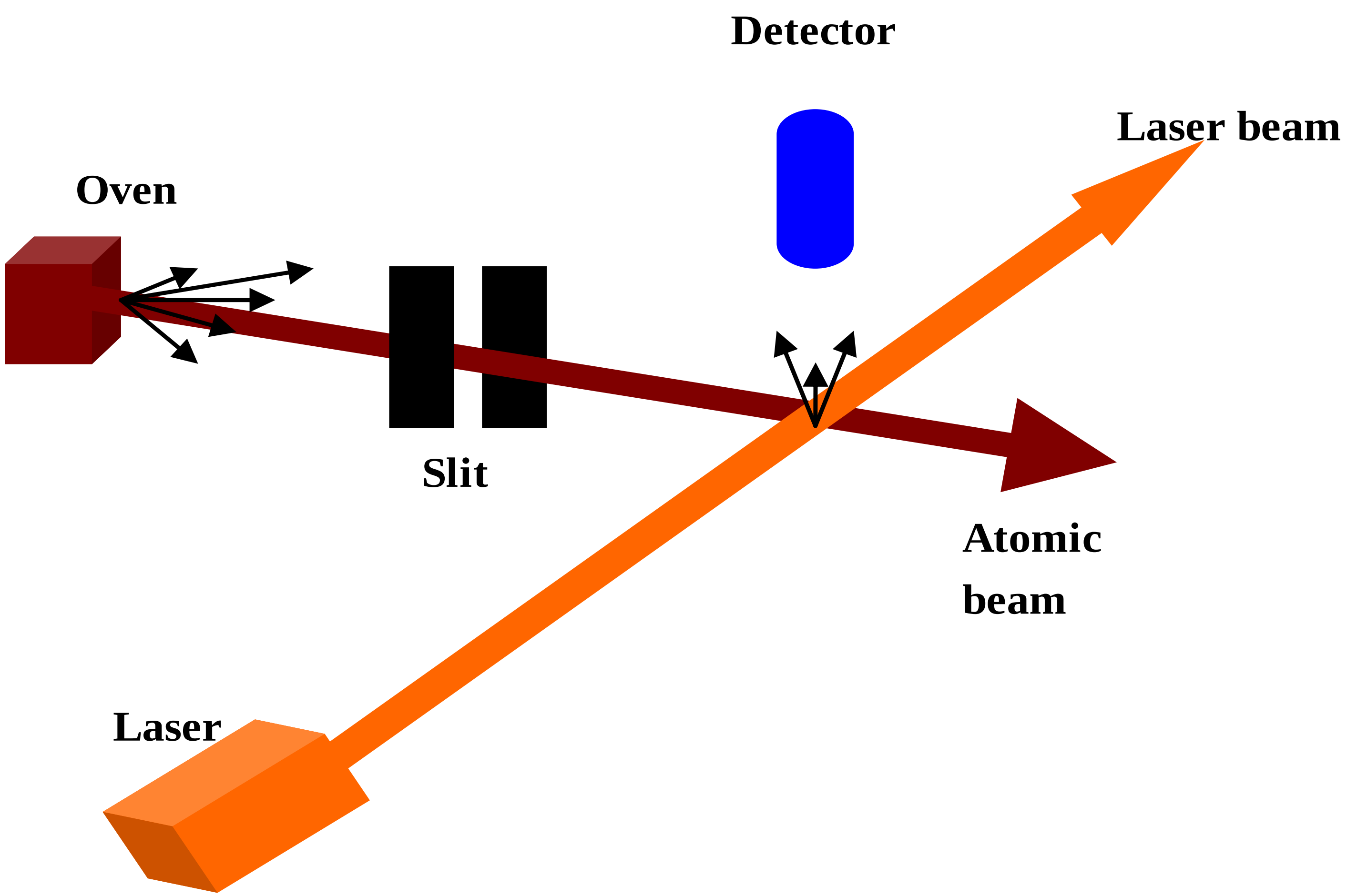


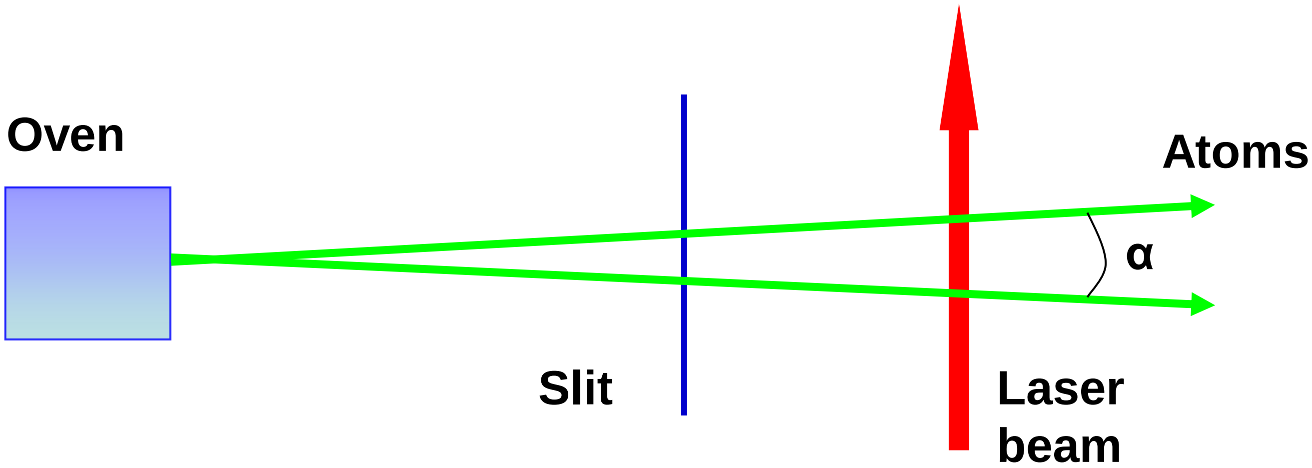
If the atom absorbs one photon from each of the counter-propagating beams then the Doppler shifts cancels in the rest frame of the atom

$$\omega(1+\frac{v}{c})+\omega(1-\frac{v}{c})=\omega$$

► there are many more methods of Doppler-free spectroscopy

<u>solution 2</u>: cold atom beams
for example *crossed beams technique*





$$\Delta f \approx \frac{\alpha v_{beam}}{\lambda} \approx \alpha \Delta f_D$$

Δf_D **is the Doppler width of a gas at the same temperature as the beam.**

► **thus: we have to create ultracold atomic beams**

The **analysis of compressible fluid flow** involves four equations of particular interest:
Energy - Continuity - Momentum - The equation of state

Conservation of energy, isentropic flow (no heat exchange, no friction) between x1 and x2:

$$h_1 - h_2 = \tfrac{1}{2}\left(v_2^2 - v_1^2\right) = C_p\left(T_1 - T_2\right)$$ [eq. 1]

Enthalpy h, v velocity in x-direction, Cp heat capacity, T1, T2 temperatures at x1, x2.

Change (decrease) in enthalpy is equal to the change (increase) in kinetic energy

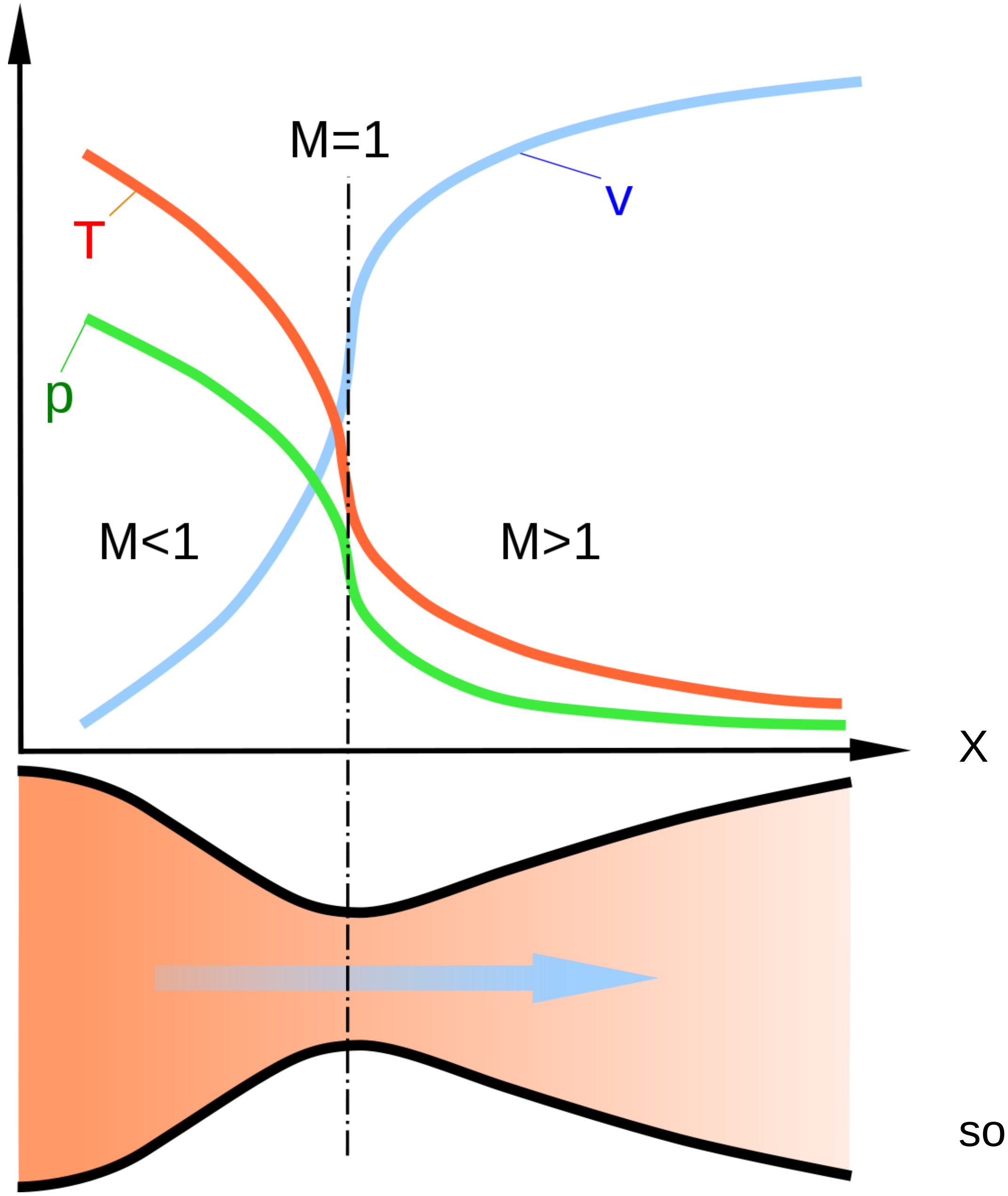
► heat of the fluid is being used to accelerate the flow!

For isentropic flow: temperature, pressure, and fluid density ρ

$$\frac{T_o}{T} = \left(\frac{P_o}{P}\right)^{\frac{k-1}{k}} = \left(\frac{\rho_o}{\rho}\right)^{k-1}$$ [eq. 2], with k: ratio of specific heats $k \equiv \frac{C_p}{C_v} = \frac{C_p}{C_p - R}$

and R = R'/mol.weight, R': Avogadro's constant

application to nozzle flow



source: Wikipedia

role of the Mach number

a: local sonic velocity
M: the Mach number (ratio of the flow velocity to the local sonic velocity)

$$a = \sqrt{k R T} \qquad M = \frac{v}{a} \qquad \text{[eq. 3]}$$

From eq. 1, 2, and 3 we derive

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2 \qquad \text{[eq. 4]}$$

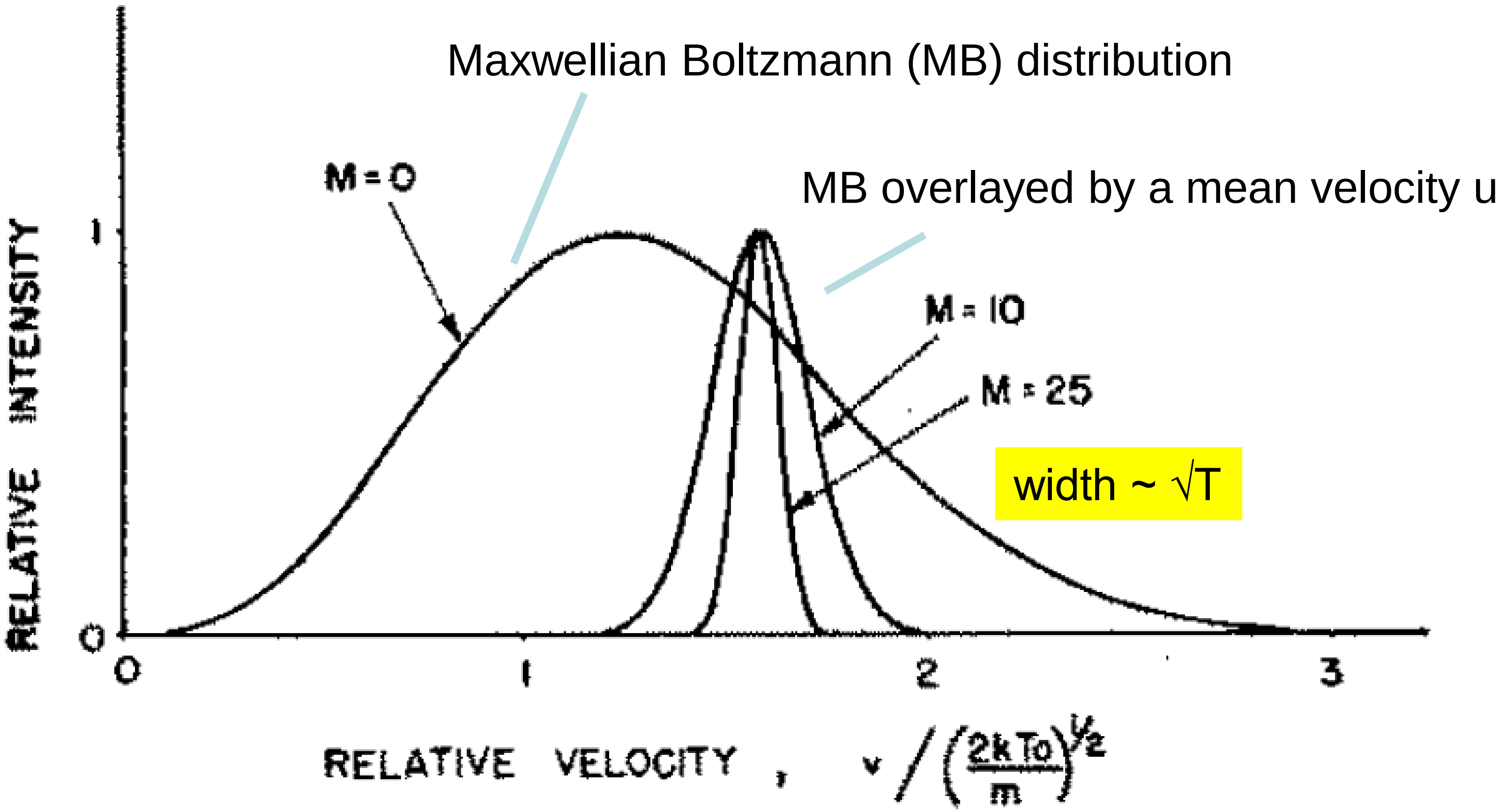
Further considerations:
From [eq. 4], the first law $\frac{P}{\rho^k} = \text{constant}$, and the eq. of state $P = \rho R T$:

$$\frac{P_o}{P} = \left(1 + \frac{k-1}{2} M^2\right)^{\frac{k}{k-1}}$$

$$\frac{\rho_o}{\rho} = \left(1 + \frac{k-1}{2} M^2\right)^{\frac{1}{k-1}}$$

In our case: T_0, P_0, ρ_0
the values before expansion

consequences for the atomic beam



original work: Andersen and Fenn, The physics of fluids 8 (1965) 780

preparation of ultracold atomic beams
by supersonic jet expansion

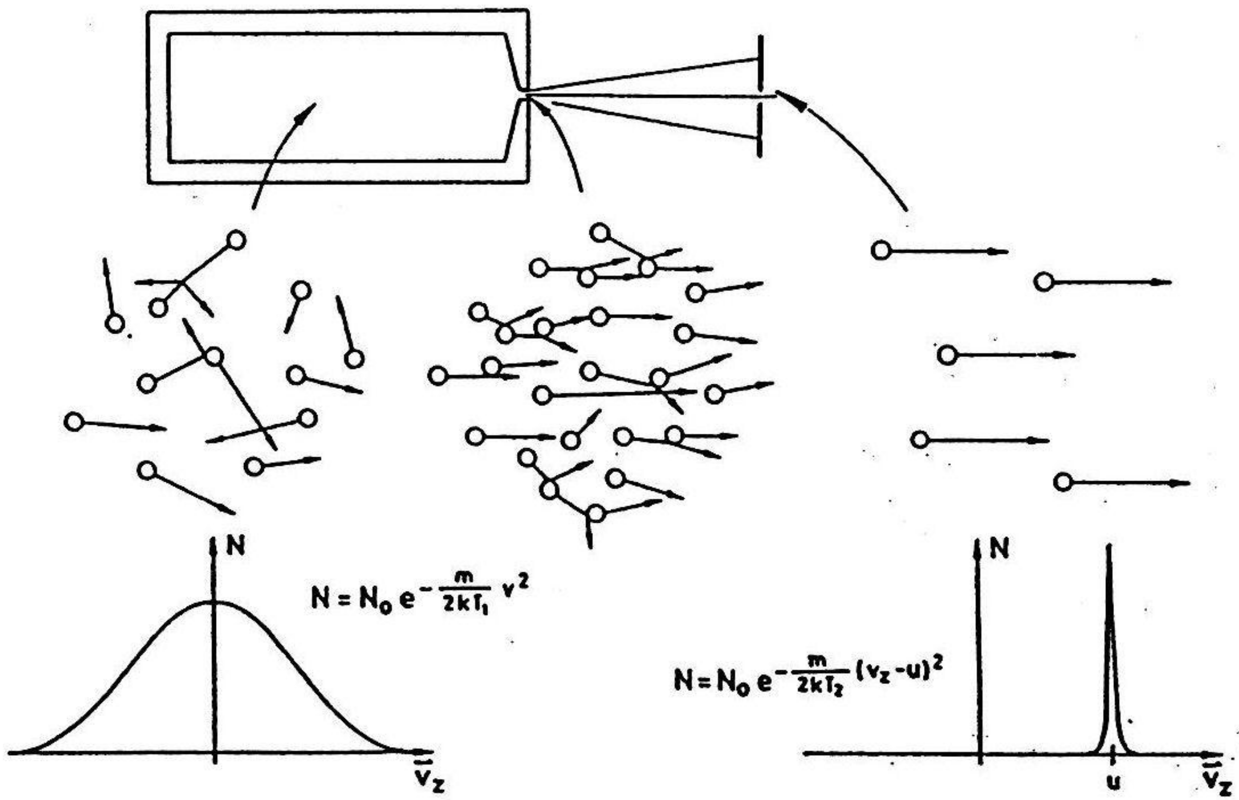
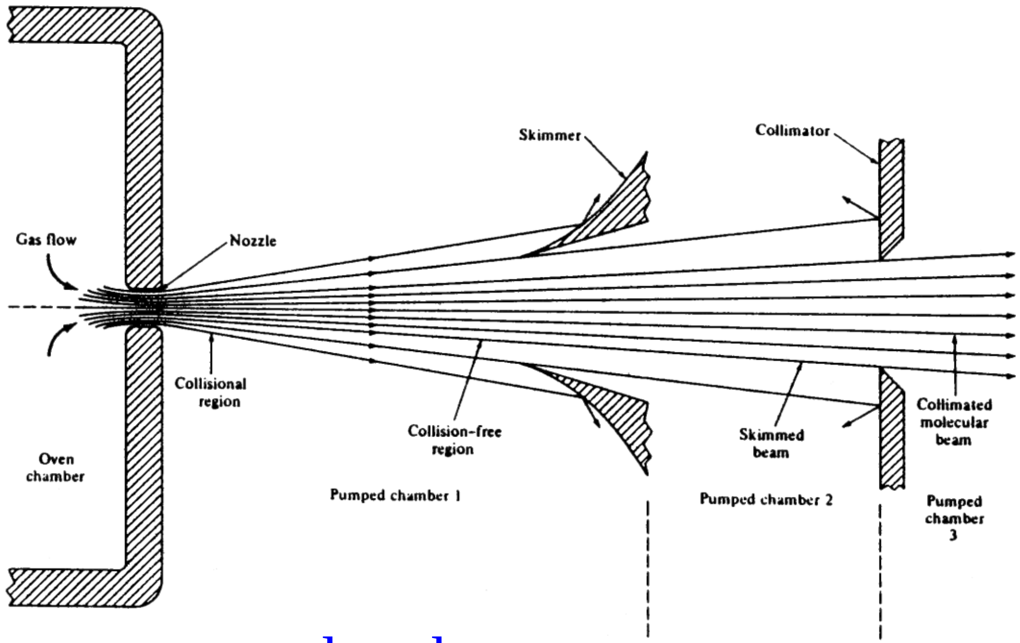


Fig. 8: Die mikroskopische Ursache für die Temperaturerniedrigung und Clusterbildung bei der adiabatischen Expansion [13]. Im Ausgangsbehälter herrscht vor der Expansion thermisches Gleichgewicht. Die ungerichtete Geschwindigkeitsverteilung der Teilchen ist durch die Maxwellverteilung bestimmt. Bei der Expansion des Gases durch eine Düse kommt es durch Stöße mit den anderen Gaspartikeln zur Abnahme der inneren Energie zu Gunsten der Expansionsgeschwindigkeit *u*. Die Relativgeschwindigkeit im kalten Molekularstrahl nimmt stark ab, wodurch die "kalten" Atome zu Clustern zusammenlagern.

technical realization of an atomic beam

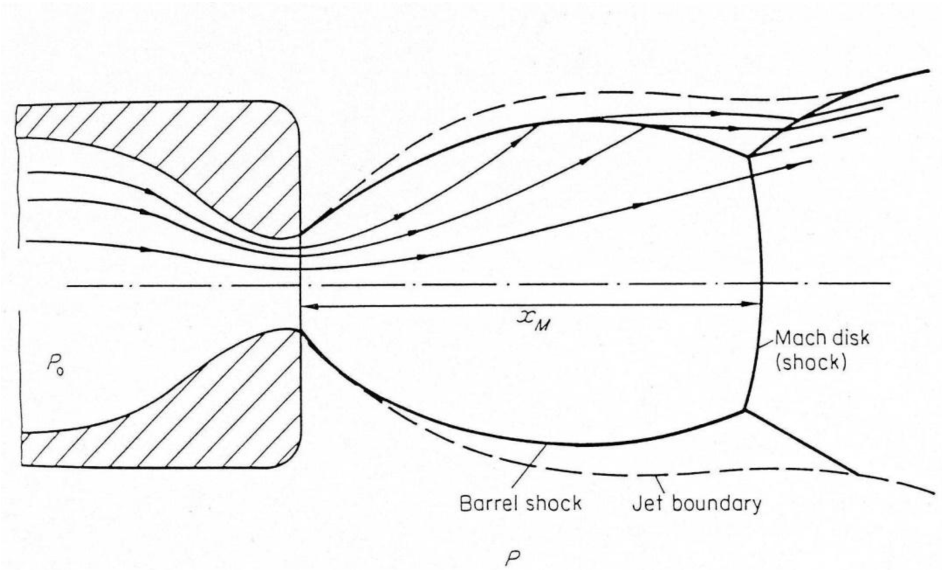


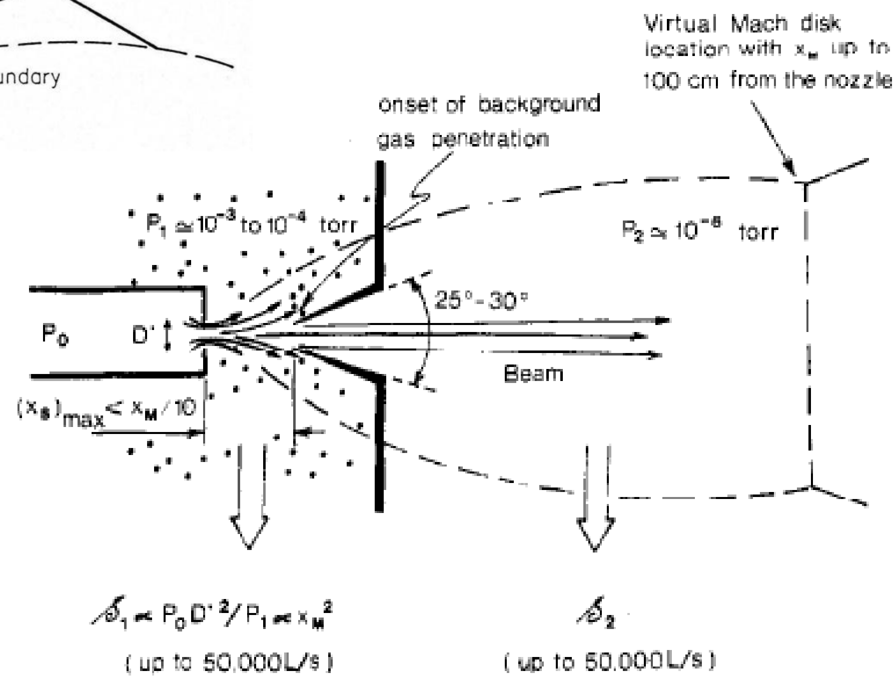
backing pressure P_0:
0.1 ~ 100 atm

source chamber:
$10^{-6} \sim 10^{-2}$ torr (far away from nozzle)

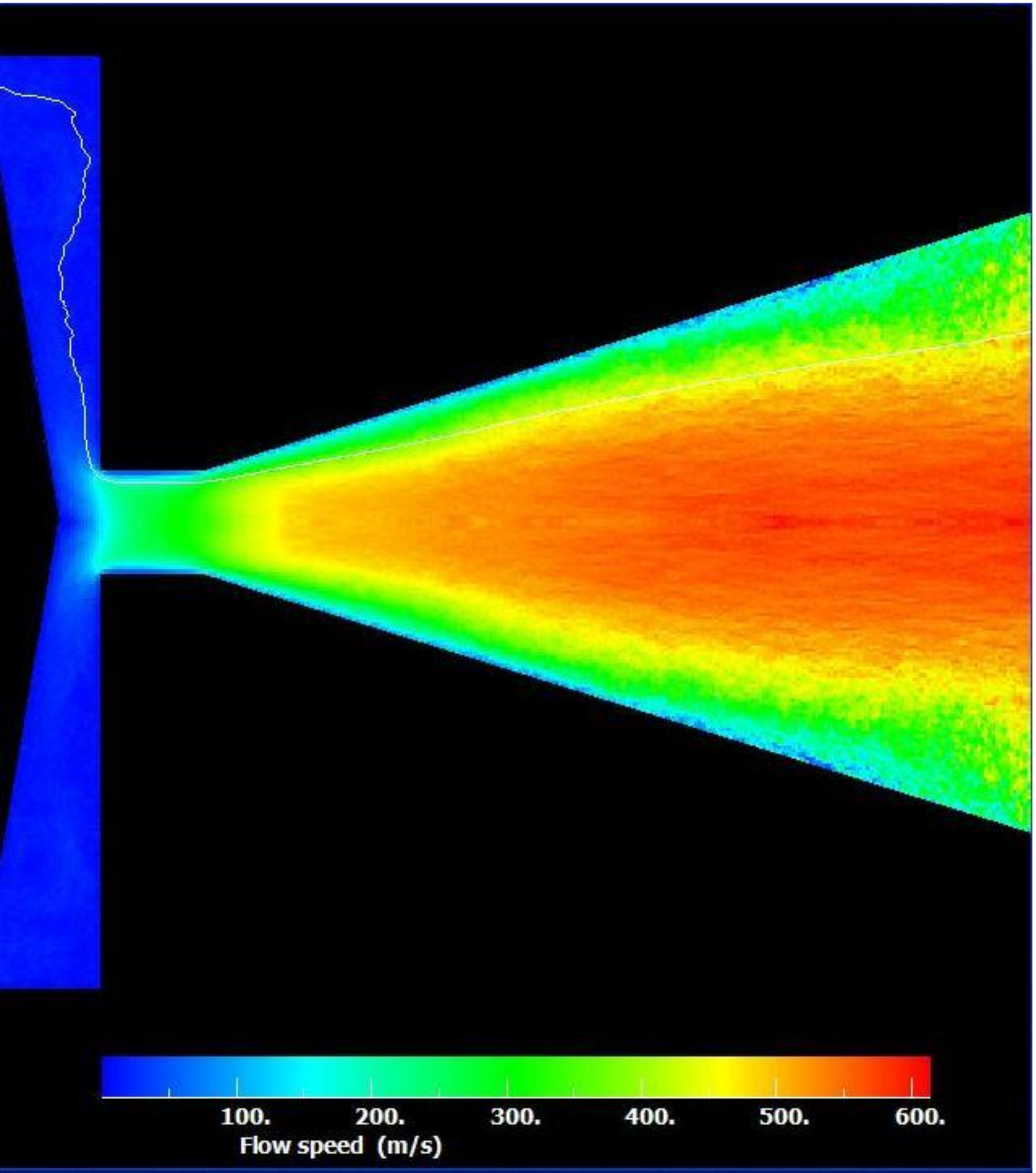
Expansion (Huge pressure drop $>10^3$)

supersonic jet expansion





acceleration in nozzles (simulated)



1. expansion shown for Argon
2. the gas reaches 600m/s over a distance of 2 nozzle diameters in 1 μs
3. the acceleration is enormous:

   $a>5*10^8$ m/s^2 for Argon
   $a>5*10^9$ m/s^2 for Helium

   Interesting inertial effects in spectroscopy??