

## **5. Lichtkräfte und Laserkühlung**

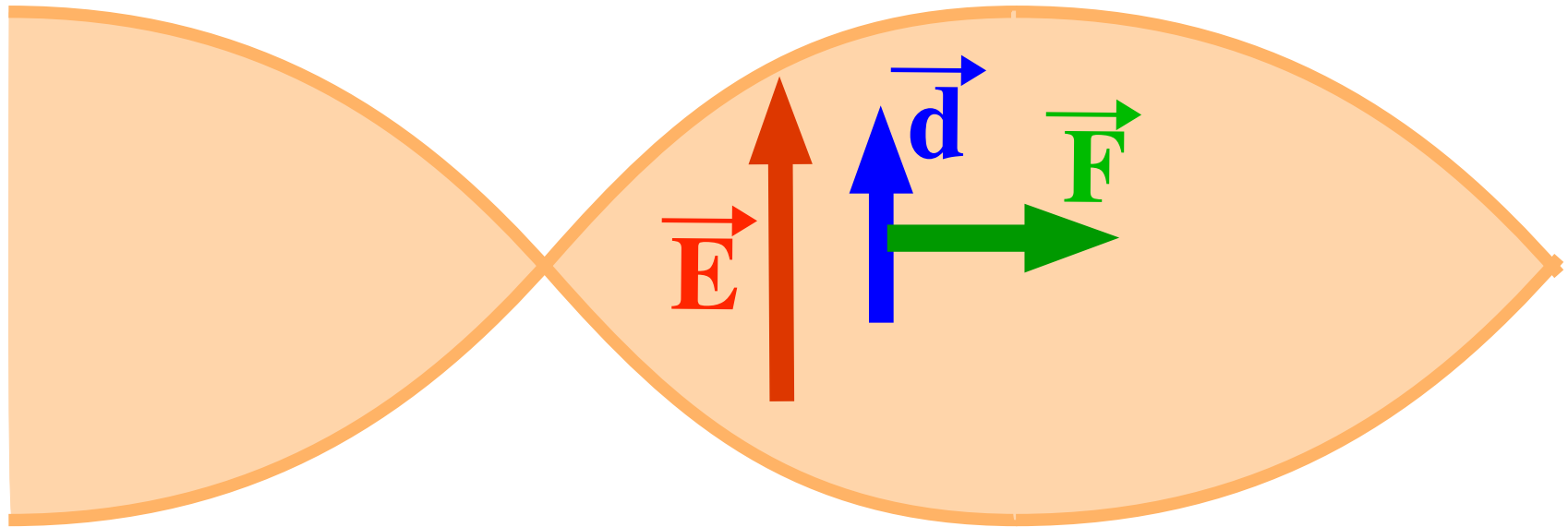
**5.1 Lichtkräfte**

**5.2 Dopplerkühlung**

**5.3 Konservative Kräfte**

# Kräfte und Potenzial

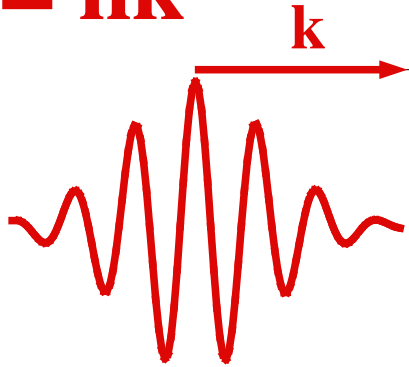
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# Impulsübertrag

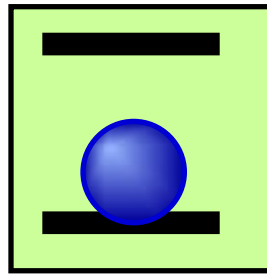
$$E = \hbar\omega$$

$$p = \hbar k$$

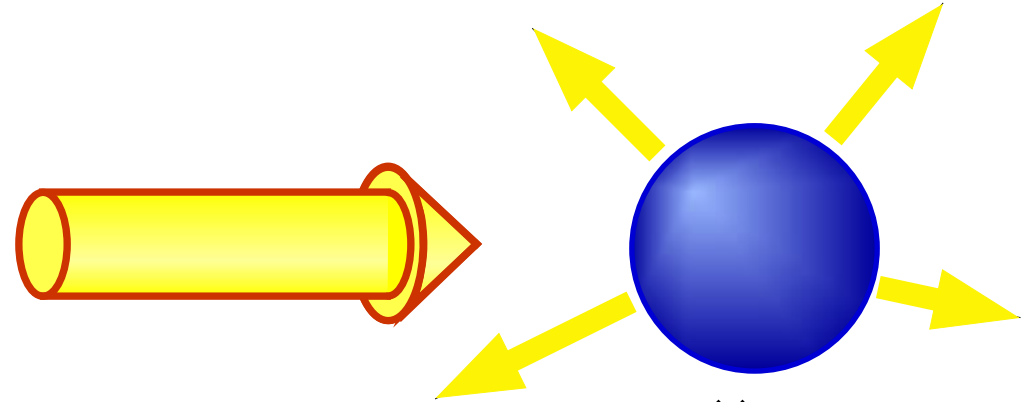


$$E = 0$$

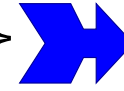
$$p = 0$$



experimentelle Situation



Absorption ist gerichtet }  
Emission ist isotrop }



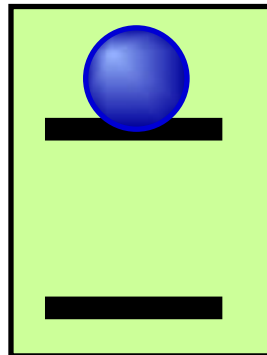
{ Kraft  $\uparrow\uparrow$  Laserstrahl  
{ mittlere Kraft = 0

Absorption



$$E = \hbar\omega$$

$$p = \hbar k$$



# Beschleunigung

**maximaler Effekt:**

**$n \leq 10^8$  Absorptionszyklen  
pro Sekunde**

**resultierende Beschleunigung =**

$$\frac{n \hbar k}{\text{sec } M_{\text{atom}}} = 1.7 \cdot 10^6 \frac{\text{m}}{\text{sec}^2}$$

**$\sim 170000 \text{ g}$**



**Space shuttle : 3g**

# Das erste Experiment

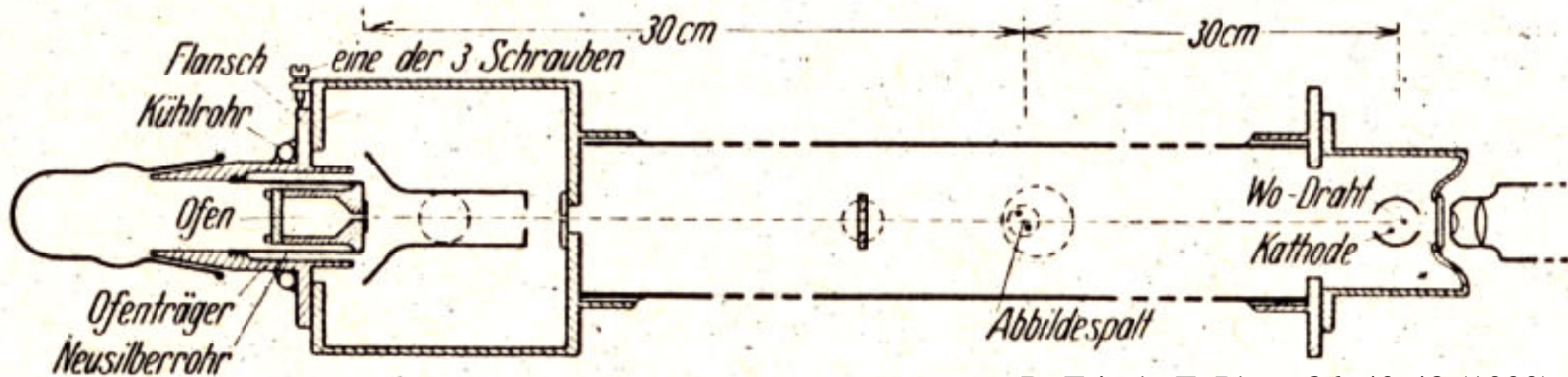
(Untersuchungen zur Molekularstrahlmethode aus dem Institut für physikalische Chemie der Hamburgischen Universität. Nr. 30.)

## Experimenteller Nachweis des Einsteinschen Strahlungsrückstoßes.

Von R. Frisch in Hamburg.

Mit 6 Abbildungen. (Eingegangen am 22. August 1933.)

Ein langer dünner Strahl von Na-Atomen wird mit Resonanzlicht bestrahlt; die Ablenkung der Atome infolge der Impulsübertragung bei der Absorption und Emission wird nachgewiesen.



# Das erste Experiment

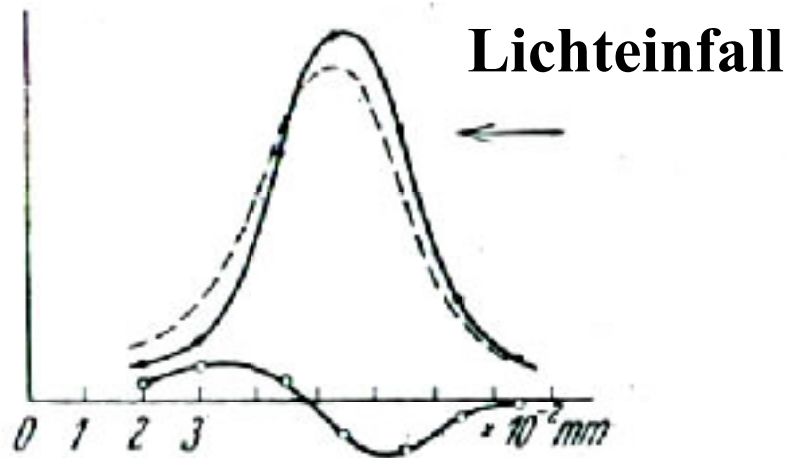


Fig. 5. Versuch mit seitlicher Beleuchtung.

Abszisse: Stellung des Auffängers.

Ordinate: Elektrometerrausschlag.

- Intensität ohne Beleuchtung.
- Wirkung der Beleuchtung.
- - - - Summe dieser beiden, also Intensität mit Beleuchtung.

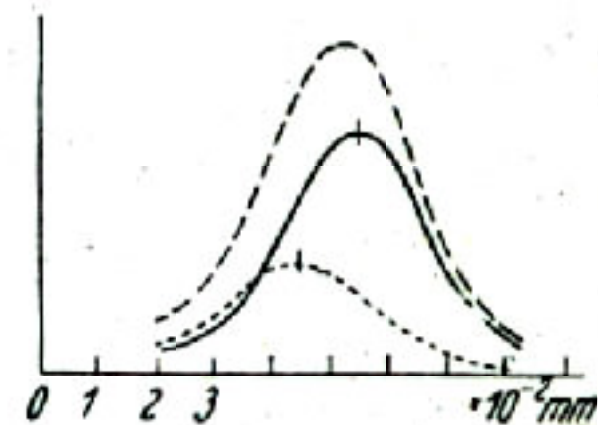
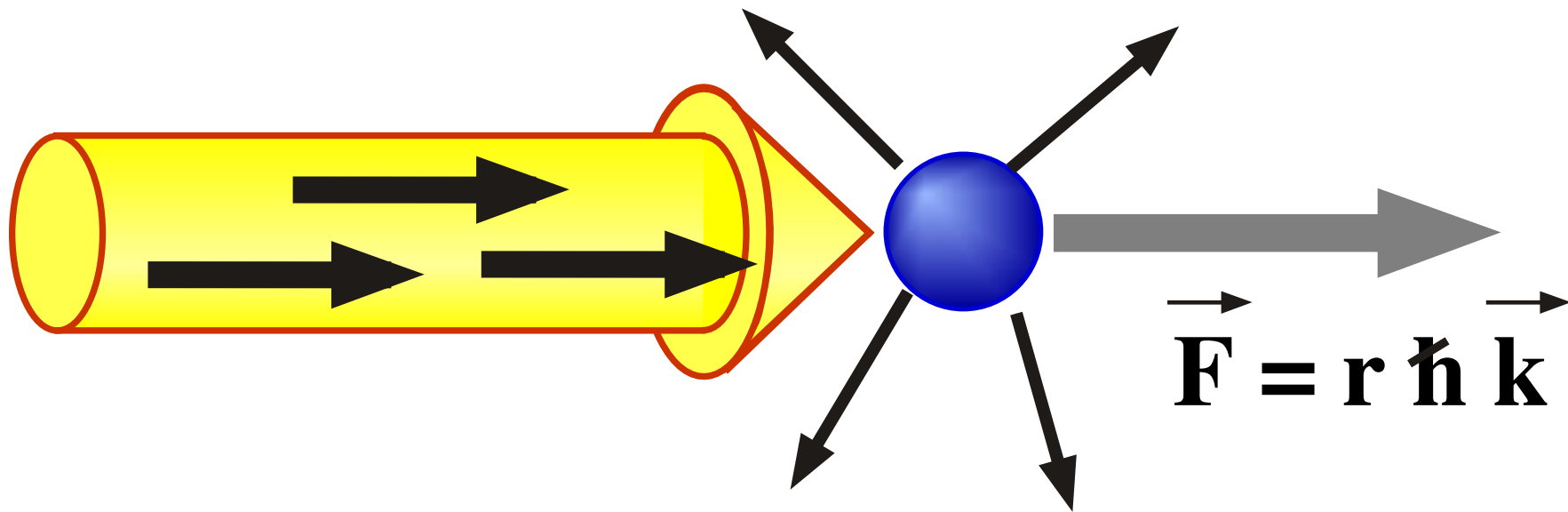


Fig. 6.

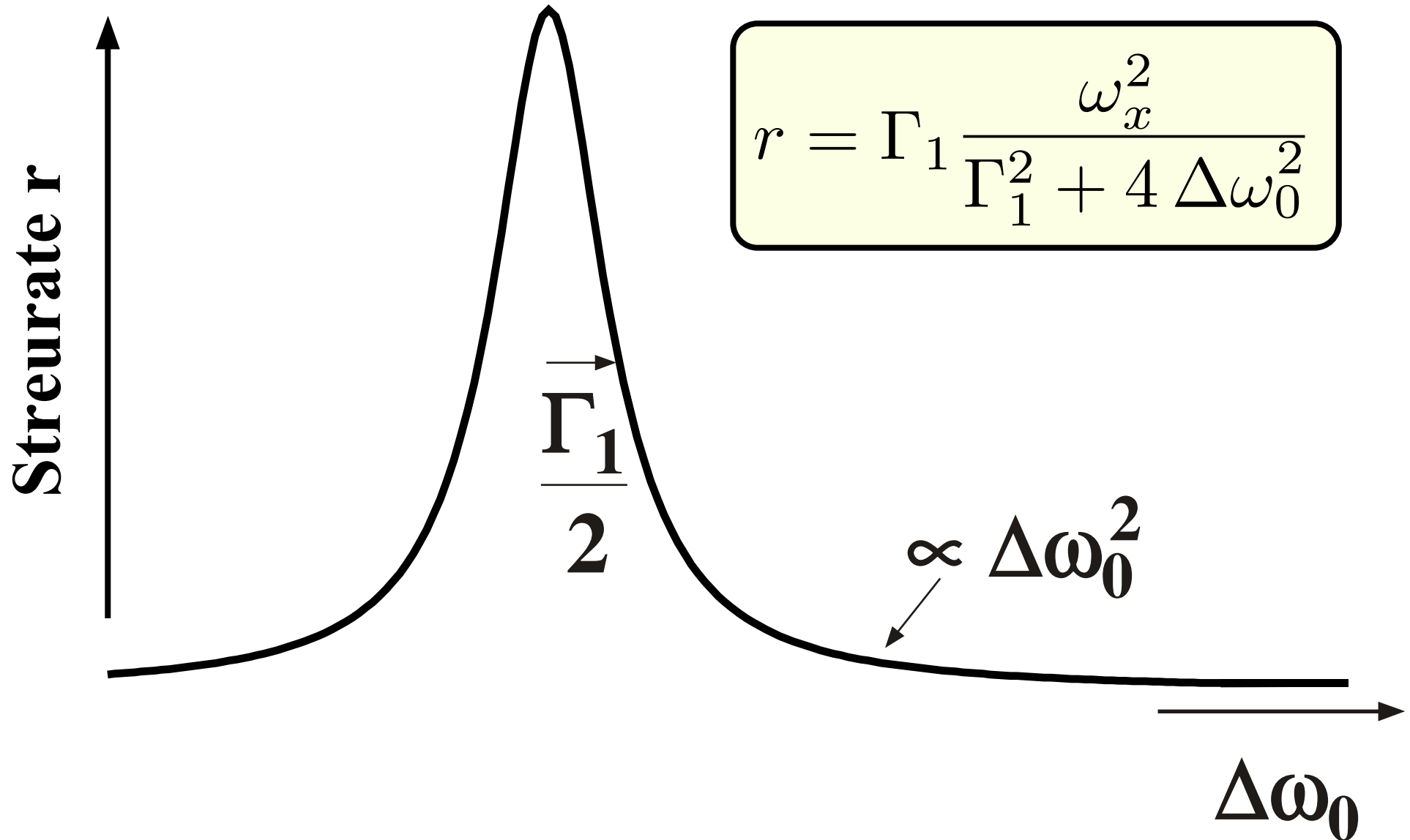
- - - - Strahl mit Beleuchtung.
- — —  $\frac{2}{3}$  vom Strahl ohne Beleuchtung.
- ..... Differenz dieser beiden, also Verteilung der abgelenkten Atome.

# Spontane Streukraft

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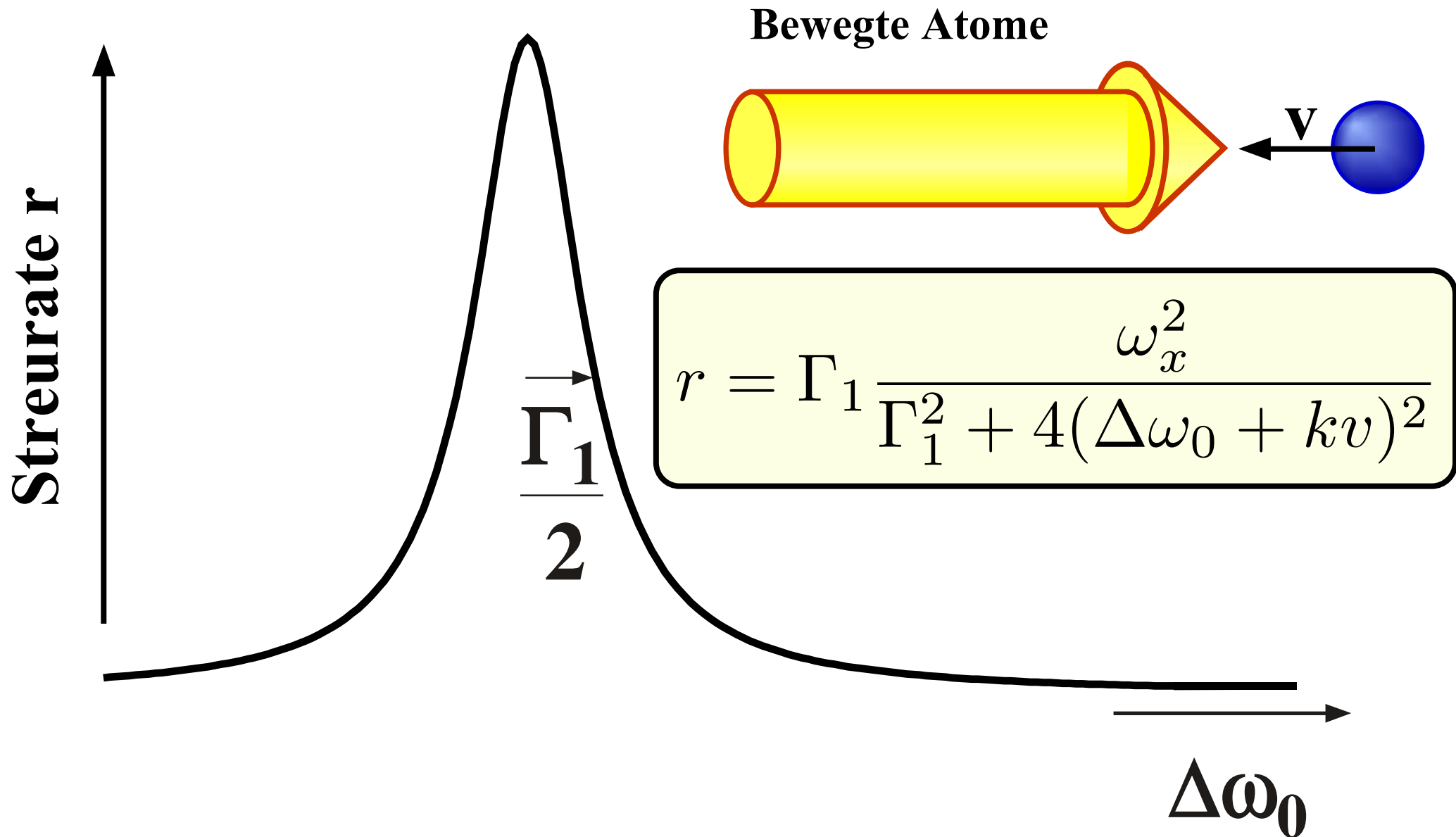


# Streurate



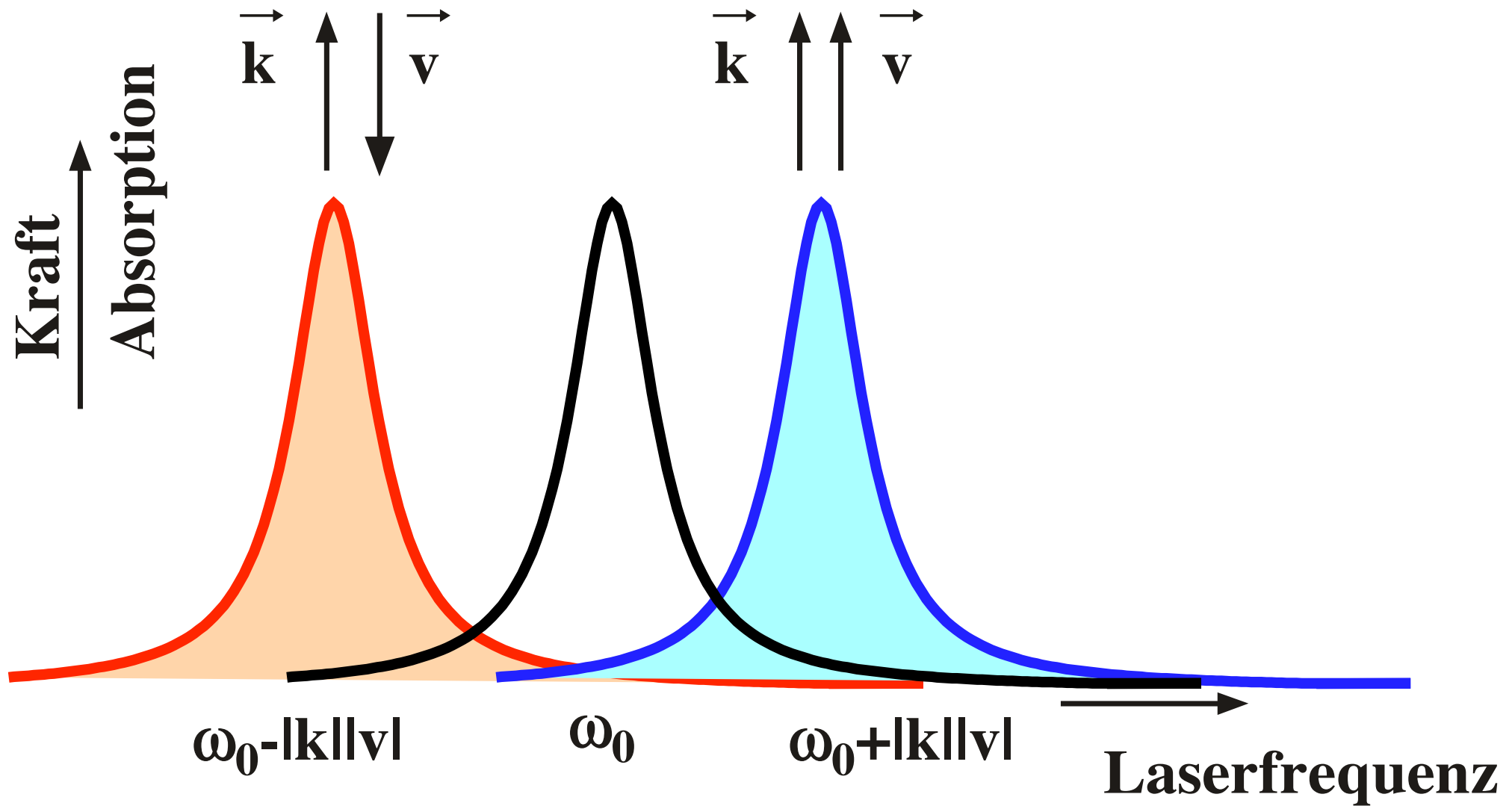


# Dopplerverschiebung



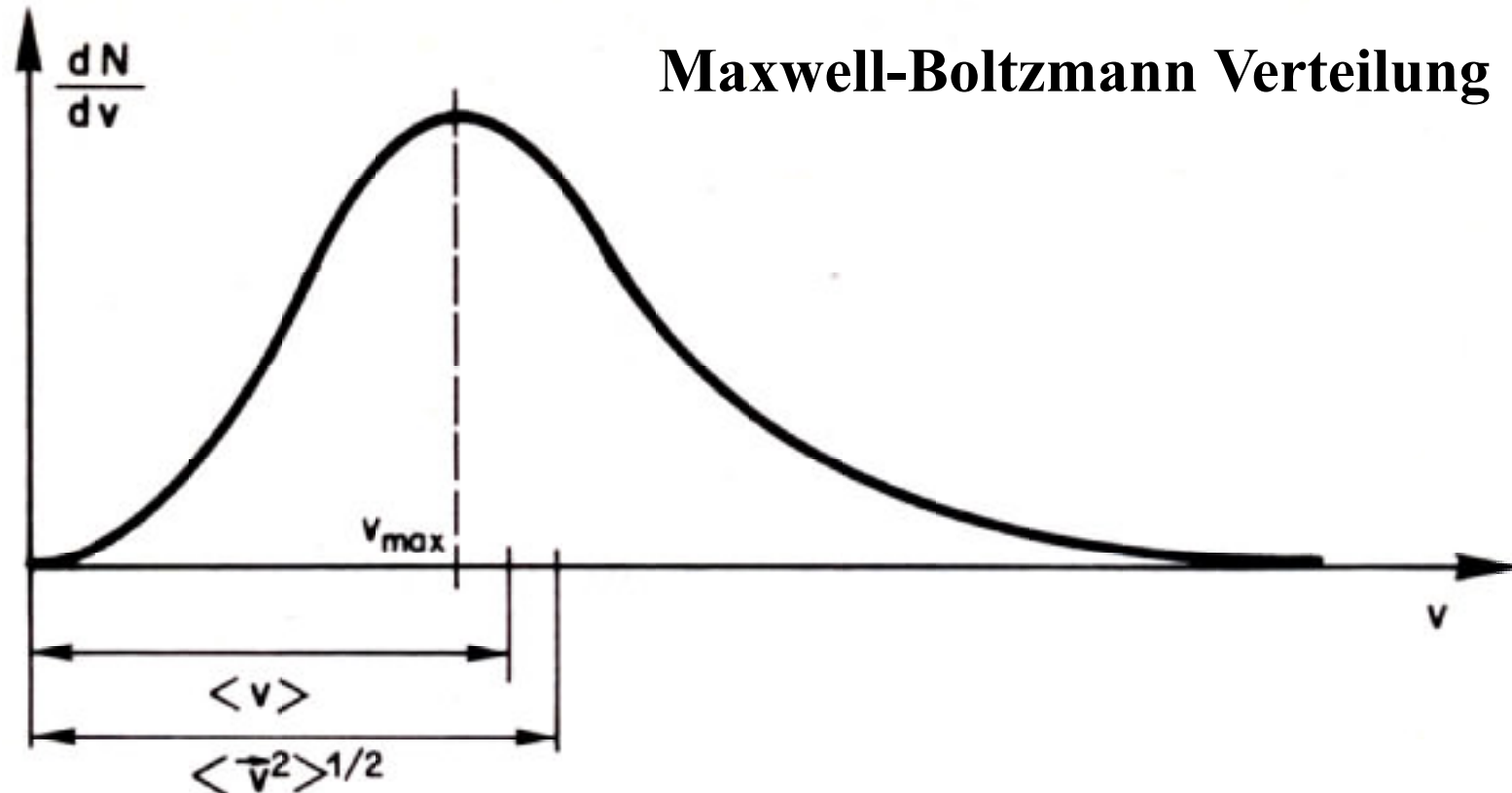
# Kraft

$$F = \hbar k \Gamma_1 \frac{\omega_x^2}{\Gamma_1^2 + 4(\Delta\omega_0 + kv)^2}$$

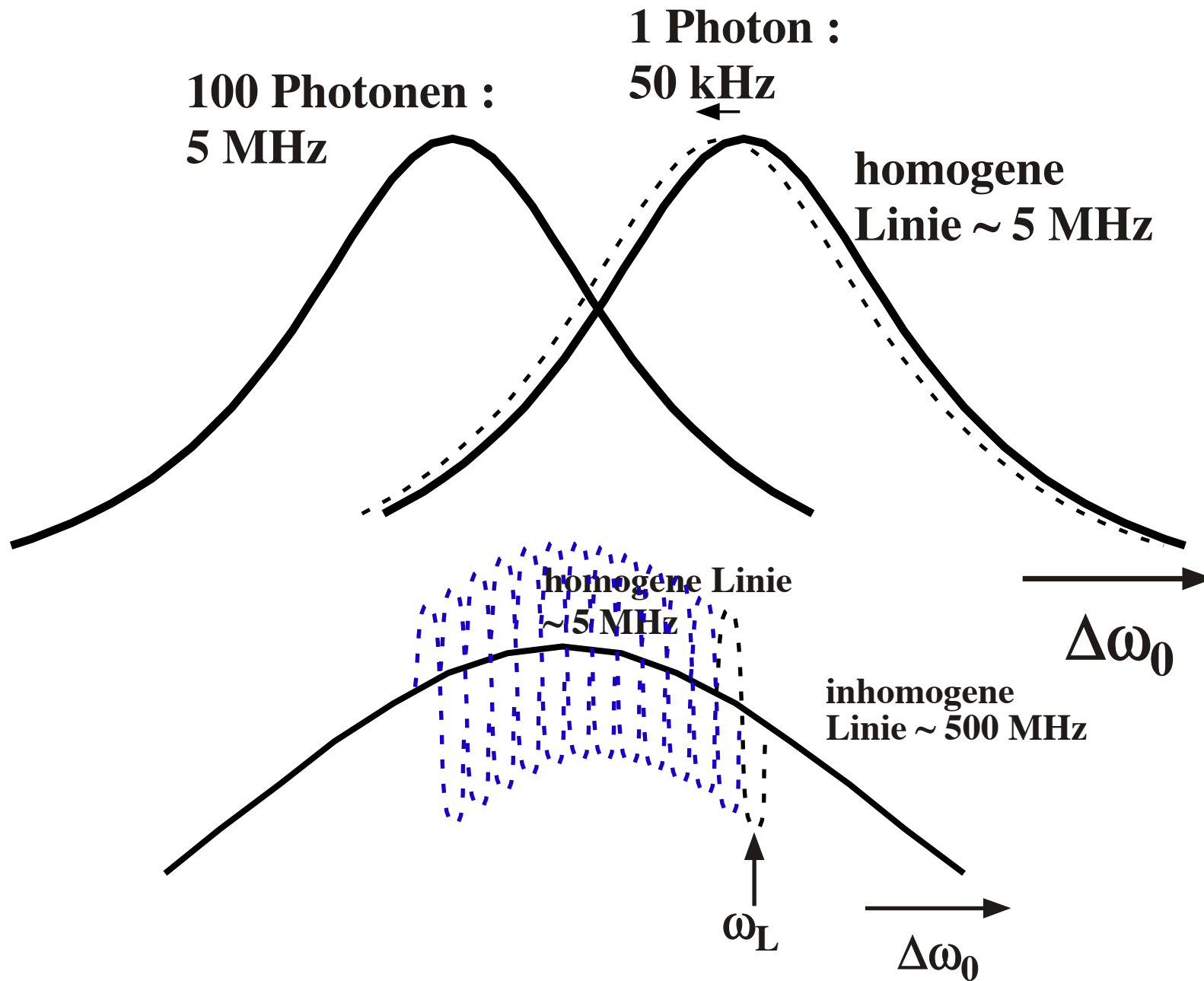


# Geschwindigkeit

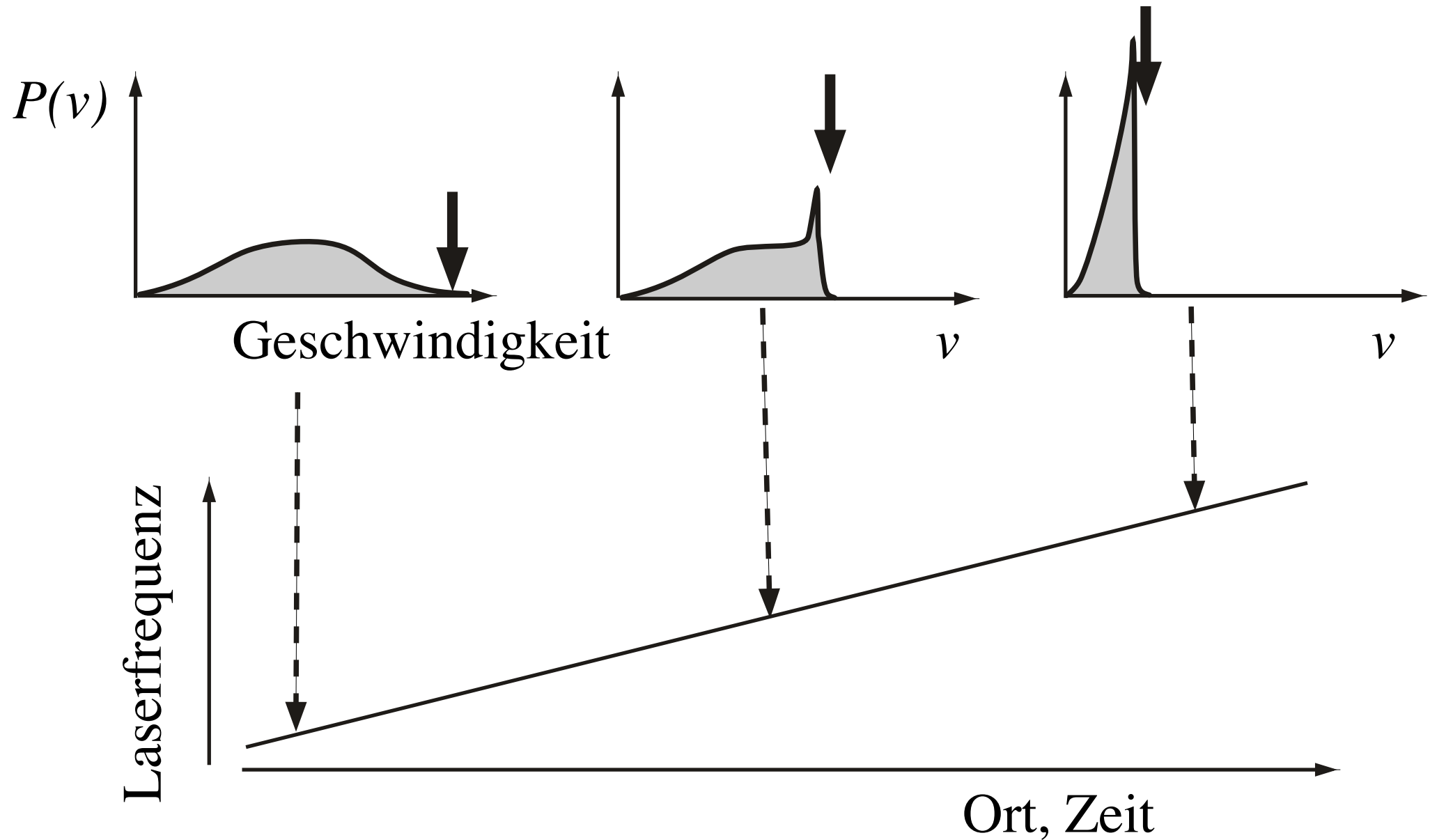
$$dN(v) = N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} v^2 dv$$



# Rückstoßverschiebung

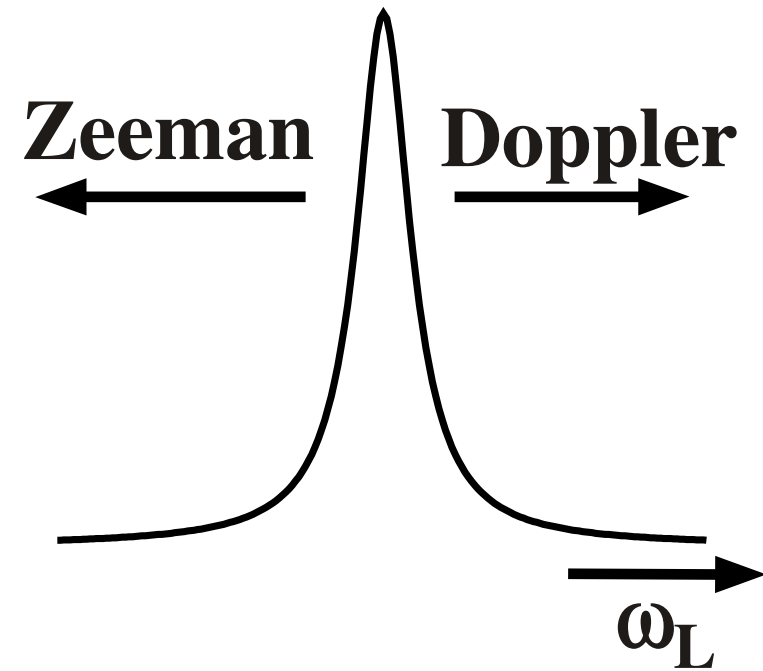
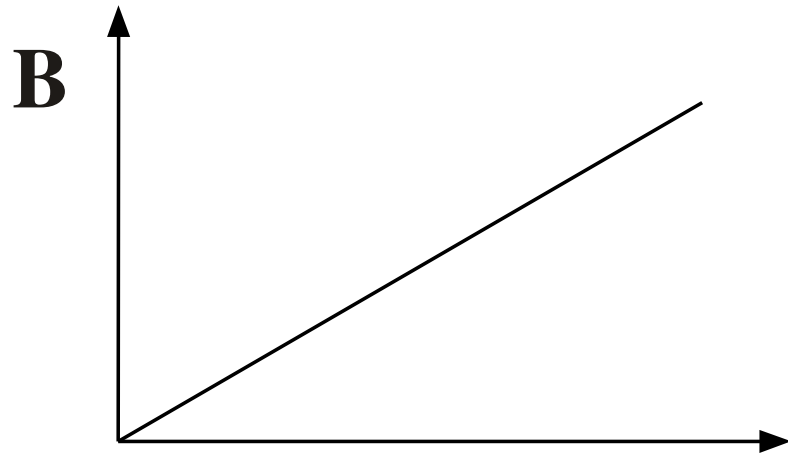


# Frequenzchirp



# Zeeman-Tuning

Ortsabhängiges B-Feld



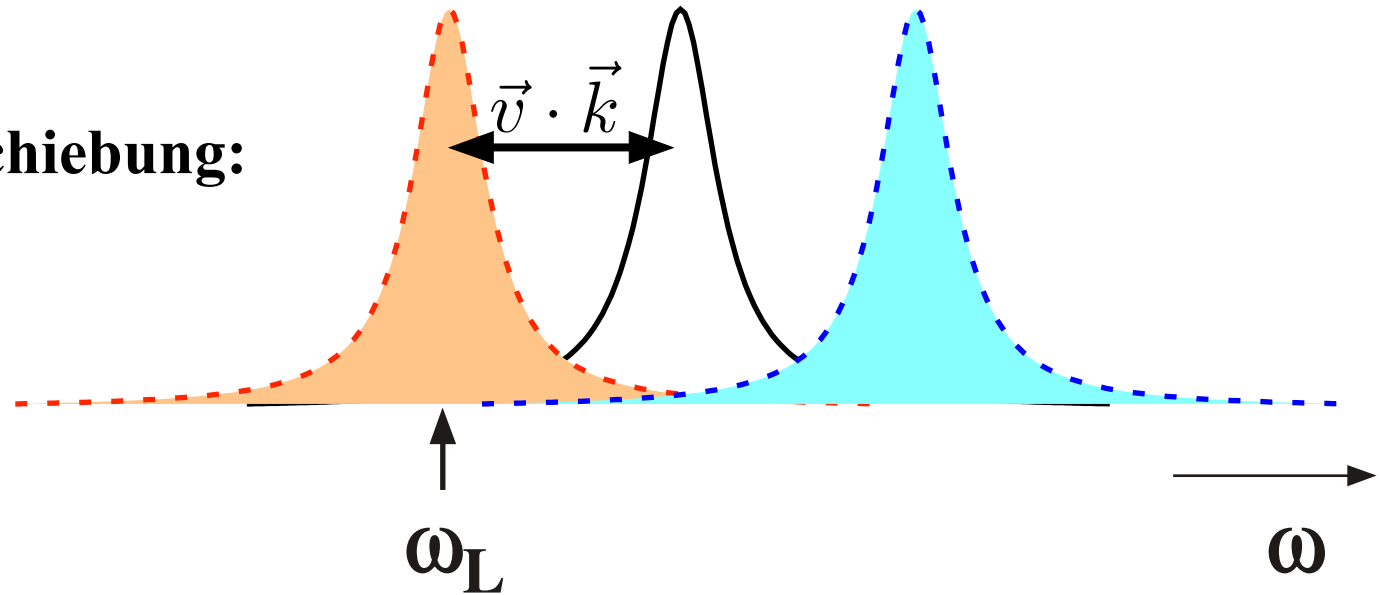
Beispiel eines "Zeeman-slower"s

# Optische Molasse

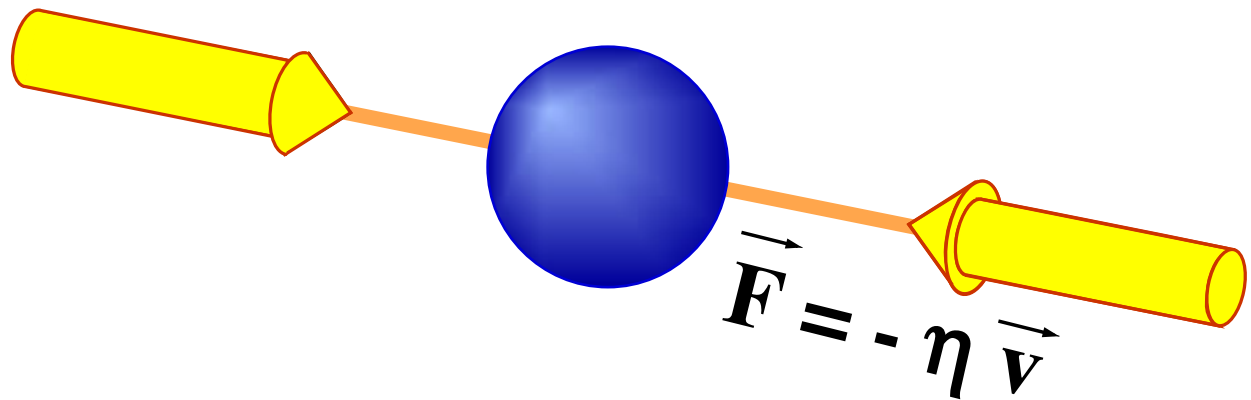
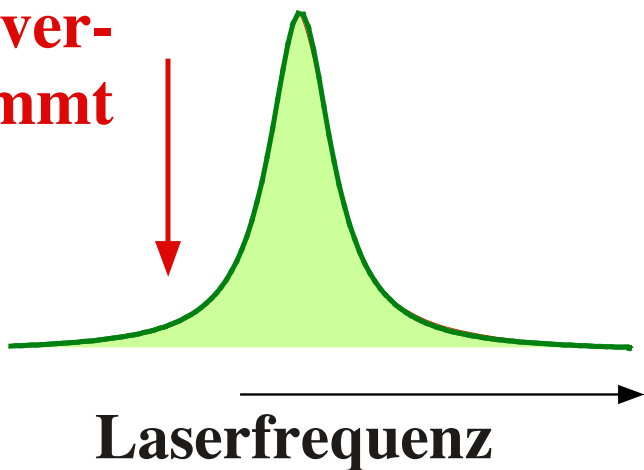
Atom fliegt auf Laser zu

vom Laser weg

Dopplerverschiebung:

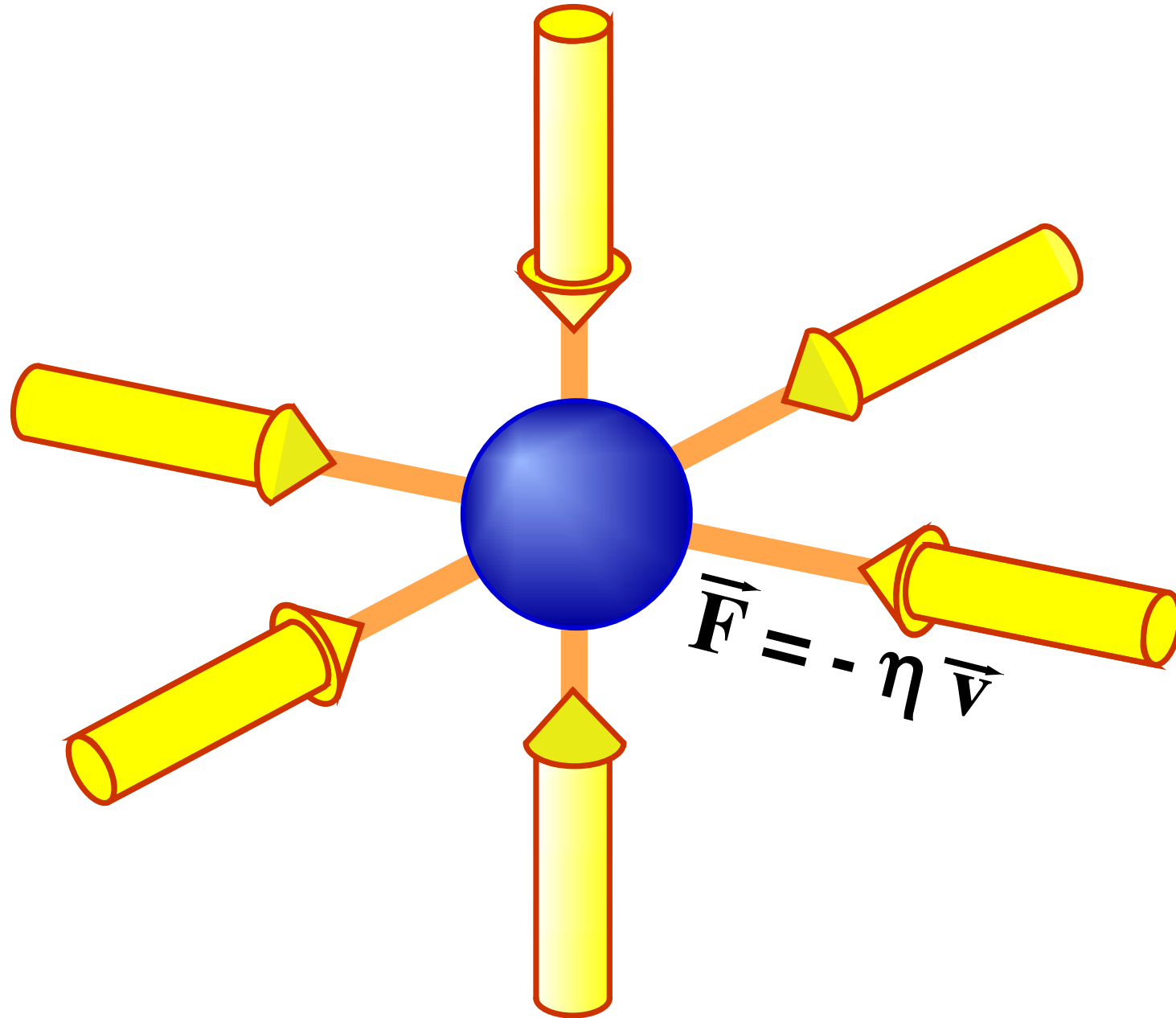
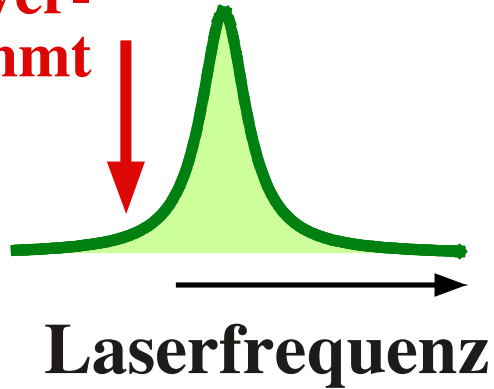


rotver-  
stimmt



# Optische Melasse

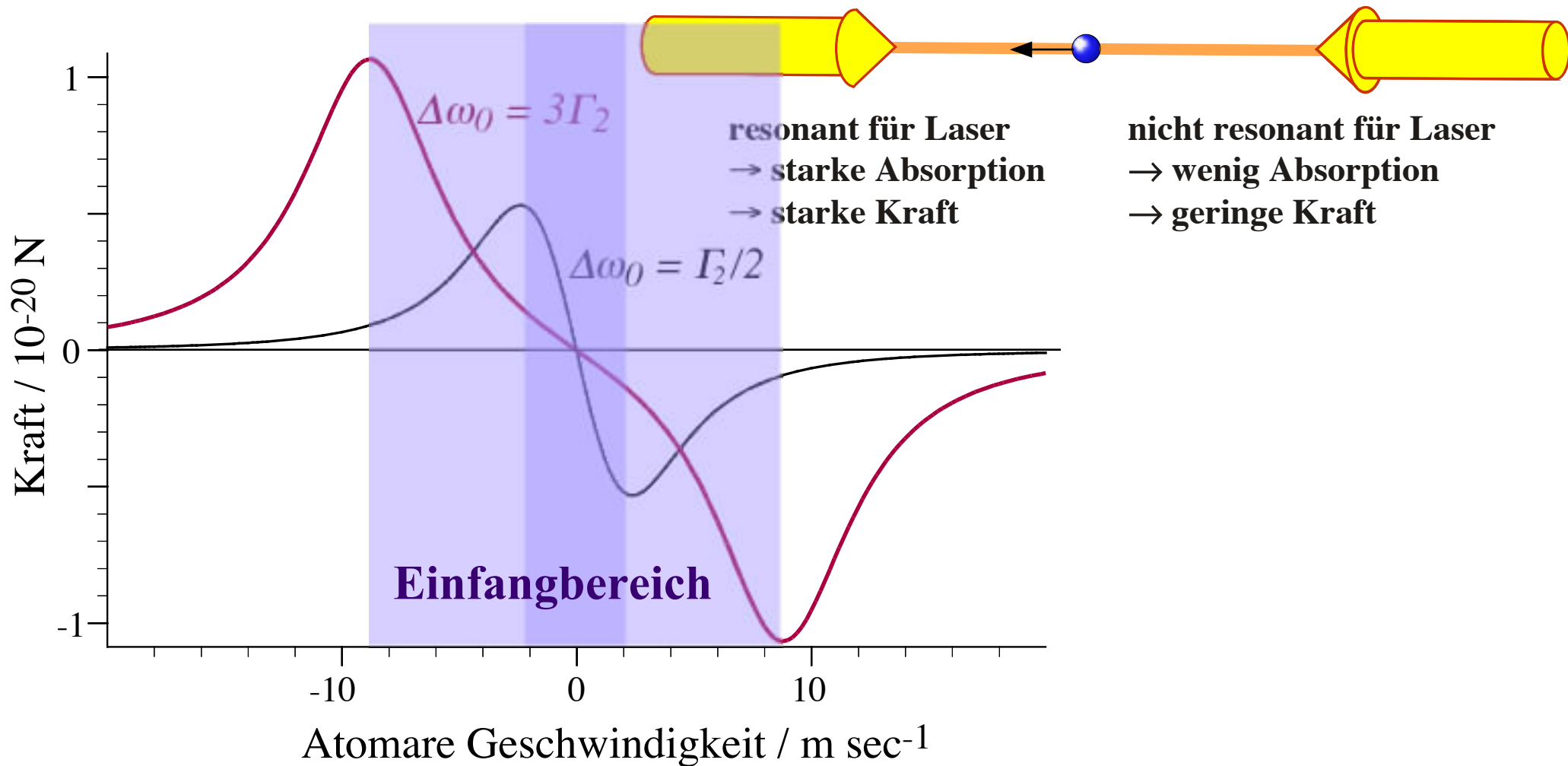
rotver-  
stimmt



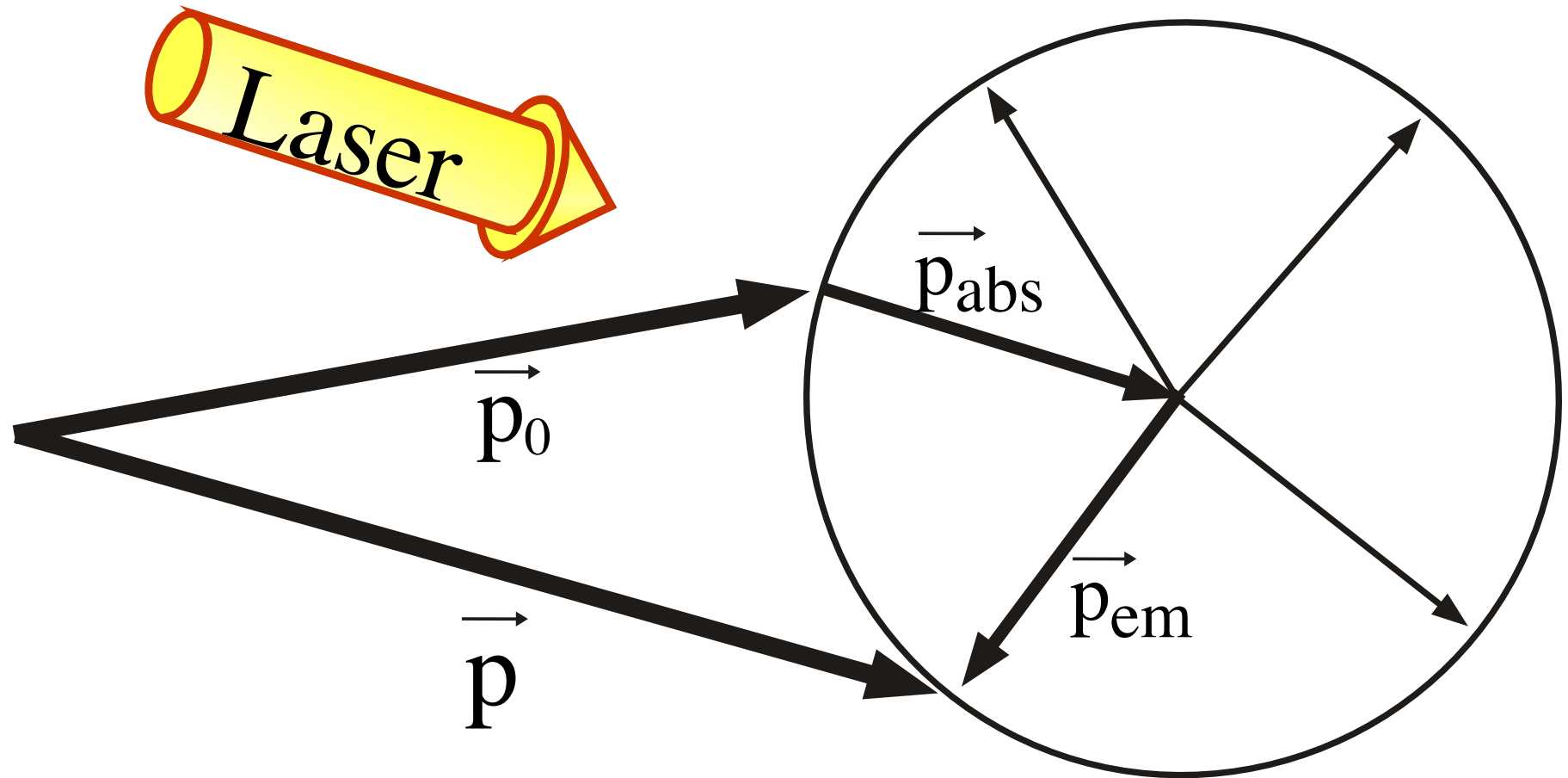


# Optische Molasse

$$F_{om} = \hbar k \Gamma_1 \omega_x^2 \left( \frac{1}{\Gamma_1^2 + 4(\Delta\omega_0 + kv)^2} - \frac{1}{\Gamma_1^2 + 4(\Delta\omega_0 - kv)^2} \right)$$



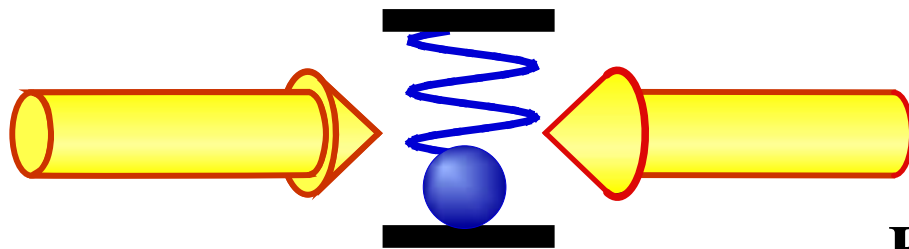
# Geschwindigkeitsdiffusion



# Historische Entwicklung

1. Vorschlag : *T.W. Hänsch and A.L. Schawlow ( 1975)*  
*D. Wineland and H. Dehmelt, (1975).*

1. Experiment : *S. Chu, L. Hollberg, J.E. Bjorkholm, A. Cable, and A. Ashkin (1985).*



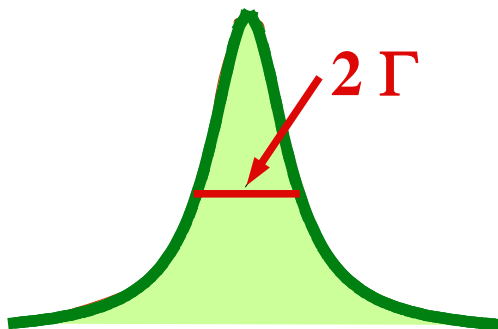
**Minimal erreichbare Temperatur :**

$$T_{\min} = \frac{\hbar\Gamma}{2k_B} = 240 \mu\text{K} \text{ (for Na)}$$

**Erreichte Temperatur:** Chu 85    240  $\mu\text{K}$

Lett 88    43  $\mu\text{K}$

Chu 92    12 fK

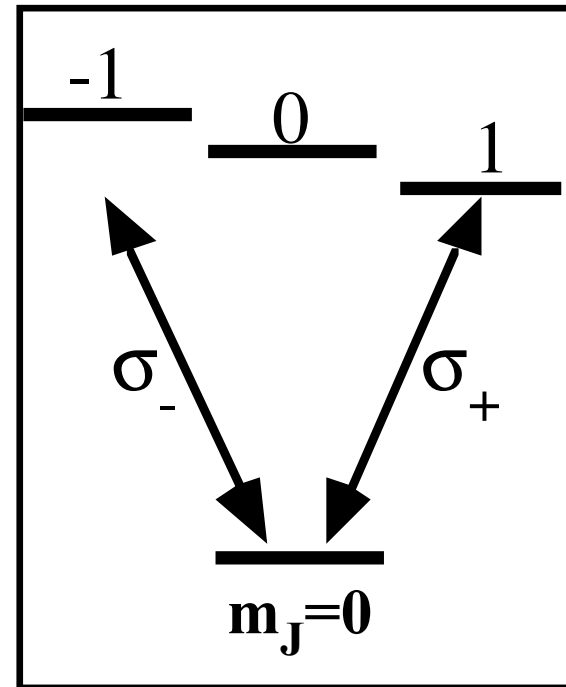
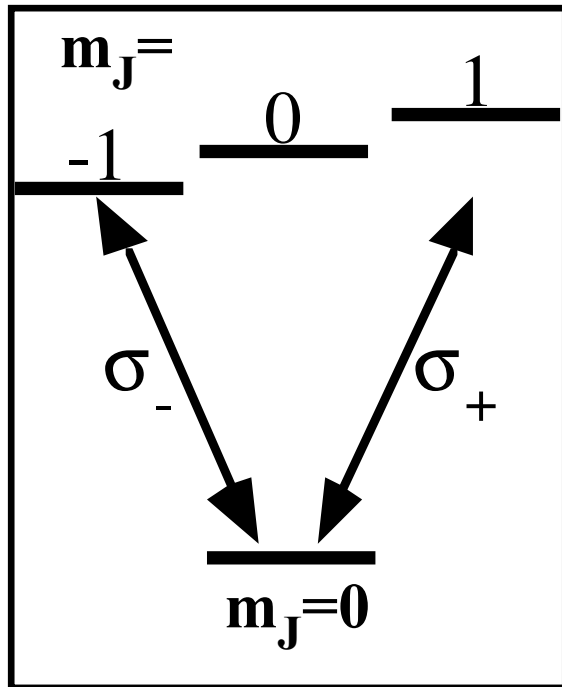
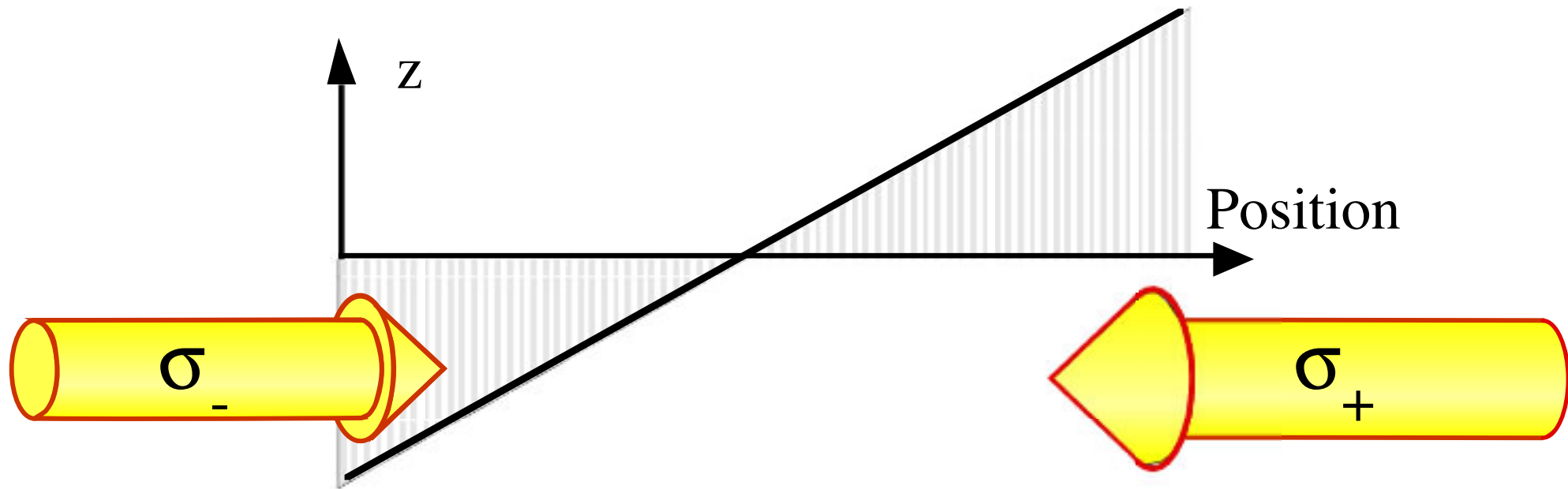


**außerdem:** - Speicherzeit zu lang  
- Empfindlichkeit auf Imperfektionen zu niedrig

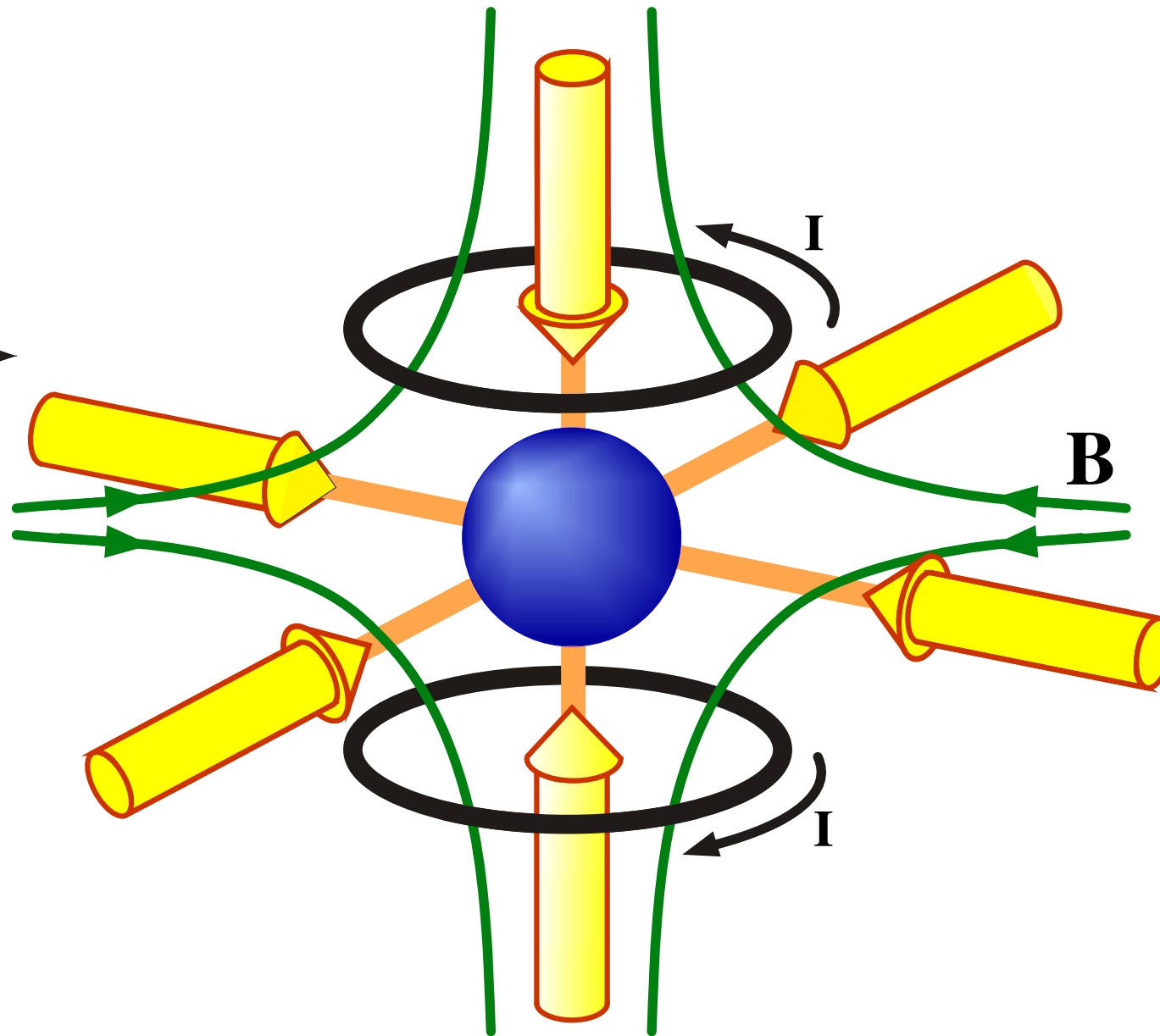
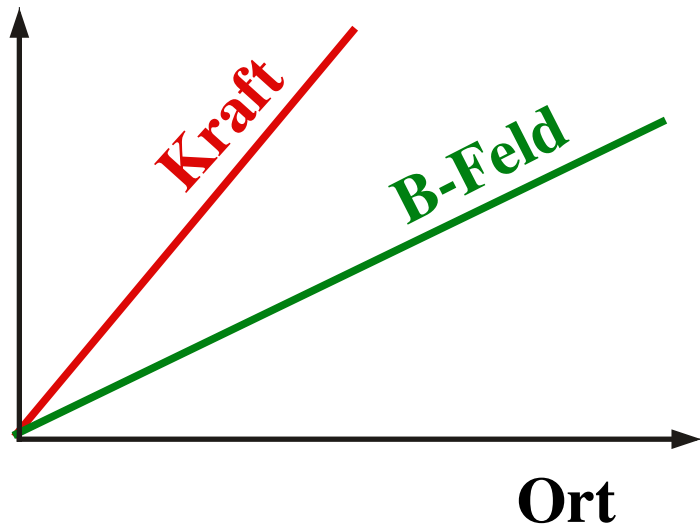
**" In virtually all respects, the optical cooling of atoms has worked far better than anticipated; the work is a rare but spectacular violation of Murphy's law "**

*S. Chu, Science 253, 861 (1991)*

# Magnetfeld-Gradient



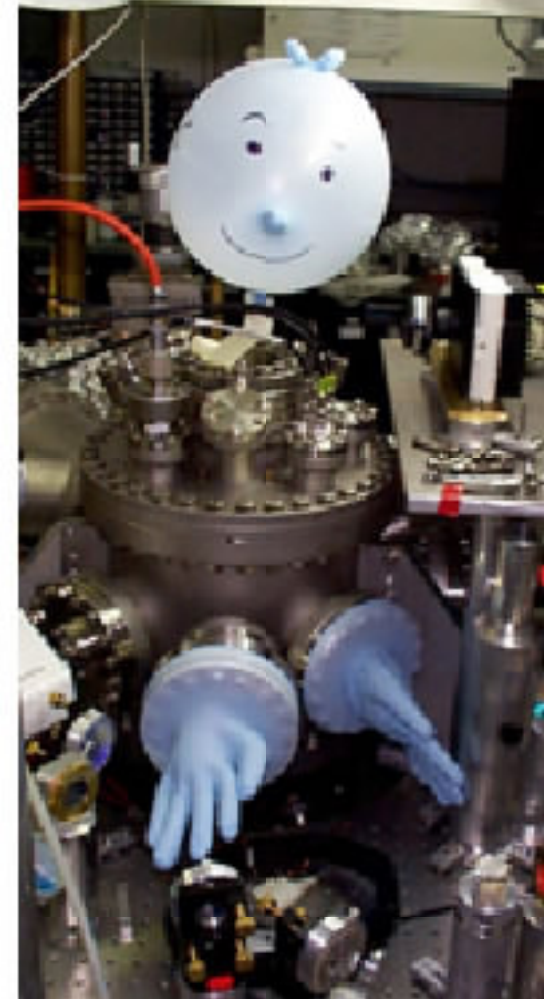
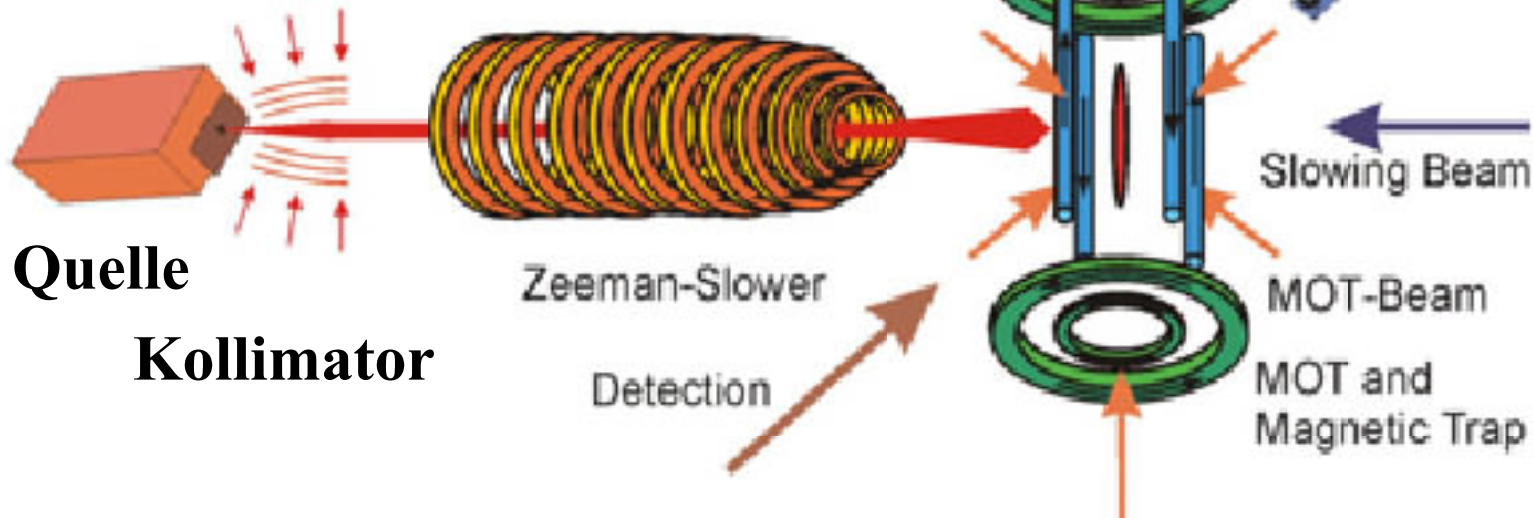
# Magneto-Optische Fallen



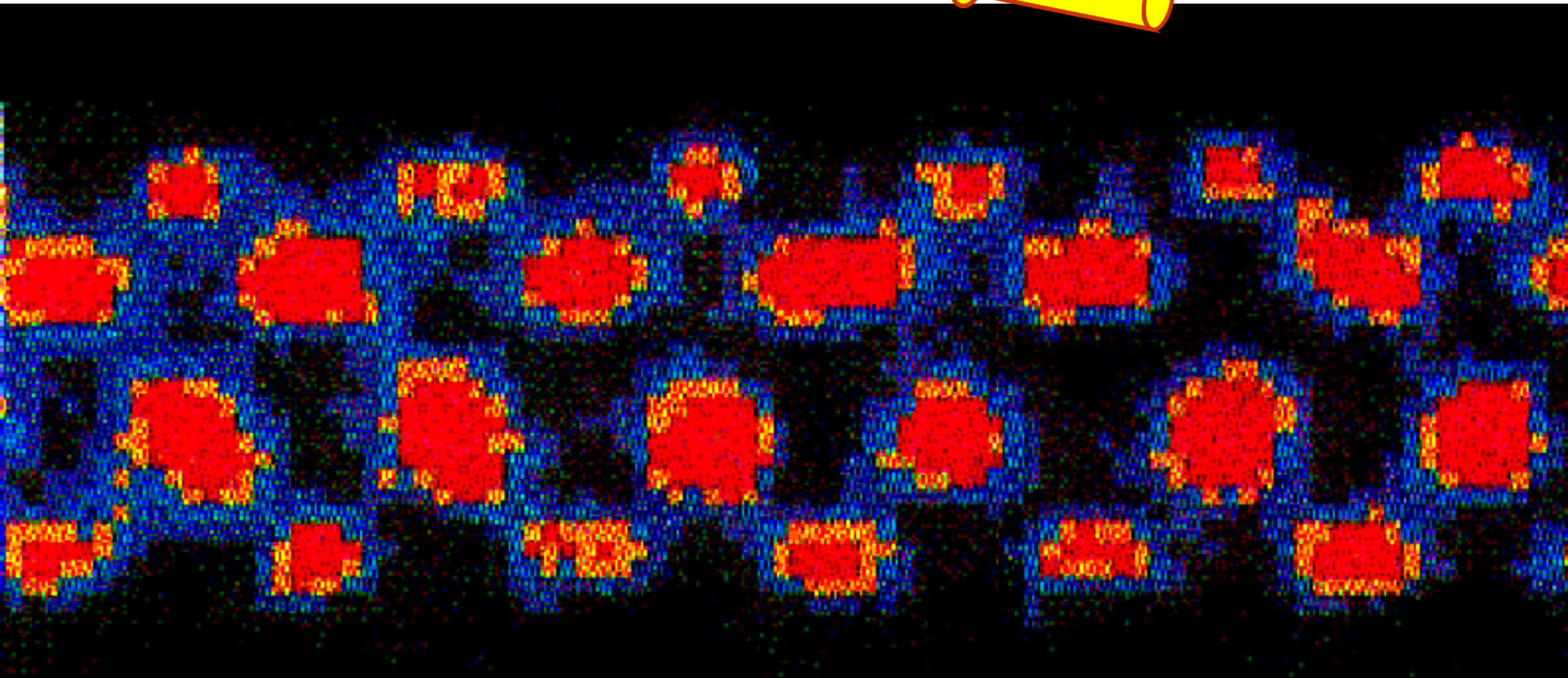
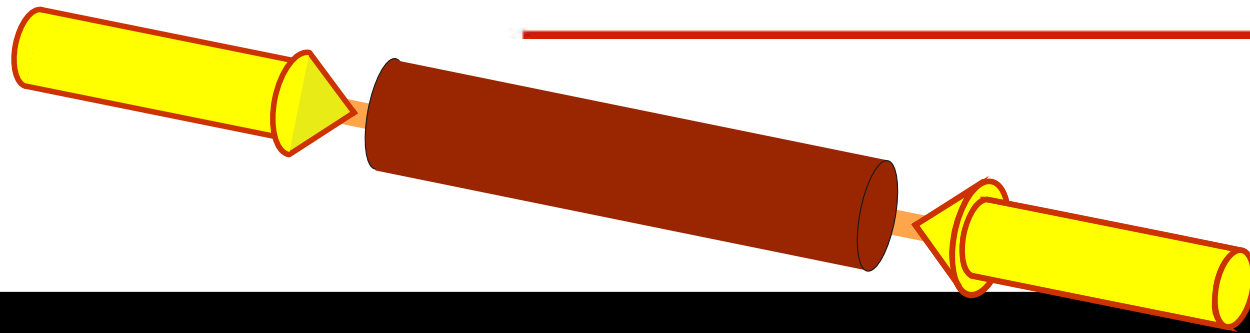
sollen Atome kühlen  
und festhalten

Dazu muss die Kraft eine  
ortsabhängige rücktrei-  
bende Komponente  
enthalten

# Abbremsen + Einfangen



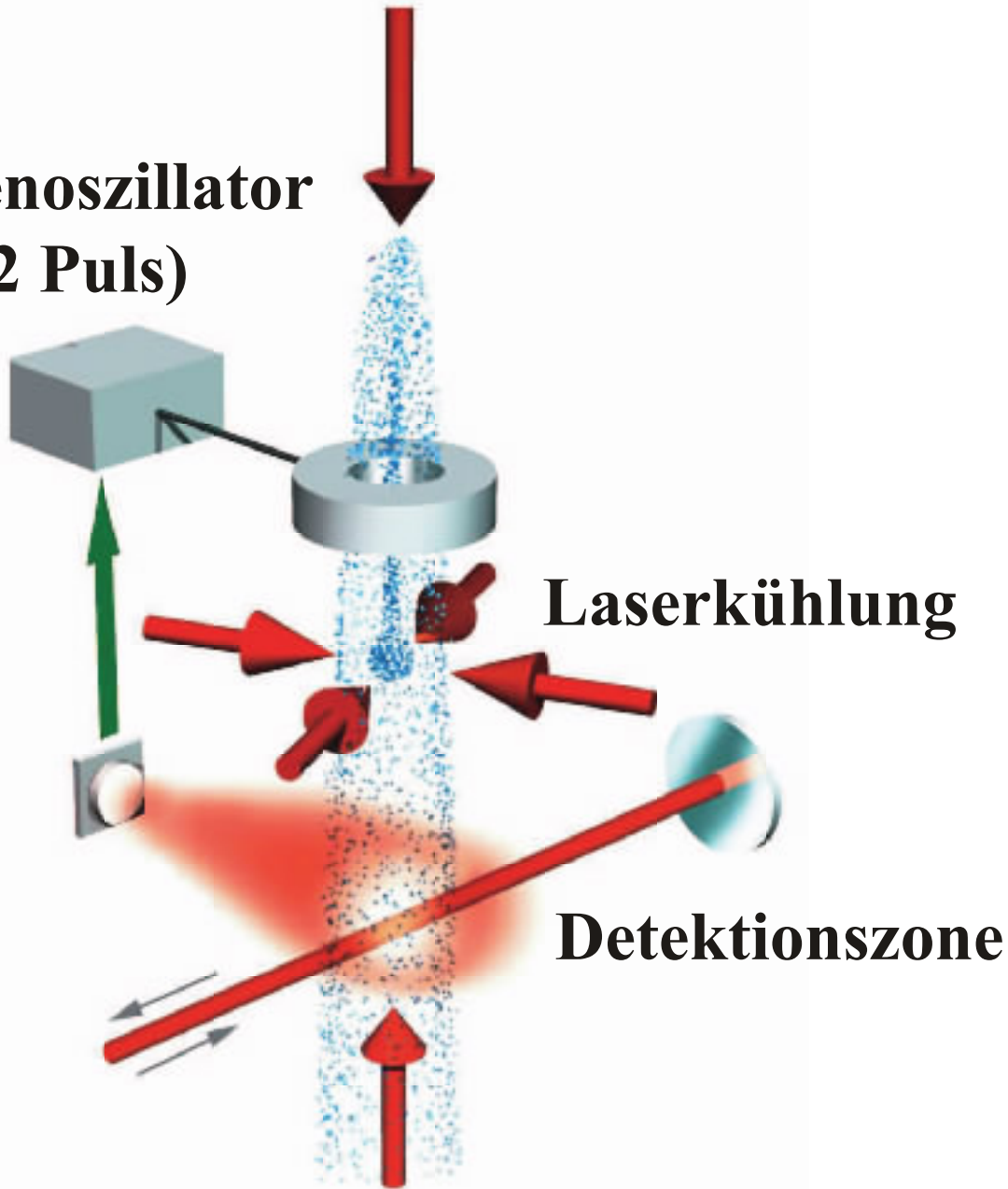
# lonenkristalle



50  $\mu\text{m}$

# Atomarer Springbrunnen

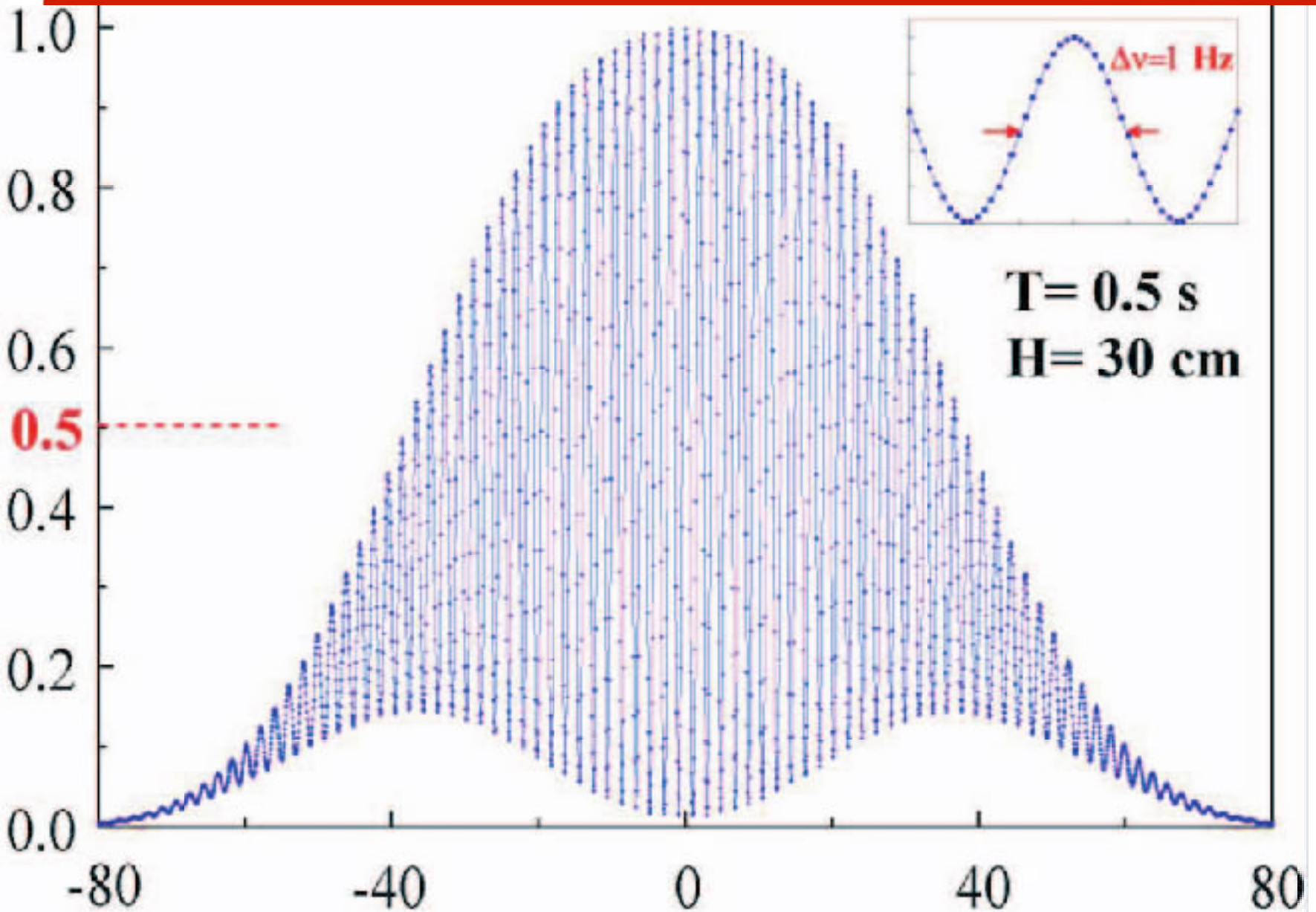
Mikrowellenoszillator  
(  $\pi/2$  Puls)





# Atomarer Springbrunnen

Besetzung des angeregten Zustandes

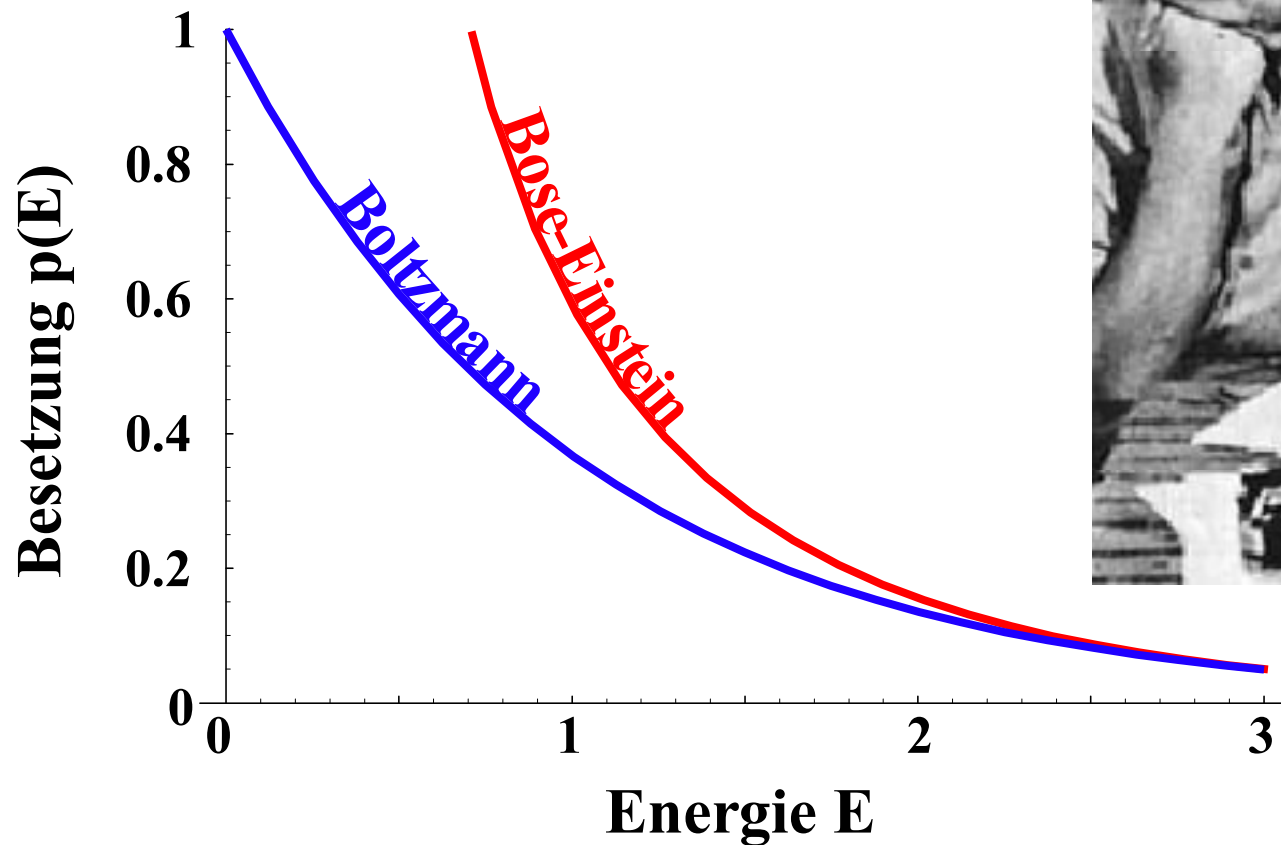


Verstimmung  $\delta$  / Hz

# Bose-Einstein Statistik

nicht-unterscheidbare Bosonen

$$p_i = \frac{1}{e^{\frac{\epsilon - \mu}{k_B T}} - 1}$$

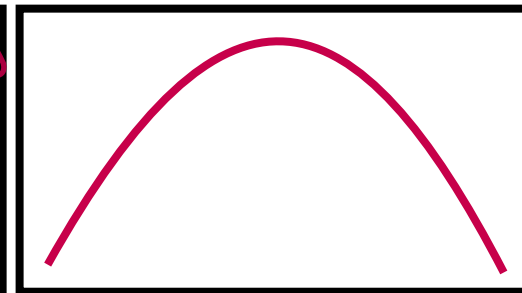
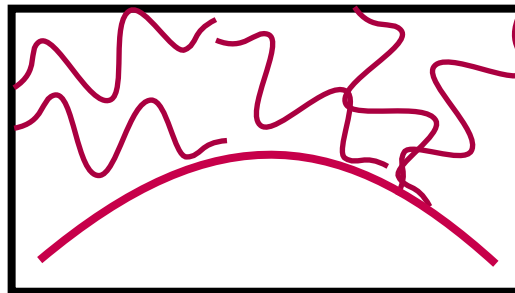
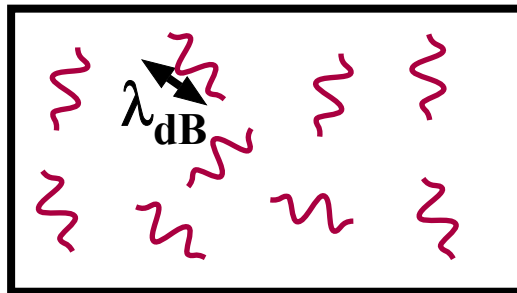
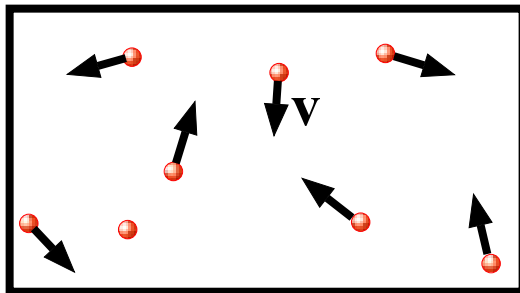


# Bose-Einstein Kondensation

Hohe Temperatur    Tiefe Temperatur

$T_{\text{crit}} : l_{\text{dB}} \sim d$

$T=0$



thermische  
Geschwindigkeit

$v$

“Kugeln”

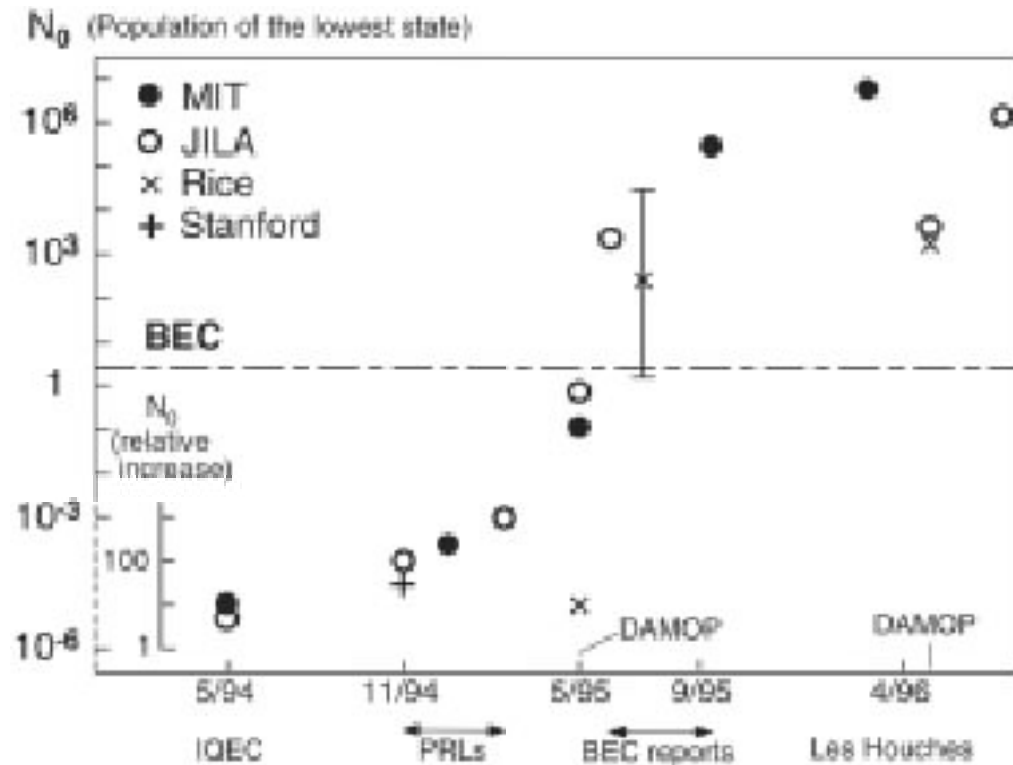
“Wellenpakete”  
de Broglie  
Wellenlänge

$$l_{\text{dB}} = \frac{h}{mv} \propto \frac{1}{\sqrt{T}}$$

Bose-Einstein  
Kondensation

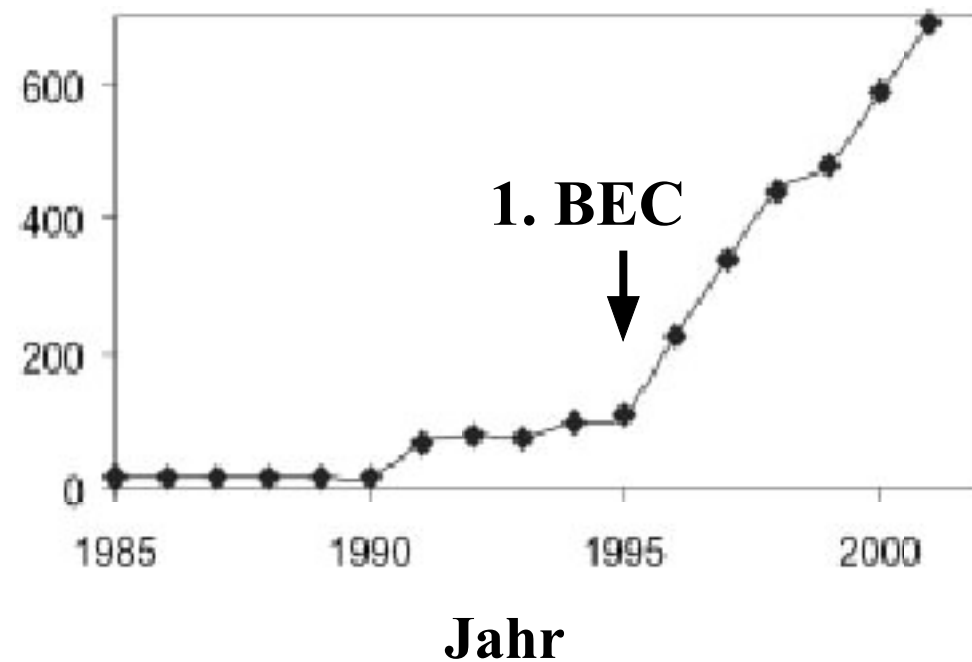
Reines  
Bose-Einstein  
Kondensat  
Makroskopischer  
Quantenzustand

# Bose-Einstein Kondensation

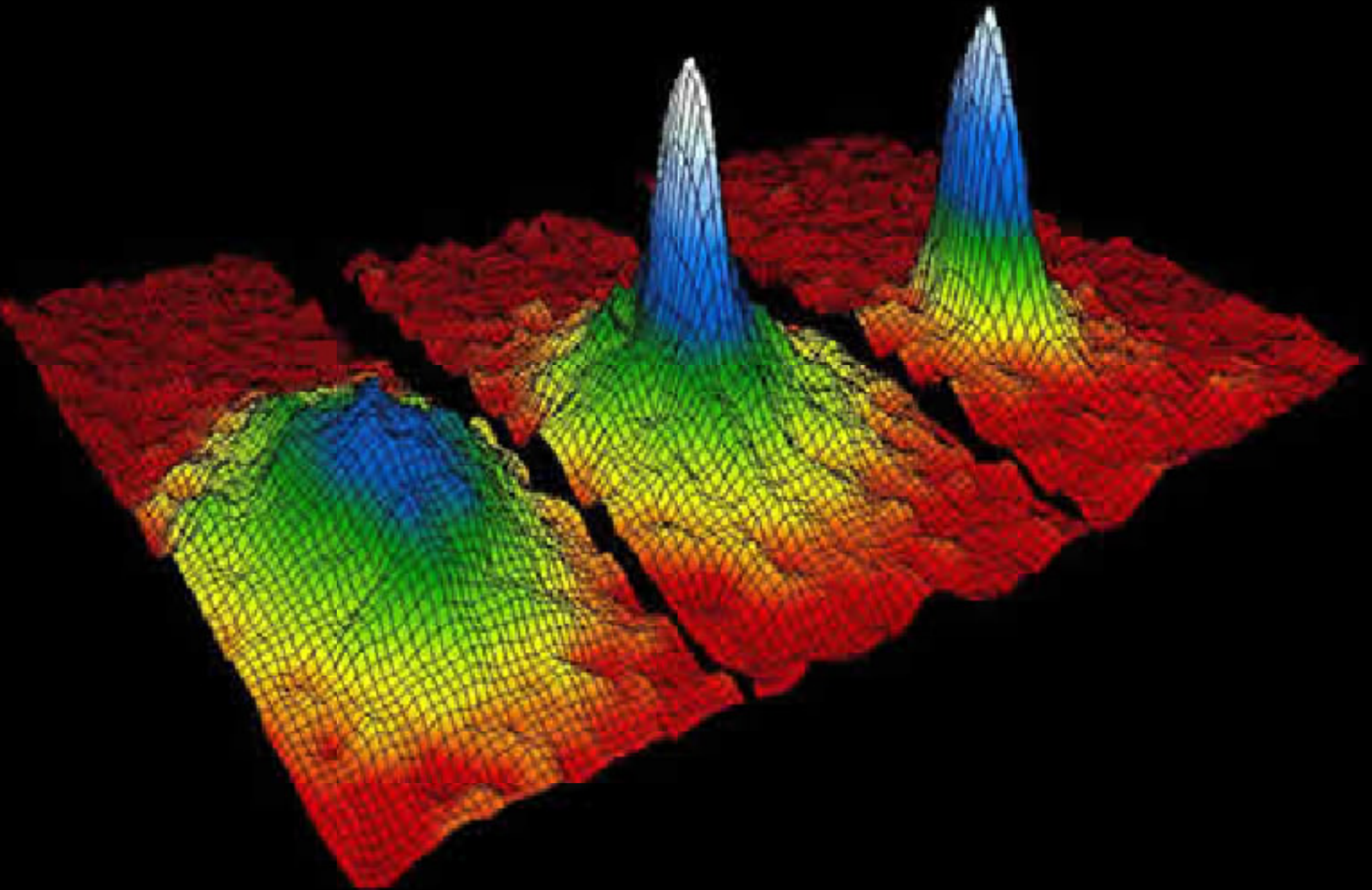


Publikationen pro Jahr

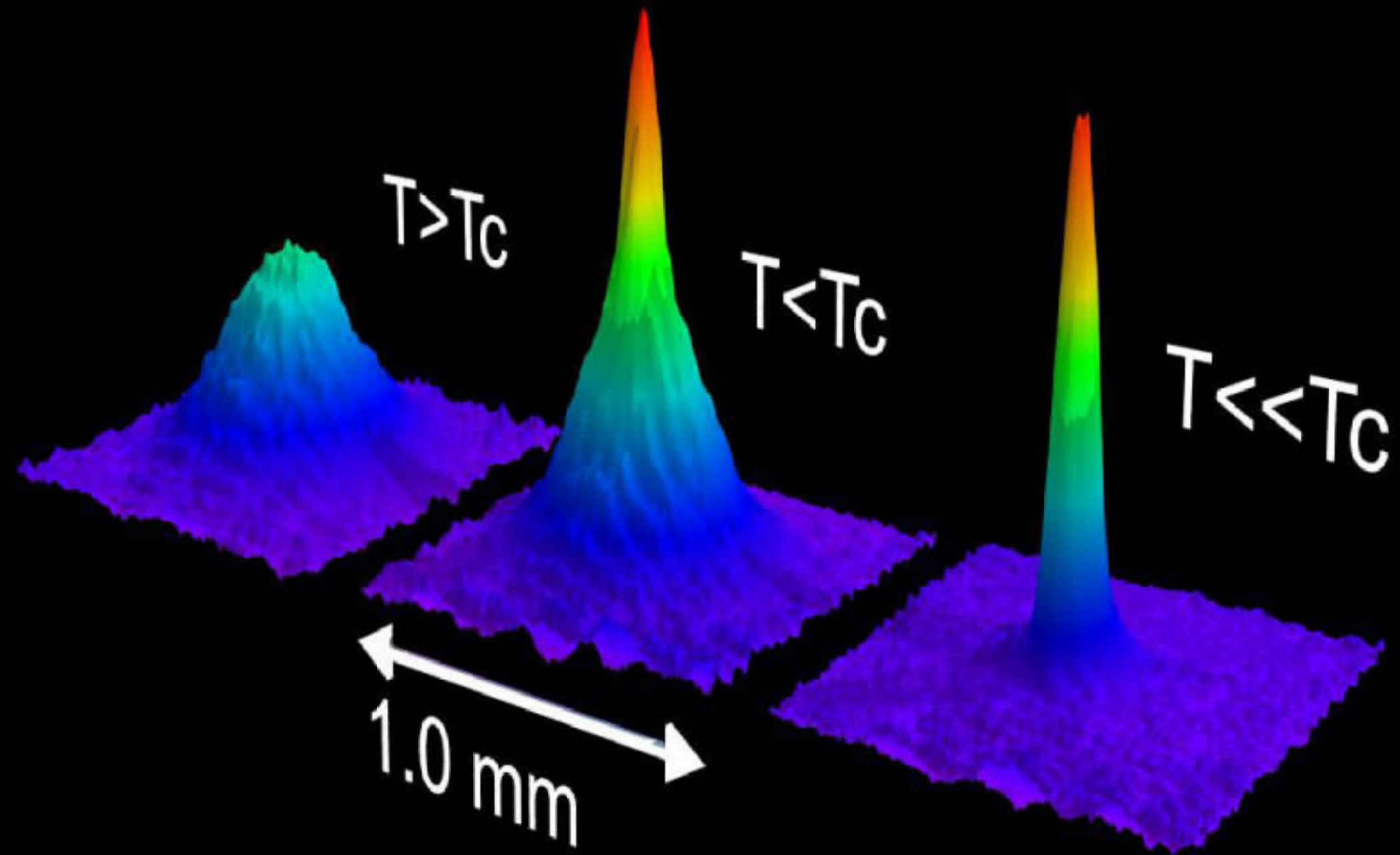
Anzahl Publikationen pro Jahr zu "Bose" und "Einstein"



# Bose-Einstein Kondensation



# Bose-Einstein Kondensation



# Atomlaser

VOLUME 67, NUMBER 15

PHYSICAL REVIEW LETTERS

12 AUGUST 1991

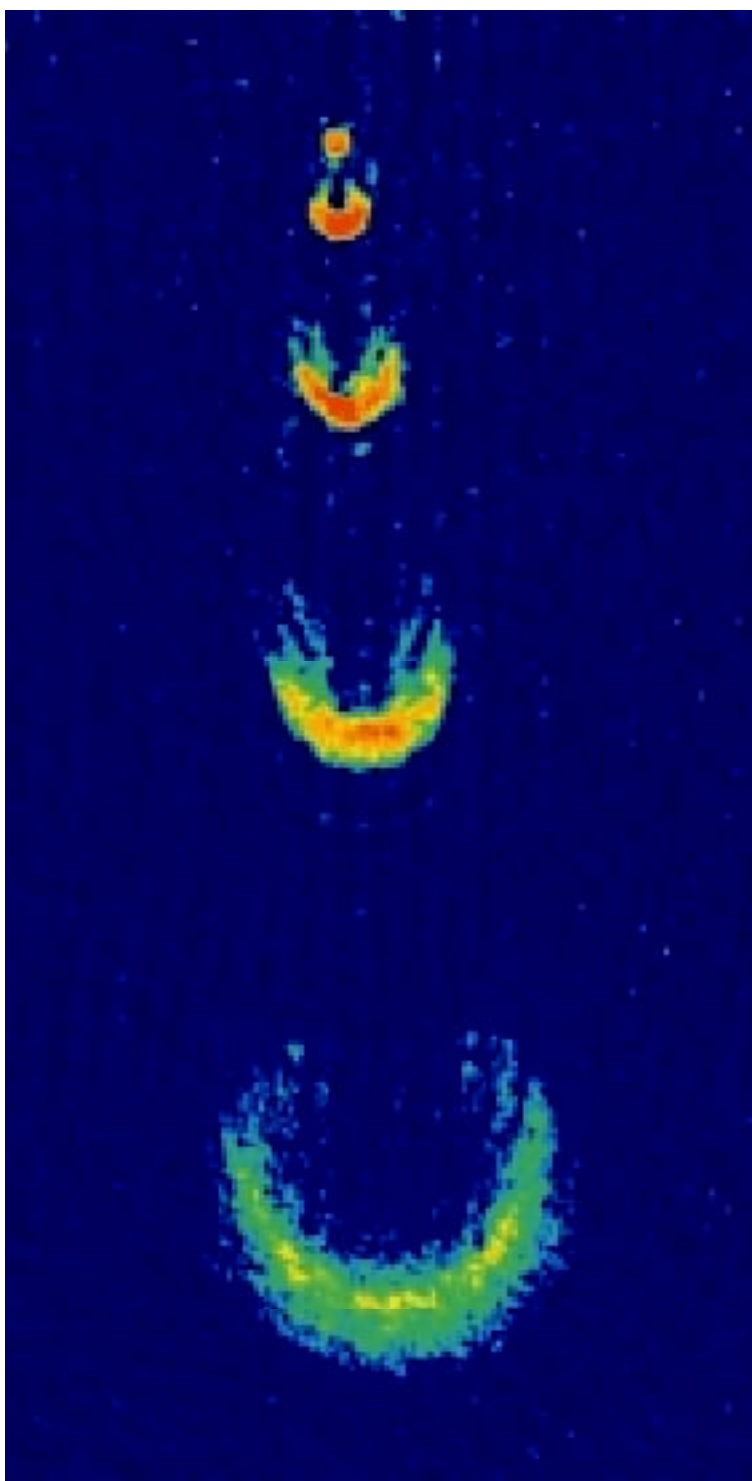
## Atom Laser with a cw Output Coupler

Immanuel Bloch, Theodor W. Hänsch, and Tilman Esslinger

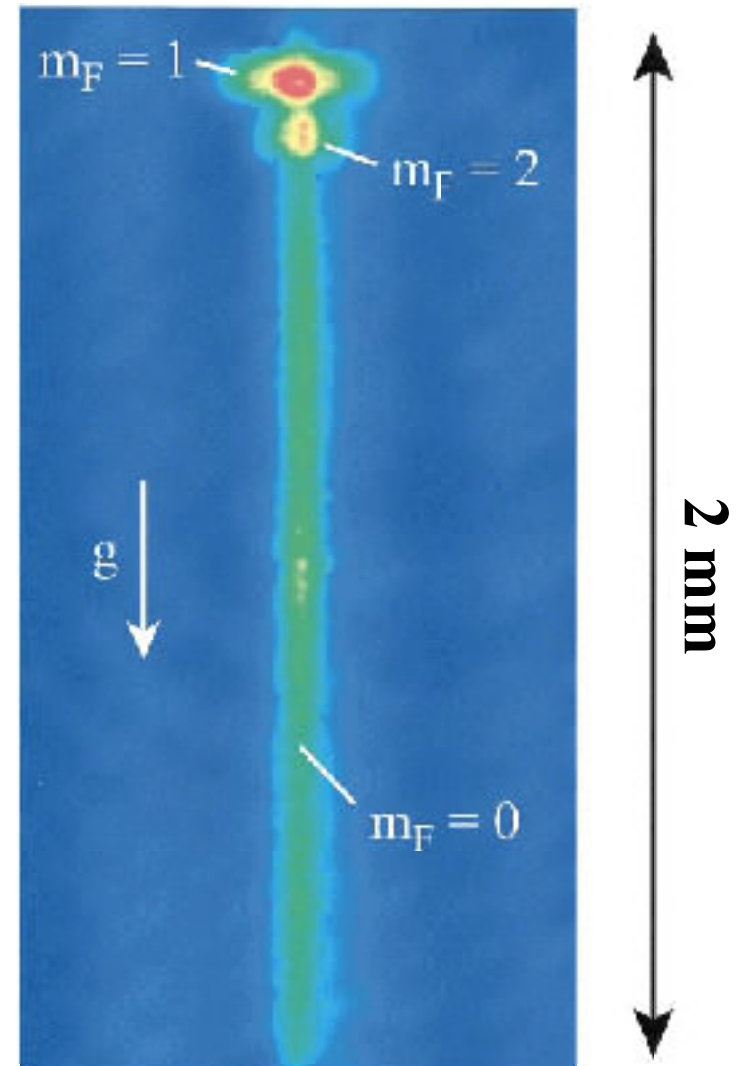
*Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany*

*and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*

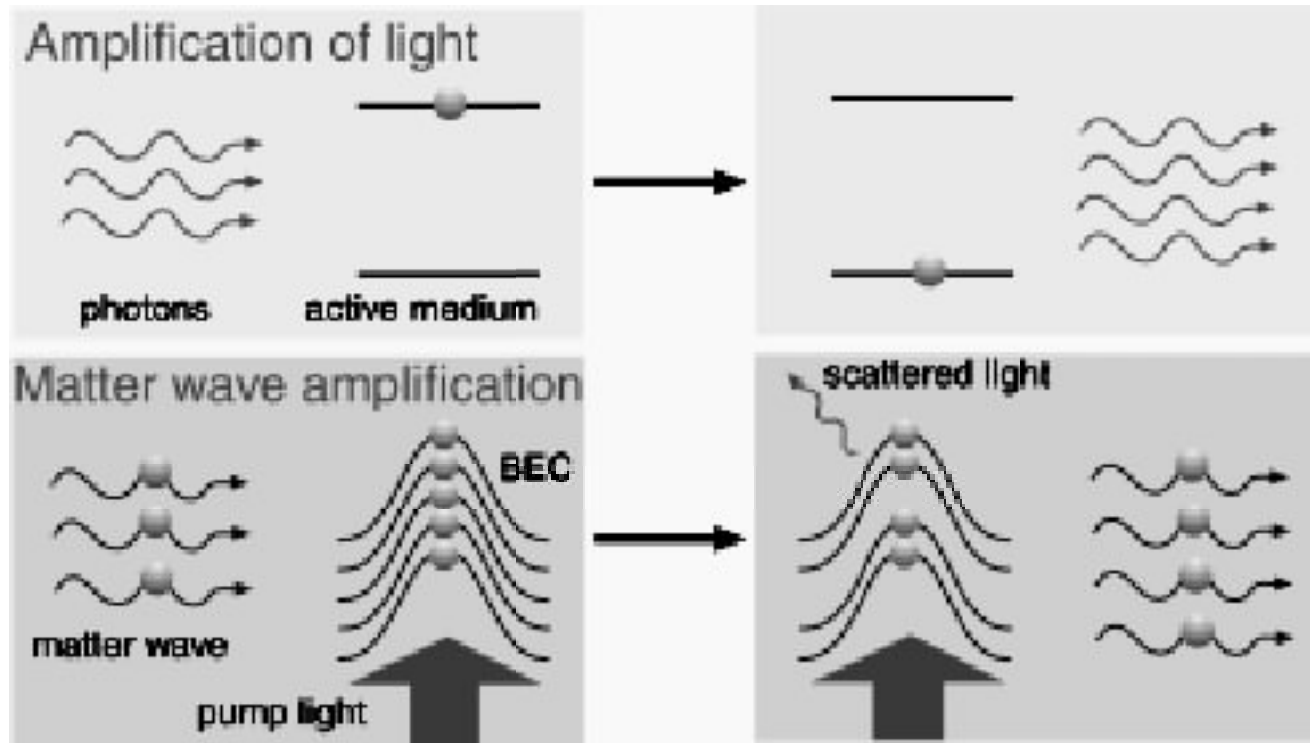
(Received 3 December 1998)



gepulster Atomlaser mit 200 Hz



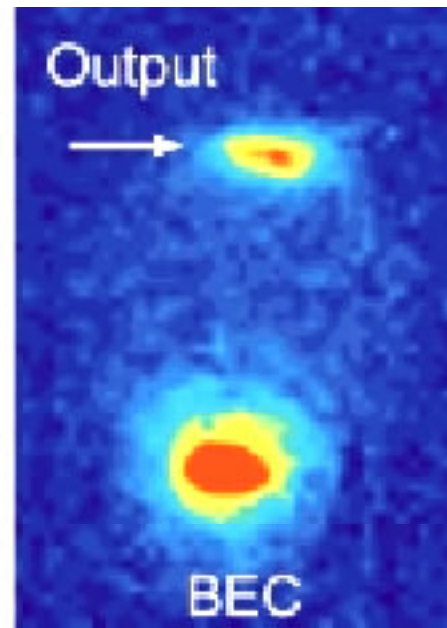
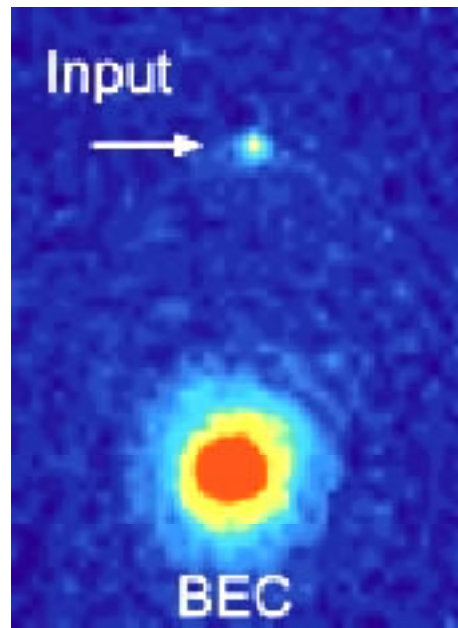
# Materie-Verstärker



“Input” wurde ohne  
Laser durch das  
BEC geschickt



keine Verstärkung



Laser aktiviert  
Verstärkung



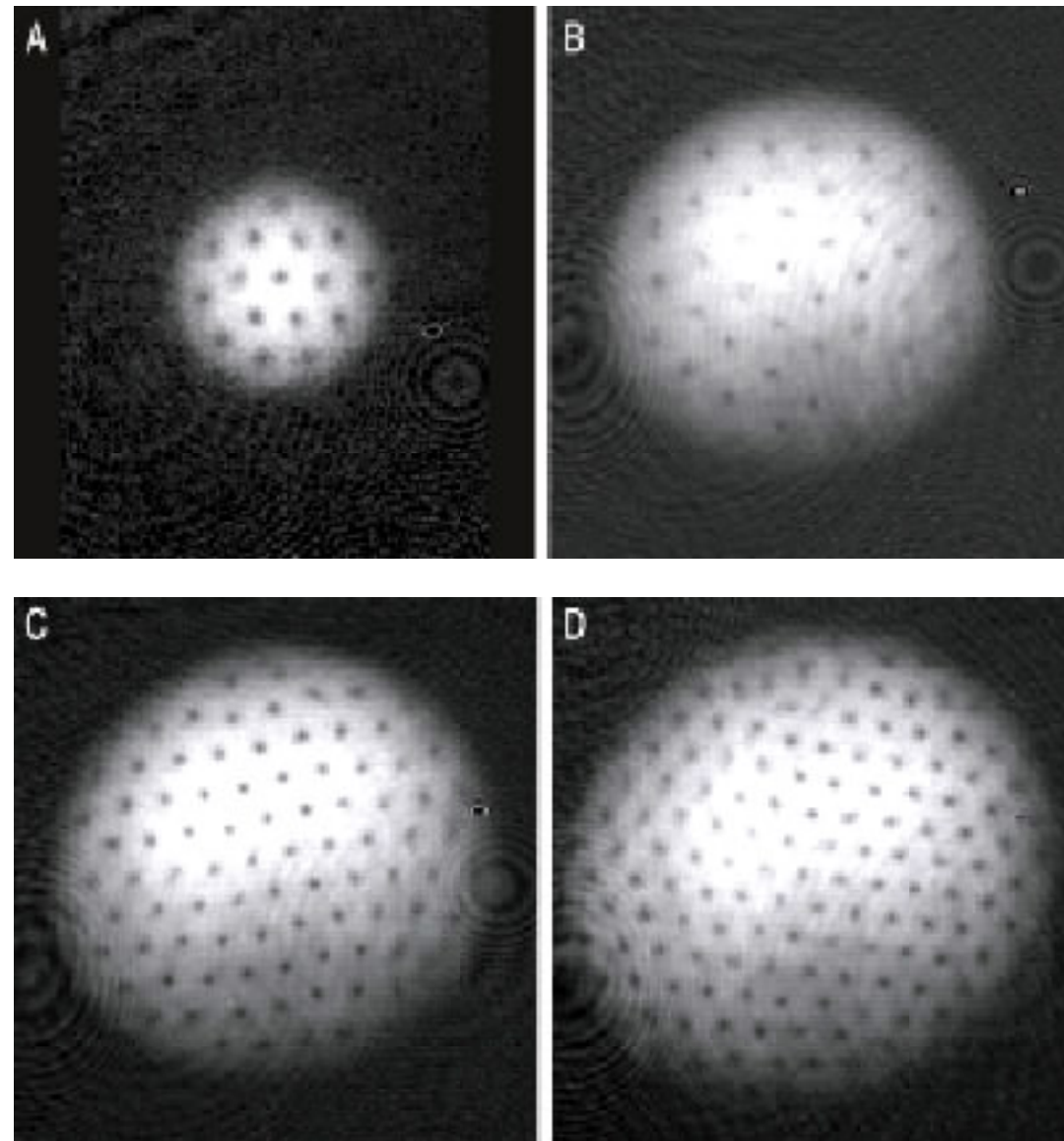
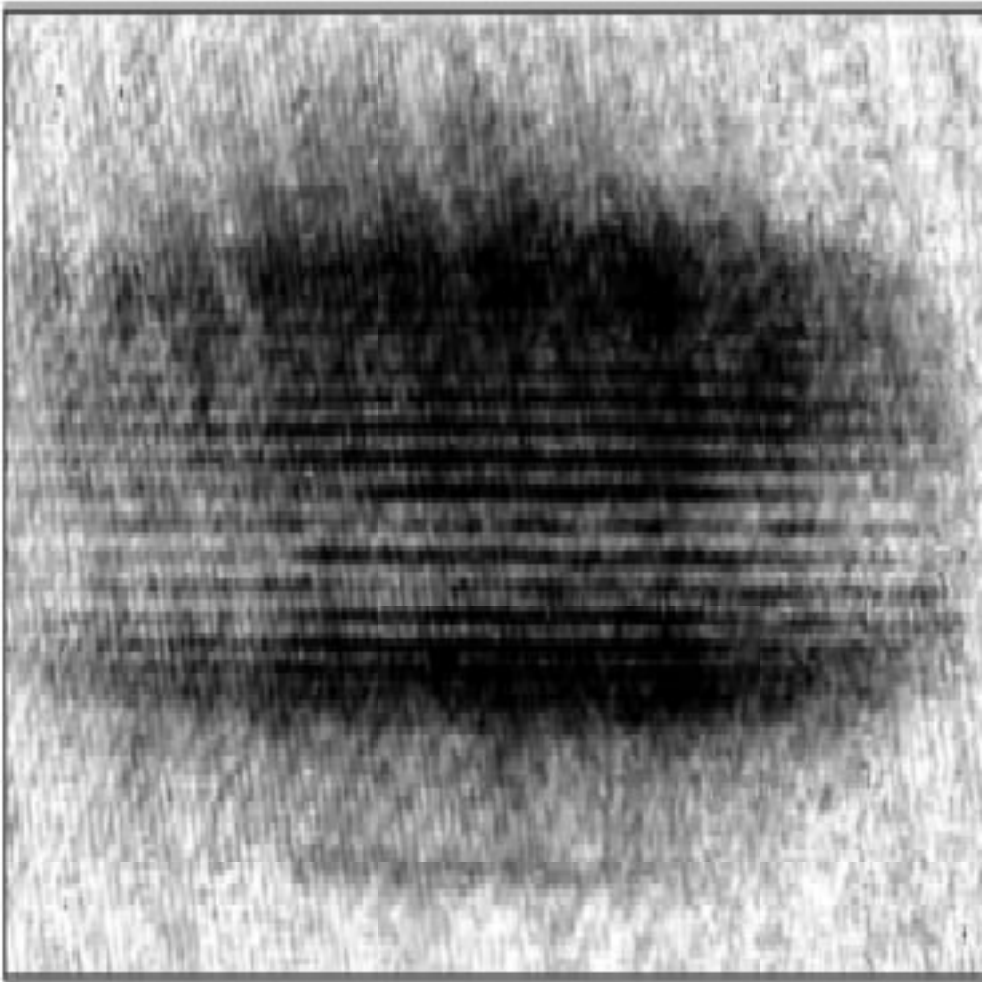
Verstärkung 10-100



# Interferenzeffekte

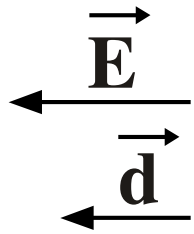
Interferenz 2er BEC's

“Flusslinien” in rotierenden BEC's



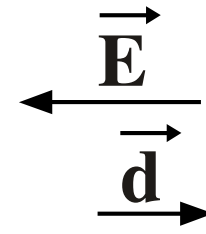
# Induzierter Dipol

langsame Anregung  
Dipol in Phase

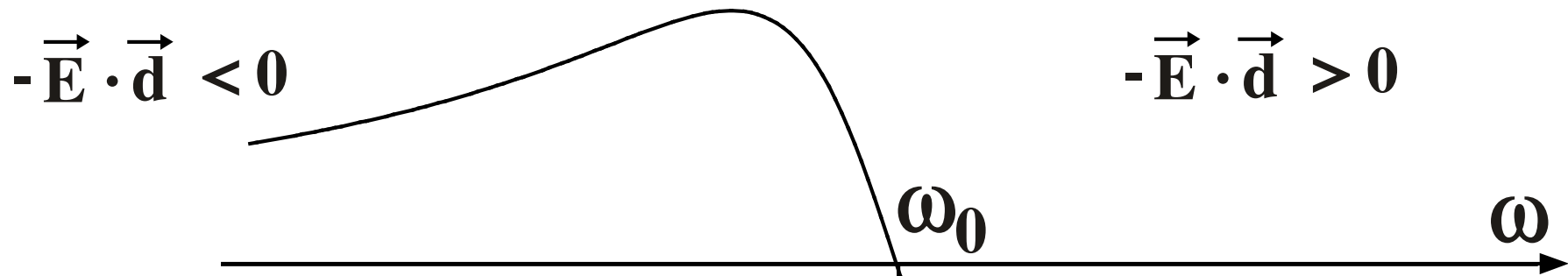


$$-\vec{E} \cdot \vec{d} < 0$$

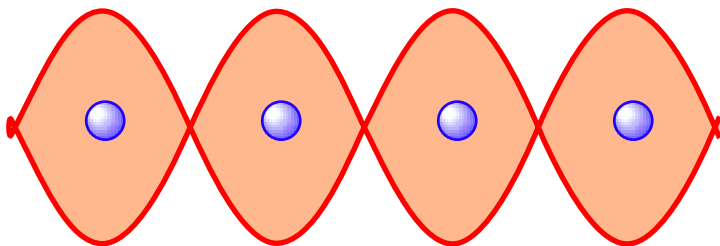
schnelle Anregung  
Dipol außer Phase



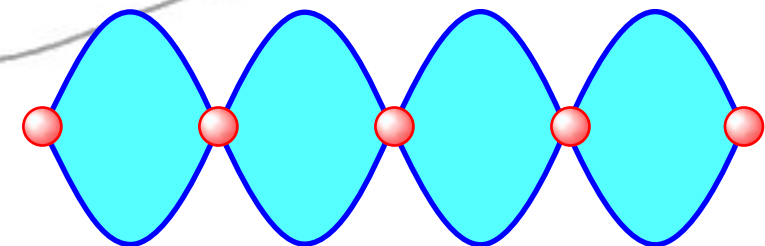
$$-\vec{E} \cdot \vec{d} > 0$$



Kraft zum hohen Feld

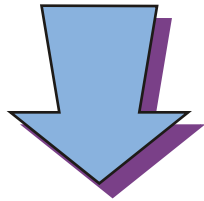


Kraft zum niedrigen Feld

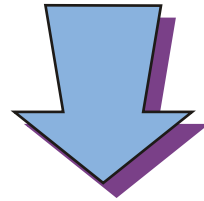


# Optische Kräfte

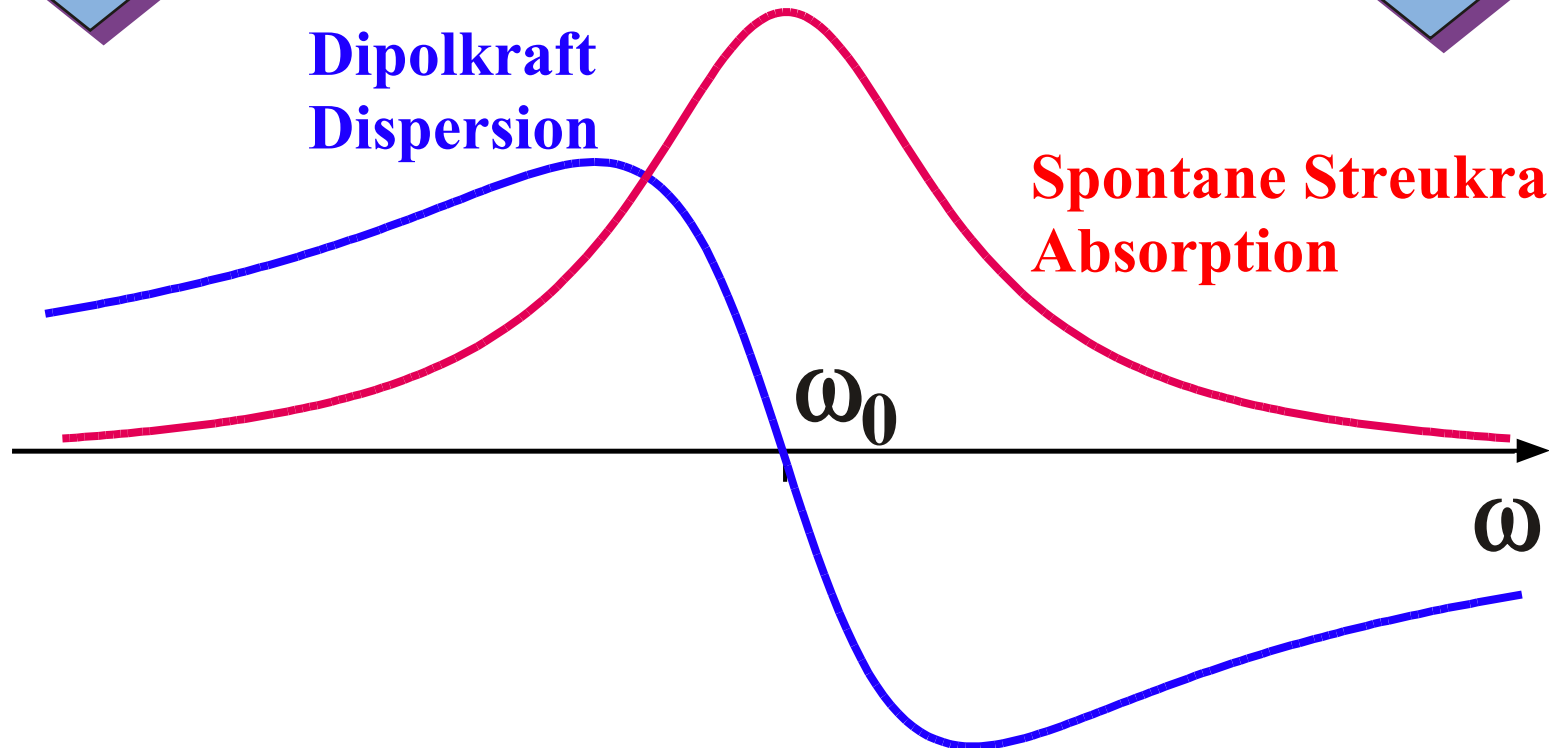
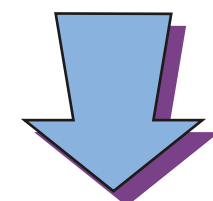
Dipolkraft dominiert  
Richtung zum Feld-  
maximum



Spontane Streukraft  
dominiert

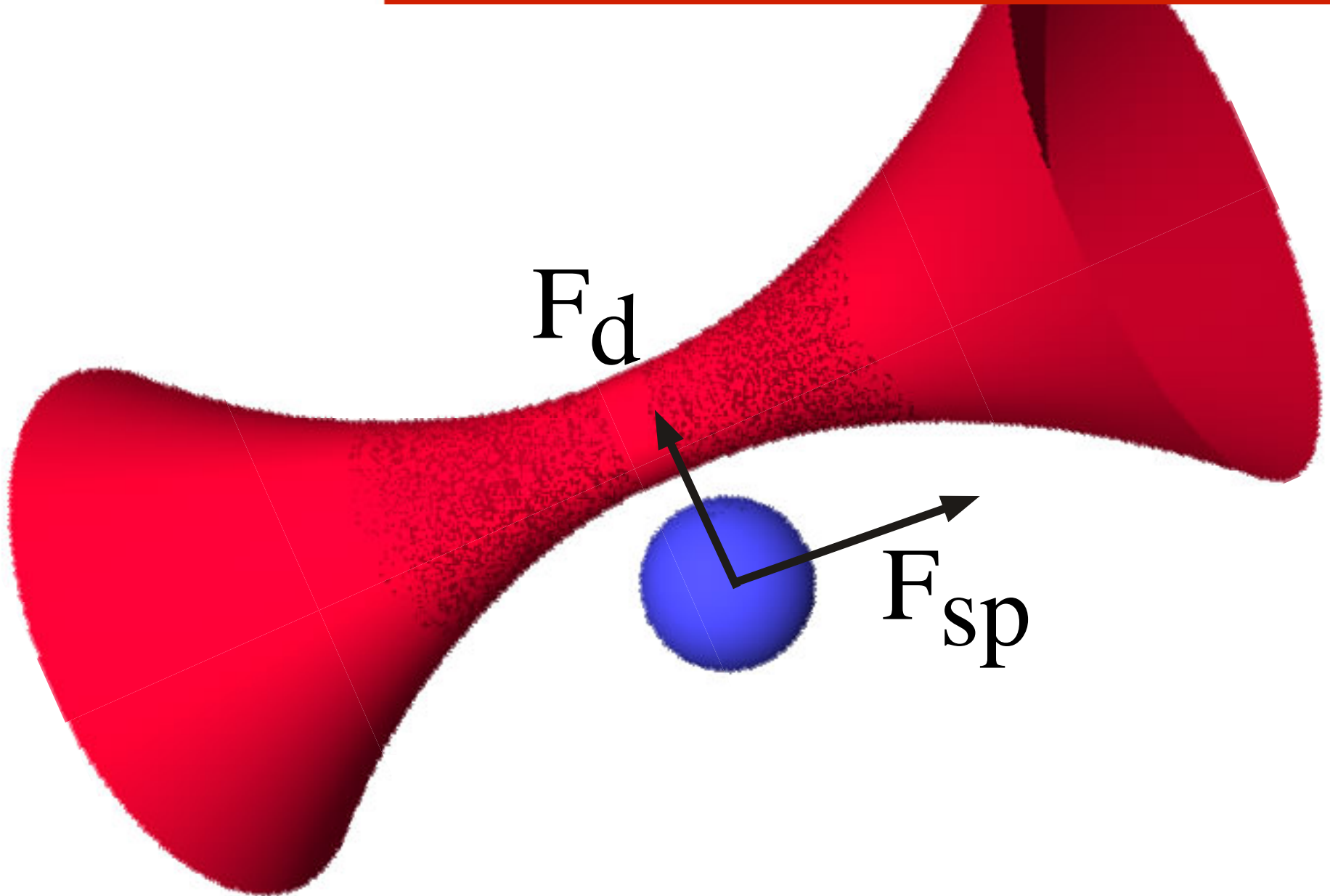


Dipolkraft dominiert  
Richtung zum Feld-  
minimum

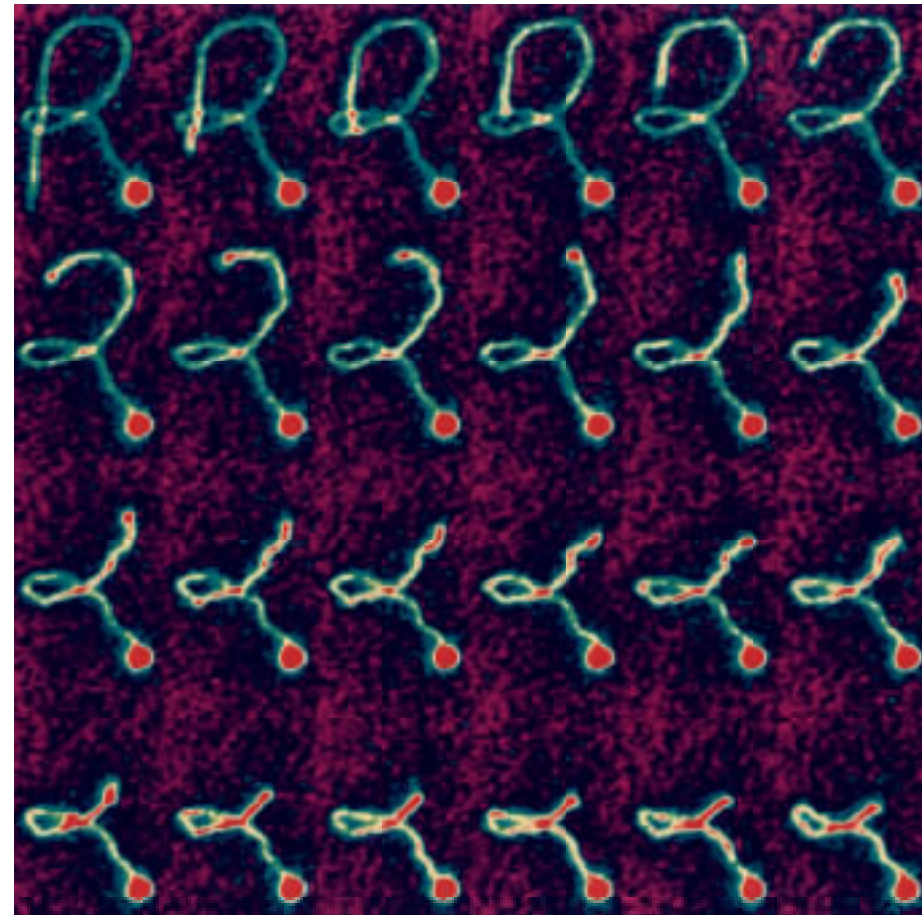
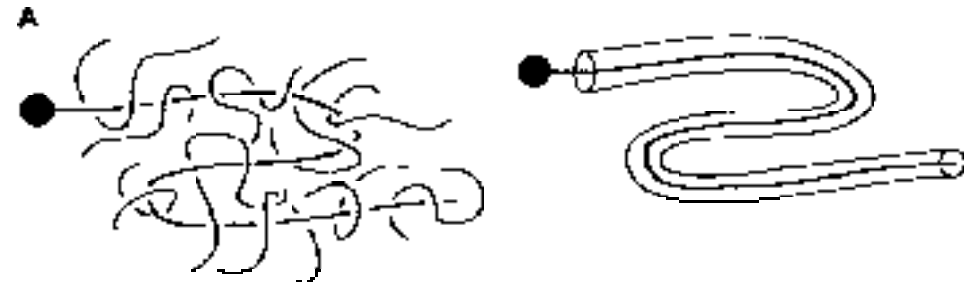
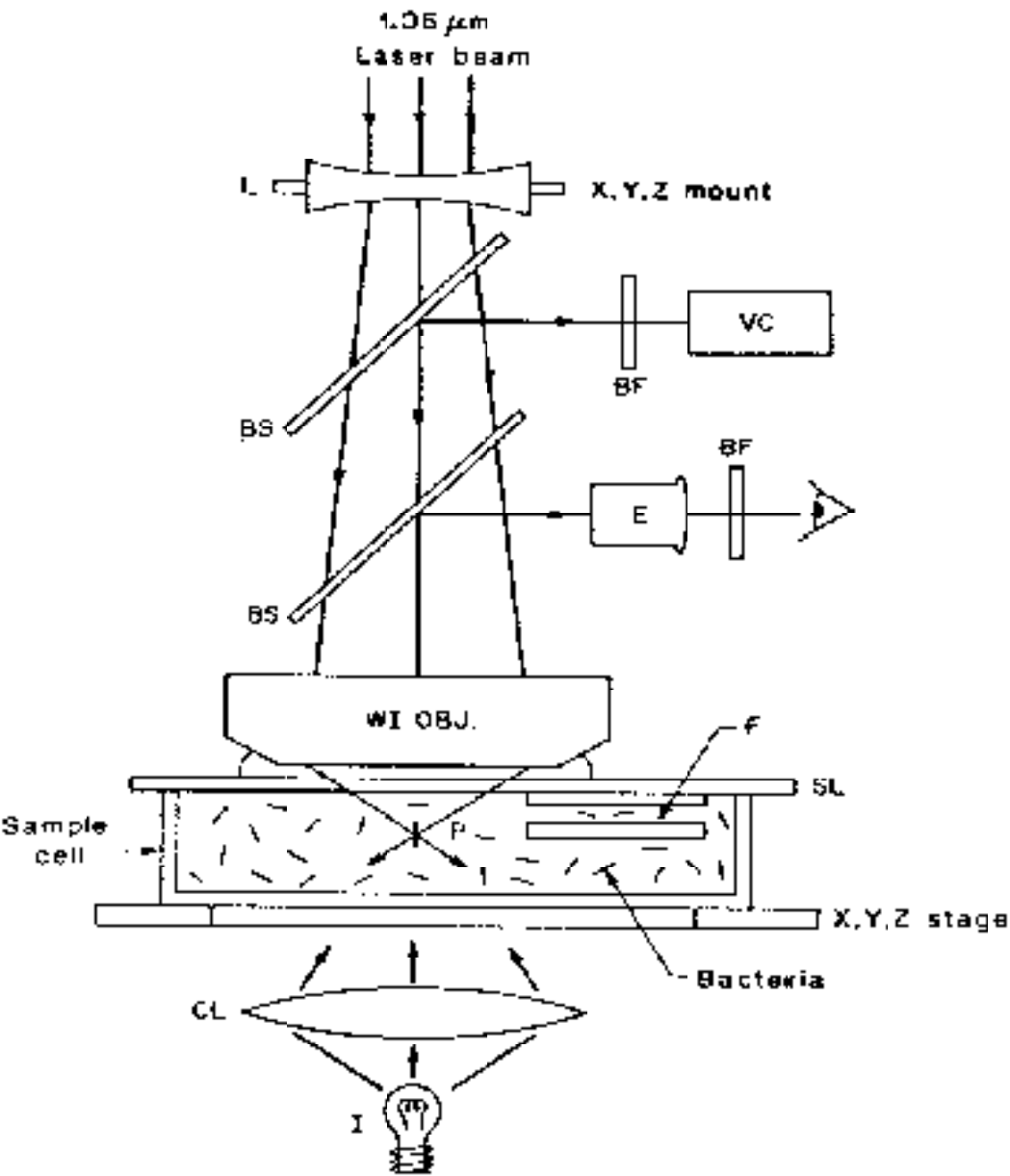


# Kraft beim Fokus

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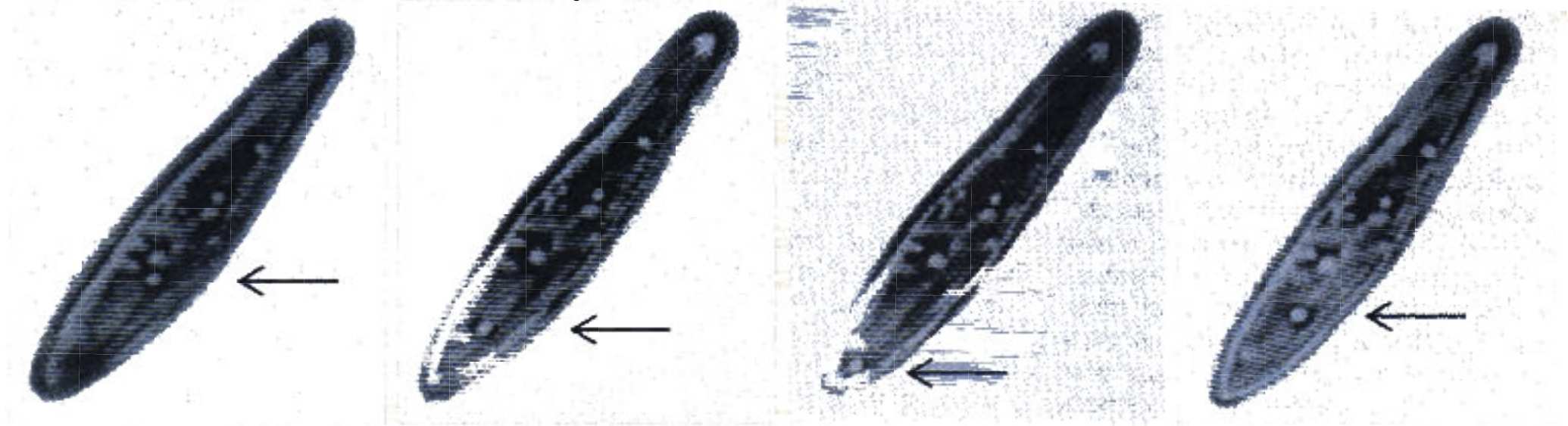
# Optische Pinzetten



S. Chu, *'The manipulation of neutral particles'*,  
Rev. Mod. Phys. 70, 685-706 (1998).

# Optische Pinzetten

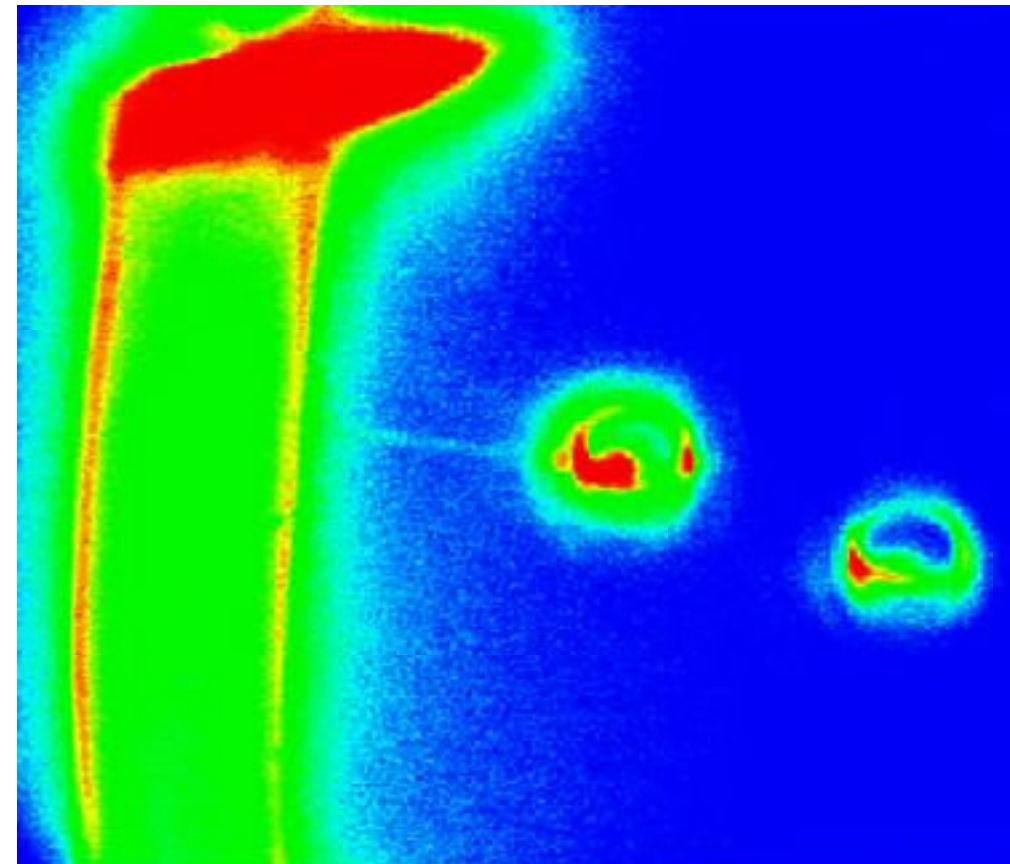
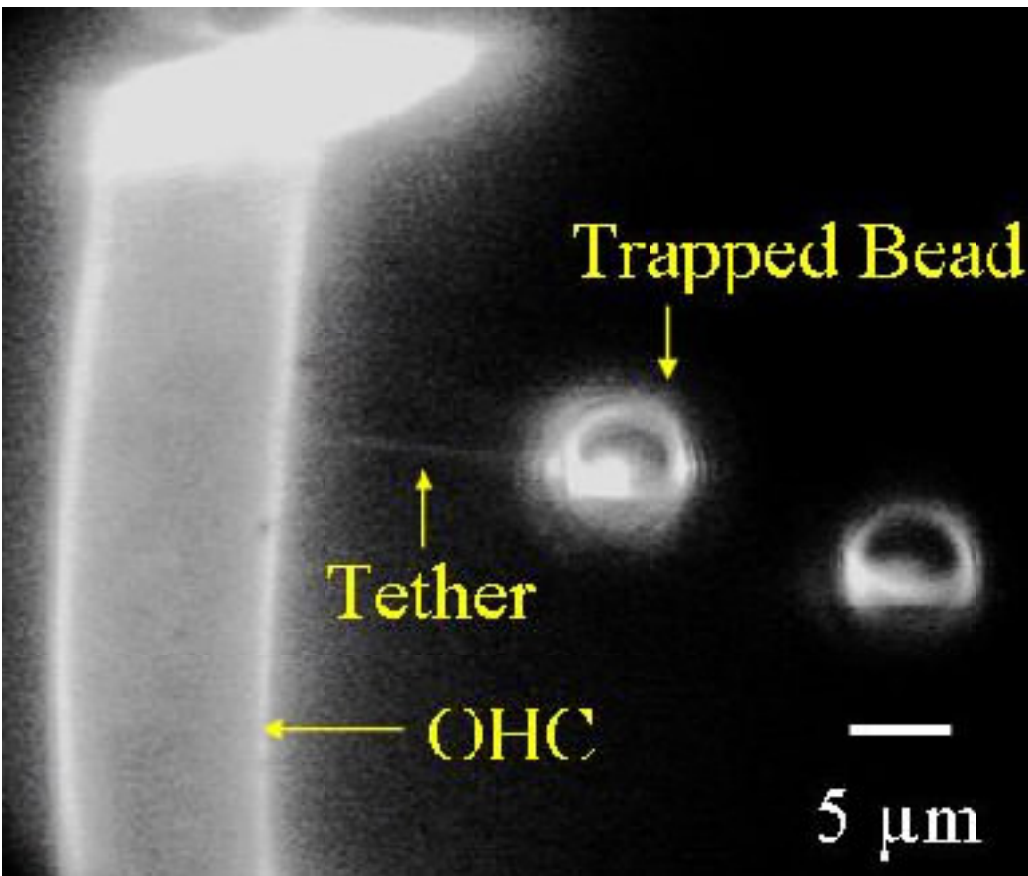
S. Chu, '*Laser trapping of neutral particles*',  
Scientific American February 1992, 49-54 (1992).



ORGANELLE inside a protozoan was dragged to one end of the cell using an optical tweezers, as shown in the first three

photographs. The image seen at the far right shows the organelle after it was released.

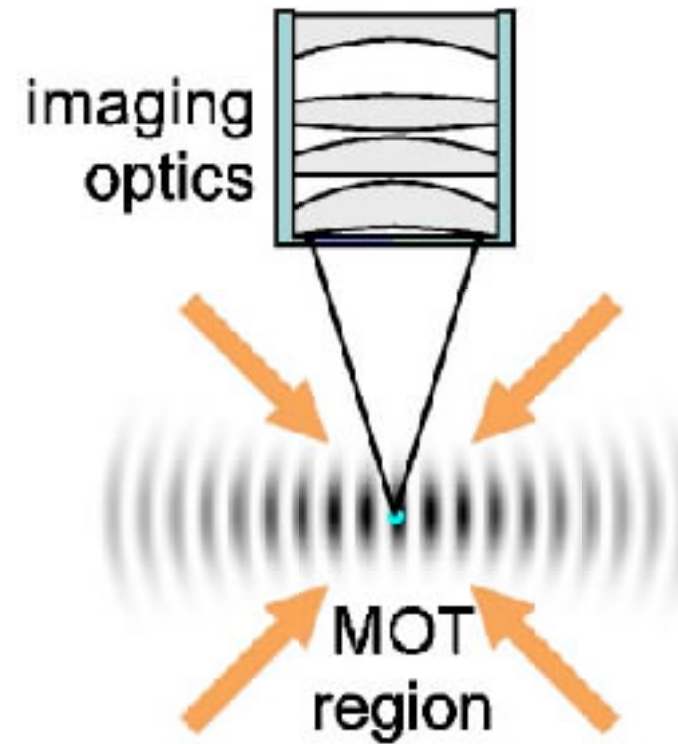
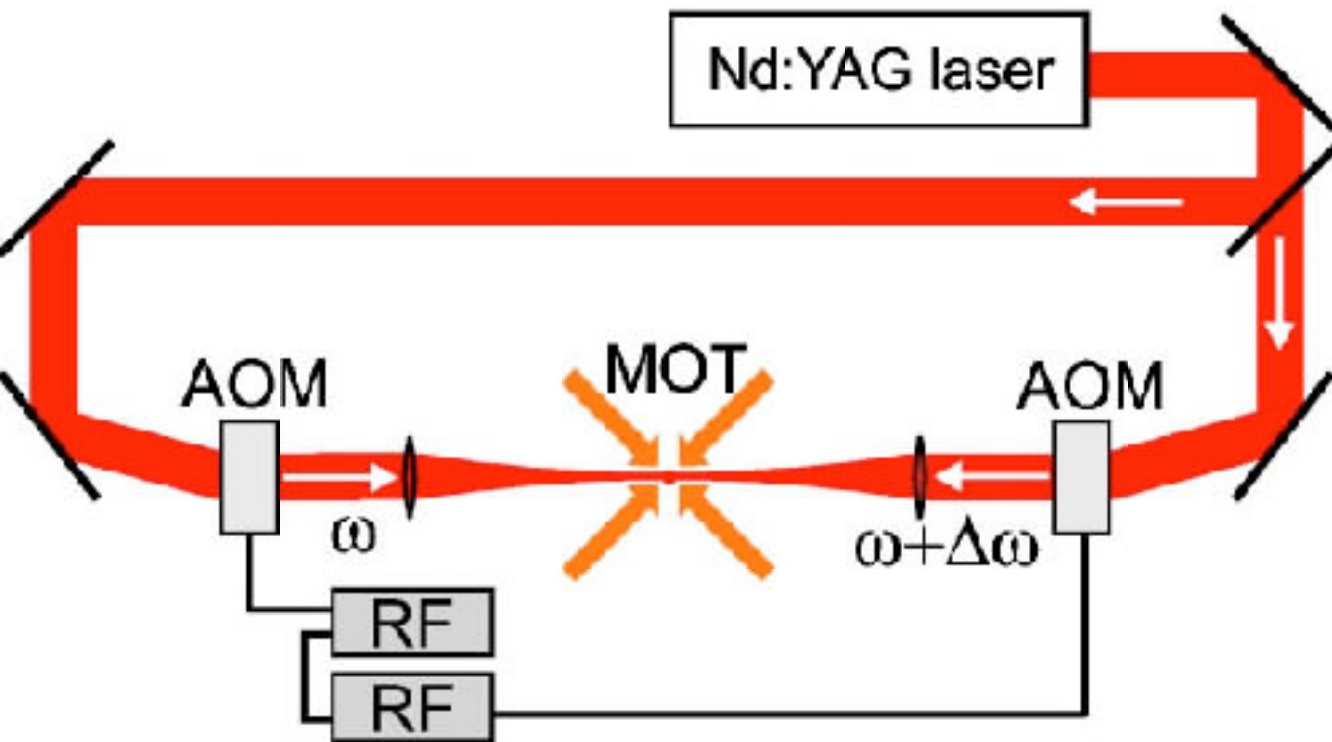
# Anwendung



**Anwendung: Messung der Elastizität  
einer äußeren Haarzelle des Innenohrs**

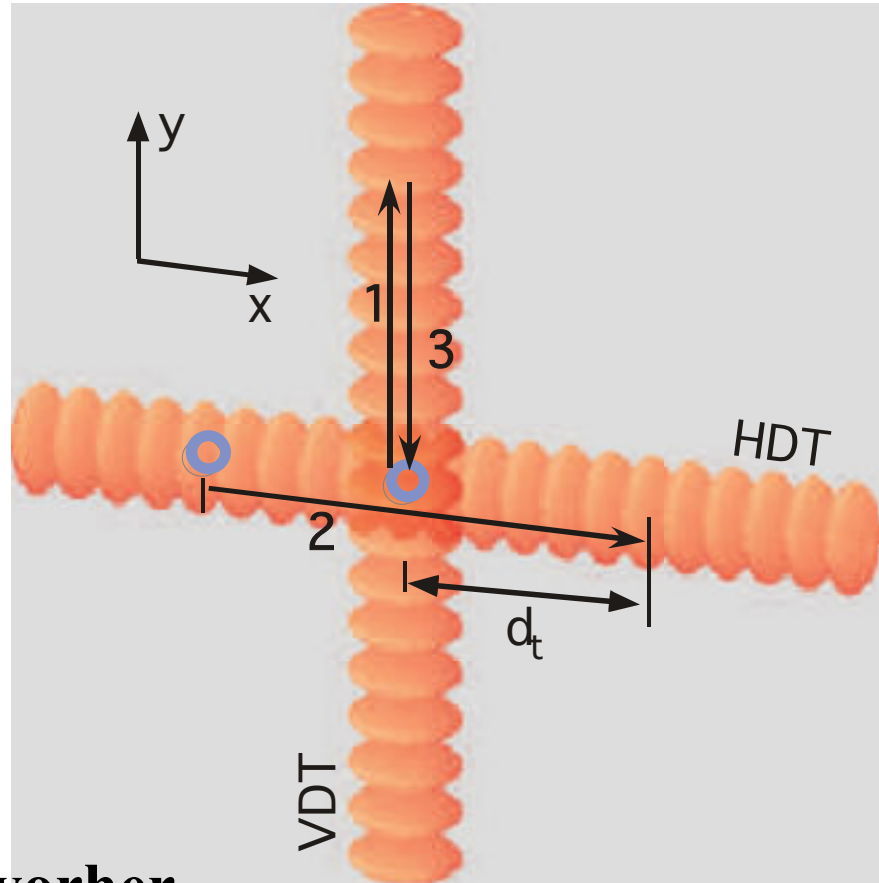
[http://www.ruf.rice.edu/~amistry/BIOE577/Optical\\_Tweezers.htm](http://www.ruf.rice.edu/~amistry/BIOE577/Optical_Tweezers.htm)

# Stehwellen



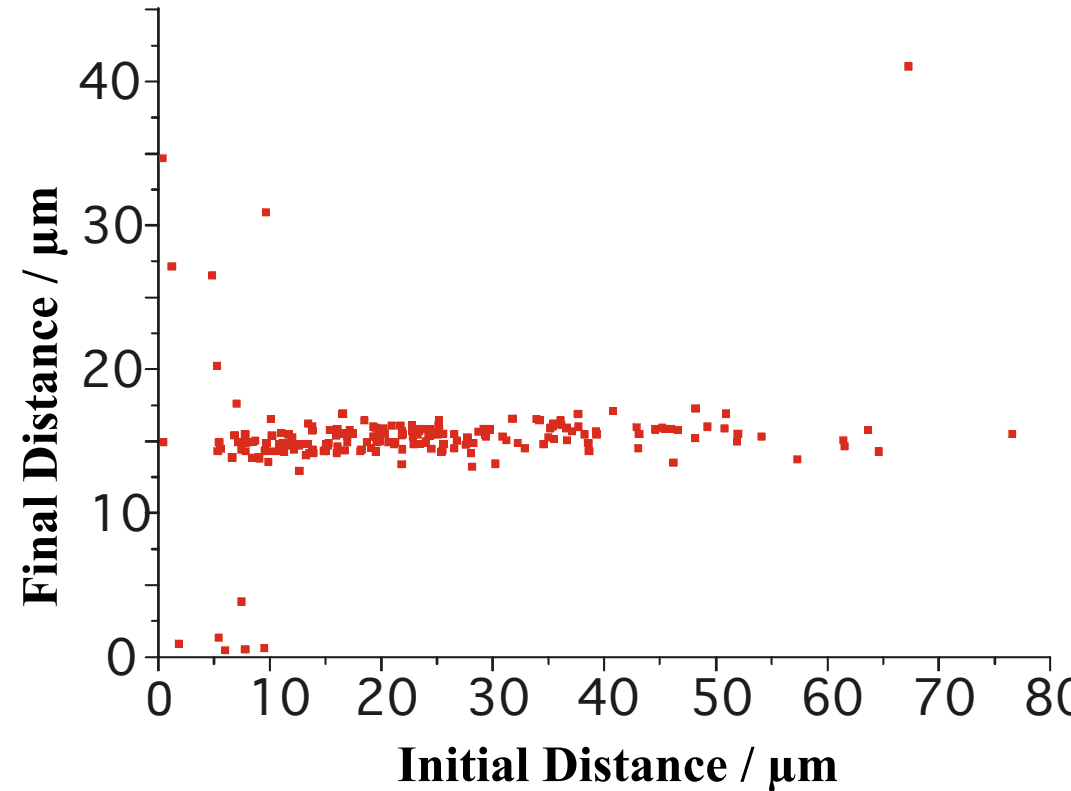


# Atomare Sortiermaschine



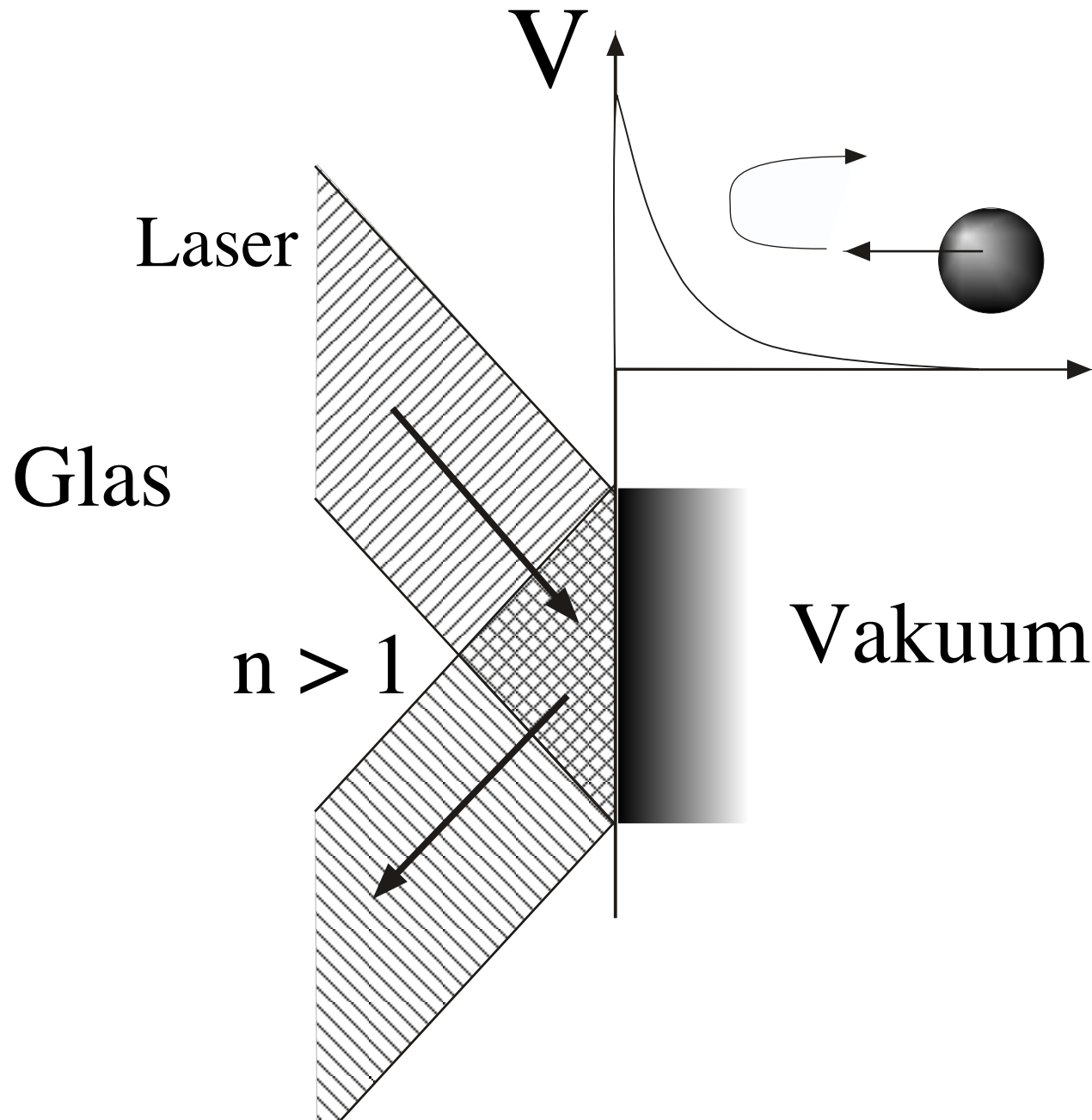
vorher

*Miroshnychenko et al., Nature 442, 151 (2006)*



nachher

# Reflexion von Atomen



# Atom-Resonator

VOLUME 71, NUMBER 19

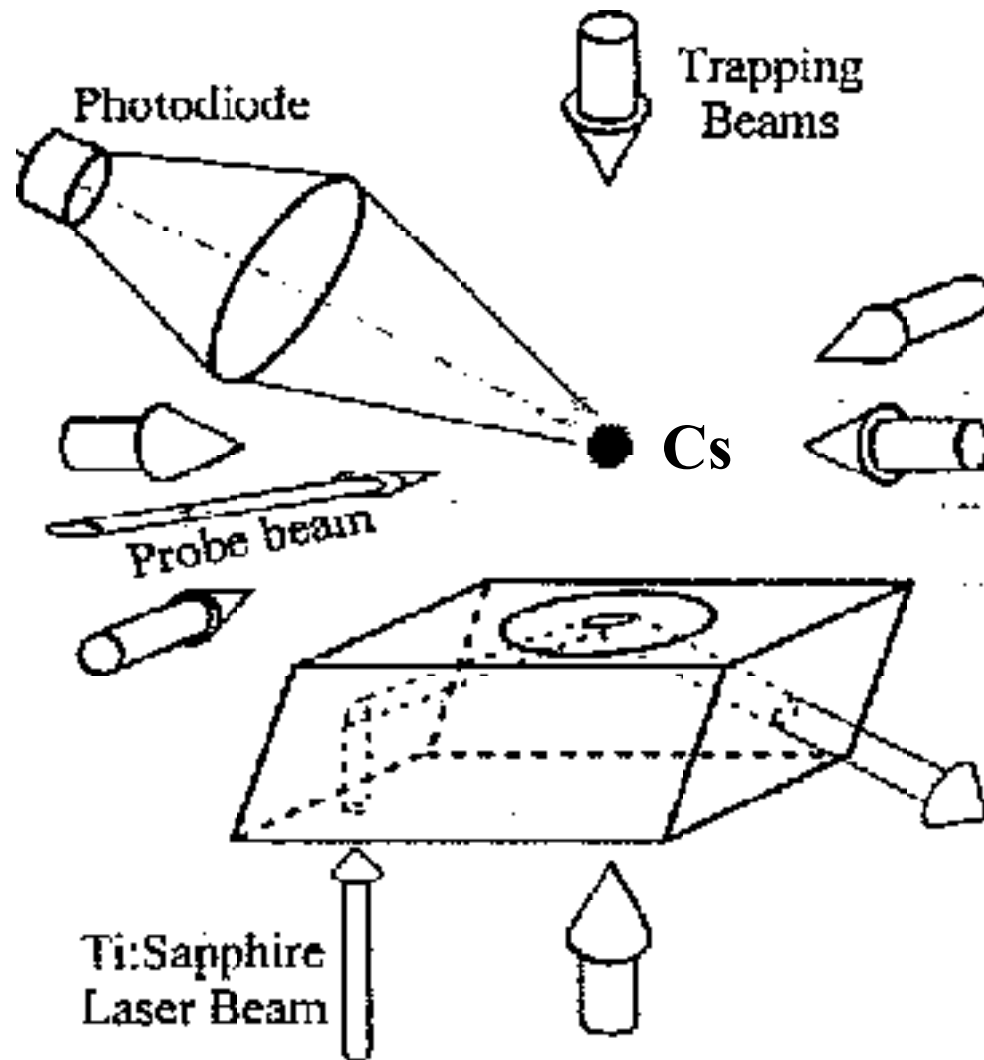
## Cesium Atoms Bouncing in a Stable Gravitational Cavity

C. G. Aminoff,\* A. M. Steane, P. Bouyer, P. Desbiolles, J. Dalibard, and C. Cohen-Tannoudji

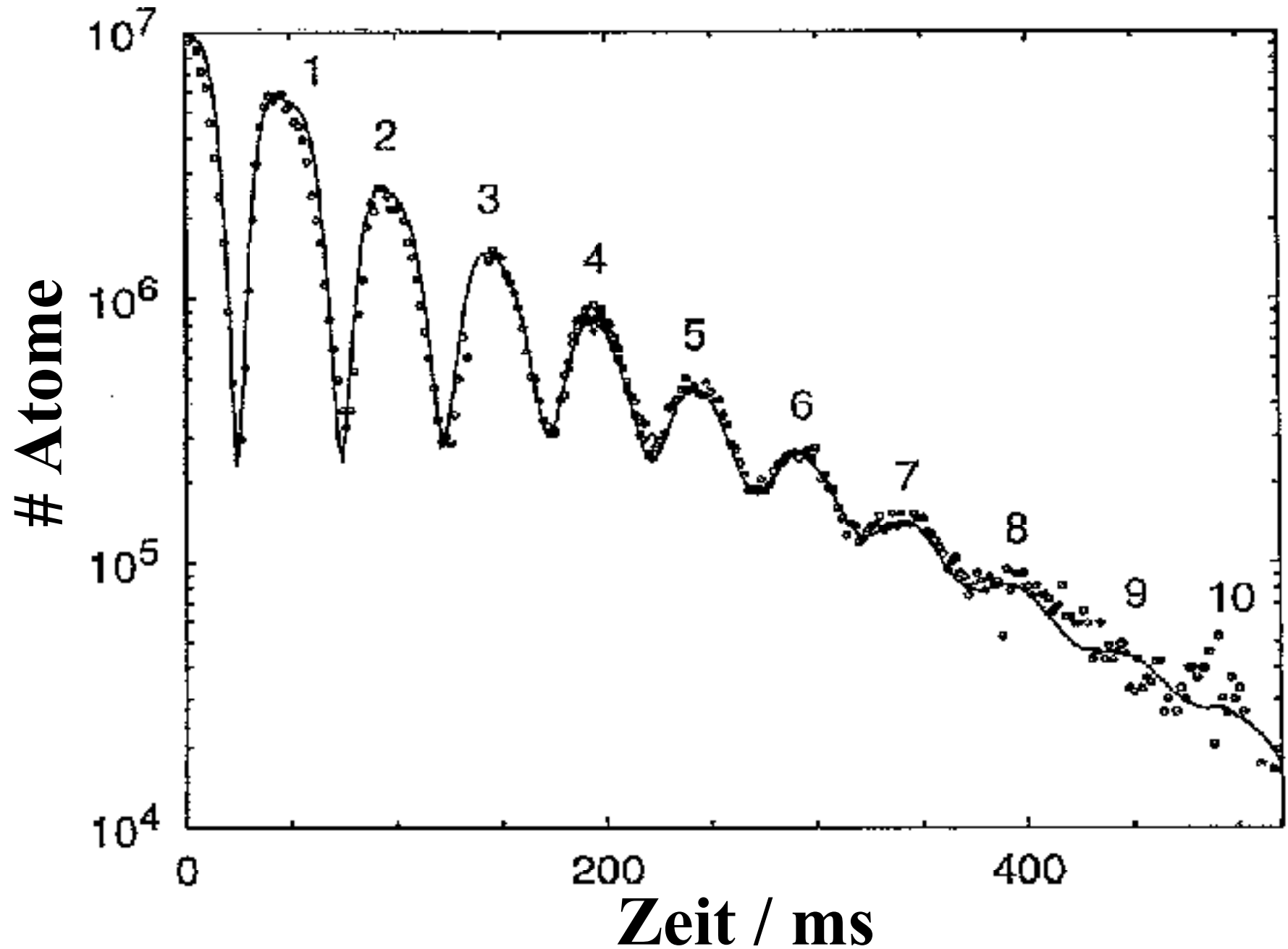
*Laboratoire de Spectroscopie Hertzienne de l'École Normale Supérieure and Collège de France,*

*24 rue Lhomond, F-75231 Paris CEDEX 05, France*

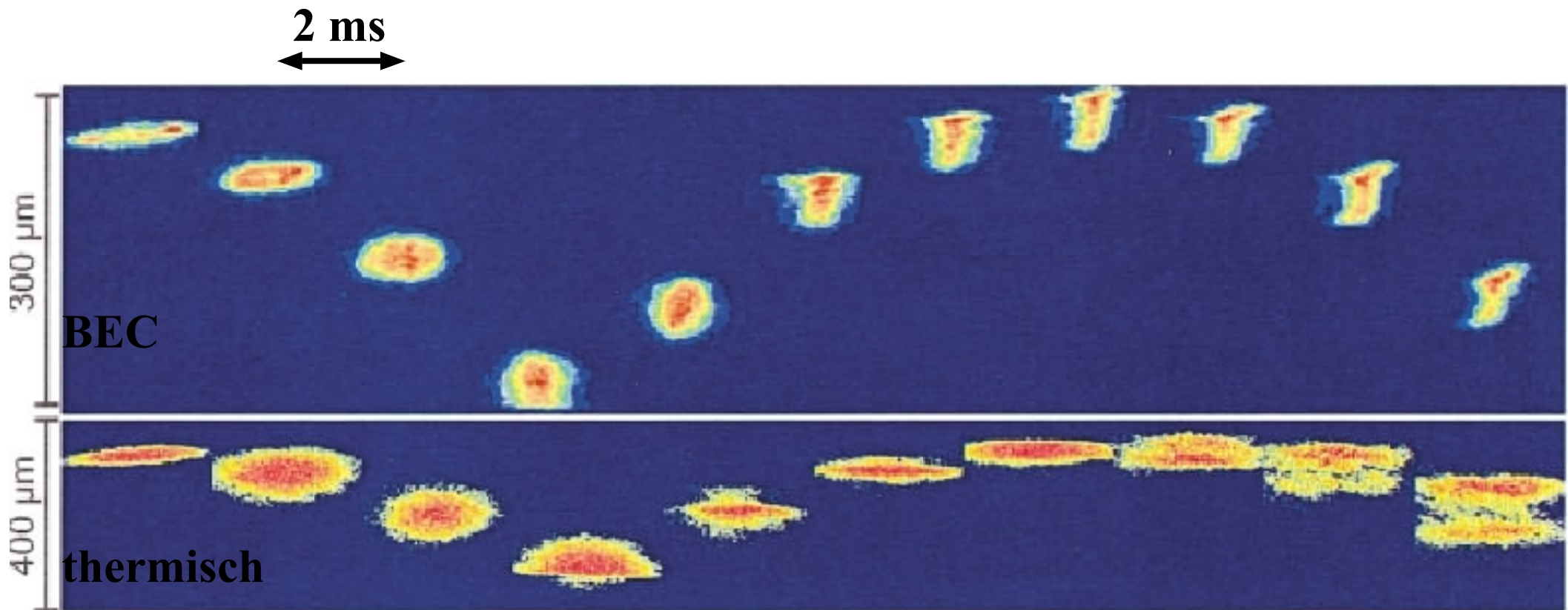
(Received 2 August 1993)



# Springende Atome

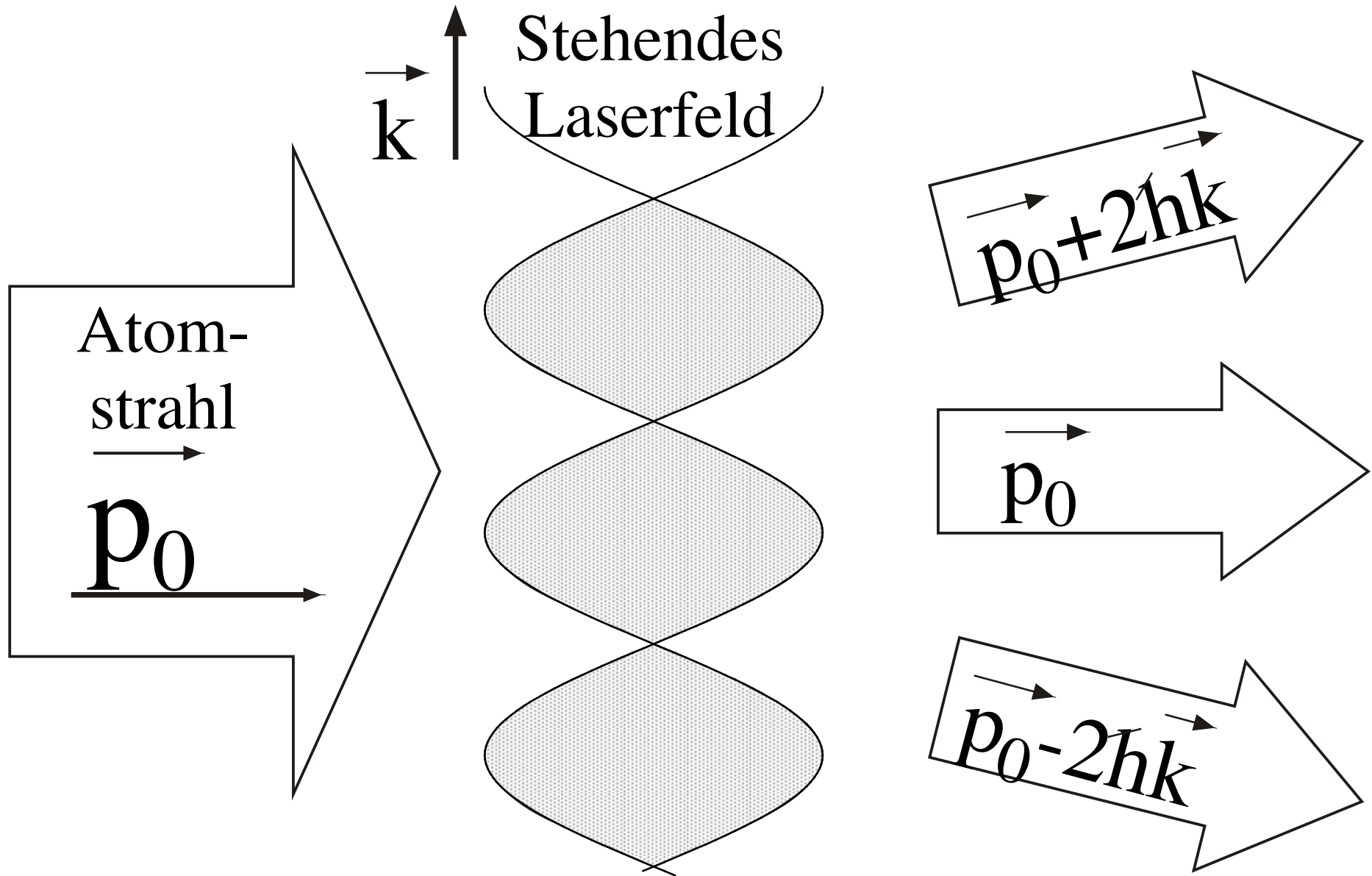


# Springendes BEC



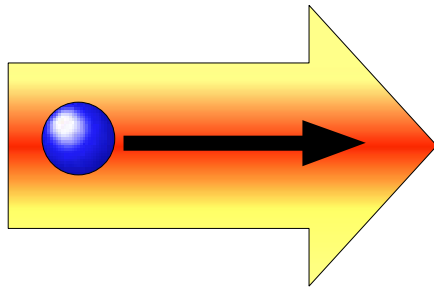
*Bongs et al., Phys. Rev. Lett. 83, 3577 (1999).*

# Strahlteiler



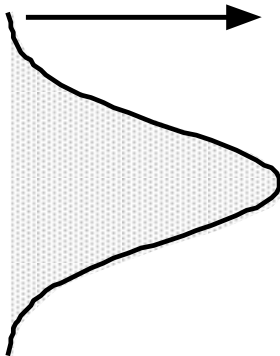
# Linsen und Wellenleiter

Copropagierend  
Gaußförmig

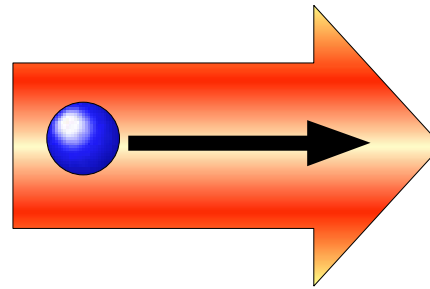


$$\Delta\omega_0 > 0$$

Intensität

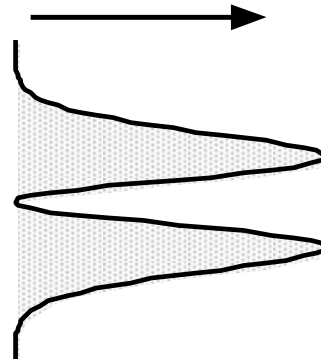


Copropagierend  
TEM<sub>01</sub>

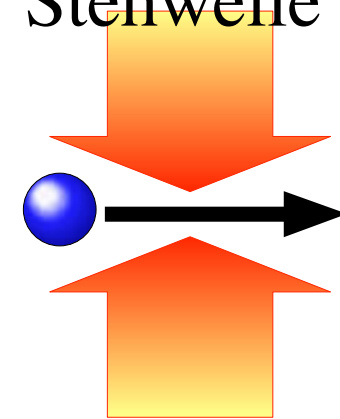


$$\Delta\omega_0 < 0$$

Intensität

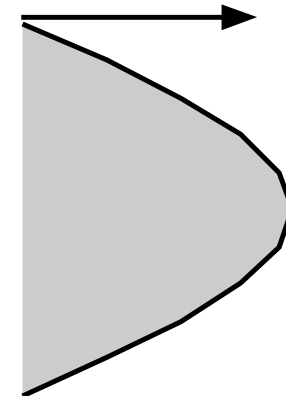


Senkrechte  
Stehwelle



$$\Delta\omega_0 > 0$$

Intensität



# Lithographie

Minimizing feature width in atom optically fabricated chromium nanowires

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(Received 20 August 1999)

## Atome

