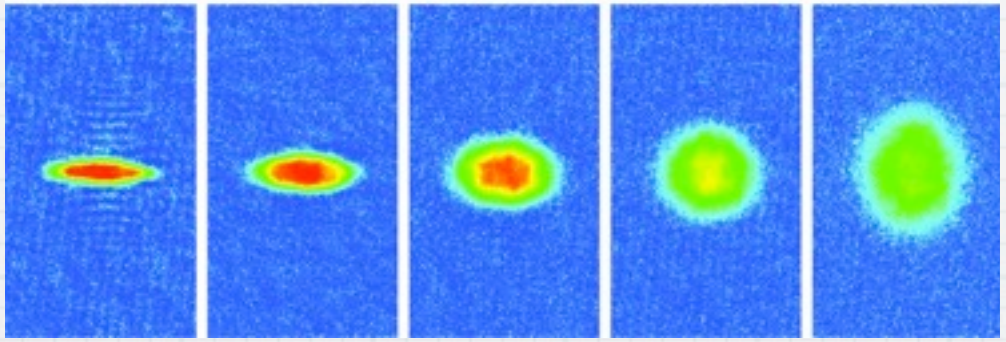
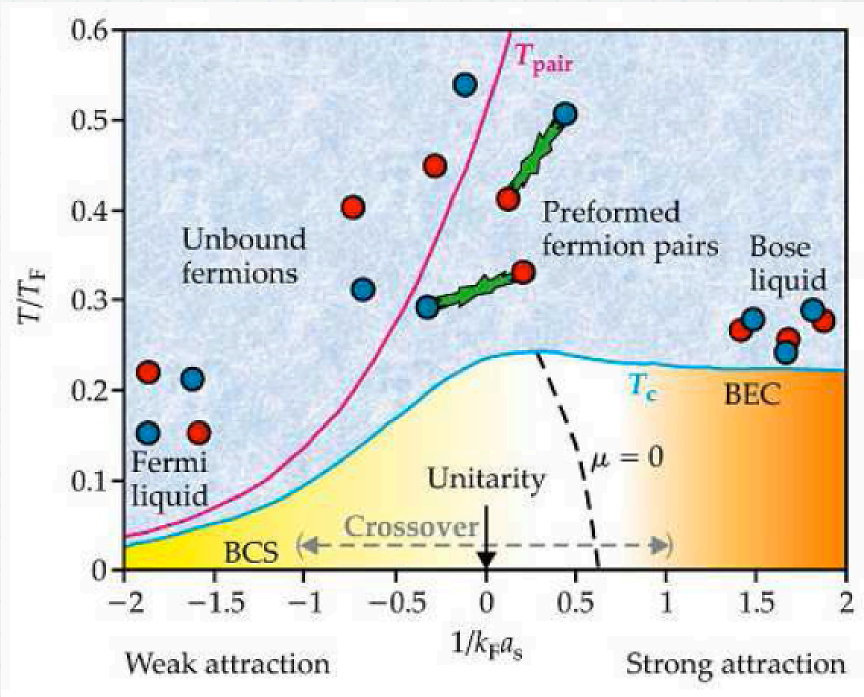
Kolde atomare gasser
Skræddersyet kvantemekanik



Georg M. Bruun

Fysiklærerdag 2011



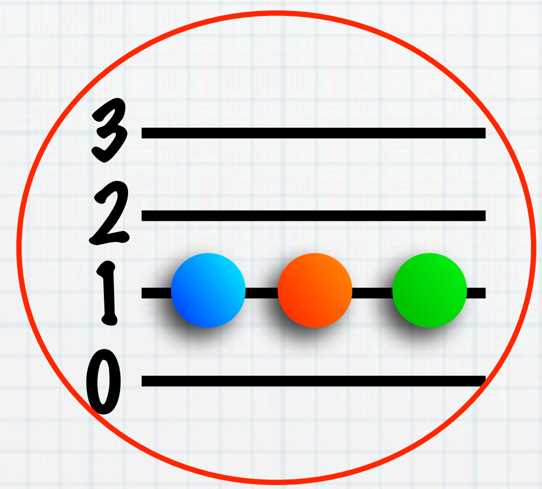
Hovedbudskaber

* Bose-Einstein Kondensation = Identitetskrise for kvantepartikler
* BEC i atomare ultrakolde gasser
* Skræddersyet vekselvirking
* Stærk vekselvirkning: Den perfekte væske

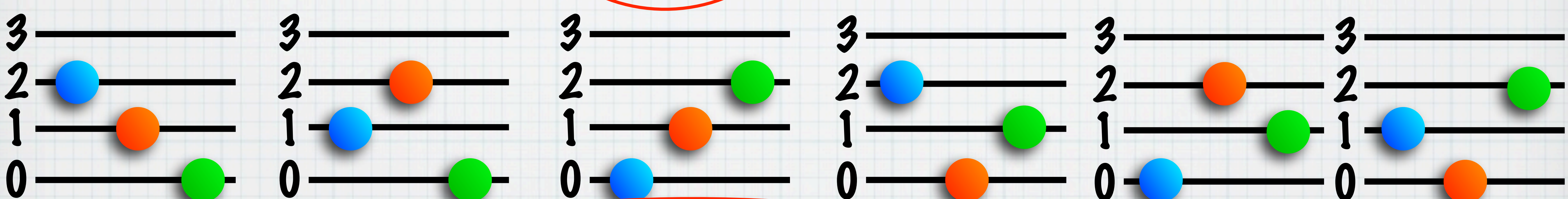
Bose-Einstein Kondensation

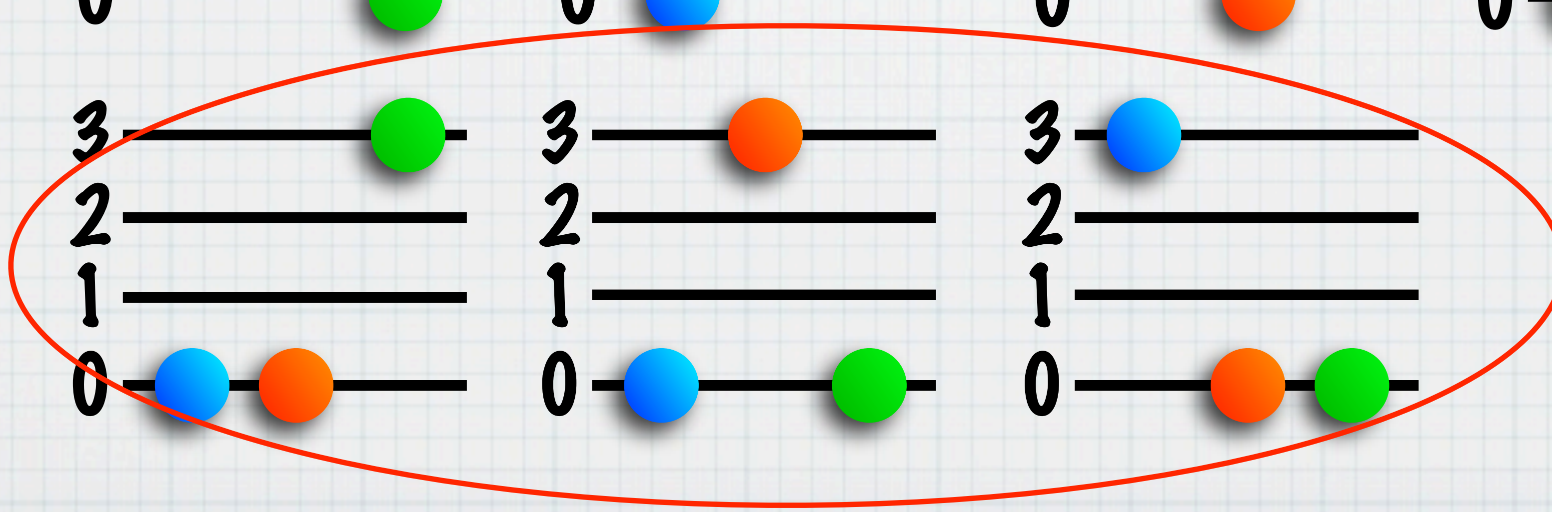
3 partikler med energien 3 in 4 niveauer

Klassisk fysik **Forskellige:** 10 tilstande



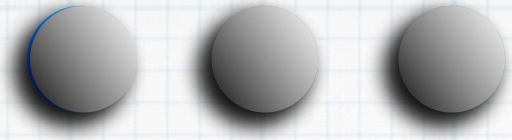
10% sandsynlighed for tredobbelt okkupation





30% sandsynlighed for dobbelt okkupation

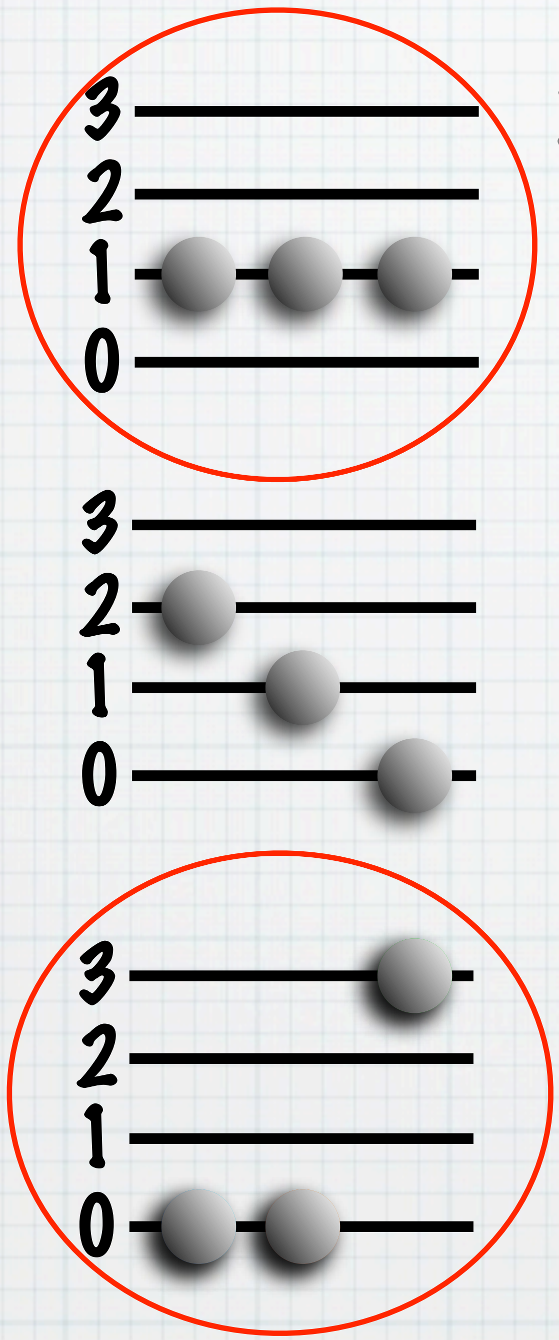
Kvantefysik



Identiske

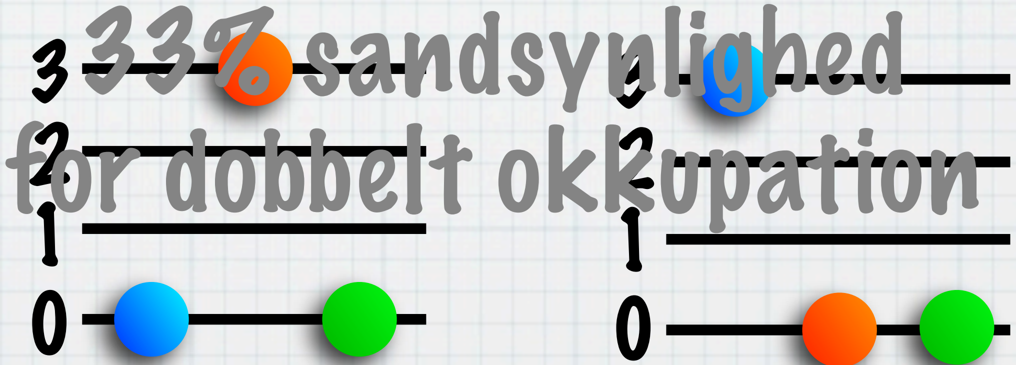
Bosoner:

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) = \Psi(\mathbf{r}_2, \mathbf{r}_1, \mathbf{r}_3)$$



33% sandsynlighed
for tredobbelt
okkupation

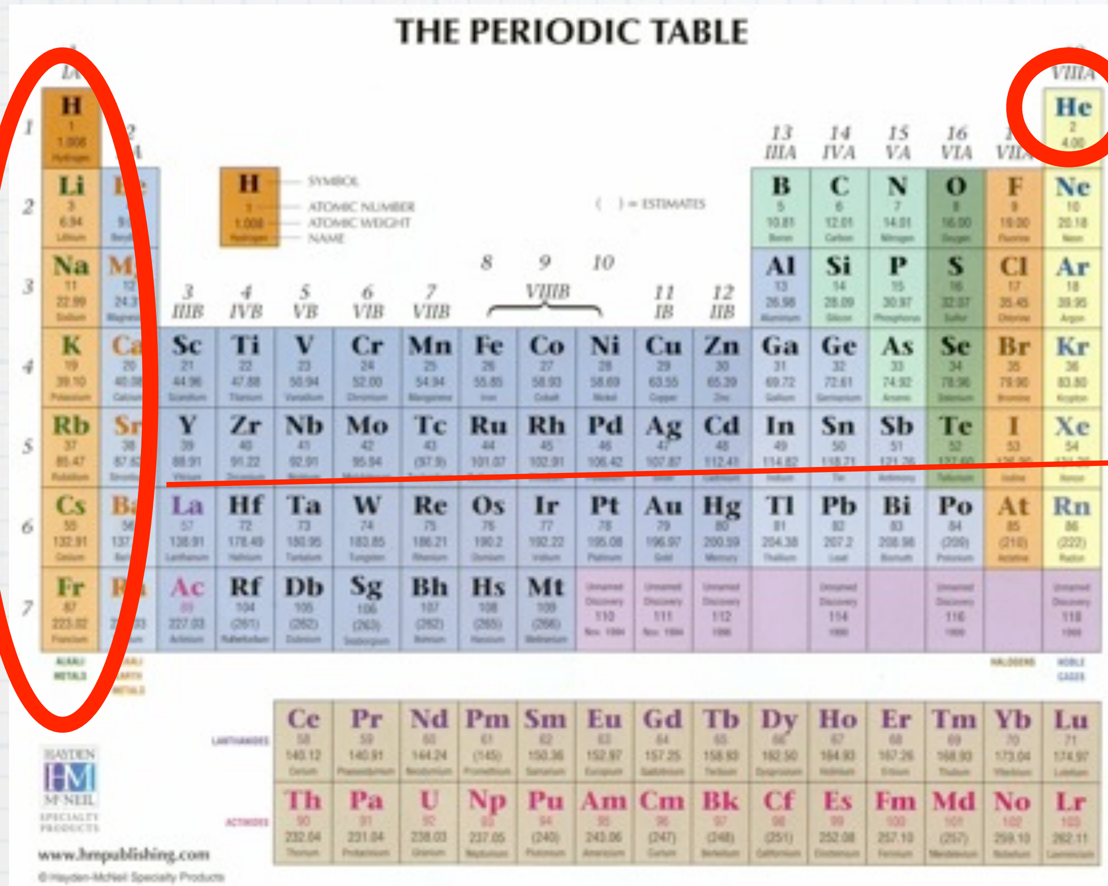
3 tilstande

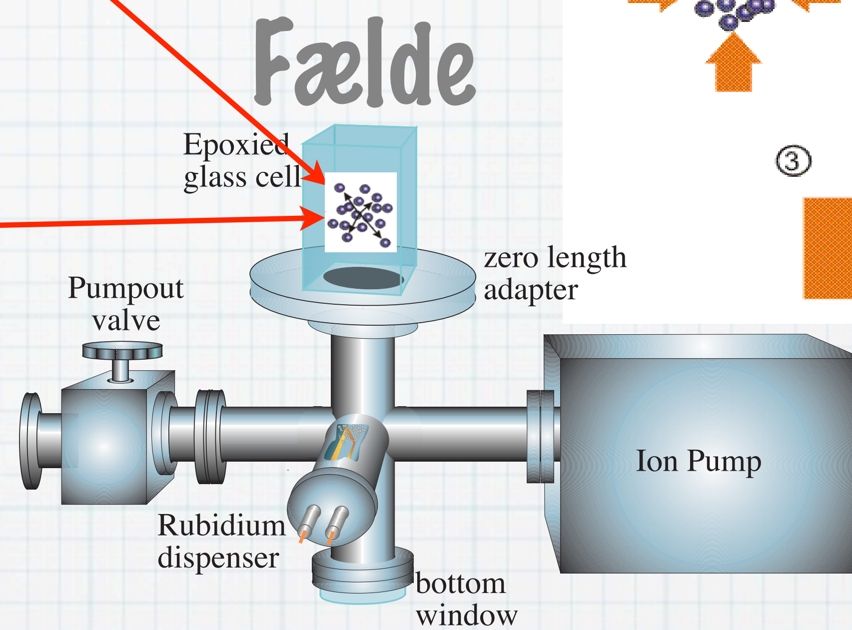


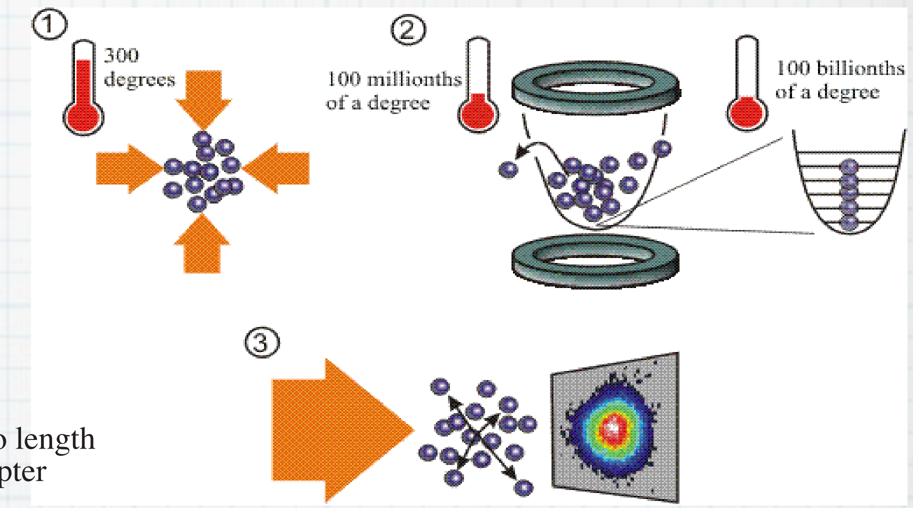
33% sandsynlighed
for dobbelt okkupation

Bosoner er sociale

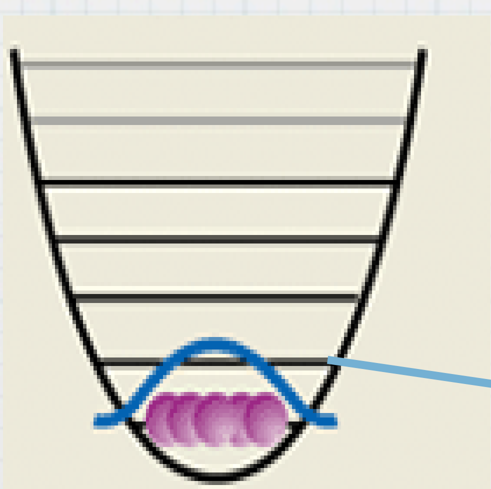
Kolde atomare gasser

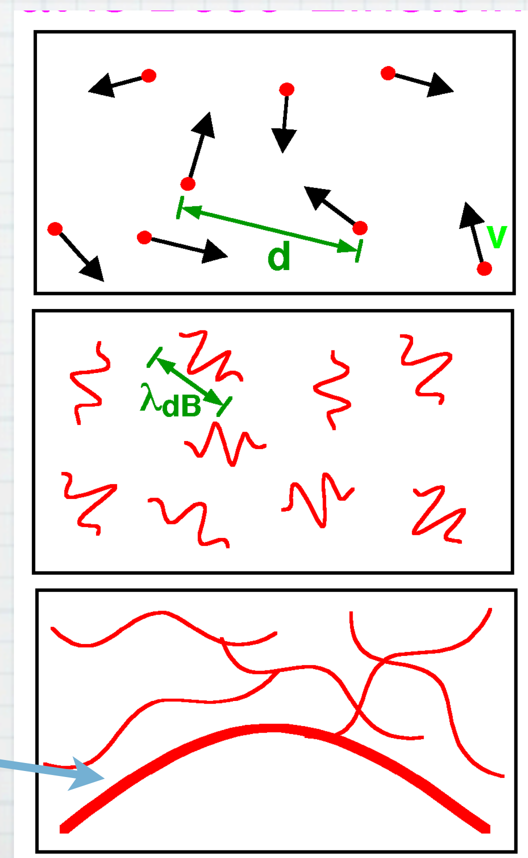




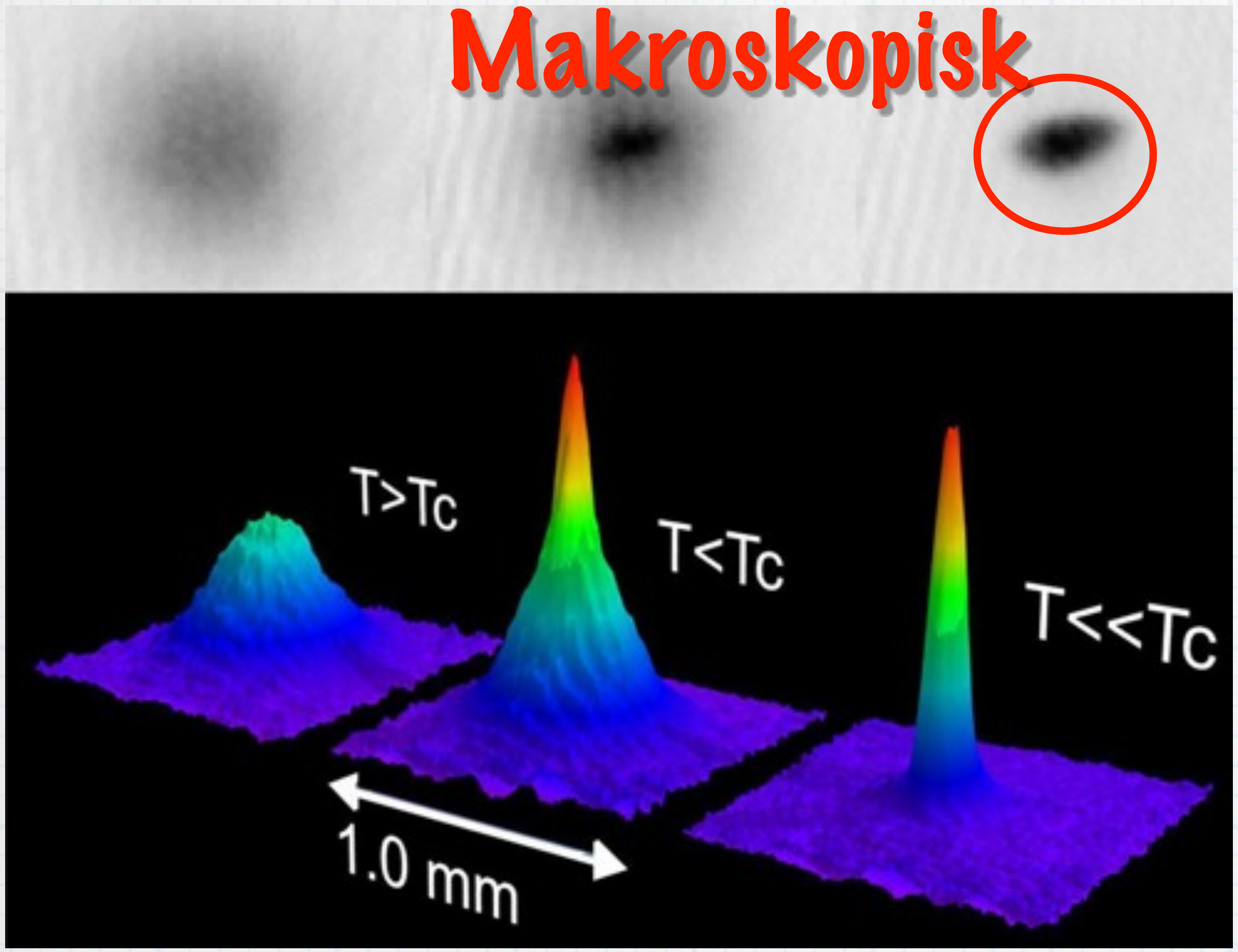


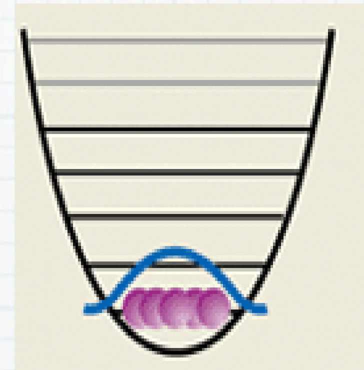
Bose-Einstein kondensation:





BEC i atomare gasser

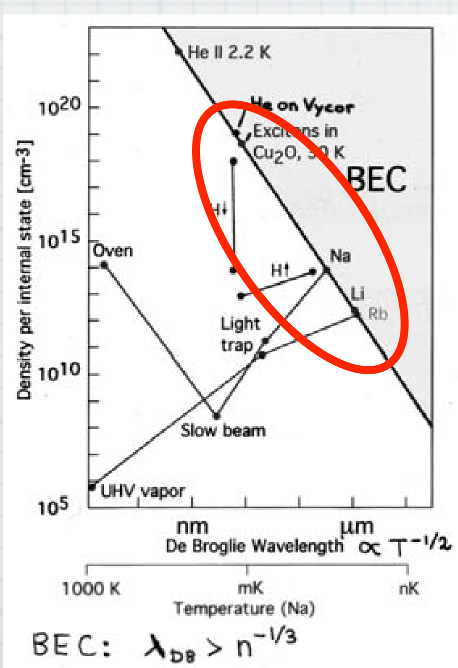


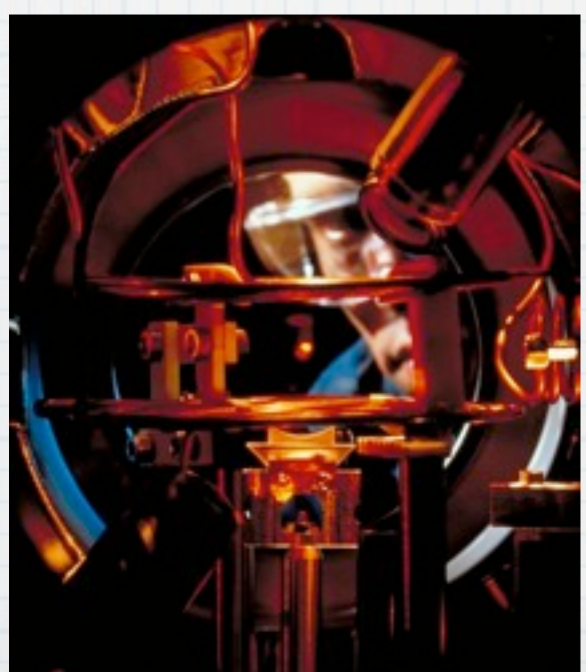


$$\phi(\mathbf{r}) \propto e^{-r^2/2a^2}$$

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N) = \prod_{i=1}^{N} \phi(\mathbf{r}_i)$$

$$|\Psi|^2 = N\phi(\mathbf{r})^2$$





Nobel Price 2001

Eric A. Cornell | Wolfgang Ketterle | Carl E. Wieman

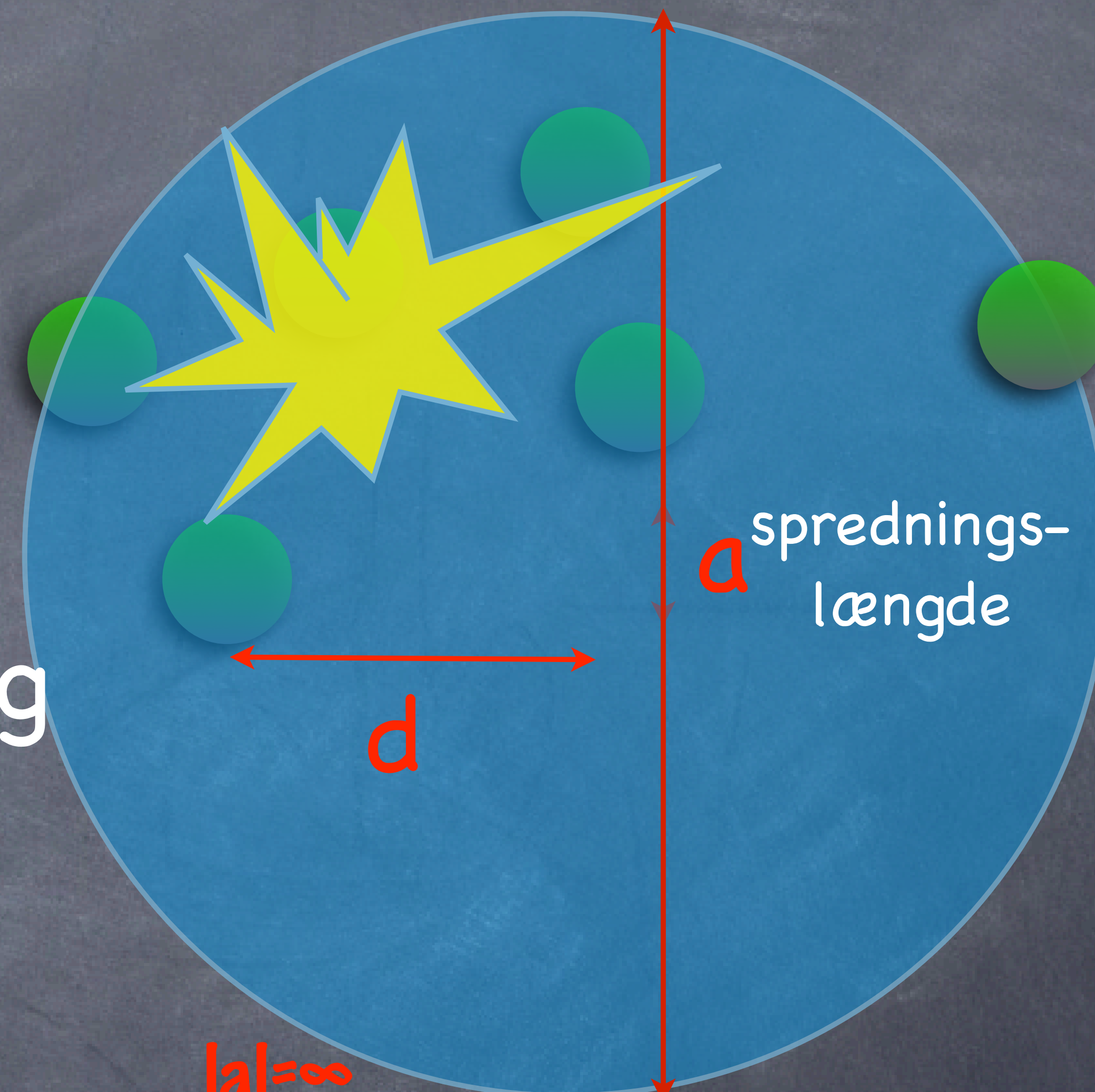
Skræddersyet vekselvirkning

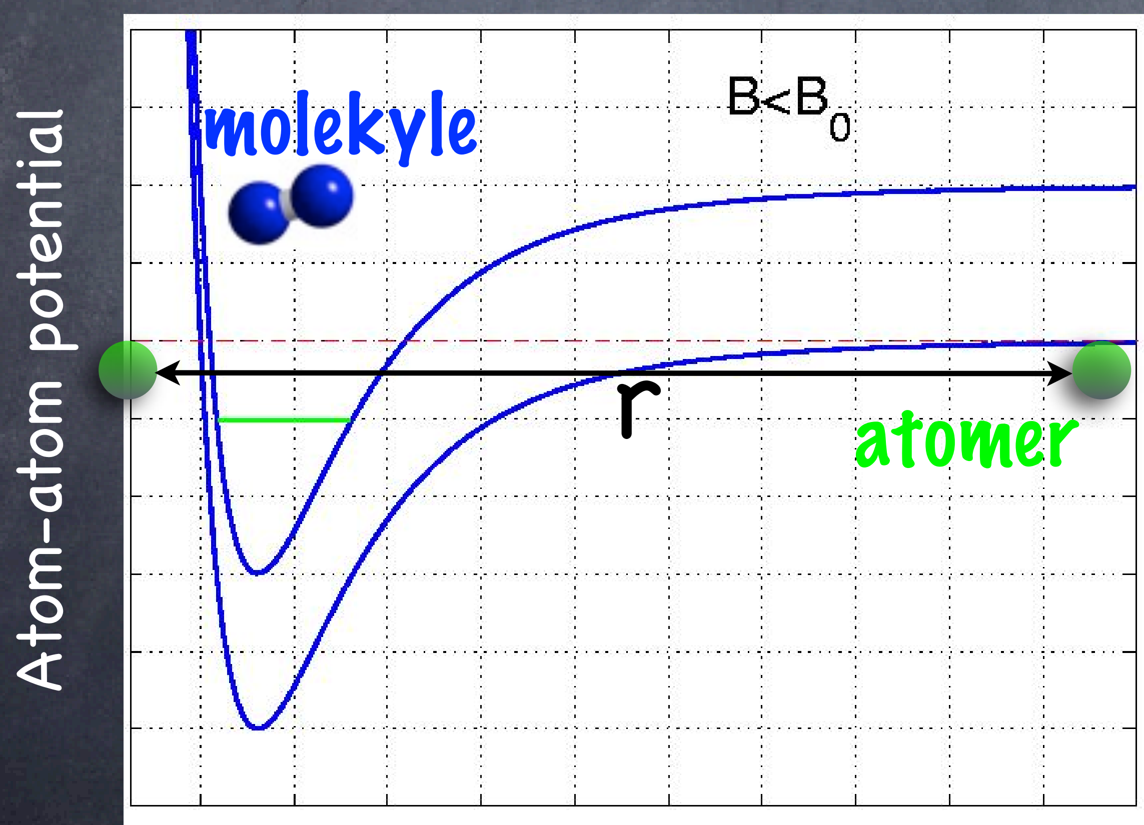
Kollisioner:

Styrke af vekselvirkning: a/d

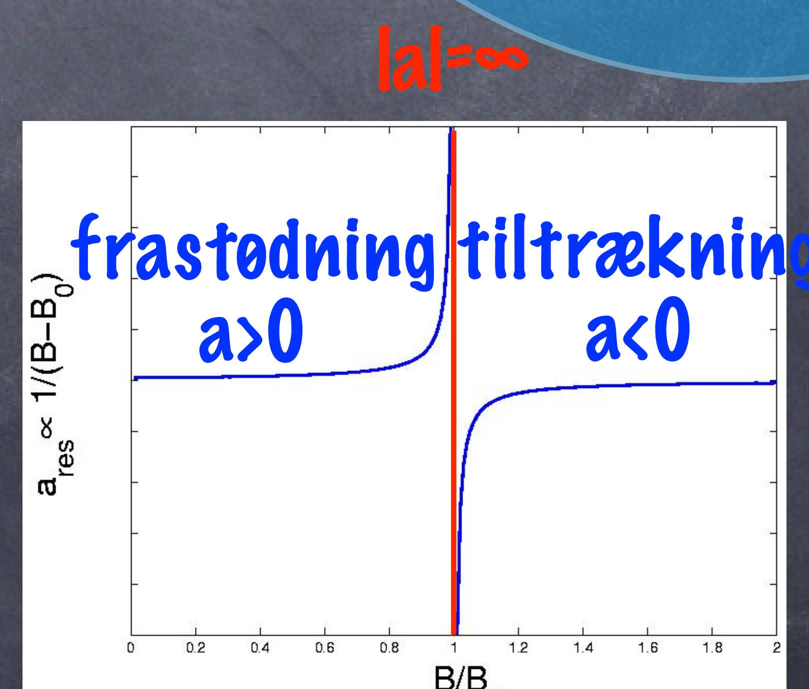
a/d« 1 svag vekselvirkning

a/d» 1 stærk vekselvirkning



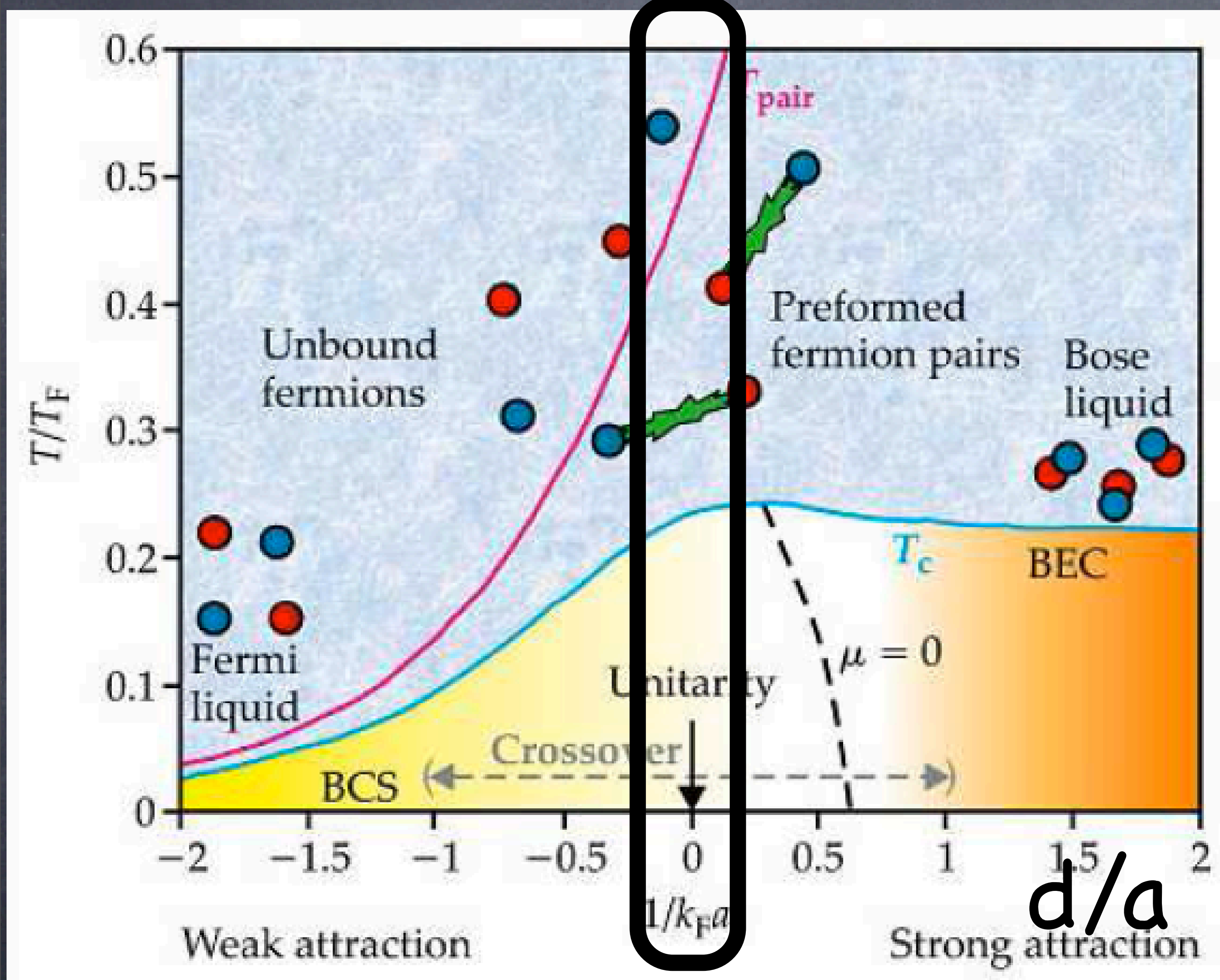


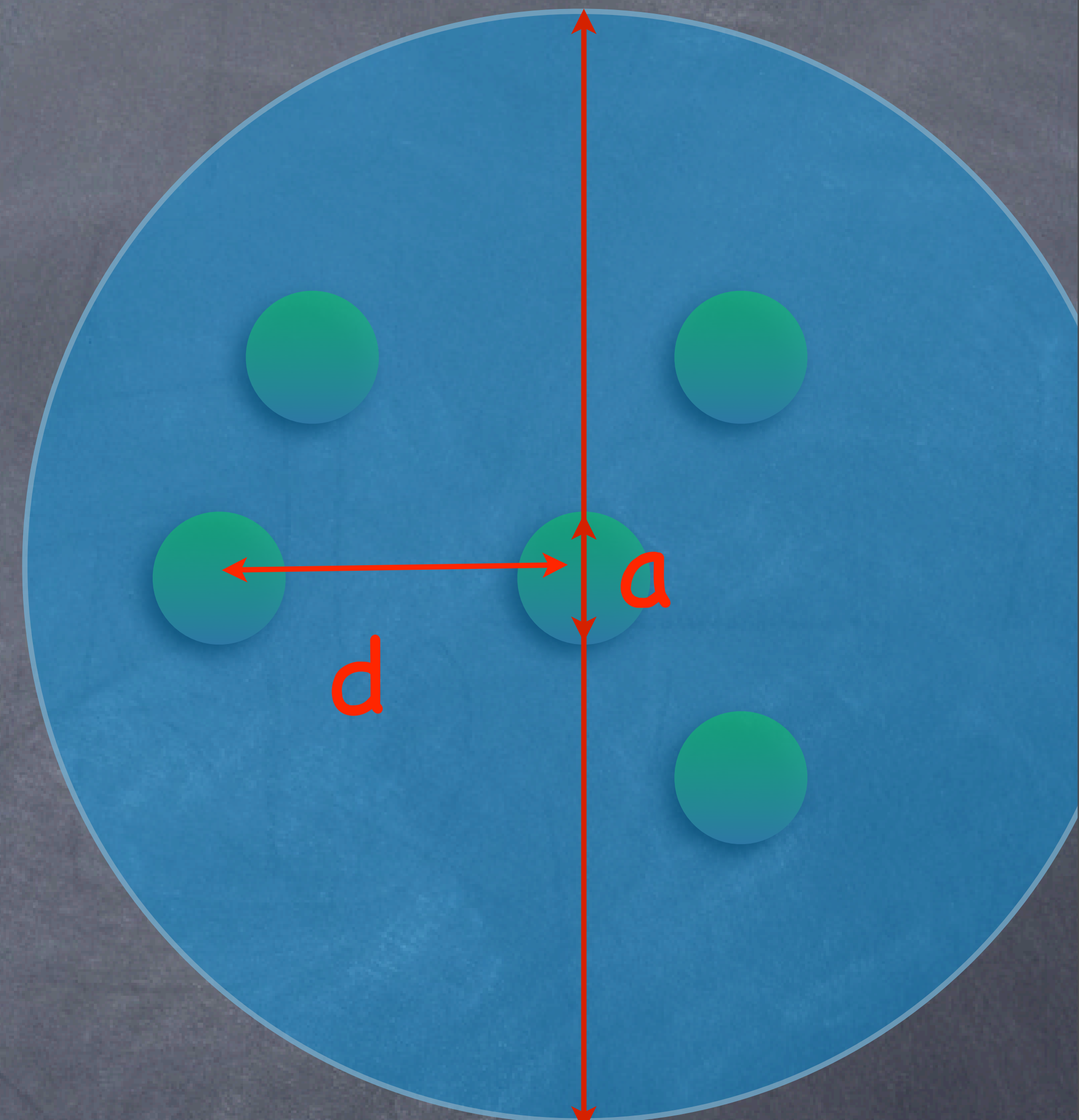
Fano-Feshbach resonans



Den perfekte væske

Fasediagram



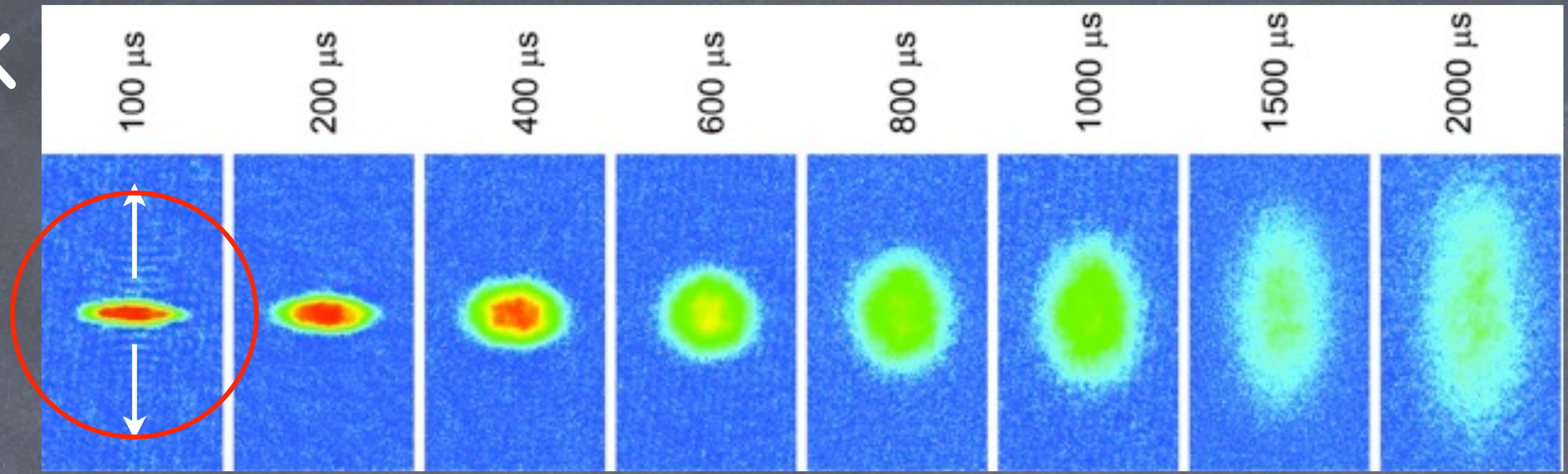


Stærk vekselvirkning |a|>>d

Den perfekte væske

Hydrodynamisk ekspansion

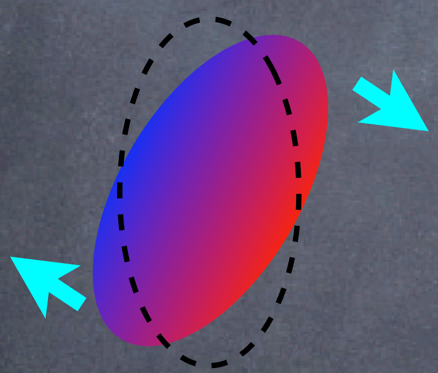
$$\rho \partial_t \mathbf{u} = -\nabla P$$

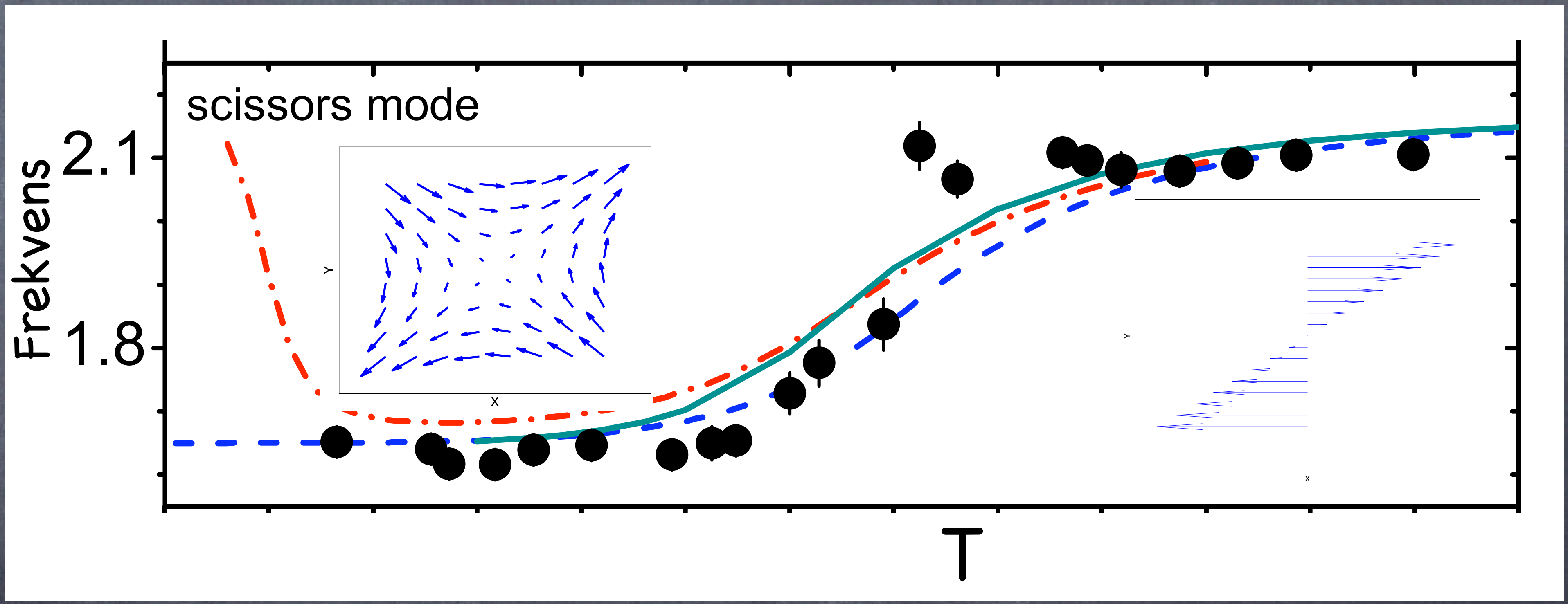


Thomas Lab, Duke 2004

Svingninger

Scissors Mode





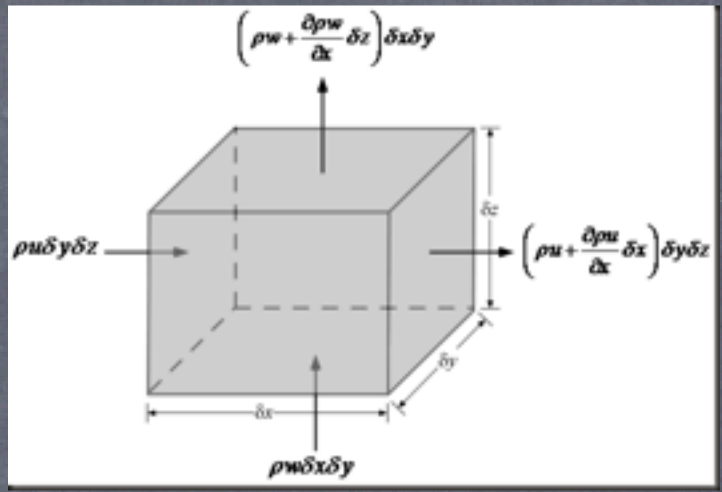
Grimm Lab, Innsbruck 2009

“Perfekt” væske
10000 mere fortyndet
end luft

Ideelle og viskøse væsker

Hydrodynamik:

- Bevarelse af partikler $\partial_t \rho + \nabla(\rho \mathbf{v}) = 0$



- Bevarelse af impuls $\partial_t(\rho v_i) + \partial_k \Pi_{ik} = 0$

$$\Pi_{ik} = P\delta_{ik} + \rho v_i v_k$$

Ideel væske
Tabsfri

L. Euler 1707–1783

Alle væsker har tab og friktion

① $\partial_t \rho + \nabla(\rho \mathbf{v}) = 0$ ② $\partial_t(\rho v_i) + \partial_k \Pi_{ik} = 0$

$$\Pi_{ik} = P\delta_{ik} + \rho v_i v_k - \eta\left(\partial_i v_j - \partial_j v_i - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{v}\right) - \zeta\delta_{ij}(\nabla\mathbf{v})$$

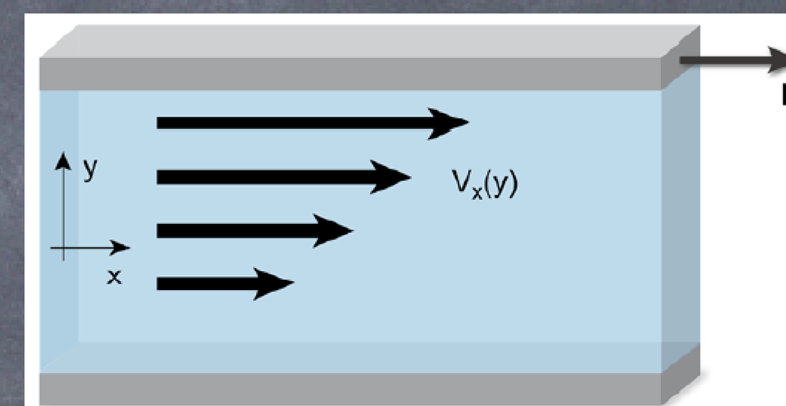
Viskositet

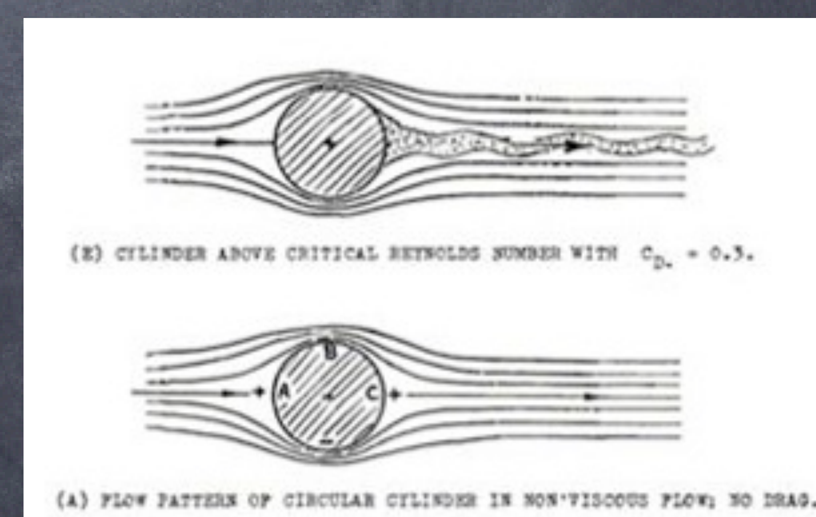
"Friktion"

Stigende viskositet →

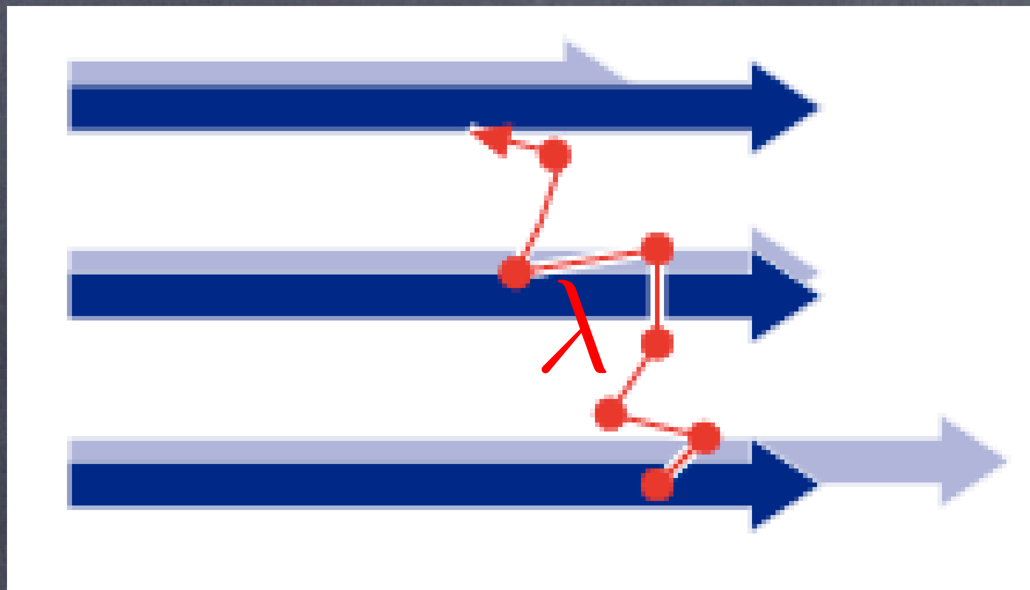
C. Navier
1785-1836

$$\frac{F}{A} = \eta\partial_y v_x$$





Kinetisk billede

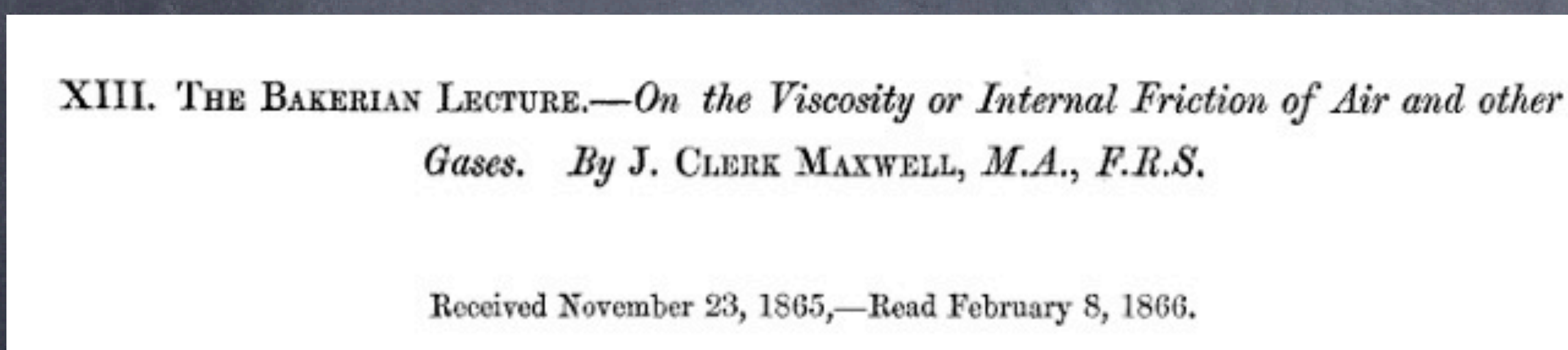


Impuls transport $\Pi_{xy} = -\eta \dfrac{\partial v_x(y)}{\partial y}$

Viskositet $\eta \sim np\lambda$

Middel fri vejlængde $\lambda = \dfrac{1}{n\sigma}$

Viskositet uafhængig af tæthed!

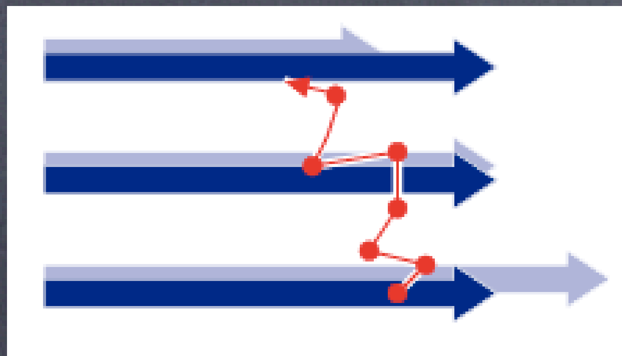


XIII. THE BAKERIAN LECTURE.—*On the Viscosity or Internal Friction of Air and other Gases.* *By* J. CLERK MAXWELL, *M.A.*, *F.R.S.*

Received November 23, 1865,—Read February 8, 1866.

James Clerck Maxwell
1831-1879

Kinetisk billede:



Få kollisioner → Høj viskositet

Mange kollisoner → Lav viskositet

Lille viskositet ⇒ stærk vekselvirkning

Viskositet har ingen øvre grænse

Men tilsyneladende en nedre grænse

Table 8.4.1. *Viscosities η for some common materials in units of centipoise (10^{-2} erg s/cm^3).*

Substance	Temperature	Viscosity (cp)
Air	18°C	0.018
Water	0°C	1.8
Water	20°C	1
Water	100°C	0.28
Glycerin	20°C	1500
Mercury	20°C	1.6
n-Pentane	20°C	0.23
Argon	85K	0.28
He^4	4.2K	0.033
Superfluid He^4	< 2.1K	0
Glass		$> 10^{15}$

Note that, by popular convention, the designation "glass" is applied to any disordered material once its viscosity exceeds 10^{15}cp.

Minimum? $\eta \sim np\lambda \gtrsim \hbar n$

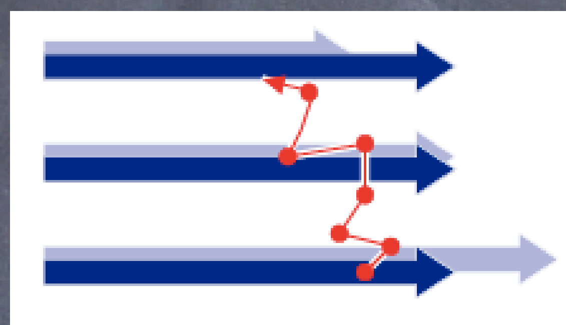
Heisenberg $\Delta x \Delta p \geq \hbar/2$

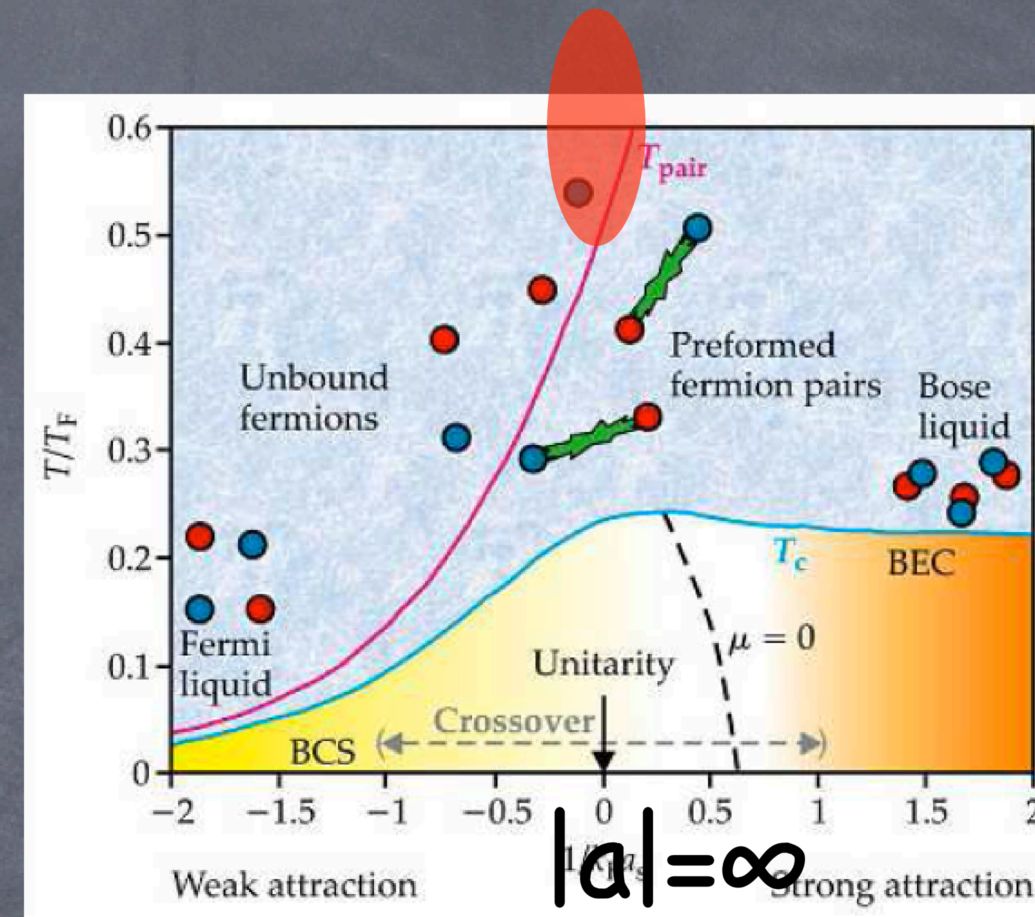
- Stærke vekselvirkninger
- Kvantesystem

Viskositet af en atomar gas

Høj temperatur:

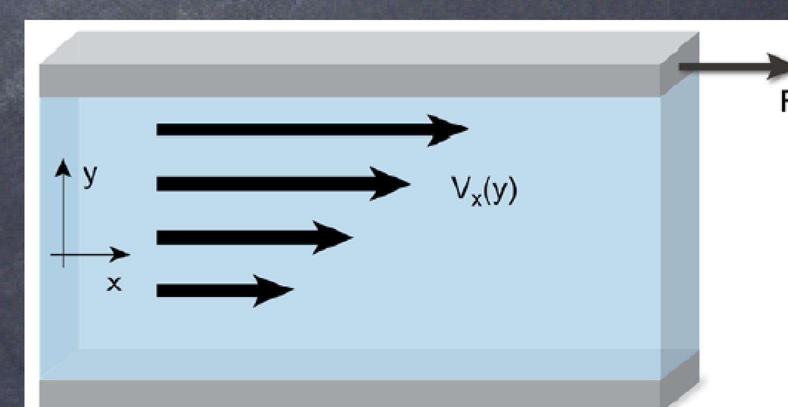
Veldefinerede partikler





Boltzmann ligningen

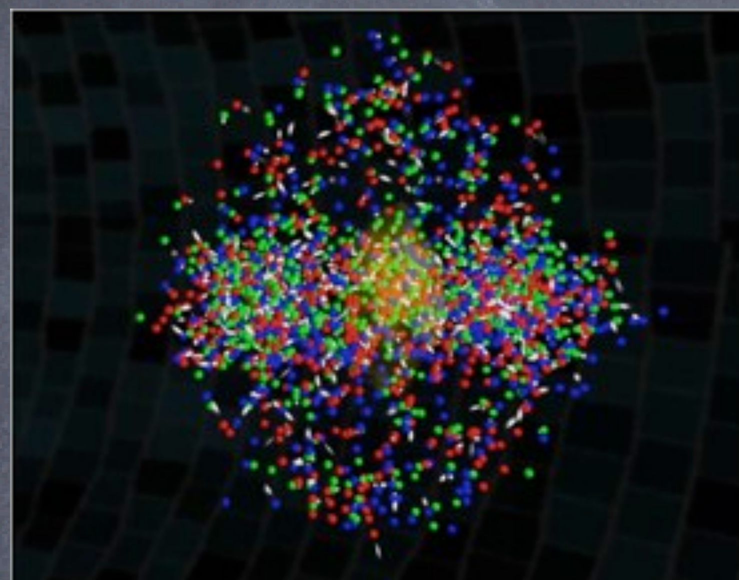
$$\frac{\partial f}{\partial t} + \dot{\mathbf{r}} \cdot \frac{\partial f}{\partial \mathbf{r}} + \dot{\mathbf{p}} \cdot \frac{\partial f}{\partial \mathbf{p}} = -I[f]$$



$$\boxed{\eta = \frac{15(mkT)^{3/2}}{32\sqrt{\pi}\hbar^2} \propto T^{3/2}}$$

Viskositet af en atomar gas

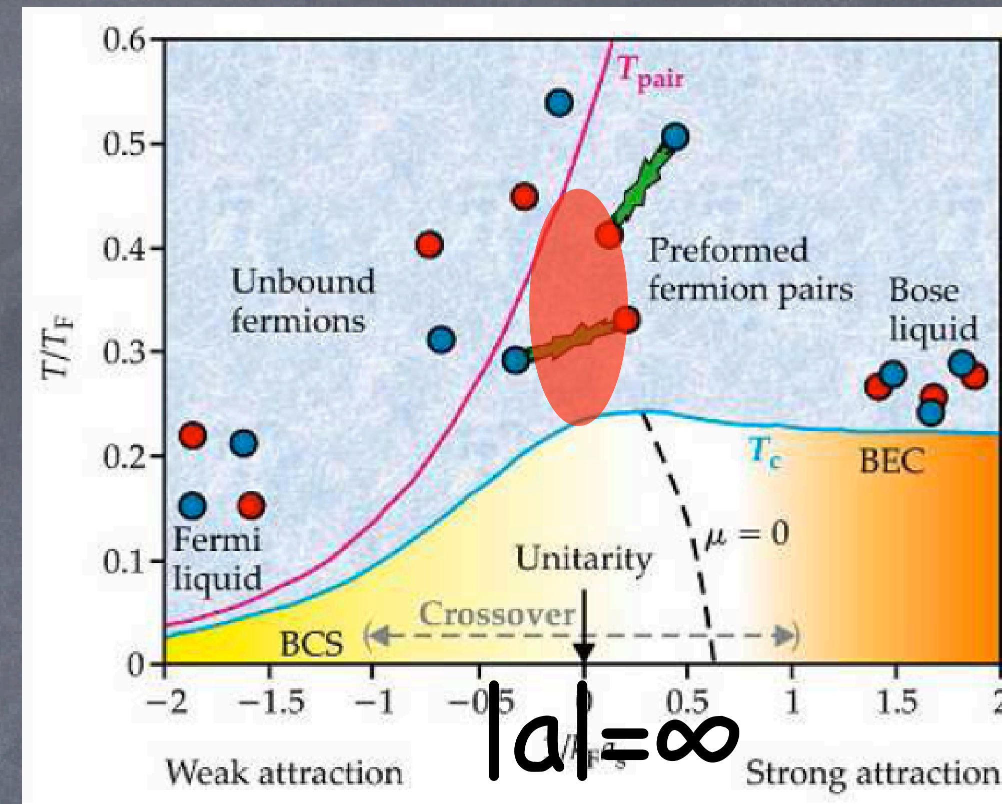
Ingen veldefinerede partikler



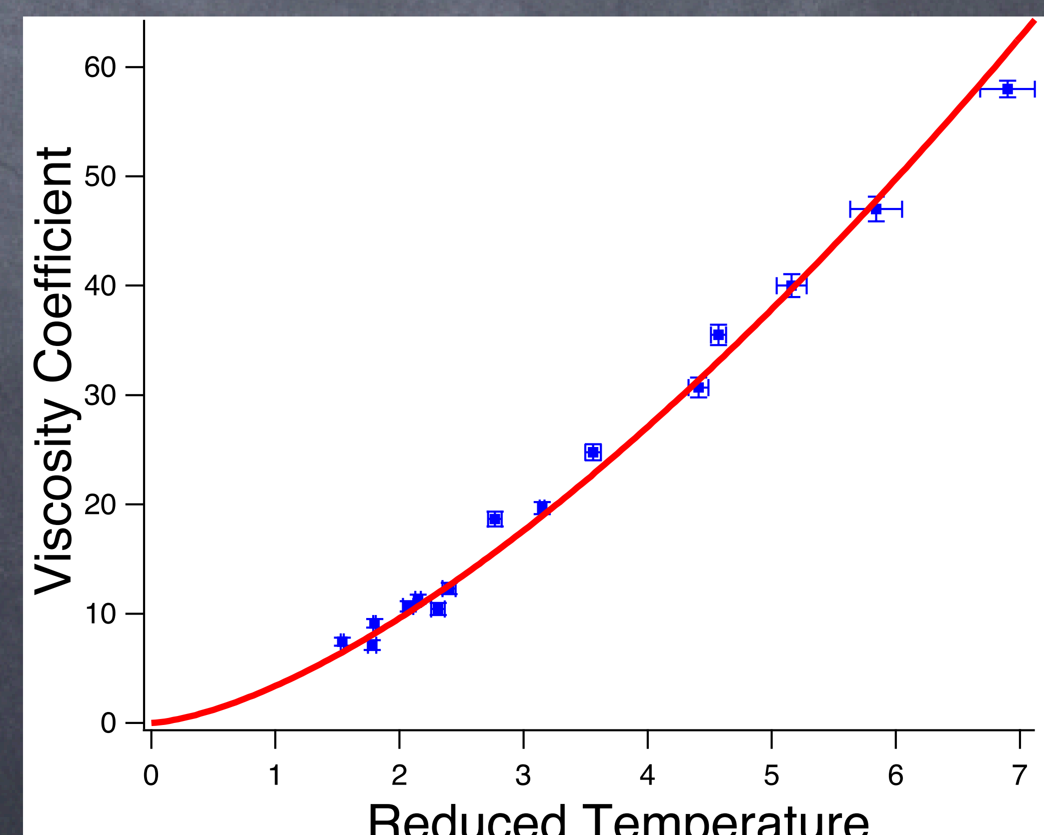
Kvantevæske

$$\eta = \alpha(T/T_F)n\hbar$$

$$\alpha(T_c/T_F) \simeq 0.2$$



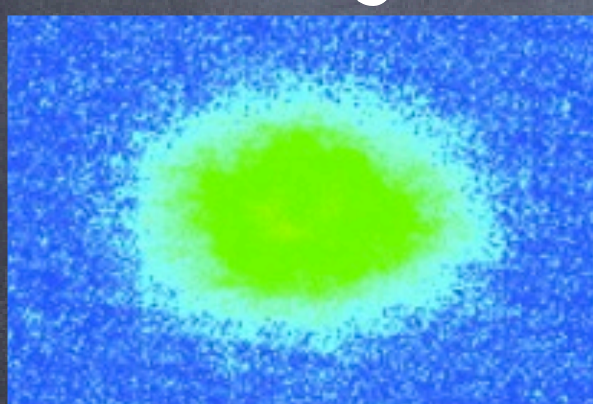
Thomas Lab, Science 2010



Mindste viskositet i universet

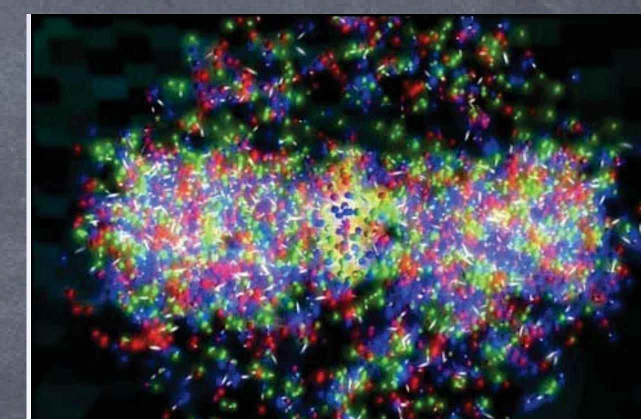
Mulige kandidater:

Atomare gasser



Flydende Helium

Quark-Gluon Plasma



T≈10^{-7}K

Koldeste sted på jorden

$$\eta \sim 10^{-15} Pa \cdot s$$

T≈1K

$$\eta \sim 10^{-6} Pa \cdot s$$

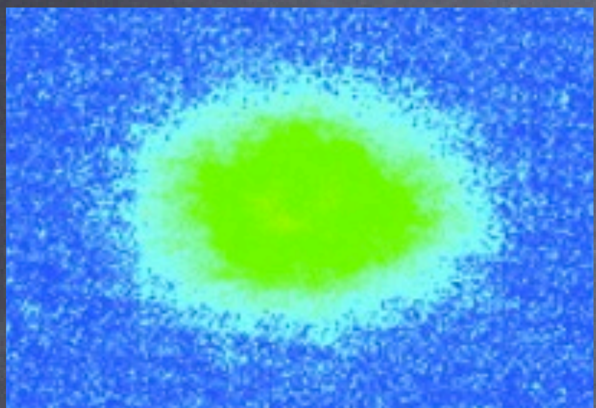
T≈10^{12}K

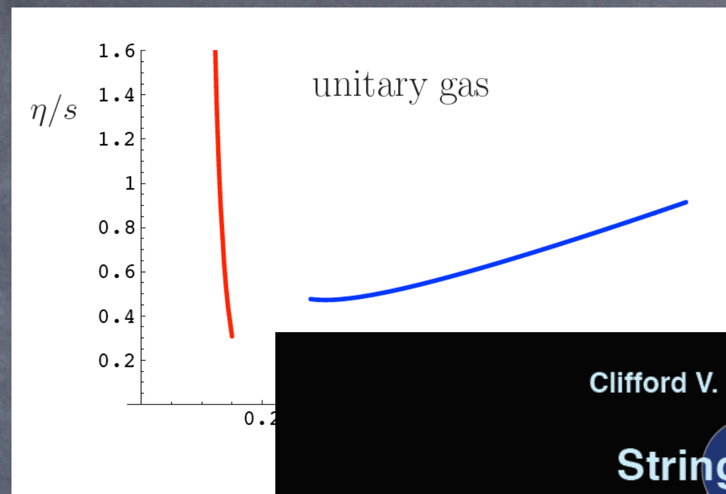
Varmeste sted på jorden

$$\eta \sim 10^{11} Pa \cdot s$$

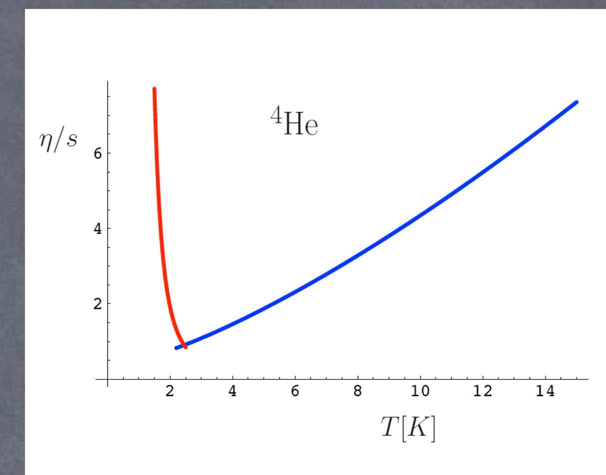
Strengteori: $\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$

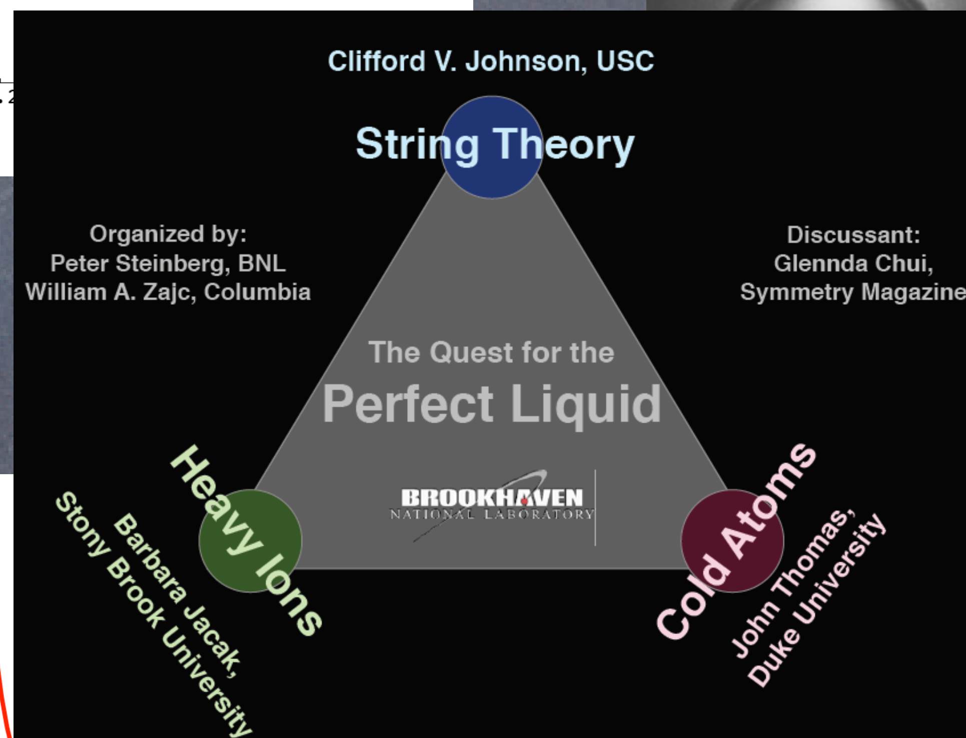
Atomare gasser $T \approx 10^{-7}$K



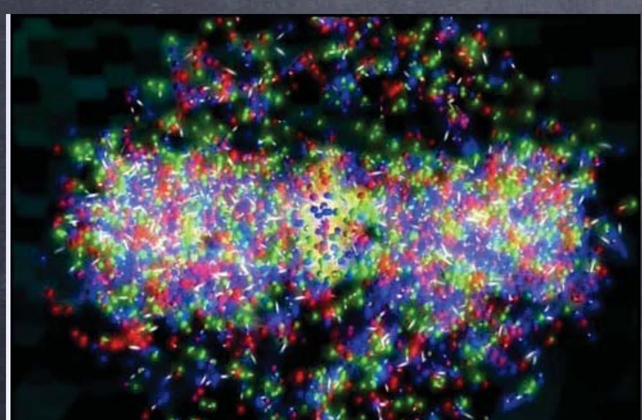


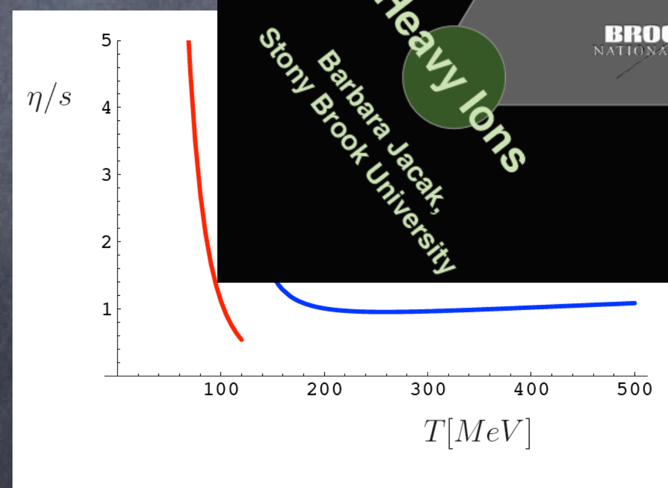
Flydende Helium $T \approx 1$K

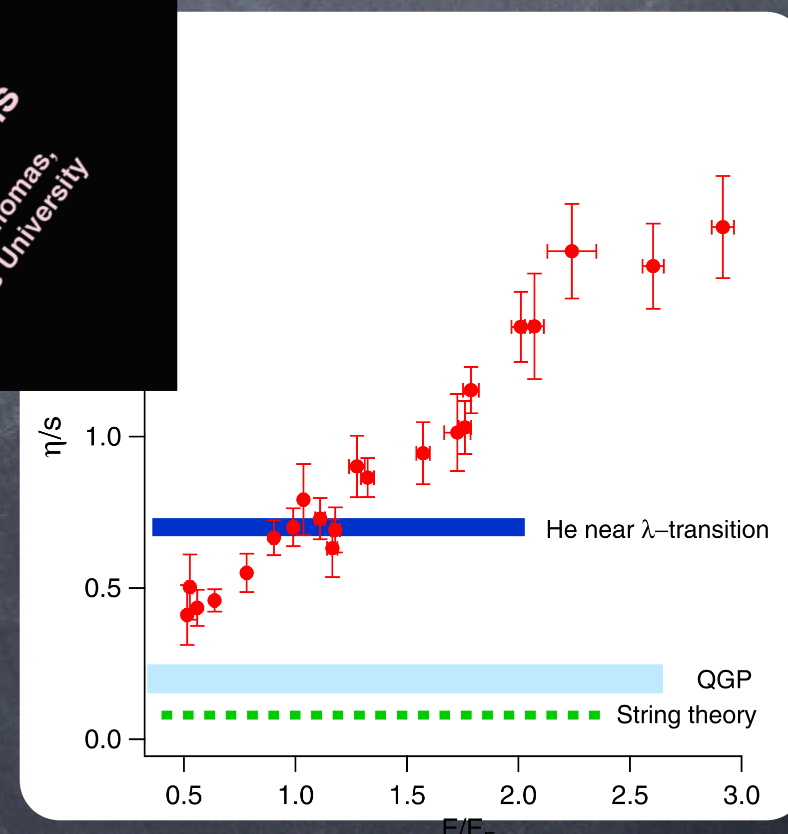




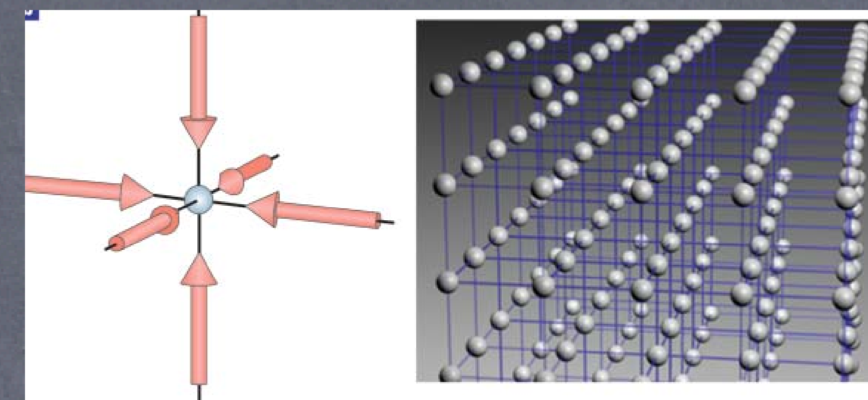
Quark-Gluon Plasma $T \approx 10^{12}$K



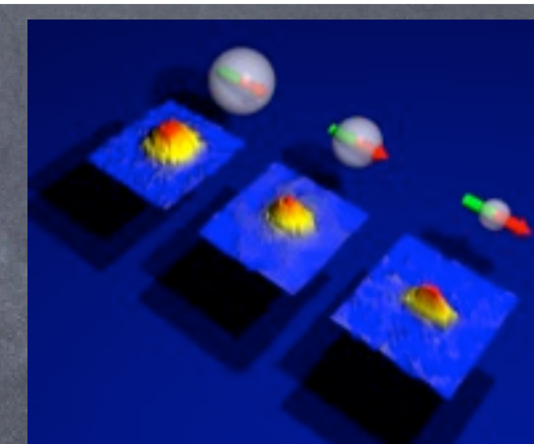




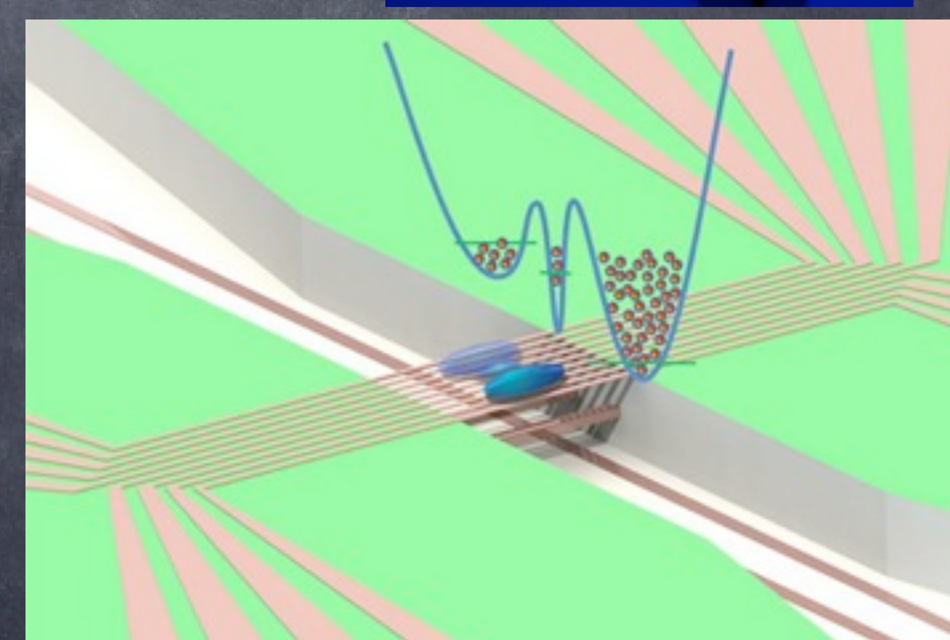
Perspektiver



- Nye stærkt/svagt vekselvirkende kvantesystemer, fundamental fysik



- Optiske gitre. Højtemperatur superledning, kvantekomputere, ...
- Dipolar molecules/atoms. Bose-Fermi blandinger, ny eksotisk fysik...



- Mesoskopiske/nano-systemer, atomtronics, kvanteinformation, ...