Evaporative Cooling

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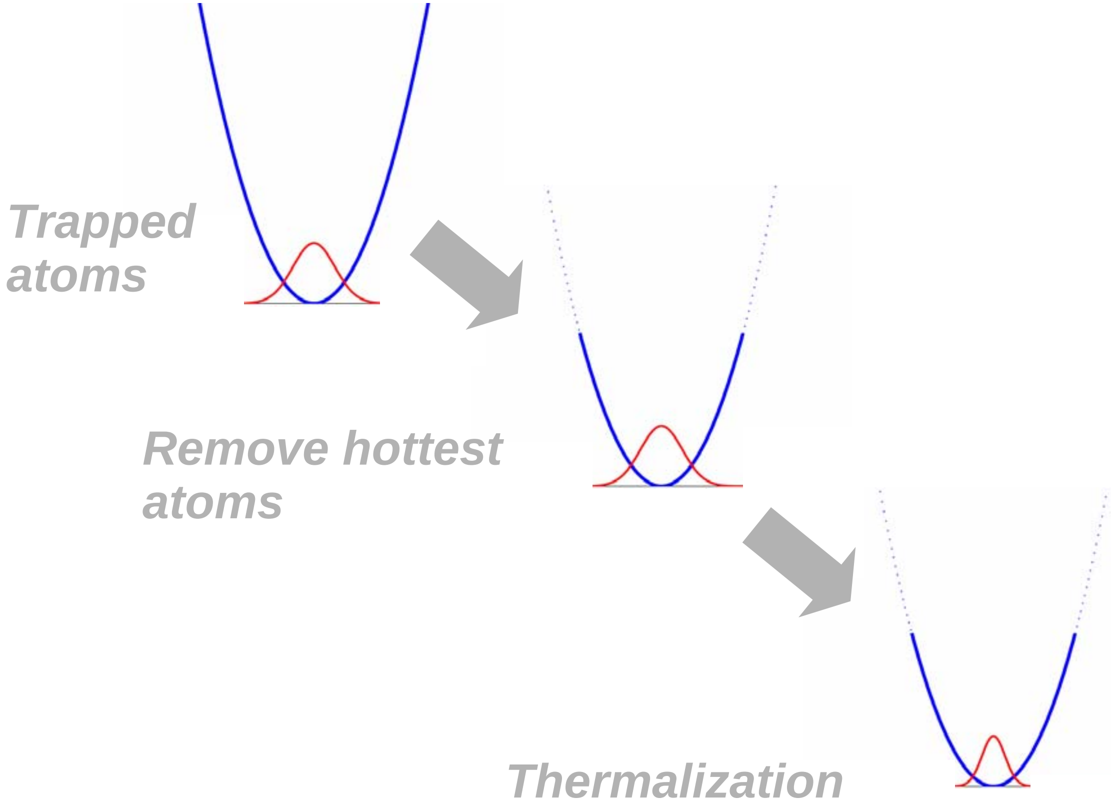
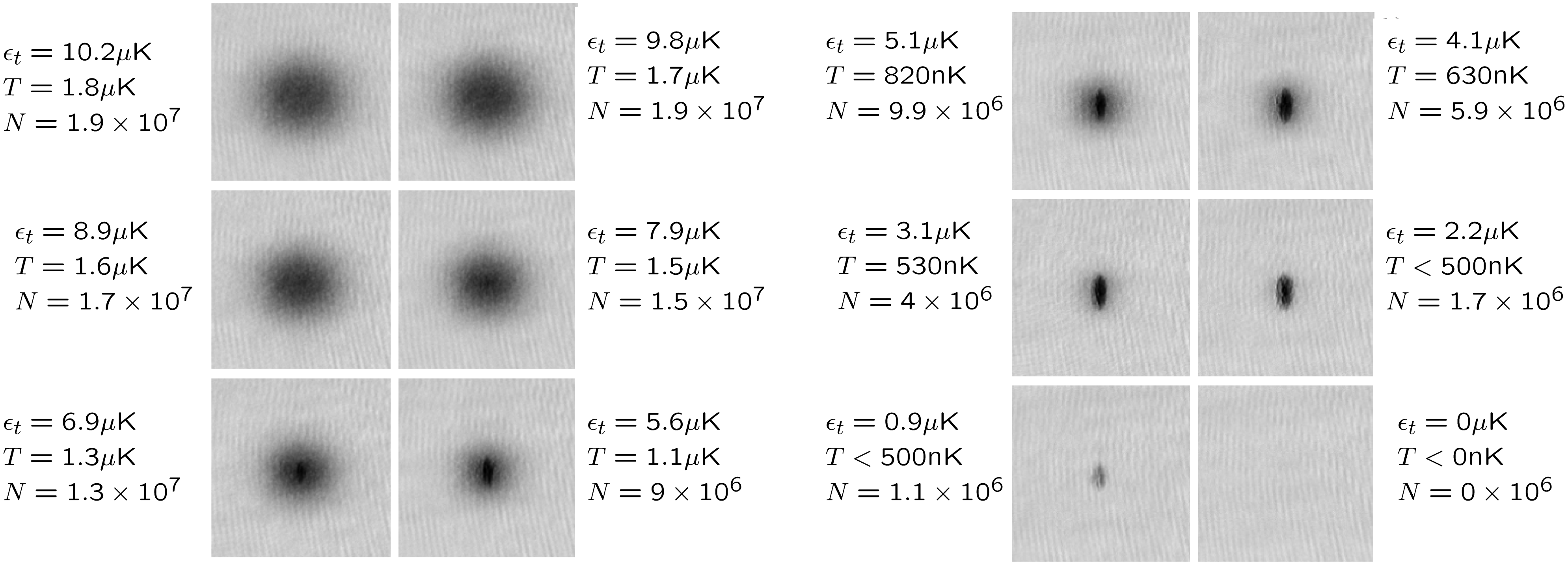
What is evaporative cooling?

In the Office:

In the Lab:



Evaporation in the Lab



K. Dieckmann, Thesis, University of Amsterdam (2001)

Outline

- Thermalization of an ultracold gas
- Model of evaporation
- Efficiency of evaporative cooling
  - Speed of evaporative cooling
  - Influence of loss processes
- Conclusion

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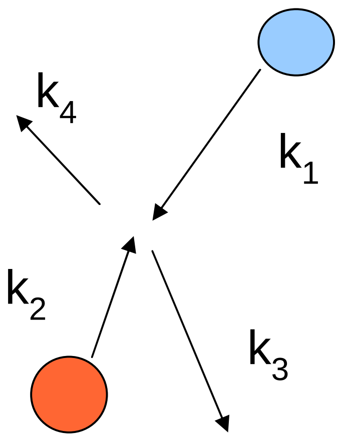
Elastic collisions in a dilute and cold gas



- **Dilute gas**
  → only binary collisions
- **Elastic collision of two particels**
  → Exchange of energy and momentum
- **S-wave cross-section and collision rate**

$$\sigma = \frac{8\pi a^2}{1+k^2a^2}$$

$$\sigma = 8\pi a^2 \;\; for \;\; k^2a^2 \ll 1$$ *Zero – energy limit*

$$\sigma = \frac{8\pi}{k^2} \;\; for \;\; k^2a^2 \gg 1$$ *Unitärity limit*

$$\tau^{-1} = n\overline{v}_r\sigma$$

- **Thermal Equlibrium:**
  → Ocupation number (for Bosons)

$$f(\vec{k}) = \left(\exp\left(\frac{E-\mu}{k_BT}\right) - 1\right)^{-1}$$

Thermalization of an ultracold gas

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Numerical simulation of the thermalization

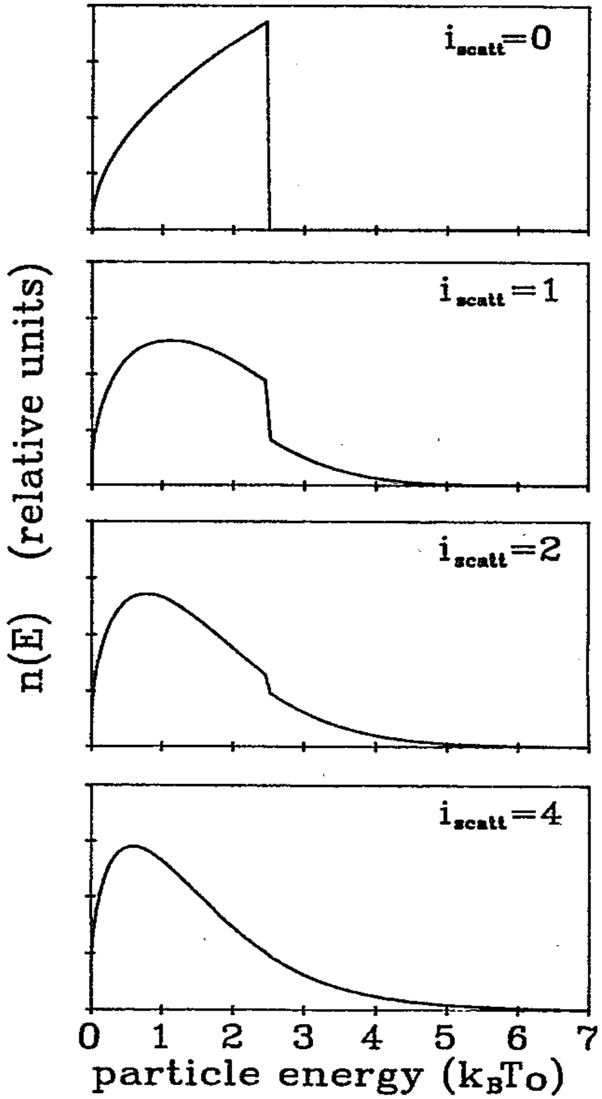
- **Starting with an uneqilibrium**
  e.g. $f(k) = f_0 \ \delta(k-k_0)$
- **Probability for bosons with wavevectors (k1 , k2) to scatter to (k3, k4):**

$$S(\mathbf{k}_1, \mathbf{k}_2; \mathbf{k}_3, \mathbf{k}_4) =$$
$$M^2 \delta(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4)\delta(E_1 + E_2 - E_3 - E_4)$$
$$\times f(\mathbf{k}_1) f(\mathbf{k}_2)[1 \pm f(\mathbf{k}_3)][1 \pm f(\mathbf{k}_4)]$$

- **Scattering rate into/ out of state with momentum k:**

$$\Gamma_{in}(\mathbf{k}) = \int d^3k_1 d^3k_2 d^3k_3 S(\mathbf{k}_1, \mathbf{k}_2; \mathbf{k}_3, \mathbf{k})$$
$$\Gamma_{out}(\mathbf{k}) = \int d^3k_1 d^3k_2 d^3k_3 S(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{k}_3)$$

- **Equlibrium:**
  Only **4** collision events necessary
  *(harmonic quadrupole trap: **2.7** collisions)*



Thermalization of an ultracold gas

Measurement of thermalization

- Density of a thermalized sample in a anisotropic harmonic tran ($\sigma \neq \sigma$):

$$n = n_0 \exp\left[-\beta\left(\left(\frac{x}{2\sigma_x}\right)^2 + \left(\frac{y}{2\sigma_y}\right)^2 + \left(\frac{z}{2\sigma_z}\right)^2\right)\right]$$

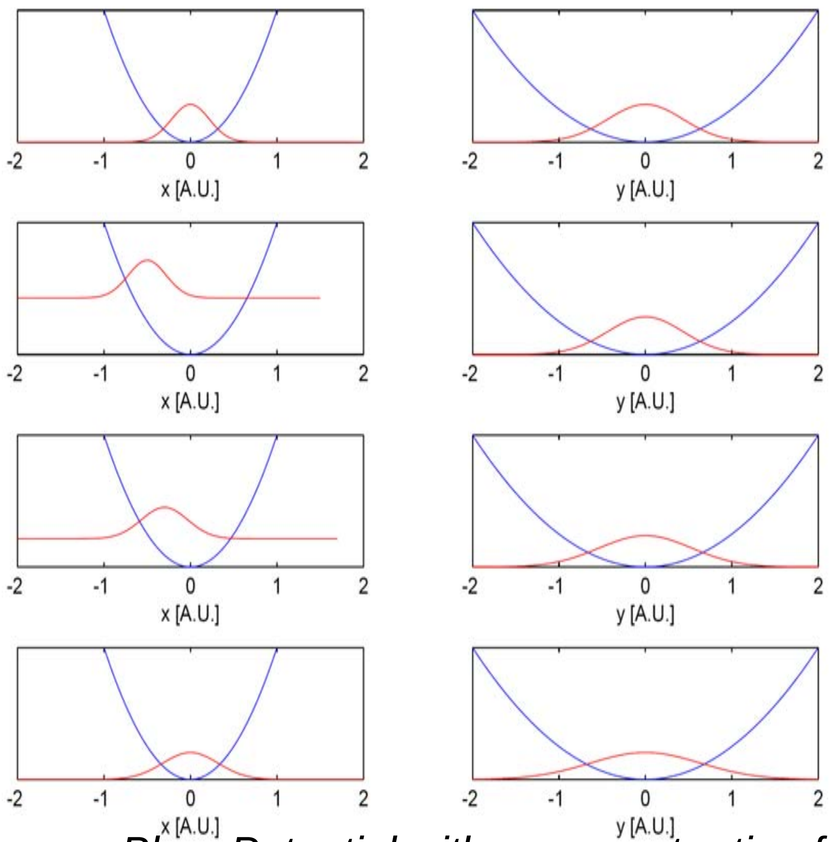
- Elongation of the cloude along one axisleads to oszillation along this axis

- Elastic collisions distribute the energy to all degreas of freedom

→ Thermalization when the aspect ratio reached his original value

Mesurement principle

Radial direction *Axial direction*



Blue: Potential with an aspect ratio of 2:1
Red: Density distributions along two axis

Thermalization of an ultracold gas

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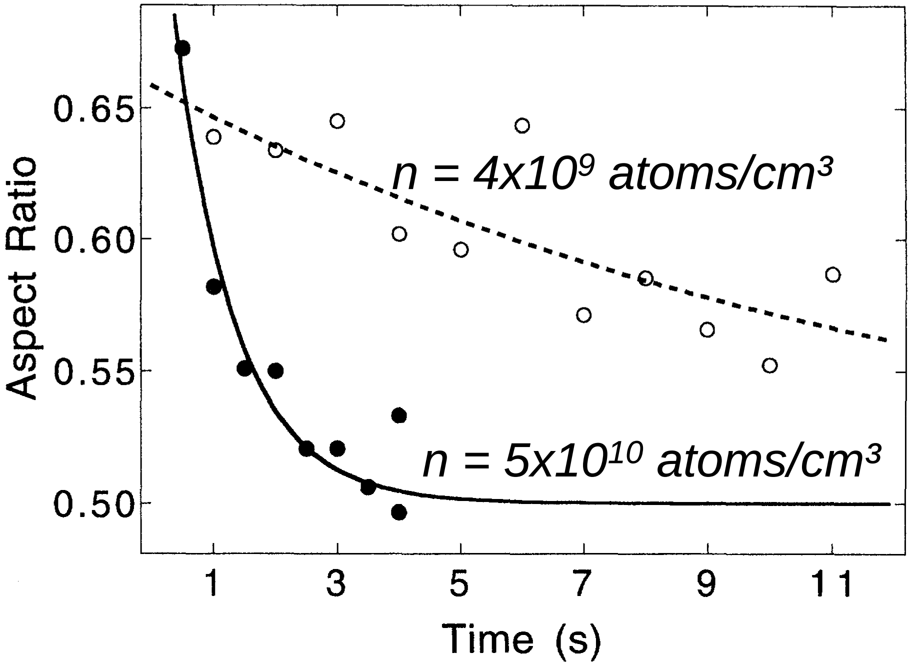
Thermalization of sodium atoms in a quadrupol trap with an aspect ratio of 2:1



Determinating the elastic cross section:

τ= 1s for n = 5×10^{10} atoms/cm³

τ = 13s for n = 4×10^{9} atoms/cm³

$$n_{\text{eff}}\sigma v = 2.7/\tau$$
$$\sigma = (6.0 \pm 3.0) \times 10^{-12}\text{cm}^2$$
$$\sigma = 8\pi a^2$$
$$\Rightarrow a = \pm(92 \pm 25)a_0$$

Thermalization near a resonance

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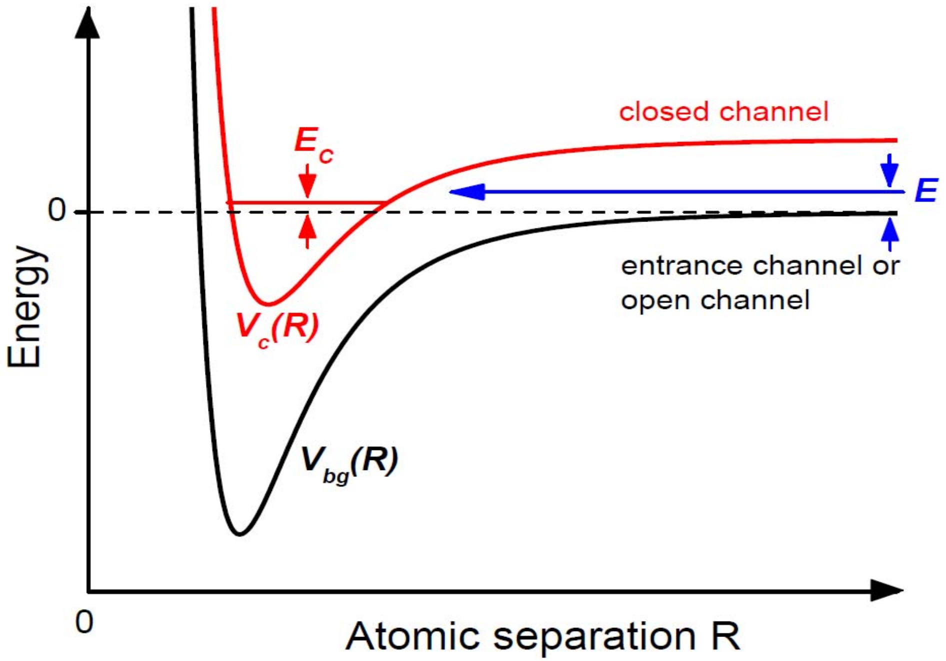
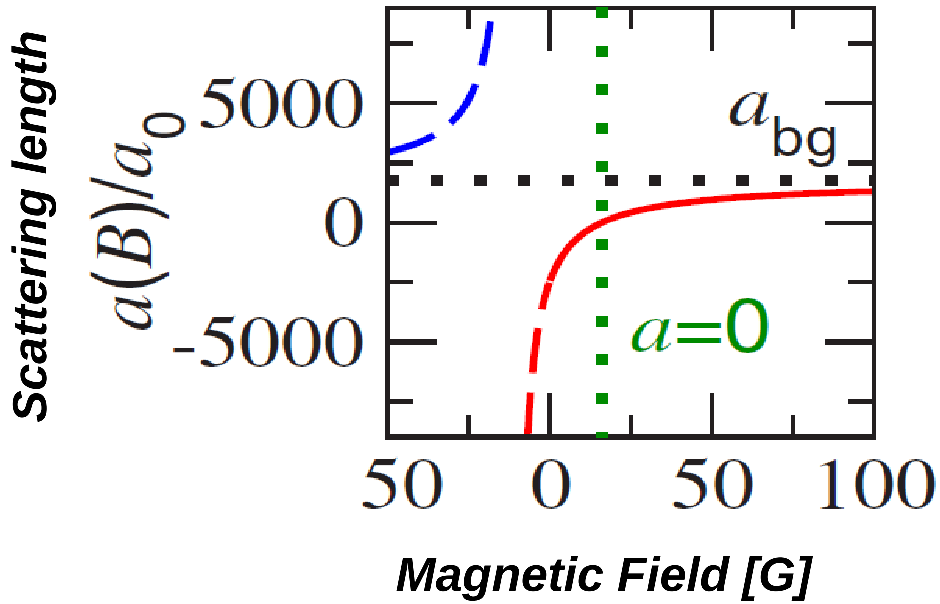
Feshbach -Resonances



C. Chin et all., arXiv 0812.1496v2

Zero-Energy resonance in ^{133}Cs in F=3 m_F=+3

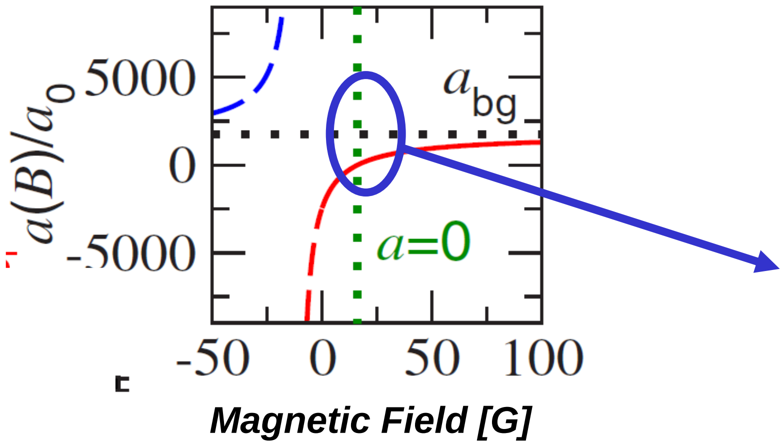


M. Lee et all., Phys. Rev. A **76**,12720 *(2007)*

$$a(B) = a_{bg}\left(1 - \frac{\Delta B}{B - B_0}\right)$$

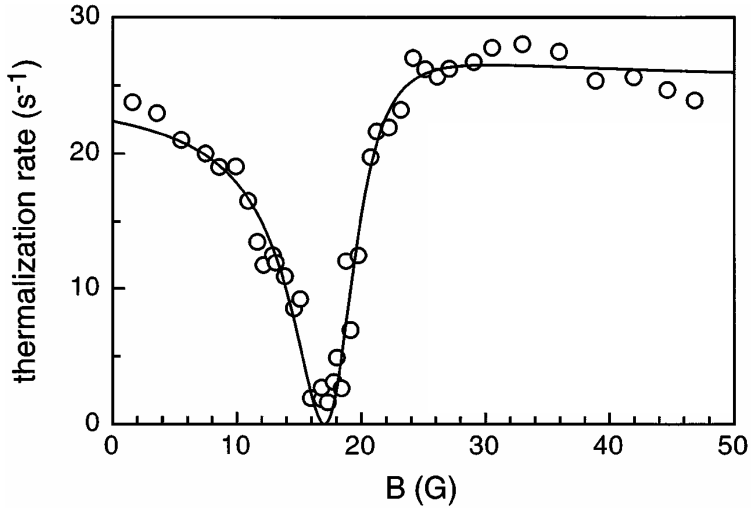
Thermalization near a resonance

Thermalization at a=0



$$\sigma = 8\pi a^2$$
$$\Rightarrow \sigma = 0 \;\; for \;\; a = 0$$

Thermalization rate for Cs near 17G



-> no thermalization at a=0

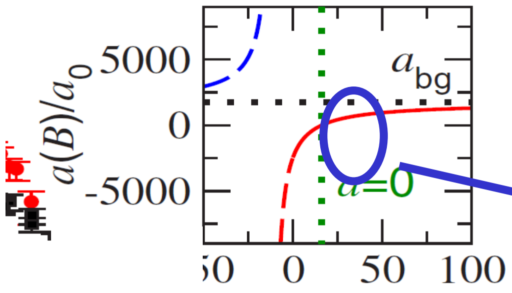
Thermalization near a resonance

Thermalization in the unitarity limit

$$\sigma(k) = \frac{8\pi}{k^2}$$
$$k^{-1} = \lambda_{deB} = [4k_B T m/(\pi\hbar^2)]^{-1/2}$$

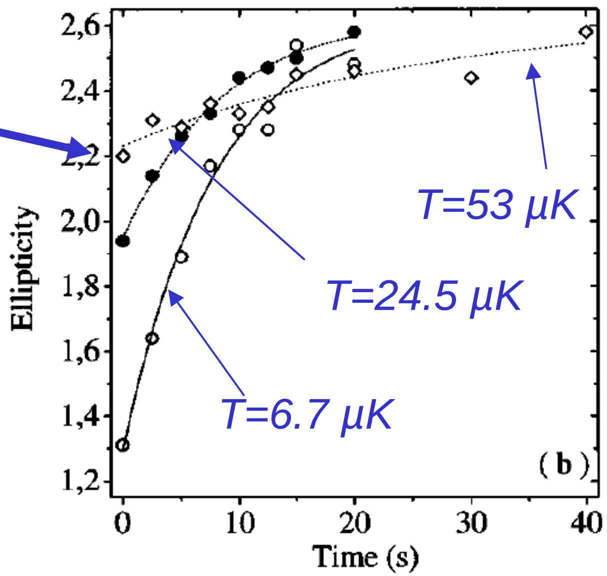
Collision rate now depends on the relative velocity: $\gamma_c = 128 n\hbar^2/vM^2$

Monte-Carlo simulations: 10.7 collisions instead of 2.7 needed for thermalization

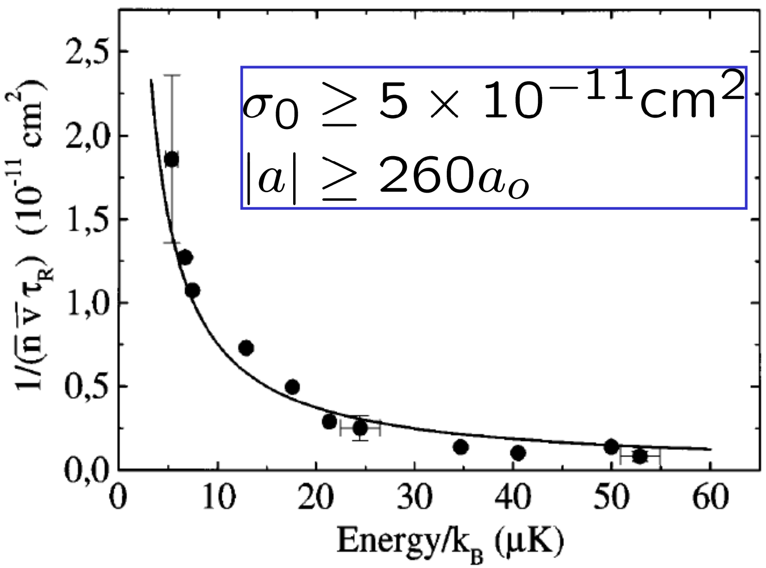


Magnetic Field [G]

Messurement of the thermalization



Temperatur dependent cross-section



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- Efficiency of evaporative cooling
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Evaporation in the Lab

$\epsilon_t = 10.2\mu$K
$T = 1.8\mu$K
$N = 1.9 \times 10^7$

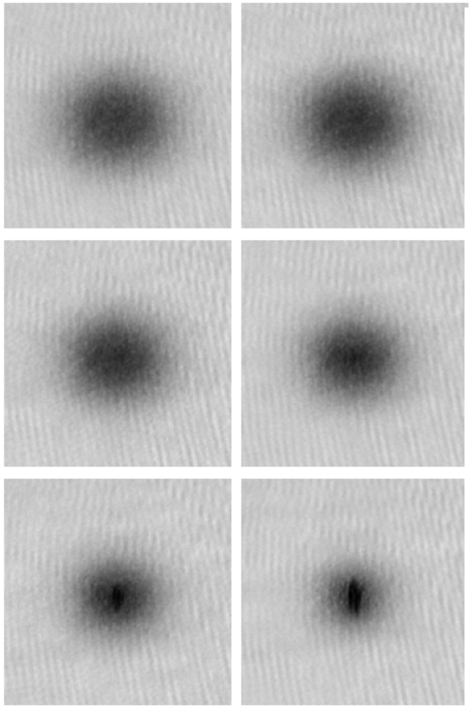
$\epsilon_t = 9.8\mu$K
$T = 1.7\mu$K
$N = 1.9 \times 10^7$

$\epsilon_t = 8.9\mu$K
$T = 1.6\mu$K
$N = 1.7 \times 10^7$

$\epsilon_t = 7.9\mu$K
$T = 1.5\mu$K
$N = 1.5 \times 10^7$

$\epsilon_t = 6.9\mu$K
$T = 1.3\mu$K
$N = 1.3 \times 10^7$

$\epsilon_t = 5.6\mu$K
$T = 1.1\mu$K
$N = 9 \times 10^6$



$\epsilon_t = 5.1\mu$K
$T = 820$nK
$N = 9.9 \times 10^6$

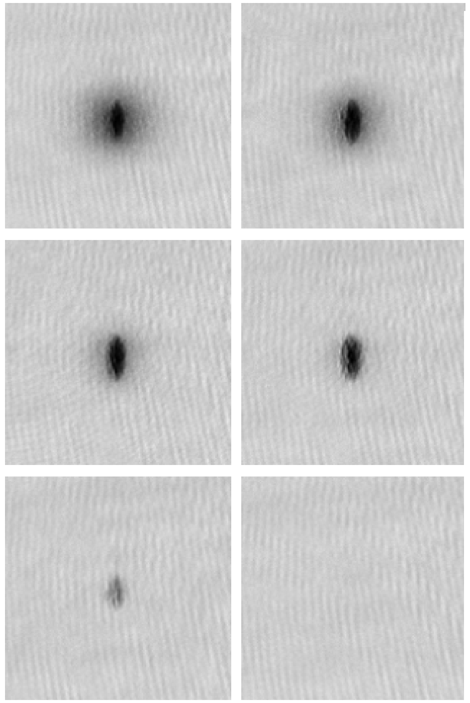
$\epsilon_t = 4.1\mu$K
$T = 630$nK
$N = 5.9 \times 10^6$

$\epsilon_t = 3.1\mu$K
$T = 530$nK
$N = 4 \times 10^6$

$\epsilon_t = 2.2\mu$K
$T < 500$nK
$N = 1.7 \times 10^6$

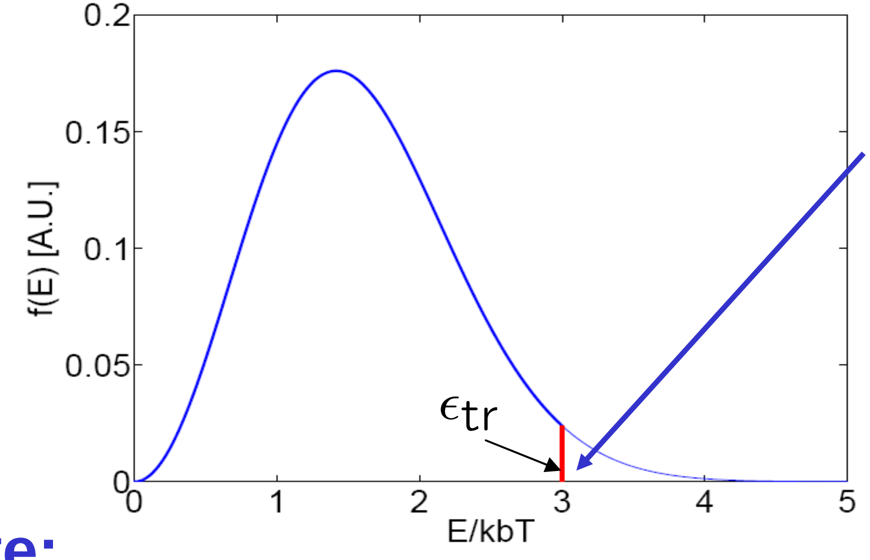
$\epsilon_t = 0.9\mu$K
$T < 500$nK
$N = 1.1 \times 10^6$

$\epsilon_t = 0\mu$K
$T < 0$nK
$N = 0 \times 10^6$



Model of evaporative cooling

Truncated Boltzman distribution



$$\eta = \frac{\epsilon_{\text{tr}}}{k_B T}$$

Truncation parameter

$$\eta = \frac{\epsilon_{\text{tr}}}{k_B T}$$

Evaporation rate:

- Removing all particels with an energie E>ϵ

$$\Gamma_{\text{ev}} = \frac{N_{\text{untruncated}}(E > \epsilon_{tr})}{\tau_{\text{el}}}$$

- For large η :fraction of atoms with E>ϵ

$$\frac{N(E > \epsilon_{\text{tr}})}{N} = 2e^{-\eta}\sqrt{\eta/\pi}$$

- Rate of evaporation:

$$\dot{N} = -N n_0 \sigma v \eta e^{-\eta} = \frac{-N}{\tau_{ev}}$$

- Ratio of elastic collisions and time constant for evaporation:

$$\lambda = \frac{\sqrt{2}e^{\eta}}{\eta}$$

Model of the evaporation

Temperature change:

Remove atoms with potential energy

$$\epsilon_{tr} = \eta k_B T$$

The system looses the energy

$$\dot{E} = (\eta + 1)\dot{N} k_B T$$

Total Energy of the system:

$$E = 3N k_B T$$

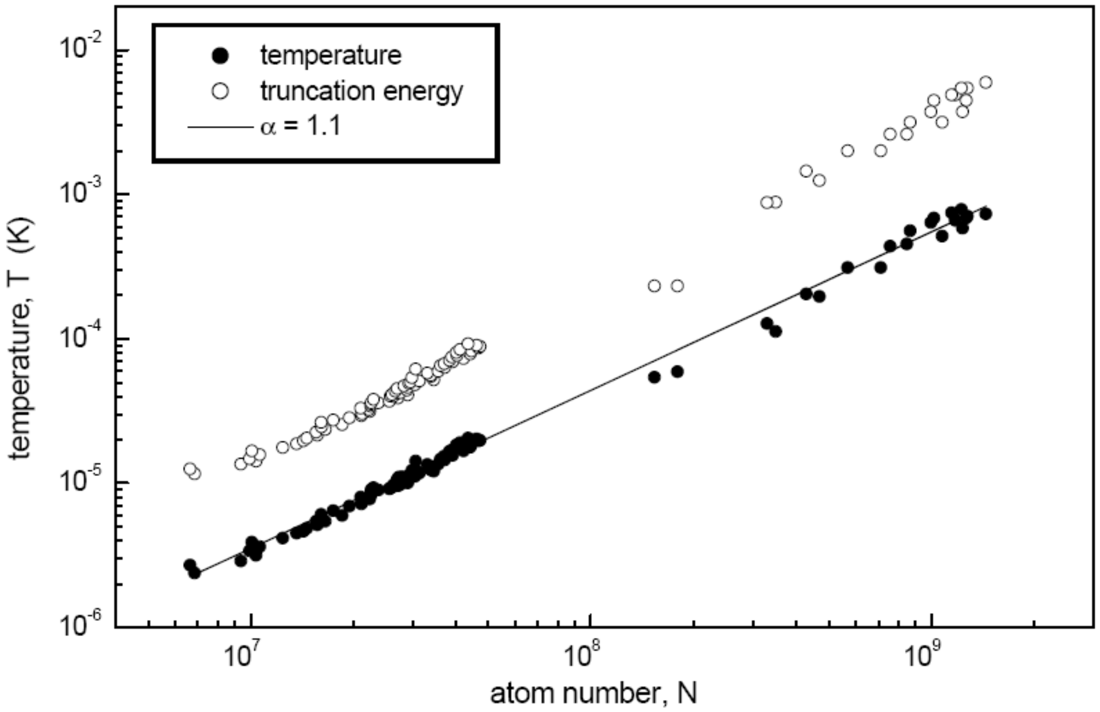
$$\Rightarrow \dot{E} = 3\dot{N} k_B T + 3N k_B \dot{T}$$

$$\Rightarrow \frac{\dot{T}}{T} = \frac{1}{3}(\eta - 2)\frac{\dot{N}}{N}$$

$$\Rightarrow \frac{T}{T_0} = \left(\frac{N}{N_0}\right)^{\alpha};$$

$$\alpha = \frac{1}{3}(\eta - 2)$$

Decrease of the temperature



K. Dieckmann. Thesis, University of Amsterdam (2001)

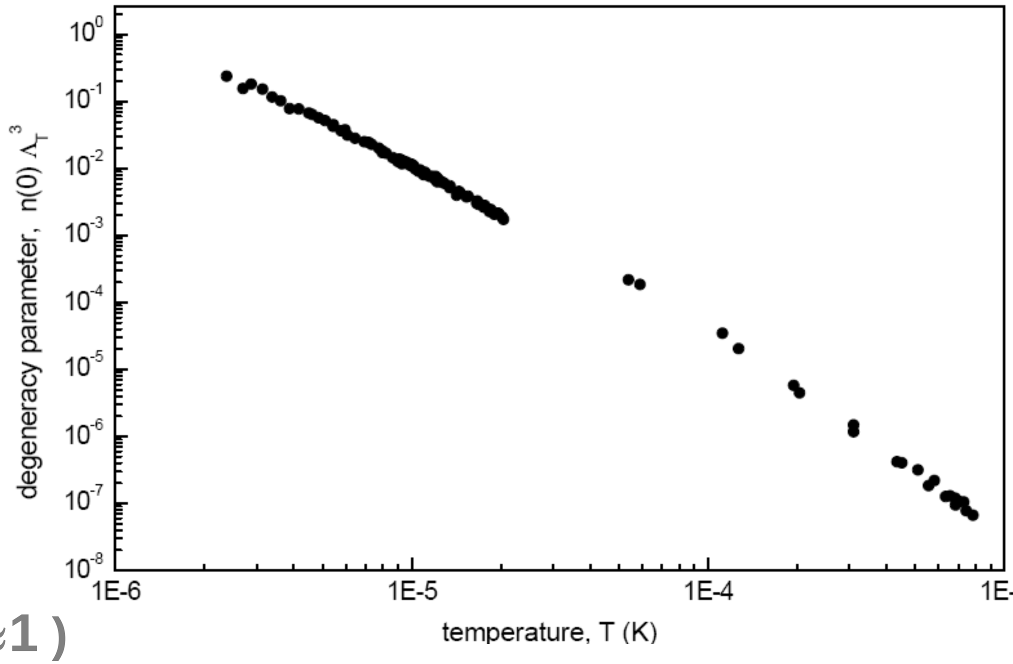
O. Luiten et all., Phys. Rev. A **53**, *381* (1996)

Model of the evaporation

Density and phasespace-density behavior:

$$N = n_0 V_e$$
$$V_e = \int e^{-U(r)/K_B T} d^3 r$$
$$\Rightarrow \frac{\dot{n}_0}{n_0} = \frac{\dot{N}}{N} - \frac{\dot{V}_e}{V_e}$$
$$\Rightarrow \frac{\dot{n}_0}{n_0} = \frac{\dot{N}}{N} - \frac{3}{2}\frac{\dot{T}}{T}$$
$$\Rightarrow \frac{\dot{n}_0}{n_0} = \frac{1}{2}(4-\eta)\frac{\dot{N}}{N}$$

Increase of the phasespace-density



K. Dieckmann. Thesis, University of Amsterdam (2001)

Phasespace density D (for BEC: D≈1)

$$D = n_0 \lambda^3$$
$$\lambda = \sqrt{2\pi^2\hbar/(2mk_B T)}$$
$$\boxed{\Rightarrow \frac{\dot{D}}{D} = (3-\eta)\frac{\dot{N}}{N}}$$

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Loss Processes

Collisions in an ultracold sample

"Good collisions": Elastic collisions

→ Thermalization

$$\Gamma_{\text{el}} = n\sigma v$$

$$\Gamma_{\text{el}} \sim n \times T^{1/2}$$

"Bad collisions": Inelastic collisions

→ Loos of atoms

- Inelastic one-body collisions
  - Collisions with background gas

$$\Gamma_{\text{Bg}} \sim p$$

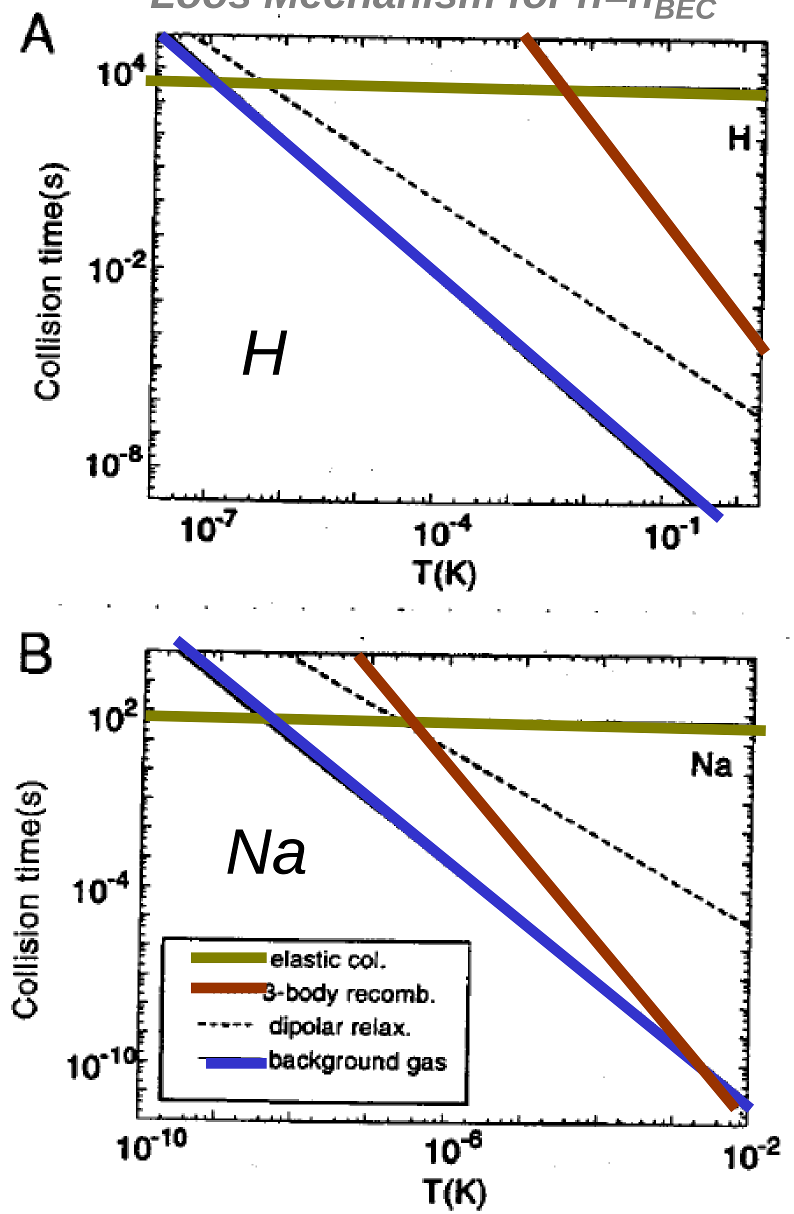
- Inelastic two-body collisions
  - Dipolar and spin relaxation

$$\Gamma_{\text{2body}} \sim n$$

- Inelastic three-body collisions
  - Three-body recombination

$$\Gamma_{\text{3body}} \sim n^2$$

Loos Mechanism for $n=n_{BEC}$



Speed of evaporation

Change of the elastic collision rate:

$$\frac{d(n\sigma v)}{dt}/n\sigma v = \frac{\dot{n}}{n} + \frac{\dot{v}}{v} - \frac{1}{\tau_{loss}}$$

$$= \frac{\dot{n}}{n} + \frac{1}{2}\frac{\dot{T}}{T} - \frac{1}{\tau_{loss}}$$

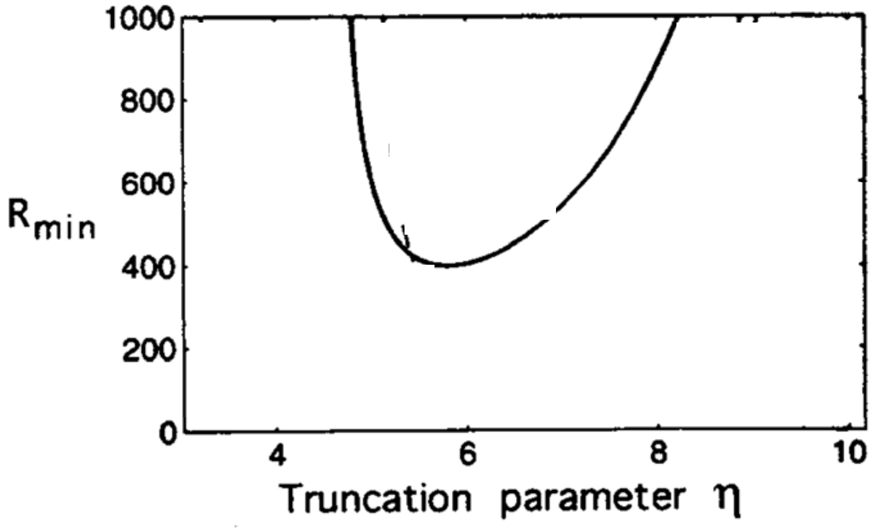
$$\frac{\dot{T}}{T_0} = \alpha \frac{\dot{N}}{N_0}$$

$$\frac{\dot{n}}{n} = \frac{\dot{N}}{N} - \frac{3}{2}\frac{\dot{T}}{T} \Rightarrow$$

$$\frac{d(n\sigma v)}{dt}/n\sigma v = \left(\frac{\alpha-1}{\tau_{ev}} - \frac{1}{\tau_{loss}}\right)$$

→ Elasitic collision rate increases
for $\frac{\tau_{el}}{\tau_{loss}} \geq R_{min}$ („Runaway Evaporation")

Limit for Runaway evaporation
In a harmonic trap



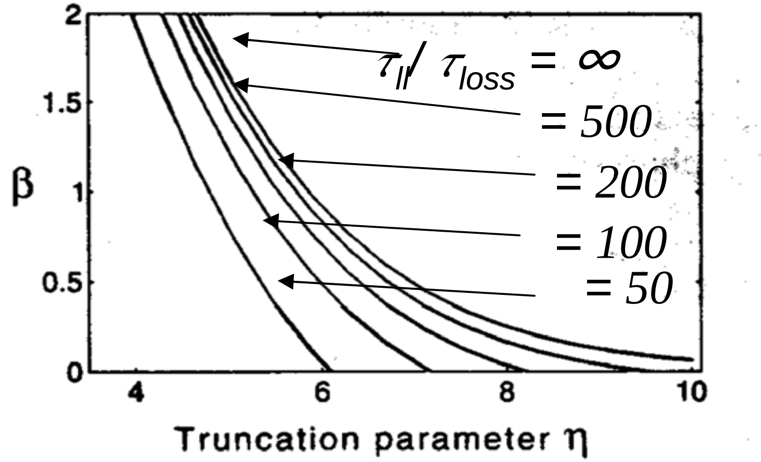
Efficiency of evaporative cooling

Maximizing phase-space density

Increase of phase space density
(per 100 elastic collisions)

$$\beta = 100\tau_{el}\frac{d}{dt}(log_{10}D) = \frac{100}{ln10}\left(\frac{\alpha-1}{\lambda} - \frac{1}{\tau_{loss}/\tau_{el}}\right)$$

Calculated Phasespace density increase



Efficiency of evaporative cooling:

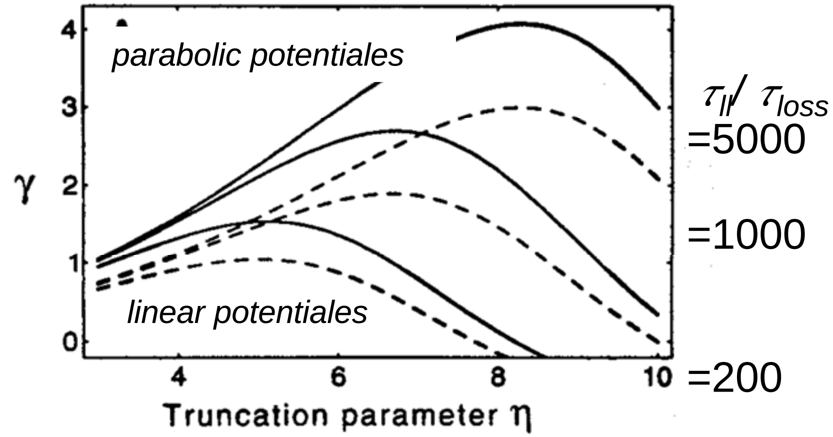
Efficiency of one step:

$$\gamma = -\frac{d(lnD)}{d(lnN)} = \frac{\alpha}{1+\lambda/R} - 1$$

Efficiency of the whole process:

$$\gamma_{tot} = \frac{ln(D_{final}/D_{init})}{ln(N_{final}/N_{init})}$$

Calculated efficiency parameter



Efficiency of evaporative cooling

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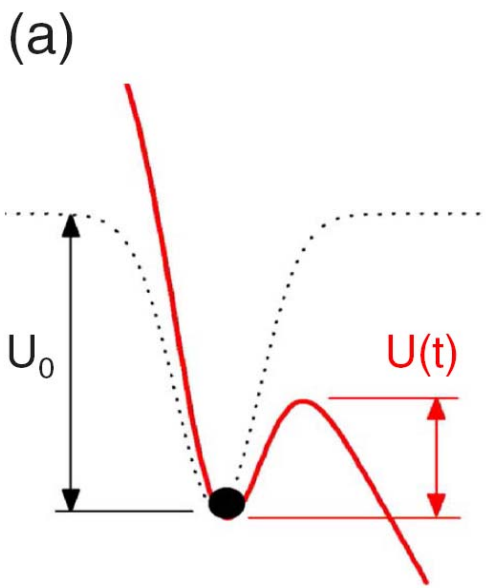
Evaporation in an optical dipole trap

Problem:

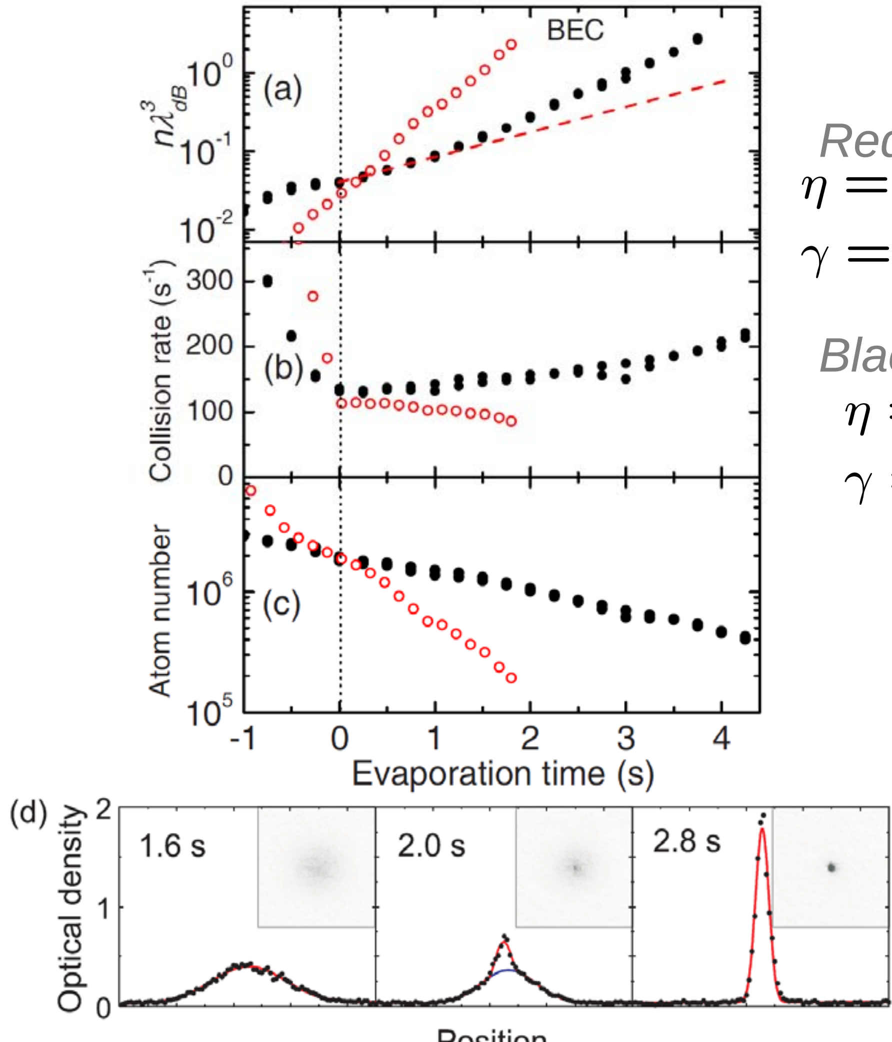
Lowering the trap depth also decreases the collision rate

Solution:

Evaporation via a magnetic gradiant



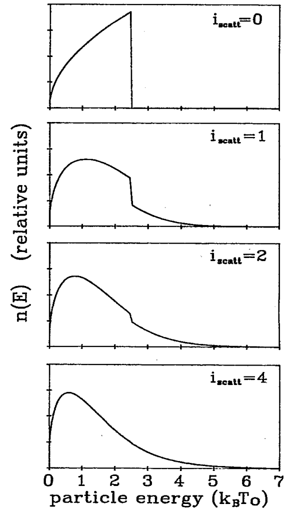
Evaporation of Cs atoms in an optical trap at different truncation parameters



Red: $\eta = 4.6$ $\gamma = 1.9$

Black: $\eta = 6.5$ $\gamma = 3.4$

Conclusion



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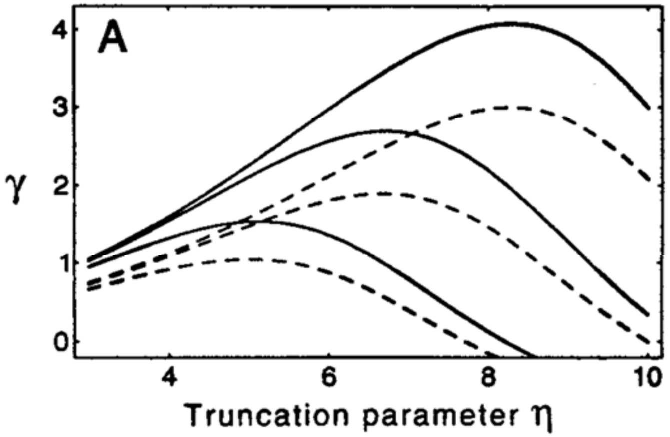

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- *Kai Dieckmann*

  Bose-Einstein Condensation with High Atom Number in a Deep Magnetic Trap

  University of Amsterdam, 2 March 2001 ;Thesis advisor: Prof. Dr. J.T.M. Walraven

  from www.staff.science.uva.nl/~walraven/walraven/Theses.htm