Universität Hannover

Cold Metastable Neon Atoms

Towards Degenerated Ne*- Ensembles

Supported by the DFG Schwerpunktprogramm SPP 1116
and the European Research Training Network „Cold Quantum Gases“

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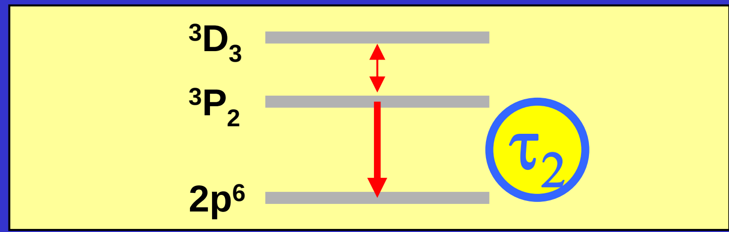
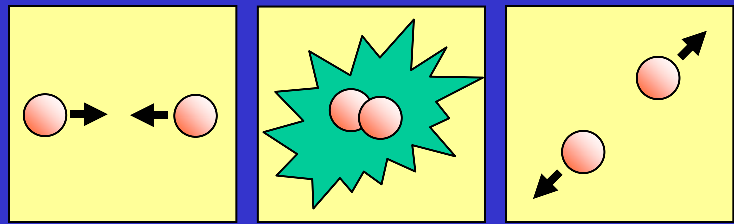
IQ Institut für Quantenoptik

Outline

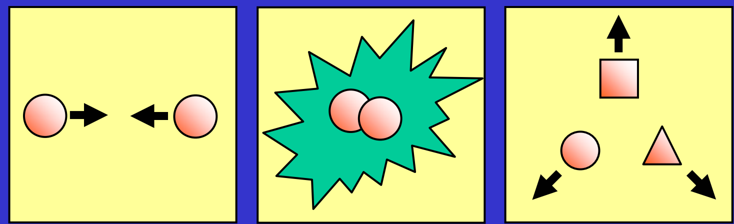
- Metastable neon
- $^3P_2$-Lifetime



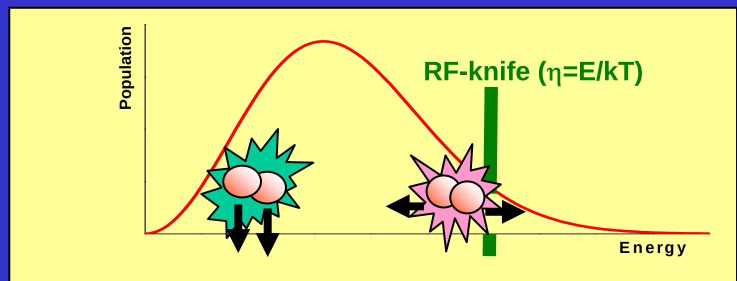
- Elastic collisions and scattering length



- Inelastic collisions and their suppression



- Evaporative cooling

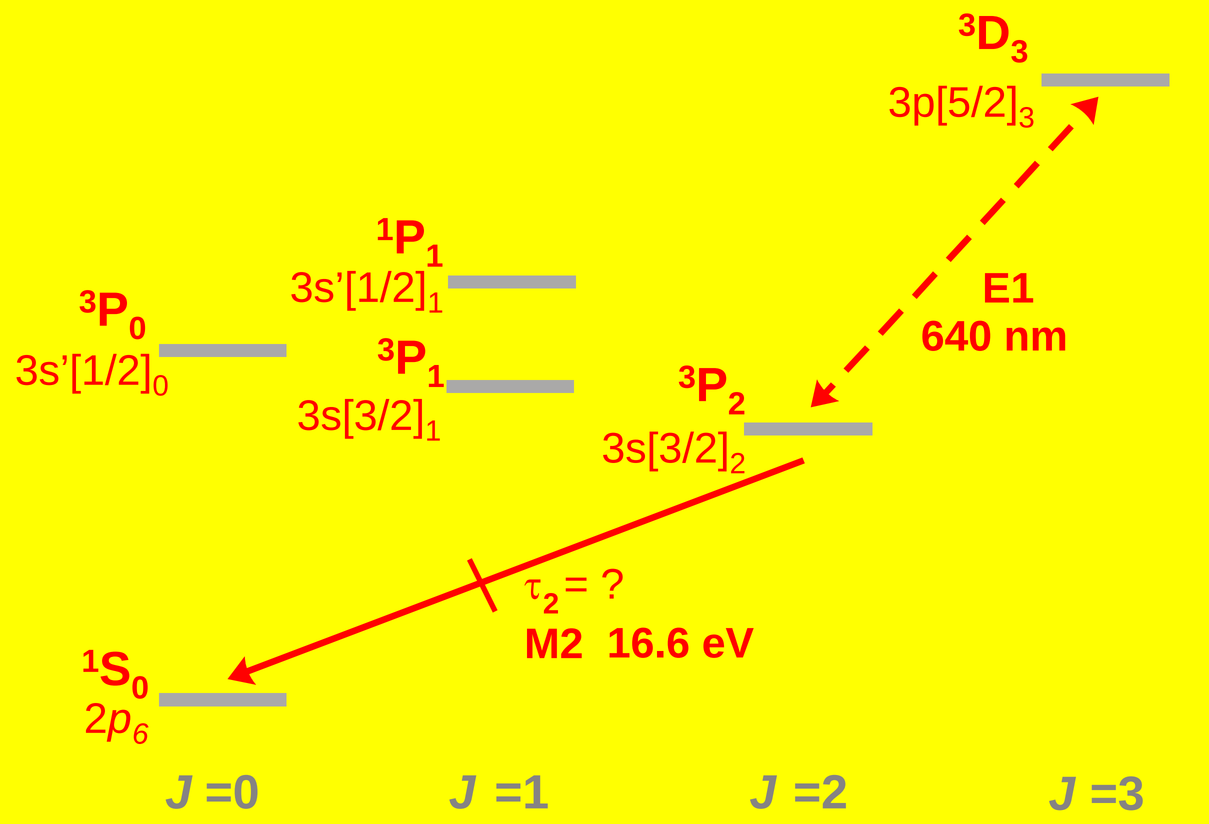


- Outlook

Neon

Naturally occurring Neon-Isotopes

Mass	Abundance [%]	Nuclear Spin
20	90.48	0
21	0.27	3/2
22	9.25	0



- Laser-cooling parameters:

Wavelength	640 nm
Doppler limit	200 µK
Recoil limit	2.3 µK

Penning-Ionization:

$$Ne^* + Ne^* \longrightarrow Ne^+ + Ne + e^-$$

From atomic physics to BEC

Atomic physics

- Lifetime of the metastable state: ?

M. Zinner et al., PRA 67, 010501(R) (2003)

Collision physics

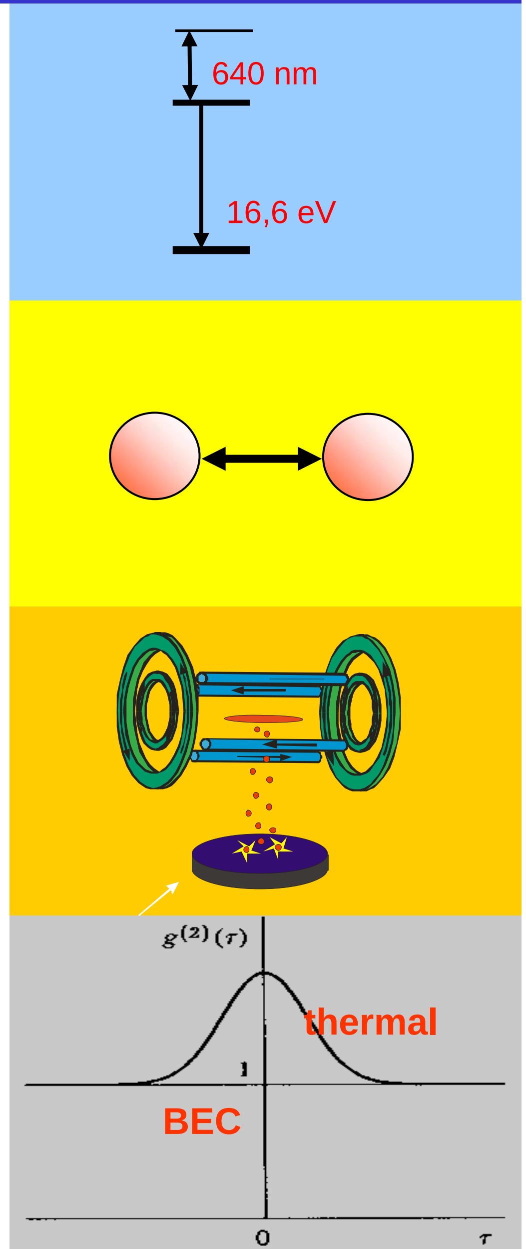
- Rates of elastic and inelastic collisions
- Suppression of Penning-Ionization by spin-polarization: 10^4 ?

Electronic Detection

- Direct, highly efficient detection of Ne^* and Ne^+
- Real-time detection of ions
- Spatially resolved detection of atoms

Bose-Einstein-Condensation

- Investigation of collective excitations
- Measurement of higher order correlation functions



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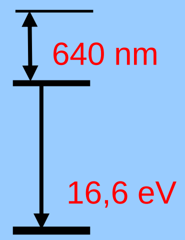

Collision physics

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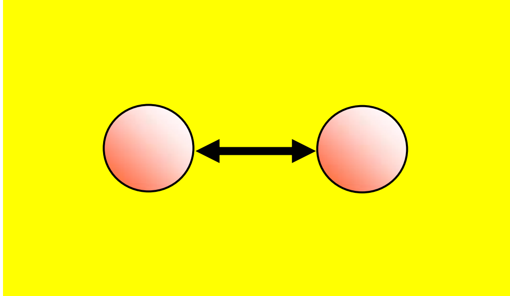

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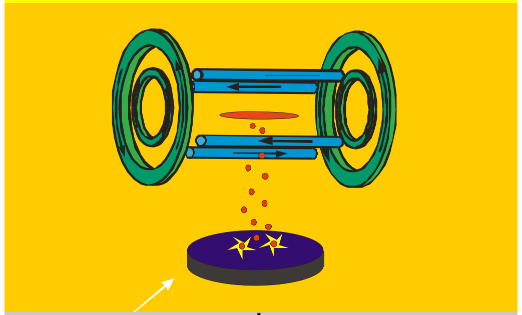

Bose-Einstein-Condensation

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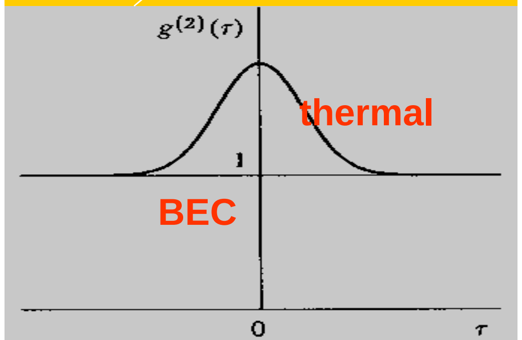
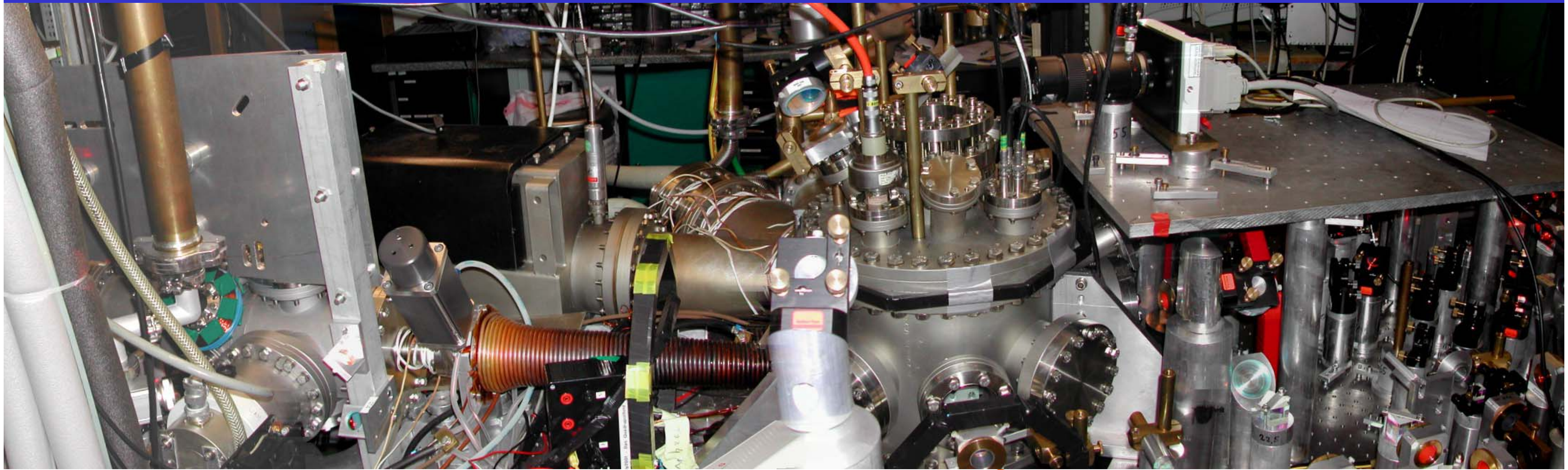
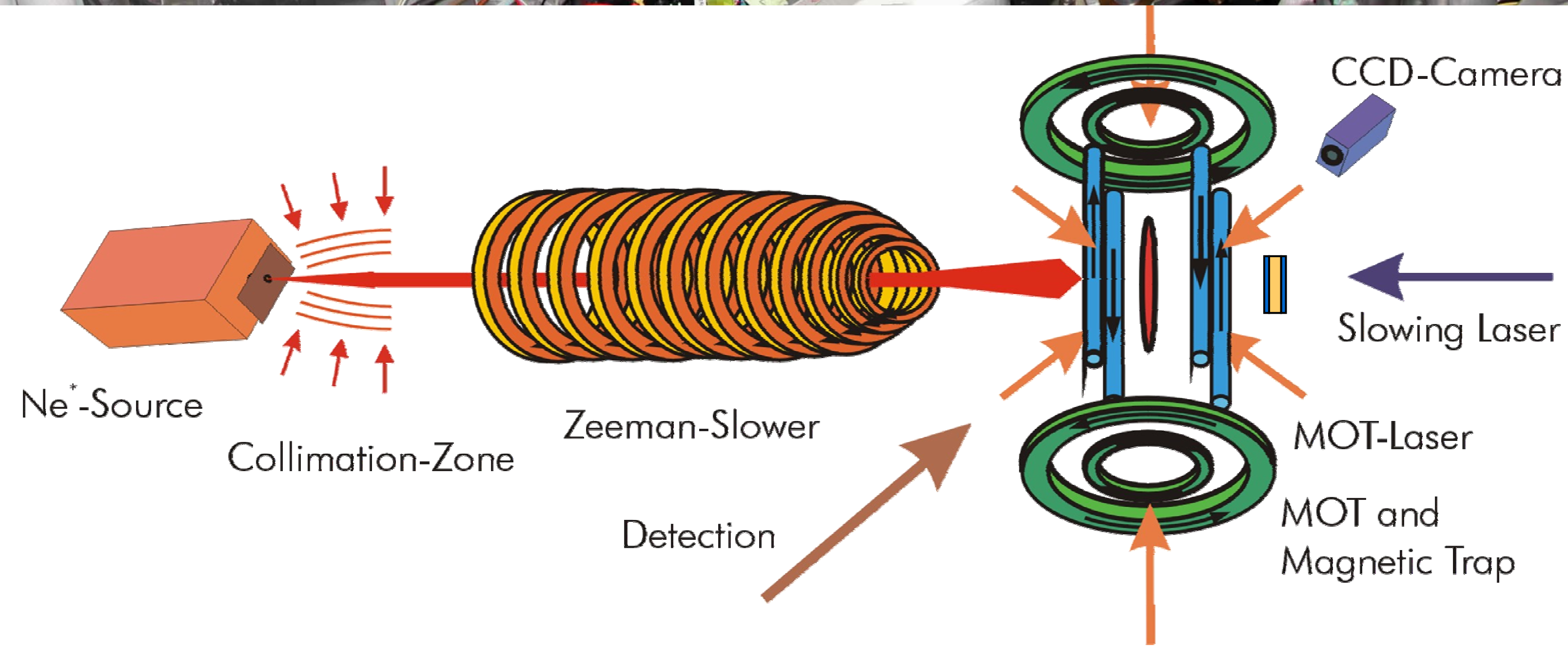
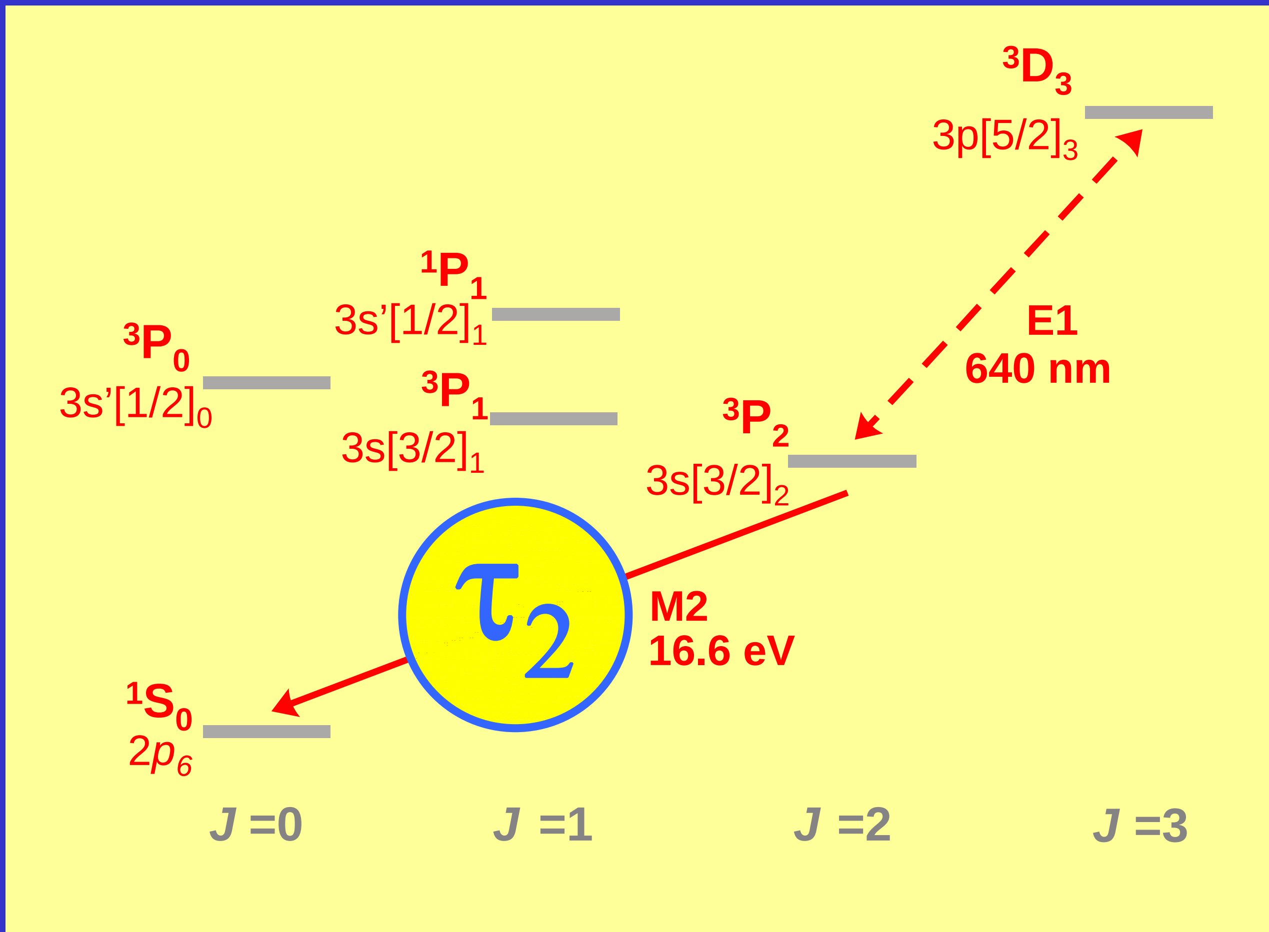


Experimental Setup



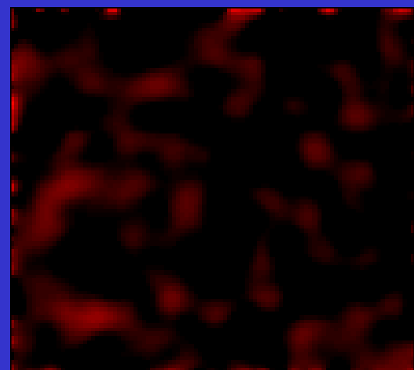


Lifetime of the metastable state



After Loading the MOT

observation of decay by fluorescence



Fluorescence of ^{20}Ne in a MOT

- MOT decay

$$\dot{N} = -\alpha N - \beta \frac{N^2}{V_{eff}}$$

- Origins of one-body losses

$$\alpha = \frac{\pi_2}{\tau_2} + \frac{\pi_3}{\tau_3}$$

radiative decay

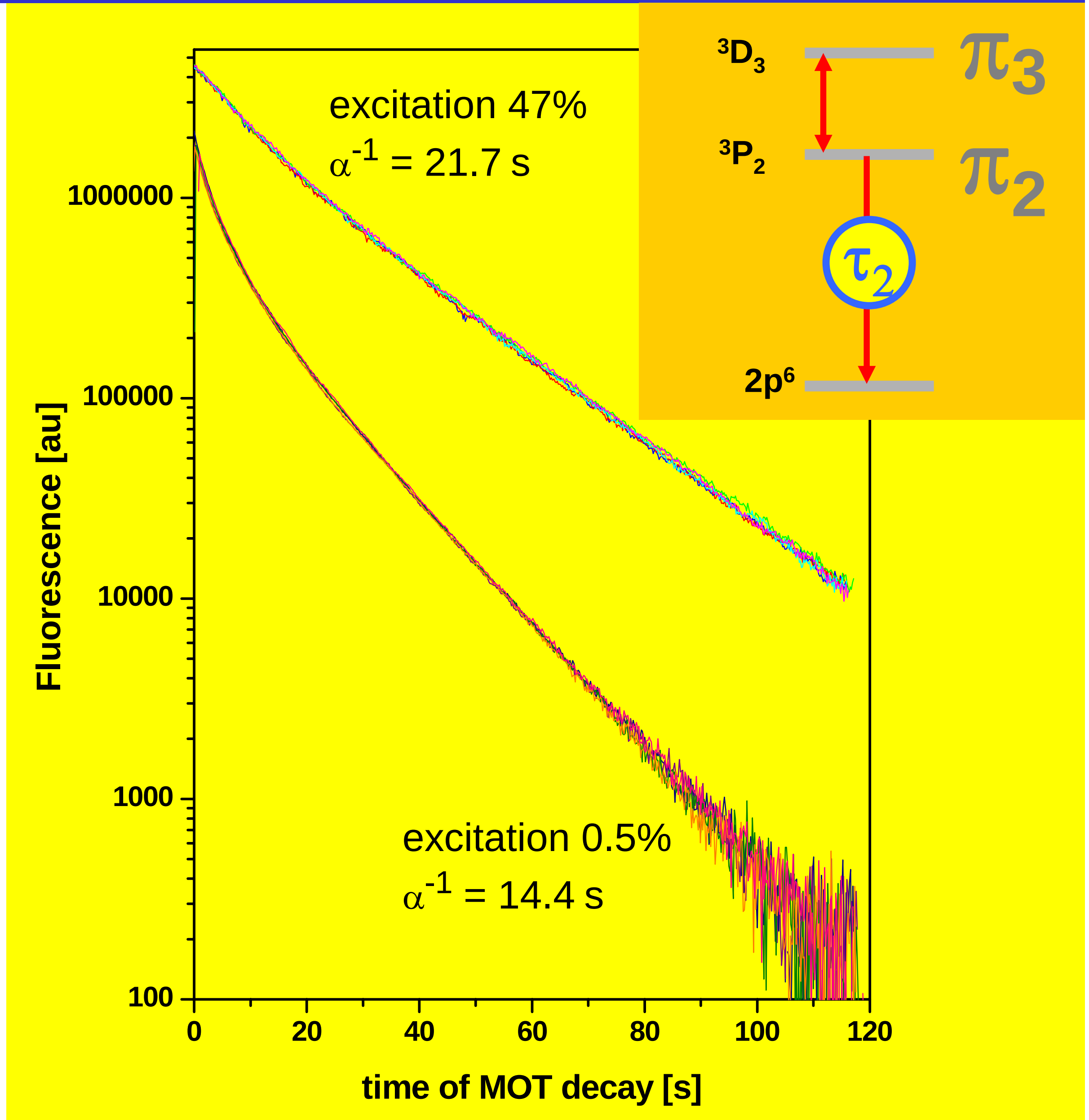
$$+ \gamma \cdot p$$

background collisions

$$+ \alpha_{FT}$$

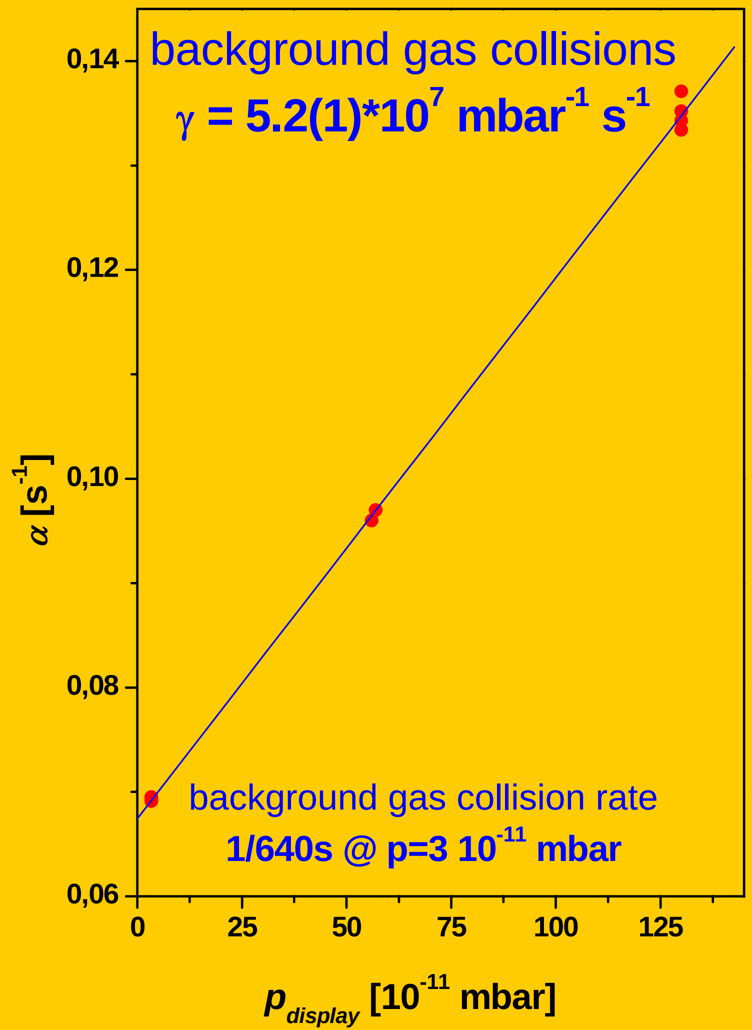
finite trap depth

- population of $^3P_2$-state: π_2
- population of $^3D_3$-state: π_3



Background gas collisions: $\gamma \cdot p$

- Pressure dependency of MOT decay



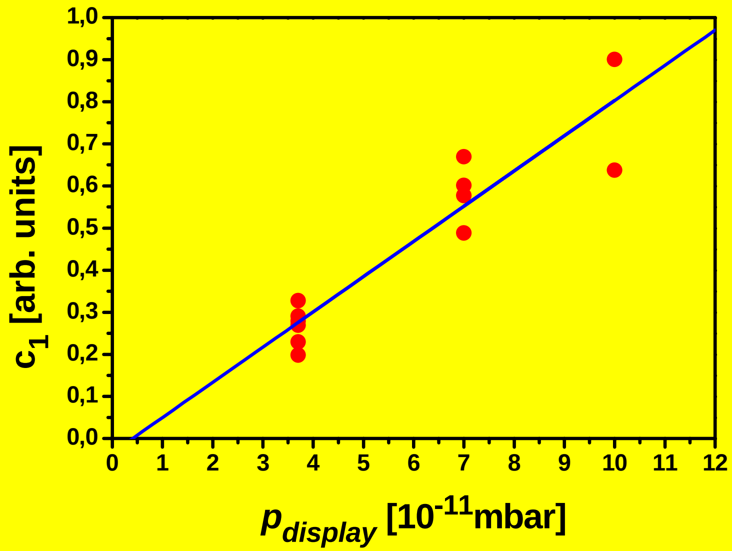
- Offset of pressure gauge: **$4(7)\ 10^{-12}$ mbar**

- Ionization processes:

$$Ne^* + X = Ne + X^+ + e^-$$

- Ion signal on MCP:

$$R_{ion}(t) \quad = c_1(p)\, N(t) + c_2\, N^2(t)$$



Influence of finite trap depth

• For an infinitely large MOT:

trap depth and

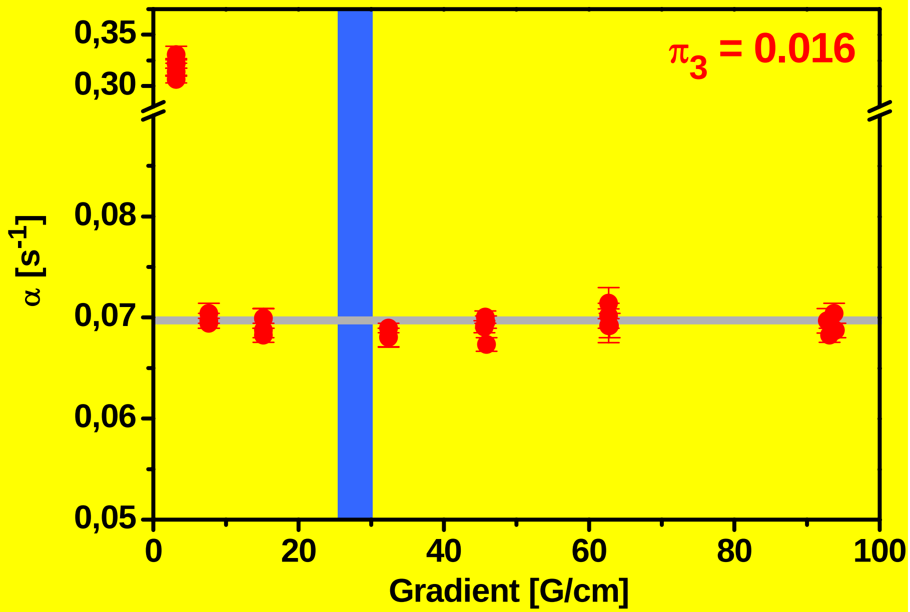
escape velocity become infinite

• therefore: let the gradient B‘ approach zero!

• In practice:

Trap depth remains finite

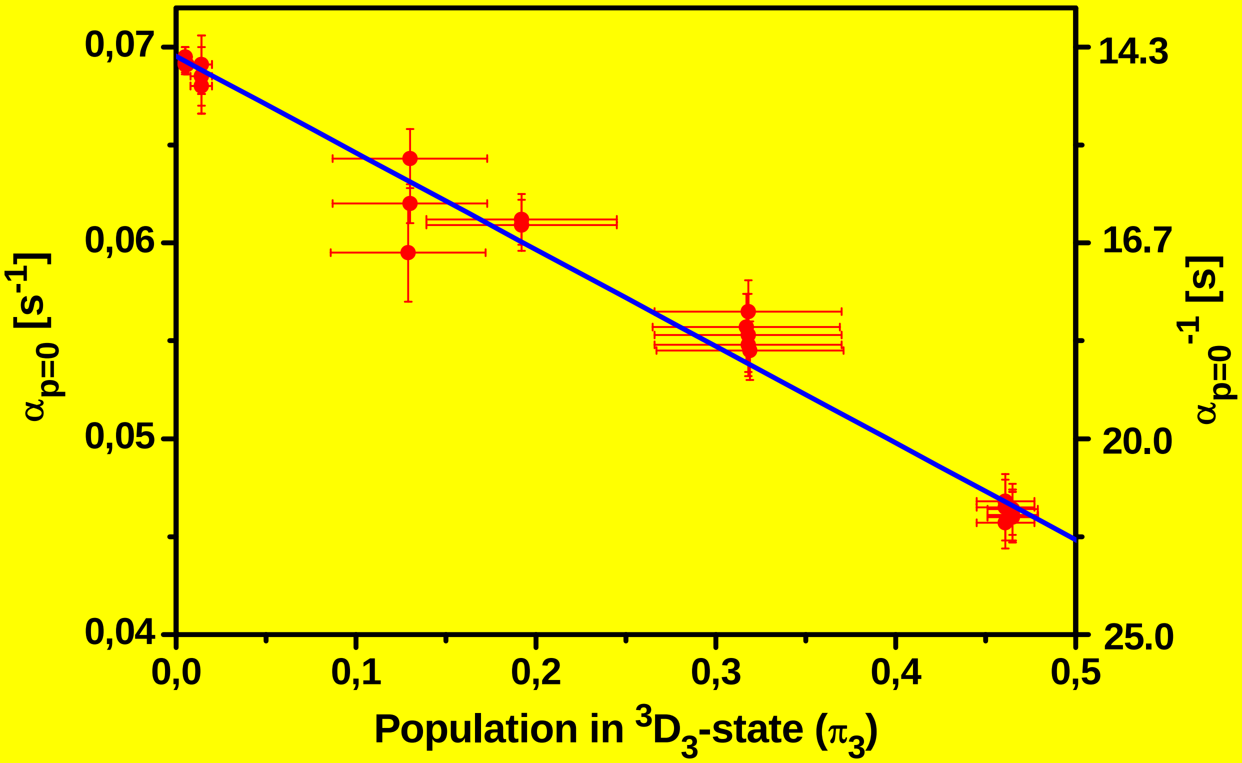
due to finite size of laser beams

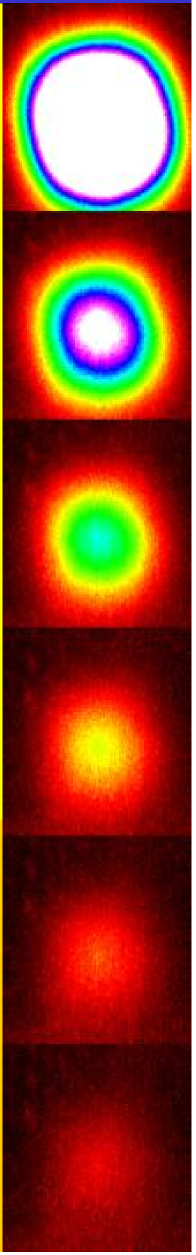


• **No significant dependency of α on B’**

• **No correction needed for low excitation measurements**

Lifetime τ_2 of the metastable $^3P_2$-state





Error budget:			
	measured α		0.06918(51) s^{-1}
	p=0 extrapolation	-	0.00156(37) s^{-1}
	π=0 extrapolation	+	0.00028(13) s^{-1}
thus:	α(p=0, π=0)		0.06790(64) s^{-1}

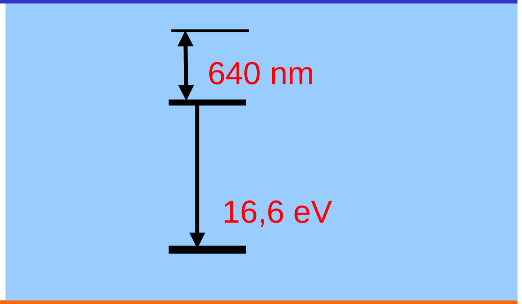
τ_2 **14.73(14) s**

From atomic physics to BEC

Atomic physics

- Lifetime of the metastable state: 14.73(14)s

M. Zinner et al., PRA 67, 010501(R) (2003)



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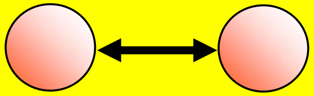
- Suppression of Penning-Ionization by spin-polarization: 10^4 ?



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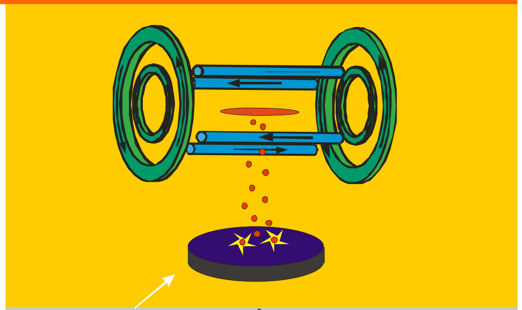

Bose-Einstein-Condensation

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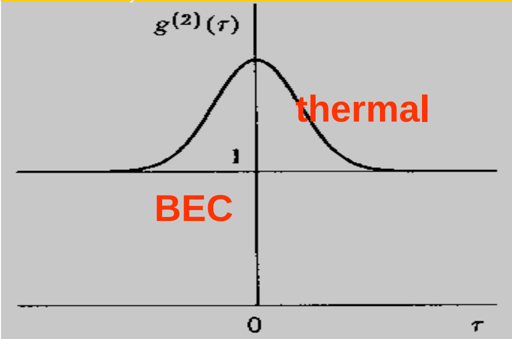
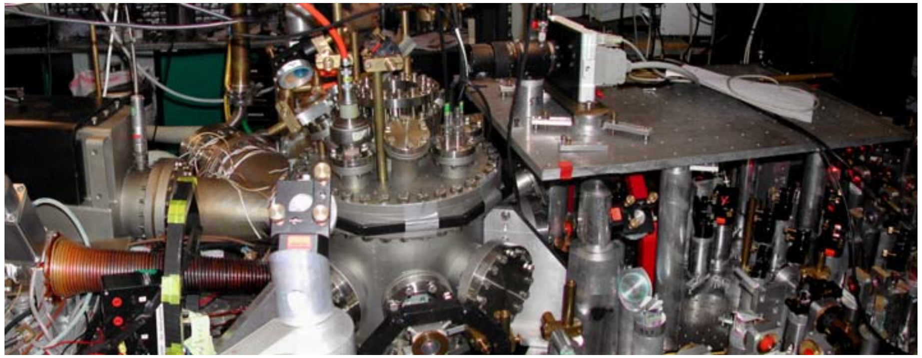


Preparation of spin-polarized atoms

Sequence

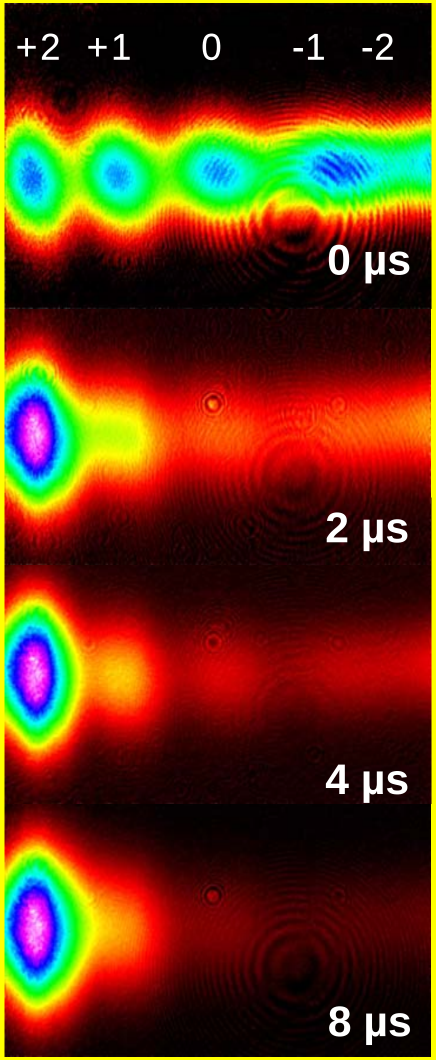
Beam collimation and slowing	MOT loading	Compressed MOT
	400 ms	**σ_r=1.3mm**
	N=6x10^8	



Doppler Cooling	Transfer to MT and adiabatic compression
PSD = 4.5x10^{-7}	**B_0= 25 G**
axial: ~200 µK	**N = 3x10^8**
radial: ~450 µK	

spin polarization

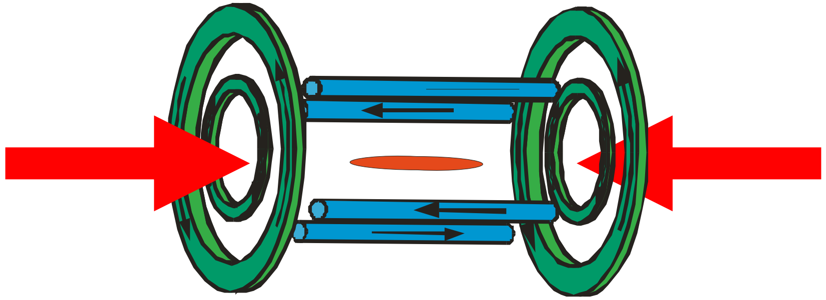
78% in m_J=+2



Stern-Gerlach Experiment

Doppler-cooling in the magnetic trap

- σ^+-σ^+- irradiation in axial direction of magnetic trap



Axial: Doppler cooling

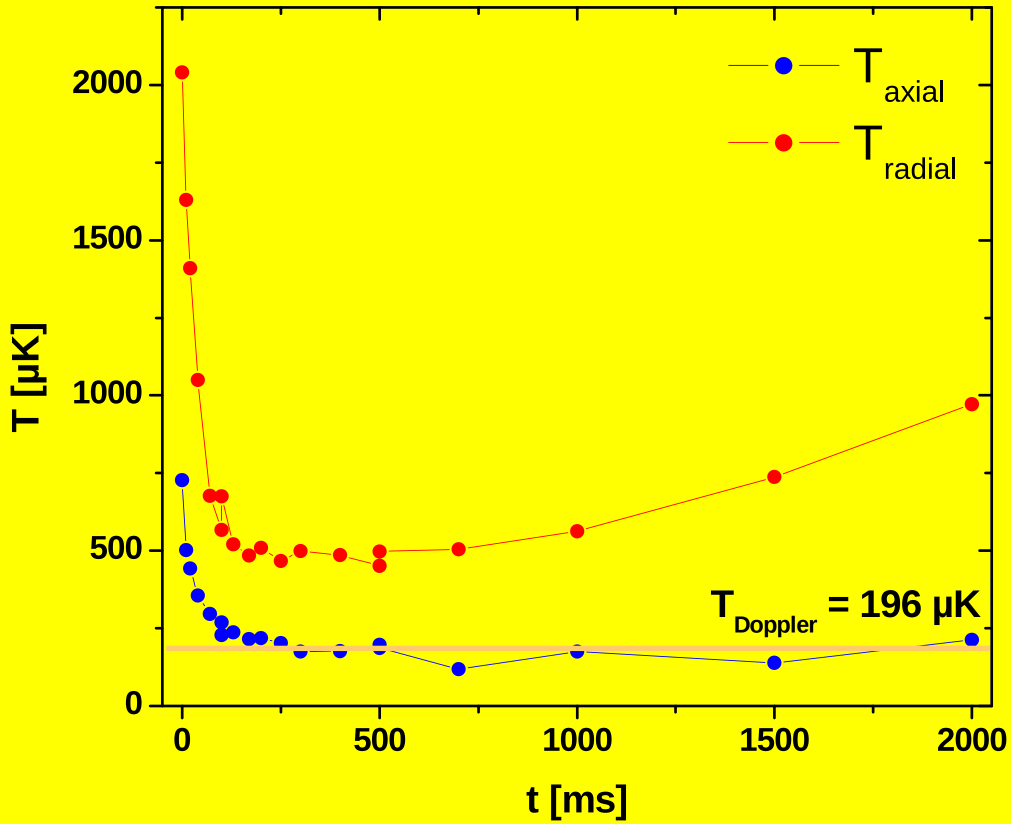
Radial: cooling by reabsorption

- Optimized parameters:

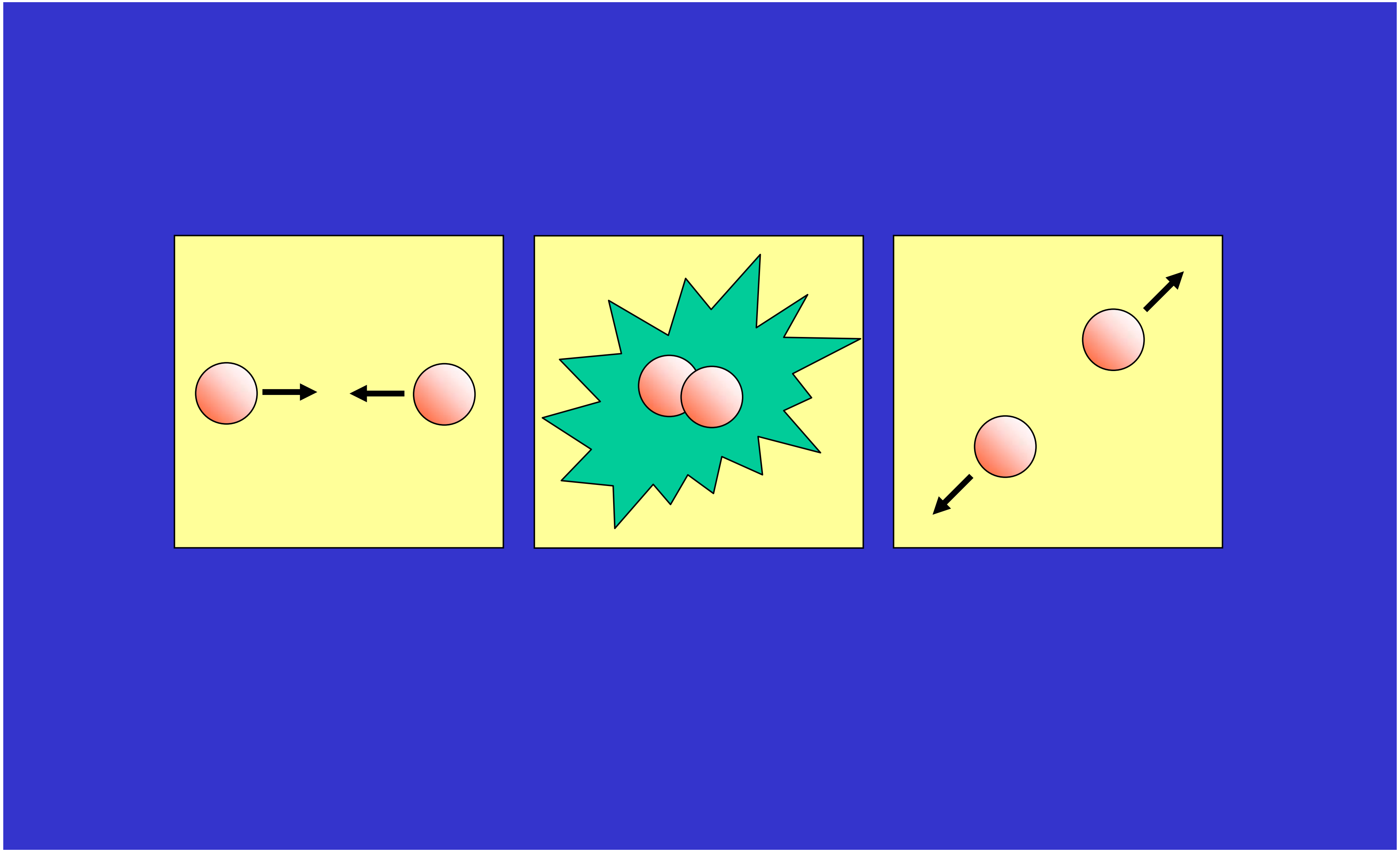
Δ = -0.5 Γ

$I = 5x10^{-3} I_{sat}$

- **50**-fold gain in phase space density



Elastic collisions

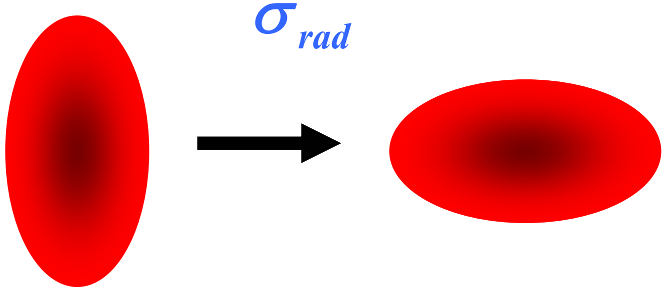


Cross-dimensional Relaxation

- Kinetic energy is not in equilibrium after Doppler-cooling

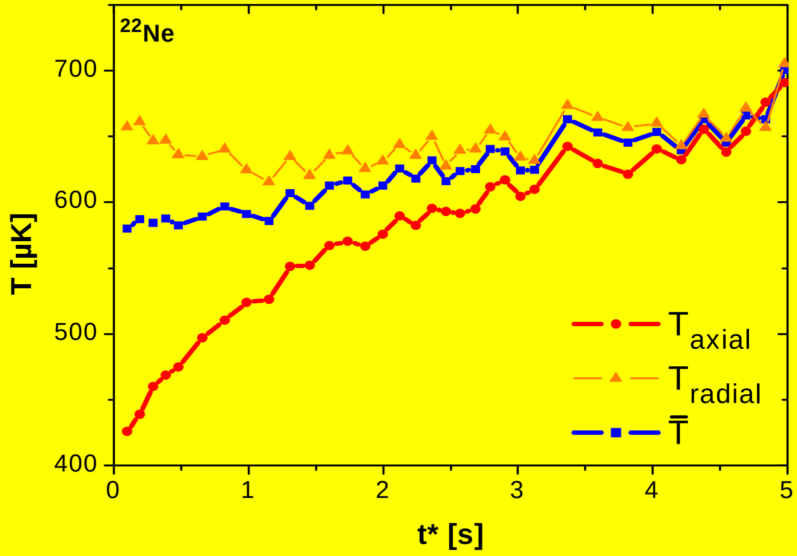
- Aspect ratio of the cloud changes

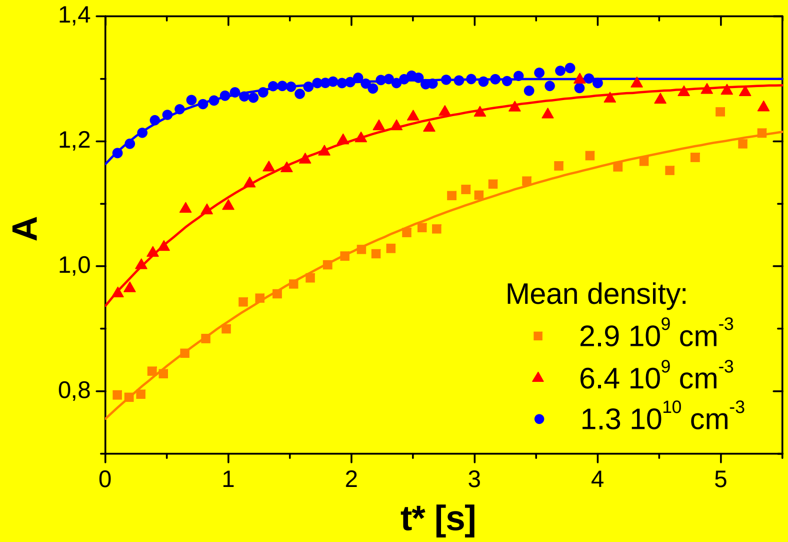
$$A = \frac{\sigma_{ax}}{\sigma_{rad}}$$



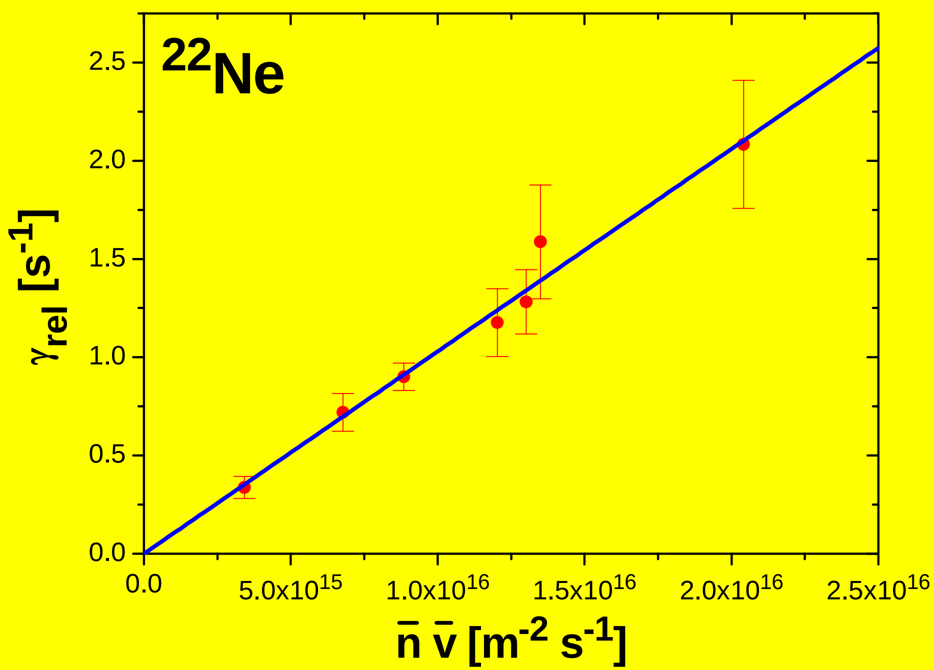
- Determination of the relaxation rate

$$\dot{A} = \gamma_{rel}\left(A(t) - A_{eq}\right)$$





Cross-dimensional Relaxation



- Relaxation rate is proportional to density:

Kinetic energy is redistributed by elastic collisions!

- Description of the relaxation rate

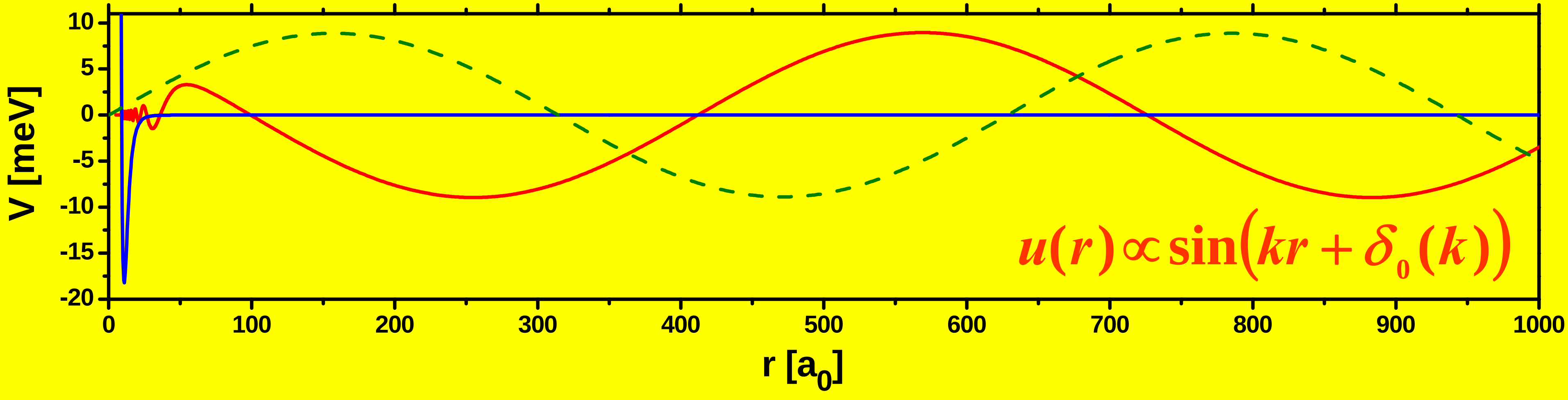
$$\gamma_{rel} = \sigma_{rel}\, \bar{n}\, \bar{\mathrm{v}}$$

- Connection to elastic collisions

$$\sigma_{rel} = \frac{\left\langle \sigma_{el} \cdot \mathrm{v}_{\mathrm{rel}}^{5} \right\rangle_T}{4.24 \left\langle \mathrm{v}_{\mathrm{rel}}^{4} \right\rangle_T \bar{v}}$$

G. M. Kavoulakis, C. J. Pethick, and H. Smith
Phys. Rev. A 61, 053603 (2000)

Cross Section of elastic collisions



- Centrifugal barrier for d-waves: 5,8 mK → **Regime of s-wave-scattering**

- Interaction potential:

  Short range: **S. Kotochigova et al., PRA 61, 042712 (2000)**

  Long range: **A. Derevianko und A. Dalgarno, PRA 62, 062501(2000)**

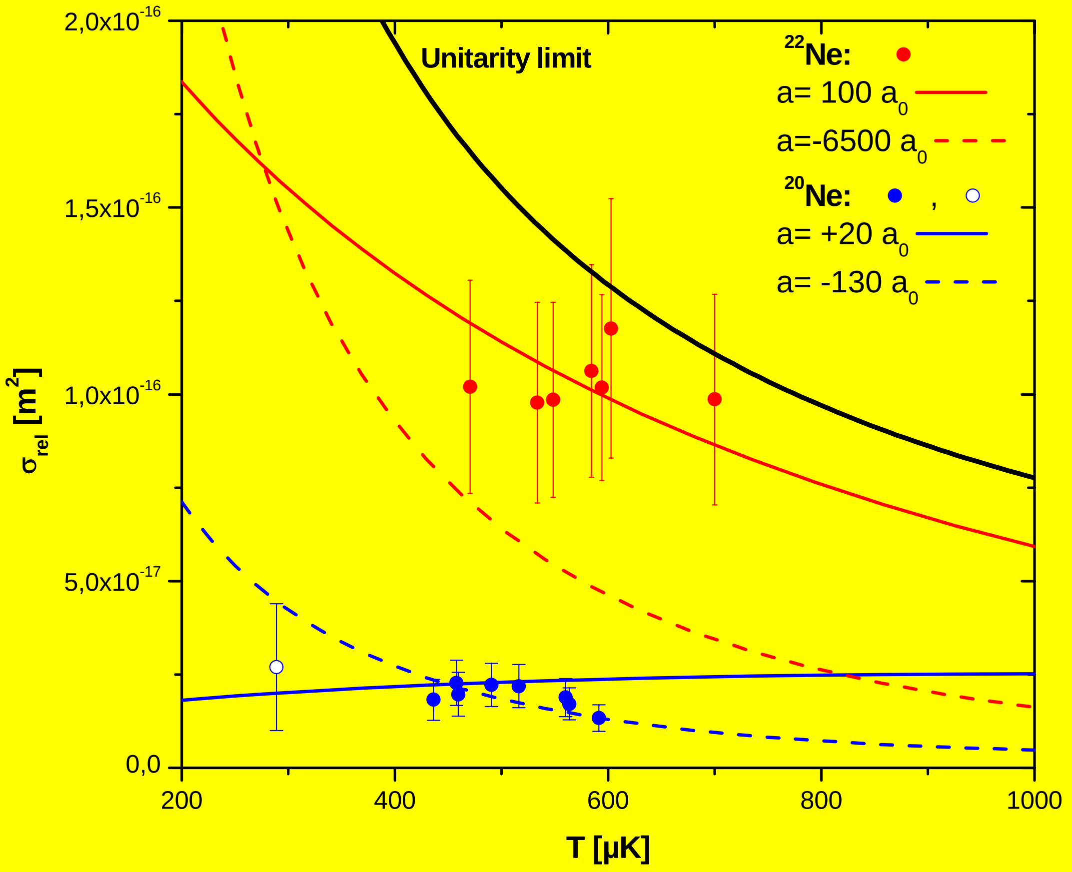
- Cross section:

$$\sigma_{el}(k) = \frac{8\pi}{k^2}\sin^2\left(\delta_0(k)\right)$$

Effective-range approximation:

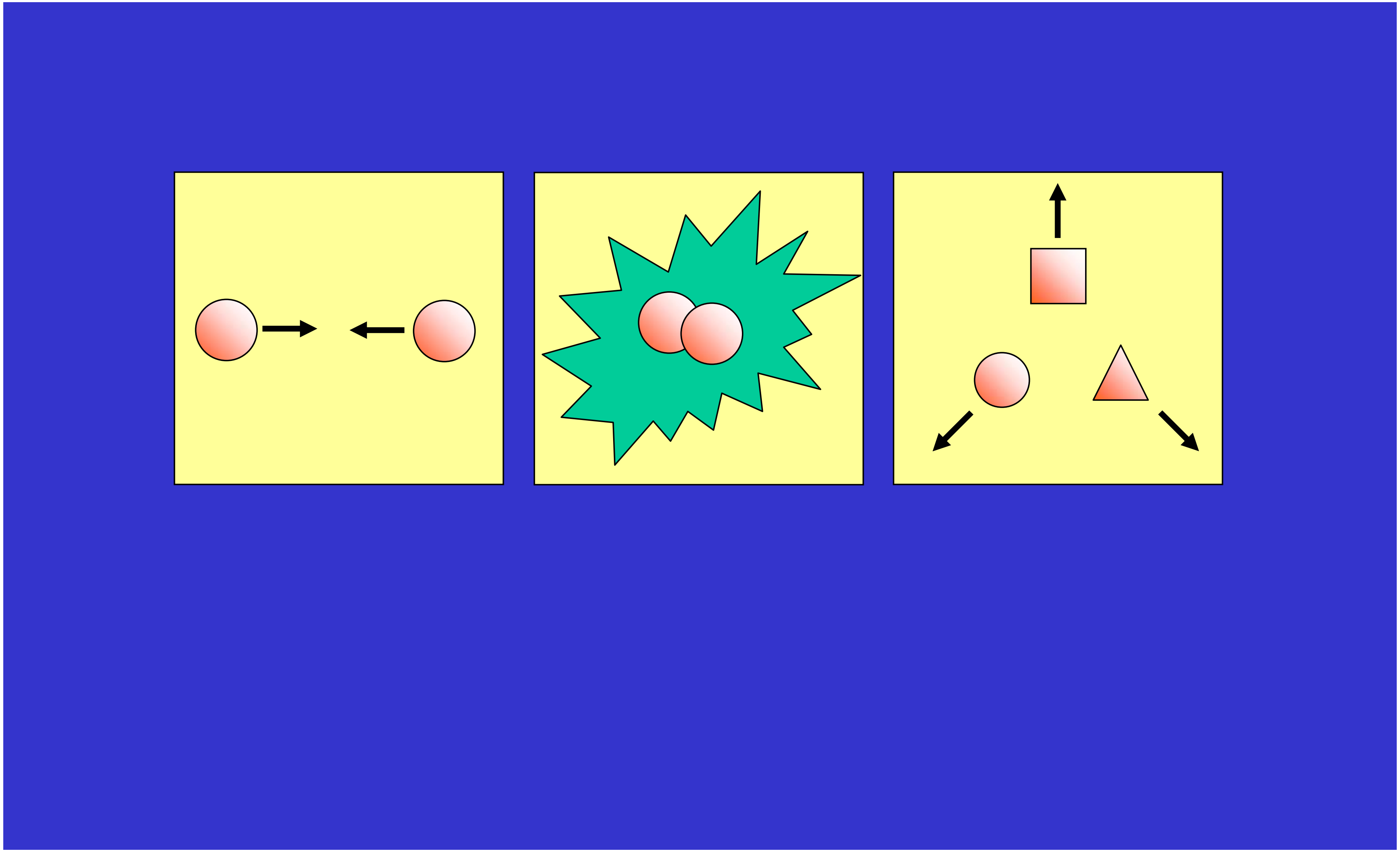
$$\sigma_{ER} = \frac{8\pi a^2}{k^2 a^2 + \left(\frac{1}{2}k^2 r_e a - 1\right)^2}$$

Relaxation cross section



	Effective range approximation	Numerical calculation (shown)
^{20}Ne:	-105(18) a_0 (or +14.4 a_0)	-120(10) a_0 or +20(10) a_0
^{22}Ne:	+150 a_0 < a < +1050 a_0	+70 a_0 < a < +300 a_0 (100 a_0)

Inelastic collisions



Simple model of Penning-Ionization

- Ionization with unit probability below a minimal distance

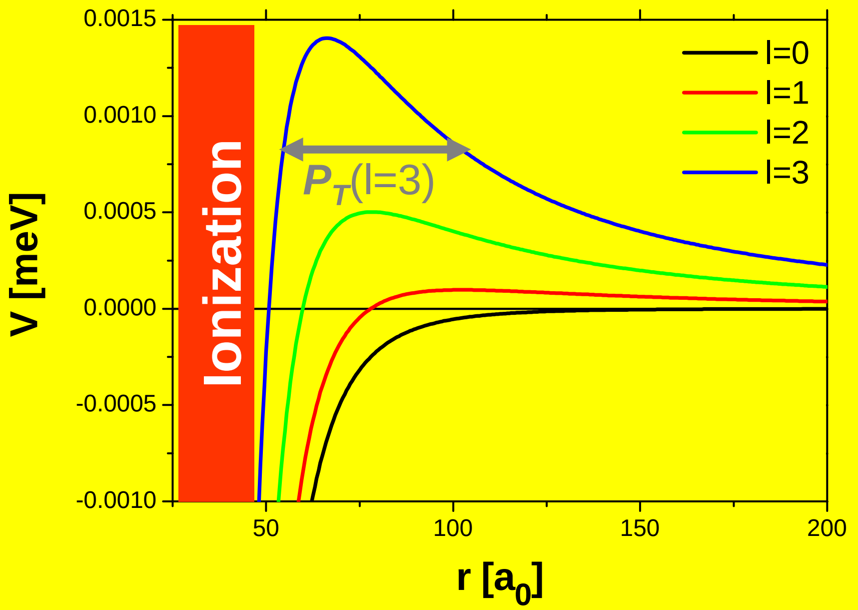
- Model (Xe*, NIST)

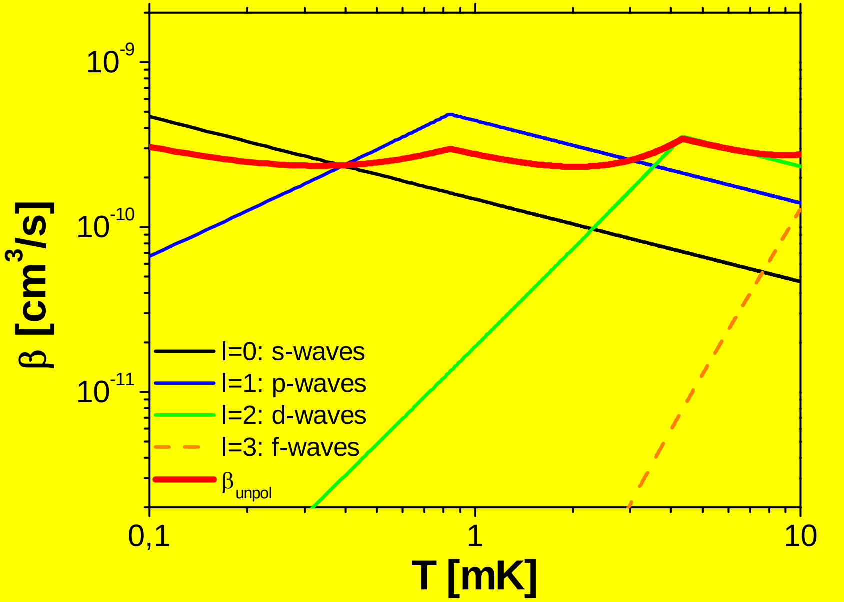
$$\sigma_{ion,l} = \frac{\pi}{k^2}(2l+1)P_T(k,l)$$

P_T.. transmission probability

- Result:

β ~ 2-3 10^{-10} cm^3s^{-1}





Unpolarized atoms

- Measurement in MOT

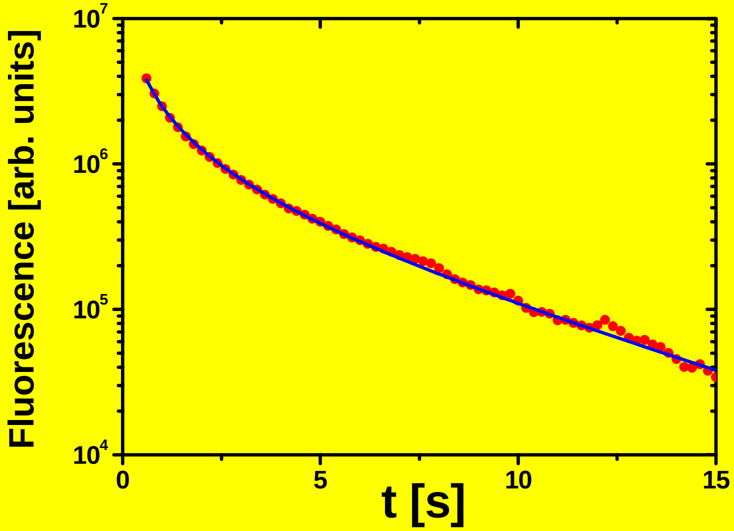
$$\dot{N} = -\alpha N - \beta \frac{N^2}{V_{eff}}$$

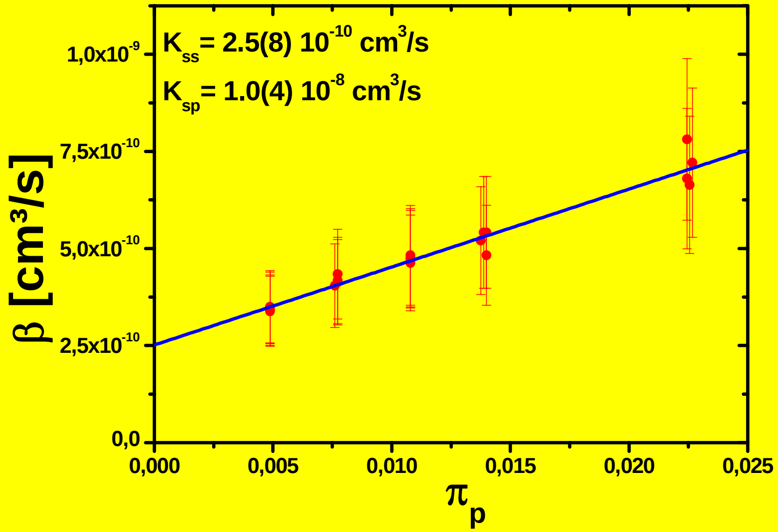
- Consideration of excited atoms

S+S collisions: K_{ss}
S+P collisions: K_{sp}

for small excitation π_p:
$\beta = K_{ss} + 2\,(K_{SP}-K_{SS})\,\pi_p$

	^{20}Ne	^{22}Ne
K_{ss} [cm³ s⁻¹]	$2.5(8)\ 10^{-10}$	$8(5)\ 10^{-11}$
K_{sp} [cm³ s⁻¹]	$1.0(4)\ 10^{-8}$	$5.9(25)\ 10^{-9}$





Suppression of Penning-Ionization

- Dominant loss process in MOT

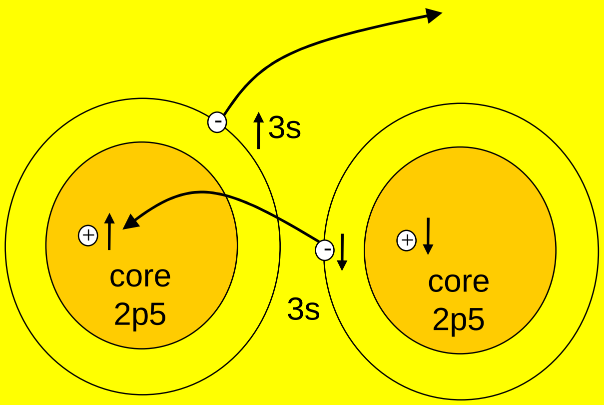
$\tau < 1s$ @ $n=10^9\ cm^{-3}$ (MOT)

- Suppression for spin polarized ensembles

Limitation of suppression by
anisotropic contributions
to the interaction during collisions

He*: $10^5 \Rightarrow$ BEC
Xe*: 1 $\Rightarrow$ ~~BEC~~
Ne* ?

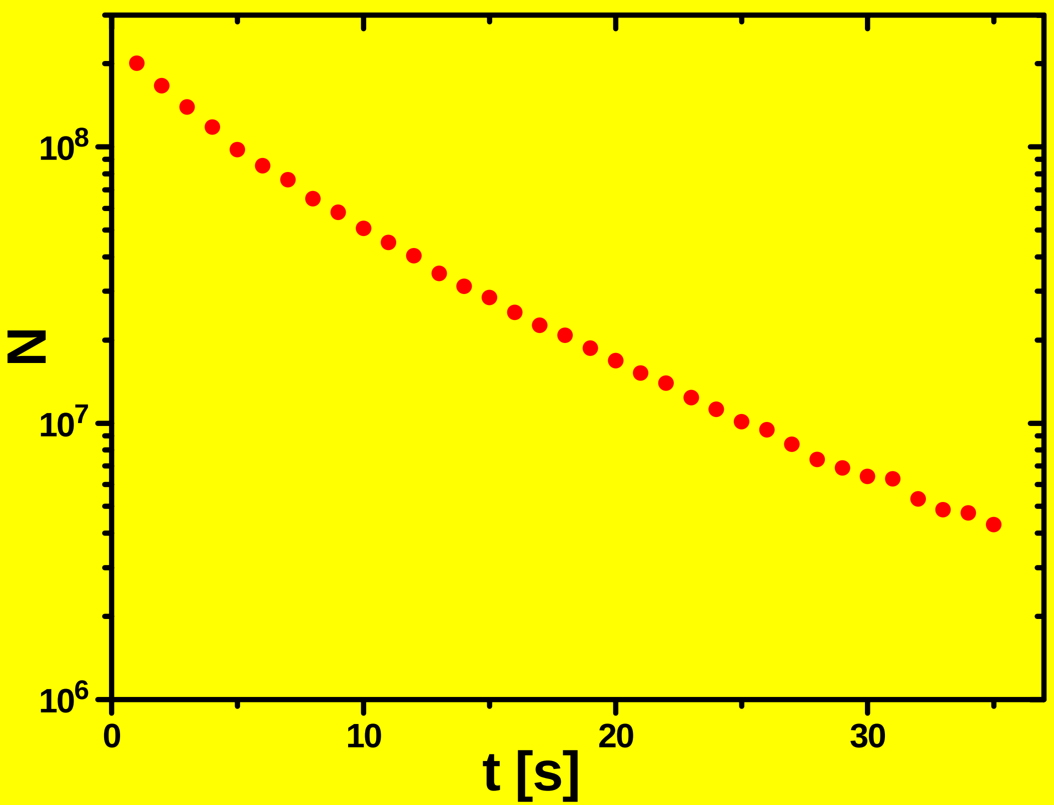
Exchange process

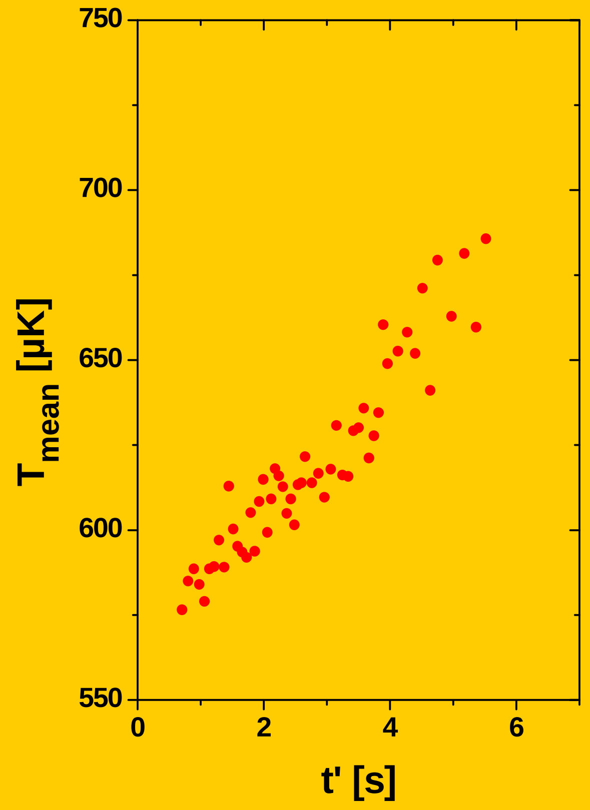


Ne*	**+**	**Ne***	$\Rightarrow$	**Ne**	**+**	**Ne^+**	**+**	**e^-**
S=1		**S=1**	$\Rightarrow$	**S=0**		**S=1/2**		**S=1/2**

$S_{tot} = 2$ $\qquad$ $S_{tot} \leq 1$

Spin polarized atoms





$$\dot{N} = -\alpha N - \beta \frac{N^2}{V_{eff}}$$

Heating!

Trap loss

Analysis:

$$\dot{N} = -\alpha N - \beta \frac{N^2}{V_{eff}} \rightarrow \frac{N(t)-N(0)}{\int_0^t N(t')dt'} = -\alpha - \beta \frac{\int_0^t \frac{N^2(t')}{V_{eff}(t')}dt'}{\int_0^t N(t')dt'}$$

^{20}Ne

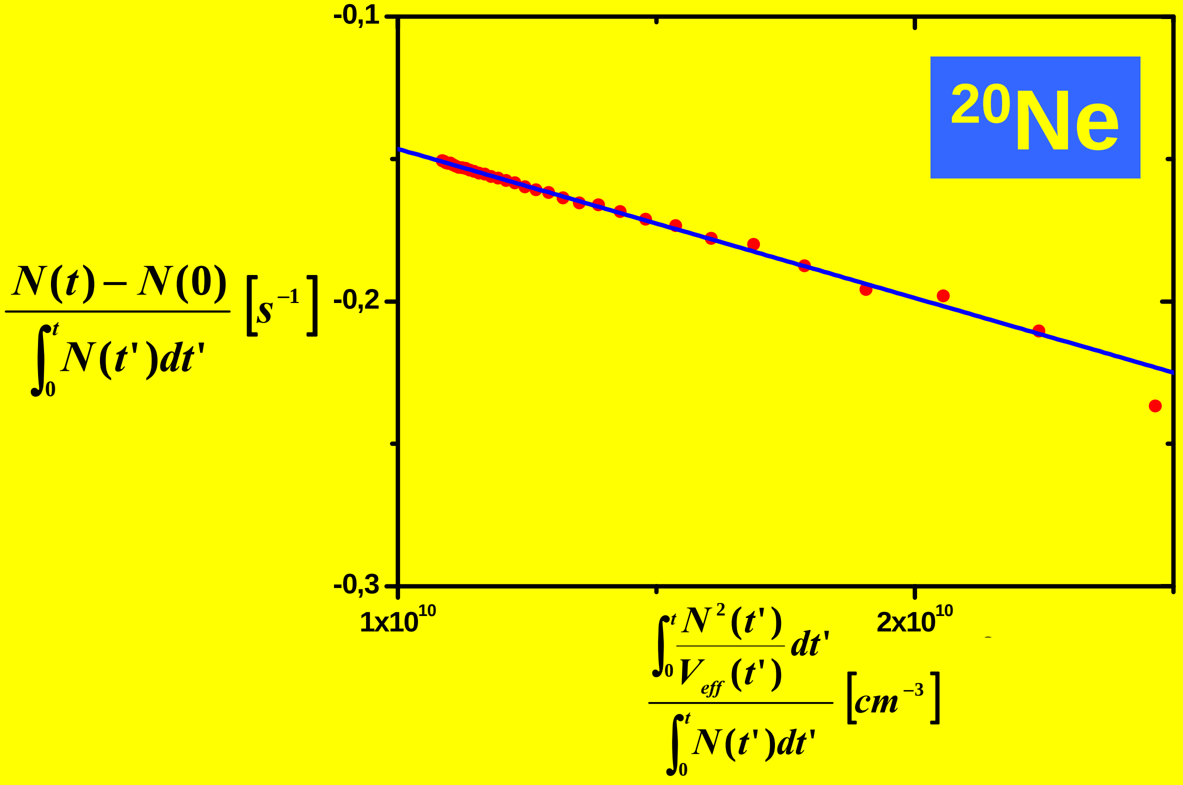
$\beta = 5.3(15)\ 10^{-12}\ cm^3\ s^{-1}$

Suppression: 50(20)

^{22}Ne

$\beta = 9.4(24)\ 10^{-12}\ cm^3\ s^{-1}$

Suppression: 9(6)



Heating

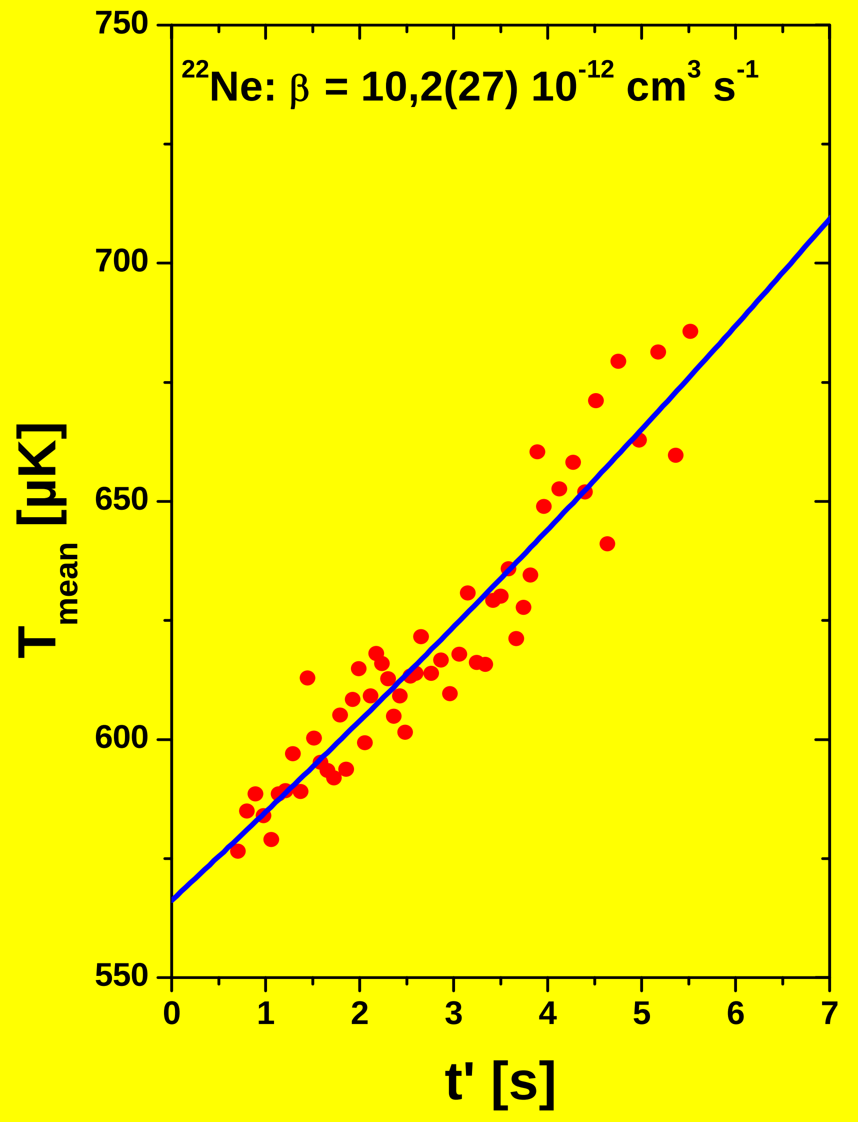
- Inherent heating due to 2-body-losses

$$\dot{N}_{inelast}(r,t) \propto -\beta n^2(r,t)$$

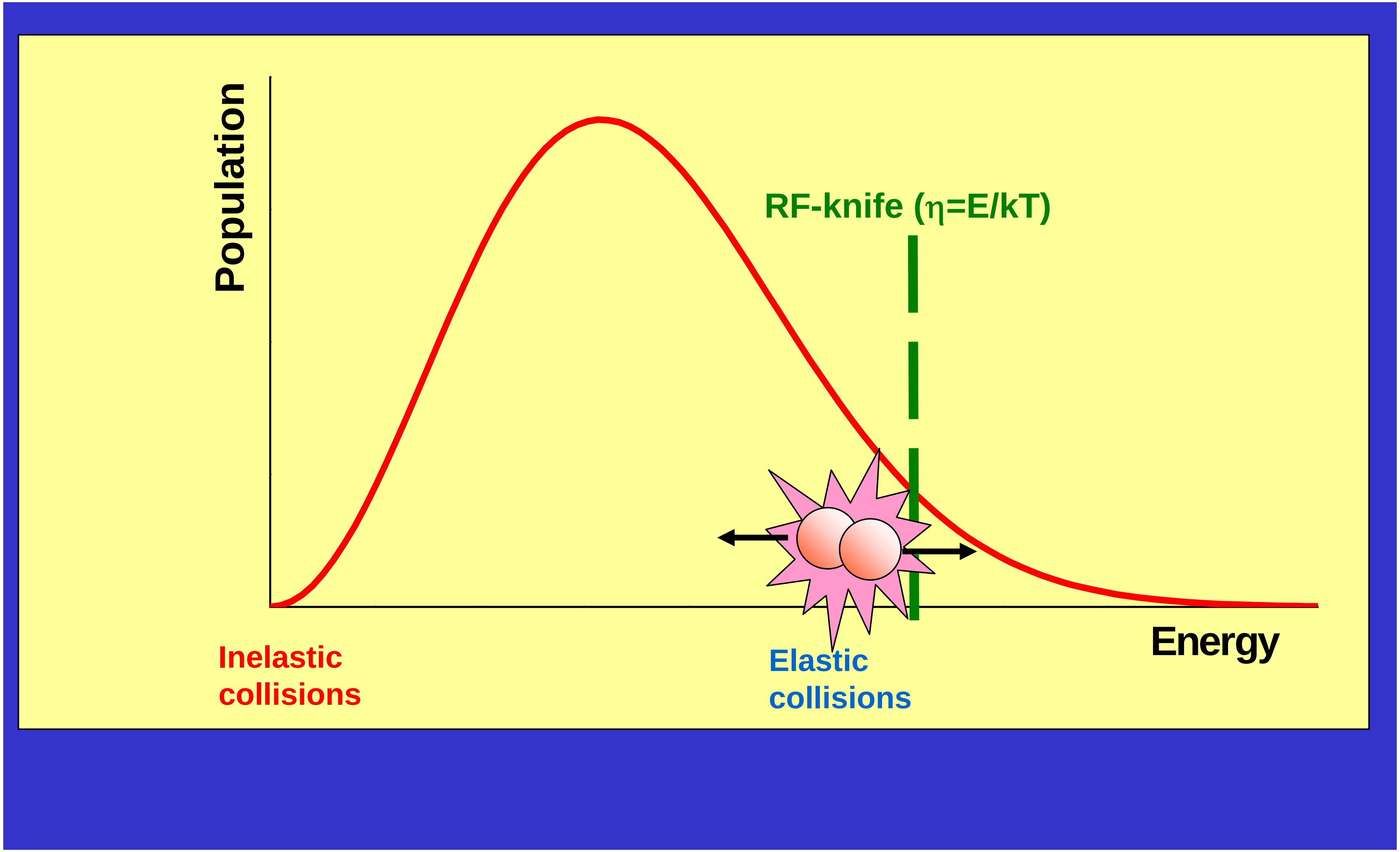
$$\frac{\dot{T}}{T} = \frac{1}{4}\beta \overline{n}$$

- other mechanisms
  - collisions with background gas
  - secondary collisions

^{20}Ne:	β_{heat} =	5.6(15)	10^{-12} cm^{3}s^{-1}
	β_{loss} =	5.3(15)	10^{-12} cm^3 s^{-1}
^{22}Ne:	β_{heat} =	10.2(27)	10^{-12} cm^{3}s^{-1}
	β_{loss} =	9.4 (24)	10^{-12} cm^3 s^{-1}



Evaporative cooling



Conditions for evaporative cooling

- „Good-to-bad“ ratio

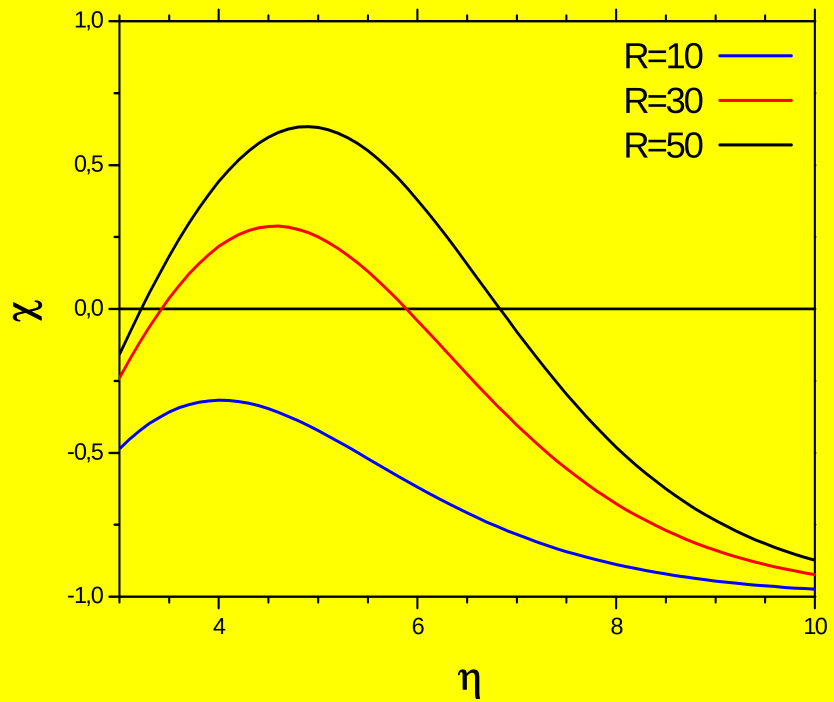
$$\mathbf{R} = \frac{\gamma_{\mathbf{el}}}{\gamma_{\mathbf{loss}}}$$

^{20}Ne: R~5-15
^{22}Ne: R~30-50

- **^{22}Ne is better suited for evaporative cooling than ^{20}Ne !**

Efficiency parameter

$$\chi = -\frac{d(\ln \rho_{\Phi})}{d(\ln \mathbf{N})}$$



Cut-off parameter $\eta = E_{Trap}/k_B T$

Experimental realization

- Ramp: from 80 MHz to 44 MHz

  Trap depth: from 5.5 mK to 1.2 mK
  Initial cut-off parameter: η=4,5

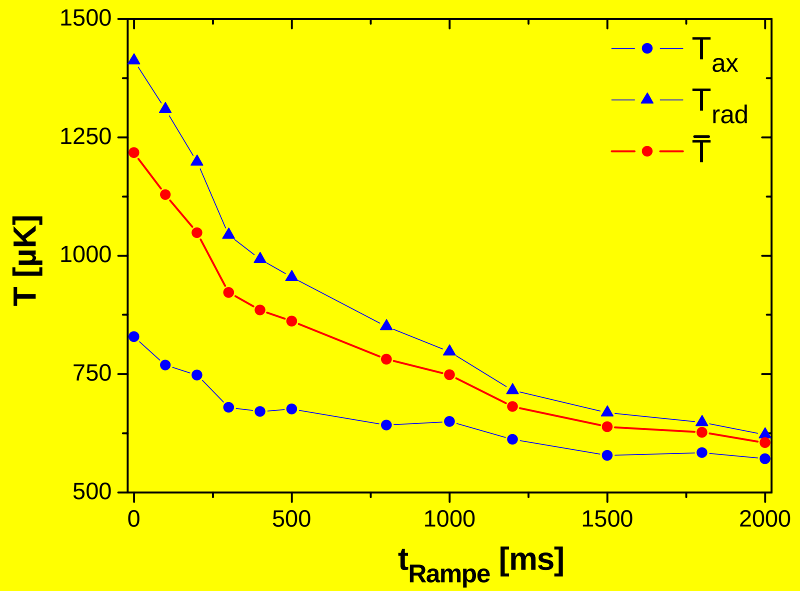
- variable duration of RF-irradiation

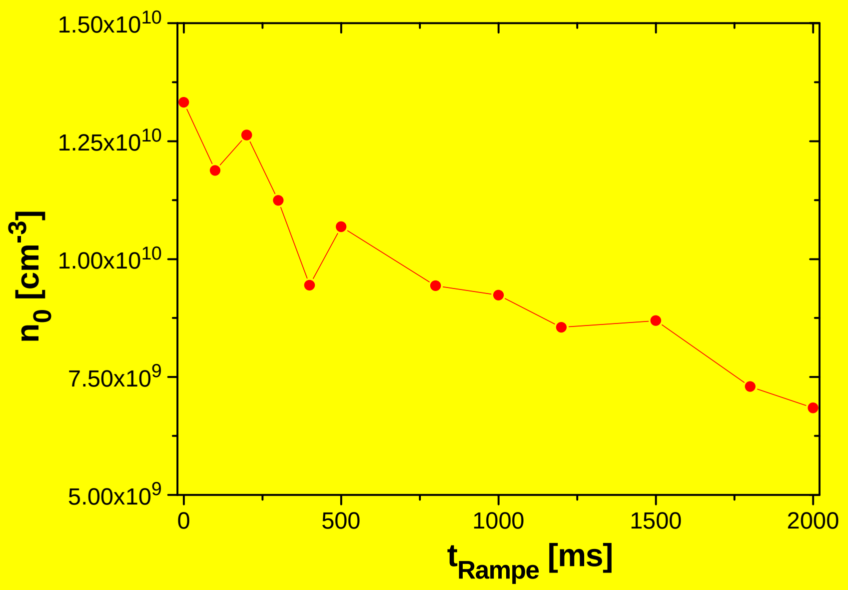
- Observation:

  T ↘

  n_0 ↘

  Phase space density ?

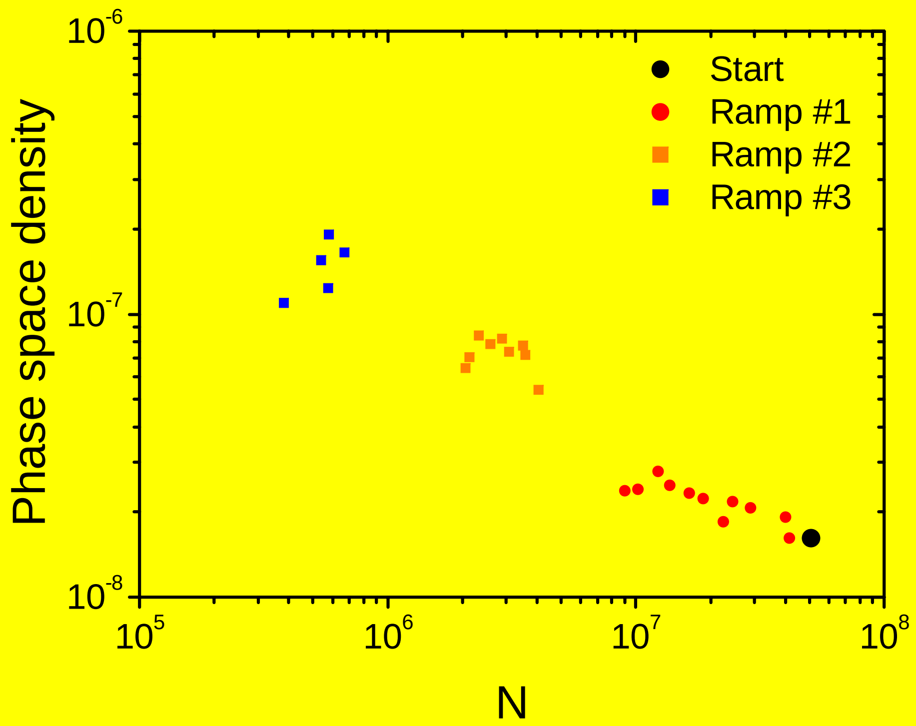




Increase in phase space density

Evaporation protocol

	RF [MHz]	E_{Trap} [mK]	η
	80	5.5	4.5
Ramp #1	44	1.2	2.7
Ramp #2	34	1.0	3.9
Ramp #3	29	0.6	4.5



- Initial conditions

$$N = 5 \times 10^{7}$$
$$n_0 = 1{,}3 \times 10^{10}\ \text{cm}^{-3}$$
$$T = 1.2\ \text{mK}$$
$$\rho = 1.6 \times 10^{-8}$$

- Final conditions

$$N = 5 \times 10^{5}$$
$$n_0 = 5 \times 10^{9}\ \text{cm}^{-3}$$
$$T = 130\ \mu\text{K}$$
$$\rho = 1.9 \times 10^{-7}$$

- Efficiency of evaporative cooling

$$\chi \approx 0.6$$

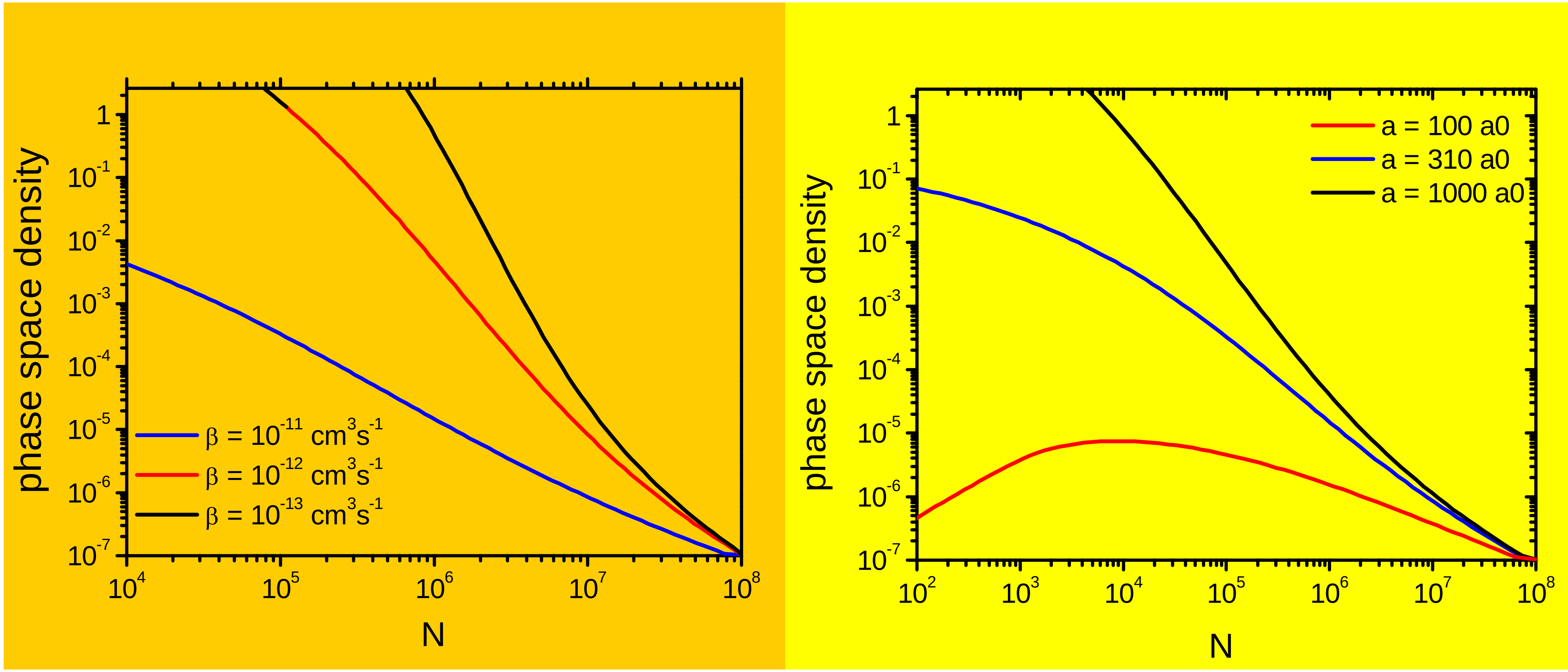
Prospects for BEC

- Ne* as compared to Bose-condensed species:

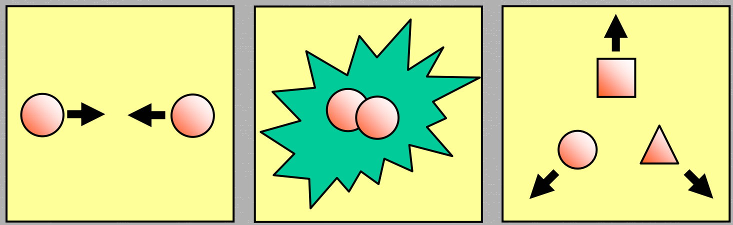
  very high loss rates

  high rates of elastic collisions

- Numerical simulation of optimized evaporative cooling



Results



- Penning ionization (unpolarized, ^{20}Ne)

  K_{ss} = 2.5(8) 10^{-10} cm³ s^{-1}
  K_{sp} = 1.0(4) 10^{-8} cm³ s^{-1}

- Penning ionization (unpolarized, ^{22}Ne)

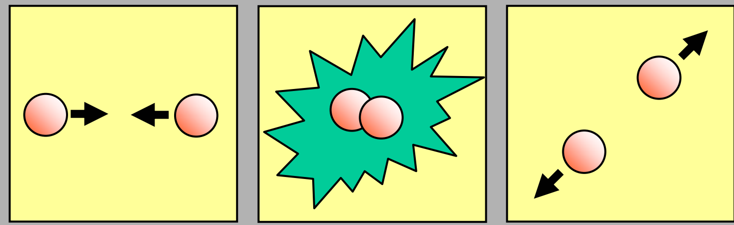
  K_{ss} = 8(5) 10^{-11} cm³ s^{-1}
  K_{sp} = 5.9(25) 10^{-9} cm³ s^{-1}

- Two-body losses (spin-polarized)

  ^{20}Ne: **β = 5.3(15) 10^{-12} cm³ s^{-1}**
  ^{22}Ne: **β = 9.4(24) 10^{-12} cm³ s^{-1}**

- Suppression of Penning ionization

  ^{20}Ne: **~ 50**
  ^{22}Ne: **~ 9**



- Elastic collisions

  ^{20}Ne: **a = +20(10) a_0 or -110(20) a_0**
  ^{22}Ne: **+70 a_0 < a < +1050 a_0**

- Evaporative cooling

  Phase space density x 10
  Efficiency χ~0,6

- Lifetime of the $^3P_2$-state (^{20}Ne):

  14.73(14) s

  M. Zinner et al., PRA 67, 010501(R) (2003)

Outlook

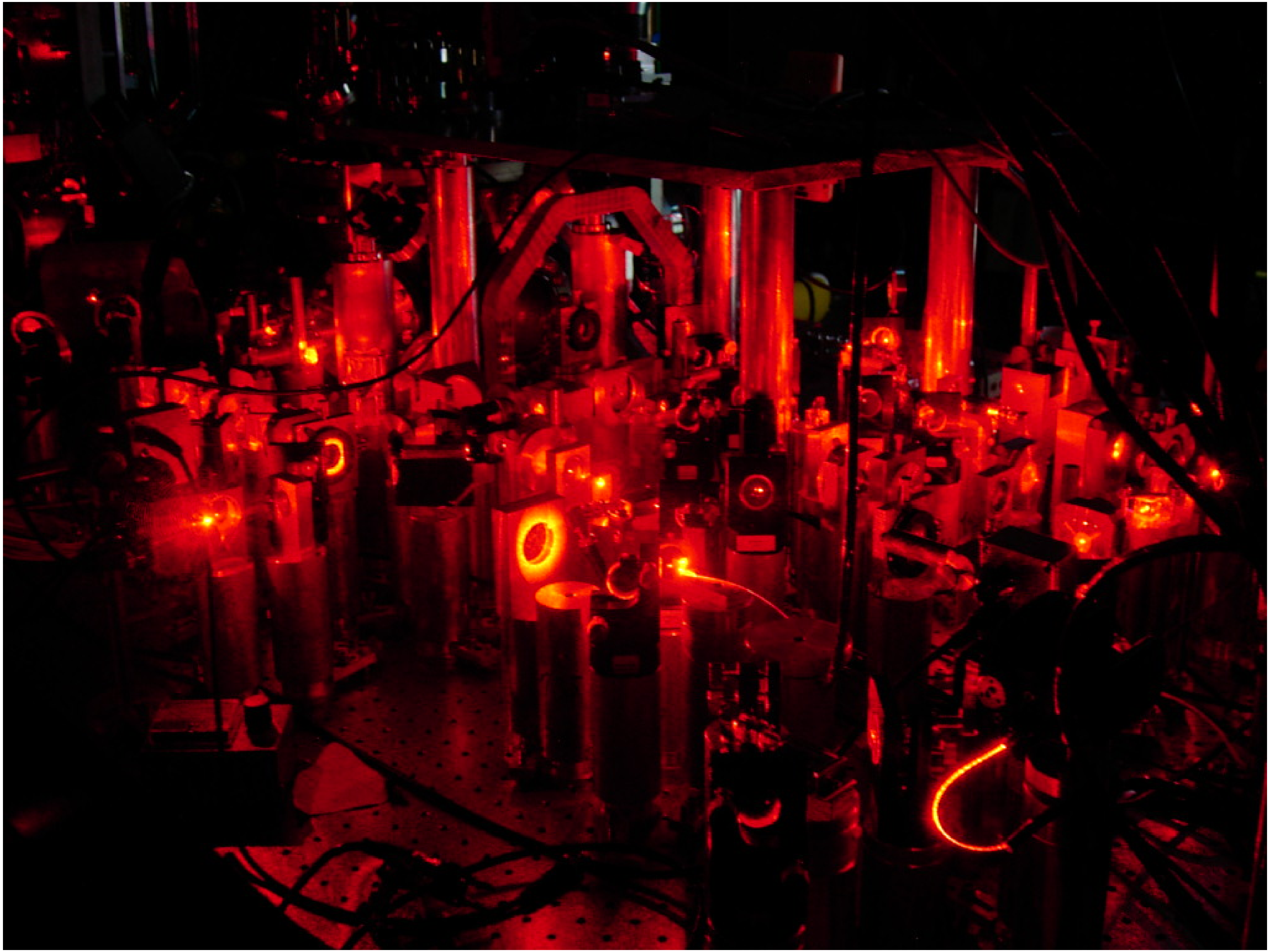
- Continue experiments on evaporative cooling of ^{22}Ne to highest possible phase space density

- Ion rate measurements with the MCP

- Investigation of collision properties, especially influence of external (magnetic) fields
- Manipulation of Interactions?

- Transfer into an optical dipole trap

- Photo-association spectroscopy



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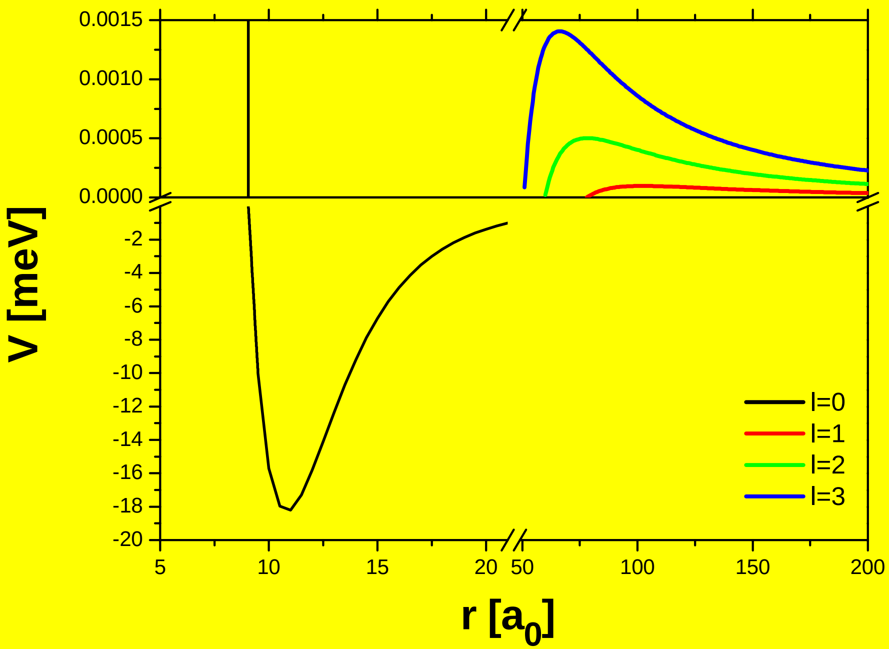
Collisions in cold gases

Interaction potential



- Potential depth: ~20 meV
- Long-range potential:

$$V_{LR}(r) = -\frac{C_6}{r^6} + \frac{\hbar^2}{2m}\frac{l(l+1)}{r^2}$$

Elastic Collisions

- Scattering length a: $\sigma_{el,T\to 0} = 8\pi a^2$
- „motor“ of evaporative cooling
- Stability of a BEC
- Scattering resonances

Inelastic Collisions

- Loss parameter β: $\sigma_{inel,T\to 0} \propto \frac{1}{k}$

$$\frac{\dot{N}_{inel}}{N} = -2\left\langle \sigma_{inel}\, v_{rel} \right\rangle_T \bar{n} = -\beta\, \bar{n}$$

- „brake“ of evaporative cooling
- Heating
- Penning-Ionization
- Influence of spin-polarization

Numerical calculation of scattering phases

- Interaction potential

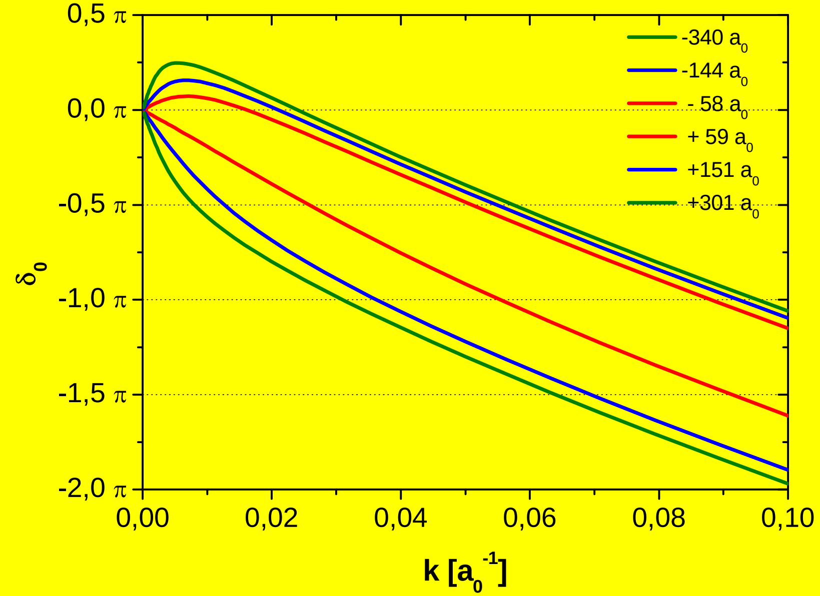
- **S. Kotochigova et al., PRA 61, 042712 (2000)**
- **A. Derevianko und A. Dalgarno, PRA 62, 062501(2000)**

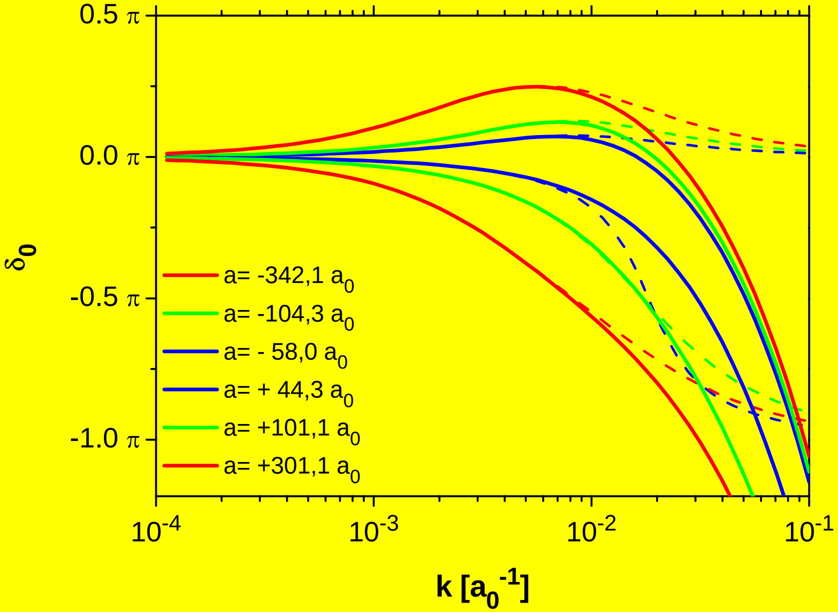
- Numerical determination of the s-wave radial wavefunction gives δ_0

$$u_l(r) \propto \sin\left(kr + \delta_0(k)\right)$$

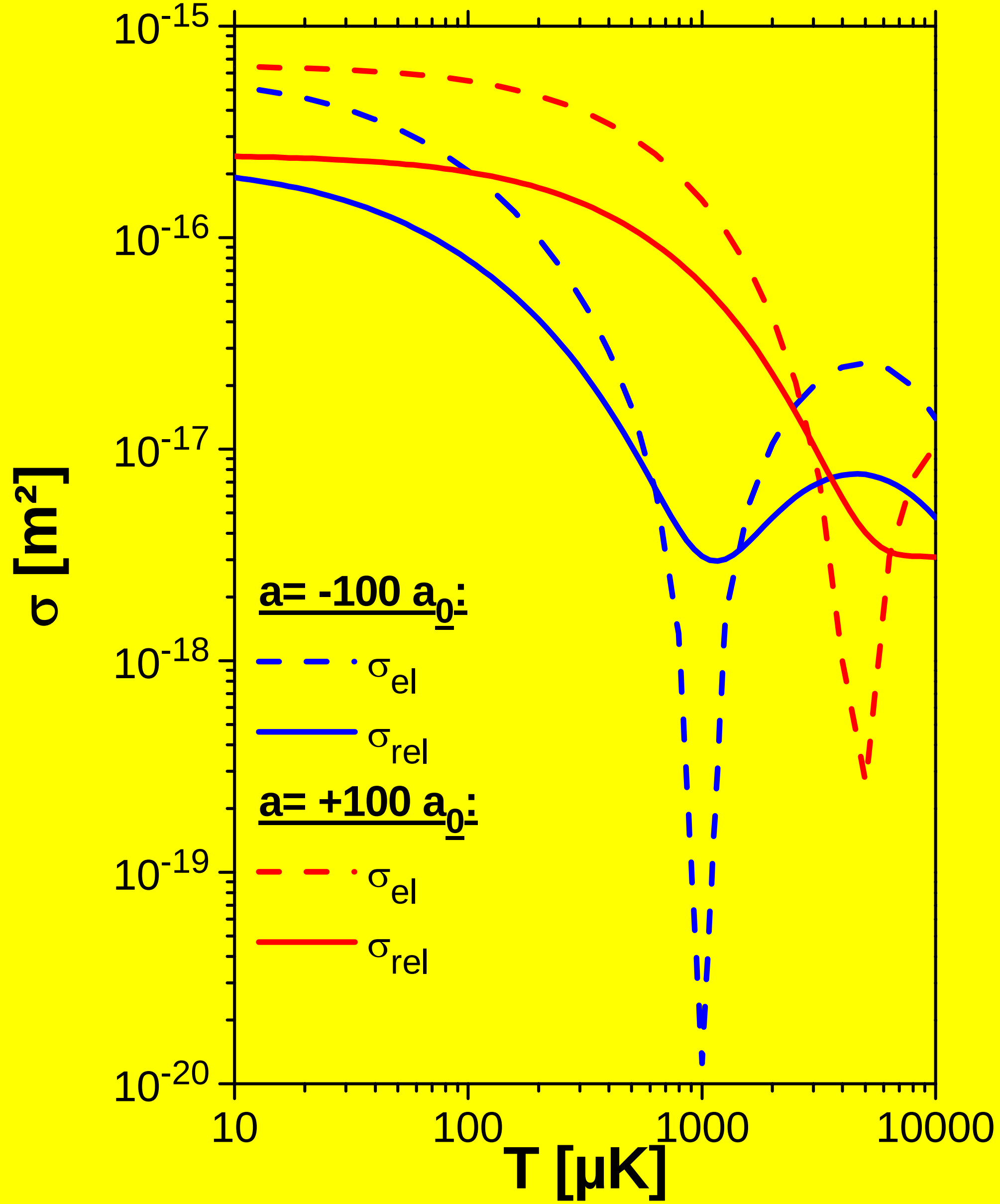
- Cross section

$$\sigma_{el}(k) = \frac{8\pi}{k^2}\sin^2\left(\delta_0(k)\right)$$





Relaxation cross sections



Inelastic collisions of metastable neon

Limit on suppression of ionization in metastable neon traps due to long-range anisotropy

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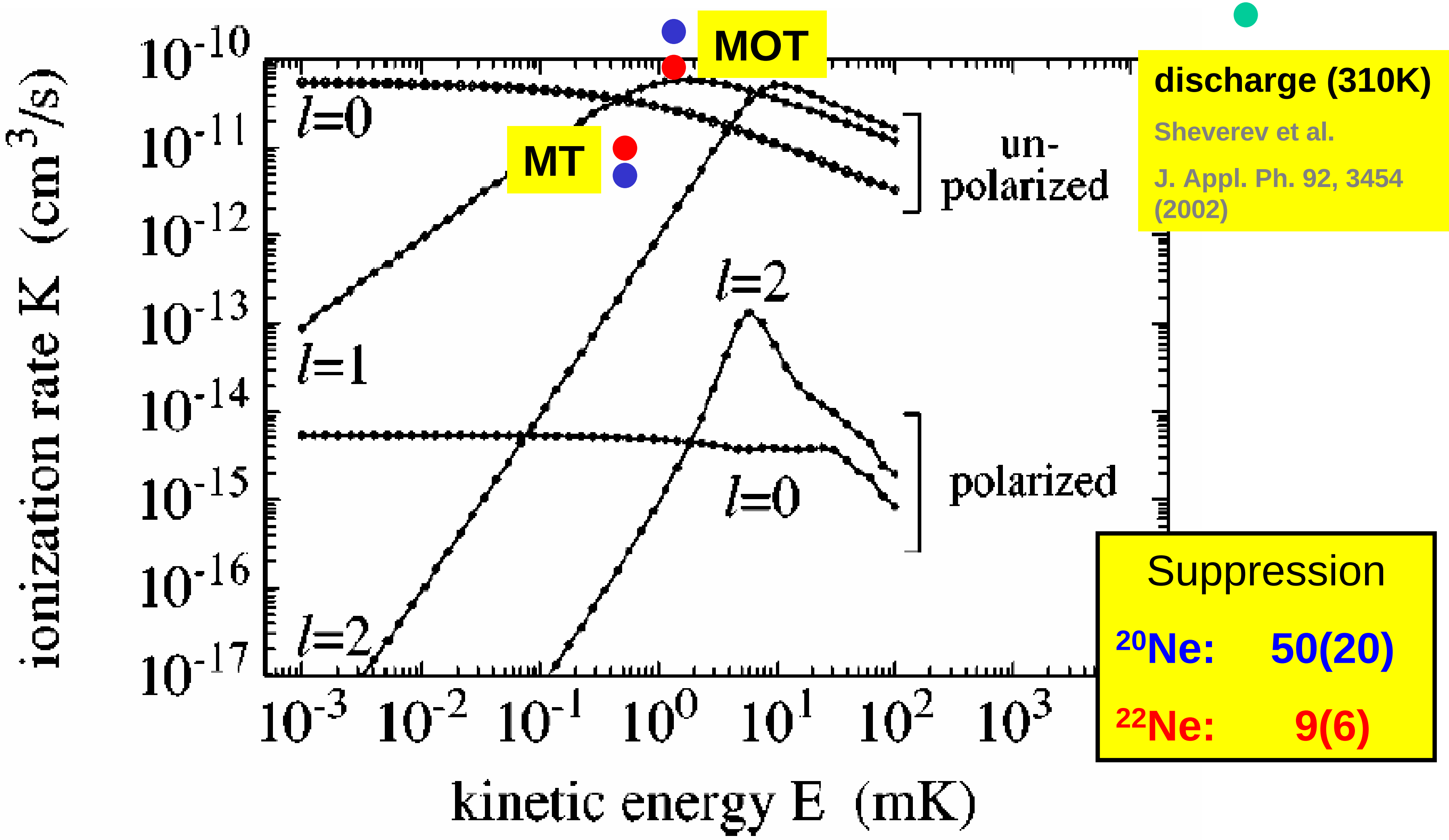
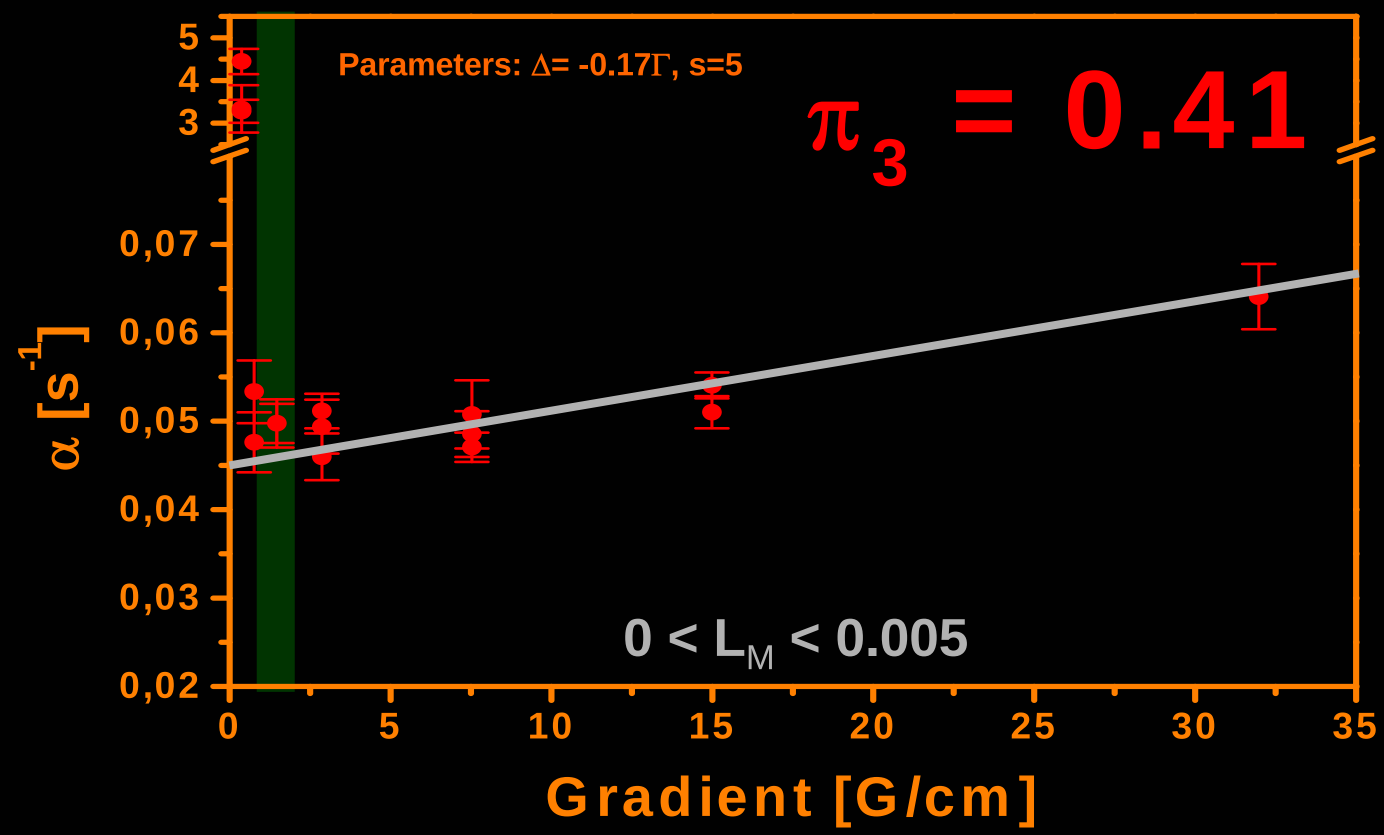
(Received 26 May 1998)



Suppression	
^{20}Ne:	50(20)
^{22}Ne:	9(6)

Decay rate vs. Gradient II



Problems:

- Theories hold for small saturation
- Models discussed fail to explain the data quantitatively
- Ionizing background collisions