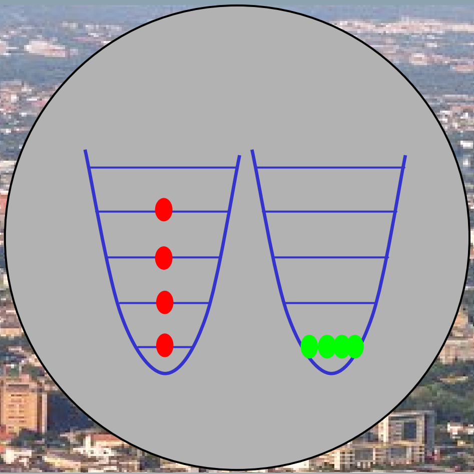
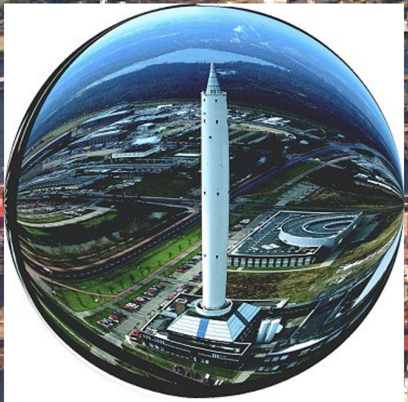
Cold Quantum Gas Group Hamburg

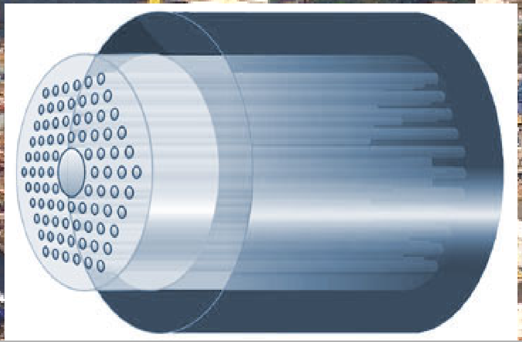


Fermi-Bose-Mixture

Spinor-BEC



BEC ‘in Space‘

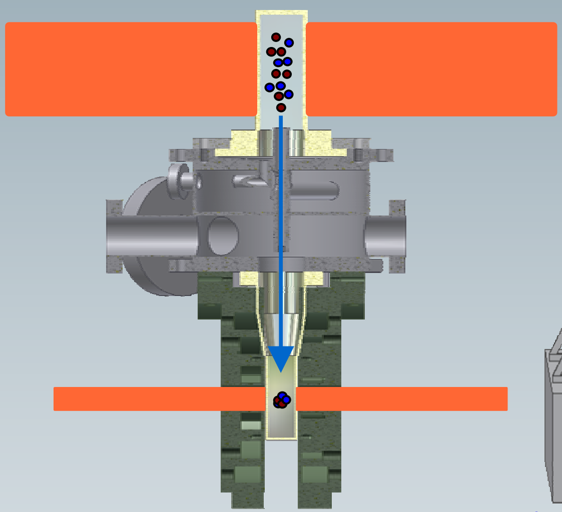


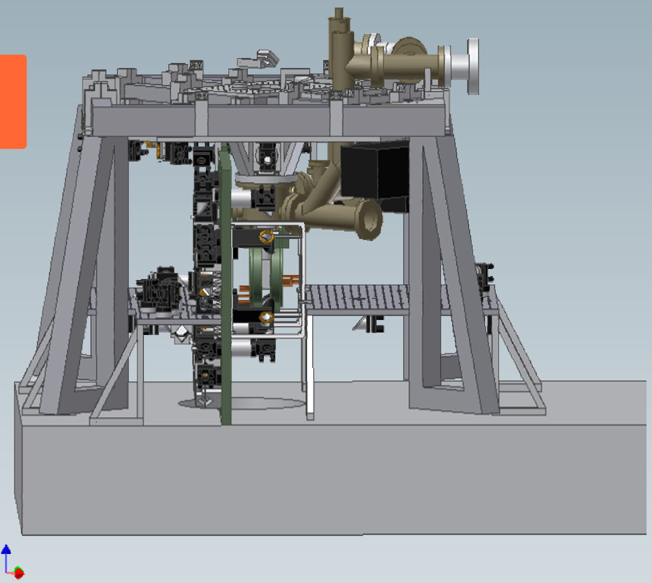
Atom-Guiding in PBF

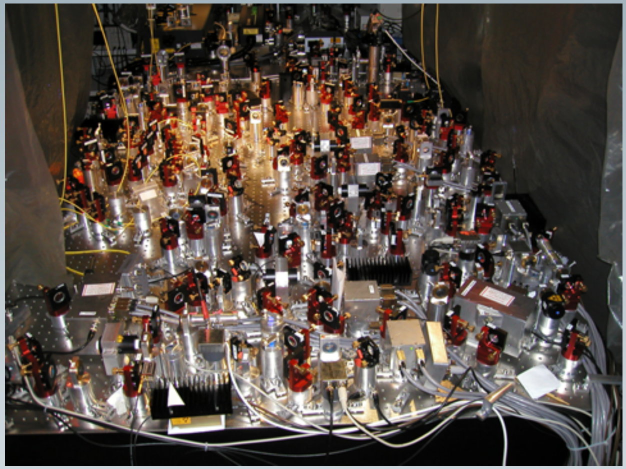
Fermi Bose Mixture Project

Quantum Degenerate Fermi-Bose Mixtures of $^{40}K/^{87}Rb$ at Hamburg:

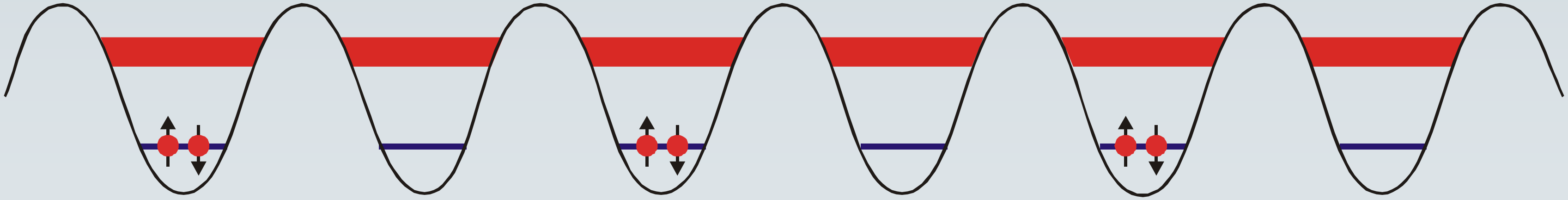
since 5/03







Special interest: Fermi-Bose Mixtures in optical lattices:



Latest Results

degenerate Fermi gas with ^{40}K in combination with Rb BEC

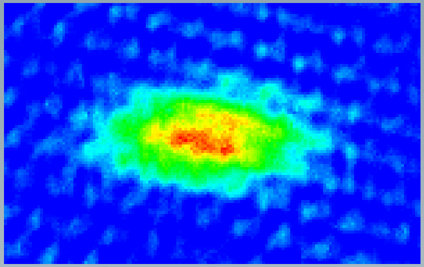
Fermion cloud

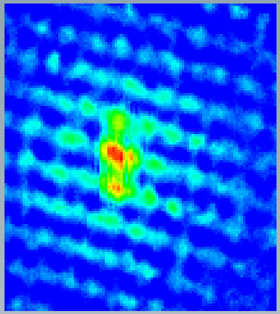
BEC

TOF: 5ms

TOF: 30ms

12.8.04





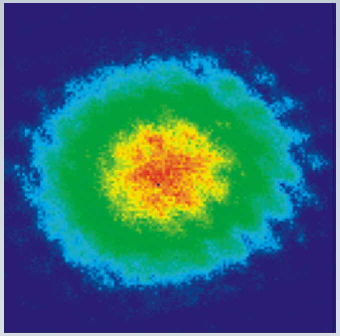
T/T_F ~ 0.75

N_F ~ 2✌10^5

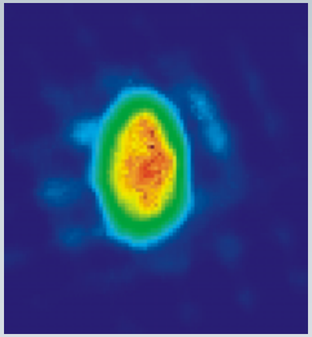
TOF: 15ms

TOF: 15ms

10.10.04



preliminary



T/T_F ~ 0.3 +/- 0.1

N_F ~ 7✌10^5

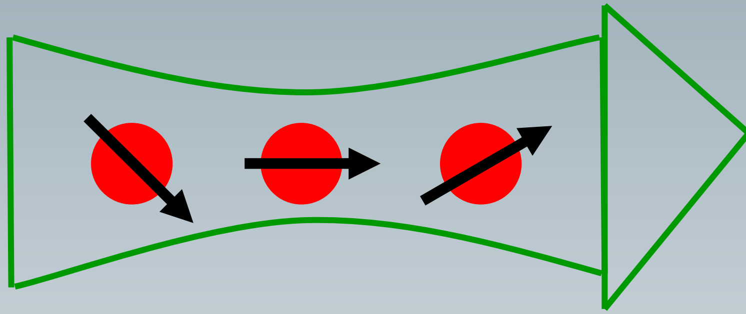
N_B ~ 1✌10^6

see Poster Nr. 10 by Silke Ospelkaus-Schwarzer

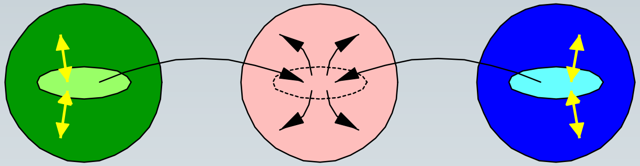
Multi-Component Quantum Gases – Magnetism and a ‘New‘ Realisation of BEC

Klaus Sengstock

Spinor quantum gas systems
-> Magnetism in quantum gases



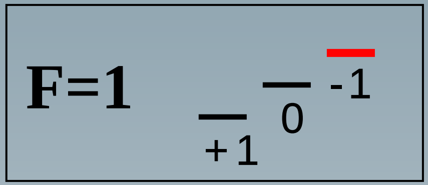
Multi-component thermodynamics
-> ‘New‘ path to BEC

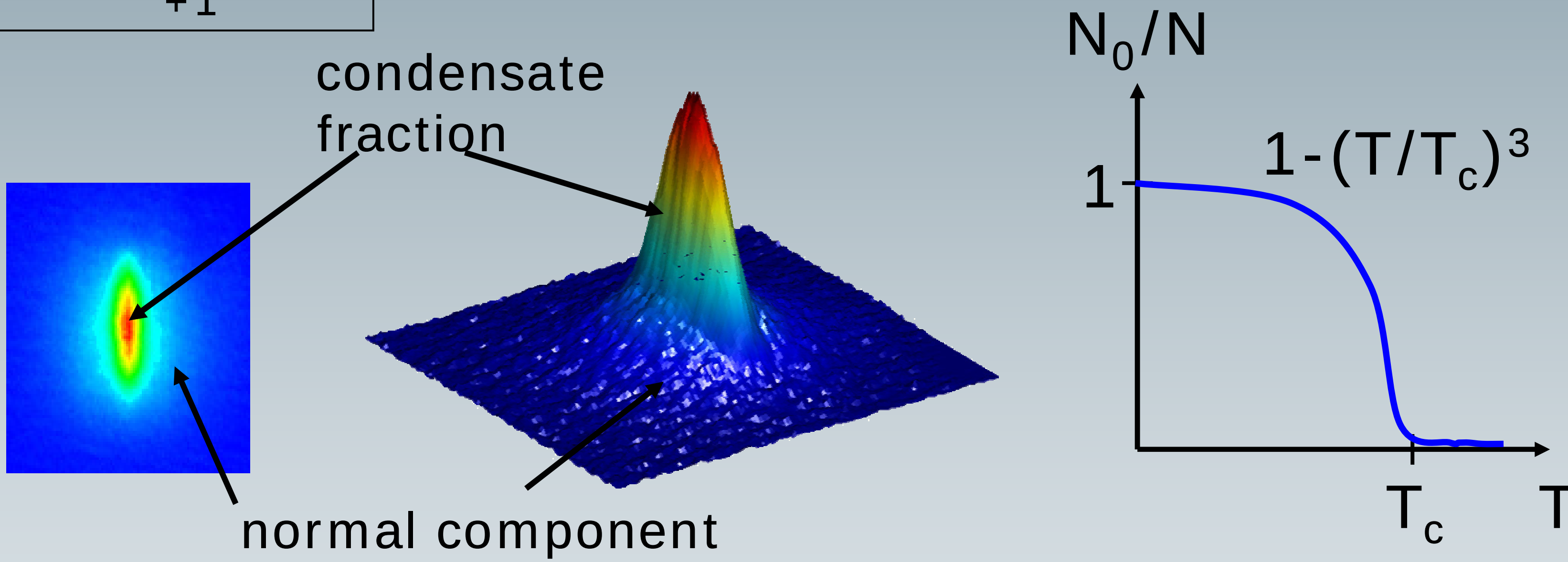


The System

Bose-Einstein condensates in weakly interacting gases:
(experiments since 1995)

usually (due to magnetic trapping): single component BEC





- simultaneous trapping of more components, e.g. trapping of all m_F-levels in optical dipole traps:
  -> multi-component spinor quantum gases

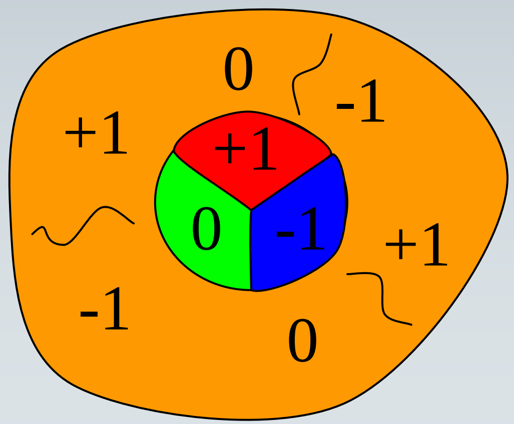
The System

Multi-component spinor-quantum-gases

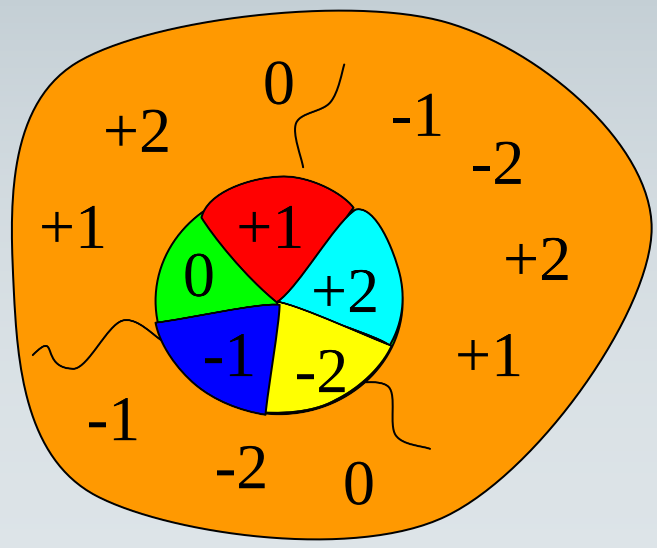
very rich sytem due to:

- several different interactions
  (within condensate fraction, within normal cloud and in between)
- exchange of population possible
  (within condensate fractions and between condensate fraction and normal cloud)

F=1



F=2

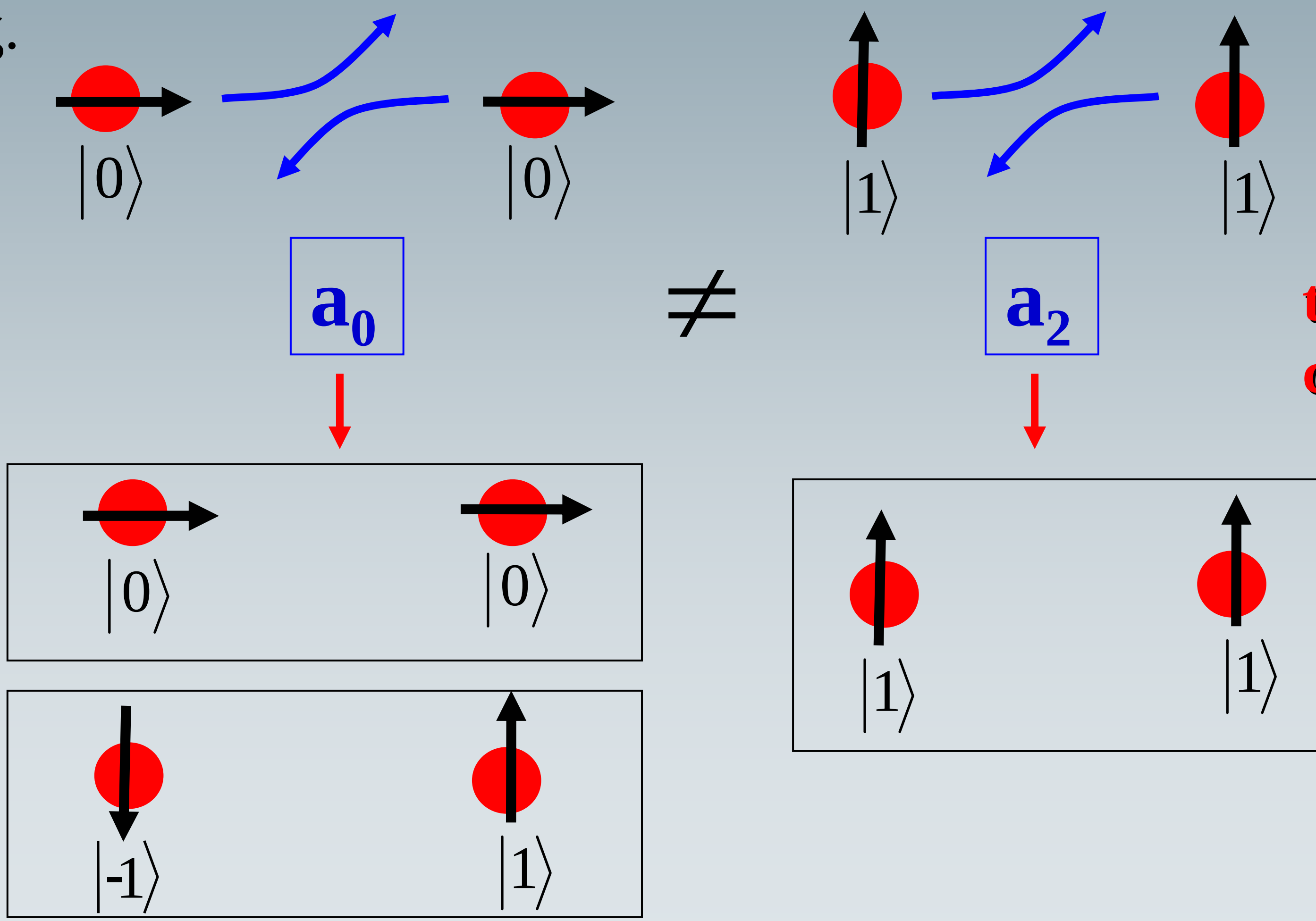


Relevant Interactions

<u>Small</u> difference in <u>weak interactions</u> of quantum gases

i.e. different s-wave scattering lengths for different total spin

e.g.

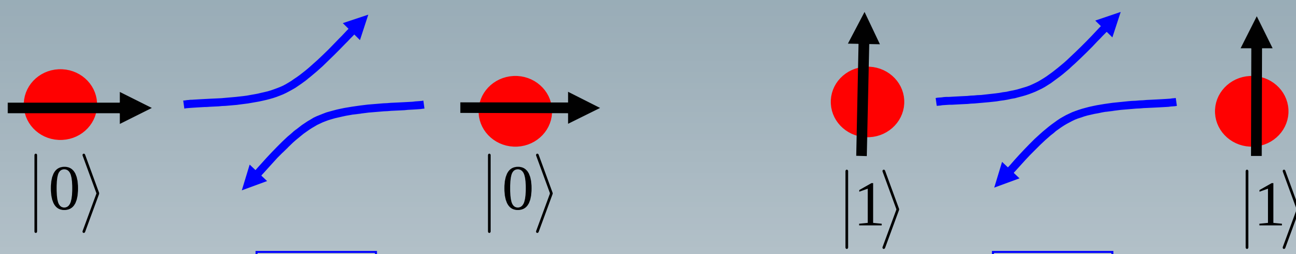


total-spin conservation!

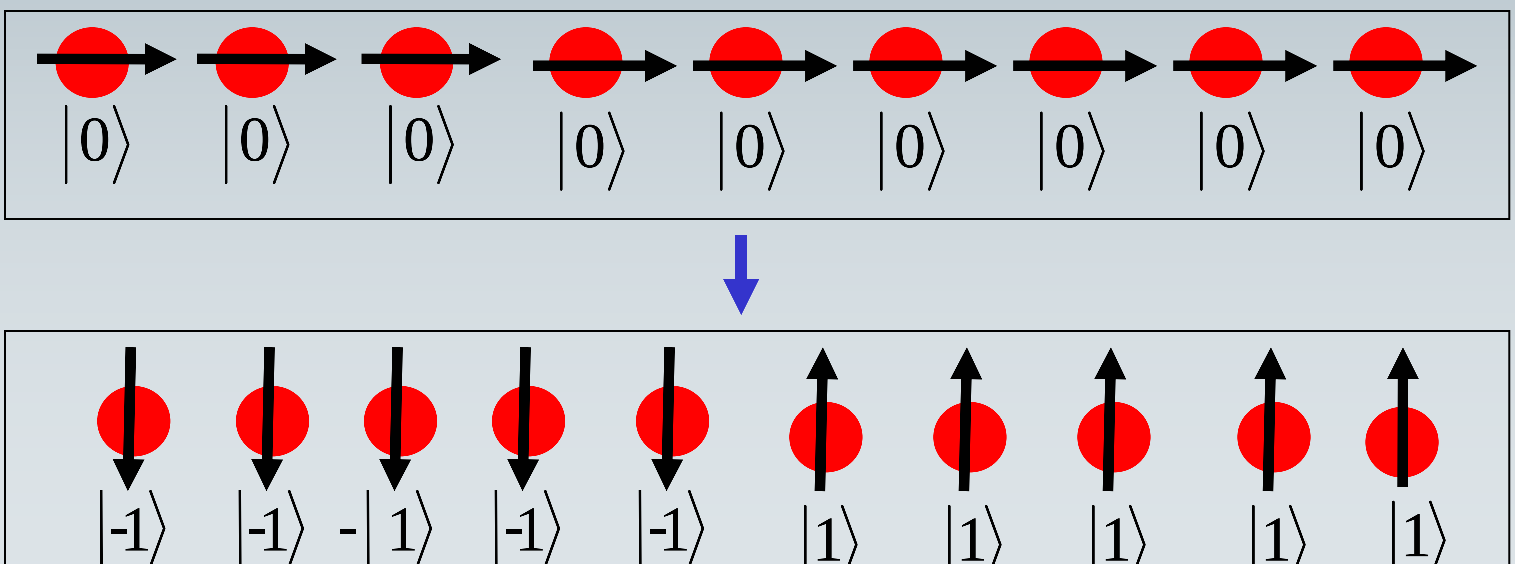
Relevant Interactions

<u>Small</u> difference in <u>weak interactions</u> of quantum gases

i.e. different s-wave scattering lengths for different total spin



e.g.: $\boxed{\mathbf{a_0}}$ **>** $\boxed{\mathbf{a_2}}$

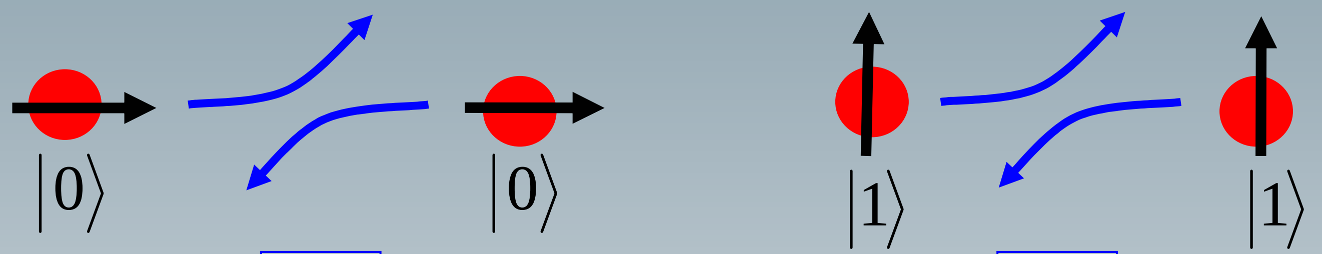


Relevant Interactions

<u>Small</u> difference in <u>weak interactions</u> of quantum gases

i.e. different s-wave scattering lengths for different total spin

e.g.



$\boxed{\mathbf{a_0}} \neq \boxed{\mathbf{a_2}}$

total spin of collision process determines s-wave scattering length

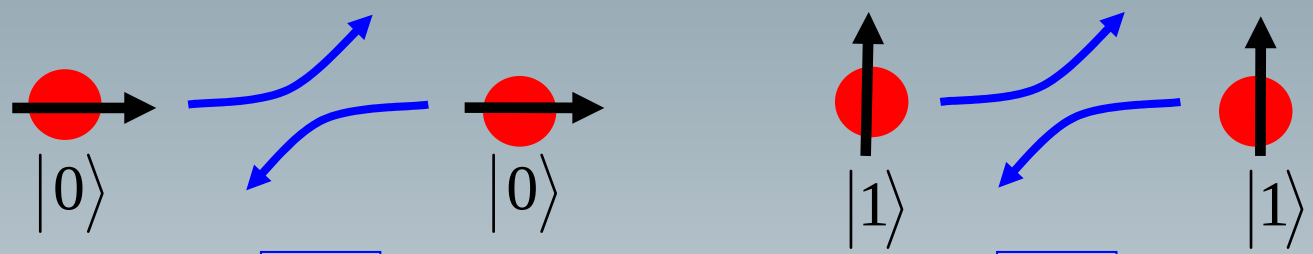
	F=1	F=2
	$\mathbf{a_0, a_2}$	$\mathbf{a_0, a_2, a_4}$
^{87}Rb:	$110{,}0\pm4a_B$, $107{,}0\pm4a_B$	$89{,}4\pm3a_B$, $94{,}5\pm3a_B$, $106{,}0\pm4a_B$,
	T.-L. Ho, PRL, **81**, 742 (1998);	C.V. Ciobanu et al., PRA **61**, 033607 (2000)
^{23}Na:	J. Stenger, et al.,Nature **396**, 345 (1998)..	

Relevant Interactions

<u>Small</u> difference in <u>weak</u> interactions of quantum gases

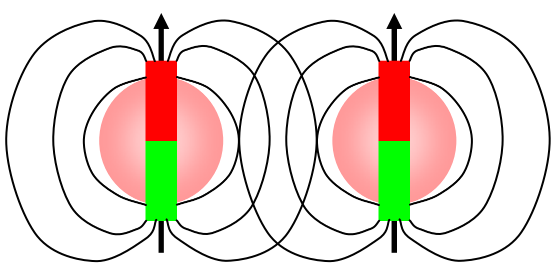
i.e. different s-wave scattering lengths for different total spin

e.g.

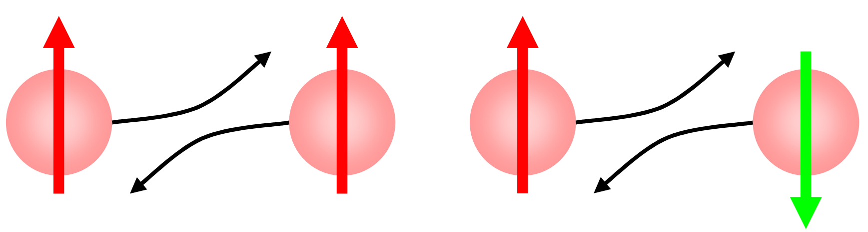


$$\boxed{\mathbf{a_0}} \neq \boxed{\mathbf{a_2}}$$

<u>note</u>: dipole-dipole interactions present but negligible



$E_{dd} \sim 10^{-33} J$



$E_{mf} \sim 10^{-32} J$

studies on dipole-dipole interactions, e.g. in Stuttgart (Cr-atoms)

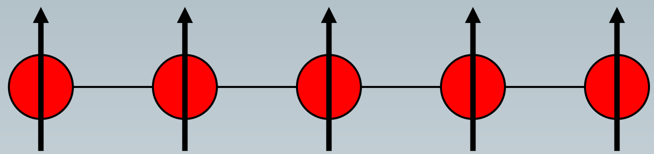
Magnetism in Solid State Sytems

spin (½) in periodic lattice + exchange interaction

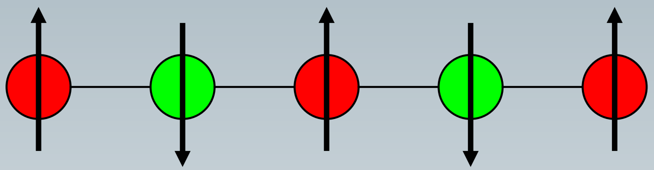
$$H_{spin} = -\tfrac{1}{2} J \sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j$$

interaction energy ~ 100 k_B K

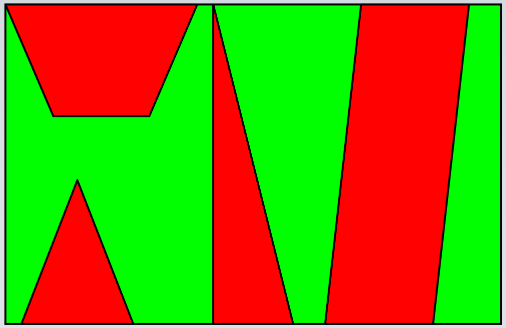
ferromagnet

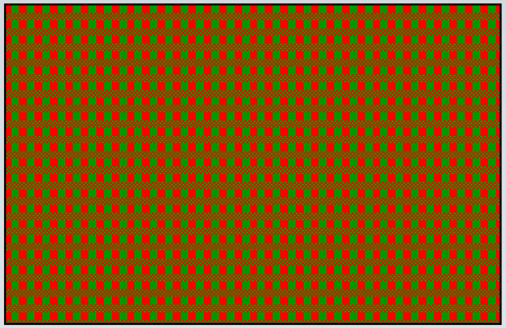


anti-ferromagnet



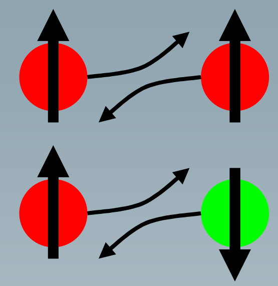
domain structures





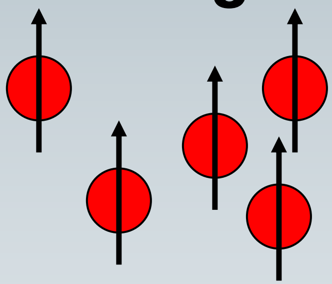
Magnetism in a Gas

free spins + collisions + external magnetic field

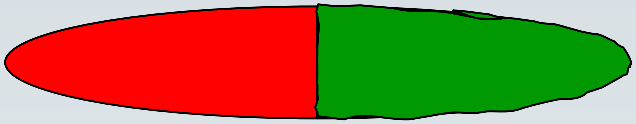


interaction energies ~ k_B **nK**

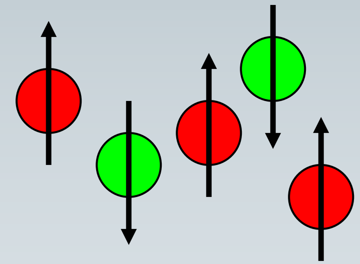
"ferromagnetism"

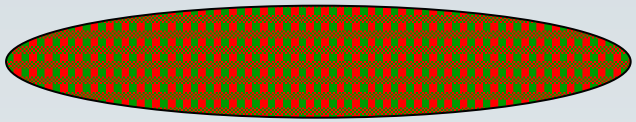


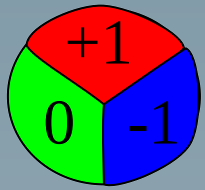
“domain structures“



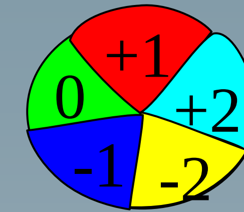
"anti-ferromagnetism"

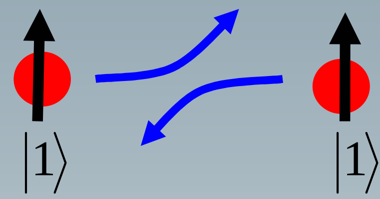
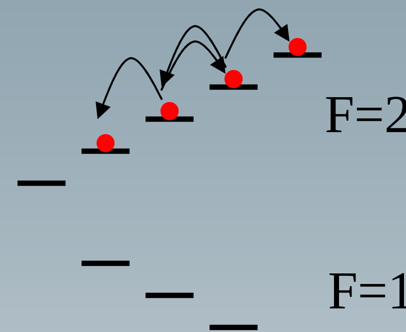
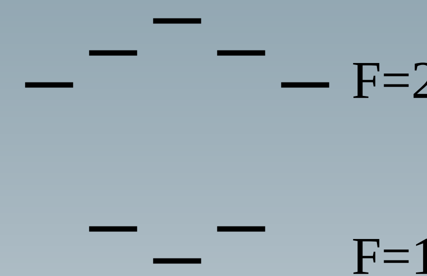






System Interactions



single comp. mean field	mean field exchange interaction	linear Zeeman	quadratic Zeeman
n_0 n_{-1} n_{+1} n_{-2} n_{+2} chemical potential ~ 120nK	 F=1: $\propto \vec{F}_1 \cdot \vec{F}_2$ g_1~10nK , g_2~0.2nK	 ~35 μK/G <u>but</u>: cancels due to spin conservation	 ~14nK/G^2

Spin-depended energy functional:

$$E_{spin} = \left(- p \langle F_z \rangle + q \langle F_z^2 \rangle + g_1 \langle F \rangle^2 n + g_2 |\langle P_0 \rangle|^2 n \right) n$$

lin. Zeeman energy

quadratic Zeeman energy

Spin dependend mean field [1]

additional mean field for F=2 [2]

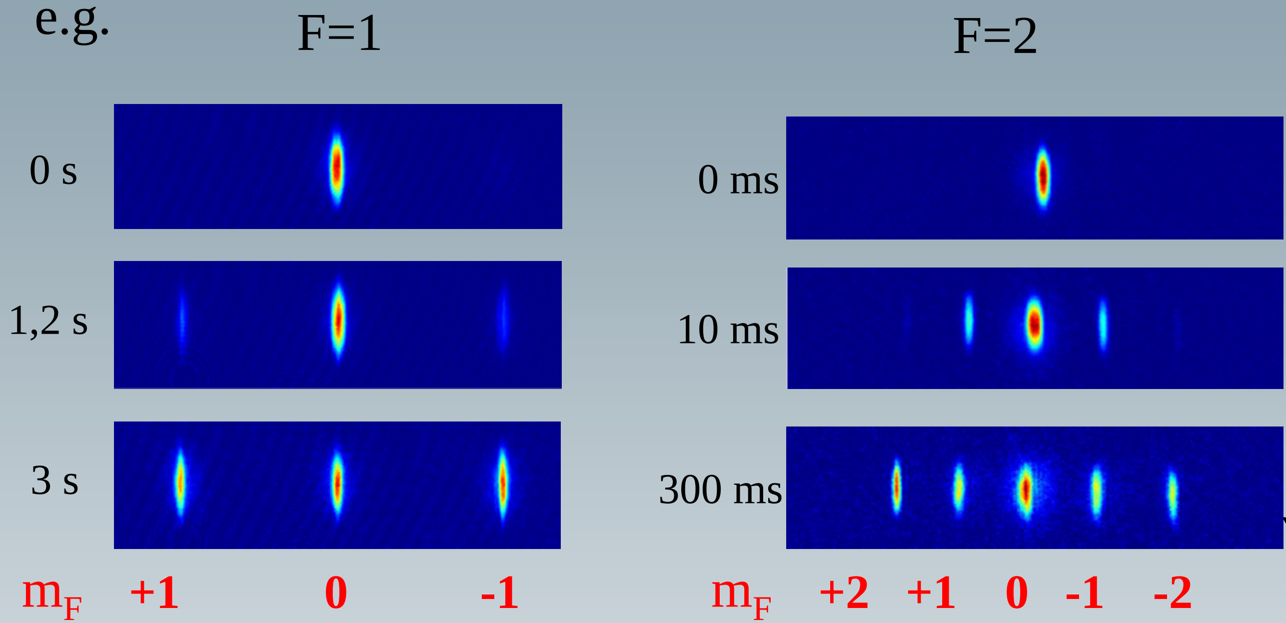
[1] T.-L. Ho, PRL, 81, p.742 (1998)

[2] M. Koashi, M. Ueda, PRL, 84, p.1066 (2000)

Magnetism in Quantum Gases

System allows studies of spinor condensate dynamics and ground state properties

e.g.



Ho et al. 98
Ketterle et al. 98
Cornell et al. 98
Bigelow et al. 98
Ueda et al. 99
Cirac, Zoller 01
You et al. 02, 04
Lewenstein et al. 04
...
Hamburg group 03
Chapman et al.03

- coupled Gross Pitaevskii equations vs.
  physics beyond GPE (entanglement, damping,...)

  ↓

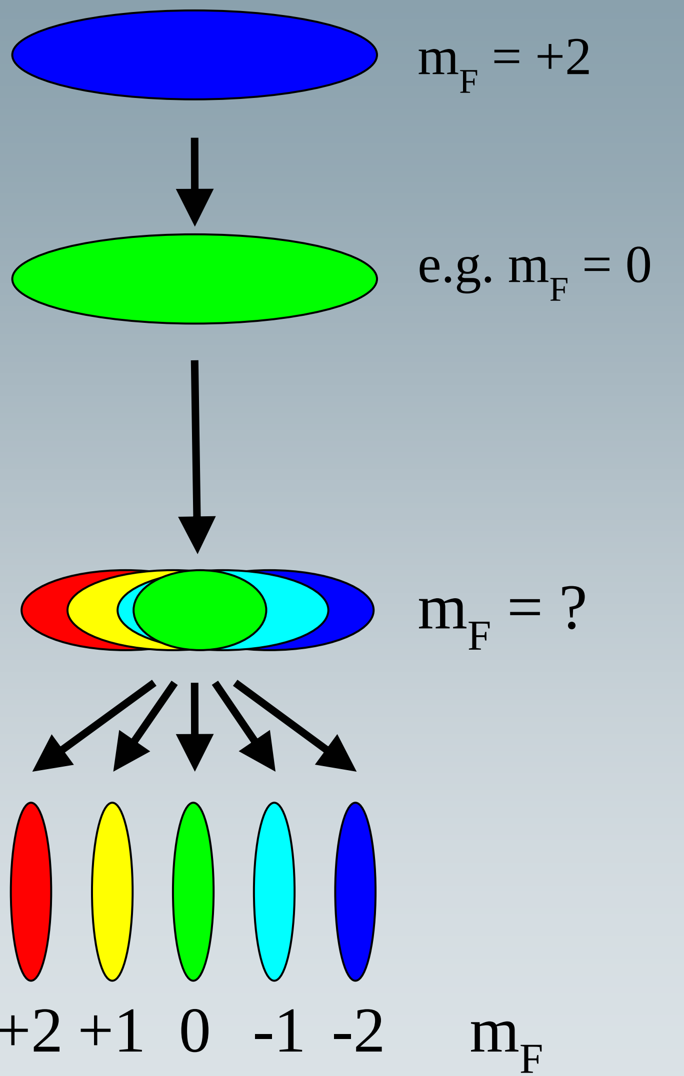
  quantum information applications

- spinor BEC in optical lattices

Experimental scheme

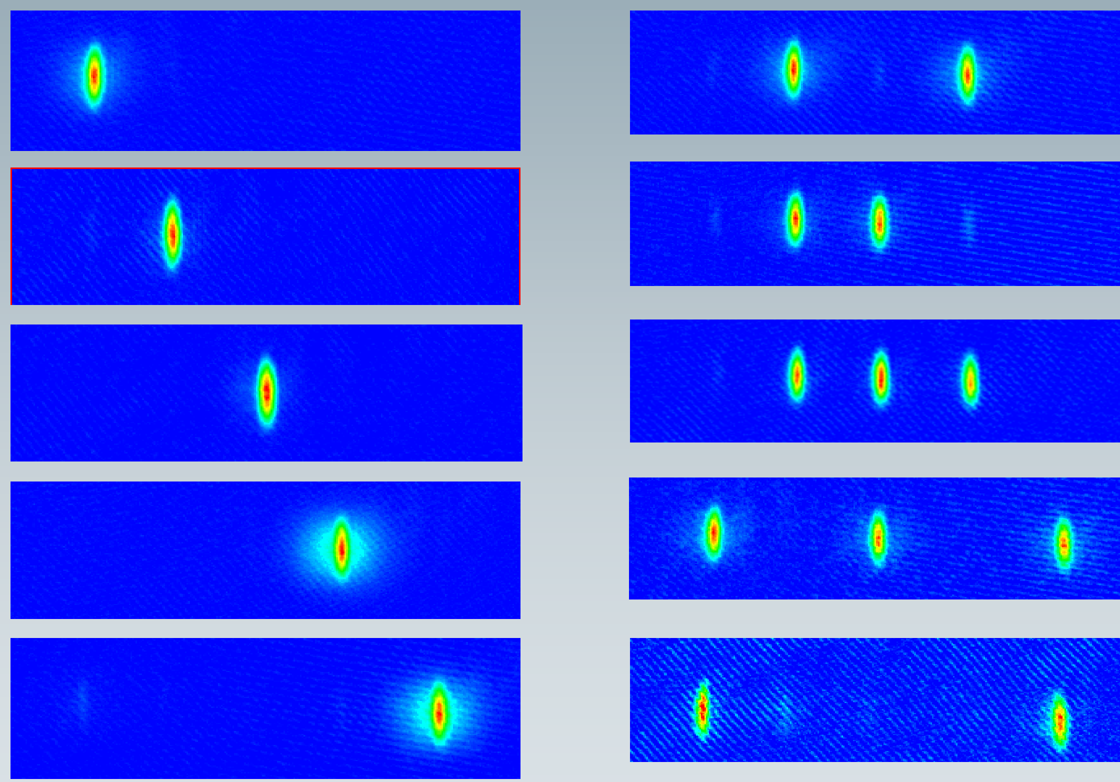
time

- creation of Rb-BEC in a far detuned optical dipole trap
- preparation of initial spin distribution
  by RAP and LZ sweeps
- **evolution of spinor condensate**
  for a variable hold time
  in the optical dipole trap at low bias field
- detection after Stern-Gerlach and time-of-flight



Experimental Scheme

initial spin preparation



m_F +2 +1 0 -1 -2 +2 +1 0 -1 -2 m_F

Experimental scheme

time

- creation of Rb-BEC in a far detuned optical dipole trap
- preparation of initial spin distribution by RAP and LZ sweeps
- **evolution of spinor condensate** for a variable hold time **in the optical dipole trap at low bias field**
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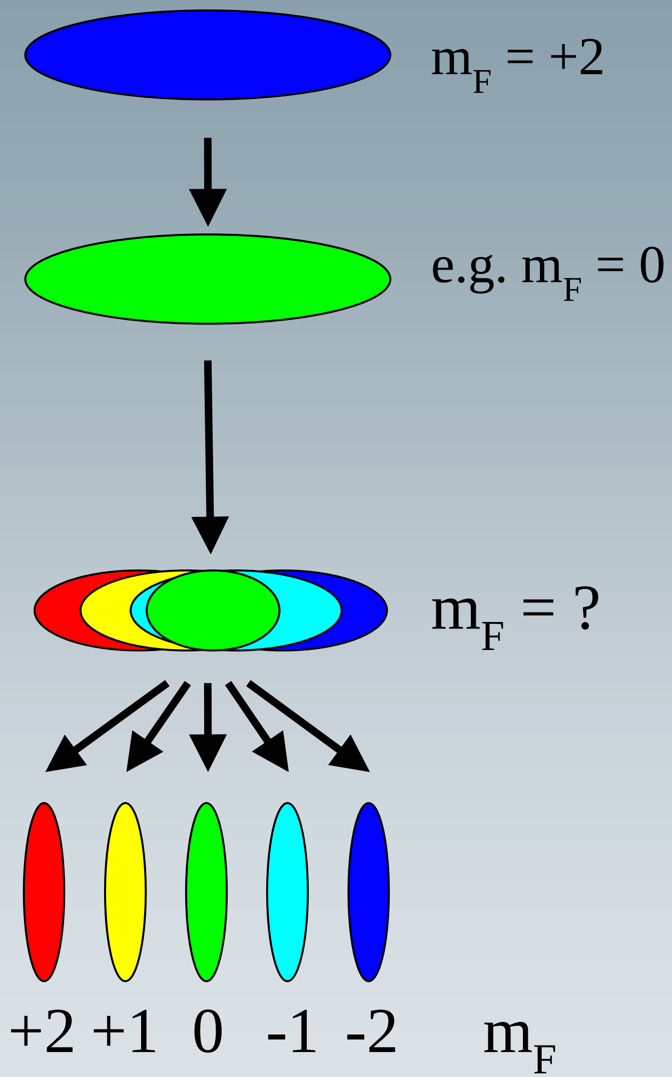


important to remember for interpretation of dynamics:
!!! pictures taken after Stern Gerlach separation !!!

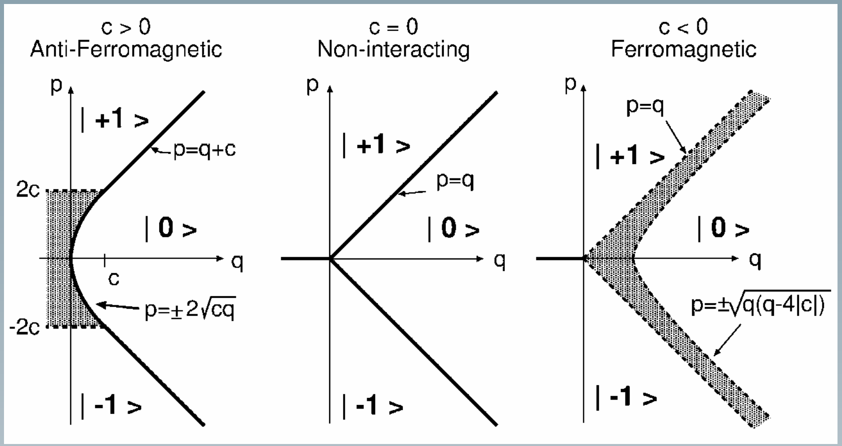
Magnetic Ground States

- **F=1**

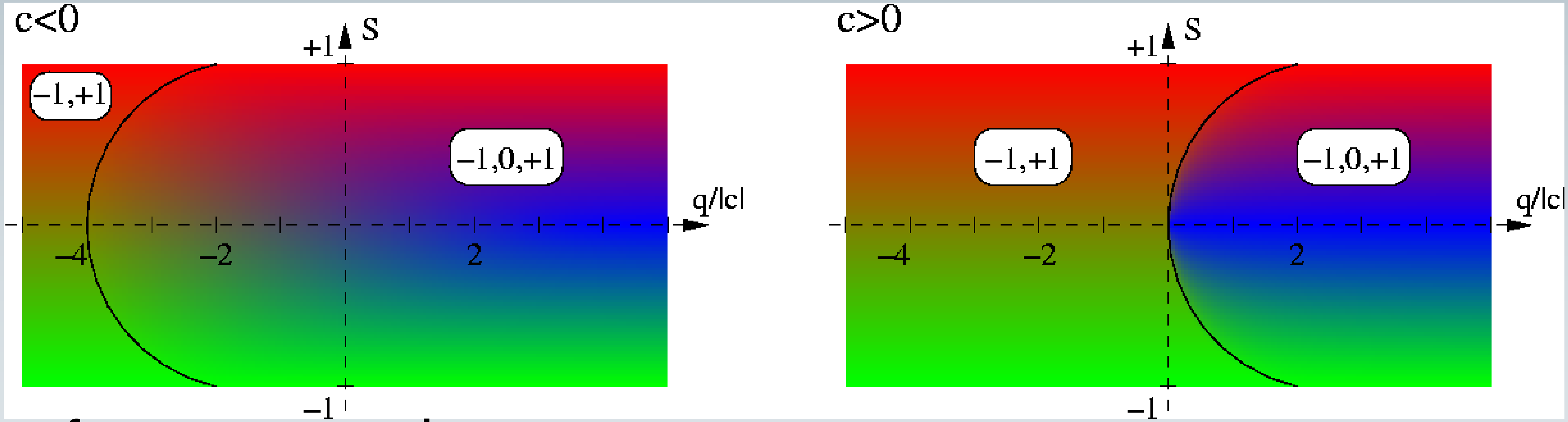
(quadr.Zeeman: ‾ _ ‾)

representation as function of total spin (s) and offset-magnetic field (q).

Schmaljohann et al. Laser Phys. 14, 1252 (2004).



J. Stenger, et al., Nature **396**, 345 (1998).

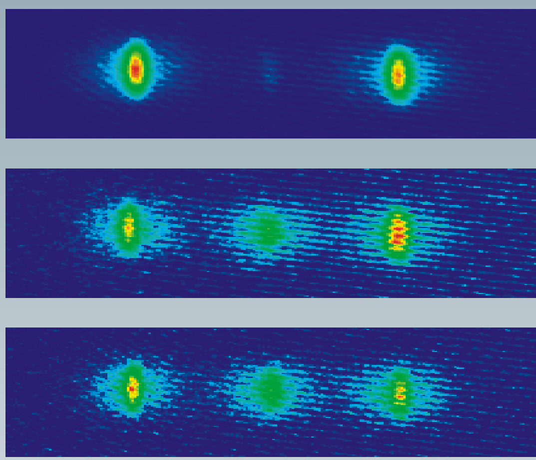


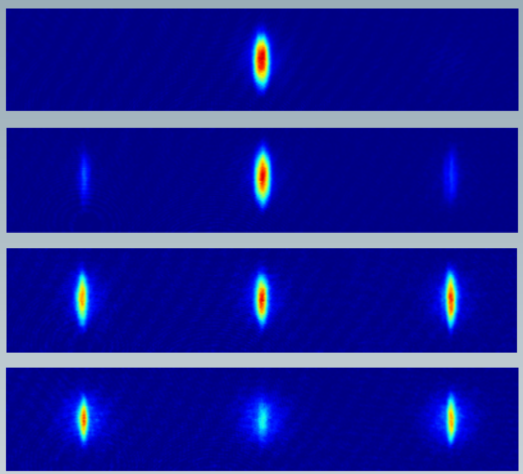
ferromagnetic

anti-ferromagnetic

Magnetic Ground States

- **Rb F = 1 is ferromagnetic!**





H. Schmaljohann et al.
Phys. Rev. Lett. 92, 040402 (2004).

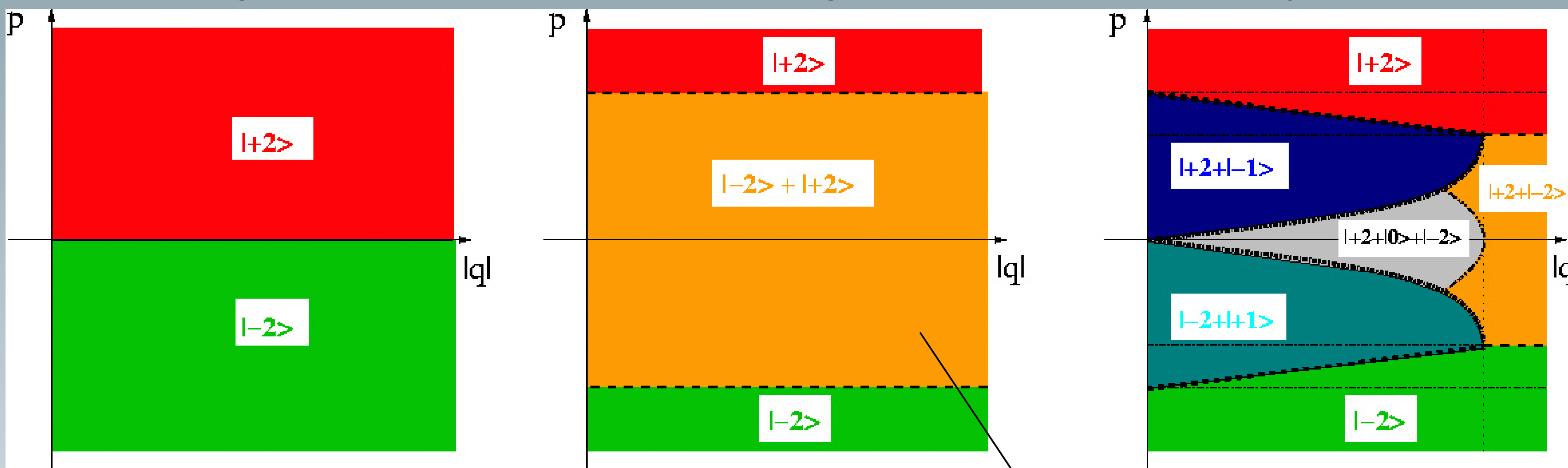
see also: work by Georgia-Tech group
M.-S. Chang et al.,
Phys. Rev. Lett. 93, 140403 (2004).

Magnetic Ground States

- **F=2**

our calculations: (quadr.Zeeman:)

ferromagnetic anti-ferromagnetic cyclic

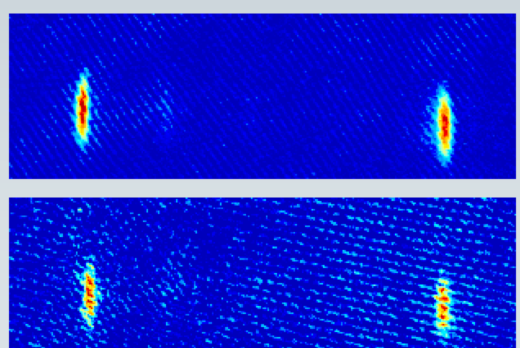


Schmaljohann et al.
J. Mod. Opt. 51,1829 (2004)

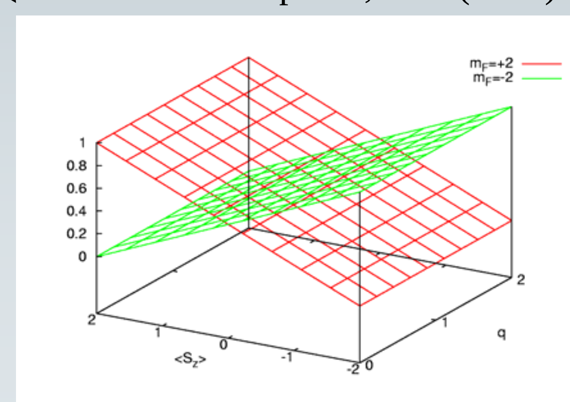
^{87}Rb F = 2
is antiferromagnetic

0 ms

200 ms



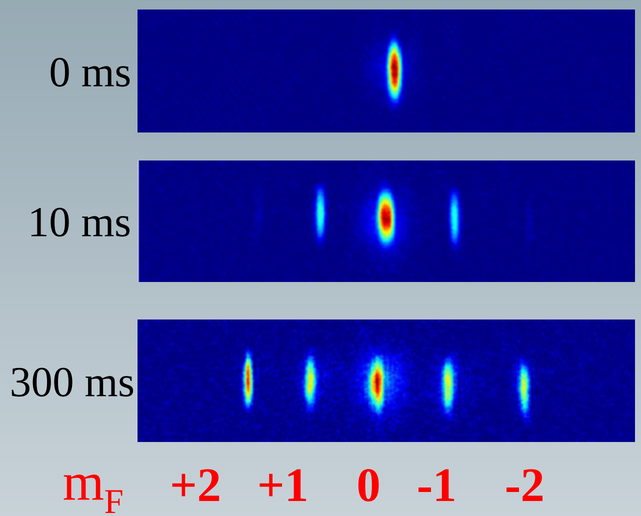
m_F= -2 -1 0 1 2

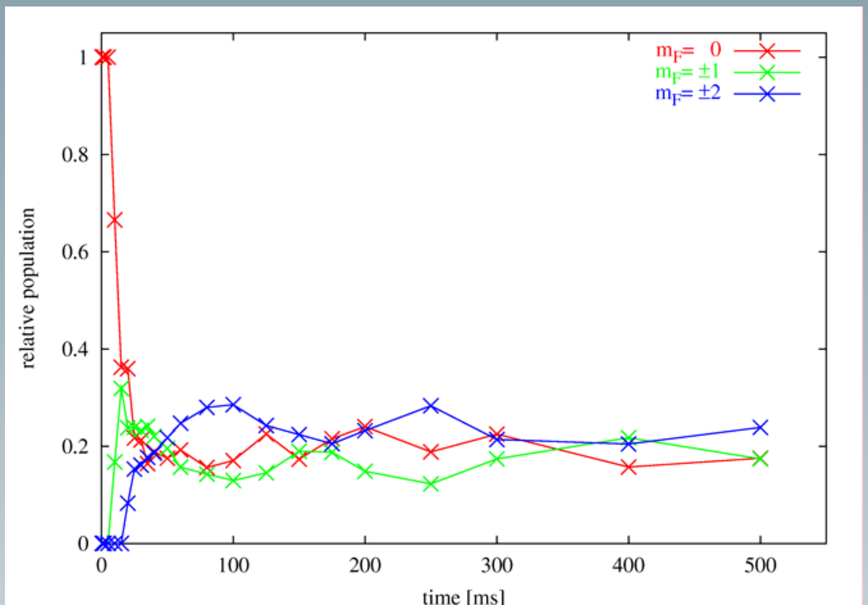


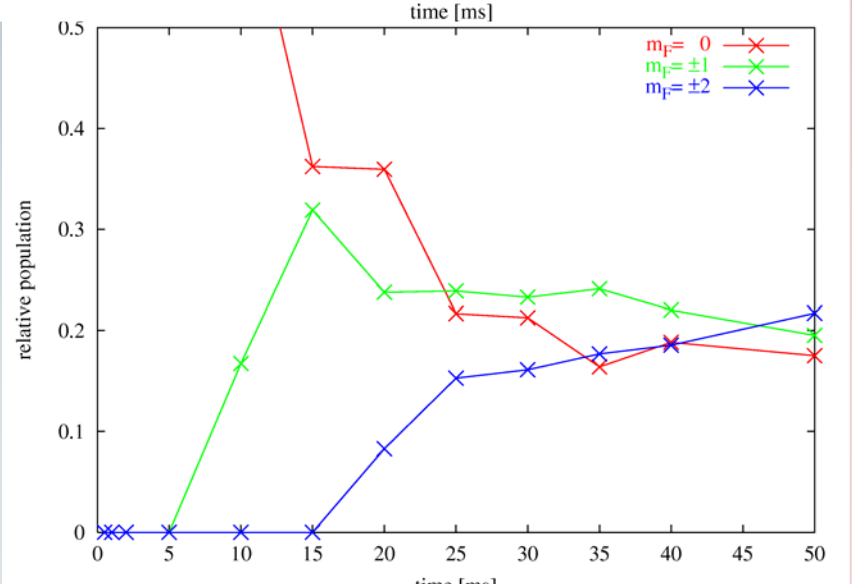
H. Schmaljohann et al.
Phys. Rev. Lett. 92, 040402 (2004).

Spin Dynamics for ^{87}Rb, F=2

- Example: Preparation in m_F = 0



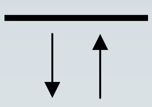




→ fast (~10 ms) spin dynamics

→ initial delay

→ oscillations
✡coherent dynamics
vs. damping



H. Schmaljohann et al.,
Phys. Rev. Lett. 92, 040402 (2004).

Spin Dynamics - Simulation

- based on coupled GPE (T = 0), homogenous case:

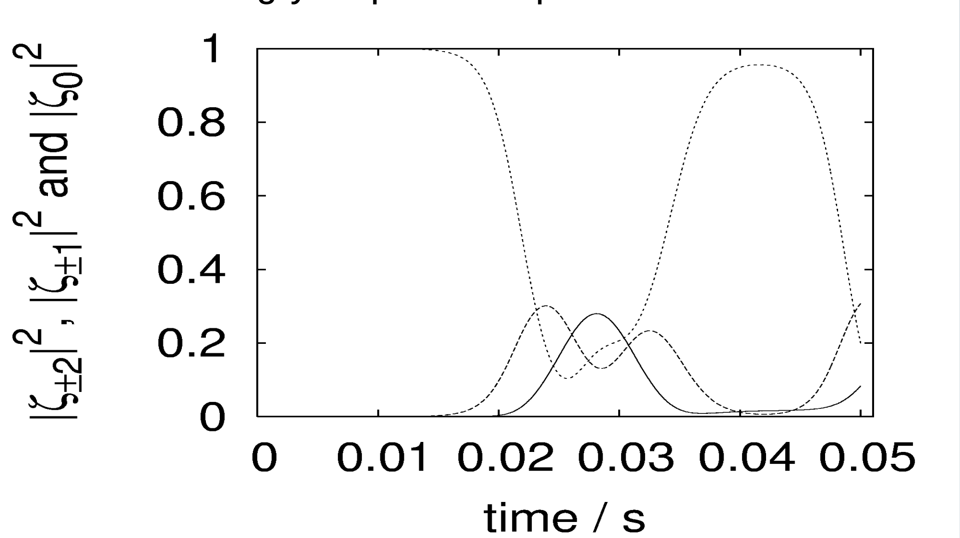
$$\vec{\varphi}(\vec{r},t) = \sqrt{n(\vec{r},t)}e^{i\phi(t)} \cdot \vec{\zeta}(\vec{r},t)$$

$$\begin{aligned}
i\hbar\frac{\partial}{\partial t}\sqrt{n(\vec{r},t)}e^{i\phi(t)} &= \left(-\frac{\hbar^2\nabla^2}{2m} + V_{ext.}(\vec{r}) + g_0 n(\vec{r})\right)\sqrt{n(\vec{r},t)}e^{\phi(t)}\,, \\
i\hbar\frac{\partial}{\partial t}\vec{\zeta}(\vec{r},t) &= \tilde{g}_2 n(\vec{r})\vec{\mathcal{S}}\vec{\zeta}(\vec{r},t)\vec{\zeta}^*(\vec{r},t)\vec{\mathcal{S}}\vec{\zeta}(\vec{r},t) \\
&\quad + \tilde{g}_4 n(\vec{r})\vec{\mathcal{S}}^2\vec{\zeta}(\vec{r},t)\vec{\zeta}^*(\vec{r},t)\vec{\mathcal{S}}^2\vec{\zeta}(\vec{r},t) \\
&\quad - p\mathcal{S}_z\vec{\zeta}(\vec{r},t) + q(\mathcal{S}_z^2\vec{\zeta}(\vec{r},t) - 4)\,.
\end{aligned}$$

$$\begin{aligned}
i\hbar\frac{\partial}{\partial t}\zeta_{+1} &= g_2 n\,\zeta_{-1}^*\zeta_0^2 - p\zeta_{+1} - 3q\zeta_{+1}\,, \\
i\hbar\frac{\partial}{\partial t}\zeta_0 &= 2g_2 n\,\zeta_0^*\zeta_1\zeta_{-1} - 4q\zeta_0\,, \\
i\hbar\frac{\partial}{\partial t}\zeta_{-1} &= g_2 n\,\zeta_{+1}^*\zeta_0^2 + p\zeta_{-1} - 3q\zeta_{-1}\,.
\end{aligned}$$

delayed build up, oscillations,...
strongly depend on phases and initial conditions

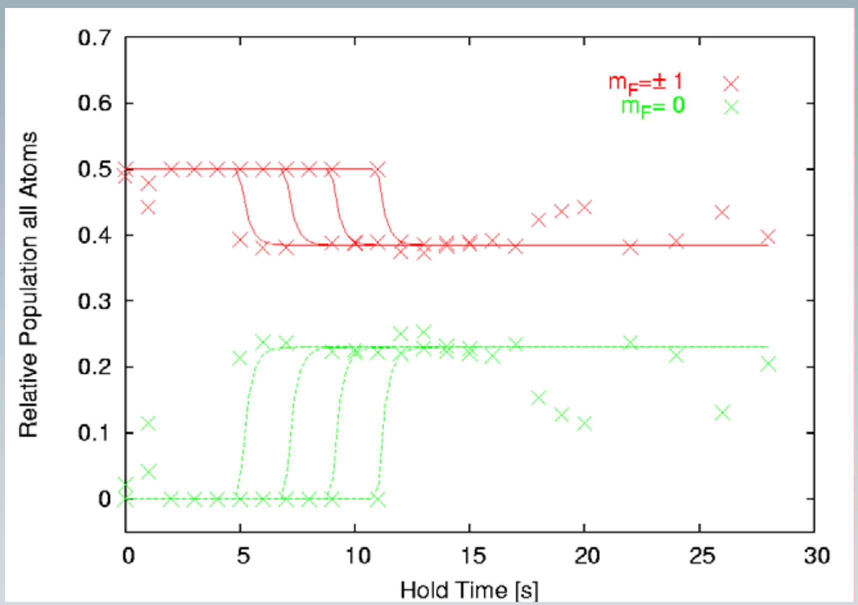
F=2:



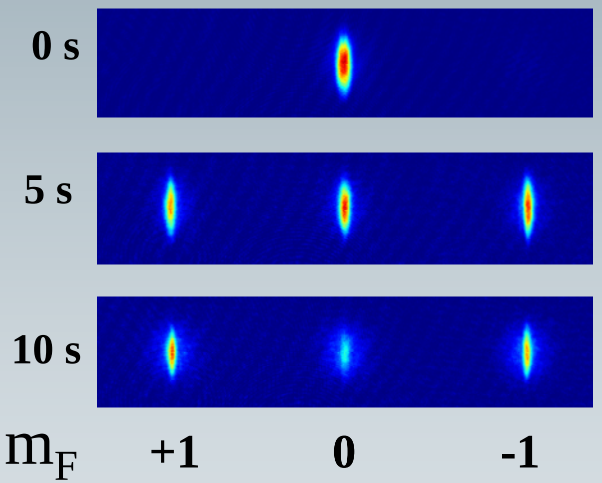
small seed in +/-1 and +/-2 comp.: 10^{-4}

Simulations for finite temperature
M. Guilleumas, M. Lewenstein et al.
Poster 13, Tuesday

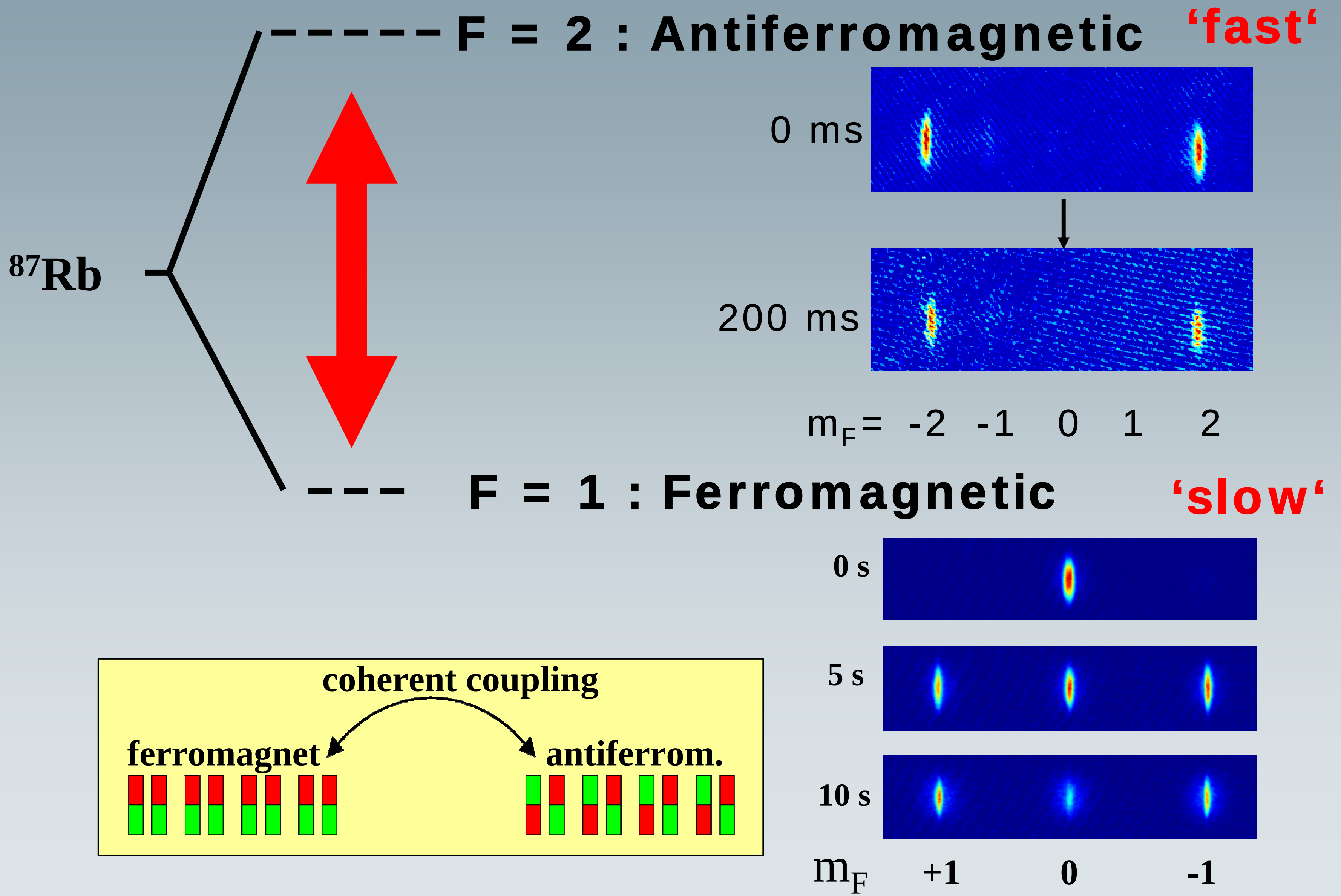
Spin Dynamics for ^{87}Rb, F=1



very slow (5..10 sec)
spin dynamics in F = 1!



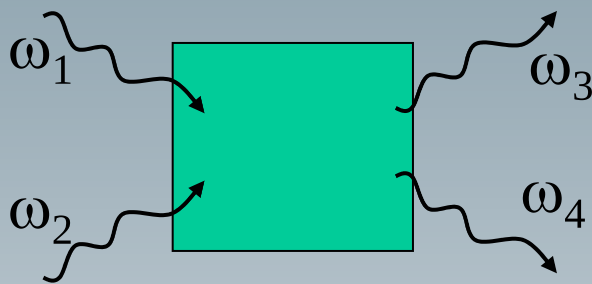
^{87}Rb Spinor-Ground States



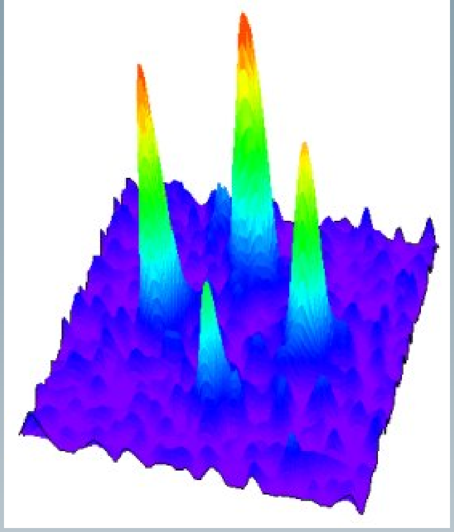
Quantum Gas Four-wave-mixing

quantum optics viewpoint ✡ four-wave-mixing

optics:

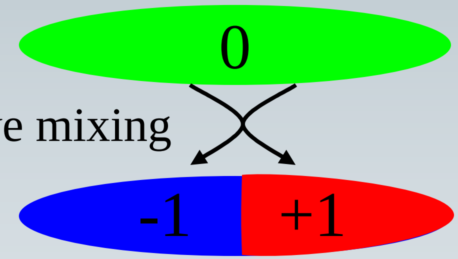


for BEC
(Phillips et al.):

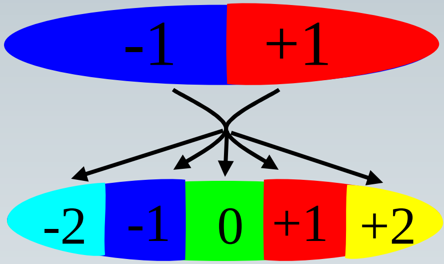


spinor condensates
(J. P. Burke et al., cond-mat/0404499)

four wave mixing



F=2: even more complex



multi mode coupling
competing four wave
mixing channels

✡ fully equivalent description
✡ to populate empty modes:
- seed
- quantum fluctuations

DGLs:

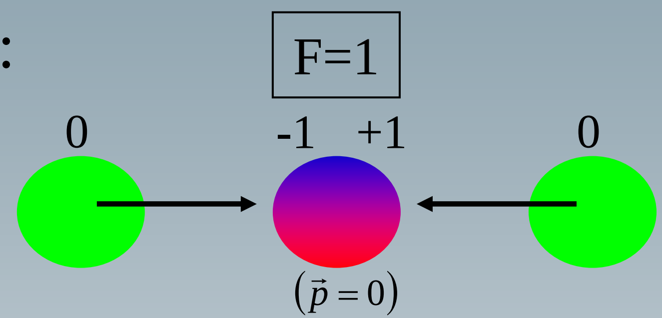
$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\zeta_{+1} &= g_2 n\,\zeta_{-1}^*\zeta_0^2 - p\zeta_{+1} - 3q\zeta_{+1}\,, \\ i\hbar\frac{\partial}{\partial t}\zeta_0 &= 2g_2 n\,\zeta_0^*\zeta_1\zeta_{-1} - 4q\zeta_0\,, \\ i\hbar\frac{\partial}{\partial t}\zeta_{-1} &= g_2 n\,\zeta_{+1}^*\zeta_0^2 + p\zeta_{-1} - 3q\zeta_{-1}\,. \end{aligned}$$

Quantum Gas Four-wave-mixing

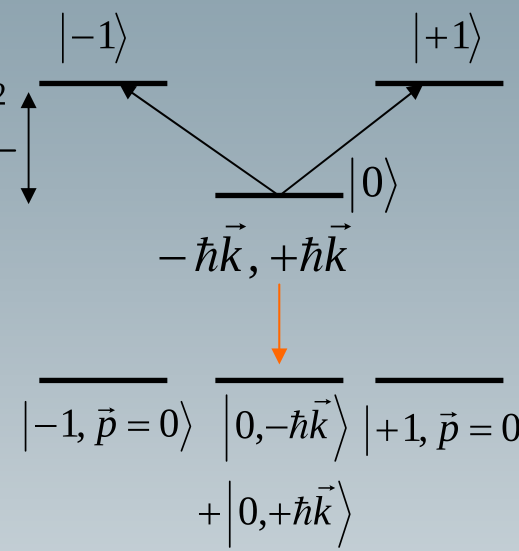
- **adding kinetic energy plus magnetic fields:**

→ additional processes possible

e.g.:

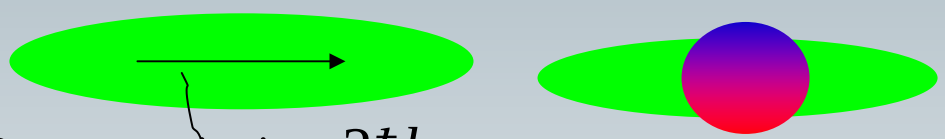


quadratic Zeeman energy $\hat{=} \dfrac{\hbar^2 k^2}{2m}$



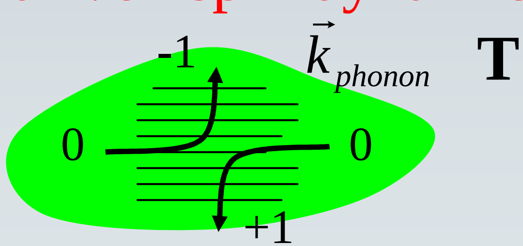
proposed experiment: FWM into zero momentum states

F=1, m_F=0

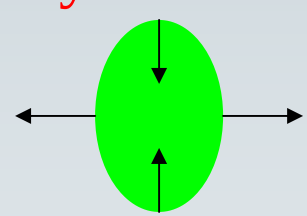


Raman excitation $2\hbar k$
offset field ~ 3G

→ phonon driven spin dynamics ??! for very small offset B-field



e.g.

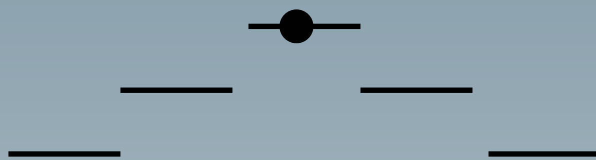


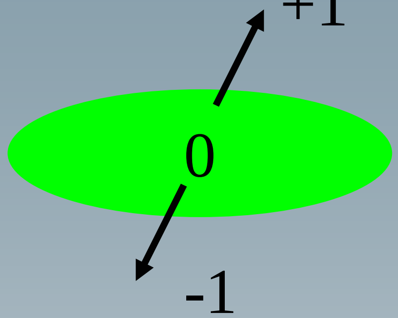
quadrupole mode coupling to spin conversion

→ coupling of spinor components and finite T excitations ?

Quantum Gas Four-wave-mixing

F=2: the other way round...





Zeeman energy ✡ kinetic energy

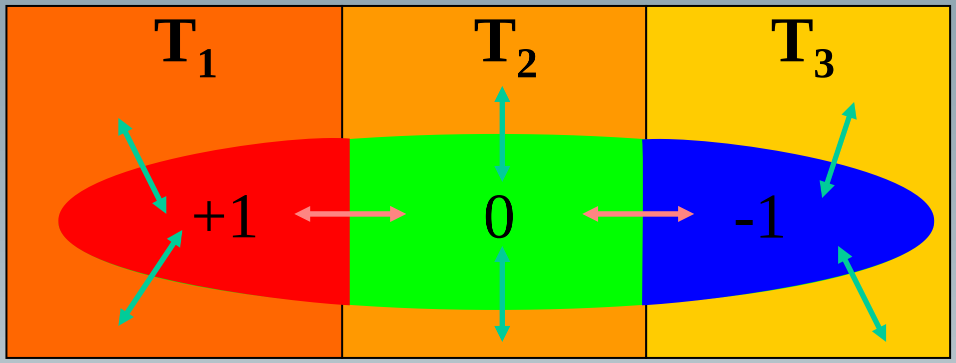
→ four wave mixing for $k_1=k_2=0$!

→ no grating !? Bragg diffraction condition not necessary for FWM?
-> spin grating present!

→ entanglement source

II. Multi Component Quantum Gas Thermodynamics

✡ How do different quantum gas components at different T do interact with each other and how do they exchange population?



temperature reservoir and particle reservoir

special here:

- different time scales for **spin dynamics** within condensate and **thermalization**

$\tau \sim 5$ s (F=1)

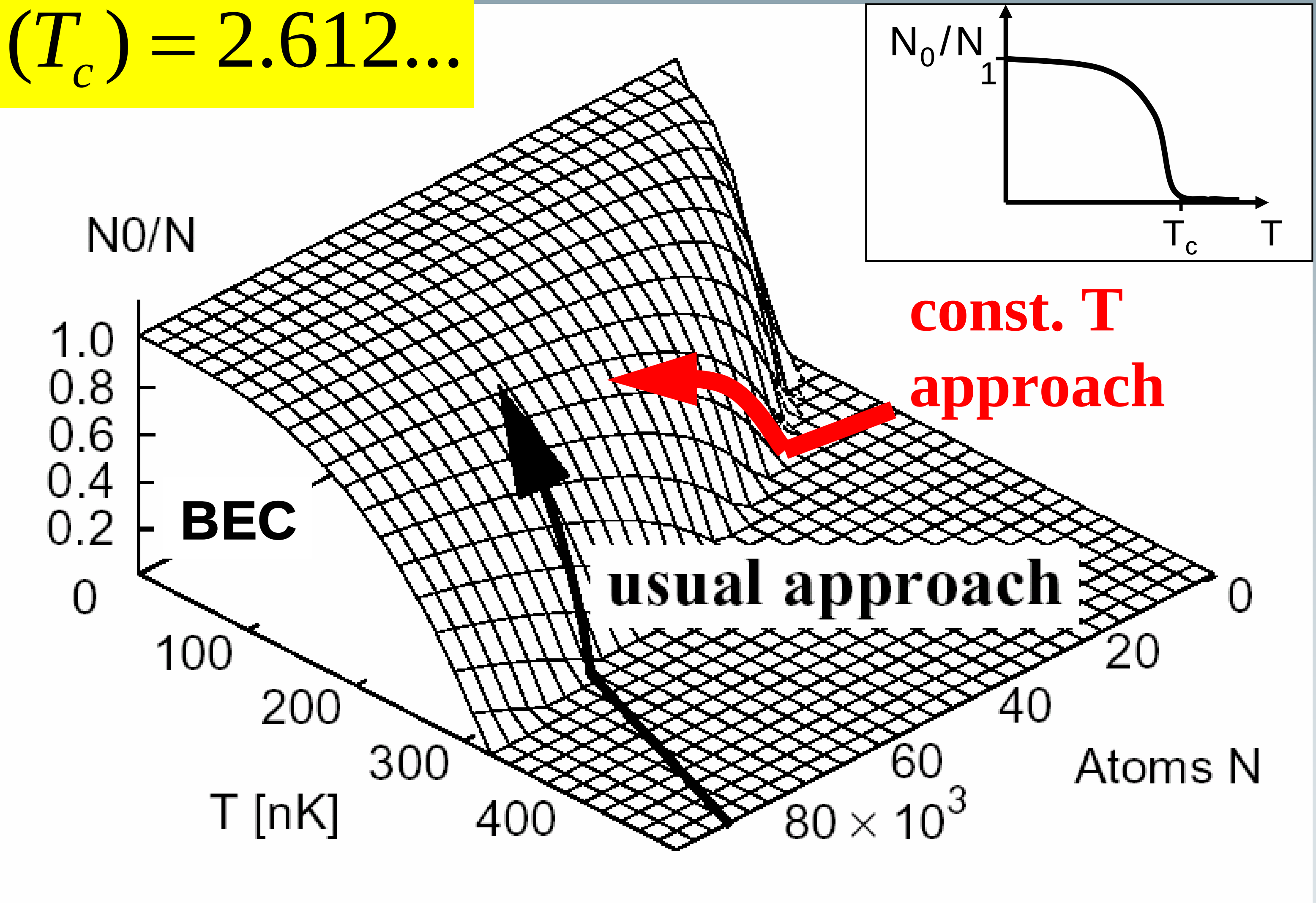
or: $\tau \sim 5$ ms (F=2)

$\tau \sim 100$ ms

- allows, **e.g.:**
  - ✡ new path to BEC
  - ✡ condensate melting
  - ✡ temperature driven magnetization !

BEC – “new“ aspects

$$n_0 \Lambda^3_{dB}(T_c) = 2.612...$$



BEC – “new“ aspects

Quantentheorie des einatomigen idealen Gases.

Zweite Abhandlung.

Von A. EINSTEIN.

---

§ 6. Das gesättigte ideale Gas.

Was geschieht nun aber, wenn ich bei dieser Temperatur $\frac{n}{V}$ (z. B. durch isothermische Kompression) die Dichte der Substanz noch mehr wachsen lasse?

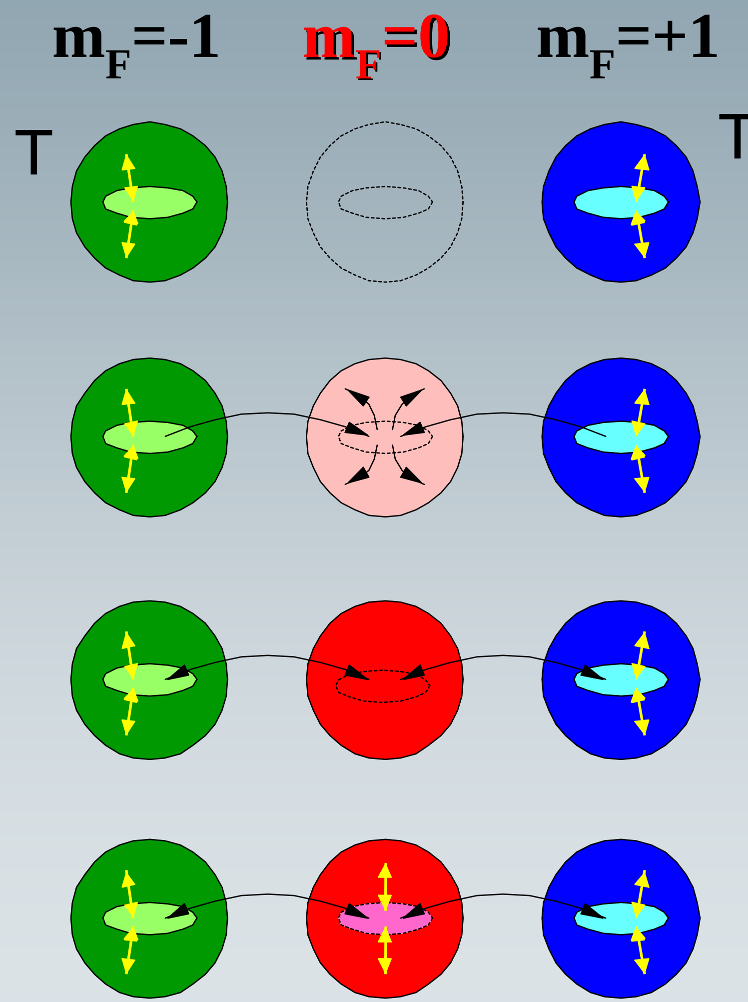
Ich behaupte, daß in diesem Falle eine mit der Gesamtdichte stets wachsende Zahl von Molekülen in den 1. Quantenzustand (Zustand ohne kinetische Energie) übergeht, während die übrigen Moleküle sich gemäß dem Parameterwert $\lambda = 1$ verteilen. Die Behauptung geht also dahin, daß etwas Ähnliches eintritt wie beim isothermen Komprimieren eines Dampfes über das Sättigungsvolumen. Es tritt eine Scheidung ein; ein Teil »kondensiert«, der Rest bleibt ein »gesättigtes ideales Gas« ($A = 0$ $\lambda = 1$).

A. Einstein,

Sitzungsber. Preuss. Akad. Wiss., 3, **1925**

Realisation for F=1

normal components +/-1: temperature reservoir
condensate fractions +/-1:particle reservoir



start:
m_F = 0 empty

no relevant
spin dynamics
in thermal cloud

slow spin dynamics
populates m_F=0
-> fast thermalisation

if critical density
for component reached:
BEC transition

only population of m_F=0
condensate component

Experimental Realisation

-1 0 +1

start:
m_F = 0 empty

t=0s

filling up m_F=0
normal component

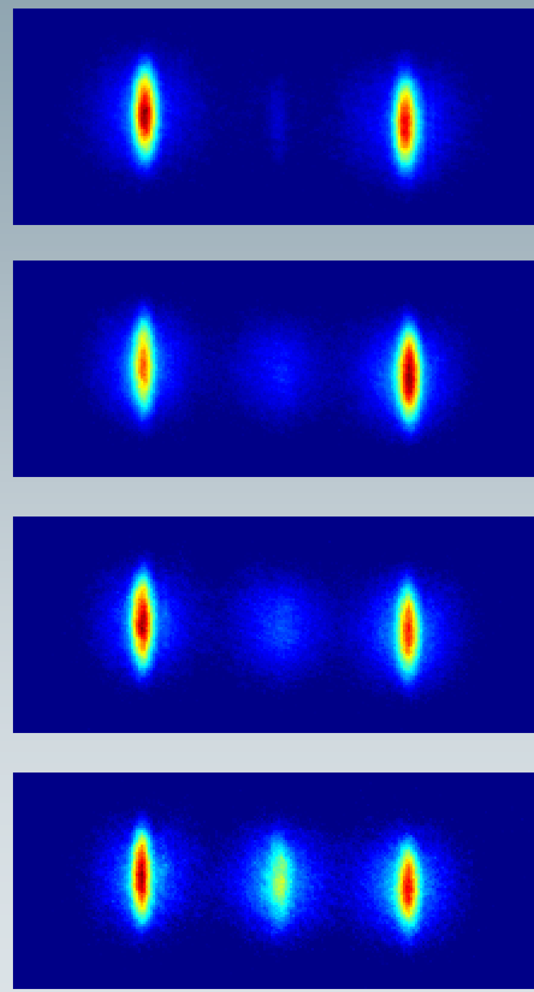
t=3s

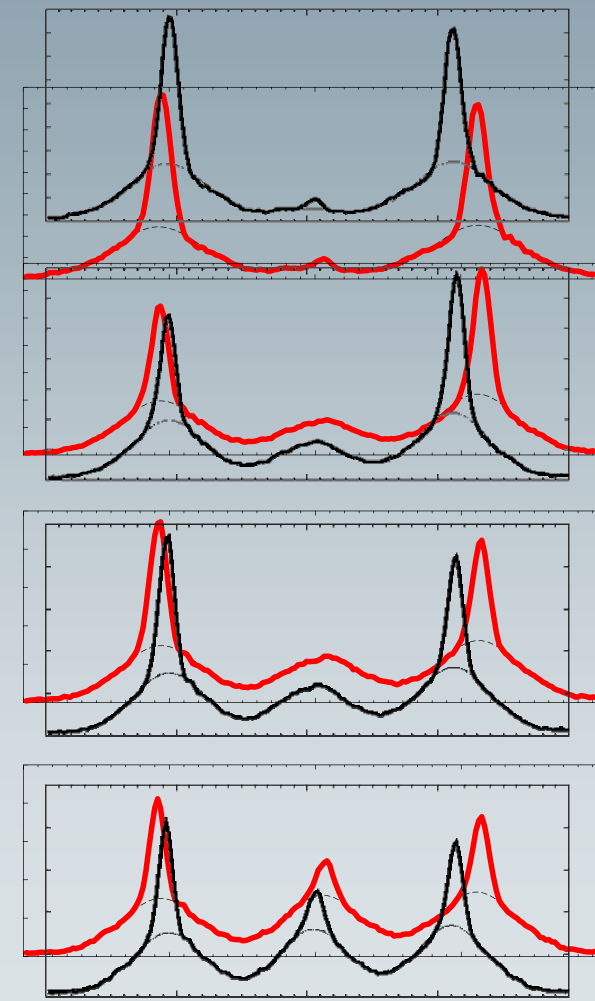
critical density
reached

t=8s

population of
m_F=0 condensate

t=10s



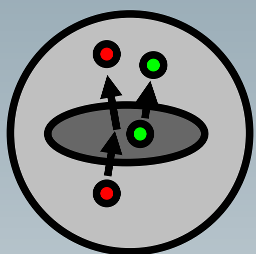


Multi Component Thermodynamics

description by a rate equation model

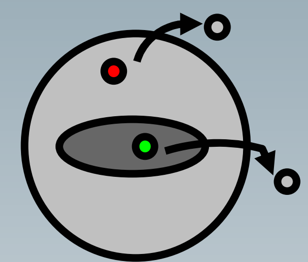
based on 7 variables $\{N_0^-, N_0^0, N_0^+, N_t^-, N_t^0, N_t^+, T\}$

thermalisation



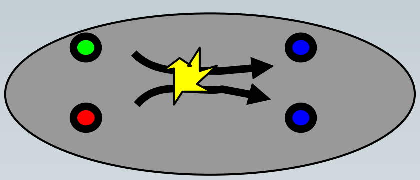
$$\dot N^X_{0,th} = -\tilde\gamma_{th} N_0^X N_t$$
$$\dot N^X_{t,th} = +\tilde\gamma_{th} N_0^X N_t$$
$$\dot T_{th} = -\tilde\gamma_{th} T N_0$$

1-body losses



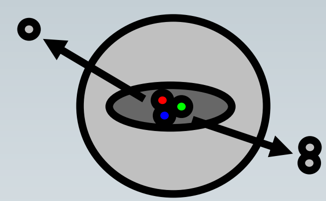
$$\dot N^X_{0,1b} = -\gamma_1 N_0^X$$
$$\dot N^X_{t,1b} = -\gamma_1 N_t^X$$

spin dynamics



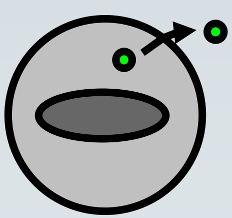
$$\dot N^-_{0,sp} = \tilde\gamma_{sp1} N_0^0 N_0^0 - \tilde\gamma_{sp2} N_0^+ N_0^-$$
$$\dot N^0_{0,sp} = -2\tilde\gamma_{sp1} N_0^0 N_0^0 + 2\tilde\gamma_{sp2} N_0^- N_0^+$$

3-body losses



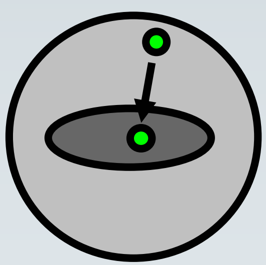
$$\frac{\dot N^X_{0,3b}}{N_0^X} = -L c_3 (N_0)^{4/5}$$

evaporation



$$\dot N^X_{t,ev} = -\gamma_e N_t^X$$
$$\dot T_{ev} = \gamma_e (T - T_e)$$

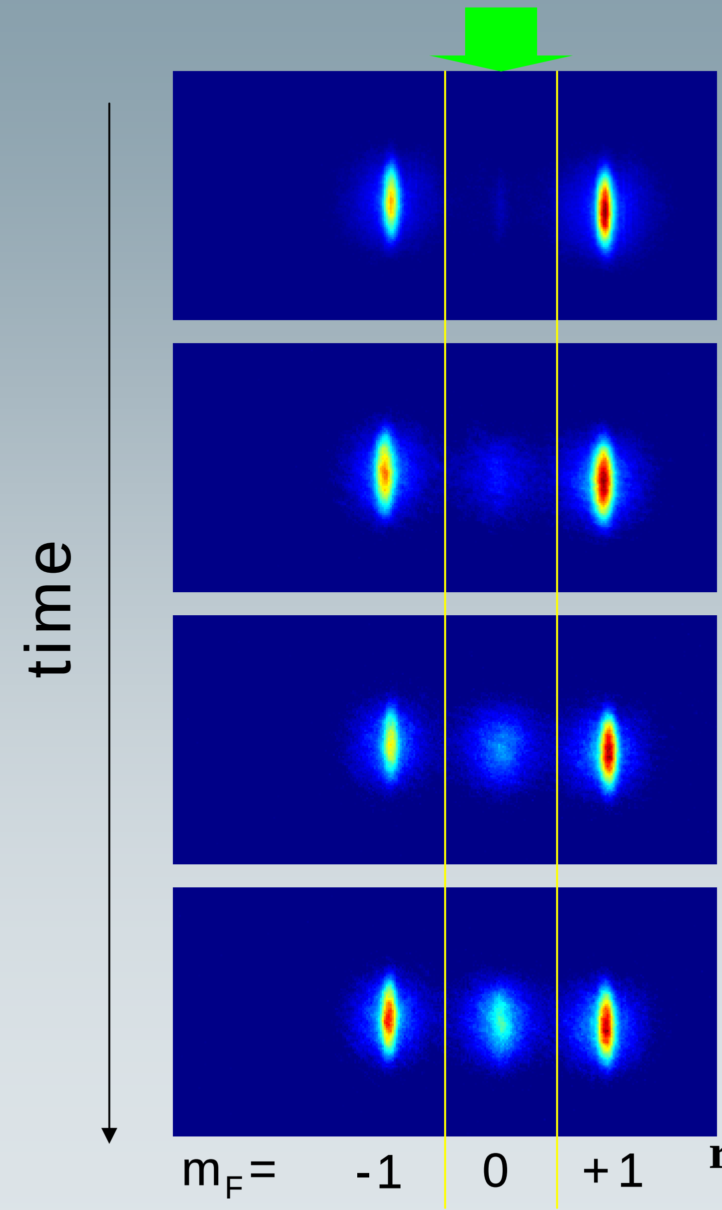
<u>phase space redistribution</u>

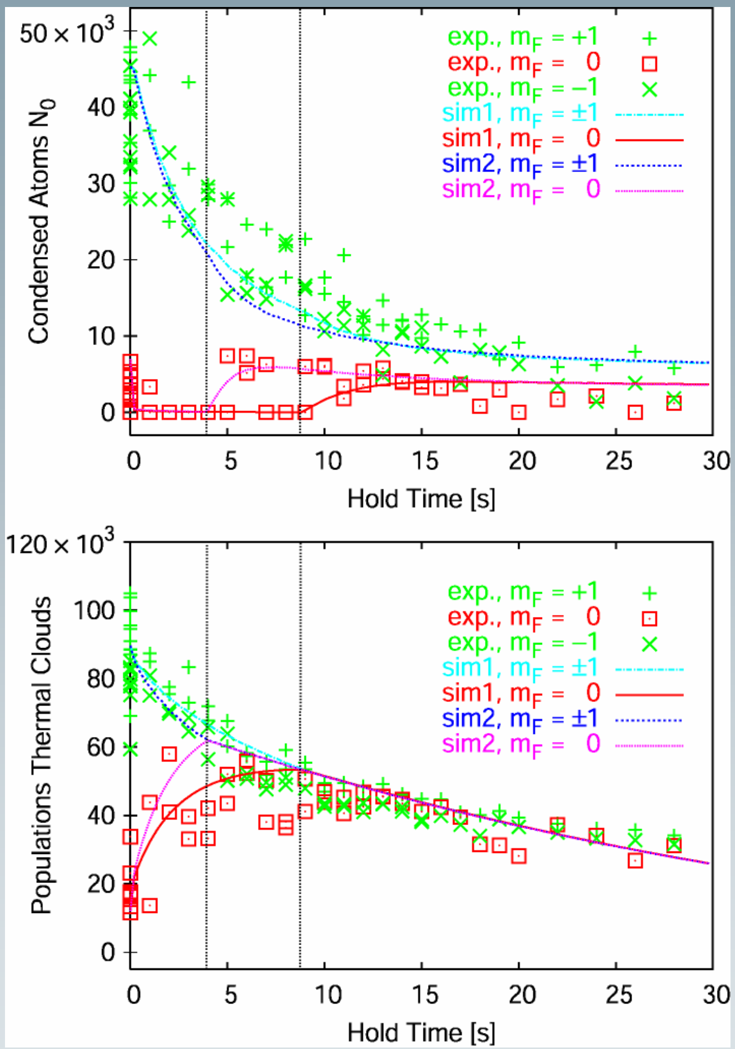


If $(N_t^X > N_c(T))$:

$$N_0^X(t+\Delta t) = N_0^X(t) + N_t^X(t) - N_c$$
$$N_t^X(t+\Delta t) = N_c$$
$$T(t+\Delta t) = T(t)\left(1+\frac{N_0(t+\Delta)-N_0(t)}{N_t(t+\Delta t)}\right)$$

Constant Temperature BEC





M. Erhard et al. cond-mat/0402003.

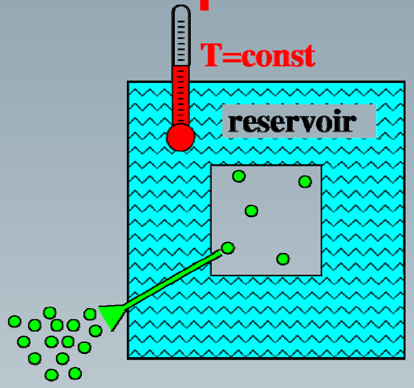
related work: Ketterle et al.: dimple trap

Cornell et al.: decoherence driven cooling

"Free" Condensate Fraction

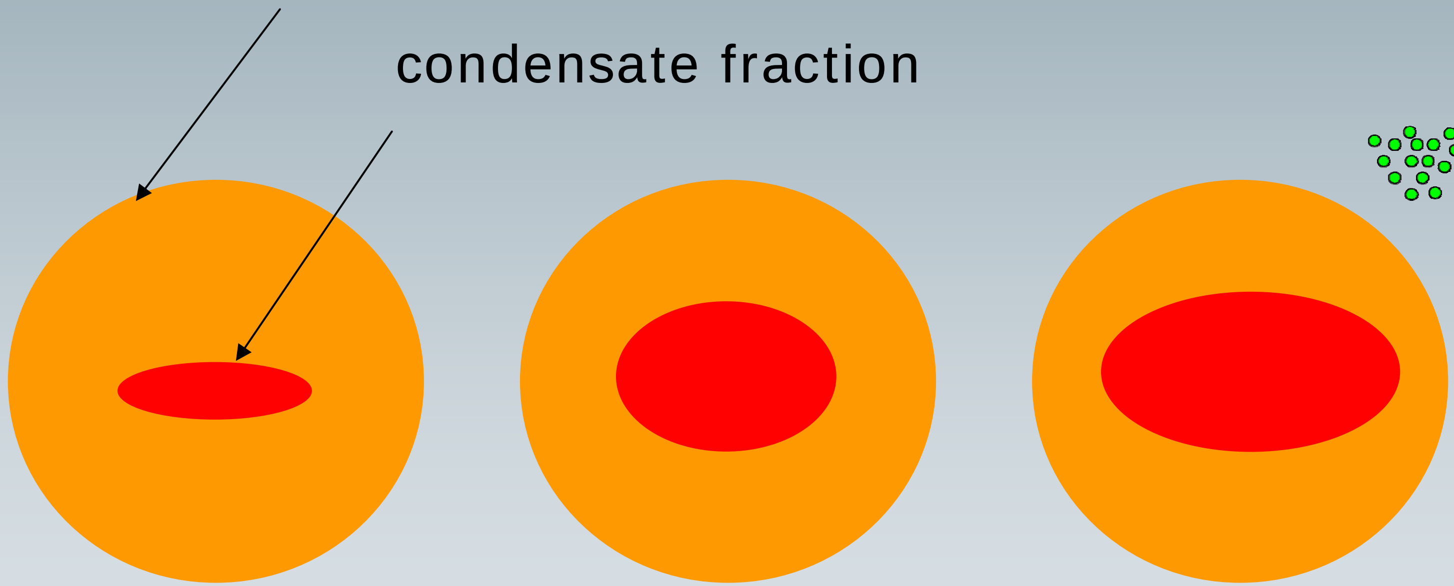
- Important aspect:

Condensate fraction is independend of normal component



saturated normal component (“Einstein“)

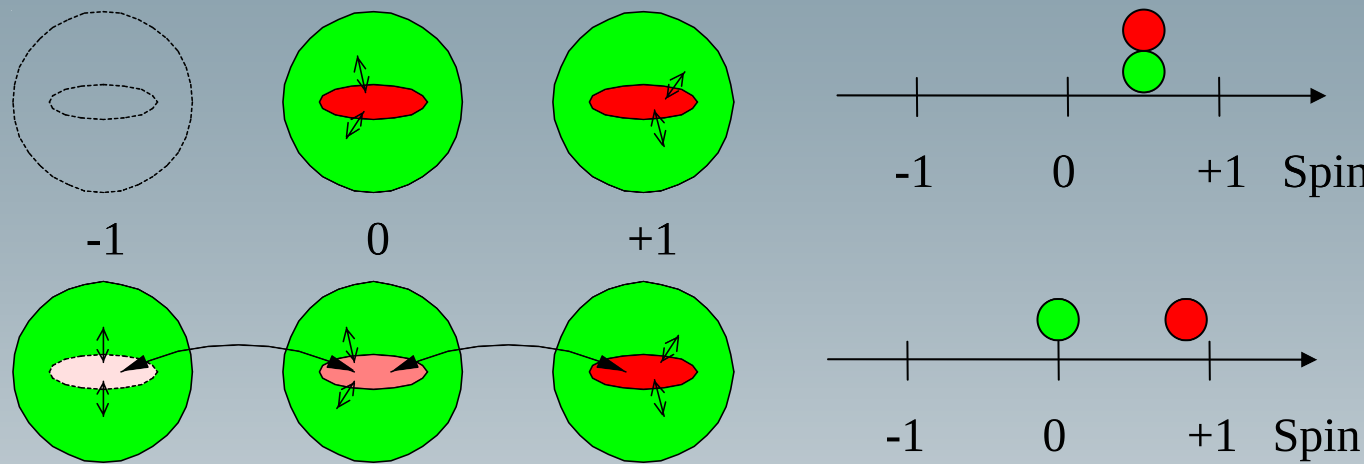
condensate fraction



Possibility to add more and more particles to the condensate fraction without changing $N_{thermal}$

Multi Component BEC at Finite T
Another example: Magnetisation of a BEC

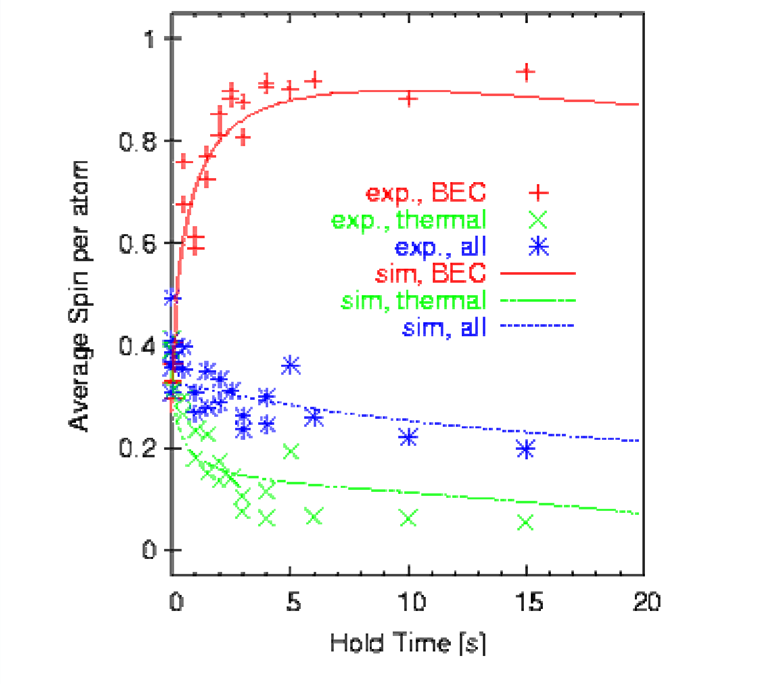
preparation of mixture 0,+1:



- normal components equalise, (via spin dynamics)
  -> total spin = 0

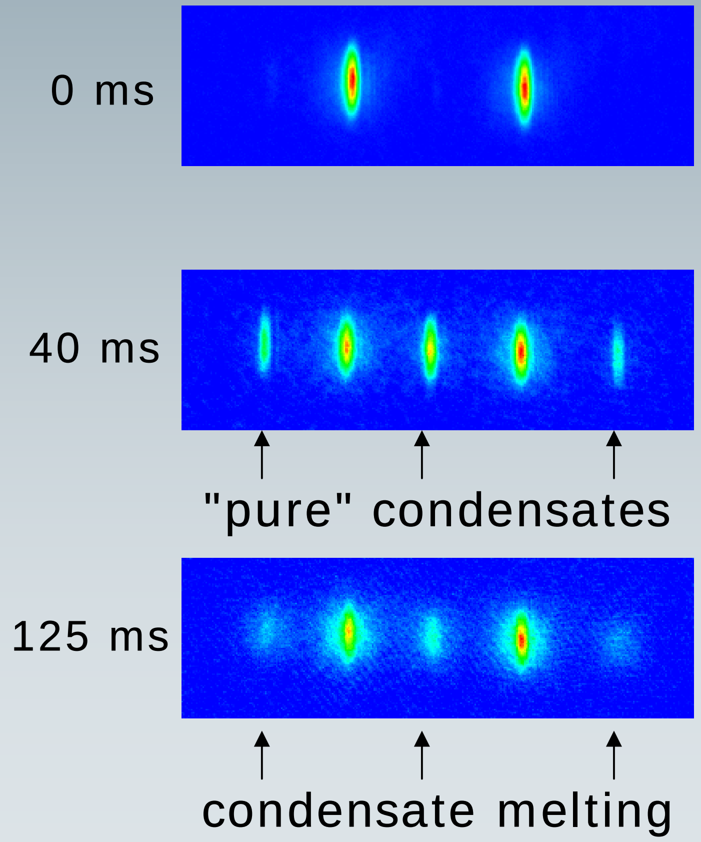
→ condensate spin increases!

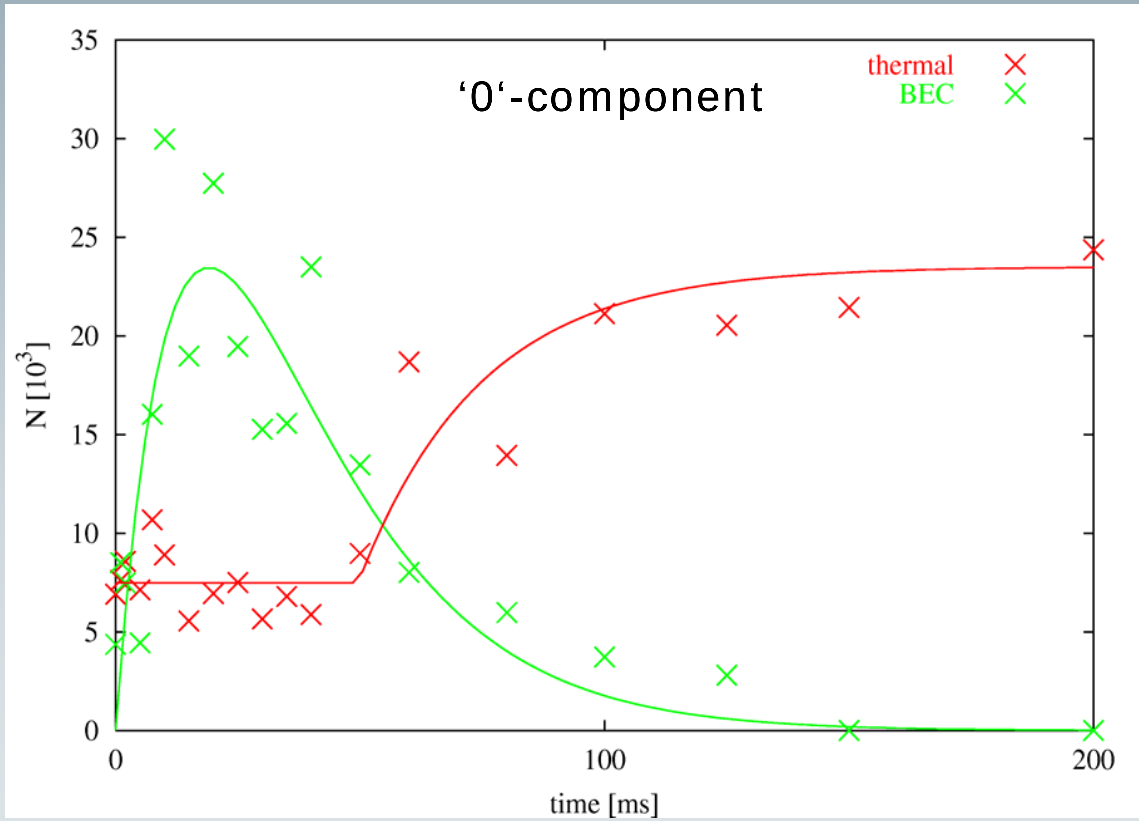
temperature driven magnetisation of BEC!



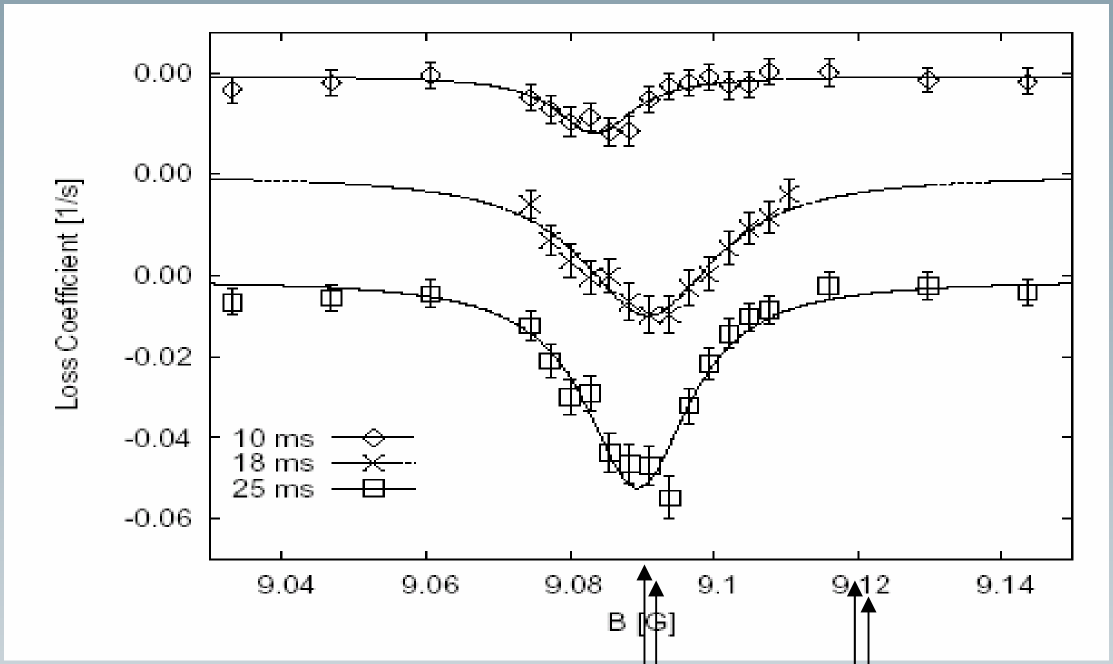
Realization of Condensate Melting

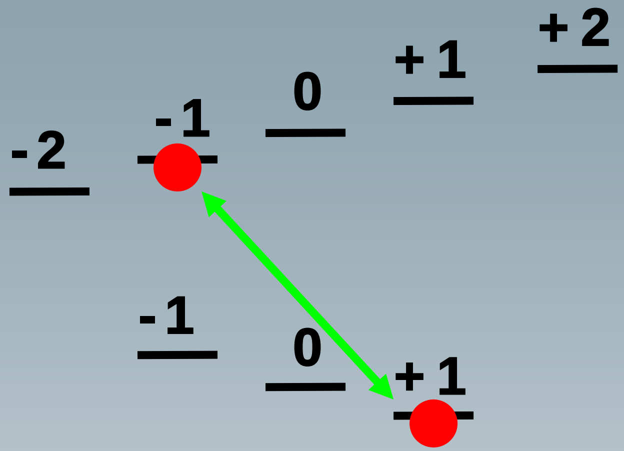
^{87}Rb offers both regimes, condensate melting in F=2:
Fast spin dynamics, slow thermalisation





Mixed Hyperfine State Feshbach Resonance in ^{87}Rb





offers further opportunities for manipulation of 87Rb spin mixtures and entanglement

1.) theoretical prediction
(E. van Kempen et al. PRL 88, 093201 (2002))

2.) experiment, this work
M. Erhard et al., PRA in press
(9.09 +/- 0.01 G)

3.) experiment, München
A. Widera et al., cond-mat/0310719
(9.121 +/- 0.005 G)

4.) theoretical calculation
Tiemann, priv. com.

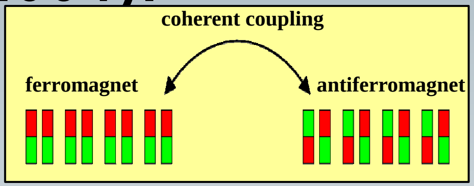
Multi-Component BEC

- Magnetic properties of spinor condensates

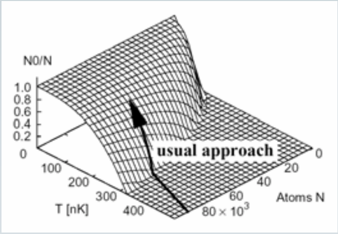
H. Schmaljohann et al. **Phys. Rev. Lett. 92, 040402 (2004),**
J. Mod. Opt. 51,1829 (2004),
Laser Phys. 14, 1252 (2004).

Text book quantum gas thermodynamics

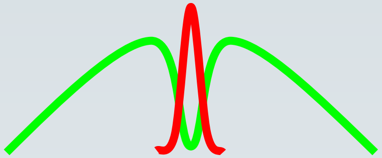
M. Erhard et al. **Phys. Rev. A . 70, 032705 (2004),**
H. Schmaljohann et al. **Apl. Phys. B, in press (2004).**



Advanced studies on spin-dynamics
- coupling ferro- and antiferromagnetic states
- **investigation of coherence and entanglement**
- **physics beyond 'Gross-Pitaevskii equation'**



- Playing text-book thermodynamics
  - exploration of new regimes
- Filled Spinor Solitons
- <u>**Spinor BEC in optical lattices**</u>



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K. Se

Kai Bongs - Atom optics

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(Michael Erhard)
Jochen Kronjäger
Christoph Becker
Thomas Garl
Martin Brinkmann

Fermi-Bose mixtures K-Rb:

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Silke Ospelkaus-Schwarzer
Oliver Wille
Marlon Nakat

BEC in Space:

Anika Vogel
Malte Schmidt

Atom guiding in PCF:

Stefan Vorath

Q. Gu - Theory

V. M. Baev - Fibre lasers

Stefan Salewski
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Oliver Back
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Staff

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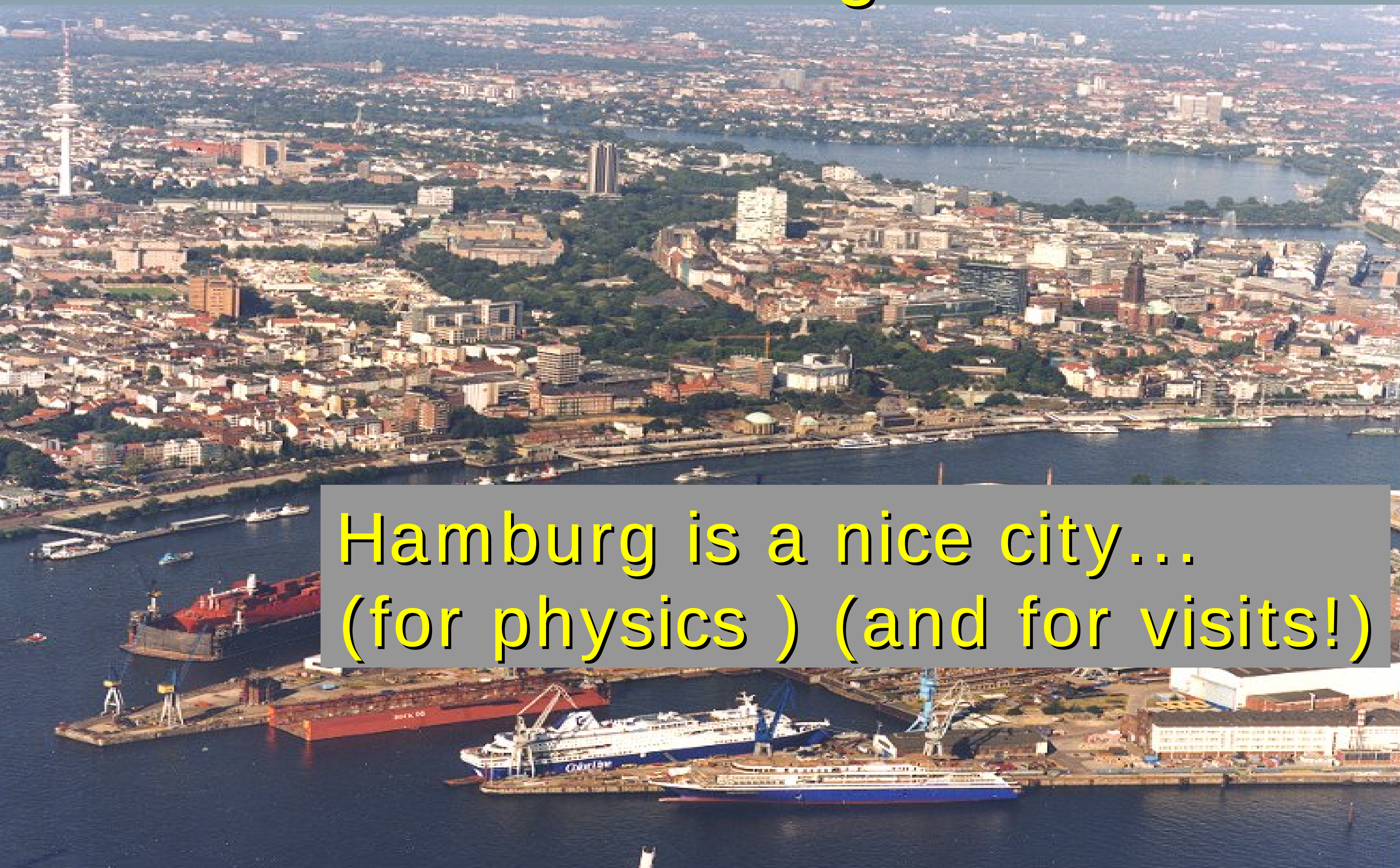
Dieter Barloesius
Reinhard Mielck

Cold Quantum Gas Group Hamburg



Hamburg is a nice city…
(for physics) (and for visits!)