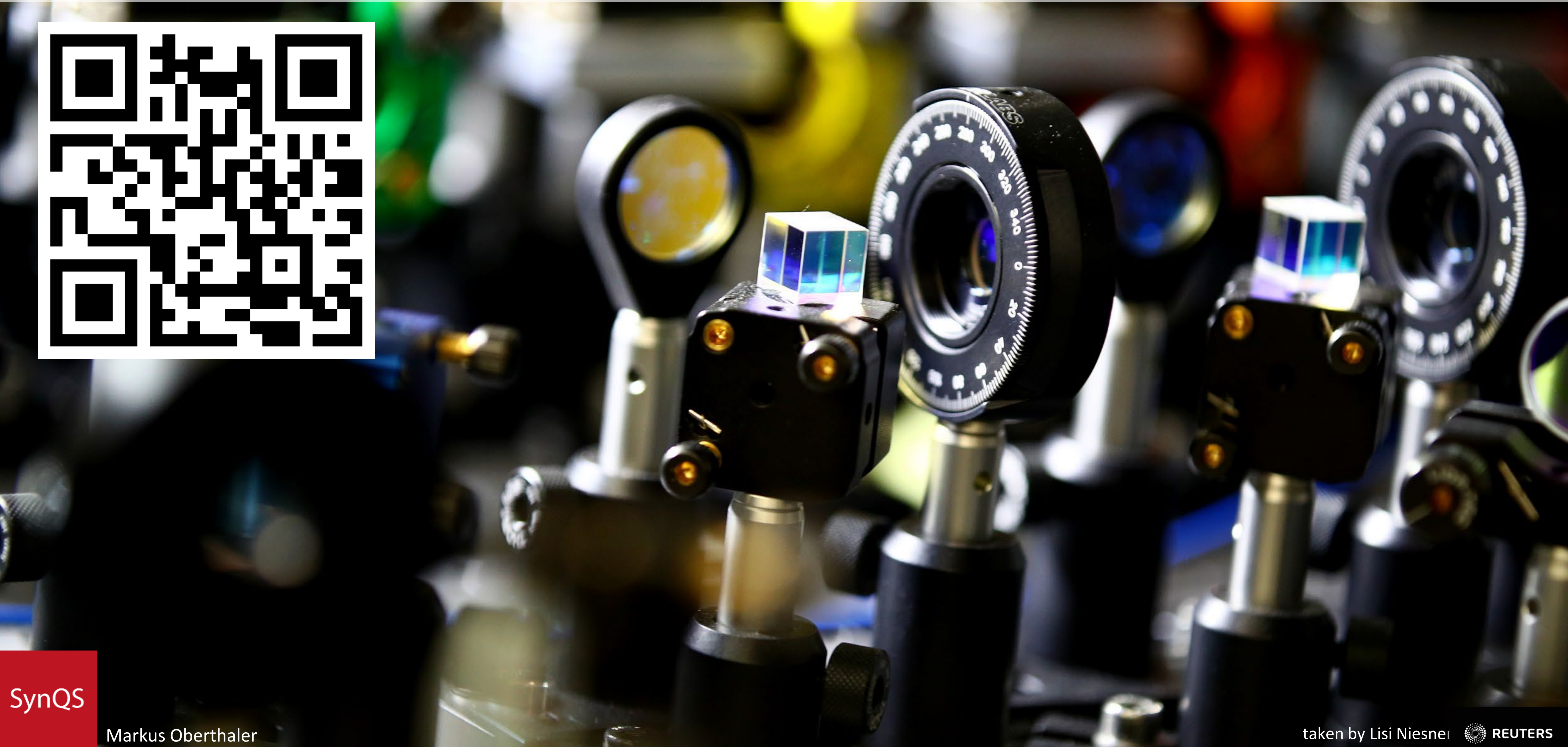
(Quantum)Mixtures @ Synthetic Quantum Systems/Heidelberg University

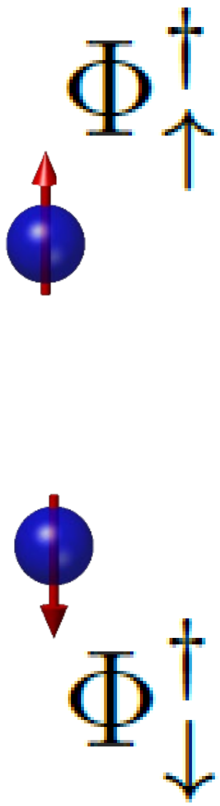


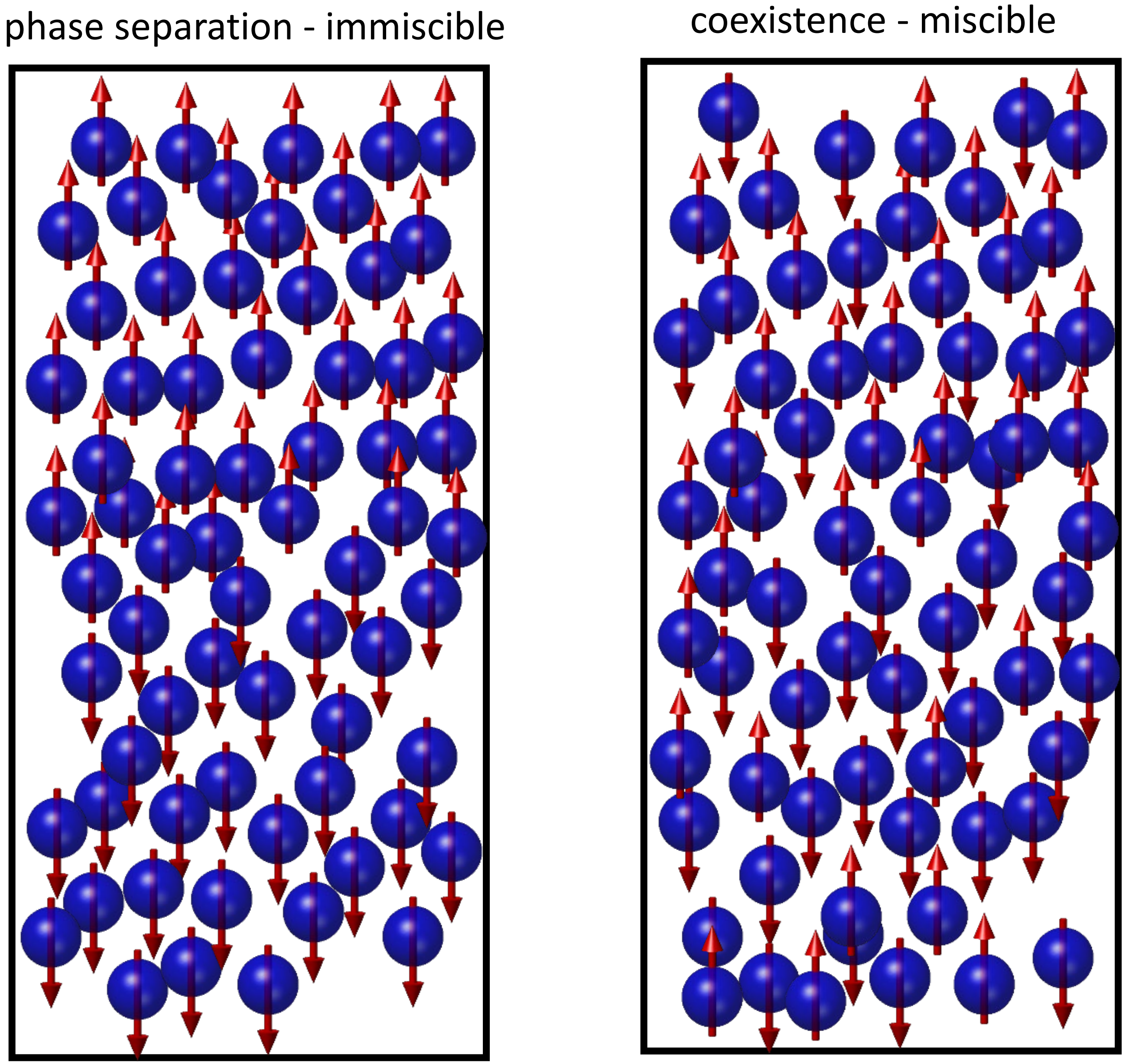
SynQS

Markus Oberthaler

taken by Lisi Niesner REUTERS

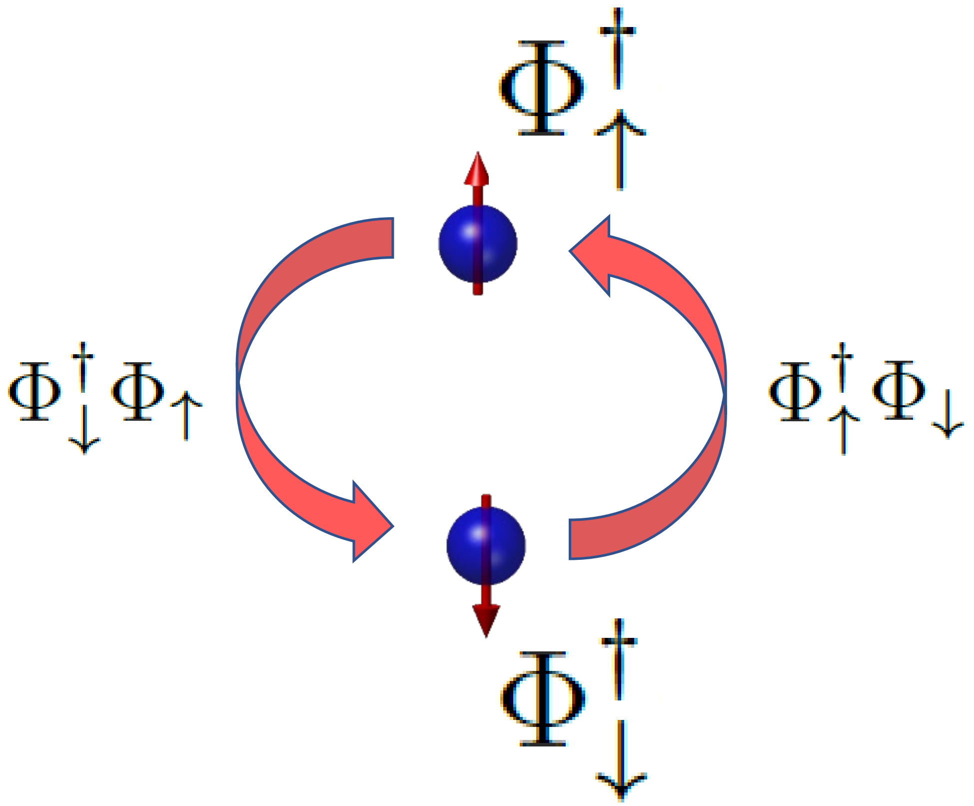
Mixtures



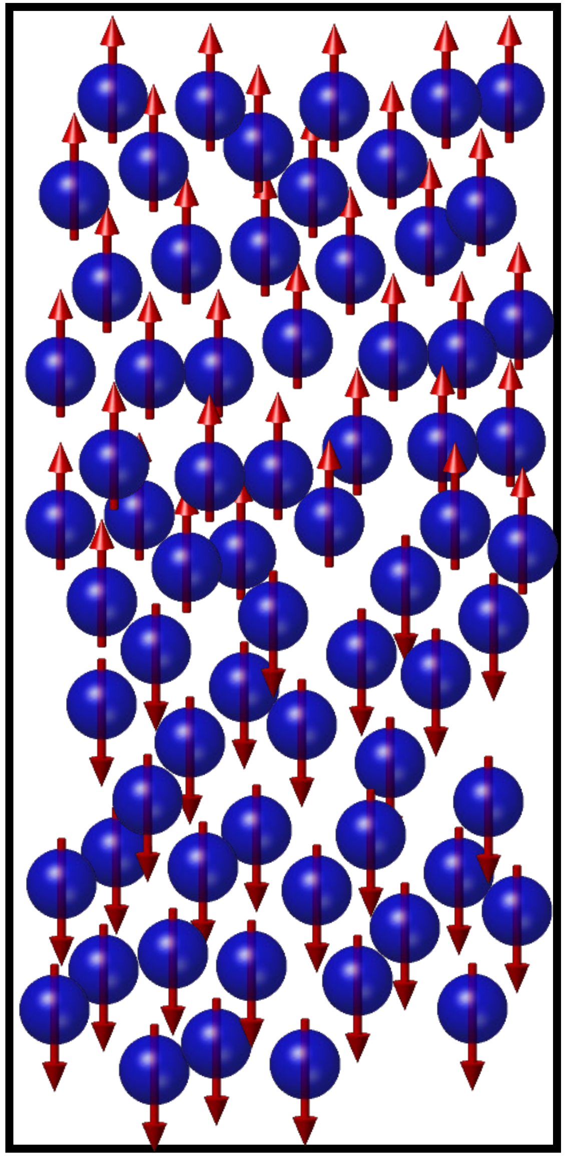


SynQS

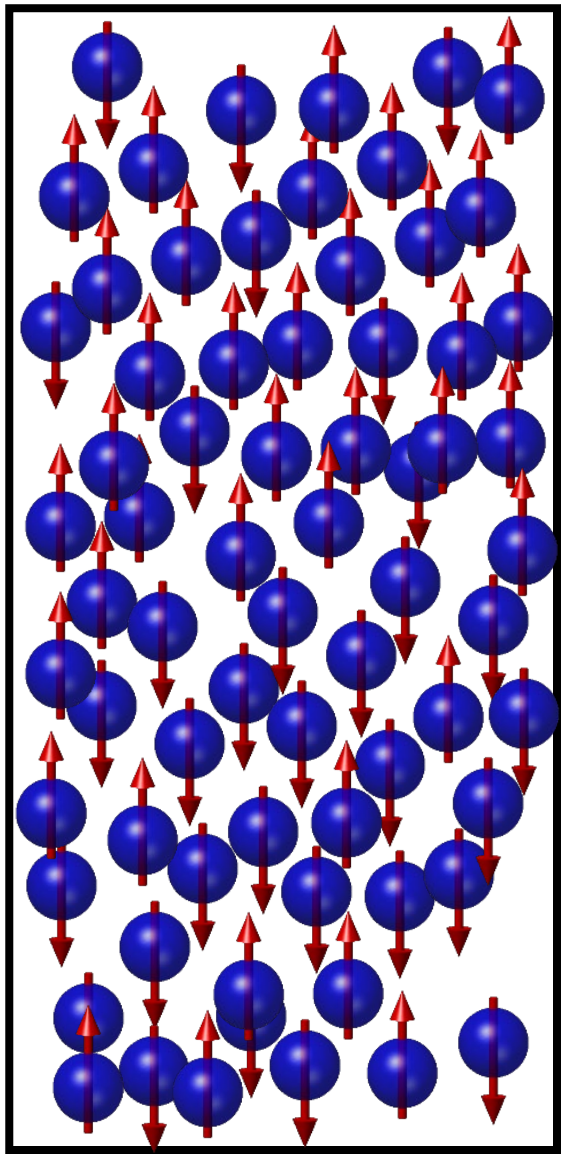
Coherent Mixtures



phase separation - immiscible

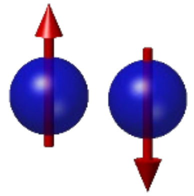


coexistence - miscible



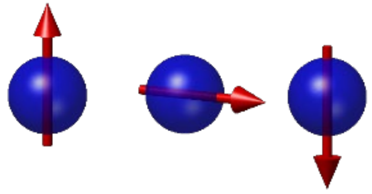
SynQS

Coherent mixtures with increasing complexity



pseudo spin ½

- one dimensional
  - miscible to immiscible transition via linear coupling
  - ‚critical‘ scaling after a quench towards a quantum critical point
- quantum features in zero dimensional situation (no motion)
  - introduce collective spin dynamics
  - squeezing and quantum bifurcation



spin 1

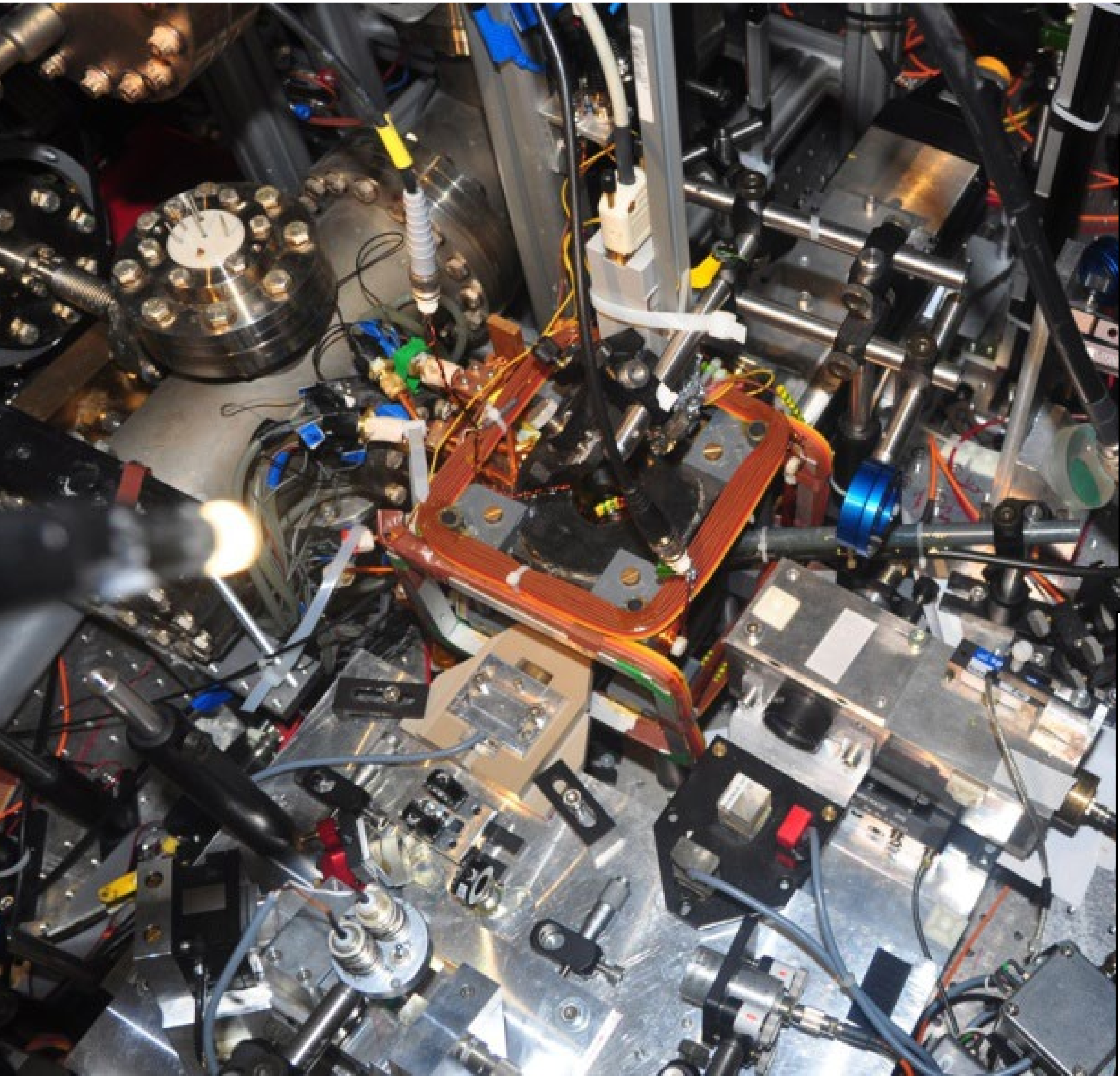
- non-local entanglement
  - EPR correlation from 0d to 1d
- one dimensional
  - POVM readout
  - universal dynamics
  - topological excitations such as solitons

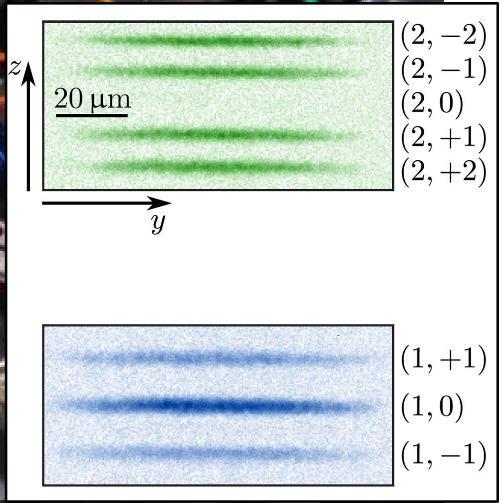
Question

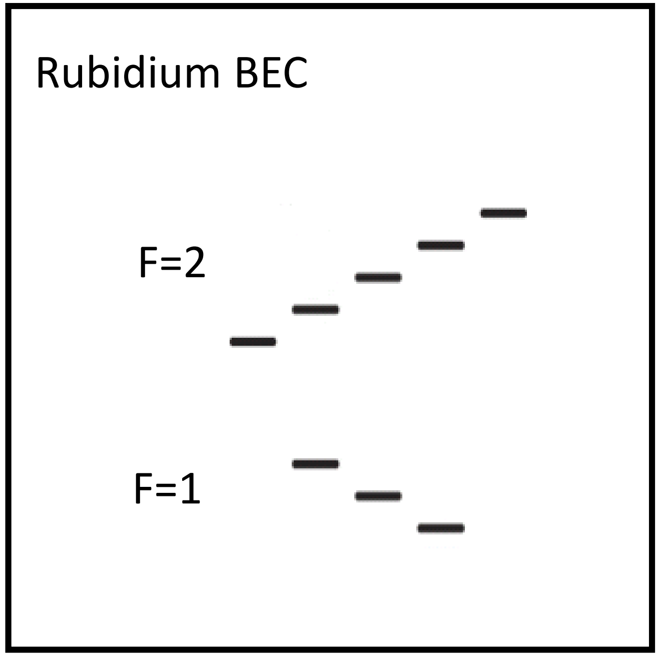
Experimental details

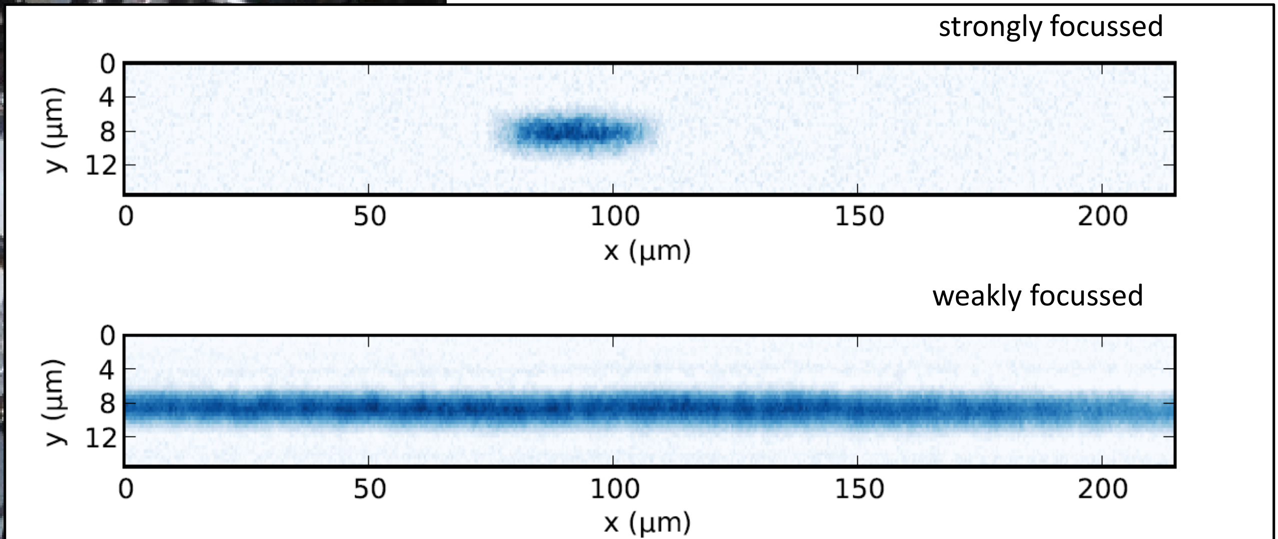
Please bear with me

Vacuum since 2000, with one day break

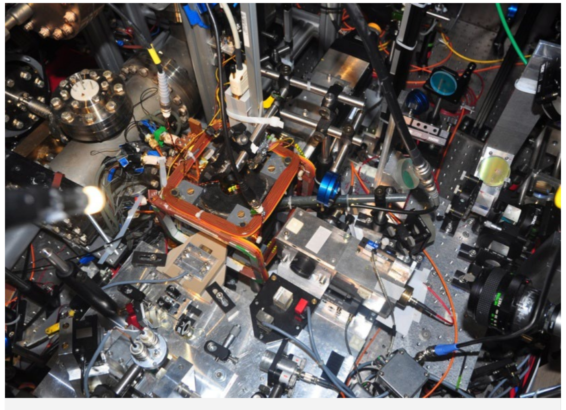


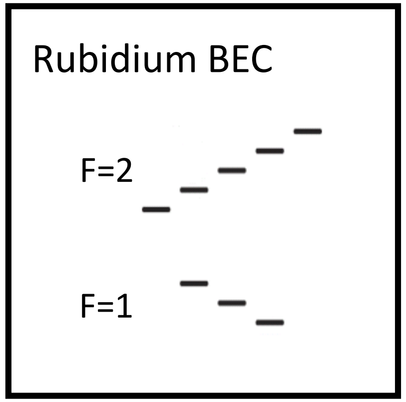


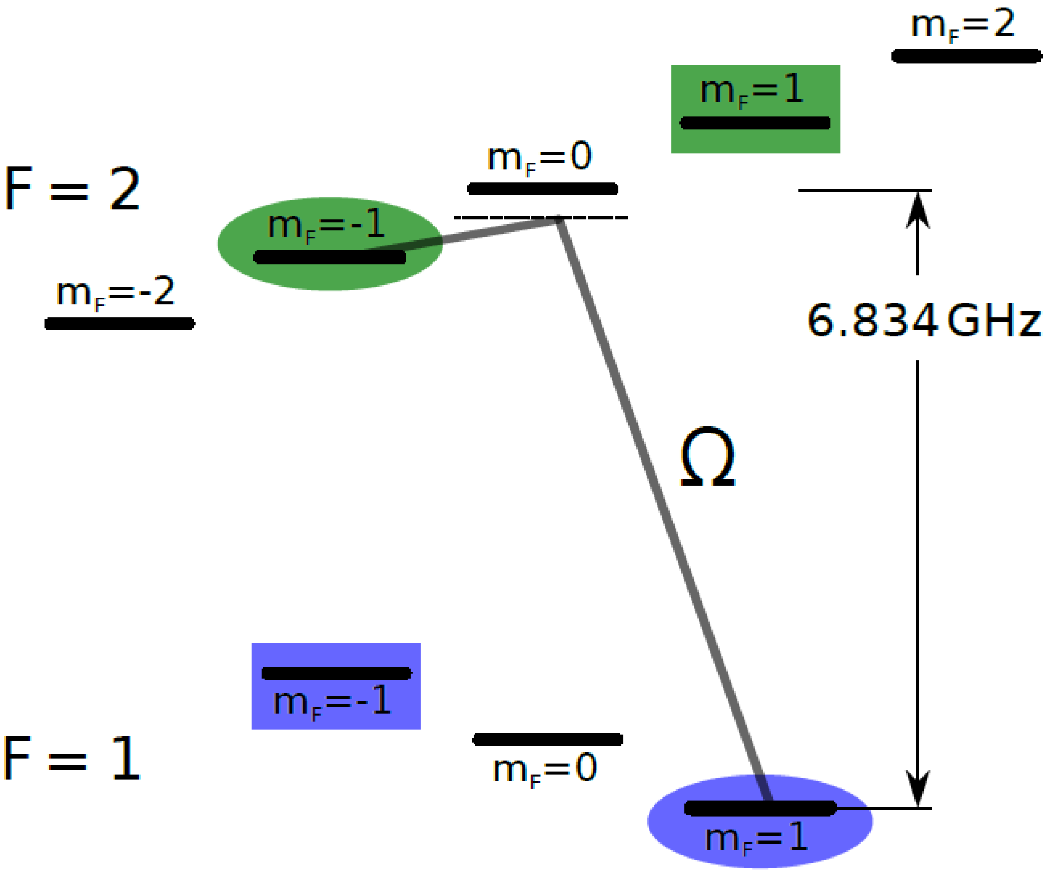




The system





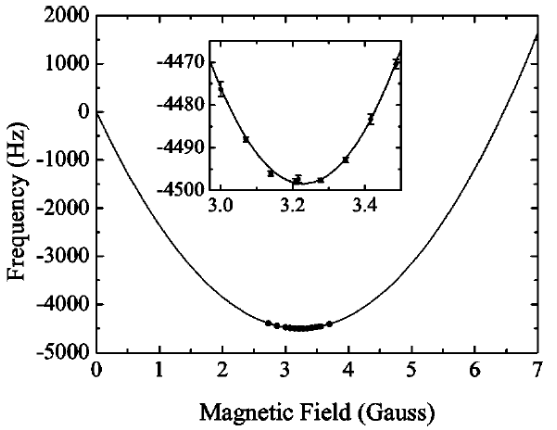


Two mixtures with special properties

|2 >

|1 >

magic field: 3.23 G

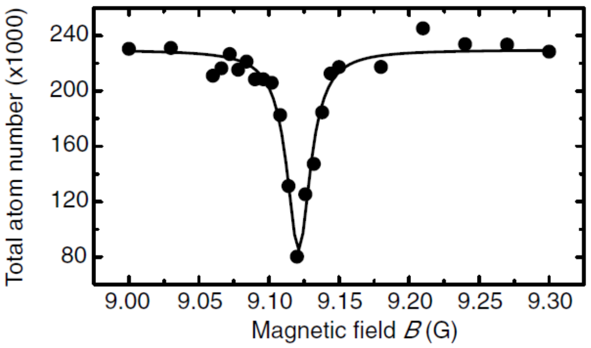


PRA 66, 053616 (2002)

|2 >

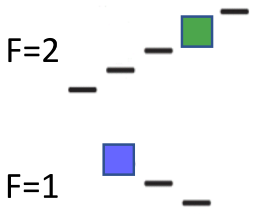
|1 >

Feshbach resonance:
9.09 G but 20mG width

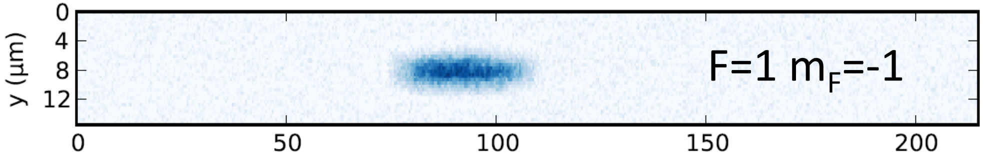


PRL 92, 160406 (2004)
PRA 69, 032705 (2004)

Rubidium BEC



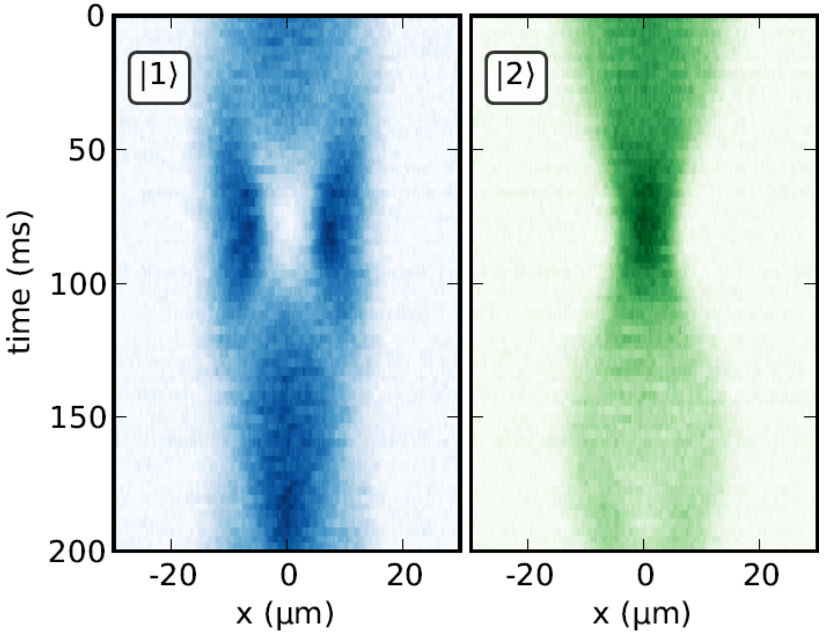
strongly focussed dipol trap



Question

$|1>$ $|2>$

What happens if the superposition @ t=0 is generated?



$$\hat{H} = \hat{H}_0 + \hat{H}_{\text{int}}$$

$$\hat{H}_0 = \sum_{i=1,2} \int \mathrm{d}x\, \hat{\Psi}_i^\dagger \left(-\frac{\hbar^2}{2m}\nabla^2 + V \right) \hat{\Psi}_i$$

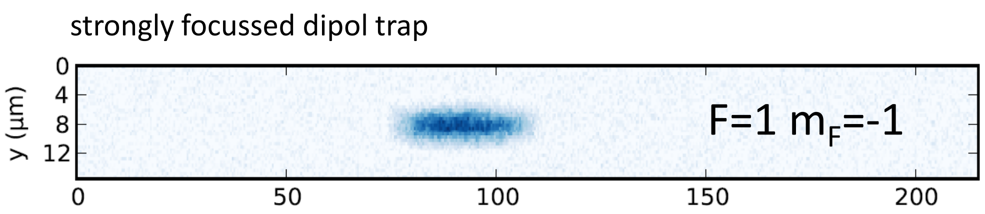
$$\hat{H}_{\text{int}} = \frac{1}{2} \sum_{i,j=1,2} g_{ij} \int \mathrm{d}x\, \hat{\Psi}_i^\dagger \hat{\Psi}_j^\dagger \hat{\Psi}_j \hat{\Psi}_i \qquad g_{ij} = \frac{4\pi\hbar^2 a_{ij}}{m}$$

Rubidium is special:

$$a_{11} : a_{22} : a_{12} = 100.44 a_B : 95.47\, a_B : 97.7 a_B$$

$$i\hbar \frac{\partial}{\partial t}\psi_1 = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{11}|\psi_1|^2 + g_{12}|\psi_2|^2 \right] \psi_1$$

$$i\hbar \frac{\partial}{\partial t}\psi_2 = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{22}|\psi_2|^2 + g_{12}|\psi_1|^2 \right] \psi_2$$



$$i\hbar\frac{\partial}{\partial t}\psi_1 = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{11}|\psi_1|^2 + g_{12}|\psi_2|^2\right]\psi_1$$

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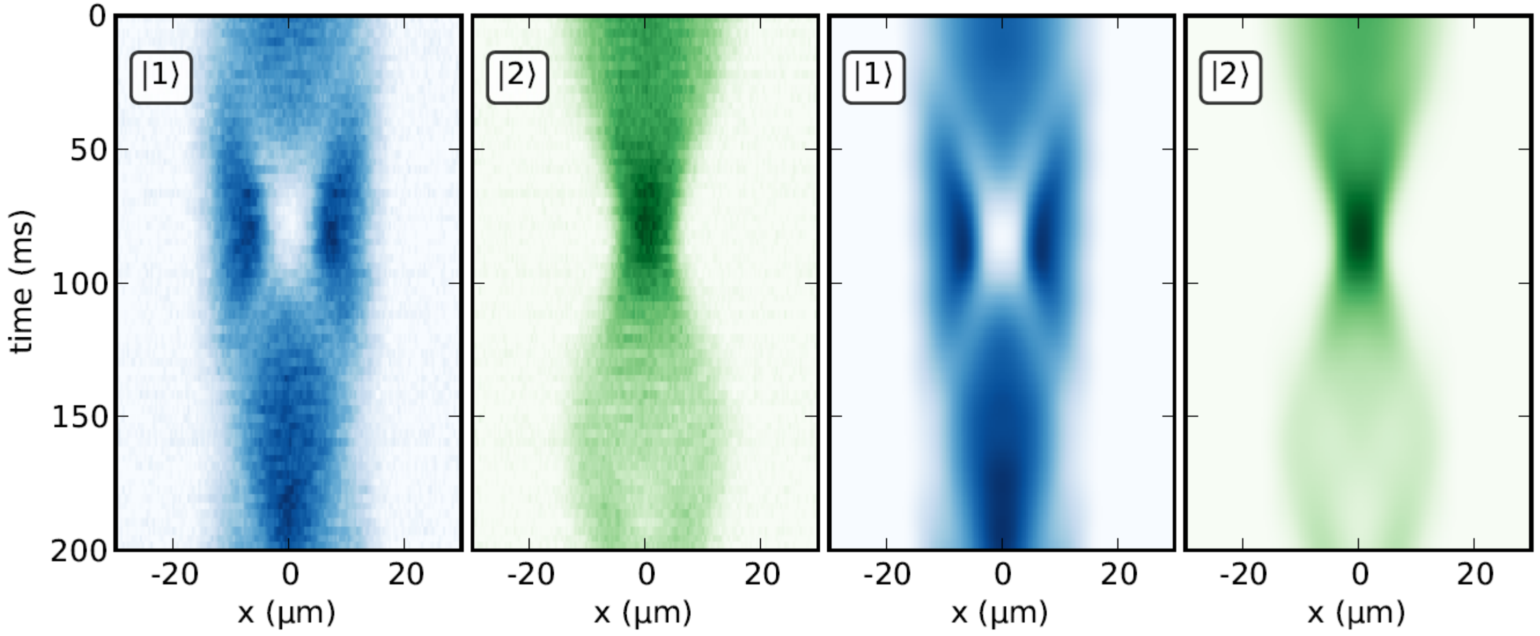


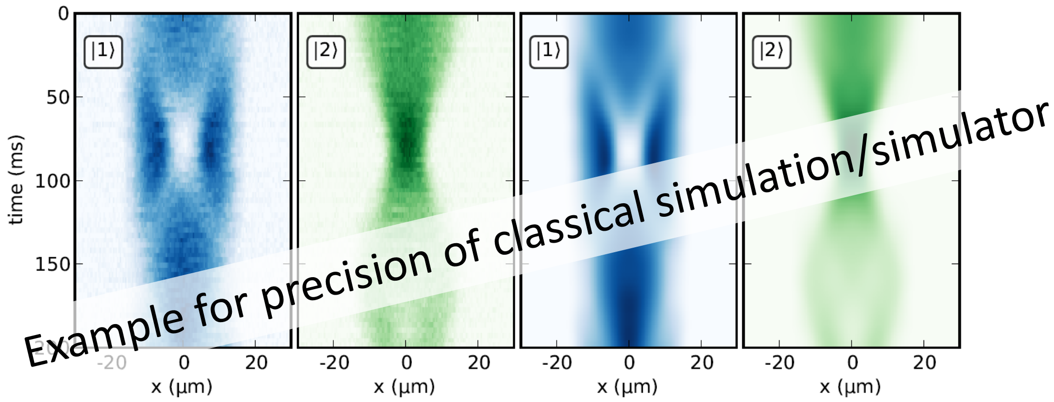
Component F=2 has smaller repulsive interaction than F=1 !

Potential separation – no phase separation!

VOLUME 81, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1998

Phase Separation of Bose-Einstein Condensates

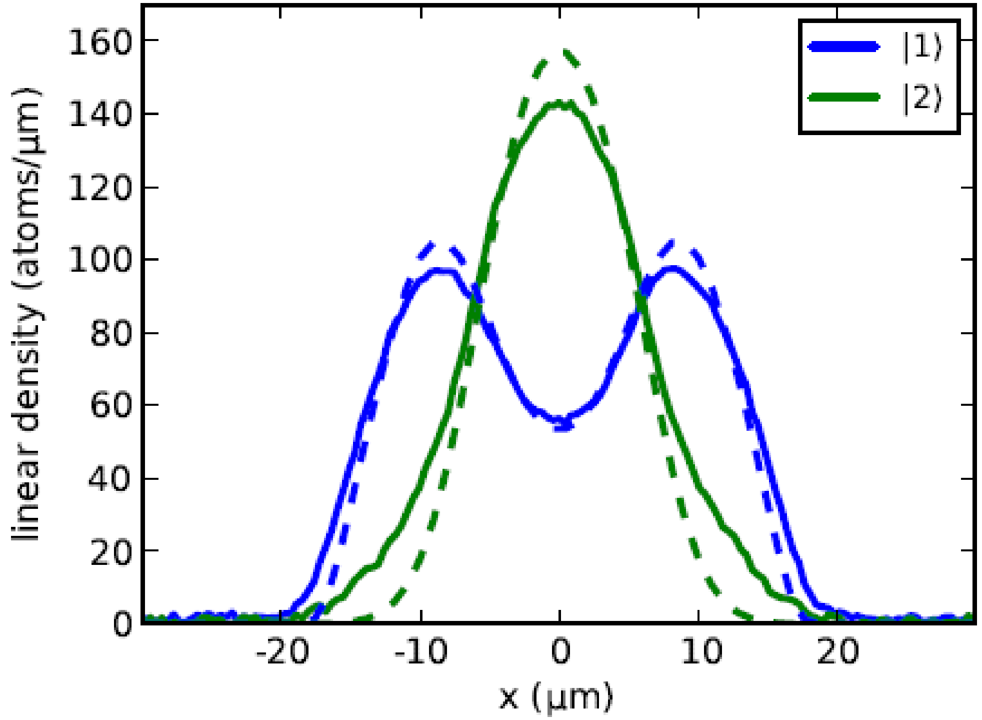
E. Timmermans*
Institute for Atomic and Molecular Physics, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138
(Received 26 August 1997; revised manuscript received 10 September 1998)



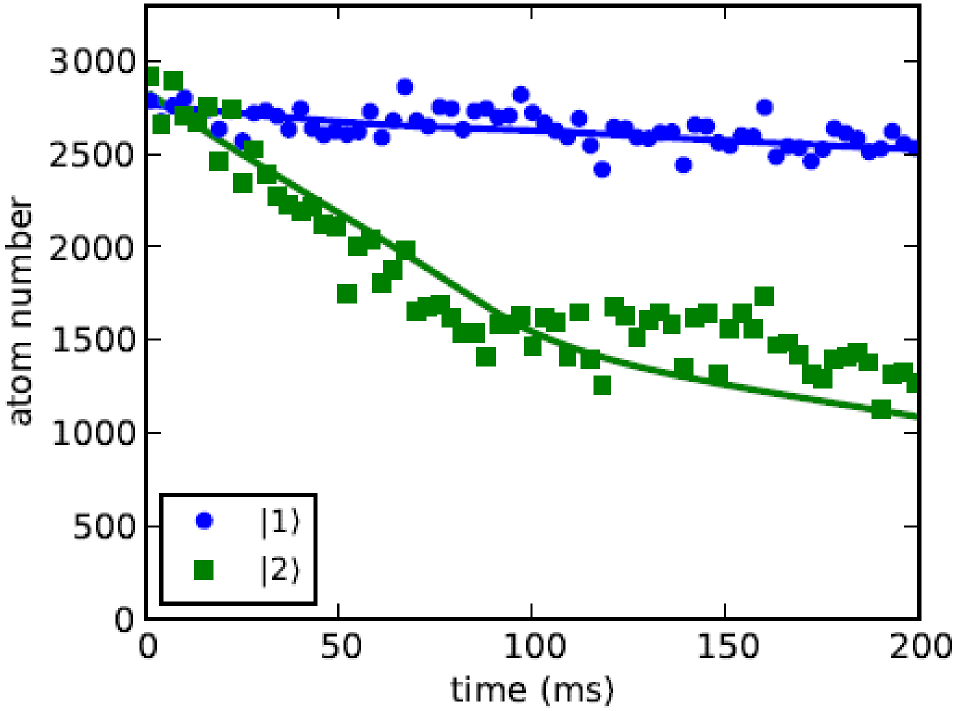
$$i\hbar\frac{\partial}{\partial t}\psi_1 = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{11}|\psi_1|^2 + g_{12}|\psi_2|^2\right]\psi_1$$

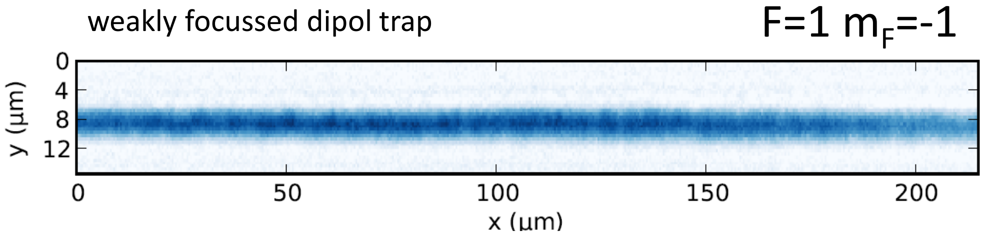
$$i\hbar\frac{\partial}{\partial t}\psi_2 = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{22}|\psi_2|^2 + g_{12}|\psi_1|^2\right]\psi_2$$

time averaged experiment –
stationary theory solution --



Losses are well understood and have to be taken into account.

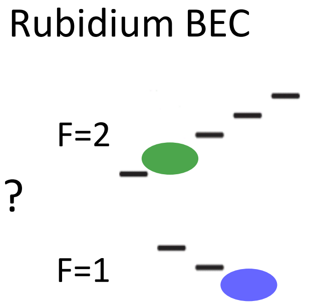


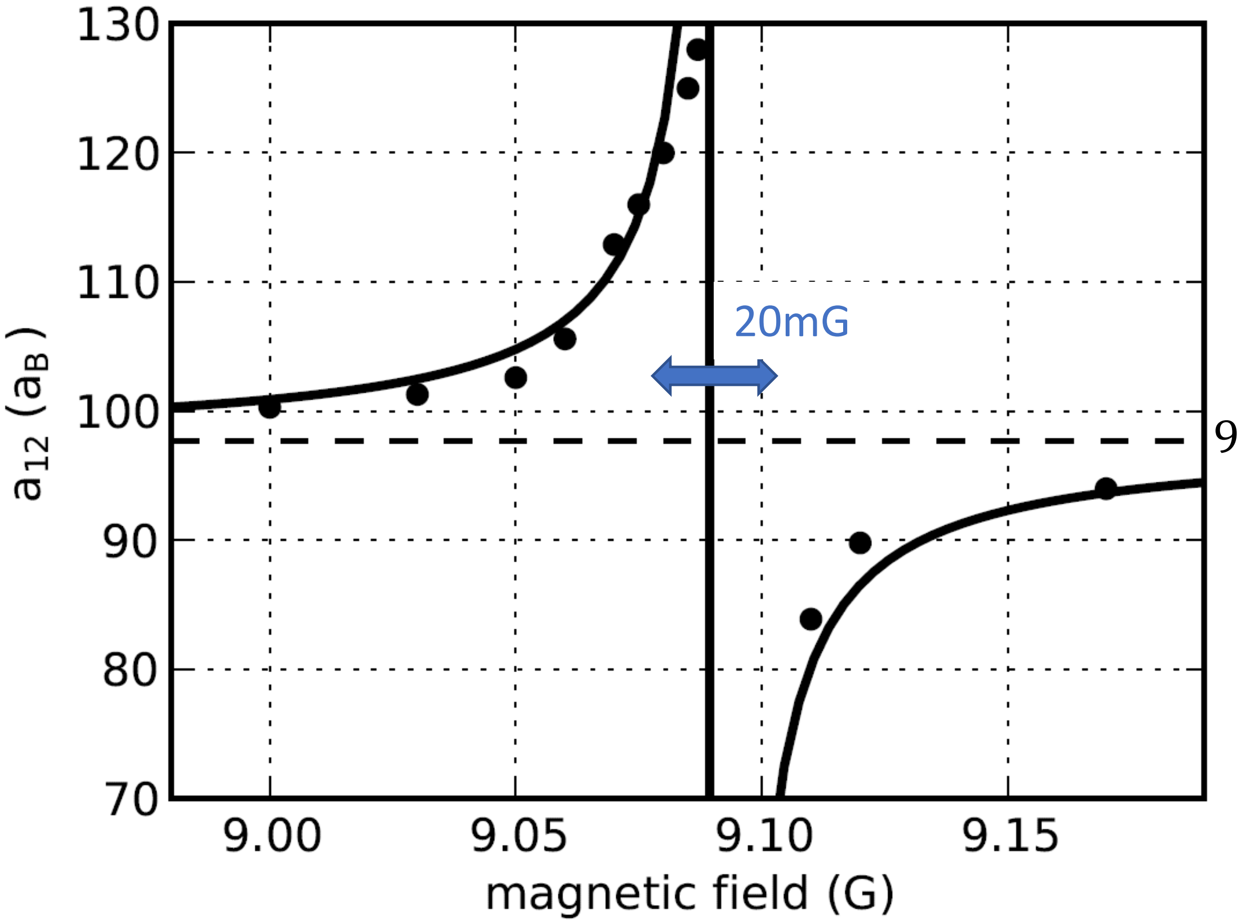


Question

What happens if the superposition @ t=0 is generated?

|1 > |2 >



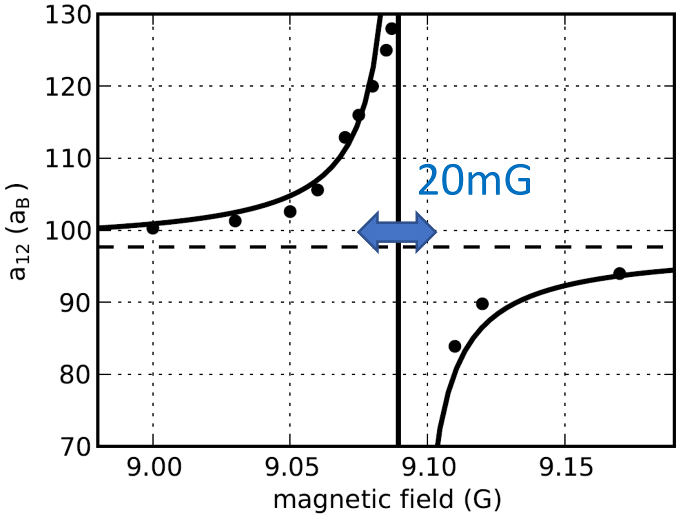


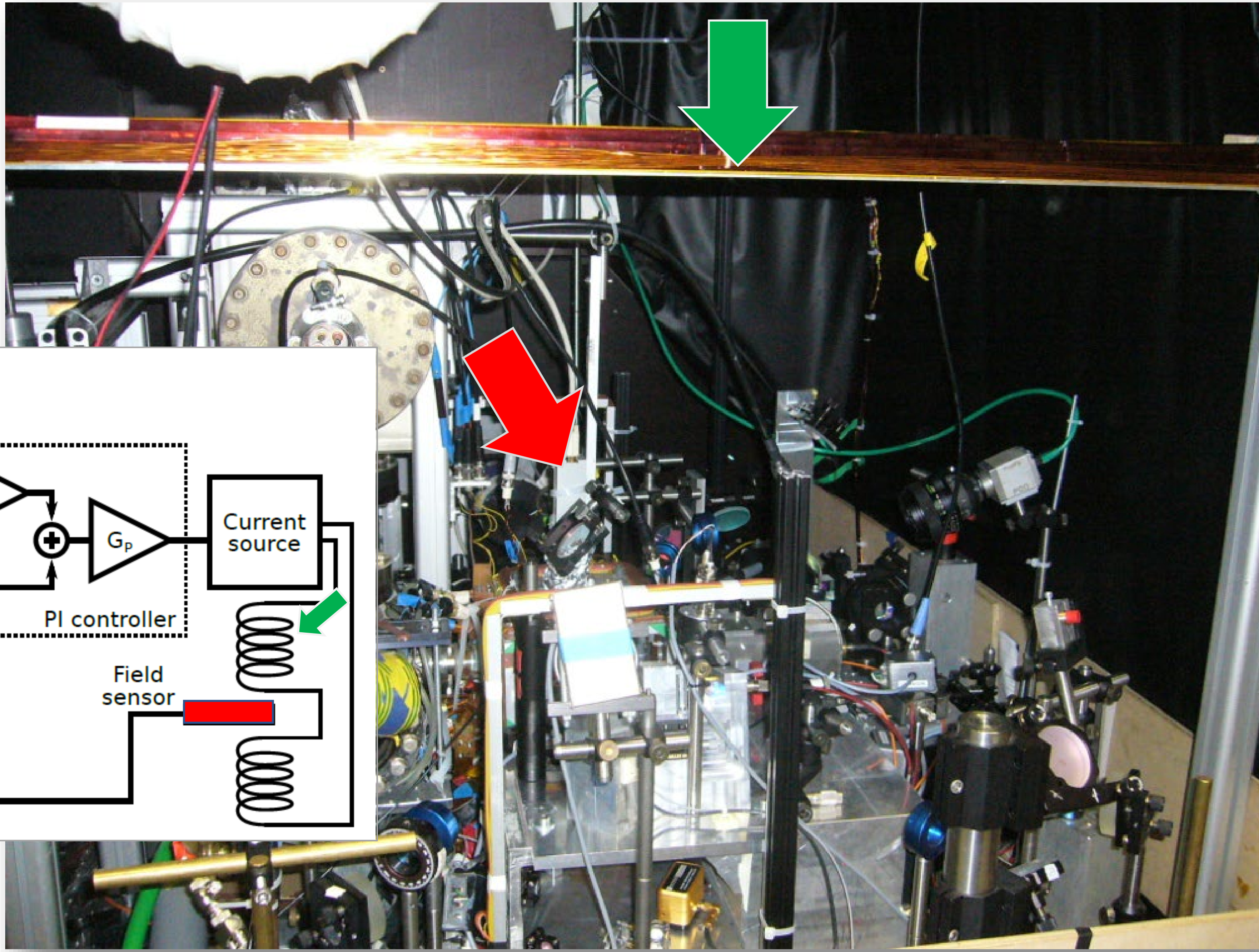
Rubidium is special:

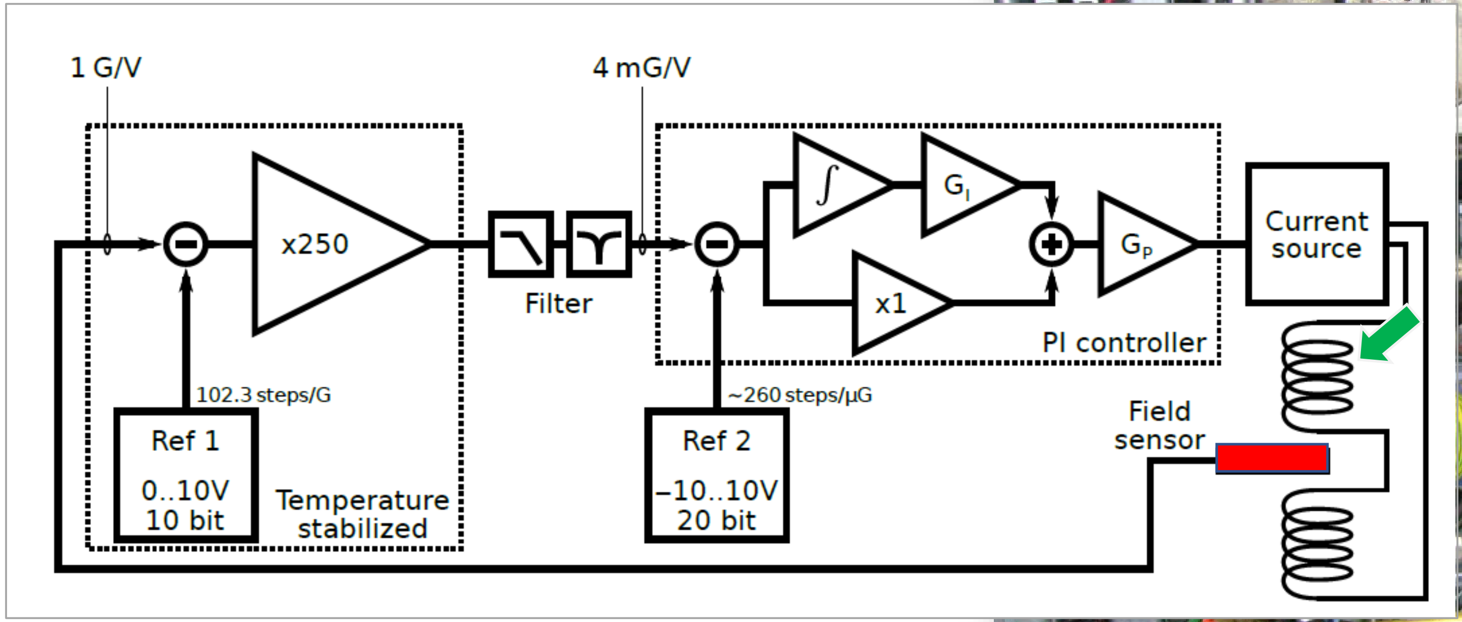
$$a_{11} : a_{22} : a_{12} = 100.44 a_B : 95.47\, a_B : 97.7 a_B$$

Experimental details

Is a magnetic field stability @ 9.1G an issue for a standard setup?



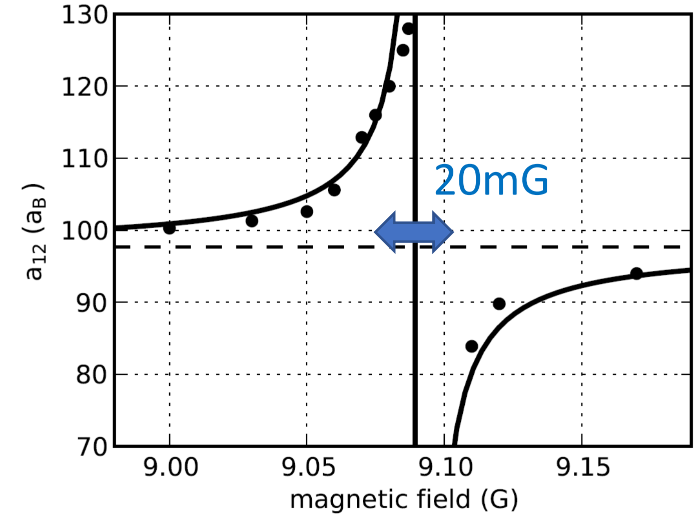




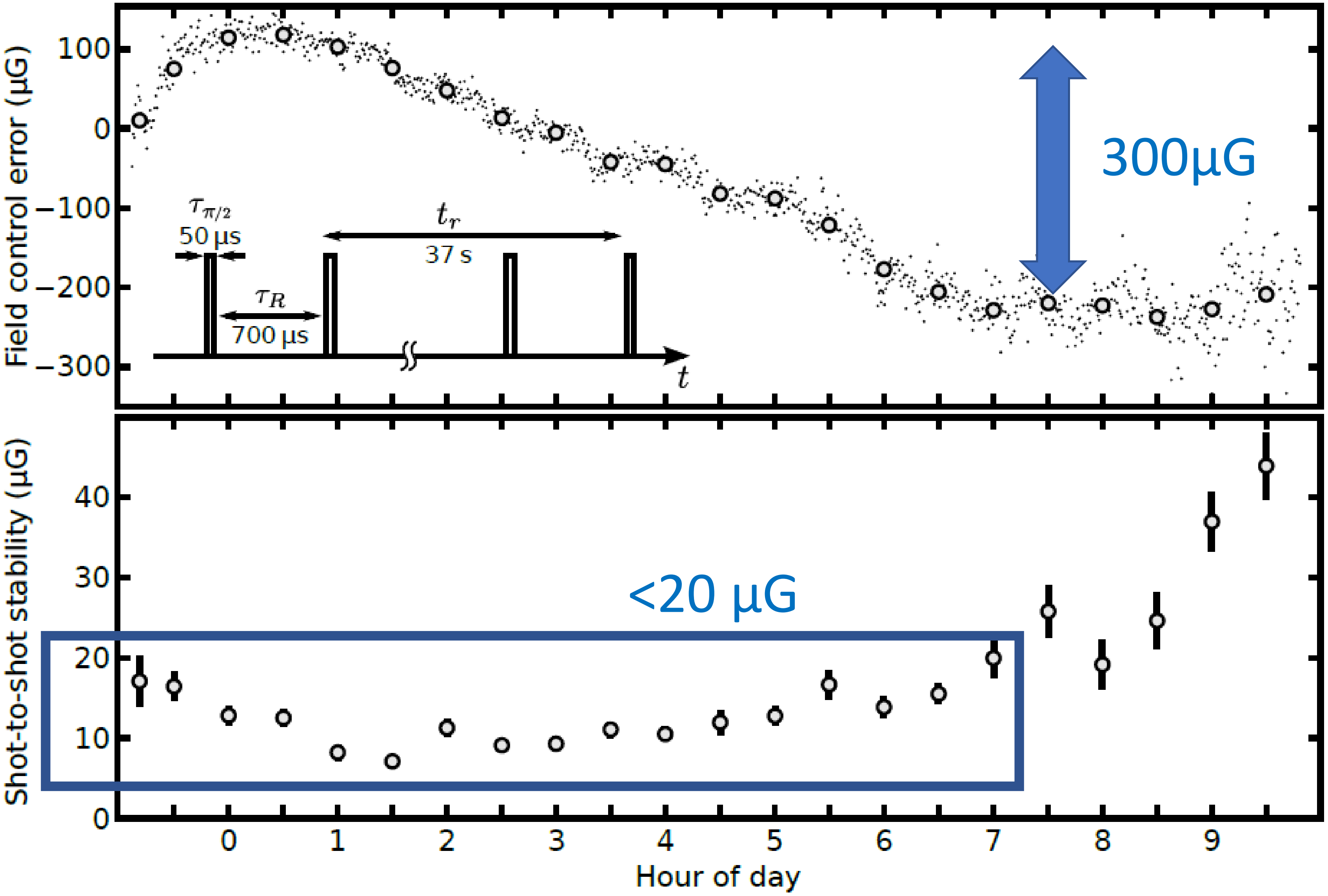
Is a magnetic field stability @ 9.1G an issue for a standard setup?

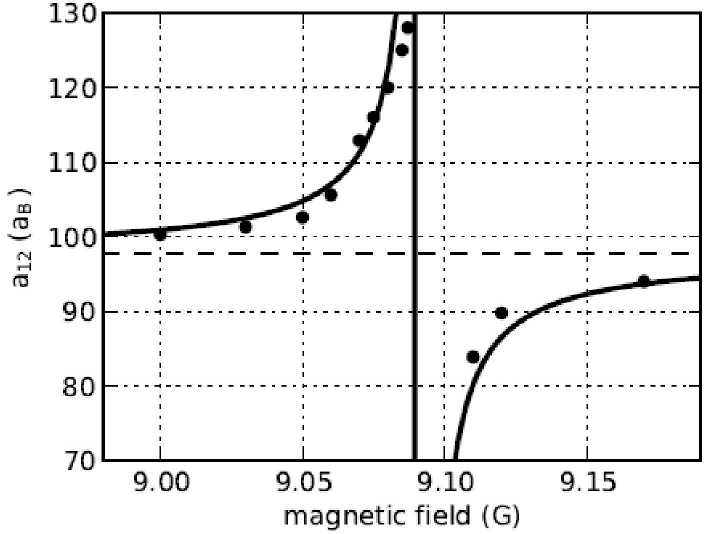
NO

Experimental details



Limited by temperature dependence of flux-gate sensor: 300µG = 75mK change



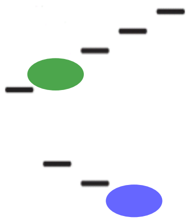


Question

|1 > |2 >

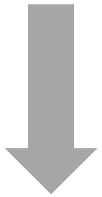
What happens if the superposition @ t=0 is generated?

Rubidium BEC



miscible

$$\sqrt{g_{11}g_{22}} < g_{12}$$

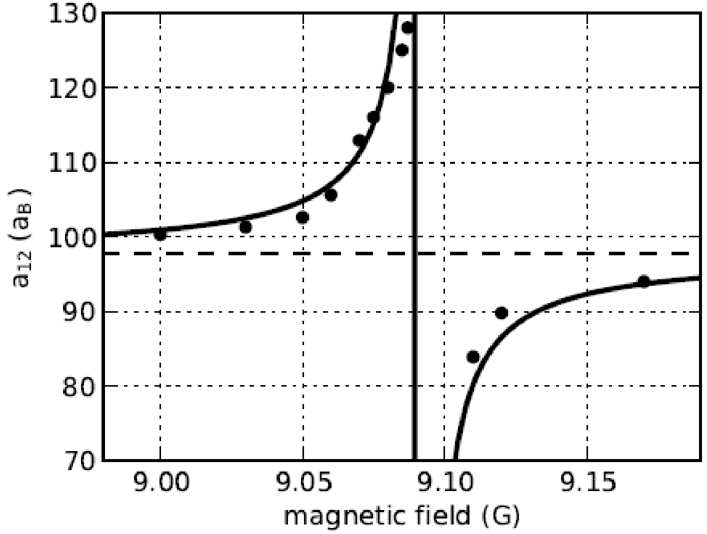


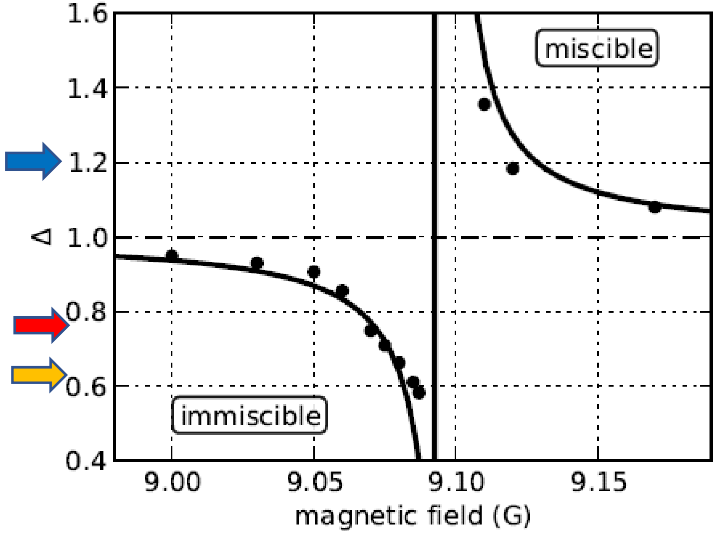
$$\Delta = \frac{g_{11}g_{22}}{g_{12}^2} < 1$$

immiscible

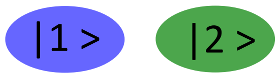
$$E_{\text{unif}} = \frac{g_{11}}{2}\frac{N_1^2}{L} + \frac{g_{22}}{2}\frac{N_2^2}{L} + g_{12}\frac{N_1 N_2}{L}$$

$$E_{\text{sep}} = \frac{g_{11}}{2}\frac{N_1^2}{L} + \frac{g_{22}}{2}\frac{N_2^2}{L} + \sqrt{g_{11}g_{22}}\frac{N_1 N_2}{L}$$

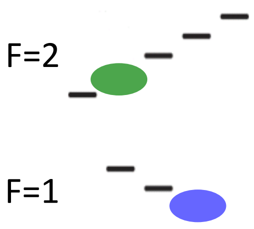


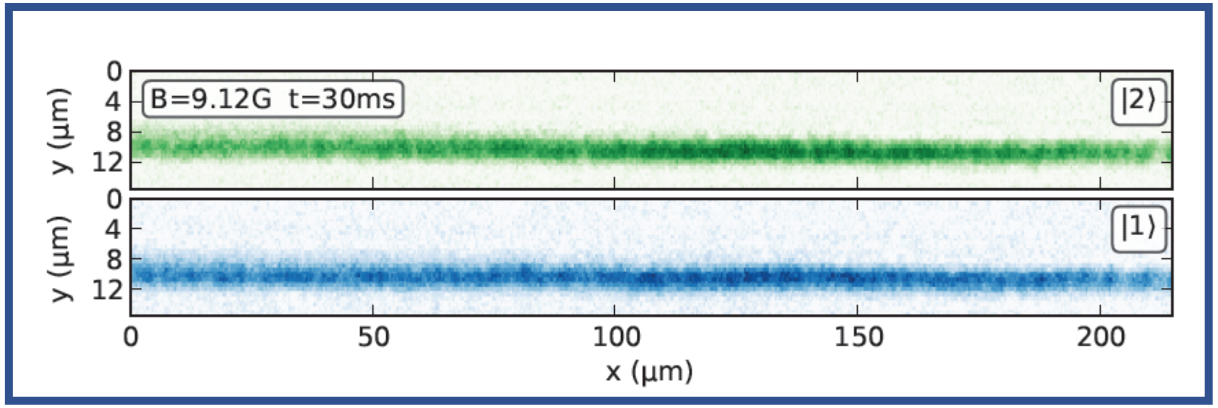


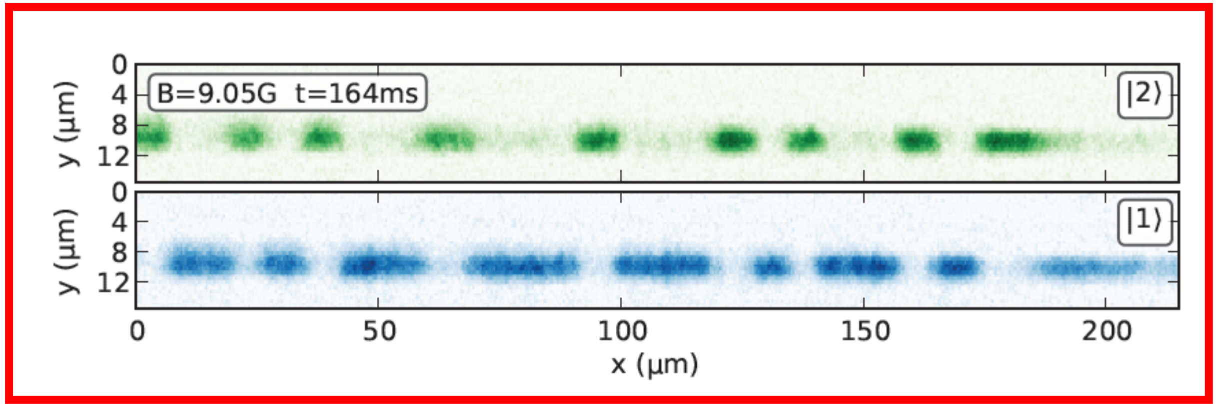
Rubidium BEC

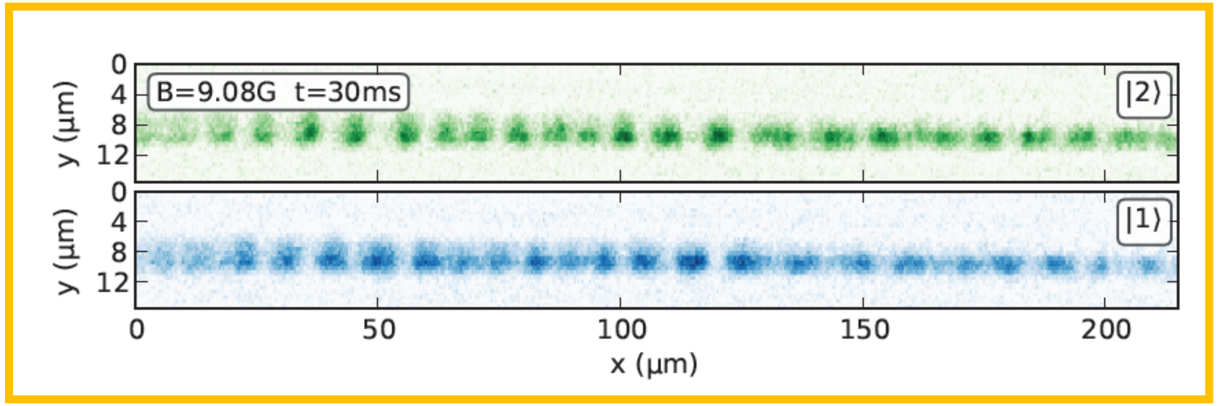


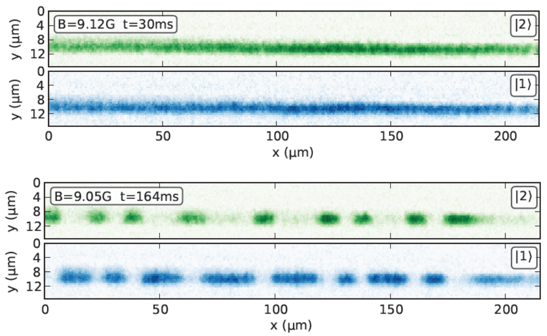
superposition @ t=0 is generated?











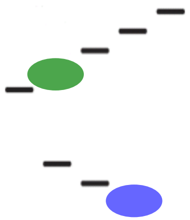
miscible

immiscible

Question

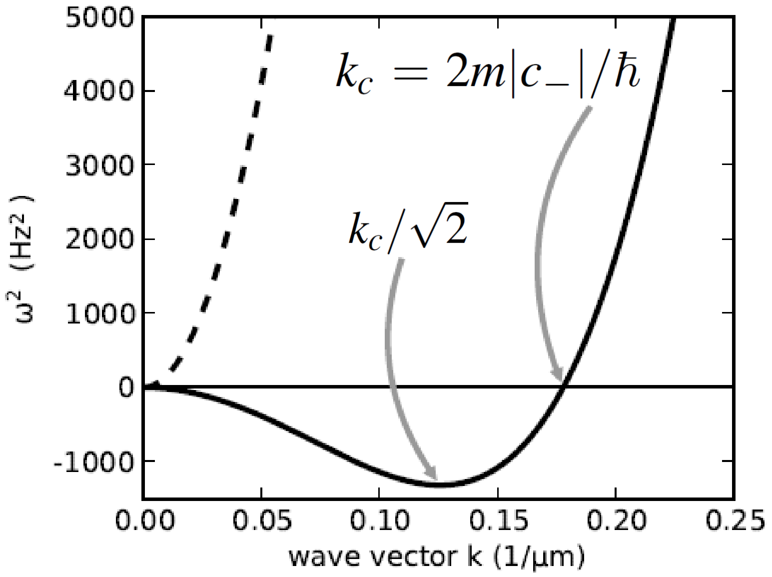
Where does the length scale come from ?

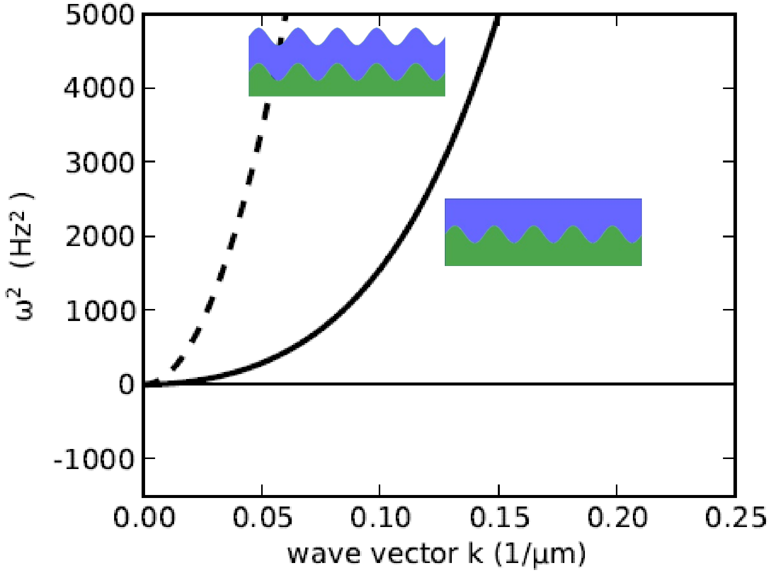
Rubidium BEC



Bogoliubov treatment: $\hbar^2\omega_\pm^2(k) = c_\pm^2\hbar^2k^2 + \left(\frac{\hbar^2k^2}{2m}\right)^2$

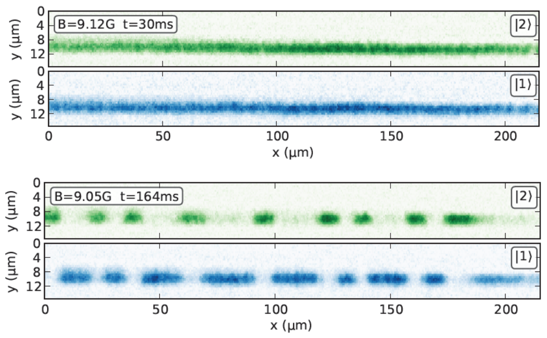
$$c_\pm^2 = \frac{1}{2}\left[(\tilde{c}_1^2+\tilde{c}_2^2) \pm \sqrt{(\tilde{c}_1^2-\tilde{c}_2^2)^2 + 4(g_{12}^2/g_{11}g_{22})\tilde{c}_1^2\tilde{c}_2^2}\right]$$





1

immiscible <1 >1 miscible $\Delta = \frac{g_{11}g_{22}}{g_{12}^2}$



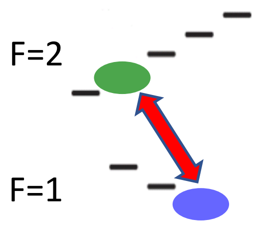
miscible

immiscible

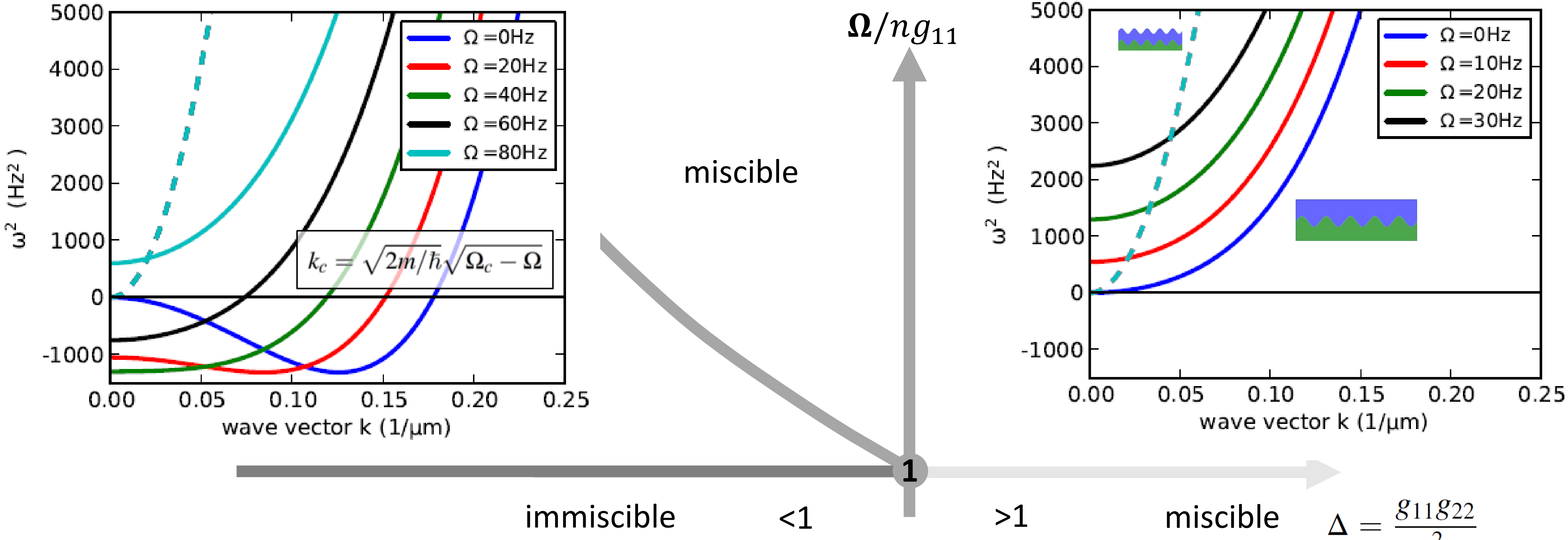
Question

What happens if linear coupling is added ?

Rubidium BEC



$$\hat{H}_{\rm cpl} = -\frac{1}{2}\int {\rm d}x \left[\hbar\tilde{\Omega}\hat{\Psi}_1^\dagger\hat{\Psi}_2 + \hbar\tilde{\Omega}^*\hat{\Psi}_2^\dagger\hat{\Psi}_1\right] + \frac{1}{2}\hbar\delta\int {\rm d}x \left[\hat{\Psi}_2^\dagger\hat{\Psi}_2 - \hat{\Psi}_1^\dagger\hat{\Psi}_1\right]$$



$$\Delta = \frac{g_{11}g_{22}}{g_{12}^2}$$

Bogoliubov theory for mutually coherent condensates
Paolo Tommasini et al. PRA **67**, 023606 (2003)

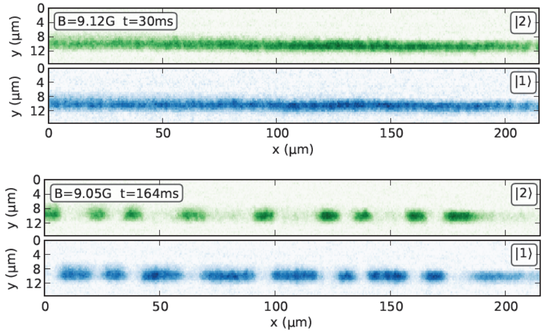
A study of coherently coupled two-component Bose-Einstein condensates
M. Abad and A. Recati, Eur. Phys. J D 67, 148 (2013)

Question

|1 > |2 >

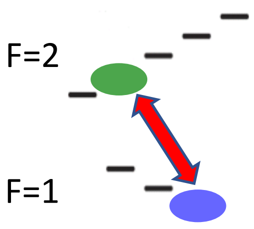
Rubidium BEC

Rabi oscillations in the miscible and immiscible regime ?

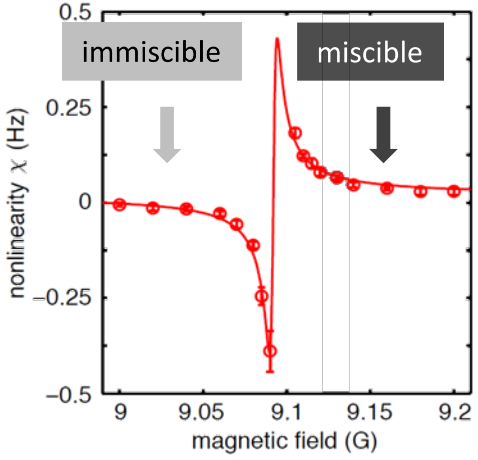


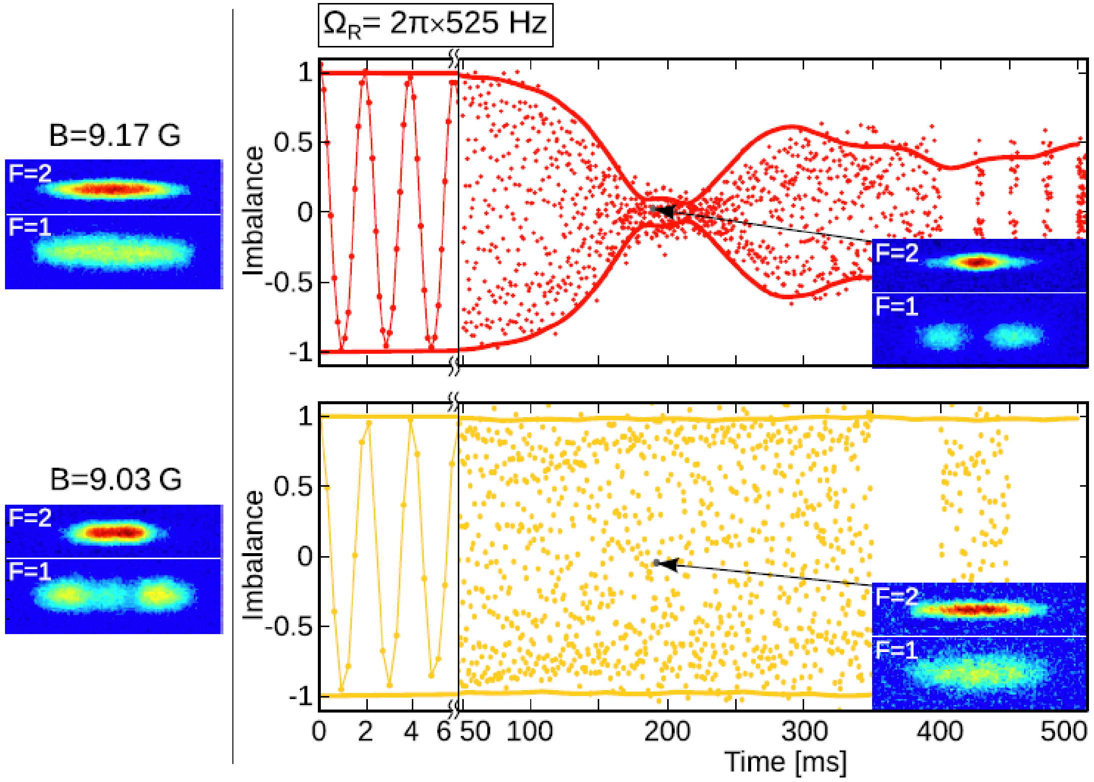
miscible

immiscible

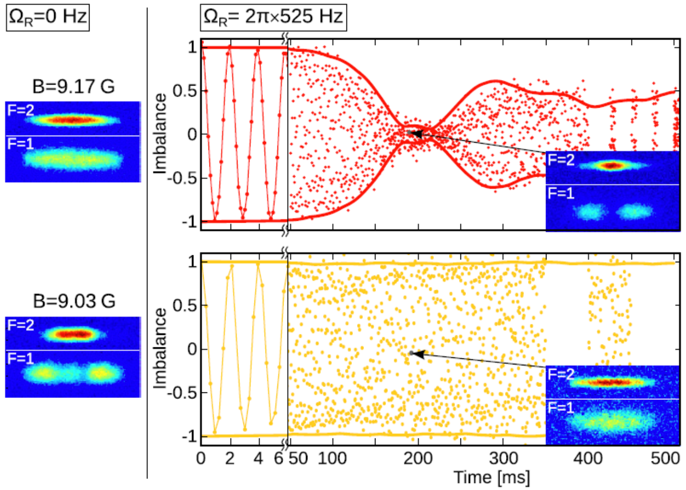


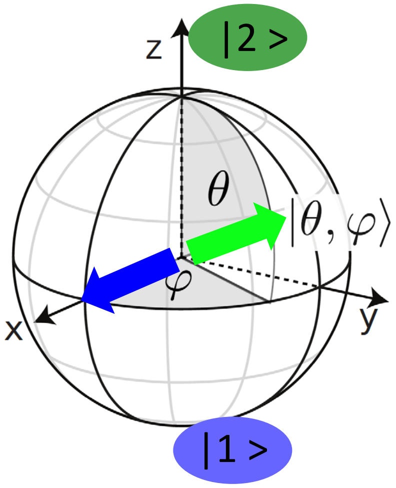
Feshbach resonance





E. Nicklas PRL 107, 193001, 2001





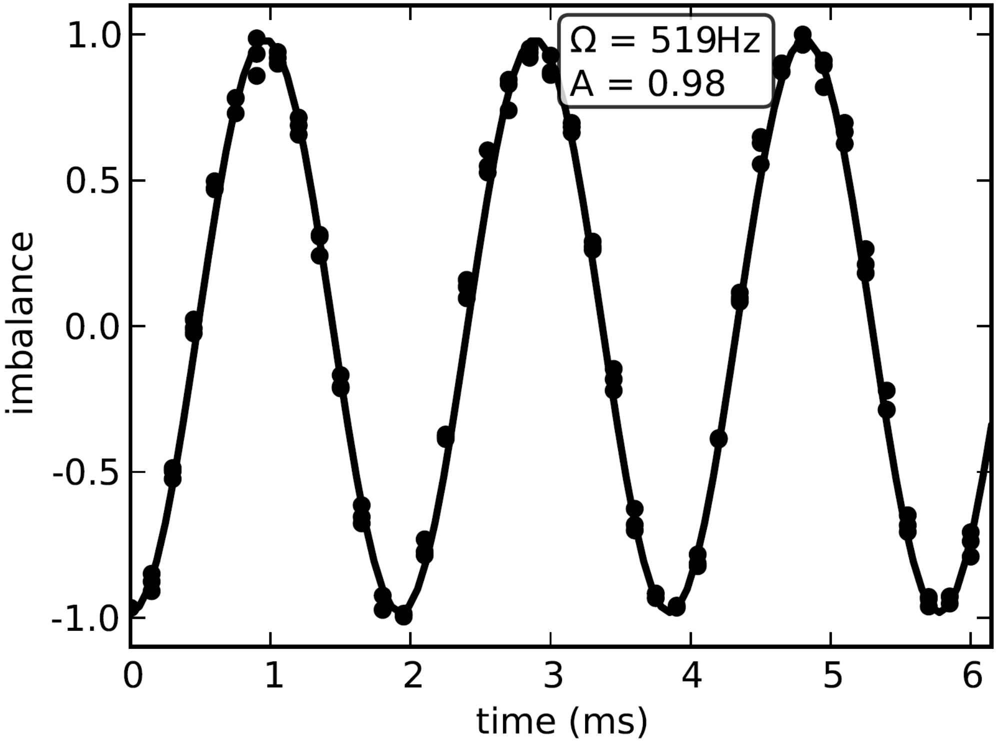
$$\hat{H}_{\rm cpl} = -\frac{1}{2}\hbar\begin{pmatrix} \delta & \tilde{\Omega} \\ \tilde{\Omega}^* & -\delta \end{pmatrix} = -\frac{1}{2}\hbar\begin{pmatrix} \delta & \Omega e^{i\varphi} \\ \Omega e^{-i\varphi} & -\delta \end{pmatrix}$$

dressed states

$$|+\rangle = e^{i\varphi/2}\sin(\theta/2)|1\rangle + e^{-i\varphi/2}\cos(\theta/2)|2\rangle$$

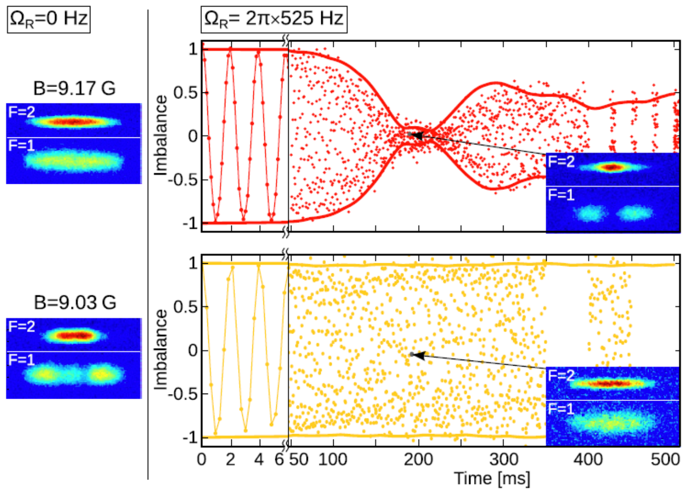
$$|-\rangle = e^{i\varphi/2}\cos(\theta/2)|1\rangle - e^{-i\varphi/2}\sin(\theta/2)|2\rangle$$

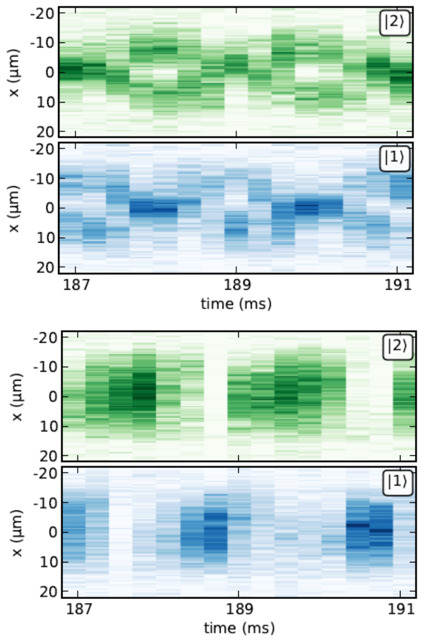
$$E_\pm = \frac{\hbar}{2}(\mp\Omega_{\rm eff} - \delta) \qquad \Omega_{\rm eff} = \sqrt{\Omega^2 + \delta^2}$$



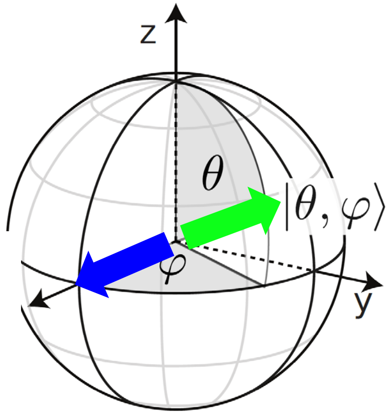
$$|\psi(t)\rangle = \cos(\Omega/2\,t)|1\rangle + \sin(\Omega/2\,t)|2\rangle$$

$$= \frac{1}{\sqrt{2}}\left(e^{-i\Omega/2\,t}|+\rangle + e^{+i\Omega/2\,t}|-\rangle\right)$$

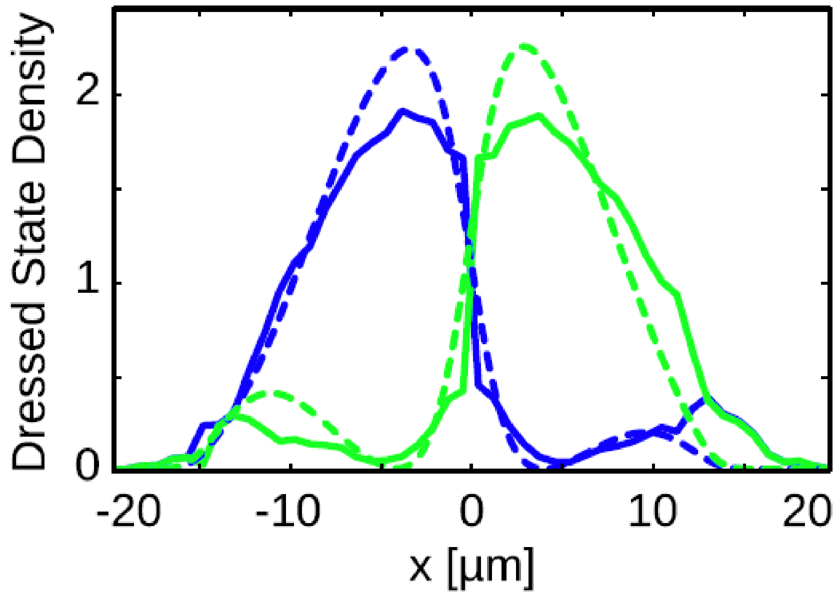


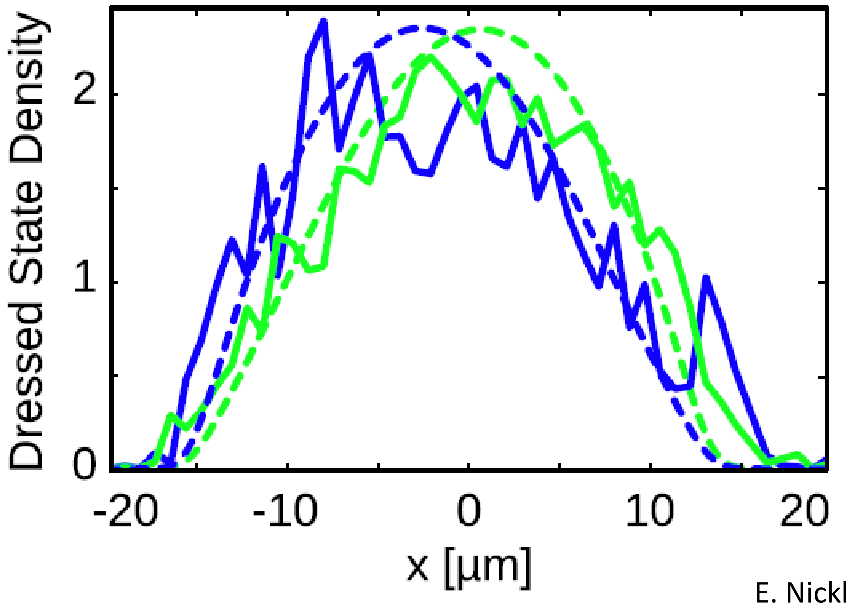


$$|\psi(t)\rangle = \cos\alpha \cdot e^{-i\Omega t/2} e^{-i\varphi/2}|+\rangle + \sin\alpha \cdot e^{+i\Omega t/2} e^{+i\varphi/2}|-\rangle$$
$$= \frac{1}{\sqrt{2}}(\cos\alpha \cdot e^{-i(\Omega t+\varphi)/2} + \sin\alpha \cdot e^{+i(\Omega t+\varphi)/2})|1\rangle$$
$$+ \frac{1}{\sqrt{2}}(\cos\alpha \cdot e^{-i(\Omega t+\varphi)/2} - \sin\alpha \cdot e^{+i(\Omega t+\varphi)/2})|2\rangle$$

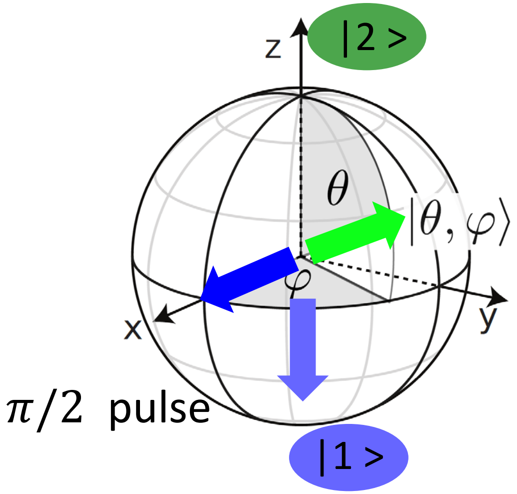


Dressed states reconstructed: miscibility <-> immiscibility





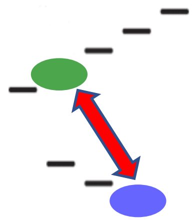
E. Nicklas PRL 107, 193001, 2001

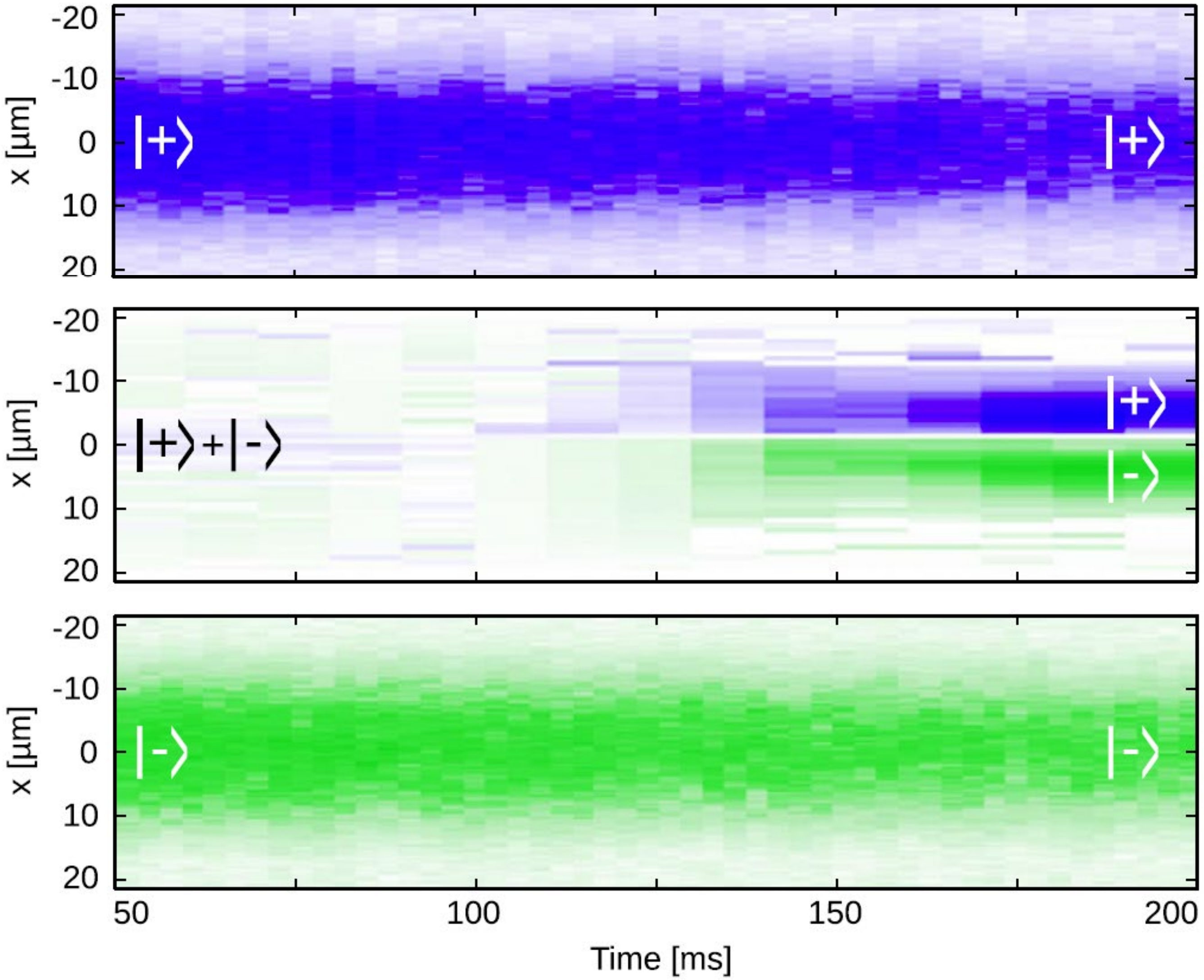


Question

Rabi oscillations in the miscible regime with initial condition |1 > + |2 >

Rubidium BEC





PRL 107, 193001 (2011)

Ω is the dominating energy scale

PHYSICAL REVIEW A **68**, 053607 (2003)

Dynamic stability of dressed condensate mixtures

Stewart D. Jenkins[*,‡] and T. A. B. Kennedy[†,‡]
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA
(Received 10 July 2003; published 17 November 2003)

See also: C.P. Search, P.R. Berman PRA 63, 043612 (2001)

$$a_{++} = a_{--} = \frac{1}{4}(a_{11} + a_{22} + 2a_{12})$$

$$a_{+-} = \frac{1}{2}(a_{11} + a_{22})$$

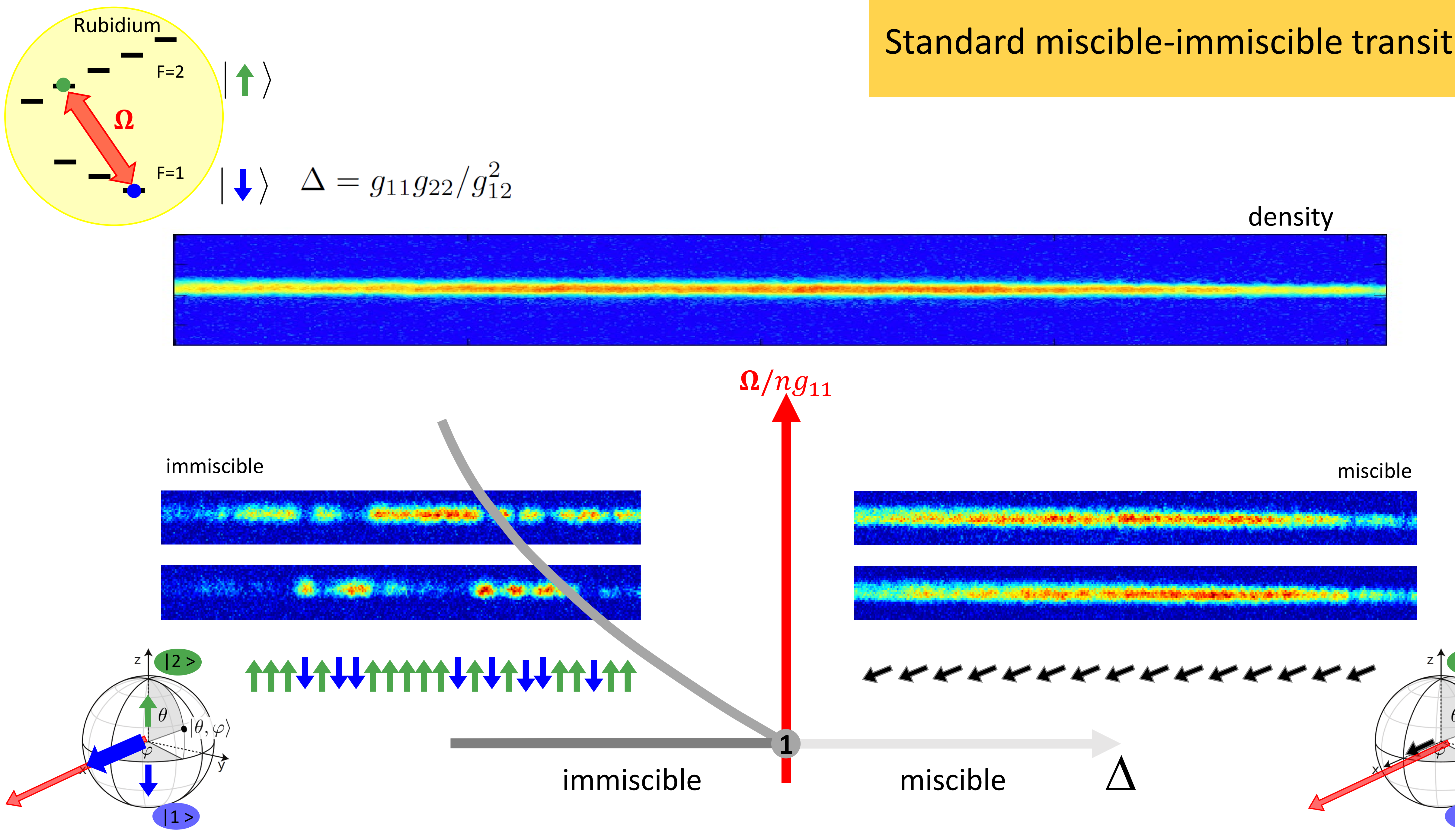
Miscibility of dressed states:

$$a_{+-}^2 < a_{++}a_{--}$$

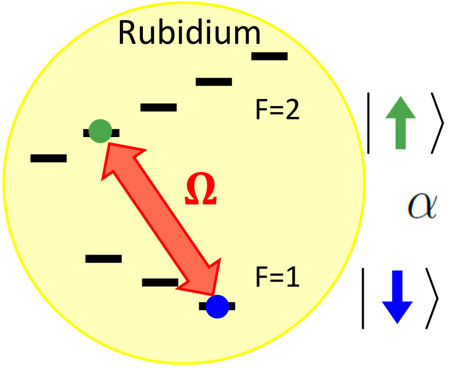
implies immiscibility of bare states a_{11}~a_{22}:

$$a_{12}^2 > a_{11}\,a_{22}$$

Standard miscible-immiscible transition



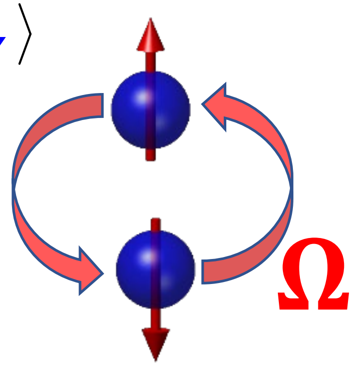
Effective B field: miscible-immiscible transition

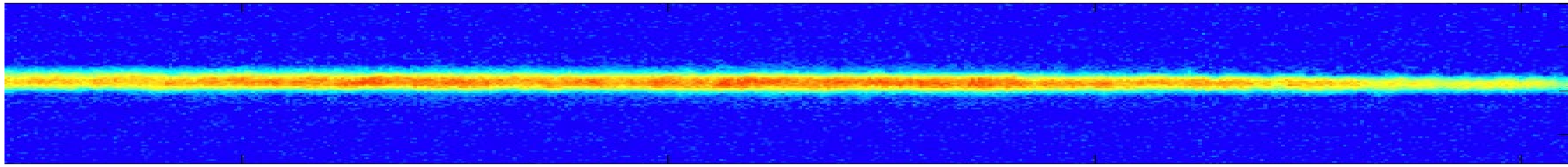


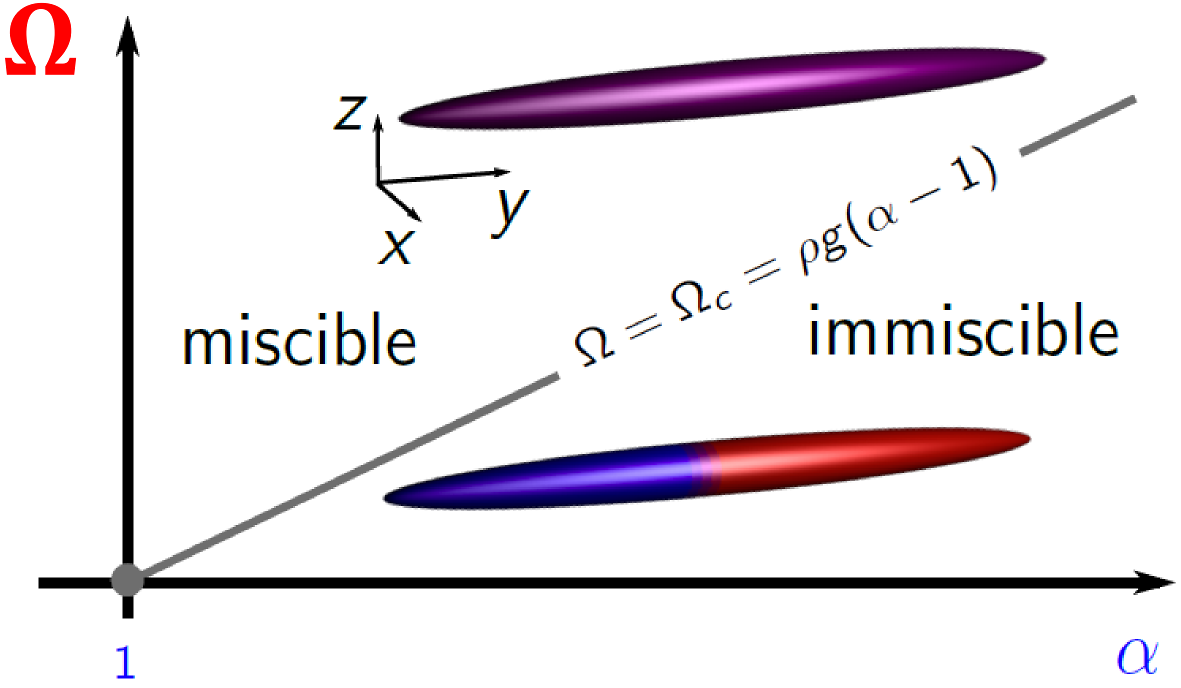
$|\uparrow\rangle$

$$\alpha = a_{\uparrow\downarrow}/\sqrt{a_{\uparrow\uparrow}a_{\downarrow\downarrow}}$$

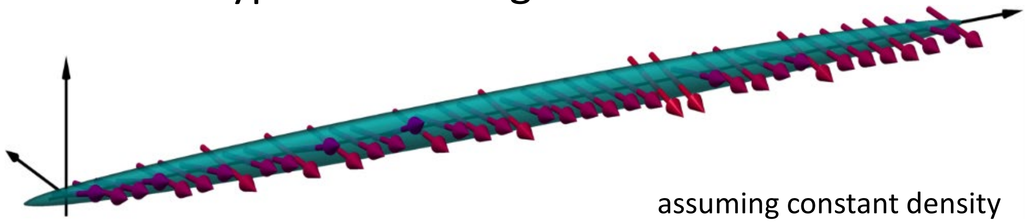
$|\downarrow\rangle$





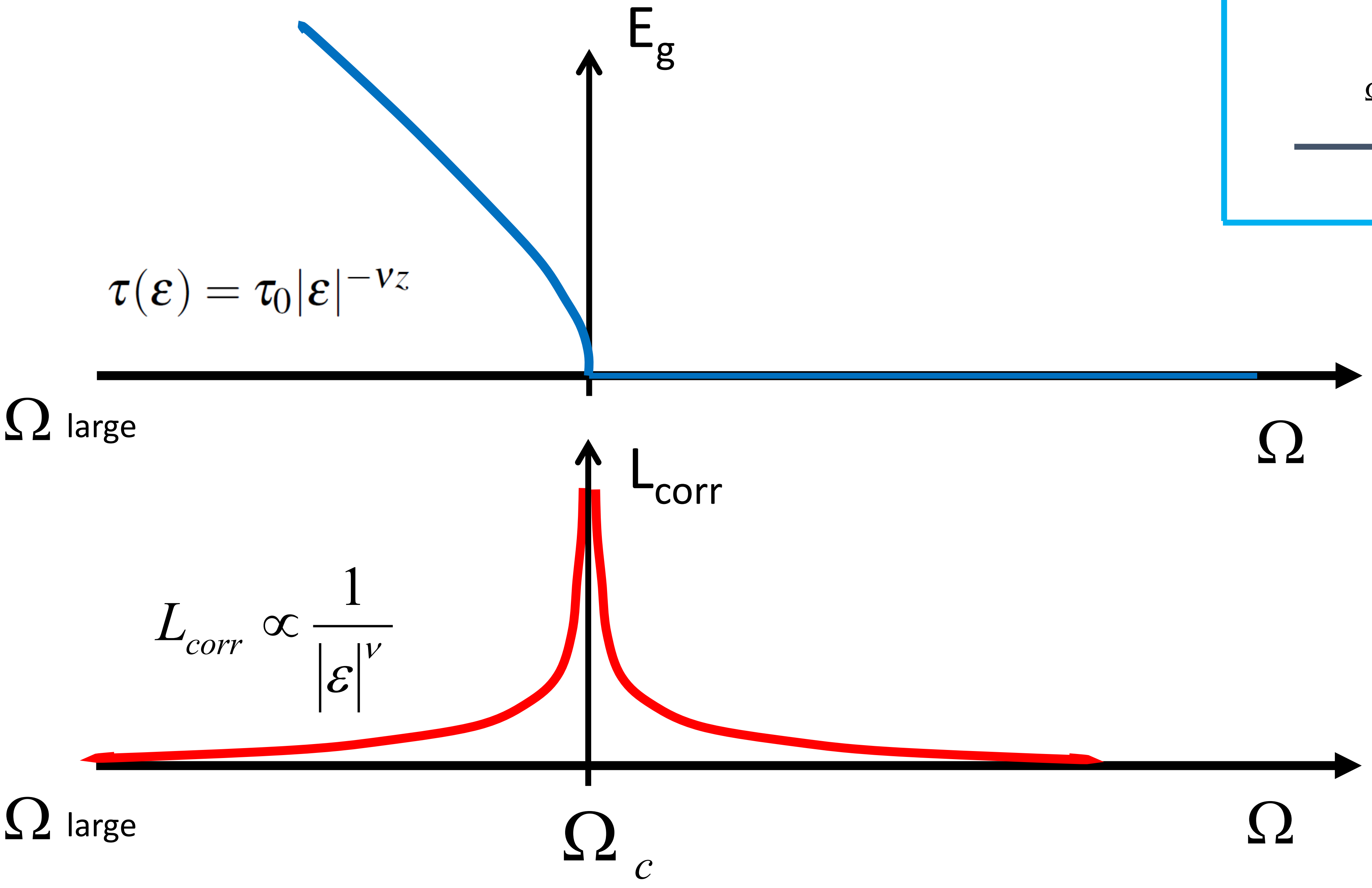


Effective 1D XXX-type Heisenberg model

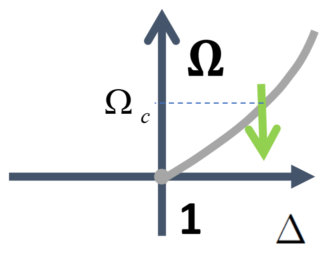


$$\mathcal{H} = \left[|\partial_y \mathbf{S}|^2/4 + \Omega S_x - \Omega_c S_z^2/2\right] n_0/2.$$

Characteristic time & length

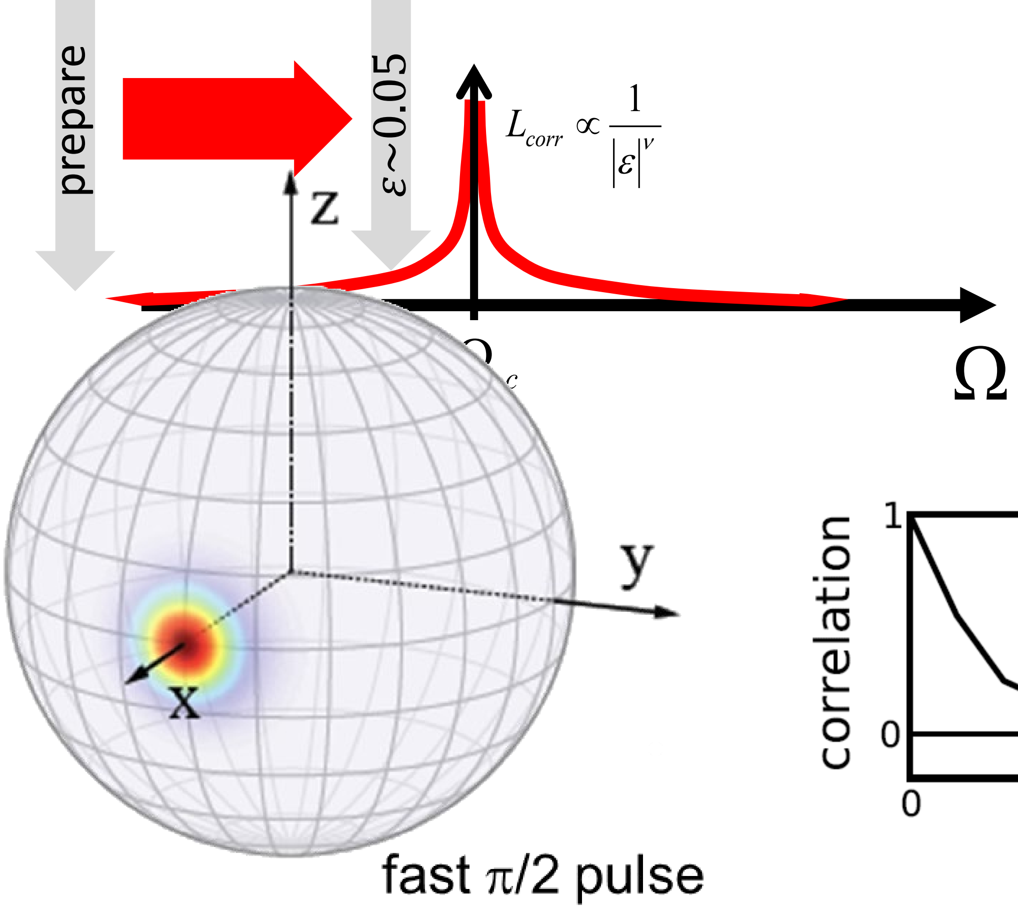


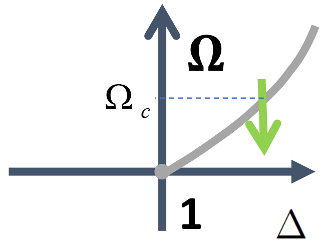
Relevant parameters

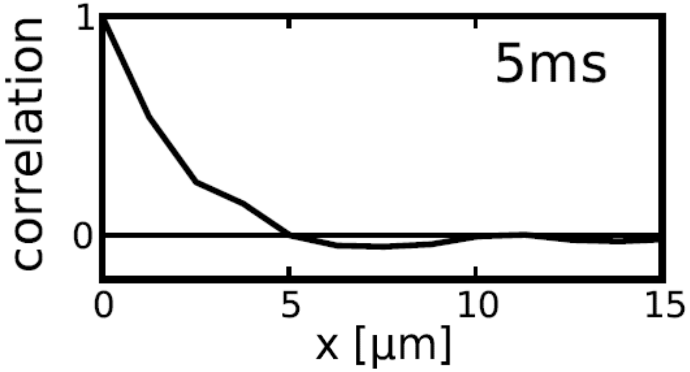


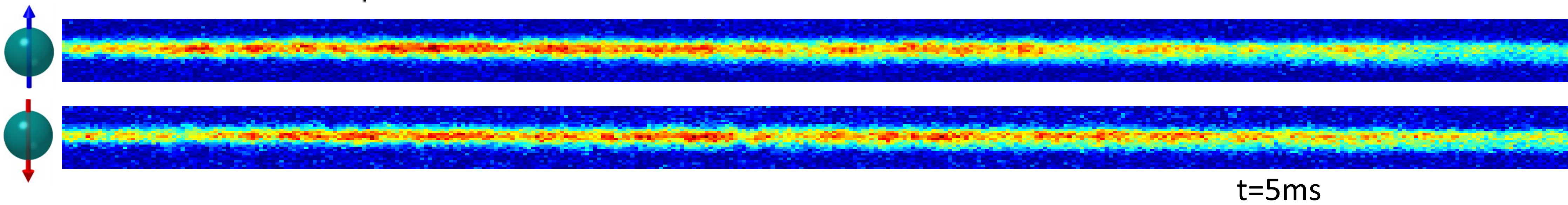
Access correlation length

PRL 115, 245301 (2015)







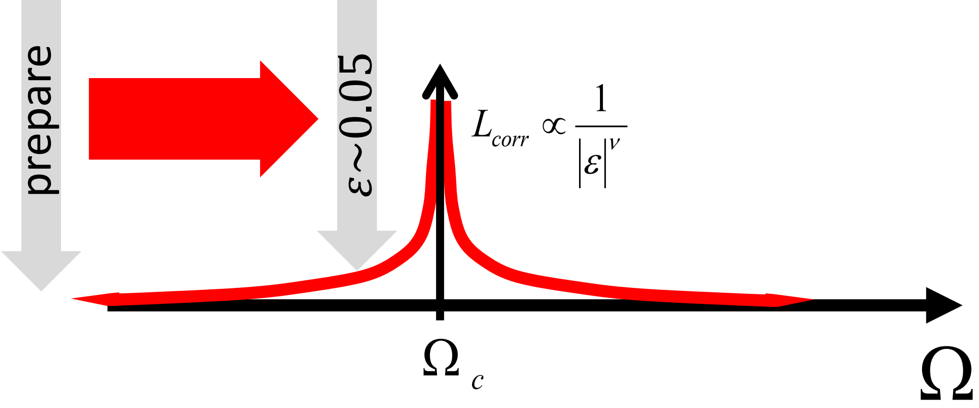


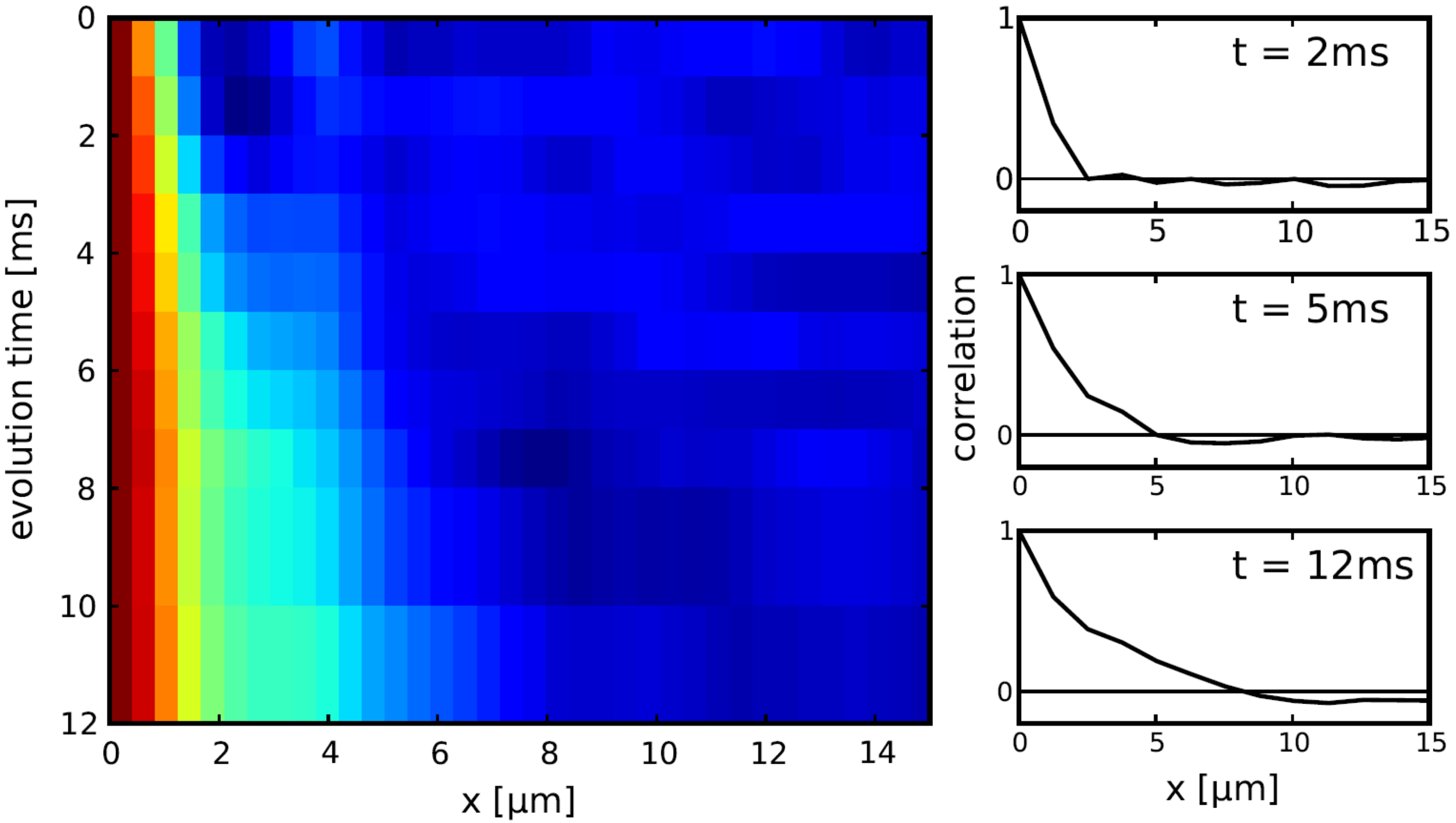
$$\langle J_z(x) J_z(x') \rangle = \langle \Delta n(x) \Delta n(x') \rangle$$

with 1µm spatial resolution !!!

~5µm spin healing length for Ω=0

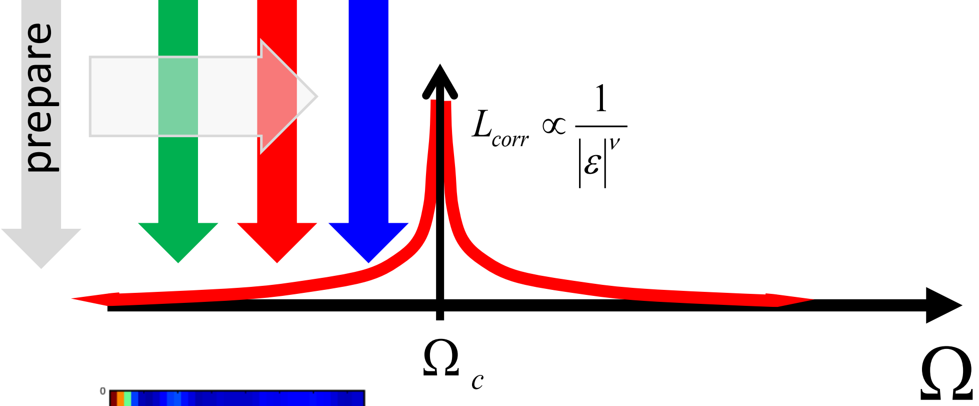
Temporal evolution of correlation functions

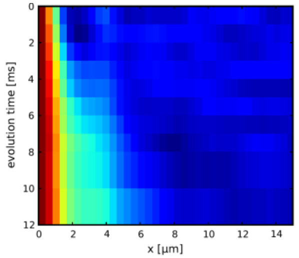


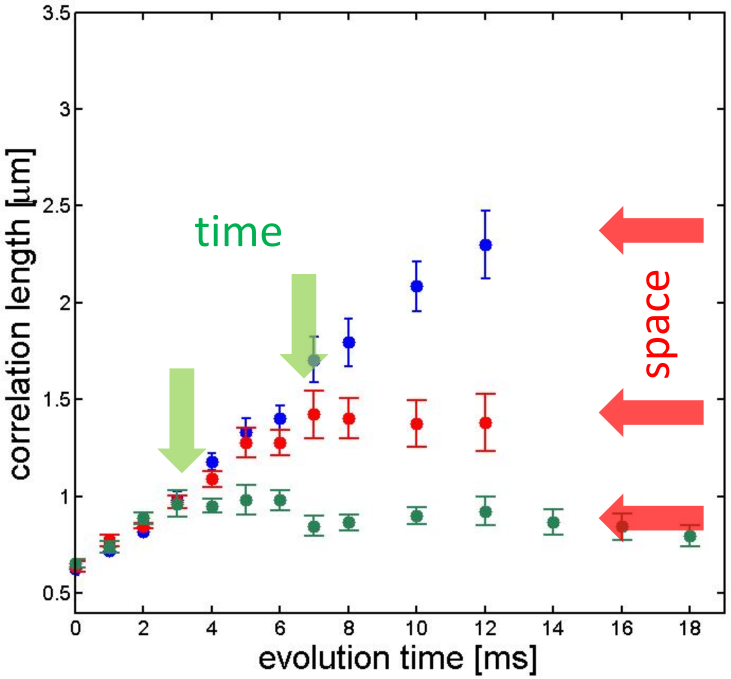


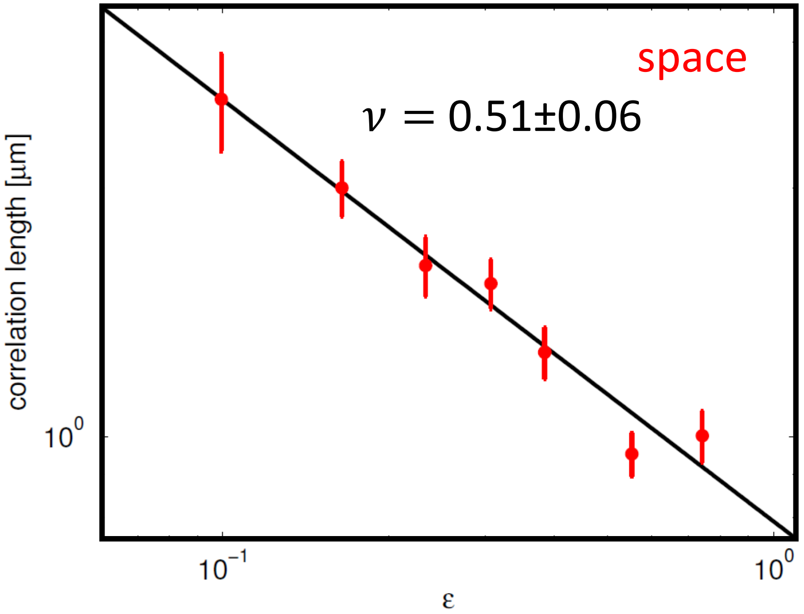
Scaling of correlation functions

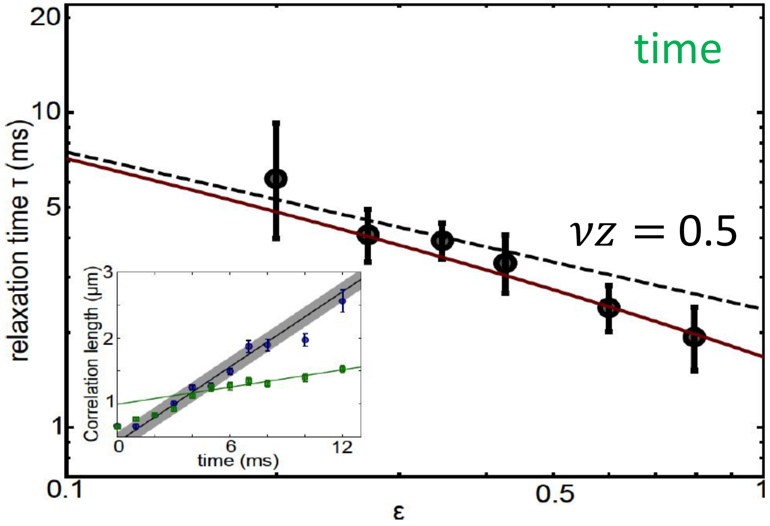
PRL 115, 245301 (2015)





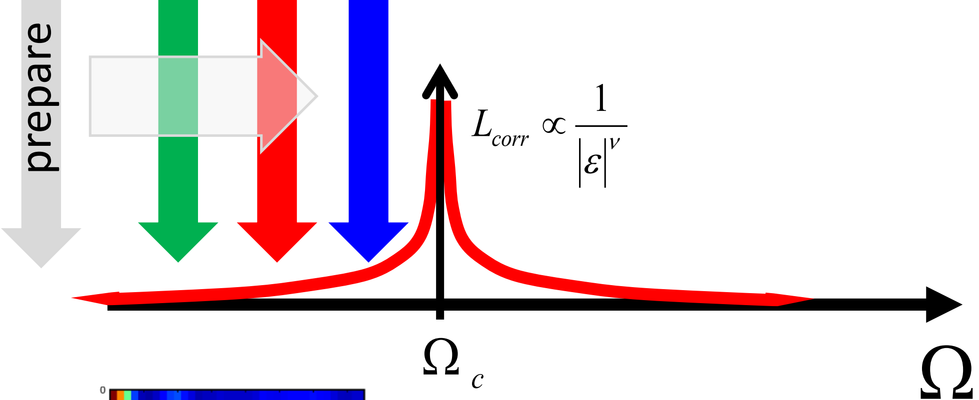


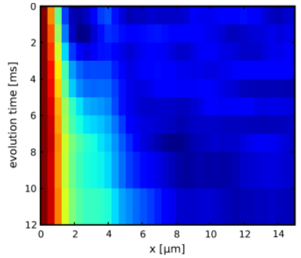


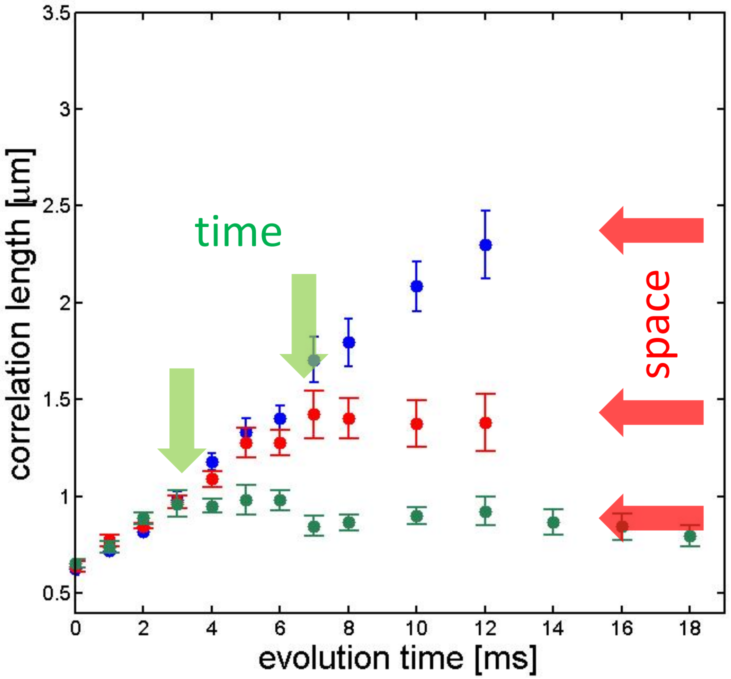


Scaling of correlation functions

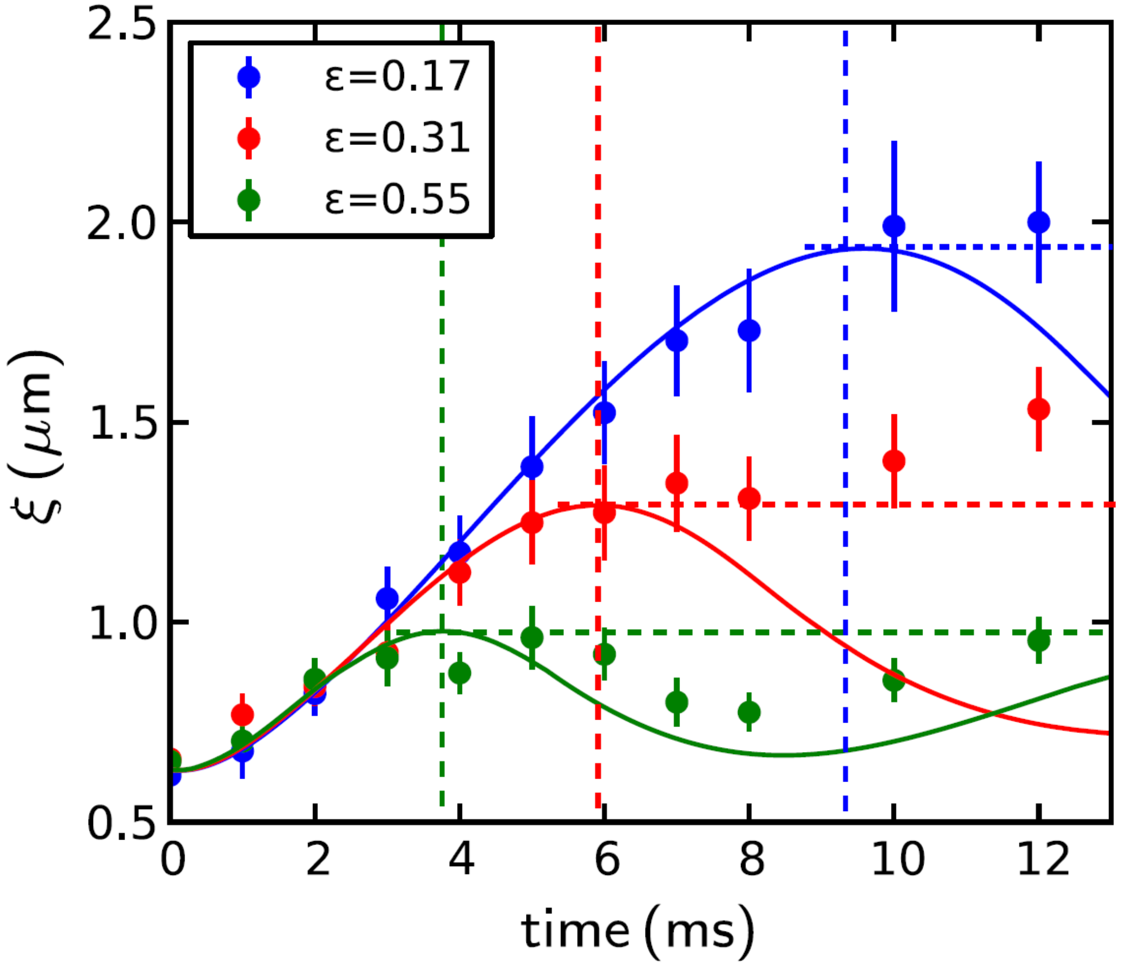
PRL 115, 245301 (2015)





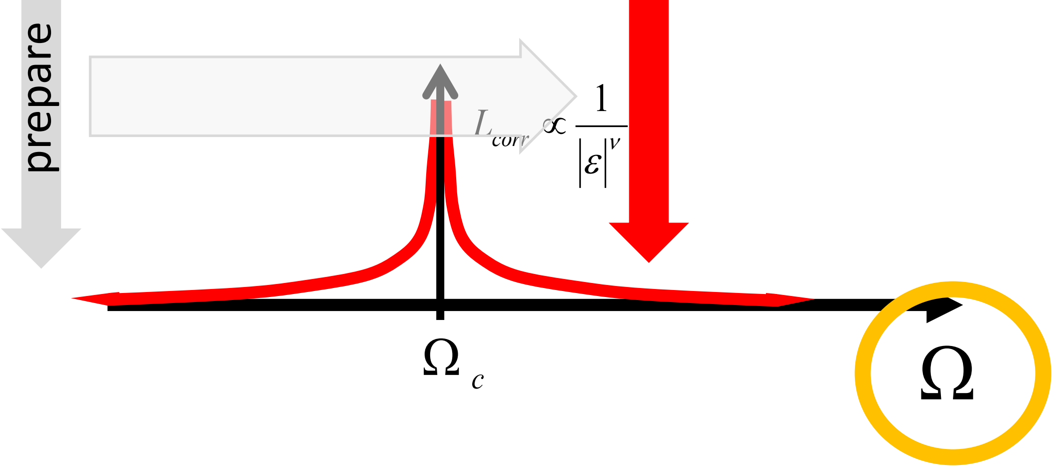


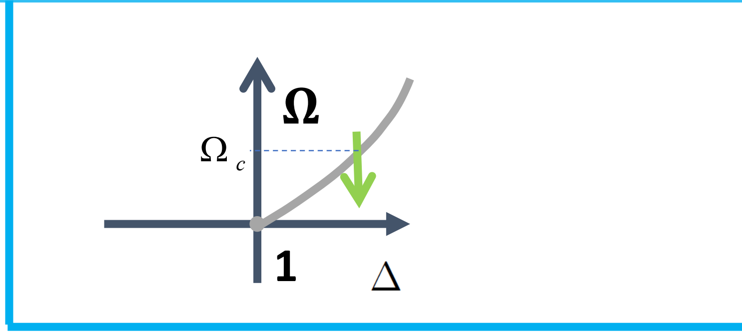
Bogoliubov pediction by I. Bouchoule

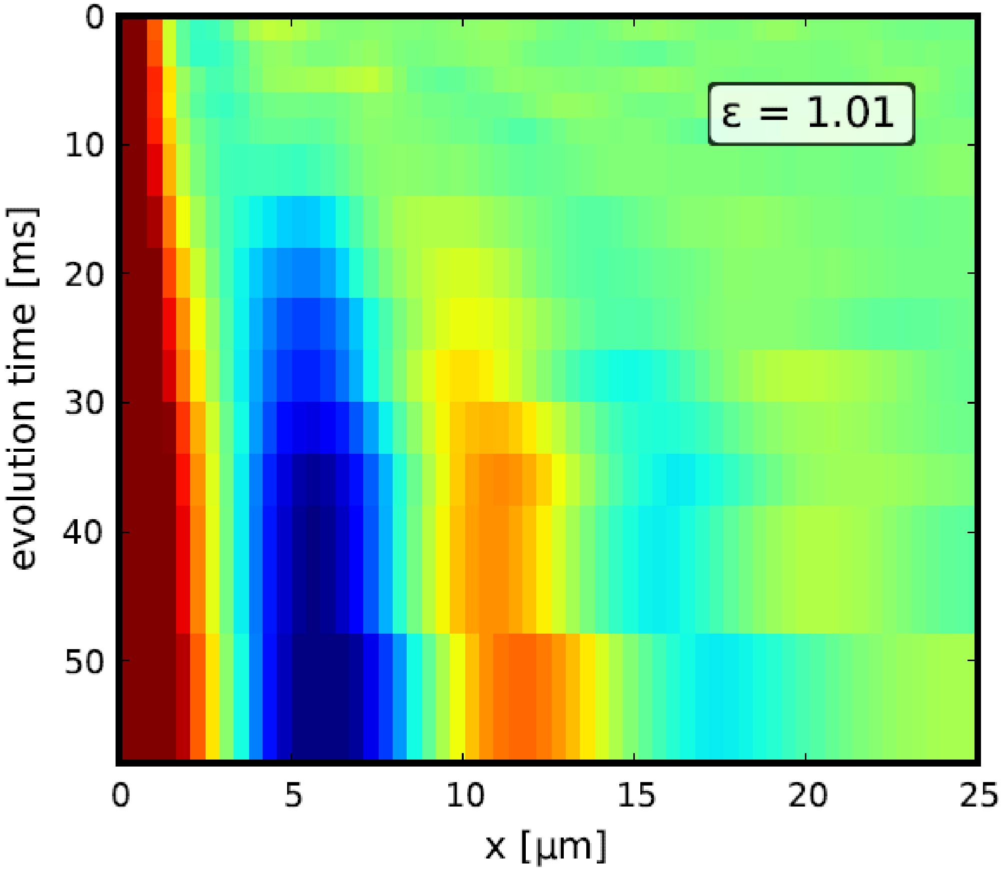


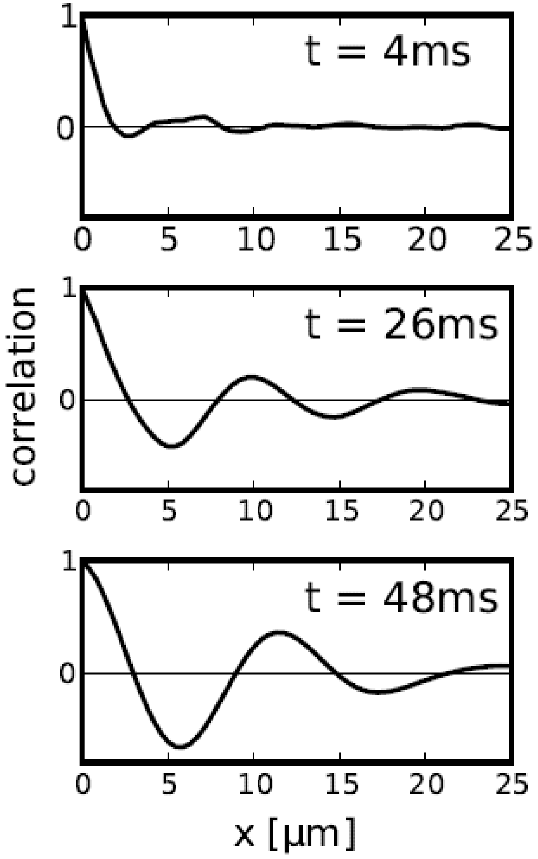
Markus Oberthaler

power law in the immiscible regime

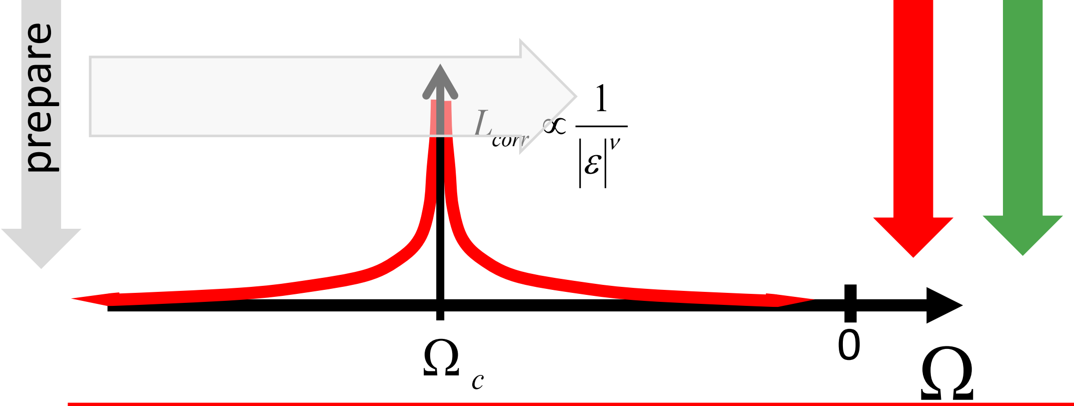


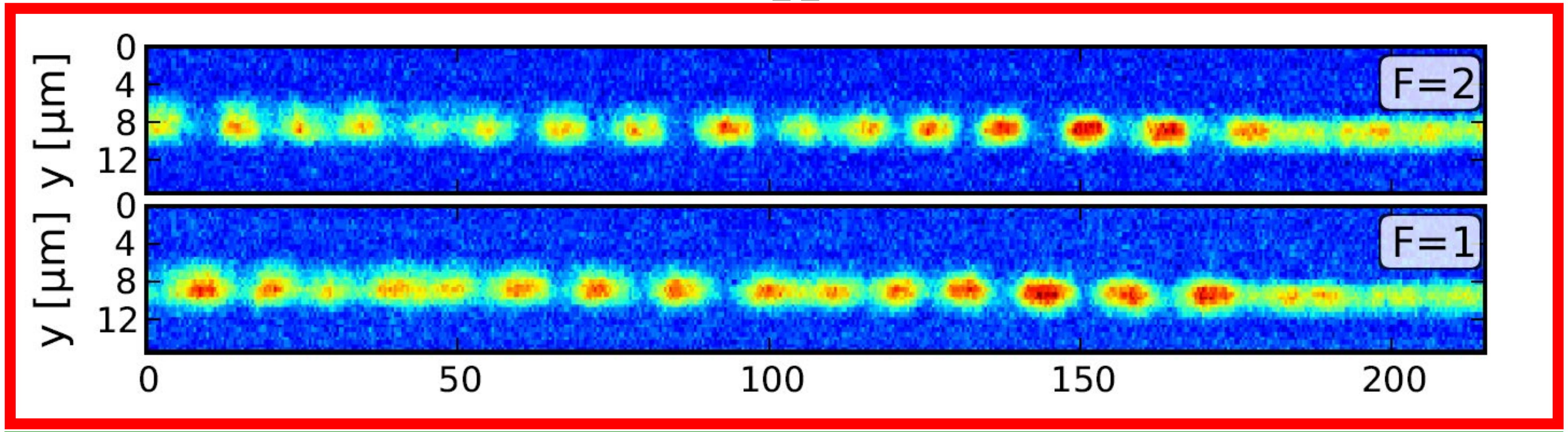


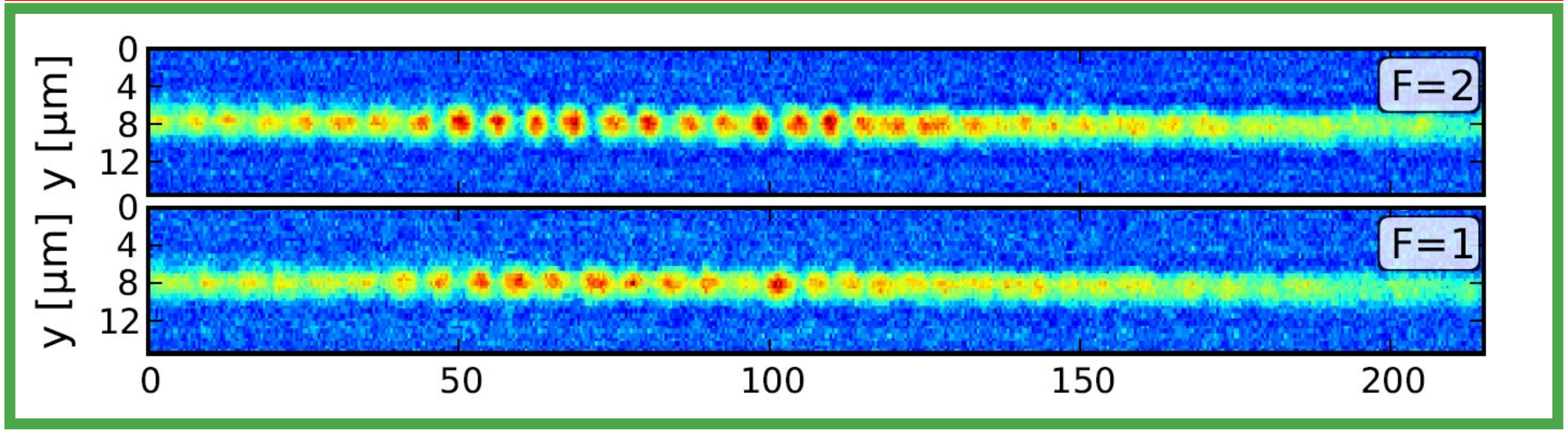




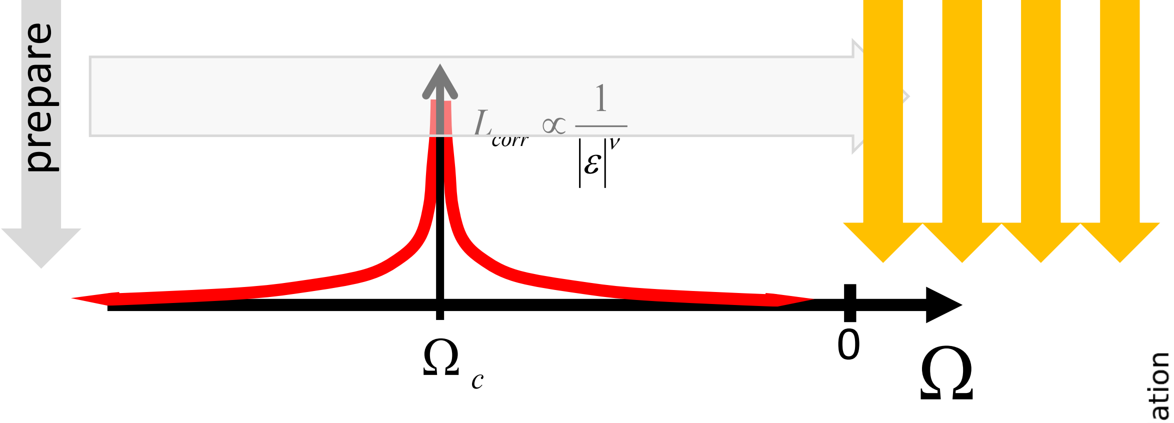
extension to positiv Ω

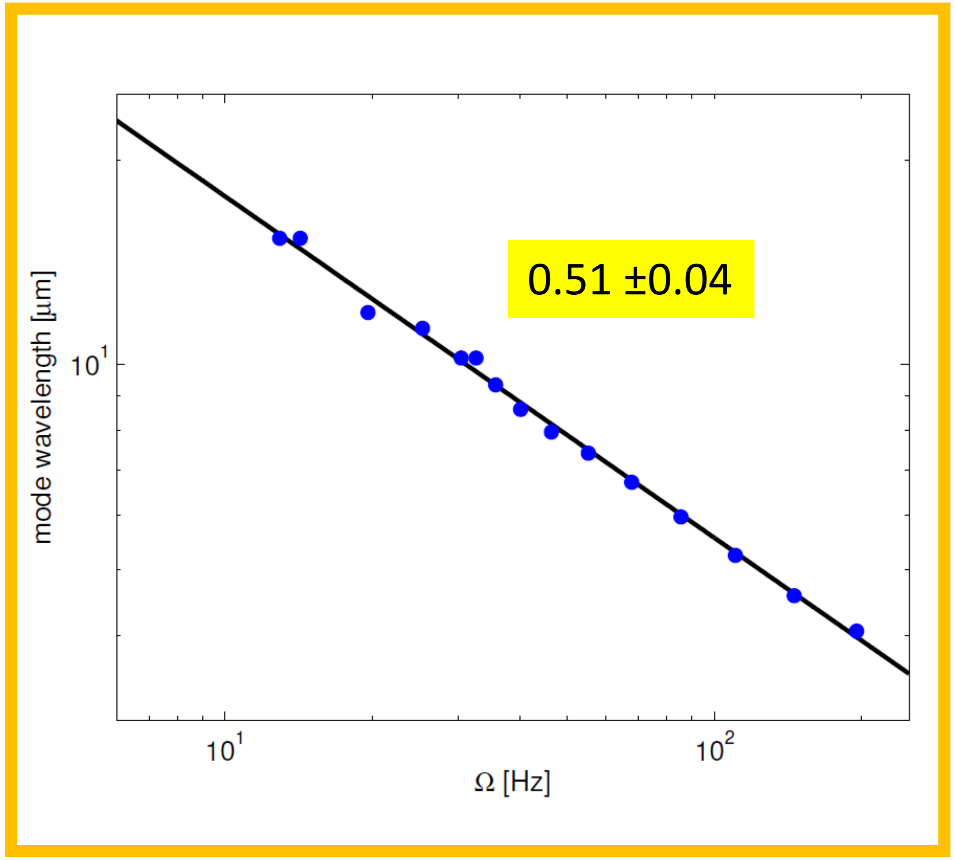


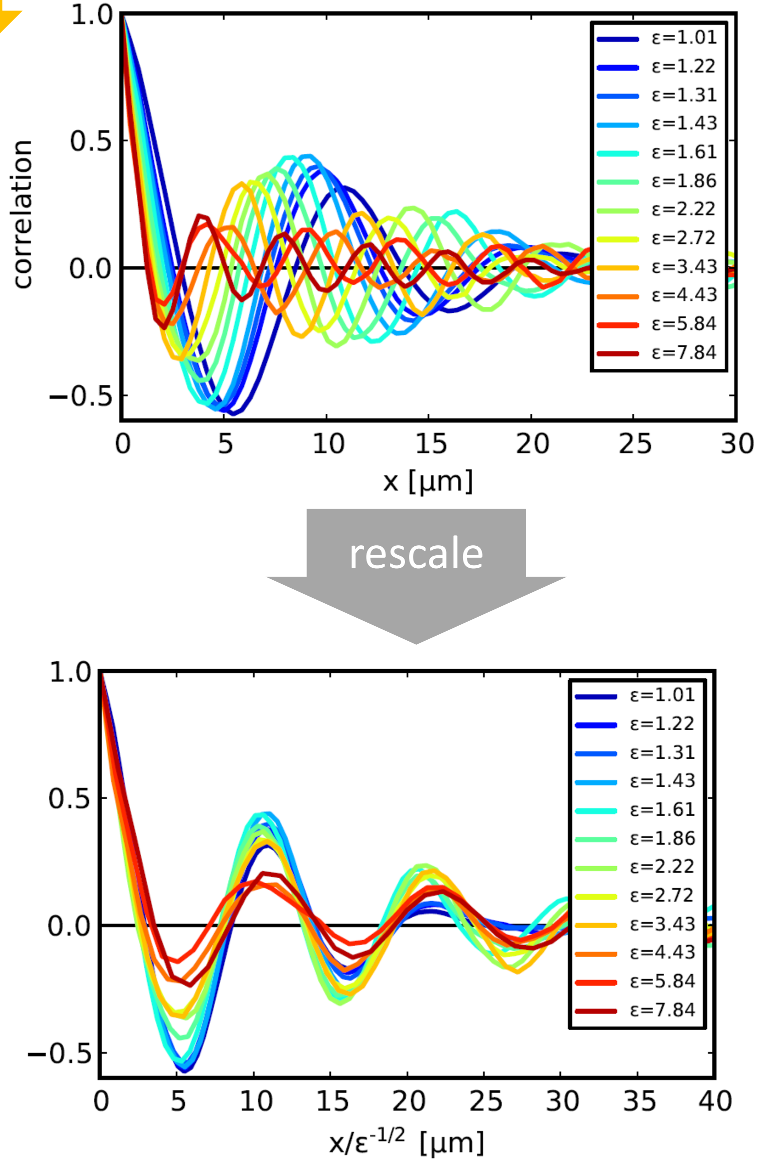




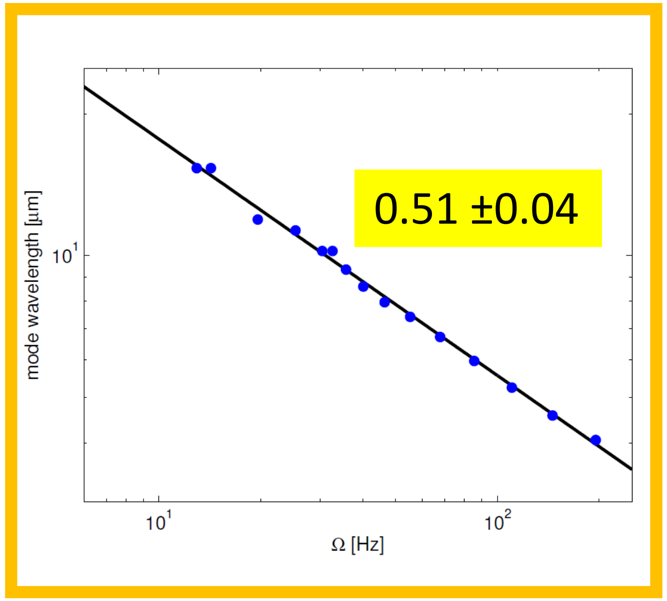
Scaling in the immiscible regime

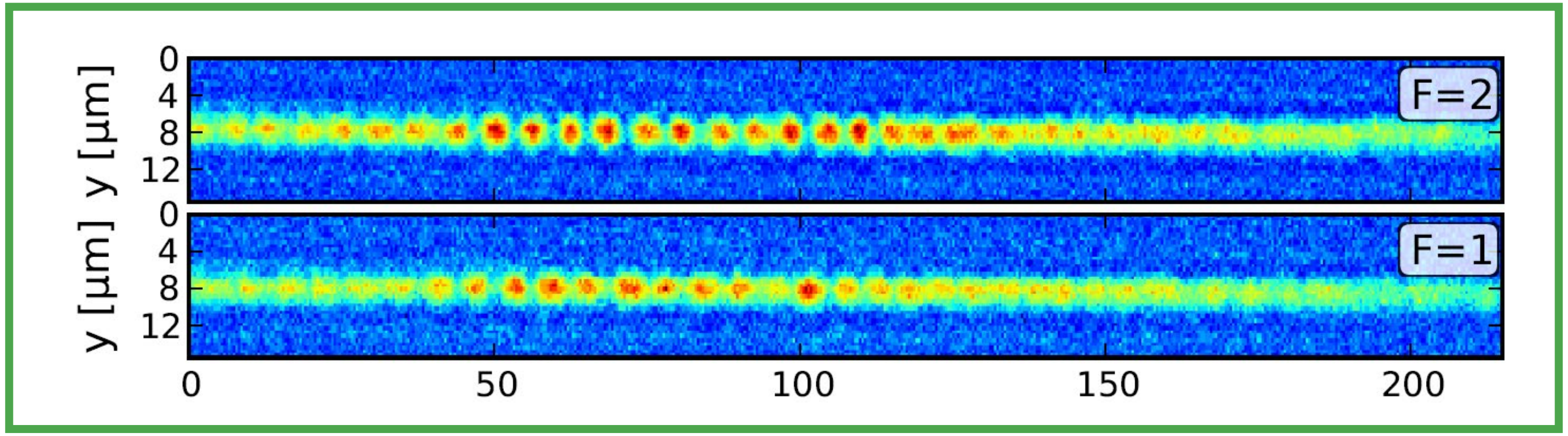


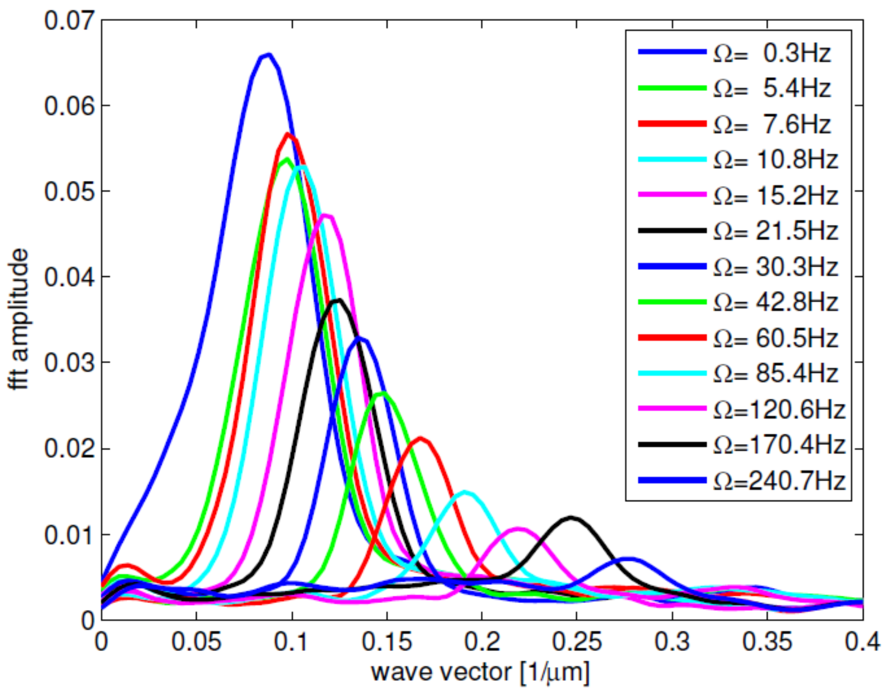


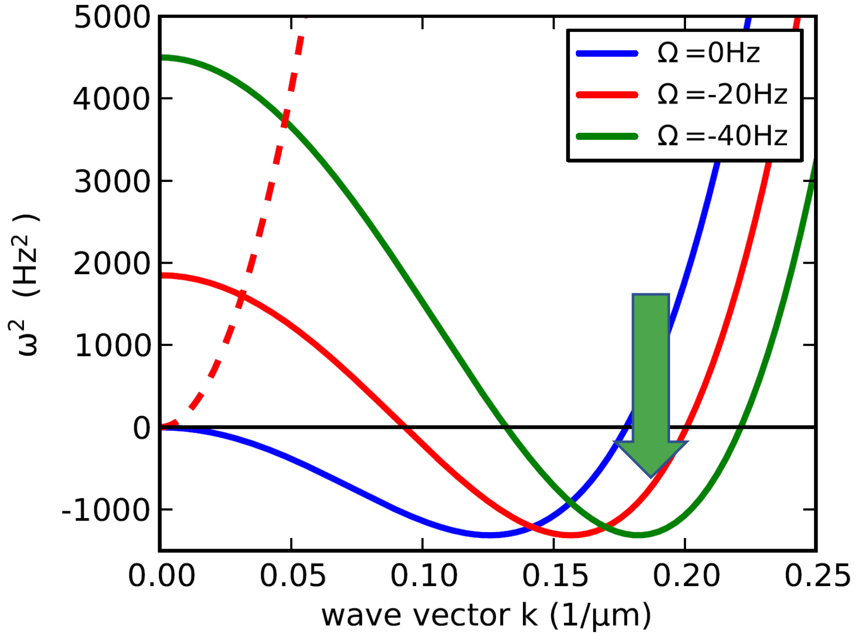


Bogoliubov for positive and negative Ω



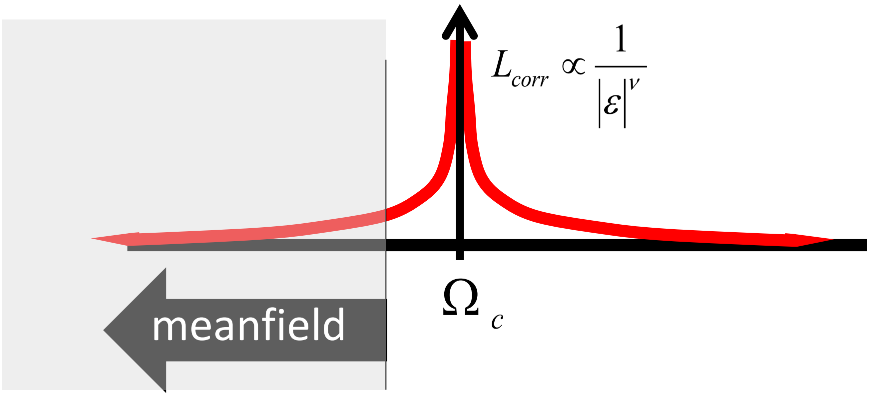




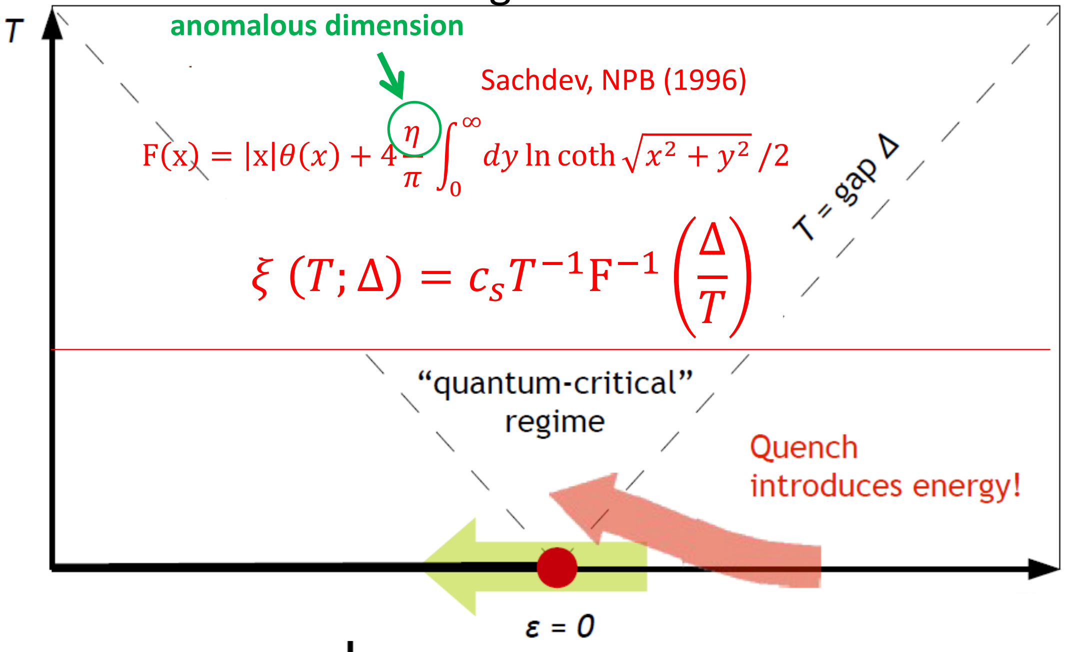


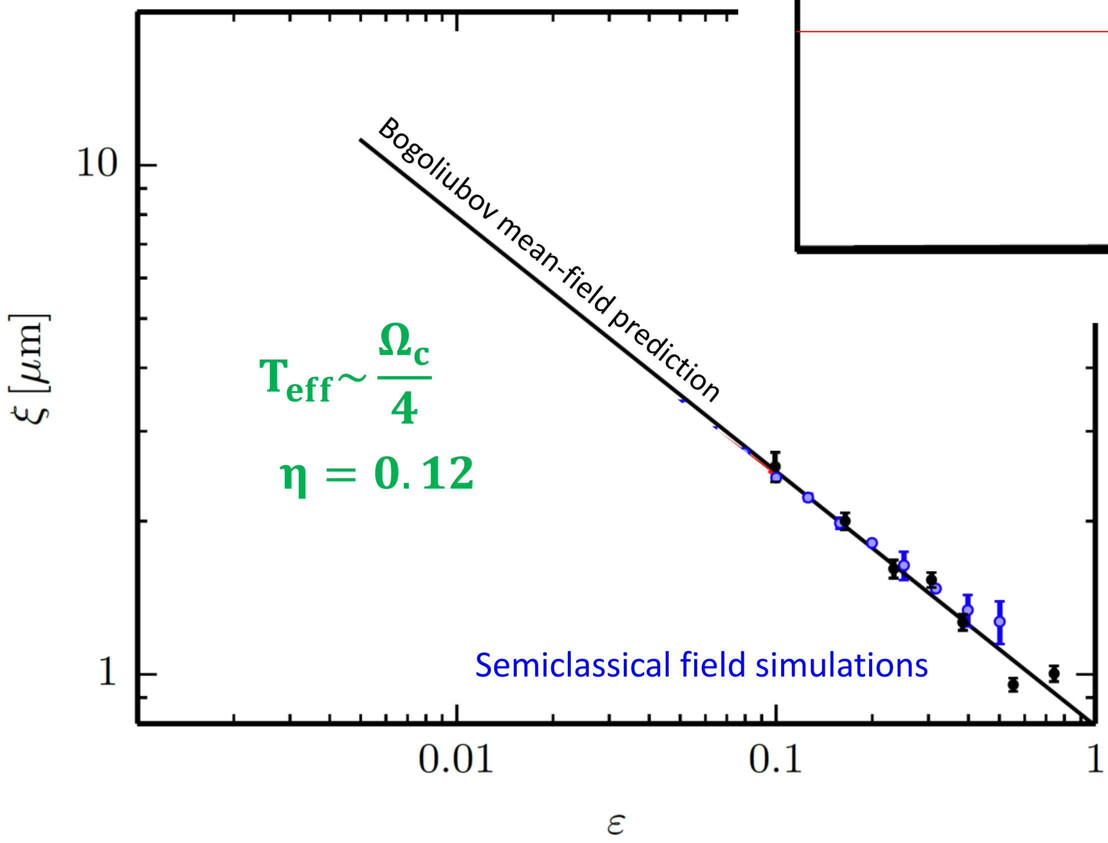
Ginzburg criterium

Thomas Gasenzer group: Markus Karl



1D transverse field Ising model

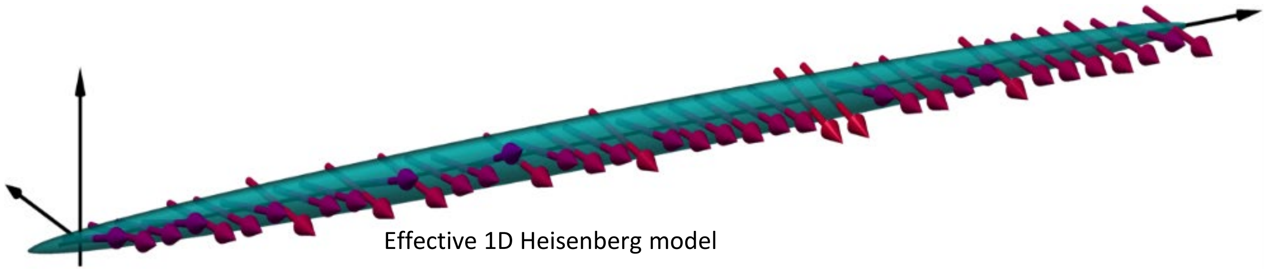




SUMMARY

Ultracold gas systems simulate classical
non-linear coupled equations with high precision

Two component interacting gases + linear coupling
additional experimentally accessible controll

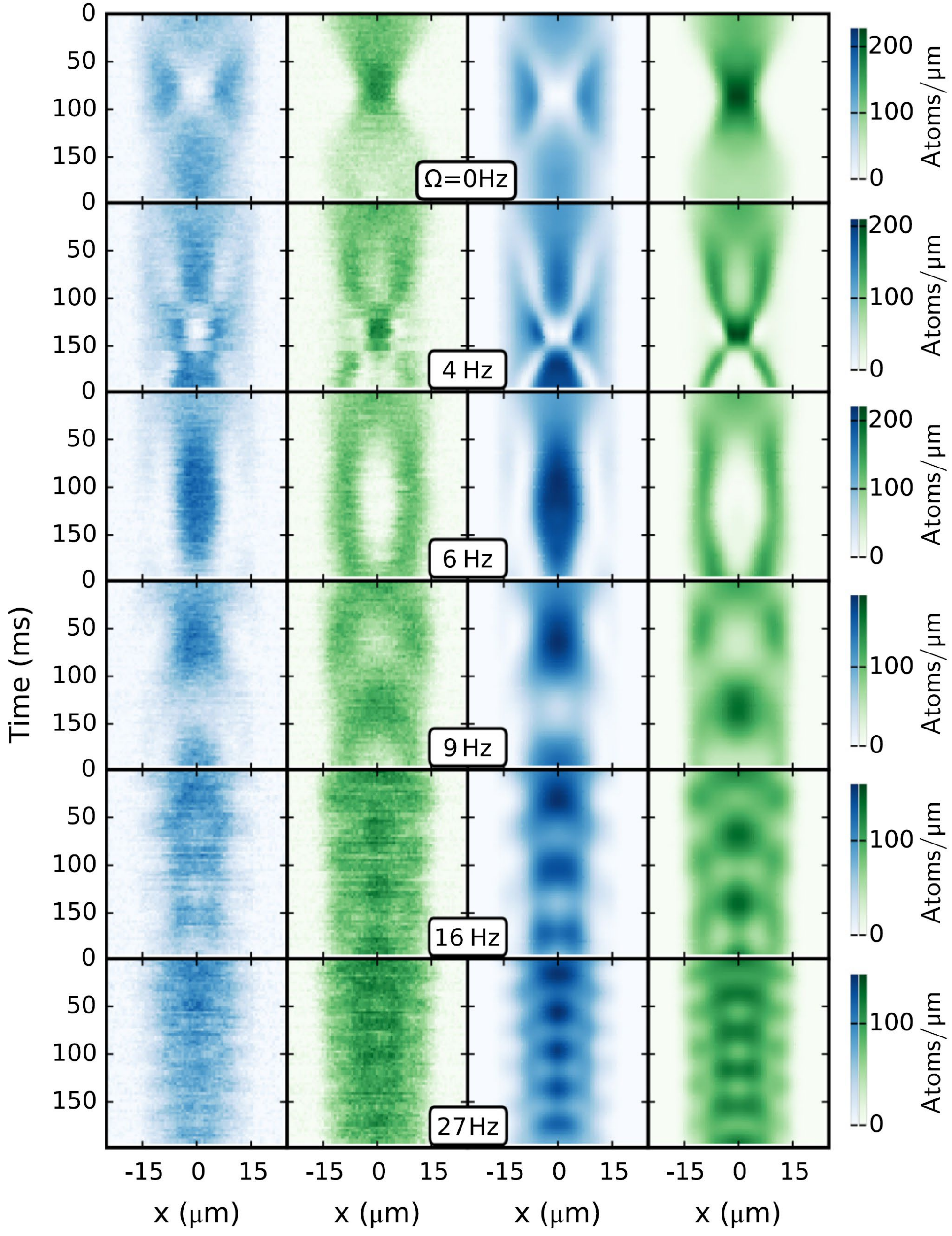


Effective 1D Heisenberg model

Many new developments:

Trento Group – Lectures by Giacomo Lamporesi
Bourdel Group – Poster 17, tomorrow – Alfred Hammond
Tarruell Group – Poster 9, yesterday – Craig Chisholm

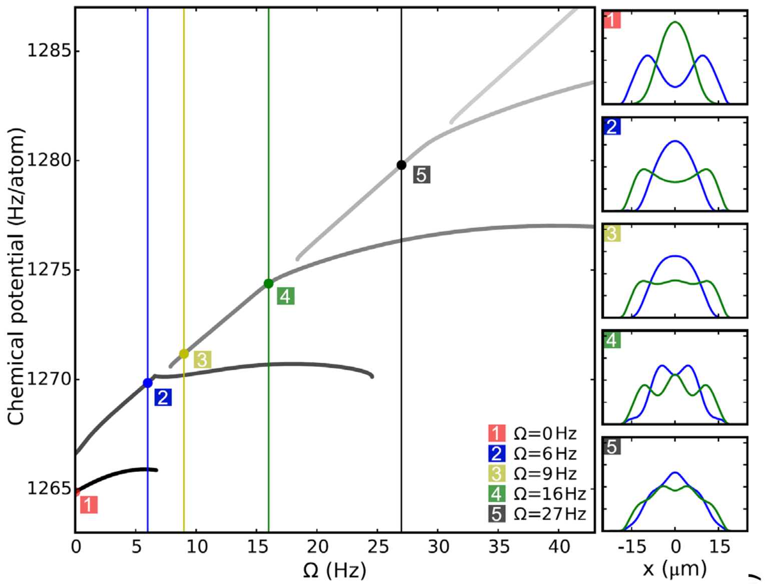
PRA 92, 053614 (2015)

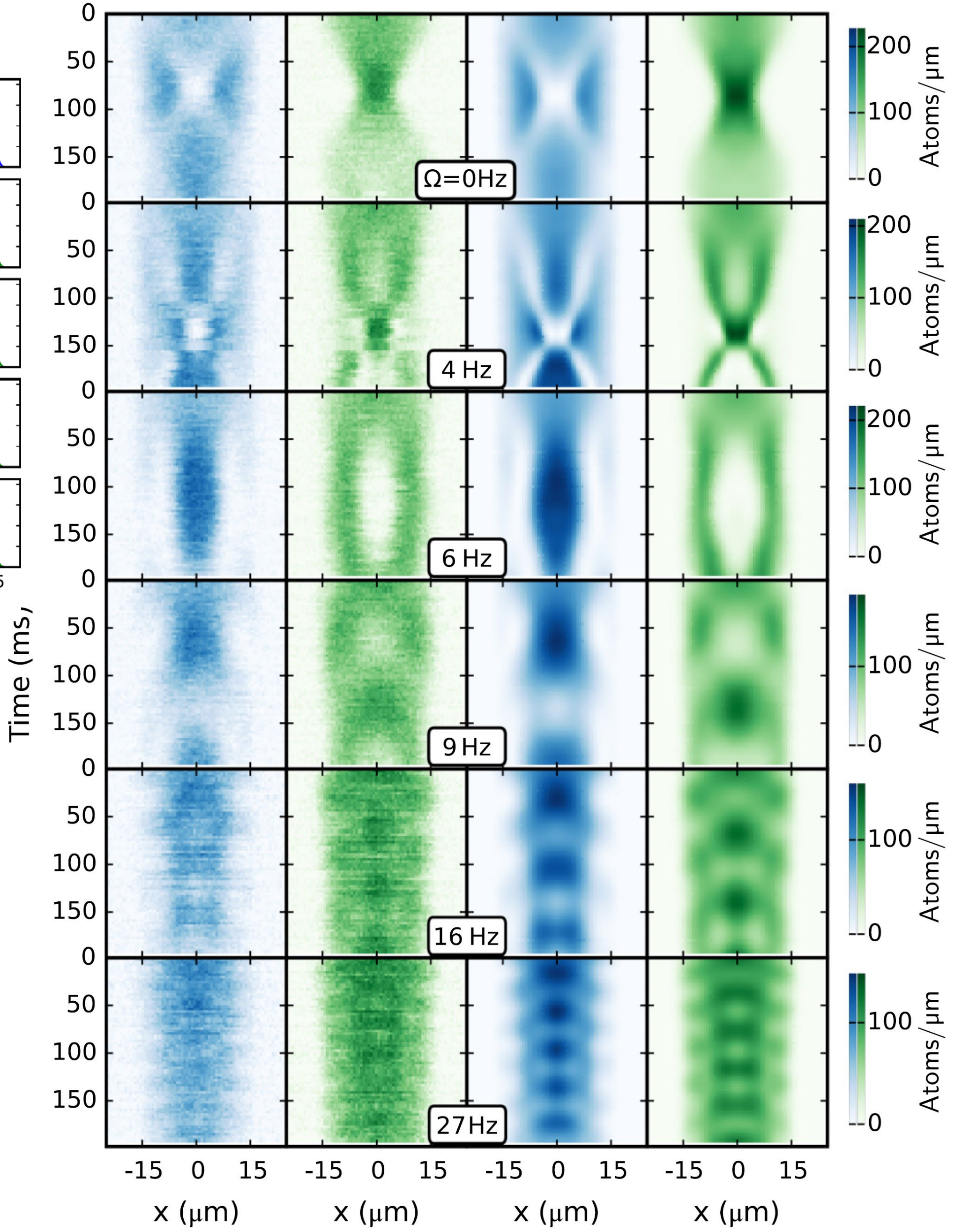


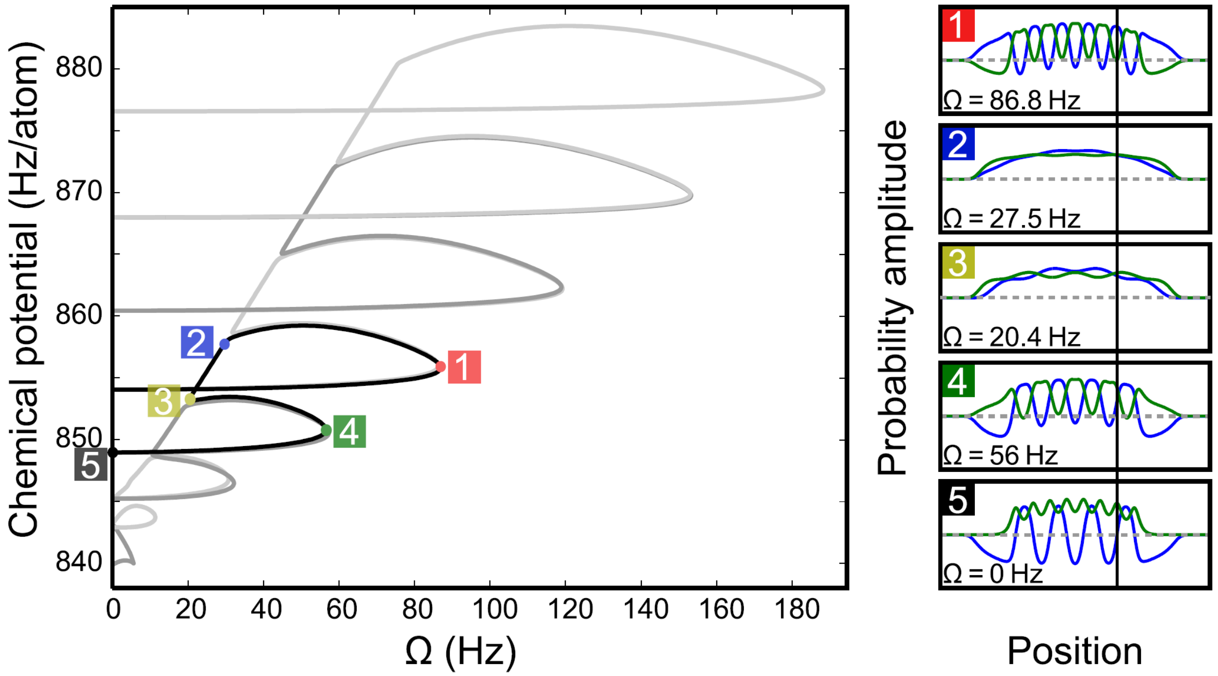
Nonlinear dressed states – applied mathematics

Panos Kevrikidis

PRA 92, 053614 (2015)







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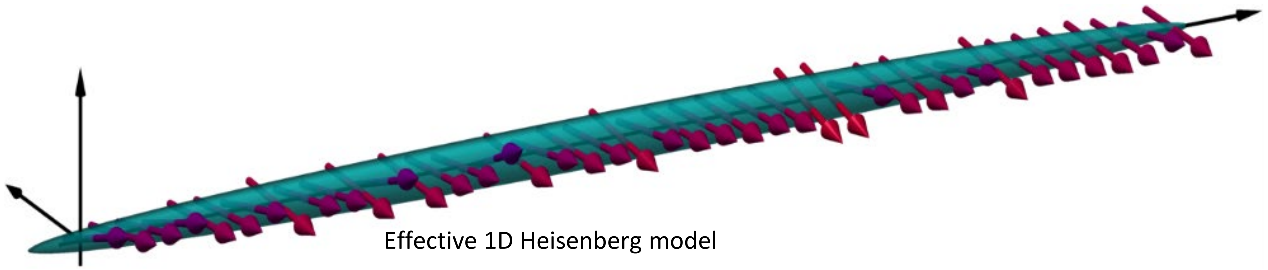

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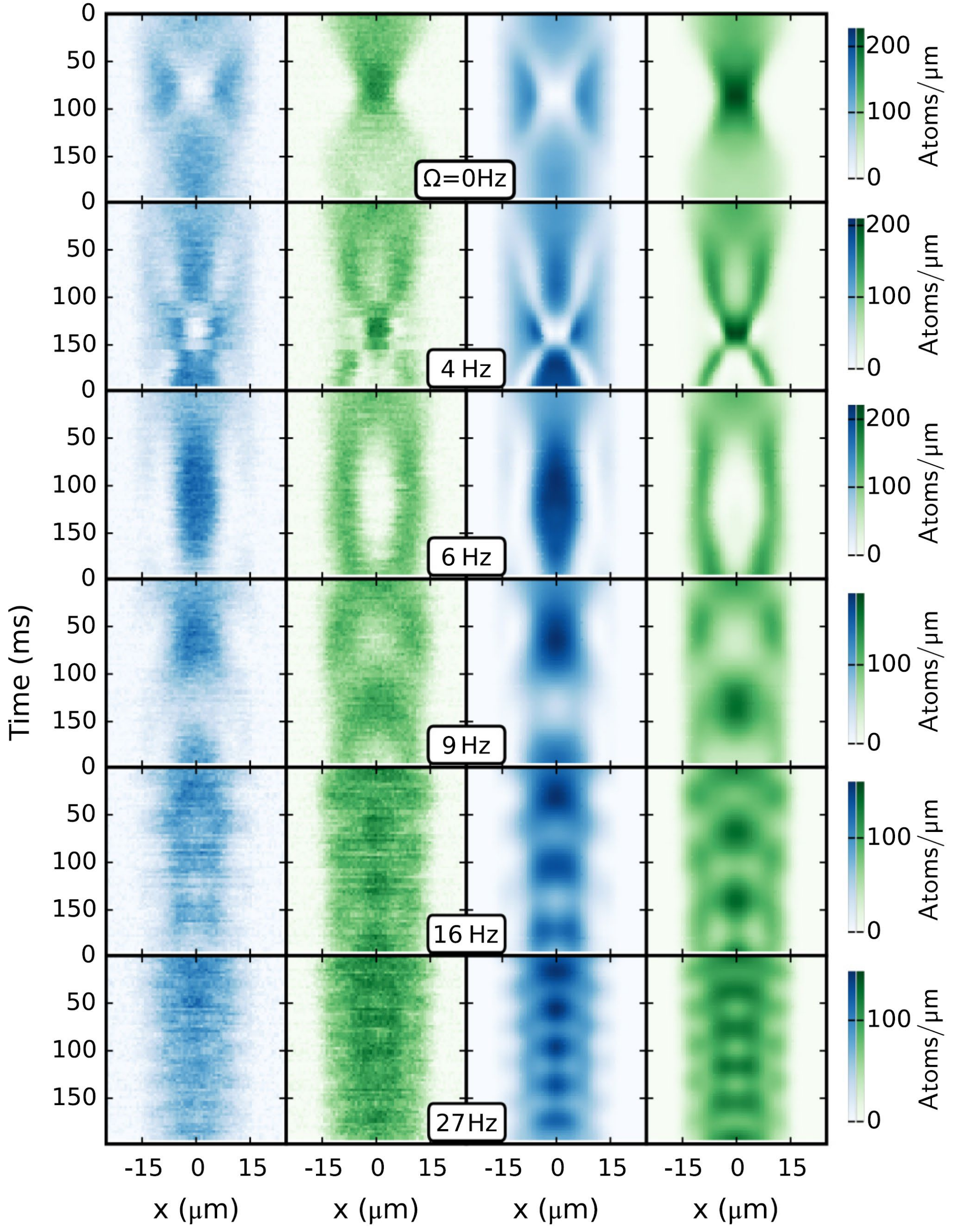
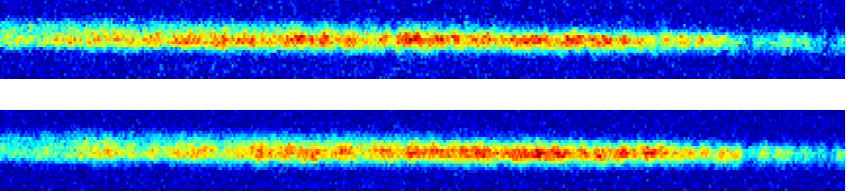
PRA 92, 053614 (2015)





Ginzburg criterium

$$J_x = 2\rho^{-1}\sqrt{\rho_\downarrow\rho_\uparrow}\cos\varphi$$
$$J_y = 2\rho^{-1}\sqrt{\rho_\downarrow\rho_\uparrow}\sin\varphi$$
$$J_z = \rho^{-1}(\rho_\downarrow - \rho_\uparrow)$$

$$\varphi = \varphi_\downarrow - \varphi_\uparrow$$
$$\phi_j = \sqrt{\rho_j}\exp(\mathrm{i}\varphi_j)$$

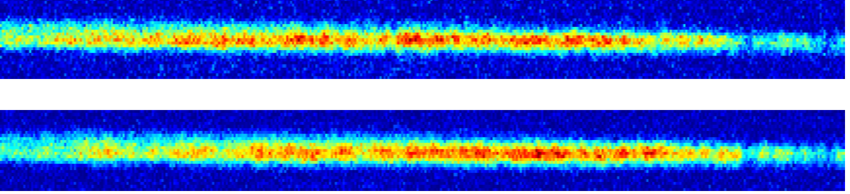
$$H_0 = \sum_{i=\downarrow,\uparrow}\int \mathrm{d}y\, \Phi_j^\dagger\Big[-\frac{\hbar^2}{2m}\partial_y^2 + V(y)\Big]\Phi_j,$$
$$H_{\mathrm{cpl}} = \frac{\hbar}{2}\int \mathrm{d}y\Big[\Omega\Big(\Phi_\downarrow^\dagger\Phi_\uparrow + \mathrm{h.c.}\Big) + \delta\Big(\Phi_\downarrow^\dagger\Phi_\downarrow - \Phi_\uparrow^\dagger\Phi_\uparrow\Big)\Big],$$
$$H_{\mathrm{int}} = \frac{1}{2}\sum_{i,j=\downarrow,\uparrow} g_{ij}\int \mathrm{d}y\,\Phi_i^\dagger\Phi_i\Phi_j^\dagger\Phi_j.$$

Rewritten in spin operators

$$H = \frac{1}{2}\int \mathrm{d}y\,\Big\{m^{-1}(\partial_y\sqrt{\rho})^2 + \frac{\rho}{4m}|\partial_y\mathbf{J}|^2 + \rho(V + mv_{\mathrm{eff}}^2)$$
$$+ g\rho^2 + \frac{g\rho^2}{2}(\alpha - 1)\left[1 - (J_z)^2\right] + \Omega\rho J_x + \delta\rho J_z\Big\}.$$

Assuming constant density

$$\mathcal{H} = \rho\big[|\partial_y\mathbf{J}|^2/4 + v_{\mathrm{eff}}^2 + \Omega J_x - \Omega_c J_z^2/2\big]/2$$



Ginzburg criterium

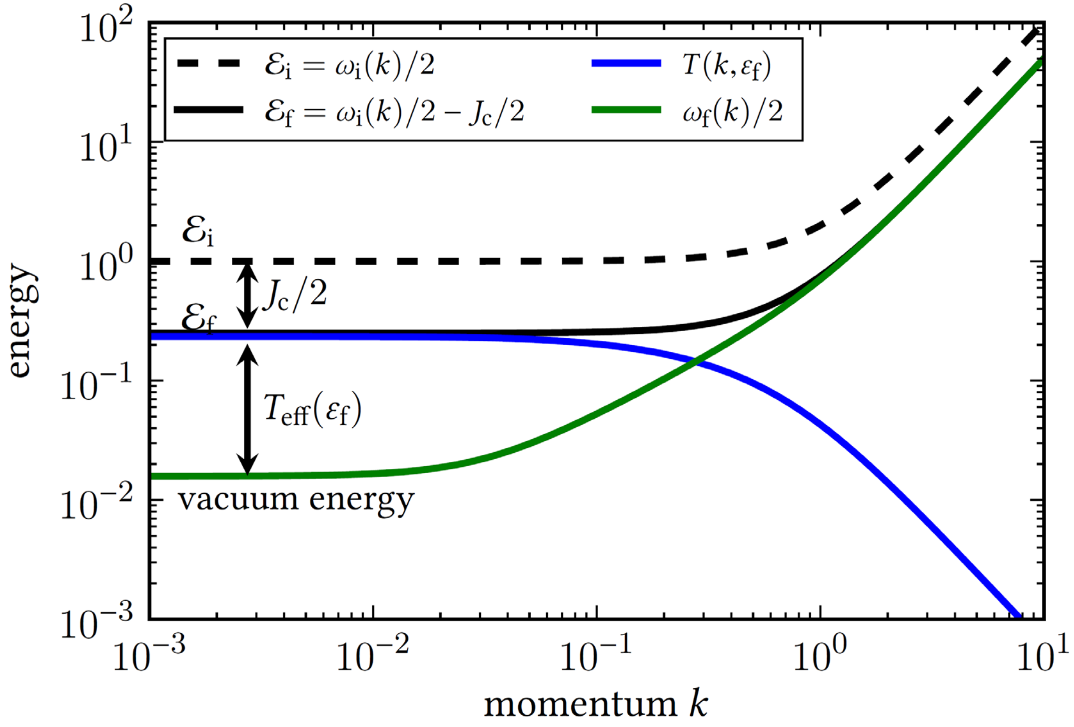
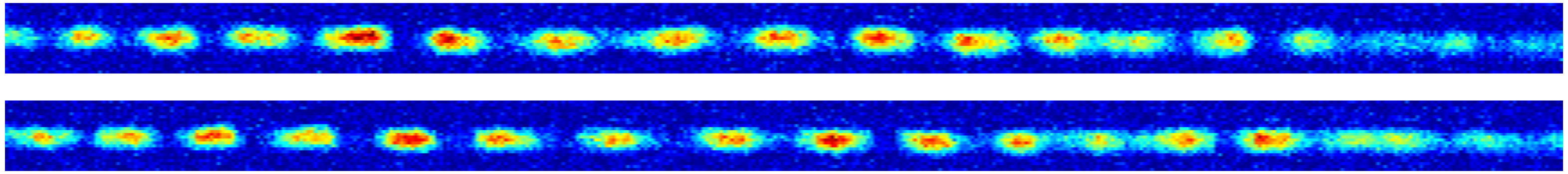


Figure III.6: The figure illustrates the energetic configuration before and after the quench at the example of a quench to $\varepsilon = 0.001$, which leads to a thermal post-quench quasi-particle occupation. The infrared parts of the pre-quench energy spectrum (dashed black line), $\mathcal{E}_i$, which is identical to the pre-quench vacuum energy spectrum, the post-quench energy spectrum (solid black line), $\mathcal{E}_i$, the post-quench vacuum energy spectrum (solid green line), and, finally, the resulting mode temperatures (solid blue line). Details are discussed in the main text.

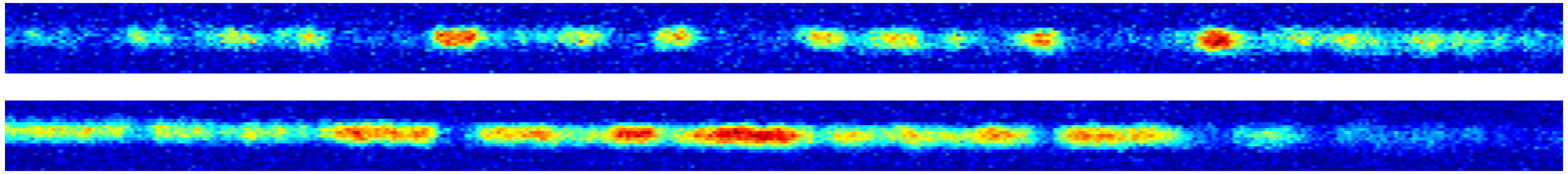
Finite time quenches

$$\xi(\hat{t}) = \xi_0(\tau_Q/\tau_0)^{\nu/(1+\nu z)}$$

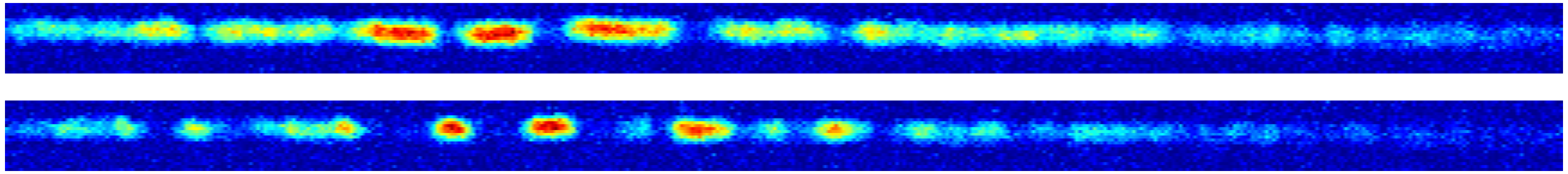
$\tau_Q = 1ms$



$\tau_Q = 5ms$



$\tau_Q = 10ms$



$\tau_Q = 30ms$