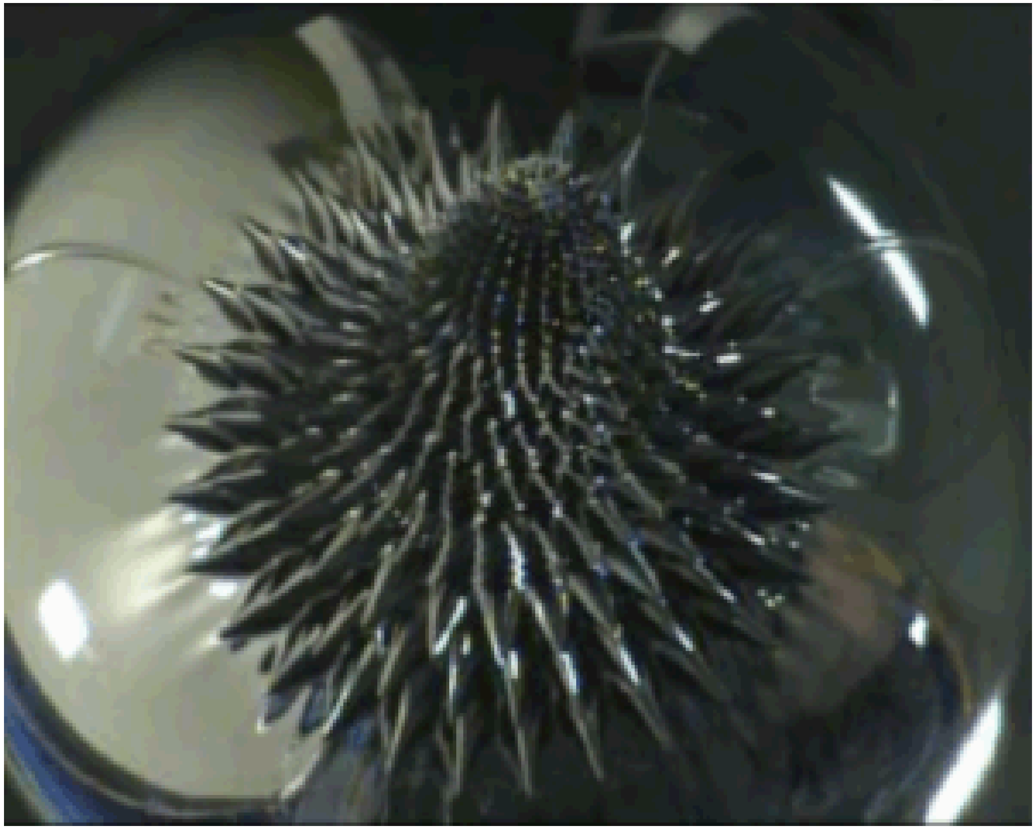
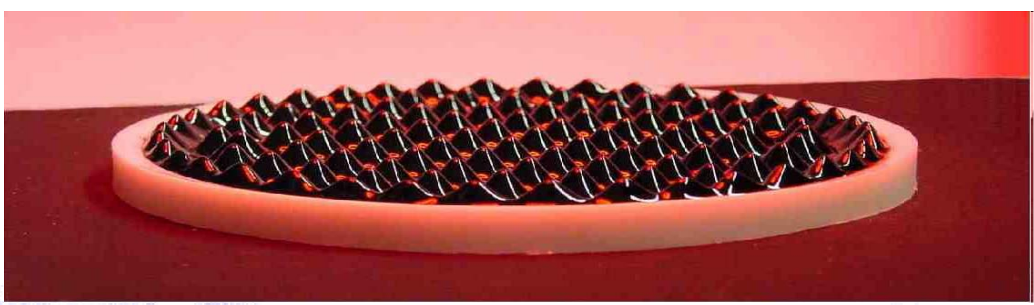
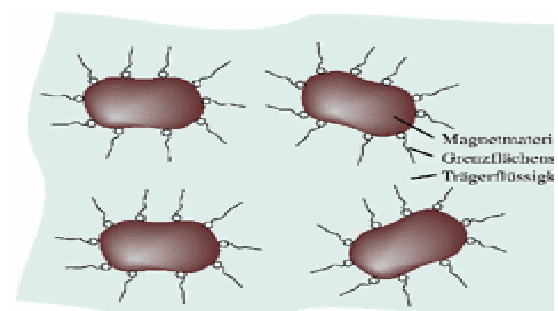
Fluids with dipolar coupling







- **Rosensweig instability**

M. D. Cowley and R. E. Rosensweig, J. Fluid Mech. **30**, 671 (1967)

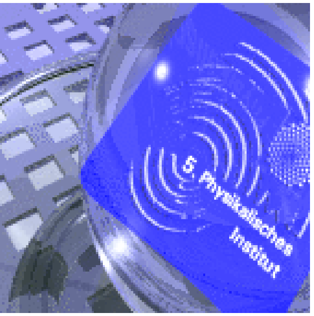
Deutsche Forschungsgemeinschaft DFG

CO.CO.MAT
SFB/TRR21 – STUTTGART, ULM, TÜBINGEN

LANDESSTIFTUNG Baden-Württemberg

STUTTGART

FerMix 2009 Meeting, Trento



A "Quantum Ferrofluid"
Experiments with dipolar BECs

Jonas Metz, Ashok Mohapatra, Stefan Müller,
Thierry Lahaye, Axel Griesmaier, Tilman Pfau

Universität Stuttgart, Germany
5. Physikalisches Institut

Dipolar Gases Team

Members 2009:

Ashok Mohapatra
Jonas Metz
Stefan Müller
Yong Wan
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Tilman Pfau

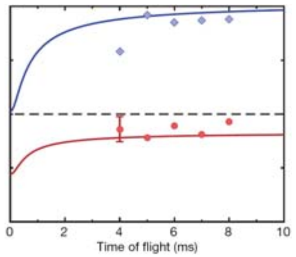
Former members:

Thierry Lahaye
Marco Fattori
Jürgen Stuhler
Tobias Koch
Bernd Fröhlich

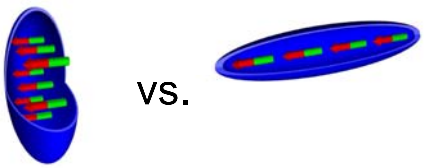
Theory: L. Santos, S. Giovanazzi, M. Ueda,Y. Kawaguchi, H. Saito

Outline

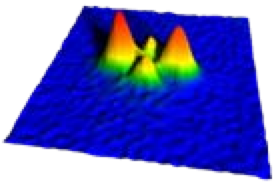
- **A quantum ferrofluid**
  Nature **448**, 672 (2007)



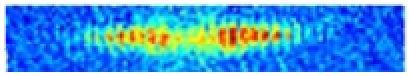
- **Stability of a dipolar condensate**
  Nature Physics **4**, 218 (2008)



- **d-wave collapse**
  Phys. Rev. Lett. **101**, 080401 (2008),



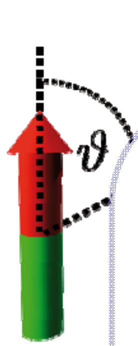
- **Coherence**
  New. J. Phys. *(2009)*



Interactions of ultra cold atoms

dipole-dipole interaction

- long range
- anisotropic



with atoms (magne

Cr: Stuttgart (2005),

Alkalis: Firenze (20

(2008)

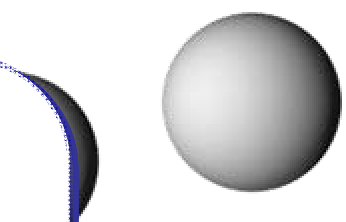
heteronuclear mole

no condensates yet but many to come

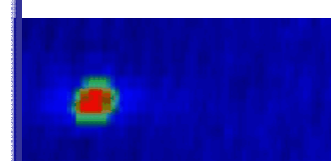
e.g. Boulder, Heidelberg

contact interaction

- short range
- isotropic

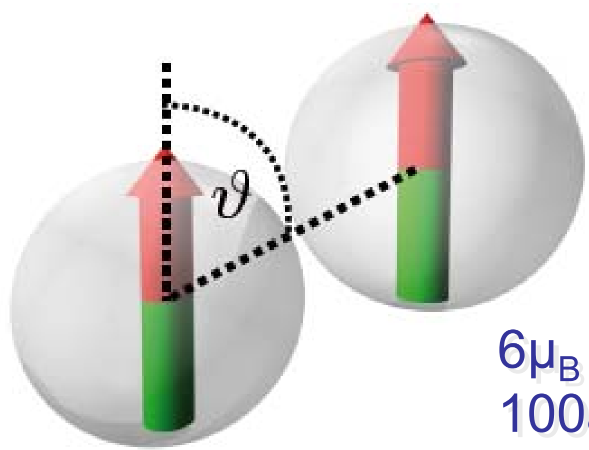


e scattering



le Group, MIT

chromium atoms



$6\mu_B$

$100a_0$

New effects in dipolar quantum gases

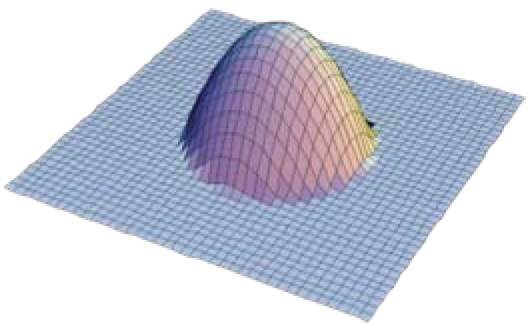
- long range
  - **Structured superfluid phases**
  - «**checkerboard**» (isolating, one atom every second site)
    e.g.. K. Góral *et al.*, PRL **88**, 170406 (2002).
  - **Tunneling** dynamics & ground state in **double/triple well** potentials
- anisotropy
  - **roton** in the excitation spectrum
    L. Santos *et al.*, PRL **90**, 250403 (2003).
  - new equilibrium **shapes**
    S. Ronen, D. C. E. Bortolotti, and J. L. Bohn, PRL **98**, 030406 (2007);
    O. Dutta and P. Meystre, PRA **75**, 053604 (2007).
  - multidimensional **solitons**
    P. Pedri and L. Santos, PRL **95**, 200404 (2005);
    I. Tikhonenkov *et al.* PRL **100,** 090406 (2008).
- large spin S=3
  - Rich **phase diagram** for a S=3 spinor condensate
    L. Santos and T. Pfau, PRL. **96**, 190404 (2005)
    L. Santos, M. Fattori, J. Stuhler, T. Pfau, PRA **75**, 053606 (2007)

Review: T Lahaye et al. *arXiv:0905.0386v1* (2008)

Dipolar interactions in a condensate

Gross-Pitaevskii equation for the order parameter:

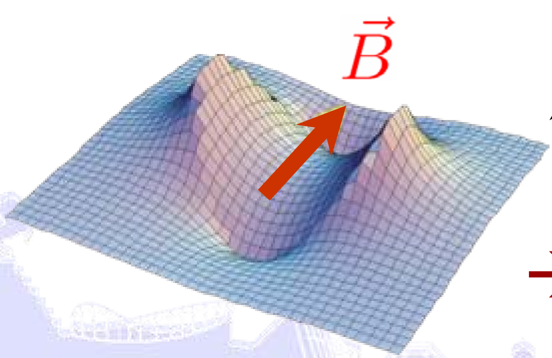
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\triangle\psi + \left(V_{\text{ext}} + g|\psi|^2 + \Phi_{\text{dd}}(\boldsymbol{r},t)\right)\psi$$



polarized sample

$$\Phi_{\text{dd}}(\boldsymbol{r},t) = \int |\psi(\boldsymbol{r}',t)|^2\, U_{\text{dd}}(\boldsymbol{r}-\boldsymbol{r}')\,\mathrm{d}^3r'$$

$$U_{\text{dd}}(\boldsymbol{r}) = \frac{\mu_0\mu^2}{4\pi}\frac{1-3\cos^2\theta}{r^3}$$

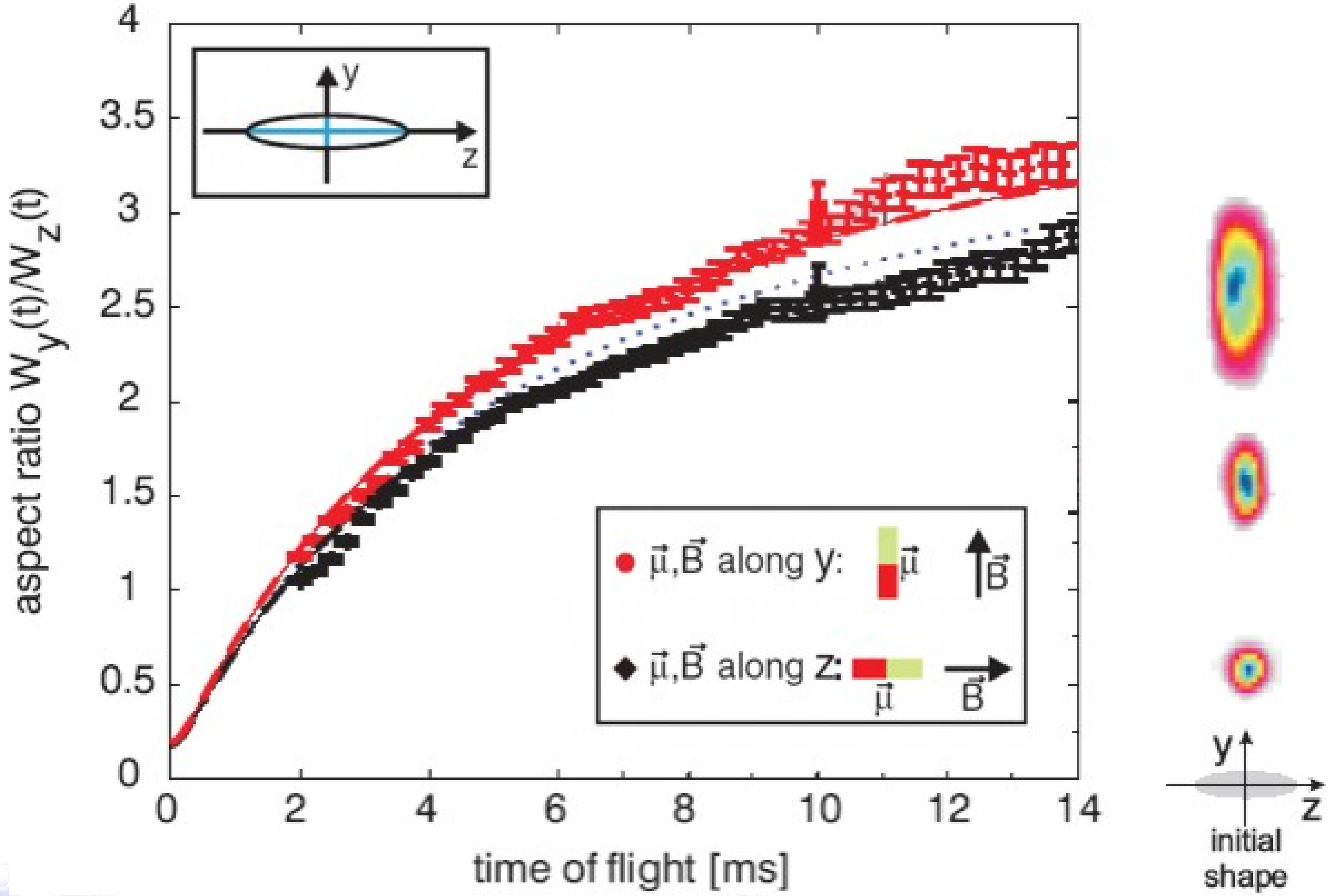


Dipolar interaction:
NON-LOCAL & ANISOTROPIC term

→ elongation of a polarized dipolar condensate

perturbative effect of DDI

Expansion of a dipolar BEC



PRL **95**, 150406 (2005), PRL **97**, 250402 (2006)

Energy scales connected with dd-interactions

Estimate for typical BECs

$n \sim 10^{15}\ cm^{-3} \rightarrow r \sim 100\ nm$

electric

heteronuclear molecules

in their ro-vib ground state

(dipolar moment & stability)

$d \approx 1$Debye

$U_{dd} \approx 10$ mK

magnetic

Chromium atoms

$\mu \approx 6\mu_B$

$U_{dd} \approx 35$ nK

Relative strength of the dipole-dipole interaction

- dipolar parameter

$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 m}{12\pi\hbar^2 a}$$

dipolar interaction ($\mu_0 \mu^2 m$)

contact interaction (a)

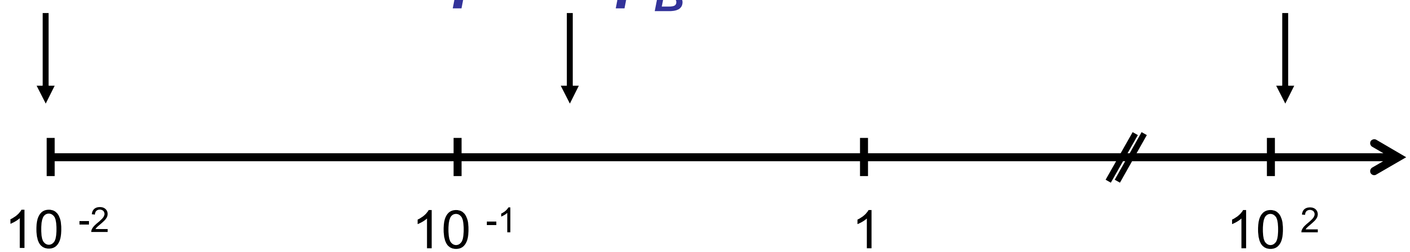
Spherical condensate becomes unstable for $\varepsilon_{dd} > 1$.

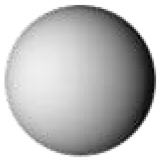
alkalis

Chromium

$\mu = 6\ \mu_B$

heteronuclear molecules ~1Debye





$\varepsilon_{dd} = 0.159$

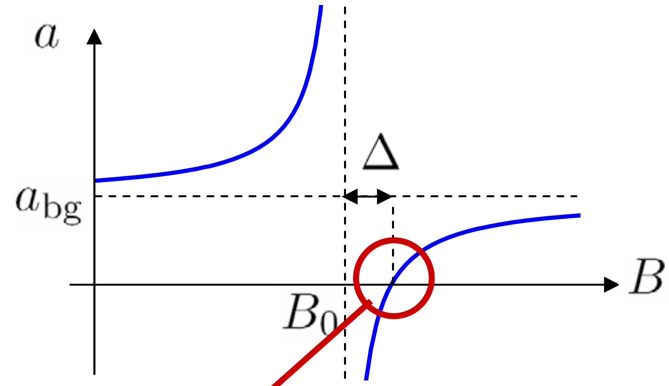
PRL **97**, 250402 (2006)

How to go beyond perturbative effects?

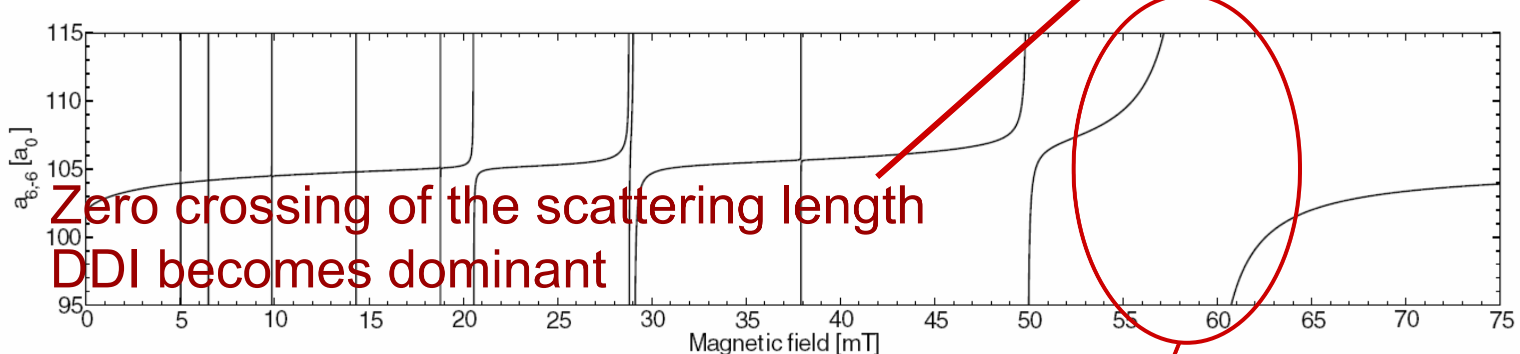
Feshbach tuning of the contact interaction

- Feshbach resonances: *a* depends on external magnetic field *B*

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



Feshbach resonances in Chromium [PRL **94**, 183201, (2005)]



Zero crossing of the scattering length

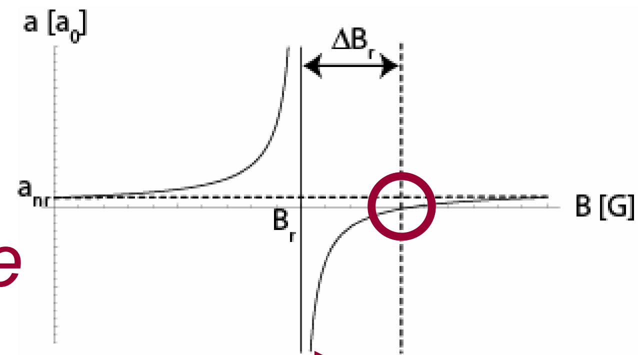
DDI becomes dominant

Broadest resonance: 589.1 G (Δ = 1.4 G):

Control of the magnetic field on **~10^{-5}** level needed!

Strength of the dipole-dipole interaction

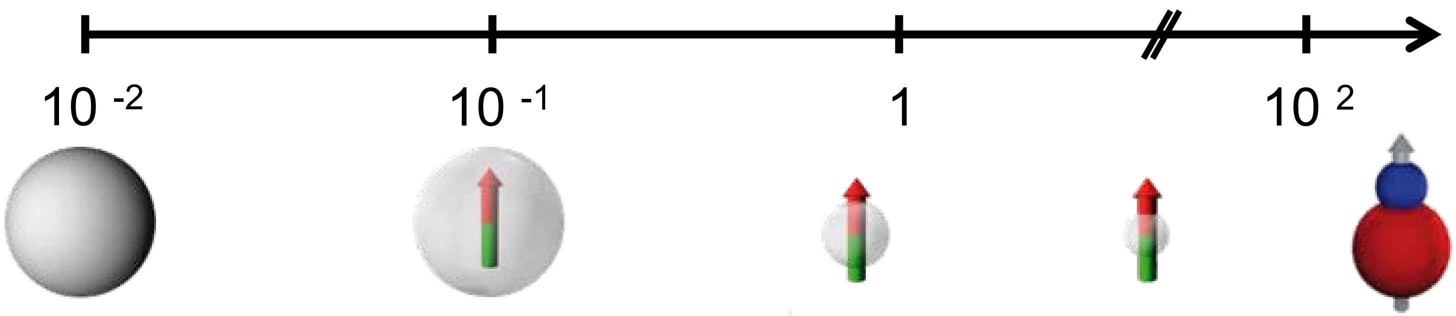
Feshbach resonance



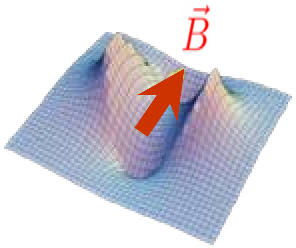
alkalis

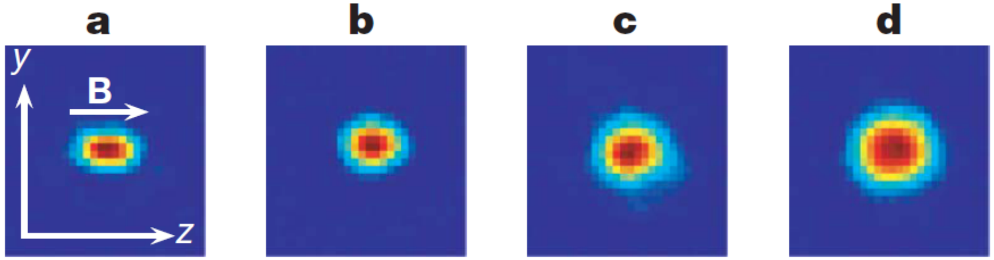
Chromium
$\mu = 6\,\mu_B$

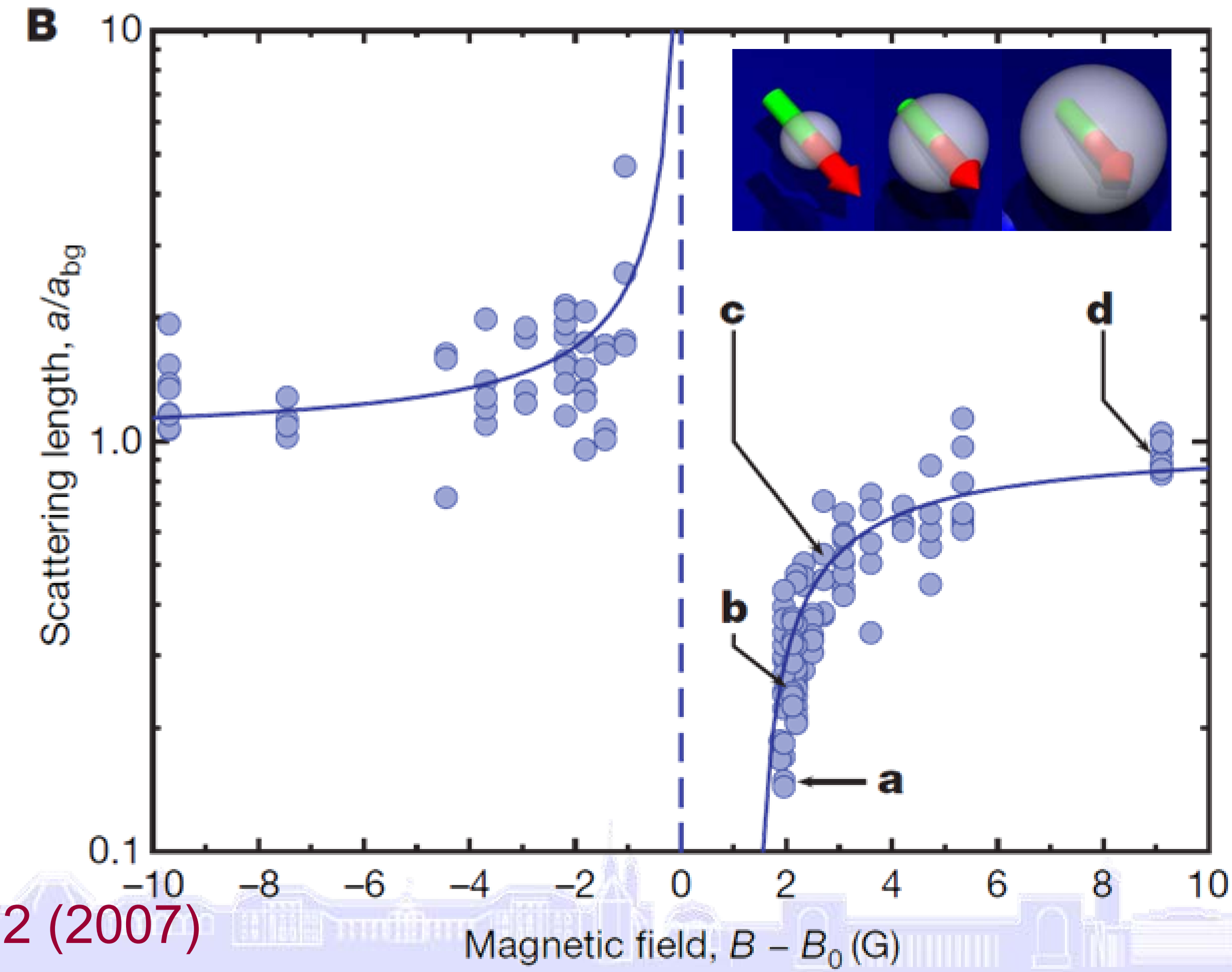
heteronuclear molecules ~1Debye



Feshbach tuning of ε_{dd}

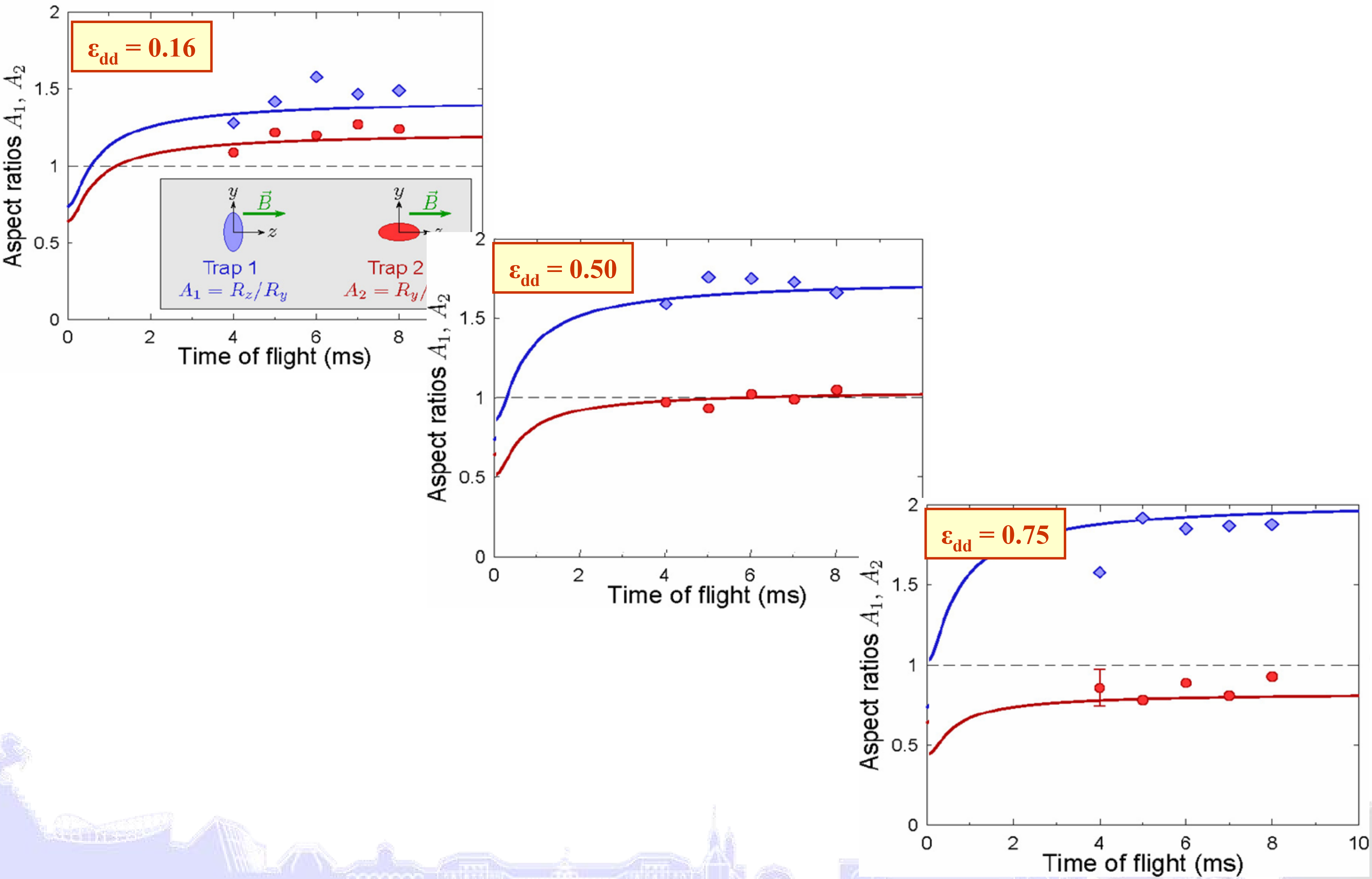




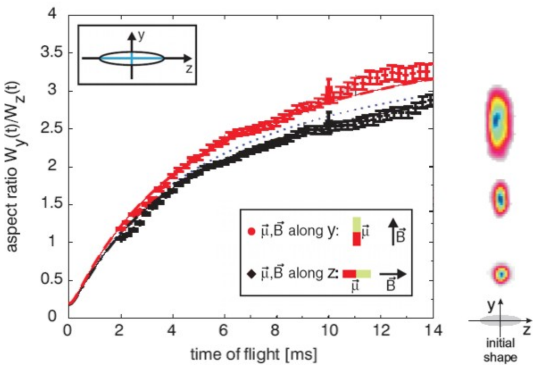


Nature **448**, 672 (2007)

Time of flight experiments for various ε_{dd}



Strong dipolar effect ε_{dd} ~1



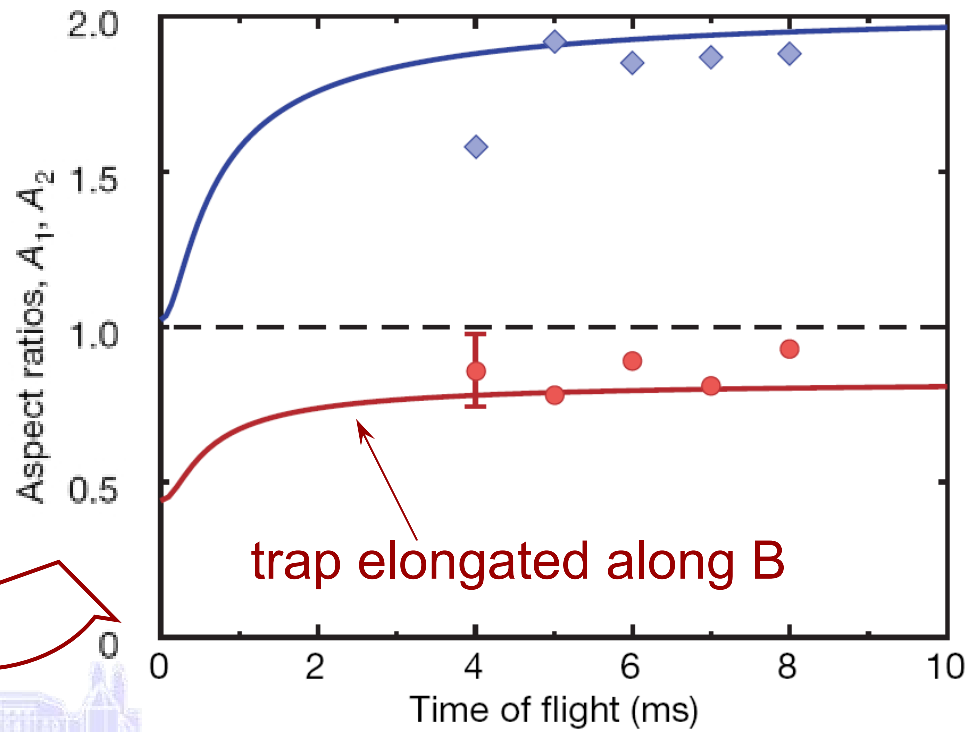
$\varepsilon_{dd} \approx 0.15$

perturbative effect of DDI

$\varepsilon_{dd} = 0.75$

strong dipolar effect

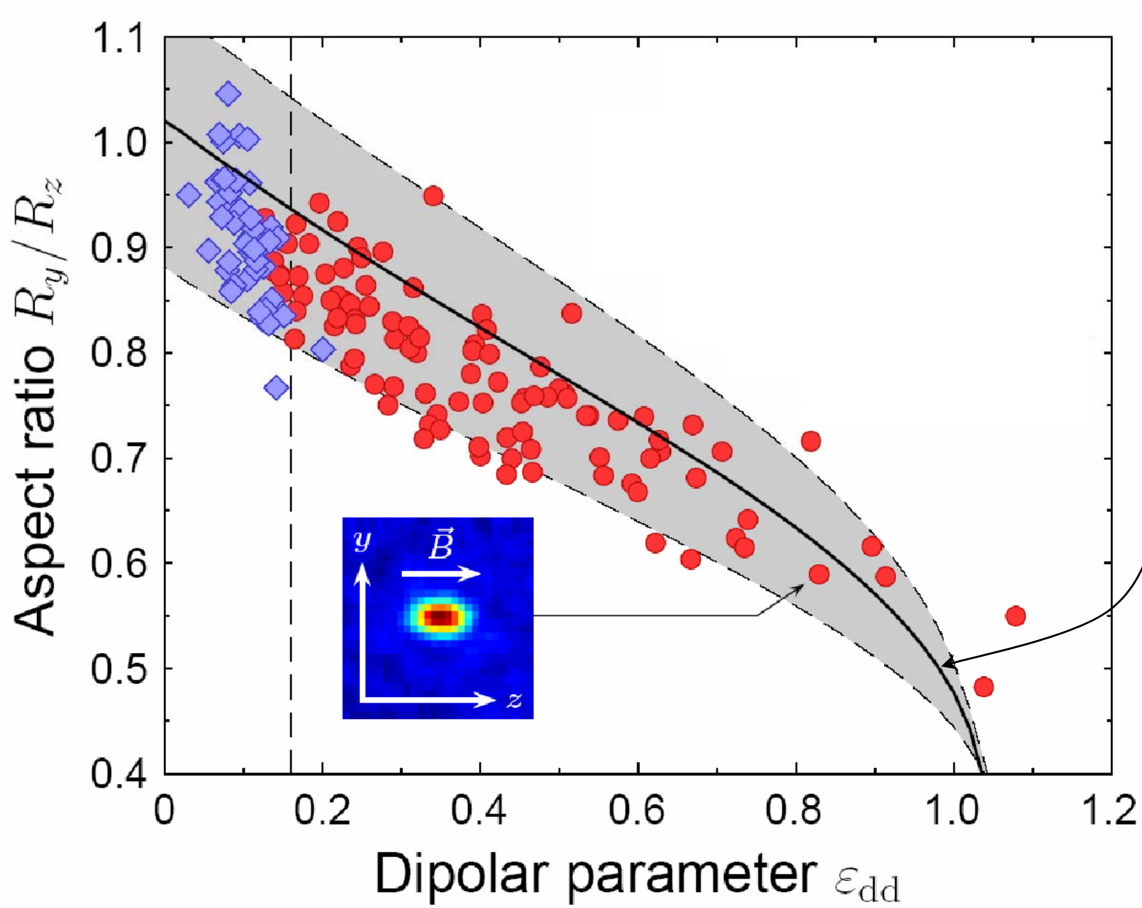
Inhibits the inversion of ellipticity!



Nature **448**, 672 (2007)

Aspect ratio as a function of ε_{dd}

- **Dipolar interactions:** elongation al$\vec{B}$g



Prediction of the hydrodynamic equations (no adjustable parameter)

Nature **448**, 672 (2007)

How to go beyond $\varepsilon_{dd} \sim 1$?

→ Stability of a condensate

with partially *attractive* interactions?

Stabilzation of a dipolar condensate

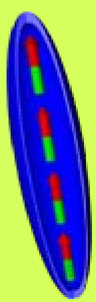
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\triangle\psi + \left(V_{\rm ext} + g|\psi|^2 + \Phi_{\rm dd}(\boldsymbol{r},t)\right)\psi$$

polarized sample

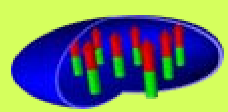
$$U_{\rm dd}(\boldsymbol{r}) = \frac{\mu_0\mu^2}{4\pi}\frac{1-3\cos^2\theta}{r^3}$$

„*Spherical* condensate becomes unstable for $\varepsilon_{dd} > 1$."

geometry

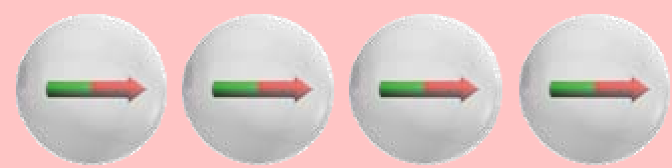


λ < 1
mainly attractive
unstable



λ > 1
mainly repulsive
stable

contact interaction



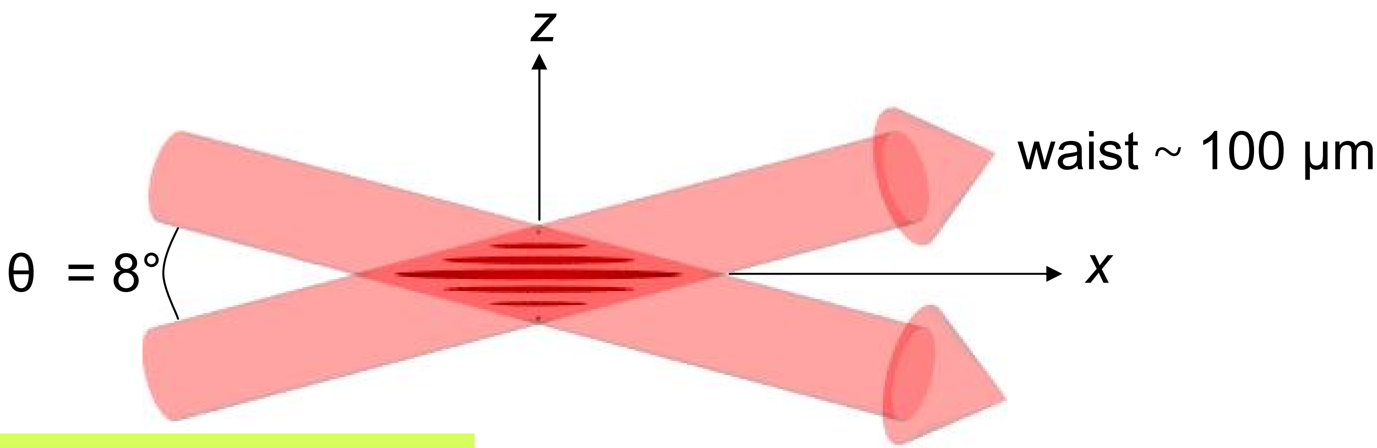
stable but small ε_{dd}

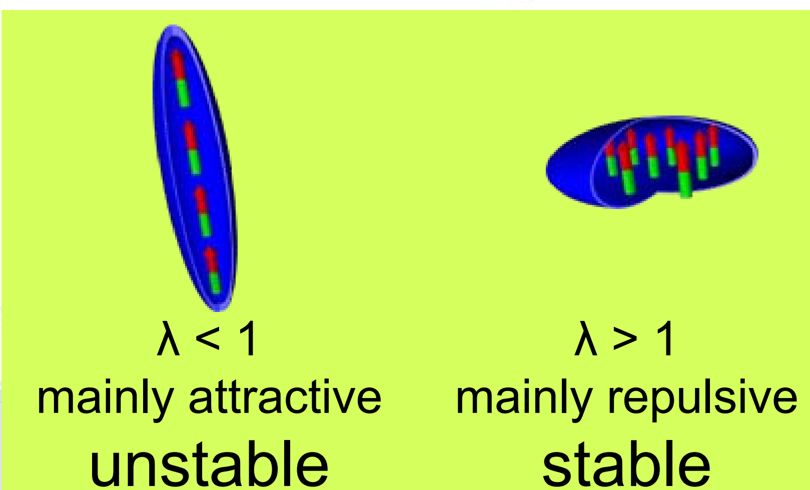
unstable

Experimental setup

How to vary the trap aspect ratio?

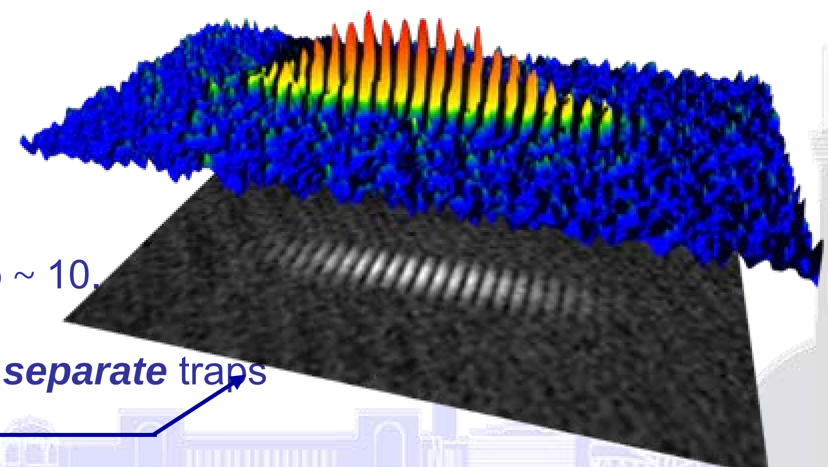
► Superimpose an optical lattice onto the ODT





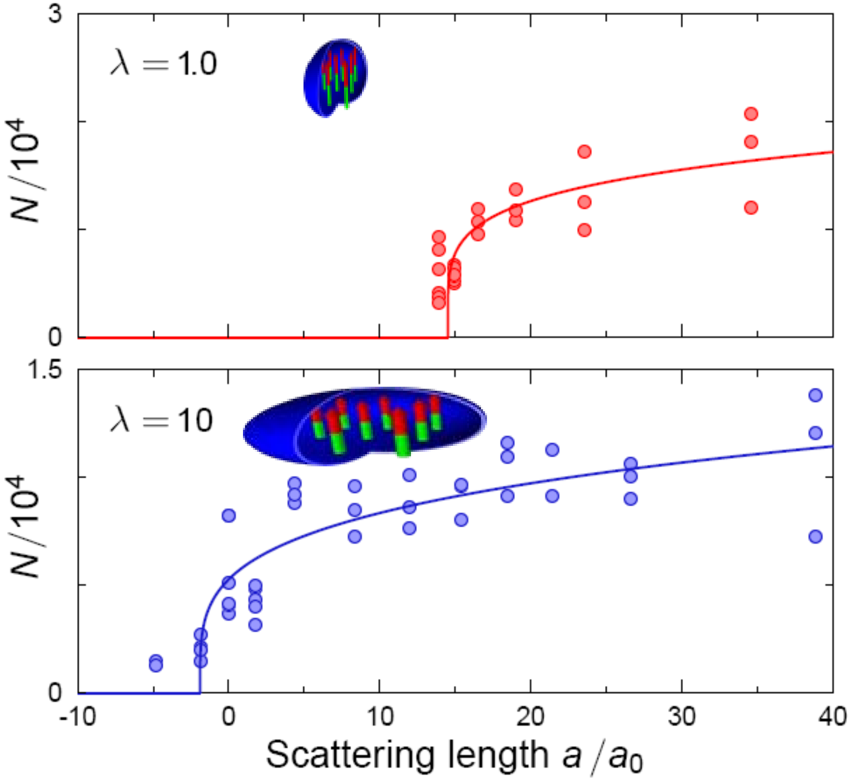
lattice) to ~ 10,

› BECs in ***separate*** traps



A purely dipolar quantum gas

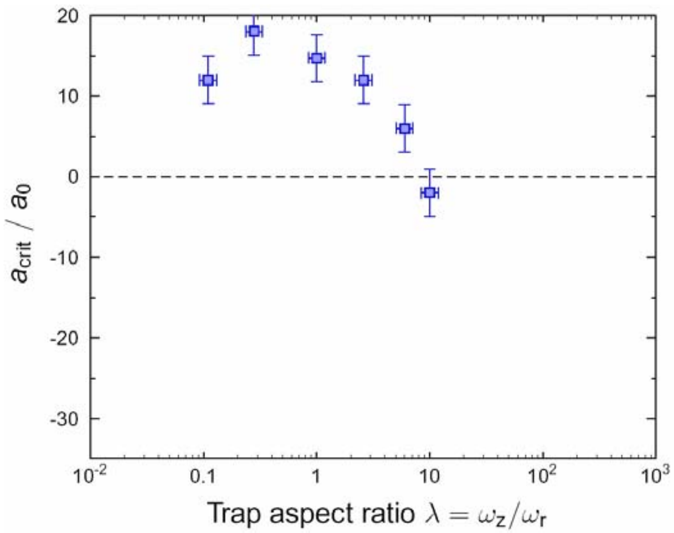
(i) Create a condensate in a trap with aspect ratio λ
(ii) Reduce the scattering length a



For both traps:

$$\bar{\omega} = (\omega_\rho^2 \omega_z)^{1/3}$$

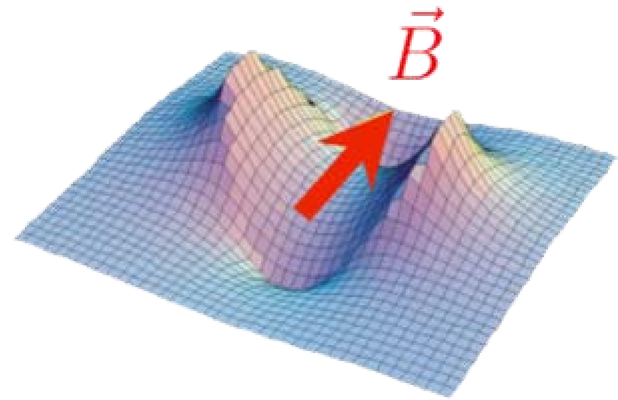
$$\simeq 2\pi \times 800\,\mathrm{Hz}$$



A condensate in an oblate trap is more stable!

Nature Physics **4**, 218 (2008)

Stability criterion with dipole-dipole interaction



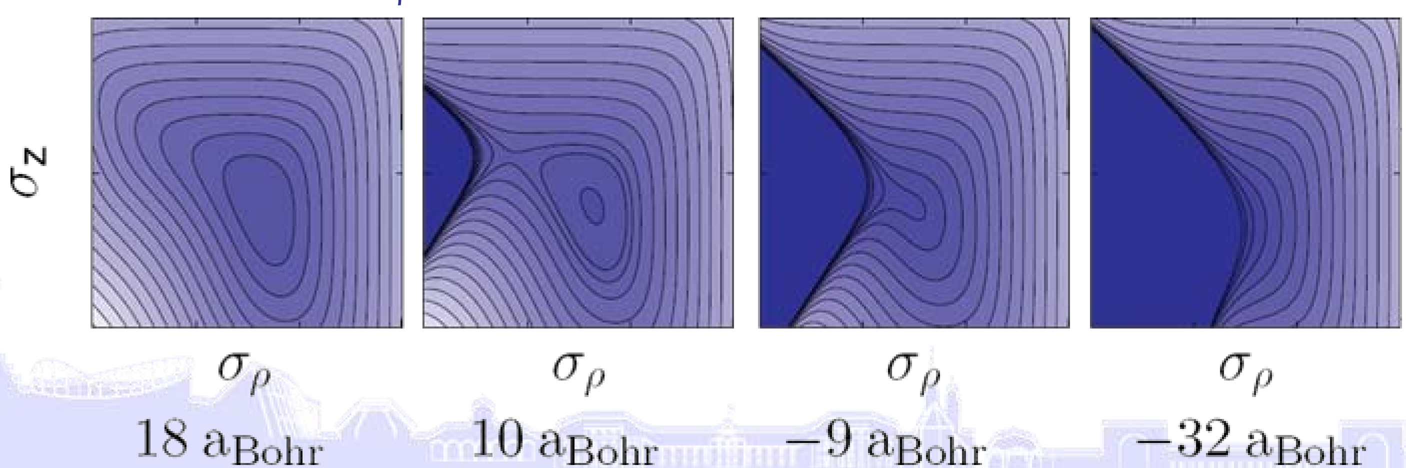
- Gaussian Ansatz:

$$\Phi(\rho, z) \propto \left(\frac{1}{\sigma_\rho^2 \sigma_z}\right)^{1/2} \exp\left[-\frac{\rho^2}{2\sigma_\rho^2} + \frac{z^2}{2\sigma_z^2}\right]$$

- Gross-Pitaevskii energy functional:

$$E[\Phi] = \int d^3r \left[\mathrm{kin.} + \mathrm{trap} + \underbrace{\mathrm{contact} + U_{\mathrm{dd}}}_{\propto \frac{1}{\sigma_\rho^2 \sigma_z}\left[\frac{1}{\epsilon_{\mathrm{dd}}} - f\left(\frac{\sigma_\rho}{\sigma_z}\right)\right]}\right]$$

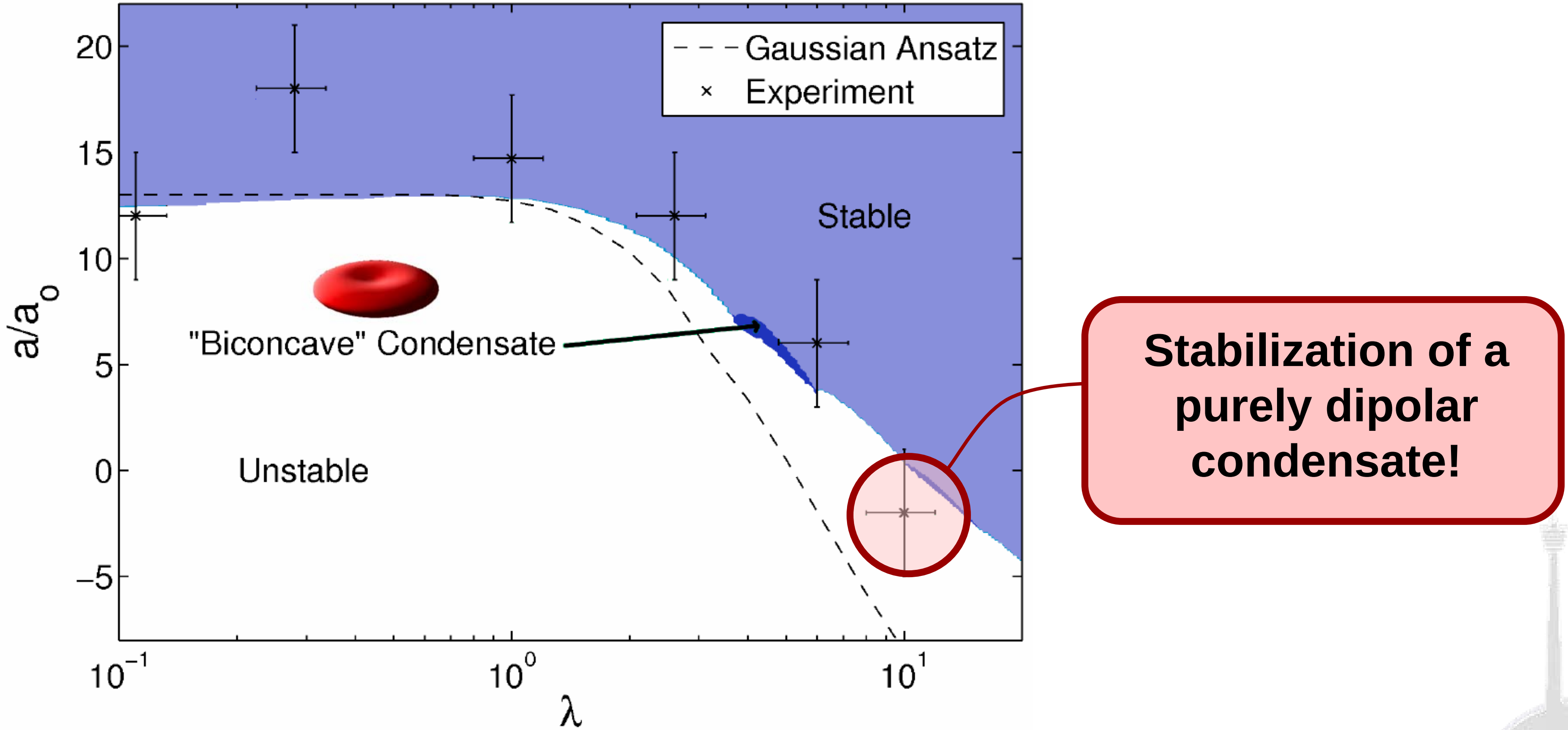
- the local minimum vanishes for $a \leq a_{crit}$:
(example $\lambda = \omega_z/\omega_\rho = 10$)



Exact stability diagram

- a_{crit} as a function of the trap aspect ratio λ (N = 20,($\bar{\omega} \simeq 2\pi \times 800\,\mathrm{Hz}$)

Full solution of the 3D GPE (John Bohn's group, JILA)

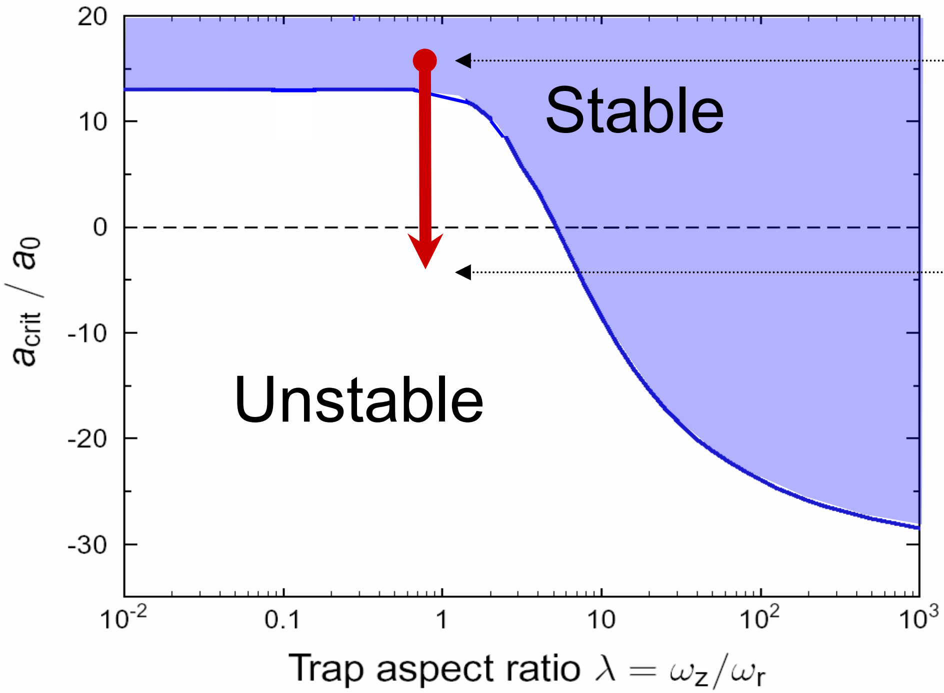


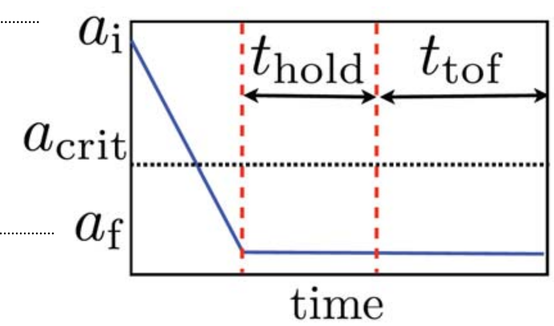
Nature Physics **4**, 218 (2008)

How does the cloud collapse ?

Initiating the collapse

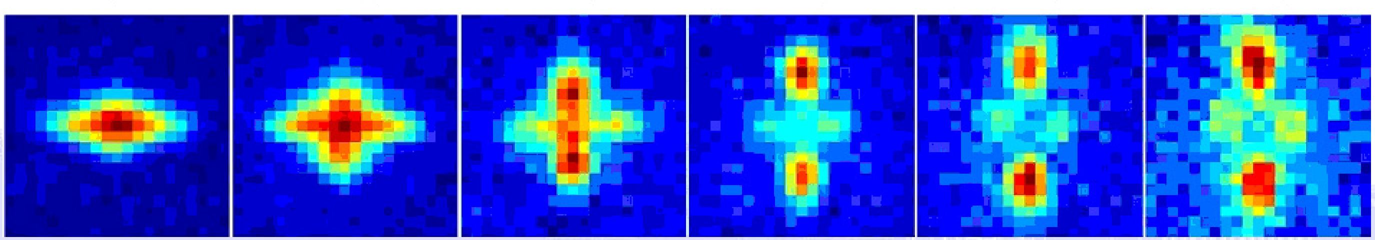
Fast quench of *a* to $a_f < a_{crit}$.





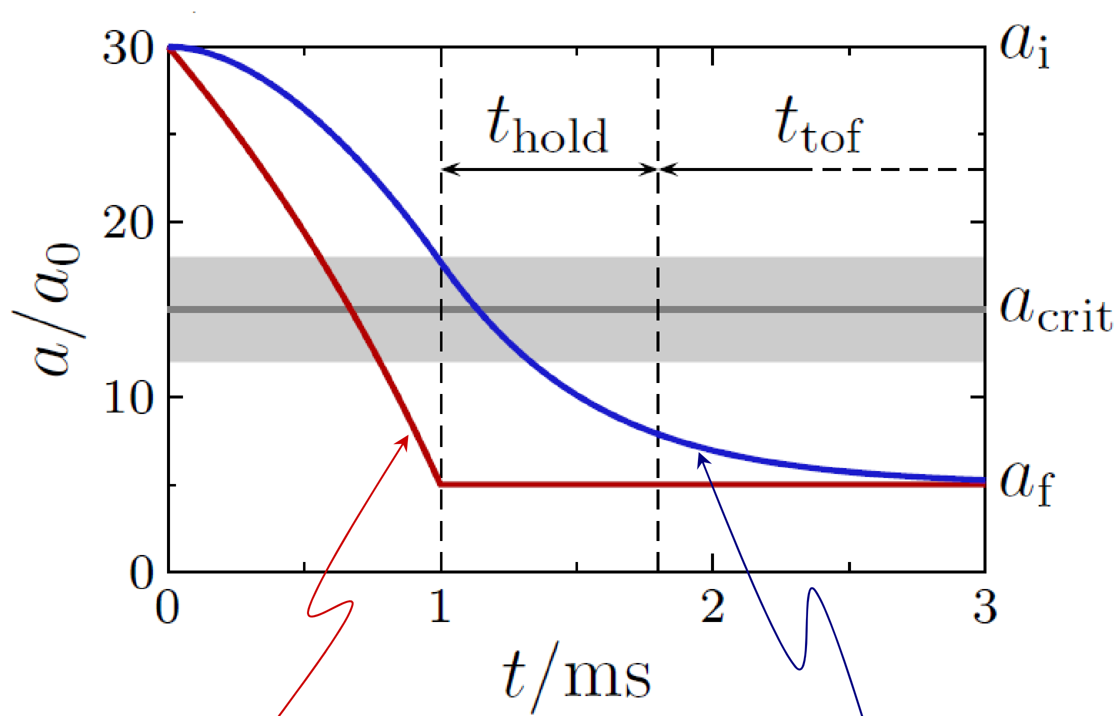
Vary t_{hold}

0 µs 100 µs 200 µs 300 µs 400 µs 500 µs



Theory vs. practice

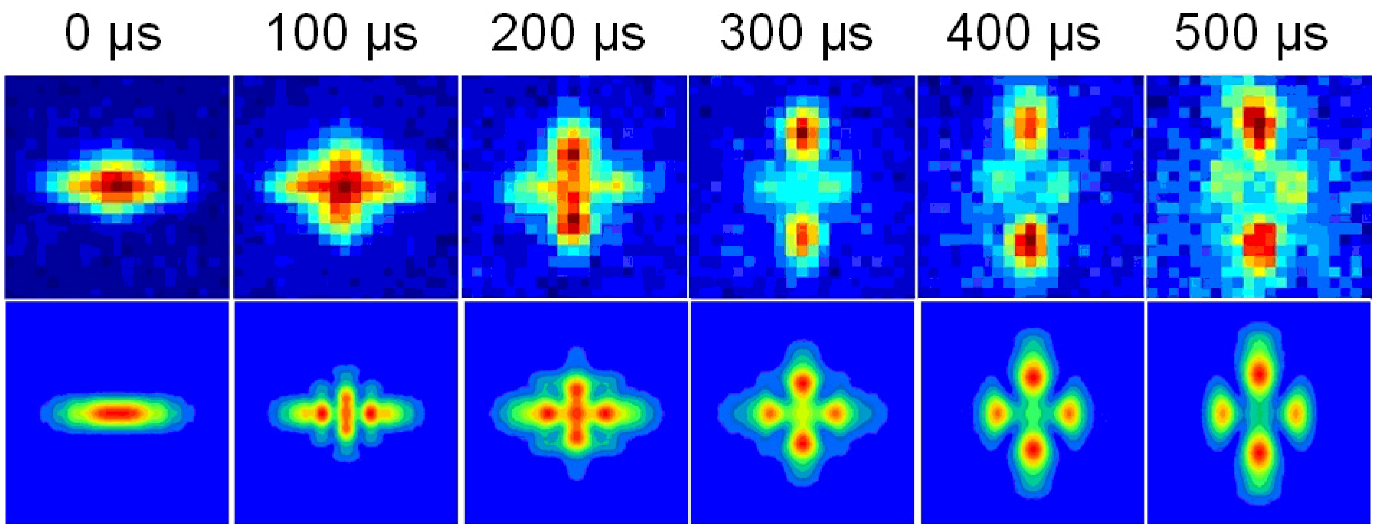
Eddy currents determine time dependence



Setpoint (current in the coils)

Actual value of *a* (due to eddy currents)

Dipolar collapse (theory vs. exp.)

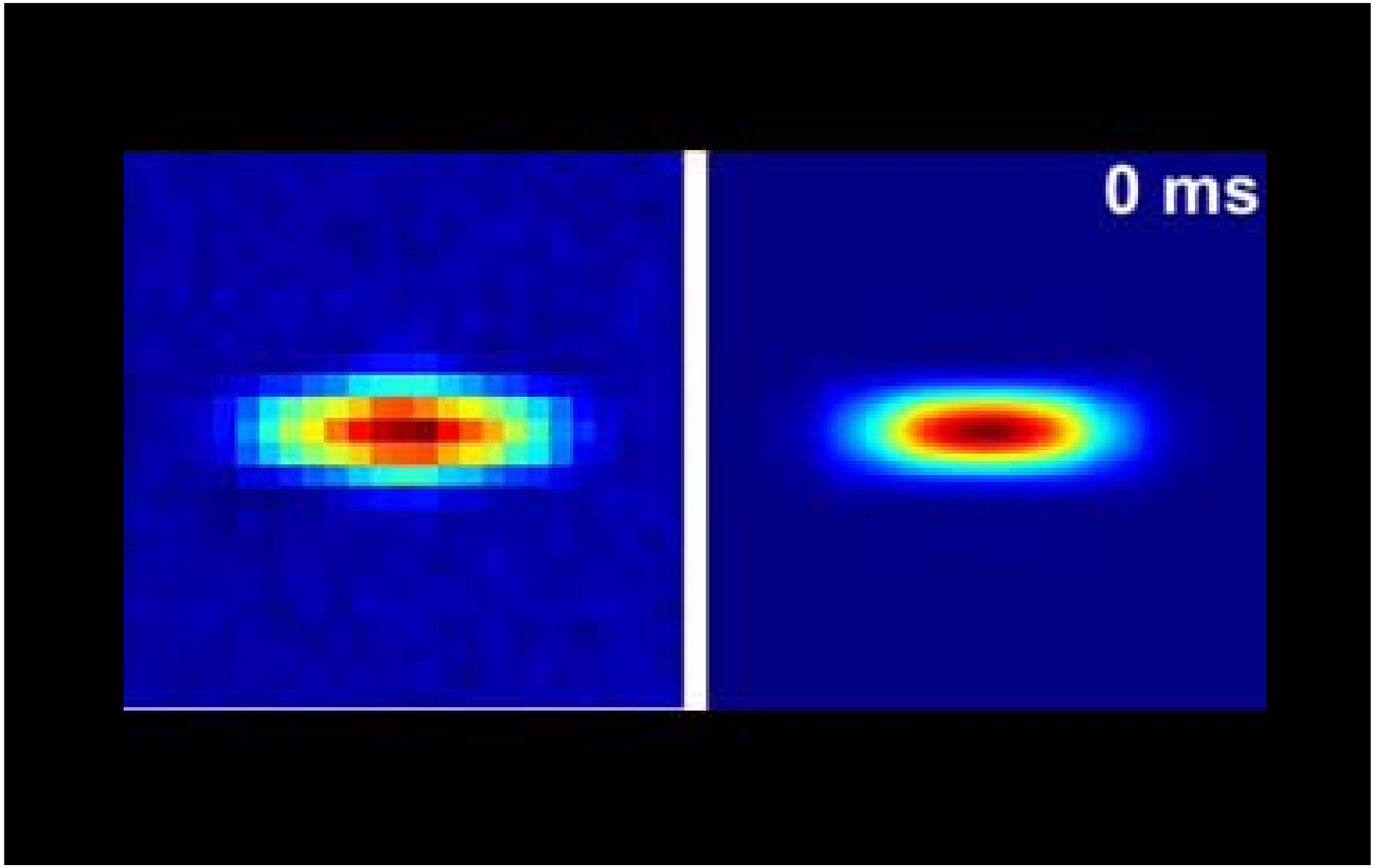


Phys. Rev. Lett. ***101****, 080401 (2008)*

Theory by Masahito Ueda‘s group, Tokyo

No free parameters …
but correct evolution of the magnetic field!

Experiment vs. Simulation

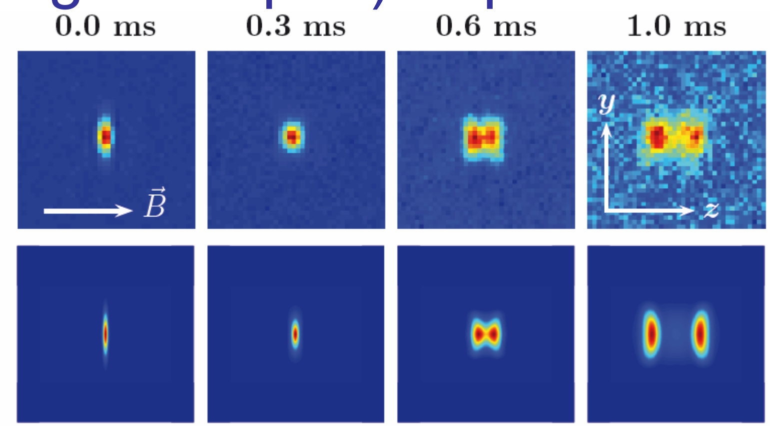


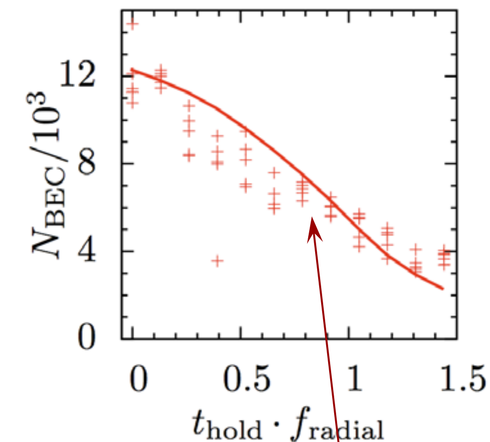
Experiment GPE Simulation

Dynamics in different trap geometries

- prolate (cigar shaped) trap

$\lambda \simeq 0.12$



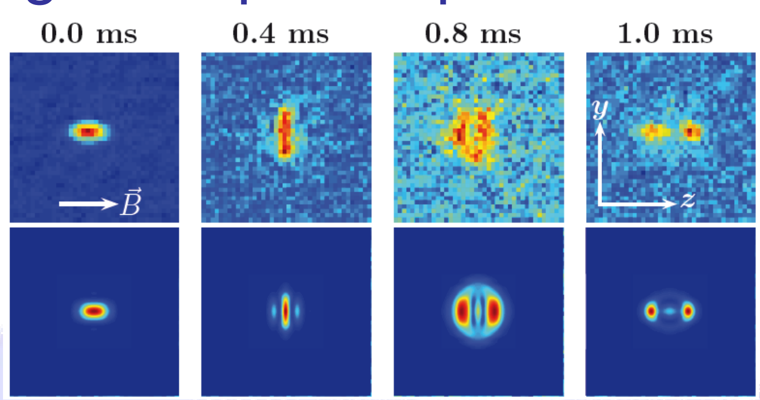


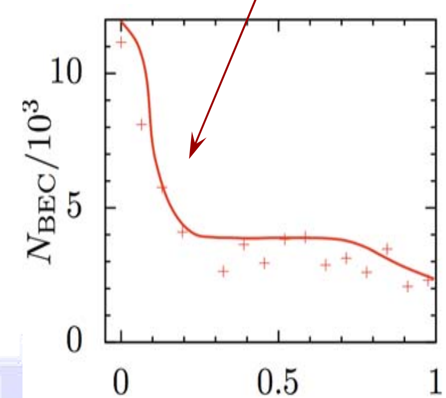
$$i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t) = \left\{ -\frac{\hbar^2}{2m}\nabla^2 + V_{\mathrm{trap}} + \int U(\vec{r}-\vec{r}',t)|\psi(\vec{r}',t)|^2 \mathrm{d}^3r' - \frac{i\hbar L_3}{2}|\psi(\vec{r},t)|^4 \right\} \psi(\vec{r},t)$$

no free parameters, using measured $L_3 = 2 \times 10^{-40}$ m^6/s

- weakly cigar shaped trap

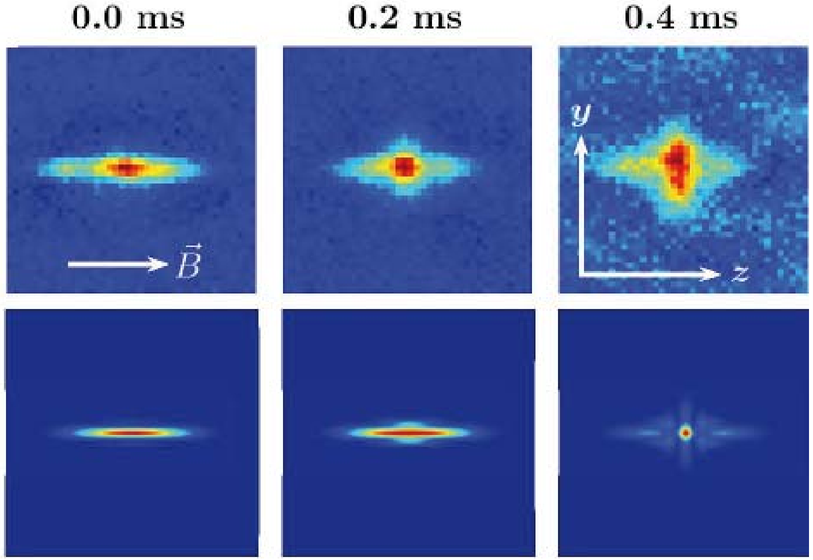
$\lambda \simeq 0.7$





Collapse in a pancake shaped trap

oblate (pancake) trap

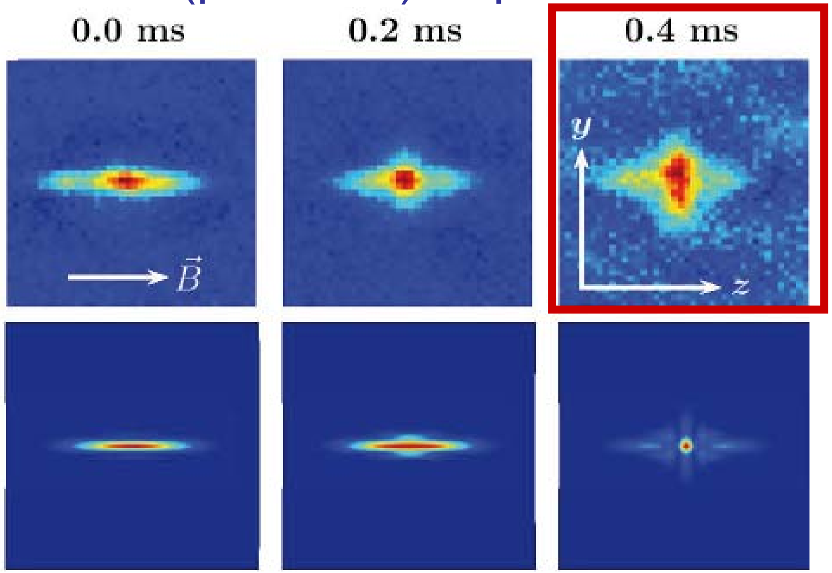


-Dipole-dipole interaction is mainly repulsive in an oblate trap, without s-wave scattering, the BEC would be stable

→ Collapse happens at negative scattering length

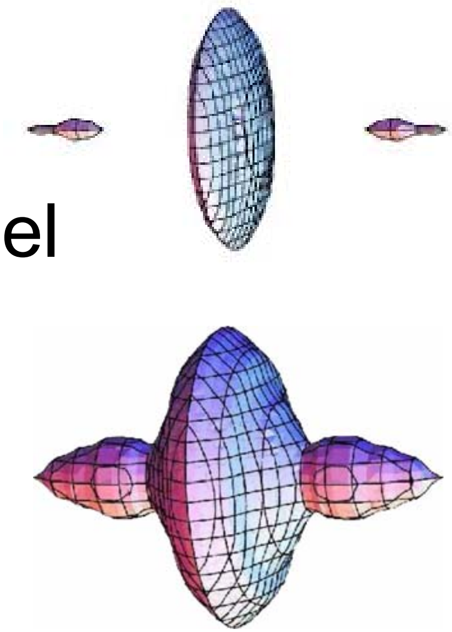
D-wave symmetry

oblate (pancake) trap



Inverse Abel transform

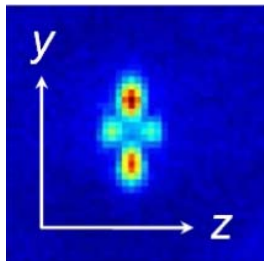
Iso-density surfaces



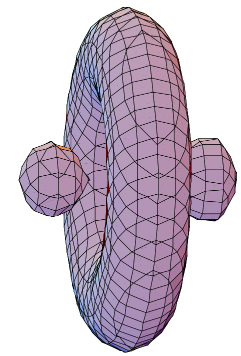
D-wave symmetry of the collapse

Recover 3D structure from 2D projection

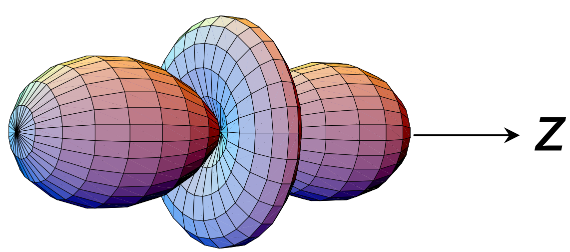
Iso-density surfaces



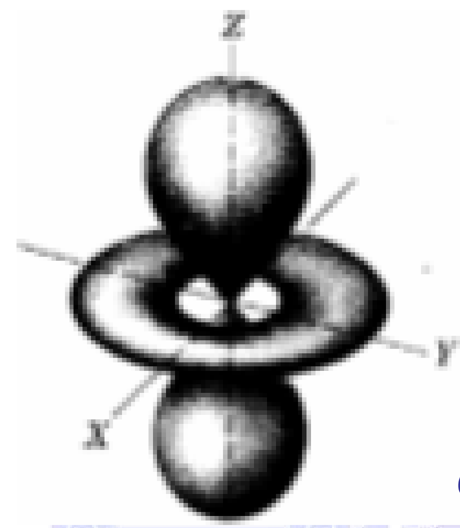
Inverse Abel transform



Reminiscent of the angular ($1-3\cos^2\theta$) dependence of the underlying interaction (*d*-wave)



$$1 - 3\cos^2\theta$$

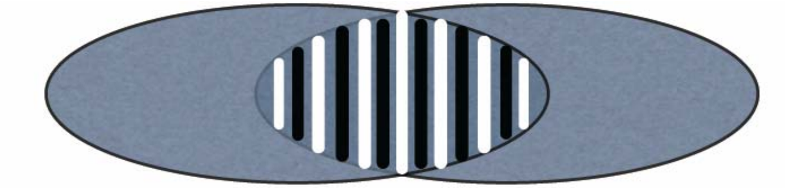


d-orbital

Does coherence survive the collapse?

Excellent agreement with GPE simulation suggests:
„YES“

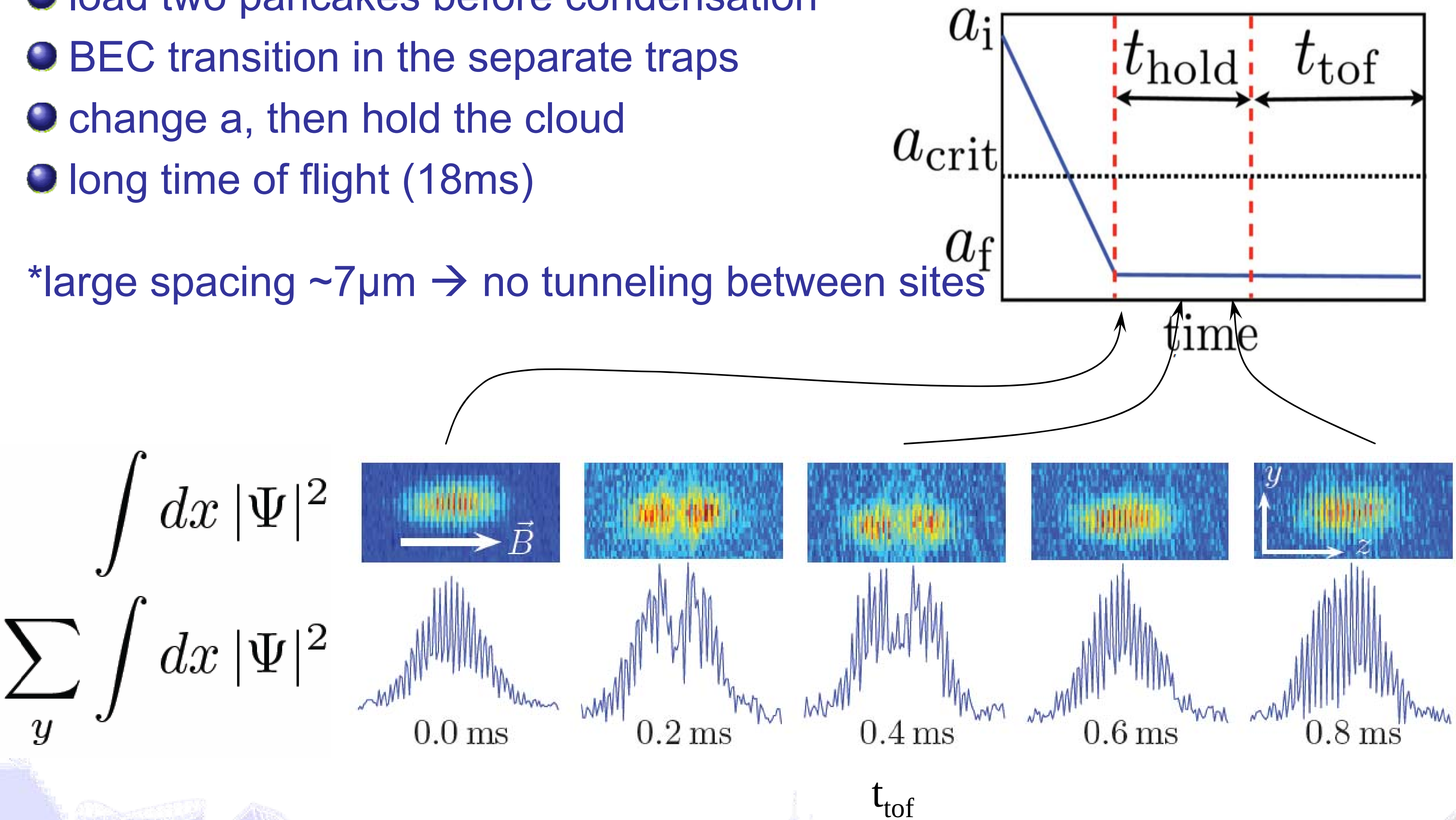
Direct observation of coherence by interference would give better insight



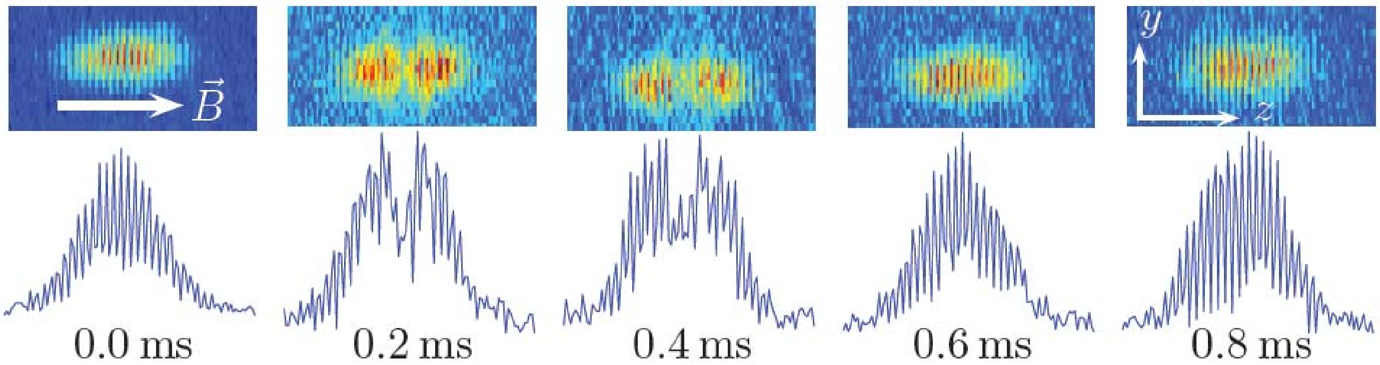
Coherence of the remnant cloud

- load two pancakes before condensation*
- BEC transition in the separate traps
- change a, then hold the cloud
- long time of flight (18ms)

*large spacing ~7µm → no tunneling between sites



Coherence can survive even violent processes like a collapse

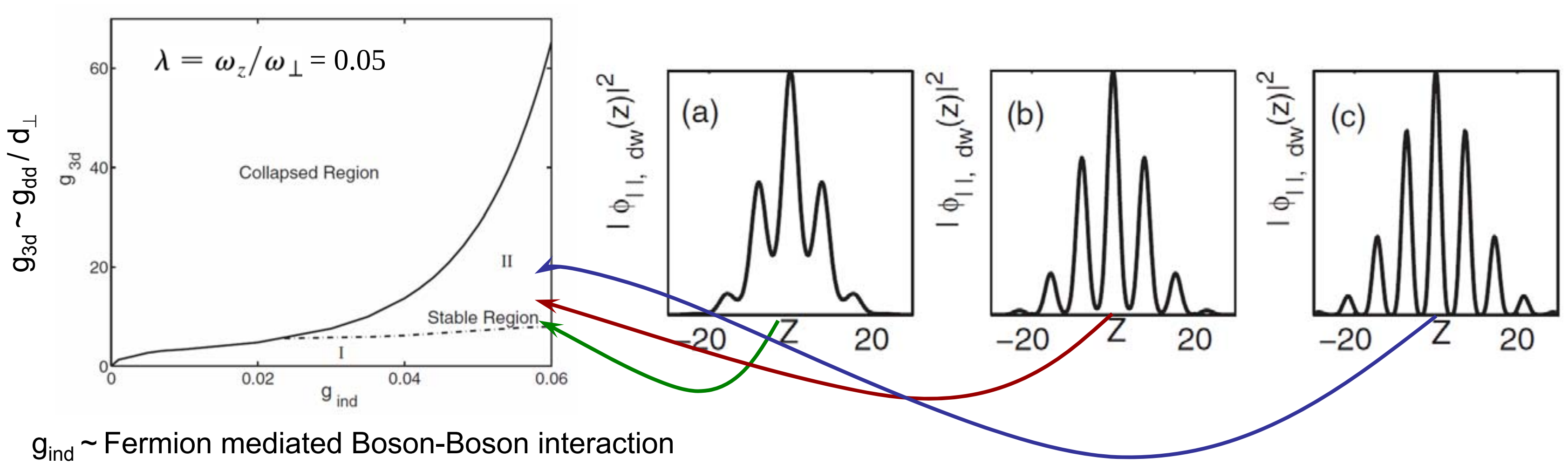


Future directions: Bose-Fermi mixtures

Motivation:

- Fermion mediated boson-boson interaction could lead to a stabilization of density waves

O. Dutta, R. Kanamoto, and P. Meystre, PRL **99,** 110404 (2007)



g_{ind} ~ Fermion mediated Boson-Boson interaction

- Existence of the fermionic isotope ^{53}Cr

(laser cooled in Paris: R. Chicireanu *et al.*, PRA **73** 053406 (2006))


First BEC church window, Brigitte Simon, Lohmar (Germany)
Thank You For Your Attention !
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