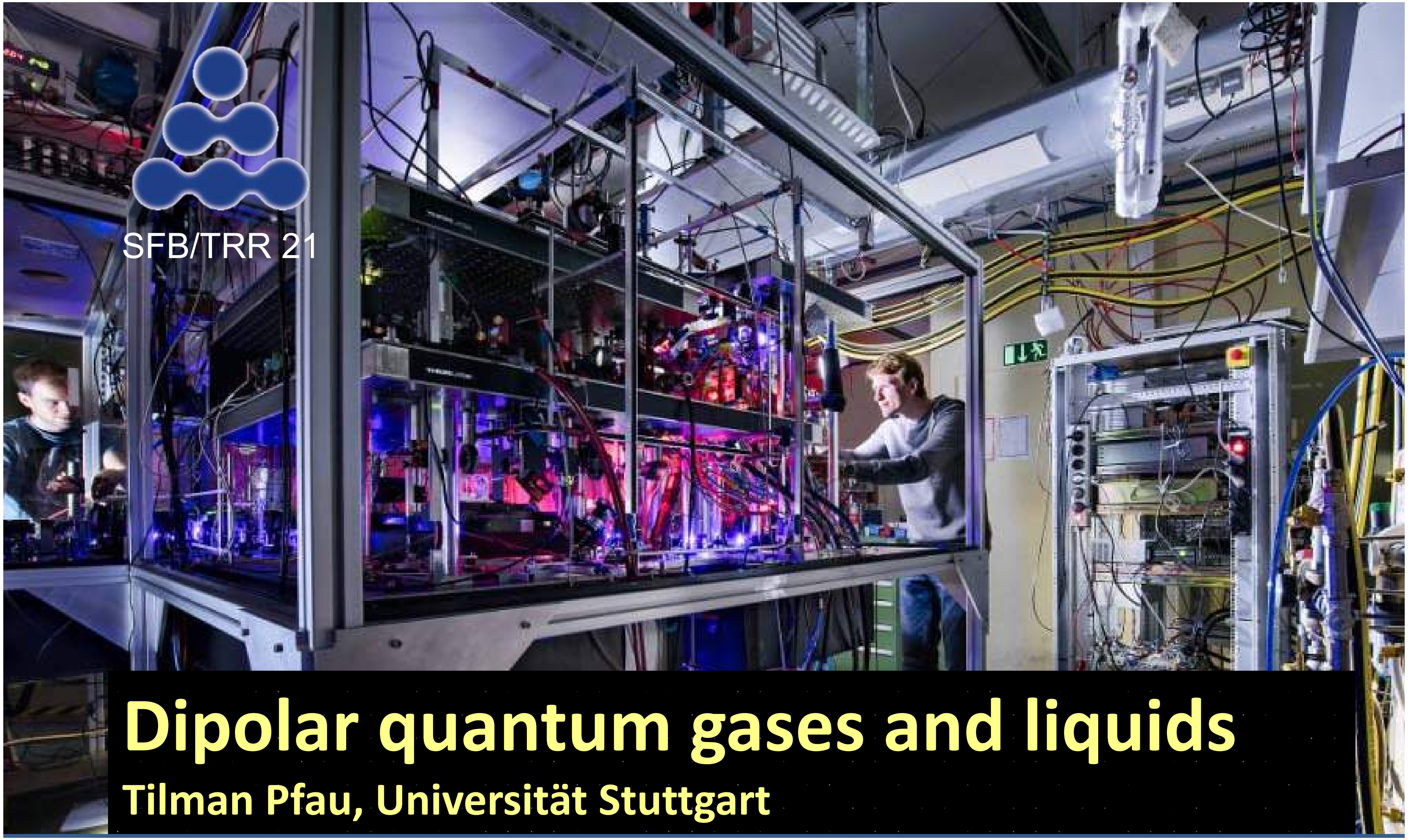


SFB/TRR 21

Dipolar quantum gases and liquids

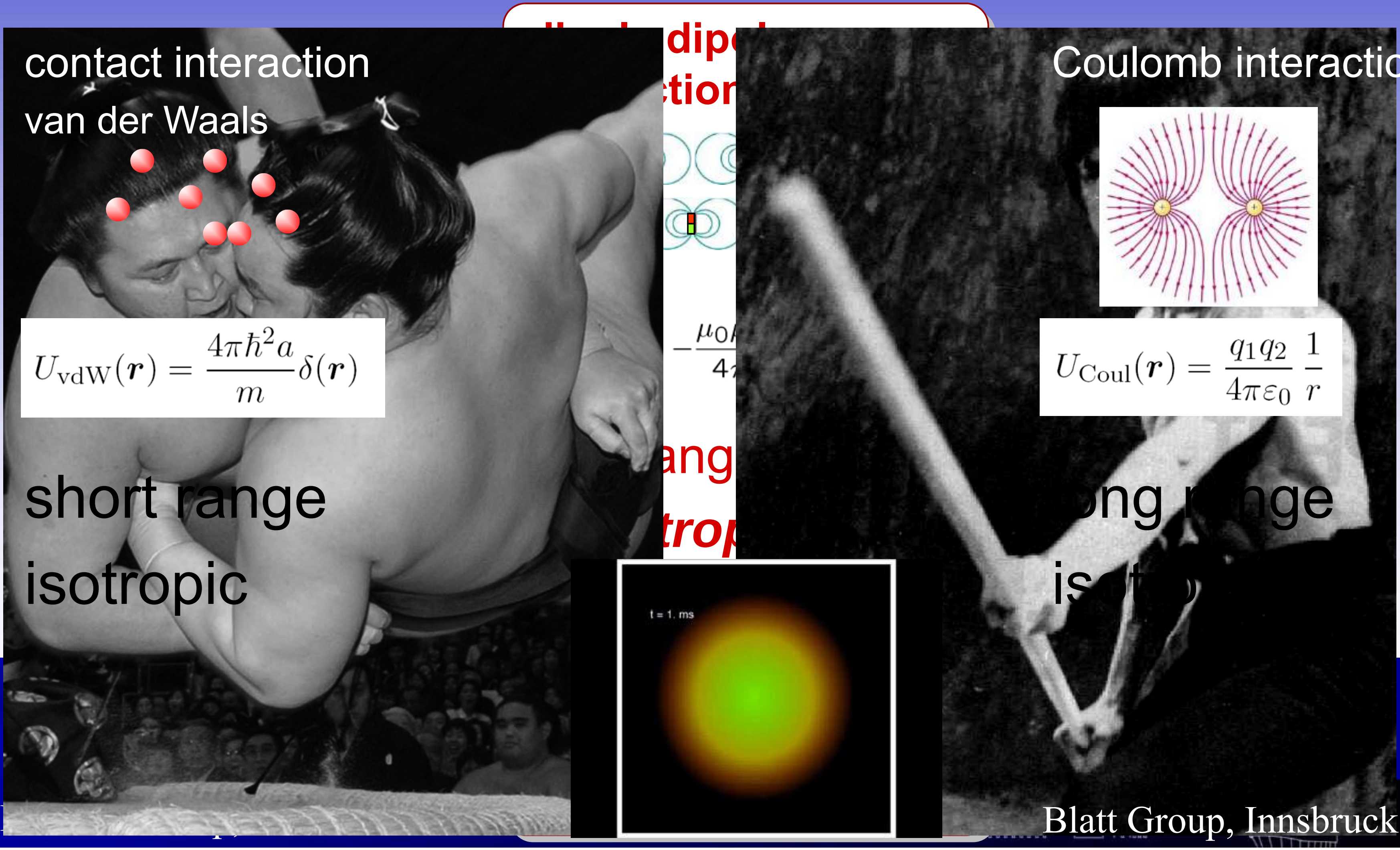
Tilman Pfau, Universität Stuttgart

IQST INTEGRATED QUANTUM SCIENCE AND TECHNOLOGY

Interactions make life interesting

Short range interactions

Long range interactions



contact interaction

van der Waals

$$U_{\mathrm{vdW}}(\boldsymbol{r}) = \frac{4\pi\hbar^2 a}{m}\delta(\boldsymbol{r})$$

short range

isotropic

Coulomb interaction

$$U_{\mathrm{Coul}}(\boldsymbol{r}) = \frac{q_1 q_2}{4\pi\varepsilon_0}\frac{1}{r}$$

ong range

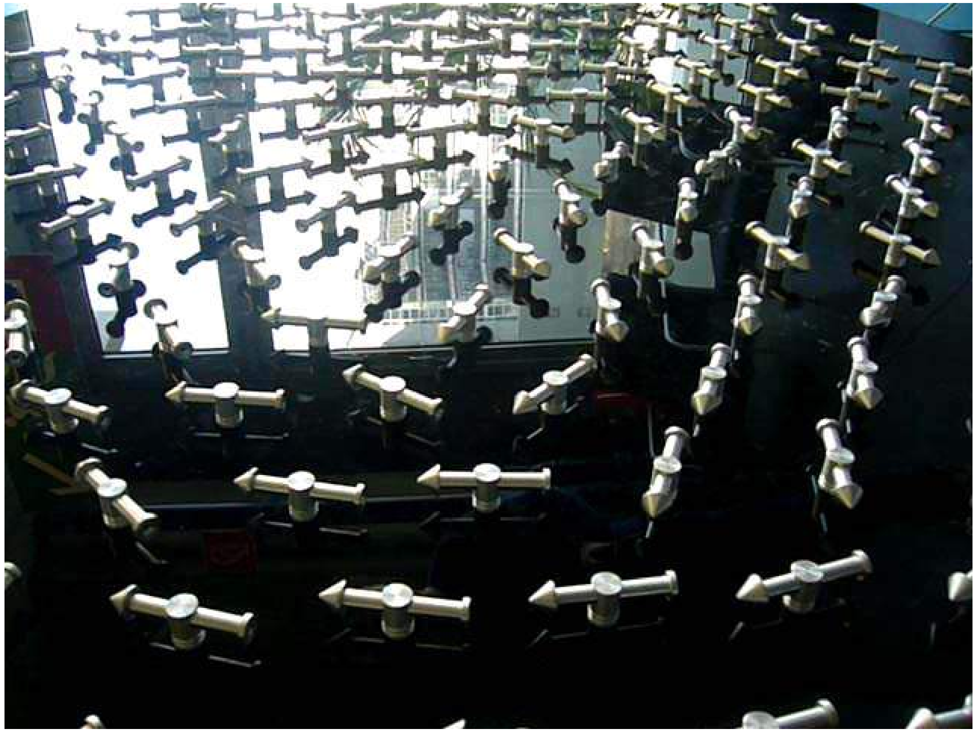
is

Blatt Group, Innsbruck

Early interest in dipoles

- Compass needles
- 1970 DeGennes:

  anisotropic gas; chains
- 1980’s ferrofluids



Rosensweig instability

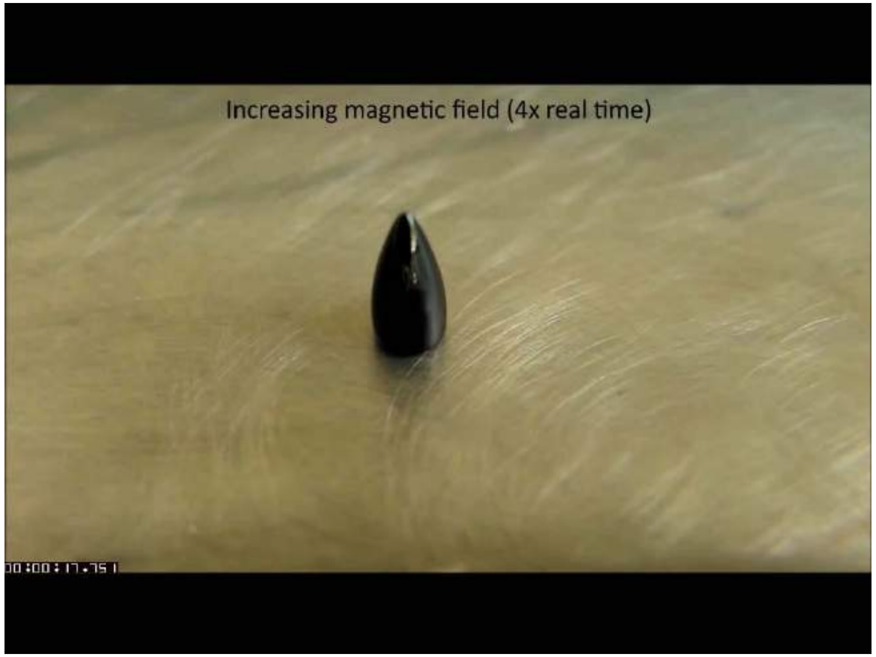
M. D. Cowley and R. E. Rosensweig, J. Fluid Mech. **30**, 671 (1967)

The Rosensweig instability

Classical ferrofluid

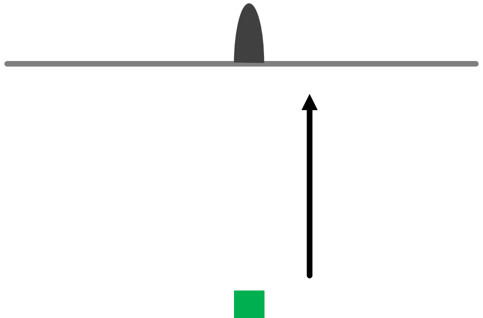
- dipolar interaction
  surface tension
  gravity
- tune magnetization

➡ Rosensweig instability



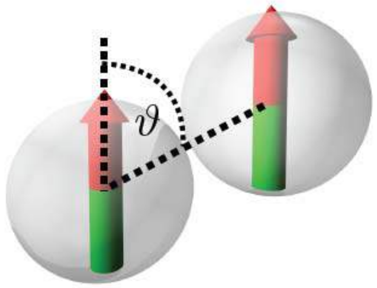
Timonen et al., *Science* **341**, 253 (2013)

Let’s add quantum mechanics



increasing magnetization i.e.
dipolar interaction

Dipolar gases

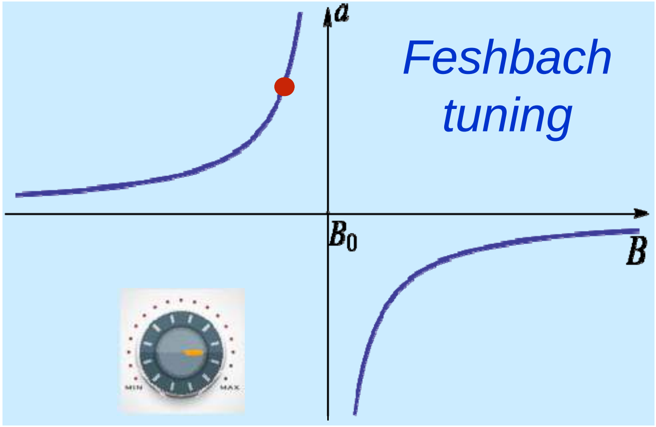


$$\varepsilon_{dd} = \frac{a_{dd}}{a} \propto \frac{m\mu^2}{a}$$

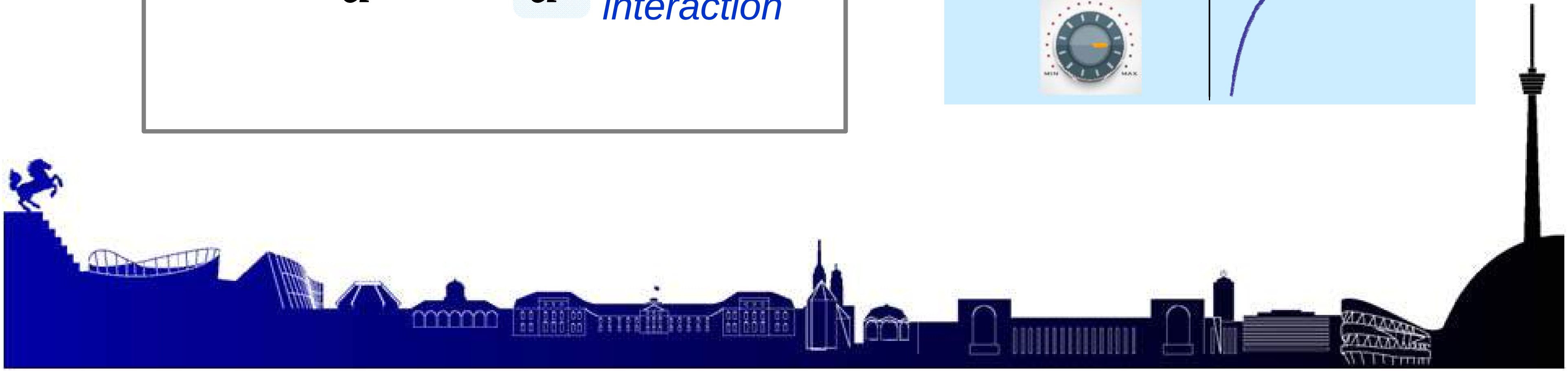
dipolar interaction

contact interaction

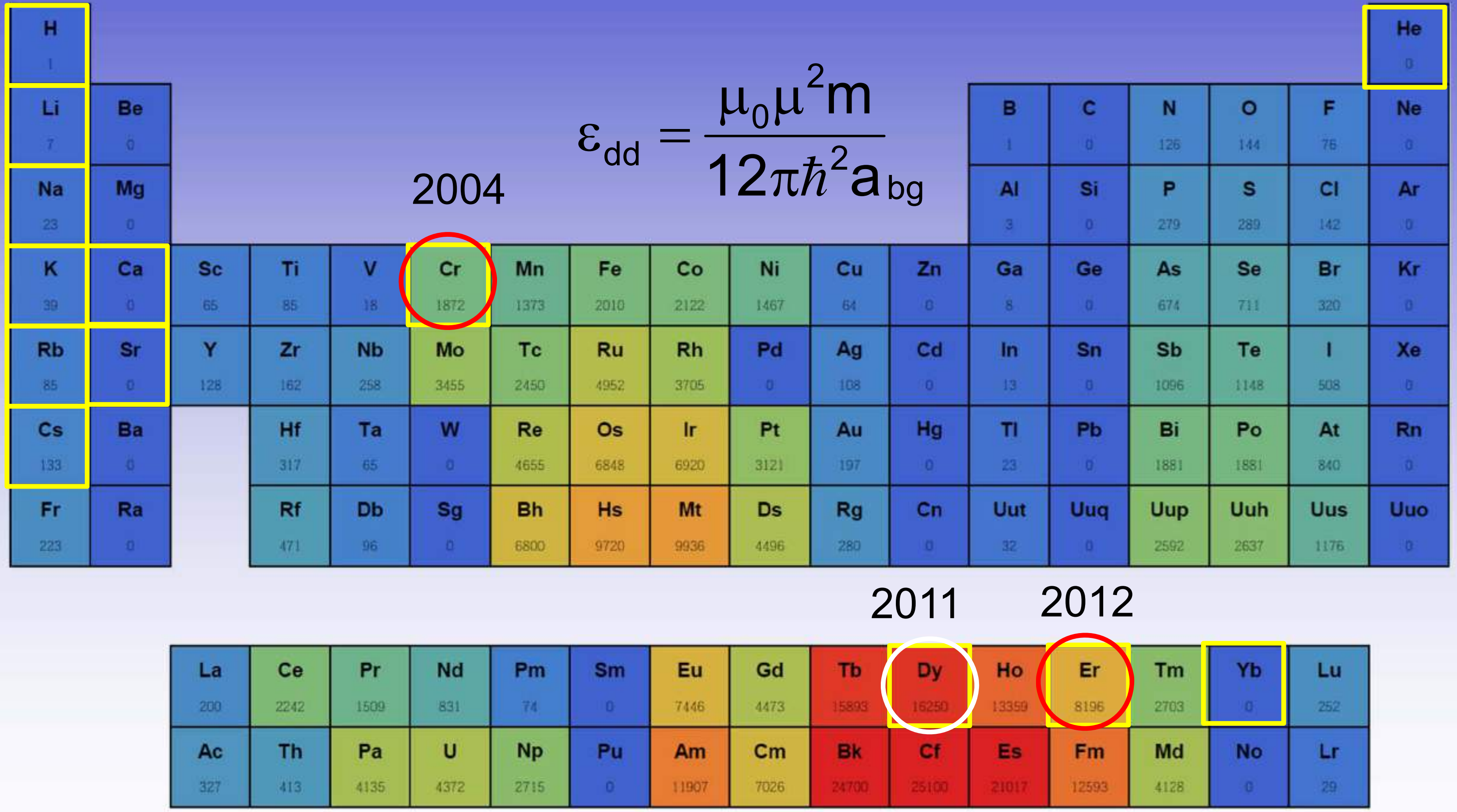
$$V_{dd}(r) \propto \frac{\mu^2}{r^3}(1 - 3\cos^2\vartheta)$$



Feshbach tuning



Periodic table
of magnetic moments



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

2004

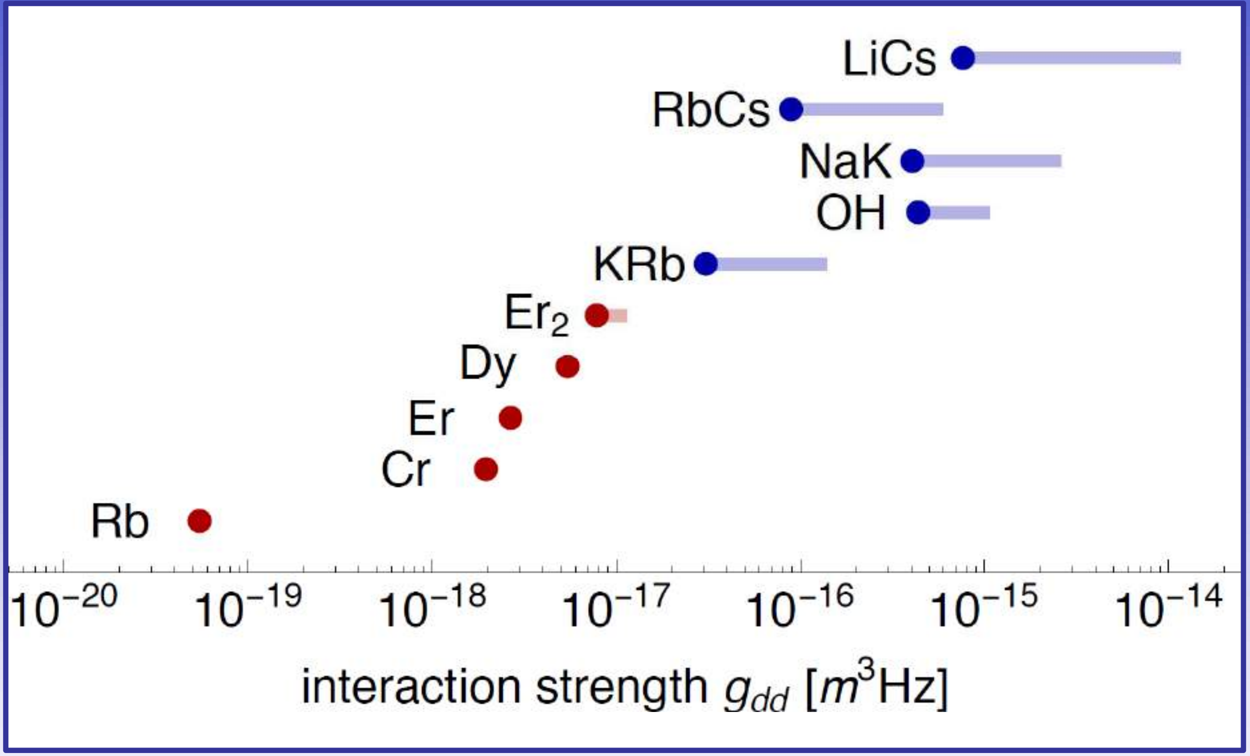
H 1																	He 0
Li 7	Be 0											B 1	C 0	N 126	O 144	F 76	Ne 0
Na 23	Mg 0											Al 3	Si 0	P 279	S 289	Cl 142	Ar 0
K 39	Ca 0	Sc 65	Ti 85	V 18	Cr 1872	Mn 1373	Fe 2010	Co 2122	Ni 1467	Cu 64	Zn 0	Ga 8	Ge 0	As 674	Se 711	Br 320	Kr 0
Rb 85	Sr 0	Y 128	Zr 162	Nb 258	Mo 3455	Tc 2450	Ru 4952	Rh 3705	Pd 0	Ag 108	Cd 0	In 13	Sn 0	Sb 1096	Te 1148	I 508	Xe 0
Cs 133	Ba 0		Hf 317	Ta 65	W 0	Re 4655	Os 6848	Ir 6920	Pt 3121	Au 197	Hg 0	Tl 23	Pb 0	Bi 1881	Po 1881	At 840	Rn 0
Fr 223	Ra 0		Rf 471	Db 96	Sg 0	Bh 6800	Hs 9720	Mt 9936	Ds 4496	Rg 280	Cn 0	Uut 32	Uuq 0	Uup 2592	Uuh 2637	Uus 1176	Uuo 0

2011

2012

La 200	Ce 2242	Pr 1509	Nd 831	Pm 74	Sm 0	Eu 7446	Gd 4473	Tb 15893	Dy 16250	Ho 13359	Er 8196	Tm 2703	Yb 0	Lu 252
Ac 327	Th 413	Pa 4135	U 4372	Np 2715	Pu 0	Am 11907	Cm 7026	Bk 24700	Cf 25100	Es 21017	Fm 12593	Md 4128	No 0	Lr 29

How about electric dipole moments?



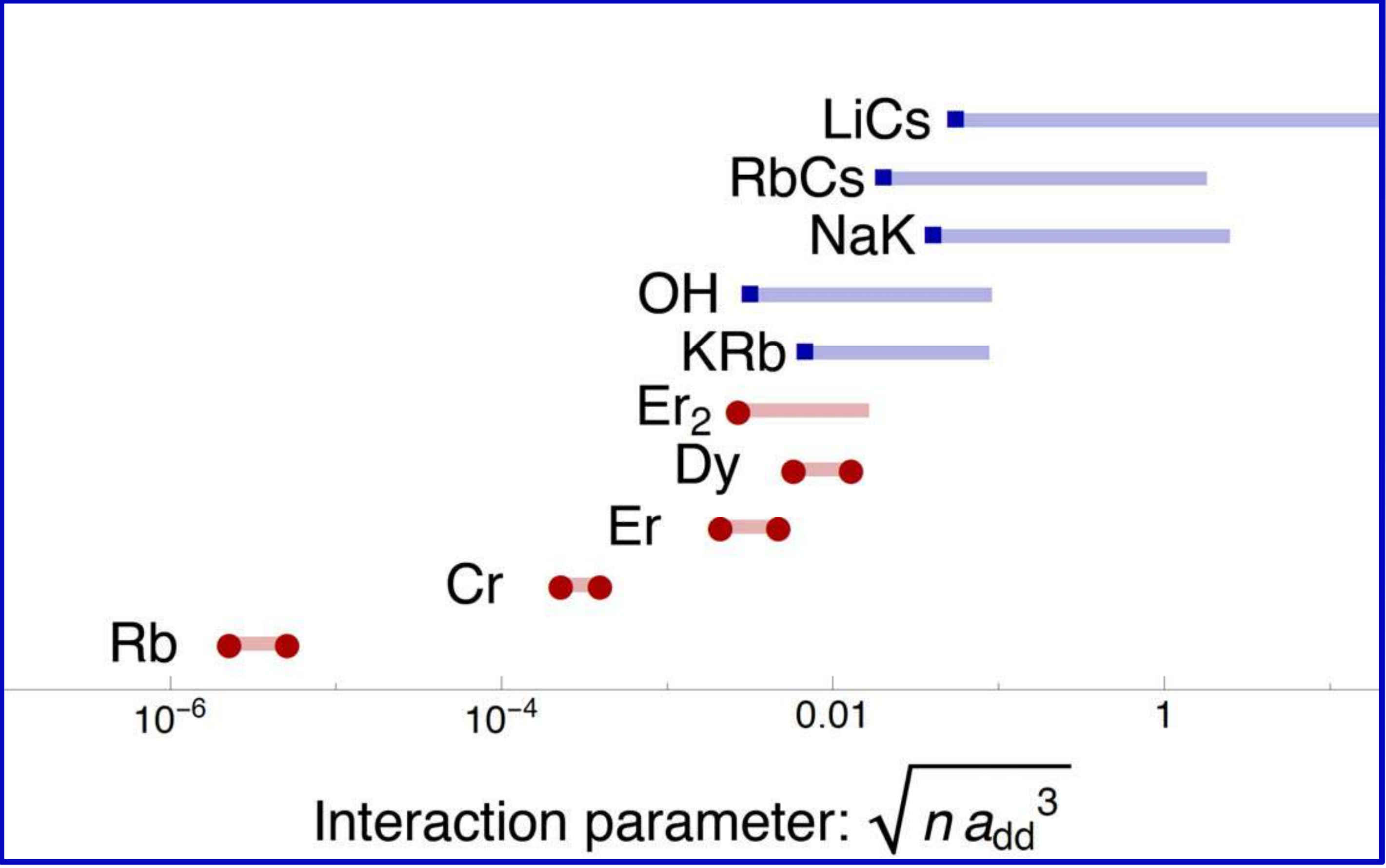
$$g_{dd} \propto \mu^2$$

Increasing dipole moment

Weakly-interacting regime

Dipolar gases

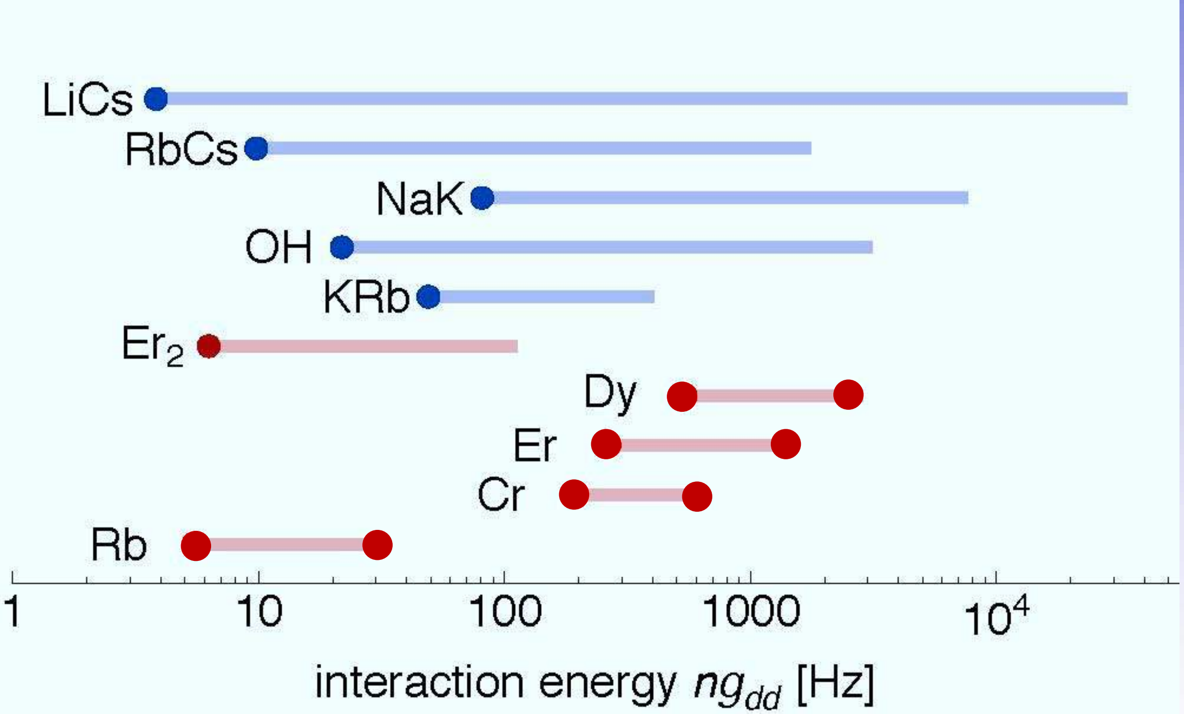
Strongly-interacting regime

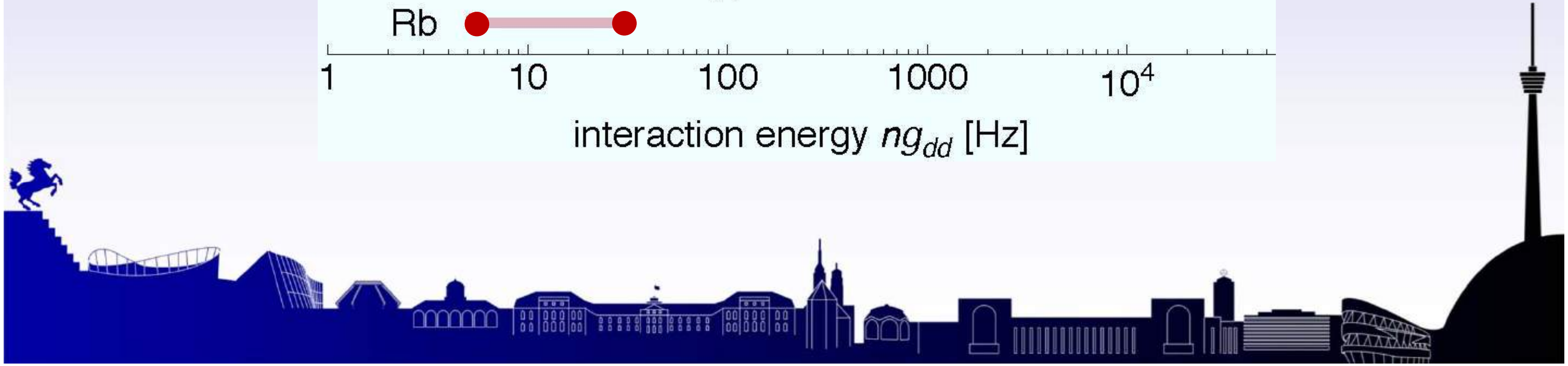


Weakly-interacting regime

Dipolar gases

Strongly-interacting regime





How to describe a dipolar quantum gas

Kinetic energy

Trap

Contact (tune by Feshbach res.)

$$g = 4\pi\hbar^2 \frac{a}{m}$$

$$i\hbar\partial_t\psi(r) = \Big[-\frac{\hbar^2\Delta}{2m} + V_{ext} + g|\psi|^2$$

Dipolar (tune by geometry)

$$+ \int d\underline{r}'\, V_{dd}(\underline{r}-\underline{r}')\,|\psi(\underline{r}')|^2$$

$$+ \cdot$$

Quantum fluctuations (LDA)

$$\ldots\Big]\psi(r)$$

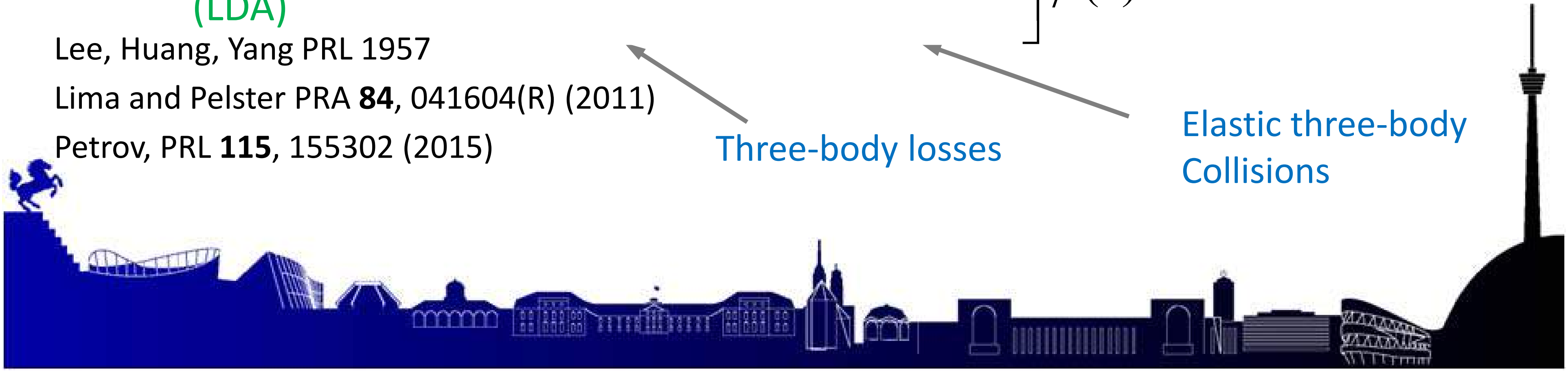
Lee, Huang, Yang PRL 1957

Lima and Pelster PRA **84**, 041604(R) (2011)

Petrov, PRL **115**, 155302 (2015)

Three-body losses

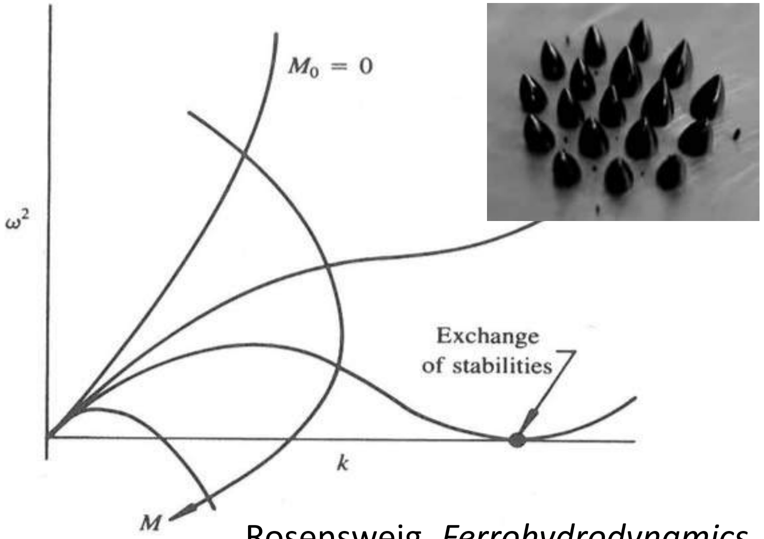
Elastic three-body Collisions



The Rosensweig instability

Classical ferrofluid

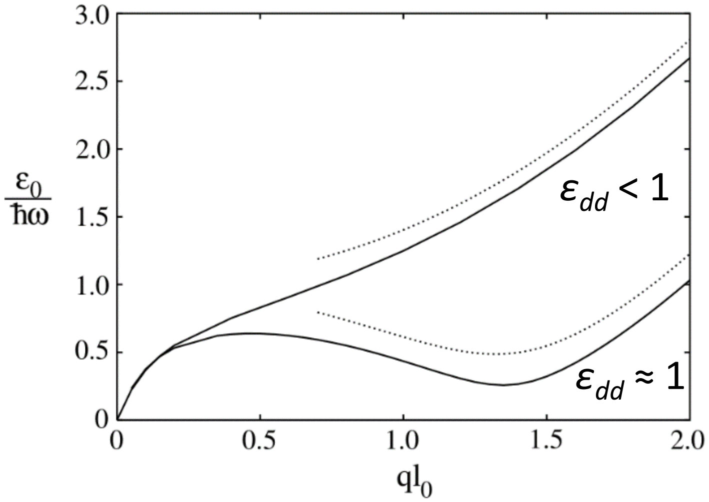
- dipolar interaction
  surface tension
  gravity
- tune magnetization M
- Rosensweig instability



Rosensweig, *Ferrohydrodynamics*
Cambridge Univ. Press (1985)

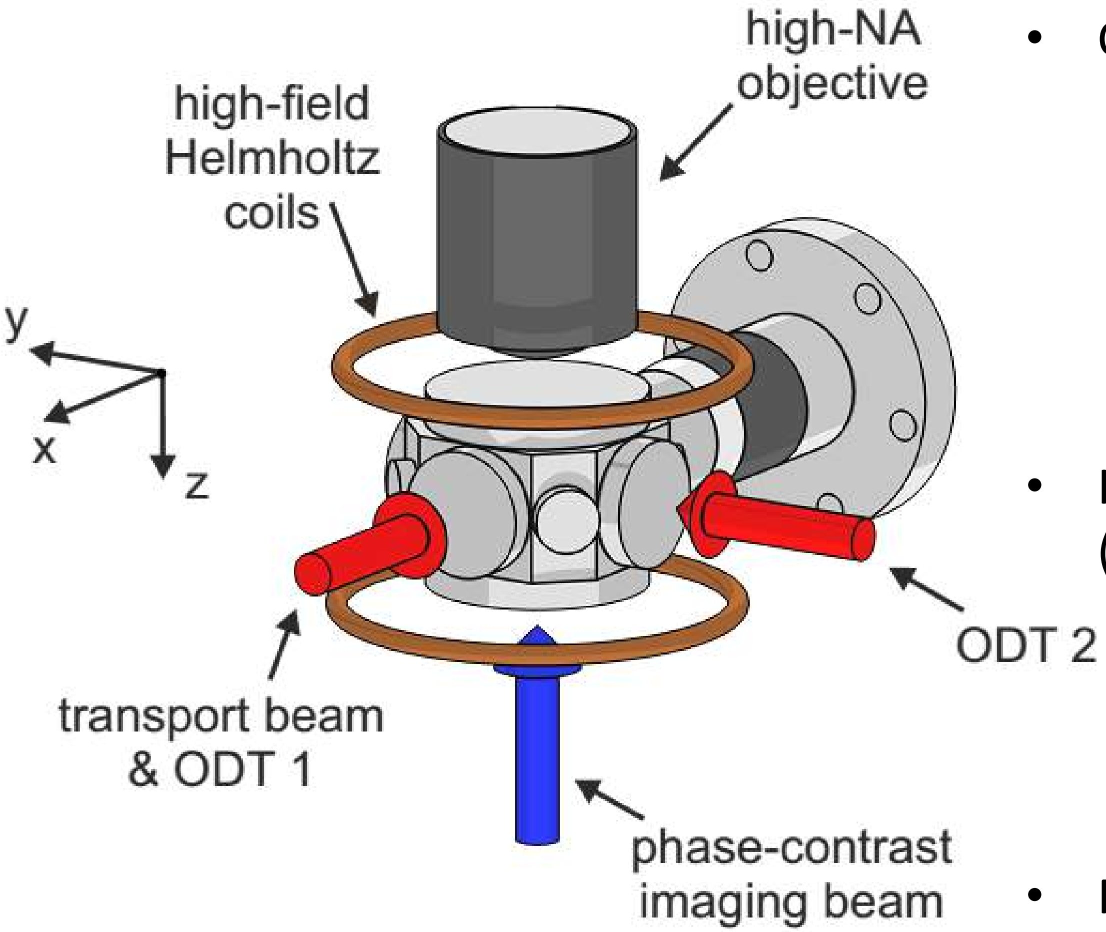
Quantum ferrofluid

- dipolar interaction
  quantum pressure + contact
  trapping potential
- tune dipolar strength ε_{dd}
- Roton-Maxon spectrum

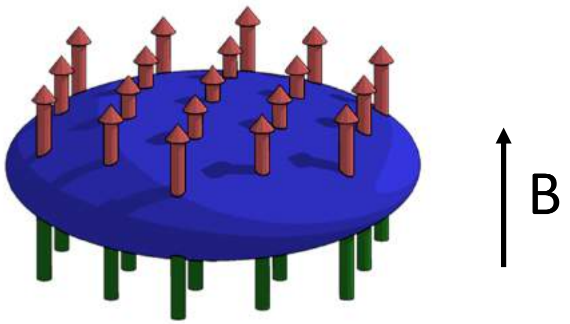


L. Santos et al., *PRL* **90**, 250403 (2003)

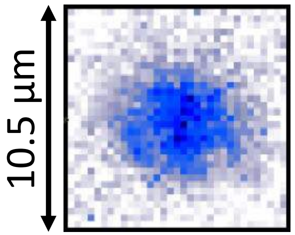
Dysprosium BEC in a glass cell



- Crossed ODT: oblate trap



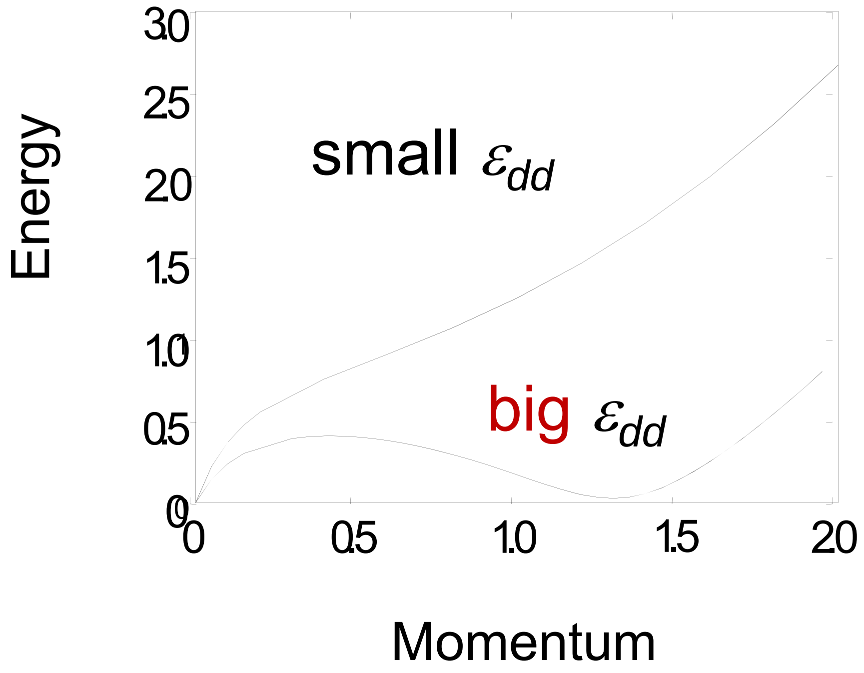
- In situ phase-contrast imaging (1 μm resolution)

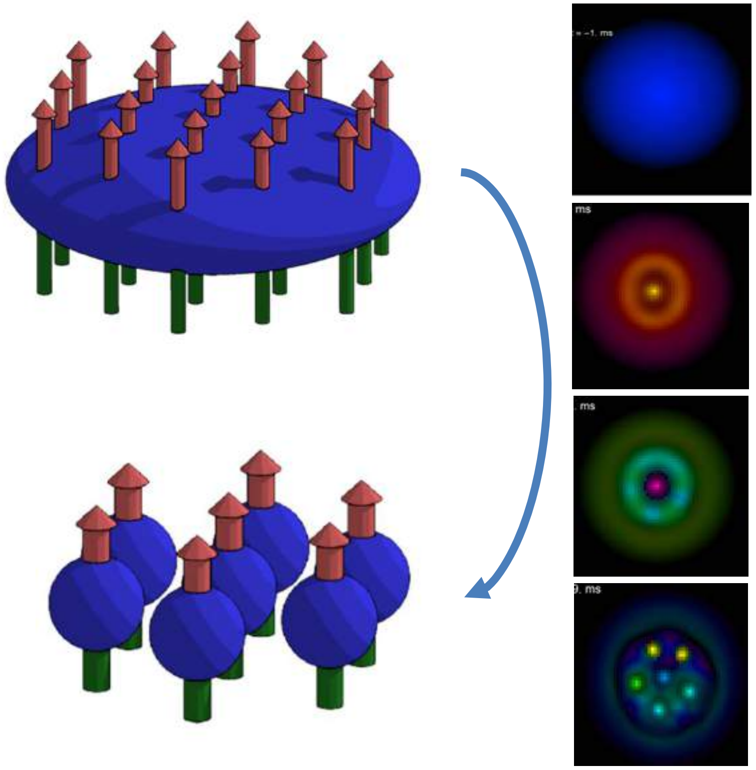


Single-shot measurements

- Feshbach resonance to tune relative interaction strength ε_{dd}

Selforganized structures:
the roton in dipolar BEC



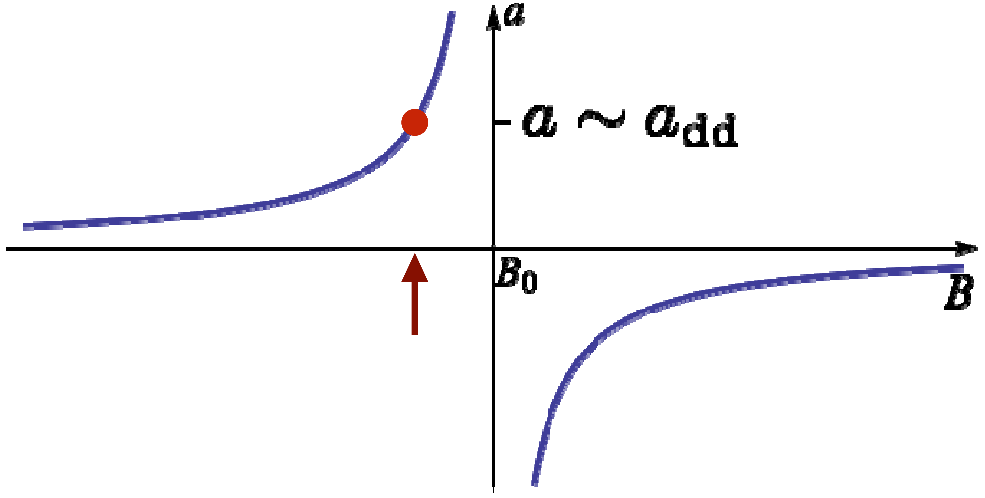


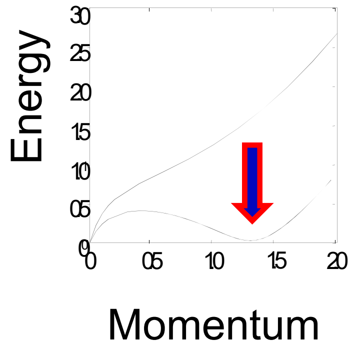
Angular Roton instability
and subsequent droplet formation

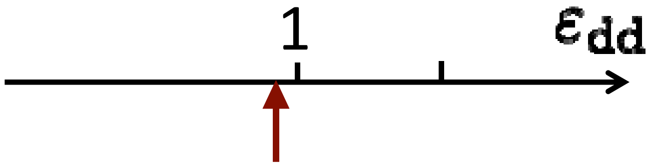
Santos, Shlyapnikov, and Lewenstein PRL 90, 250403 (2003)

Inducing the Rosensweig instability

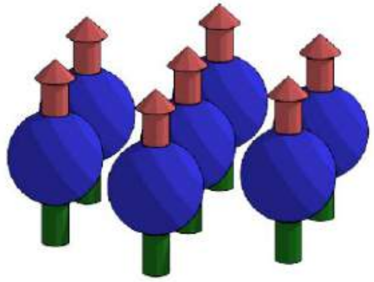
Trap aspect ratio λ = 2.9(1) = 133 Hz / 46 Hz



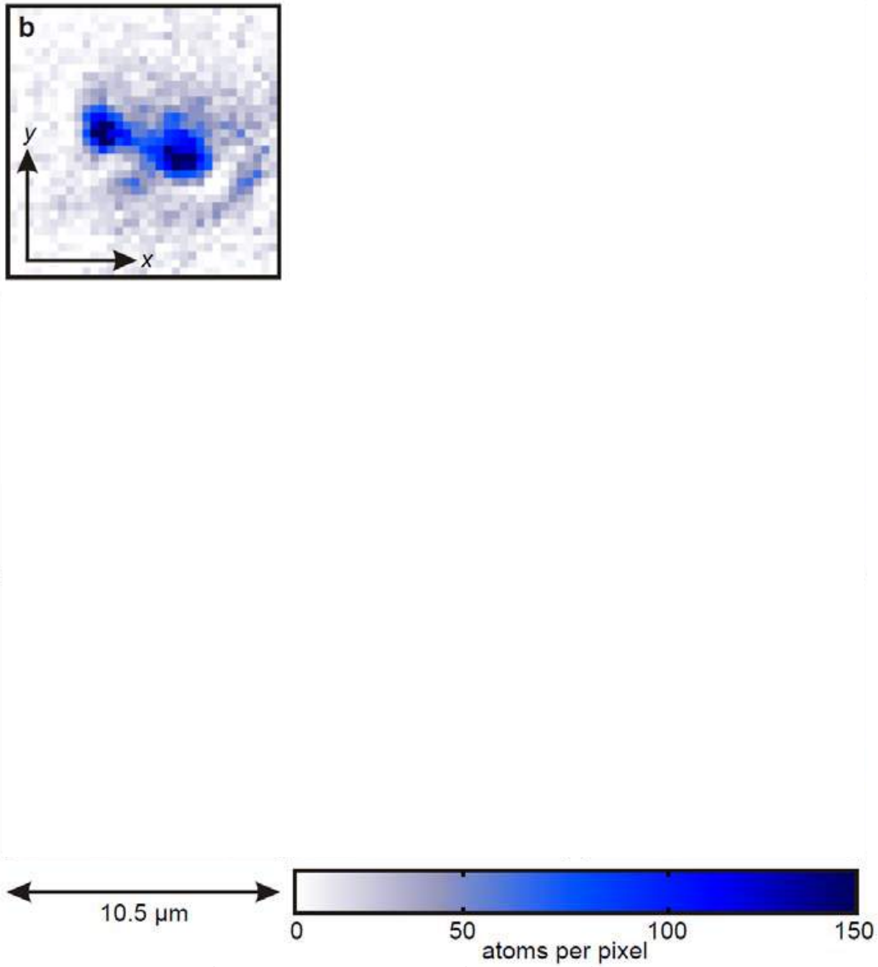




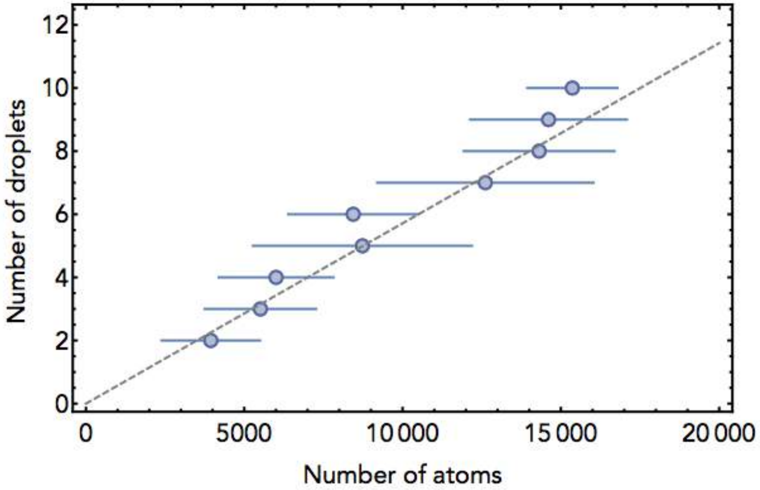
$$\varepsilon_{dd} = \frac{a_{dd}}{a}$$



Rosensweig instability



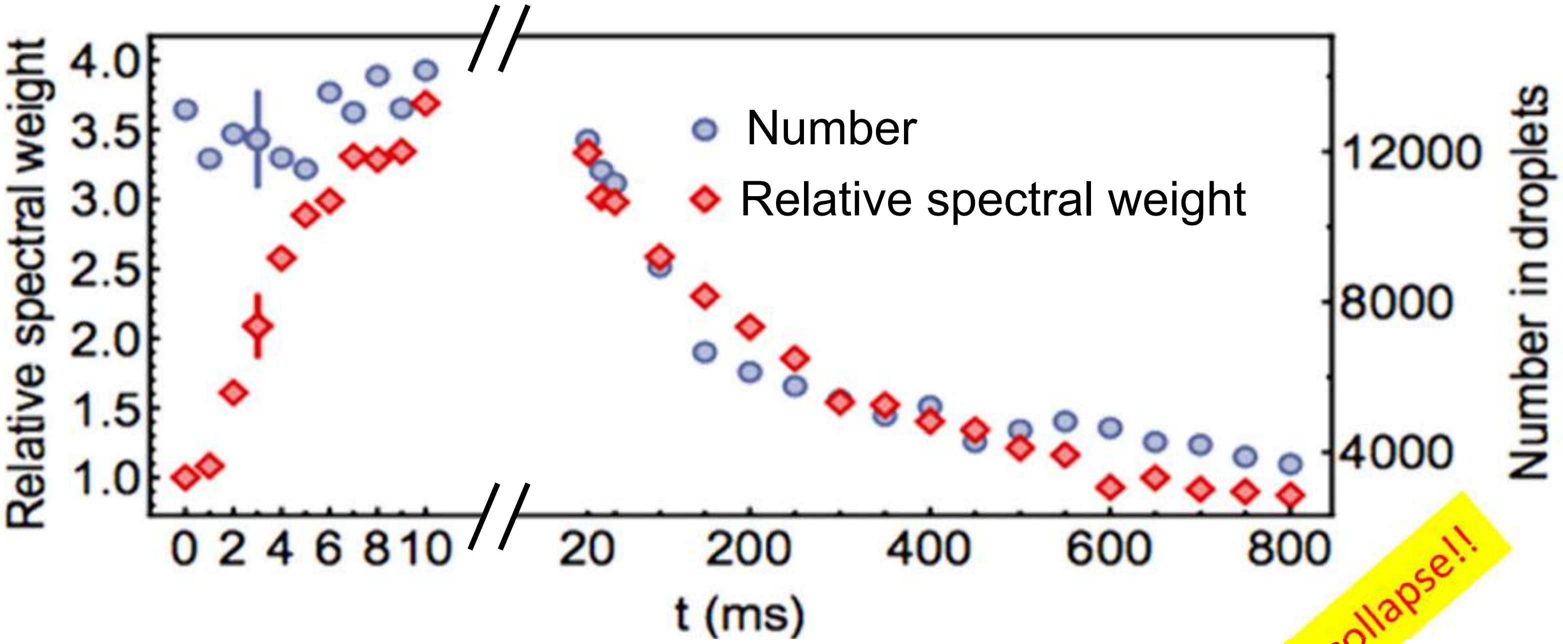
Ronald E. Rosensweig
* 1932



1750(300) atoms / droplet

H. Kadau, M. Schmitt, M. Wenzel, C. Wink, T. Maier, I. Ferrier-Barbut, T. Pfau
*Nature **530**, 194 (2016)*

Growth dynamics and lifetime



No collapse!!

Quench time to low $B \sim 500\ \mu s$

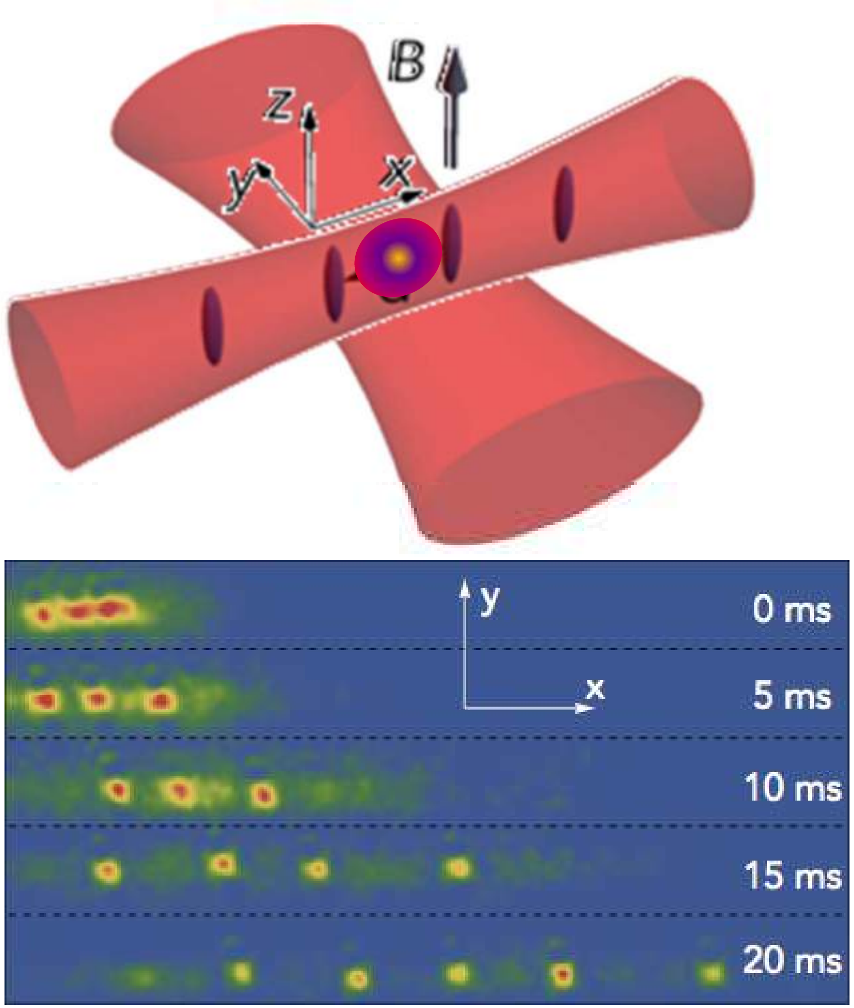
Long lived ~ several 100 msec

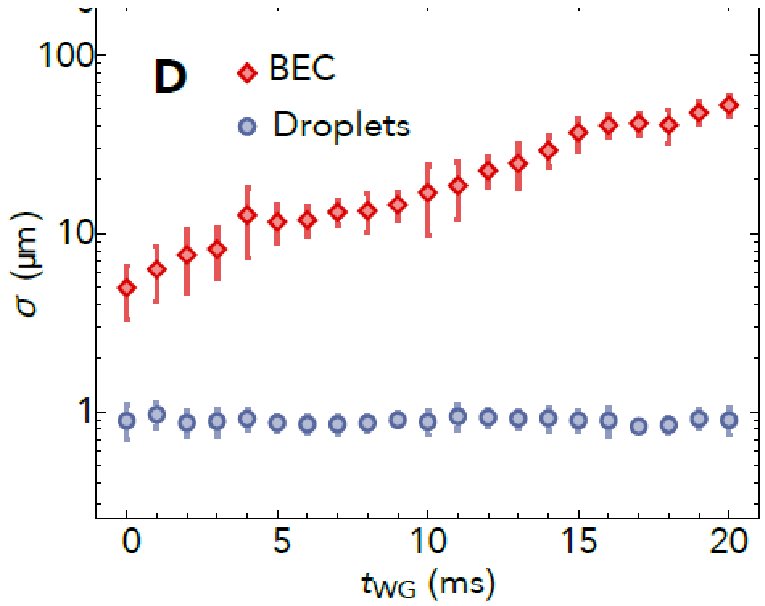
inside a droplet $n \sim 4\ 10^{14}\ cm^{-3}$

Three-body losses as decay mechanism

H. Kadau et al., Nature **530**, 194 (2016)

Probing droplets in a waveguide

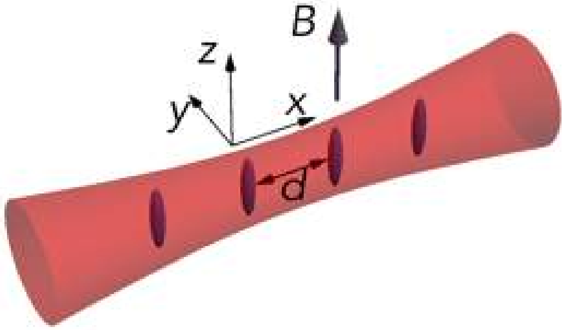


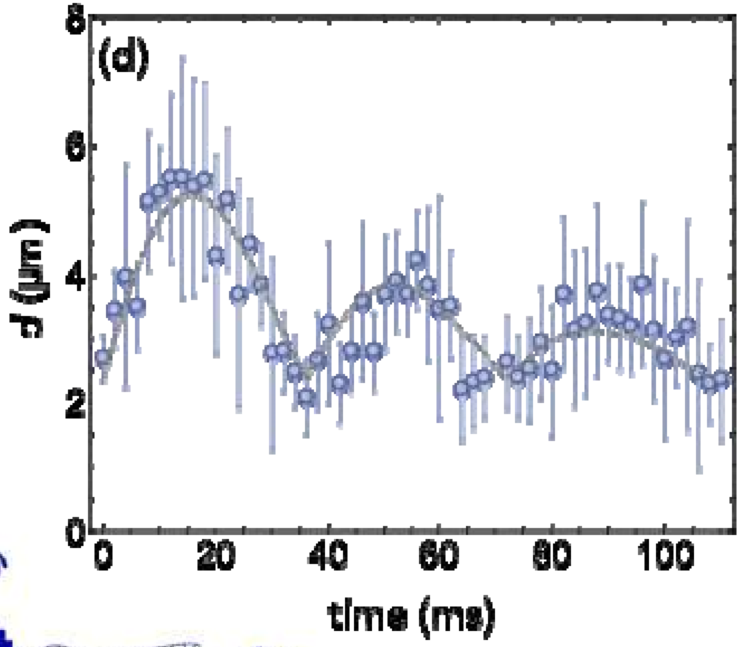


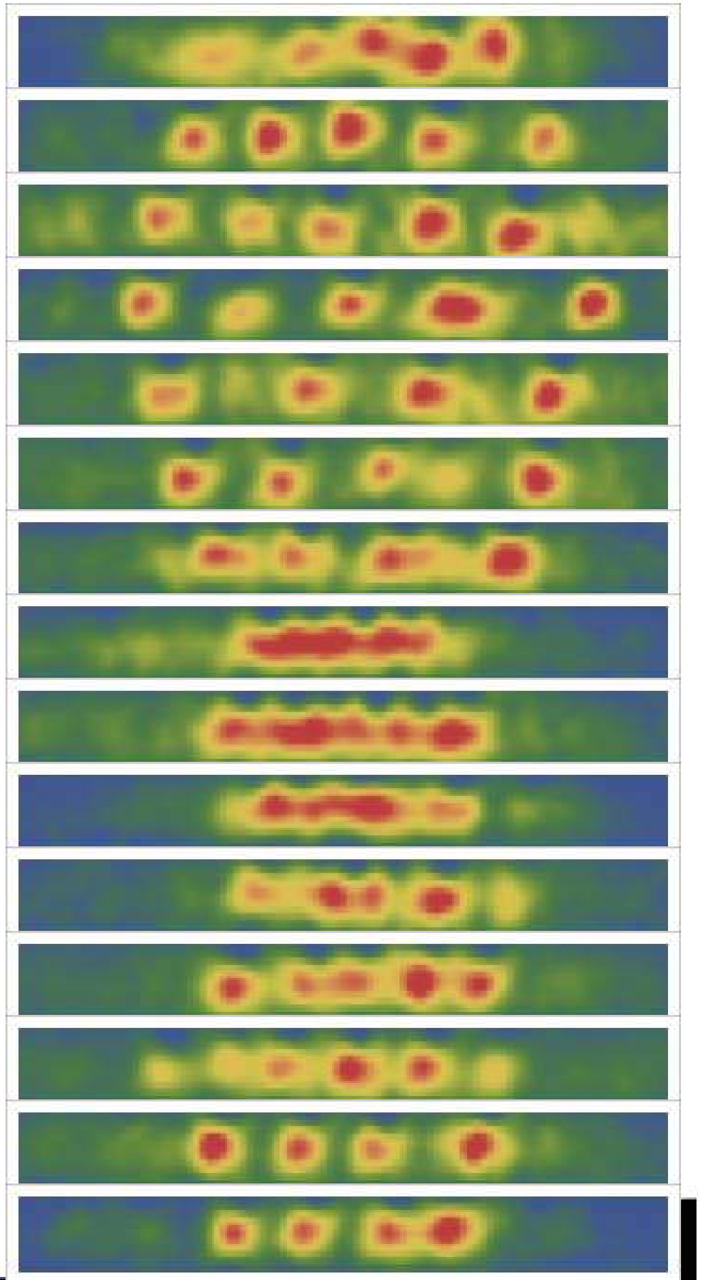
I. Ferrier-Barbut et al., PRL **116**, 215301 (2016)

Probing droplets in a waveguide

Keeping a week axial confinement along x







J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 214004

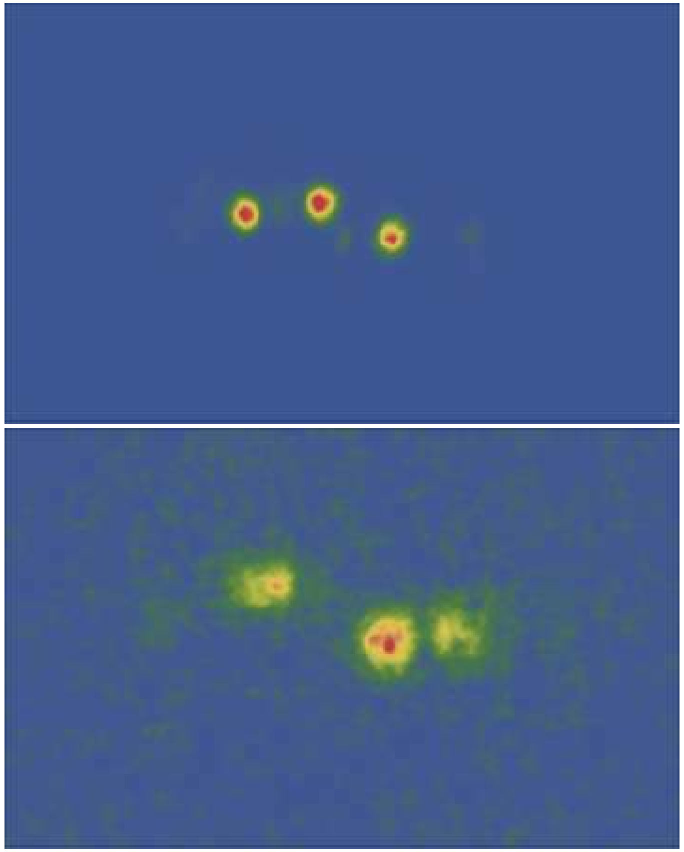
Feshbach boost → re-evaporation

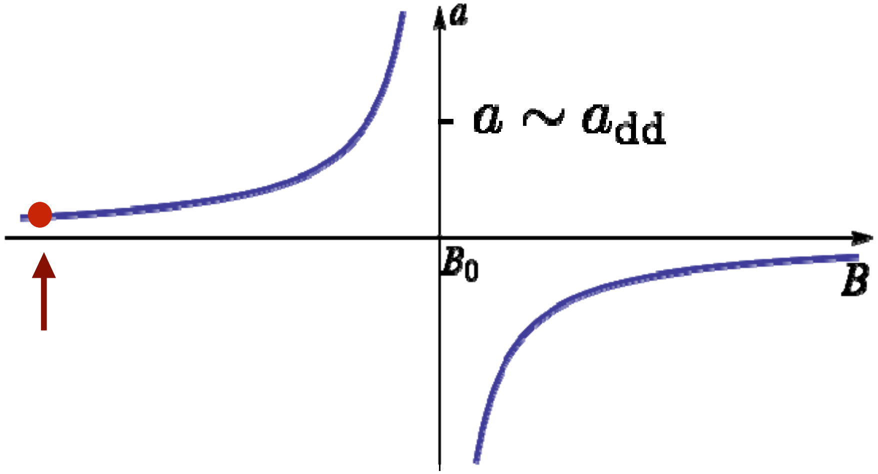
Time of flight

B = 6.656 G

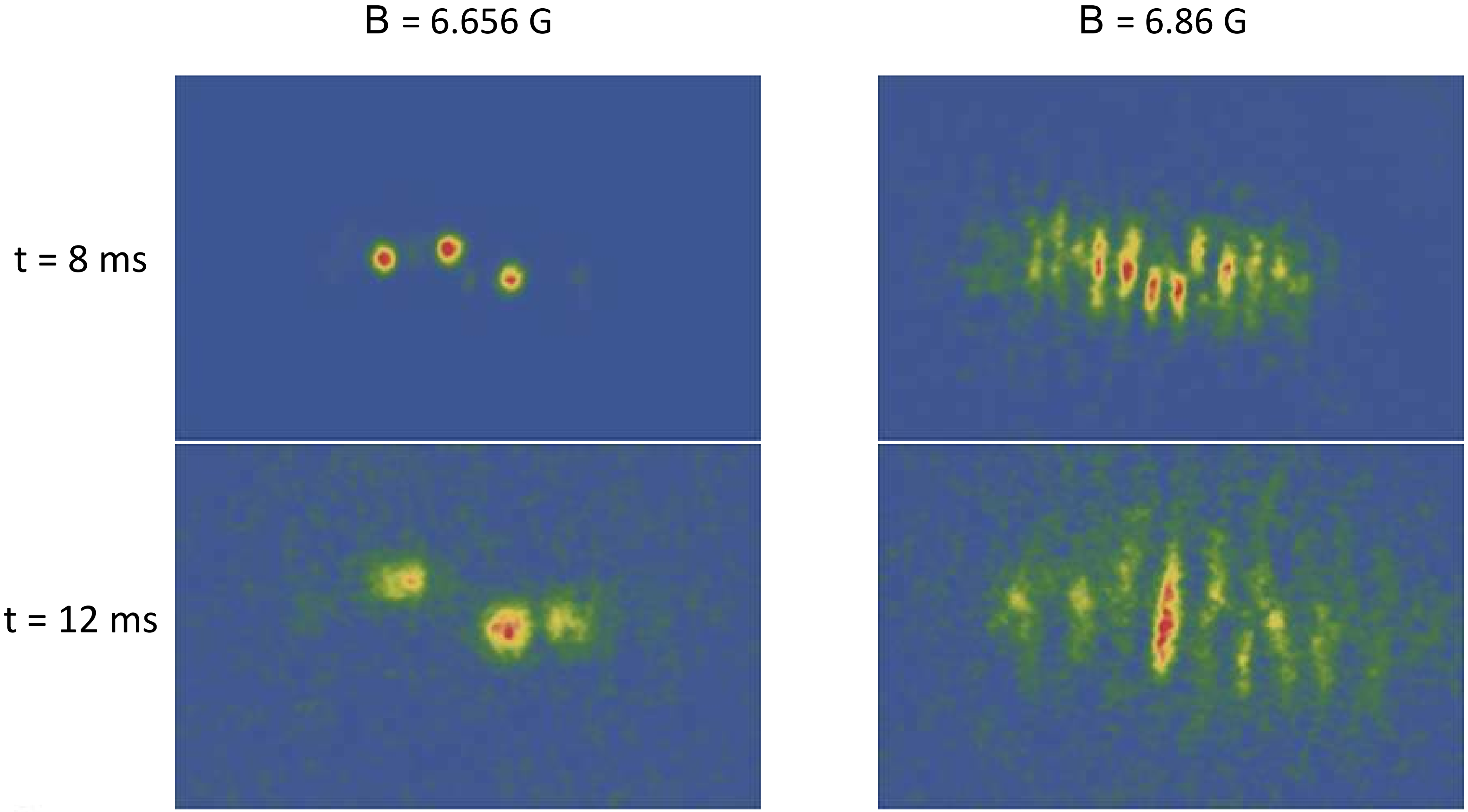
t = 8 ms

t = 12 ms



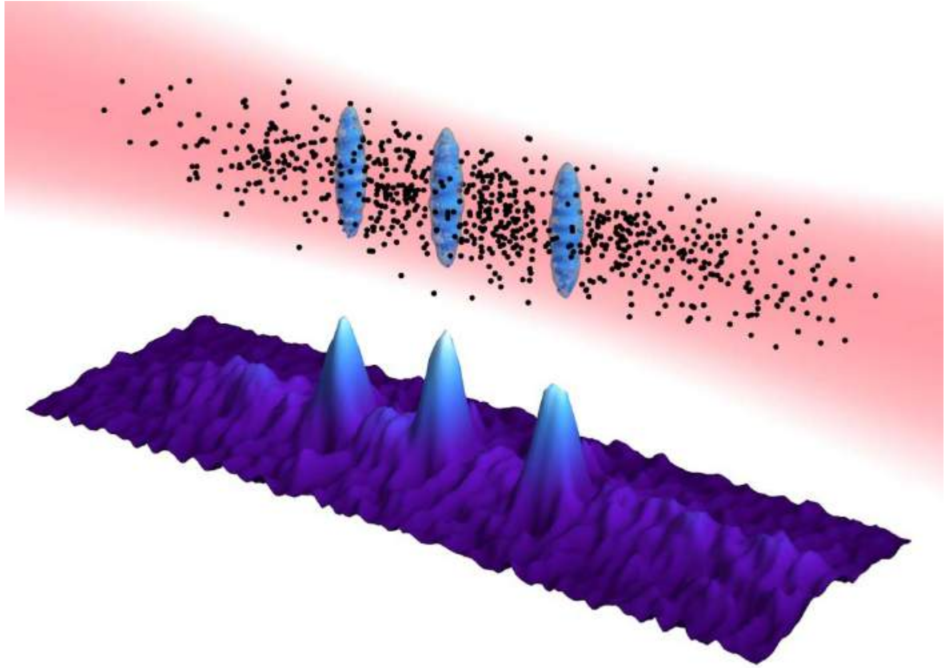


Quantum droplets interfere !



I. Ferrier-Barbut et al., PRL **116**, 215301 (2016)

Why are the droplets stable?



H. Kadau, M. Schmitt, M. Wenzel, C. Wink, T. Maier, I. Ferrier-Barbut, T. Pfau, *Nature* ***530***, *194 (2016)*

How to describe a dipolar quantum gas

Kinetic energy

Trap

Contact (tune by Feshbach res.)

$$i\hbar\partial_t\psi(r)=\Bigg[-\frac{\hbar^2\Delta}{2m}+V_{ext}+g|\psi|^2$$

$$+\int d\underline{r}'V_{dd}(\underline{r}-\underline{r}')|\psi(\underline{r}')|^2$$

$$+\frac{32g\sqrt{a^3}}{3\sqrt{\pi}}\left(1+\frac{3}{2}\varepsilon_{dd}^2\right)|\psi|^3$$

$$-i\frac{\hbar}{2}L_3|\psi|^4+F_{el3body}|\psi|^4+....\Bigg]\psi(r)$$

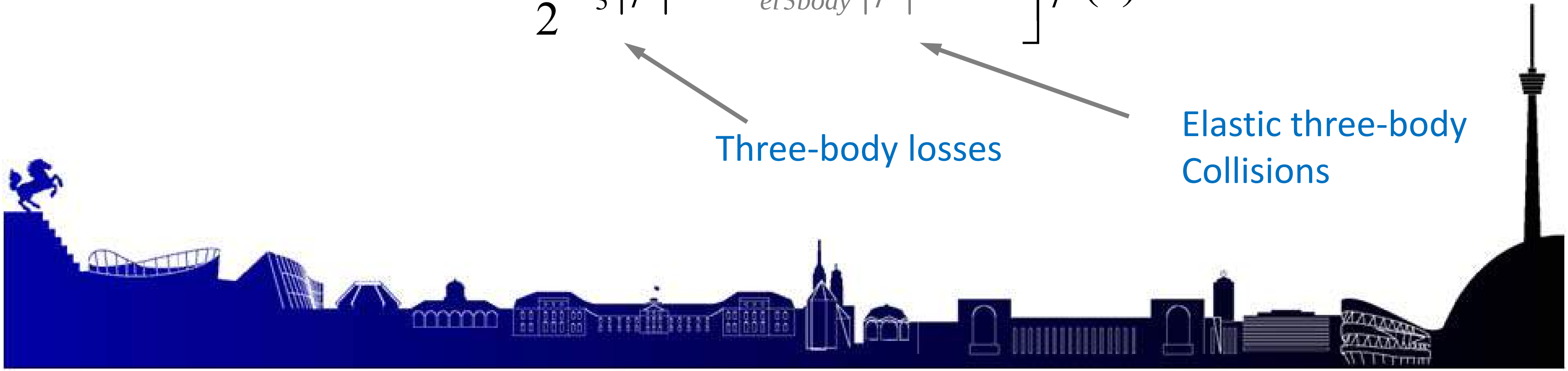
Dipolar (tune by geometry)

Quantum fluctuations

$$\sim\left(na^3\right)^{3/2}$$

Three-body losses

Elastic three-body
Collisions



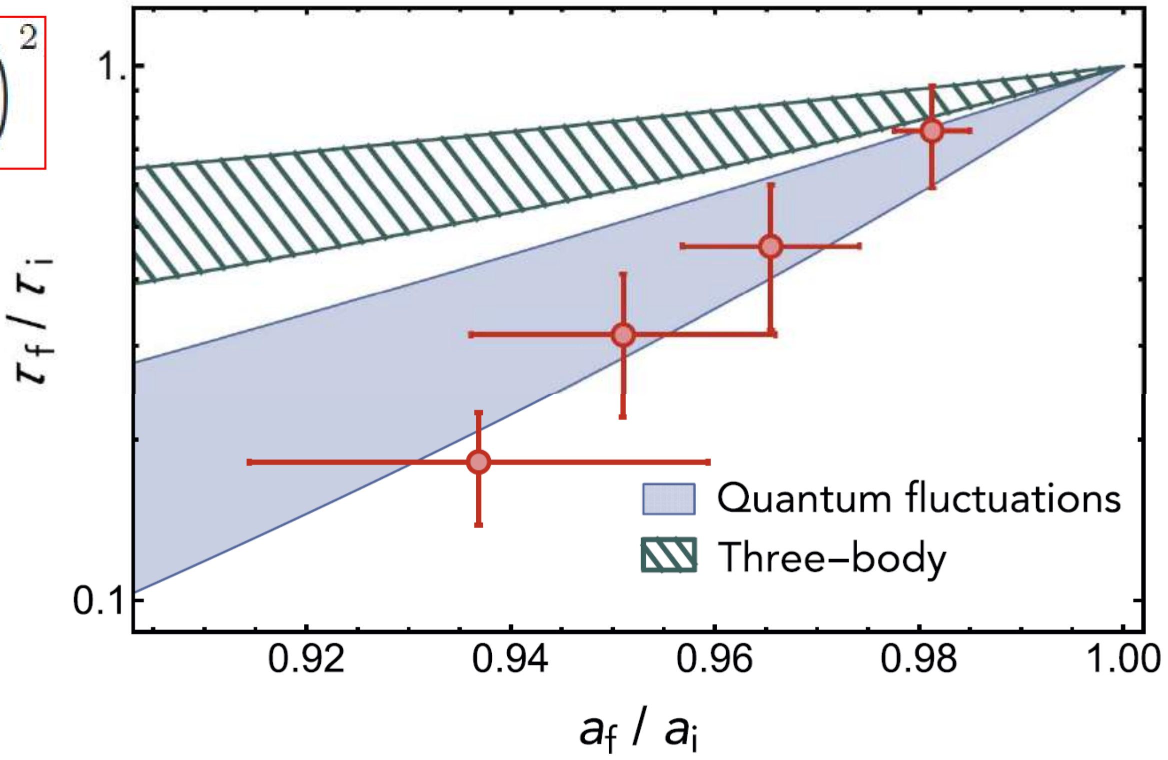
Quantum fluctuations stabilitze droplets?

I. Ferrier-Barbut et al., PRL **116**, 215301 (2016)

Check scaling bevaviour

$$n_0 = \frac{\pi}{a^3}\left(\frac{\epsilon_{\mathrm{dd}} f_{\mathrm{dip}}(\kappa) - 1}{16(1 + 3\epsilon_{\mathrm{dd}}^2/2)}\right)^2$$

$$\tau = 1/L_3\langle n^2\rangle$$

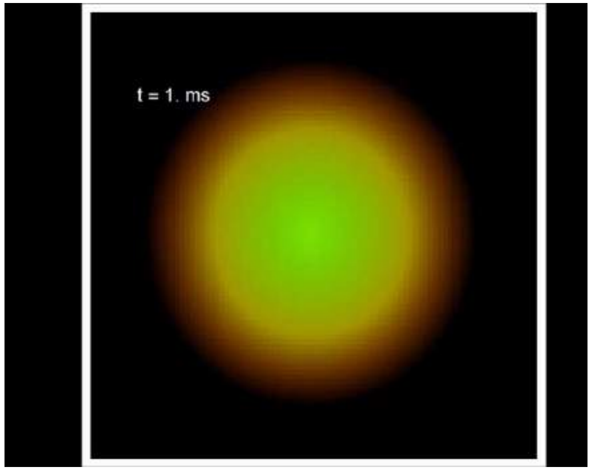


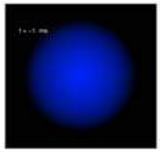
→ **Quantum liquid:** but at 8 orders lower density than lHe

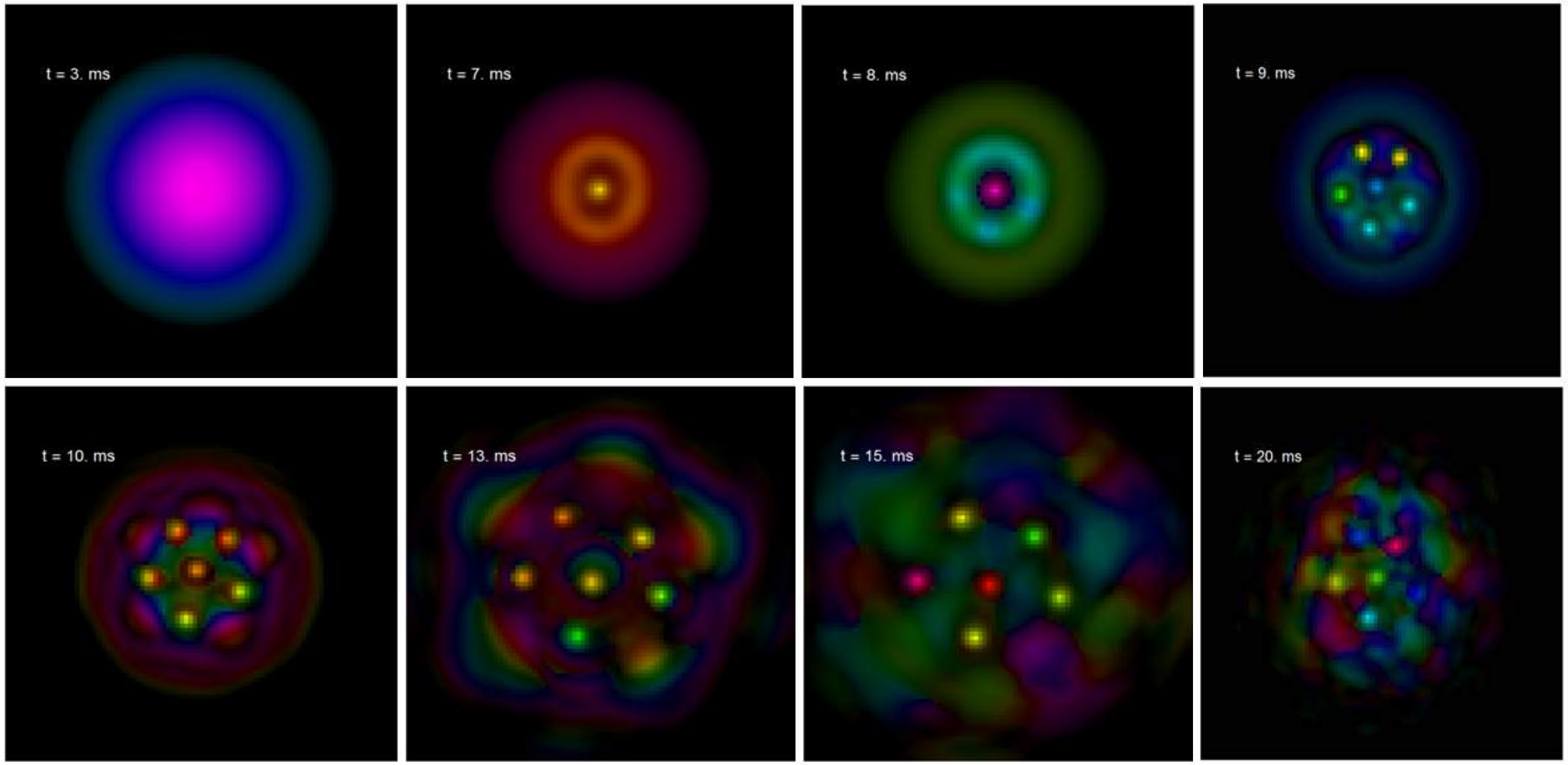
Recently also confirmed for Er by F.Ferlaino/L.Santos group

Simulated formation dynamics

GPE by M. Wenzel
plus Qfluctuations in LDA
plus inelastic 3body loss







See also **arXiv:1607.07184:** A. Macia et al.: using exact Path Integral Ground State Monte Carlo

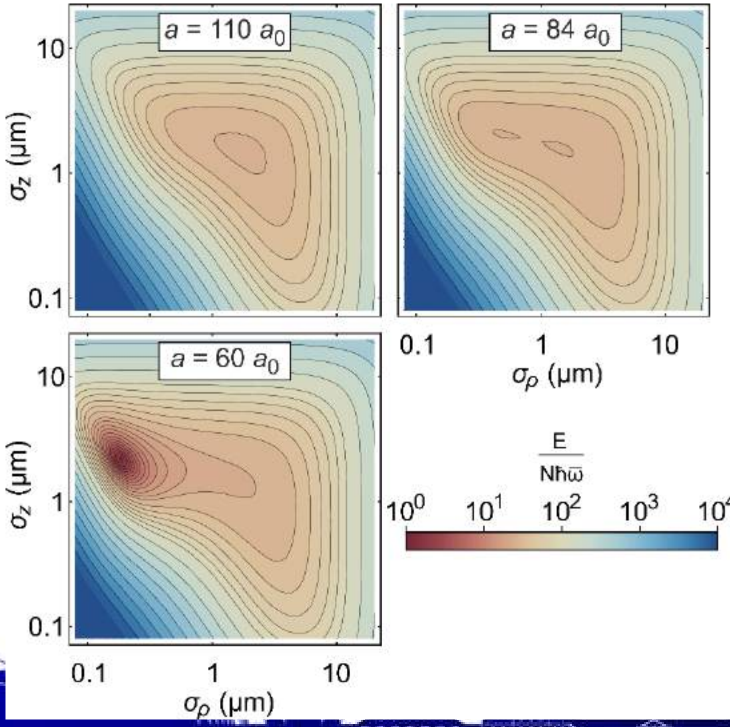
Properties of a trapped dipolar BEC

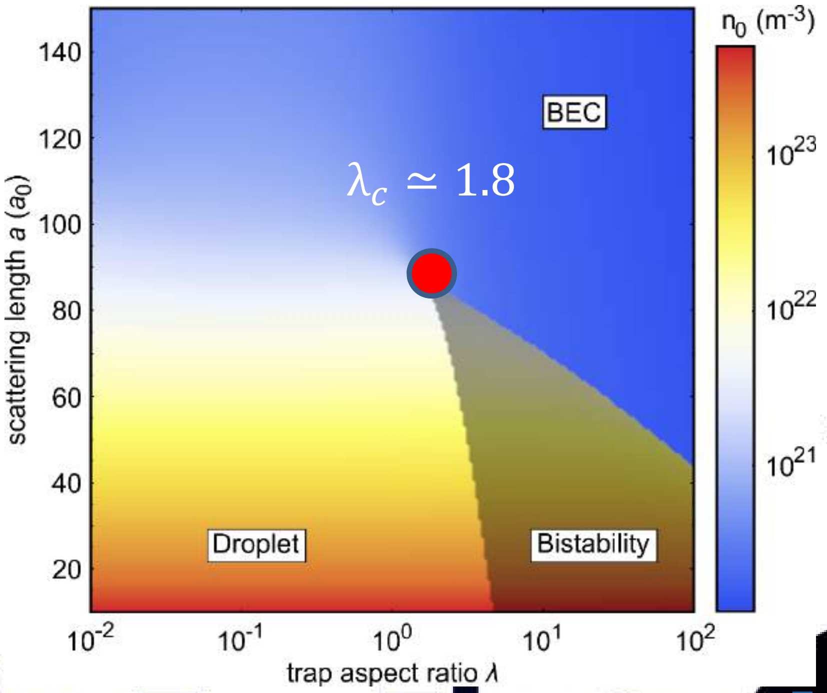
Energy density

Quantum fluctuations

$$e = e_{MF} + e_{BMF} = \frac{\hbar^2 \nabla^2}{2m} n + V_{\text{ext}}(\boldsymbol{r}) n + \frac{g n^2}{2} + \frac{n}{2} \int d^3 r' V_{\text{dd}}(\boldsymbol{r} - \boldsymbol{r}') n(\boldsymbol{r}') + \boxed{\frac{64}{15} g n^2 \sqrt{\frac{n a^3}{\pi}} \left(1 + \frac{3}{2} \varepsilon_{\text{dd}}^2\right)}$$

- energy functional to calculate energy landscape ($\lambda = 2;\ N = 8.000$)

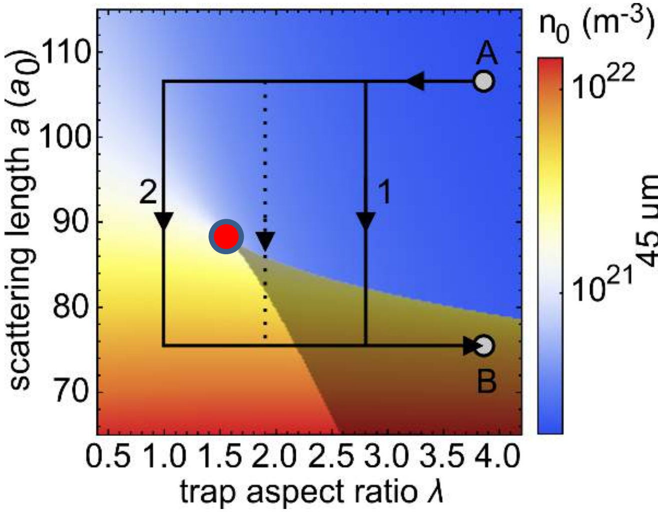


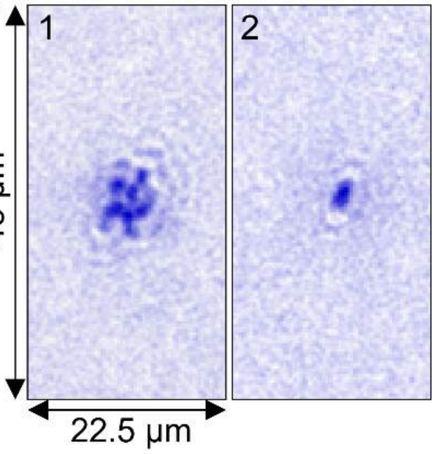


$\lambda_c \simeq 1.8$

PRA 94, 033619 (2016), PRA 94, 043618 (2016)

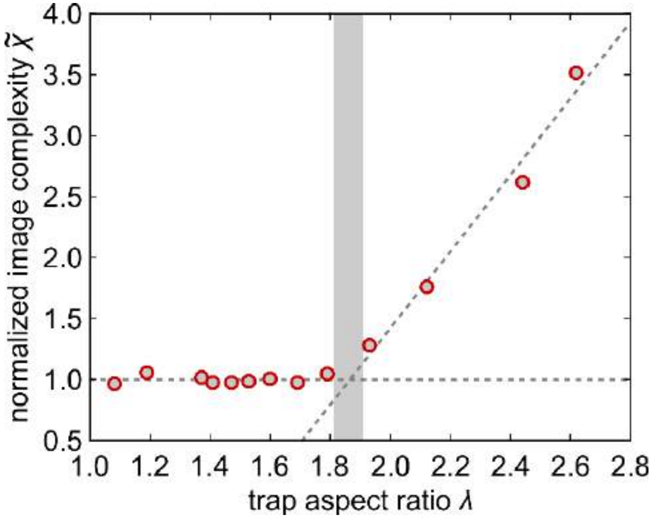
„critical“ trap aspect ratio





- Principal component analysis
- extract image complexity

$$\lambda_c = 1.87(8)$$

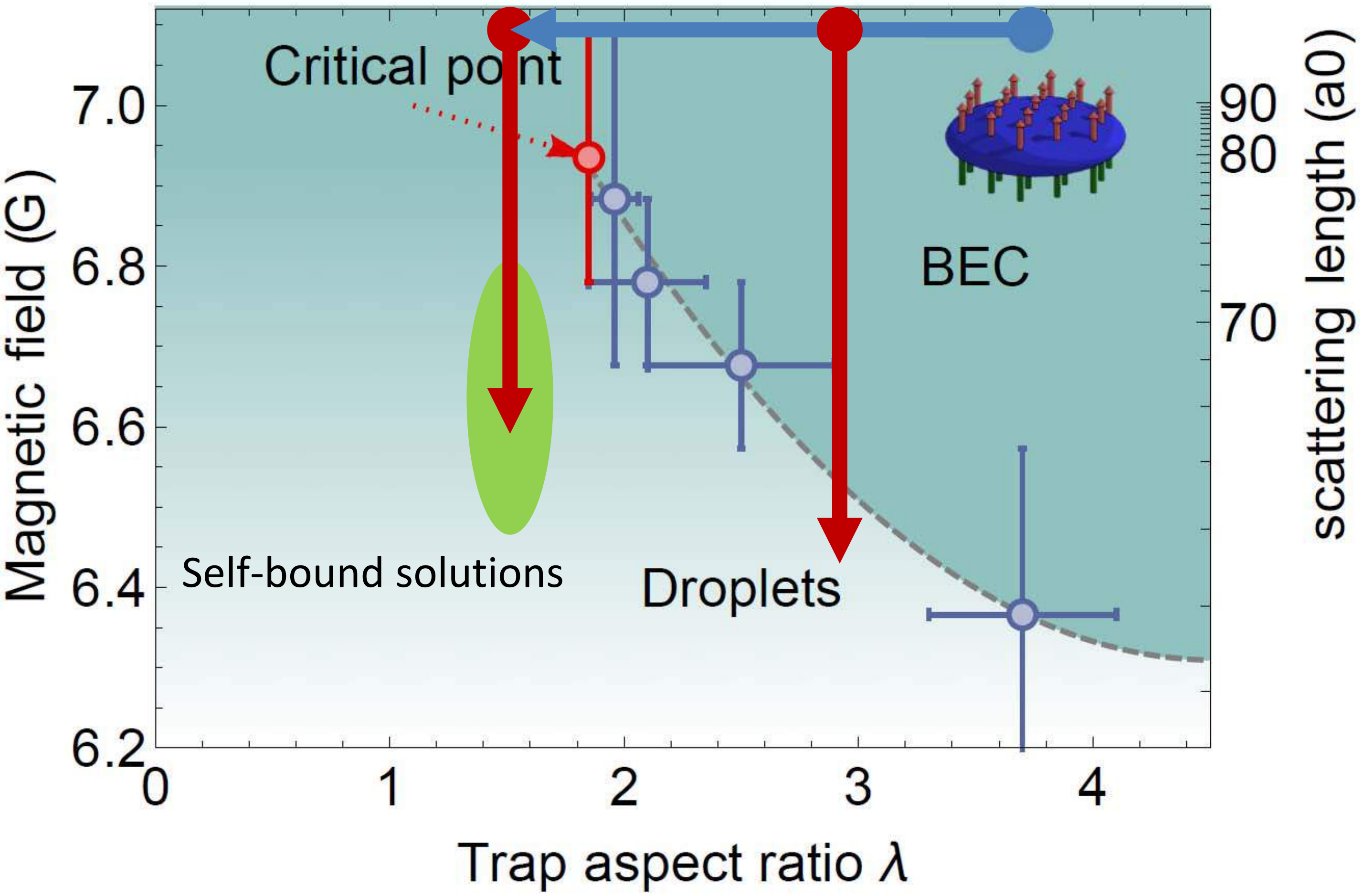


- simulations on effective Gross-Pitaevskii equation predict:

$$\lambda_c \simeq 1.8$$

*PRA **93**, 033644 (2016)*
*PRA **94**, 043618 (2016)*

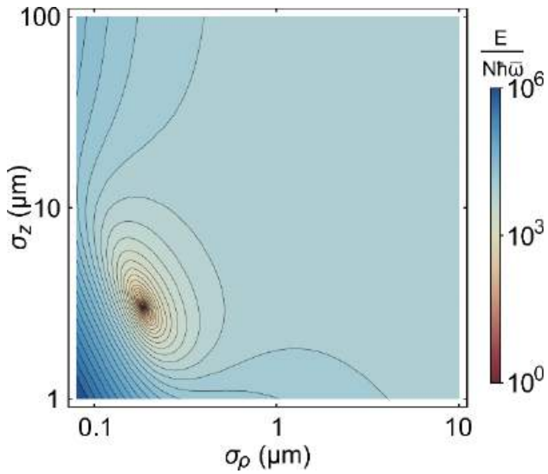
Prepare single self-bound droplets



See theory by Blakie, Santos, Saito

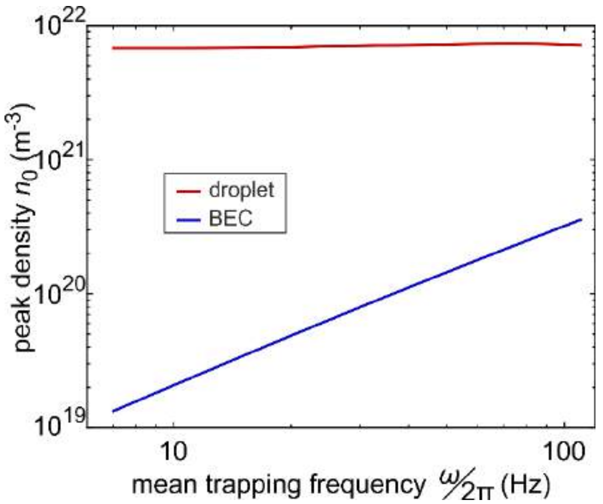
Droplet state

remove trapping potential

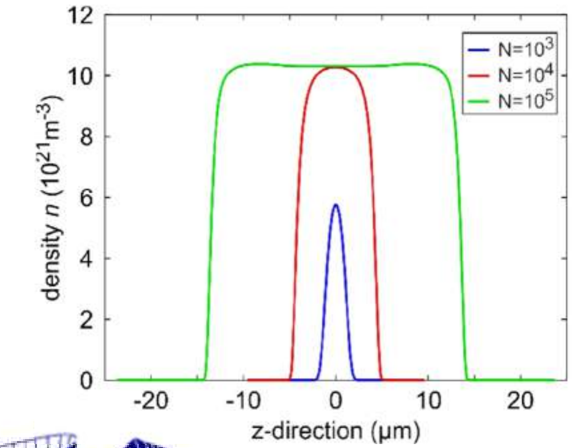


droplet is self-bound in 3D

Compression of a droplet vs. BEC



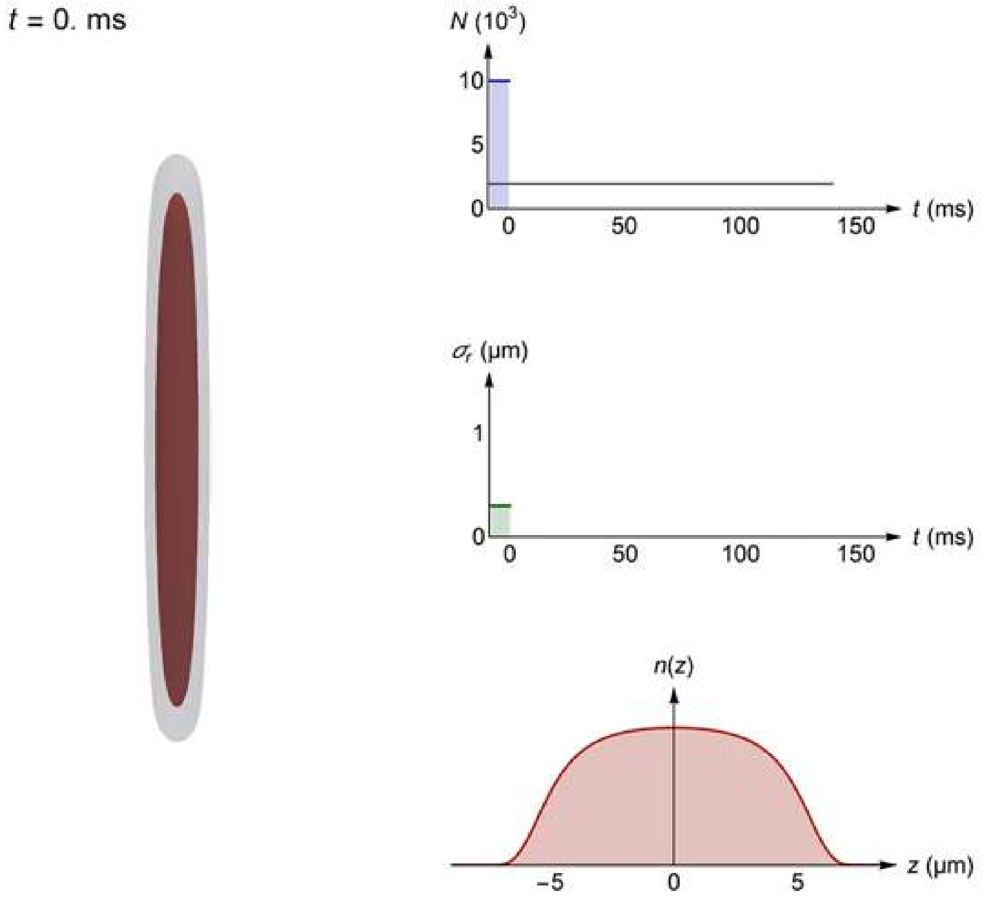
droplet is nearly incompressible



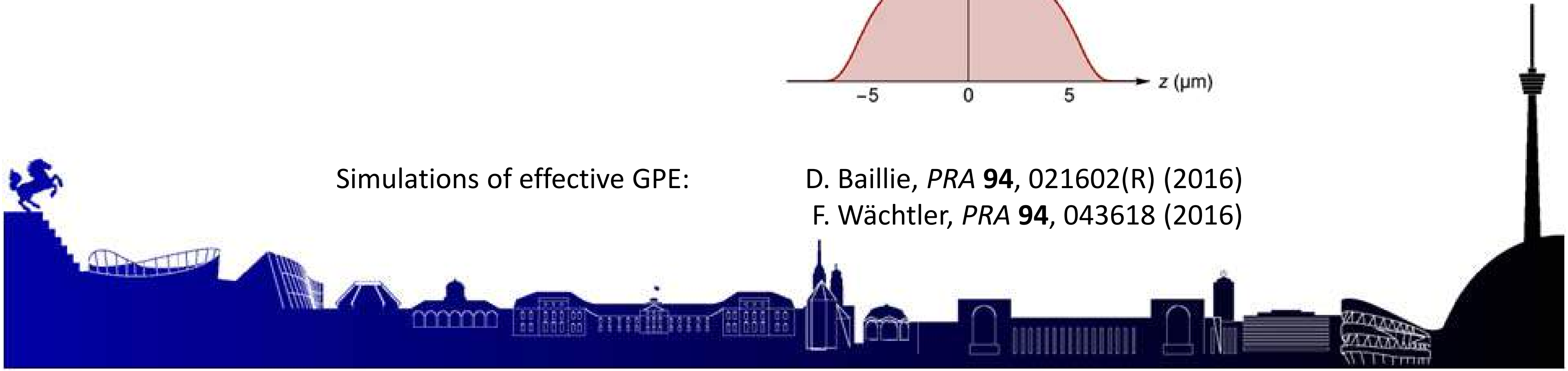
→ **quantum liquid**

predicted by:
*PRA **94**, 021602(R) (2016)*
*PRA **94**, 043618 (2016)*

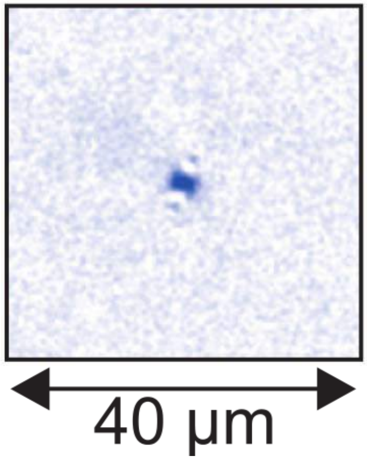
Droplet Time Evolution

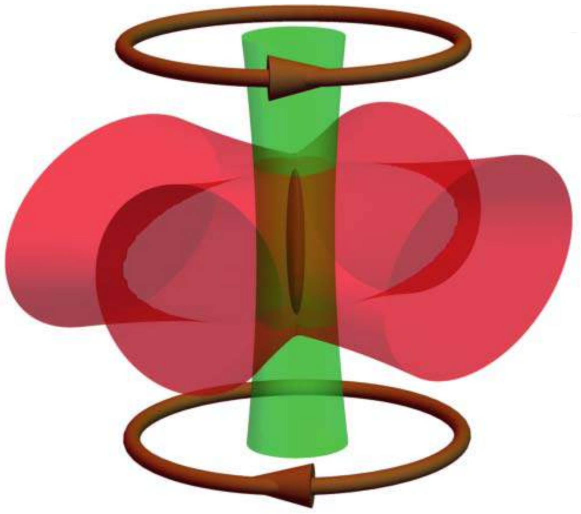


Simulations of effective GPE: D. Baillie, *PRA* **94**, 021602(R) (2016)
F. Wächtler, *PRA* **94**, 043618 (2016)

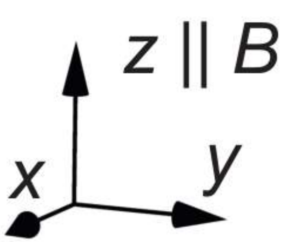


Experimental Scheme

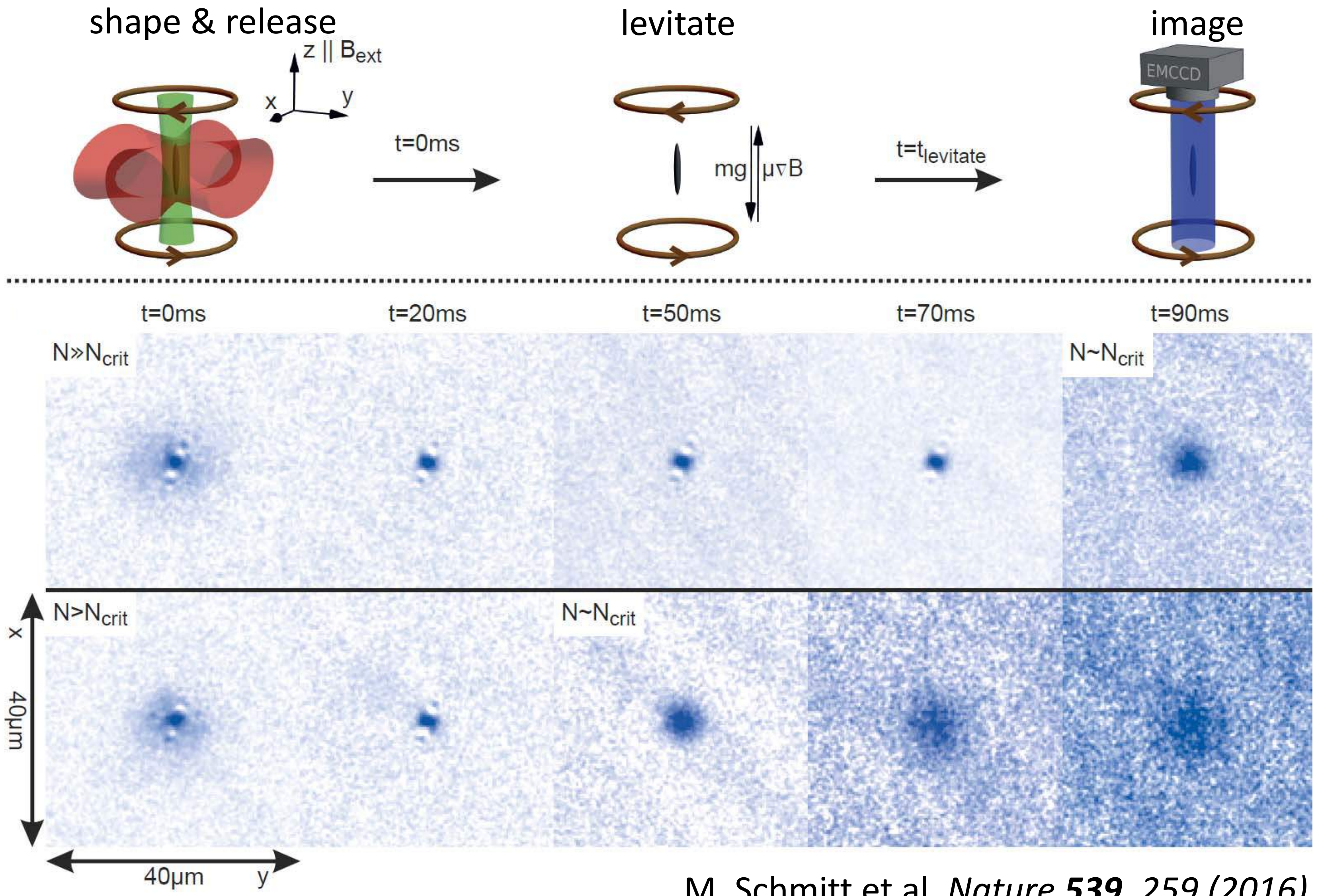




1. Prepare in traps
   $\lambda = \omega_z/\omega_r = 1.5$
   at certain B

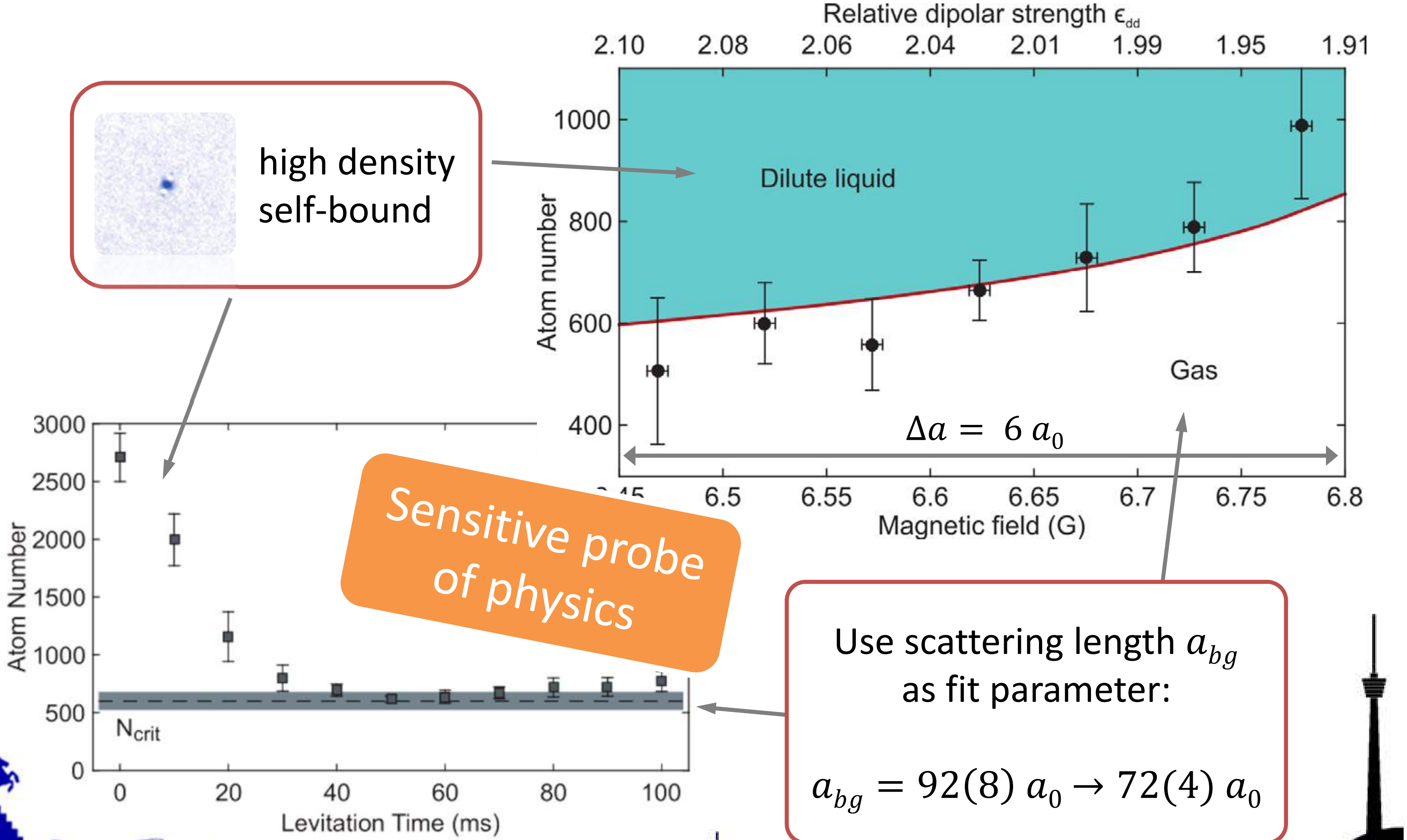


Self-bound droplet preparation



M. Schmitt et al. *Nature* ***539****, 259 (2016)*

Phase Transition



high density
self-bound

$\Delta a = 6\ a_0$

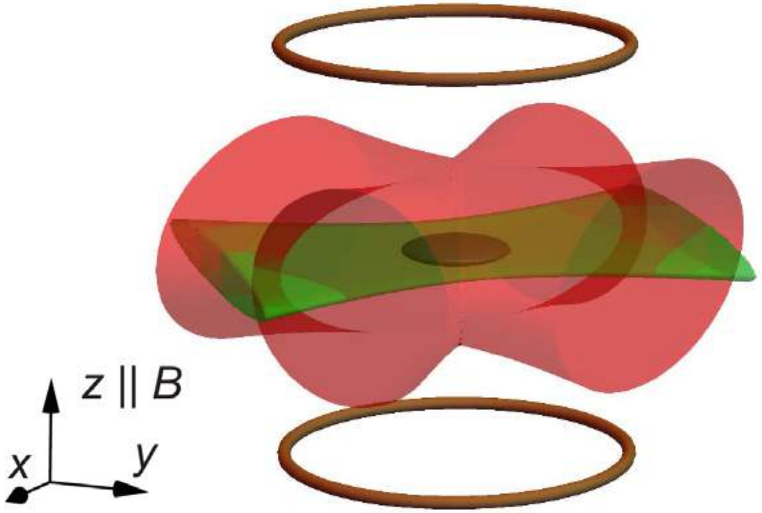
Sensitive probe of physics

Use scattering length a_{bg}
as fit parameter:

$$a_{bg} = 92(8)\ a_0 \rightarrow 72(4)\ a_0$$

M. Schmitt, *Nature* **539**, 259 (2016)

Change dimensionality

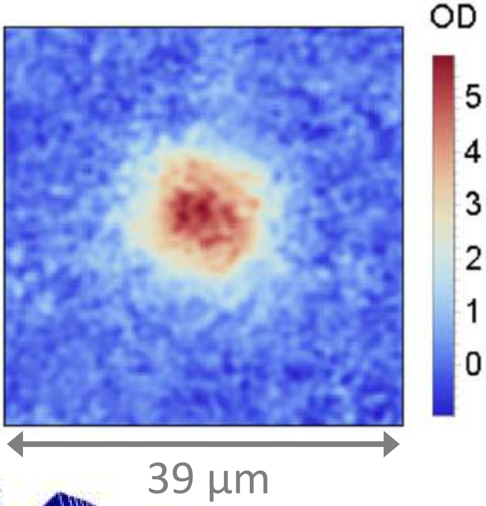


- Scaling of quantum fluctuations:
  - 3D: $e_{LHY} \propto n^{5/2}$ repulsive and $e_{MF} \propto n^2$

    Lee, Huang & Yang, *Phys. Rev.* **106**, 1135 (1957)
  - 2D: $e_{LHY} \propto n^2 \log(n)$ in BBM ?

    Petrov & Astrakharchik, *PRL* **117**, 100401 (2016)
  - 1D: $e_{LHY} \propto n^{\approx 3/2}$ attractive ?

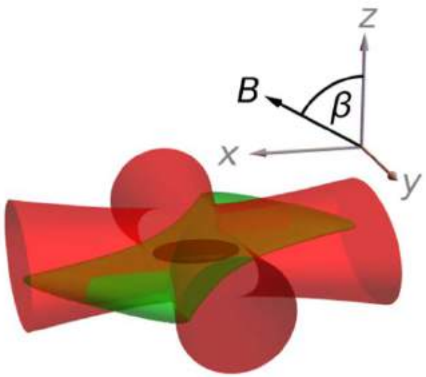
    Mishra et al., arXiv:1610.09176 (2016)



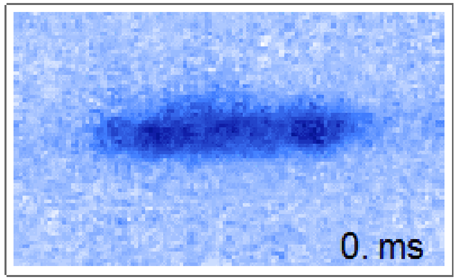
- Lightsheet at 532 nm:
  - short axis: $w_z \approx 3$ µm
  - $\omega_z = 2\pi$ (200 – 2000) Hz
- Dy BEC in a flat trap
  - $\omega = 2\pi$ (46, 43, 930) Hz

Strong confinement in z

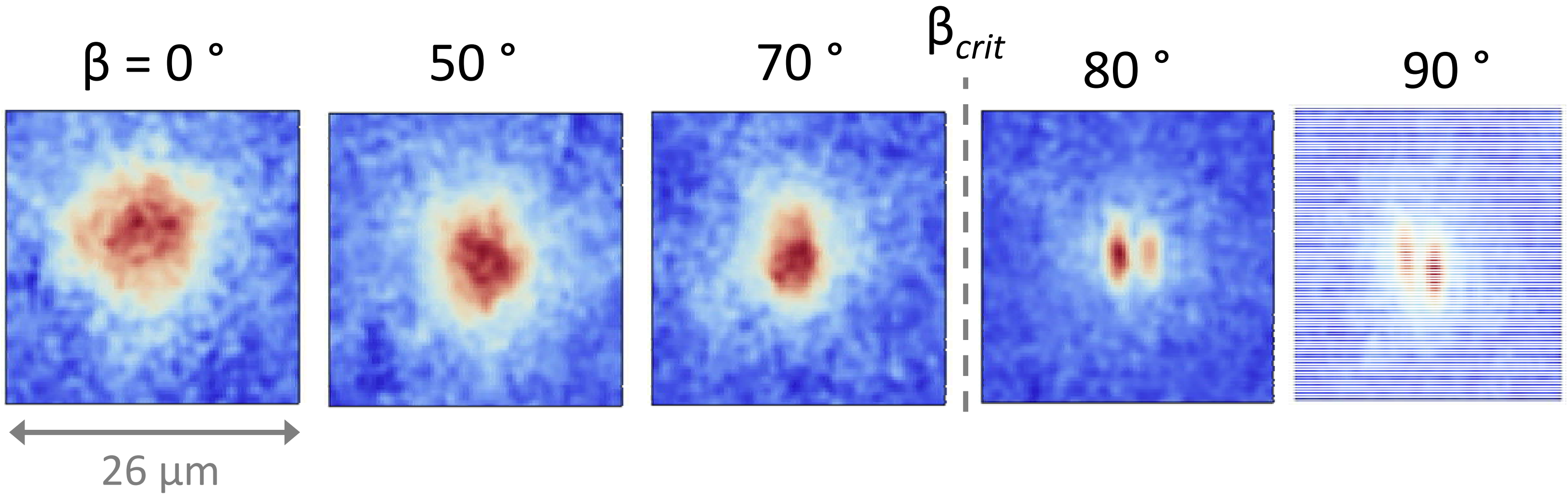
and tilt of magnetic field from z to x

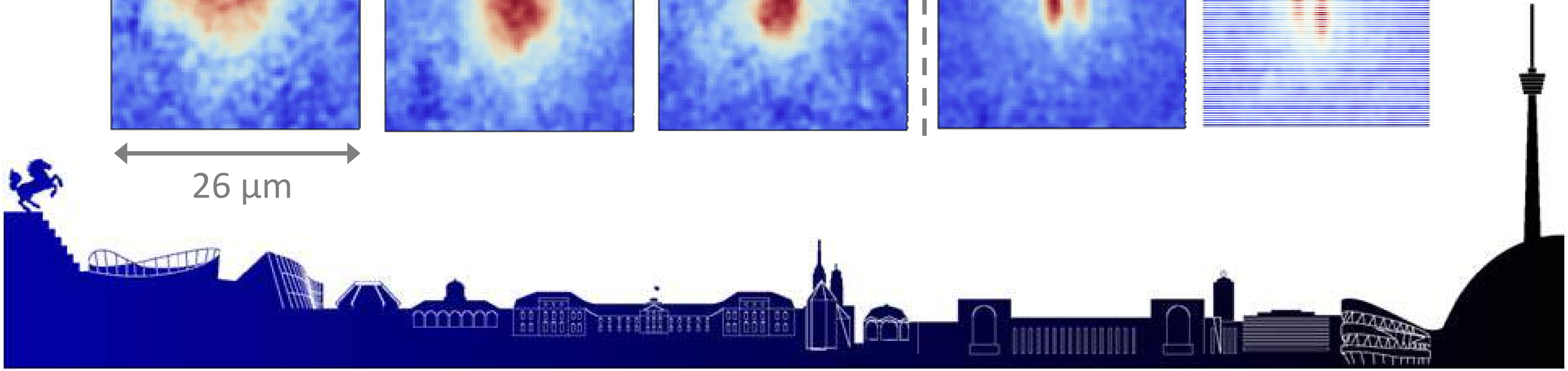


Fast quench: collapse

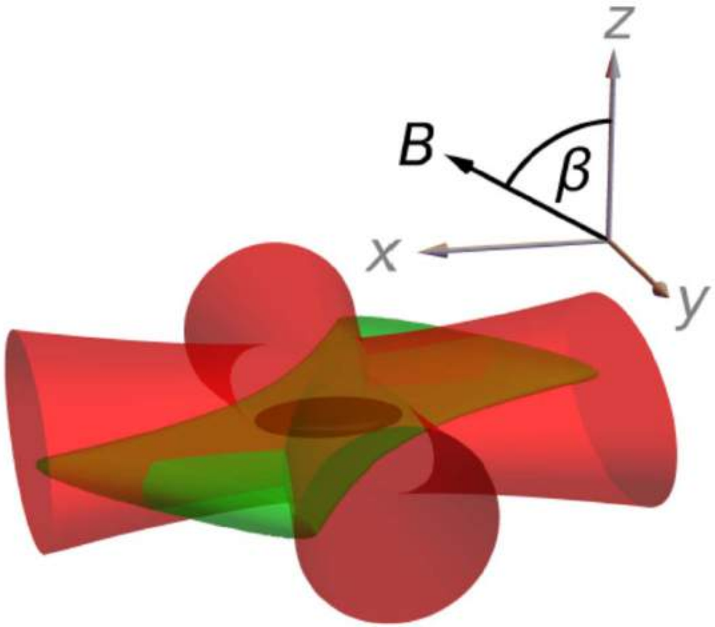


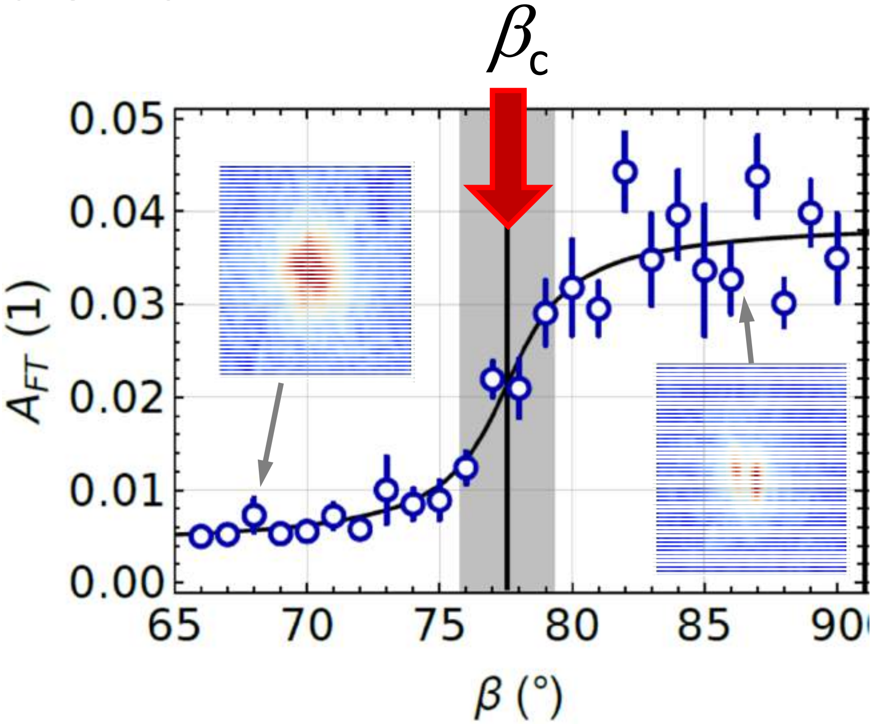
Slow quench: stripe formation

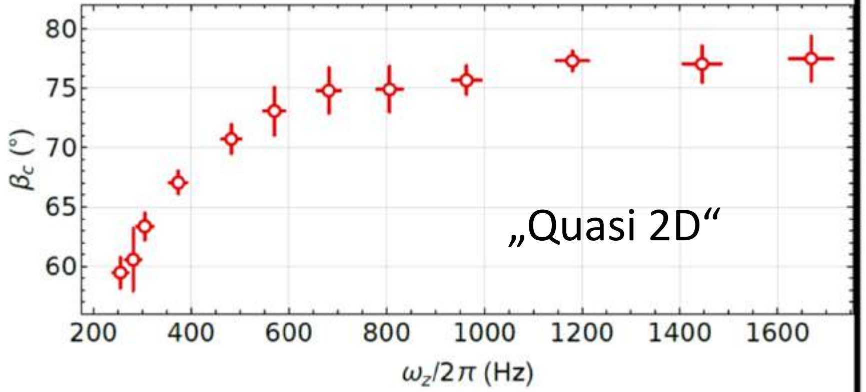




Slow quench

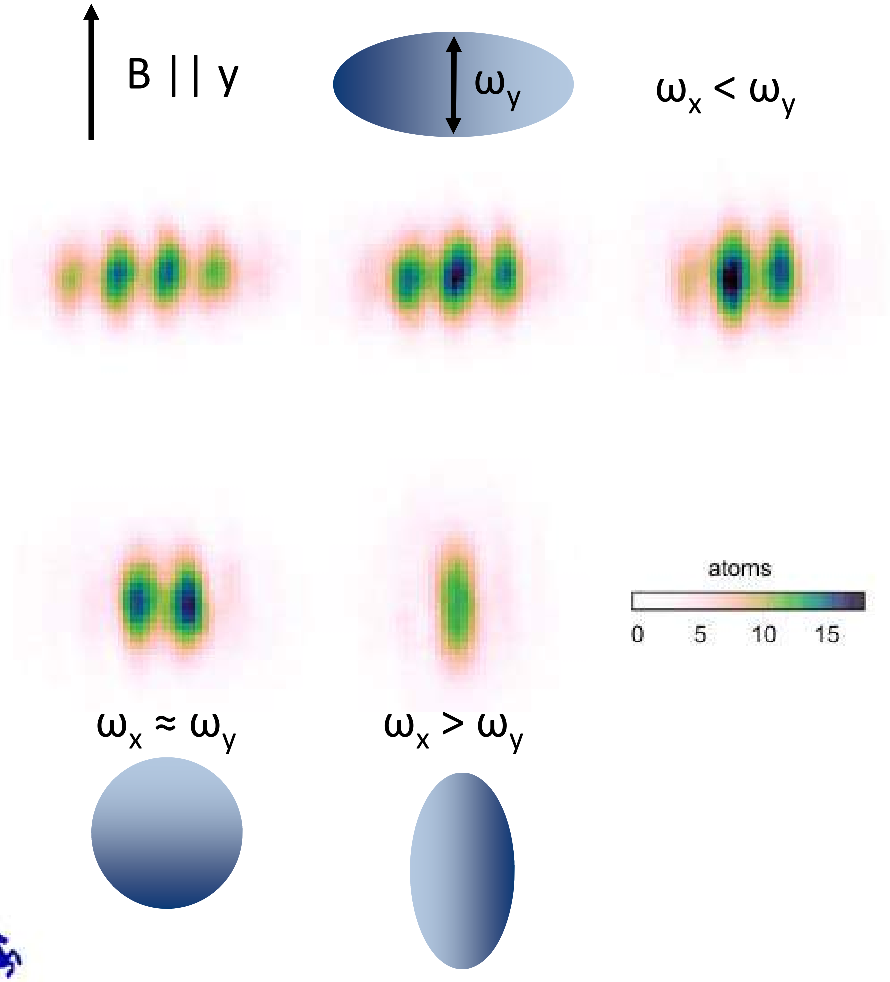






„Quasi 2D“

Stripe phase: Experiment & Theory



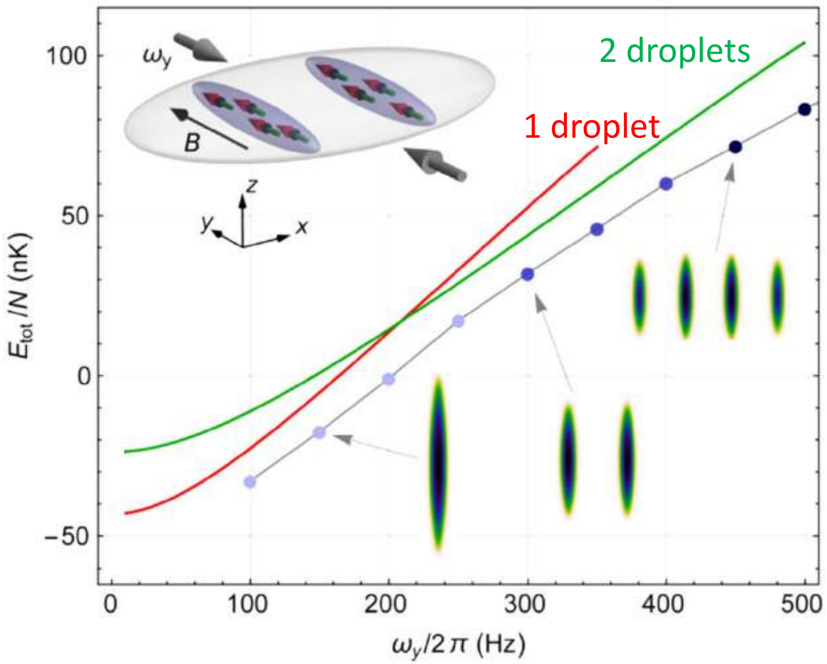
B || y

ω_y

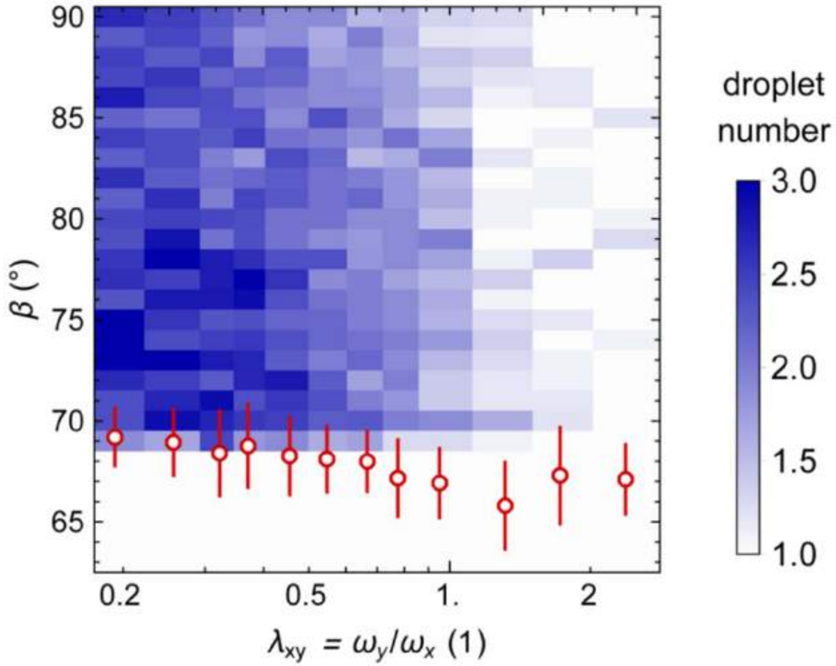
$\omega_x < \omega_y$

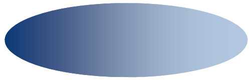
$\omega_x \approx \omega_y$

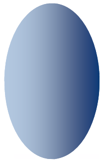
$\omega_x > \omega_y$

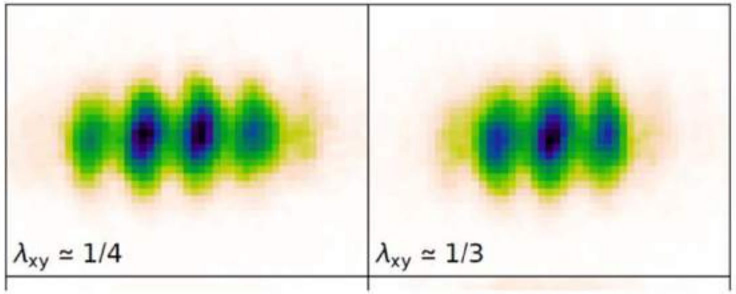


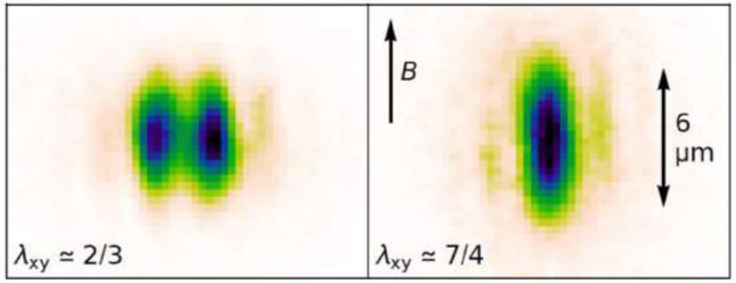
Systematic study of stripe formation





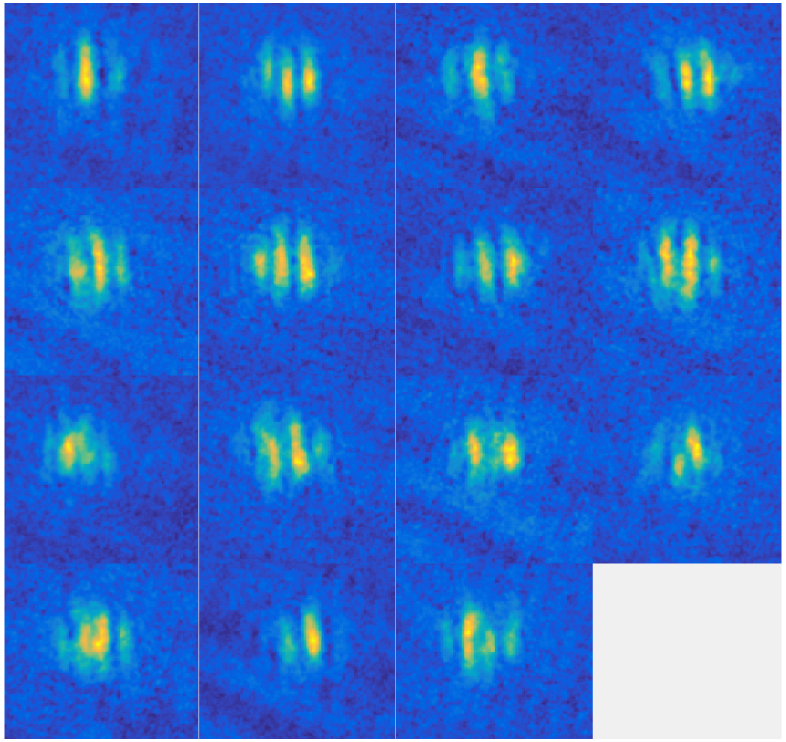


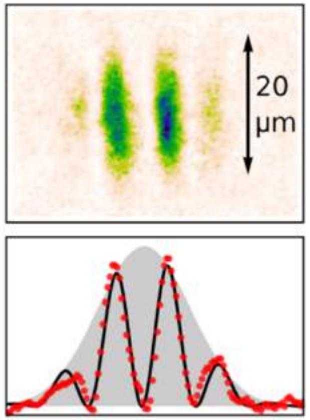


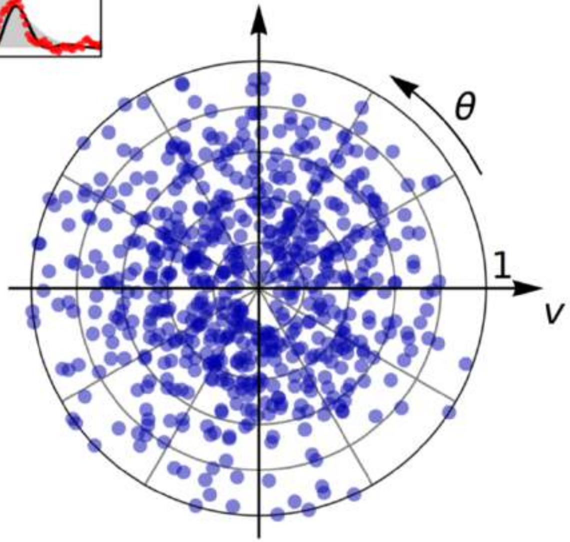


Interference? ➡ no phase coherence ☹

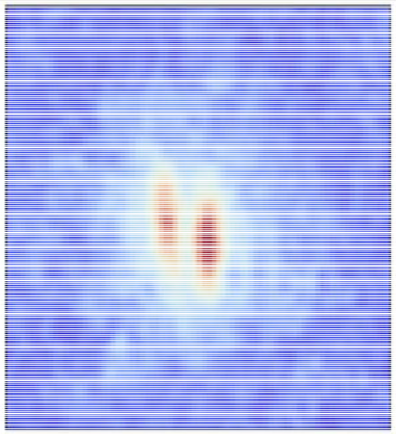
8 ms expansion with Feshbach boost
Initial state: Double droplets







Phase coherence?

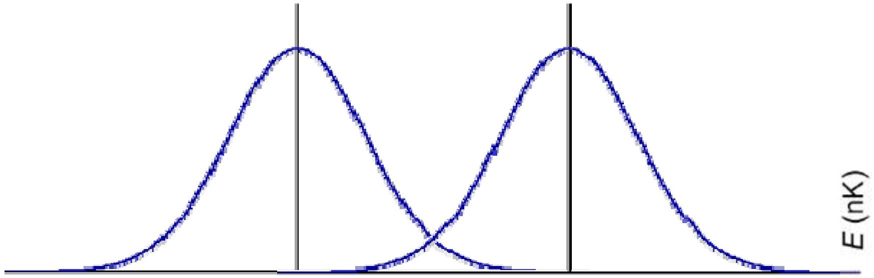


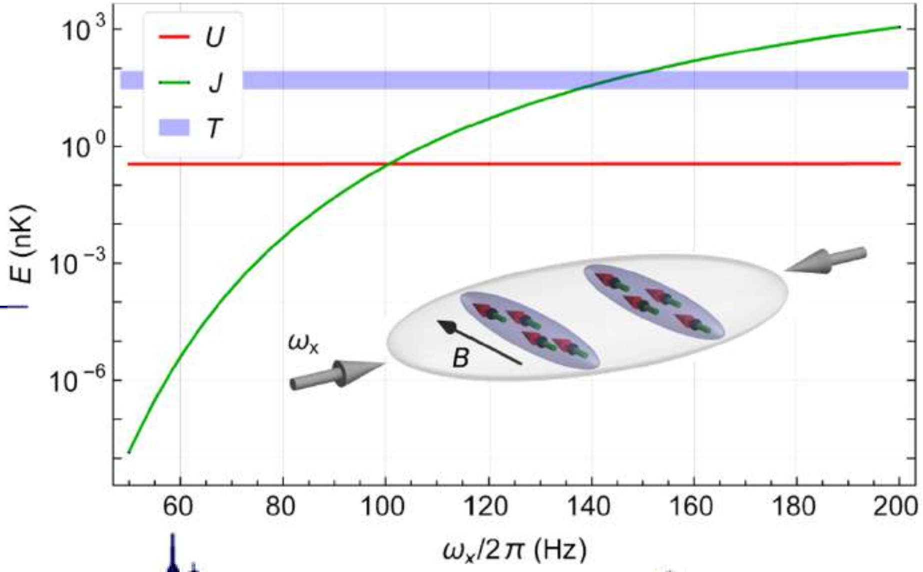
$\Delta\mu \propto \Delta N$

Josephson - tunnel coupling J

Interaction U

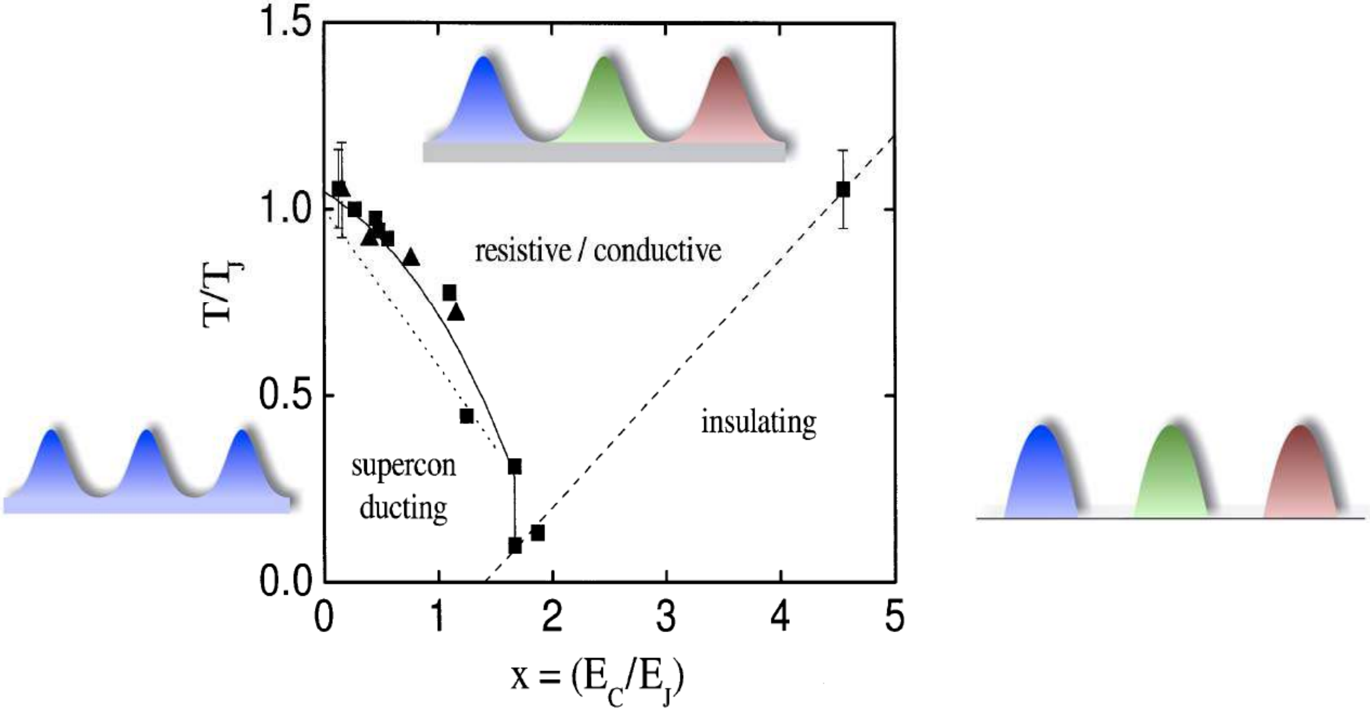
$e^{-iE_1 t/\hbar}$ $e^{-iE_2 t/\hbar}$





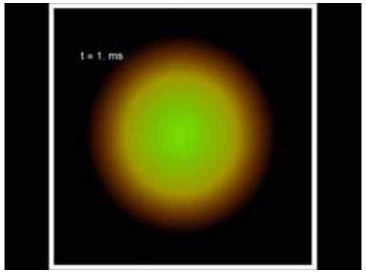
Quantum phase transitions and vortex dynamics in superconducting networks

R. Fazio, H. van der Zant / Physics Reports 355 (2001) 235–334



Can there be a super solid state of matter?

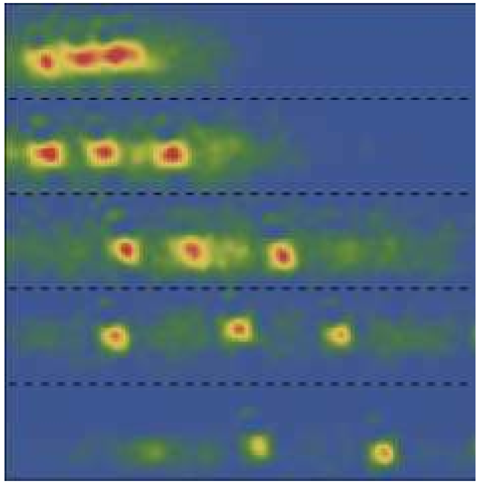
H.S.J. van der Zant, W.J. Elion, L.J. Geerligs, J.E. Mooij, Phys. Rev. B 54 (1996) 10081.
J.V. Josè, C. Rojas, Physica B 203 (1994) 481; Phys. Rev. B 54 (1996) 12361.



Conclusion & Outlook

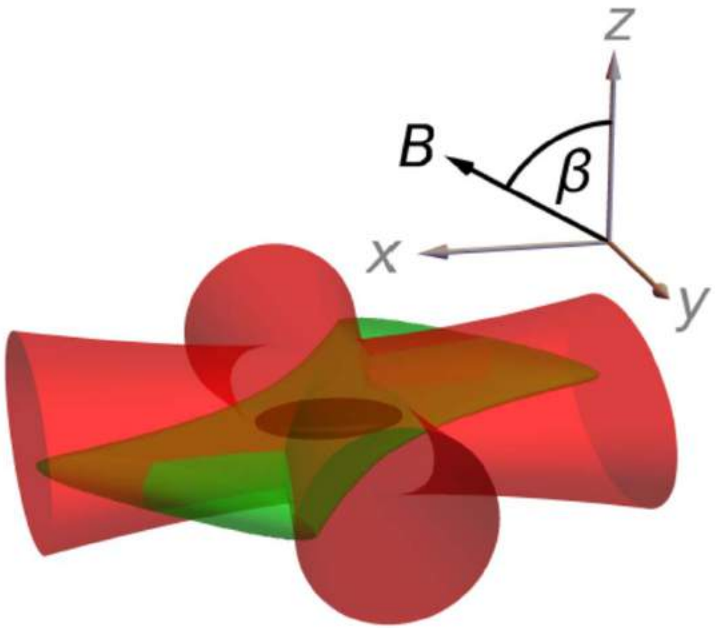
- Instability leads to stable droplets
- Droplets bounce and interfere
- Stabilization by LHY term

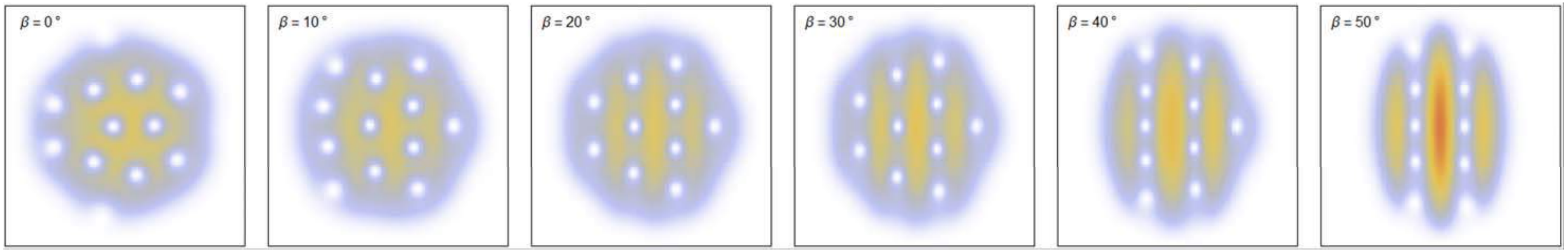
  Santos, Blakie, Saito
  Erbium exp. (F. Ferlaino)
  ^{39}K/^{41}K exp. (L. Tarruell ICFO)



- Dy droplets are selfbound in 3D
- Stripe formation in „Quasi-2D“ regime
- Rotating droplets

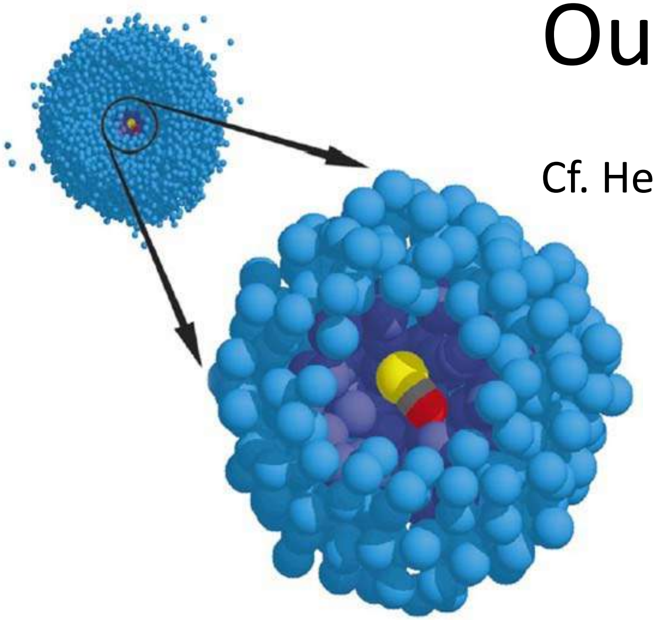
Coming up in the lab: Stripe formation in a dipolar vortex lattice



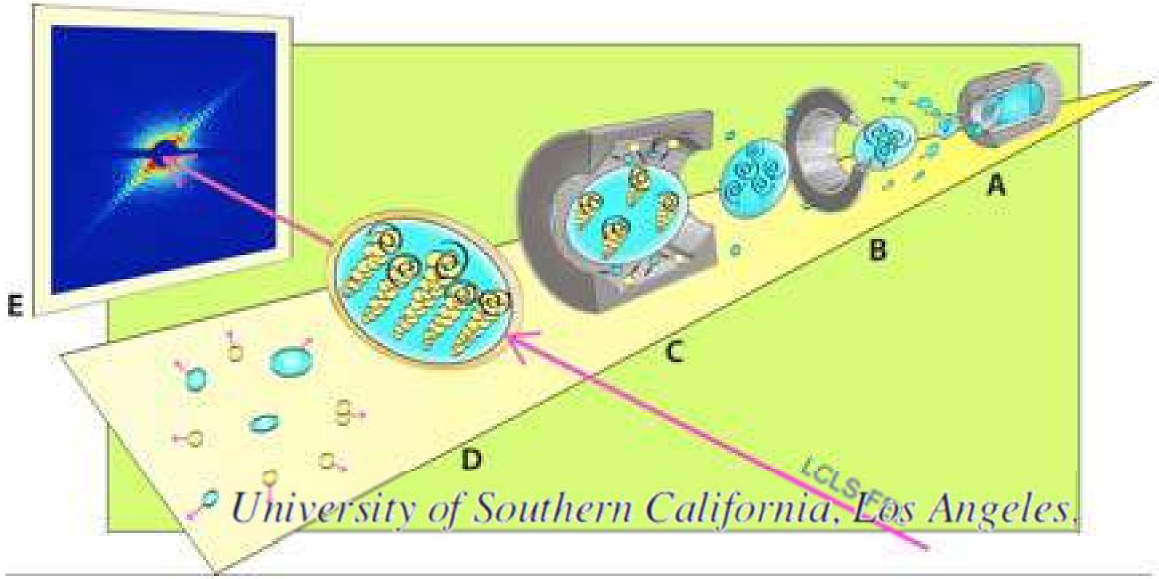


N. R. Cooper, E. H Rezayi and S. H. Simon,
Phys. Rev. Lett. **95**, 200402 (2005)
J. Zhang and H. Zhai,
Phys. Rev. Lett. **95**, 200403 (2005)

Outlook on quantum droplets:

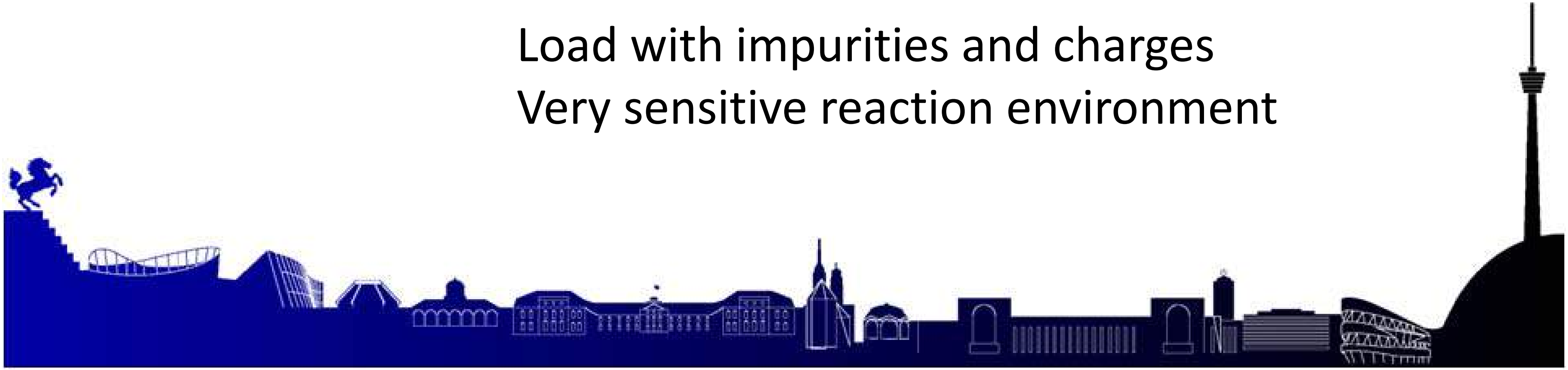


Cf. Helium droplets (Toennies, Vilesov et al.)



Load with impurities and charges

Very sensitive reaction environment



The Team

Now @ Trumpf

Matthias Schmitt

Igor Ferrier-Barbut

Matthias Wenzel

Fabian Böttcher

Tim Langen
(not on pic)

Positions available

Thank you for your attention!

H. Kadau, el al.
Nature ***530****, 194 (2016)*

I.Ferrier-Barbut et al.,
PRL ***116****, 215301 (2016)*

I. Ferrier-Barbut, et al.
J. Phys. B: ***49,*** *214004* (2016)

M. Schmitt et al.
Nature ***539****, 259 (2016)*