Soliton-to-droplet crossover in attractive Bose-Bose mixtures

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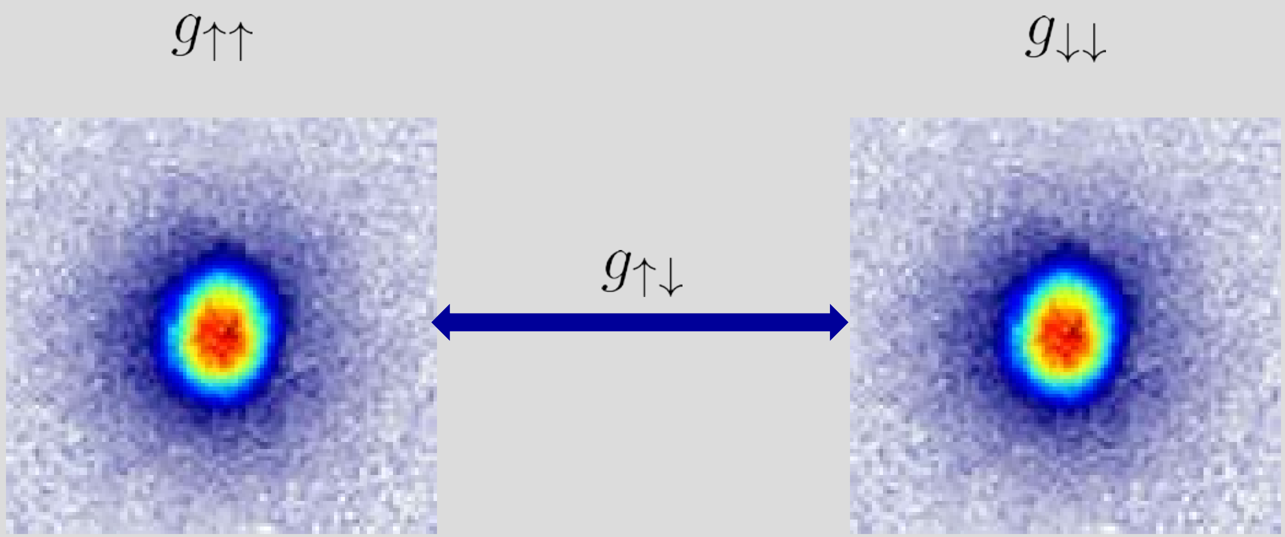
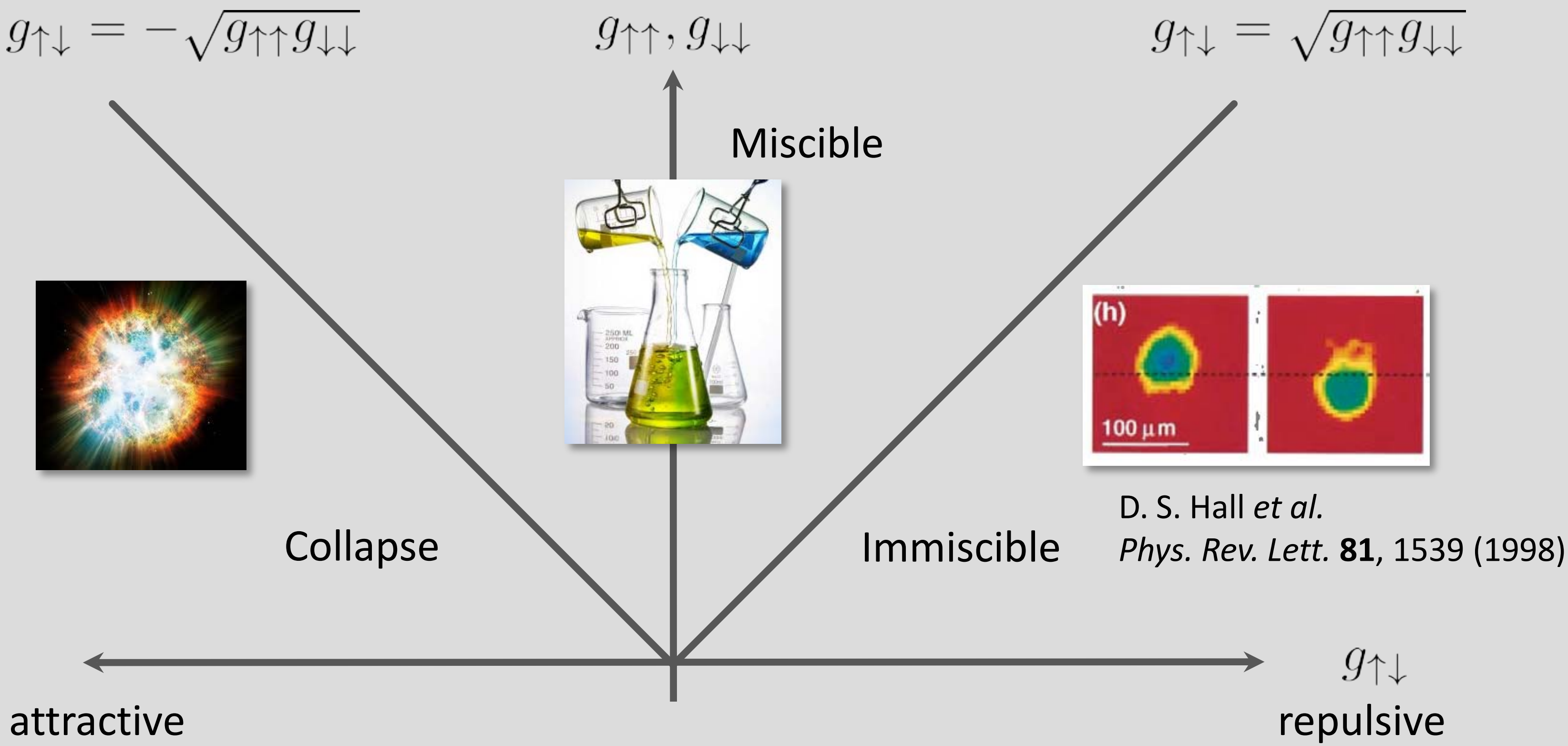
KITP – 18/11/2016

Bose-Bose mixtures



2 spin states or 2 different atoms

Mean field phase diagram



Collapse

Interaction energy of the mixture:

$$\mathcal{E}_{\rm int} = \frac{1}{2}\left(g_{\uparrow\uparrow}n_\uparrow^2 + g_{\downarrow\downarrow}n_\downarrow^2\right) + g_{\uparrow\downarrow}n_\uparrow n_\downarrow$$

$g = g_{\uparrow\uparrow} = g_{\downarrow\downarrow}$

$\delta g = -|g_{\uparrow\downarrow}| + g$

$|\delta g| \ll g$

$$\mathcal{E}_{\rm int} \sim g(n_\uparrow - n_\downarrow)^2 - \frac{|\delta g|}{2}(n_\uparrow + n_\downarrow)^2$$

Hard mode

$n_\uparrow \sim n_\downarrow$

Maximize overlap of the two components

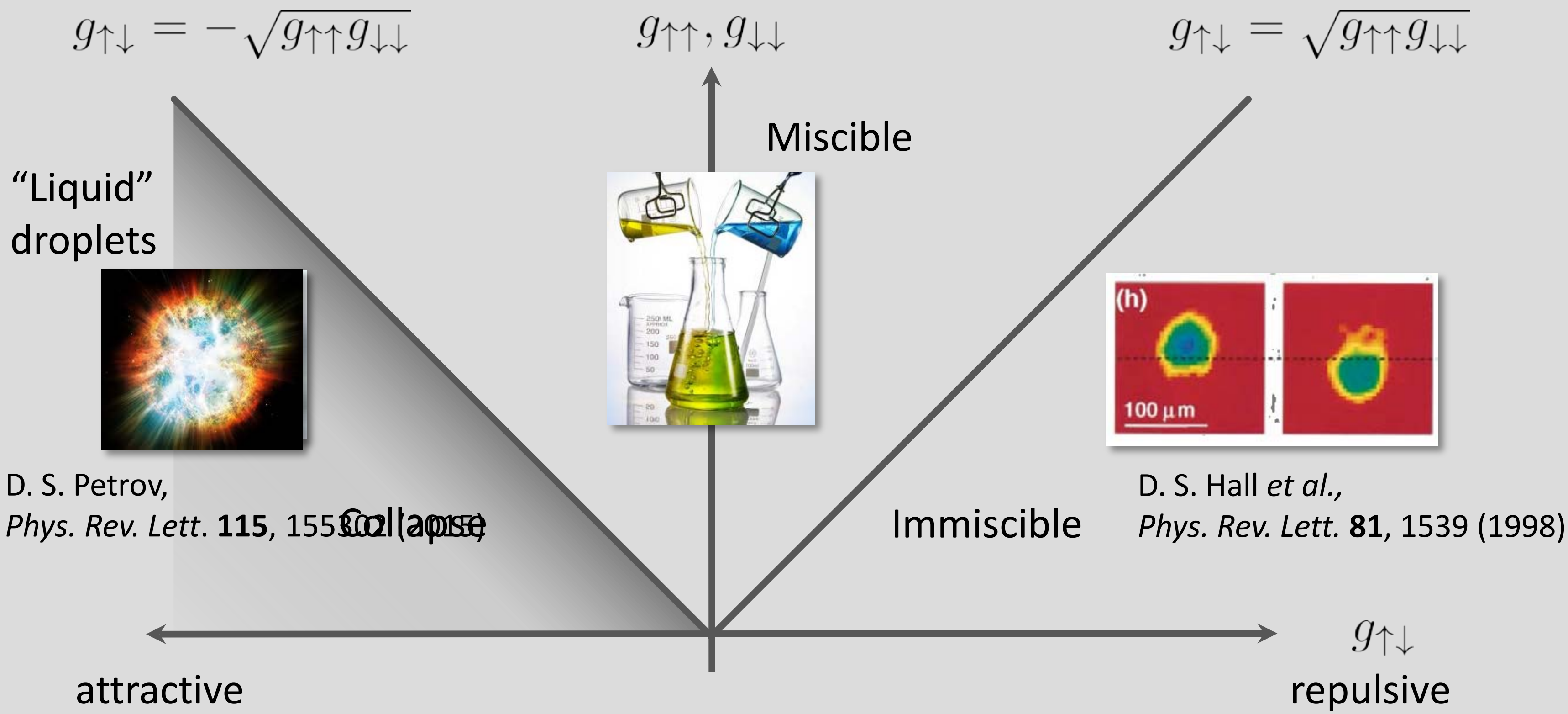
Soft mode

$n_\uparrow + n_\downarrow \to \infty$

Collapse

Beyond mean field

What about quantum fluctuations?



Energy modified by quantum depletion (Lee, Huang and Yang, 1957)

A liquid phase

$$\mathcal{E}_{\rm int} \sim g(n_\uparrow - n_\downarrow)^2 - \frac{|\delta g|}{2}(n_\uparrow + n_\downarrow)^2 + \frac{8}{15\pi^2} f\left(\frac{\delta g}{g}, \frac{n_\uparrow}{n_\downarrow}\right)\left(\frac{m}{\hbar^2}\right)^{3/2}(g n_\uparrow)^{5/2}$$

$$n_\uparrow \sim n_\downarrow = n$$

$$\mathcal{E}_{\rm int} \sim -2|\delta g|n^2 + \frac{8}{15\pi^2} f(\delta g/g)\left(\frac{m}{\hbar^2}\right)^{3/2}(gn)^{5/2}$$

Attractive
mean-field interactions

Repulsive
Lee-Huang-Yang contribution

$\mathcal{E}_{\rm MF\,soft} \propto -|\delta g| n^2$

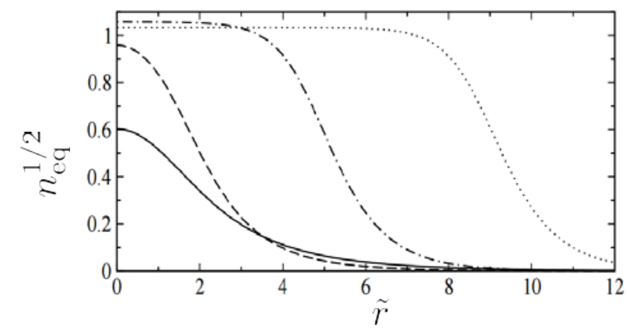
$\mathcal{E}_{\rm LHY} \propto (gn)^{5/2}$

Compensation at equilibrium density $n_{\rm eq} \propto \frac{|\delta g|^2}{g^5}$

Stable liquid droplet

- Self-bound
- Homogeneous bulk density

Ultradilute!



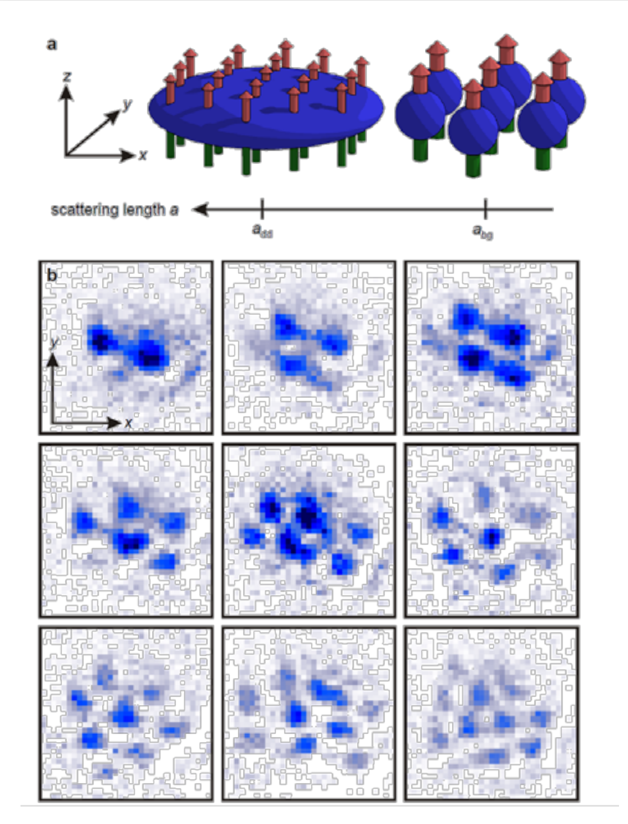
D.S. Petrov, *Phys. Rev. Lett.* **115**, 155302 (2015)

Dipolar droplets

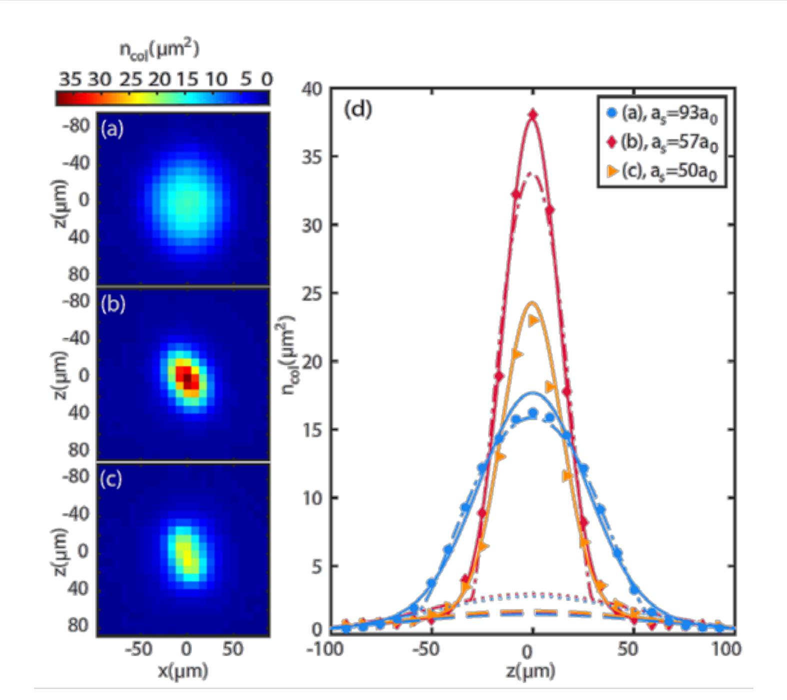
Dipolar gases: one component, two types of interactions

Dipolar (attractive) $g_{\mathrm{dd}} \Leftrightarrow g_{\uparrow\downarrow}$

Contact (repulsive) $g \Leftrightarrow g_{\uparrow\uparrow}, g_{\downarrow\downarrow}$



H. Kadau *et al., Nature* **530**, 194 (2016)
I. Ferrier-Barbut *et al., Phys. Rev. Lett.* **116**, 215301 (2016)
M. Schmitt *et al., Nature* **539**, 259 (2016)



L. Chomaz *et al.* arxiv:1607.06613 (2016)

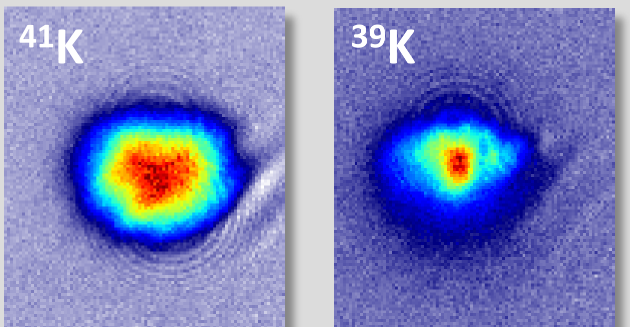
Theory:

A. Lima and A. Pelster, *Phys. Rev. A.* **84** 041604 (2011)
F. Wächtler and L. Santos, *Phys. Rev. A* **94**, 043618 (2016)
D. Baillie *et al., Phys. Rev. A.* **94**, 021602 (2016)
H. Saito, *J. Phys. Soc. Jpn.* **85**, 053001 (2016) …

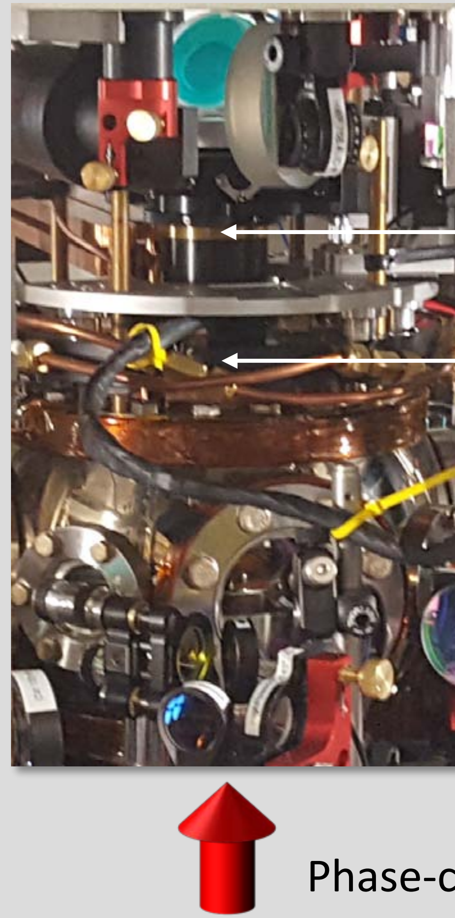
Our potassium mixture experiment

ICFO

Sympathetic cooling of ^{39}K by ^{41}K



Pure BECs of 2×10^5 atoms



Imaging objective (1.5 μm resolution)

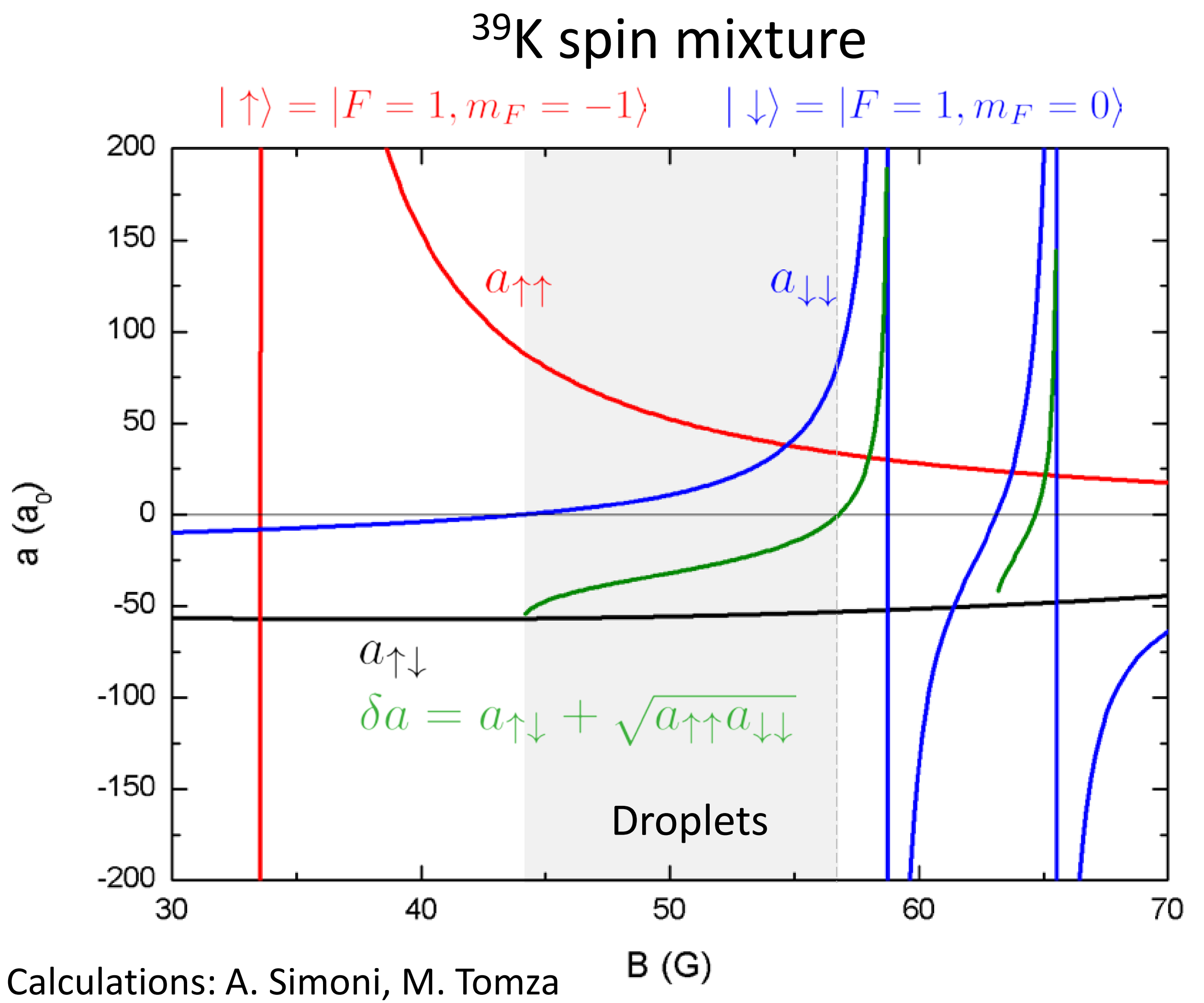
Feshbach coils

Phase-contrast imaging beam

Bose-Bose mixture: ^{39}K in 2 spin states

Adjusting interactions

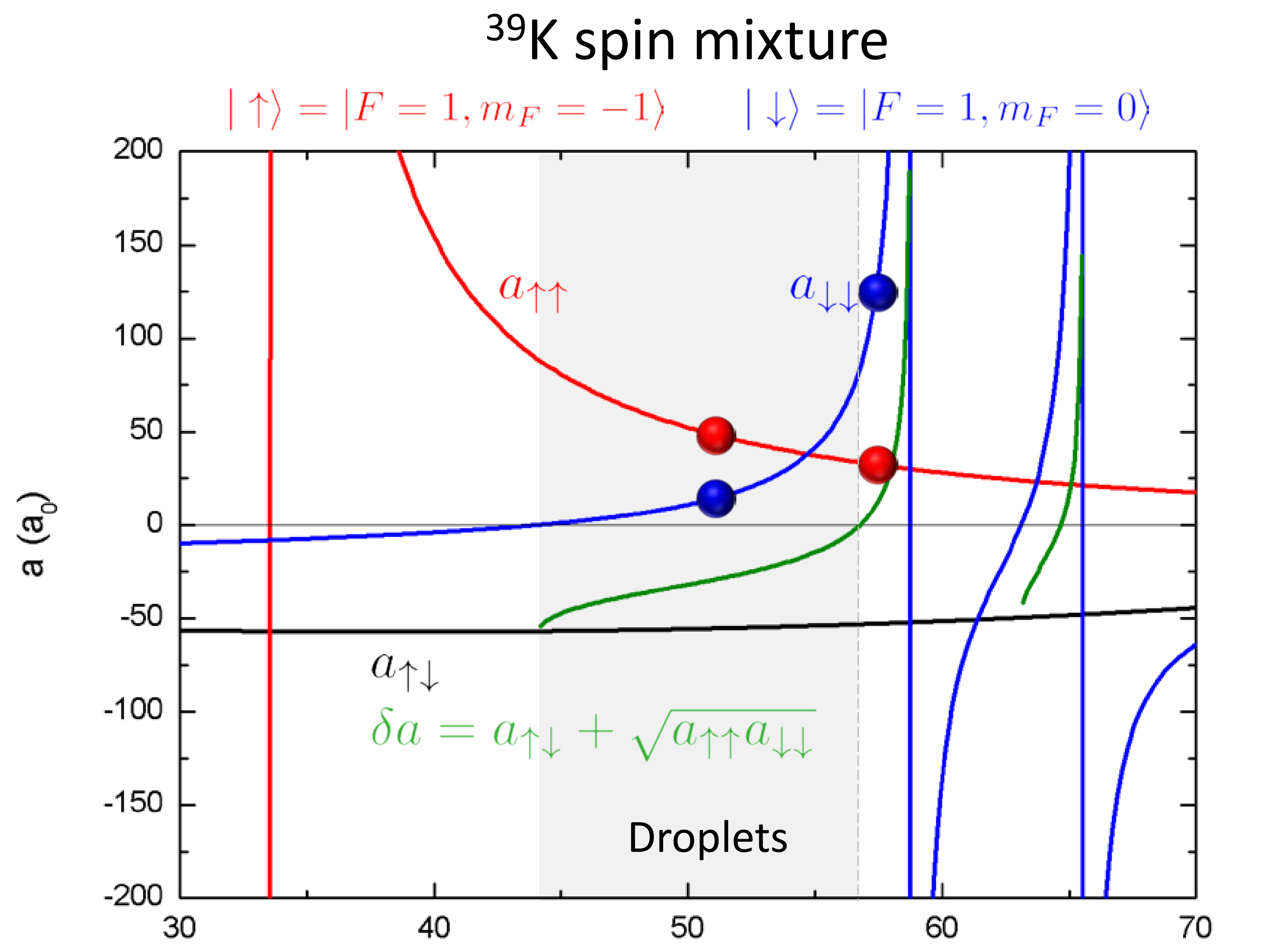
Droplets: $a_{\uparrow\uparrow}, a_{\downarrow\downarrow} > 0$ and $a_{\uparrow\downarrow} < 0$, tunable (Feshbach resonances)



Calculations: A. Simoni, M. Tomza

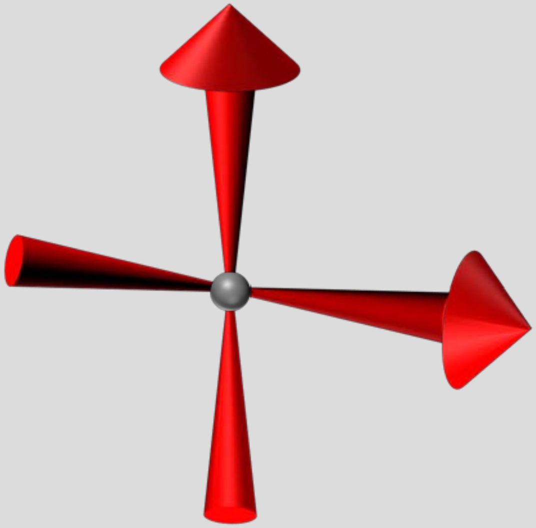
Experimental sequence

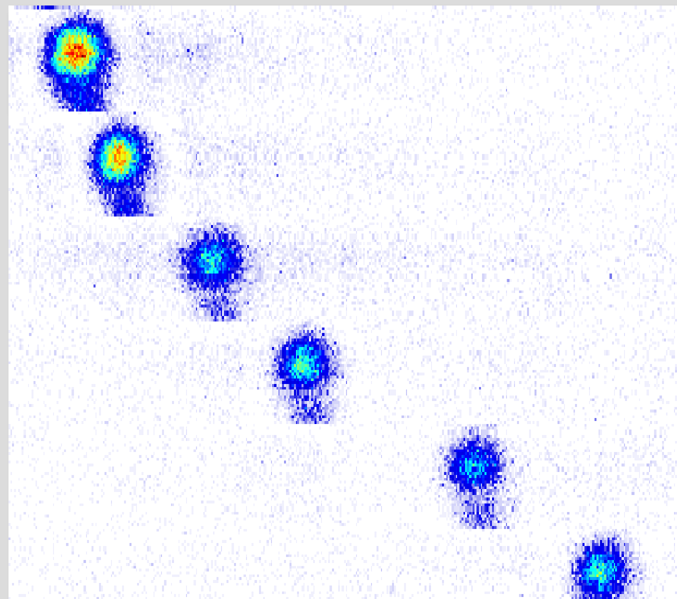
2. Prepare spin mixture (RF pulse)
3. Ramp B field ($\delta a < 0$)

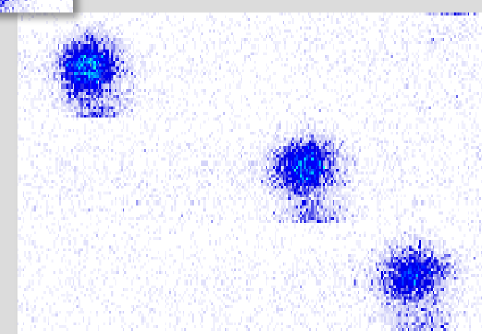


Calculations: A. Simoni, M. Tomza

Propagation in a waveguide





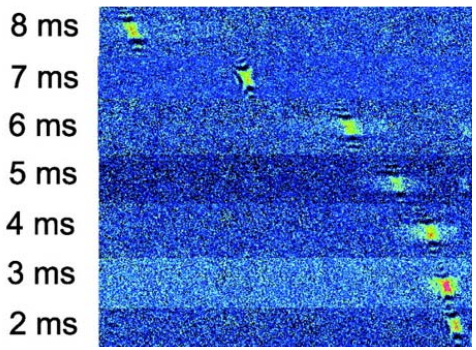


Observation of a self-bound state
(propagation without expansion)

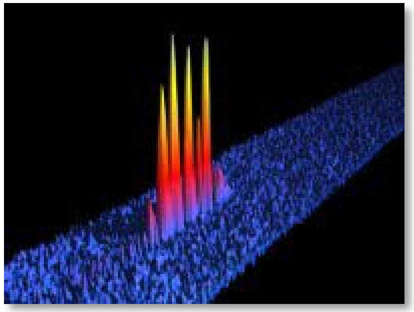
Solitons or droplets?

A known self-bound solution in a waveguide: **bright soliton**

$$\mathcal{E} = \mathcal{E}_{\text{trap}} + \mathcal{E}_{\text{kin}} + \mathcal{E}_{\text{MF}}$$



L. Khaykovich *et al.*, *Science* **296**, 1290 (2002)



K. Strecker *et al.*, *Nature* **417**, 150 (2002)

Here:

Two components: **composite object**

Additional Lee-Huang-Yang term: **droplets**

$$\mathcal{E} = \mathcal{E}_{\text{trap}} + \mathcal{E}_{\text{kin}} + \mathcal{E}_{\text{MF}} + \mathcal{E}_{\text{LHY}}$$

A composite object

$$\mathcal{E}_{\text{int}} \sim g(n_\uparrow - n_\downarrow)^2 - \frac{|\delta g|}{2}(n_\uparrow + n_\downarrow)^2 + \frac{8}{15\pi^2} f\left(\frac{\delta g}{g}, \frac{n_\uparrow}{n_\downarrow}\right)\left(\frac{m}{\hbar^2}\right)^{3/2}(g n_\uparrow)^{5/2}$$

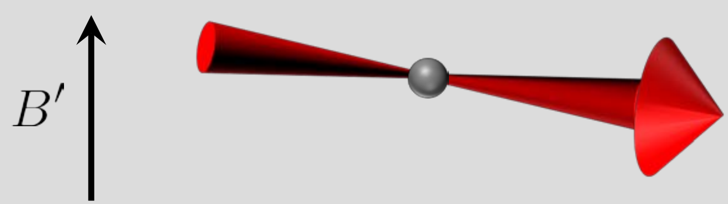
Hard mode

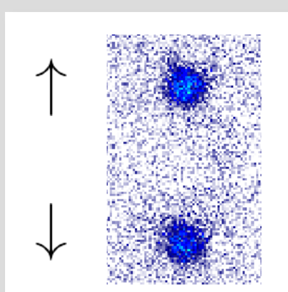
$n_\uparrow \sim n_\downarrow$

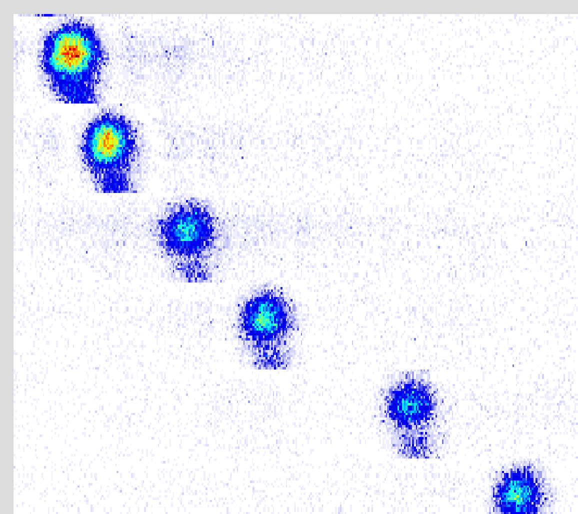
Maximize overlap
of the two components

If $g_{\uparrow\uparrow} \neq g_{\downarrow\downarrow}$

$$\frac{1}{2}(n_\uparrow\sqrt{g_{\uparrow\uparrow}} - n_\downarrow\sqrt{g_{\downarrow\downarrow}})^2 \rightarrow n_\uparrow \sim \sqrt{\frac{g_{\downarrow\downarrow}}{g_{\uparrow\uparrow}}} n_\downarrow$$

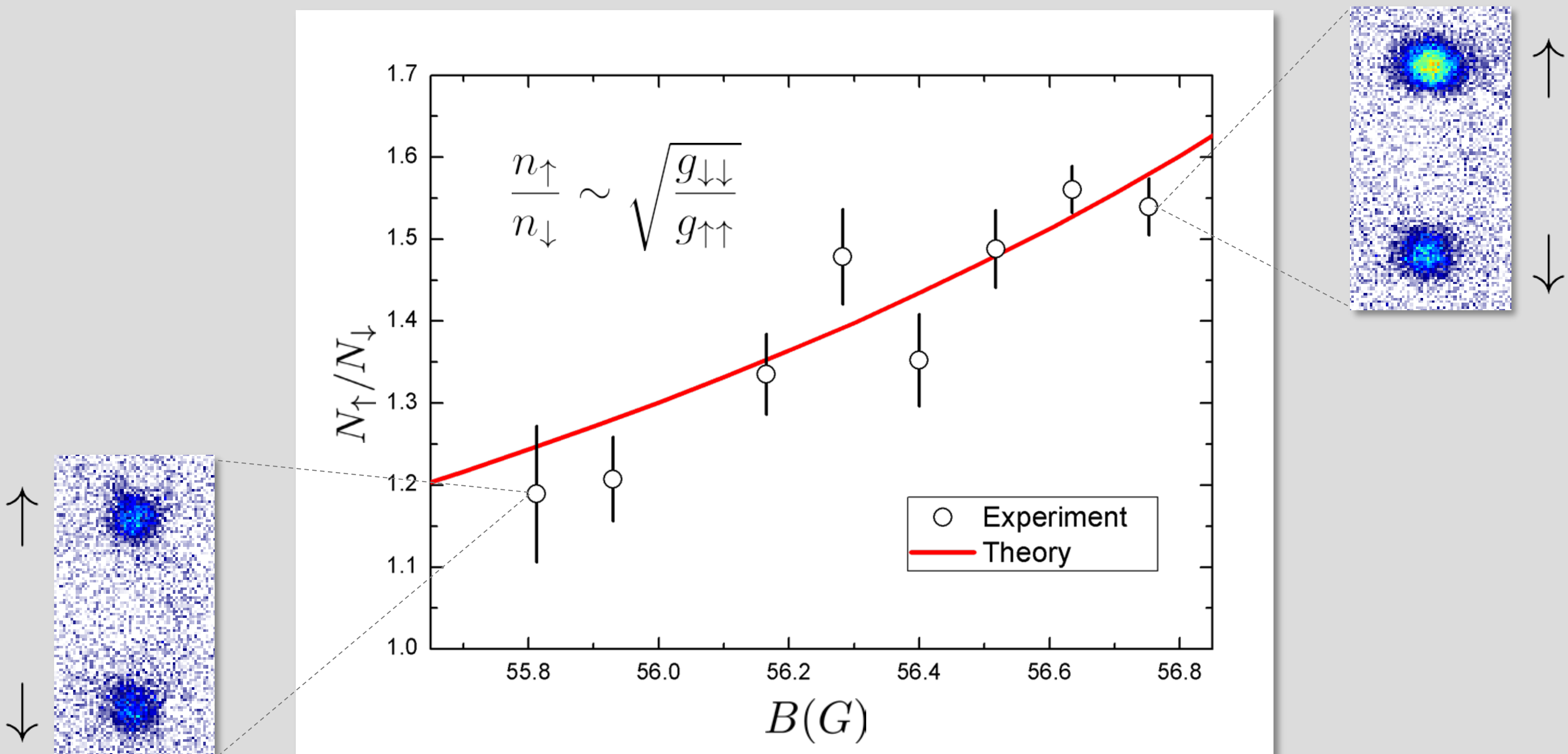






A composite object

Experiment: control $g_{\downarrow\downarrow}/g_{\uparrow\uparrow}$ with magnetic field (Feshbach)



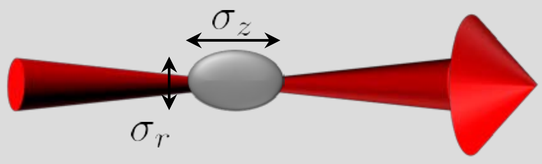
Toy model

Effective theory: generalized Gross-Pitaevskii equation with **additional LHY term**

$$\mathcal{E} = \mathcal{E}_{\rm trap} + \mathcal{E}_{\rm kin} + \mathcal{E}_{\rm MF} + \mathcal{E}_{\rm LHY}$$

Gaussian ansatz:

$$\psi_i = \sqrt{\frac{N_i}{\pi^{3/2} a_{\rm ho}^3 \sigma_z \sigma_r^2}}\, e^{-\frac{1}{2a_{\rm ho}^2}\left(\frac{z^2}{\sigma_z^2} + \frac{r^2}{\sigma_r^2}\right)} \qquad i = \uparrow, \downarrow$$



$$a_{\rm ho} = \sqrt{\frac{\hbar}{m\omega}}$$

$$a = a_{\uparrow\uparrow} = a_{\downarrow\downarrow}$$
$$\delta a = -|a_{\uparrow\downarrow}| + a$$
$$N_\uparrow = N_\downarrow = N/2$$

$$\frac{E(\sigma_z, \sigma_r)}{N\hbar\omega} = \alpha\sigma_r^2 + \beta\left(\frac{1}{\sigma_z^2} + \frac{2}{\sigma_r^2}\right) - \gamma\left(\frac{N|\delta a|/a_{\rm ho}}{\sigma_z\sigma_r^2}\right) + \xi\left(\frac{N^{3/2}(a/a_{\rm ho})^{5/2} f(\delta a/a)}{\sigma_z^{3/2}\sigma_r^3}\right)$$

trap | kinetic | MF | LHY

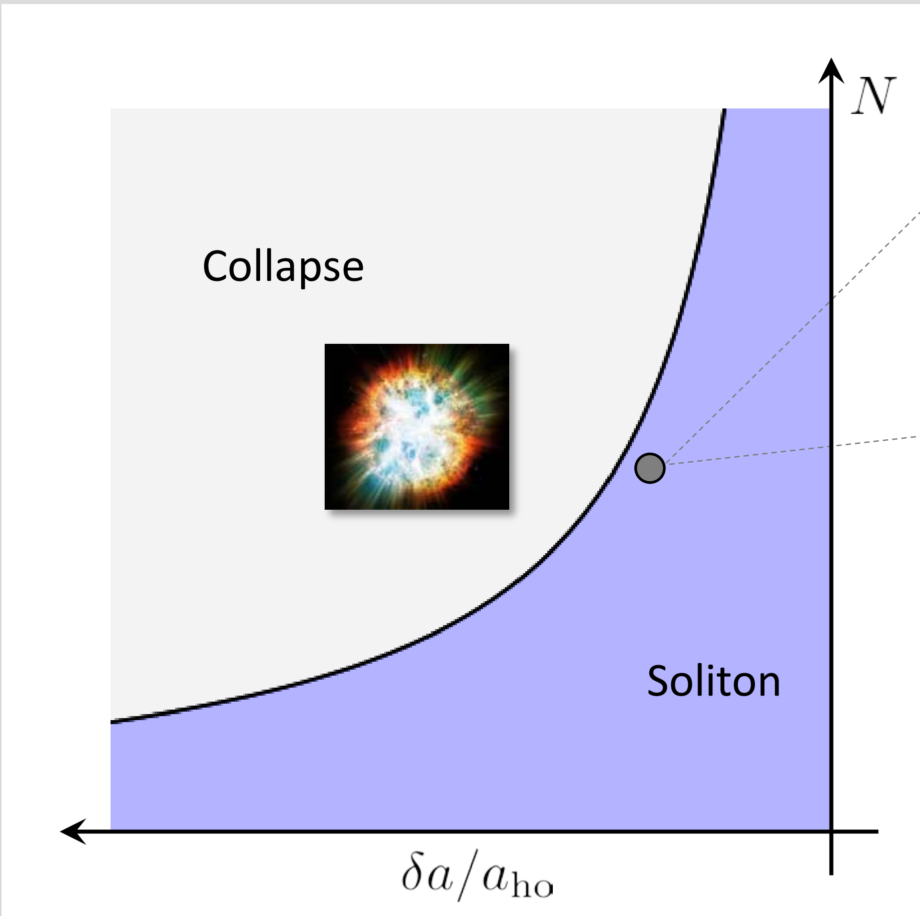
Solitons | Droplets

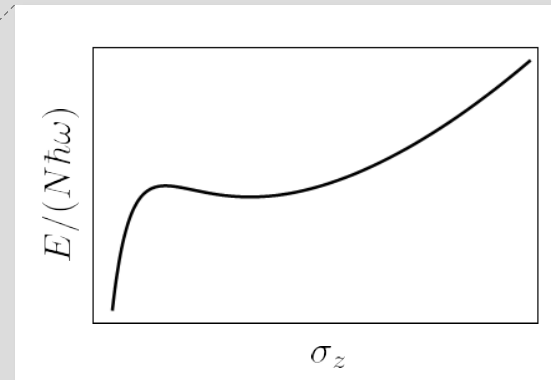
Find σ_z and σ_r which minimize the energy

Phase diagram

$$\frac{E(\sigma_z,\sigma_r)}{N\hbar\omega} = \alpha\sigma_r^2 + \beta\left(\frac{1}{\sigma_z^2}+\frac{2}{\sigma_r^2}\right) - \gamma\left(\frac{N|\delta a/a_{\text{ho}}|}{\sigma_z\sigma_r^2}\right)$$

trap kinetic MF





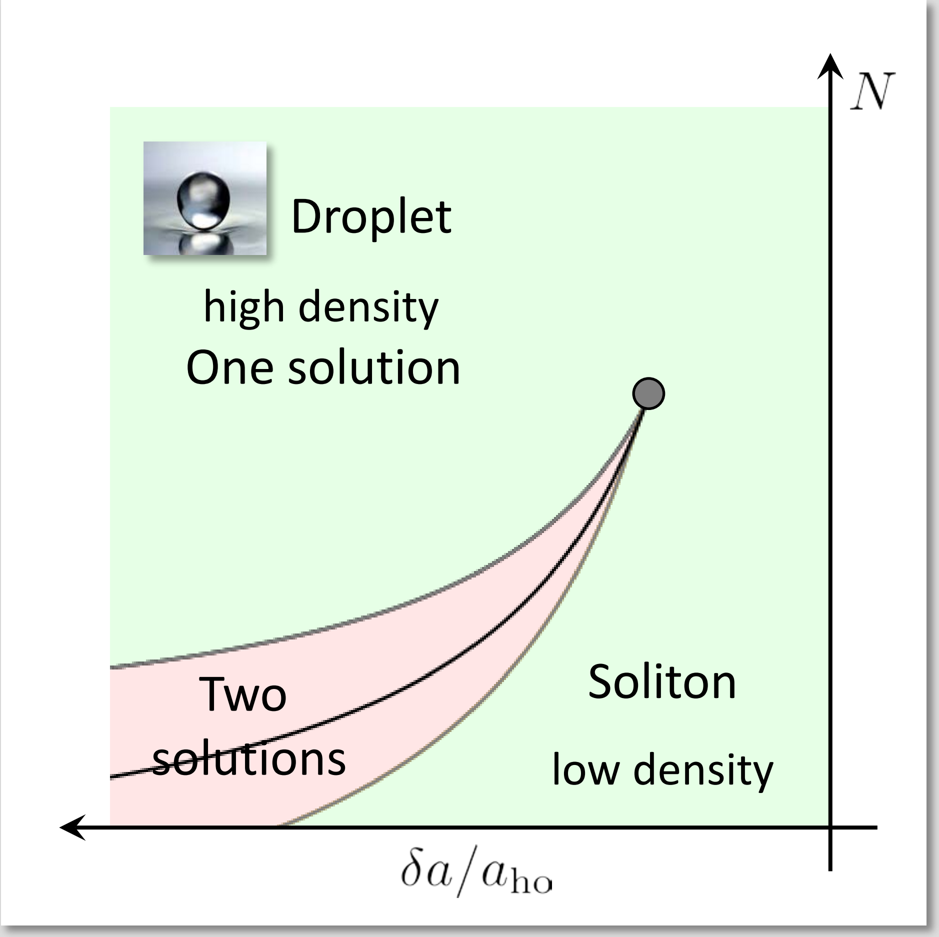
Collapse criterion

$$\frac{N|\delta a|/a_{\text{ho}}}{2} \simeq 0.6$$

Phase diagram

$$\frac{E(\sigma_z,\sigma_r)}{N\hbar\omega} = \alpha\sigma_r^2 + \beta\left(\frac{1}{\sigma_z^2}+\frac{2}{\sigma_r^2}\right) - \gamma\left(\frac{N|\delta a/a_{\rm ho}|}{\sigma_z\sigma_r^2}\right) + \xi\left(\frac{N^{3/2}(a/a_{\rm ho})^{5/2}f(\delta a/a)}{\sigma_z^{3/2}\sigma_r^3}\right)$$

trap kinetic MF LHY



Above:
soliton-to-droplet crossover

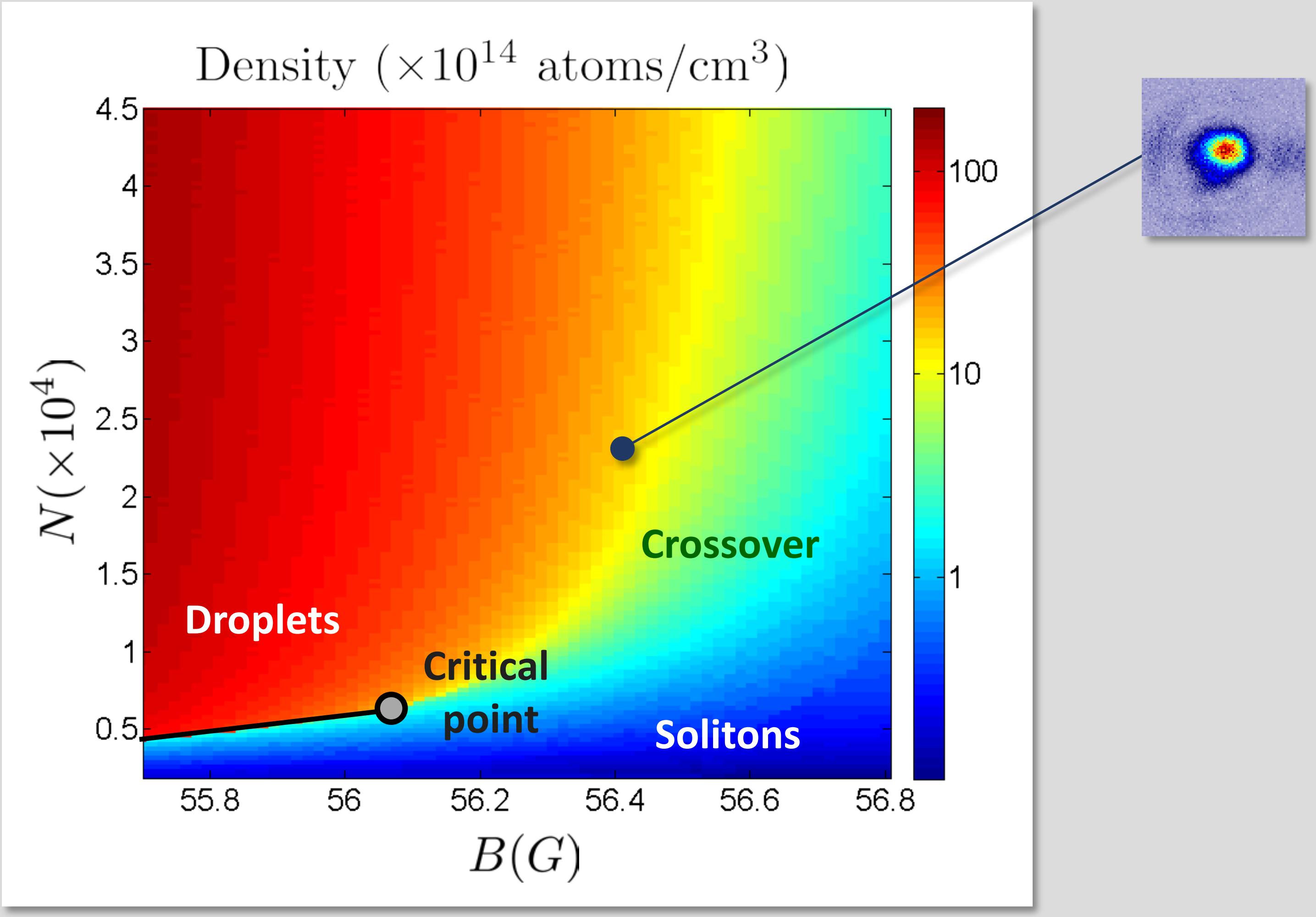
Critical point

First order phase transition

Both solitons and droplets stable

Phase diagram

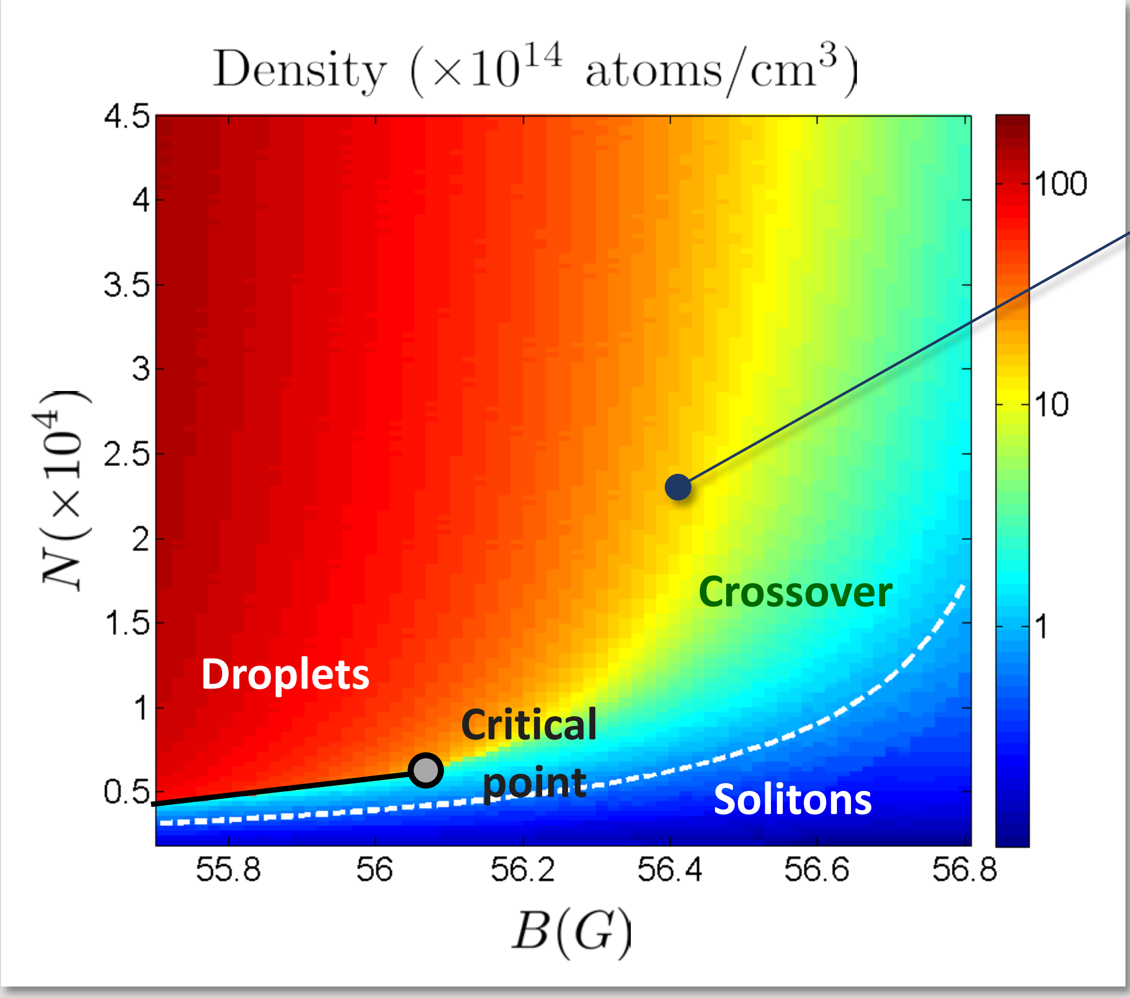
Experiment: control $a_{\downarrow\downarrow}, a_{\uparrow\uparrow}$ and δa with magnetic field B (Feshbach)

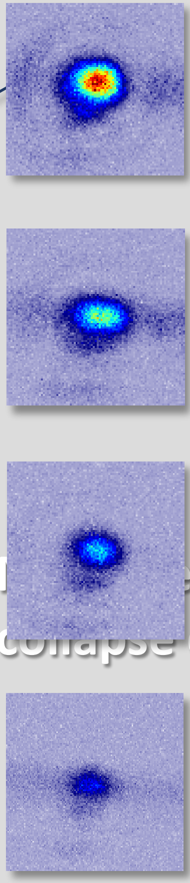


First order phase transition line

Phase diagram

Experiment: control $a_{\downarrow\downarrow}, a_{\uparrow\uparrow}$ and δa with magnetic field B (Feshbach)

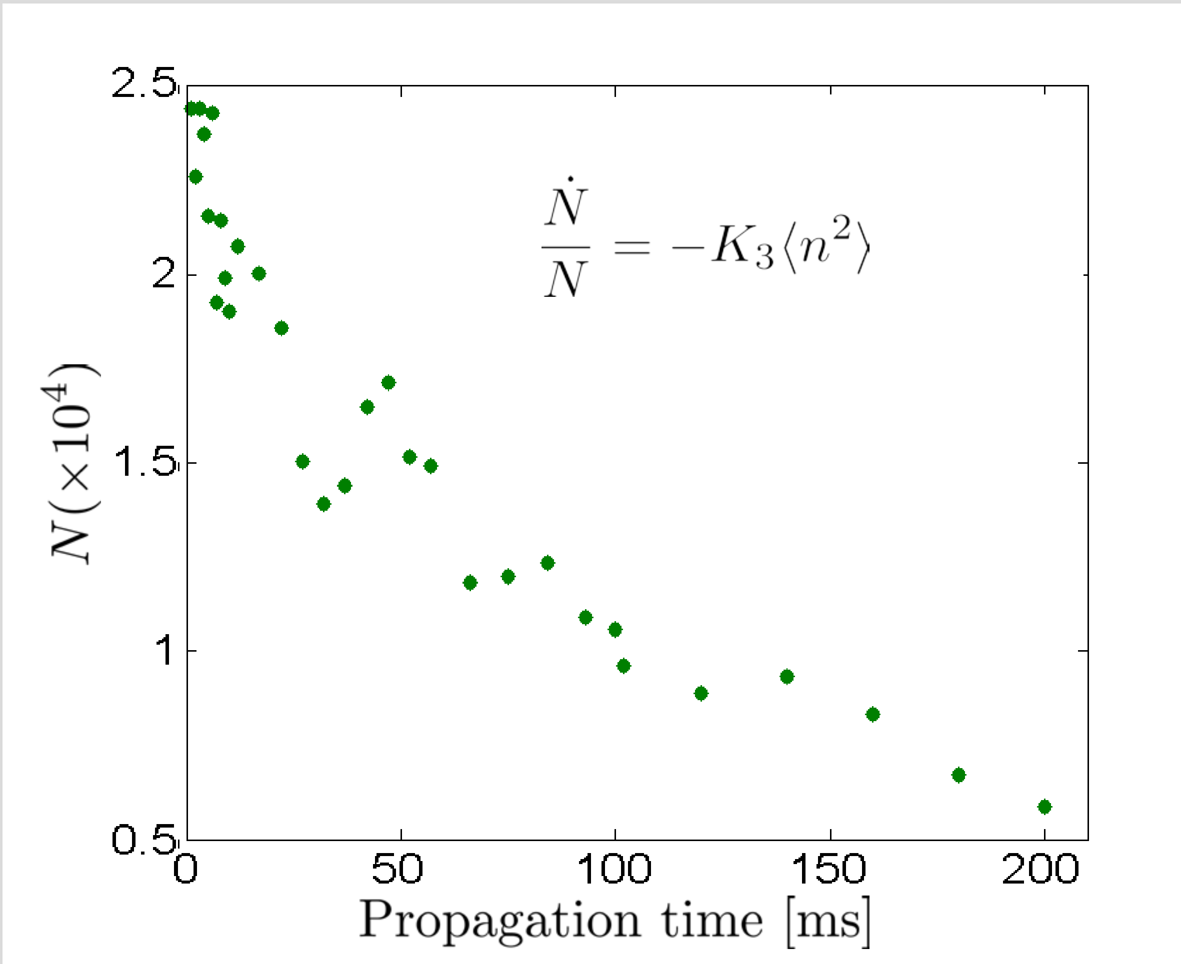


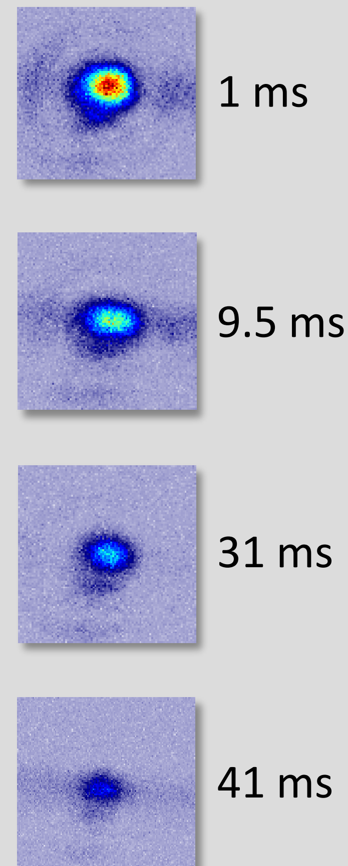


First order phase transition line

Lifetime

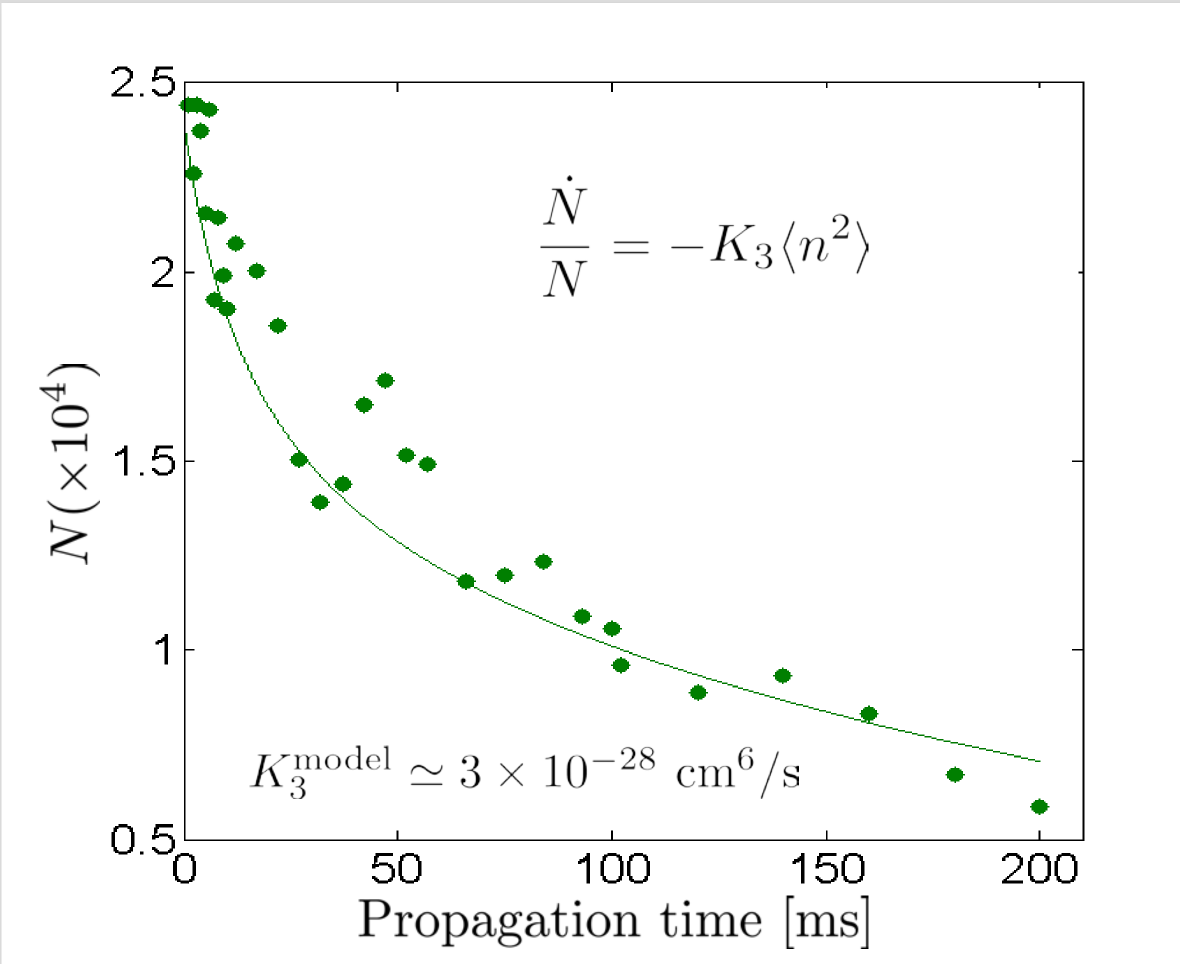
High density: atom number decay due to 3-body recombination

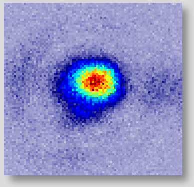




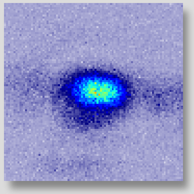
Lifetime

High density: atom number decay due to 3-body recombination

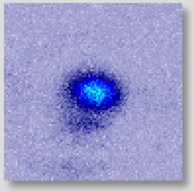




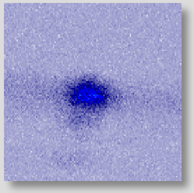
1 ms



9.5 ms



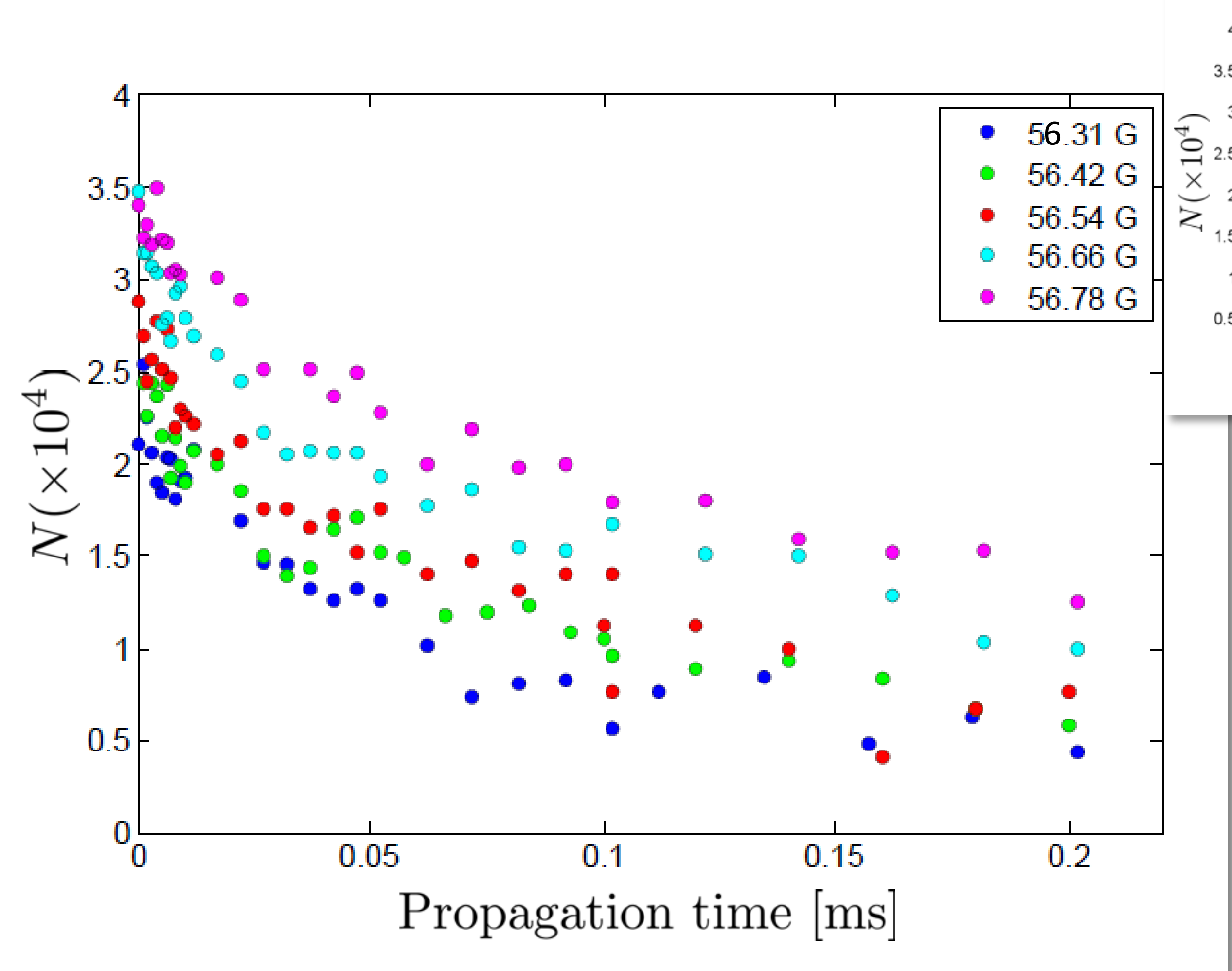
31 ms

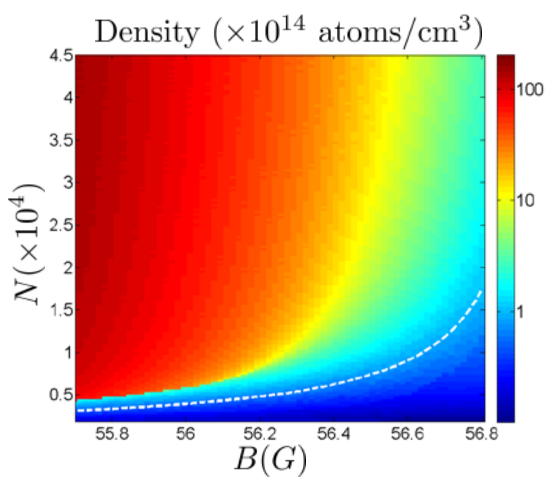


41 ms

Compatible with independent measurement $K_3 \leq 3.8 \times 10^{-28}\ \text{cm}^6/\text{s}$

Lifetime

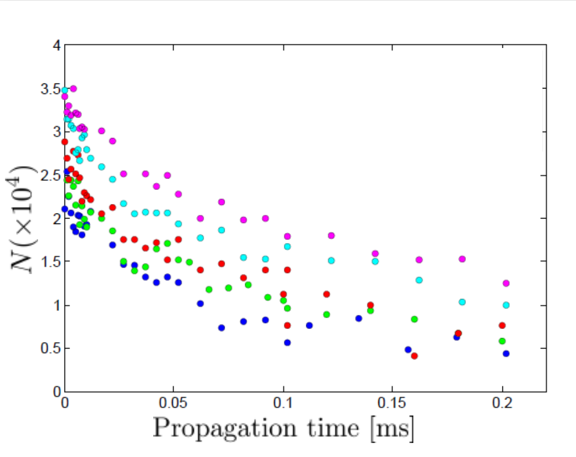


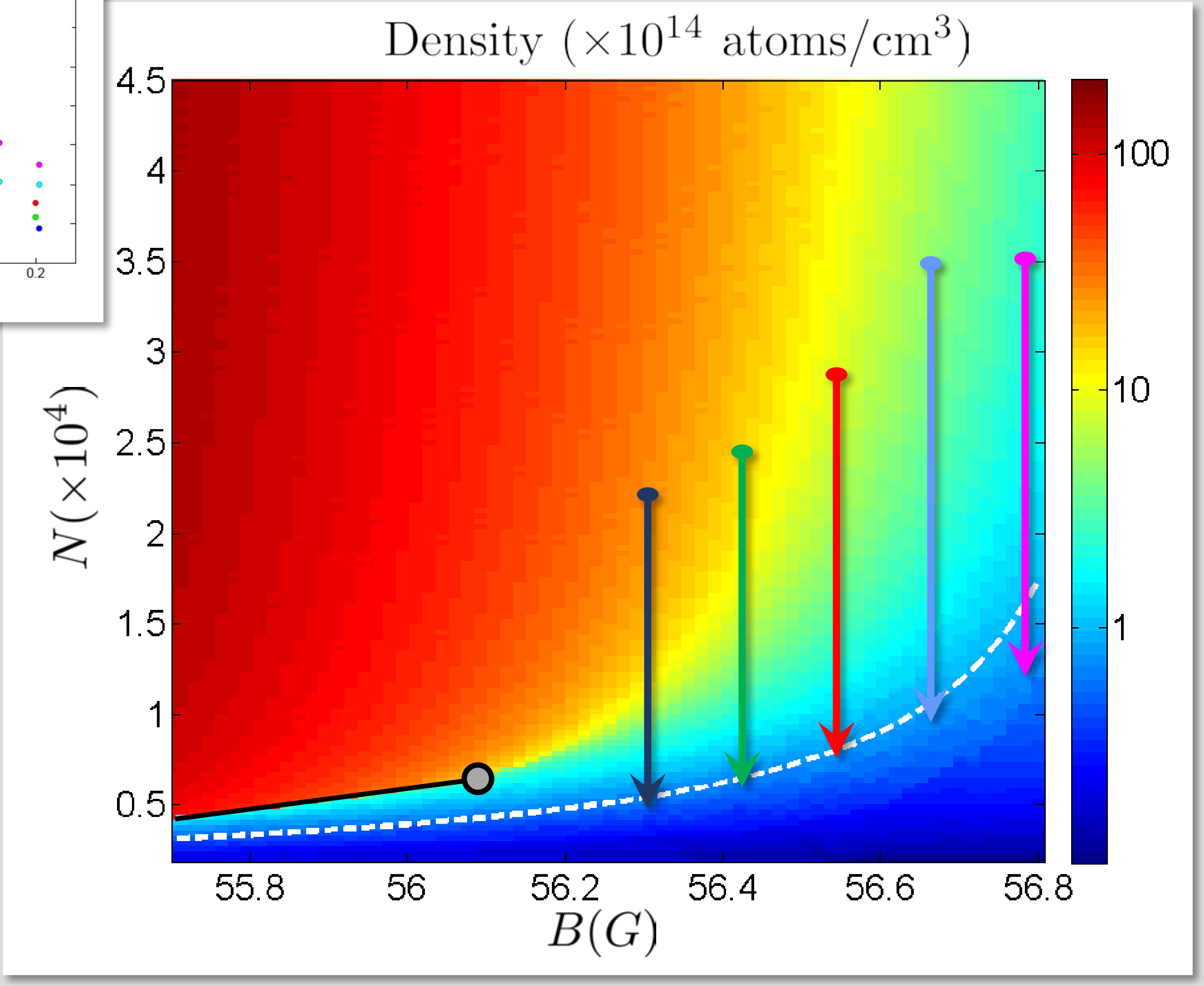


$$\tau = 1/K_3\langle n^2\rangle$$

Increasing B (decreasing $|\delta a|$) $\longrightarrow$ longer lifetimes

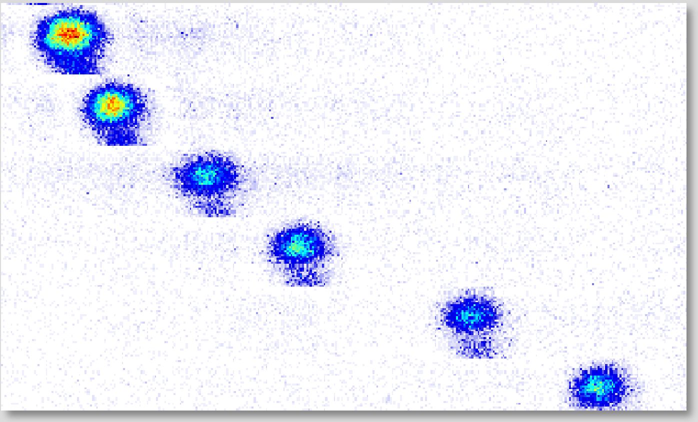
Phase diagram





Conclusion

Summary



Observation of self-bound states

Spin composition

Lifetime given by 3-body recombination

Exploring soliton-to-droplet crossover

Outlook

Speed-up preparation (shortcuts to adiabaticity)

Droplets in lower dimensions

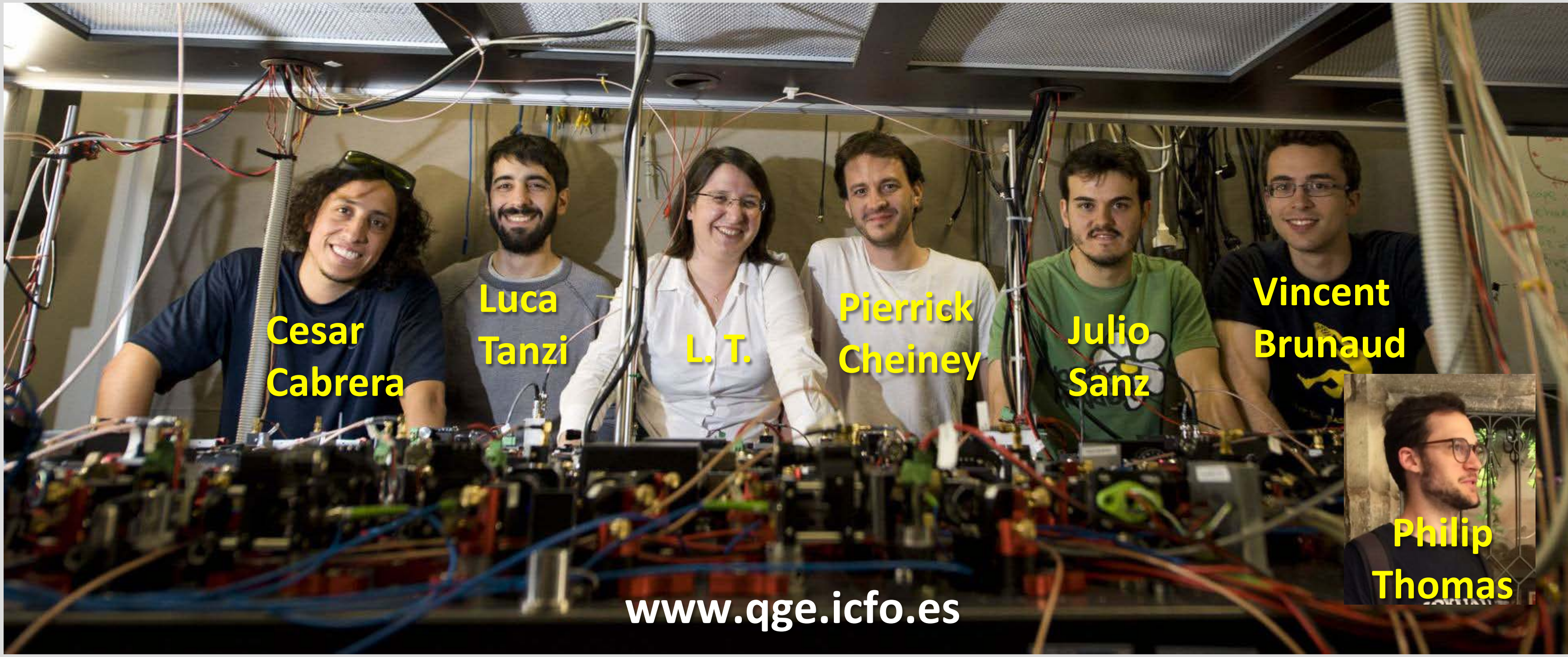
D. S. Petrov and G. E. Astrakharchik, *Phys. Rev. Lett.* **117**, 100401 (2016)

Excitation spectrum

D. S. Petrov, *Phys. Rev. Lett*. **115**, 155302 (2015)

The ICFO Quantum Gases group

ICFO



Thank you for your attention!

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