Heteronuclear quantum droplet in an ultracold Na and Rb mixture

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Supported by:

RGC Hong Kong

- Introduction
- Na and Rb double BEC with tunable interactions
- Observation of heteronuclear quantum droplet
- Conclusion and outlook

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Double BEC

Binary Mixtures of Bose Condensates of Alkali Atoms

PRL, 1996

Tin-Lun Ho and V. B. Shenoy
Physics Department, The Ohio State University, Columbus, Ohio 43210
(Received 20 May 1996)

We show that binary mixtures of Bose condensates of alkali atoms have a great variety of ground state and vortex structures which can be accessed experimentally by varying the particle numbers of different alkalis. We have constructed a simple algorithm to determine the density profiles of the mixtures within

Properties of Two-Species Bose Condensates

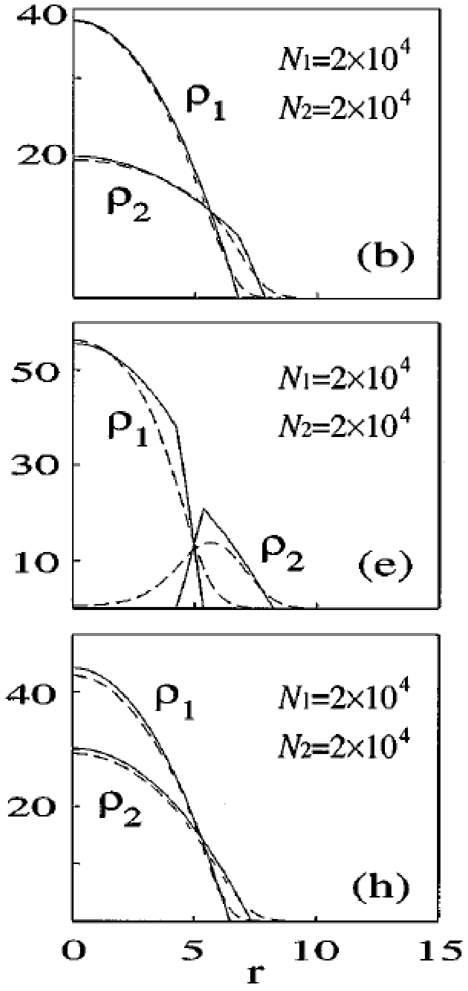
PRL, 1998

H. Pu and N. P. Bigelow
Department of Physics and Astronomy, and Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627
(Received 25 March 1997)

We present theoretical studies of a two-species Bose condensate. Using a new numerical method, we have calculated ground state wave functions and show that, due to interspecies interactions, the

Miscibility

a_{12}



1.8 nm

3.6 nm

0nm

Double BEC

Production of Two Overlapping Bose-Einstein Condensates by Sympathetic Cooling

C. J. Myatt, E. A. Burt, R. W. Ghrist, E. A. Cornell, and C. E. Wieman
JILA and Department of Physics, University of Colorado and NIST, Boulder, Colorado 80309
(Received 20 September 1996)

PRL, 1997

Alkalis:

Two hyperfine levels of same species: 87Rb, 39K…

Different isotopes: 87Rb-85Rb, K39-K41…

Different elements: Rb-K, Rb-Cs, Na-Rb, Na-K…

Alkali + alkali earth

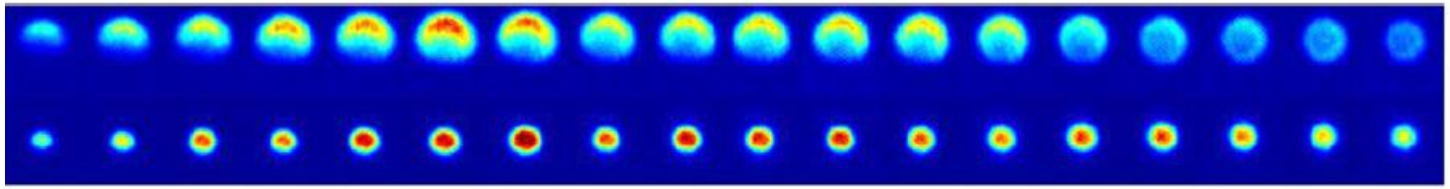
Rb-Sr, Cs-Yb…

Others

Also many theoretical investigations

Na

Rb



502 412 353 312 256 198 114 64 58 53 47 34 19 3 -3 -10 -18 -28

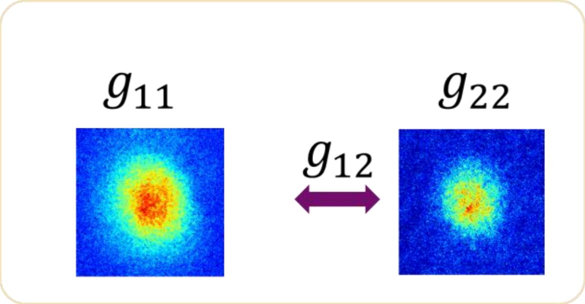
a_{12} (a_0)

From CUHK lab

Two-body interaction:

$$g_{ij} = \frac{2\pi\hbar^2 a_{ij}}{\mu}$$

with μ the reduced mass

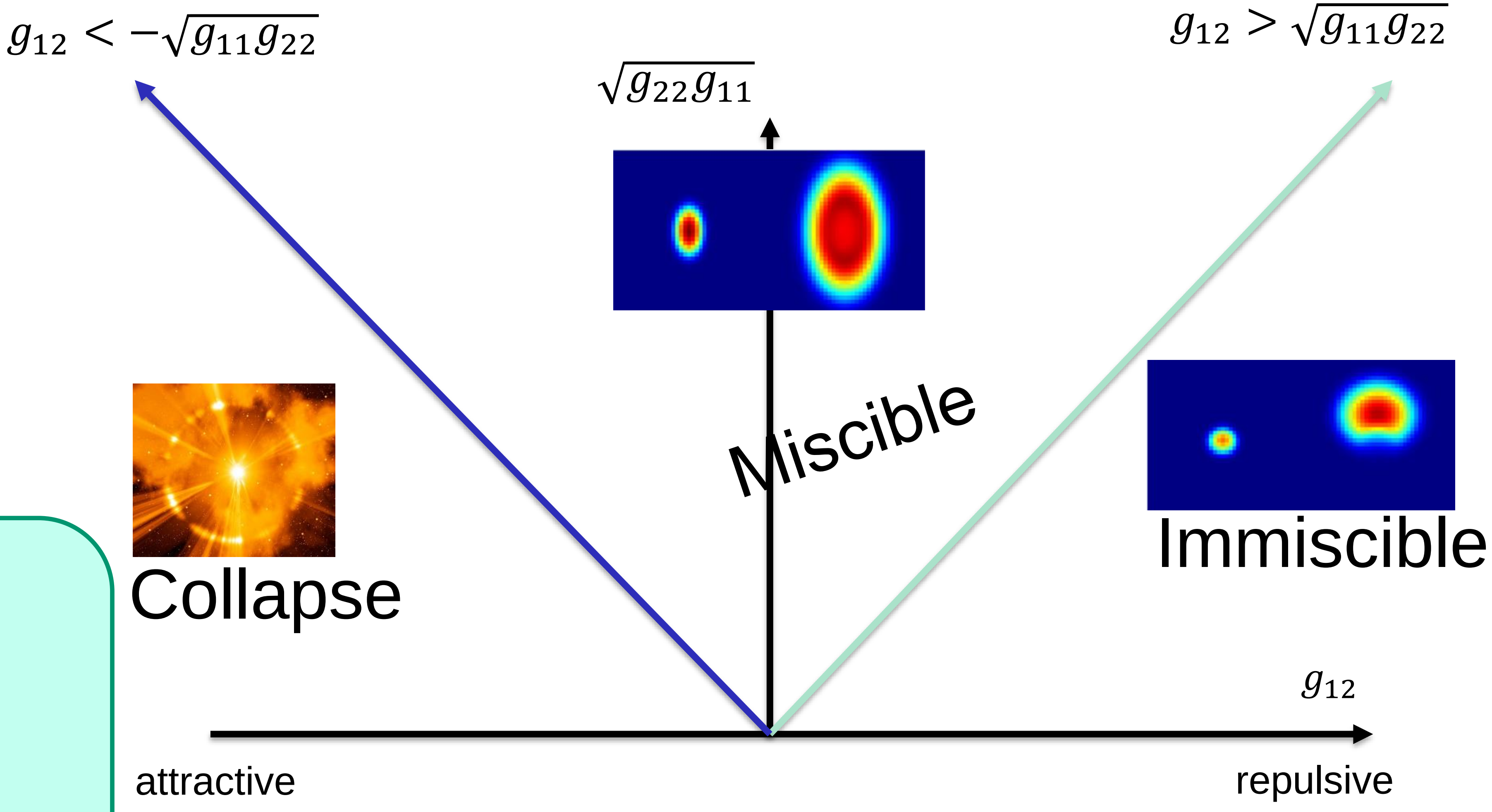


For single BEC with a < 0:

Collapse when

$$N > N_c \approx a_{ho}/|a|$$

Donley et al., Nature 412, 295 (2001)



Beyond mean-field effects

PRL **115,** 155302 (2015)

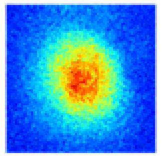
Quantum Mechanical Stabilization of a Collapsing Bose-Bose Mixture

D. S. Petrov
Université Paris-Sud, CNRS, LPTMS, UMR8626, Orsay, F-91405, France
(Received 28 June 2015; published 7 October 2015)

According to the mean-field theory a condensed Bose-Bose mixture collapses when the interspecies attraction becomes stronger than the geometrical average of the intraspecies repulsions, $g_{12}^2 > g_{11}g_{22}$. We show that instead of collapsing such a mixture gets into a dilute liquidlike droplet state stabilized by quantum fluctuations thus providing a direct manifestation of beyond mean-field effects. We study various properties of the droplet and find, in particular, that in a wide range of parameters its excitation spectrum lies entirely above the particle emission threshold. The droplet thus automatically evaporates itself to zero temperature, the property potentially interesting by itself and from the viewpoint of sympathetic cooling of other systems.

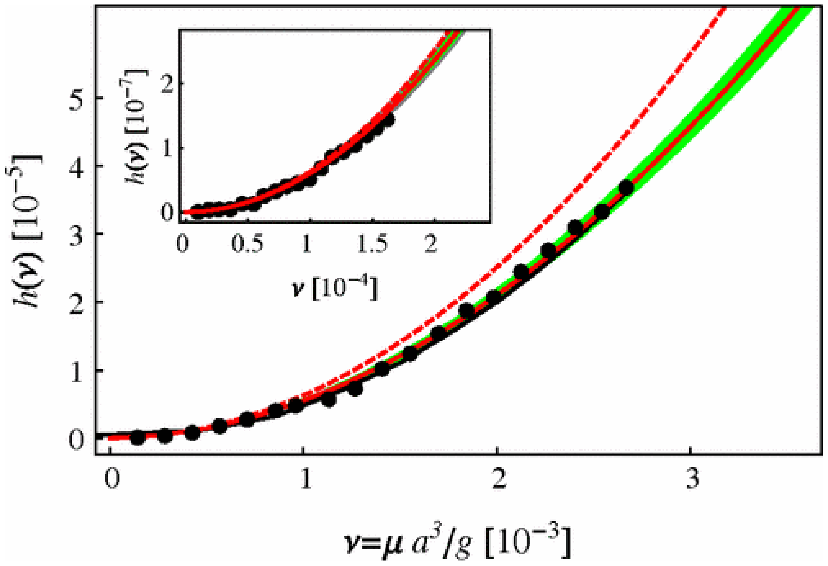
The Lee-Huang-Yang correction: single species

g



$$\frac{E}{V} = \frac{1}{2} g n^2 \left(1 + \frac{128}{15\sqrt{\pi}} \sqrt{na^3} + \cdots \right)$$

LHY, Phys. Rev. **106,** 1135–1145 (1957)



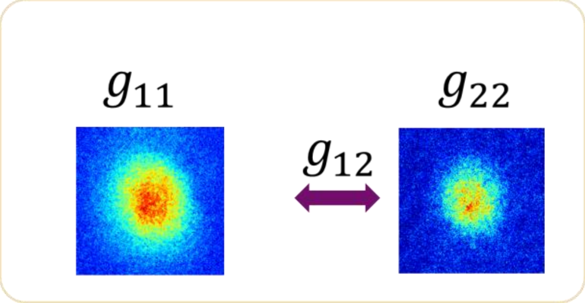
Equation of state of the homogeneous Bose gas expressed as the normalized pressure h as a function of the gas parameter ν.

na^3 is usually small:
~10^{-5} for typical ^{87}Rb BECs

Typically, the system is dominated by the mean-field interaction.

Strong interaction is needed to observe the LHY contribution

N. Navon et al. Phys. Rev. Lett. **107,** 135301 (2011)



Petrov, PRL 115, 155302 (2015)

$$\varepsilon = \varepsilon_{MF} + \varepsilon_{LHY}$$

$$\varepsilon_{MF} = \frac{1}{2}(g_{11}n_1^2 + g_{22}n_2^2) + g_{12}n_1n_2 \propto \boldsymbol{n^2}$$

$$\varepsilon_{LHY} = \frac{8\, m_1^{3/2}}{15\pi^2\hbar^3} f(\frac{m_2}{m_1}, \frac{g_{12}^2}{g_{11}g_{22}}, \frac{g_{22}n_2}{g_{11}n_1})(g_{11}n_1)^{\frac{5}{2}} \propto \boldsymbol{n^{5/2}}$$

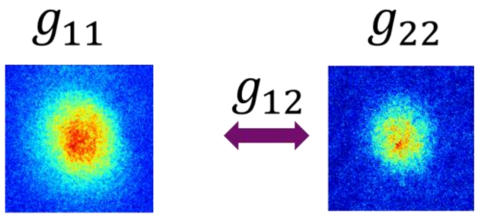
For the special case
with the same m, g_{ii} and n:

$$\varepsilon_{MF} = \frac{1}{4}n^2\delta g \propto \boldsymbol{n^2}$$ ***attractive for*** $\delta g<0$

For $g_{12}<0$
$\delta g = g_{12} + \sqrt{g_{11}g_{22}}$

$$\varepsilon_{LHY} = \frac{8\, m_1^{3/2}}{15\pi^2} f(1, \frac{g_{12}^2}{g^2}, 1)(gn)^{\frac{5}{2}} \propto \boldsymbol{n^{5/2}}$$ ***repulisve***

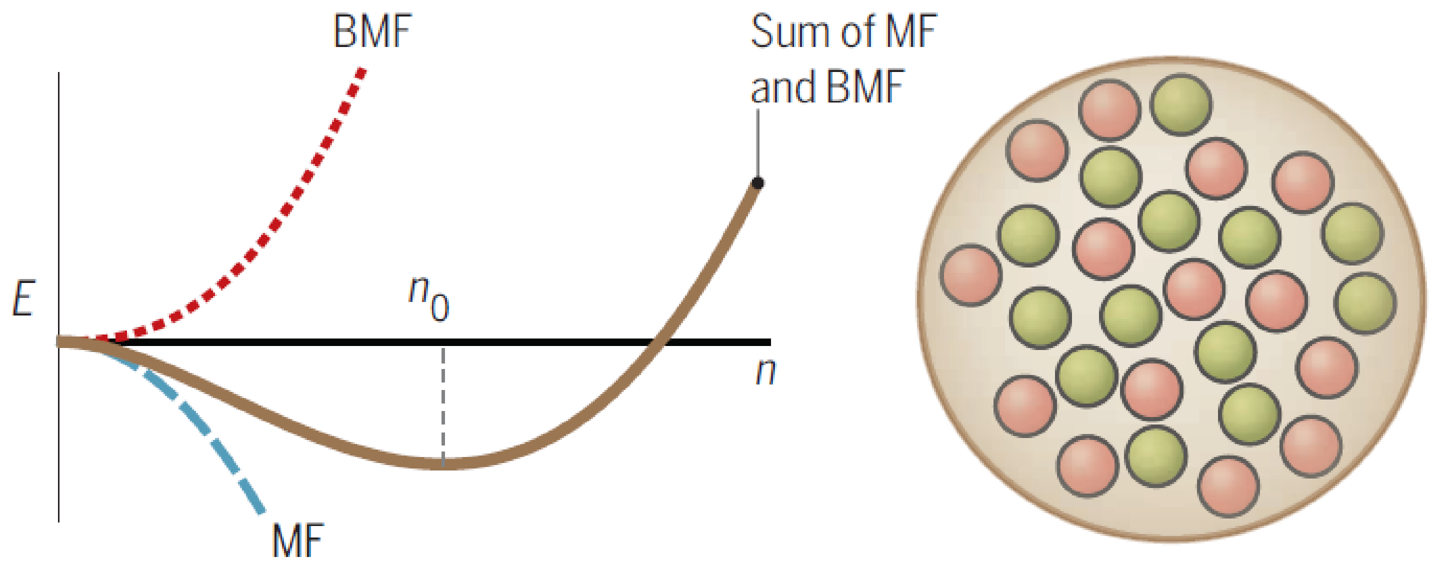
Quantum liquid droplet



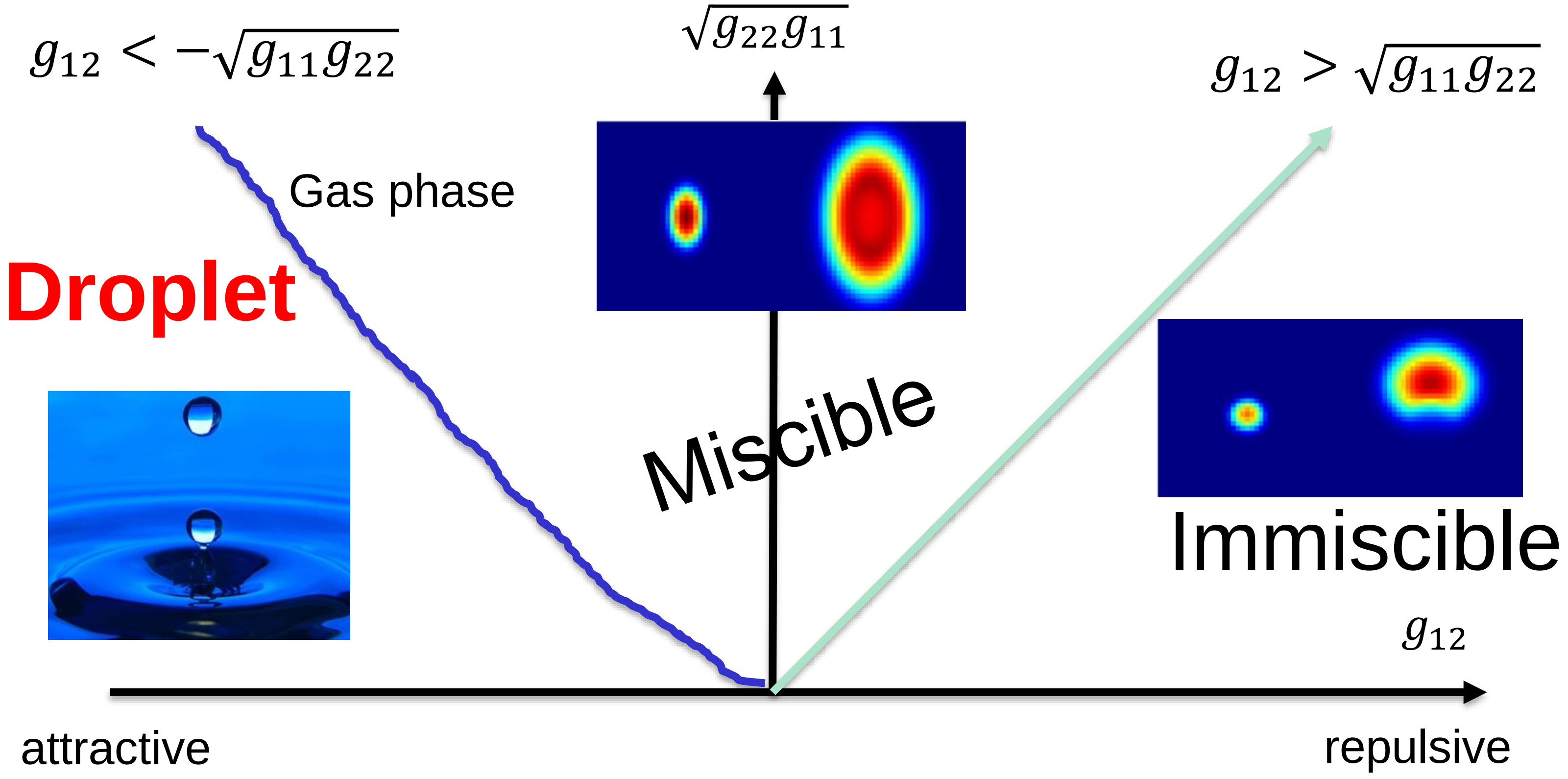
Ferrier-Barbut and Pfau,
Science **359,** 274–275 (2018)

Quantum liquid

When two types of atoms are mixed, MF effects nearly cancel out, creating a weak attraction that is counterbalanced by BMF corrections. A liquid forms at a particular density n_0 that minimizes energy.



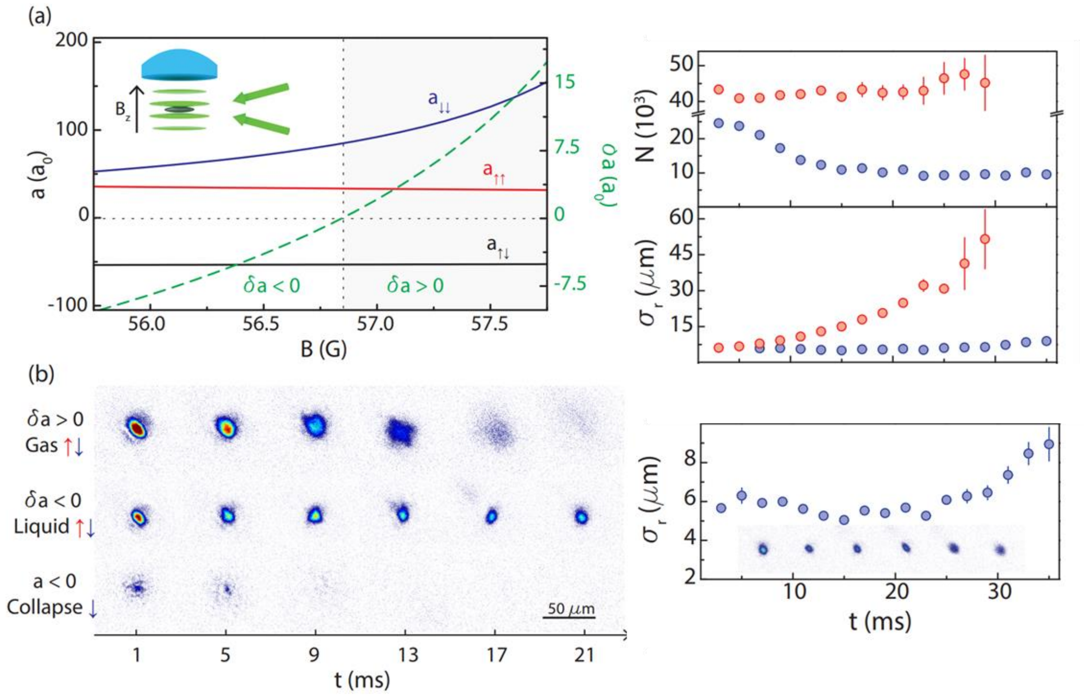
Phase diagram for double BEC



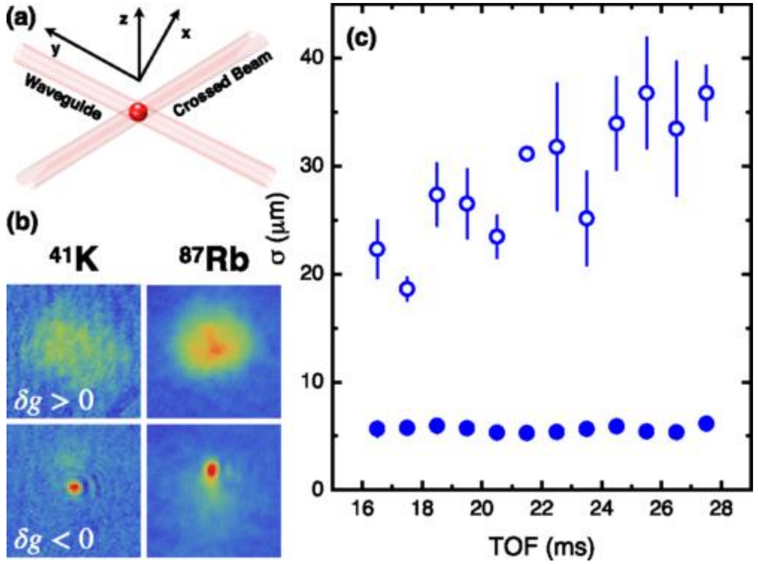
The droplet is “self-bound”:
no size expansion in free space

Experimental observation

$|F = 1, mF = 0\rangle$ and $|F = 1, mF = 1\rangle$ of ^{39}K



Cabrera et al., Science 359, 301–304 (2018)
Semeghini et al., PRL, 120, 235301 (2018)



Phys. Rev. Research 1, 033155 (2019)

Also in single Dy and Er BECs with magnetic dipole-dipole interaction:

T. Pfau and F. Ferlaino groups

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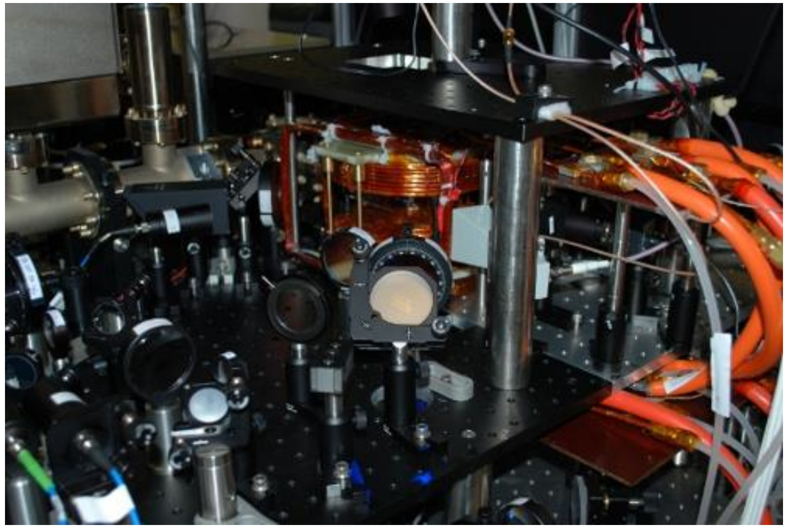
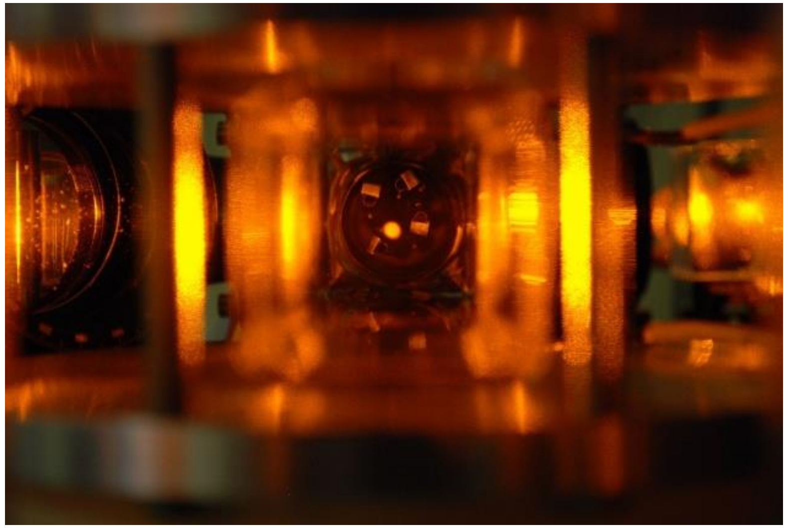
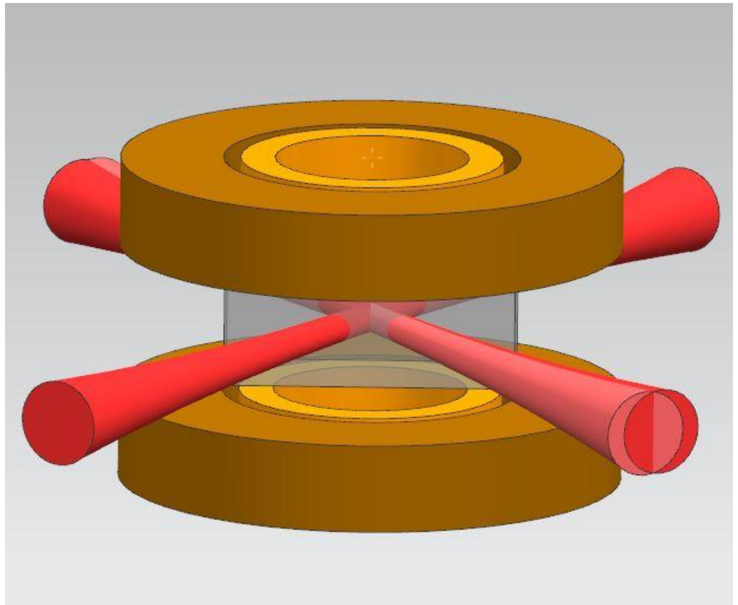
The setup



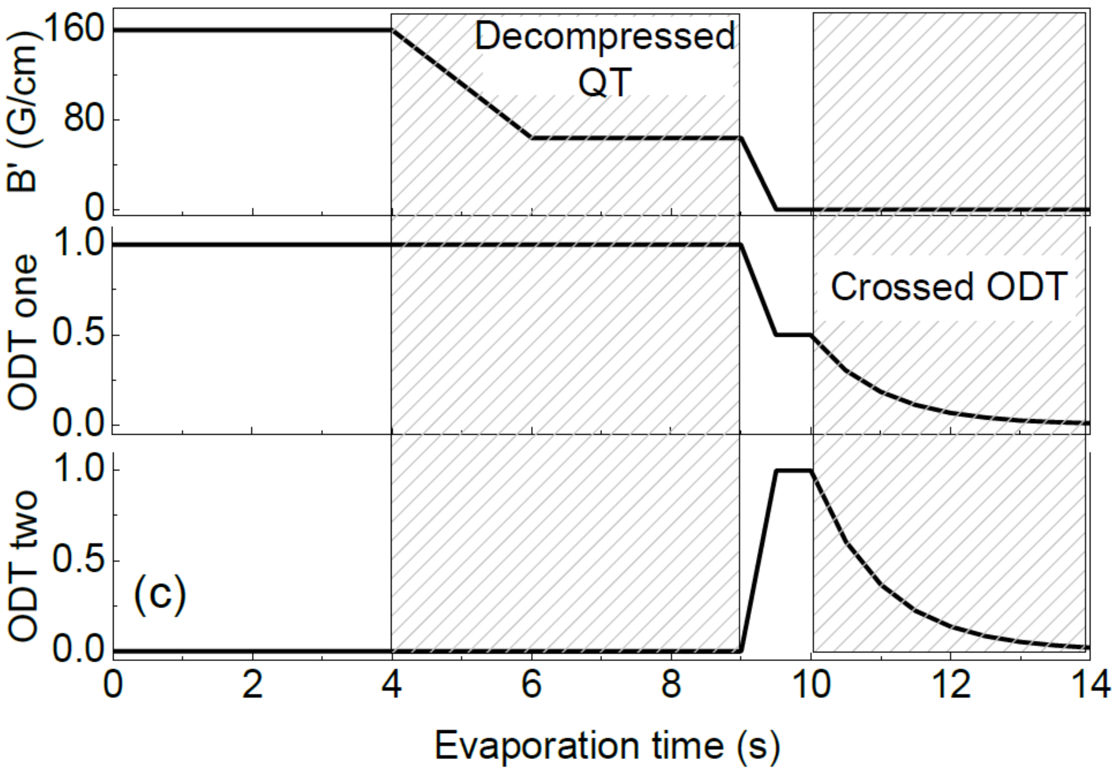


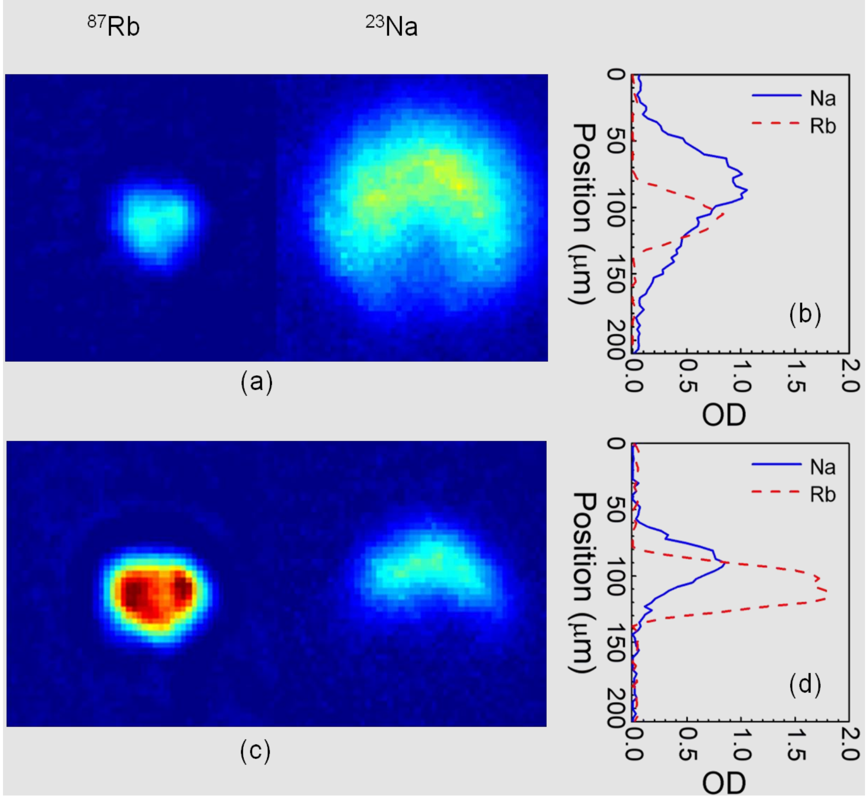
A small MOT of Na with ~ 5×10^{6} atom



1. Single chamber; UV LIAD assisted loading of both Na and Rb to obtain 20 s lifetime
2. Magnets for up to 1200 G with < 10 mG resolution
3. Microwave and RF manipulation of atoms’ spins
4. Hybrid quadrupole + optical trap for evaporation

Double BEC



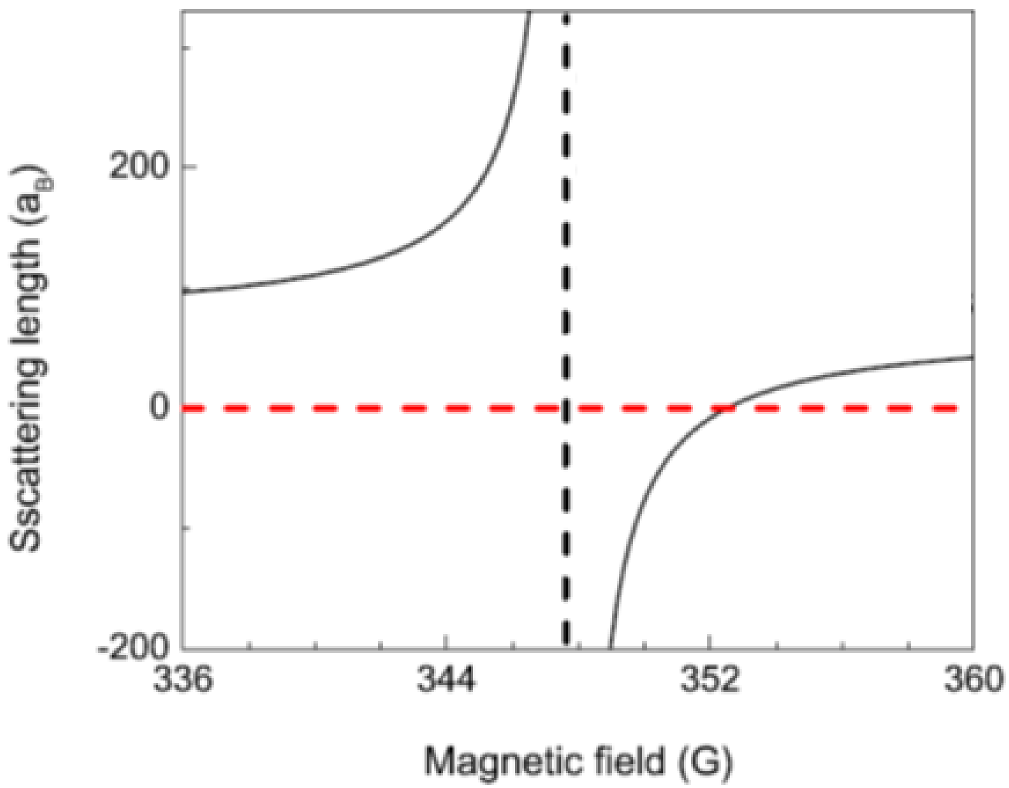


Up to 4x10^5 atoms each; but immiscible

$$\left\{\begin{array}{l} a_{Rb87} = 100.4a_0 \\ a_{Na} = 54.5a_0 \\ a_{NaRb} = 66.7a_0 \end{array}\right. \Rightarrow g_{12} > \sqrt{g_{11}g_{22}}$$

Feshbach resonance

347 G resonance between Na |1,1> and Rb |1,1>



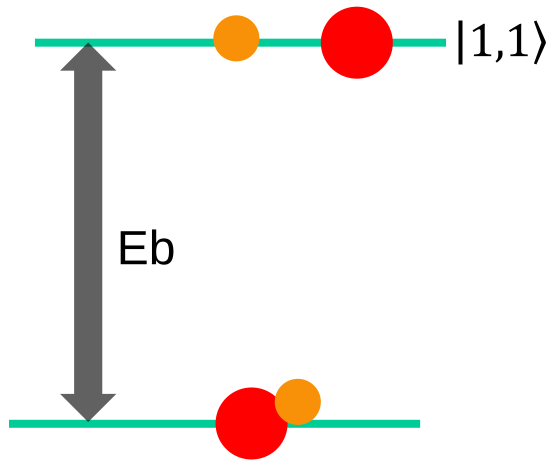
Fudong Wang *et al* 2015 *New J. Phys.* **17** 035003

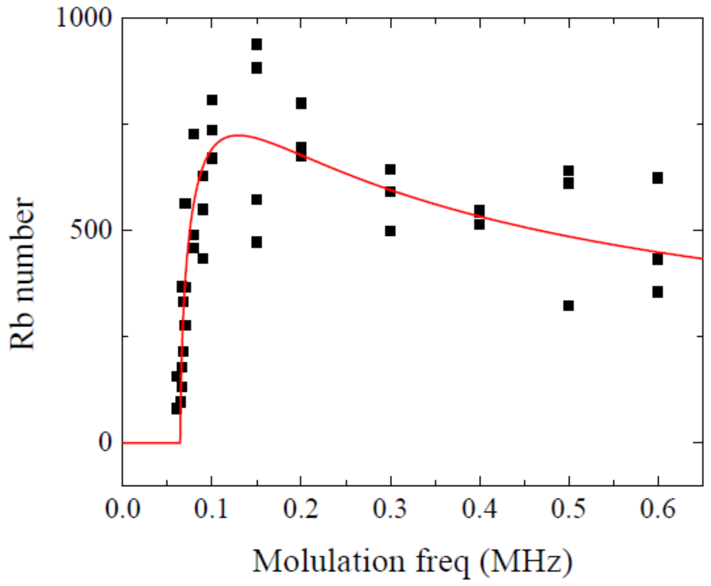
$$a_{NaRb} = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

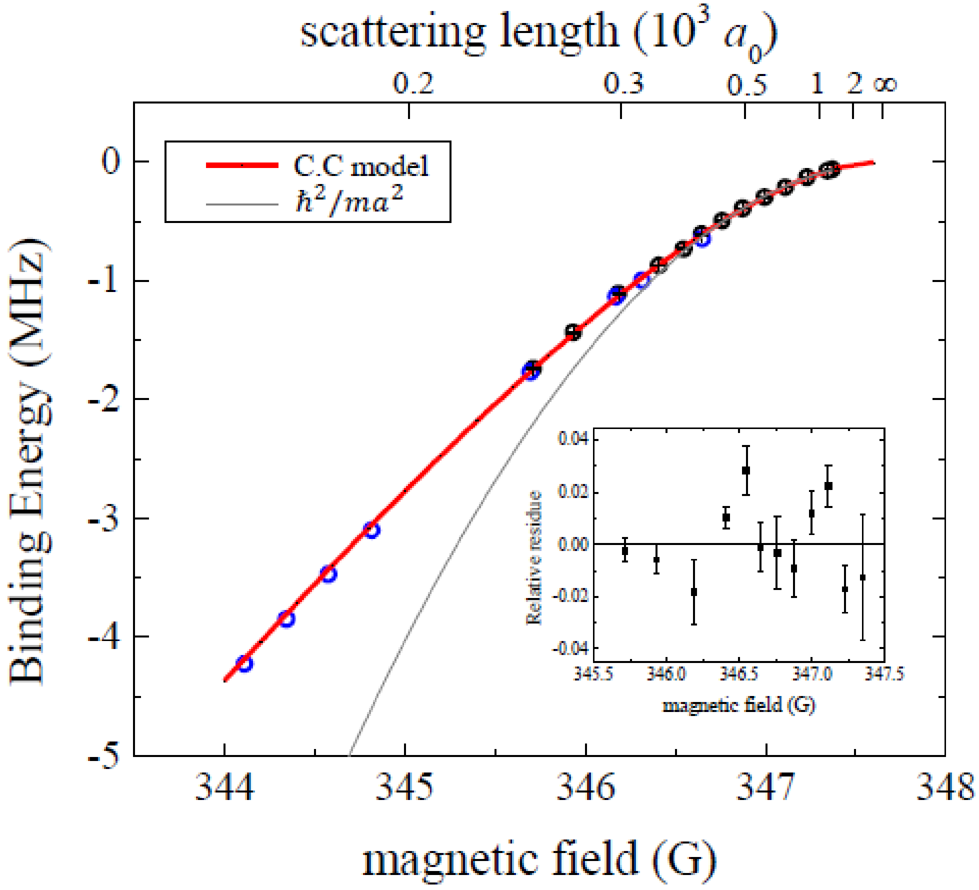
$$a_{bg} = 66.7a_0$$
$$B_0 = 347.64\ G$$
$$\Delta = 5.20\ G$$

Feshbach resonance recalibration

Measuring Feshbach molecule binding energy by dissociation





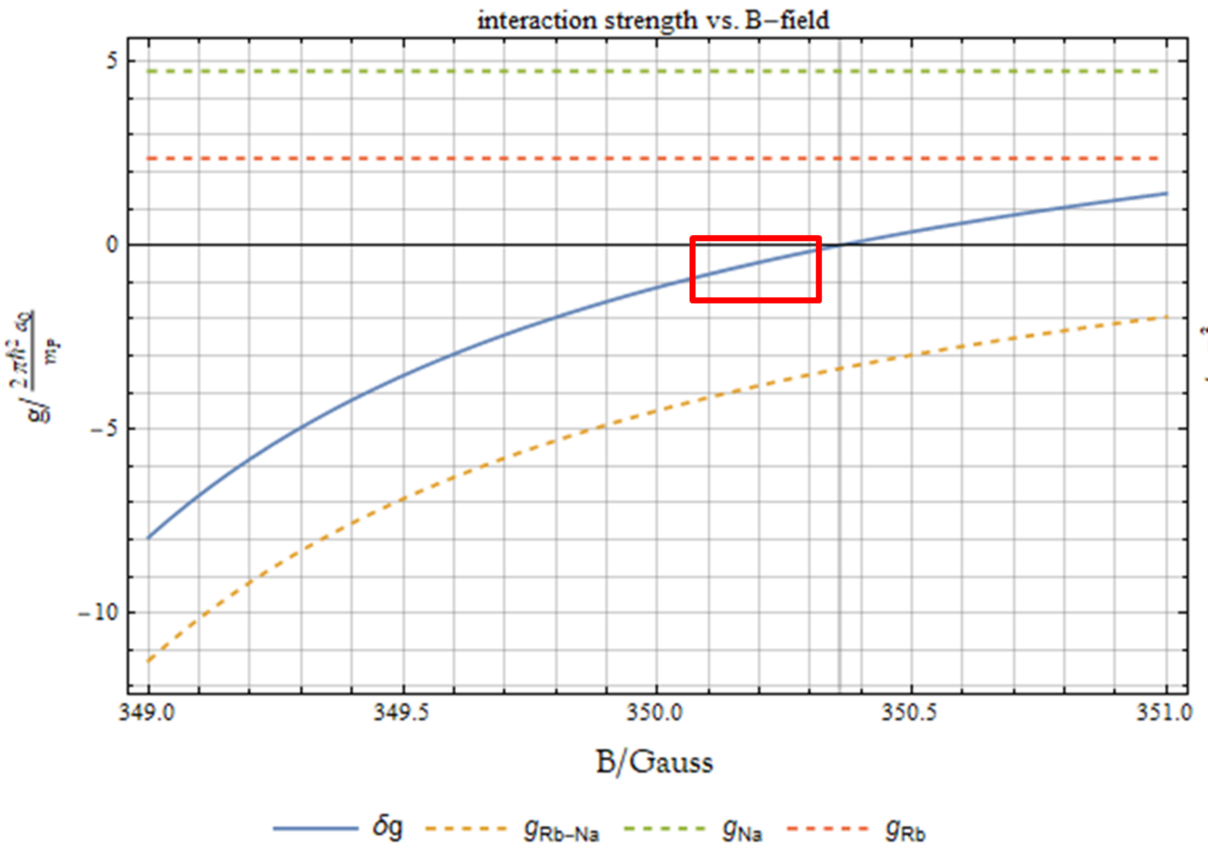


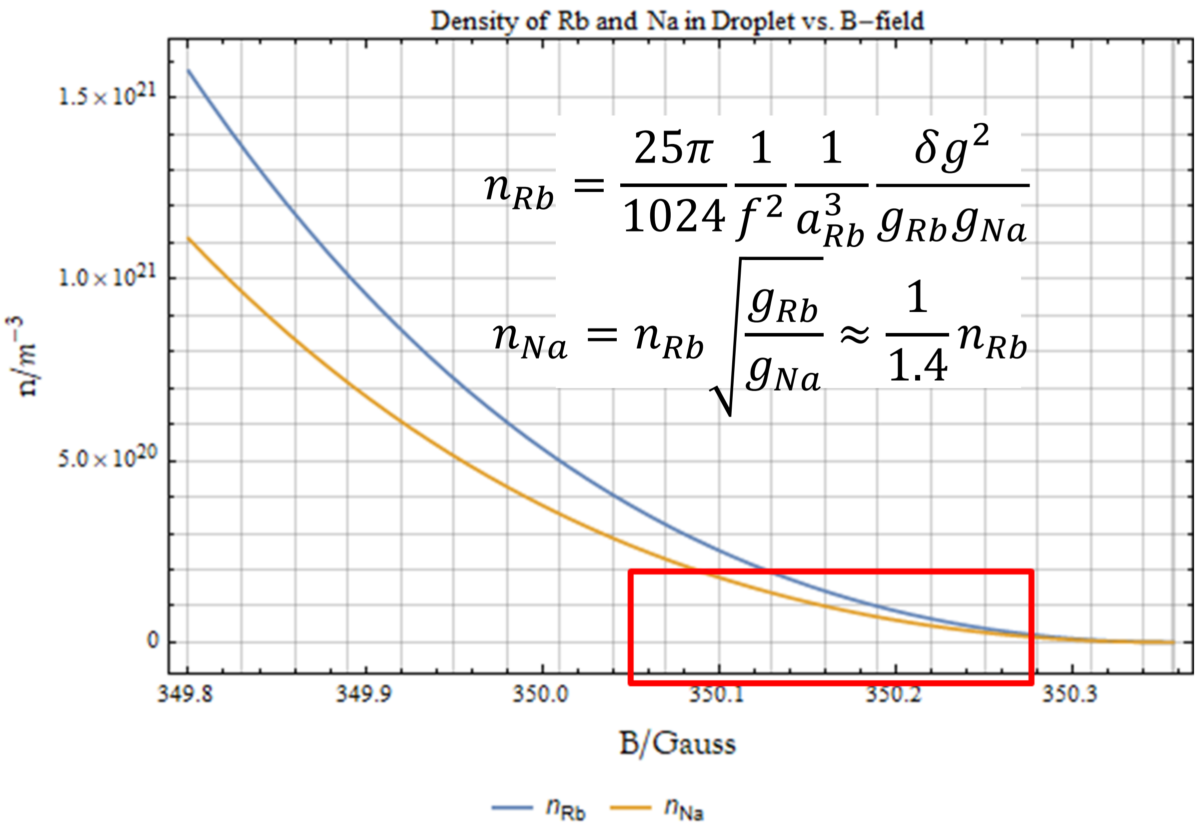
$$a_{NaRb} = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

$$a_{bg} = 76.33a_0$$
$$B_0 = 347.648\ G$$
$$\Delta = 4.255\ G$$

CC modelling by Jeremy Hutson

Window of observation





$$n_{Rb} = \frac{25\pi}{1024}\frac{1}{f^2}\frac{1}{a_{Rb}^3}\frac{\delta g^2}{g_{Rb}g_{Na}}$$

$$n_{Na} = n_{Rb}\sqrt{\frac{g_{Rb}}{g_{Na}}} \approx \frac{1}{1.4}n_{Rb}$$

$\delta g < 0$ when

$a_{NaRb} < -60\ a_0$
$(B < 350.326\ G)$

Following Petrov, PRL 115, 155302 (2015)

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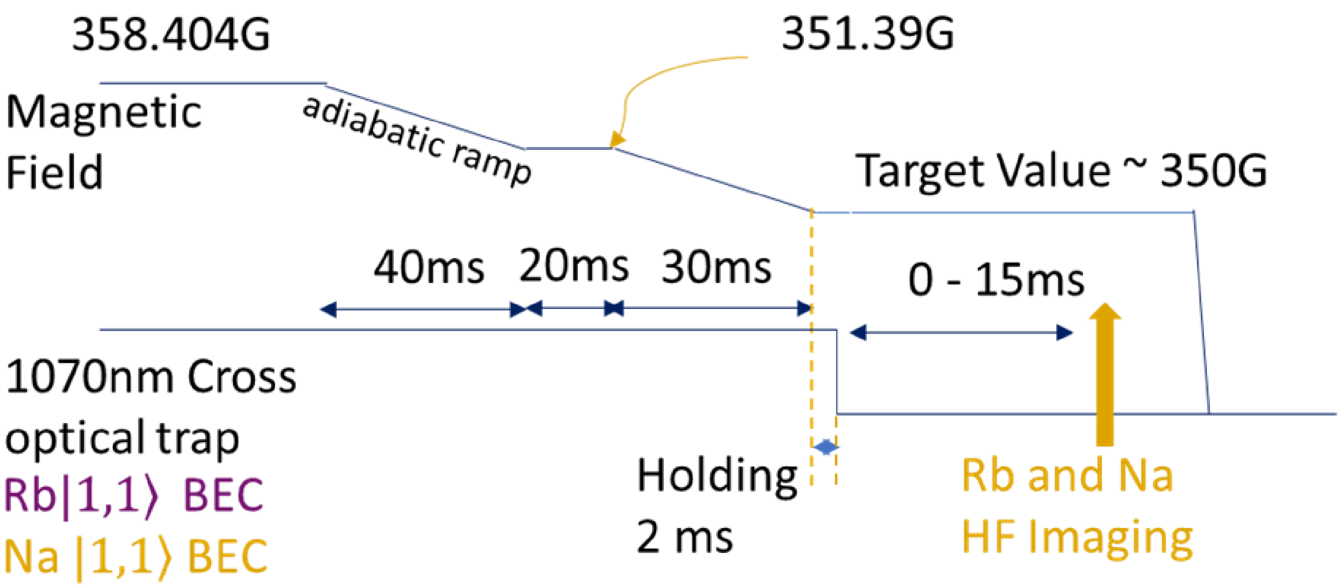
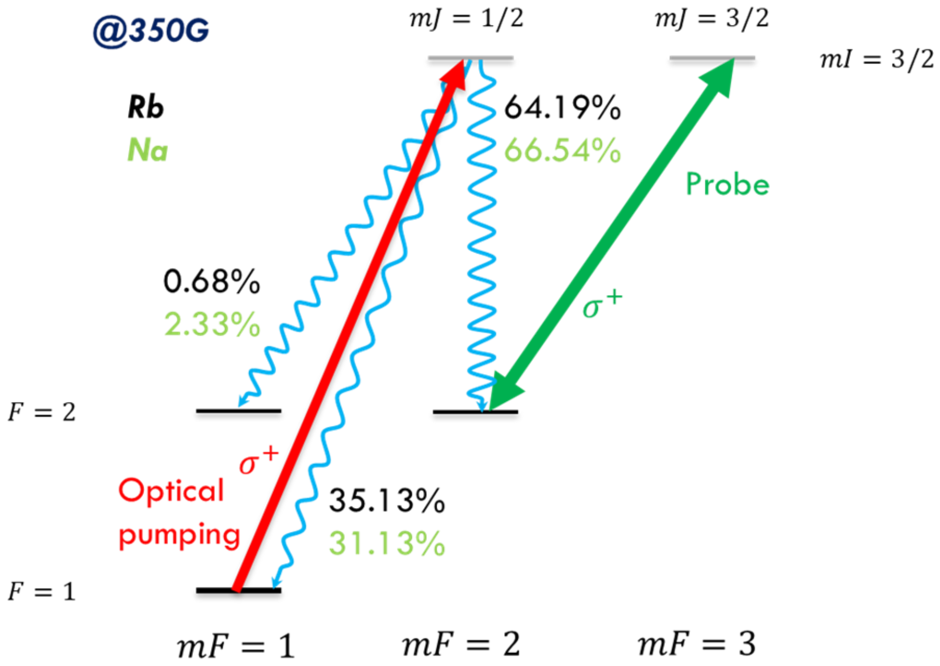
Time sequence



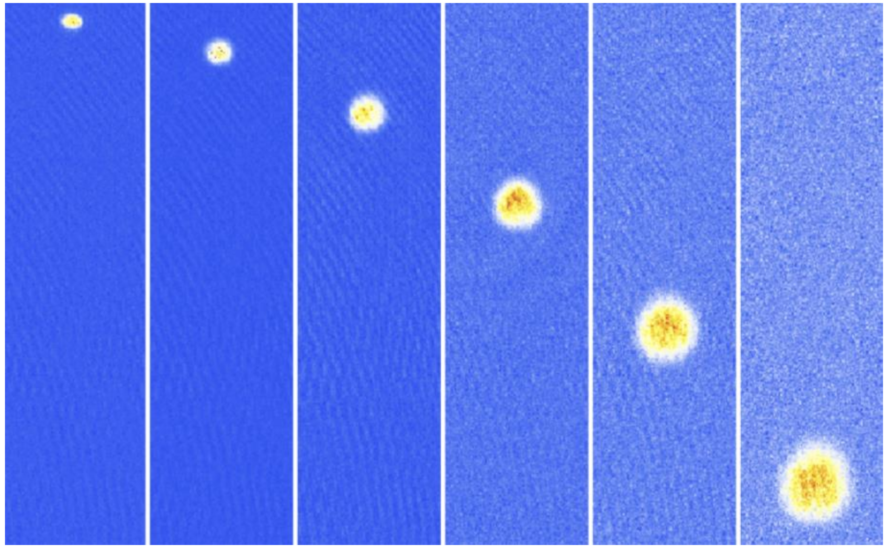
High-field image



In a nearly spherical optical trap

First signal: BEC expansion

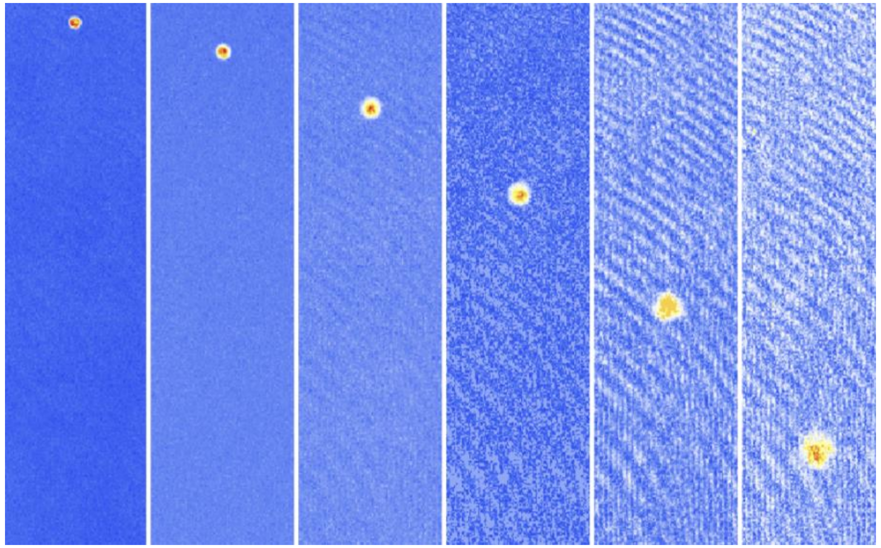
Na



2

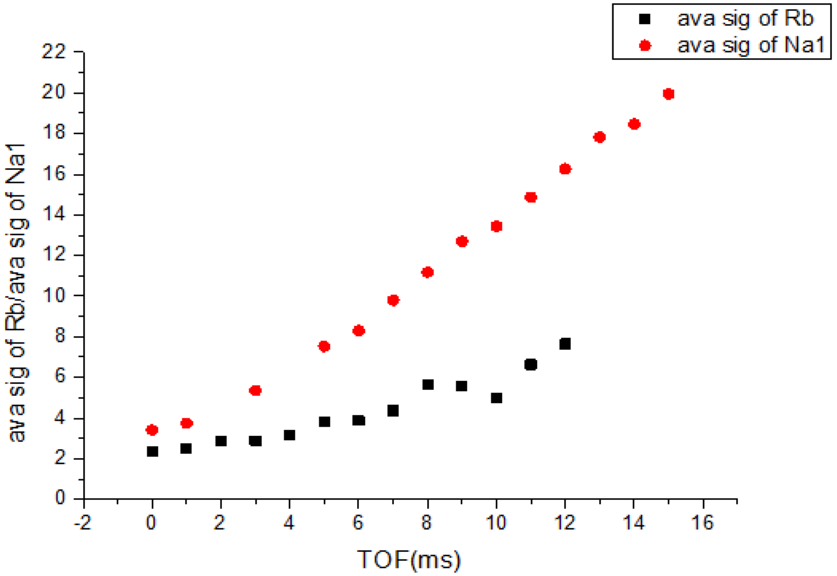
12 ms

Rb



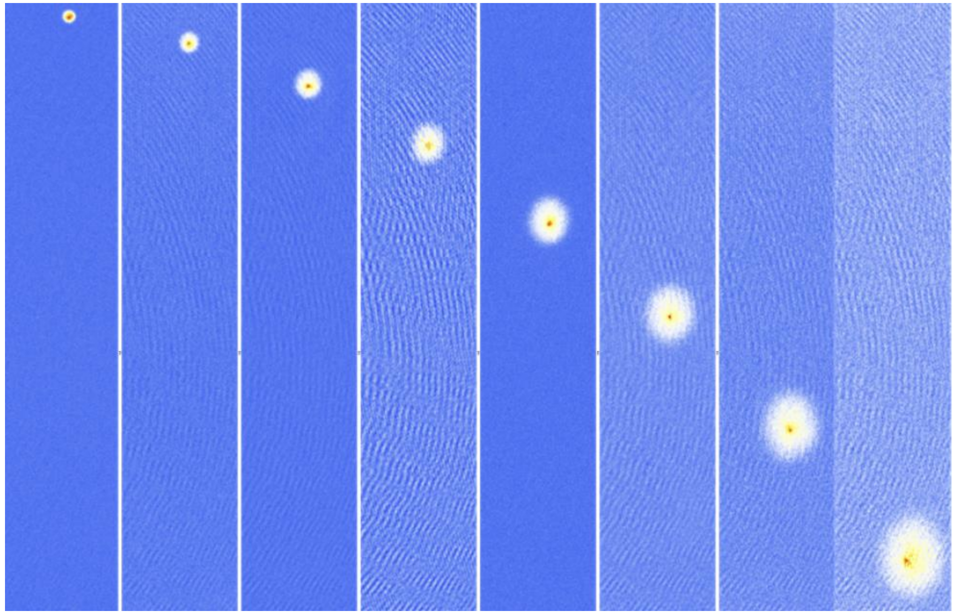
352.806 G

miscible double BEC



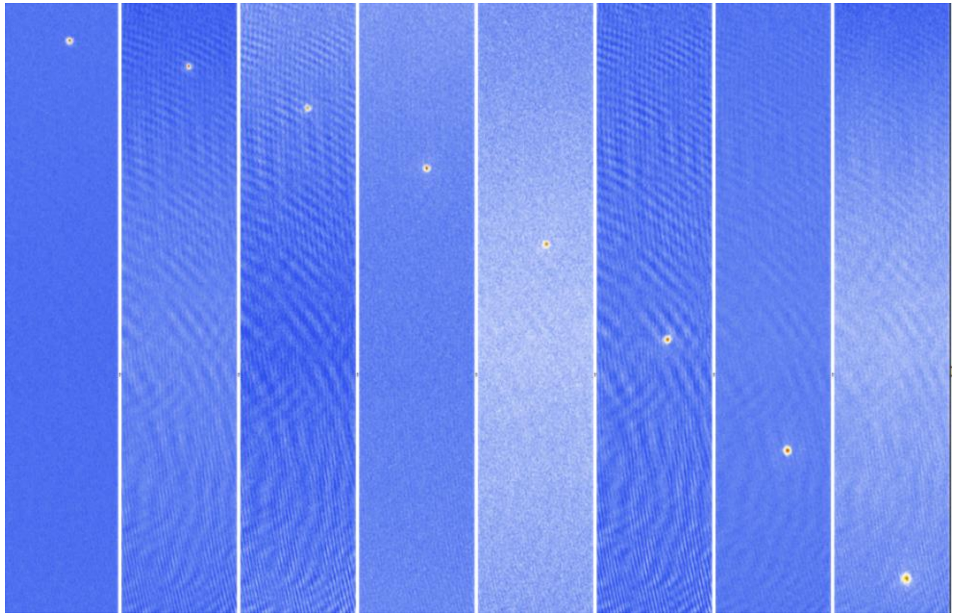
First signal: self-bound behavior

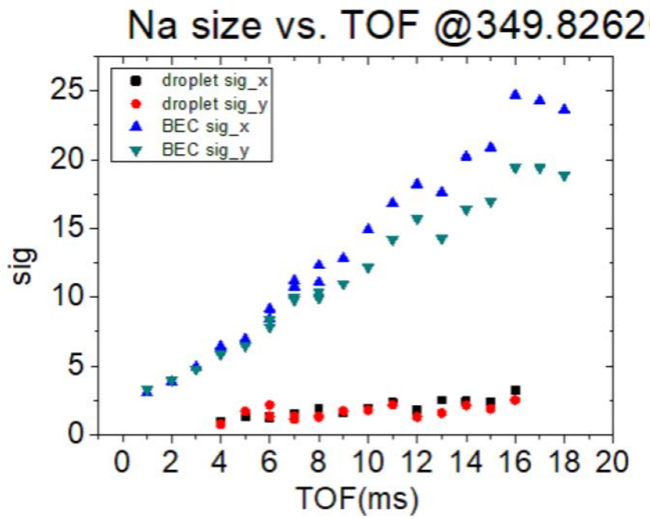
Na 9×10^4 $atoms$

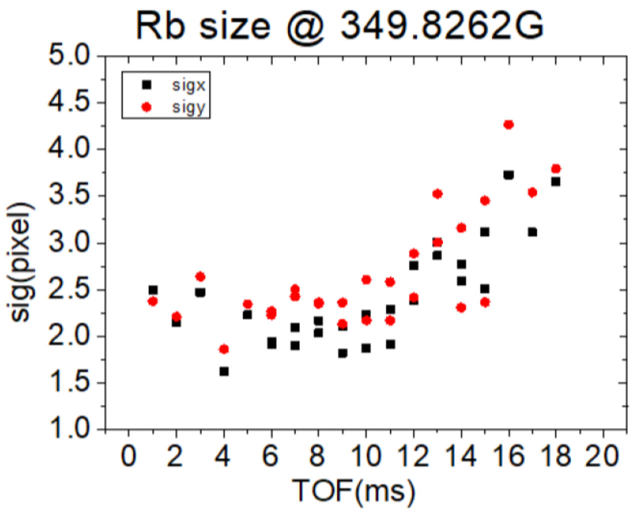


2 → 16 ms

Rb 3×10^4 $atoms$

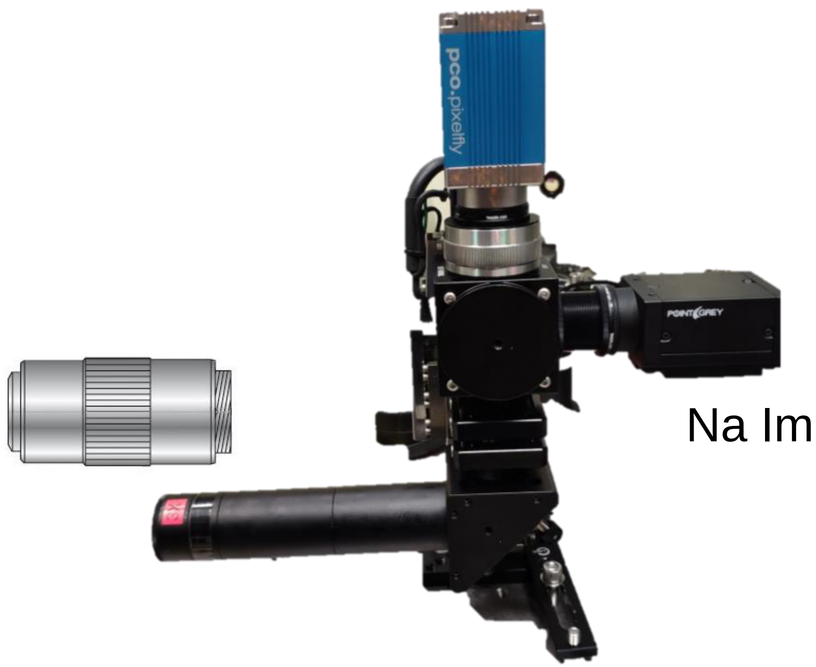






Improved imaging system

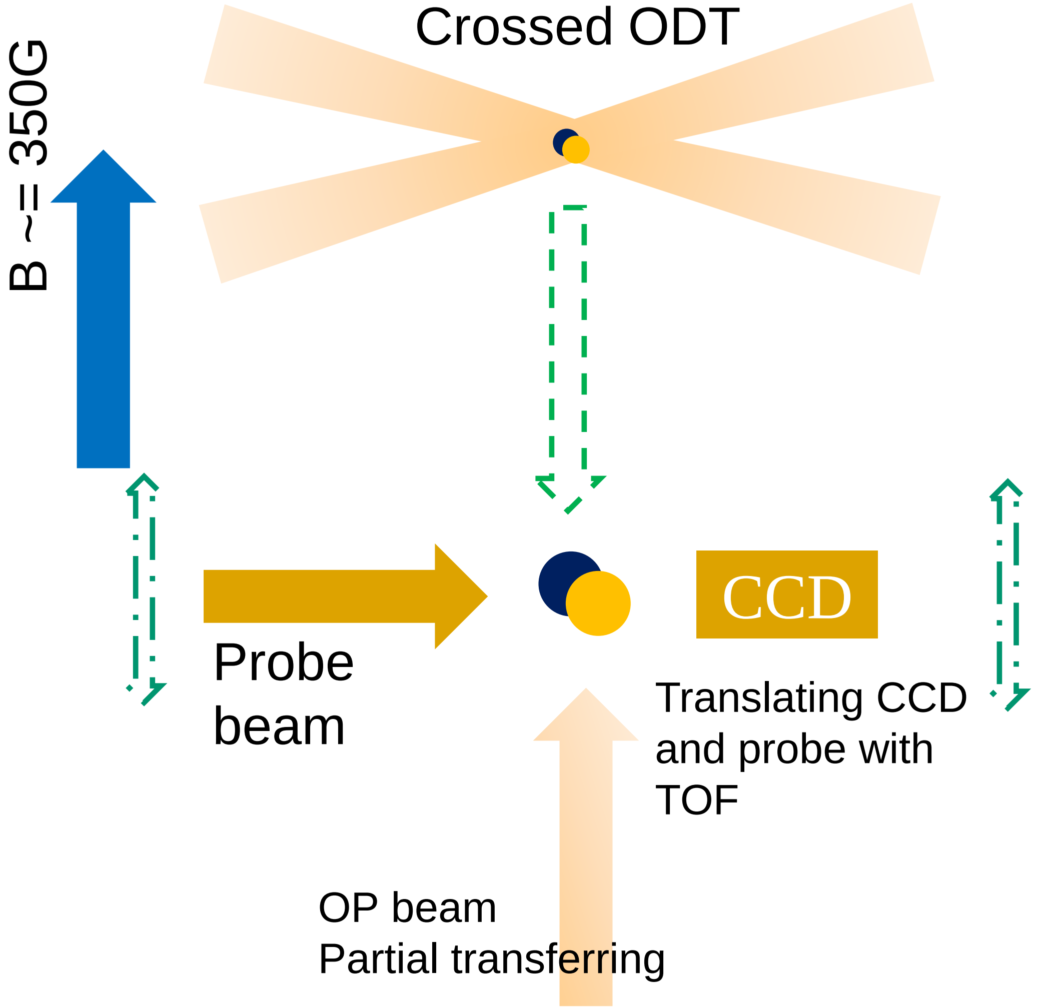
Imaging $|1,1\rangle$ state atoms with better resolution



Long working distance
objective with 0.28 N.A.

Achieved resolution:
~1 µm (rms Gaussian width)

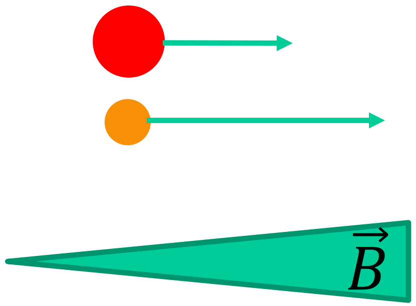
Magnification: ~15

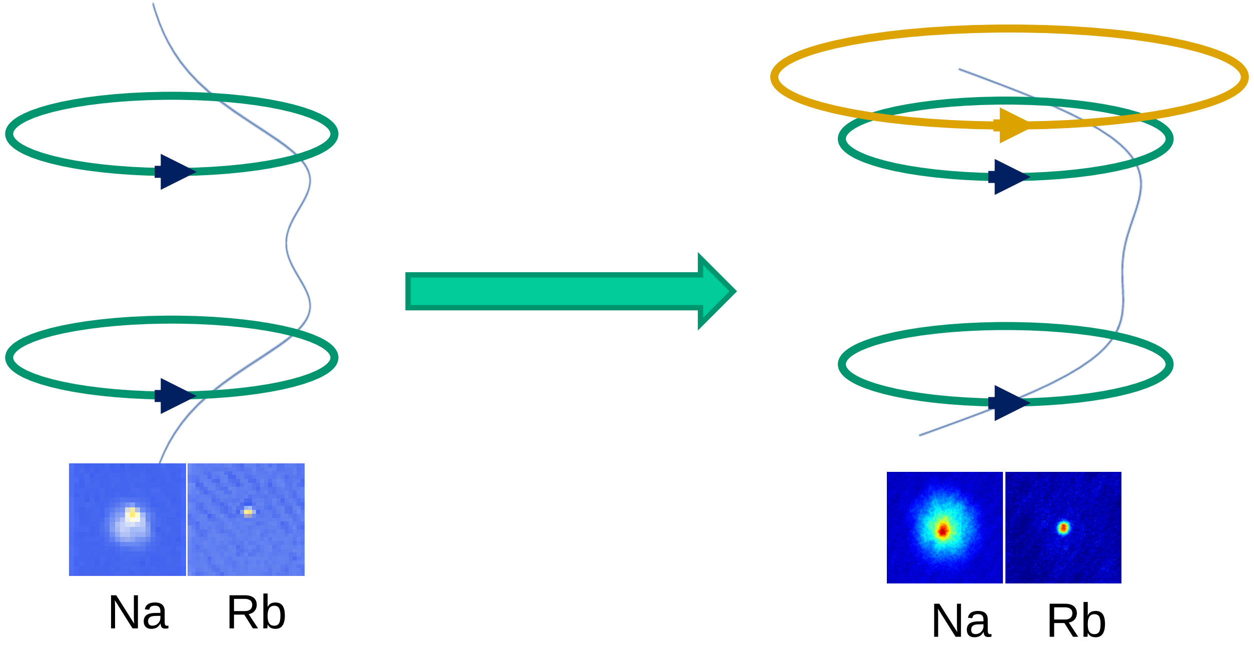


Magnetic field gradient compensation

Difference responses to magnetic response

87Rb: 0.837 MHz/G
23Na: 1.084 MHz/G

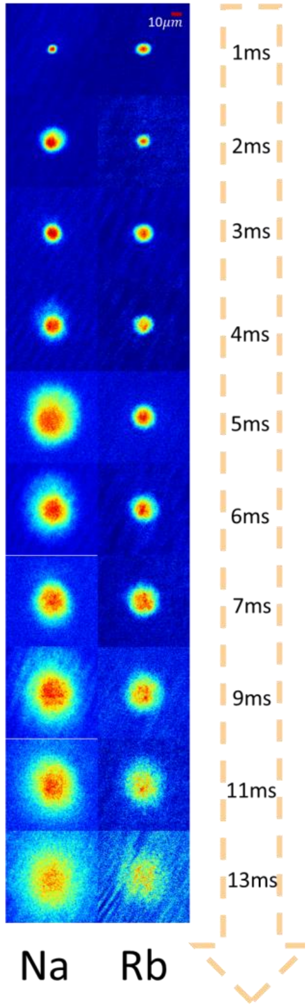




Still not prefect: residue gradient ~100 mG/cm

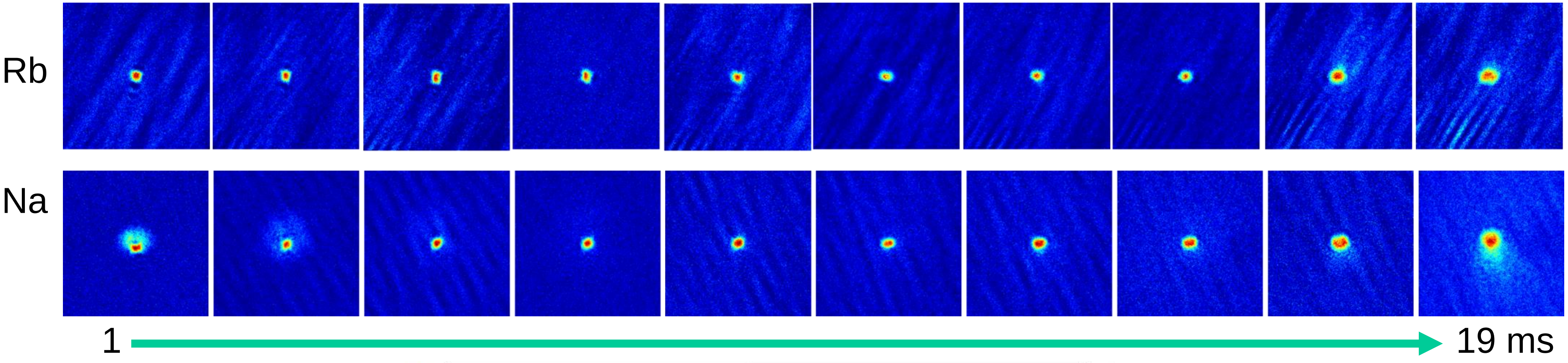
Na-Rb droplet in free space

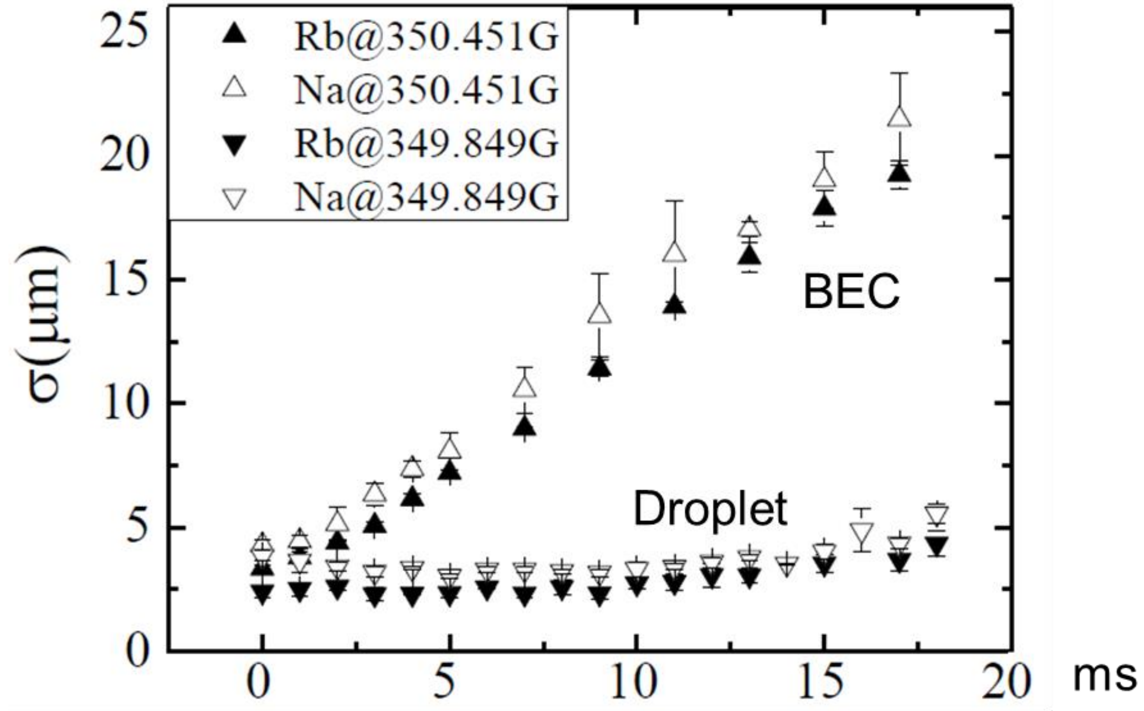
B = 350.458G



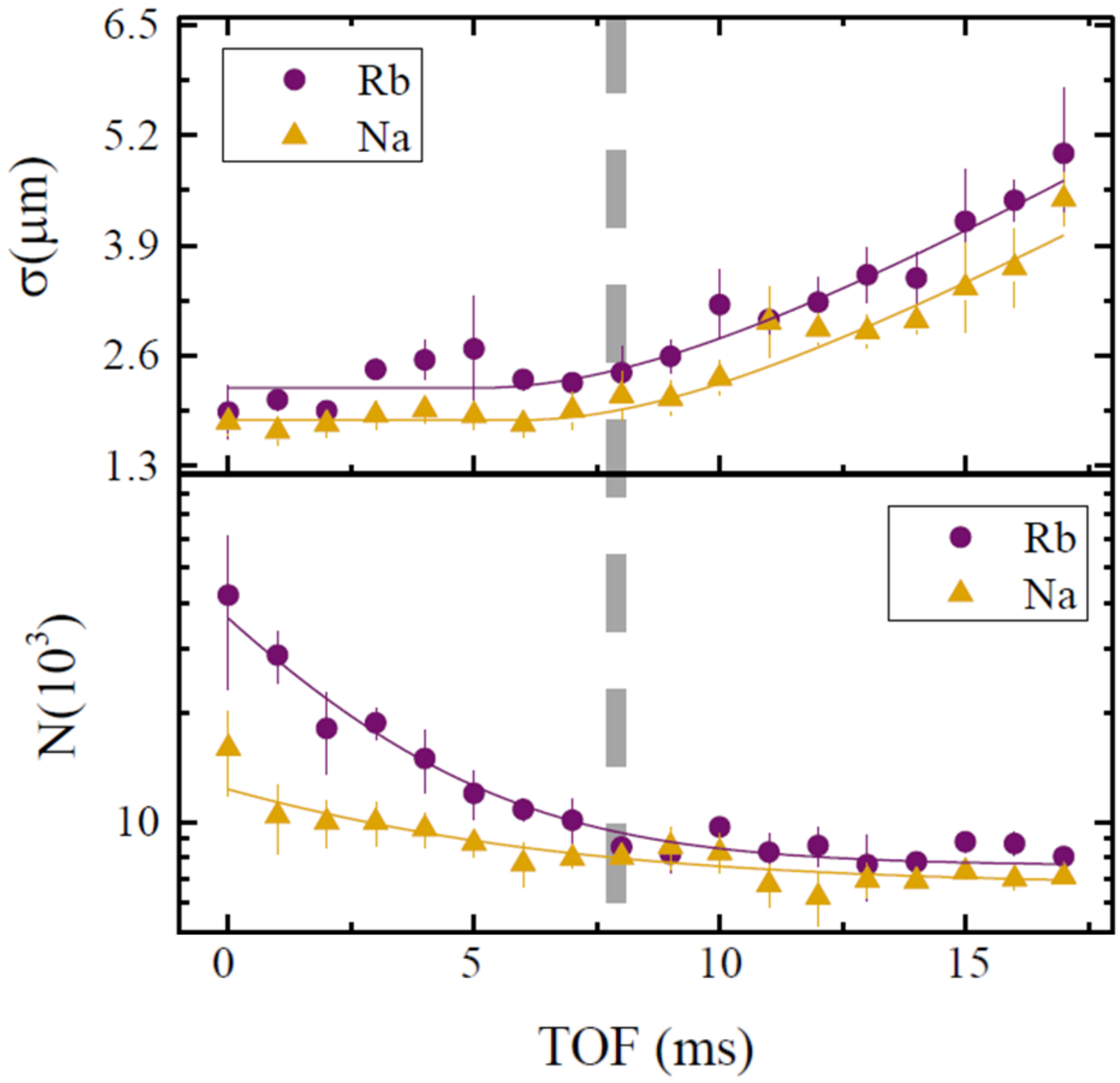
BEC

Droplet @ 349.851 G





Droplet lifetime and liquid to gas transition

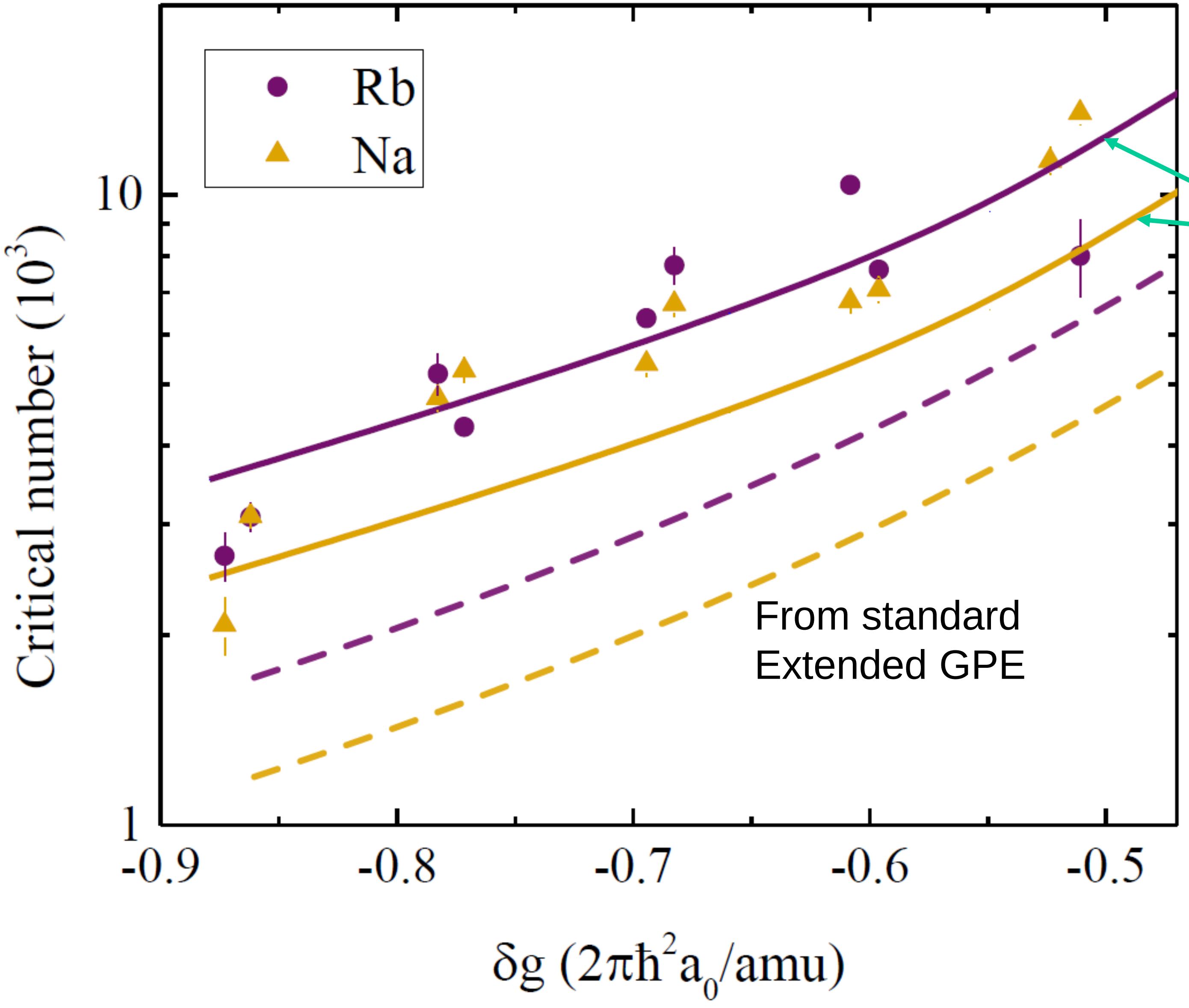


Droplet density: ~10^{15} cm^{-3} for both Na and Rb

3-body loss constants:
$L_3 \sim 8 \times 10^{-30} cm^6 s^{-1}$ for 87Rb BEC
$L_3 \sim 2 \times 10^{-30} cm^6 s^{-1}$ for 23Na BEC

Also droplet requires number ratio:
N_{Rb}/N_{Na} ~ 1.4

Fast loss is due to the interplay between the two mechanisms

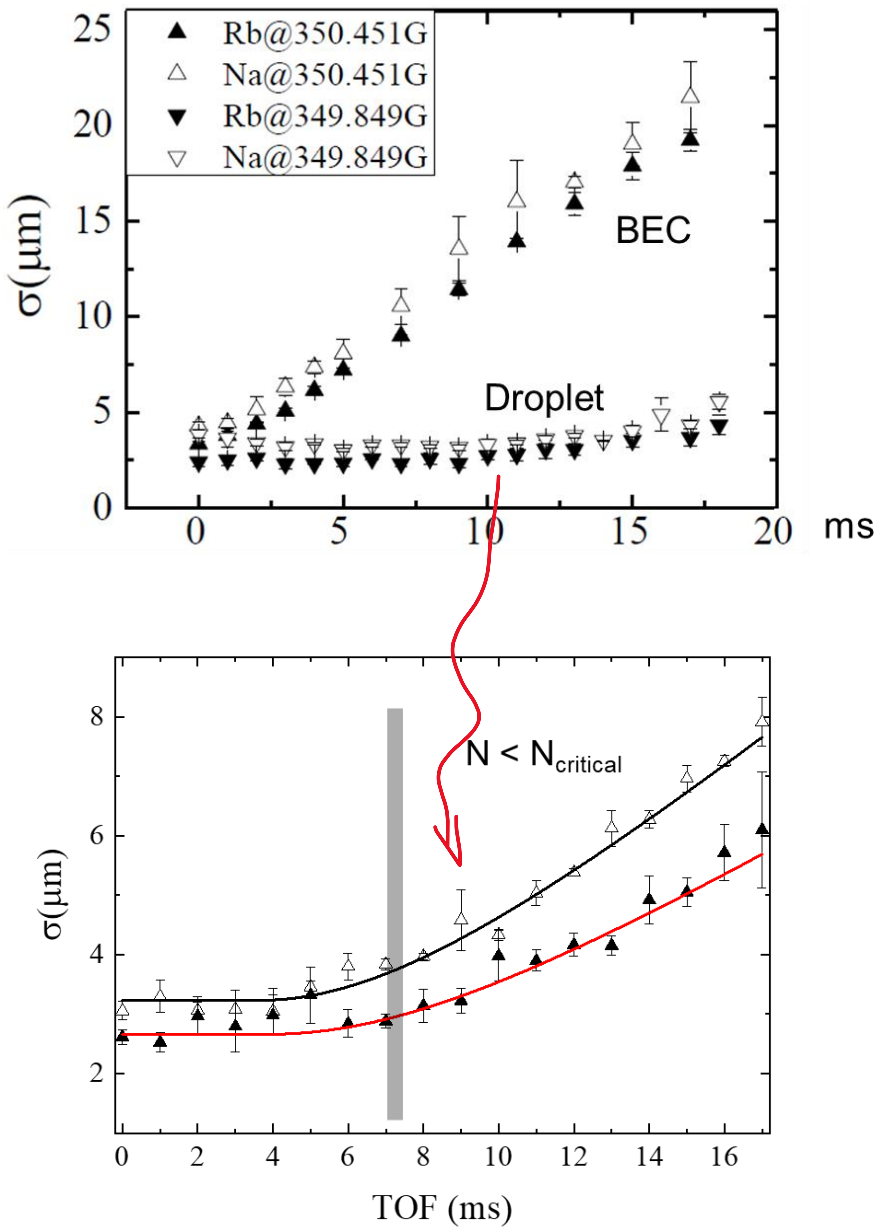


Extended GPE
+ B field gradient

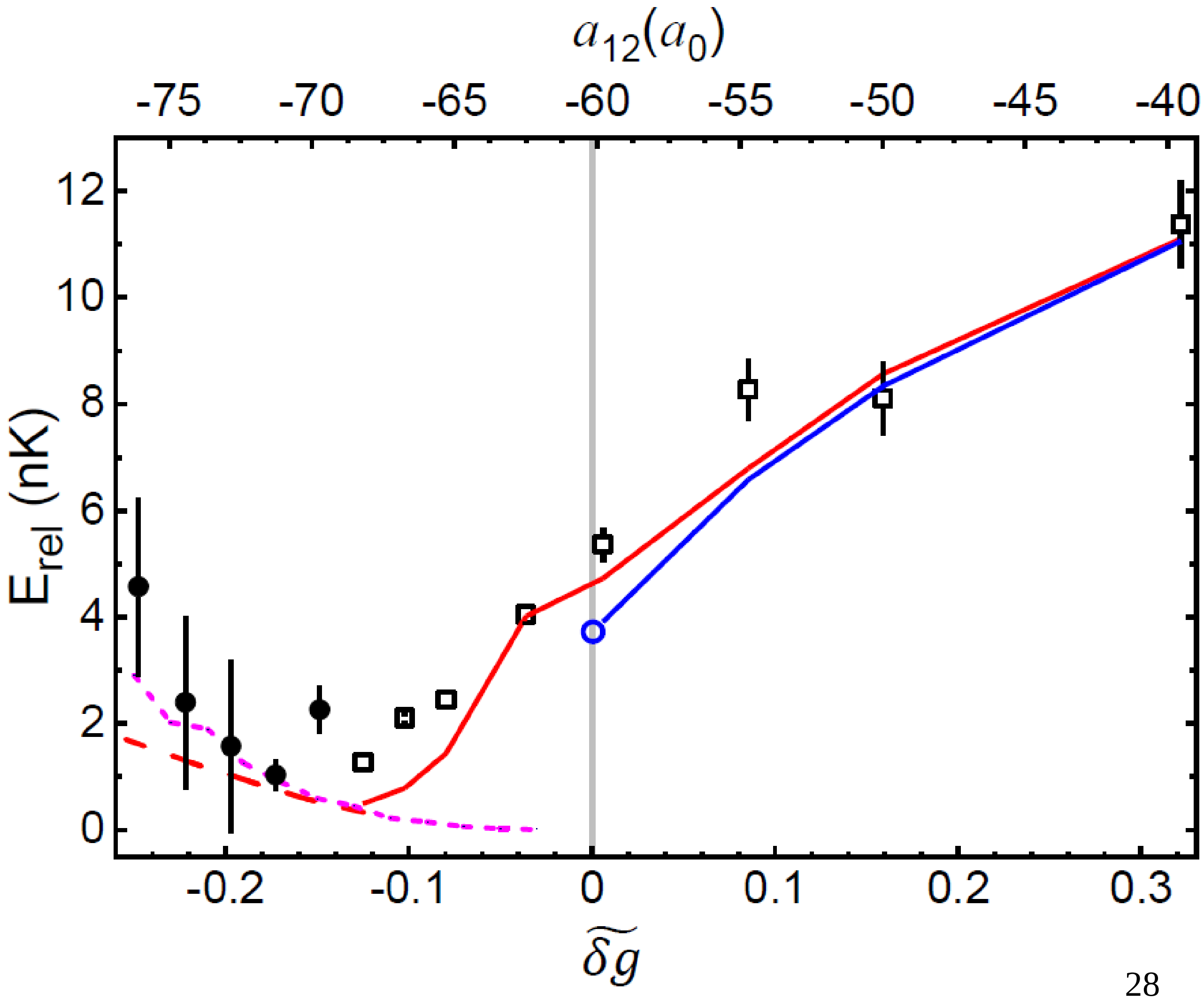
Theory:

Yinfeng Ma and Xiaoling Cui

The gas phase expansion



Release energies vs. δg



- Droplet of Na-Rb observed
- Liquid to gas phase transition: extended GPE works reasonably well
- A gas with dominating LHY energy

Outlook:

- Droplet in different dimension
- Droplet with large # of atoms: flat-top density
- Collective excitation of droplet

The team

NaRb polar molecule

He Junyu

Lin Jun-Yu

Jin Mucan

Chen Guanghua

Na + Rb atomic mixture

Li Lintao

Guo Zhichao

Jia Fan

Former students:

Xin Ye, Mingyang Guo, Fudong Wang,
Bing Zhu, Xiaoke Li, Jun Chen

Former postdocs:

Lele Chen, Shi Yu, Bo Lu, Xiaodong He,
Dezhi Xiong, Jie Ma

Thanks for your attention!