Quantum mixtures of ultracold gases

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CNR - Istituto Nazionale di Ottica
Research and Development Center on Bose-Einstein Condensation
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BOSE EINSTEIN CONDENSATION

Mixtures of Bose gases

homonuclear

VOLUME 78, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JANUARY 1997

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)

A new apparatus featuring a double magneto-optic trap and an Ioffe-type magnetic trap was used to create condensates of 2×10^6 atoms in either of the $|F = 2, m = 2\rangle$ or $|F = 1, m = -1\rangle$ spin states of ^{87}Rb. Overlapping condensates of the two states were also created using nearly lossless sympathetic cooling of one state via thermal contact with the other evaporatively cooled state. We observed that (i) the scattering length of the $|1, -1\rangle$ state is positive, (ii) the rate constant for binary inelastic collisions between the two states is $2.2(9) \times 10^{-14}$ cm^3/s, and (iii) there is a repulsive interaction between the two condensates. Similarities and differences between the behaviors of the two spin states are observed. [S0031-9007(96)02208-9]

heteronuclear

VOLUME 89, NUMBER 19 PHYSICAL REVIEW LETTERS 4 NOVEMBER 2002

Two Atomic Species Superfluid

G. Modugno, M. Modugno, F. Riboli, G. Roati, and M. Inguscio
LENS, Università di Firenze and INFM, Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy
(Received 23 May 2002; published 21 October 2002)

We produce a quantum degenerate mixture composed by two Bose-Einstein condensates of different atomic species, ^{41}K and ^{87}Rb. We study the dynamics of the superfluid system in an elongated magnetic trap, where off-axis collisions between the two interacting condensates induce scissorlike oscillations.

- **Interactions are repulsive within each component (stability requirement)**
- **Between the two components interactions can be attractive or repulsive**

Simple mean-field theory (T=0)

$$\frac{E}{V} = \frac{1}{2} g_{11} n_1^2 + \frac{1}{2} g_{22} n_2^2 + g_{12} n_1 n_2$$

$g_{11} > 0 \quad g_{22} > 0 \quad g_{12}$ either positive or negative

Miscible mixture: compressibility matrix must be positive definite

$$\det \begin{pmatrix} \partial^2 (E/V)/\partial n_1^2 & \partial^2 (E/V)/\partial n_1 \partial n_2 \\ \partial^2 (E/V)/\partial n_2 \partial n_1 & \partial^2 (E/V)/\partial n_2^2 \end{pmatrix} = g_{11} g_{22} - g_{12}^2 > 0$$

if $g_{11} g_{22} - g_{12}^2 < 0$

a) $g_{12}>0$ **vanishing compressibility leads to phase separation**

b) $g_{12}<0$ **vanishing compressibility leads to collapse**

Overview

Most interesting scenario if $g_{11}=g_{22}=g$ and $|g_{12}|$ close to g

A. Attractive Bose mixtures and formation of quantum droplets

two hyperfine states of ^{39}K (LENS + ICFO)

- Mean-field term would lead to collapse
- Repulsive beyond mean-field quantum fluctuations stabilise system

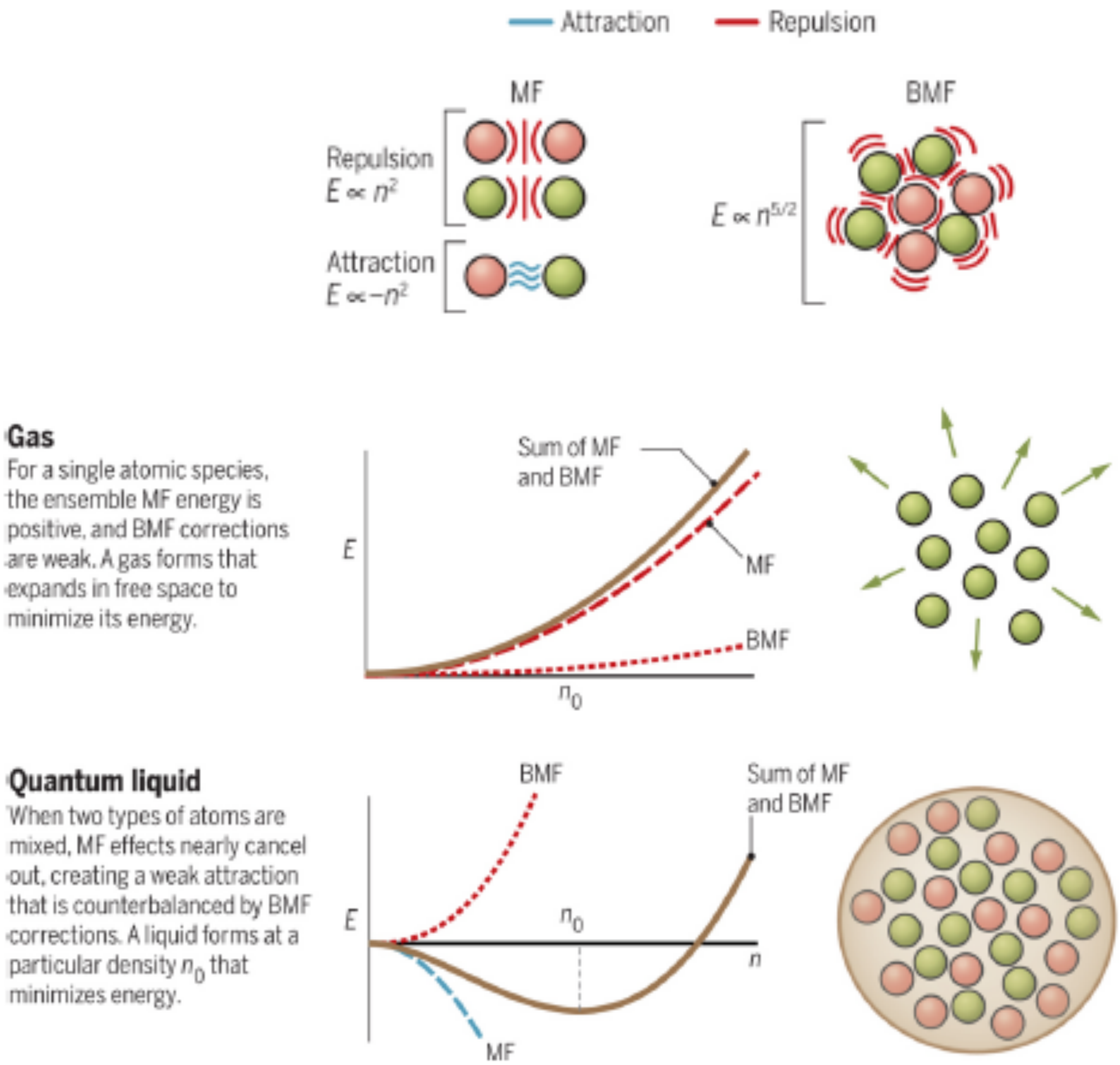
B. Repulsive Bose mixtures and phase separation transition

two hyperfine states of ^{23}Na (Trento)

- Mean-field terms give miscible state of mixture
- Beyond mean-field thermal fluctuations lead to phase separation

• Case A: Quantum droplets (Petrov 2015)

GRAPHIC: K. SUTLIFF/*SCIENCE*”



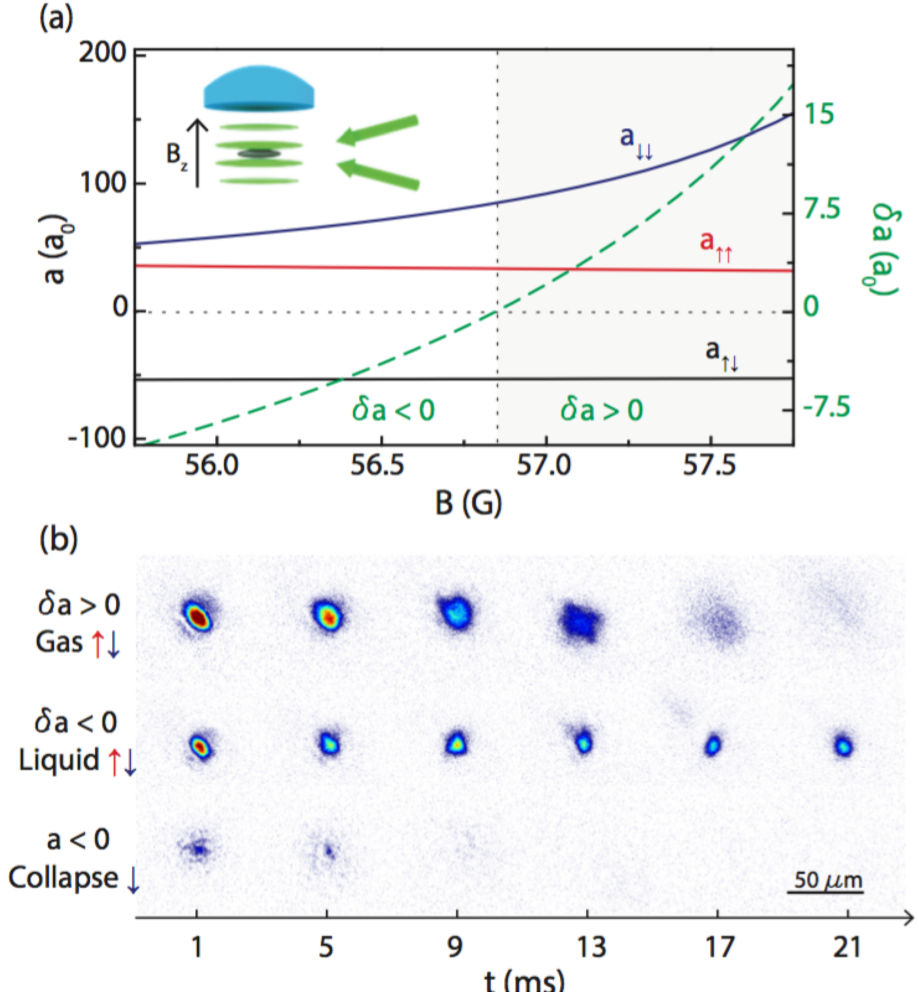
Two experimental realisations with ^{39}K in 2017

REPORT

QUANTUM FLUIDS

Quantum liquid droplets in a mixture of Bose-Einstein condensates

C. R. Cabrera,* L. Tanzi,* J. Sanz, B. Naylor, P. Thomas, P. Cheiney, L. Tarruell†

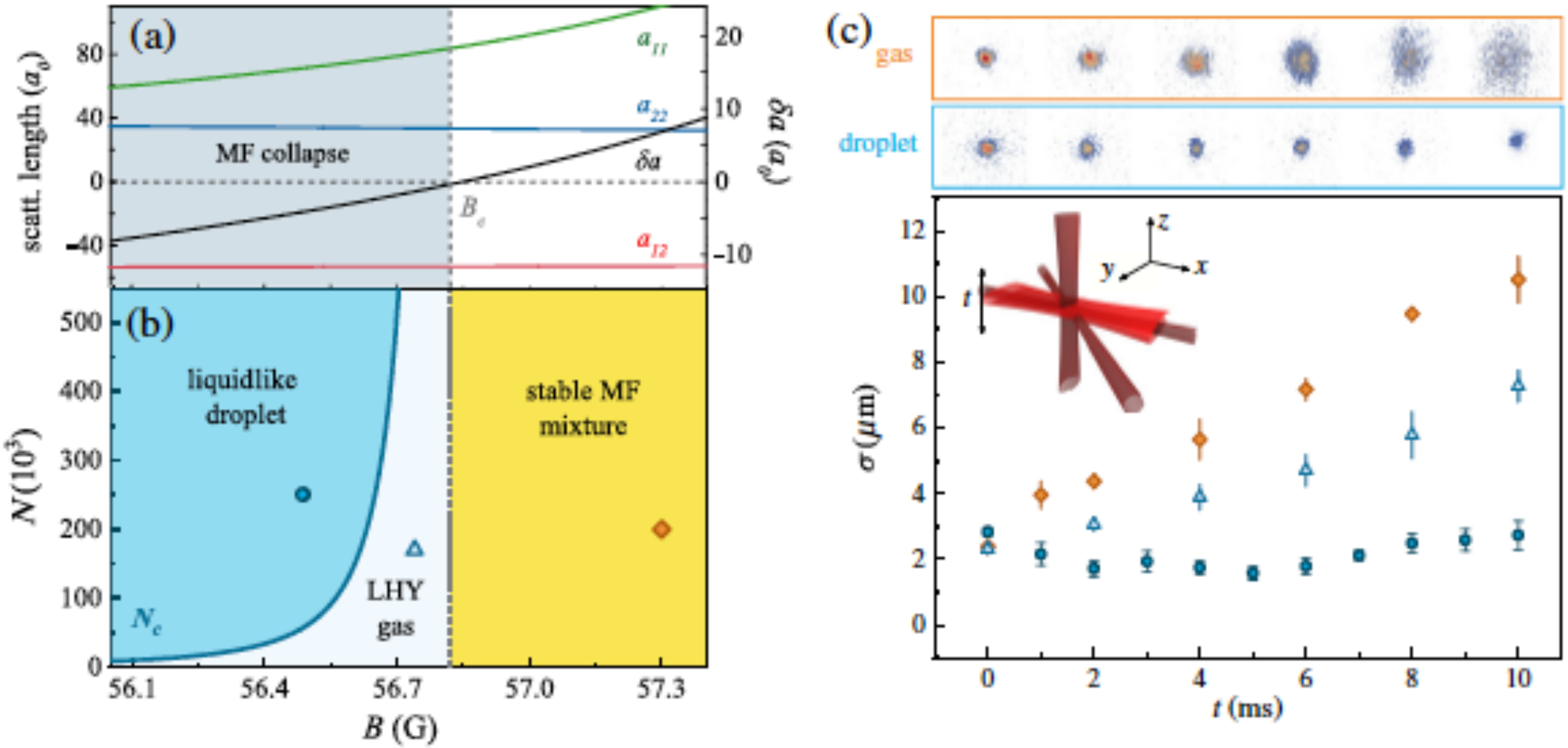


After being released the cloud

- expands (gas)
- shrinks (collapse)
- remains stable (liquid)

Self-Bound Quantum Droplets of Atomic Mixtures in Free Space

G. Semeghini,[1,2,*] G. Ferioli,[1,2] L. Masi,[1,2] C. Mazzinghi,[1] L. Wolswijk,[1] F. Minardi,[2,1,3] M. Modugno,[4,5] G. Modugno,[1,2] M. Inguscio,[2,1] and M. Fattori[1,2]



Bose mixtures in 1D present peculiar features

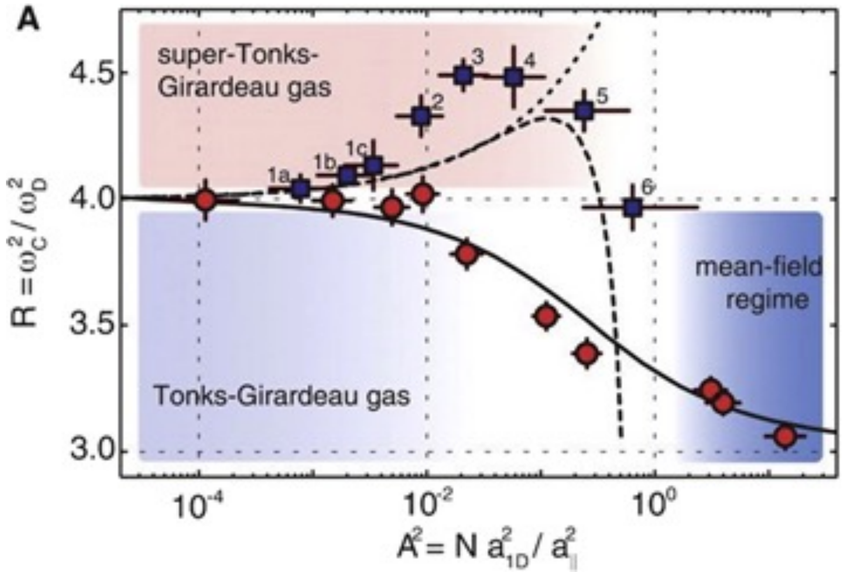
i. low-energy dynamics is universal and described by Luttinger liquid model
ii. at low energy spin and charge degrees of freedom are decoupled
iii. regimes of strong interactions have been achieved

Single-component Bose gas in 1D with contact interactions:
Lieb-Linger model (exactly solvable)

g **small: mean-field regime**
Bogoliubov theory

g **large: Tonks-Girardeau regime**
impenetrable bosons (like fermions)

Frequency of breathing mode (Haller et al. 2009)



- **We consider attractive mixtures in 1D**

Microscopic Hamiltonian

$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{N_a}\frac{\partial^2}{\partial x_i^2} + g\sum_{i<j}\delta(x_i - x_j) - \frac{\hbar^2}{2m}\sum_{\alpha=1}^{N_b}\frac{\partial^2}{\partial x_\alpha^2} + g\sum_{\alpha<\beta}\delta(x_\alpha - x_\beta) + \tilde{g}\sum_{i,\alpha}\delta(x_i - x_\alpha),$$

- **same mass m for the two components**
- **same intra-species coupling** $g>0$
- **inter-species coupling is attractive** $\tilde{g} < 0$

Regimes of strong interactions where both g and $\tilde{g}$ are large are investigated

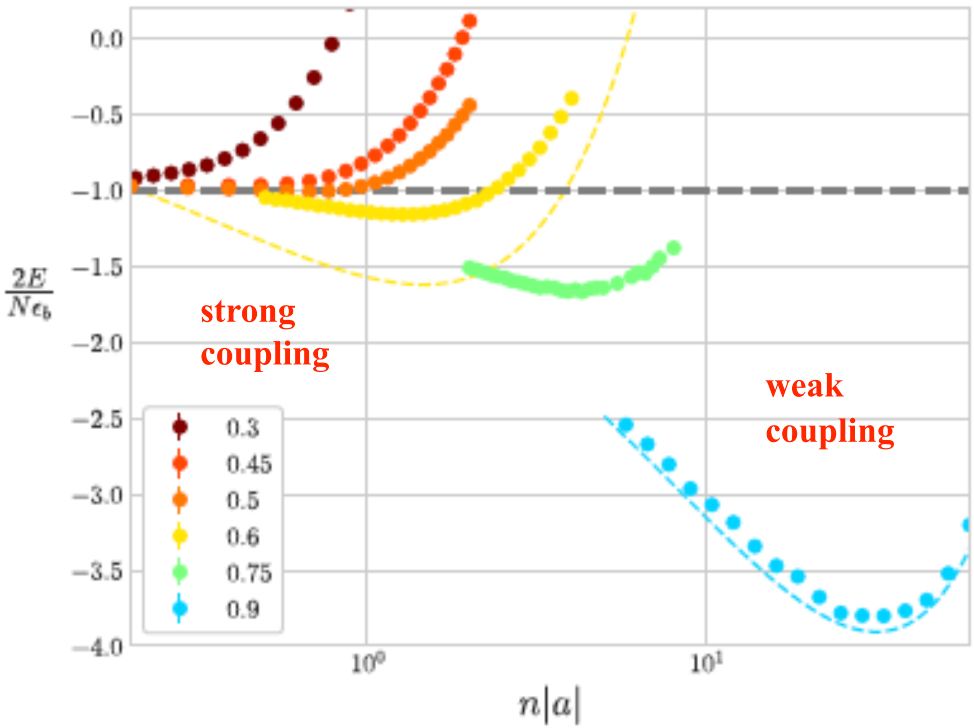
Use of exact diffusion Monte Carlo methods allows use to go beyond regime of applicability of perturbation theory

Energy per particle

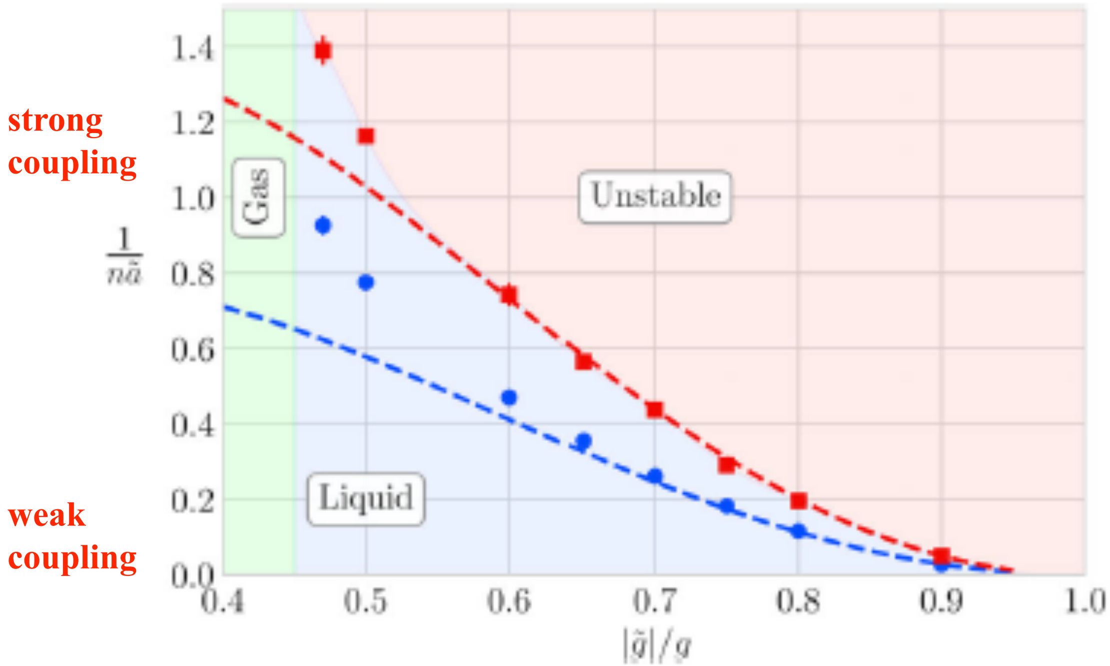
transition from

liquid (minimum exists at finite density)

to gas (minimum at zero density)



Phase diagram

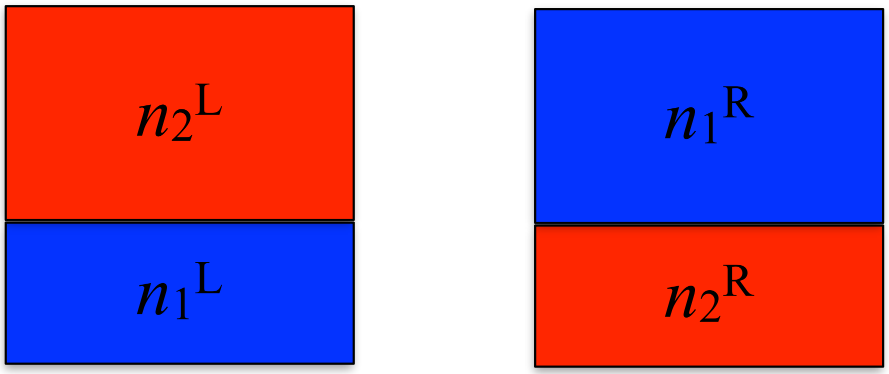


Case B: Phase separation at finite temperature for repulsive mixtures

Conditions for a phase separated state

a) **thermal equilibrium** $T^L = T^R$

b) **pressure equilibrium** $p^L = p^R$



Left (-m<0) **Right** (m>0)

$n_1^L = n_2^R$ and $n_2^L = n_1^R$

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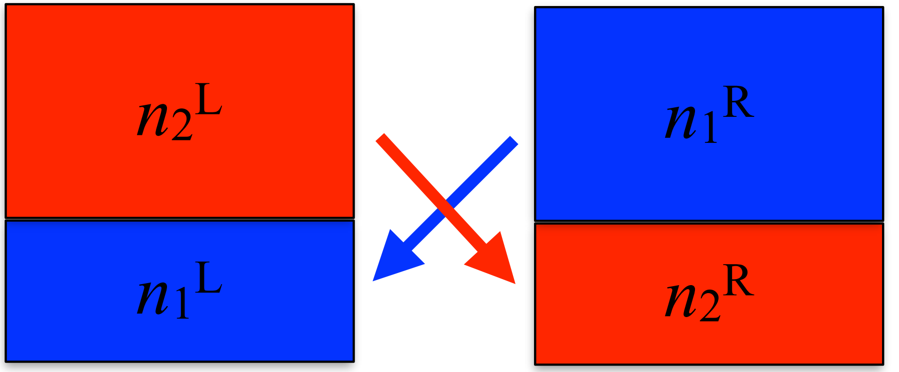

$n_1^L = n_2^R$ and $n_2^L = n_1^R$

process that reduces m

Left (-m<0) **Right** (m>0)

c) **chemical stability** $\mu_1^L - \mu_1^R + \mu_2^R - \mu_2^L > 0$

T=0

$$g(n_1^L - n_2^L) + g_{12}(n_2^L - n_1^L) > g(n_1^R - n_2^R) + g_{12}(n_2^R - n_1^R)$$

$$\Rightarrow (g - g_{12})m < 0 \Rightarrow g - g_{12} < 0$$

If *g>g*$_{12}$ equilibrium state is *m=0*

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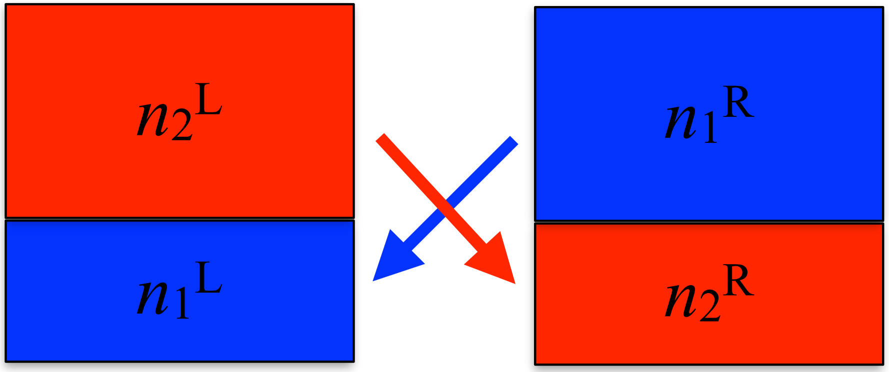

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process that reduces m

Left (-m<0) **Right** (m>0)

c) **chemical stability** $\mu_1^L - \mu_1^R + \mu_2^R - \mu_2^L > 0$

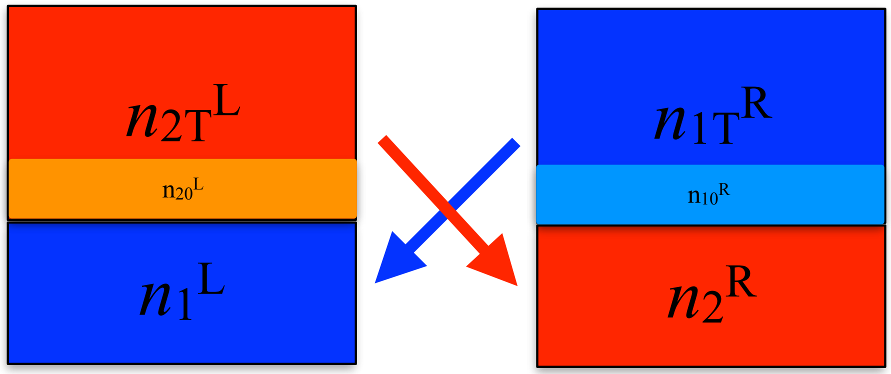
T>>Tc $$(2g - g_{12})m + k_B T \log \frac{1 + m/n}{1 - m/n} < 0$$

assuming $m << n = n_1 + n_2$

$$(2g - g_{12})n + 2k_B T < 0$$

Since $k_B T >> gn$ equilibrium state is $m=0$

Phase separated state



$$n_1^L = n_2^R$$

$$n_{2T}^L = n_{1T}^R \text{ and } n_{20}^L = n_{10}^R$$

$$\Rightarrow \ p_L = p_R$$

Left (-m<0) **Right** (m>0)

process that reduces m

State with m>0 stable if

$$\mu_2^R - \mu_1^R > 0$$

Notice that condensate is fully phase separated

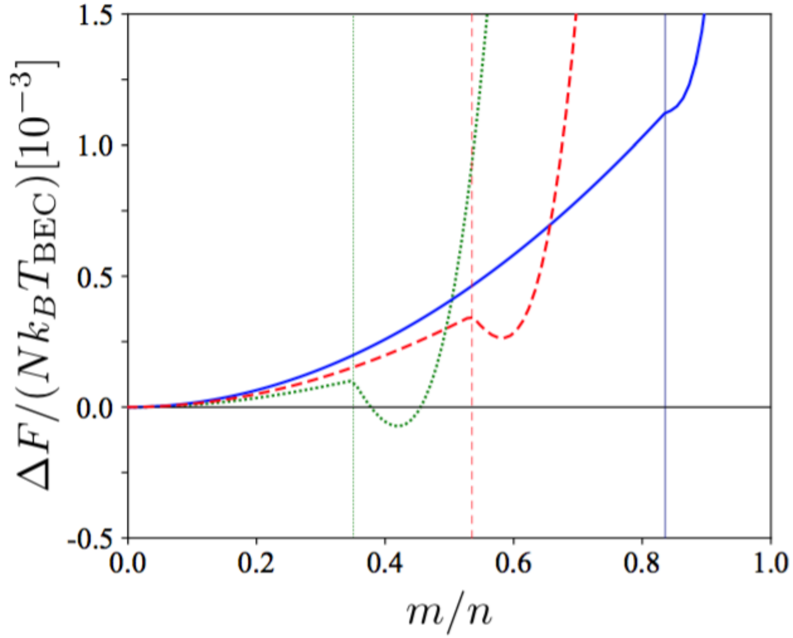
Such a state is an absolute minimum of the free energy

Hartree-Fock theory at T>0

$$\frac{F^{\mathrm{HF}}}{V} = \frac{g}{2}(n_1^2 + n_2^2) + g_{12} n_1 n_2 + g\frac{\zeta(3/2)^2}{\lambda_T^6} + \frac{1}{\beta V}\sum_i \sum_{\mathbf{k}} \ln\left(1 - e^{-\beta(\varepsilon_{\mathbf{k}} + g n_{i,0})}\right)$$

Free energy develops a minimum at finite polarization

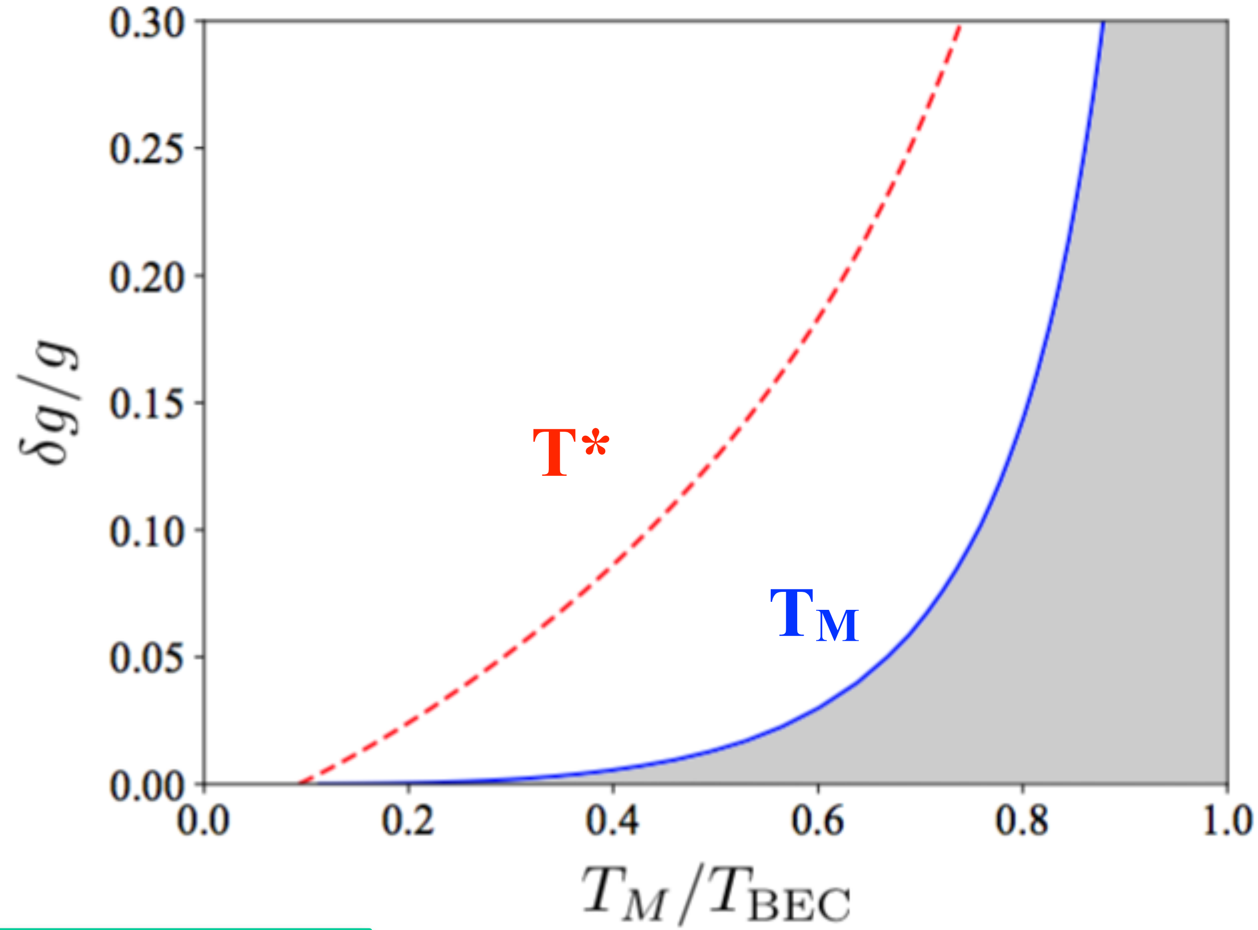
if T<T* only minimum at m=0 (mixed state)
if T>T* minimum exists at finite m (PS state)
if T>T_M minimum becomes lower than m=0



Transition temperature

Difference of coupling constants
(e.g. ^{23}Na $|F=1, m_F=\pm 1\rangle$ - $\delta g/g = 0.07$)

$$\delta g = g - g_{12} > 0$$



If $\delta g = 0$ then $T^* = 0.1 T_{BEC}$

Thank you for your attention