Fragmentation and Stillbirth of Condensation in the Rapidly Evaporative Cooling of a Dual Species Bose Mixture

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Outline

1. Review of Experimental Results
2. Stochastic Projected GPEs
3. Numerical Simulations
4. Summary

1. Experimental Results

PRL **101,** 040402 (2008) PHYSICAL REVIEW LETTERS week ending 25 JULY 2008

Tunable Miscibility in a Dual-Species Bose-Einstein Condensate

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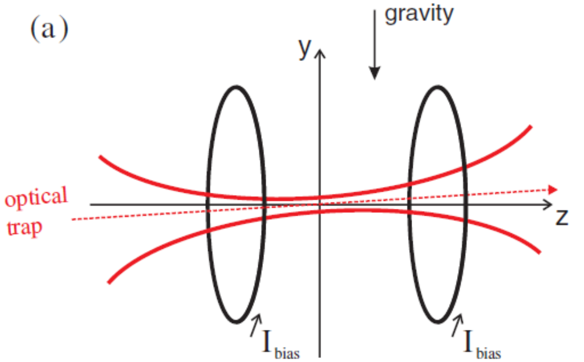
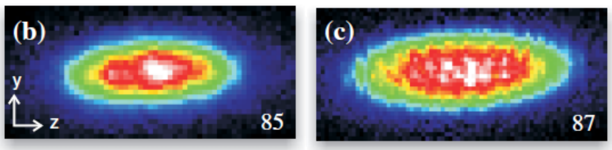
(Received 19 February 2008; published 24 July 2008)

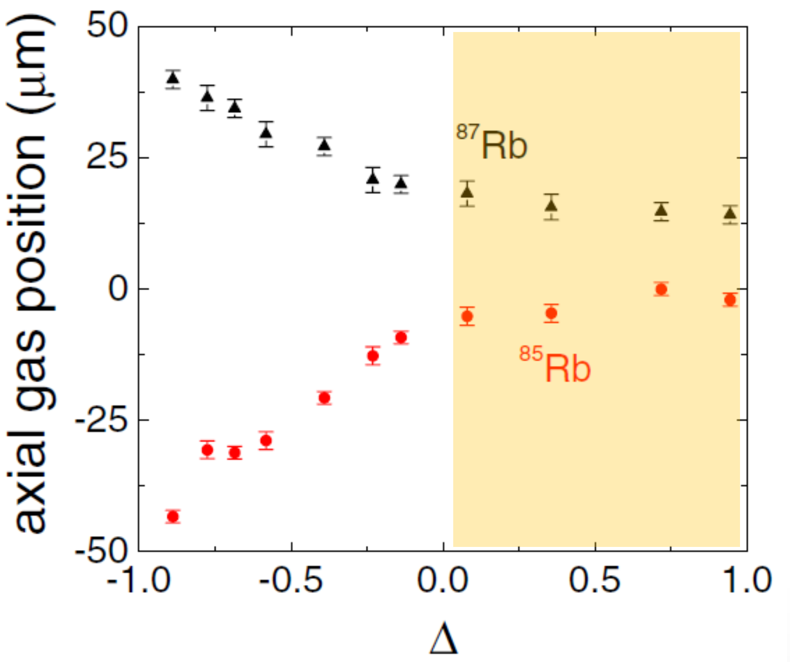
We report on the observation of controllable phase separation in a dual-species Bose-Einstein condensate with ^{85}Rb and ^{87}Rb. Interatomic interactions between the different components determine the miscibility of the two quantum fluids. In our experiments, we can clearly observe immiscible behavior via a dramatic spatial separation of the two species. Furthermore, a magnetic-field Feshbach resonance is used to change them between miscible and immiscible by tuning the ^{85}Rb scattering length. The spatial density pattern of the immiscible quantum fluids exhibits complex alternating-domain structures that are uncharacteristic of its stationary ground state.

1. Experimental Results





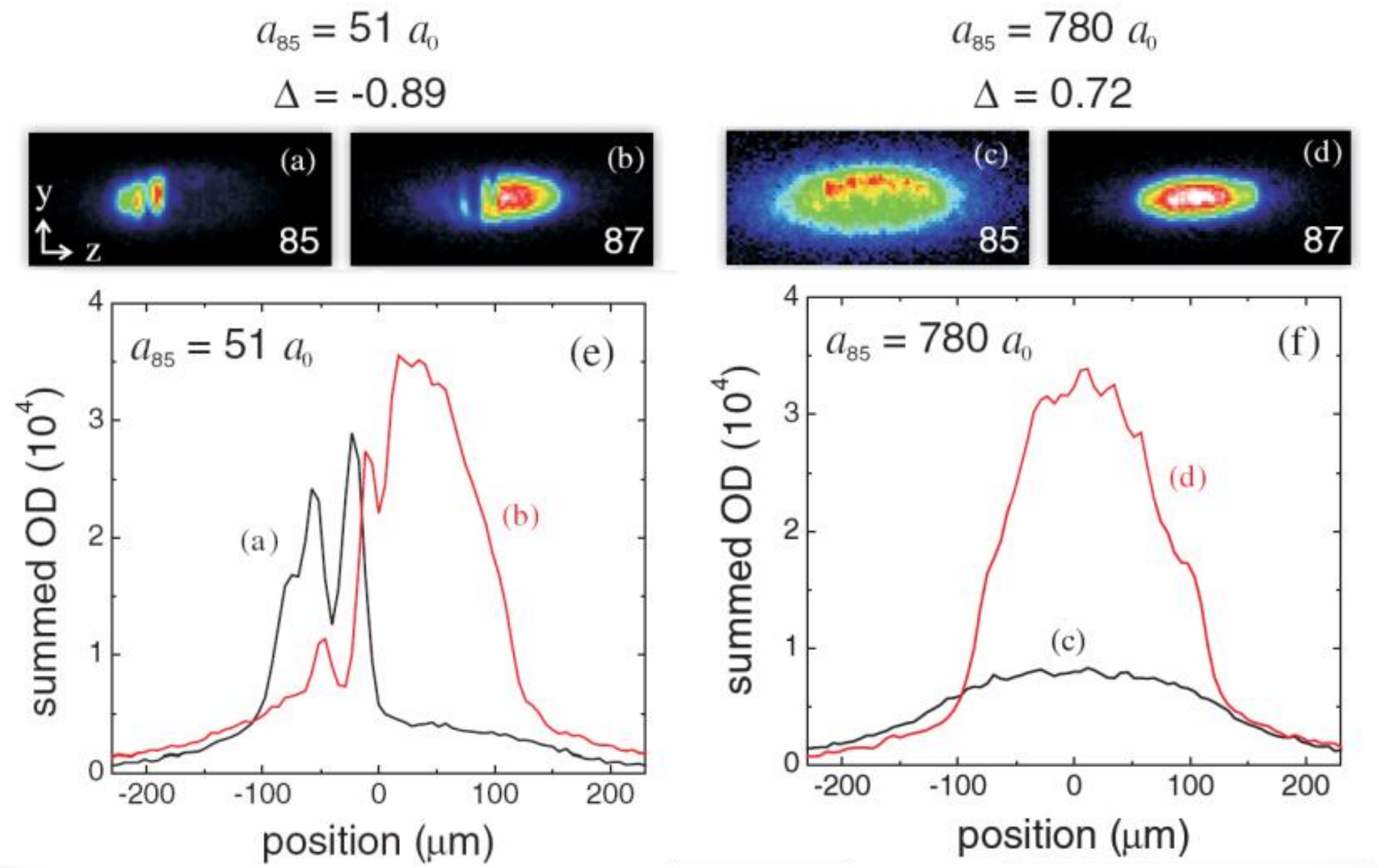
$$\Delta \equiv \frac{a_{85-85} a_{87-87}}{a_{85-87}^2} - 1$$



Phys. Rev. Lett. 101, 040402(2008)

1. Experimental Results

$$^{85}Rb\ \left|f=2, m_f=-2\right\rangle,\ ^{87}Rb\ \left|f=1, m_f=-1\right\rangle$$



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1. Experimental Results

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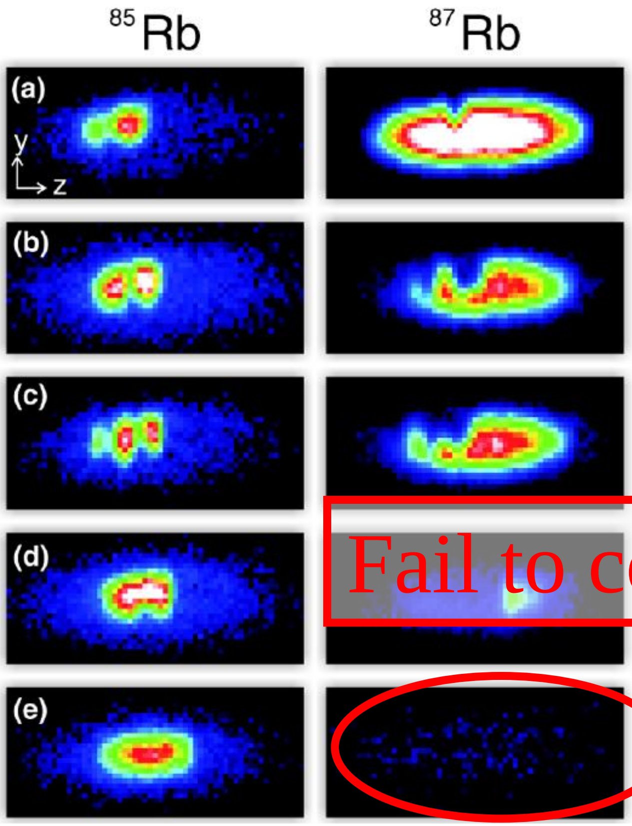
- S. B. Papp *et. al*. reported that **the two-component BEC may fail to form if the particle number of one component is too large at the start of evaporation.** The experiment is carried out in **an extremely elongated cigar-shape trap**.

1. Experimental Results



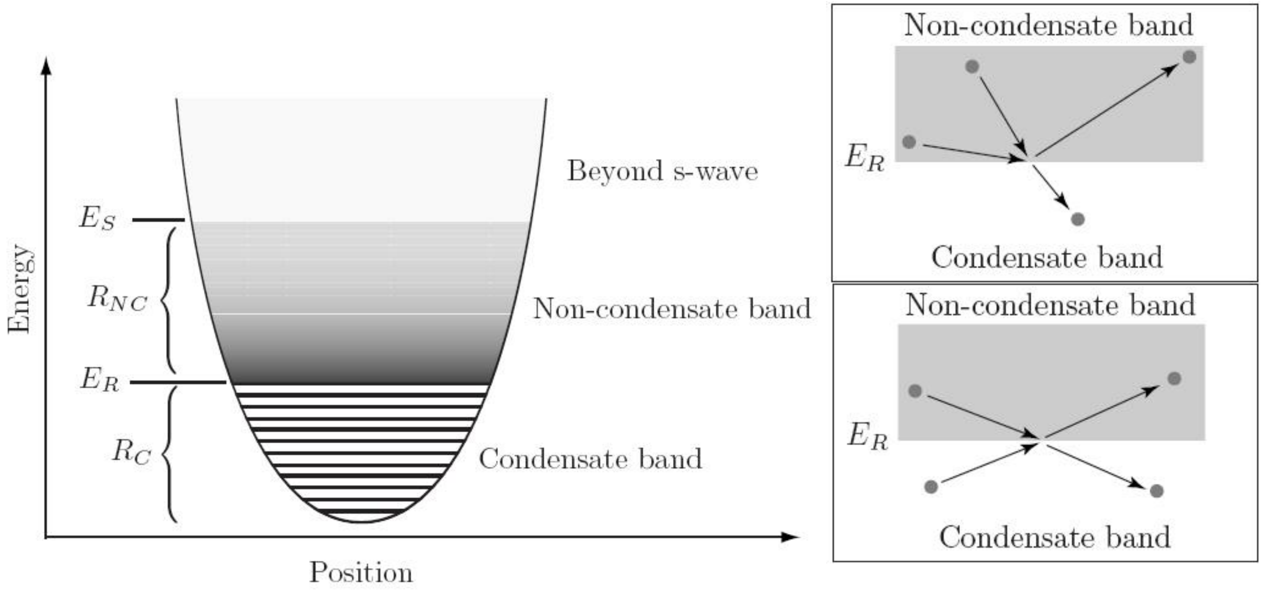
$N_{85}=1.2\text{x}10^4$ → $N_{85}=2.2\text{x}10^4$

$N_{87}=1.4\text{x}10^5$ → $N_{87}=3\text{x}10^3$

Fail to condense

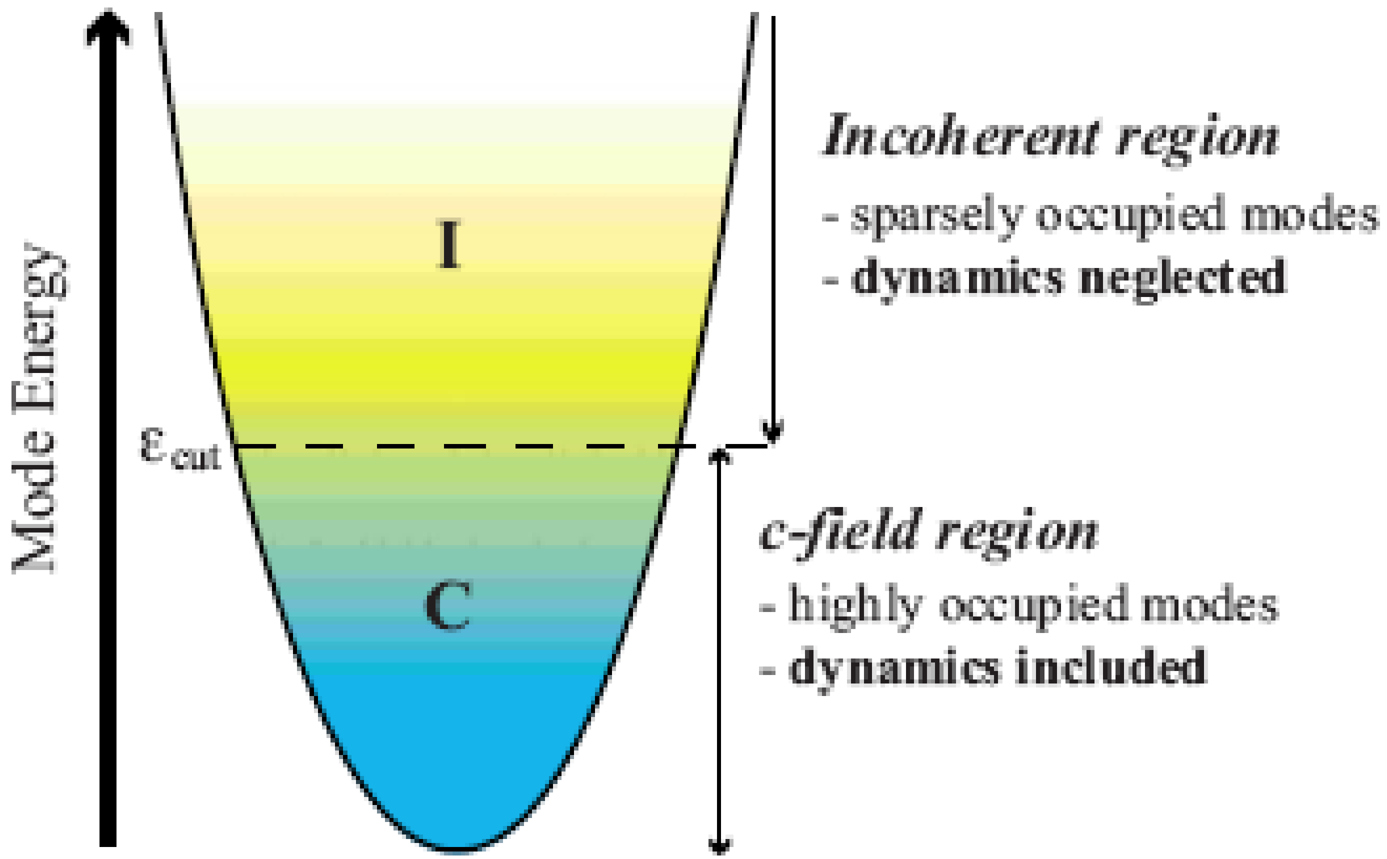
Phys. Rev. Lett. 101, 040402(2008)

2. Stochastic Projected GPEs

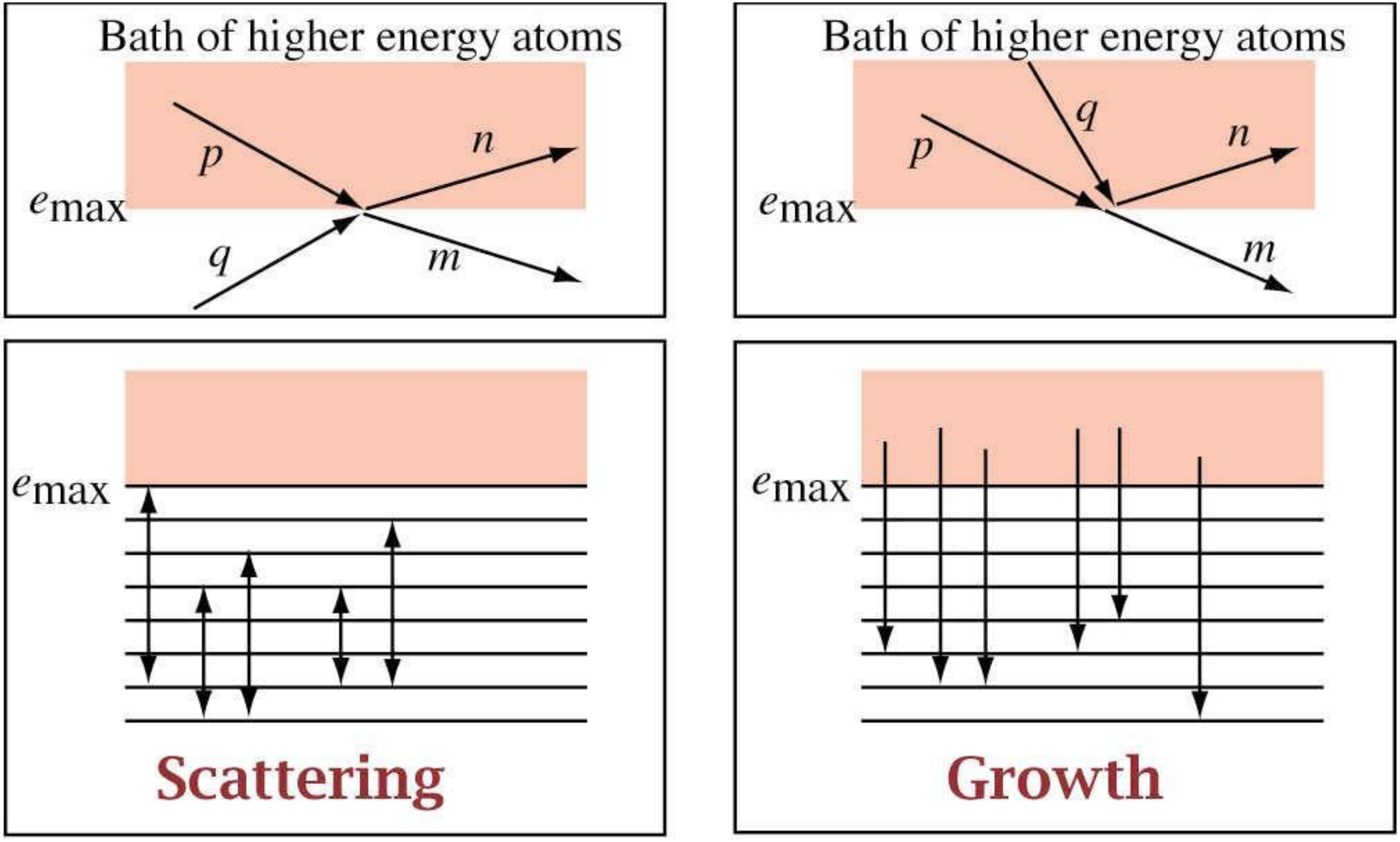


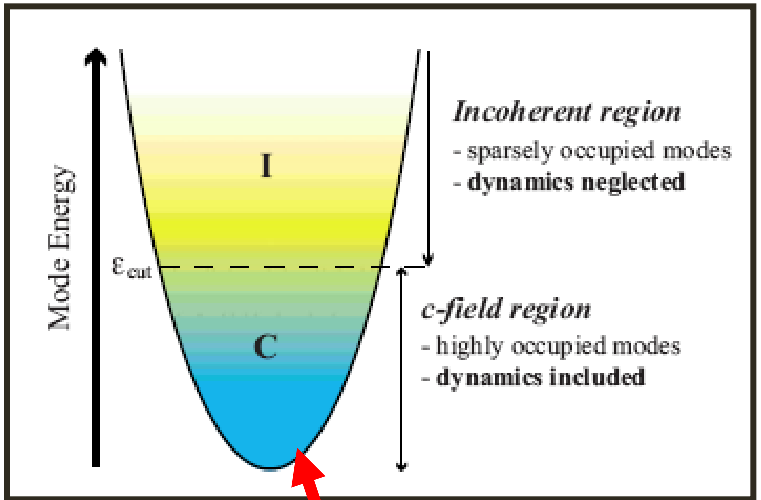
Phys. Rev. A 77, 033616 (2008).

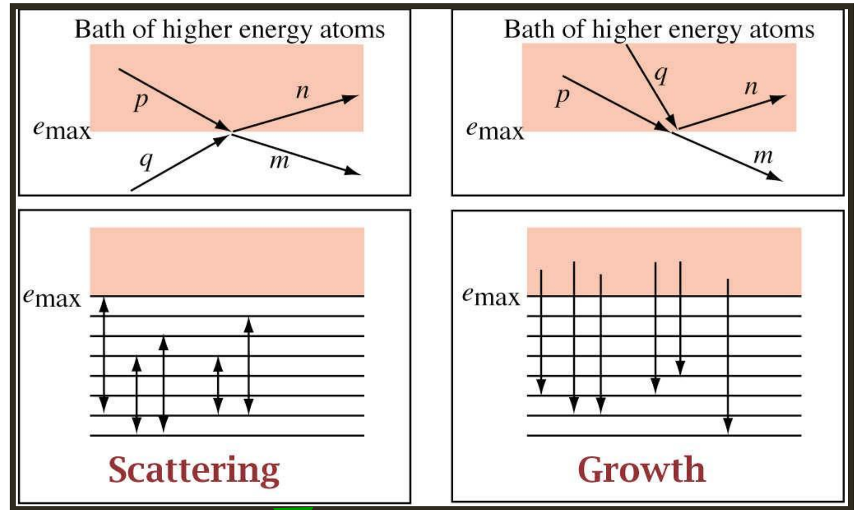
The c-field theory



Scattering and growth of the condensate particles







$$i\hbar\frac{\partial\psi(\mathbf{x},t)}{\partial t} = P\left\{ H_{GP}\psi(\mathbf{x},t) + \frac{\hbar\gamma}{k_B T}\left(\mu - H_{GP}\right)\psi(\mathbf{x},t) + \frac{dW(\mathbf{x},t)}{dt} \right\}$$

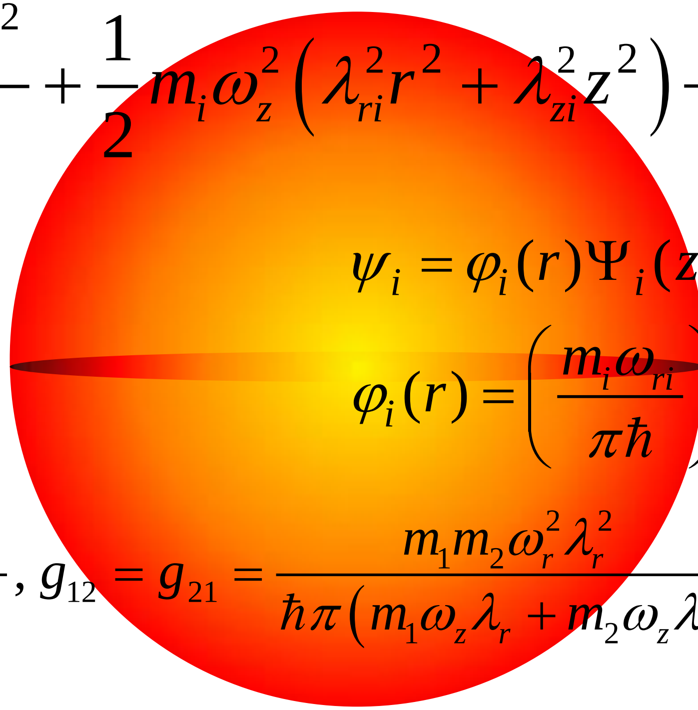
$$H_{GP} = -\frac{\hbar^2\nabla^2}{2m} + V(\mathbf{x}) + g\left|\psi(\mathbf{x},t)\right|^2$$ (BEC in rotation)

$$dW = \sum_j \phi_j(\mathbf{x})\sqrt{\gamma k_B T dt/\hbar}\left(\eta_j + i\zeta_j\right)$$ (random white noise)

2. Stochastic Projected GPEs

- The atoms are confined in an elongated trap with.

$$\omega_{87z} = 2\pi \times 2.9\text{Hz and } \omega_{87r} = 2\pi \times 130\text{Hz}$$



$$H_{GP}^{(i)}\Psi_i = \left(-\frac{\hbar^2\nabla^2}{2m_i} + \frac{1}{2} m_i \omega_z^2 \left(\lambda_{ri}^2 r^2 + \lambda_{zi}^2 z^2 \right) + \sum_{j=1,2} g_{ij} \left| \Psi_j \right|^2 \right) \Psi_i$$

$$\psi_i = \varphi_i(r)\Psi_i(z)$$

$$\varphi_i(r) = \left(\frac{m_i \omega_{ri}}{\pi\hbar} \right) \exp\left(-\frac{m_i \omega_{ri}}{2\hbar} r^2 \right)$$

$$g_{ii} = \frac{m_i \lambda_r \omega_z}{2\hbar\pi} \frac{4\pi\hbar^2 a_{ii}}{m_i}, \; g_{12} = g_{21} = \frac{m_1 m_2 \omega_r^2 \lambda_r^2}{\hbar\pi \left(m_1 \omega_z \lambda_r + m_2 \omega_z \lambda_r \right)} \frac{2\pi\hbar^2 \left(m_1 + m_2 \right) a_{12}}{m_1 m_2}$$

2. Stochastic Projected GPEs

$$\frac{\partial \Psi_i}{\partial t} = \hat{P}\left\{ -\frac{i}{\hbar} H_{GP}^{i} \Psi_i(\mathbf{x},t) + \frac{\gamma_i}{k_B T}\left(\mu_i - H_{GP}^{i}\right)\Psi_i(\mathbf{x},t) + \frac{dW_i(\mathbf{x},t)}{dt} \right\} \qquad i = 1,2$$

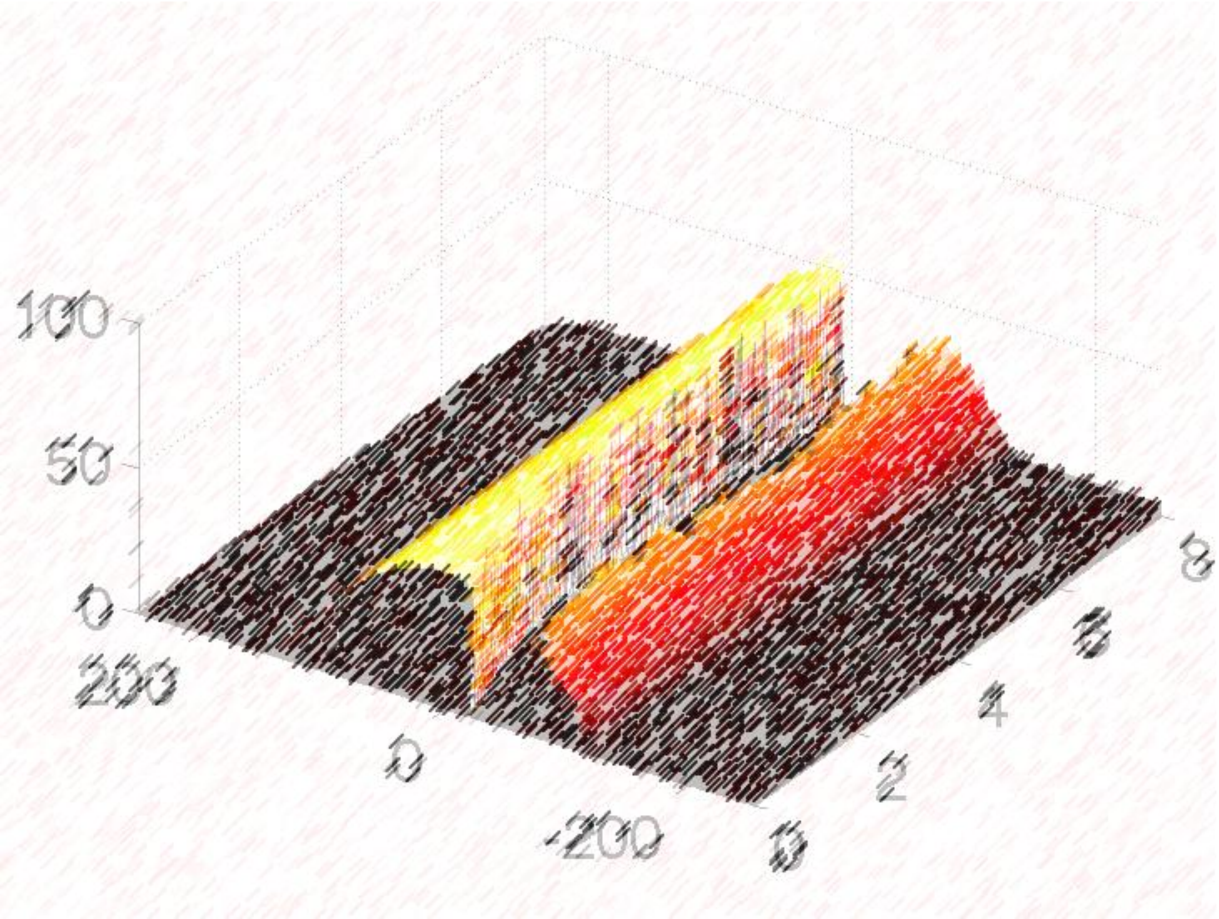
$$H_{GP}^{(i)}\Psi_i = \left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + \frac{1}{2} m_i \lambda_i \omega_z (z - z_{ci})^2 + \sum_{j=1,2} g_{ij} \left|\Psi_j\right|^2 \right)\Psi_i$$

$dW = \sum \phi_j(\mathbf{x}) \sqrt{\gamma k_B T dt}\left(\eta_j + i\zeta_j\right)$: complex white noise

a_{ij} : s-wave scattering lengths.

Phys. Rev. A 77, 033616 (2008).

3. Numerical Result and Fragmentation



3. Numerical Result

- **Parameters:**

1. aspect ratio of scattering length

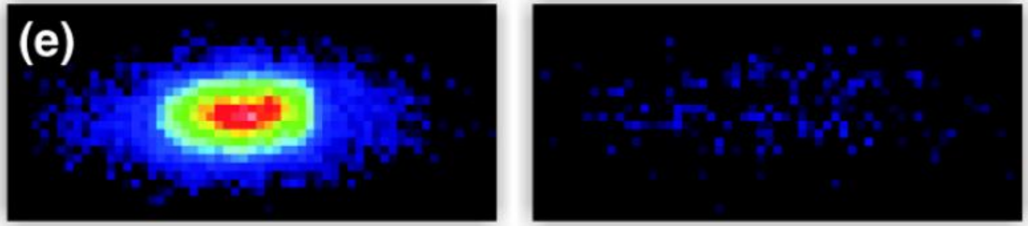
   $\alpha_2 \equiv a_2 / a_1$

   $\alpha_{12} \equiv a_{12} / a_1$

2. T=100nK

3. Numerical Result

- **Case of No Condensation**



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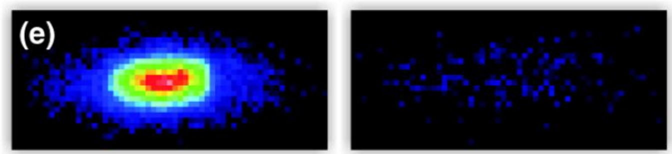
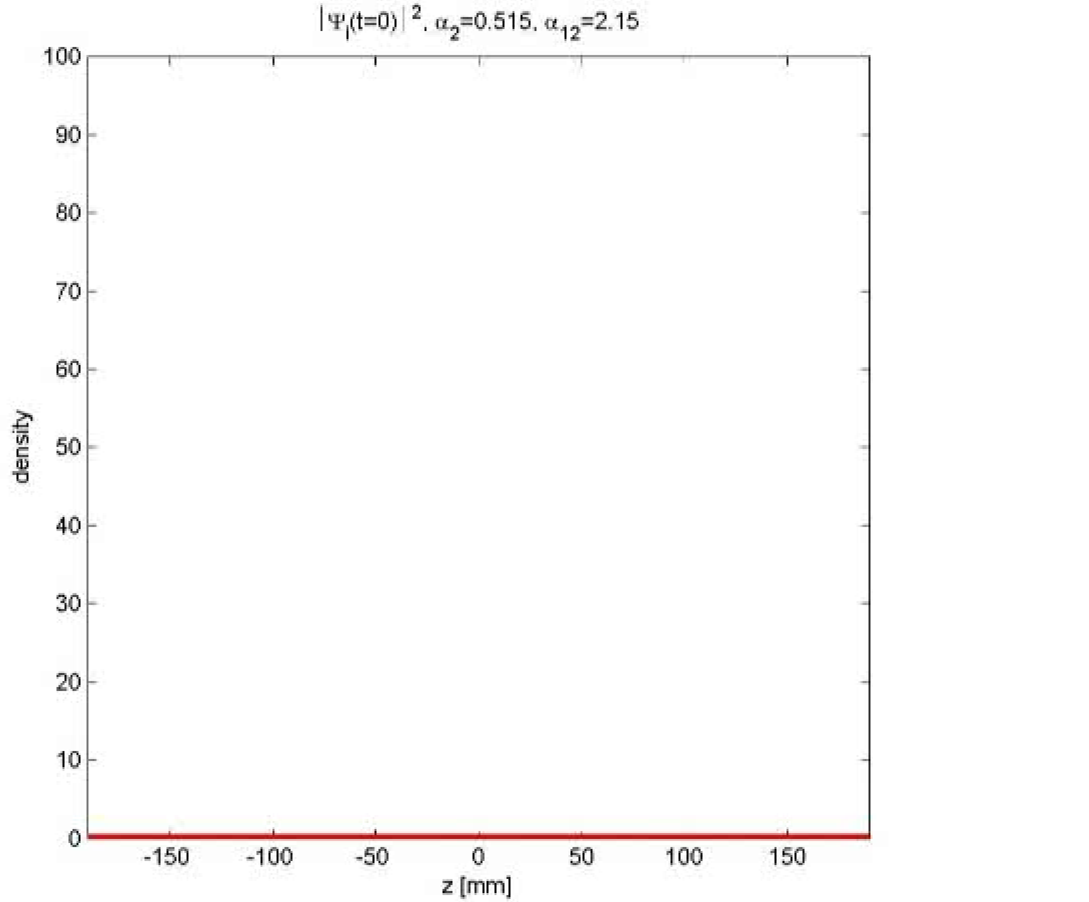
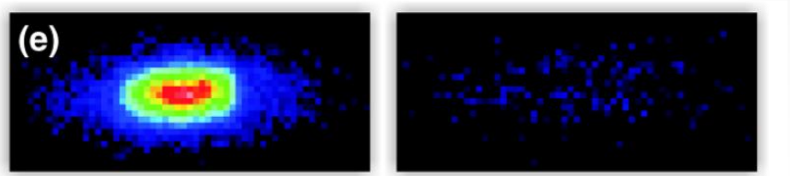
3. Numerical Result



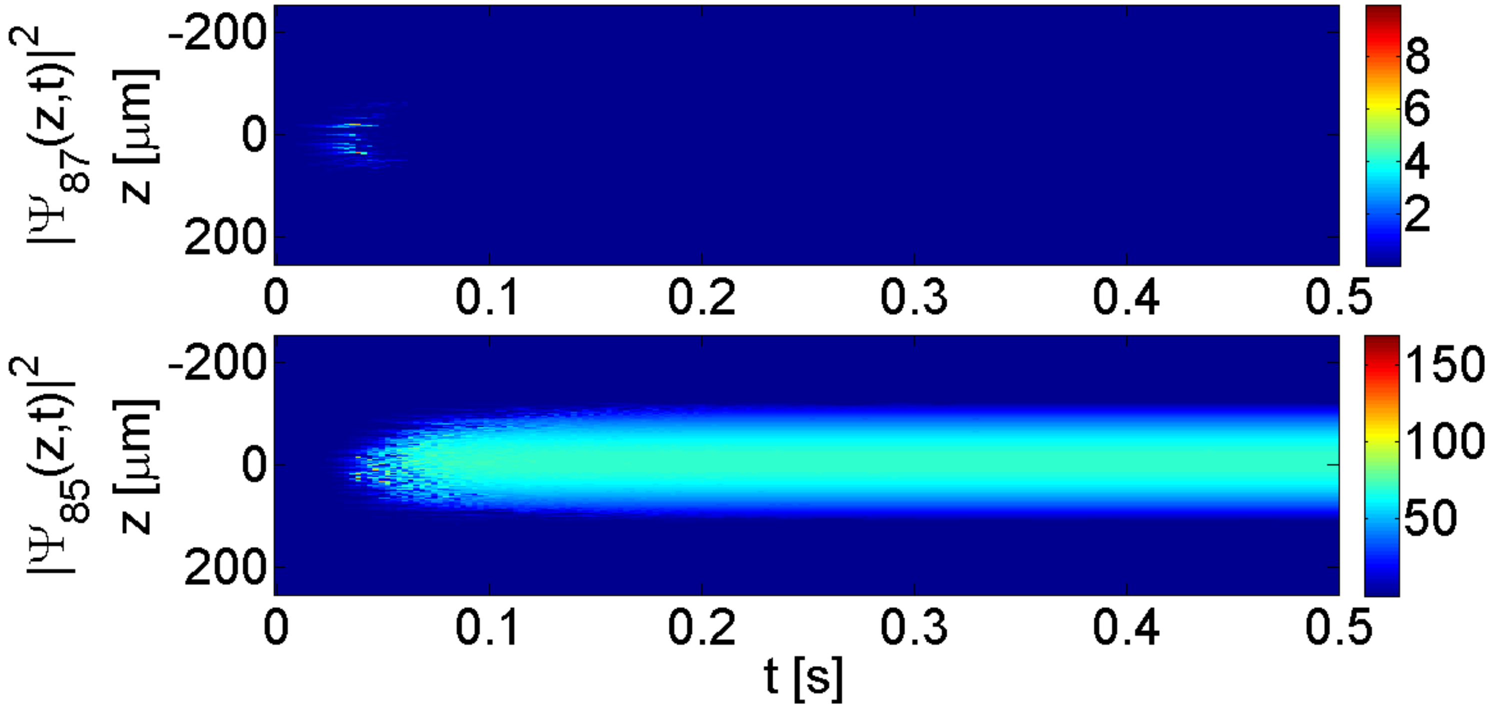
α_2=0.515, α_{12}=2.15
μ_{Rb87}=120, μ_{Rb85}=170
γ=0.03



3. Numerical Result



α_2=0.515, α_{12}=2.15
μ_1=120, μ_2=170, γ=0.03



3. Fragmentation

- Fragmentation of condensate means that
- **there are more than one macroscopically populated state in the system.**
- In other word, there is more than one comparable eigenvalue of one particle density matrix (Onsager criterion).

3. Fragmentation

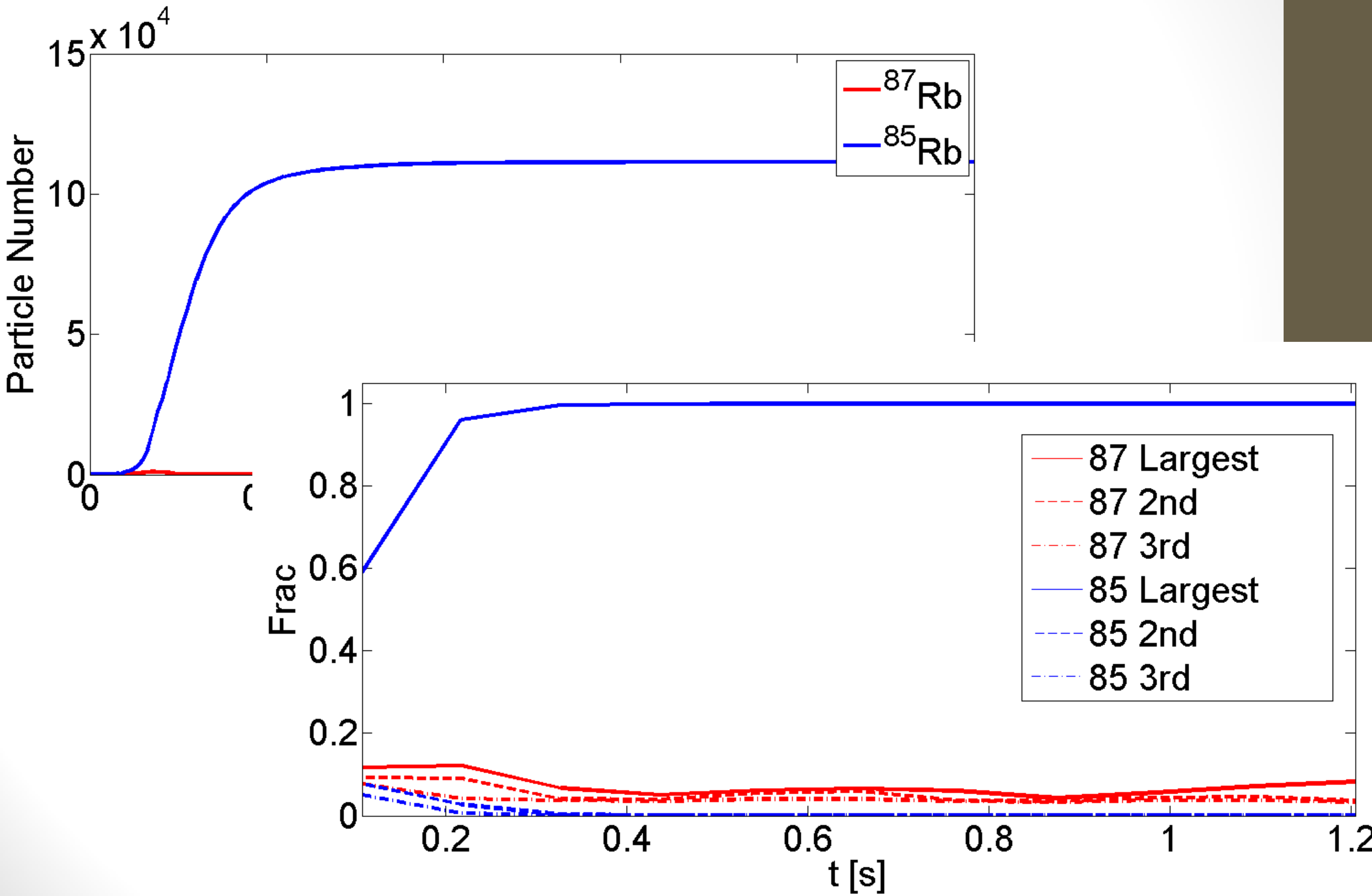
- We diagonalize the density matrix of each component to verify the condensate is fragmented or not.

$$\rho_i(t) = \frac{1}{\Delta t}\int_{t-\Delta t/2}^{t+\Delta t/2} dt \frac{|\psi_i(t)\rangle\langle\psi_i(t)|}{Tr\left(|\psi_i(t)\rangle\langle\psi_i(t)|\right)}$$

- (**Averaging via a short time** to approach the **ensemble** under the **ergodic hypothesis**)
- If the order of number of occupied state N_s approach to the order of particle number,

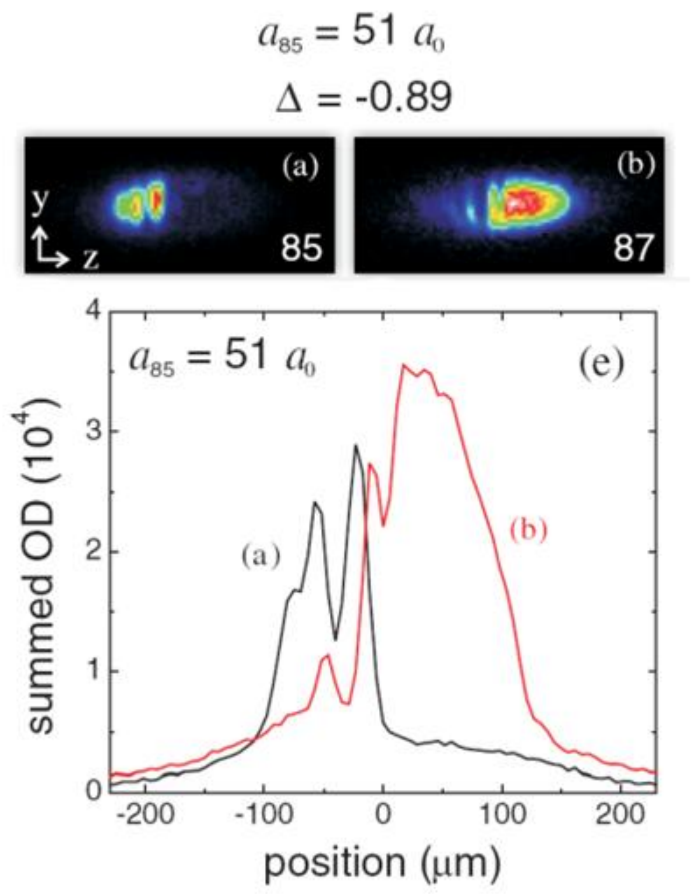
→Fail To Condense

3. Numerical Result



3. Numerical Result

- **Asymmetrically Immiscible Case**



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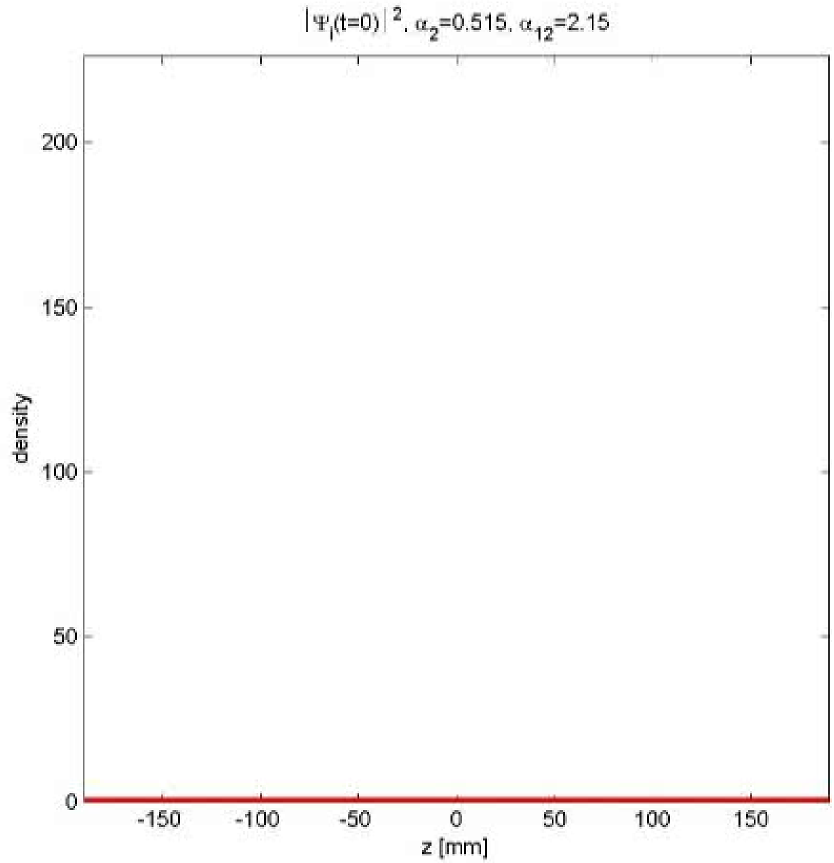
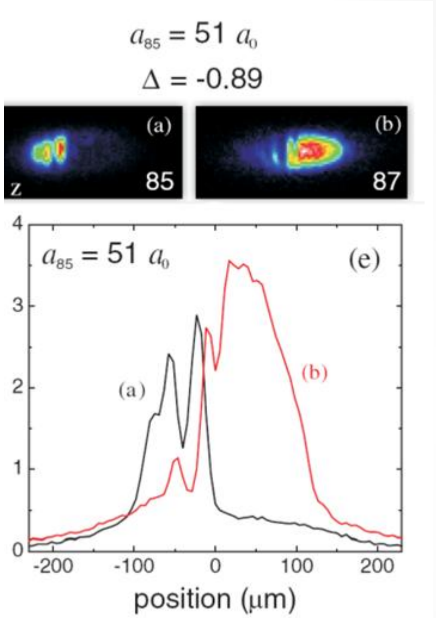
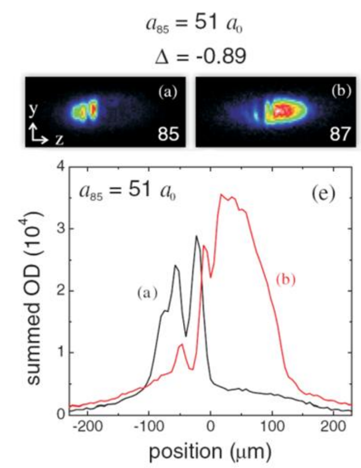
3. Numerical Result





α_2=0.515, α_{12}=2.15
μ_1=325, μ_2=166, γ=0.1

3. Numerical Result



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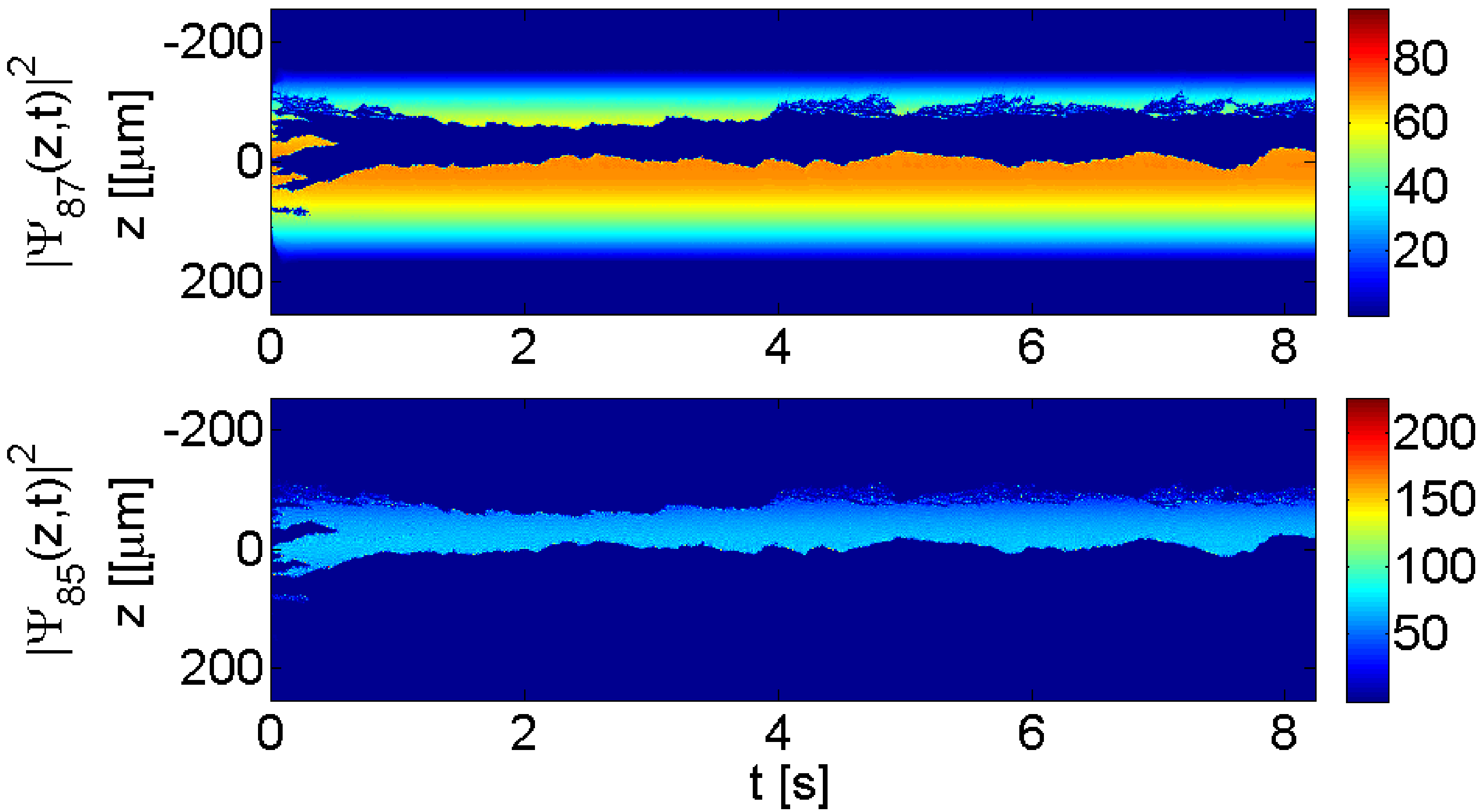
μ_1=325, μ_2=166, γ=0.03



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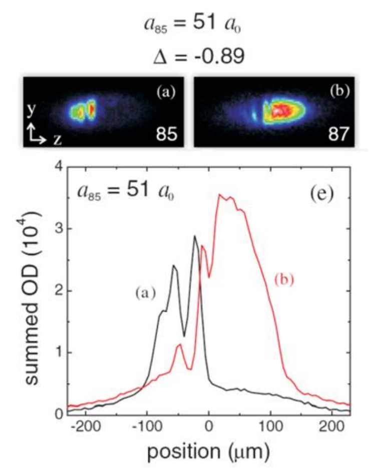

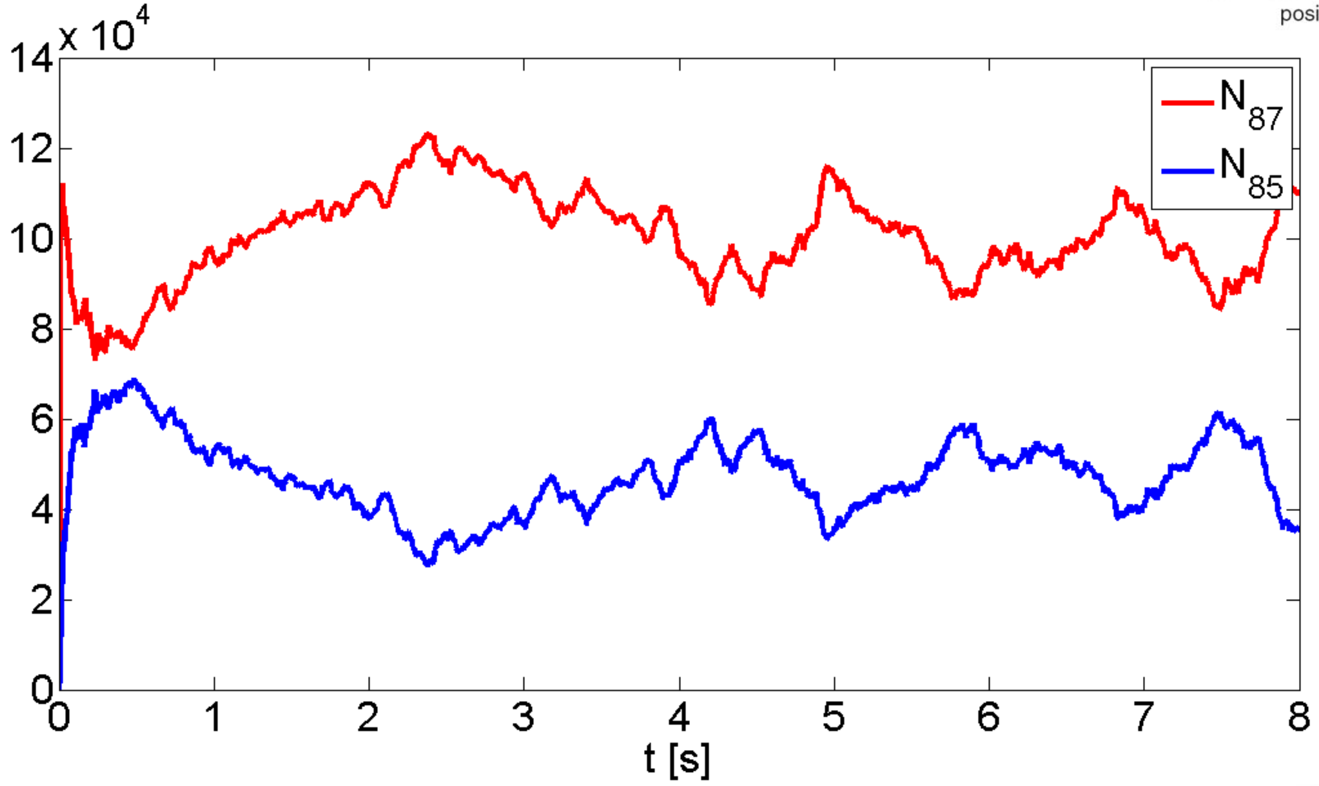

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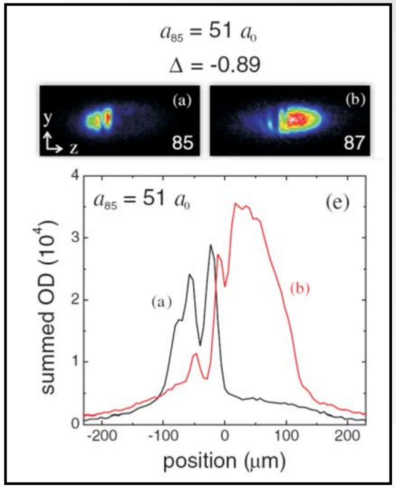

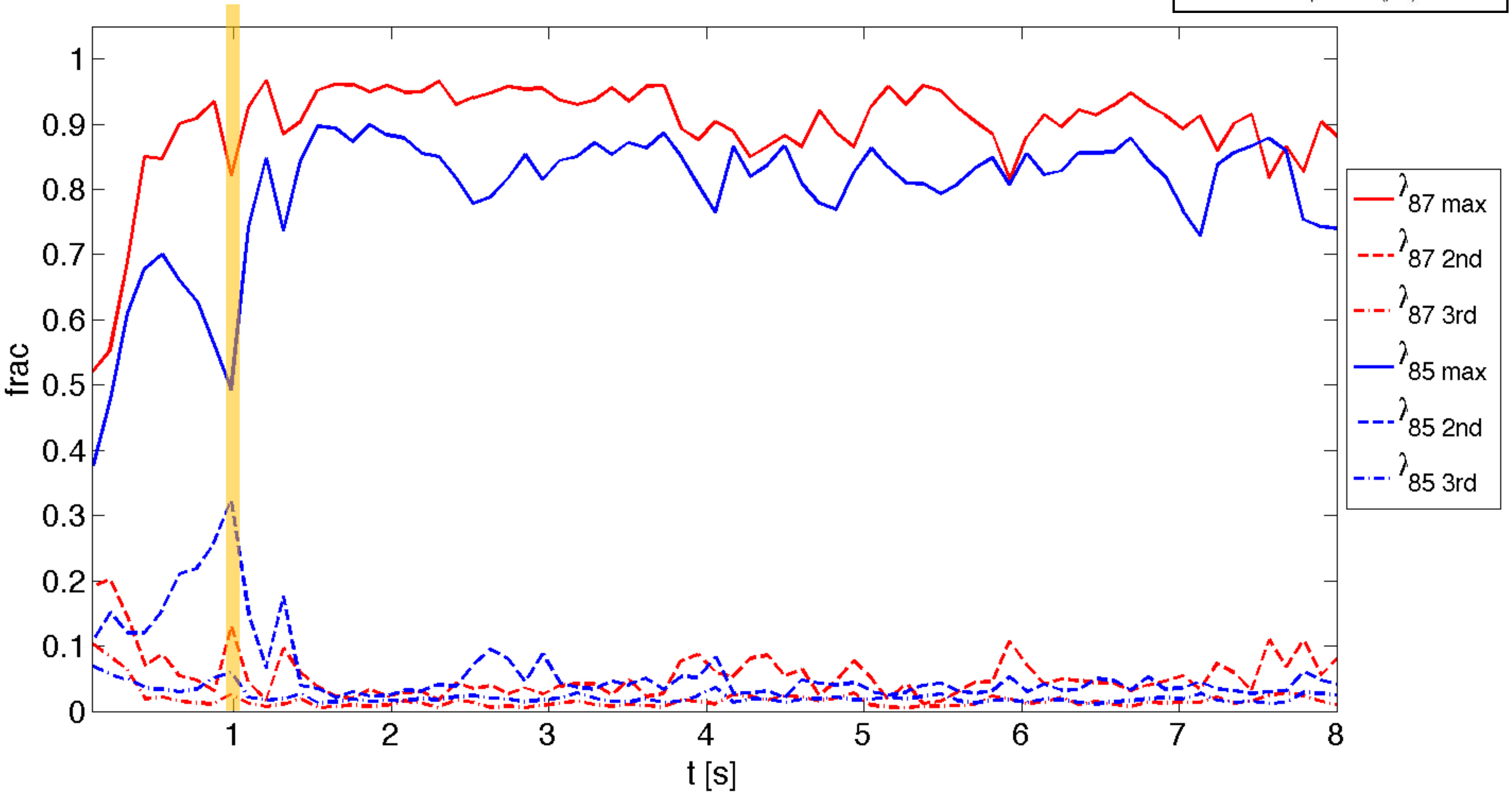

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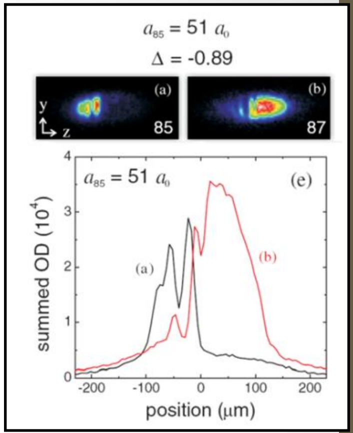
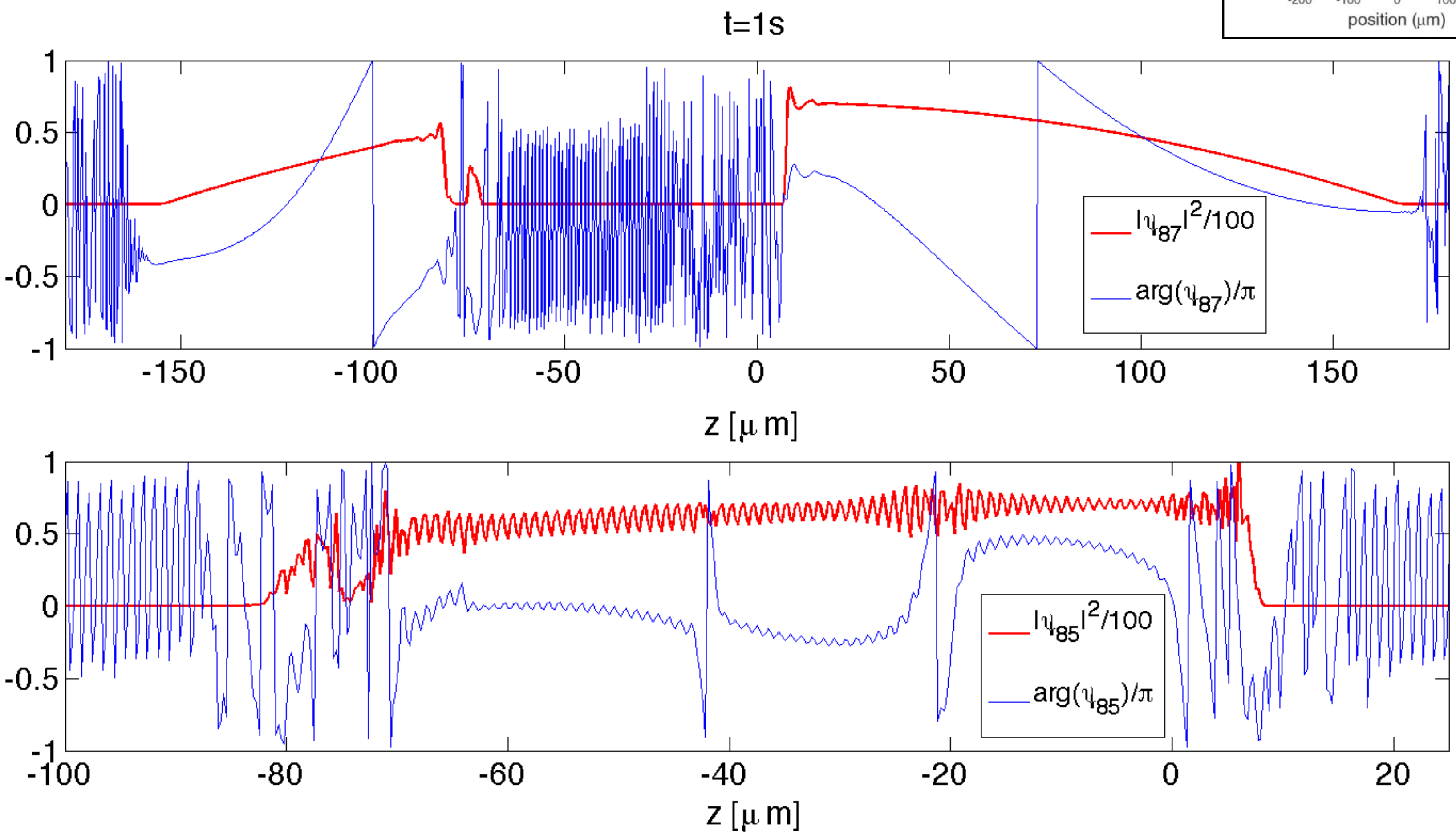
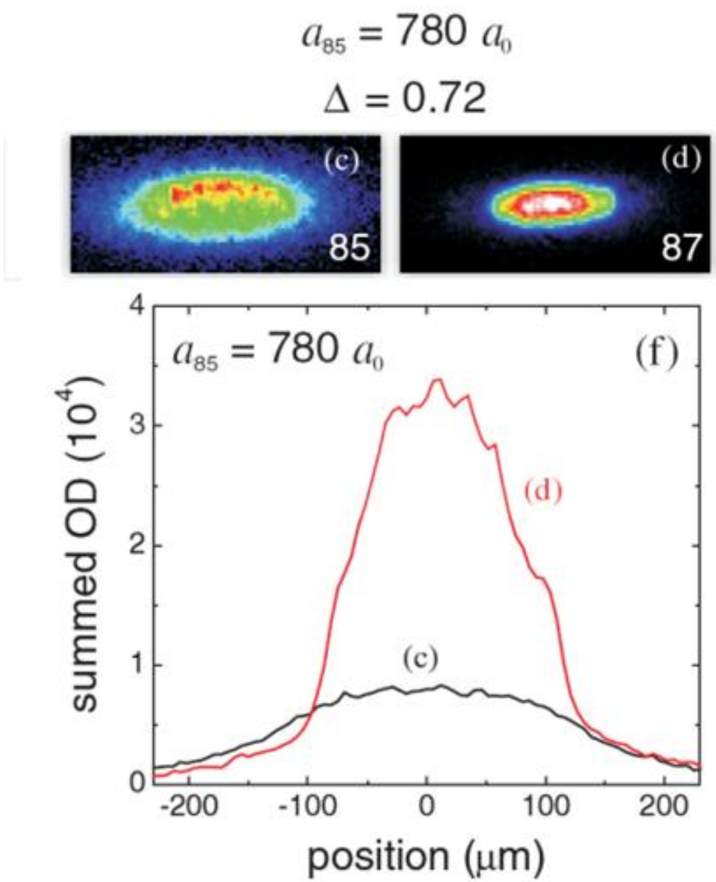




Multi Domain Formation Induced by Modulation Instabilit in Two Component BEC, Phys. Rev. Lett. 93, 100402(2004)

3. Numerical Result

- **Miscible Case**



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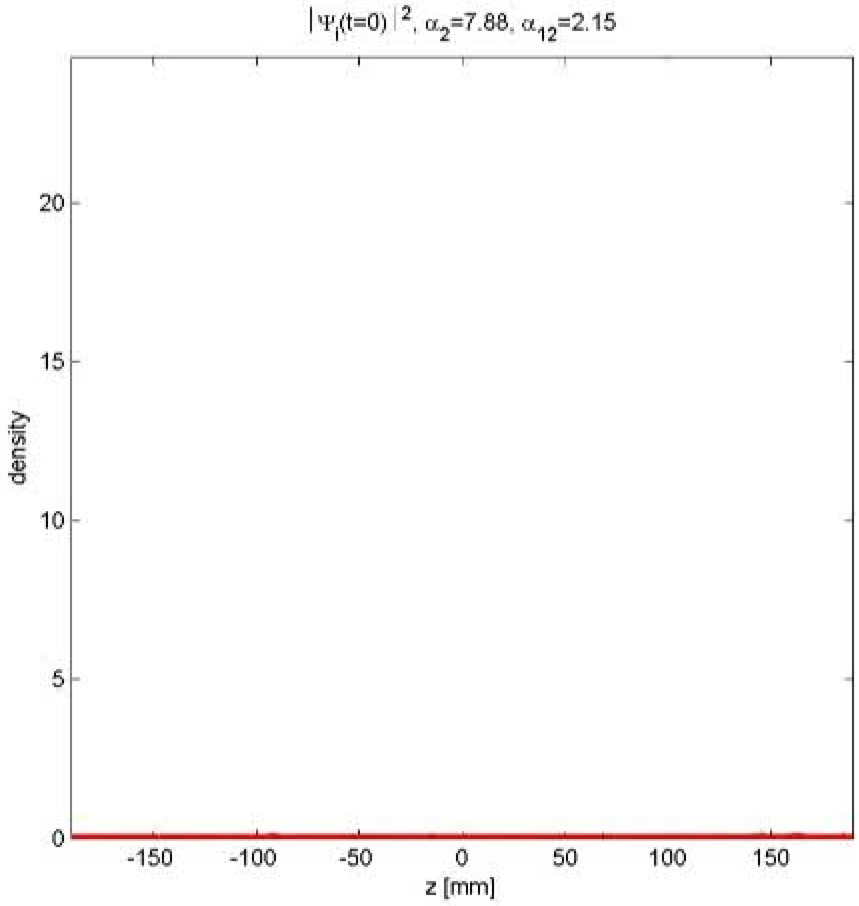
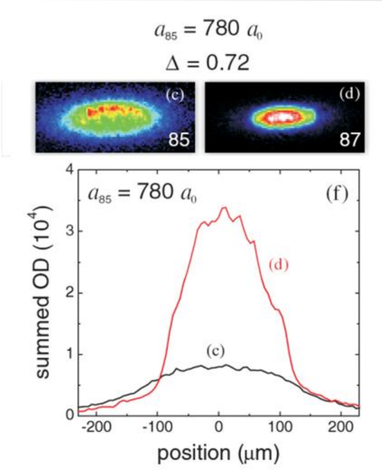
3. Numerical Result

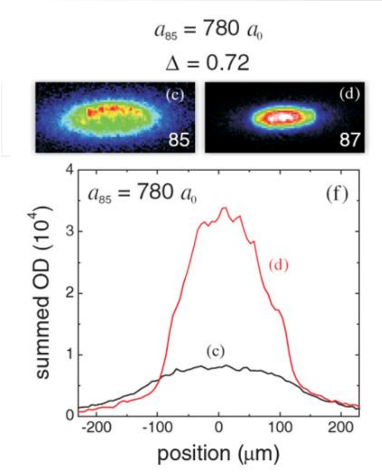




α_2=7.88, α_{12}=2.15

μ_1=125, μ_2=300, γ=0.12

3. Numerical Result



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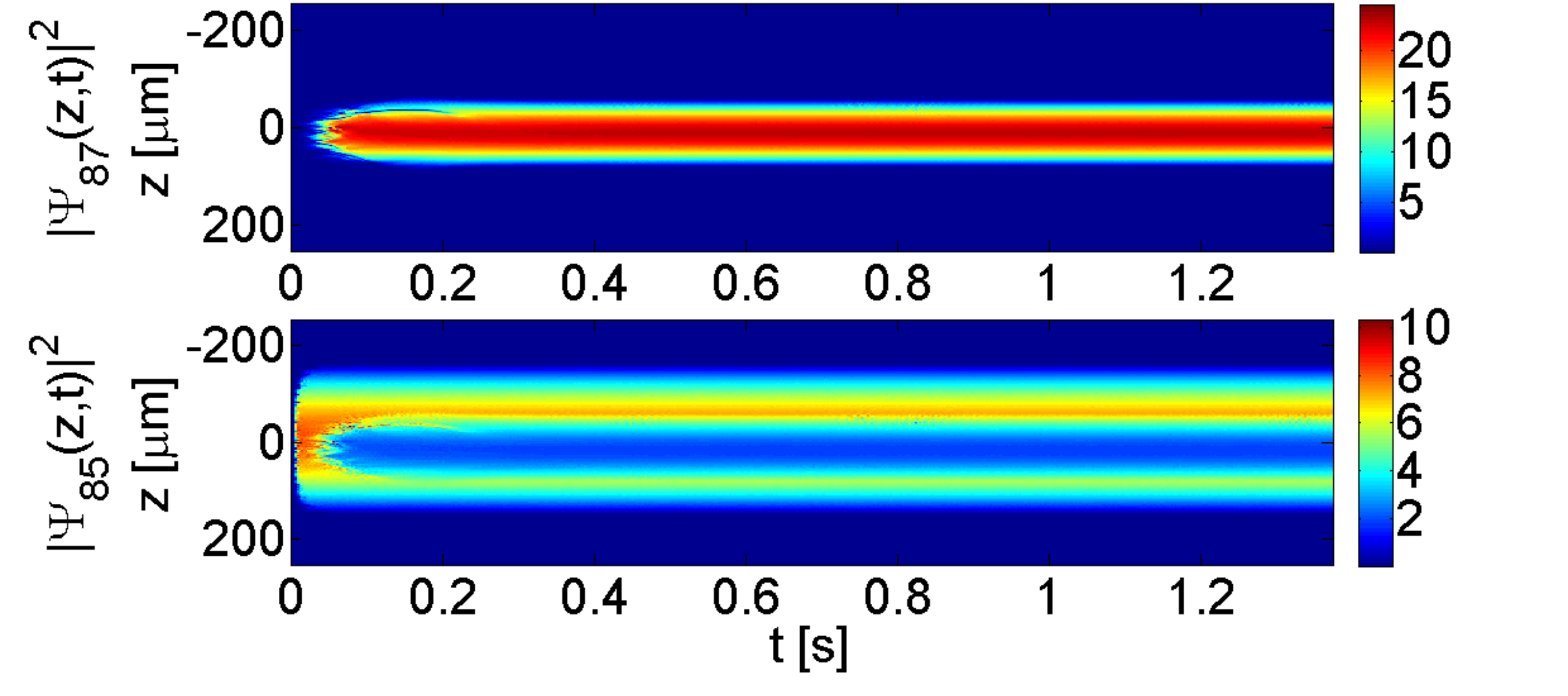

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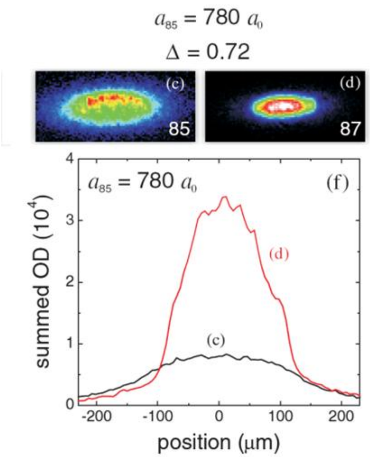

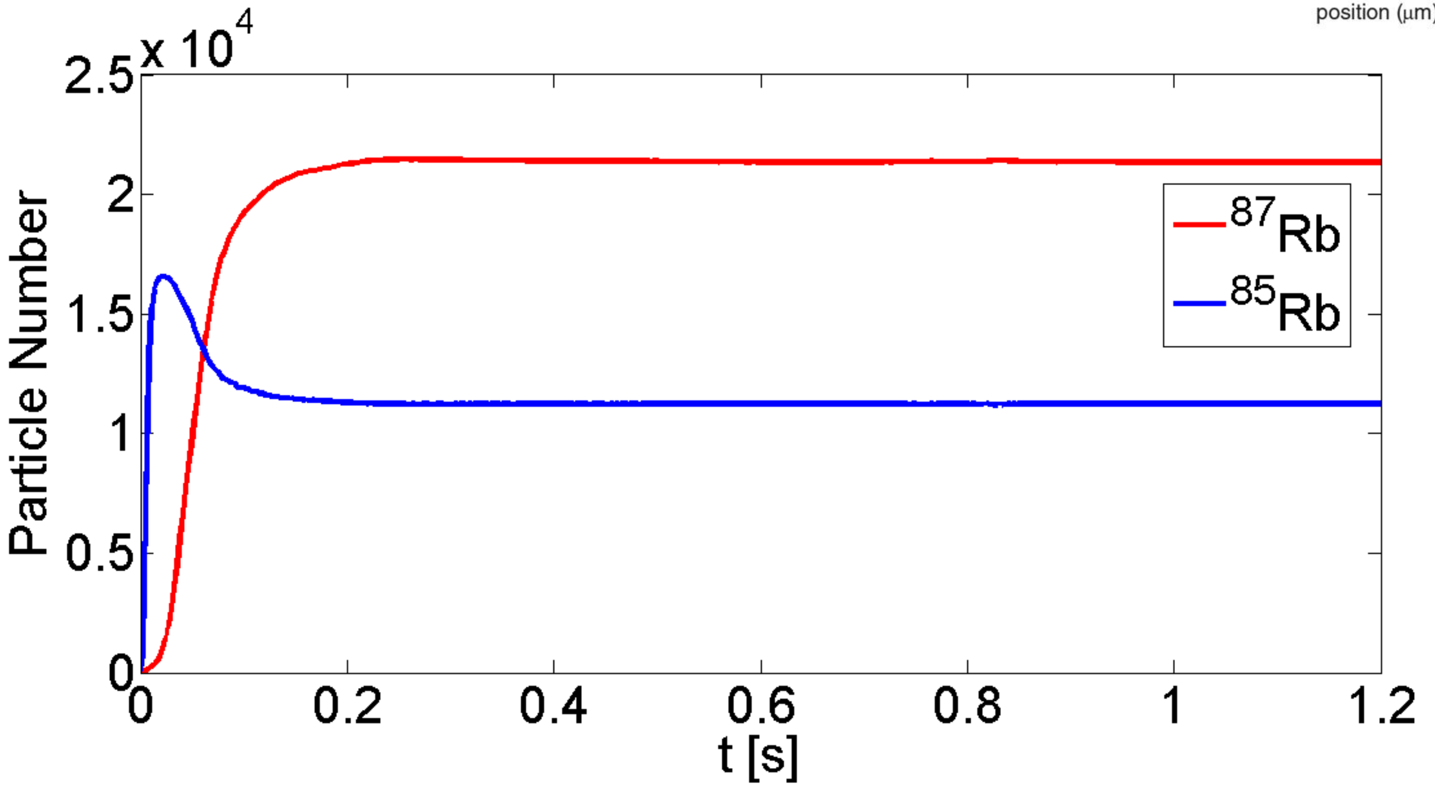

4. Summary

1. We apply the SPGPEs to dual-species condensate, and get a good agreement with experimental results.
2. We verify three scenarios for the growth of phase-separated condensates:
   (1) The successful formation of two BECs without fragmentation.
   (2) The formation of two BECs, yet one of them is fragmented.
   (3) One species is condensed without fragmentation, while the other is stillborn.
3. Attempt to simulate the synthetic cooling of ^{133}Cs-^{87}Rb mixture by using SPGPE + PGPE.

Reference

- [1] S. B. Papp et. al., Phys. Rev. Lett. 101, 040402 (2008).
- [2] A. S. Bradley et. al., Phys. Rev. A 77, 033616 (2008).
- [3] Alexej I. Streltsov et. al., Phys. Rev. A 70, 053607 (2004).
- [4] M. Ueda, Fundamentals and New Frontiers of Bose-Einstein Condensation(2010).

Thanks for your attention.