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Title:	Tiny Bubbles in my BEC
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Abstract

Ultracold atomic gases provide a unique way for exploring many-body quantum phenomena that are inaccessible to conventional low-temperature experiments. Nearly two decades ago the Bose-Einstein condensate (BEC) -- an ultracold gas of bosons in which almost all bosons occupy the same single-particle state -- became experimentally feasible. Because a BEC exhibits superfluid properties, it can provide insights into the behavior of low-temperature helium liquids.

We describe the case of a single distinguishable atom (an impurity) embedded in a BEC and strongly coupled to the BEC bosons. Depending on the strength of impurity-boson and boson-boson interactions, the impurity self-localizes into two fundamentally distinct regimes. The impurity atom can behave as a tightly localized “polaron,” akin to an electron in a dielectric crystal, or as a “bubble,” an analog to an electron bubble in superfluid helium. We obtain the ground state wavefunctions of the impurity and BEC by numerically solving the two coupled Gross-Pitaevskii equations that characterize the system. We employ the methods of imaginary time propagation and conjugate gradient descent. By appropriately varying the impurity-boson and boson-boson interaction strengths, we focus on the polaron to bubble crossover. Our results confirm analytical predictions for the polaron limit and uncover properties of the bubble regime. With these results we characterize the polaron to bubble crossover. We also summarize our findings in a phase diagram of the BEC-impurity system, which can be used as a guide in future experiments.

Tiny Bubbles in my BEC

Characterizing the Polaron to Bubble Crossover

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Student Symposium 2012

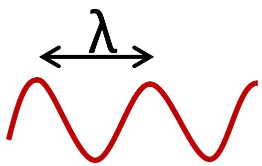
Overview

- What is a BEC?
- Why is it useful and interesting?

- Background theory and what we want to know
- Numerical method we used to find out

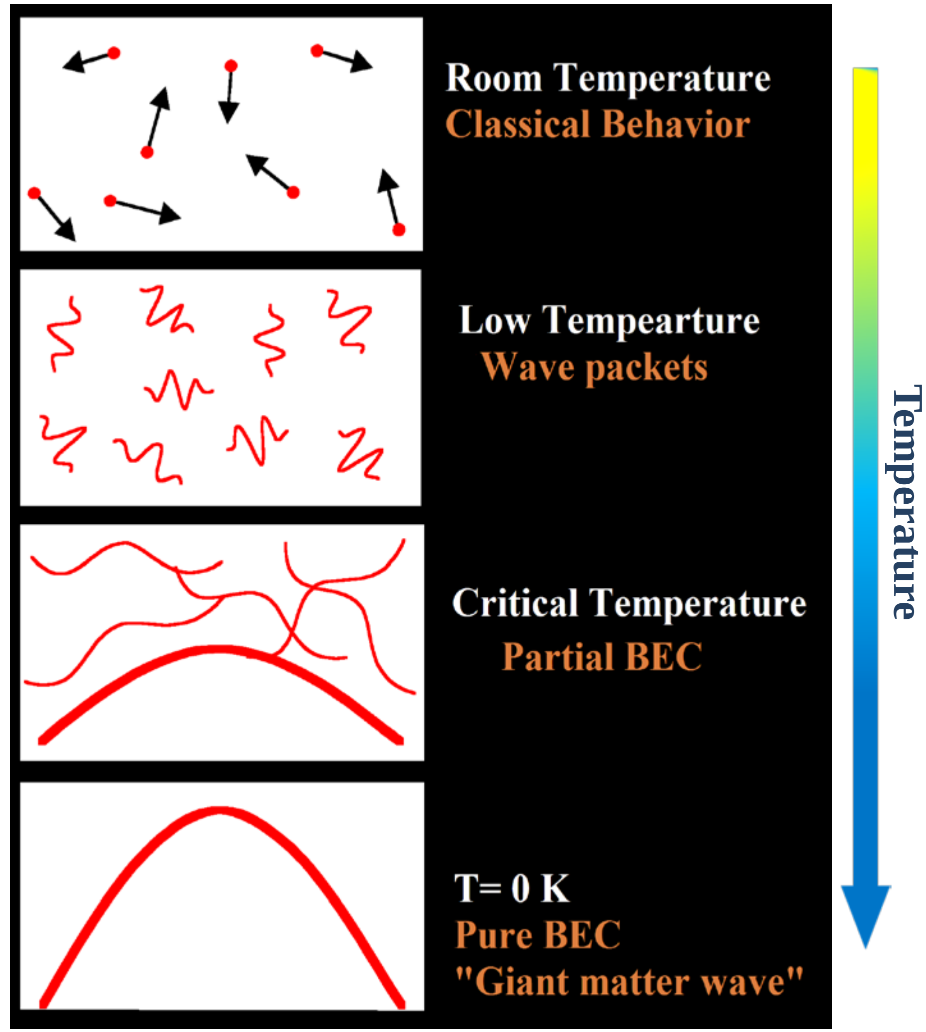
- Results
- Summary & Looking beyond

What is a Bose-Einstein Condensate?



$$\lambda = \frac{h}{mv} \propto \frac{1}{\sqrt{T}}$$

Louis de Broglie



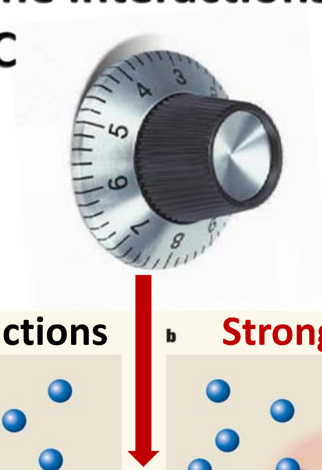
A ***wavefunction*** **gives the** ***probability*** **of finding a particle at a given location**

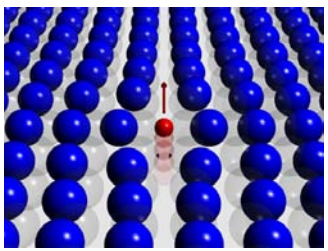
Critical Temperature when
λ ≈ distance between atoms

Why use the BEC?

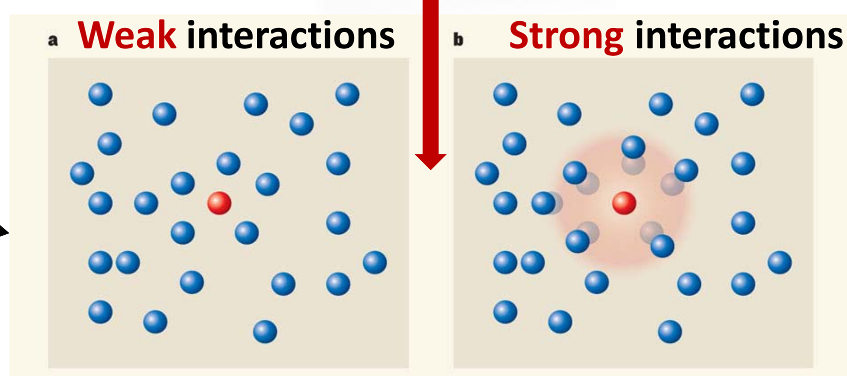
“The quantum behavior of atomic objects (electrons, protons, neutrons, photons, and so on) is the same for all.” – Richard Feynman

We can tune the interactions between atoms in a BEC

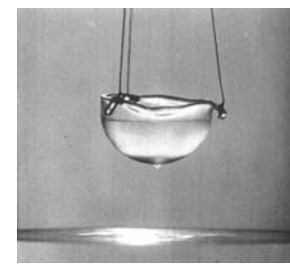




Electron in crystal



Impurity Atom in a BEC



Electron in superfluid Helium

Background Theory

System's total energy given by energy functional:

$$E[\phi,\chi] = \int \Big[\phi^*\Big(\frac{-\hbar^2}{2\,m}\nabla^2\Big)\phi + \chi^*\Big(\frac{-\hbar^2}{2\,m}\nabla^2\Big)\chi + \lambda_{IB}\,(\phi^*\phi)\,(\chi^*\chi) + \frac{1}{2}\lambda_{BB}\,(\phi^*\phi)^2 \Big]\, dV$$

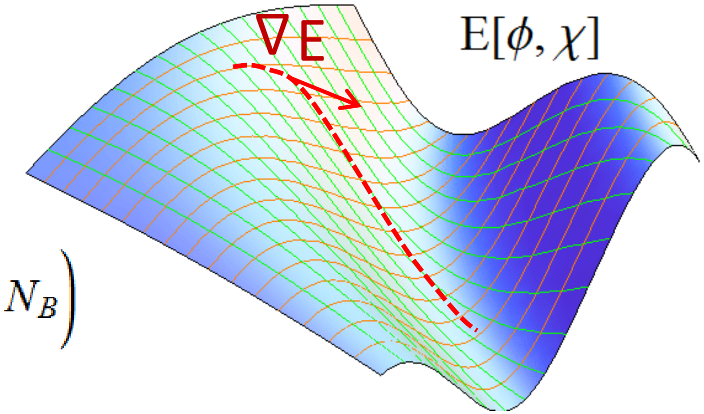
→ χ = **Impurity wavefunction** → ϕ = **BEC wavefunction**

- **5 relevant parameters:**
  - ρ_B : **density of BEC**
  - λ_{IB} : **impurity – boson interaction strength** 
  - λ_{BB} : **boson – boson interaction strength** 
  - **impurity and boson masses:** $\dfrac{m_I}{m_B} = 1$
- **Rescaled parameters:**

$$\beta \propto \sqrt{\rho_B \frac{{\lambda_{IB}}^4}{\lambda_{BB}}} \qquad \gamma \propto \sqrt{\rho_B\, {\lambda_{BB}}^3}$$

Method

Minimize the energy functional $\mathrm{E}[\phi, \chi]$



Using Lagrange Multipliers:

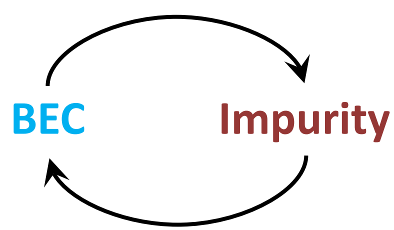
$$E[\phi,\ \chi] - E_I\left(\int \chi^* \chi\, dV - 1\right) - E_B\left(\int \phi^* \phi\, dV - N_B\right)$$

Normalization: $\int \chi^* \chi\, dV = 1$ $\qquad \int \phi^* \phi\, dV = N_B$ = **number of bosons**

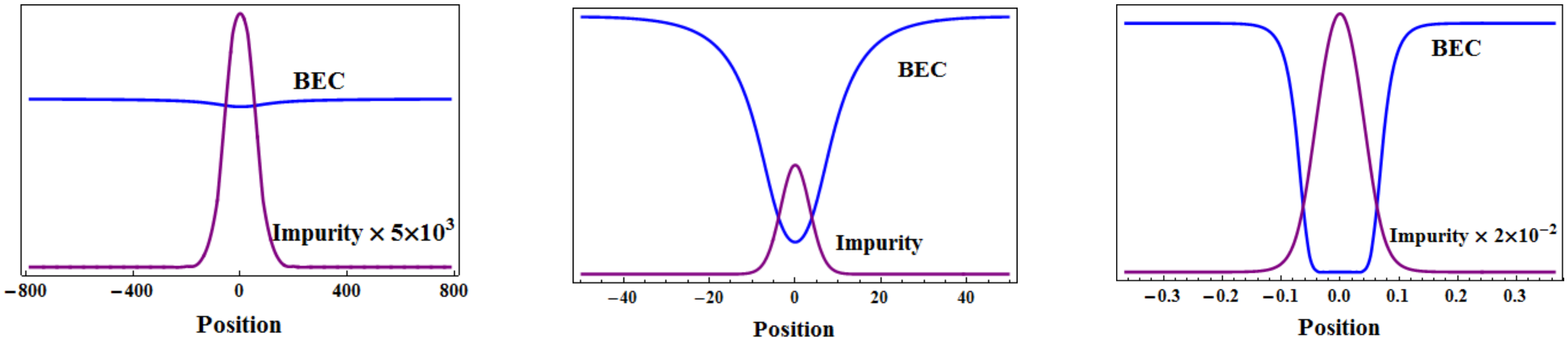
Using the **gradients**:

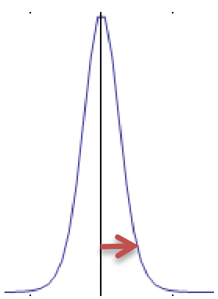
$$\nabla E_B = \frac{-\hbar^2}{2m} \nabla^2 \phi + \lambda_{\mathrm{IB}} \|\chi\|^2 \phi + \lambda_{\mathrm{BB}} \|\phi\|^2 \phi - E_B \phi$$

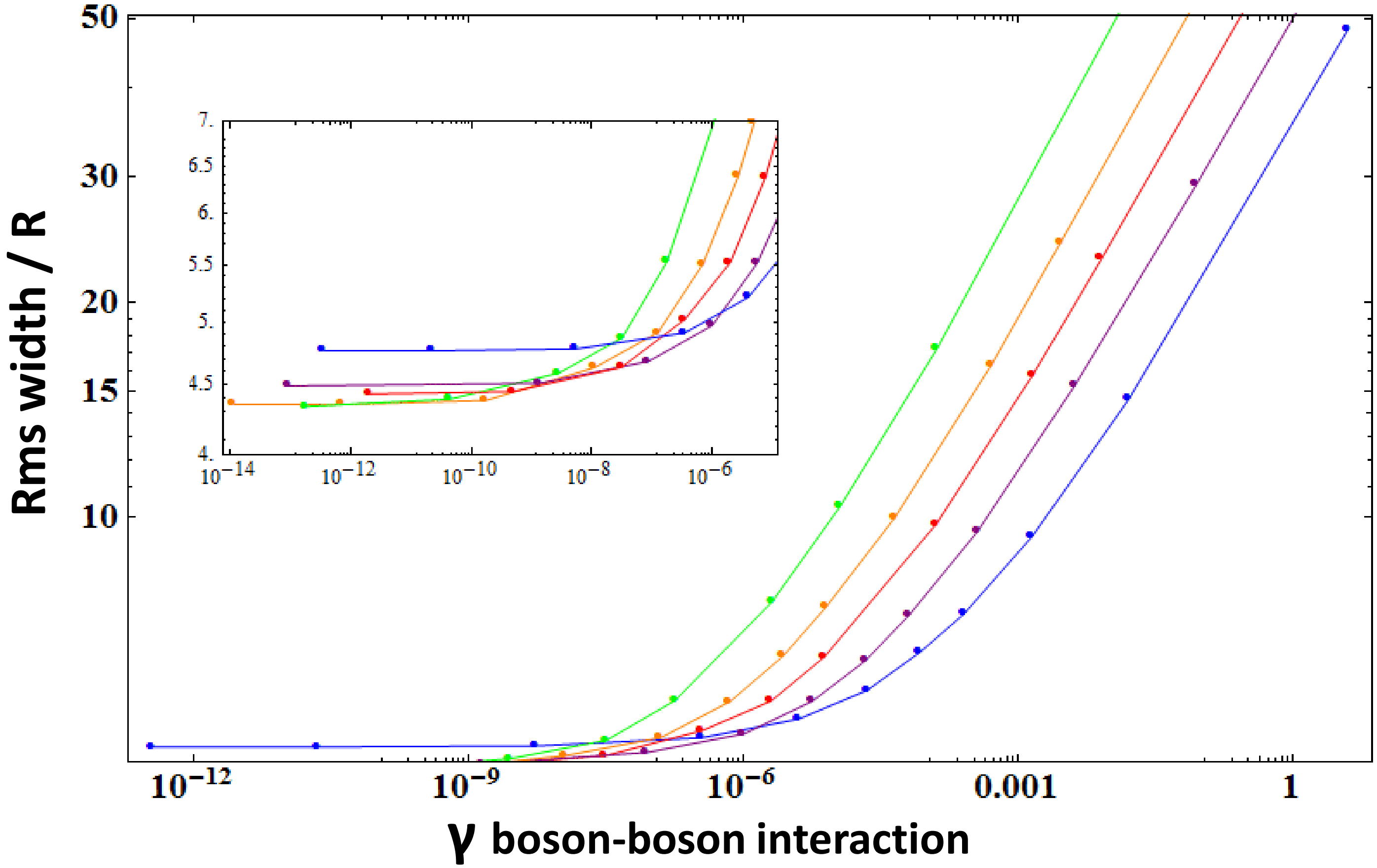
$$\nabla E_I = \frac{-\hbar^2}{2m} \nabla^2 \chi + \lambda_{\mathrm{IB}} \|\phi\|^2 \chi - E_I \chi$$



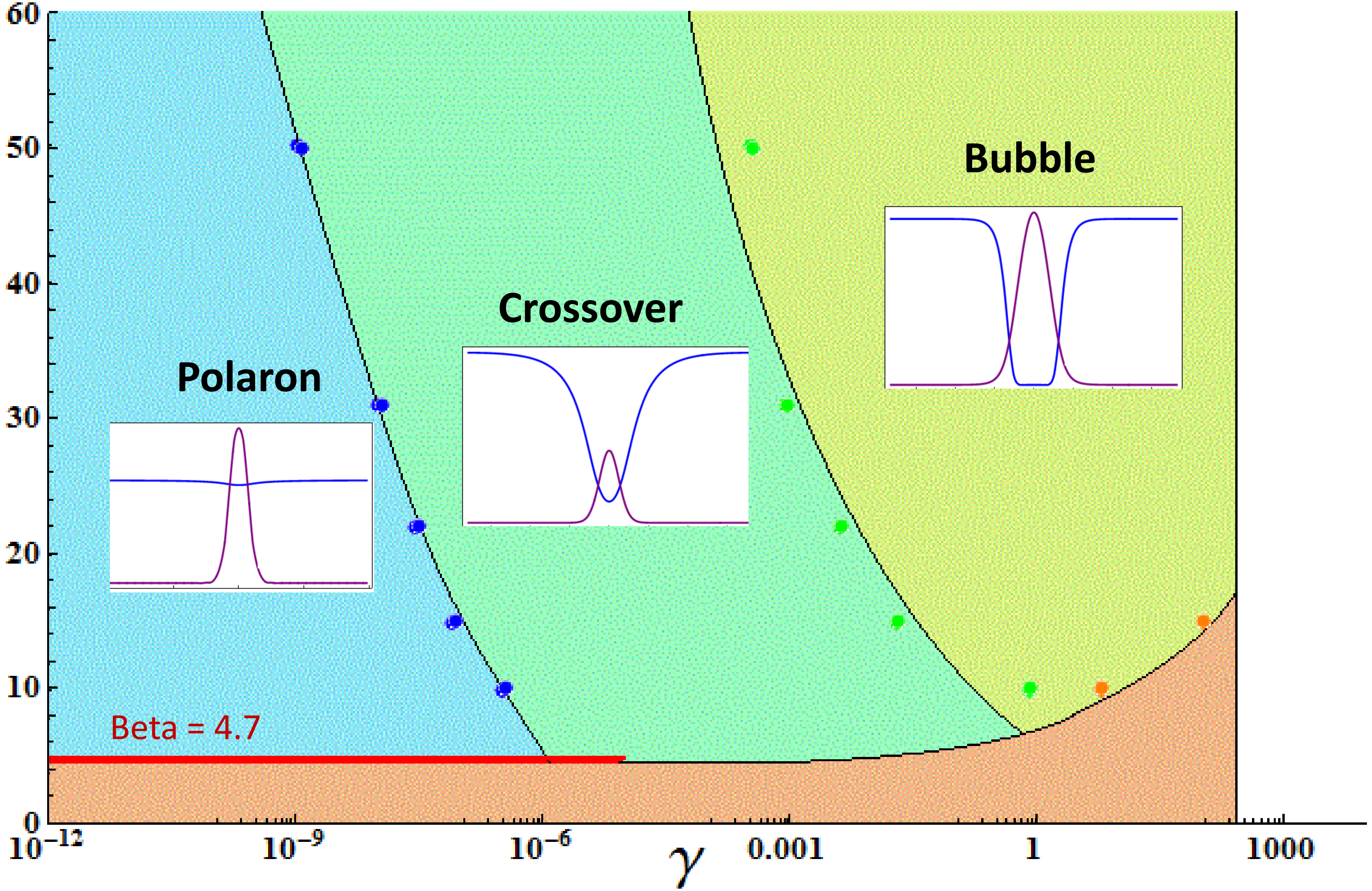
Results 1


BEC
Impurity × 5×10^3
−800
−400
0
400
800
Position
BEC
Impurity
−40
−20
0
20
40
Position
BEC
Impurity × 2×10^−2
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
Position


rms width


Rms width / R
50
30
20
15
10
7.
6.5
6.
5.5
5.
4.5
4.
10^−14
10^−12
10^−10
10^−8
10^−6
10^−12
10^−9
10^−6
0.001
1
γ boson-boson interaction

Results 2: BEC-Impurity Phase Diagram



Summary

- BEC's can help us understand other many-body systems
- We study the case of a single impurity atom in a BEC
- Our numerical results characterize the polaron – bubble crossover
- Phase diagram as road map for experimentalists

Future Directions

- Experimental confirmation of our results
- Simulations of dynamics of BEC-Impurity systems
- 2-D systems