Bubbles in a ferromagnetic superfluid

Candidate: Giorgio Micaglio
Supervisor: dr. Alessandro Zenesini

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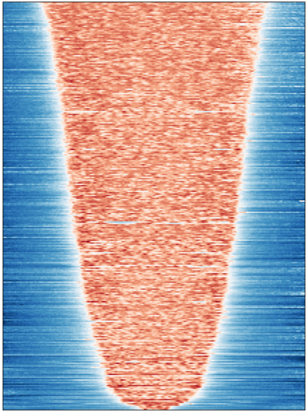
UNIVERSITÀ DI TRENTO

Overview

This presentation will cover:

- **Introduction**
- **Theoretical background**: Ferromagnetism in coherently coupled two-component spin-mixtures
- **Data analysis**: Characterization of false vacuum decay bubbles
- **Conclusions**



Introduction

Why **bubbles** in a ferromagnetic superfluid?

- First **experimental observation** of false vacuum decay (FVD) in the Pitaevskii BEC Center laboratories of the University of Trento.
- FVD provides information on **metastability** and is studied from quantum systems to cosmology
- Framework: **quantum gas** of ^{23}Na atoms optically trapped and cooled below the condensation temperature

Theoretical background: Gross-Pitaevskii equation

A system of **weakly-interacting bosons** can be described by a mean-field approximation with a single wavefunction, yielding the GPE:

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(x,t) + g|\psi(x,t)|^2\right]\psi(x,t)$$

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In the stationary case:

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(x) + g|\psi(x)|^2\right]\psi(x) = \mu\psi(x)$$

When the interaction dominates on the kinetic term:

$$n(x) = \frac{\mu - V(x)}{g} \quad \Rightarrow \quad R_{\mathrm{TF}} = \sqrt{\frac{2\mu}{m\omega^2}}$$

Theoretical background: Two-component mixtures

In a two-component gas, the GPEs are **coupled** because of the inter-species interaction constant:

$$\left[-\frac{\hbar^2}{2m_a}\nabla^2 + V(x) + g_{aa}|\psi_a(x)|^2 + g_{ab}|\psi_b(x)|^2\right]\psi_a(x) = \mu_a\psi_a(x)$$
$$\left[-\frac{\hbar^2}{2m_b}\nabla^2 + V(x) + g_{ab}|\psi_a(x)|^2 + g_{bb}|\psi_b(x)|^2\right]\psi_b(x) = \mu_b\psi_b(x)$$

Depending on the values of g_{aa}, g_{bb} and g_{ab}, the **ground state** of the system can behave in different manners

Theoretical background: Coherent coupling

When species of the same atom, **coupling radiation** between $|a\rangle$ and $|b\rangle$:

$$\hbar\Omega_R \exp\{-i\omega_{\rm cpl} t + \phi\} \quad \text{with} \quad \omega_{\rm cpl} = \omega_{ab} + \delta_B$$

Two distinct **energy channels**: spin $nZ = n_a - n_b$ and total density $n = n_a + n_b$

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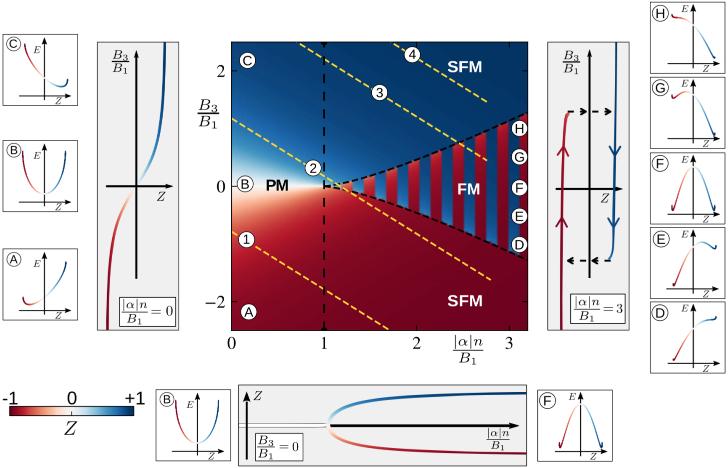
Double-well energy landscape

$$E_{\mathrm{MF}}(Z) = -\hbar\left(|\delta g| n Z^2 + 2\Omega_R\sqrt{1 - Z^2} + 2\delta_{\mathrm{eff}} Z\right)$$

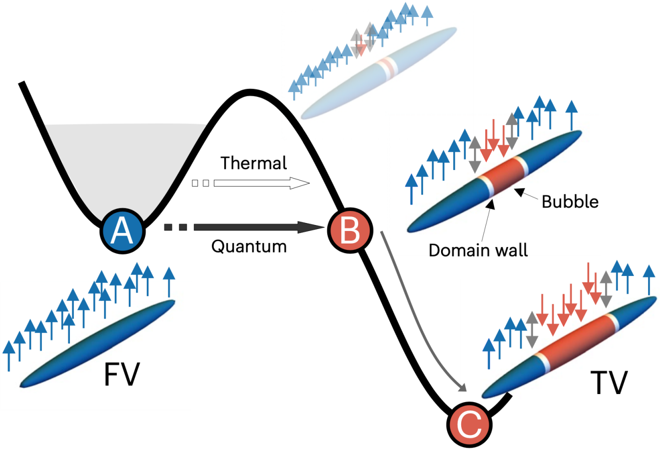
The order parameter is the ratio $\dfrac{|\delta g| n}{\hbar\Omega_R}$, the effective detuning is $\delta_{\mathrm{eff}} = \delta_B - n(g_{aa} - g_{bb})$



$$\alpha \to \delta g$$
$$B_3 \to \delta_{\text{eff}}$$
$$B_1 \to \Omega_R$$

Theoretical background: False Vacuum Decay

- Quantum tunnelling from A to B (stochastic)
- Decay from B to C
- Problem: when to take the shot?



Data analysis: Experimental platform

- ^{23}Na atoms prepared in the state $|F, m_F\rangle = |2, -2\rangle = |\uparrow\rangle$, which is coupled to the state $|1, -1\rangle = |\downarrow\rangle$
- **Harmonic trapping** potential with $\omega_\perp/2\pi = 2$ kHz and $\omega_x/2\pi = 20$ kHz
- Thomas-Fermi radii $R_\perp = 2$ µm and $R_x = 200$ µm (cigar-shaped)
- Reduction to **1D system** and spin-selective imaging yield the densities $n_\uparrow(x)$, $n_\downarrow(x)$ and the magnetization $Z(x)$

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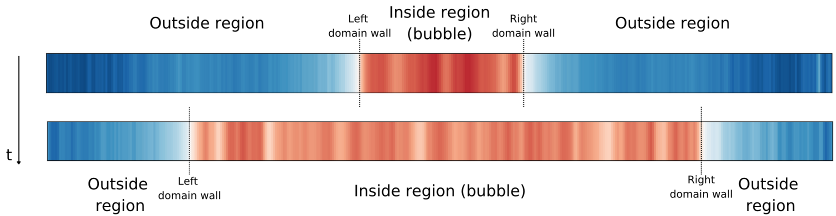
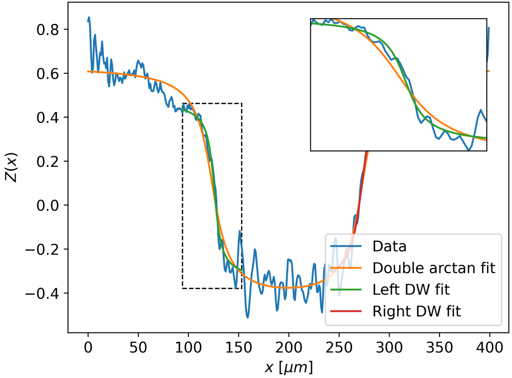
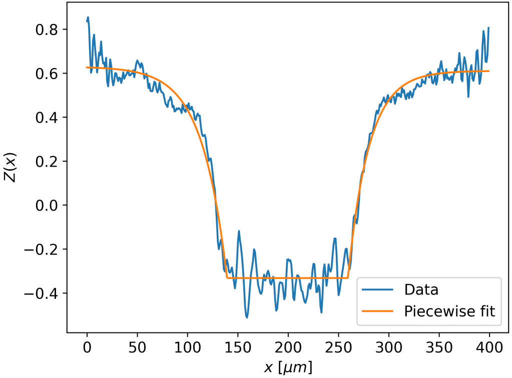


Data analysis: Bubble fits

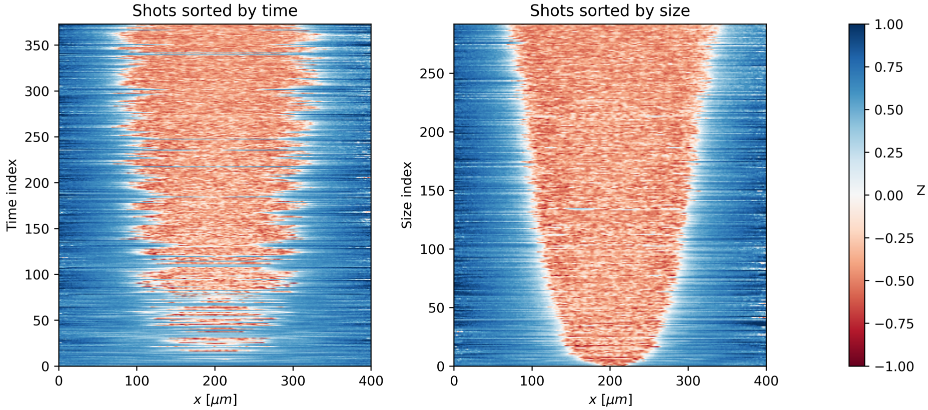
Example of fitting routines, $\Omega_R/2\pi = 400$ Hz and $\delta = 596.5$ Hz



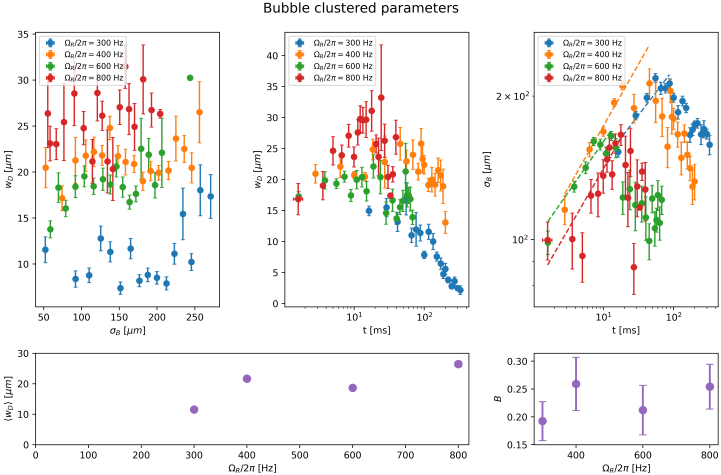


Data analysis: Shot sorting

Bubble shots with $\Omega_R/2\pi = 400$ Hz and $\delta = 596.5$ Hz



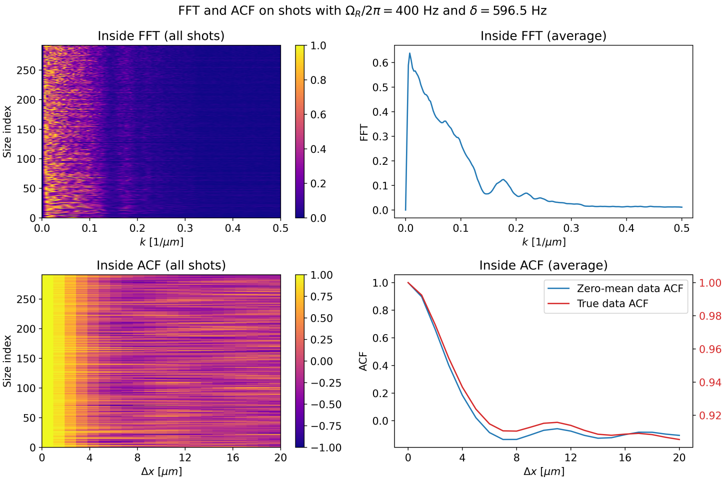
Data analysis: Parameters clustering



Fit function:

$$\sigma_B(t) = A\left(\frac{t}{1\ \mathrm{ms}}\right)^B$$

Data analysis: FFT and ACF



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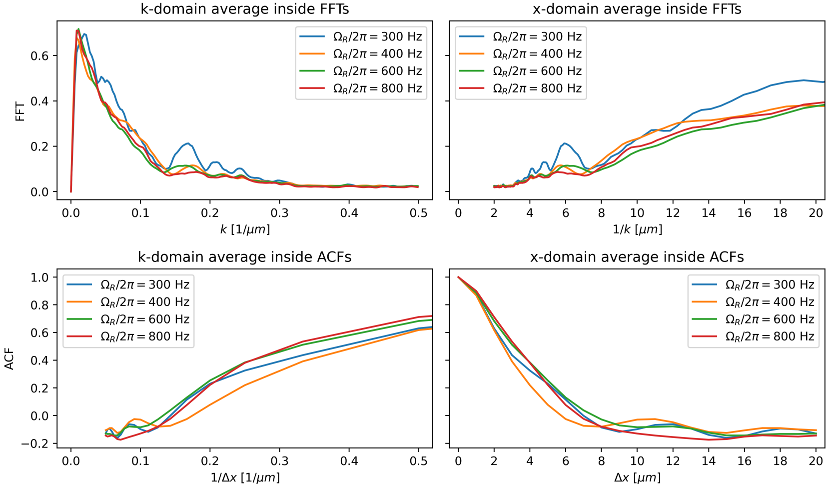
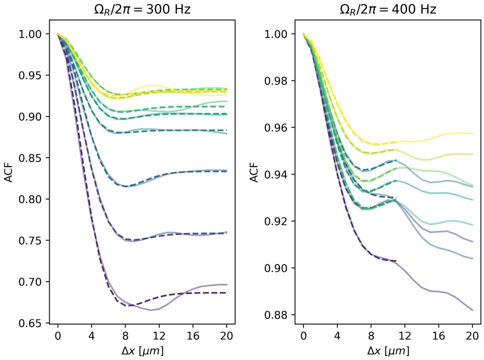


Data analysis: ACF inside (fits)



Fit function:

$$\mathcal{A}_{\text{fit}}(x) = (1-\Delta)\cos\left(\frac{\pi x}{\ell_2}\right)\exp\left[-\frac{1}{2}\left(\frac{x}{\ell_1}\right)^{\alpha}\right]+\Delta$$

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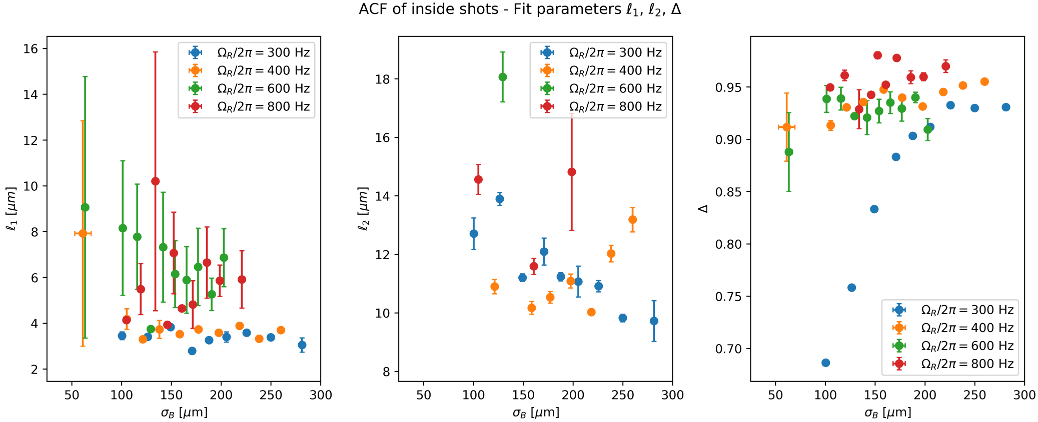

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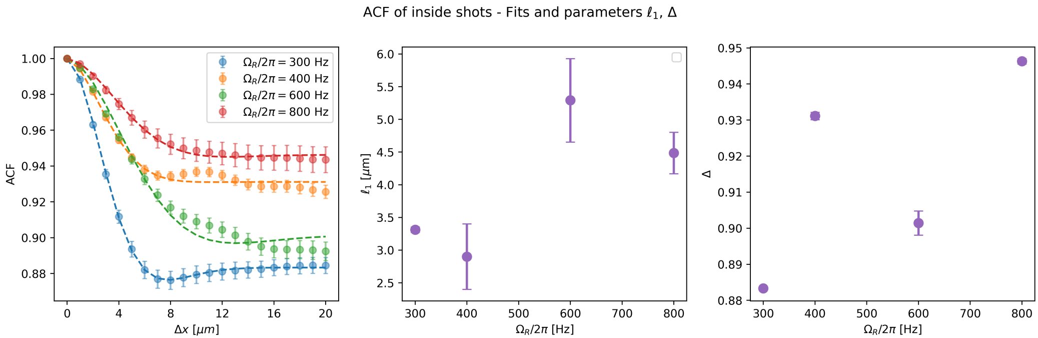
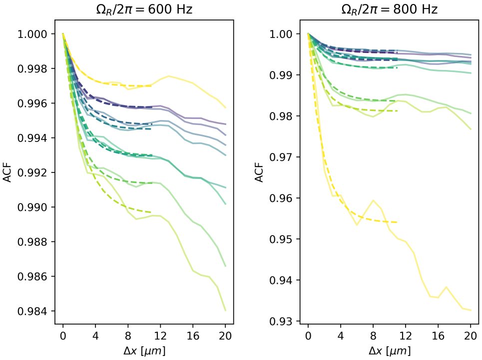


Data analysis: ACF outside (fits)

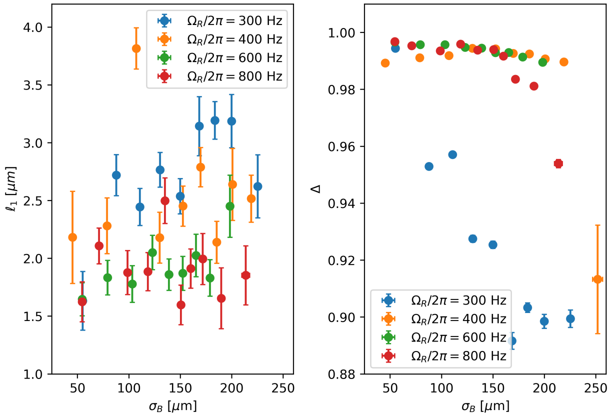


Fit function:

$$\mathcal{A}_{\rm fit}(x) = (1-\Delta)\exp\left[-\frac{x}{2\ell_1}\right] + \Delta$$

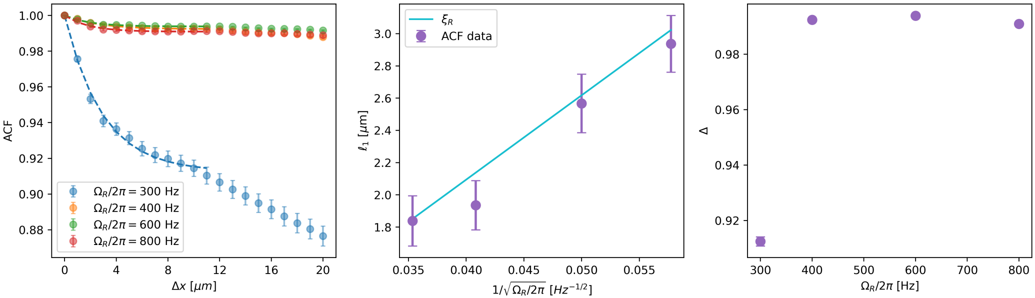
Data analysis: ACF outside (parameters)

ACF of outside shots - Fit parameters ℓ_1, Δ



Data analysis: ACF outside (parameters)

ACF of outside shots - Fits and parameters ℓ_1, Δ



Conclusions

What did we learn?

- The system shows **different properties** between inside and outside of the bubble
- Border width of the bubble **depends on the coupling** strength Ω_R
- Growth factor of the bubble size in time is **independent** of Ω_R
- In the bubble, periodic structures **disappear** with size increasing. They **appear**, instead, outside of the bubble.
- Length scale of information outside is related to the Rabi **healing length**

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Future research:

- Analysis of the **density** channel
- Comparison with numerical GPE **simulations**
- Behavior at different **temperatures**

Thank you for your attention!