

Bubbles in a ferromagnetic superfluid

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Bachelor's Degree in Physics

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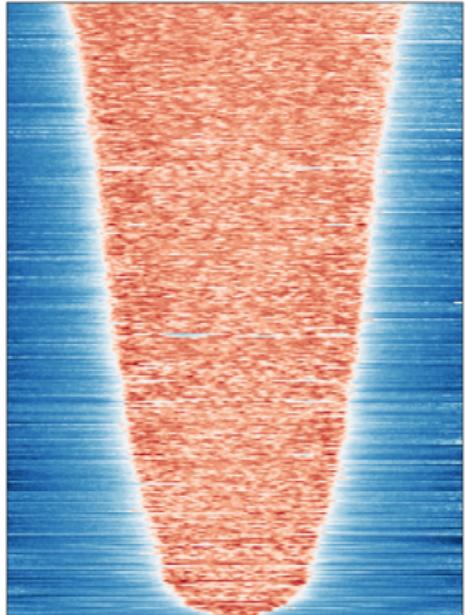
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Overview

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:

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

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 $|b\rangle$:

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

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

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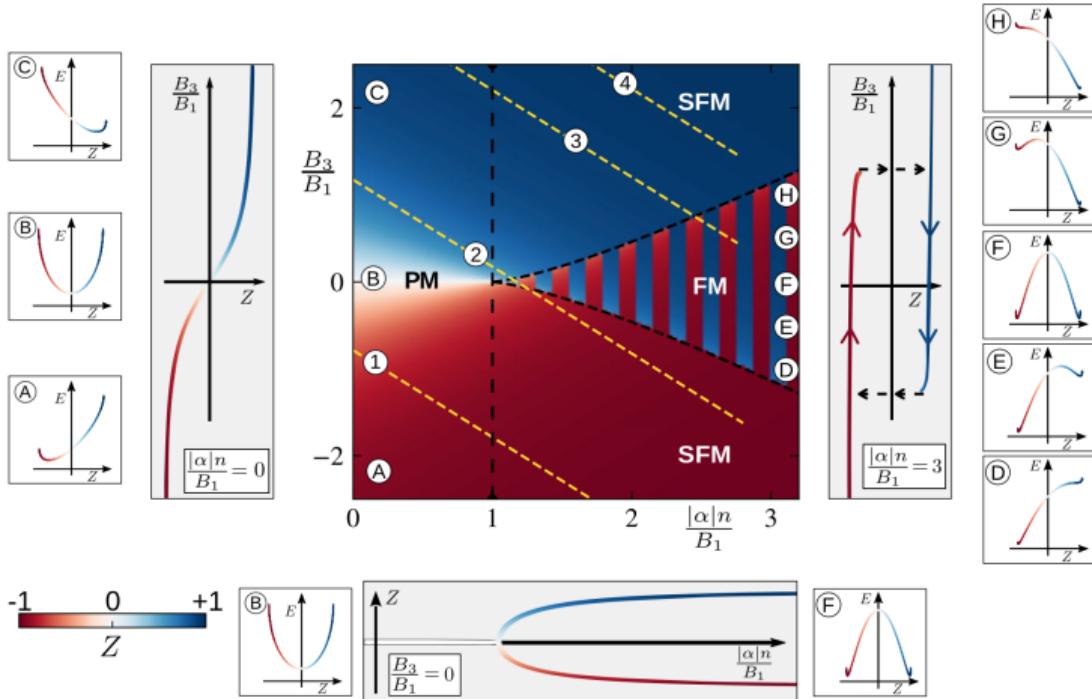
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Double-well energy landscape

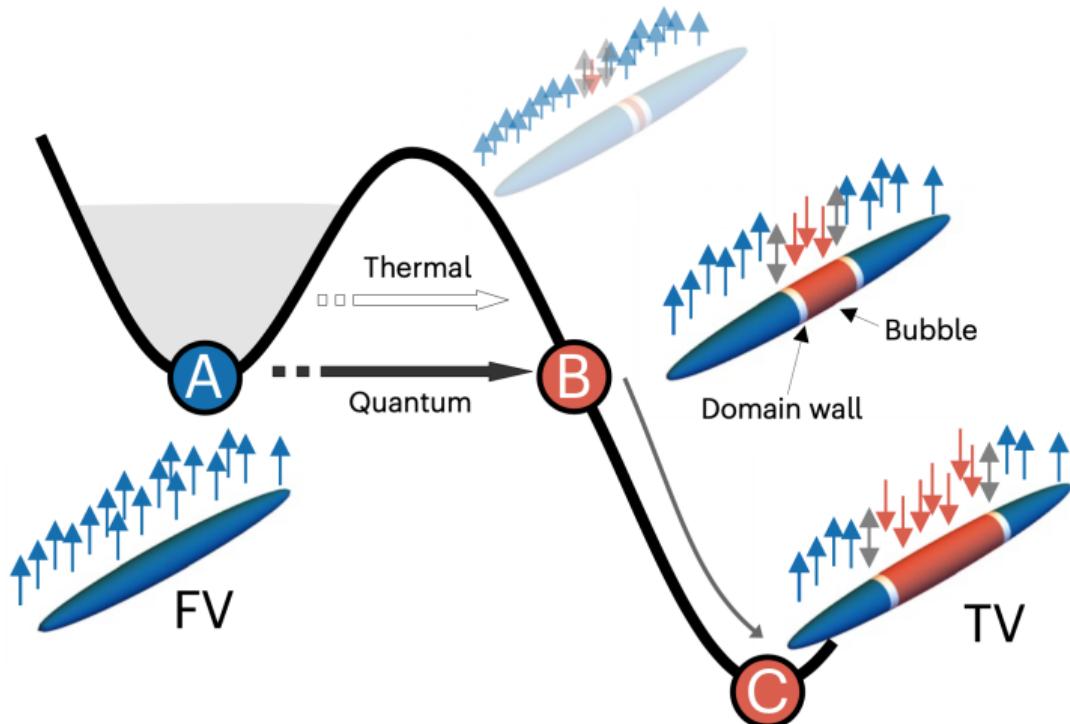
$$E_{\text{MF}}(Z) = -\hbar \left(|\delta g|nZ^2 + 2\Omega_R \sqrt{1 - Z^2} + 2\delta_{\text{eff}}Z \right)$$

The order parameter is the ratio $\frac{|\delta g|n}{\hbar\Omega_R}$

Theoretical background: Ferromagnetism



Theoretical background: False Vacuum Decay

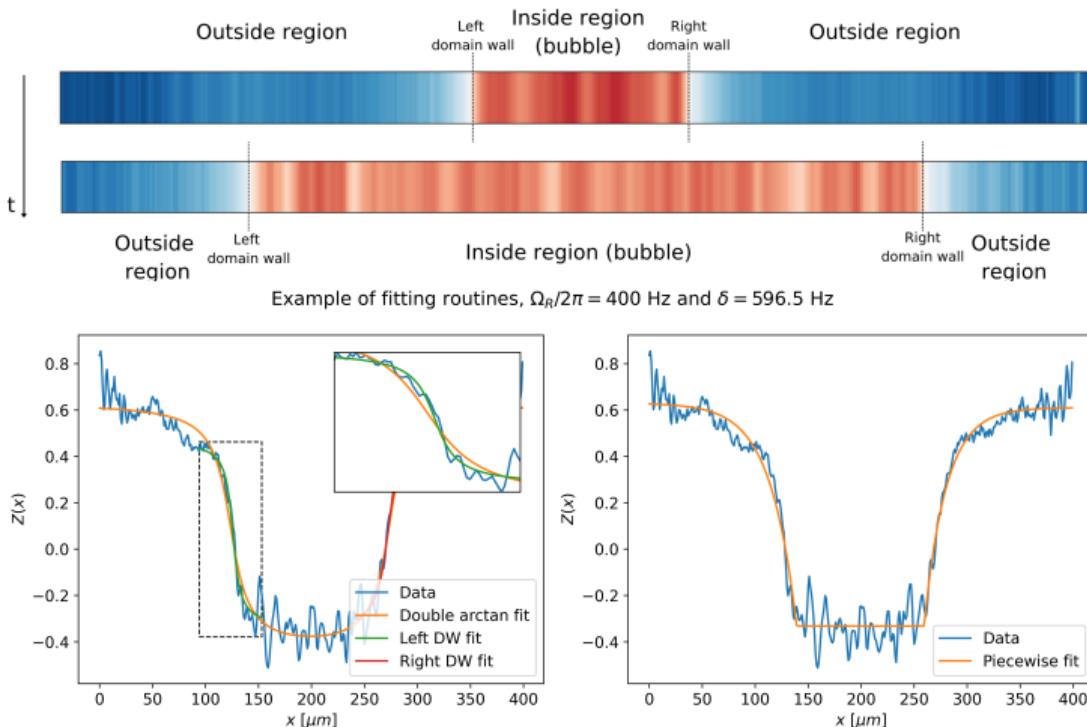


Data analysis: Experimental platform

- ▶ ^{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 $\omega_\perp/2\pi = 2 \text{ kHz}$ and $\omega_x/2\pi = 20 \text{ kHz}$
- ▶ Thomas-Fermi radii $R_\perp = 2 \mu\text{m}$ and $R_x = 200 \mu\text{m}$ (cigar-shaped)
- ▶ Reduction to **1D system** and spin-selective imaging yield the densities $n_\uparrow(x)$, $n_\downarrow(x)$ and the magnetization

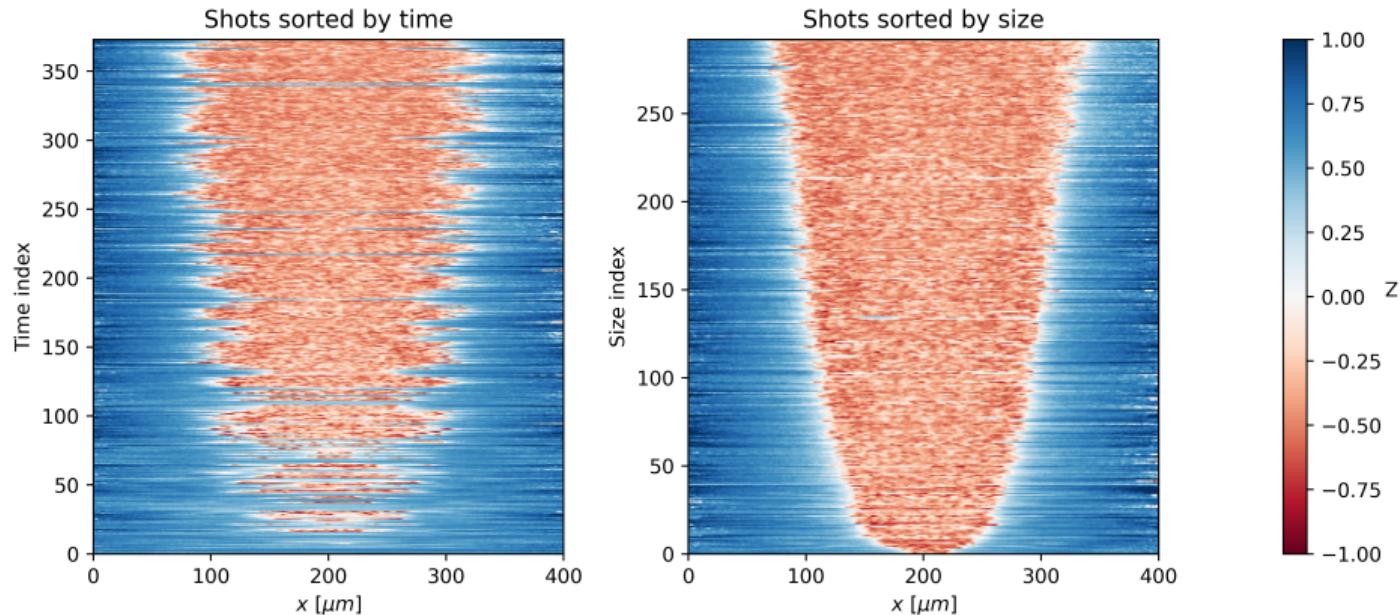
$$Z(x) = \frac{n_\uparrow(x) - n_\downarrow(x)}{n_\uparrow(x) + n_\downarrow(x)}$$

Data analysis: Bubble shots and fits



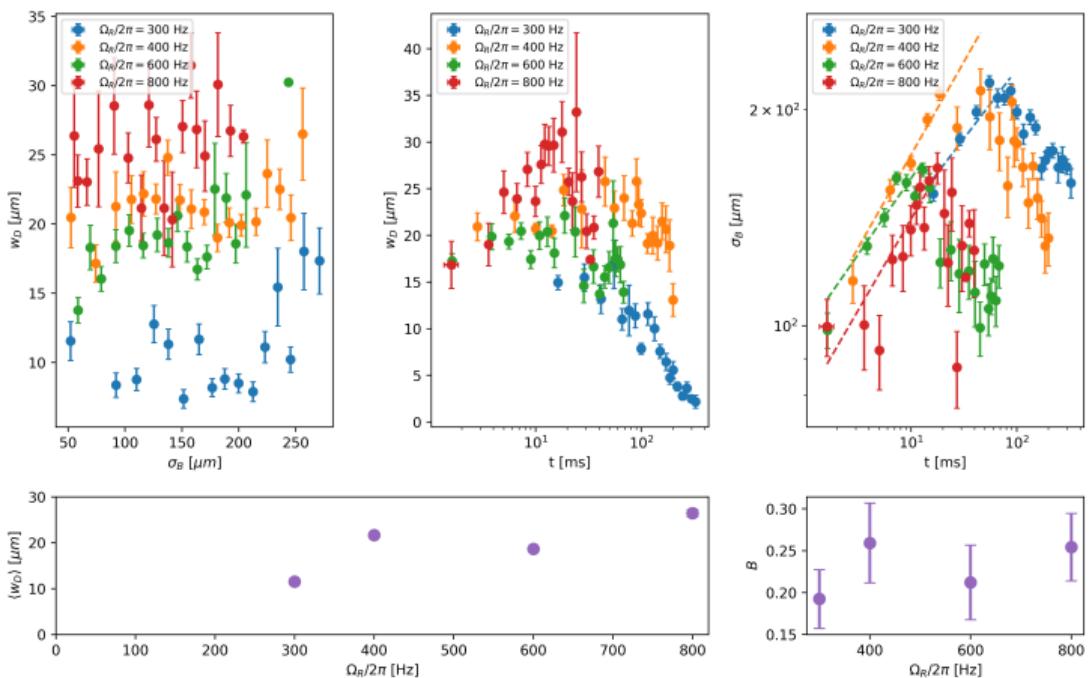
Data analysis: Shot sorting

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

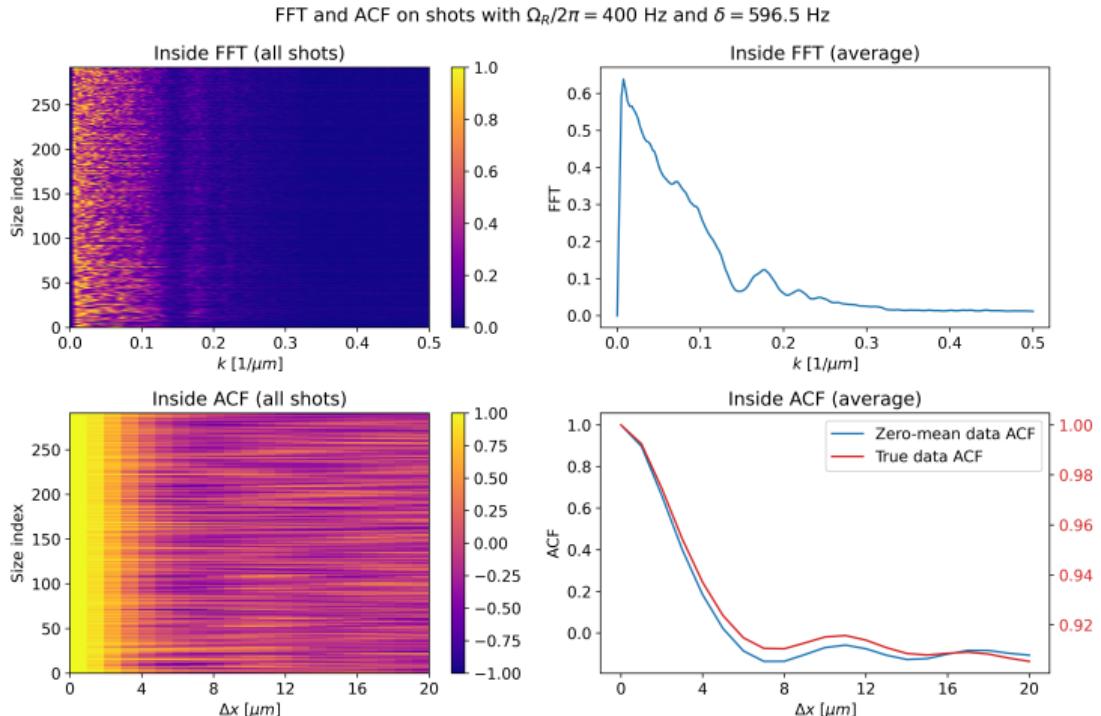


Data analysis: Parameters clustering

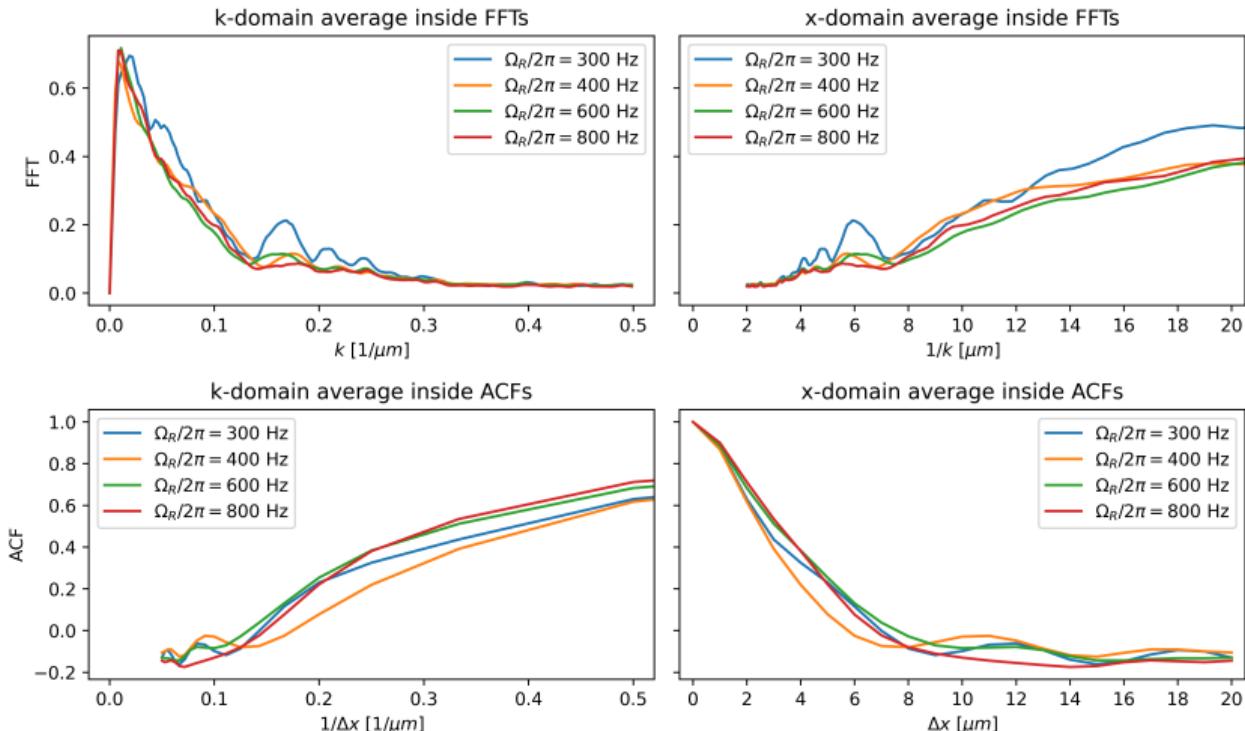
Bubble clustered parameters



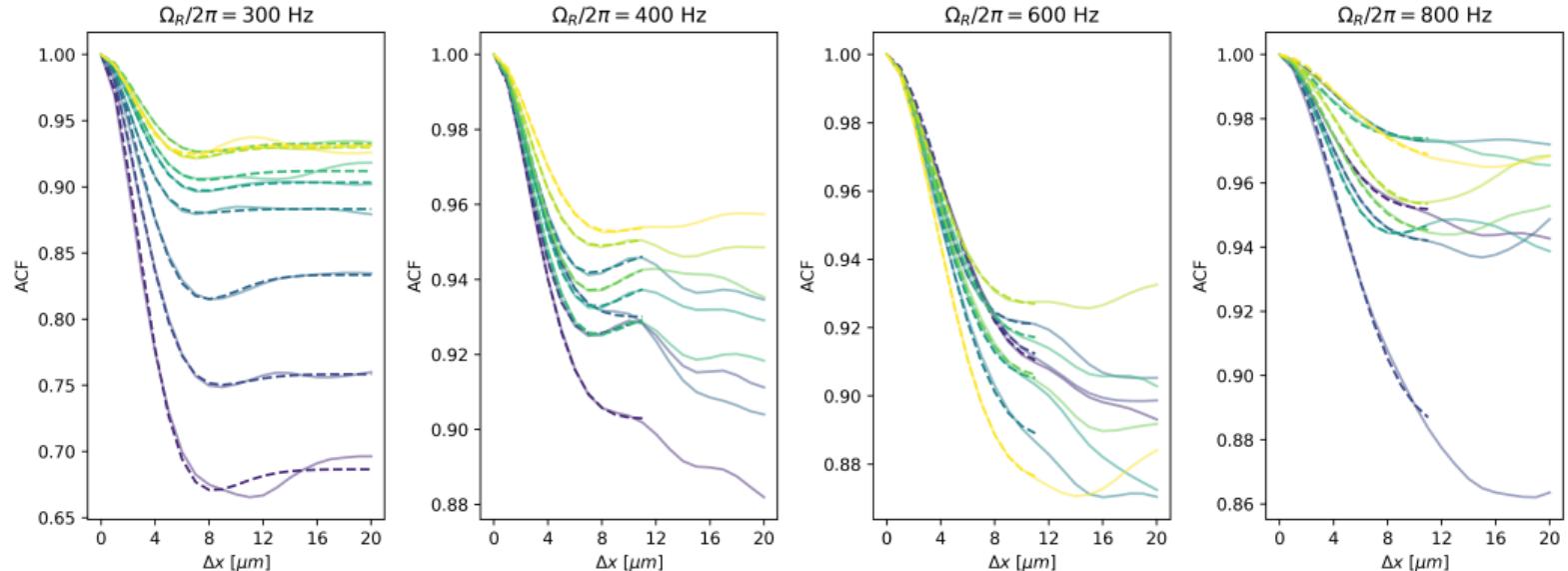
Data analysis: FFT and ACF



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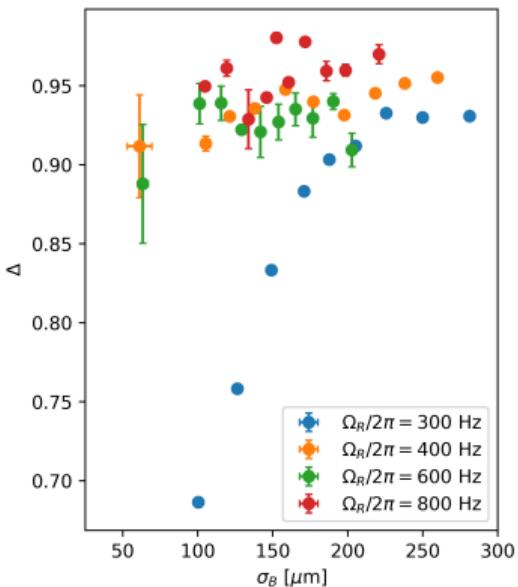
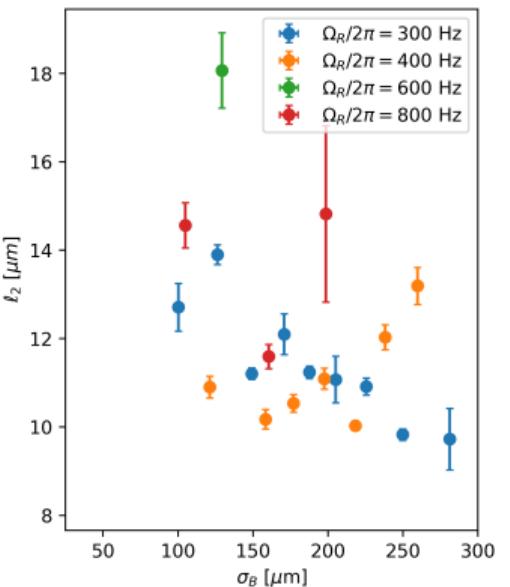
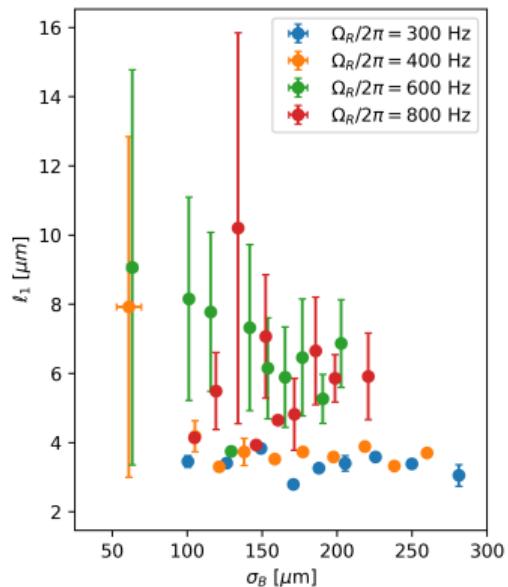


Data analysis: ACF inside (fits)

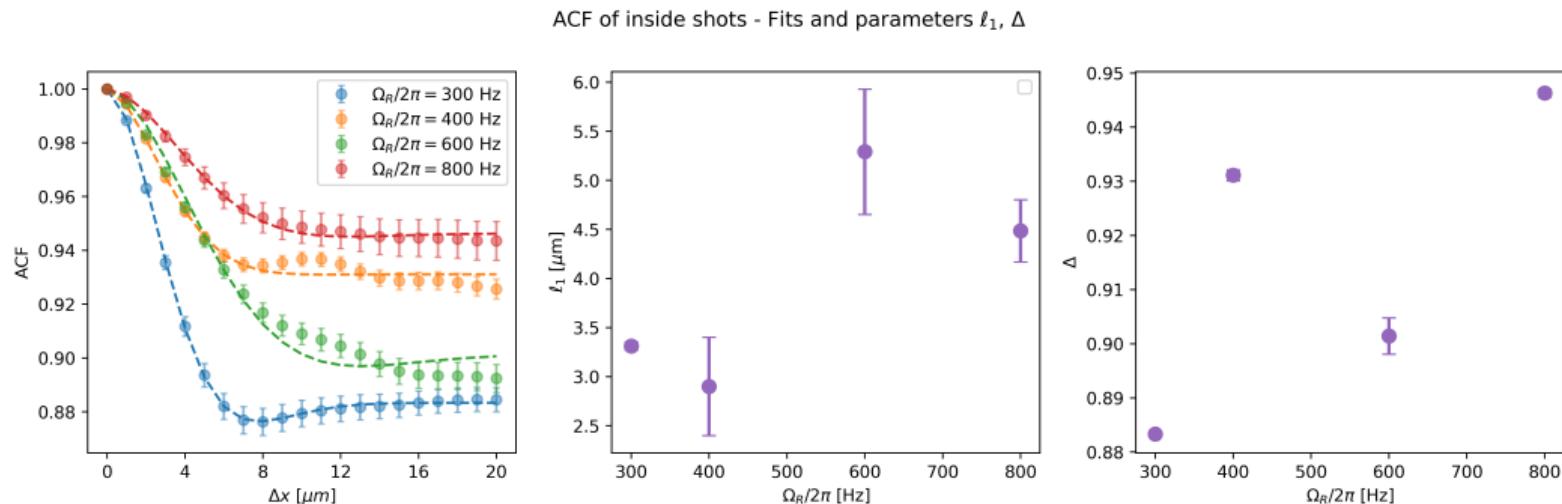


Data analysis: ACF inside (parameters)

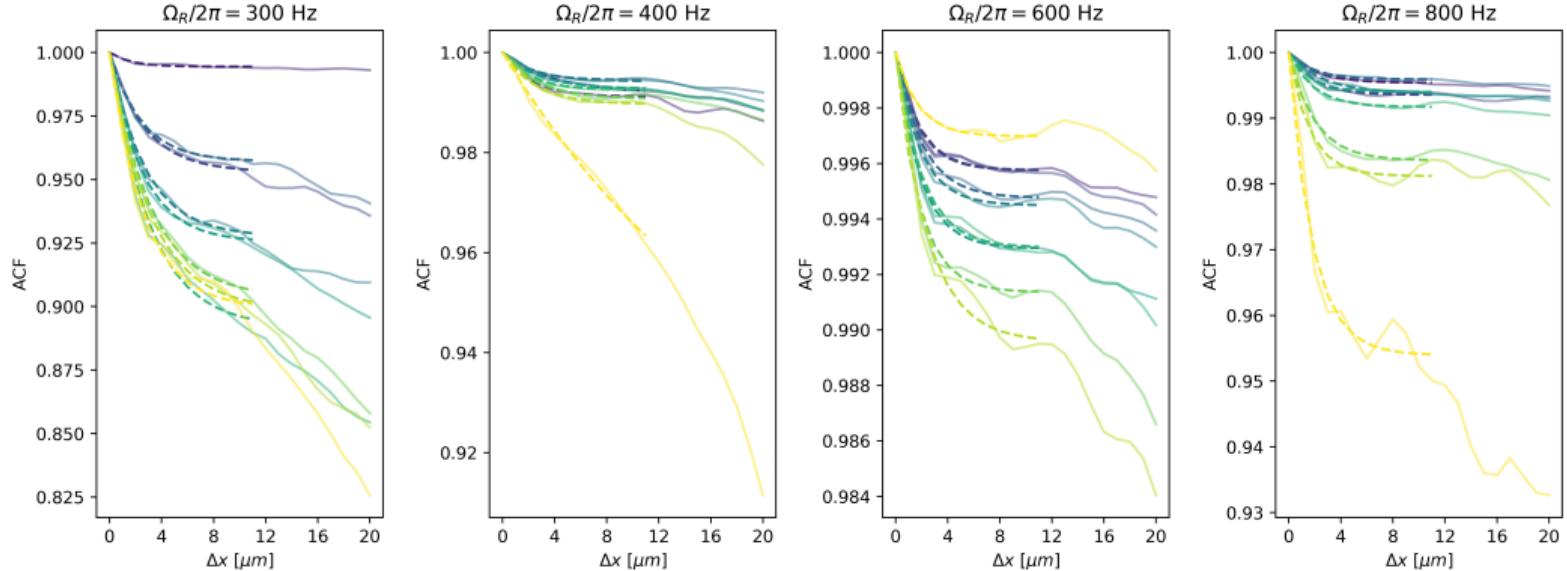
ACF of inside shots - Fit parameters ℓ_1, ℓ_2, Δ



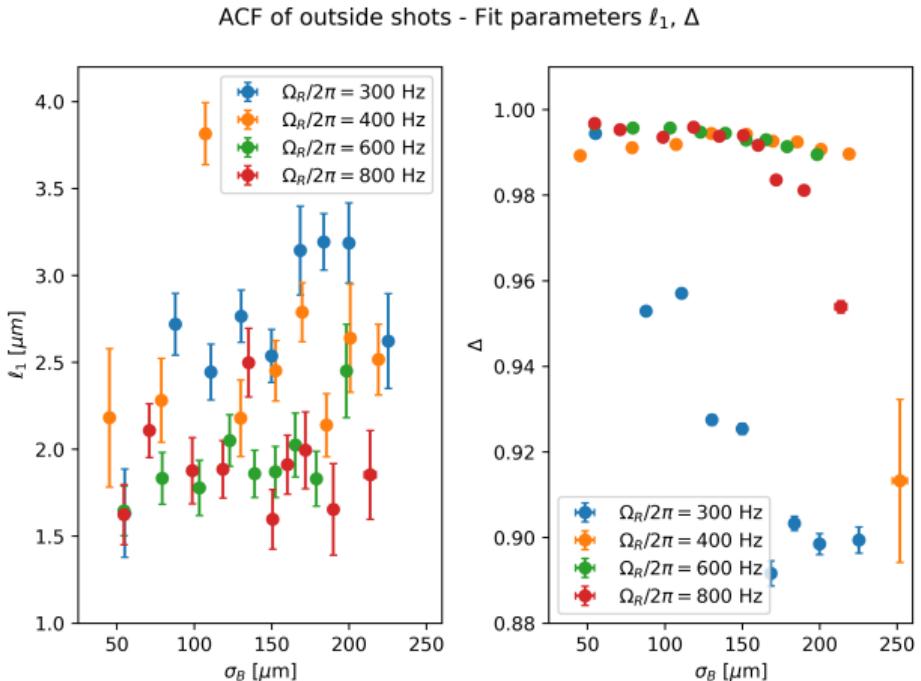
Data analysis: ACF inside (parameters)



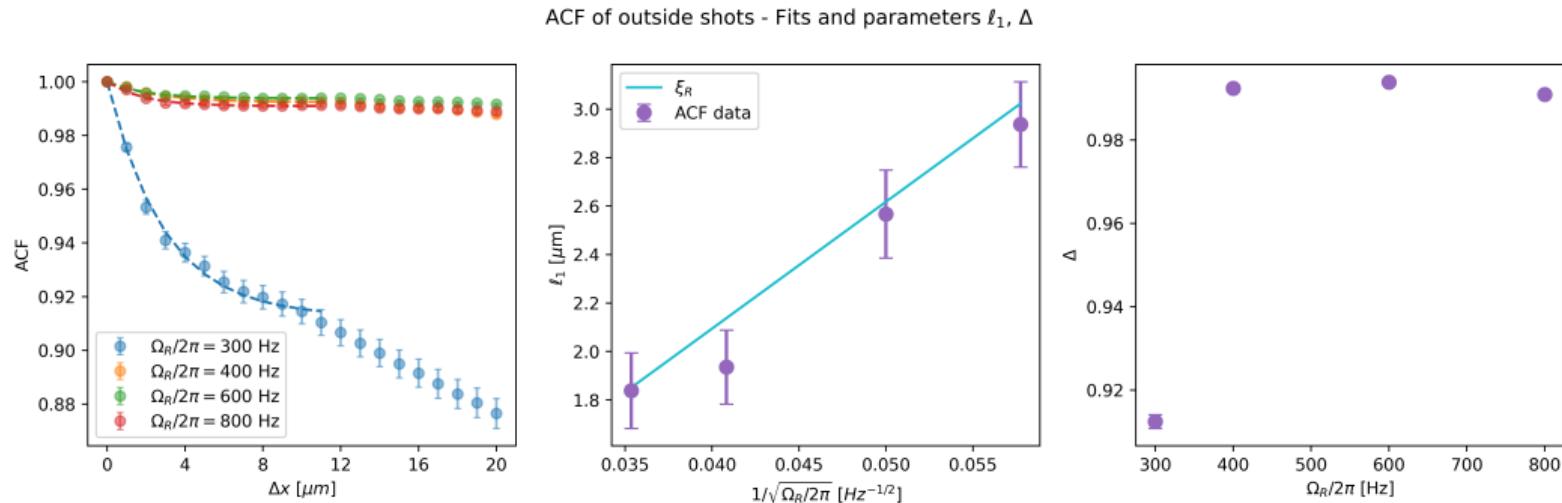
Data analysis: ACF outside (fits)



Data analysis: ACF outside (parameters)



Data analysis: ACF outside (parameters)



Conclusions

What did we learn from this work?

- ▶ 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**
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Thank you for your attention!