Bubbles in a ferromagnetic superfluid

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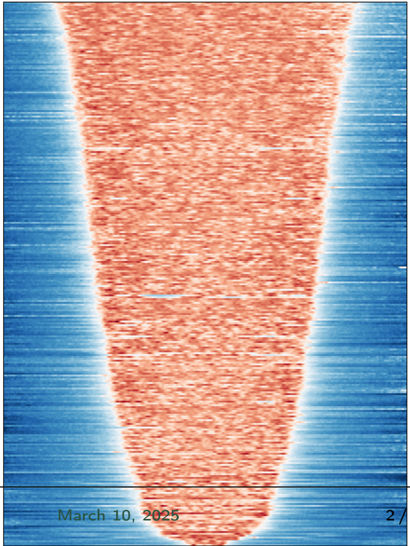
Overview

This presentation will cover:

- **Introduction**: Why this thesis?
- **Theoretical background**: Ferromagnetism in coherently coupled BEC 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 spin mixture** optically trapped and cooled below the condensation temperature

Theoretical background: Ideal Bose gas

The ideal Bose gas is a quantum system of N non-interacting bosons, described by statistical mechanics.

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The occupation number of the ground state $N_0 = \langle n_0 \rangle$ corresponds to the condensation. There is a phase transition at $T = T_c$.

$$\frac{N_0}{N} = 1 - \left(\frac{T}{T_c}\right)^{\alpha} \quad \text{for } T < T_c$$

In a finite box $\alpha = 3/2$, in harmonic confinement $\alpha = 3$.

Theoretical background: Gross-Pitaevskii equation

A system of weakly-interacting bosons can be described by a single wavefunction by a mean-field approximation, 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

$$n(x) = \frac{\mu - V(x)}{g}$$

Theoretical background: Two-component mixtures

The GPEs are coupled because of the inter-species interaction constant

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

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

Theoretical background: Coherent coupling

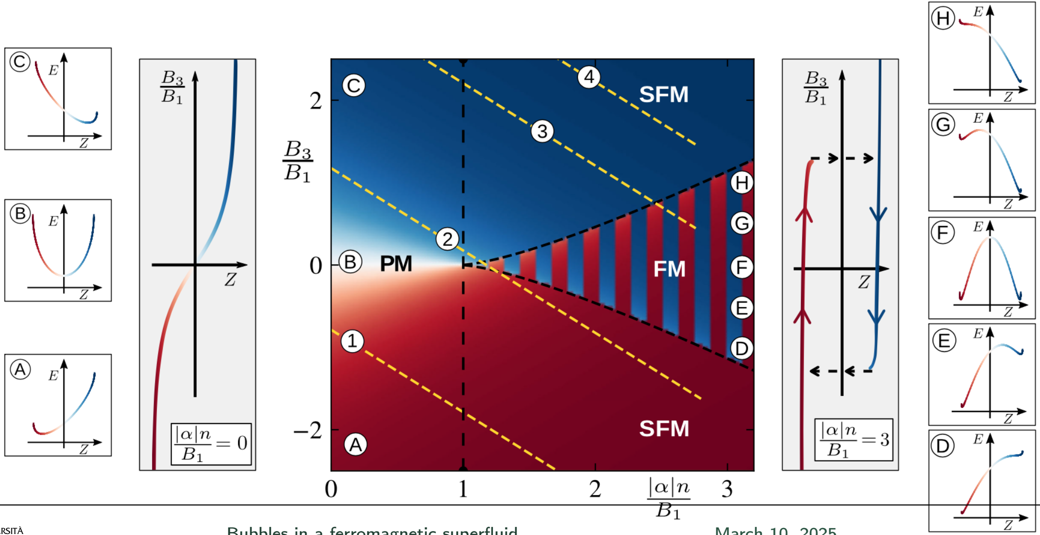
Coupling radiation between $|a\rangle$ and $|b\rangle$:

$$\Omega_R(t)\exp\{-i\omega_{\rm cpl}t+\phi\} \quad \omega_{\rm cpl}=\omega_{ab}+\delta_B$$

Double-well energy landscape

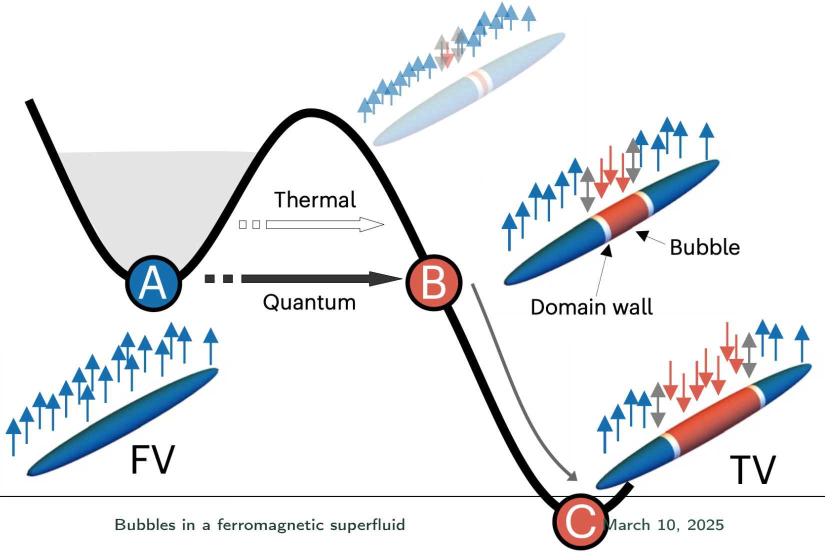
$$E_{\rm MF}(Z)=-\hbar\left(|\delta g|nZ^2+2\Omega_R\sqrt{1-Z^2}+2\delta_{\rm eff}Z\right)$$

The order parameter is the ratio $|\delta g|n/\hbar\Omega_R$



C
B
A
E
Z
$\frac{B_3}{B_1}$
$\frac{|\alpha|n}{B_1} = 0$
2
0
−2
0
1
2
3
$\frac{|\alpha|n}{B_1}$
SFM
PM
FM
SFM
1
2
3
4
H
G
F
E
D
$\frac{|\alpha|n}{B_1} = 3$

Theoretical background: False Vacuum Decay



Data analysis: Experimental platform

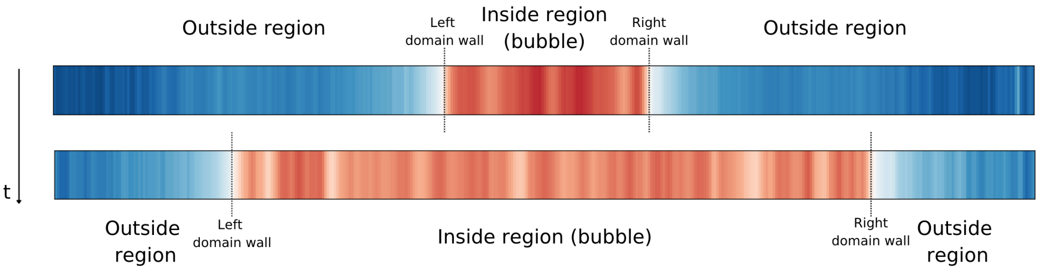
The experiment uses ^{23}Na atoms prepared in the state $|F, m_F\rangle = |2, -2\rangle = |\uparrow\rangle$, which is coupled to the state $|1, -1\rangle = |\downarrow\rangle$.
The system is cigar-shaped with Thomas-Fermi radii

$$R_x = 200\ \mu\text{m} \quad R_\rho = 2\ \mu\text{m}$$

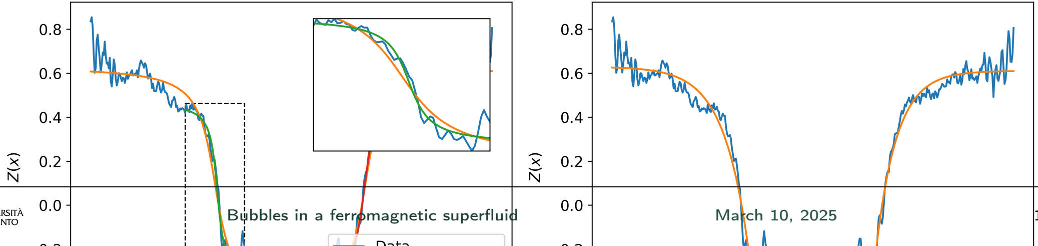
The magnetization is computed from the densities $n_\uparrow(x)$, $n_\downarrow(x)$

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

Data analysis: Bubble shots and fits

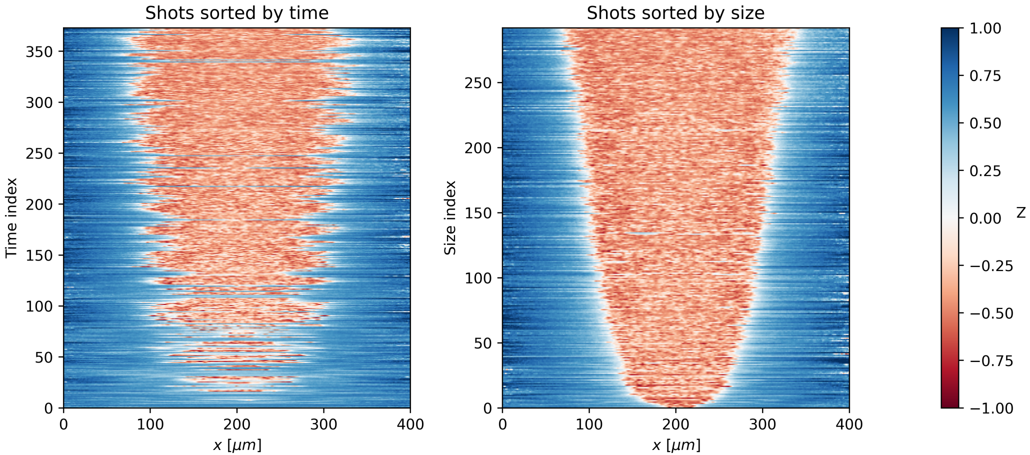


Example of fitting routines, $\Omega_R/2\pi = 400$ Hz and $\delta = 596.5$ Hz

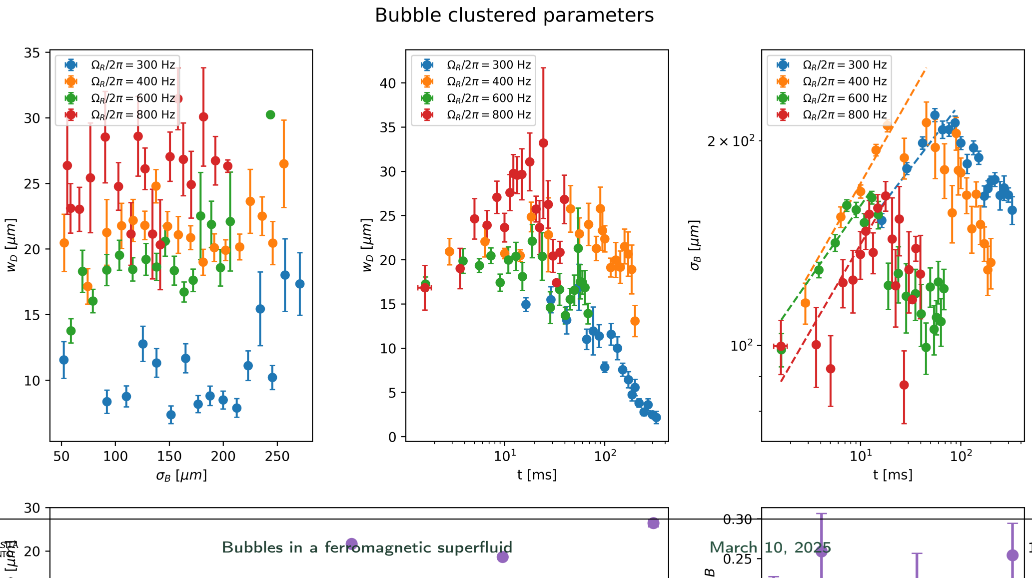


Data analysis: Shot sorting

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

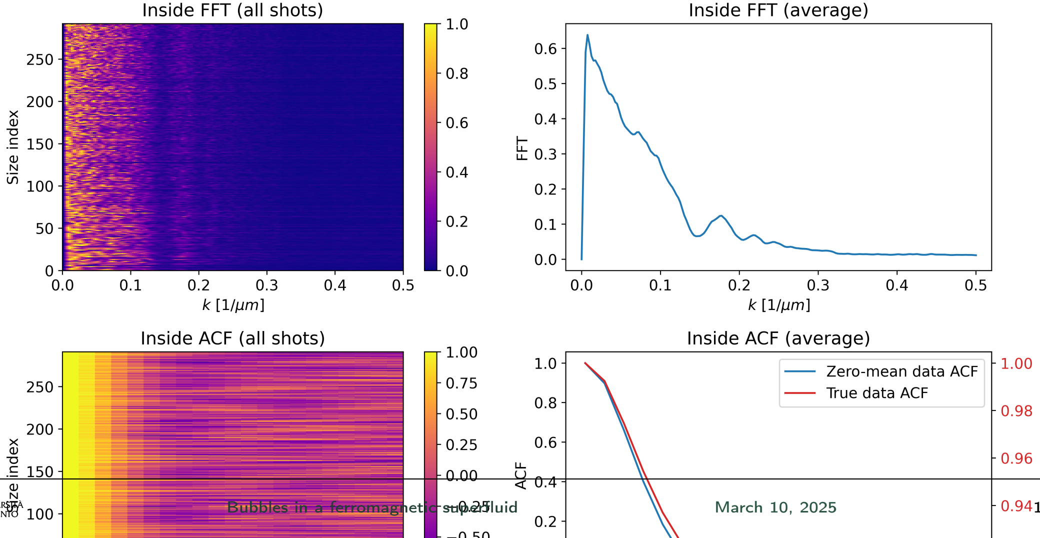


Data analysis: Parameters clustering

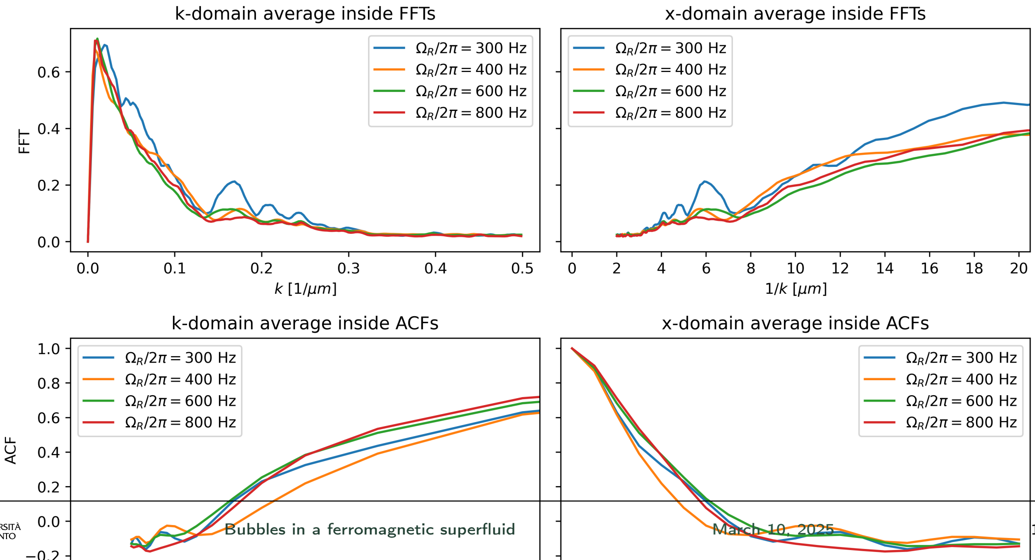


Data analysis: FFT and ACF

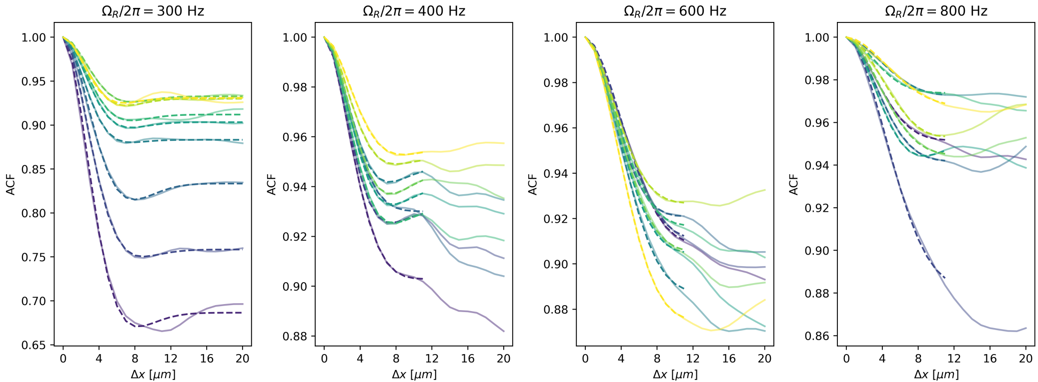
FFT and ACF on shots with $\Omega_R/2\pi = 400$ Hz and $\delta = 596.5$ Hz

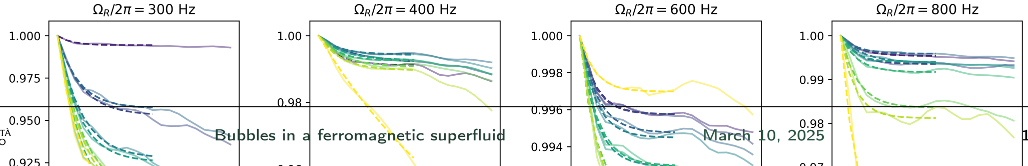


Data analysis: FFT and ACF

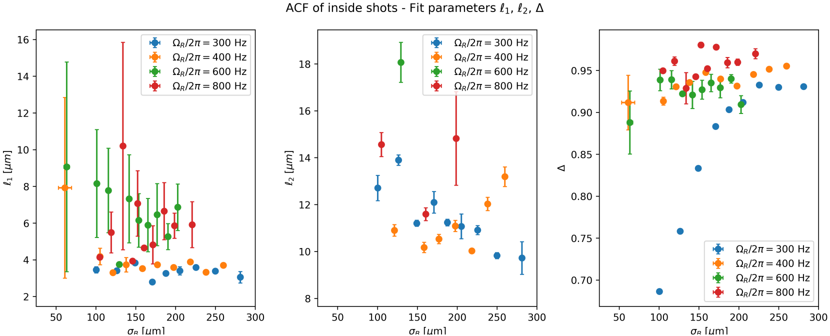


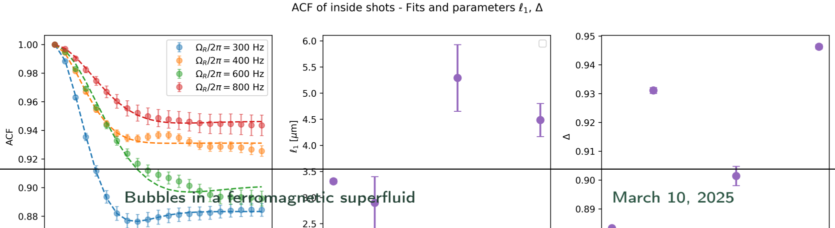
Data analysis: ACF fits



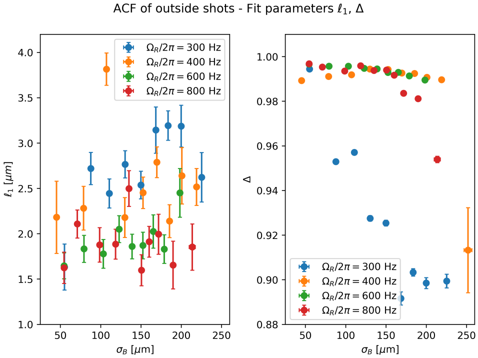


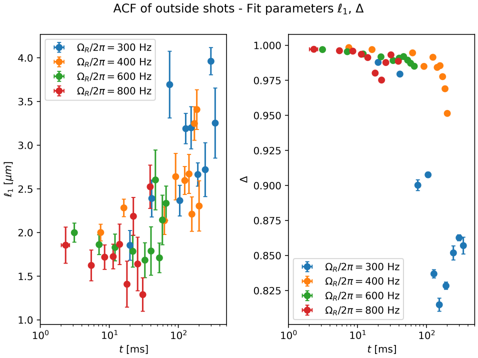
Data analysis: ACF inside

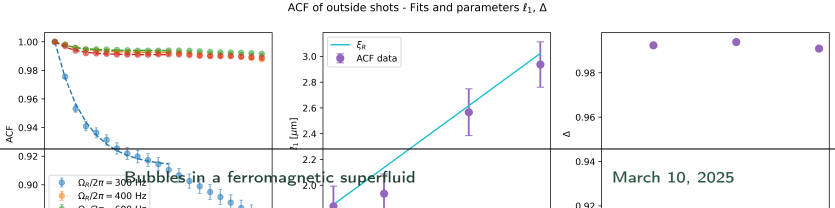




Data analysis: ACF outside







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**

Thank you for your attention!