Bubbles in a ferromagnetic superfluid

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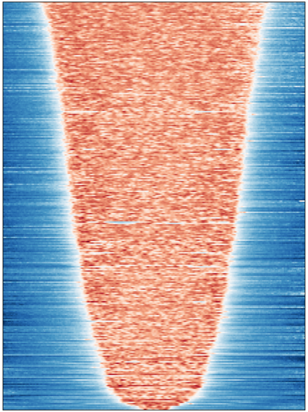
Overview

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?

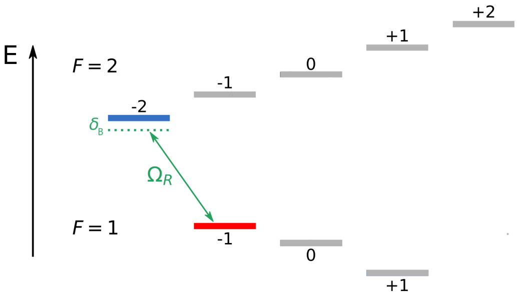
- First **experimental observation** of false vacuum decay (FVD) via bubble formation in the *Pitaevskii BEC Center* laboratories of the University of Trento.
- **Superfluidity**: high degree of coherence of the system
- **Ferromagnetism**: double well energy landscape
- Study of FVD provides information on metastability, from quantum systems to cosmology

Experimental platform

- $N \sim 10^6$ condensed ^{23}Na atoms in the hyperfine states:

$$|F=2, m_F=-2\rangle = |\uparrow\rangle$$
$$|F=1, m_F=-1\rangle = |\downarrow\rangle$$

- Contact interaction constants $g_{\uparrow\uparrow}$, $g_{\downarrow\downarrow}$, $g_{\uparrow\downarrow}$
- Interconversion due to Rabi coupling: strength Ω_R and detuning δ_B
- Harmonic trapping potential (cigar-shaped, 1D)



Coherently coupled two-component spin mixtures

The GPEs contain the intra and inter-species interaction constants and the coupling between the states:

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(x) - \frac{\delta_B}{2} + g_{\uparrow\uparrow}|\psi_\uparrow(x)|^2 + g_{\uparrow\downarrow}|\psi_\downarrow(x)|^2\right]\psi_\uparrow(x) - \frac{\hbar\Omega_R}{2}\psi_\downarrow(x) = \mu_\uparrow\psi_\uparrow(x)$$

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(x) + \frac{\delta_B}{2} + g_{\uparrow\downarrow}|\psi_\uparrow(x)|^2 + g_{\downarrow\downarrow}|\psi_\downarrow(x)|^2\right]\psi_\downarrow(x) - \frac{\hbar\Omega_R}{2}\psi_\uparrow(x) = \mu_\downarrow\psi_\downarrow(x)$$

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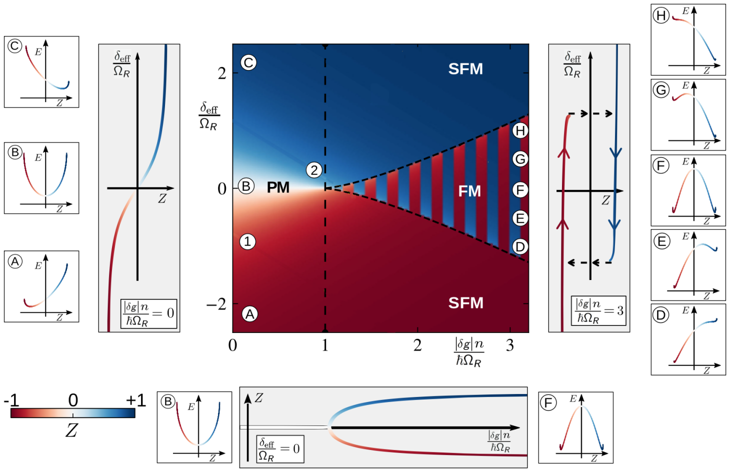
Magnetization $Z = (n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow)$ produces a double well energy landscape:

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

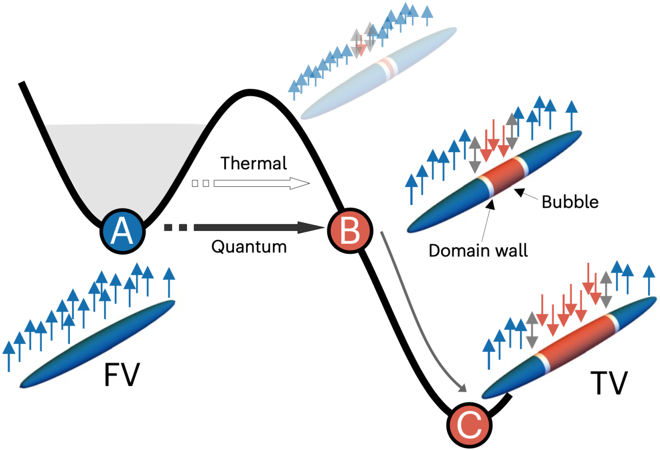
Magnetic model phase diagram: ground state configuration



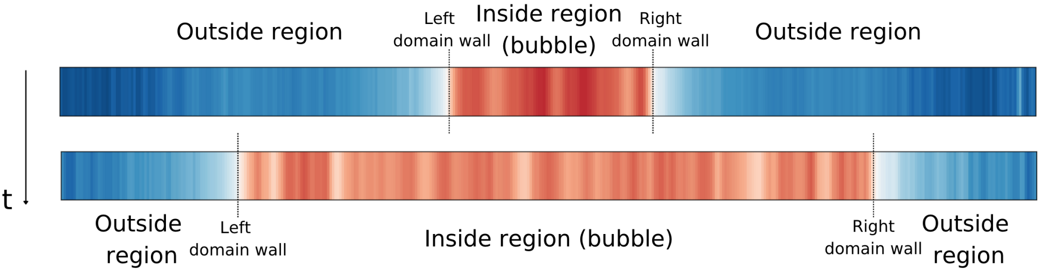
- Set $\dfrac{|\delta g| n}{\hbar \Omega_R}$ to a fixed value by adjusting Ω_R
- Probe the magnetic properties by changing δ_{eff}

False vacuum decay bubbles

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



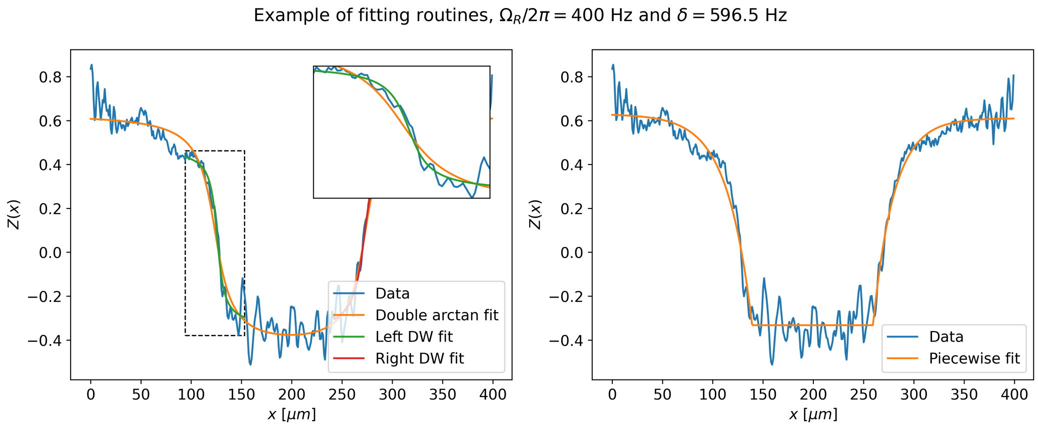
Example of bubble shots



Our aim is to study:

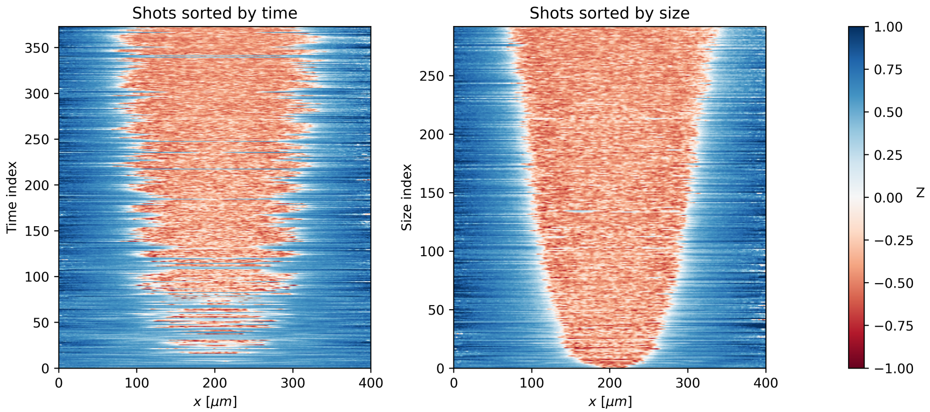
- Size σ_B and domain wall width w_D
- Excitation structures inside/outside

Bubble fitting routines

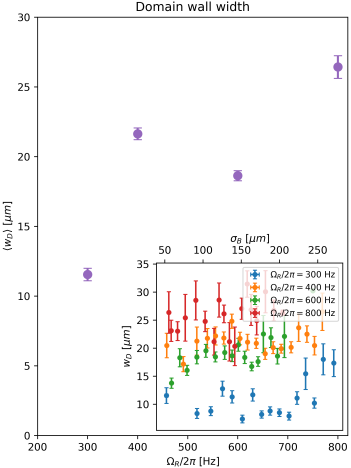


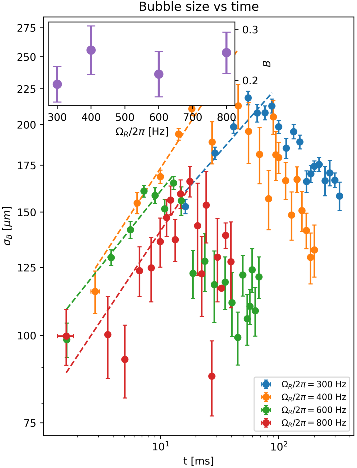
Shot sorting

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



Analysis of domain wall width and bubble size

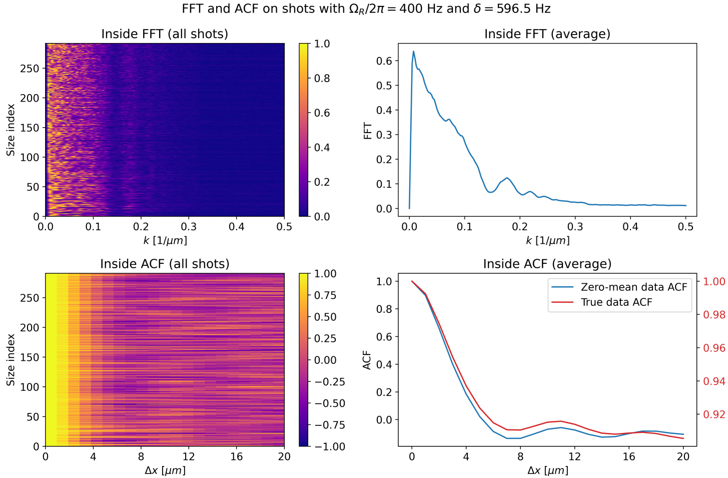


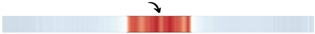


- Shots clustered by size (left) or time (right)
- Fit function:

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

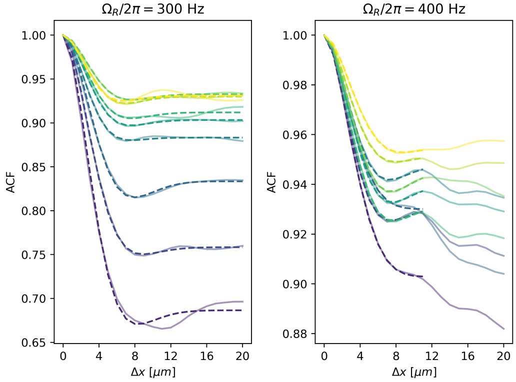
Spectral analysis in the inside region

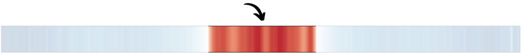




- FFT: broad peak at $k \sim 0.01\ \mu\text{m}^{-1}$
- ACF: peak at $\Delta x \sim 11\ \mu\text{m}$

ACF analysis in the inside region vs σ_B

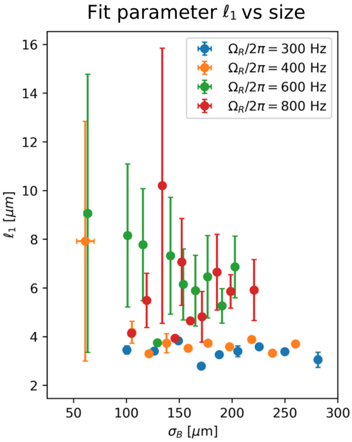


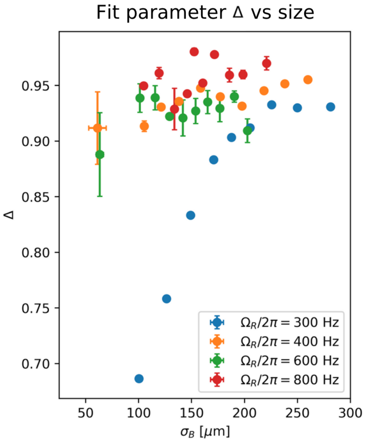


- Shots clustered by increasing size (darker to lighter colors)
- Fit function $\mathcal{A}_{\mathrm{fit}}(x) =$

$$(1-\Delta)\cos\left(\frac{\pi x}{\ell_2}\right)\exp\left[-\frac{1}{2}\left(\frac{x}{\ell_1}\right)^{1.7}\right]+\Delta$$

ACF analysis in the inside region vs σ_B





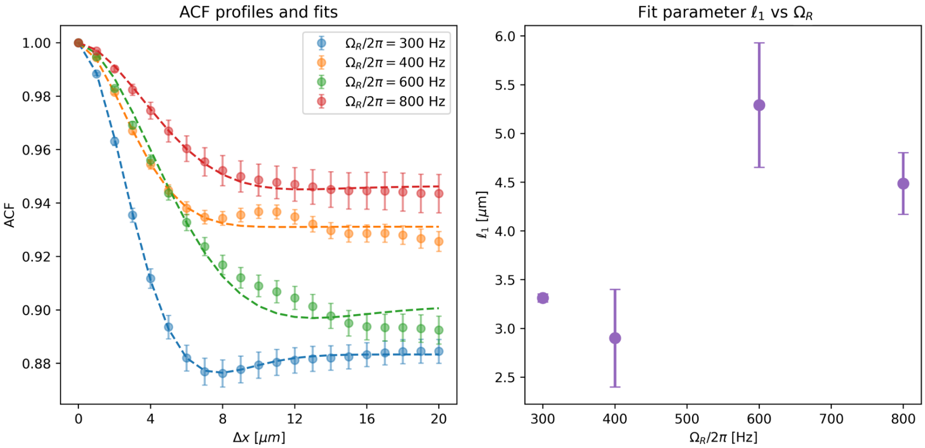
Healing lengths:

$$\xi_s = \frac{\hbar}{\sqrt{2mn|\delta g|}} \approx 0.5 \ \mu\text{m}$$

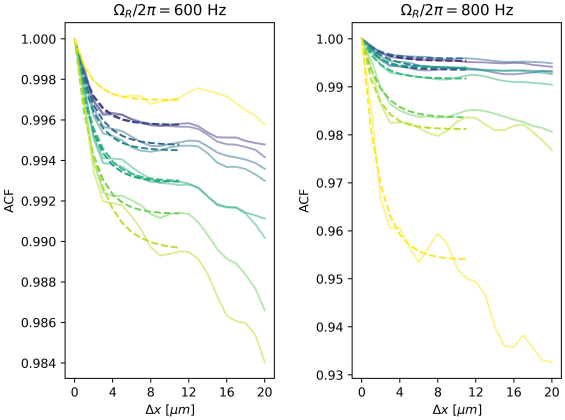
$$\xi_d = \frac{\hbar}{\sqrt{2mn\overline{g}}} \approx 0.01 \ \mu\text{m}$$

$$\xi_R = \sqrt{\frac{\hbar}{m\Omega_R}} \approx 1.8 - 3.0 \ \mu\text{m}$$

ACF analysis in the inside region vs Ω_R



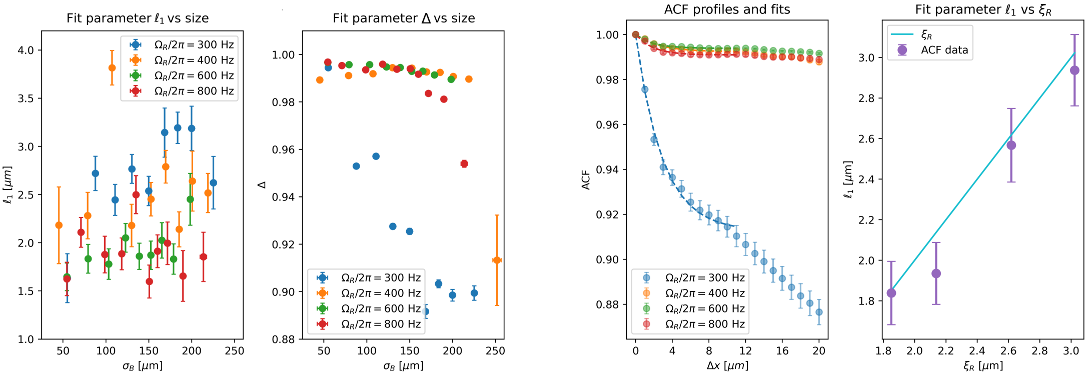
ACF analysis in the outside region vs σ_B



- Shots clustered by increasing size (darker to lighter colors)
- Fit function:

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

ACF analysis in the outside region vs σ_B and Ω_R



Conclusions

What did we learn?

- System shows **different properties** between inside and outside of the bubble
- Domain wall width **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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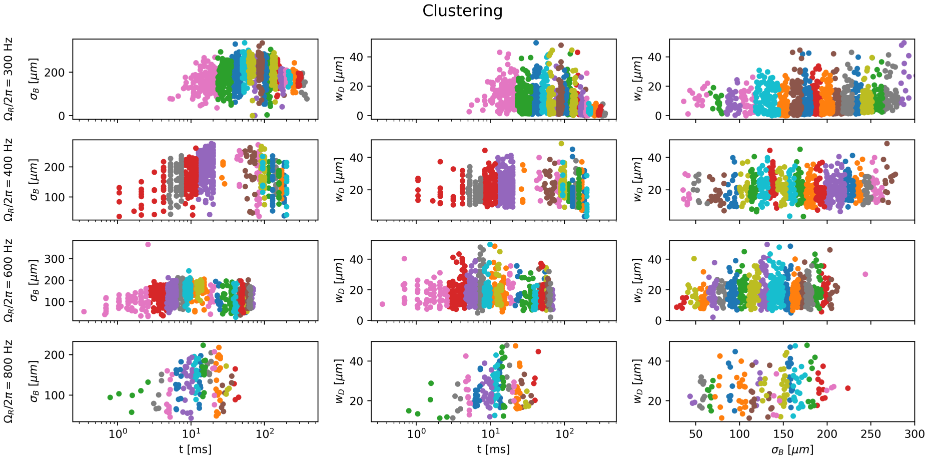
Future research:

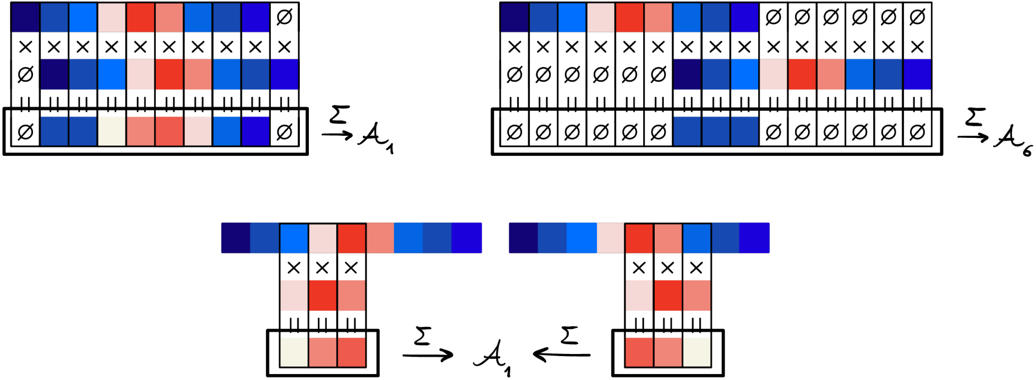
- Analysis of the **density** channel
- Comparison with numerical GPE **simulations**
- Behavior at different **temperatures**

Thank you for your attention!

Data clustering



Windowed ACF



FFT and ACF averages in the inside region