

Bubbles in a ferromagnetic superfluid

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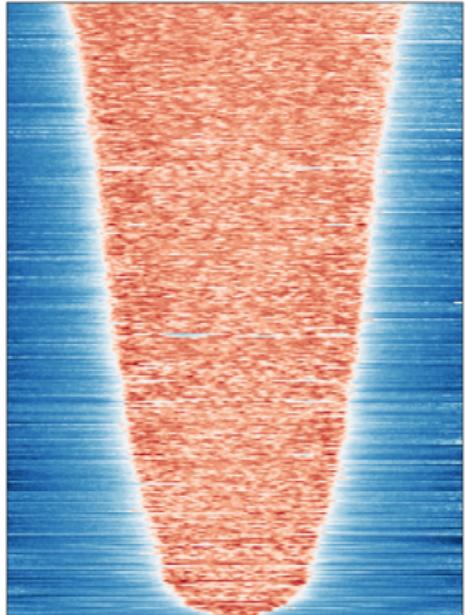
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Overview

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?

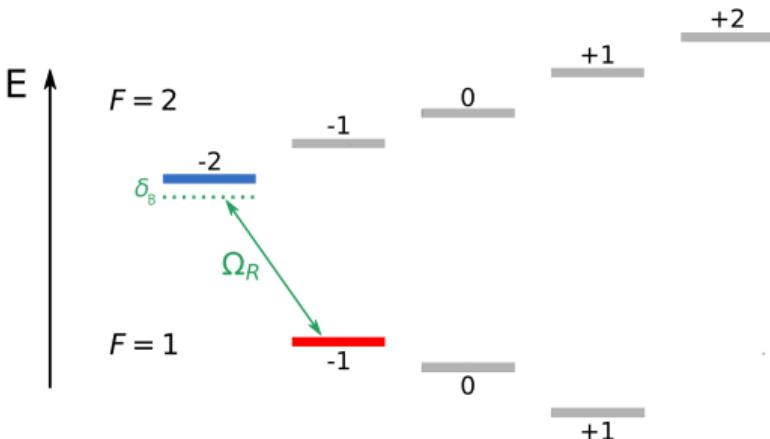
- ▶ First **experimental observation** of false vacuum decay (FVD) in the *Pitaevskii BEC Center* laboratories of the University of Trento.
- ▶ **Superfluidity:** high degree of coherence of the system
- ▶ **Ferromagnetism:** double well energy landscape
- ▶ Study of FVD provides information on metastability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

Experimental platform

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

$$\begin{aligned}|F, m_F\rangle &= |2, -2\rangle = |\uparrow\rangle \\|F, m_F\rangle &= |1, -1\rangle = |\downarrow\rangle\end{aligned}$$

- ▶ 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:

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

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

Coherently coupled two-component spin mixtures

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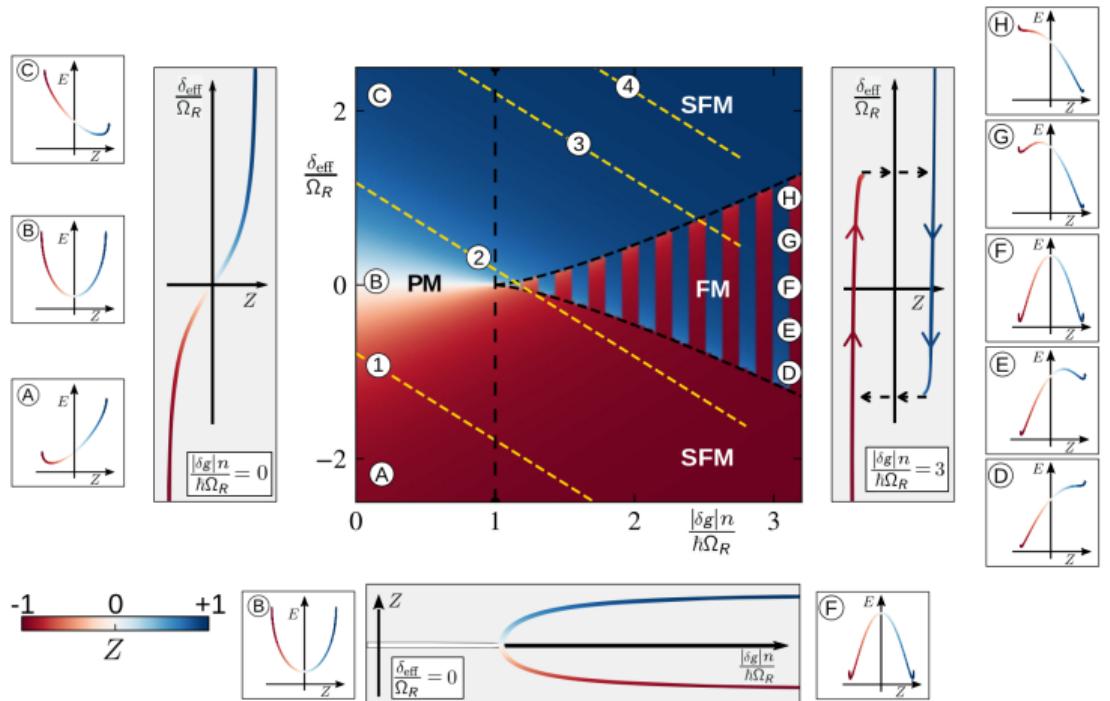
$$\left[-\frac{\hbar^2}{2m} \nabla^2 + V(x) - \frac{\delta_B}{2} + g_{\uparrow\uparrow} |\psi_{\uparrow}(x)|^2 + g_{\uparrow\downarrow} |\psi_{\downarrow}(x)|^2 \right] \psi_{\uparrow}(x) - \frac{\hbar\Omega_R}{2} \psi_{\downarrow}(x) = \mu_{\uparrow} \psi_{\uparrow}(x)$$

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

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

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

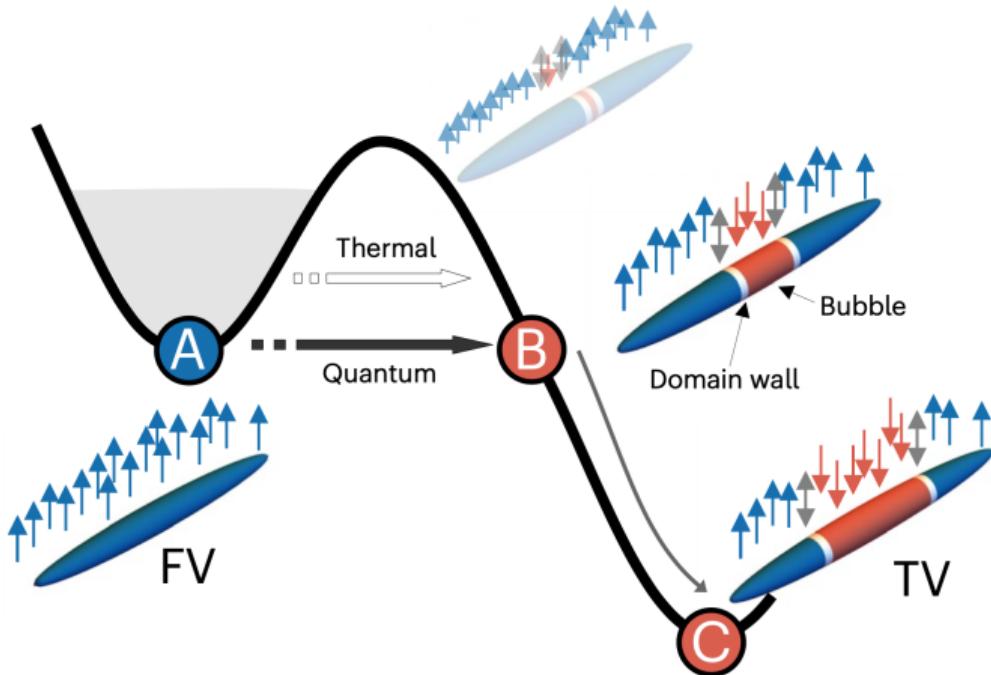
Magnetic model phase diagram: para and ferro



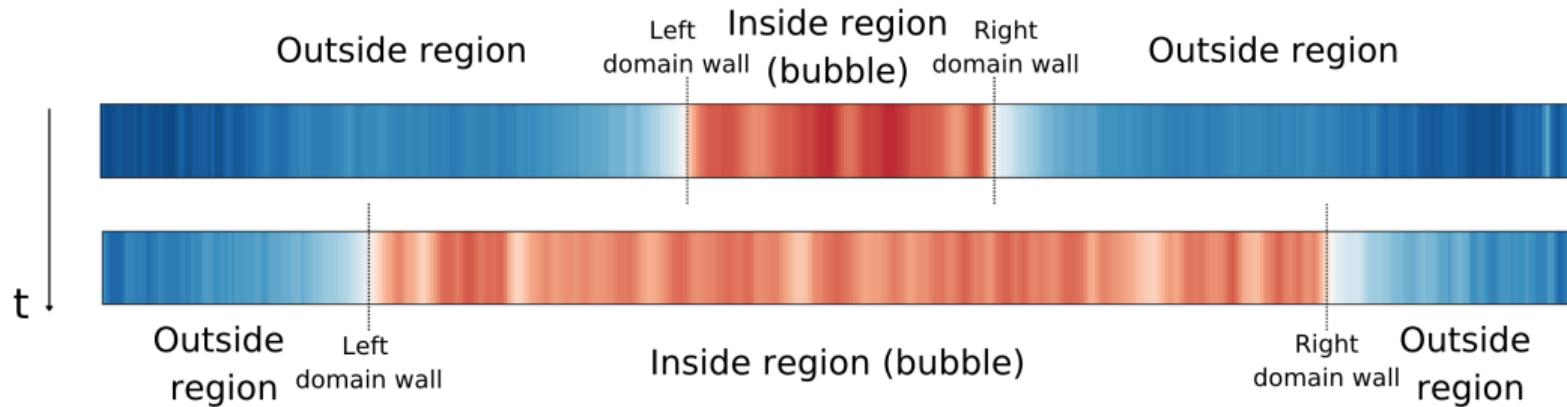
- ▶ Set $\frac{|\delta g|n}{\hbar\Omega_R}$ to a fixed value by adjusting Ω_R
- ▶ Probe the magnetic properties by changing δ_{eff}

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

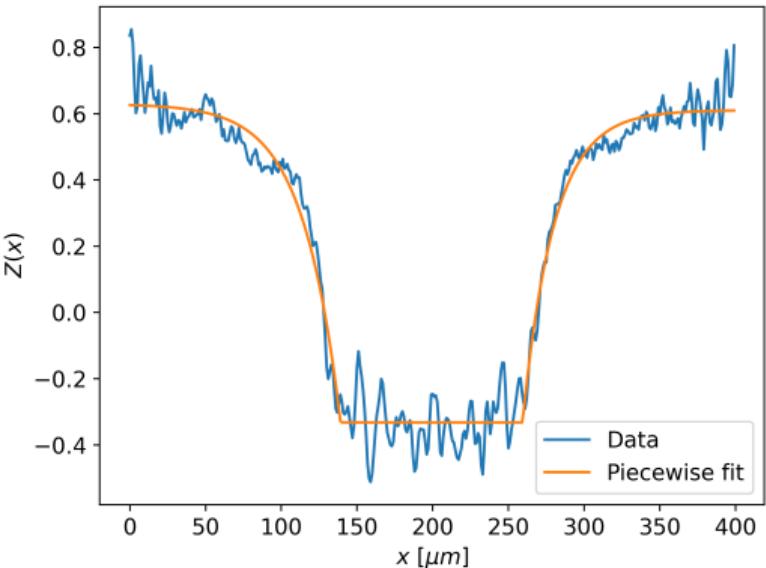
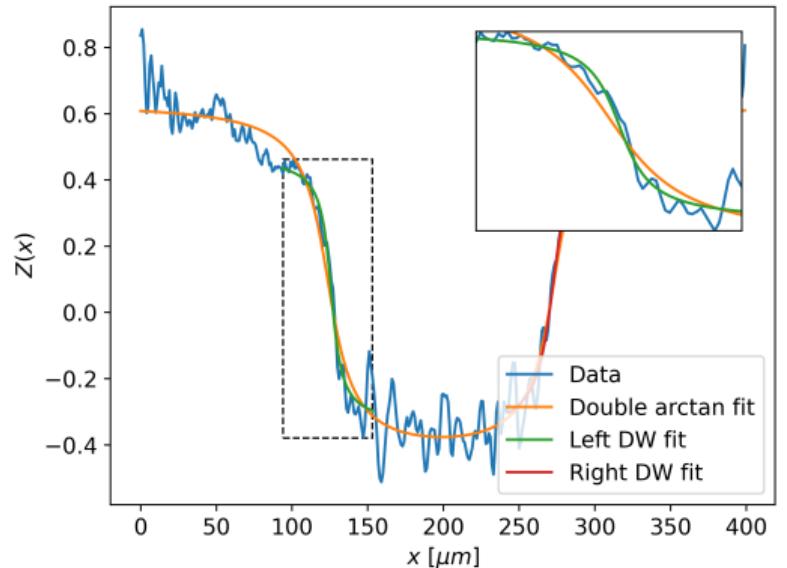


Our aim is to study:

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

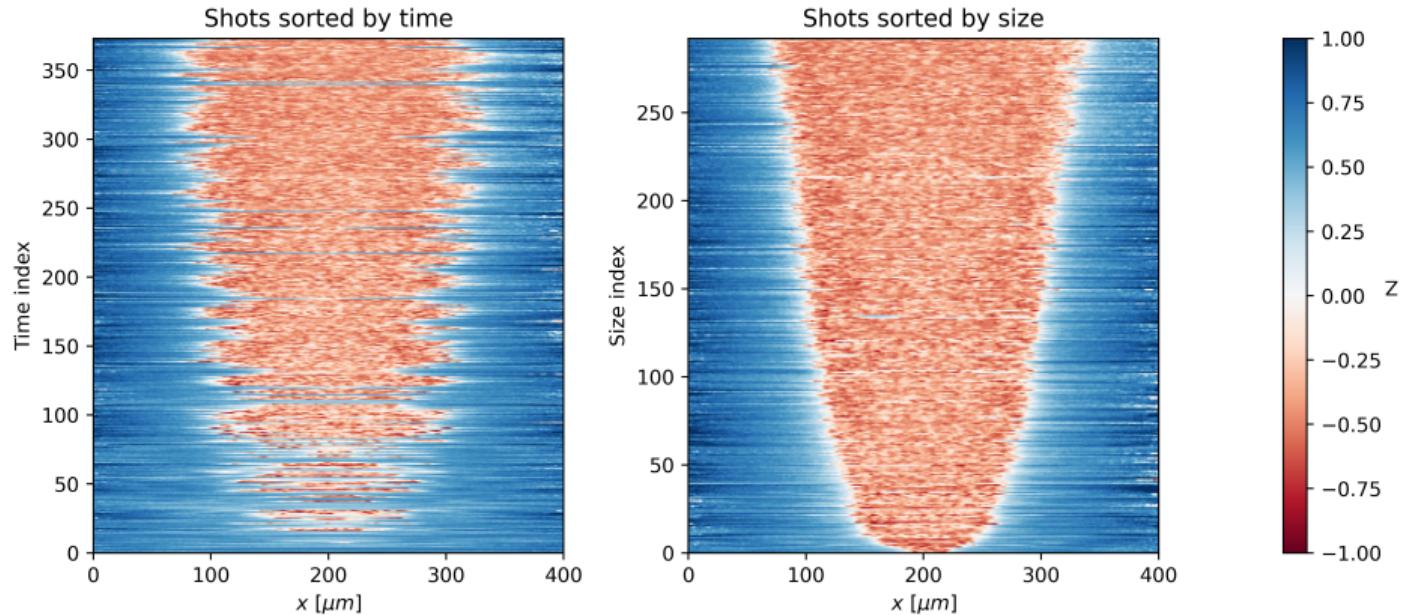
Bubble fitting routines

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

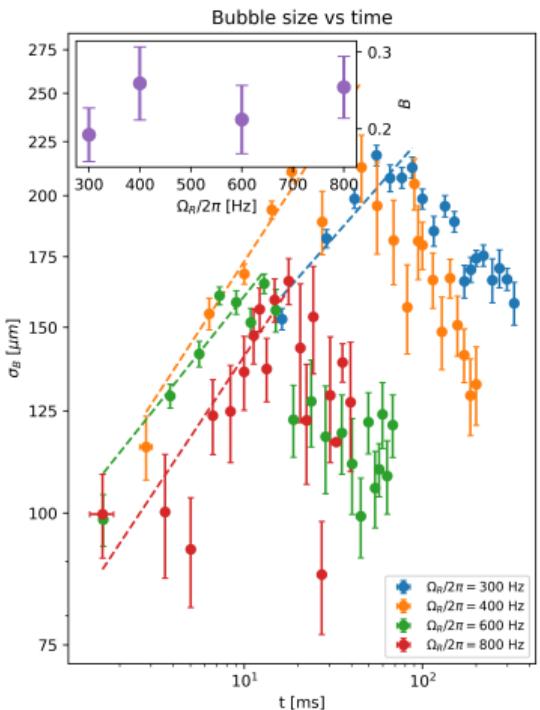
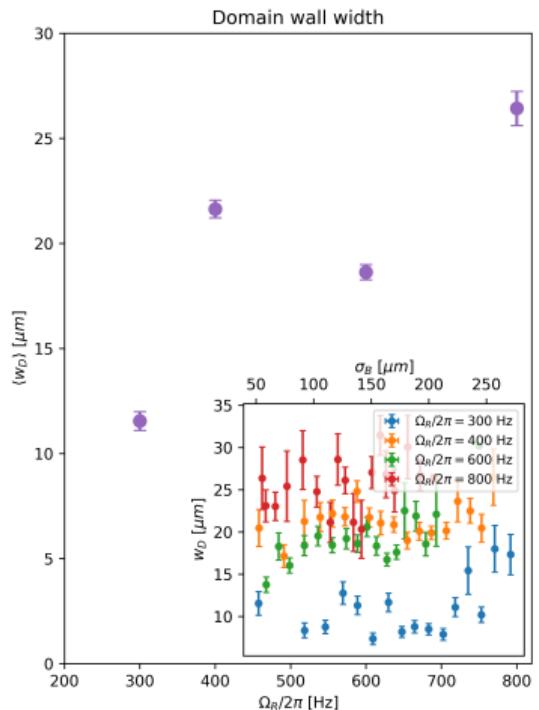


Shot sorting

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



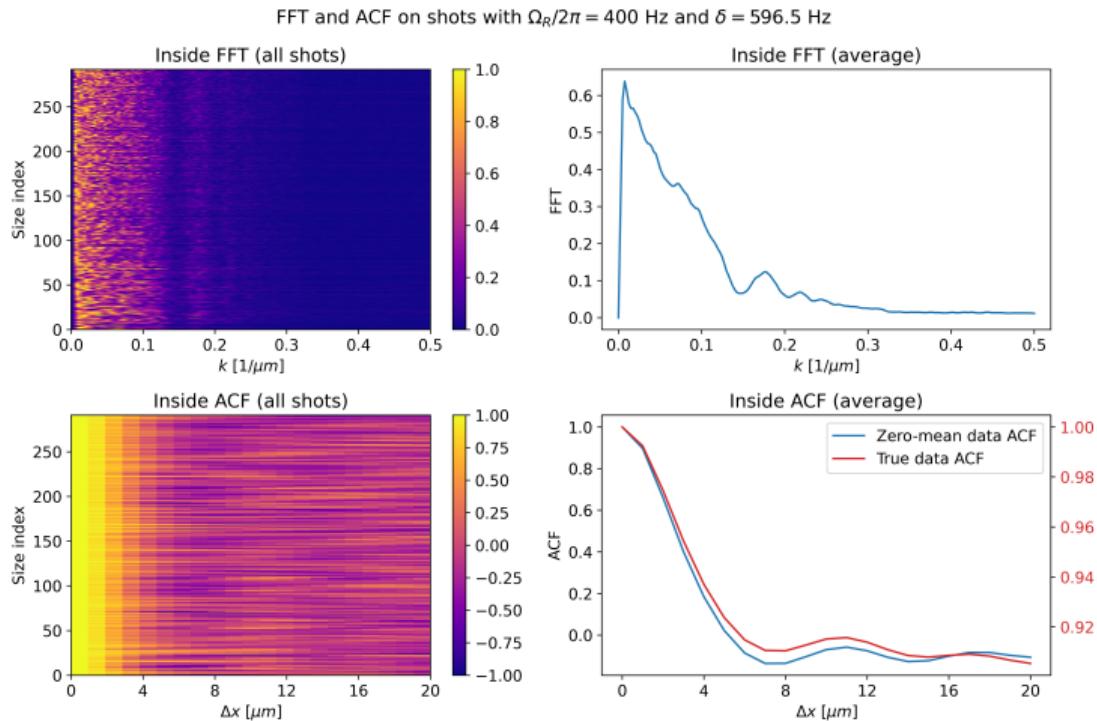
Analysis of domain wall width and bubble size



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

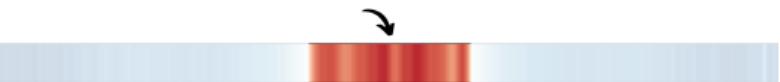
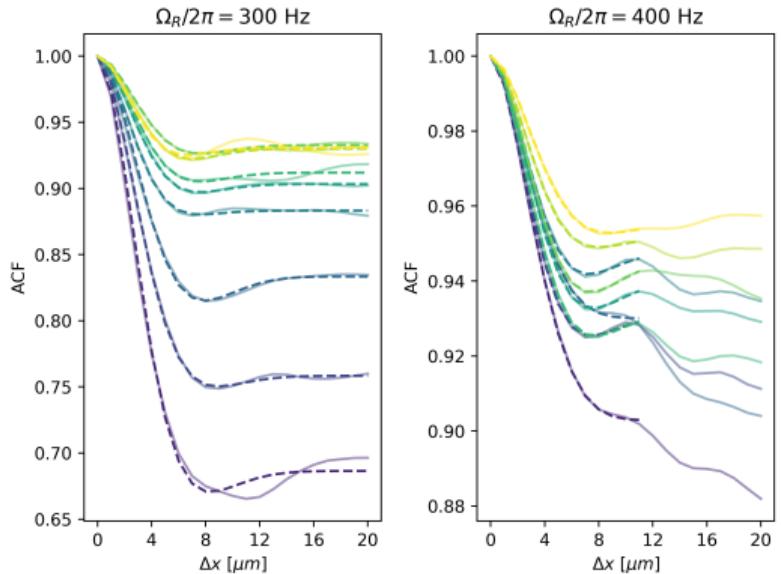
$$\sigma_B(t) = A \left(\frac{t}{1 \text{ ms}} \right)^B$$

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 (fits)

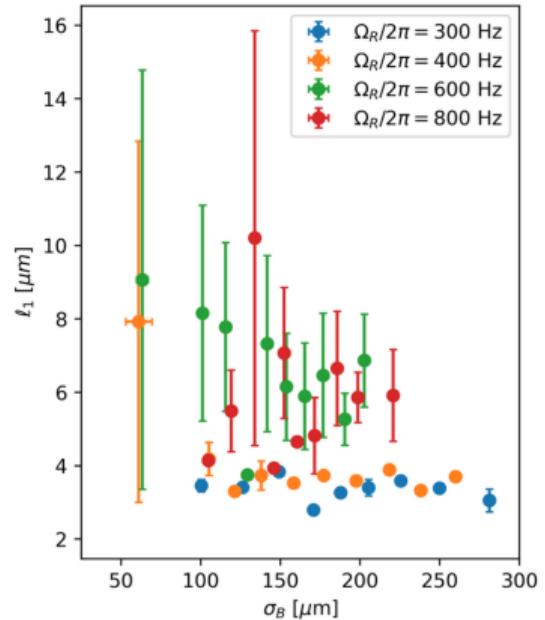


- ▶ Shots clustered by increasing size (darker to lighter colors)
- ▶ Fit function $\mathcal{A}_{\text{fit}}(x) =$

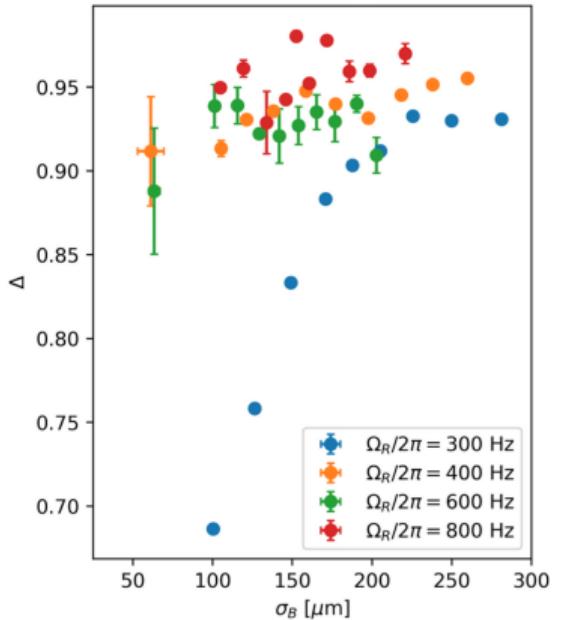
$$(1-\Delta) \cos\left(\frac{\pi x}{\ell_2}\right) \exp\left[-\frac{1}{2} \left(\frac{x}{\ell_1}\right)^{1.7}\right] + \Delta$$

ACF analysis in the inside region vs σ_B (parameters)

Fit parameter l_1 vs size



Fit parameter Δ vs size



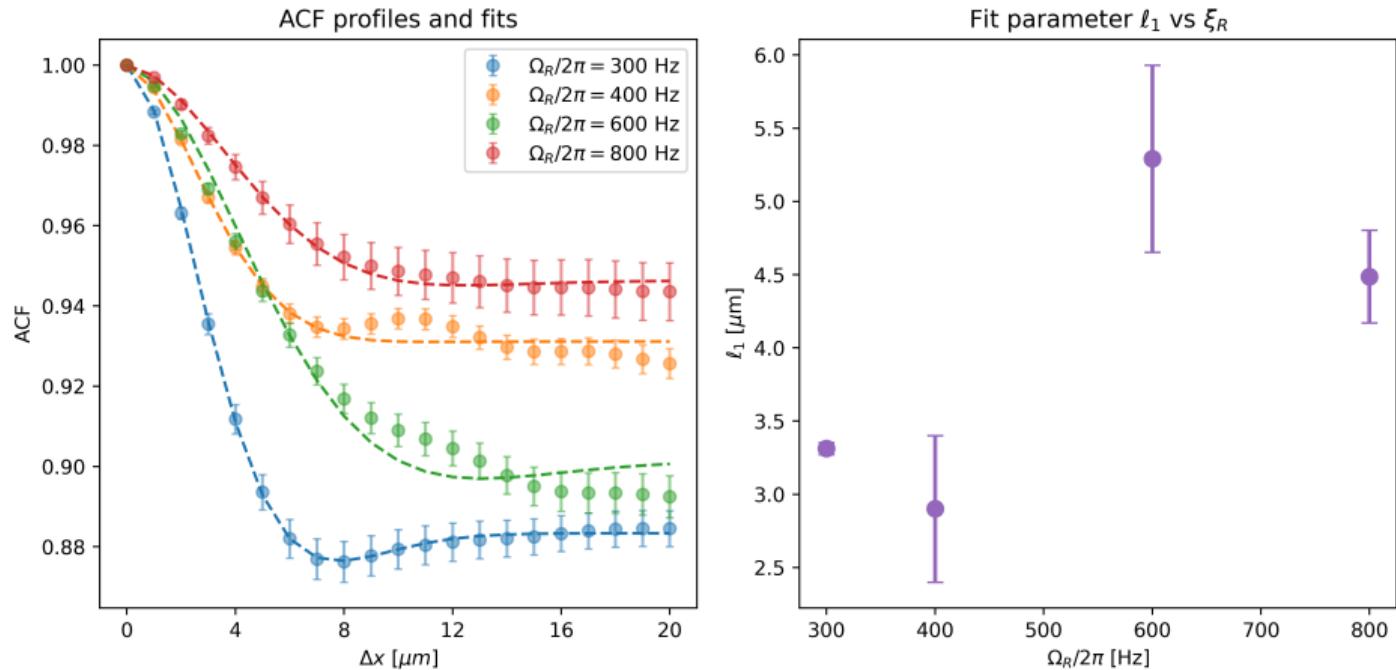
Healing lengths:

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

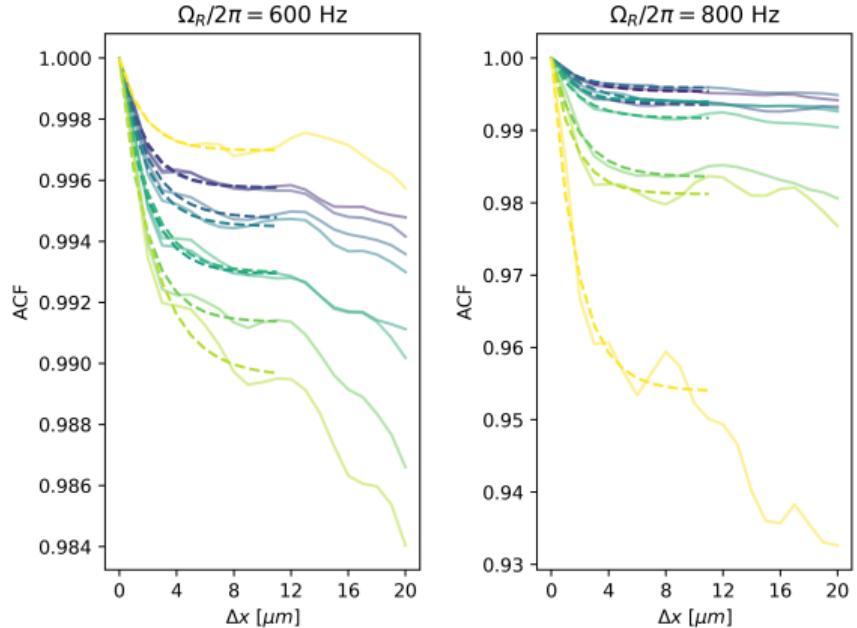
$$\xi_d = \frac{\hbar}{\sqrt{2mng}} \approx 0.01 \text{ } \mu\text{m}$$

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

ACF analysis in the inside region vs Ω_R (fit and parameters)



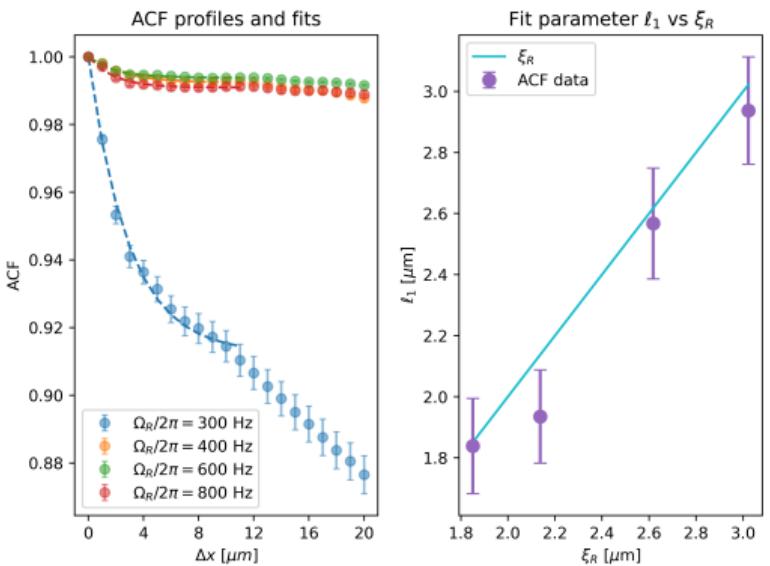
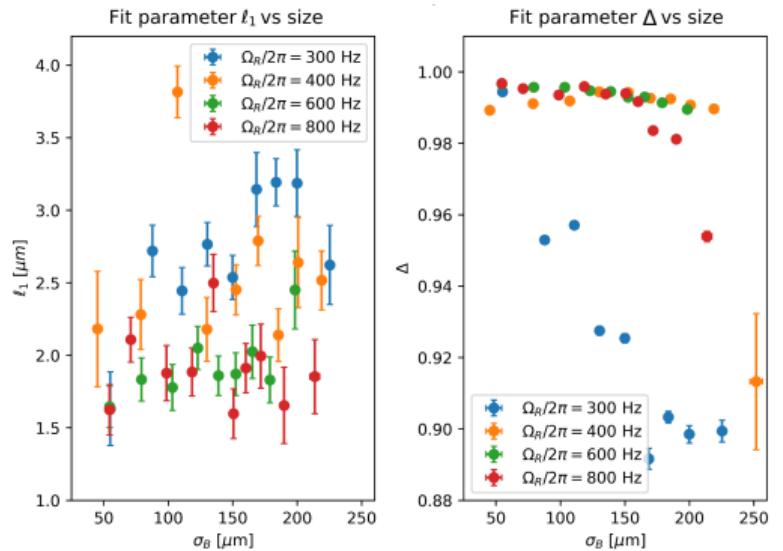
ACF analysis in the outside region vs σ_B (fits)



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

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

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!