

# Bubbles in a ferromagnetic superfluid

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UNIVERSITÀ  
DI TRENTO

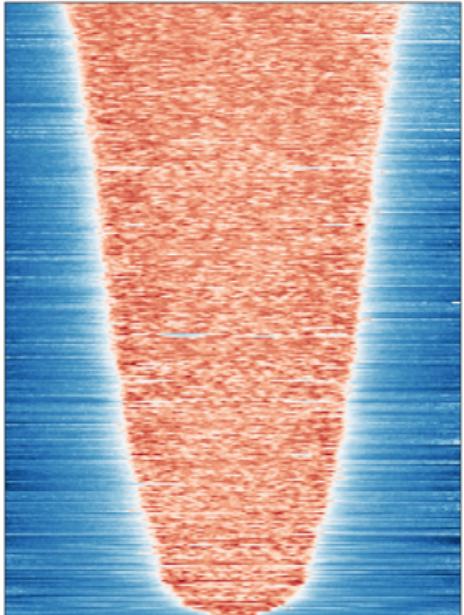


# Overview

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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

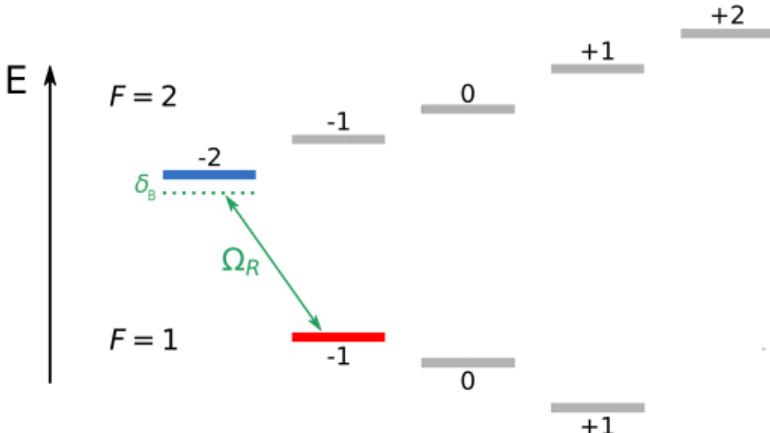
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Why **bubbles** in a ferromagnetic superfluid?

- ▶ 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: energy landscape
- ▶ FVD provides information on **metastability** and is studied from quantum systems to cosmology

# Experimental platform

- ▶  $^{23}\text{Na}$  atoms in the hyperfine states  
 $|F, m_F\rangle = |2, -2\rangle = |\uparrow\rangle$  and  
 $|F, m_F\rangle = |1, -1\rangle = |\downarrow\rangle$
- ▶ Contact interaction constants  $g_{\uparrow\uparrow}$ ,  $g_{\downarrow\downarrow}$ ,  $g_{\uparrow\downarrow}$
- ▶ Rabi coupling strength  $\Omega_R$  and detuning  $\delta_B$
- ▶ Harmonic trapping potential (cigar-shaped)
- ▶ Cooled below the condensation temperature



# Coherently coupled two-component spin mixtures

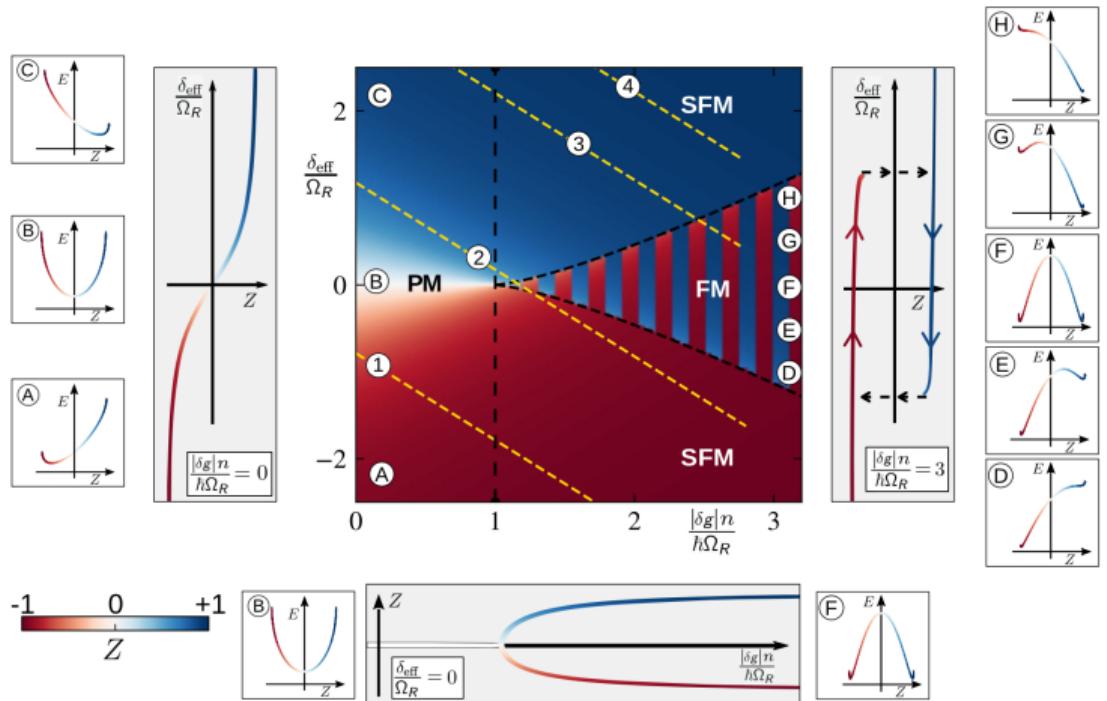
The GPEs contain the intra and inter-species interaction constants and the coupling between the states:

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

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

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

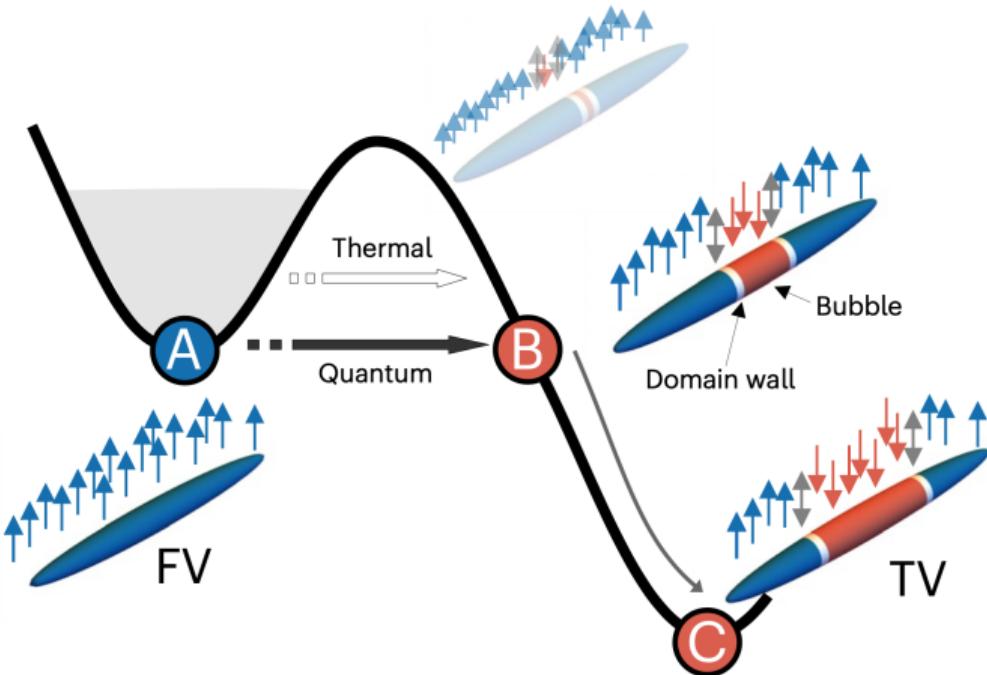
# Magnetic model phase diagram: para and ferro



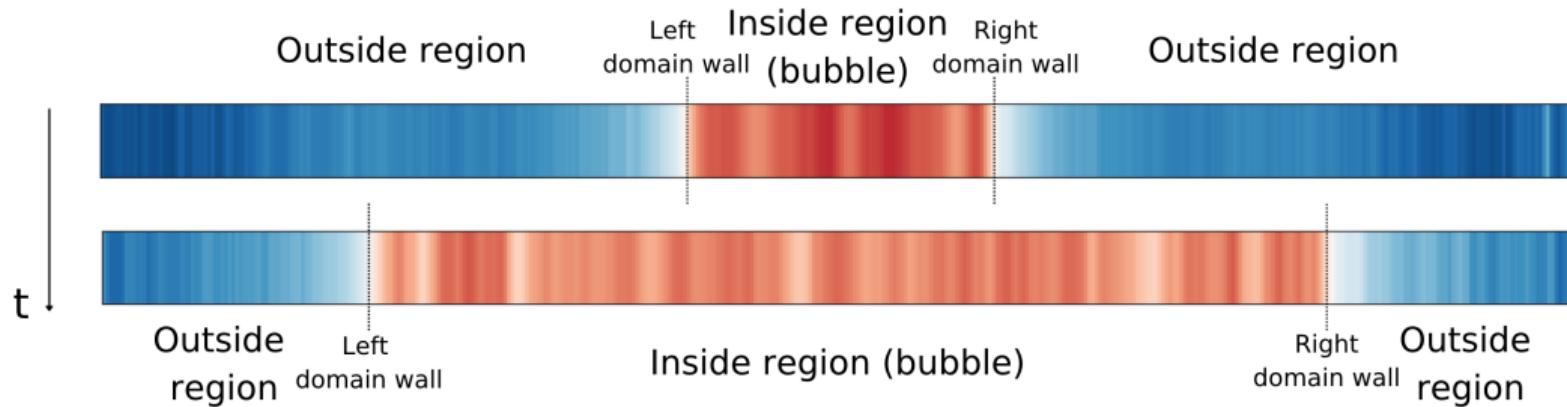
- ▶ Set  $\frac{|\delta g|n}{\hbar\Omega_R}$  to a fixed value by adjusting  $\Omega_R$
- ▶ Probe the magnetic properties by changing  $\delta_{\text{eff}}$

# 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

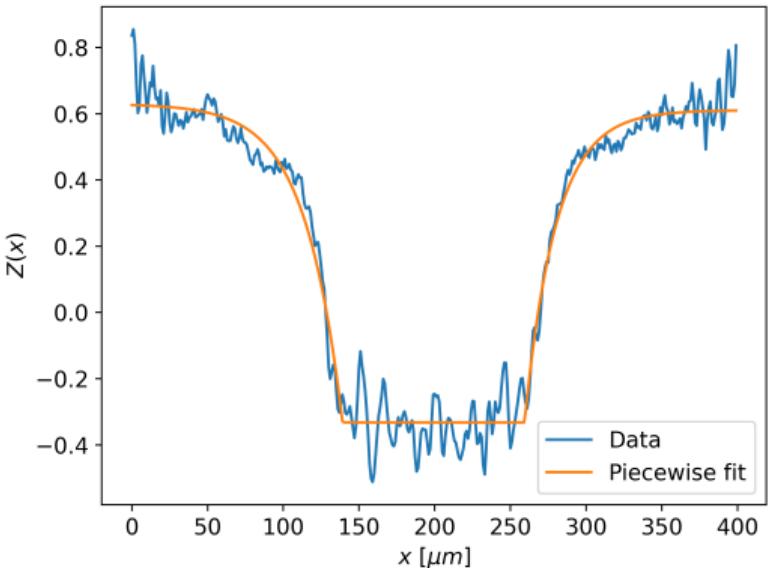
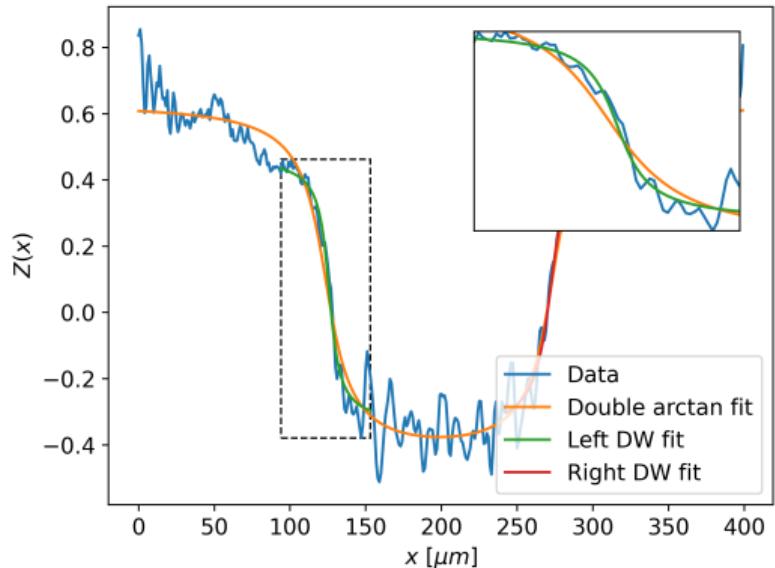


Our aim is to study:

- ▶ Size  $\sigma_B$  and domain wall width  $w_D$
- ▶ Spectrum inside/outside

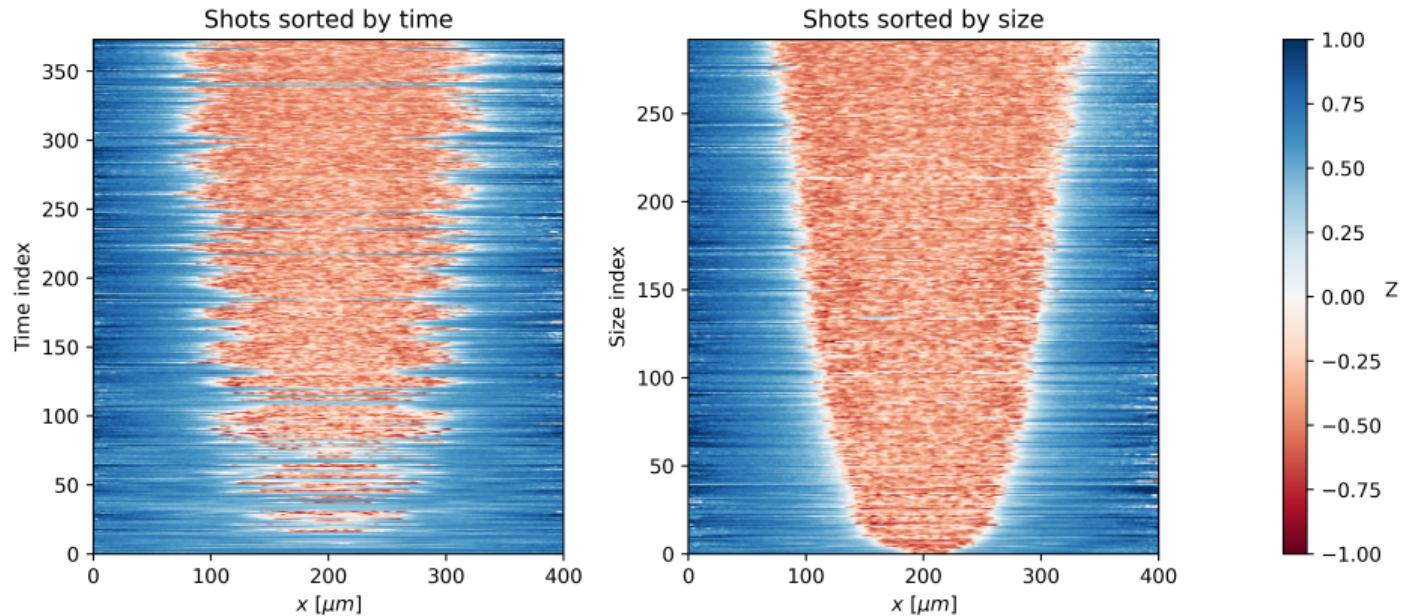
# Bubble fitting routines

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

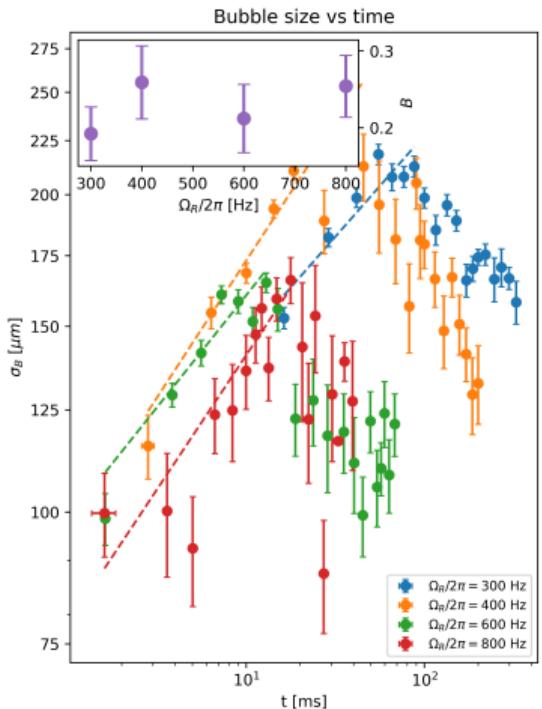
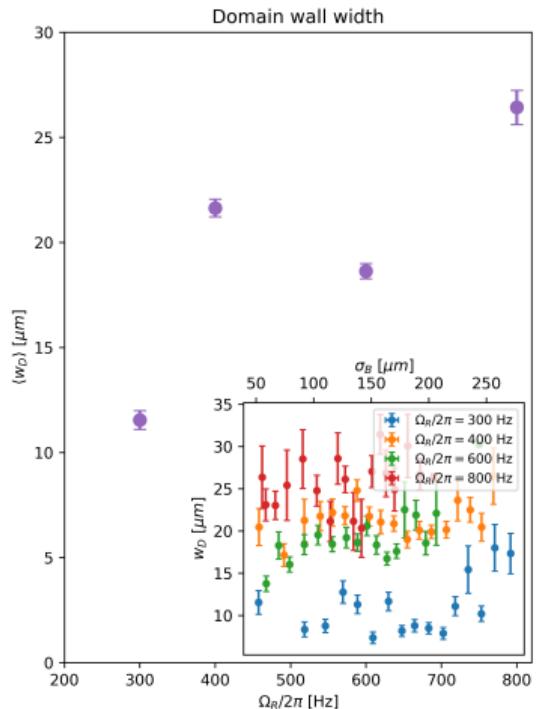


# Shot sorting

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



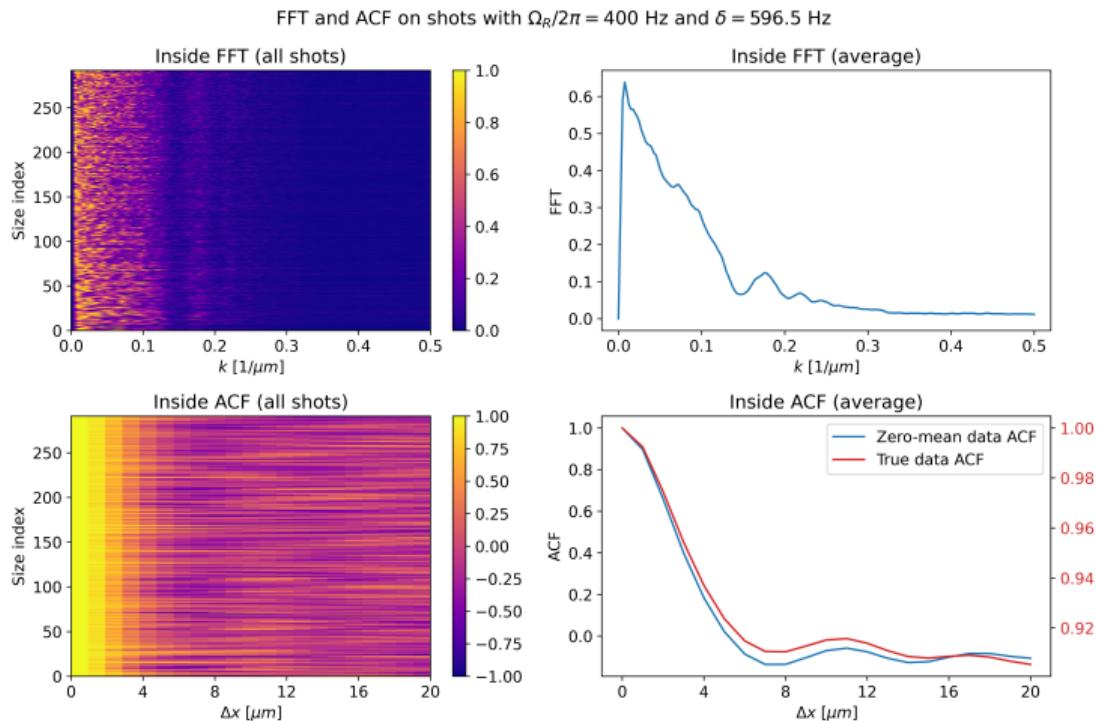
# Analysis of size and domain wall width



Fit function:

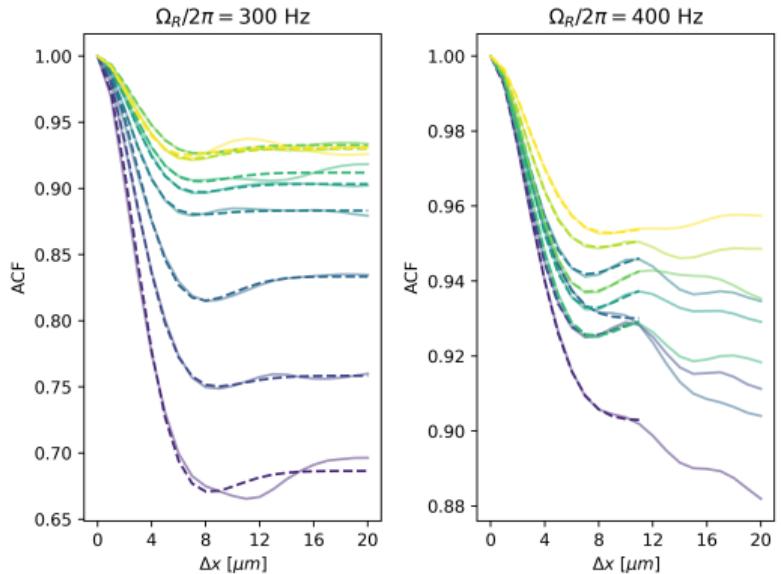
$$\sigma_B(t) = A \left( \frac{t}{1 \text{ ms}} \right)^B$$

# 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 (fits)

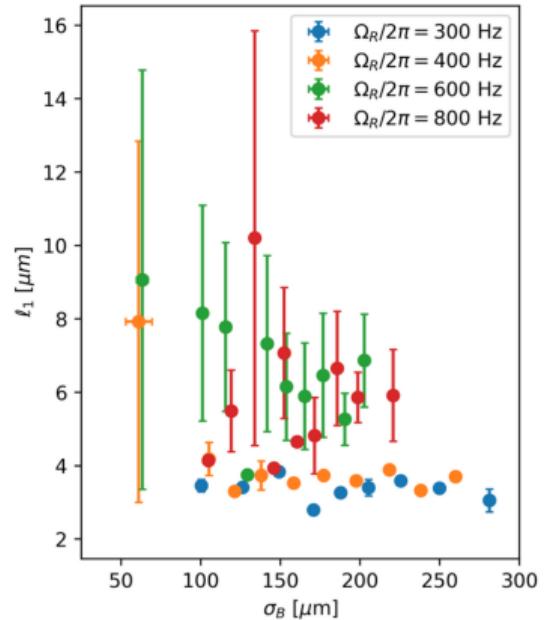


- ▶ Shots clustered by increasing size (darker to lighter colors)
- ▶ Fit function  $\mathcal{A}_{\text{fit}}(x) =$

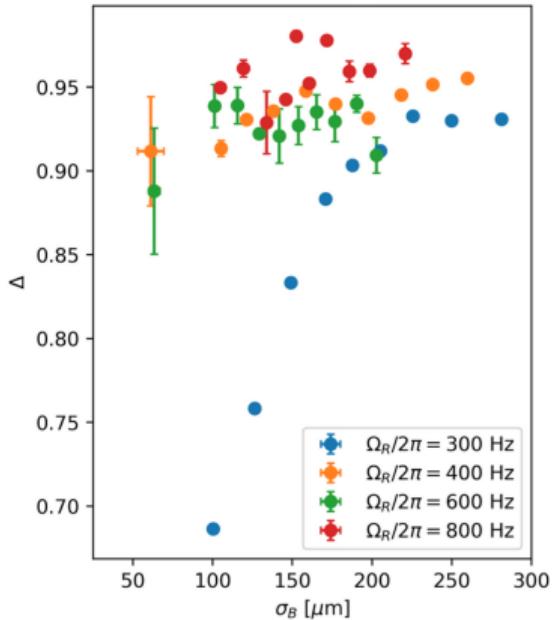
$$(1 - \Delta) \cos\left(\frac{\pi x}{\ell_2}\right) \exp\left[-\frac{1}{2} \left(\frac{x}{\ell_1}\right)^{1.7}\right] + \Delta$$

# ACF analysis in the inside region (parameters)

Fit parameter  $\ell_1$  vs size



Fit parameter  $\Delta$  vs size



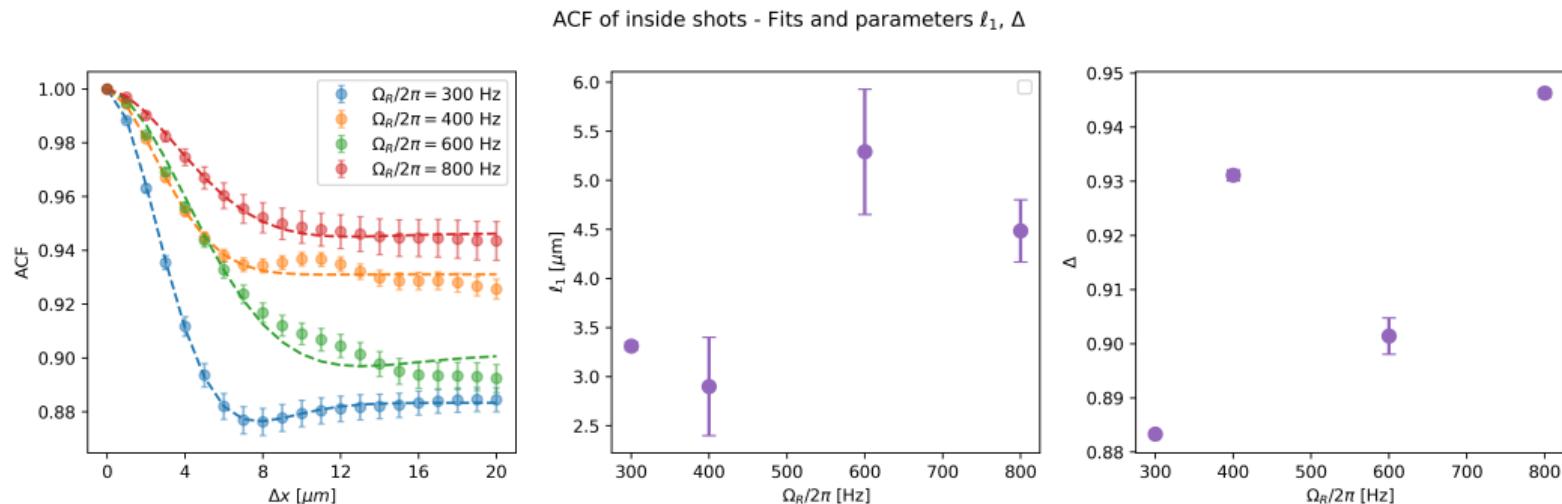
Healing lengths:

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

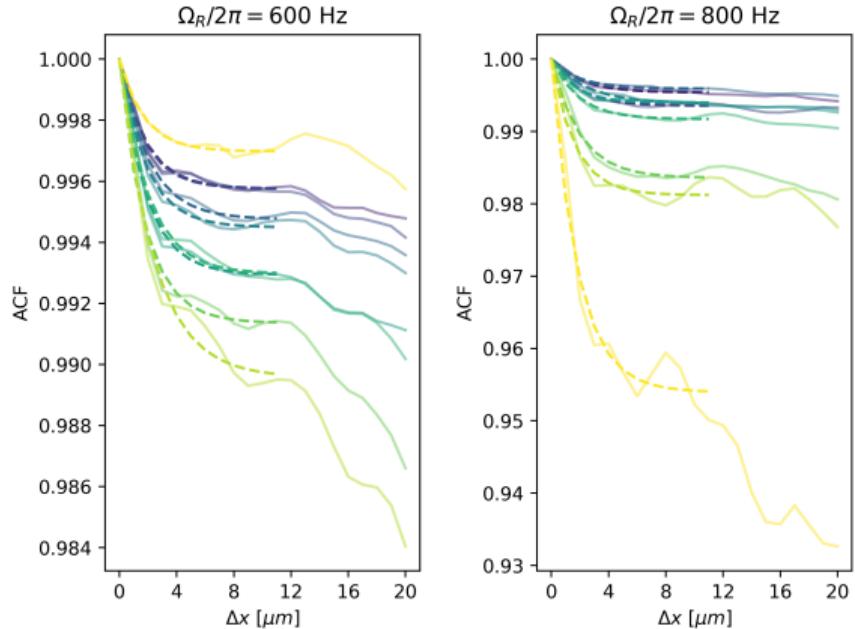
$$\xi_d = \frac{\hbar}{\sqrt{2mng}} \approx 0.01 \text{ } \mu\text{m}$$

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

# ACF analysis in the inside region (parameters)



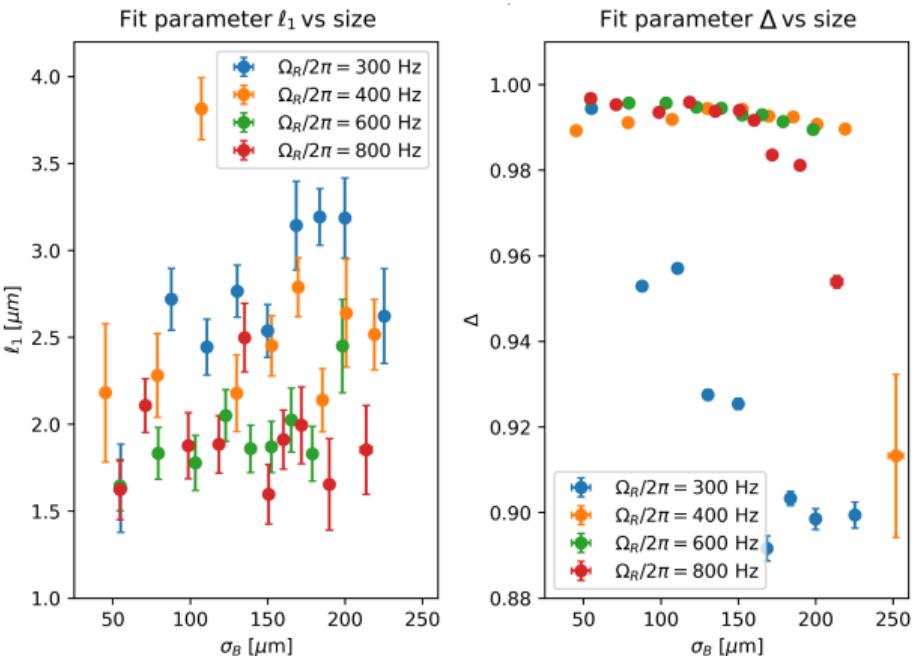
# ACF analysis in the outside region (fits)



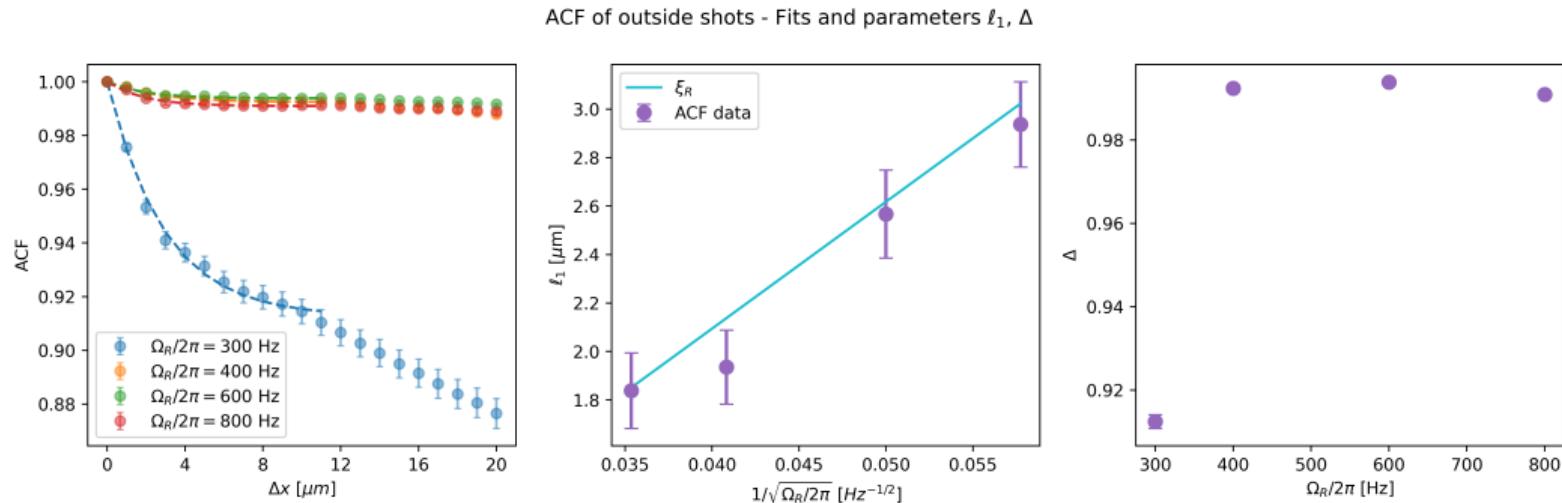
- ▶ Shots clustered by increasing size (darker to lighter colors)
- ▶ Fit function:

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

# ACF analysis in the outside region (parameters)



# ACF analysis in the outside region (parameters)



# Conclusions

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What did we learn?

- ▶ System shows **different properties** between inside and outside of the bubble
- ▶ Domain wall width **depends on the coupling strength**  $\Omega_R$
- ▶ Growth factor of the bubble size in time is **independent** of  $\Omega_R$
- ▶ 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!