



UNIVERSITÀ  
DI TRENTO

## Bubbles in a ferromagnetic superfluid

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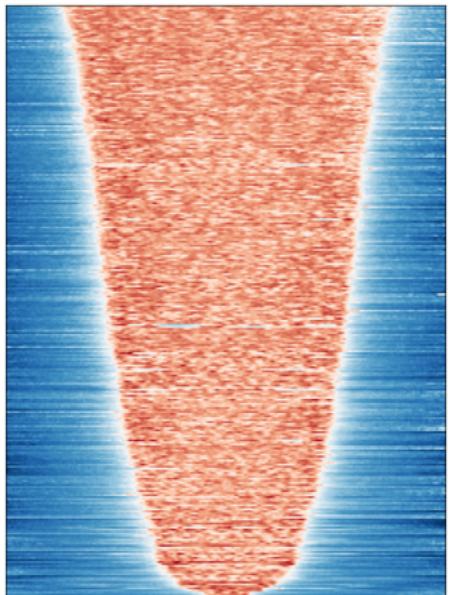
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**Supervisor:** dr. Alessandro Zenesini

Bachelor's Degree in Physics

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- **Introduction**
- **Theoretical background:**  
Ferromagnetism in coherently coupled BEC spin-mixtures
- **Data analysis:** Characterization of false vacuum decay bubbles
- **Conclusions**





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

Bubbles originate in

# Theoretical background: Ideal Bose gas



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

$$\langle n_i \rangle = \frac{1}{e^{\beta(\epsilon_i - \mu)} - 1}$$

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  $\alpha = 3$ .



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

$$i\hbar \frac{\partial \psi(x, t)}{\partial t} = \left[ -\frac{\hbar^2}{2m} \nabla^2 + V(x, t) + g|\psi(x, t)|^2 \right] \psi(x, t)$$

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

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



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

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

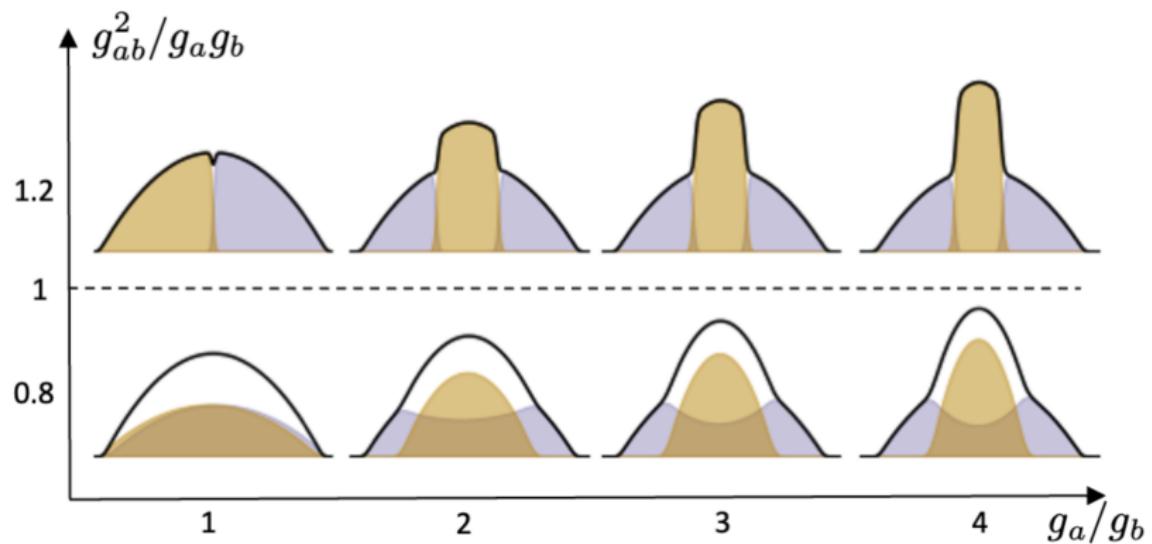
$$\left[ -\frac{\hbar^2}{2m} \nabla^2 + V(x) + g_{ab}|\psi_a(x)|^2 + g_{bb}|\psi_b(x)|^2 \right] \psi_b(x) = \mu_b \psi_b(x)$$

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

# Theoretical background: Two-component mixtures



The mixture can be miscible or immiscible: buoyancy effect



# Theoretical background: Coherent coupling



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

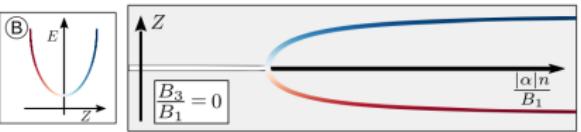
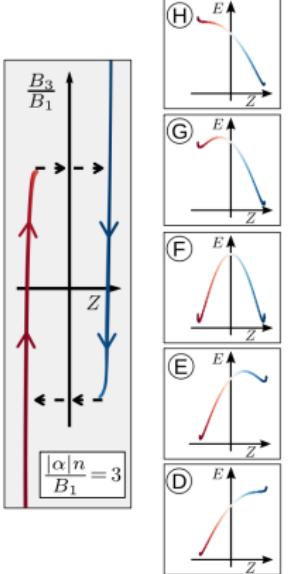
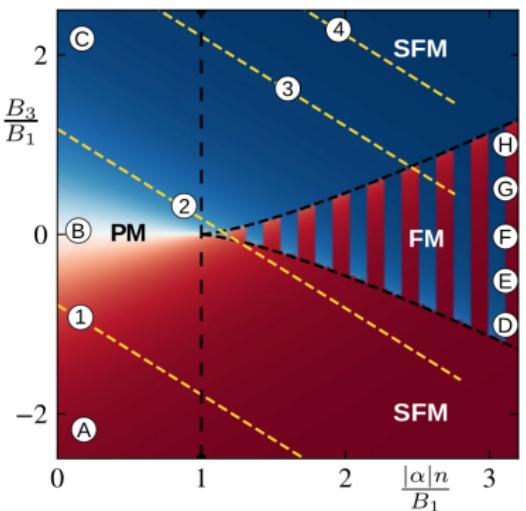
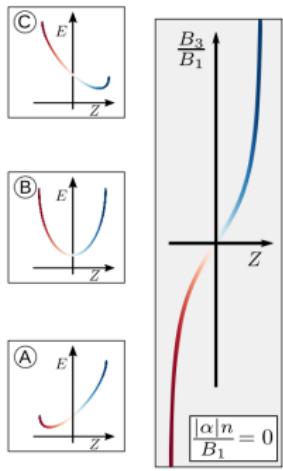
$$\Omega_R(t) \exp\{-i\omega_{\text{cpl}}t + \phi\} \quad \omega_{\text{cpl}} = \omega_{ab} + \delta_B$$

Double-well energy landscape

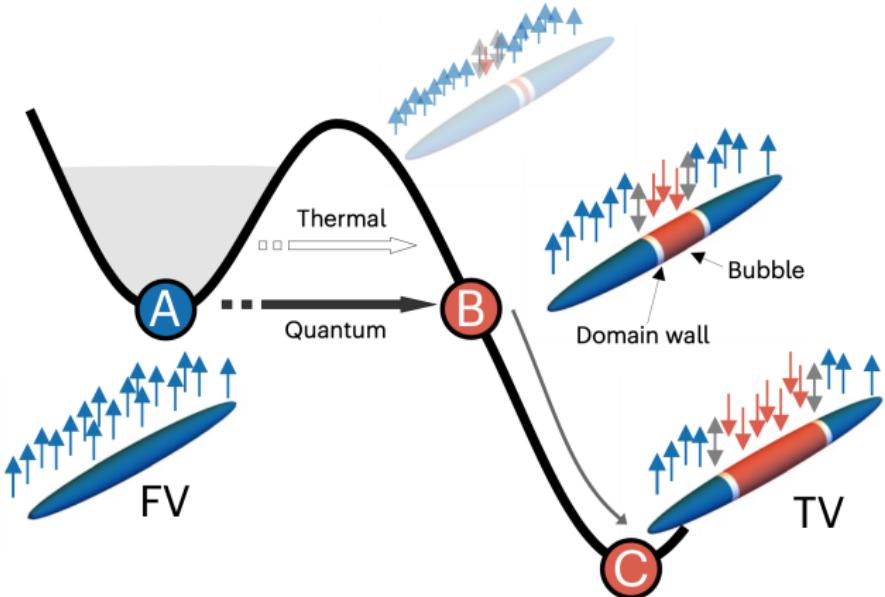
$$E_{\text{MF}}(Z) = -\hbar \left( |\delta g| n Z^2 + 2\Omega_R \sqrt{1 - Z^2} + 2\delta_{\text{eff}} Z \right)$$

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

# Theoretical background: Ferromagnetism



# Theoretical background: False Vacuum Decay



# Data analysis: Experimental platform



The experiment uses  $^{23}\text{Na}$  atoms prepared in the state  $|F, m_F\rangle = |2, -2\rangle = |\uparrow\rangle$ , which is coupled to the state  $|1, -1\rangle = |\downarrow\rangle$ .

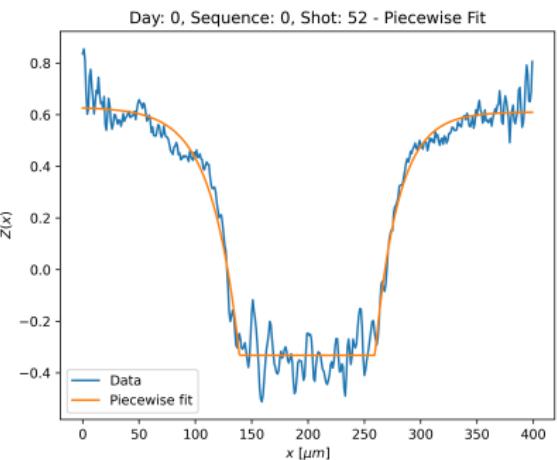
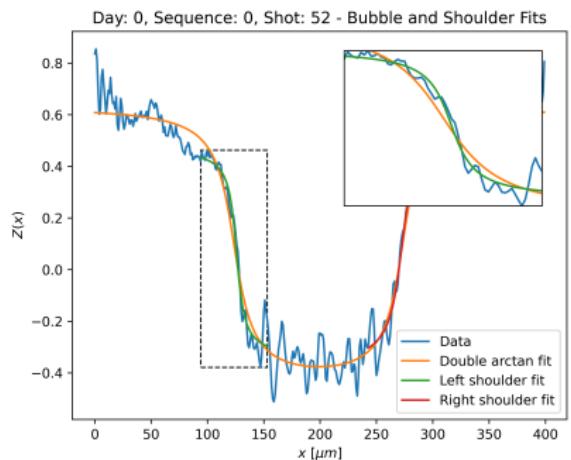
The system is cigar-shaped with Thomas-Fermi radii

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

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

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

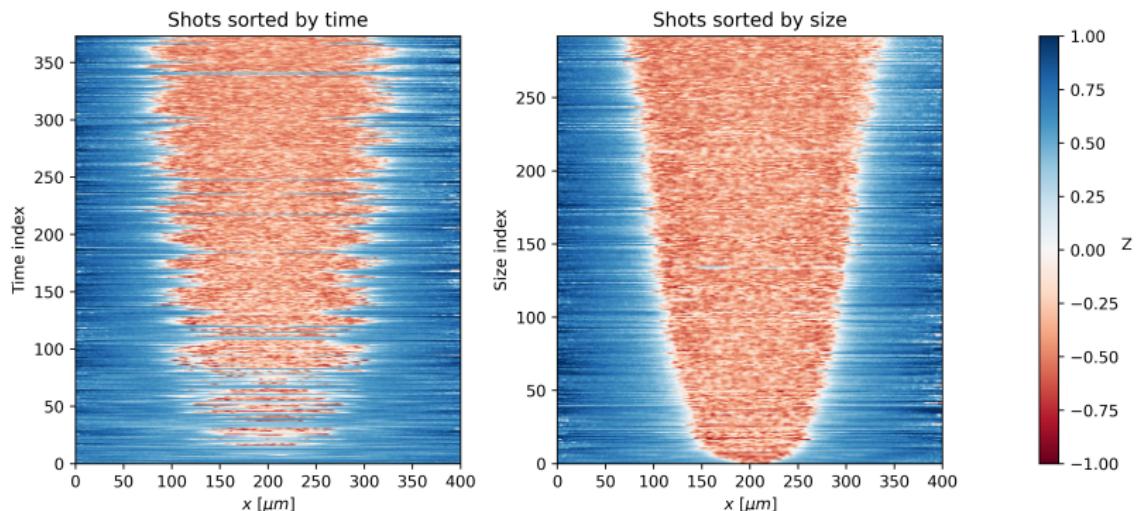
# Data analysis: Bubble fit



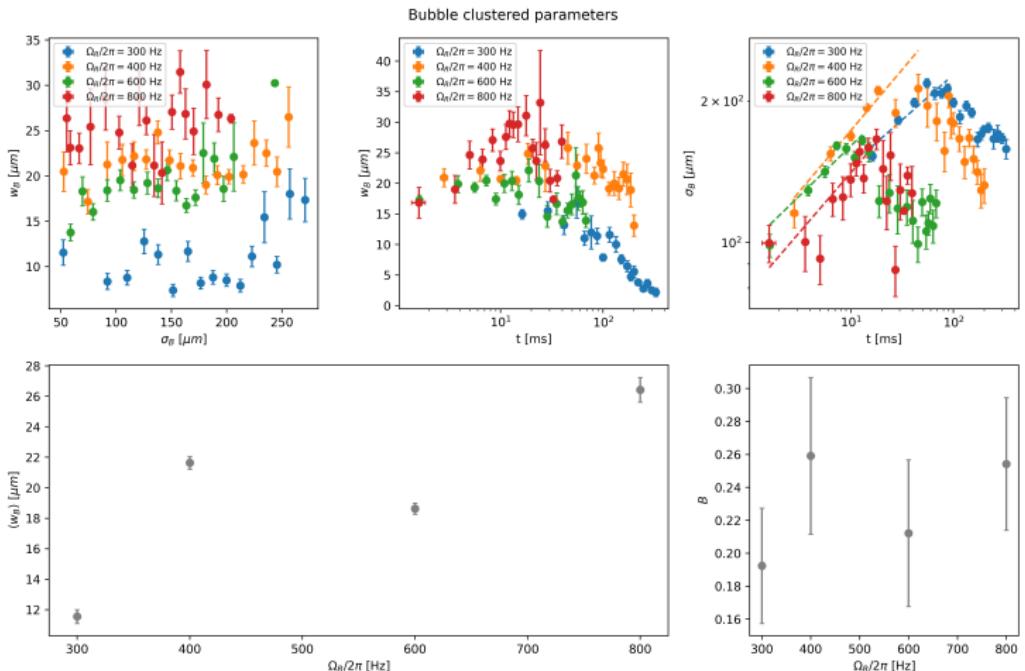
# Data analysis: Shot sorting



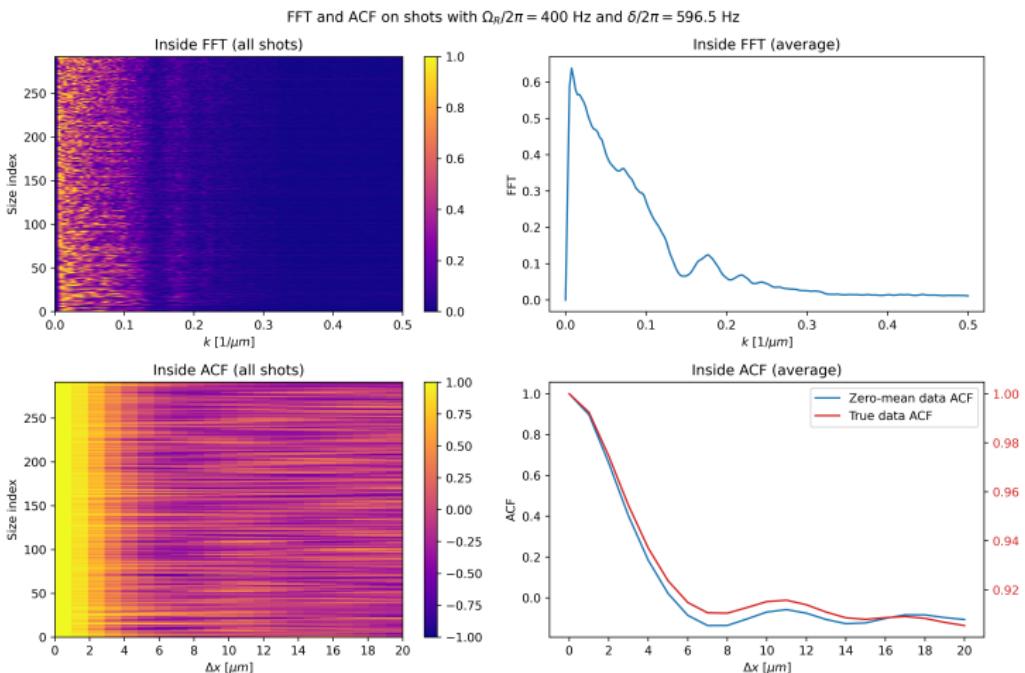
Bubble shots with  $\Omega_R/2\pi = 400$  Hz and  $\delta/2\pi = 596.5$  Hz



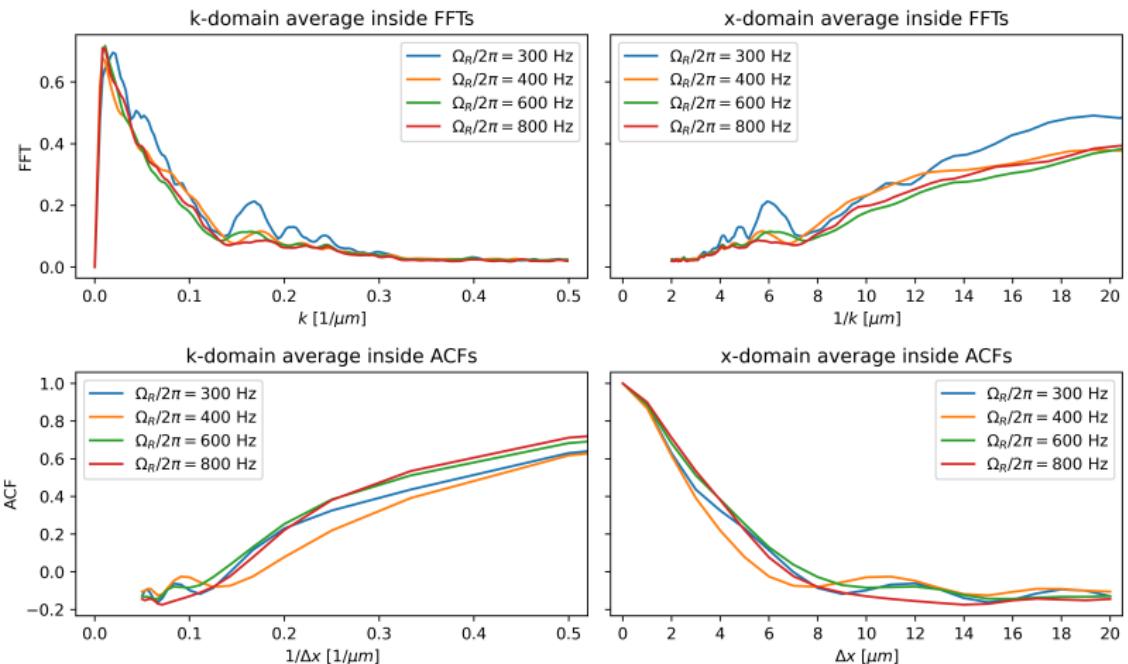
# Data analysis: Parameters clustering



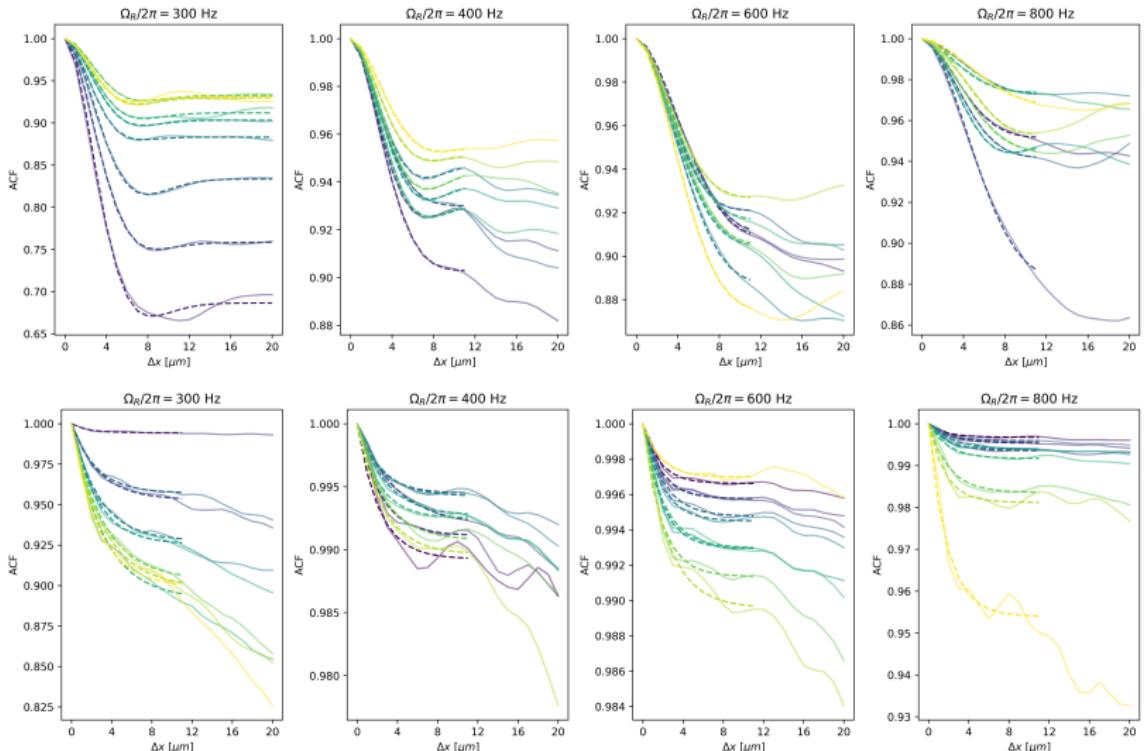
# Data analysis: FFT and ACF



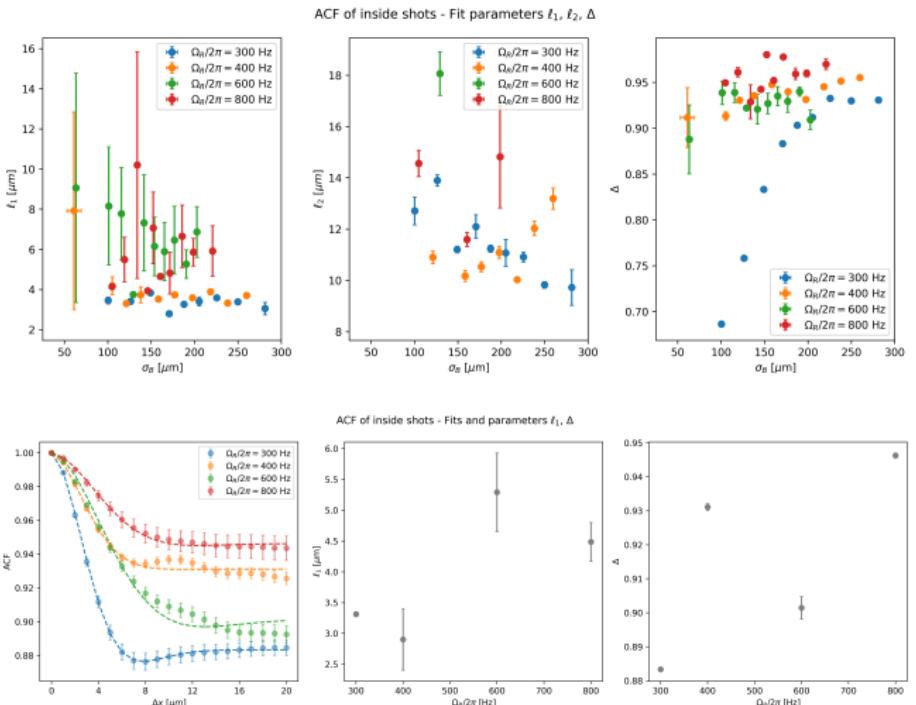
# Data analysis: FFT and ACF



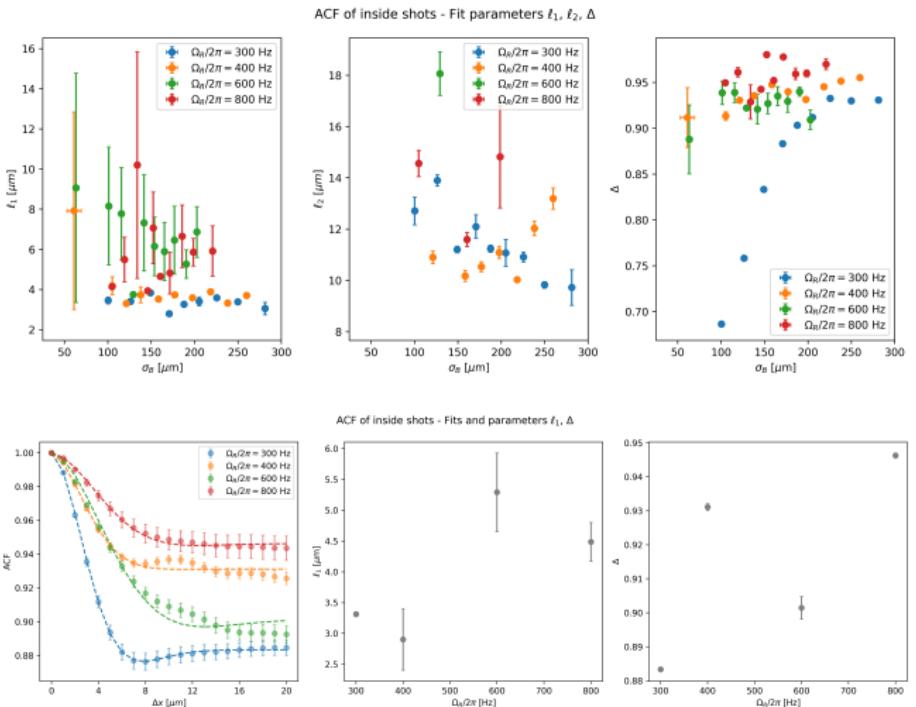
# Data analysis: ACF fits



# Data analysis: ACF inside



# Data analysis: ACF outside



# Conclusions





Thank you for your attention

