Ultracold atoms for quantum simulations

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BOSE EINSTEIN CONDENSATION

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

UNIVERSITÀ DI TRENTO

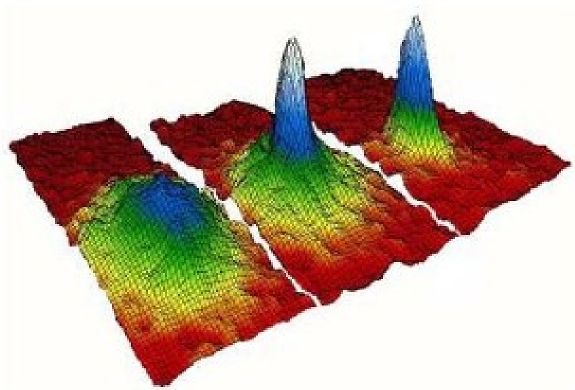
BEC1 running since 2012, topics covered:

- **Kibble-Zurek physics**
- dynamics and interactions of **quantized vortices**
- relaxation dynamics in temperature-quenched Bose gases
- equation of state of weakly interacting Bose gases

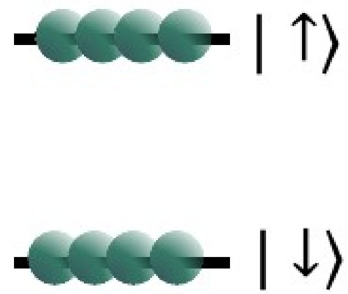
BEC2 running since 2018, topics covered:

- **coherently-coupled BECs**
- magnetism in superfluid media
- engineering of novel phases of matter
- **quantum simulation** of quantum field models
- study of the properties of **quantum vacuum**

the experimental platform

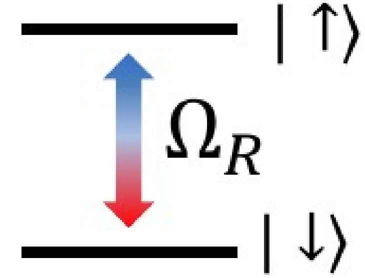


Bose-Einstein
Condensate



Spin
Mixture

+



Coherent
Coupling

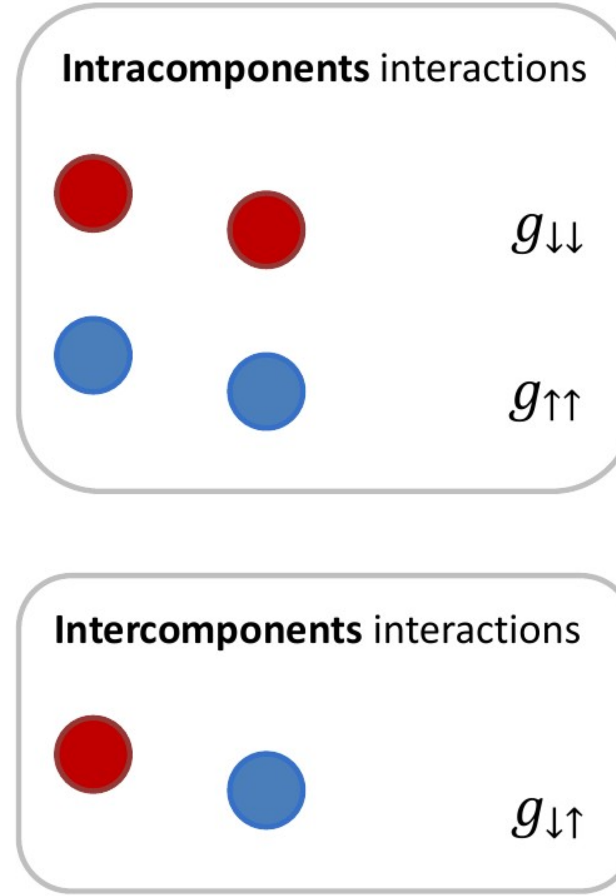
from one component to spin mixtures

- U(1)xU(1) symmetry

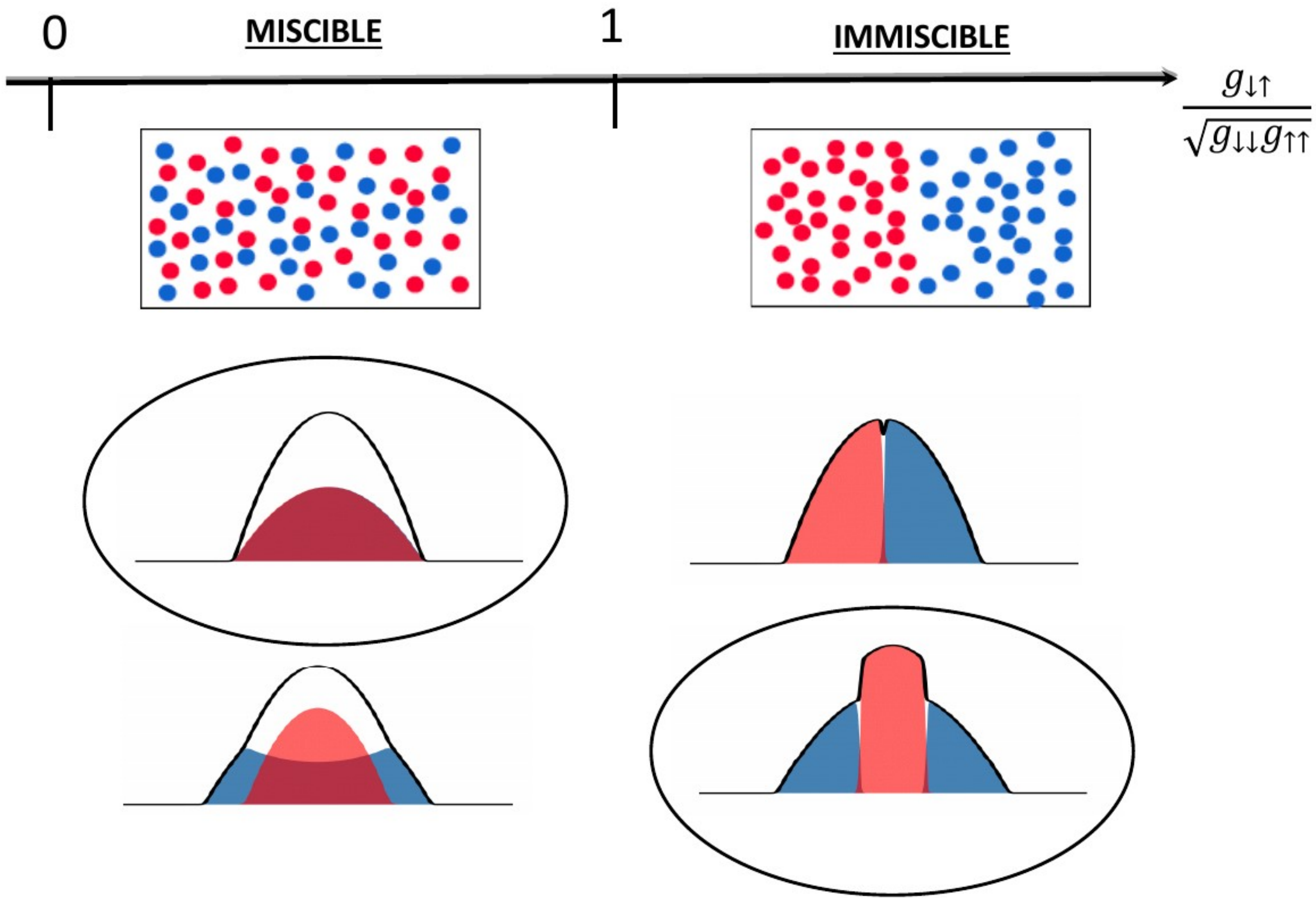
- Three interaction parameters $g_{ij} = \frac{4\pi\hbar^2 a_{ij}}{m}$

$$i\hbar\partial_t\psi_\downarrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\downarrow\downarrow}|\psi_\downarrow|^2 + g_{\downarrow\uparrow}|\psi_\uparrow|^2\right]\psi_\downarrow$$

$$i\hbar\partial_t\psi_\uparrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\uparrow\uparrow}|\psi_\uparrow|^2 + g_{\downarrow\uparrow}|\psi_\downarrow|^2\right]\psi_\uparrow$$



from one component to spin mixtures



$g_{\downarrow\downarrow} = g_{\uparrow\uparrow} = g$

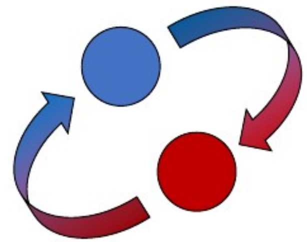
Buoyancy condition
for $g_{\downarrow\downarrow} \neq g_{\uparrow\uparrow}$

… to Rabi-coupled spin mixtures

- U(1) symmetry

$$i\hbar\partial_t\psi_\downarrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\downarrow\downarrow}|\psi_\downarrow|^2 + g_{\downarrow\uparrow}|\psi_\uparrow|^2\right]\psi_\downarrow - \frac{\hbar\Omega_R}{2}\psi_\uparrow$$

$$i\hbar\partial_t\psi_\uparrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\uparrow\uparrow}|\psi_\uparrow|^2 + g_{\downarrow\uparrow}|\psi_\downarrow|^2\right]\psi_\uparrow - \frac{\hbar\Omega_R}{2}\psi_\downarrow$$



N_1 and N_2 not independently conserved

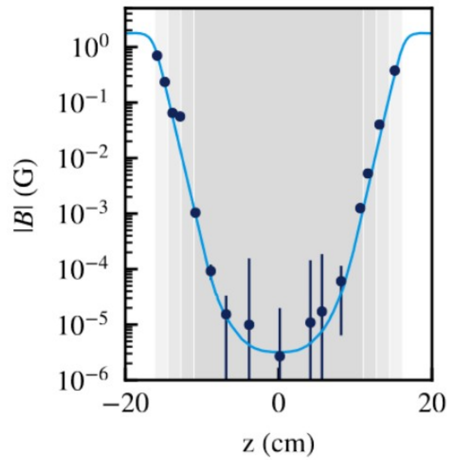
$$\delta g = \frac{g_{\downarrow\downarrow} + g_{\uparrow\uparrow}}{2} - g_{\uparrow\downarrow}$$

Set the relevant energy scale

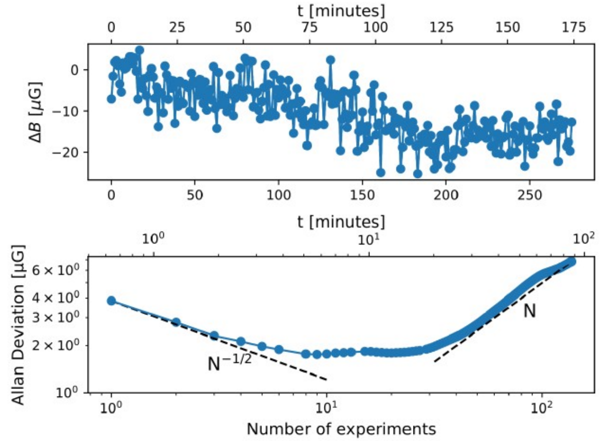
Energy scale	$\mu_B\delta B$	$\ll \hbar\Omega_R$	$< \|\delta g\|\, n$
Temperature			$15 \div 60$ nK
Frequency	10 Hz	$100 \div 600$ Hz	$300 \div 1200$ Hz
Magnetic field	5 μG	$50 \div 100$ μG	

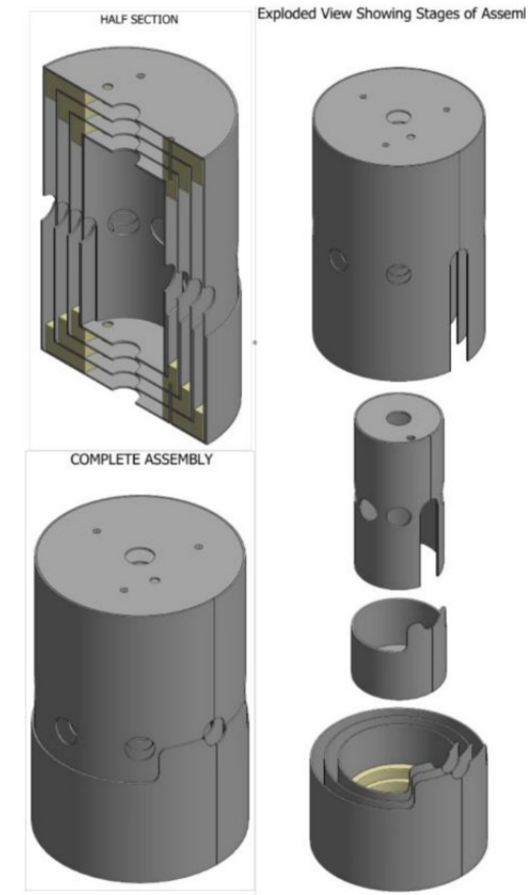
… in a magnetically shielded environment

Fluctuation attenuation: 10^5



B field stability: a few μG over an hour





Energy scale	$\mu_B \delta B$	$\ll \hbar\Omega_R$	$< \lvert\delta g\rvert\, n$
Temperature			15 ÷ 60 nK
Frequency	10 Hz	100 ÷ 600 Hz	300 ÷ 1200 Hz
Magnetic field	5 μG	50 ÷ 100 μG	

A. Farolfi et al., Rev. Scient. Instr. **90**, 115114 (2019)

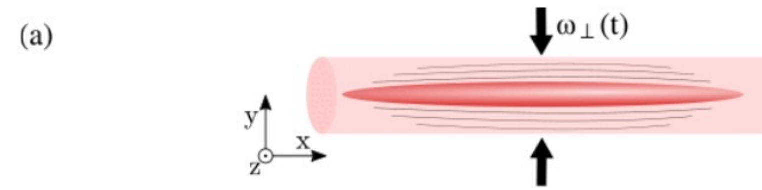
Scilight 2019, 471101 (2019)

AIP Publishing Scilight

miscible mixture, Ω=0: elementary excitations

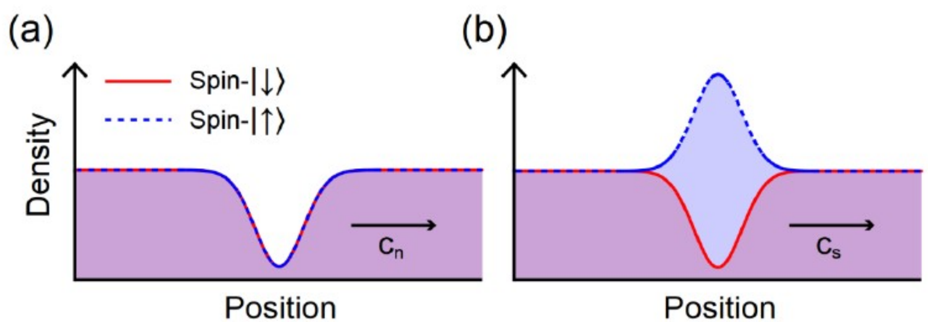
Faraday spectroscopy to measure the **dispersion relations** of the normal modes:

$$\omega_{d,s}(k) = \sqrt{\frac{\hbar k^2}{2m}\left(\frac{\hbar k^2}{2m} + \frac{2mc_{d,s}^2}{\hbar}\right)}$$



Density | Spin

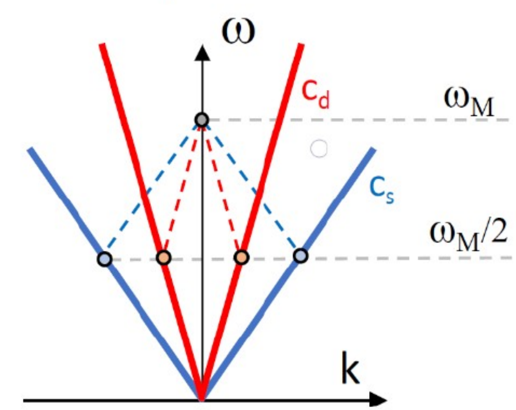
$$d(\vec{r}) = n_\uparrow(\vec{r}) + n_\downarrow(\vec{r}) \qquad s(\vec{r}) = n_\uparrow(\vec{r}) - n_\downarrow(\vec{r})$$



$$c_d = \frac{(g + g_{\downarrow\uparrow})n}{2m} \gg c_s = \frac{(g - g_{\downarrow\uparrow})n}{2m}$$

Massless density excitation

Massless spin excitation



Creation of correlated pairs of excitations via parametric amplification of vacuum if classical fluctuations are absent.

miscible mixture, Ω=0: elementary excitations

Faraday spectroscopy to measure the **dispersion relations** of the normal modes:

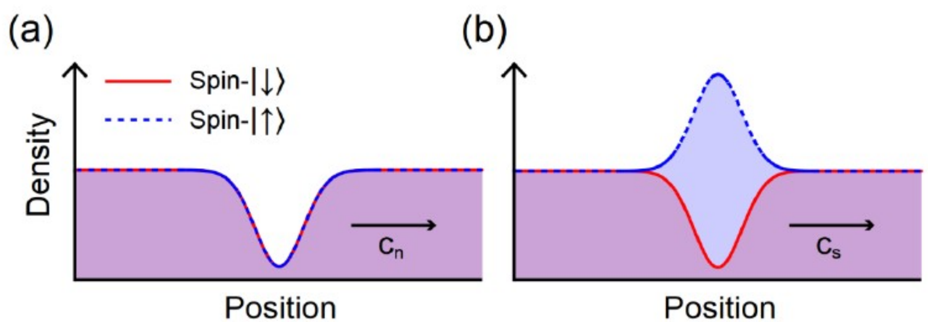
$$\omega_{d,s}(k) = \sqrt{\frac{\hbar k^2}{2m}\left(\frac{\hbar k^2}{2m} + \frac{2mc_{d,s}^2}{\hbar}\right)}$$

Density

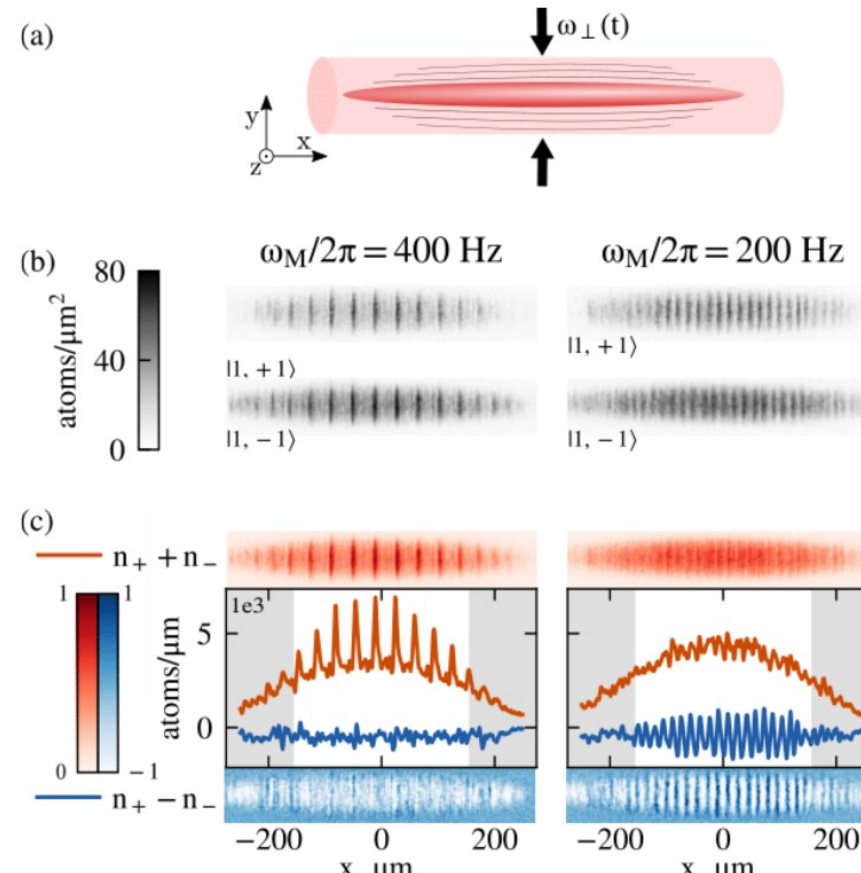
$$d(\vec{r}) = n_\uparrow(\vec{r}) + n_\downarrow(\vec{r})$$

Spin

$$s(\vec{r}) = n_\uparrow(\vec{r}) - n_\downarrow(\vec{r})$$

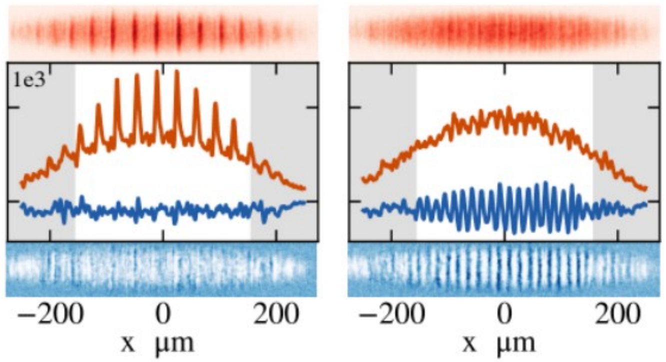


$$c_d = \frac{(g + g_{\downarrow\uparrow})n}{2m} \gg c_s = \frac{(g - g_{\downarrow\uparrow})n}{2m}$$

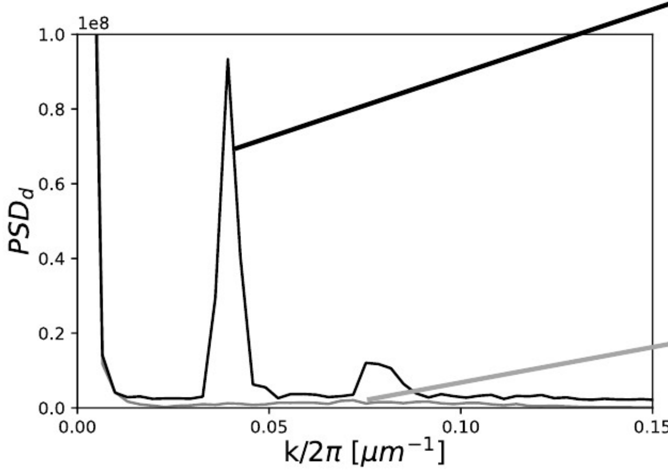


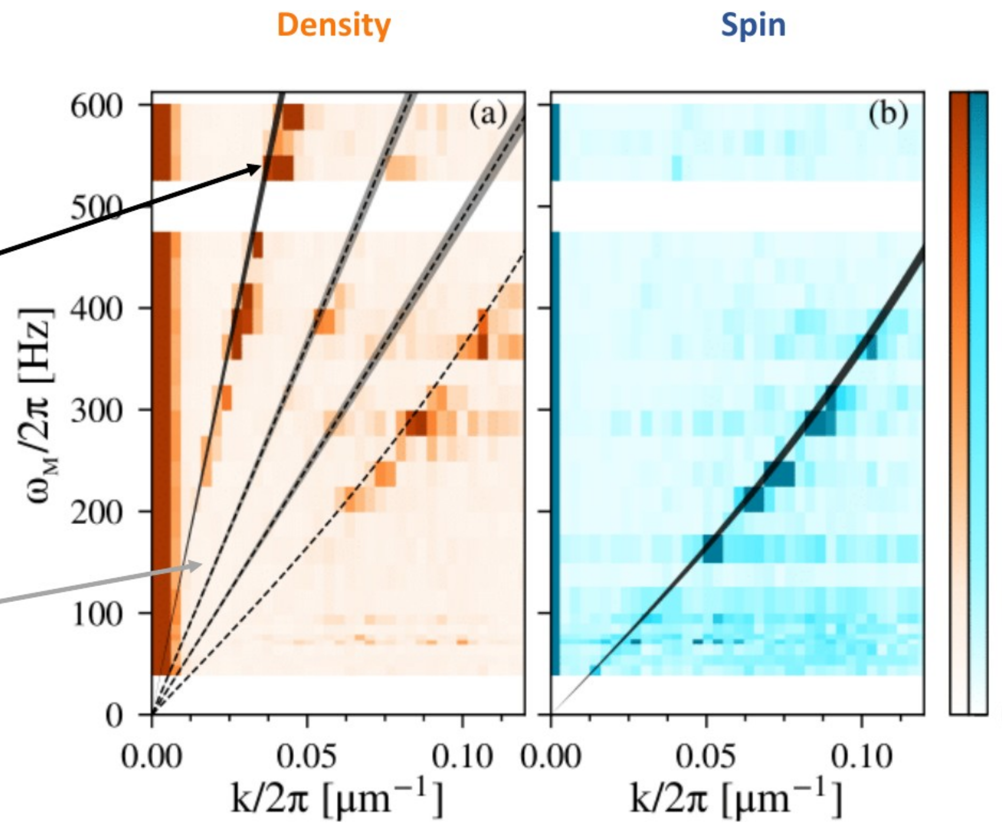
R. Cominotti et al., Phys. Rev. Lett. **128**, 210401 (2022)

miscible mixture, Ω=0: elementary excitations



$$PSD_{d,s}(k) = \int (n_+ \pm n_-) e^{ikx} dx$$

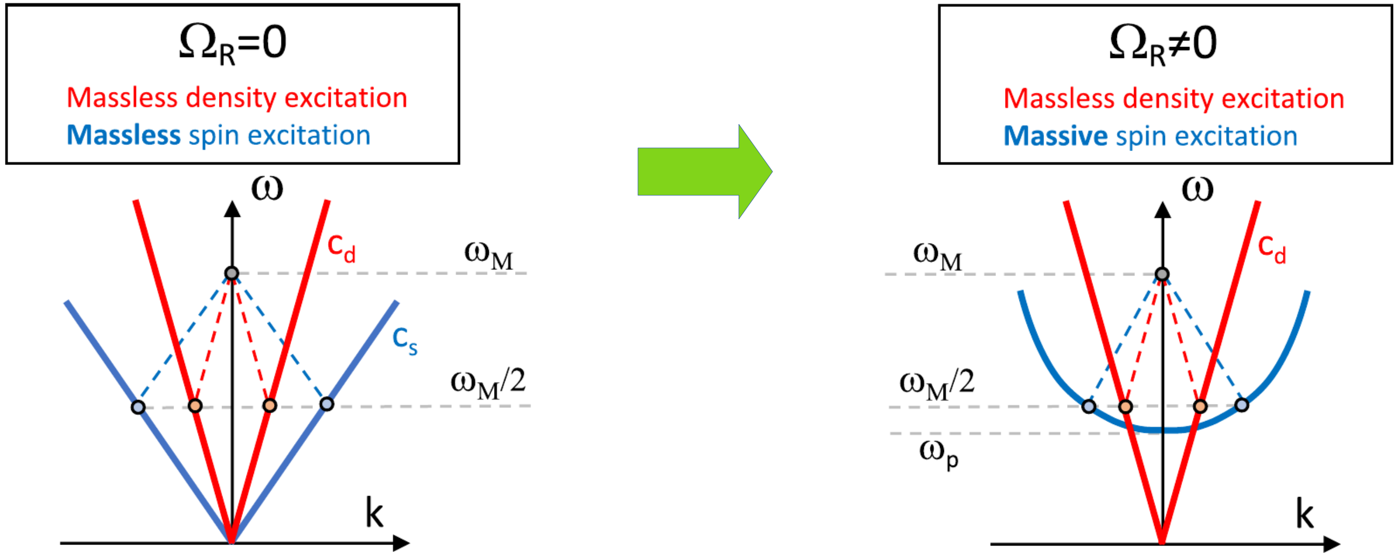




miscible mixture, Ω≠0,

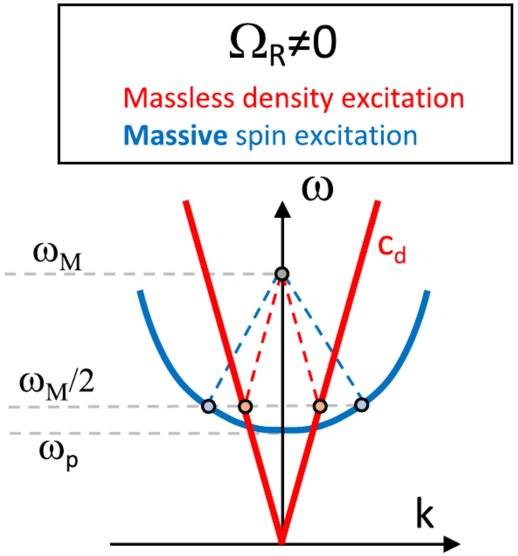
The coupling breaks one U(1) symmetry by locking the relative phase, spin excitations becomes gapped:
elementary manybody spin excitations acquire a massive character.

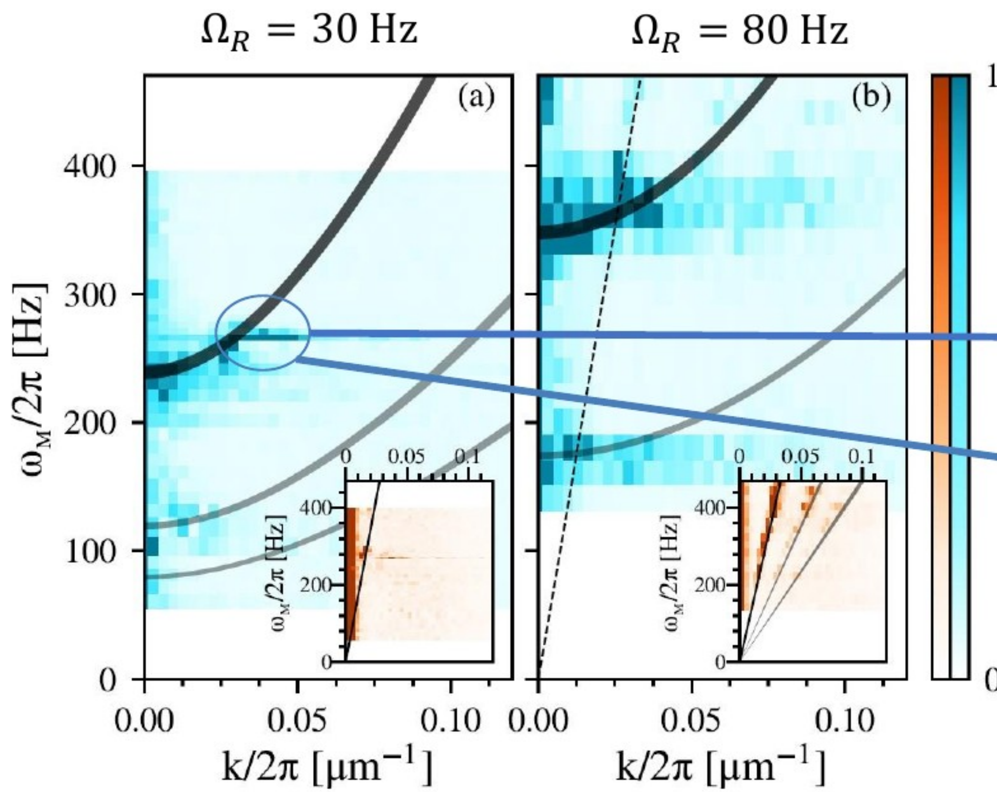
$$\varepsilon_s(k) = \sqrt{\left(\frac{\hbar^2 k^2}{2m} + \hbar\Omega\right)\left(\frac{\hbar^2 k^2}{2m} + \hbar\Omega + 2mc_s^2\right)}$$

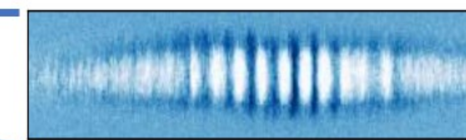


miscible mixture, Ω≠0

Phys. Rev. Lett. **128**, 210401 (2022)







Experimental demonstration of collective excitations with massive character

<u>Correlated pairs of massive quasiparticles created via parametric amplification of vacuum fluctuations</u>

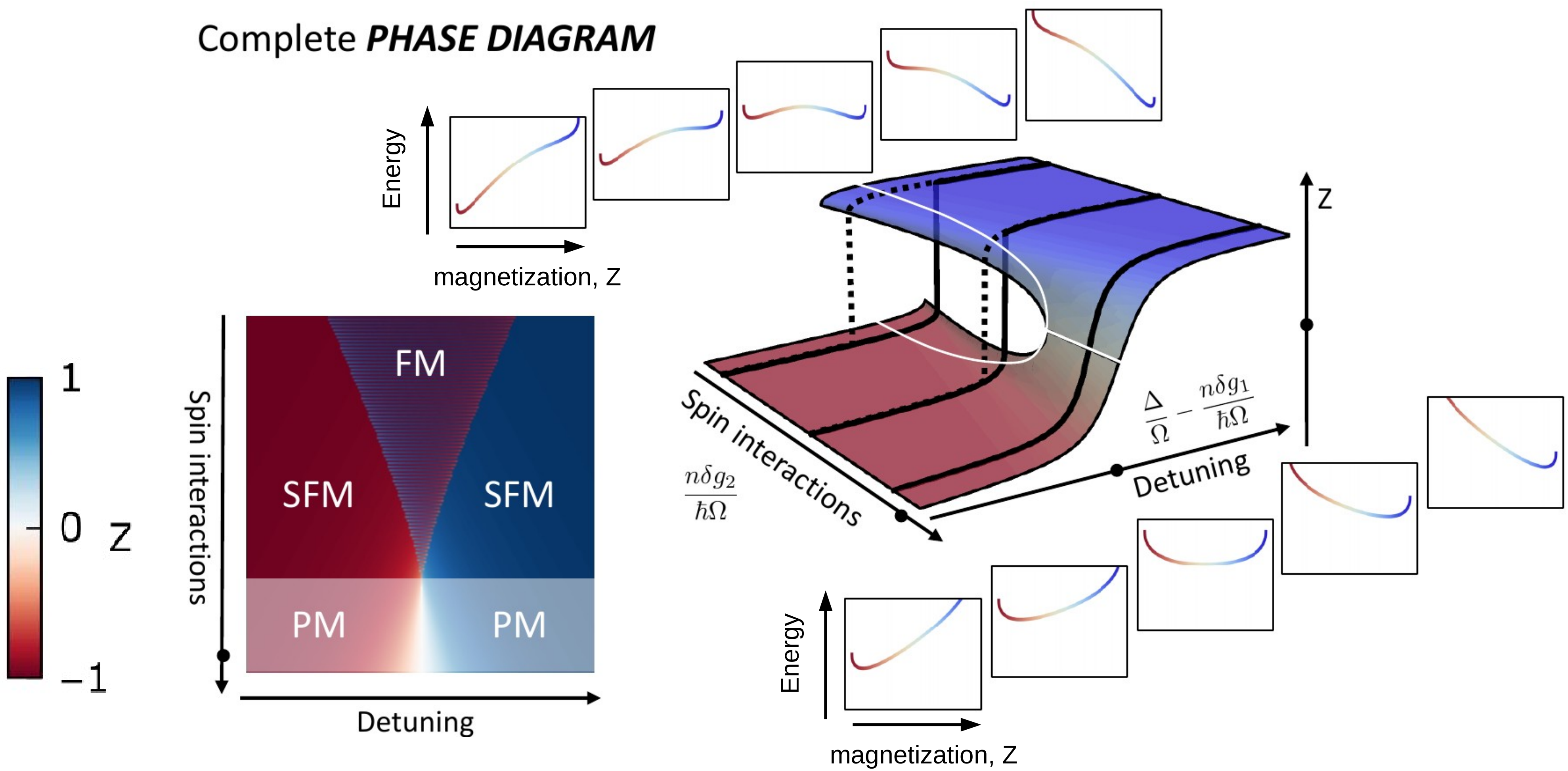
Acoustic analog of the **dynamical Casimir Effect**

$$\hbar\omega_p = \sqrt{\hbar\Omega_R(\hbar\Omega_R + 2\mu_s)} \qquad \epsilon(k) \simeq \hbar\omega_p + \frac{\hbar^2 k^2}{2M}; \qquad M = \frac{2m\omega_p\Omega_R}{\omega_p^2 + \Omega^2}$$

immiscible mixture, Ω≠0

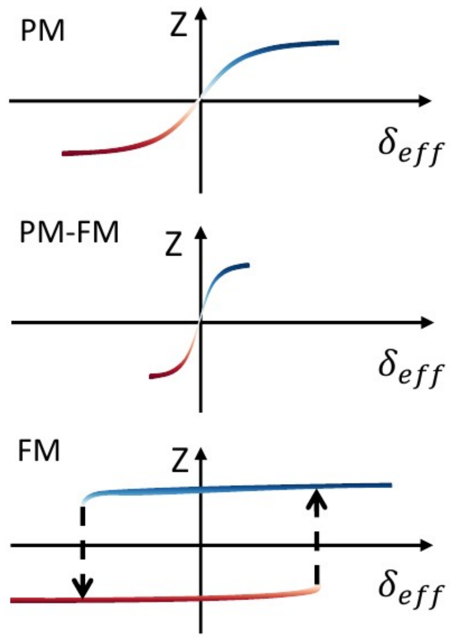
The immiscible (repulsive) mixture in the presence of a coherent coupling is formally equivalent to a **spin ½ Ising model in transverse field**, at zero temperature.

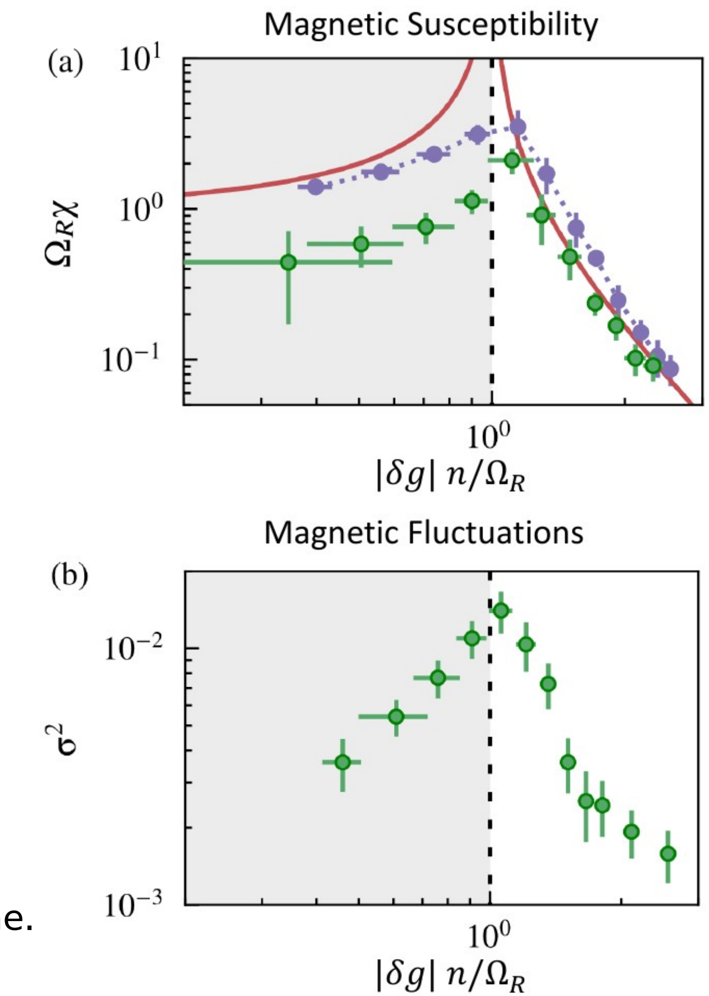
Paramagnetic to ferromagnetic phase transition accessible via easily tunable experimental parameters (Ω, δ,...)



characterization of the key quantities

$$\chi = \left.\frac{\partial Z}{\partial \delta_{eff}}\right|_{\delta_{eff}=0}$$





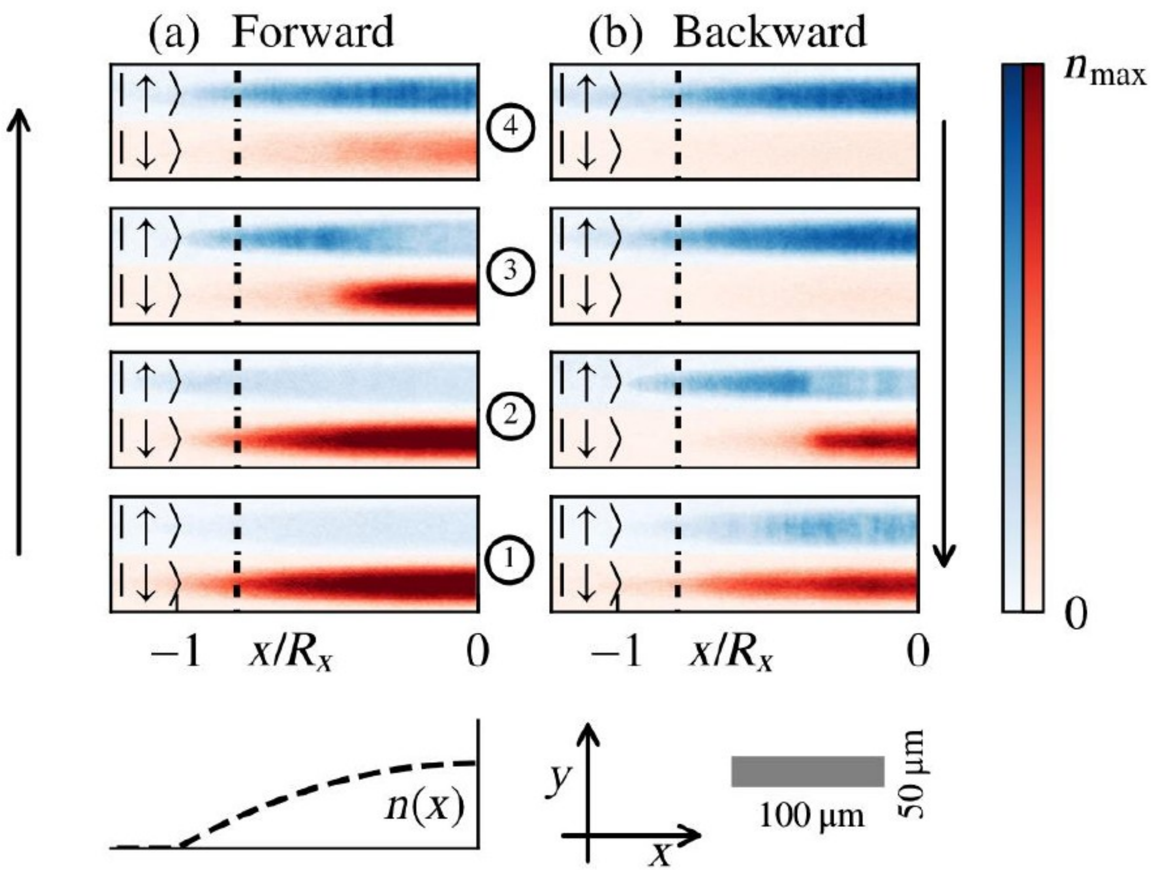
Improving the accuracy of the measurement will allow to **validate the fluctuation-dissipation theorem** in the quantum regime.

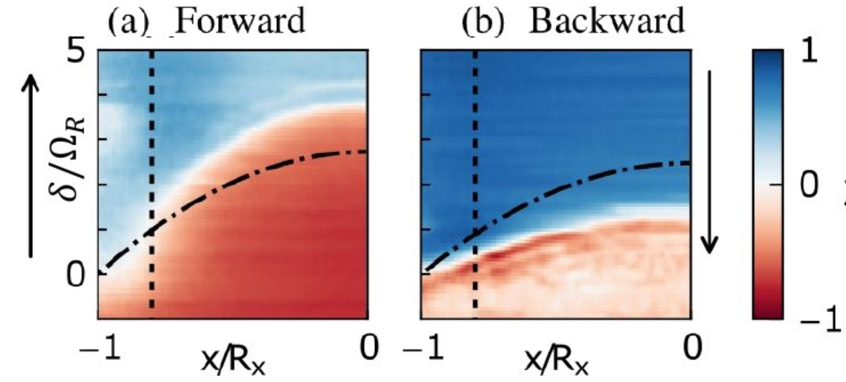
R. Cominotti et al., Phys. Rev. X. **13**, 021037 (2023)

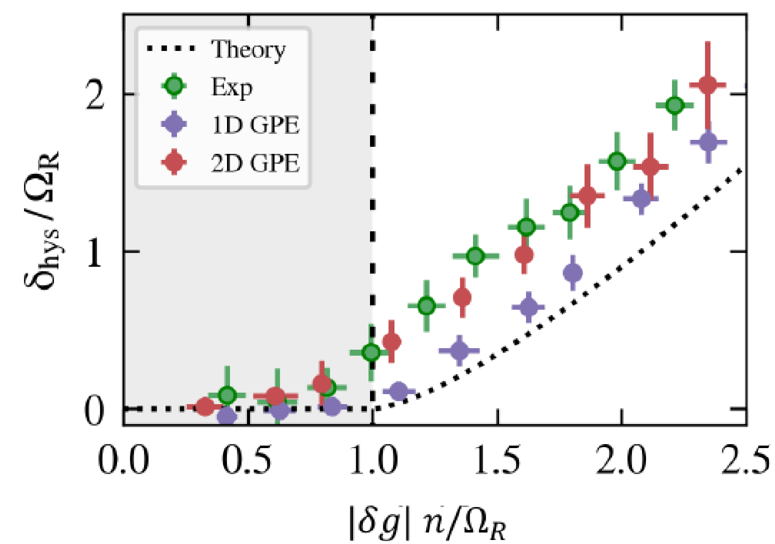
characterization of hysteresis

- **Parabolic dome** due to **density-dependent detuning** $\delta_{eff} = \delta - n(x)(g_{\downarrow\downarrow} - g_{\uparrow\uparrow})$

Experiment: Adiabatic Rapid Passage from |↓⟩ or |↑⟩ to map ground state structure



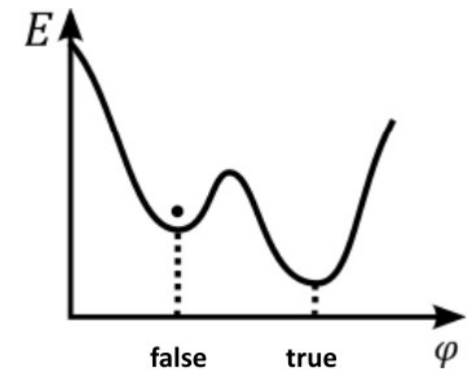


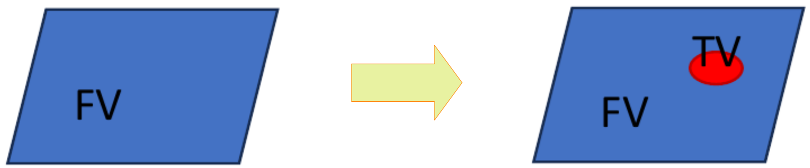


R. Cominotti et al., Phys. Rev. X. **13**, 021037 (2023)

False vacuum decay

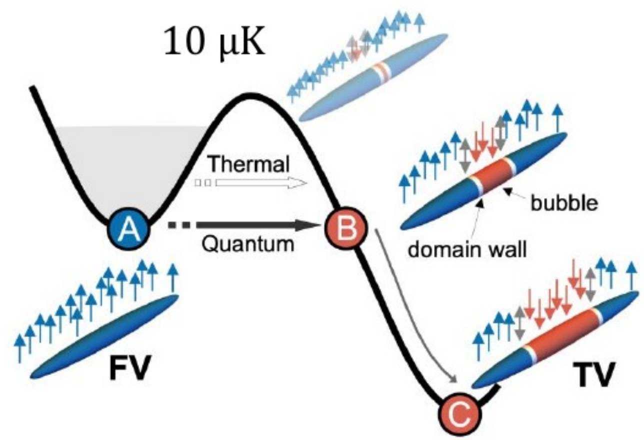
- System in a **metastable** state of a **field** theory
- Decay occurs through **stochastic** generation of expanding **true vacuum bubbles**, driven by quantum fluctuations
- Universe might be in a metastable state, or could have already decayed in the true vacuum



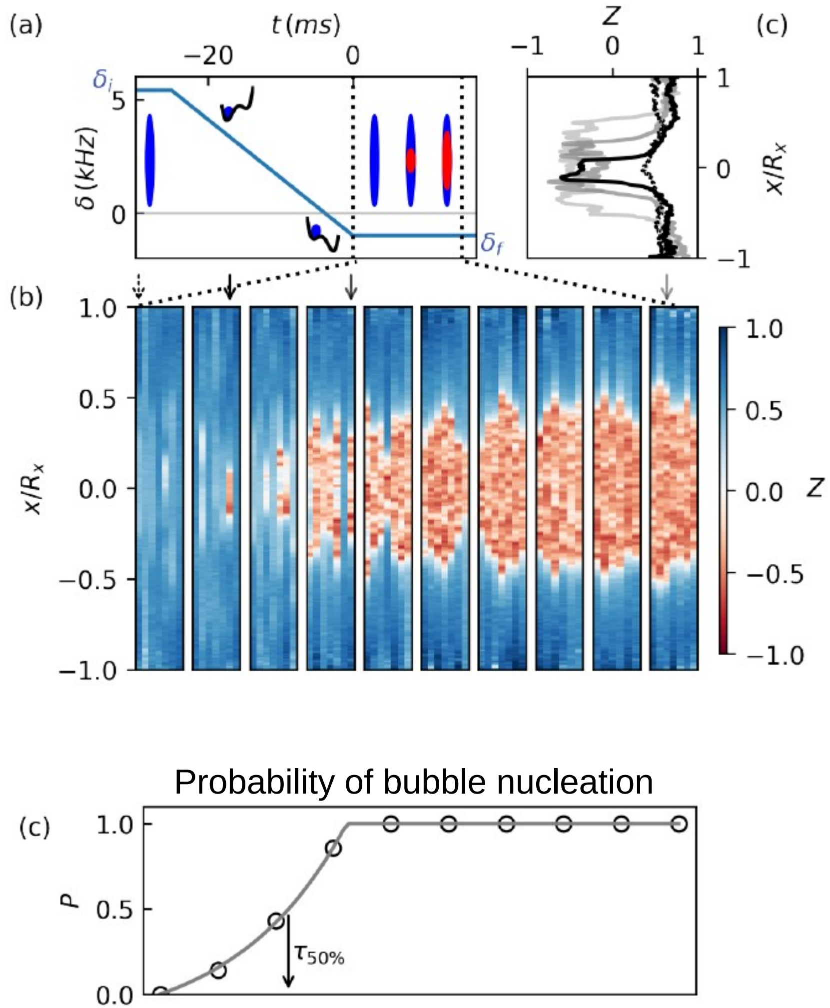


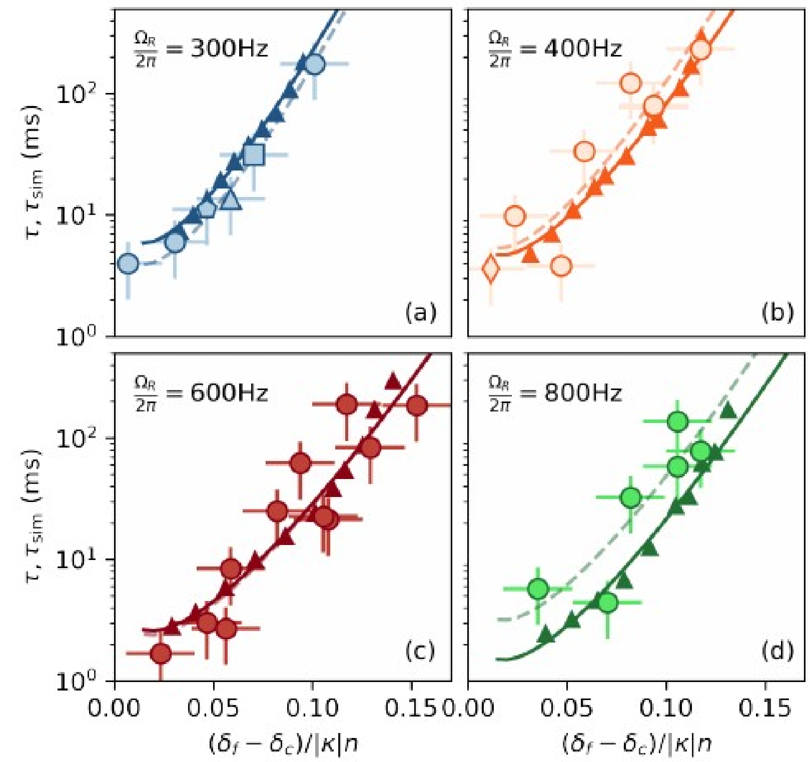
Instanton theory (S.R. Coleman, PRD 15, 2929 (1977))

- **Many-Body** energy barrier ($\neq$ external potential)
- **Macroscopic tunneling** of the field (single particle is prohibited by $\nabla^2 Z$)
- Quantum or **thermal activation**



First observation of nucleation of vacuum Bubbles





A. Zenesini et al., arXiv:2305.05225

Nature Physics (2024) online

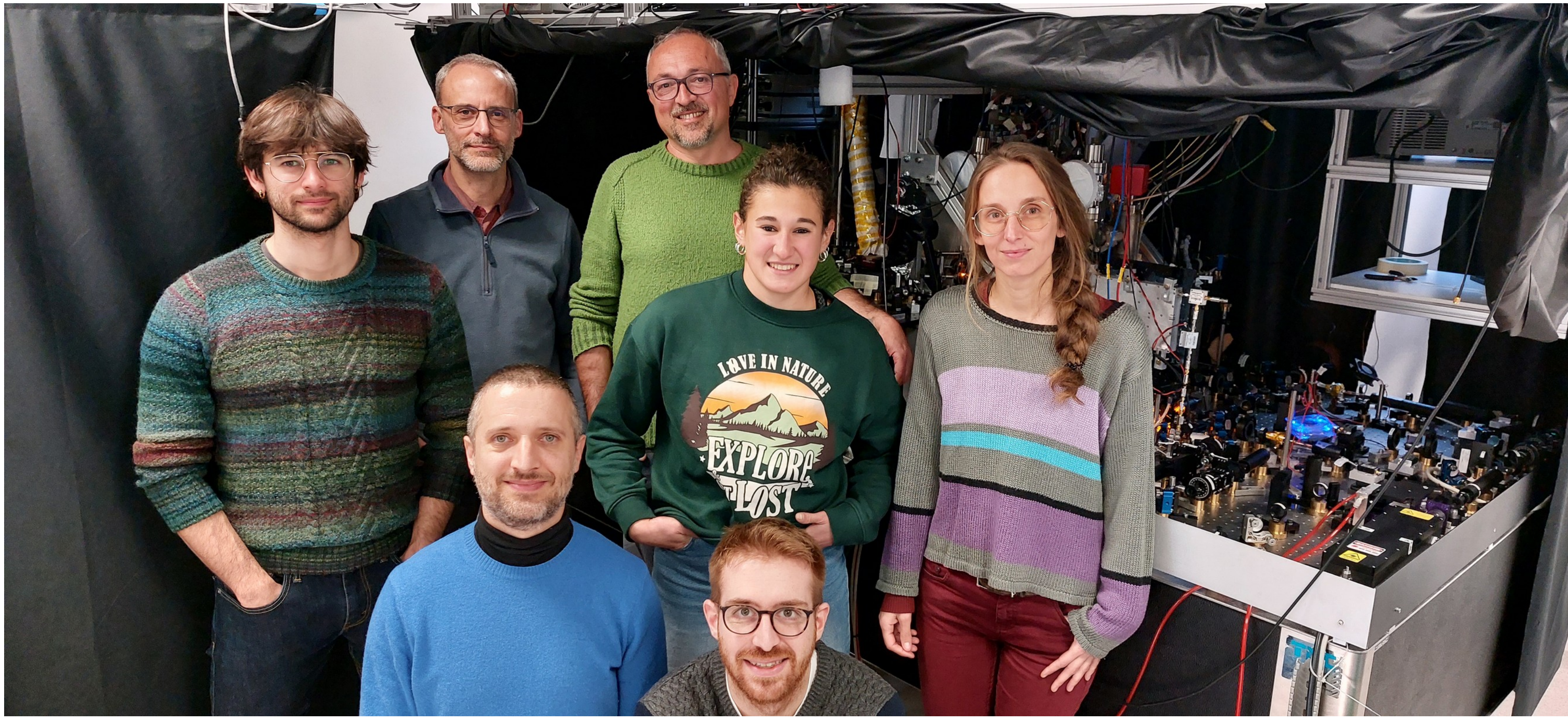
- First experimental benchmark of the 1D instanton model.
- experimental extension is simple, opening to regimes not accessible with modern computers.

Spin superfluid for quantum simulation

Mixtures of ultracold atoms in different internal hyperfine states offer:

- field-like order parameter with vector character,
- choice of contact interaction parameters by mixing different hyperfine states,
- flexibility of engineering the spin-energy landscape via experimentally tunable parameters (Rabi freq., detuning and phase of the coherent coupling),
- trapping in 0, 1, 2 dimensions,
- preparation of the sample at zero temperature, where **fluctuations have a pure quantum origin**.

Ultracool physicists



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