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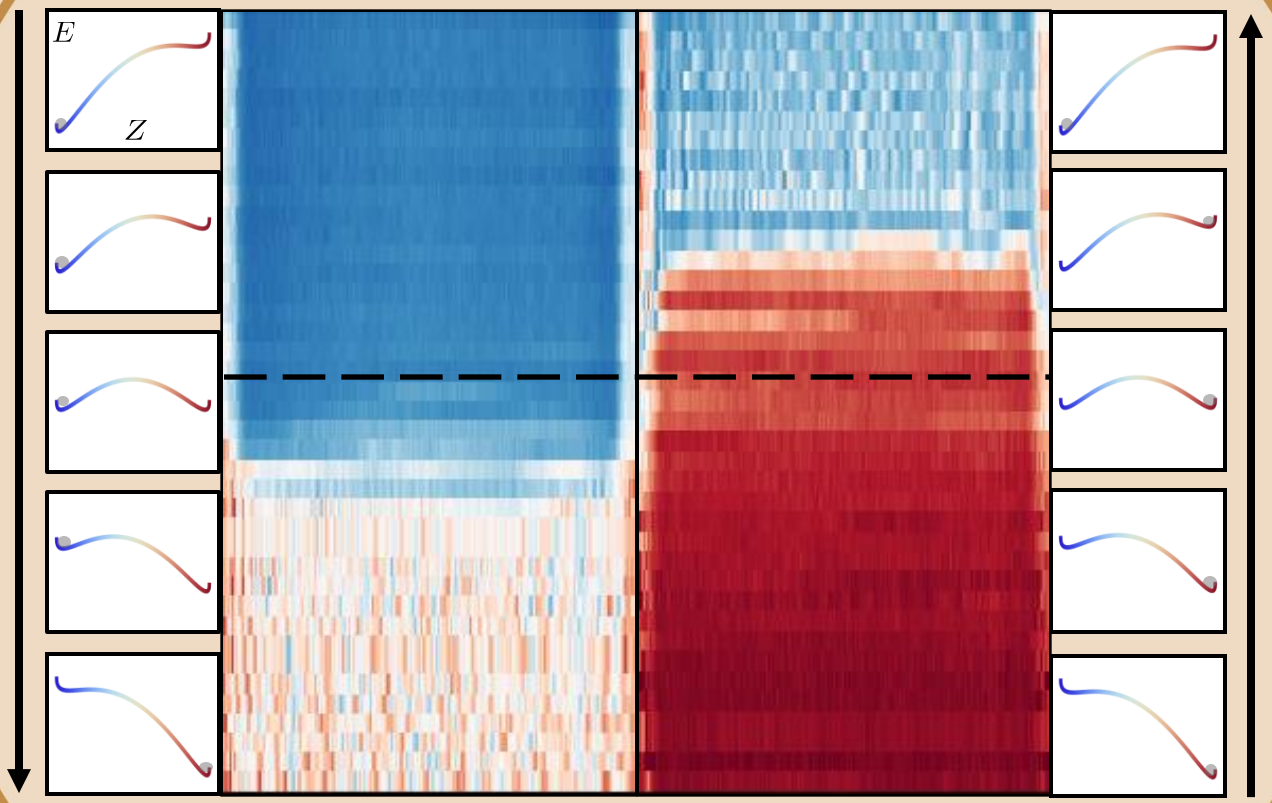
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

Ferromagnetism in an atomic quantum spin mixture

Giacomo Lamporesi

CNR-INO Trento

06/02/2025



PNRR PE4 - NQSTI

Spoke 6 ***Integration***

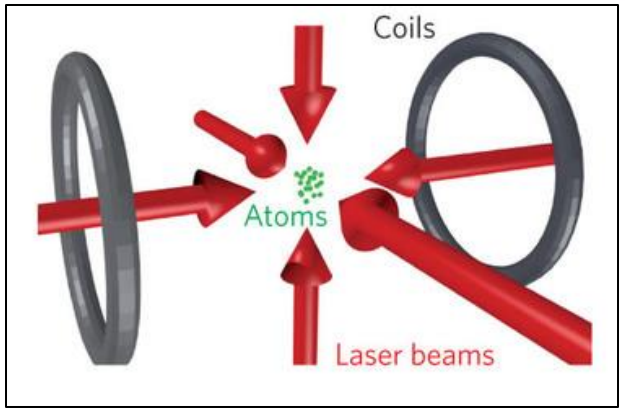
Activity A6.1 ***Integration of atomic devices***

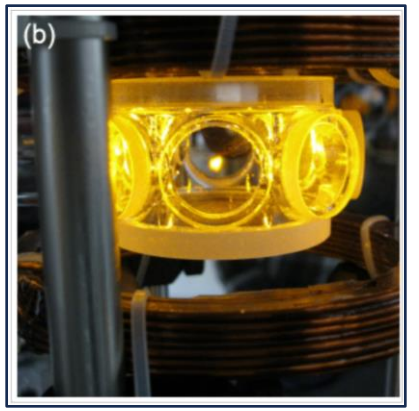
Design and implementation of atomic circuits to resemble electron-based networks of different classes of conductors, semiconductors, superconductors or magnets. Design and implementation of fully controllable quantum devices based on strongly interacting degenerate atomic gases with tunable interactions trapped in engineered and fully programmable optical structures.

Direct connection to **Spoke 2** (theory) and **Spoke 3** (experimental techniques)

FLORENCE	fermions	^{6}Li	(Giacomo Roati)
TRENTO	bosons	^{23}Na	

EXPERIMENTAL PLATFORM
Sodium bosonic atoms in two different spin states

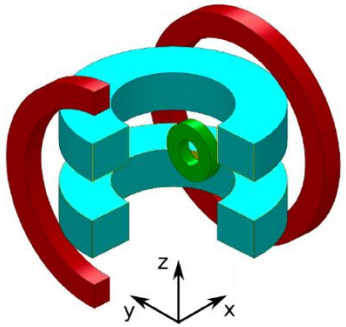


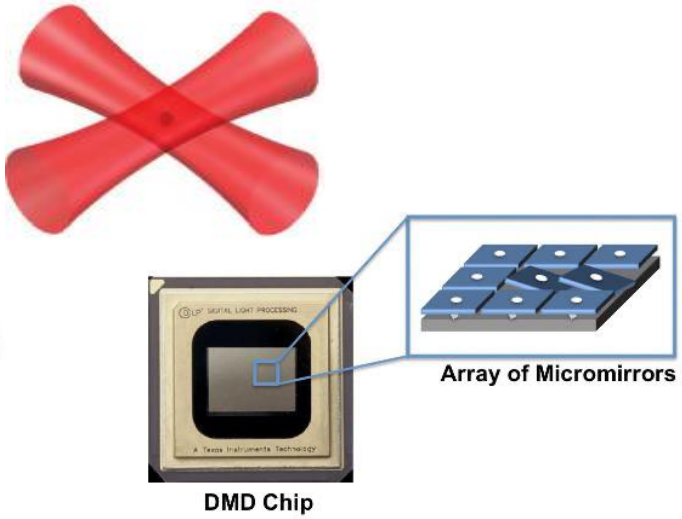


Laser-cooling → Ultracold gas (T=μK) → BEC / Superfluid

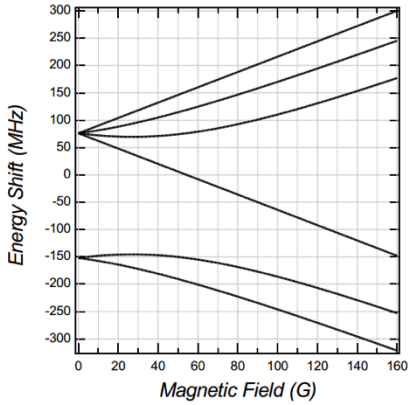
Ultimate control of external and internal degrees of freedom

Magnetic and Optical traps

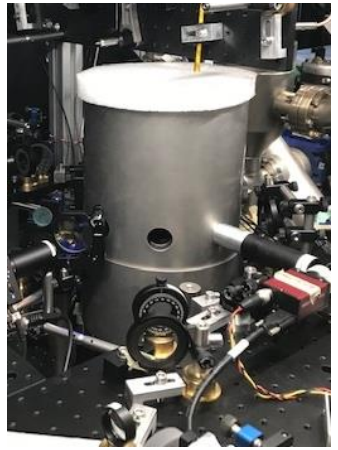




Interparticle interaction



Ultrastable magnetic field (ΔB=μG)



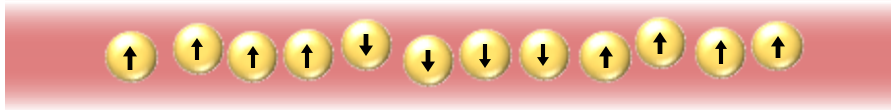
State manipulation

Farolfi *et al.*, RSI **90**, 115114 (2019)
Rogora *et al.*, PRA **110**, 113319 (2024)

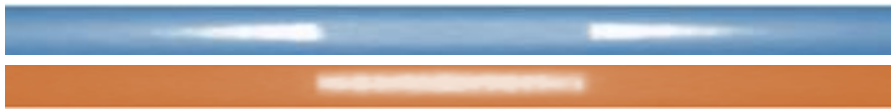
Quantum mixture

Baroni et al., Nat. Rev. Phys. **6**, 736 (2024)

Quasi 1D geometry



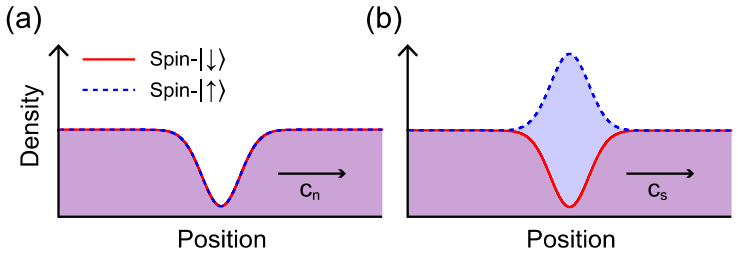
Spin selective imaging



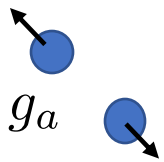
Total DENSITY **SPIN density** (magnetization)

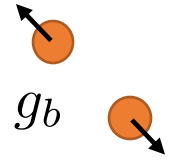
$$n = n_a + n_b \qquad m = n_a - n_b$$

$$\Phi = \phi_a + \phi_b \qquad \phi = \phi_a - \phi_b$$

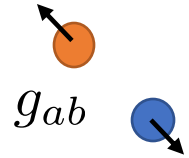


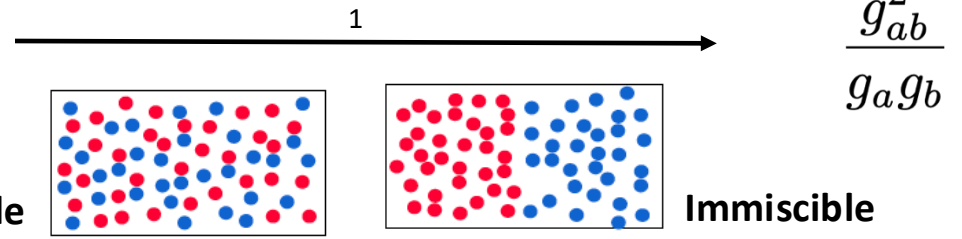
Intracomponent interactions

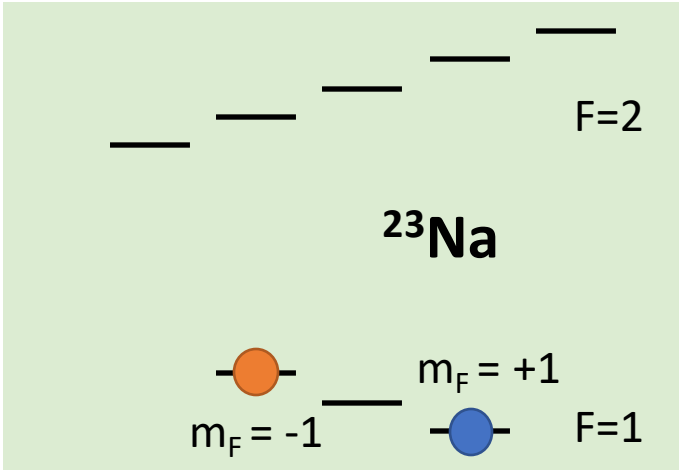


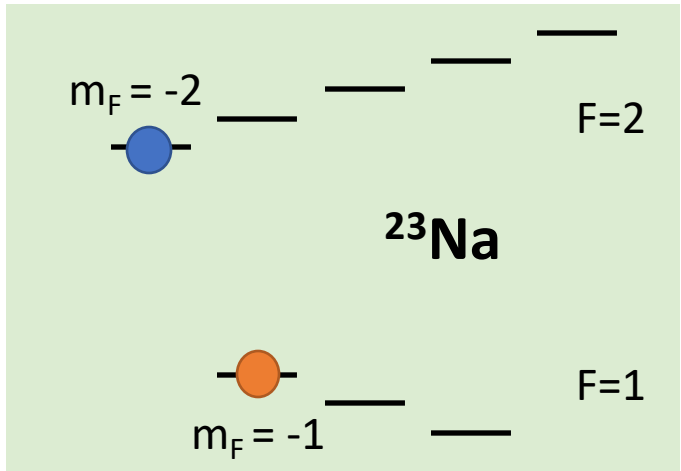


Intercomponent interactions



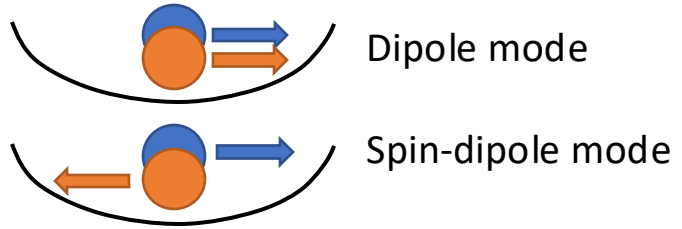


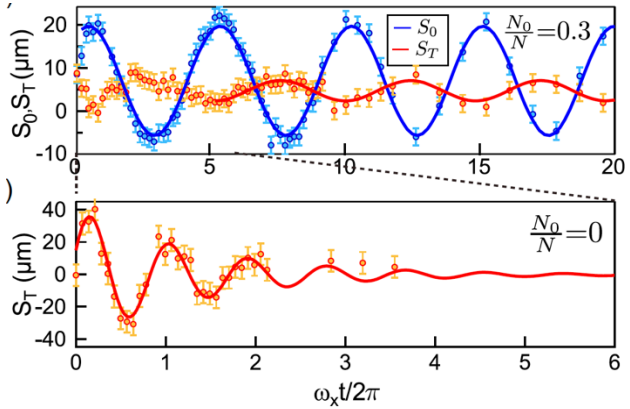




Miscible spin mixture

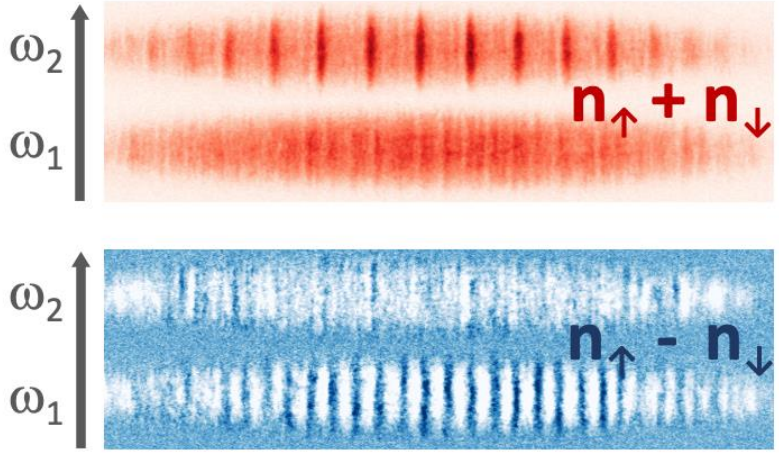
- Measurement of spin dipole mode
- Observation of spin superfluidity
- Faraday waves
- Measurement of the Bogoliubov spectrum for density and spin channels
- Magnetic solitons



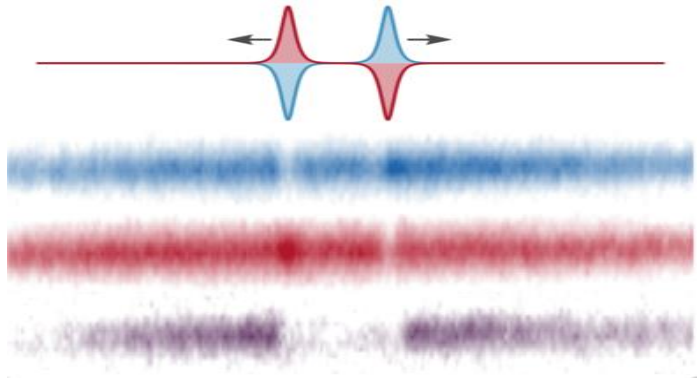


Bienaimé *et al.*, PRA **94**, 063652 (2016)

Fava *et al.*, PRL **120**, 170401 (2018)



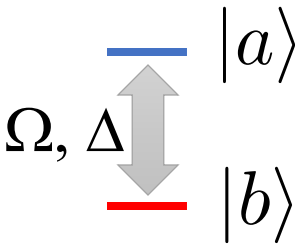
Cominotti *et al.*, PRL **128**, 210401 (2022)



Farolfi *et al.*, PRL **125**, 030401 (2020)

Immiscible spin mixture

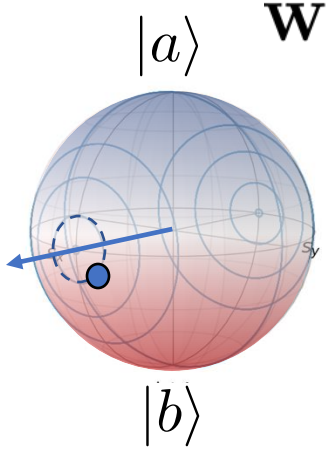
Coherent coupling



Competition between **interactions** and **coupling**

Non interacting system

$$\mathbf{W} = (\Omega, 0, \Delta)$$

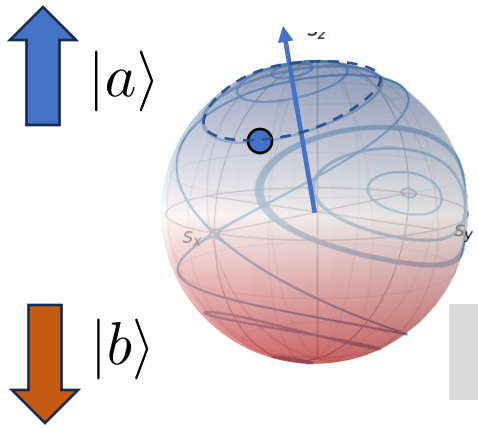


Coupling dominates

PARAMAGNETIC

Many-body interacting system

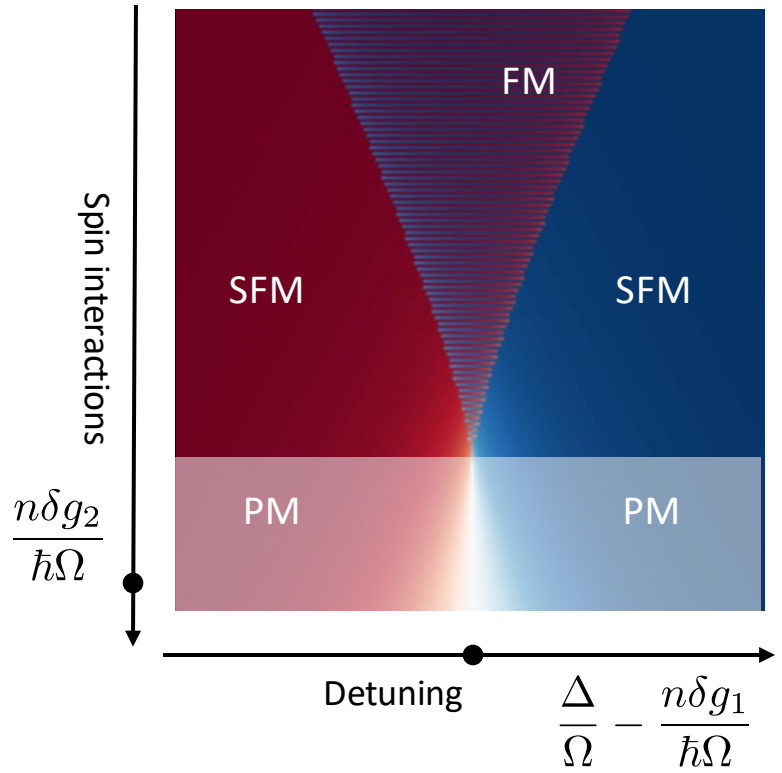
$$\mathbf{W}_{\text{eff}} = \left(\Omega, 0, \Delta - \frac{n\delta g_1}{\hbar} - \frac{n\delta g_2 Z}{\hbar}\right)$$

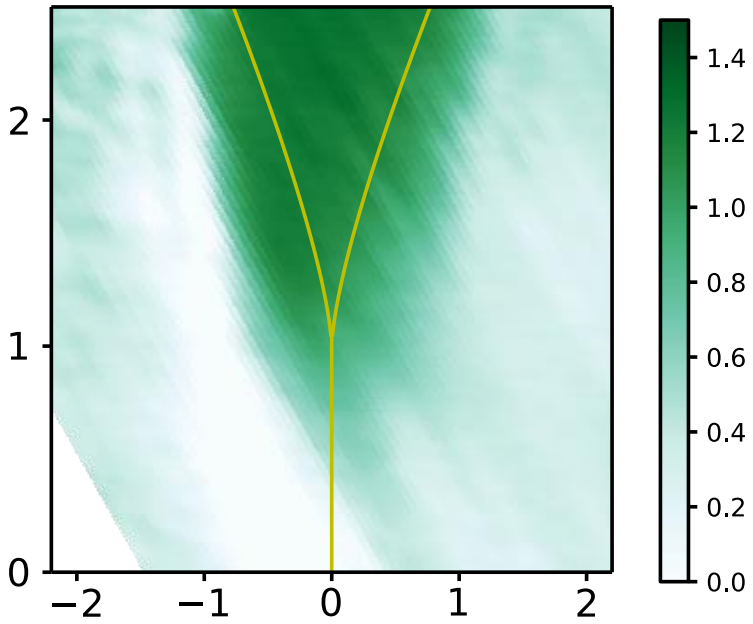


Spin interactions dominate

FERROMAGNETIC

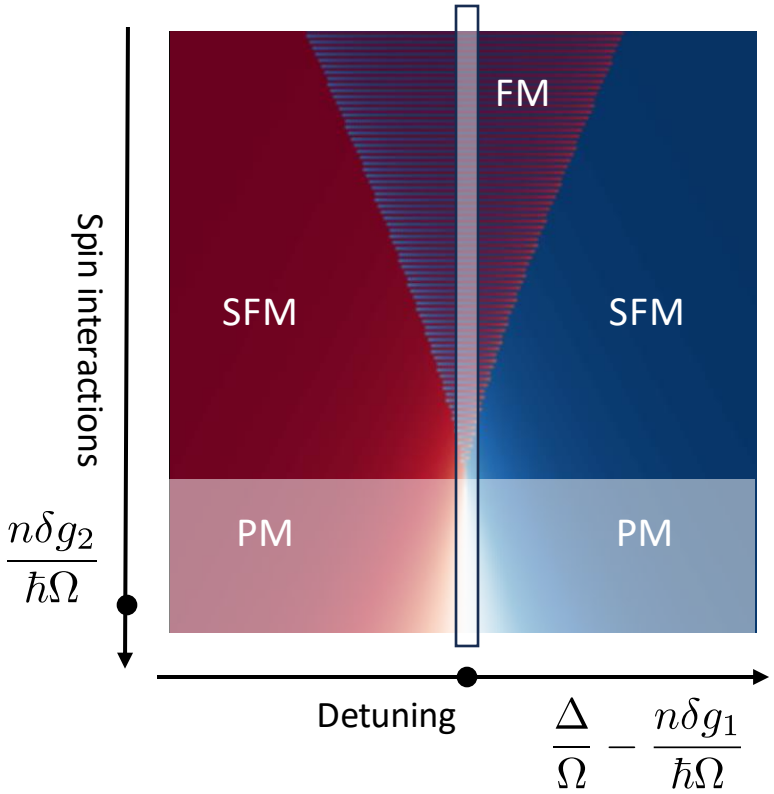
Simulation of magnetic material





Phase diagram

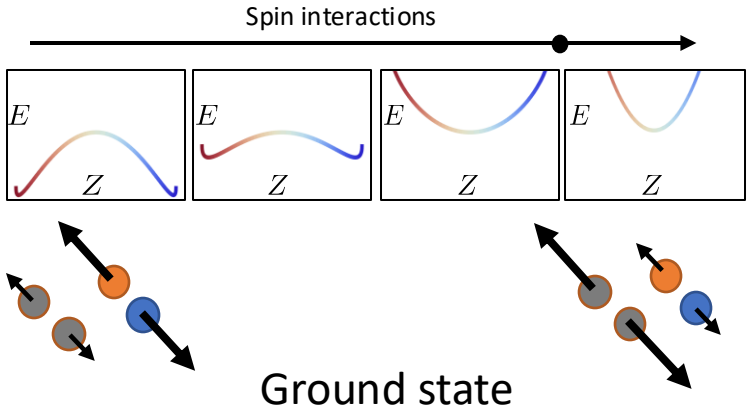
Ferromagnetism in an Extended Coherently Coupled Atomic Superfluid
Cominotti *et al.*, Phys. Rev. X **13**, 021037 (2023)



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

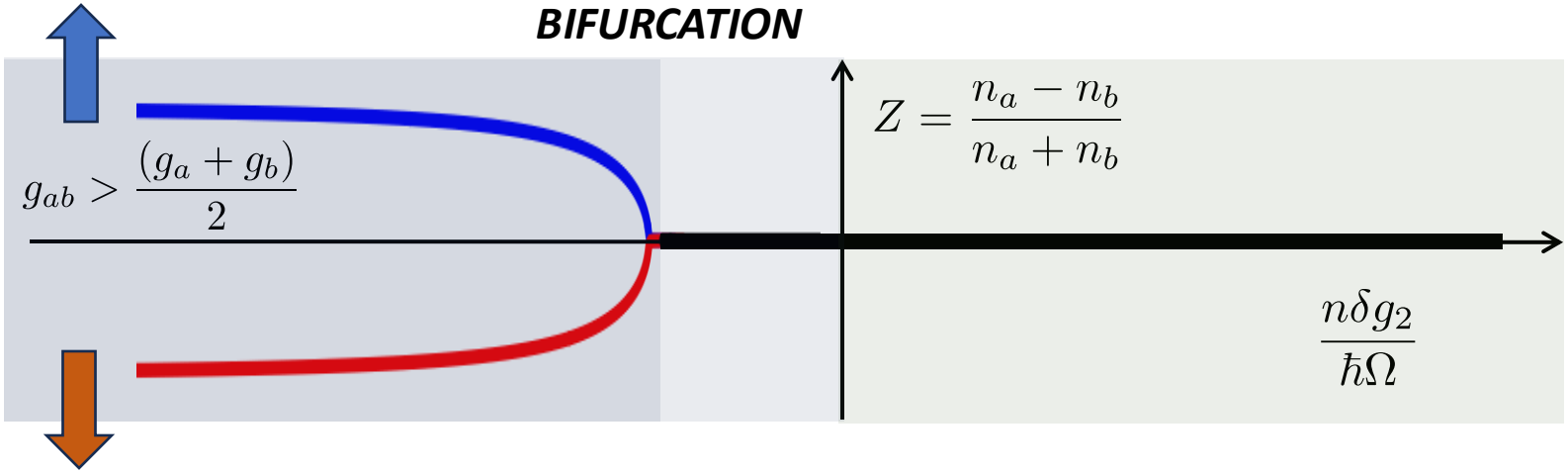
Δ=0, vary spin interactions

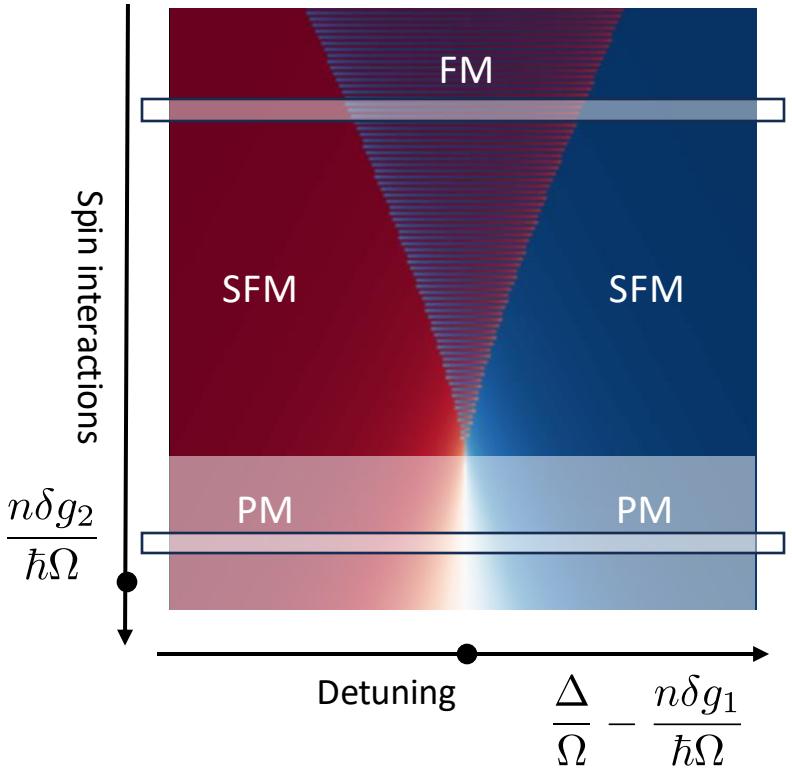
SECOND ORDER QPT Para-Ferromagnetic



Ground state

BIFURCATION

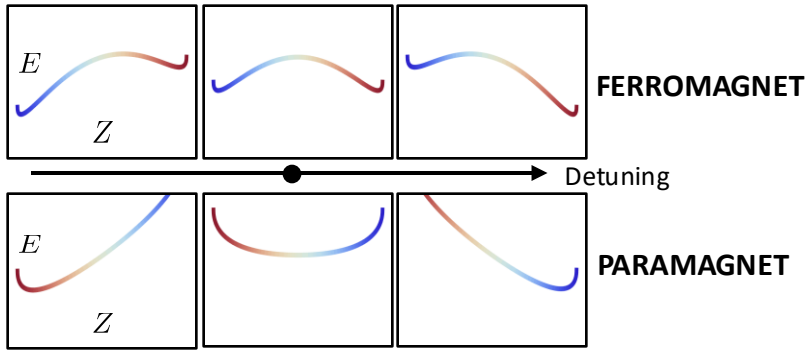




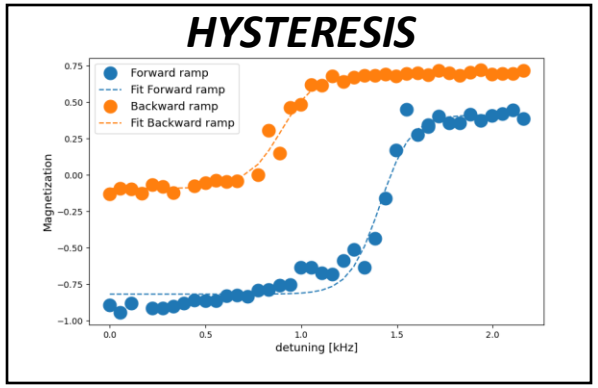
Fixed spin interactions, vary Δ

FIRST ORDER QPT

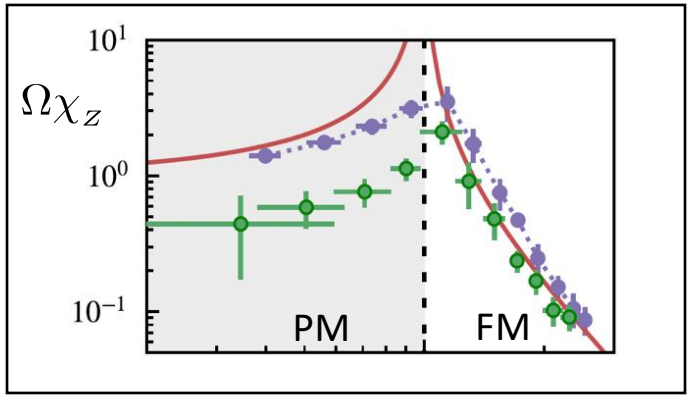
Hysteresis in the Ferrom. region



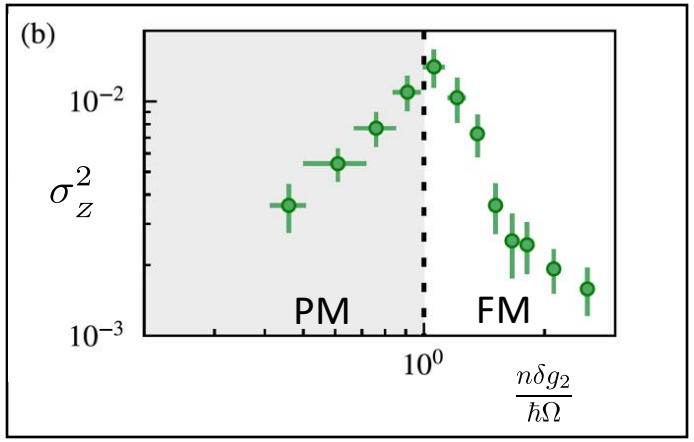
HYSTERESIS



MAGNETIC SUSCEPTIBILITY



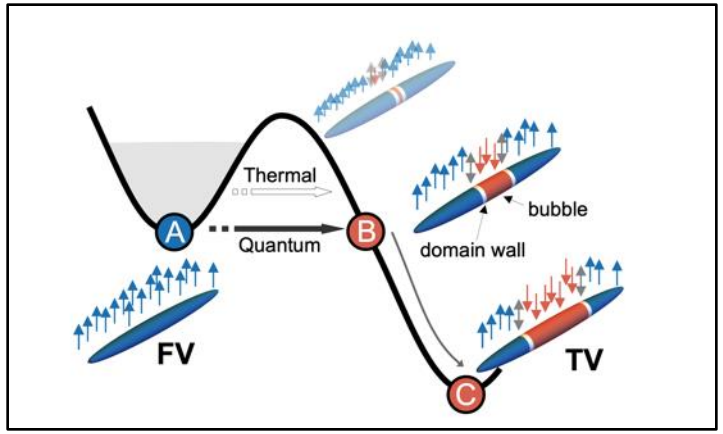
FLUCTUATIONS OF THE MAGNETIZATION

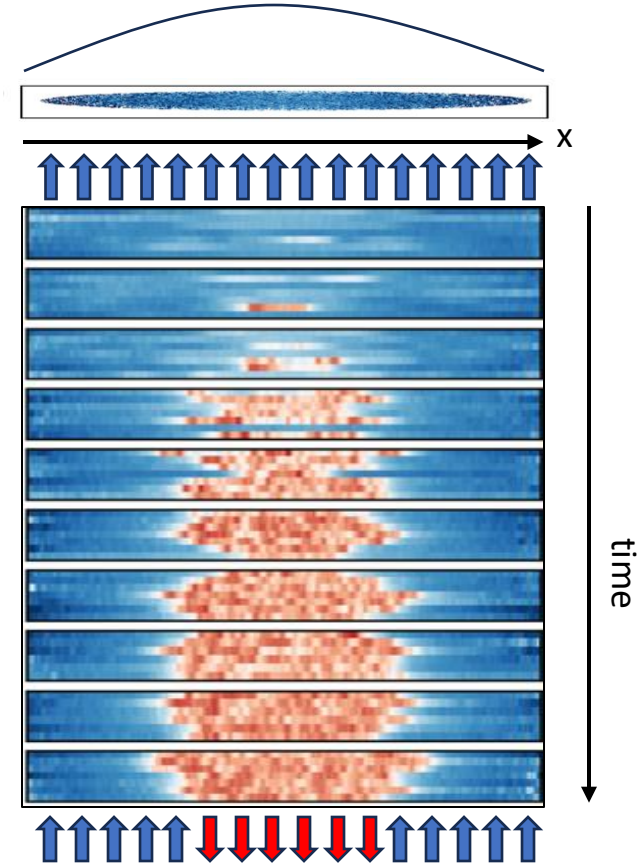


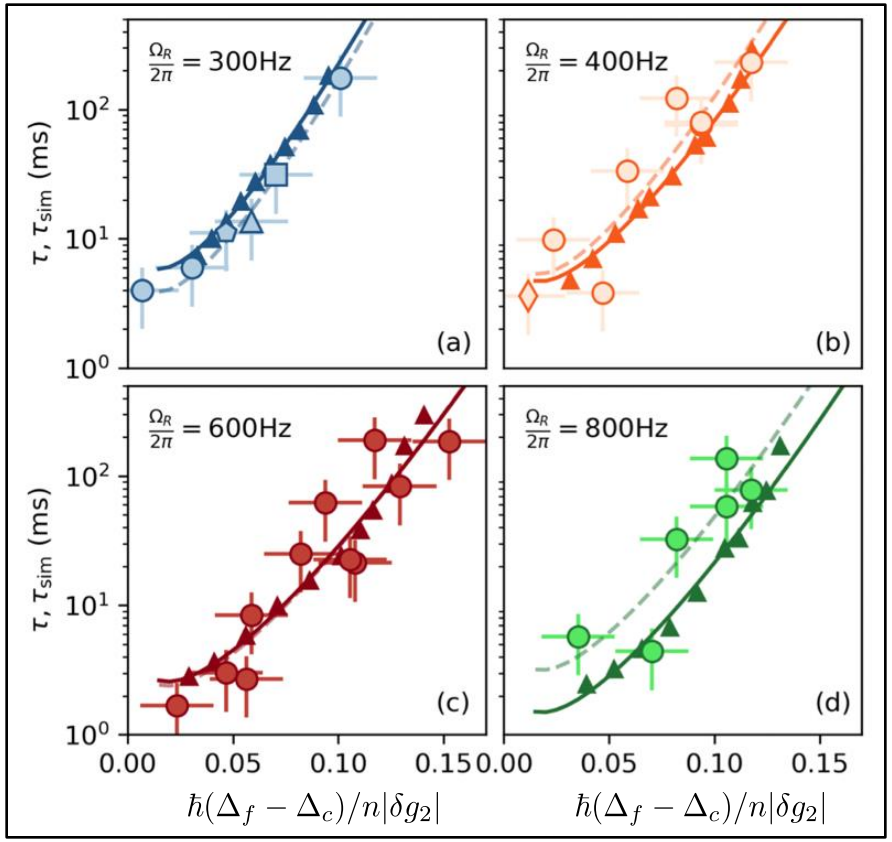
Cominotti *et al.*, Phys. Rev. X **13**, 021037 (2023)

Decay of metastable states

Simulation of False Vacuum Decay mechanism in quantum Field theory

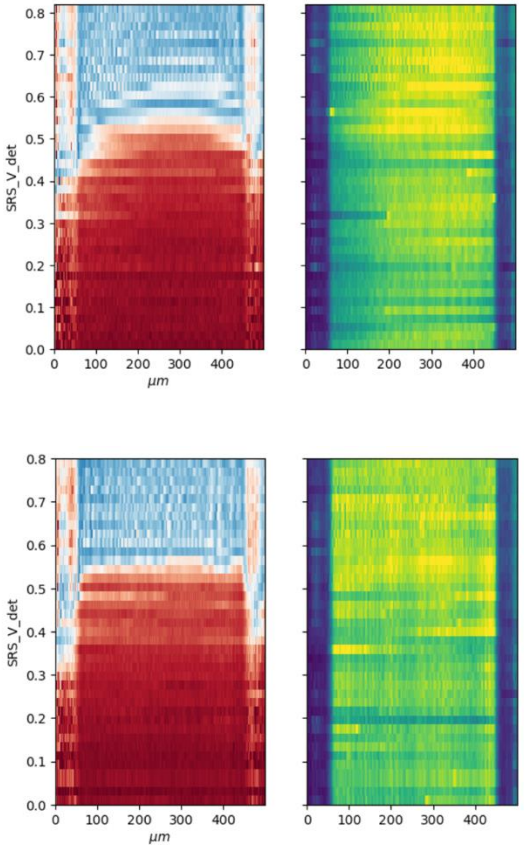




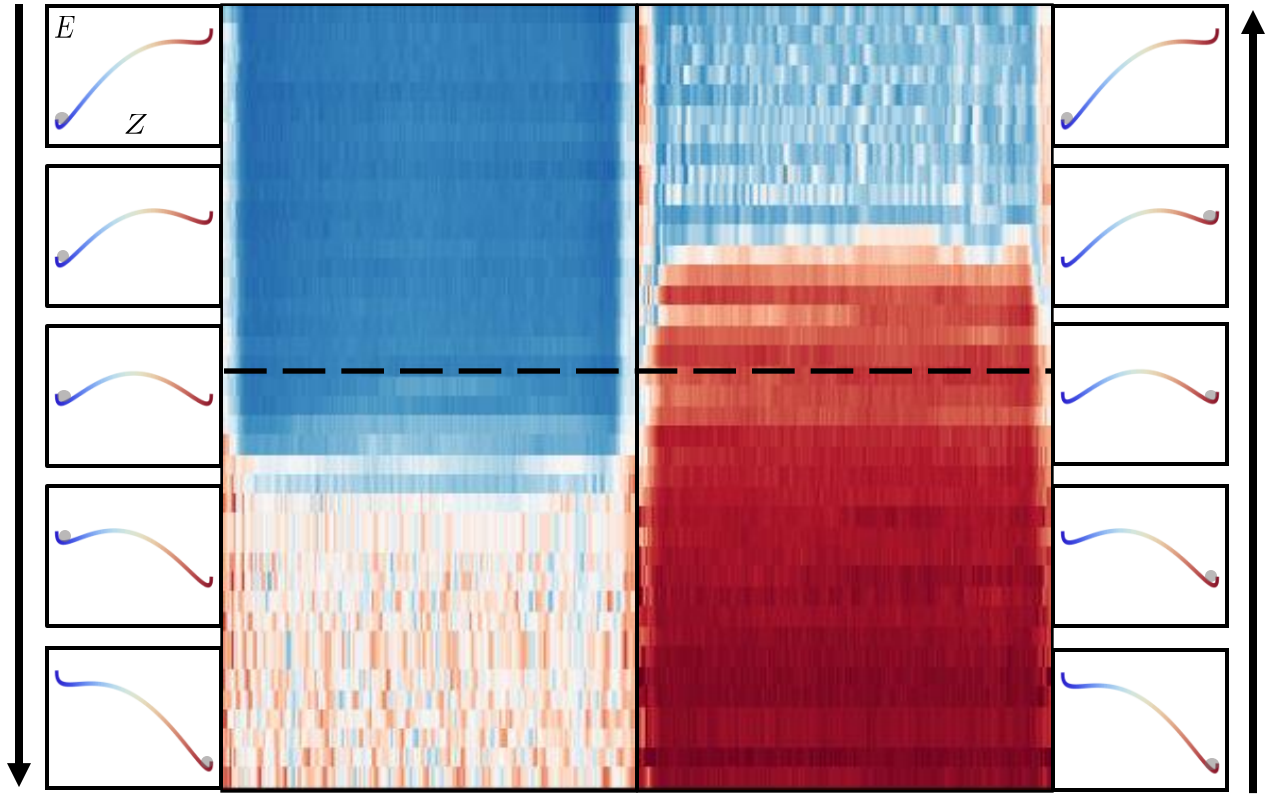


Zenesini et al., Nature Physics **20**, 558 (2024)

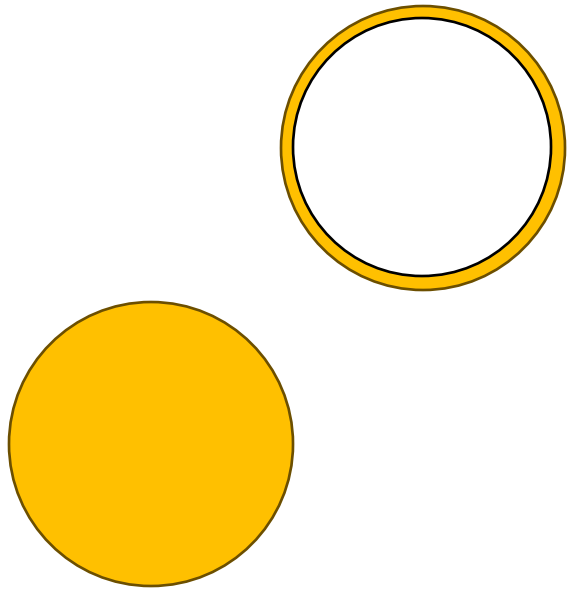
Harmonic to **flat potential**



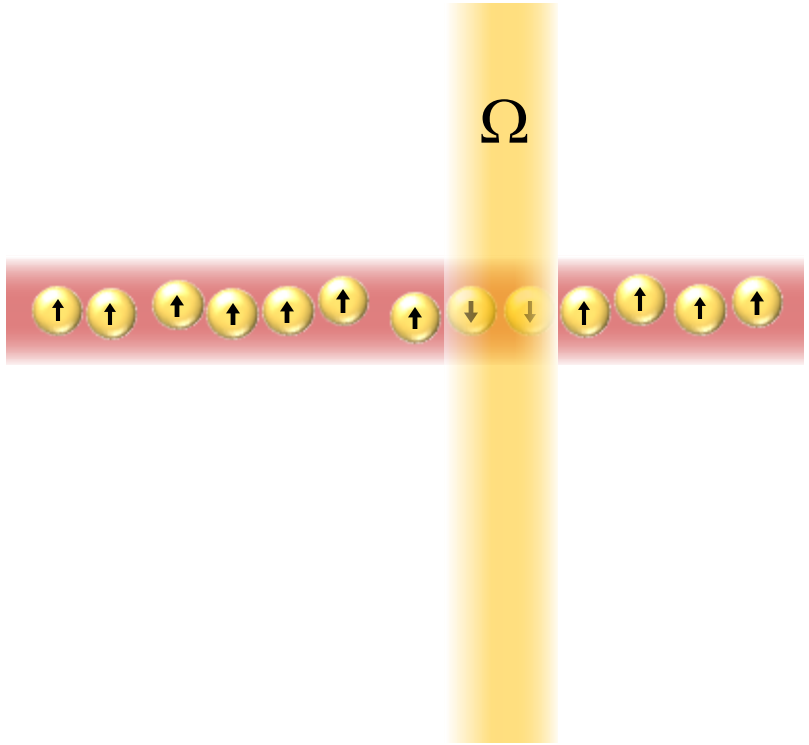
Large extended uniform region to study



1D linear geometry
to
1D Ring
2D Disk



Uniform to **local coupling**



Two **different spin currents**
(flat total density)

CW spin current

Pulsed current
(magnetic solitons)

Spoke 3

Spoke 6

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Giacomo Guarda *Diego Andreoni* *Chiara Rogora* *GL*

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Spoke 2

Theory team

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