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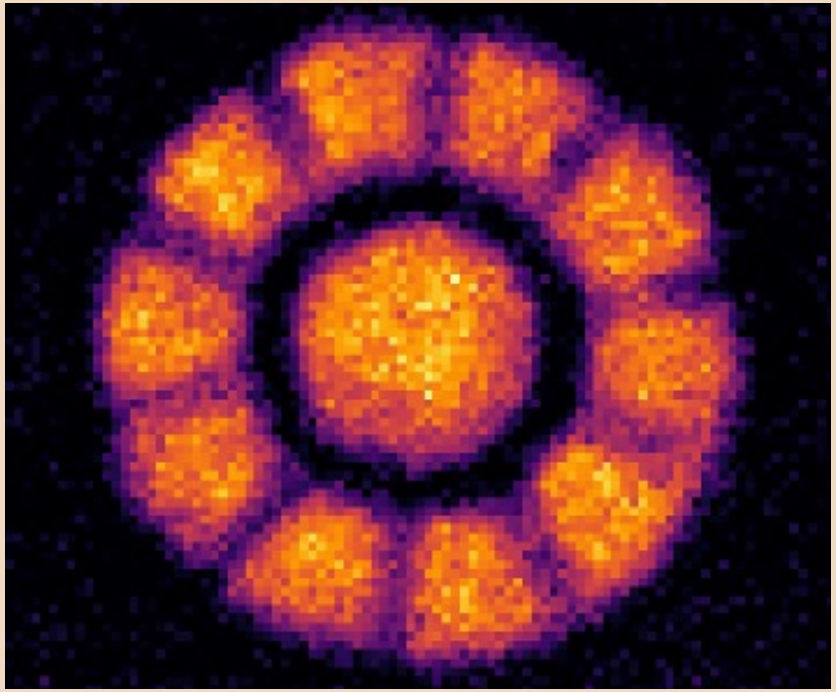
PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI
National Quantum Science and Technology Institute

Atomtronics and spintronics with ultracold quantum gases

Giulia Del Pace,
Giacomo Roati,
Giacomo Lamporesi

CNR-INO

16/01/2024



THE PROJECT

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.

Milestone M12 Design of atomtronic components for integrated quantum systems
Milestone M36 Design developed and first characterization performed of atomtronic circuits

Direct connection to **Spoke 2** and **Spoke 3**

EXPERIMENTAL TEAM

Giacomo Roati

CNR-INO
Florence

Giacomo Lamporesi

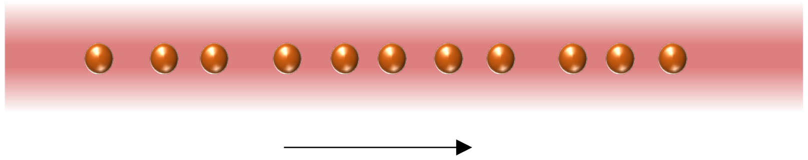
CNR- INO
Trento

EXPERIMENTAL PLATFORM 1 (Florence)
Lithium fermionic atoms

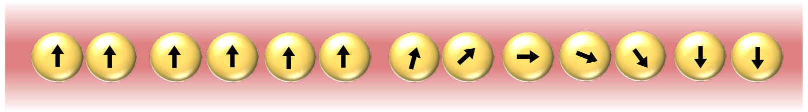
OBJECTIVE
Engineer elementary ***atomtronic*** circuits

EXPERIMENTAL PLATFORM 2 (Trento)
Sodium bosonic atoms in two different spin states

OBJECTIVE
Engineer elementary ***spintronic*** circuits



Atomic currents

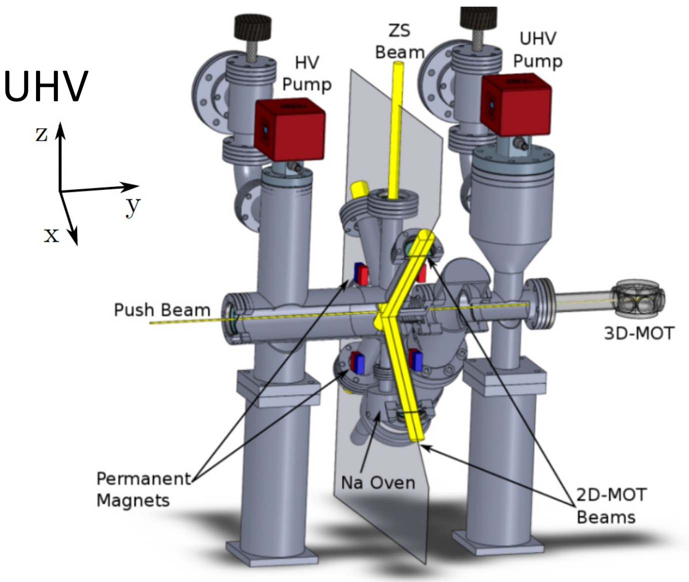


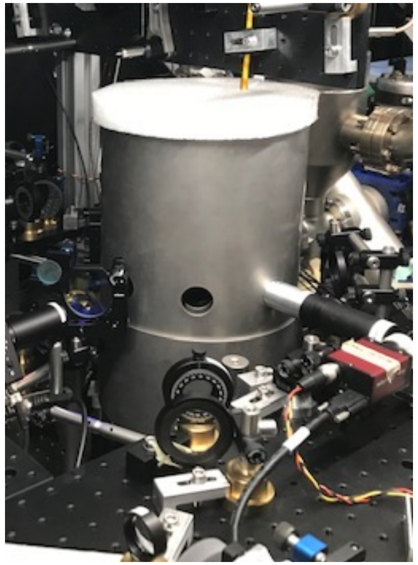
Spin currents

EXPERIMENTAL PLATFORM

ISOLATION
Neutral gases in a clean UHV

Pressure
10^{-10} mbar





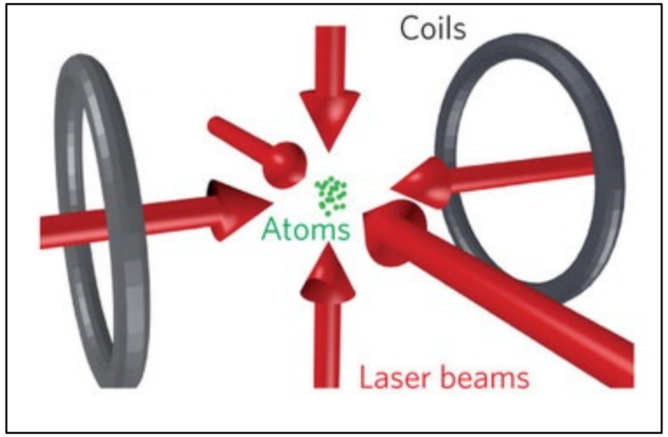
Magnetic shielding

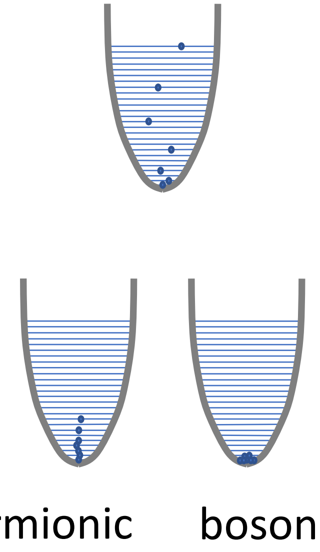
Field stability
10^{-5} Gauss

COOLING
Laser cooling + evaporative cooling

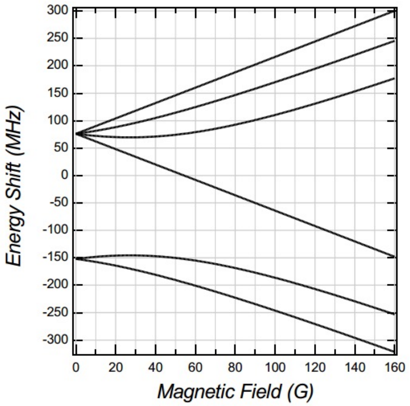
Temperatures	10-100 nK
Densities	10^{14} atoms/cm^3

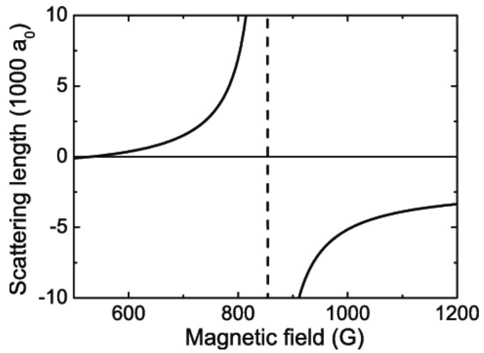
Ultracold gases (quantum degenerate)





ULTIMATE CONTROL of internal and external degrees of freedom



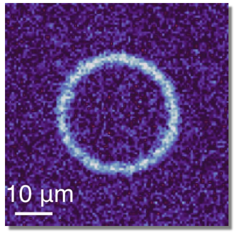


Typically we can chose/modify the **internal state** of the atomic **population** and their **interactions**

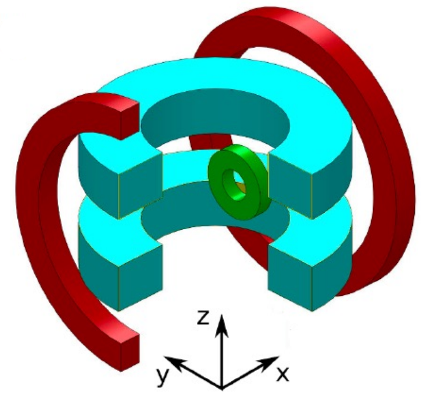
Microwave fields (uniform)
Raman coupling (local)

Technology developed in Spoke 3

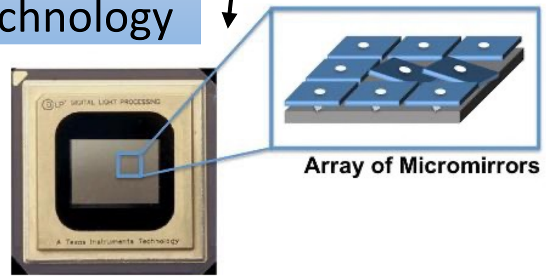
Control the **external degrees of freedom** generating superfluid currents



Trap the gas in magnetic or optical potentials with different geometries

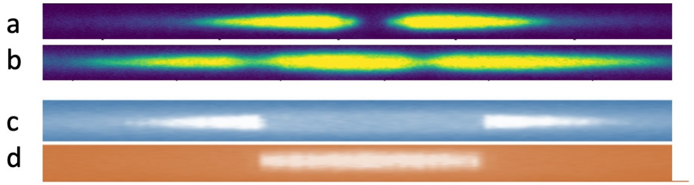


DMD technology



DMD Chip

Destructive absorption imaging (HR)
Non-destructive imaging (live)

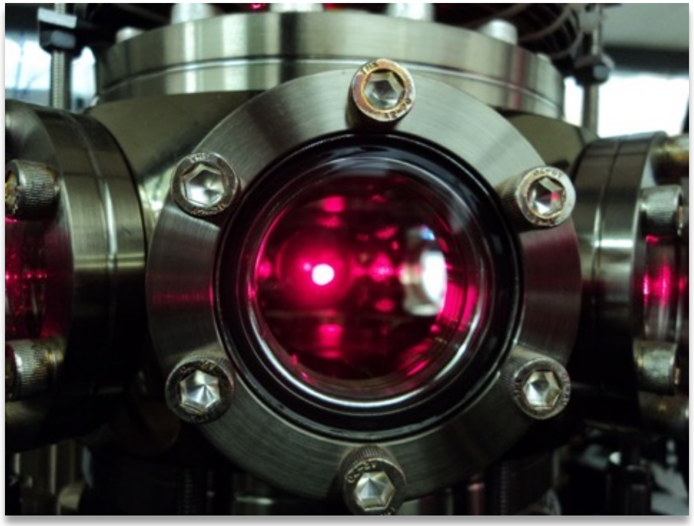


EXPERIMENTAL PLATFORM 1 (Florence)
Lithium fermionic atoms

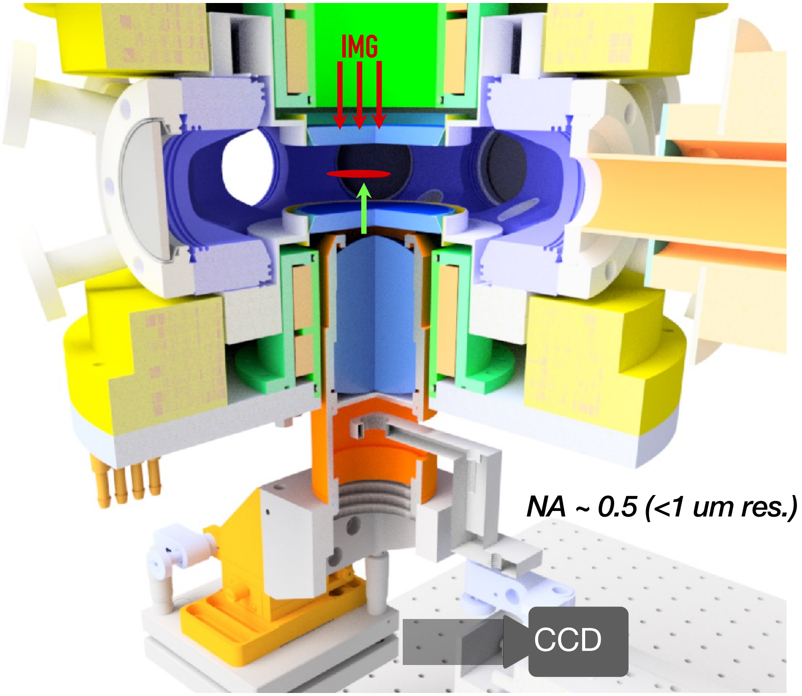
OBJECTIVE
Engineer elementary ***atomtronic*** circuits

^{6}Li

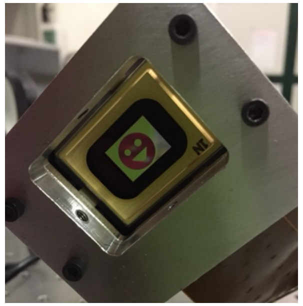
Cold fermionic lithium sample

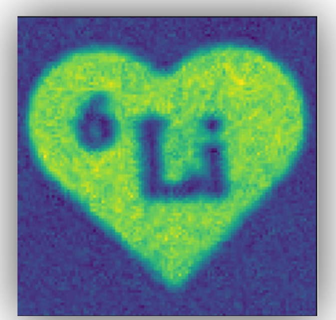


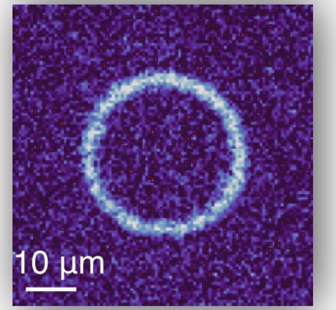
HR imaging system

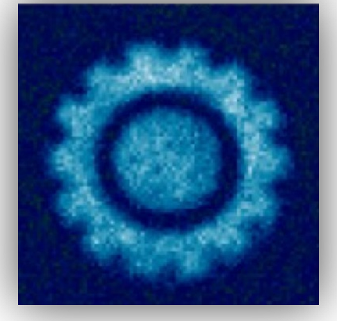


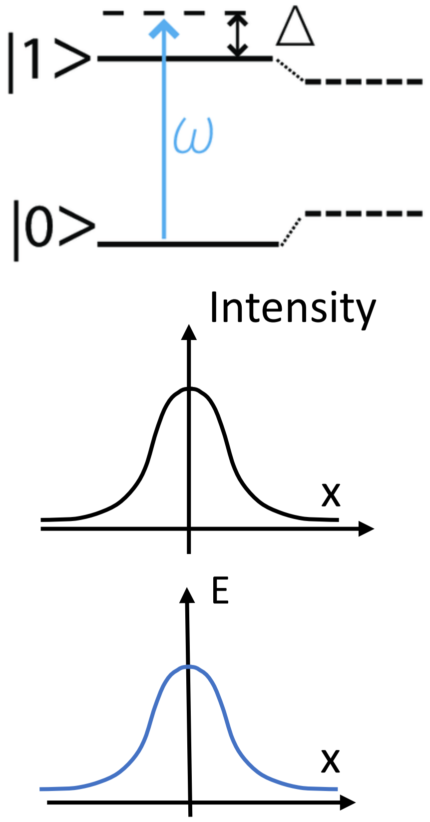
Arbitrary-shaped optical trapping potentials



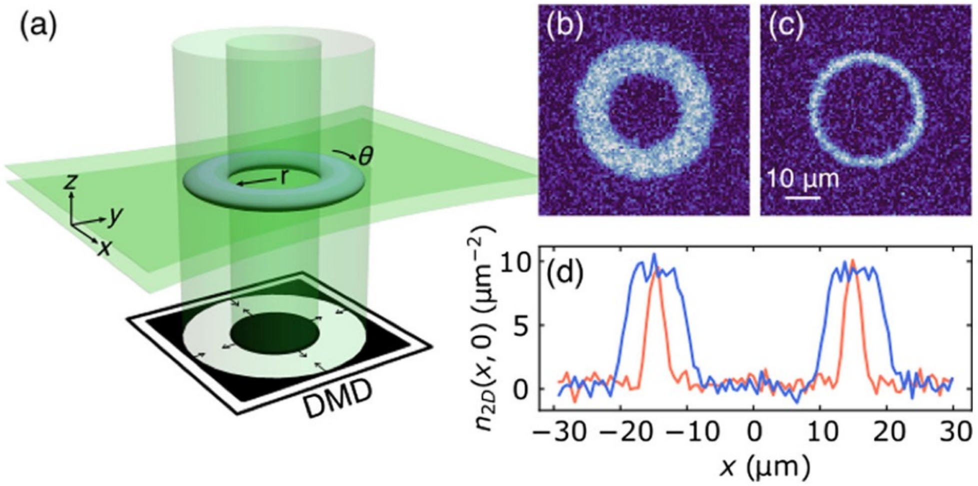




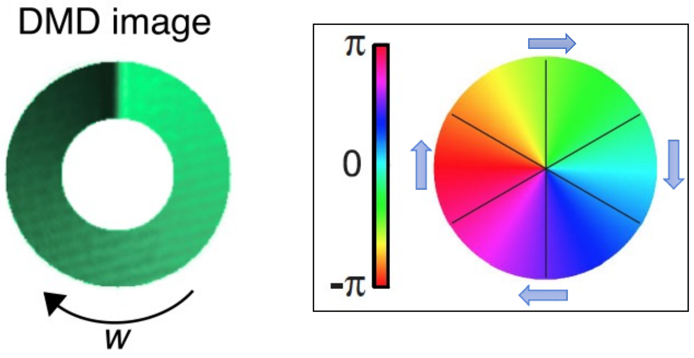




Optical trap
(repulsive light)



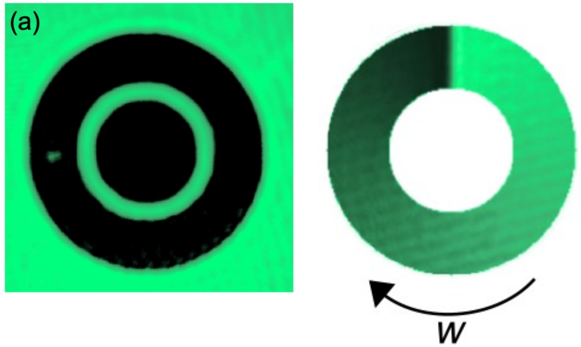
Phase imprinting (pulsed light)

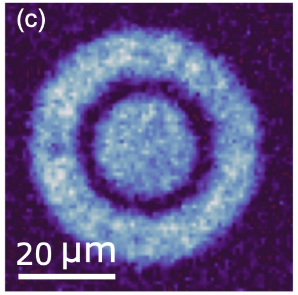


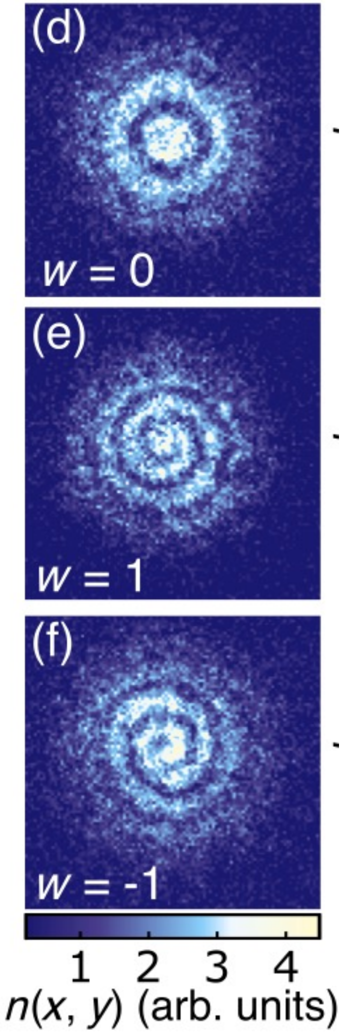
Generating atomic superfluid currents

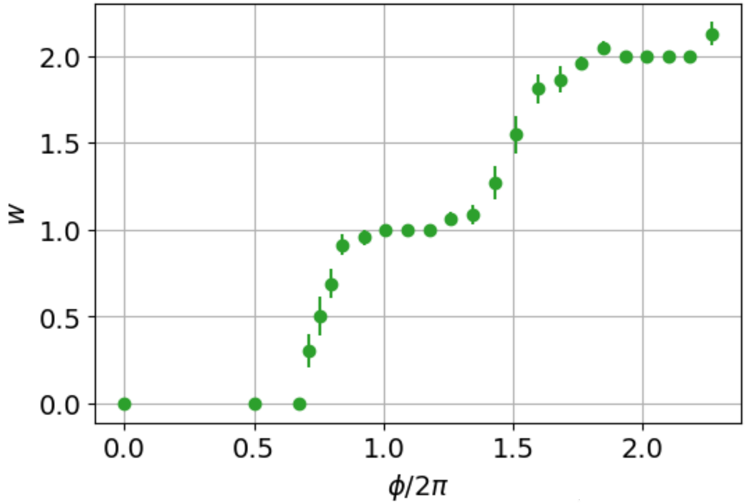
Loop -> Quantized circulation

Vortex imprinting + counting



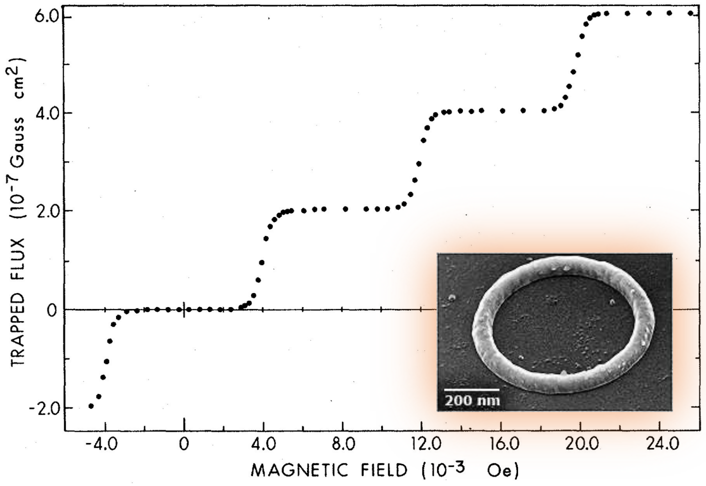






Quantization of circulation

Quantization of magnetic flux



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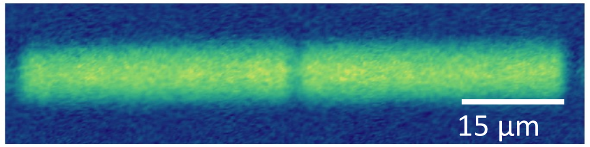
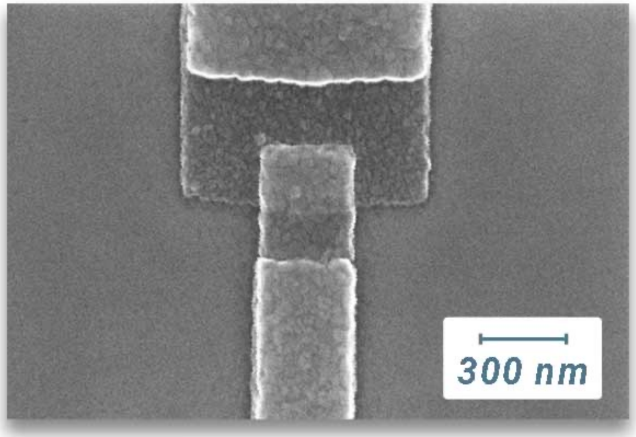
Josephson effect

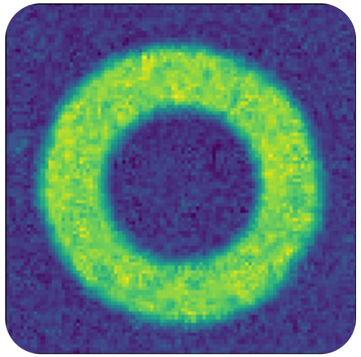


Kwon et al., Science 369 (2020)

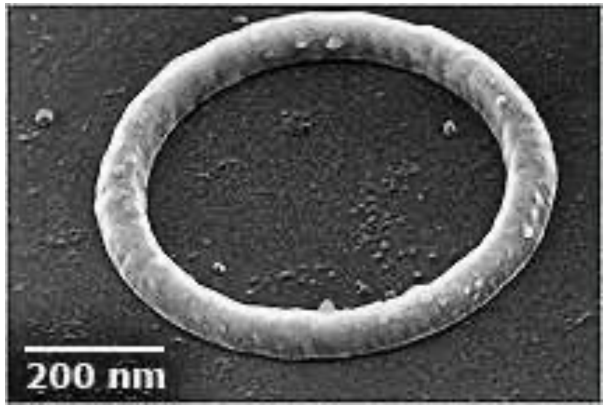


SEM image courtesy of the Institute for Quantum Computing (IQC) at the University of Waterloo

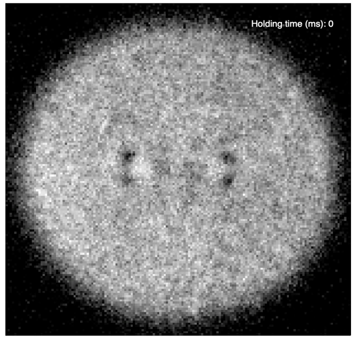
Persistent currents



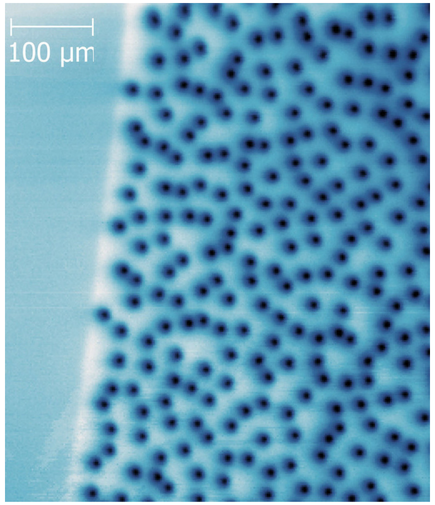
Del Pace et al., PRX 12 (2022)



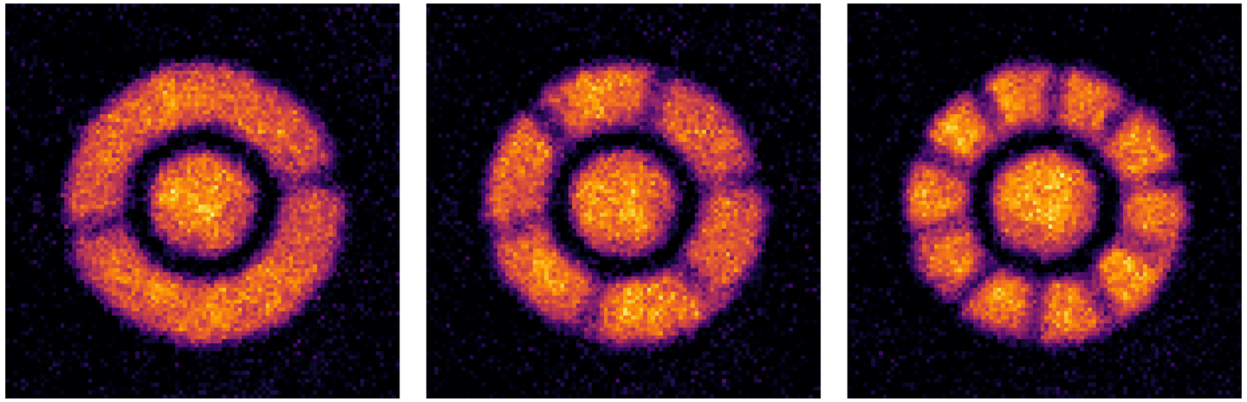
Vortex dynamics



Kwon et al., Nature 600 (2021)



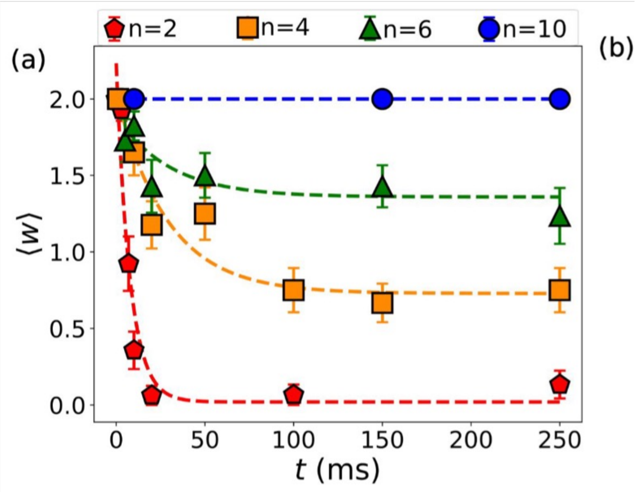
Josephson-junction arrays



Pezzè et al. arXiv:2311.05523 (2023)

Josephson _persistent_ currents as a function of barriers number (V_0~1.3 m and w_b~2ξ):

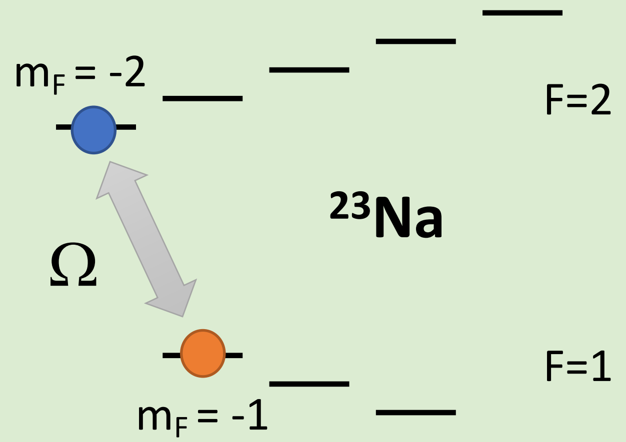
Adding Josephson links stabilizes persistent currents.

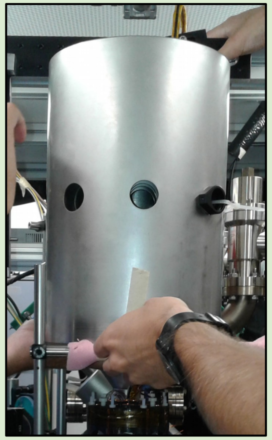


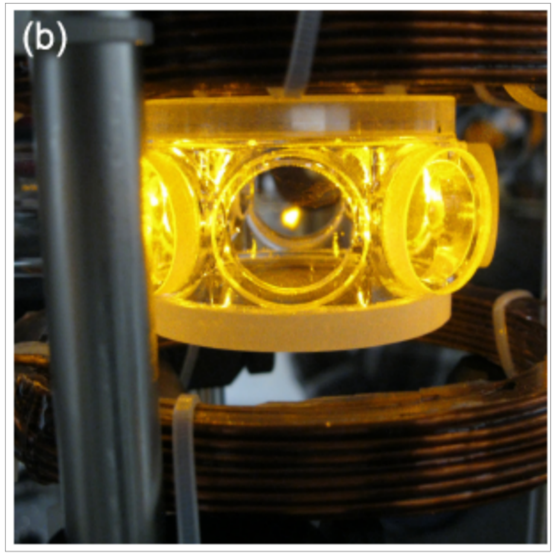
EXPERIMENTAL PLATFORM 2 (Trento)
Sodium bosonic atoms

OBJECTIVE
Engineer elementary ***spintronic*** circuits

Two-component superfluid spin mixture







Total DENSITY

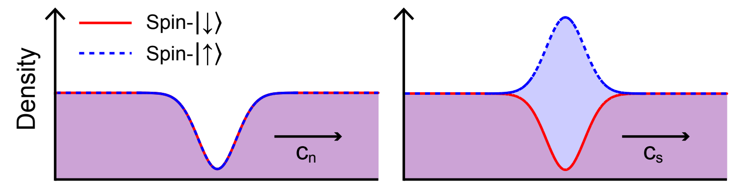
$$n = n_a + n_b$$

$$\Phi = \phi_a + \phi_b$$

SPIN density (magnetization)

$$m = n_a - n_b$$

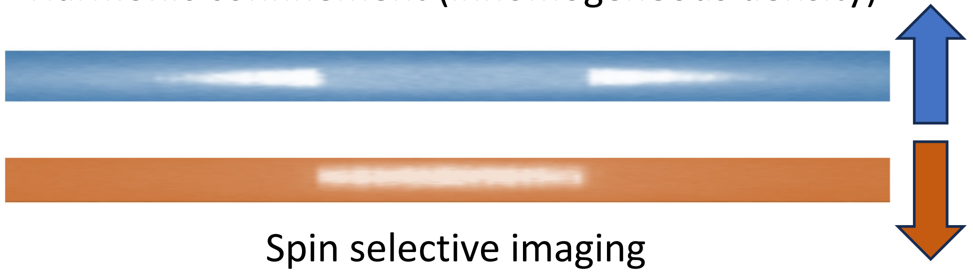
$$\phi = \phi_a - \phi_b$$



Common mode

Differential mode

Elongated quasi 1D system
Harmonic confinement (inhomogeneous density)



Spin selective imaging

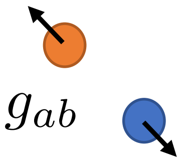
Coupled two-component spin system

$$i\hbar\frac{\partial}{\partial t}\psi_a = \left(-\frac{\hbar^2}{2m}\nabla^2 + V + g_a|\psi_a|^2 + g_{ab}|\psi_b|^2\right)\psi_a - \frac{\hbar\Omega}{2}\psi_b$$

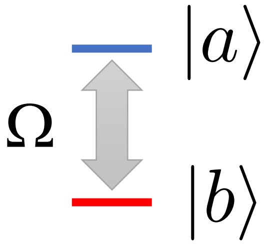
$$i\hbar\frac{\partial}{\partial t}\psi_b = \left(-\frac{\hbar^2}{2m}\nabla^2 + V + g_b|\psi_b|^2 + g_{ab}|\psi_a|^2 - \hbar\Delta\right)\psi_b - \frac{\hbar\Omega^*}{2}\psi_a$$

Intracomponent interactions

Intercomponent interactions



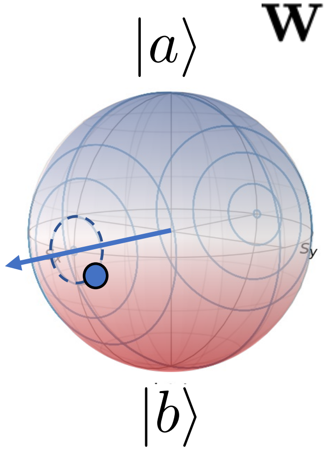
Coherent coupling



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

Non interacting system

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

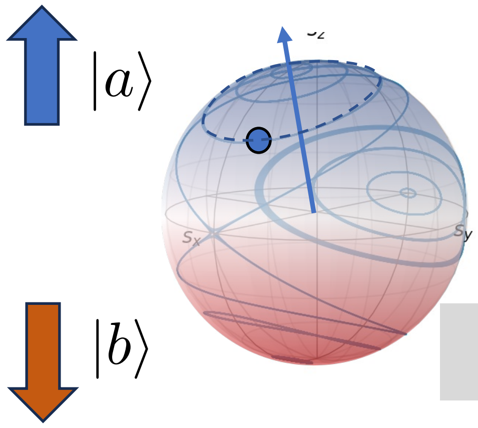


Coupling dominates

PARAMAGNETIC

Many-body interacting system

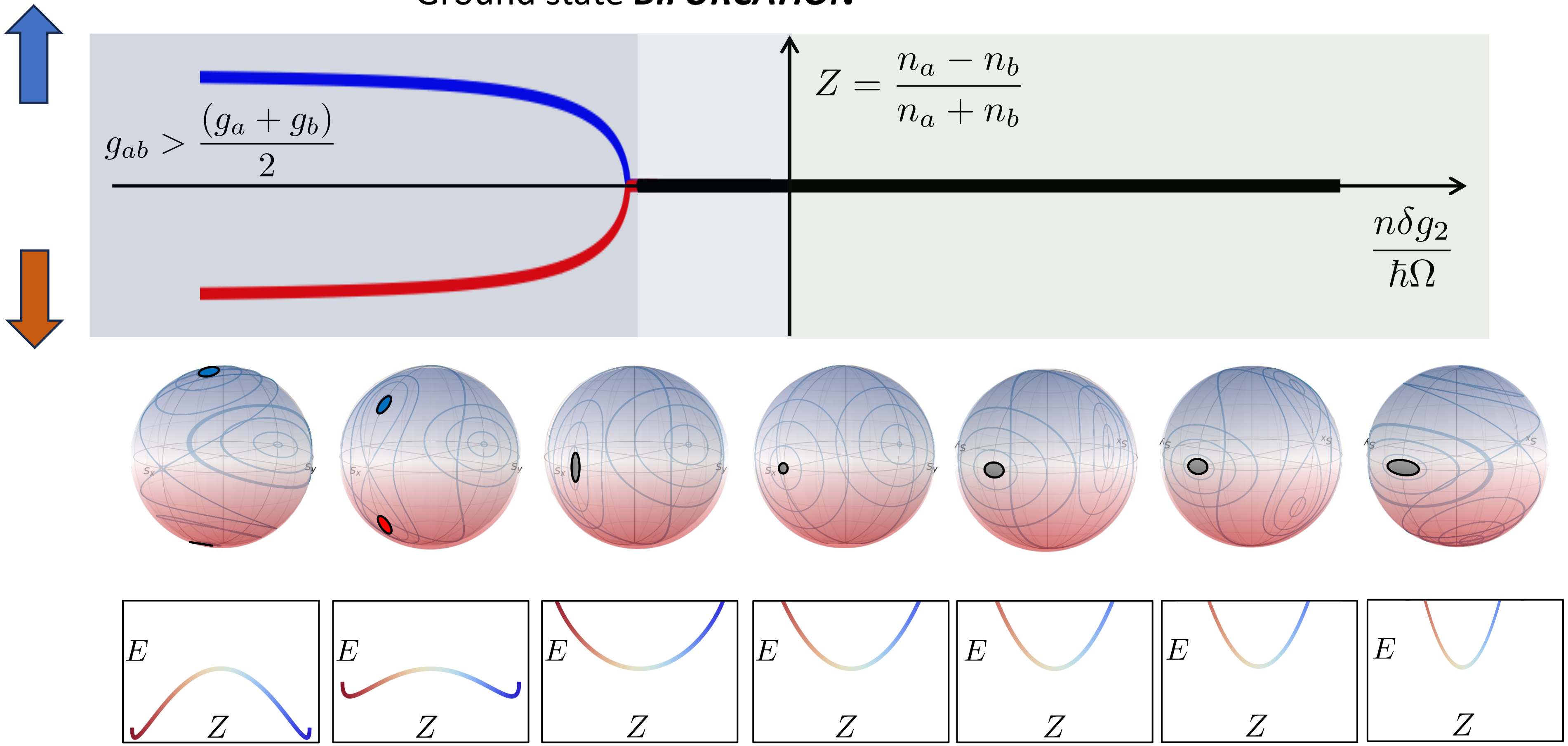
$$\mathbf{W}_{\text{eff}} = \left(\Omega, 0, \Delta - \frac{n\delta g_1}{\hbar} - \frac{n\delta g_2 Z}{\hbar}\right)$$



Spin interactions dominate

FERROMAGNETIC

Ground state ***BIFURCATION***

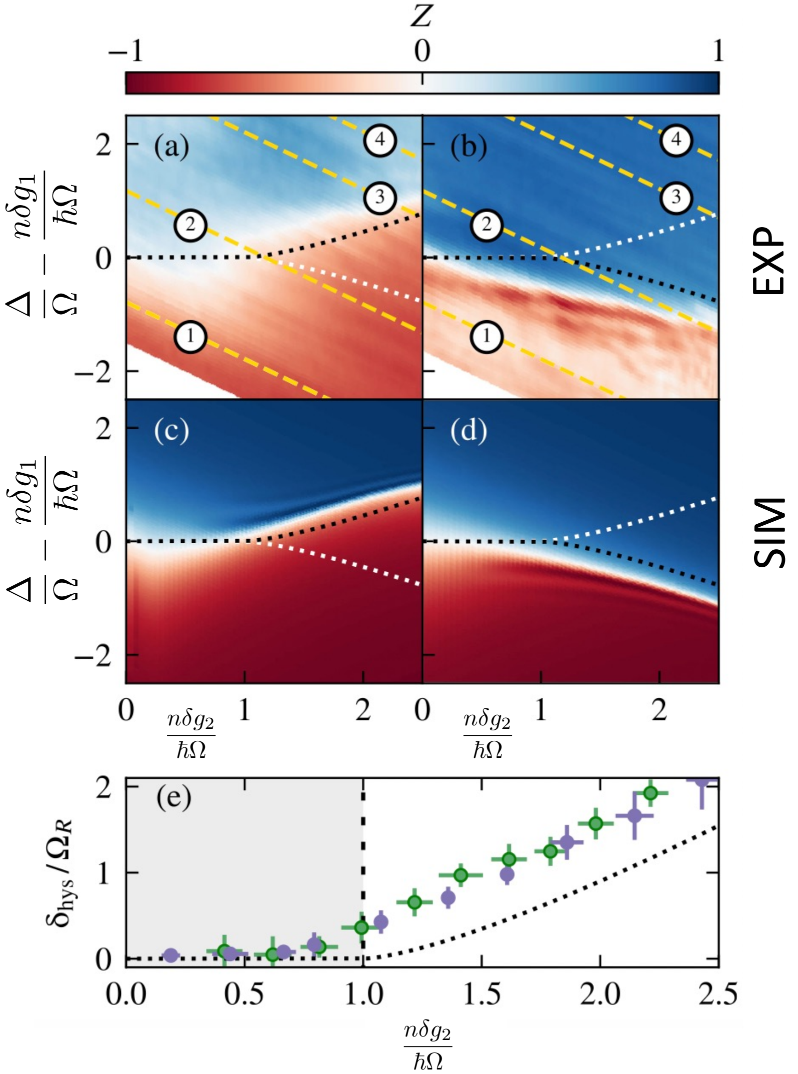


$$\delta g_1 = \frac{(g_a - g_b)}{2}$$

$$\delta g_2 = \frac{(g_a + g_b)}{2} - g_{ab}$$

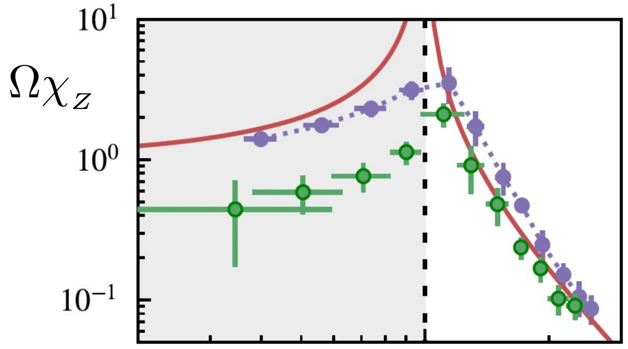
$$E(Z,\phi) \propto (n\delta g_1 - \hbar\Delta)\, Z + \frac{n\delta g_2}{2} Z^2 - \hbar\Omega\sqrt{1 - Z^2}\cos\phi$$

Characterization of the PARA-FERRO **phase diagram**

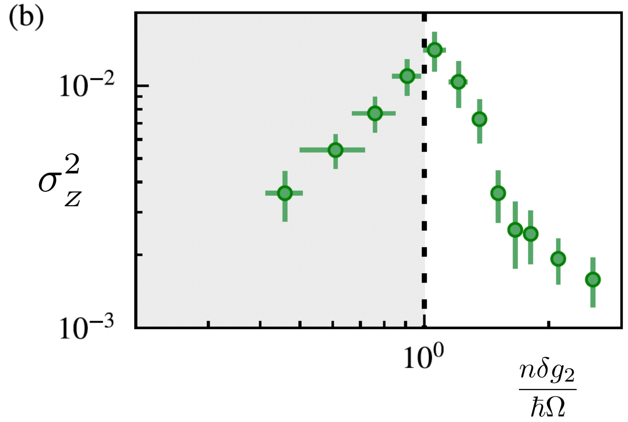


Observation of **divergence** across the transition

MAGNETIC SUSCEPTIBILITY

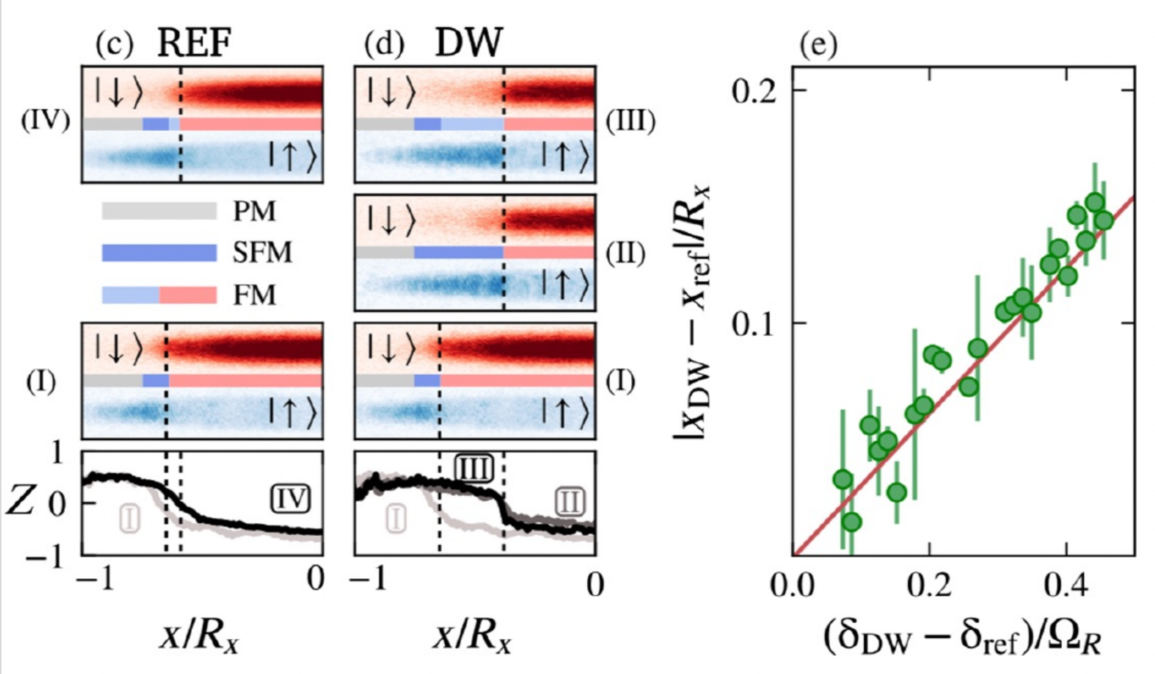


FLUCTUATIONS OF THE MAGNETIZATION



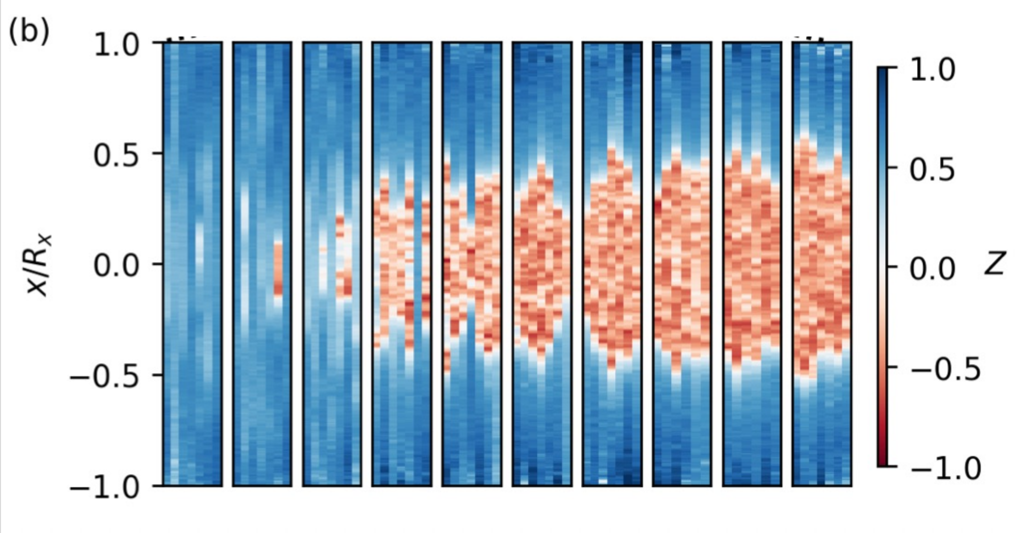
Generation of Ferromagnetic **DOMAIN WALLS**

On demand
(controlled position and time)

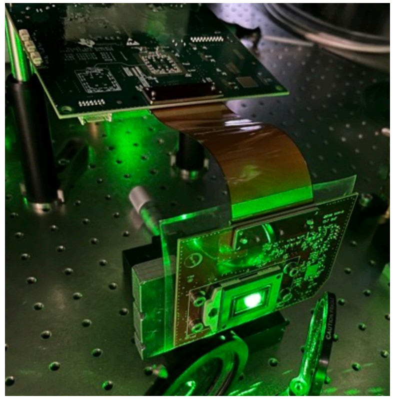


R. Cominotti et al., PRX **13**, 021037 (2023)

Spontaneously formed via false vacuum decay mechanism
(random position and time)

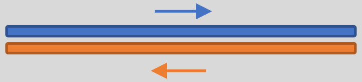


A. Zenesini et al., arXiv: 2305.05225, next week on Nature Physics

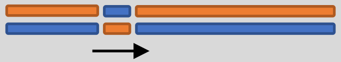


Use DMDs to
trap atoms in an arbitrary potentials (circuits)
Manipulate magnetic properties in space and time

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

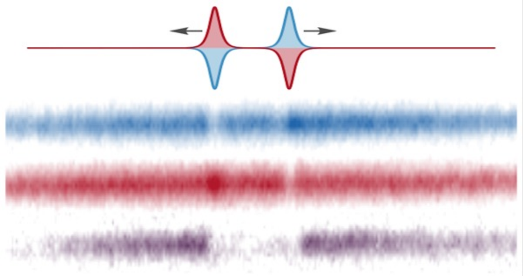


CW spin current



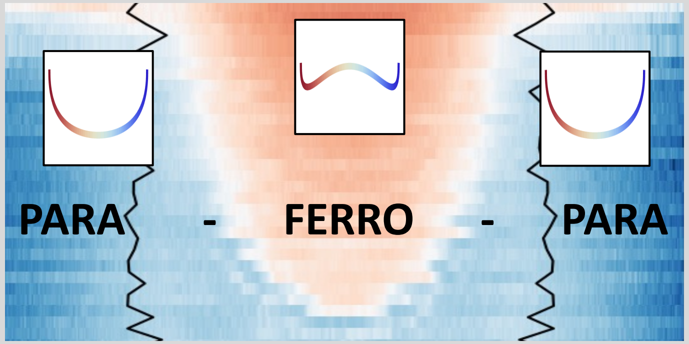
Pulsed current (magnetic solitons)

Controlled production of magnetic solitons



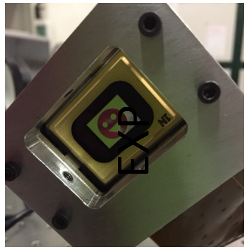
A. Farolfi et al., PRL **125**, 030401 (2020)

Study **transport across magnetic heterostructures**



R. Cominotti et al., PRX **13**, 021037 (2023)

CONCLUSIONS



Spatial control of laser intensity

Shape the geometry
Set atoms into motion

Local interactions
Induce spin current

CNR-INO, Florence

CNR- INO, Trento

EXPERIMENTAL PLATFORM 1 (Florence)
Lithium fermionic atoms

OBJECTIVE
Engineer elementary ***atomtronic*** circuits

EXPERIMENTAL PLATFORM 2 (Trento)
Sodium bosonic atoms in two different spin states

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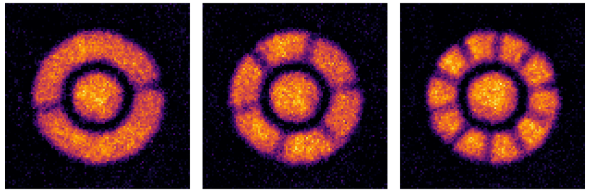
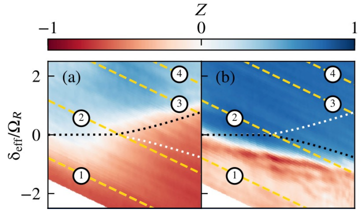
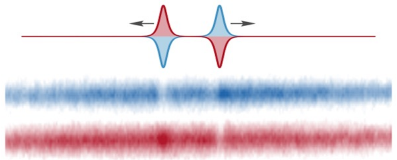
Engineer elementary ***spintronic*** circuits







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CNR-INO, Florence

CNR- INO, Trento

EXPERIMENTAL PLATFORM 1 (Florence)
Lithium fermionic atoms

OBJECTIVE
Engineer elementary ***atomtronic*** circuits

EXPERIMENTAL PLATFORM 2 (Trento)
Sodium bosonic atoms in two different spin states

OBJECTIVE
Engineer elementary ***spintronic*** circuits