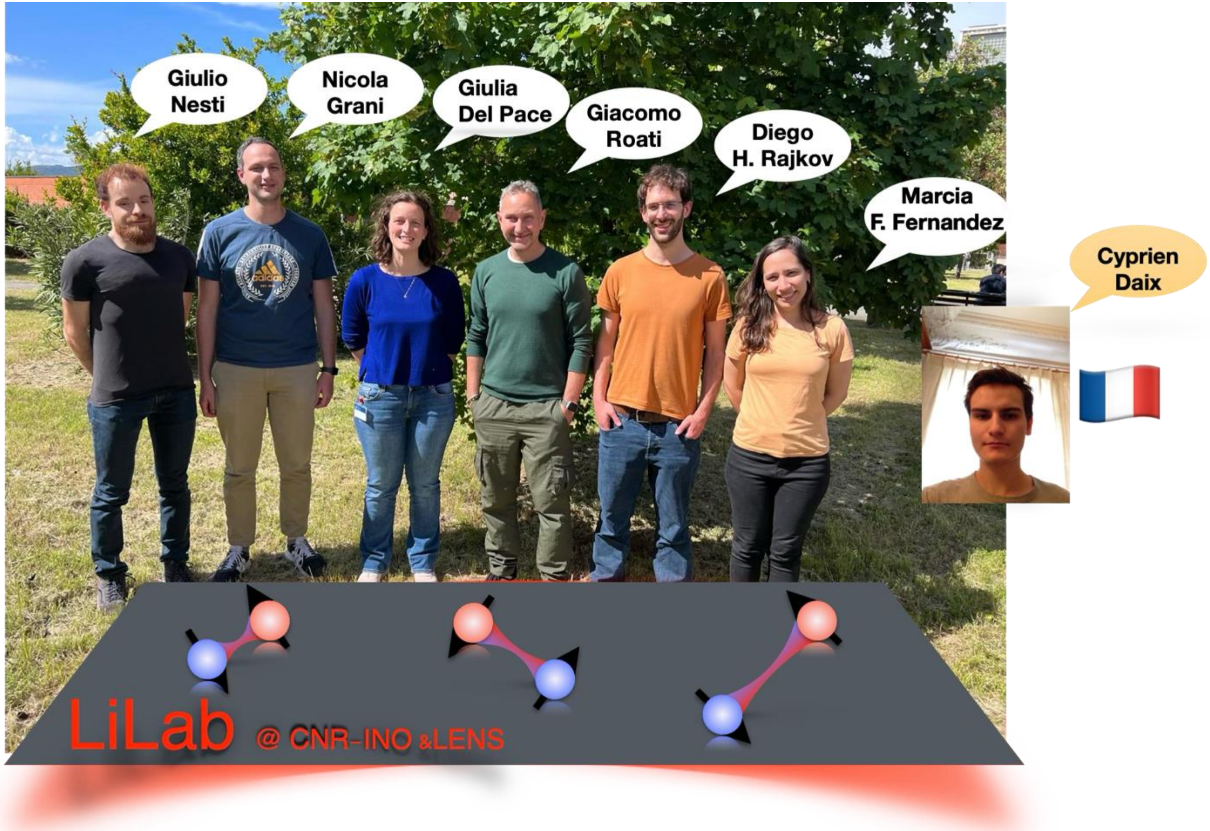
CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

INO Sesto Fiorentino

Giacomo Roati, Spoke 6

Secondo Congresso NQSTI, Roma 5-7 Febbraio 2025



LiLab collaborators:

Kwon, Scazza, Inguscio, Marino, Daix

Xhani, Pezze’, Donelli, Fort, Modugno, Galantucci, Singh, Amico, Barresi, Magierski, Wlazlowski

Spoke 6 @ CNR-INO in Sesto Fiorentino

A6.1 Integration of atomic devices:

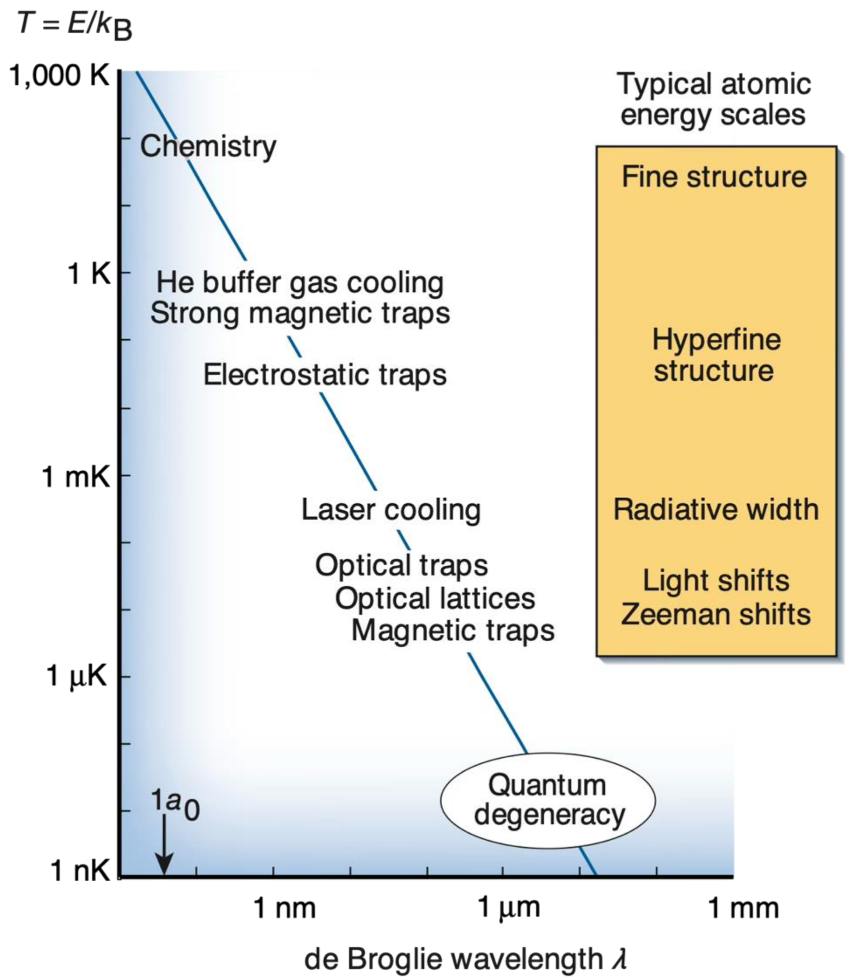
-Design and implementation of atomic circuits to resemble electron-based networks of different classes of conductors, semiconductors, superconductors or magnets.

-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.

(M12): A6.1 Design of atomtronic components for integrated quantum systems completed.

(M24): A6.1 Design developed and first characterization performed of atomtronic circuits.

(M36): A6.1 Demonstration of advanced sensing functionality of atomtronic circuits with integrated read-out.


$T = E/k_B$
1,000 K
1 K
1 mK
1 μK
1 nK
Chemistry
He buffer gas cooling
Strong magnetic traps
Electrostatic traps
Laser cooling
Optical traps
Optical lattices
Magnetic traps
Quantum degeneracy
$1a_0$
1 nm
1 μm
1 mm
de Broglie wavelength λ
Typical atomic energy scales
Fine structure
Hyperfine structure
Radiative width
Light shifts
Zeeman shifts

Introducing the context:

Atomtronics *is the emerging quantum technology of matter-wave circuits that coherently guide propagating ultracold atoms*

Amico et al., Rev. Mod. Phys. (2022)
Amico et al. Roadmap on atomtronics AVS Quantum Sci. 3 (2021)

Atomtronic circuits are suitable as cold-atom quantum simulators in which matter-wave currents are harnessed as probes to explore the physics of the system.

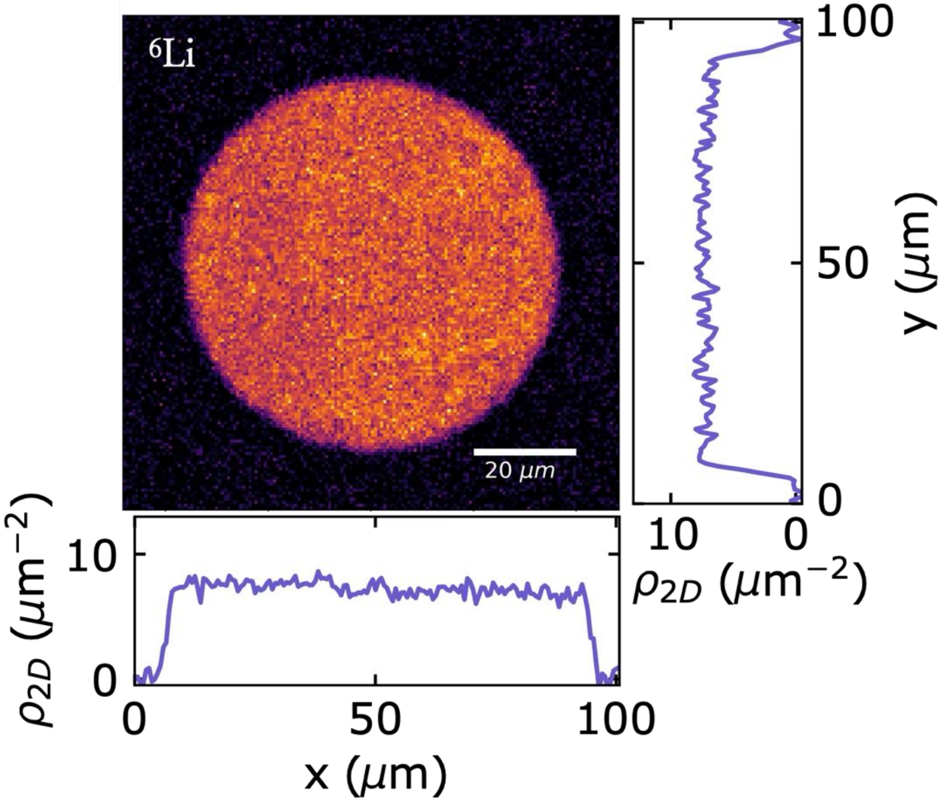
Atoms vs Electrons

Parameter	**Electrons in solids**	**Fermionic atoms**
Spin	1/2	1/2, 3/2, ...
Mass	$\sim 10^{-30}$ kg	10^{-26}–10^{-25} kg
Lattice constant	~0.5 nm	~500 nm **engineerable**
Tunneling rate / energy	$\sim 10^{14}$ Hz / $\sim 10^{4}$ K	100–1,000 Hz / 5–50 nK
Interactions	Coulomb	Van der Waals, on-site **tunable**
Density	$\sim 10^{23}$ cm^{-3}	10^{13}–10^{14} cm^{-3}
Fermi temperature (T_F)	$\sim 10^{4}$ K	~100 nK
Temperature	~ 1 K ($\sim 10^{-4}\,T_F$)	~10 nK ($\sim 0.1\,T_F$)

Schäfer et al. Nature Reviews Physics (2020)

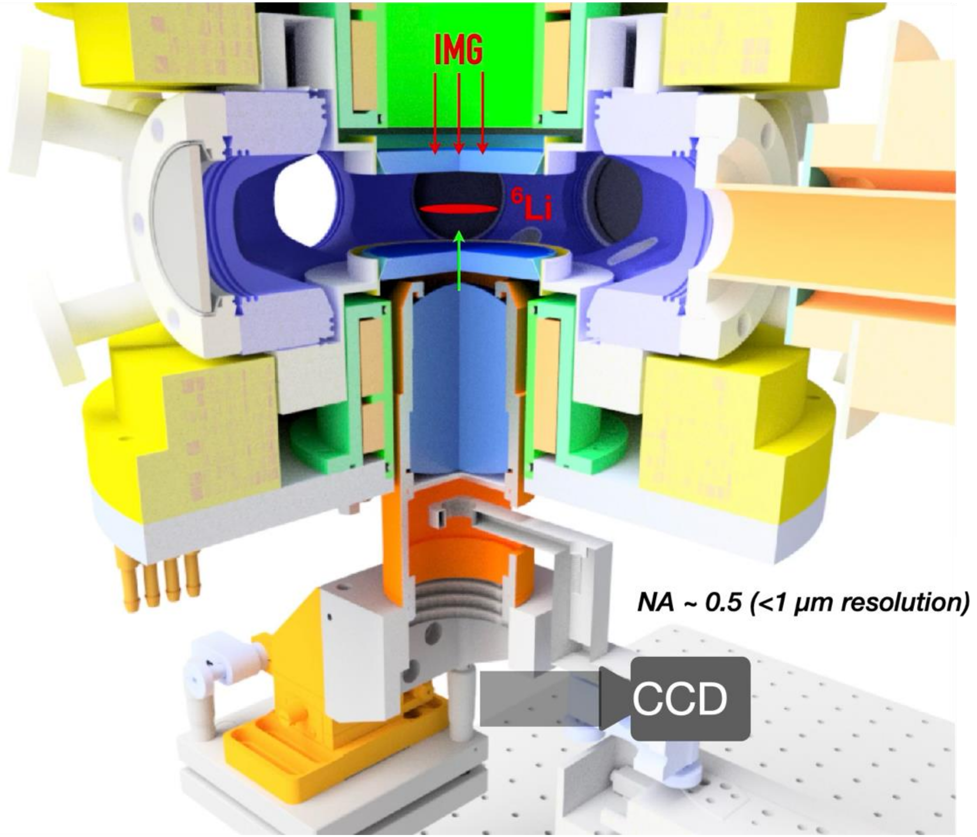
M12 Ingredient #1: homogeneous Fermi gases

$N_\uparrow = N_\downarrow \simeq 50000$ @ $T/T_F \sim .1$ -> $T < T_C$ ($T_C \sim 100$ nK)



M12

Ingredient #2: high-resolution imaging



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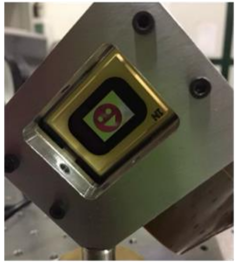
M12 Ingredient #3: shaping optical potentials



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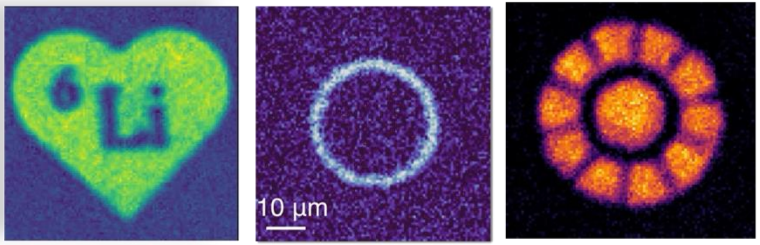
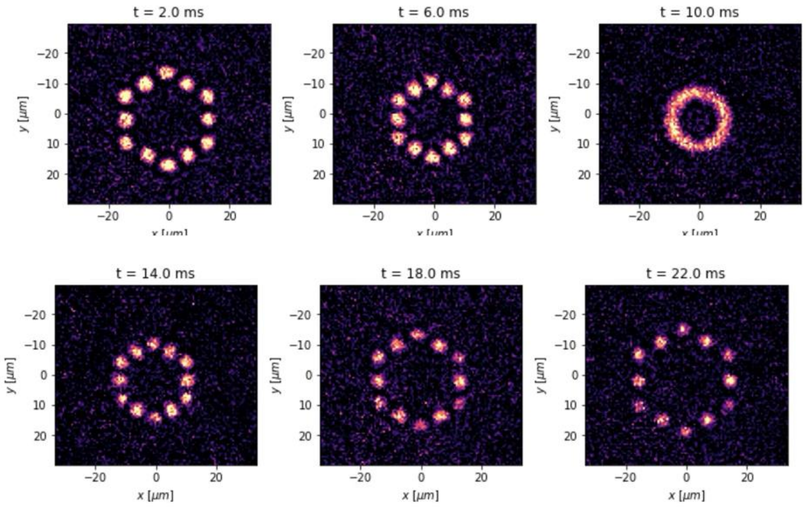
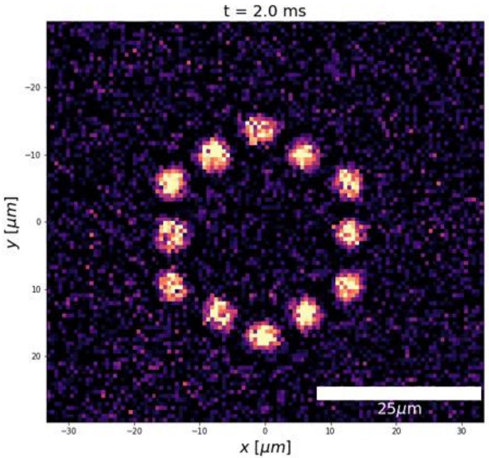


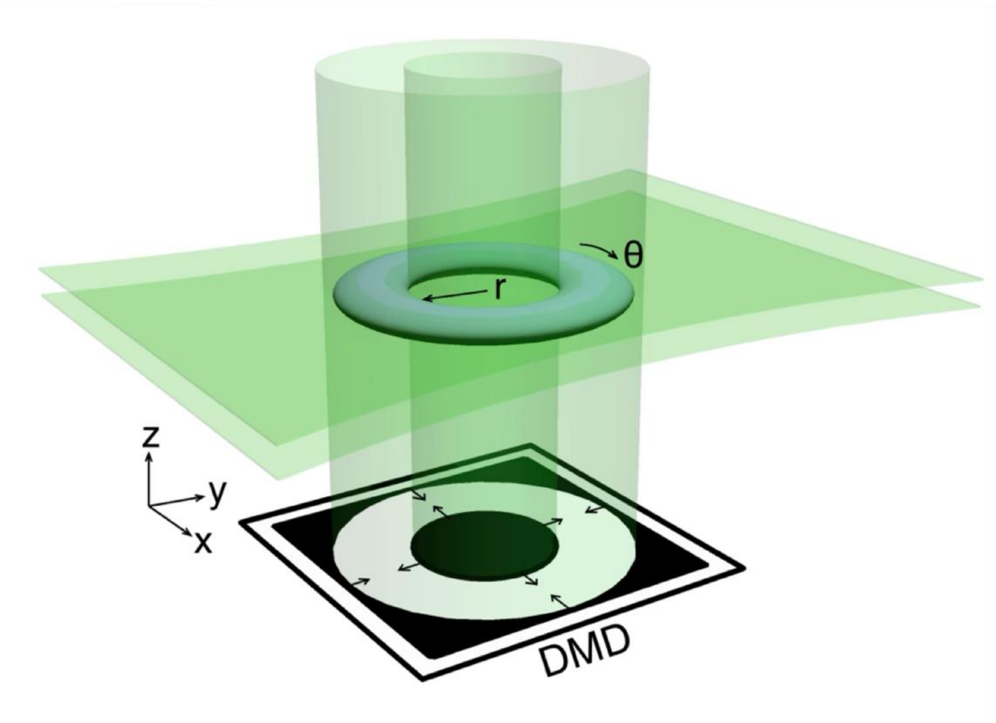


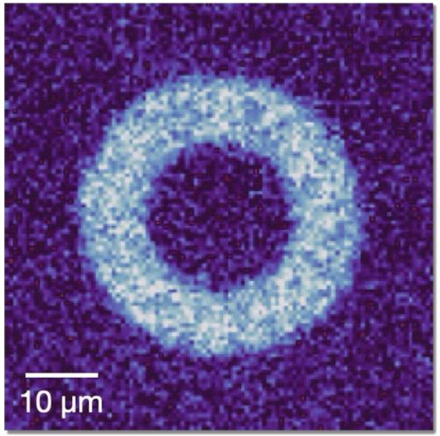


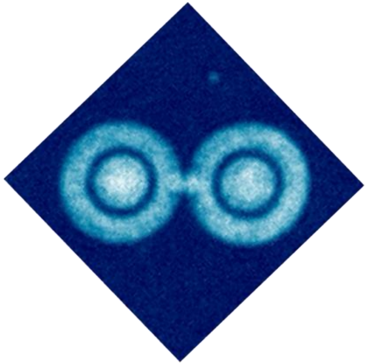
Ring geometry: touching macroscopic phase-coherence

Del Pace et al., PRX (2022)

Annular Fermi superfluids





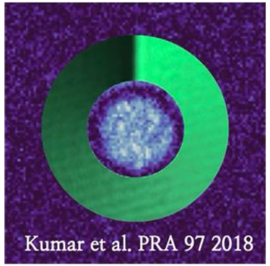


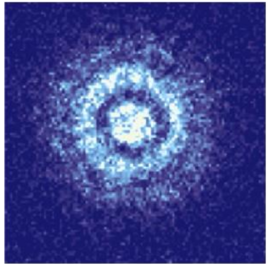
$N \simeq 10000$ per spin state @ $T/T_c \sim 0.3$

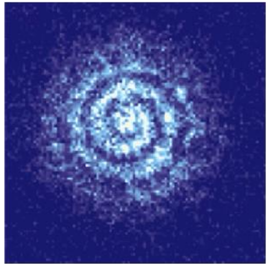
Del Pace et al. PRX (2022)

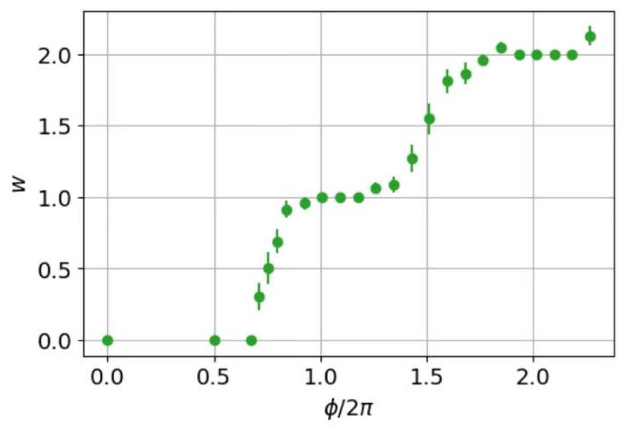
Exciting and detecting supercurrents

> counting spirals: an effective ampere-meter <



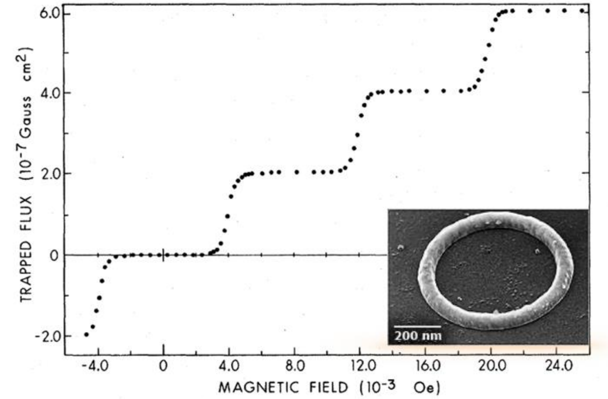






Quantisation of circulation

Quantisation of magnetic flux



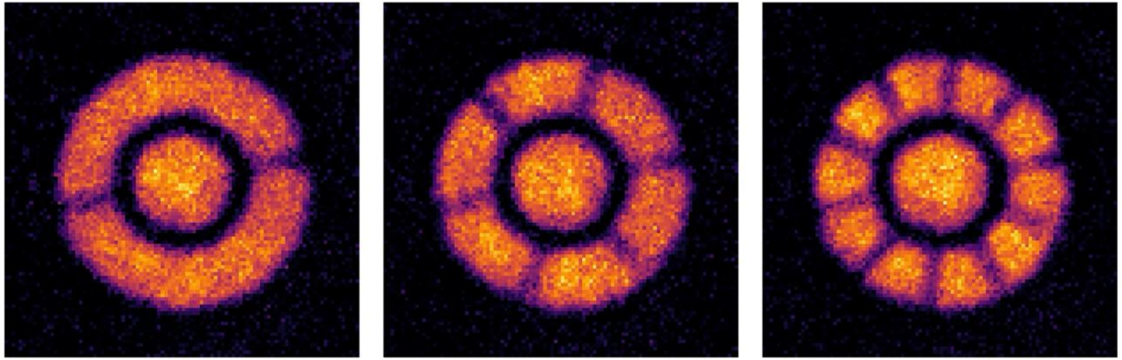
Eckel et al., PRX 2014

Corman et al. PRL 2014

Pezze' et al. Nat. Comm. (2024)

Marino et al. in preparation (2025)

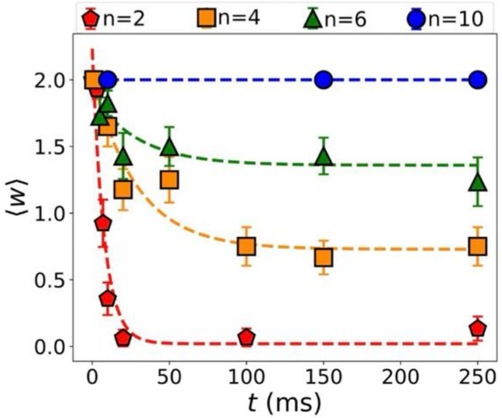
A Josephson junction necklace



Josephson Hamiltonians in ring potential: supercurrent stability a multi Josephson-links geometry.

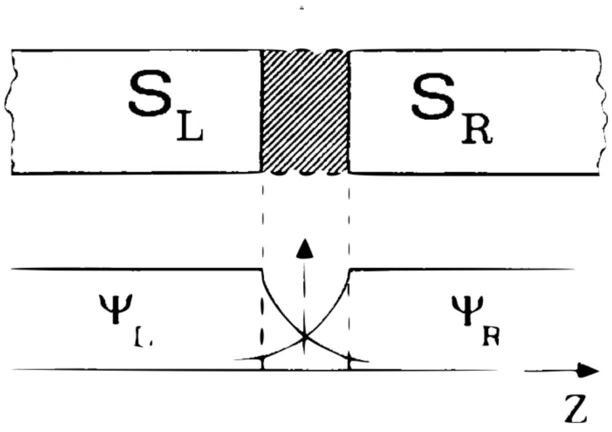
Full control of junctions properties (size, heights, clean environment).

Kuramoto-like models: network of JJ



M24 our atomic circuit #2

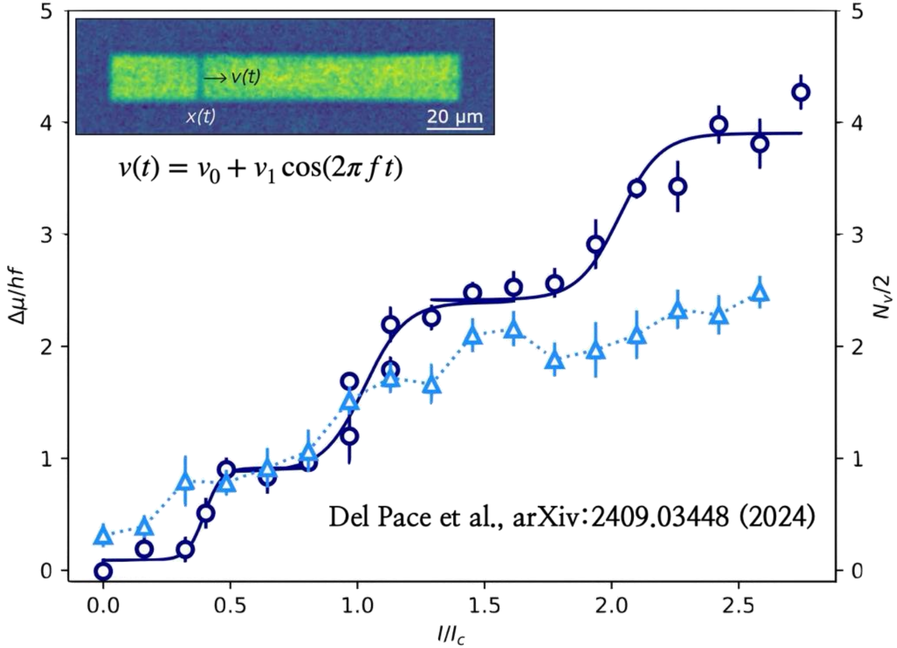
a Josephson junction: a paradigmatic quantum circuit



Shapiro steps in Fermi superfluids (new)

Injecting AC currents into homogeneous atomic Josephson junction: driven strongly-correlated Fermi superfluids. Shapiro steps: **synchronisation** effect in many-body quantum systems

in coll. with Seman @ UNAM, Amico & Singh @ TII Abu Dhabi



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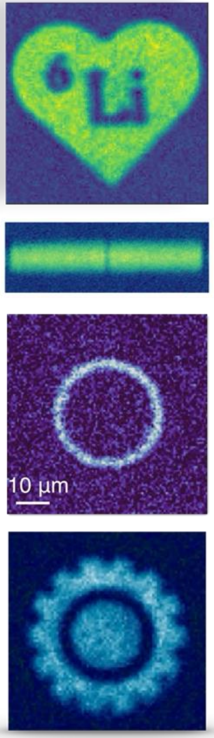
M36 On-going

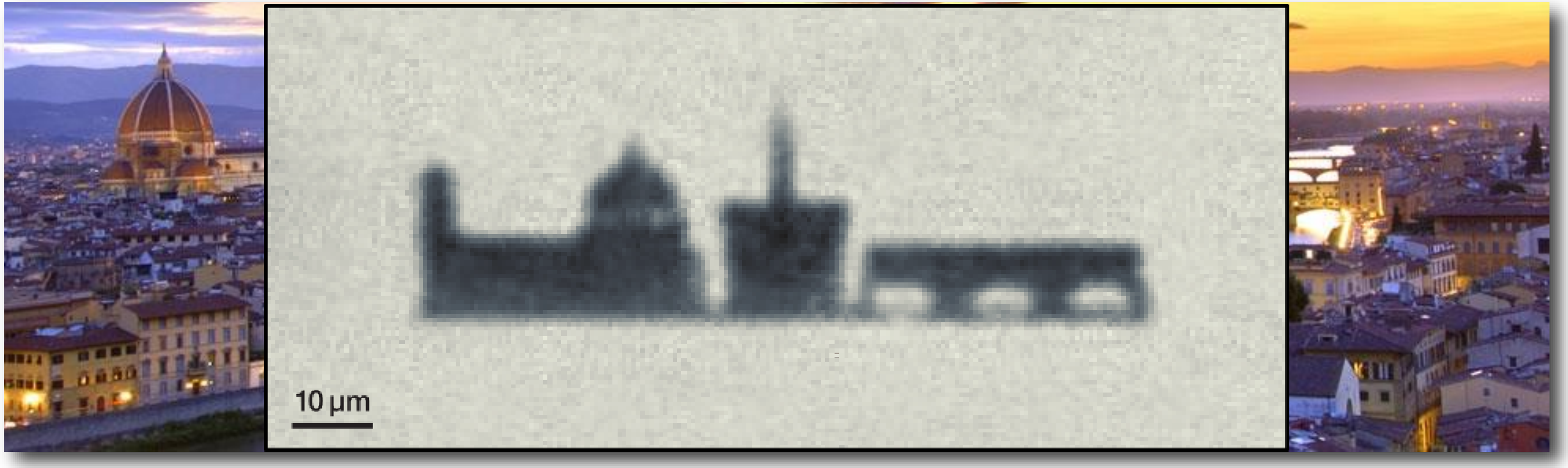


Open-access quantum simulator with integrated read-out:

New control system for remote access: multiple data acquisition

Machine learning protocols for the optimisation of the experimental cycle and performance

Li new−generation machine (experimental cycle 〈 500 ms) & standardised components



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http://quantumgases.lens.unifi.it//exp/li