Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

UNIVERSITÀ DEGLI STUDI FIRENZE

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

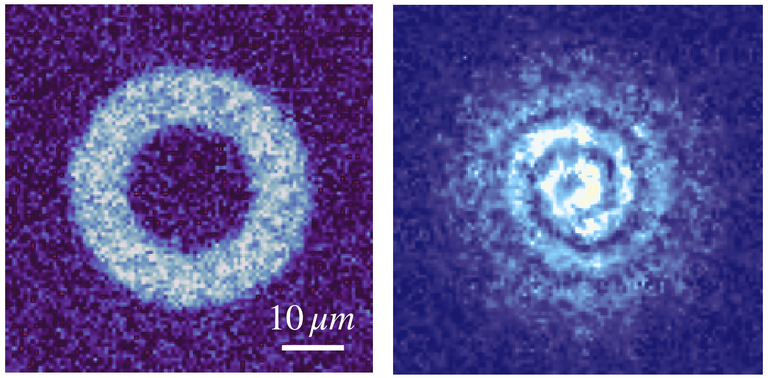
Lens European Laboratory for Non-Linear Spectroscopy

PASQuanS^2

ATOMIC SYSTEMS: PERSISTENT CURRENTS IN ATOMIC SUPERFLUID RINGS

Giulia Del Pace

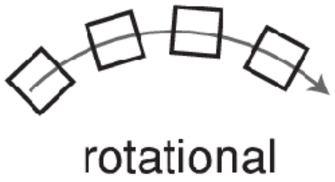
University of Florence



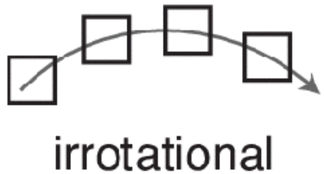
G. Del Pace, et al., '*Imprinting Persistent Currents in Tunable Fermionic Rings*' Phys. Rev. X **12**, 041037 (2022)

25/11/2024 - Workshop on Quantum Integration and Topology

SUPERFLOW UNDER ROTATION



rotational



irrotational

Classical fluid

Superfluid

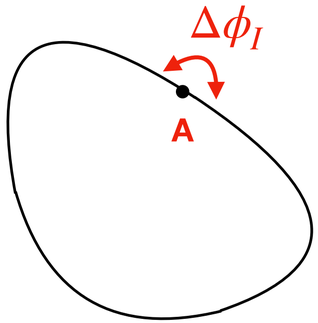
The motion of an inviscid fluid is irrotational

$$\nabla \times v = 0$$

Why irrotational?

$$v = \frac{\hbar}{m}\nabla\phi \quad \rightarrow \quad \nabla \times v \sim \nabla \times \nabla\phi = 0$$

Quantized circulation



$$\Gamma = \oint v \cdot dl = \frac{\hbar}{m}\Delta\phi = \frac{\hbar}{m} 2\pi\, w$$

For a superfluid:

$$v = \frac{\hbar}{m}\nabla\phi$$

$\Delta\phi = 2\pi\, w \rightarrow$ single-valuedness of wavefunction

$w \quad \rightarrow$ winding number

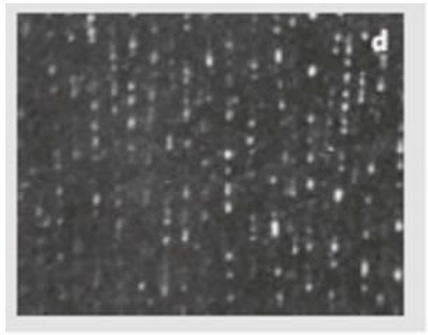
For $w \neq 0 \rightarrow n(r = 0) = 0$: the density vanishes at the center

Topological excitations in a multiply-connected geometry
Vortices, (meta)stable currents in rings

EXCITATIONS AT FINITE CIRCULATION

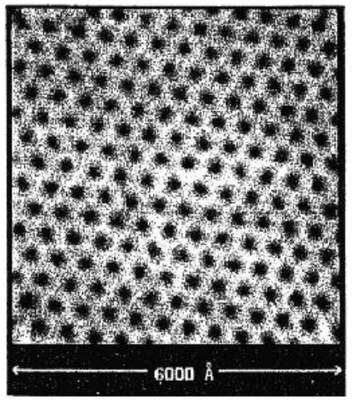
Quantized vortices in superfluids

Helium



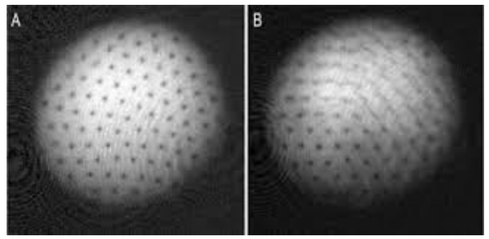
From: G. Bewley, et al., *Nature* 441, 588 (2006).

Superconductors



From: A. Abrikosov, *Nobel Lecture*, 2003: 254.

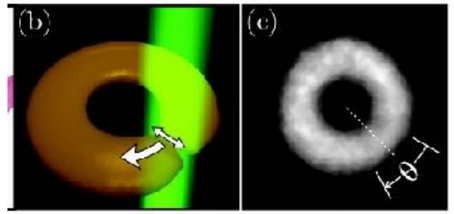
Atomic condesates

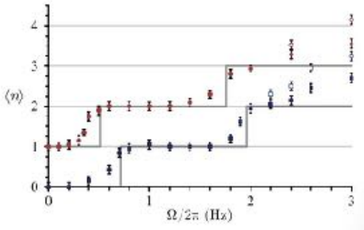


From: J. R. Abo-Shaeer, et al., Science 292, Issue 5516, pp. 476-479 (2001)

Quantized circulation in ring geometry

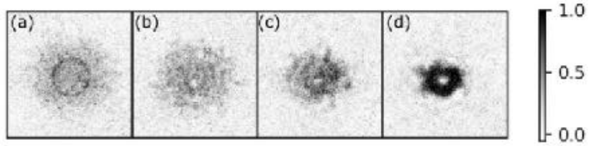
BEC





From: K. Wright, et al. Phys. Rev. Lett. 110.2 (2013)
Campbell group (NIST)
Dalibard group (ENS)
Perrin group (Sorbonne- CNRS)

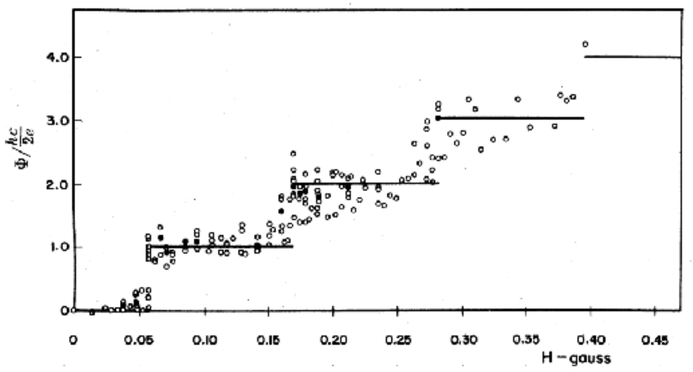
Fermionic superfluids



Y. Cai,et al., PRL128, 150401 (2022).

PERSISTENT CURRENTS

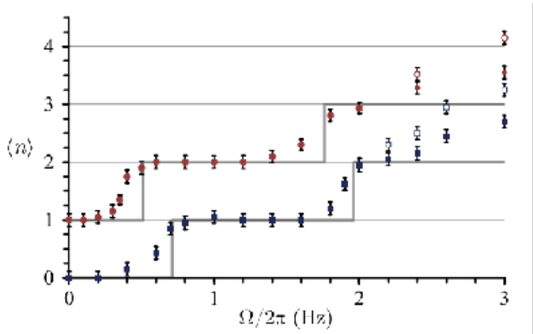
Superconducting ring pierced by magnetic field



B. S. Deaver and W. M. Fairbank PRL 7, 43 (1961)

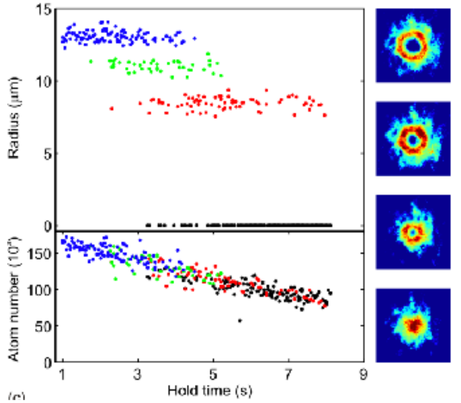
Persistent currents = **ground state** in the presence of the magnetic field

Rotating neutral superfluid ring



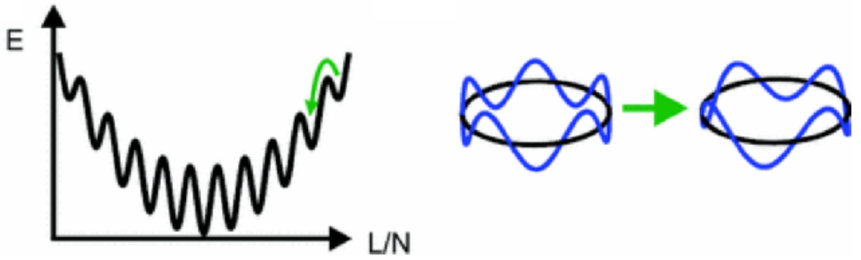
K. C. Wright, et al. PRL 110, 025302 (2013).

Fermions: Y. Cai,et al., PRL128, 150401 (2022).



S. Moulder, et al., PRA 86, 013629 (2012).

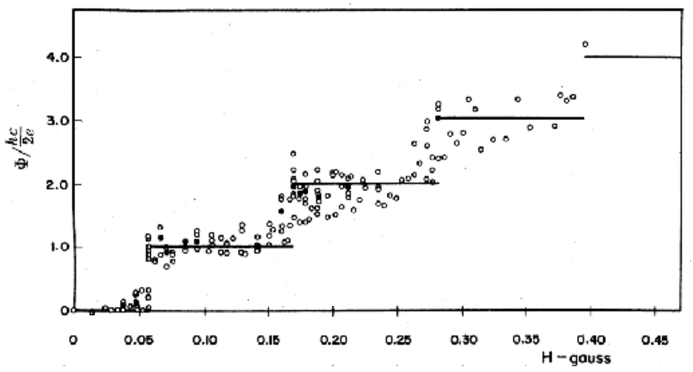
Persistent currents = **metastable** states



Picture taken from: S. Moulder, et al., PRA 86, 013629 (2012).

PERSISTENT CURRENTS

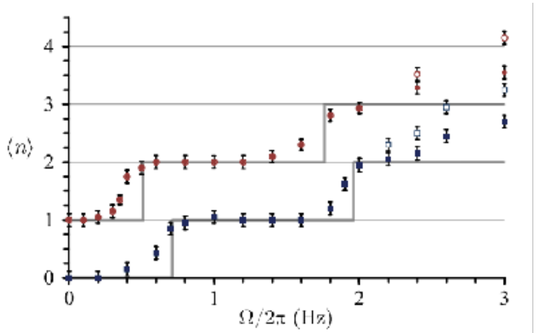
Superconducting ring pierced by magnetic field



B. S. Deaver and W. M. Fairbank PRL 7, 43 (1961)

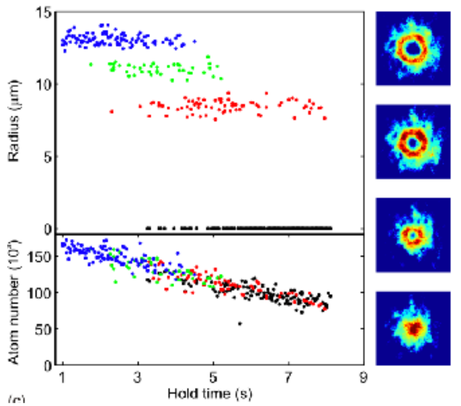
Persistent currents = **ground state** in the presence of the

Rotating neutral superfluid ring



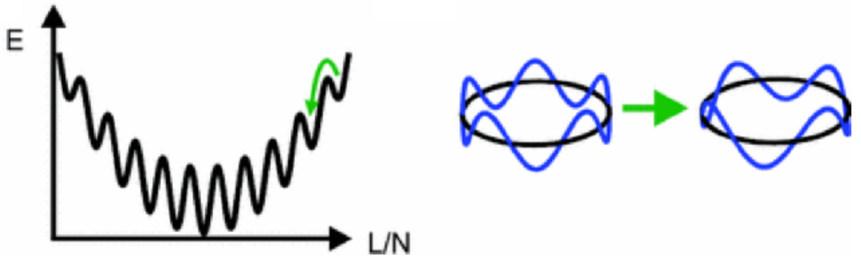
K. C. Wright, et al. PRL 110, 025302 (2013).

Fermions: Y. Cai,et al., PRL128, 150401 (2022).



S. Moulder, et al., PRA 86, 013629 (2012).

Persistent currents = **metastable** states



Picture taken from: S. Moulder, et al., PRA 86, 013629 (2012).

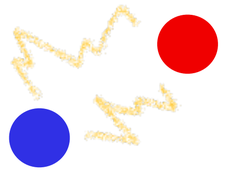
Persistent currents in ring atomic condensate

Manifestation of the **macroscopic phase coherence**, and of great interest for **quantum technologies**

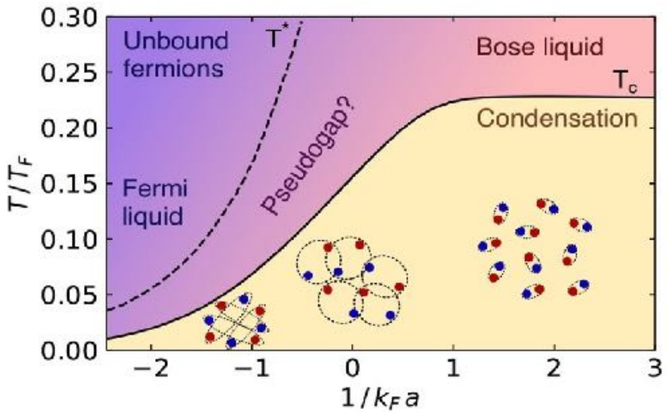
Review on atomtronics: L. Amico, et al., *Roadmap on Atomtronics: State of the art and perspective*, AVS Quantum Science 3, 039201 (2021).

TUNABLE FERMIONIC RINGS

BEC-BCS crossover



$a \rightarrow$ scattering lenght

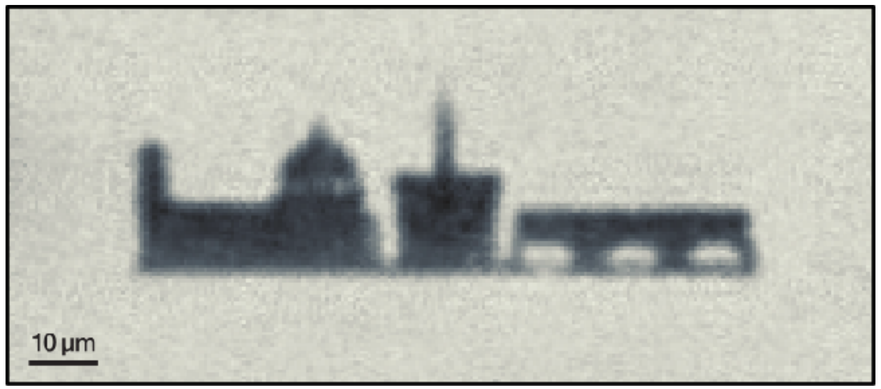


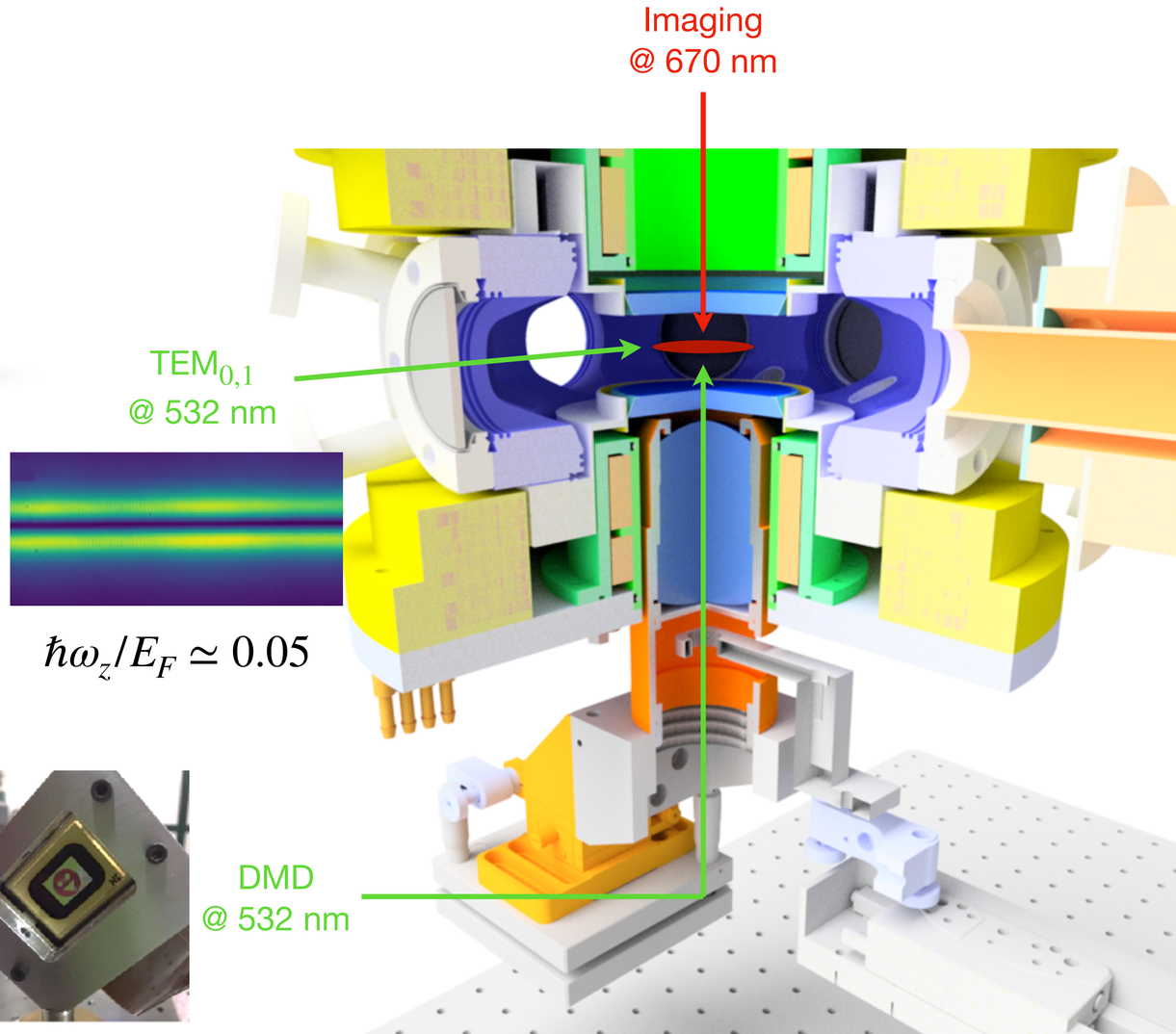
BEC
$1/k_F a = 3.6$

UFG
$1/k_F a = 0$

BCS
$1/k_F a = -0.4$

Arbitrary optical potential on a micron scale

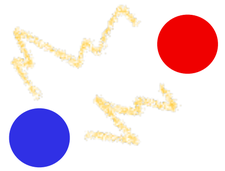




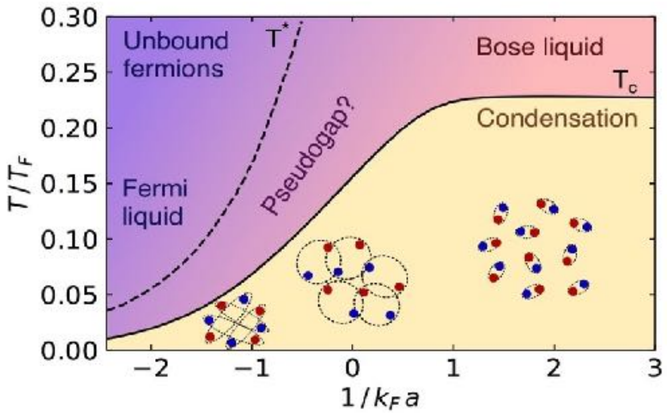
$\hbar\omega_z/E_F \simeq 0.05$

TUNABLE FERMIONIC RINGS

BEC-BCS crossover



$a \rightarrow$ scattering lenght

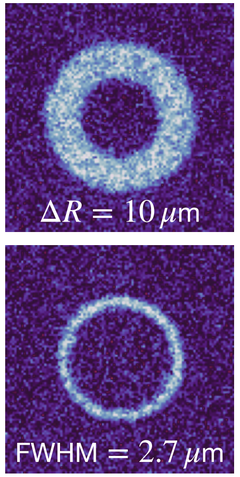


BEC
$1/k_F a = 3.6$

UFG
$1/k_F a = 0$

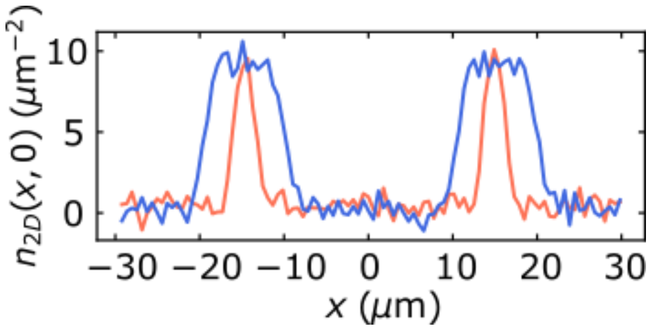
BCS
$1/k_F a = -0.4$

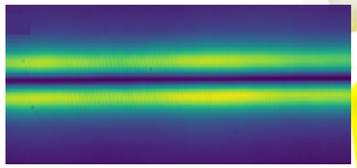
Tunable fermionic rings



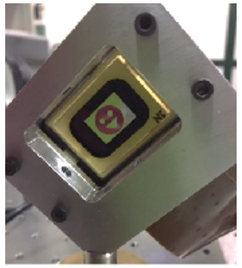
$N = 7.5 \times 10^3$ $\quad E_F/2\pi\hbar \simeq 9$ kHz

$T = 0.4\,T_c \simeq 60$ nK $\quad h\nu/E_F \simeq 0.05$





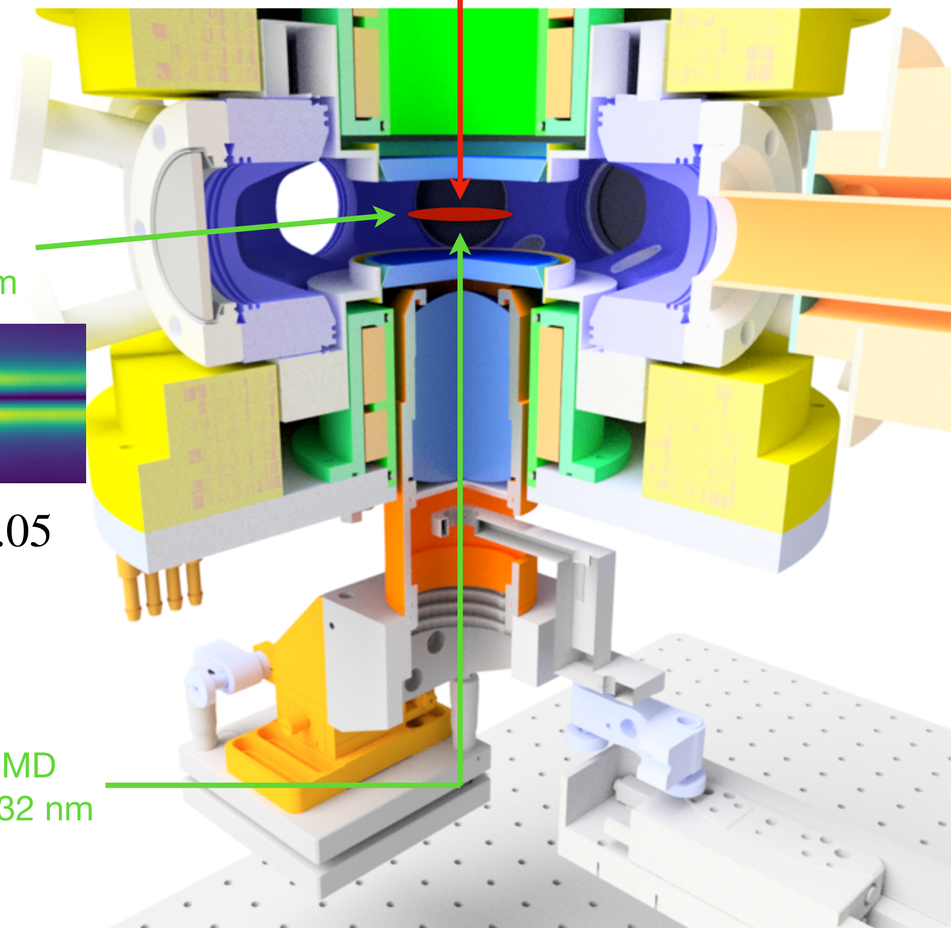
$\hbar\omega_z/E_F \simeq 0.05$



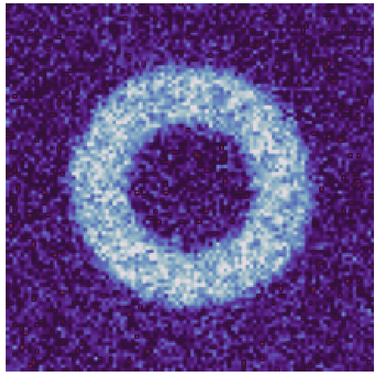
Imaging
@ 670 nm

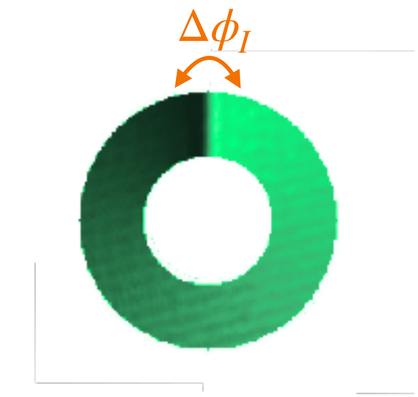
$TEM_{0,1}$
@ 532 nm

DMD
@ 532 nm

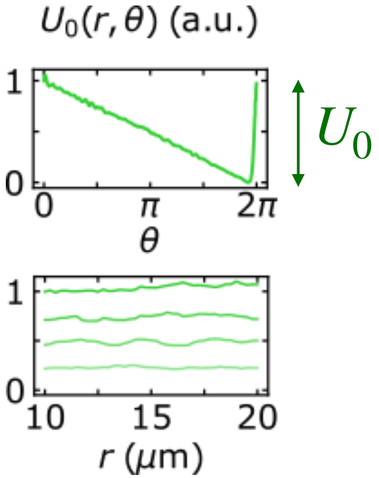


PHASE IMPRINTING OF PERSISTENT CURRENTS





On for an imprinting time t_I



Phase imprinting for $t_I < \hbar/\mu$:

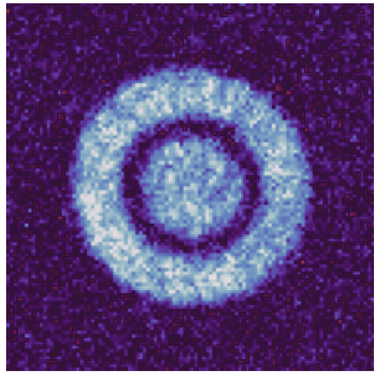
$$\phi(r,\theta) = U_0(r,\theta)\, t_I$$

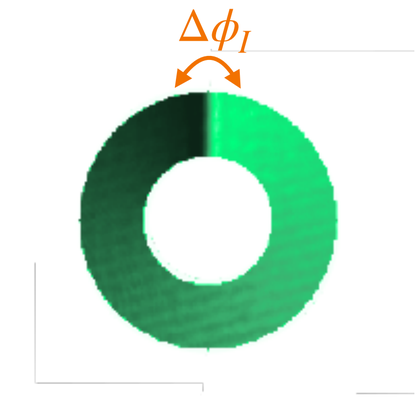
The imprinted phase at the gradient discontinuity is:

$$\Delta\phi_I = U_0\, t_I$$

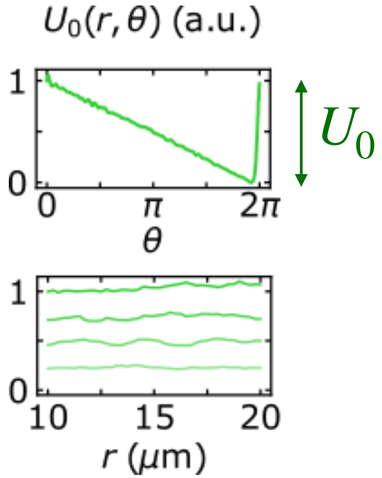
A. Kumar, et al., *Producing superfluid circulation states using phase imprinting*, Phys. Rev. A 97, 043615 (2018).

PHASE IMPRINTING OF PERSISTENT CURRENTS





On for an imprinting time t_I



Phase imprinting for $t_I < \hbar/\mu$:

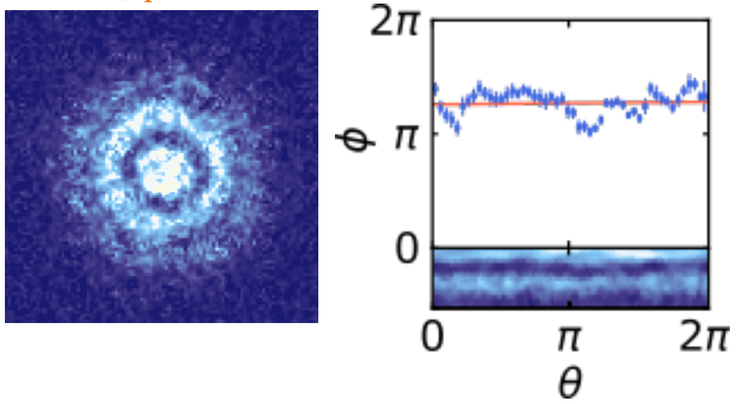
$$\phi(r,\theta) = U_0(r,\theta)\, t_I$$

The imprinted phase at the gradient discontinuity is:

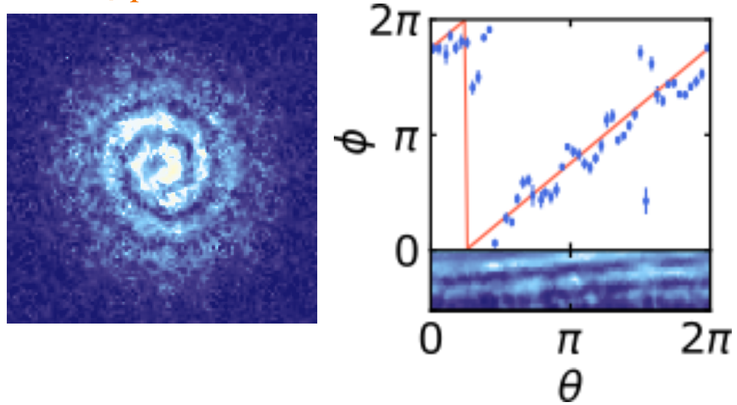
$$\Delta\phi_I = U_0\, t_I$$

Interferograms after a time of flight expansion

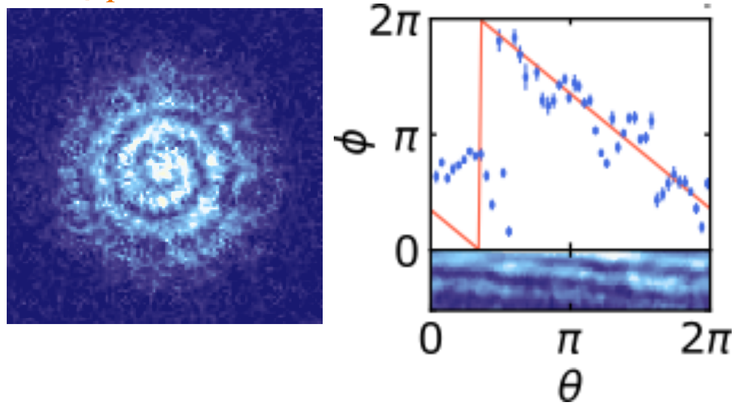
$\Delta\phi_I = 0$



$\Delta\phi_I = 2\pi$

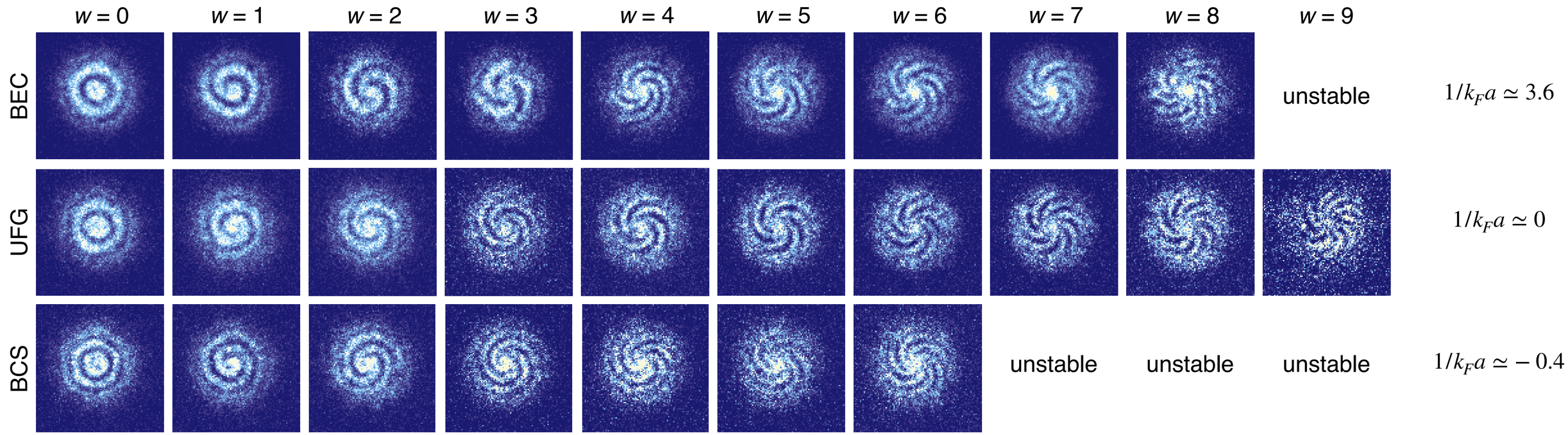


$\Delta\phi_I = -2\pi$

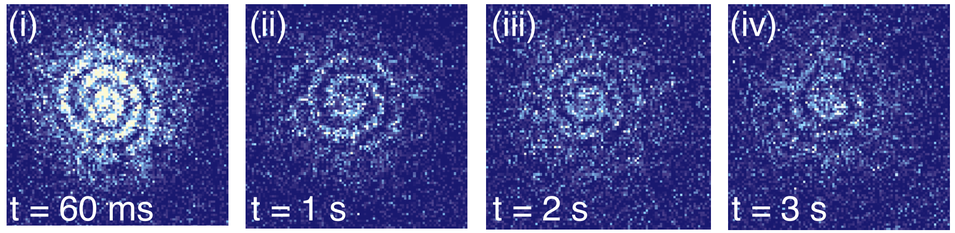


A. Kumar, et al., *Producing superfluid circulation states using phase imprinting*, Phys. Rev. A 97, 043615 (2018).
S. Eckel, et al., *Interferometric measurement of the current-phase relationship of a superfluid weak link*, Phys. Rev. X 4, 031052 (2014).
L. Corman, et al., *Quench-induced supercurrents in an annular Bose gas*, Phys. Rev. Lett. 113, 135302 (2014).

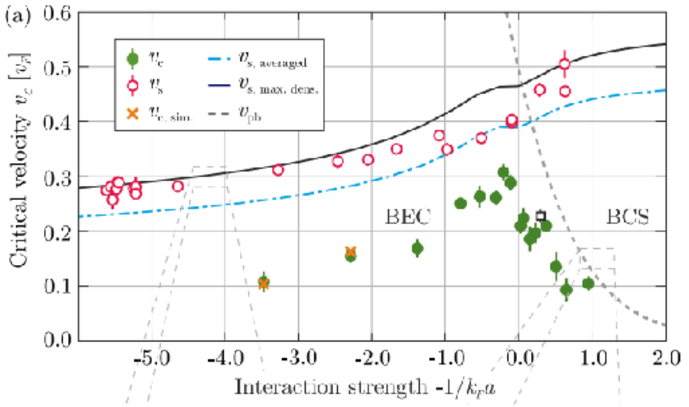
PERSISTENT CURRENTS IN ATOMIC FERMI SUPERFLUIDS



Current Lifetime



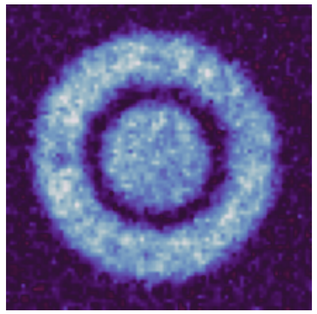
Long-lived and robust against particle-losses



Compatible with the critical velocity measurement in the BEC-BCS crossover.

W. Weimer et al., Phys. Rev. Lett. 114.9 095301 (2015)

CURRENT STABILITY IN THE PRESENCE OF A DEFECT



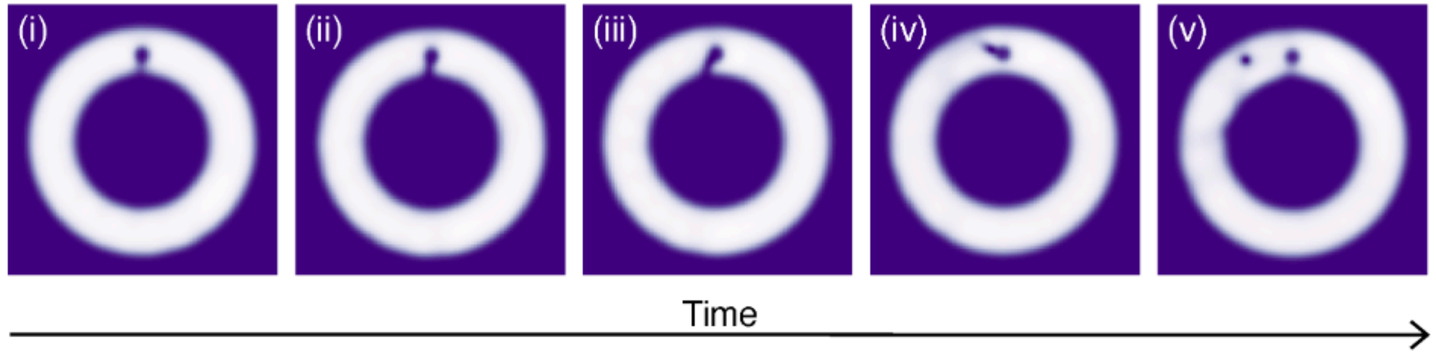
To investigate the interplay between the current instability and the emission of vortices, we trigger the current decay with a defect.

Localized Gaussian obstacle:

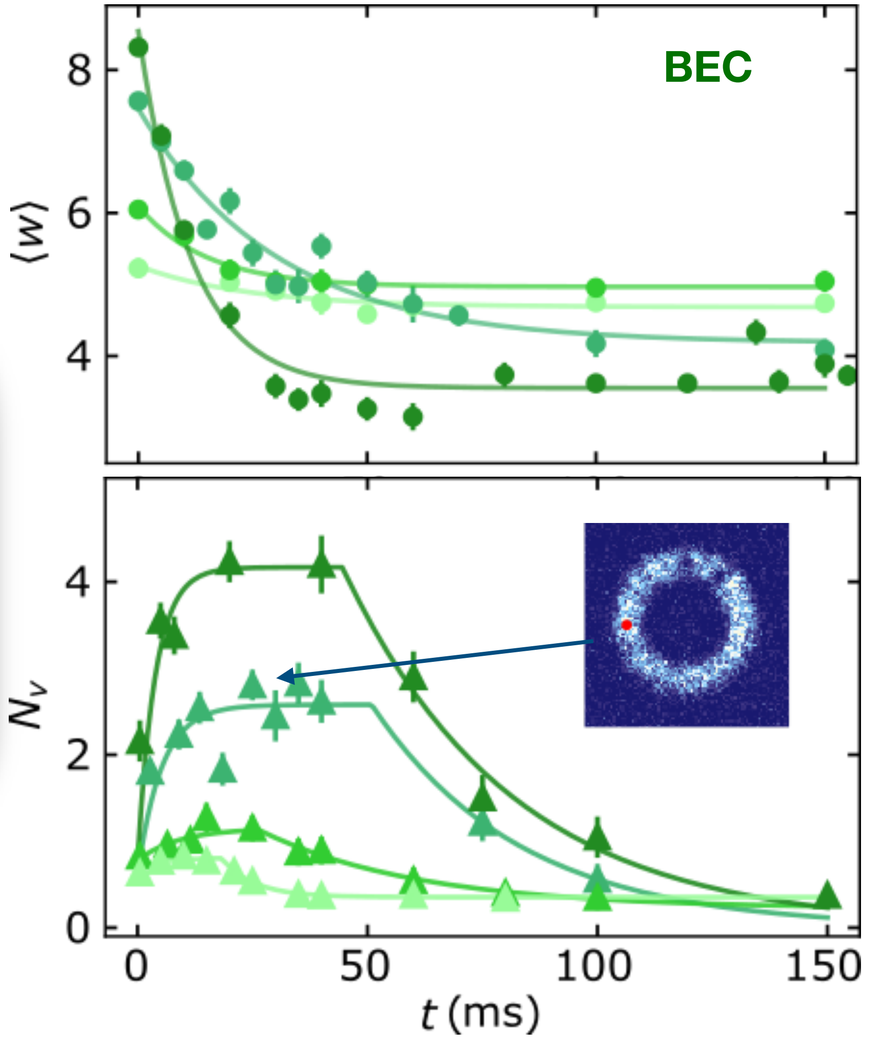
FWHM = 1.6 μm

$V_0/E_F = 0.1$ @ BEC

Microscopic vortex emission process



K. Xhani, et al., Atoms **2023**, 11(8), 109

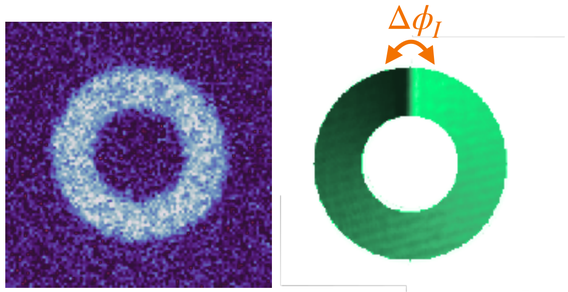


The global current in the ring decays **via the emission of a vortex** in the bulk superfluid, bringing away one quantum of circulation

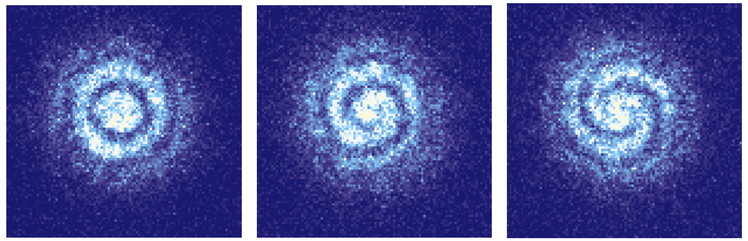
CONCLUSIONS

G. Del Pace, et al., '*Imprinting Persistent Currents in Tunable Fermionic Rings*' Phys. Rev. X **12**, 041037 (2022)

Phase imprinting to inject a controlled current of finite w in the ring



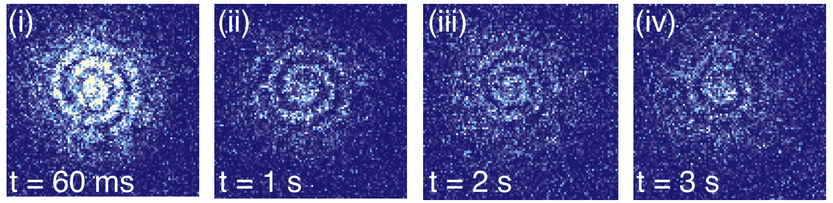
Interferometric probe to detect the current in the ring



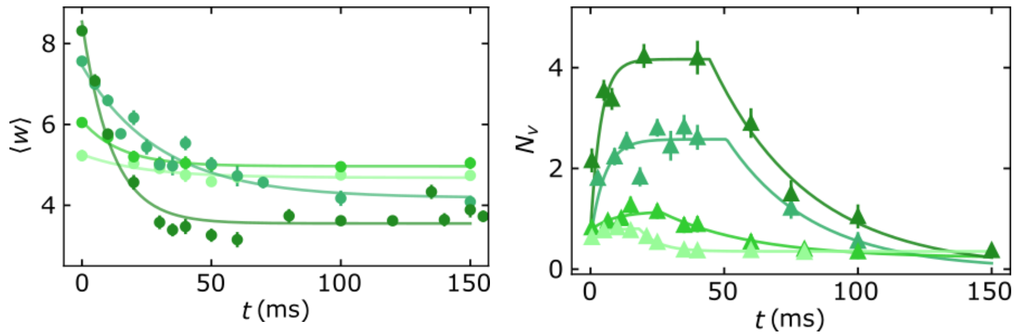
Quantum technologies

- Fast production of on-demand circulation state
- Reliable read-out of the current
- Control of the current stability in the presence of obstacles

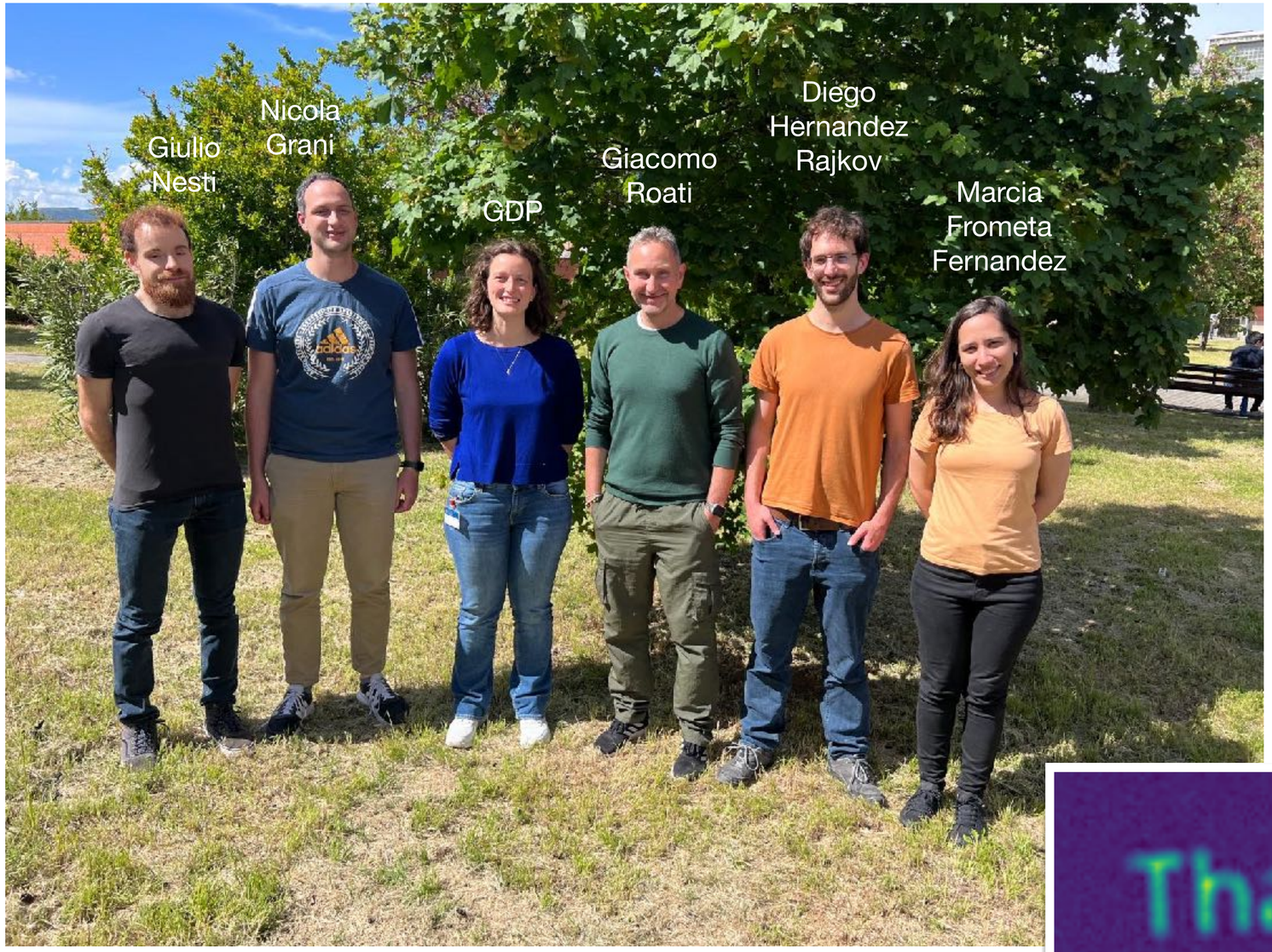
We detect **persistent current** in fermionic superfluid ring



We connect the **current decay** to **vortex emission**, excitazions trhat share the same topological nature



LITHIUM TEAM @ LENS



Collaborators on persistent currents:

Klejdja Xhani, INO-CNR, Florence

Alessandro Muzi Falconi, University of Trieste

Francesco Scazza, University of Trieste

Woo Jin Kwon, University of Milan

Massimo Inguscio, INO-CNR, Florence

Our website: