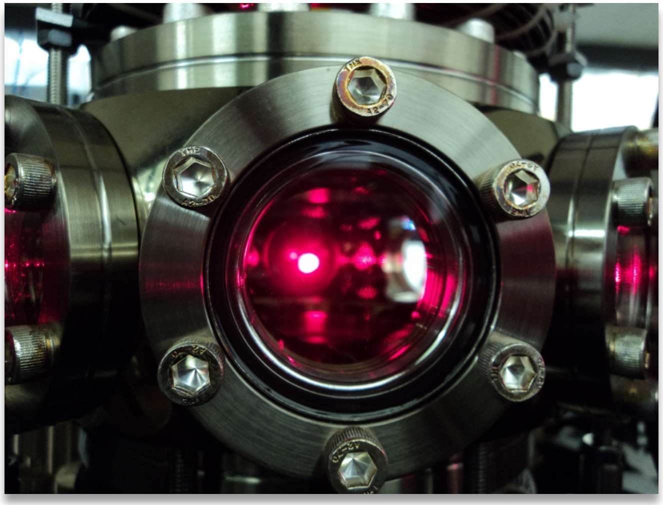
EXPLORING THE DC AND AC JOSEPHSON EFFECTS IN FERMIONIC SUPERFLUIDS ACROSS THE BEC-BCS CROSSOVER

… AND EXTRACTION OF THE ORDER PARAMETER

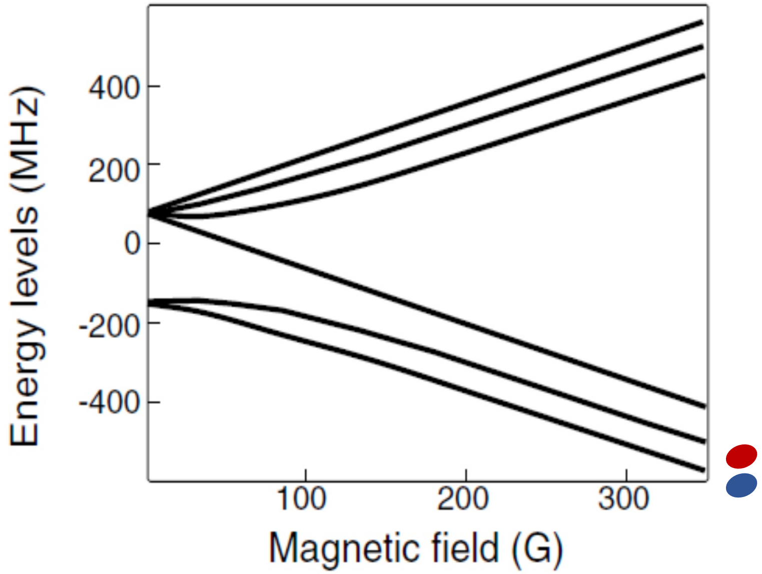
Giulia Del Pace

W. Kwon, GDP, R. Panza, M. Inguscio, W. Zwerger, M. Zaccanti, F. Scazza, and G. Roati,
arXiv 1908.09696 (2019).

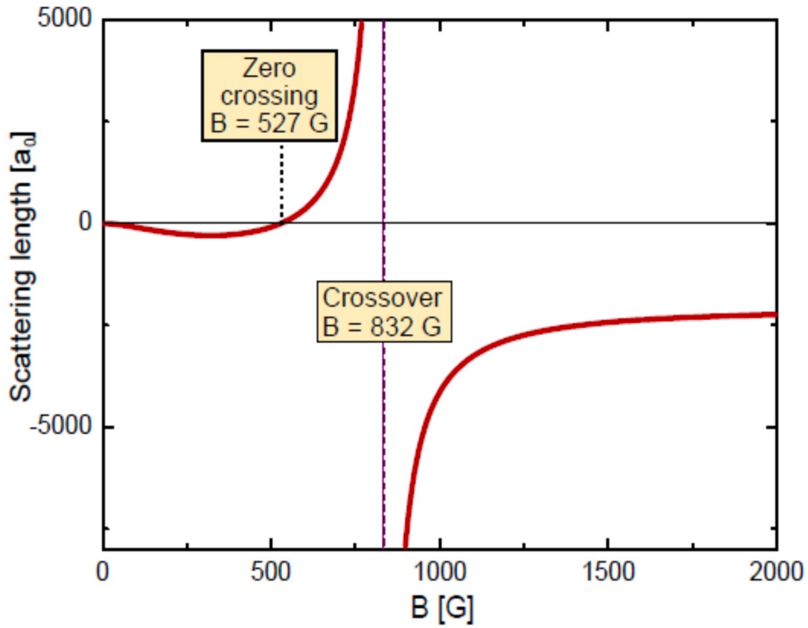
FERMIONIC SUPERFLUIDS

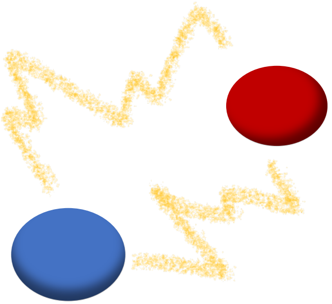


N $\sim 10^5$ at T ~ 30 nK
Magneto-Optical Trap + D_1 molasses
+ Evaporative Cooling



Feshbach resonance

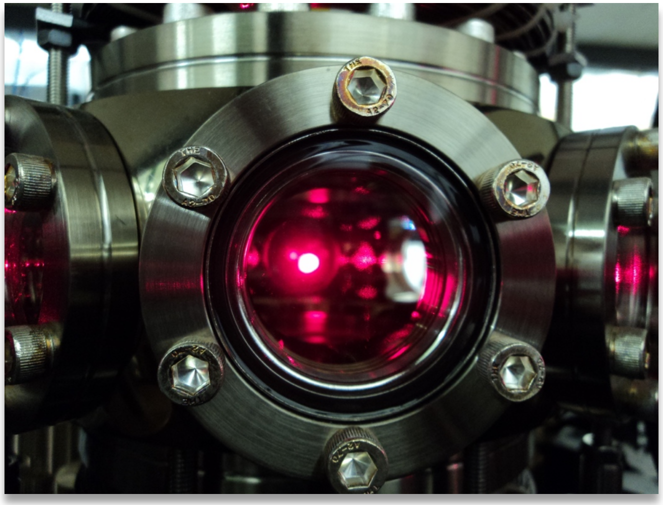




$$\sim \frac{4\,\pi\,\hbar^2}{m}\,a\,\delta(\boldsymbol{r})$$

$a \longrightarrow$ scattering length

FERMIONIC SUPERFLUIDS



N ~ 10^5 at T ~ 30 nK
Magneto-Optical Trap + D_1 molasses
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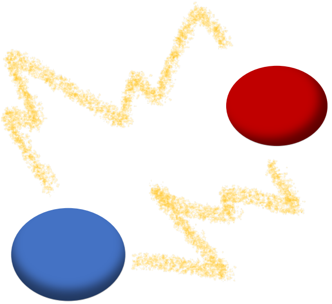
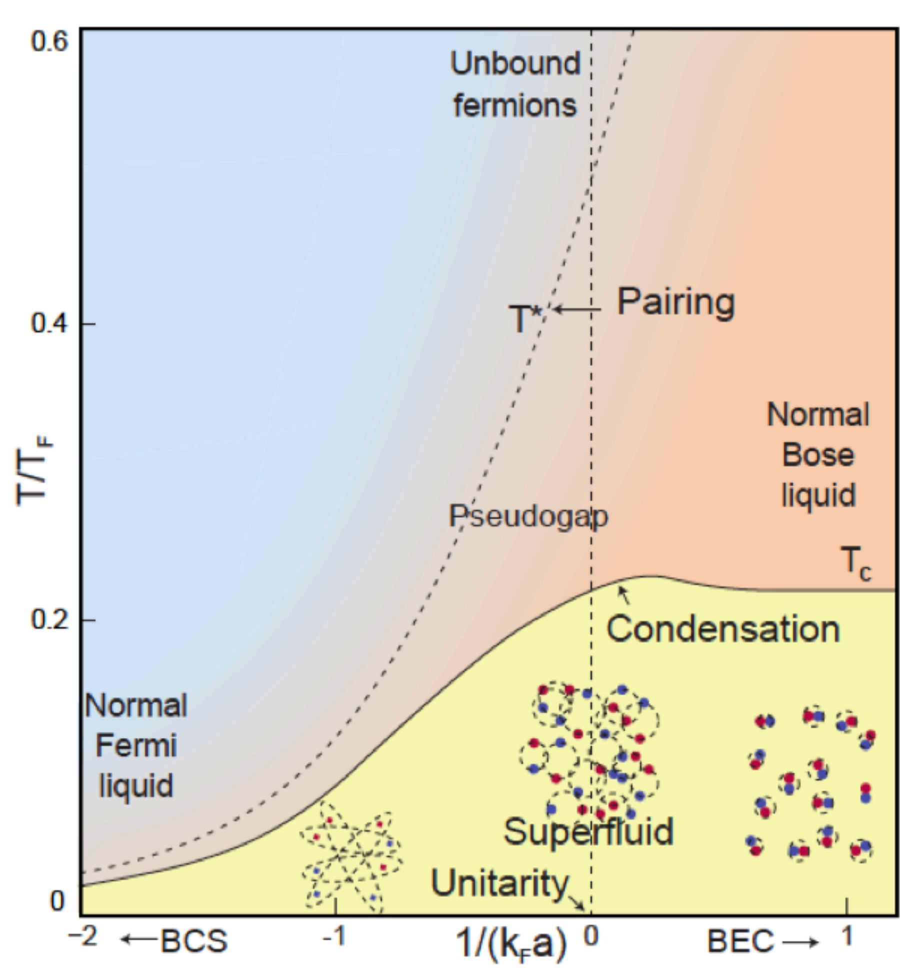


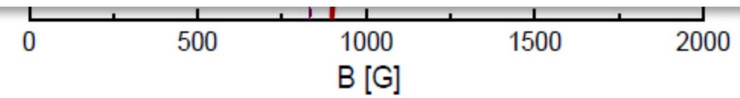
$$\sim \frac{4\,\pi\,\hbar^2}{m}\, a\, \delta(\boldsymbol{r})$$

$a \longrightarrow$ scattering length

BEC-BCS crossover

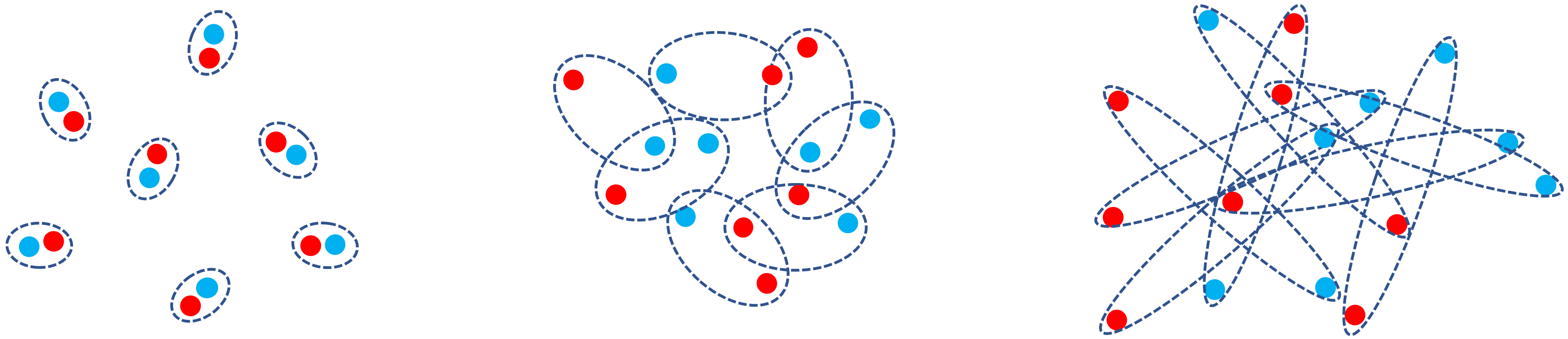


Randeria, *Nature Phys.* **6**, 561 (2010)



ORDER PARAMETER OF FERMIONIC SUPERFLUIDS

BEC-BCS crossover



BEC | Unitary gas | BCS

$$\psi_{BEC} = \sqrt{n_c}e^{i\phi} \longleftrightarrow \psi_{BCS} = |\Delta|e^{i\phi}$$

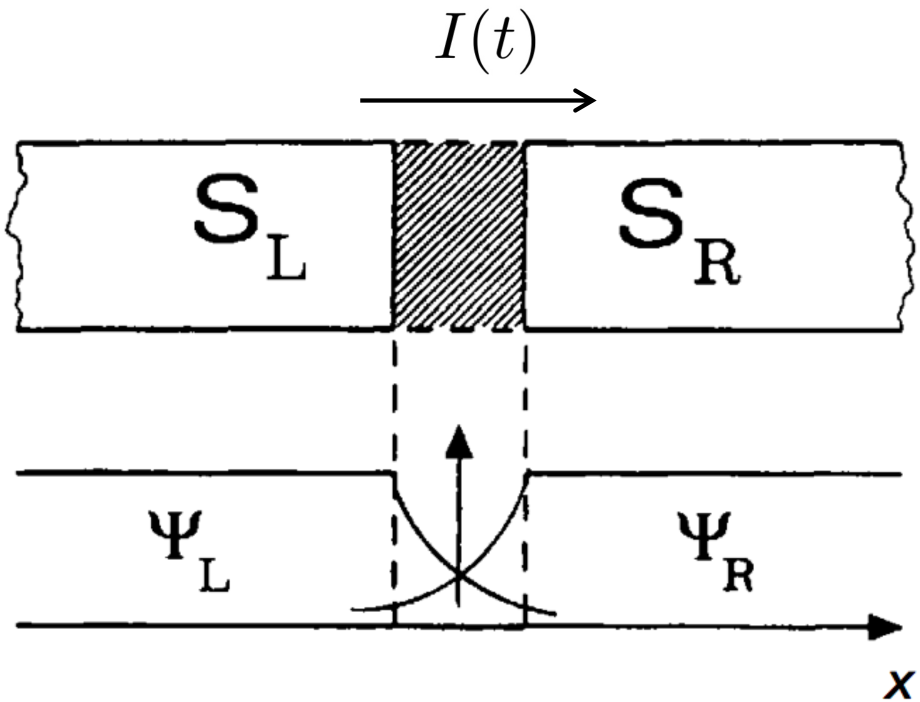
Usual way of extracting n_c: rapid-ramp technique

M. W. Zwierlein, et al., Phys. Rev. Lett. 92, 120403 (2004).
C. A. Regal, M. Greiner, D. S. Jin, *Phys. Rev. Lett.* 92, 040403 (2004).

Direct and quantitative measurement of the order parameter:
phase sensitive transport measurement

JOSEPHSON EFFECT

JOSEPHSON EFFECT



$\psi_L = |\Delta_L| e^{i\phi_L}$ $\psi_R = |\Delta_R| e^{i\phi_R}$

Josephson-Anderson equations:

$$I(t) = I_c \sin\phi$$

$$\dot{\phi} = \frac{2e}{\hbar} V$$

$\phi = \phi_L - \phi_R \longrightarrow$ relative phase

$I_c \longrightarrow$ critical current

$V \longrightarrow$ potential difference

- Barrier thinner than the healing length
- Small tunneling probability through the barrier

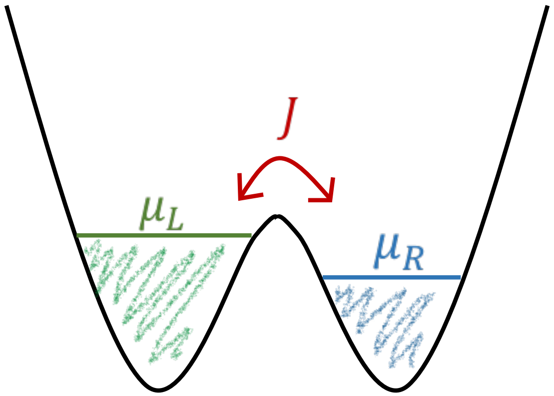
Ambegaokar-Baratoff relation

$$I_c \propto \Delta$$

B. D. Josephson, *Phys. Lett.* 1, 251 (1962).

P. W. Anderson, *Lectures on The Many-Body Problems*, vol. 2 (Elsevier, 1964).

ATOMIC JOSEPHSON JUNCTION



$$\psi_L = |\psi_L| e^{i\phi_L} \quad \psi_R = |\psi_R| e^{i\phi_R}$$

Josephson-Anderson equations:

$$I(t) = I_c \sin\phi$$

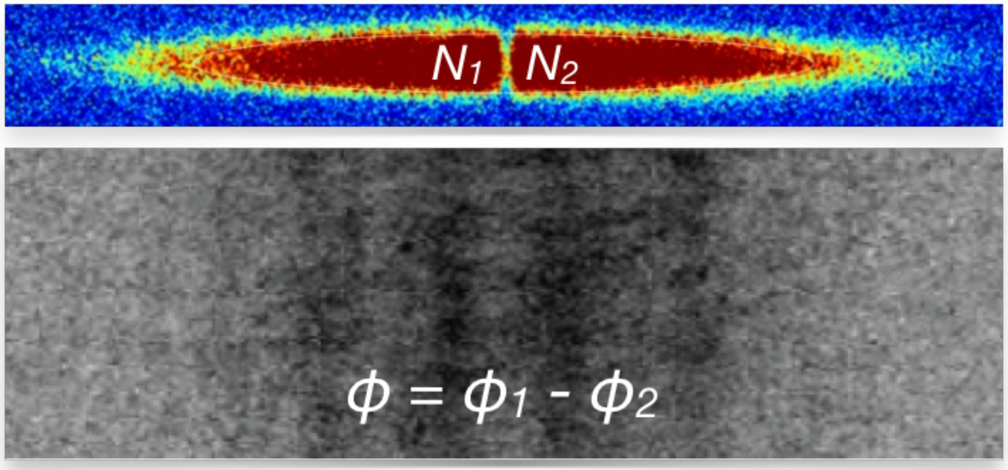
$$\dot{\phi} = -\frac{\Delta\mu}{\hbar}$$

$\Delta\mu = \mu_L - \mu_R \longrightarrow$ chemical potential difference

$\phi = \phi_L - \phi_R \longrightarrow$ relative phase

$\Delta N = N_L - N_R \longrightarrow$ imbalance

$I = (\dot{N}_L - \dot{N}_R)/2 \longrightarrow$ current

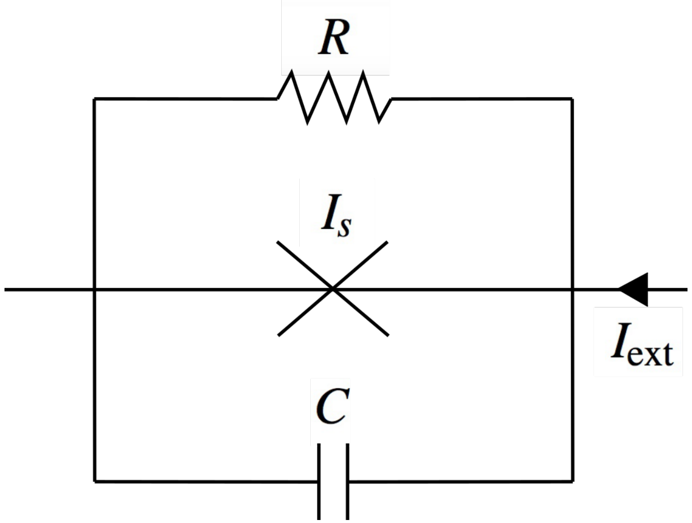


In situ imaging: Number of particles/current

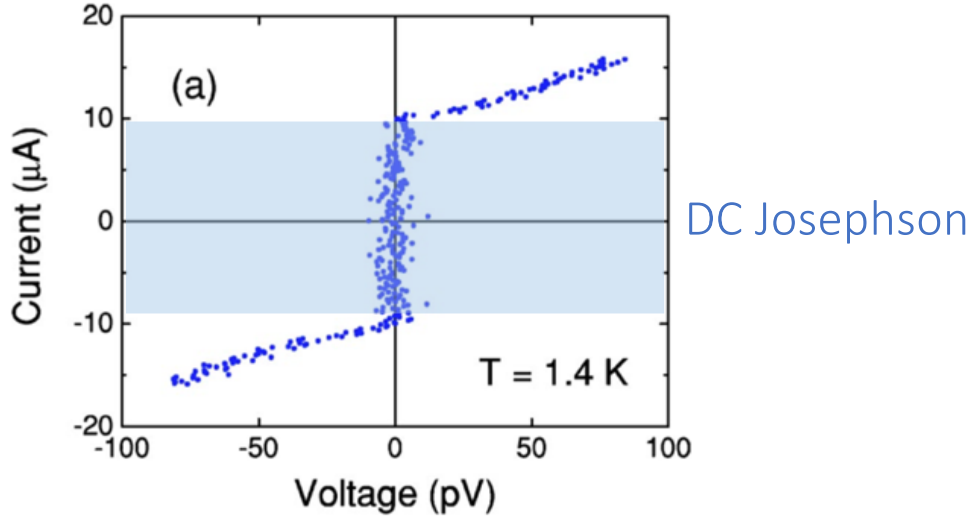
Time-of-flight imaging: phase across the junction

CURRENT-BIASED JOSEPHSON JUNCTION

With superconductors

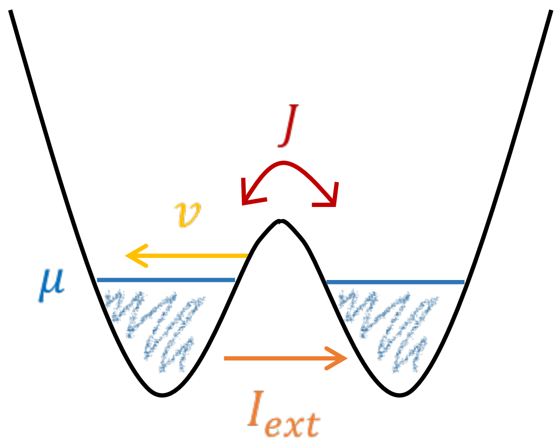


SFS Josephson junction of Nb-CuNi-Nb



Frolov et al., *Phys. Rev. B* **70**, 144505 (2004)

With atomic superfluids



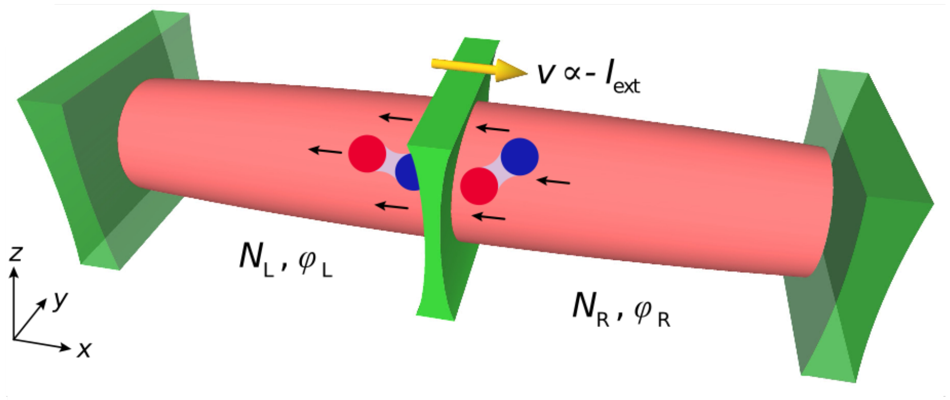
Inject an external current I_{ext} in the junction, by moving the tunneling barrier with a constant velocity v.

$$\Delta\mu(t = 0) = 0$$
$$I(t = 0) = I_{ext}$$

Ultracold bosonic gases:

Giovanazzi et al., *PRL* **84** (2000)
Levy et al., *Nature* 449, 579 (2007)
Ryu et al., *PRL* **111** (2013)

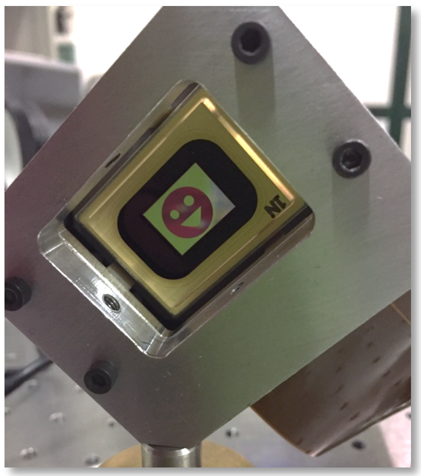
CURRENT-BIASED JUNCTION: EXPERIMENTAL REALIZATION



Atomic cloud:
$N_{R,L} \simeq 3.5 \times 10^4$ atom pairs
$T/T_F \simeq 0.06\ (2)$

Tunneling barrier:
532 nm light
$w \simeq 0.95\ (10) \mu$m
$V_0 \gtrsim \mu$

Digital Micromirror Device (DMD)

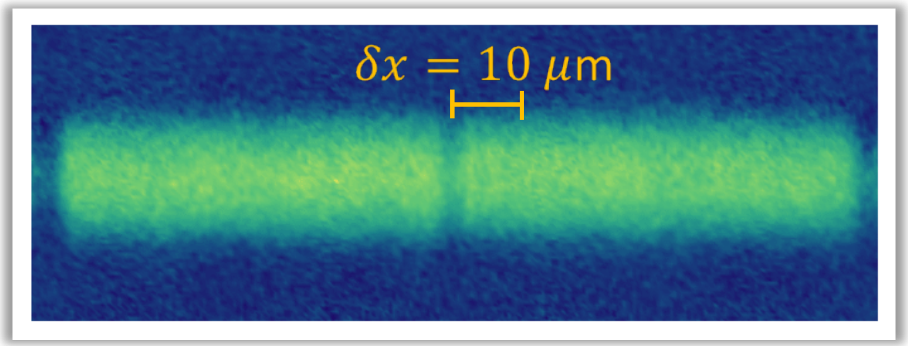


Vialux V-7000

1024×768 mirrors

13.68 μm pitch

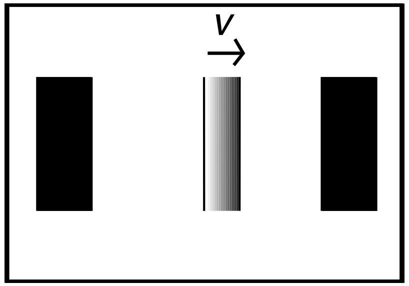
Barrier translation via dynamical control of DMD picture



BARRIER CREATION AND CALIBRATION

Current-biased junction

DMD image



High resolution microscope objective:

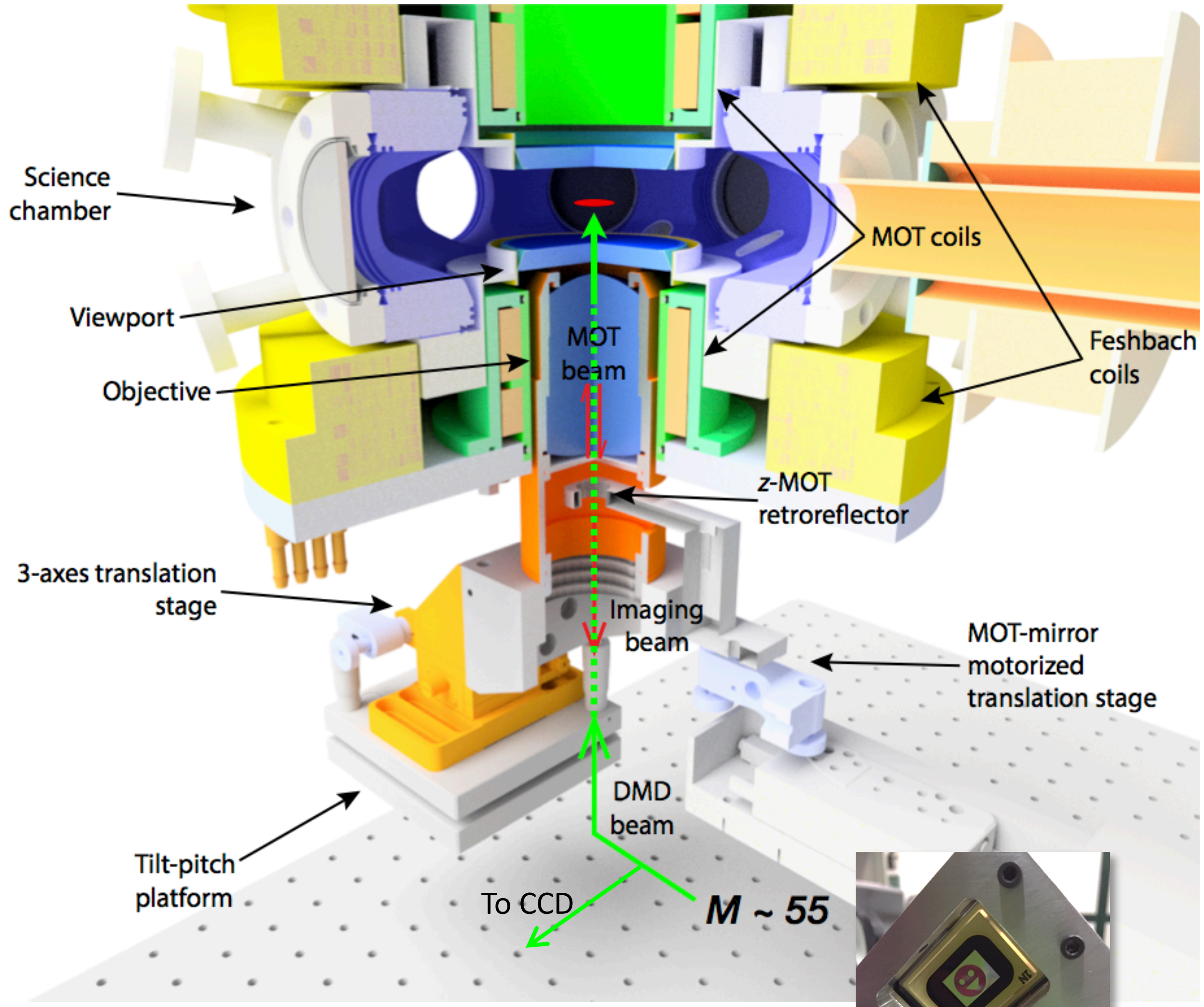
$NA = 0.45$

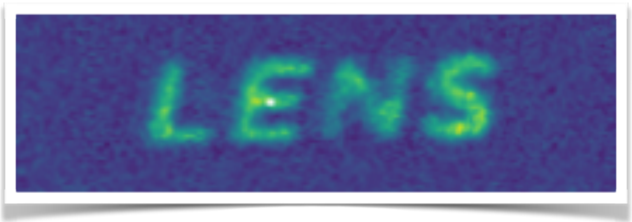
Effective Focal Length: 47mm

Field Of View: 0.3 mm

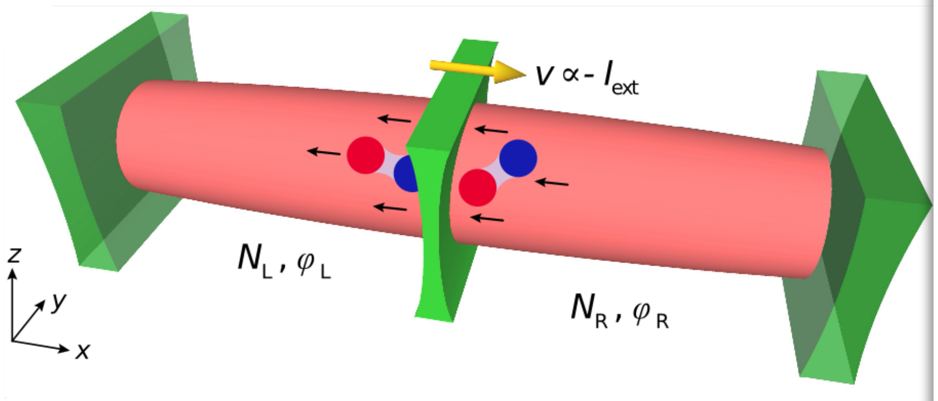
Working Distance: 25.1 mm

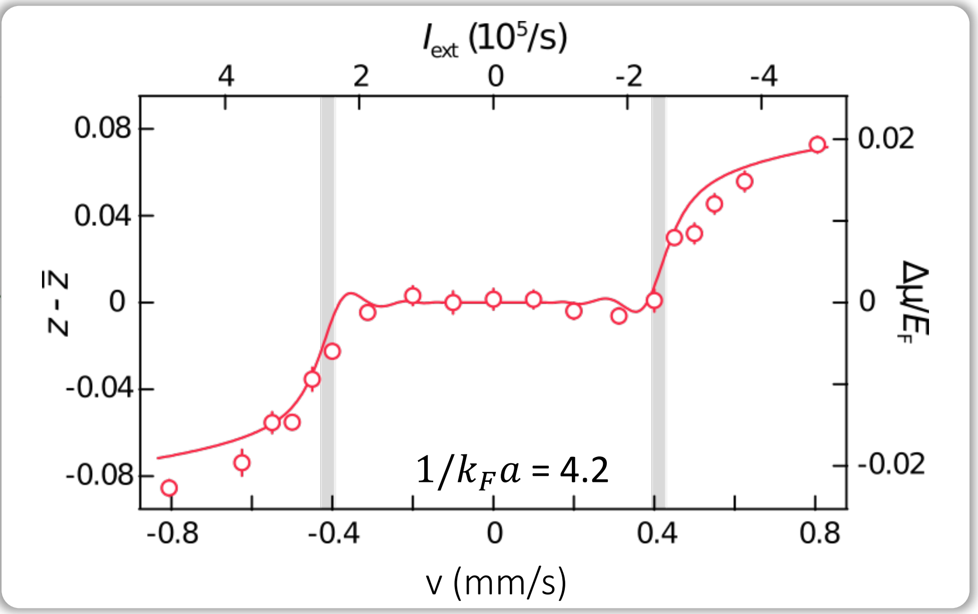
Resolution: 0.9 μm @ 670 nm,
0.7 μm @ 532 nm



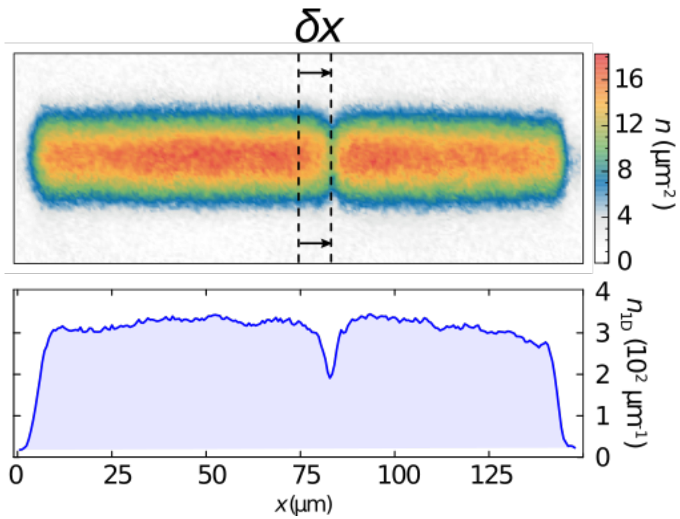


CURRENT-BIASED JUNCTION





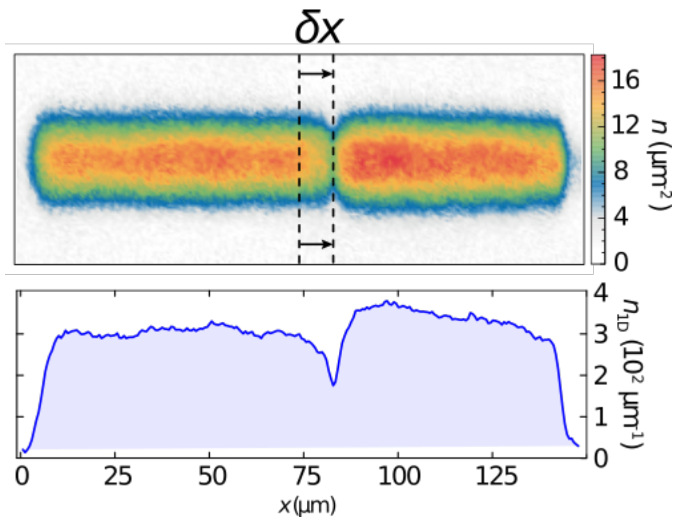
DC Josephson effect



$I_{ext} < I_C$

$\Delta\mu = 0$

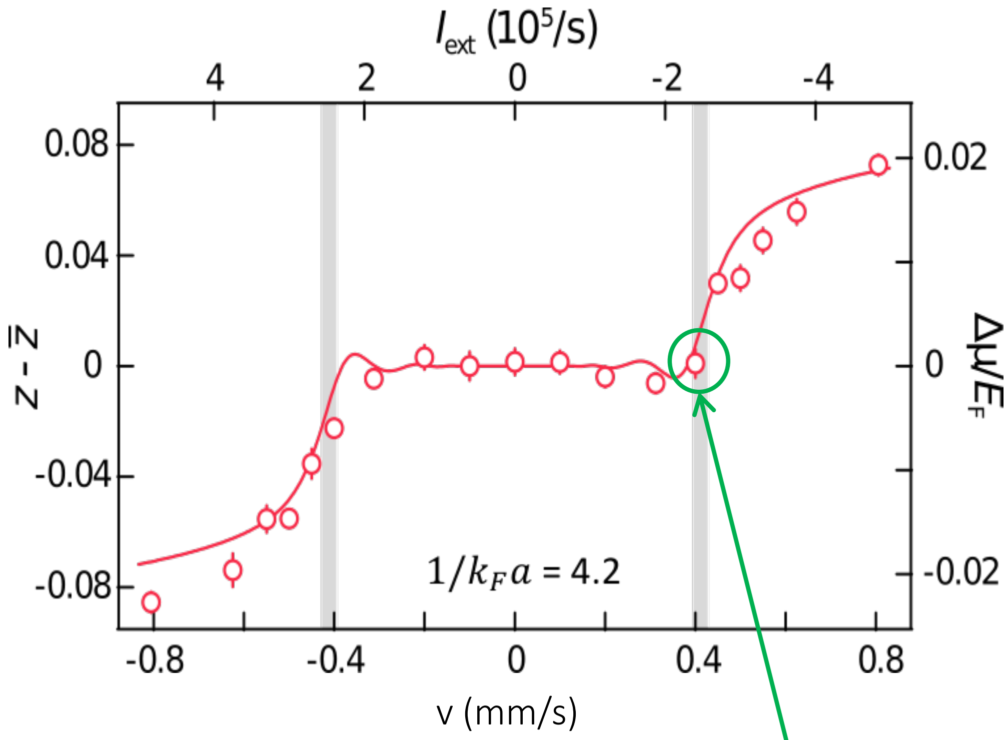
Finite-voltage branch



$I_{ext} > I_C$

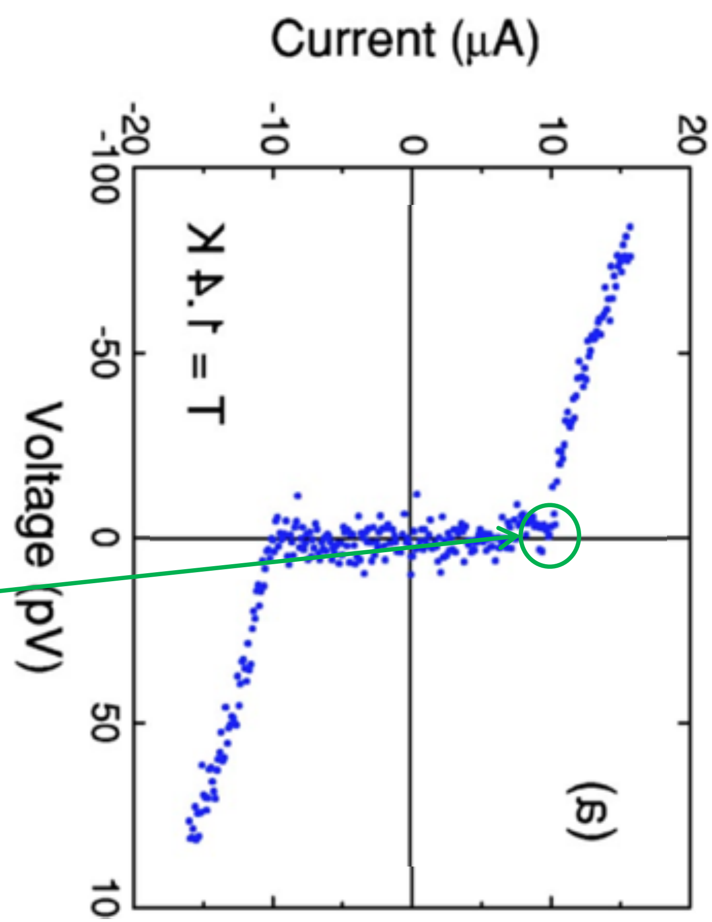
$\Delta\mu = \Delta\mu_0$

CURRENT-BIASED JUNCTION



Atomic Josephson junction

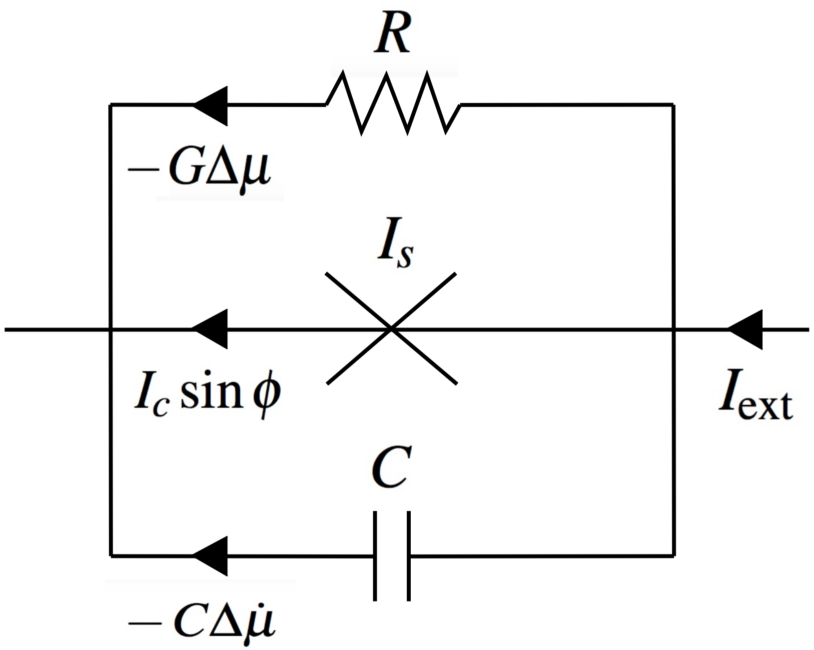
Superconducting Josephson junction

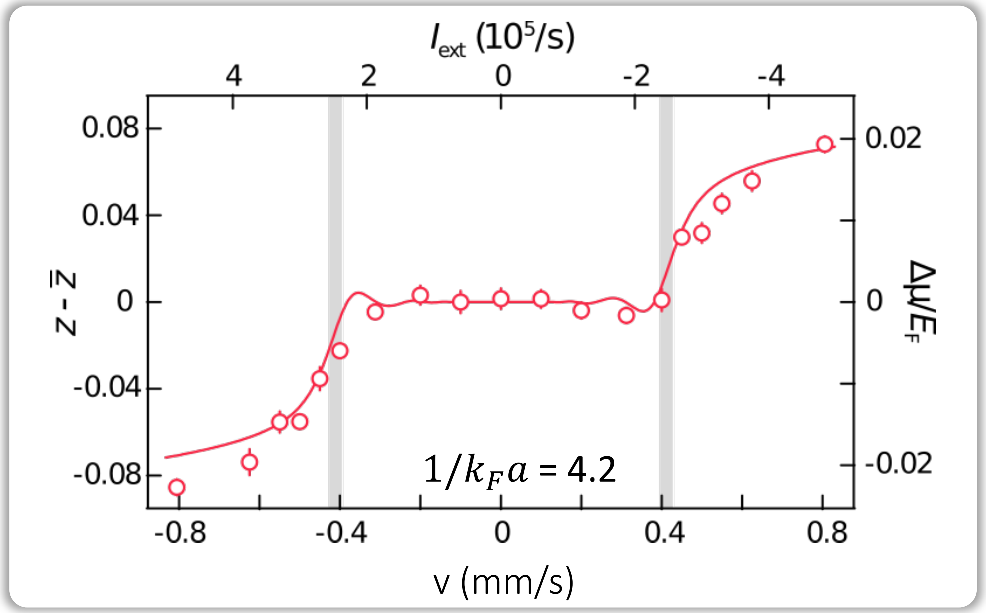


Critical current

QUANTUM SIMULATOR

RCSJ CIRCUIT MODEL





Josephson equations:

$$I_{ext} = I_c \sin\phi \;-G\,\Delta\mu - C\Delta\dot{\mu}$$

$$\hbar\dot{\phi} = -\Delta\mu$$

$$G = \frac{1}{R} \longrightarrow \text{conductance}$$

$$\Delta\mu = \frac{N}{2}\,E_c(z-\bar{z})$$

$$E_c = \frac{\partial\mu_L}{\partial N_L} + \frac{\partial\mu_R}{\partial N_R}$$

$z \longrightarrow$ population imbalance

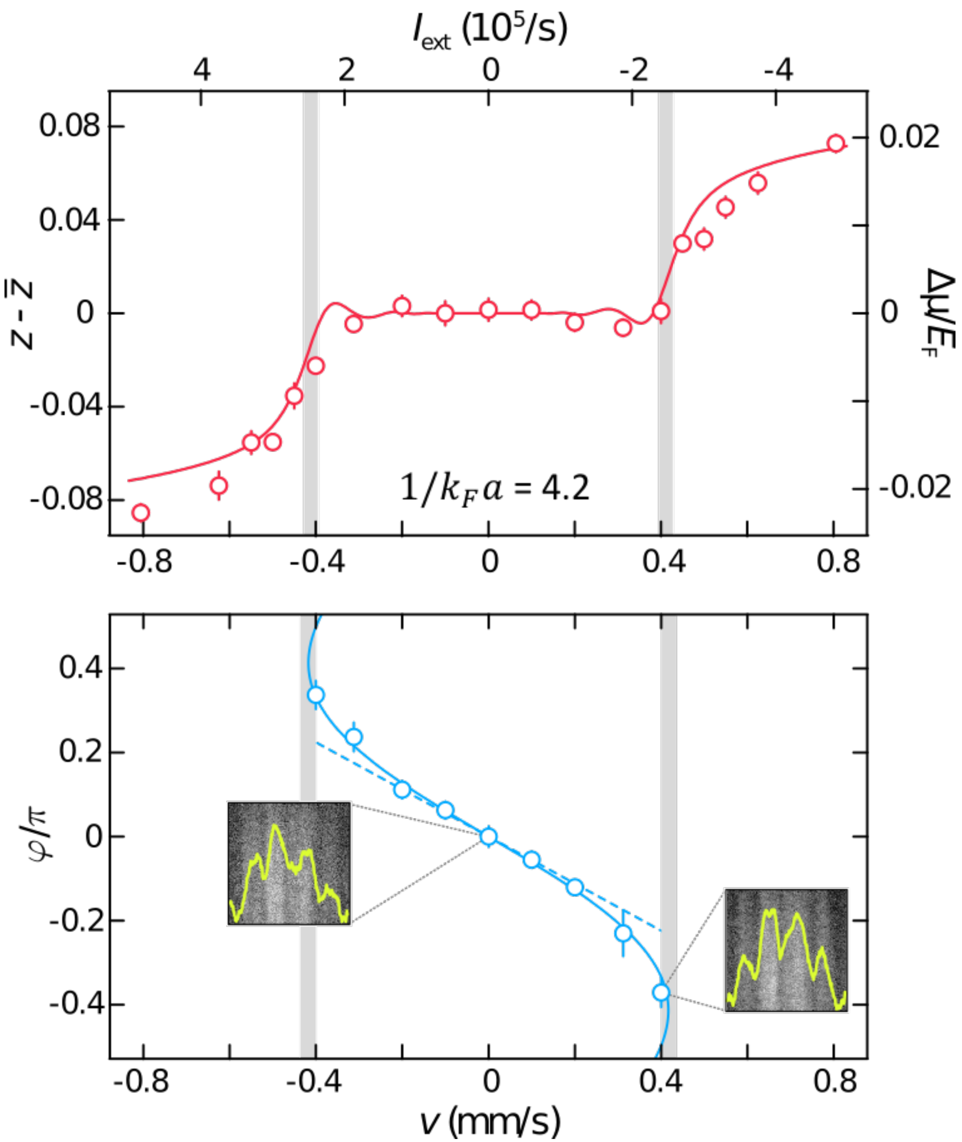
$\bar{z} \longrightarrow$ equilibrium population imbalance

$$\frac{N}{2}\dot{z} = I_c \sin\phi \;-G\,\Delta\mu$$

E_c calculated

I_c, G free fitting parameters

CURRENT-PHASE RELATION



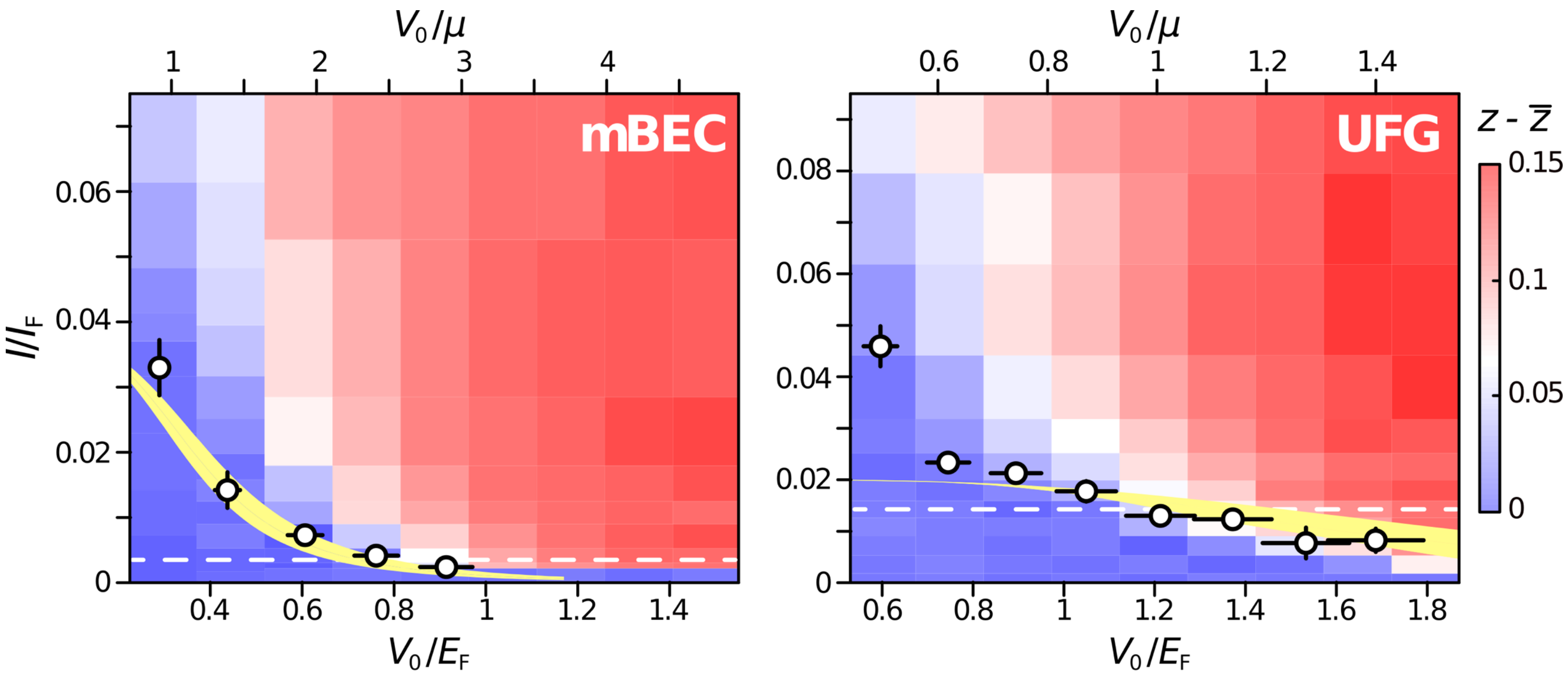
We measure the phase difference after the barrier translation by fitting the interference pattern aring after 18 ms TOF

$$I(t) = I_c \sin\phi \longrightarrow \text{Josephson equation}$$

We access the **dc Josephson** regime, and $\mathrm{I} < I_c$ is a **Josephson supercurrent**.

First observation of dc Josephson together with:
N. Luick et al., *arxiv: 1908.09776* (2019).

CRITICAL CURRENT VERSUS BARRIER HEIGHT



$$E_F = \frac{\hbar^2 k_F^2}{2m} \longrightarrow \text{Fermi energy}$$

$$k_F = (6\,\pi^2 n)^{1/3} \longrightarrow \text{Fermi momentum}$$

Semi-analytic model [1]:

$$\hbar j_c = \frac{\mu\, n_c}{2\,k\,(\mu)}\,|t|(\mu)$$

$k(\mu) = \frac{\sqrt{2\,M\,\mu}}{\hbar} \longrightarrow$ wavevector of a pair

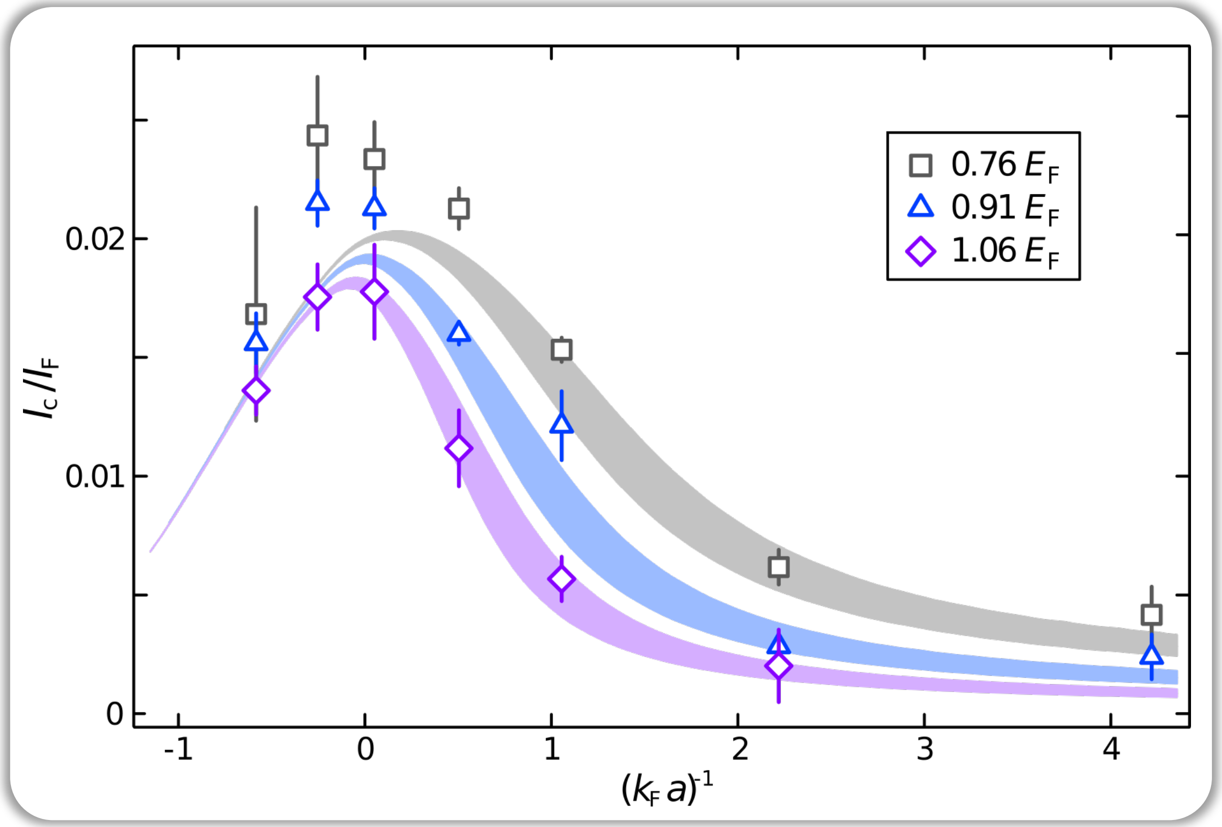
$n_c = n_s\,\lambda_0 \longrightarrow$ density of condensed pair

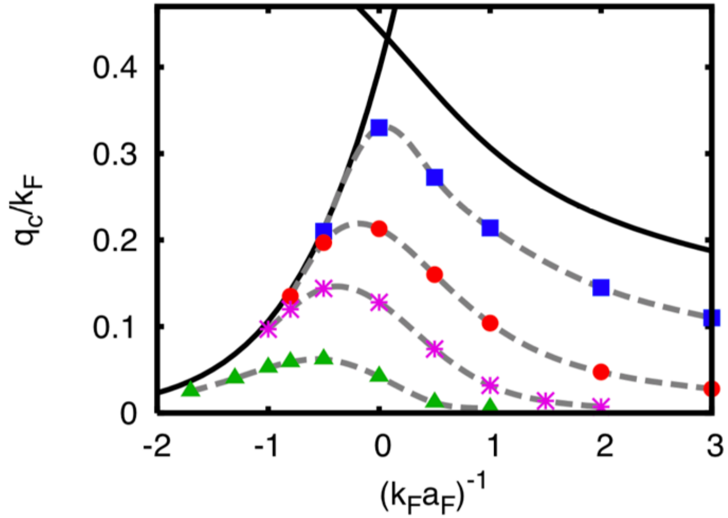
$\lambda_0 \longrightarrow$ condensed fraction

[1] M. Zaccanti, W. Zwerger, *arxiv:1907.08052* (2019).

CRITICAL CURRENT IN THE CROSSOVER

Extract critical velocity across BEC-BCS crossover as a function of $1/(k_F a)$





Spuntarelli et al., *Phys. Rev. Lett.* **99** (2007).

Consistent with mean-field simulations and previous study in Josephson-plasma regime.

Valtolina et al., *Science* **350** (2015)
Burchianti et al., *Phys. Rev. Lett.* **120** (2018)
P. Zou, F. Dalfovo, J. Low Temp. Phys. **177**, 240 (2014)

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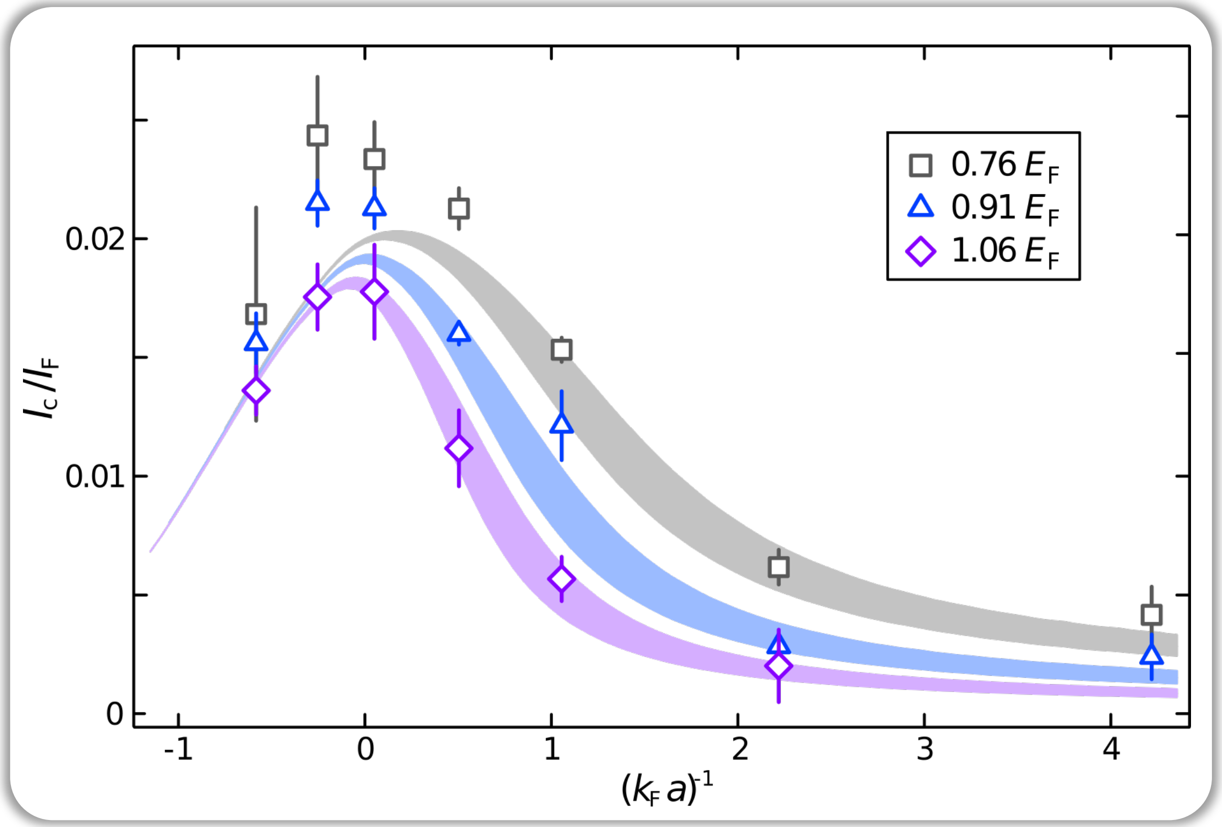
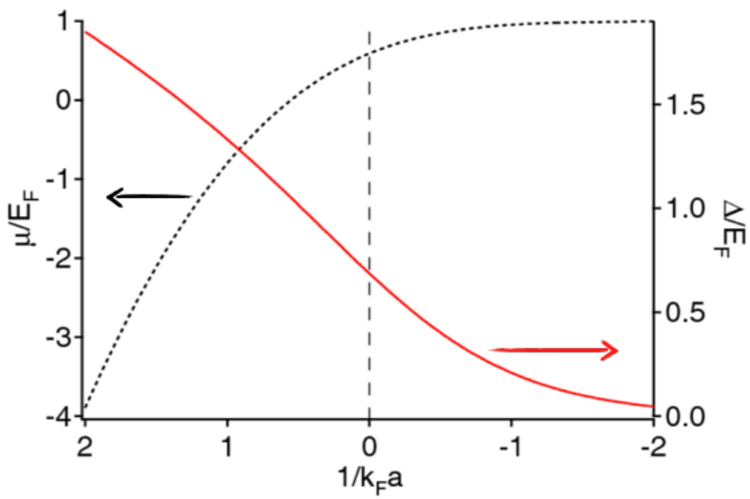
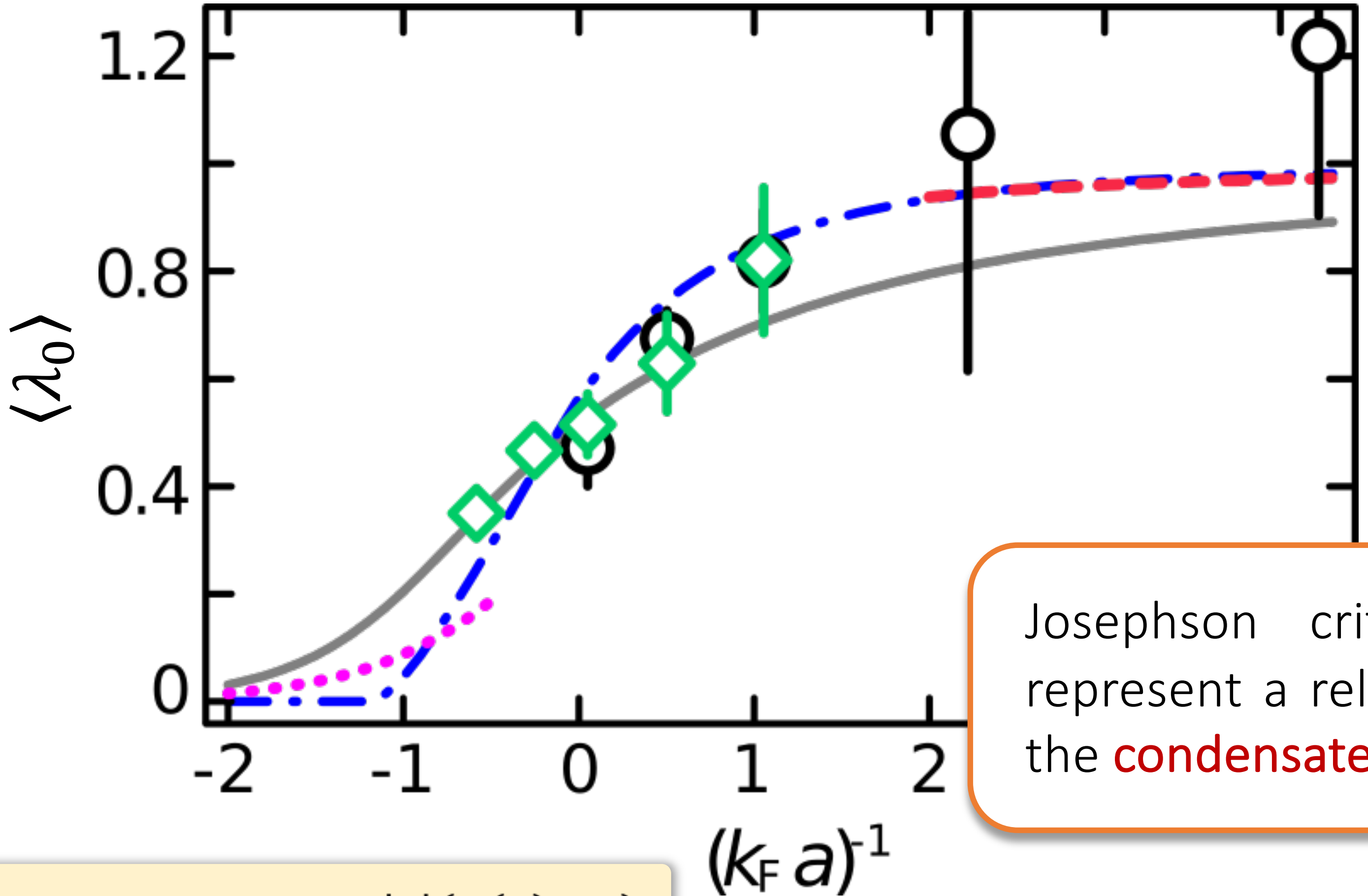




Proceedings of the International School of Physics "Enrico Fermi", Course CLXIV, Varenna. Edited by M. Inguscio, W. Ketterle, and C. Salomon (IOS Press, Amsterdam, 2008)

It's **condensation**, and not superfluidity, at the basis of Josephson effect

DENSITY-WEIGHTED CONDENSED FRACTION



Josephson critical currents represent a reliable probe of the condensate density

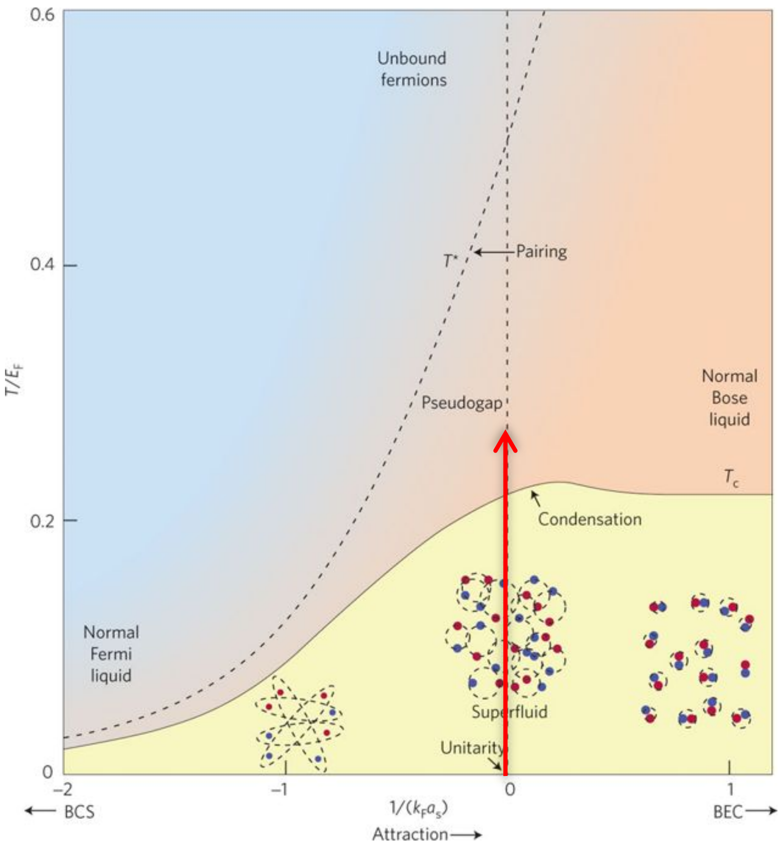
$$\hbar I_c \approx \langle \lambda_0 \rangle \times \int d^3r \, n_s(\boldsymbol{r}) \frac{|t|(\mu(\boldsymbol{r}), V_0)}{4\,k(\mu(\boldsymbol{r}))R_x}$$

- average of all data with $V_0/\mu > 0.6$
- $V_0/E_F \simeq 1.06$ data set only
- homogeneous Luttinger-Ward [1]
- Quantum Monte Carlo simulations [2]
- BCS approximation [3]
- Bogoliubov approximation [4]

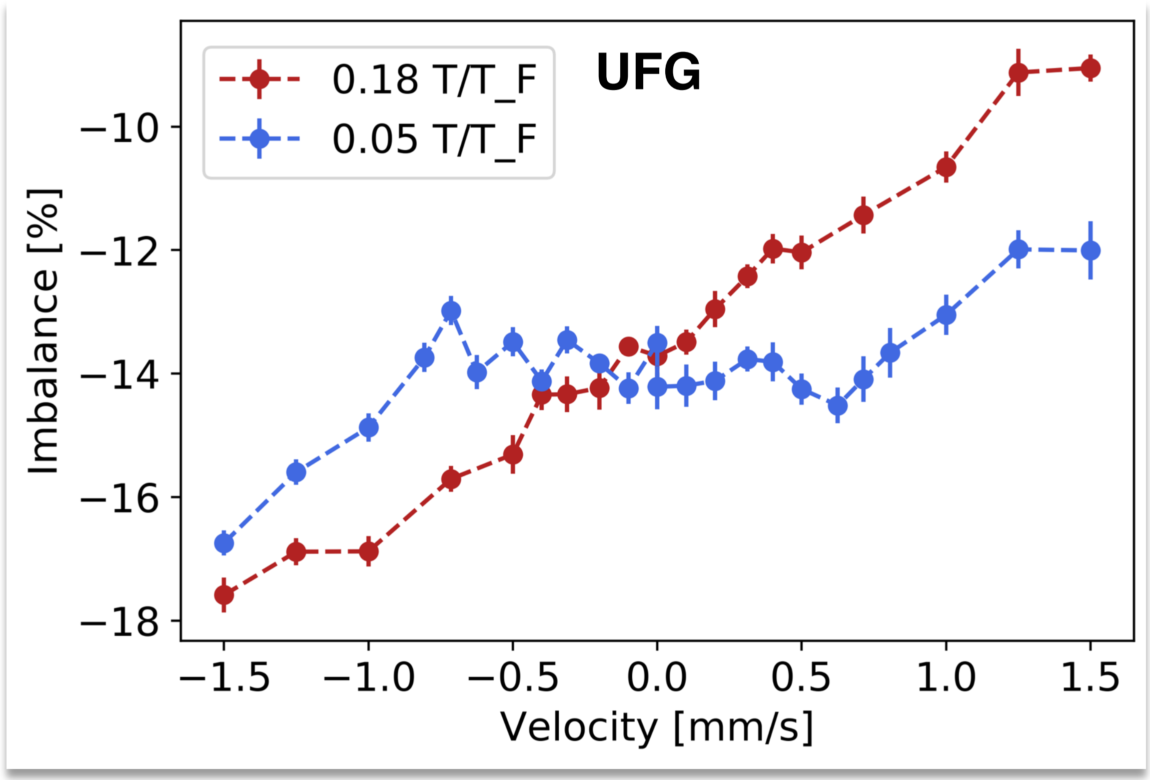
[1] R. Haussmann et al., *Phys. Rev. A* 75, 023610 (2007).
[2] G. E. Astrakharchik et al., *Phys. Rev. Lett.* 95, 230405 (2005).
[3] L. Gorkov, T. Melik-Barkhudarov, *Sov. Phys. JETP* 13, 1018 (1961).
[4] S. Giorgini, L. P. Pitaevskii, S. Stringari, *Rev. Mod. Phys.* 80, 1215 (2008).

CRITICAL CURRENT: TEMPERATURE EFFECT

Use critical current to measure the critical temperature of a UFG



Picture taken from: M. Randeria, Nat. Phys 6, 561 (2010)



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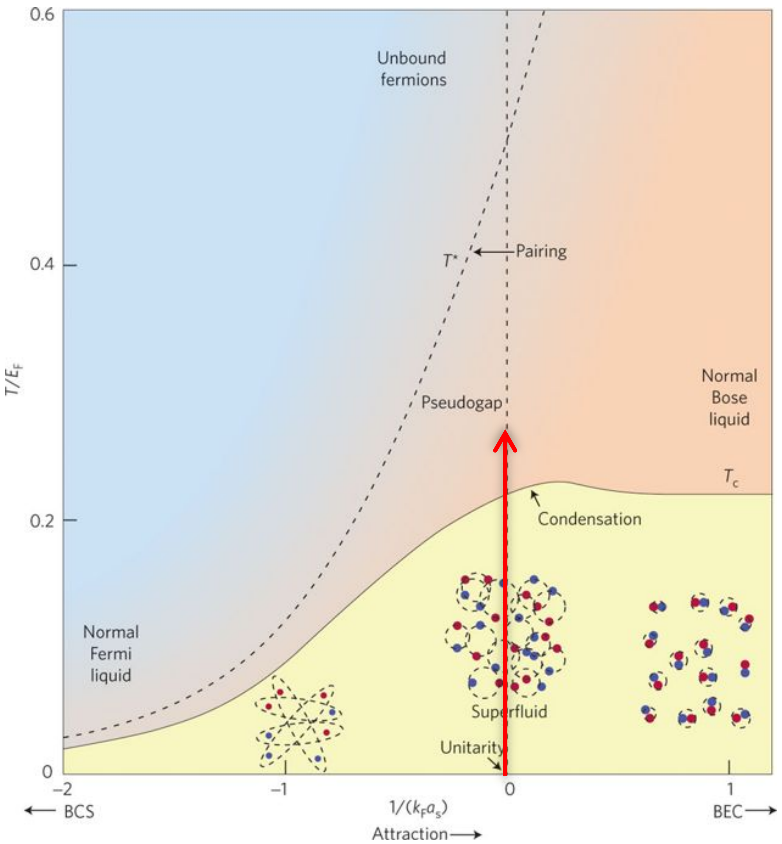

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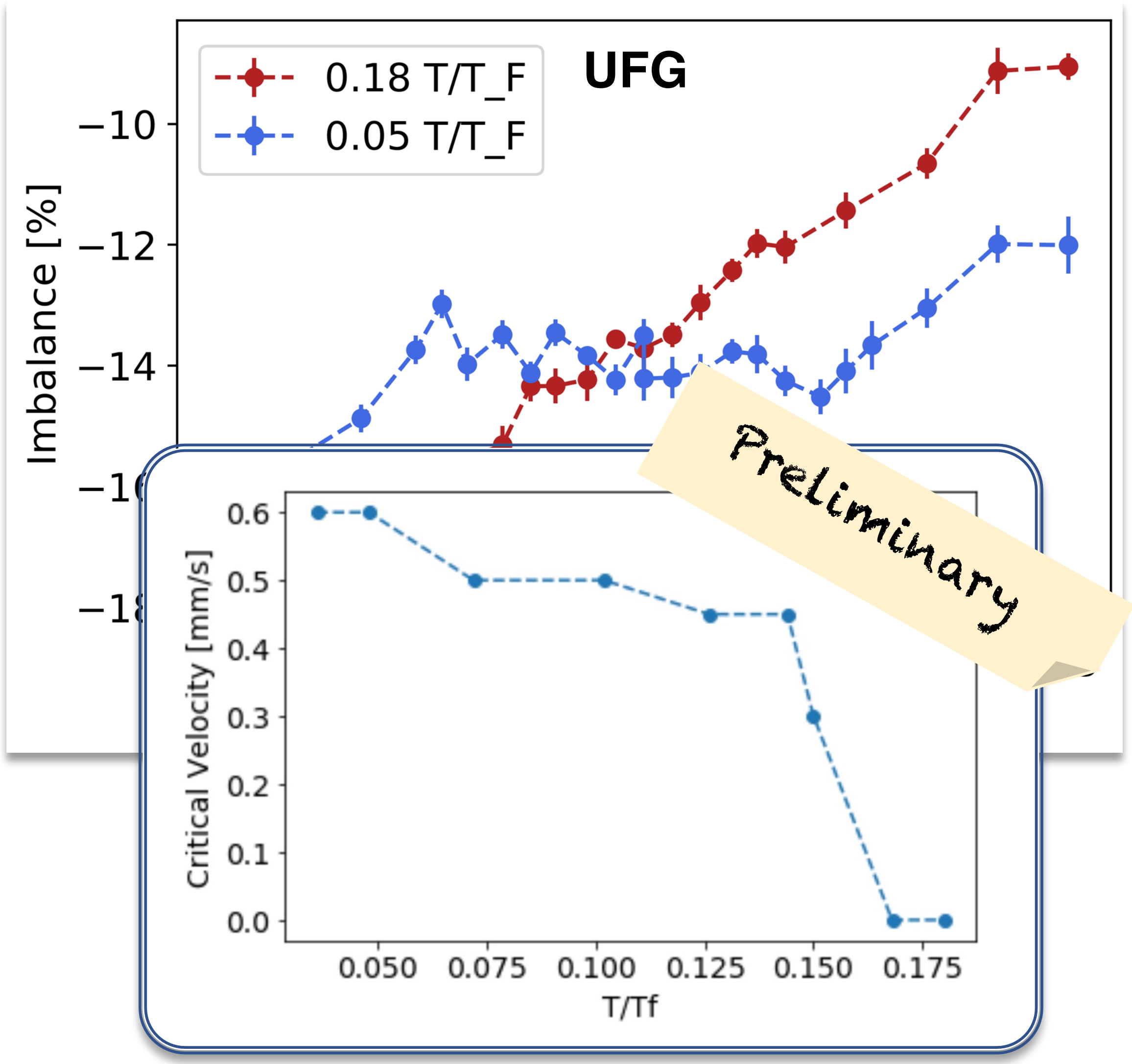


CONCLUSIONS

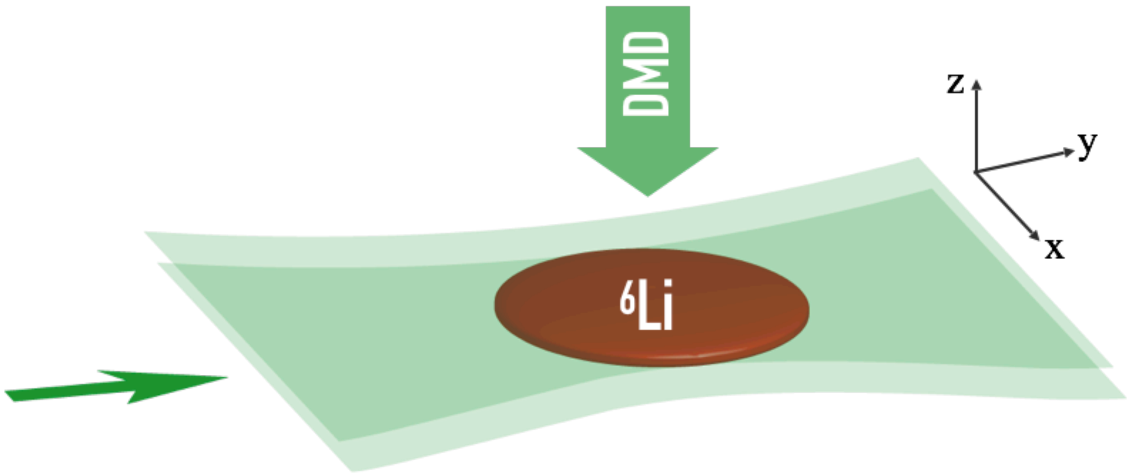
○ QUANTUM SIMULATION

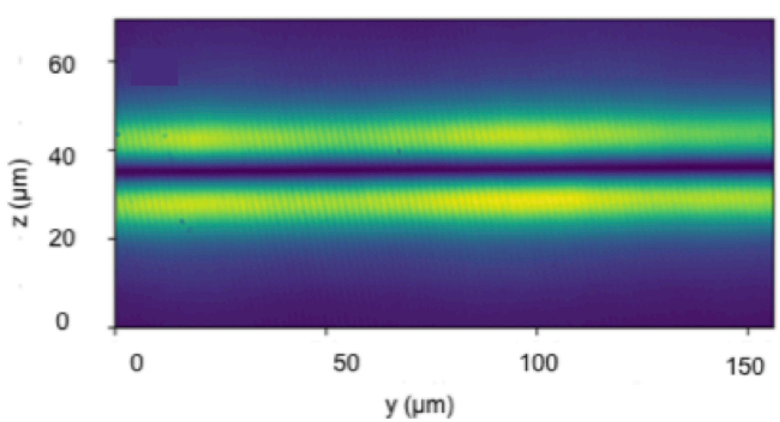
We implemented for the first time a tunable **current-biased Josephson junction** with fermionic superfluids. We access **dc Josephson** effect and measure a **sinusoidal current phase relation**. The $I - \Delta\mu$ characteristic we measured resembles the $I - V$ characteristic of a SJJ, and allow for the **direct extraction of the Josephson critical current** I_c.

○ TRANSPORT MEASUREMENT

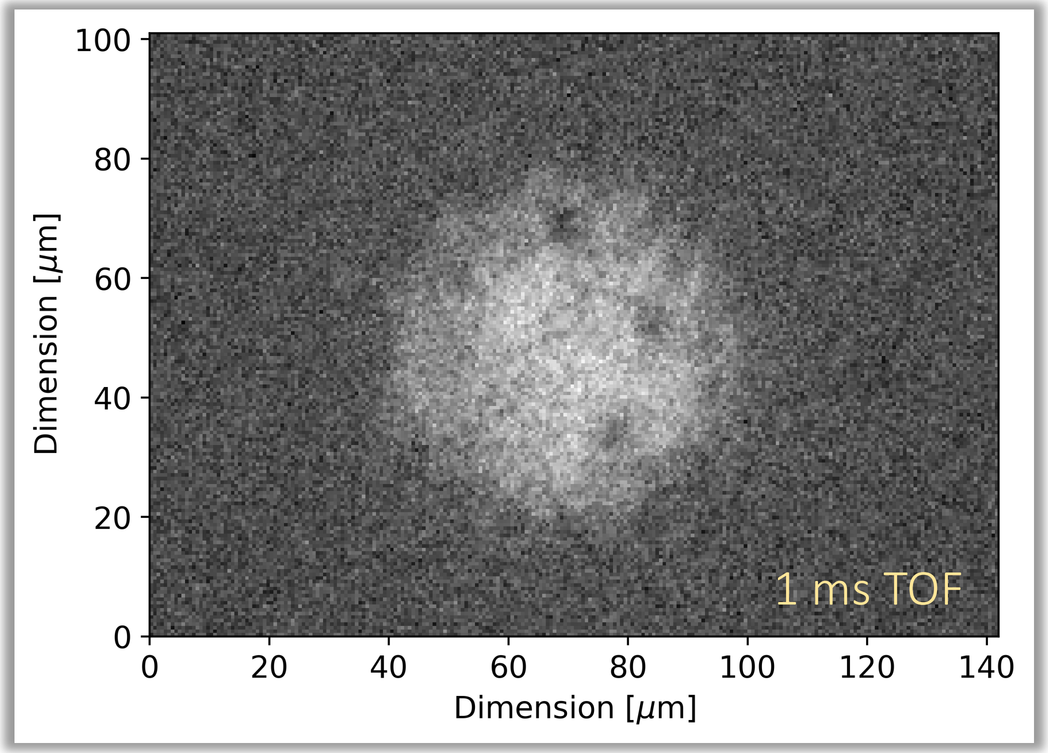
From the measurement of I_c in the BEC-BCS crossover we extract the **order parameter** of the fermionic superfluids, namely the **condensed fraction**, confirming that it is **condensation**, rather than superfluidity, **at the basis of the Josephson effect**. Our measurement highlights the key role of transport measurement to disclose the intrinsic quantum nature of quantum materials. Our protocol can be applied in different systems as a **probe for condensation**.

2D FERMI GAS



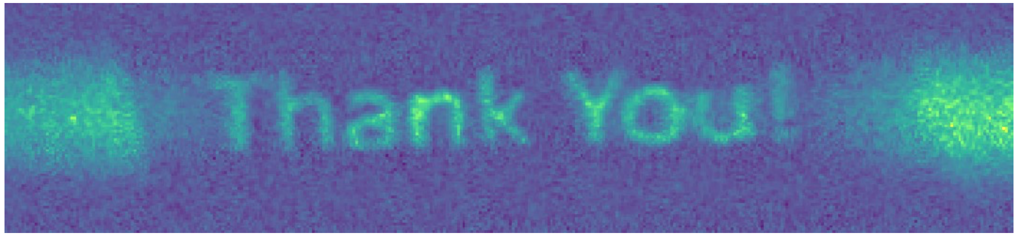


$\nu_z \simeq 6$ kHz, $\nu_r \simeq 30$ Hz
2D Fermi Energy = $0.21\ \mu K$
Quasi-2D: $\hbar\nu_z/E_F = 1.4$
Atom number: 25×10^3



… still working on it

LITHIUM LAB @ LENS



Matteo Zaccanti

Wilhelm Zwerger

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Andrea Amico

PhD and Internship position available!

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Nick Proukakis (Newcastle)
Luca Galantucci (Newcastle)
Luca Pezzè (Florence)