Tunnelling transport in strongly-interacting atomic Fermi gases

Giacomo Roati
CNR-INO & LENS, Florence Italy

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ICAP2026, Wuhan, China

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Lens European Laboratory for Non-Linear Spectroscopy
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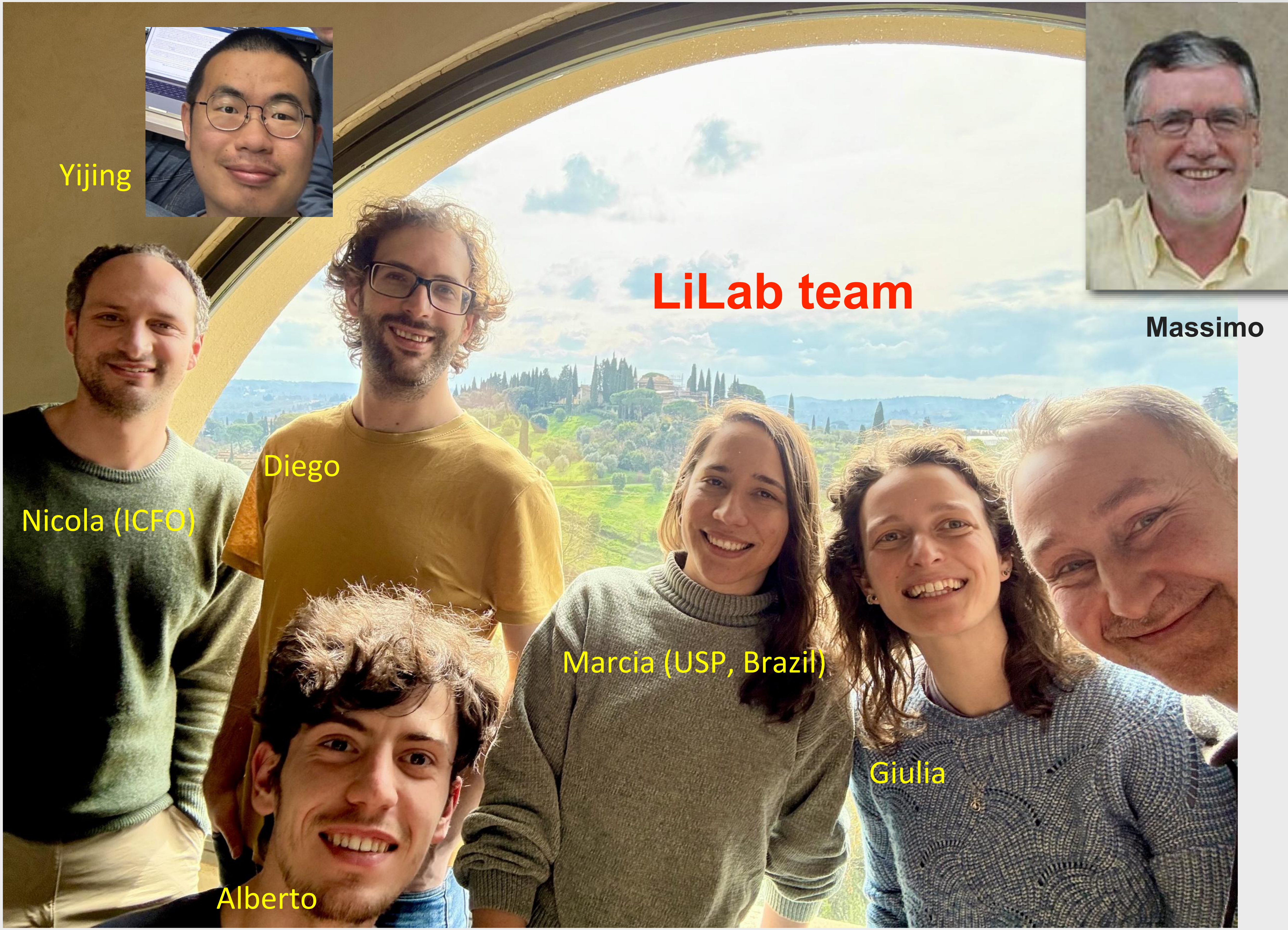


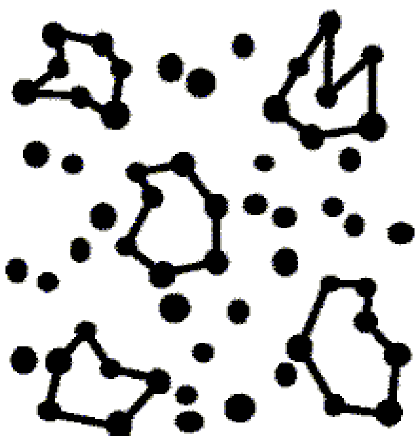
LiLab friends/collaborators: De Natale, Scazza, Kwon, Stringari, Recati, Marino, Xhani, Smerzi, Pezze', Donelli, Fort, M. Modugno, Galantucci, Singh, Amico, Barresi, Magierski, Wlazlowski, Pieri, Pini…

Transport measurements: fundamental tool to investigate matter.

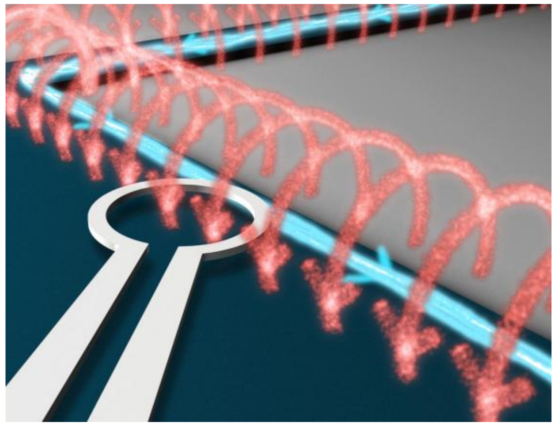
Extracting microscopic properties of a quantum many-body systems via global measurements, typically current (T. Giamarchi).

Datta, *Electronic transport in mesoscopic systems* (Cambridge University Press, 1997)

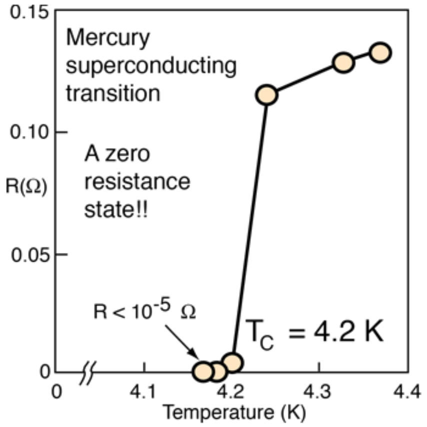
Localization

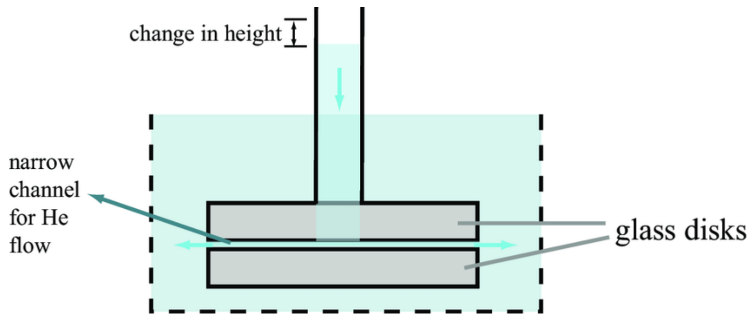


Topological currents

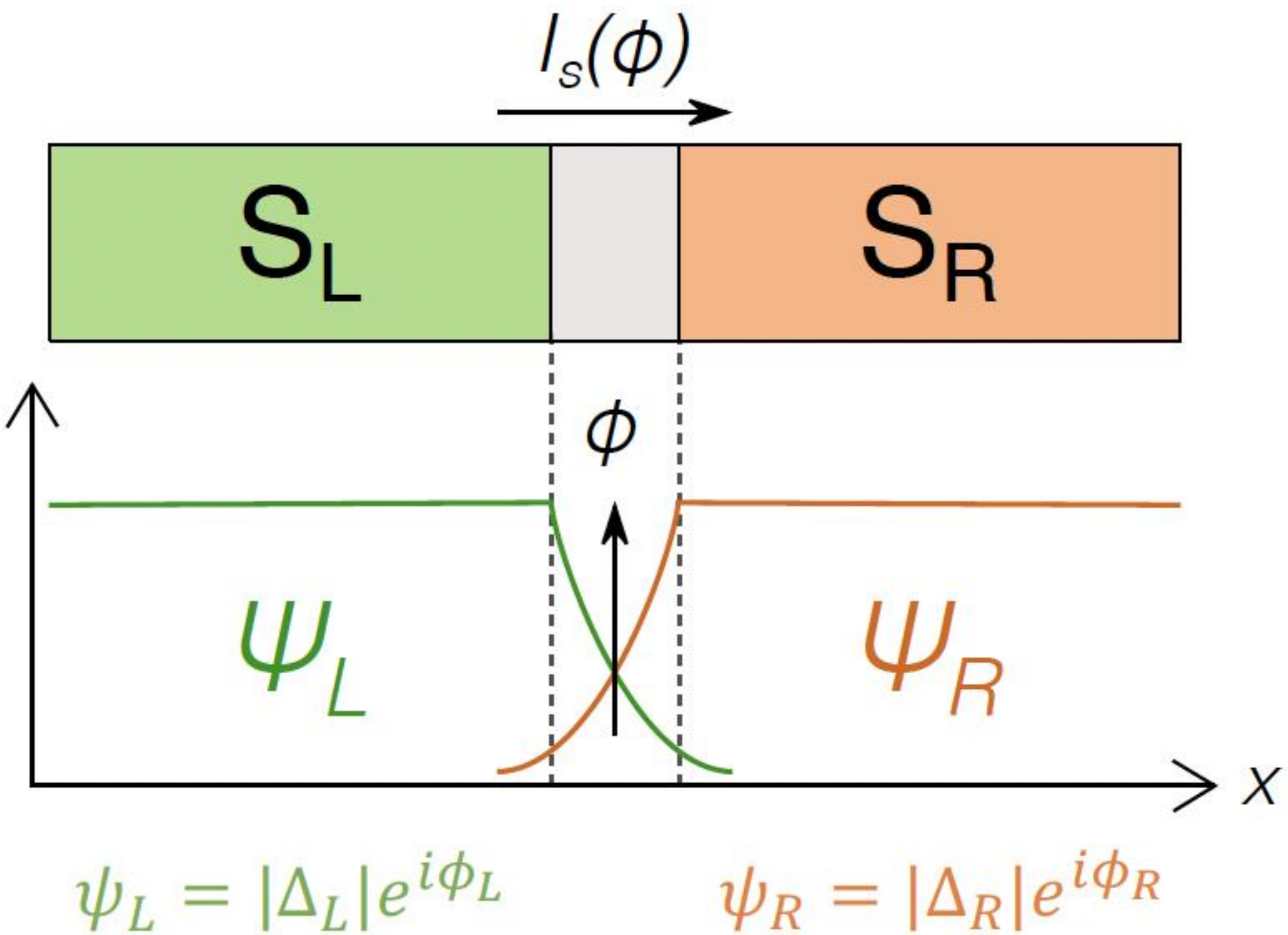


Superconductivity and superflui





A paradigmatic example: a Josephson junction



Josephson-Anderson equations:

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

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

$\phi = \phi_L - \phi_R \rightarrow$ **relative phase**

I_c →critical current

V →potential difference

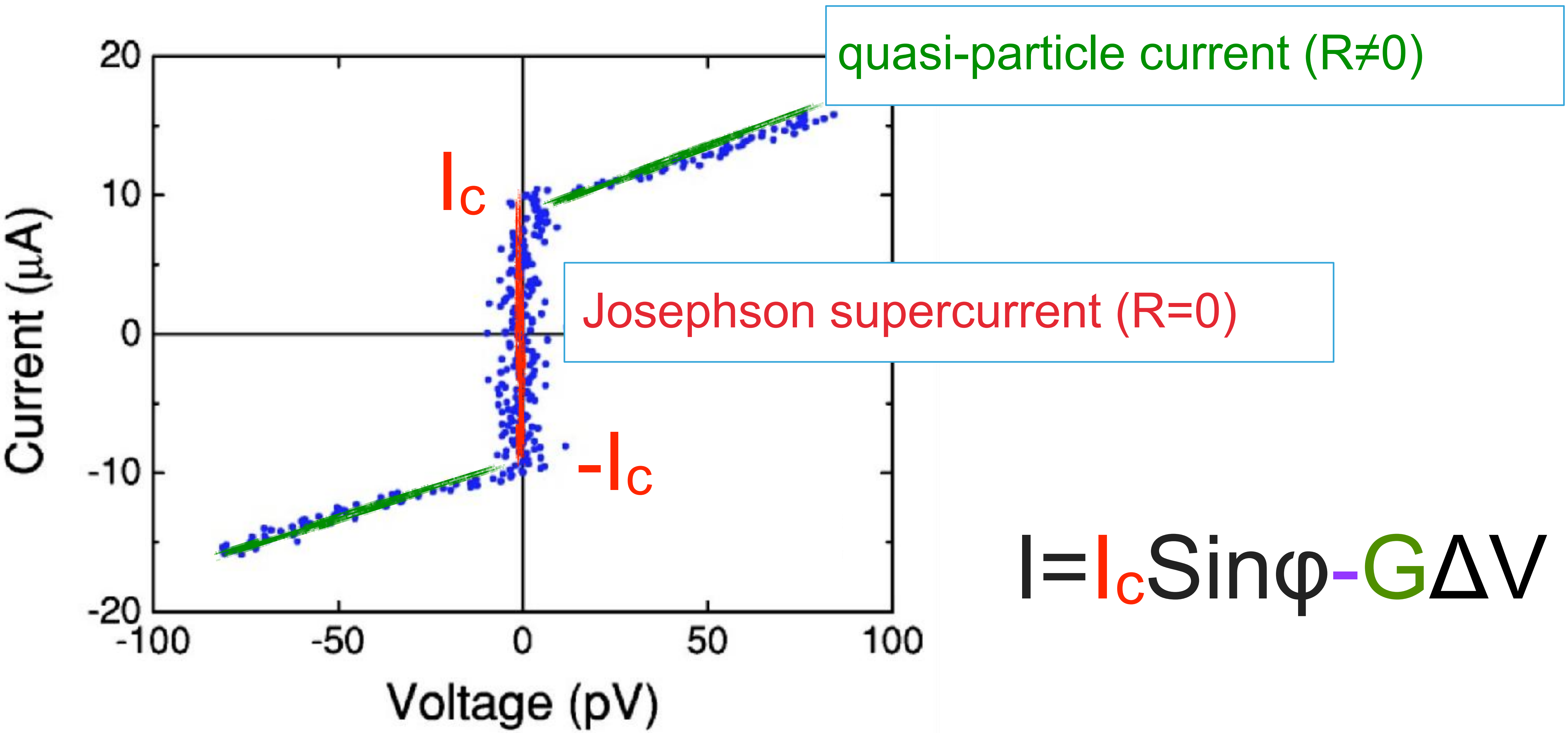
- ☑ Thin barrier: quantum tunneling regime

Josephson, Phys. Lett. (1962).
Anderson, Lectures on The Many-Body Problems, vol. 2 (Elsevier, 1964).

Josephson, Phys. Lett. (1962)

DC Josephson effect

$\varphi = \varphi_1 - \varphi_2$: *"quantum voltage"* $I = I_c \sin\varphi$



$I = I_c \sin\varphi - G\Delta V$

Why Josephson tunneling?

Ambegaokar-Baratoff relation (BCS)

BEC-BCS crossover: Zaccanti and Zwerger PRA (2019)

$$\hbar I_c \equiv E_J \sim \Delta \sim n_c$$

Measurable current (macro)

↓

Condensate fraction (micro)

(challenging for strongly-interacting gases)

The Josephson effect (Anderson's viewpoint)

… *In the case of superconductivity things are quite different.* The internal long-range order parameter — the phase — is not a parameter for which suitable instruments exist; we do not normally walk around with objects which have phase order. *A superconductor has rather perfect internal phase order, but as we have shown the zero-point motion of the total order parameter of an isolated superconductor is large and rather rapid.*

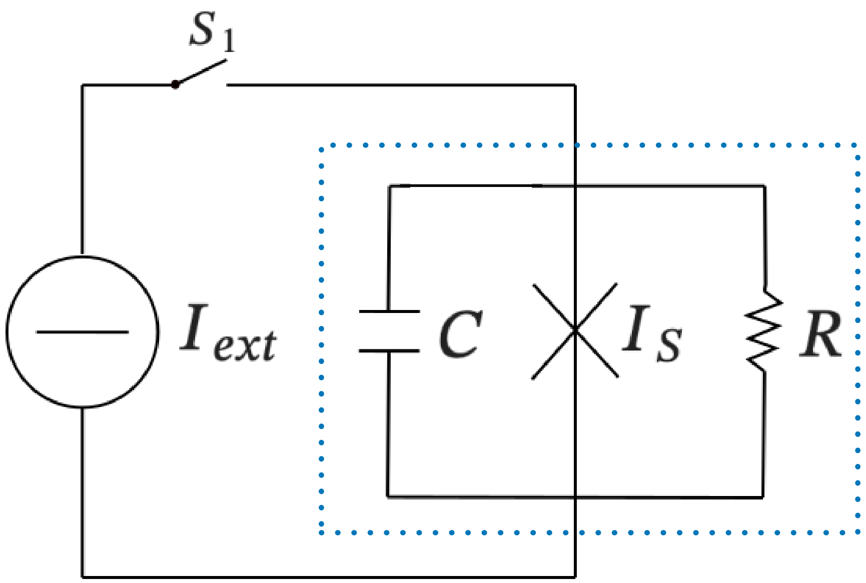
The importance of the Josephson effect, then, is that it provides for the first time an instrument which can act like a clamp for a solid or a coercive field for a ferromagnet: <u>it can pin down the order parameter</u> …

But most important of all, it frees us conceptually from the mystery surrounding superconductivity, and places it in line with all of the other condensation phenomena.

Anderson in Lectures on the Many-body Problems, **E.R. Caianiello, Elsevier Science (1964)**

RCSJ model: an operative mechanical model

Tinkham, Introduction to Superconductivit



Kirchhoff law:

$$I_{ext} = I_c \sin(\phi) + GV + C\dot{V} \quad + \quad \dot{\phi} = \frac{2e}{\hbar} V$$

$$\frac{C\hbar}{2e}\ddot{\phi} = I_{ext} - I_C \sin(\phi) - \frac{G\hbar}{2e}\dot{\phi}$$

C →capacitance

R →resistance

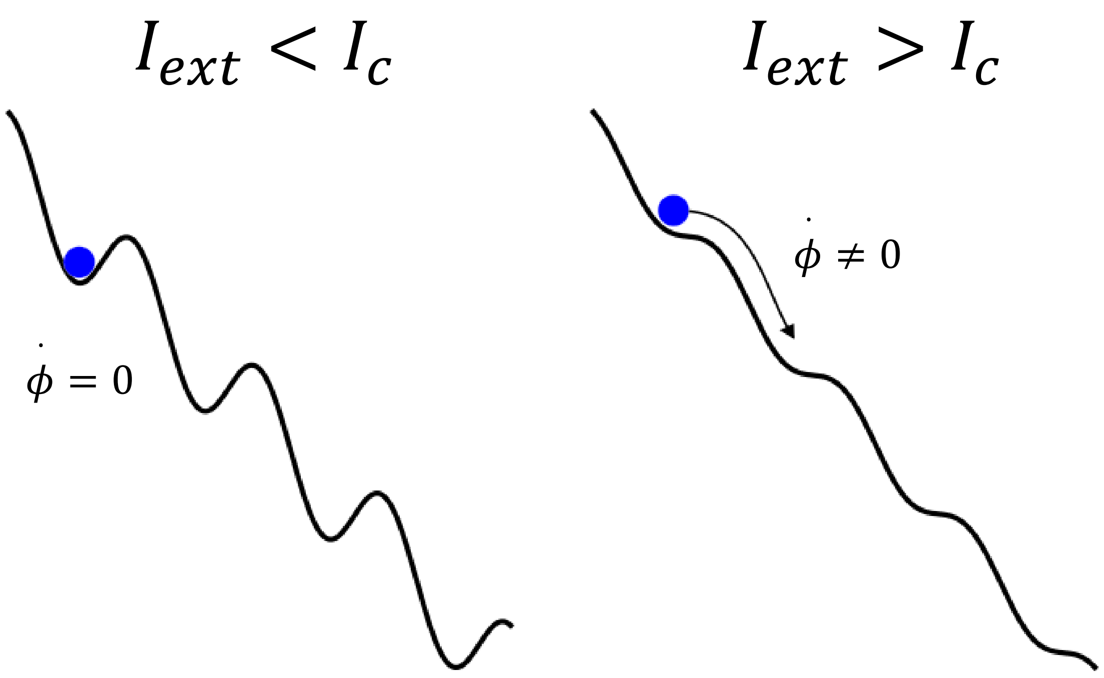
$G = 1/R$ →conductance

Equation of motion for a phase particle of mass ~ C subject to a viscous force ~G in the **washboard potential**:

$$U(\phi) = -I_{ext}\phi + I_c \cos(\phi)$$

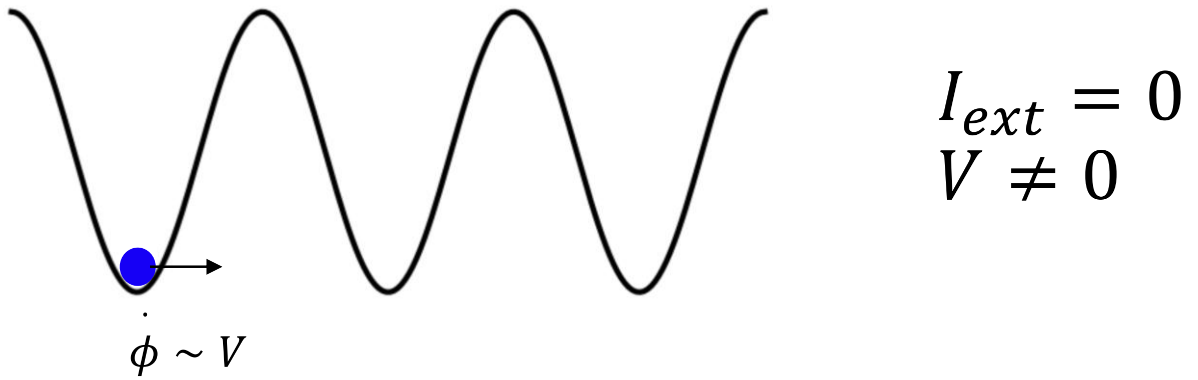
Washboard potential

DC Josephson effect



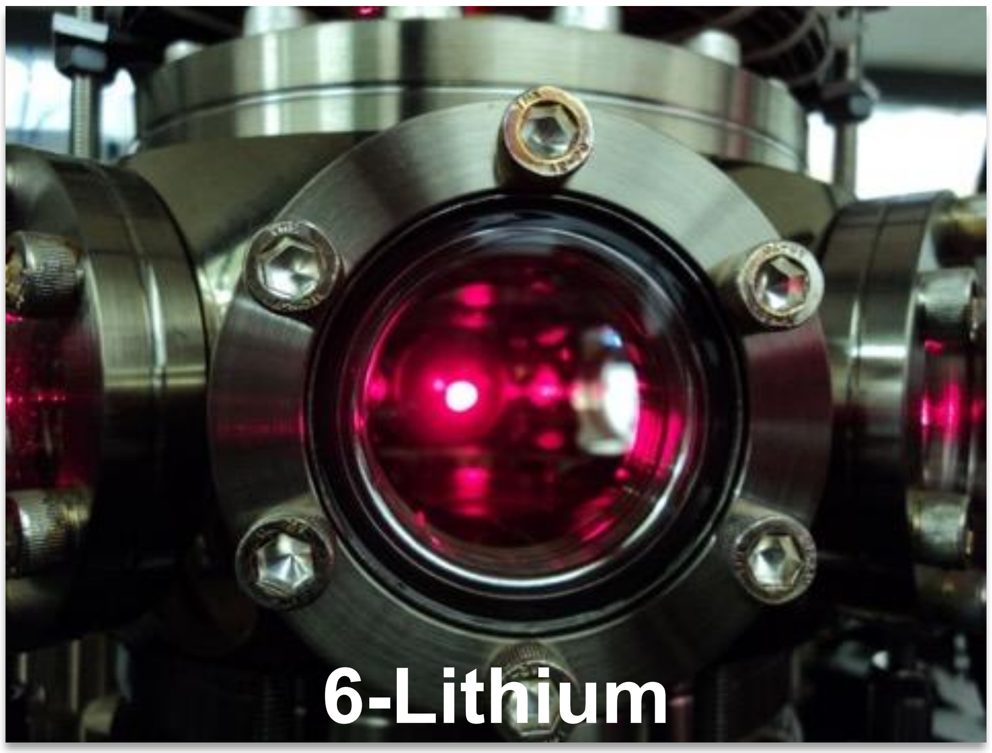
$I_{ext} < I_c$: the phase particle remains in one washboard potential minima: dissipationless current.

AC Josephson effect



The phase particle oscillates in one washboard potential minima: Josephson oscillations @ $\omega_J \sim \Delta V/\hbar$

^{6}Li and BEC-BCS crossover



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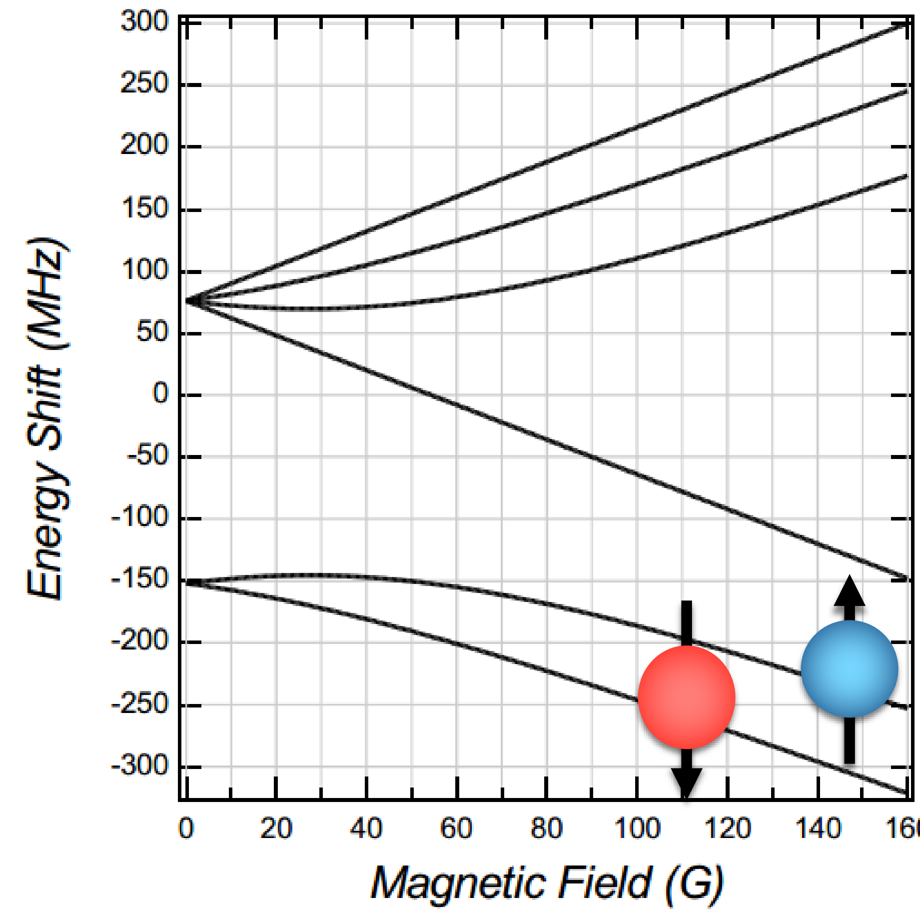
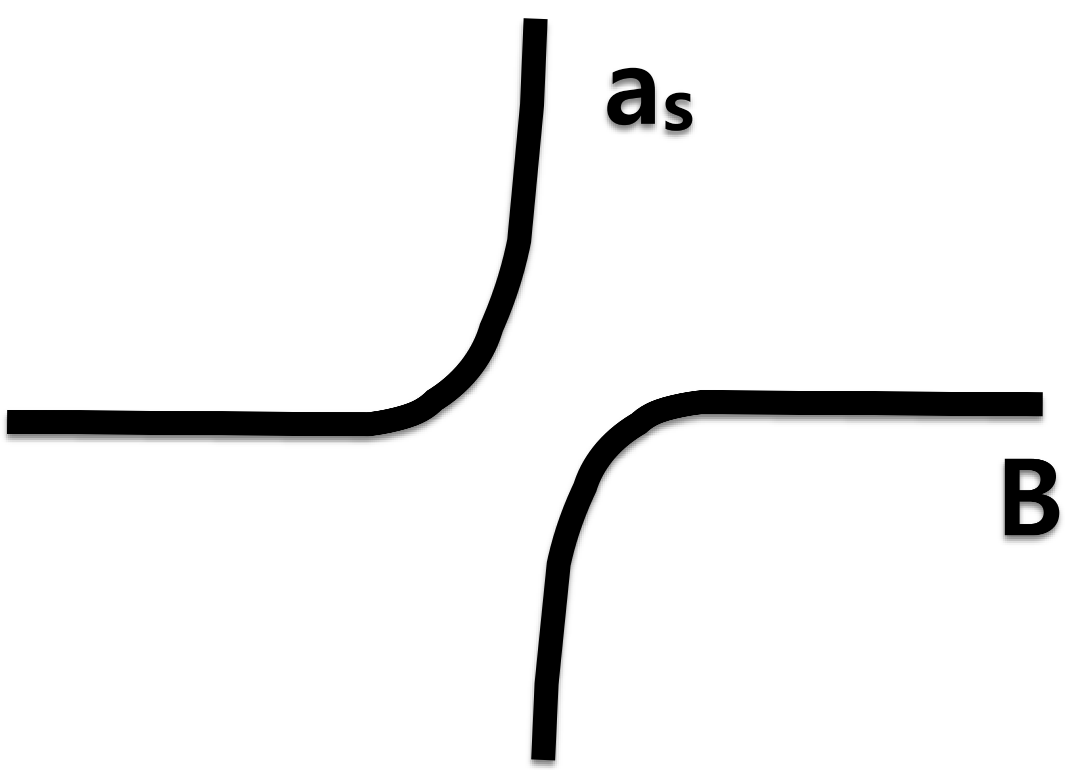
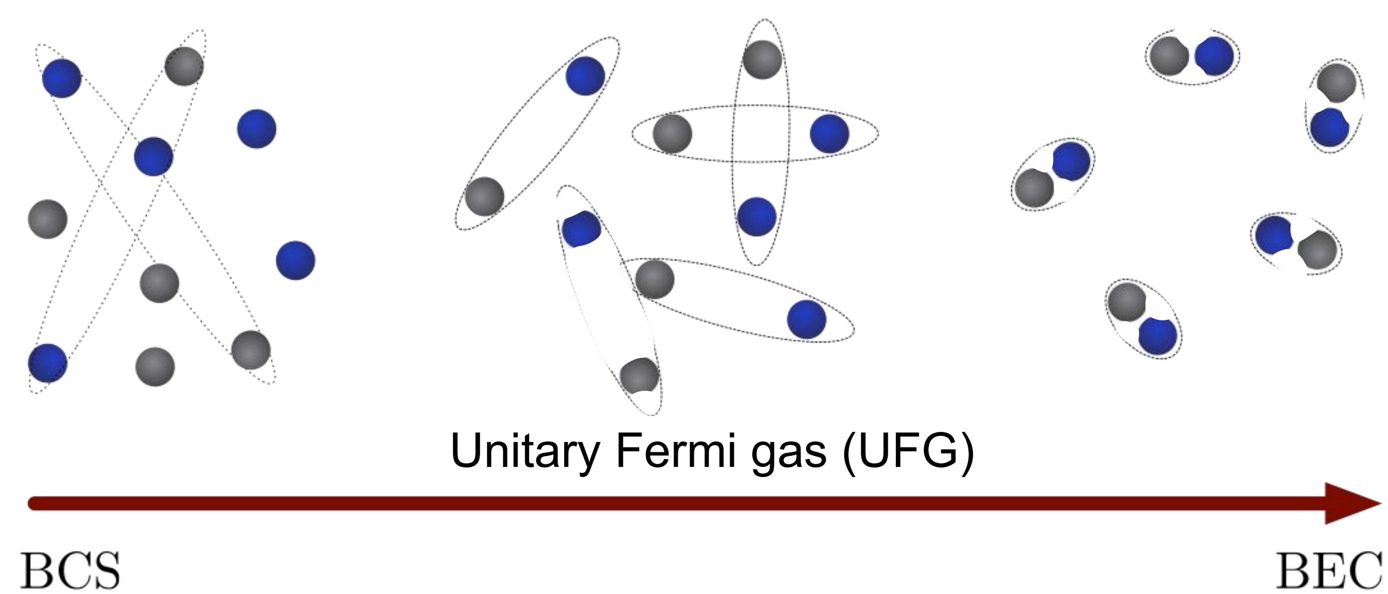






Holland, Kokkelmans, Chiofalo, and Walser PRL (2001)

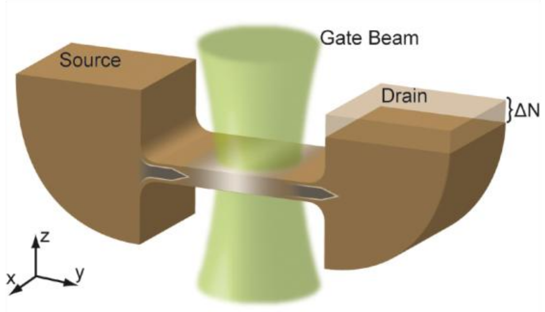
Randeria, Nat. Phys. (2010)

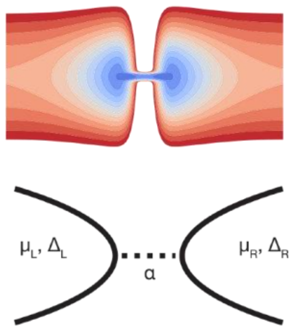
Quantum Transport with Fermi Gases

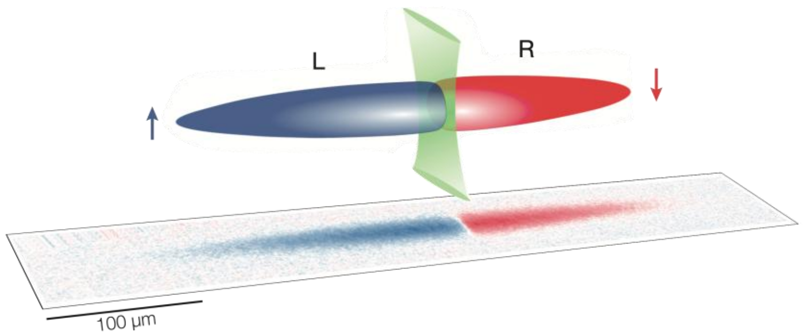
Transport through narrow ballistic channels

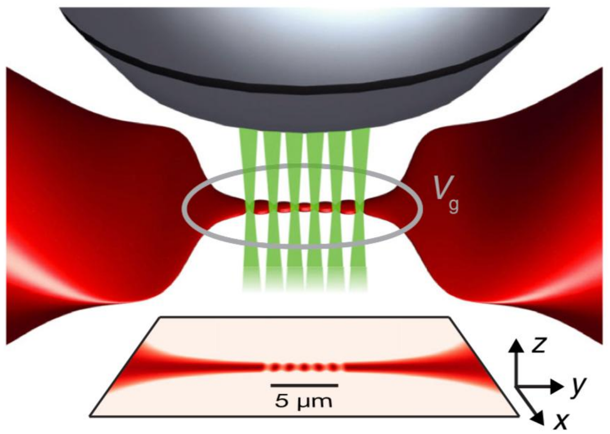
Spin, sound and heat transport..

Tunneling through structures









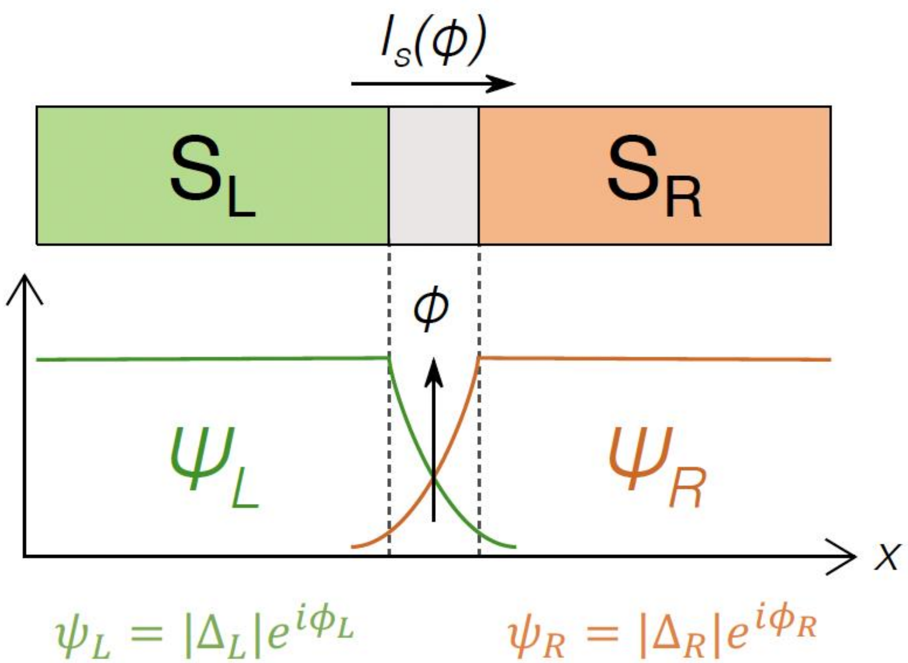
ETH, Geneva

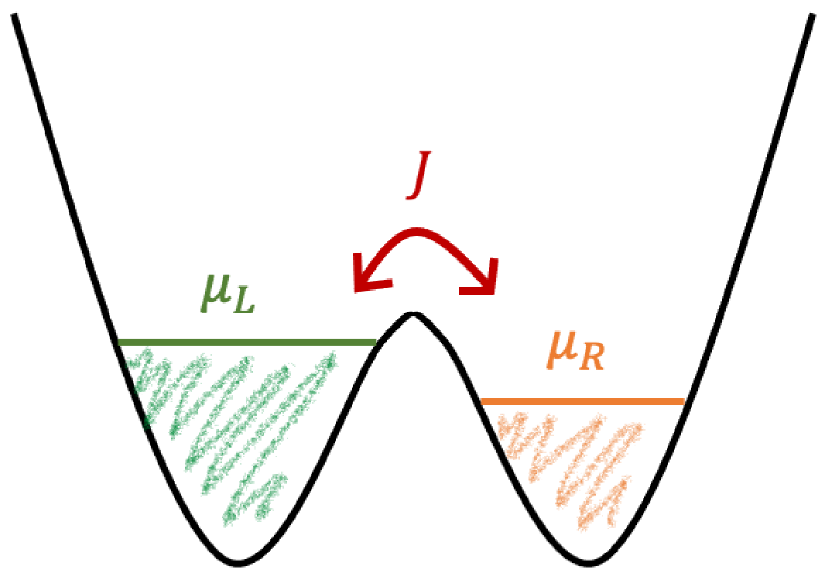
MIT, Harvard, Innsbruck, Toronto, ETH, LENS, MPQ, Rice, Hamburg,…

ETH, LENS, Princeton, Toronto,…

For a review: Krinner et al., *J. Phys.: Condens. Matter* **29** (2017)

Electrons vs neutral atoms





Josephson-Anderson equations:

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

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

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

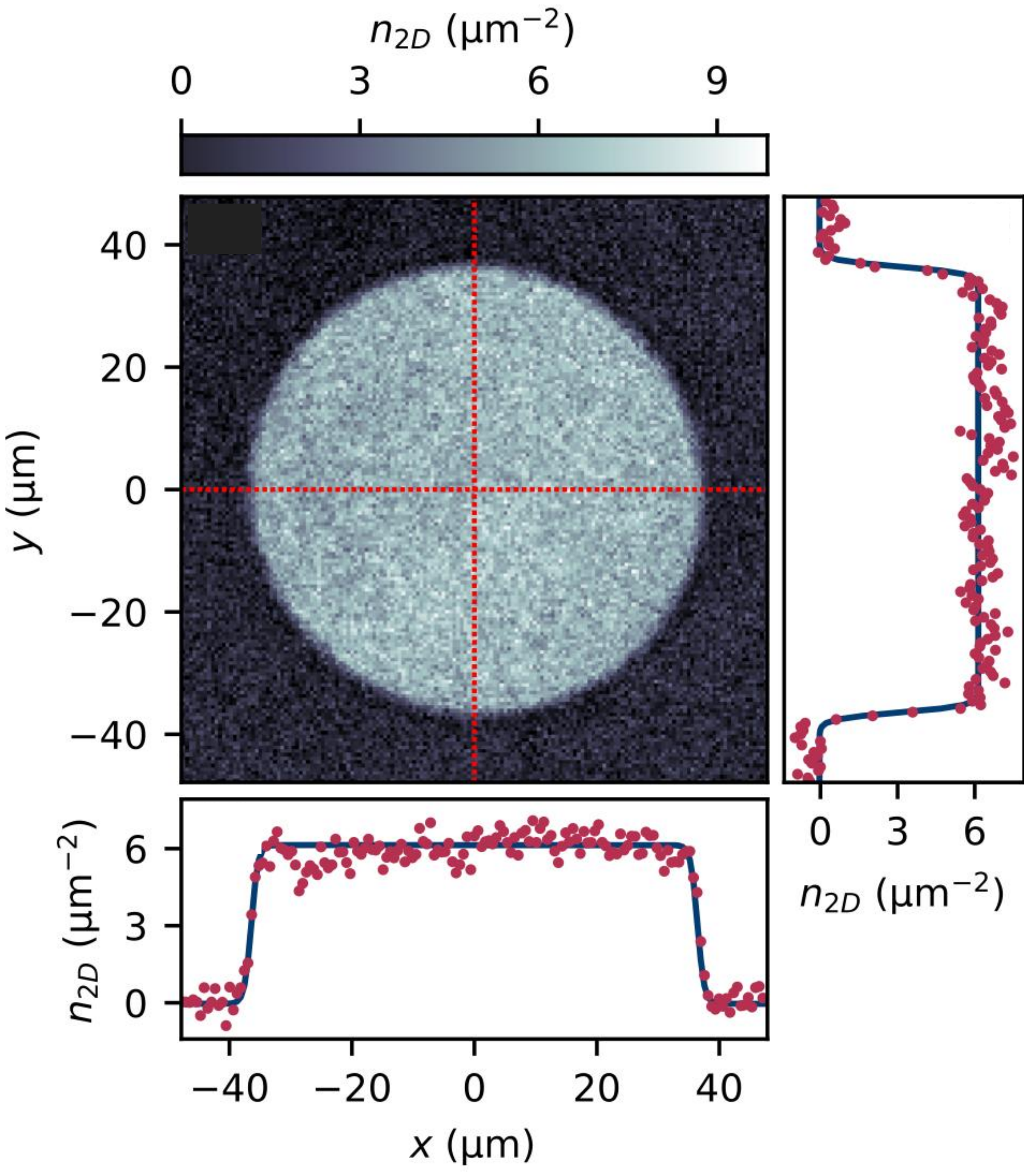
$$I = I_c \sin(\phi)$$

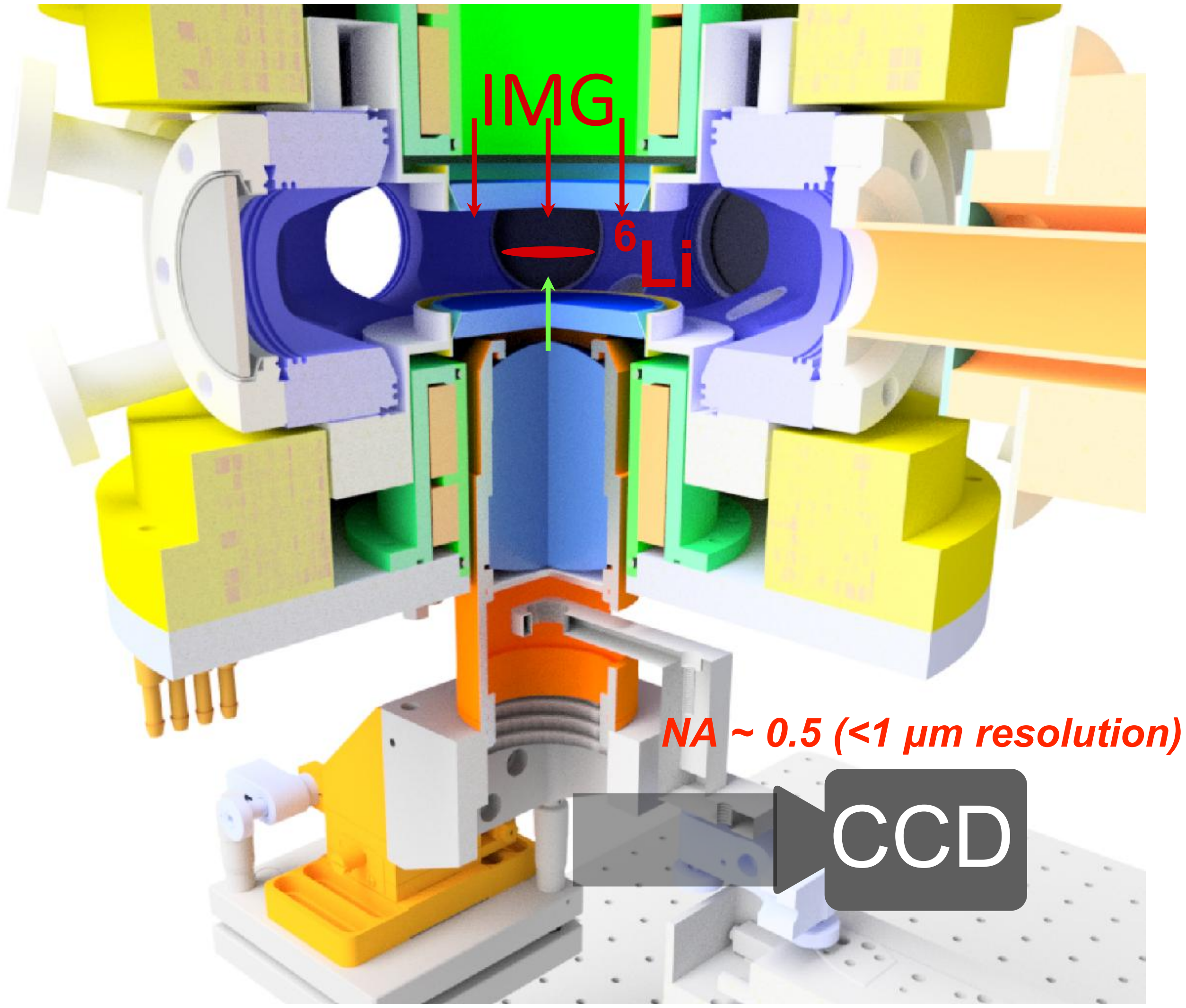
$$\dot{\phi} = -\frac{\Delta\mu}{\hbar}$$

Giovanazzi, Smerzi, and Fantoni PRL (2000)

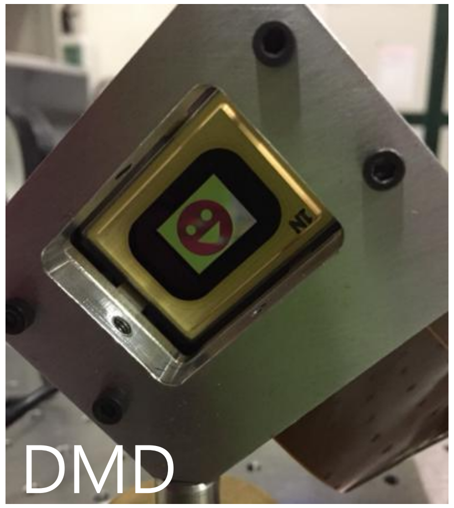
Atomic Fermi gases @ LENS

Quasi-homogeneous 3D superfluids: $N_{\uparrow}=N_{\downarrow}\simeq 50000$ @ $T/T_F \sim .1$ -> $T<T_C$





Ingredients: shaping dynamical optical potentials



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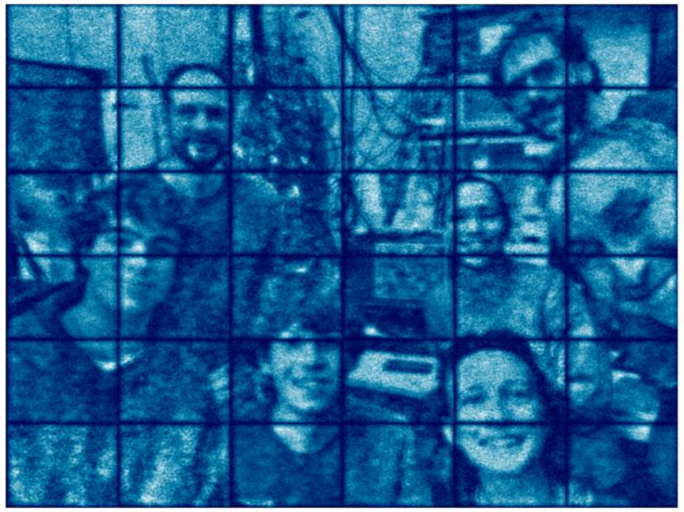
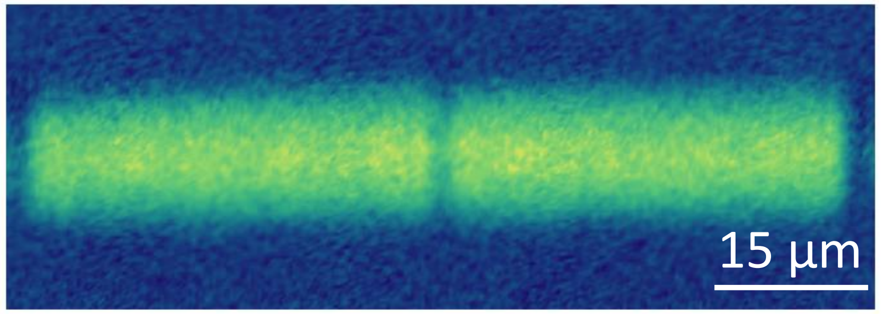
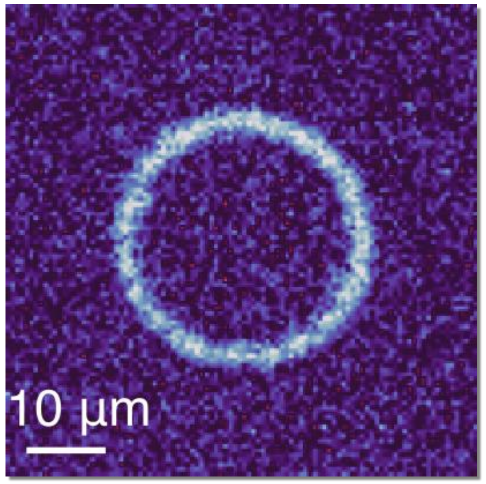
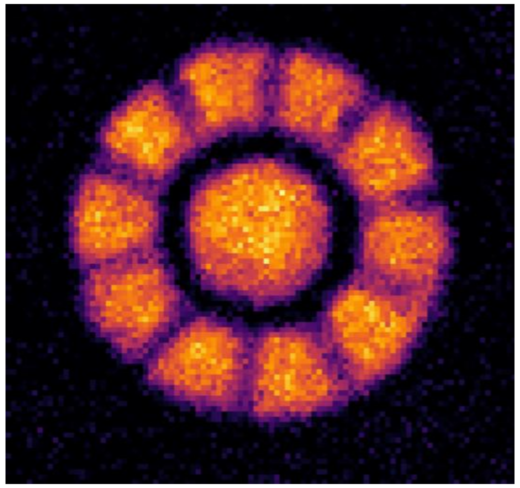
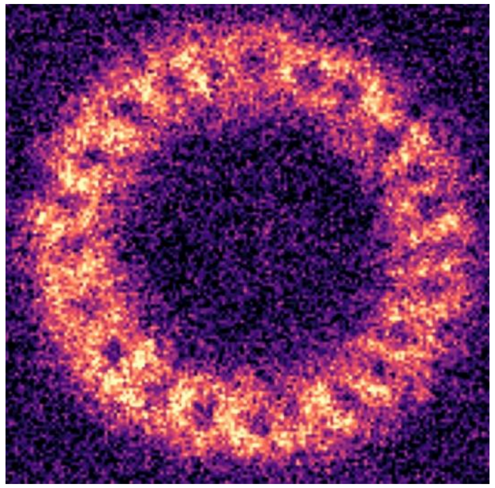










Valtolina et al., Science (2015)
Kwon et al., Science (2020)
Del Pace et al., PRL (2021)
Del Pace et al., Science (2025)

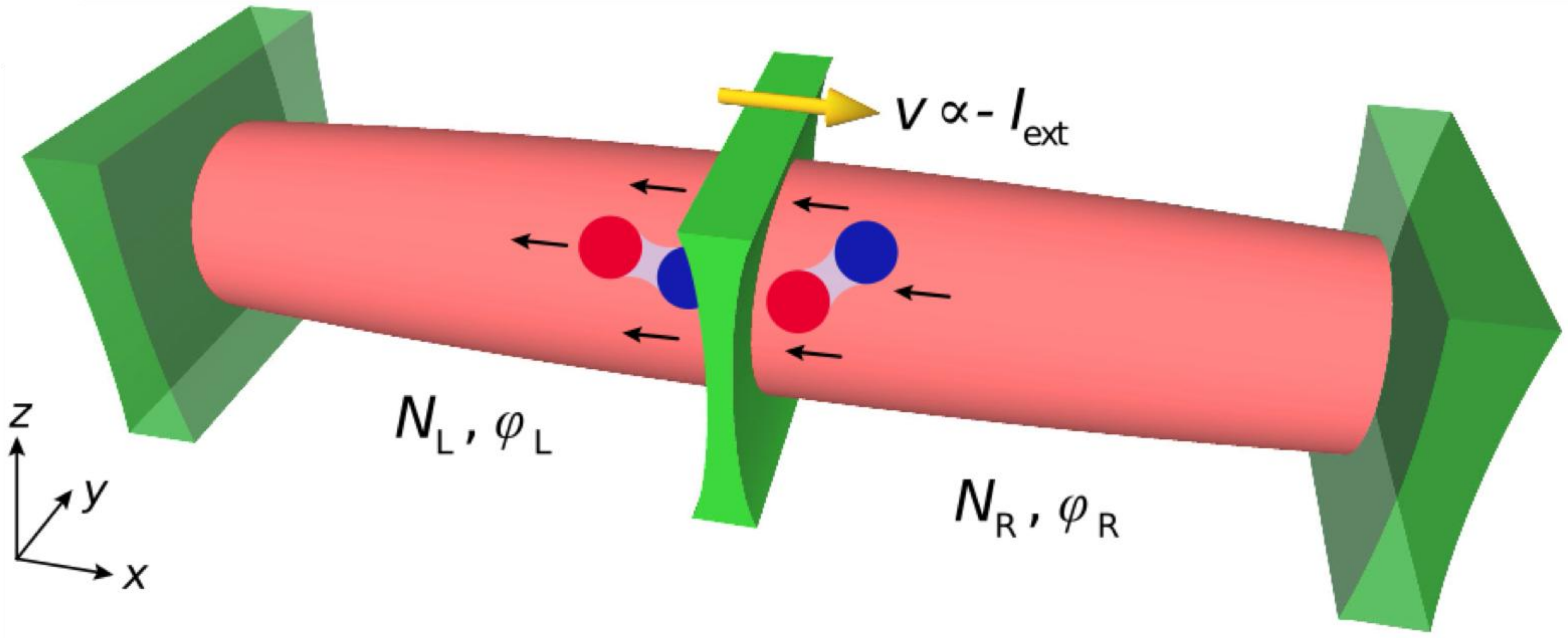
Del Pace et al., PRX (2022)
Pezze' et al., Nat. Comm. (2024)
Frometa et al., arXiv:2511.02664v2 (2025)
Ciszak, et al.,arXiv:2601.15121v2 (2026)

Kwon et al., Nature (2021)
Rajkov et al., Nat. Phys. (2024)
Grani et al., Nat Comm. (2025)
Grani et al., Eur. Phys. J. (2025)

Kwon et al. Science (2020)

DC Josephson effect

Injecting a current: moving the optical barrier at controllable velocity



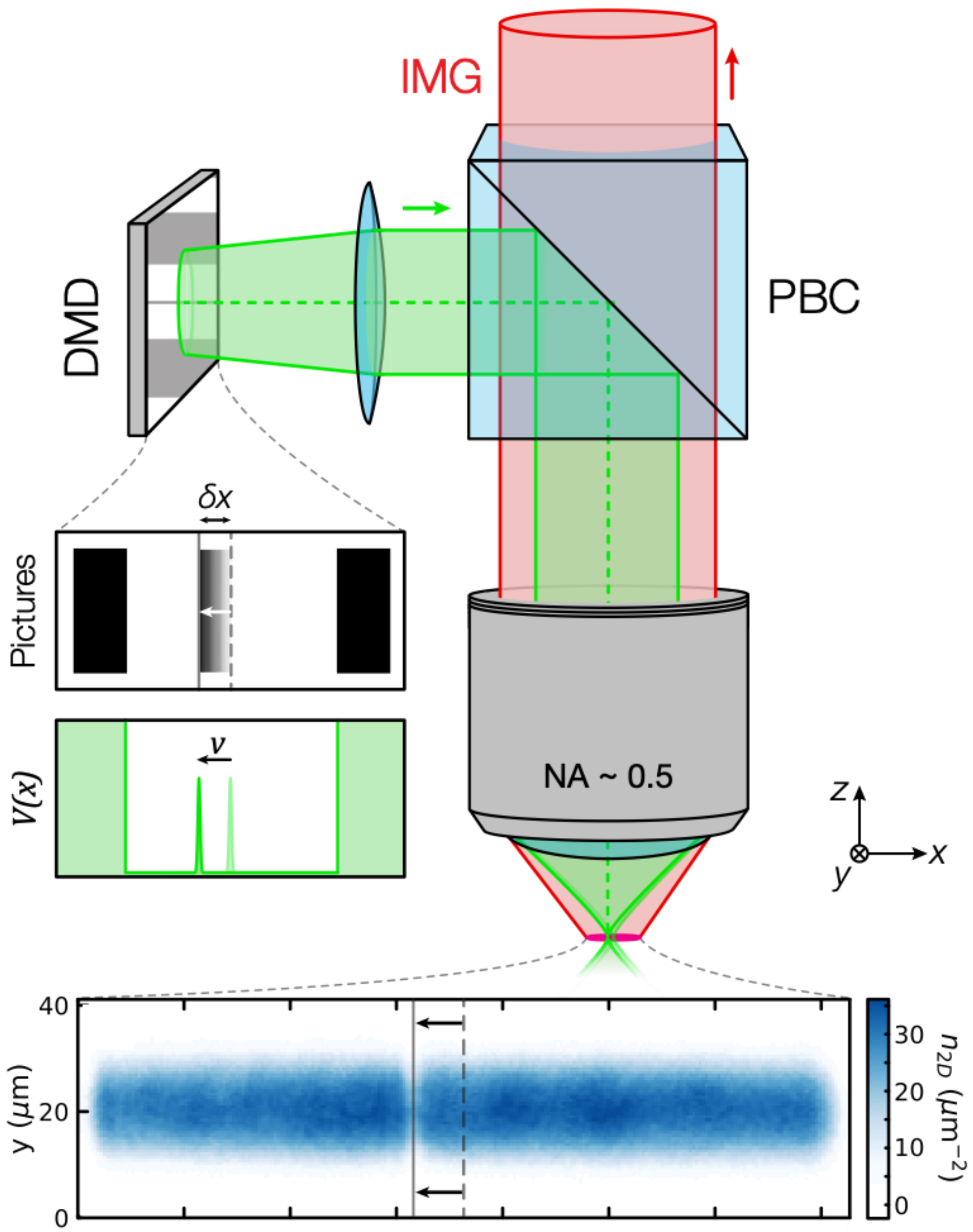
Atomic cloud:
$N_{R,L} \simeq 3.5 \times 10^4$ atom pairs
$T/T_F \simeq 0.06\ (2)$

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

Giovanazzi, Smerzi, and Fantoni PRL (2000)

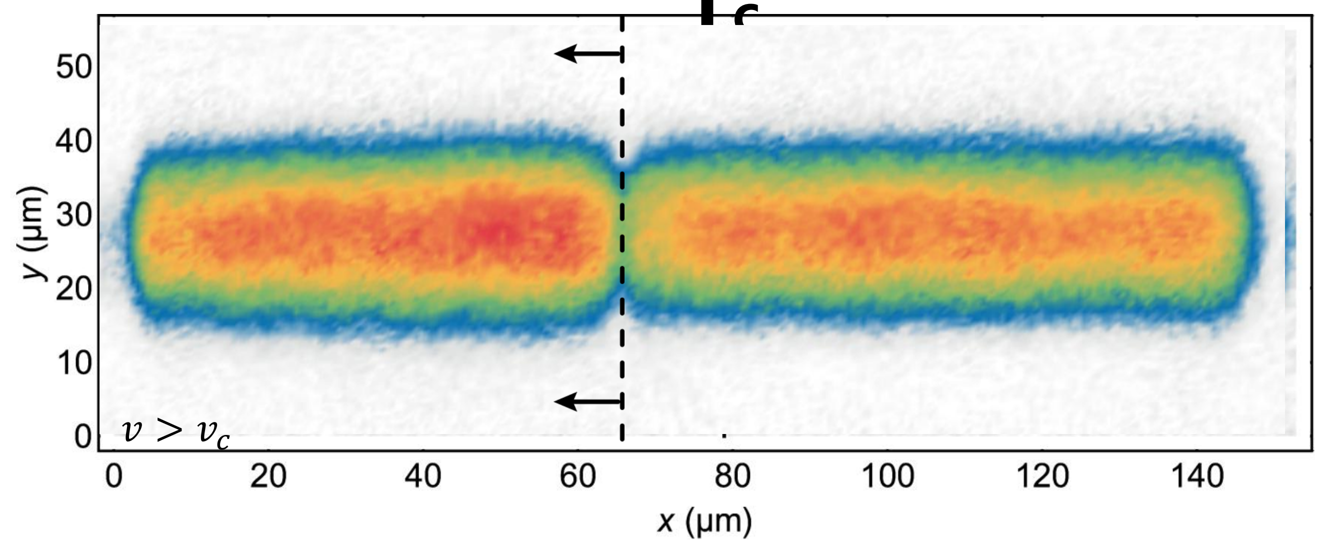
Kwon et al. Science (2020)

DC Josephson effect



δx

3D unitary gas at T~0.3 T_c



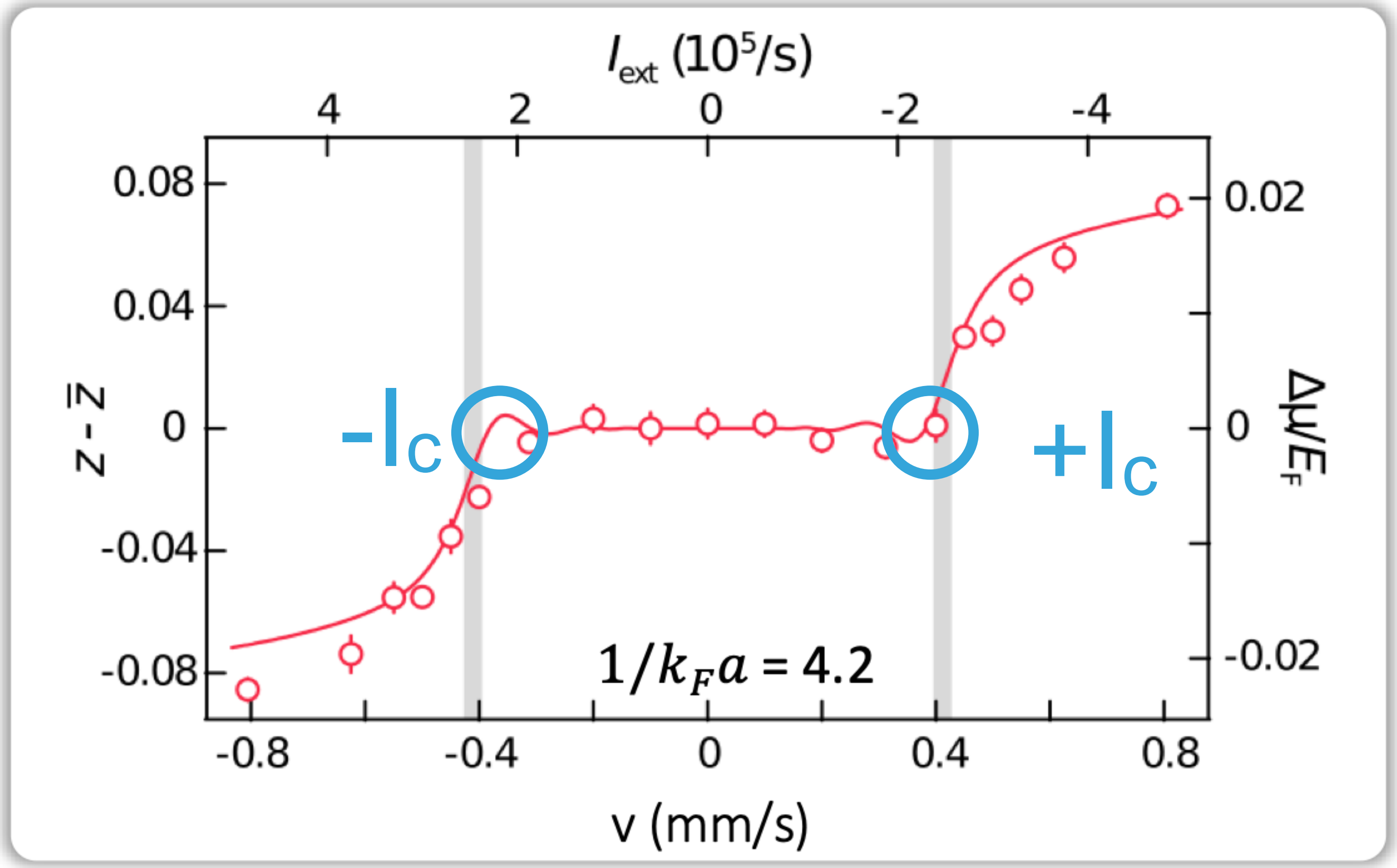
Below a critical current, the gas flows entirely through the tunnelling barrier → Superfluid coherent transport!

$\delta x = 10\mu m$
$v = 0.1 mm/s$
$\sigma = 1.5\mu m$
$V_0/\varepsilon_F \simeq 0.8$

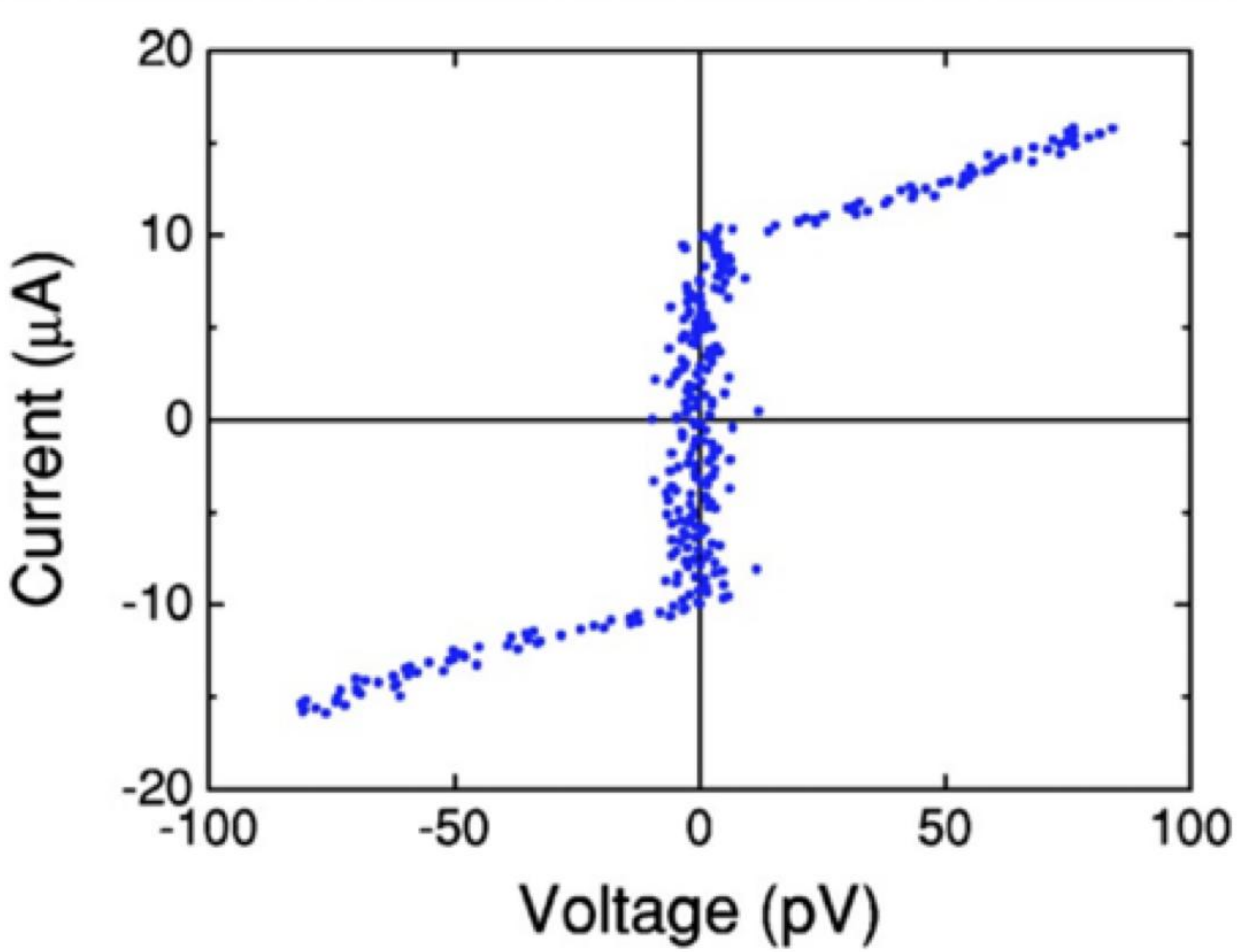
Sound velocity (bulk):
$c \approx 10$ mm/s

RCSJ circuit model

M. Tinkham, Introduction to Superconductivit



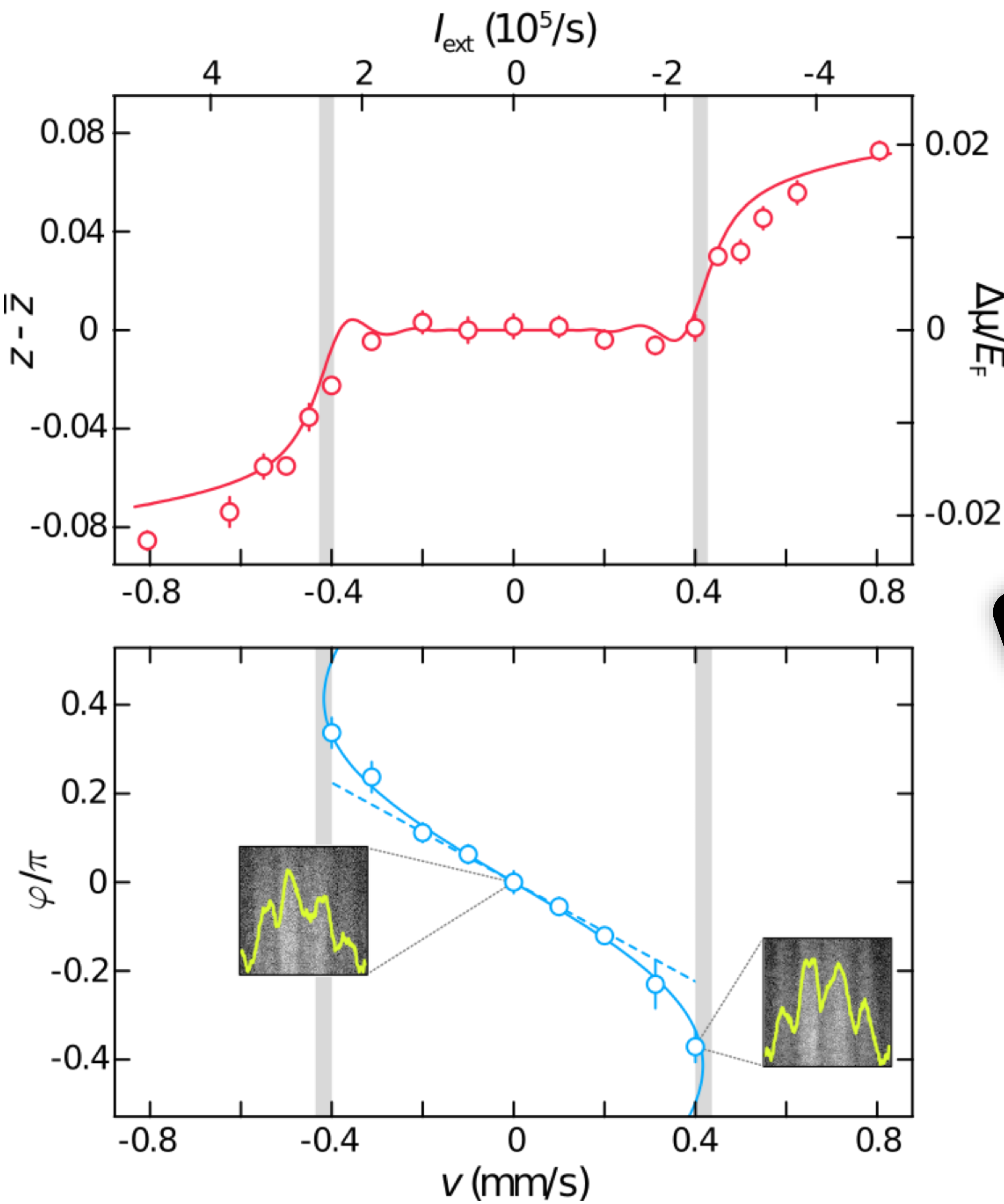
I_c and G free parameters

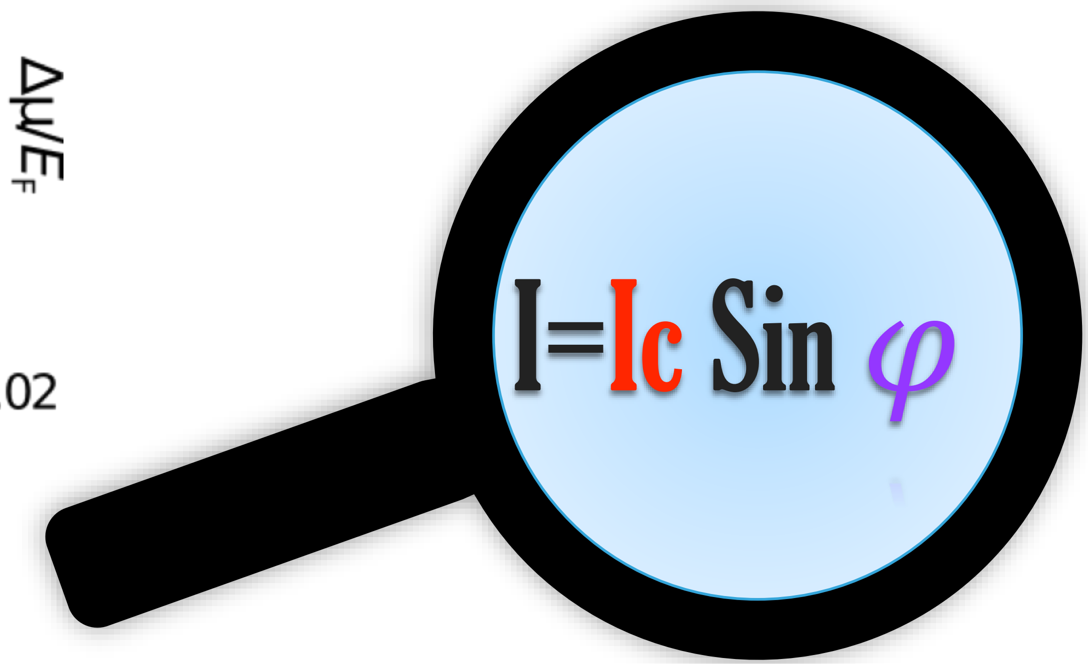


$$I = I_c \sin\varphi - G\Delta\mu$$

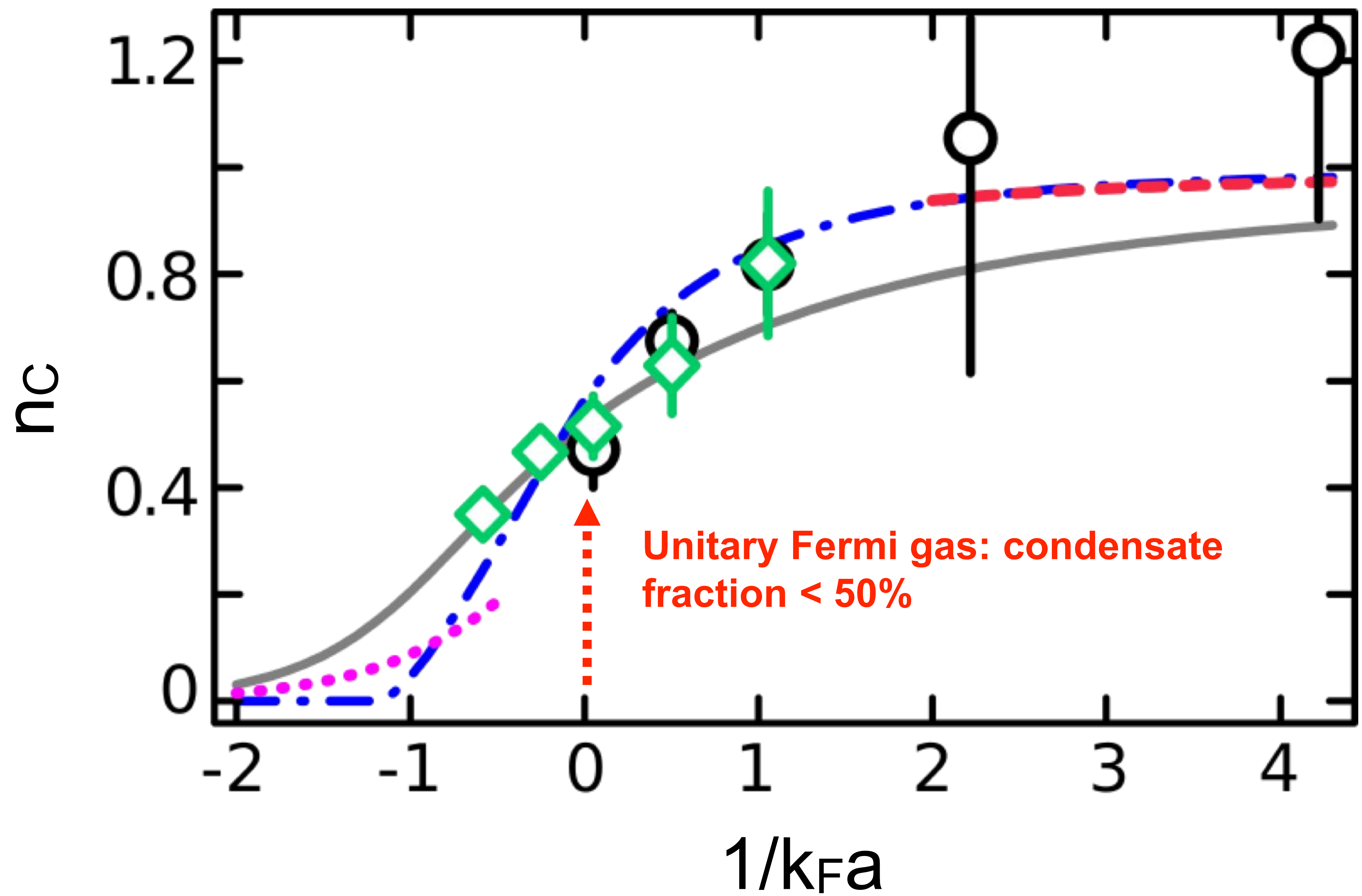
Kwon et al. Science (2020)

DC Josephson effect





Luick et al., Science (2020)



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] Haussmann et al., *PRA* (2007).

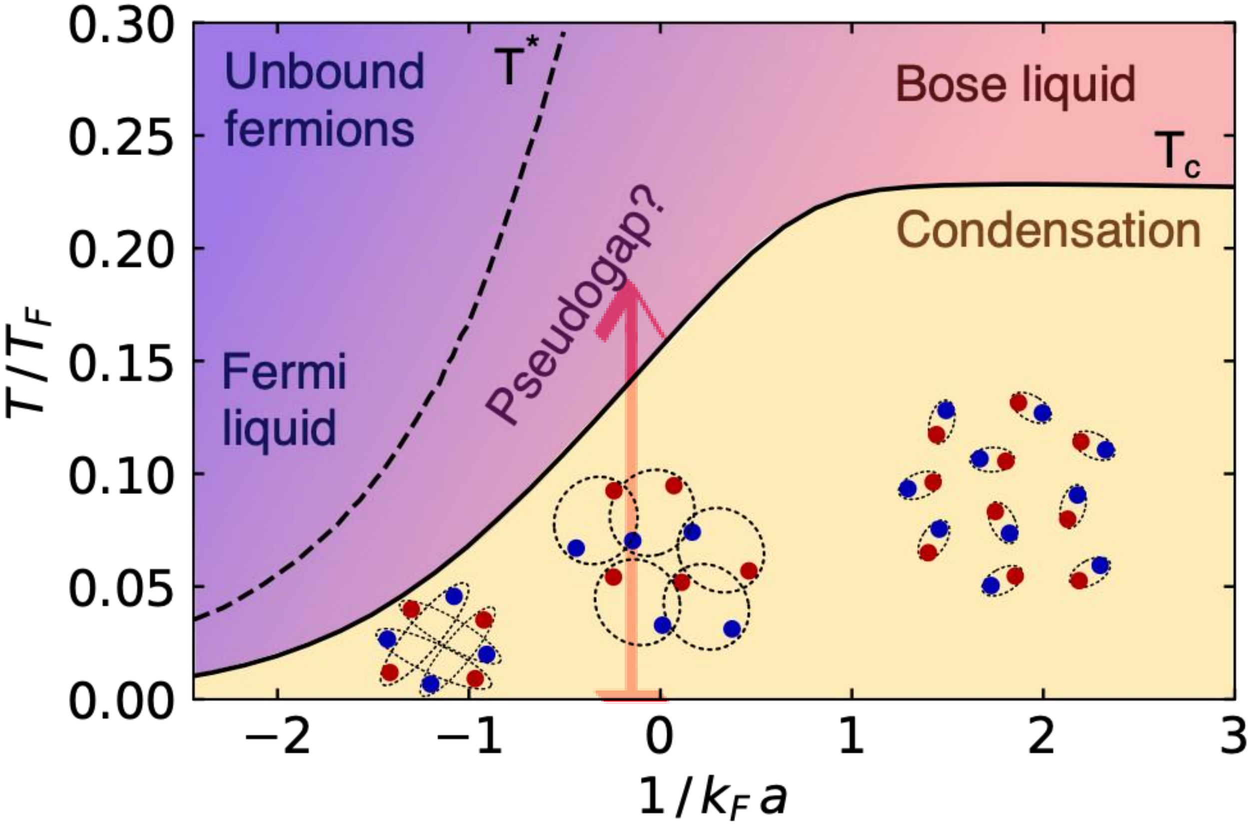
[2] Astrakharchik et al., *PRL* (2005).

[3] Gorkov, T. Melik-Barkhudarov, *Sov. Phys. JETP* (1961).

[4] Giorgini, L. P. Pitaevskii, S. Stringari, *RMP* (2008).

Del Pace et al., PRL (2021)

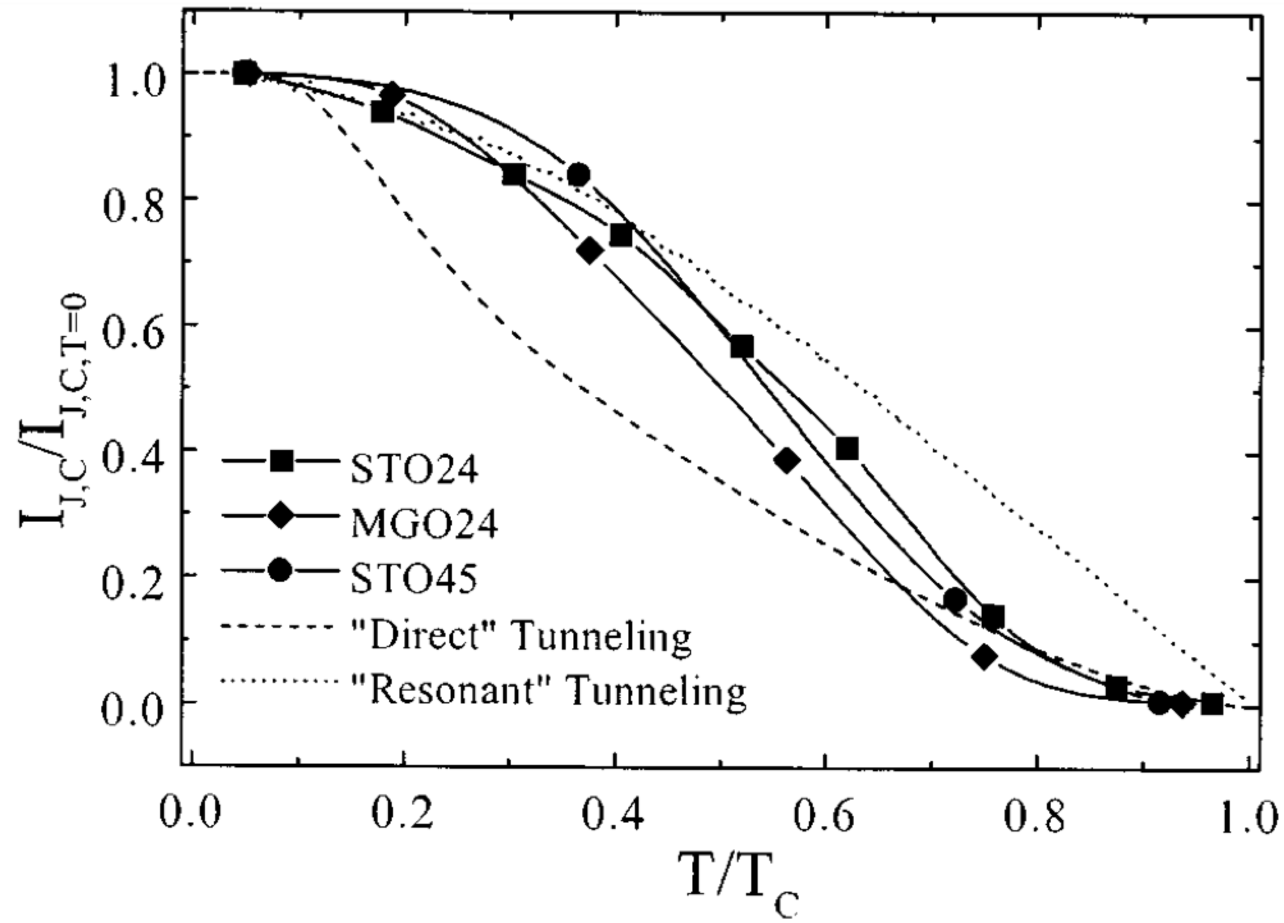
DC Josephson effect across T_c

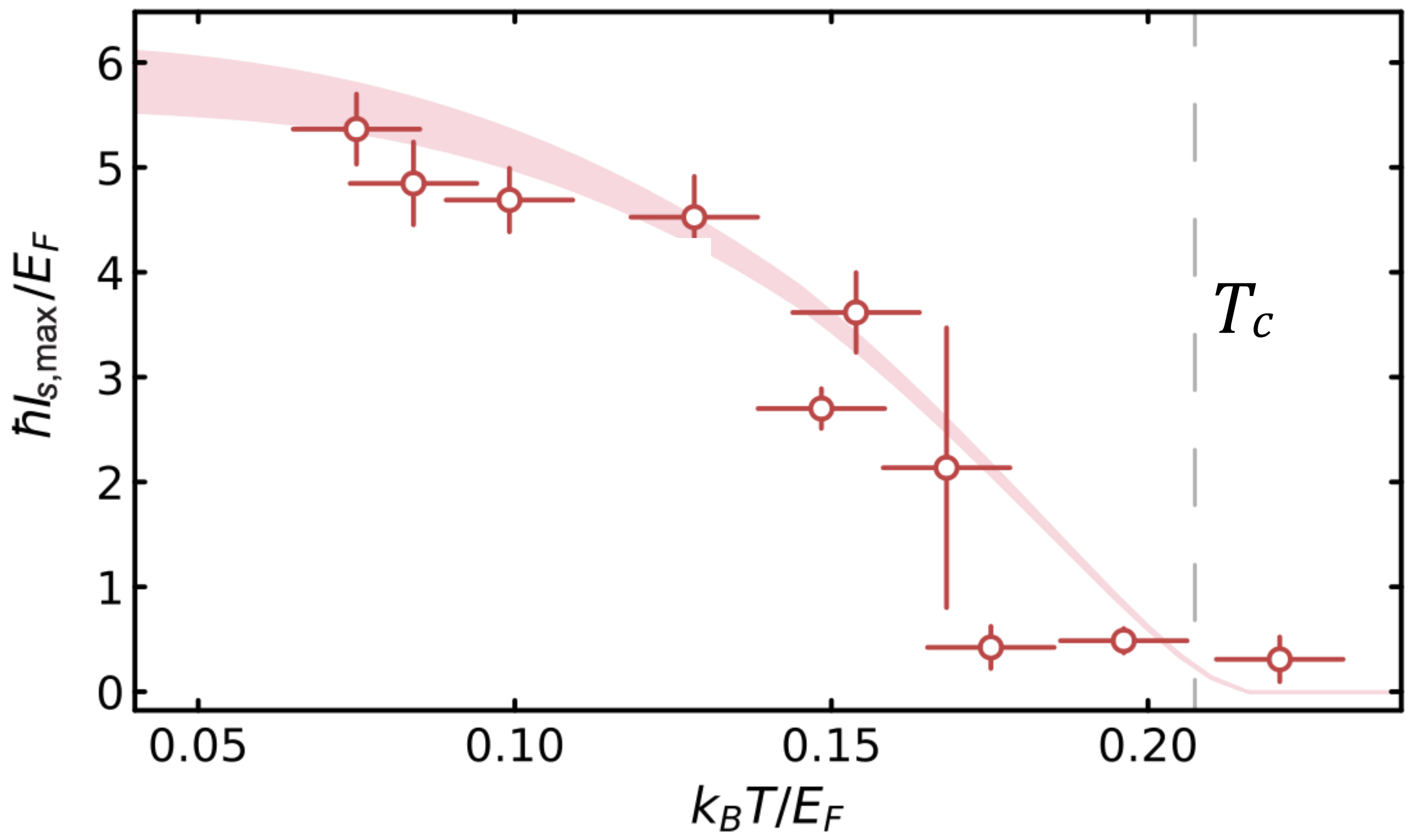


Controlled (parametric) heating

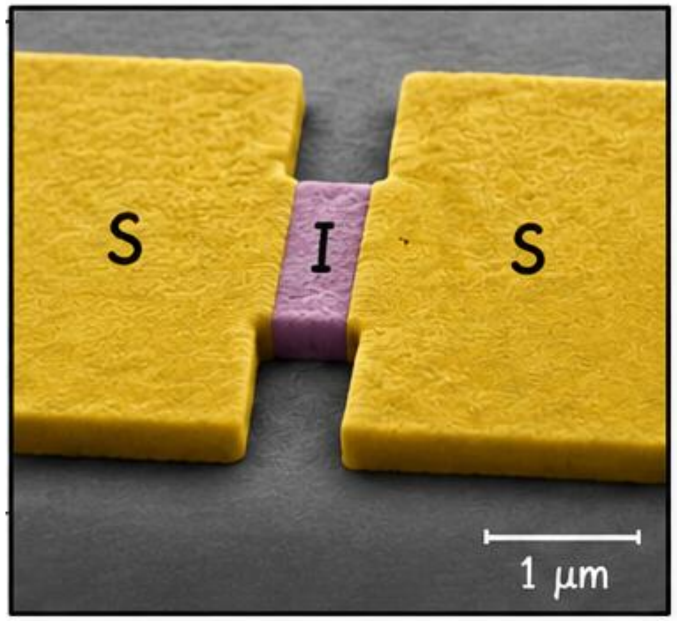
Signature of phase transition in unitary Fermi gas.

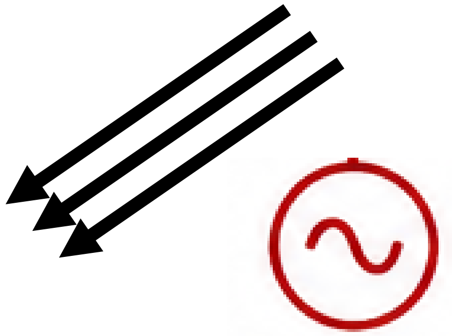
Haussmann et al., PRA (2008)
Pini et al., NJP (2020)



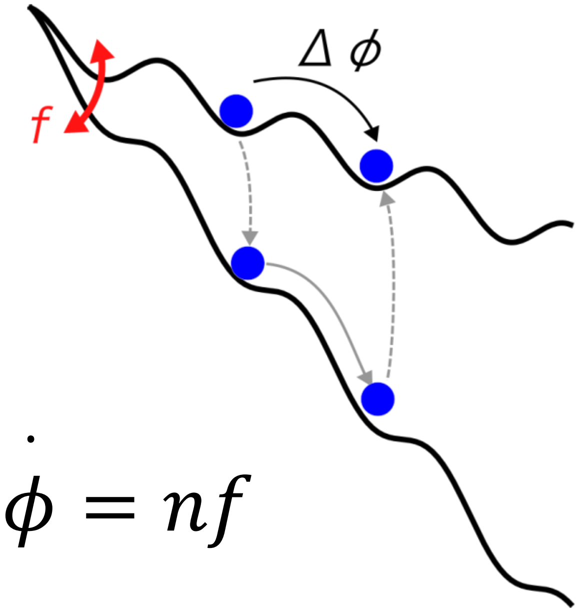


AC-drive: Shapiro steps





Irradiating the junction with an oscillatory microwave field: Shapiro steps



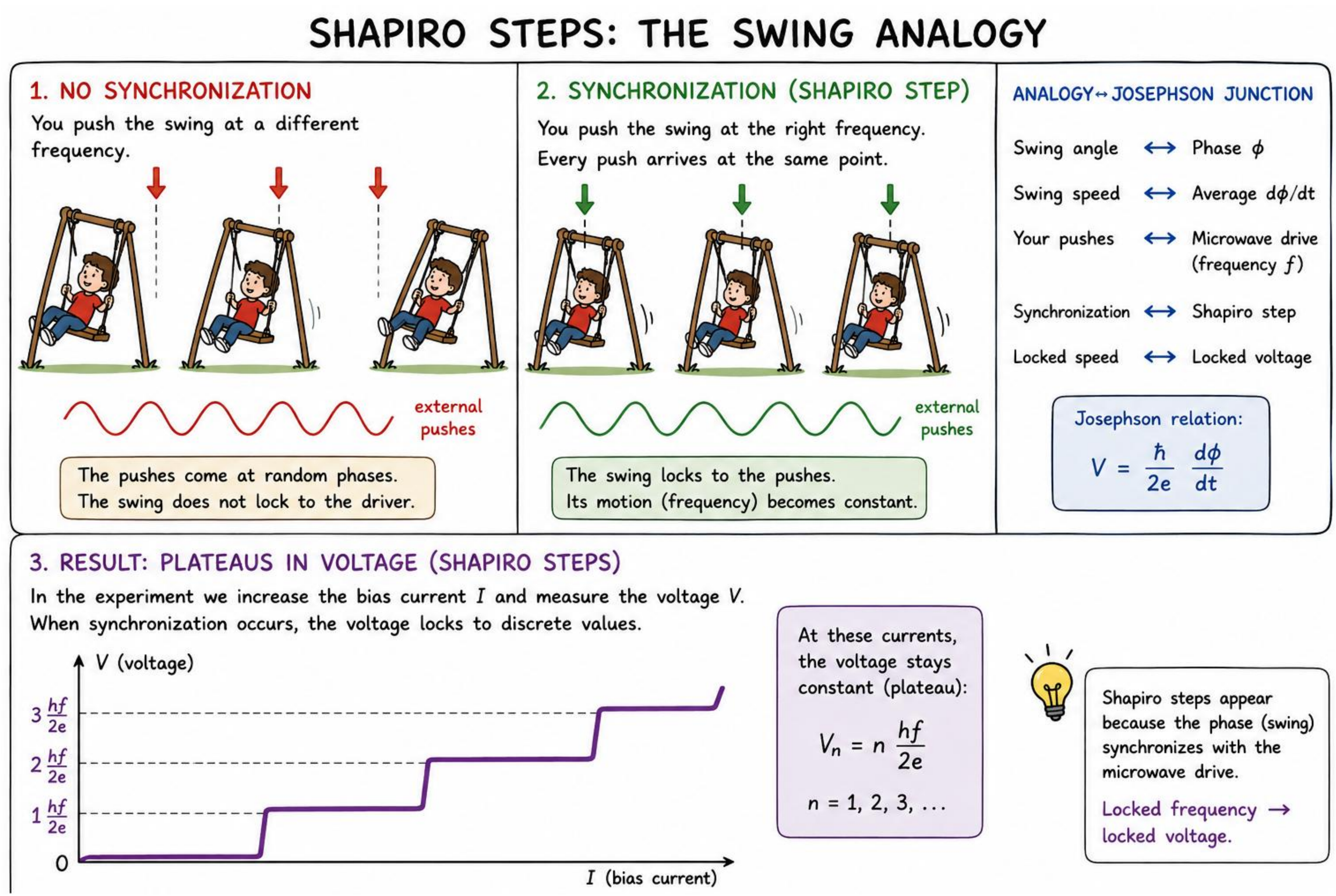
$$\dot{\phi} = nf$$

$$U(\phi) = -I_{ext}(t)\phi + I_c\cos(\phi)$$

$$I_{ext}(t) = I_0 + I_1\cos(2\pi f t)$$

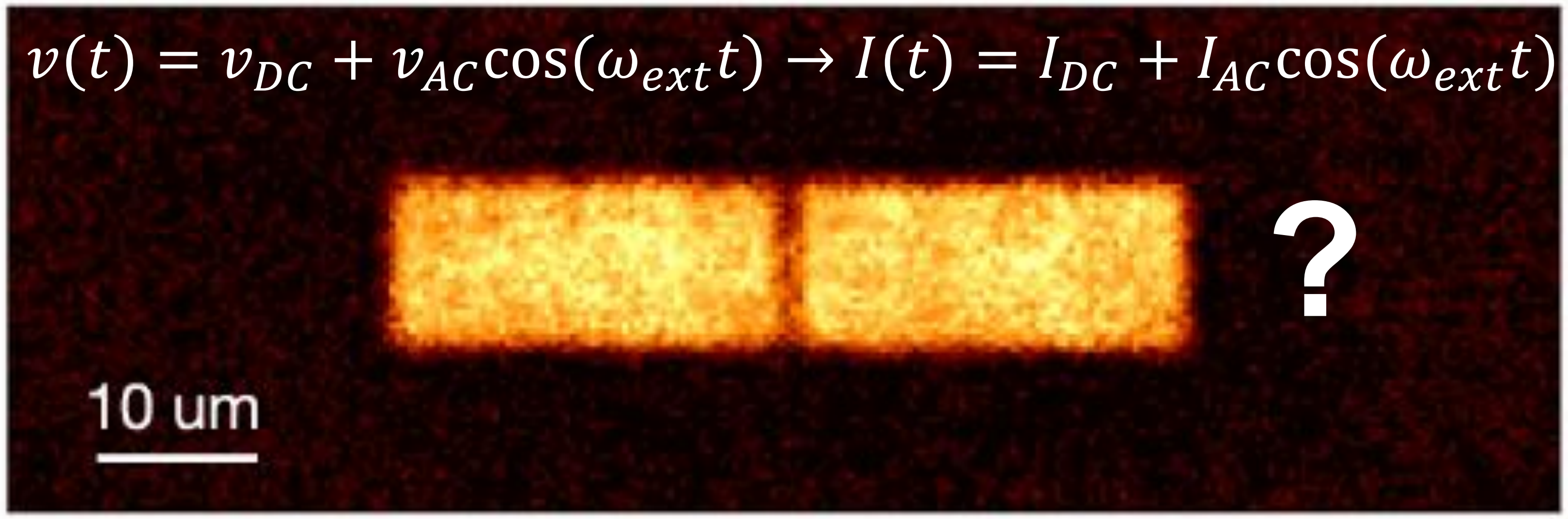
The phase particle jump by n minima over one modulation period, when its velocity $\dot{\phi}$ is **resonant** with a multiple of the driving frequency f. The phase jumps by $2\pi n$ every modulation period.

AC-drive: Shapiro steps

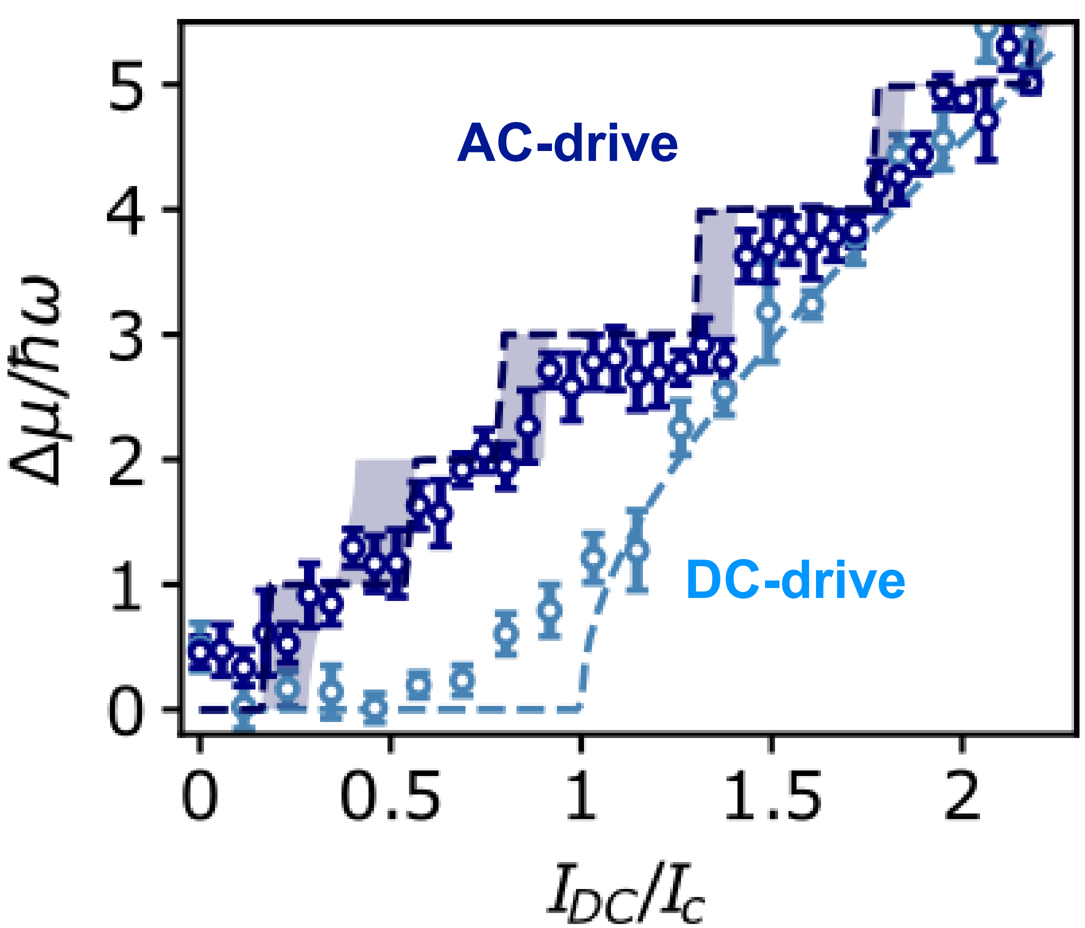


Del Pace et al., Science (2025)

AC-drive: Shapiro steps

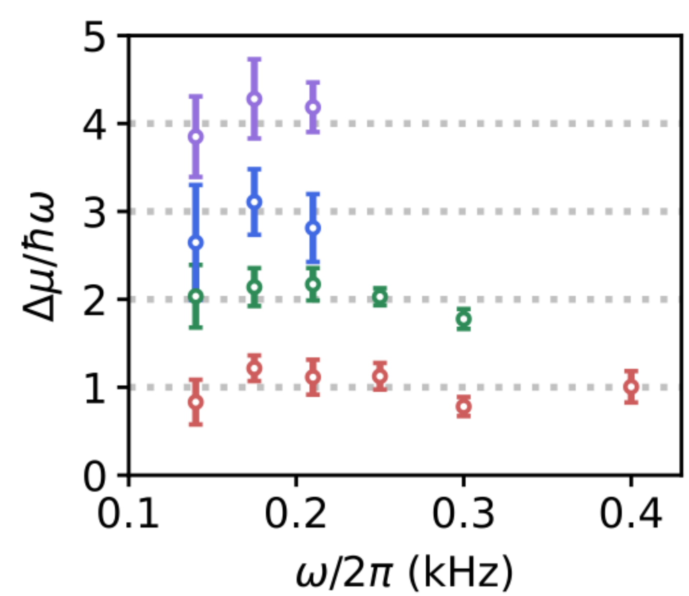


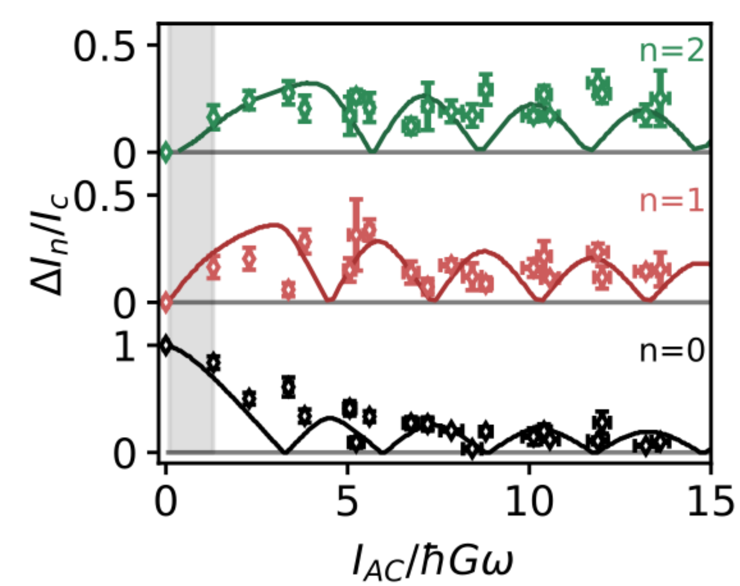
Singh et al, PRL (2024)
Bernhart et al., Science (2025)



1. Steps in the I-V characteristic

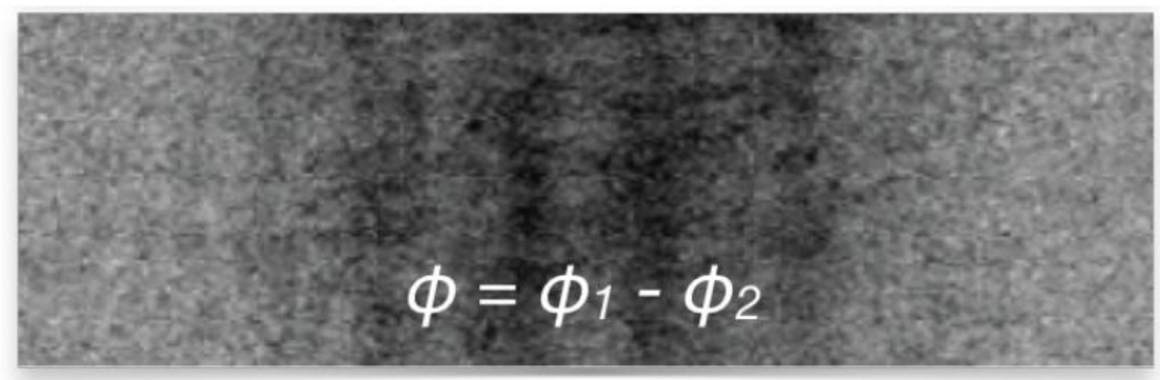
2. Step heights linearly growing with the driving external frequency. Step widths follows Bessel behaviour.



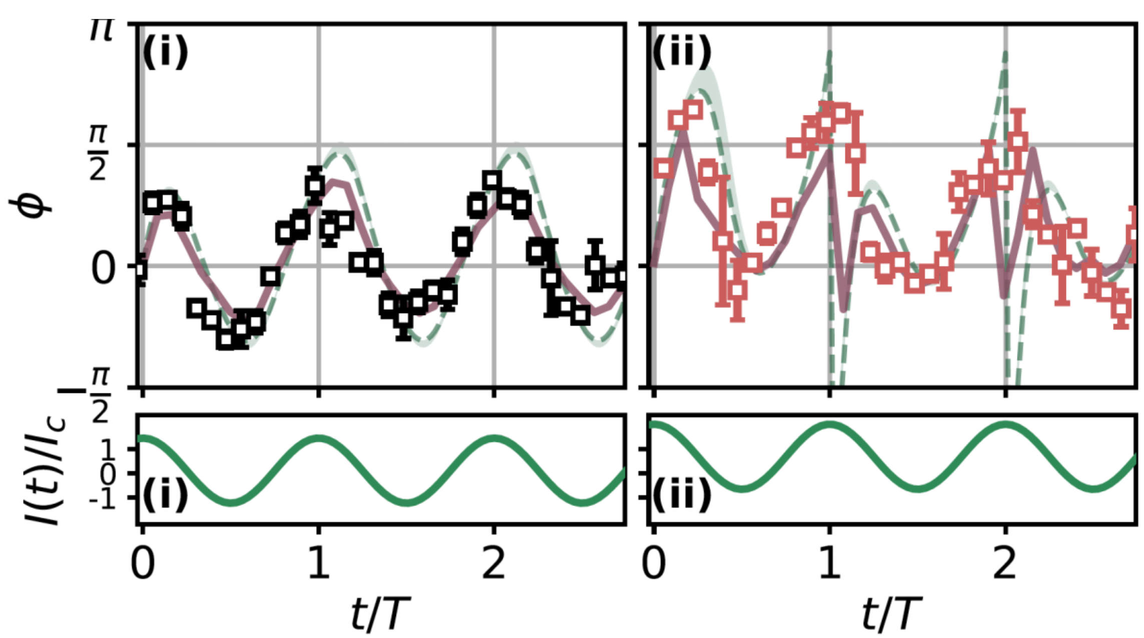


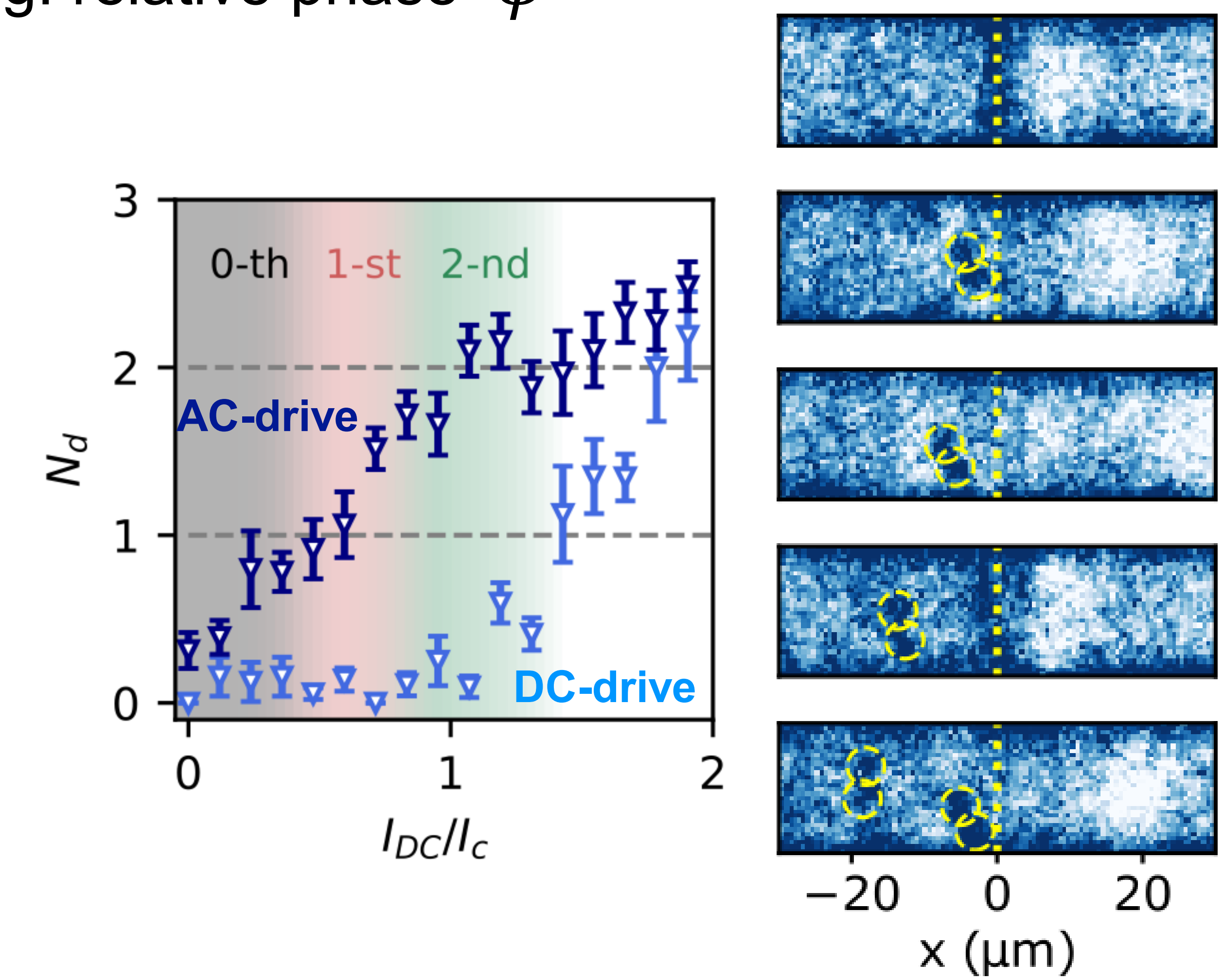
Del Pace et al., Science (2025)

AC-drive: Shapiro steps



Time-of-flight imaging: relative phase ϕ





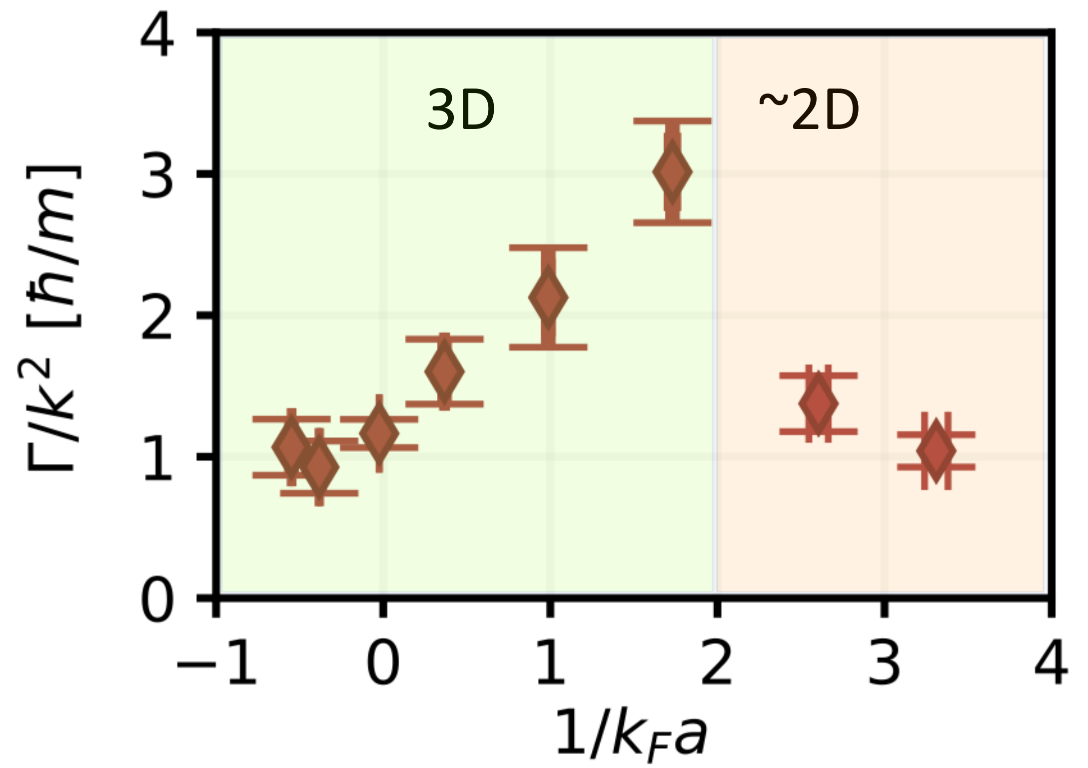
φ is synchronised with the external drive. We observe phase-slippage mechanisms as vortex-anti vortex pairs. Impossibile for ordinary JJ, due to the different time scale: detection time >> electrons dynamics time

Other projects:

“*Sagnac*” phonon-interferometer with annular Fermi superfluids (S. Stringari):

Quantum of circulation: angular momentum per particle of BEC-BCS superfluids

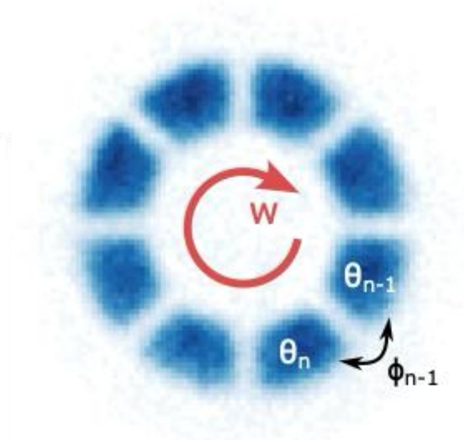
Frometa et al., arXiv:2511.02664v2 (2025), Nat.Phys. in press

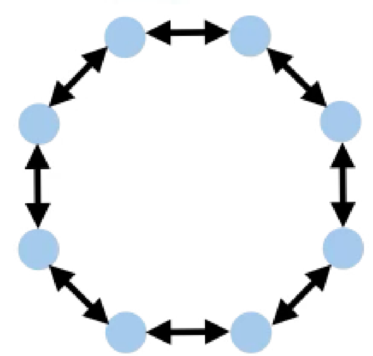


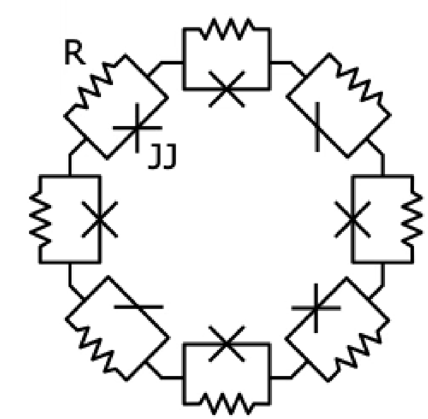
MIT, USTC, Yale, Hamburg, Cambridge, ENS…

Cooperative stabilization of persistent currents in superfluid ring networks: Josephson junction necklace as closed chains of locally coupled **Kuramoto-like oscillators: synchronization phenomena in many-body systems.**

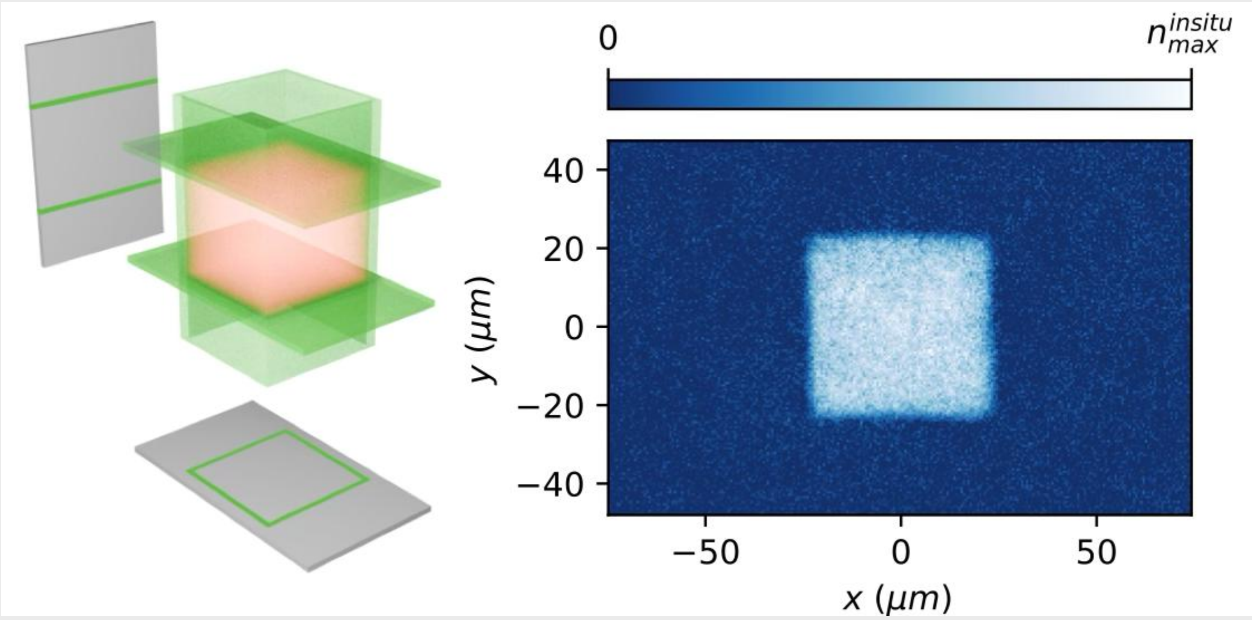
Ciszak et al.,arXiv:2601.15121v2 (2026)





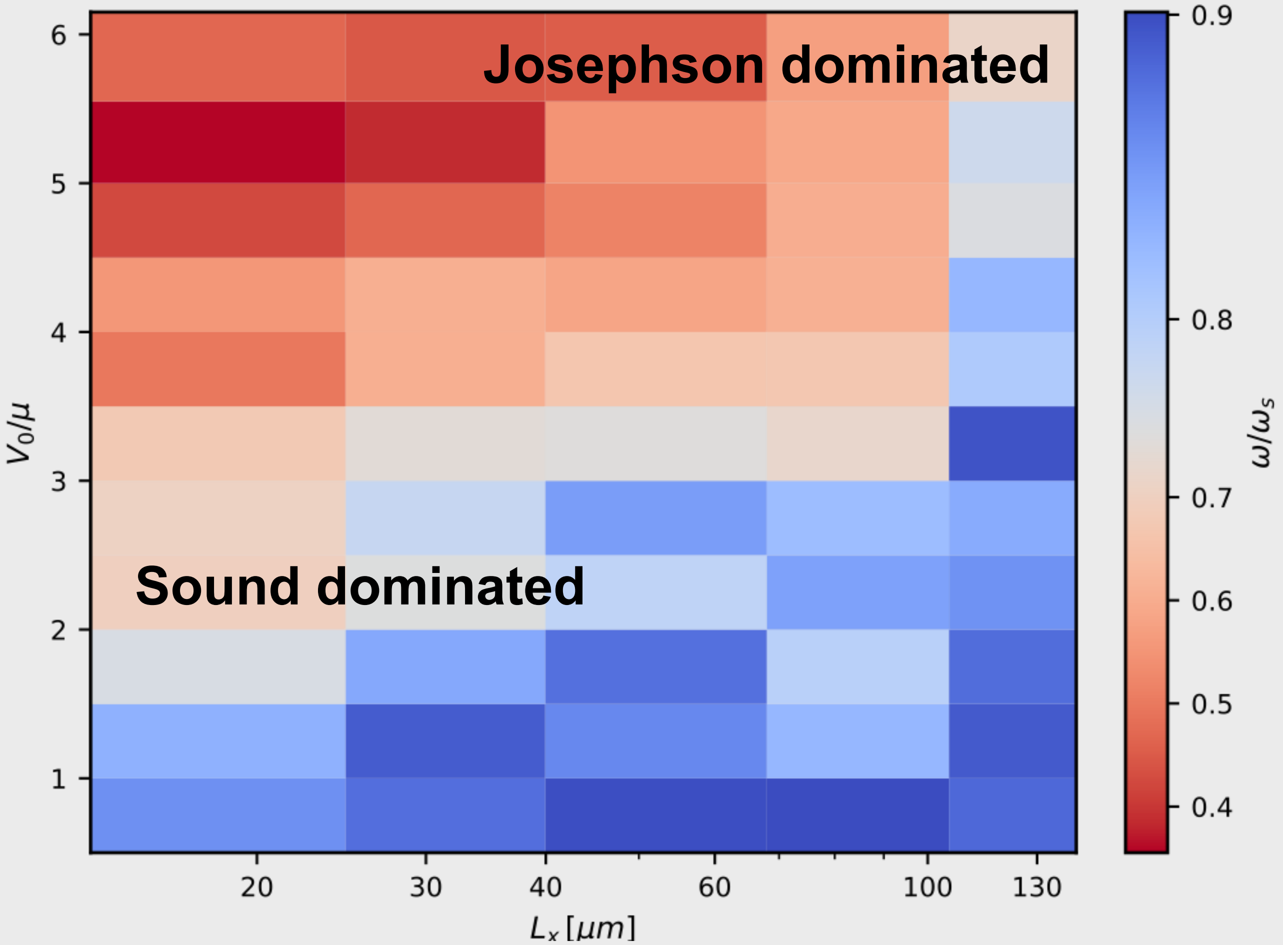


3D Fermi box (with crossed DMDs):

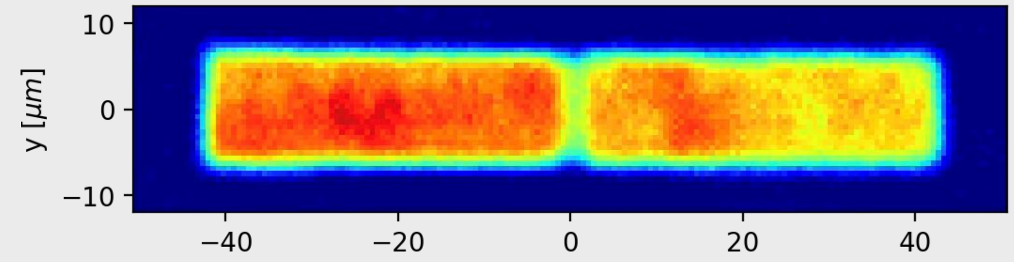


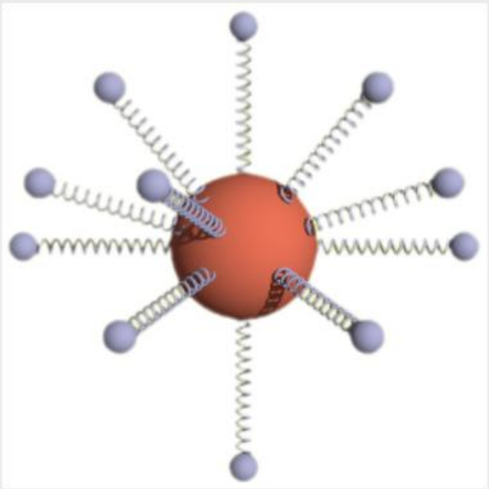
Collaborations and comparison with other Fermi-boxes (MIT, Yale, USTC, Hamburg, EPFL, …)

Navon et al., Nat. Phys. (2021)



Del Pace et al., *in preparation*





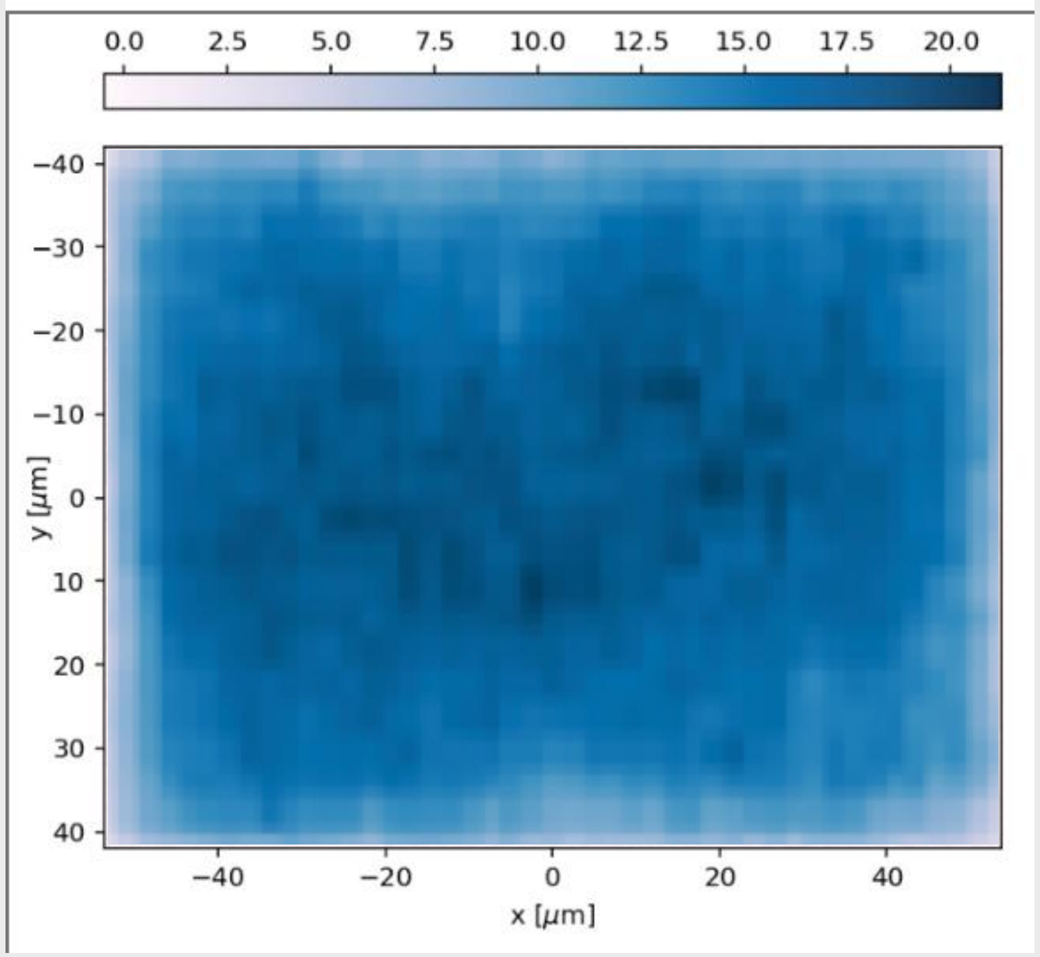
Caldeira and Leggett, Annal. Phys. (1983)

Multiplexed homogenous Fermi boxes:

(Rajkov et al., *in preparation*)

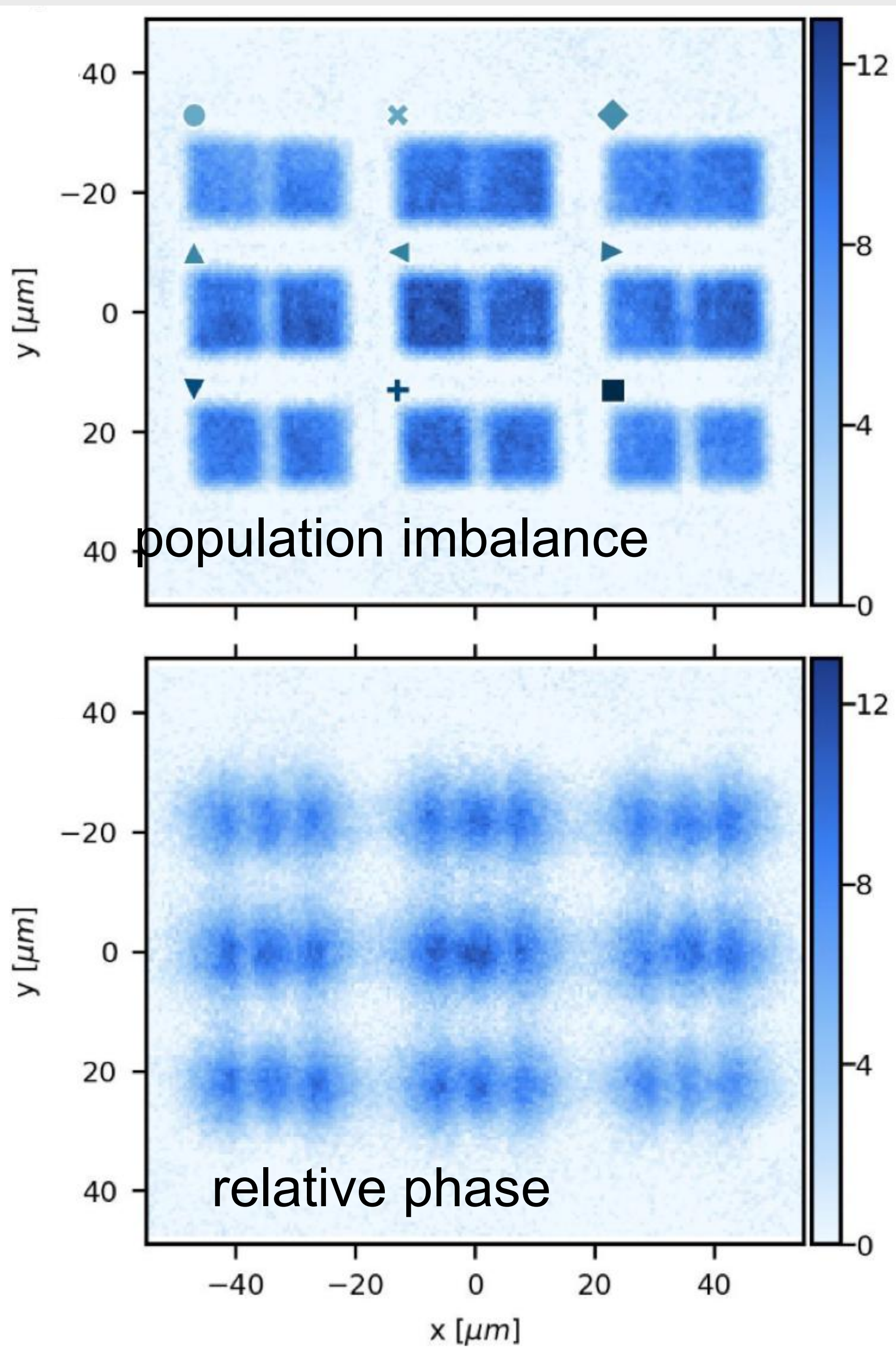
We realise several identical and independent **q-simulation units** with **locally** tunable parameters.

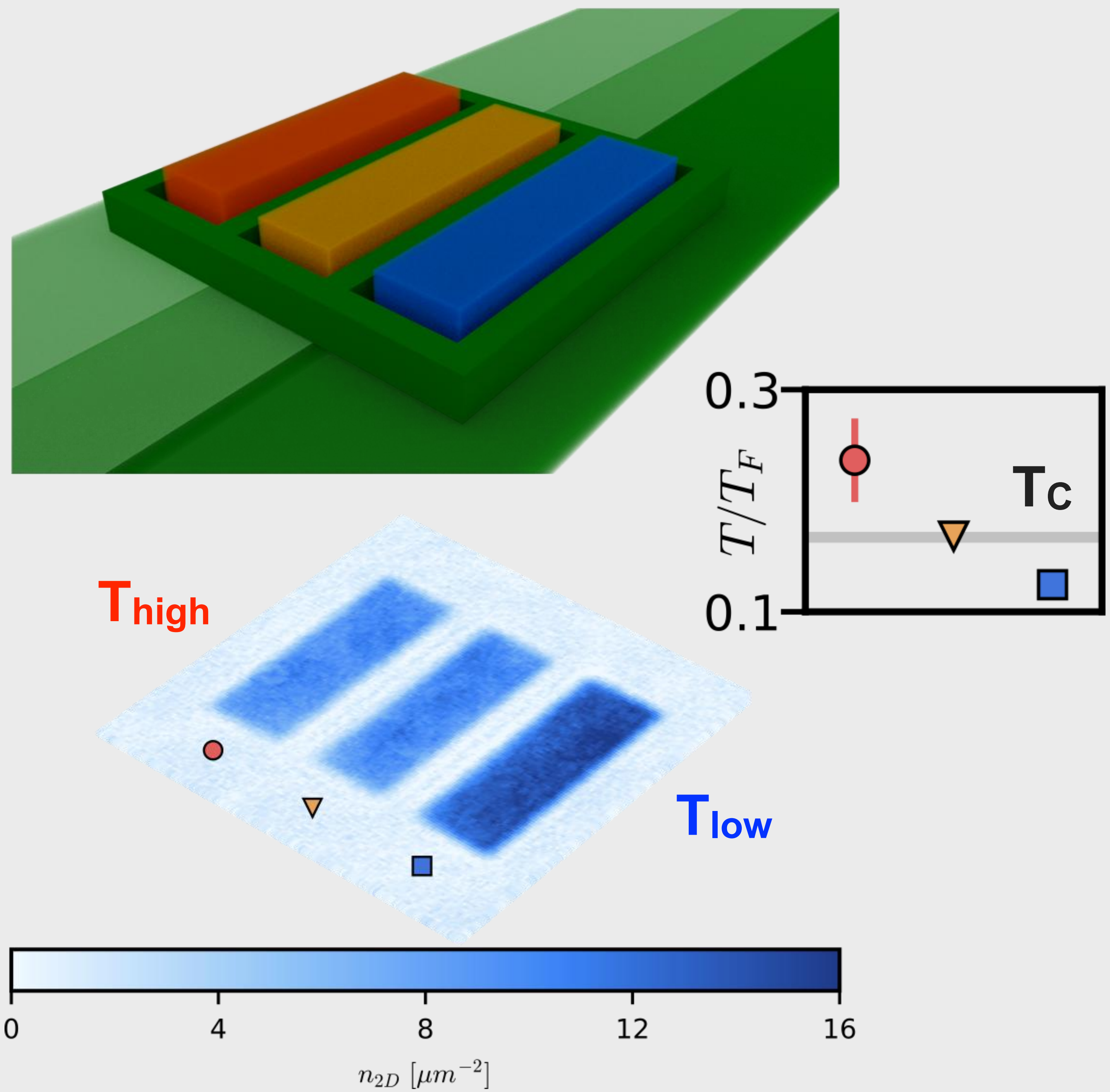
- Parallel execution of the same Hamiltonian with different parameters
- Reconfigurability of the position of each simulating units.



Parallel experiments: ground-state phases, driven dynamics and quantum transport phenomena…

1. Josephson junctions with local phase control.





roati@lens.unifi.it

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