Tunnelling transport in strongly-interacting atomic Fermi gases

Giacomo Roati

Fermi legacy in low energy physics

5-6 February 2026

Accademia dei Lincei, Roma

CNR-INO

lens European Laboratory for Non-Linear Spectroscopy

PASQuanS2

erc

Cold Fermi(ons) at LENS: the beginning

PHYSICAL REVIEW A VOLUME 57, NUMBER 2 FEBRUARY 1998

Magneto-optical trapping of Fermionic potassium atoms

F. S. Cataliotti, E. A. Cornell,* C. Fort, M. Inguscio, F. Marin, M. Prevedelli, L. Ricci,† and G. M. Tino‡
Dipartimento di Fisica and European Laboratory for Nonlinear Spectroscopy (LENS), Università di Firenze, and Istituto Nazionale per la Fisica della Materia, Largo E. Fermi 2, I-50125 Firenze, Italy
(Received 13 August 1997)

PHYSICAL REVIEW A VOLUME 60, NUMBER 5 NOVEMBER 1999

Sub-Doppler laser cooling of fermionic ^{40}K atoms

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INFM–European Laboratory for Non Linear Spectroscopy (LENS), Università di Firenze, Largo E. Fermi, 2, I-50125 Firenze, Italy
(Received 9 July 1999)

VOLUME 89, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 2002

Fermi-Bose Quantum Degenerate ^{40}K-^{87}Rb Mixture with Attractive Interaction

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(Received 1 May 2002; published 23 September 2002)

PHYSICAL REVIEW A **68**, 011601(R) (2003)

Production of a Fermi gas of atoms in an optical lattice

G. Modugno, F. Ferlaino, R. Heidemann,* G. Roati, and M. Inguscio
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(Received 10 April 2003; published 7 July 2003)

Cold Fermi(ons) at LENS: the beginning

distinguishable Fermi(ons) at LENS

Quantum Science & Technology Division

- q sensing
- q simulation
- q computing
- q communications

https://quantumgases.lens.unifi.it

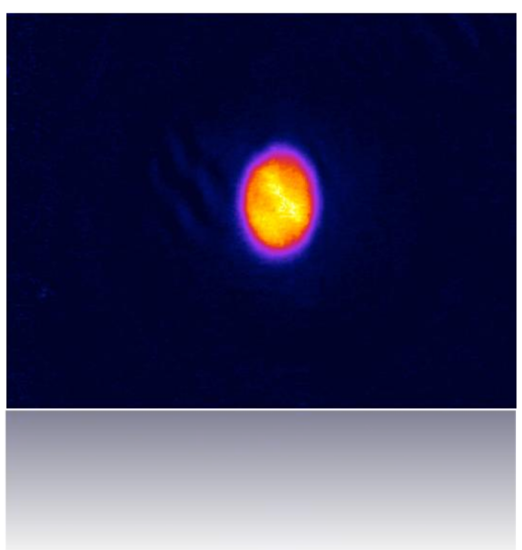
... “*we observe superfluid flow in an expanded Fermi gas down to densities of about* 10^{11} *cm*$^{-3}$.

At these densities, the average distance between two atoms is 2 μm!

The average distance between neutrons in a neutron star is a few fm (10^{-9} *μm), corresponding to densities of* 10^{38} *cm*$^{-3}$.

This nicely illustrates how general the phenomenon of (fermionic) superfluidity is.”

M. Zwierlein (MIT)



T = 10^{-8} K

T = 2 K

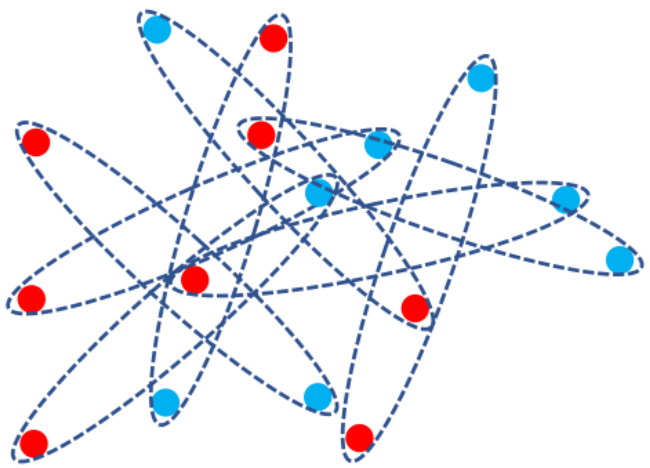
T = 100 K

T = 10^{11} K

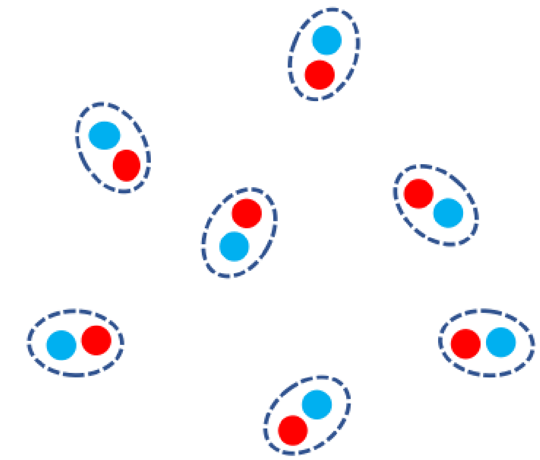
"Good morning. I am delighted to be here today to tell you about some exciting new results from our lab […] What we report is the first observation of a **fermionic condensate** *in an ultracold gas of atoms.* **This is a new form of matter** *that is related to a Bose-Einstein condensate and related to superconductivity. But our fermionic condensate* **is not a Bose-Einstein condensate and not a superconductor but really something new** *that may link these two behaviors […]. This work gives the scientific community a new tool for understanding the basic physics behind superconductivity.*

January 27, 2004

BEC-BCS crossover (Martin’s talk)



BCS



BEC

“weak” attractive interactions

s

“strong” attractive interactions

Large pair size:
pairing in *k*-space

Small pair size:
pairing in r-space

S. Giorgini, L. P. Pitaevskii, and S. Stringari Rev. Mod. Phys. 80 (2008); *Ultracold Fermi Gases, Proceedings of the International School of Physics "Enrico Fermi", Course CLXIV, Varenna 2006*, edited by M. Inguscio, W. Ketterle, and C. Salomon (IOS Press, Amsterdam, 2008); M. W. Zwierlein, *Superfluidity in ultracold atomic Fermi gases in* Novel Superfluids Vol.2 (Oxford Academic, 2014)

Order parameter

$$\Psi = |\Psi_0| e^{i\theta}$$

$|\Psi_0|^2$=condensate/superfluid density

$\nabla\theta$~superfluid velocity

The order parameter discloses the intimate & microscopic properties of the condensate/superfluid state.

Quantum statistics “shape” the excitation spectrum that determines the macroscopic quantum behavior of superfluids, limiting its robustness against dissipation.

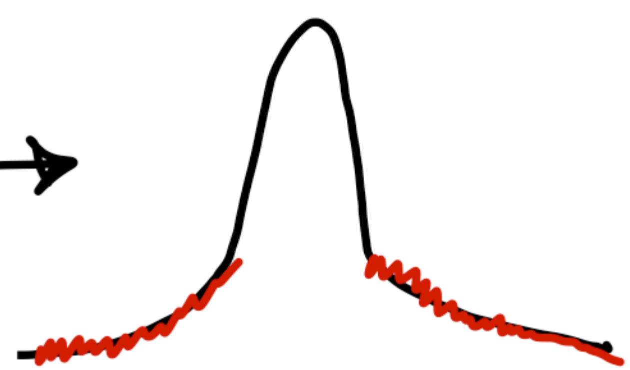
Which is the order parameter for a 3D BEC?

$$\Psi(r) = \sqrt{n_c(r)}\, e^{i\theta}$$

→ condensate fraction is the order parameter

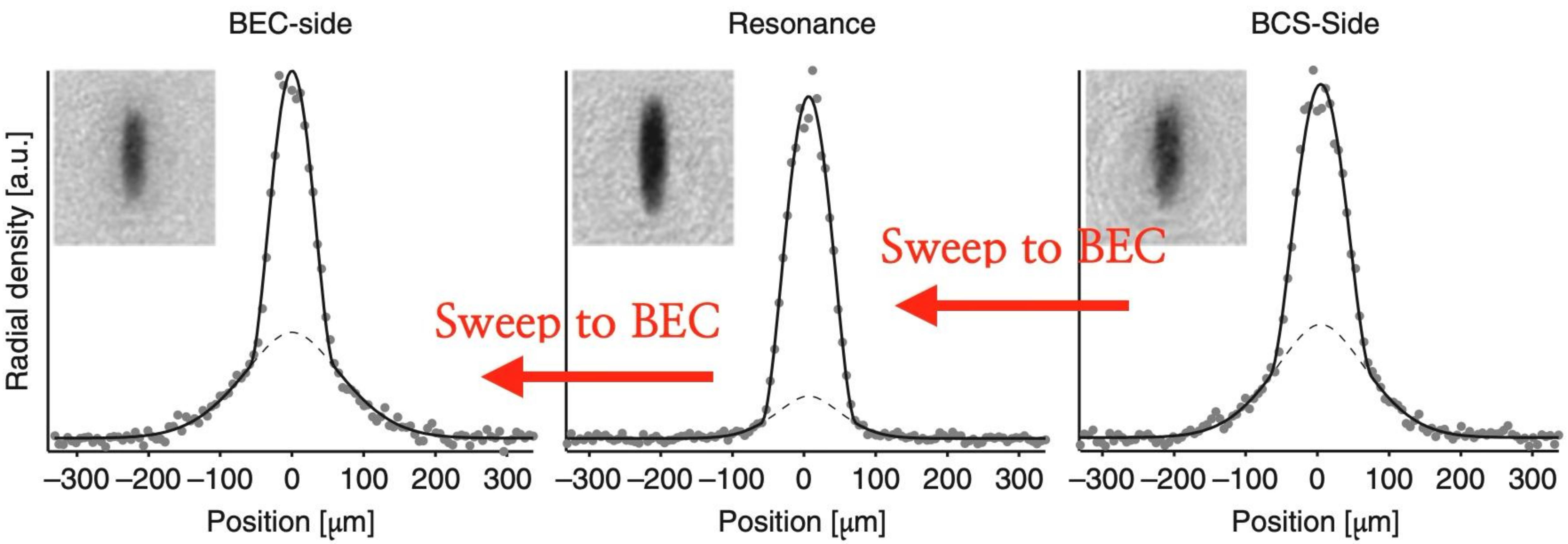
n_c increases to 1 @ $T=0$

$$n_c = \frac{N_c}{N} = \left(1 - \frac{T}{T_c}\right)^3$$ →



MEASURABLE!
(weak interactions)

Strongly-interacting Fermi superfluids: interactions limit momentum distribution analysis. Condensate fraction: sweeping into the weakly interacting BEC regime: ***"indirect"* measurement** of the order parameter amplitude .



Ultracold Fermi Gases, Proceedings of the International School of Physics "Enrico Fermi", Course CLXIV, Varenna 2006, edited by M. Inguscio, W. Ketterle, and C. Salomon (IOS Press, Amsterdam, 2008)

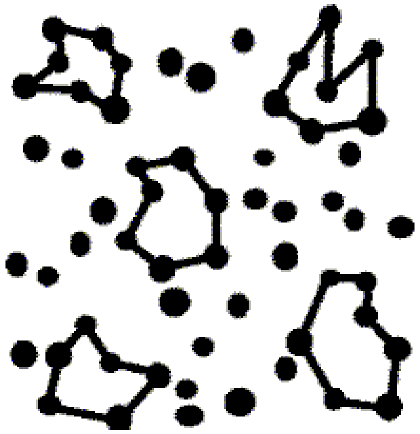
Alternative approach?

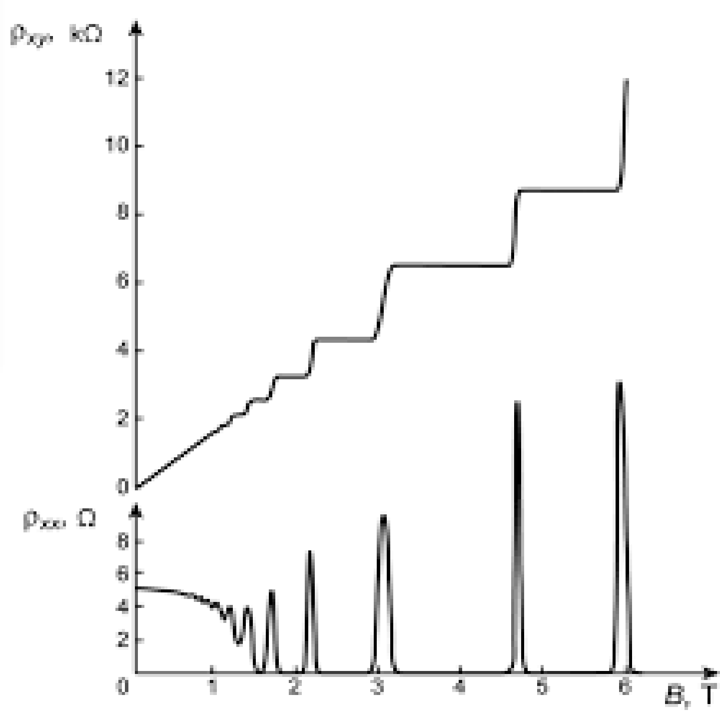
Transport measurements: fundamental tool to investigate matter.

Extracting microscopic properties of a quantum many-body systems via measuring *bulk* parameters (I,V…) **(Prof. Von Klitzing's talk)**

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

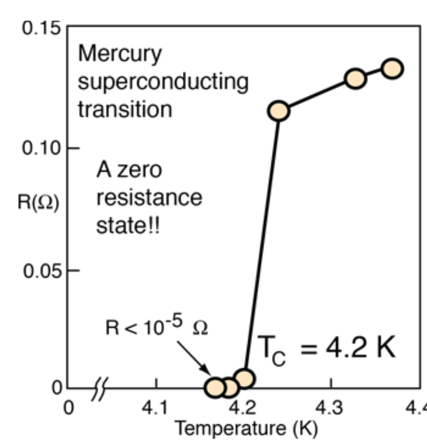
Localization

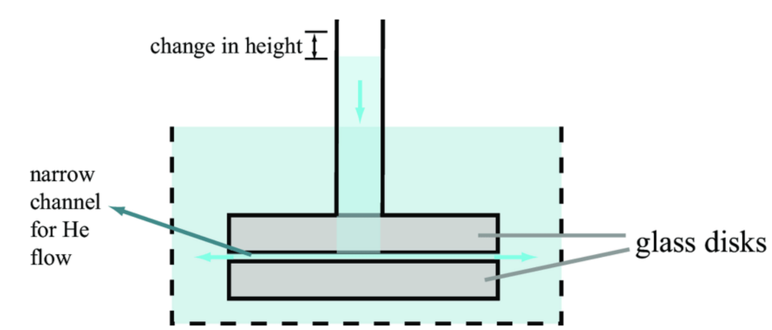




ents

Superconductivity and superflu



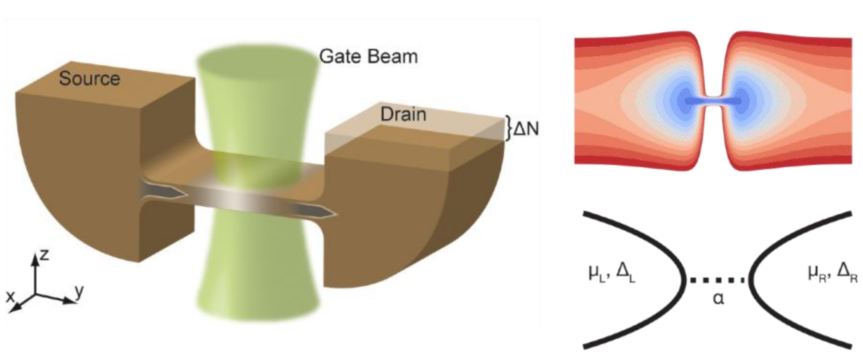


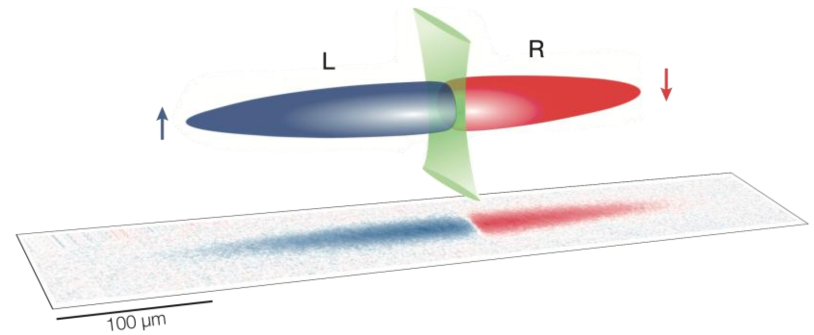
Quantum Transport with Fermi Gases

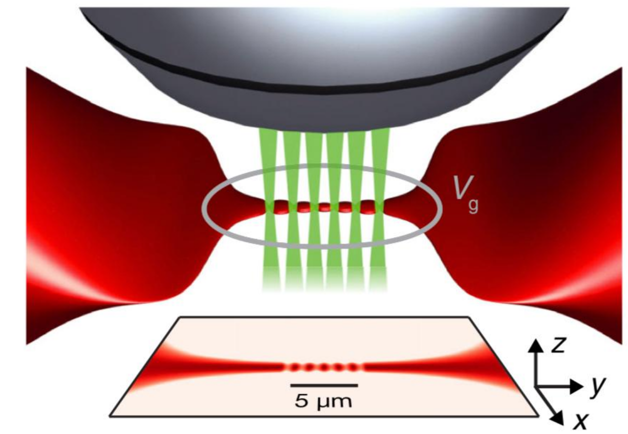
Transport through narrow ballistic channels

Spin, sound, heat transport

Tunneling through structures







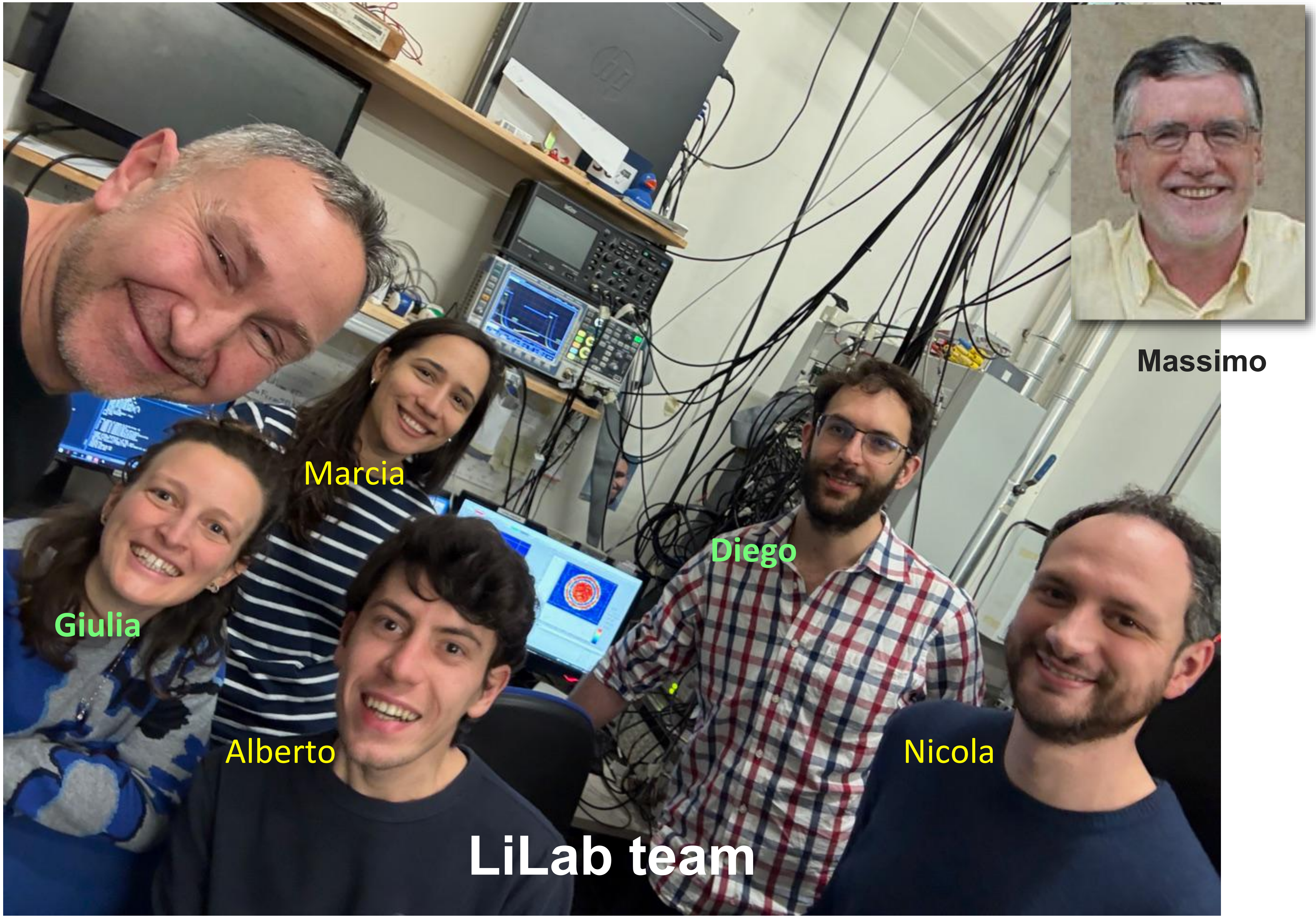
ETH, Geneva

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

ETH, LENS, Princeton, Toronto, MPQ, MIT, …

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

Let’s go to LENS

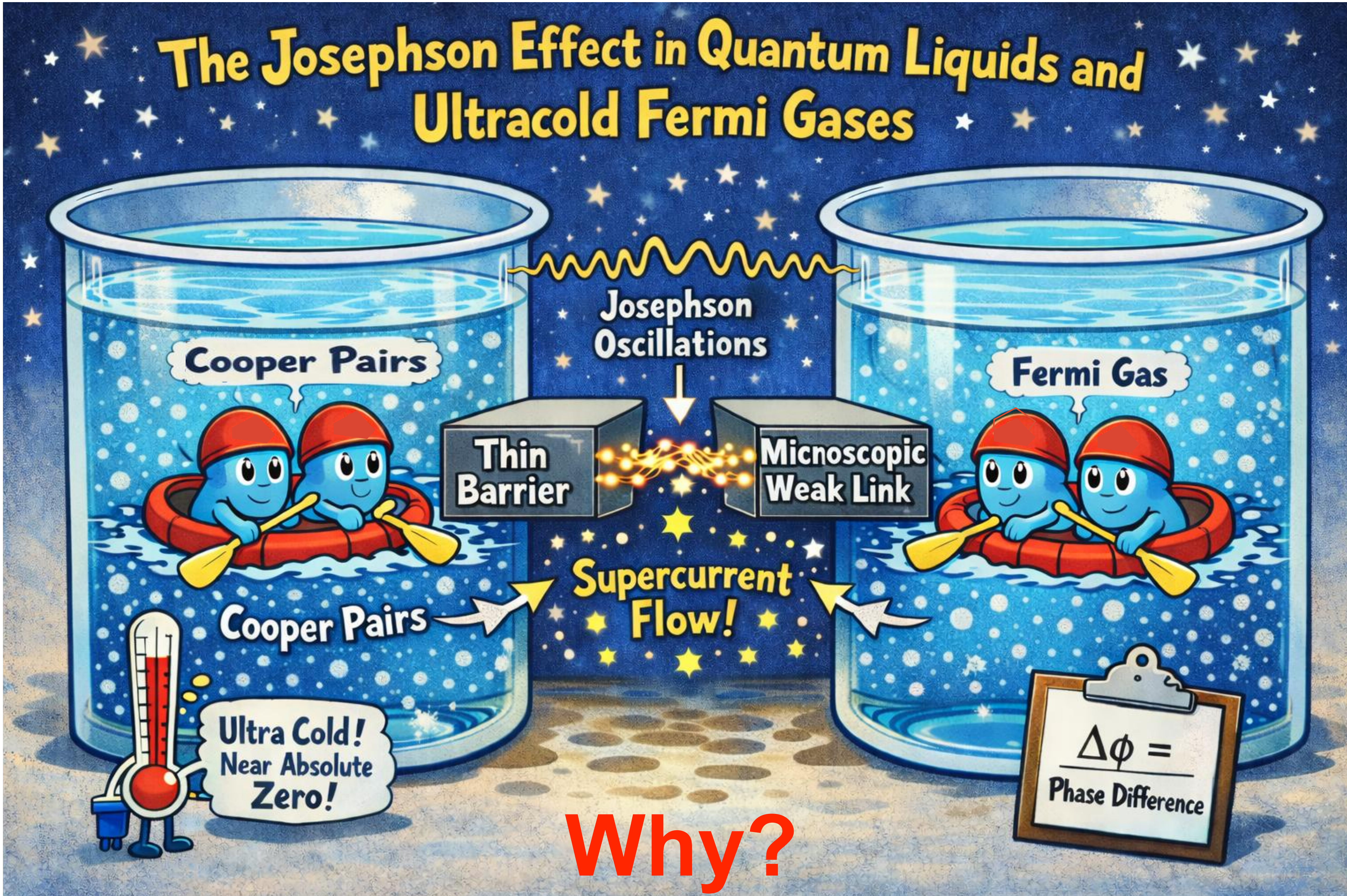


Massimo

LiLab friends & collaborators:

Stringari, Scazza, Kwon, Recati, Marino, Xhani, Smerzi, Pezze', Donelli, Fort, M. Modugno, Galantucci, Singh, Amico, Barresi, Magierski, Wlazlowski, **Strinati**, **Pieri**, Pini, Minguzzi, Polo…

Summary


The Josephson Effect in Quantum Liquids and Ultracold Fermi Gases
Cooper Pairs
Josephson Oscillations
Fermi Gas
Thin Barrier
Micnoscopic Weak Link
Cooper Pairs
Supercurrent Flow!
Ultra Cold! Near Absolute Zero!
$\Delta\phi$ =
Phase Difference

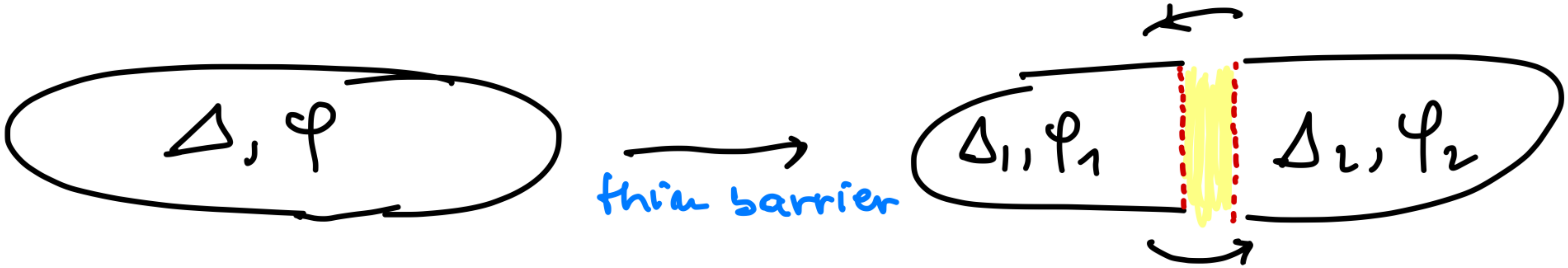
Why?

How to probe the order parameter?

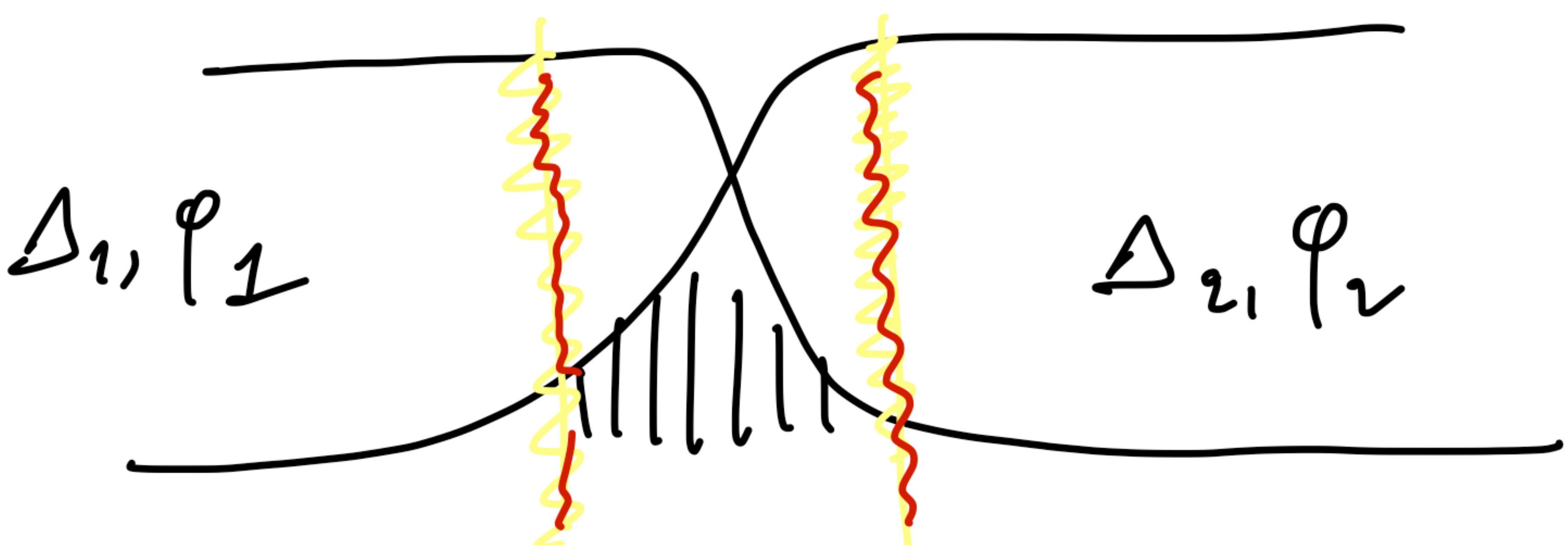
We need a measurement that is sensitive to both amplitude and phase.

$$\Psi = |\Psi_0| e^{i\varphi}$$

Can we do the same for a superfluid ?



Josephson Junction :



→ Josephson interferometer !!

The Josephson effect (P. W. Anderson's point of view)

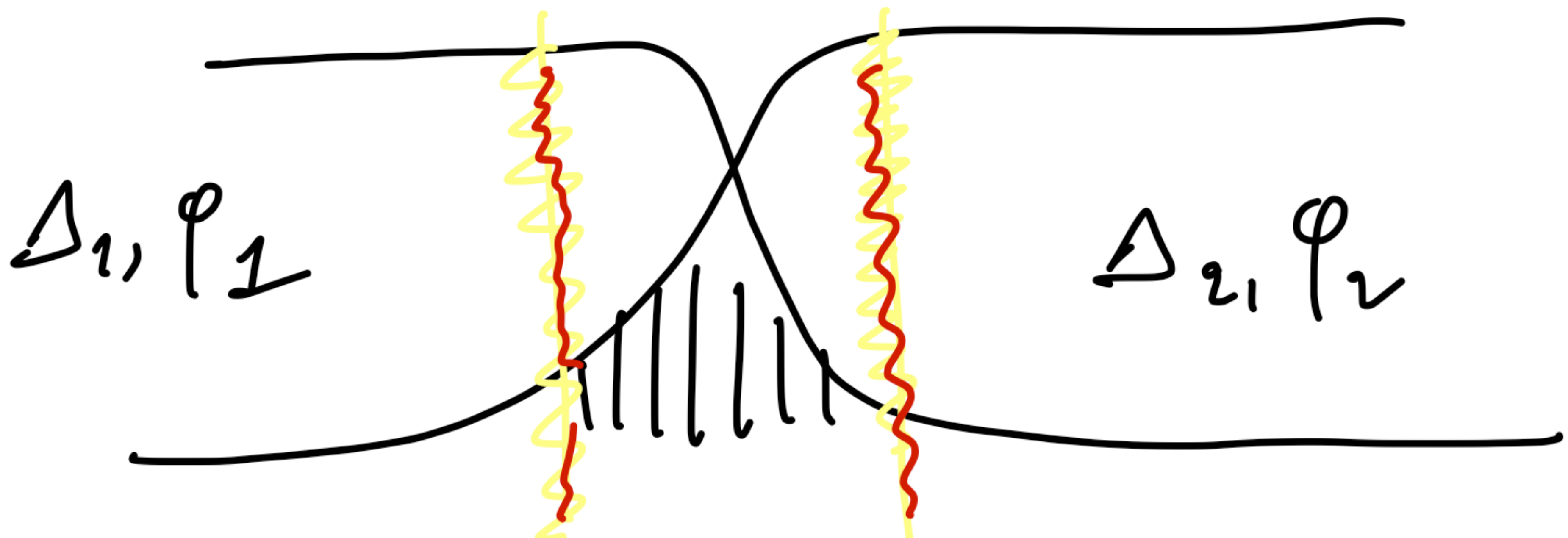
… In the case of superconductivity things are quite different. The internal long-range order parameter — the phase — is not a parameter for which suitable instruments exist; we do not normally walk around with objects which have phase order. A superconductor has rather perfect internal phase order, but 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: it can pin down the order parameter …

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.

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

Josephson Junction:



→ Josephson interferometer !!

Barone and Paterno, *Physics and Applications of the Josephson Effect,* (Wiley, New York, 1982)

Josephson coupling energy E_J

$$E_J \approx \frac{\Delta_1 \Delta_2}{\Delta_1 + \Delta_2} \cos(\varphi_1 - \varphi_2)$$

$E_J = \hbar I_c$ → macroscopic (measurable)

↓ Δ

Microscopic (intimate)

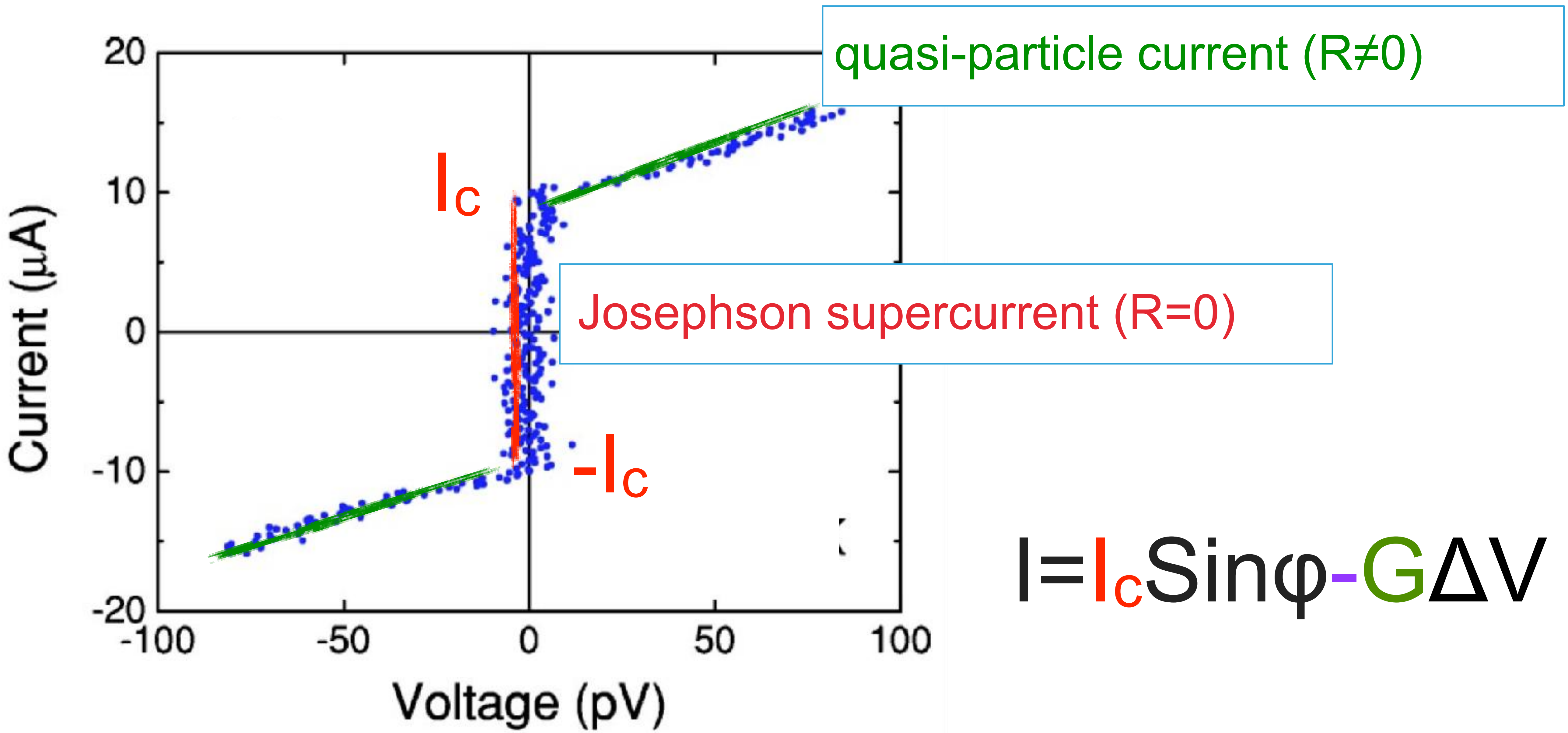
Essence of the Josephson effect

microscopic ⟷ macroscopic

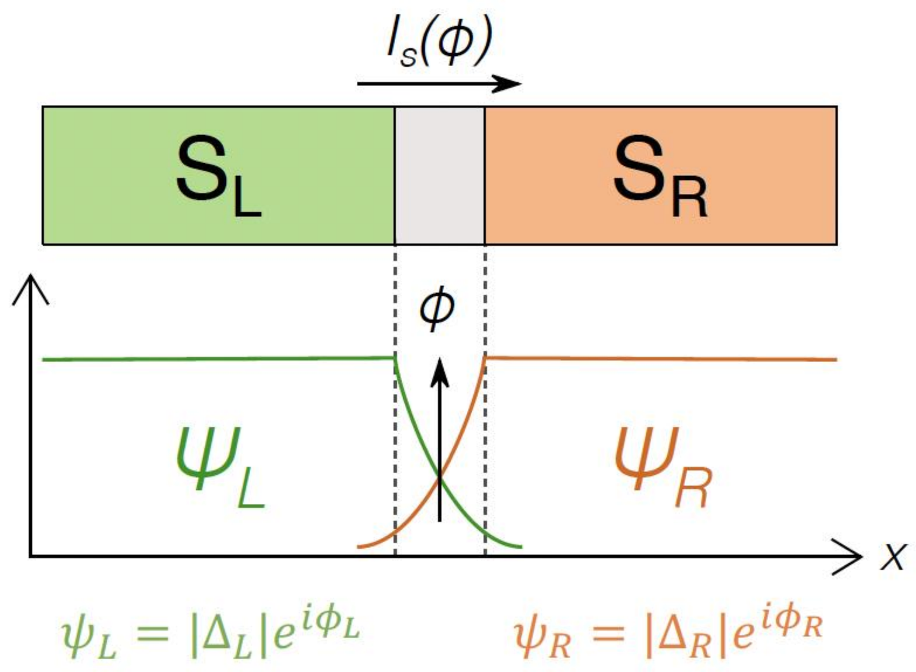
$$\hbar I_c = E_J \sim \Delta \sim n_c$$

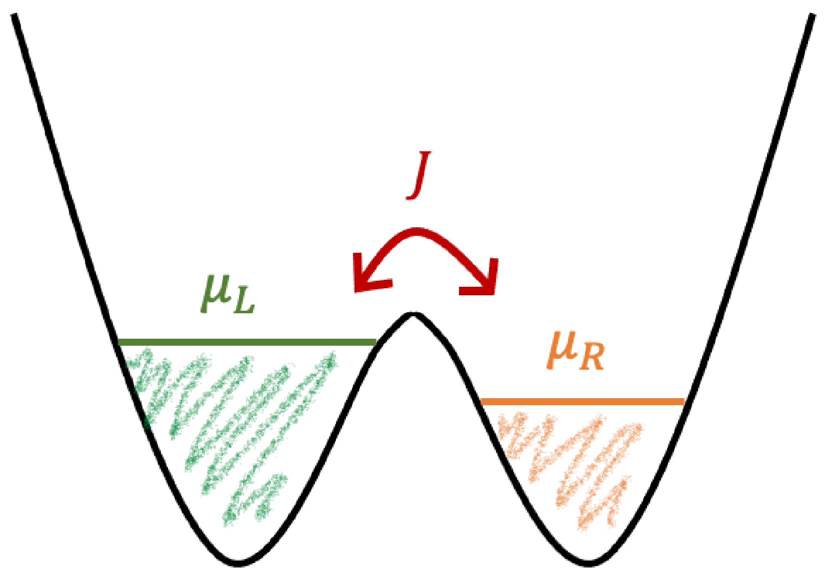
DC Josephson effect

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



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





Josephson-Anderson equations:

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

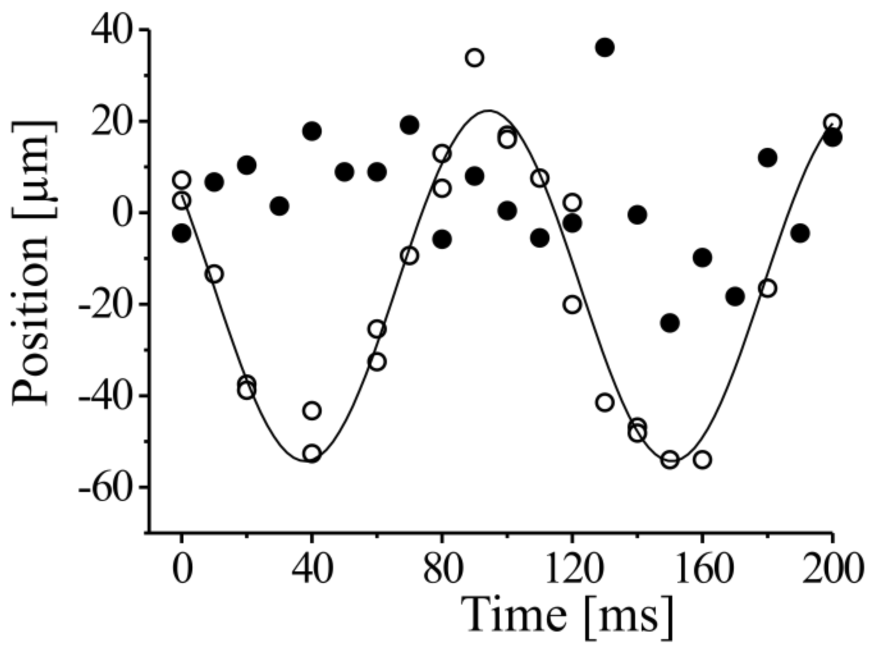
$$\dot{\phi} = -\frac{2e}{\hbar} V$$

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

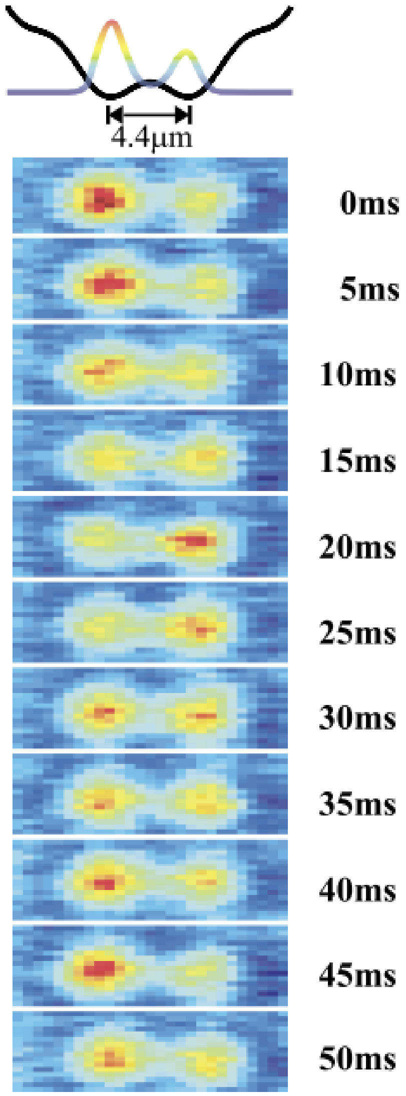
$$I = I_c \sin(\phi)$$

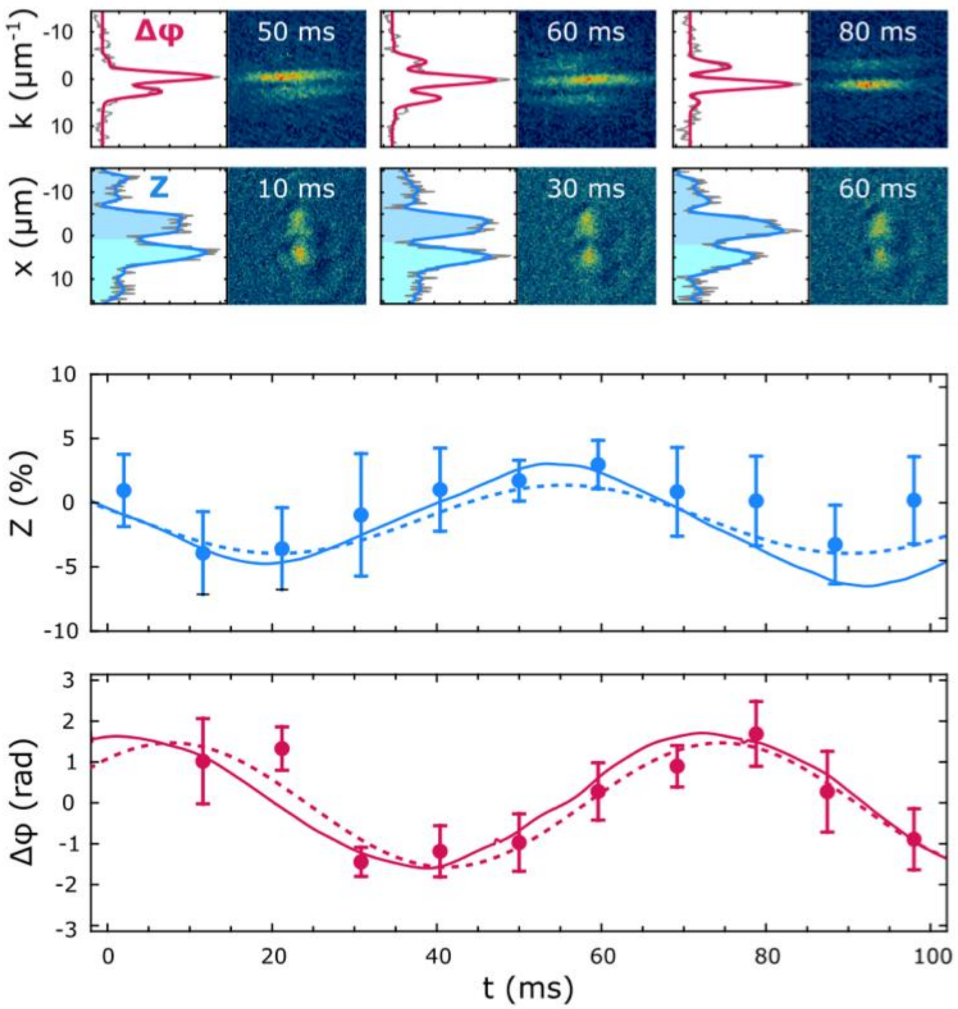
$$\dot{\phi} = -\frac{\Delta\mu}{\hbar}$$

Josephson effect in atomic BEC



Josephson junction arrays: BEC in optical lattices





BEC in a double well

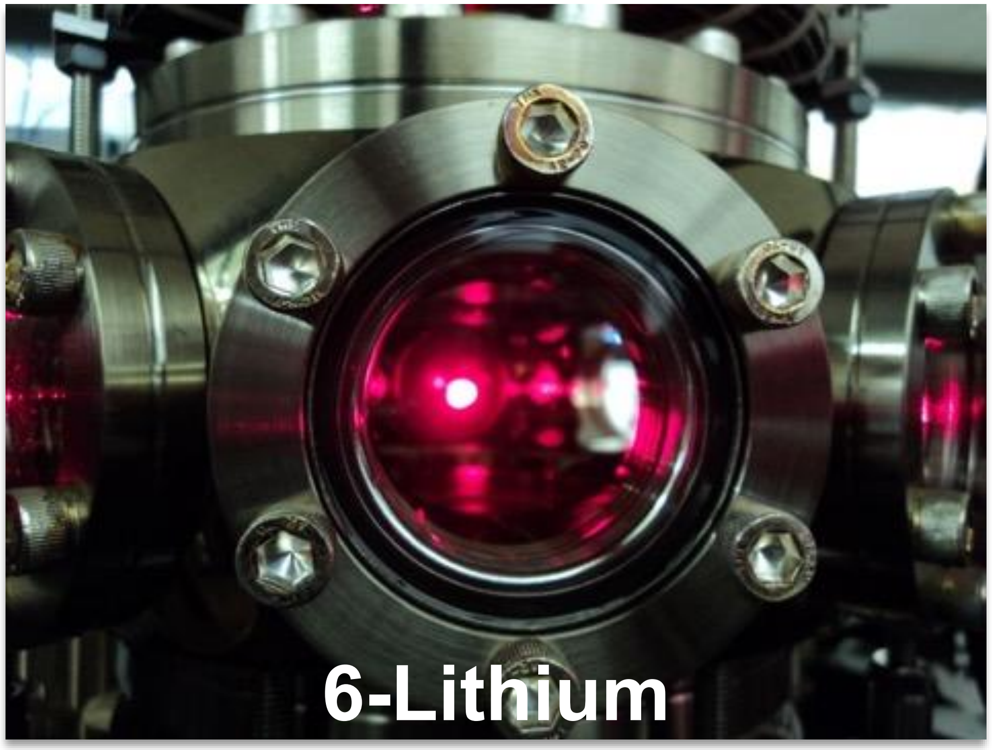
Supersolid state

Cataliotti et al., Science (2001)

Albiez et al., PRL (2005)
Levy et al., Nature (2007)
Ryu et al., PRL (2013)
Spagnolli et al., PRL (2017)
…

Biagioni et al., Nature (2024)
Poli et al., Nat. Phys. (2025)

Ultra-low energy fermions but very strongly-interacting



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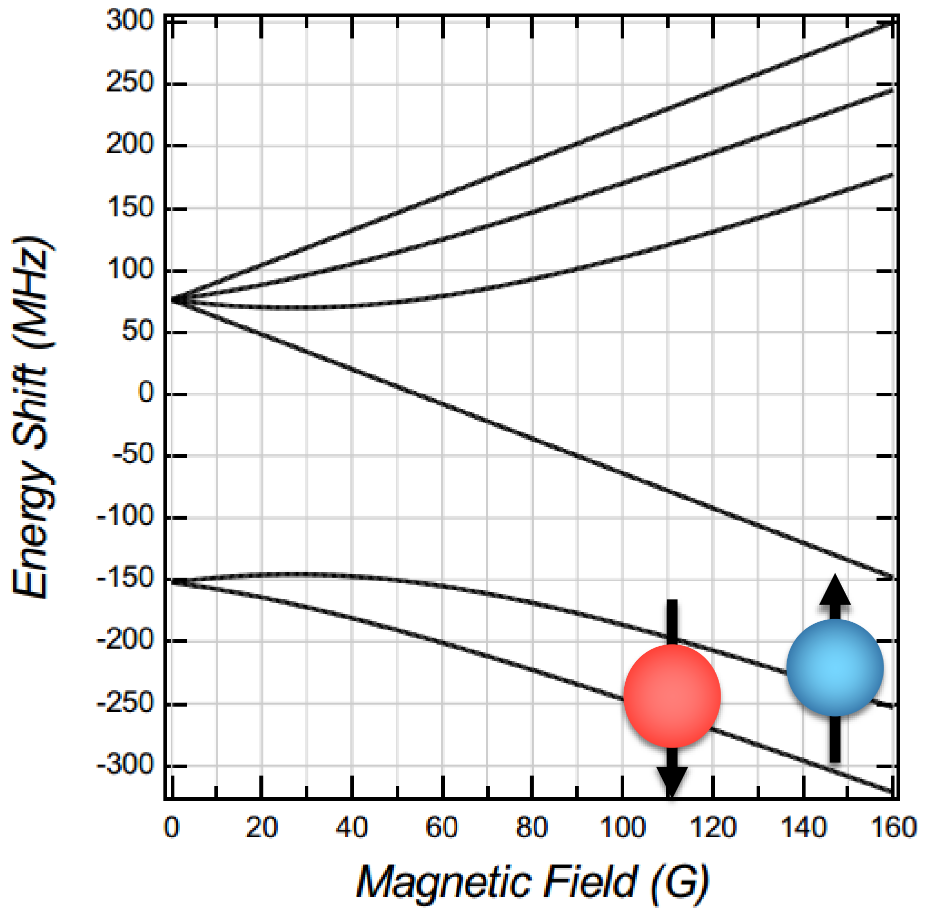
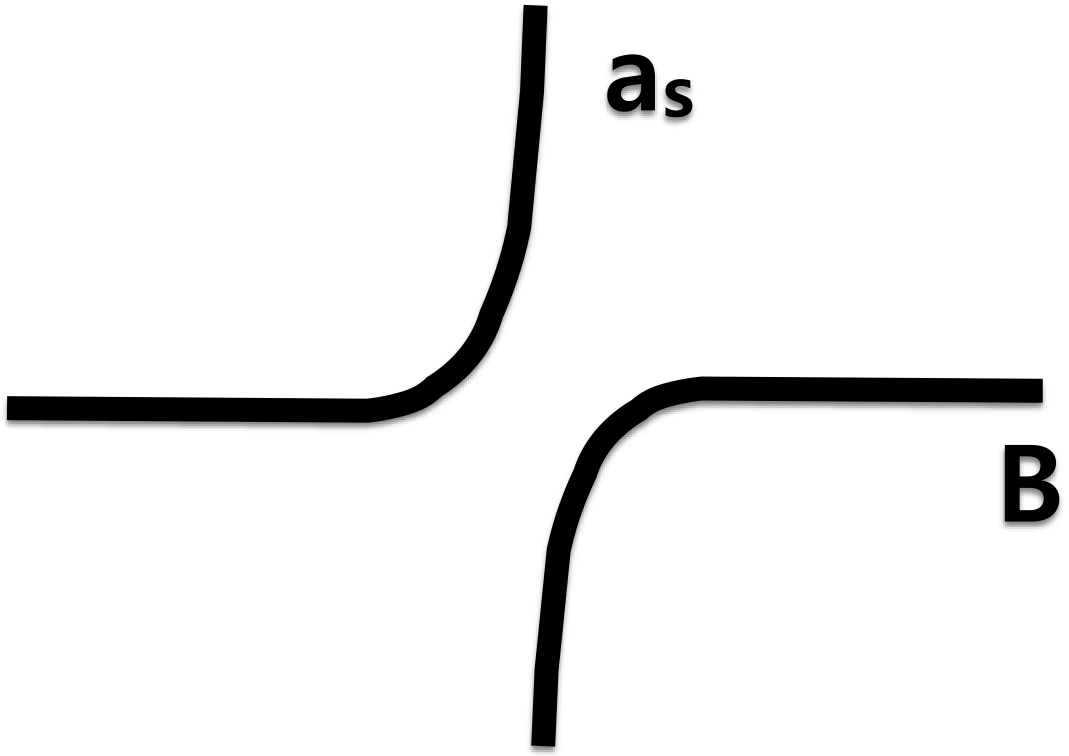
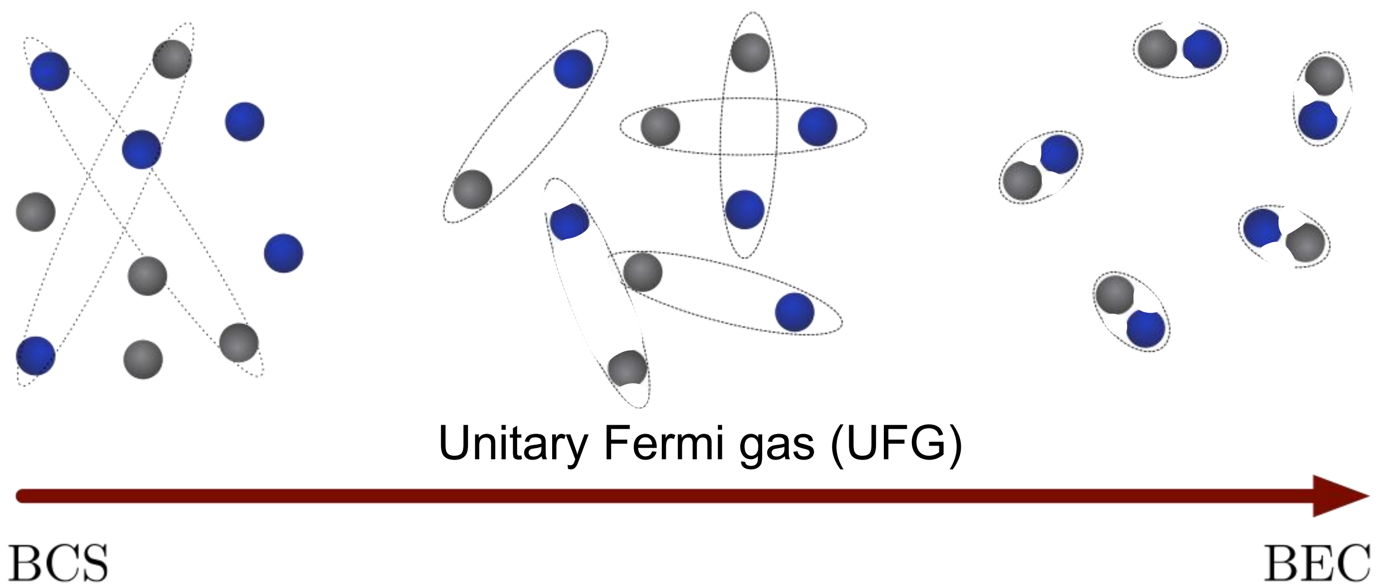




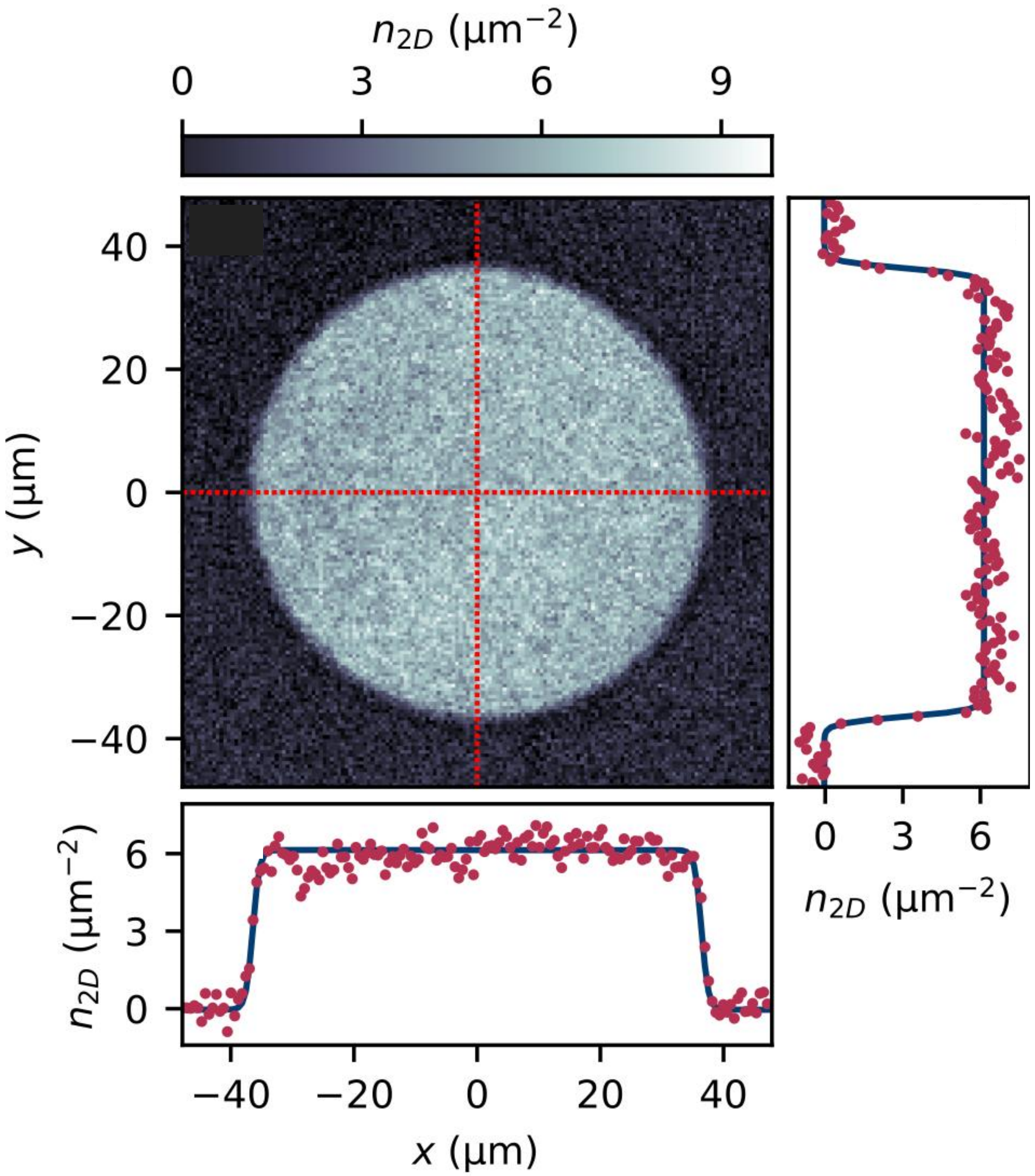


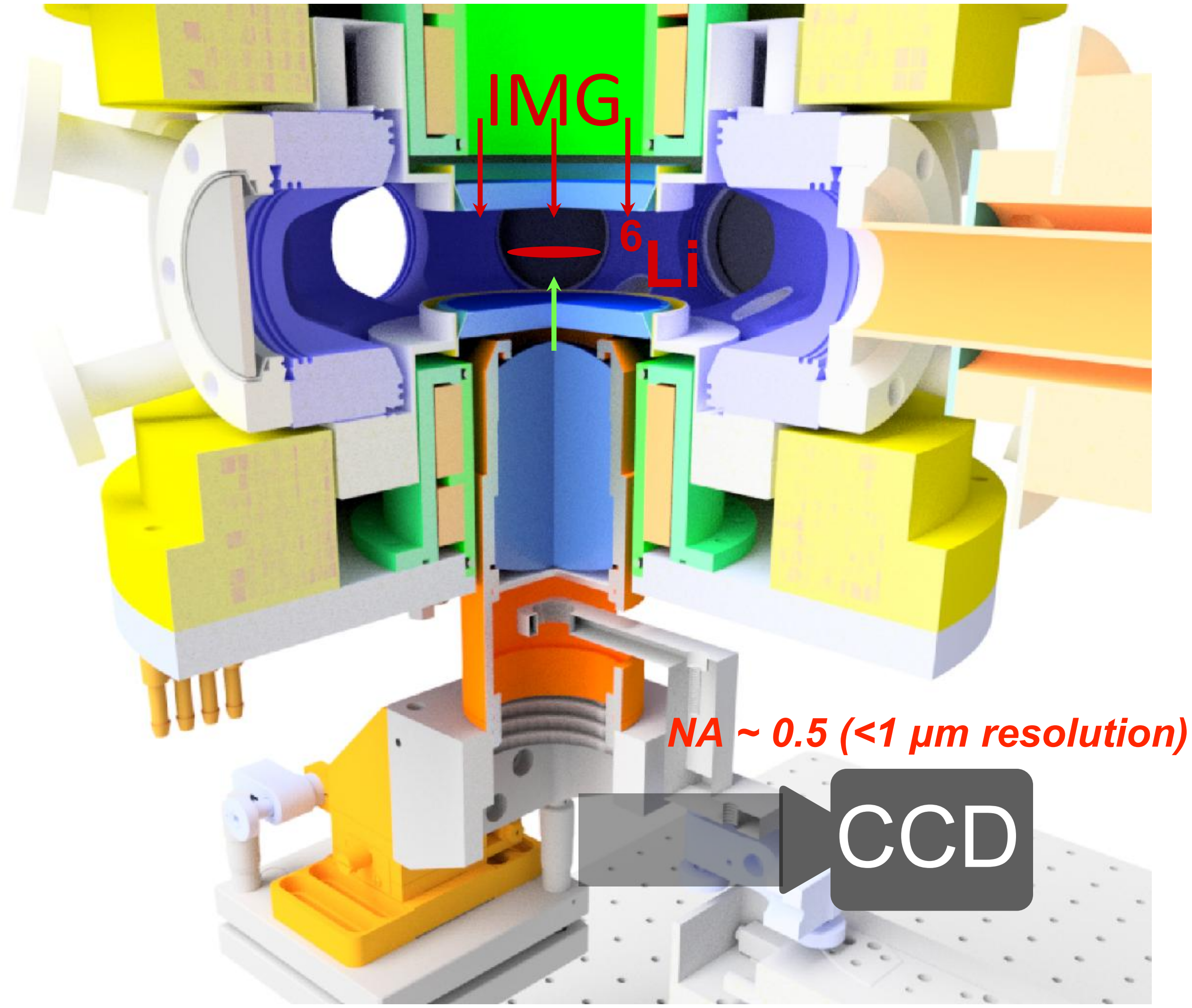
Holland, Kokkelmans, Chiofalo, and Walser PRL (2001)

Randeria, Nat. Phys. (2010)

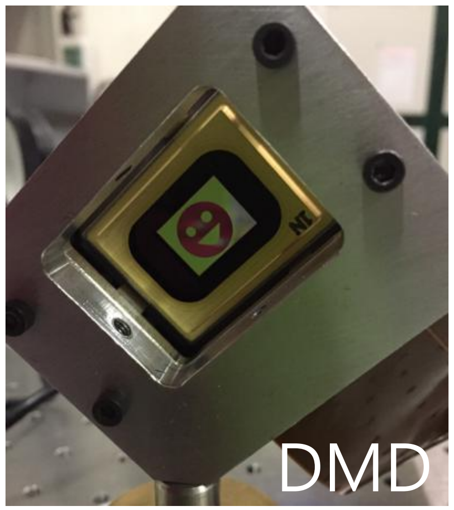
Ingredients: atomic Fermi gases

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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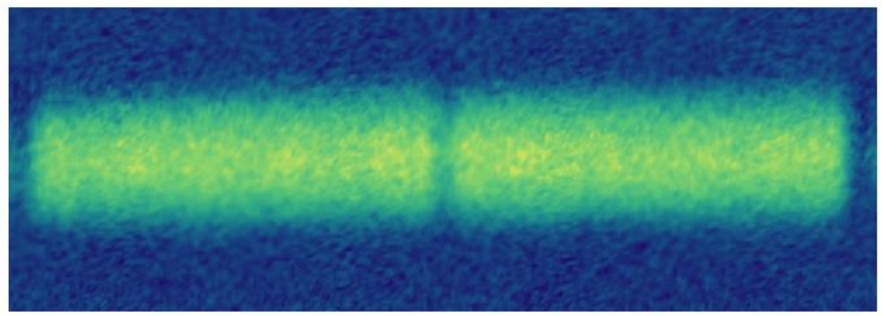
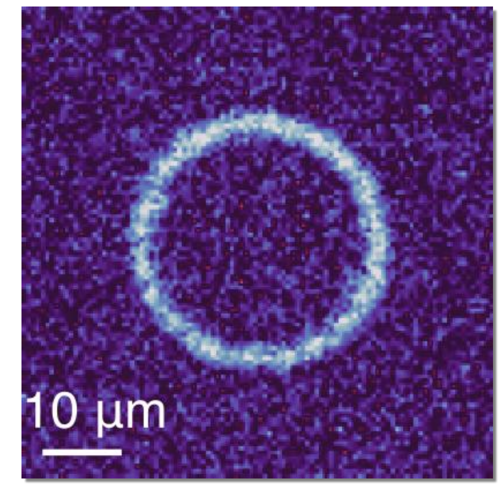
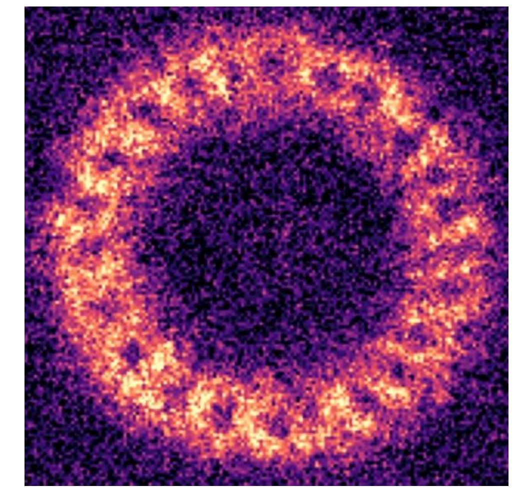
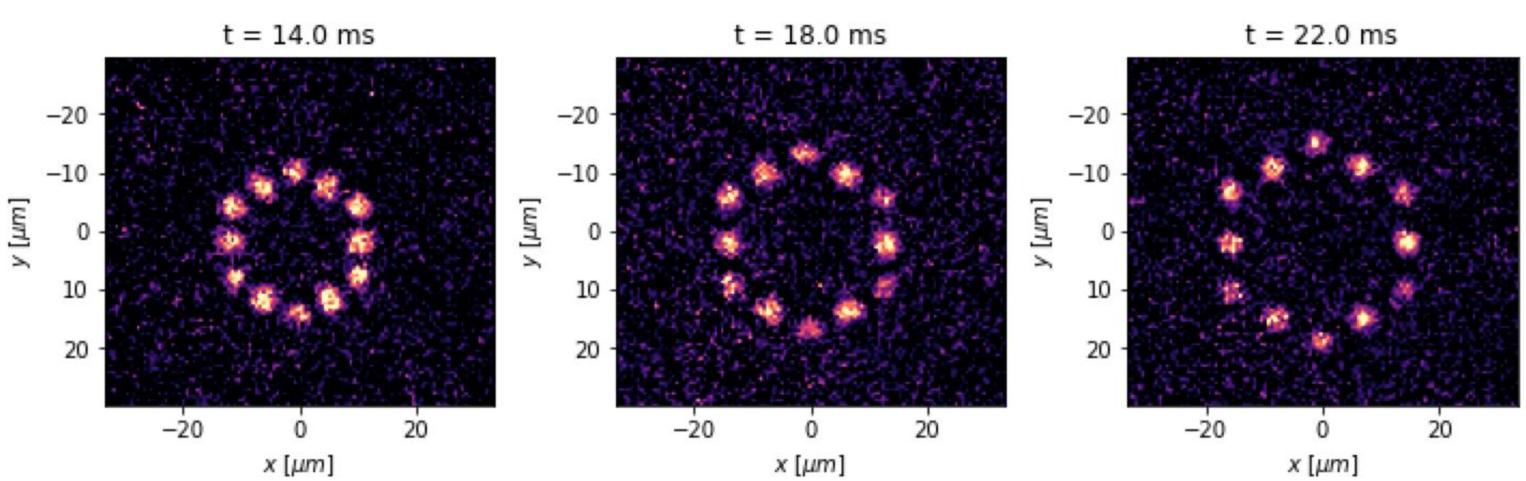
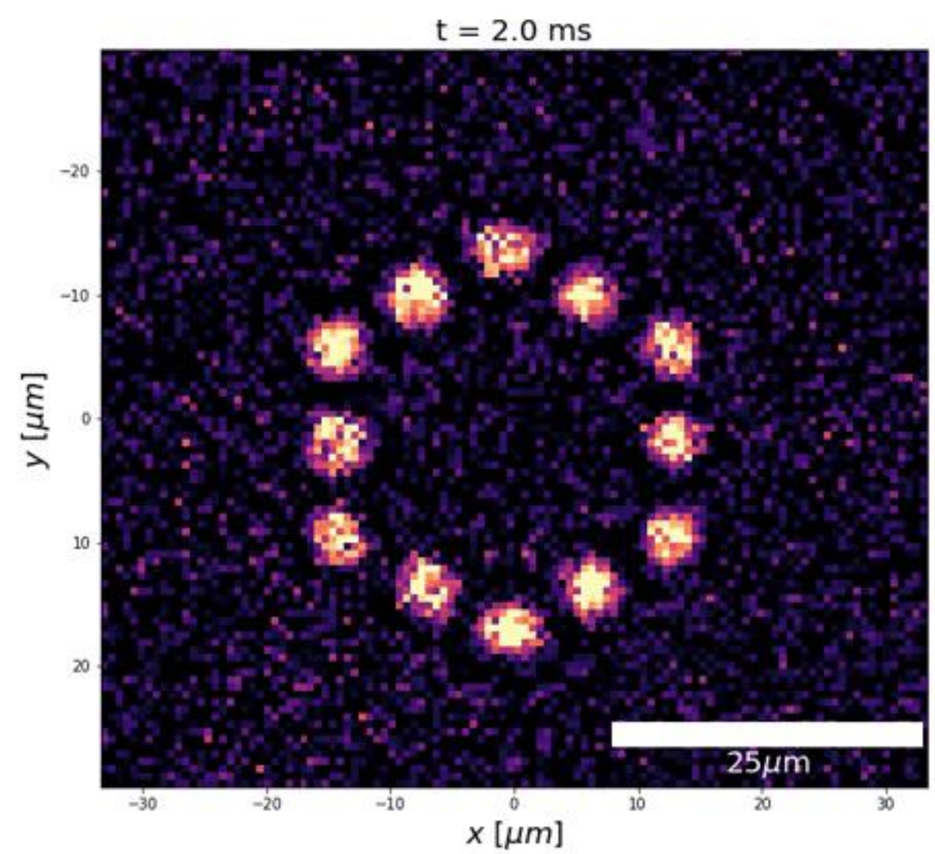








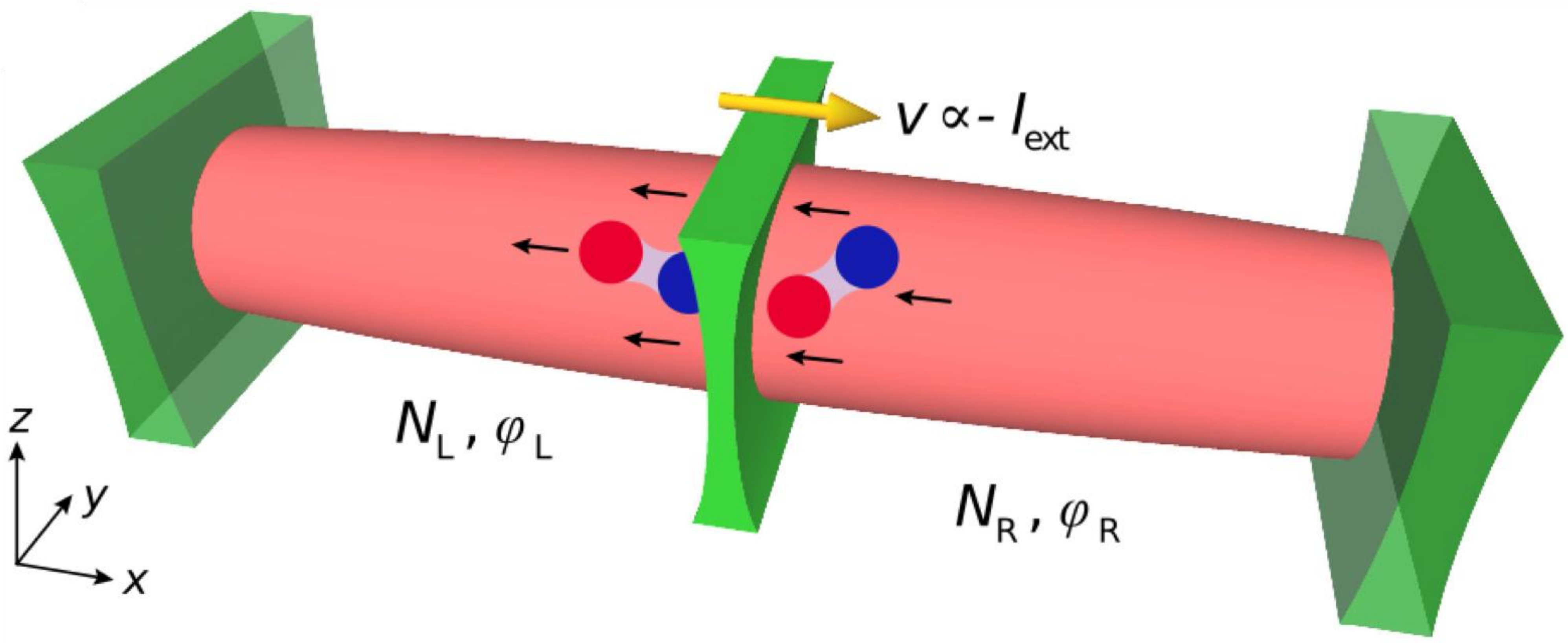


~ 100 atoms per lattice site. Tunable *mesoscopic* Josephson junction arrays

Kwon et al. Science (2020)

DC Josephson effect

Injecting a current: moving the optical barrier at controllable velocity



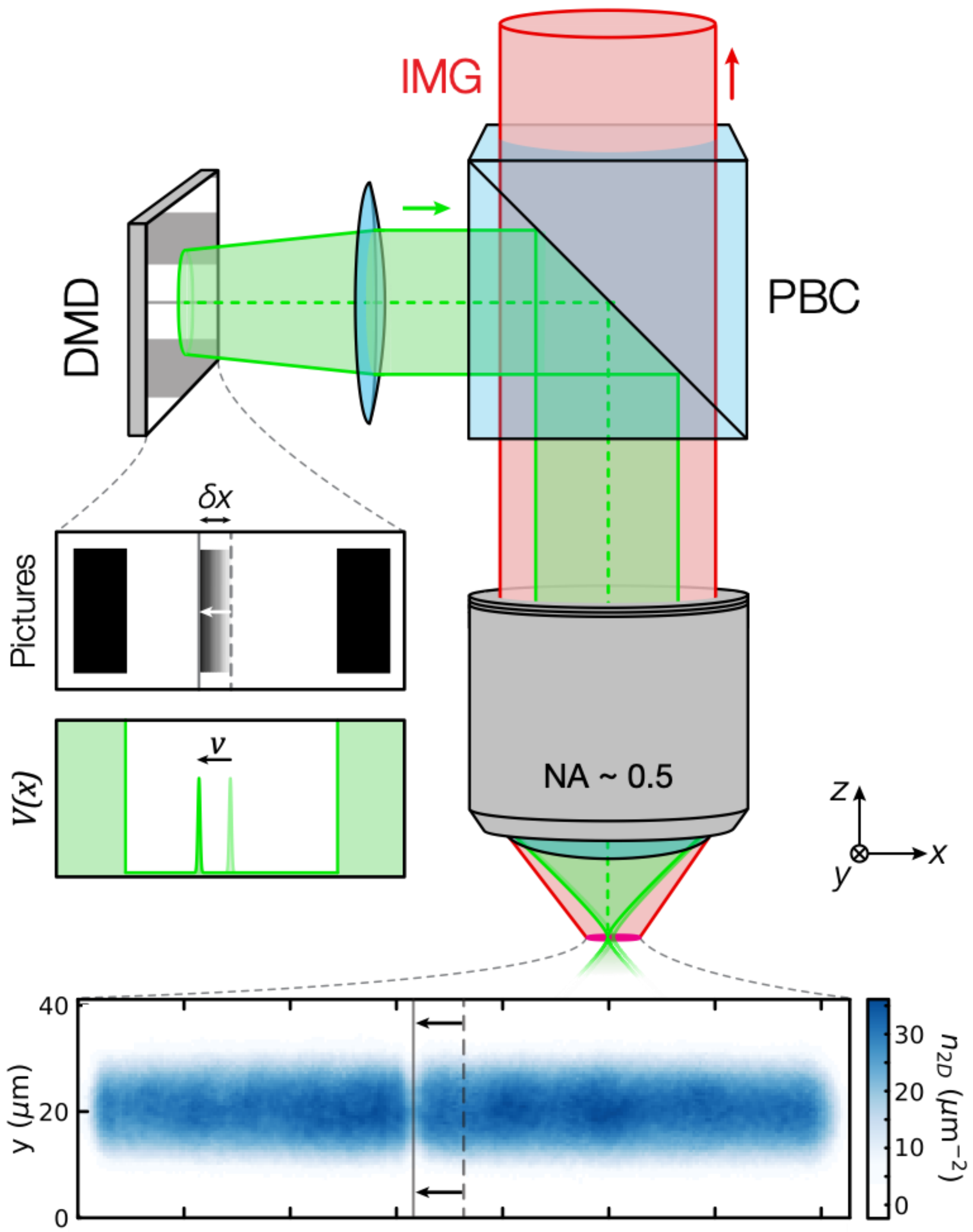
Atomic cloud:
$N_{R,L} \simeq 3.5 \times 10^4$ atom pairs
$T/T_F \simeq 0.06\ (2)$

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

Giovanazzi, Smerzi, and Fantoni PRL (2000)

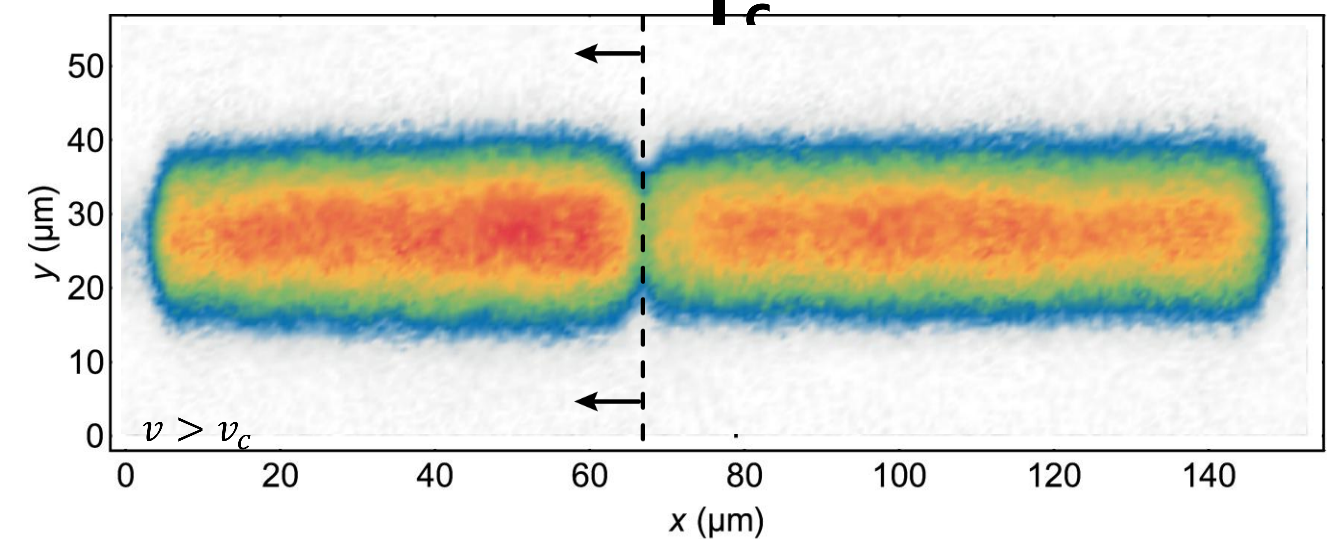
Kwon et al. Science (2020)

DC Josephson effect



δx

3D unitary gas at T~0.3 T_c



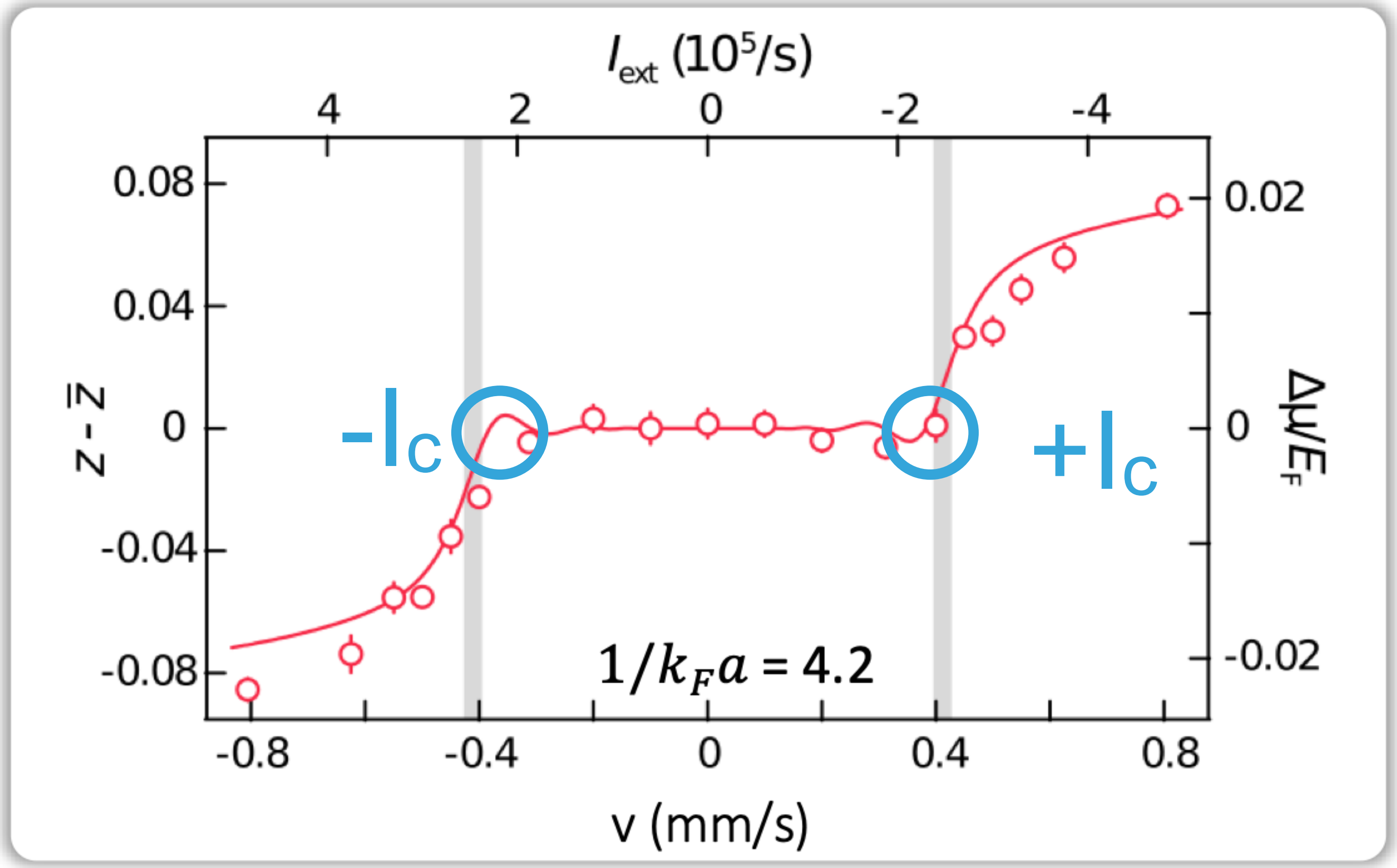
Below a critical current, the gas flows entirely through the tunnelling barrier → Superfluid coherent transport!

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

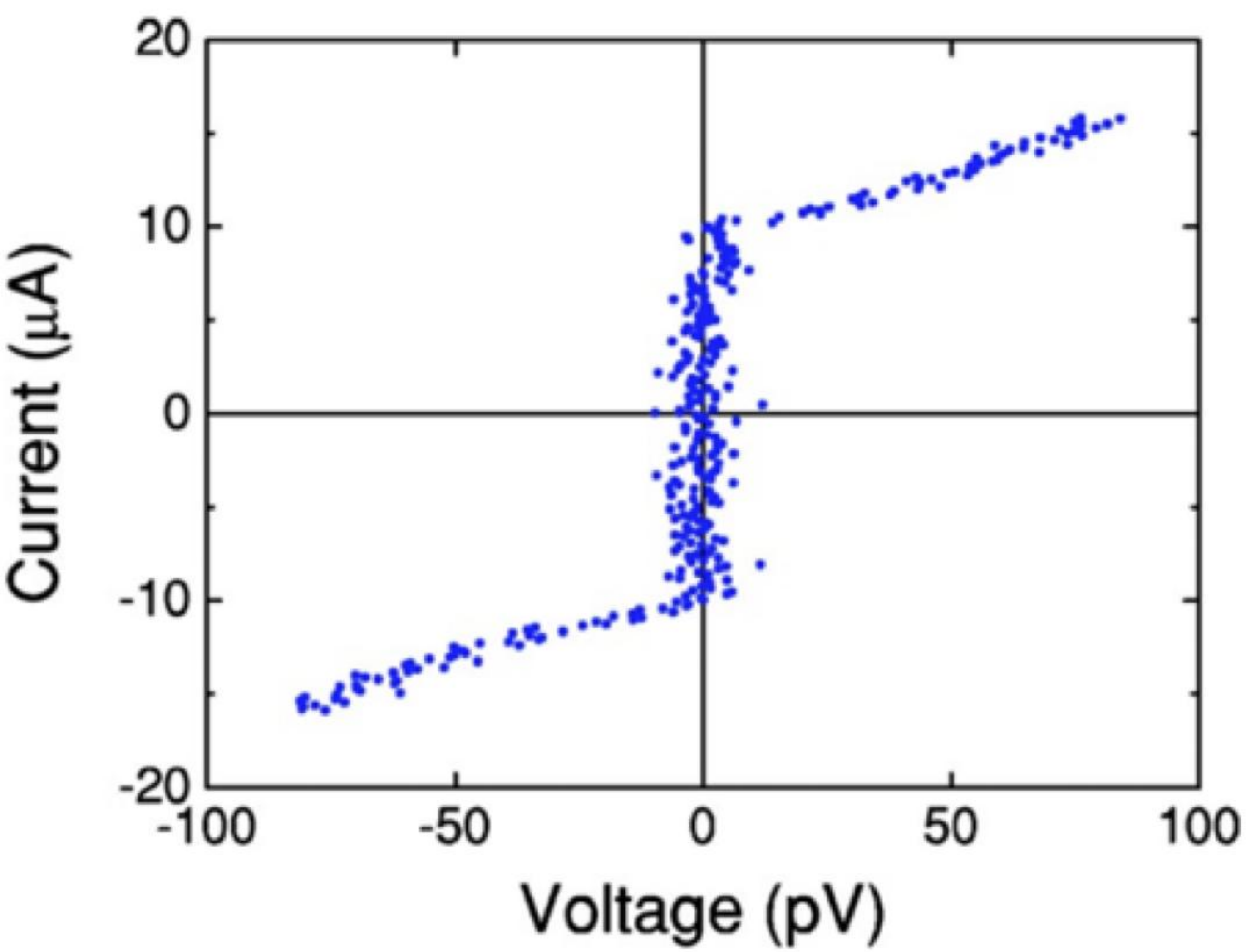
Sound velocity (bulk):
$c \approx 10$ mm/s

RCSJ circuit model

M. Tinkham, Introduction to Superconductivit



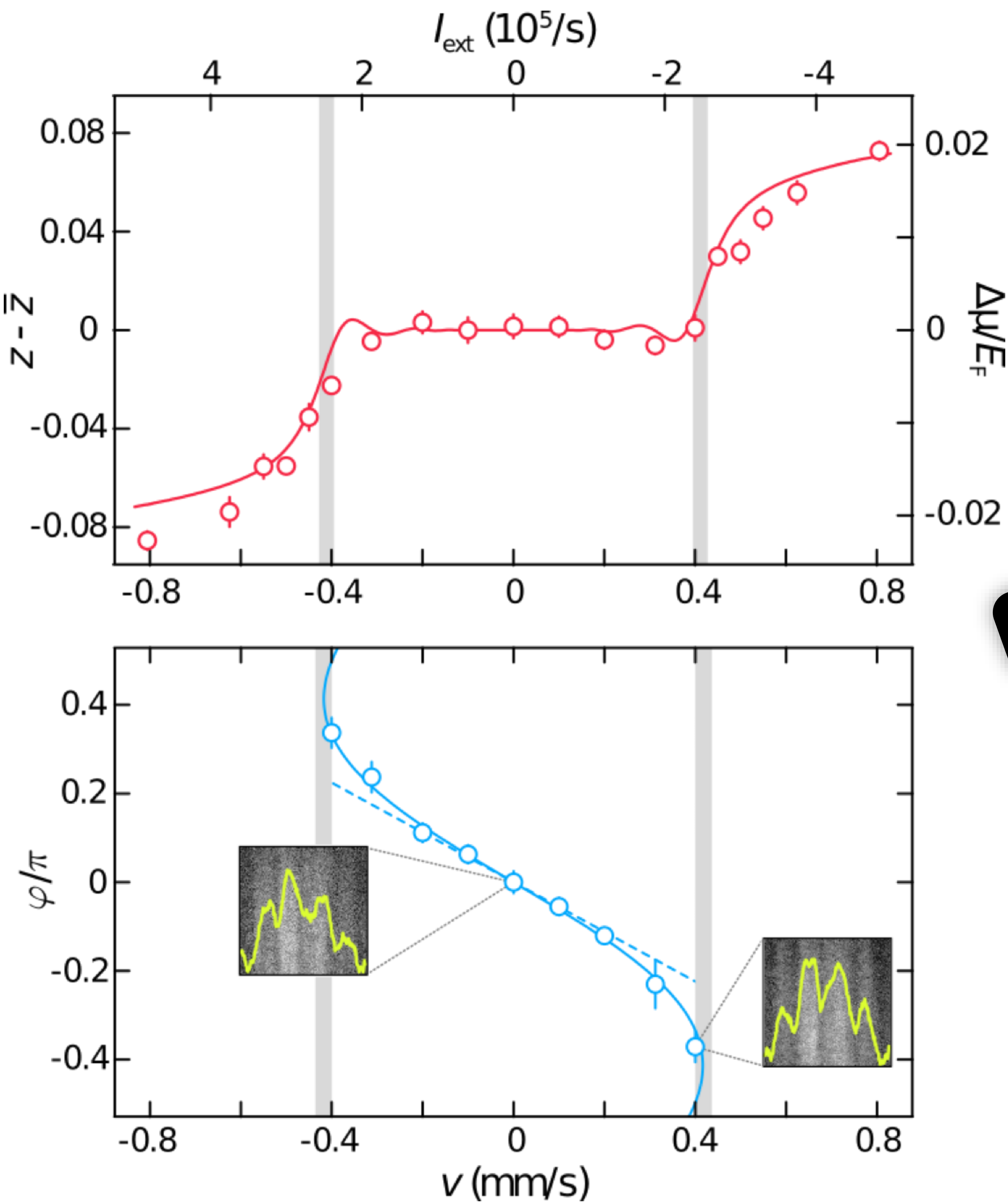
I_c and G free parameters



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

Kwon et al. Science (2020)

DC Josephson effect



$I = I_c \sin \varphi$

Luick et al., Science (2020)

Extracting condensate fraction for BEC-BCS gases

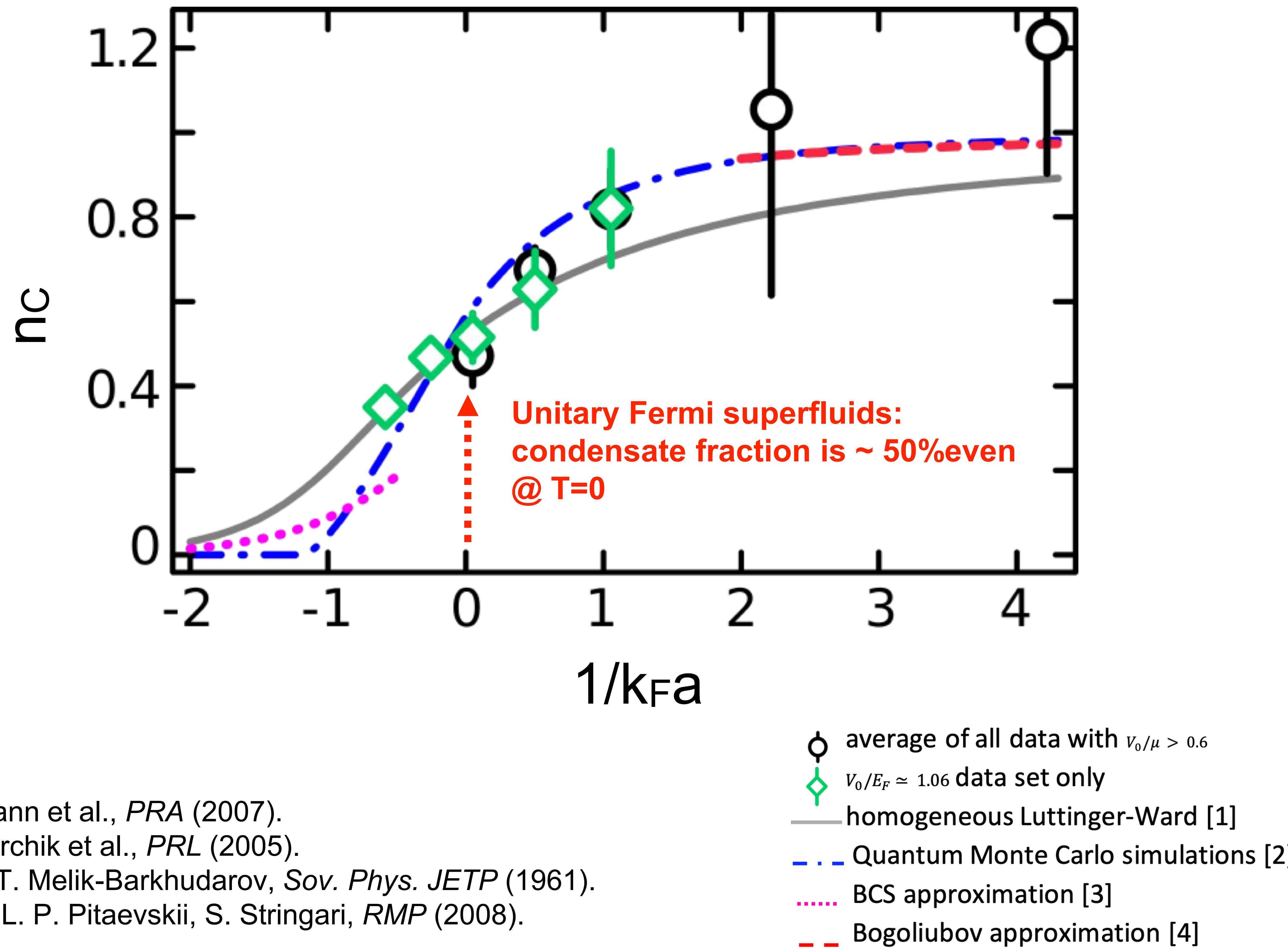
Ambegaokar-Baratoff relation (BCS)

$$\hbar I_c = E_J \sim \Delta \sim n_C$$

Extension to BEC-BCS crossover

$$\hbar I_c \sim \mu \, n_C \, |\tau|(\mu)$$

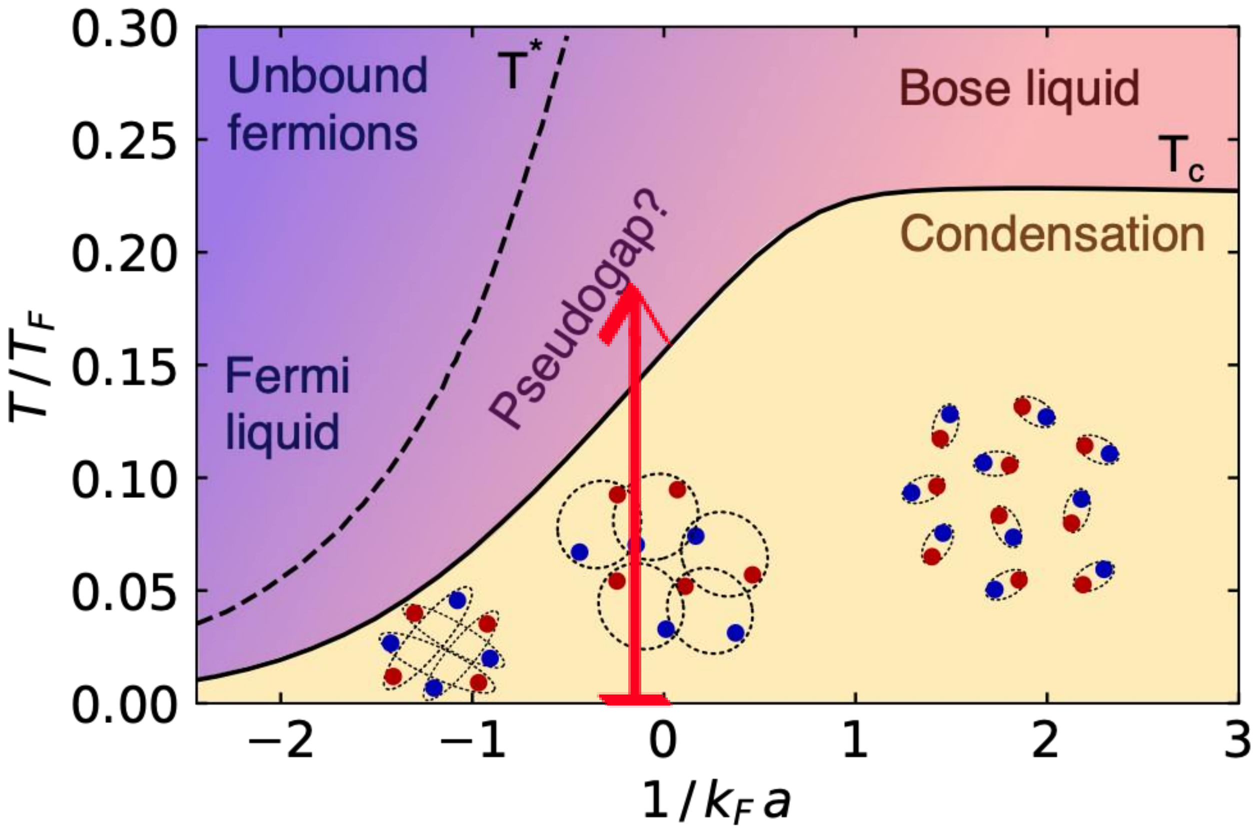
Zaccanti and Zwerger PRA (2019)



[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)

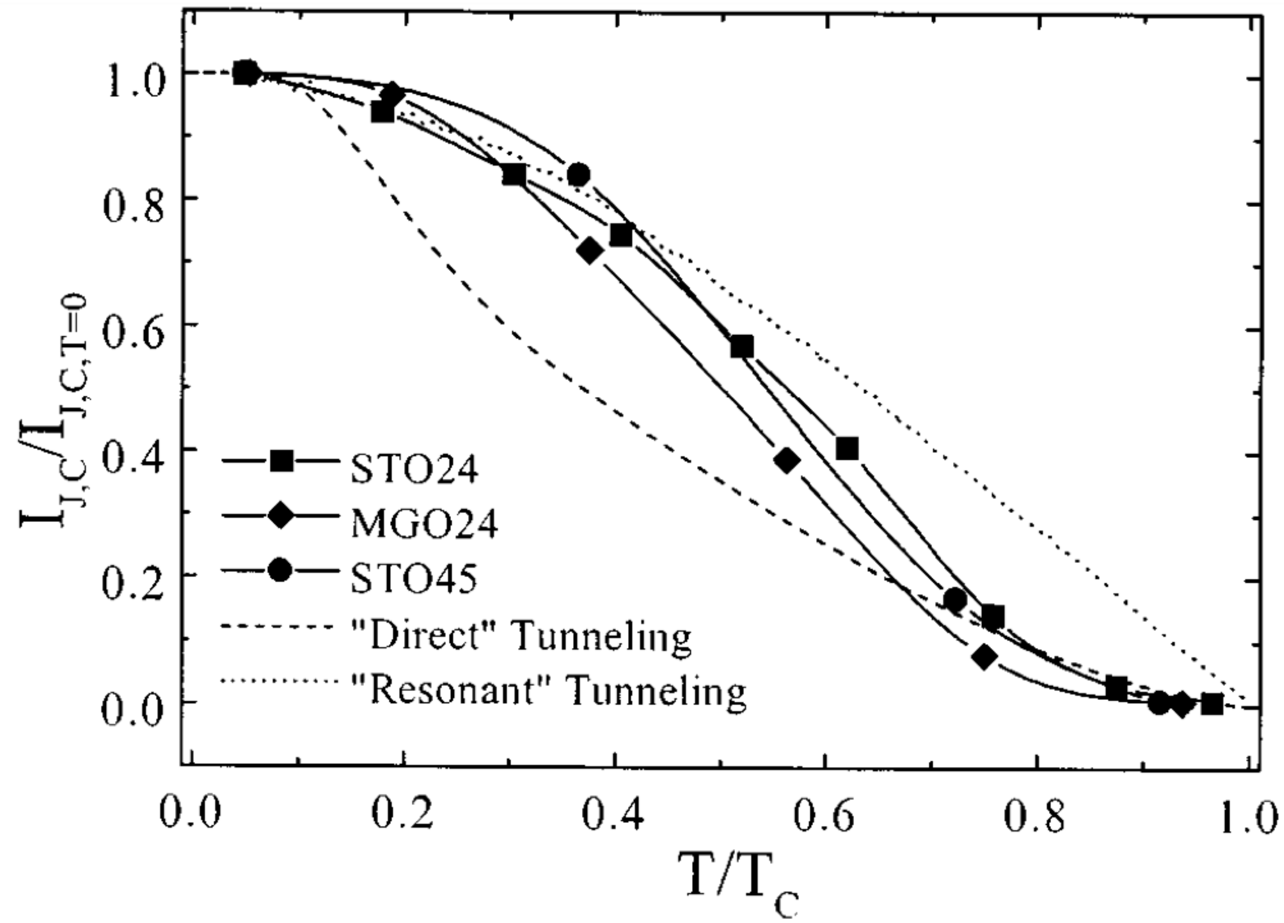
Josephson effect across T_c

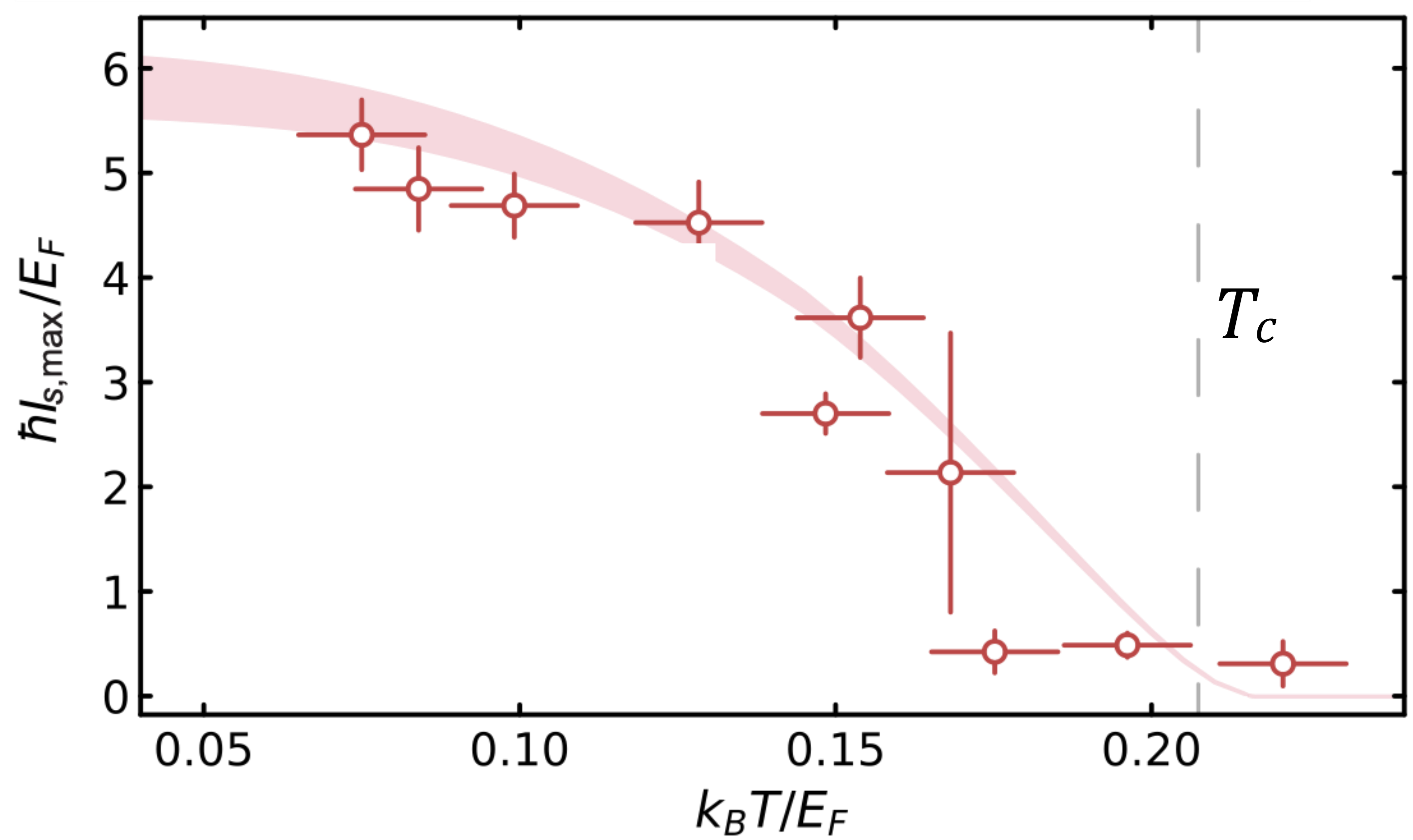


Controlled (parametric) heating

Striking signature of superfluid phase transition in unitary Fermi gas

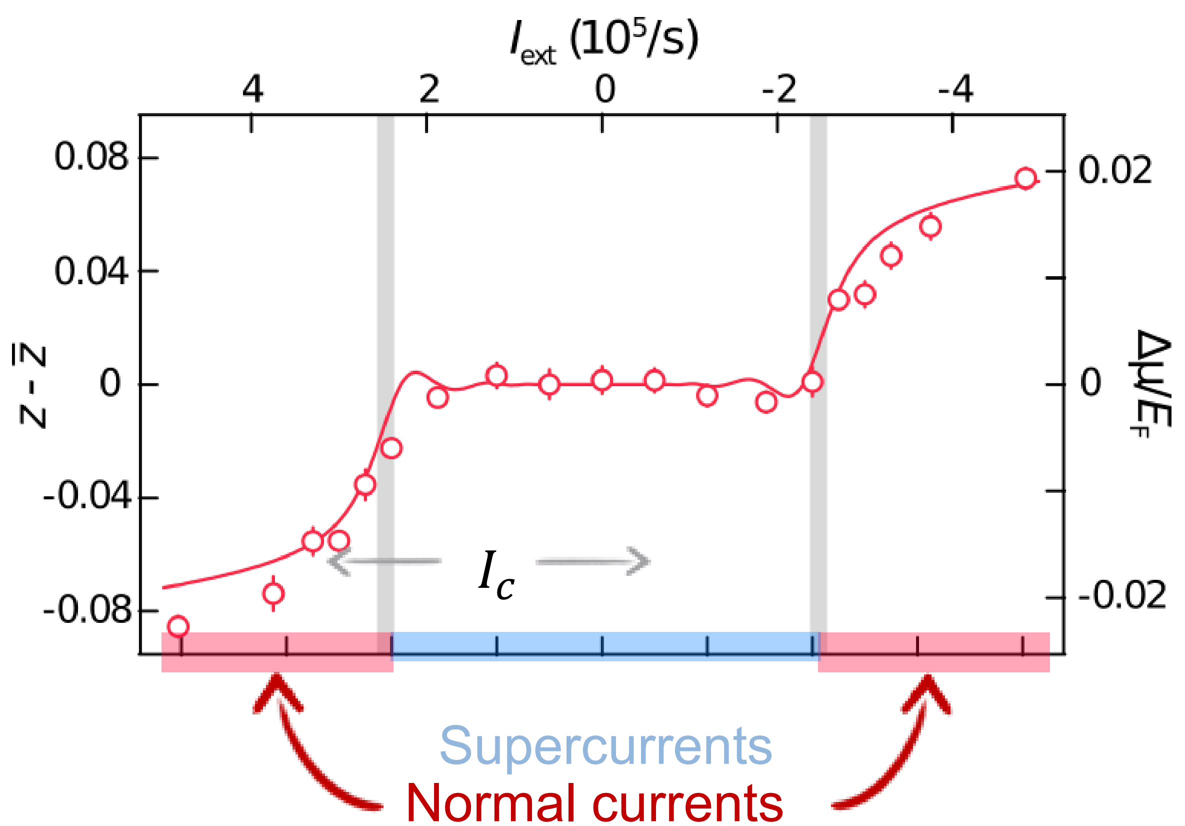
Haussmann et al., PRA (2008)
Pini et al., NJP (2020)





Del Pace et al., PRL (2021)

Josephson effect across T_c



$$I_n = G\Delta\mu$$

EXCITATIONS

Weakly interacting BEC: phonons

$$G = G_{an} + G_{nc-nc}$$

$G_{an} \longrightarrow$ condensate - phonon

$G_{nc-nc} \longrightarrow$ phonon tunneling

Superconductors: pair breaking

$G = G_n \longrightarrow$ normal state $\qquad \dfrac{I_c}{G_n} = \dfrac{\pi\Delta_0}{2\,e}$

Neutral Fermi superfluid (BCS): BA phonons

$$G = G_{an} + G_n$$

$G_{an} \longrightarrow$ condensate - BA phonon

$G_n \longrightarrow$ quasiparticle tunneling

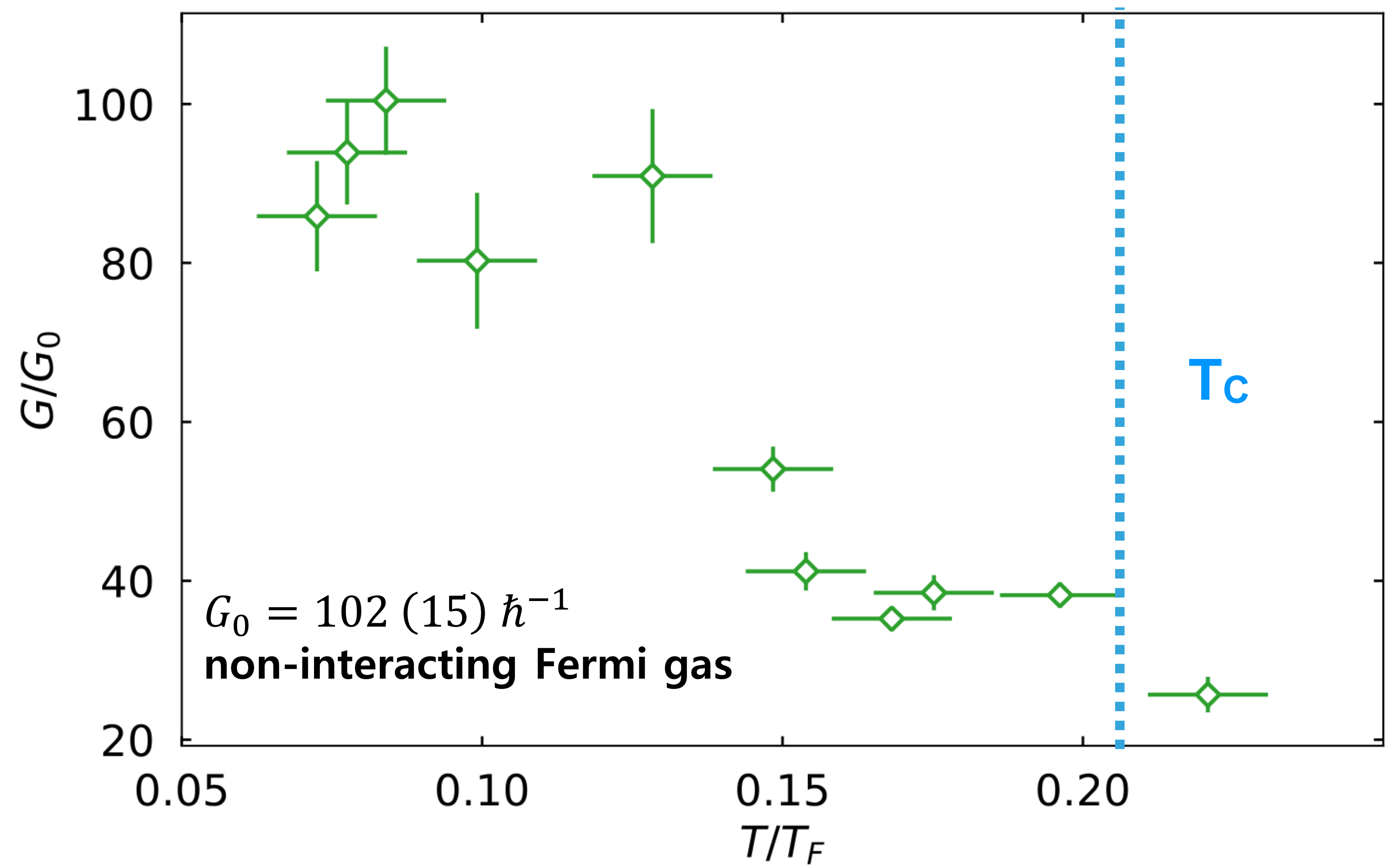
Unitary Fermi gas

?

Meier and Zwerger. PRA (2001)
Ambegaokar and Baratoff, PRL (1963)
Uchino, PRR (2020)
Uchino and Brantut, PRR (2020)

Del Pace et al., PRL (2021)

Josephson effect across T_c



Low temperature:

- $G \gg G_0 \rightarrow$ bosonic collective exc.
- G decreases with $T \rightarrow$ anomalous

Anomalous conductance $\sim n_0$

High temperatures:

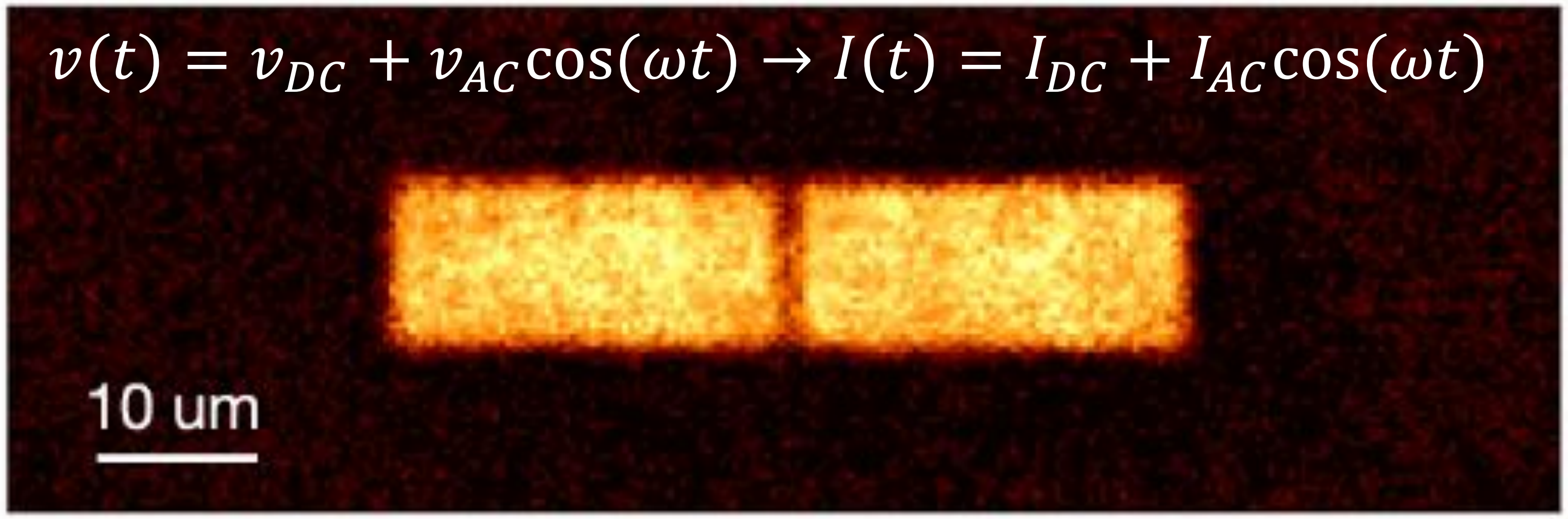
- $G \gg G_0$ **even for** $T \gtrsim T_c$

Phonons tunneling in hydrodynamic fluid of unpaired fermions

Patel et al., Science (2020)

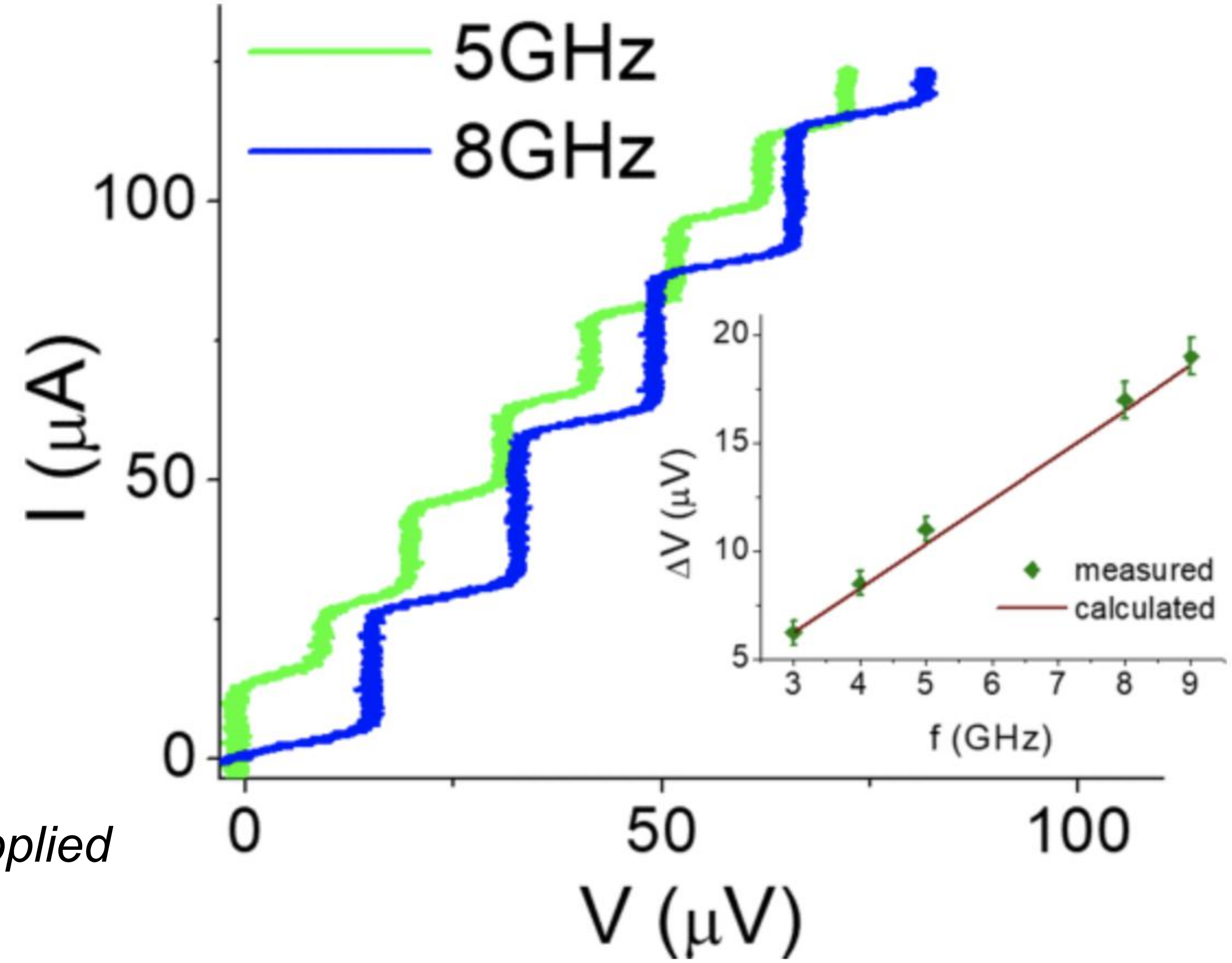
Del Pace et al., Science (2025)

AC-drive: Shapiro steps



Singh et al, PRL (2024)

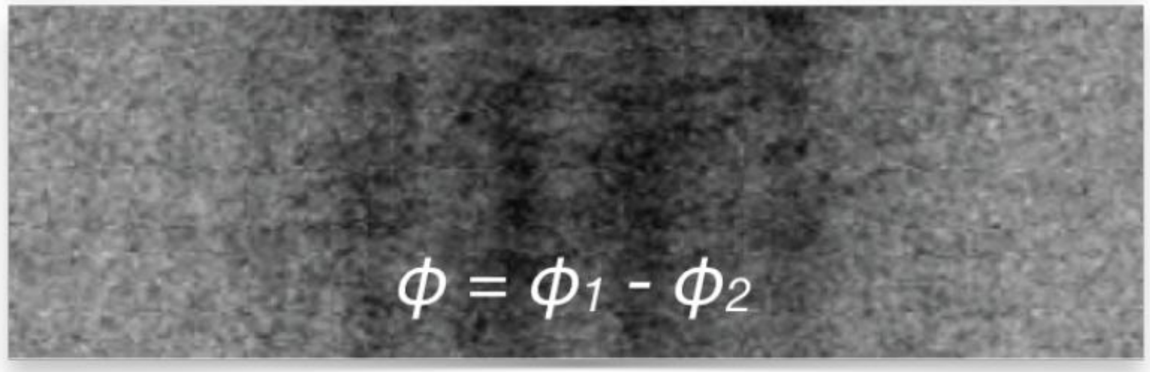
Bernhart et al., Science (2025)



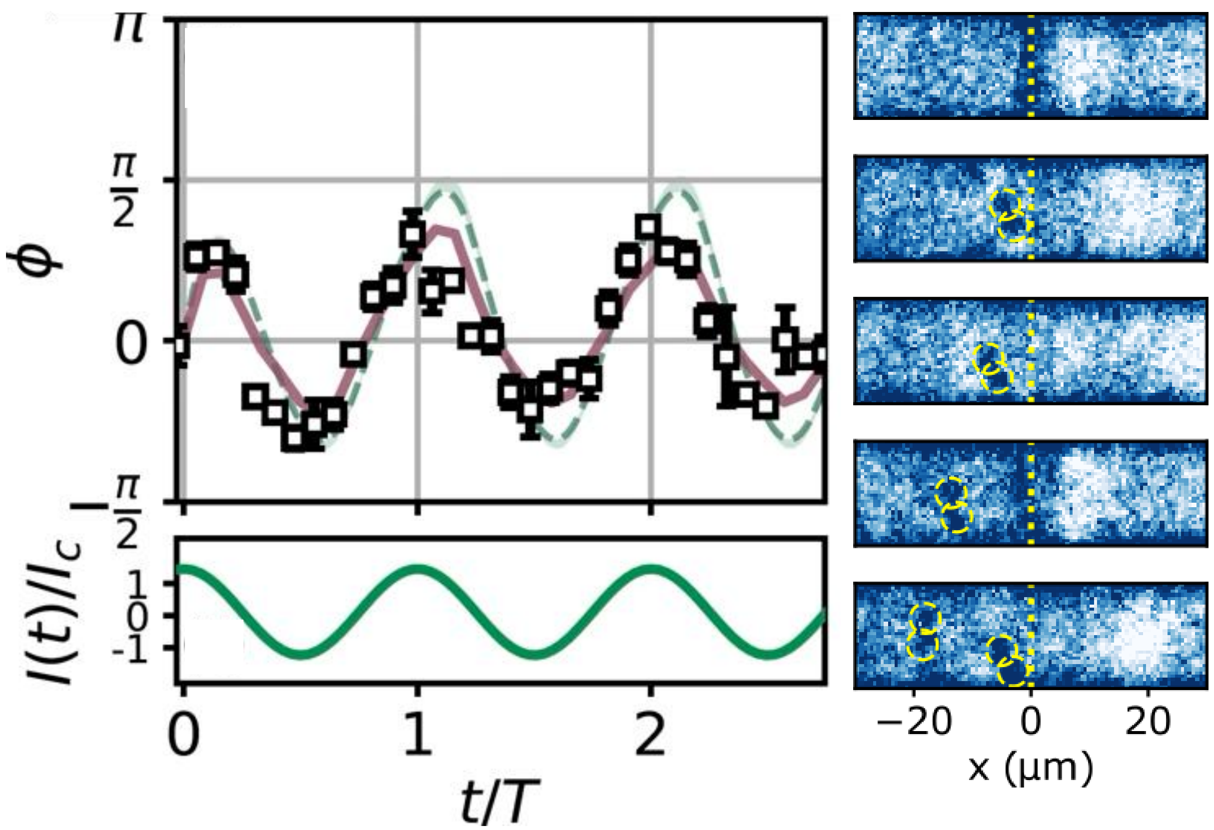
Caruso, *IEEE Transactions on Applied Superconductivity* (2018)

Del Pace et al., Science (2025)

AC-drive: Shapiro steps



Time-of-flight imaging: relative phase ϕ



ϕ is **synchronised** with the external drive. When current overcomes the threshold for **phase slippage**, we observe vortex-anti vortex pairs.

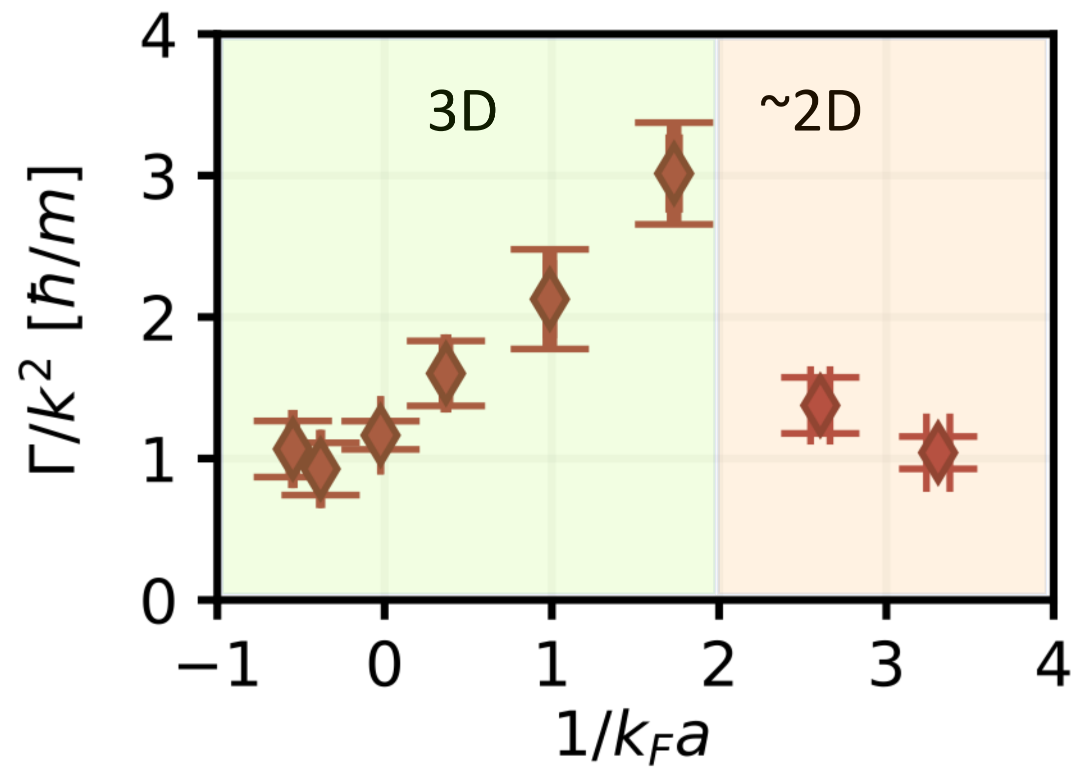
Synchronization in strongly-interacting quantum liquids

Latest news from LiLab: sound engineering

"*Sagnac*" phonon-interferometer with annular Fermi superfluids (proposed by S. Stringari):

Quantum of circulation: angular momentum per particle of BEC-BCS superfluids -atomic Cooper pairs are "really" made by two atoms-

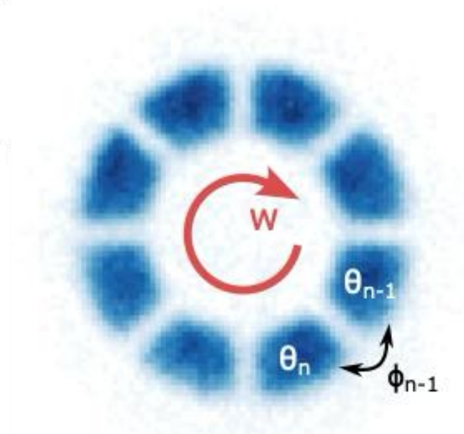
Frometa et al., arXiv:2511.02664v2 (2025)

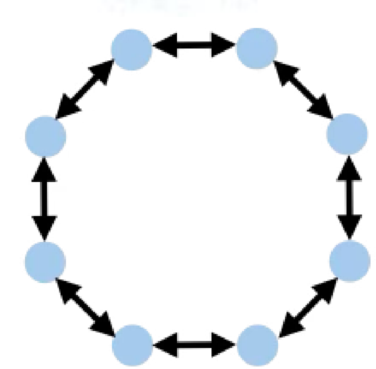


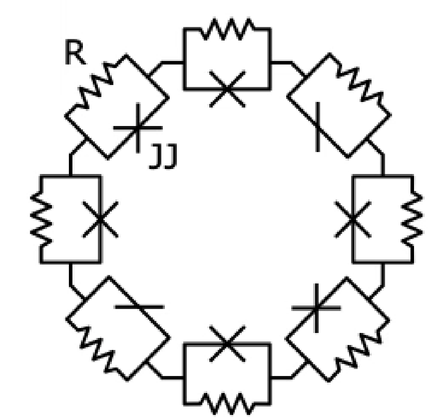
MIT, USTC, Yale, Hamburg, Cambridge, ENS…

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)

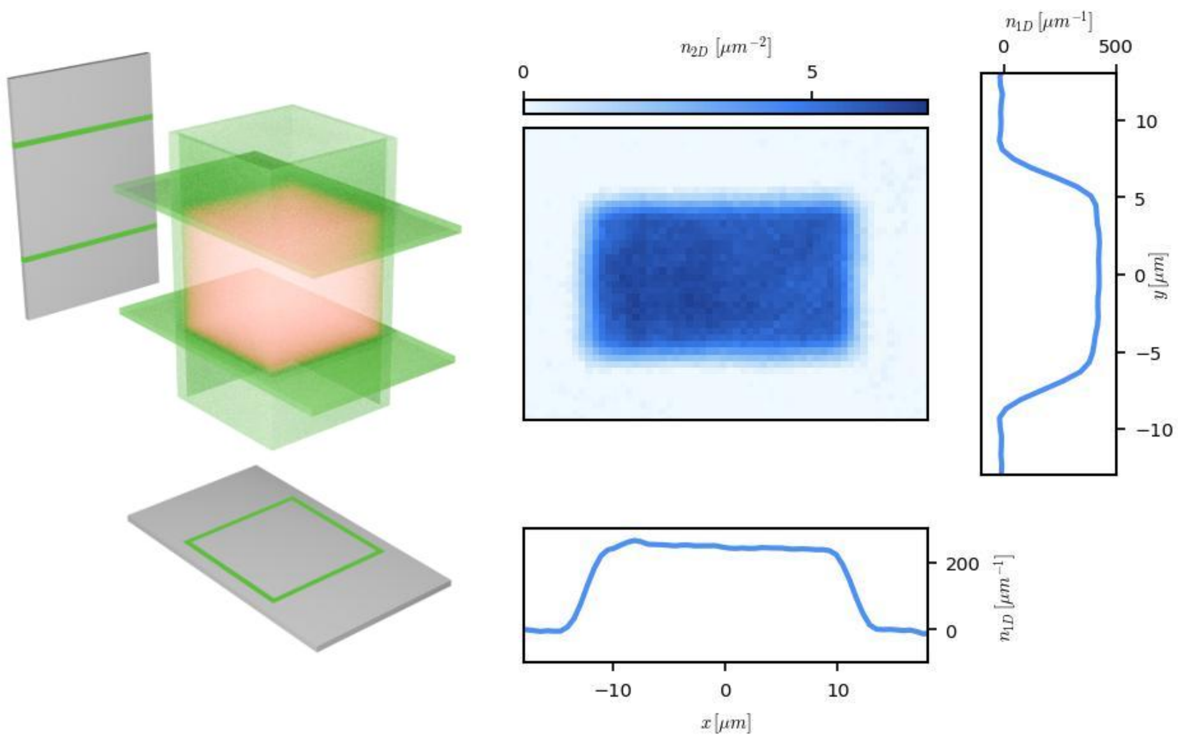






The Italian 3D Fermi box (with crossed DMDs). Thierry: we have listened to you

$N_\uparrow = N_\downarrow \simeq 40000$



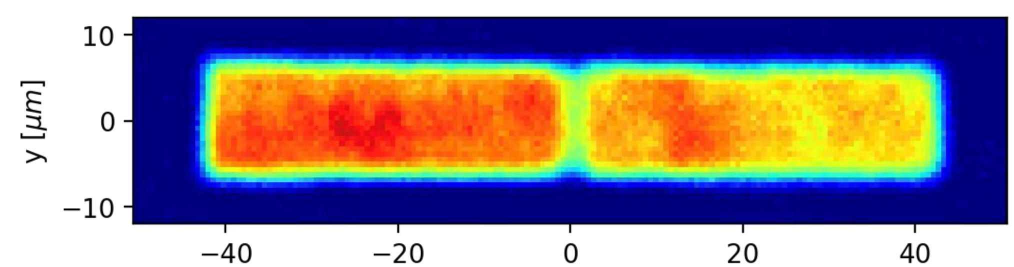
Fostering further collaborations and comparison with other Fermi-box friends in the world (MIT, Yale, USTC, Hamburg…) Mukherjee et al., PRL (2017)

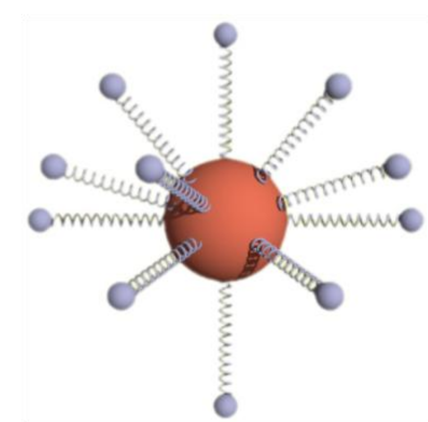
Benchmarking theories for defining new and effective theoretical approaches

Large-reservoirs **Josephson dynamics:**

Josephson dynamics in **fully homogeneous** superfluids (tunneling regime V_0/μ up to 7). Transition from phonon-dominated to Josephson-dominated regimes: Caldeira-Leggett model ?

Del Pace et al., *in preparation*





Caldeira and Leggett, Annal. Phys. (1983)

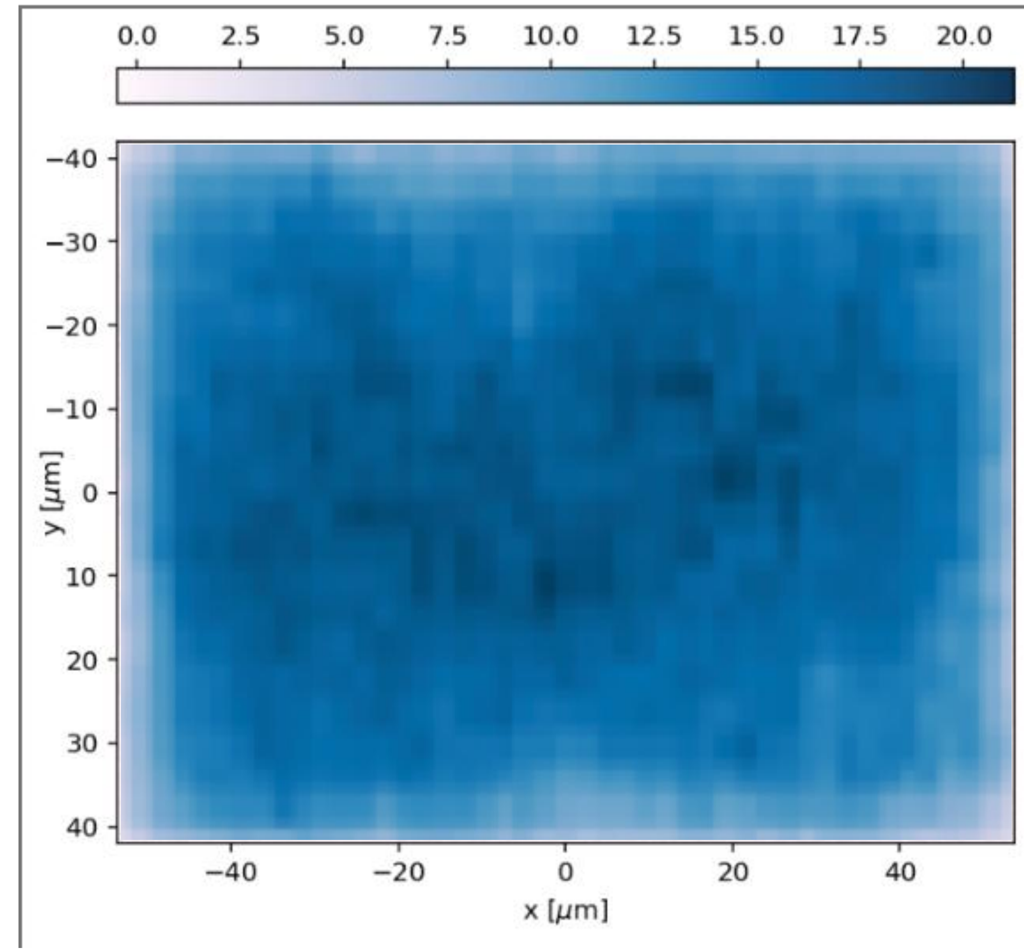
Polo et al., PRL (2018)

Multiplexing for **parallel *analog* quantum simulation**

(Rajkov et al., *in preparation*)

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

- Parallel execution of the same Hamiltonian with different parameters
- Reconfigurability of the simulating units for accessing phase diagrams and non-equilibrium dynamics on single experimental runs

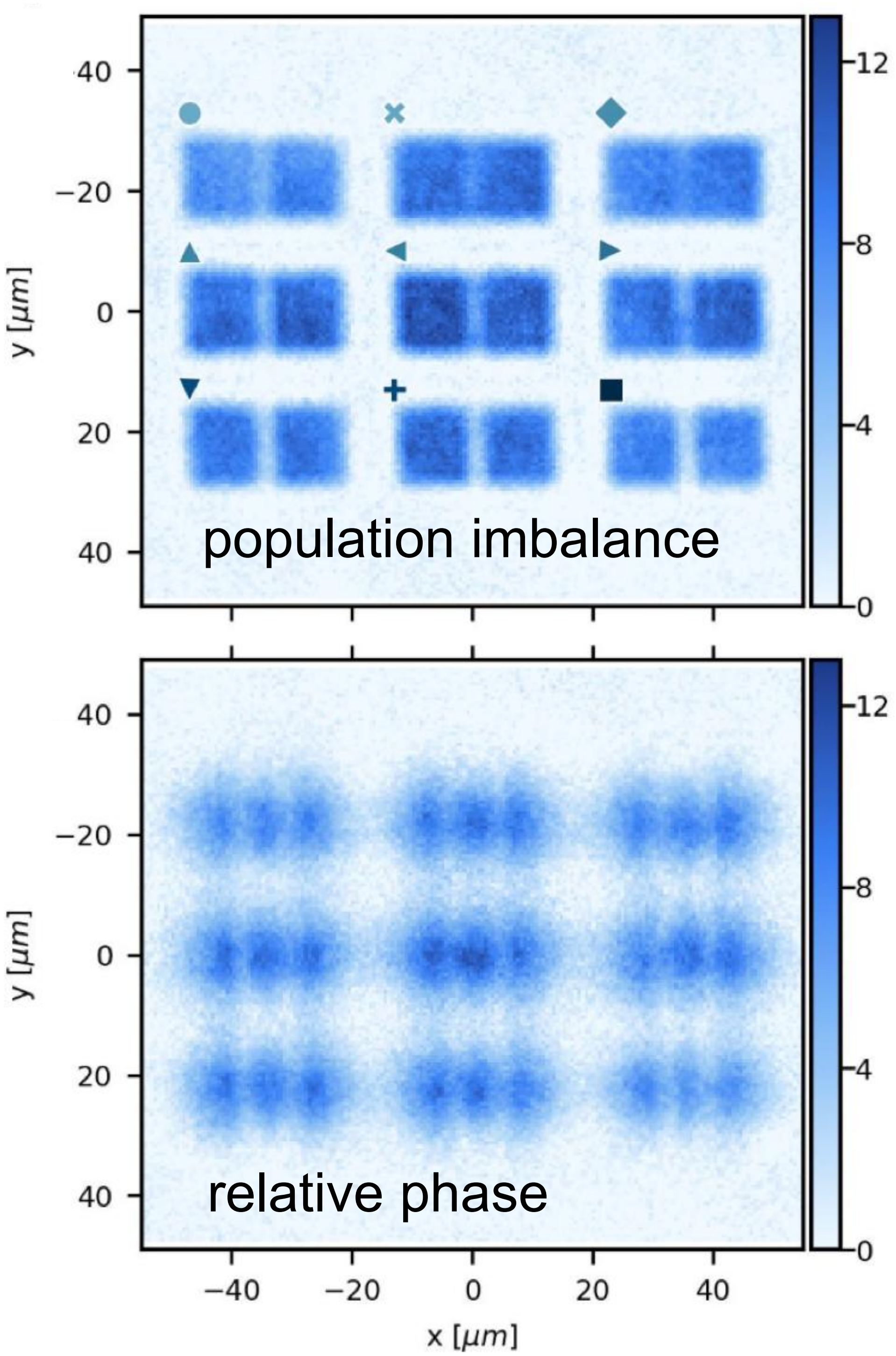


Parallel experiments for exploring ground-state phases, driven dynamics and quantum transport phenomena in the presence of strong interactions and disorder…

Having reproducible, high-volume data from parallel runs could make training and validation of AI and ML-based analysis methods more robust.

First example:

Multiplexed homogeneous Josephson junctions with local phase control (independently phase-imprinting each simulation unit) (Rajkov et al., *in preparation*)



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