A TUNABLE JOSEPHSON JUNCTION BETWEEN BEC-BCS CROSSOVER SUPERFLUIDS

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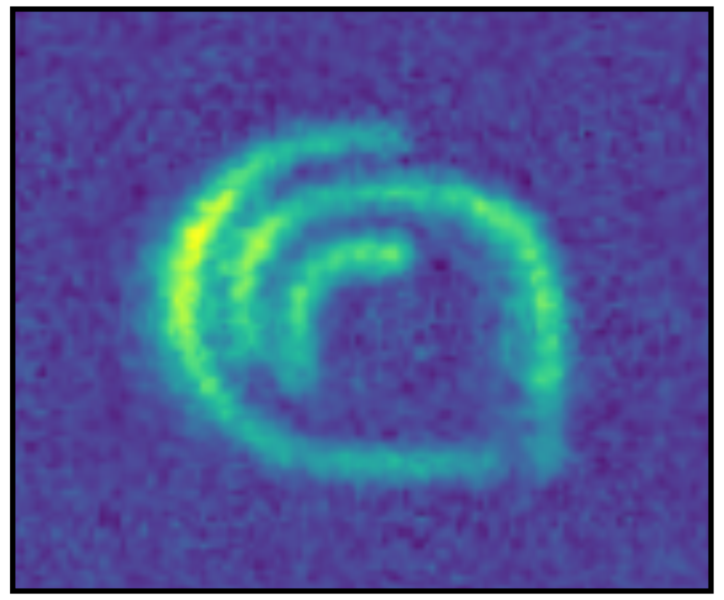
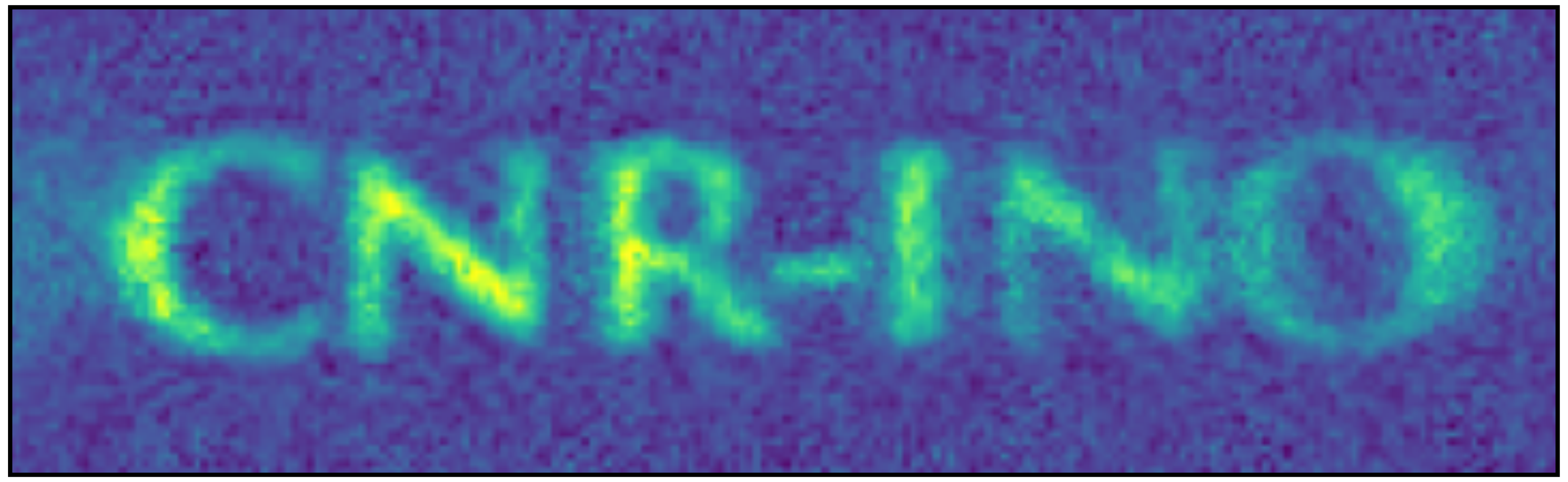
Atomtronics 2019

Centro de Ciencias de Benasque Pedro Pascual - 9 May 2019

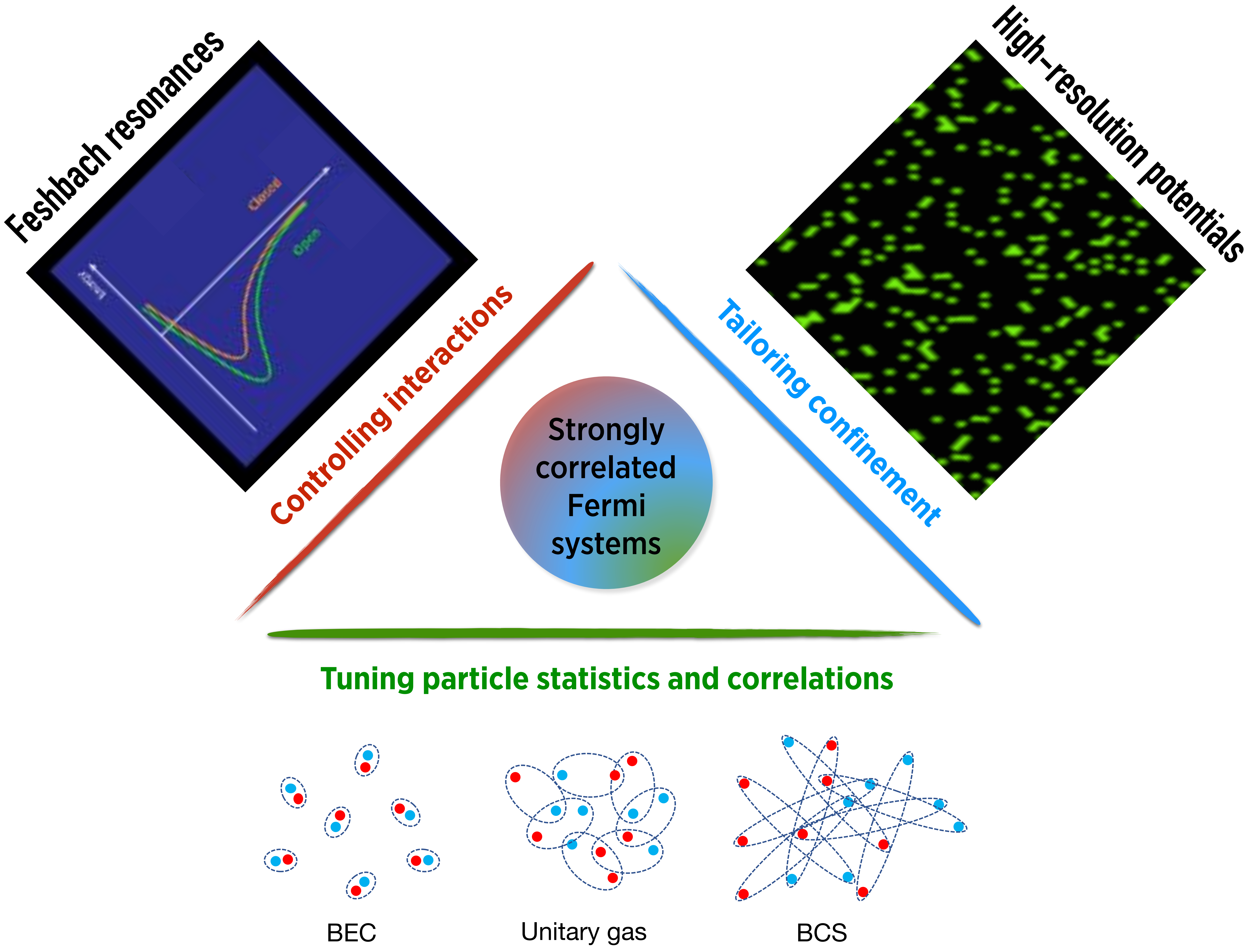




CNR-INO

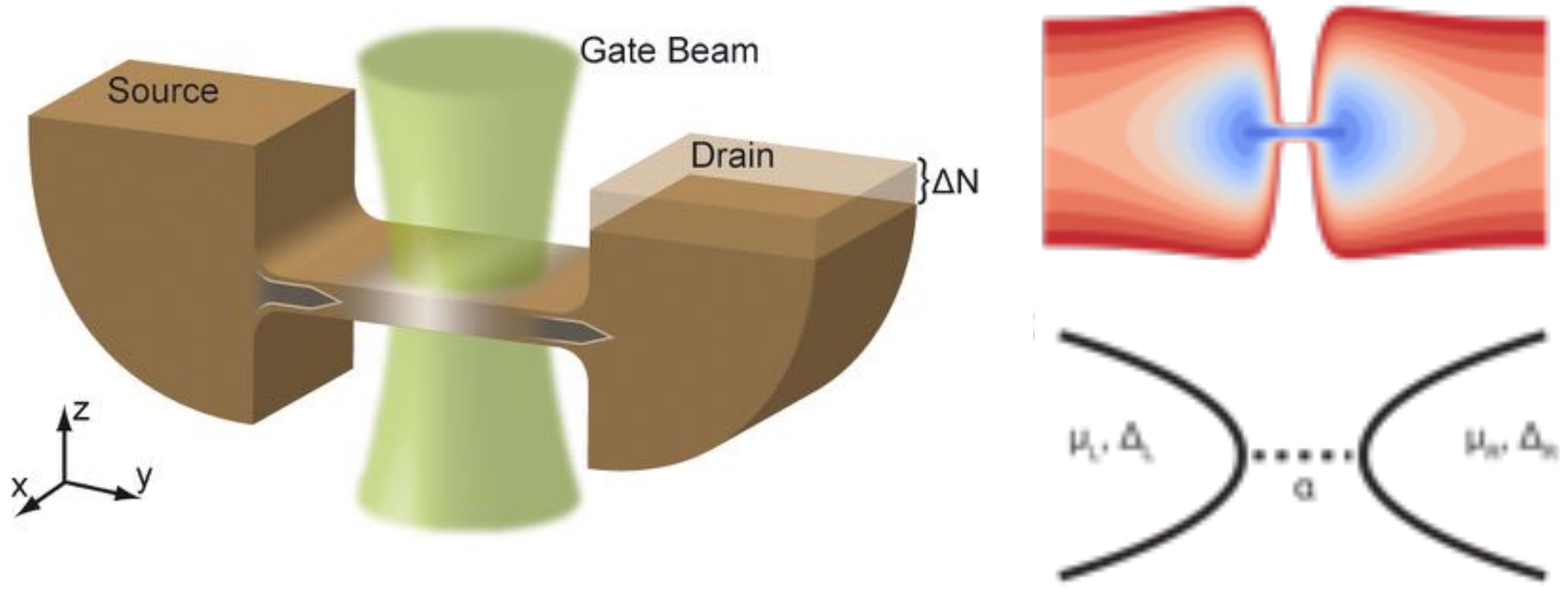
Lens
European Laboratory for Non-Linear Spectroscopy

Ultracold Atomic Fermi Gases



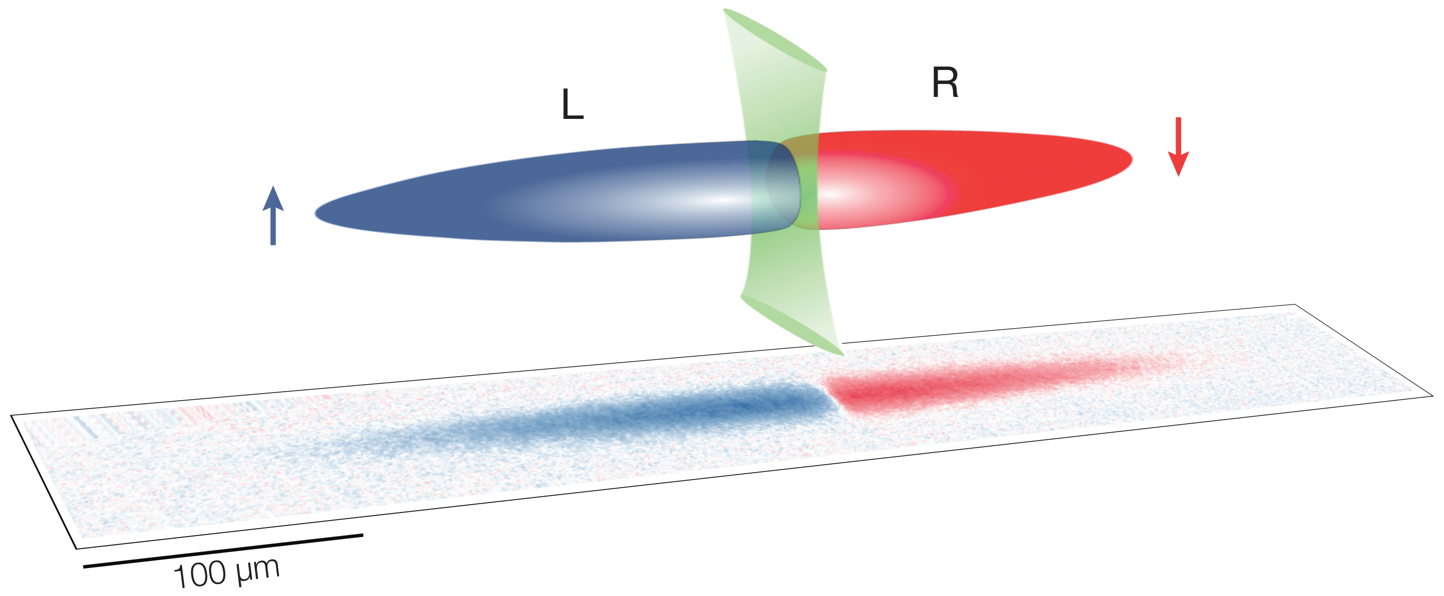
QUANTUM TRANSPORT WITH FERMI GASES

Transport through narrow ballistic channels



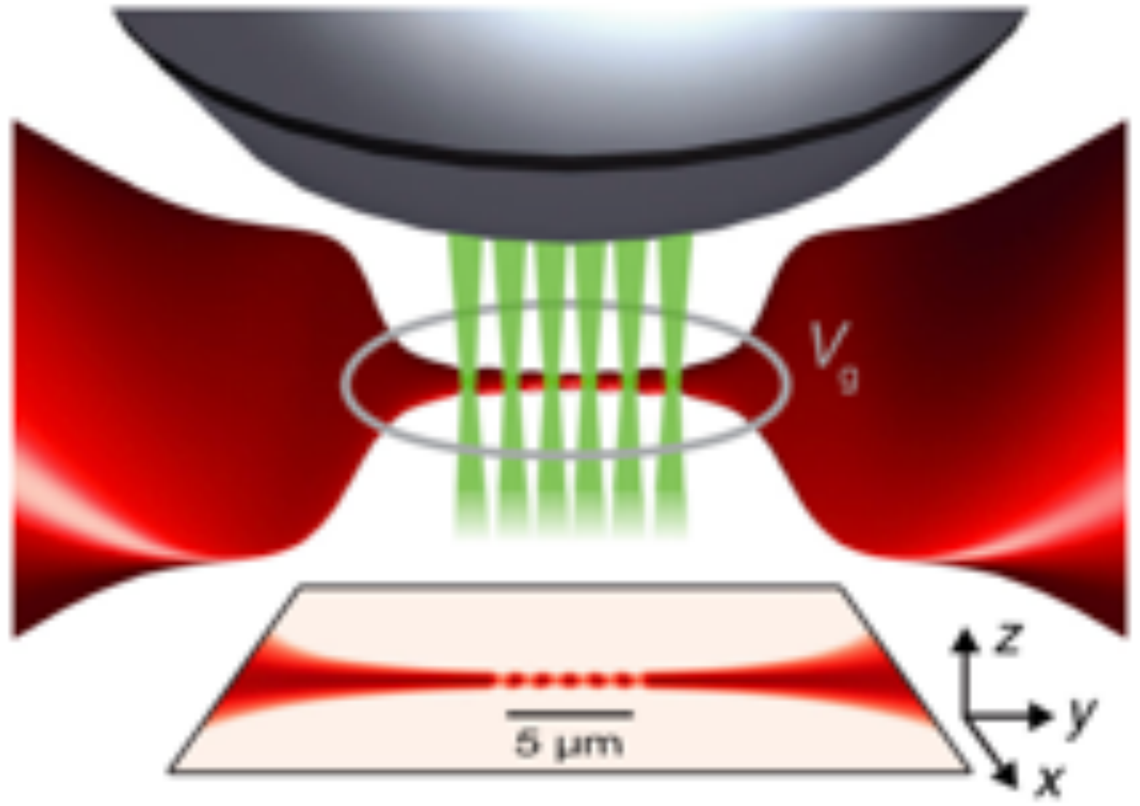
ETH, Zürich

Spin and heat transport



MIT (Boston), Univ. Toronto,
LENS (Florence), ETH (Zürich)

Tunnelling through mesoscopic structures



ETH (Zürich), LENS (Florence)

Brantut et al., *Science* **337** (2012)
Stadler et al., *Nature* **491** (2012)
Krinner et al., *Phys. Rev. Lett.* **110** (2013)
Krinner et al., *Nature* **517** (2015)
Husmann et al., *Science* **350** (2015)

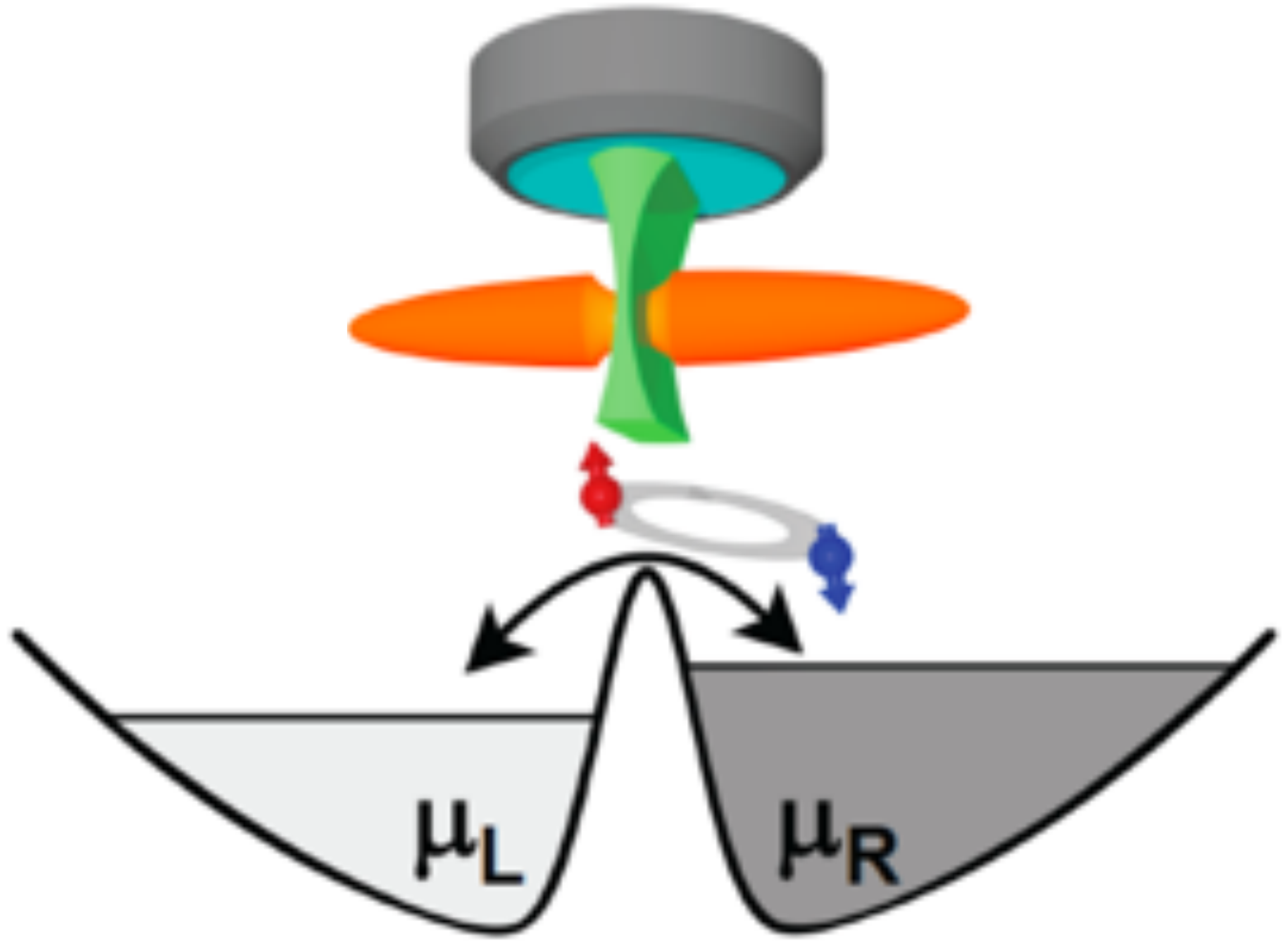
Sommer et al., *Nature* **472** (2011)
Brantut et al., *Science* **342** (2013)
Bardon et al., *Science* **344** (2014)
Krinner et al., *PNAS* **113** (2016)
Valtolina et al., *Nature Phys.* **13** (2017)
Lebrat et al., arXiv:1902.05516 (2019)

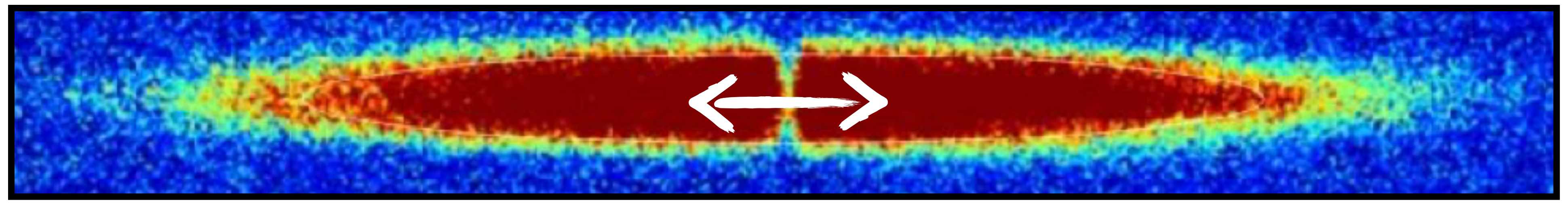
Valtolina et al., *Science* **350** (2015)
Burchianti et al., *Phys. Rev. Lett.* **120** (2018)
Lebrat et al., *Phys. Rev. X* **8** (2018)

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

Fermionic Many-Body Dynamics at LENS

Superfluid transport in tunnel junctions





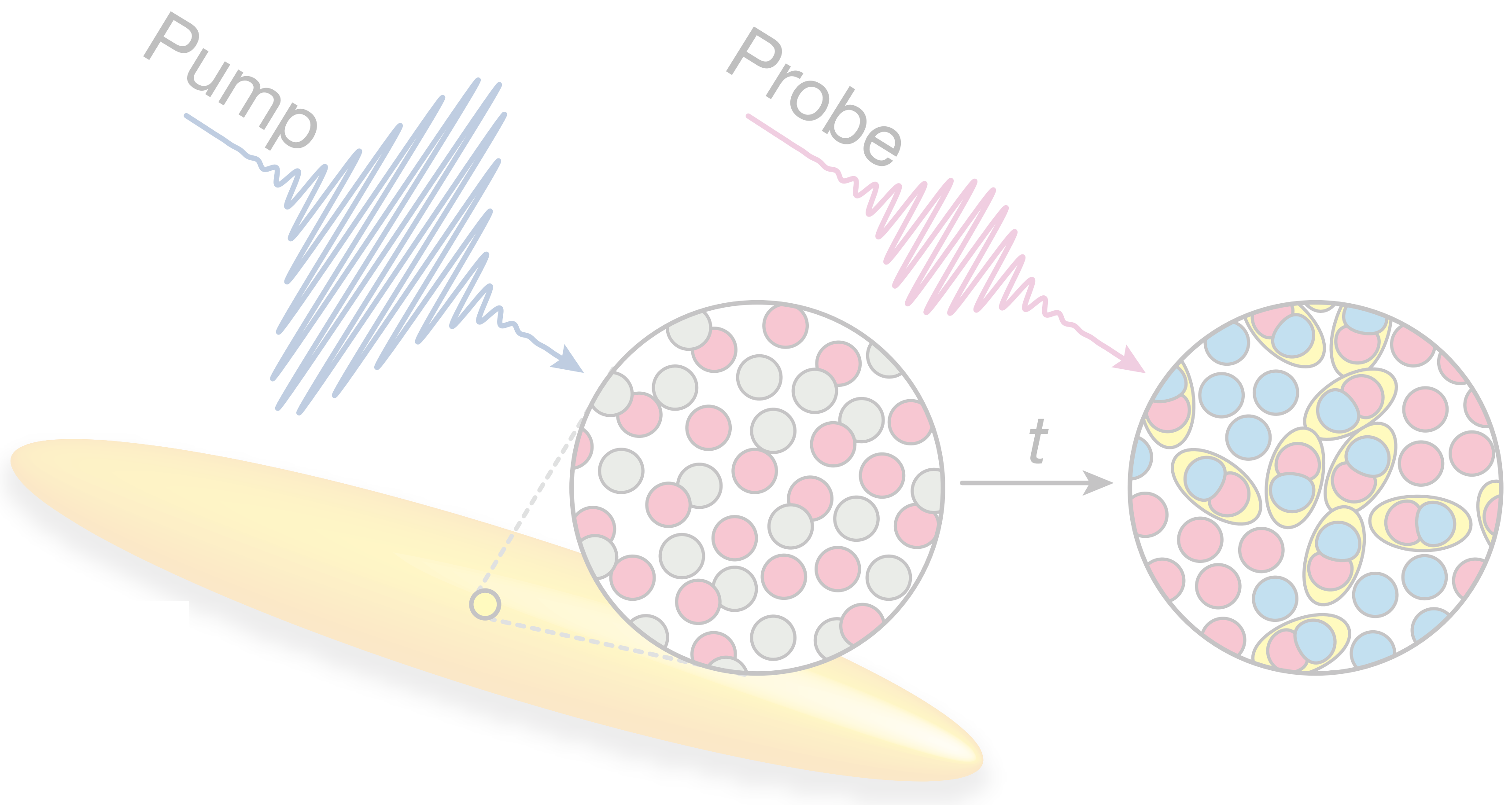
- Weak-link geometry between Fermi superfluids
  → **tuneable Josephson junction**
- Critical superflow and dissipation mechanisms

Valtolina et al., *Science* **350** (2015)
Burchianti et al., *Phys. Rev. Lett.* **120** (2018)
Kwon et al., in preparation (2019)

Spin dynamics in repulsive Fermi gases

- Spin diffusion at an artificial domain wall

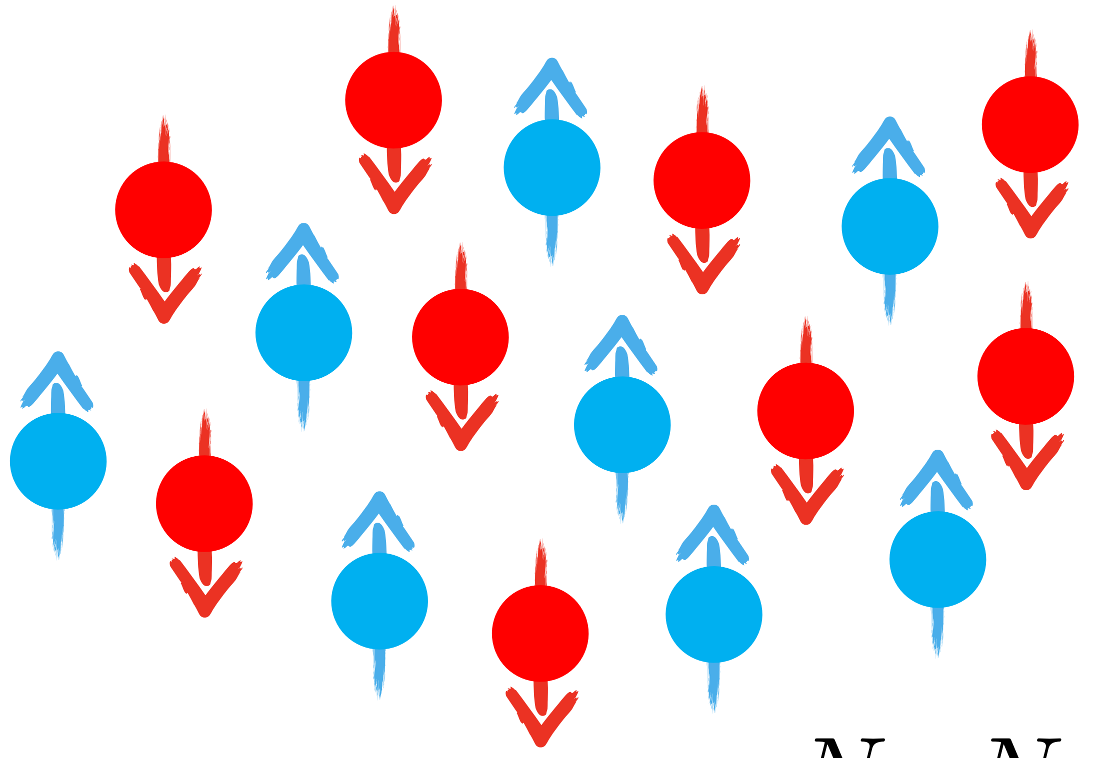
Valtolina et al., *Nature Phys.* **13** (2017)



- Pump-probe spectroscopy of repulsive Fermi gas

Scazza et al., *Phys. Rev. Lett.* **118** (2017)
Amico et al., *Phys. Rev. Lett.* **121** (2018)

Ultracold Fermi Gases



$N_\uparrow, N_\downarrow$

Concentration: $x = \frac{N_\downarrow}{N_\uparrow + N_\downarrow}$ 1/2

Density: $n = \frac{N_\uparrow + N_\downarrow}{V}$

Fermi wavevector: $k_F = (6\pi^2 n)^{1/3}$

Fermi energy: $\varepsilon_F = \frac{\hbar^2 k_F^2}{2m}$

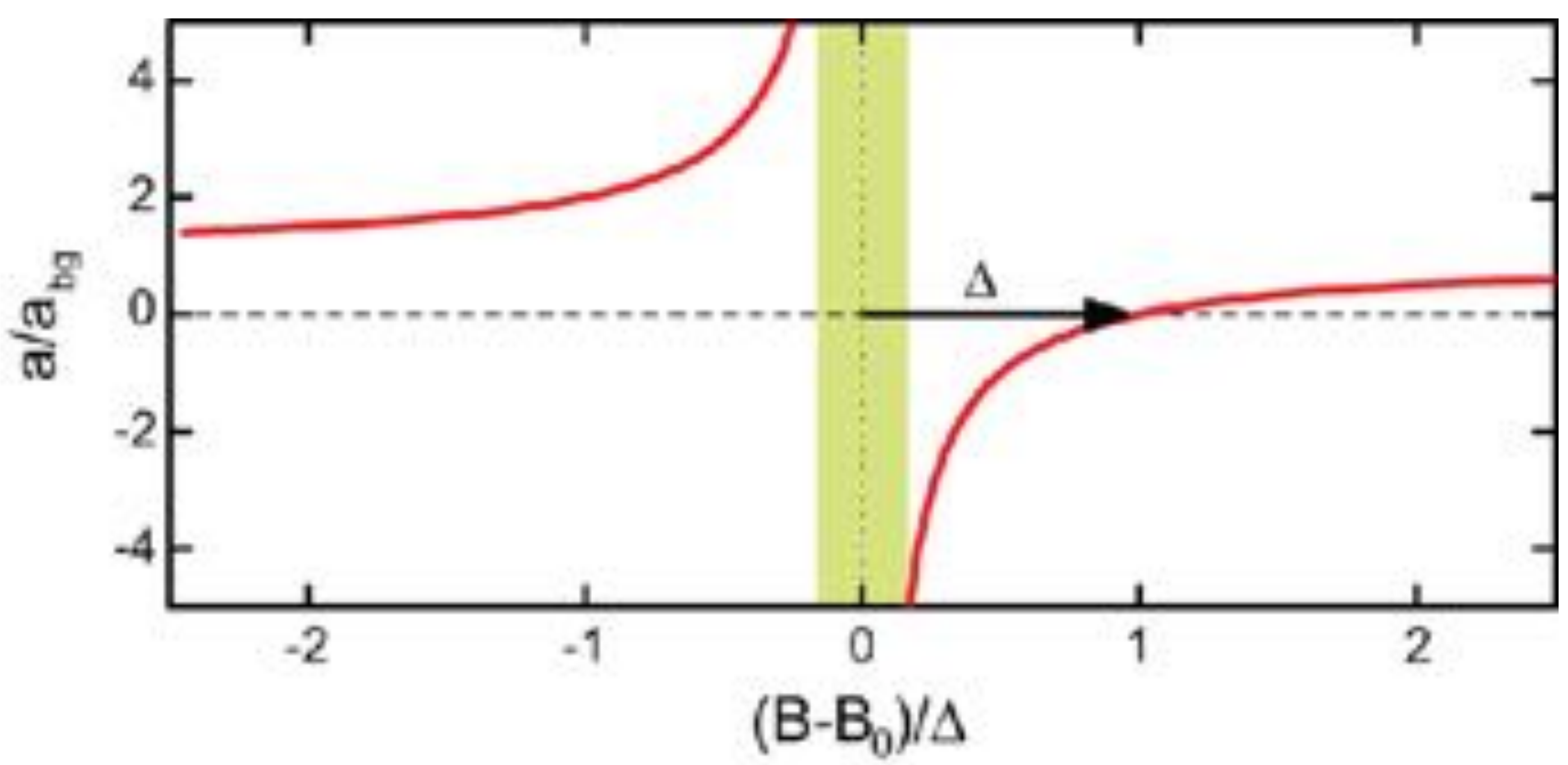
- Two-component Fermi gas with **short-range (contact-like) interactions**

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

s-wave scattering length ⟵ **Fano-Feshbach resonance**

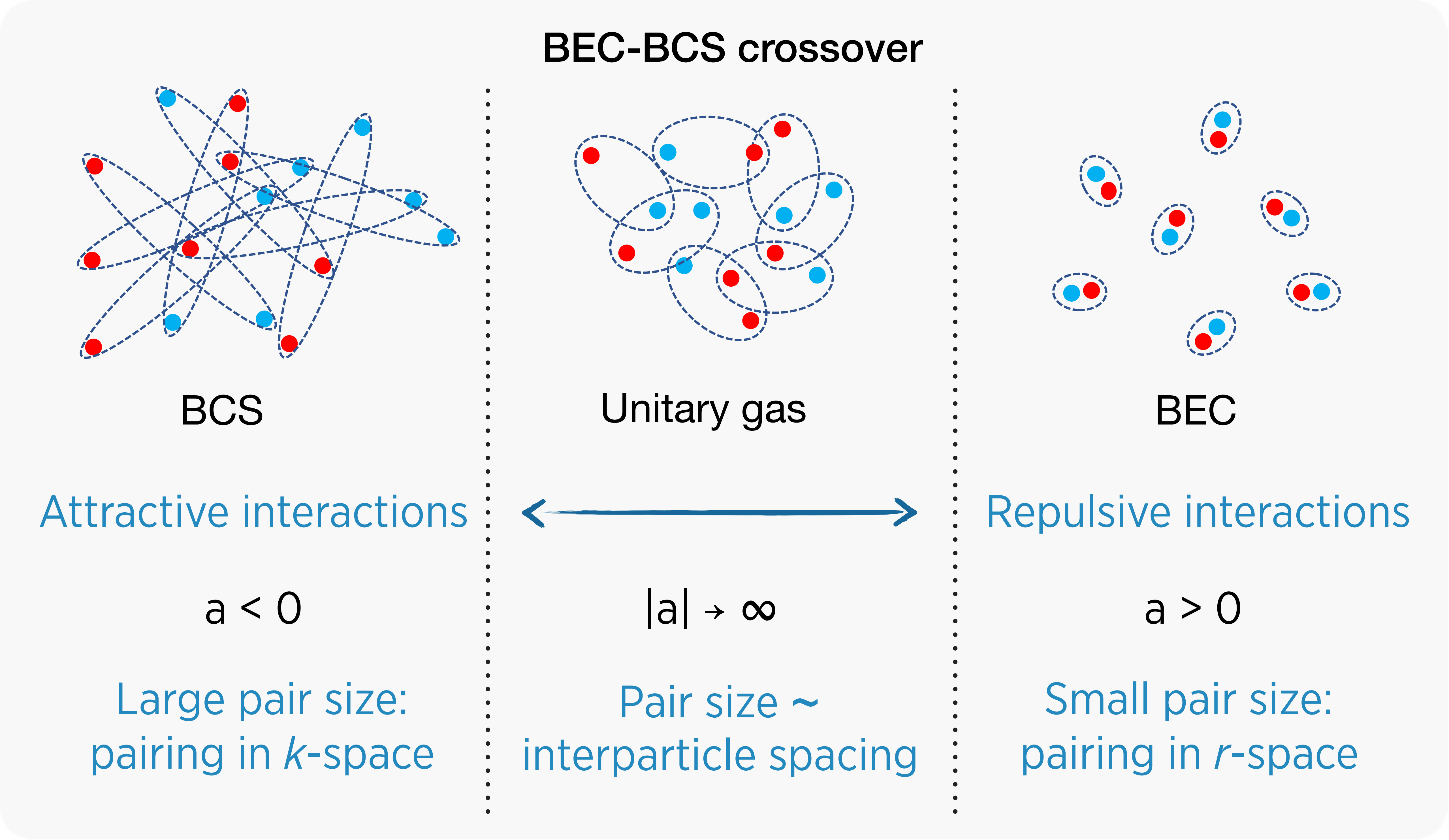
a

Scattering length tuning



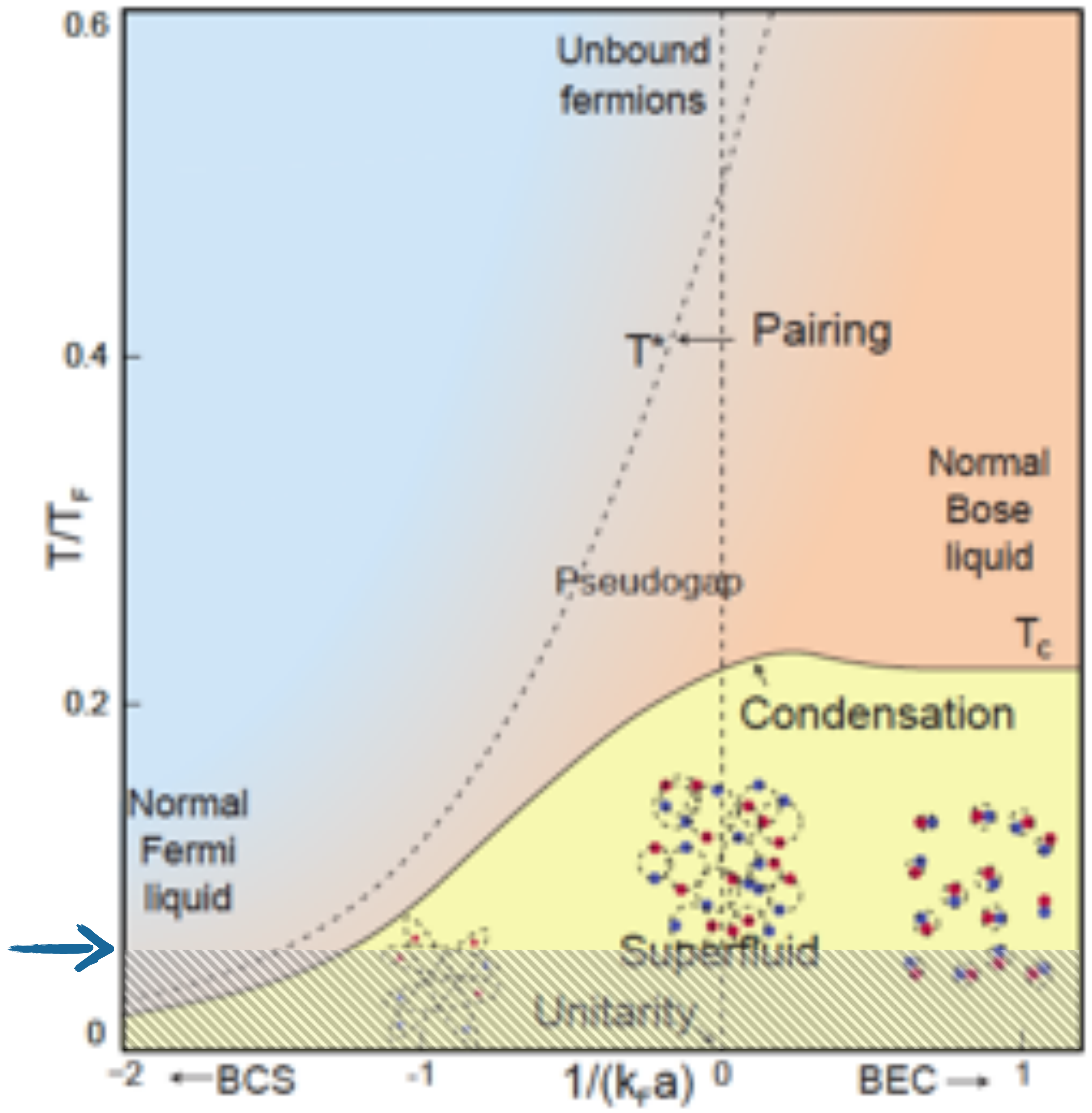
The BEC-BCS crossover

- Two-component Fermi gas with strong interactions between distinguishable spins: **crossover from BEC to BCS superfluidity**



Temperature-interaction phase diagram

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



$T/T_F \sim 0.05$ →

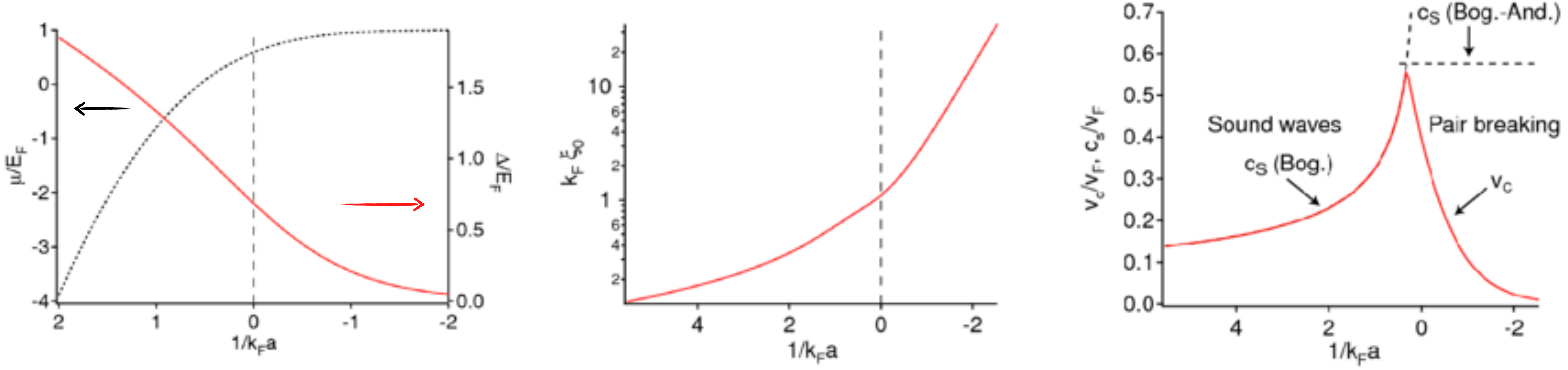
$k_F a$ (adimensional) quantifies interactions

- Explore different paradigms of superfluidity within a single system!

The BCS-BEC crossover and the unitary Fermi gas.
Lecture notes in physics, 836, Edited by W. Zwerger (Springer, Berlin, 2012).

BEC-BCS Crossover Superfluids

Chemical potential and superfluid gap | **Pair correlation length** | **Landau critical velocity (bulk)**



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)

- Crossover **from two-body to many-body pairing**, from tightly bound pairs to Cooper pairs, from **bosonic to fermionic excitations**: binding energy of pairs approaches ε_F near unitarity
- Bosonic theories are appropriate for $\epsilon_B \simeq \dfrac{\hbar^2}{ma^2} \ll \varepsilon_F$

THE PLAN

- Introduction: **ultracold Fermi gases** across the BEC-BCS crossover
- **Josephson junction basics**
- Our experimental setup: a **thin tunable Josephson junction** between Fermi superfluids
- Dynamics in **population-biased** junctions:
  Josephson-plasma oscillations and dissipative flow through vortex nucleation
- **Current-driven** junctions:
  probing the critical current via the **DC Josephson** effect
- Outlook: local phase manipulation and quantum transport of **two-dimensional gases**

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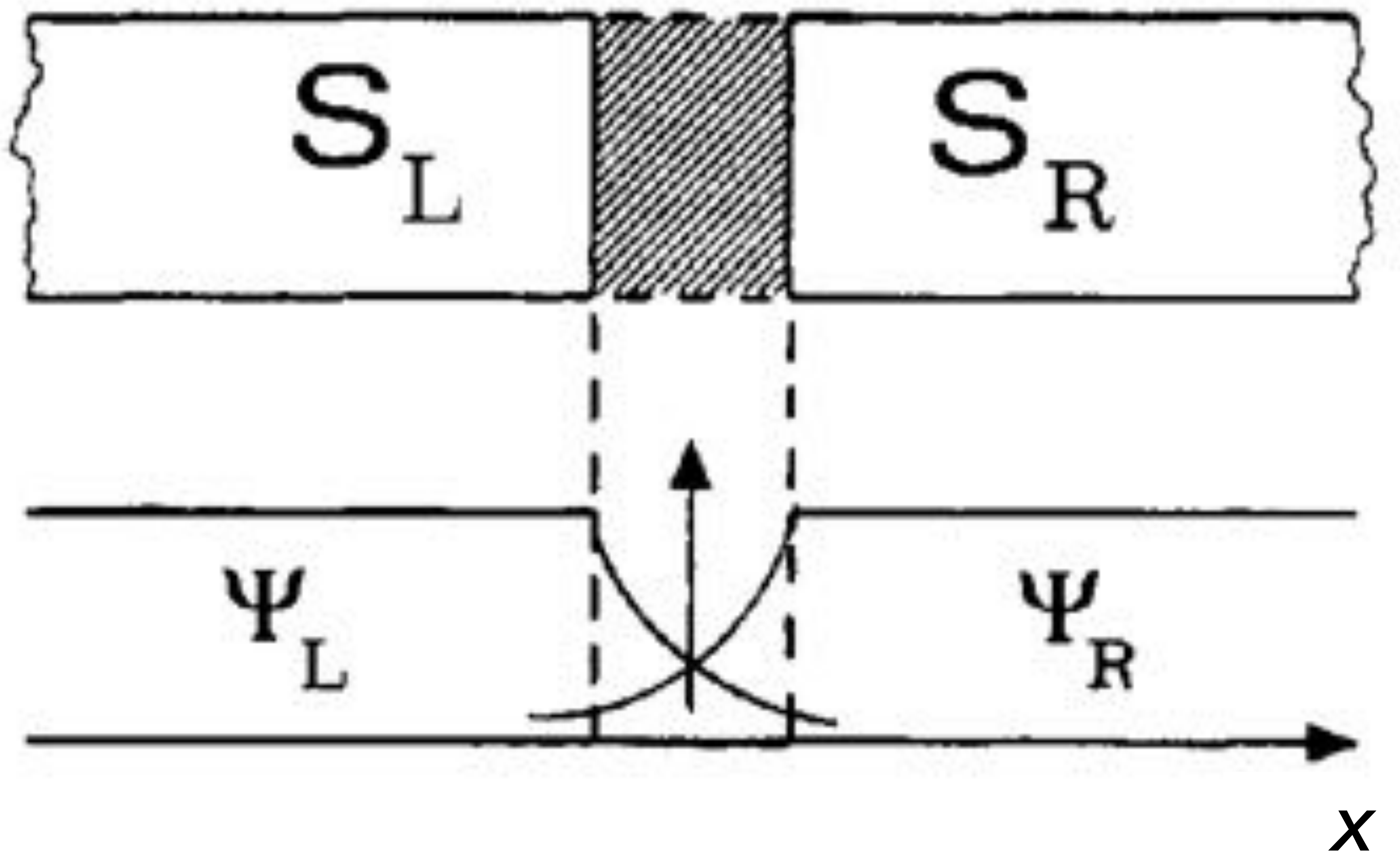
Josephson Junction basics



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

In BEC regime: $|\Delta| \sim \sqrt{n_c}$

- **Relative phase:** $\phi = \phi_L - \phi_R$
- **Supercurrent induced by phase jump:** $v_s = \frac{\hbar}{m} \nabla \phi$

- **Josephson effect:** quantum coherent tunnelling superfluid of order parameter
  → Demonstrating the **macroscopic phase coherence** of condensed state i.e. superfluids
  → Pin down the **order parameter**

For sufficiently small ***T***

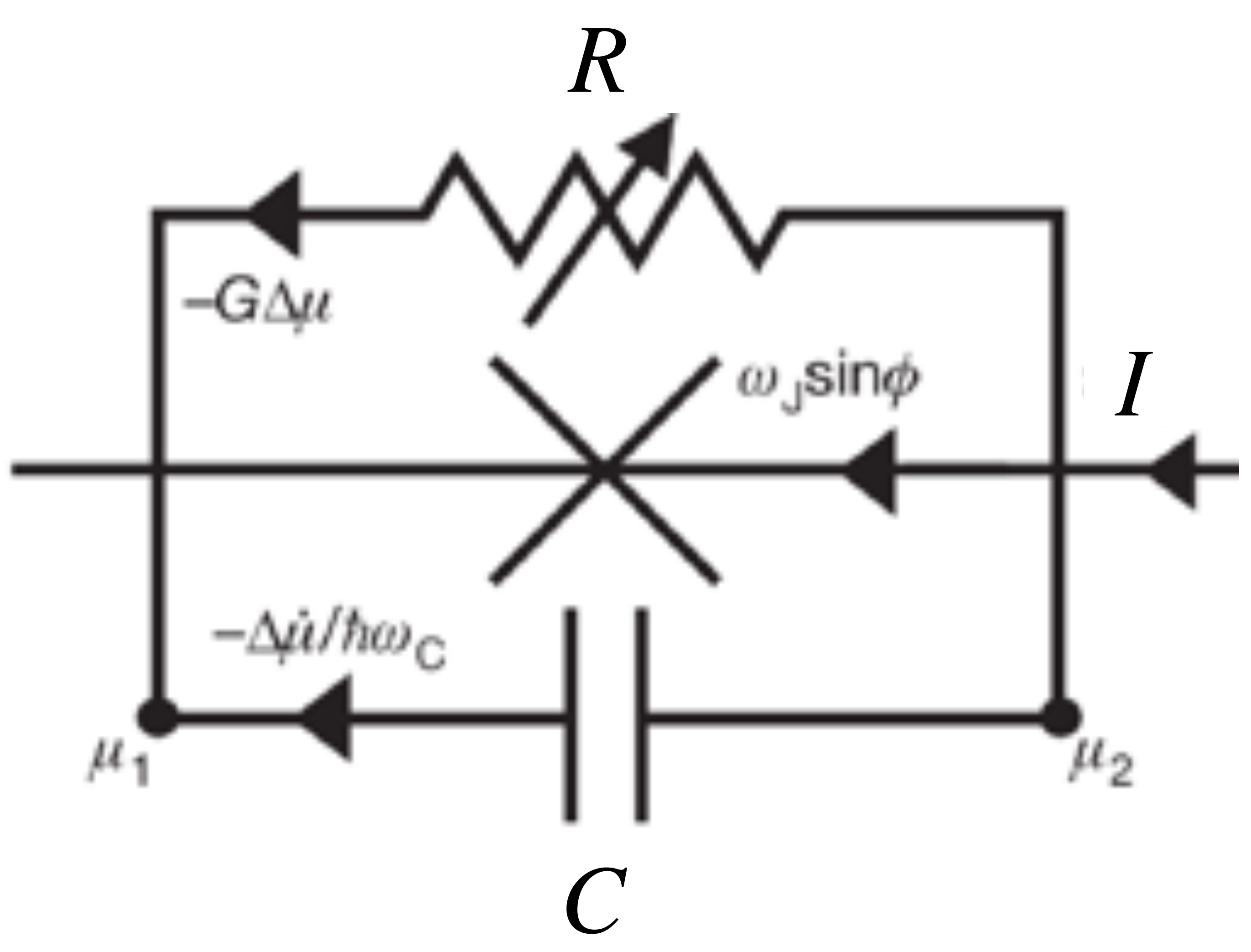
Critical current

- **Josephson current:** $I(t) = I_c \sin \phi(t)$
- **Ambegaokar-Baratoff relation:** $I_c \propto \Delta \sim n_c$
- **Josephson-Anderson relation:** $\hbar \dot{\phi}(t) = -\Delta\mu = \mu_R - \mu_L$

Bias potential

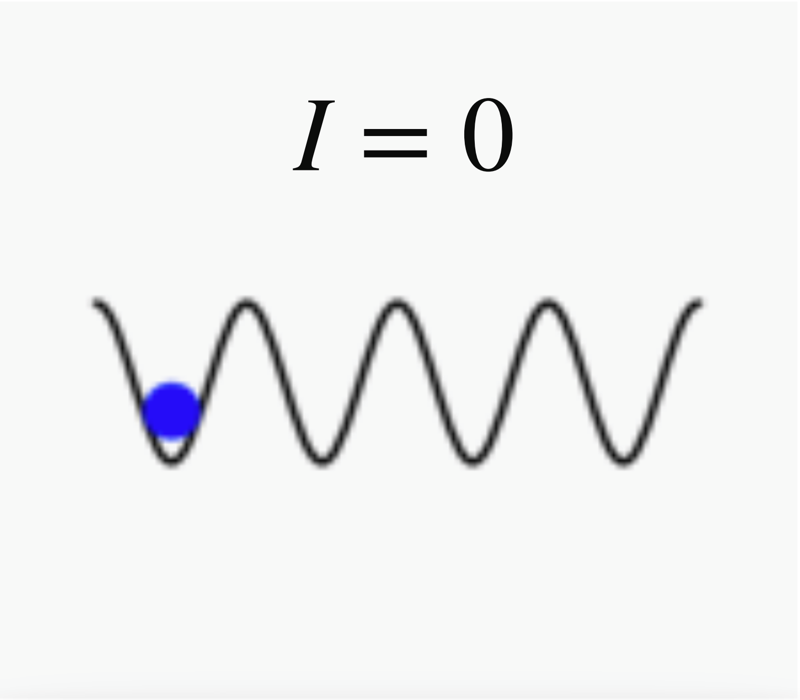
[e.g. population imbalance]

Josephson Junction basics

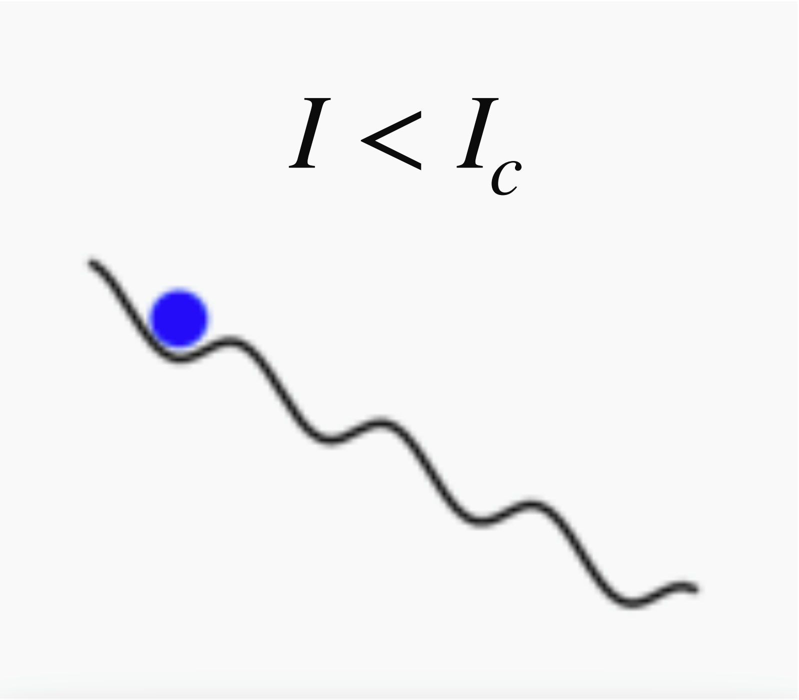


Flow a current: current-biased junction

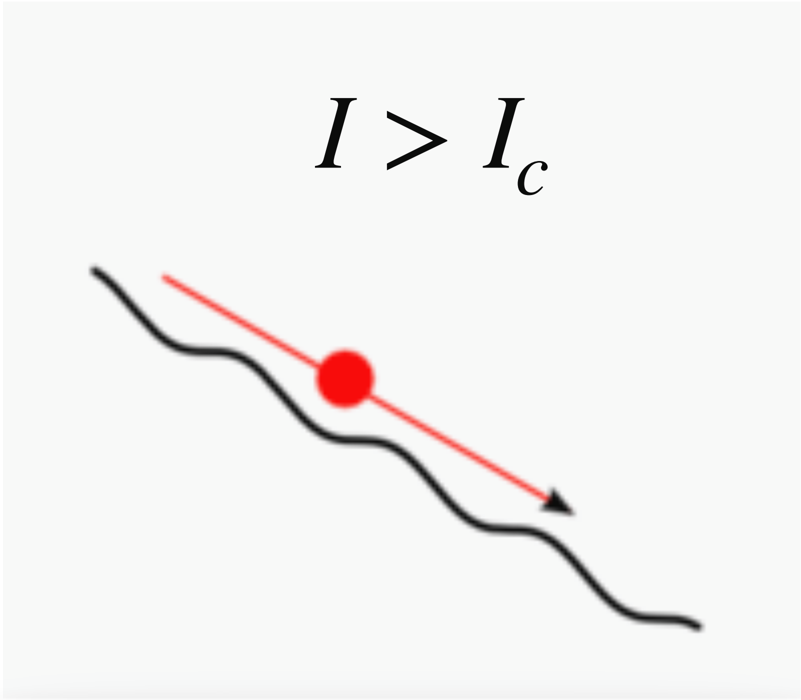
- Mass ~ C
- Friction coefficient ~ $G = 1/R$
- Potential energy ~ $-1/C\,(I\phi + I_c \cos\phi)$



No applied current

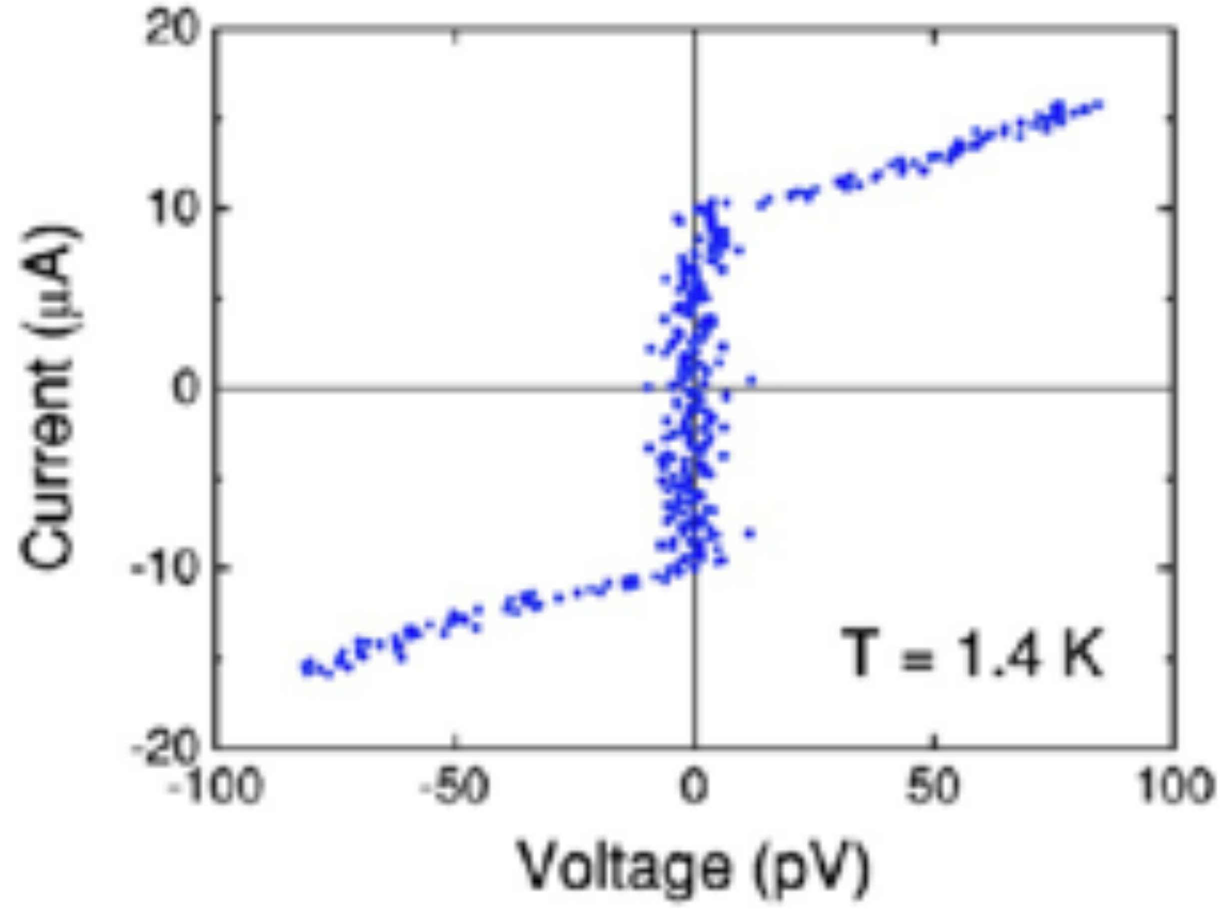


DC Josephson Effect



Running-phase regime

I-V curve



Current flow with no potential drop

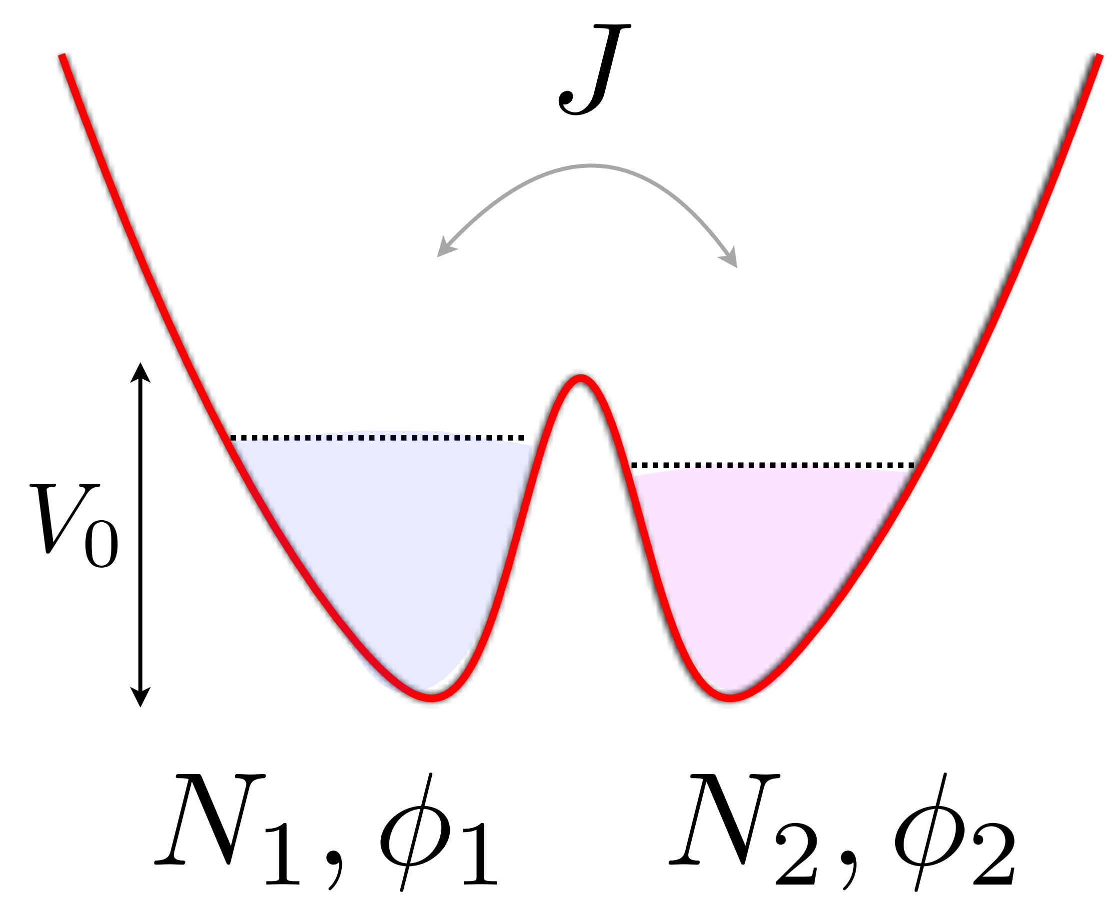
Frolov et al., *Phys. Rev. B* **70**, 144505 (2004)

JOSEPHSON-PLASMA OSCILLATIONS

- **Charge the junction: population-biased junction dynamics**
- (Forget about resistance for now) **Two relevant energies:**

Josephson energy: $E_J \sim J(\mu, V_0, w)N_0,\ E_J > k_B T$

Charging energy: $E_C \sim \dfrac{\partial \mu}{\partial n} = \dfrac{1}{\kappa}$ (junction capacity)



Josephson relation ($V_0 \gtrsim \mu$)
→ Pendulum-like dynamics:

$$\hbar \dot{z} \propto -E_J \sin(\phi)$$
$$\hbar \dot{\phi} \propto E_C z$$

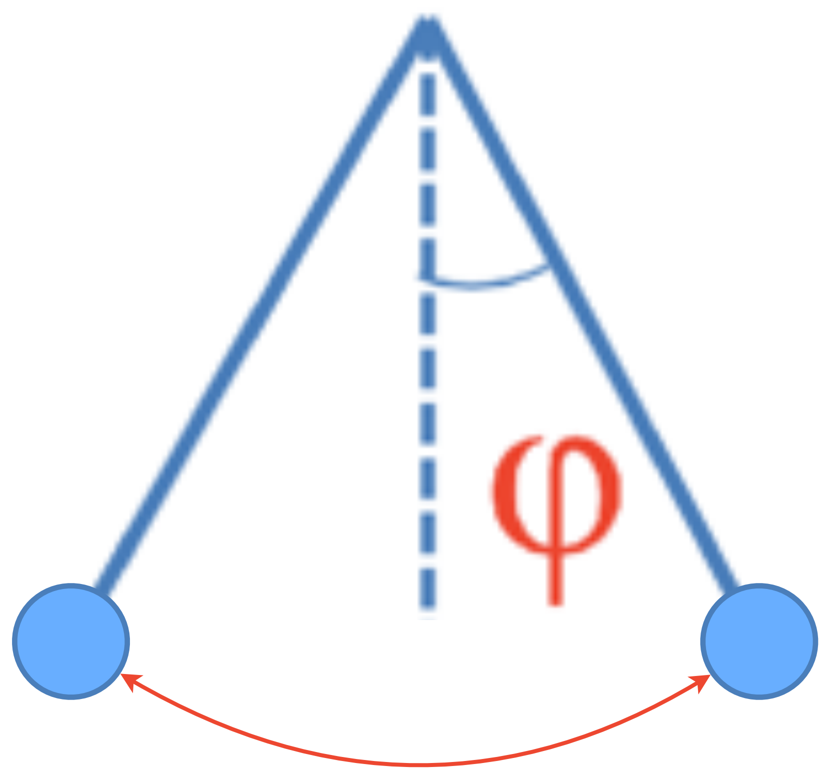
$z = \Delta N / N$

Relative imbalance

Josephson-Plasma oscillations: $\hbar \omega_J = \sqrt{E_J E_C}$

Josephson-Plasma frequency

Pendulum-like evolution



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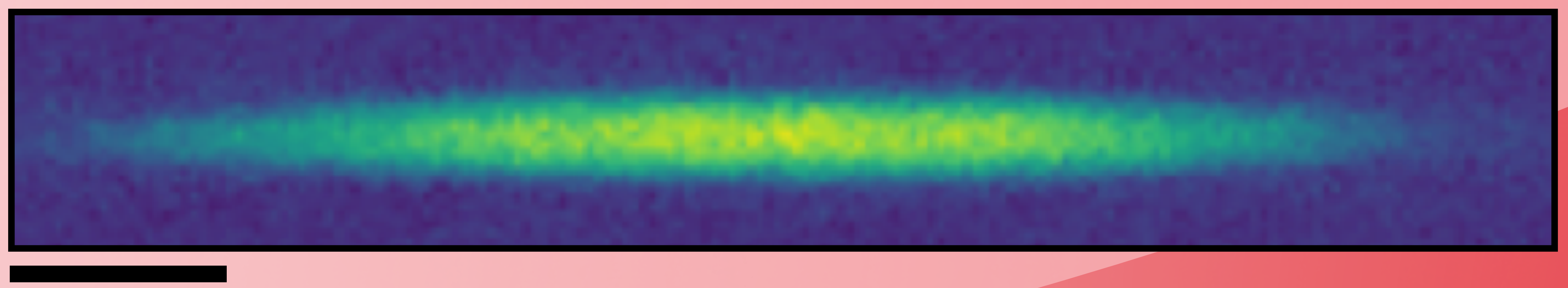
Fermi Gases of Lithium-6

Ultracold lithium-6 cloud

$N \sim 10^5$ at $T \sim 30\,nK < 0.1\,T_F$

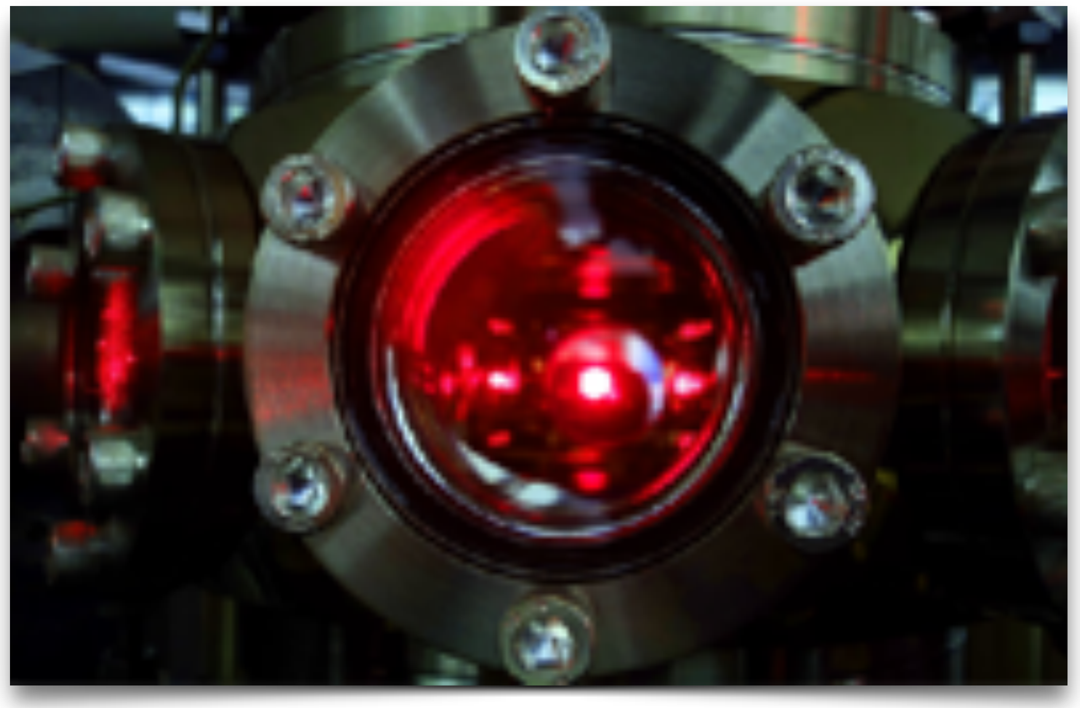
Optical dipole trap 1064 nm



Optical dipole trap 1070 nm

$N \sim 10^8$ at $T \sim 50\,\mu K$

Magneto-Optical Trap + D_1 molasses



All-optical preparation of ultracold lithium gases

Burchianti *et al.*, *Phys. Rev. A* **90** (2014)

Fermi Gases of Lithium-6

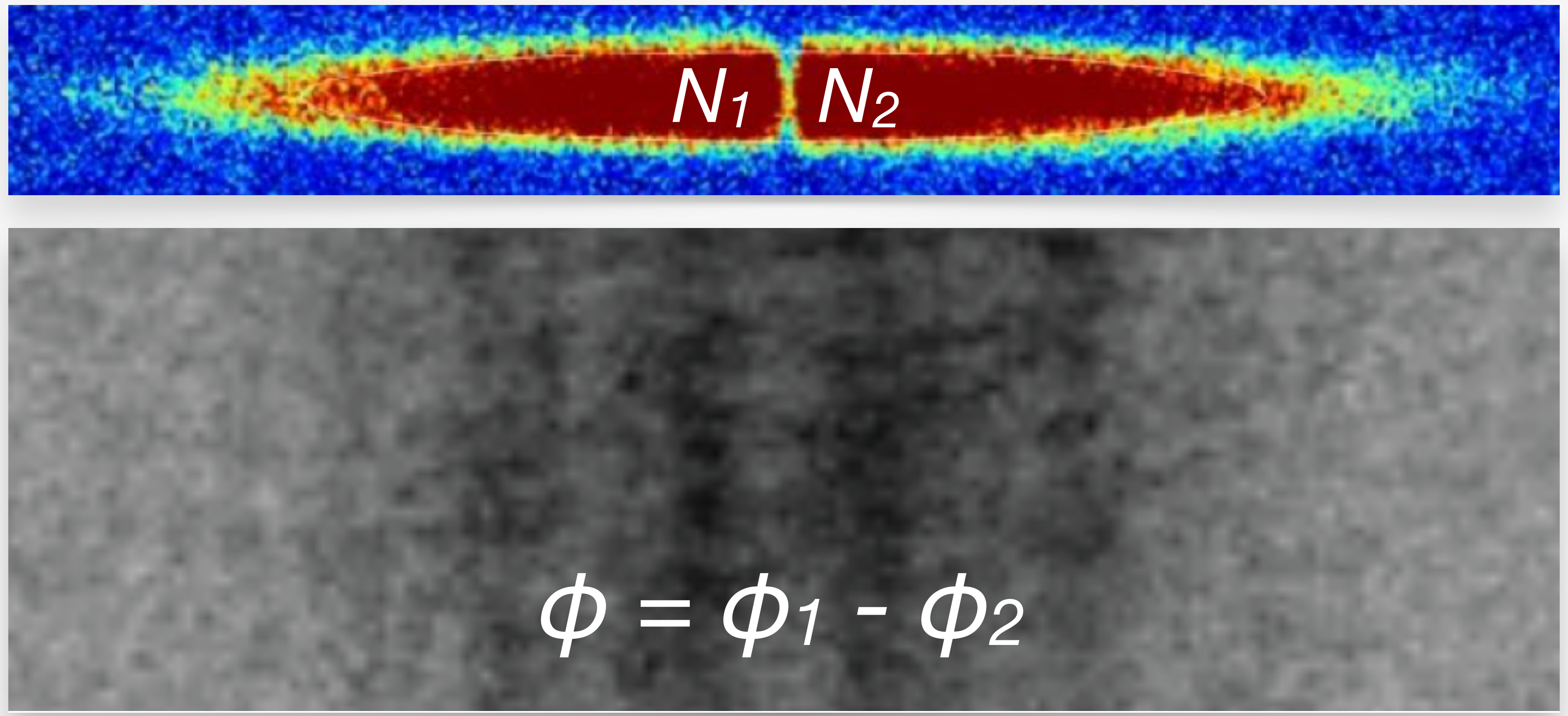
All-optical preparation of ultracold lithium gases

Burchianti *et al.*, *Phys. Rev. A* **90** (2014)

OUR JOSEPHSON JUNCTION

- **Ultracold lithium Fermi gas bisected by thin insulating barrier $w_b \gtrsim 3\xi$**

Order parameters: $\psi_i = \sqrt{N_i} e^{-i\phi_i}$

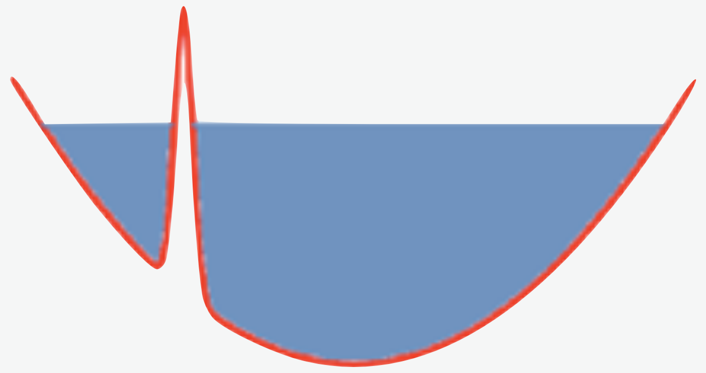


- Relative phase: $\phi = \phi_1 - \phi_2$
- Imbalance: $\Delta N = N_1 - N_2$
- Current: $I = (\dot{N}_1 - \dot{N}_2)/2$

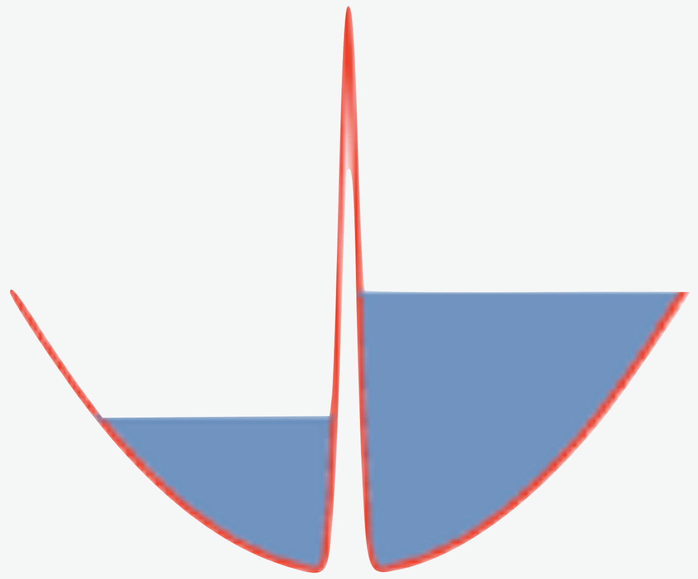
In situ imaging ➞ Current through junction
Time-of-flight imaging ➞ Phase diff. across junction

Preparation of tuneable Δμ

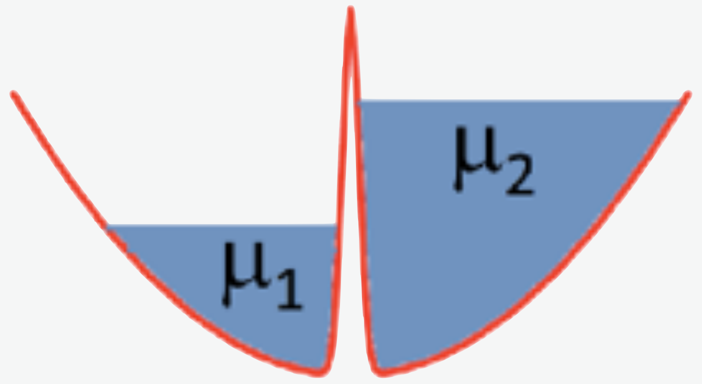
Step 1
Prepare imbalanced reservoirs at rest



Step 2
Slowly raise barrier and move trap to create imbalance



Step 3
Rapidly lower barrier to target value of V_0



Our Josephson Junction

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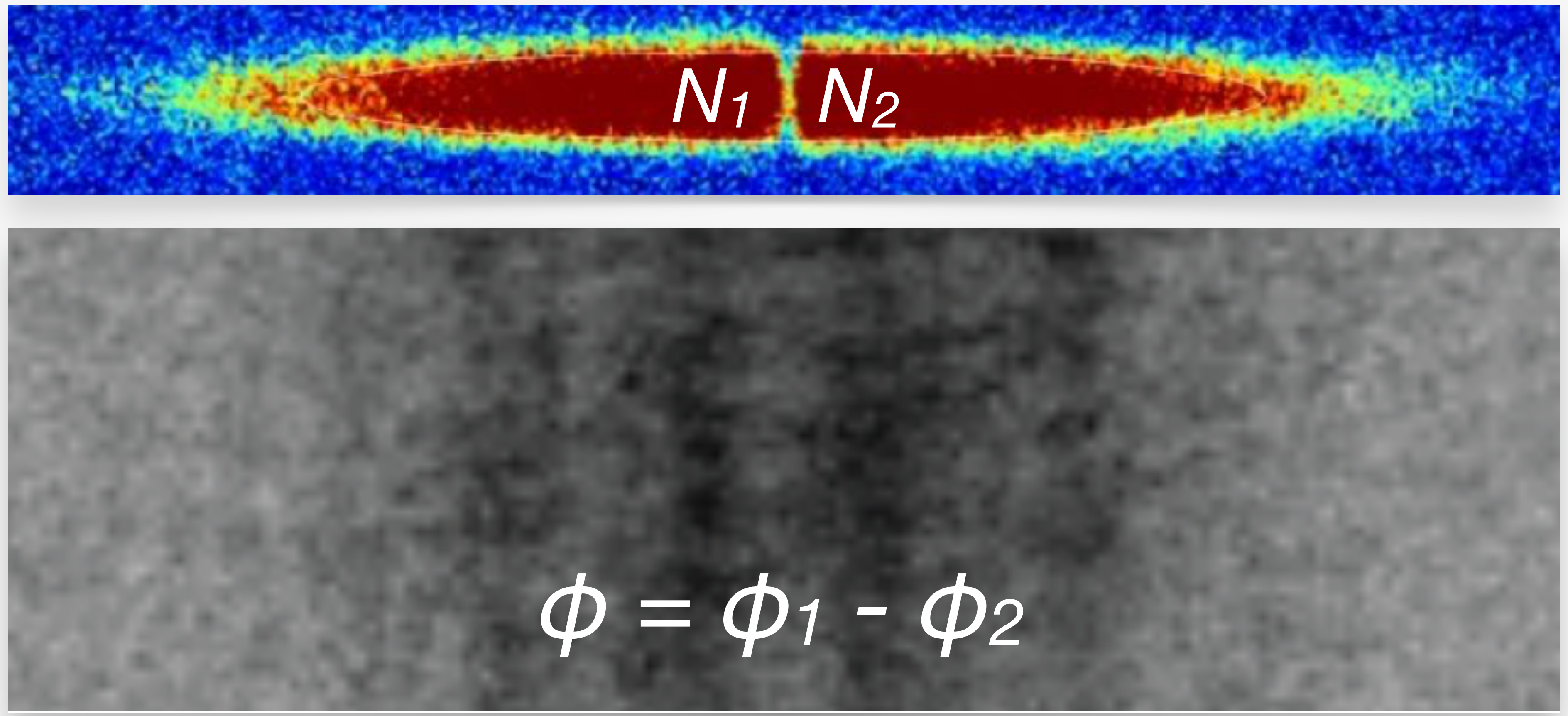
Order parameters: $\psi_i = \sqrt{N_i} e^{-i\phi_i}$



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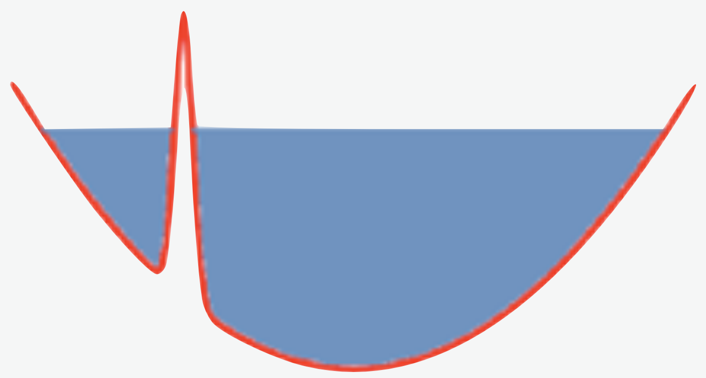

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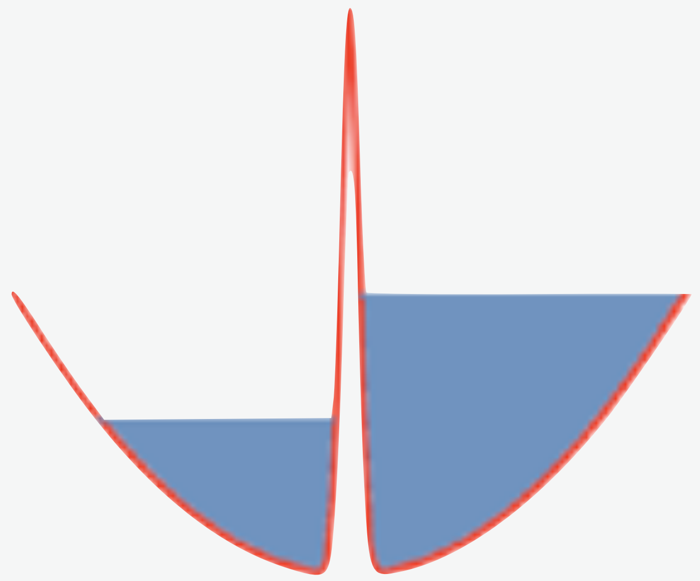
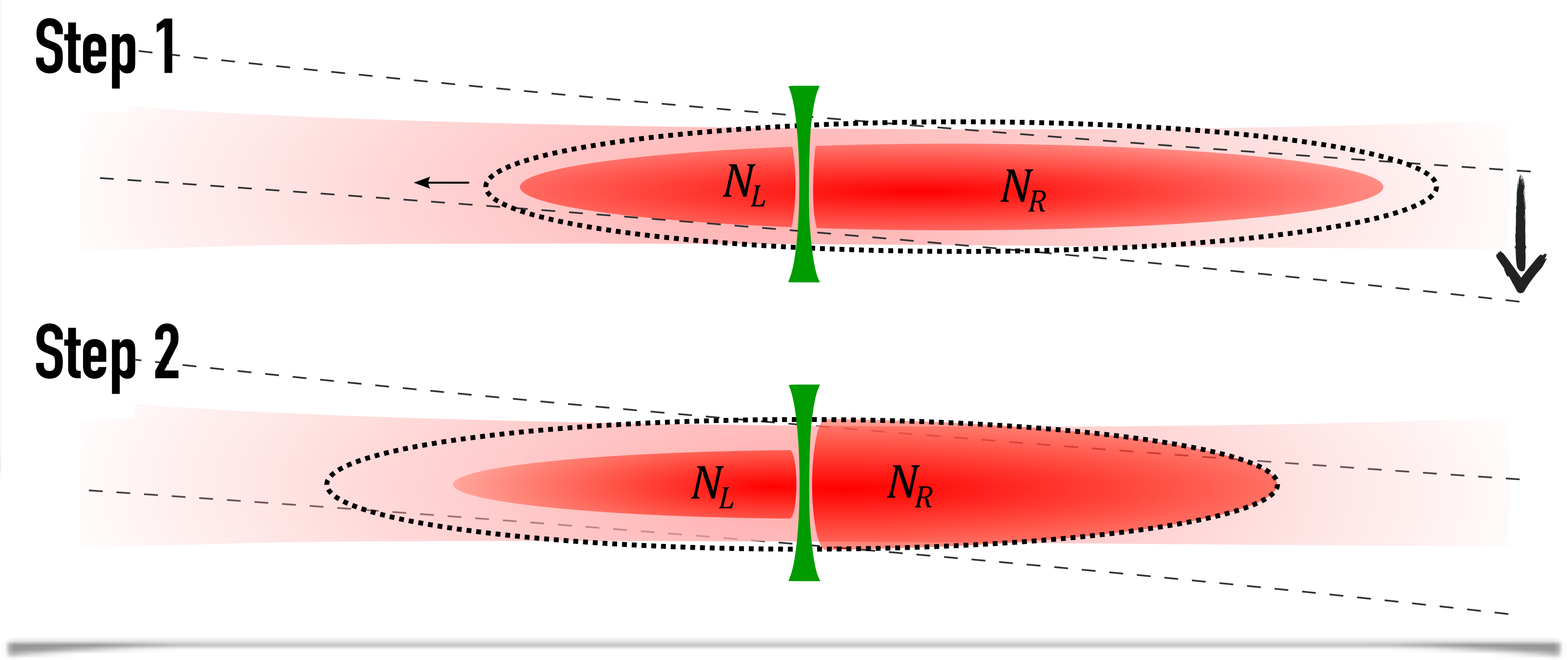
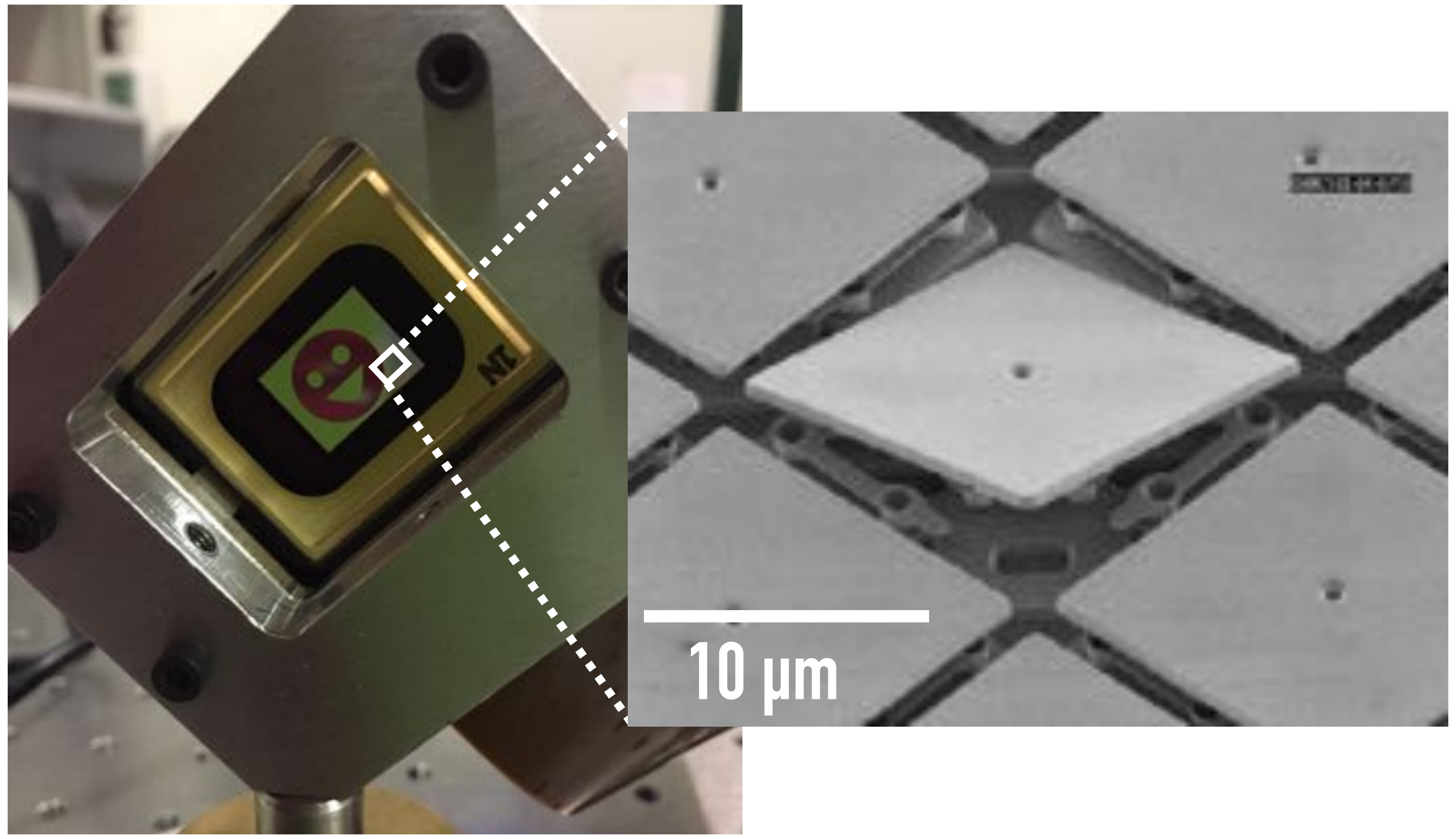
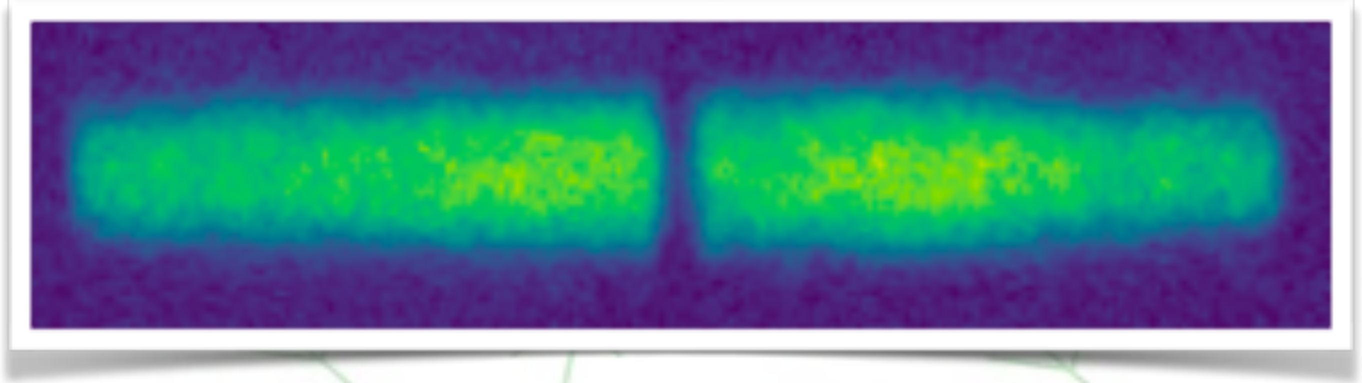




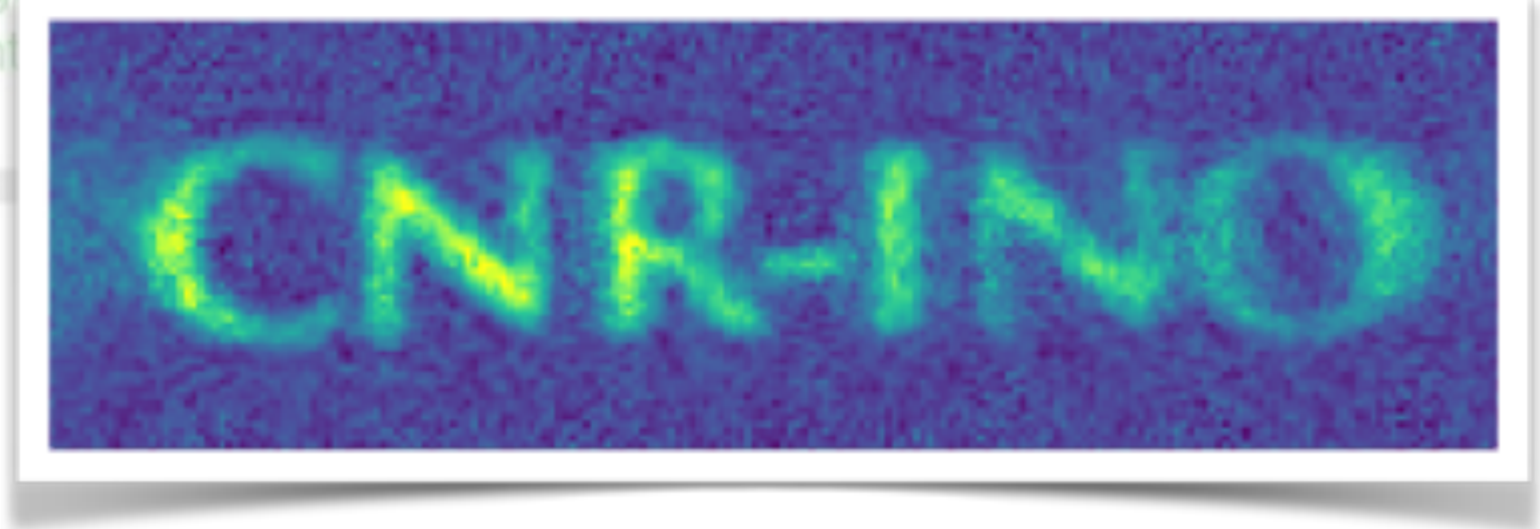
Recent Upgrades: Objective and DMD

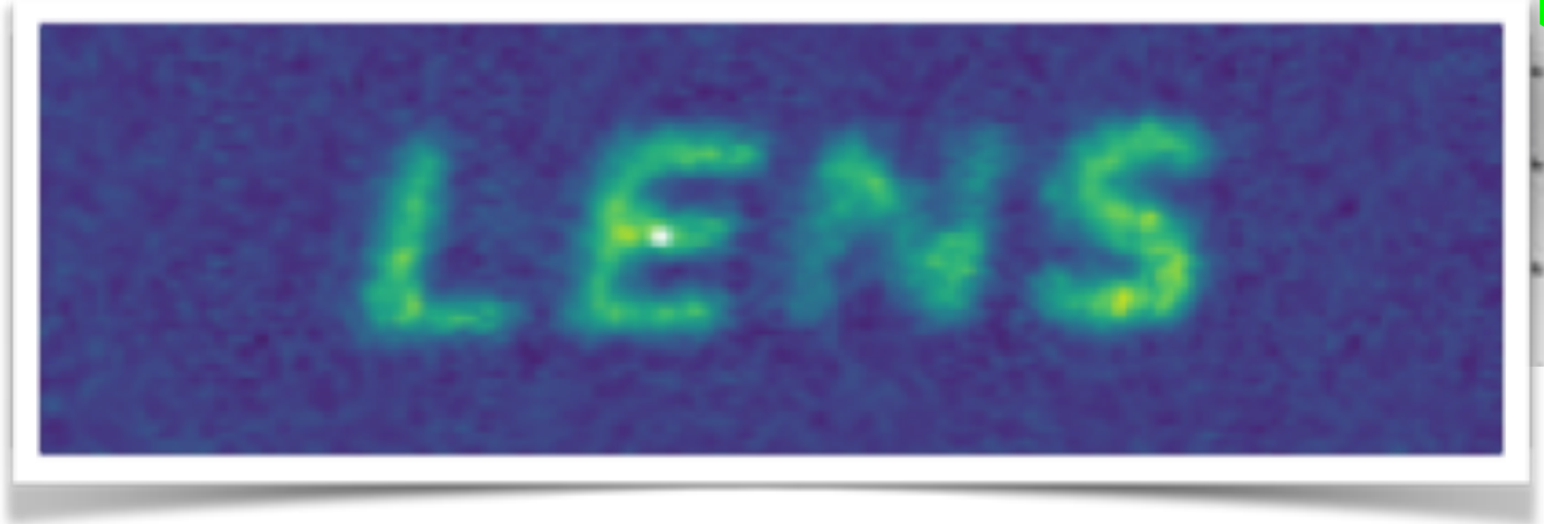
Digital Micromirror Device (DMD)

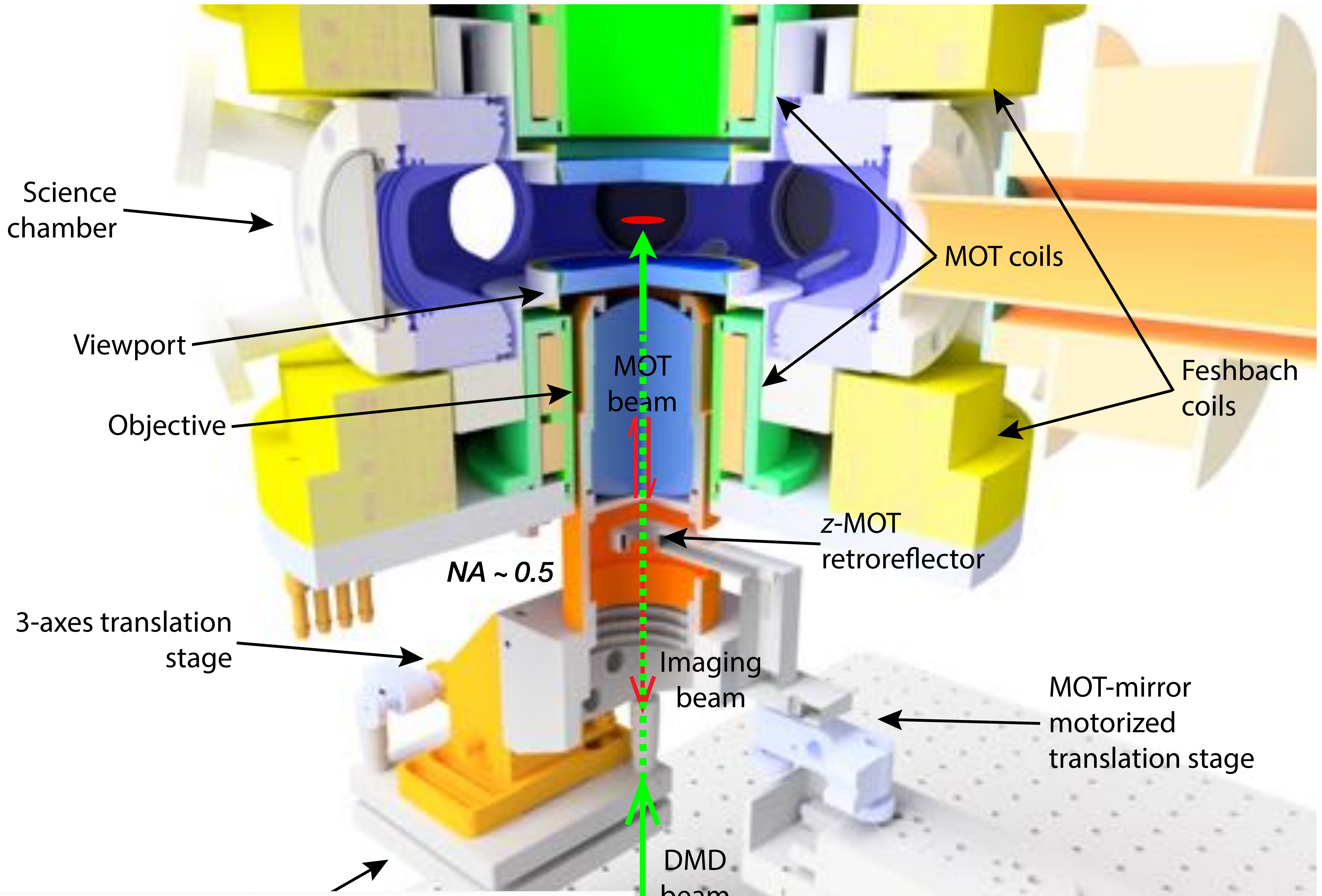




20 µm







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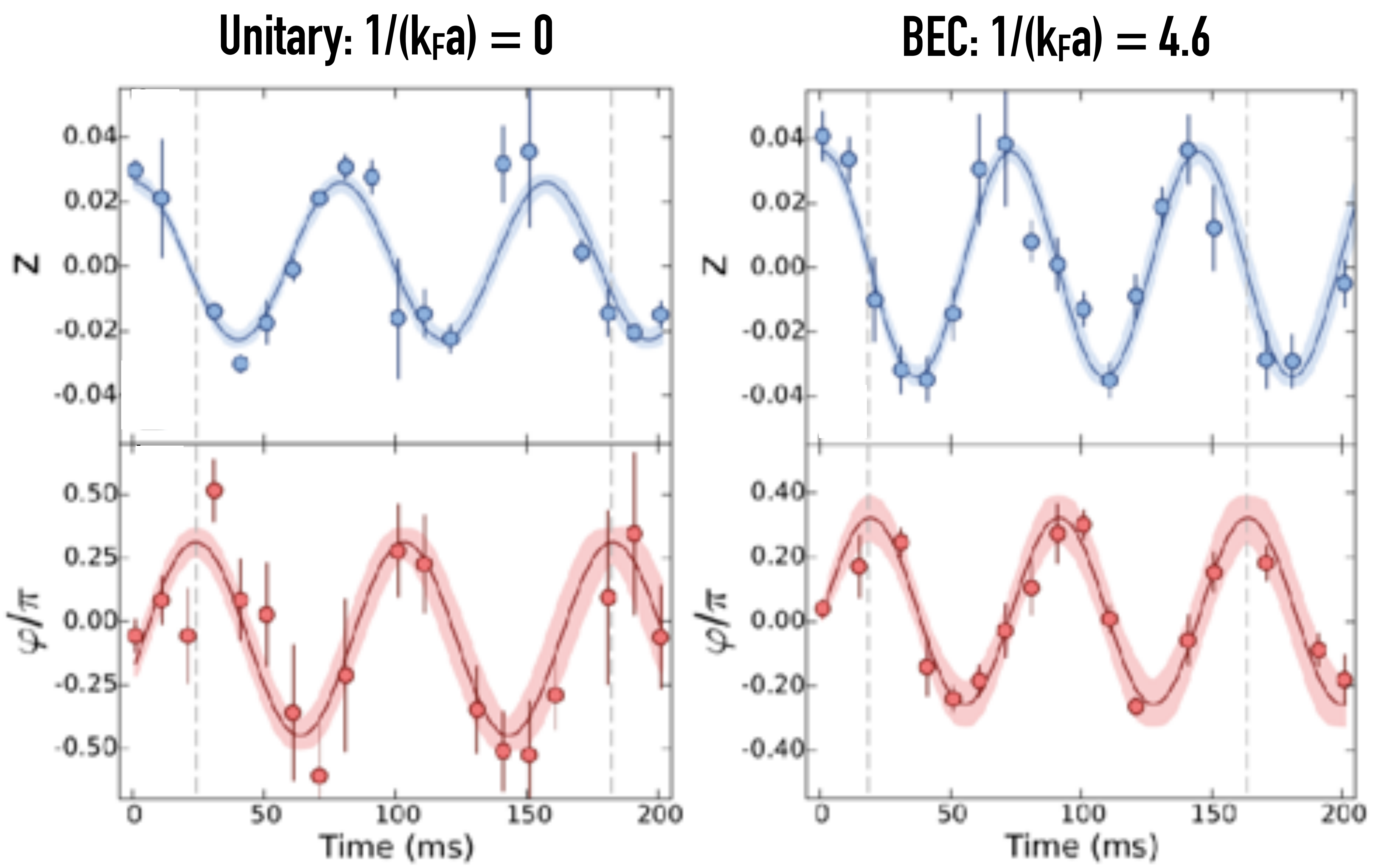
Josephson-Plasma Regime

- For small excitations (small population bias): **Josephson-Plasma oscillations**

$$\hbar\dot{\phi} \propto E_C z$$
$$\hbar\dot{z} \propto -E_J \phi$$

Plasma frequency: $\omega_J = \sqrt{E_J E_C}/\hbar$



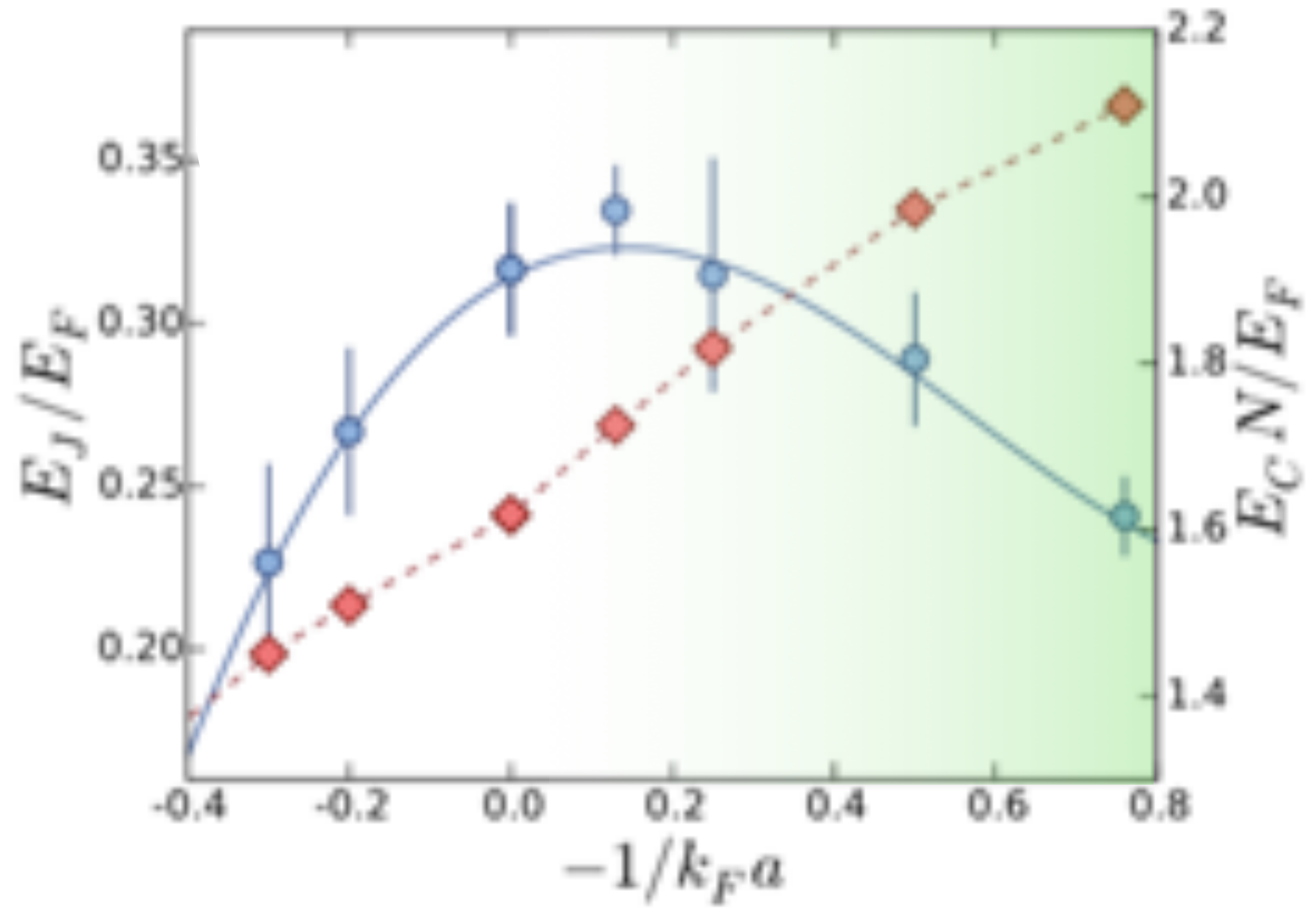
Universality of Josephson-Anderson relation over BEC-BCS crossover

Imbalance and **phase oscillate in quadrature**
→ conjugate observables

Valtolina et al., *Science* **350** (2015)

JOSEPHSON-PLASMA REGIME

- **Constant barrier height** $V_0 > E_F$, **varying the interaction strength** $1/(k_F a)$
- Use measured Josephson-Plasma frequency to **extract Josephson energy:** $\omega_J = \sqrt{E_J E_C}/\hbar$



$I_c \propto E_J = J N_0$

Number of condensed pairs

- Towards BEC side, E_C decreases because of decreasing chemical potential

$E_J^{BCS} \propto \Delta$

Ambegaokar-Baratoff relation

- Towards BCS side, E_C grows but condensed fractions decreases linearly with **Δ**

→ Overall decrease of E_J towards BCS side!

→ Maximum Josephson energy near unitarity!

The Running-Phase Regime

- If charging energy exceeds Josephson energy: **running-phase evolution**

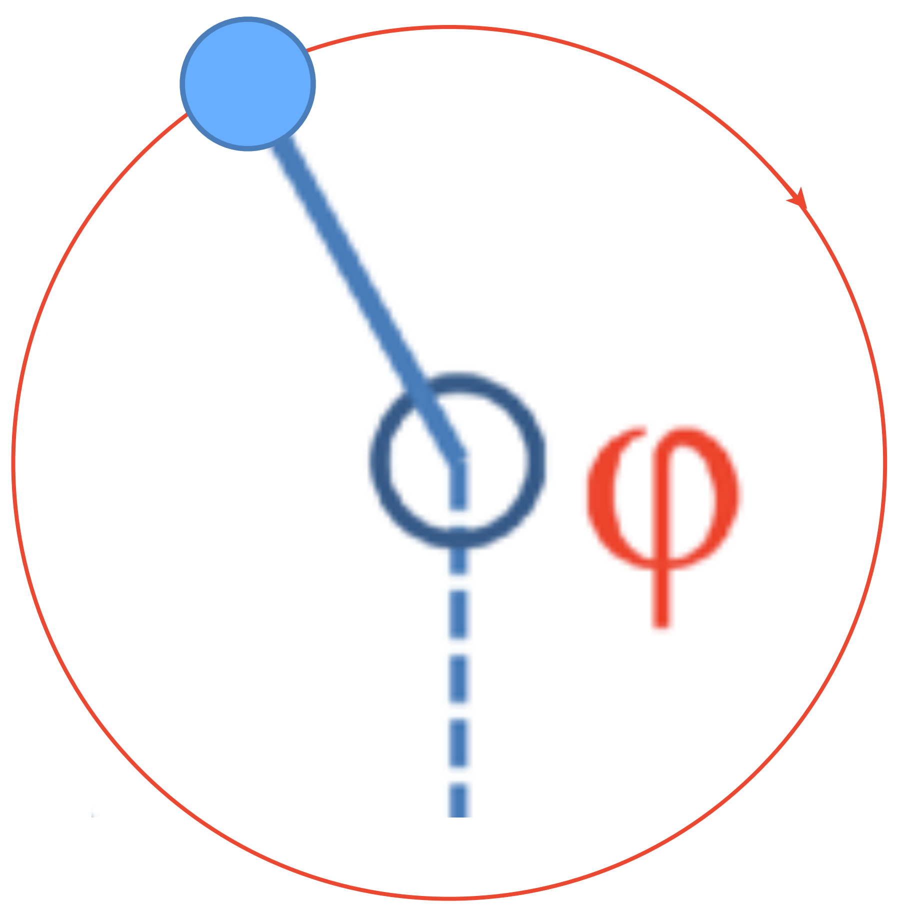
$$\Delta N > \sqrt{\frac{2E_J}{E_C}}$$

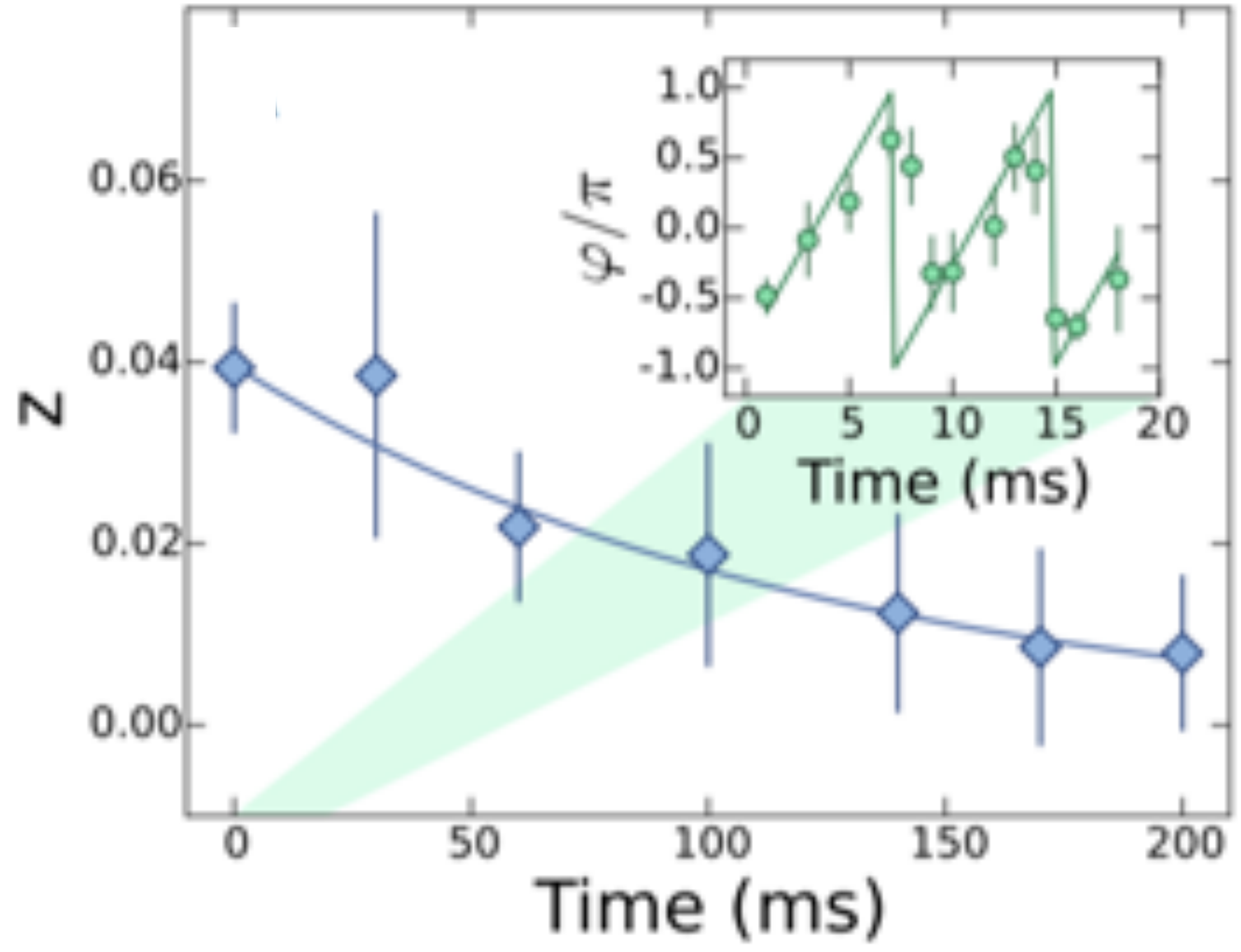
$$\hbar\phi(t) \sim E_C \Delta N(0) t$$

Small imbalance oscillation at Josephson frequency $\omega \simeq \Delta\mu_0/\hbar$

- One way to reach this: raise the barrier to $V_0 \gg \mu$, so as to strongly reduce E_J

Running pendulum evolution





Valtolina et al., *Science* **350** (2015)

Linear phase evolution is observed: phase coherence is clearly there, but large shot-to-shot fluctuations

Population imbalance decays: no Josephson oscillations observed, no “quantum self-trapping” (MQST)

A. Smerzi et al, *Phys. Rev. Lett*. **79**, 4950 (1997)
I. Zapata et al., *Phys. Rev. A* **57**, R28, (1998)

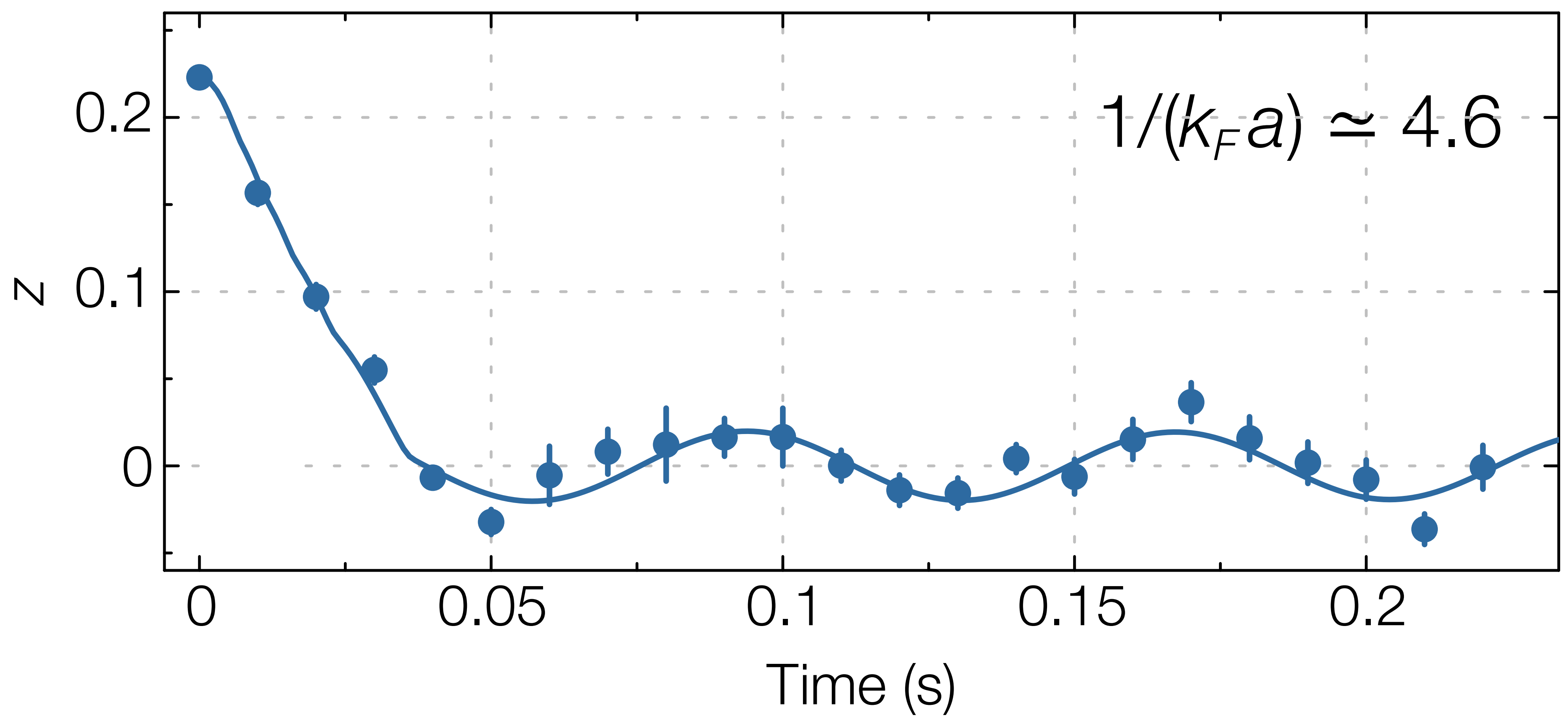
What is the origin of incoherent transport?

INCREASING THE INITIAL POPULATION BIAS

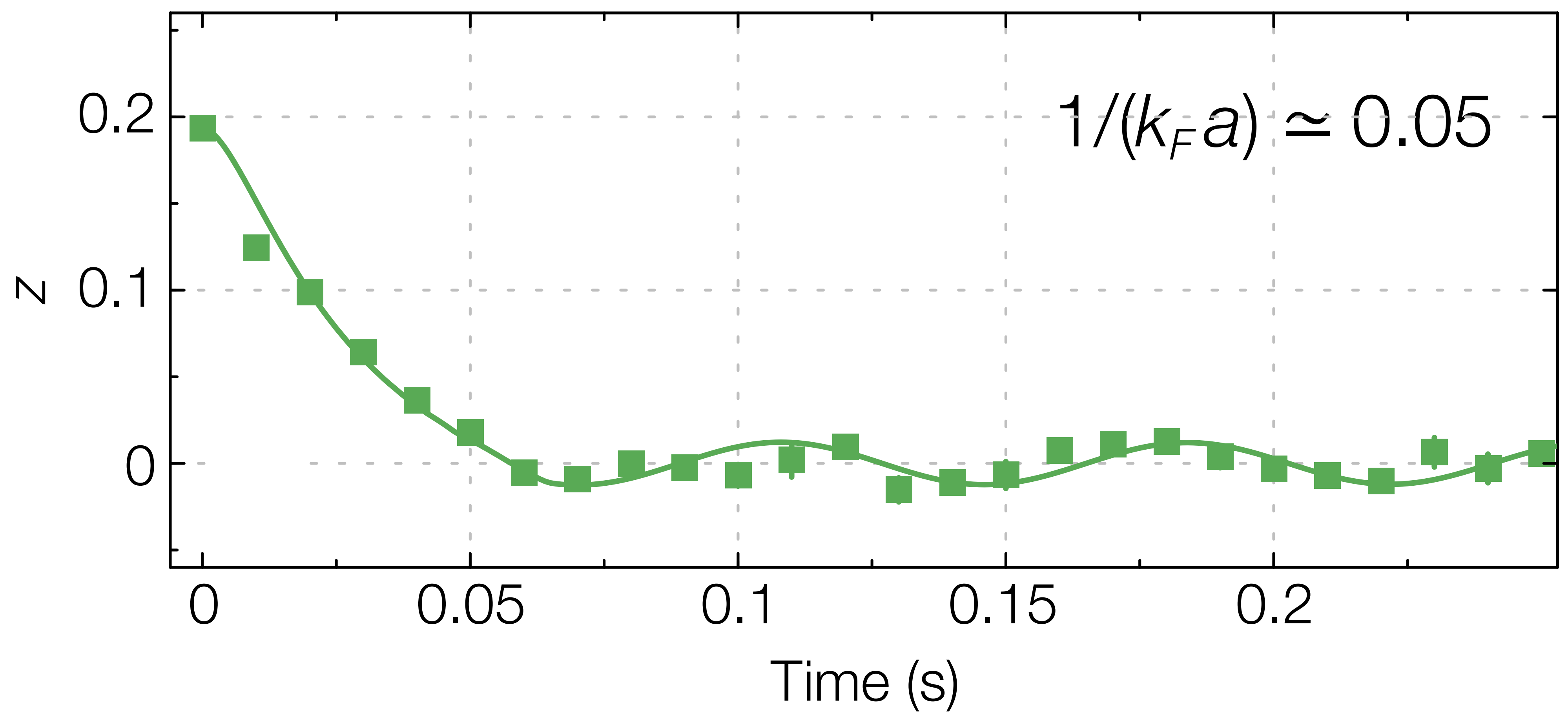
- **Increase the initial imbalance** while keeping E_J constant at $V_0 \simeq \mu$

A. Burchianti et al., *PRL* **120** (2018)

BEC



Unitary gas



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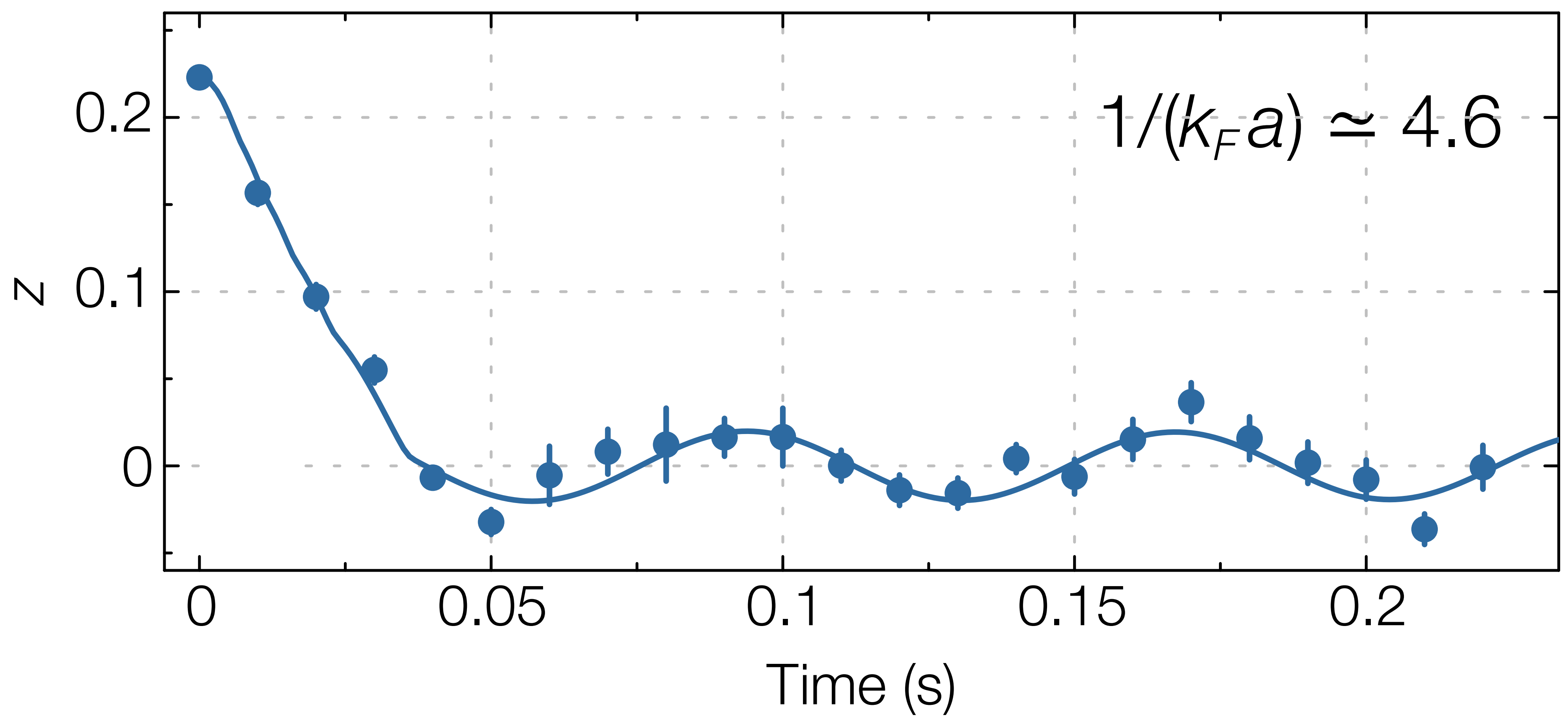
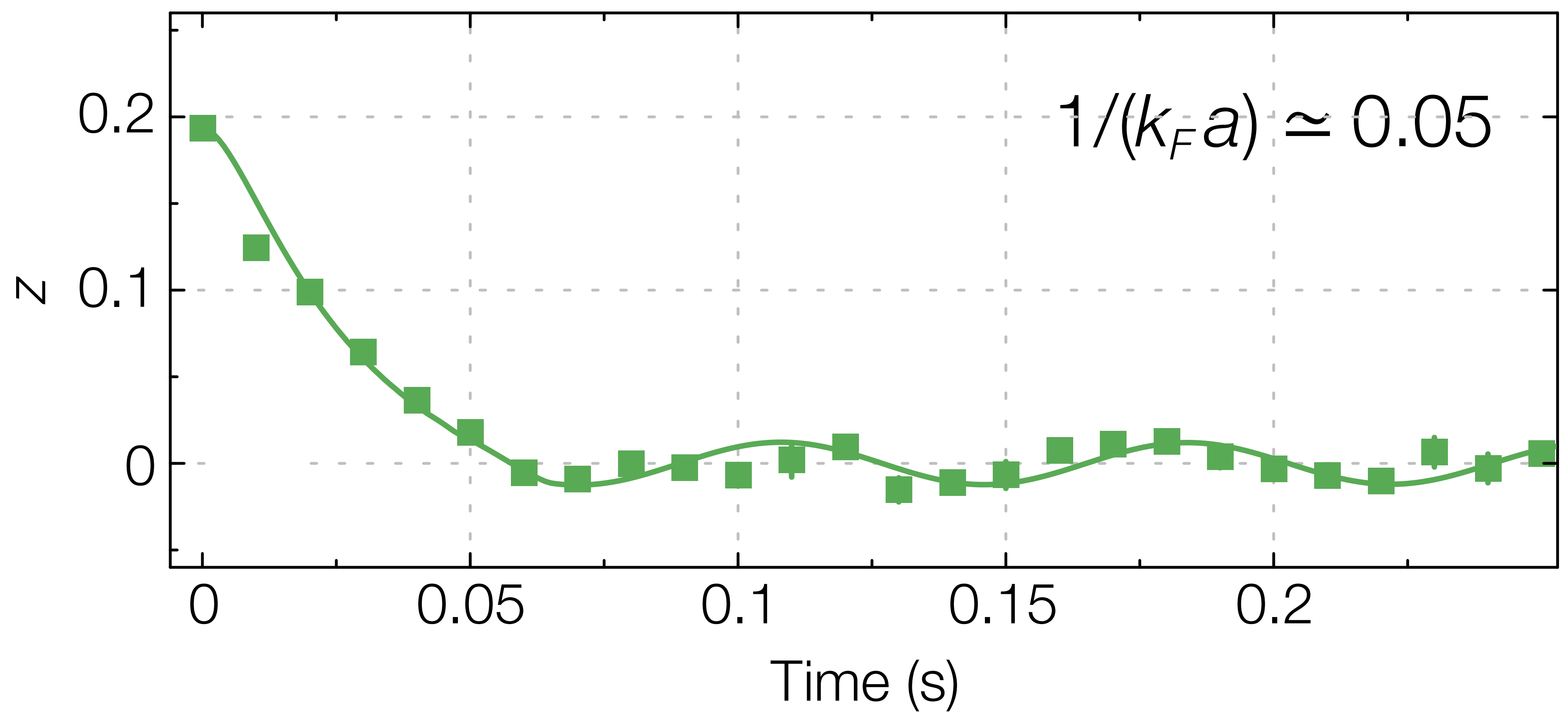
A. Burchianti et al., *PRL* **120** (2018)

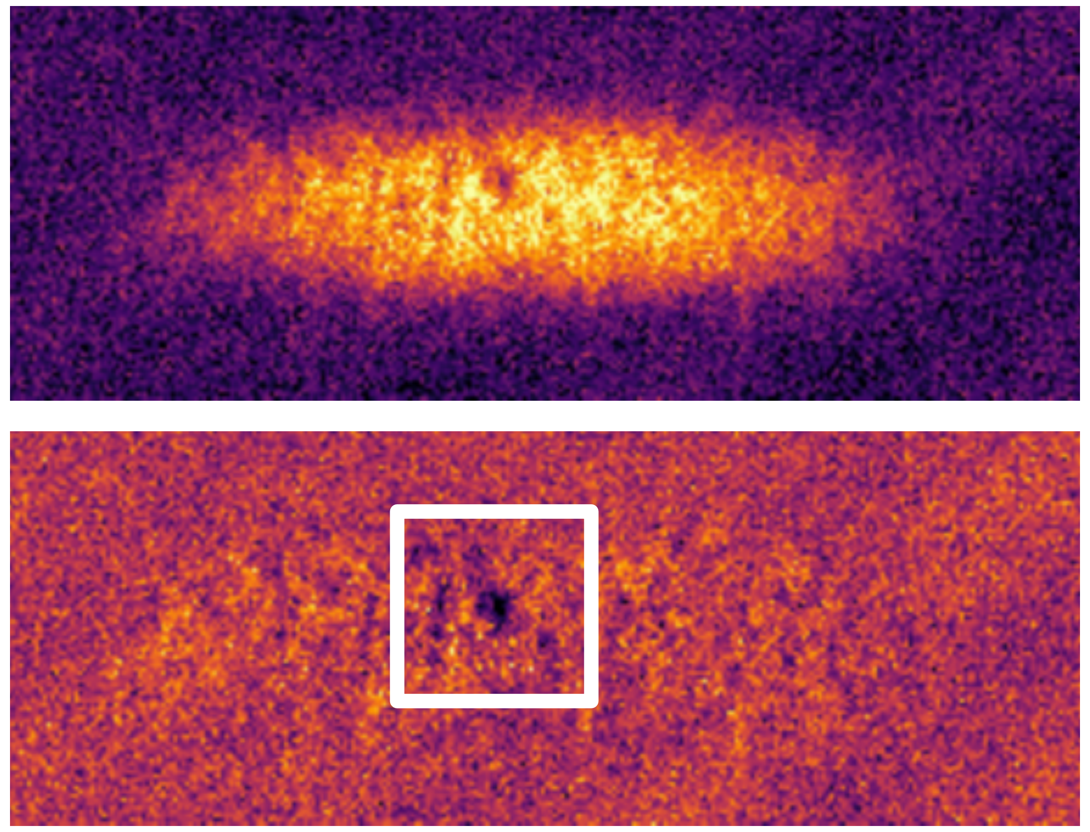
BEC



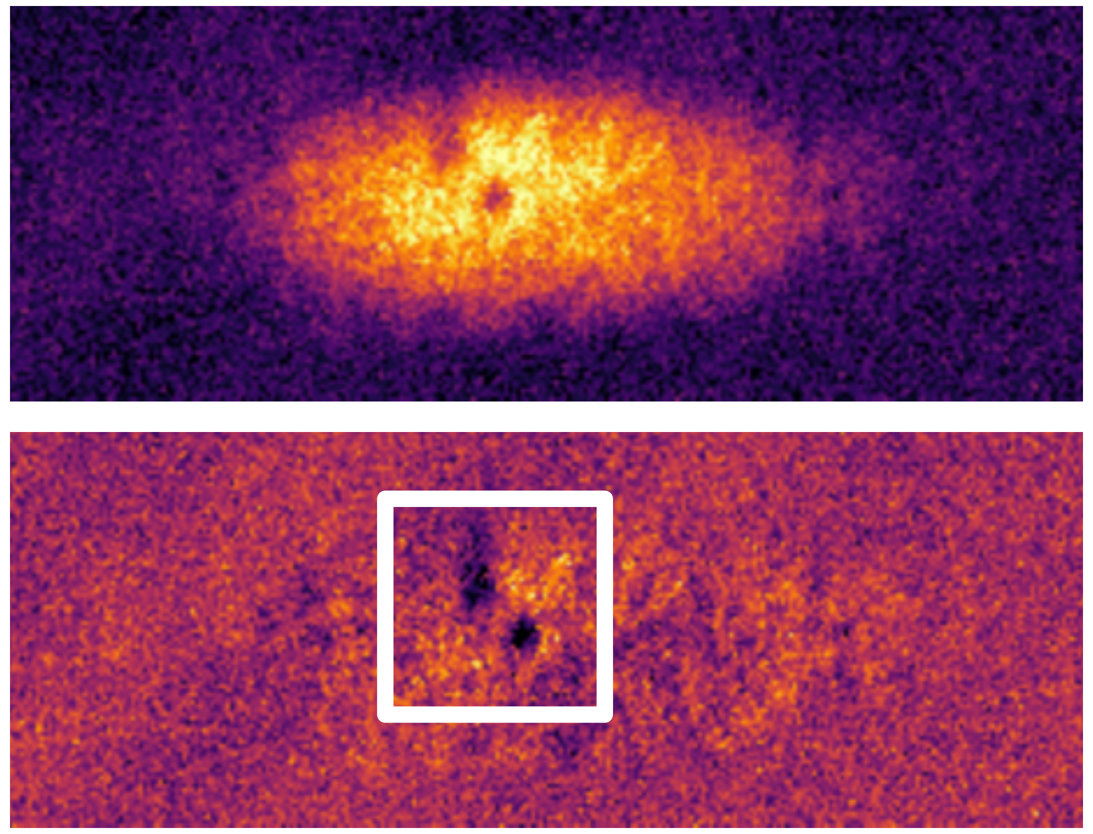
Unitary gas



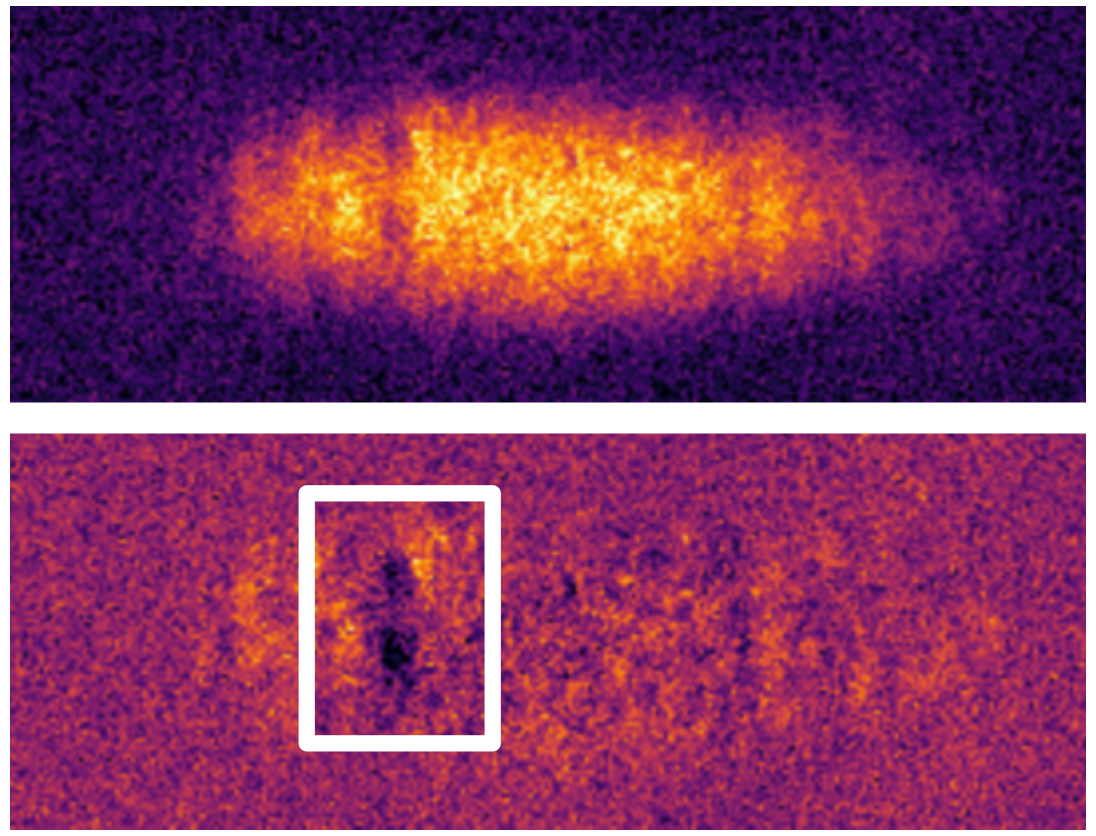
BEC



Unitary gas



BCS

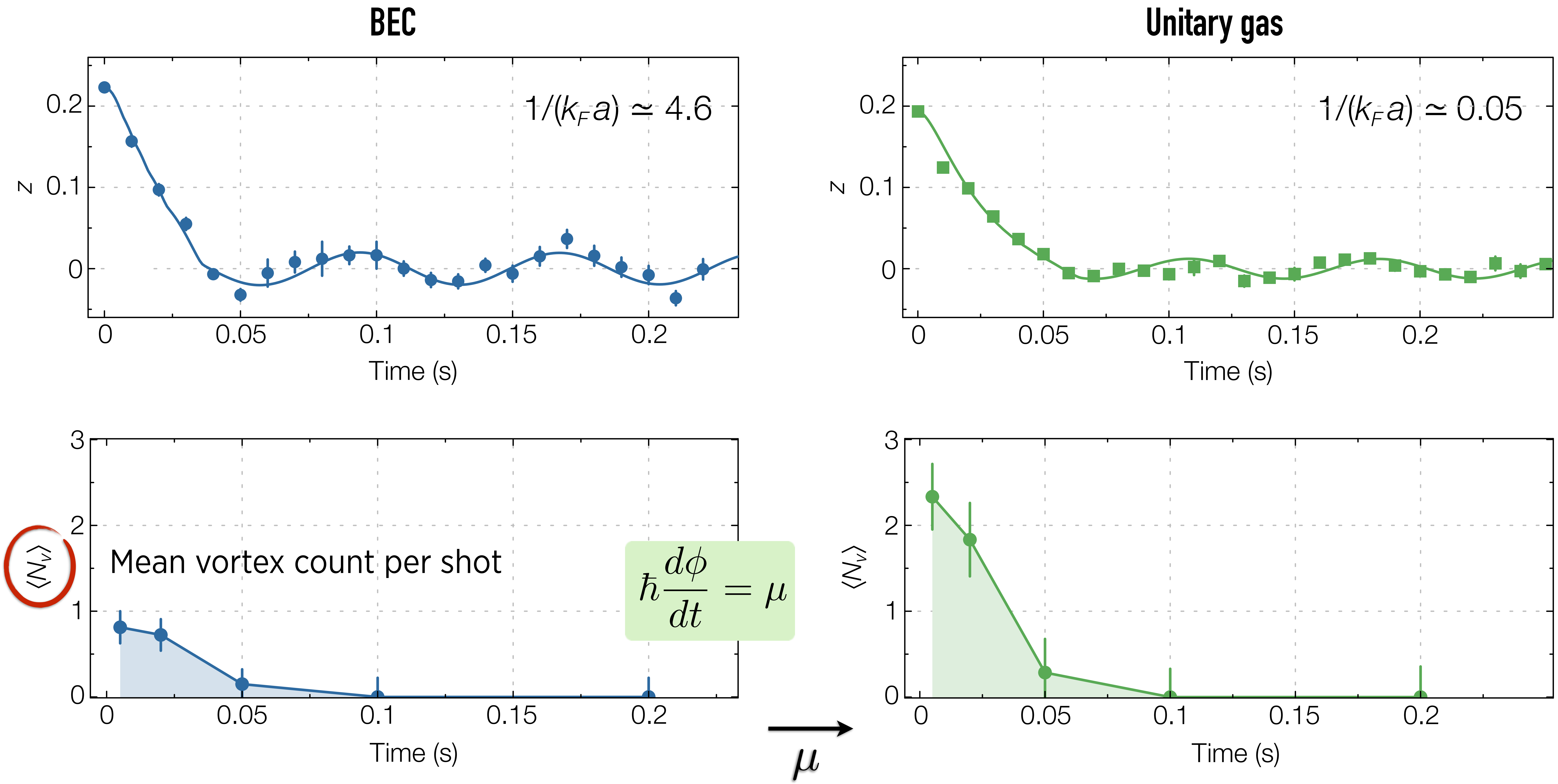


Topological defects are present!

INCREASING THE INITIAL POPULATION BIAS

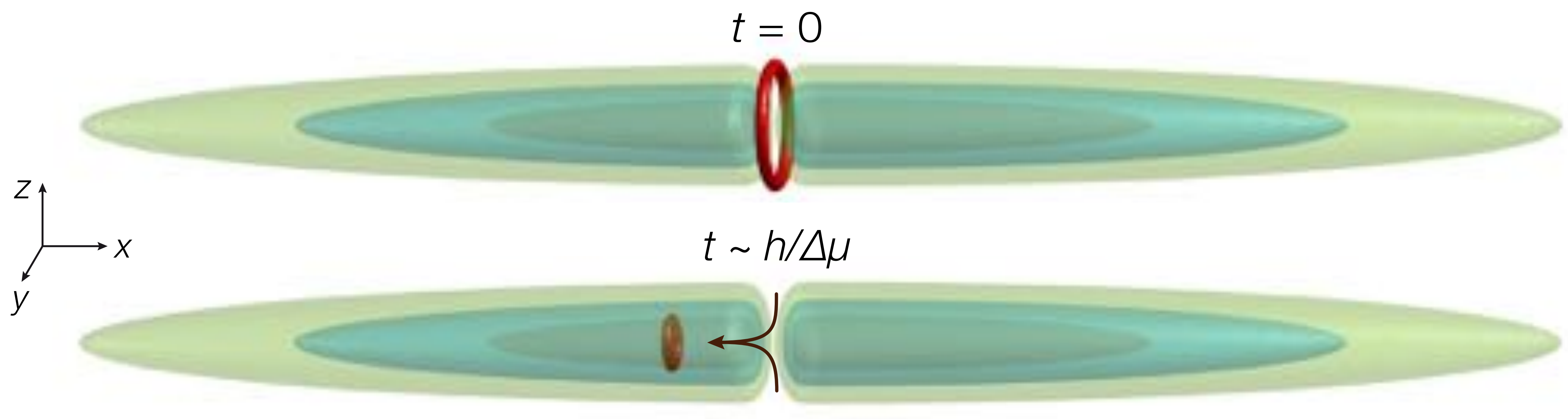
- **Increase the initial imbalance** while keeping E_J constant at $V_0 \simeq \mu$

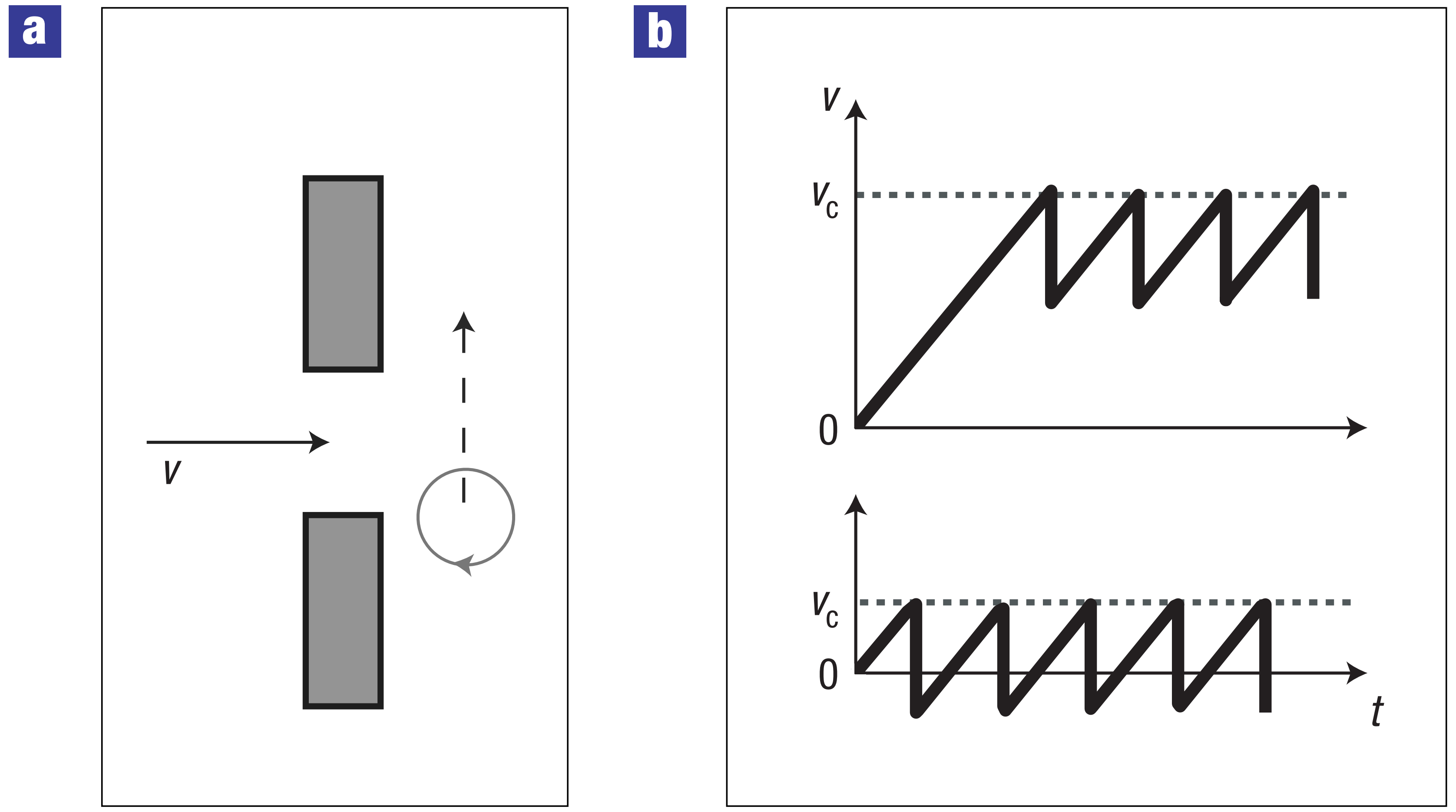
A. Burchianti et al., *PRL* **120** (2018)



Vortex Nucleation: Phase-Slippage

- **Phase coherence is preserved**, ruling out pair-breaking effects or quasiparticle currents [cf. Levy et al., *Nature* **449**, 579 (2007)]
- **Dissipation** can originate from **(topological) vortex excitations** rather than by (Landau) single-particle excitations
  ➙ analogous to phase slippage for liquid ^{4}He through orifice
  [see also recent work by Gauthier et al., arXiv:1903.04086]





$$\hbar\frac{d\phi}{dt} = \mu$$

$$v_S > v_{crit}$$

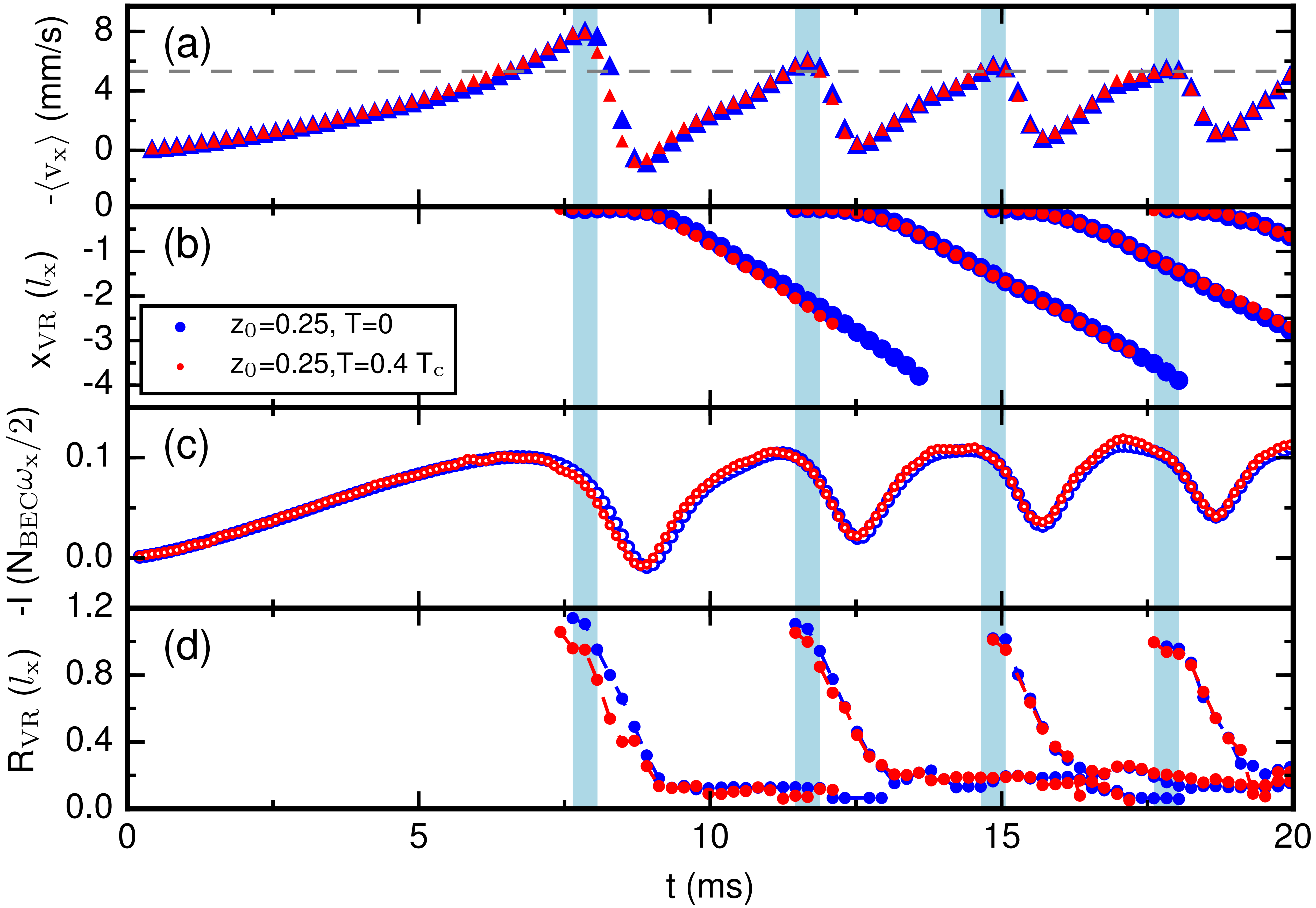
P. W. Anderson, *Rev. Mod. Phys.* **38**, 2 (1966)
E. Hoskinson et al. *Nature Phys.* **2**, 23 (2006)

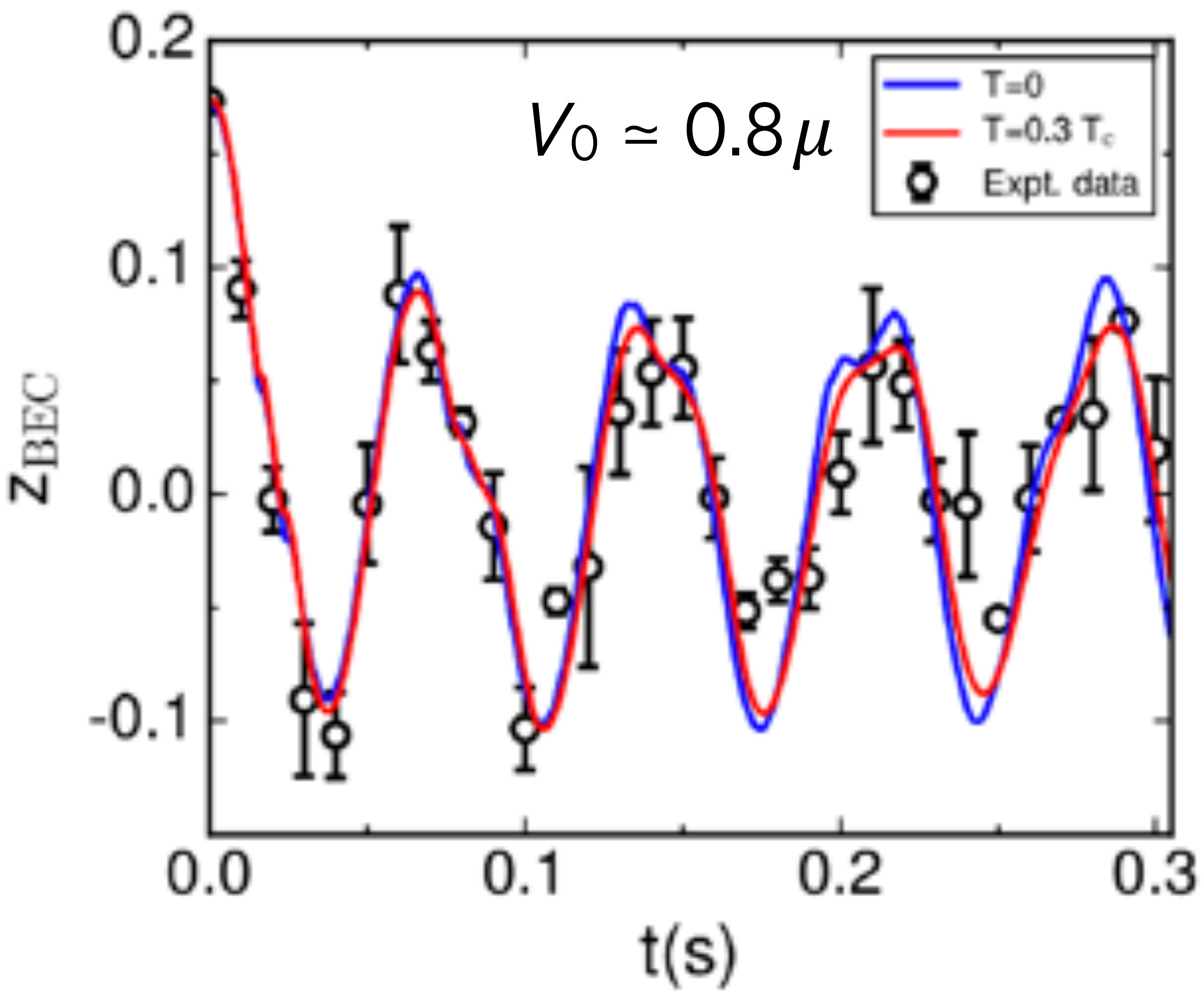
- When a vortex line crosses the superflow, dissipation arises: **phase slippage**
  ➙ **Energy transfer from the superflow to vortex motion**
  The phase slips and the superfluid velocity jumps
- Our thin 3D junction geometry favours **vortex nucleation and shedding into bulk**
  Vortex dynamics affects superflow through junction ➙ initial imbalance decay!

Vortex Nucleation: Simulations

- Phase slippage and vortex shedding is well reproduced by **GP simulations of junction dynamics in BEC regime** [see also early works e.g. Piazza et al., *New J. Phys.* **13** (2011)]

- Phase slippage can be clearly seen in the superfluid velocity

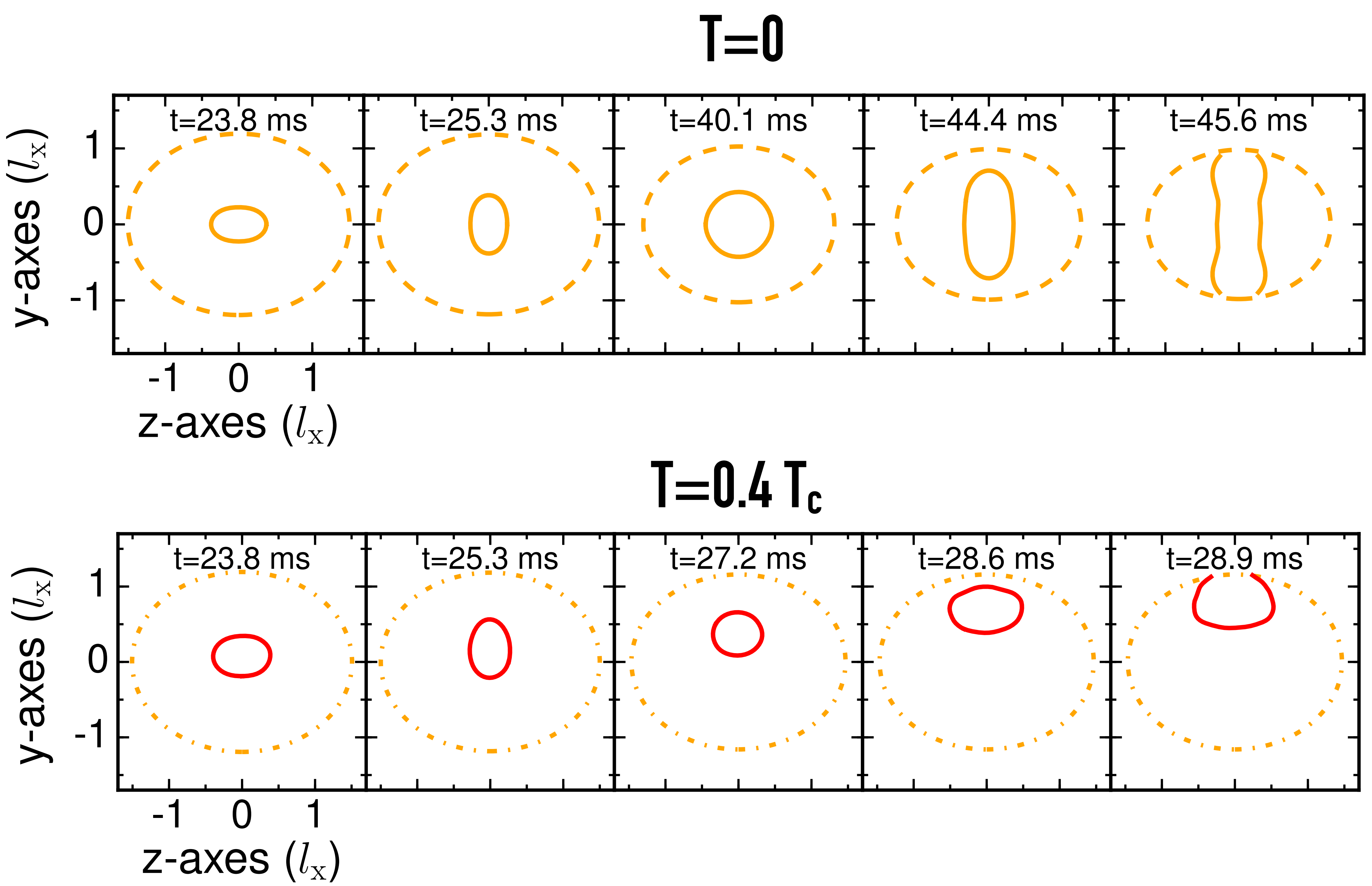


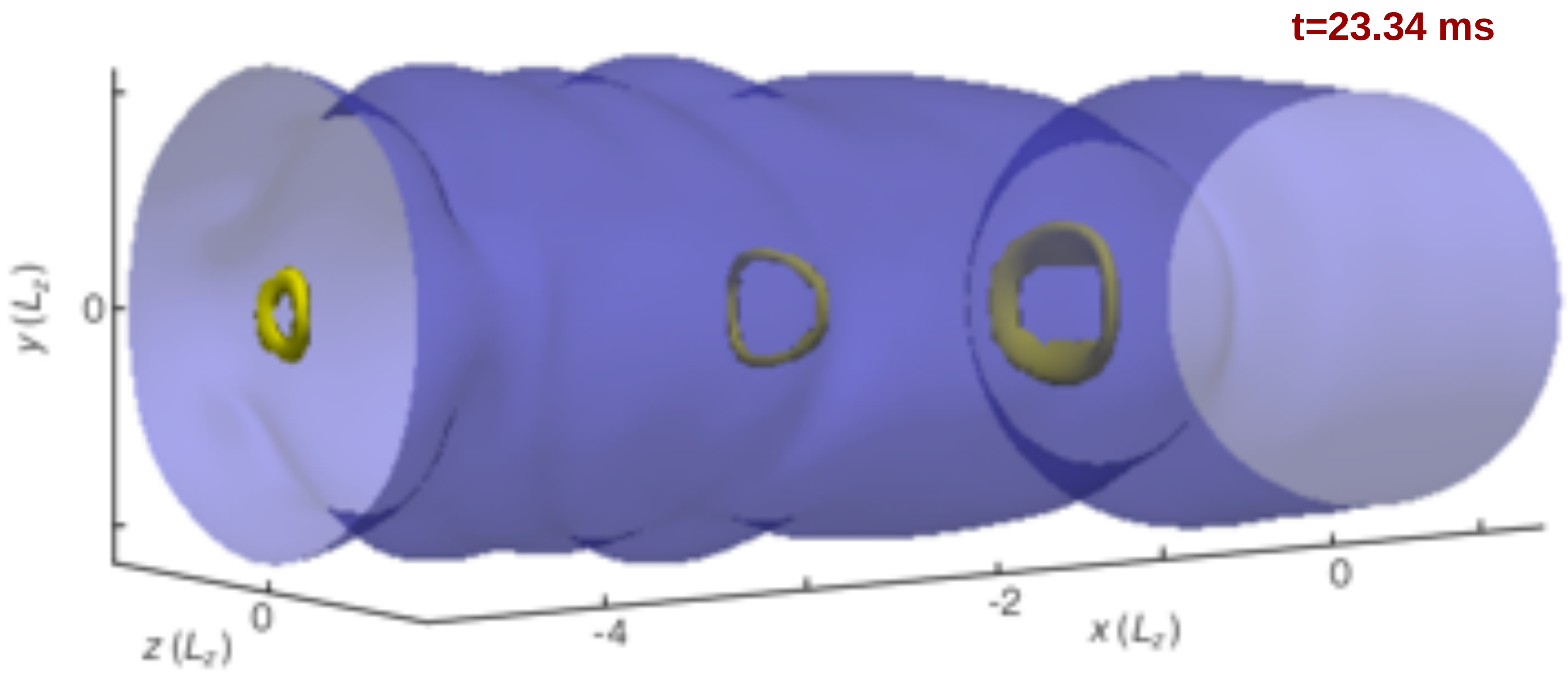


Simulations by:
K. Xhani, N. Proukakis

Xhani et al., *in preparation* (soon on arXiv).

Simulations of Vortex Dynamics

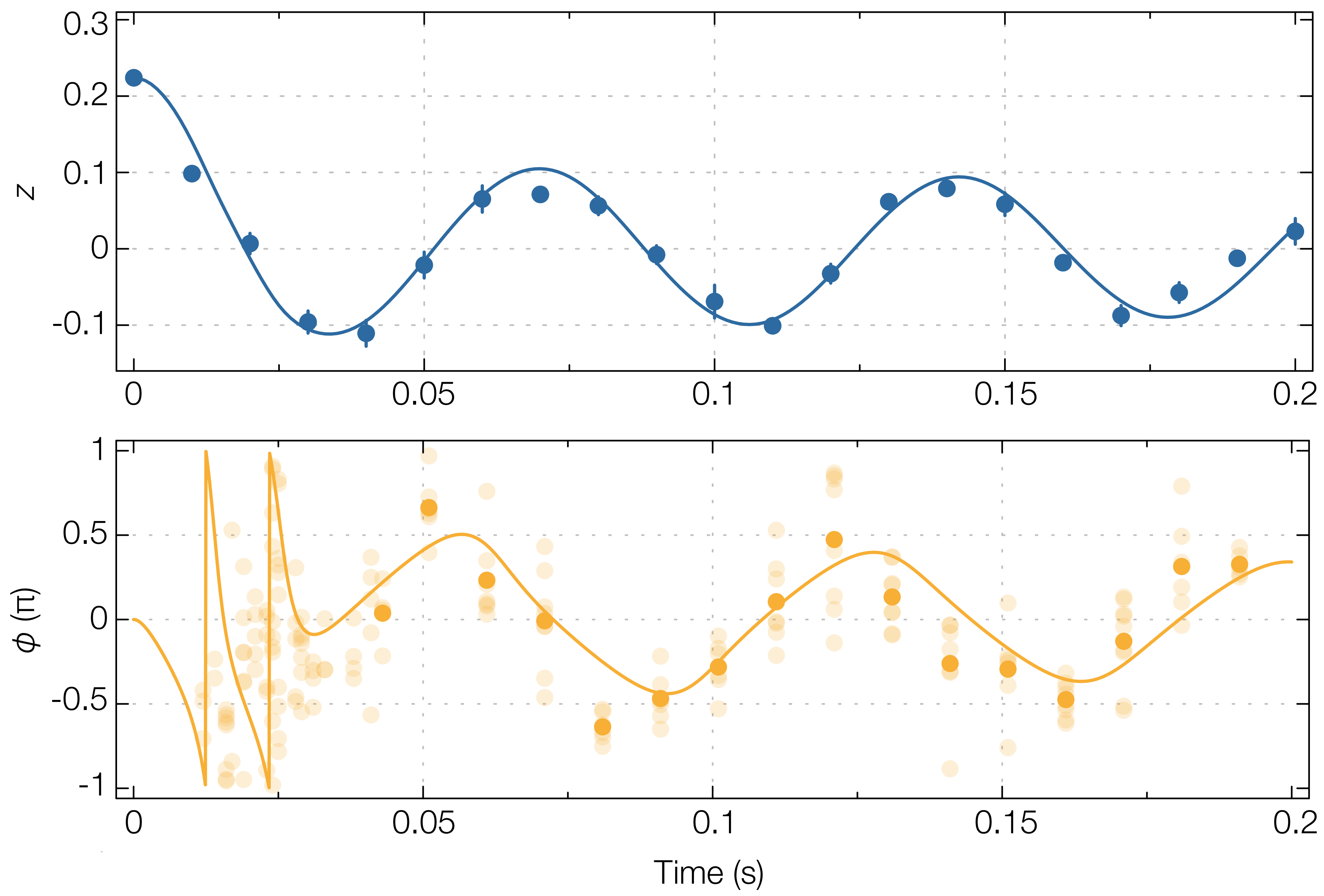


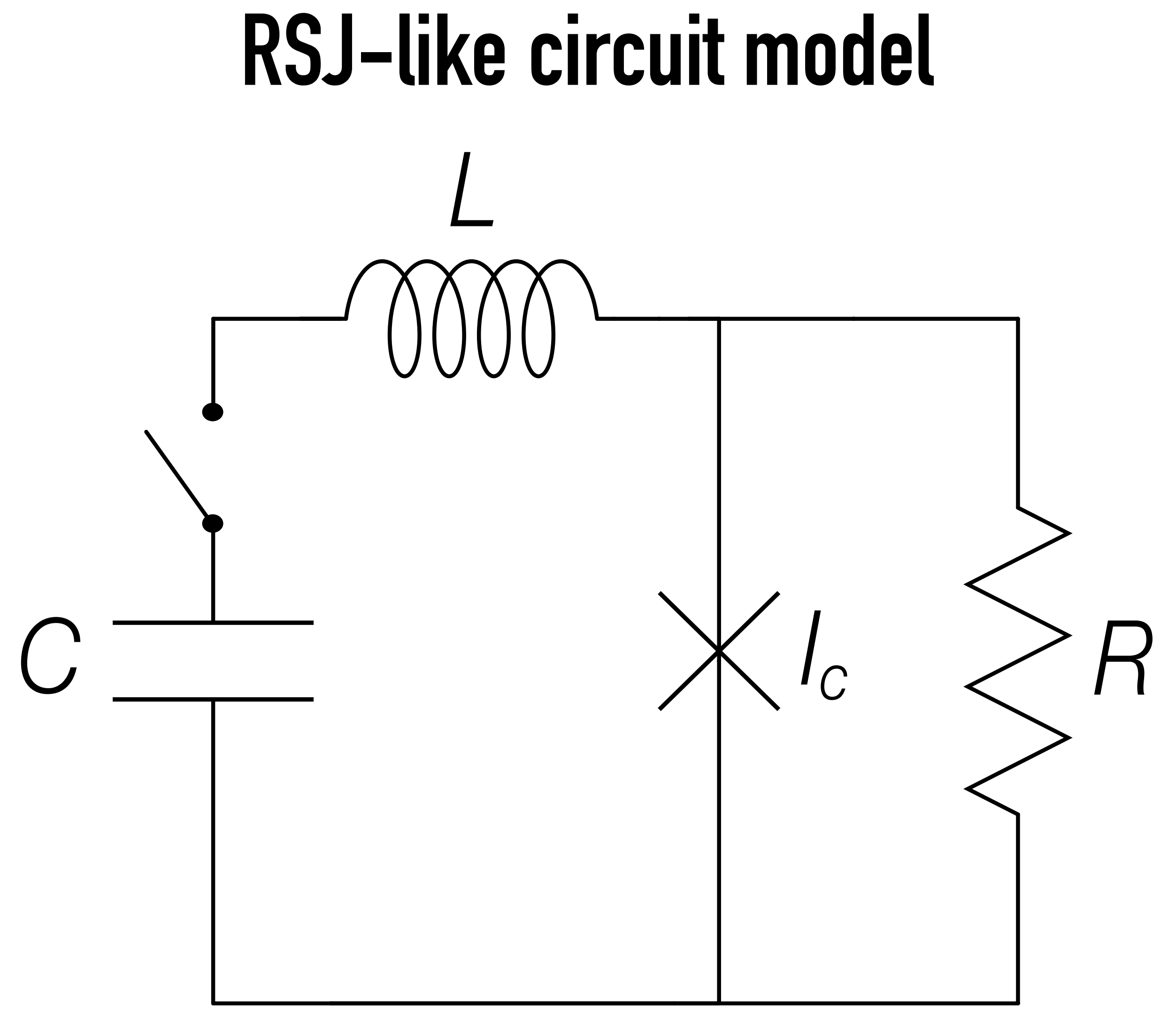


Xhani et al., *in preparation* (soon on arXiv).

RESISTIVE FLOW AND RSJ CIRCUIT MODEL

- **Model the evolution of imbalance and phase with RC-shunted Josephson Junction circuit**





- Imbalance $z(t)$ and phase $\phi(t)$ evolution well fitted by numerical solution of RLCJ model: **resistively shunted Josephson (RSJ) junction circuit → incorporates all Ohmic dissipation into resistor *R***

Extract *R* and I_c

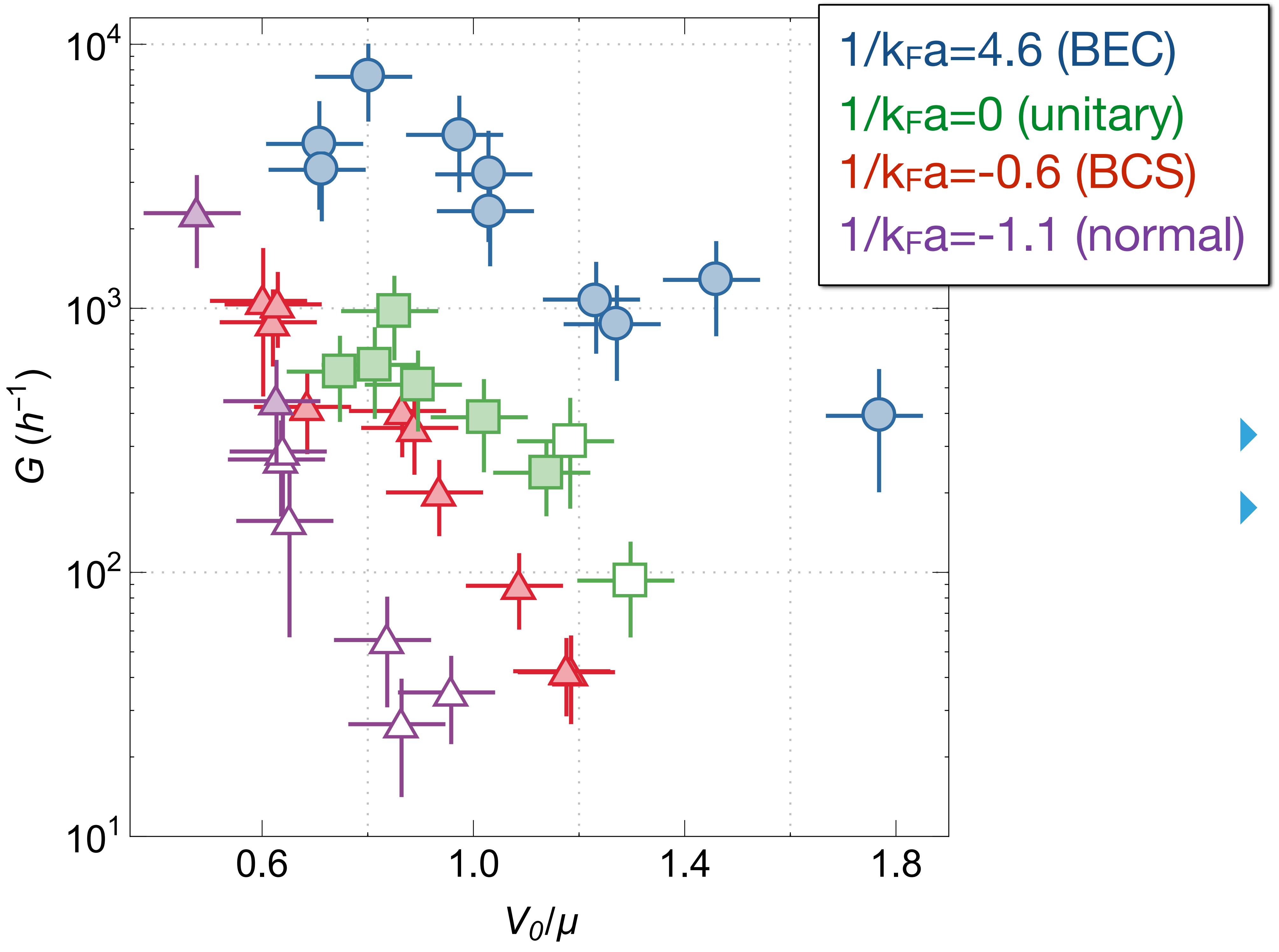
$$L\ddot{k} + R(\dot{k} + I_c \sin\varphi) + k/C = 0$$

$$\hbar\dot{\varphi} + R(\dot{k} + I_c \sin\varphi) = 0$$

From trap frequency

Burchianti et al., *Phys. Rev. Lett.* **120** (2018)
See also: Bidasyuk et al., *J. Phys. B* **51** (2018)
Gauthier et al., arXiv:1903.04086i

CONDUCTANCE $G = R^{-1}$



$$\hbar \frac{d\phi}{dt} = \mu$$ $$I_R = G\,\Delta\mu$$

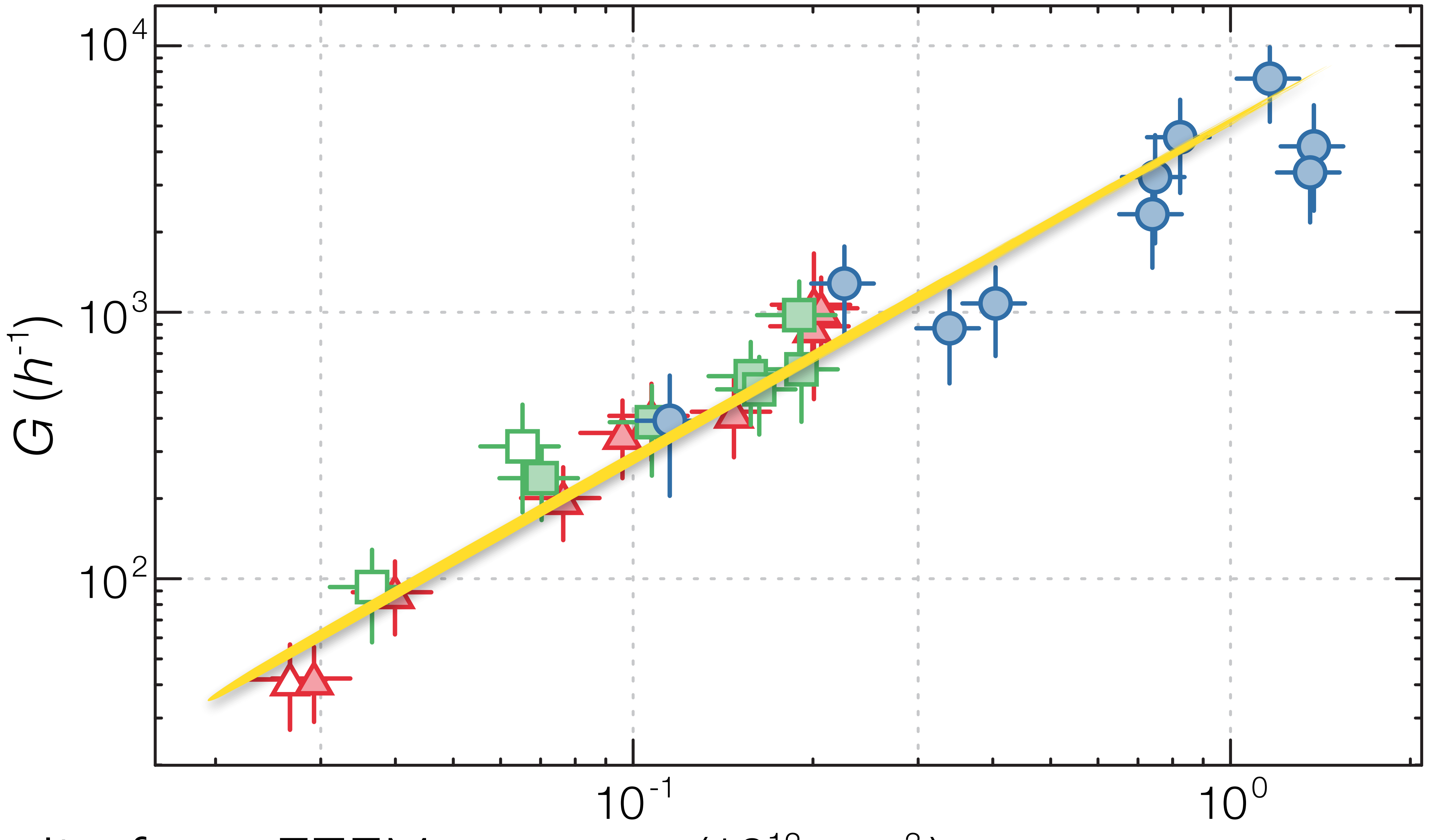
$$I_R \propto \gamma N_{ex} = N_{ex}\,\Delta\mu/h$$
$$\rightarrow G \propto N_{ex}/h \propto n_0$$

Jendrzejewski et al., *PRL* **113**, 045305 (2014)

Fitting the data with $G \propto n_0^{\alpha}$

α=1.0(3) BEC
α=1.2(2) Unitary
α=1.5(2) BCS (pair breaking?)

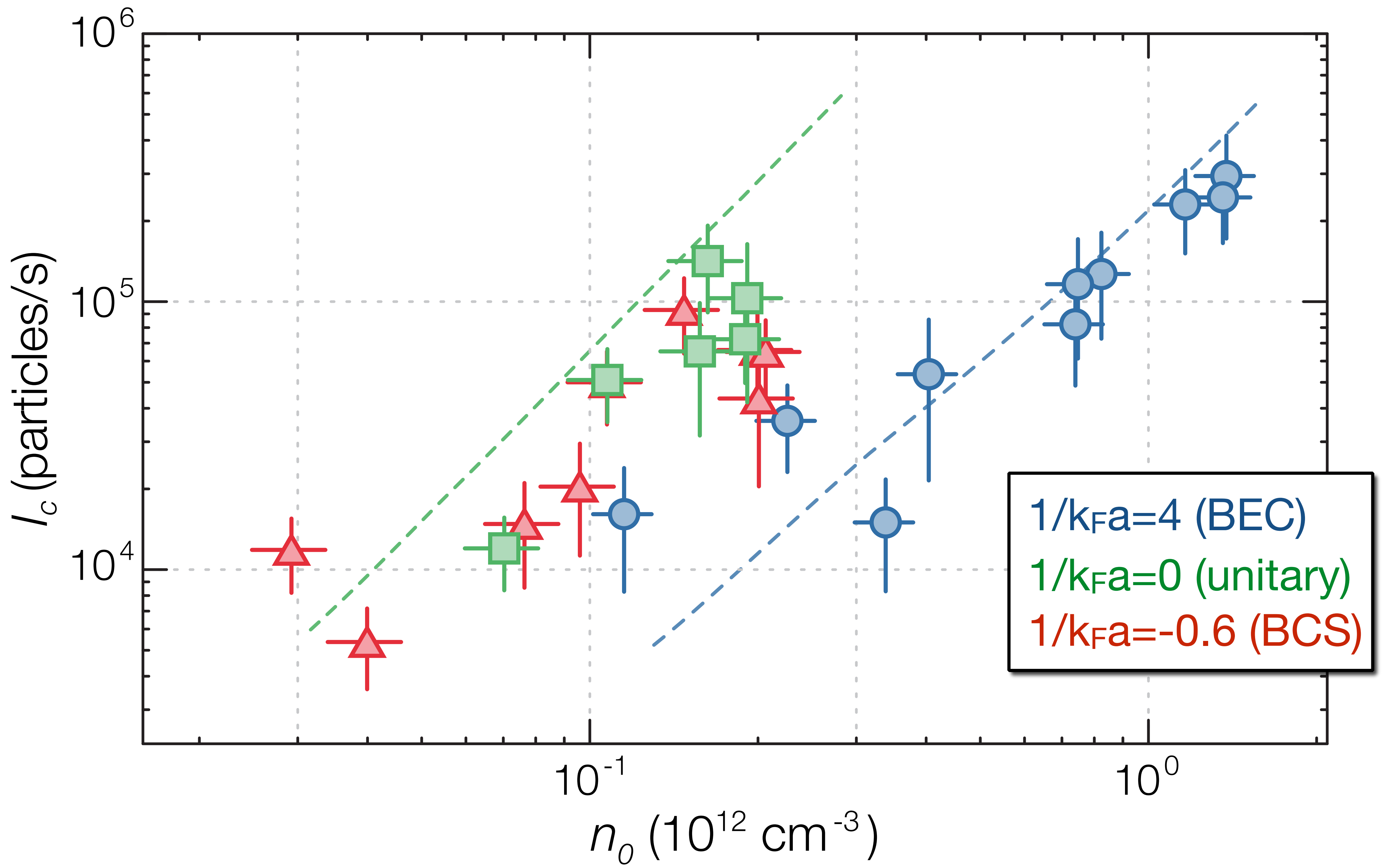
- **Same origin of resistive transport throughout BEC-BCS crossover!**
- **Large *G* →** composite "bosonic" nature of the tunneling particles [cf. Krinner et al. *Nature* **517** (2015)]



Central density from ETFM ⟵ n_0 (10^{12} cm^{-3})

CRITICAL CURRENT I_c

$$I_c \propto E_J = J N_0$$ Condensed pairs



- Measure conductance of normal state on BCS side of resonance:

$$I_c = \frac{\pi\Delta}{2eR_n}$$ Gap

- Calculated upper bound on I_c :

$$I_c = n_{0x}\, c_0$$

Inspired by hydrodynamic scenario, barrier as an obstacle
→ seems ok also for tunnelling regime

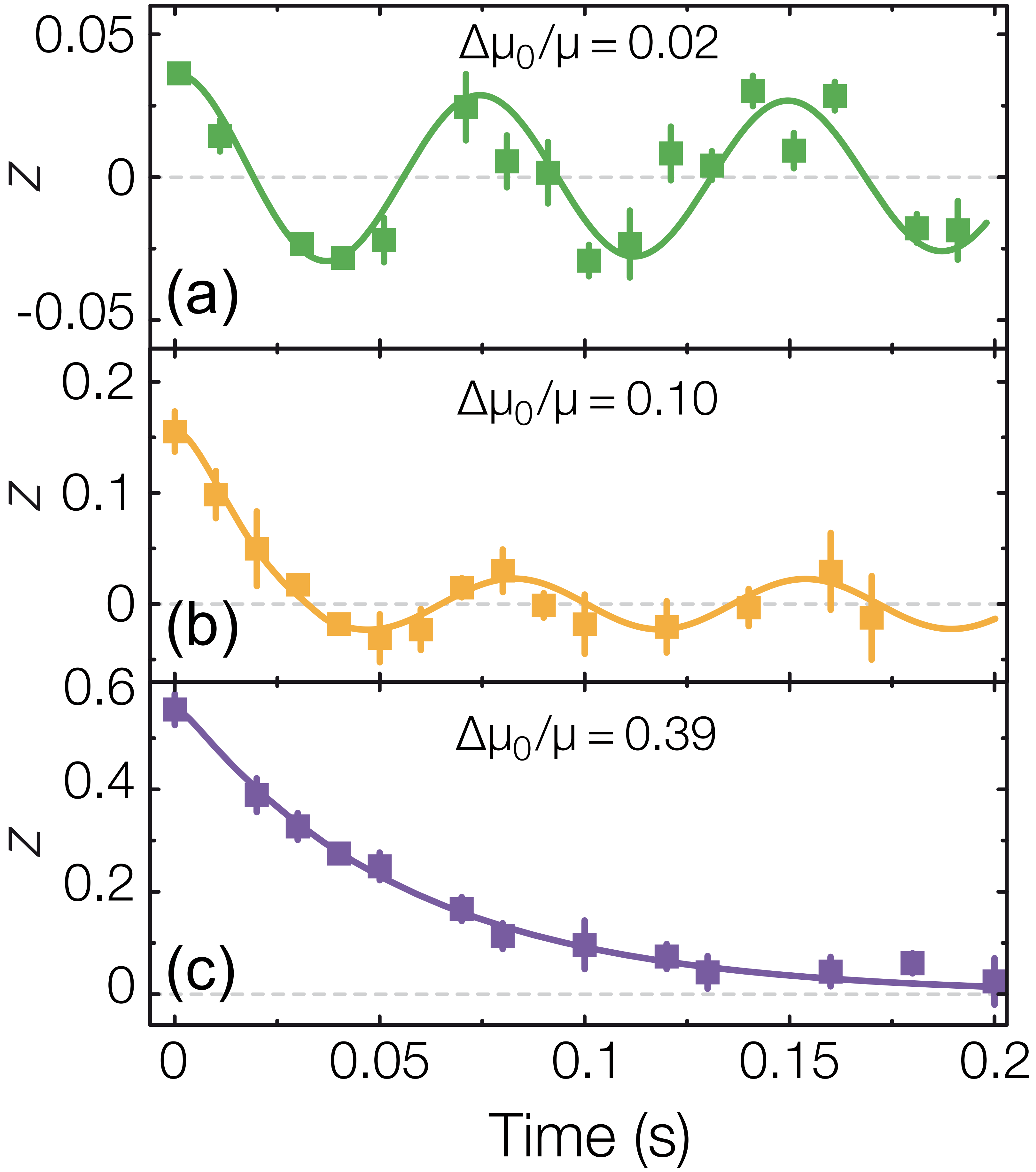
Spuntarelli et al., *PRL*. **99**, 040401 (2007)
Watanabe et al., *PRA* **80**, 053602 (2009)

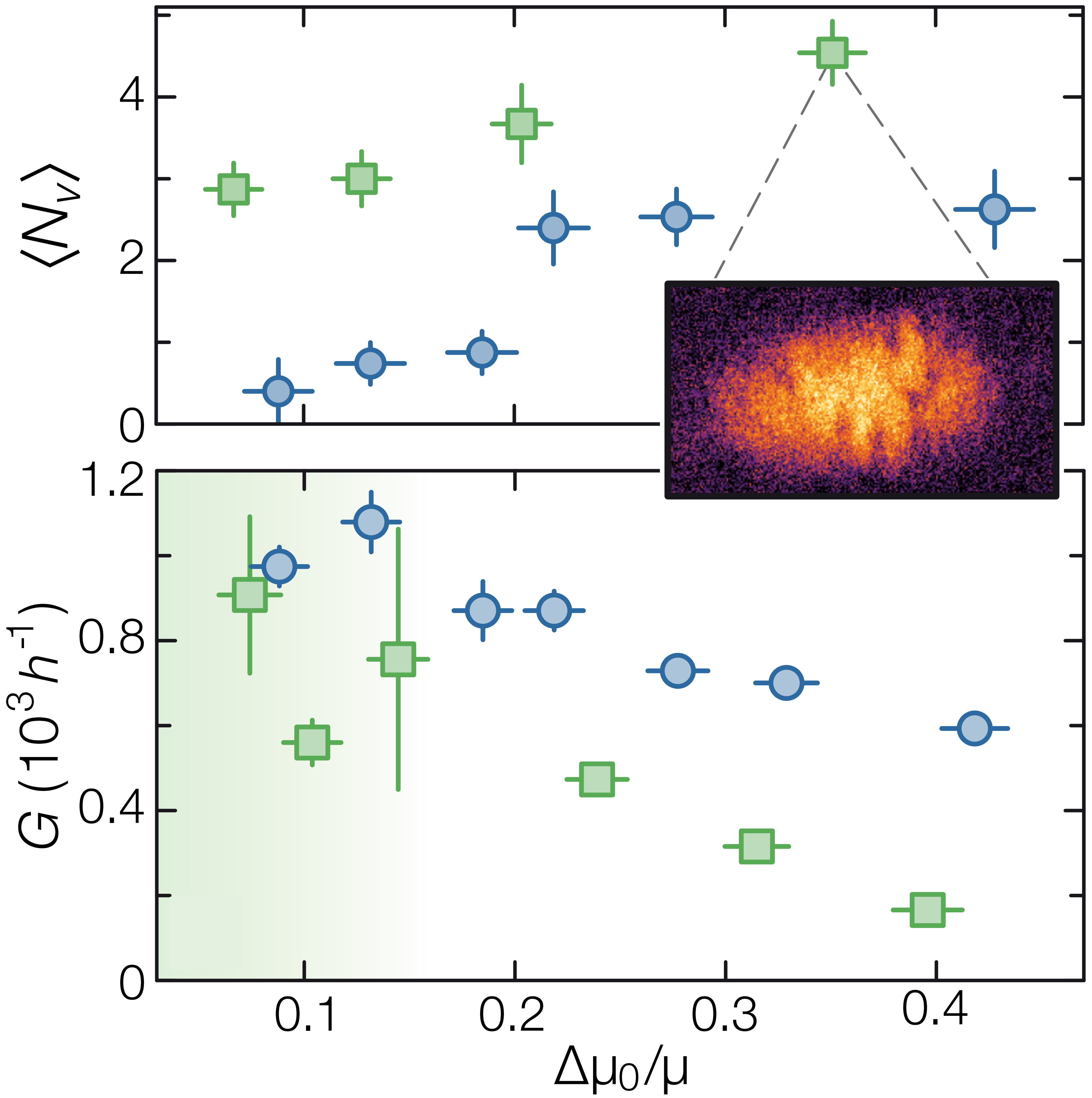
What limits the critical current on BCS side? Pair-breaking or condensate depletion?

Miller et al., *PRL* **99** (2007)
Valtolina et al., *Science* **350** (2015)

Incoherent Tunnelling Regime

- Increasing the initial imbalance $z_0 > 0.3$ ➞ **Disappearance of coherent oscillations**



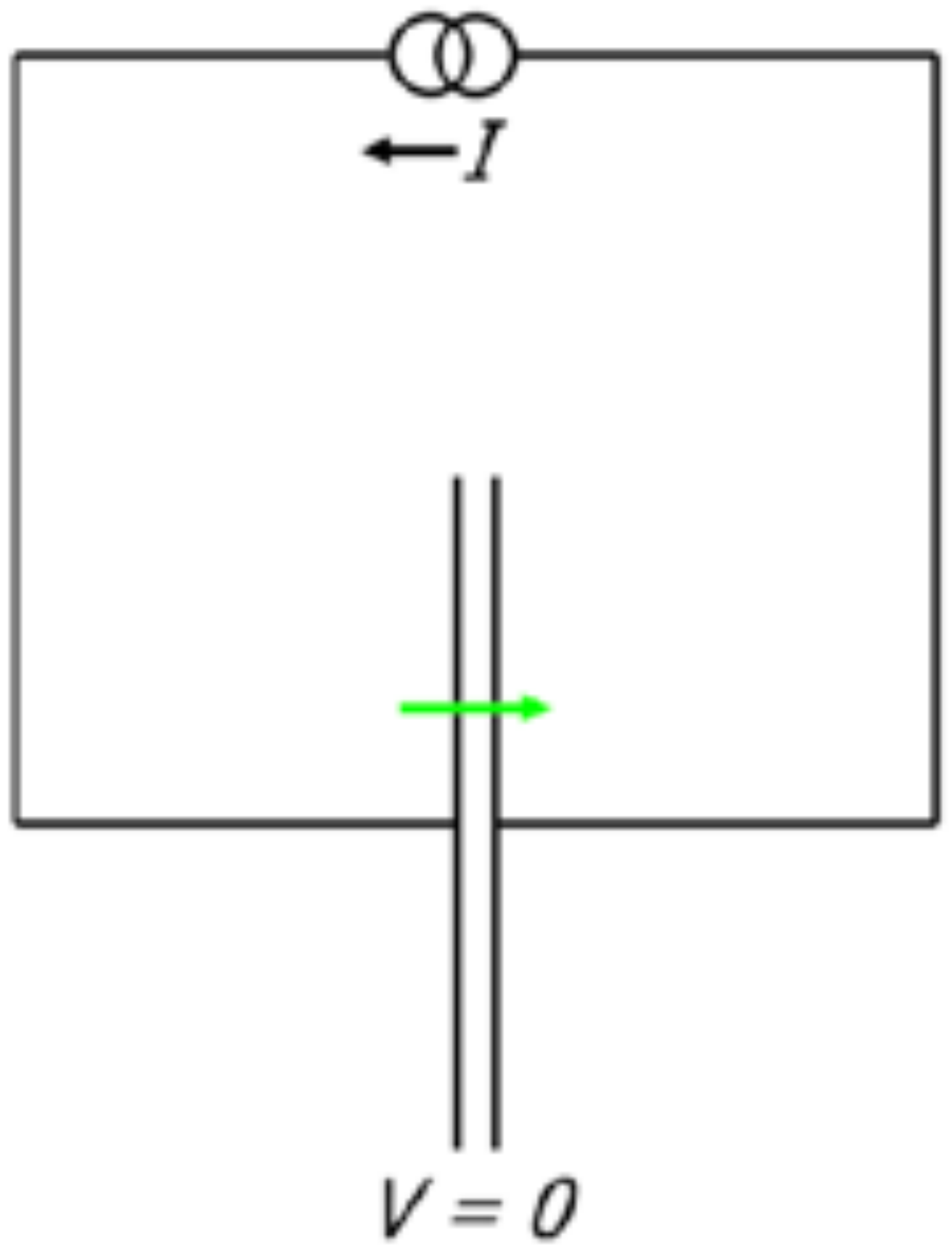


- Conductance decreases: saturation of phase-slippage rate. What is the cause?

THE PLAN

- Introduction: **ultracold Fermi gases** across the BEC-BCS crossover
- **Josephson junction basics**
- Our experimental setup: a **thin tunable Josephson junction** between Fermi superfluids
- Dynamics in **population-biased** junctions:
  Josephson-plasma oscillations and dissipative flow through vortex nucleation
- **Current-driven** junctions:
  probing the critical current via the **DC Josephson** effect → Ongoing...
- Outlook: local manipulation and quantum transport of **two-dimensional gases**

Current-Biased Junction



DC Josephson current

Tunnelling super current without bias $I < I_c$

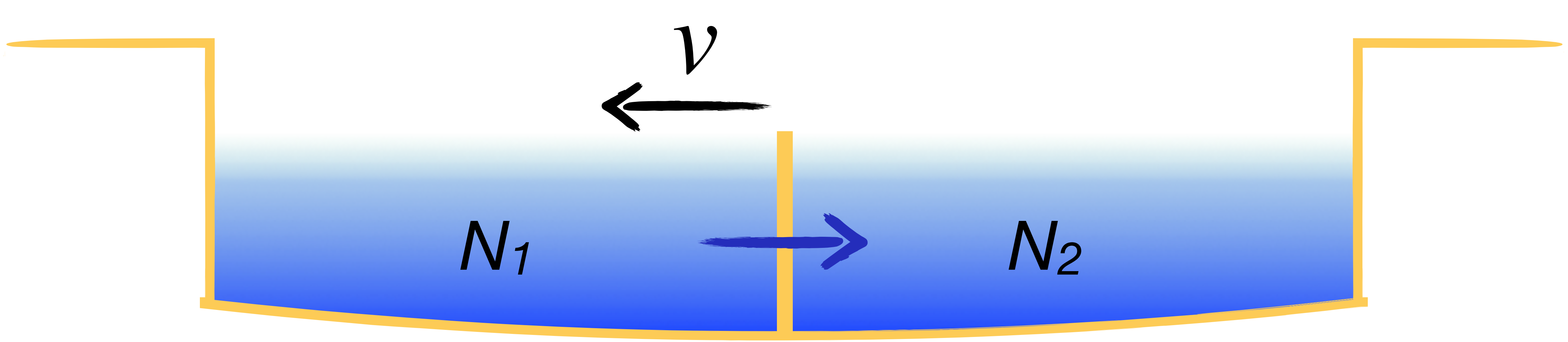
Ultracold bosons:

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

$$\hbar\dot{\phi}(t) = -\Delta\mu = \mu_R - \mu_L$$
$$I = I_c \sin\phi - G\Delta\mu \xrightarrow[I < I_c]{\Delta\mu = 0} \Delta\mu(t) = 0$$

❶

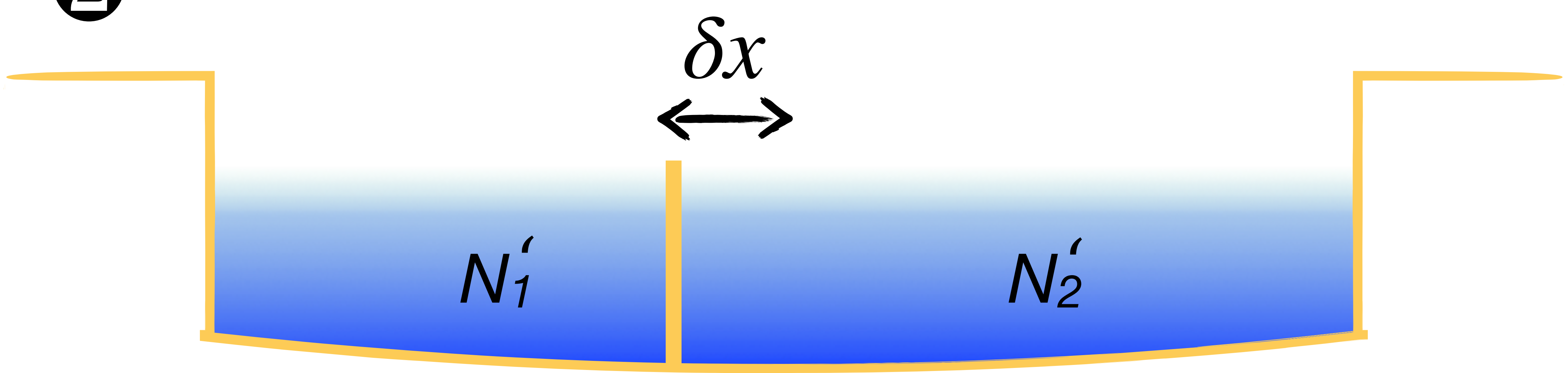
$t = 0$



$$z = \Delta N/N \qquad \Delta\mu = E_C z$$

$t = v\,\delta x$

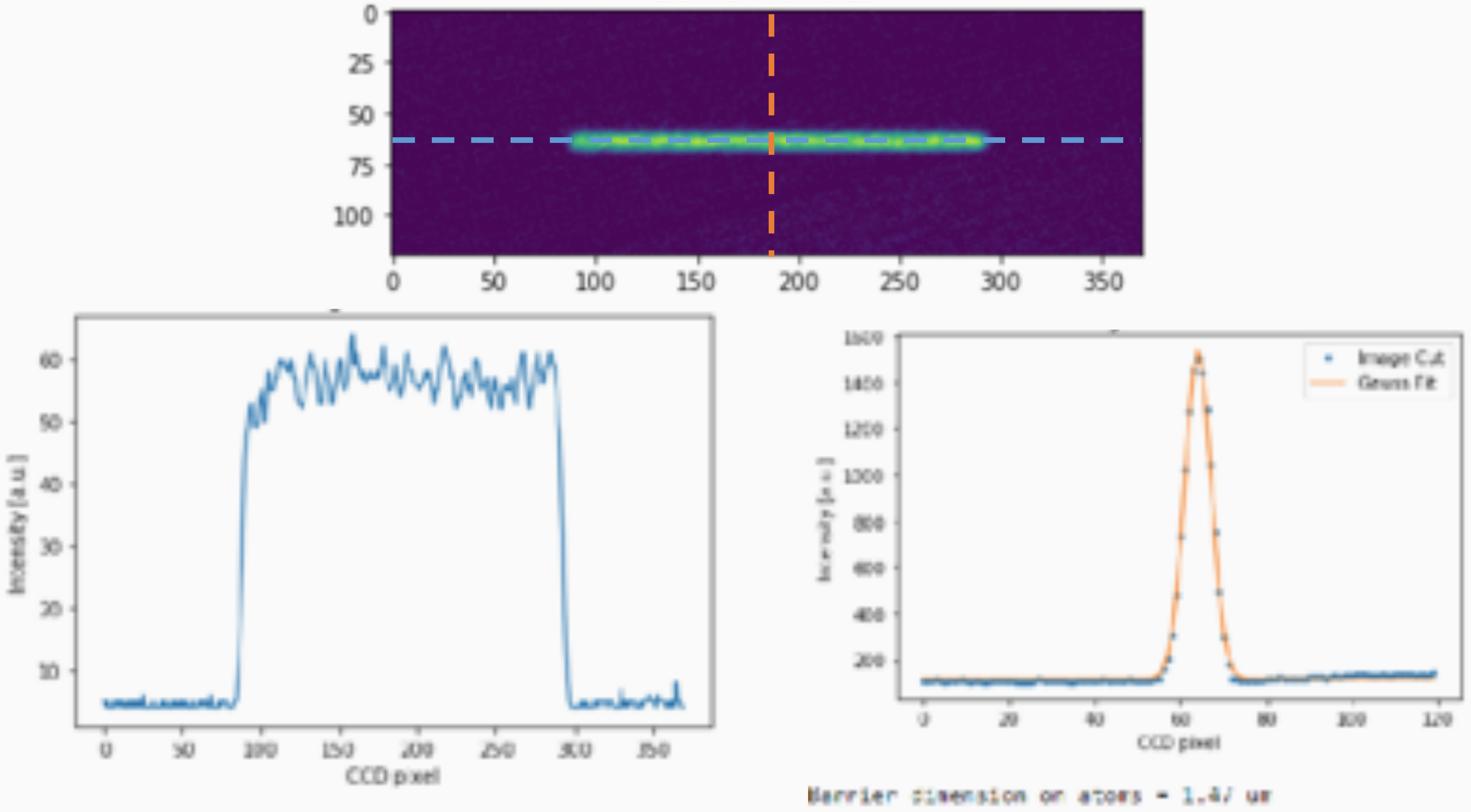
❷



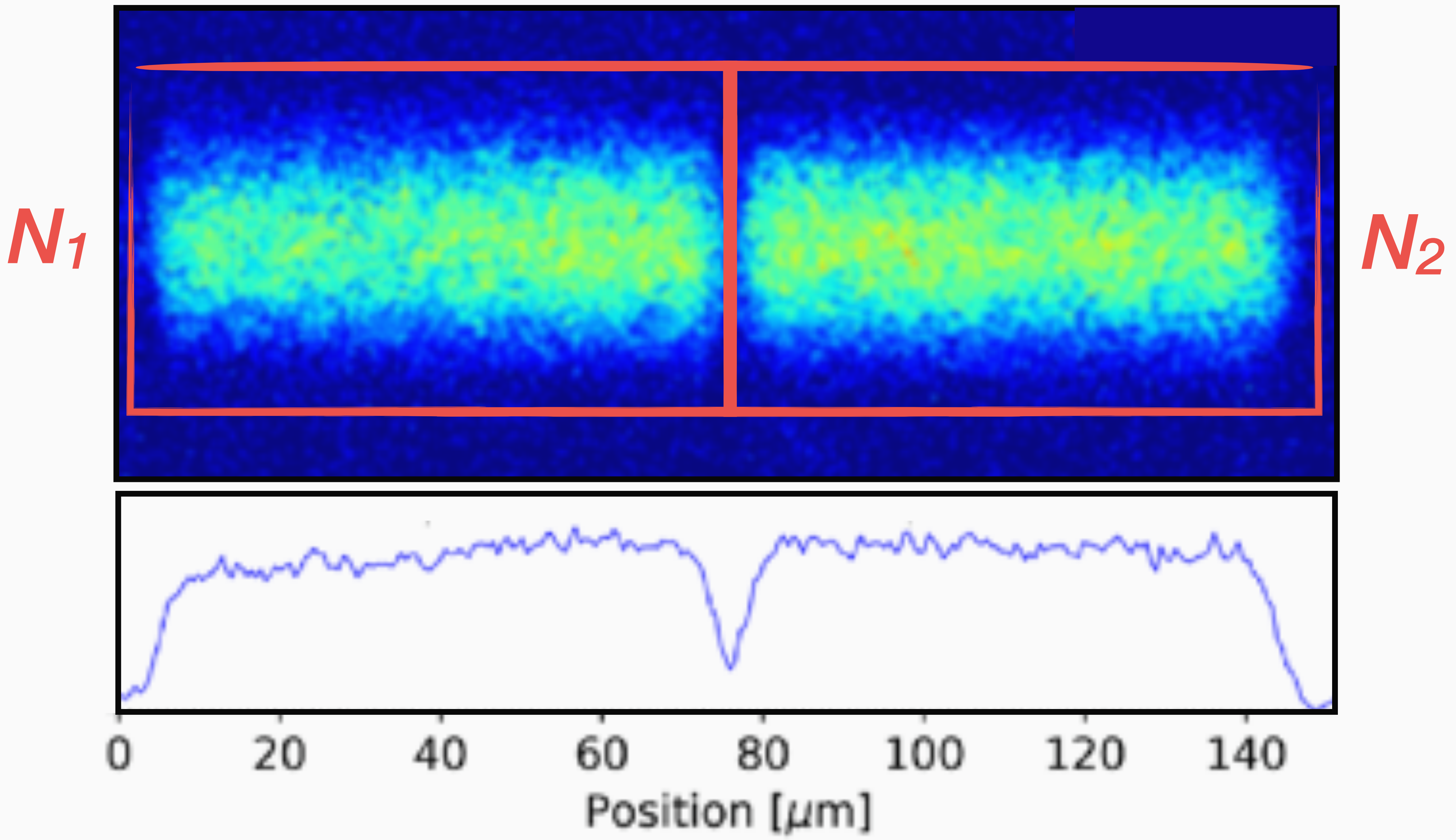
$$\Delta\mu = E_C(z - z_{eq})$$

CURRENT-BIASED JUNCTION: EXPERIMENT

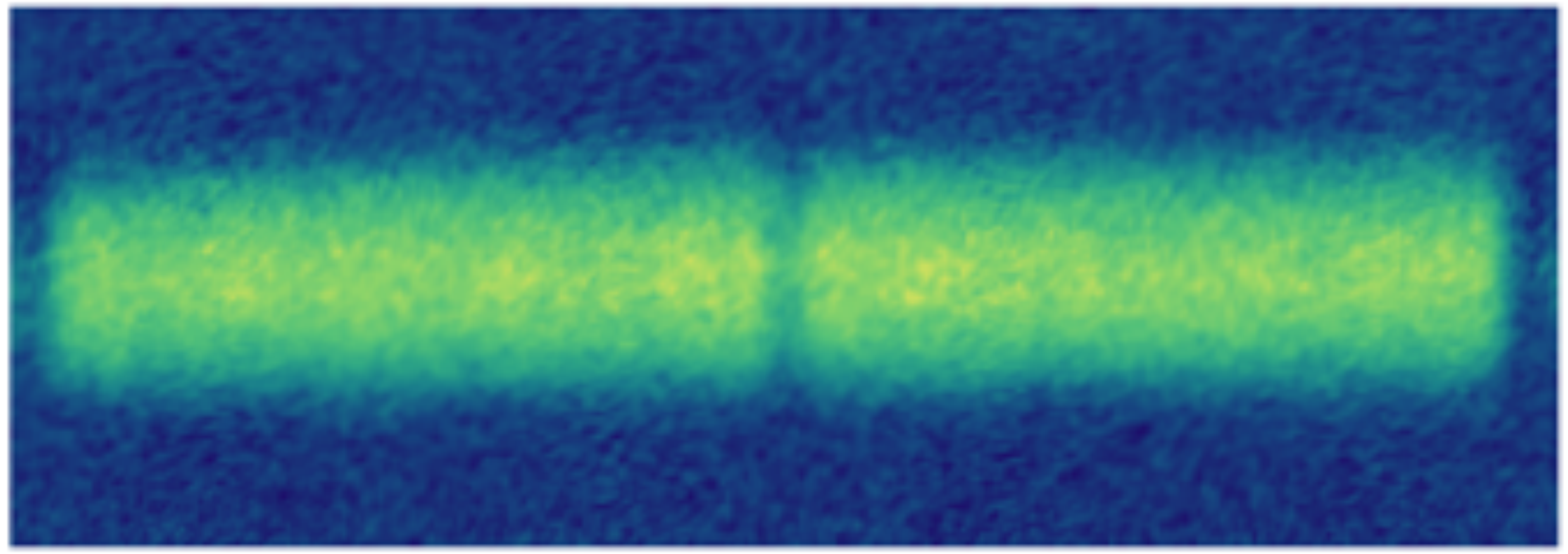
Homogeneous barrier (DMD feedback - dithering)



6 μm thick barrier (just for visualization)



Unitary gas (raw images, single shots)



$\delta x = 10\,\mu m$

$v = 0.1\,\mathrm{mm/s}$

$V_0/\varepsilon_F \simeq 0.8 \rightarrow V_0/\mu > 1$

$w = 1.5\,\mu m\,, k_F w \approx 3$

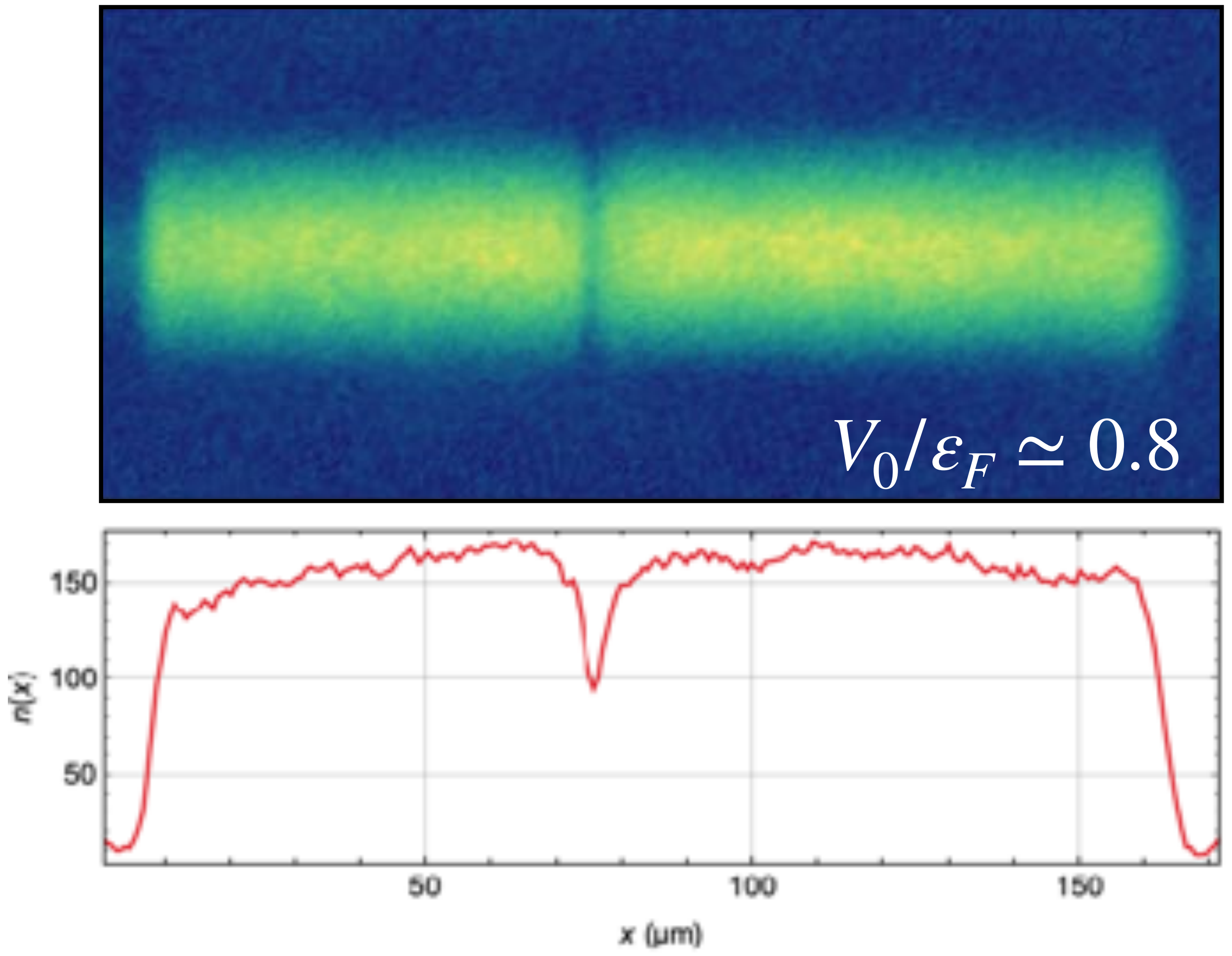
DC Josephson Effect

- Move barrier through the gas at constant velocity along 10 μm
- For final off-centered barrier, $z_{eq} \neq 0$

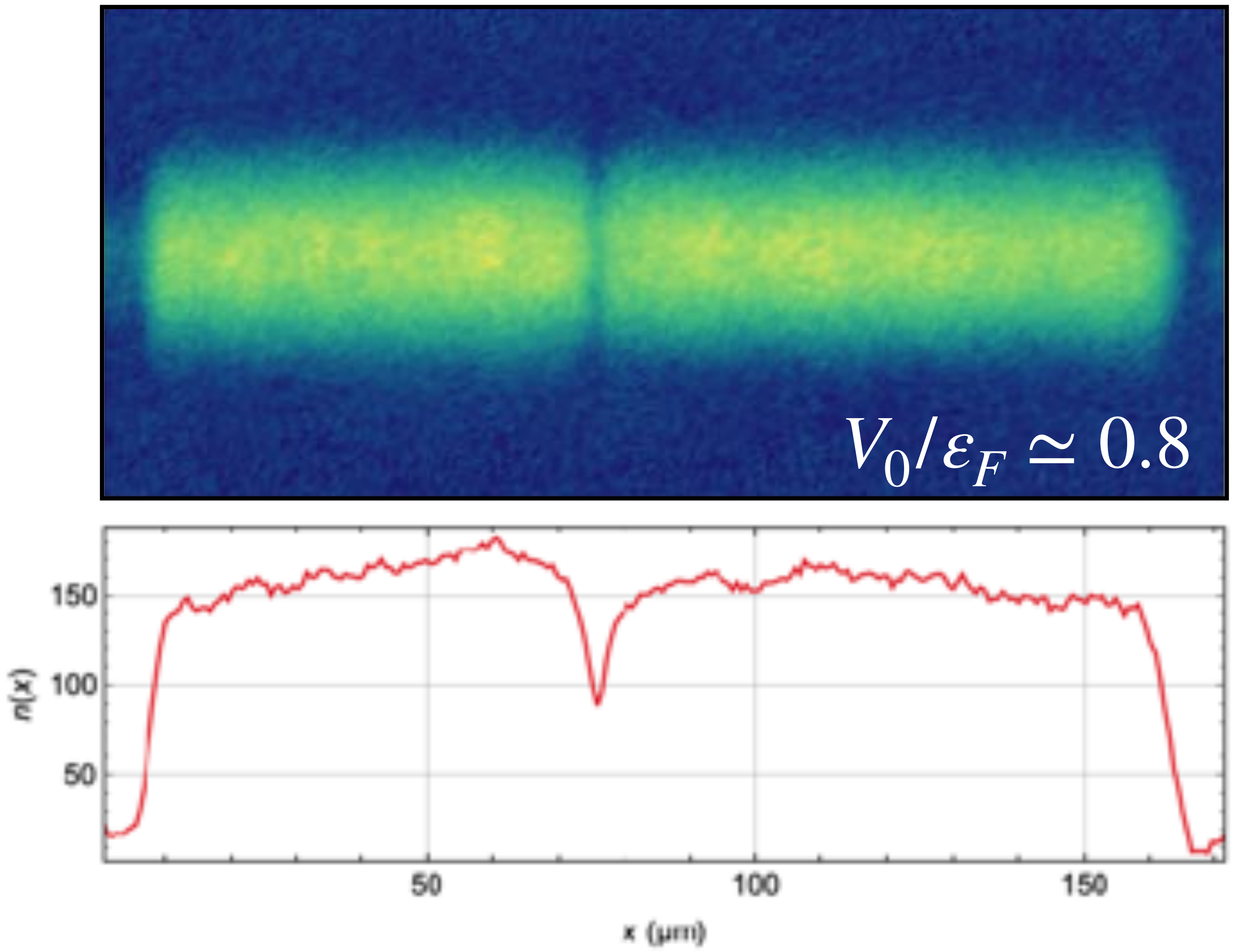
$$\Delta\mu = E_C(z - z_{eq}) \longrightarrow |z_{eq}| \simeq 0.15$$ for 10 μm movement

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

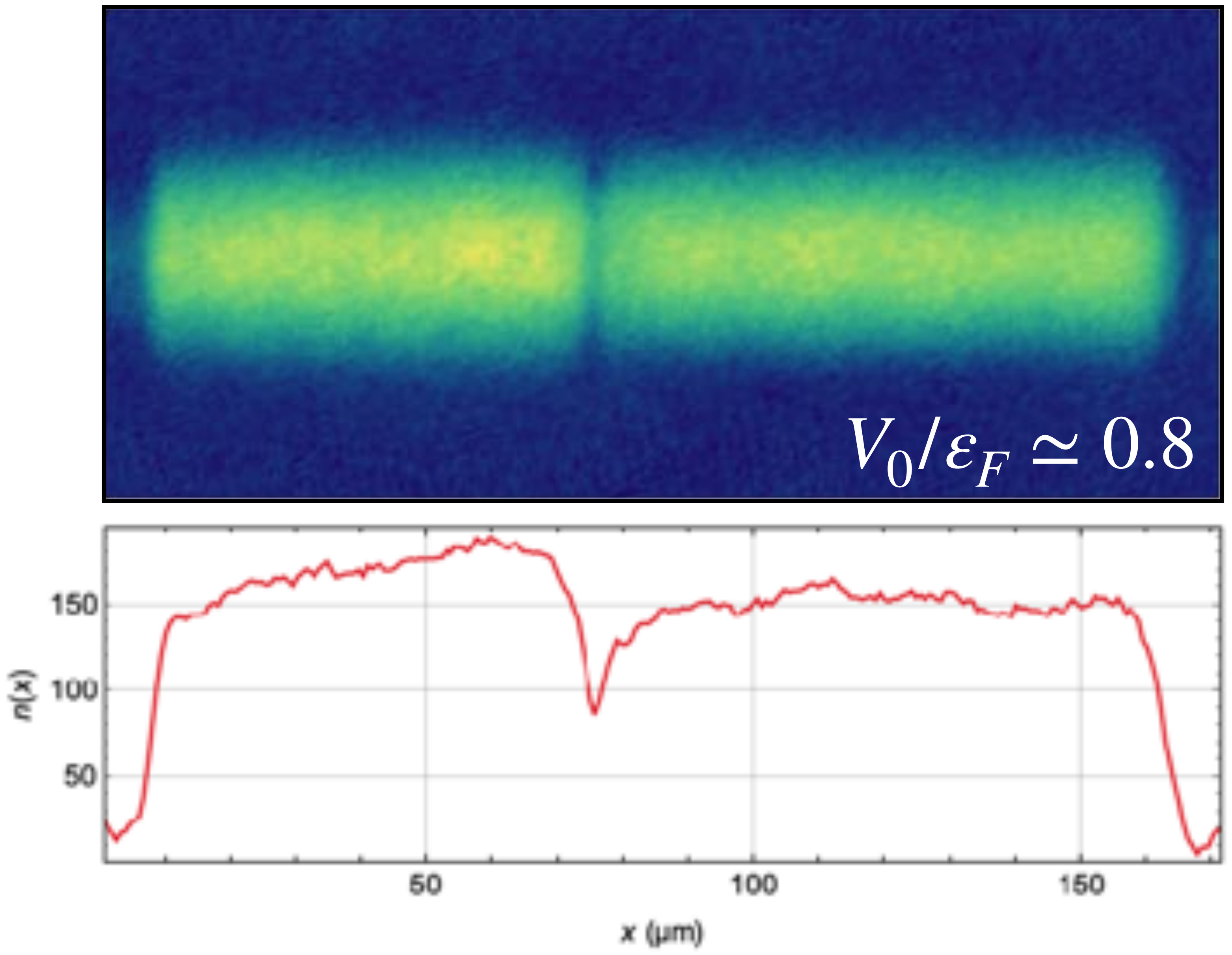
$v \simeq 0.3$ mm/s



$v \simeq 0.8$ mm/s

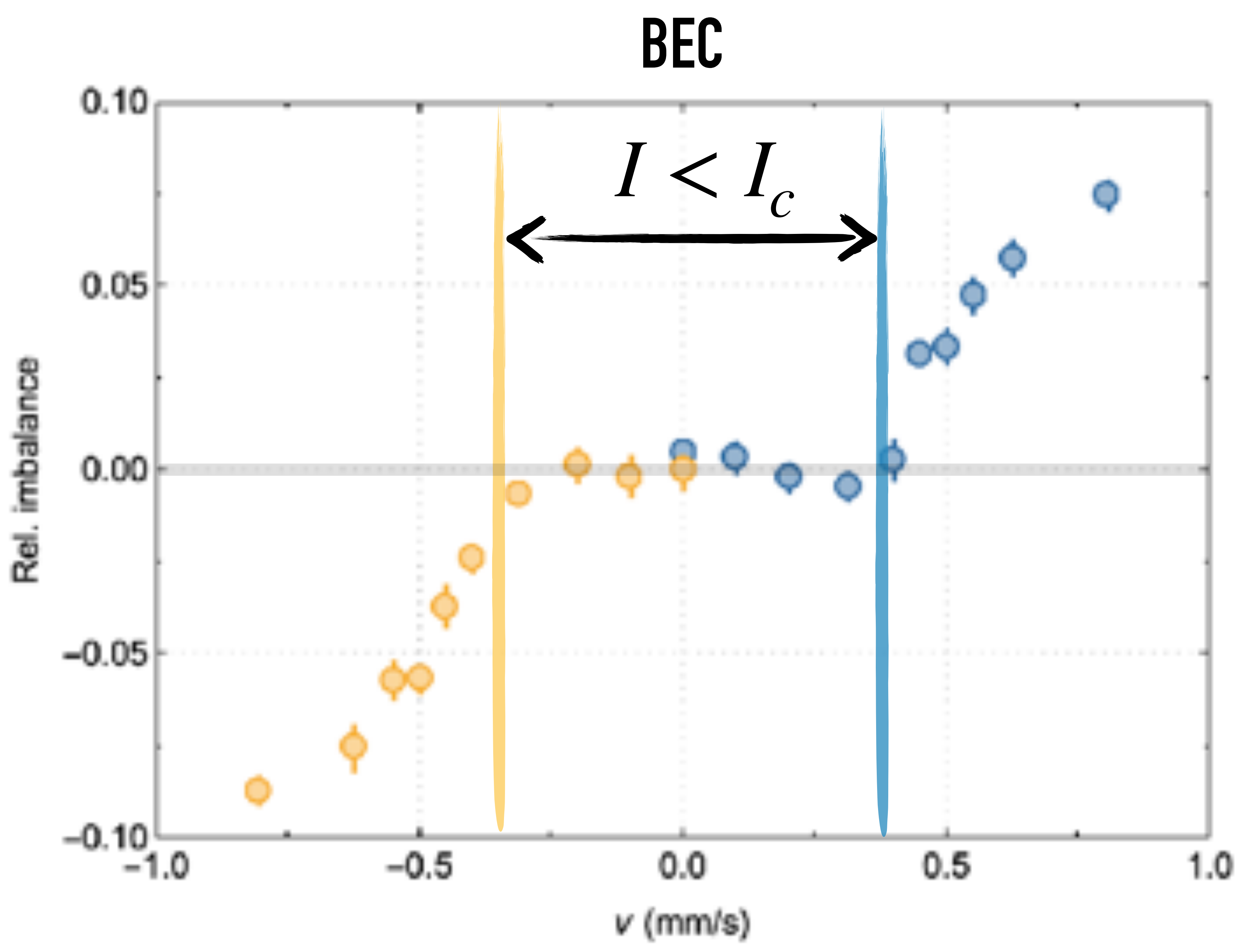


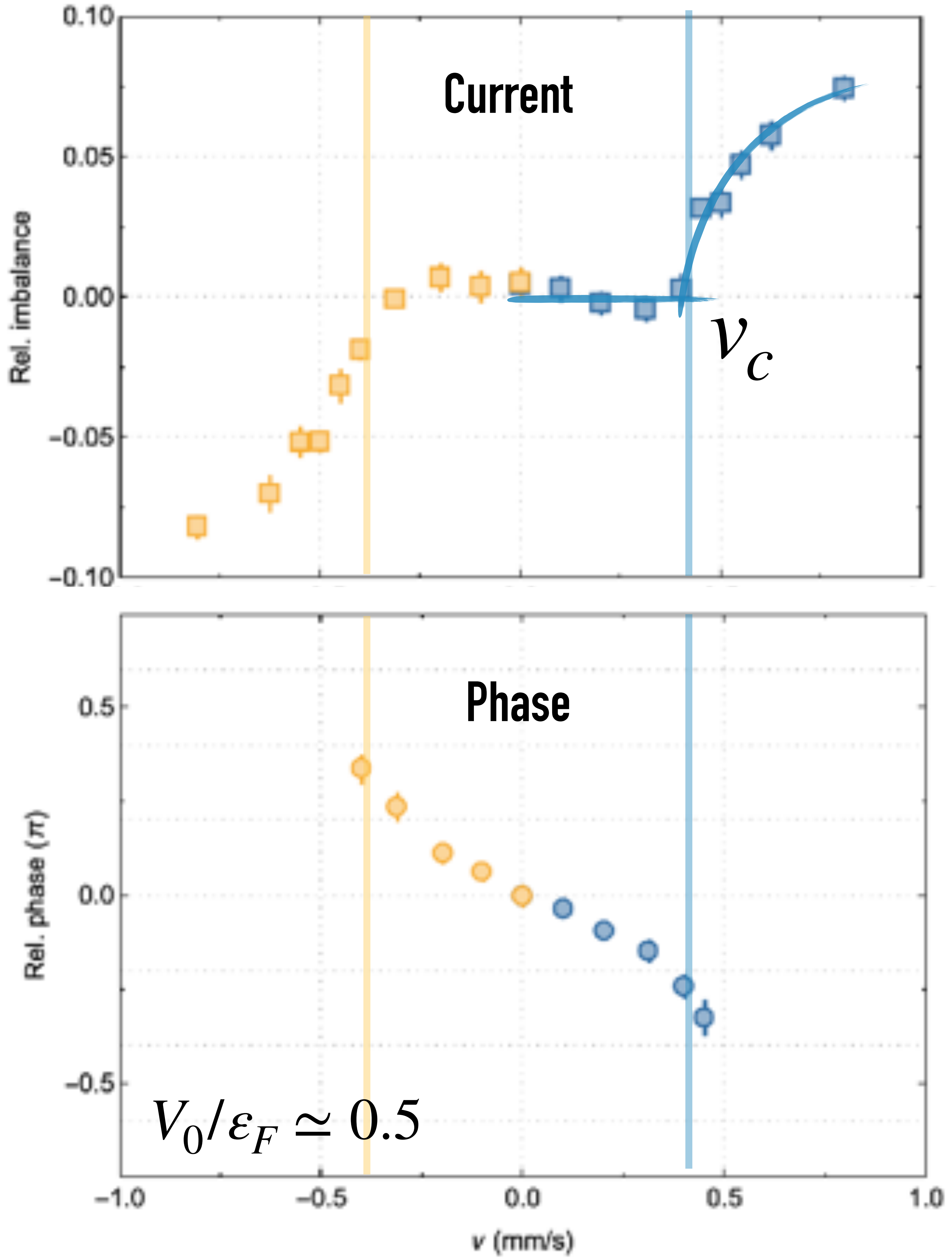
$v \simeq 1.5$ mm/s



Below critical velocity, superfluid flows entirely through barrier!

IV curve and Current-Phase Relation

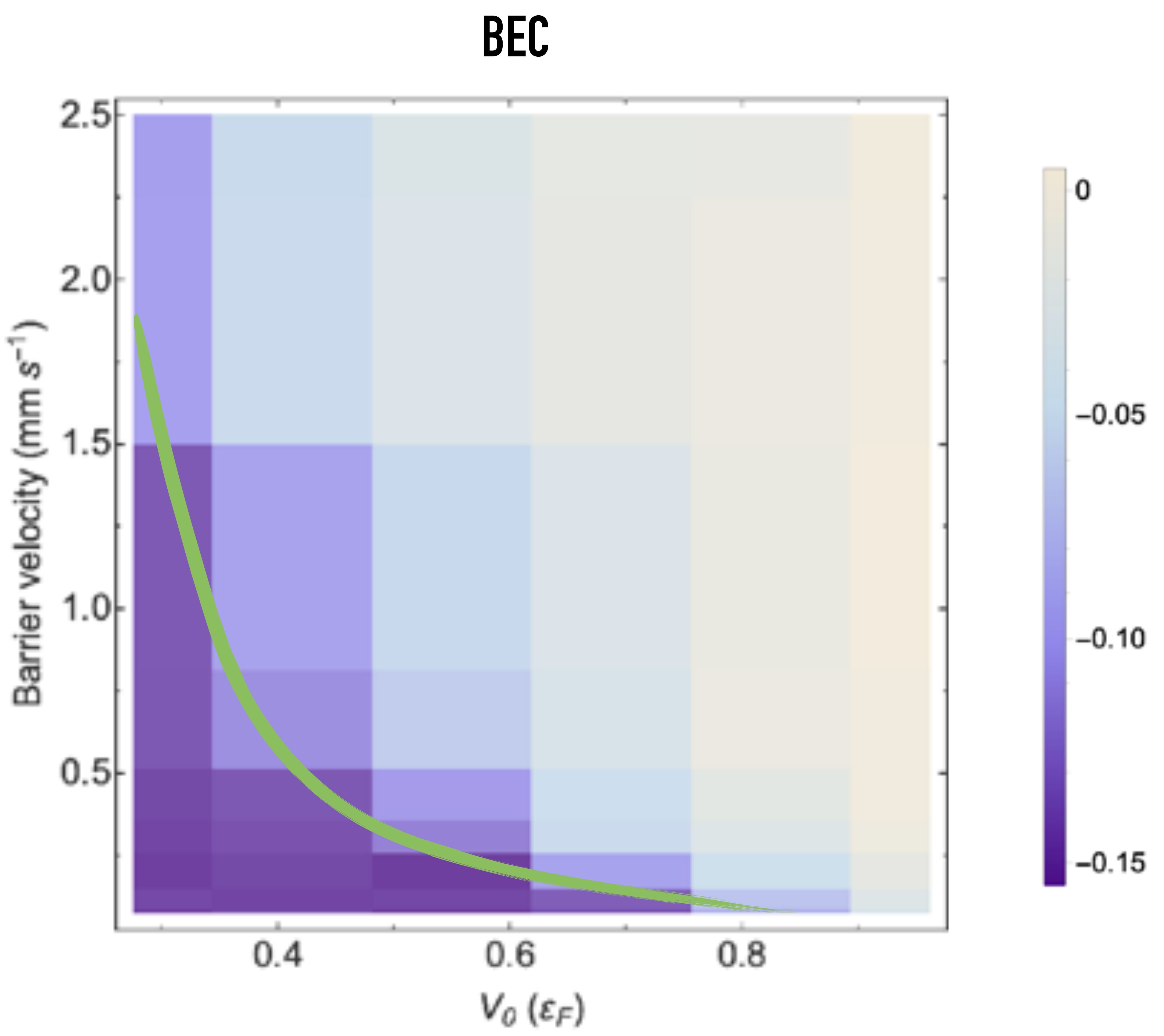


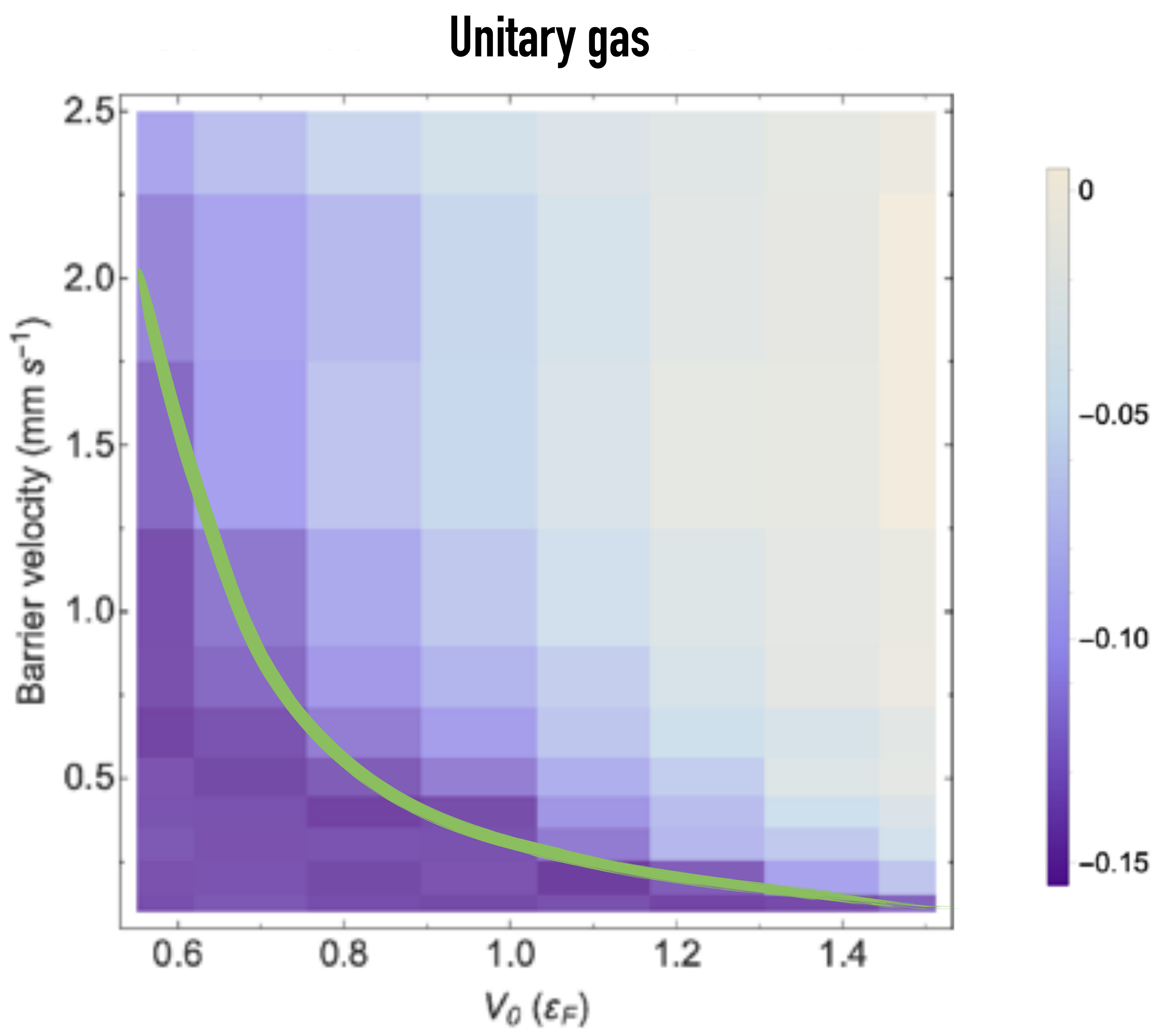


- Clear footprint of **DC Josephson effect !** Evolution can be modelled by RC-shunted junction circuit (...ongoing)
- Above critical current: finite Δμ is created, but smaller than superfluid gap ➛ **no excitation of quasiparticle branch** Only AC/MQST branch (unstable)

Critical Velocity

- Map out imbalance after barrier movement at **variable height V_0 and speed v**

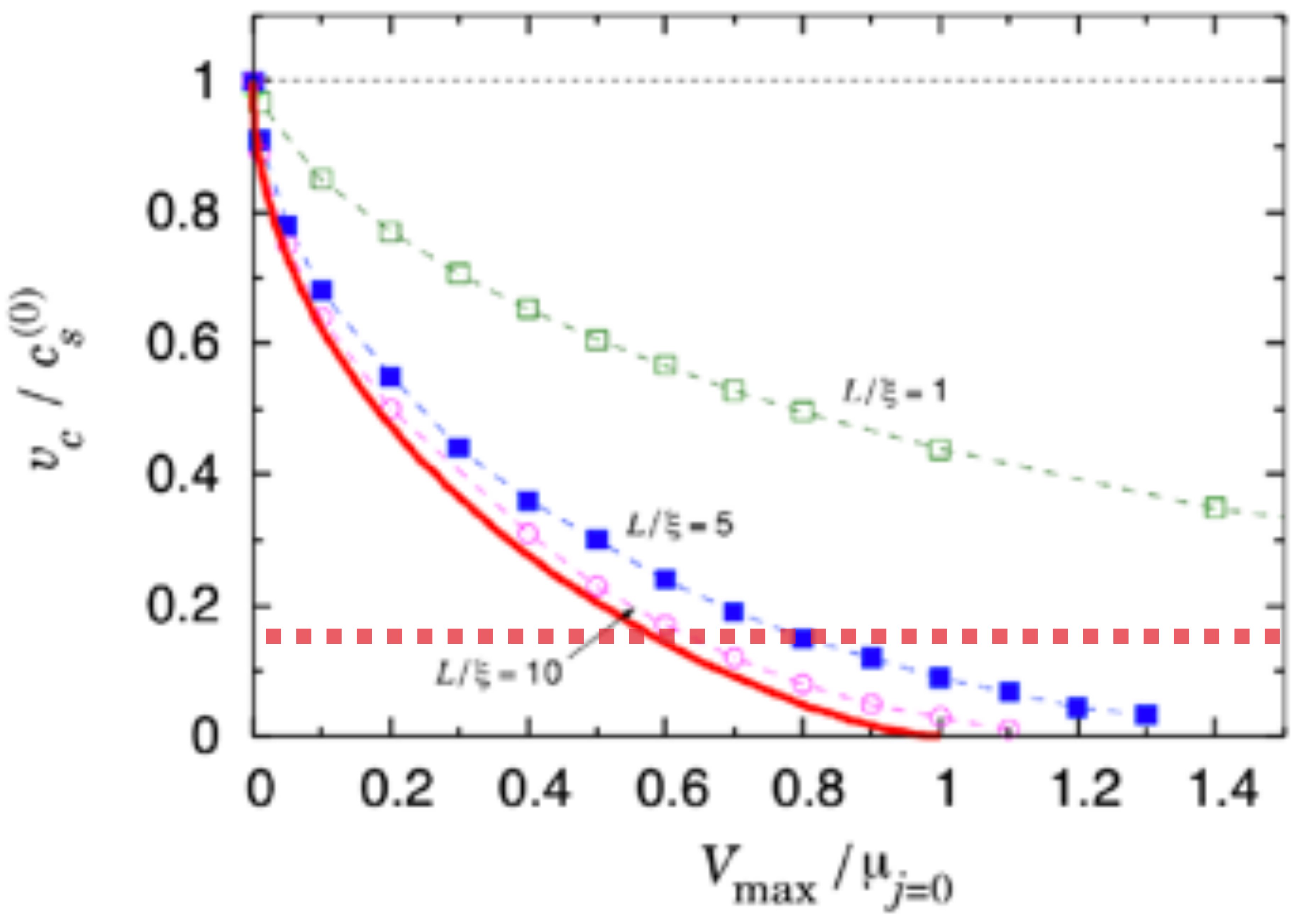


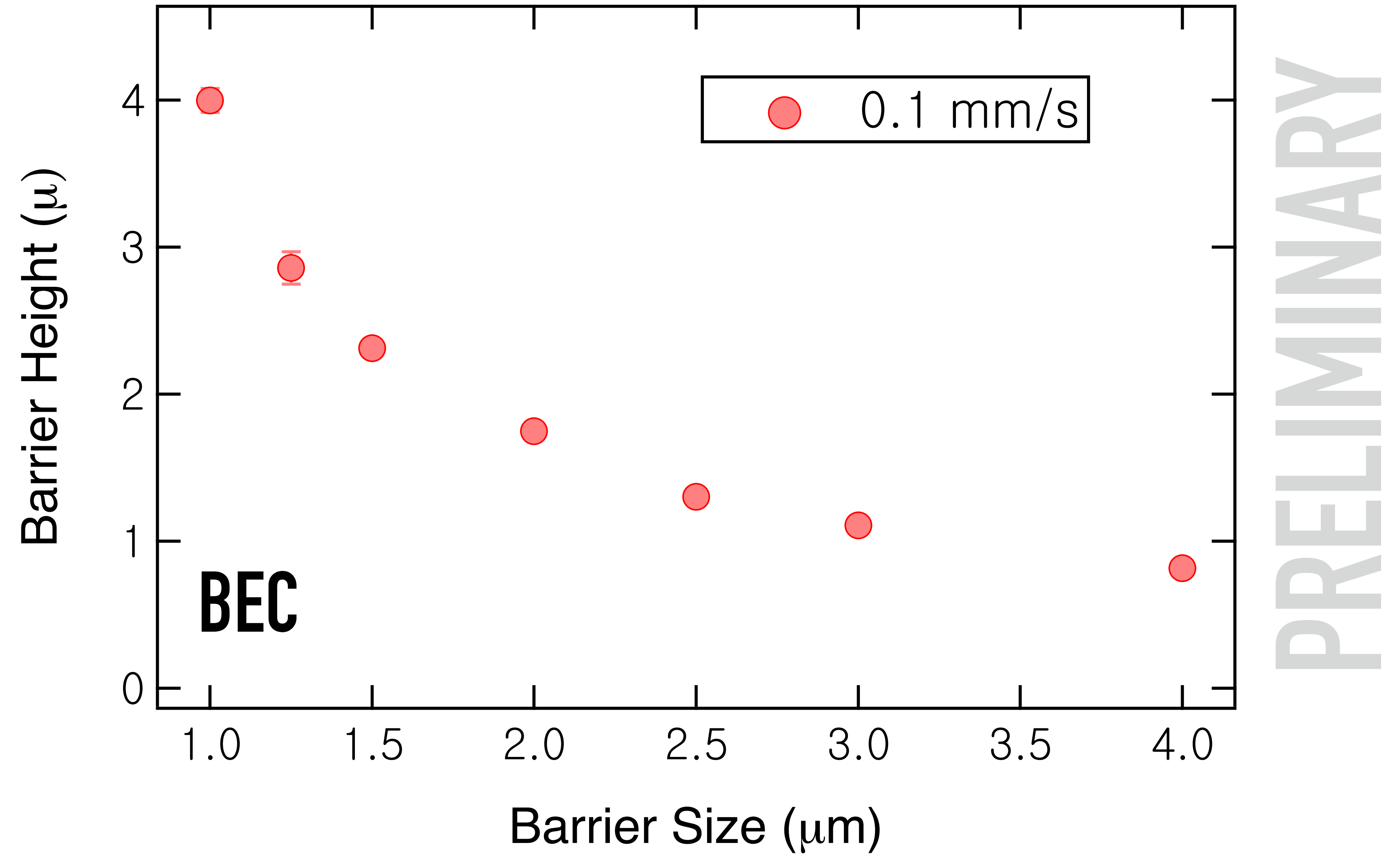


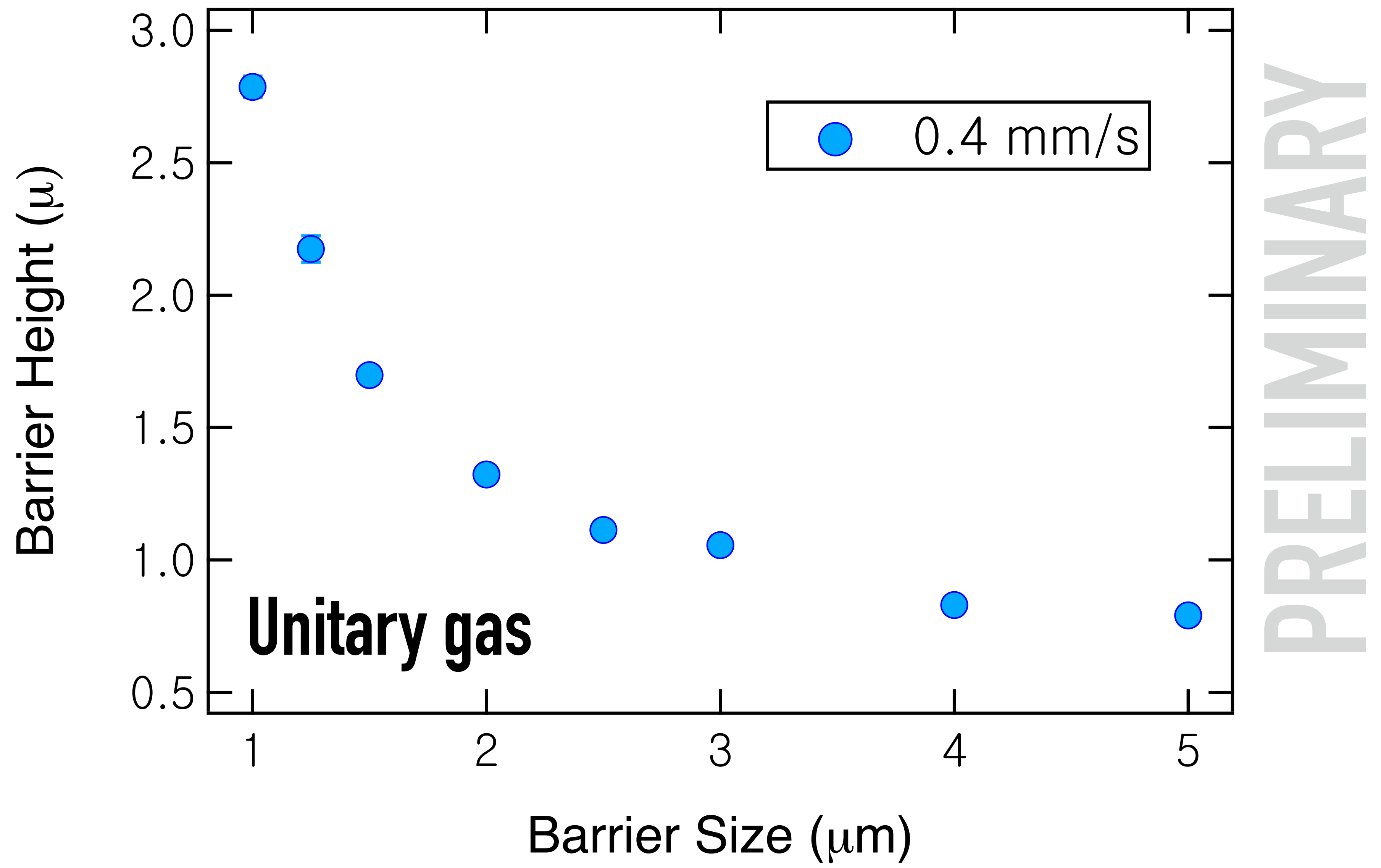
CRITICAL BARRIER HEIGHT VS SIZE

- **Extract critical barrier height V_0 at constant velocity v**
  ➙ varying the barrier size

Watanabe et al., “Critical velocity of superfluid flow through single barrier and periodic potentials”. *PRA* **80**, 053602 (2009)

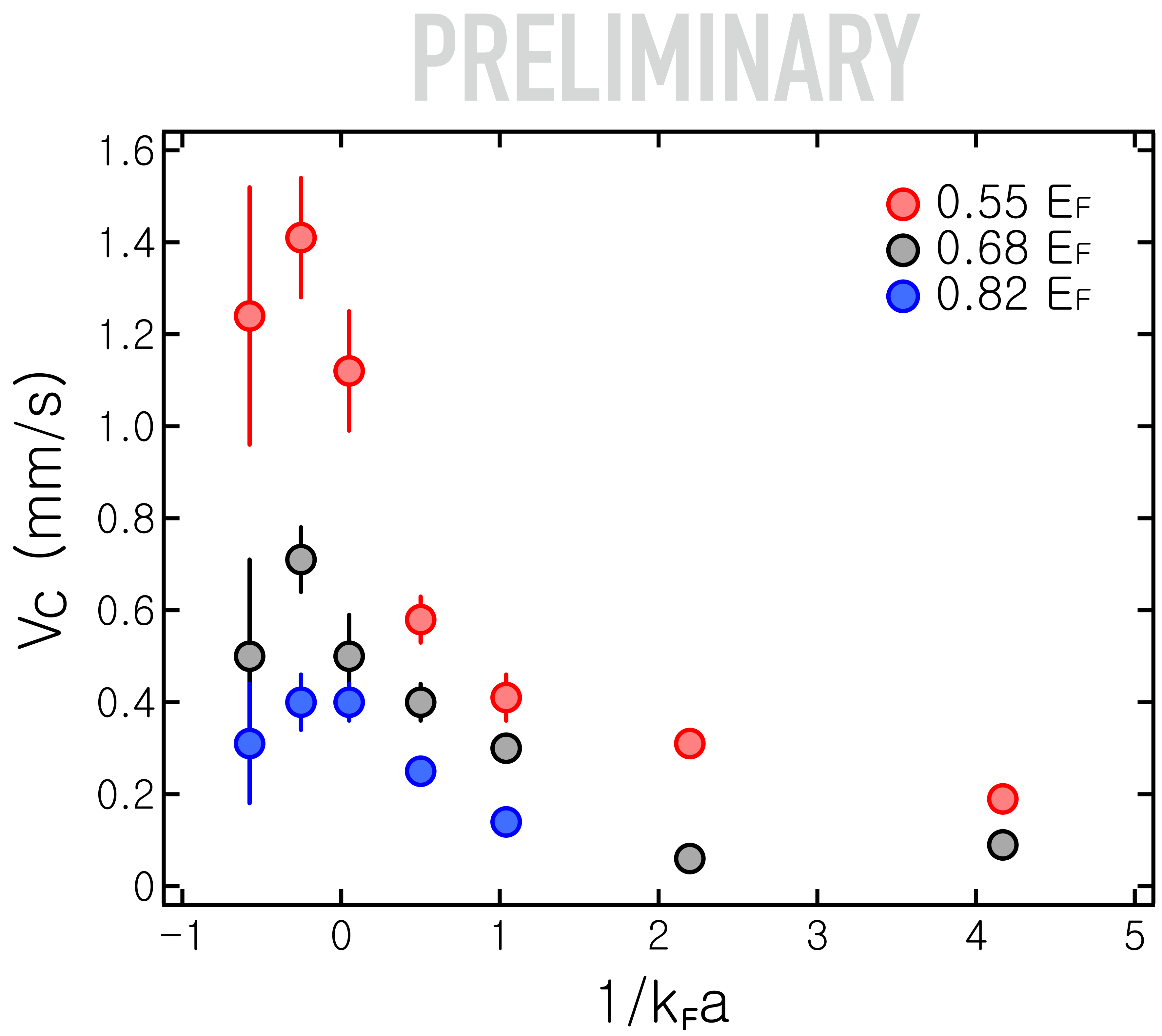




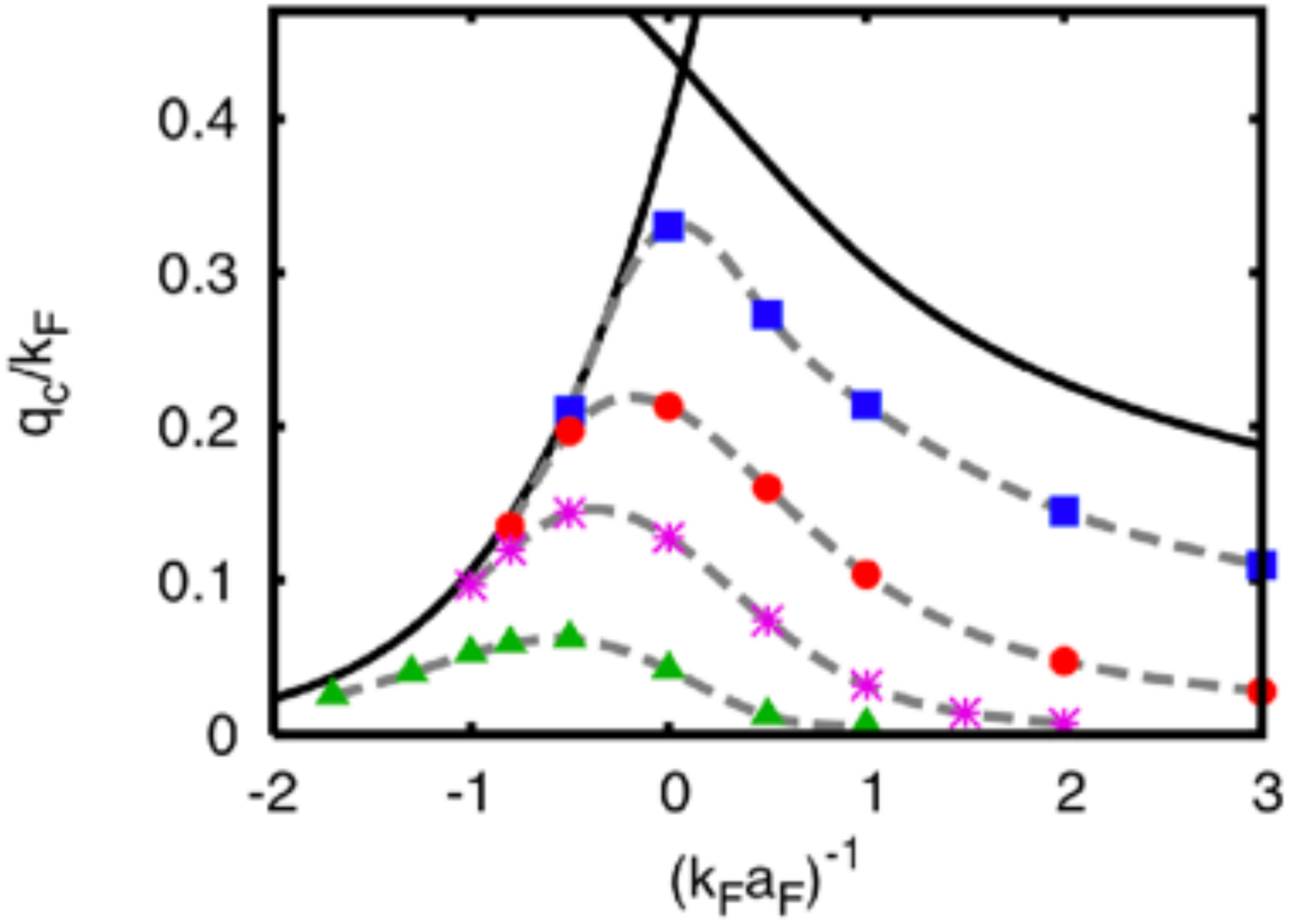


Critical Velocity vs Interaction Strength

- **Extract critical velocity as a function of 1/(*k*F*a*)**



Spuntarelli et al., *PRL* **99**, 040401 (2007)



- **Maximum critical velocity is located slightly on BCS side of resonance**

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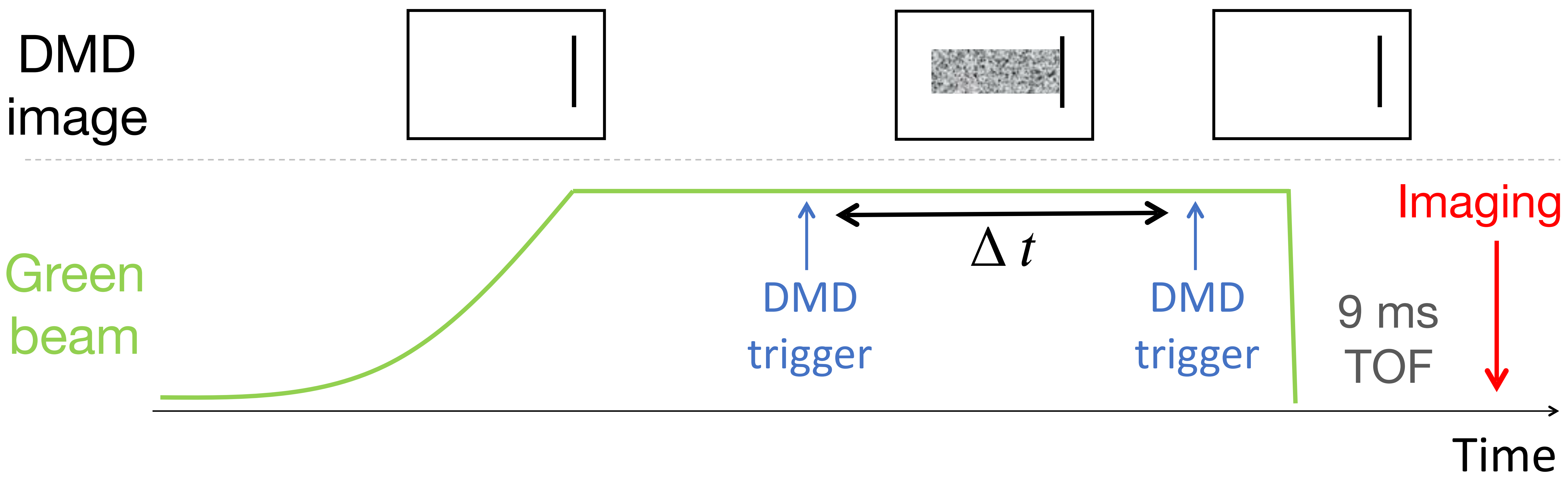
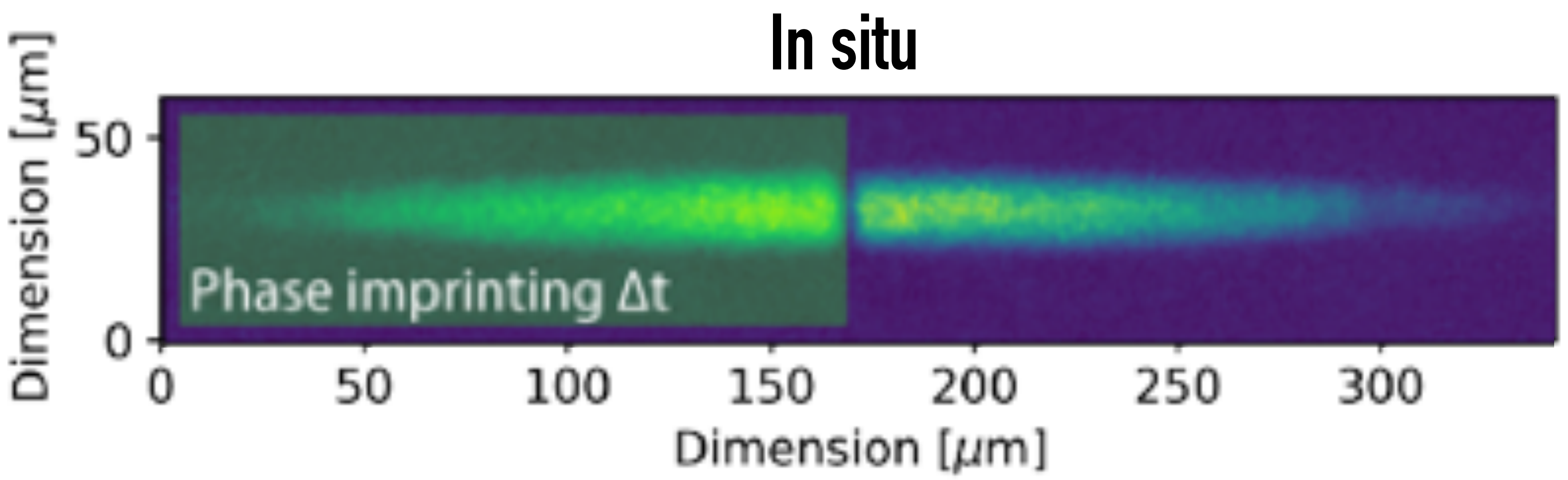
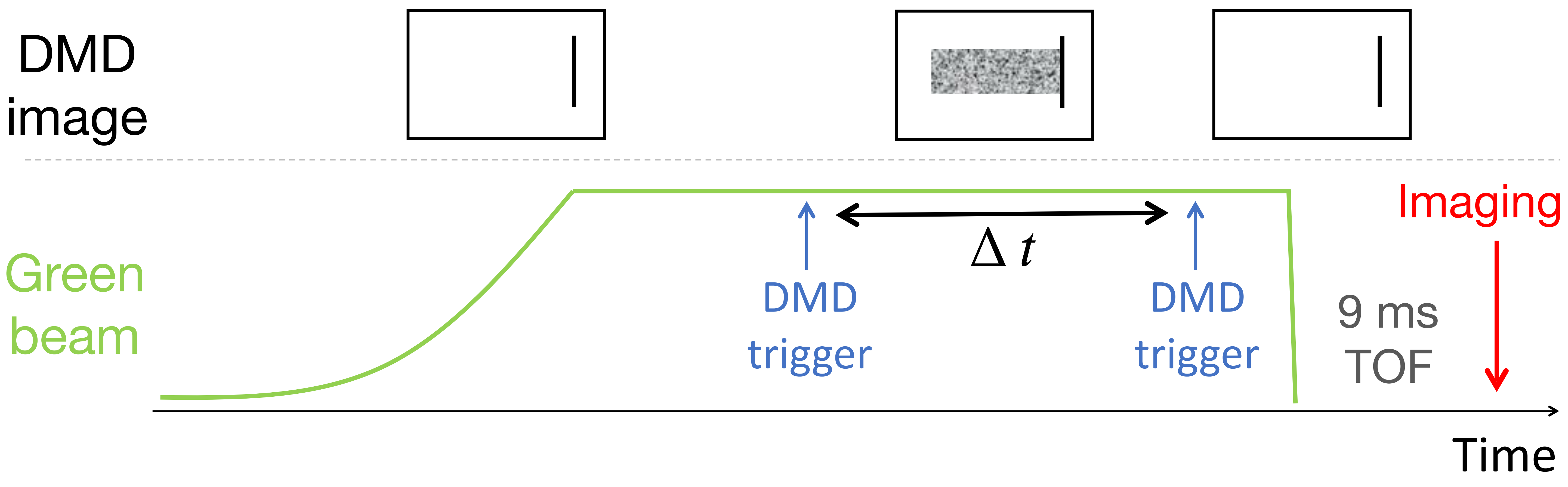
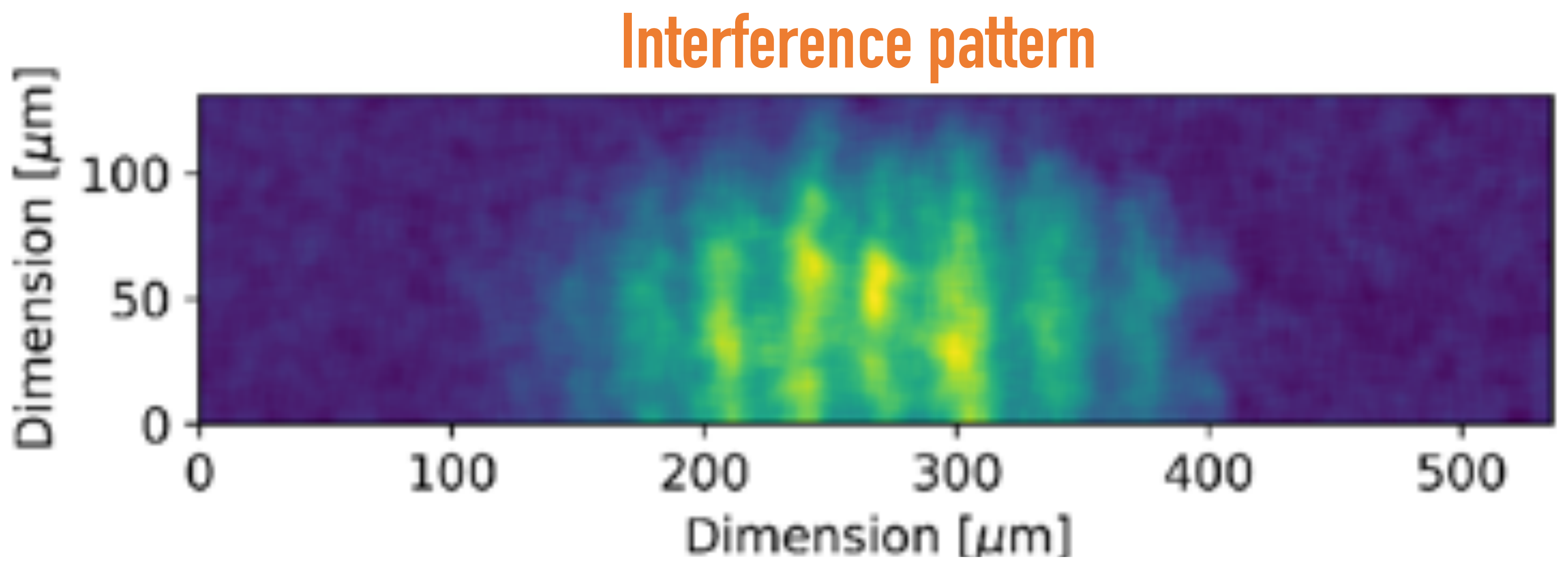
Local Phase Control: Phase Imprinting

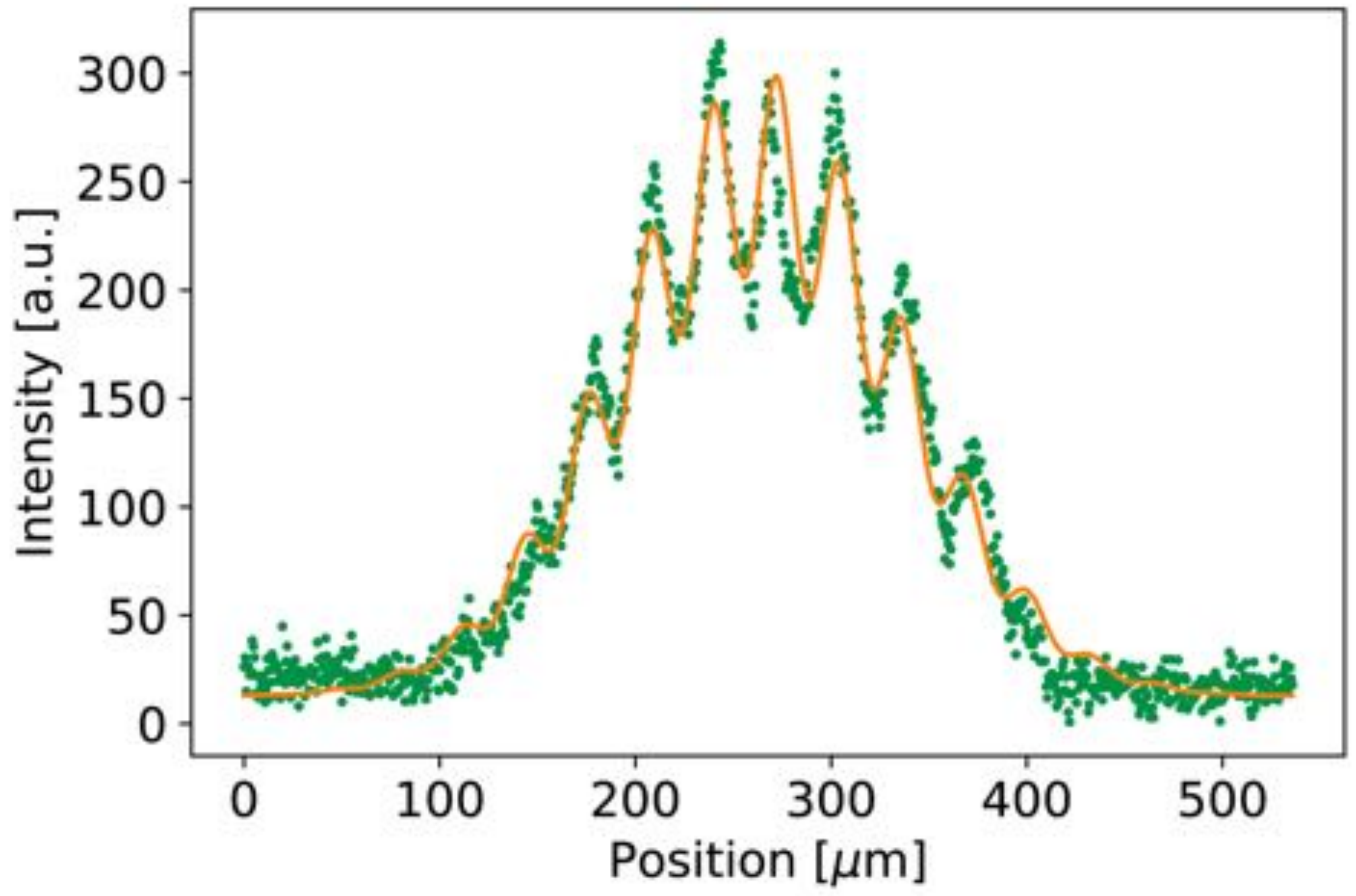




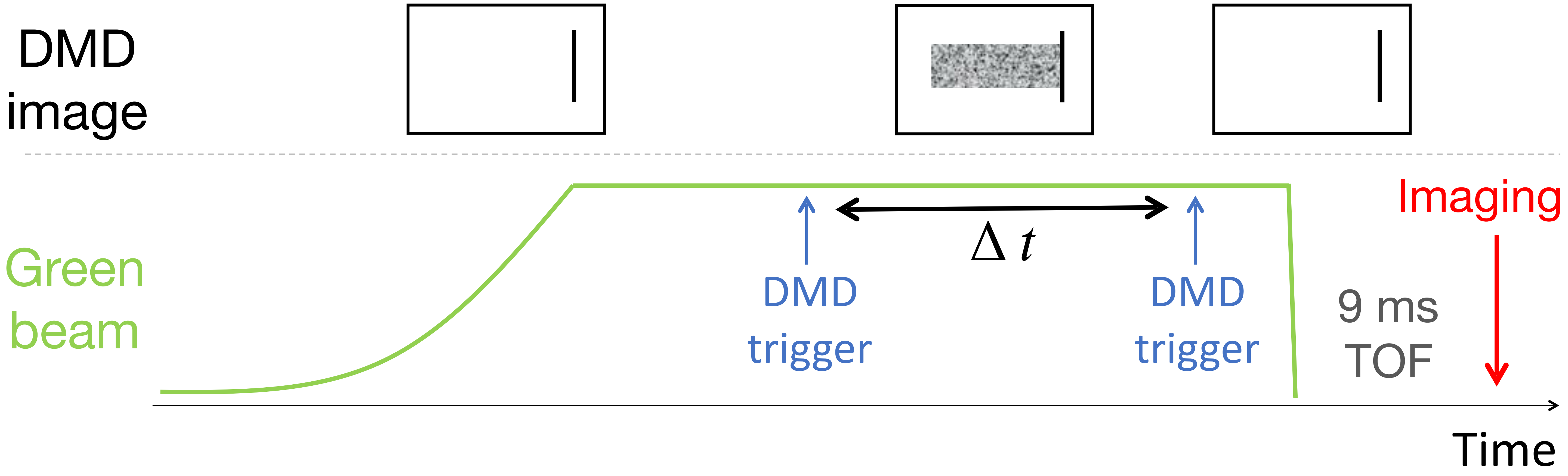
Local Phase Control: Phase Imprinting



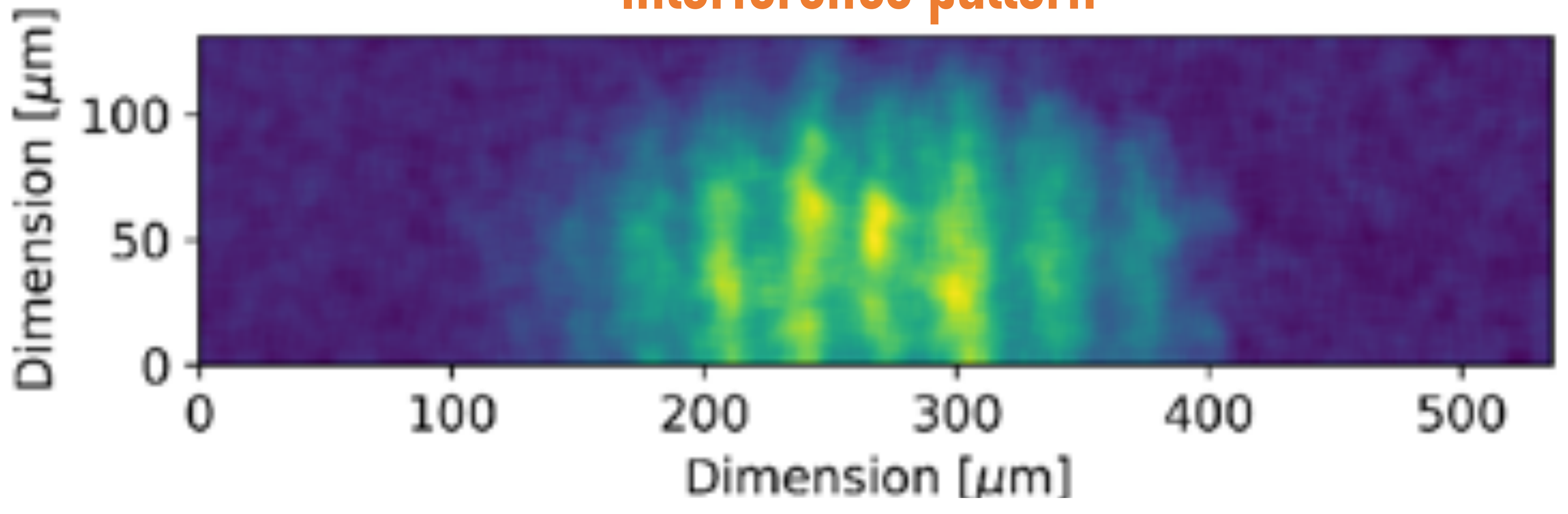




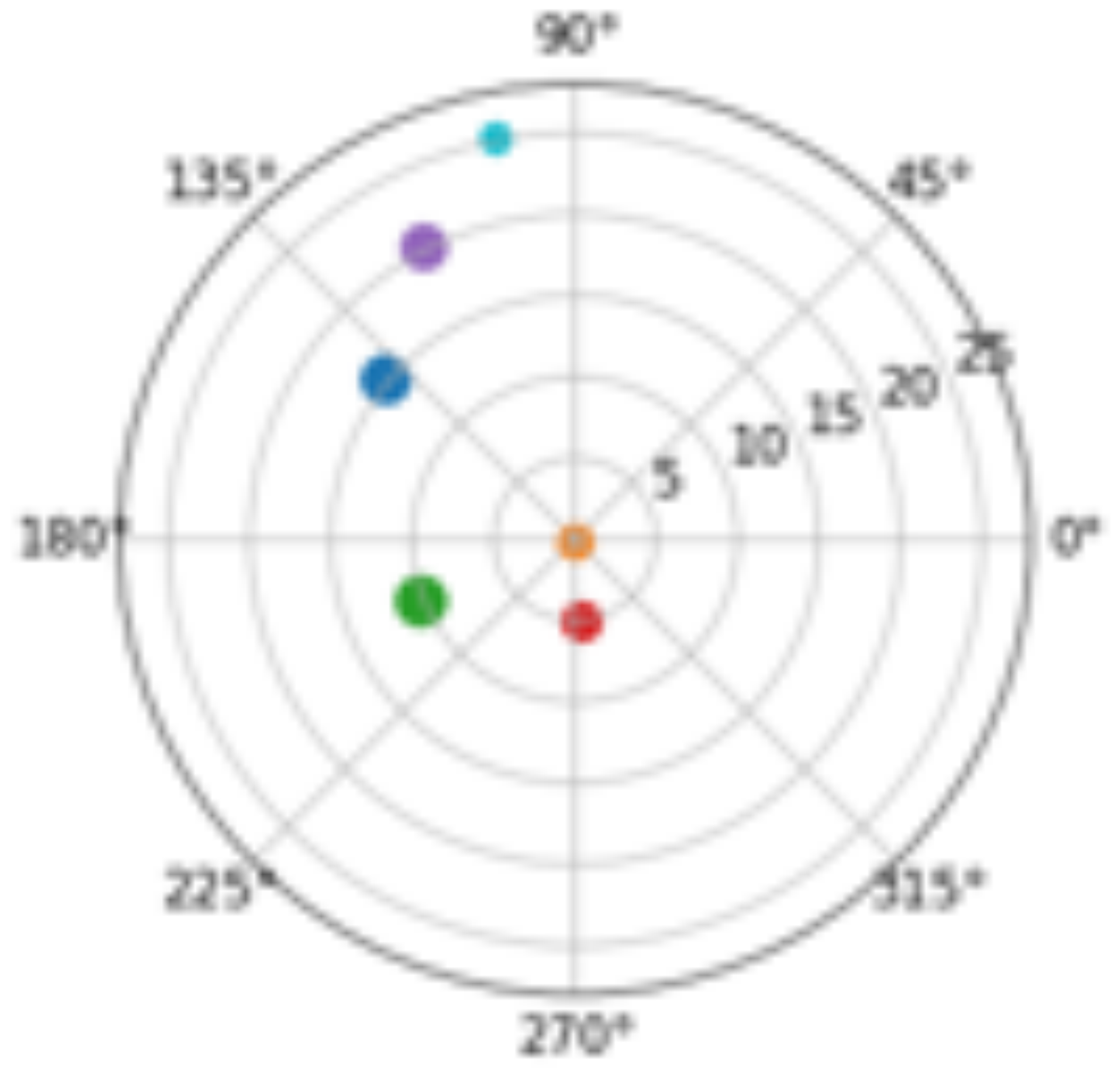
Local Phase Control: Phase Imprinting

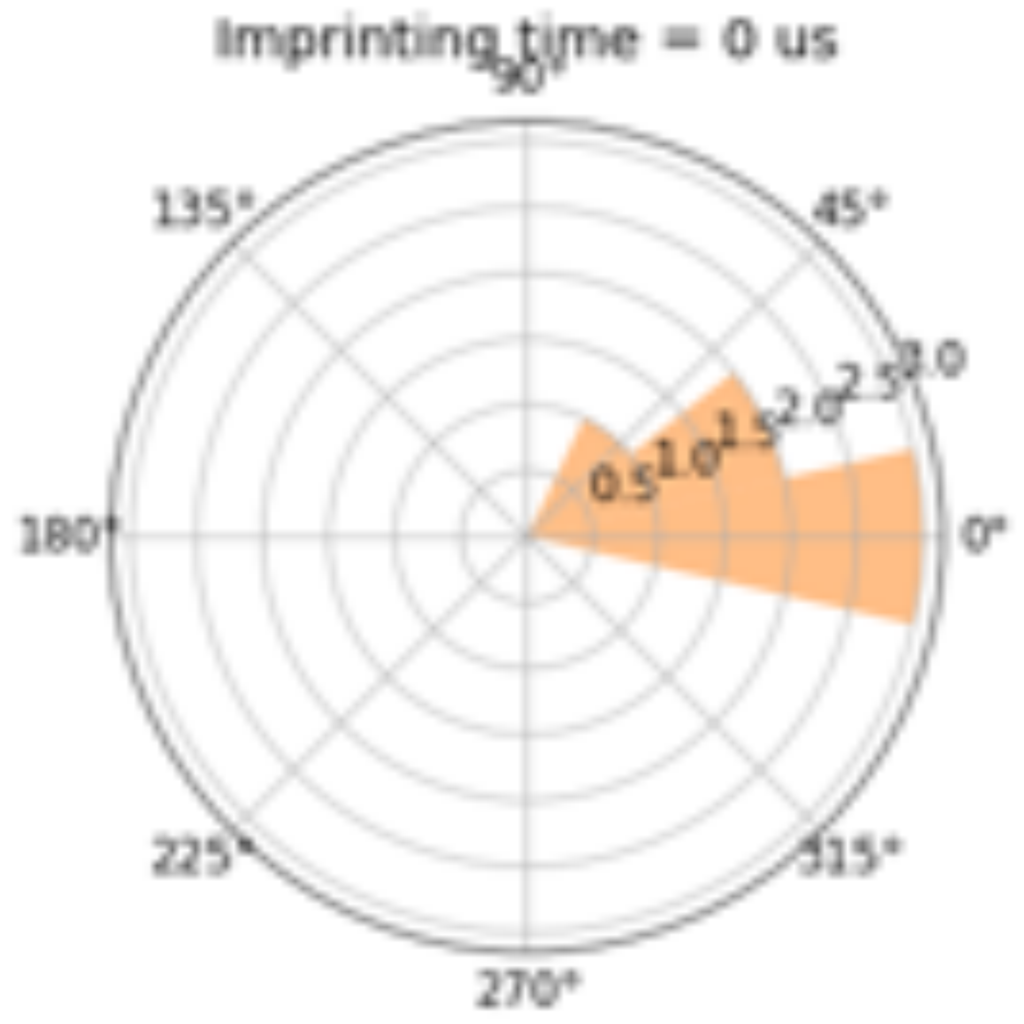


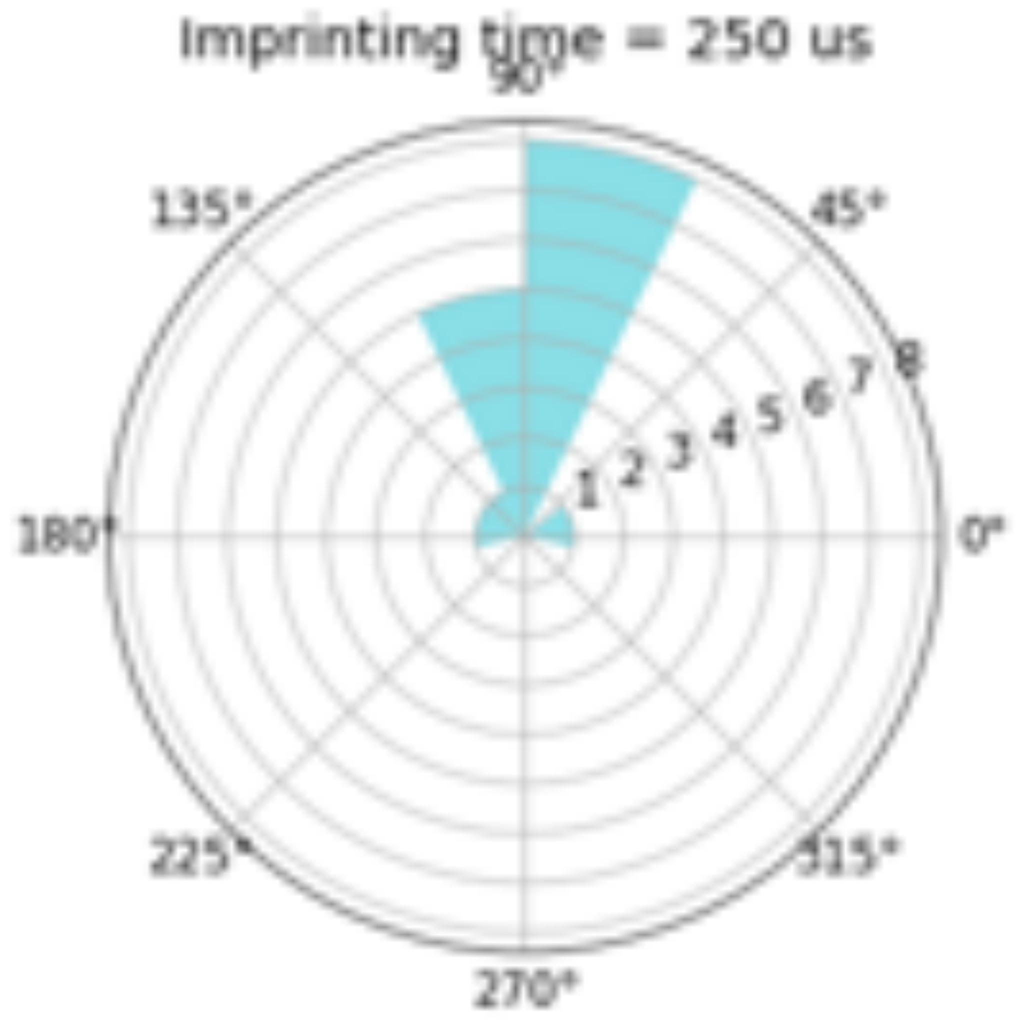
Interference pattern



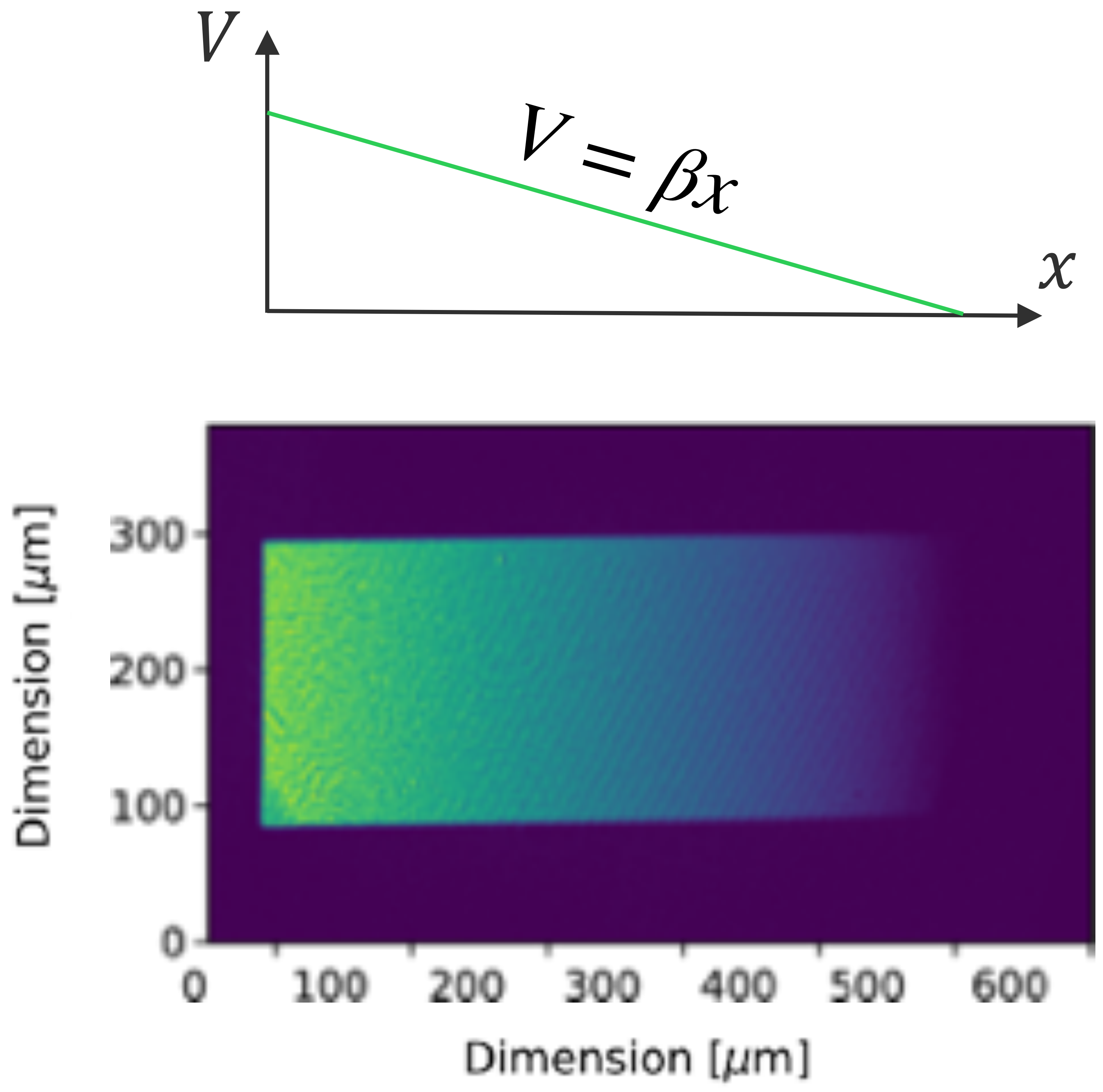
Imprinted phase

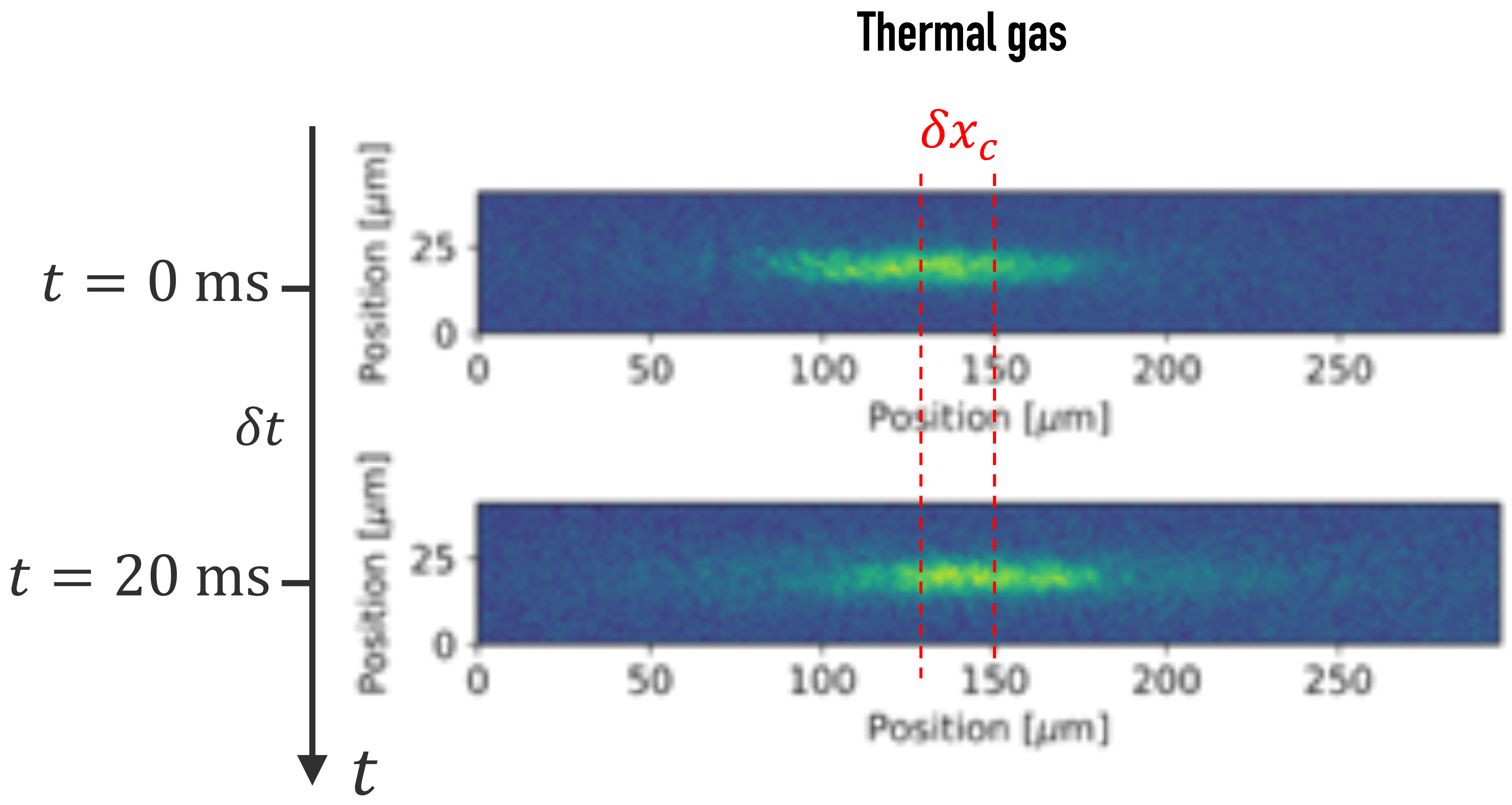






Local Phase Control: Velocity Imprinting



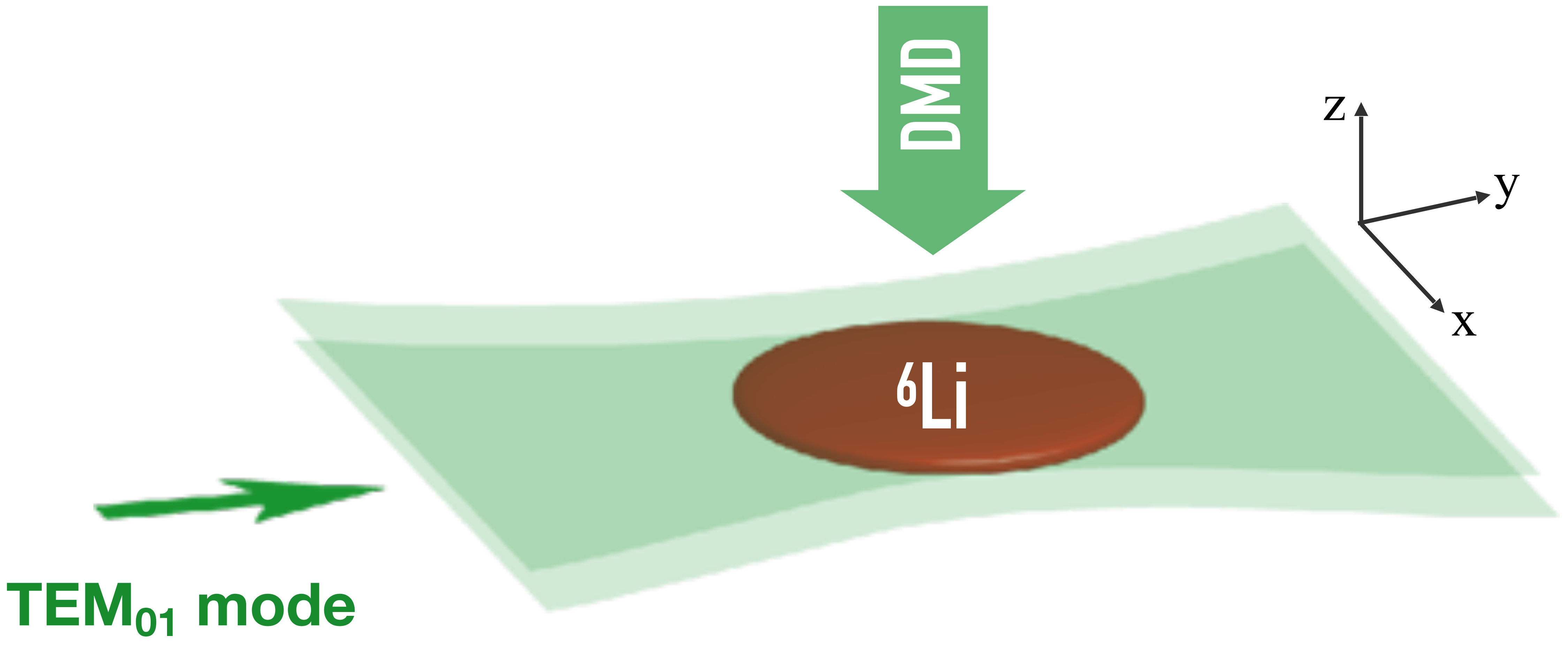


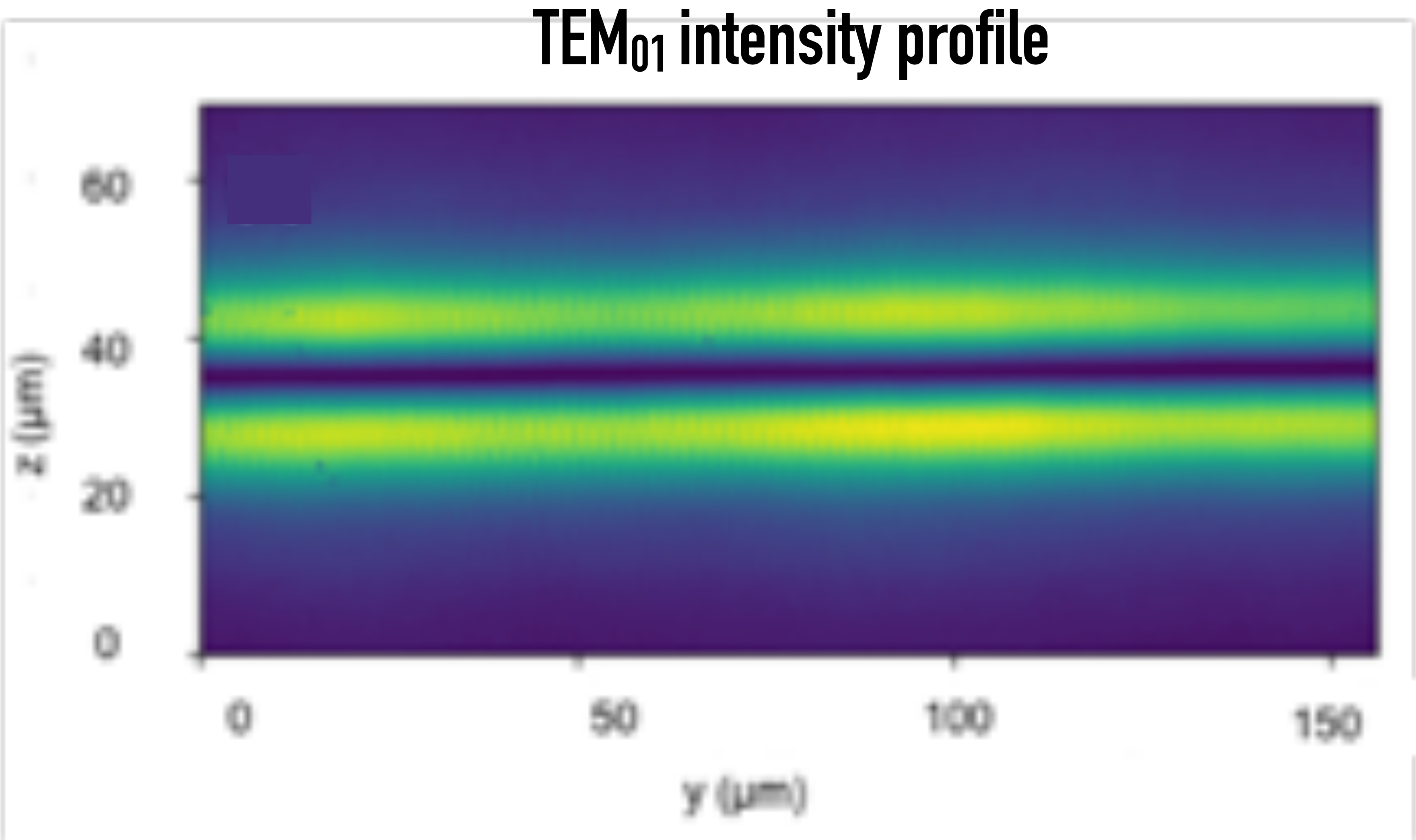
$$v(t) = \frac{1}{m}\beta t \longrightarrow$$

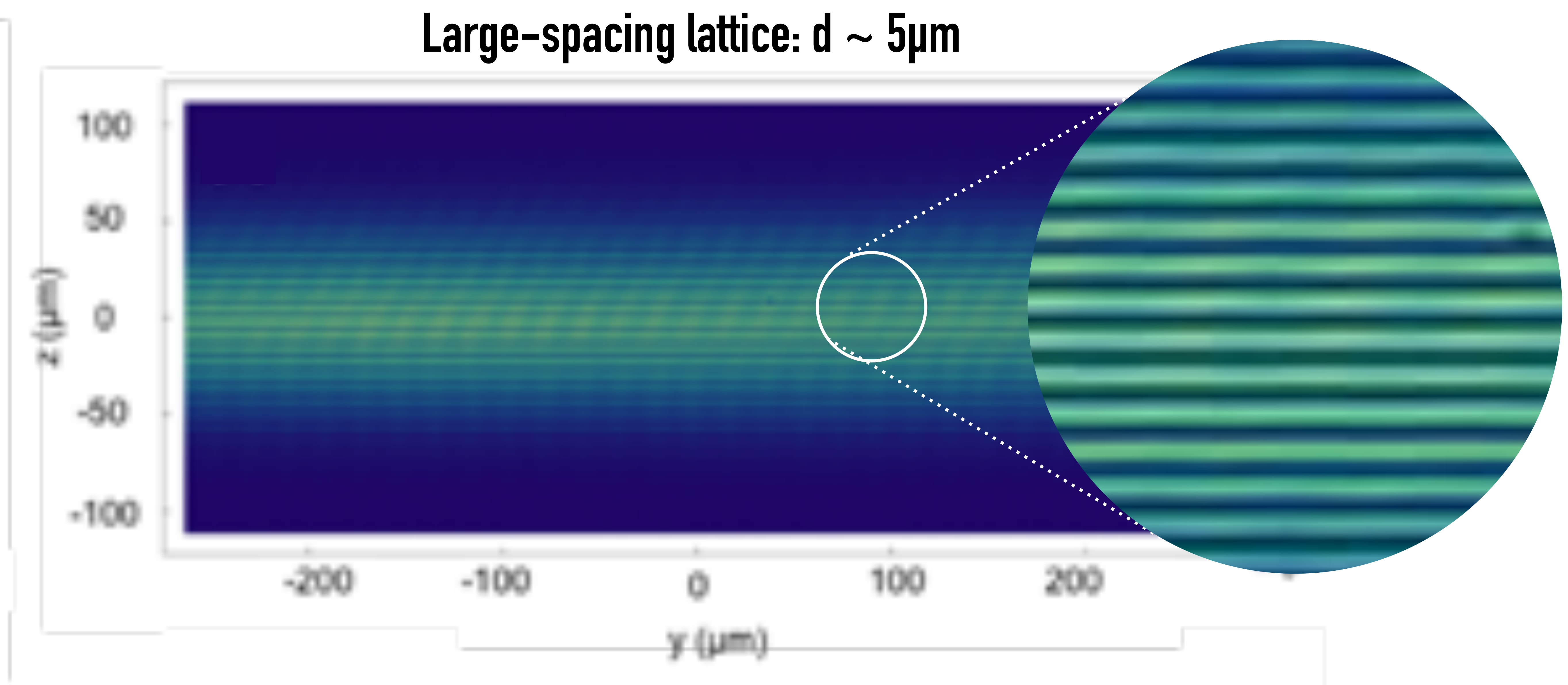
$$\left(\frac{\hbar}{m_{Li}}\right)_t \approx 1.06\times10^{-8}\ \frac{\mathrm{m}^2}{\mathrm{s}}$$

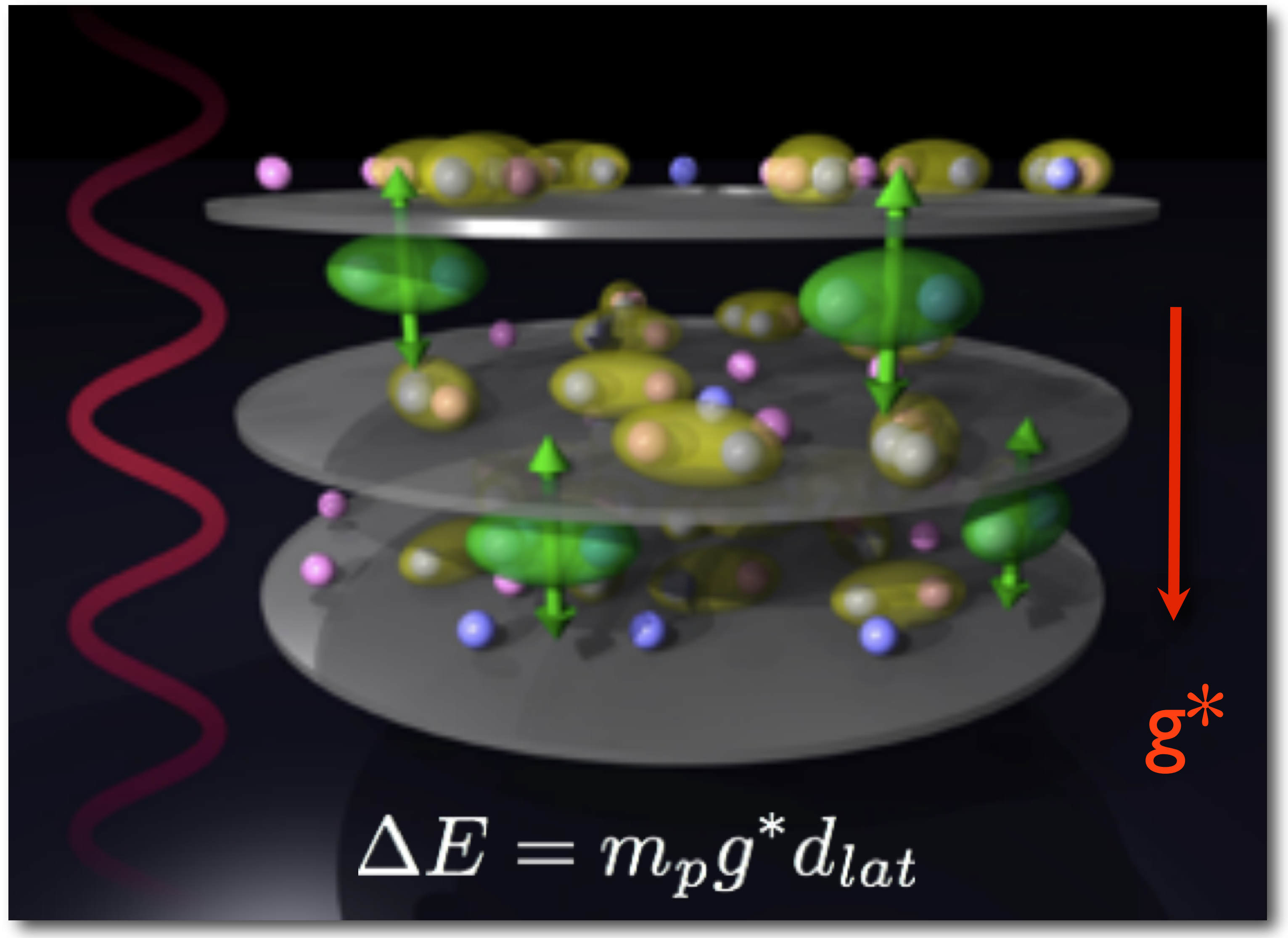
$$\left(\frac{\hbar}{m_{Li}}\right)_m \approx (1.4 \pm 0.2)\times10^{-8}\ \frac{\mathrm{m}^2}{\mathrm{s}}$$

Two-Dimensional Potentials

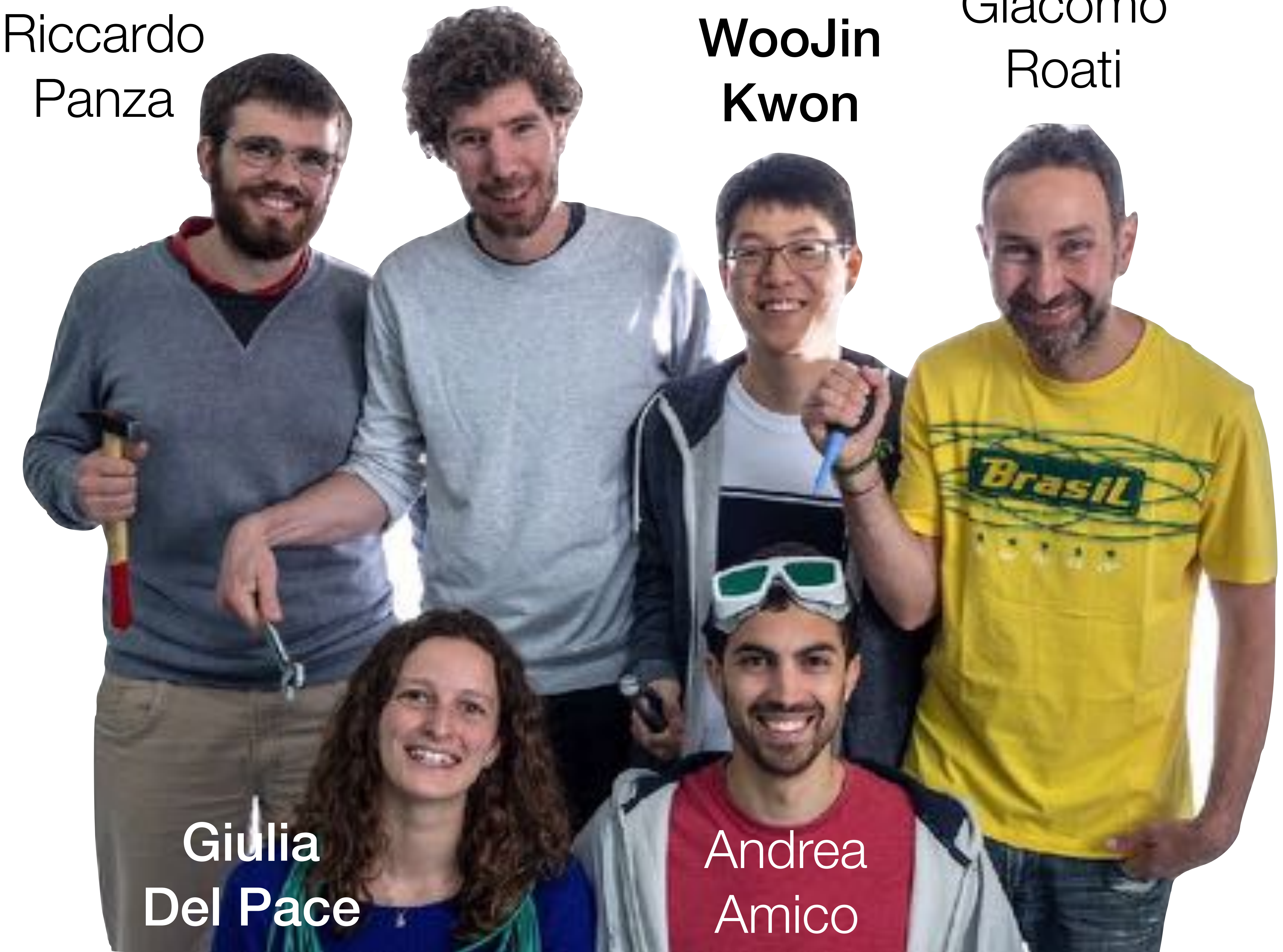








The Lithium Lab at LENS



Matteo Zaccanti

Massimo Inguscio

Visit us!

THANK YOU!

Collaborators and former members:

Nick Proukakis (Newcastle)
Andrea Trombettoni (Trieste)
Pietro Massignan (UPC)
Wolfgang Ketterle (MIT)
Luca Pezzé (CNR-INO)

Giacomo Valtolina (JILA)
Alessia Burchianti (CNR-INO)
Chiara Fort (University of Florence)
Eleonora Lippi (Heidelberg)