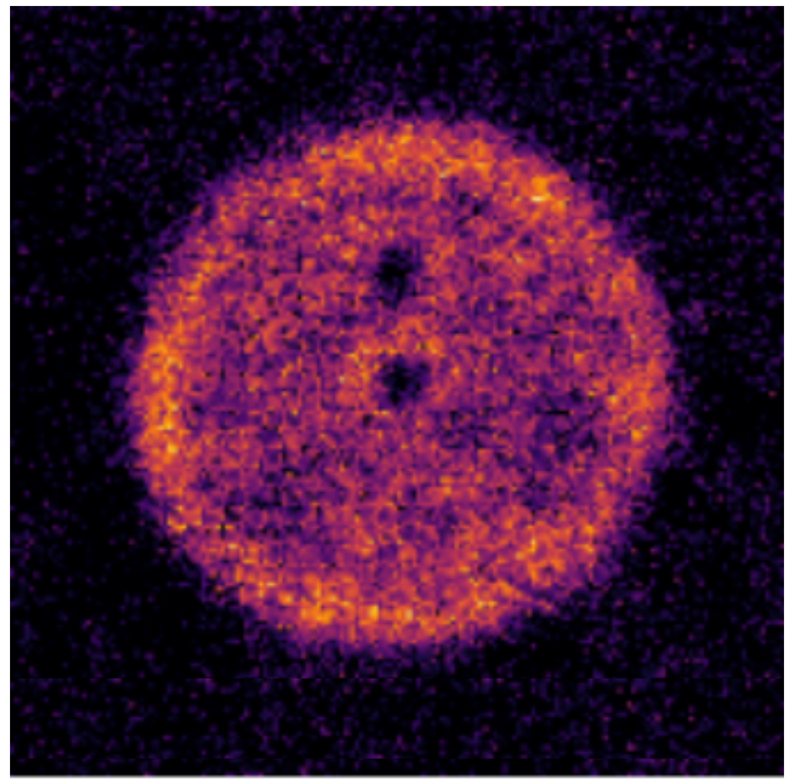
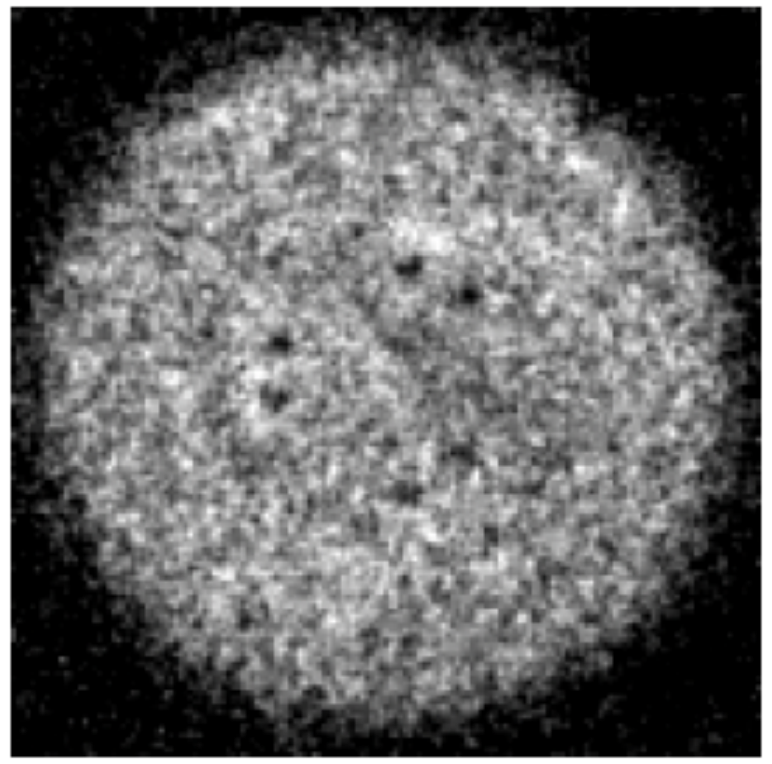
VORTEX DYNAMICS IN STRONGLY-INTERACTING ATOMIC FERMI SUPERFLUIDS: FROM FEW TO MANY

Giulia Del Pace

University of Florence





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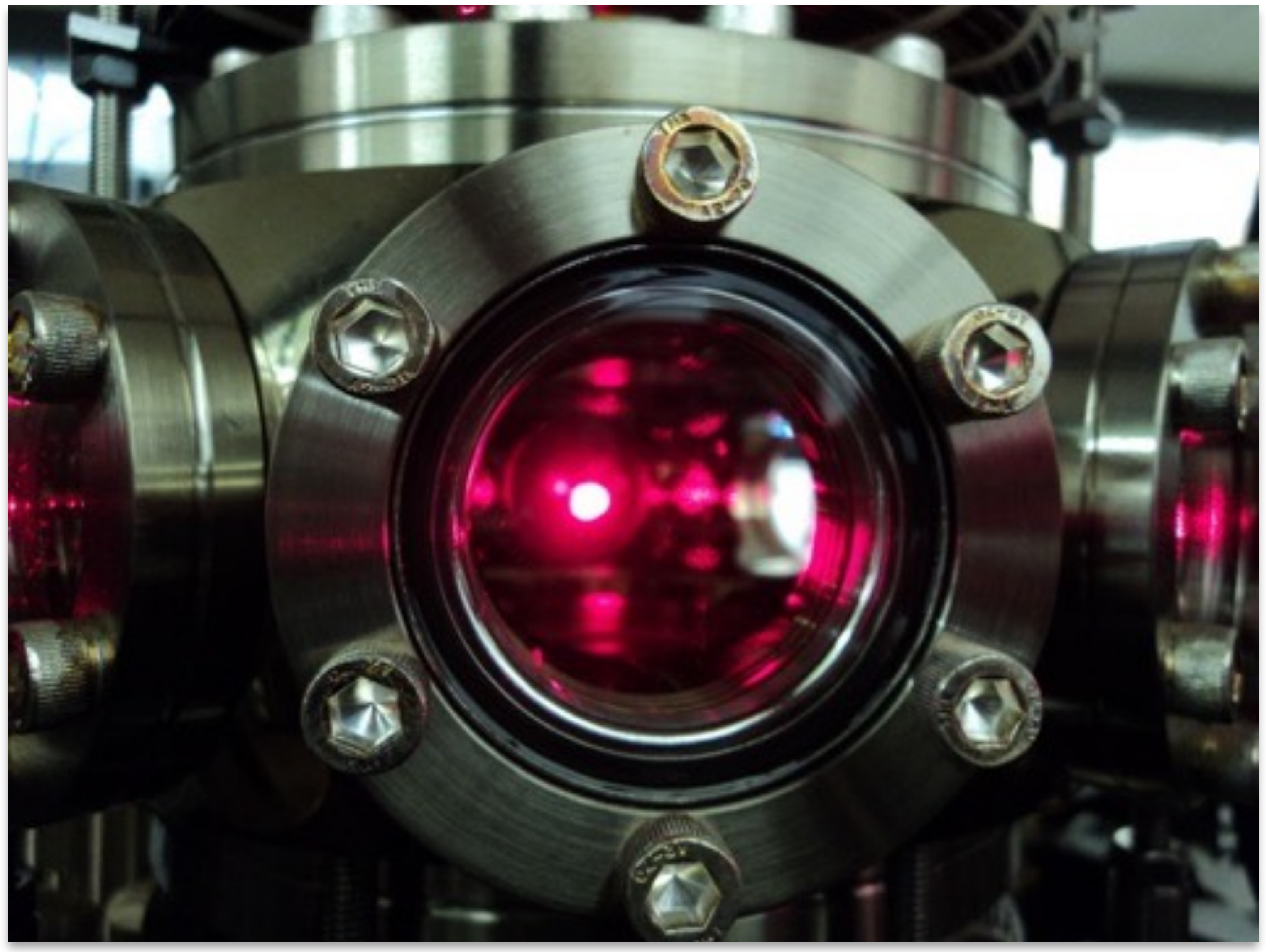
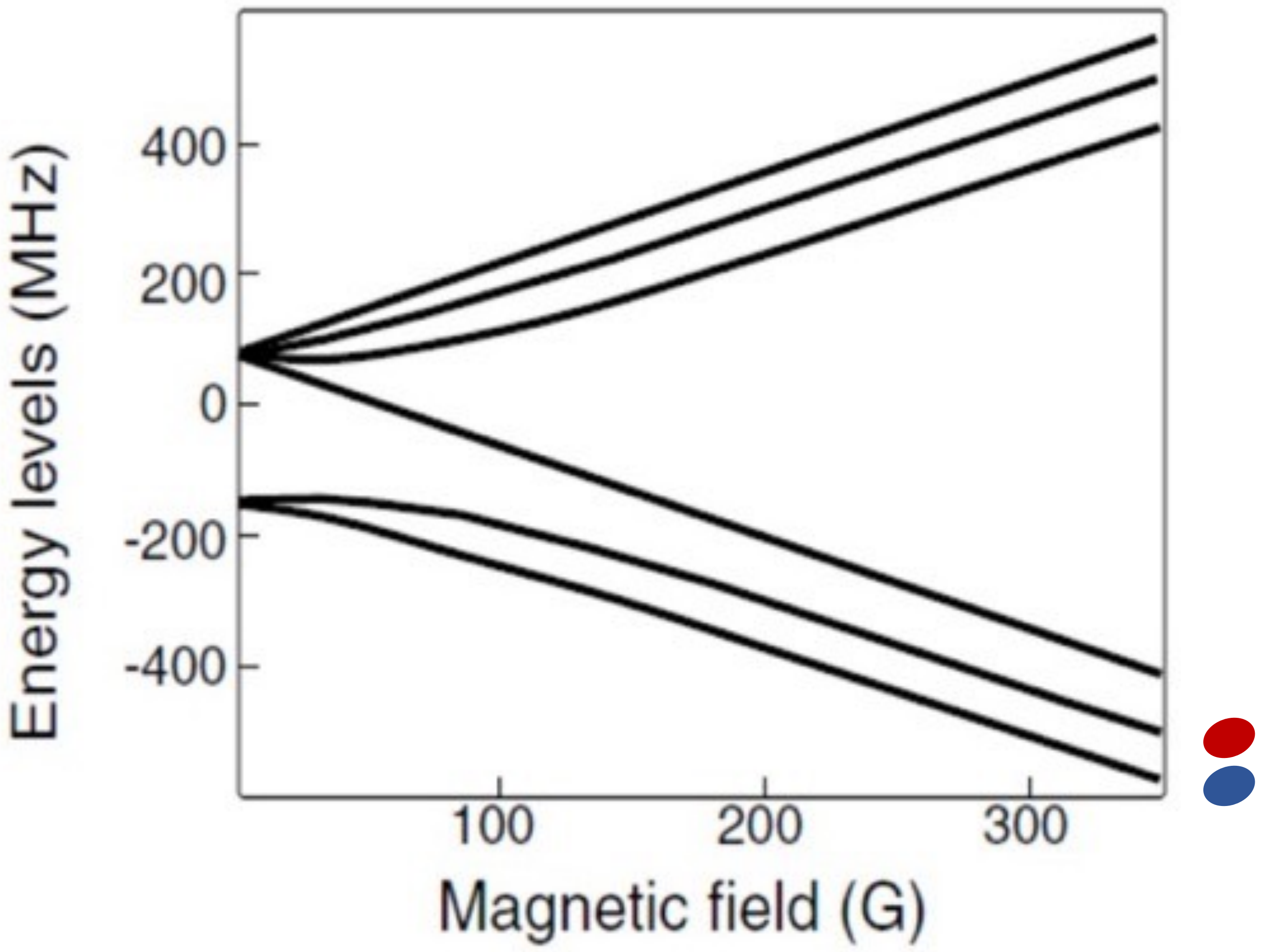
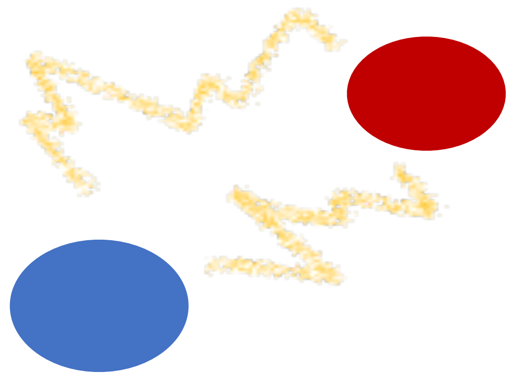
LITHIUM-6 FERMI SUPERFLUIDS





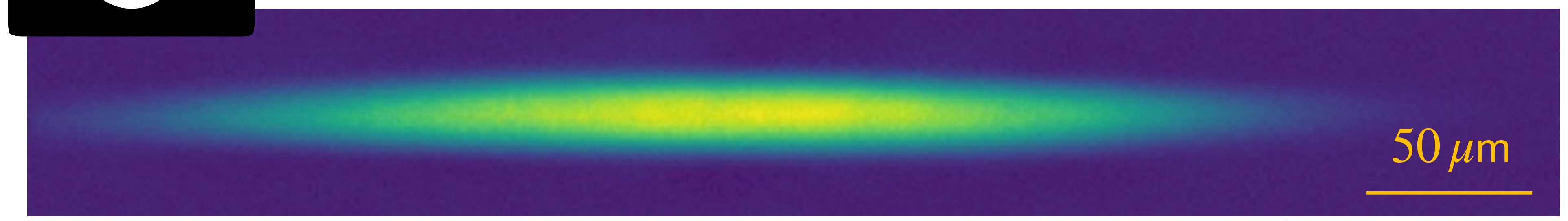


$\sim \frac{4\pi\hbar^2}{m} a\, \delta(r)$

a → Scattering length

N $\sim 10^5$ at $T \sim 30$ nK

Magneto optical trap + D_1 molasses
+ Evaporative cooling



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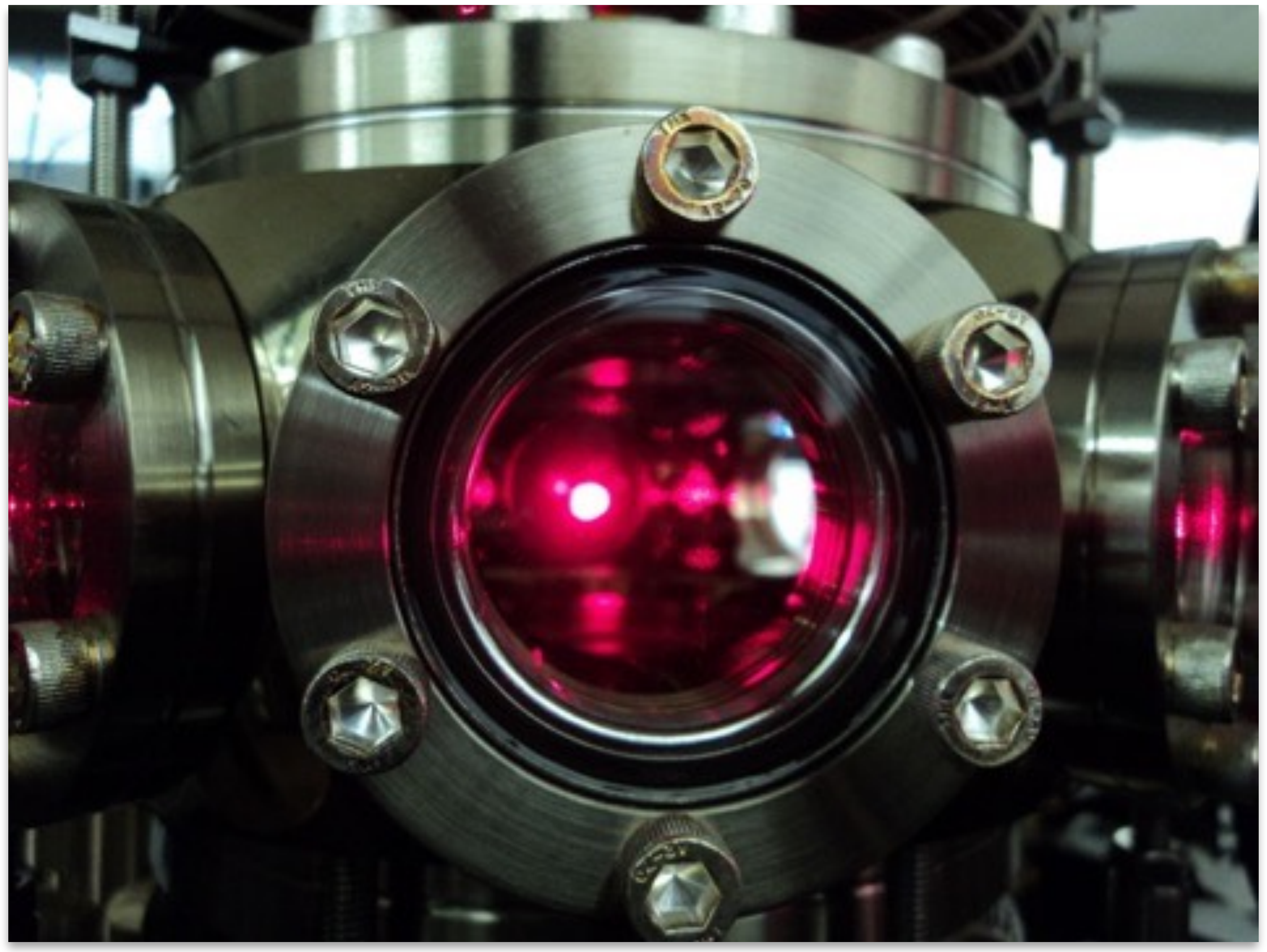

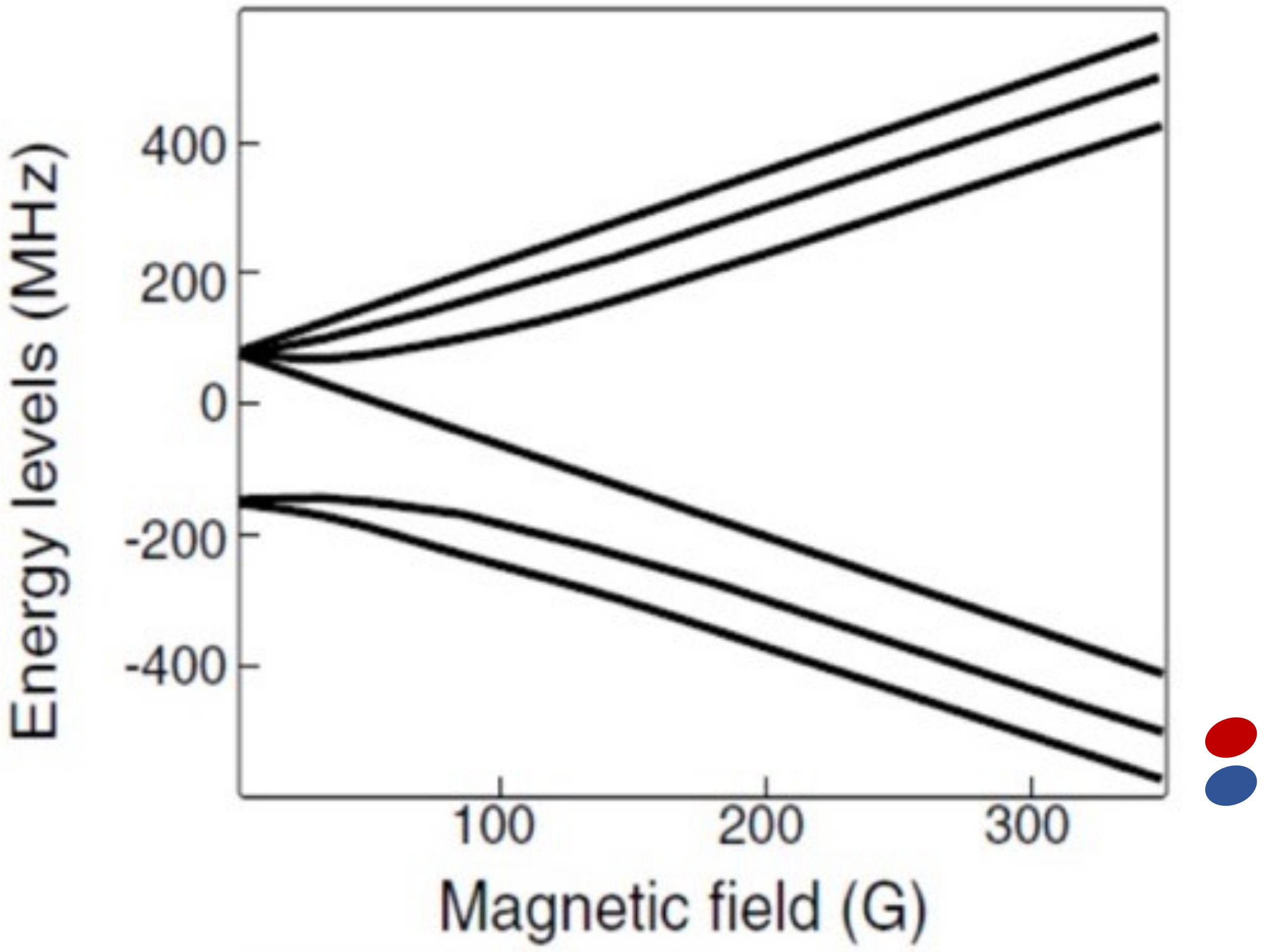

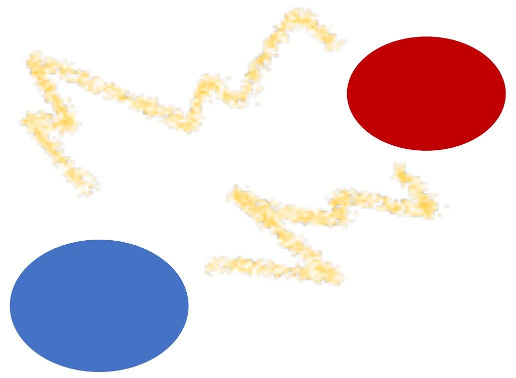

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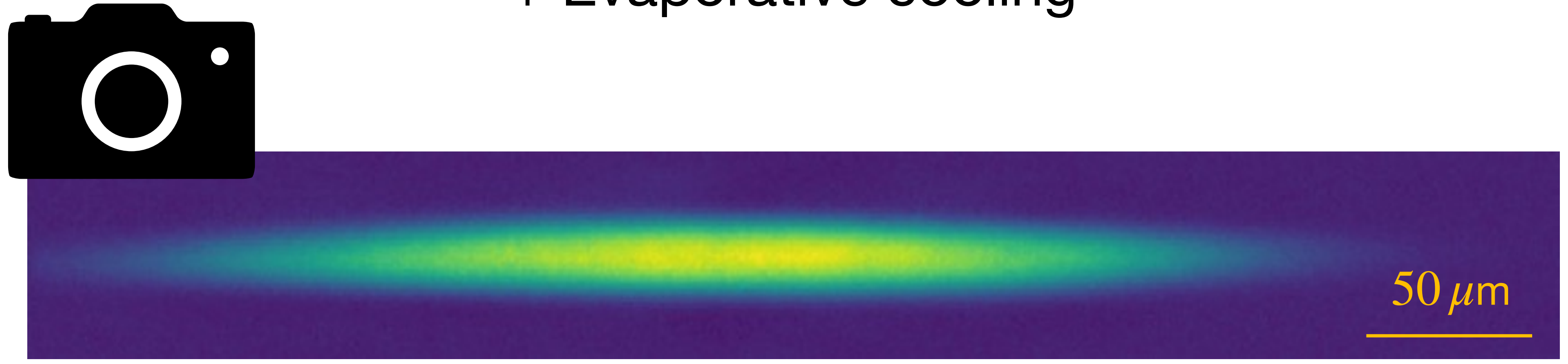
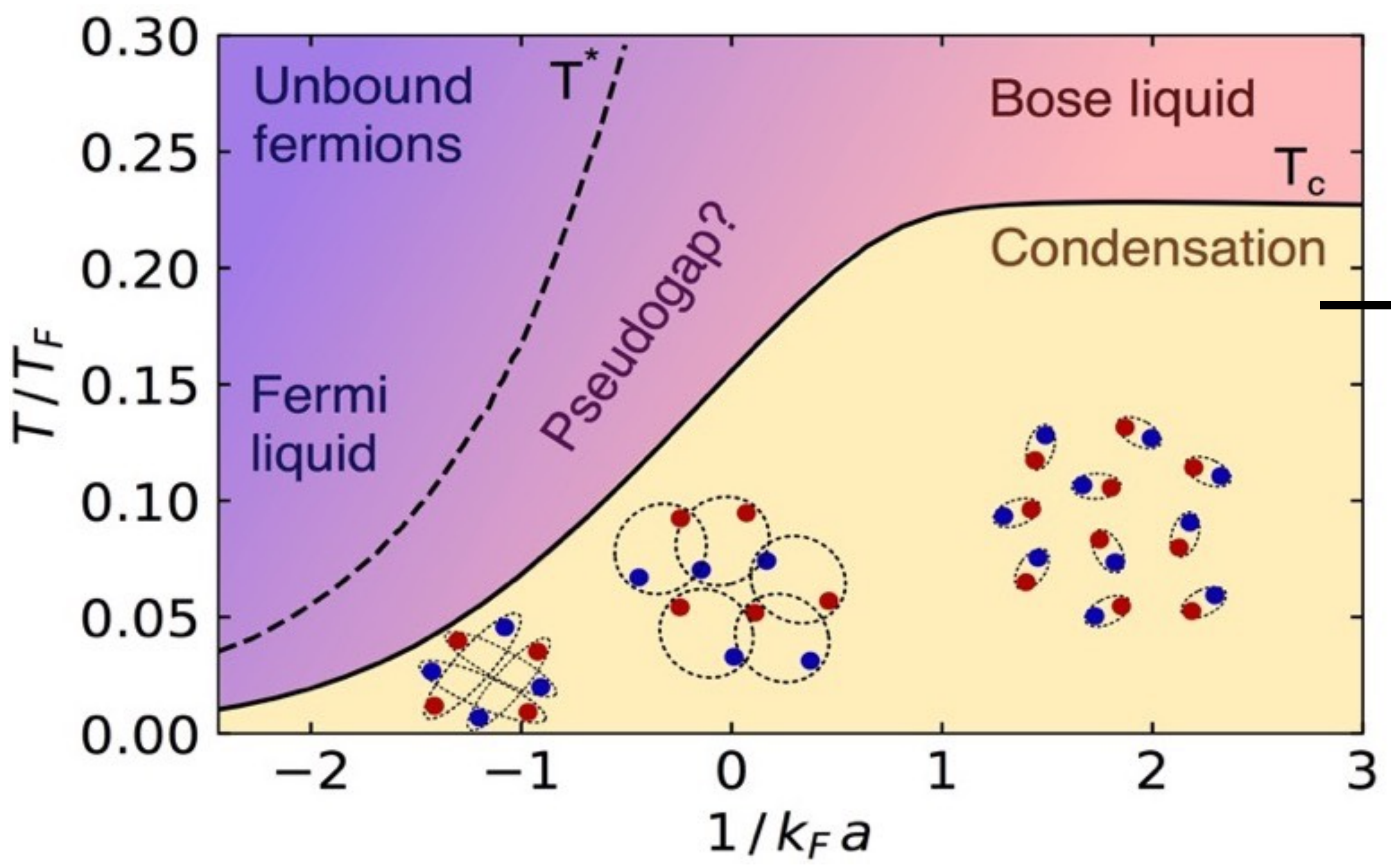
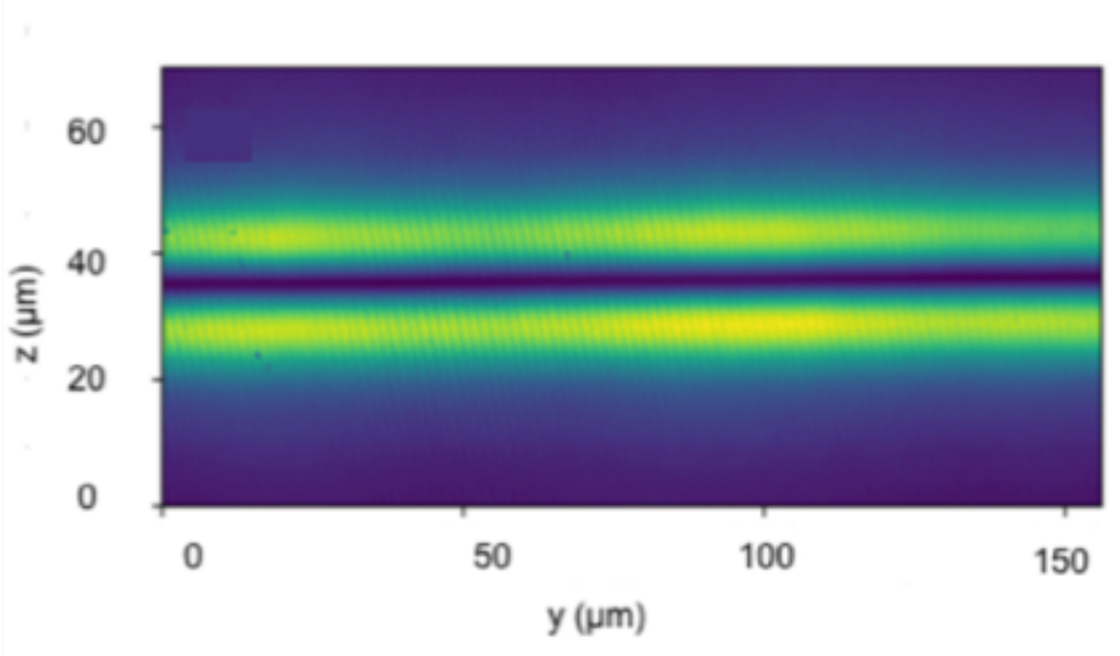


BEC-BCS crossover



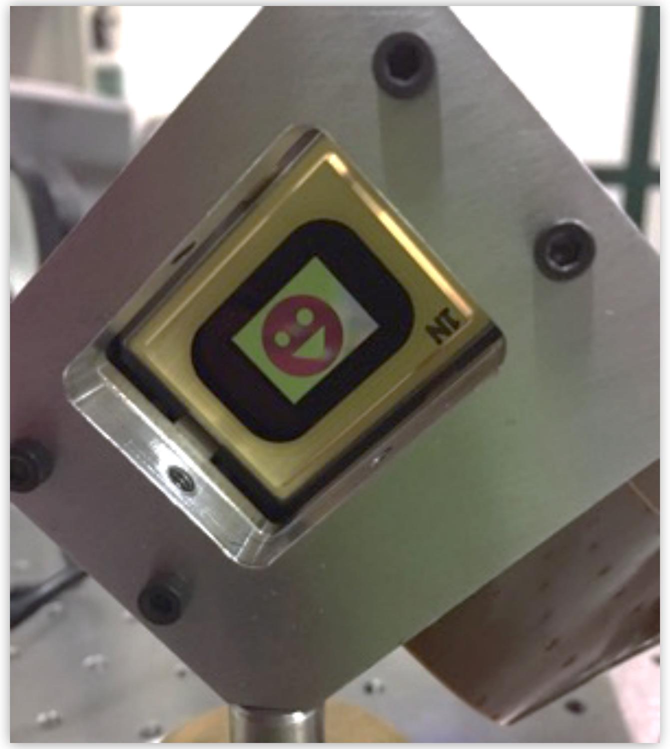
→ 100% superfluid
<100% condensed

LITHIUM-6 FERMI SUPERFLUIDS @ LENS



$TEM_{0,1}$ – like beam @ 532 nm

Squeeze the cloud along the vertical direction and create from oblate to quasi-2D geometries



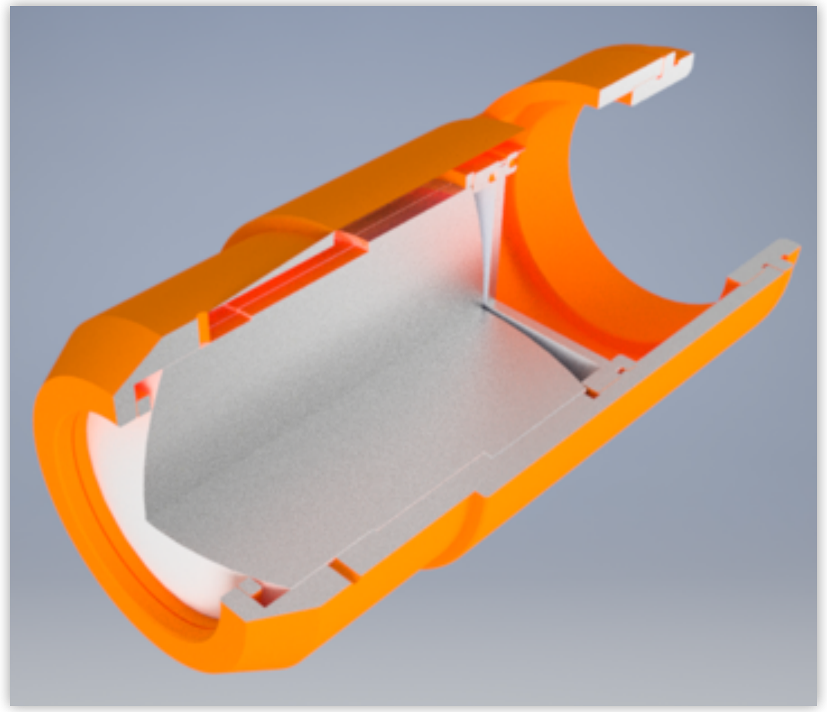
Digital Micromirror Device (DMD)

Vialux V-7000

1024×768 mirrors

$13.68\ \mu$m pitch

Maximum framerate: 22 kHz



High resolution microscope objective:

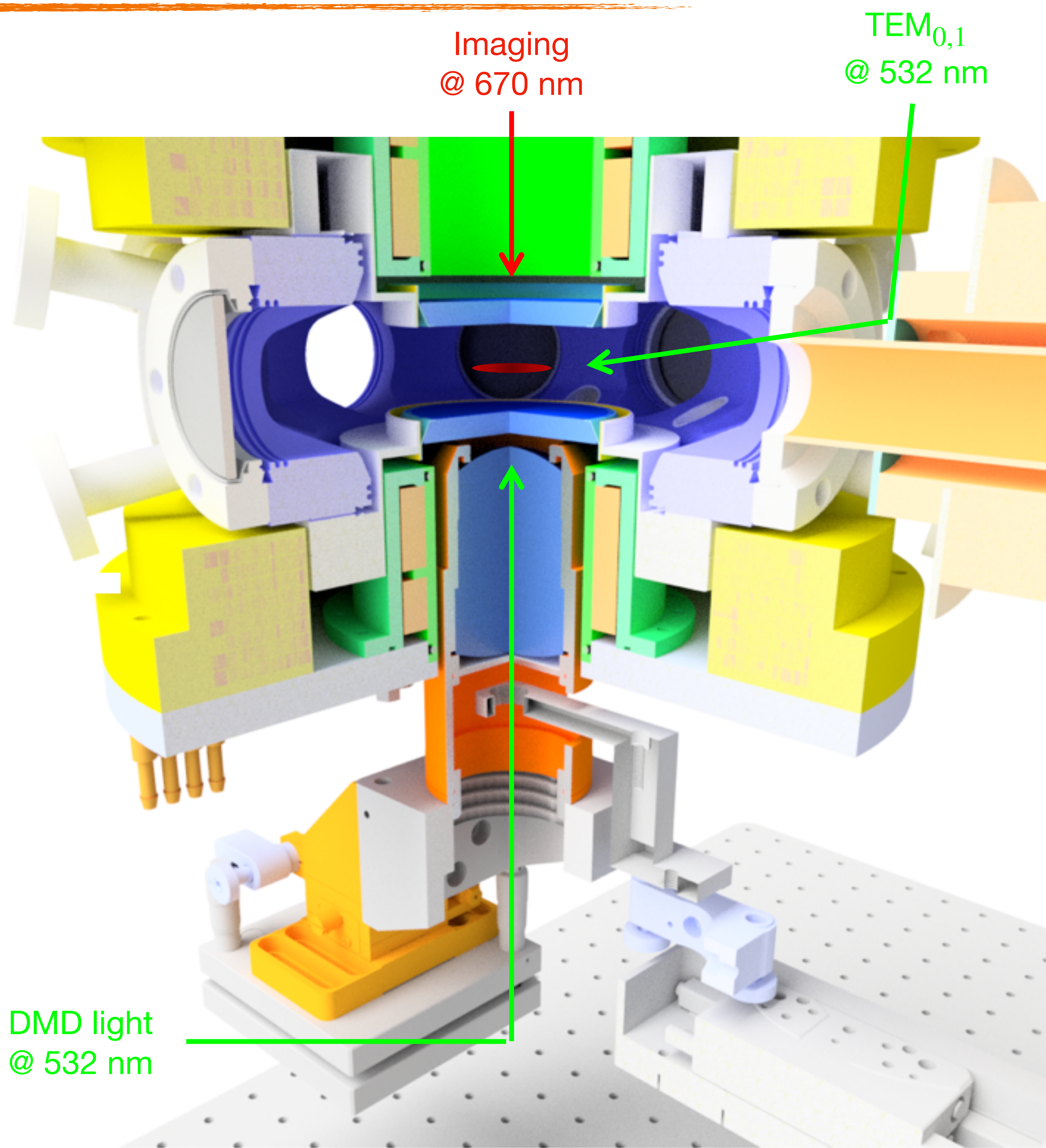
$NA = 0.45$

Effective Focal Length: 47mm

Field Of View: 0.3 mm

Working Distance: 25.1 mm

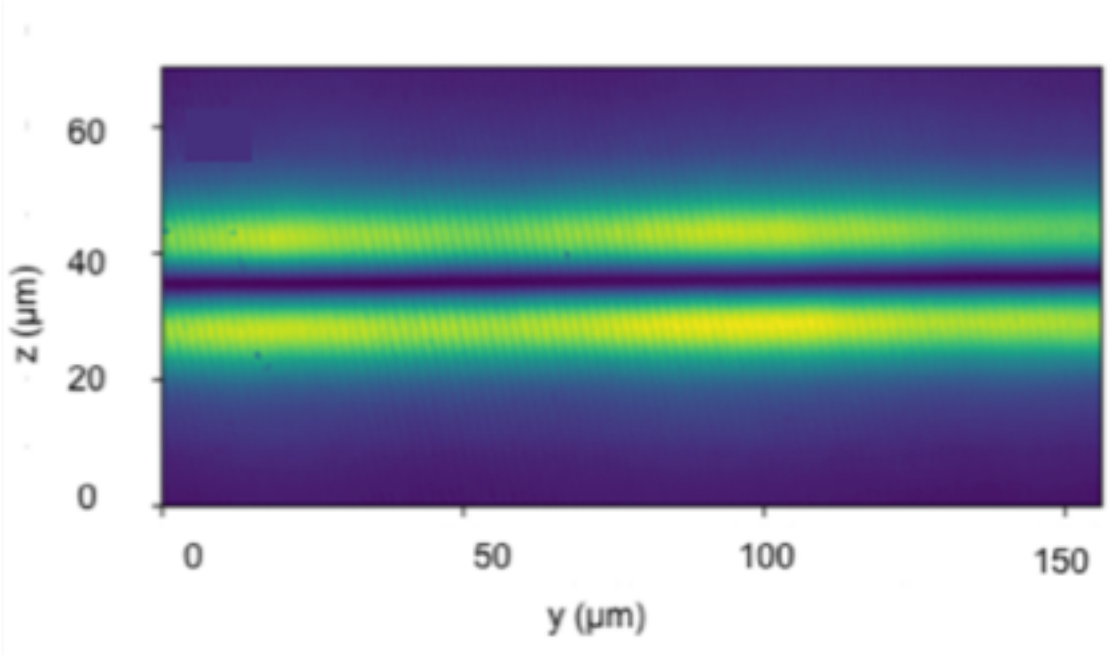
Resolution: $0.9\ \mu$m @ 670 nm, $0.7\ \mu$m @ 532 nm



LITHIUM-6 FERMI SUPERFLUIDS @ LENS

UNIVERSITÀ DEGLI STUDI FIRENZE

NQSTI National Quantum Science and Technology Institute



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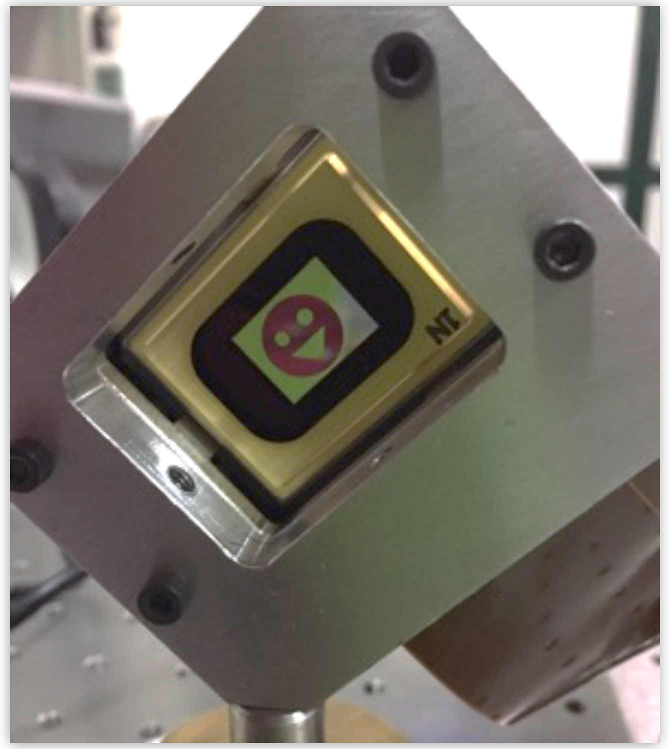


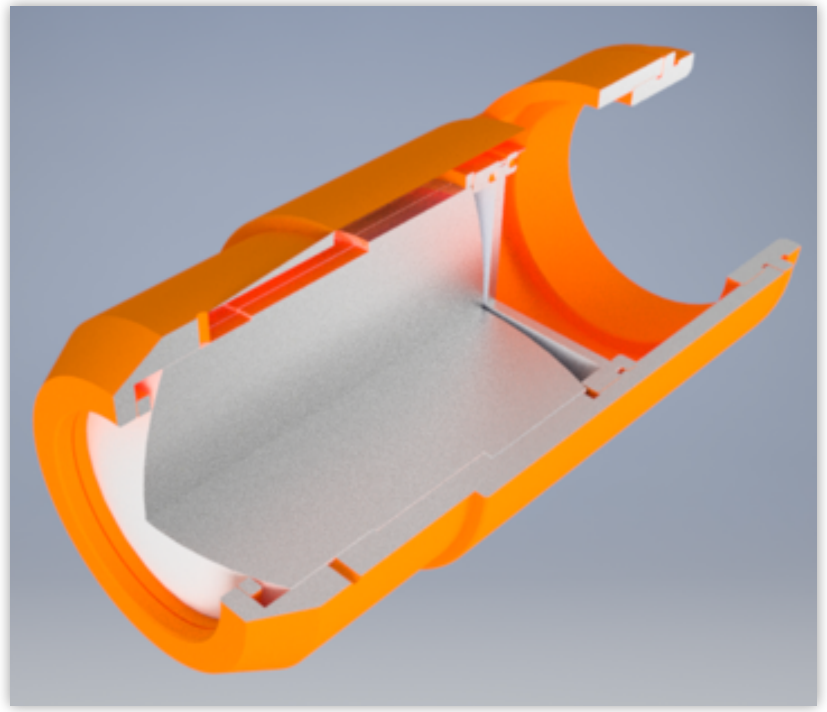
Digital Micromirror Device (DM

Vialux V-7000

1024×768 mirrors

$13.68\ \mu$m pitch

Maximum framerate: 22 kHz



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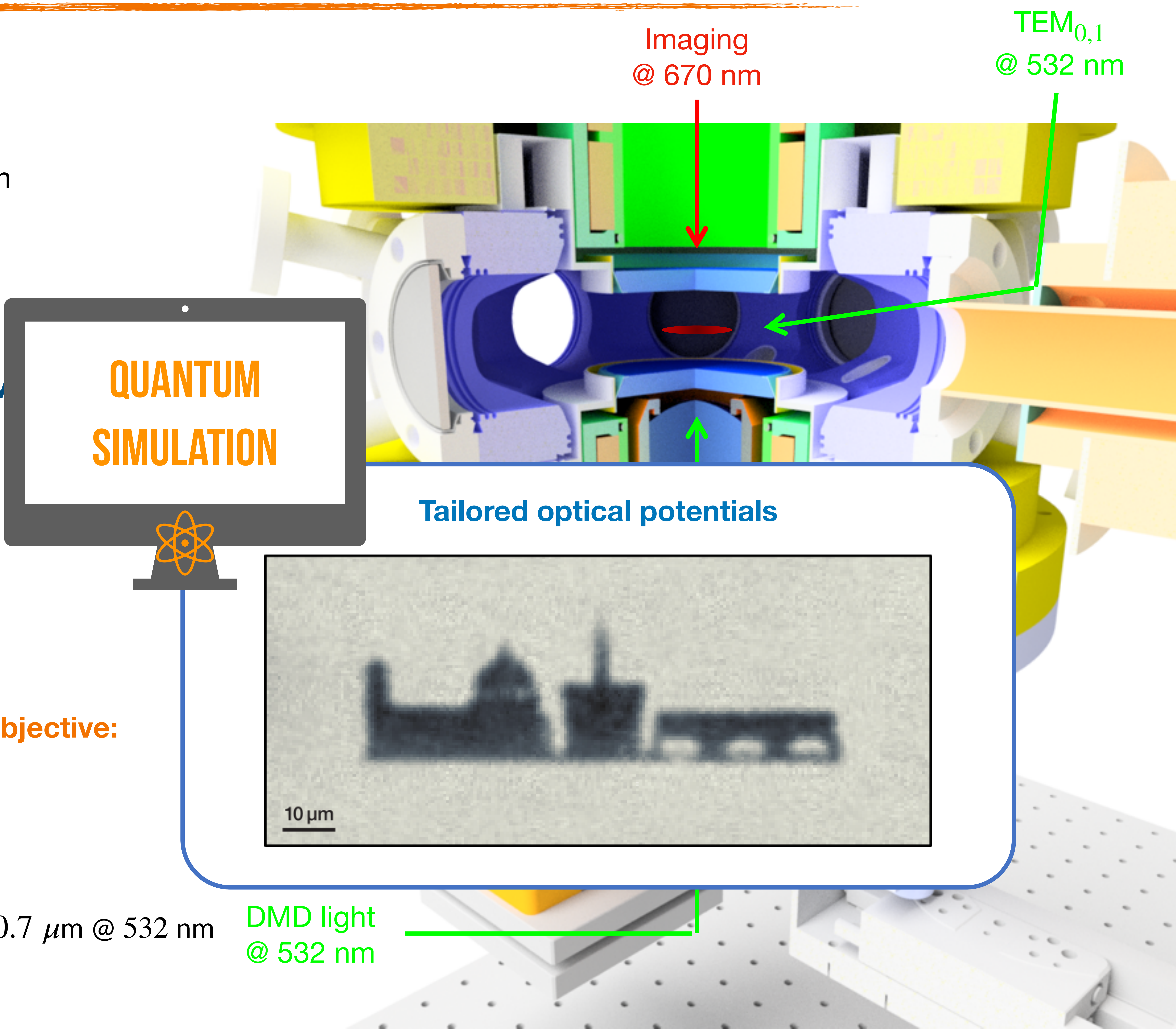
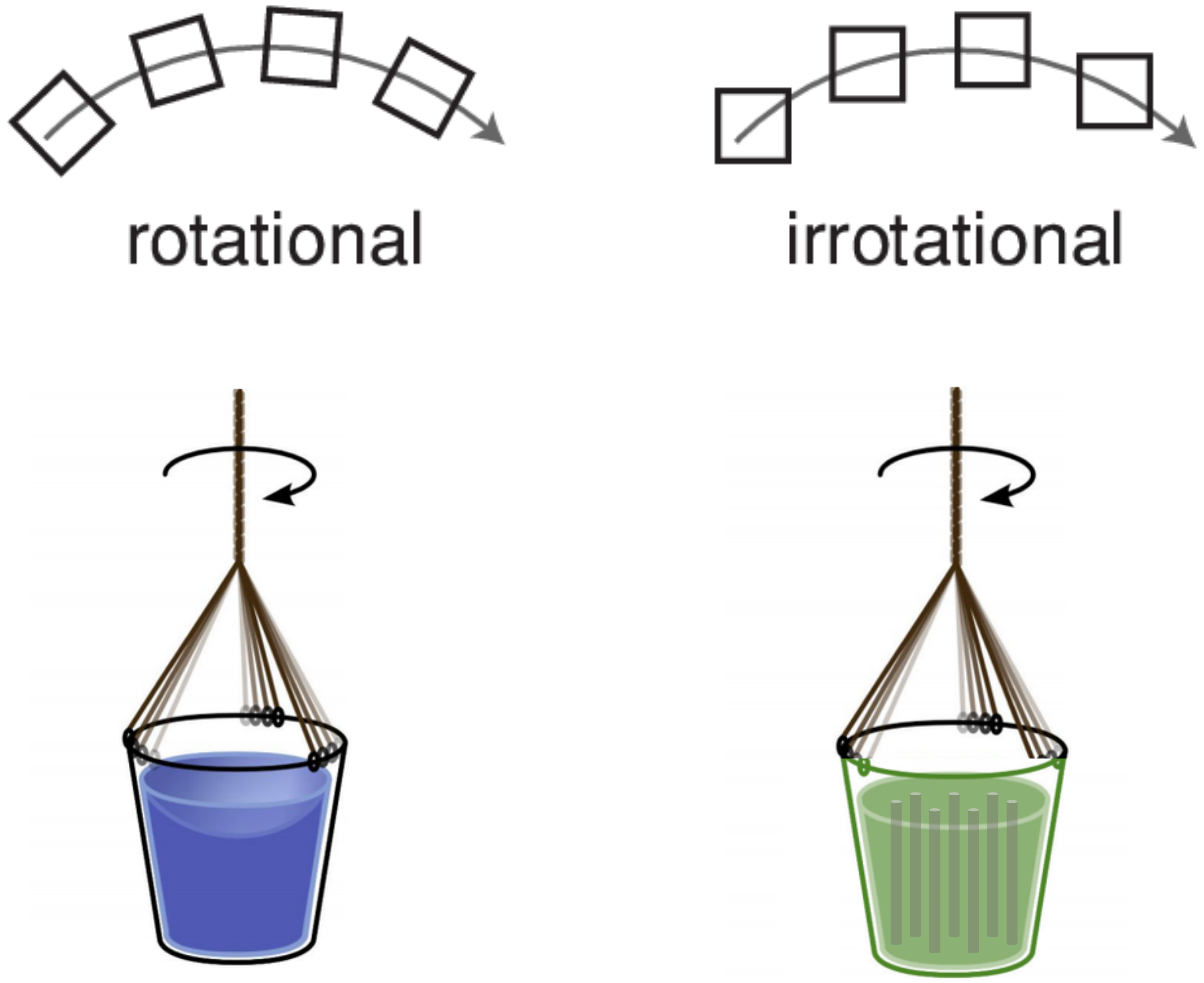


TOPOLOGICAL EXCITATIONS IN ATOMIC SUPERFLUIDS

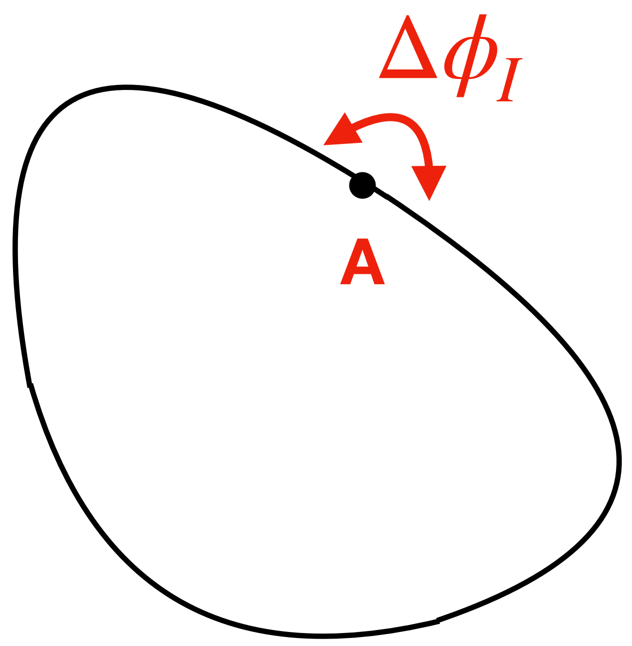


Classical fluid

Superfluid

The motion of an inviscid fluid is irrotational

$$\nabla \times v = 0$$



Quantized circulation

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

For a superfluid:

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

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

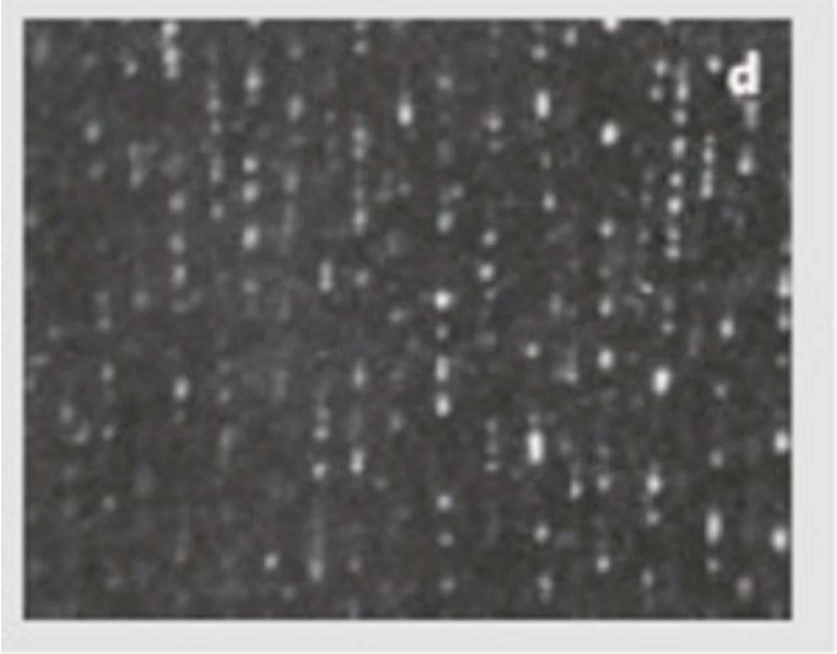
$w \rightarrow$ winding number

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

TOPOLOGICAL EXCITATIONS IN ATOMIC SUPERFLUIDS

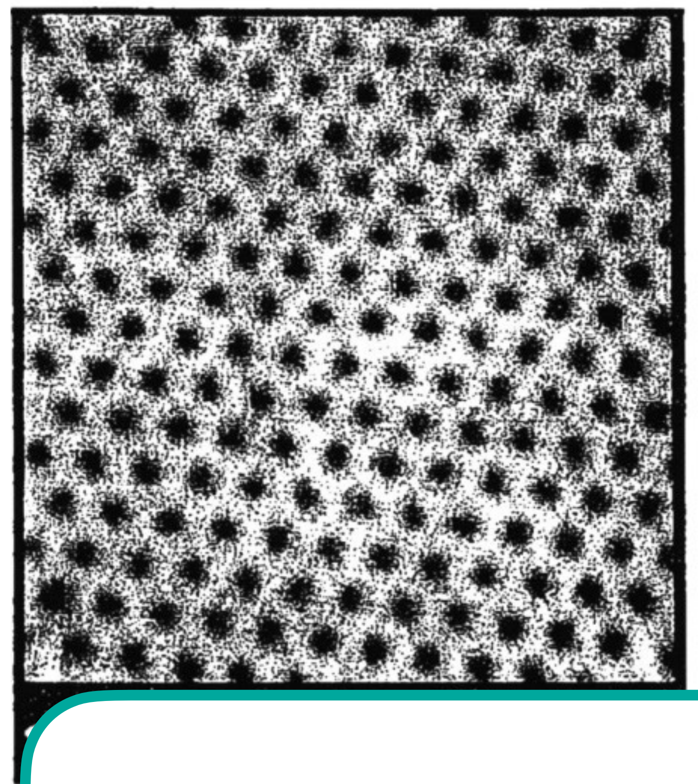
Quantized vortices in superfluids

Helium

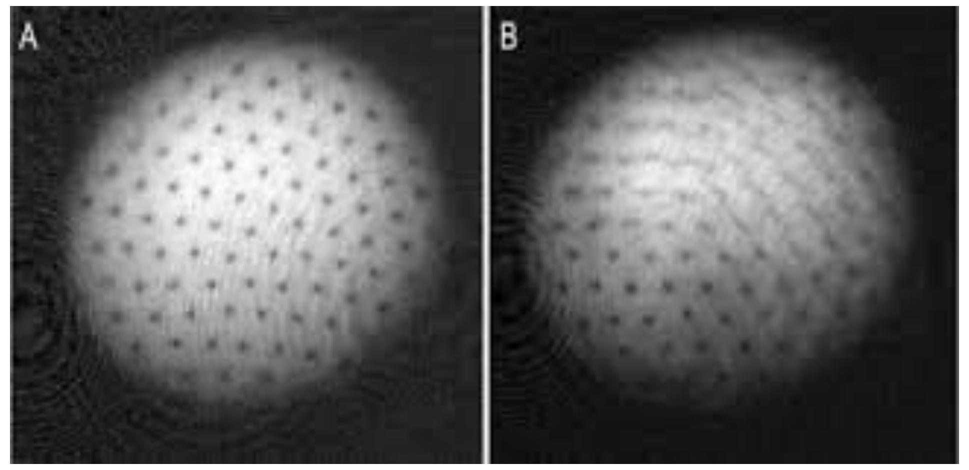


From: G. Bewley, et al., *Nature* 441, 588 (2006).

Superconductors



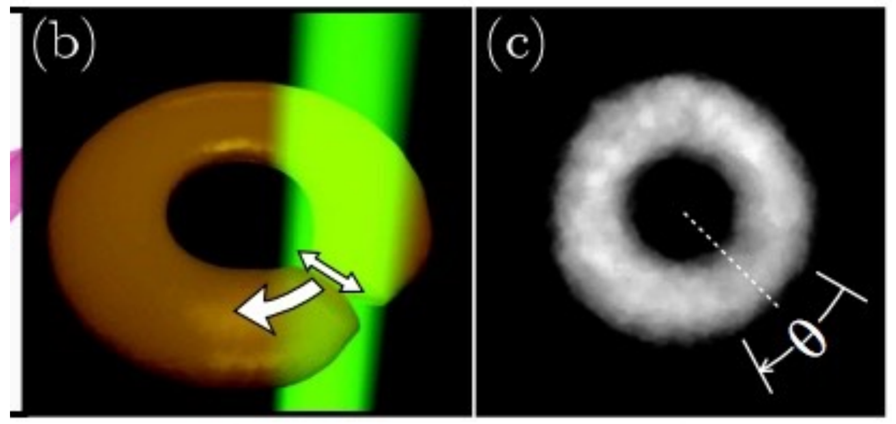
Atomic condesates

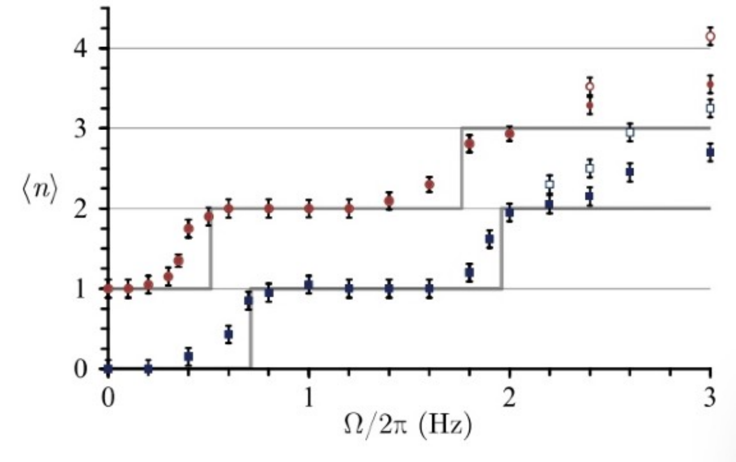


From: J. R. Abo-Shaeer, et al., Science 292, Issue 5516, pp. 476-479 (2001)

Quantized circulation in ring geometry

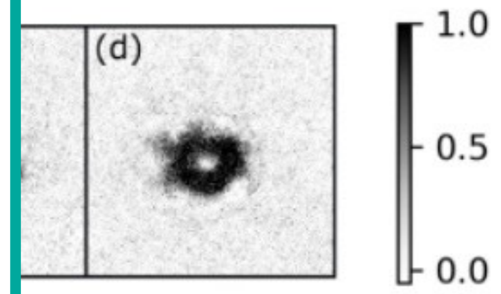
BEC



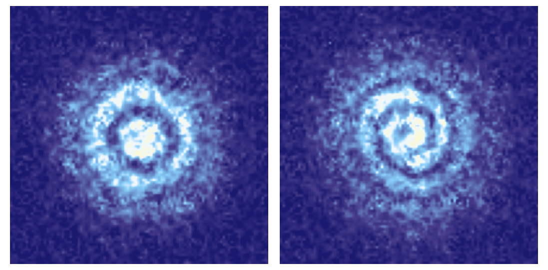


From: K. Wright, et al. Phys. Rev. Lett. 110.2 (2013)
Campbell group (NIST)
Dalibard group (ENS)
Perrin group (Sorbonne- CNRS)
Neely group (University of Queensland)

ermionic superfluids



401 (2022).



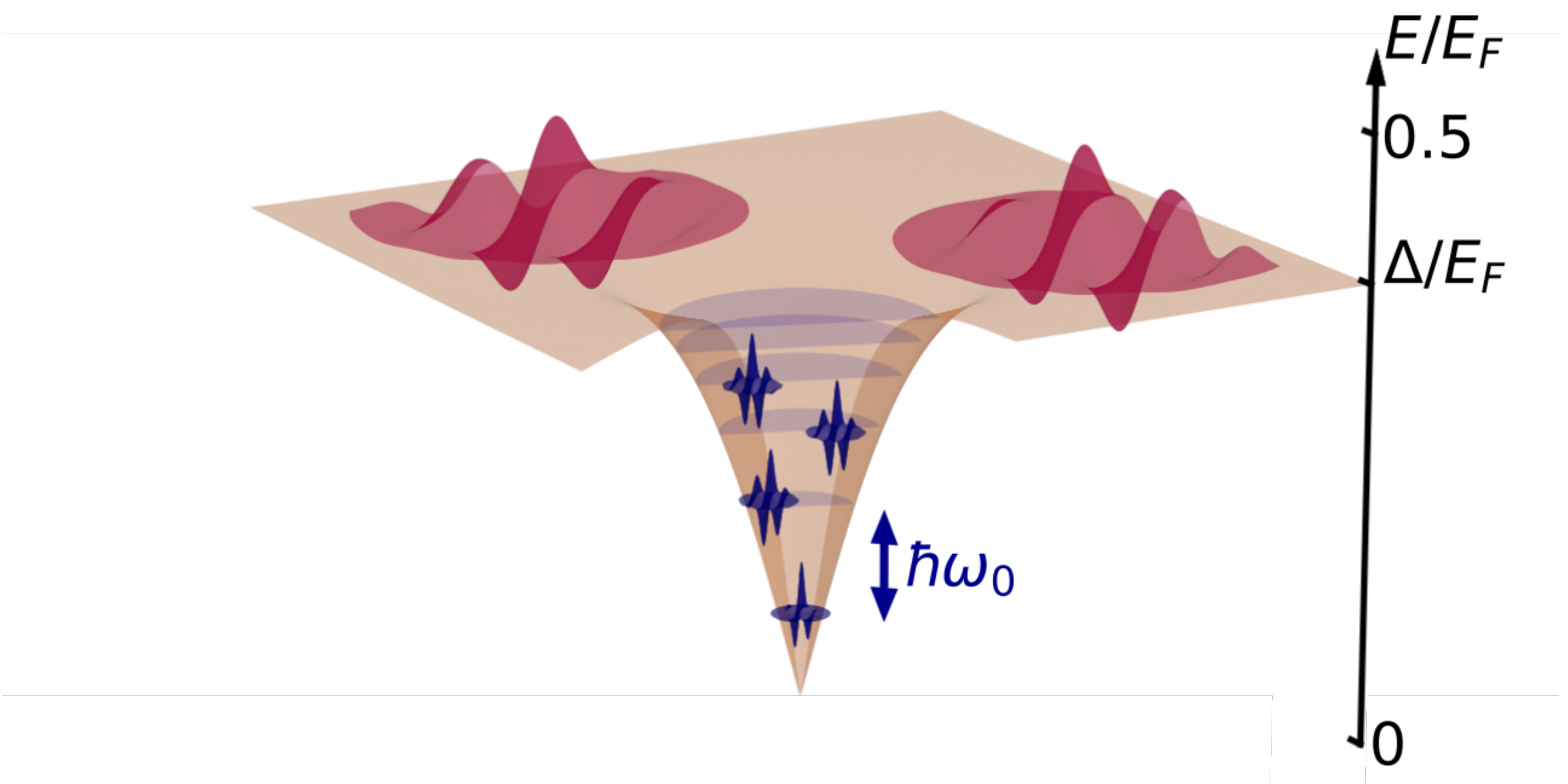
GDP, et al. *Phys. Rev. X* 12.4 041037 (2022)

Topological excitations are long-lived as they are topologically protected:

- Fundamental physics and quantum simulation
- Quantum technologies

How can they **dissipate**?

VORTEX DISSIPATION



Caroli, De Gennes, and Matricon. *Phys. Lett.* 9.4 307-309 (1964)
R. Sensarma, et al., *Phys. Rev. Lett.* 96.9 090403 (2006)

Mutual friction

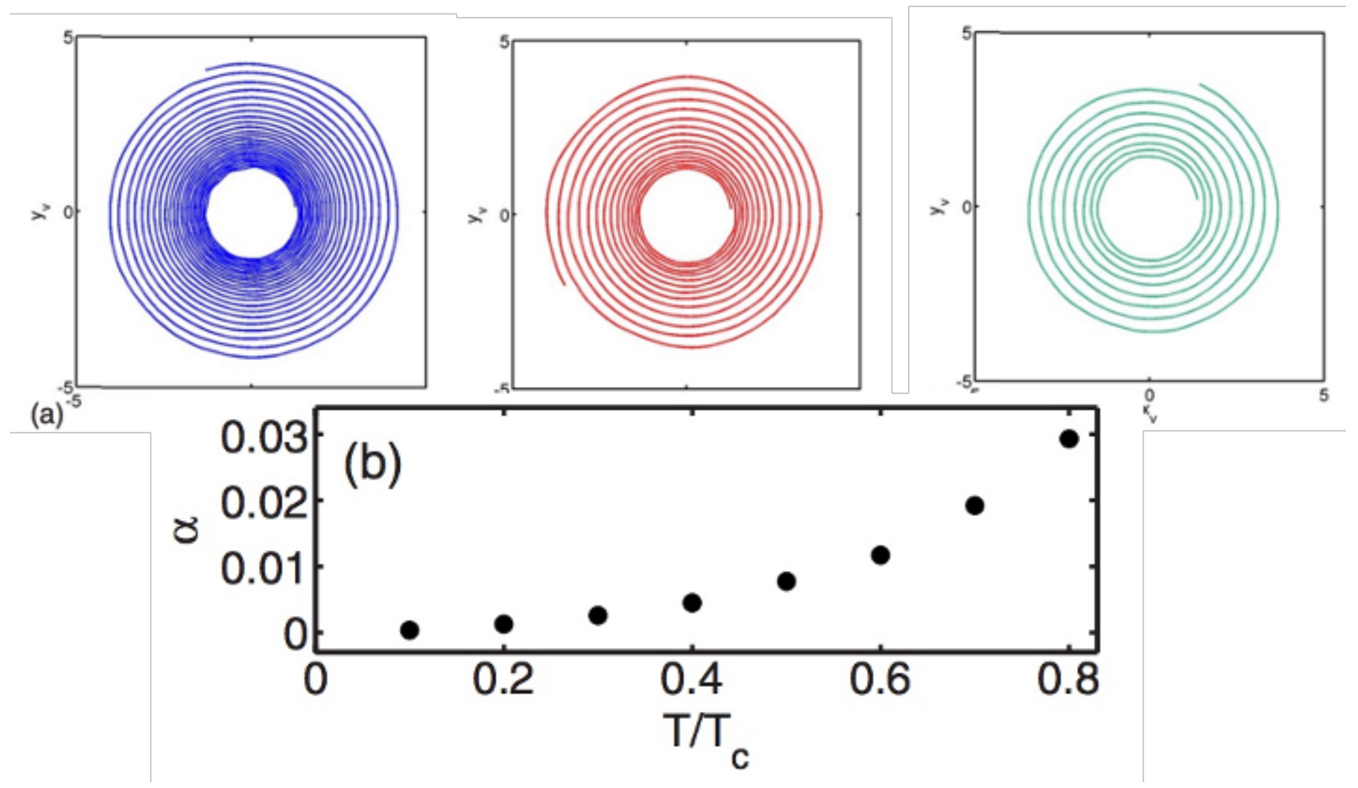
The vortex interacts with **quasiparticle** excitations of the superfluid:

* Delocalized quasiparticles (sound) → bosons, fermions
* Localized quasiparticle (bound states) → fermions

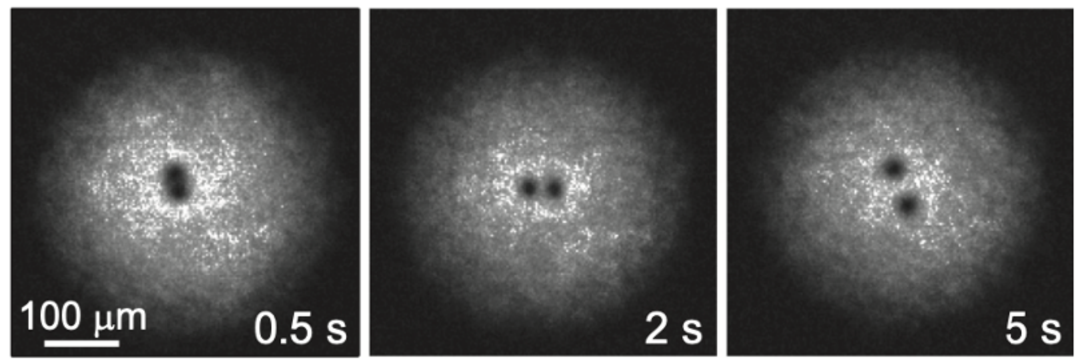
Finite temperature effect

Atomic BEC

Mutual friction determines the motion of single and many vortices



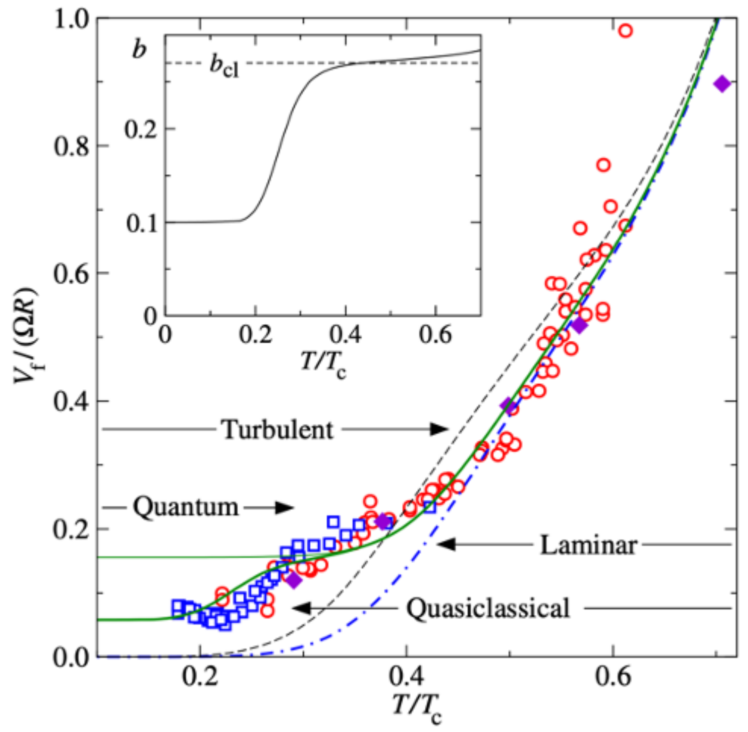
B. Jackson, et al., Phys. Rev. A **79**, 053615 (2009)



Moon et al., PRA **92**, 051601(R) (2015)

Superfluid Helium

Mutual friction is introduced as a phenomenological force to account for dissipation

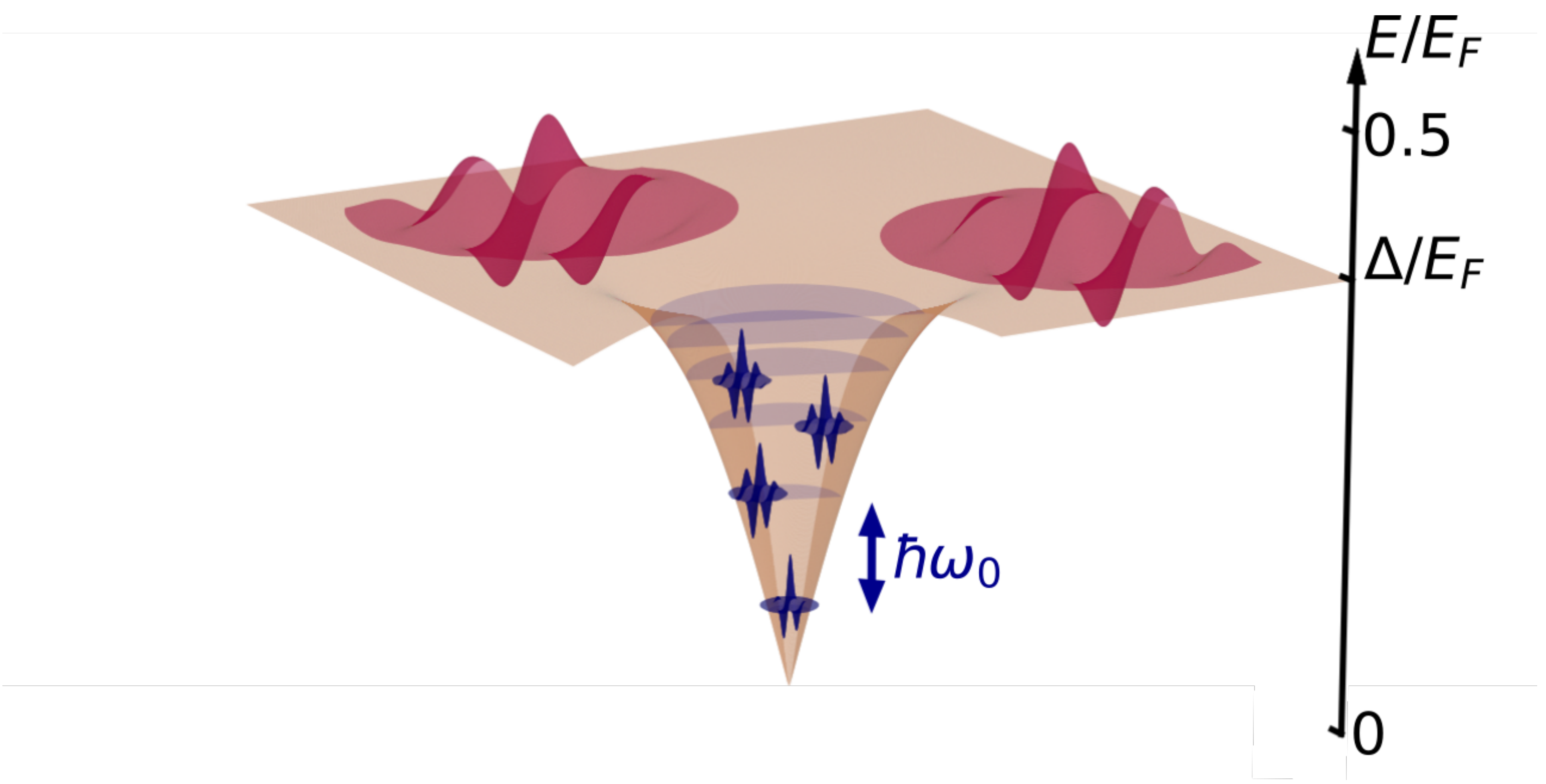


H. E. Hall and W. F. Vinen, *The rotation of liquid helium II – II. The theory of mutual friction in uniformly rotating helium II,* Proc. R. Soc. Lond. 238, 215 (1956).

P. M. Walmsley et al., PRL 99, 265302 (2007)
J. T. Mäkinen, and V. B. Eltsov. *Phys. Rev. B* 97.1 014527 (2018)

From: V. B. Eltsov et al., PRL 99, 265301 (2007)

VORTEX DISSIPATION



Caroli, De Gennes, and Matricon. *Phys. Lett.* 9.4 307-309 (1964)
R. Sensarma, et al., *Phys. Rev. Lett.* 96.9 090403 (2006)

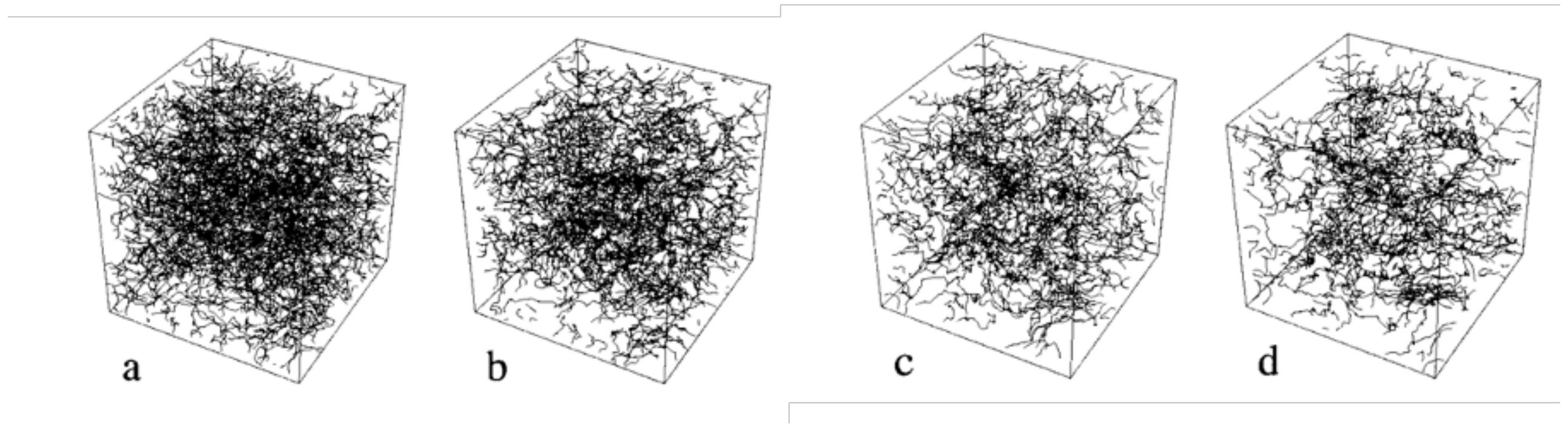
Sound interaction

The **incompressible** energy of the vortex can be transformed into **compressible** energy of the superfluid: sound emission

Also at zero temperature

3D

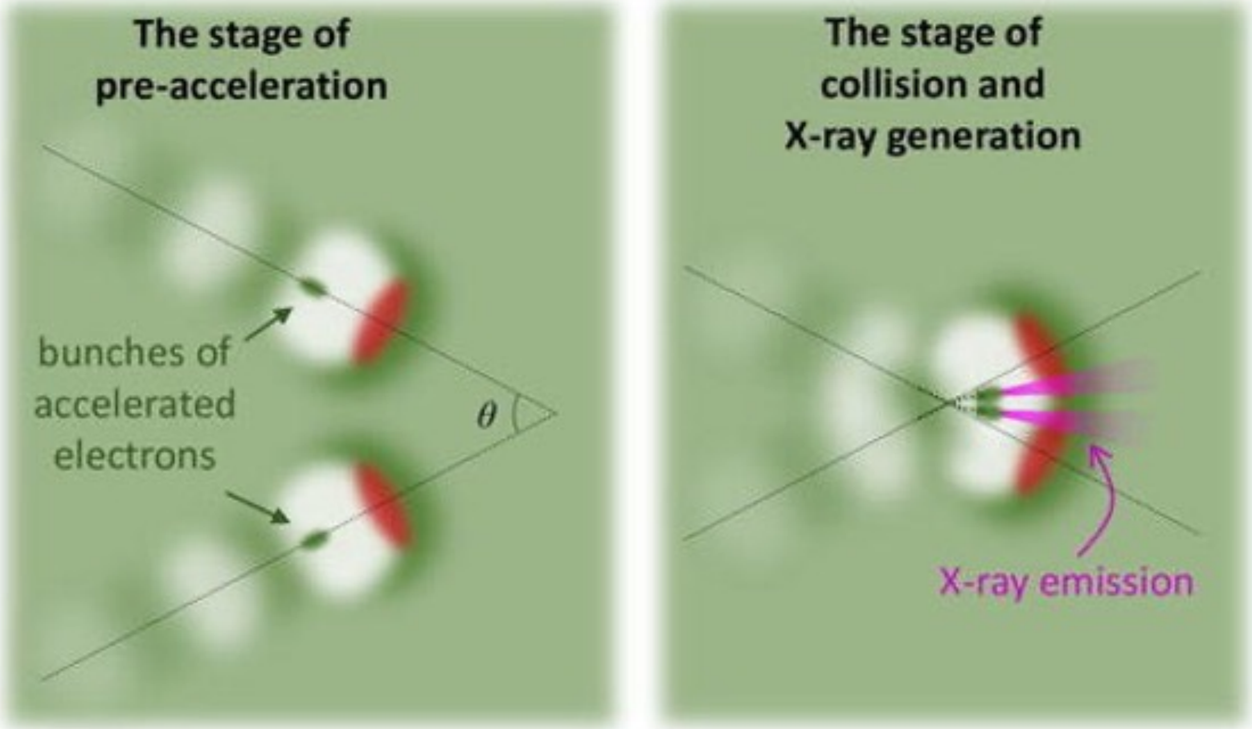
Vortex reconnection, Kelvin waves



Stagg et al., PRA 94, 053632 (2016)
Y. Minowa, et al., Nat. Phys. **21**, 233–238 (2025).
M. Tsubota et al., PRB 62, 11751 (2000)

2D

Accelerating vortices <—> accelerating charges?



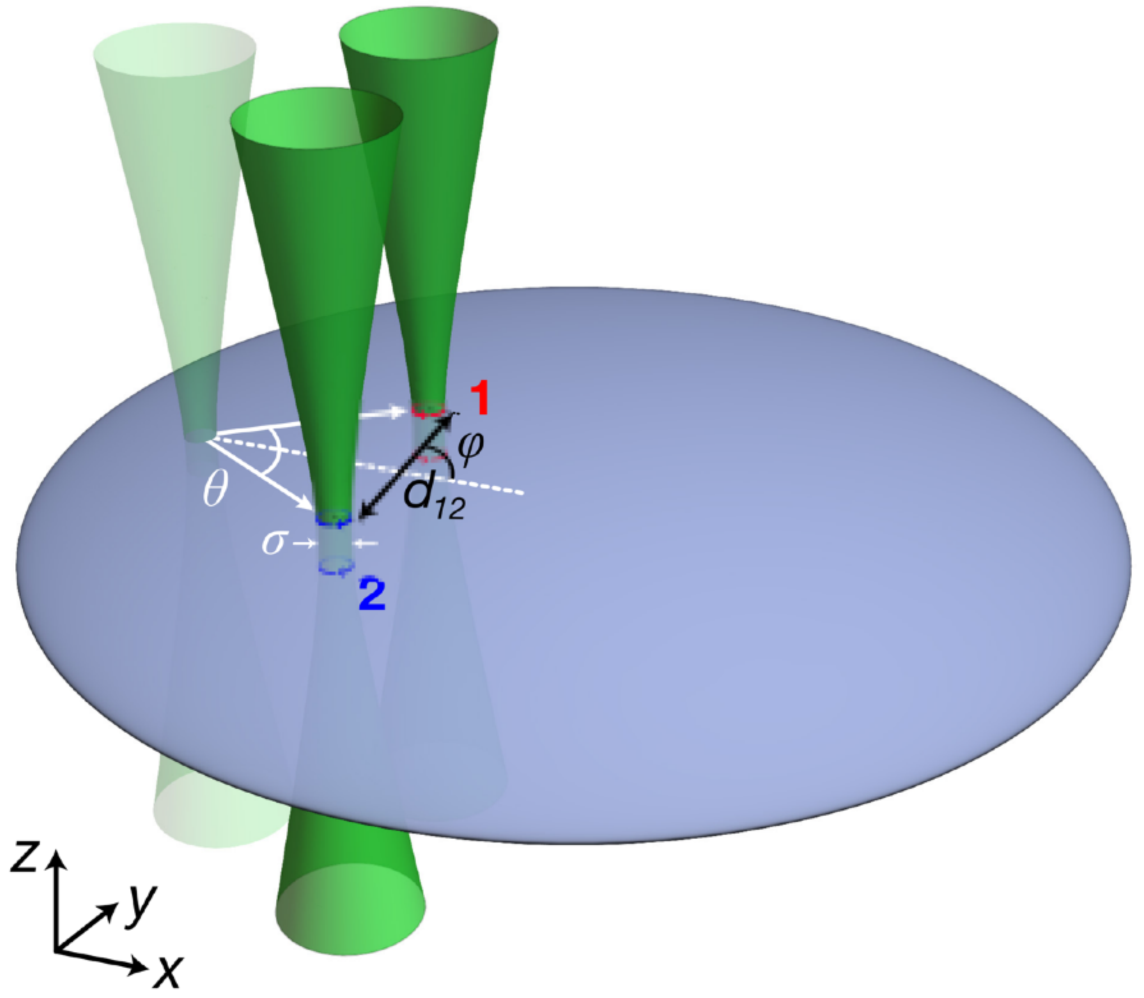
Picture taken from: E. Vallin et al., *Physics of Plasmas* **24**, 093101 (2017)

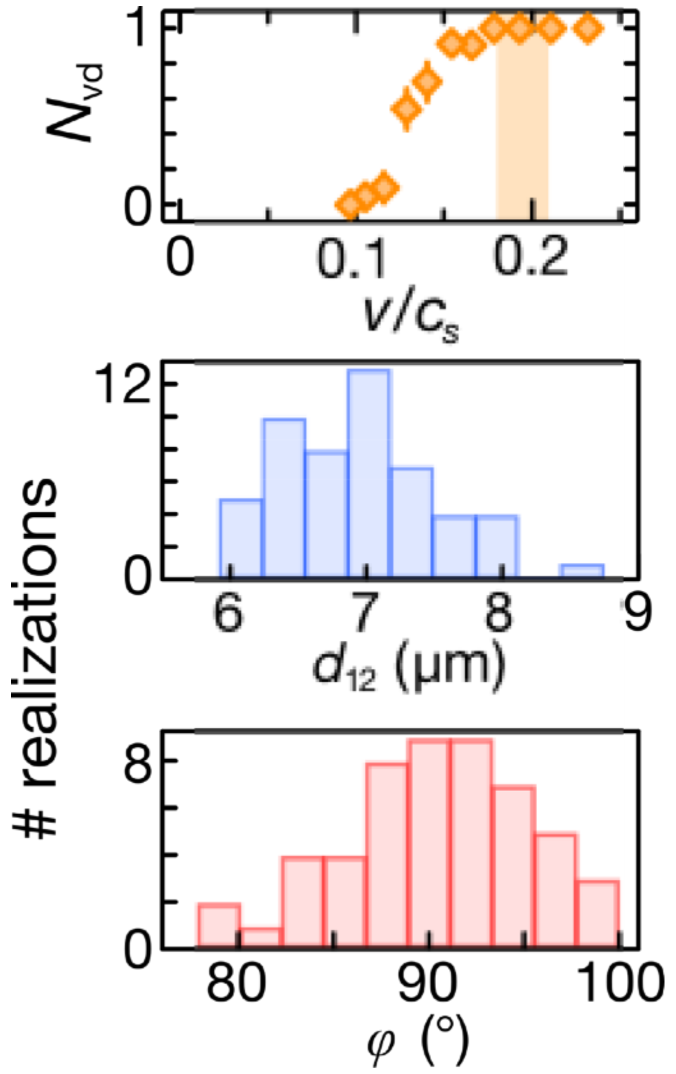
VORTICES IN ATOMIC FERMI SUPERFLUIDS

W. J. Kwon, et al. *Nature* **600**, 64–69 (2021).

Excitation of vortices

Chopstick method

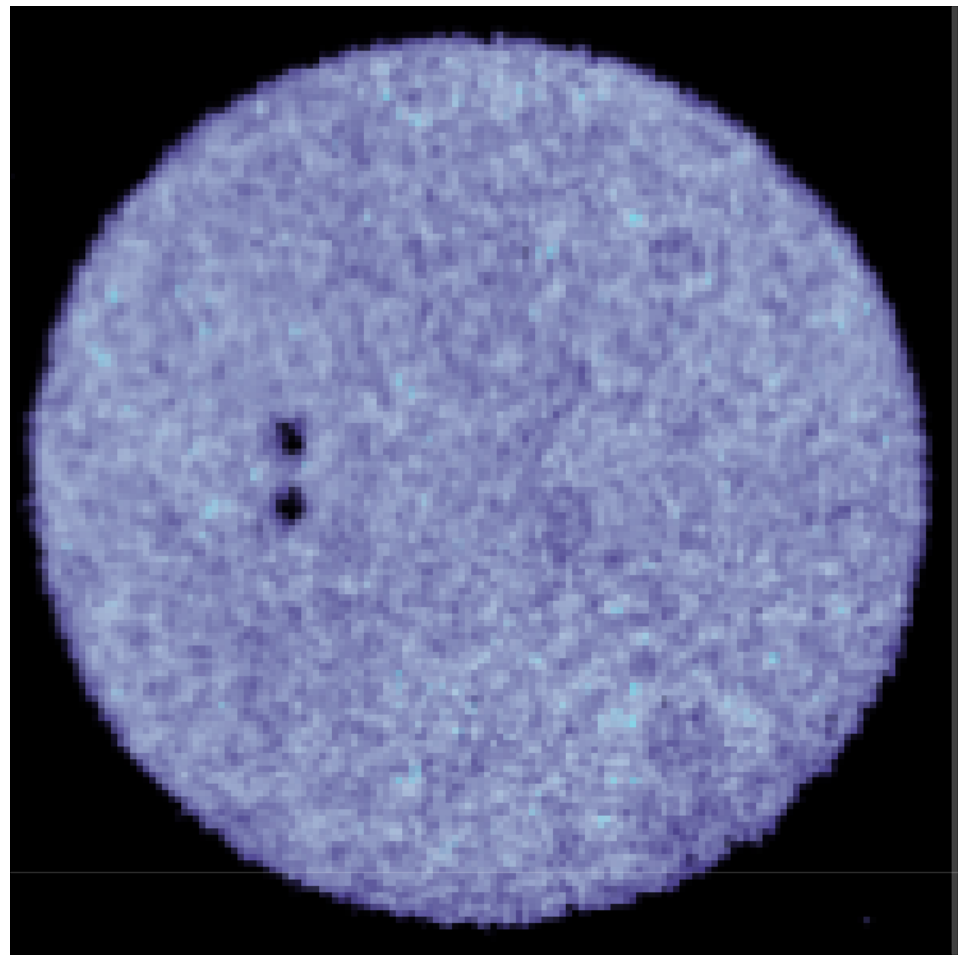




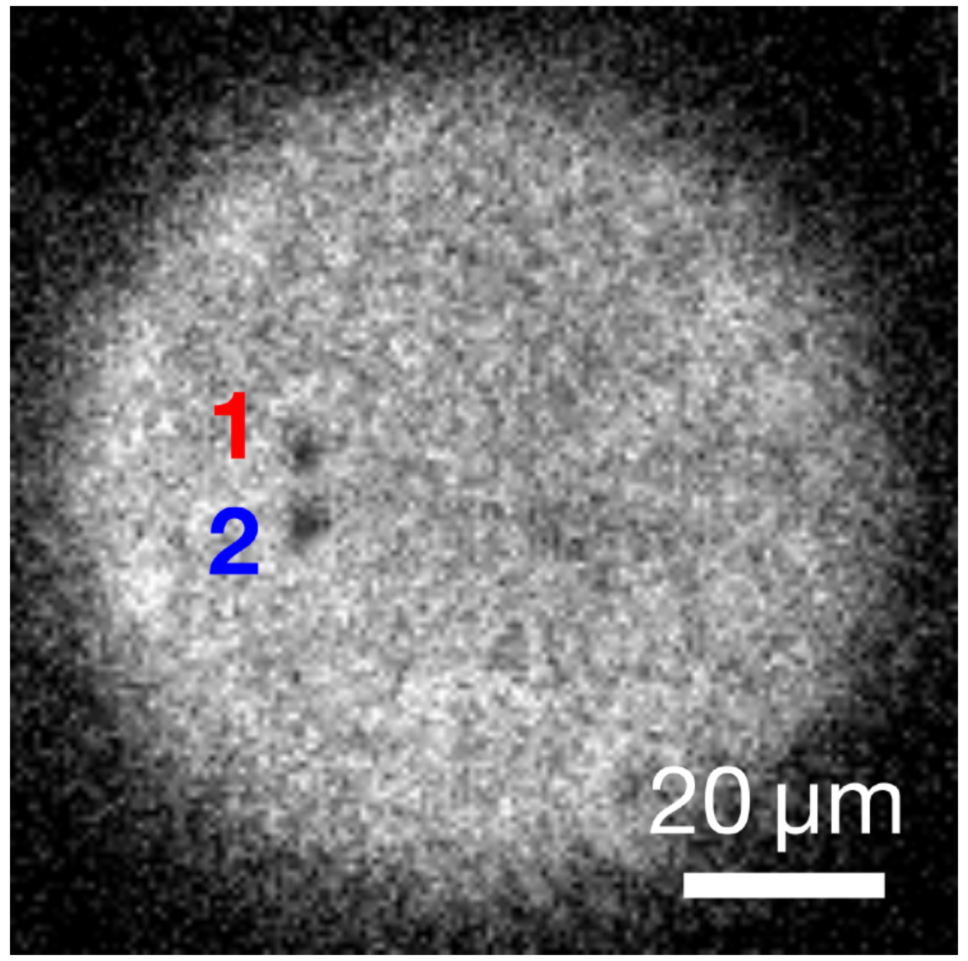
With Bose superfluids:
E. C. Samson, *Phys. Rev. A* **93**, 023603 (2016).
T. Neely et al., arXiv:2402.09920v2

Detection of vortices

Chopstick ON
In situ



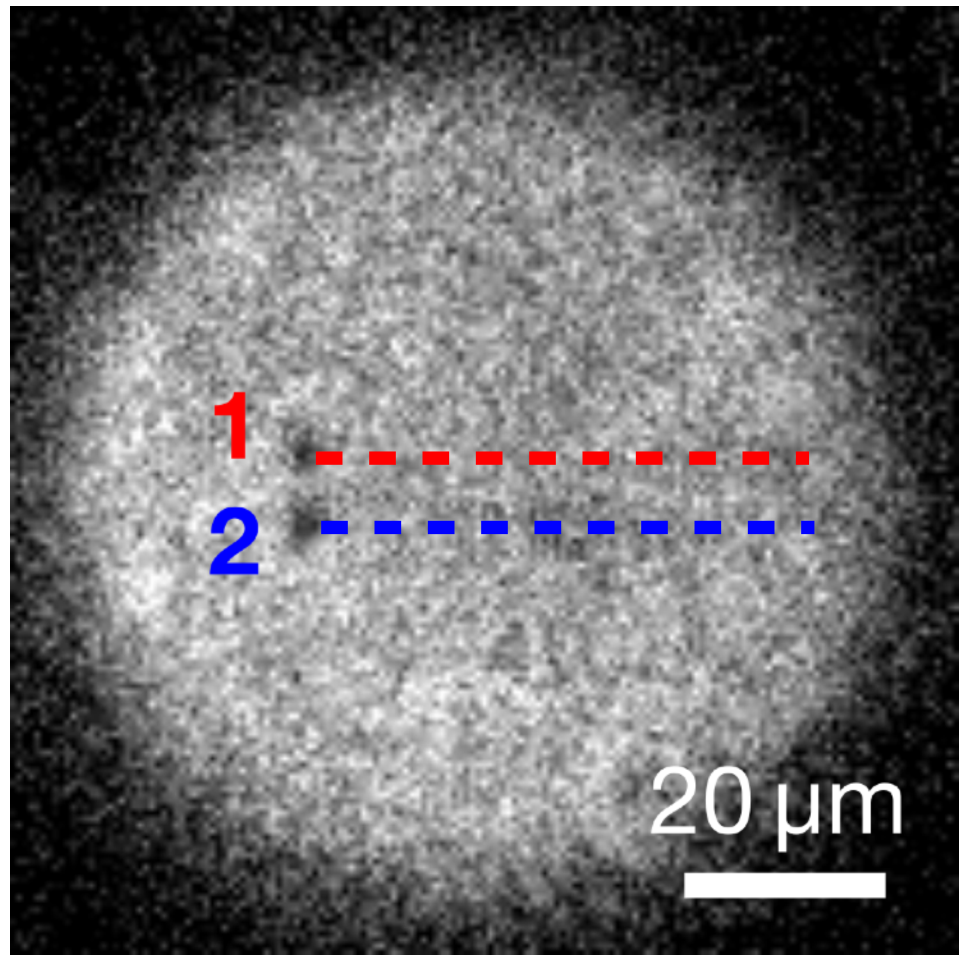
Chopstick OFF
Time-of-fligth

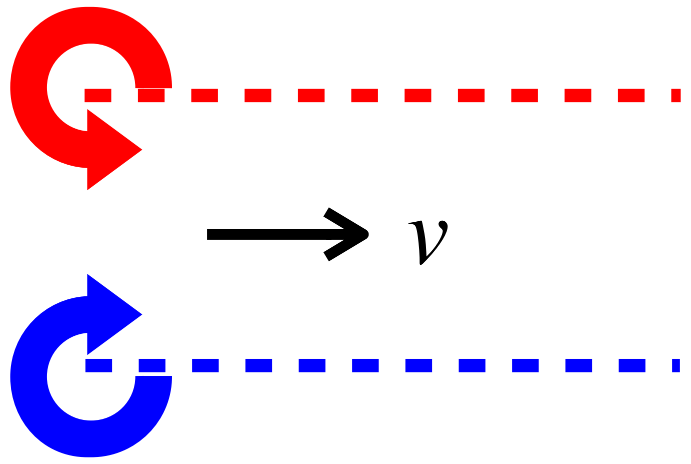


- Create arbitrary configuration of **vortex dipole**
- Precisely track the vortex position

SINGLE DIPOLE DYNAMIC

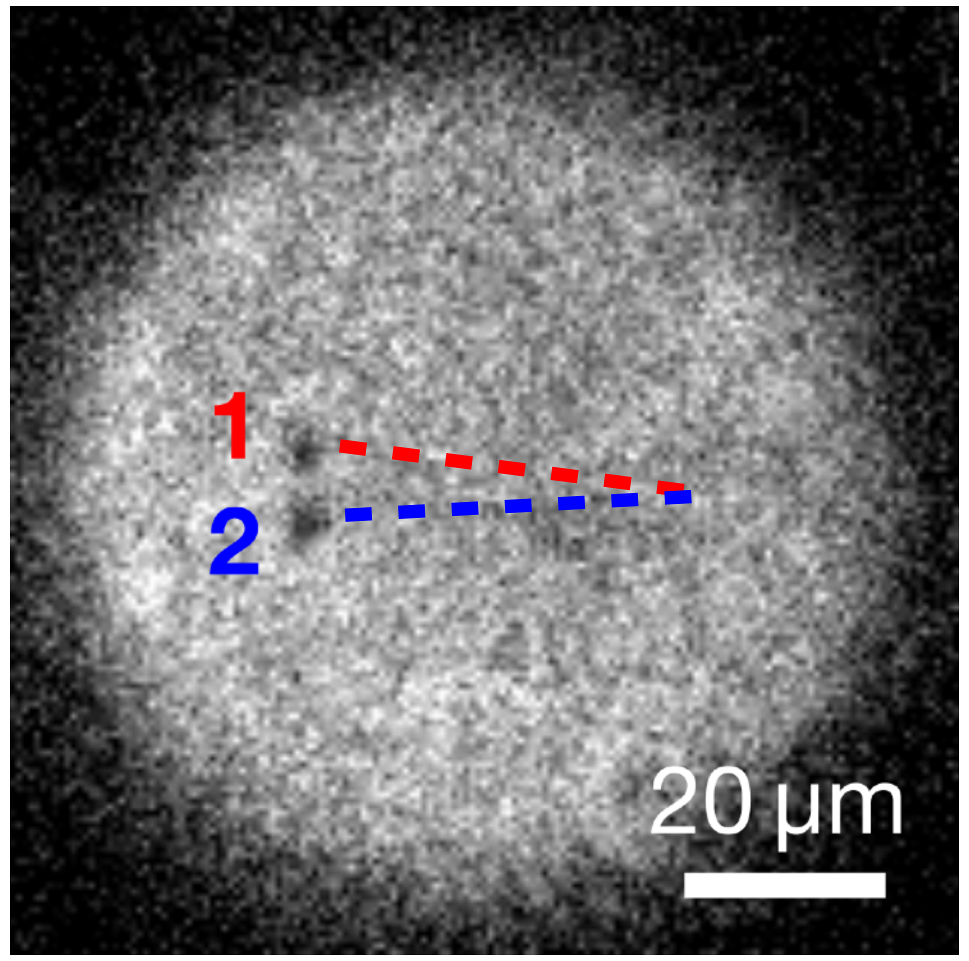
Without dissipation

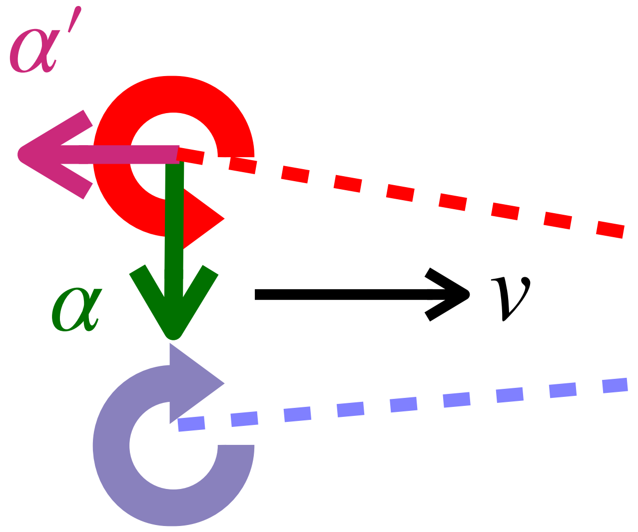




$E_i = E_f$

With dissipation



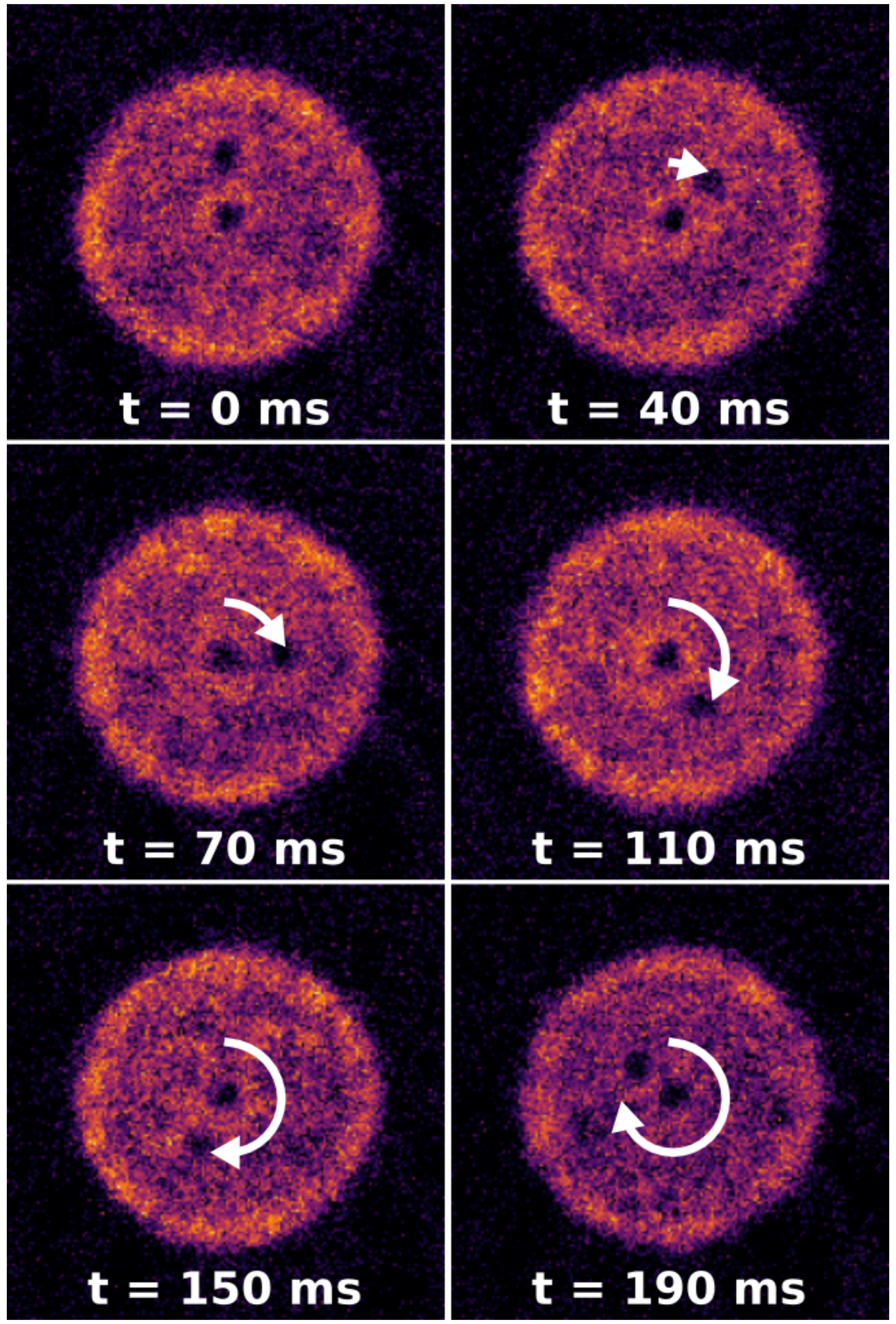


$E_i > E_f$

$E \propto \log d$

$v \propto 1/d$

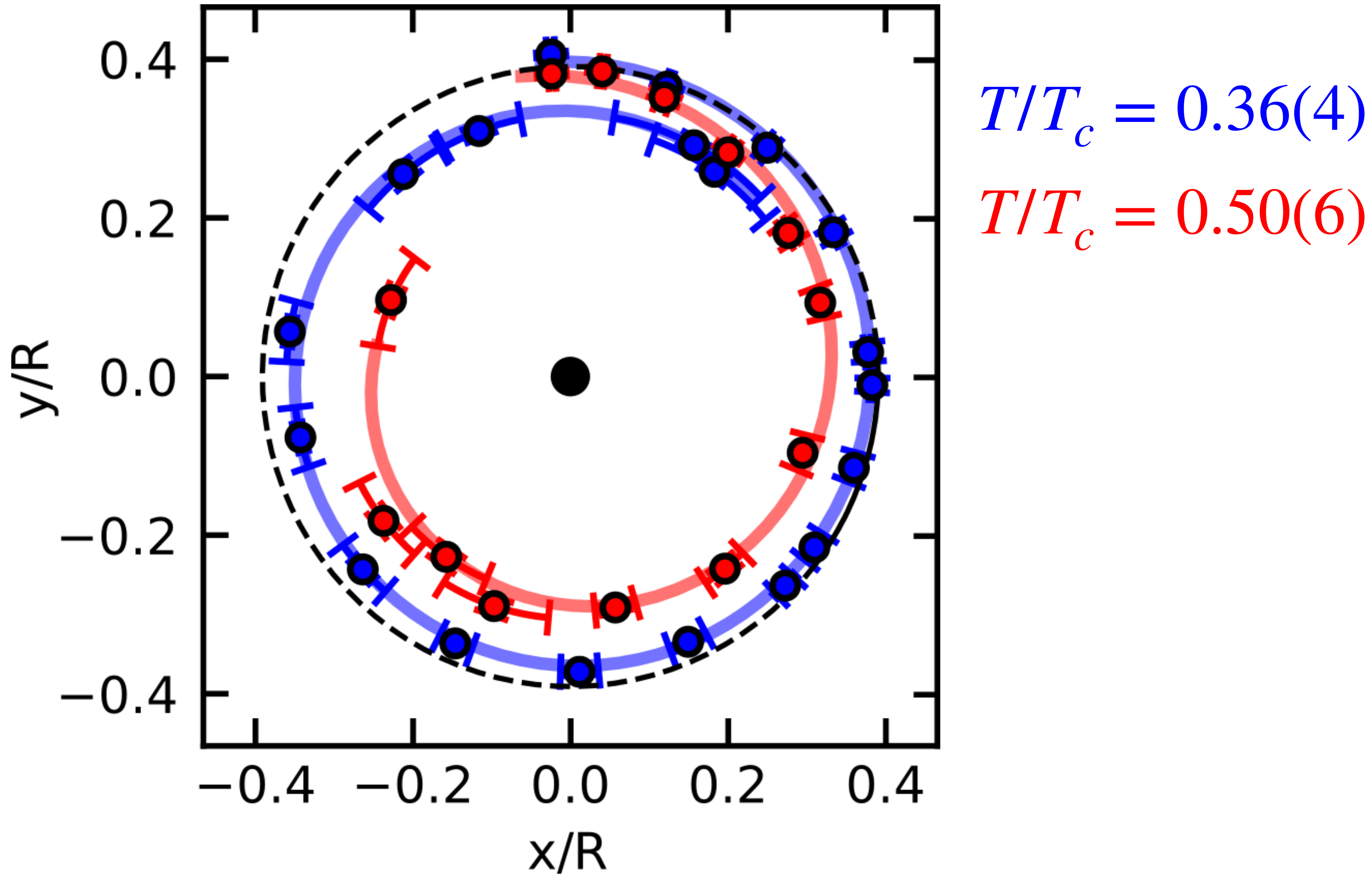
Experimental realization



N. Grani, et al., arXiv:2503.21628 (2025)

MUTUAL FRICTION IN A VORTEX DIPOLE

N. Grani, et al., arXiv:2503.21628 (2025)



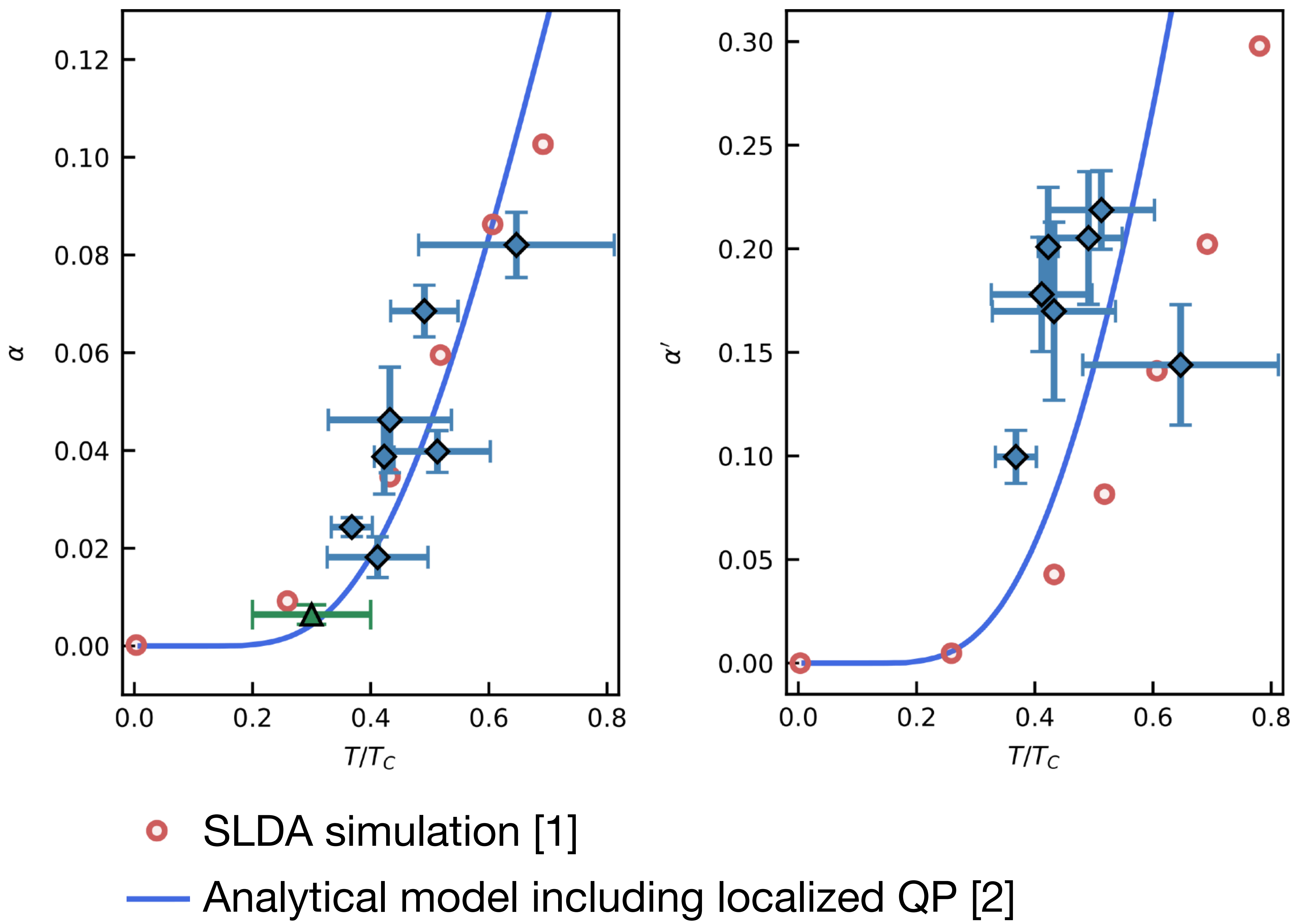
Point Vortex Model (PVM)

$$\frac{d\vec{r}}{dt} = (1 - \alpha')\vec{v}_s^0 - \alpha\sigma\hat{z} \times \vec{v}_s^0$$

σ → Circulation

v_s^0 → Superfluid velocity

Mutual friction coefficients

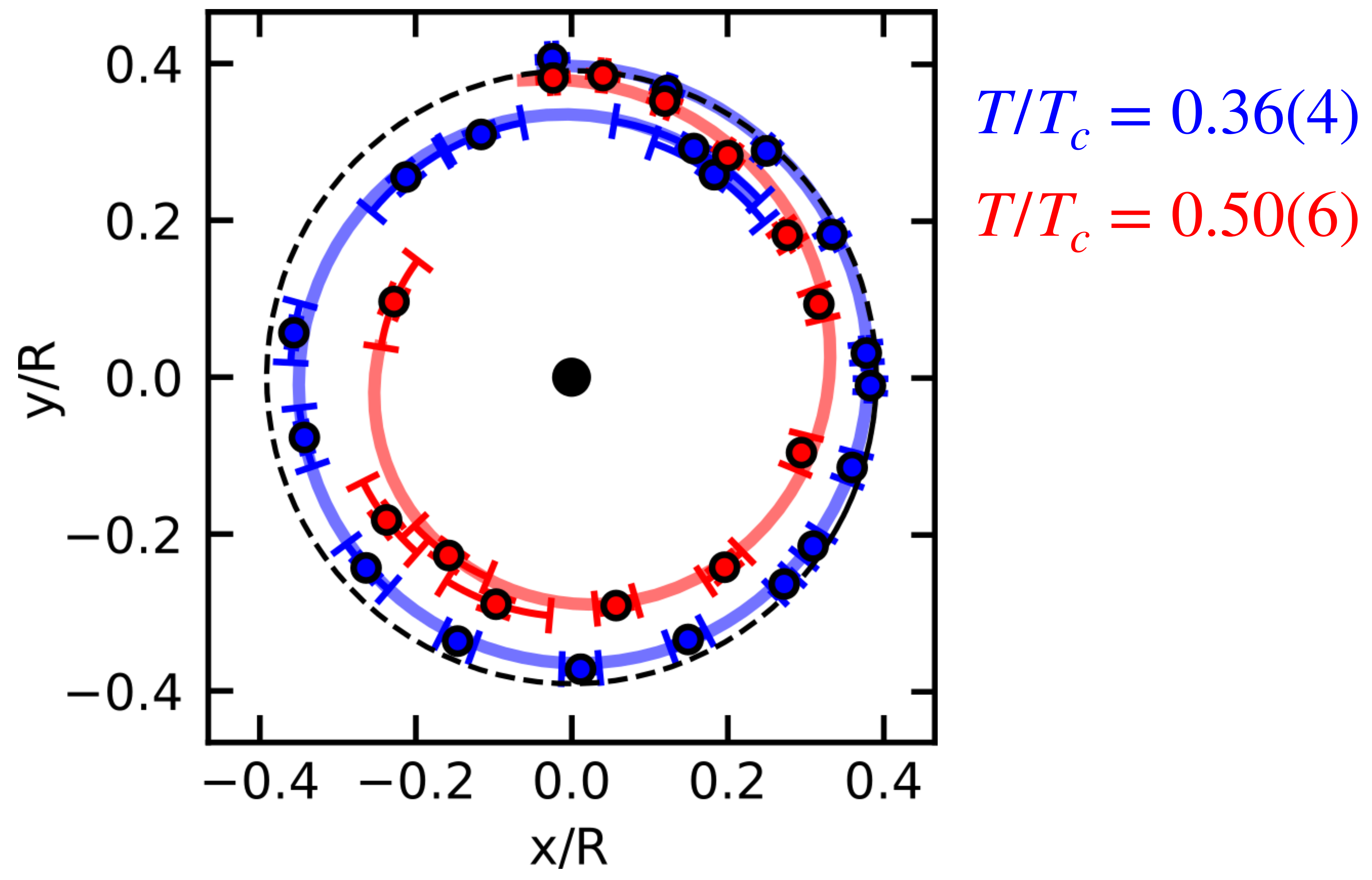


[1] A. Bulgac, Phys. Rev. A 76, 040502 (2007)

[2] N. B. Kopnin, Reports on Progress in Physics 65, 1633 (2002)

MUTUAL FRICTION IN A VORTEX DIPOLE

N. Grani, et al., arXiv:2503.21628 (2025)



Point Vortex Model (PVM)

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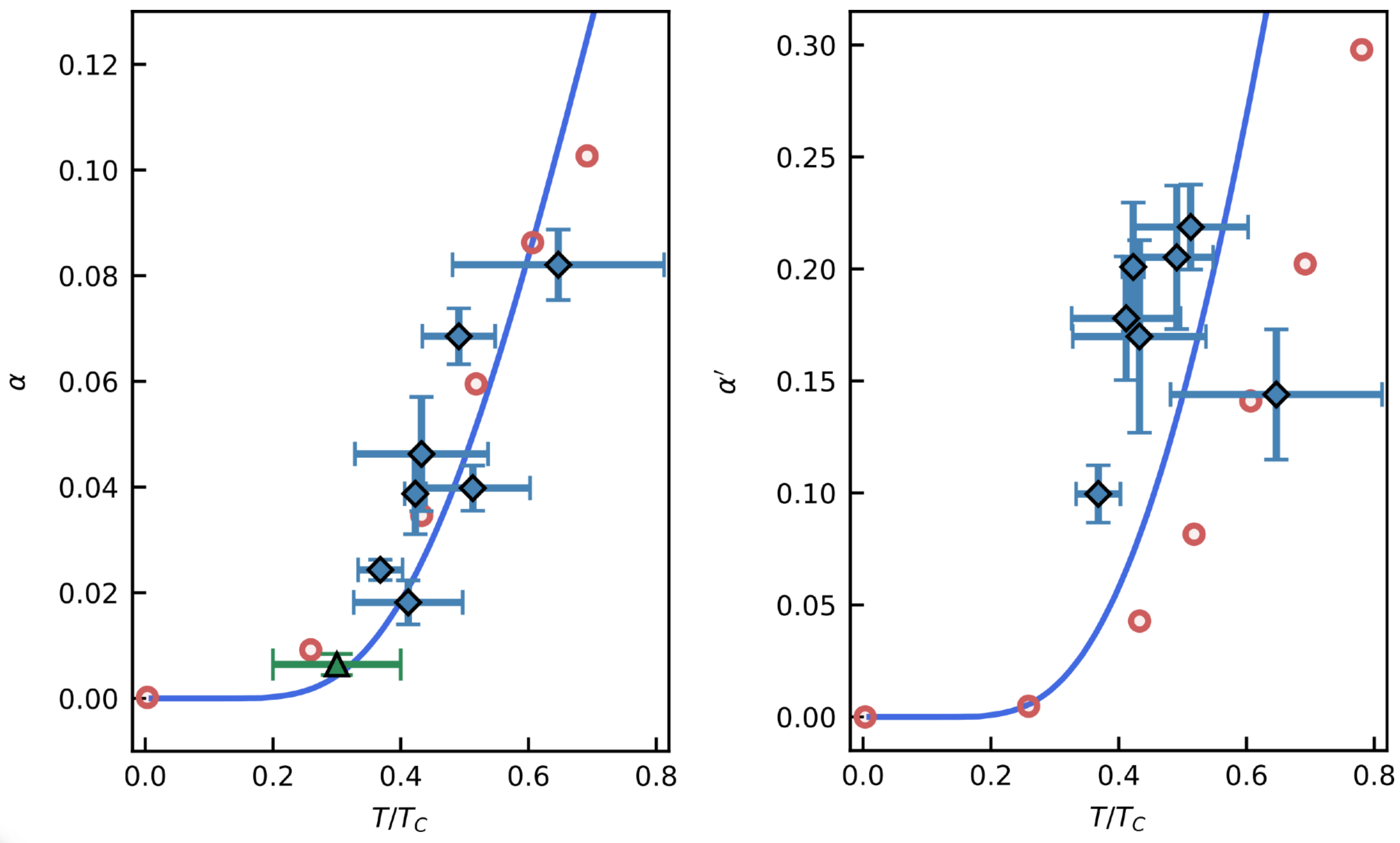


- SLDA simulation [1]
- Analytical model including localized QP [2]

- First experimental observation of **nonzero** α' in ultra cold atoms
- Connection with **microscopic mechanism** of dissipation

[1] A. Bulgac, Phys. Rev. A 76, 040502 (2007)

[2] N. B. Kopnin, Reports on Progress in Physics 65, 1633 (2002)

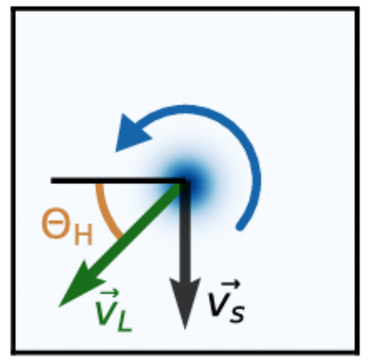
MICROSCOPIC DISSIPATION

N. Grani, et al., arXiv:2503.21628 (2025)

Can we extract information on **microscopic quantities** given the **phenomenological** parameters α and α' ?

- Hall angle: direction of the vortex motion with respect to the superfluid velocity

$$\Theta_H = \tan^{-1}\frac{1-\alpha'}{\alpha} = \omega_0\tau$$

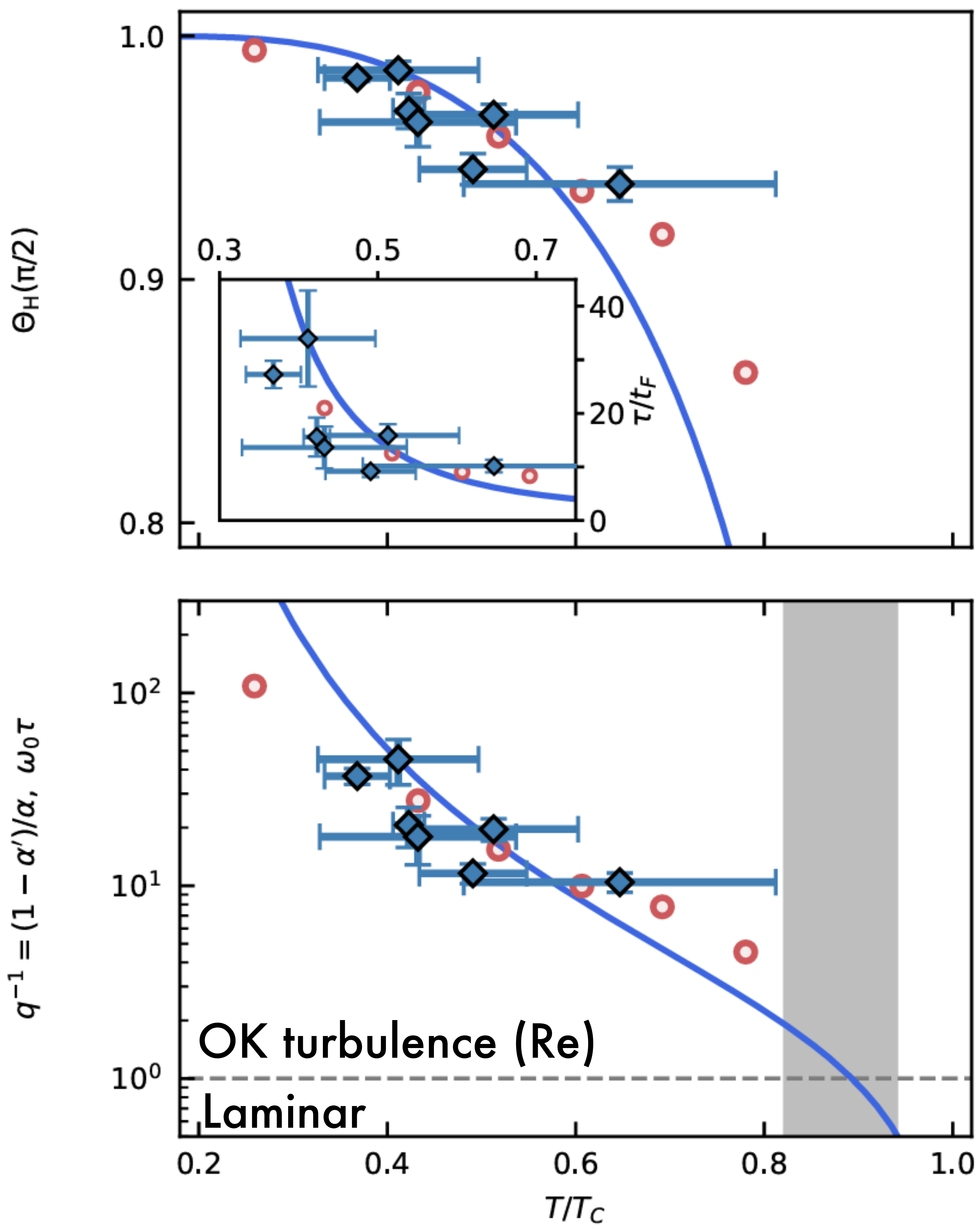


- Localized quasiparticle lifetime

$$\tau = \Theta_H/\omega_0 \qquad \hbar\omega_0 = |\Delta|^2/E_F$$

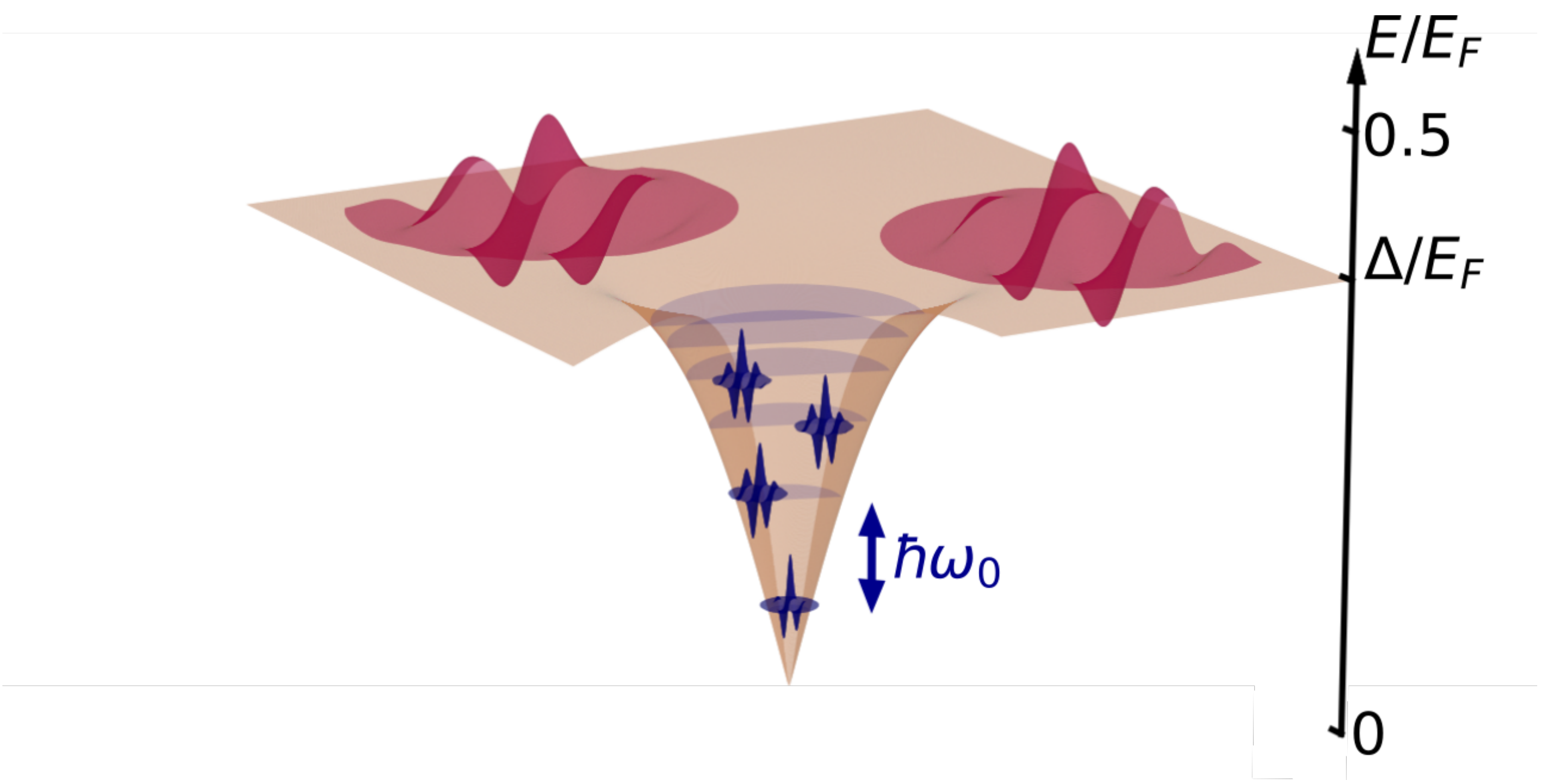
- Intrinsic superfluid parameter: regime for superfluid turbulence

$$q = \frac{\alpha}{1-\alpha'}$$



M. Heyl, et al.,, Nat. Comm. 13, 6986 (2022).
N. Kopnin and M. Salomaa, Phys. Rev. B 44, 9667 (1991).
A. Finne, et al., Nature 424, 1022 (2003).

SOUND INTERACTION

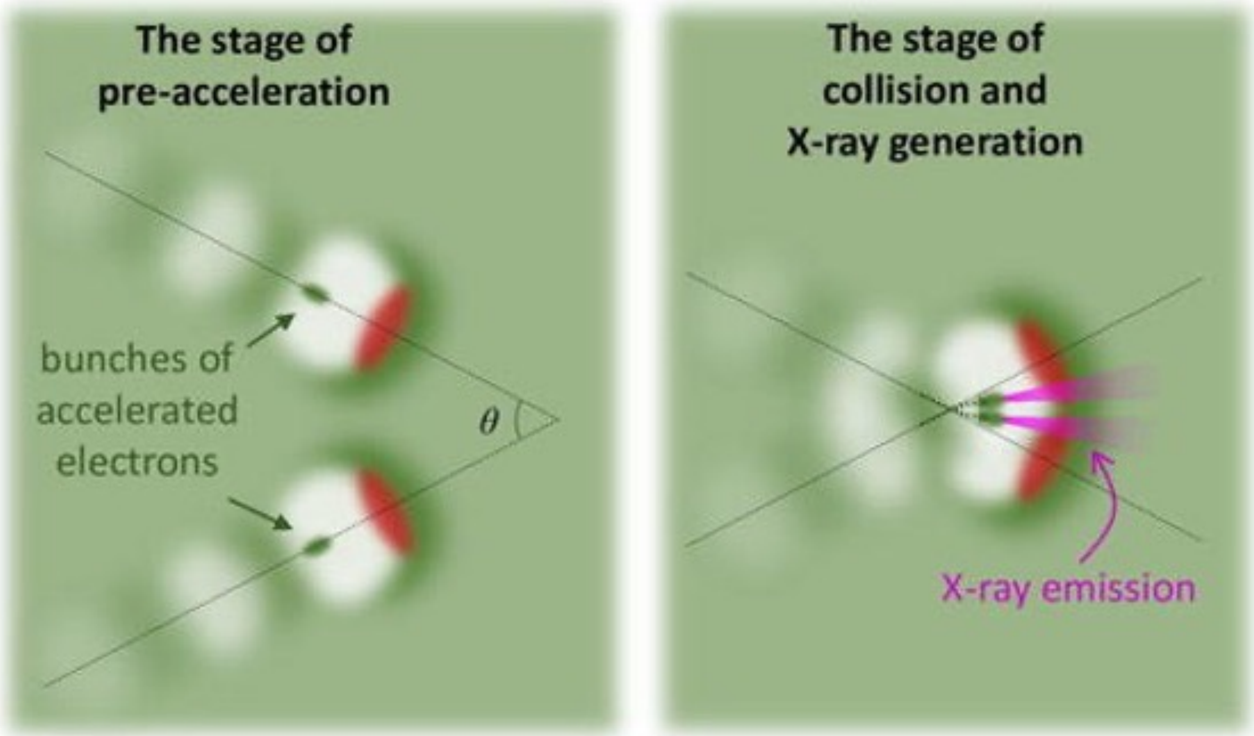


Caroli, De Gennes, and Matricon. *Phys. Lett.* 9.4 307-309 (1964)
R. Sensarma, et al., *Phys. Rev. Lett.* 96.9 090403 (2006)

Sound interaction

The **incompressible** energy of the vortex can be transformed into **compressible** energy of the superfluid: sound emission

Also at zero temperature



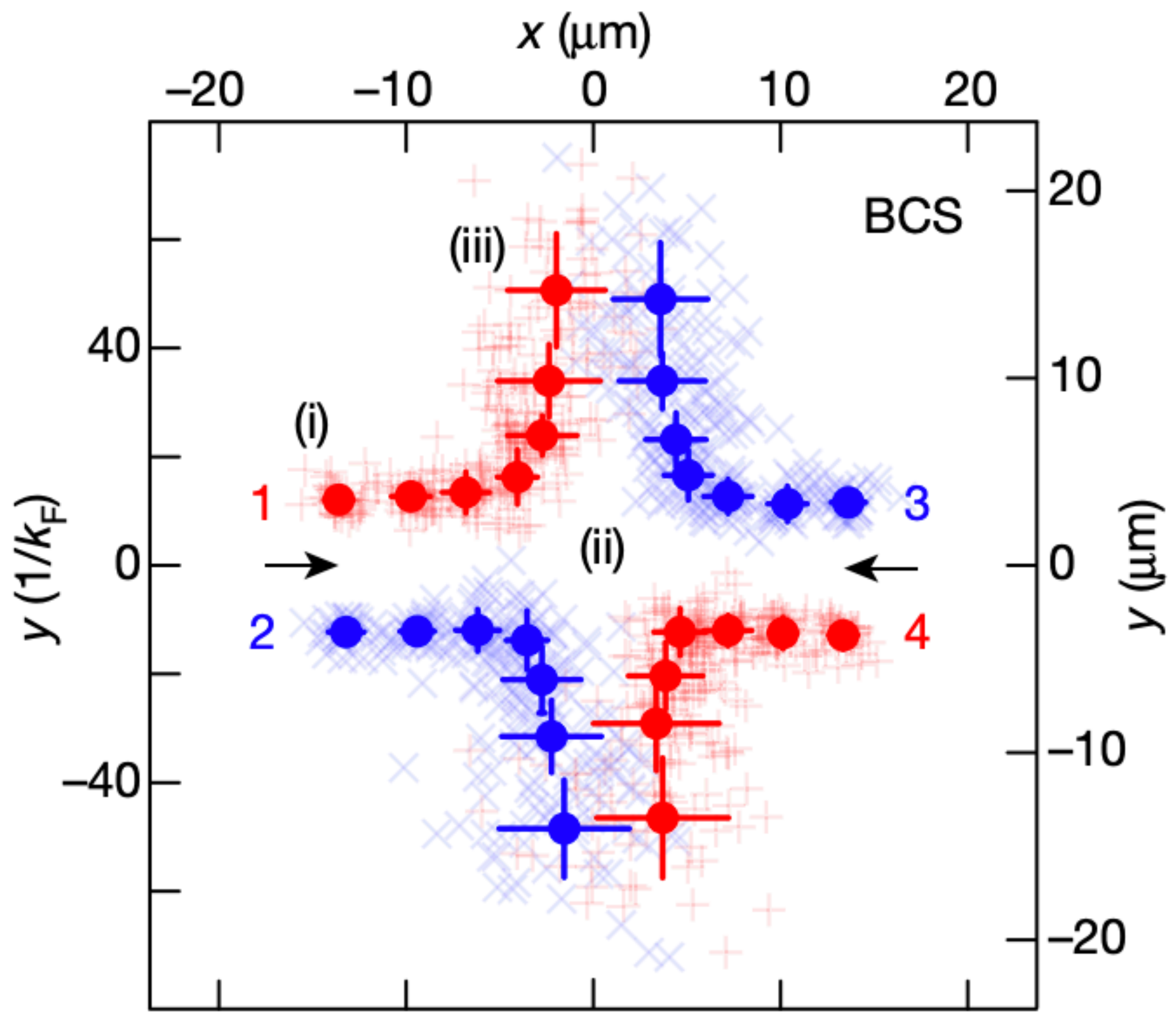
Picture taken from: E. Vallin et al., *Physics of Plasmas* **24**, 093101 (2017)

- Vortices at short distance
- Acceleration —> sound emission
- Vortex-dipole collisions

DIPOLE-DIPOLE COLLISIONS

W. J. Kwon, et al. *Nature* **600**, 64–69 (2021).

To promote **sound dissipation** we work at T=0 and we engineer collisions between short-distance dipole



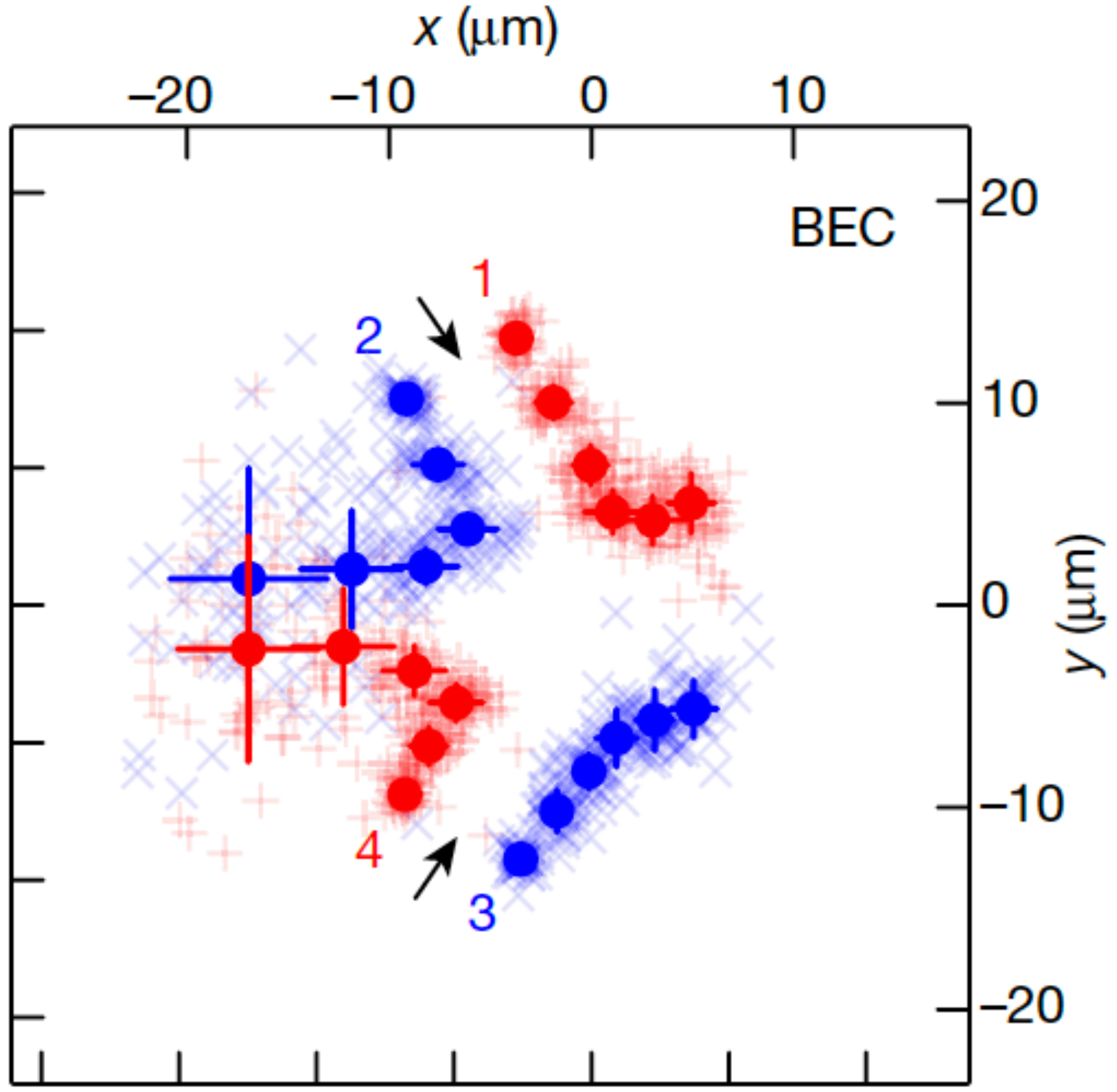
Head-on collision

Dissipation

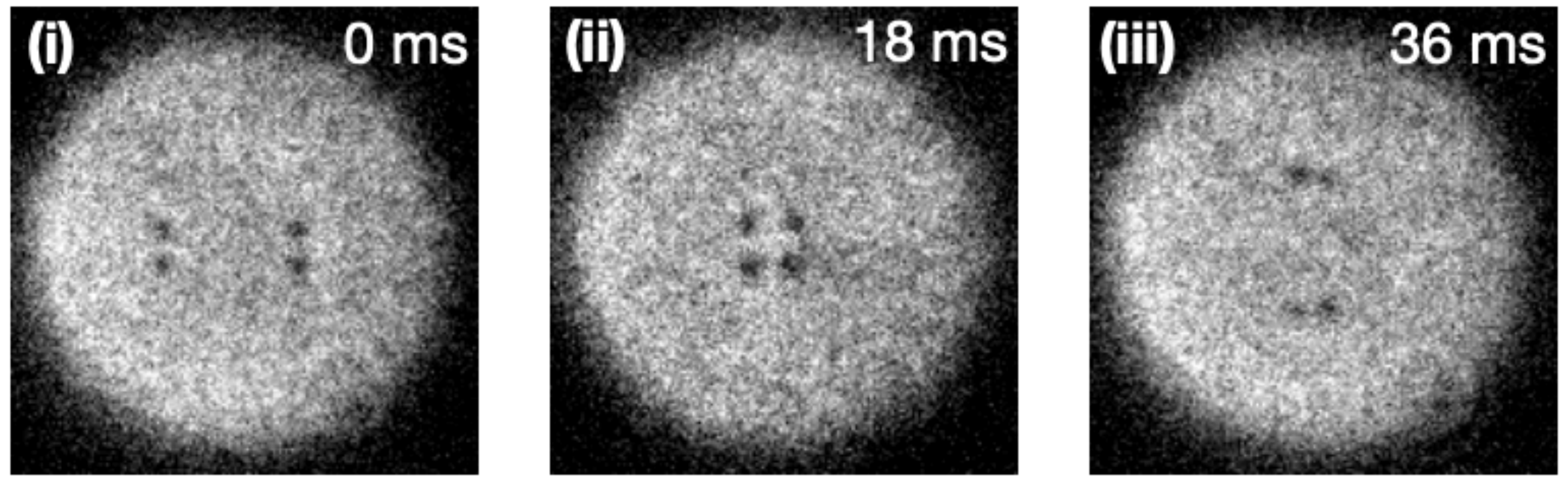
$$E \propto \log d$$

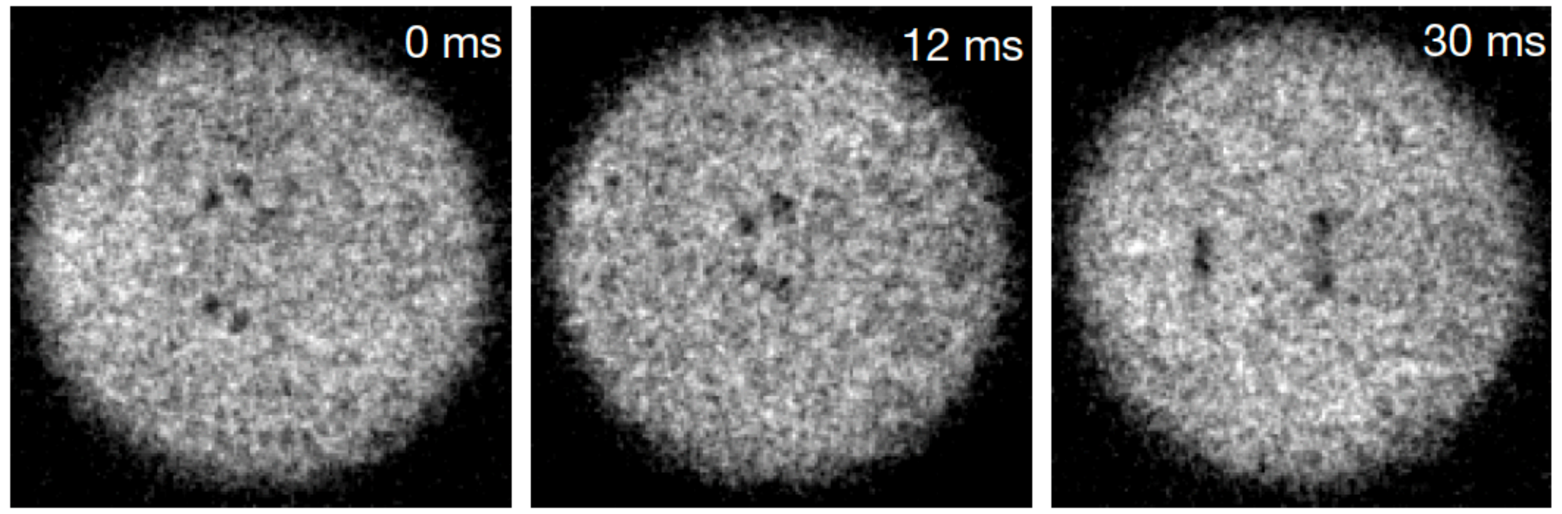
Dipole size ratio after/before the collision

$$\Gamma = \frac{d_{13}d_{24}}{d_{12}d_{34}}$$



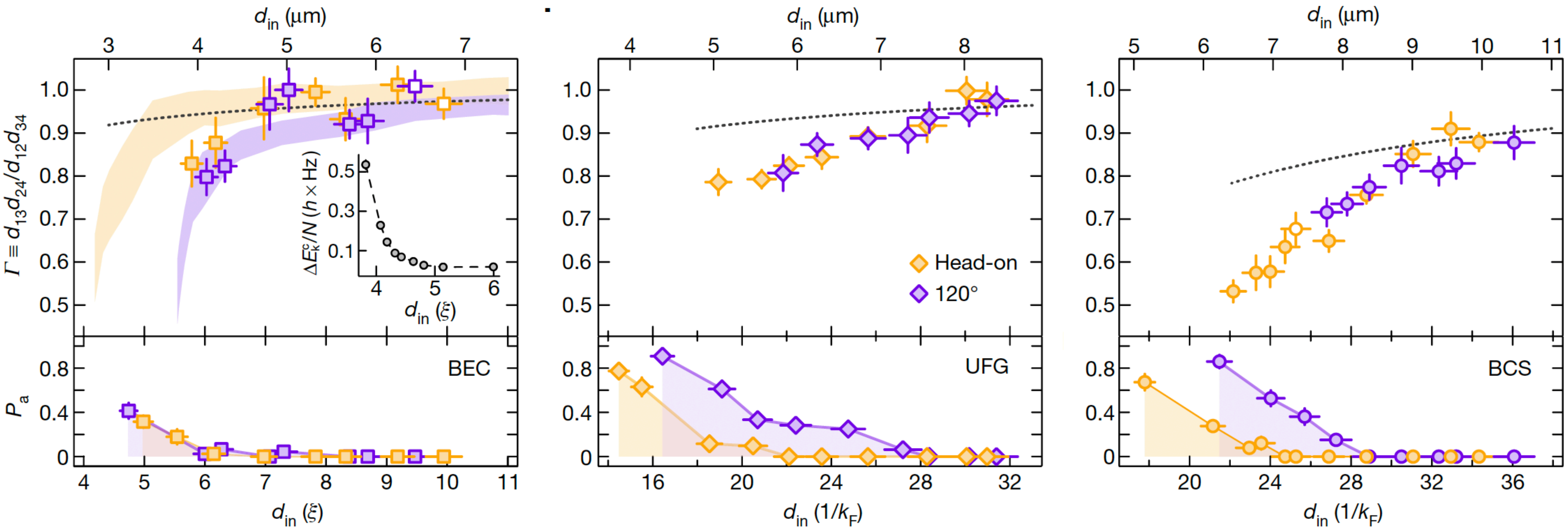
120° collision





SOUND DISSIPATION IN VORTEX COLLISION

W. J. Kwon, et al. *Nature* **600**, 64–69 (2021).



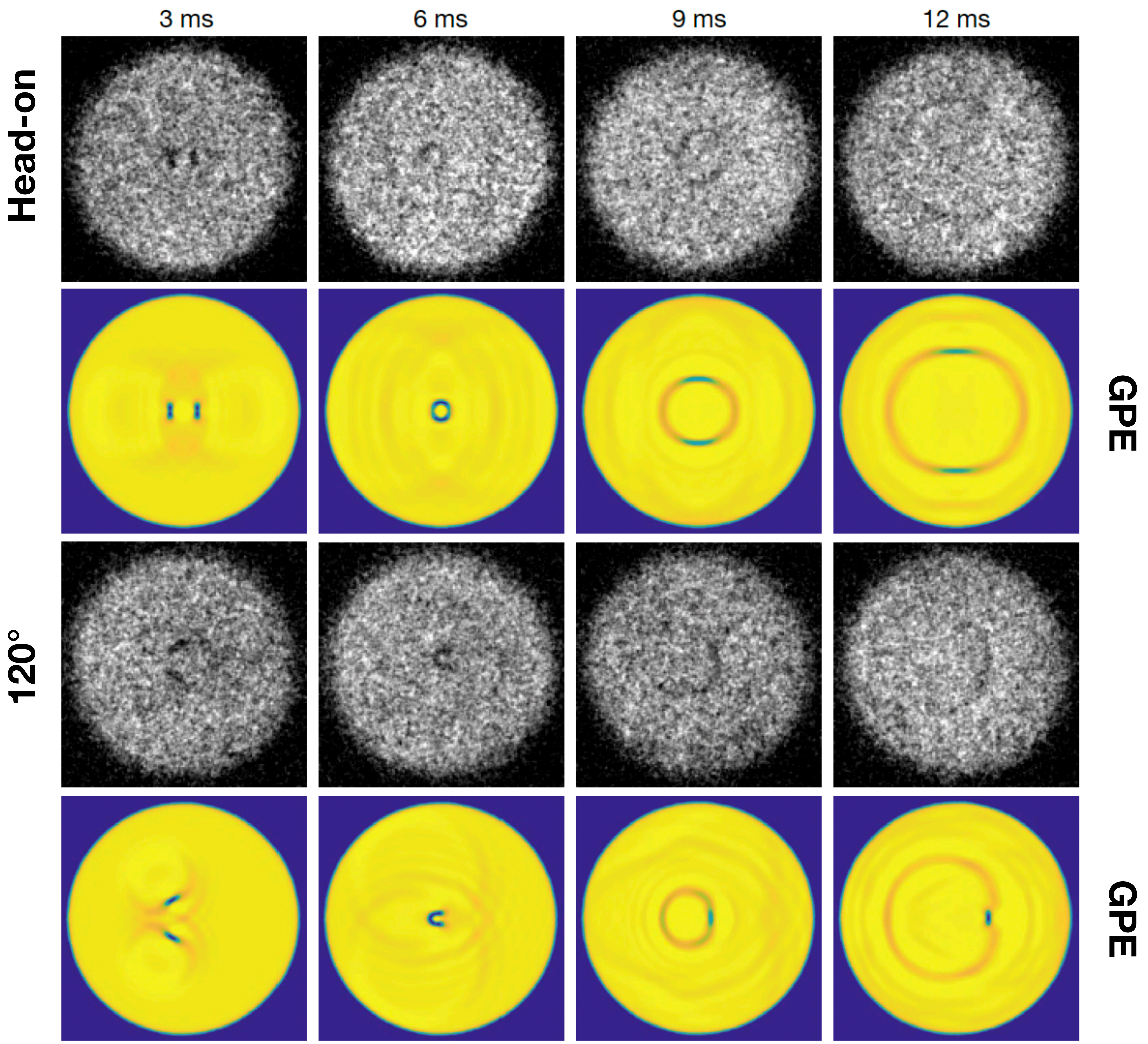
...... PVM

GPE

- The disagreement with PVM signal the presence of a different source of dissipation at short distance: **sound**
- The sound dissipation increases for **fermionic** superfluids
- For shorter dipole the probability of **annihilation** increases

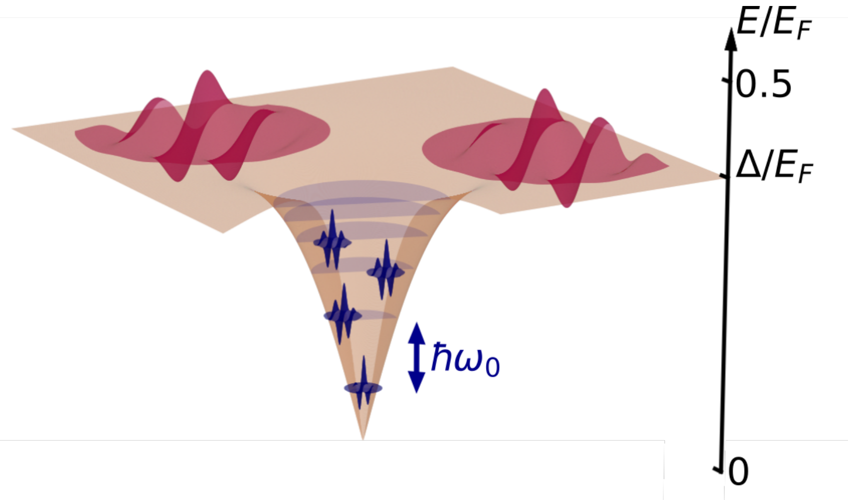
VORTEX - ANTIVORTEX ANNIHILATION

W. J. Kwon, et al. *Nature* **600**, 64–69 (2021).

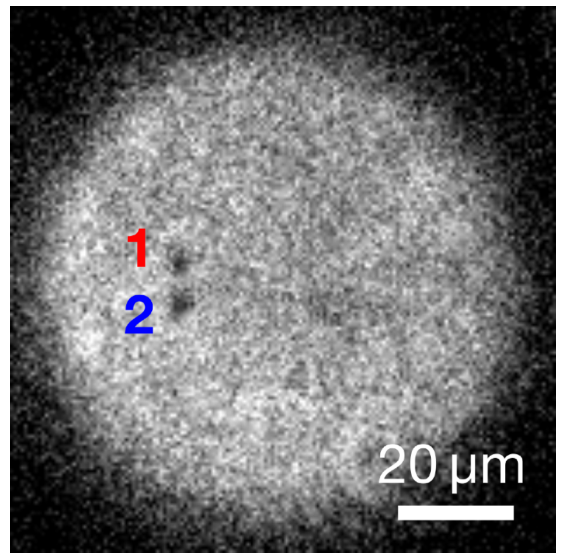


- Vortex-antivortex annihilation via **sound emission:** the incompressible energy of the dipole is fully converted in compressible sound energy
- The sound emission is non-symmetric (rarefaction pulse)

CONCLUSIONS

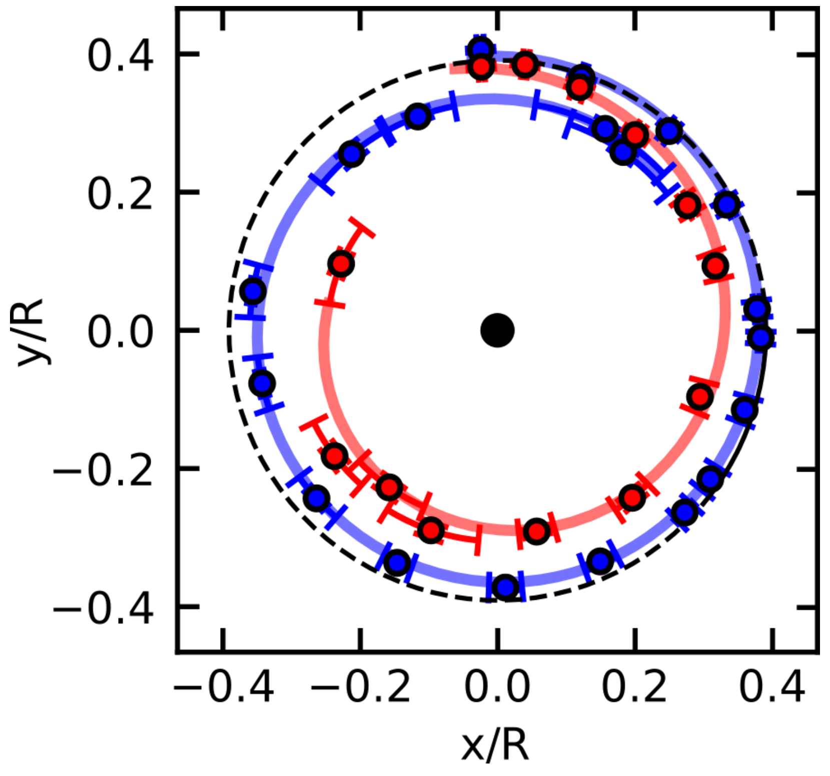


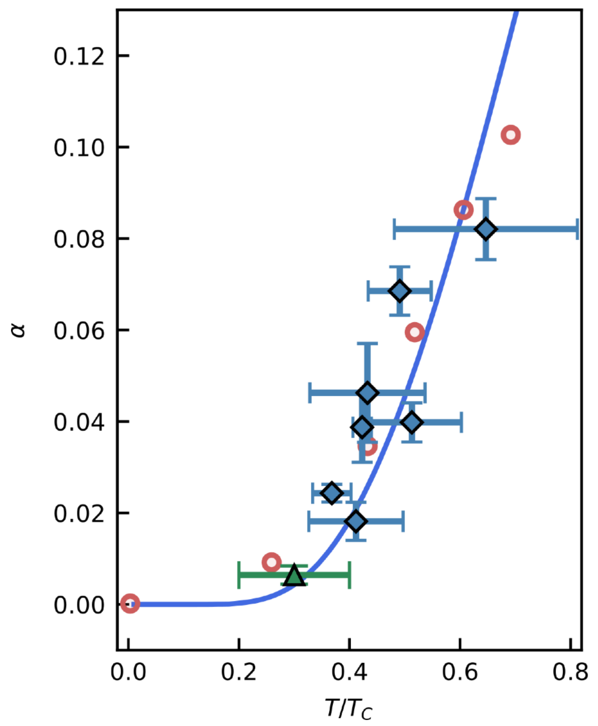
- Ultracold atoms a an ideal platform for **studying vortex dynamic in a bottom-up approach**: create on-demand vortex configuration, detect with micron-scale resolution
- We reconstruct the vortex configuration dynamics by following the **vortex trajectories**

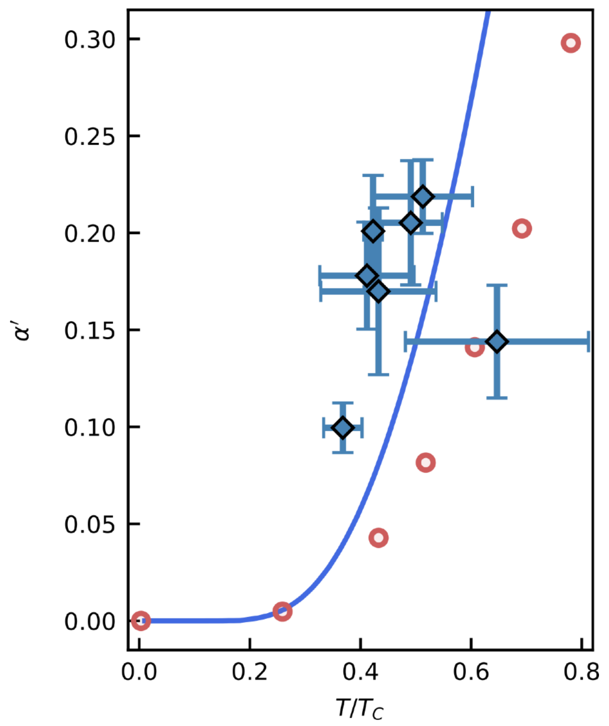


Mutual friction

- We observe an **increase of mutual friction** for increasing temperature, and extract the mutual friction coefficients
- We identify a role of **localized quasiparticles** in dissipation of vortices in Fermi superfluids



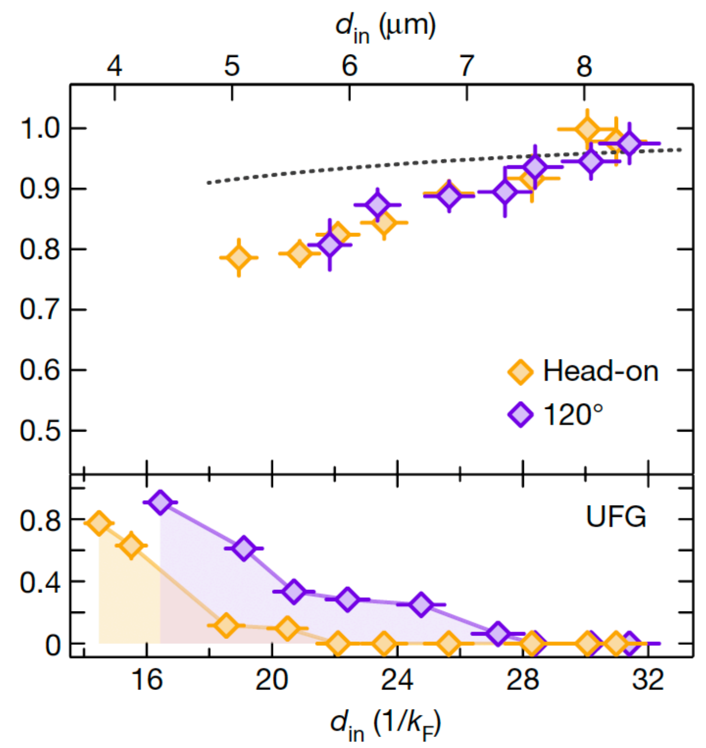


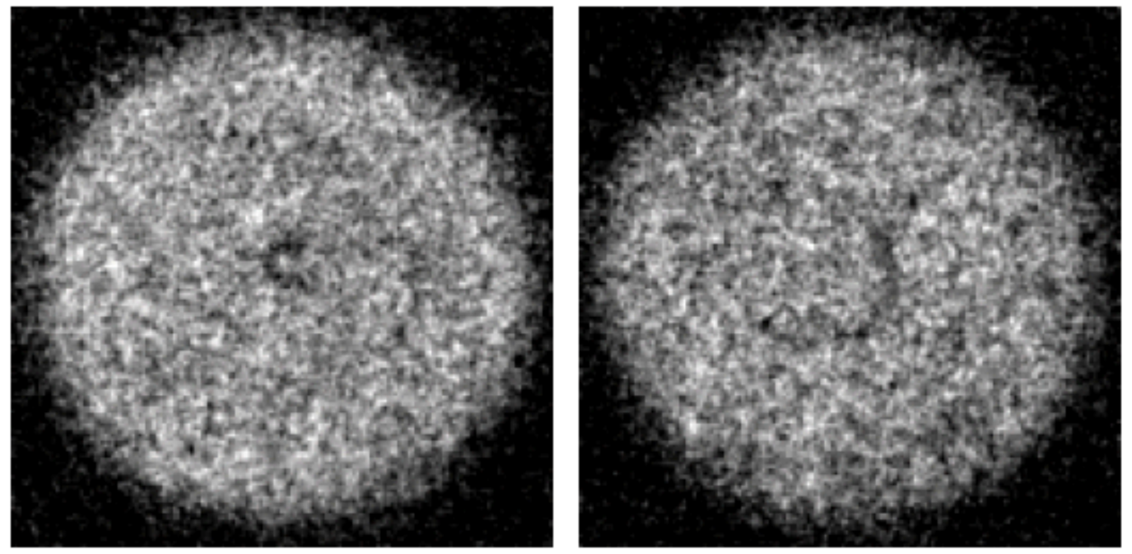


N. Grani, et al., arXiv:2503.21628 (2025)

Sound interaction

- In colliding dipoles at short distance we observe an excess dissipation due to **sound interaction** (incompressible —> compressible energy)
- We directly visualize **vortex-antivortex annihilation** via sound emission

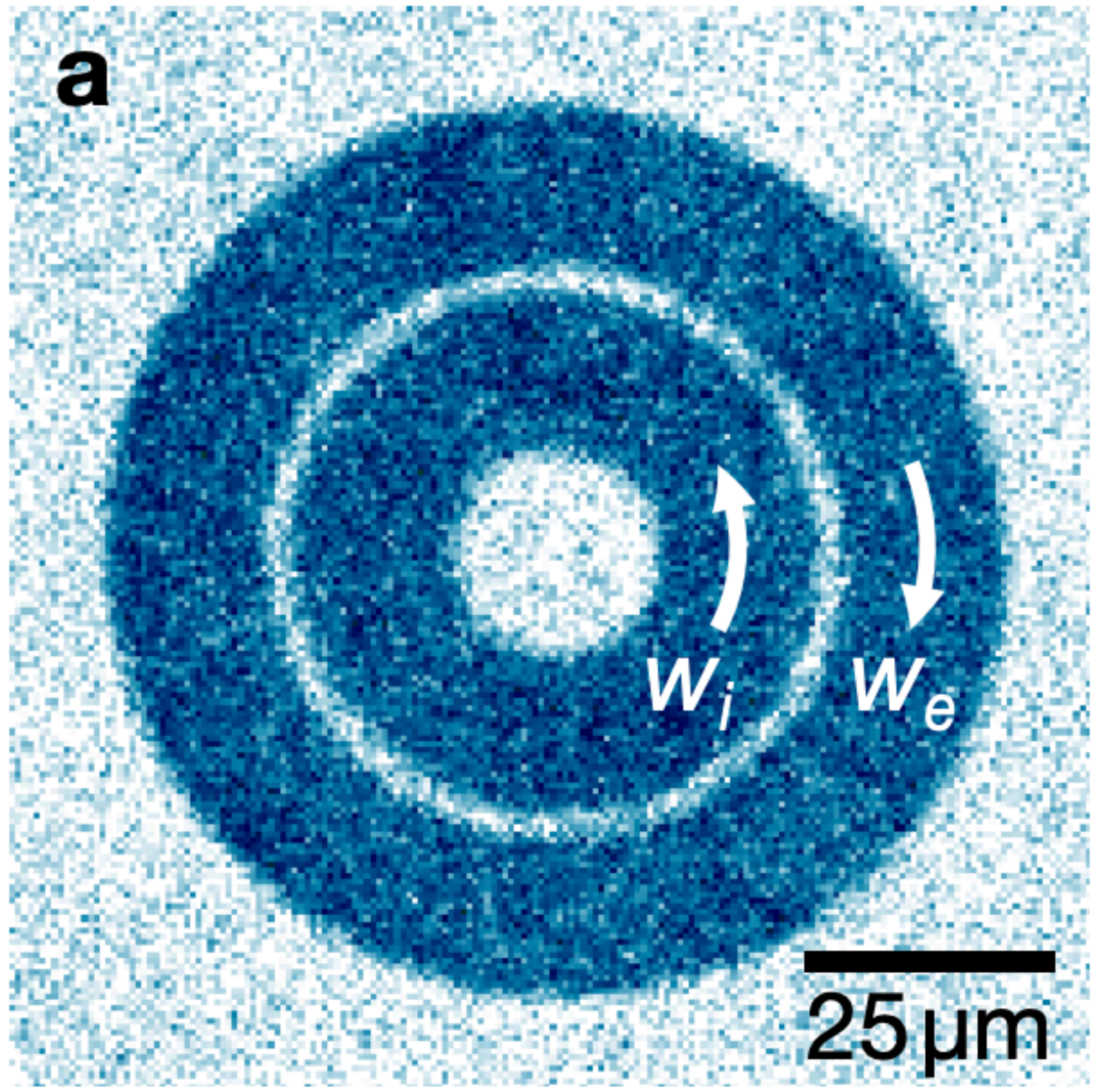




W. J. Kwon, et al. *Nature* **600**, 64–69 (2021).

MORE VORTICES?

D. Hernández-Rajkov, et al. *Nat. Phys.* **20**, 939–944 (2024).



Double concentric ring geometry

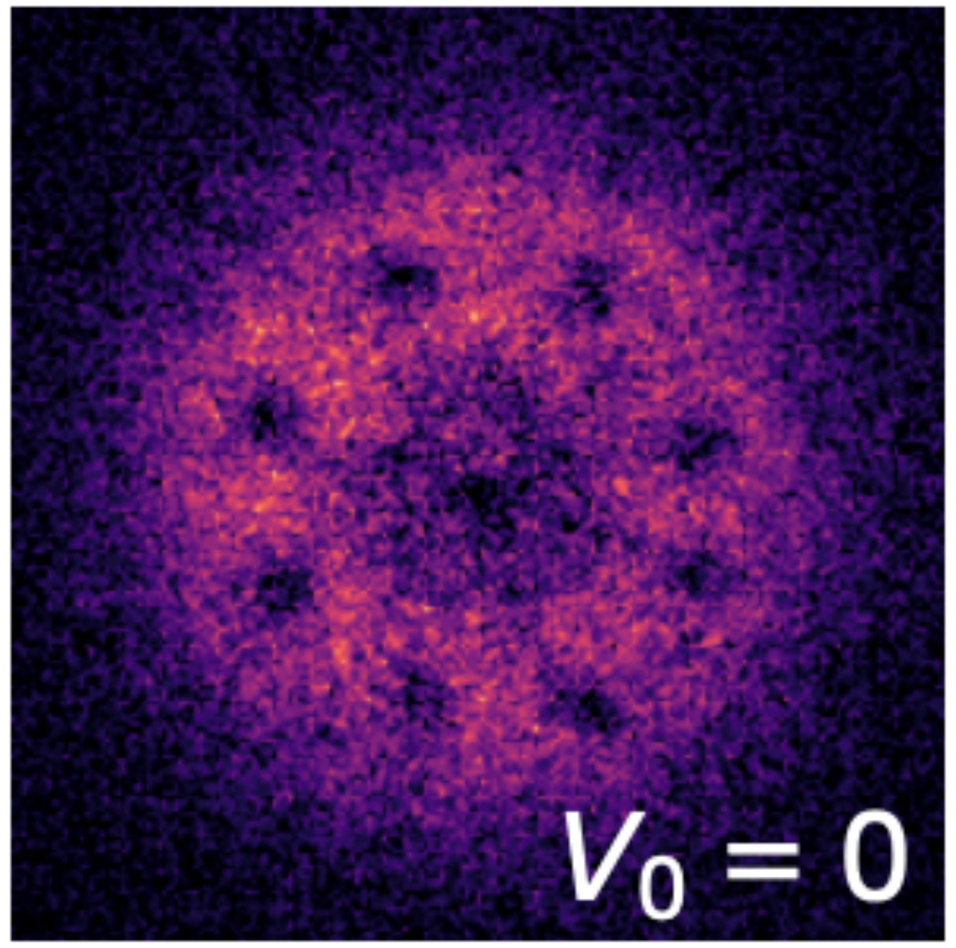
We imprint opposite winding $w_i = - w_e$ in the two rings

The relative velocity at the interface of radius R_0 is:

$$\Delta v = \frac{\hbar(w_e - w_i)}{mR_0}$$

Remove the barrier

See Diego Hernandez Rajkov talk on Thursday!

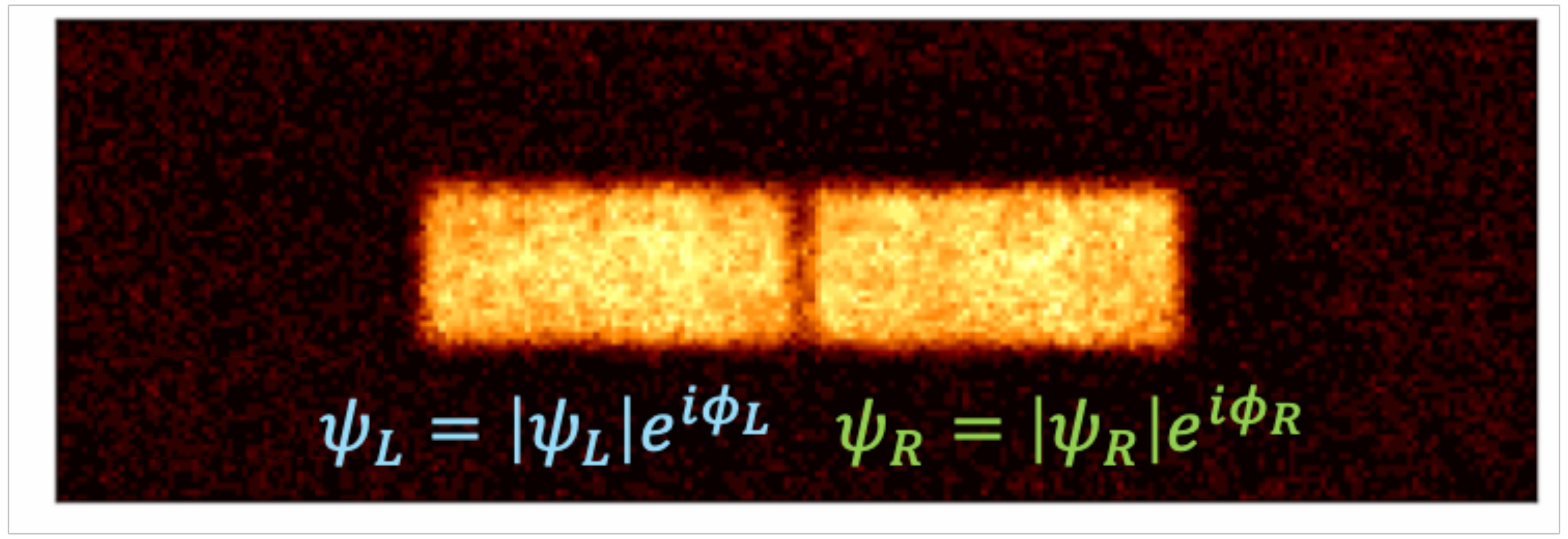


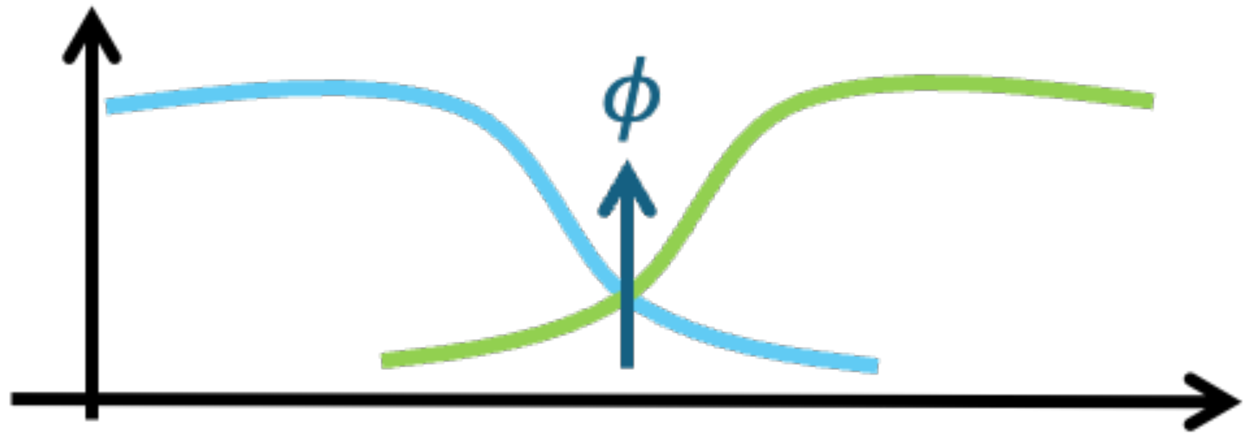
Vortex necklace

With a number of vortices $N_v = \Delta w$

MORE FROM LILAB?

W. J. Kwon, et al. Science 369.6499: 84-88 (2020)
G. Del Pace, et al., arXiv preprint arXiv:2409.03448 (2024)



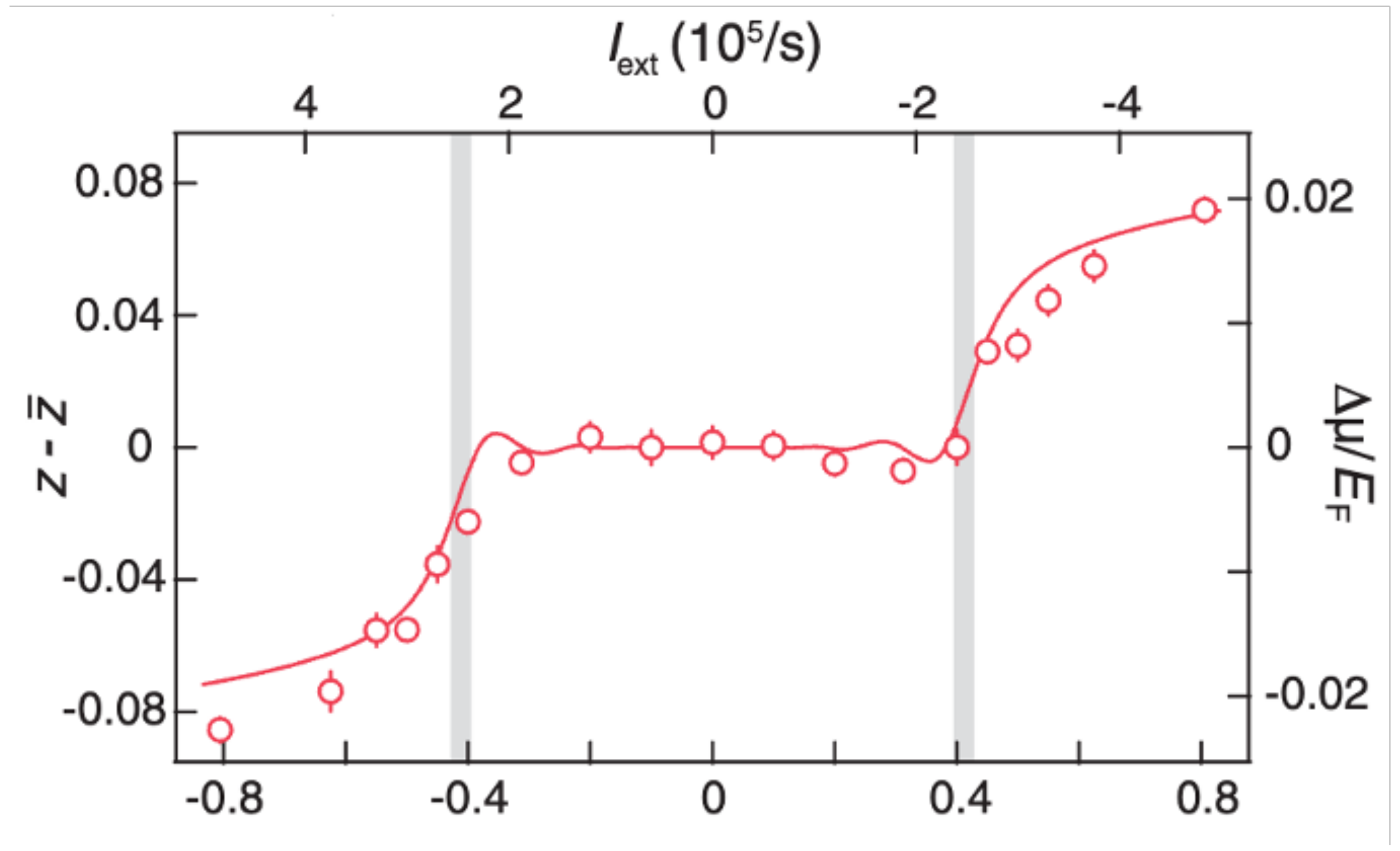


Josephson-Anderson equations:

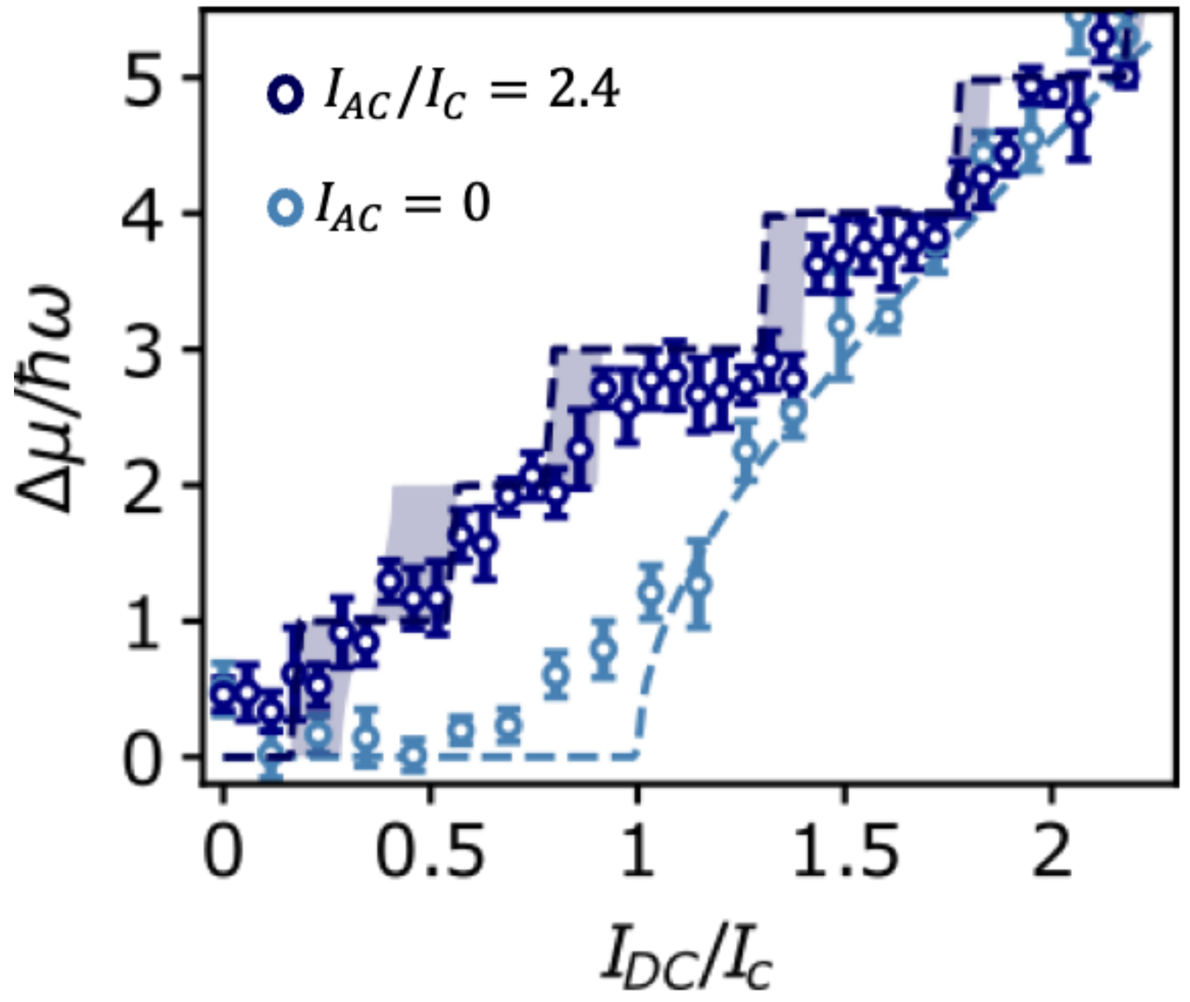
$$I = I_c \sin(\phi)$$

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

DC Josephson effect



Shapiro steps under AC drive



See Marcia Frometa Fernandez poster this afternoon!

LITHIUM TEAM @ LENS

Our website:

Finanziato dall'Unione europea NextGenerationEU

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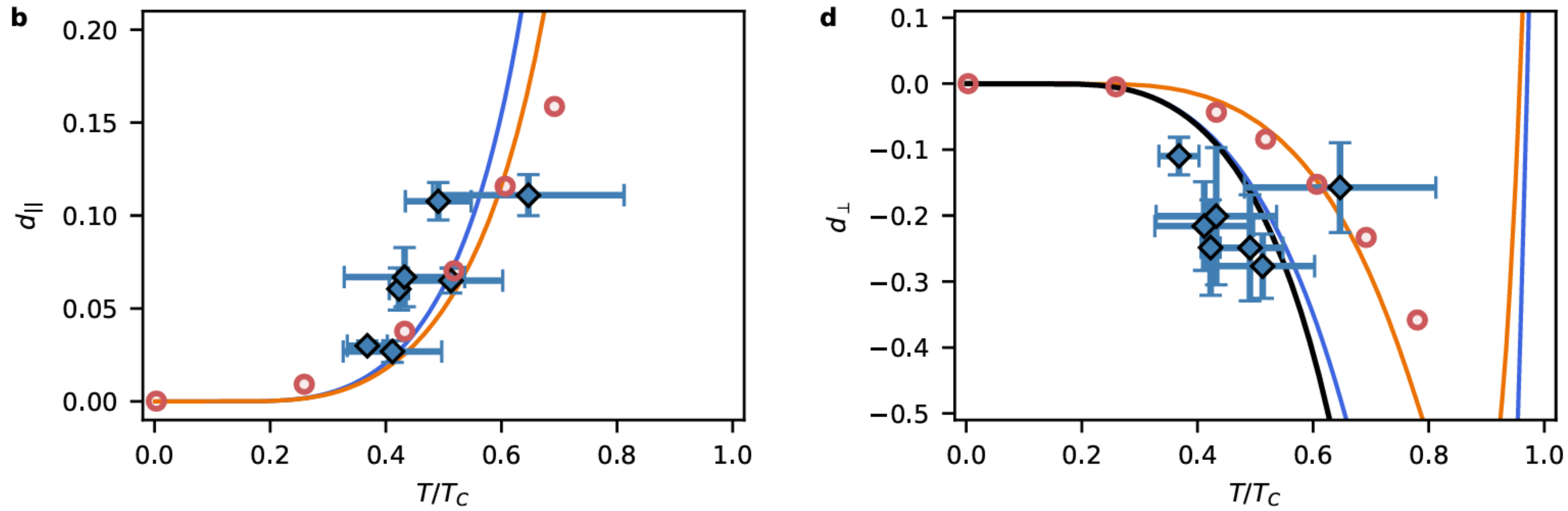
Gabriel Wlazlowski, Warsaw University of Technology
Keljdja Xhani, Politecnico di Torino
Luca Galantucci, IAC-CNR

FORCES ON VORTICES

$$\vec{F}_N = D(\vec{v}_n - \vec{v}_L) + D'\hat{z} \times (\vec{v}_n - \vec{v}_L),$$

$$\vec{F}_M = \kappa \rho_s (\vec{v}_s - \vec{v}_L) \times \hat{z}$$

$$\vec{F}_N + \vec{F}_M = 0,$$



$$\alpha = \frac{d_{||}}{d_{||}^2 + (1 - d_\perp)^2},$$

$$\alpha' = 1 - \frac{1 - d_\perp}{d_{||}^2 + (1 - d_\perp)^2},$$

$$d_{||} = \frac{D}{\kappa_c \rho_s}, \qquad d_\perp = \frac{D'}{\kappa_c \rho_s}.$$

$$\alpha = \frac{\rho_s}{\rho}\left(\omega_0 \tau \tanh \frac{|\Delta|}{2k_B T}\right)^{-1},$$

$$\alpha' = 1 - \frac{\rho_s}{\rho}\left(\tanh \frac{|\Delta|}{2k_B T}\right)^{-1},$$

$$d_{||} = \frac{\rho}{\rho_s} \frac{\omega_0 \tau}{1 + \omega_0^2 \tau^2} \tanh\left(\frac{\Delta}{2k_B T}\right),$$

$$d_\perp = 1 - \frac{\rho}{\rho_s} \frac{\omega_0^2 \tau^2}{1 + \omega_0^2 \tau^2} \tanh\left(\frac{\Delta}{2k_B T}\right),$$