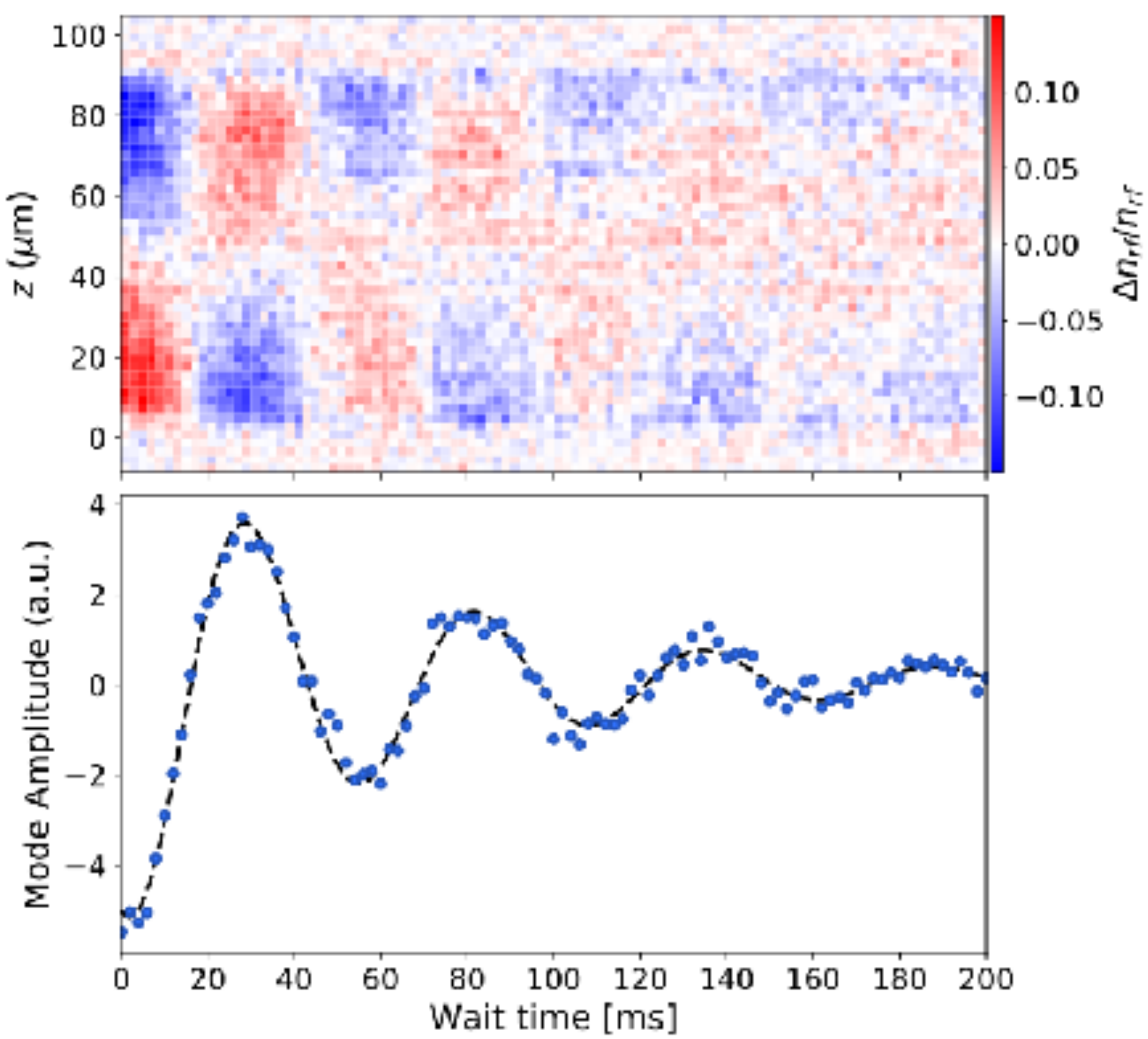
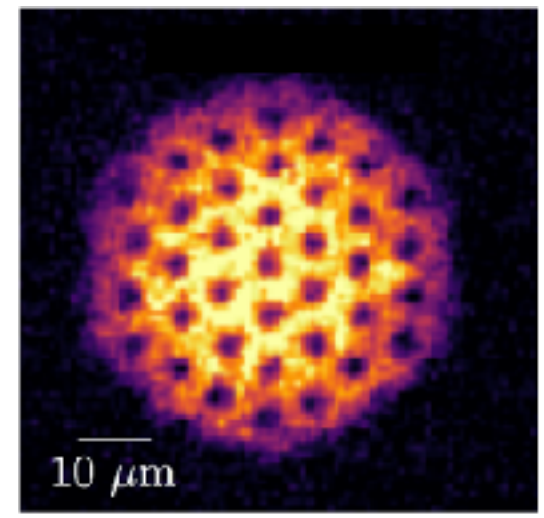
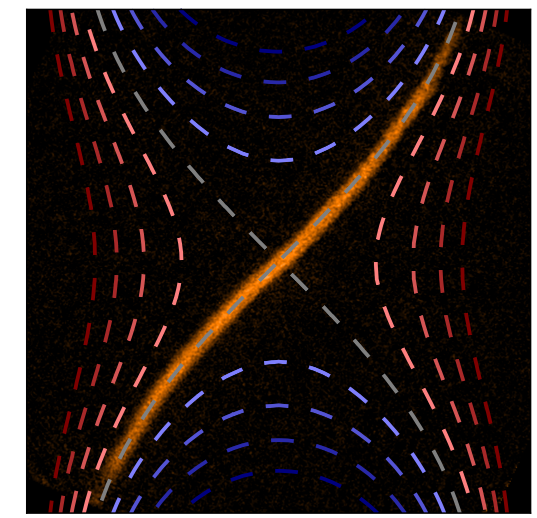
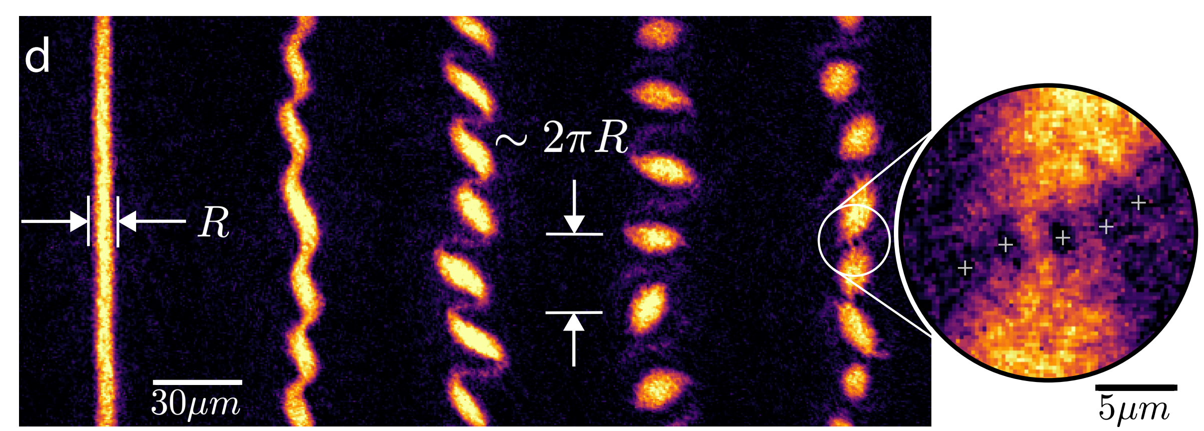
Dynamics and transport in strongly-interacting quantum fluids

Richard Fletcher



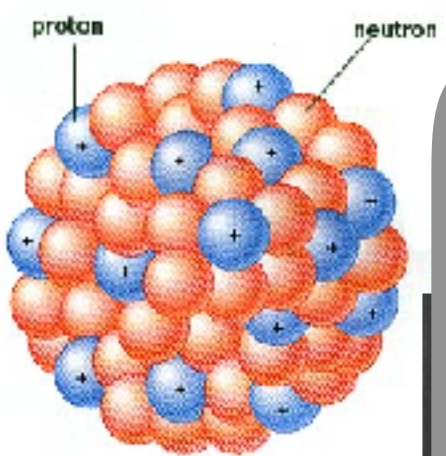






Two routes to strongly-correlated matter

Strong interactions	Quenched kinetic energy



10^{-15} m

No small parameter
Sign problem (for fermions)
Breakdown of quasiparticles/Fermi liquid
Macroscopically degenerate
Exponential growth of Hilbert space
Non-perturbative behaviour
...

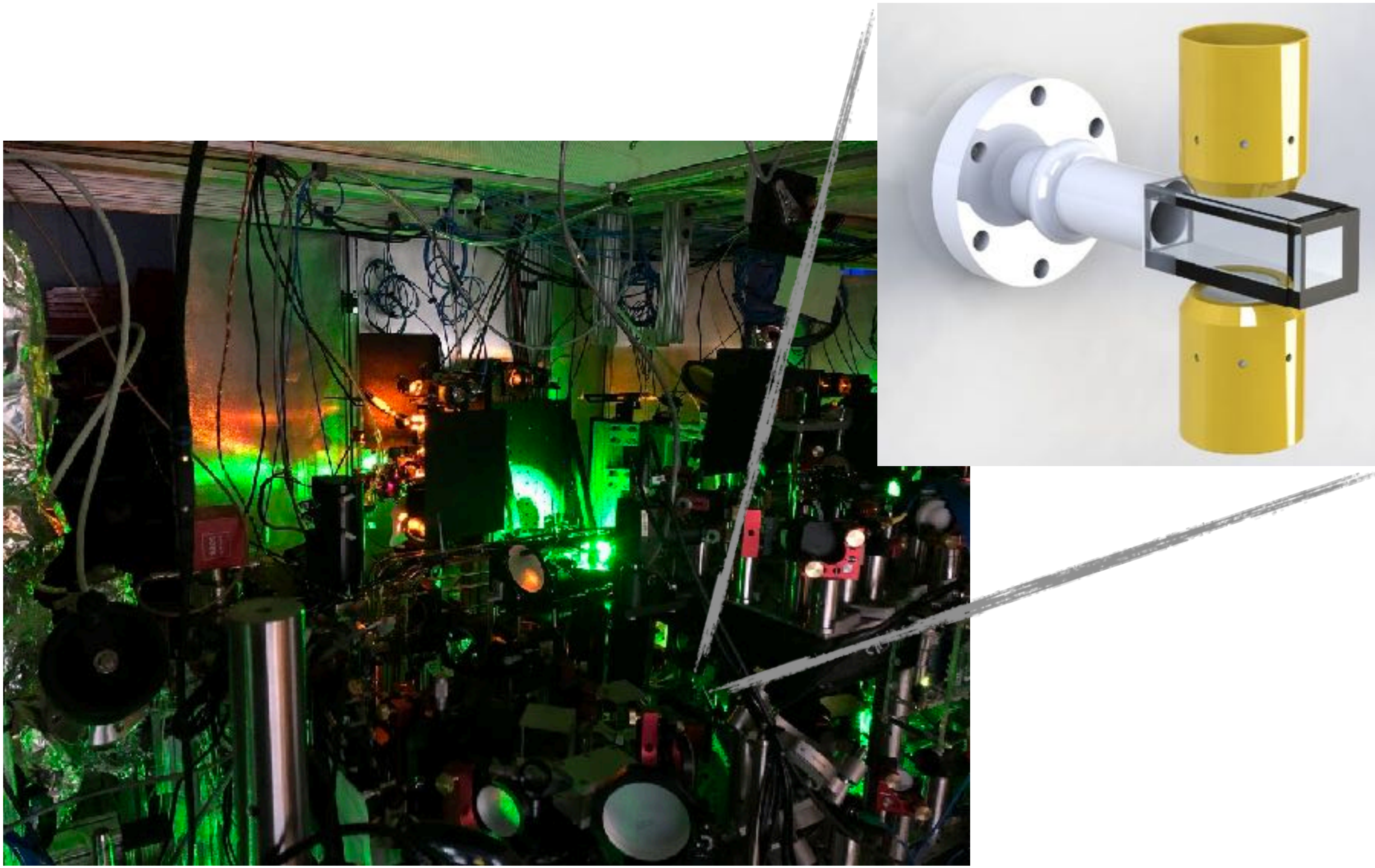
Equilibrium properties difficult
-> Dynamic and transport even harder

degenerate
s reorganise into
correlated states

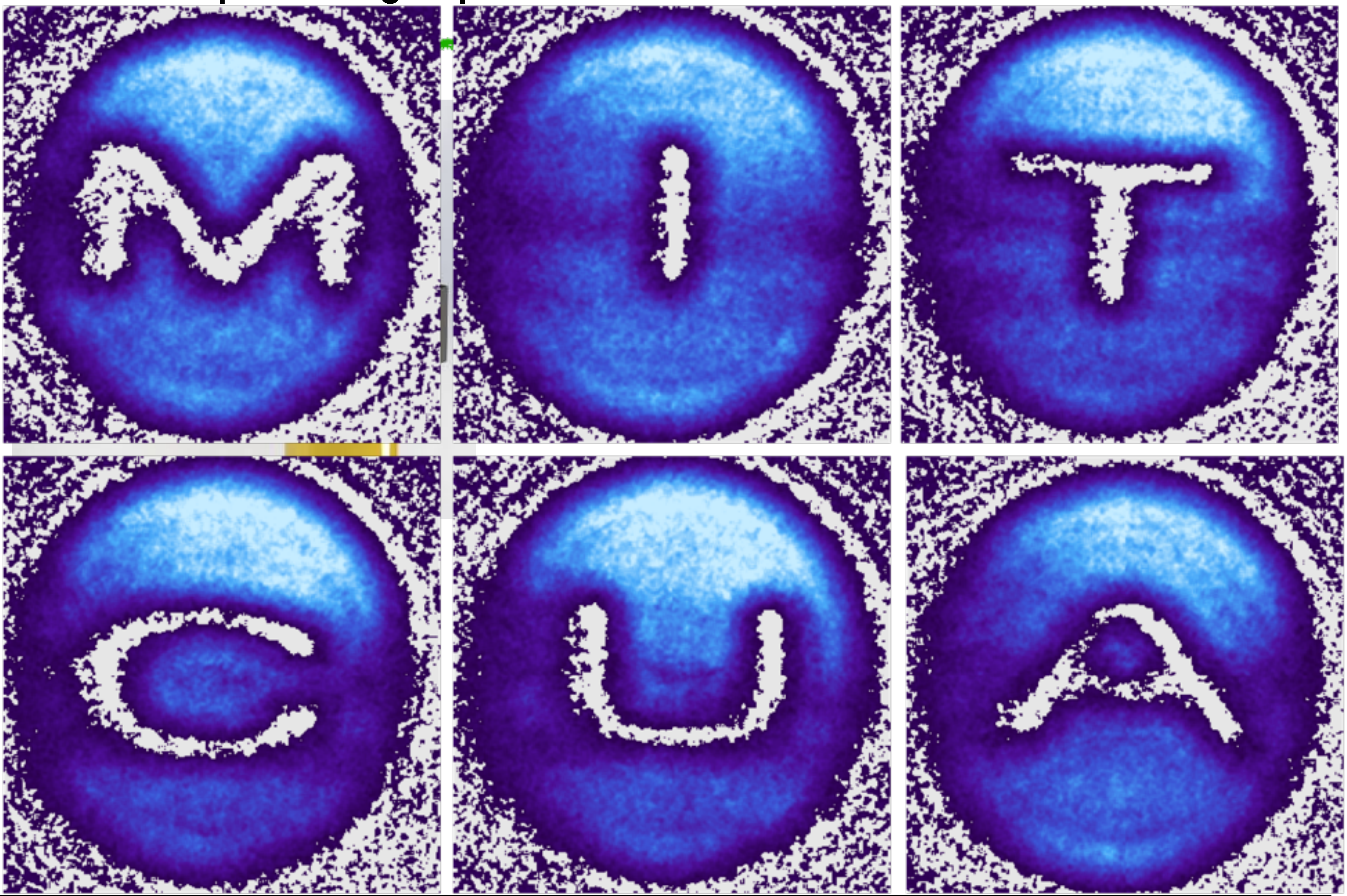
ipationless flow
ctional quasiparticles
ctional statistics

..P. Jarillo-Herrero
556, 43–50 (2018)

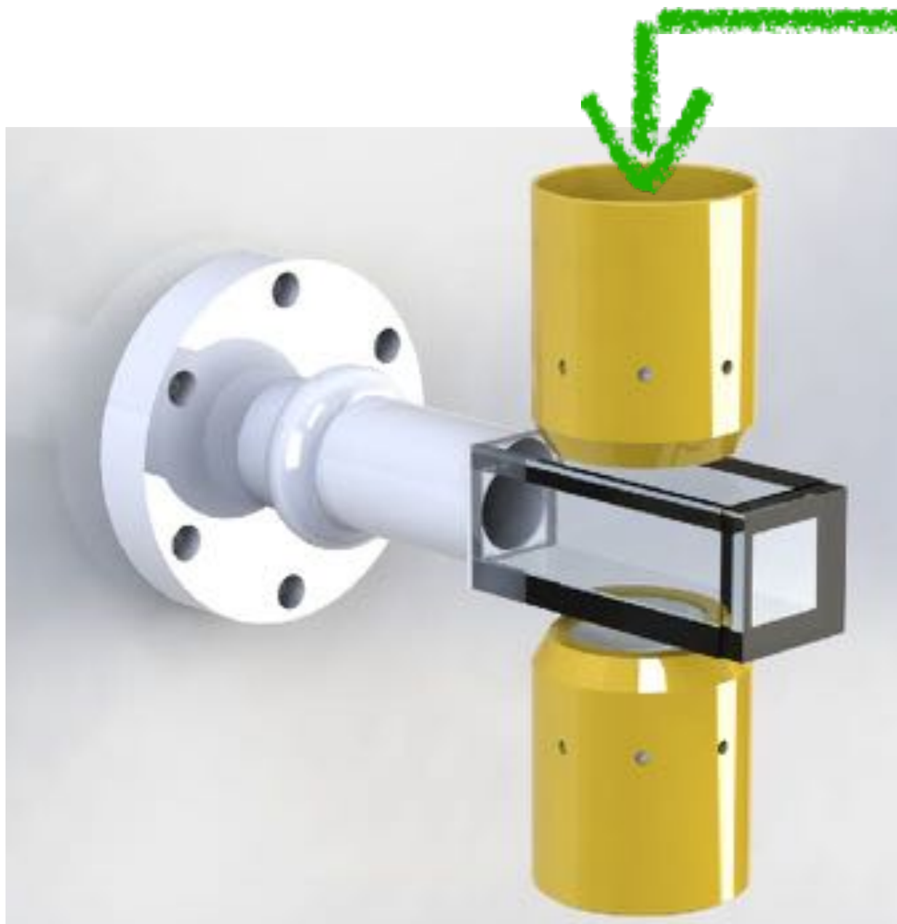
Ultracold quantum gas platform

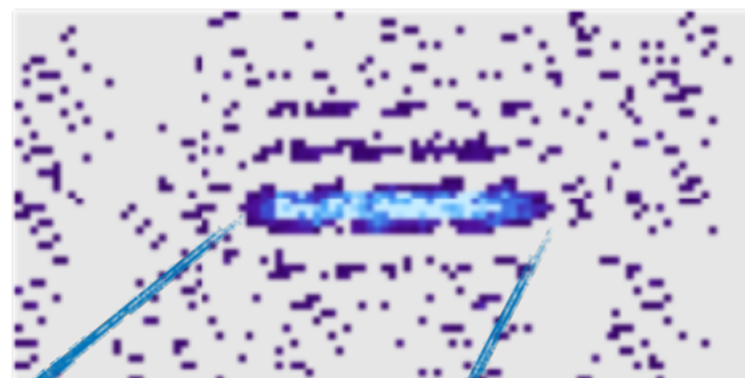


Ultracold quantum gas platform

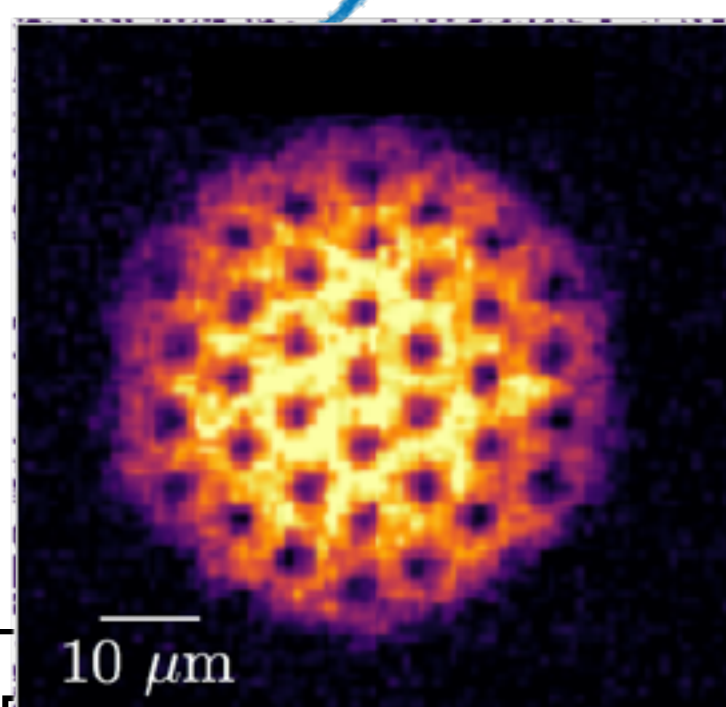


Ultracold quantum gas platform



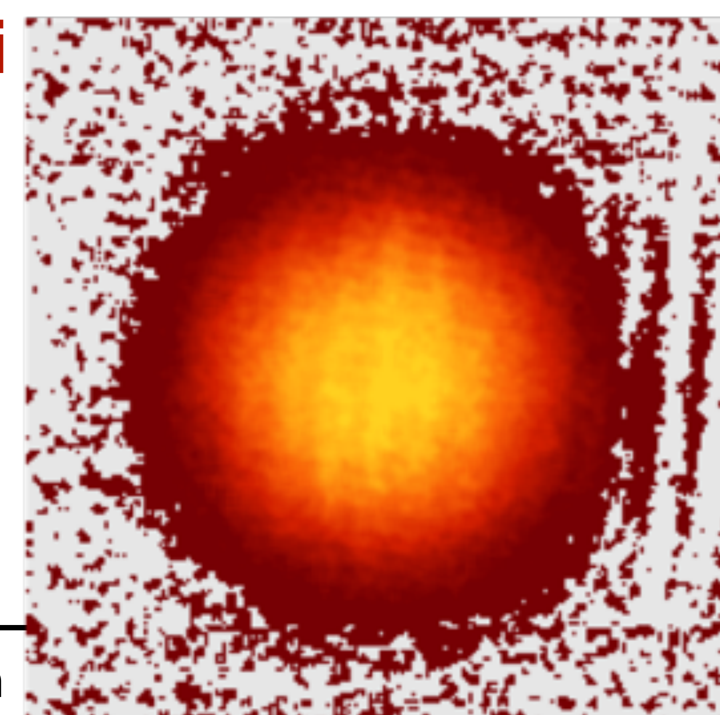


Na



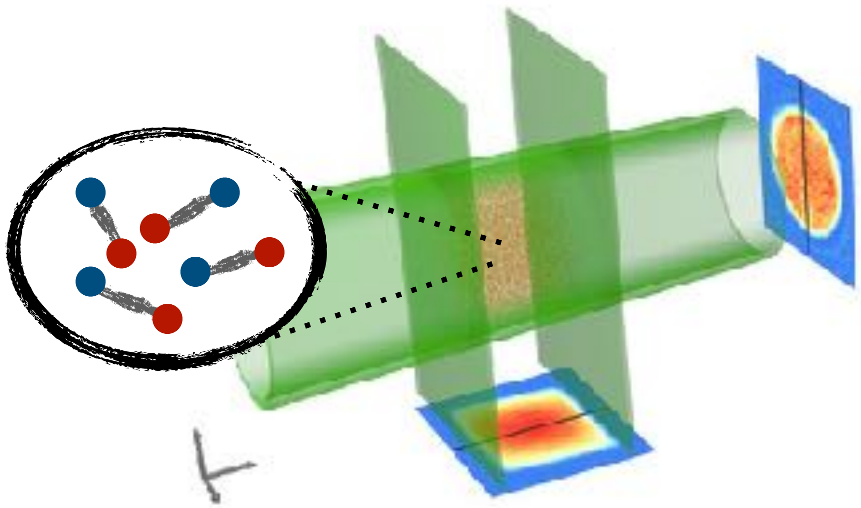
10 μm

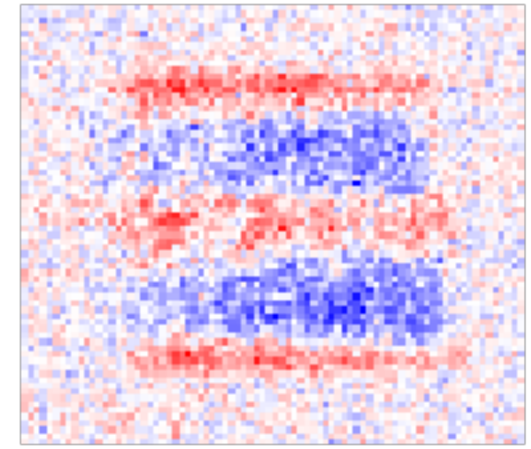
Li



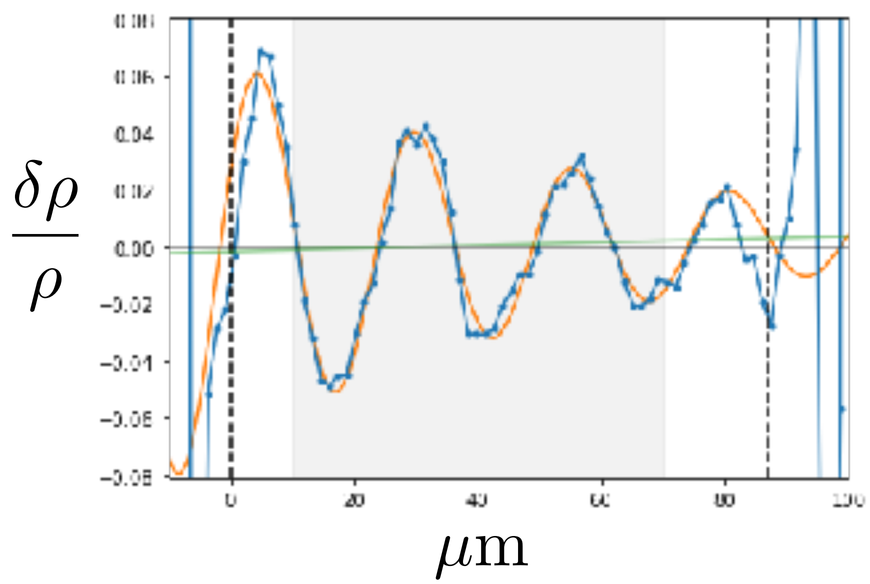
25 μm

1. Banging the Fermi drum





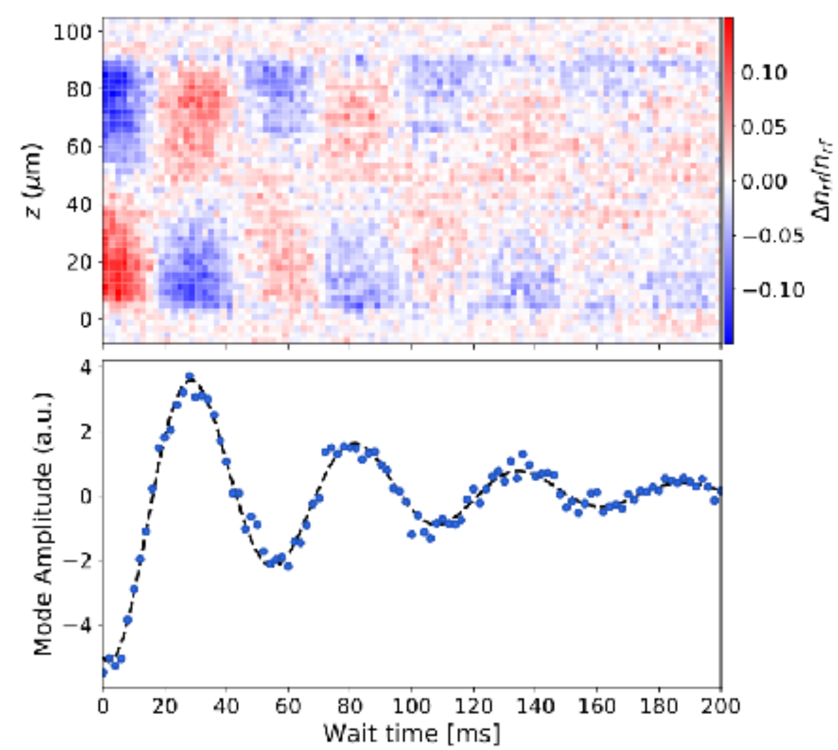
'Universal' diffusion of first sound



$$\omega^2 = c^2k^2 + i\omega Dk^2$$

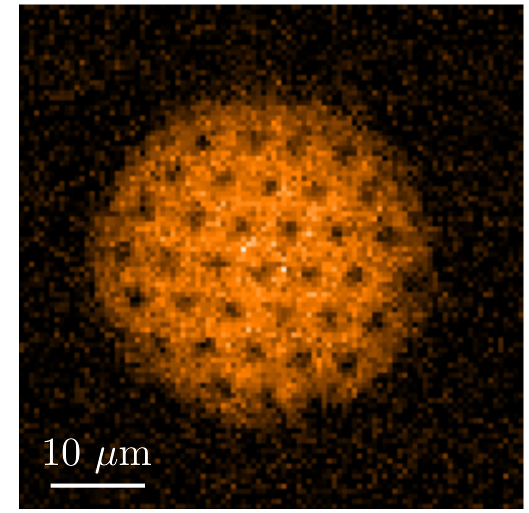
$$\Gamma = Dk^2$$

In situ thermometry of second sound

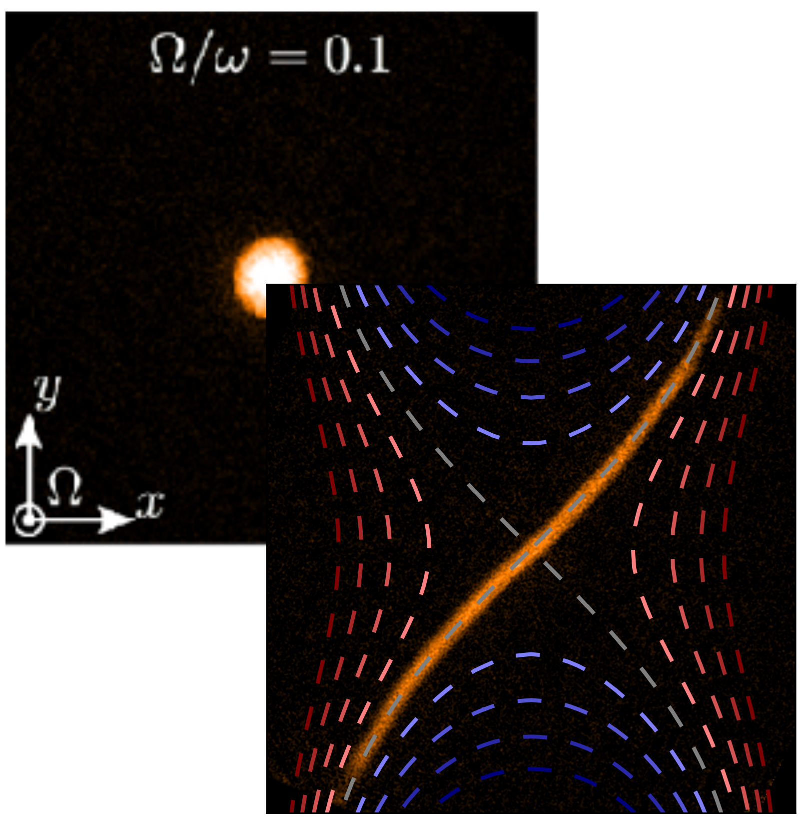


P. Patel, Z. Yan, B. Mukherjee, R. Fletcher, J. Struck, M. Zwierlein, arXiv:1909.02555 (2019), Science, accepted

2. *In situ* physics of a rotating quantum gas

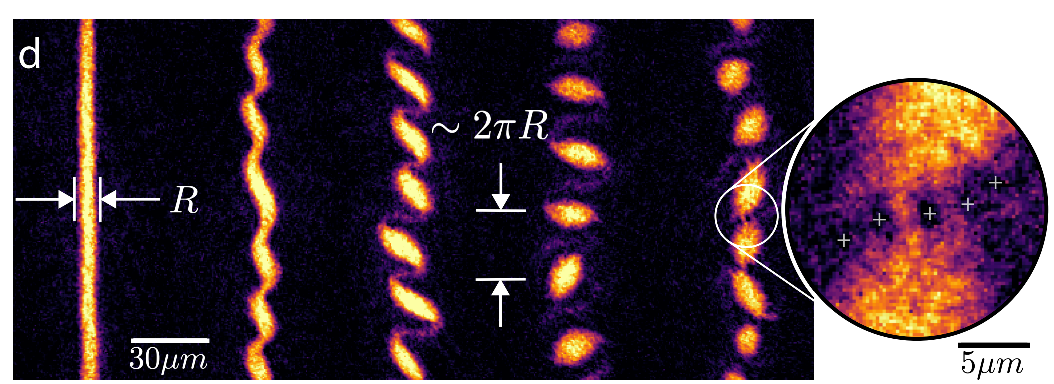


Geometric squeezing

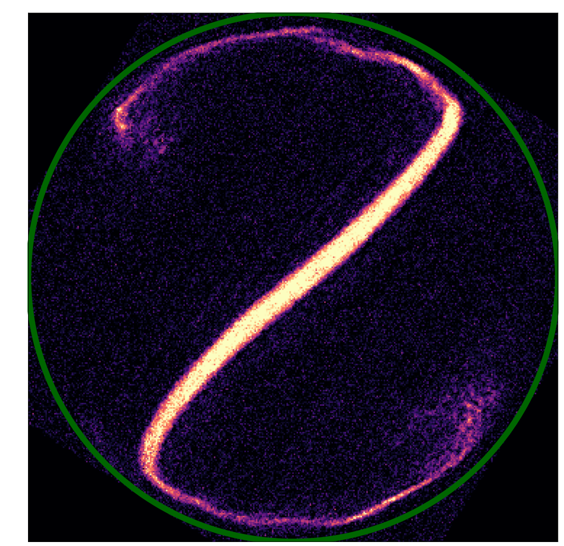


Dynamics of superfluid under gauge field + interactions

Flat LL dispersion -> purely interaction-driven physics

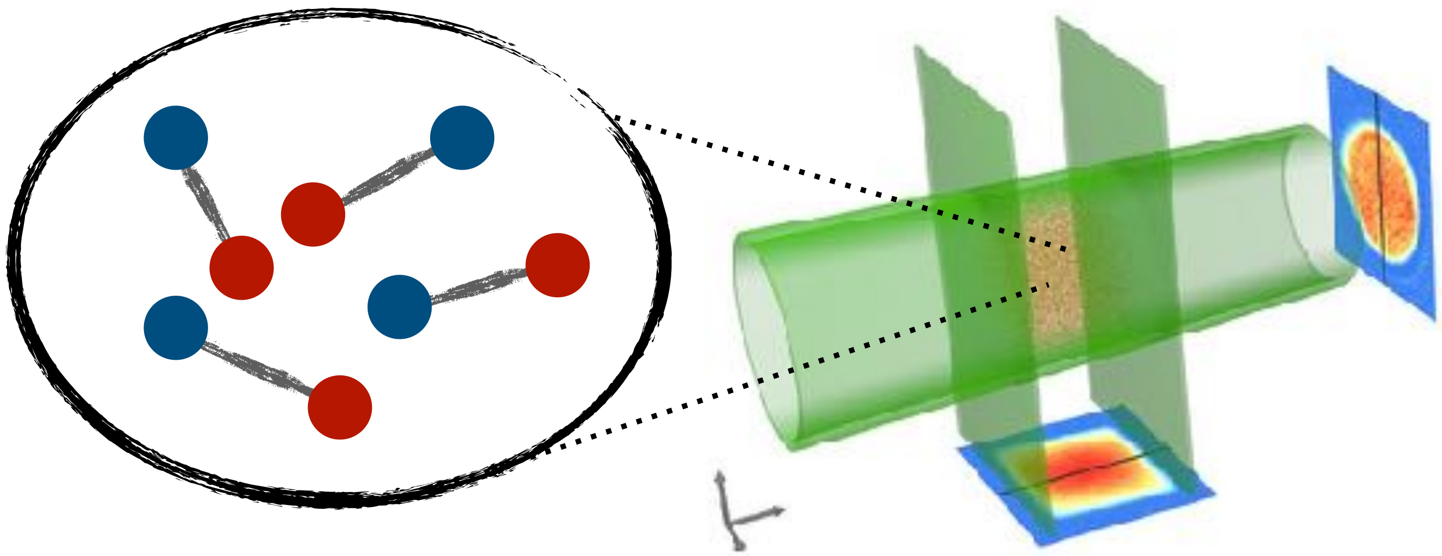


Chiral edge modes



R. Fletcher, A. Shaffer, C. Wilson, P. Patel, Z. Yan, V. Crepel, B. Mukherjee, M. Zwierlein, arXiv:1911.12347 (2019) Science, accepted

Unitary Fermi gas



Unitary Fermi gas $a \to \infty$

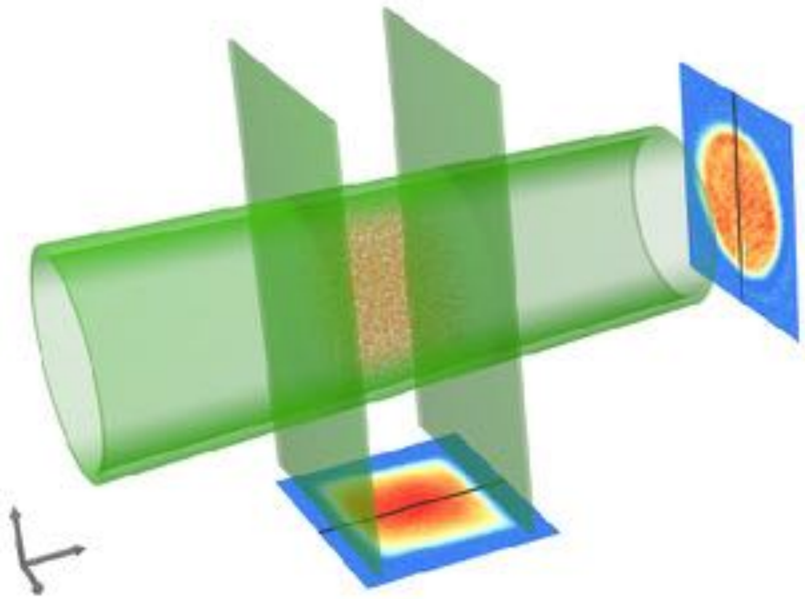
Box potential
- Critical phenomena
- Correlation functions
- Transport properties
- Spectral response
- ...

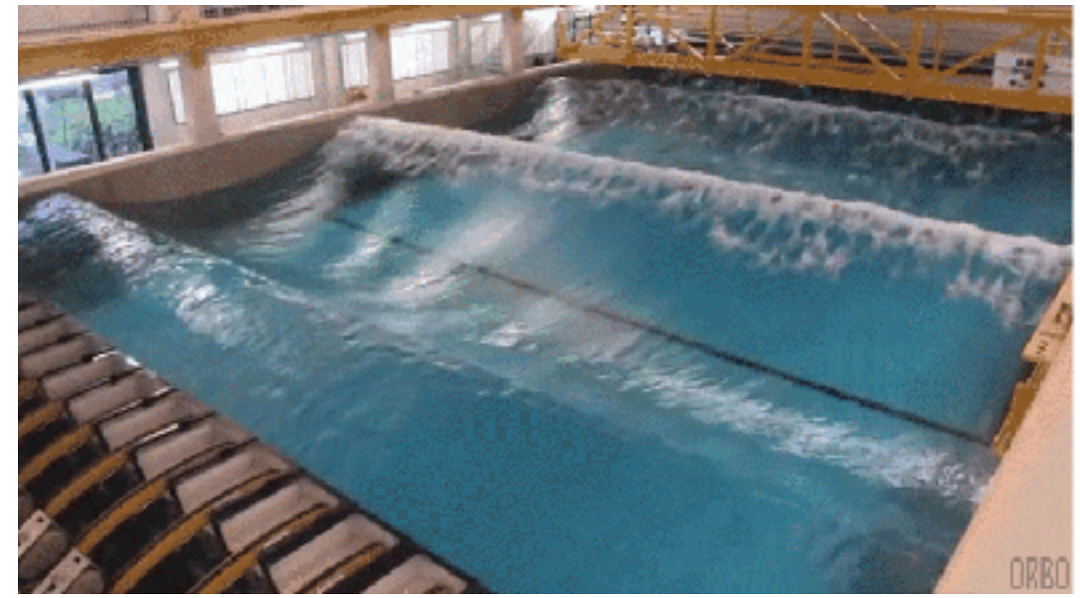
Two lengthscales: $\lambda_{\rm th},\ n^{-1/3}$ ⟷ Two energy scales: $k_{\rm B}T,\ E_{\rm F}$

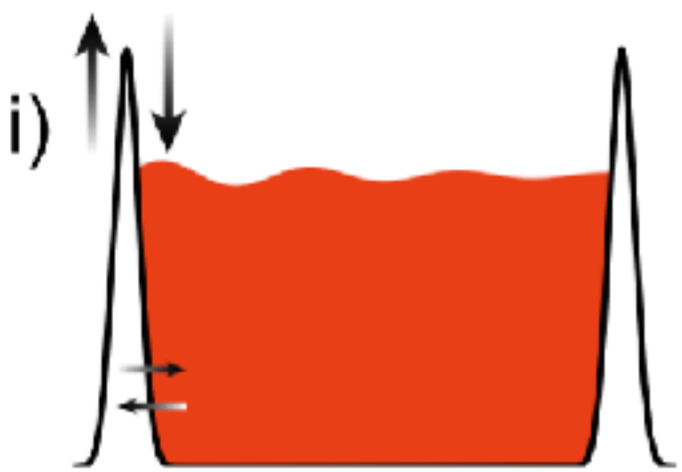
Scale invariant system:

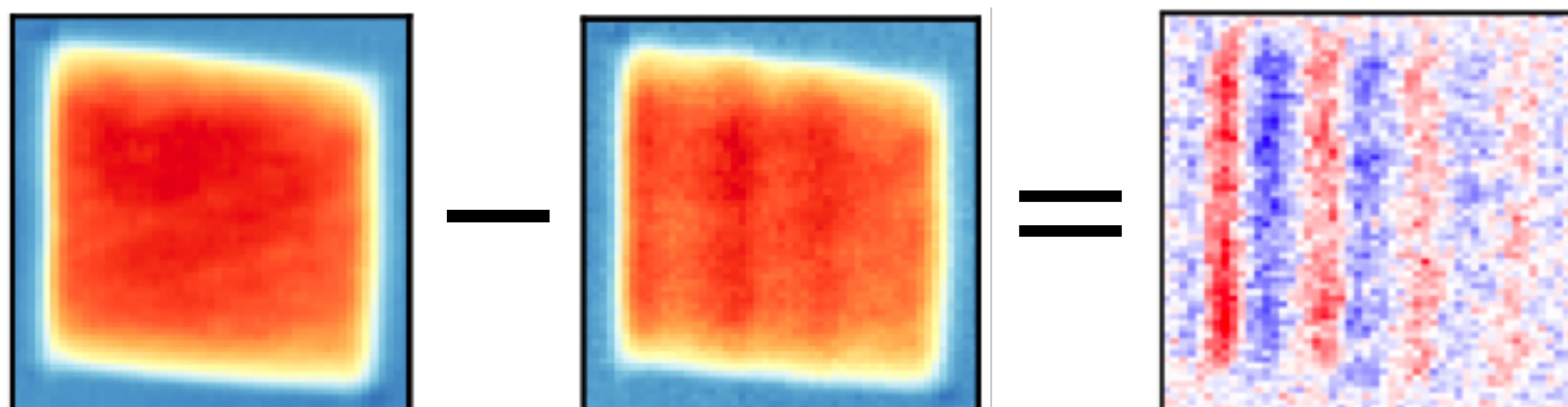
$$E(T) = \frac{3}{5} N E_{\rm F} \times f\left(\frac{T}{T_{\rm F}}\right)$$

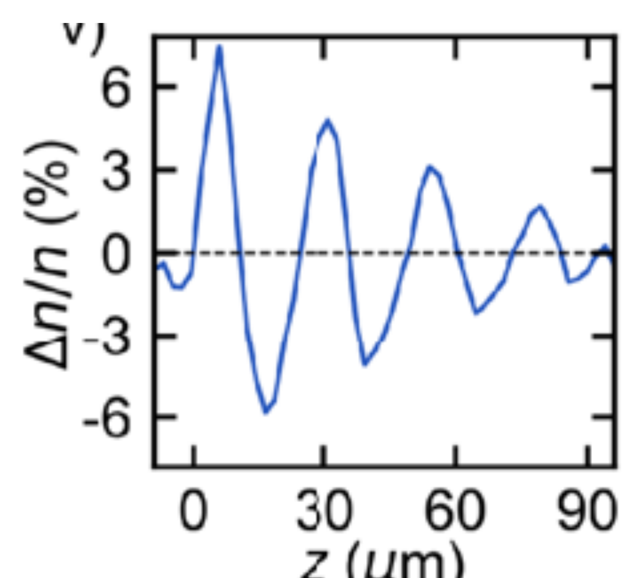
Injecting sound waves











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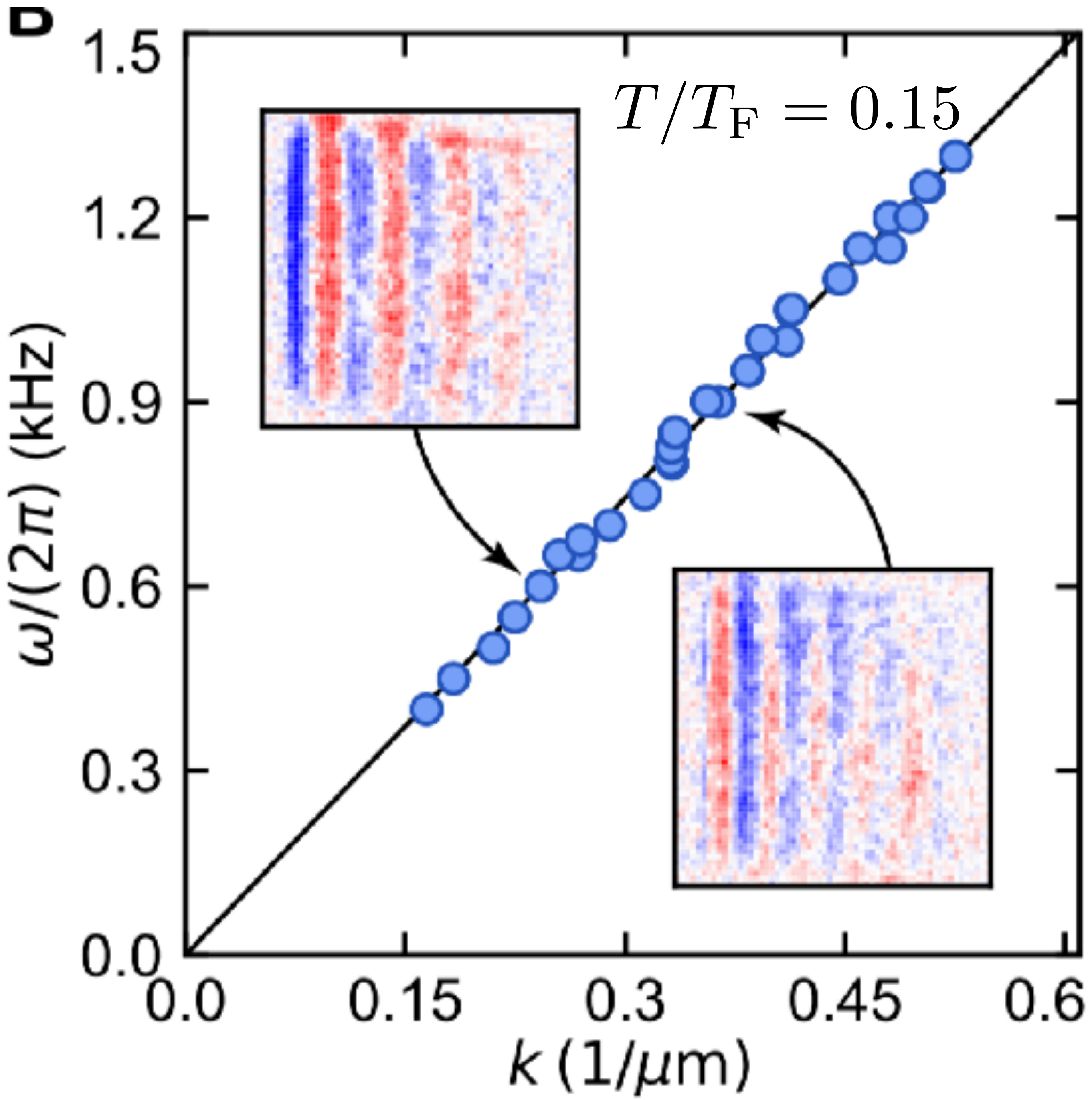


Extract sound speed

$$c = 15.5(4)\ \mathrm{mm/s}$$

Prediction from EoS:

$$c = 15.2(4)\ \mathrm{mm/s}$$

E=(0.9)mc²

Consequence of scale invariance

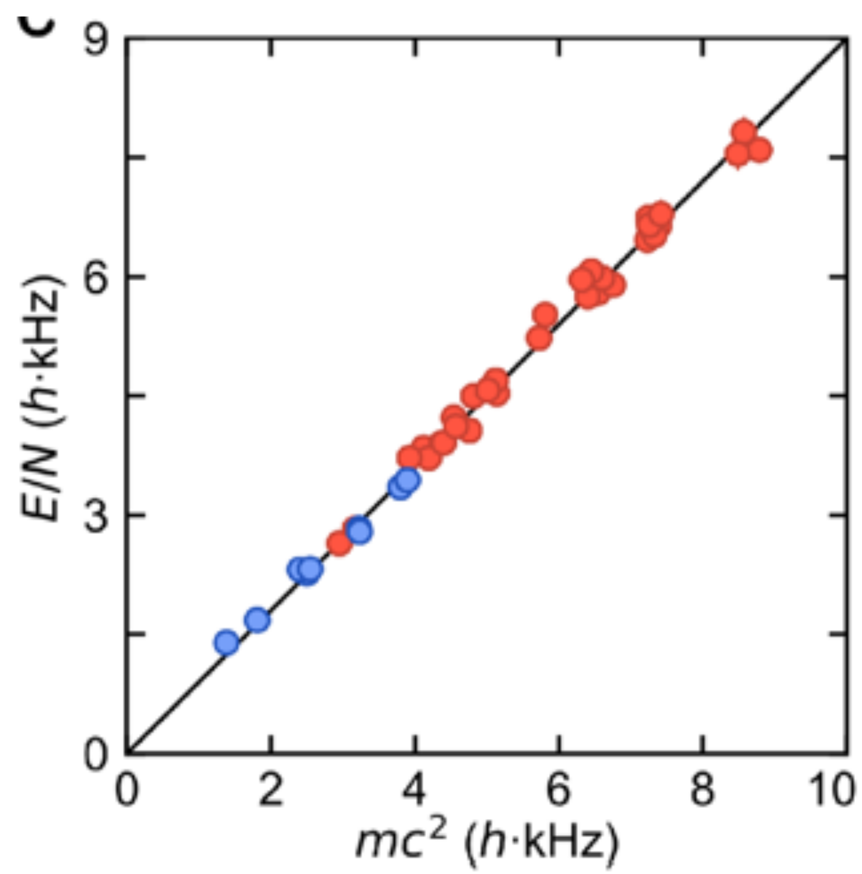
$$c^2 = \left.\frac{\partial P}{\partial \rho}\right|_s = \left.\frac{V^2}{N}\frac{\partial^2 E}{\partial V^2}\right|_s$$

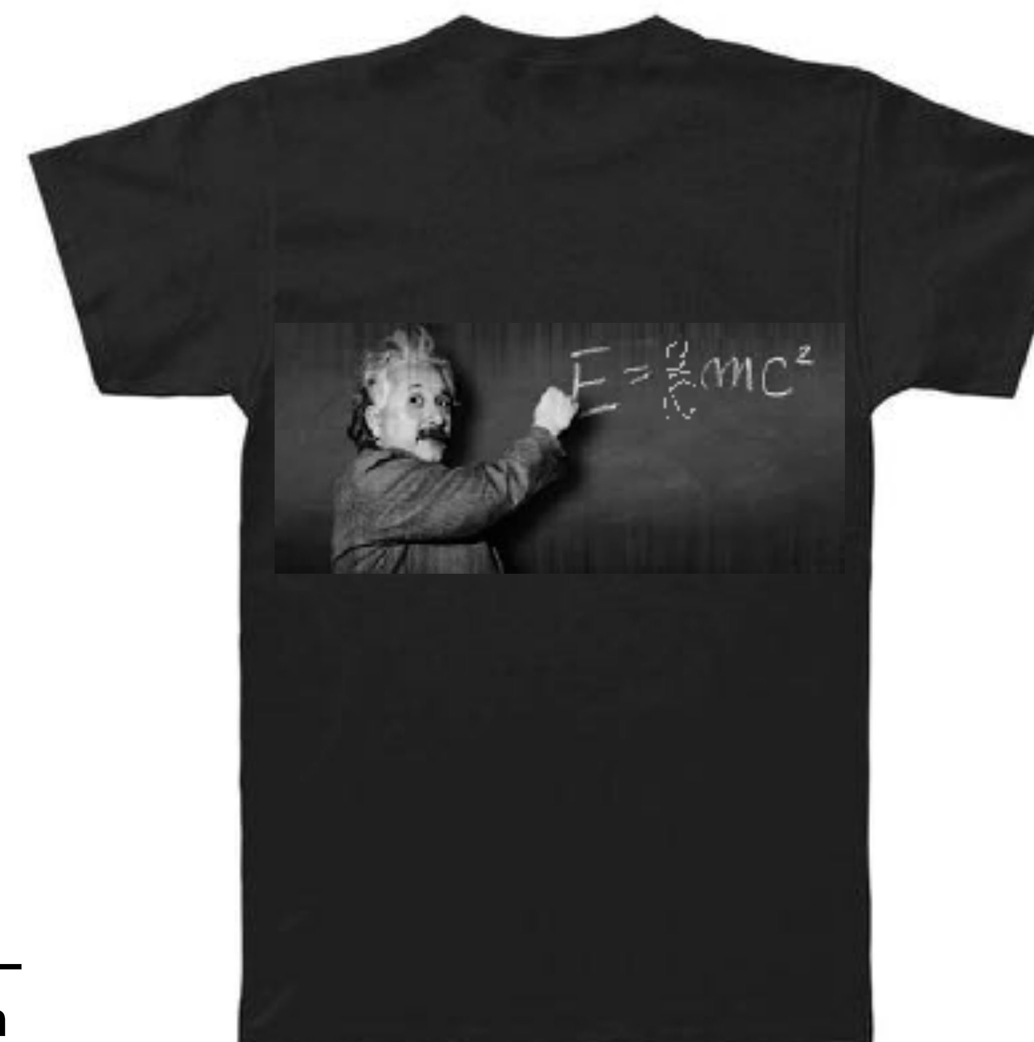
$$E \propto V^{-2/3} \quad \text{if} \quad E \to \frac{E}{\lambda^2}$$

$$E/N = \frac{9}{10} mc^2$$

Normal fluid

Superfluid

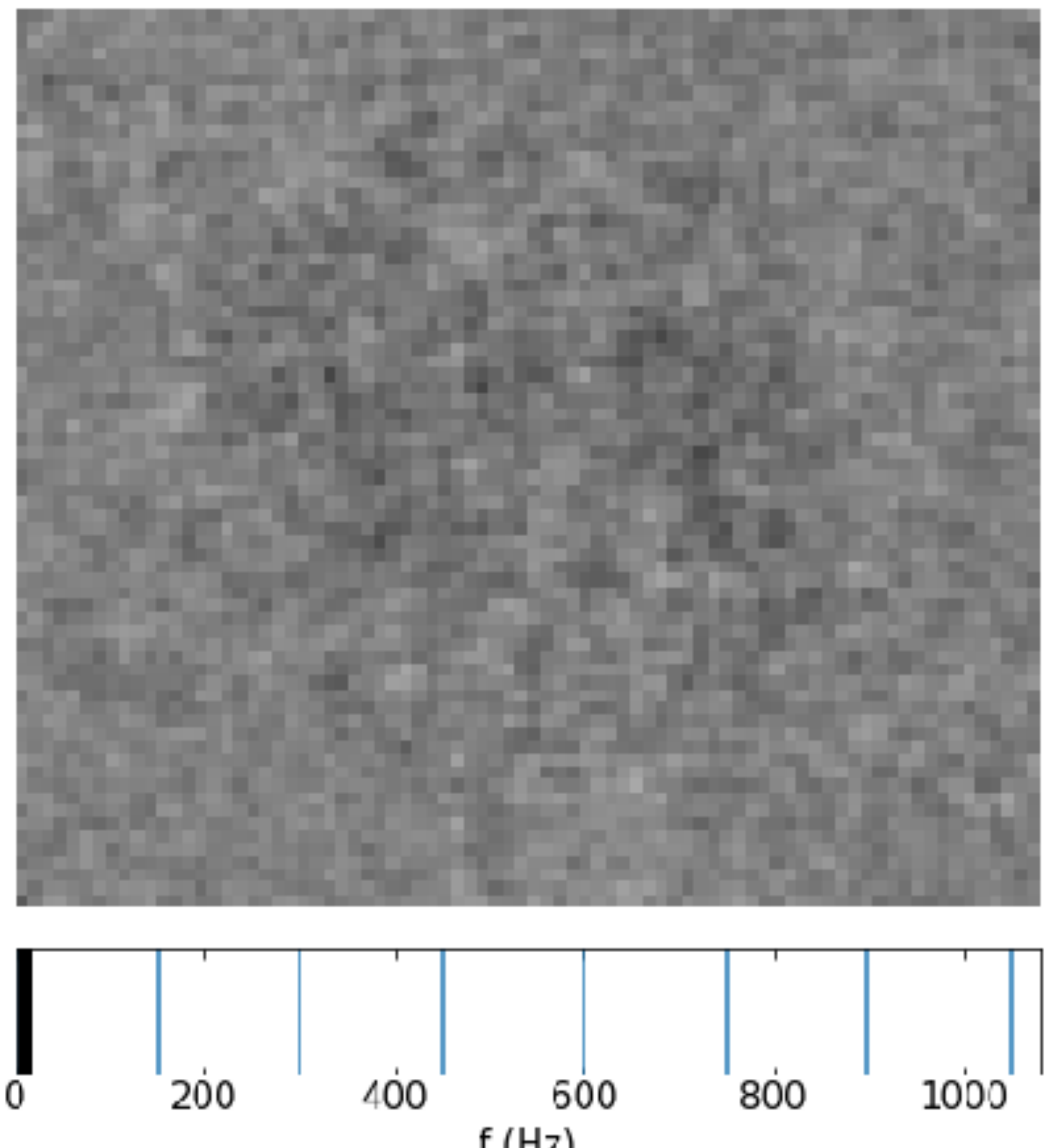




Attenuation of sound waves

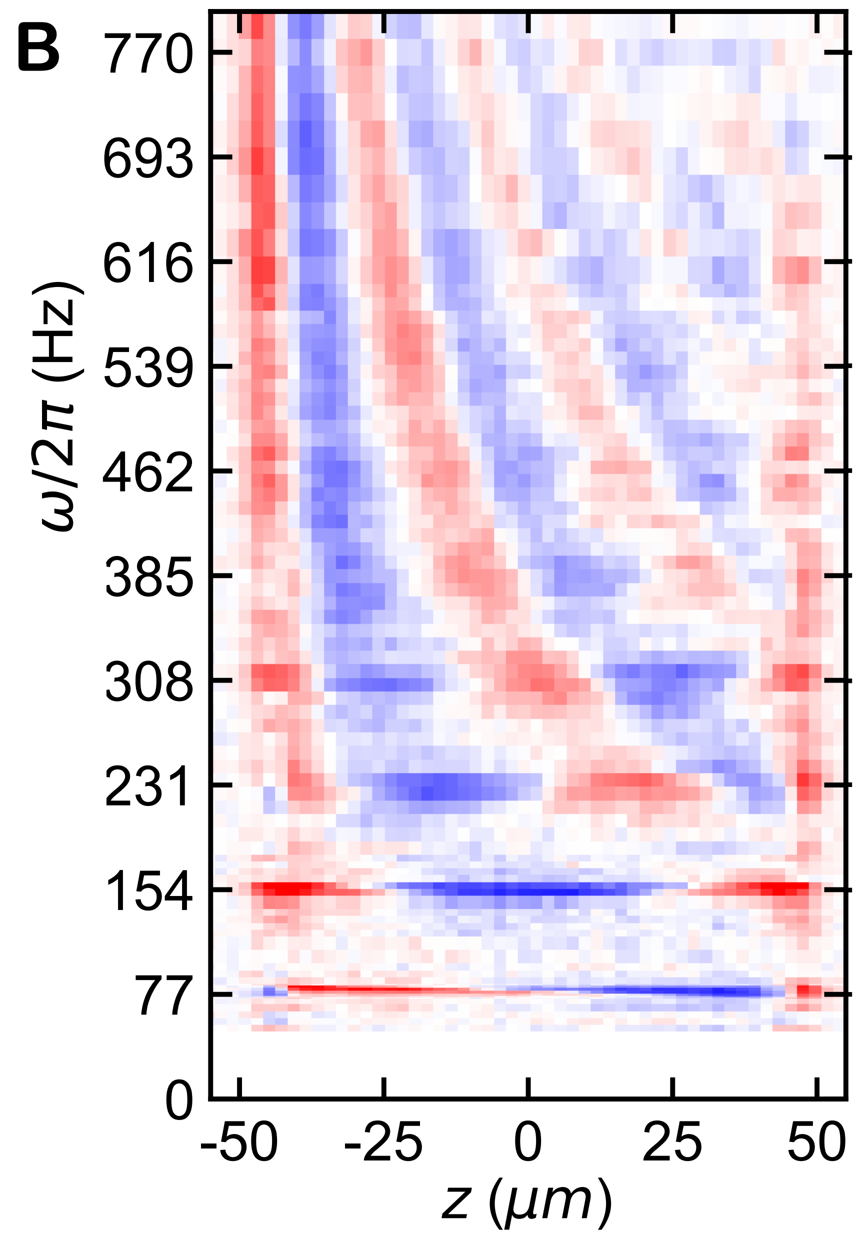
One-sided shaking: restricted to $t < \frac{L}{c}$

Instead: drive resonant modes of box



Integrate along 'boring' direction and plot as function of drive frequency…

Attenuation of sound waves

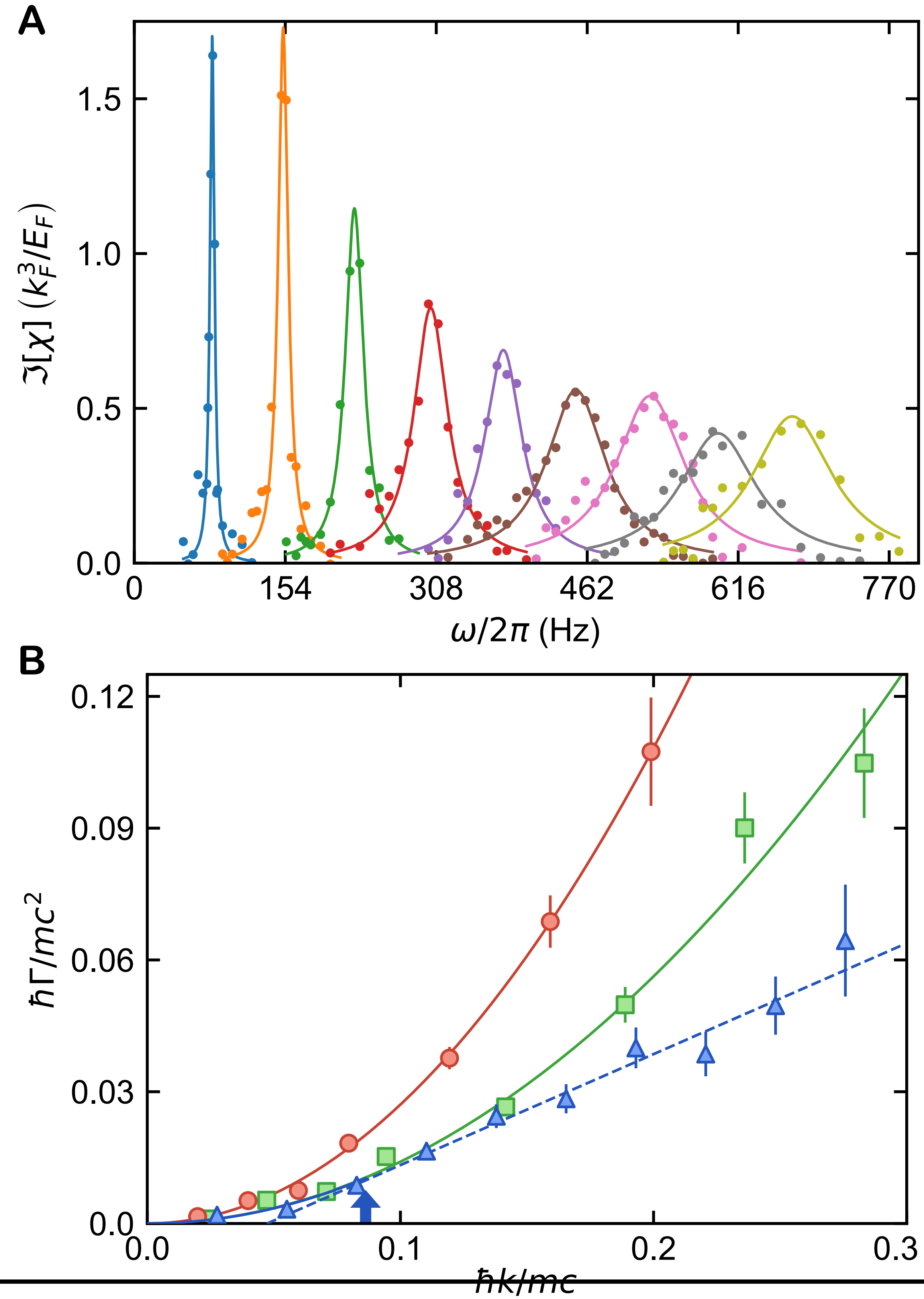


Hydrodynamic equations

Mass	$\frac{\partial \rho}{\partial t} + \frac{\partial j}{\partial z} = 0$	Continuity equation
Momentum	$\frac{\partial j}{\partial t} + \frac{\partial p}{\partial z} = \frac{4}{3}\eta \frac{\partial^2 v}{\partial z^2}$	Navier-Stokes equation - viscosity damps velocity gradients
Heat	$\frac{\partial s}{\partial t} + \frac{\partial (vs)}{\partial z} = \frac{\kappa}{T}\frac{\partial^2 T}{\partial z^2}$	Thermal conduction damps temperature variations, increases entropy

$$\omega^2 = c^2 k^2 + i\omega D k^2 \qquad \Gamma = D k^2 \qquad D = \frac{4}{3}\frac{\eta}{\rho} + \frac{\kappa}{\rho}\left(\frac{1}{c_v} - \frac{1}{c_p}\right)$$

Attenuation of sound waves



Spectral response broadens with frequency

- $T/T_{\mathrm{F}} = 0.36$
- $T/T_{\mathrm{F}} = 0.21$
- $T/T_{\mathrm{F}} = 0.13$

Obtain diffusivity as function of temperature

Diffusivity of first sound

Dimensional grounds: $D \sim vl \sim v_{\mathrm{F}} \frac{k_{\mathrm{F}}^2}{n} \sim \frac{\hbar}{m}$ $D = \frac{\hbar}{m} f_D \left(\frac{T}{T_{\mathrm{F}}} \right)$

Diffusivity of first sound

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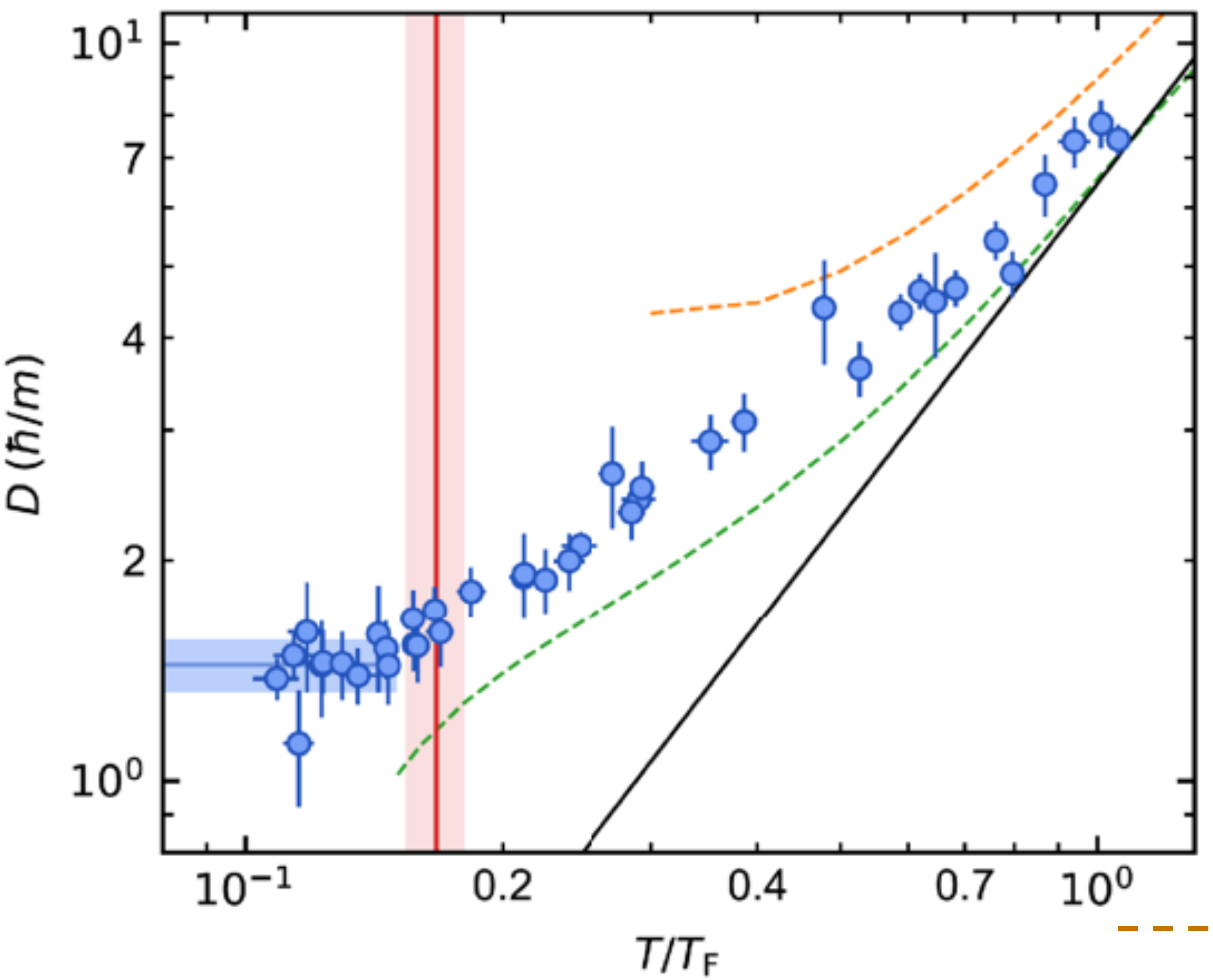


High temperature limit:

$$D \sim vl \qquad v \sim \frac{\hbar}{m\lambda} \qquad l \sim \frac{1}{n\lambda^2}$$

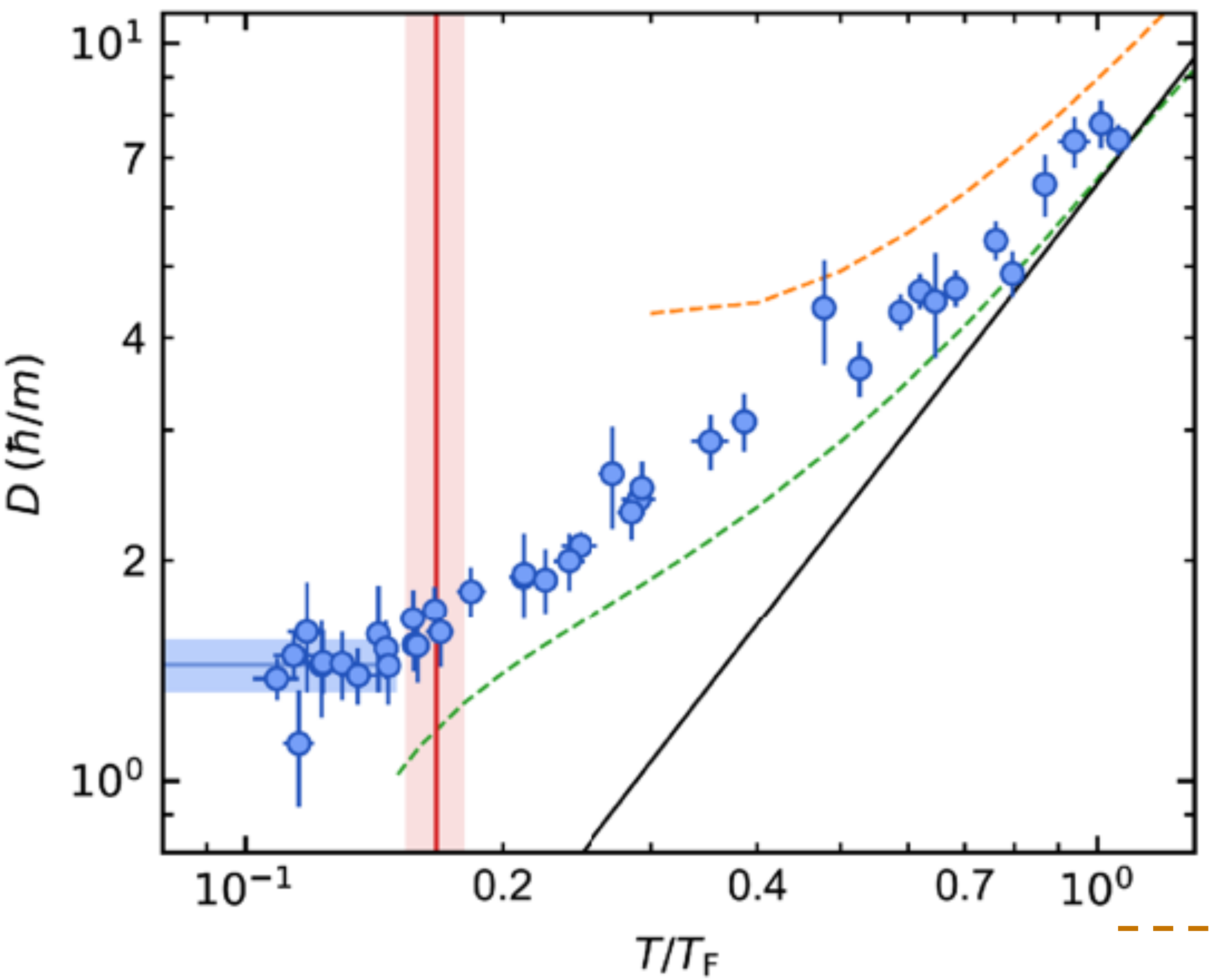
$$D = \beta \frac{\hbar}{m}\left(\frac{T}{T_{\mathrm{F}}}\right)^{3/2}$$

Schäfer et al., PRA 2010

$\frac{7}{3}\frac{\eta}{\rho}$ η from Enss, Haussmann, Zwerger, Ann. Phys. (2011)

Diffusivity of first sound

Dimensional grounds: $D \sim vl \sim v_F \frac{k_F^2}{n} \sim \frac{\hbar}{m}$ $D = \frac{\hbar}{m} f_D\left(\frac{T}{T_F}\right)$



Low temperature limit:

$D \sim v\, l\, \frac{n_q}{n}$ $l \sim \frac{1}{n_q \sigma}$

$\sim \frac{v}{\sigma n}$

Gapped excitations:

$v \sim v_F$ $\sigma \sim \frac{1}{k_F^2}\left(\frac{\Delta}{E_F}\right)^2$

$D \sim \frac{\hbar}{m}\left(\frac{E_F}{\Delta}\right)^2$

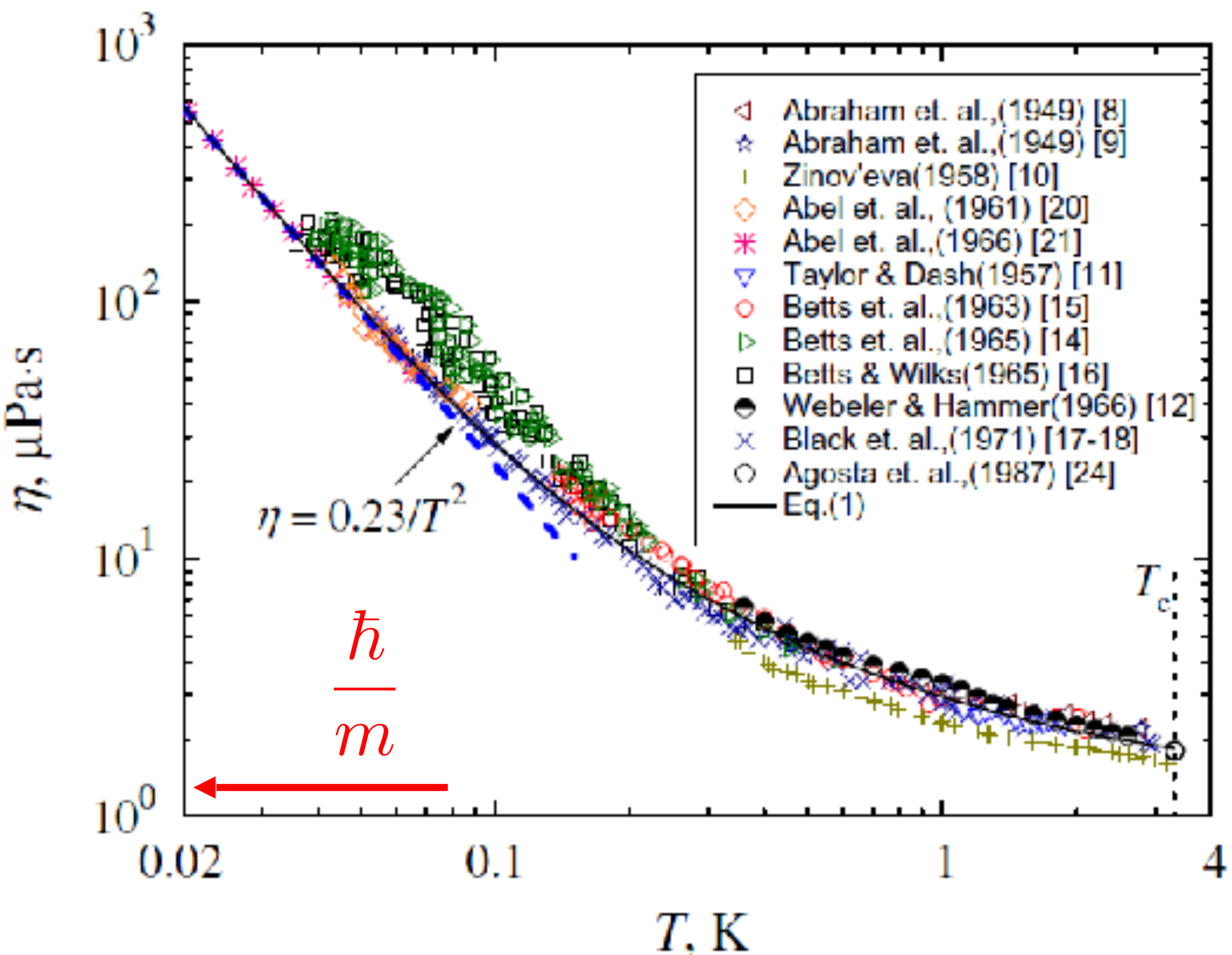
Schäfer et al., PRA 2010

$\frac{7}{3}\frac{\eta}{\rho}$ η from Enss, Haussmann, Zwerger, Ann. Phys. (2011)

Comparison to 3He

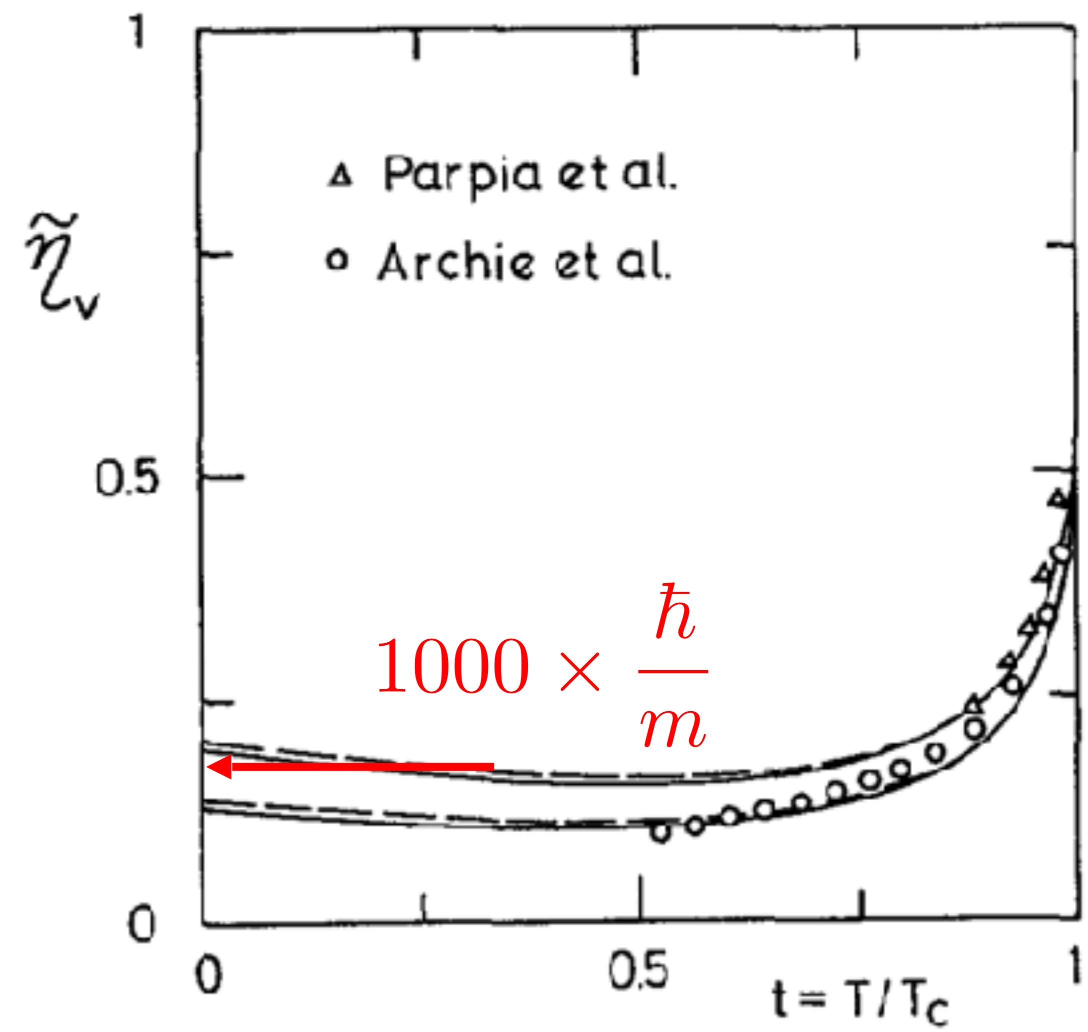
$$D \sim \frac{\hbar}{m}\left(\frac{E_\mathrm{F}}{\Delta}\right)^2$$

Above Tc, Fermi liquid



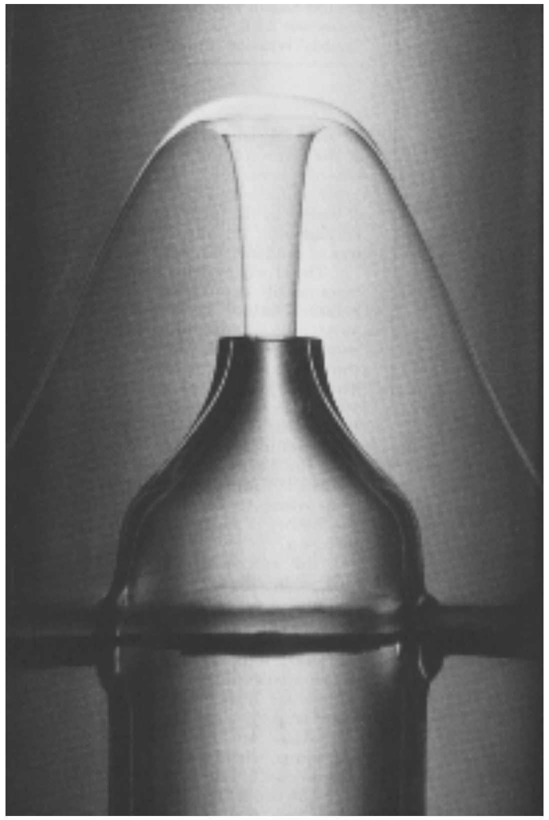
Huang et al., Cryogenics 52, 538 (2012)

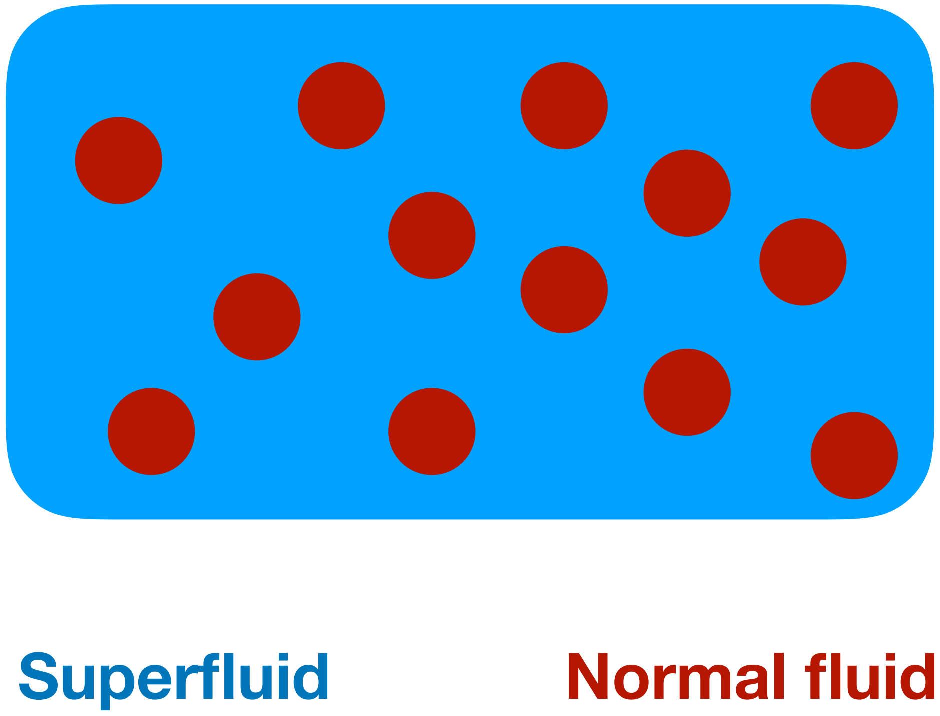
Below Tc, constant D



Ono et al., JLTP 48, 167 (1982)

Two-fluid hydrodynamics





In situ spectroscopy

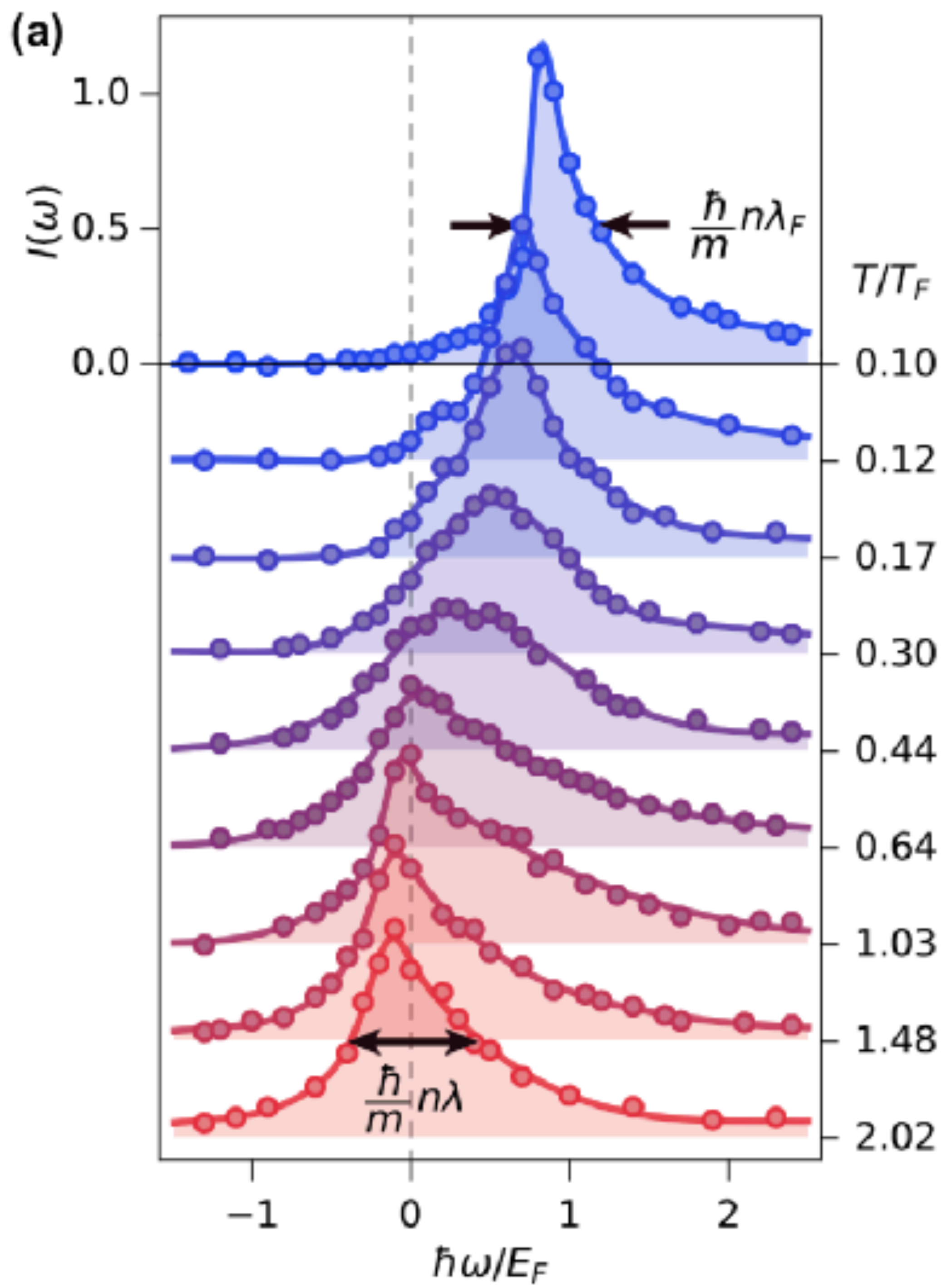
Density respo

artin 1965

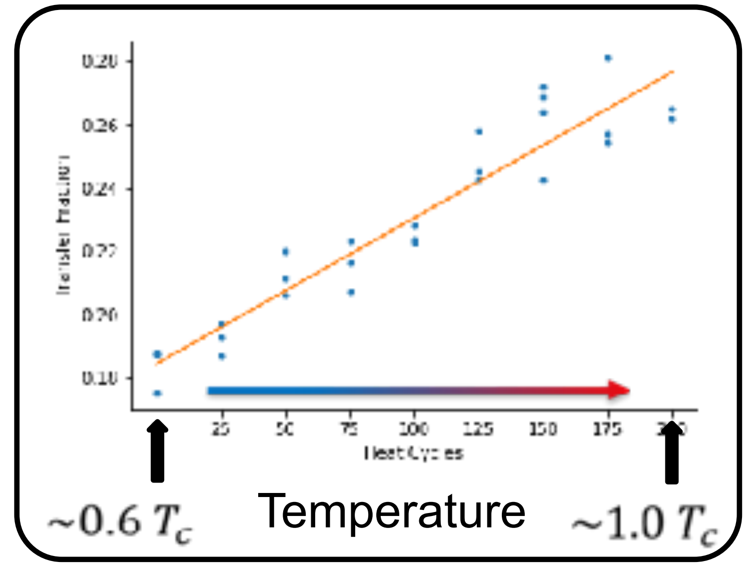
χ

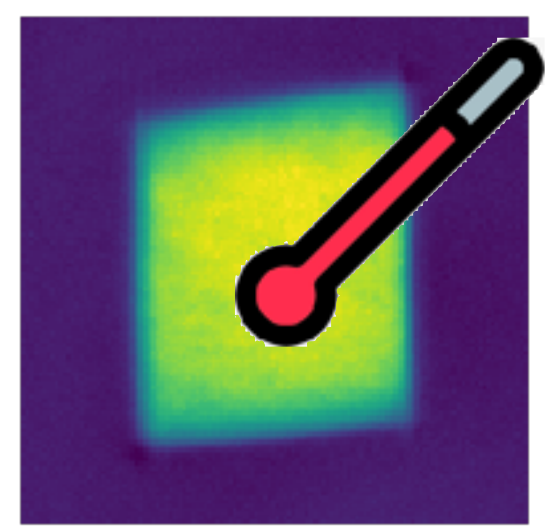
s^2

Spectroscopy of unitary Fermi gas



Number of flipped spins gives probe of local temperature

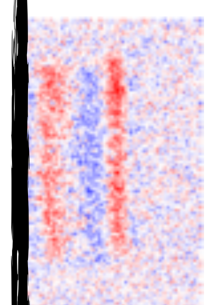




Biswaroop Mukherjee, Parth B. Patel, Zhenjie Yan, Richard J. Fletcher, Julian Struck, and Martin W. Zwierlein
Phys. Rev. Lett. 122, 203402 (2019)

First sound

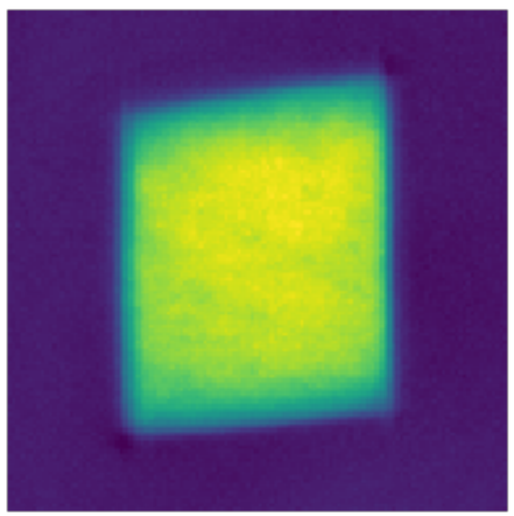
Second sound



Injection of second sound

(Isentropic) expansivity of UFG $$\left.\frac{\partial \rho}{\partial T}\right|_s = -\frac{3}{2}\frac{\rho}{T}$$

Drive temperature wave using potential (coupled to density)



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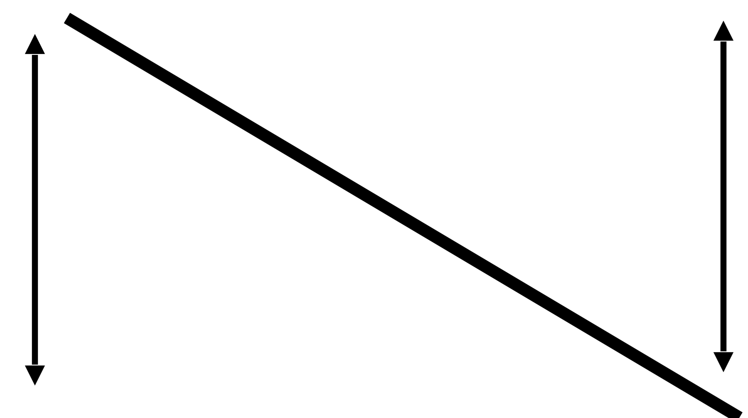
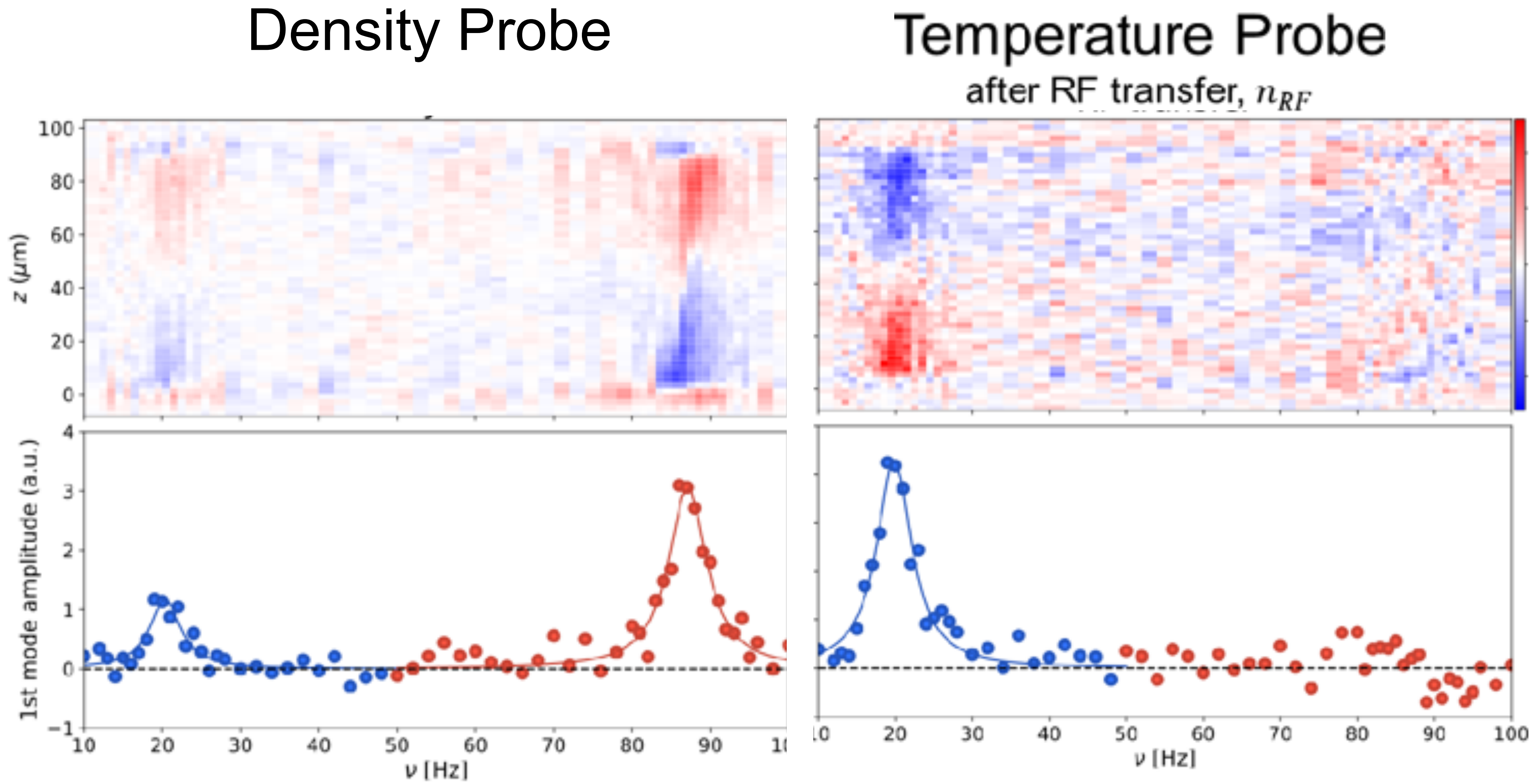


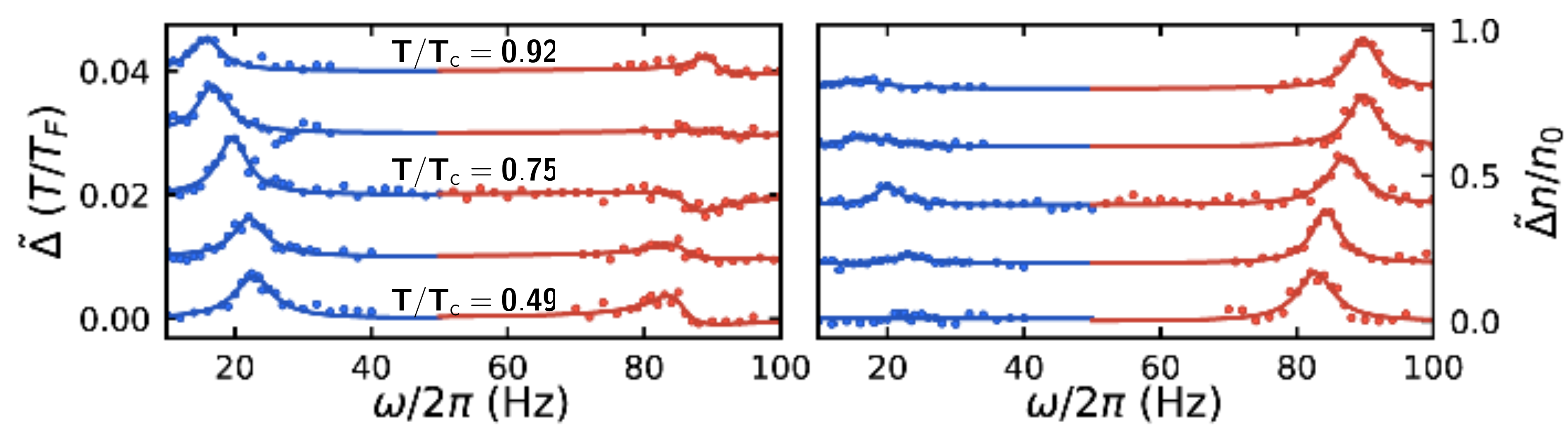
Observation of Second Sound in Quasi-1D geometry:
Sidorenkov et al., Grimm, Stringari&Piatevskii, Nature 2013

On bosons: weakly interacting situation: JILA (Debbie Jin 1996), MIT
Hydrodynamic gas: van der Straten

Observation of first and second sound



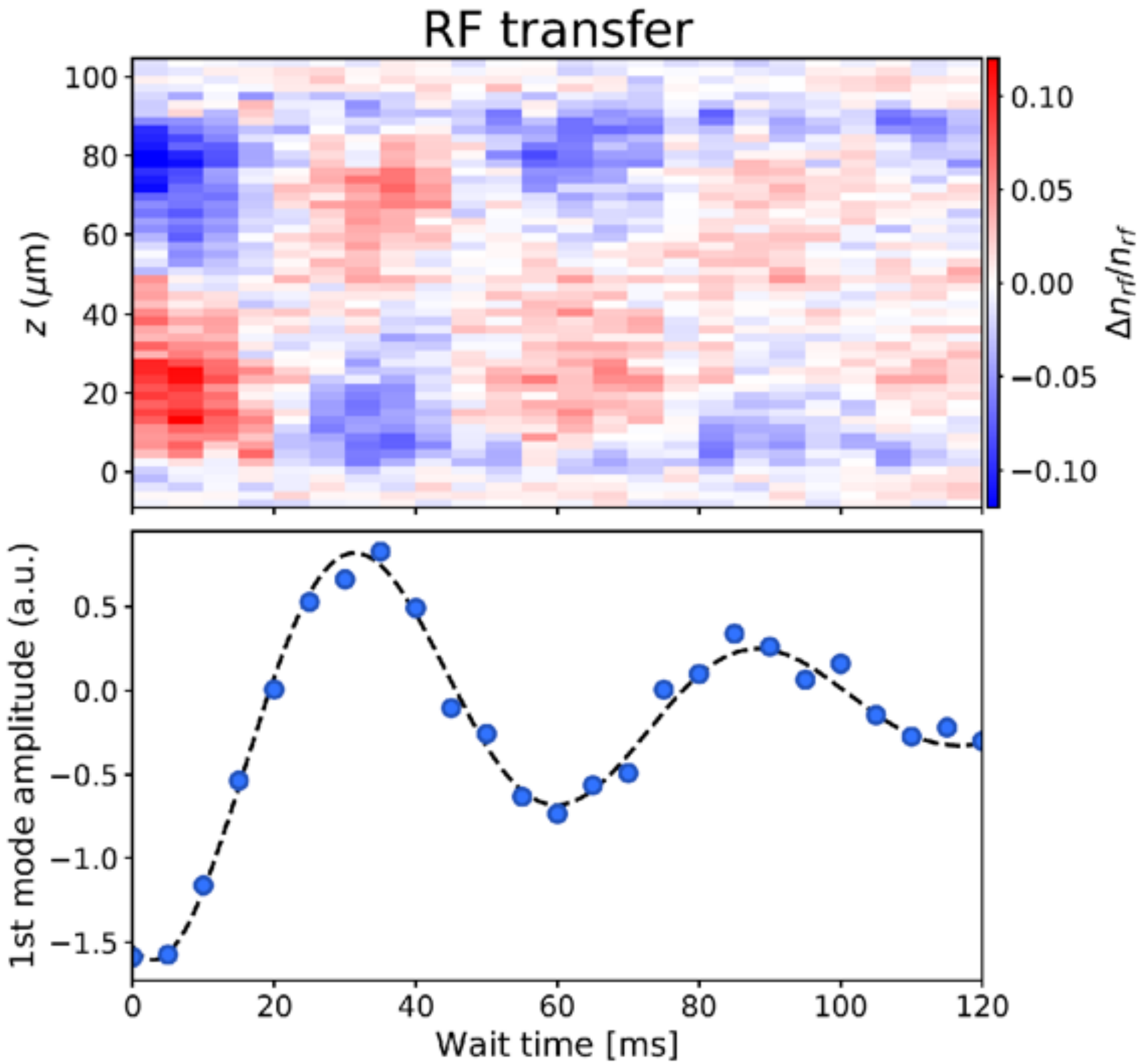
→ Speeds and decay rates of first and second sound



Z. Yan, P. Patel, B. Mukherjee, R. Fletcher, M. Zwierlein, in prep. (2020)

Damping of second sound

Decay of standing wave of second sound



Z. Yan, P. Patel, B. Mukherjee, R. Fletcher, M. Zwierlein, in prep. (2020)

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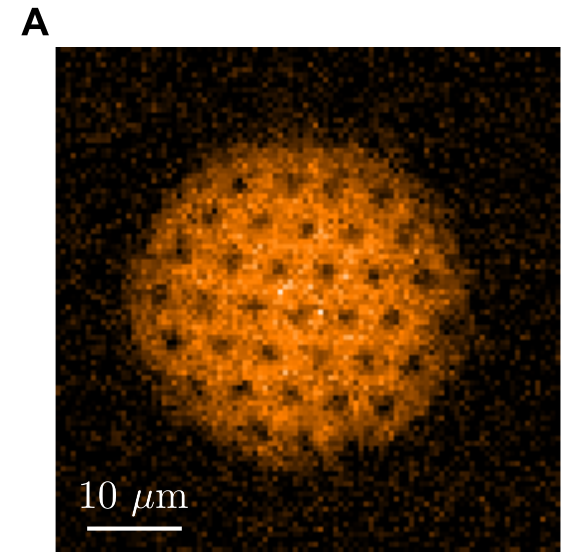
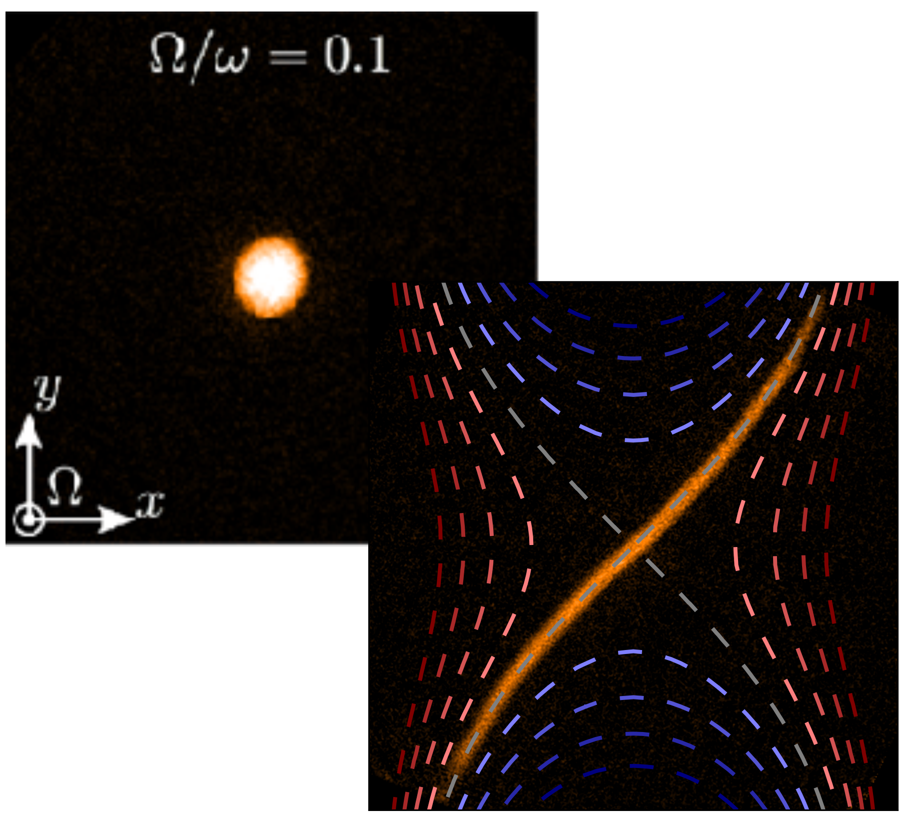
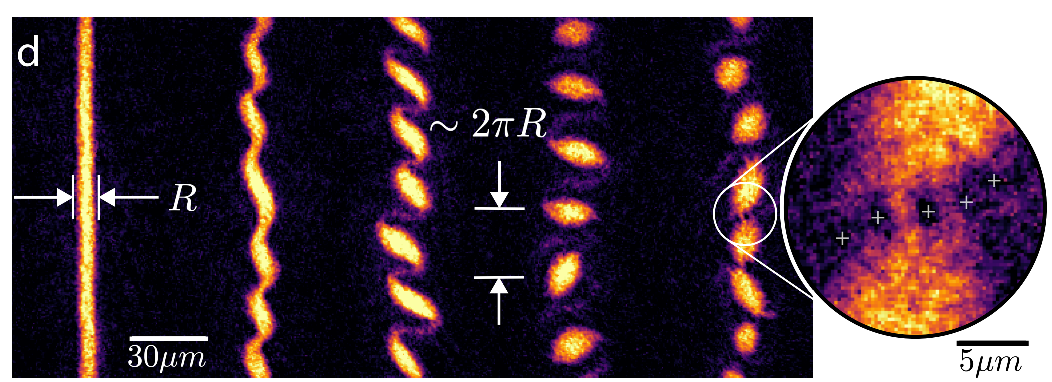


Geometric squeezing

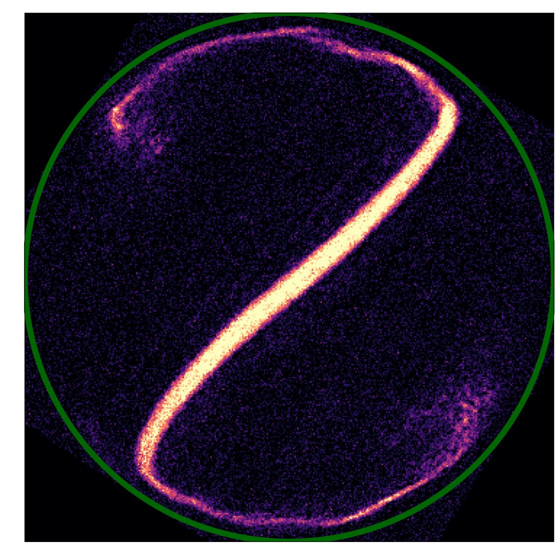


Dynamics of superfluid under gauge field + interactions

Flat LL dispersion -> purely interaction-driven physics

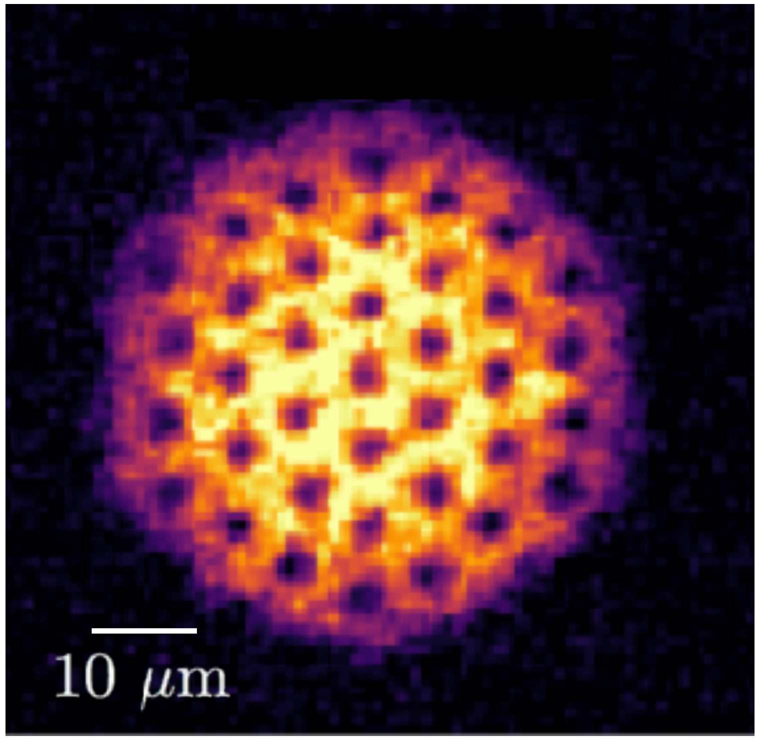


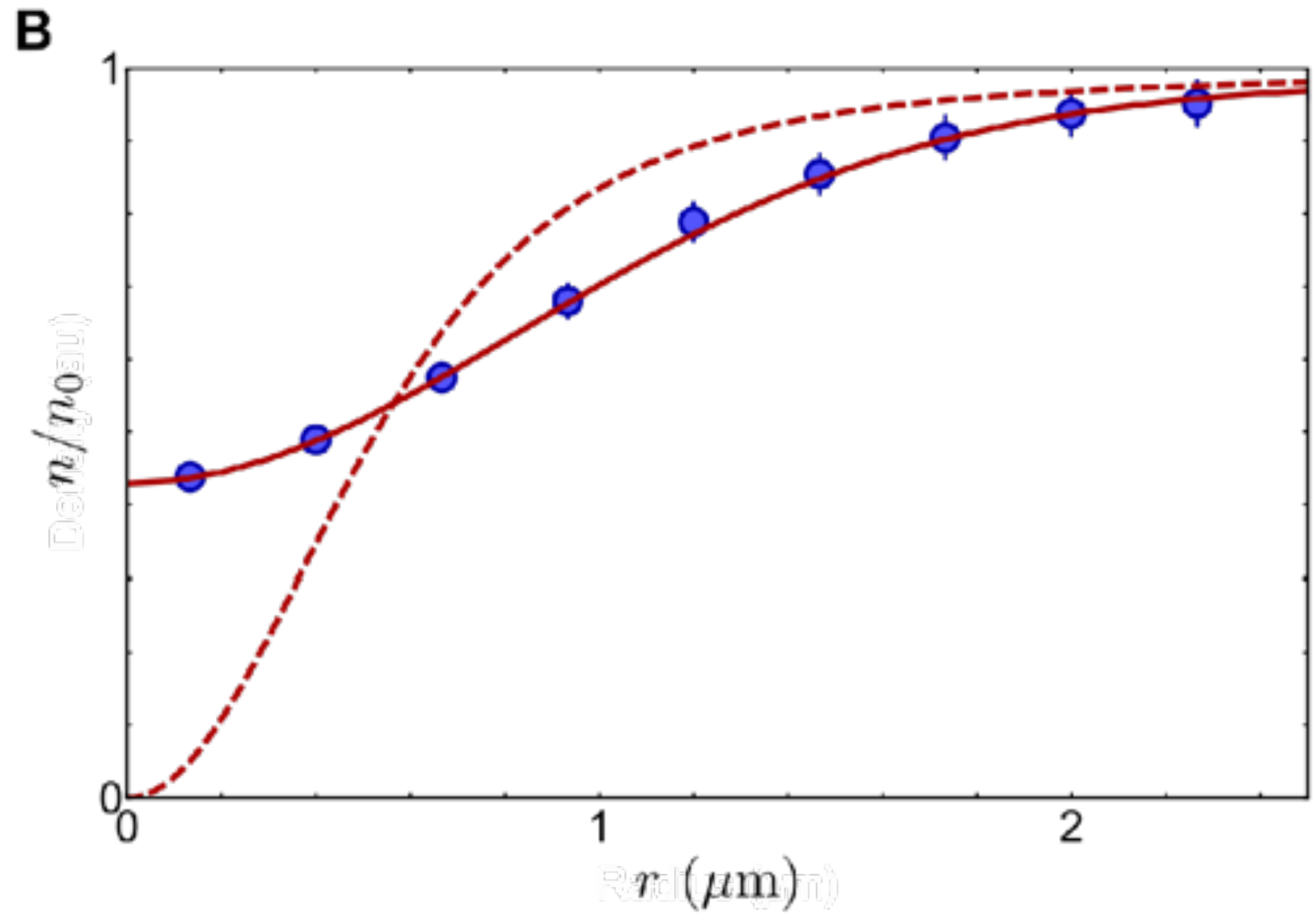
Chiral edge modes



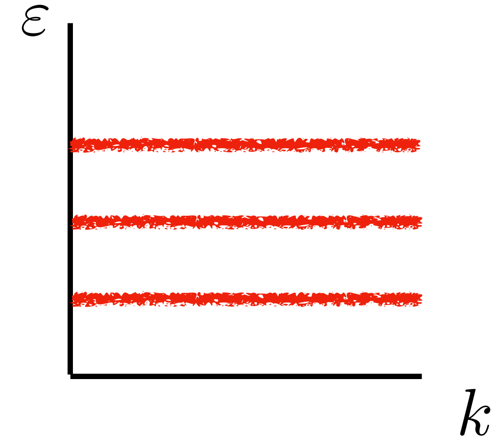
R. Fletcher, A. Shaffer, C. Wilson, P. Patel, Z. Yan, V. Crepel, B. Mukherjee, M. Zwierlein, arXiv:1911.12347 (2019) Science, accepted

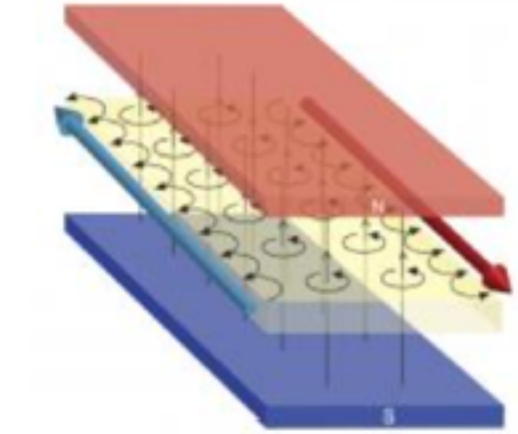
In situ detection of quantum vortices



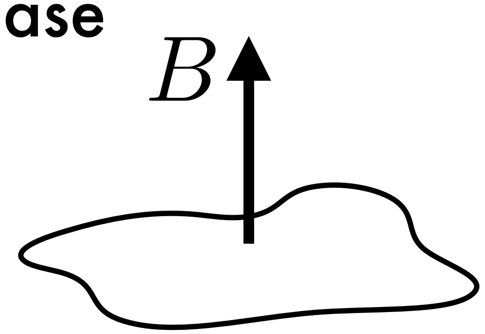


Artificial magnetic fields:



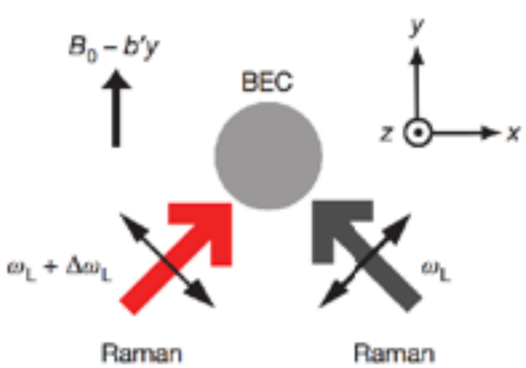


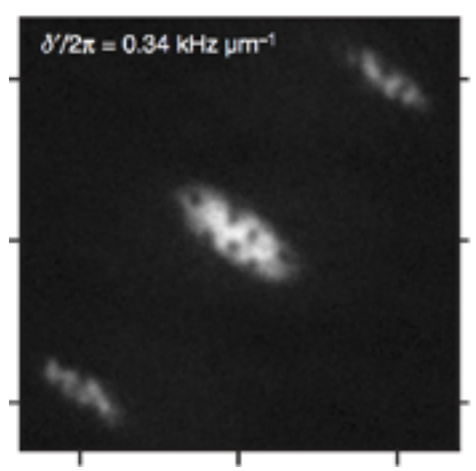
Construct analog of Aharonov-Bohm phase



$$\phi = \frac{q}{m}\int \vec{B}\cdot \mathrm{d}\vec{S}$$

Spin-orbit coupling





Y.-J. Lin, R. L. Compton, K. Jimenez-Garcia, J. V. Porto, I. B. Spielman, Nature 462, 628 (2009)

Direct phase imprinting

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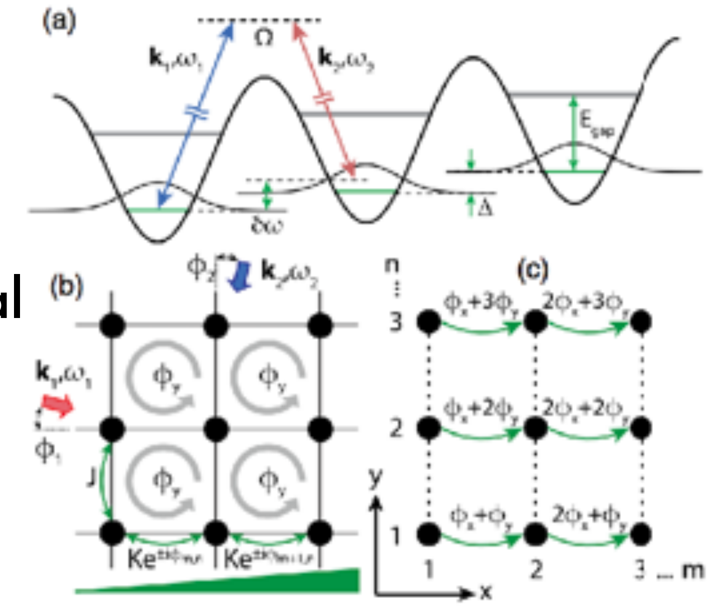

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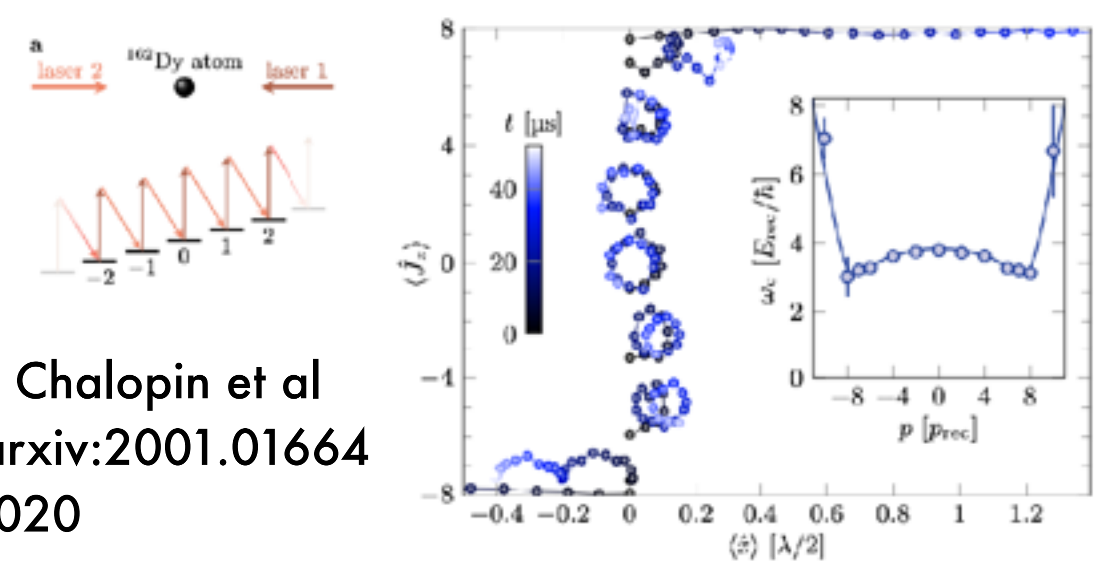
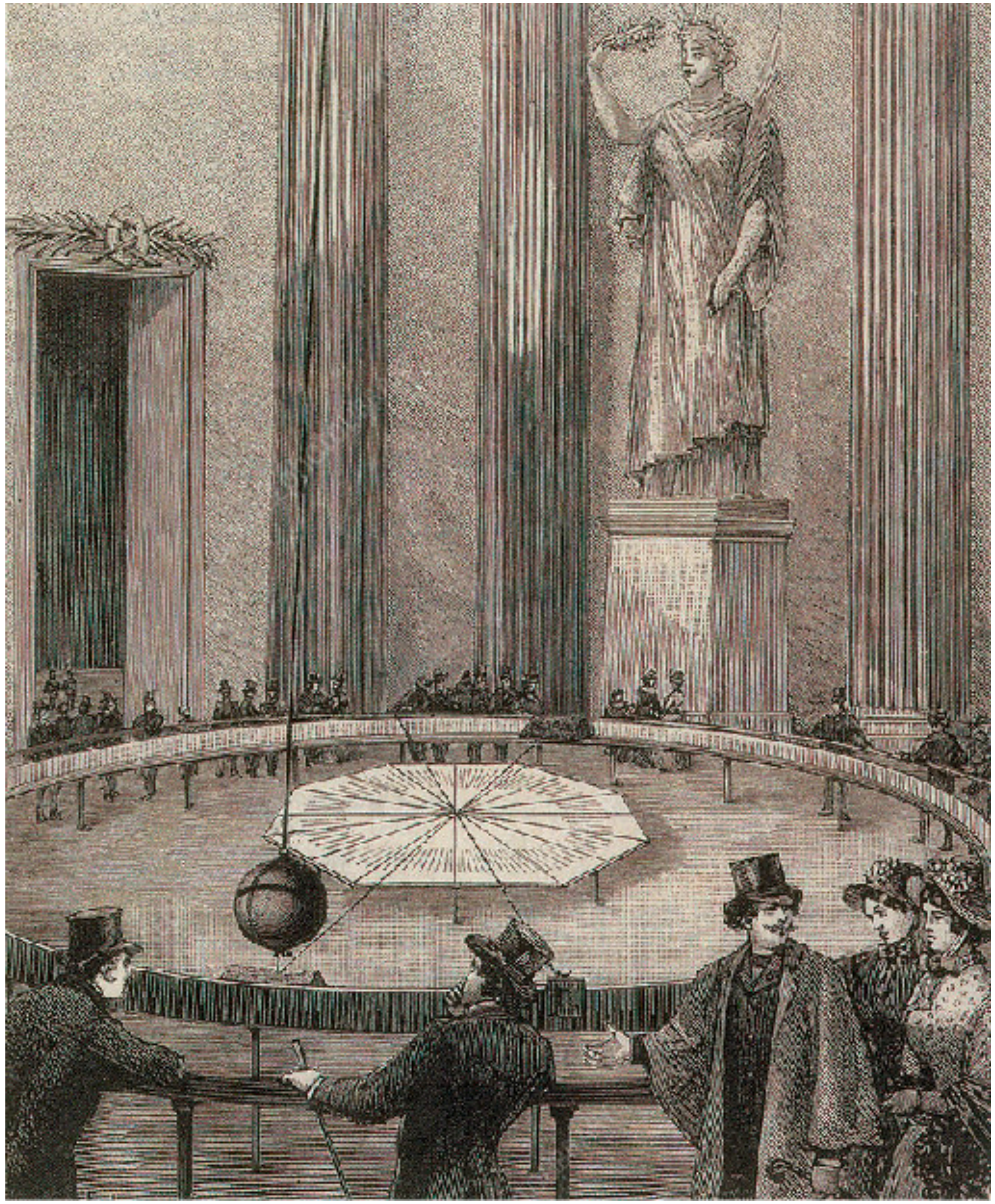


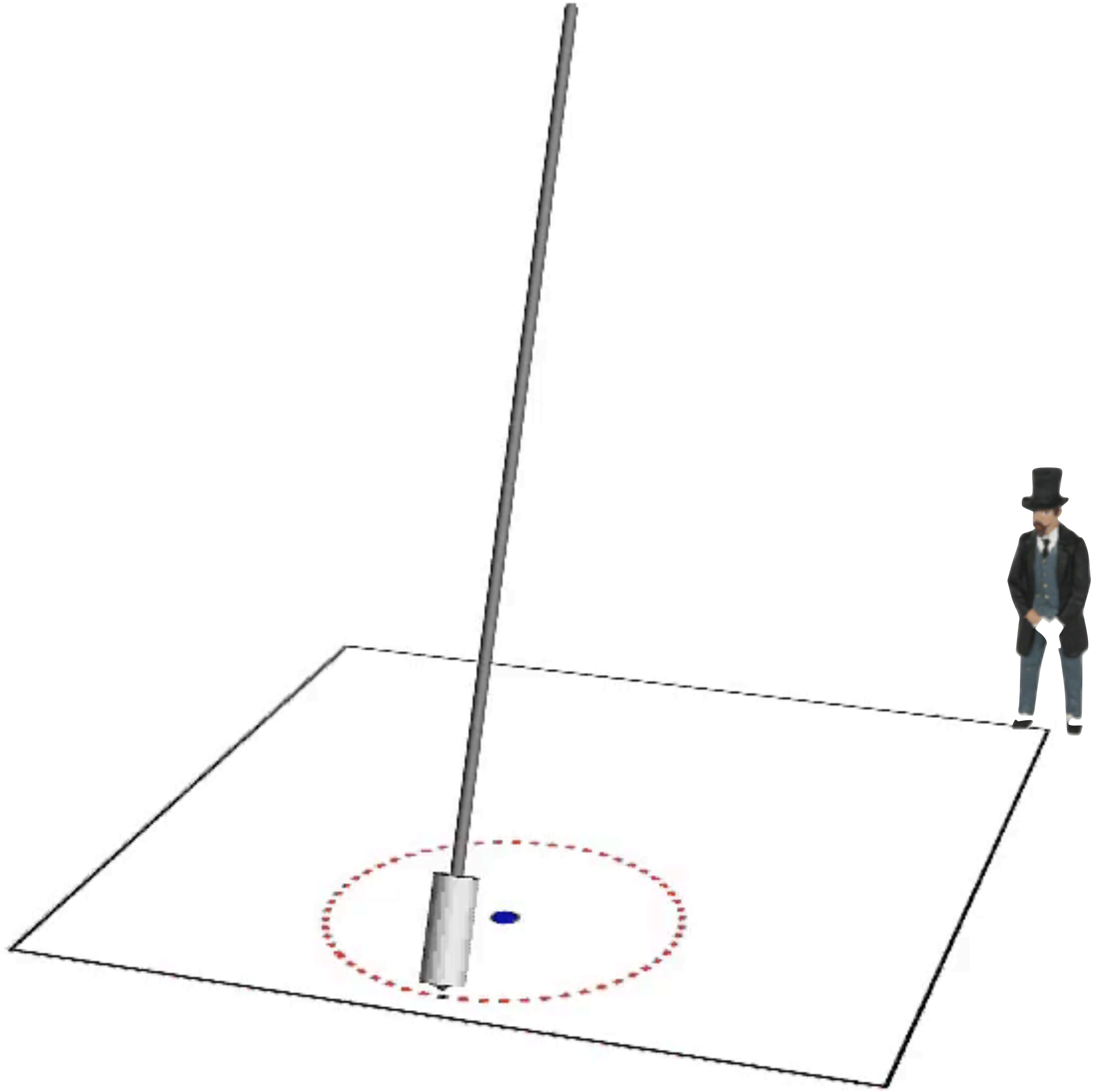
T. Chalopin et al arxiv:2001.01664 2020

Basics: Foucault pendulum



Basics: Foucault pendulum

$\Omega = 0.1$



Basics: Foucault pendulum

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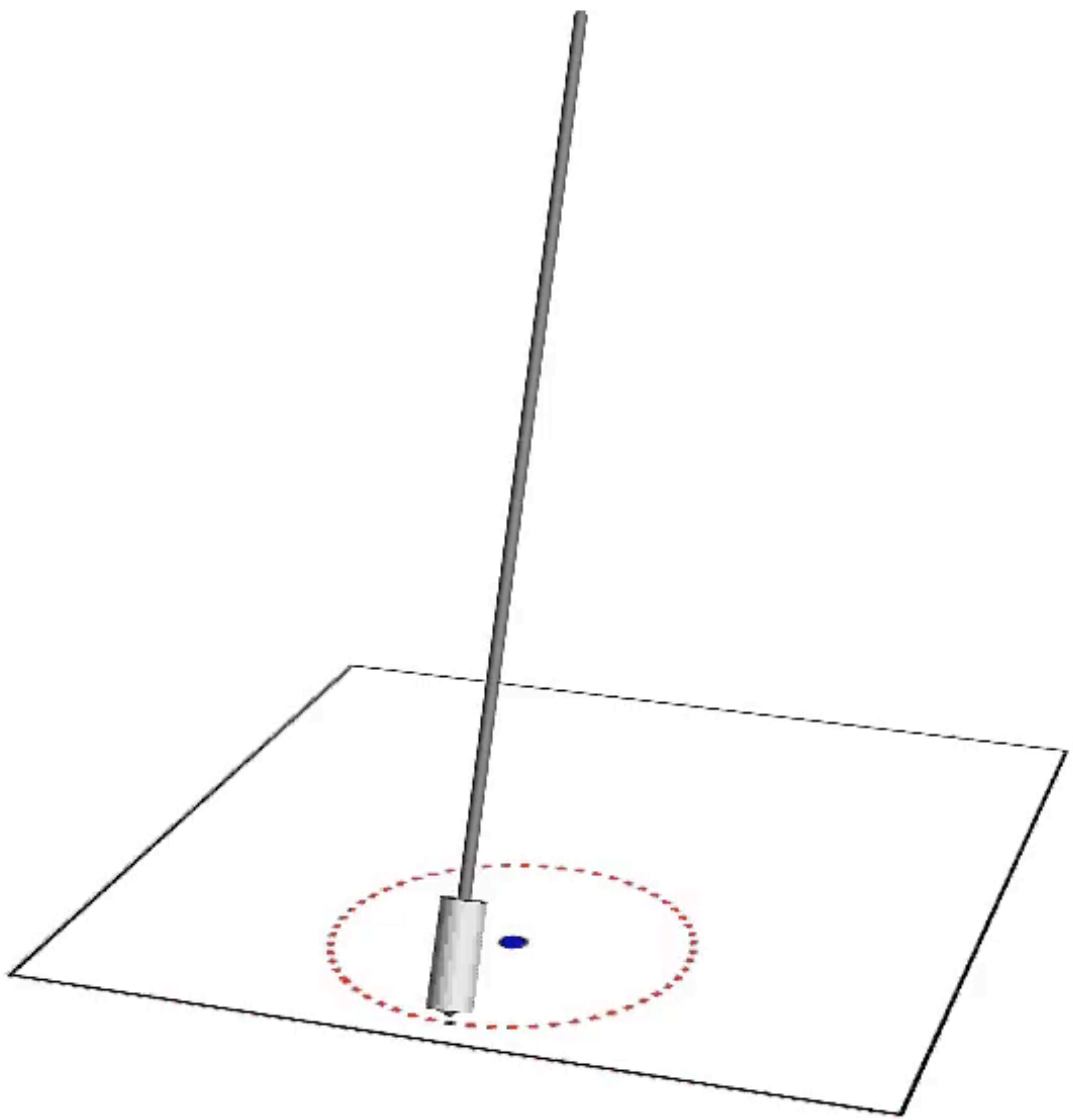
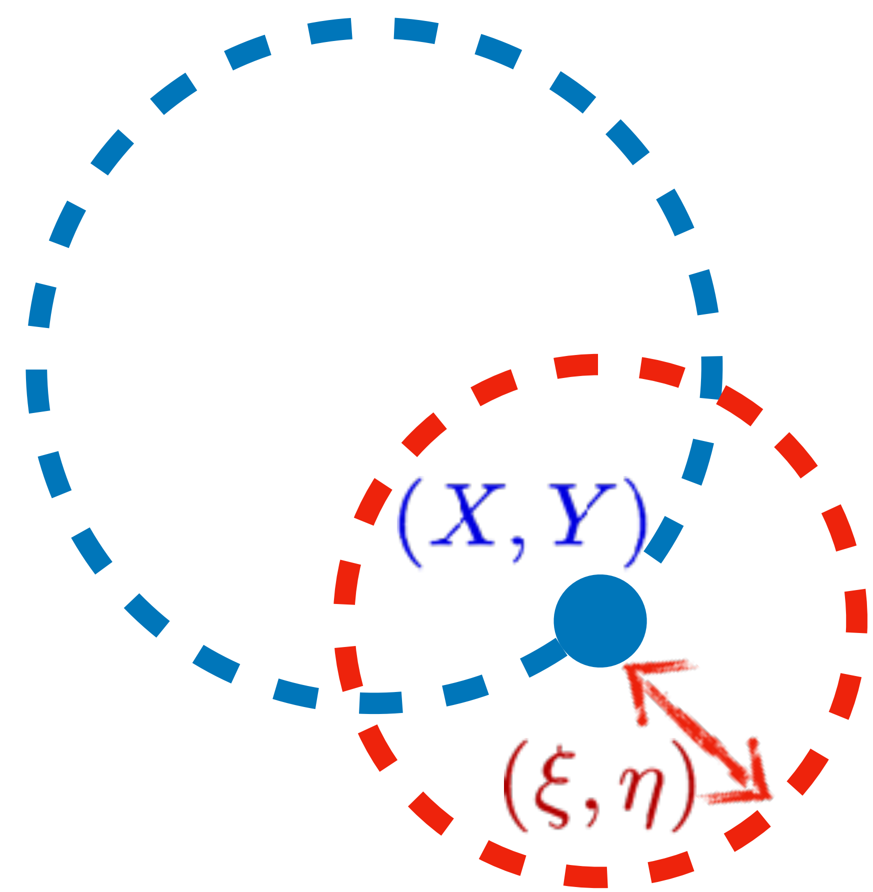
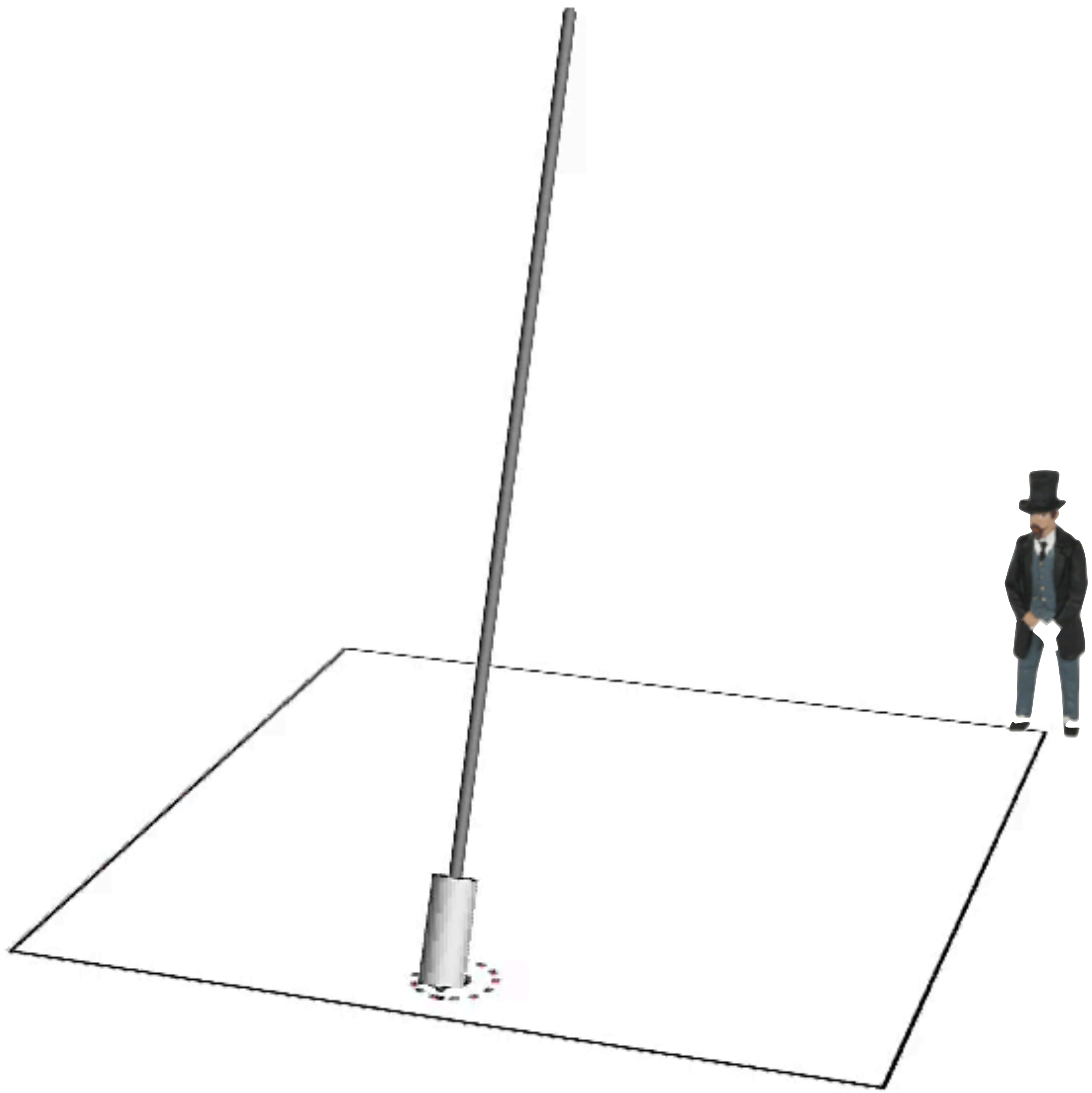




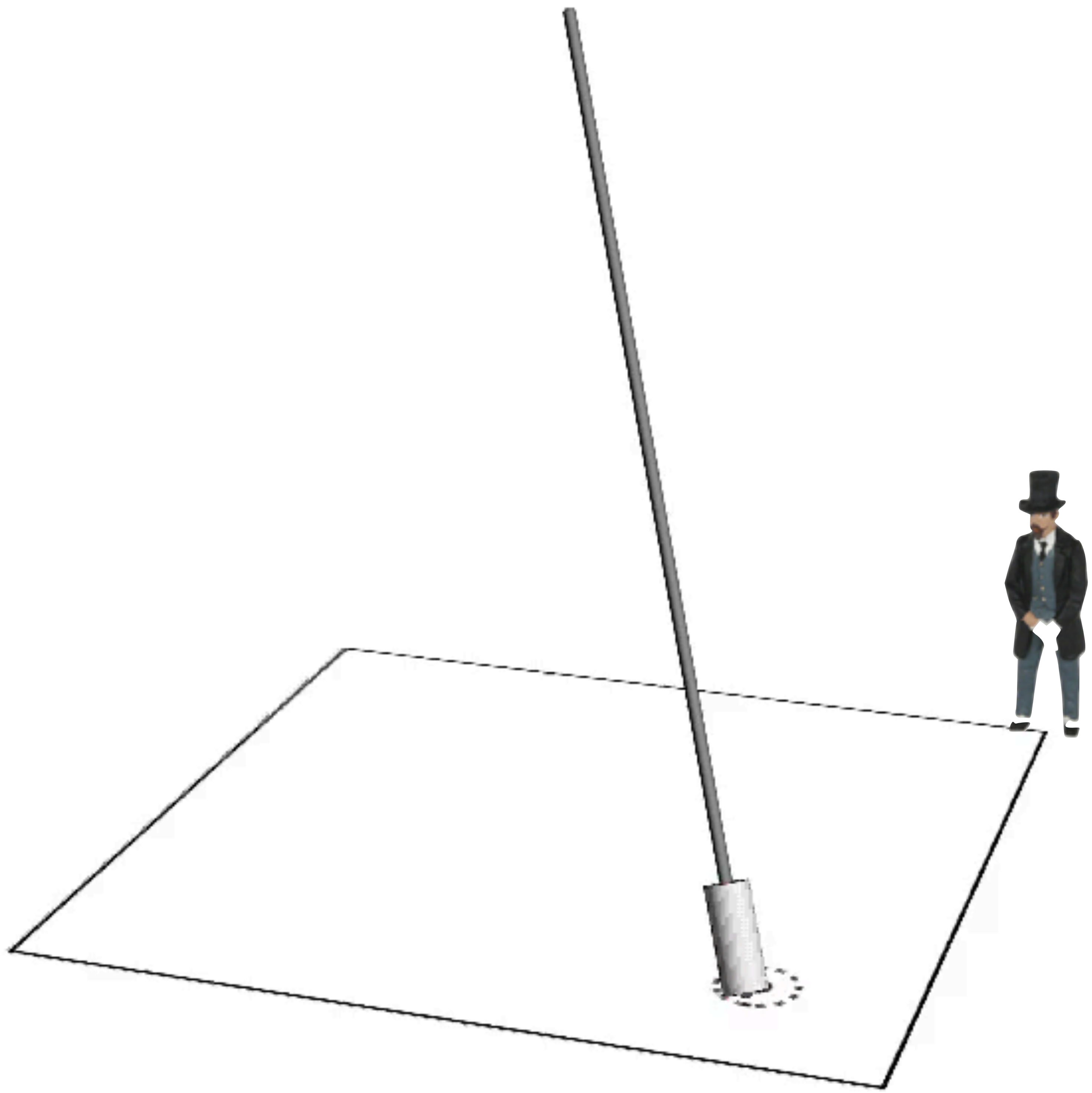
Basics: Foucault pendulum

$\Omega = 0.8$



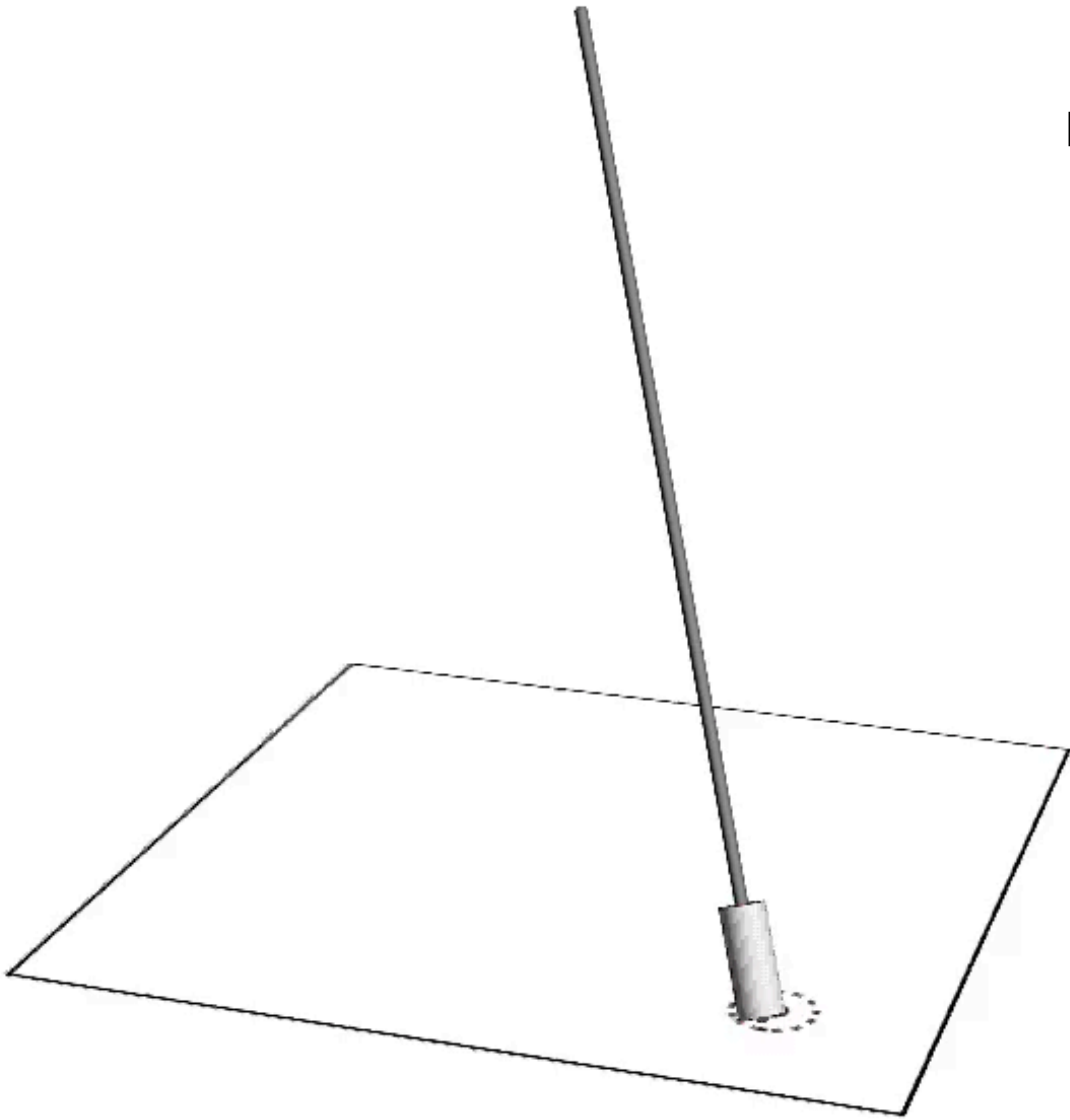
Basics: Foucault pendulum

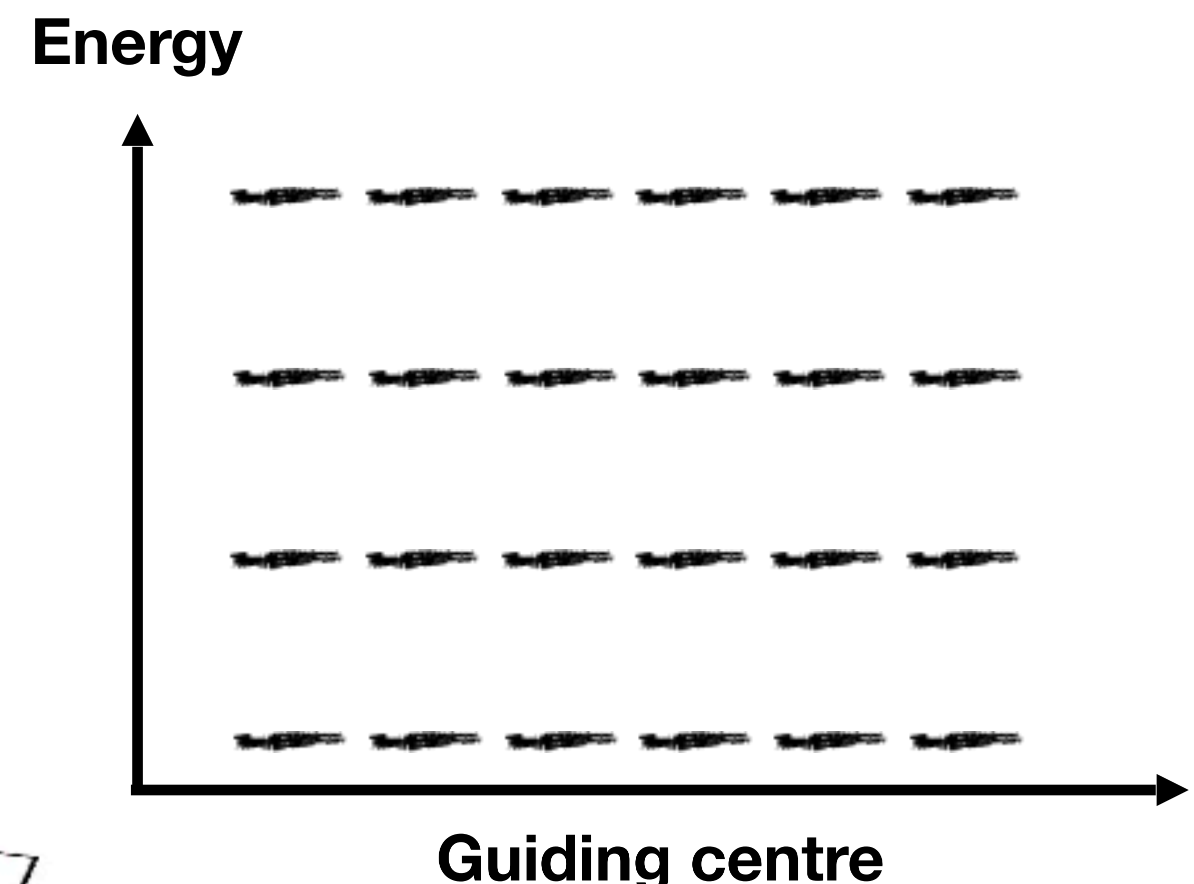
$\Omega = 1$



Basics: Foucault pendulum

$\Omega = 1$





Quantum description

$$H = \hbar\omega(\omega+\Omega)(\xi^2+\eta^2) + \hbar\omega(\omega-\Omega)(X^2+Y^2)$$
$$= \hbar(\omega+\Omega)\hat{a}^\dagger\hat{a} + \hbar(\omega-\Omega)\hat{b}^\dagger\hat{b} + \hbar\omega$$

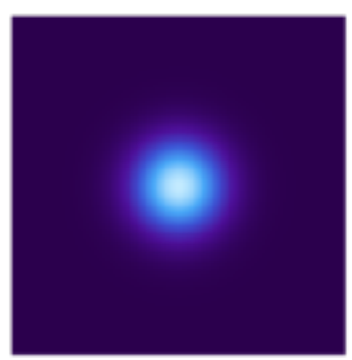
Cyclotron **Guiding centre**

$$\hat{a} \sim \hat{\xi} + i\hat{\eta} \qquad \hat{b} \sim \hat{X} - i\hat{Y}$$

$$[\hat{\xi},\hat{\eta}] = il_{\mathrm{B}}^2 \qquad [\hat{X},\hat{Y}] = -il_{\mathrm{B}}^2 \qquad l_{\mathrm{B}} = \sqrt{\frac{\hbar}{2m\omega}}$$

If potential $V(x,y)$ varies slowly, can't resolve cyclotron motion

$$V(x,y) \to V(X,Y)$$

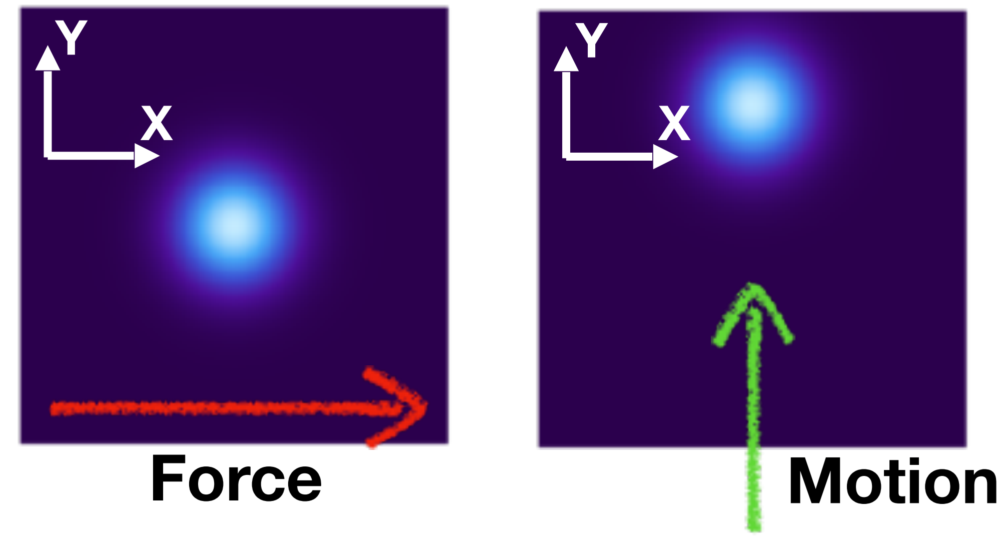


Particle moves within non-commutative space

Life in a non-commuting space $[\hat{X}, \hat{Y}] = -il_{\mathrm{B}}^2$

Transverse Hall response $V \sim FX$

$$\hat{U}(t) = \exp\left(-\frac{i}{\hbar}Vt\right) = \hat{T}_Y\left(\frac{Ft}{2m\Omega}\right)$$

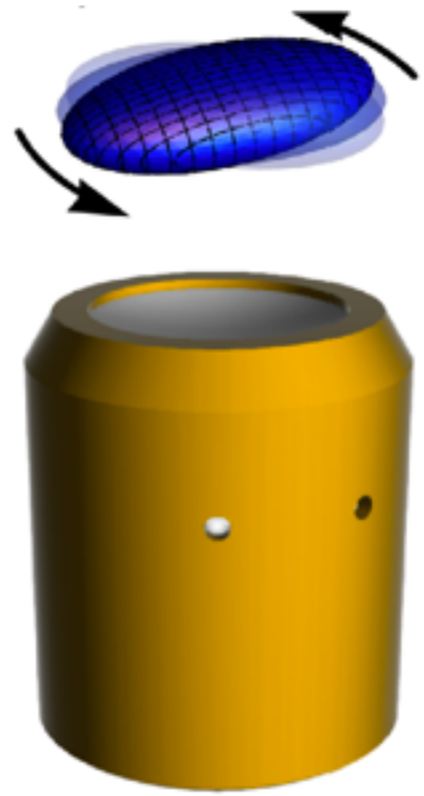


Isopotential flow

$$\vec{v}_{\mathrm{d}} = \frac{1}{2m\omega}\hat{\Omega} \times \nabla V \qquad \nabla \cdot \vec{v}_{\mathrm{d}} = 0$$

Time evolution under generic spatial potential
=
Geometric transformation

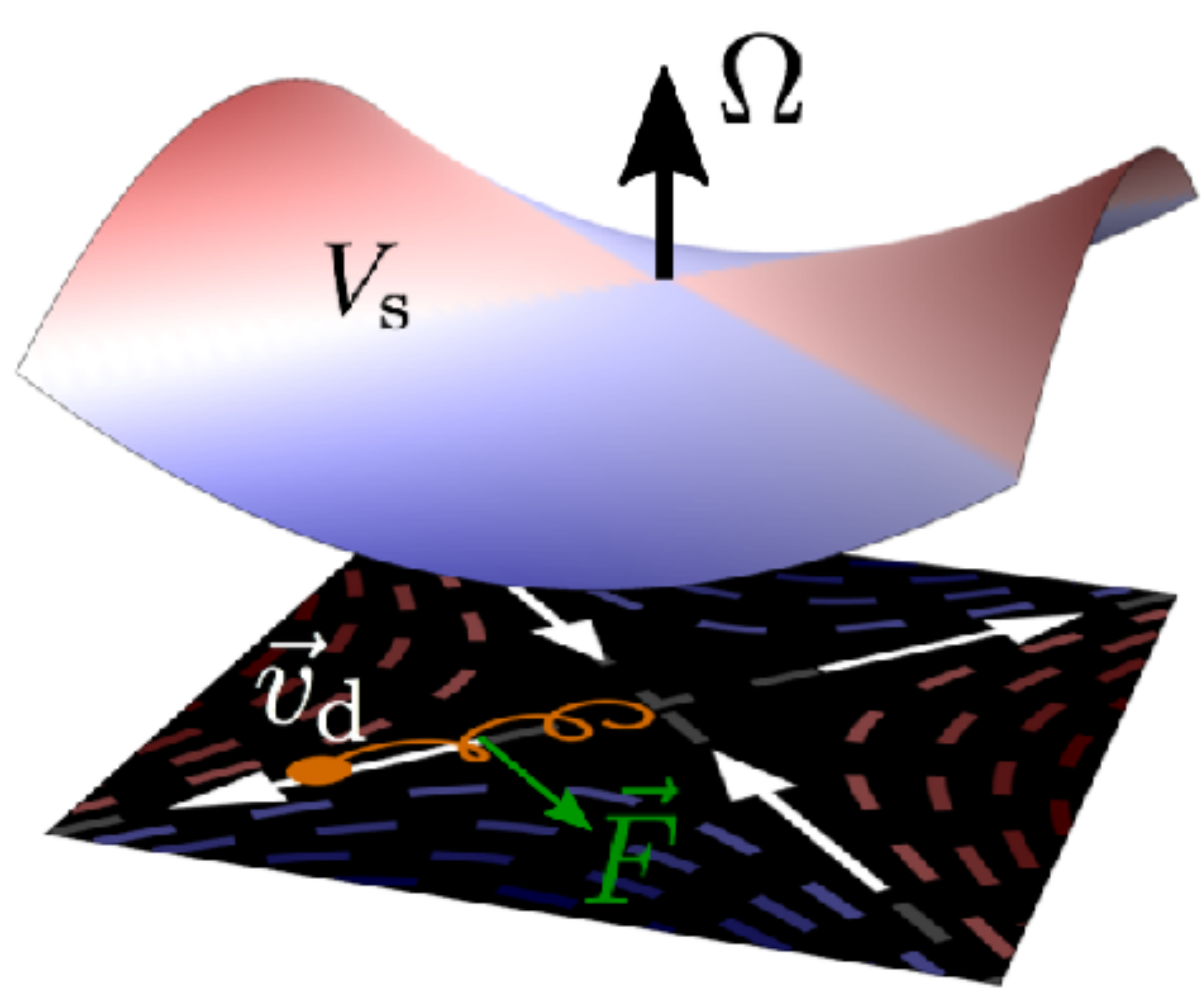
Our experiment: BEC in a rotating elliptical trap



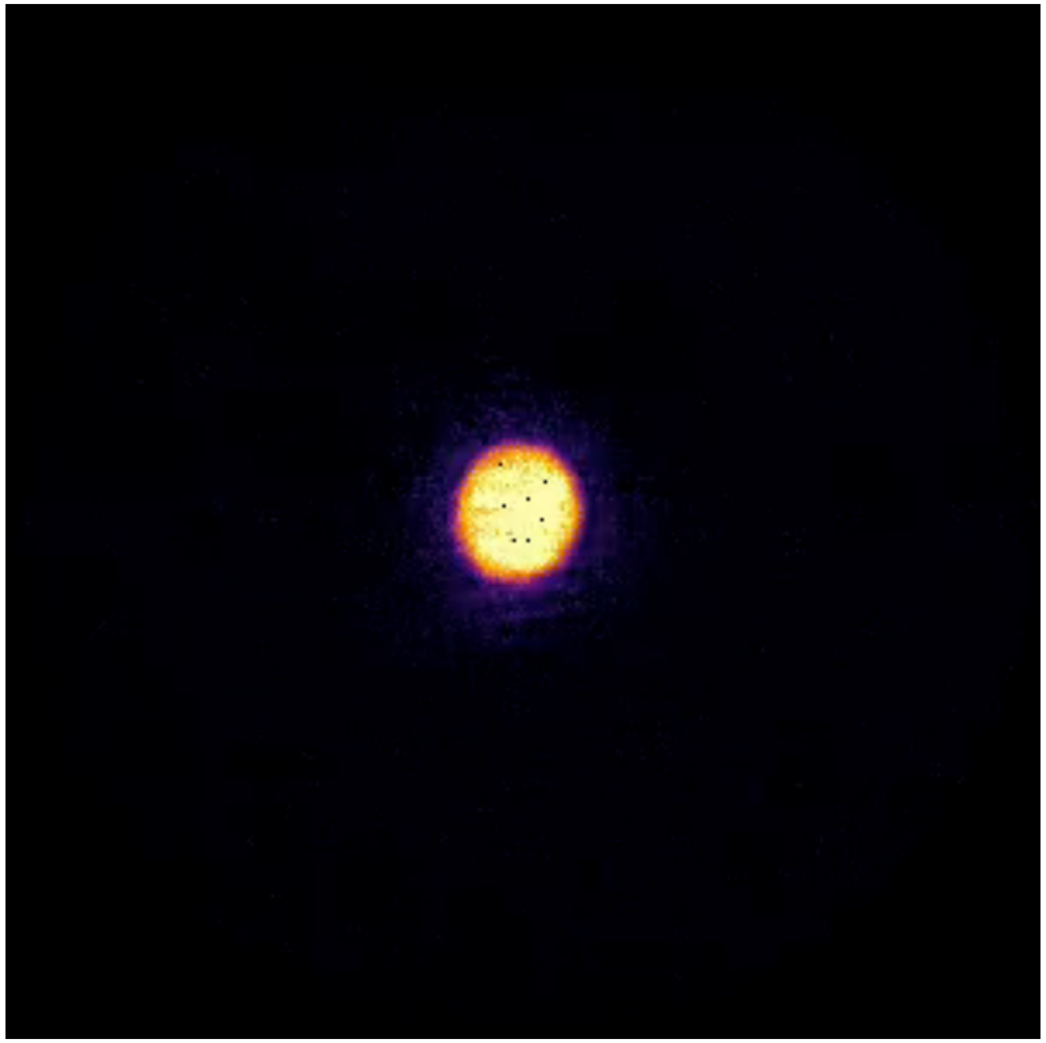
Elliptical harmonic potential

$$V = \frac{1}{2} m\omega^2 \left[(1+\varepsilon)x^2 + (1-\varepsilon)y^2\right]$$

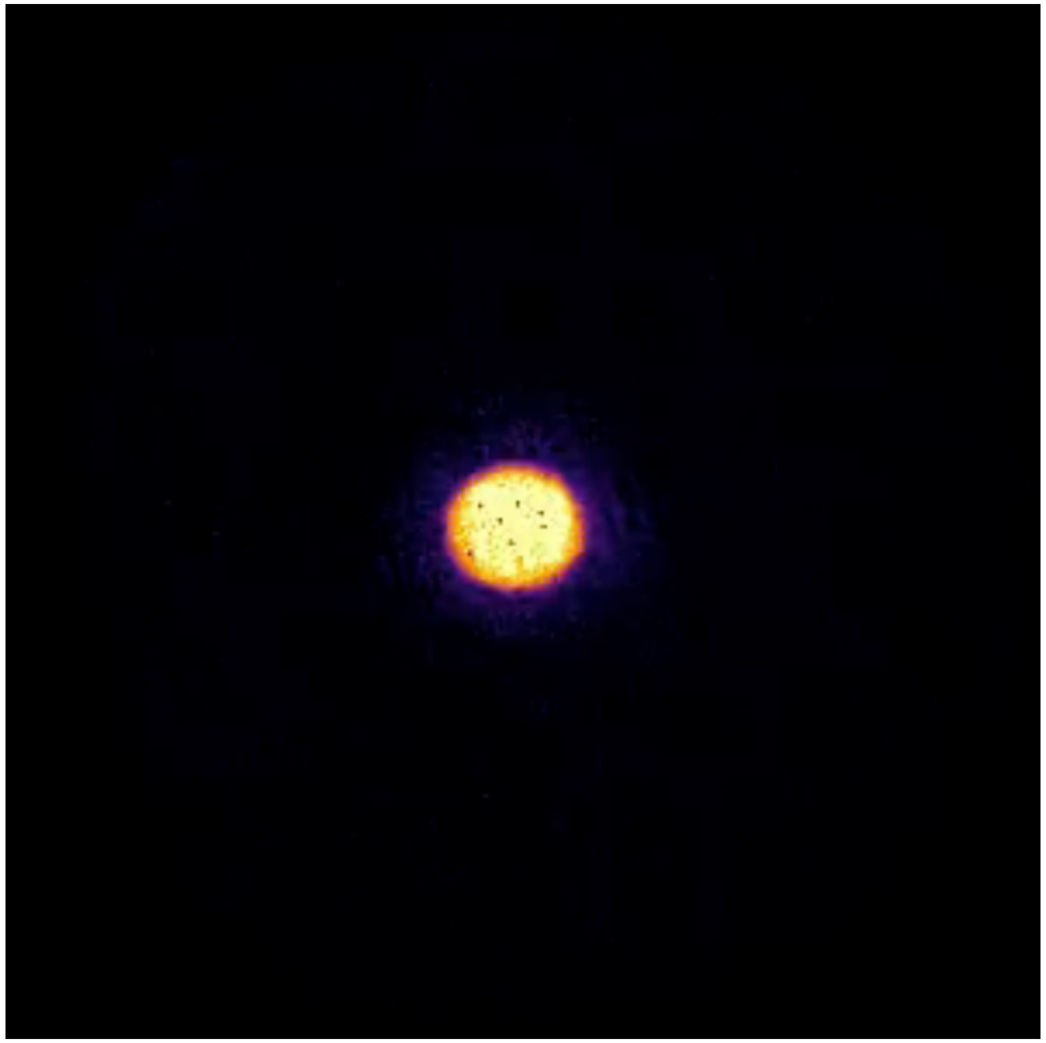
Rotate at frequency Ω, ramp up to trap frequency ω and hold



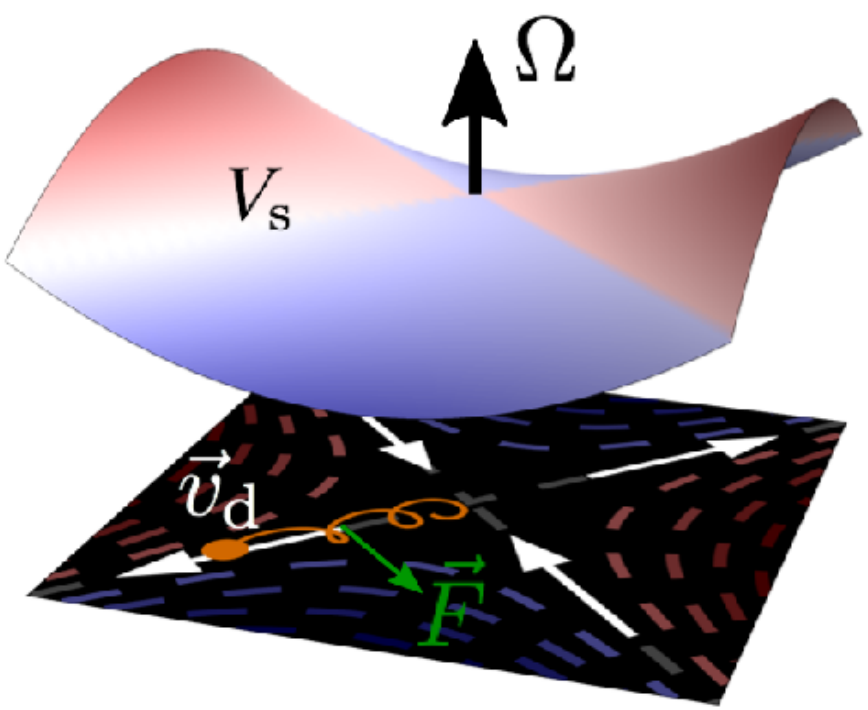
Lab frame

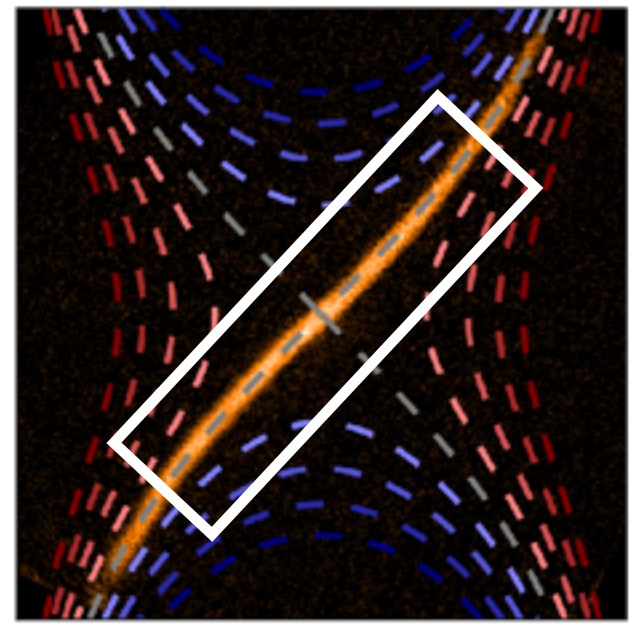


Rotating frame

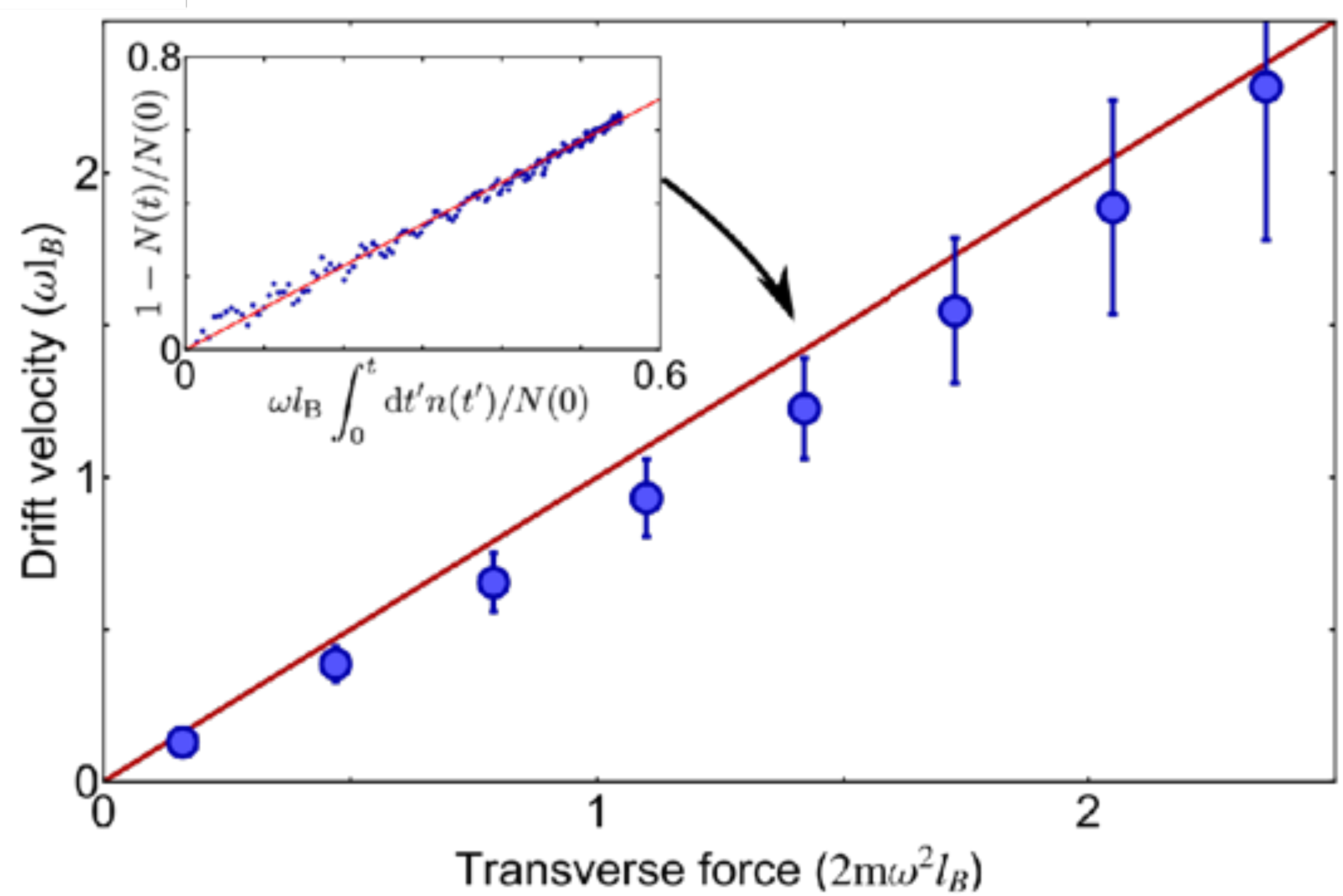


Drift velocity





$$\frac{\mathrm{d}N}{\mathrm{d}t} = -2v_\mathrm{d}n$$



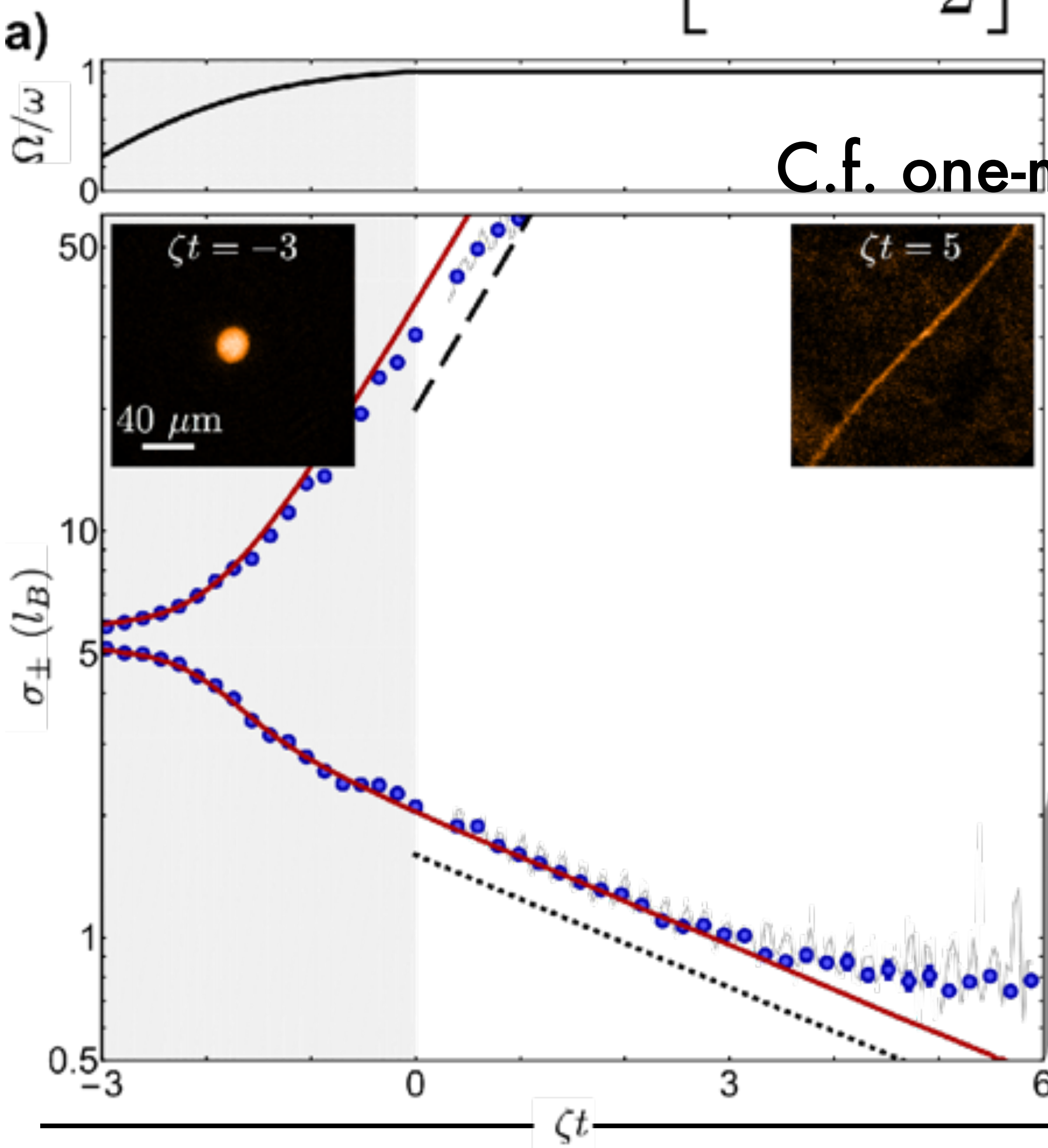
Geometric squeezing

Hamiltonian under saddle potential

$$\hat{H} = 2\hbar\omega\left[\hat{a}^\dagger\hat{a} + \frac{1}{2}\right] + \frac{\hbar\zeta}{2}\left[\hat{b}\hat{b} + \hat{b}^\dagger\hat{b}^\dagger\right]$$

Squeezing rate

$$\zeta = \frac{\varepsilon\omega}{2}$$



C.f. one-mode squeezing operator:

$$\hat{S}(\alpha) = \exp\left(\alpha^*\hat{b}\hat{b} - \alpha\hat{b}^\dagger\hat{b}^\dagger\right)$$

Geometric squeezing

Hamiltonian under saddle potential

$$\hat{H} = 2\hbar\omega\left[\hat{a}^\dagger\hat{a} + \frac{1}{2}\right] + \frac{\hbar\zeta}{2}\left[\hat{b}\hat{b} + \hat{b}^\dagger\hat{b}^\dagger\right]$$

Squeezing rate

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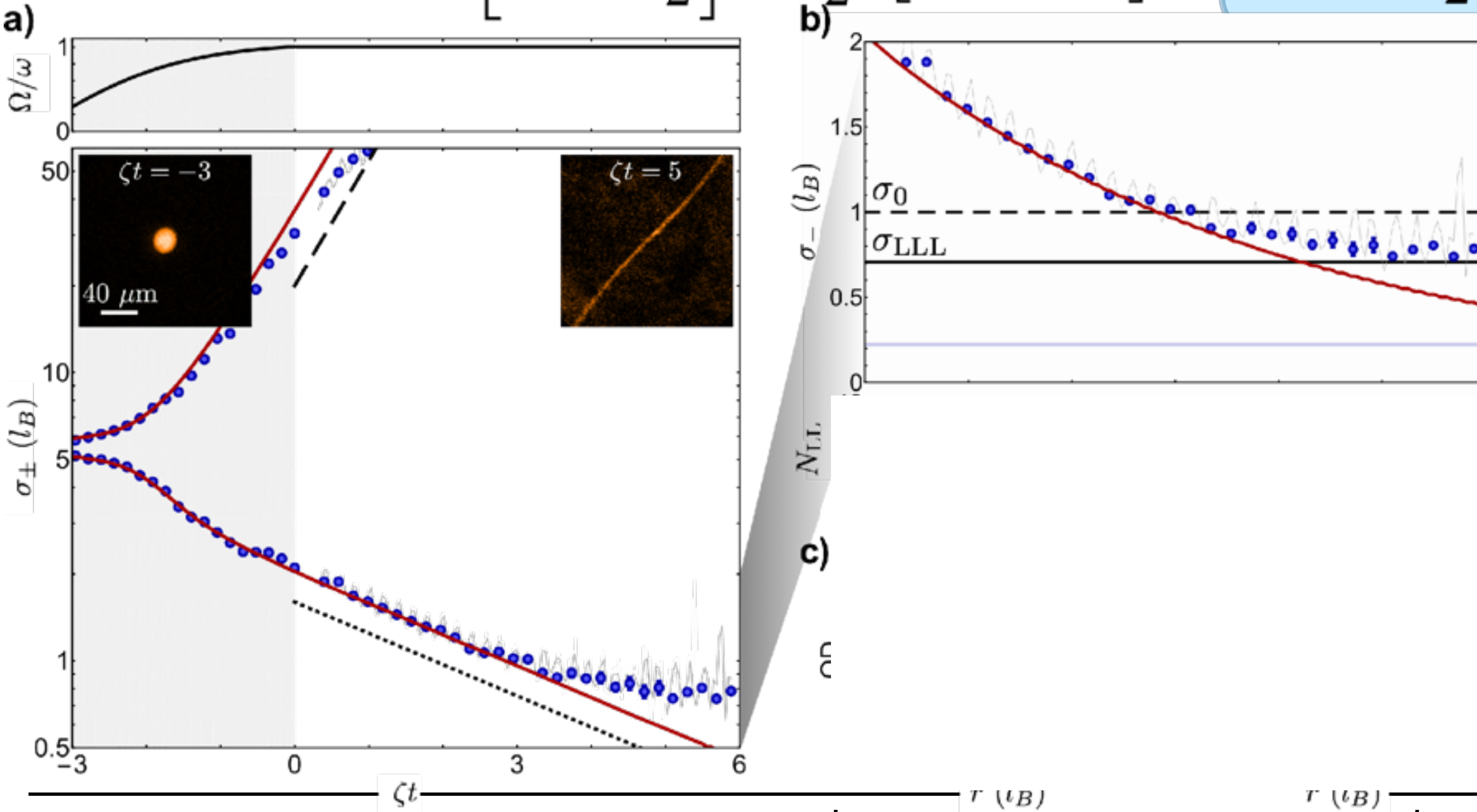
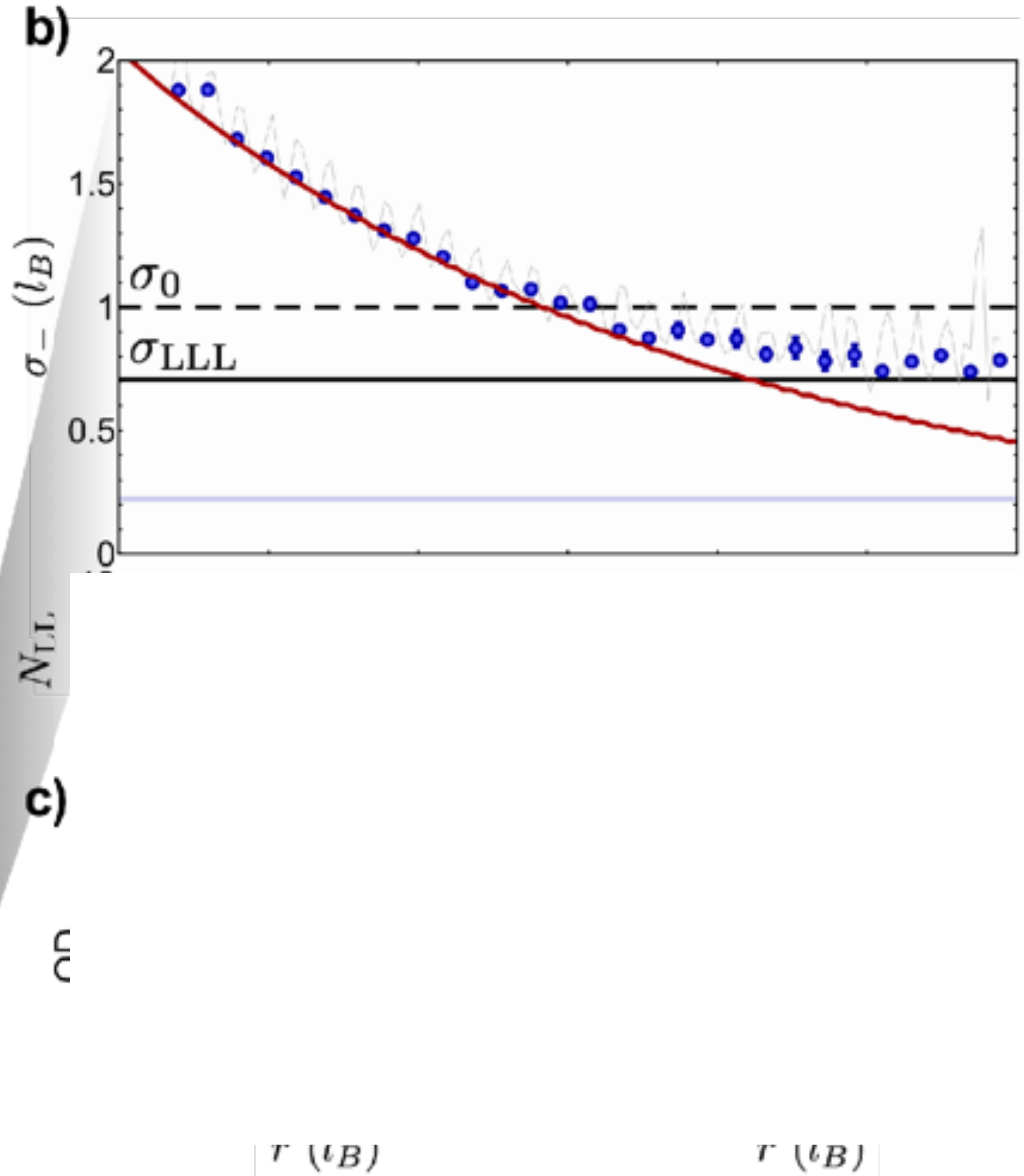


Geometric squeezing



$$\Delta\xi = \Delta\eta = \Delta X = \Delta Y = \frac{l_{\mathrm{B}}}{\sqrt{2}}$$

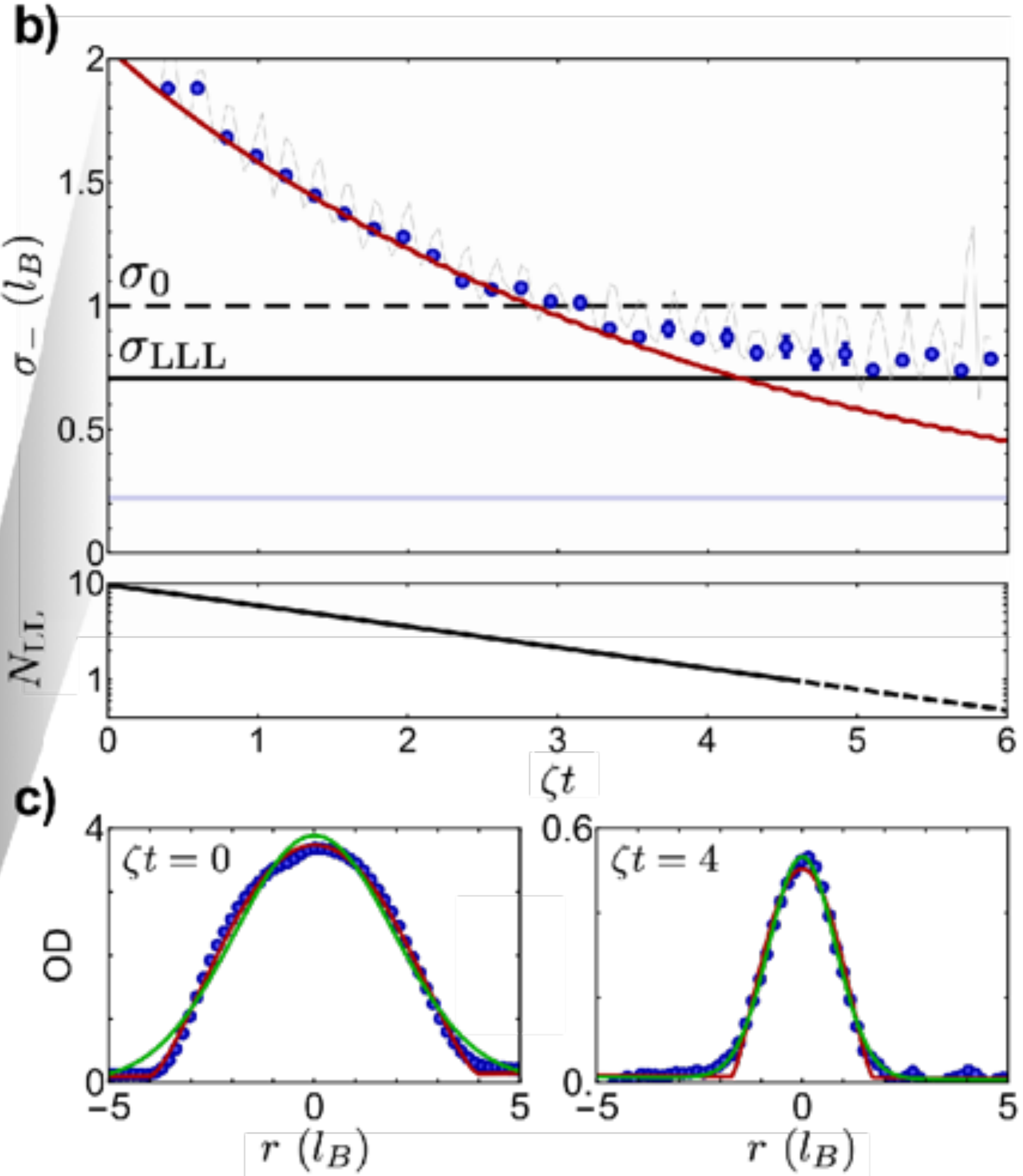
Guiding centre

Cyclotron

$$\Delta\xi = \Delta\eta = \frac{l_{\mathrm{B}}}{\sqrt{2}}$$

Geometric squeezing

$$\Delta\xi = \Delta\eta = \Delta X = \Delta Y = \frac{l_\mathrm{B}}{\sqrt{2}}$$

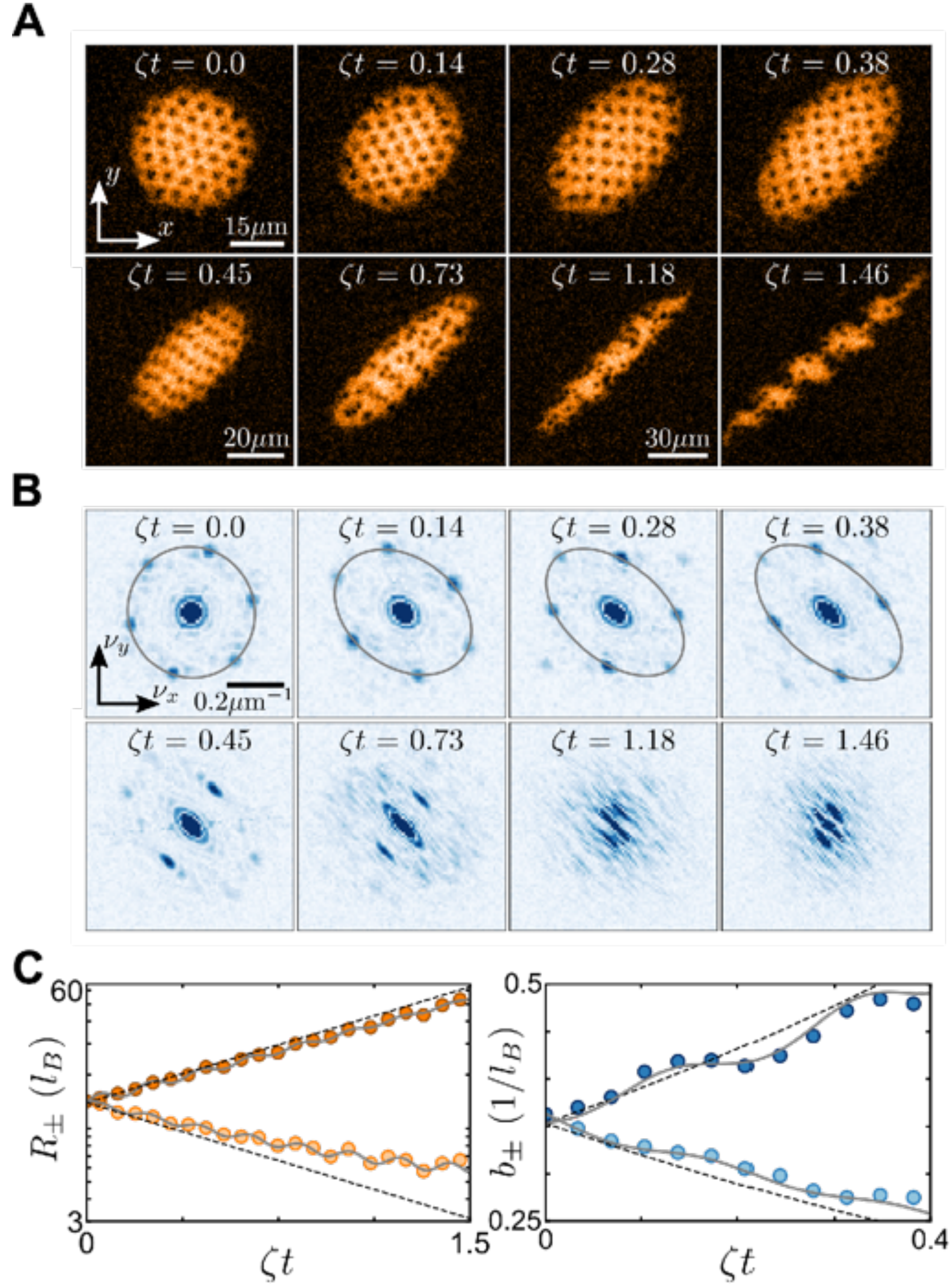


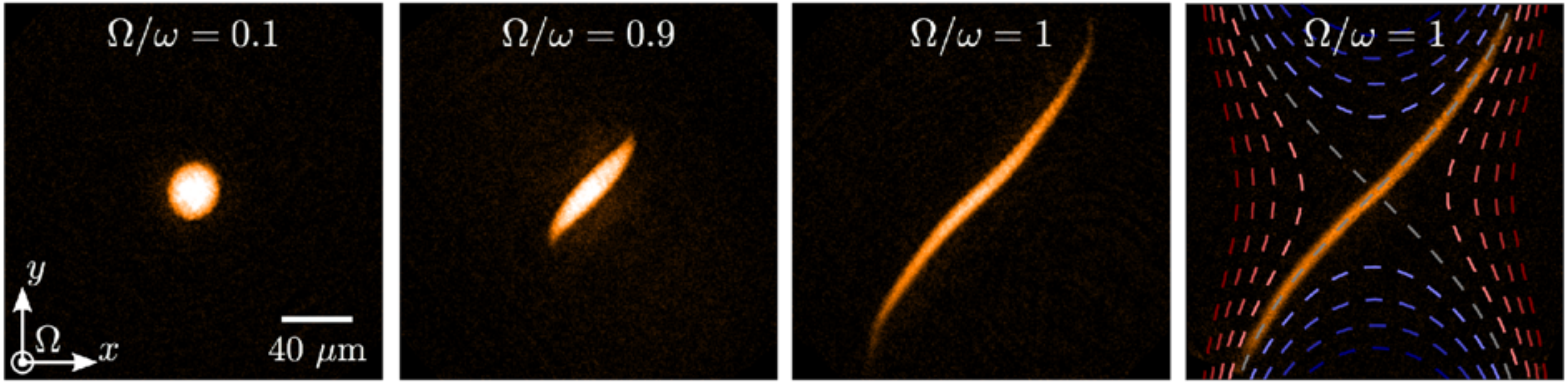
Guiding centre

Cyclotron

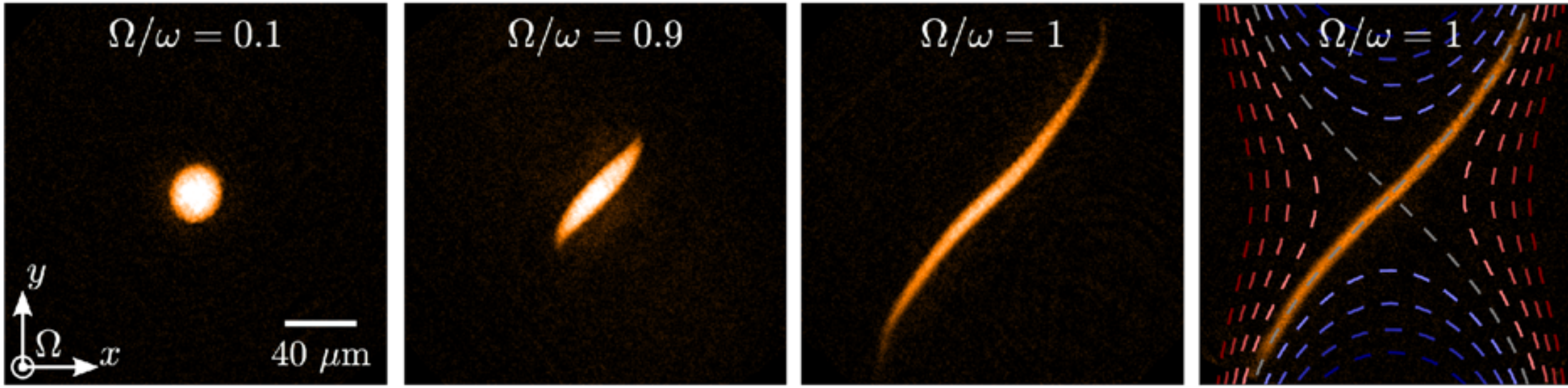
$$\Delta\xi = \Delta\eta = \frac{l_\mathrm{B}}{\sqrt{2}}$$

Geometric squeezing of a vortex lattice





R. Fletcher, A. Shaffer, C. Wilson, P. Patel, Z. Yan, V. Crepel, B. Mukherjee, M. Zwierlein, arXiv:1911.12347 (2019) Science, accepted



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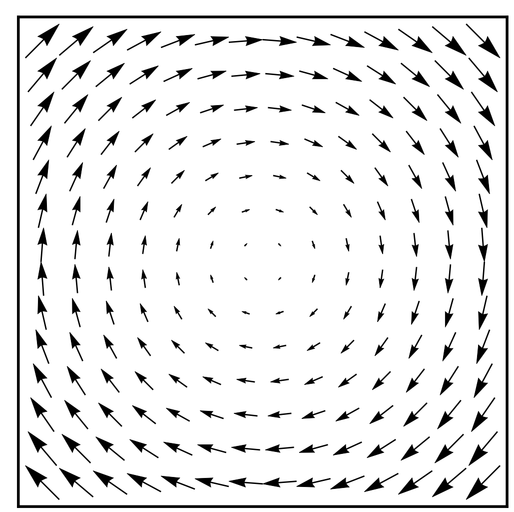
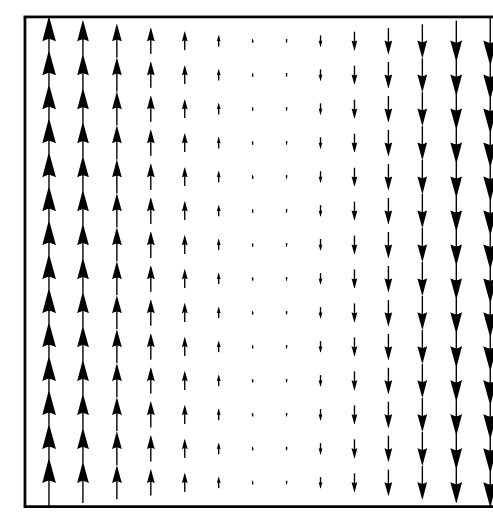
Transformation from a 'symmetric gauge' to 'Landau gauge' condensate

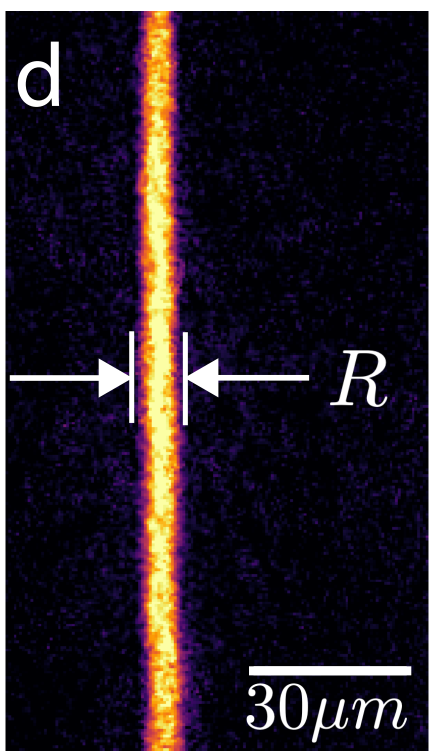
$$\hat{H} = \int \mathrm{d}^2 r \, \hat{\Psi}^\dagger \left[\frac{(\hat{\mathbf{p}} - q\mathbf{A})^2}{2m} + \frac{g}{2} \hat{\Psi}^\dagger \hat{\Psi} \right] \hat{\Psi}$$

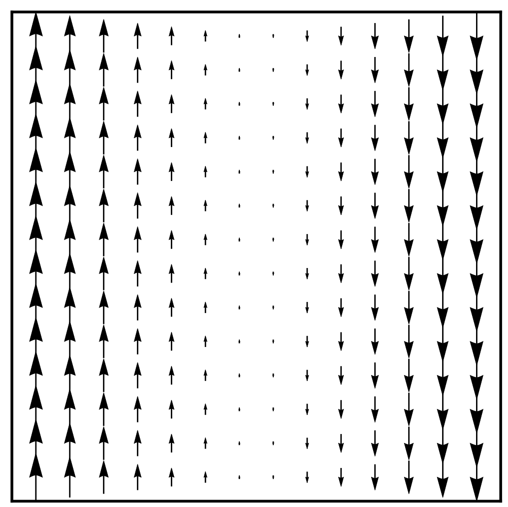
$$\mathbf{v} = \frac{1}{m} \left(\hbar \nabla \theta - q\mathbf{A} \right)$$





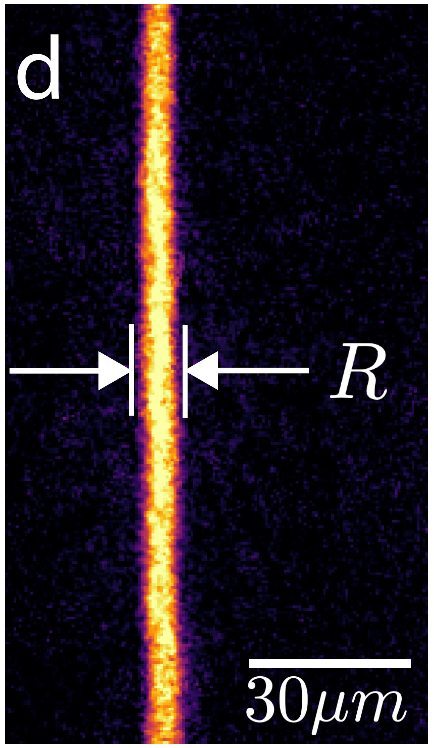
Landau gauge condensate



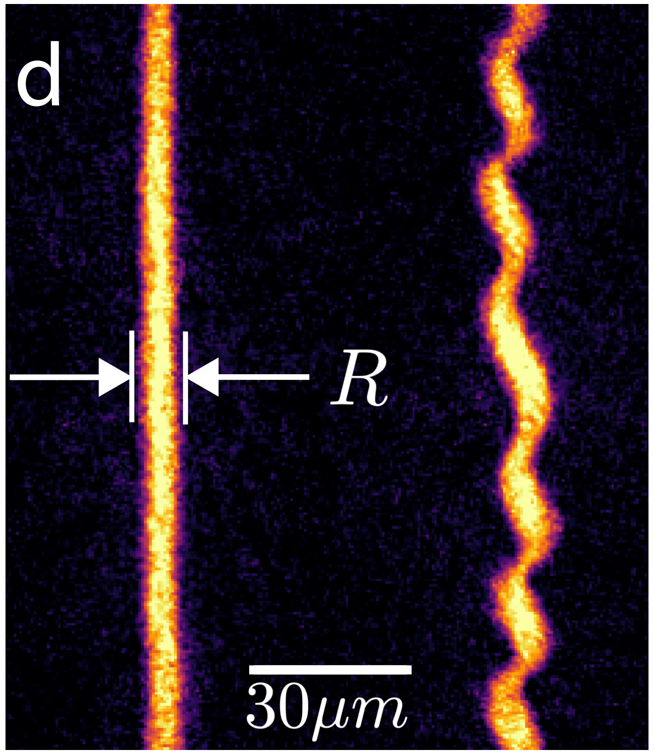


$$\hat{H} = \int \mathrm{d}^2 r\, \hat{\Psi}^\dagger \left[\frac{\hat{p}_x^2}{2m} + 2m\omega^2 \left(\hat{x} - \frac{\hat{p}_y l_\mathrm{B}^2}{\hbar} \right)^2 + \frac{g}{2} \hat{\Psi}^\dagger \hat{\Psi} \right] \hat{\Psi}$$

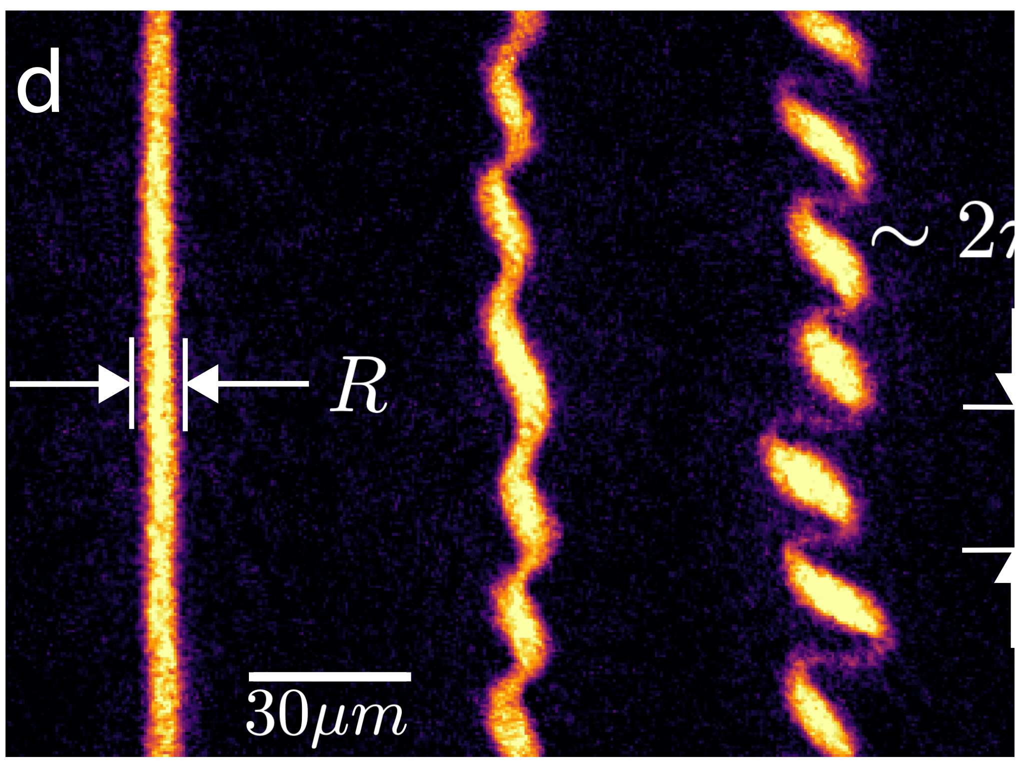
Interplay of gauge field and interactions



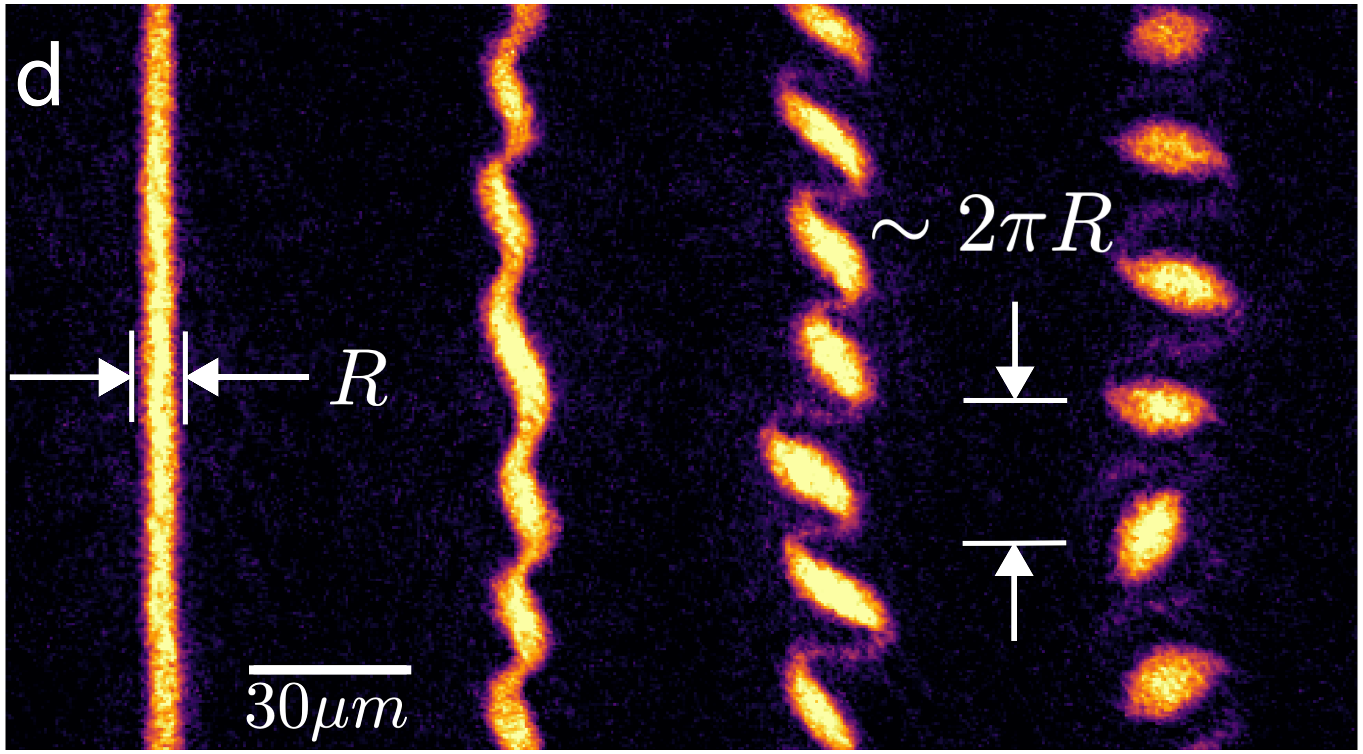
Interplay of gauge field and interactions



Interplay of gauge field and interactions



Interplay of gauge field and interactions



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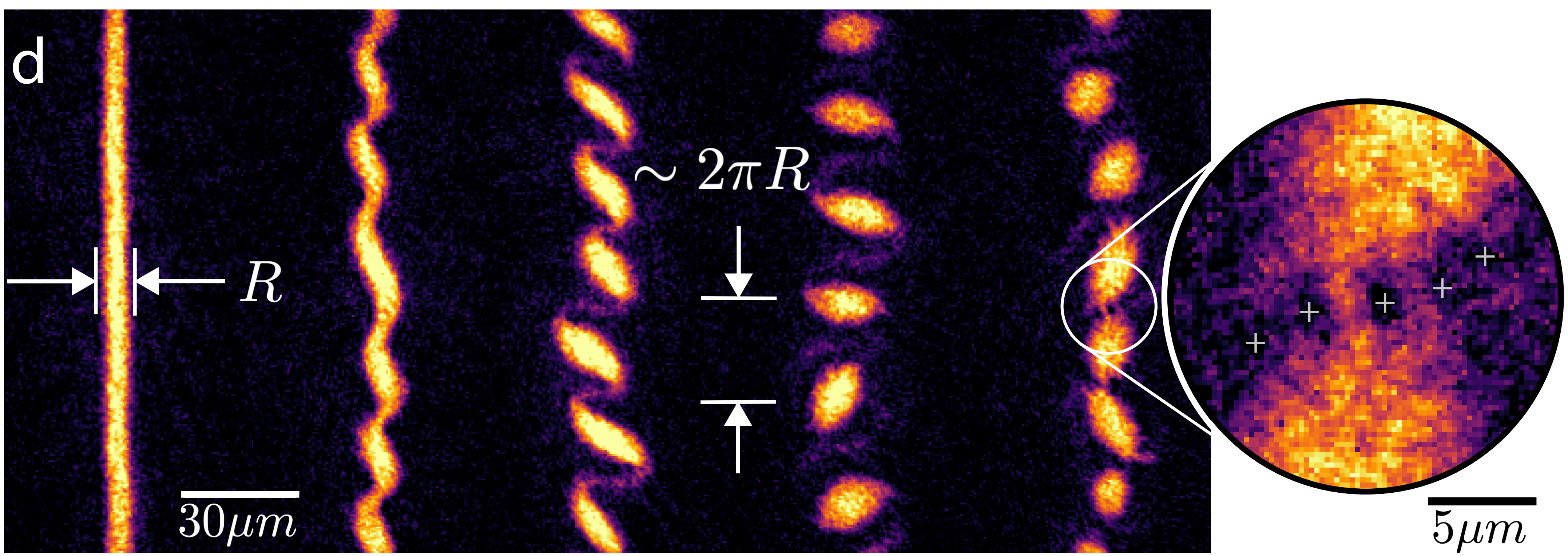
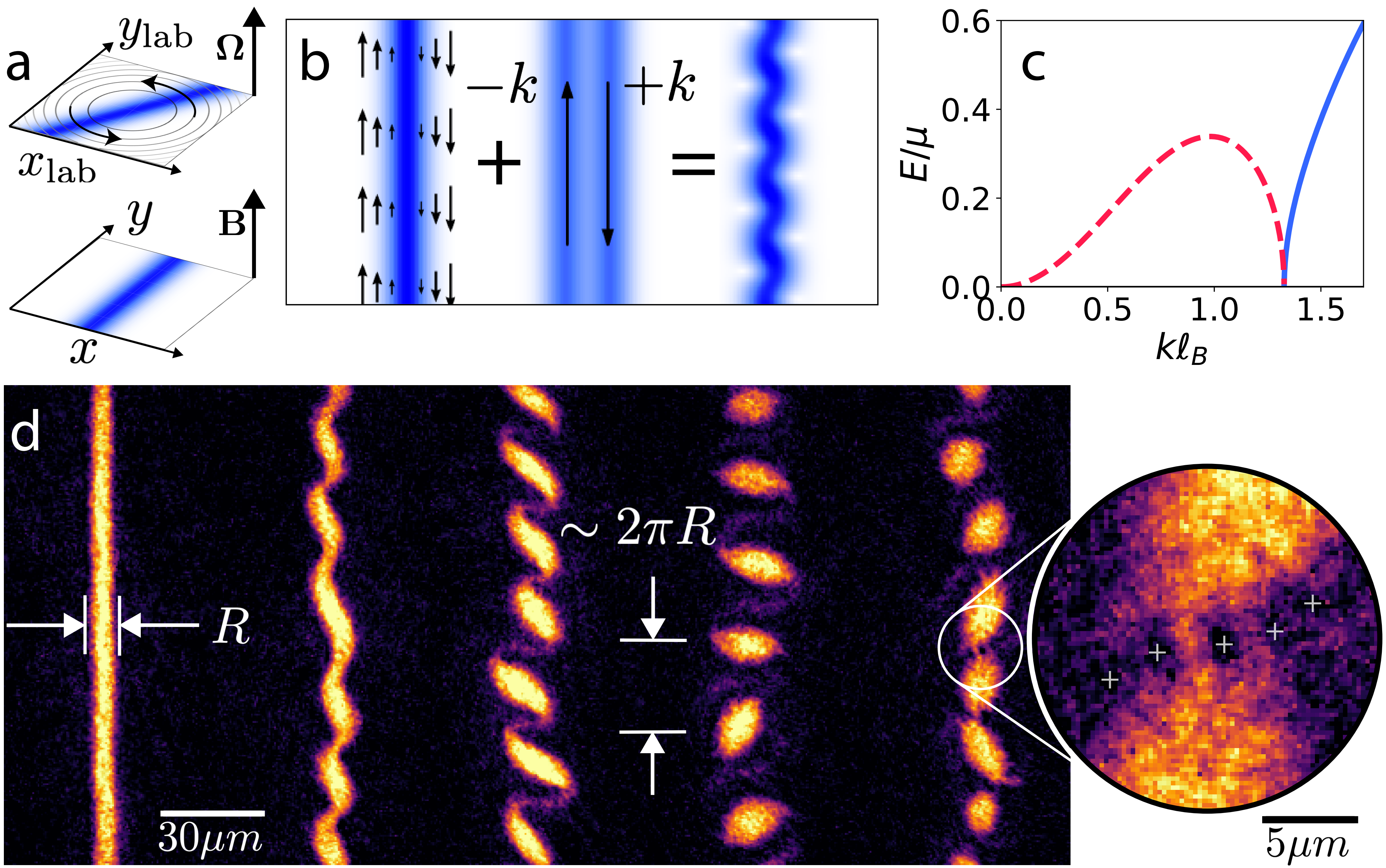
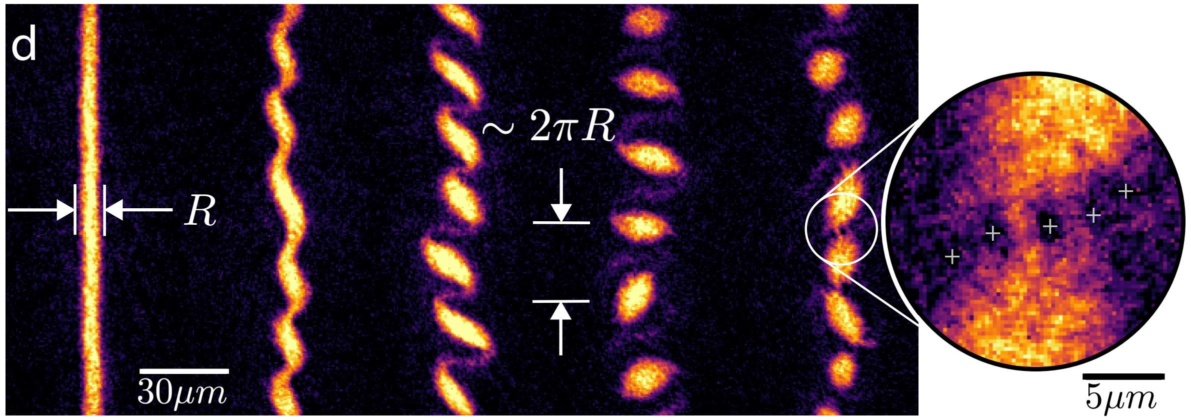


Interplay of gauge field and interactions

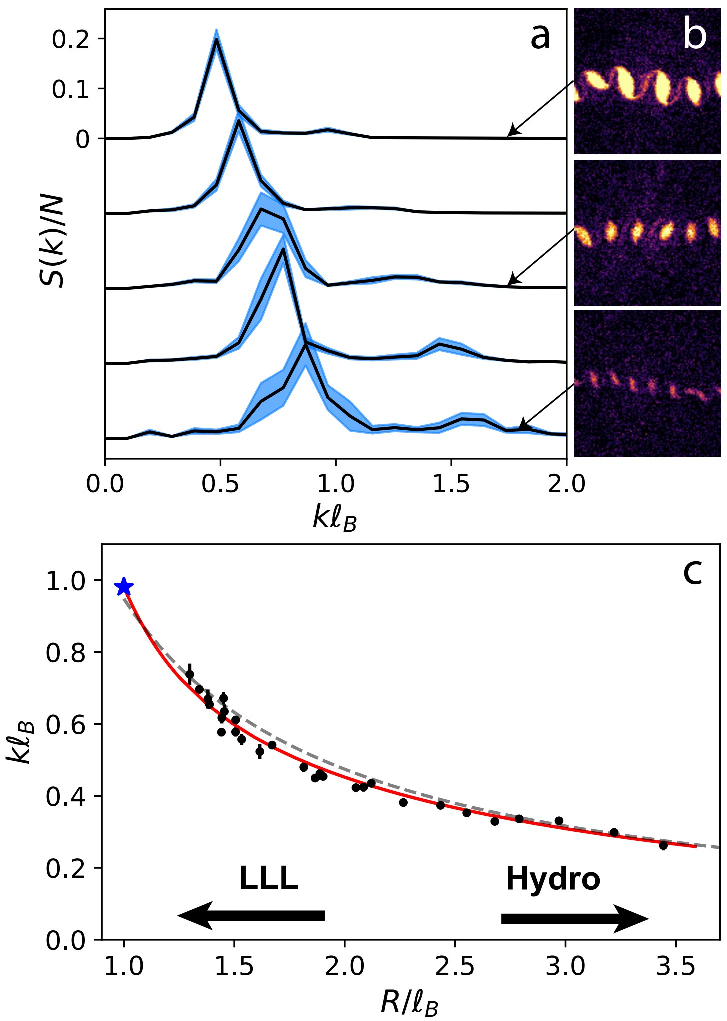


Instability of the Landau gauge wavefunction



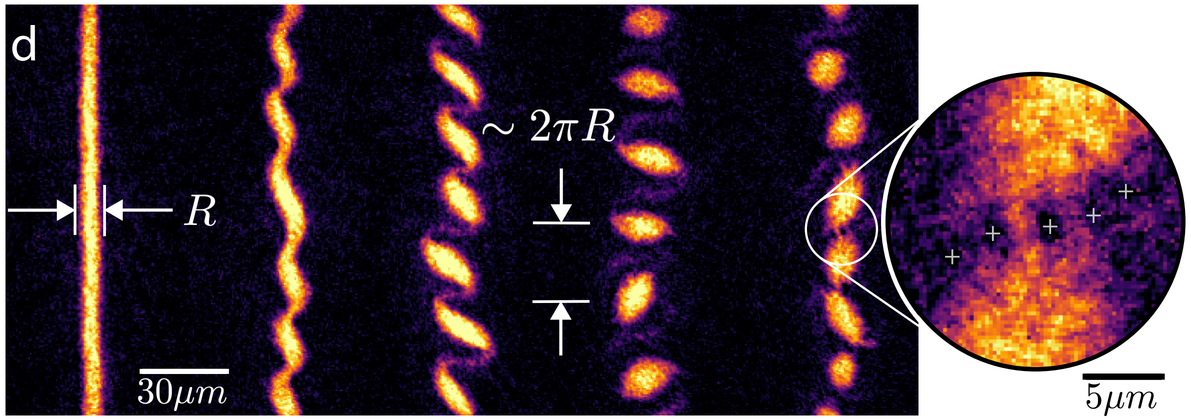
Spontaneous crystallisation of superfluid

Occurs in the absence of *any* single-particle dynamics



Crystal lengthscale

Instability of the Landau gauge wavefunction



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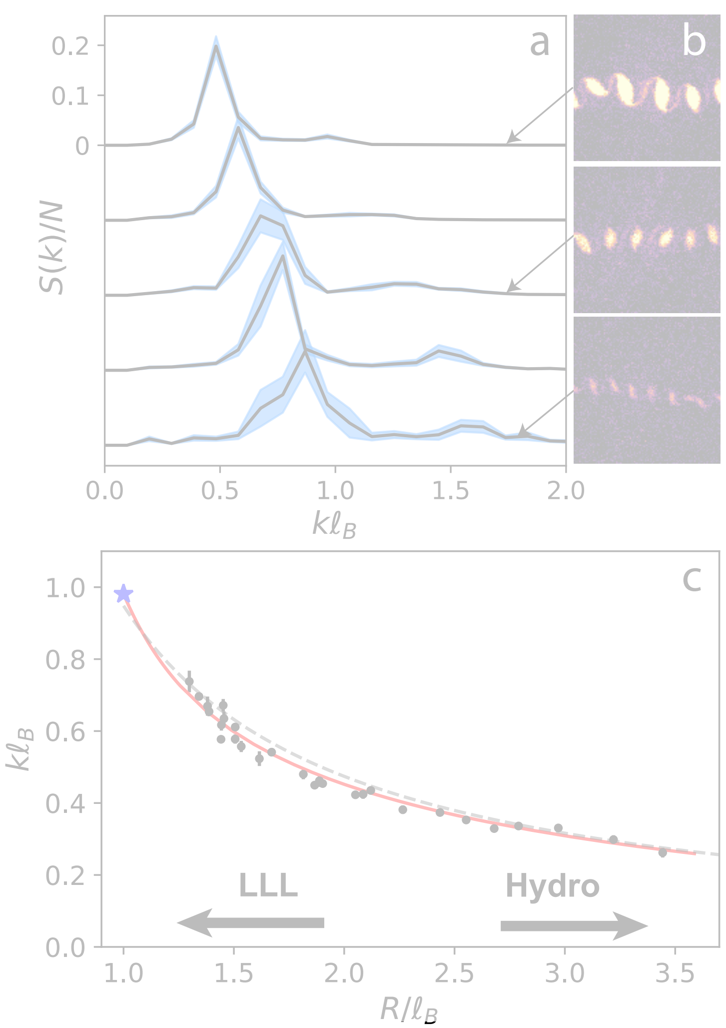
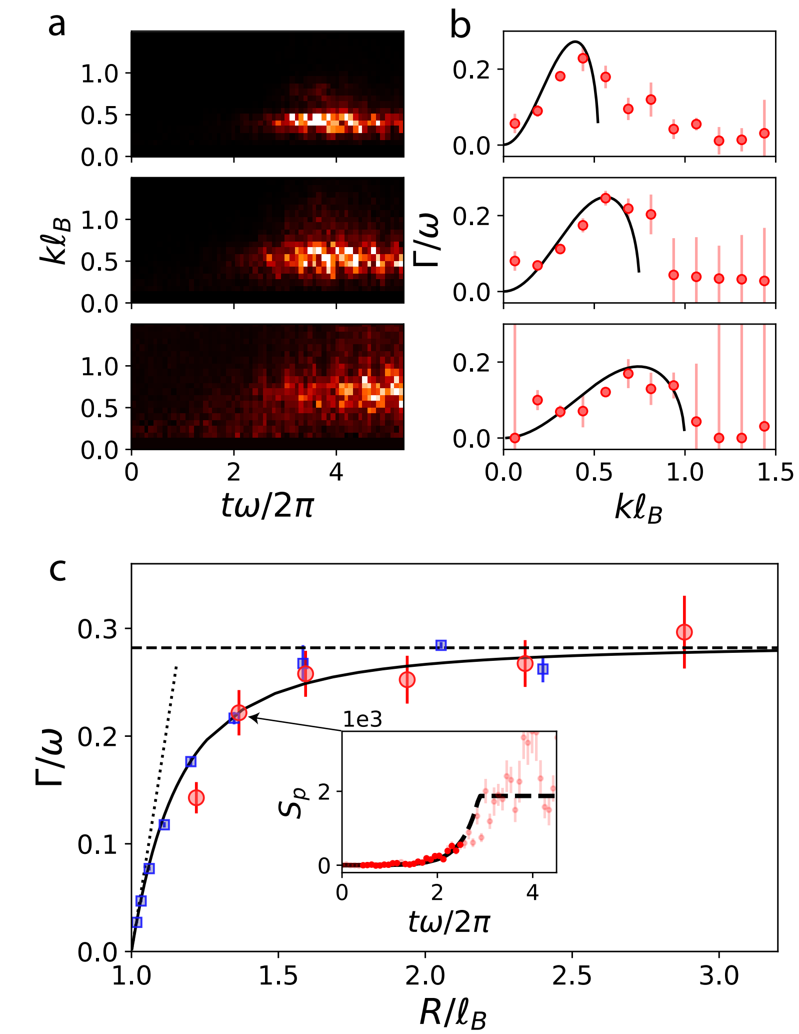
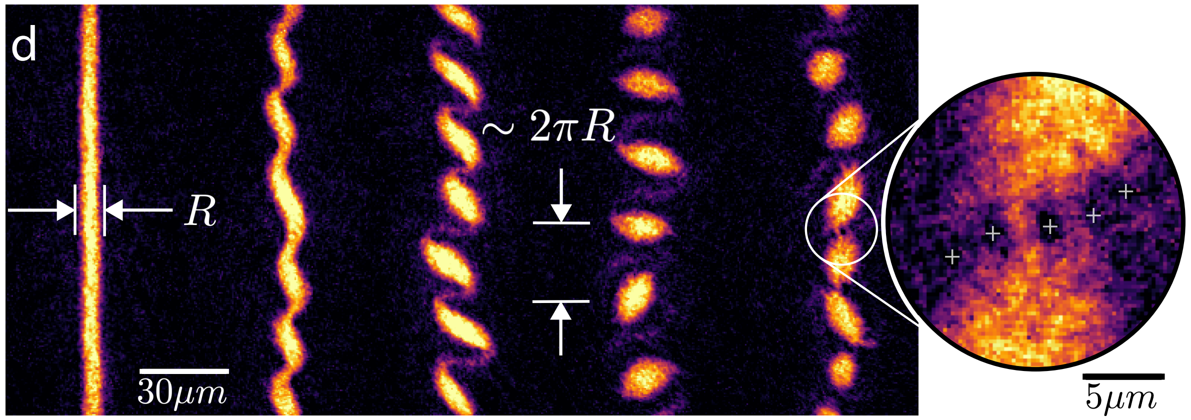


Crystal lengthscale



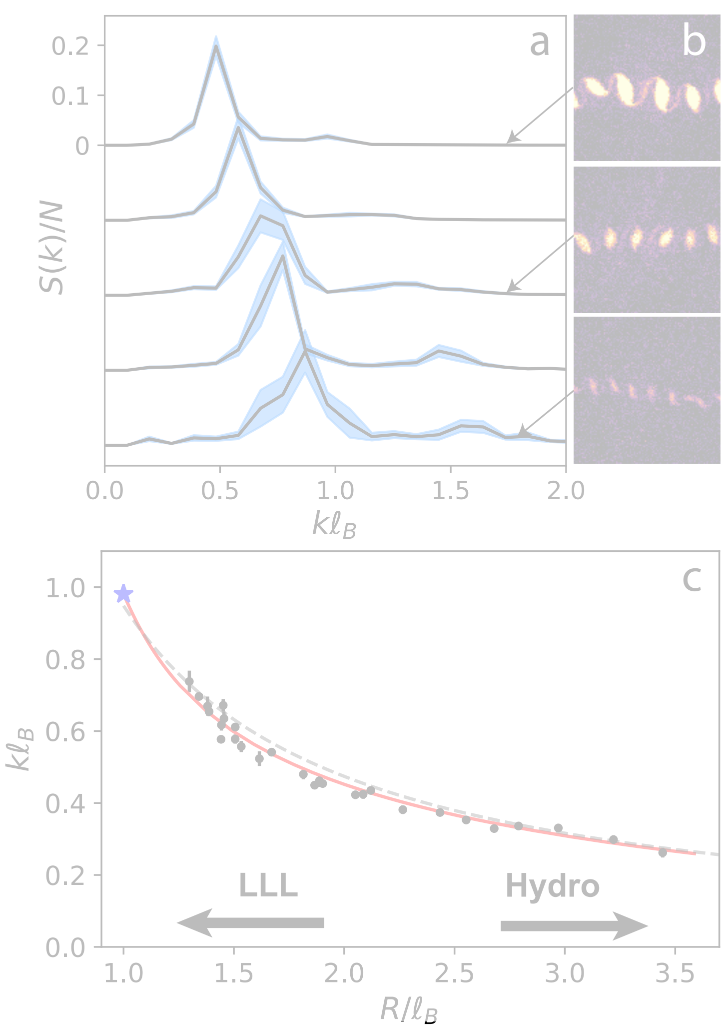
Crossover to LLL dynamics

Instability of the Landau gauge wavefunction



Spontaneous crystallisation of superfluid

Occurs in the absence of *any* single-particle dynamics



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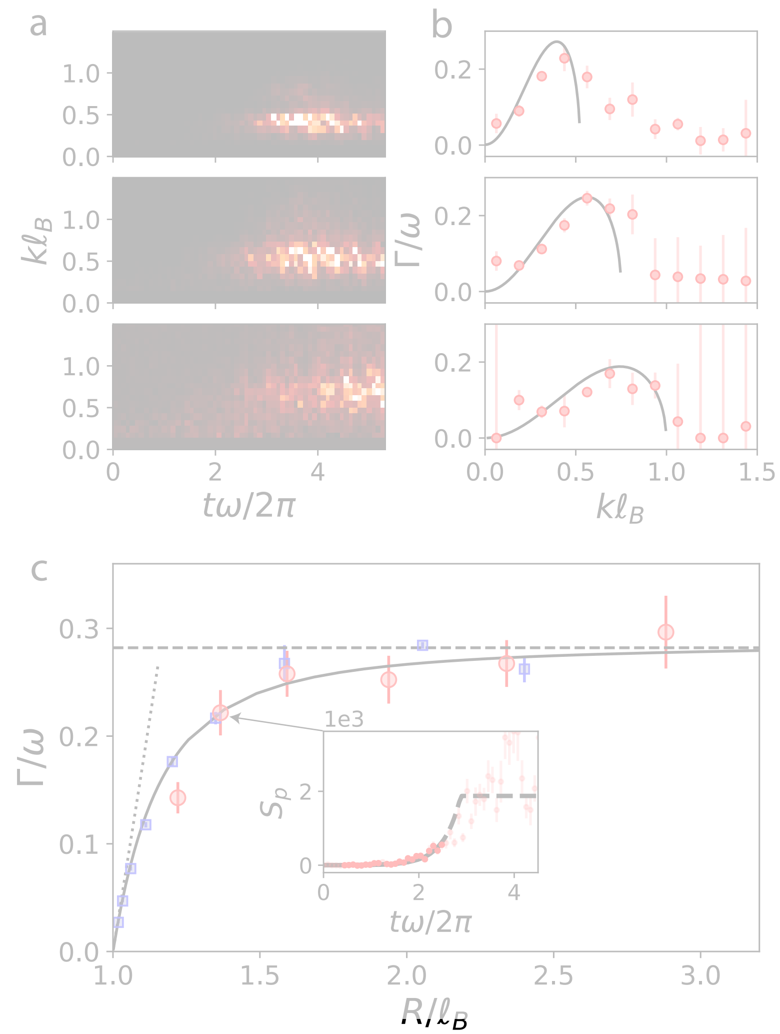
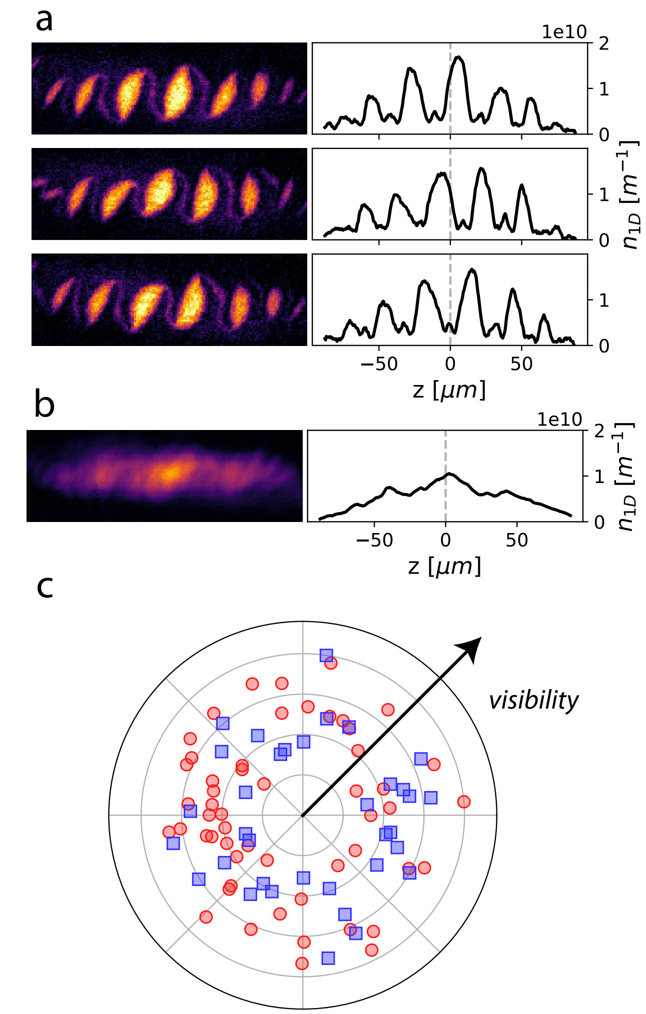


Crossover to LLL dynamics



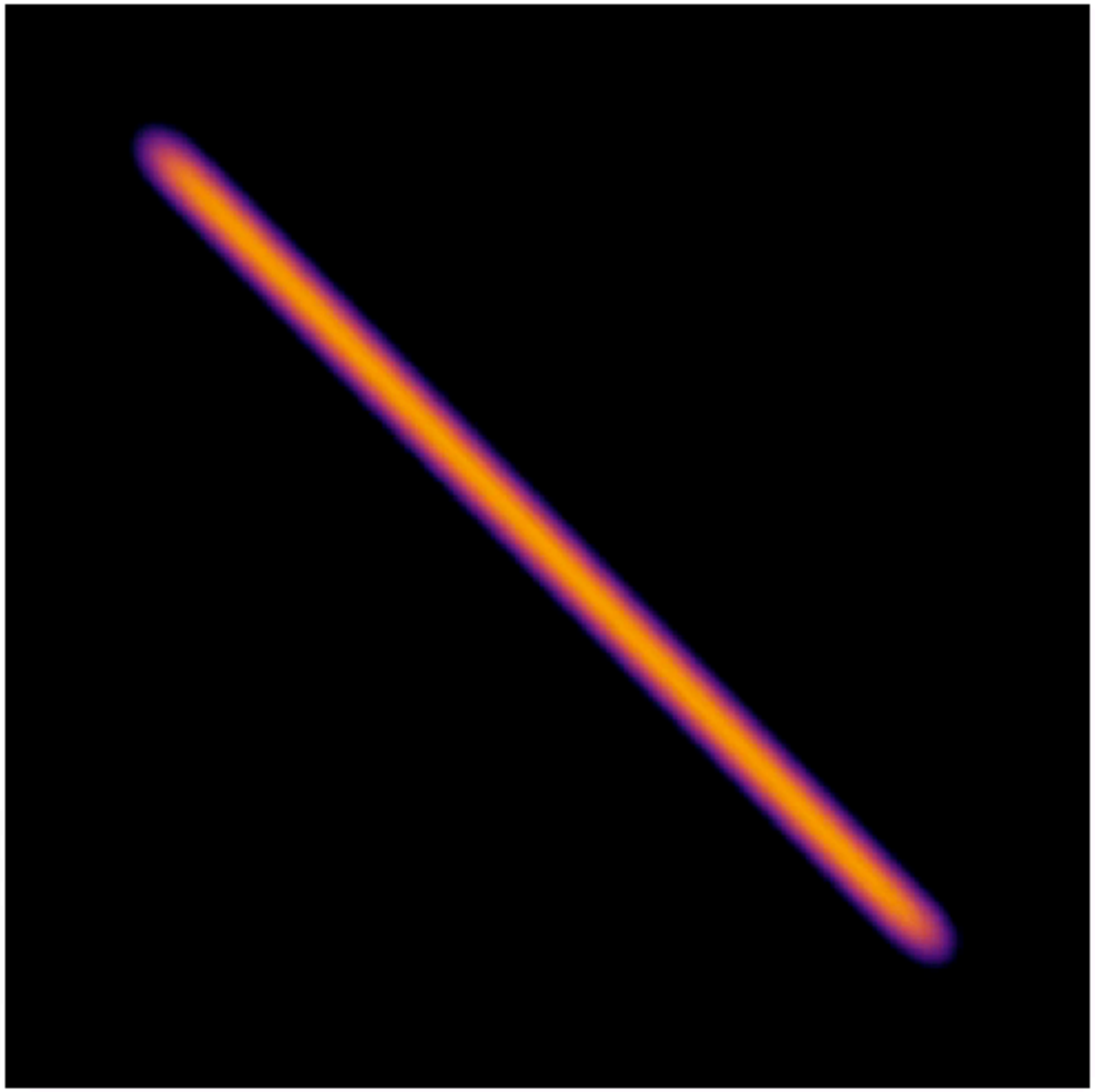
Spontaneous symmetry breaking

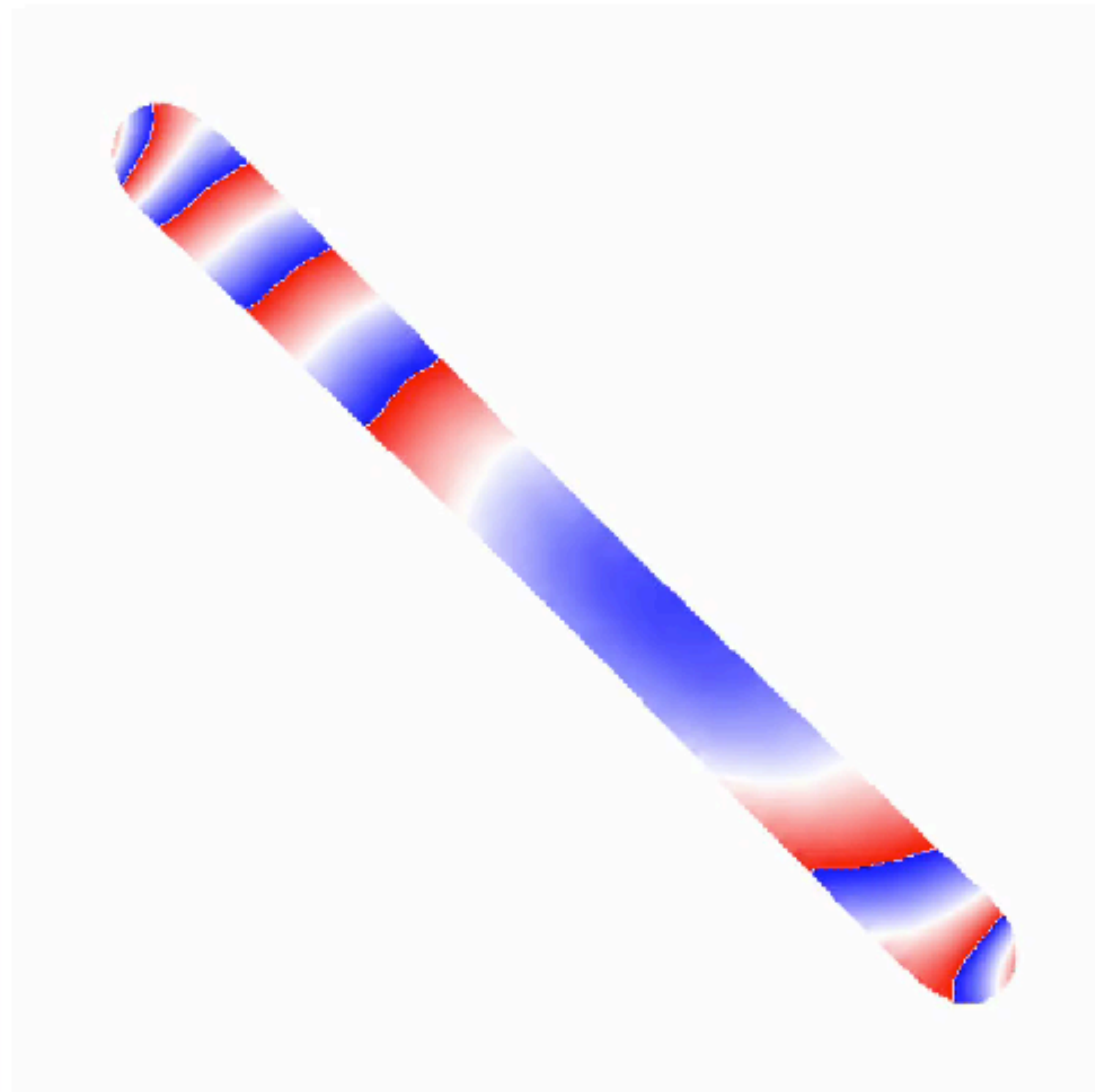
Richard Fletcher

Dynamics and transport in strongly-interacting quantum fluids

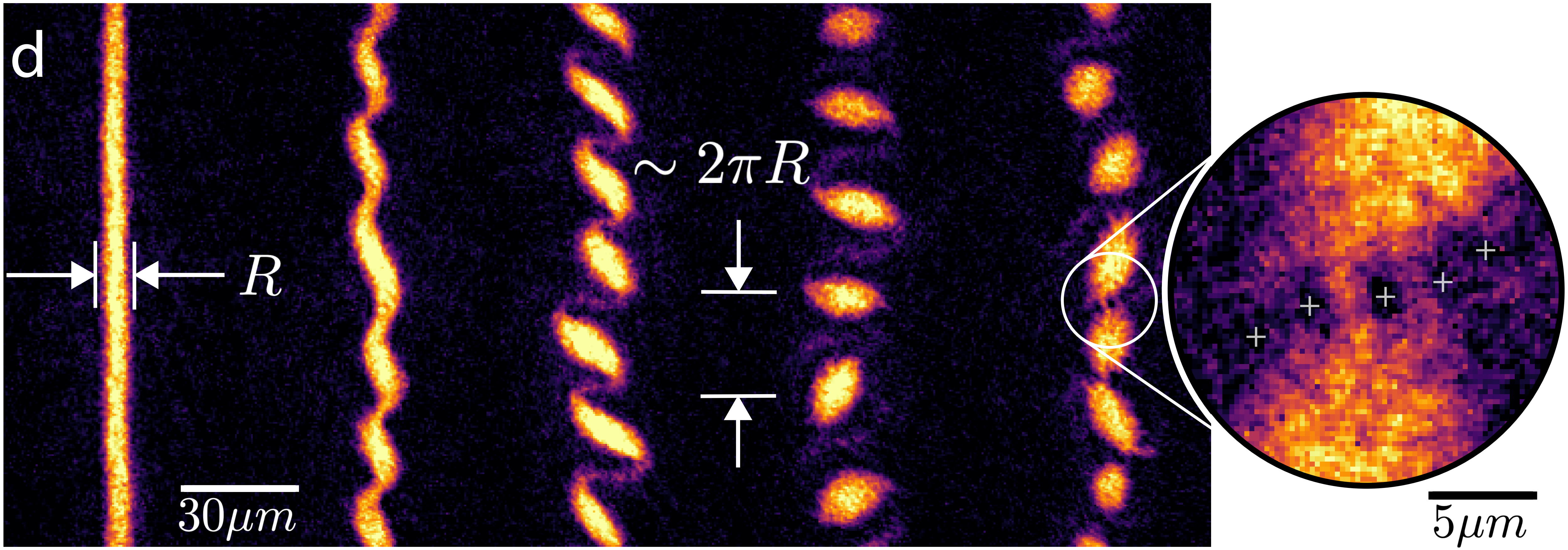
EFT methods from bound states to binary systems

Alternate ‘vortex dynamics’ view





Alternate 'vortex dynamics' view



The team

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Lev Kendrick
Thatcher Chamberlin

Martin Zwierlein

+ CUA community

The team

Parth Patel

Biswaroop Mukherjee

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Struck

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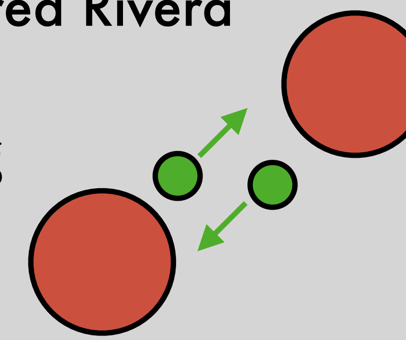
From July 2020

Jasmine Kalia

Jared Rivera

Exotic fermionic pairing
Single vortex control
Impurity physics



Martin Zwierlein

+ CUA community

Thank you!