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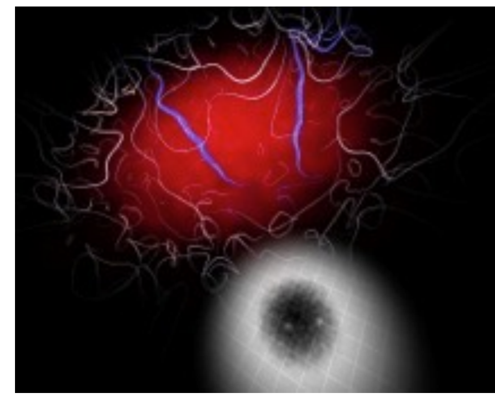
Nonequilibrium Transport in a Superfluid Josephson Junction Chain

Matthew Davis[1,2]

Matt Reeves[2], Sam Begg[2]



Matt Davis BEC

ARC Centres' of Excellence in:
[1]Engineered Quantum Systems /
[2]Future Low-Energy Electronics Technologies,
School of Mathematics and Physics,
University of Queensland, Australia.

FLEET
ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

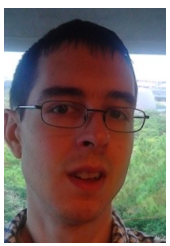
EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

UQ nonequilibrium superfluid theory

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA





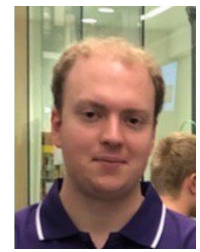



Staff
- Matthew Davis
- Matt Reeves
- Andrew Groszek
- Lewis Williamson
- Angela White
- Matthew Edmonds
- Emma Laird
- Sam Begg (now Korea)

Students
- John Deng PhD
- Tim Edmonds Hons, PhD
- Abitha Muniraj Saraswathy, PhD
- Charlotte Quirk, Hons -> PhD

Graduated
- Jemima Goodhew, Hons
- Oliver Sandberg Hons, MPhil
- Oliver Stockdale Hons, Mphil
- Tim Harris Hons, MPhil








FINESS 2024

FInite temperature Non-Equilibrium Superfluid Systems

Gold Coast, Queensland, Australia
2 – 6 September 2024.

Organisers:
Matthew Davis
Meera Parish
Tyler Neely
Elena Ostrovskaya
Kris Helmerson
Thomas Volz

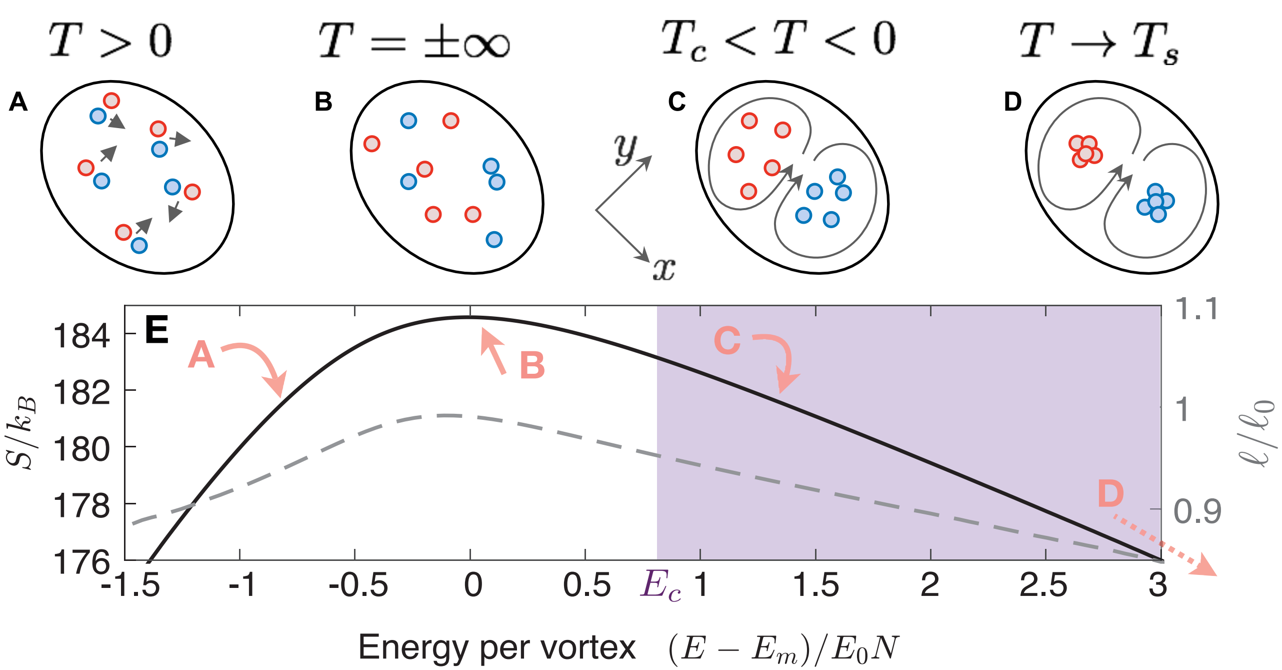
Save the date!

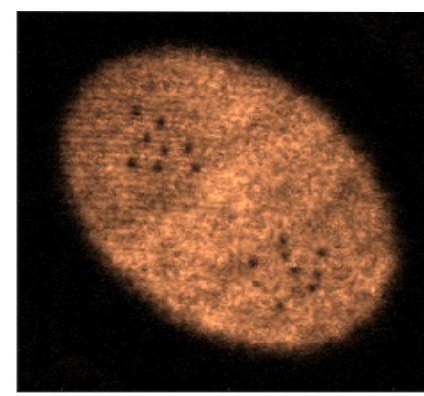
Aside: Vortex matter in 2D

Work with **Tyler Neely** and UQ BEC experimental team : **Talk at Sant Feliu**

Dynamics and statistical mechanics of the neutral 2D vortex gas

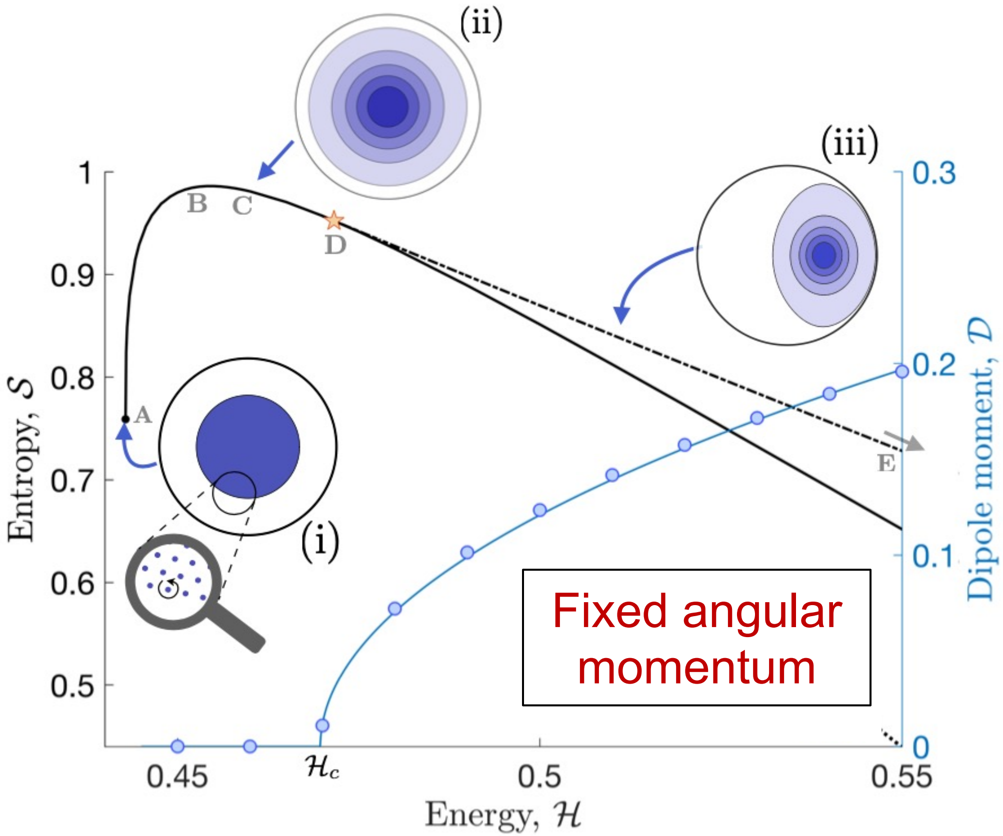
$$H = -\frac{\rho_0}{4\pi}\sum_{j\neq i}\Gamma_i\Gamma_j \ln|\mathbf{r}_i - \mathbf{r}_j|$$



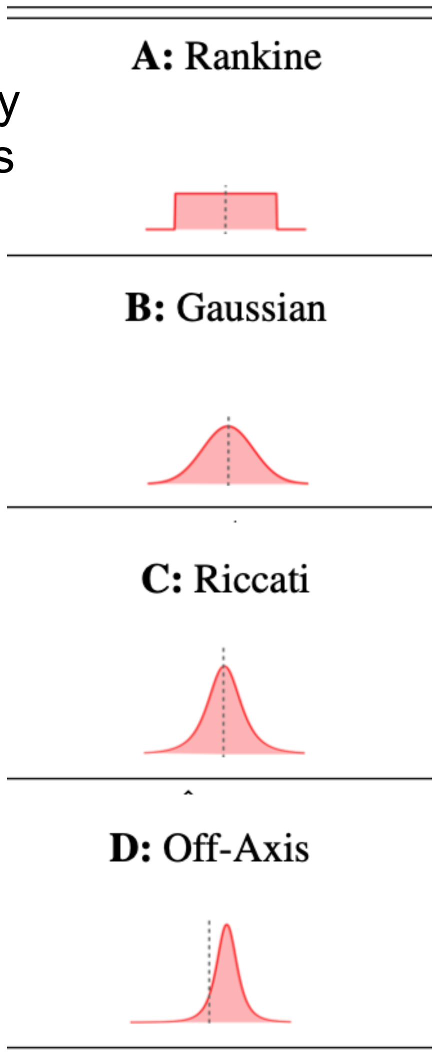


G. Gauthier, M. T. Reeves, *et al.*, Science **364**, 1264 (2019).

Chiral vortex matter



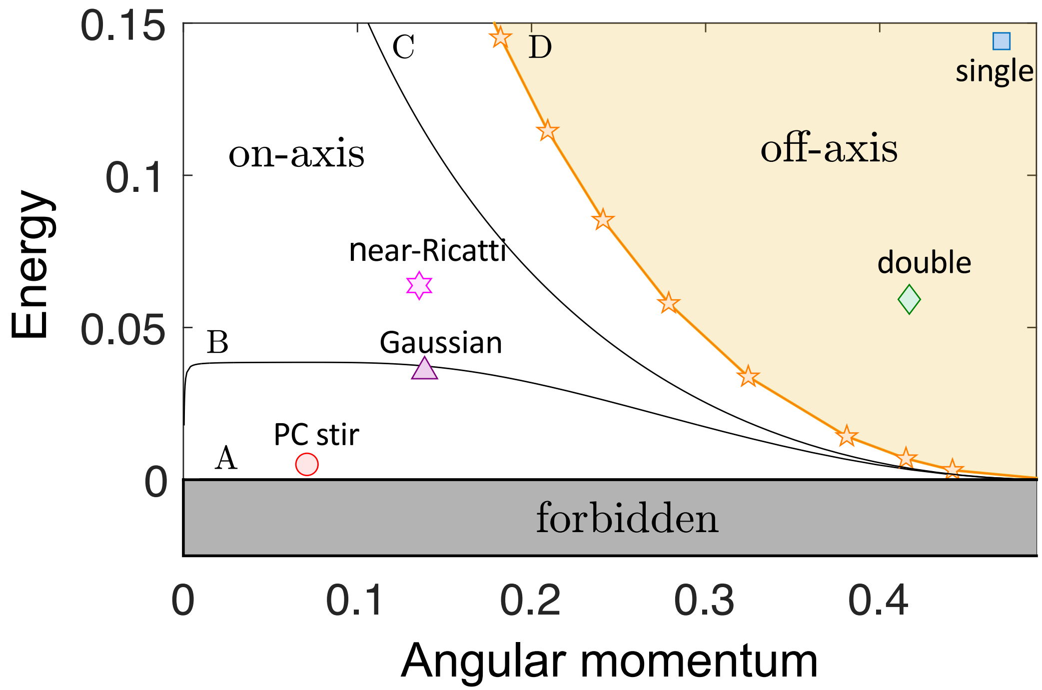
Density profiles



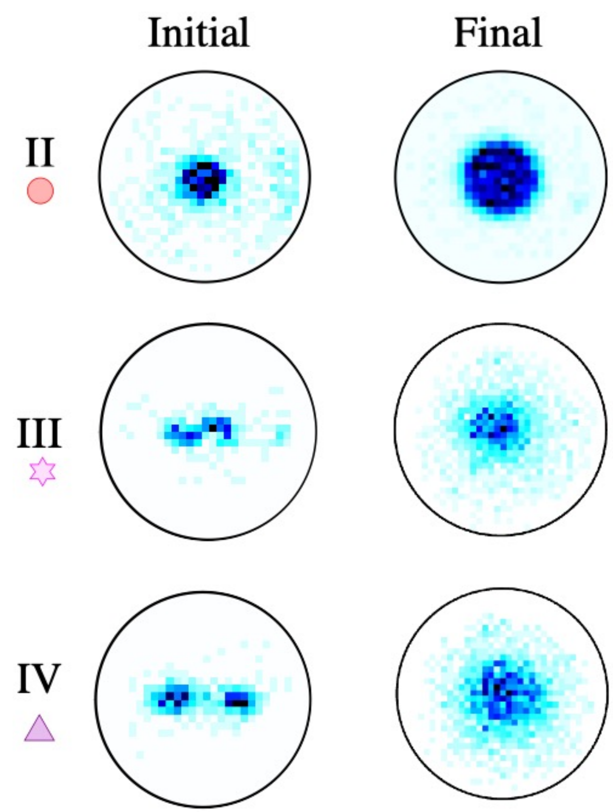
Turbulent Relaxation to Equilibrium in a Two-Dimensional Quantum Vortex Gas, M. T. Reeves, K. Goddard-Lee, G. Gauthier, O. R. Stockdale, H. Salman, T. Edmonds, X. Yu, A. S. Bradley, M. Baker, H. Rubinsztein-Dunlop, M. J. Davis, T. W. Neely, Phys. Rev. X **12,** 011031 (2022).

Phase diagram of chiral vortex matter

Create vortices by stirring, allow to relax:



Experimental vortex histograms



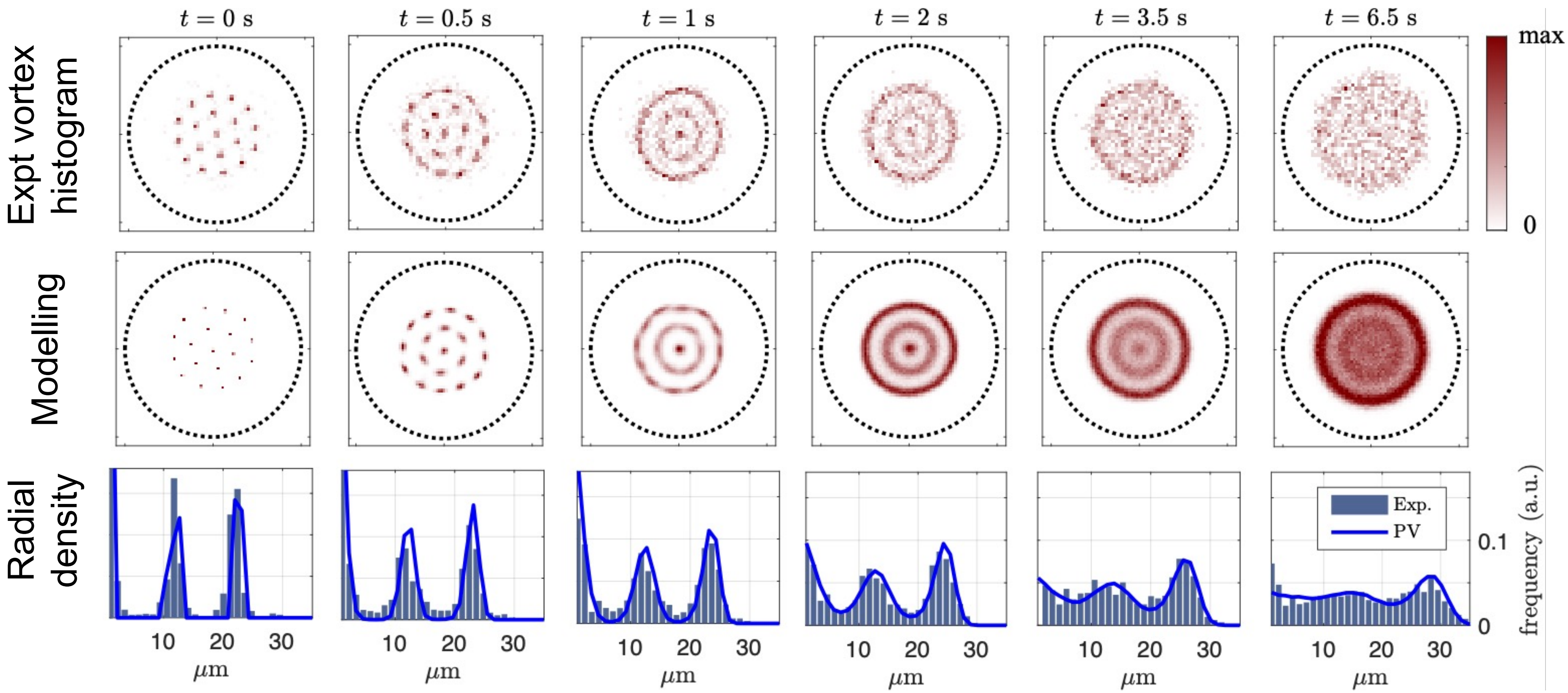
Turbulent Relaxation to Equilibrium in a Two-Dimensional Quantum Vortex Gas, M. T. Reeves, K. Goddard-Lee, G. Gauthier, O. R. Stockdale, H. Salman, T. Edmonds, X. Yu, A. S. Bradley, M. Baker, H. Rubinsztein-Dunlop, M. J. Davis, T. W. Neely, Phys. Rev. X **12,** 011031 (2022).

1. Melting of a vortex lattice

T. Neely talk
Sant Feliu

The University of Queensland
Australia

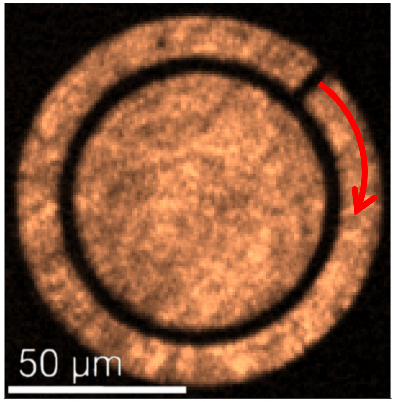
Create perfect lattice in homogeneous BEC, allow to heat up:

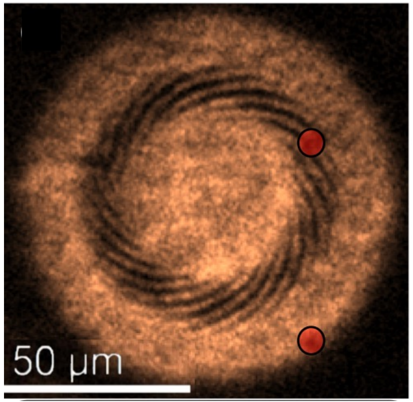


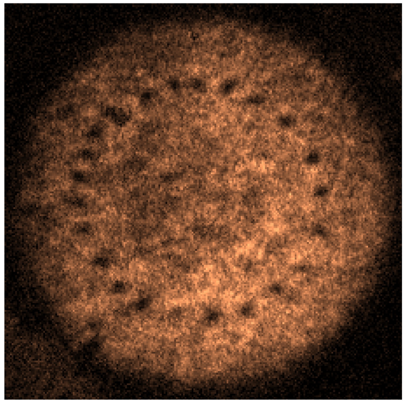
2. Kelvin-Helmholtz-like instability

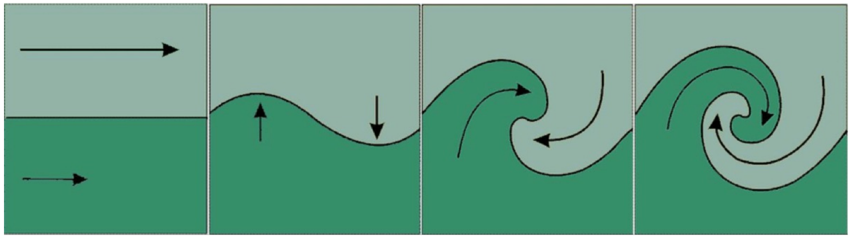
T. Neely poster
Also G. Roati

Stir in a persistent current	Expansion -> spiral interference	Merging condensates -> Shear layer of vortices









Shear flow

Kelvin Helmholtz in a cloud layer

Back to the advertised schedule:

Nonequilibrium Transport in a Superfluid Josephson Junction Chain

Matt Reeves

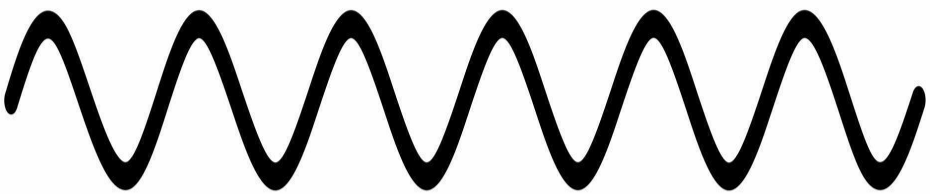
Sam Begg

S. E. Begg, M. T. Reeves and M. J. Davis, arXiv2307.14590

Cigar-shaped BEC in a 1D optical lattice

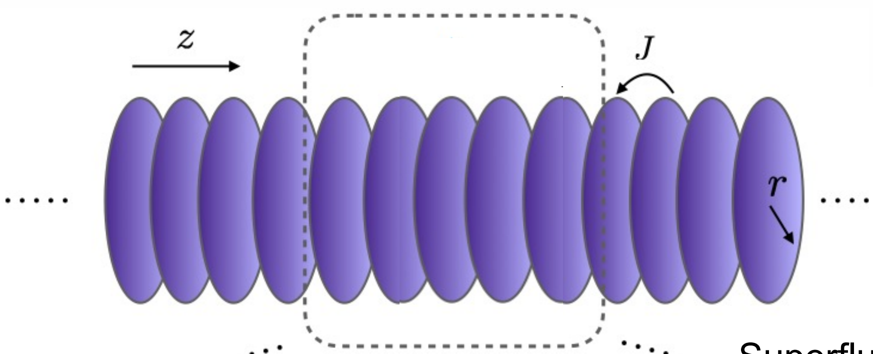
Cigar-shaped BEC

+



1D optical lattice

=



Superfluid Josephson junction chain

Tunnel coupled BECs

Each pancake has several hundred atoms

Lots and lots of experiments…

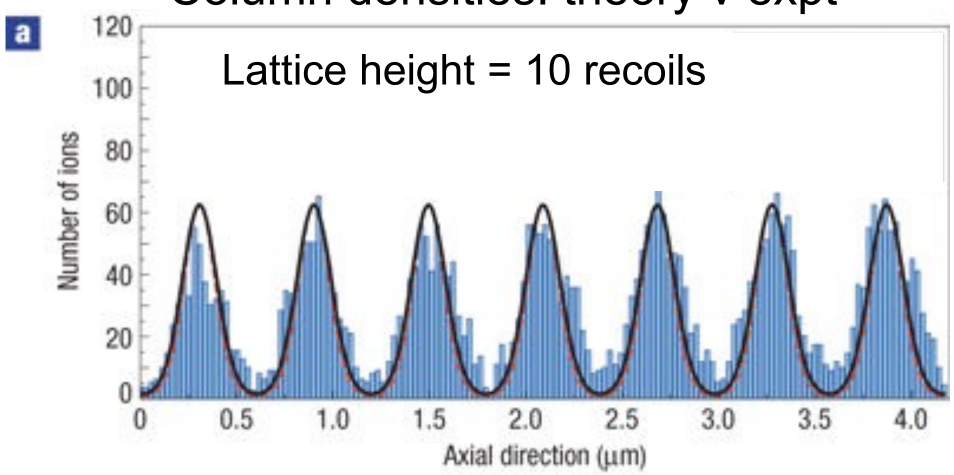
Ott group

T. Gericke *et al.*, Nature Physics **4**, 949 (2008)

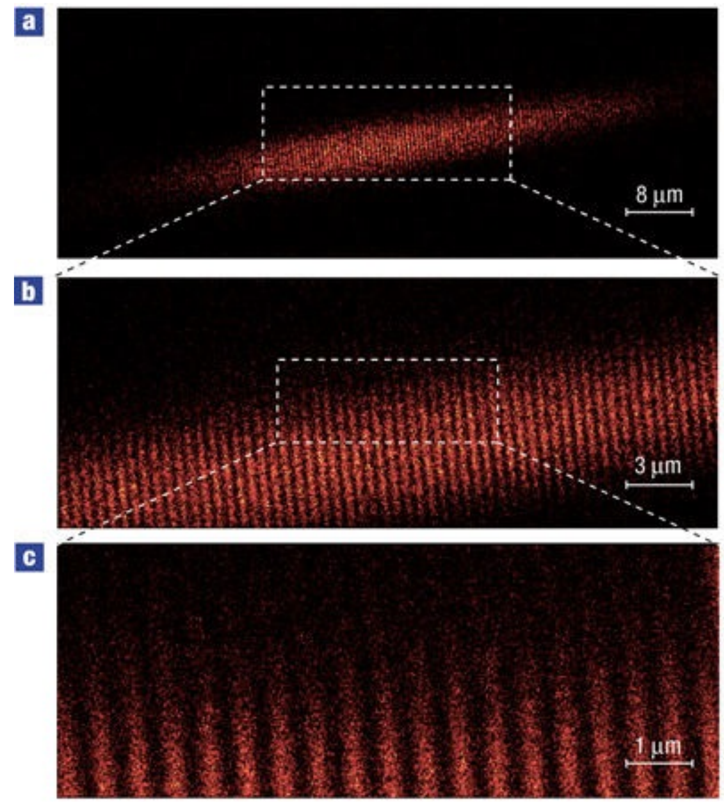
Novel feature: **focused electron beam**

Allows for
- high resolution imaging
- controllable, localized dissipation

Column densities: theory v expt

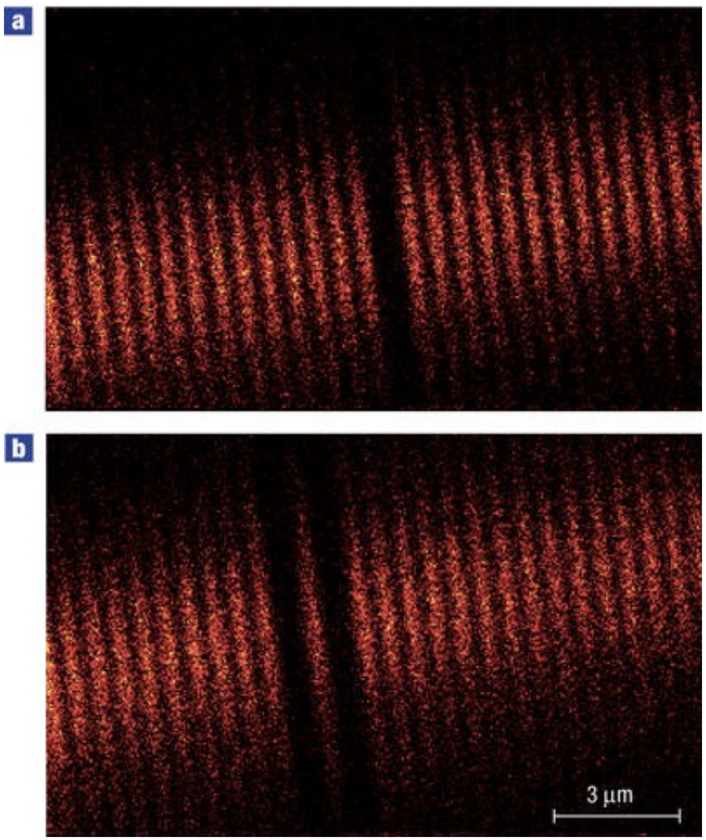


Stack of BECs in 1D optical lattice

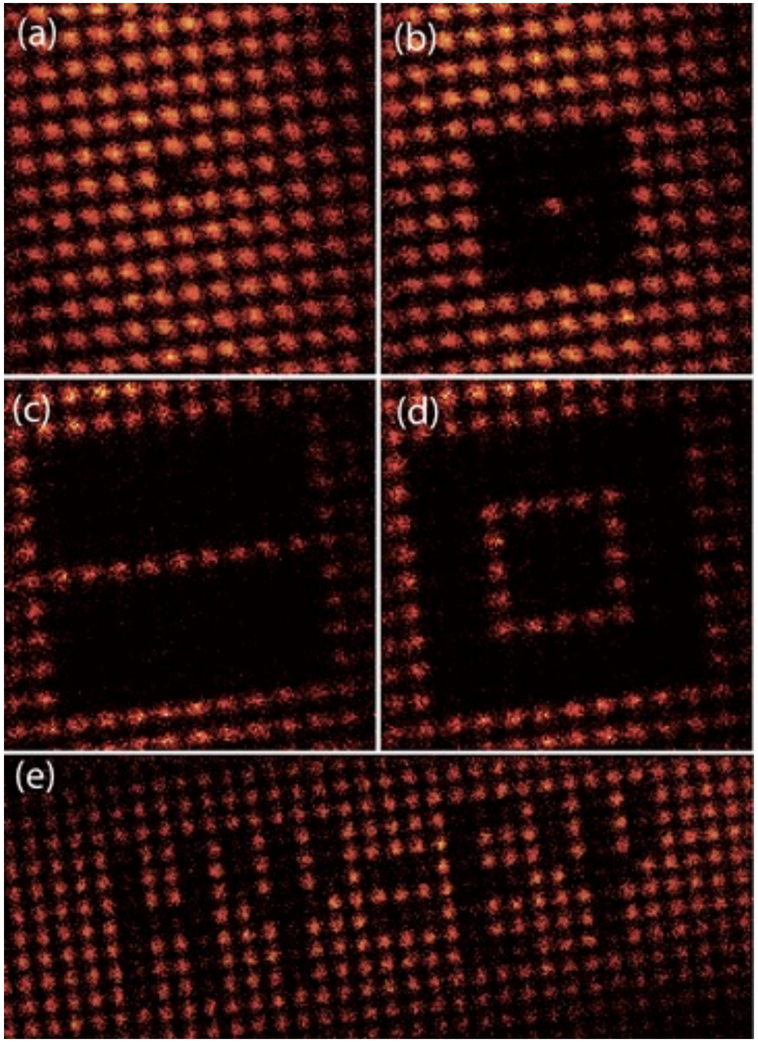


Can also generate nonequilibrium states

1D optical lattice:
T. Gericke *et al.*,
Nature Physics **4**, 949
(2008)



2D optical lattice:
P. Würtz *et al.*, Phys. Rev. Lett. **103**, 080404 (2009)

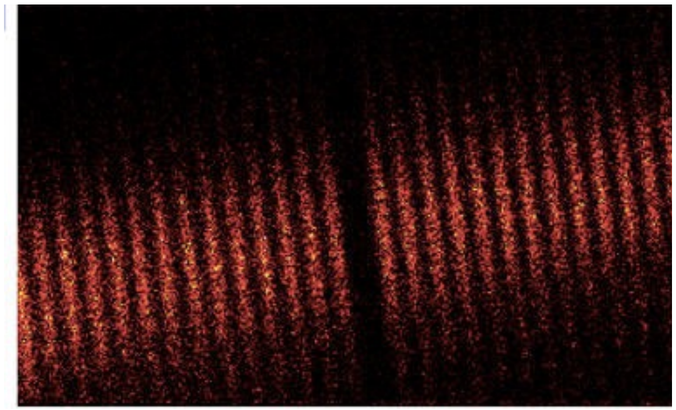


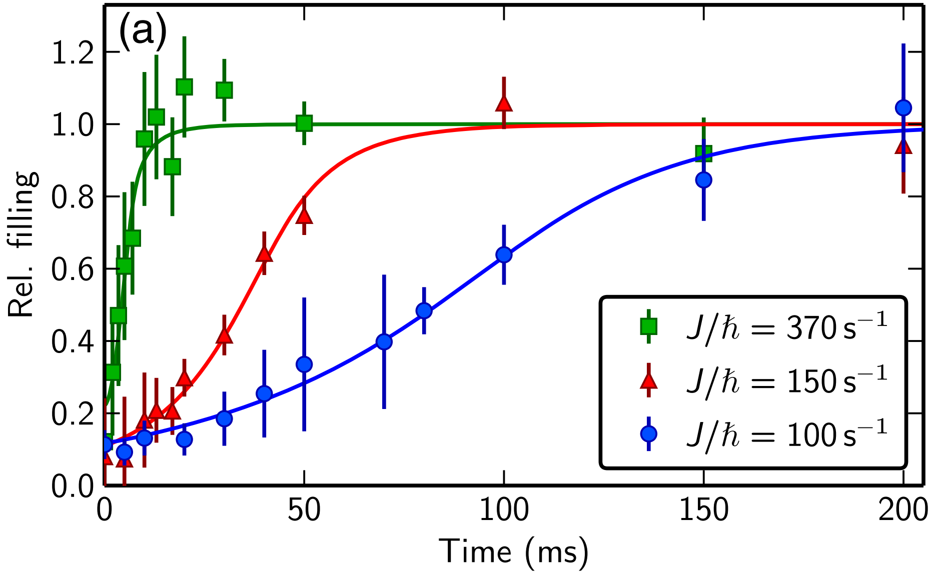
How does a single site refill?

Remove atoms from one site.

R. Labouvie *et al.* Phys. Rev. Lett. **115**, 050601 (2015).

Observe refilling dynamics as a function of tunnelling *J*.





Solid lines: 1D Bose-Hubbard model with decoherence

$\nu_{\mathrm{radial}} = 165\,\mathrm{Hz}$

$\nu_z = 40 - 100\,\mathrm{kHz}$

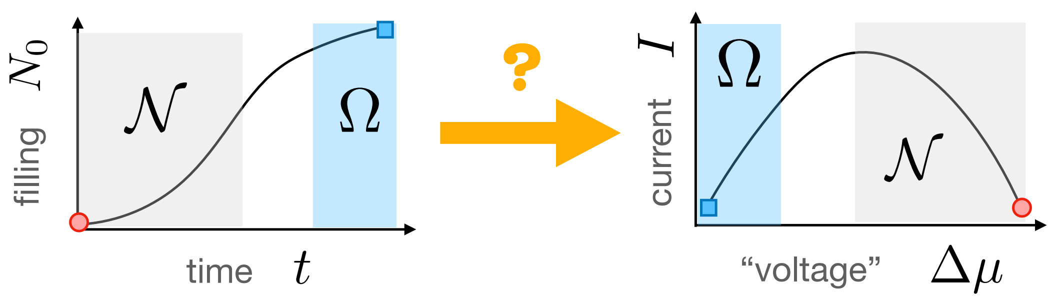
$J/\hbar = 30 - 370\,\mathrm{s}^{-1}$

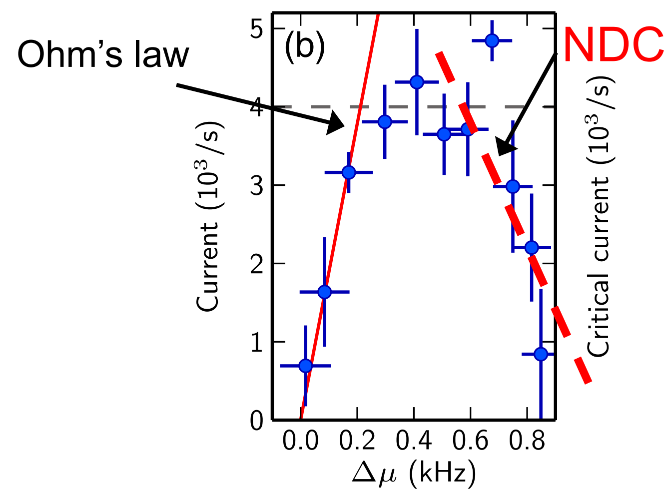
Interpretation: Negative differential conductance

Experiment found characteristic S-shaped refilling curves

Calculate current as a function of difference in chemical potential.

Conductance: $G_{\text{static}} = \dfrac{I}{V} \to \dfrac{I}{\Delta\mu}$ $\qquad G_{\text{diff}} = \dfrac{dI}{dV} \to \dfrac{dI}{d(\Delta\mu)}$





Useful for atomtronics applications?

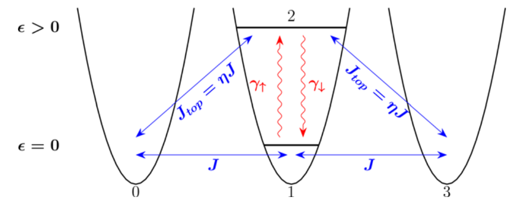
– atomtronic diode?

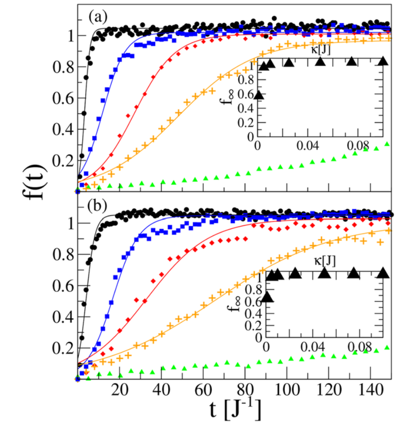
R. Labouvie *et al.* Phys. Rev. Lett. **115**, 050601 (2015).

Previous modelling

Few mode Bose-Hubbard

- System would be self-trapped under unitary dynamics
- Decoherence – attributed to collisions – leads to filling.

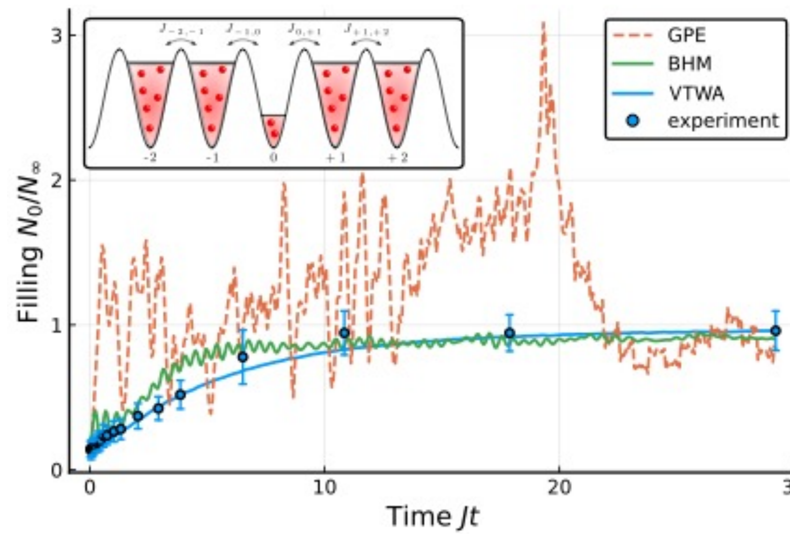




D. Fischer & S. Wimberger,
Annalen Der Physik, **74**, 1600327 (2017).

M. K. Olsen and J. F. Corney,
Phys. Rev. A **94**, 033605 (2016).

Variational truncated Wigner

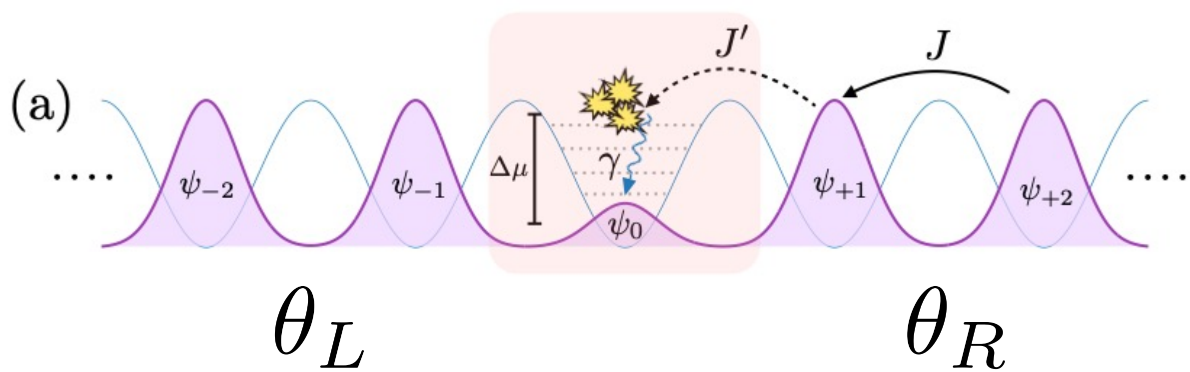


C. D. Mink, A. Pelster, J. Benary, H. Ott, M. Fleischhauer, *SciPost Phys.* **12**, 051 (2022).

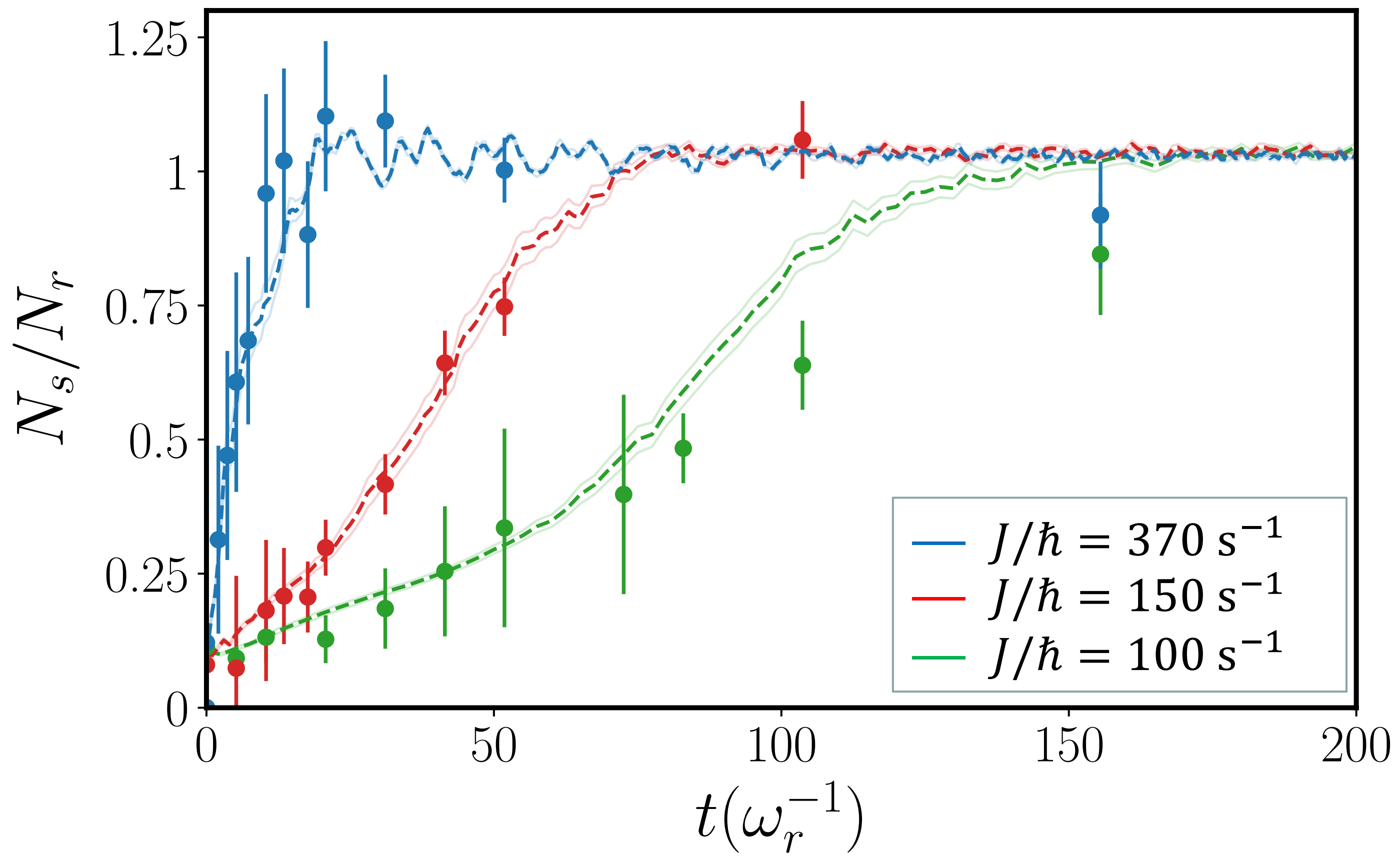
Multimode c-field model

S. E. Begg, M. T. Reeves and M. J. Davis, arXiv2307.14590

- Unitary dynamics, **no decoherence**.
  - truncated Wigner approximation: essentially GPE.
- Stack of independent 21 pancake BECs
  - Each **side** starts with **random phase** + **initial quantum noise.**
- Delete population of middle pancake.
- Turn on tunnelling



Truncated Wigner results

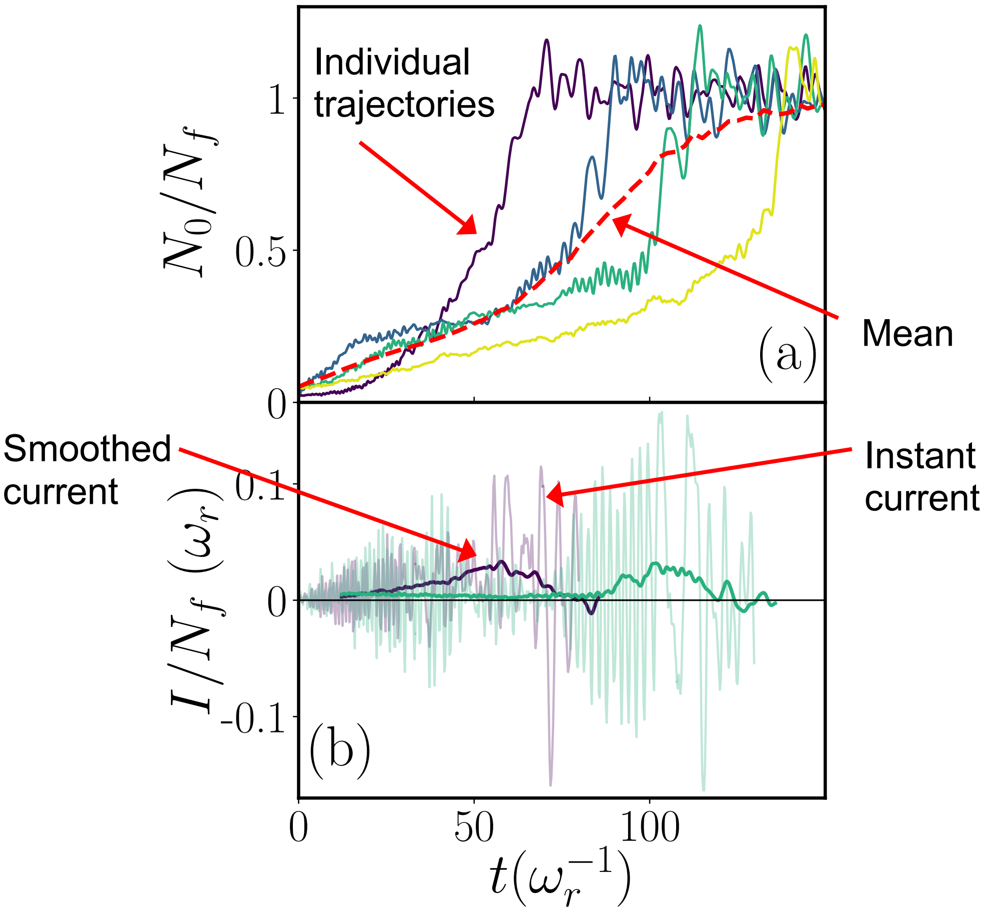


Looks good. So what?

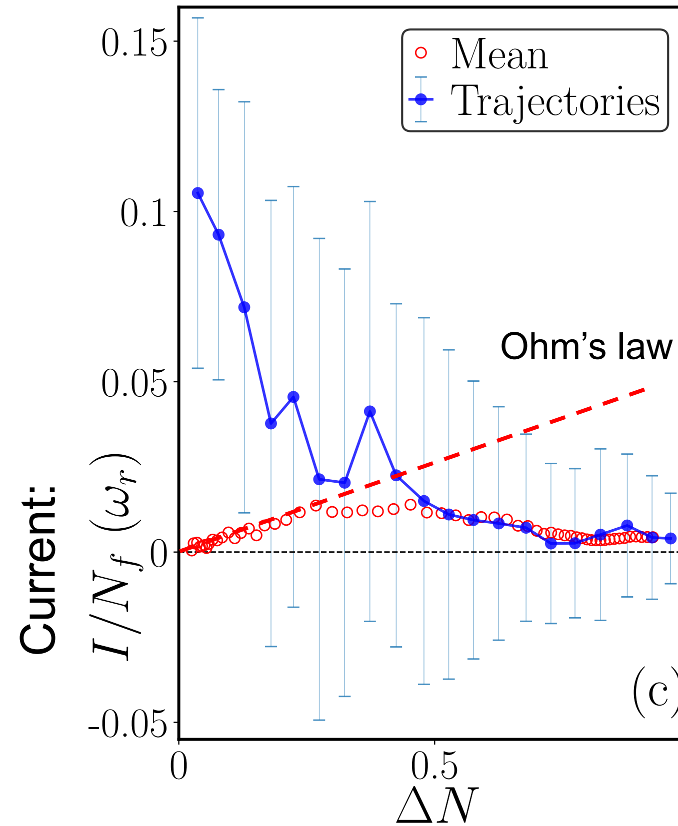
S. E. Begg, M. T. Reeves and M. J. Davis, arXiv2307.14590

Individual trajectories

S-shape is only apparent in averaging



Negative differential conductivity everywhere!?



~ Potential difference

Is this negative differential conductivity?

We think not : **system is far from equilibrium.**

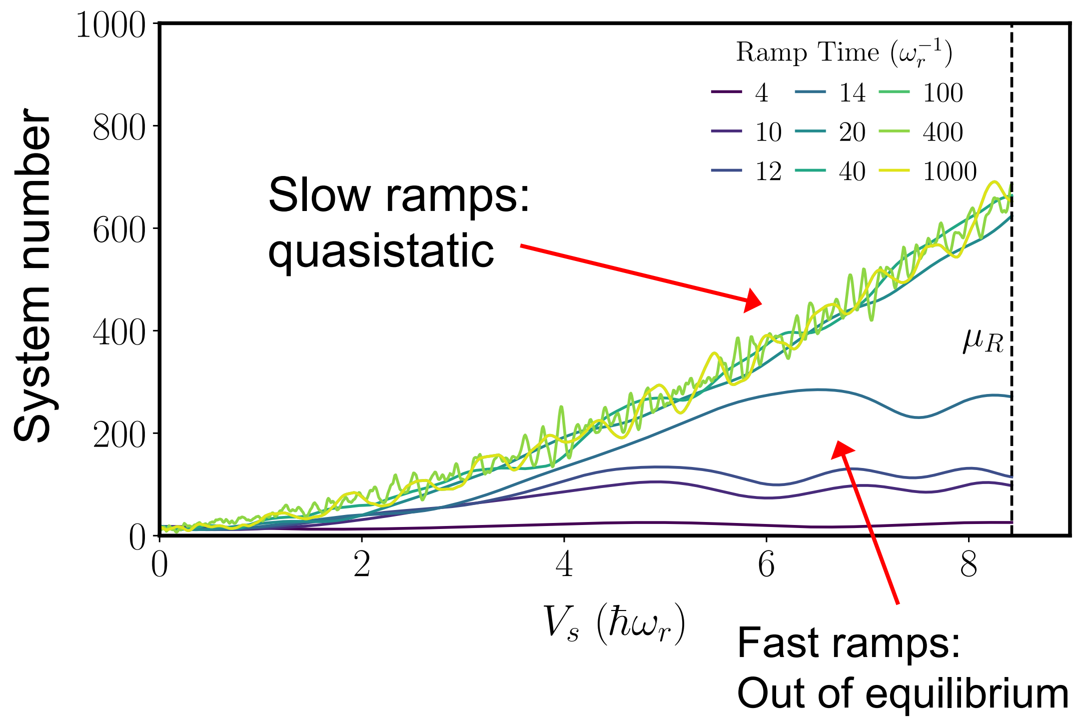
You can't define a chemical potential difference $(\mu_R - \mu_s)$

But – you can if J is small enough, and chemical potential difference is ramped slowly enough.

Start with system site shifted in energy so that equilibrium initial occupation is empty.

Ramp shift off at a finite rate.

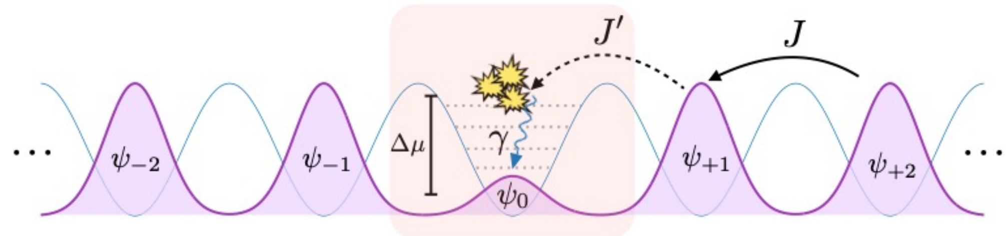
Expt: ramp rate ~ $2\omega_r^{-1}$



Also: filling is phase dependent

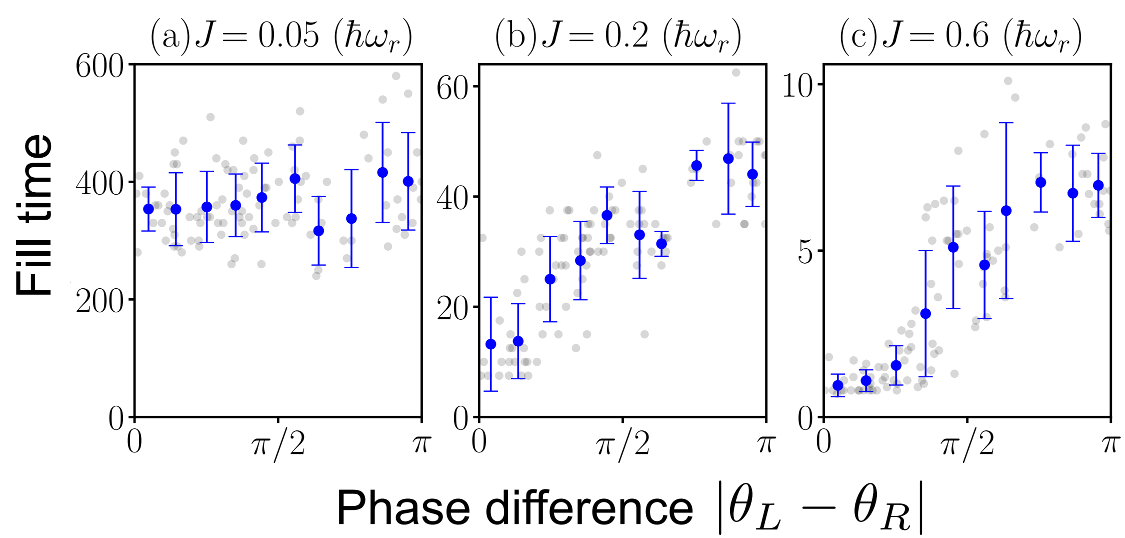
The University of Queensland Australia

Filling time is dependent on relative phase of left and right chains of pancake BECs



Initially left and right chains have random phase.

Small J → Large J



For large J: Fill time of system is much smaller when nearest neighbours are initially in phase.

Extension: continuous dissipation

Bistability and nonequilibrium condensation in a driven-dissipative Josephson array: A c-field model

Matt Reeves

M. T. Reeves and M. J. Davis, SciPost Phys. **15**, 068 (2023).

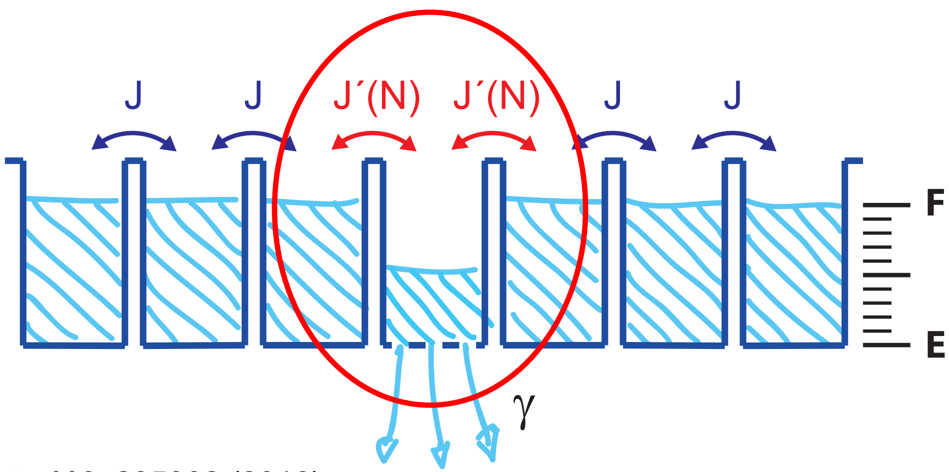
Driven-dissipative superfluid

Combine 1D optical lattice with continuous dissipation.

Control **initial state** of single site – **full** or **empty**.

Driving: rest of lattice behaves as a **reservoir.**

Dissipation: controlled loss rate γ from electron beam.



R. Labouvie *et al.*, Phys. Rev. Lett. **116**, 235302 (2016).

Experiment results

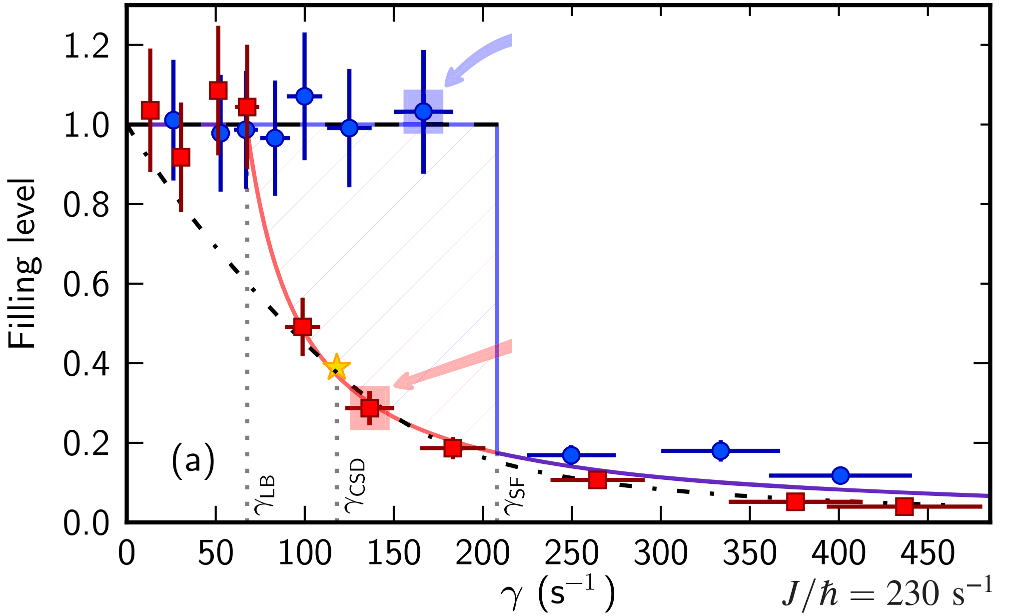
Prepare system:

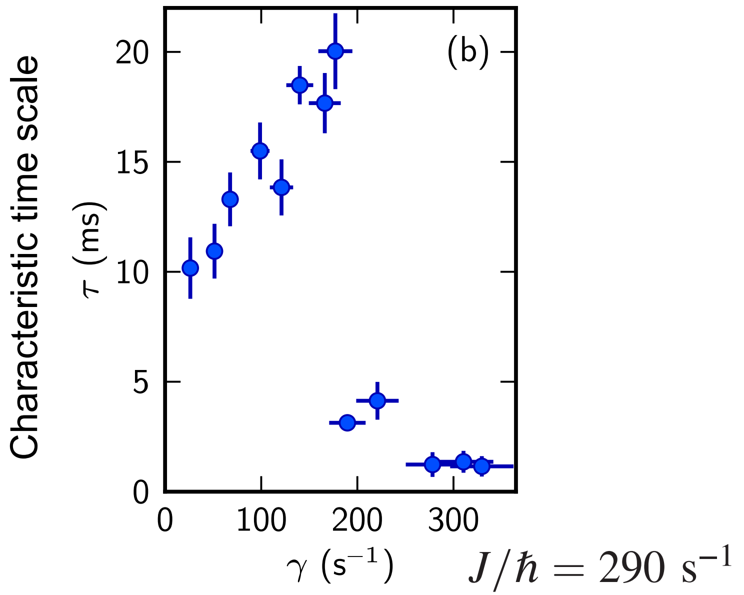
Full (blue) or **empty** (red).

Turn on dissipation, allow to reach steady state.

Steady state depends on the initial condition.

- **Time scale to reach steady state diverges?**
- **Critical slowing down?**
- **Nonequilibrium phase transition?**





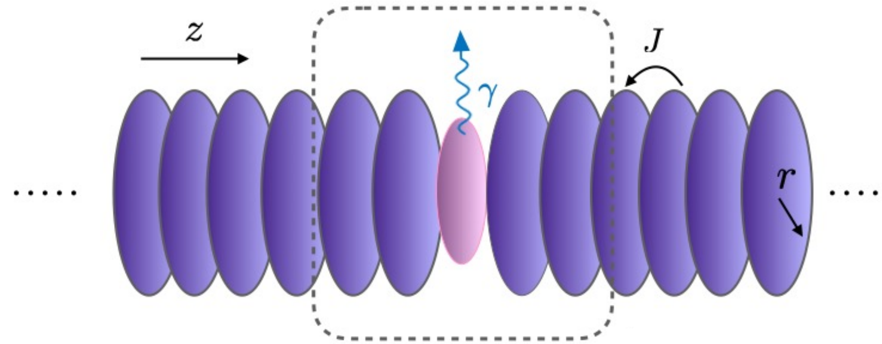
R. Labouvie *et al.*, Phys. Rev. Lett. **116**, 235302 (2016).

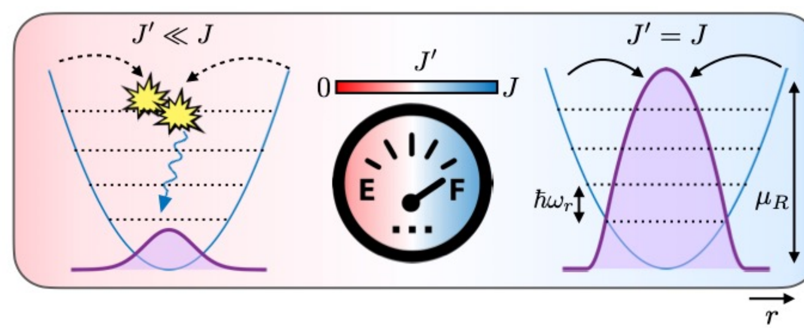
c-field model

M. T. Reeves and M. J. Davis, SciPost Phys. **15**, 068 (2023).

$$id\psi_S = -J\psi_R(\mathbf{x}) + [-\nabla^2 + V(\mathbf{x}) - i\gamma/2 - \mu_R + g|\psi_S|^2]\psi_S dt + dW$$

ψ_S	System field
J	Tunnelling from reservoir site
$\psi_R(\mathbf{x})$	Reservoir field
μ_R	Reservoir chemical potential
γ	Dissipation from electron beam
$g\|\psi_S\|^2$	Interactions





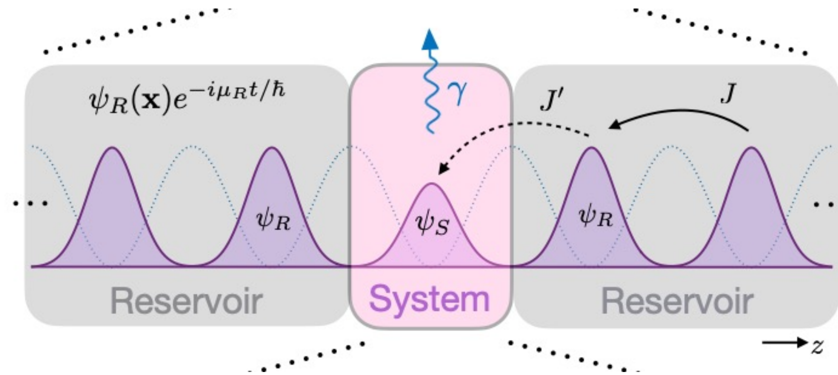
$$\langle dW(\mathbf{x},t)dW^*(\mathbf{x}',t')\rangle = \gamma\delta(\mathbf{x}-\mathbf{x}')\delta(t-t')$$

Noise correlations

Modelling of reservoir

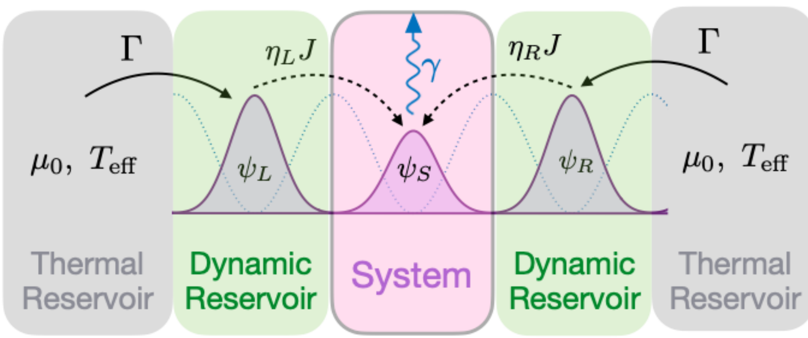
Coherent reservoir model

- Time independent GPE ground state.
- No backaction on reservoir.



Dynamical reservoir model

- Stochastic GPE dynamics for reservoir.
- Refilled by thermal reservoir.
- Effective temperature -> phase diffusion.



Steady state results

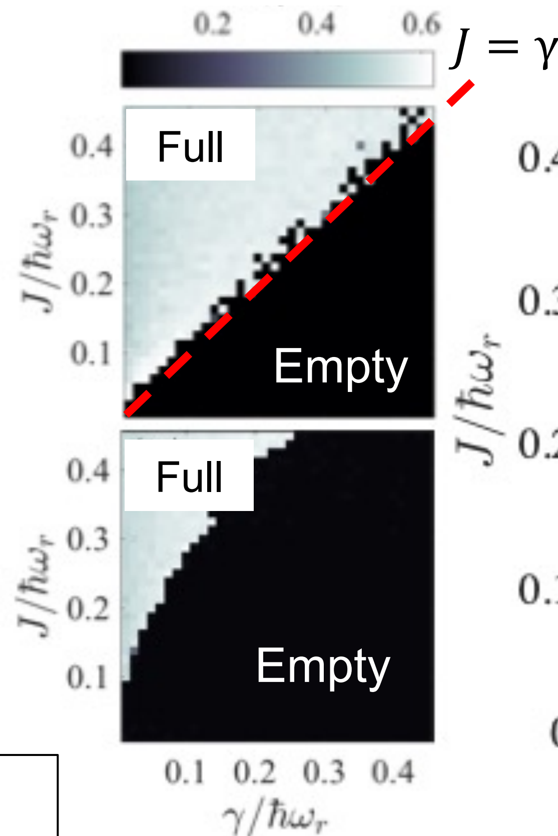
M. T. Reeves and M. J. Davis, SciPost Phys. **15**, 068 (2023).

Dynamical reservoir model

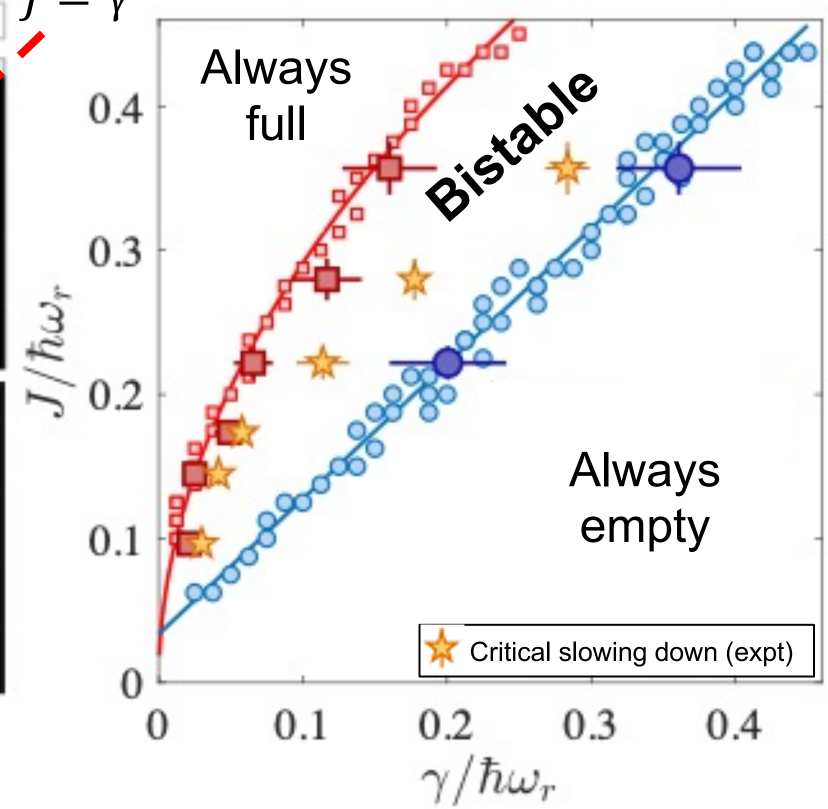
Start from full

Start from empty

Condensate fraction



Phase diagram

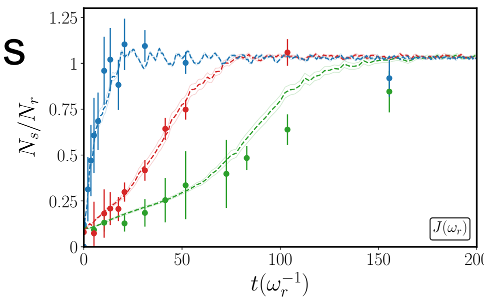


Need a high effective temperature for $J = \gamma$

Conclusions and outlook

c-field model describes experimental results

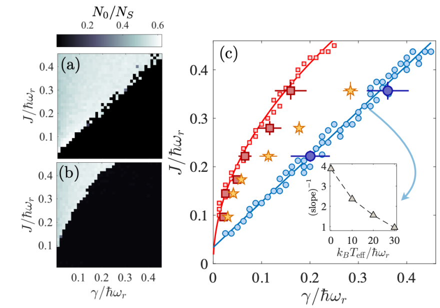
- Filling of depleted sites.
- Nonequilibrium phase diagram (proviso: with fluctuations from temperature of reservoirs).
- Provides several insights to the physics.



Future

- Dynamics in bistable region: Benary *et al,* New J. Phys. 24 103034 (2022).
- Dark soliton state.
  - pi phase difference between sides – resistant to filling – metastable.
  - Stabilised by dissipation.

Ceulemans and Wouters, Phys. Rev. A **108**, 013314 (2023)



- Transport through chains of pancakes.
- Fashioning atomtronic devices by adding junctions and controlling local well depth.