Joint Quantum Centre
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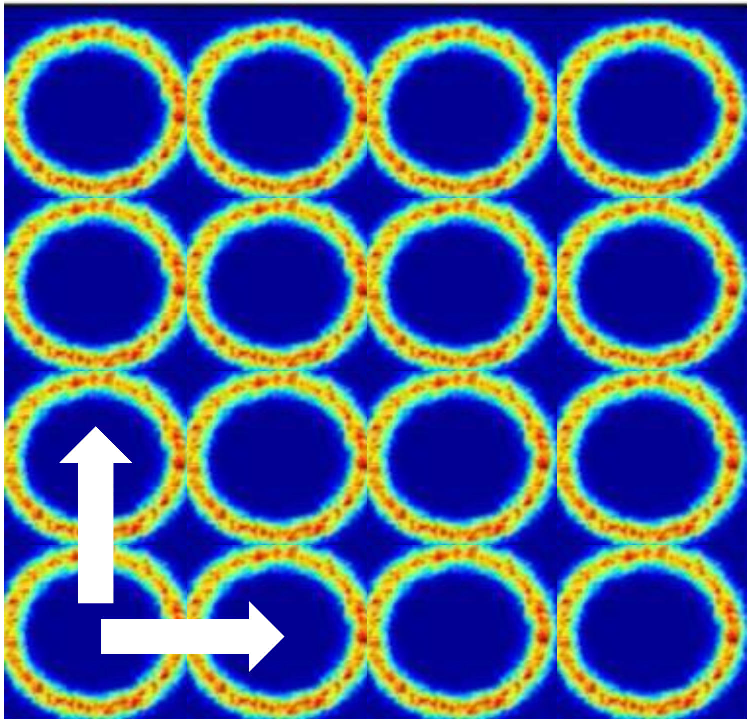
NON-EQUILIBRIUM ULTRACOLD ATOMS: DISSIPATIVE JUNCTIONS, QUENCHES AND COUPLED RINGS

Newcastle University
UK | Malaysia | Singapore

NICK PROUKAKIS

QUANTERA
EPSRC Engineering and Physical Science Research Council
行政院國家科學委員會 National Science Council
PROVINCIA AUTONOMA DI TRENTO
UNIVERSITY OF TRENTO
UCAT UltraCold Atom Theory
CNR-INO
Lens European Laboratory for Non-Linear Spectroscopy

TOWARDS SCALABLE ATOMTRONIC ARCHITECTURES



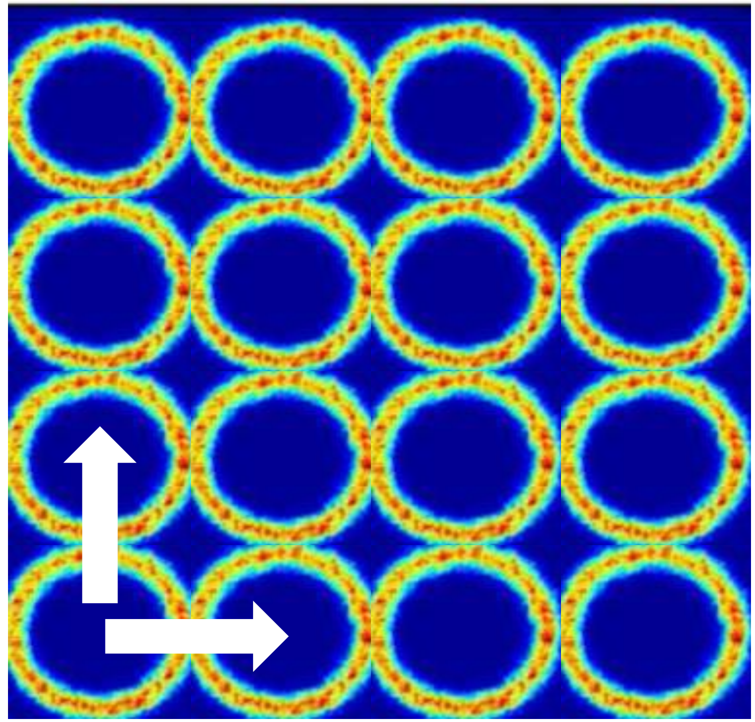
Envisaged Aim:
(Longer term)
Atomtronic
“Conveyor Belt”

THEORETICAL CHALLENGES:

*** How to best model?**

*** How to prepare initial state?**

*** How to link up?**



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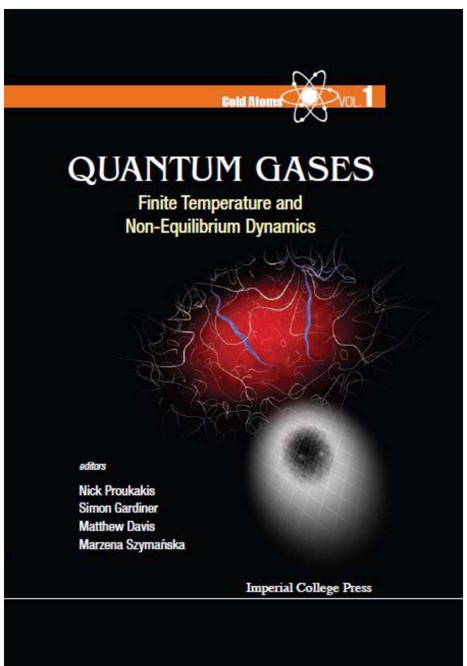

*** How to best model?** **[Part I]**

Coherent Effects *(Gross-Pitaevskii)*
Dissipation *(Thermal Dynamics: Boltzmann / ZNG ?)*
Fluctuations *(Stochasticity: Stochastic GPE ?)*

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Envisaged Aim:
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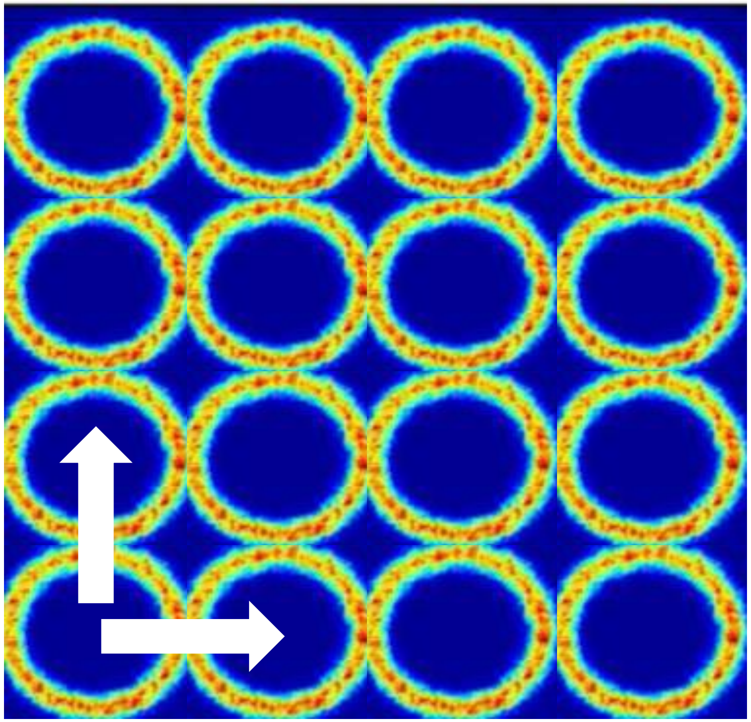

*** How to best model?** **[Part I]**

THEORETICAL CHALLENGES:

*** How ~~to~~ prepare initial state?** **[Part II]**

Not to (?)

→ Quenched Growth to Equilibrium (Phase Transition Crossing)

Liu *et al*., Comms. Phys. (Nature) 1, 24 (2018)
Comaron *et al.*, PRL 121, 095302 (2018)
Comaron *et al.*, arXiv/1905.05263

TOWARDS SCALABLE ATOMTRONIC ARCHITECTURES

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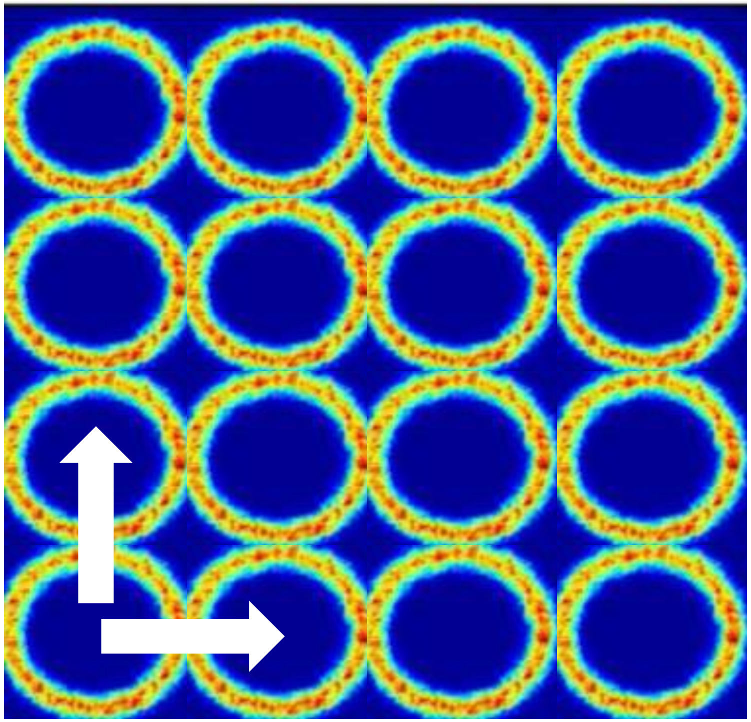


*** How to best model?** **[Part I]**

THEORETICAL CHALLENGES:

*** How to prepare initial state?** **[Part II]**

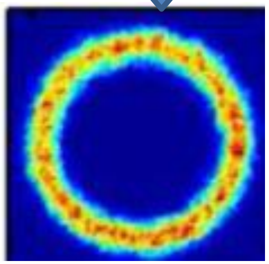
*** How to link up?** **[Part III]**

… I will discuss interesting physics in all above cases …

(… but not in an integrated manner yet …)

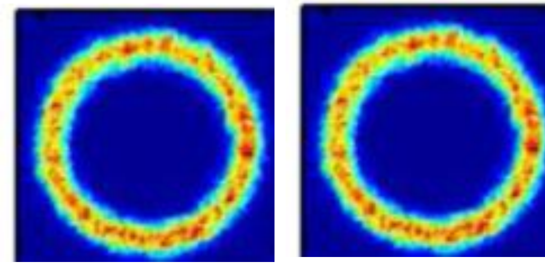
TALK SUMMARY

Methods Overview



BEC with Fluctuations

"Atomtronics Fellow"

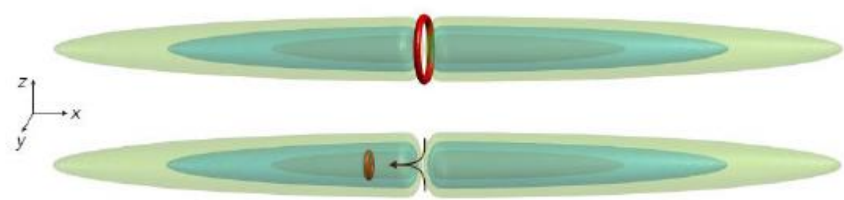


Coupled Rings

Aside 1:
Dynamical Phase Transitions

Liu *et al*., Comms. Phys. (Nature) 1, 24 (2018)
Comaron *et al.,* PRL 121, 095302 (2018)
Comaron *et al.,* arXiv:1905.05263

Aside 2:
Phase Slips (Junctions)



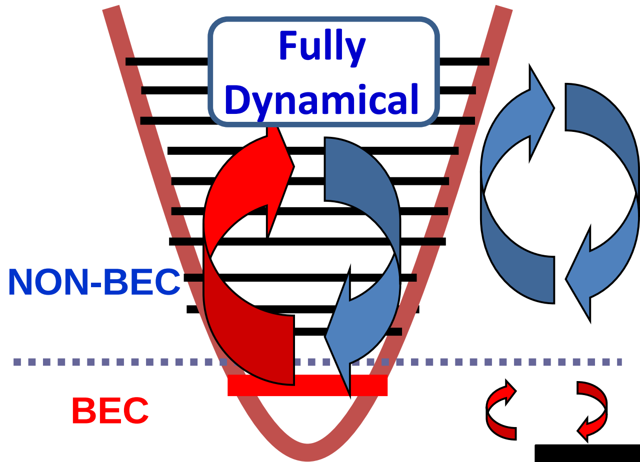
Xhani *et al.,* arXiv:1905.08893

Different, yet complementary, approaches to partially condensed (T > 0) Systems

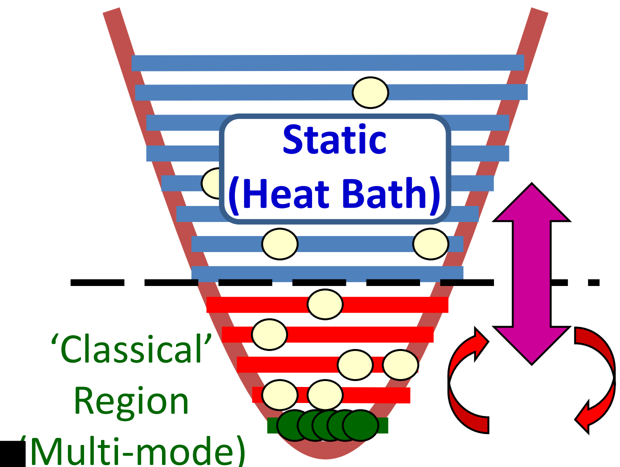
Kinetic Approaches
(explicit BEC separation)

Stochastic Approaches
(no explicit BEC separation)

BEC + Dynamical Thermal Cloud with full self-consistent coupling



Modes up to a cut-off described in a unified manner (classical field) coupled to a Heat Bath

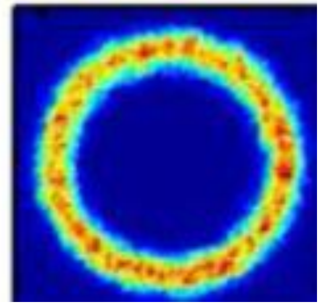


Ideally suited for:

Collective Modes/Dynamics
Full BEC – Thermal Coupling
(far from critical region)

Random (shot-to-shot) Fluctuations
Quenches / Low-D & Universality
(high-lying modes "unaffected")

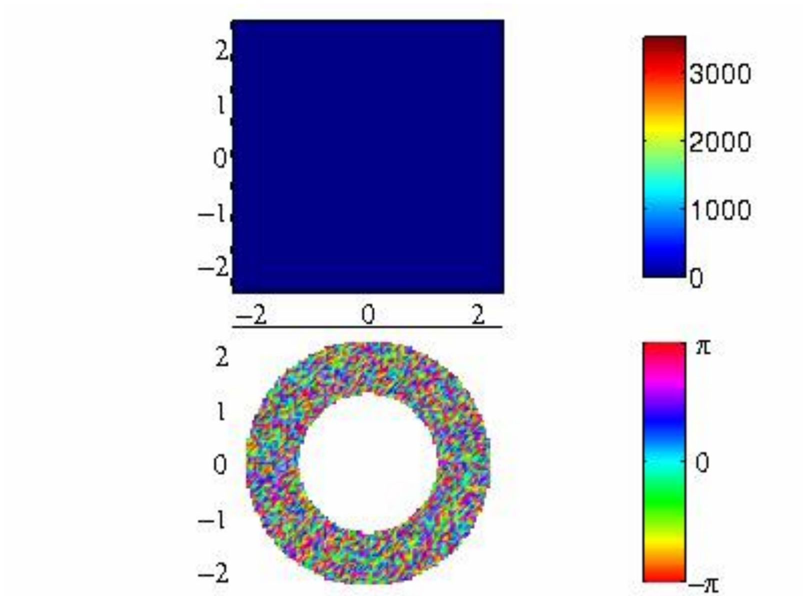
Preparation of Desired
"Initial Atomtronic State"



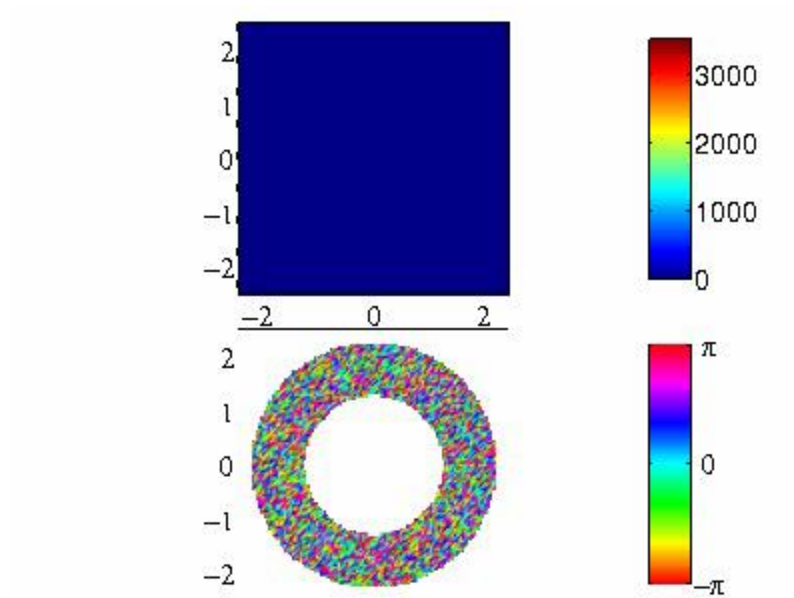
→ First Thoughts: Brute Force Numerical Generation (Stochastic GPE)

[This is a numerical Quench!]

Growth without Persistent Current



Growth with Persistent Current



See e.g Das, Sabbatini & Zurek, Scientific Reports (2012) & references therein

Aside 1:
Dynamical Phase Transitions

Liu *et al*., Comms. Phys. (Nature) 1, 24 (2018)

Comaron *et al.,* PRL 121, 095302 (2018)

Comaron *et al.,* arXiv:1905.05263

PHYSICAL PROBLEM

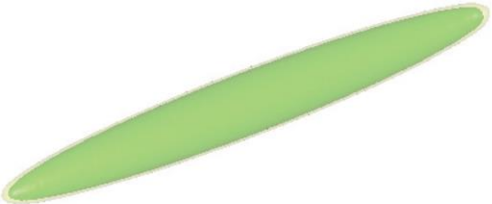
Initial Ultracold Atomic State to be generated
(on rapid timescale?) within an “Atomtronic Circuit” ???

Disordered (Thermal) State

Phase

Transition

(Quasi)Coherent State



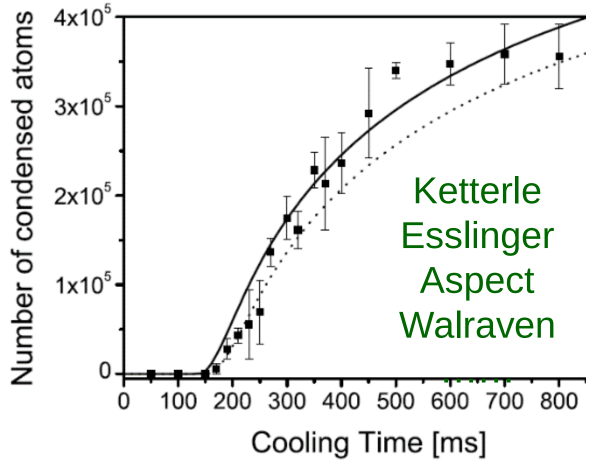
→ Need Additional Mechanism to Generate BEC

→ How Quickly is Generation Needed?

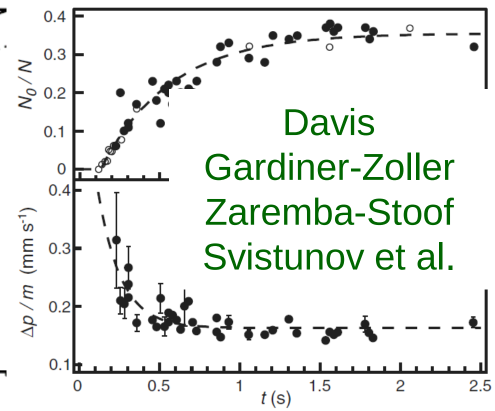
CONDENSATE GROWTH EXPERIMENTS

Early Growth Experiments (1998 – 2007)

Focused on Growth of Atom Number



Ketterle
Esslinger
Aspect
Walraven



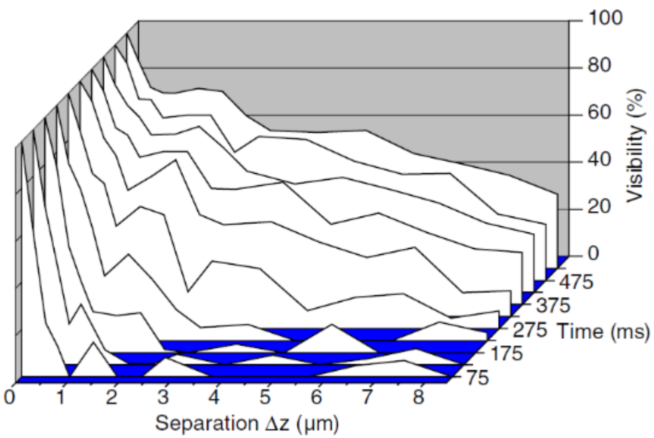
Davis
Gardiner-Zoller
Zaremba-Stoof
Svistunov et al.

Well-modelled theoretically, except for “undetermined” time delay in BEC “onset”

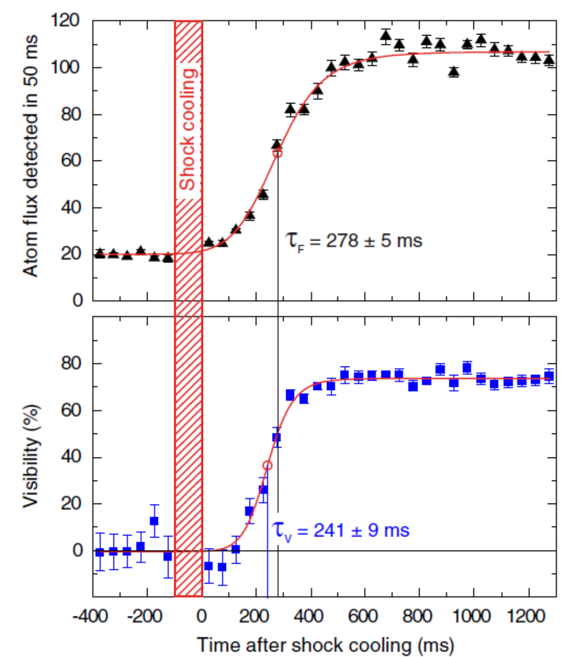
PRL 98, 090402 (2007) PHYSICAL REVIEW LETTERS week ending 2 MARCH 2007

Observing the Formation of Long-Range Order during Bose-Einstein Condensation

Stephan Ritter, Anton Öttl, Tobias Donner, Thomas Bourdel, Michael Köhl,* and Tilman Esslinger



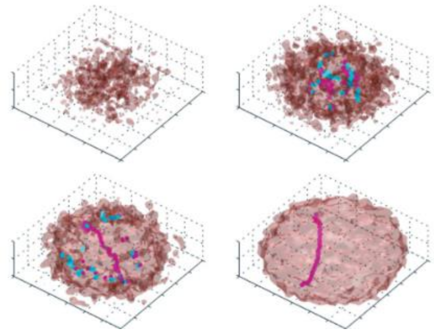
BEC Atom Number Grows on “Similar” Timescales to Coherence



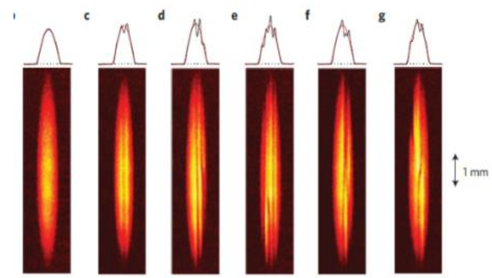
CONDENSATE GROWTH EXPERIMENTS

“2nd Generation” Growth Experiments (2008 –)

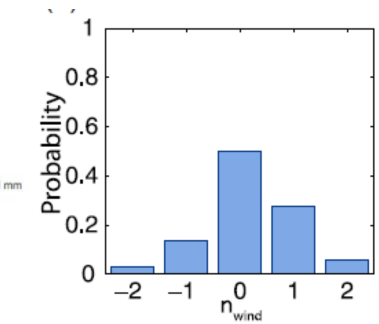
Controlled Quench Experiments: Spontaneous Generation of Defects & Persistent Currents



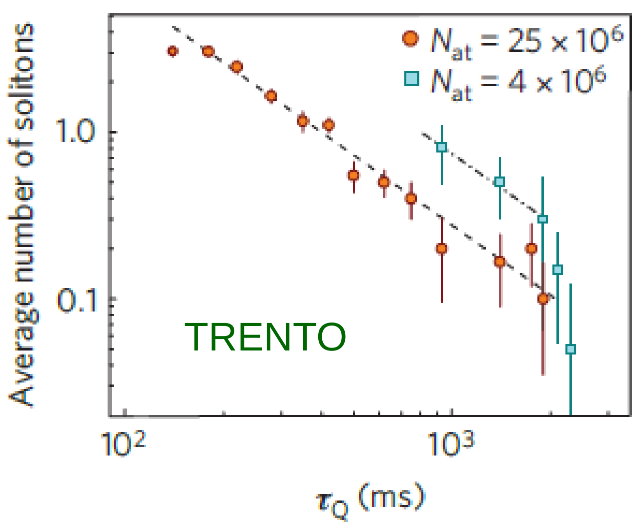
ARIZONA:
Nature 455, 948 (2008)



TRENTO:
Nat Phys 9, 656 (2013)

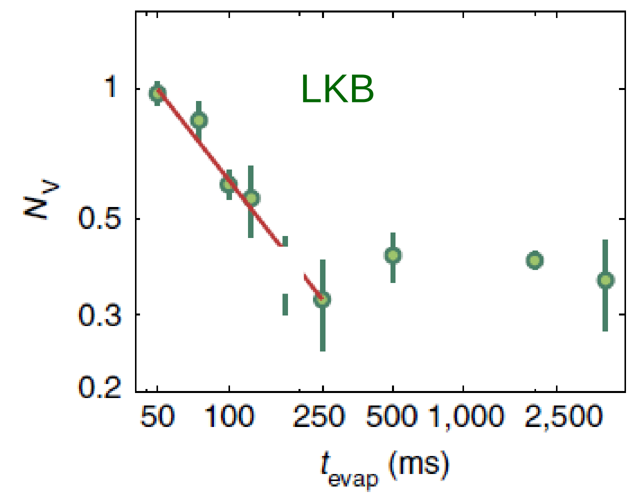


LKB:
PRL 113, 135302 (2014)



Kibble-Zurek Scaling:

$$N \propto \left(\tau_Q\right)^{-\alpha}$$

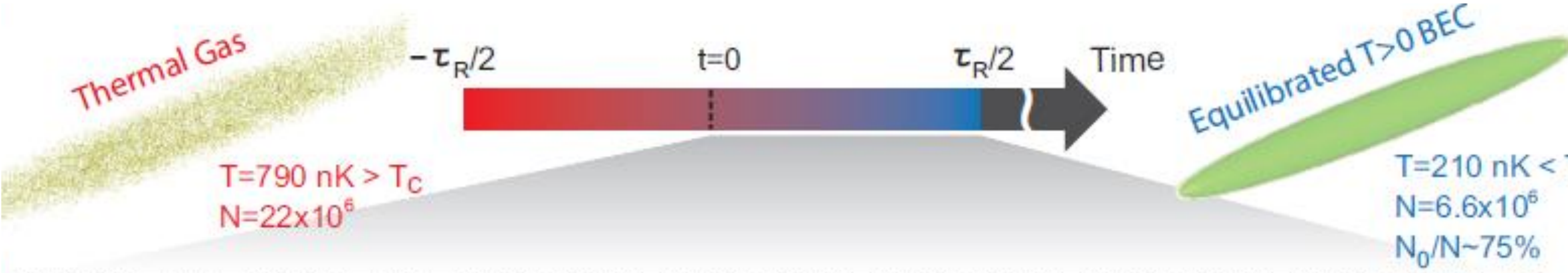


Experimentally also Characterised in a 3D/2D Box-like Trap

CAMBRIDGE: Science 347 (2015) ; LKB: Nat. Comm. (2015)

MODELLING SCHEME

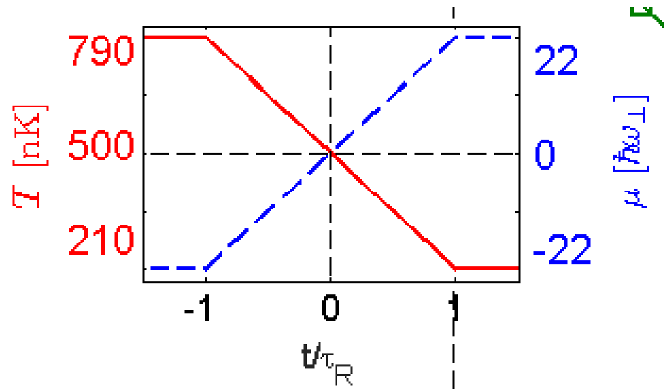
Simulations based on Stochastic Gross-Pitaevskii Equation
for typical Trento experimental parameters



$$i\hbar \frac{\partial \Phi(x,t)}{\partial t} = (1 - i\gamma)\left[-\frac{\hbar^2 \nabla^2}{2m} + V_{TRAP} - \mu + g\left|\Phi(x,t)\right|^2 \right]\Phi(x,t) + \eta(x,t)$$

Quench protocol:

(T, μ)



Results supposed to be interpreted after suitable 'trajectory' averaging

In a *Statistical* Sense:

Single numerical realisation ←→ Single Experimental Run

Dynamical Equilibration Across a Quenched Phase Transition in a Trapped Quantum Gas

I.-K. Liu[1,2], S. Donadello[3], G. Lamporesi[3], G. Ferrari[3], S.-C. Gou[2], F. Dalfovo[3], N. P. Proukakis[1]*

[1]Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics, Newcastle Univesrity, Newcastle upon Tyne, NE1 7RU, United Kingdom
[2]Department of Physics and Graduate Institute of Photonics, National Changhua University of Education, Changhua, Taiwan
[3]INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Trento, Italy

Date: 23th October 2017

Initial particle number: 22×10^6

Final particle number: 6.6×10^6

Energy cutoff: $56.3\hbar\omega_\perp$

Linear Quenches over $\tau_R = 18$ ms

Noise Sequence 1

Temperature: $T_i = 790$ nK $\rightarrow$ $T_f = 210$ nK

Chemical Potential: $\mu_i = -22\hbar\omega_\perp \rightarrow \mu_f = 22\hbar\omega_\perp$

Growth Parameter: $\gamma = 0.005$

Trap frequencies: $(\omega_x, \omega_\perp) = 2\pi\times(13,131.4)$ Hz

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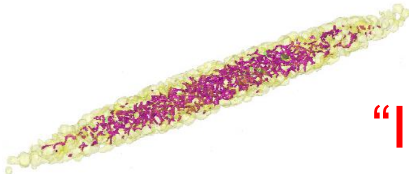
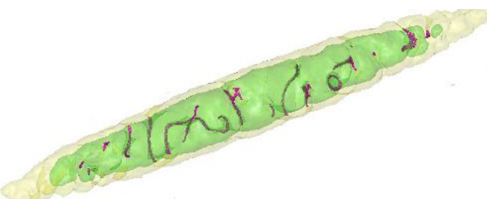
UNIVERSAL EMERGING FEATURES OF QUENCHED GROWTH

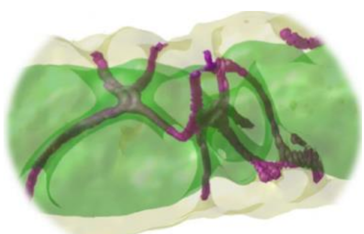
System reaches
Critical region



"Identifiable"
(defect-filled)
BEC Emerges

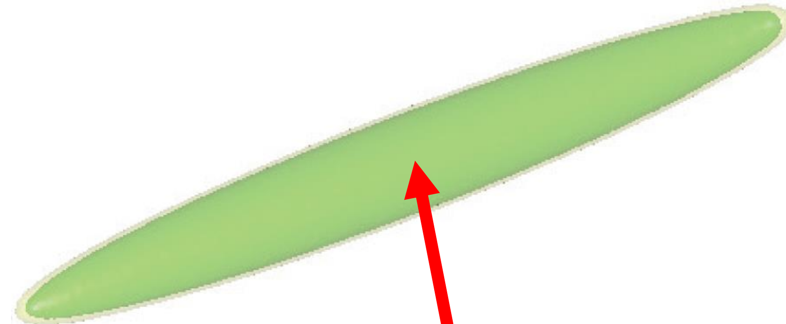


Violent Reconnections
during Rapid Growth



Interactions of Few
"Canonical" Defects

Equilibration

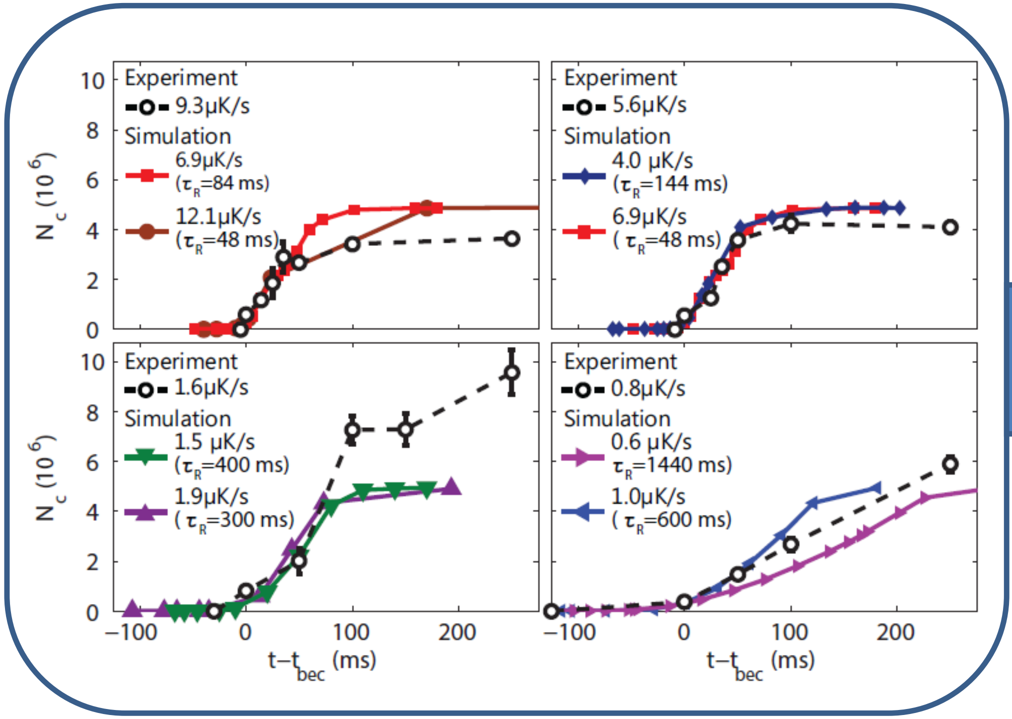


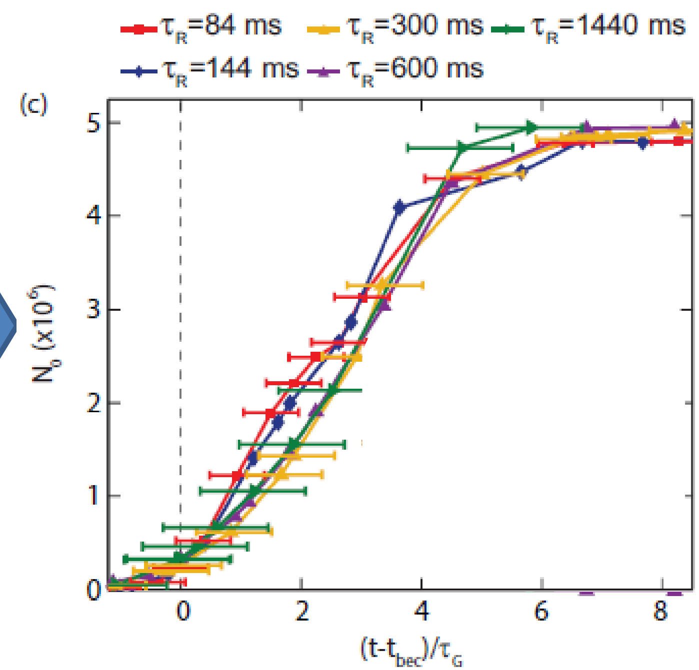
Liu *et al*.,
Comms. Phys. 1, 24 (2018)
arXiv:1712.08074

COHERENCE vs. NUMBER GROWTH

To compare & contrast *Atom Number & Coherence* Evolution, we scale out intrinsic system dynamics, through the

Scaled Time from the Effective Transition $\left(\frac{t - t_{bec}}{\tau_G}\right)$





… so that all BEC Growth Curves Overlap with each other

Liu, Donadello, Lamporesi, Ferrari, Gou, Dalfovo, NPP, Comms. Phys. (Nature) 1, 24 (2018)

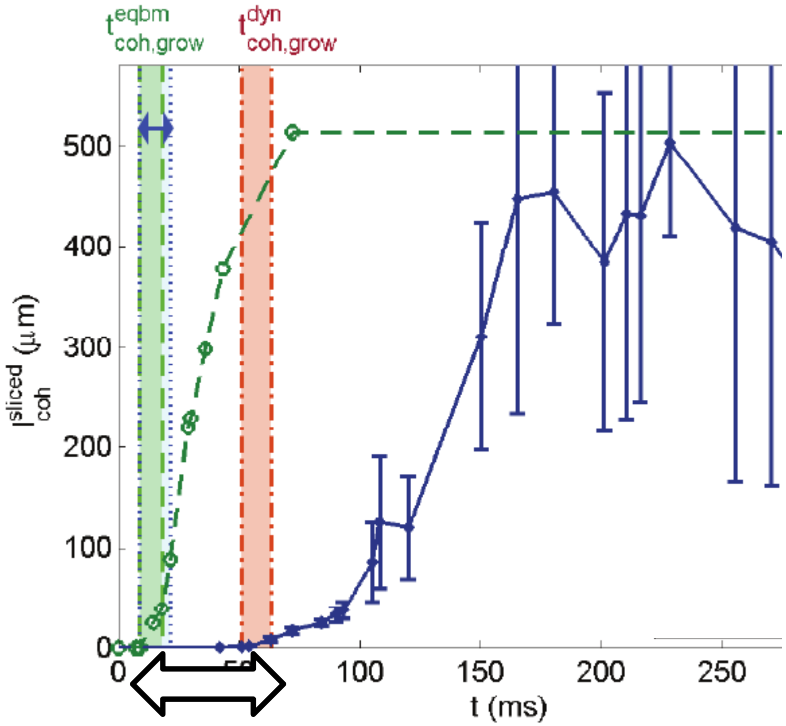
DELAYED DYNAMICAL GROWTH ($\hat{t}$)

System's Dynamical Response Probed through key Observables

→ Extract System Correlation Length

Equilibrium
[Corresponding N, T]

$l_{coh}^{equil}(\mu(t),T(t))$



Time Delay
$\hat{t}$

Dynamical

$l_{coh}^{dyn}(t)$

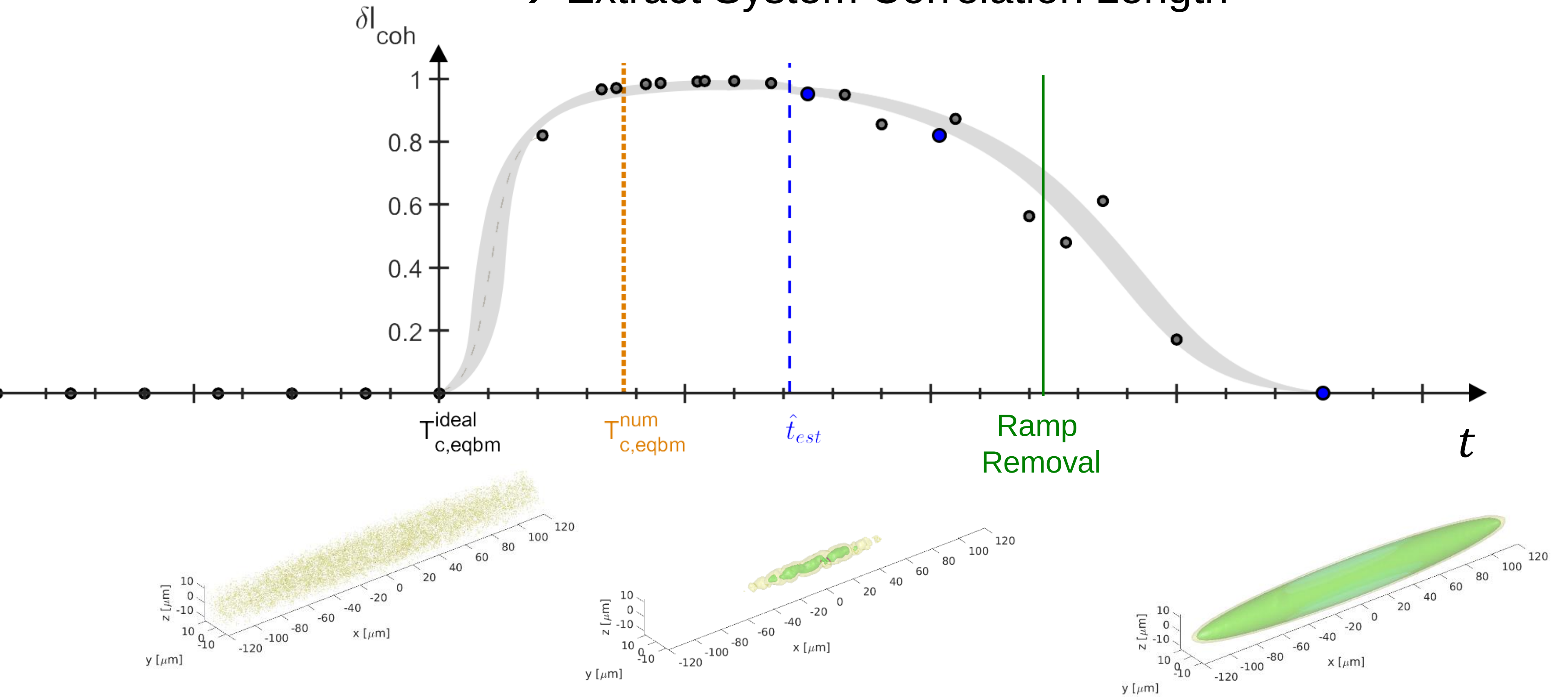
To understand entire Dynamical Non-Equilibrium Process, Introduce:

$$\delta l_{coh}(t) = \frac{l_{coh}^{equil}(\mu(t),T(t)) - l_{coh}^{dyn}(t)}{l_{coh}^{equil}(\mu(t),T(t))}$$

DELAYED DYNAMICAL GROWTH ($\hat{t}$)

System's Dynamical Response Probed through key Observables

→ Extract System Correlation Length



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$$\delta l_{coh}(t) = \frac{l_{coh}^{equil}(\mu(t),T(t)) - l_{coh}^{dyn}(t)}{l_{coh}^{equil}(\mu(t),T(t))}$$

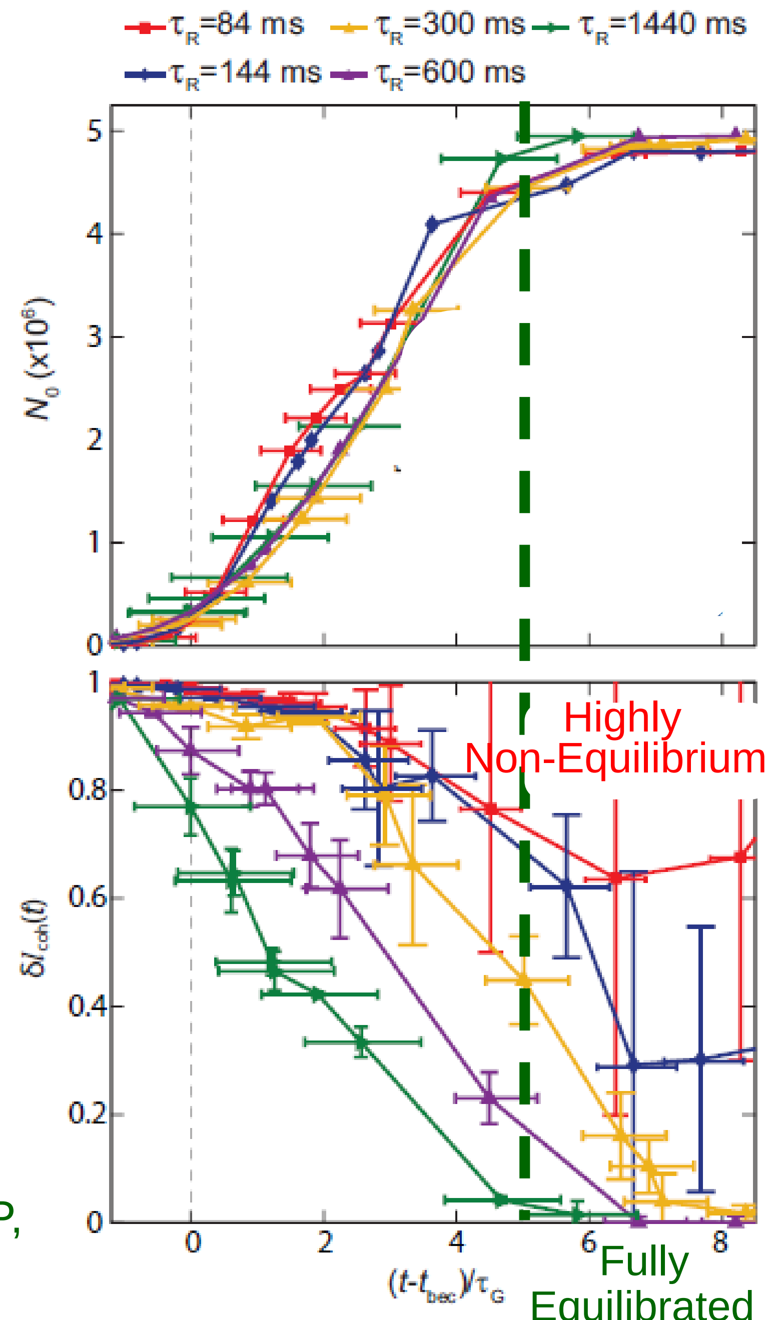
COHERENCE vs. NUMBER GROWTH

Introduce Measure of
“ReCoherence”

$$0 \le \delta l_{coh}(t) = \frac{l_{coh}^{equil}(\mu(t),T(t)) - l_{coh}^{dyn}(t)}{l_{coh}^{equil}(\mu(t),T(t))} \le 1$$

Dynamical System “In Sync” with Equilibrium

System “Maximally’ out of Equilibrium



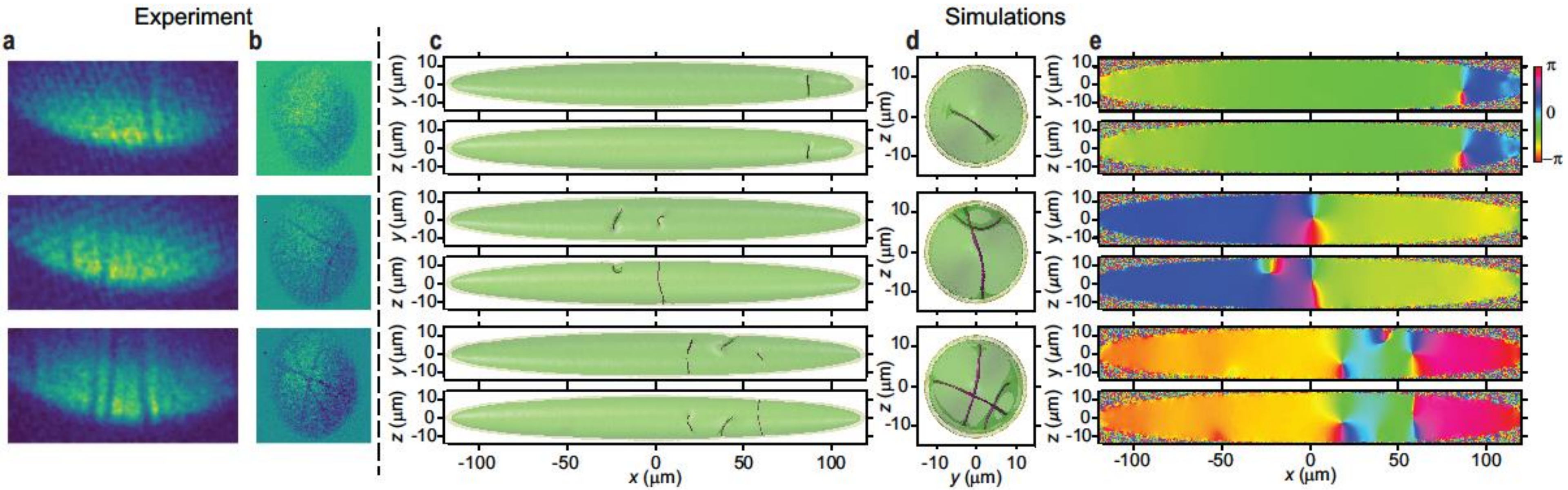
Observe

Decoupling of Number & Coherence Growth

(except for very slow ramps)

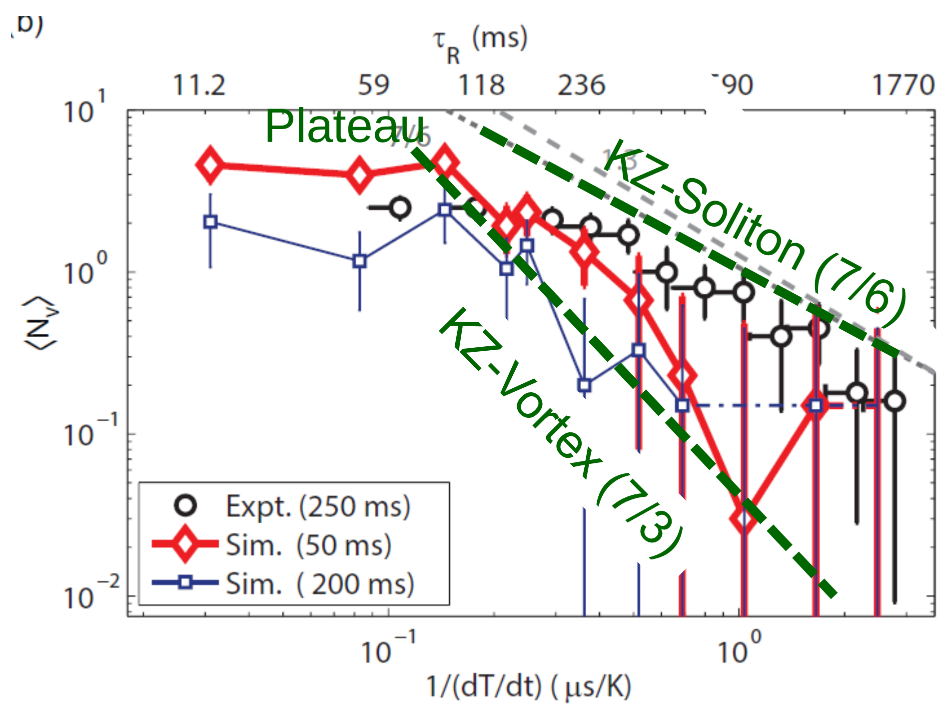
Liu, Donadello, Lamporesi, Ferrari, Gou, Dalfovo, NPP, Comms. Phys. (Nature) 1, 24 (2018)

DEFECT EMERGENCE & "SCALING"



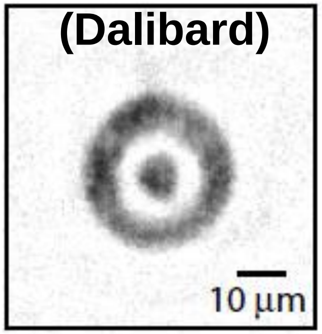
Qualitative / Quantitative Agreement
with Experiments
& "Naïve Expectations":

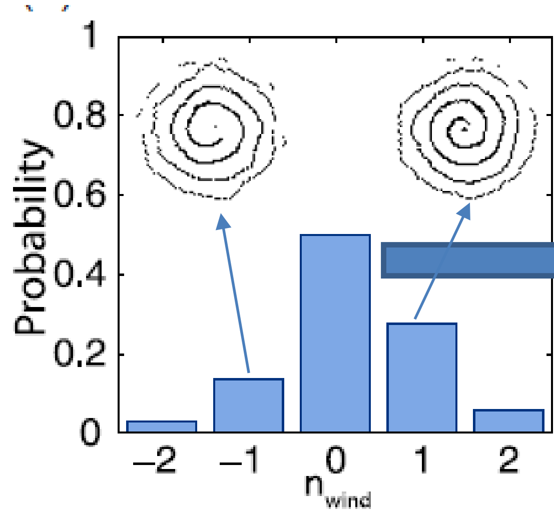
Liu *et al.*,
Comms. Phys. (Nature) 1, 24 (2018)

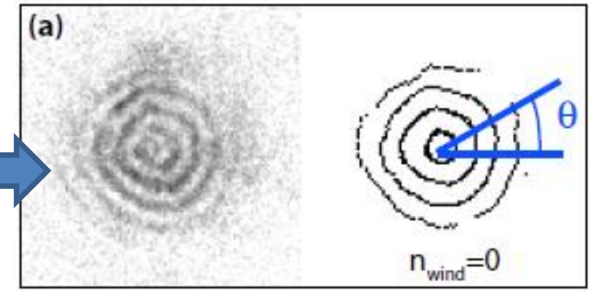


SPONTANEOUS PERSISTENT CURRENTS IN RING TRAPS

Experimental Growth (Dalibard)

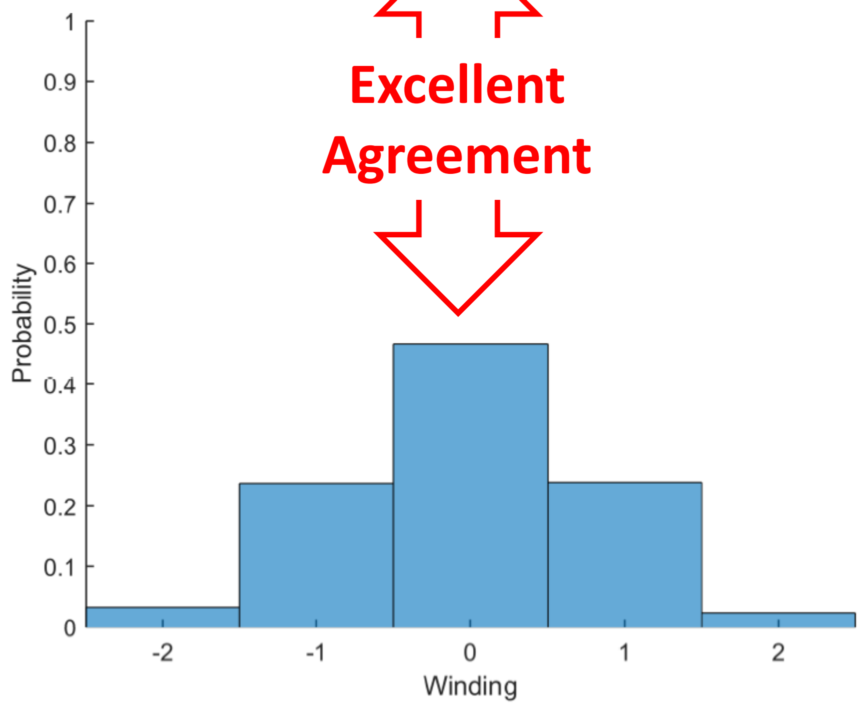






LKB:
PRL 113, 135302 (2014)

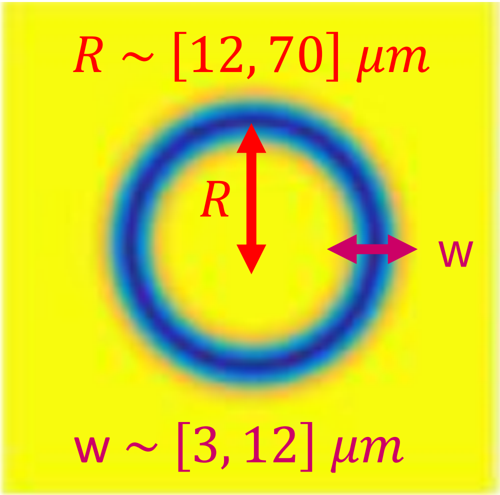
Excellent Agreement



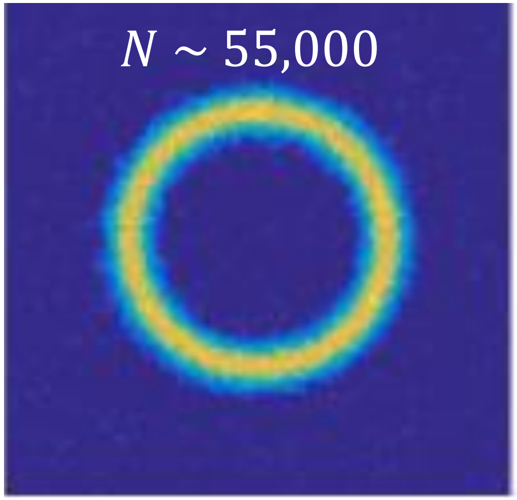
Simulations based on 5,000 numerical runs

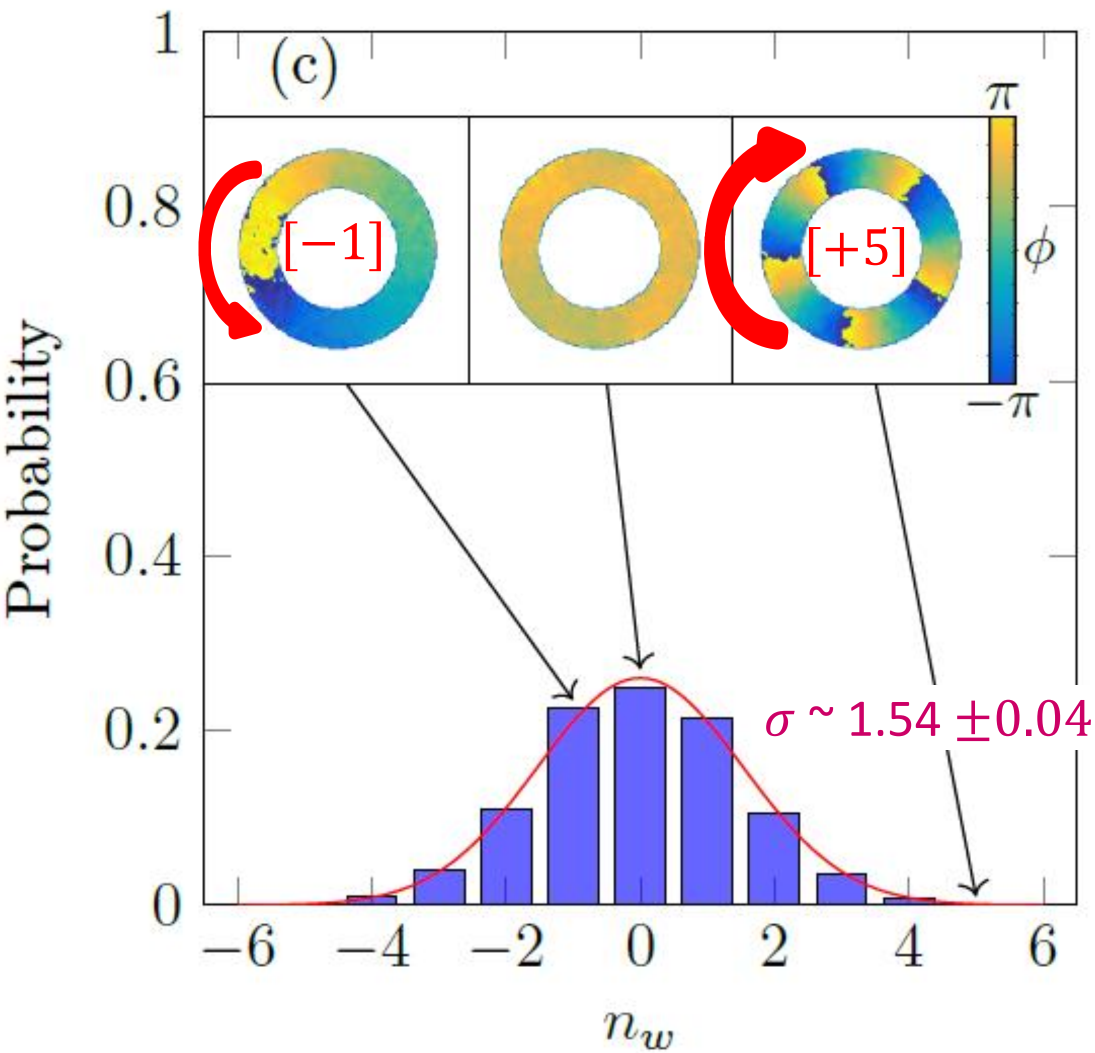
Bland *et al.*
(In Preparation, 2019)

Trap Potential



Density

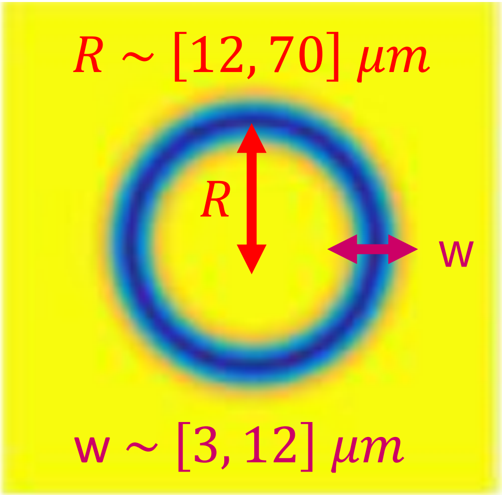




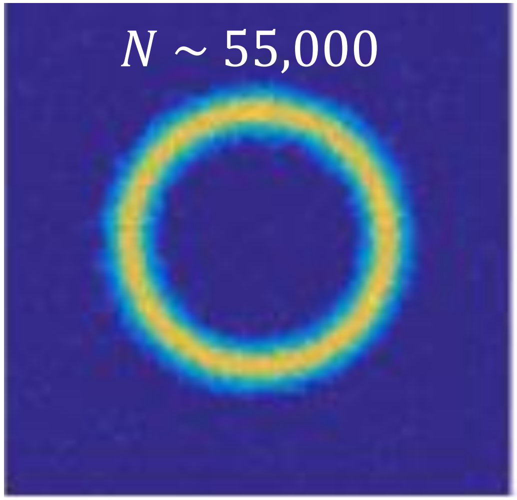
We find numerically σ ~ (R/w)

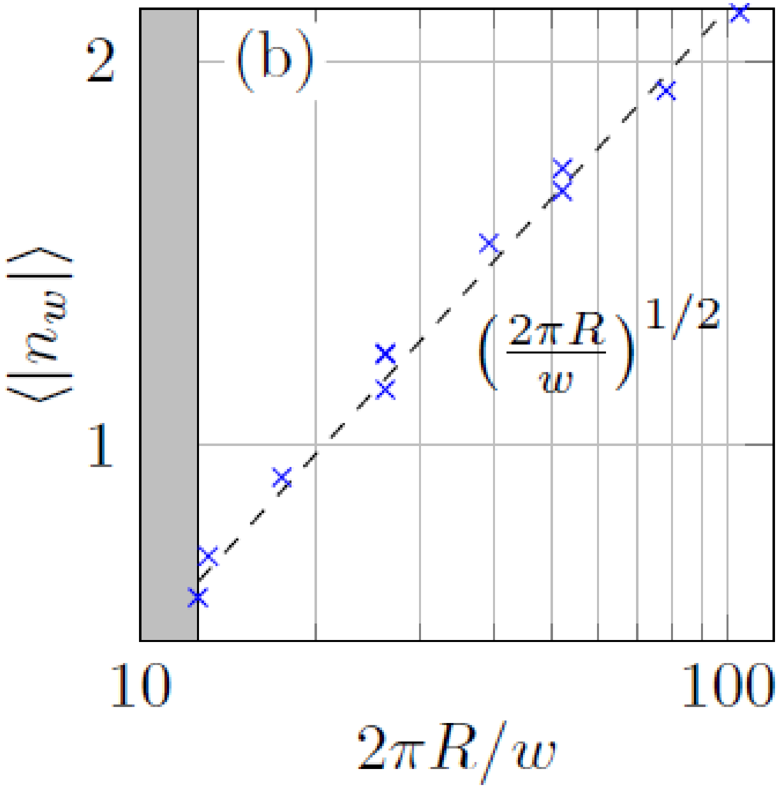
i. e. winding number increases with large & narrow rings

Trap Potential



Density

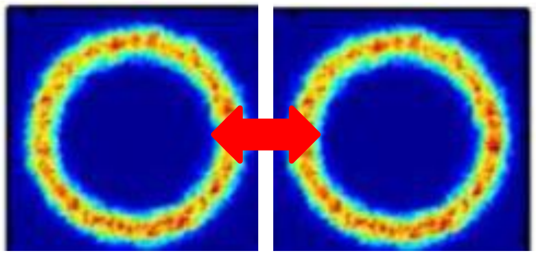




CONNECTING MULTIPLE RING TRAPS

How to Connect 2 Rings ?

Tunneling ???



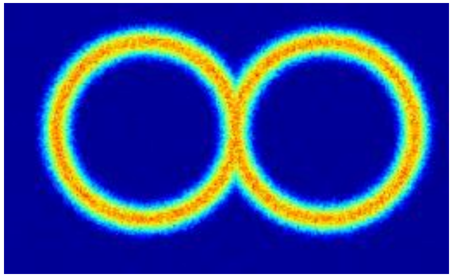
Many Talks in this Meeting

**Well Understood
at Single-Particle Level**

Role of Interactions ?

**First Discuss
Isolated Weak Link**

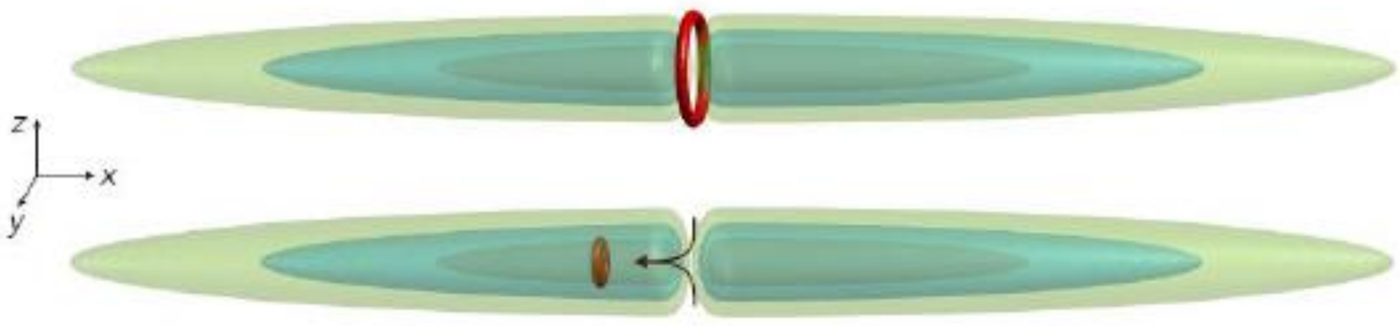
Linked Densities ?



What is Preferred Flow ?

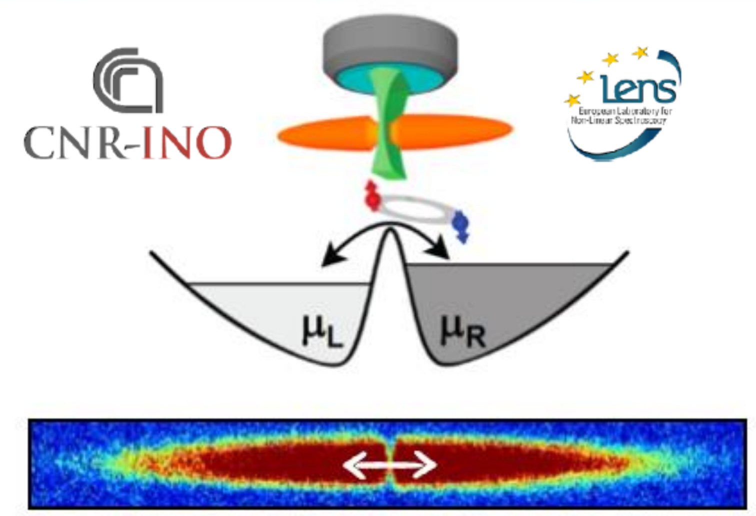
**Investigate
Density-Coupled States**

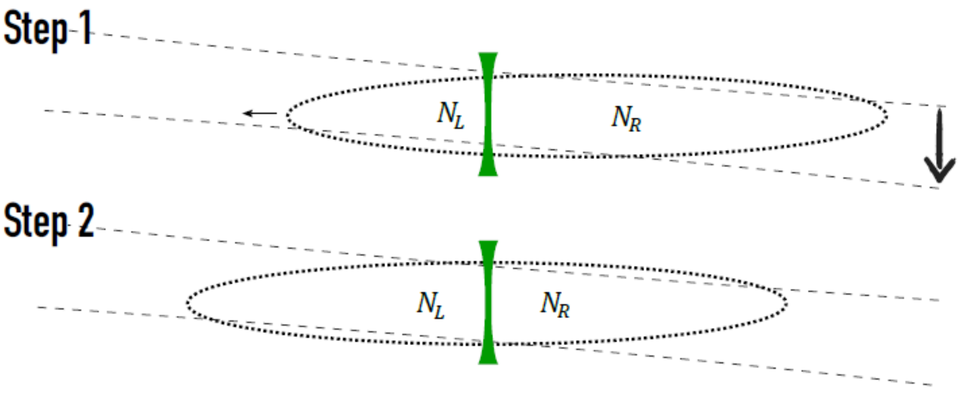
Aside 2:
Phase Slips (Junctions)



Xhani *et al.*, arXiv:1905.08893

A THIN JOSEPHSON JUNCTION (LENS Experiments)





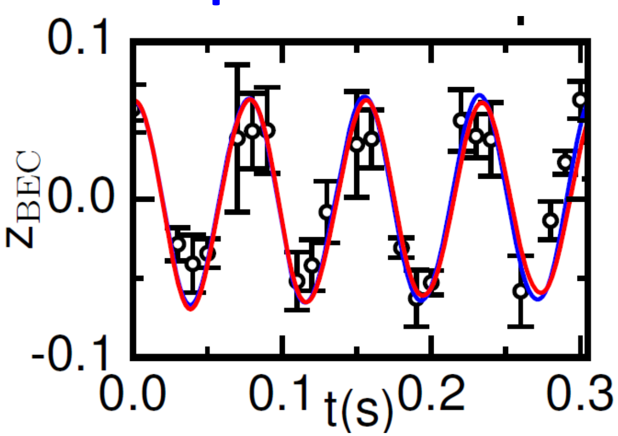
- Weak-link geometry between Fermi superfluids → **tuneable Josephson junction**
- Critical superflow and dissipation mechanisms

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

[From Francesco Scazza's Talk in this Meeting]

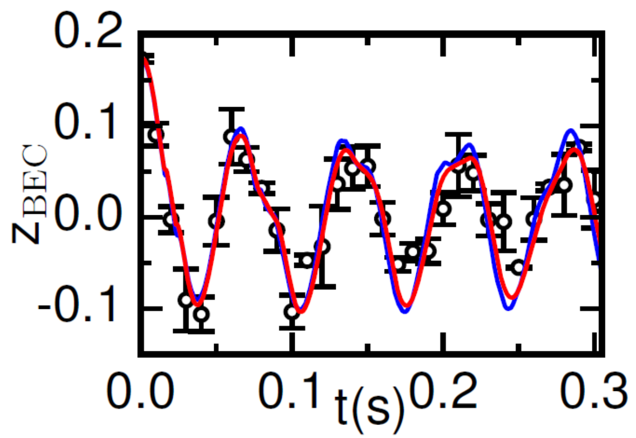
Distinguish 2 Regimes:

Josephson Oscillations



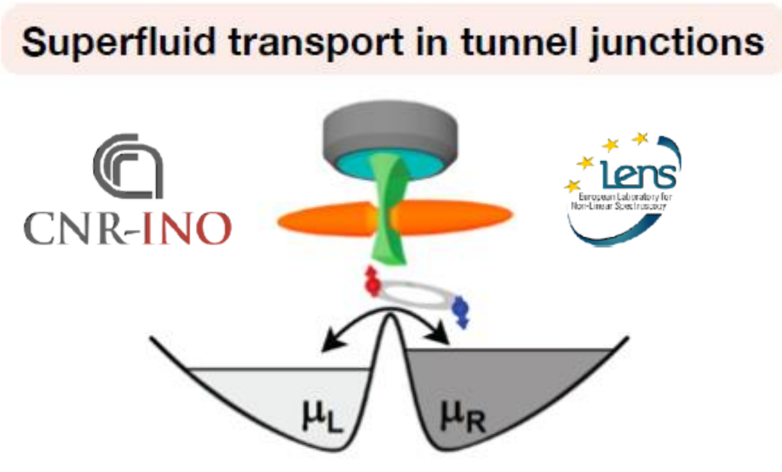
(undamped at T=0)

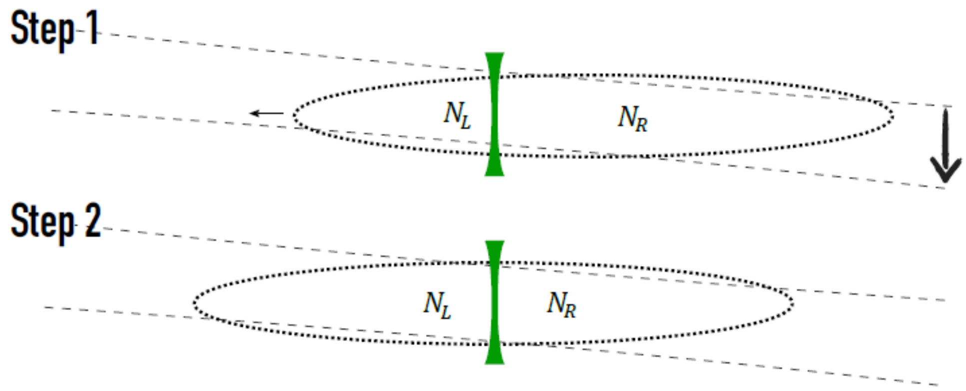
Dissipative Superflow



(flow damped at T=0)

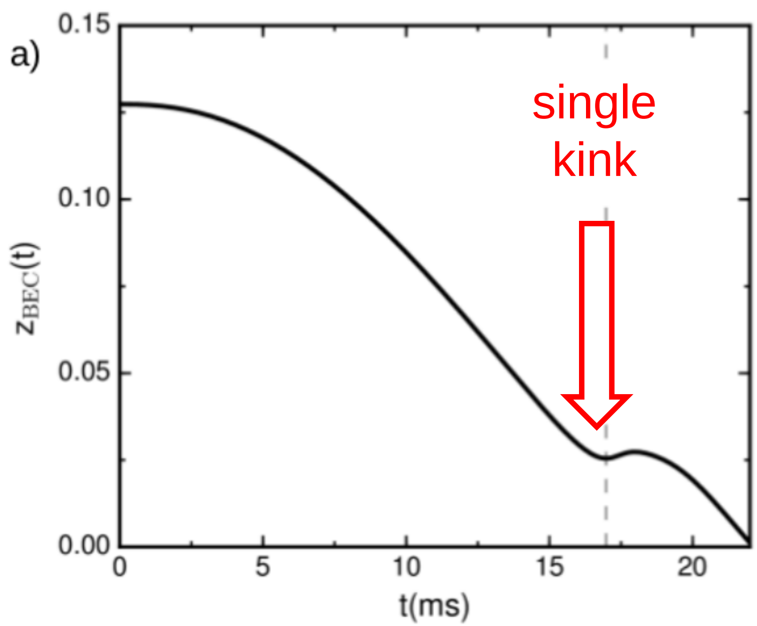
A THIN JOSEPHSON JUNCTION (LENS Experiments)

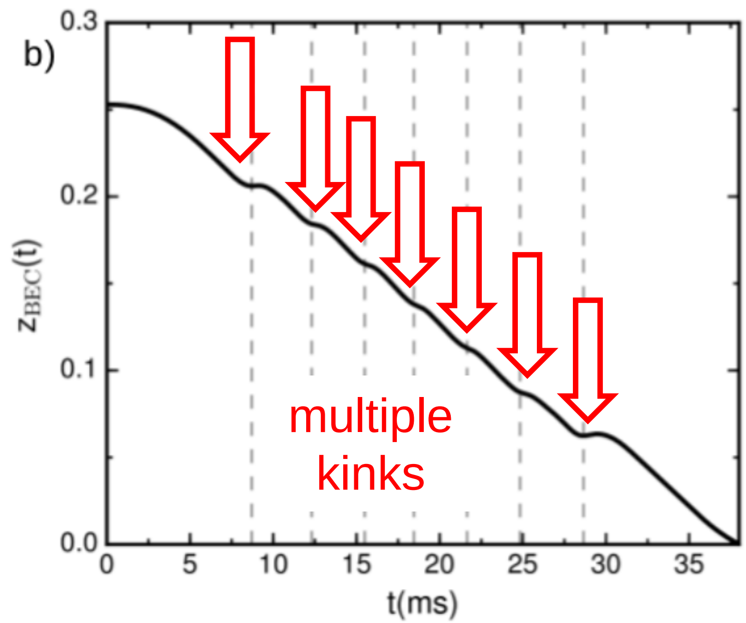




- Weak-link geometry between Fermi superfluids
  → **tuneable Josephson junction**

A Close Inspection shows “kinks” in the Population Imbalance Evolution (“Quantum Phase Slips”)





A THIN JOSEPHSON JUNCTION (LENS Experiments)

Experiment leads to a "Vortex Gun"

(in dissipative regime)

[From Francesco Scazza's Talk]

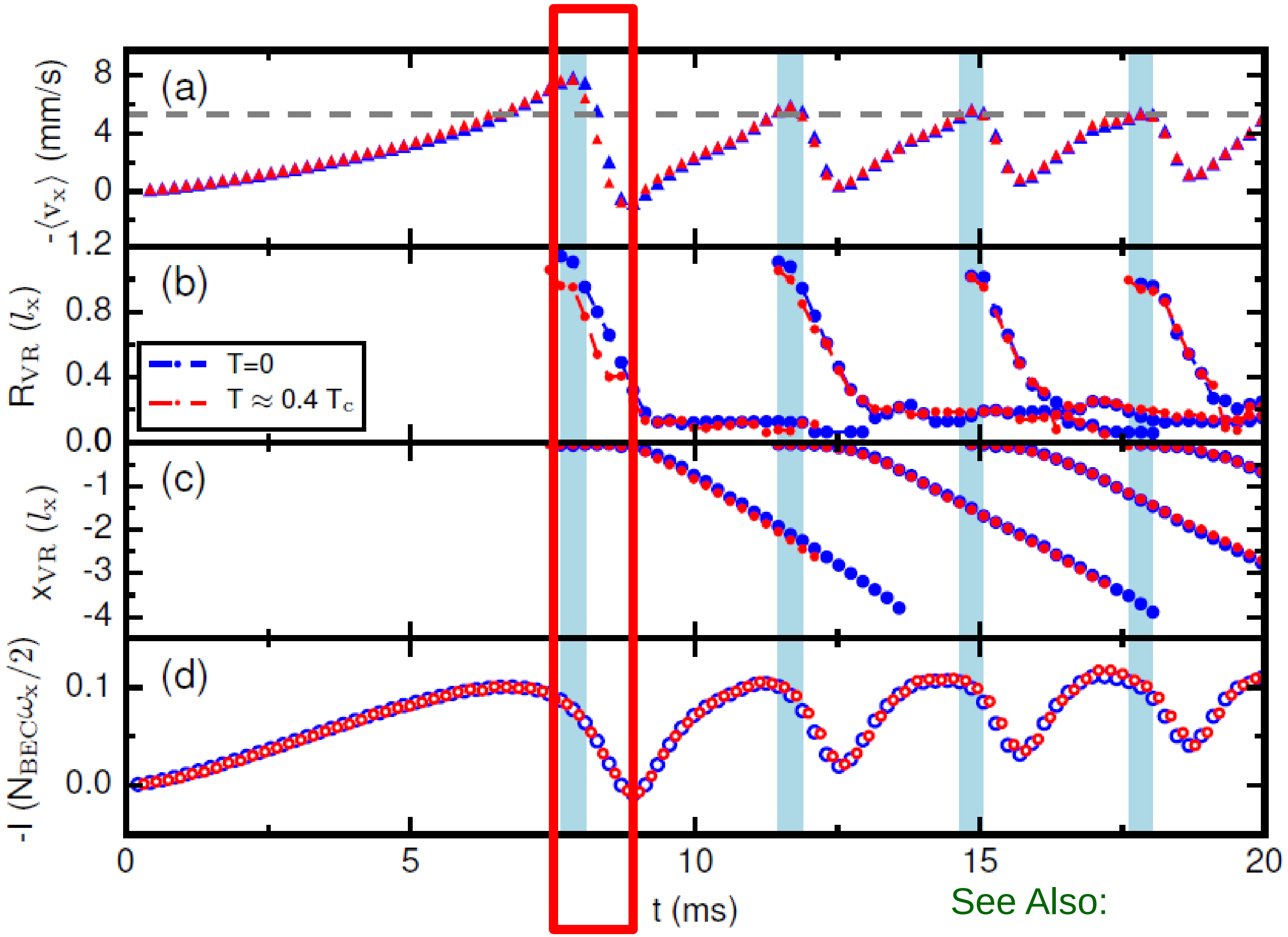
IDENTIFYING ROLE OF QUANTUM PHASE SLIPS

Superfluid Velocity

Vortex Ring Size

Vortex Ring Position

Superfluid Current

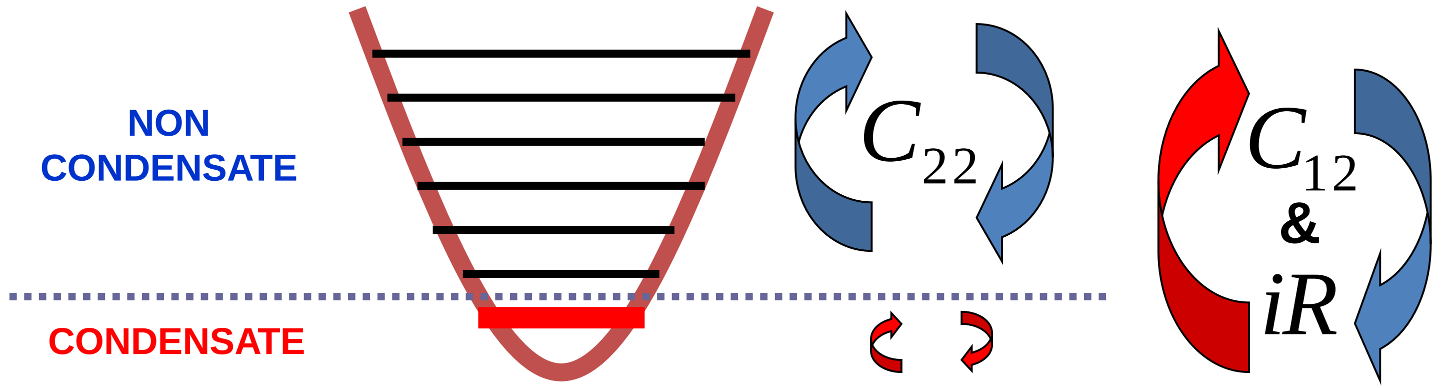


Quantum Phase Slip (Purely T=0 Effect)

Xhani *et al.*, arXiv:1905.08893

See Also:
Piazza et al. NJP (2011)
Abad et al, EPL (2015)
Roati Group (PRL 2018)
Mark Baker & Juan Polo's Talks

"BEST" KINETIC THEORY ("ZNG")



BOSE-EINSTEIN CONDENSATE

$$n_C = |\phi|^2$$

THERMAL CLOUD

$$n' = \int \frac{d^3 p}{(2\pi\hbar)^3} f$$

DISSIPATIVE GROSS-PITAEVSKII

MEAN FIELD COUPLING

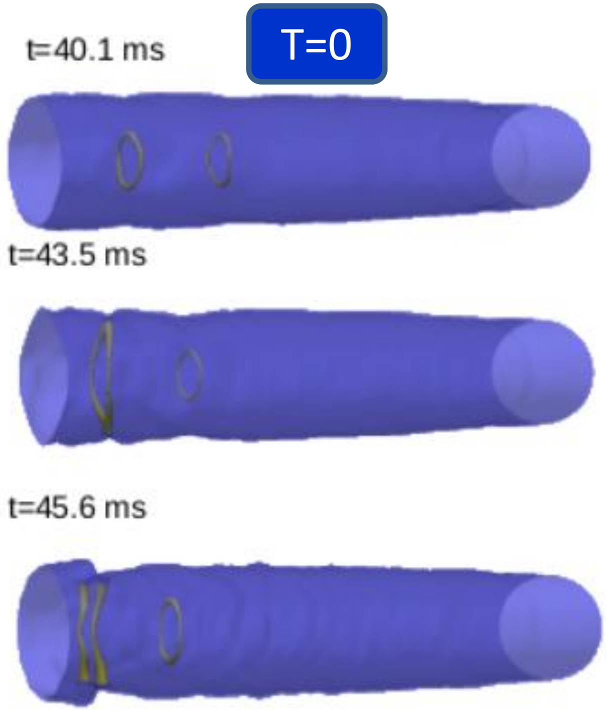
$$U(r) = V(r) + 2g(n_c + n')$$

QUANTUM BOLTZMANN

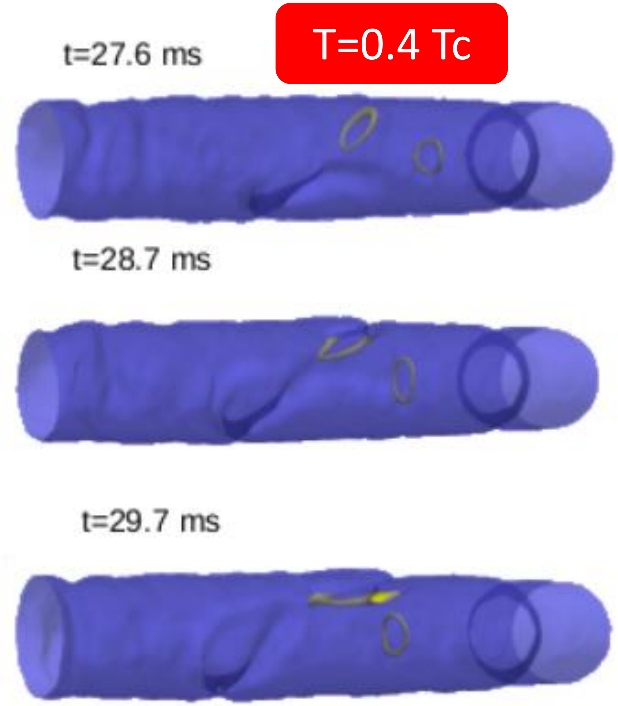
$$i\hbar \frac{\partial \phi}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2m} + V_{TRAP} + g(n_C + 2n') - iR \right) \phi$$

$$\frac{\partial f}{\partial t} + \frac{p}{m} \cdot \nabla f - \nabla U \cdot \nabla_p f = C_{12} + C_{22}$$

IDENTIFYING ROLE OF QUANTUM PHASE SLIPS

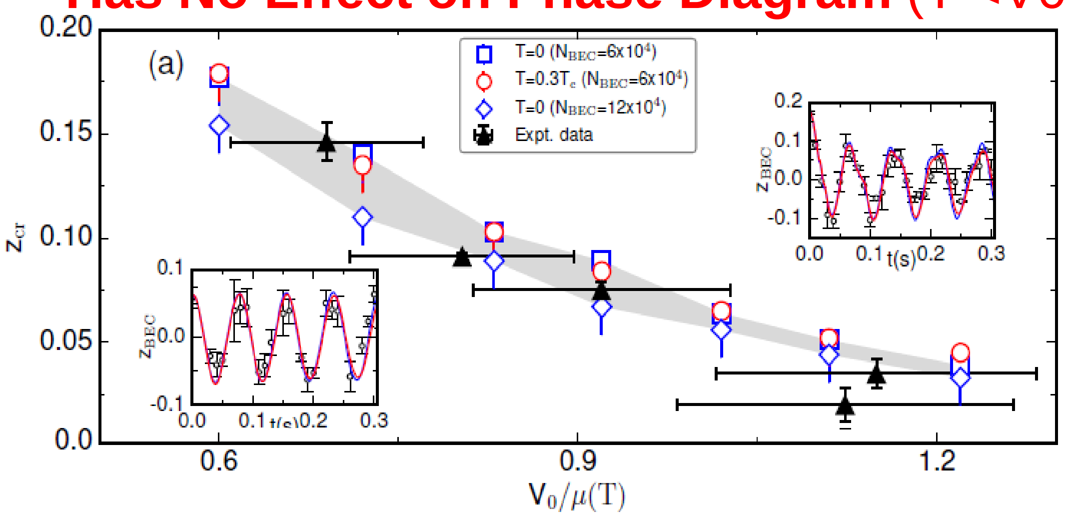


Long-Time Vortex Evolution



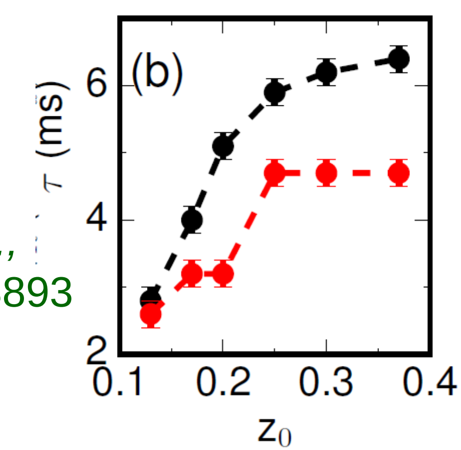
Thermal Cloud

Has No Effect on Phase Diagram (T <V0)



Decreases Vortex Ring Lifetime

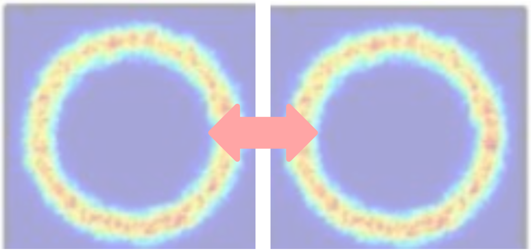
Xhani *et al.*, arXiv:1905.08893



CONNECTING MULTIPLE RING TRAPS

How to Connect 2 Rings ?

Tunneling ???



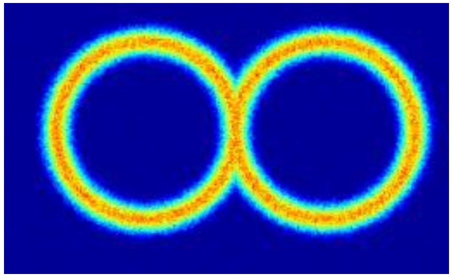
Many Talks in this Meeting

Well Understood
at Single-Particle Level

Role of Interactions ?

First Discuss
Isolated Weak Link

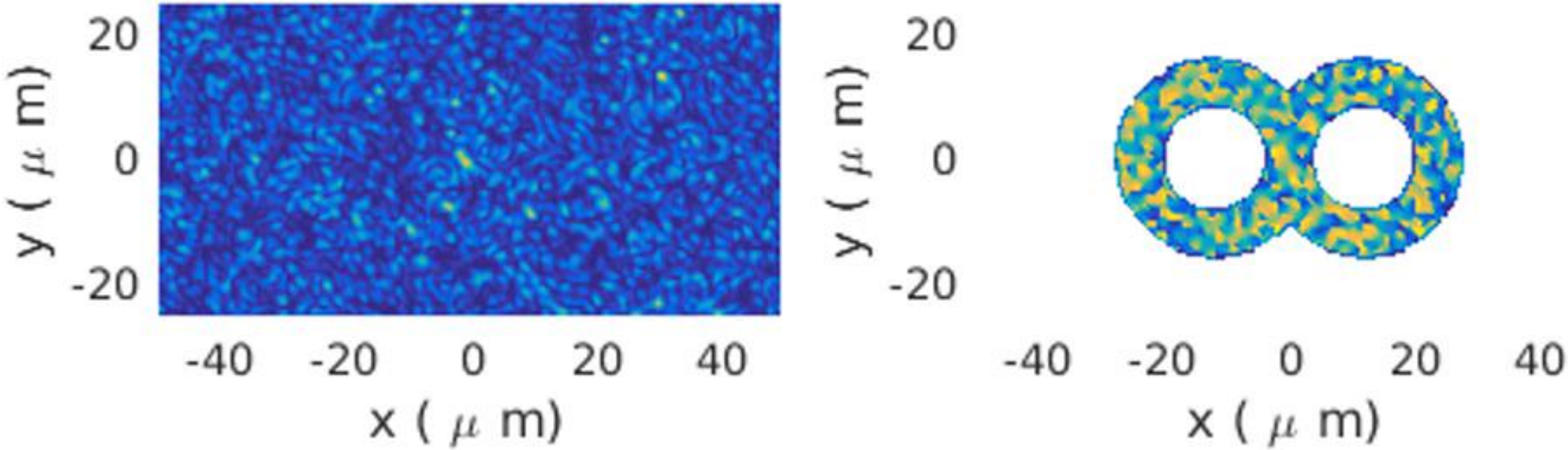
Linked Densities ?

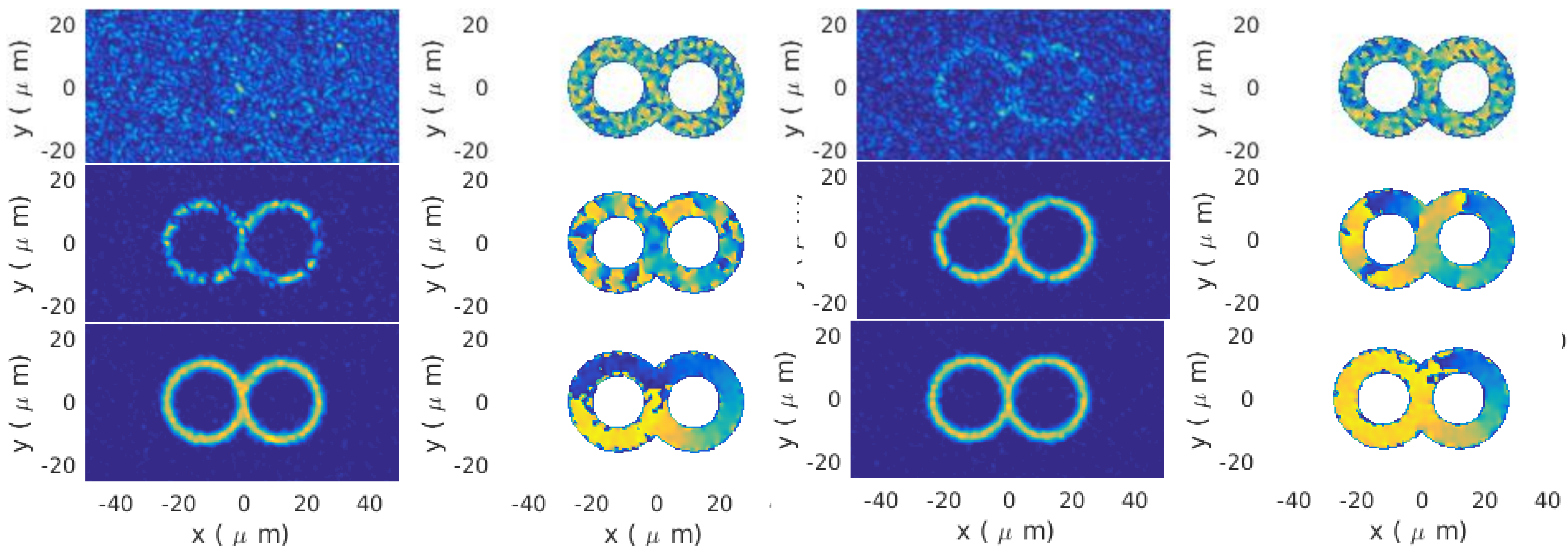


What is Preferred Flow ?

Investigate
Density-Coupled States

DENSITY-CONNECTED RING DYNAMICS

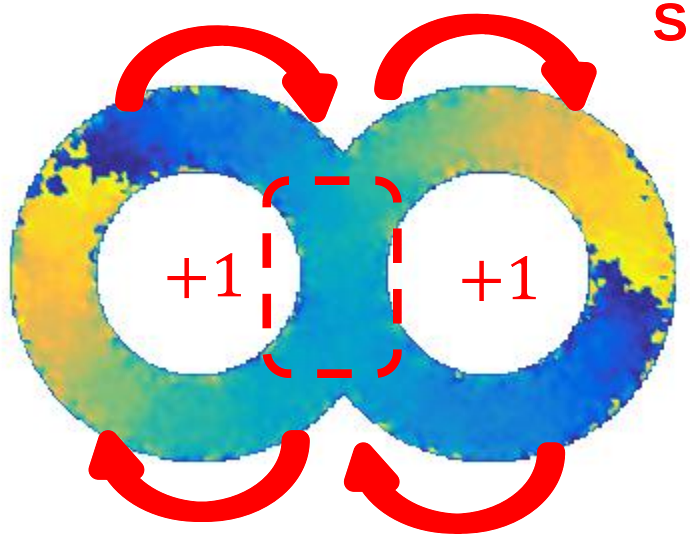




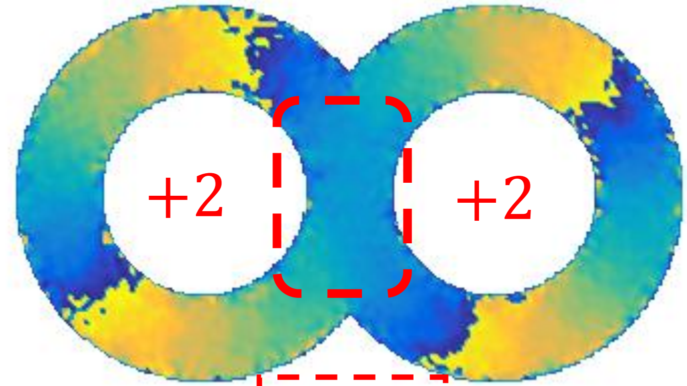
DENSITY-CONNECTED RING DYNAMICS

Can have a whole "zoo" of winding number combinations !

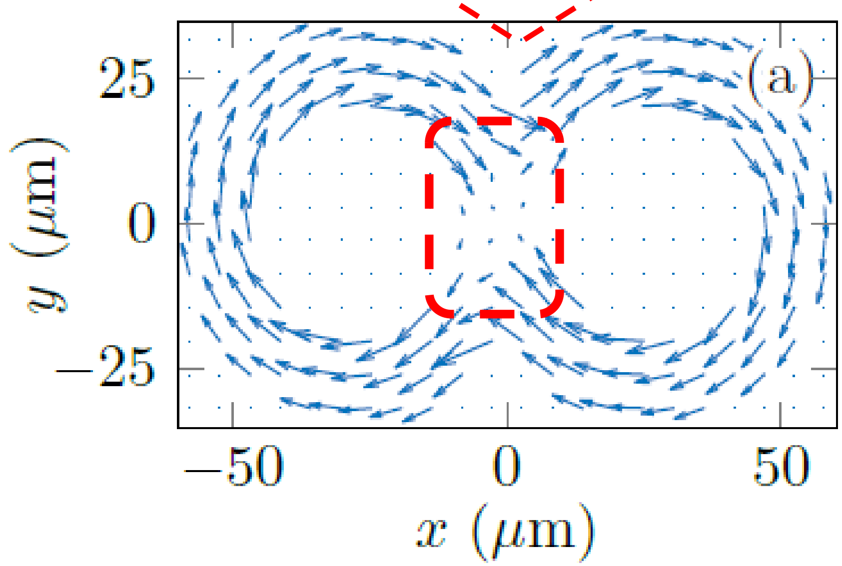
Some Examples:



Flow Along Outer Rim



Corresponding Velocity Field



Bland *et al.*
(In Preparation, 2019)

DENSITY-CONNECTED RING DYNAMICS

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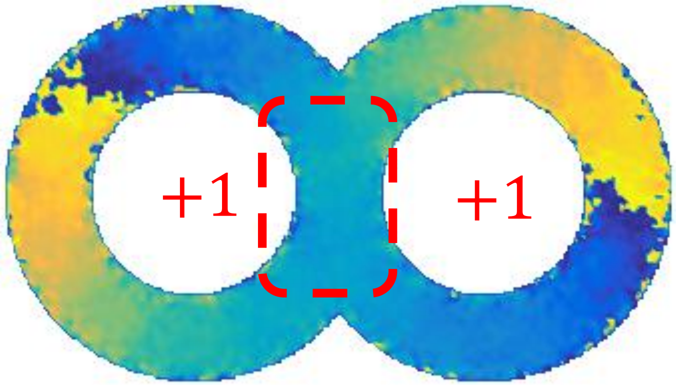
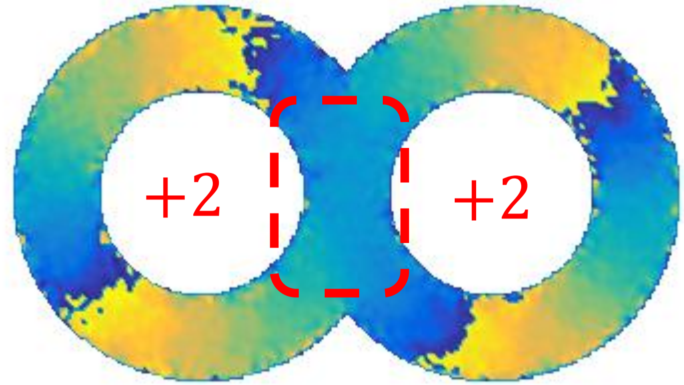
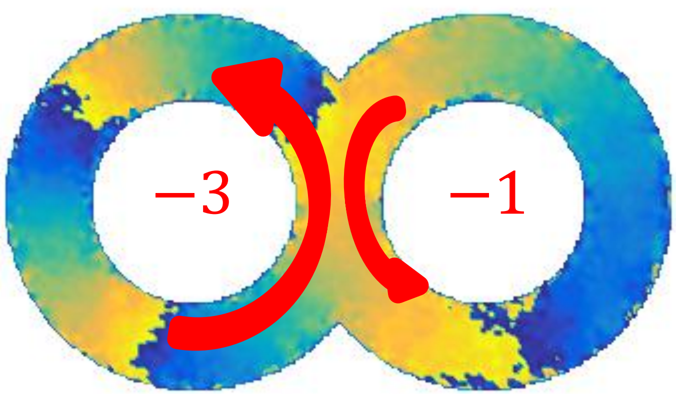
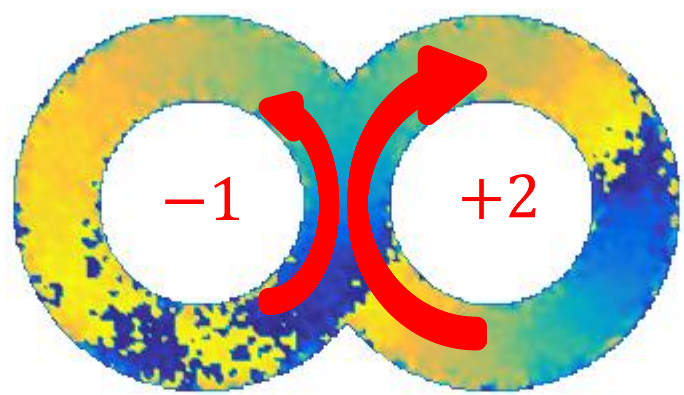


Flow Along Outer Rim



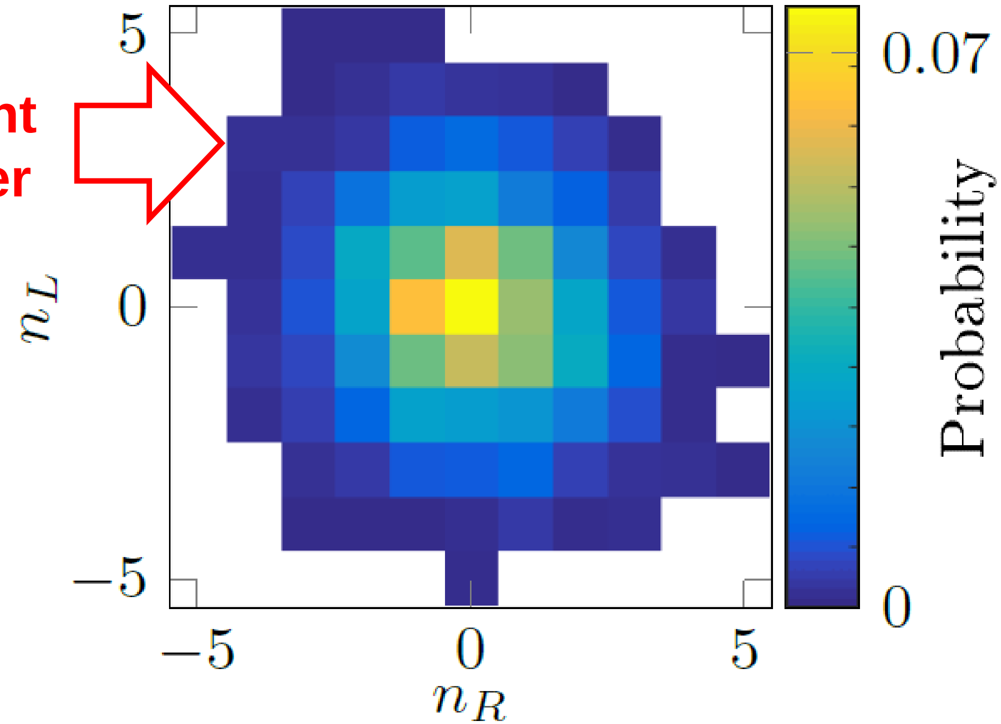


Different Flows Far From Overlap Region

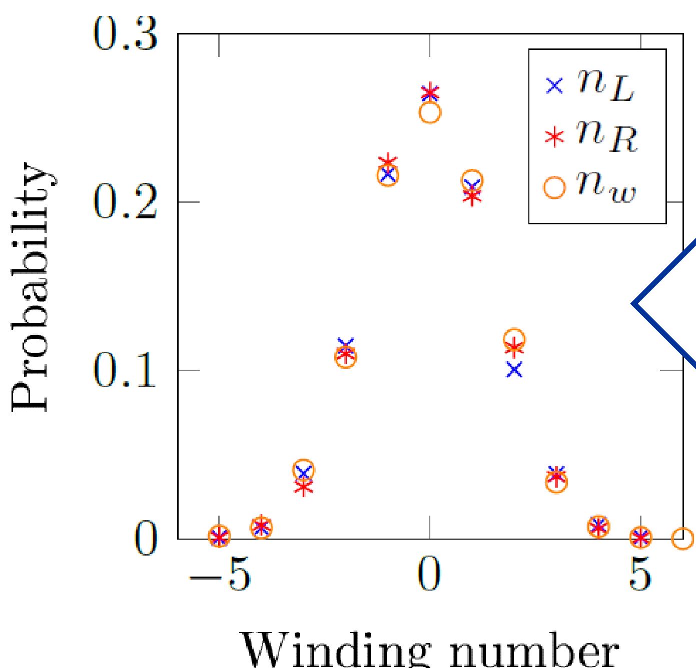


DENSITY-CONNECTED RING DYNAMICS

Analyze Probability of Different Spontaneous Winding Number Combinations



Winding Numbers in Left-Right Wells Appear Uncorrelated

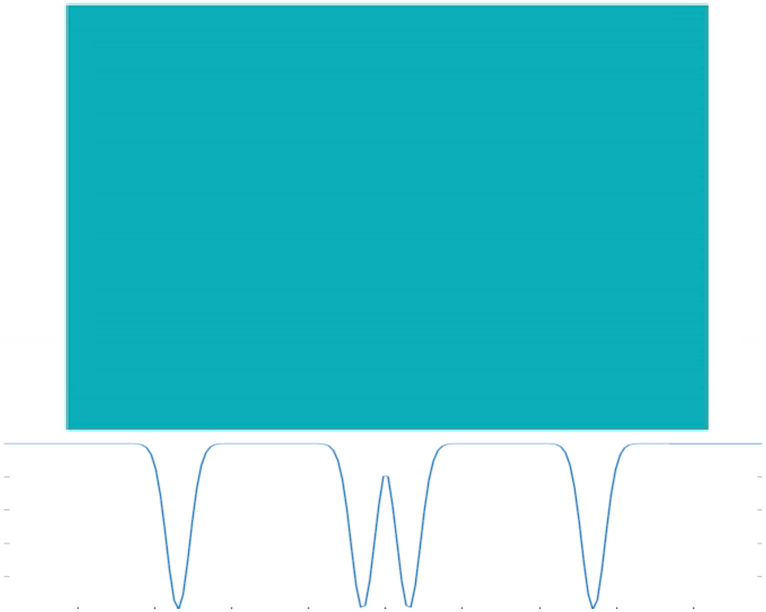


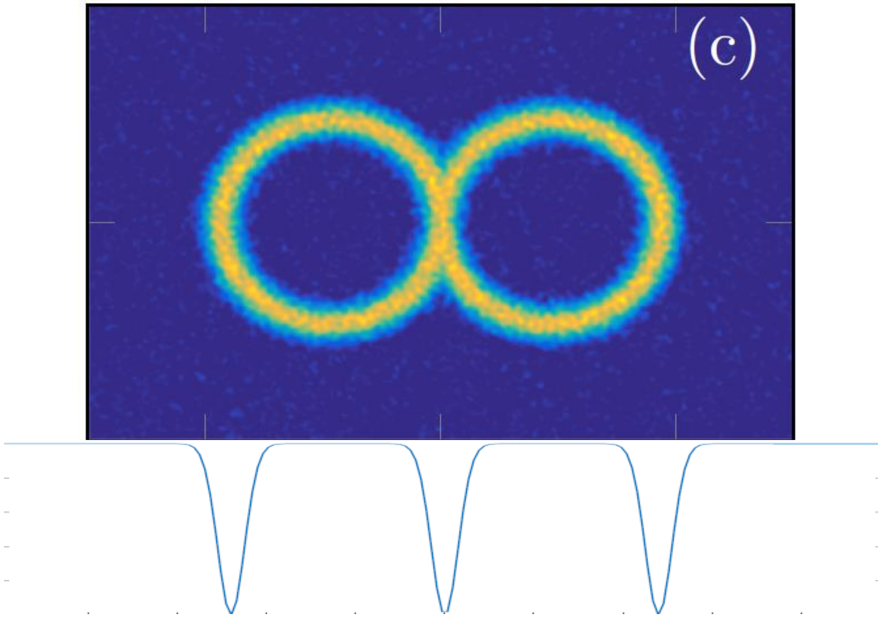
Indeed
Integrating over n_L or n_R Produces Identical Results To Single Ring Case

Bland *et al.*
(In Preparation, 2019)

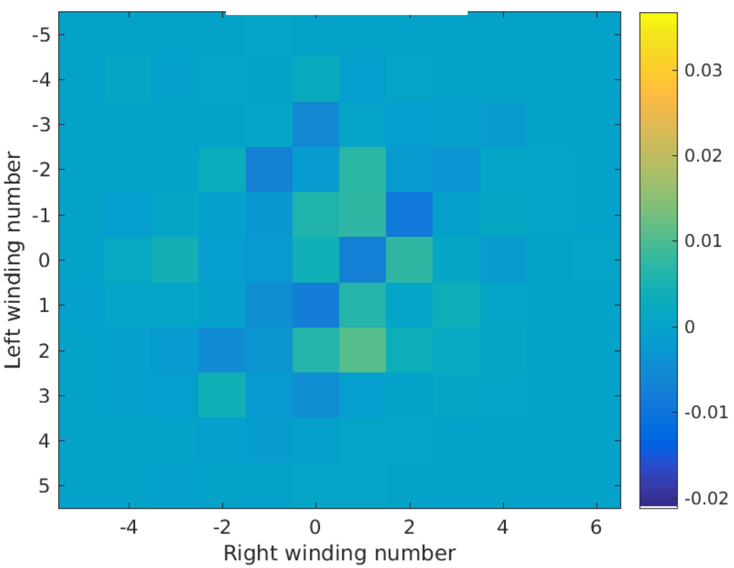
CONNECTED vs. SEPARATED RING DYNAMICS

Spatially-Separated Rings vs. Connected Rings



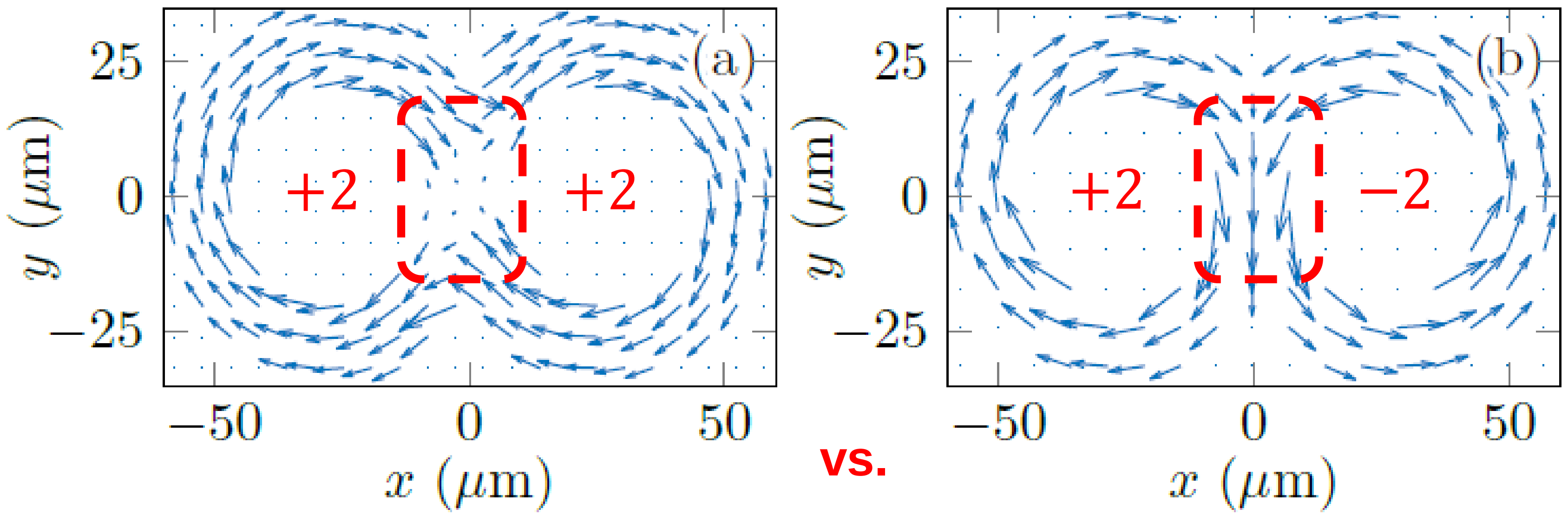


No Detectable Difference In Winding Number Combinations



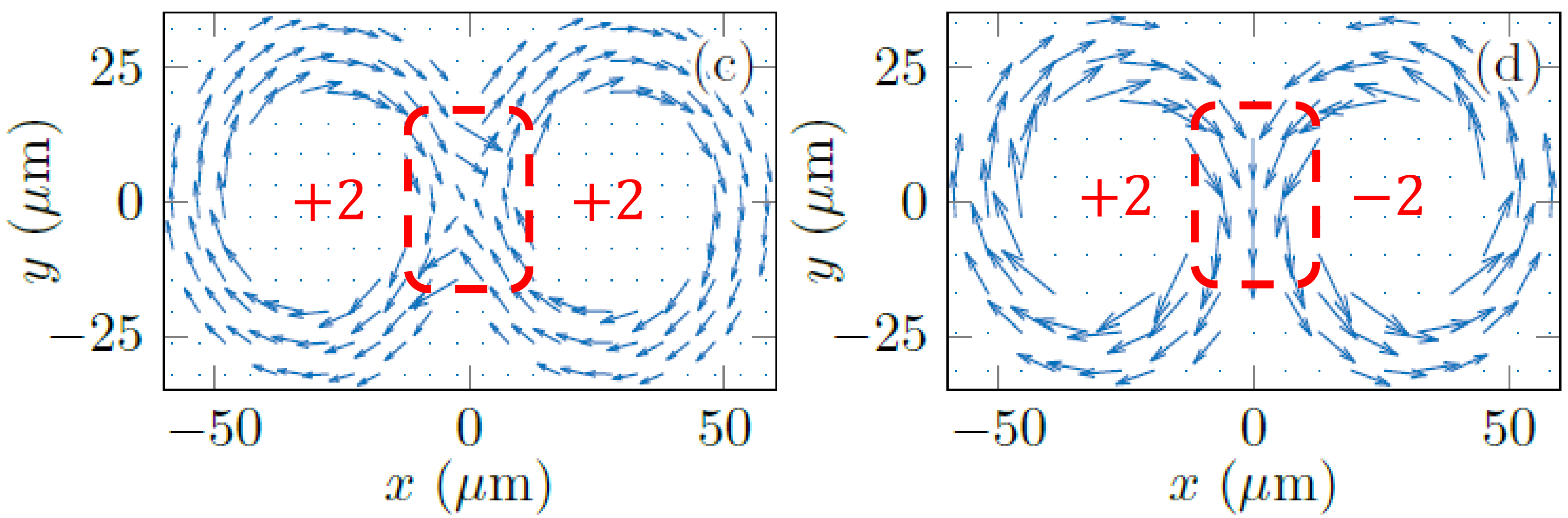
CONNECTED vs. SEPARATED RING DYNAMICS

Connected Rings



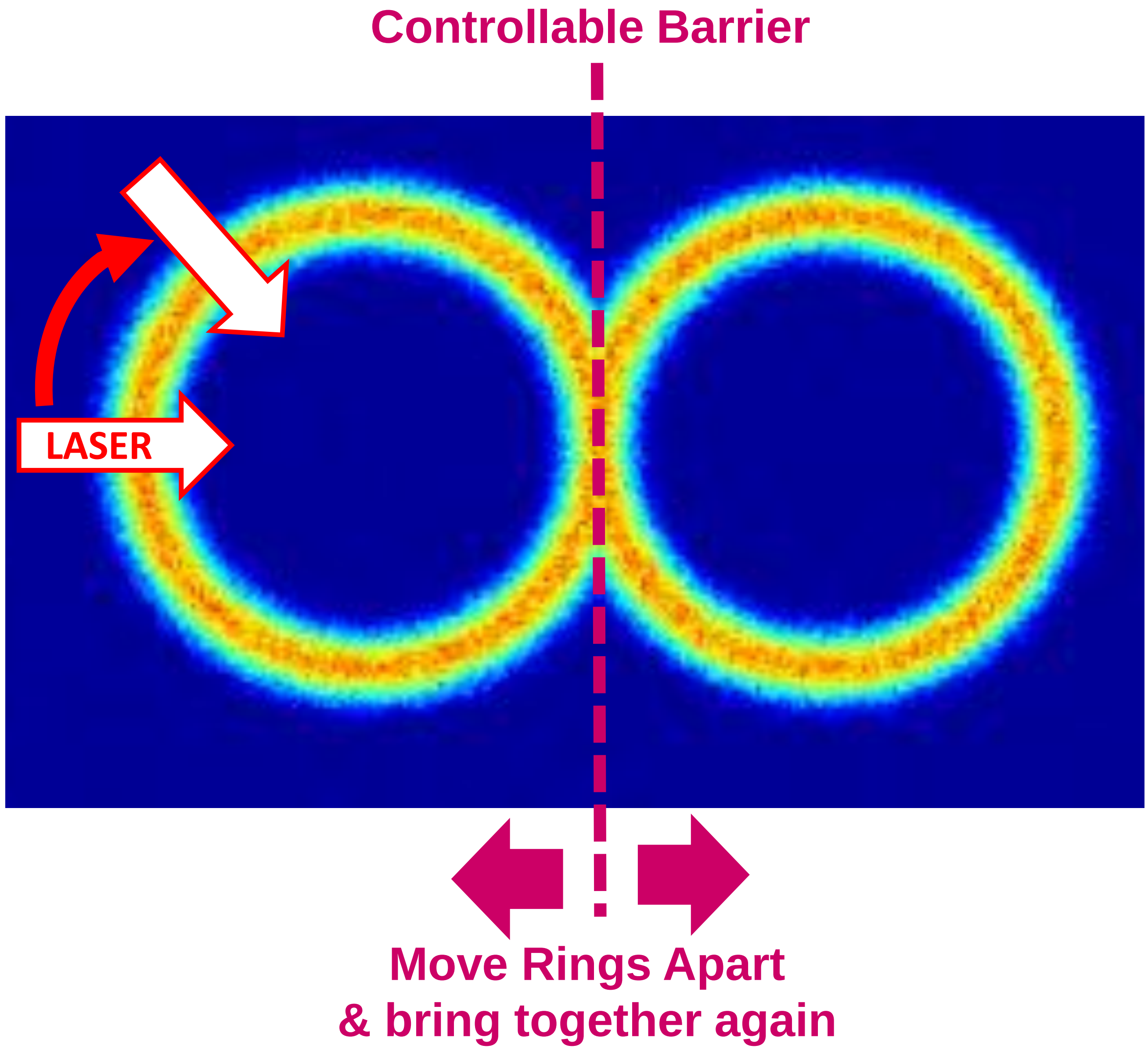
vs.

Spatially-Separated Rings



WHERE NEXT ?

Combine State Preparation, Connected Rings & Controllable Barriers

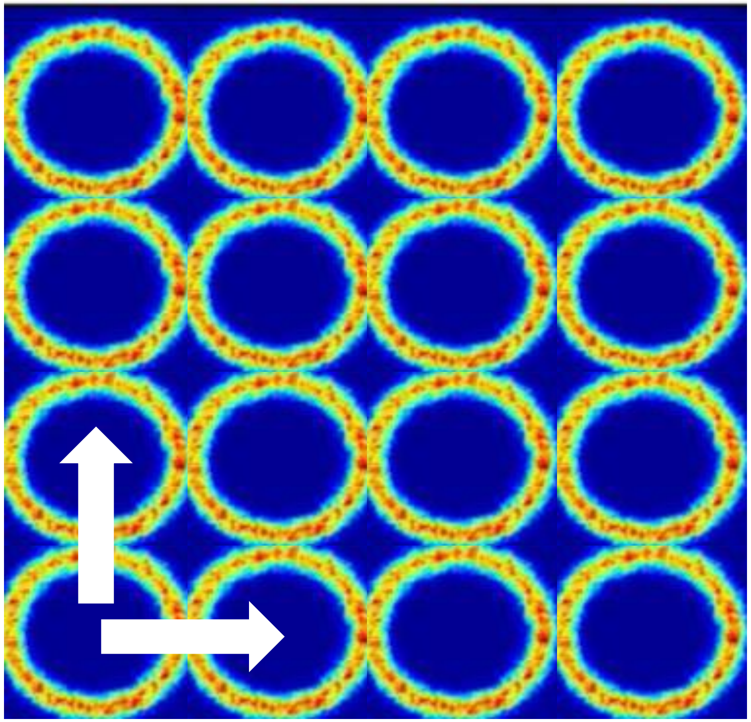


WHERE NEXT ?

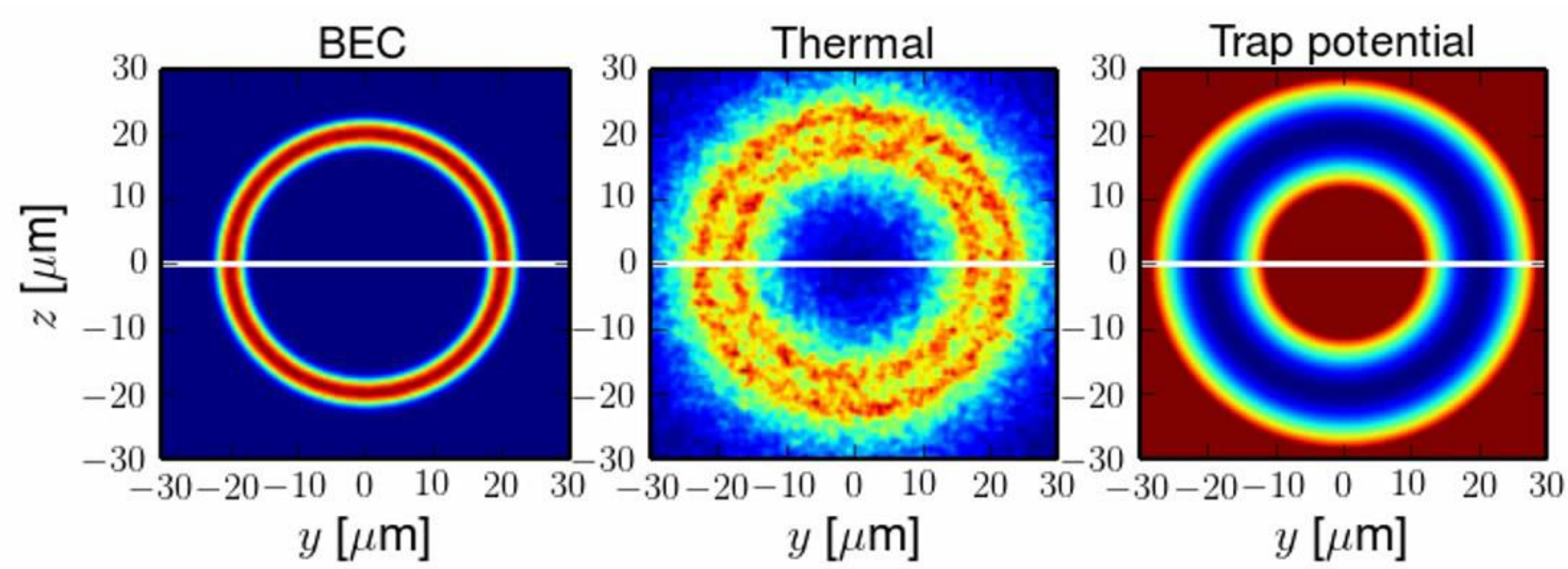
Have Analysed

Possible Initial States
Dissipation Across Weak Links
Dynamics in Single/Connected Rings

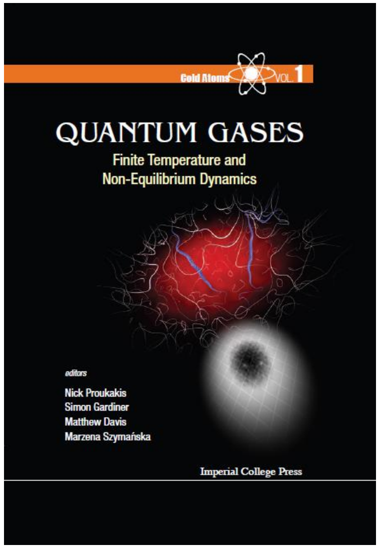
Envisaged Aim:
Atomtronic "Conveyor Belt"



ACKNOWLEDGEMENTS



ACKNOWLEDGEMENTS



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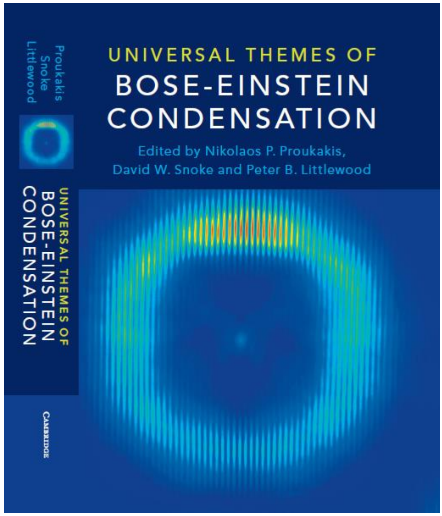
www.JQC.ORG.UK



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