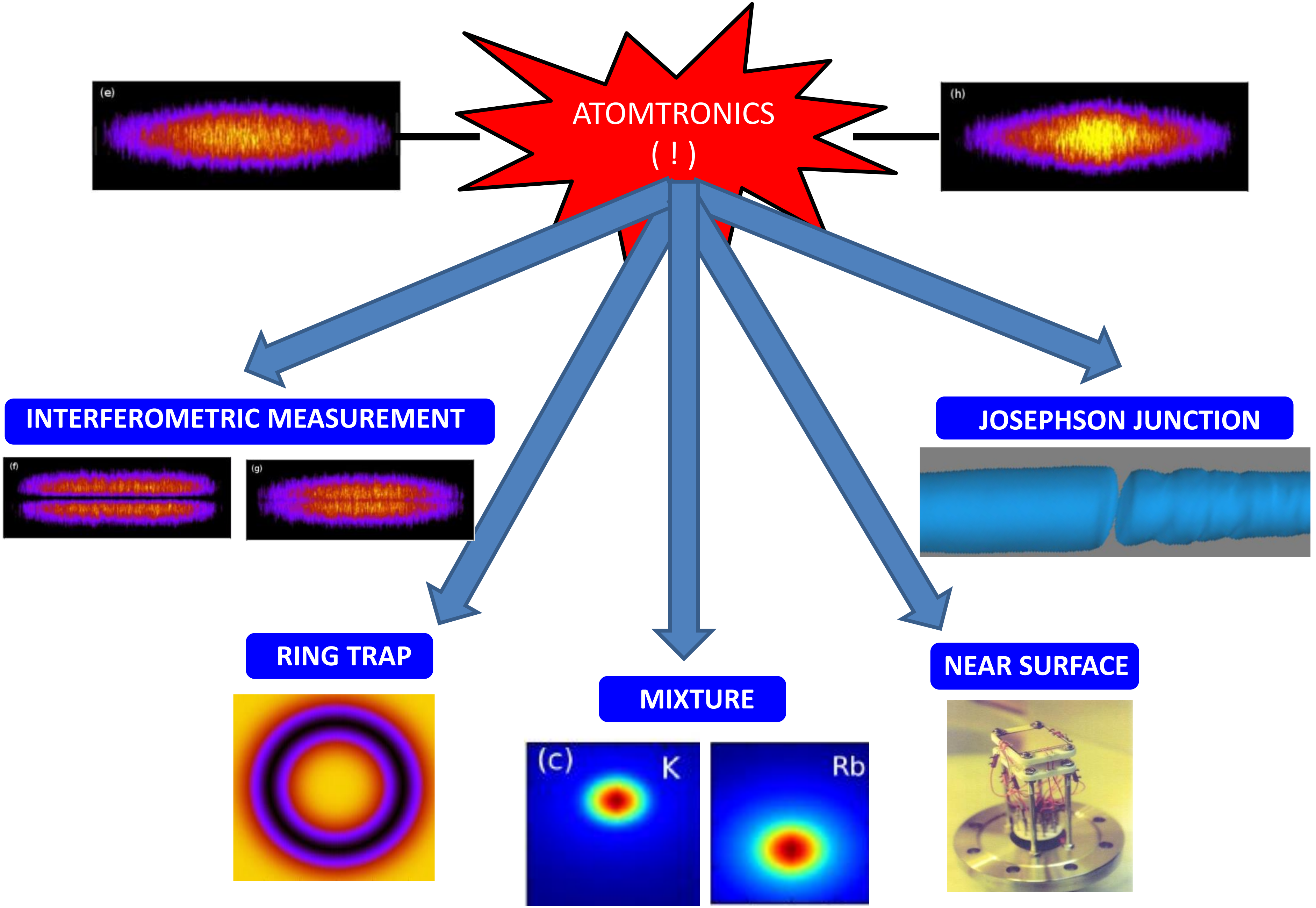
NON-EQUILIBRIUM TECHNIQUES FOR ATOMTRONIC MODELLING

NICK PROUKAKIS

Nick
Proukakis

(MY VERY BIASED) "ATOMTRONICS CARTOON"



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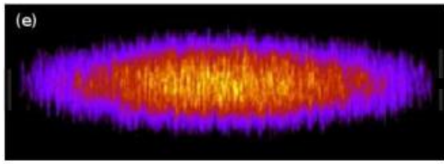
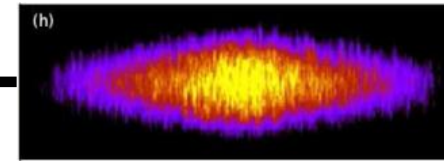


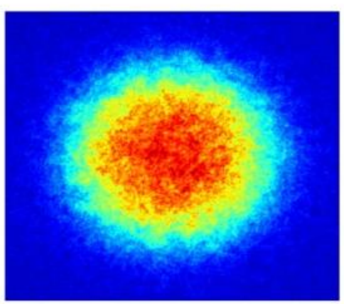
ATOMTRONICS
(!)



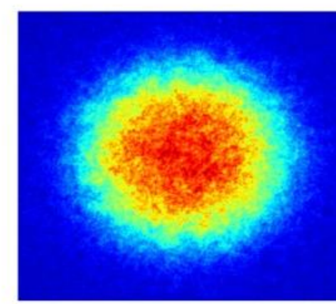
Some Desired Features?

- T = 0 (max coherence)
- 1D-ish & Close to Surface (optimal control)
- Rapid Onset (switches?)

……. Reproducibility , etc… ……….



BUT



(Some) Fluctuations always present
Particularly in 1D & upon rapid quenching

→ Need to Find Optimum Balance: Theory can (hopefully) help ?

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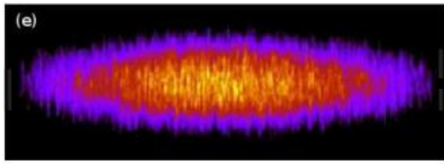
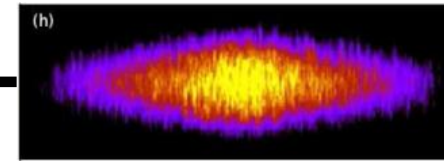
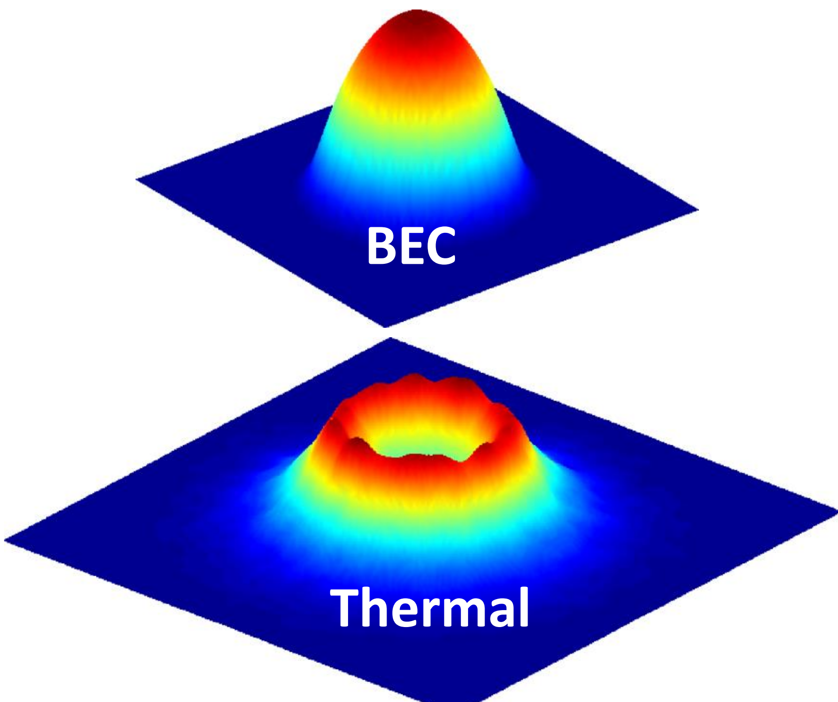


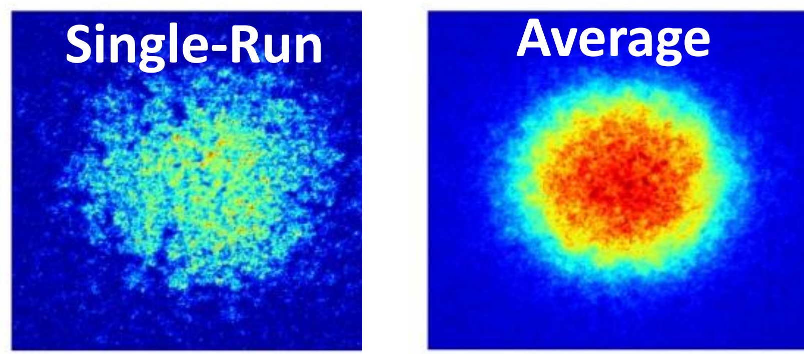
(Selected)
ATOMTRONICS
MODELLING
TECHNIQUES



Transport:
(Self-Consistent) Kinetic Theories



Rapid Dynamics / Fluctuations:
Stochastic Approaches



This Talk:
Present Methods & Selected Applications

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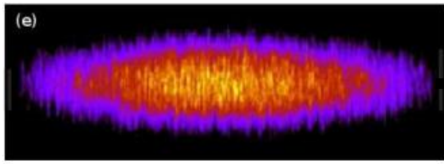
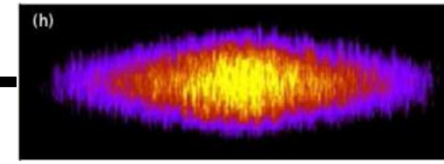
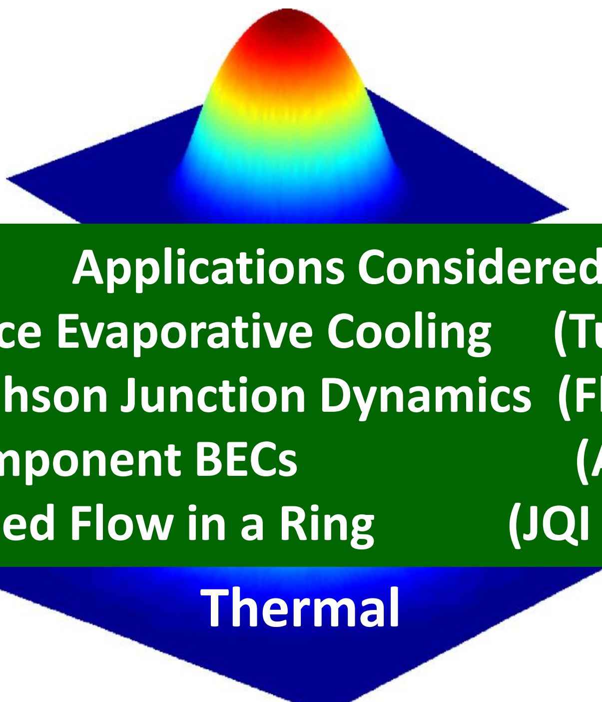


(Selected) ATOMTRONICS MODELLING TECHNIQUES



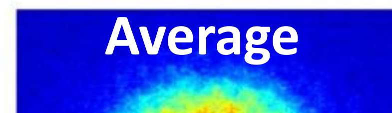
Transport: (Self-Consistent) Kinetic Theories



Applications Considered:

* Surface Evaporative Cooling (Tubingen)
* Josephson Junction Dynamics (Florence)
* 2-Component BECs (Aarhus)
* Induced Flow in a Ring (JQI Geometry)

Rapid Dynamics / Fluctuations: Stochastic Approaches



Applications Considered:

* Kibble-Zurek (Trento / Paris)
* Ring Traps (JQI Geometry)
* Double-Rings

****** Future Prospects ??? ******

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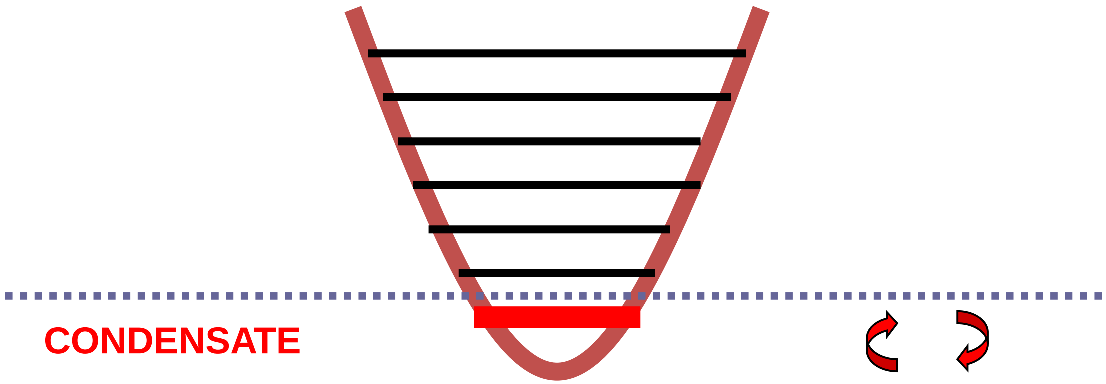
“BEST” KINETIC THEORY (“ZNG”)



BOSE-EINSTEIN
CONDENSATE

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

GROSS-PITAEVSKII

$$i\hbar \frac{\partial \phi}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2m} + V_{TRAP} + g(n_C \qquad \right) \phi$$

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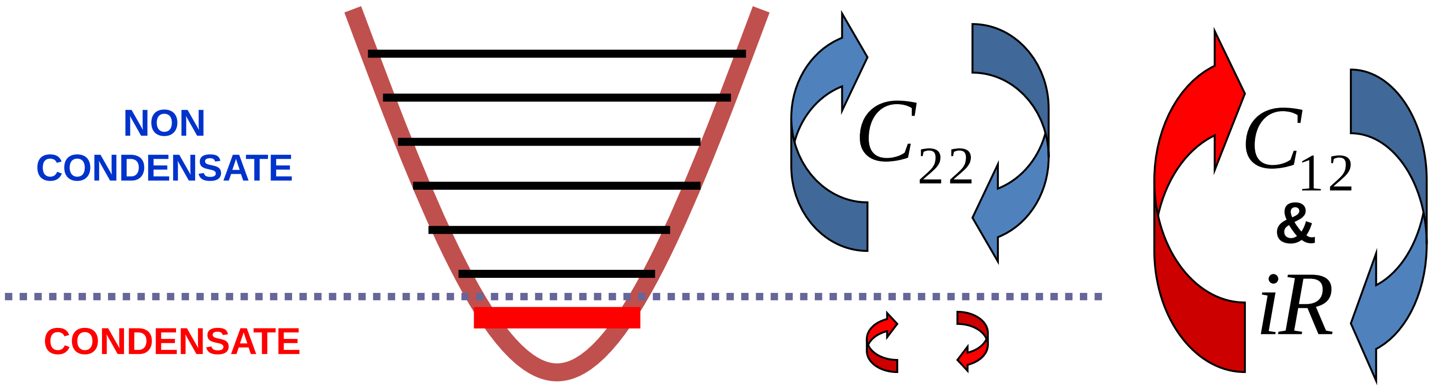
"BEST" KINETIC THEORY ("ZNG")



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

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

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

EXCHANGE OF ATOMS BETWEEN SUB-SYSTEMS

THERMAL COLLISIONS

Zaremba, Nikuni & Griffin
J Low Temp Phys 116, 277 (1999)

$$R(r,t) = (\hbar / n_C) \int dp C_{12}[f]$$

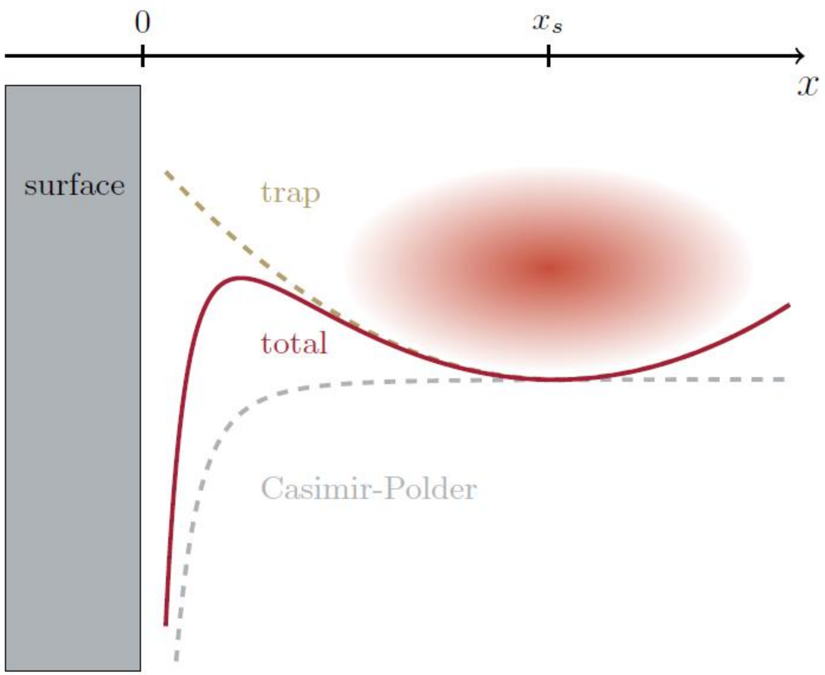
SURFACE EVAPORATIVE COOLING

Study Surface Evaporative Cooling on a Room-Temperature Surface

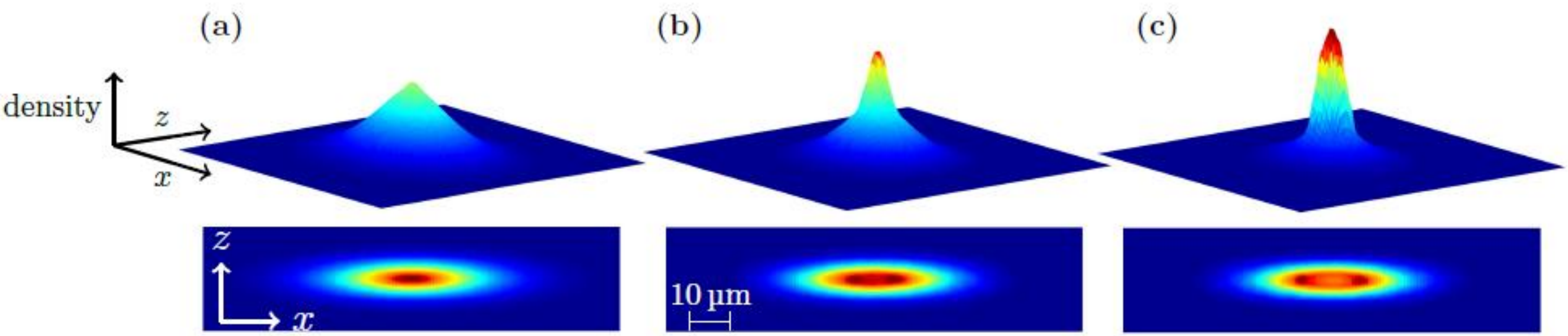
by moving thermal cloud (~100's nK) onto room-temperature surface (300 K)
from initial distance ~100µm at constant speed
& observing atom loss rate vs. time at different distances from surface

J Maerkle, AJ Allen et al., PRA 90, 023614 (2014)

Effective Potential Schematic near Surface



SURFACE EVAPORATIVE COOLING

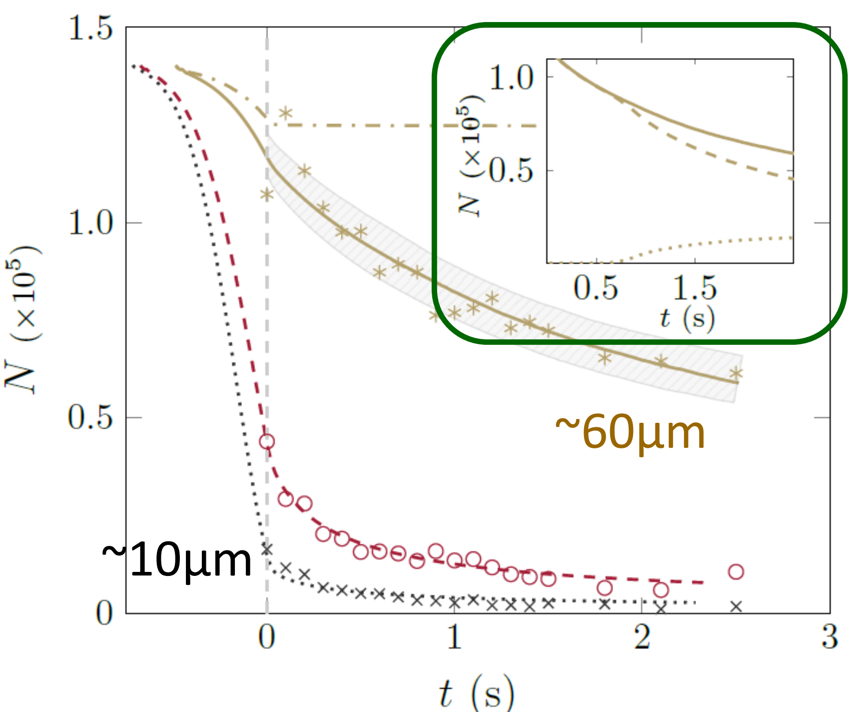


Measure atom loss rates vs. time for cloud moved towards surface

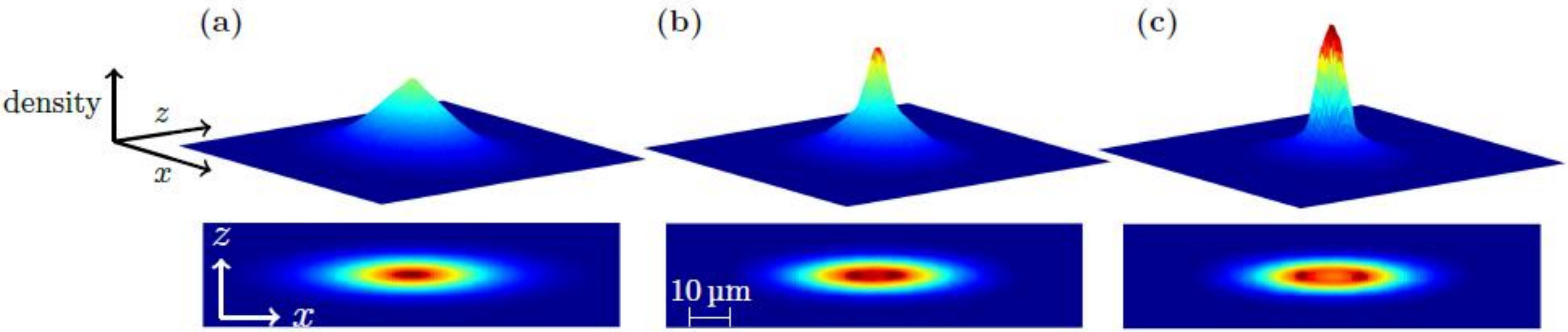
Theory-Experiment Comparison

(different "hold" positions)

J Maerkle, AJ Allen et al., PRA 90, 023614 (2014)

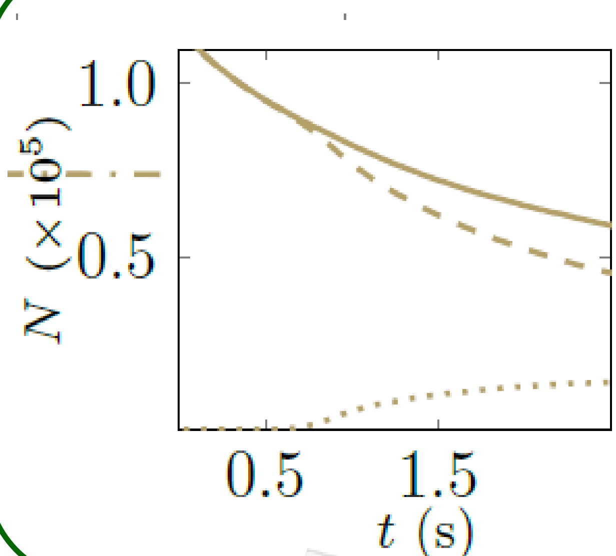


SURFACE EVAPORATIVE COOLING



Measure atom loss rates vs. time for cloud moved towards surface

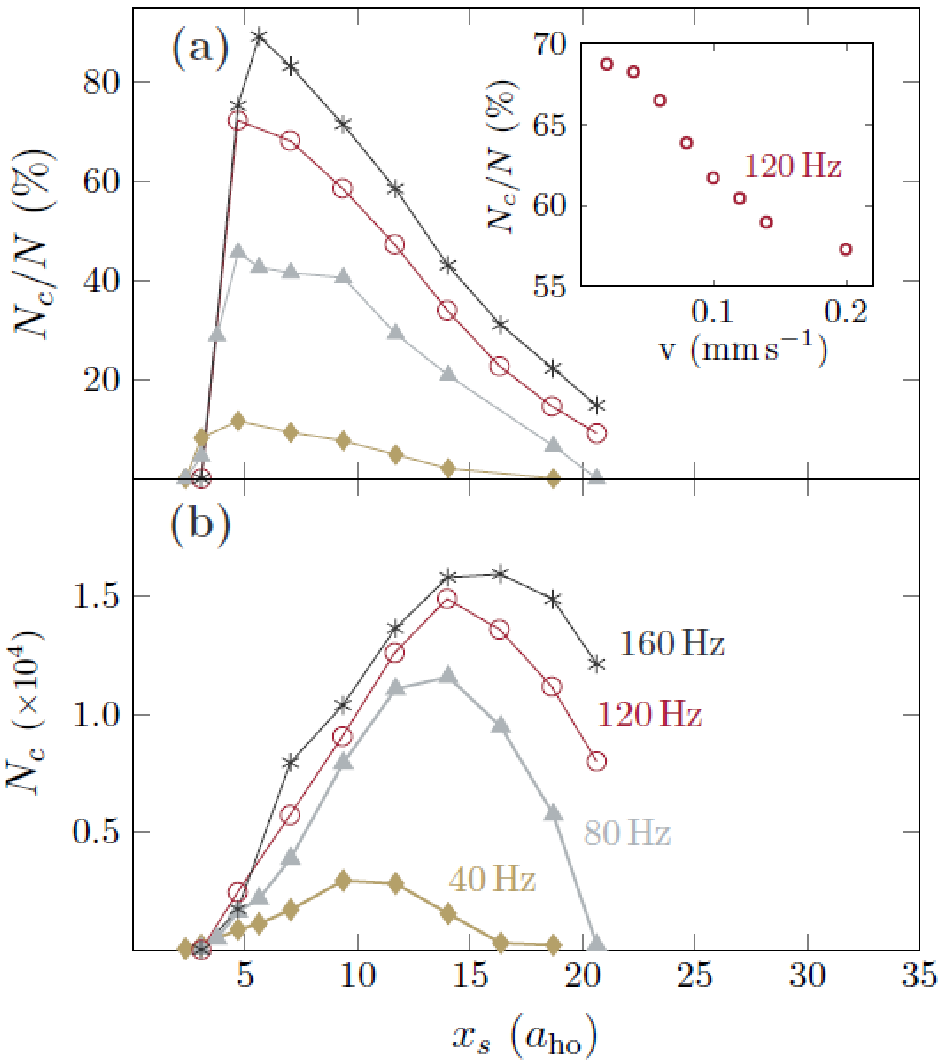
J Maerkle, AJ Allen et al.,
PRA 90, 023614 (2014)



BEC Growth!

SURFACE EVAPORATIVE COOLING

In trying to optimize surface cooling efficiency, we find:



Condensate Fraction is maximised very close to surface & saturates at very low velocities

Condensate Number is however maximised further away from the surface

J Maerkle, AJ Allen et al., PRA 90, 023614 (2014)

… suggesting the existence of an optimum distance from the surface for large pure condensates

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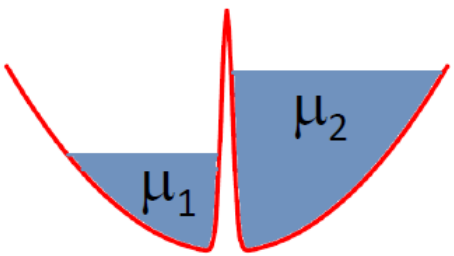
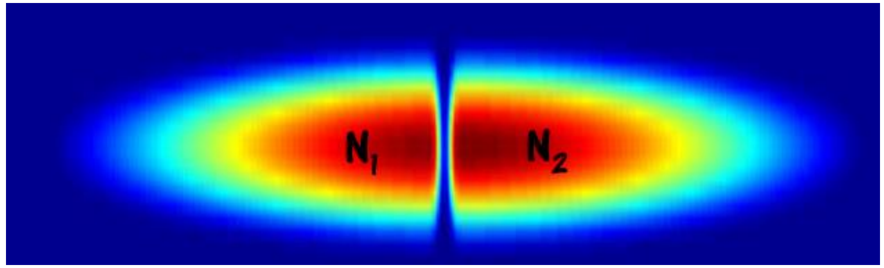
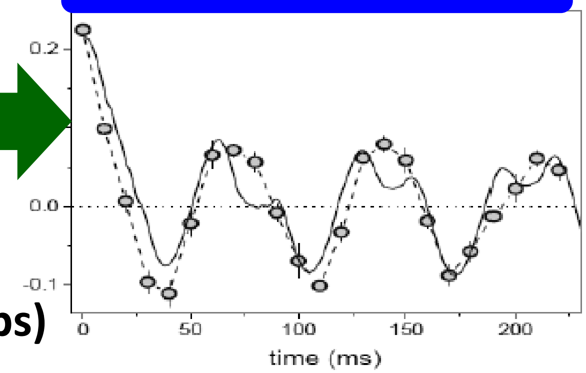
JOSEPHSON DYNAMICS MODELLING



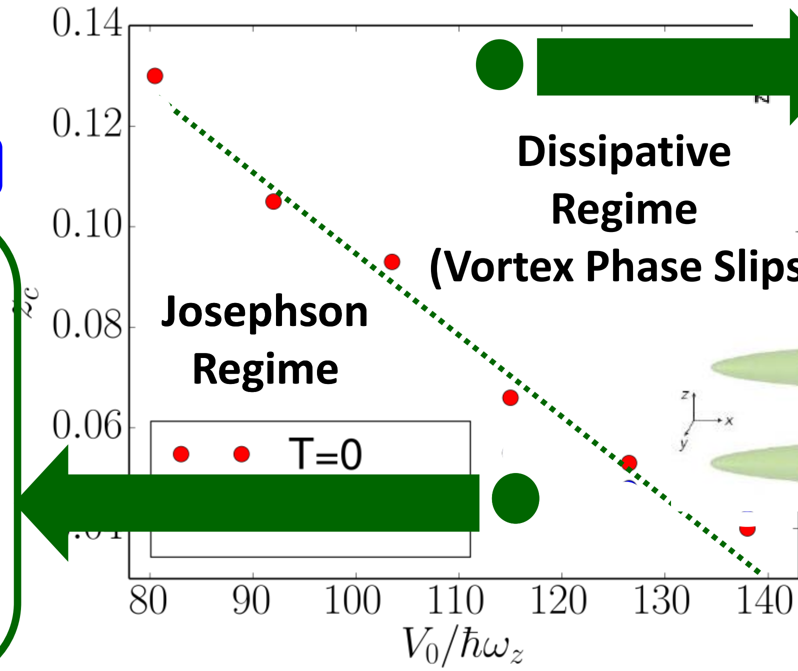


Talk by Alessia Burchianti (LENS)

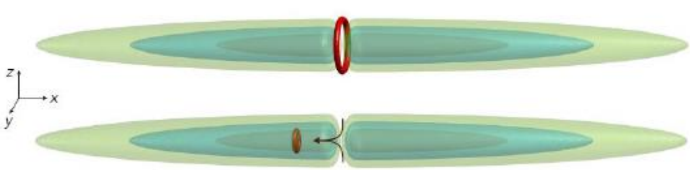
DISSIPATIVE REGIME



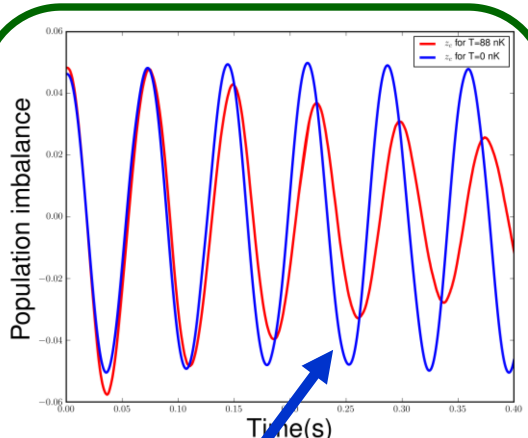
PHASE DIAGRAM



BARRIER HEIGHT



JOSEPHSON REGIME



T = 0

See also Piazza-Smerzi-Guilleumas et al. (2011+)

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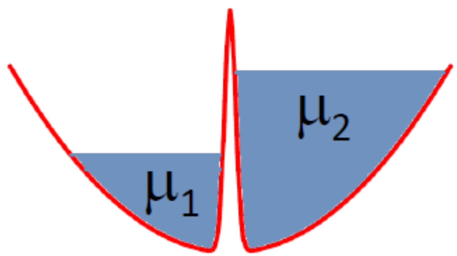
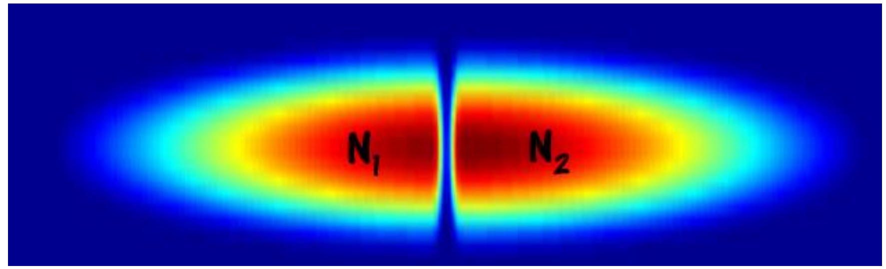
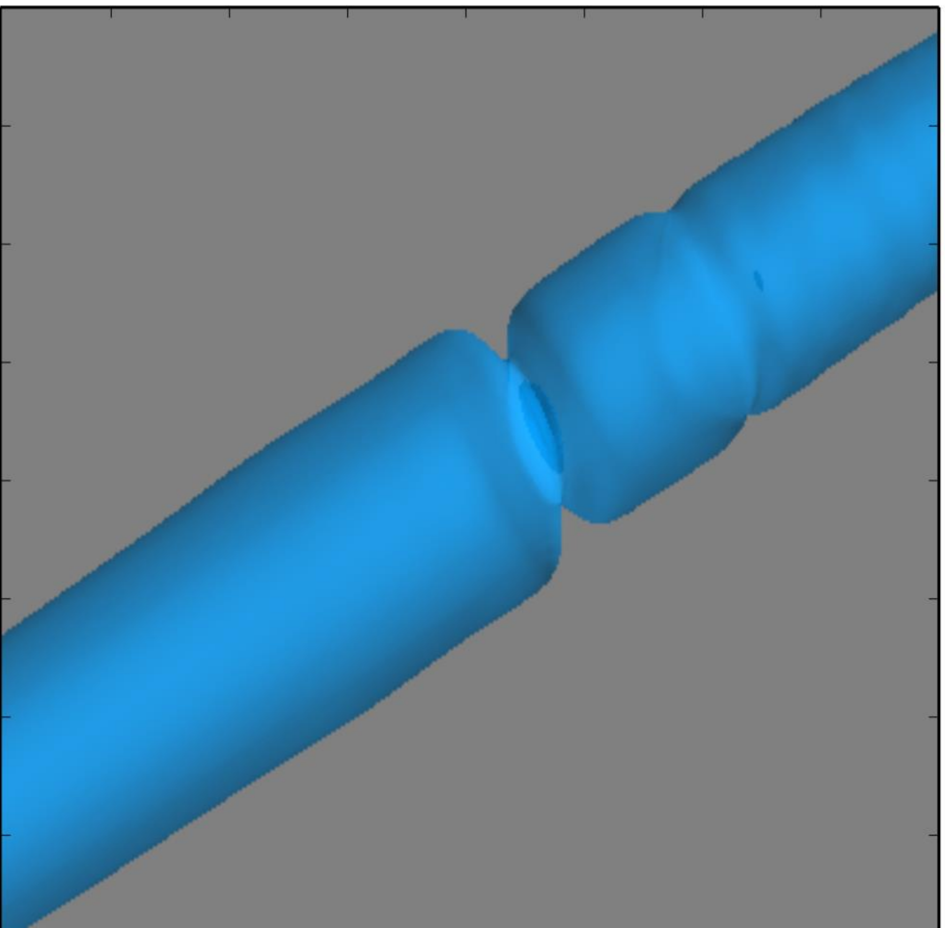
JOSEPHSON DYNAMICS MODELLING





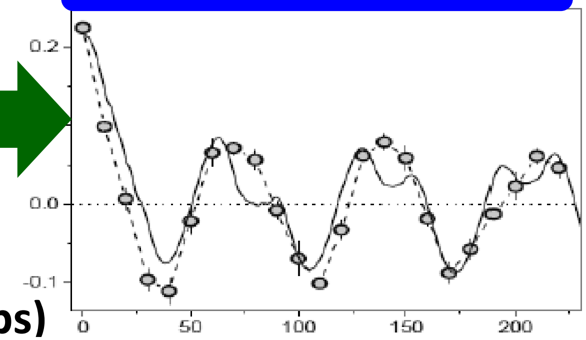
Talk by
Alessia Burchianti
(LENS)



E DIAGRAM

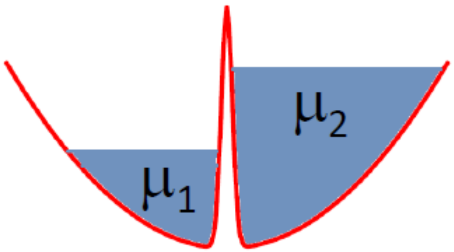
Dissipative
Regime
(Vortex Phase Slips)

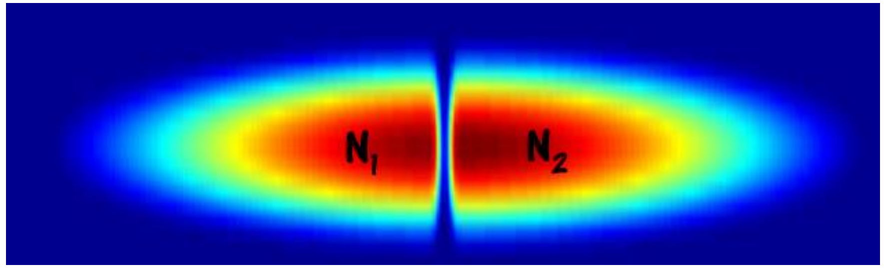
DISSIPATIVE REGIME



… but …
why do experiments see vortices
after a much longer wait time ?

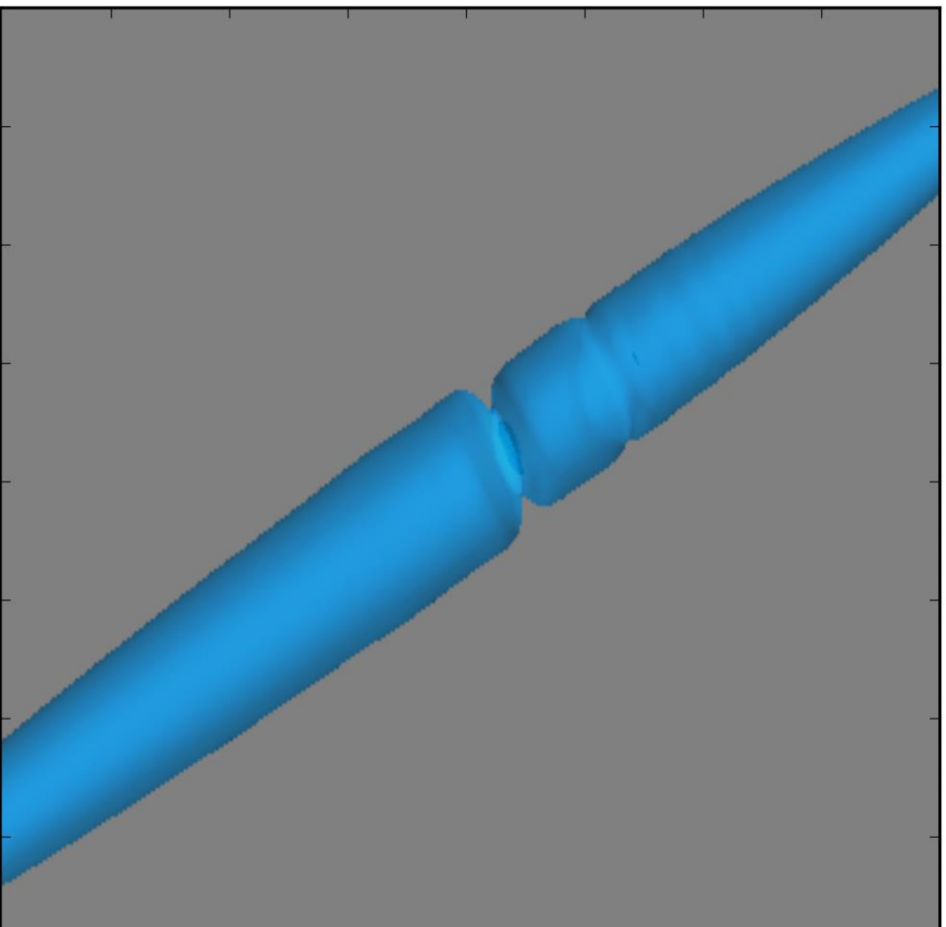
JOSEPHSON DYNAMICS MODELLING





Talk by
Alessia Burchianti
(LENS)

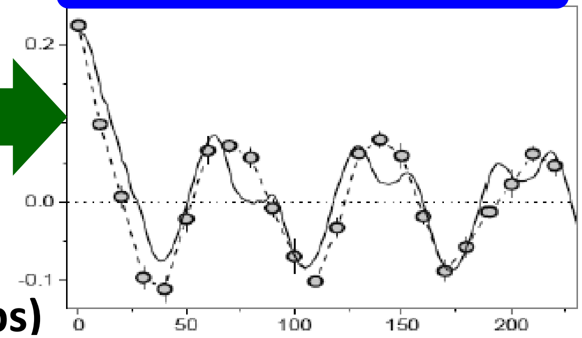
Vortex Ring Dynamics with Barrier Removal



E DIAGRAM

Dissipative Regime (Vortex Phase Slips)

DISSIPATIVE REGIME



… but …
why do experiments see vortices after a much longer wait time ?

→ Barrier Removal (for Imaging) actually *enhances* vortex ring lifetime!

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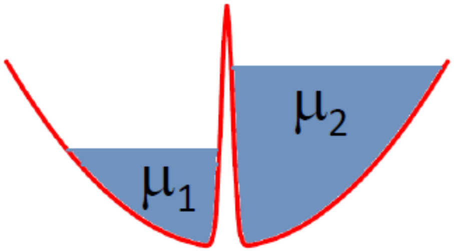
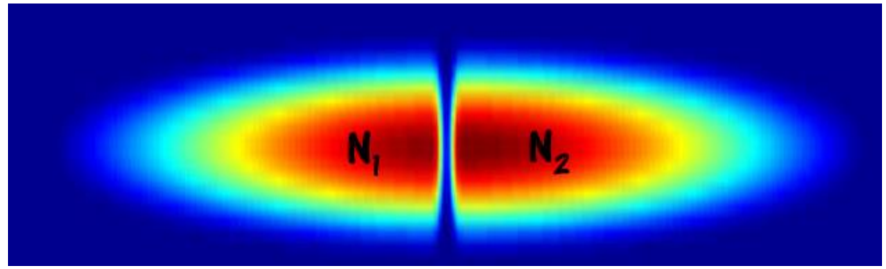
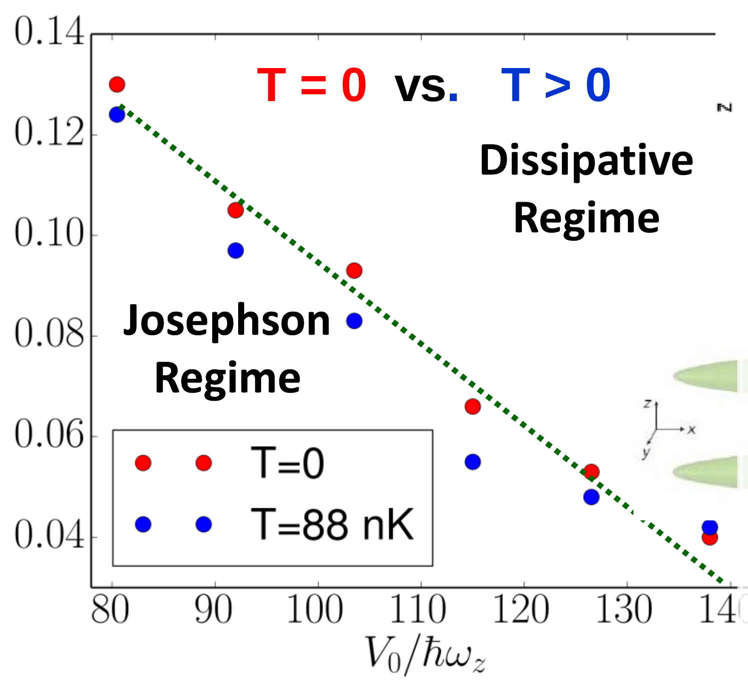
JOSEPHSON DYNAMICS MODELLING





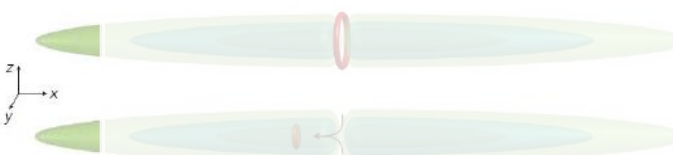
Talk by Alessia Burchianti (LENS)

PHASE DIAGRAM



BARRIER HEIGHT

DISSIPATIVE REGIME



See also Piazza-Smerzi et al. (2011+)

JOSEPHSON REGIME

Only a minor shift to *Phase Diagram* when comparing cases of equal *condensate* number !
… but … *Dynamics* within each region significantly affected !

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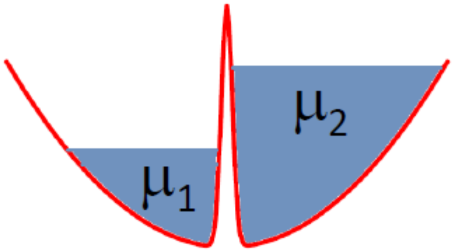
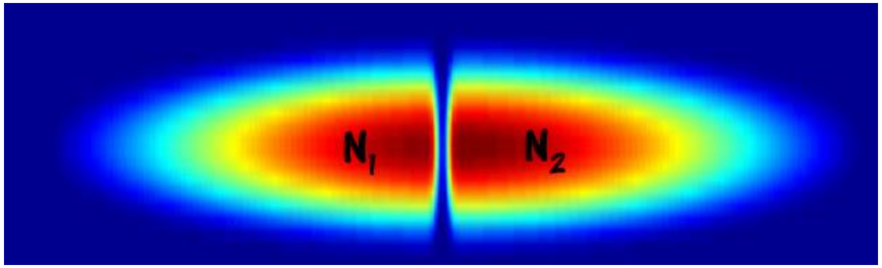
JOSEPHSON DYNAMICS MODELLING





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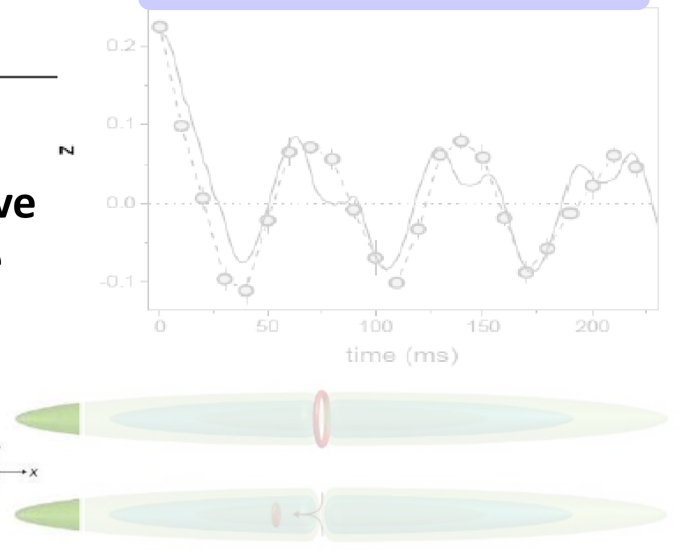
DISSIPATIVE REGIME



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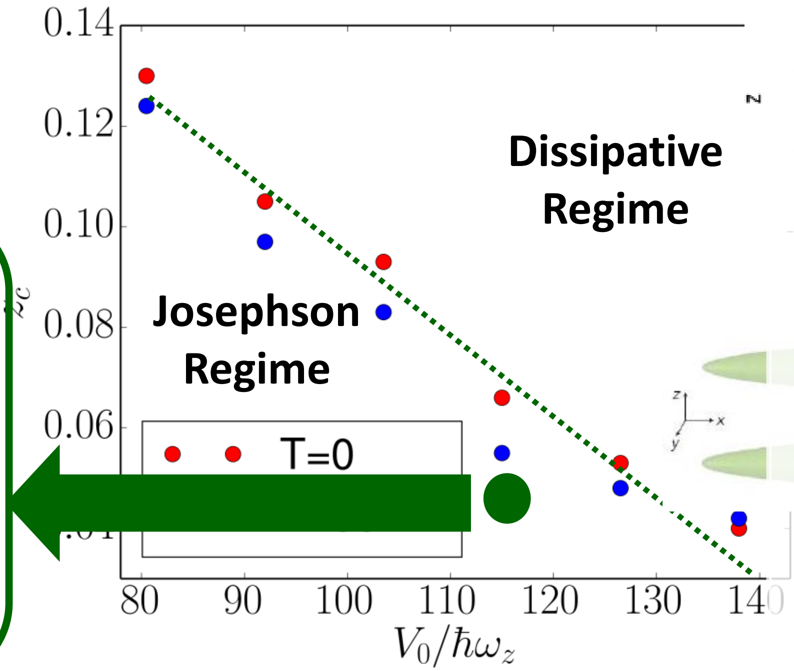
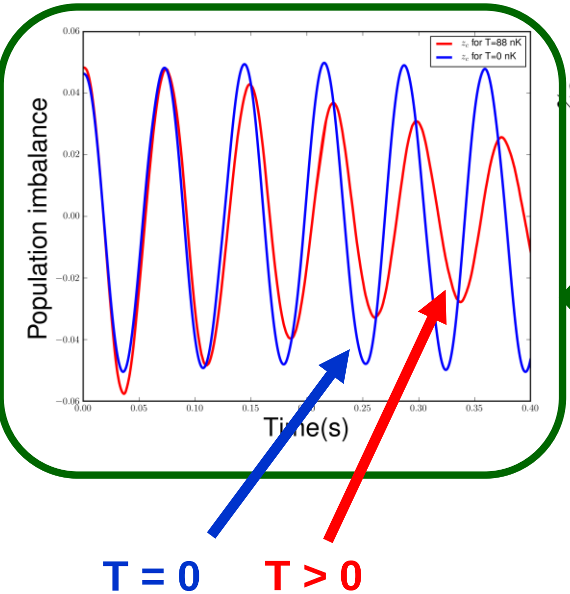


JOSEPHSON REGIME



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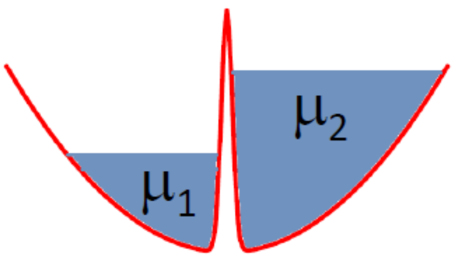
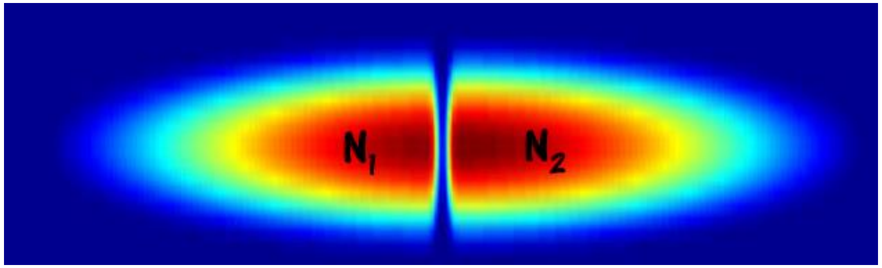
JOSEPHSON DYNAMICS MODELLING





Talk by
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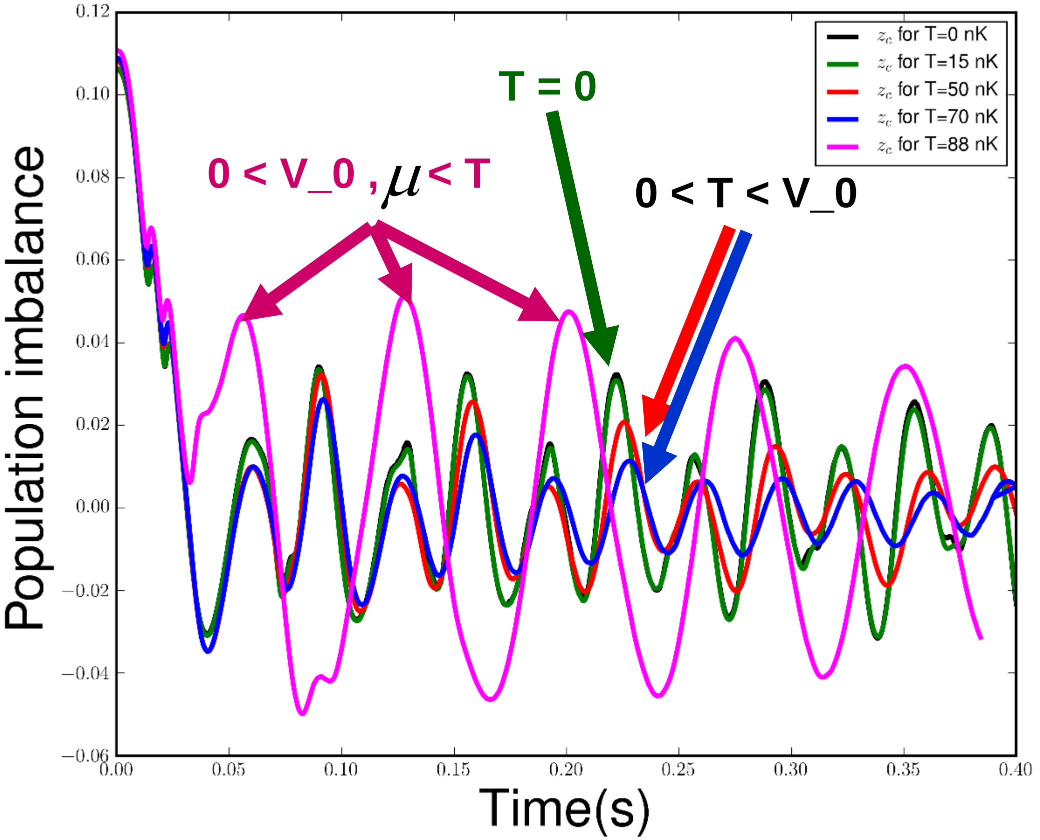
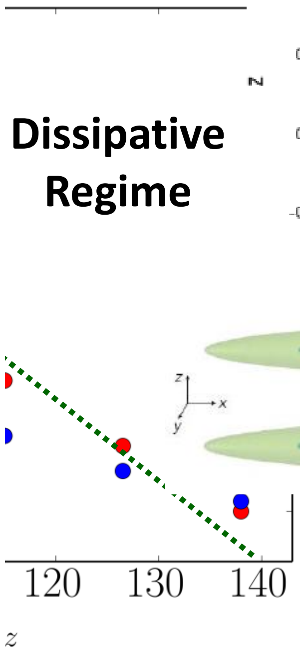
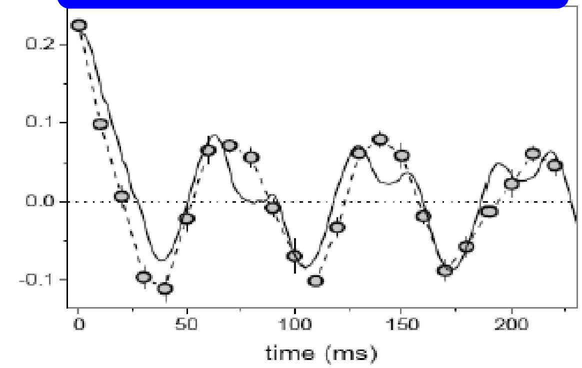
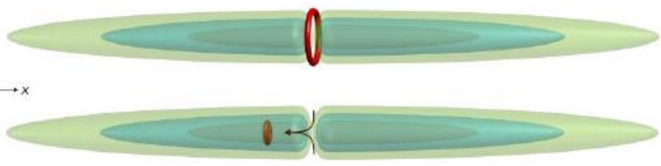
PHASE DIAGRAM





DISSIPATIVE REGIME

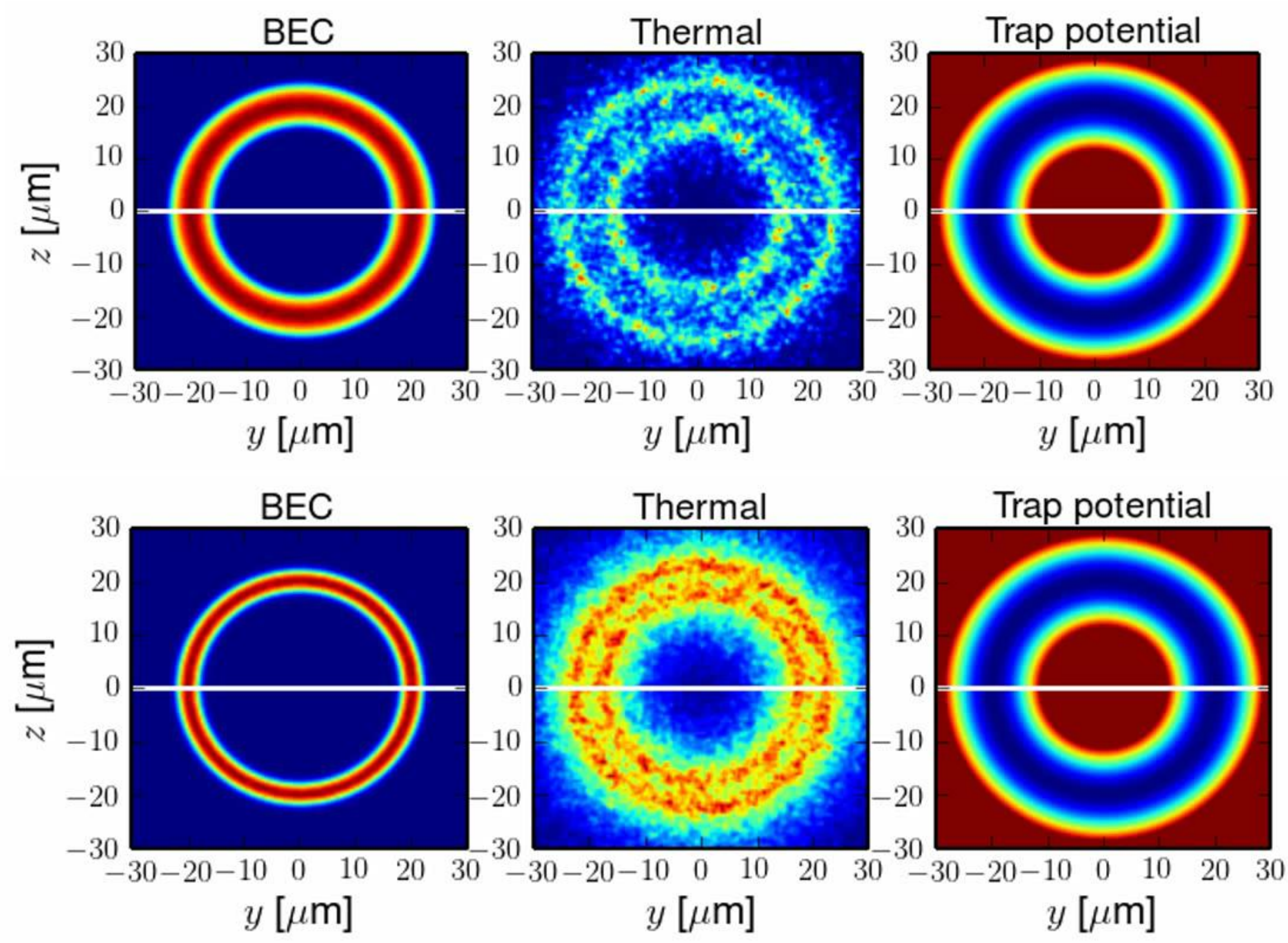




RING TRAP "TOY SIMULATIONS"

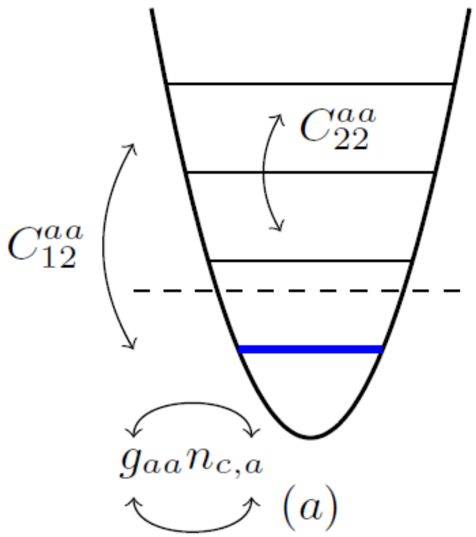
T = 300 nK

T = 600 nK



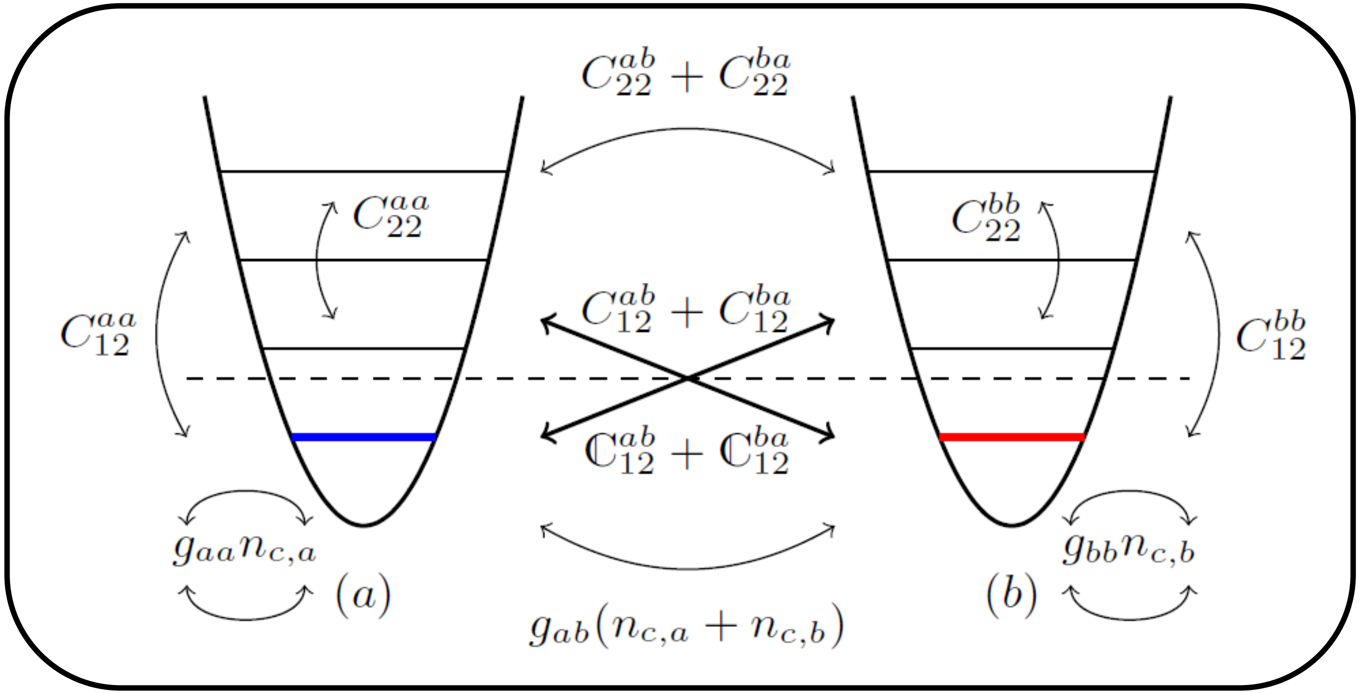
Temperature can actually *suppress* "unwanted" BEC excitations – can this be utilised ?

T > 0 TWO-COMPONENT CONDENSATE THEORY



Single-Component
Self-Consistent
Kinetic Equation
("ZNG")

T > 0 TWO-COMPONENT CONDENSATE THEORY



→ Identify & Characterise "Novel" Collisional Processes

Lee, Edmonds & NPP

PRA 91, 011602(R) (2015)
PRA 92, 063607 (2015)
J Phys B 49, 214003 (2016)
PRA 94, 013602 (2016)

and a new (improved) criterion for phase mixing/separation

[jointly with Aarhus experiments (Arlt)]

CAUTION: Expansion Imaging does not always reveal correct in-situ picture!

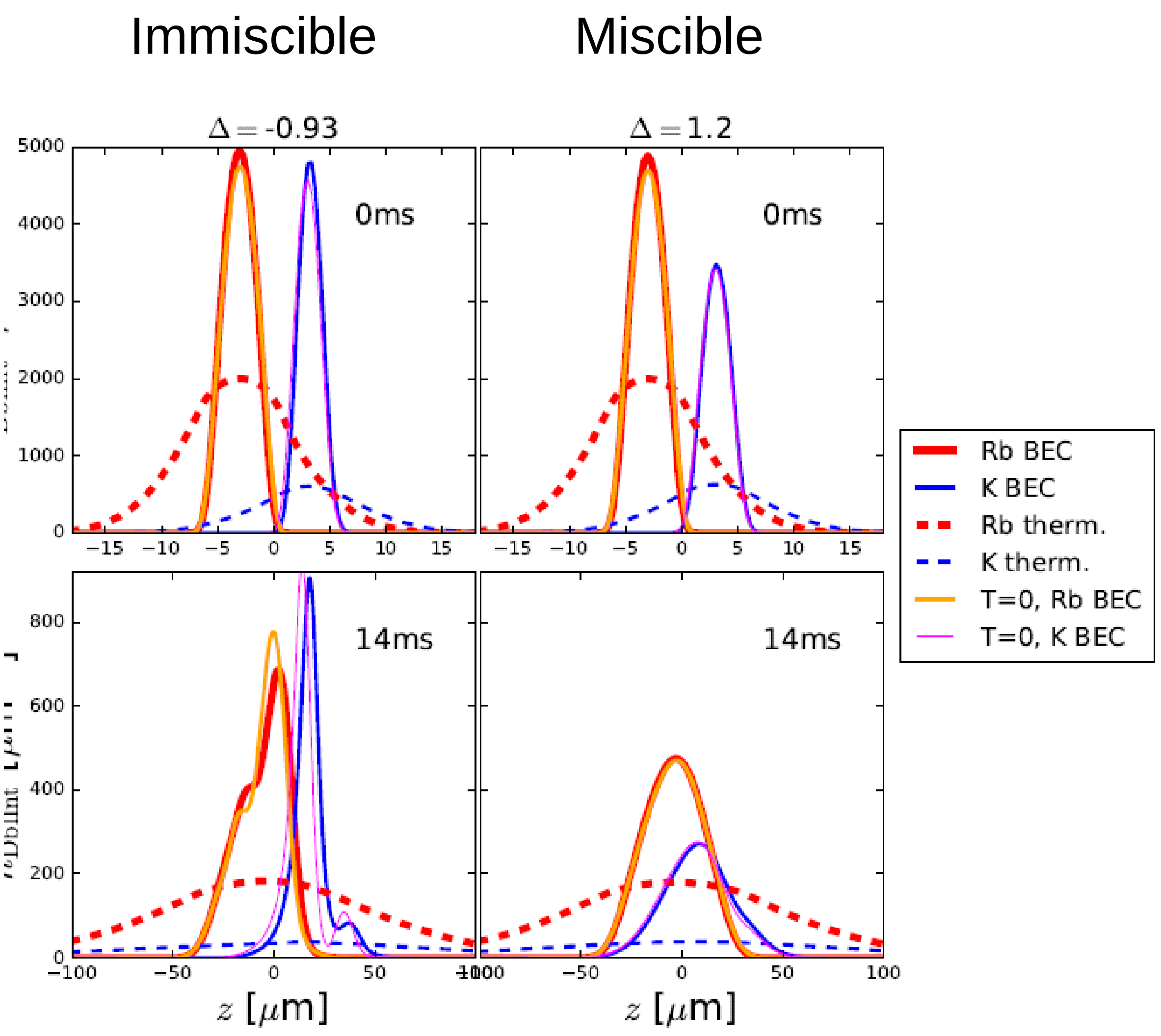
ROLE OF EXPANSION IMAGING

In Situ
Large Trap Sag

…
No Visible Effect

After TOF
Large Trap Sag

…
Distinctive Features Emerge upon Expansion



Miscibility / Immiscibilty can also appear *solely* during Expansion!

Lee, Jorgensen, Wacker, Skou, Skalmstang, Arlt & NPP, Preprint

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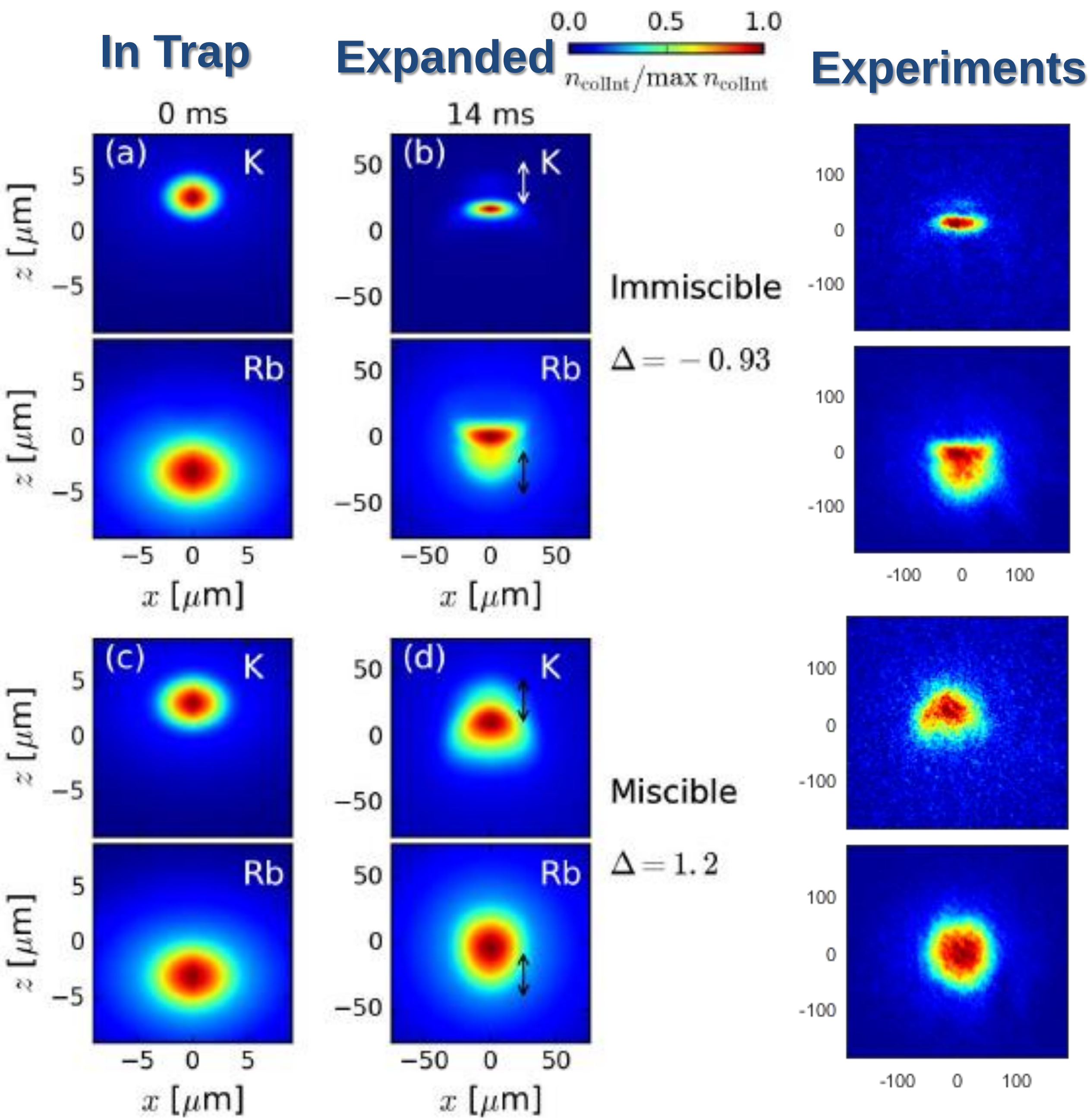
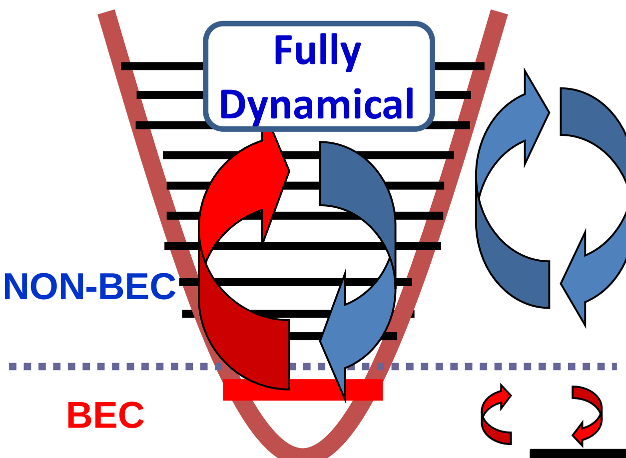
EMERGENCE OF IMMISCIBILITY IN TOF



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

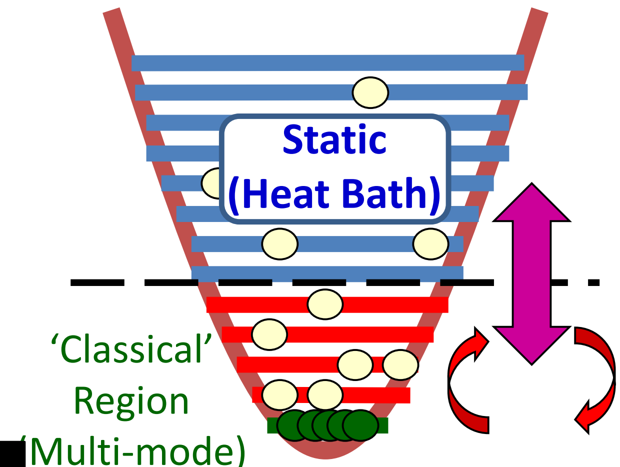
Kinetic Approaches
(explicit BEC separation)

BEC + Dynamical Thermal Cloud with full self-consistent coupling



Stochastic Approaches
(no explicit BEC separation)

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



Ideally suited for:

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

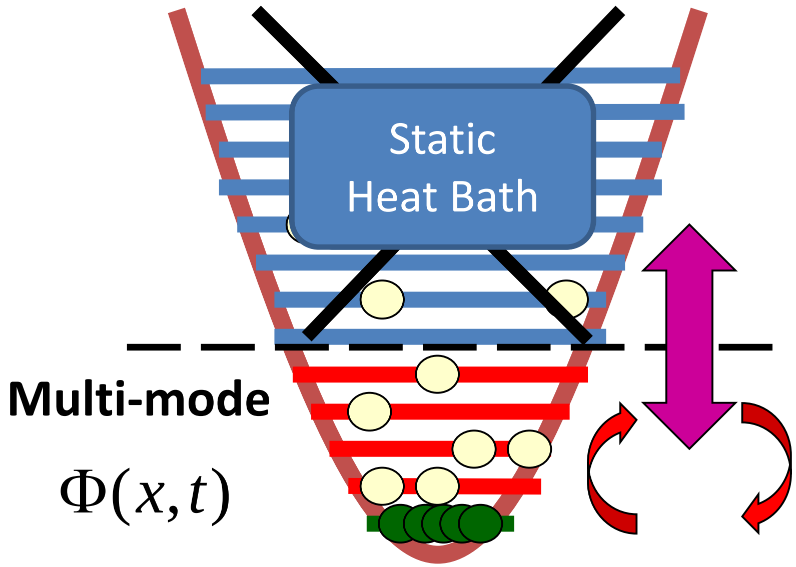
Random (shot-to-shot) Fluctuations
Quenches / Low-D & Universality
(high-lying modes "unaffected")

STOCHASTIC GROSS-PITAEVSKII (SGPE) MODEL

SGPE describes the entire multi-mode system describing the low-lying modes

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

Beyond-GPE Terms



STOCHASTIC GROSS-PITAEVSKII (SGPE) MODEL

SGPE describes the entire multi-mode system describing the low-lying modes

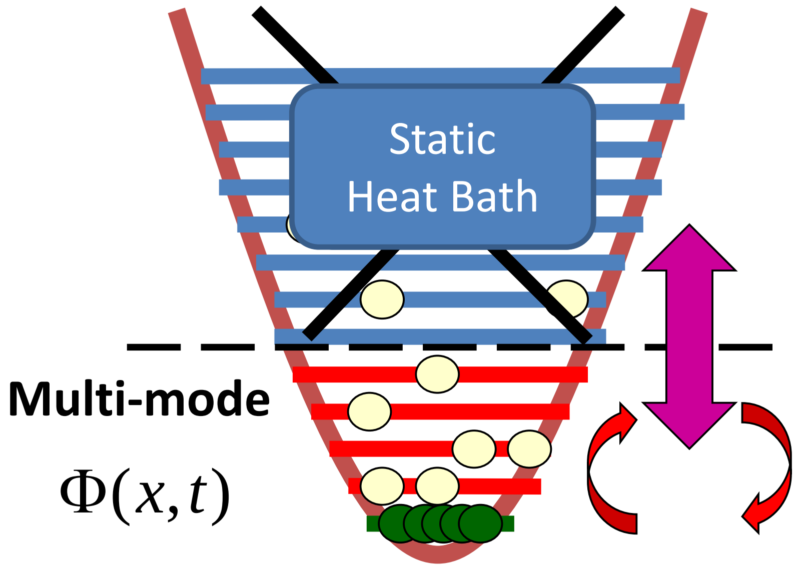
$$i\hbar \frac{\partial \Phi(x,t)}{\partial t} = (1 - i\gamma)\left[-\frac{\hbar^2 \nabla^2}{2m} + V_{TRAP} - \mu + g|\Phi(x,t)|^2 \right]\Phi(x,t) + \eta(x,t)$$

→**Results obtained by averaging over noise realizations** $\eta(x,t)$

$$\langle \eta^*(x,t)\eta(x',t') \rangle = 2\hbar\gamma k_B T \delta(x-x')\delta(t-t')$$

so supposed to be interpreted after suitable 'trajectory' averaging

Stoof-Bijlsma J Low Temp Phys 124, 431 (2001); Gardiner-Davis J Phys B 36, 4731 (2003)



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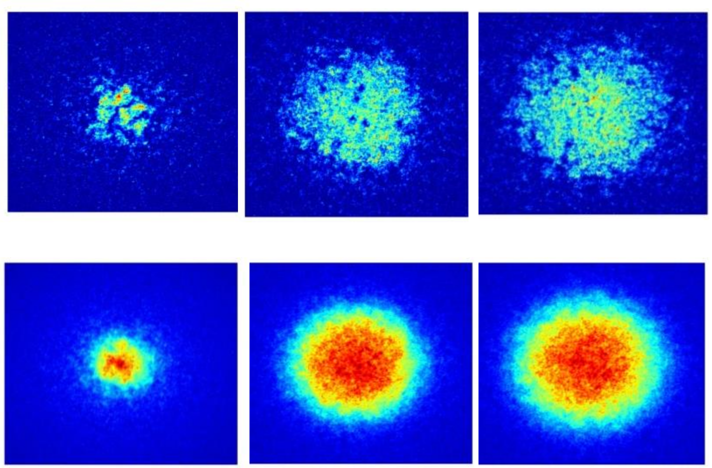
Stoof-Bijlsma J Low Temp Phys 124, 431 (2001); Gardiner-Davis J Phys B 36, 4731 (2003)

Single Run

vs.

Averaged Profiles



- * Contain element of stochasticity
- * *Qualitatively* reproduces single experimental realisations
- * Wash out density fluctuations to produce smooth profiles
- * Suitable for extracting global features (densities, correlation functions, etc.)

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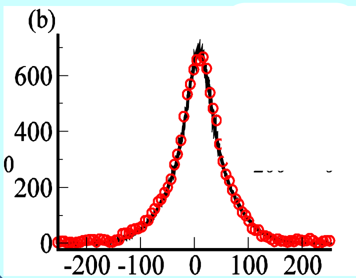
LOW-D EQUILIBRIUM PROPERTIES

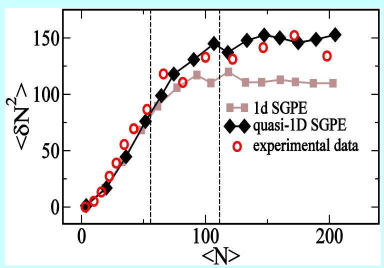
Properties Characterised by Densities & Lowest Order Correlation Functions

Quasi-1D:
Ab Initio Prediction of densities & coherences

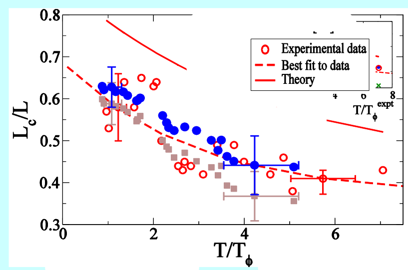
Density Profiles



Density Fluctuations



Phase Fluctuations



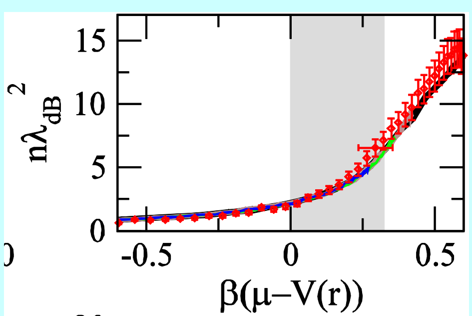
Experiments: Paris & Amsterdam

PRL 97, 250403 (2006)
PRL 100, 090402 (2008)
PRL 105, 230402 (2010)
PRL 91, 010405 (2003)
EPJD 35, 155 (2005)

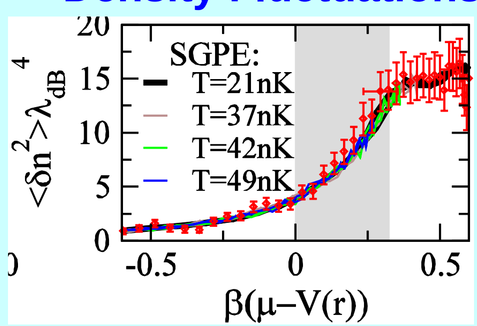
***Ab Initio* SGPE Modelling: NPP et al.,**
PRA 84, 023613 (2011)
PRA 86, 013627 (2012)

Quasi-2D:
Scale-invariance & Universality

Densities



Density Fluctuations



Experiment: Chicago

Nature 470, 236 (2011)

***Ab Initio* SGPE Modelling: Cockburn & NPP**
PRA 86, 033610 (2012)

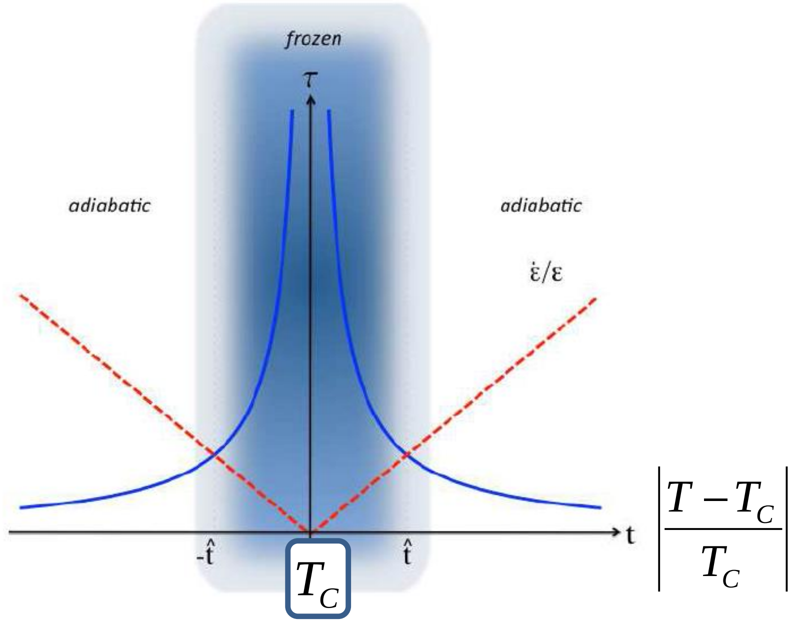
Detailed Theoretical Benchmarking: **Cockburn et al. PRA 83, 043619 (2011)**

QUENCHED CROSSING OF A PHASE TRANSITION

Consider rapidly quenching a system through the BEC phase transition

As system approaches phase transition, it cannot follow external drive (e.g. cooling ramp)

Dynamics "freezes out" with coherence forming in "local patches"



Kibble-Zurek Model:

Number of Defects: $N \propto \left(\tau_Q\right)^{-\alpha}$

Review: del Campo & Zurek, Int J Mod Phys A 29, 1430018 (2014)

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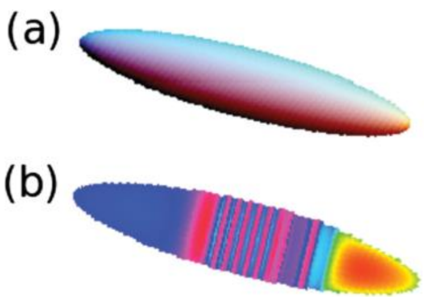
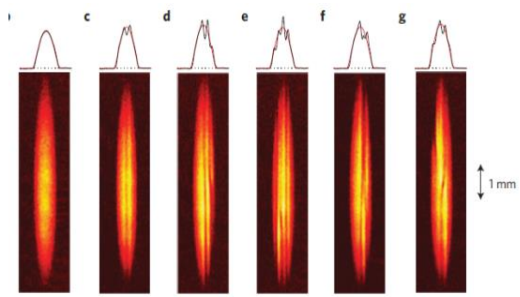
COLD ATOM KIBBLE-ZUREK GALLERY

1D: Soliton Formation



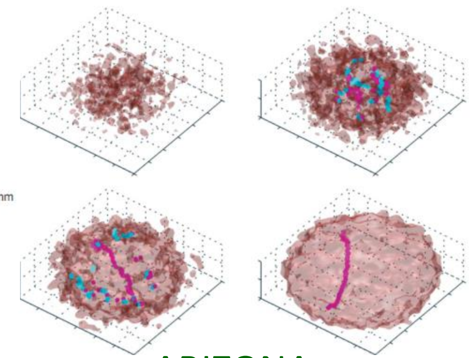
Zurek et al.
PRL 102, 105702 (2009)

Quasi-1D: Solitonic Vortices



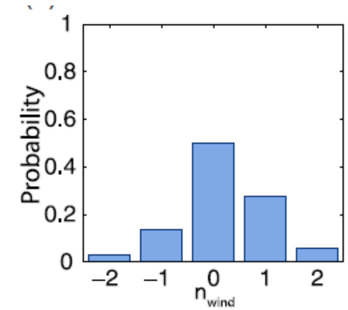
TRENTO:
Nat Phys 9, 656 (2013)

Quasi-2D / 3D: Vortex Formation



ARIZONA:
Nature 455, 948 (2008)

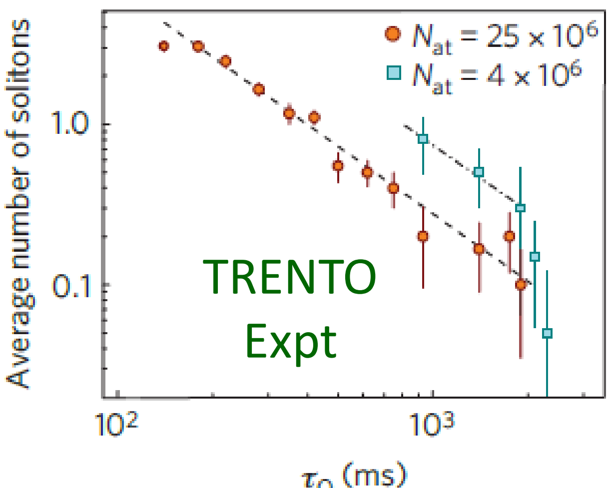
Ring Trap: Persistent Current



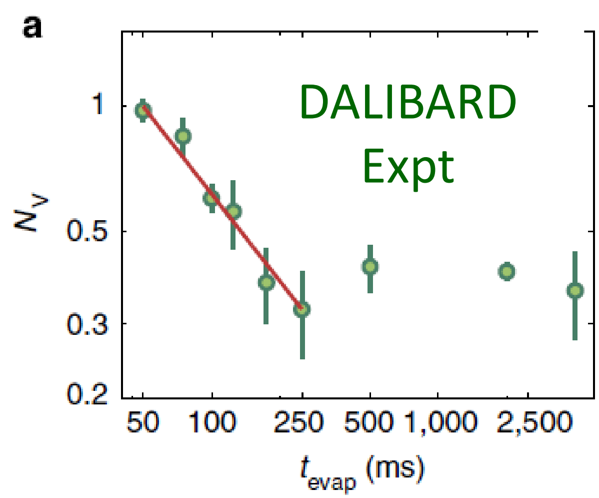
LKB:
PRL 113, 135302 (2014)

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

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



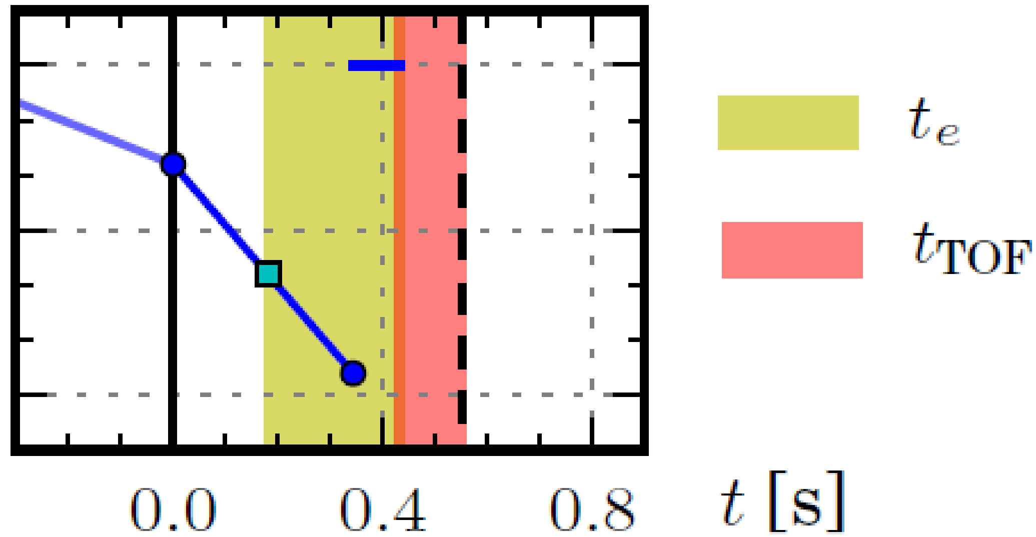
$$N \propto \left(\tau_Q\right)^{-\alpha}$$



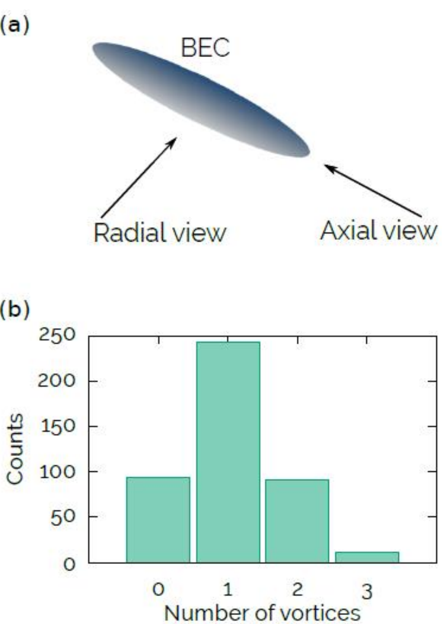
TRENTO EXPERIMENT SUMMARY

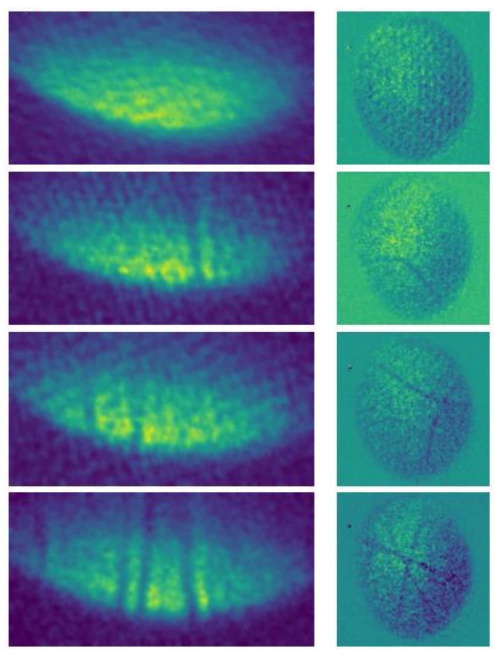
Quench Protocol (Forced Evaporative Cooling)

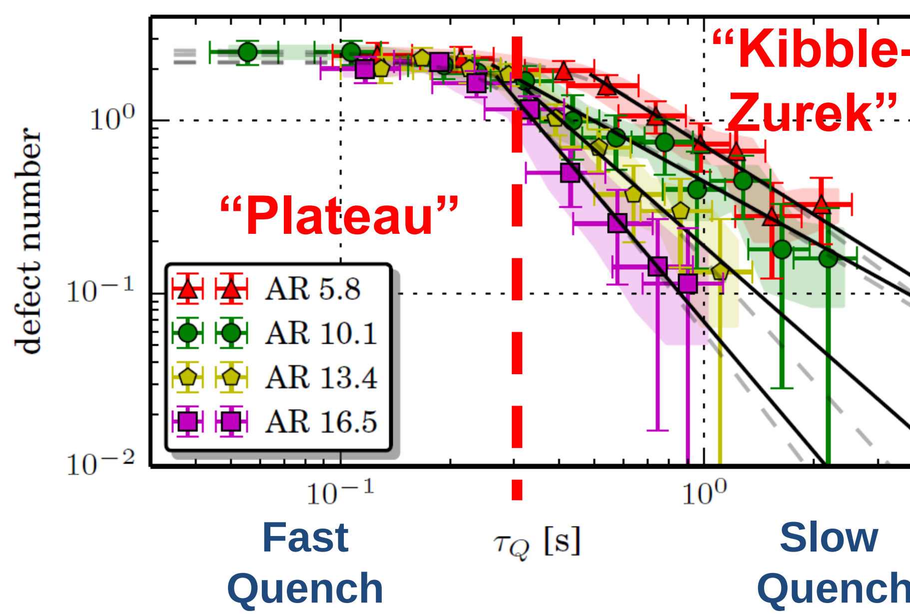
Phys. Rev. A 94, 023628 (2016)



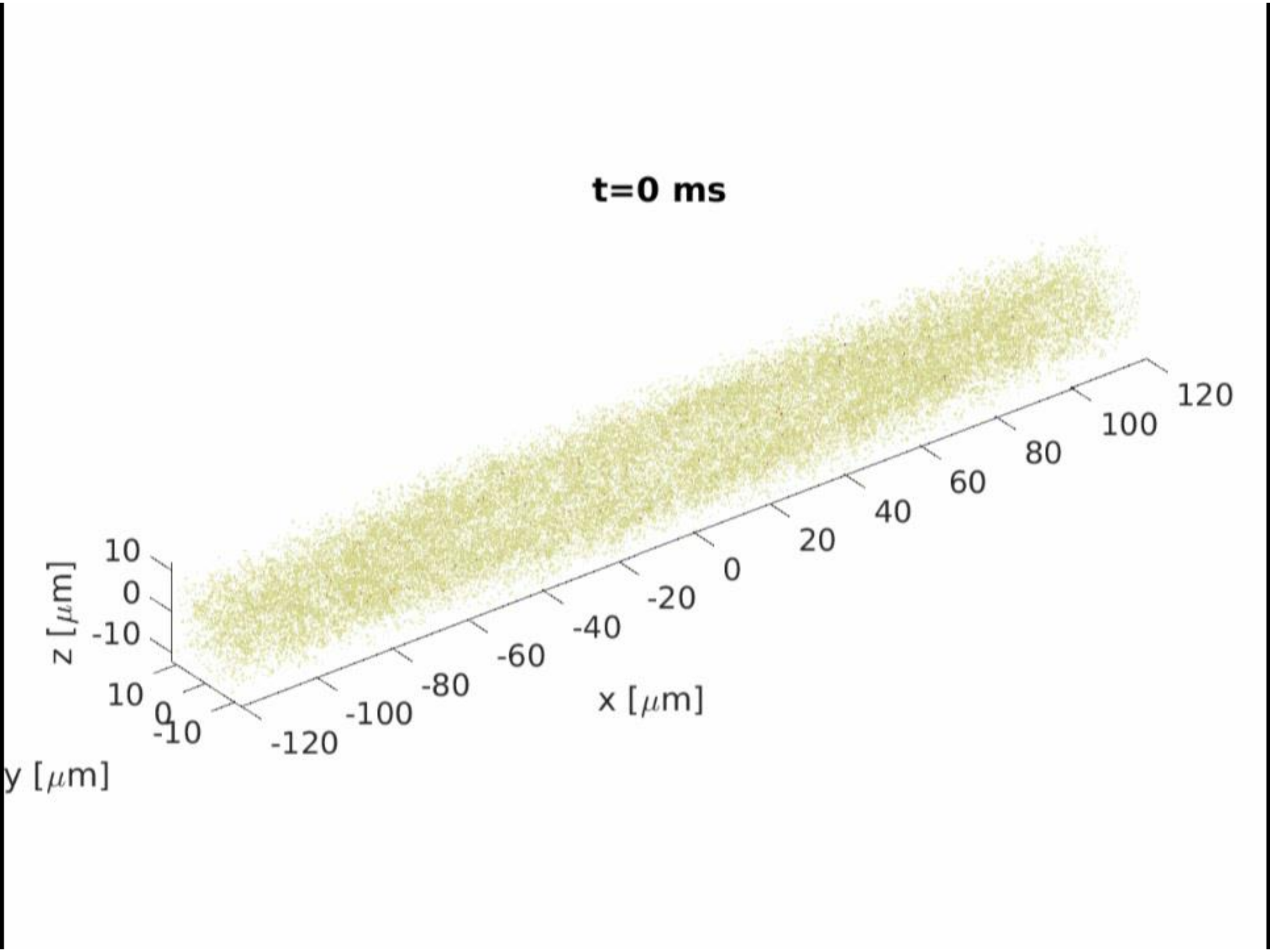
Observations (Quasi-1D System; TOF Imaging)







Model BEC Growth Dynamics via Stochastic Simulations

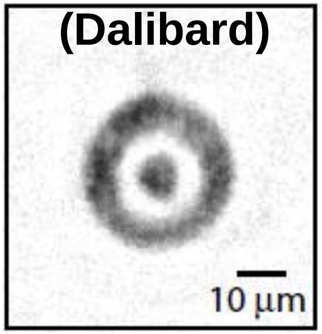


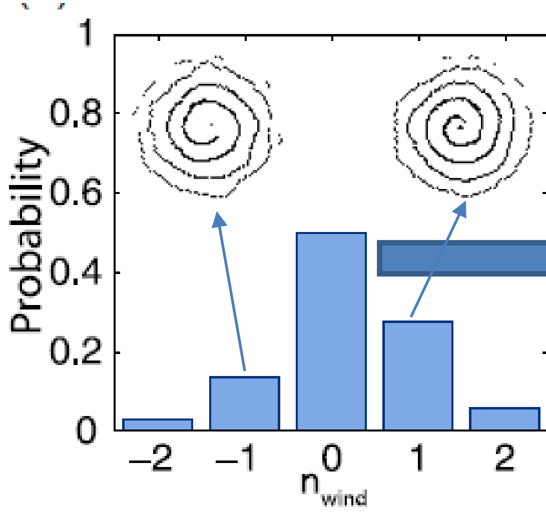
^{23}Na $\omega_z(\omega_\perp) = 2\pi \bullet 13(131) Hz$ $T = (790 \rightarrow 210) nK$ $\tau_{evap} = 18 ms$

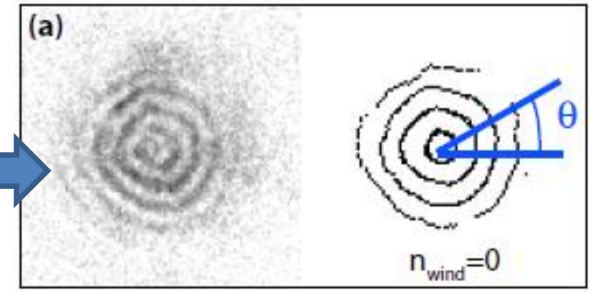
$N = (20 + 0.4) \times 10^6 \rightarrow N = (6.6 + 4.9) \times 10^6$

KIBBLE-ZUREK IN RING TRAPS

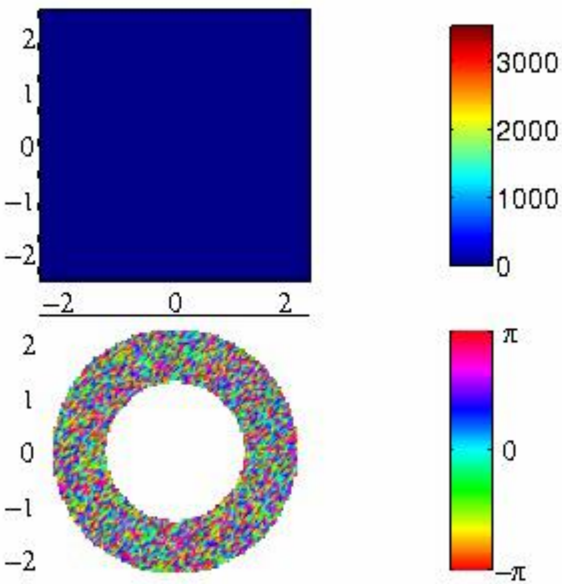
Experimental Growth (Dalibard)



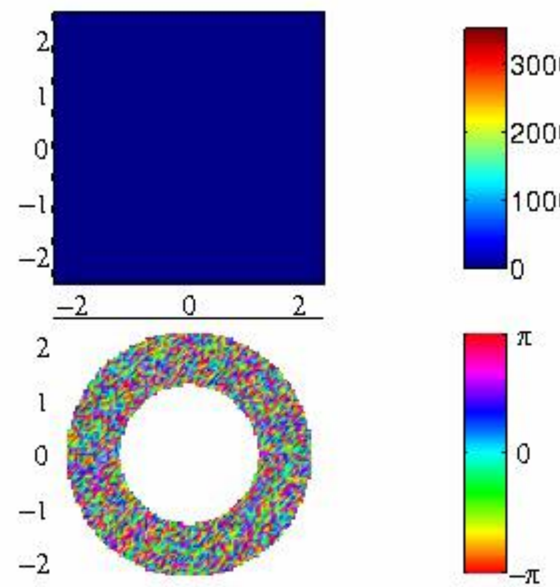




Growth with Persistent Current

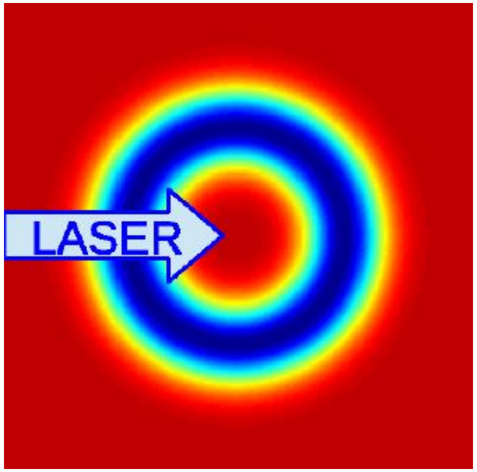


Growth without Persistent Current



See also Das, Sabbatini & Zurek, Scientific Reports (2012) & Jerome Beugnon's Talk

Next, Density Engineer a Dark-Soliton Pair of desired speed



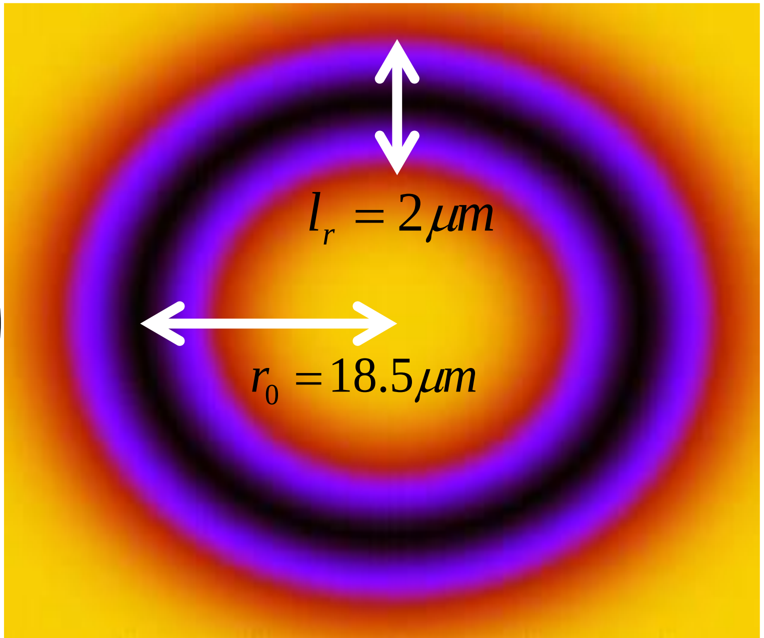
and study its dynamical evolution

Focus on JQI Ring Trap Parameters

[see also Murray et al., PRA 88, 053615 (2013) for parameter details]

Planar Geometry

$$V(r) = V_G\left(1 - e^{-2(r-r_0)^2/w^2}\right)$$



$w = 9.45\mu m$

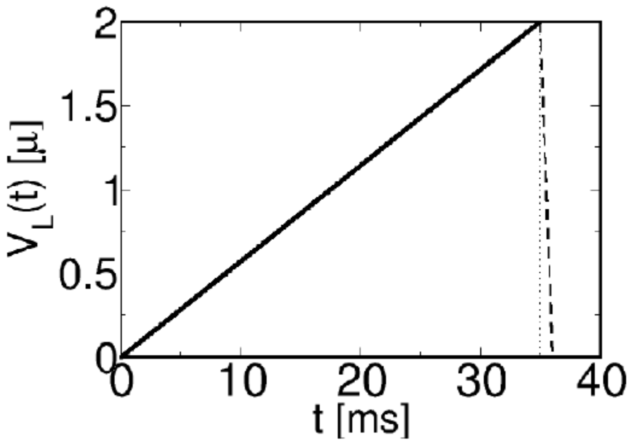
$\omega_\perp = 2\pi \times 600 Hz$

PARAMETER CHOICE & EXCITATION SCHEME

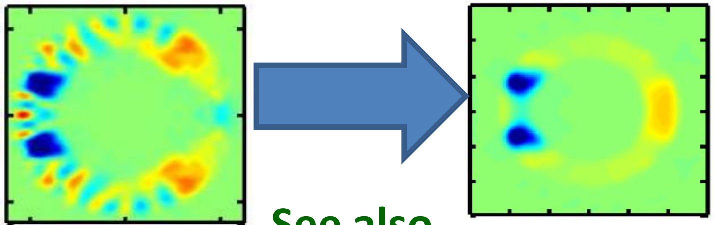
OPTIMIZING THE EXCITATION SCHEME

Laser Potential of form

$$V_L(t) = V_0 f(t)$$



Gradual Turn-on Minimises Linear (sound) excitations

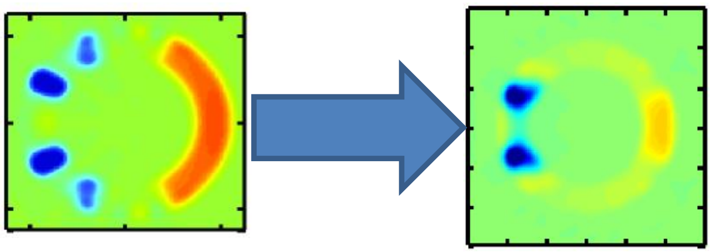


See also
Shomroni et al., Nat. Phys. 5, 193 (2009)

Narrow Width of Excitation Laser

$$V = \ldots + V_L(t) e^{-y^2/2\sigma^2}$$

Ensures only single Counter-propagating soliton pair is generated



Relevant 'control' parameters thus reduce only to: $V_0, \ \xi$

To make soliton engineering findings universal, we hence consider the following dimensionless ratios:

$$\left(\frac{l_r}{\xi}\right) \ \& \ \left(\frac{V_0}{\mu}\right)$$

Gallucci & NPP , New J Phys 18, 025004 (2016)

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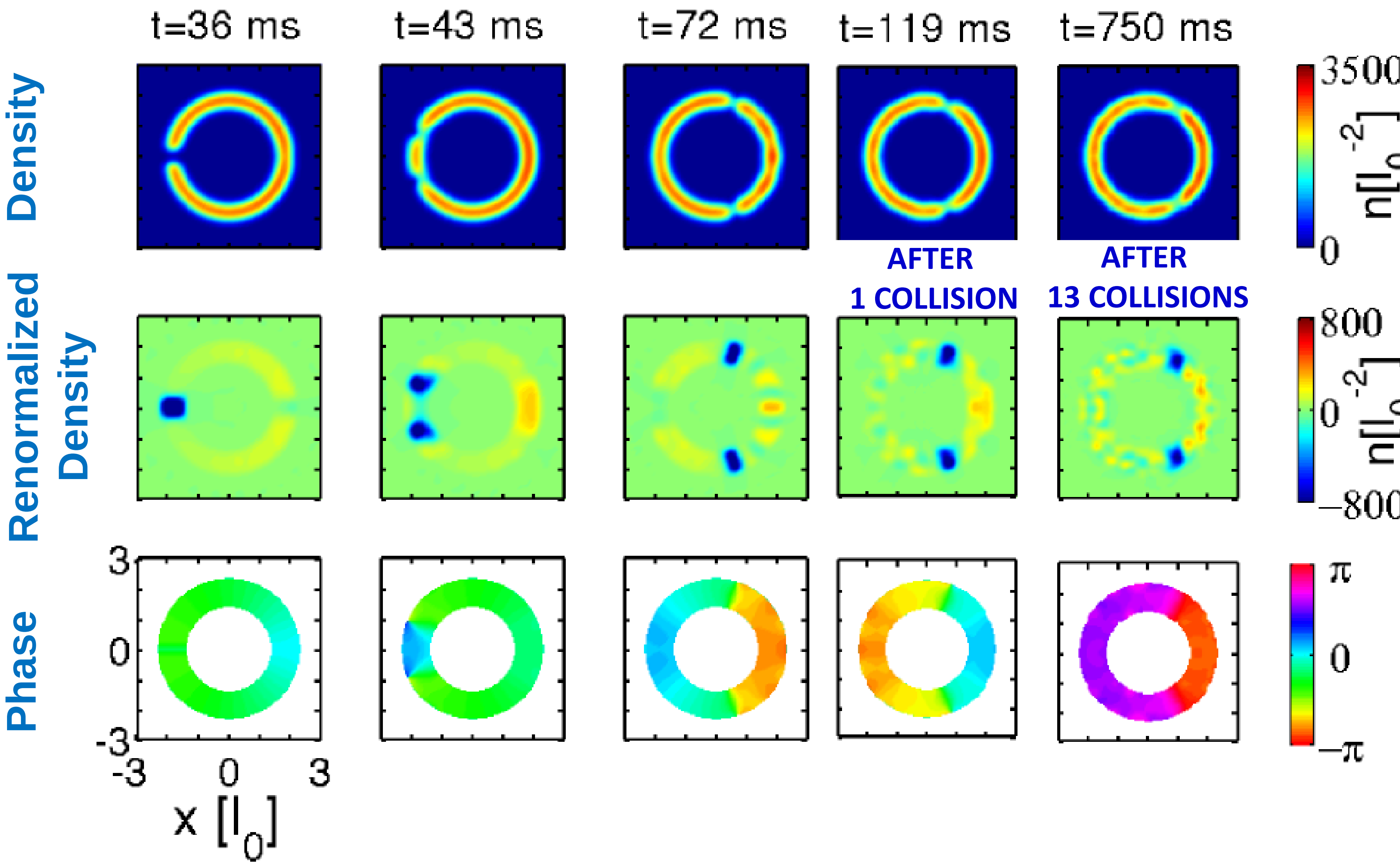
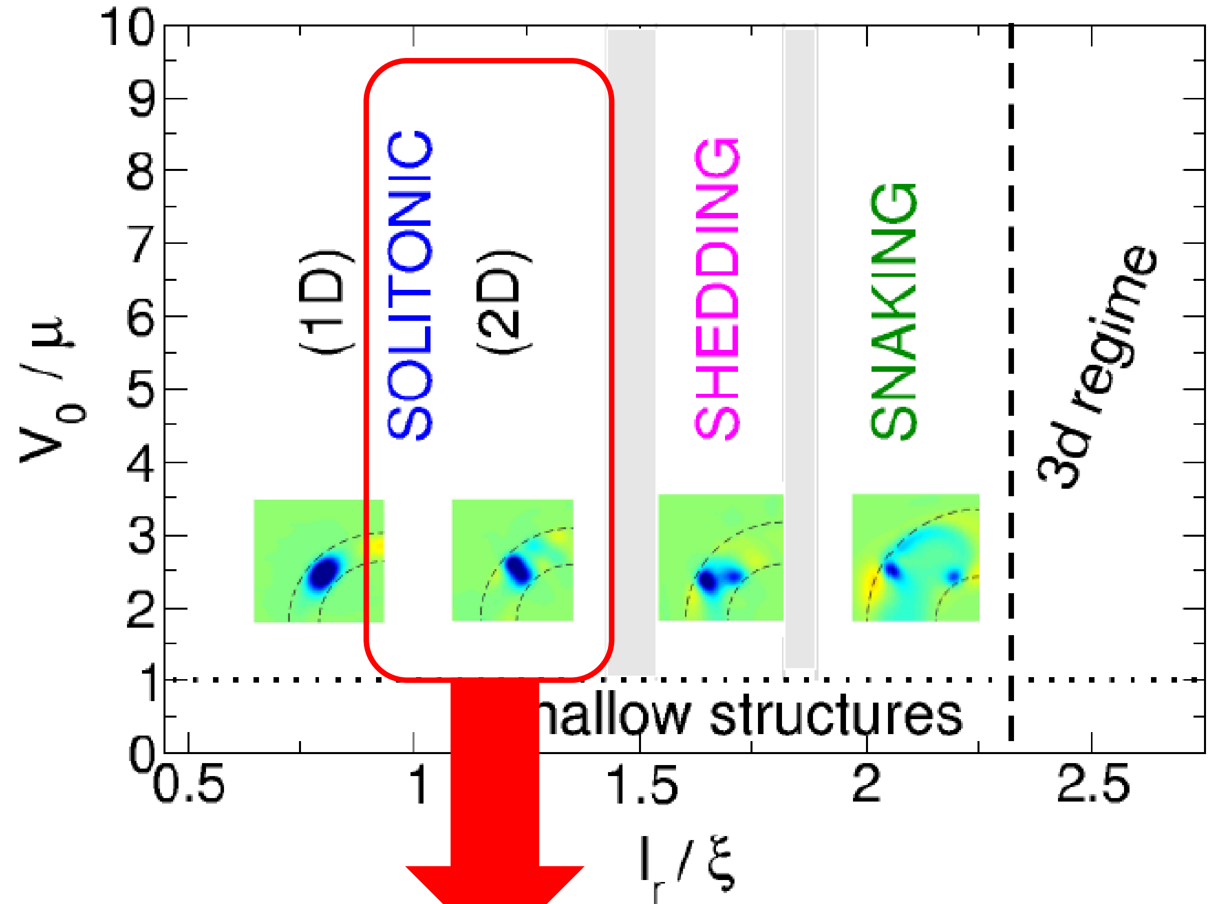
LONG-LIVED DARK SOLITONS IN RING TRAPS



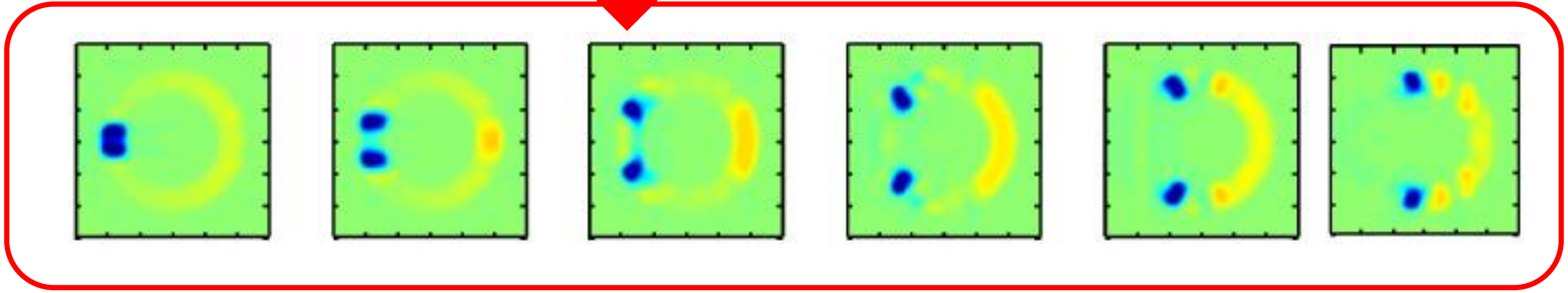
$\left(l_0 = 10\mu m\right)$ $\sigma/\xi = 0.7$ $l_r/\xi = 1.3$ $V_0/\mu = 2$ $\xi = 1.5\mu m$

Gallucci & NPP, New J Phys 18, 025004 (2016)

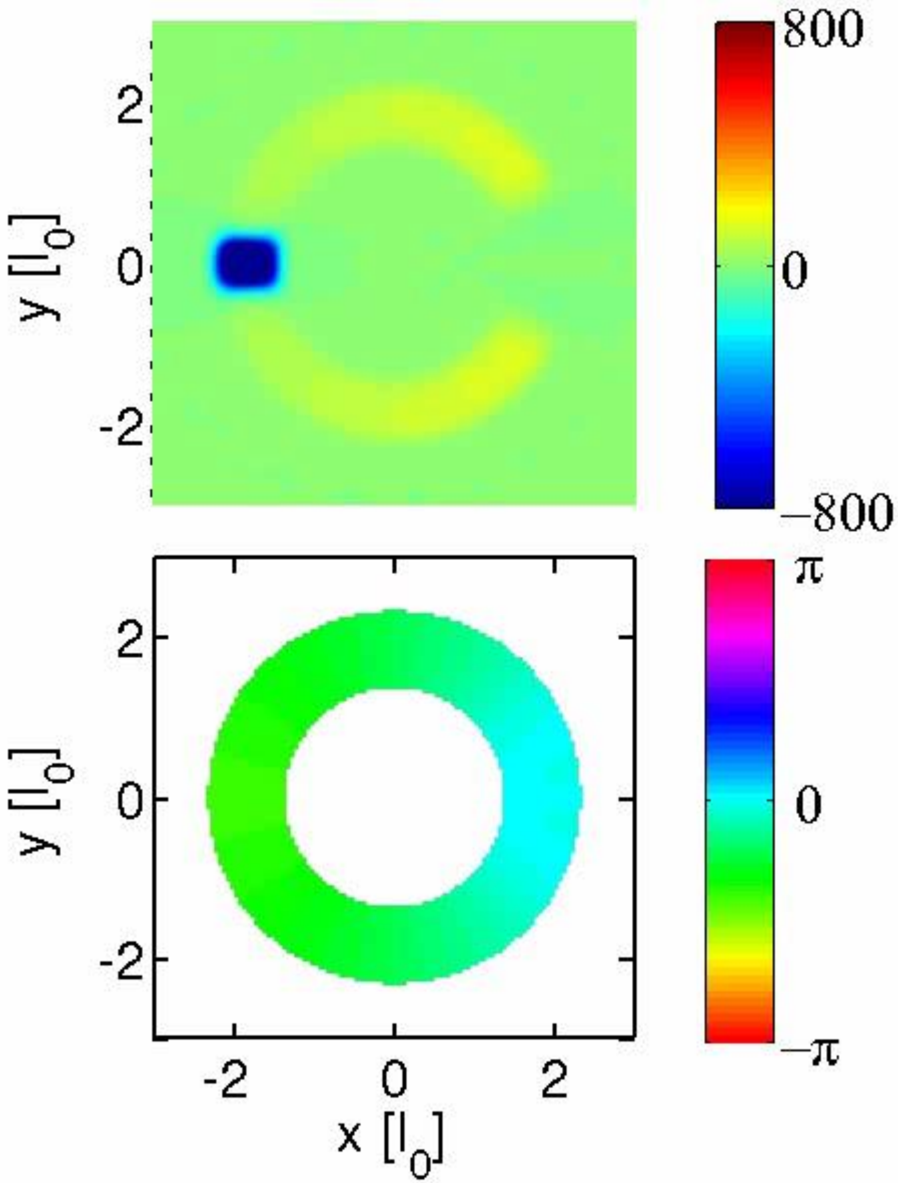
Identify T = 0 Phase Diagram Revealing Distinct Dynamics



Gallucci & NPP
New J Phys
18, 025004 (2016)



2D Solitonic Regime



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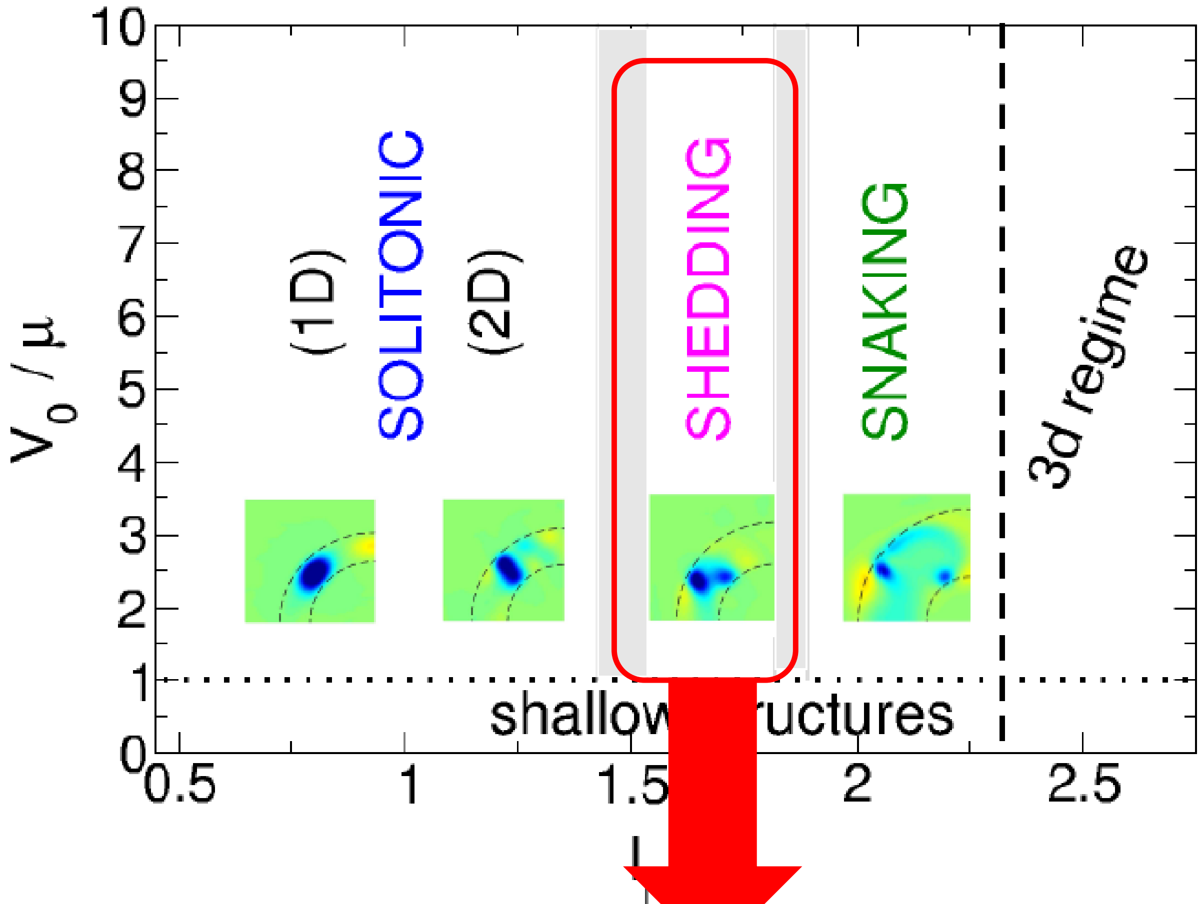

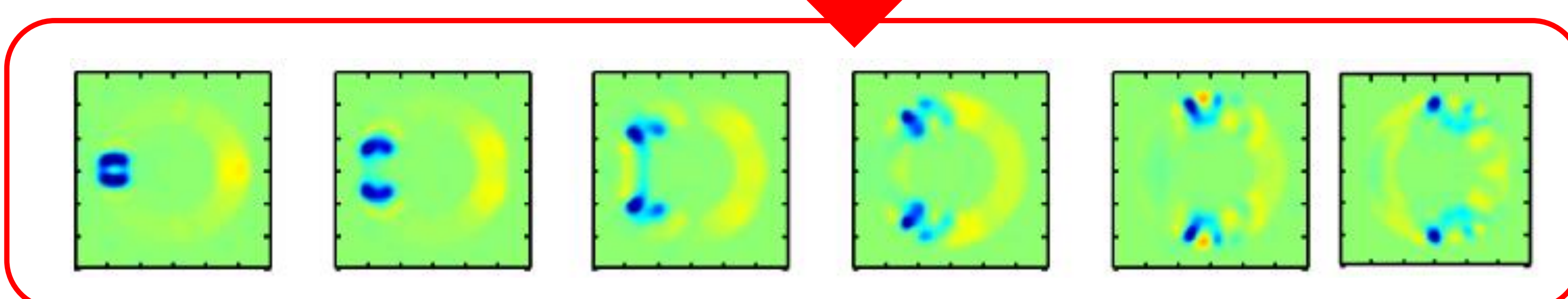

Gallucci & NPP
New J Phys
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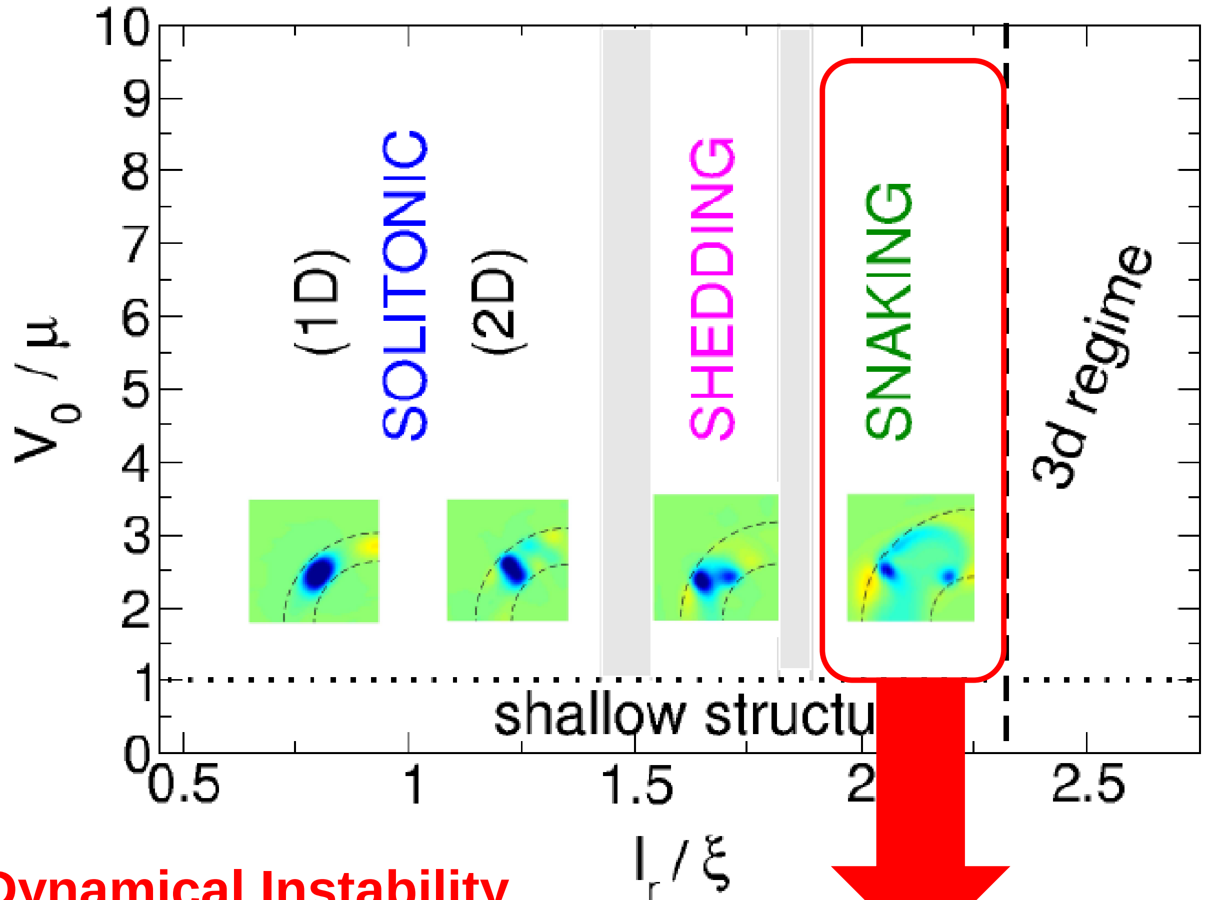
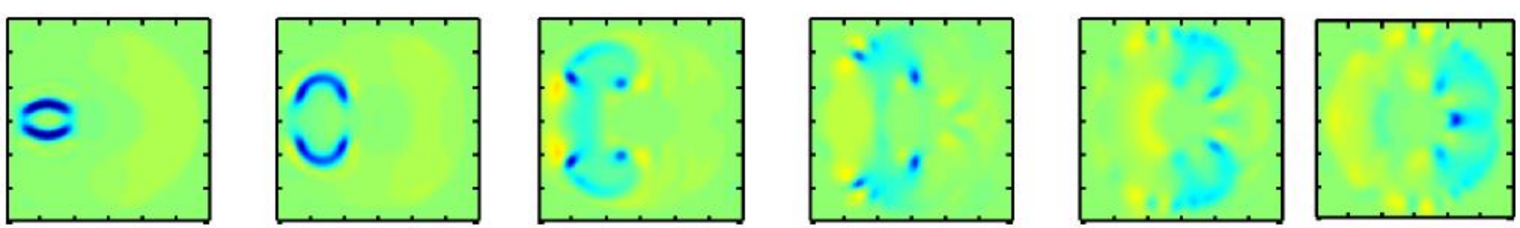


Gallucci & NPP
New J Phys
18, 025004 (2016)

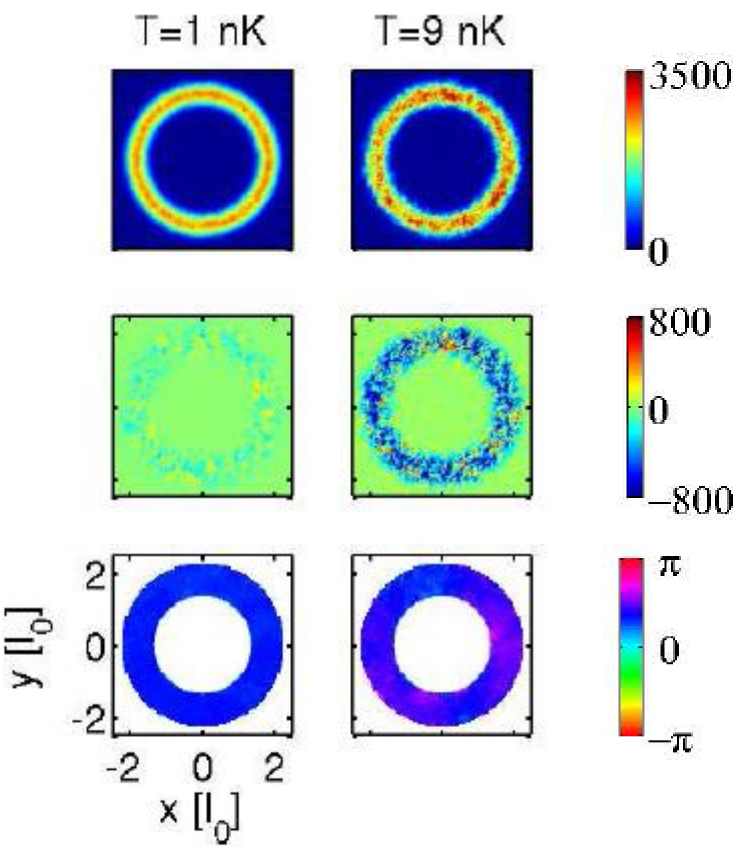
Dynamical Instability



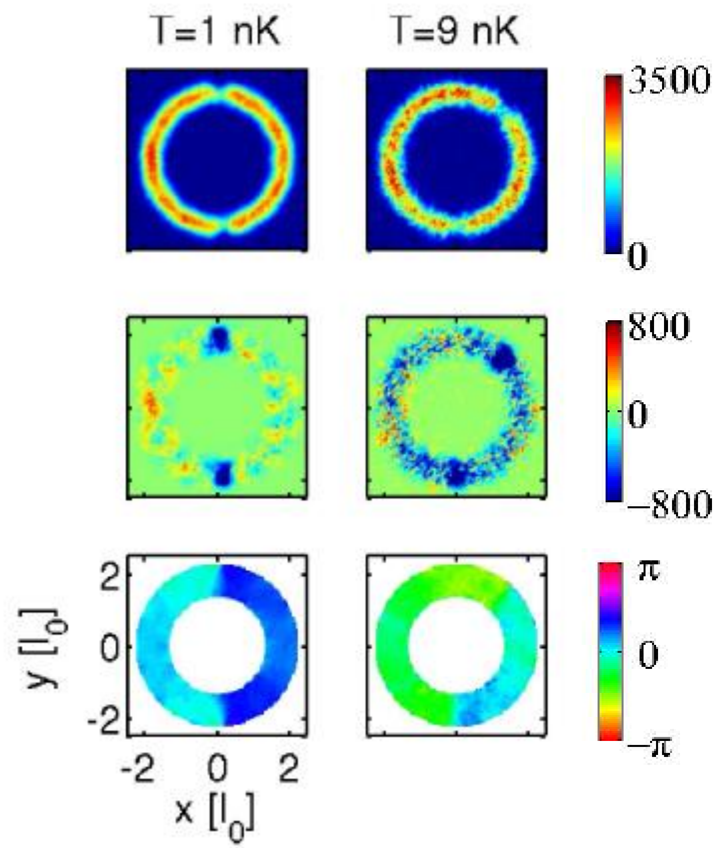
What about Thermodynamic Instabilities ?

Add realistic "noisy" background density modulation & Monitor Evolution

INITIAL CONDITION (t=0)



POST DENSITY-ENGINEERING

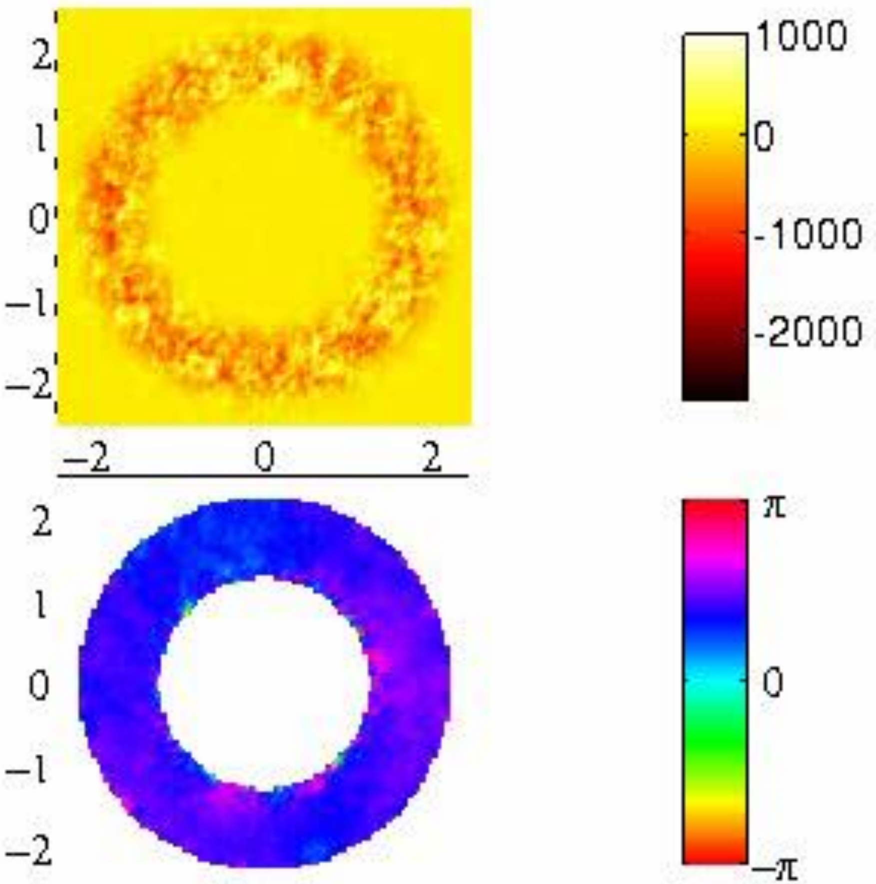


Observe Counter-Propagating Dark "Solitons" with $\Delta\phi \approx 0.4\pi$

persisting for multiple revolutions / collisional cycles

What about Thermodynamic Instabilities ?

Add realistic "noisy" background density modulation & Monitor Evolution



Optimal Parameters:

* Tight Transverse Confinement
* Small Atom Number
* Not too high Temperature

$$\mu, k_B T \leq \hbar\omega$$

* Narrow Ring Trap Radius

Gallucci & NPP
New J Phys 18, 025004 (2016)

Observe Counter-Propagating Dark "Solitons" with $\Delta\phi \approx 0.4\pi$

persisting for multiple revolutions / collisional cycles

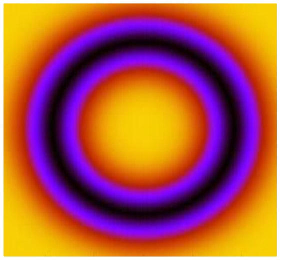
MULTIPLE RING TRAPS

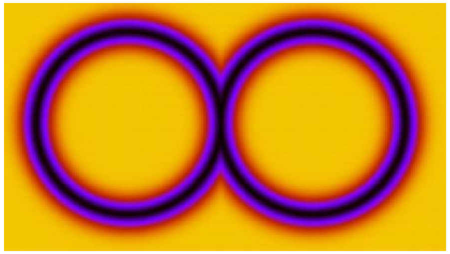
Can flow patterns in complex ring geometries be useful for measurements?

Single Ring

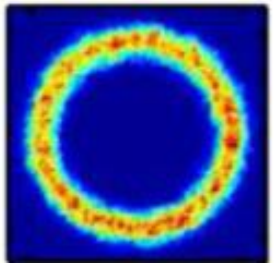
Double Rings

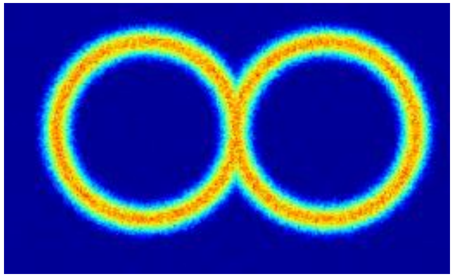
Potential



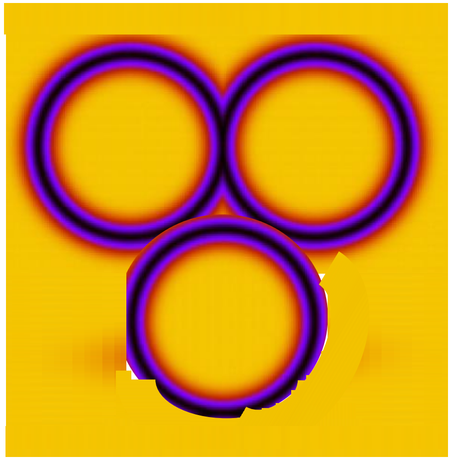


Density





**or even
more complex
Structures ?**



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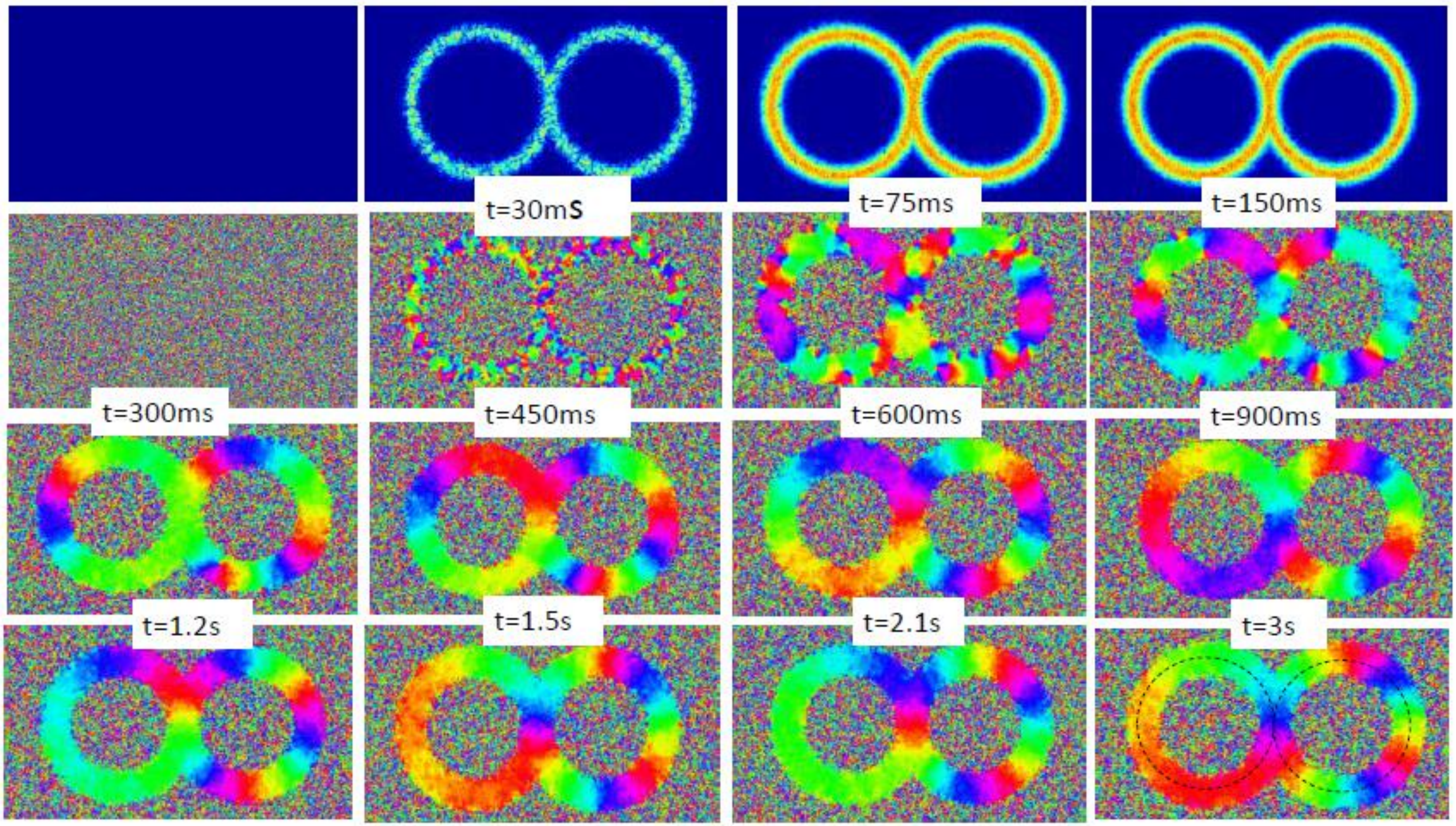
MULTIPLE RING TRAPS

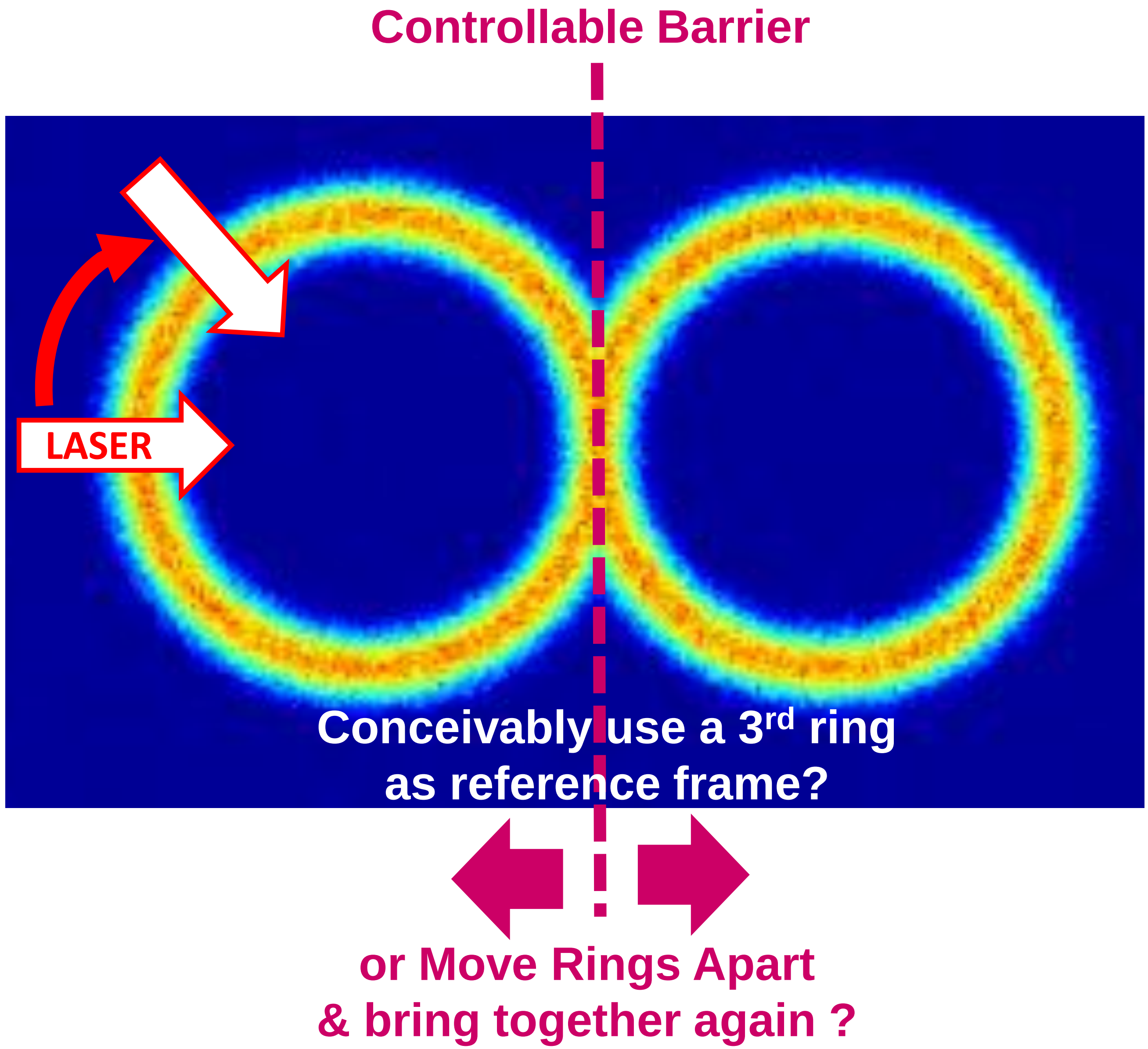
Have done basic "brute-force" investigation of emerging phase patterns

(by stochastic condensation into such geometry)



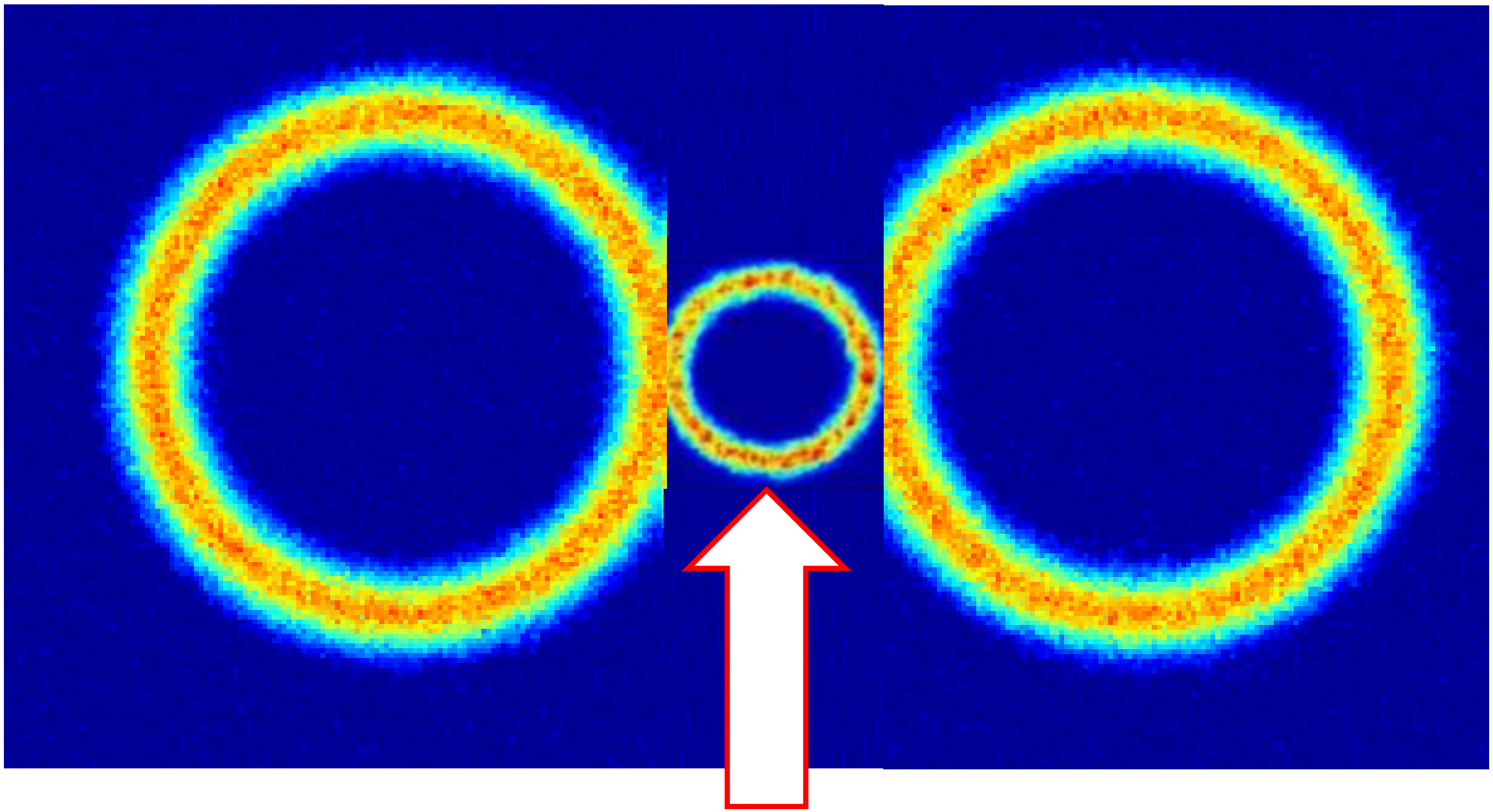
MULTIPLE RING TRAPS

Example of (an unlikely?) atomtronic scheme [work in progress]



MULTIPLE RING TRAPS

Example of (an unlikely?) atomtronic scheme [work in progress]



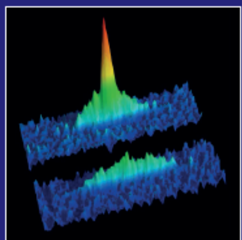
**Middle ring acts as gate
controlling flow / phase???**

… Concrete Ideas Wanted !!! …

ANNOUNCEMENTS

NJP Interdisciplinary Spotlight Collection on MultiComponent Quantum Matter

http://iopscience.iop.org/journal/1367-2630/page/Multicomponent-Quantum-Matter



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(usual NJP application/acceptance criteria apply)

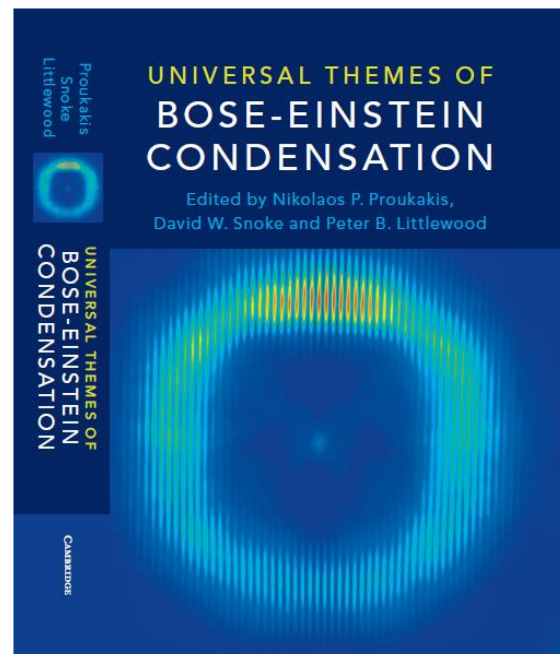
Managed by:
Frédéric Chevy (*ENS)*
Milorad Miloševic *(Antwerp)*
Nick Proukakis (*Newcastle/JQC)*

Universal Themes of Bose-Einstein Condensation

(Cambridge University Press, PUBLISHED, April 2017)

ISBN-9781316084366

Edited by NP Proukakis, DW Snoke & PB Littlewood



ANNOUNCEMENTS

The Onassis Foundation

2017 Lectures in Physics

Quantum Physics Frontiers Explored with Cold Atoms, Molecules & Photons

Hosted by Serge Haroche

Other Lecturers:
Aspect – Bloch – Dalibard
Davidovich – Proukakis - Ye

24-28 July 2017, Crete

Full Financial Support for 15 International UG/PG Students, or RAs

Nick Proukakis

ACKNOWLEDGEMENTS

Newcastle University

Kinetic Modelling:

* Kean Loon Lee *
- Klejdja Xhani *

Matthew Edmonds

EPSRC

Stochastic Modelling:

- Gary Liu *
- * Donatello Gallucci *

* Quentin Marolleau *

行政院國家科學委員會 National Science Council

UCAT UltraCold Atom Theory

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Nir Navon
Zoran Hadzibabic

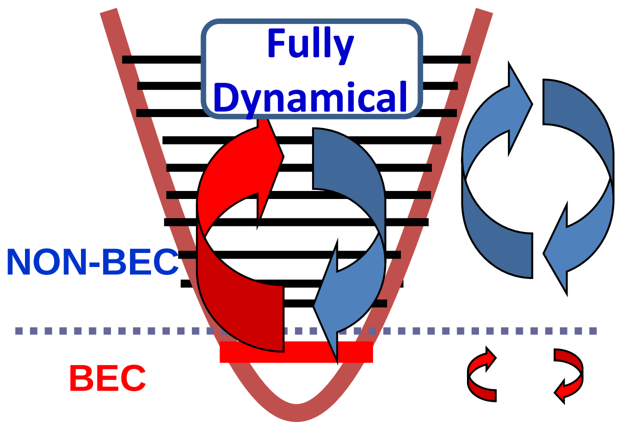
UCL

Marzena Szymanska
Alex Zamora

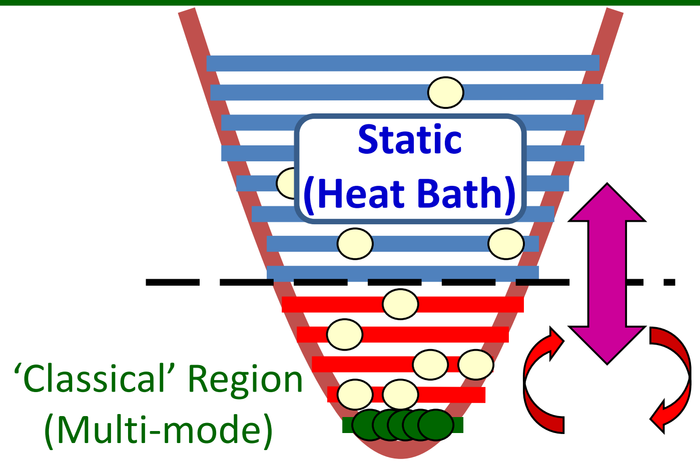
Nick
Proukakis

SUMMARY / FOR DISCUSSION

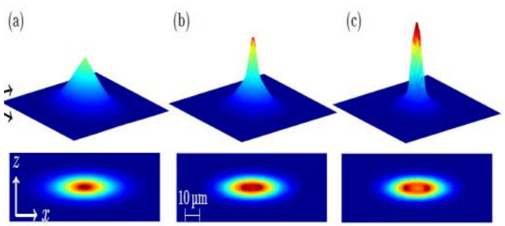
Kinetic Approaches
(explicit BEC separation)



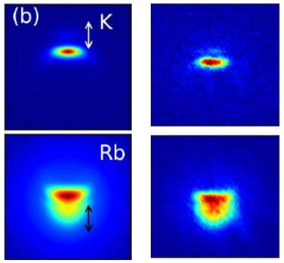
Stochastic Approaches
(no explicit BEC separation)



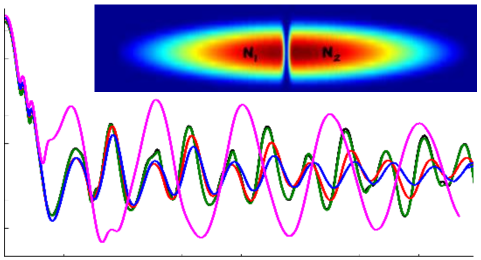
Surface Cooling



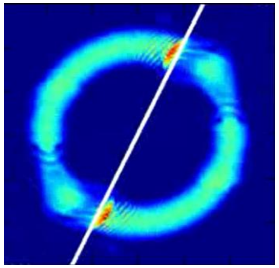
TOF Analysis



Josephson Junction

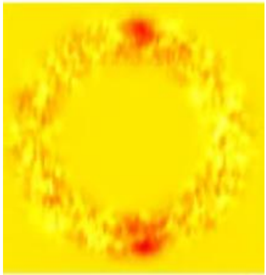


Ring Dynamics

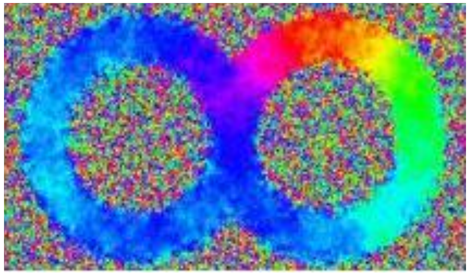


Quenched Growth

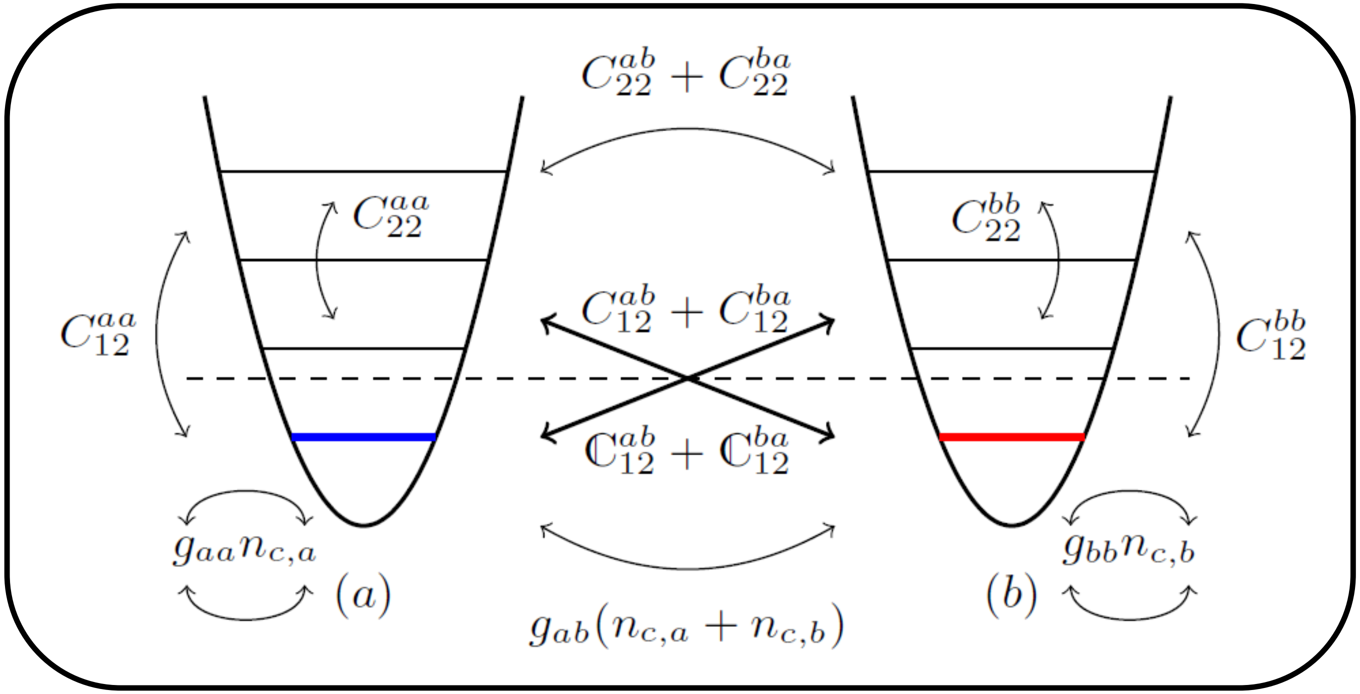
Dark Solitons



Double Ring Dynamics



T > 0 TWO-COMPONENT CONDENSATE THEORY



→ Identify & Characterise "Novel" Collisional Processes

$$i\hbar \frac{\partial \phi_j}{\partial t} = \Big[-\frac{\hbar^2}{2m_j}\nabla^2 + V_j(\mathbf{r}) + g_{jj}(n_{c,j} + 2\tilde{n}_j) + g_{kj}(n_{c,k} + \tilde{n}_k)$$

CONDENSATES

MEAN FIELD COUPLING

THERMAL CLOUDS

$$\frac{\partial}{\partial t} f^j + \frac{1}{m_j}\mathbf{p}\cdot\nabla_{\mathbf{r}} f^j - \nabla_{\mathbf{p}} f^j \cdot \nabla_{\mathbf{r}} U_{\text{eff}}^j =$$

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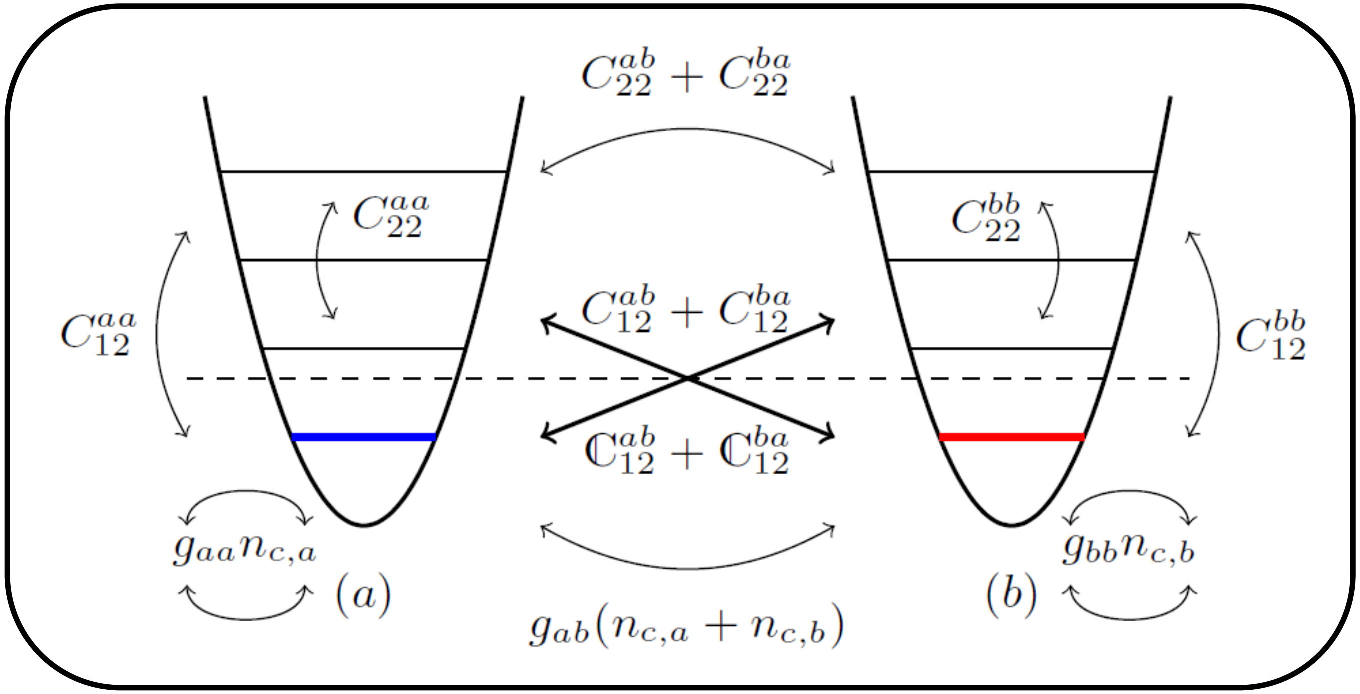
T > 0 TWO-COMPONENT CONDENSATE THEORY



→ **Identify & Characterise "Novel" Collisional Processes**

CONDENSATES

$$i\hbar\frac{\partial \phi_j}{\partial t} = \Big[-\frac{\hbar^2}{2m_j}\nabla^2 + V_j(\mathbf{r}) + g_{jj}(n_{c,j} + 2\tilde{n}_j) + g_{kj}(n_{c,k} + \tilde{n}_k) - i(R^{jj} + R^{kj}) - i\mathbb{R}^{kj} \Big]\phi_j$$

MEAN FIELD COUPLING

THERMAL CLOUDS

$$\frac{\partial}{\partial t} f^j + \frac{1}{m_j}\mathbf{p}\cdot\nabla_{\mathbf{r}} f^j - \nabla_{\mathbf{p}} f^j \cdot \nabla_{\mathbf{r}} U^j_{\mathrm{eff}} = \left(C^{jj}_{12} + C^{kj}_{12}\right) + \mathbb{C}^{kj}_{12} + \left(C^{jj}_{22} + C^{kj}_{22}\right)$$

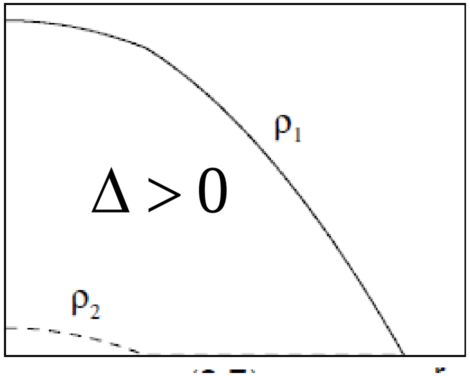
PLETHORA OF NEW COLLISIONAL TERMS

PHASE PROFILES OF 2-COMPONENT BECs

Phase Profiles Controlled by Inter- / Intra- Atomic Interactions

Phase Mixing

(overlapping components)



Interspecies interactions dominate

Consider here

repulsive interactions

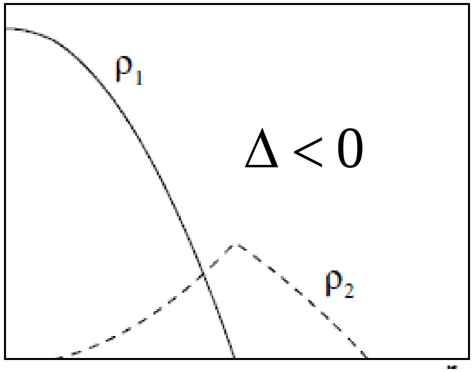
Usual Criterion

(Homogeneous)

$$\Delta = \left(\frac{g_{11} g_{22}}{g_{12}^{\;2}} - 1 \right)$$

Phase Separation

(non-overlapping components)



Intraspecies interactions dominate

$g_{11}(g_{22})$: Interactions ***within*** Species 1 (or 2)

g_{12} : Interactions ***between*** Species 1 & 2

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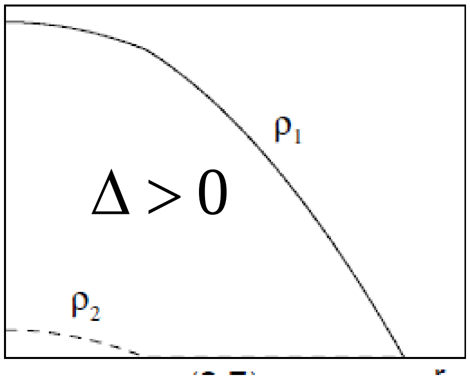

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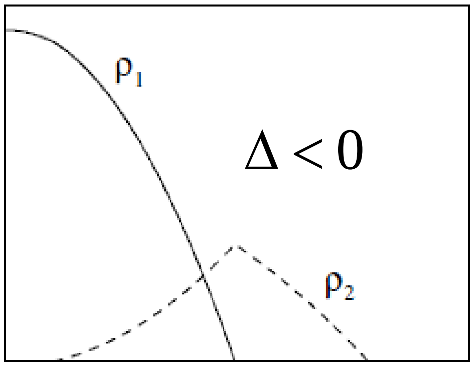


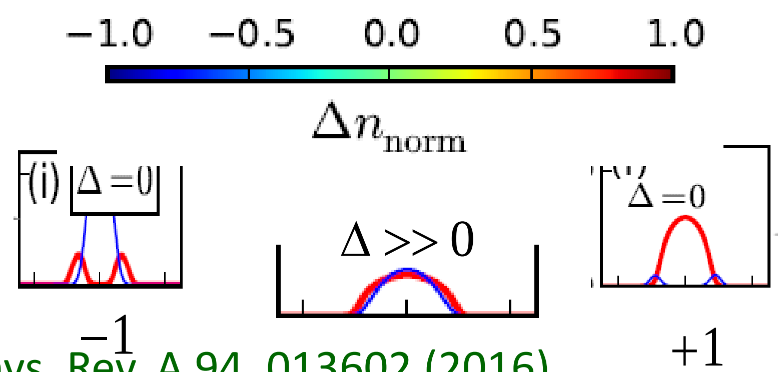
Intraspecies interactions dominate

$g_{11}(g_{22})$: Interactions ***within*** Species 1 (or 2)

g_{12} : Interactions ***between*** Species 1 & 2

Define New (Im)Miscibility Parameter for Symmetric Trapped BEC Mixtures:

$$\Delta n_{\mathrm{norm}} = \frac{n_{c,1}(\mathbf{0})}{\max n_{c,1}(\mathbf{r})} - \frac{n_{c,2}(\mathbf{0})}{\max n_{c,2}(\mathbf{r})}$$



Lee, Jorgensen, Liu, Wacker, Arlt & NPP, Phys. Rev. A 94, 013602 (2016)

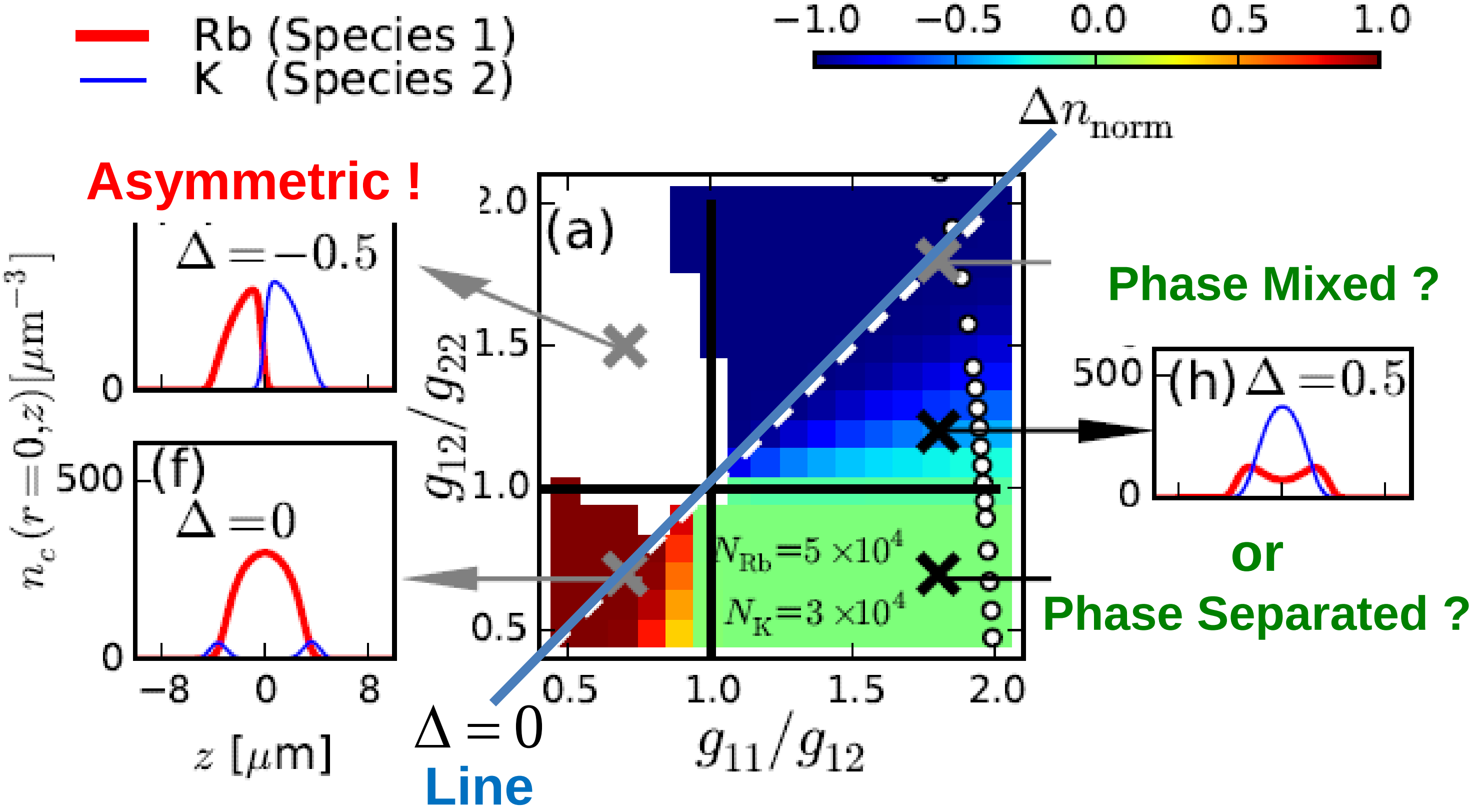
PHASE PROFILES OF 2-COMPONENT BECs

New Relevant (Im)Miscibility Parameter for Symmetric Trapped BEC Mixtures:

$$\Delta n_{\text{norm}} = \frac{n_{c,1}(\mathbf{0})}{\max n_{c,1}(\mathbf{r})} - \frac{n_{c,2}(\mathbf{0})}{\max n_{c,2}(\mathbf{r})}$$

T = 0 Analysis

(Gross-Pitaevskii)



Phase separation Boundary: Green → Blue

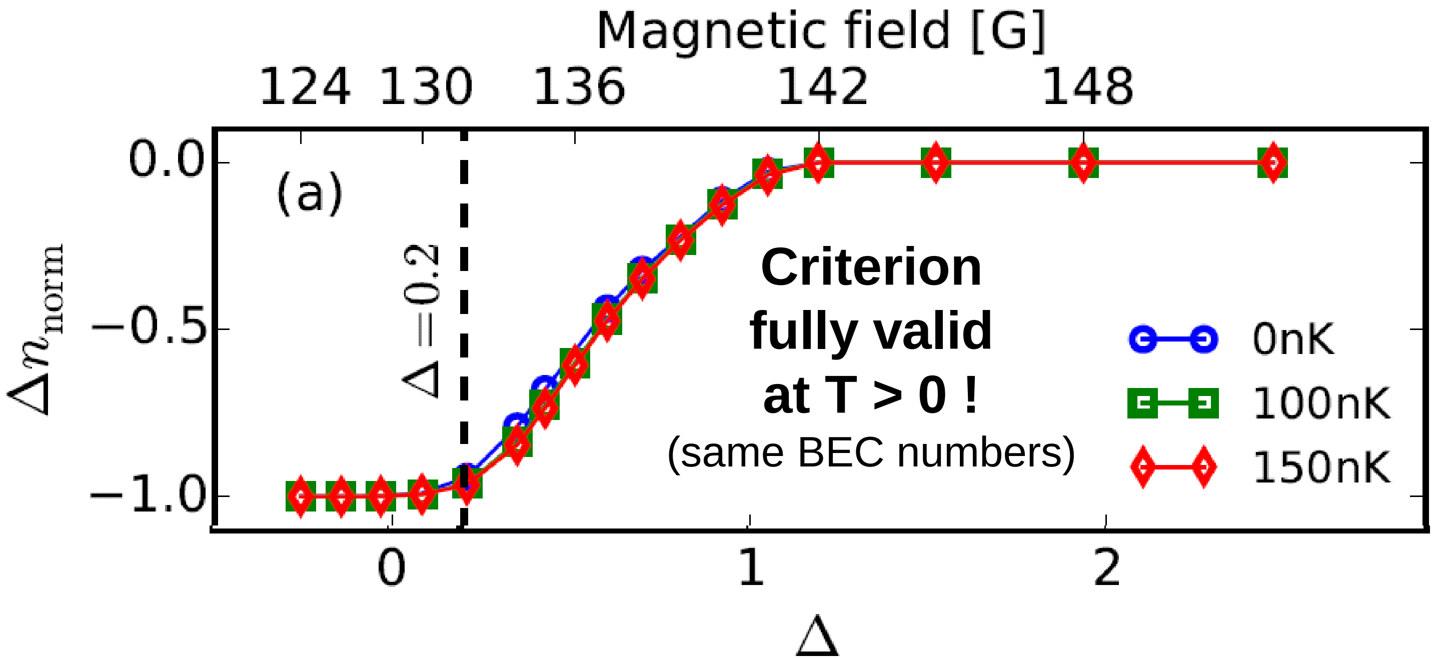
Criterion in Trap can Deviate Significantly from Homogeneous Condition !

This depends critically also on atom numbers

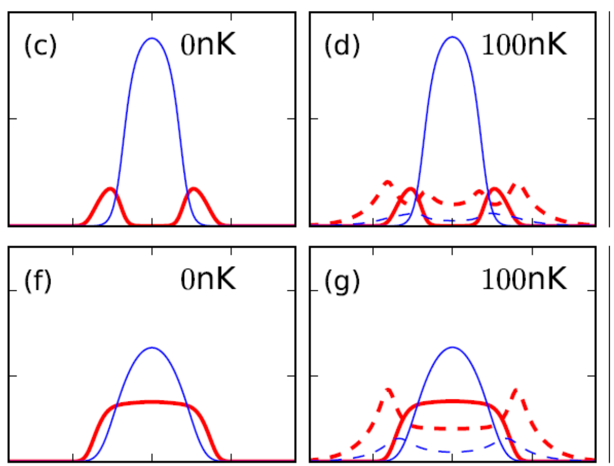
PHASE PROFILES OF 2-COMPONENT BECs

New Criterion fully captures "crossover" between separation & overlap

Probing Blue → Green Phase Separation Boundary



In Situ Density Profiles

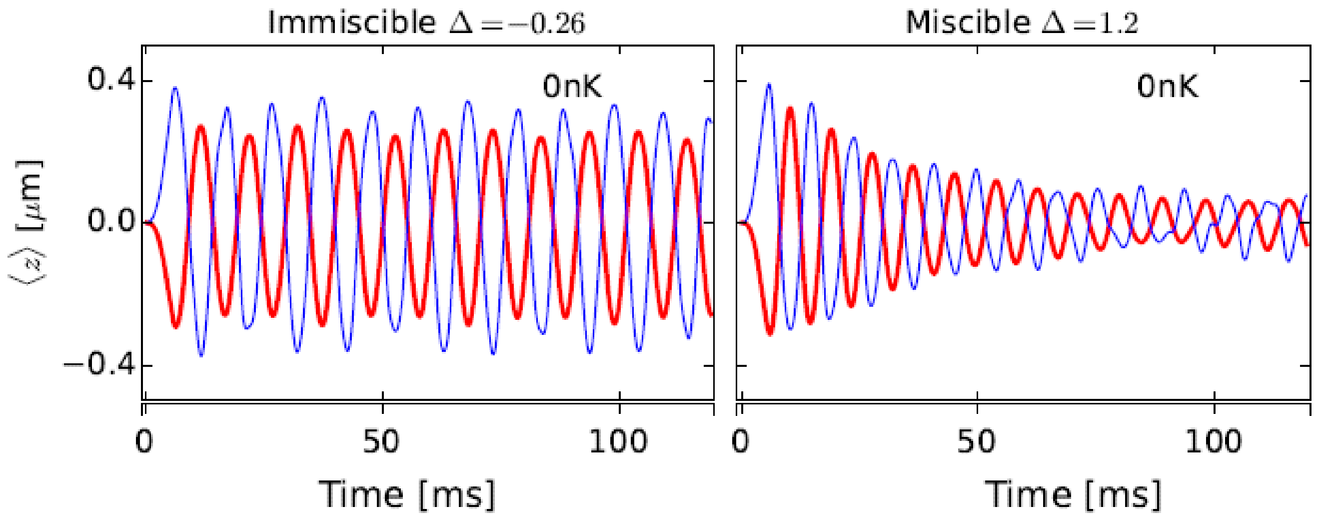


How to Characterize / Measure Experimentally ?

COLLECTIVE MODES AS IMMISCIBILITY PROBES

→ Induce Collective Modes & Study their Damping

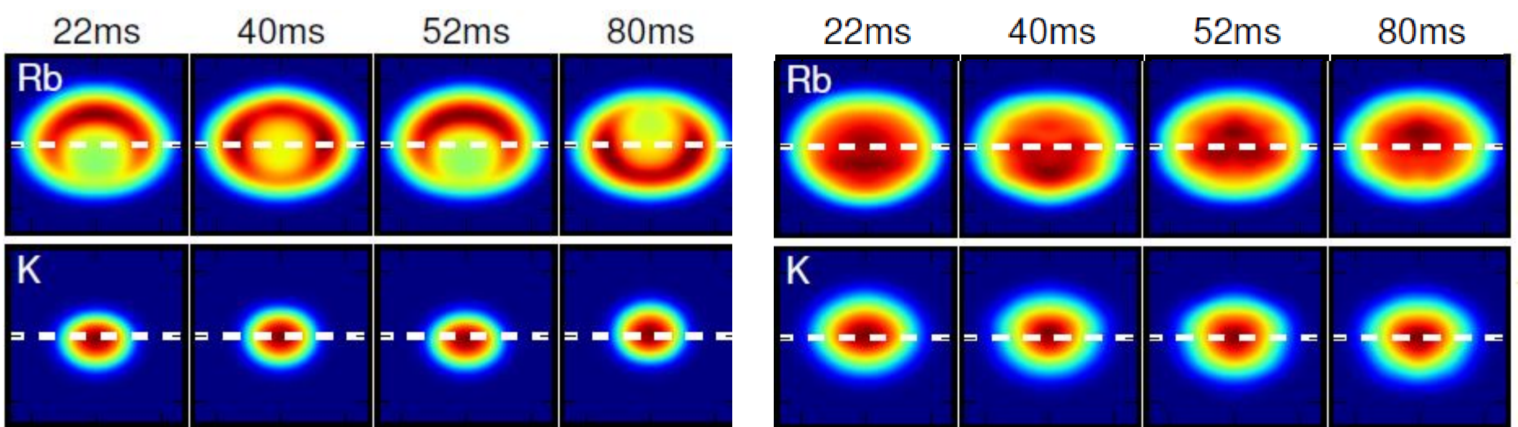
T = 0



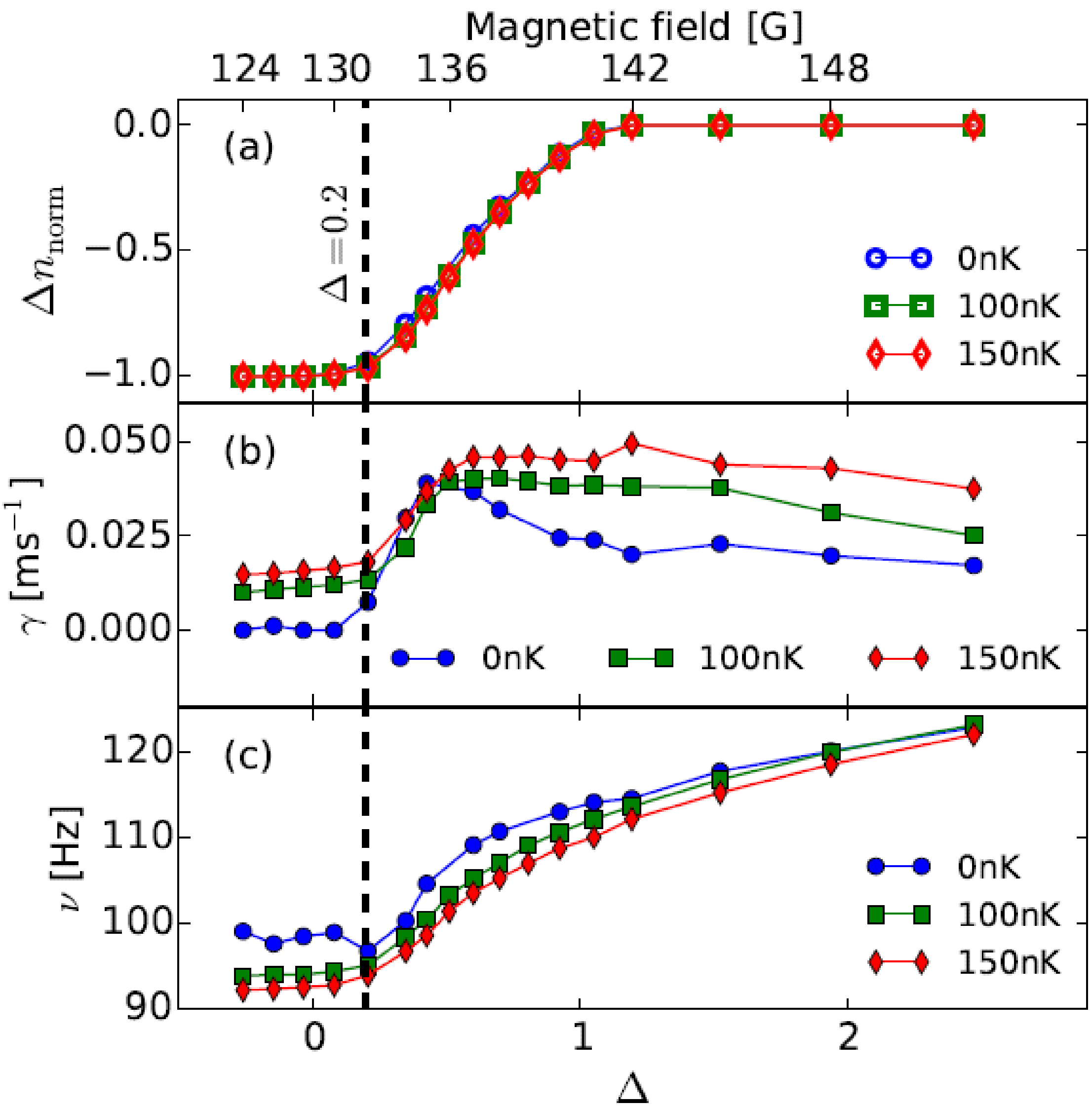
T = 0

Undamped Surface Shape Oscillations

Large Spatial Overlap Enhances Counterflow Instability



New Criterion fully captures "crossover" between separation & overlap



Our Picture is Confirmed by a Simultaneous Shift in Frequency & Damping of Collective Oscillations

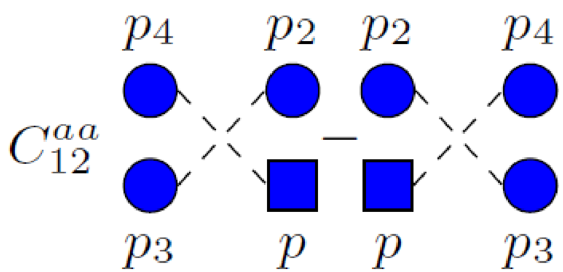
TWO-COMPONENT CONDENSATE THEORY

Component A: | Component B:

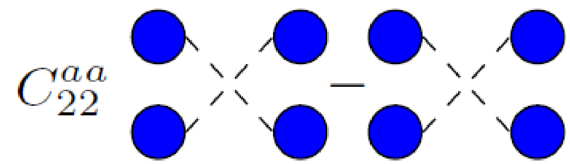
KEY:

Single Component Terms

Condensate -- Thermal



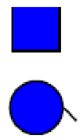
Thermal Only



TWO-COMPONENT CONDENSATE THEORY

KEY:

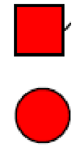
Component A:



BEC

Thermal

Component B:



BEC

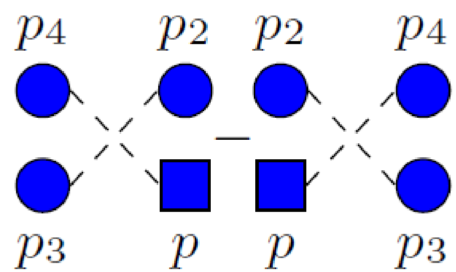
Thermal

Condensate -- Thermal

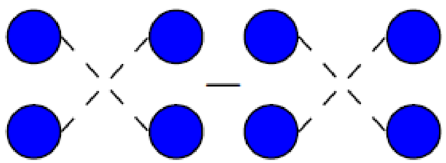
Thermal Only

Single Component Terms

C_{12}^{aa}

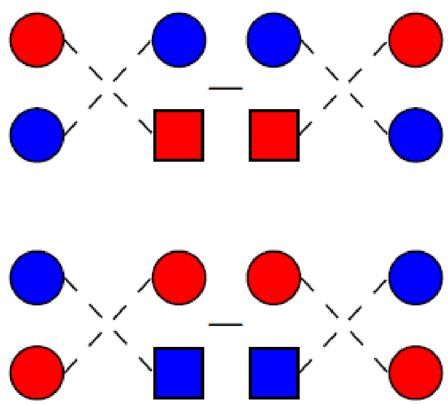


C_{22}^{aa}

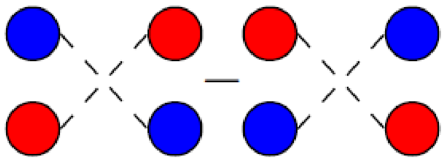


Corresponding 2-Component Terms

$C_{12}^{ab} + C_{12}^{ba}$



C_{22}^{ab}



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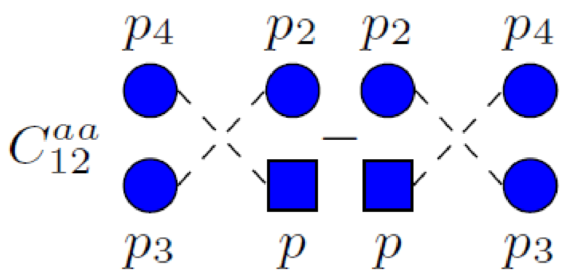
TWO-COMPONENT CONDENSATE THEORY

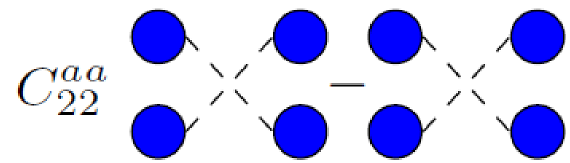
KEY:

	Component A:	Component B:
	BEC	**BEC**
	Thermal	**Thermal**

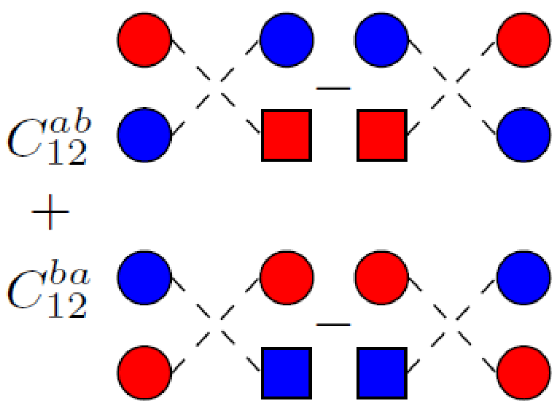
Condensate -- Thermal | Thermal Only

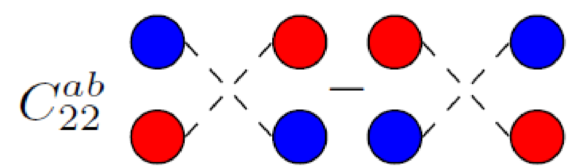
Single Component Terms



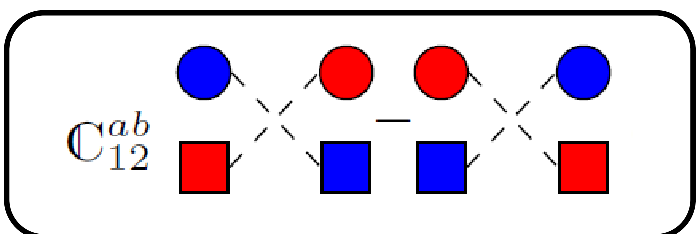


Corresponding 2-Component Terms





"Novel Cross-Coupling Processes"



Important when both components are partly condensed

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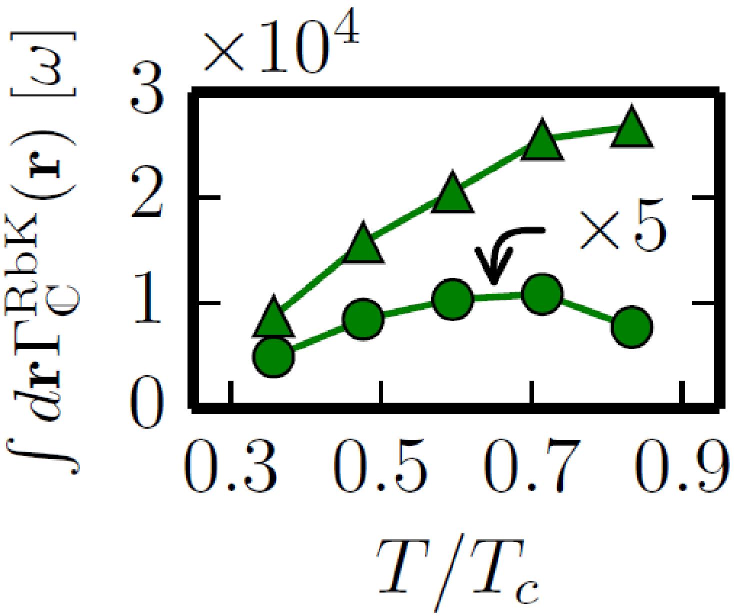
IMPORTANCE OF NOVEL COLLISIONAL TERM

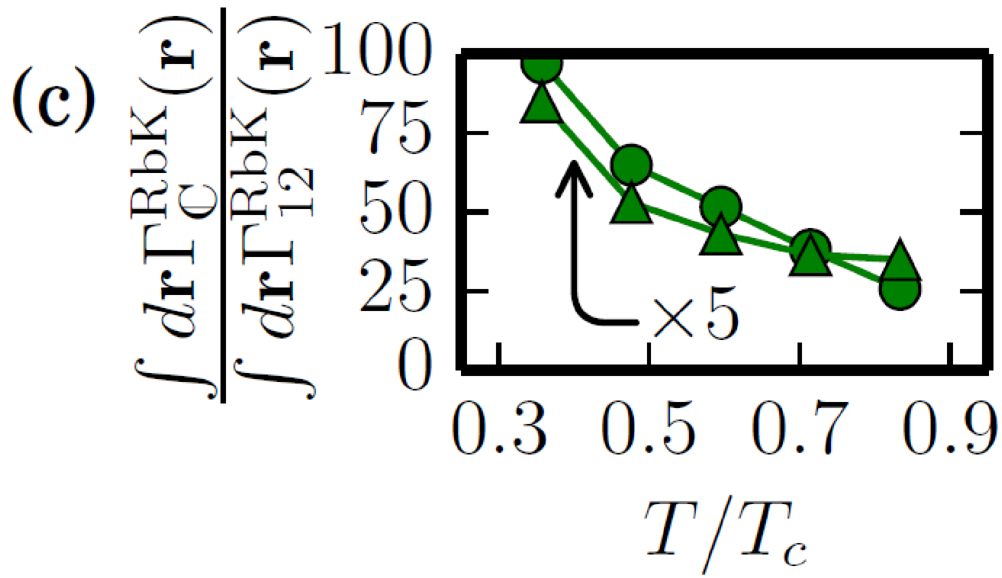
We now examine the Temperature-dependence of this collisional process

M Edmonds, K-L Lee, NP Proukakis , arXiv:1409.1725

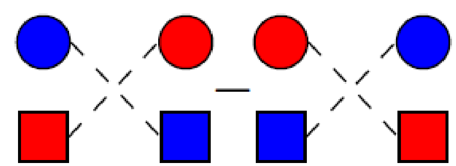
Absolute T-dependence



Relative T-dependence



Remarkably this “cross-condensate” scattering process is found to dominate near equilibrium even at rather high temperatures !



We thus anticipate it to play a dominant role in sympathetic cooling, from its early stages, completely dominating over collisions at lower Temperatures