SINGLE/MULTI-COMPONENT QUANTUM GASES:

NON-EQUILIBRUM MODELS

& APPLICATIONS TO EXPERIMENTS

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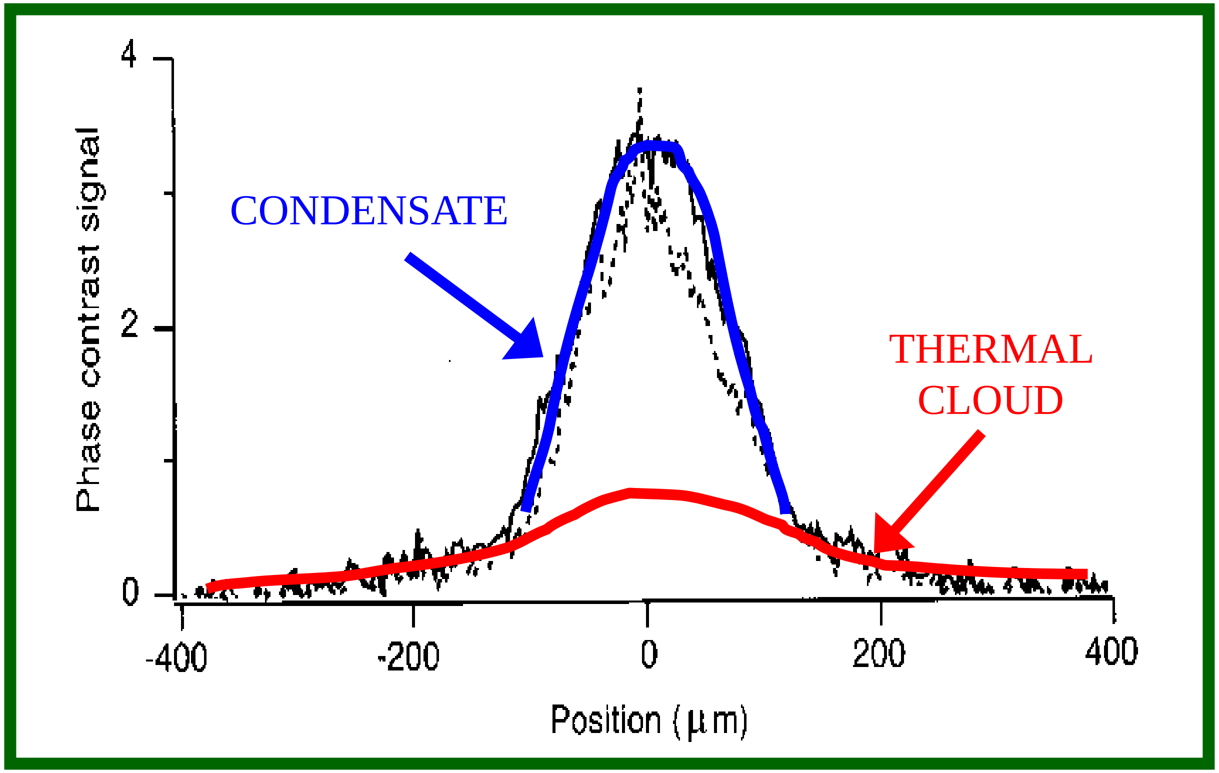
Engineering and Physical Sciences Research Council

GENERAL CASE: QUANTUM GAS AT 0 < T < Tc

A typical experiment, features both condensed and thermal atoms

$T \sim 100 nK$ $\quad N \sim 10^3 - 10^8$ atoms $\quad n_{3D} \sim 5*10^{12} \quad - 10^{14}\, cm^{-3}$



Need to go beyond the (simple) Gross-Pitaevskii Equation!

Require a self-consisent non-equilibrium finite Temperature theory to describe both “subsystems” & their couplings

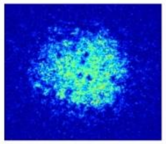
MODELLING COLD ATOMS AT T > 0

There are (at least) 2 fundamentally different, yet complementary, approaches to partially condensed (T > 0) Systems

1 **Presentation of Approaches**

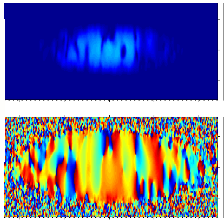
- **Kinetic**

- **Stochastic**



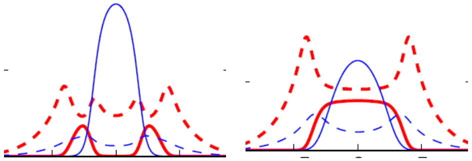
2 **Application to Dynamics of *Single-Component* Atomic BEC**

- **BEC Oscillations**
- **Soliton / Vortex**
- **Condensate Growth**

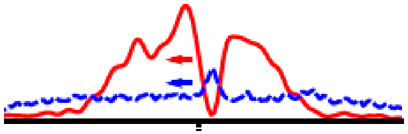


3 **Generalization to Dynamics of *Two-Component* BECs**

- **Phase Mixing vs. Separation**



- **Growth Dynamics & Thermalization**



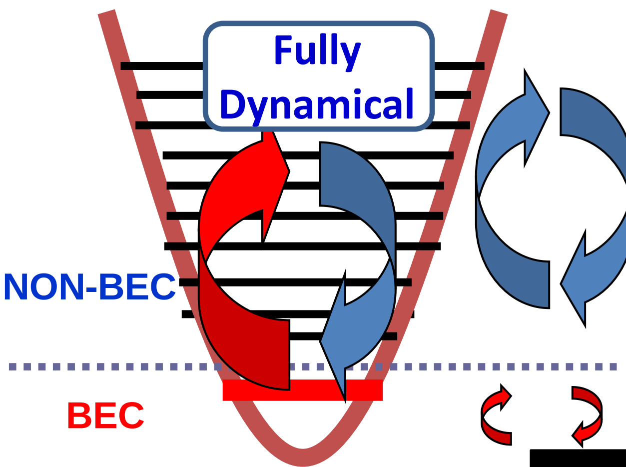
MODELLING COLD ATOMS AT T > 0

There are (at least) 2 fundamentally different, yet complementary, approaches to partially condensed (T > 0) Systems

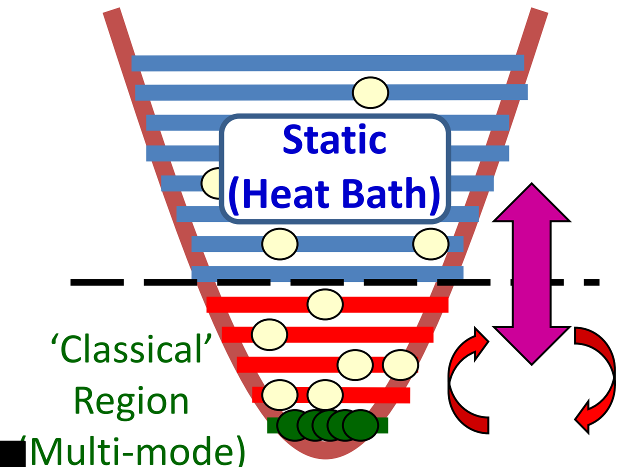
Kinetic Approaches
(explicit BEC separation)

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")

MODELLING COLD ATOMS AT T > 0

There are (at least) 2 fundamentally different, yet complementary, approache **0) Systems**

e.g. Additional Scheme

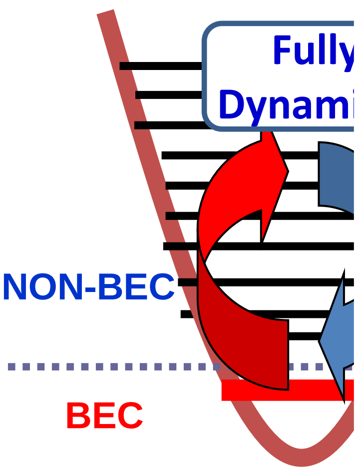
'Classical Field' Evolution

(e.g. Berloff – Barenghi – Davis)

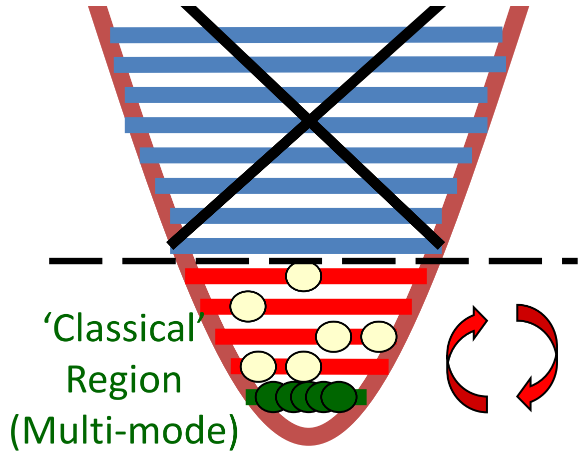
Kinetic Ap
(explicit BEC

ic Approaches
BEC separation)

BEC + Dynamica
with full self-con



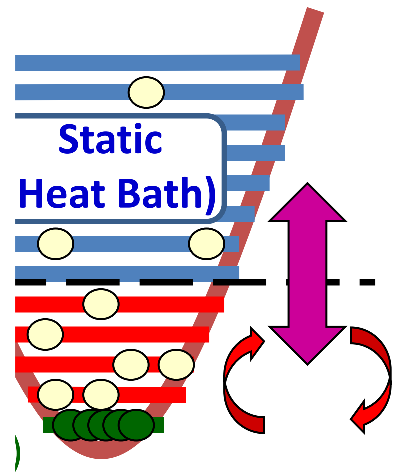
Collective Mo
Full BEC – The
(far from critica



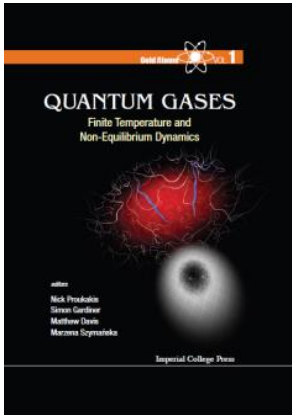
Only consider modes
populated 'clasically'
(up to some cutoff)
such that N(E) >> 1

[Microcanonical Ensemble]

a cut-off described
nner (classical field)
to a Heat Bath



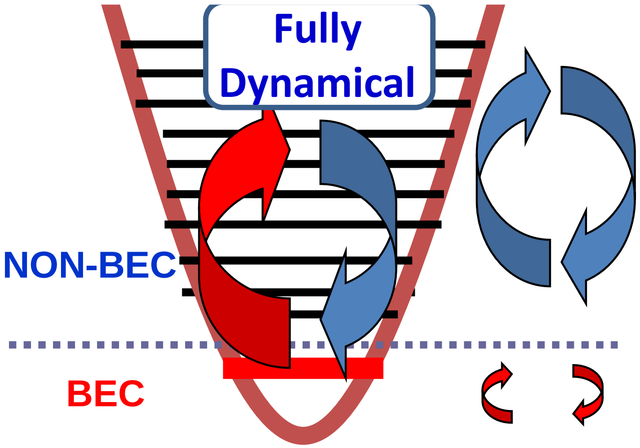
to-shot) Fluctuations
ow-D & Universality
g modes "unaffected")

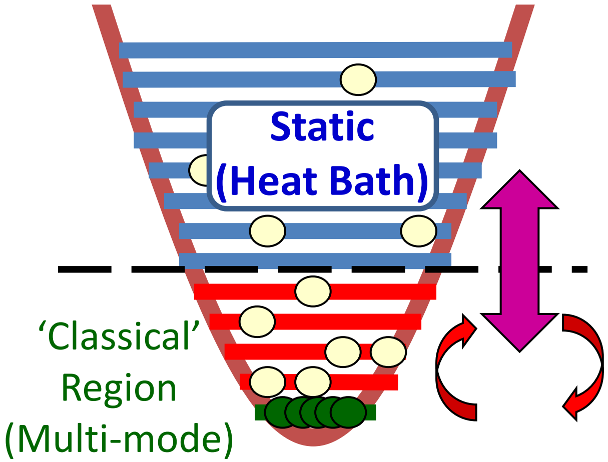


MODELLING REVIEWS:

Quantum Gases: Finite Temperature and Non-Equilibrium Dynamics
Proukakis et al. (Eds), Imperial College Press/World Scientific (2013)

Berloff, Brachet & Proukakis, PNAS 111 (Suppl. 1) 4675 (2014)
Proukakis & Jackson, J Phys B 41, 203002 (2008)
Blakie, Bradley, Davis, Ballagh & Gardiner, Adv. Phys. 57, 363 (2008)

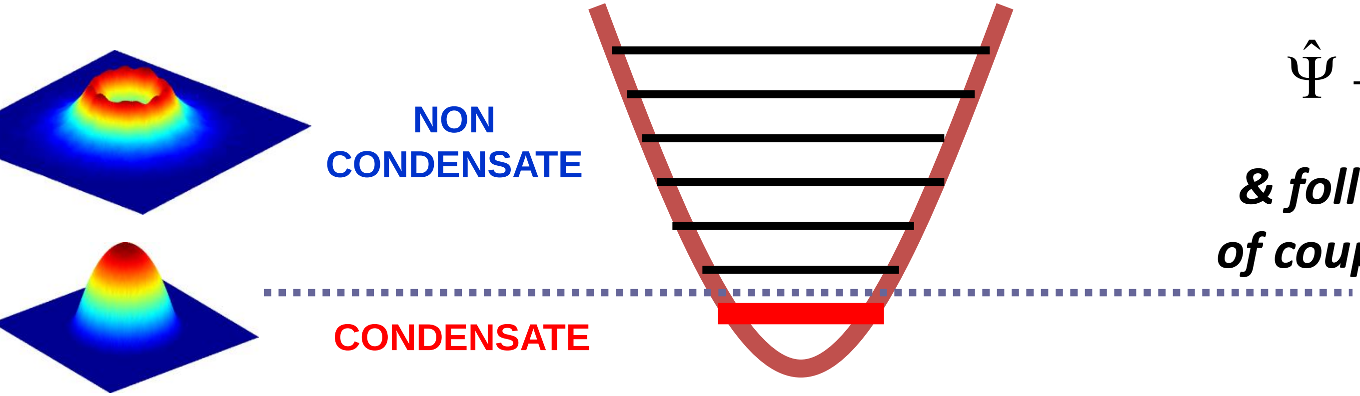




Kinetic Approaches
(explicit BEC separation)

KINETIC MODEL ("ZNG" or Gross-Pitaevskii-Boltzmann)

Based on Symmetry-breaking; System artificially (conveniently) separated into 2 parts



$$\hat{\Psi} \rightarrow \left\langle \hat{\Psi} \right\rangle + \hat{\delta} = \phi + \hat{\delta}$$

& follow truncated hierarchy of coupled equations of motion

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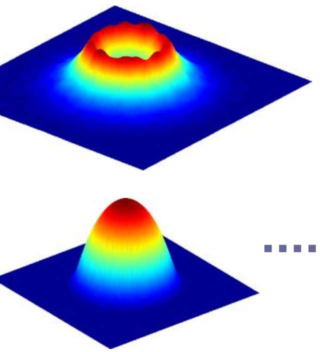
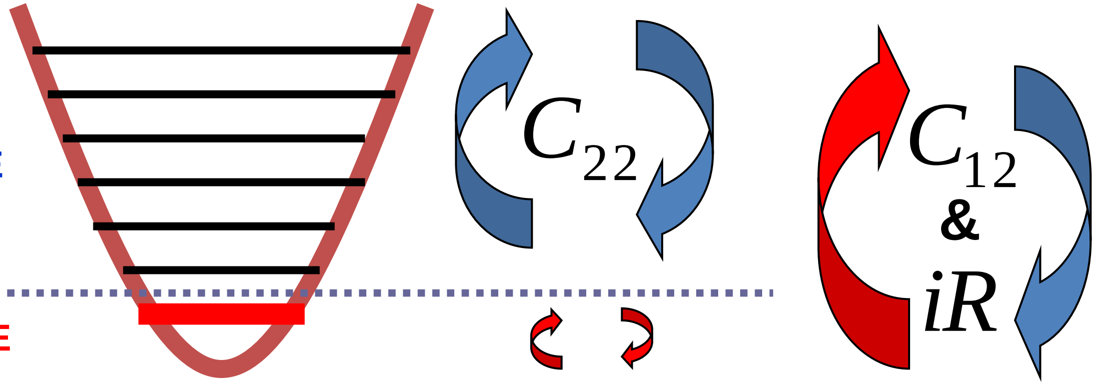


NON CONDENSATE

CONDENSATE



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

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

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

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

EXCHANGE OF ATOMS BETWEEN SUB-SYSTEMS

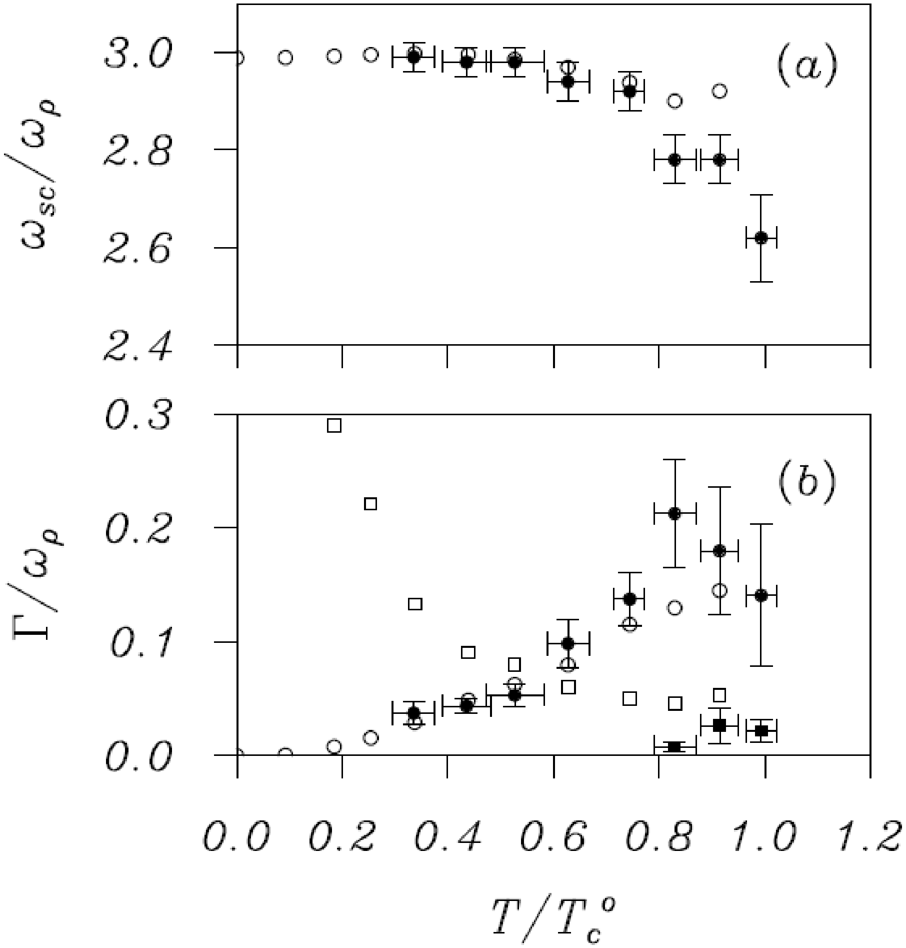
THERMAL COLLISIONS

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

APPLICATION I: EXCITATION FREQUENCIES

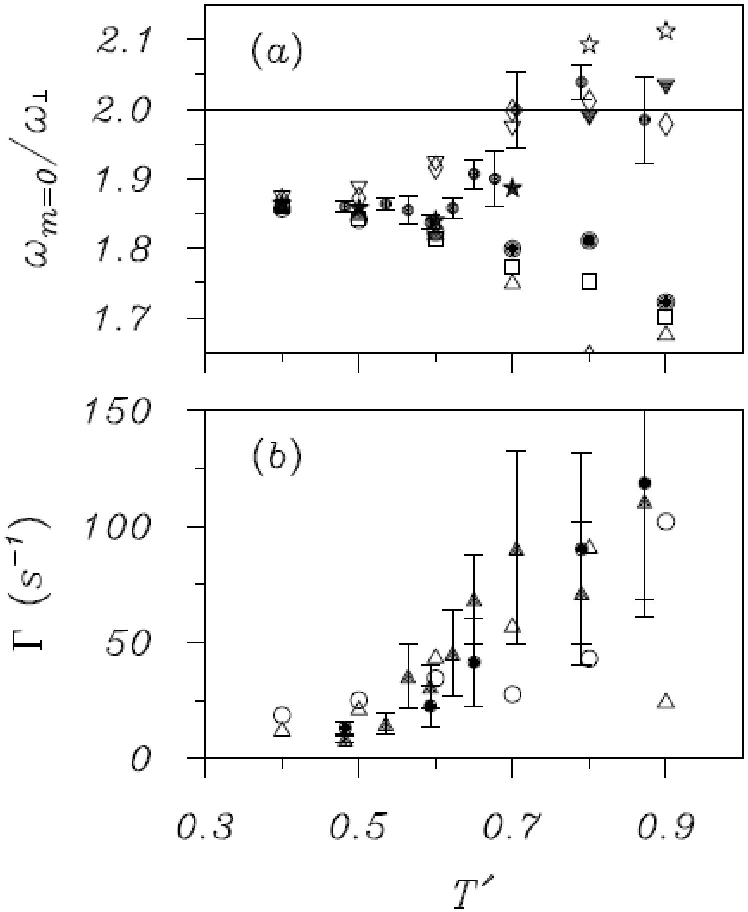
"Scissor's Mode" Excitation

Expt: Marago et al, PRL 86, 3938 (2001)
Theory: Jackson-Zaremba,
PRL 87, 100404 (2001)



Quadrupolar Excitations

Expt: Jin et al, PRL 78, 764 (1997)
Theory: Jackson-Zaremba
PRL 88, 180402 (2002)



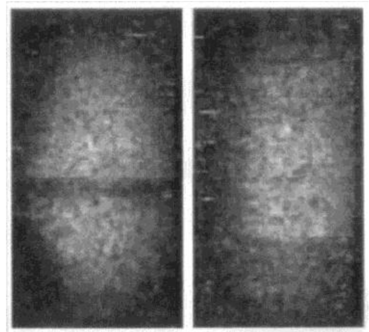
→ Excellent Quantitative Agreement with Experiments

APPLICATION II: EXPERIMENTAL DARK SOLITON DECAY

Jackson, **Proukakis** & Barenghi, Phys. Rev. A **75**, R051601 (2007)

EXPERIMENT

S Burger *et al.*
Phys. Rev. Lett.
83, 5198 (1999)



'High Temperature' $T = 0.5T_C$

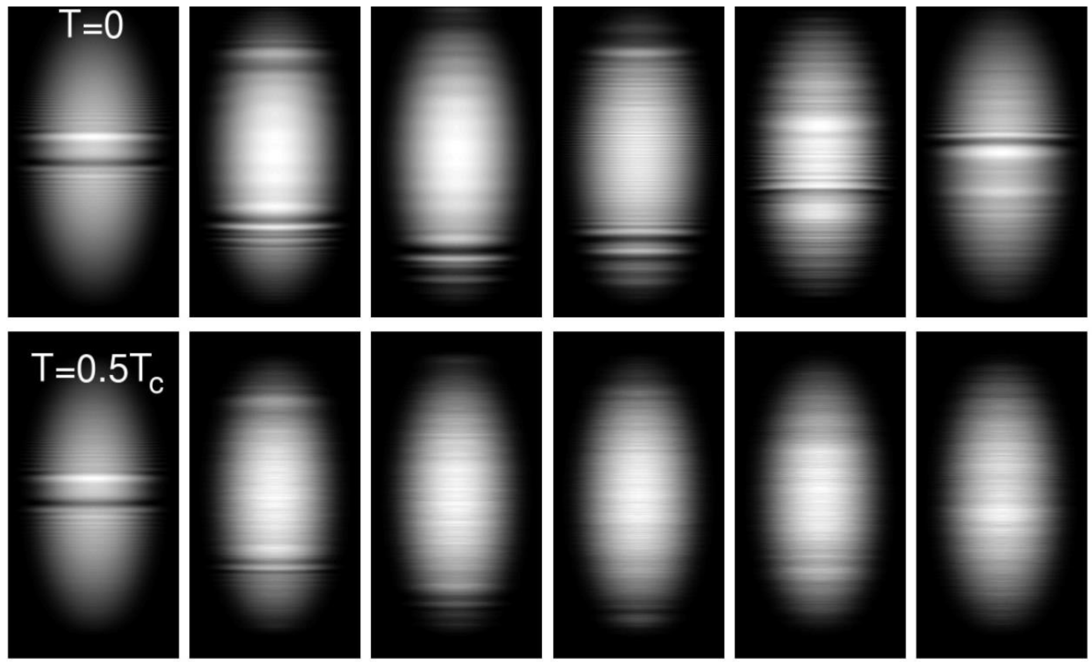
Soliton is 'lost'
in absorption images
as it reaches the trap edge

GROSS-PITAEVSKII
THEORY

T = O

GENERALIZED
MEAN FIELD
(ZNG)

T > O



0.5 ms | 12 ms | 20 ms | 40 ms | 50 ms | 60 ms

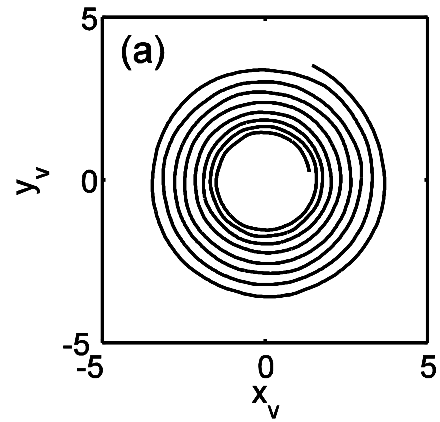
→ Soliton Disappears on Experimental Timescales

Soliton Oscillations at extremely low T, subsequently observed in Hamburg; Heidelberg

APPLICATION III: EXPERIMENTAL VORTEX DECAY

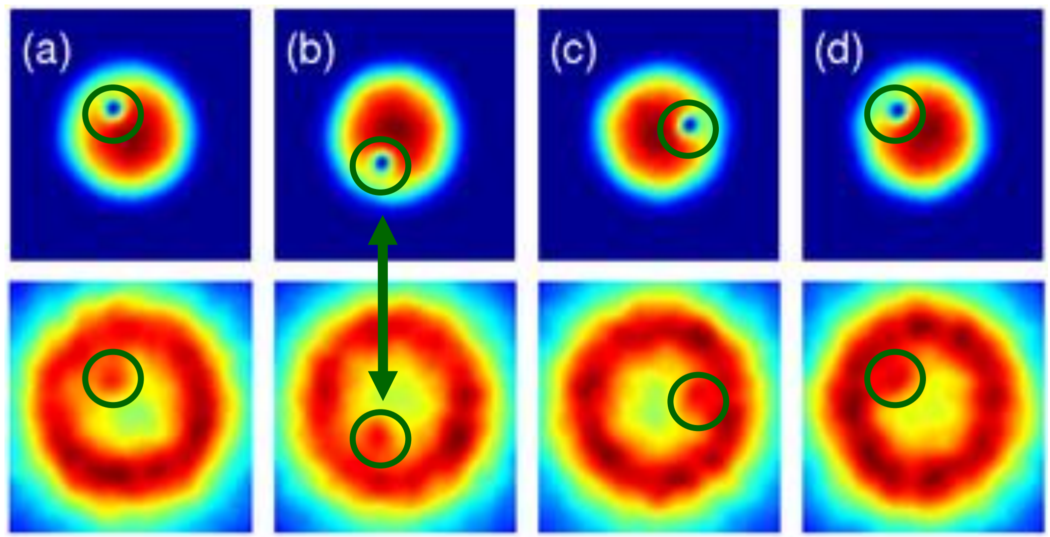
Jackson, Proukakis, Barenghi & Zaremba, Phys. Rev. A 79, 053615 (2009)

Off-centered Vortex spirals out from centre and decays gradually with sound emission



CONDENSATE DENSITY

THERMAL CLOUD DENSITY



Thermal Cloud fills in the vortex core (as it spirals out)

→ Findings are Qualitatively Consistent with Vortex Experiments

See e.g. Freilich et al., Science 329 (2010)

APPLICATION III: EXPERIMENTAL VORTEX DECAY

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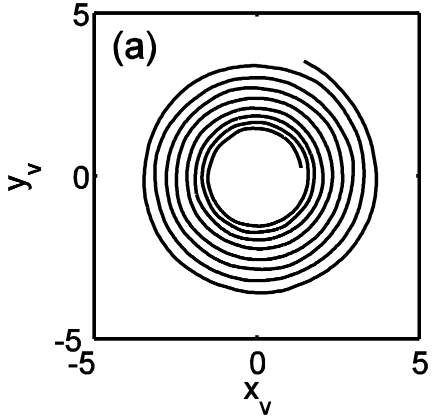
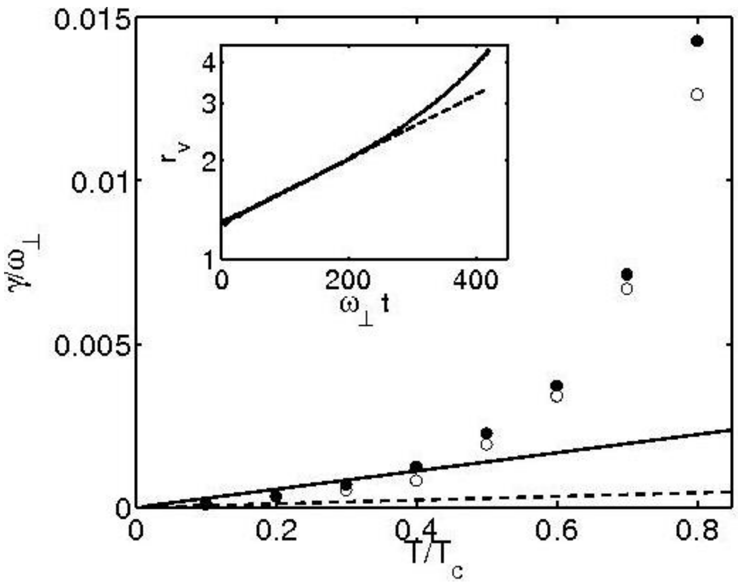
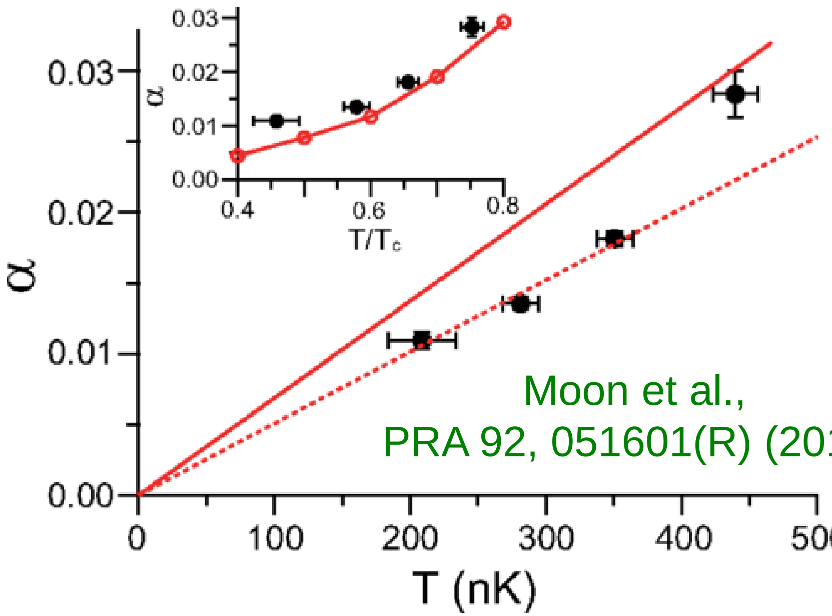


Vortex position grows exponentially

$$\frac{dr_v}{dt} = \omega\left(\frac{\gamma}{\omega}\right) r_v = \alpha\omega r_v$$





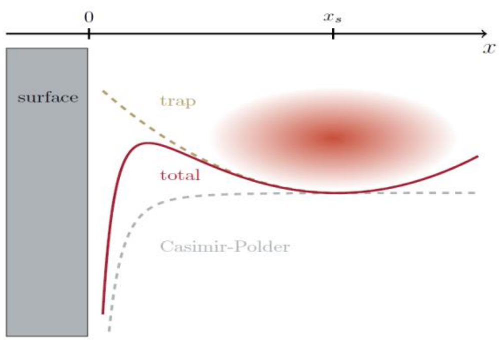
Moon et al., PRA 92, 051601(R) (2015)

Indirect Evidence from Experimental co-rotating vortex dipole decay study

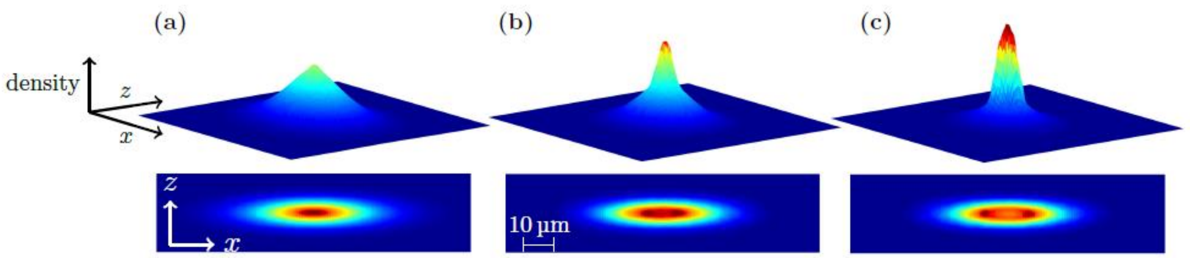
APPLICATION IV: SURFACE EVAPORATIVE COOLING

Move Thermal Cloud onto a Room-Temperature Surface
& Study Atom Loss & BEC Growth at Different Distances from Surface

Effective Potential near Surface

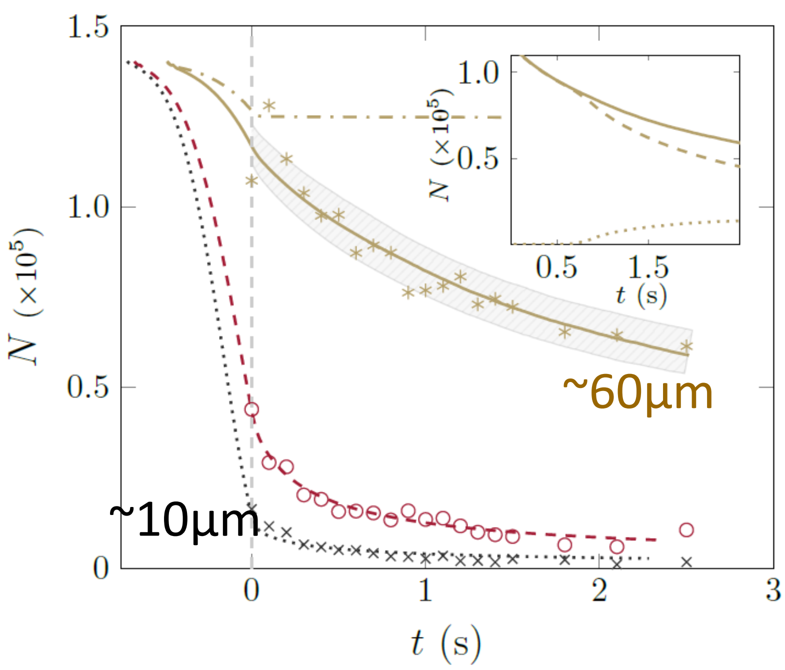


Study Atom Loss & BEC Growth at Different Distances from Surface



Theory-Experiment Comparison

(different "hold" positions)



J. Maerkle, A.J. Allen, P. Federsel, B. Jetter, A. Günther, J. Fortágh, N. P. Proukakis, and T. E. Judd
PRA 90, 023614 (2014)

MODELLING COLD ATOMS AT T > 0

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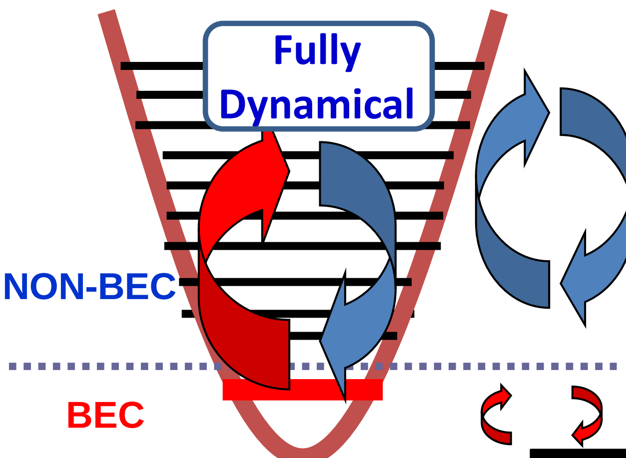

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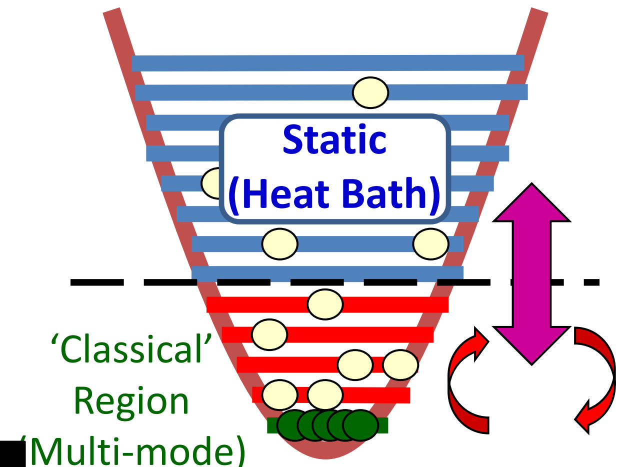

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Stochastic Approaches

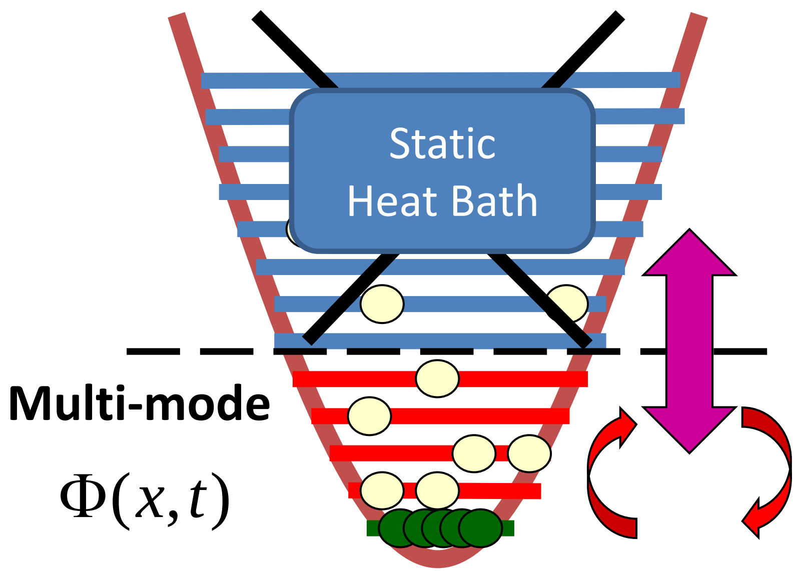
(no explicit BEC separation)

STOCHASTIC GROSS-PITAEVSKII (SGPE) MODEL

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

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

Beyond-GPE Terms



STOCHASTIC GROSS-PITAEVSKII (SGPE) MODEL

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

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

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

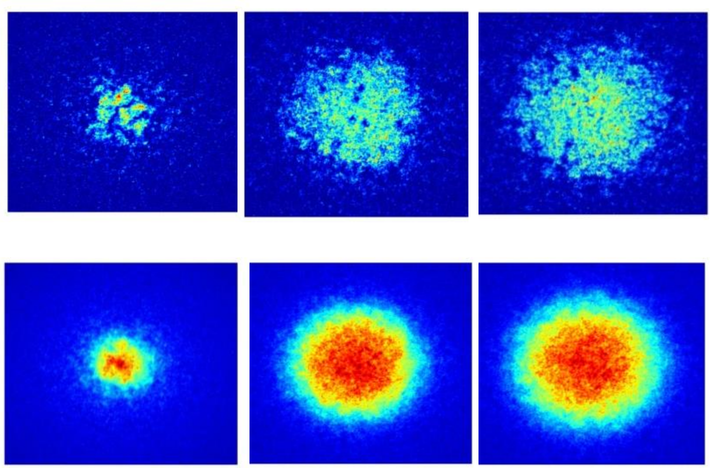
so supposed to be interpreted after suitable 'trajectory' averaging

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

Single Run

vs.

Averaged Profiles



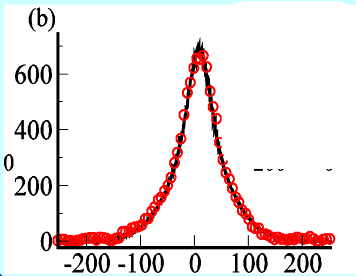
* Contain element of stochasticity
* *Qualitatively* reproduces single experimental realisations
* Wash out density fluctuations to produce smooth profiles
* Suitable for extracting global features (densities, correlation functions, etc.)

APPLICATION I: LOW-D EQUILIBRIUM PROPERTIES

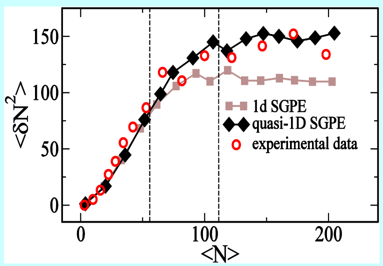
Properties Characterised by Densities & Lowest Order Correlation Functions

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

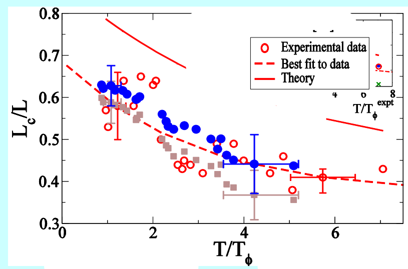
Density Profiles



Density Fluctuations



Phase Fluctuations



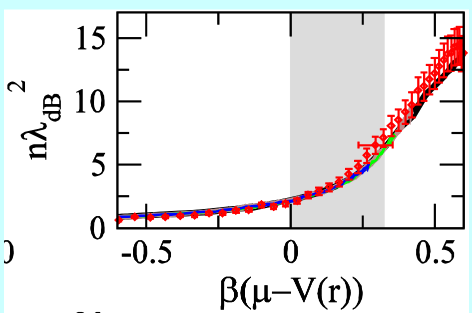
Experiments:
Paris & Amsterdam

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

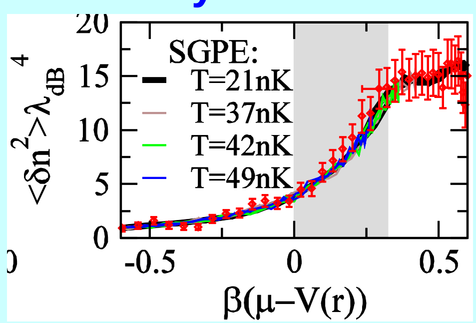
***Ab Initio* SGPE Modelling:**
NPP et al.,
PRA 84, 023613 (2011)
PRA 86, 013627 (2012)

Quasi-2D:
Scale-invariance & Universality

Densities



Density Fluctuations



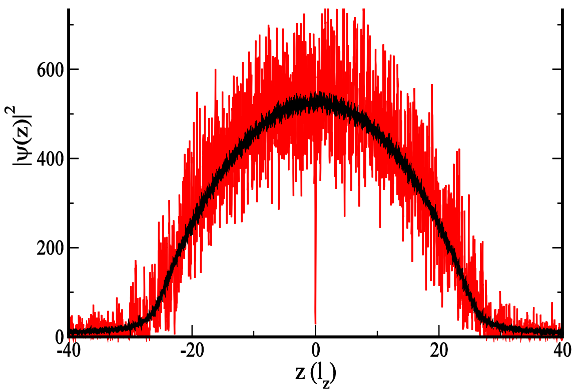
Experiment:
Chicago

Nature 470, 236 (2011)

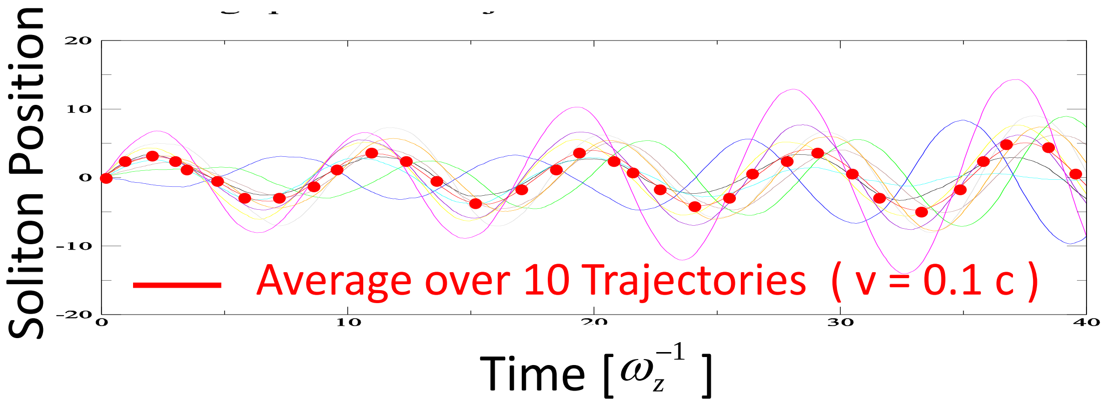
***Ab Initio* SGPE Modelling:**
Cockburn & NPP
PRA 86, 033610 (2012)

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

APPLICATION II: DARK SOLITON EVOLUTION

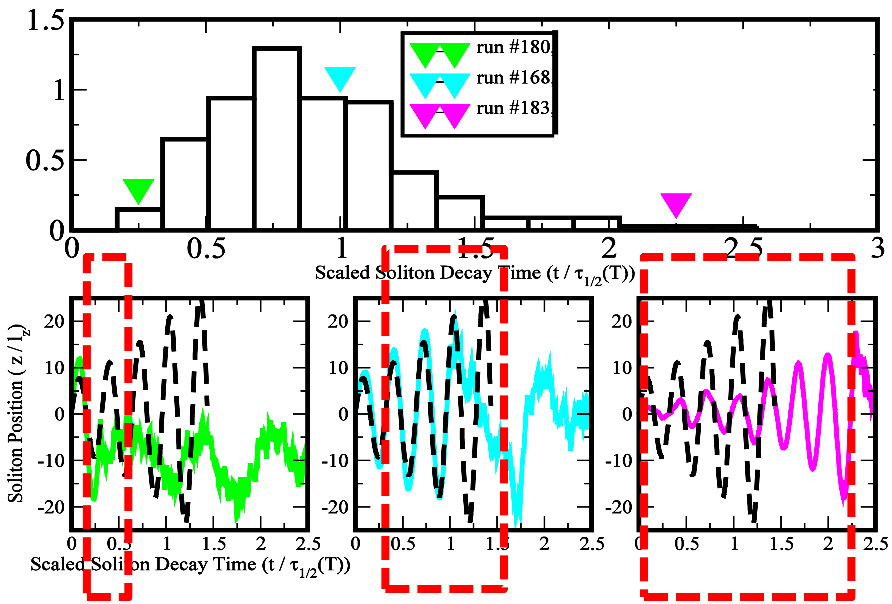


Individual Soliton Trajectories can look very different from each other due to the role of the noise term



Resort to 'statistical analysis' of soliton decay times

Soliton is 'lost' within each run, when it becomes comparable to the noise



→ Significant spread between different soliton trajectories/lifetimes

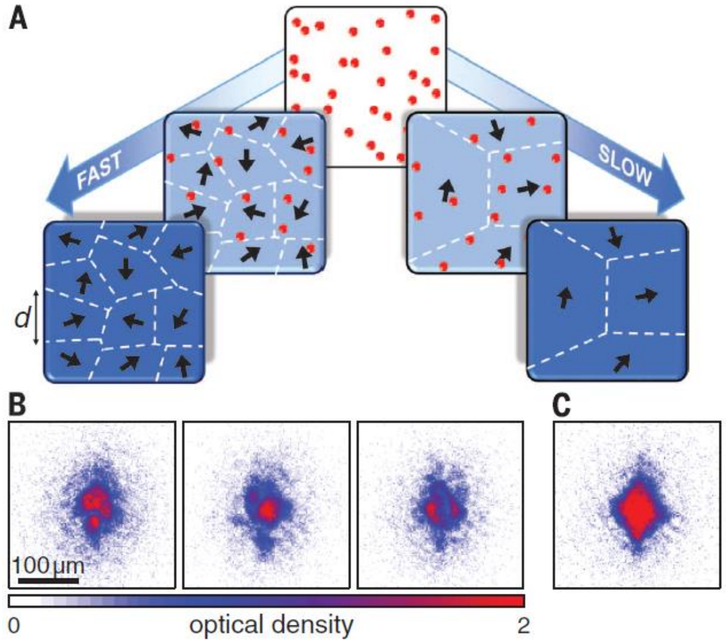
→ Predictions of few very long-lived soliton trajectories

Consistent with Experimental Findings .(but in different regime!)

Cockburn, Nistazakis, Horikis, Kevrekidis, Proukakis & Frantzeskakis PRL 104, 174101 (2010)

APPLICATION III: CONDENSATE GROWTH & KIBBLE-ZUREK

Consider rapidly quenching a system through the phase transition



Hadzibabic et al, Science 347 (2015)

→ System Grows Locally-Coherent Patches with Uncorrelated Phases Separated by Phase Defects (e.g. Dark Solitons / Vortices)

Kibble-Zurek Model:

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

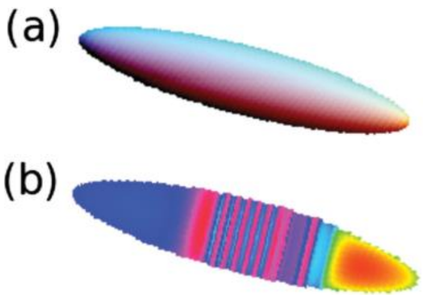
(Defect "Type" Depends on Dimensionality)

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

APPLICATION III: CONDENSATE GROWTH & KIBBLE-ZUREK

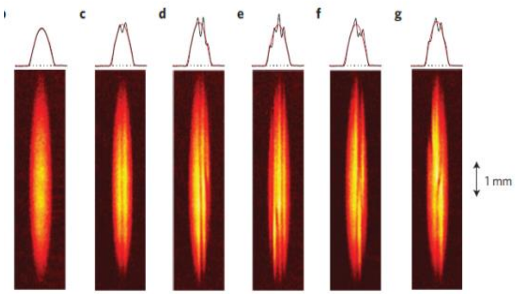
Cold Atom Kibble-Zurek Gallery

1D: Soliton Formation



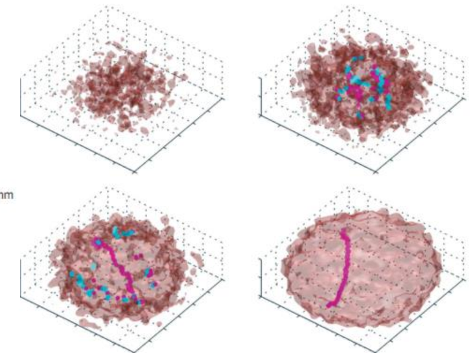
Zurek et al.
PRL 102, 105702 (2009)
PRL 104, 160404 (2010)

Quasi-1D: Solitonic Vortices



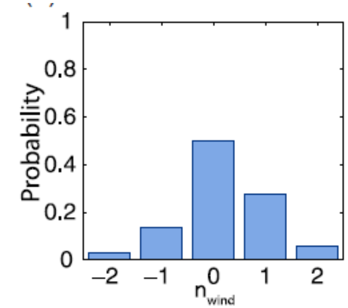
Lamporesi - Ferrari
Nat Phys 9, 656 (2013)

Quasi-2D / 3D: Vortex Formation

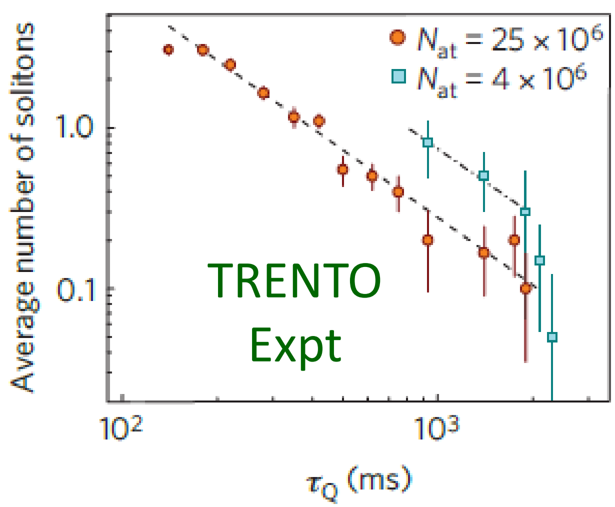


Weiler-Davis et al.
Nature 455, 948 (2008)

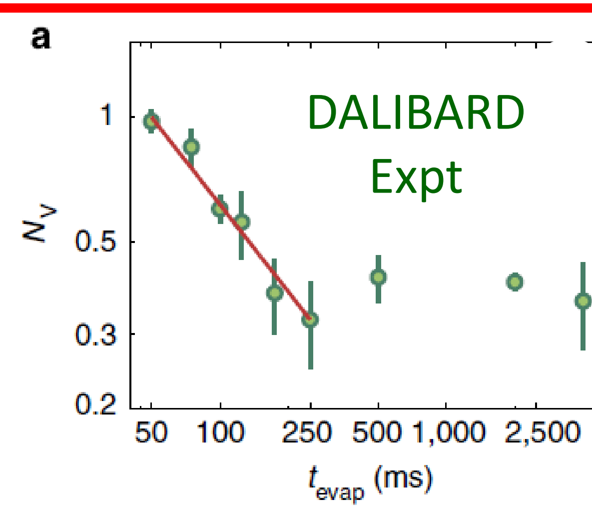
Ring Trap: Persistent Current



Dalibard/Beugnon
PRL 113, 135302 (2014)
Davis et al. PRL 107 (2011)



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



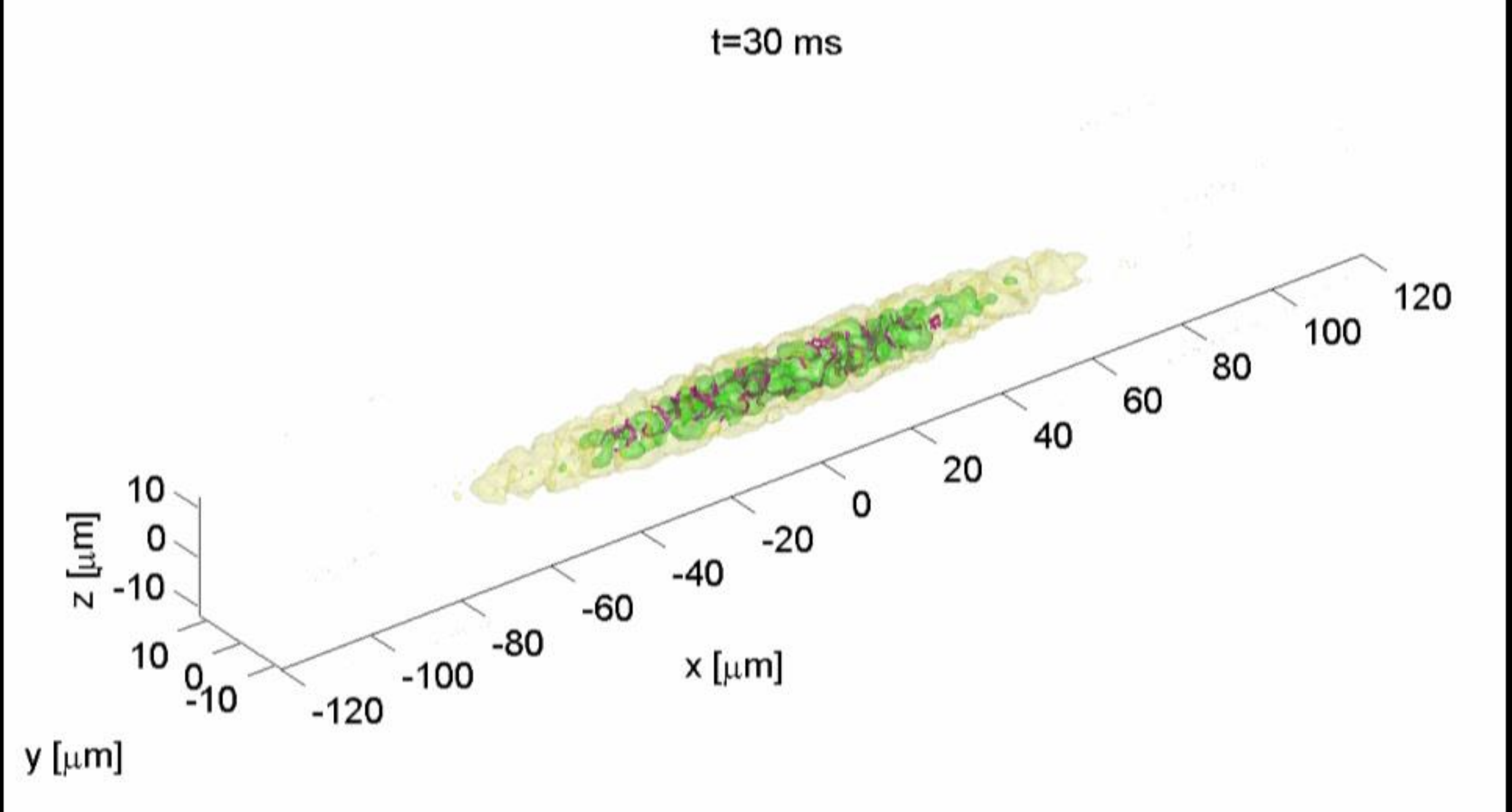
Critical Exponents Experimentally Characterised in a Box-like Trap

Hadzibabic et al, Science 347 (2015)
Dalibard et al., Nat. Comm. (2015)

APPLICATION III: CONDENSATE GROWTH & KIBBLE-ZUREK

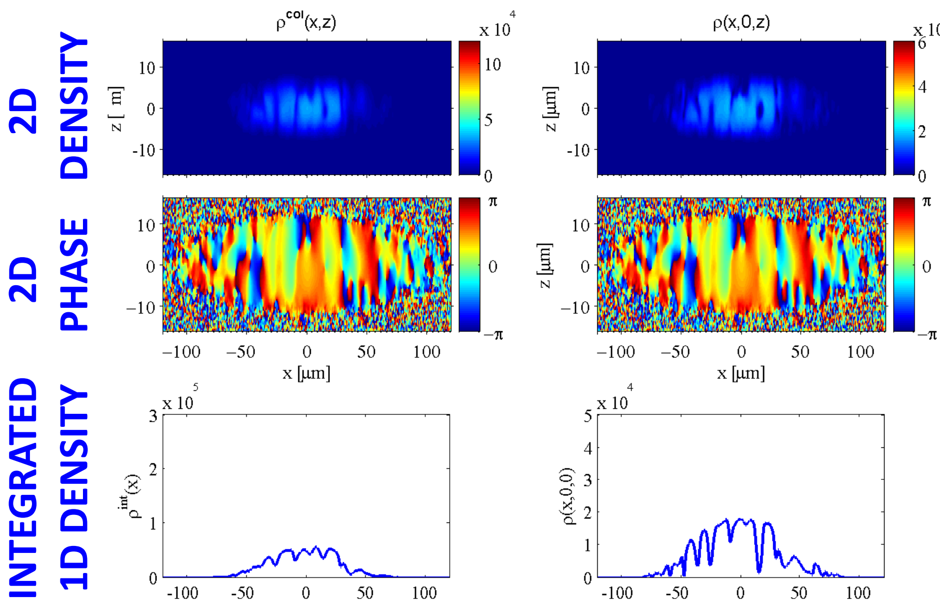
Model Trento Experimental Quench Sequence:

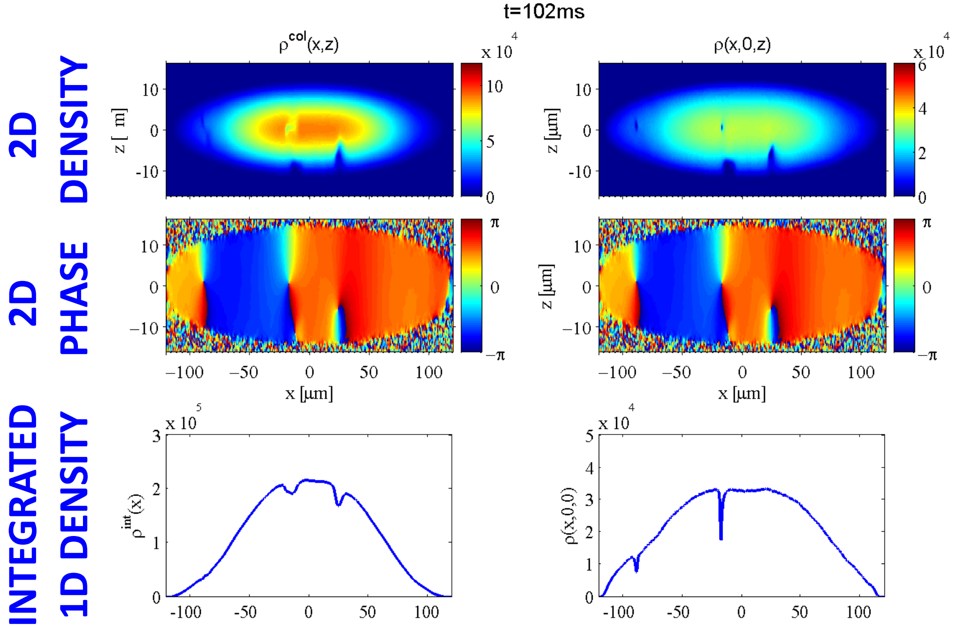
Quench from T > Tc to T < Tc over tens-hundreds of ms



APPLICATION III: CONDENSATE GROWTH & KIBBLE-ZUREK

INTEGRATED ALONG y | **y = 0 PLANE**





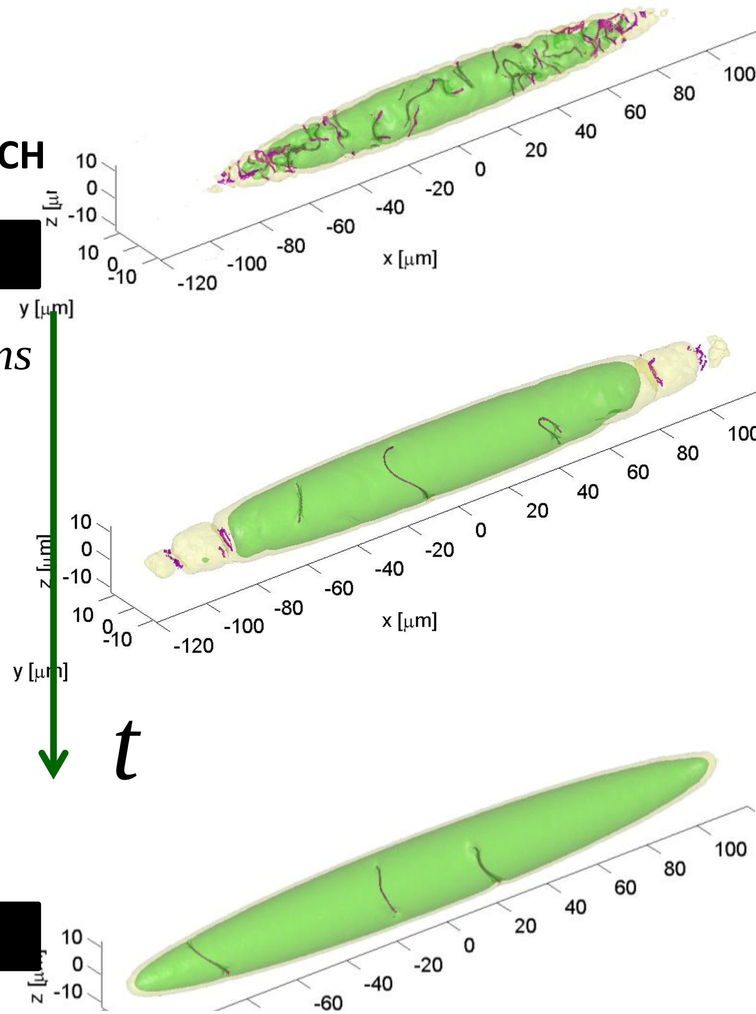
@ END OF QUENCH

$$\tau_{ramp} = 42ms$$

30 ms LATER

t

60 ms LATER

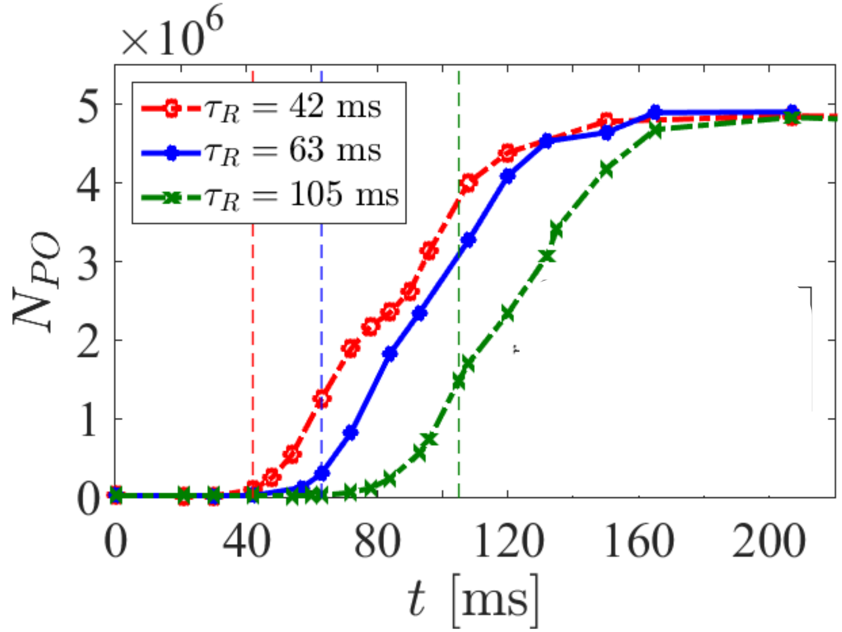


Underlying Formation Dynamics closely related to:

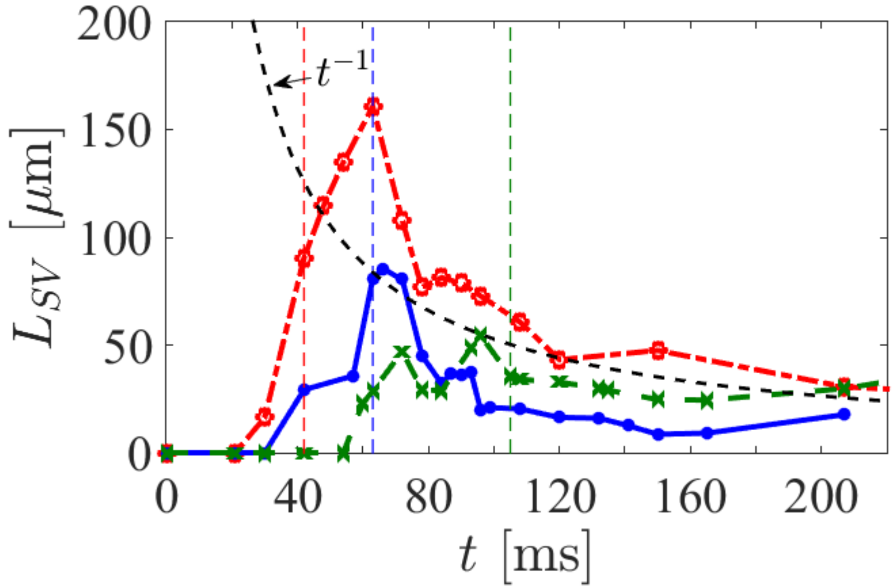
Berloff & Svistunov, PRA 66, 013603 (2002)

Consider 3 different experimentally-relevant quench rates

BEC Number Growth



Total Vortex Line Length (within BEC)



APPLICATION III: CONDENSATE GROWTH & KIBBLE-ZUREK

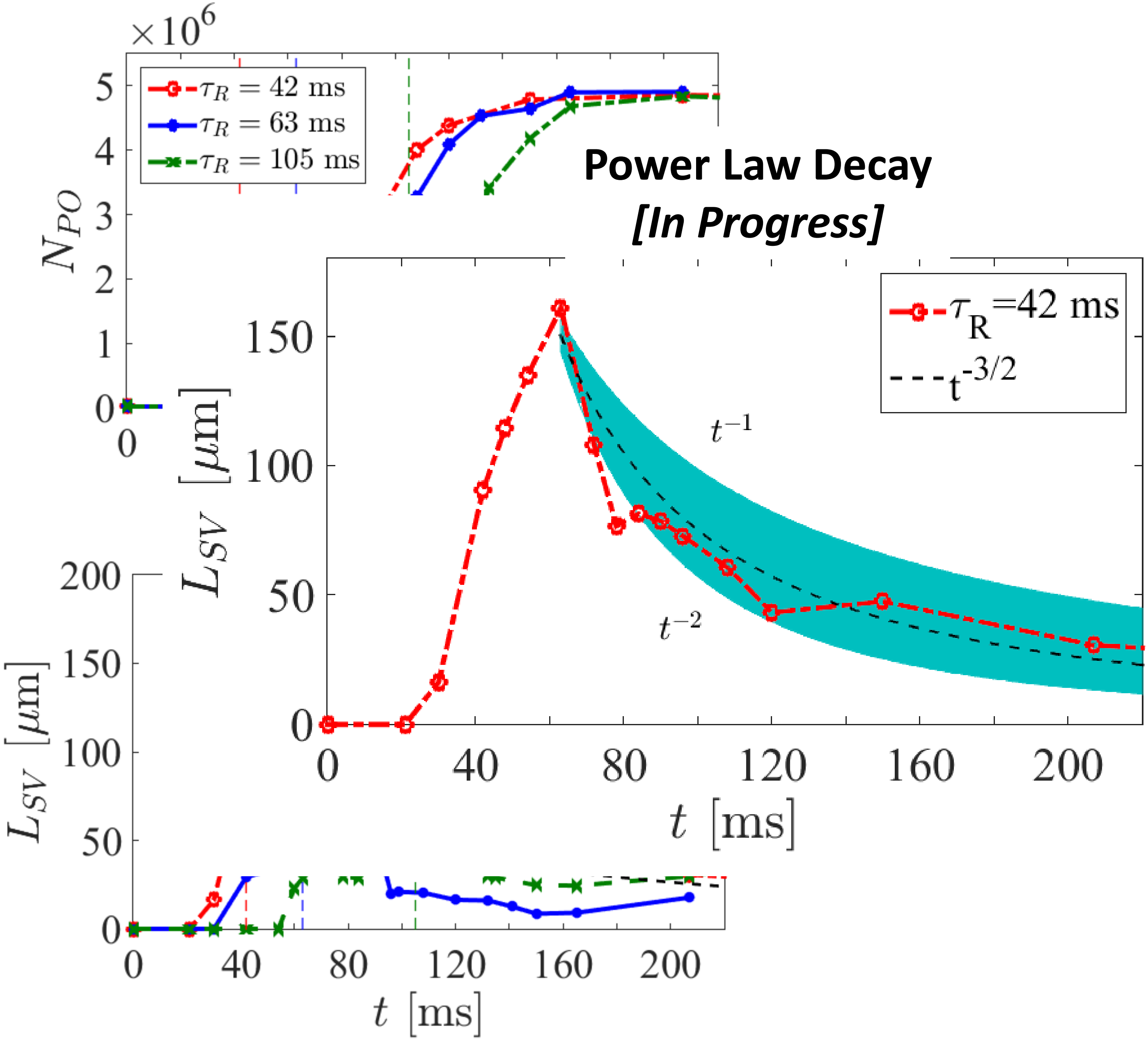
Consider 3 different experimentally-relevant quench rates

BEC Number Growth

Total Vortex Line Length (within BEC)

Power Law Decay

[In Progress]



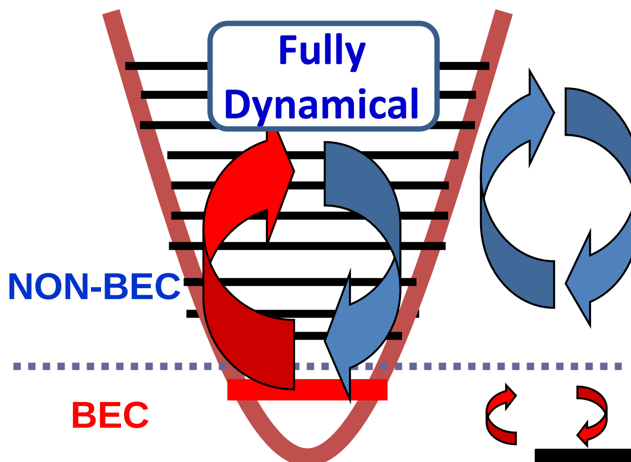
MODELLING COLD ATOMS AT T > 0

There are (at least) 2 fundamentally different, yet complementary, approaches to partially condensed (T > 0) Systems

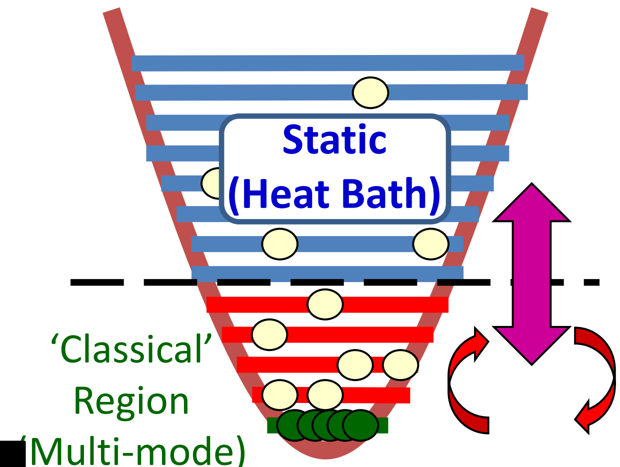
Kinetic Approaches
(explicit BEC separation)

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



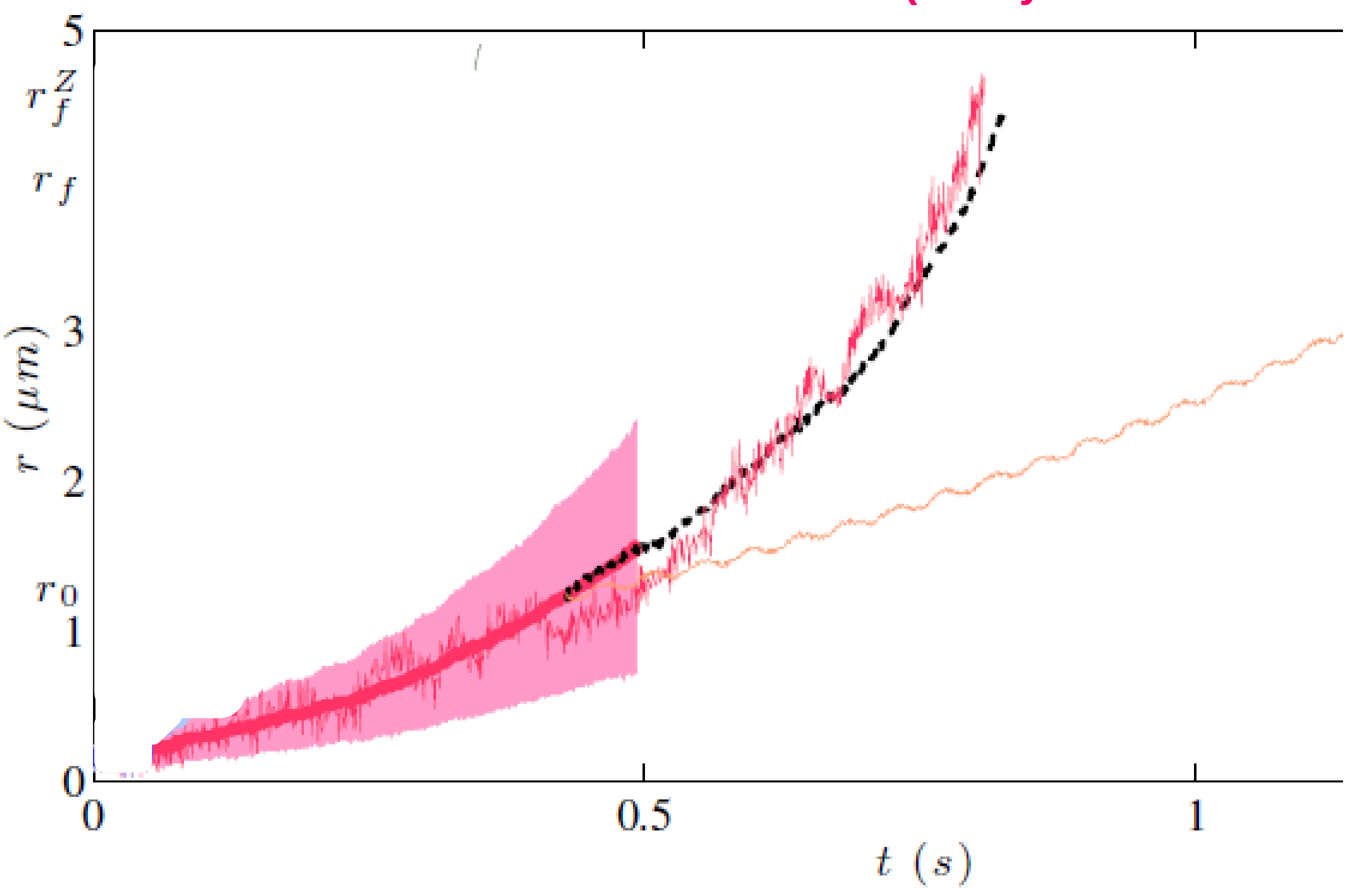
Ideally suited for:

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

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

COMPARISON OF METHODS IN MUTUAL VALIDITY REGIME:

Vortex Spiralling-Out Problem



Rooney, Allen, Zülicke, Proukakis & Bradley PRA **93**, 063603 (2016)
Allen, Allen, Zaremba, Barenghi & Proukakis, PRA **87**, 013630 (2013)

What About

2-Component

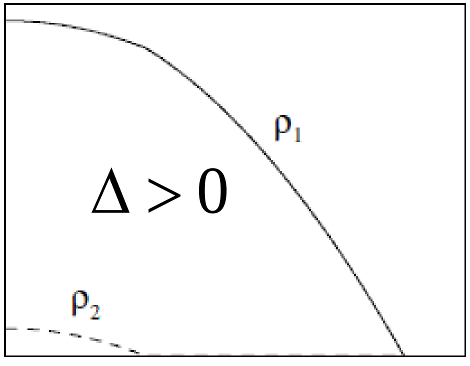
Bose-Einstein Condensates ?

PHASE PROFILES OF 2-COMPONENT BECs

Phase Profiles Controlled by Inter- / Intra- Atomic Interactions

Phase Mixing

(overlapping components)



Interspecies interactions dominate

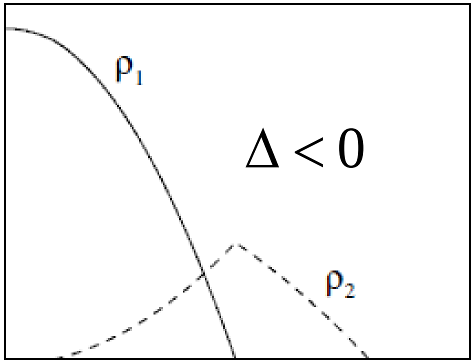
Consider here
repulsive interactions

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

Mean Field Model

(Coupled Gross-Pitaevskii Equations):

$$\boxed{i\hbar \frac{\partial \Phi_1}{\partial t} = \left[-\frac{\hbar^2 \nabla^2}{2m_1} + V_1(r) + g_{11} |\Phi_1|^2 + g_{12} |\Phi_2|^2 - \mu_1 \right] \Phi_1}$$

$$\boxed{i\hbar \frac{\partial \Phi_2}{\partial t} = \left[-\frac{\hbar^2 \nabla^2}{2m_2} + V_2(r) + g_{22} |\Phi_2|^2 + g_{12} |\Phi_1|^2 - \mu_2 \right] \Phi_2}$$

PHASE PROFILES OF 2-COMPONENT BECs

Phase Profiles Controlled by Inter- / Intra- Atomic Interactions

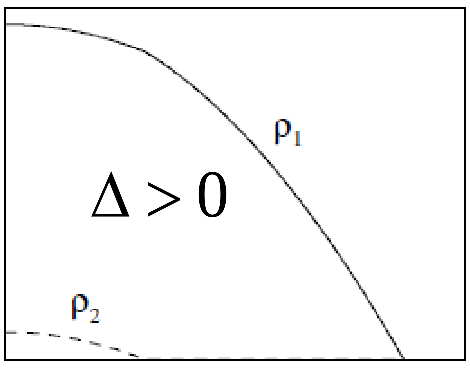
Phase Mixing

(overlapping components)

Consider here
repulsive interactions

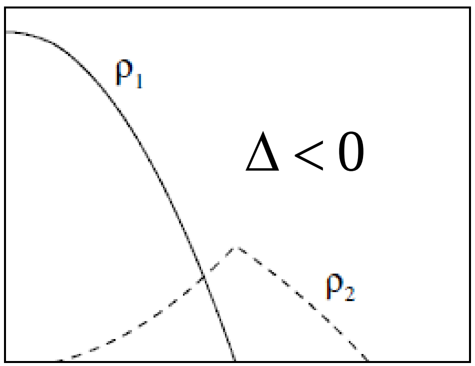
Phase Separation

(non-overlapping components)



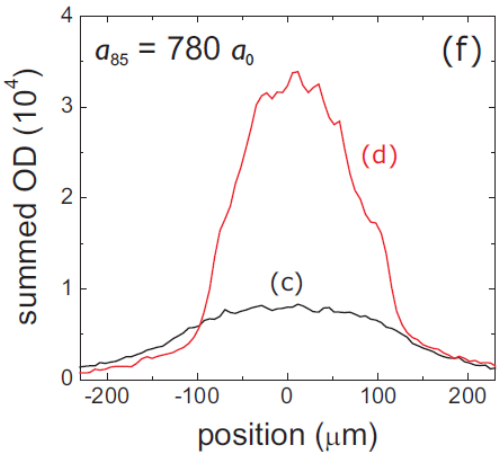
Usual Criterion
(Homogeneous)

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



Interspecies interactions dominate

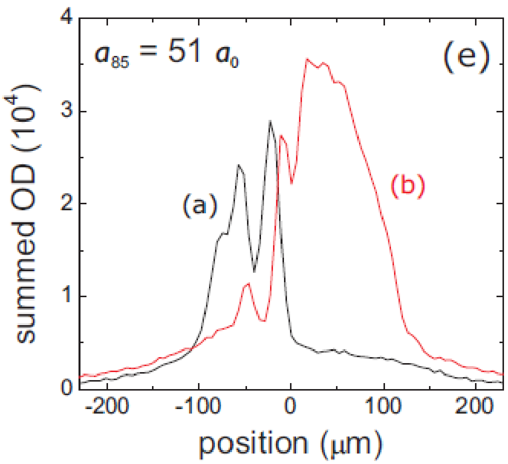
Intraspecies interactions dominate



PRL 101, 040402 (2008)

Phase Separation Tunable through Control of

Scattering Lengths via Inter- / Intra- Species Feshbach Resonances



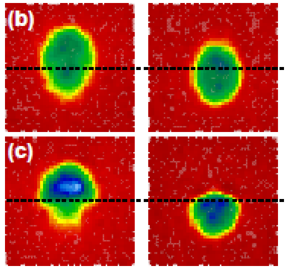
PRL 101, 040402 (2008)

2-COMPONENT BEC EXPERIMENTAL GALLERY:

Different Hyperfine Levels

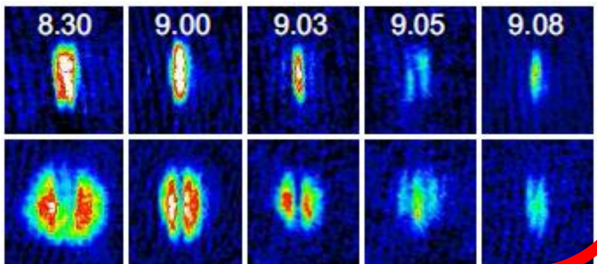
^{87}Rb – ^{87}Rb

JILA (1998)



^{87}Rb – ^{87}Rb

Tokyo



Different Isotopes

^{85}Rb – ^{87}Rb

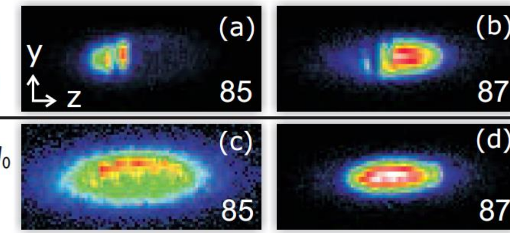
JILA (2008)

$a_{85} = 51\ a_0$

$\Delta = -0.89$

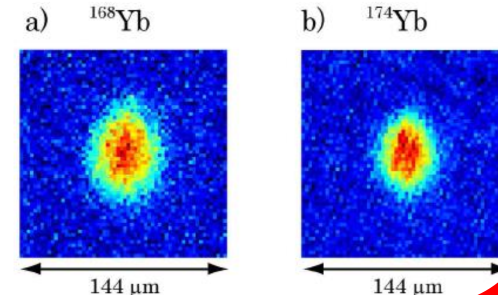
$a_{85} = 780\ a_0$

$\Delta = 0.72$



^{168}Yb – ^{174}Yb

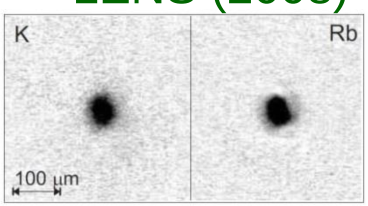
Kyoto (2011)



Different Elements

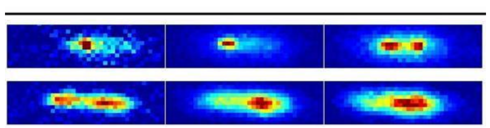
^{87}Rb – ^{41}K

LENS (2008)

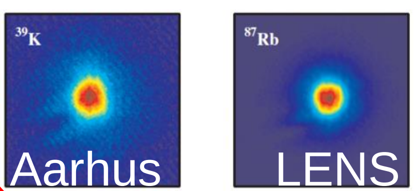


^{87}Rb – ^{133}Cs

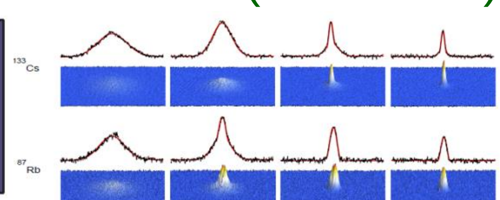
Durham (2011)



^{87}Rb – ^{39}K

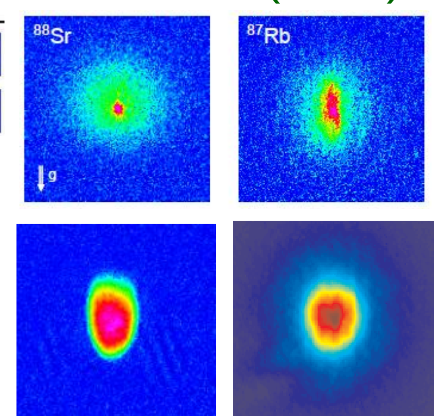


Innsbruck (2011/2013)



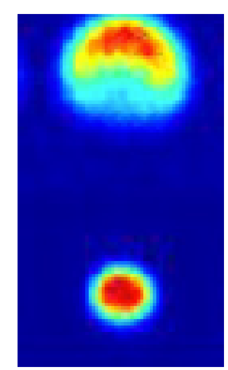
^{87}Rb – ^{88}Sr/^{84}Sr

Korea (2013)



^{87}Rb – ^{23}Na

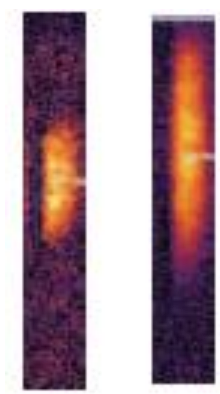
Hong-Kong (2015)



Doubly Superfluid

^{6}Li – ^{7}Li

ENS (2014



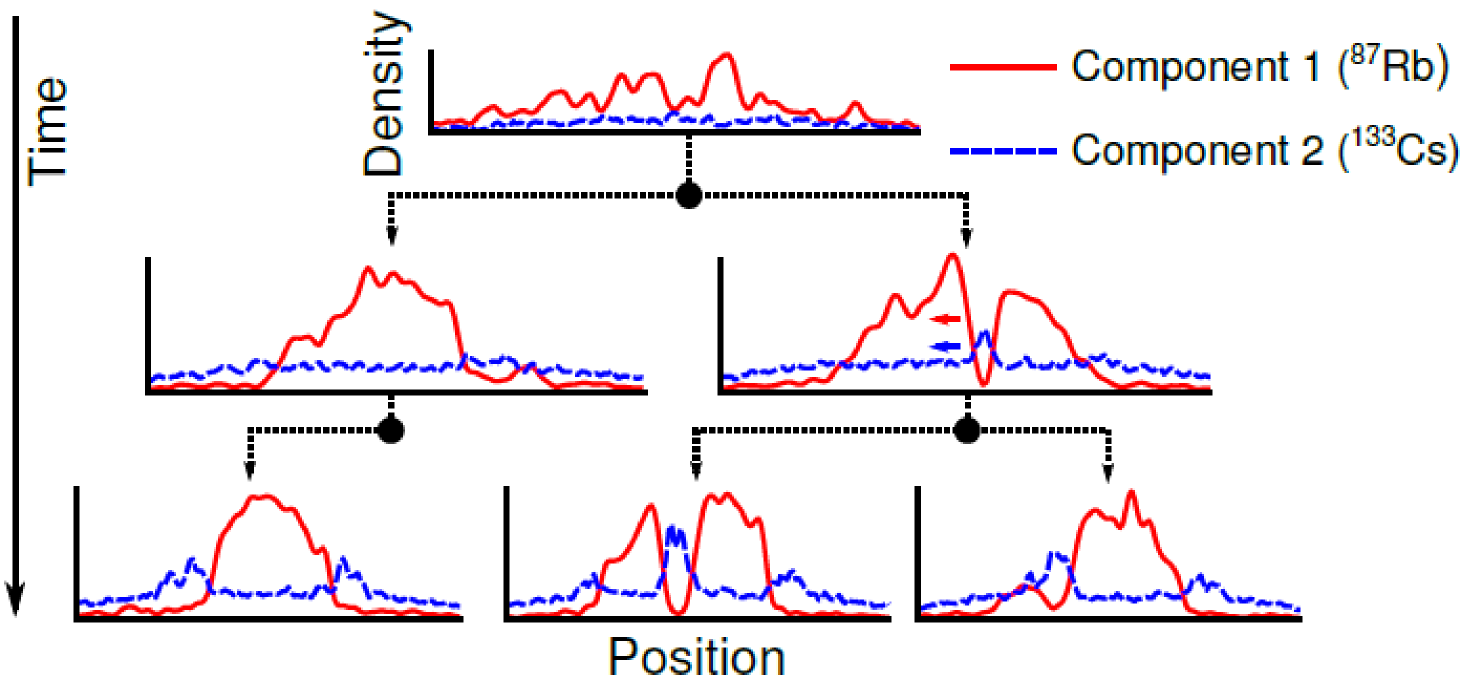
Schematic of Possible Evolutionary Dynamics

[assuming here Rb grows faster than Cs, at least initially]

Multiple KZ Solitons

Zero/One Soliton is Long-lived

Cs Grows around Rb, or within Rb Soliton



→ Profiles Observed in Experiments may only be *Metastable* Profiles

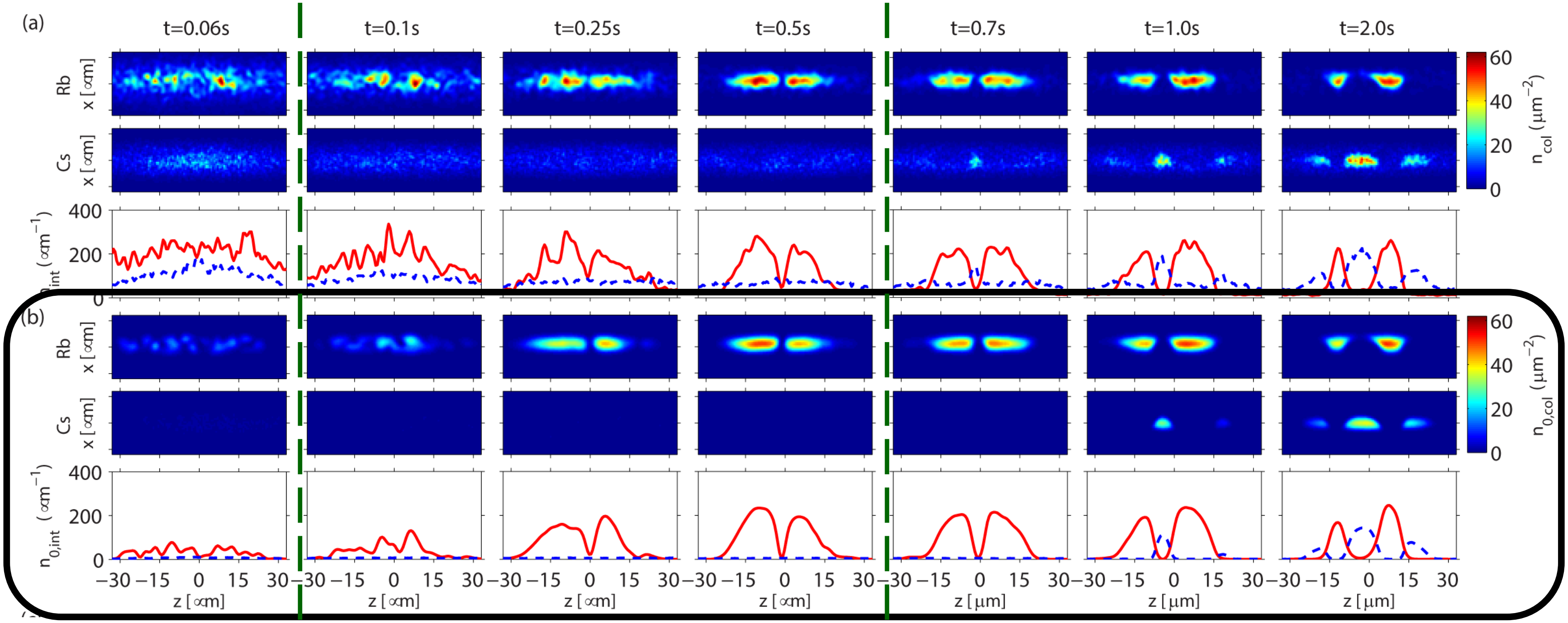
IK Liu … NPP., Phys. Rev. A 93, 023628 (2016)

IMMISCIBLE 2-COMPONENT TEMPERATURE QUENCHES

Perform Temperature & Chemical Potential Quench
on an Immiscible Quasi-1D Equilibrium Binary Mixture (here Rb-Cs)

$$T_i = 80nK \rightarrow T_i' = 20nK \qquad \mu_i \rightarrow \mu_i' \geq \mu_i$$

Observe 3 Characteristic Evolutionary Stages:



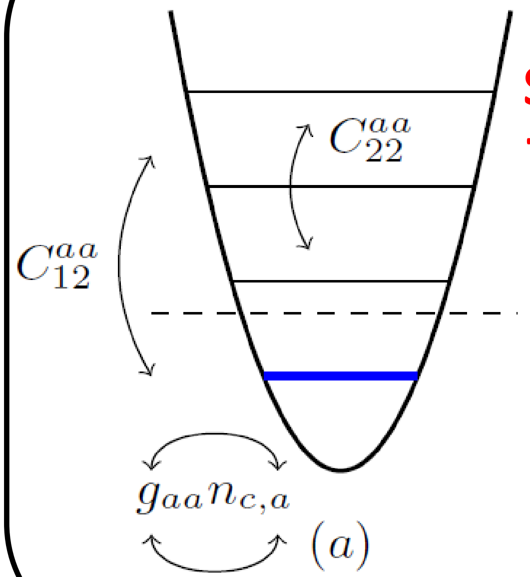
Kibble-Zurek Physics (Defect Formation)

"Coarse-Graining" Dynamics (Defect Merging / Decay)

Phase-Separation Dynamics & Slow Relaxation to Equilibrium

T > 0 TWO-COMPONENT CONDENSATE THEORY

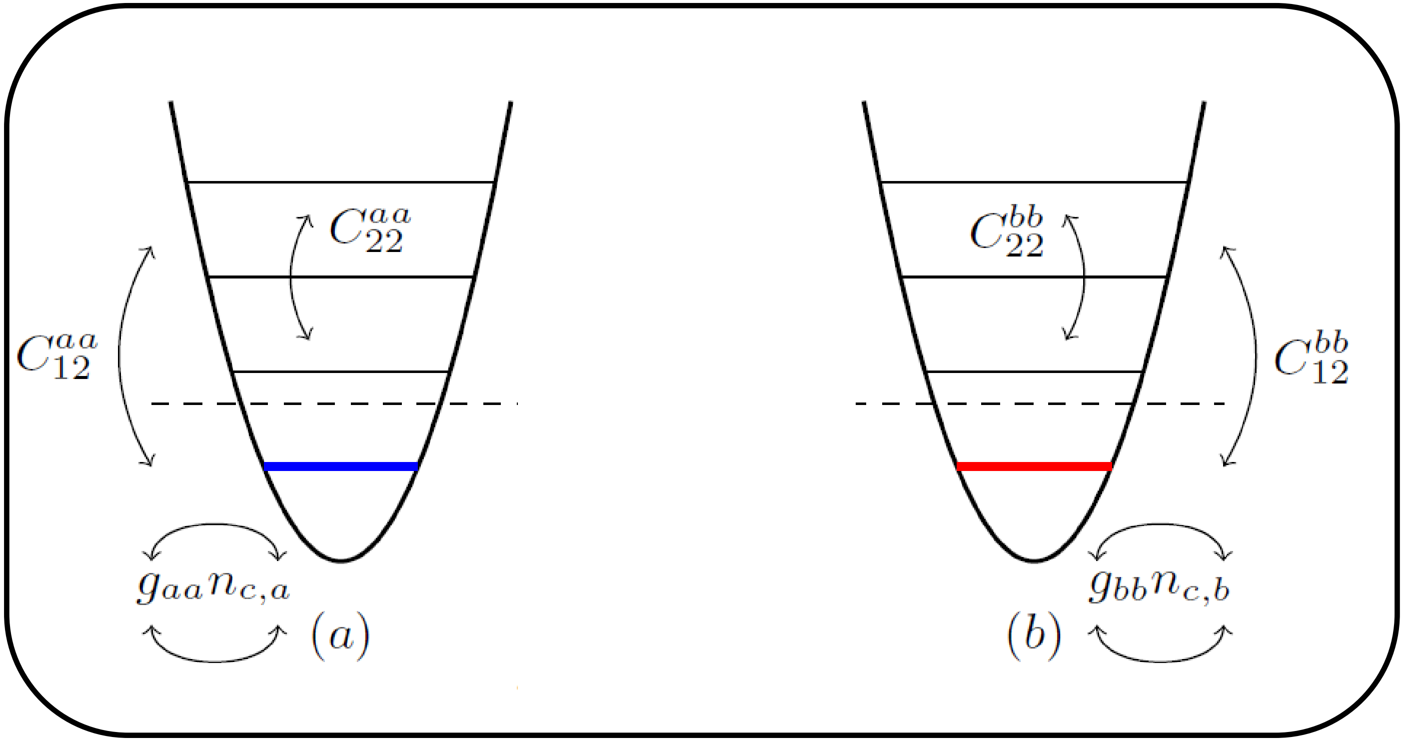
Zaremba, Nikuni & Griffin, JLTP 116, 277 (1999)



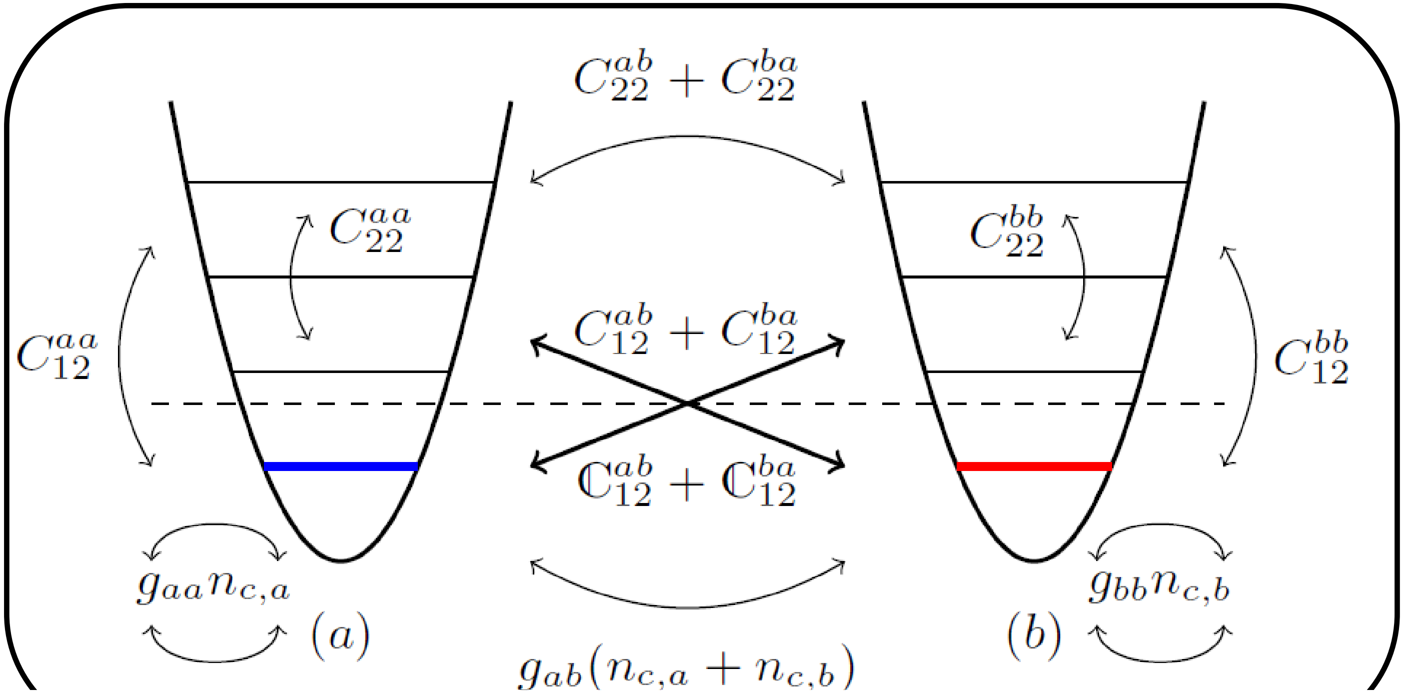
Self-Consistent Thermal Cloud (Boltzmann Equation)

Coupling

BEC Only (Generalised Gross-Pitaevskii)


C_{22}^{aa}
C_{12}^{aa}
$g_{aa}n_{c,a}$
(a)
C_{22}^{bb}
C_{12}^{bb}
$g_{bb}n_{c,b}$
(b)

T > 0 TWO-COMPONENT CONDENSATE THEORY



Edmonds, Lee & NPP

PRA 91, 011602(R) (2015)

PRA 92, 063607 (2015)

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

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

CONDENSATES

MEAN FIELD COUPLING

THERMAL CLOUDS

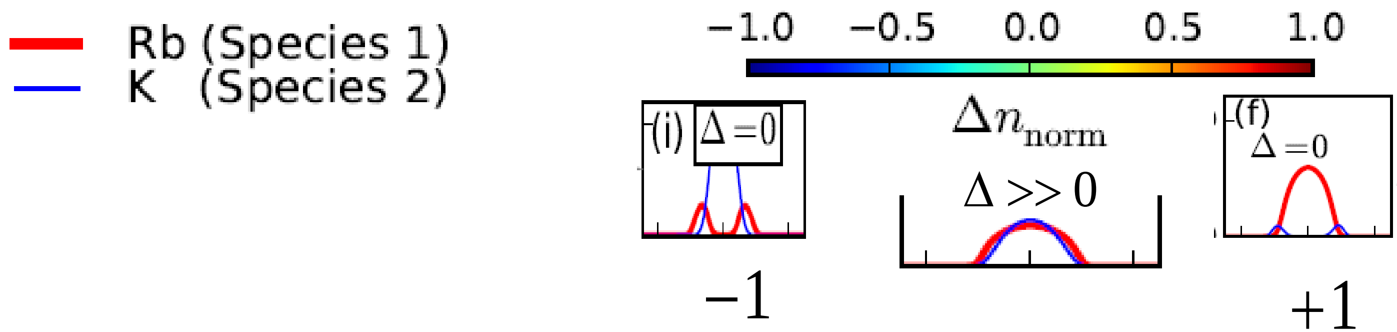
PLETHORA OF NEW COLLISIONAL TERMS

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

REVISITING THE (IM)MISCIBILITY CRITERION IN TRAPS

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

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



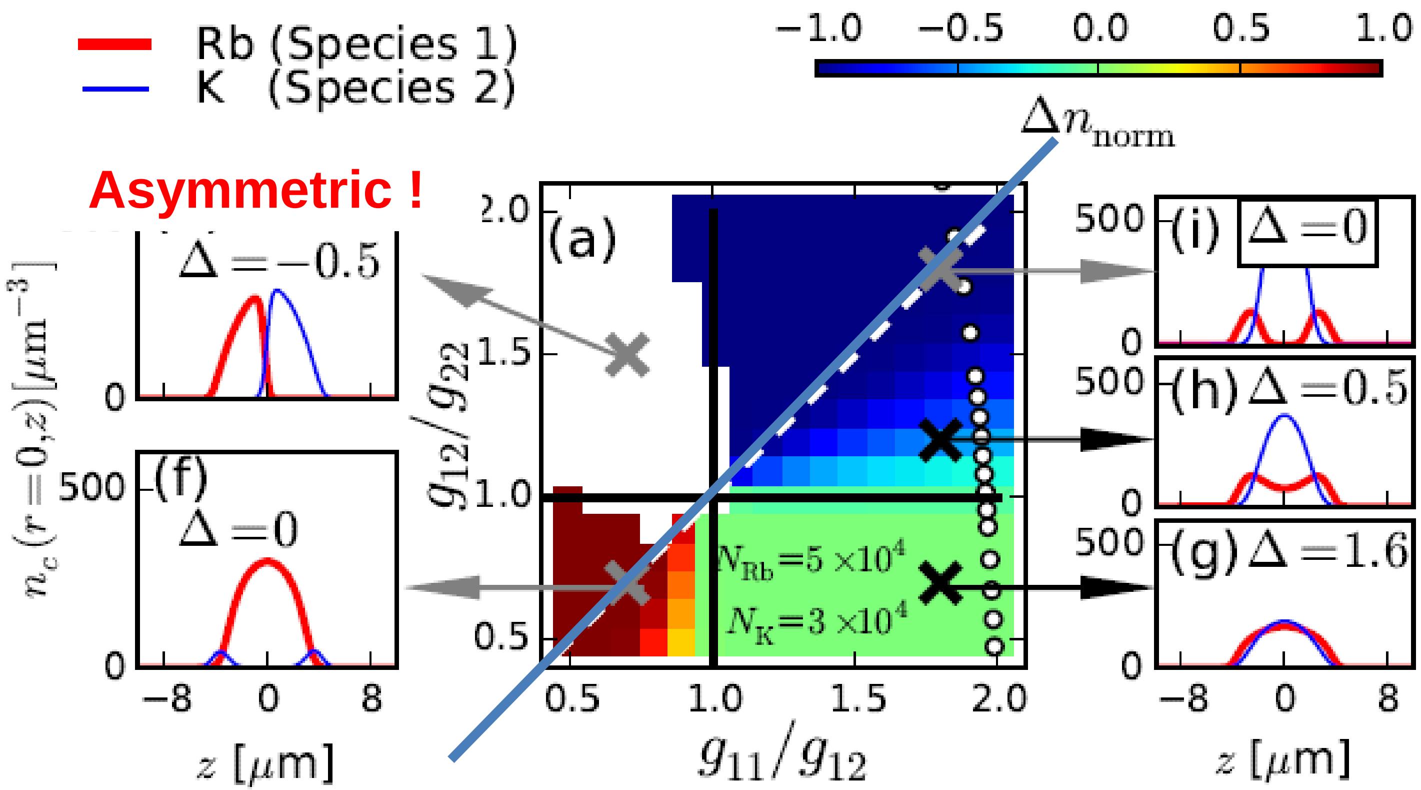
Lee, Jorgensen, Liu, Wacker, Arlt & NPP, arXiv:1604.08063 (2016)

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

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

T = 0 Analysis

(Gross-Pitaevskii)



$\Delta = 0$

Line

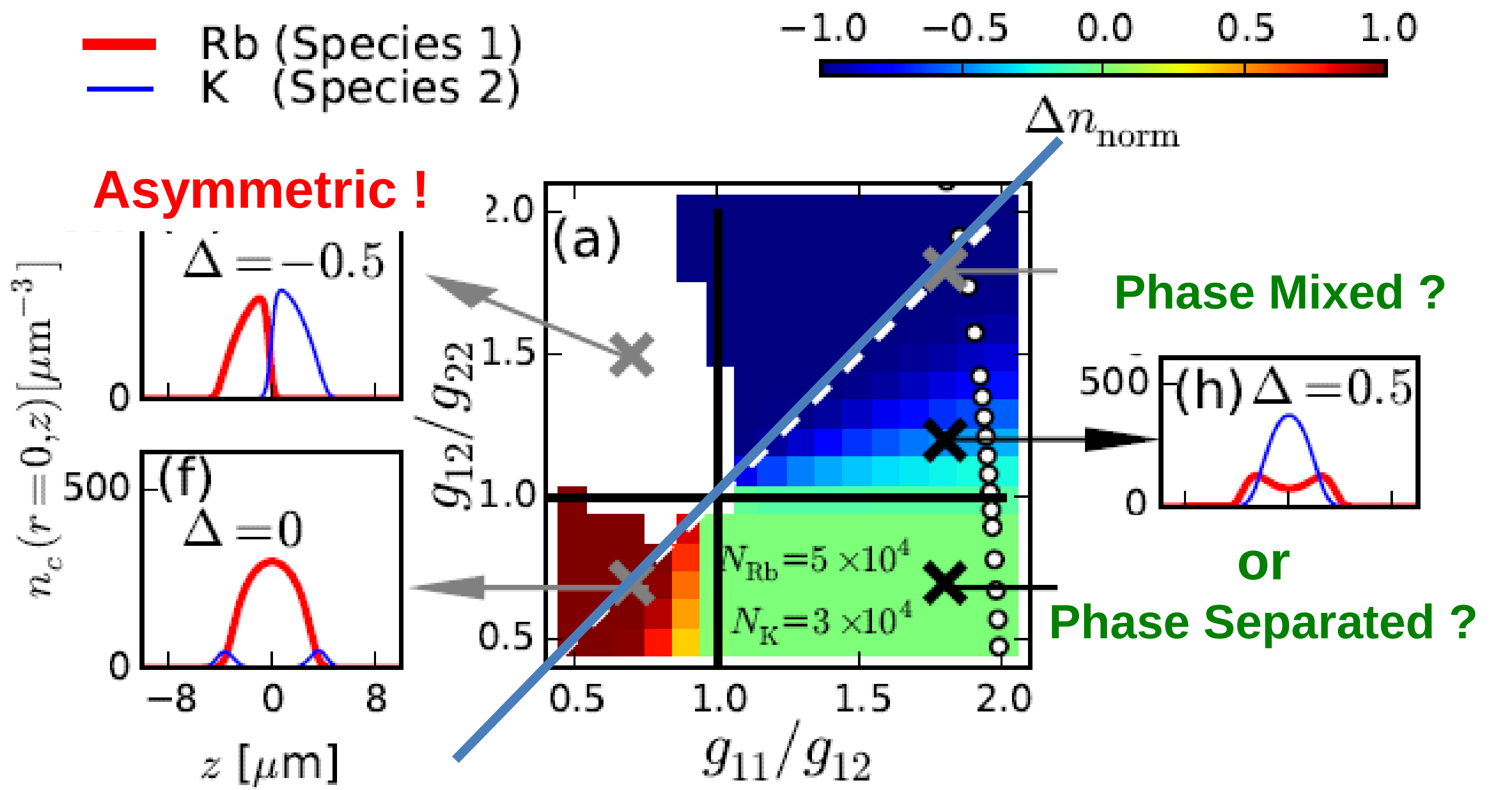
REVISITING THE (IM)MISCIBILITY CRITERION IN TRAPS

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

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

T = 0 Analysis

(Gross-Pitaevskii)



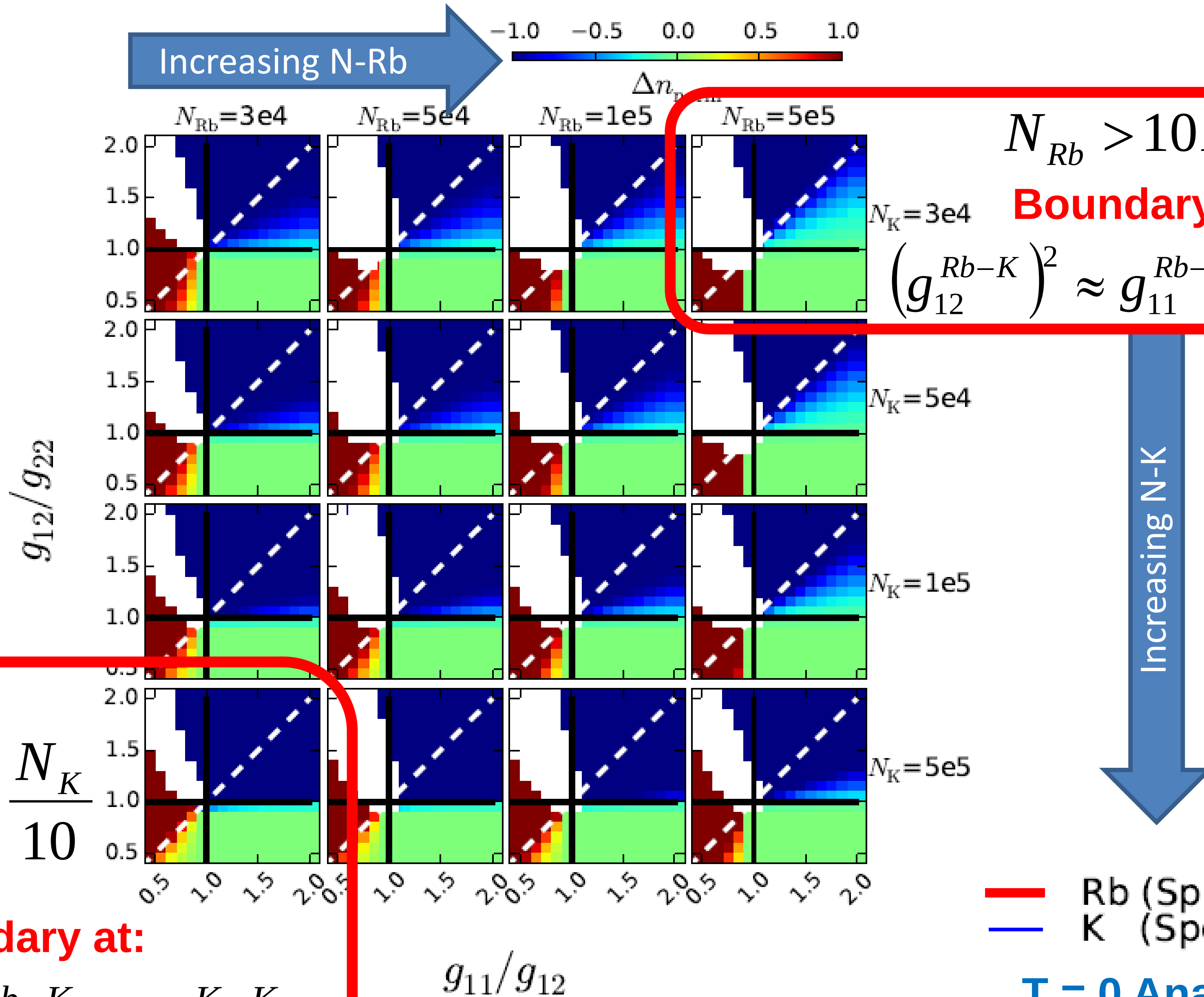
Phase separation Boundary: Green → Blue

Criterion in Trap can Deviate Significantly from Homogeneous Condition !

This depends critically also on atom numbers

Lee, Jorgensen, Liu, Wacker, Arlt & NPP, arXiv:1604.08063 (2016)

REVISITING THE (IM)MISCIBILITY CRITERION IN TRAPS



$$N_{Rb} > 10 N_K$$

Boundary at:

$$\left(g_{12}^{Rb-K}\right)^2 \approx g_{11}^{Rb-Rb} g_{22}^{K-K}$$

$$N_{Rb} < \frac{N_K}{10}$$

Boundary at:

$$g_{12}^{Rb-K} \approx g_{22}^{K-K}$$

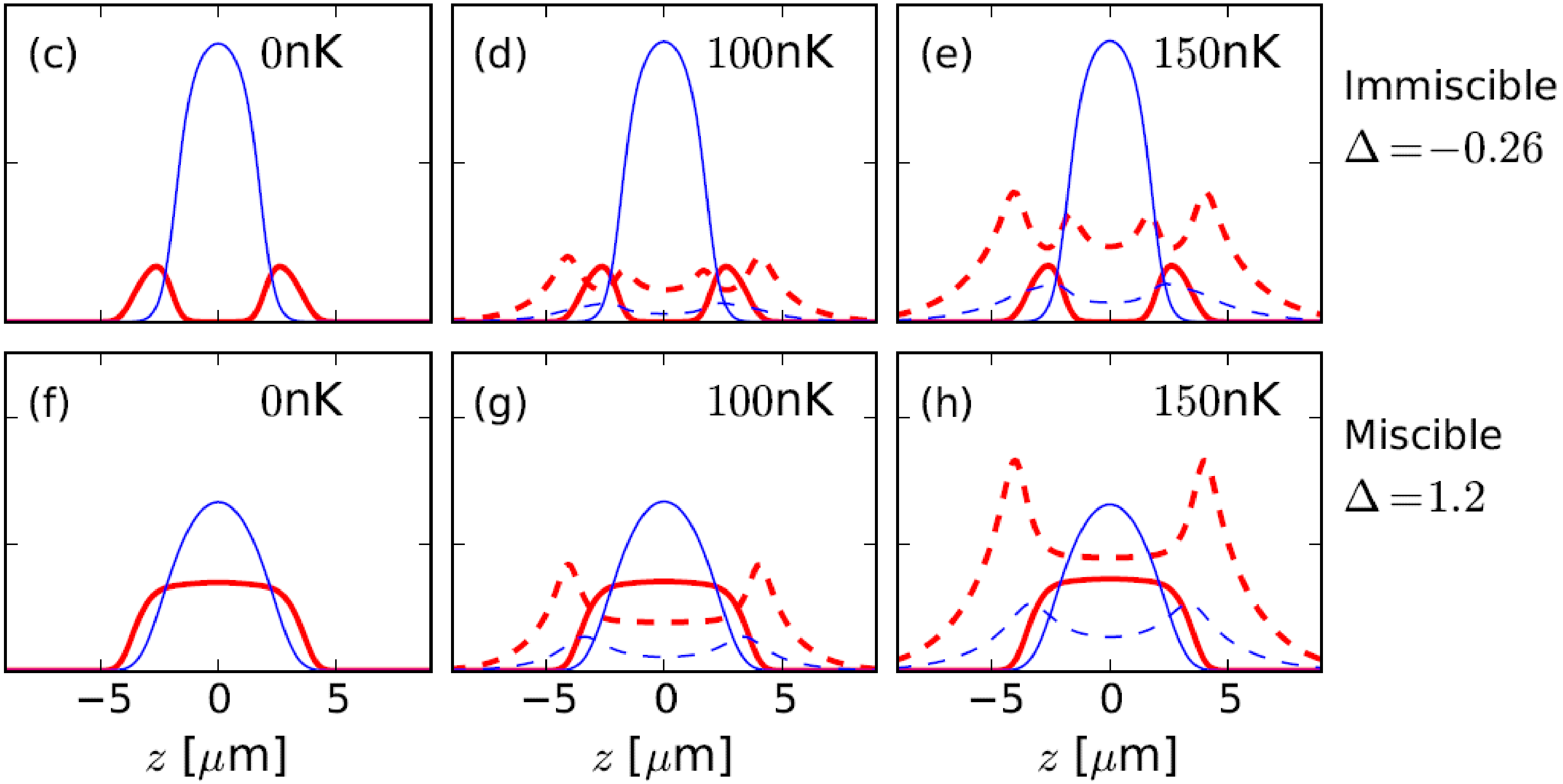
Rb (Species 1)
K (Species 2)

T = 0 Analysis

arXiv:1604.08063

Equilibrium Profiles for T > 0

(choosing to have approximately constant BEC atom number)

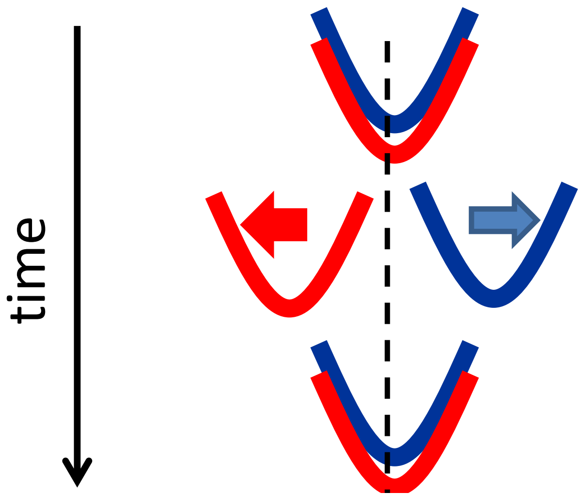


Miscibility / Immiscibility Essentially Fixed by BEC Atom Numbers / Interactions

… but … Thermal Effects are Important for Dynamics !

PROBING DYNAMICS BY DAMPING OF EXCITATIONS

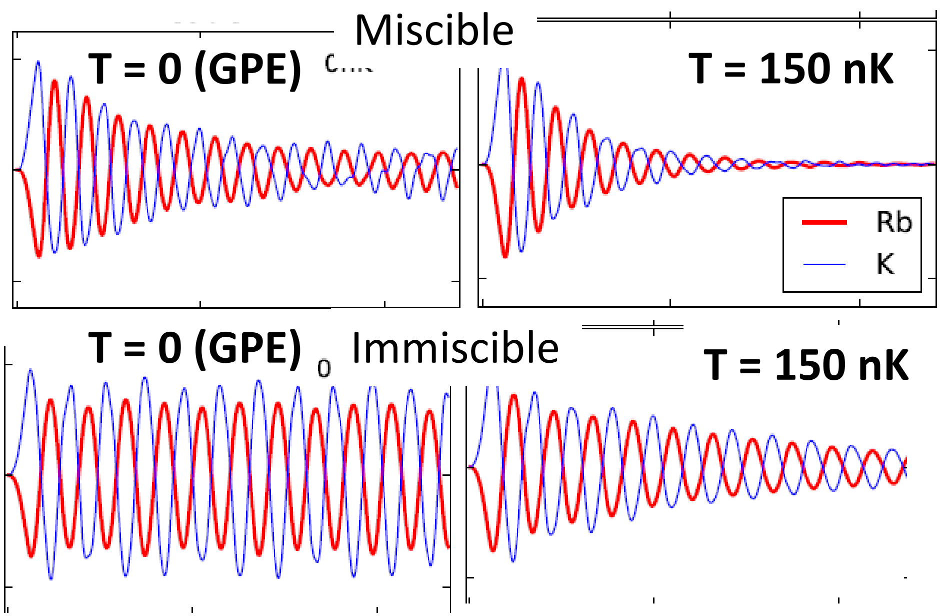
Consider Dipole Oscillations of Perturbed Co-Trapped Quantum Gases



Bose-Bose Mixture

Miscibility vs. Immiscibility

arXiv:1604.08063



Is $$\Delta n_{\rm norm} = \frac{n_{c,1}(\mathbf{0})}{\max n_{c,1}(\mathbf{r})} - \frac{n_{c,2}(\mathbf{0})}{\max n_{c,2}(\mathbf{r})}$$ **a Good Parameter to Map Out the Phase Diagram ?**

Change in Behaviour Is associated with Changing Values of

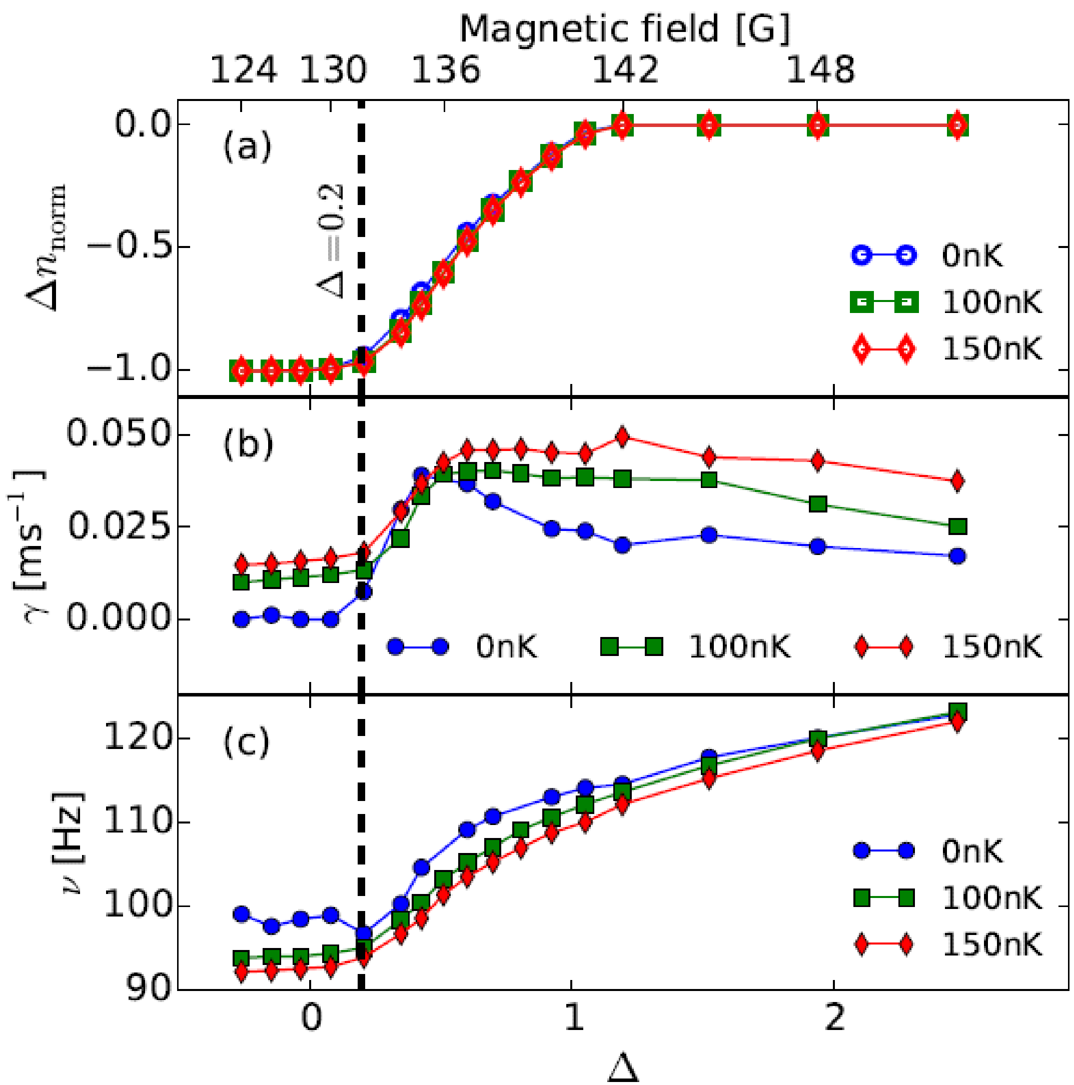
$$\Delta n_{\rm norm}$$

Temperature significantly affects Damping Rate and Frequency

Behavioural "Crossover"

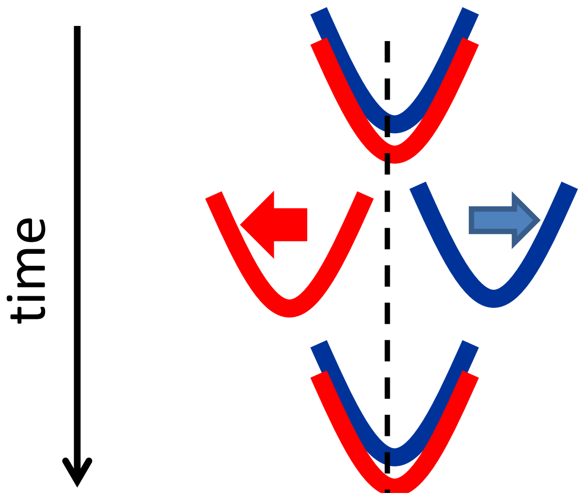
$$0 \leq \Delta \leq 0.5$$

in *Probed* Parameter Range:



PROBING DYNAMICS BY DAMPING OF EXCITATIONS

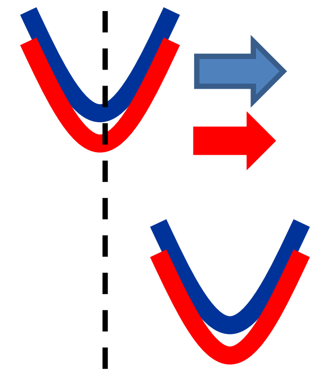
Consider Dipole Oscillations of Perturbed Co-Trapped Quantum Gases



Bose-Bose Mixture

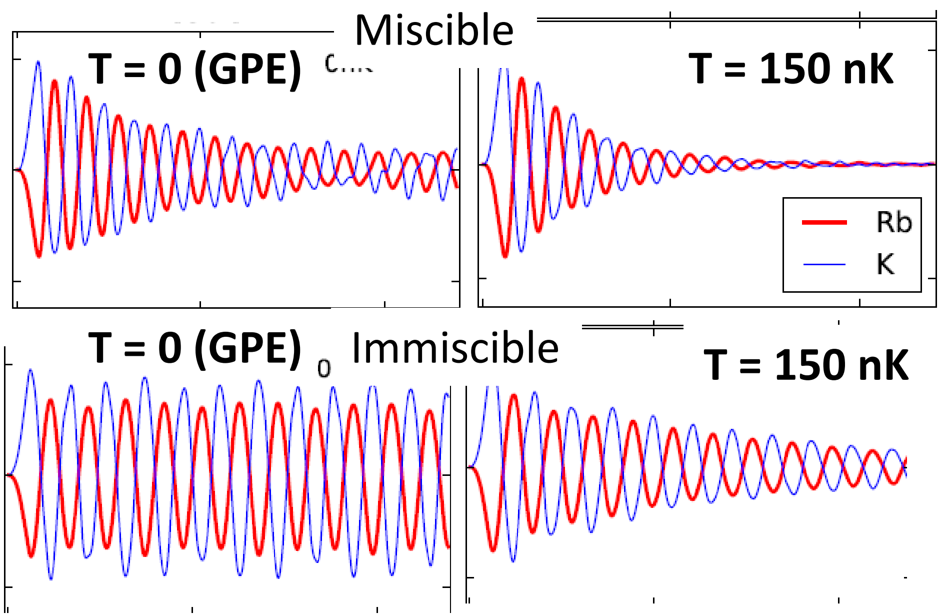
Miscibility vs. Immiscibility

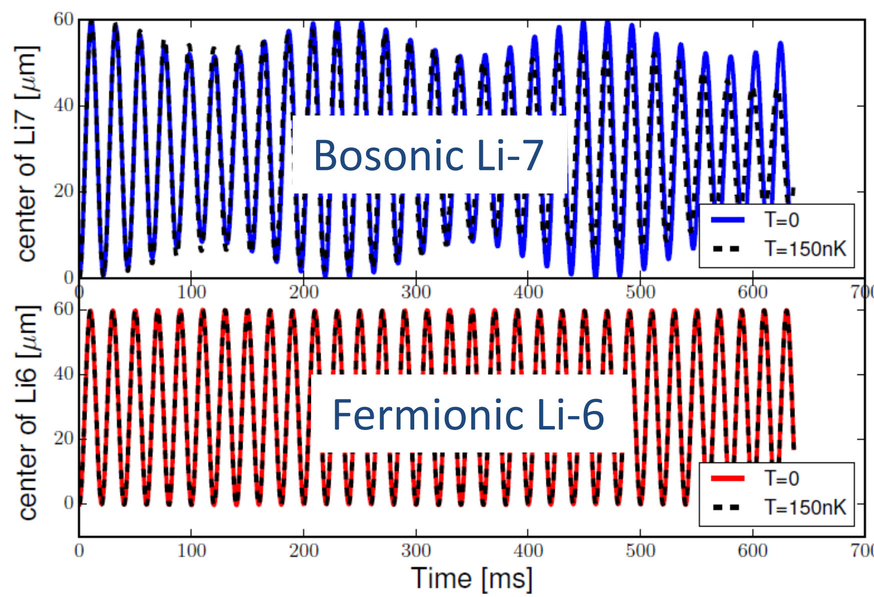
arXiv:1604.08063



Doubly Superfluid Bose-Fermi Mixture

ENS: Science 345, 1035 (2014)





→ Temperature Enhances Damping in Both Cases !

Effect of Collisions minimal in both cases (noticeable over long timescales)

Multi-component Atomic Condensates and ROtational Dynamics

Joint Quantum Centre
WWW.JQC.ORG.UK

Durham University

Newcastle University

EPSRC
Engineering and Physical Sciences Research Council

New Journal of Physics

IOP Institute of Physics
Quantum Optics, Quantum Information and Quantum Control Group

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https://conferences.ncl.ac.uk/jqcmacro/

Abstract Deadline: Thursday 30 June

JQC Colloquium: ***Jean Dalibard (College de France)***

MACRO Keynote:

Vanderlei Bagnato (Sao Paulo)
Carlo Barenghi (JQC Newcastle)
Natalia Berloff (Cambridge/Skoltech)
Halina Rubinsztein-Dunlop (Brisbane)
Ian Spielman (JQI/NIST) *(tentative)*
Masahito Ueda (Tokyo)

JQC Symposium Plenary:

Charles Adams (JQC Durham)
Clive Emary (JQC Newcastle)
Boris Malomed (Tel Aviv) *(tentative)*
Rob Nyman (Imperial)

Short-Term Postdoctoral Position

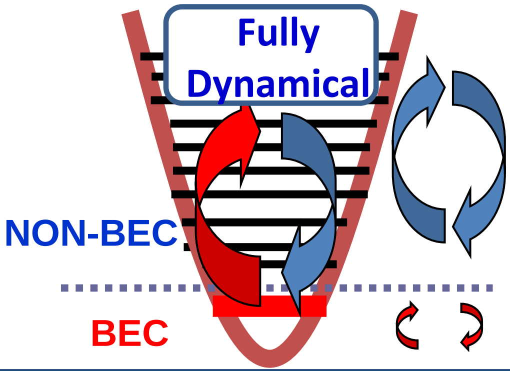
Available between Sep'16 – Feb'17

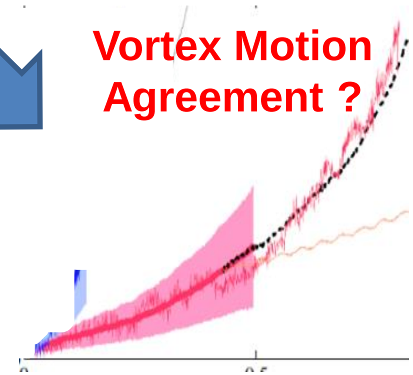
(Multi-Component BECs in Ring Traps
T > 0 Numerical Simulations)

INFO:
nikolaos.proukakis@ncl.ac.uk

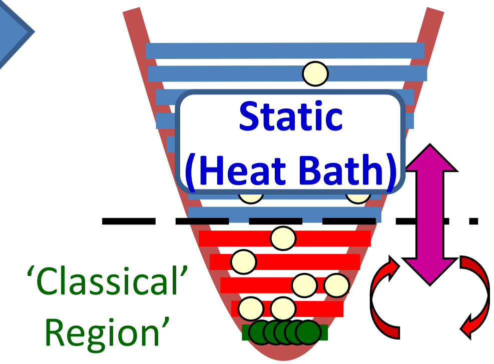
CONCLUSIONS

Kinetic Model ("ZNG"):





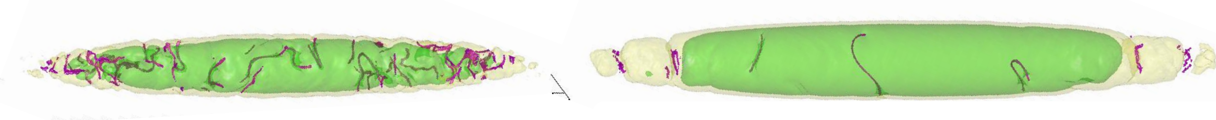
Stochastic Model:

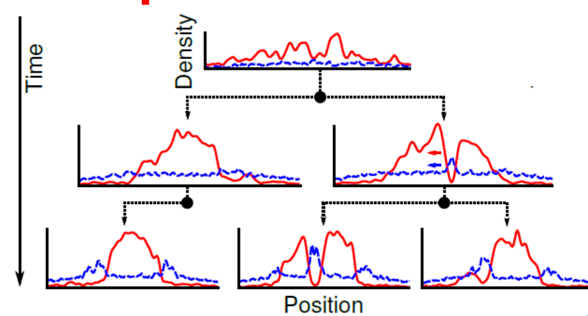


Kibble-Zurek Quenches

"Composite Defects"

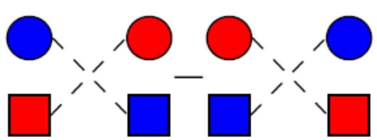
Defect Dynamics & Saturation (Quasi-1D)



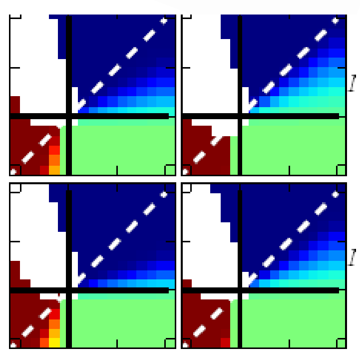


T > 0 BEC Mixtures

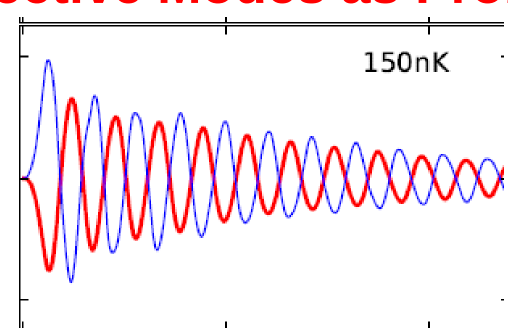
New Collisional Processes ?



Redefining (Im)Miscibility



Collective Modes as Probes



Nick Proukakis

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Matthew Edmonds

Joy Allen

Stochastic / Kibble-Zurek:

*** Gary Liu *** (Visiting PhD)

EPSRC

行政院國家科學委員會 National Science Council

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Dimitris Frantzeskakis

See Also Posters by

Kean Loon Lee	**(BEC Mixtures)**
Tom Bland	**(Dipolar BECs)**