The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

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2239-12

Workshop on Integrability and its Breaking in Strongly Correlated and Disordered Systems

23 - 27 May 2011

Quantum dynamics in a bosonic quantum gas

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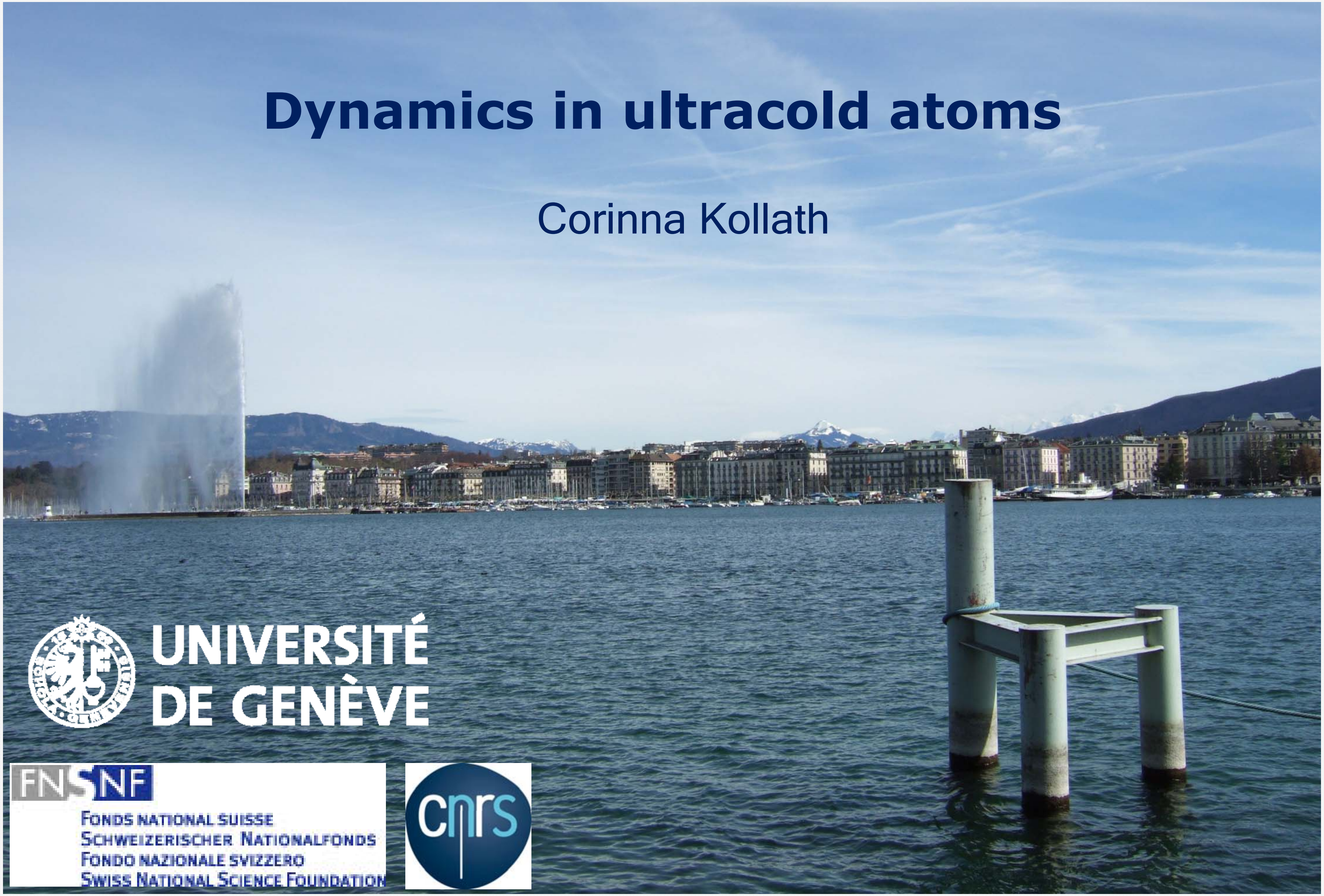
Dynamics in ultracold atoms

Corinna Kollath



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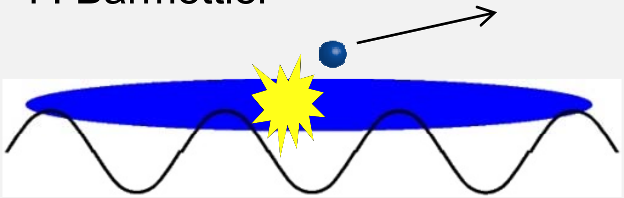
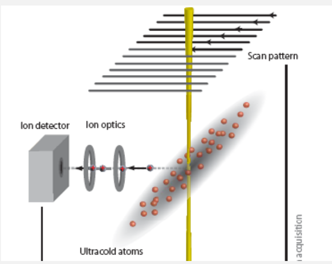
Outline

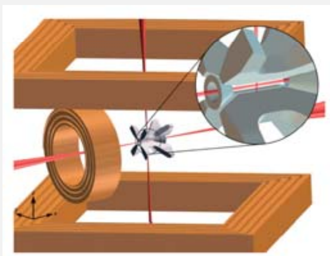
local dissipation

P. Barmettler



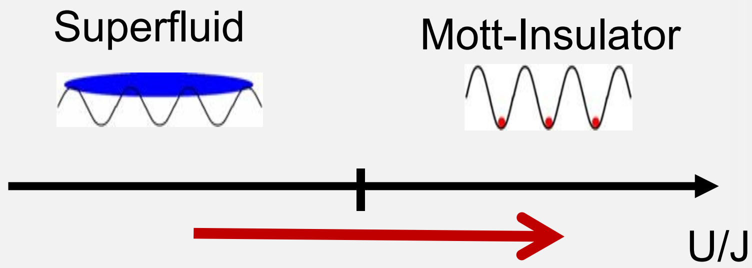
e.g. by single trapped ion or electron beam

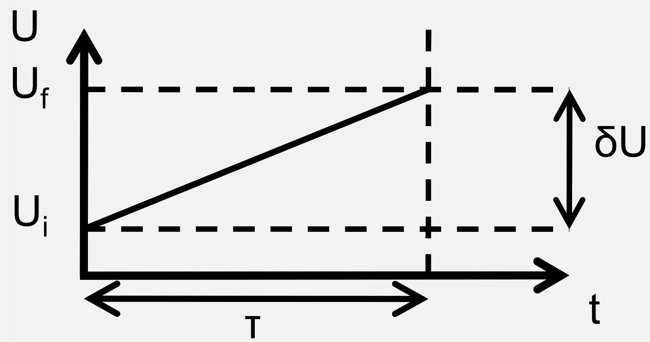




slow quench across quantum phase transition

JS. Bernier, G. Roux

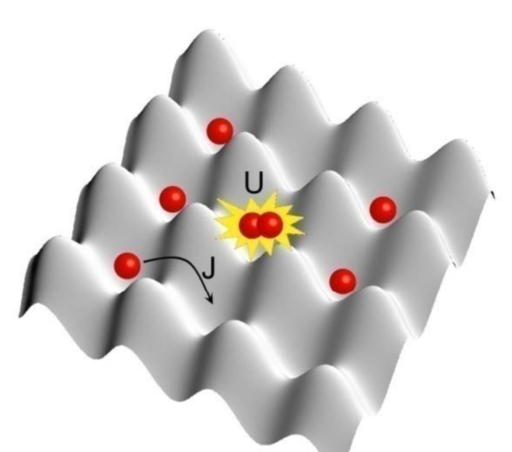




Theoretical description: Bose-Hubbard model

kinetic energy | interaction energy

$$H = -J\sum_{<ij>}(b_i^+ b_j + h.c.) + U/2\sum_j n_j(n_j - 1)$$



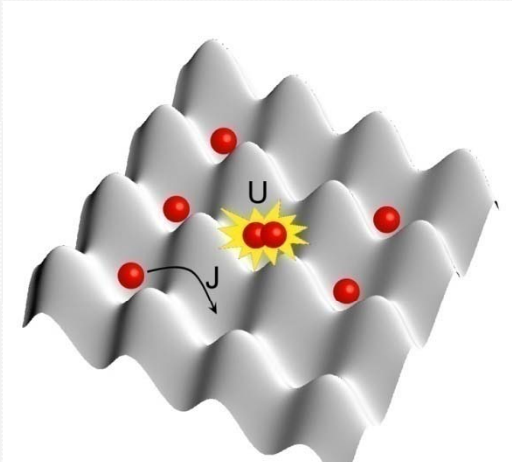
Jaksch et al. (1998)

- different mixtures possible
- good control (U/t can be tuned over several orders of magnitude)
- clean systems (no disorder, no lattice phonons)
- different geometries
- good decoupling from environment (no thermal bath)

Superfluid to Mott-insulator

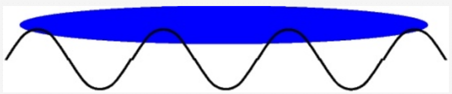
kinetic energy | interaction energy

$$H = \underbrace{-J\sum_{<ij>}(b_i^{+} b_j + h.c.)}_{\text{kinetic energy}} \underbrace{+ U/2\sum_{j} n_j(n_j - 1)}_{\text{interaction energy}}$$

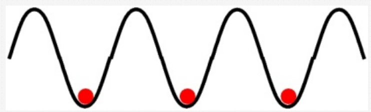


Jaksch et al. (1998)

Superfluid Phase



Mott-Insulating Phase



U/J

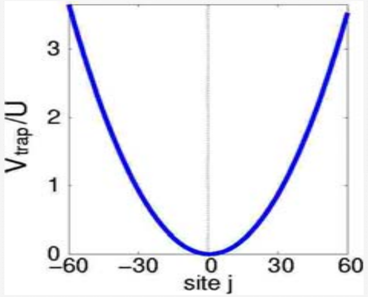
Fisher et al. (1989)

rapid tunability

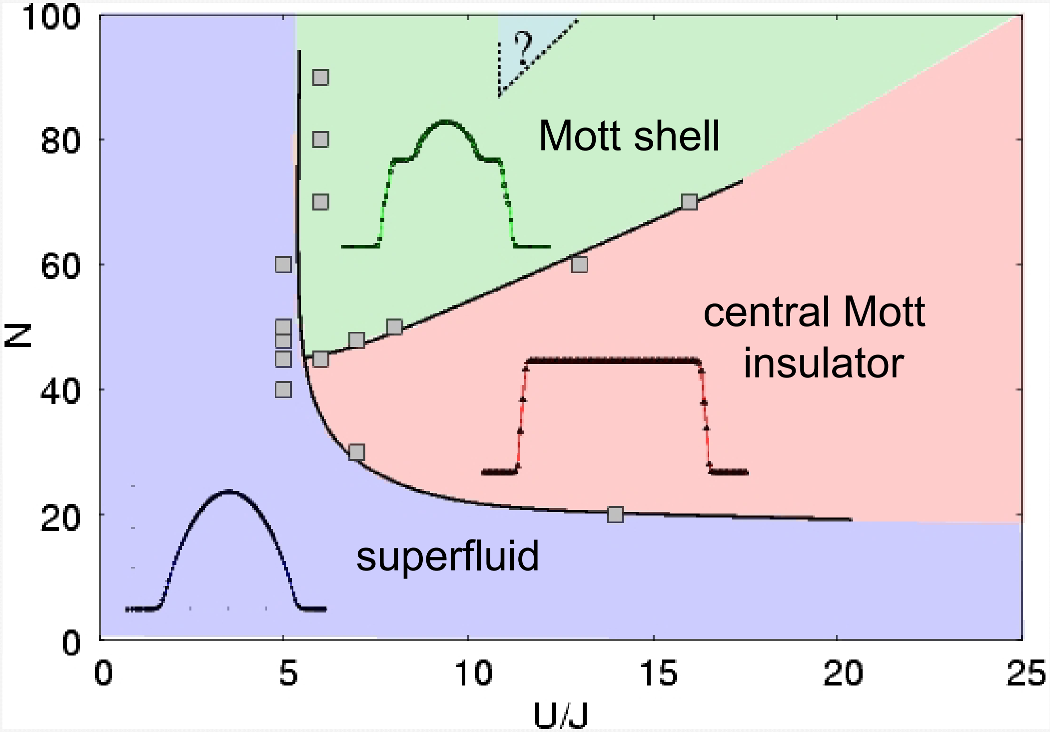
Coexistence of states in a trap

Approximate parabolic shape of the trap:

$$\mu_j = -V(j - j_0 - \frac{1}{2})^2$$



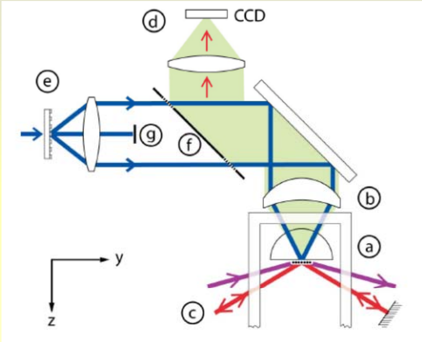
State diagram with density profiles

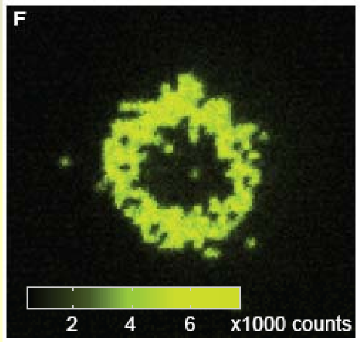


C. Kollath et al. PRA 2002

Local detection and manipulation

Local flourescence imaging

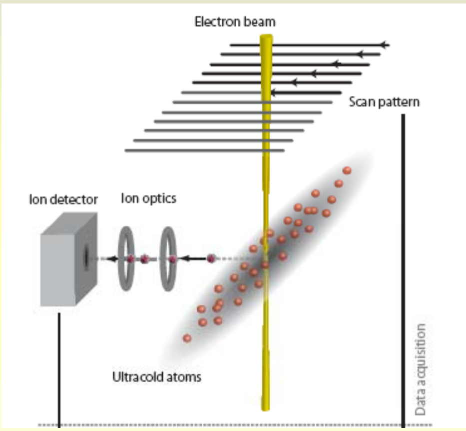


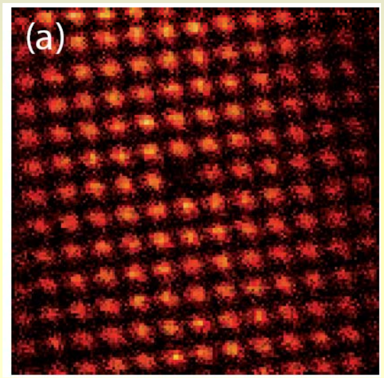


Bakr et al. 2009
Sherson et al. Nature 2010

Müller et al. 2010

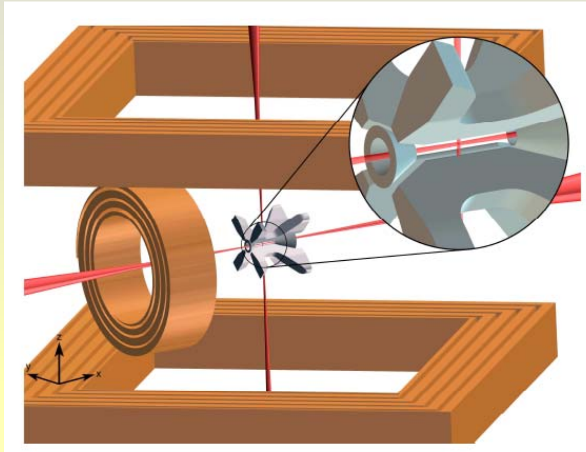
Electron beam imaging

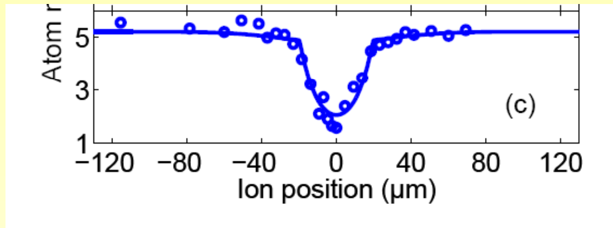




Würtz et al. PRL 2009

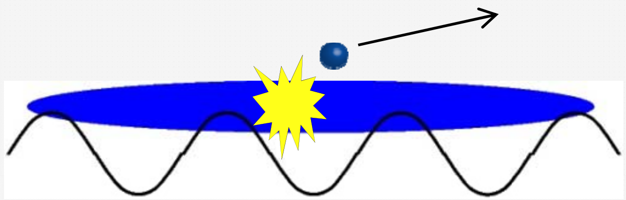
Single trapped ion





Zipkes et al. Nature 2009
Schmid et al. arXiv 2010

Local dissipative coupling



local atom losses

e.g. by single trapped ion or electron beam

weak dissipation:

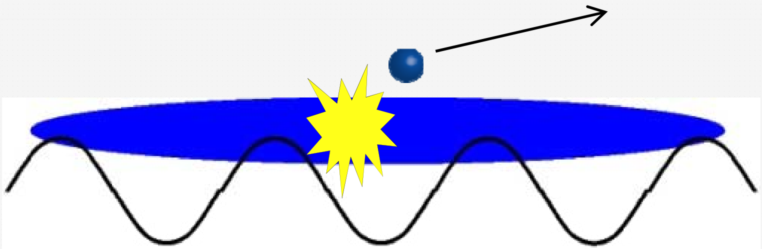
- possibility of density (correlation) detection
- signature of underlying quantum state
- fast melting of Mott insulator

strong dissipation:

- Zeno like effect
- disjoint subsystems
- but entanglement generation by dissipation

P. Barmettler

Theoretical model for local atom losses



local dissipation described by Markovian master equation:

$$\begin{aligned}\dot{\rho} &= \mathcal{L}\rho = \mathcal{L}^{\mathcal{C}}\rho + \mathcal{L}^{\mathcal{D}}\rho, \\ \mathcal{L}^{\mathcal{C}}\rho &:= -i[H,\rho], \\ \mathcal{L}^{\mathcal{D}}\rho &:= \Gamma b_0 \rho b^{\dagger}{}_0 - \frac{\Gamma}{2} n_0 \rho - \frac{\Gamma}{2} \rho n_0\end{aligned}$$

closed system dynamics

dissipative dynamics

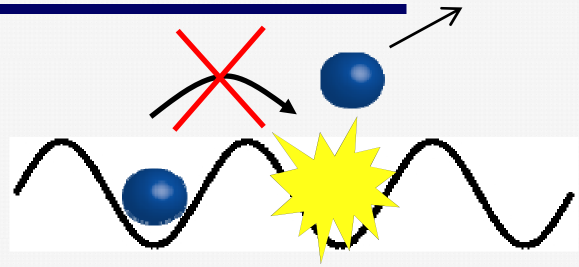
particle losses

detection of no particle losses

ρ density matrix
Γ dissipative coupling
H system Hamiltonian

P. Barmettler and C. Kollath , arXiv (2010)

Short time - probe of local features



atom loss related to local density

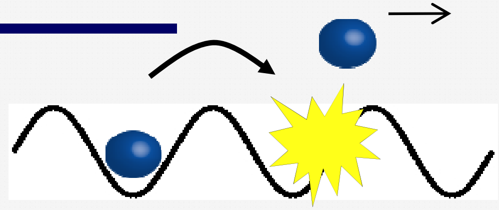
$$\dot{N}(t) = -\Gamma n_0(t)$$

at short times

$$N(t) = n_{init}(1 - e^{-\Gamma t}) \,, \quad n_0(t) = n_{init} e^{-\Gamma t}$$

no effect of underlying quantum state

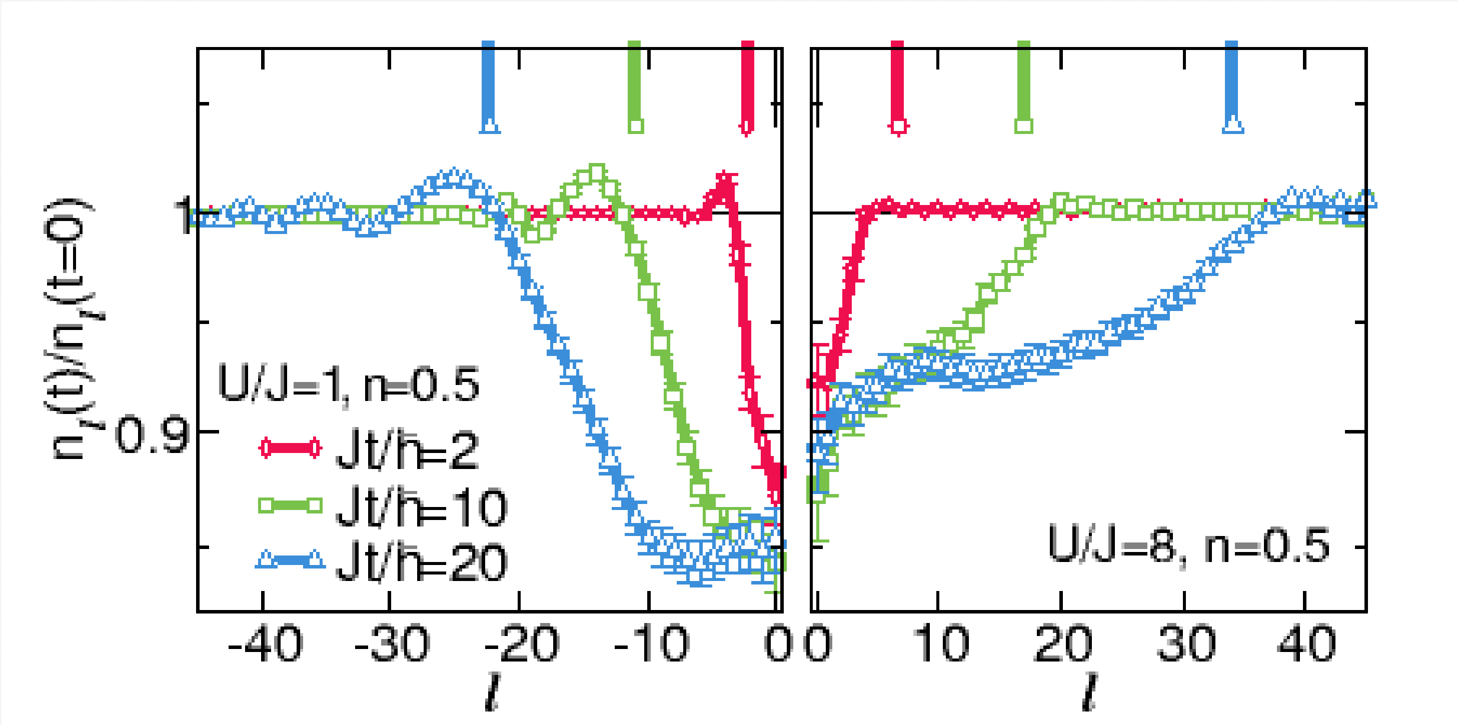
Weak coupling: many body evolution



evolution of density profiles

superfluid

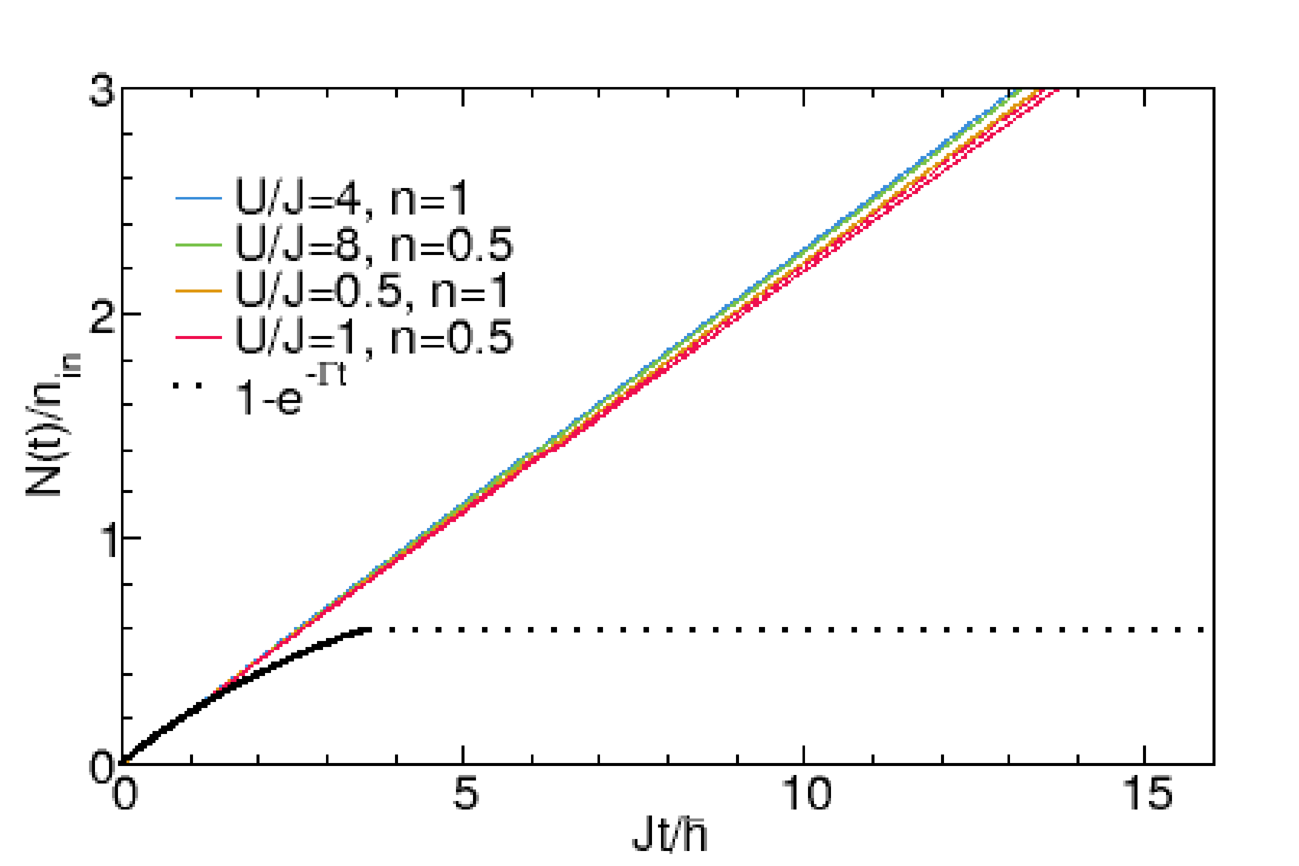
Tonks-Giradeau gas
(same for Mott-insulator)



- bright density waves
- fast melting of Mott insulating

Weak dissipation as density measurement

total atom losses

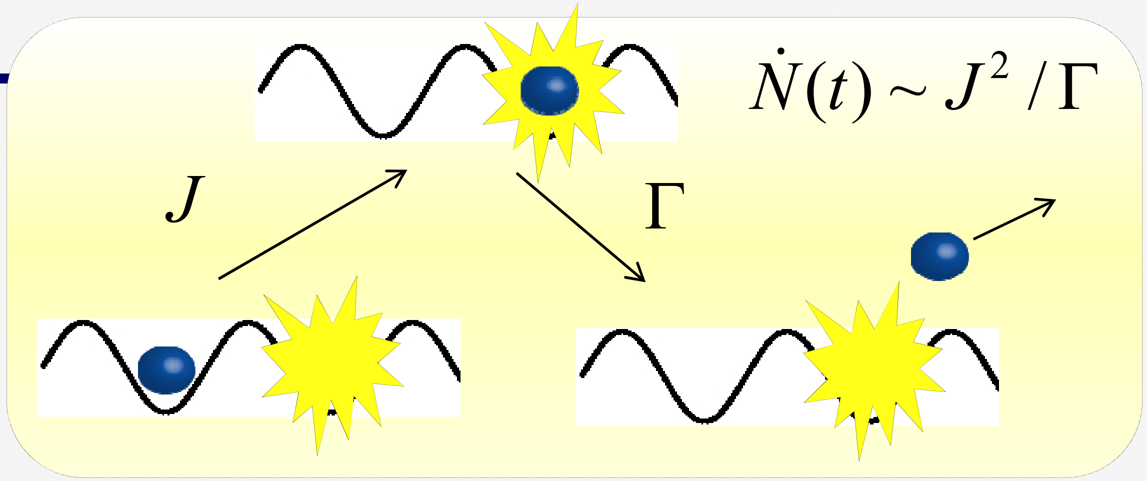


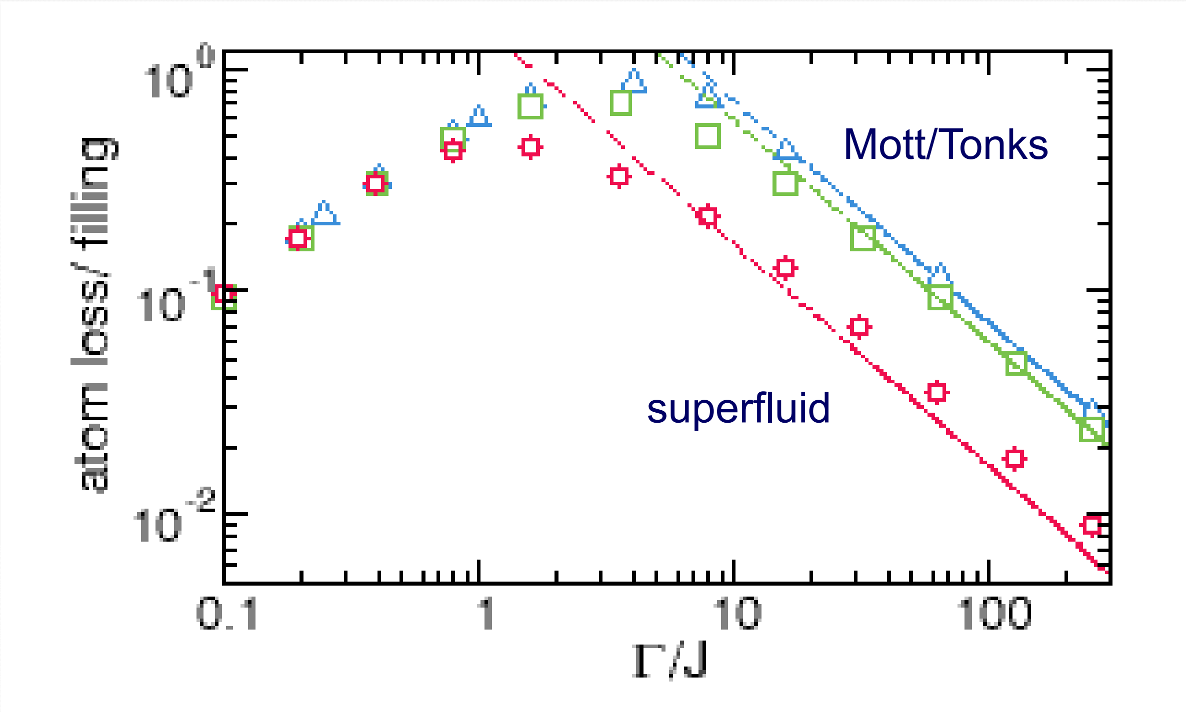
surprisingly no effect of underlying quantum state
-> probe of local density
-> enhanced signal

Zeno-like effect

strong coupling $\Gamma >> J$

suppression of atom losses

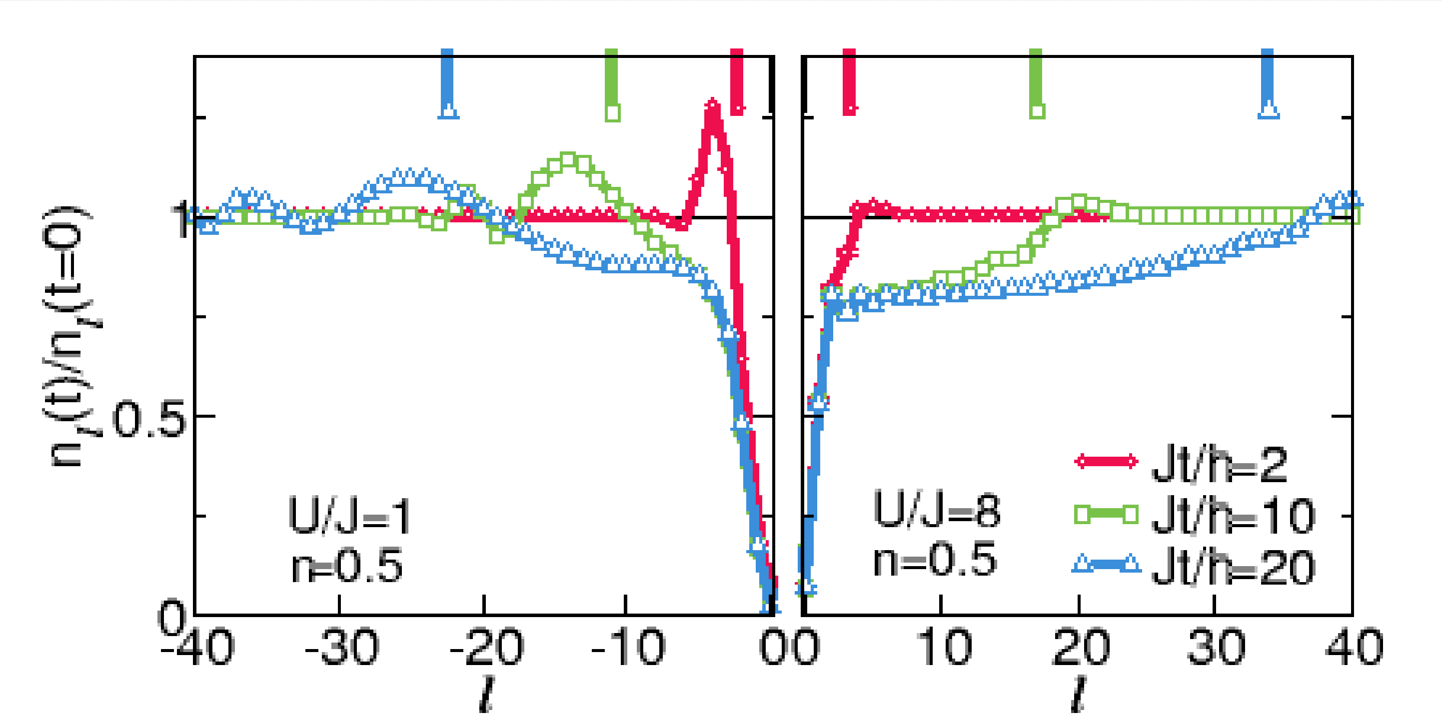




distinct behaviour for superfluid and Mott insulator

Density profiles: decoupled subsystems

strong coupling $\Gamma >> J$

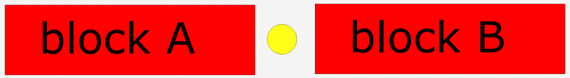


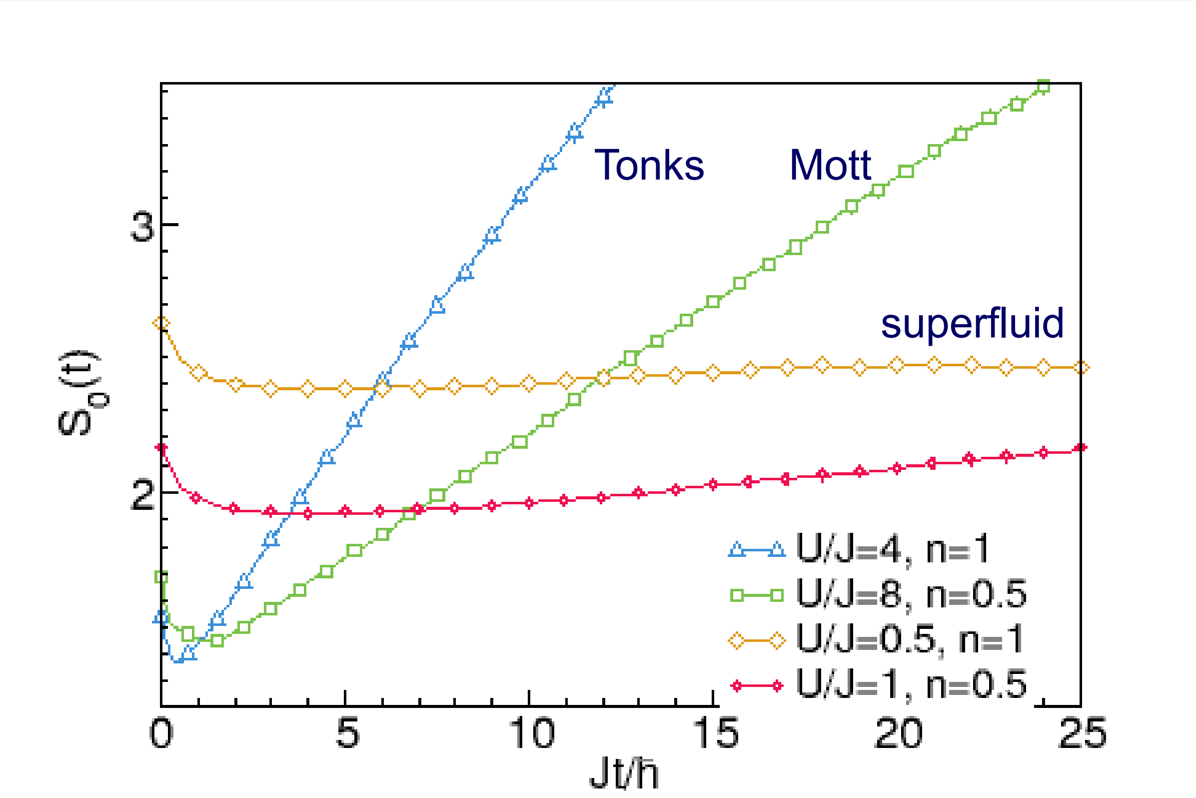
decoupled subsystems

Von-Neuman Entropy: strong entanglement

strong coupling $\Gamma >> J$

von Neuman entanglement: $S_A = -Tr_A \rho_A \log \rho_A$





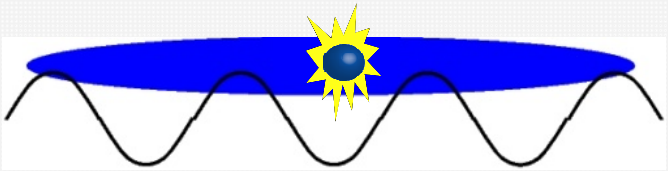
- ➢distinct behaviour for superfluid and Mott insulator
- ➢strong increase of entropy S for Mott-insulator

Von-Neuman Entropy: simplified picture

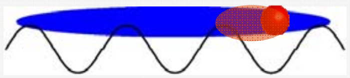
strong coupling $\Gamma >> J$

von Neuman entanglement: counts number of states in reduced density matrix

superfluid

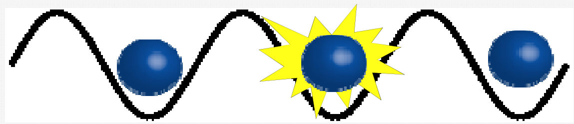


hole

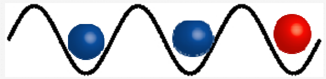
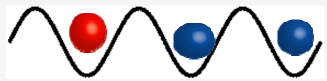
 + 

- ➢hole generation
- ➢fluctuations do already exist
- ➢weak change in entropy

Mott insulator



hole

 + 

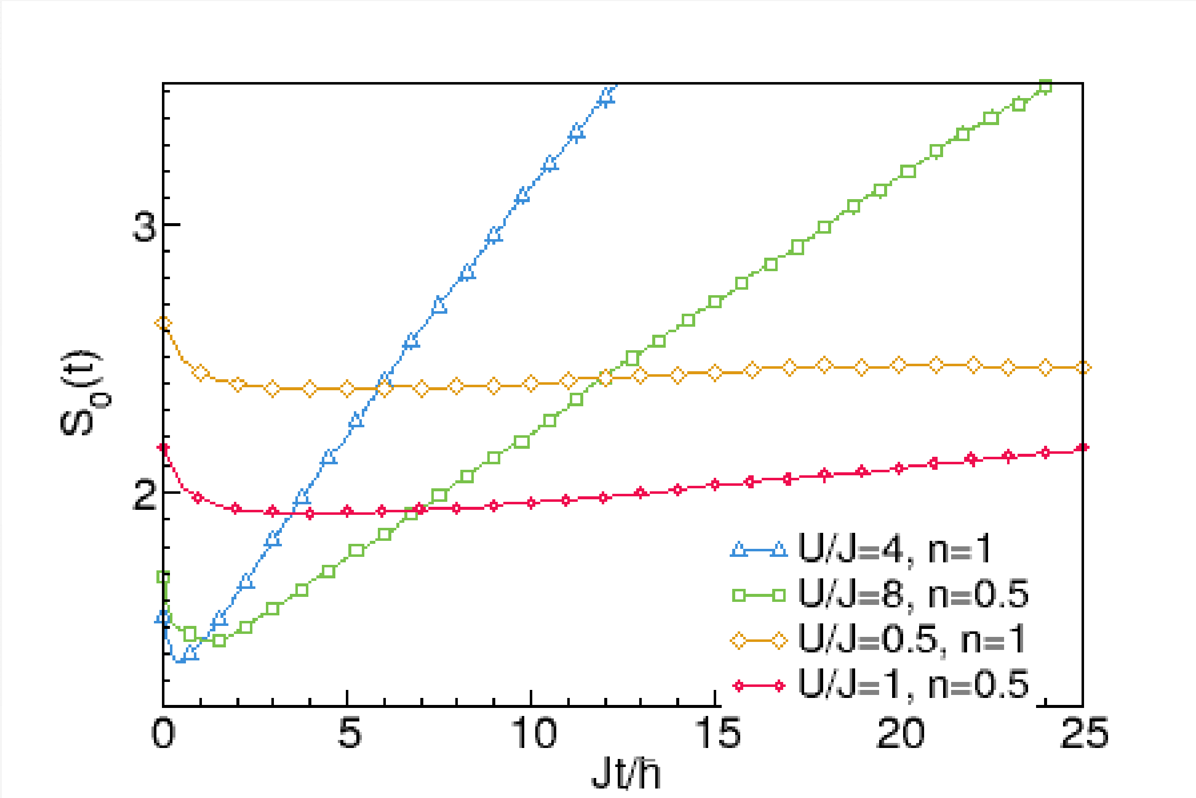
- ➢generation of entangled hole pair
- ➢new states generated
- ➢strong change in entropy

Von-Neuman Entropy: strong entanglement

strong coupling $\Gamma >> J$

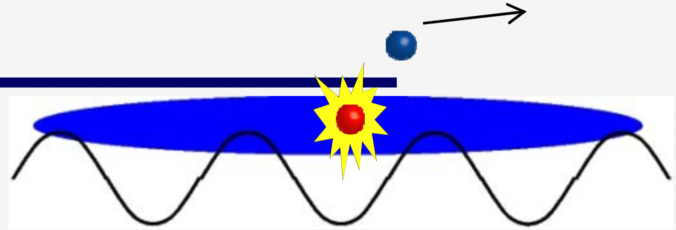
von Neuman entanglement: $S_A = -Tr_A \rho_A \log \rho_A$

block A block B

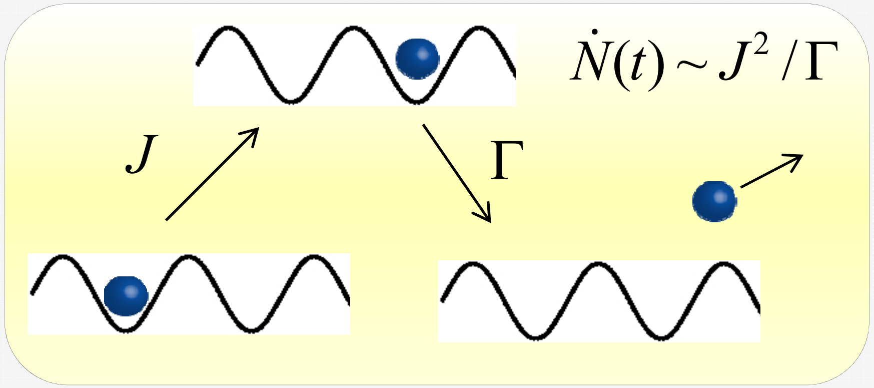


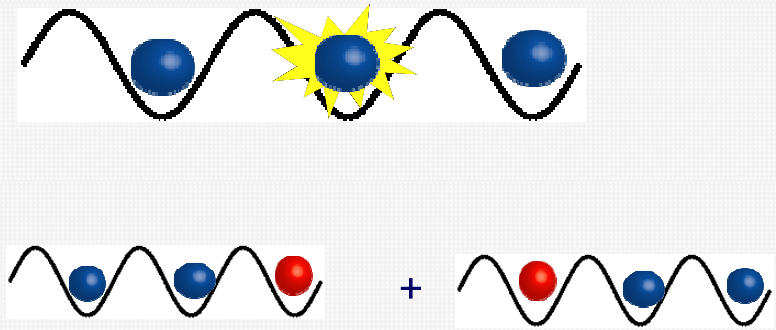
- distinct behaviour for superfluid and Mott insulator
- strong increase of S for Mott-insulator

Summary: local dissipation



- weak dissipation: constant loss rate -> density measurement possible
- strong dissipation: Zeno-like suppression of losses
  - superfluid: suppressed losses in time, bright shock wave formation
  - strong interacting: strong entanglement creation by hole pairs

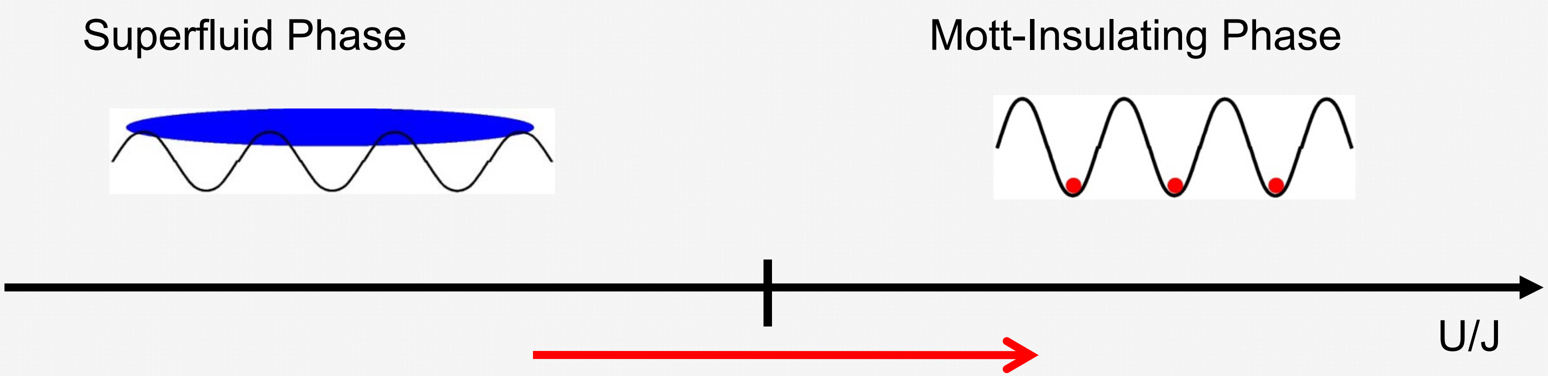




Questions for slow parameter changes

Theory ref: Zurek, Kibble,
Polkovnikov, Silva, Damski,
Eckstein, Kollar, Mueller, Biroli,
and many more

- ***adiabatic following while preparation?***
- ***is the defect production rate universal?***
- ***Kibble Zurek mechanism (early universe) valid?***
- ***influence of phase transition?***
- ***influence of trapping potential, mass transport?***

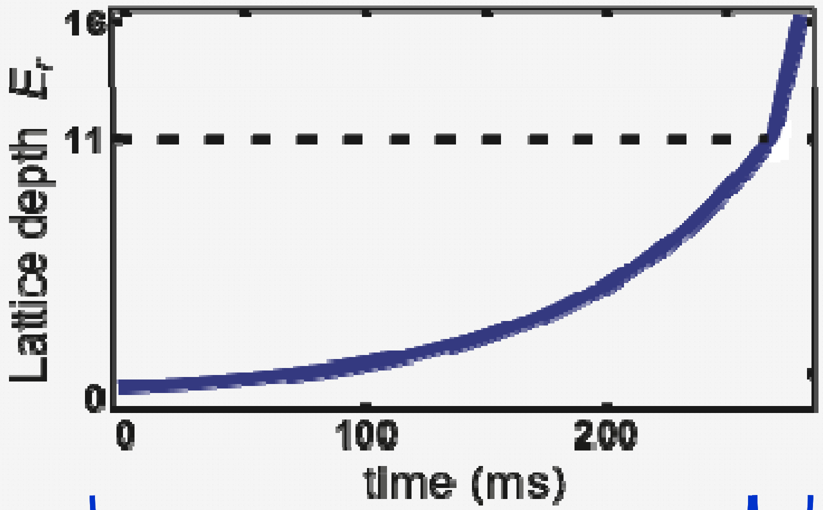


methods: DMRG
mainly quasi-1D, dissipation, temperature

1D superfluid is critical phase

Experimental results

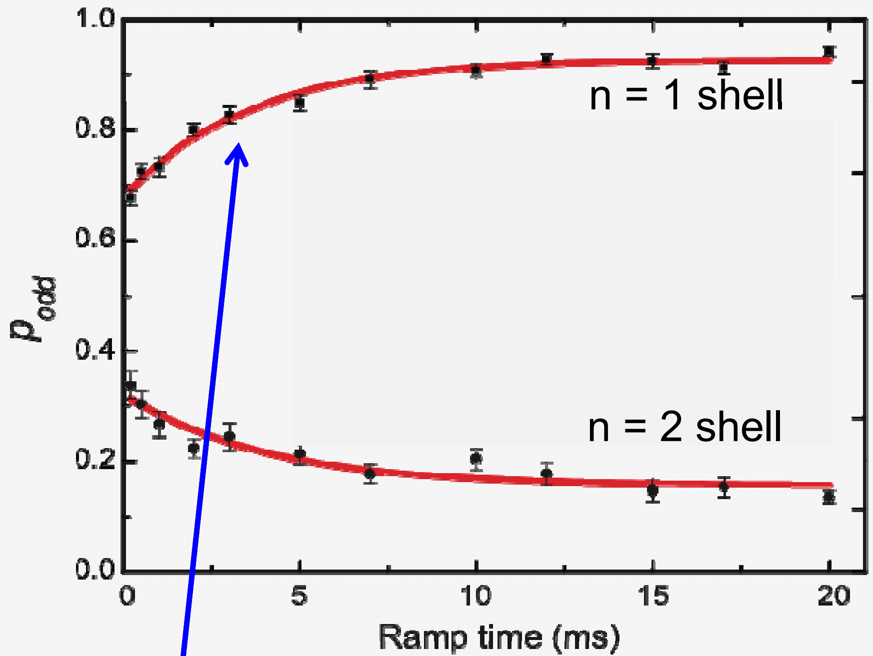
Ramping schedule



Preparation

Linear ramp
$V(t)/E_R$: 11 ➔ 16

probablitiy to find odd no of particles



Fitted time constant: ~3.5 ms <<h/J_c = 68 ms

->fast relaxation

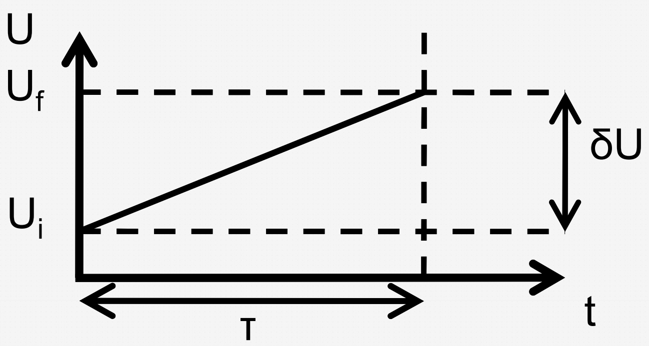
W.S. Bakr et al. Science ***329****, 547 (2010)*

Interaction change across phase transition

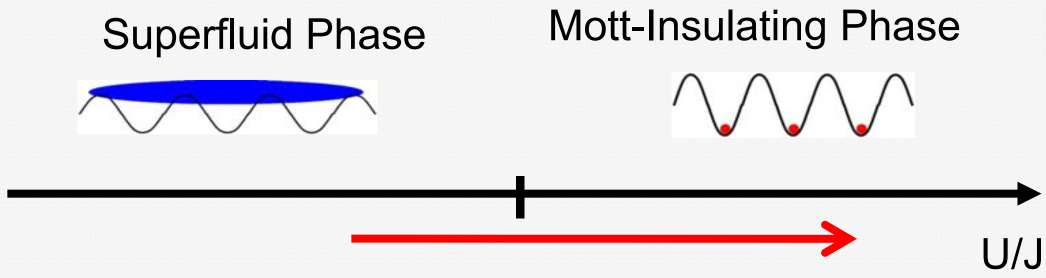
$$\mathcal{H} = -J\sum_j (b_{j+1}^\dagger b_j + \text{h.c.}) + \frac{U(t)}{2}\sum_j n_j(n_j-1) - \sum_j \mu_j\, n_j$$

kinetic interaction trap

Ramping schedule (1D):



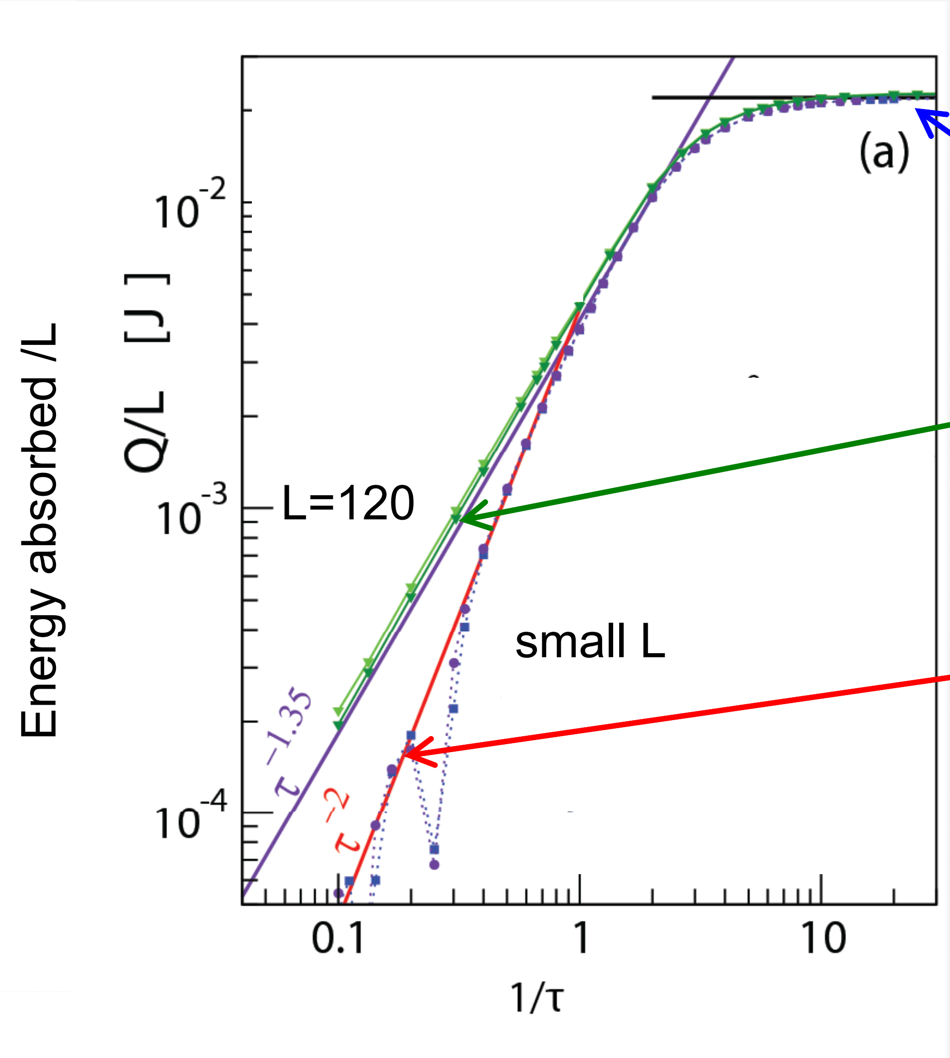
$$U(t) = U_i + \frac{t}{\tau}\,\delta U$$



- Can be achieved using a Feschbach resonance
- Cleaner perturbation scheme

Energy absorption in uniform system

$U_i = 2J \rightarrow U_f = 3J$ (uniform n=1 system)



inverse ramp time

Sudden quench limit

Non-trivial scaling regime

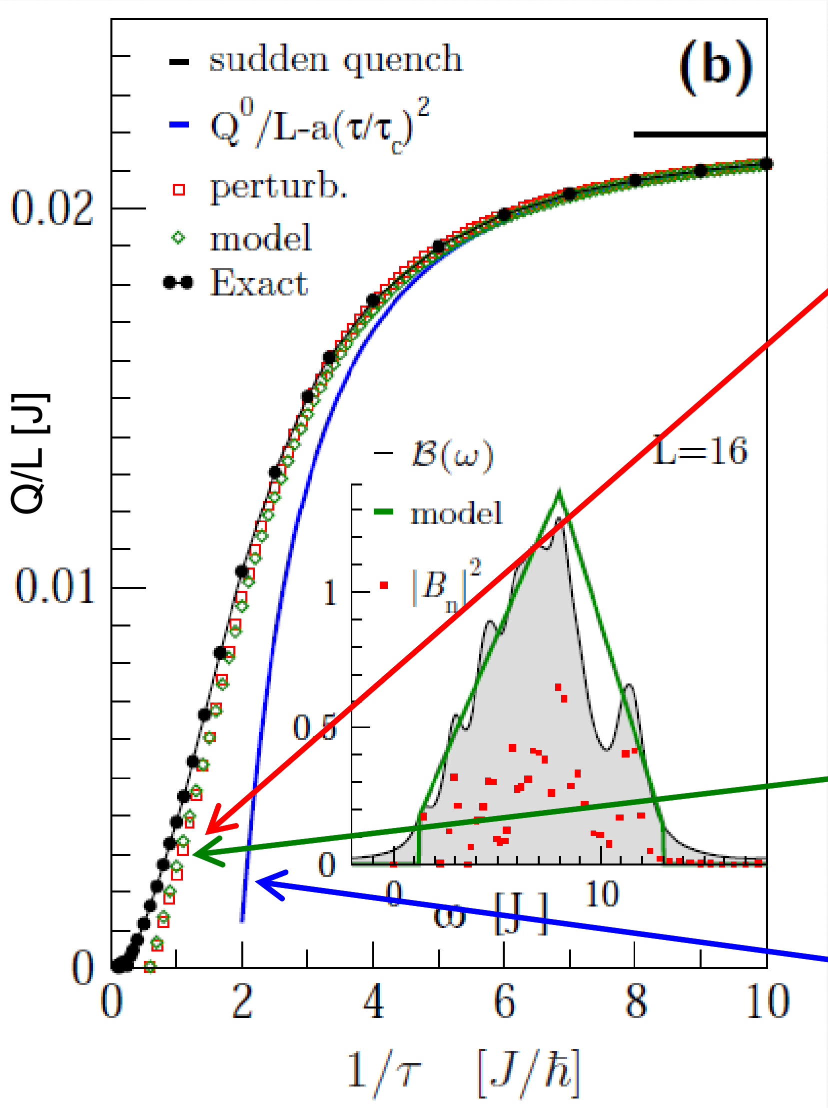
$$Q \sim \tau^{-1.35}$$

Landau-Zener like limit
due to finite-size gap

$$Q \sim \tau^{-2}$$

see also
E. Canovi et al, J. Stat. Mech. (2009) P03038
anisotropic spin-1 XY chain

Perturbation theory: short-τ limit



U_i = 2J ➔ U_f = 3J (uniform n=1 system)

absorbed energy:

$$Q(\tau,\delta U) = Q^0(\delta U) - \frac{\delta U^2}{\tau^2}\int_{0+}^{\infty} d\omega \frac{\mathcal{B}(\omega)}{\omega^3}\left[(\omega\tau)^2 - 4\sin^2\left(\frac{\omega\tau}{2}\right)\right]$$

sudden quench limit

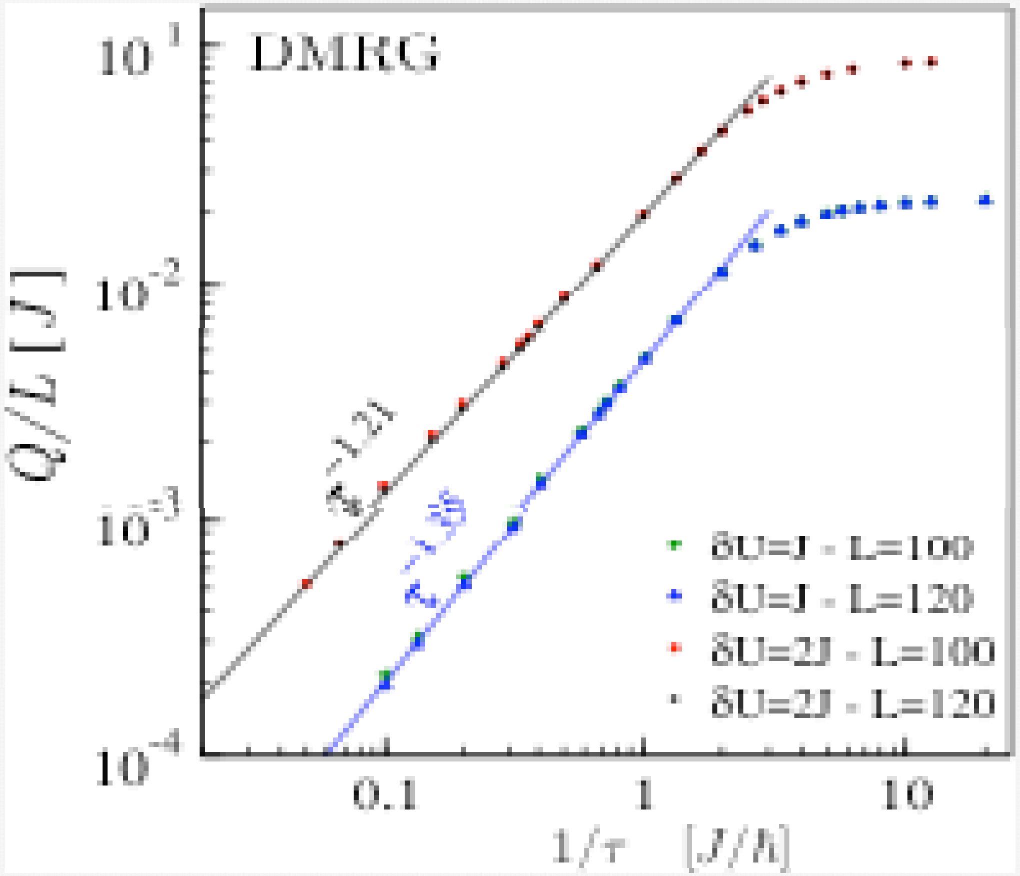
spectral function of initial state

the details of B(ω) do not alter much the short-τ regime

short-τ corrections to the sudden quench limit

see also M.Eckstein and M. Kollar, New J. Phys. (2010)

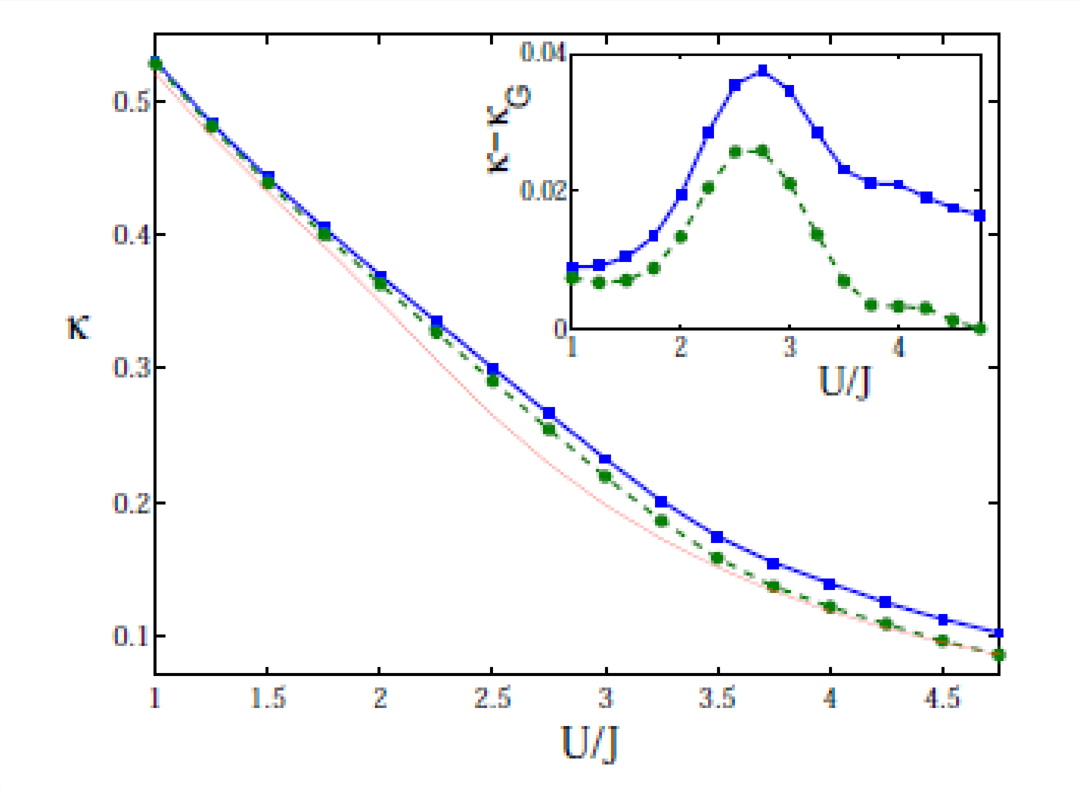
Non-trivial scaling regime



- ➢Exponent varies with δU
- ➢not predicted by adiabatic perturbation theory

see also E. Canovi et al, J. Stat. Mech. (2009) P03038
anisotropic spin-1 XY chain

Influence of phase tranisition



- different ramp function with fixed velocity
- U/J->2U/J

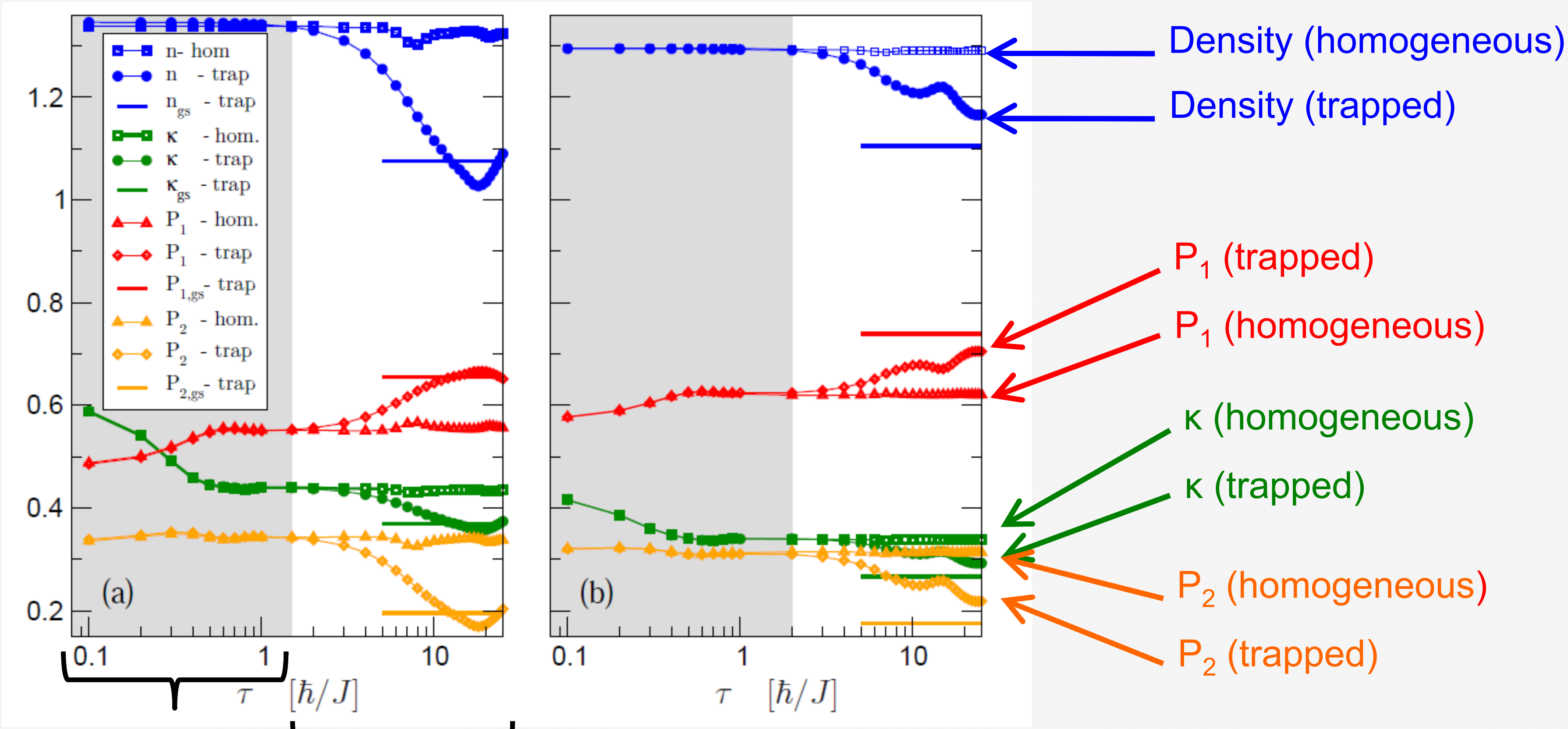
- Maximum at phase transition

D. Poletti and C. Kollath arXiv:1105.0686

Trapped gas: presence of two time regimes

Evolution of local observables at the center of the trap

$U_i = 2J \rightarrow U_f = 4J$ $\qquad$ $U_i = 4J \rightarrow U_f = 6J$

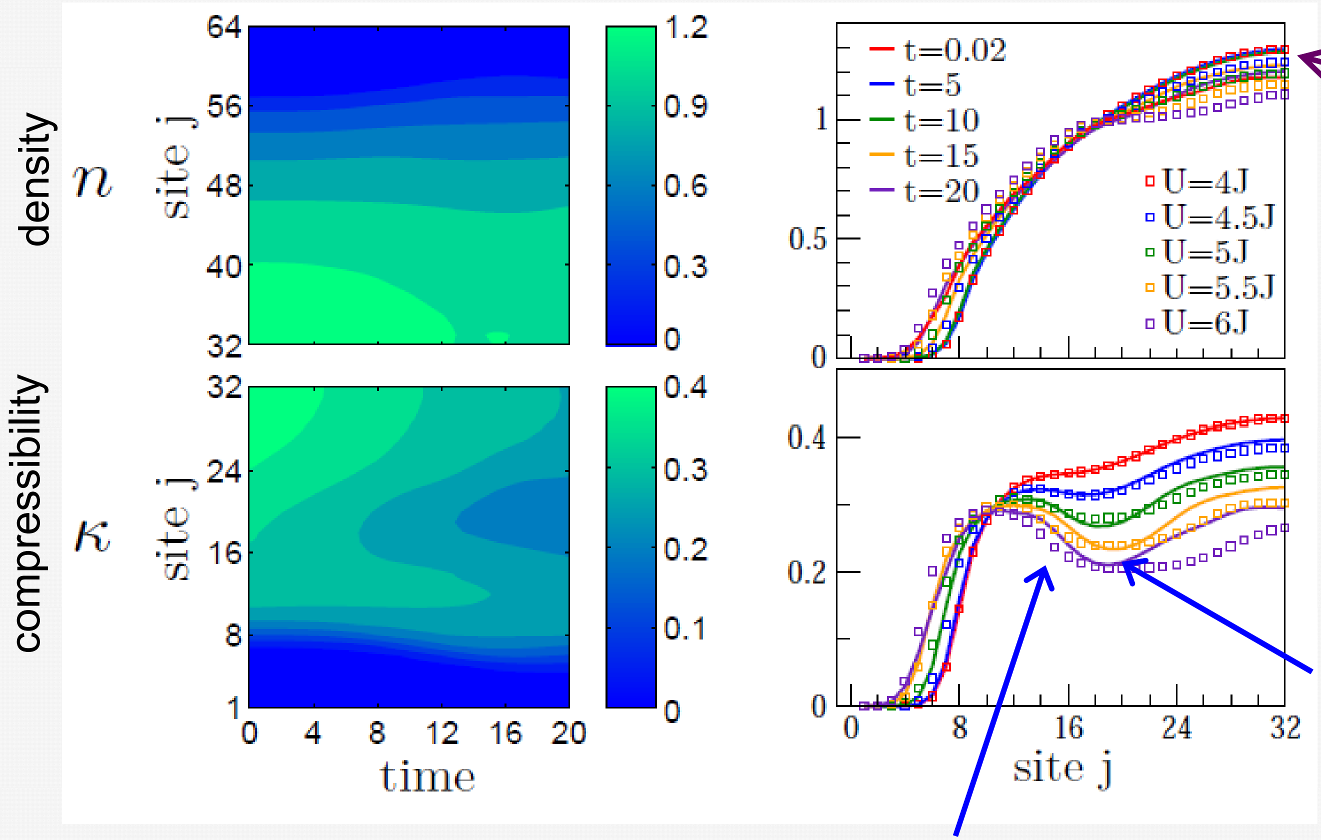


Local dynamics

Global dynamics
(Mass transport)

Mott-barriers block transport

$U_i = 4J \rightarrow U_f = 6J$ $\tau = 20\hbar/J,\ L = 64,\ V = 0.006J$



slow change of density

Dip in the compressibility: signals the presence of Mott barriers

Compressibility drops quickly

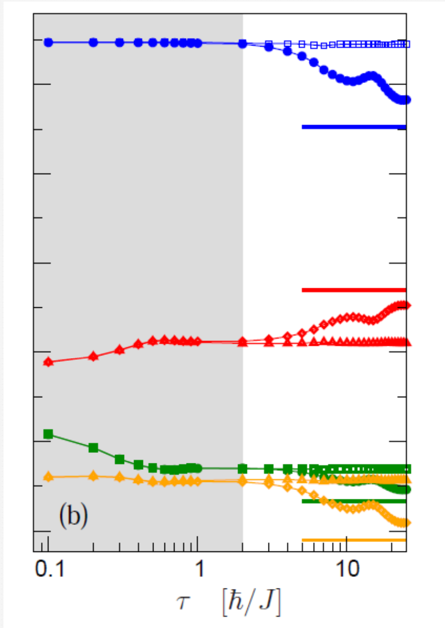
Slow quench

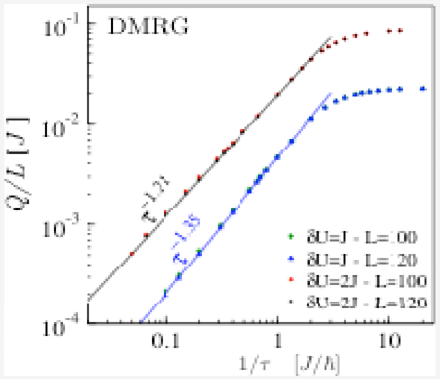
homogeneous system:

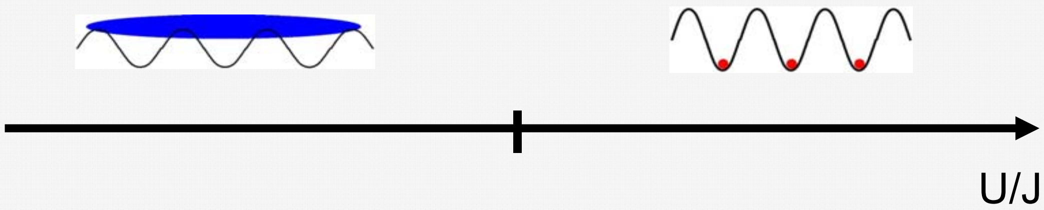
- Intermediate ramp time: non-trivial power law
- slow ramps relatively close to ground state
- maximal absorption across phase transition

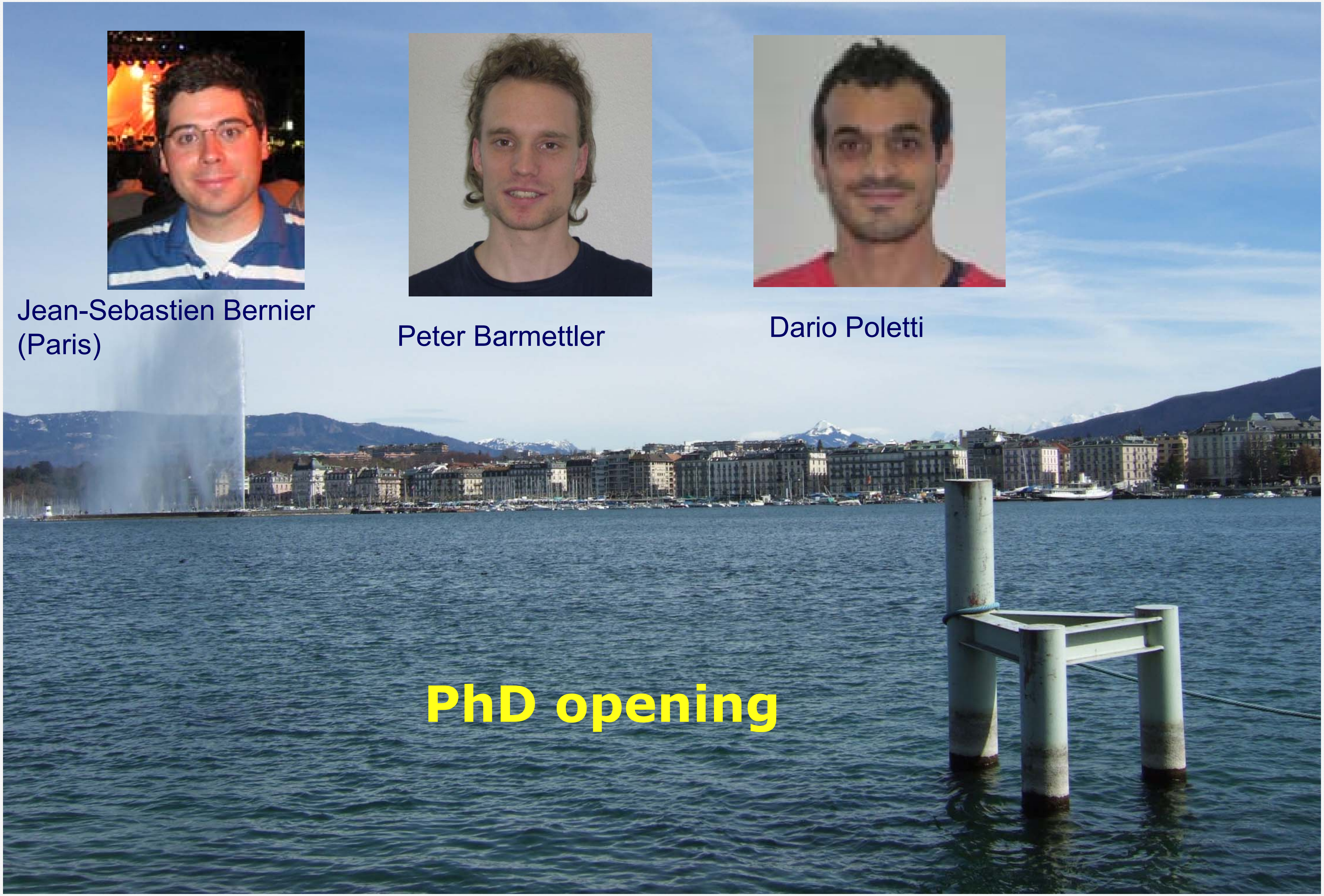
trapped system

- two time-scales: local versus global dynamics
- local dynamics can be observed
- ‘Mott-regions’ can block transport
  -> very slow following (important for experimentalists)








Jean-Sebastien Bernier
(Paris)
Peter Barmettler
Dario Poletti
PhD opening