Cooling of impurity atoms in a 2D lattice by a reservoir gas

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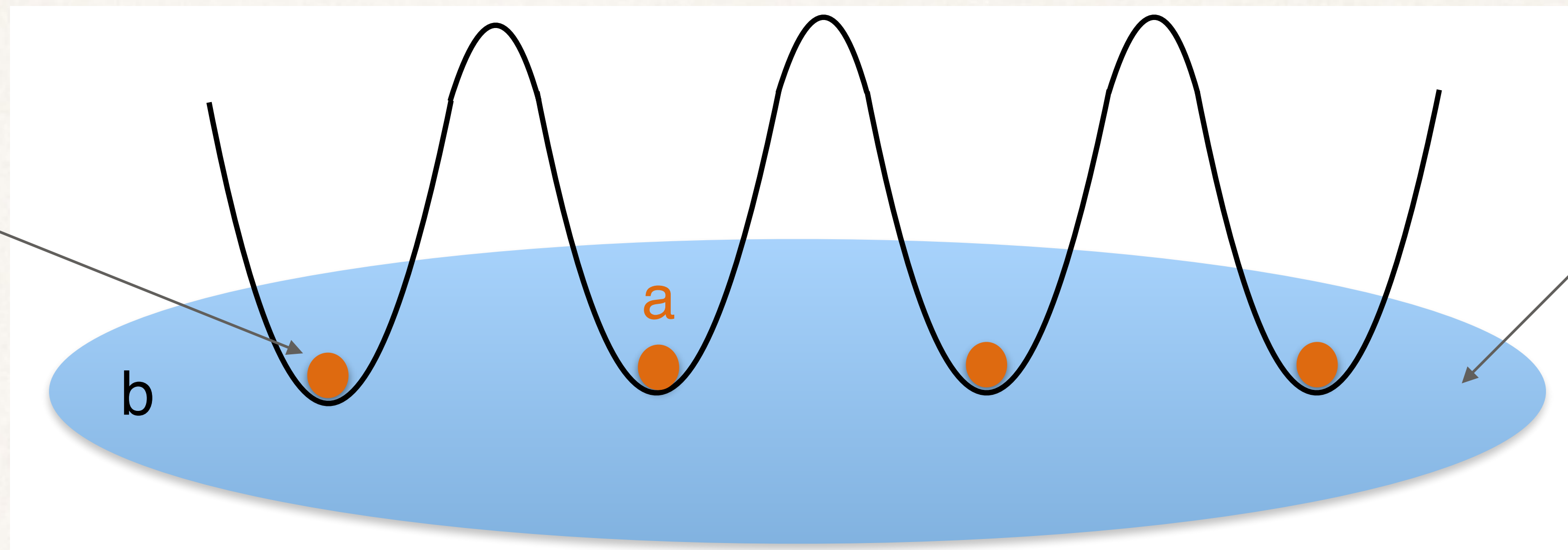
QuProCS II meeting, Palma de Mallorca, Spain

06/04/17

Model and motivations

Use of impurity atoms to probe the dynamics of a BEC

Neutral atoms (fermions)



Superfluid gas reservoir (bosons)

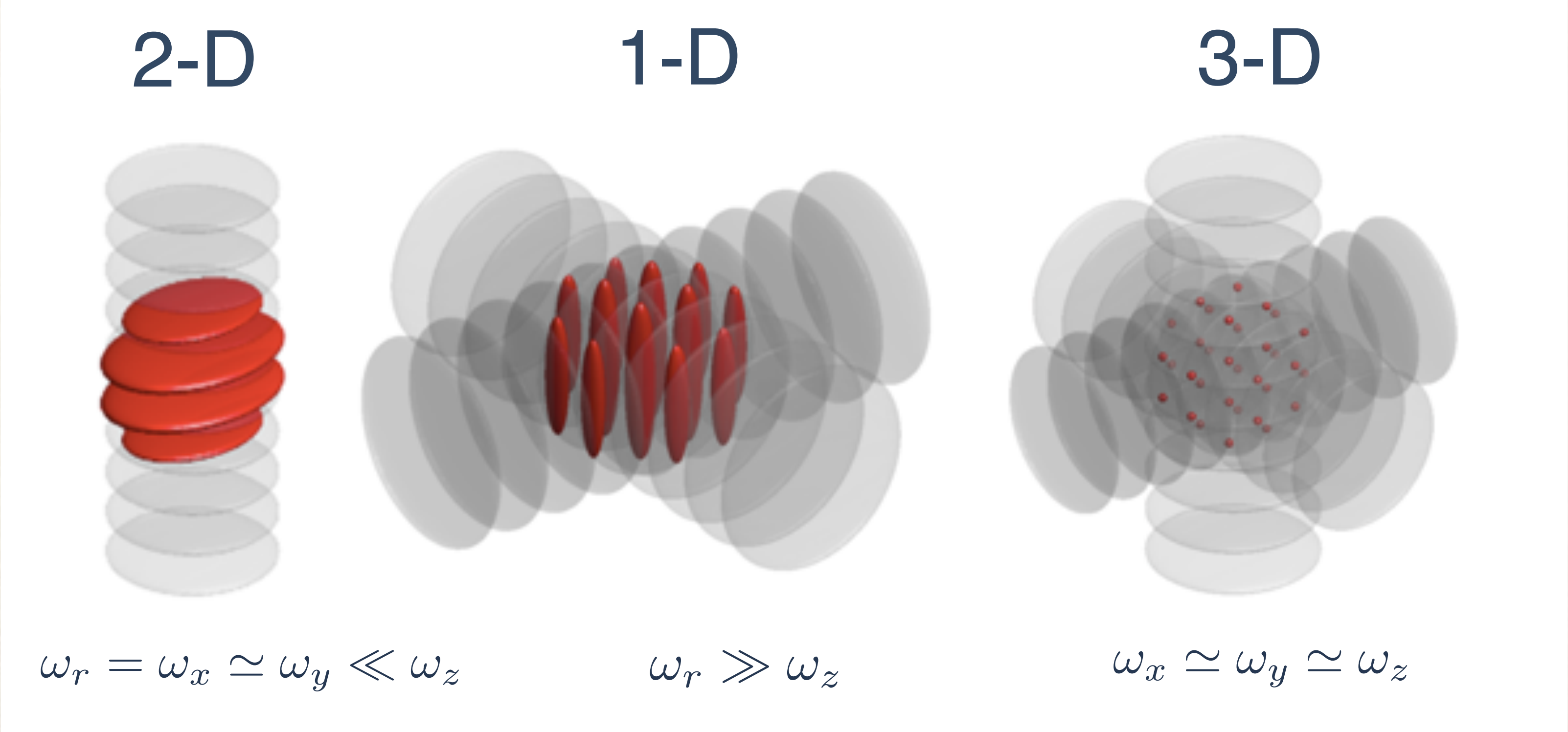
- State engineering
- Study of impurities
- Study of many-body dissipative dynamics
- Cooling within the Bloch band
- **Quantum information probes with probe-system entanglement** (connects to WP2)
- **Quantum reservoir engineering** (connects to WP3)
- **Roadmap for Strathclyde experiments with superlattices** (connects to WP1: Task 4)

Connects with Oxford, Freiburg, Turku Theory

Overview

- Single particle 1-D model
- Many particle dynamics in single sites of the lattice in 2-D:
  - Pauli blocking?
  - Decay rate
  - Finite temperature effects:

    - Reheating effects affecting the dynamics (by changing T_b and μ_b)



From left to right: 1D lattice creating 2D pancake traps, 2D lattice creating 1D tubes, 3D lattice creating a 3D crystal

Single impurity in a 1D harmonic trap

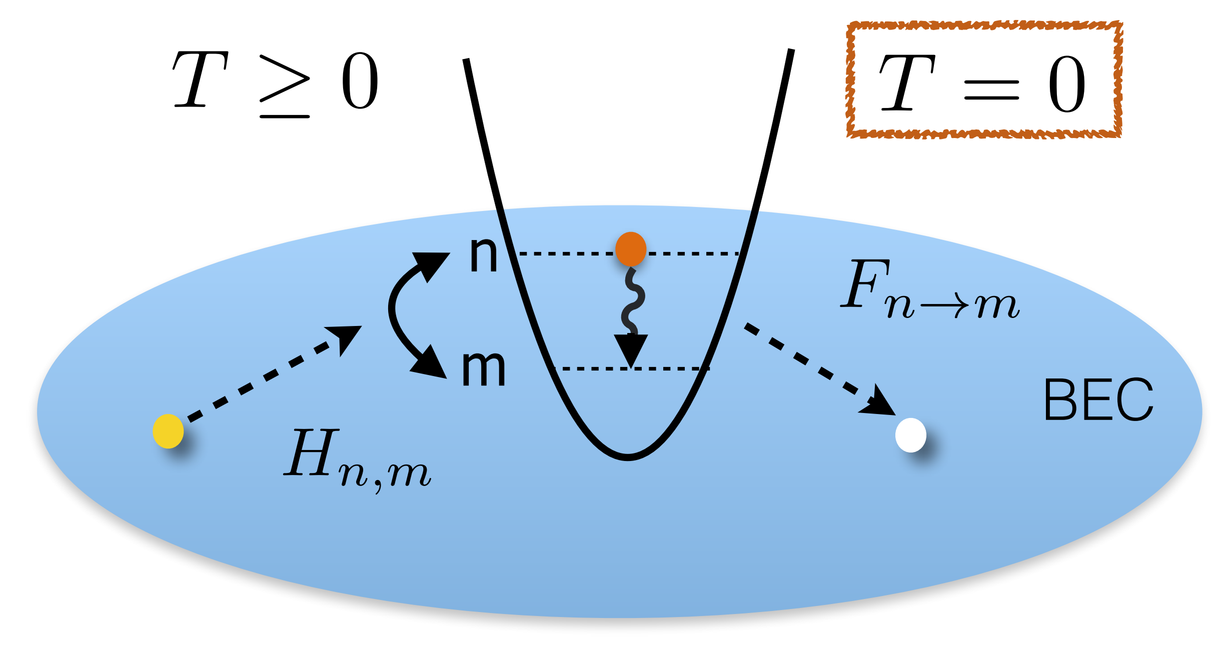
Derivation of the master equation

- Born approximation
- Rotating wave approximation
- **Markov approximation:** $\tau_{corr,R} \ll \tau_{corr,S} \longrightarrow \int_0^\infty d\tau e^{i(\epsilon-\epsilon_0)\tau/\hbar} \to \pi\hbar\delta(\epsilon-\epsilon_0)$

Evolution of the occupation probability of the state *m:*

$k_B T \ll \hbar\omega$

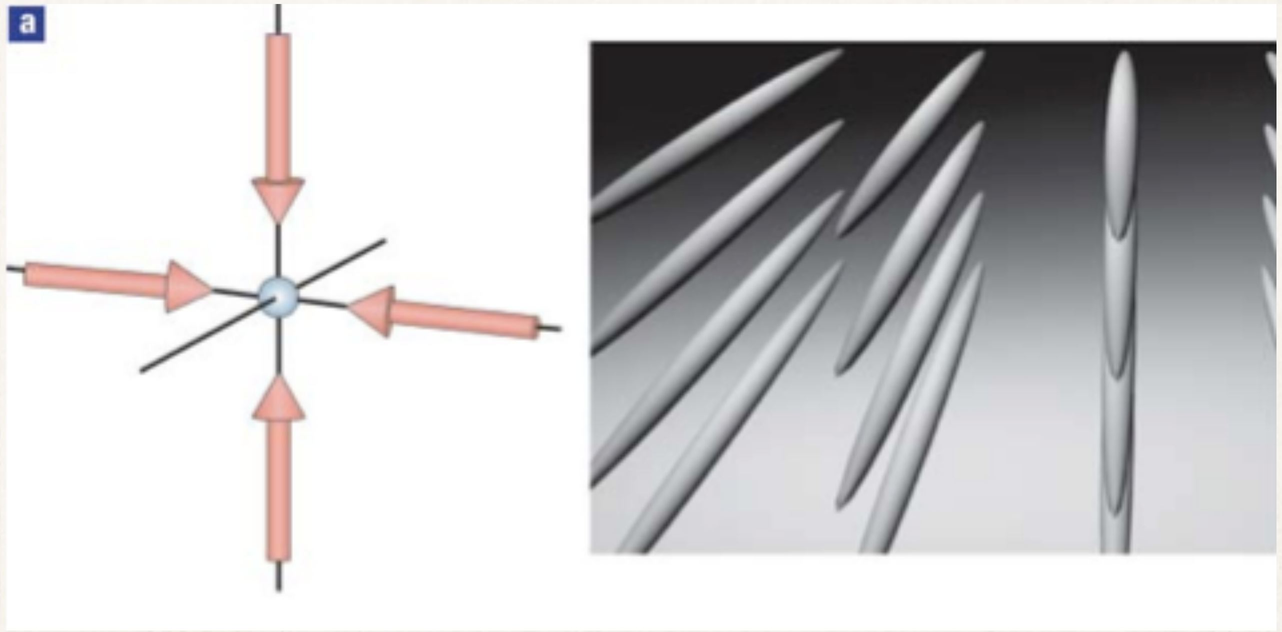
$$\dot{p}_m = \sum_{n>m} F_{n\to m} p_n - \sum_{n'<m} F_{m\to n'} p_m + \sum_n H_{n,m}(p_n - p_m)$$



$H_{n,m}$ ⟶ Thermal excitations

$$F_{n\to m} = \frac{2\pi}{\hbar} \sum_{\mathbf{q}} |Z_{n,m}(\mathbf{q})|^2 \delta(\hbar\omega(n-m) - \epsilon_q)$$ ⟶ Bogoliubov excitations

Many particle cooling in single sites: 2-D model



$$\omega_y \gg \omega_z \gg \omega_x = \omega_r$$

Dynamics at zero temperature

We excite the QHO to the first excited state along the axial direction and look at the decay along the radial one

$$|n,1\rangle \rightarrow |m,0\rangle$$

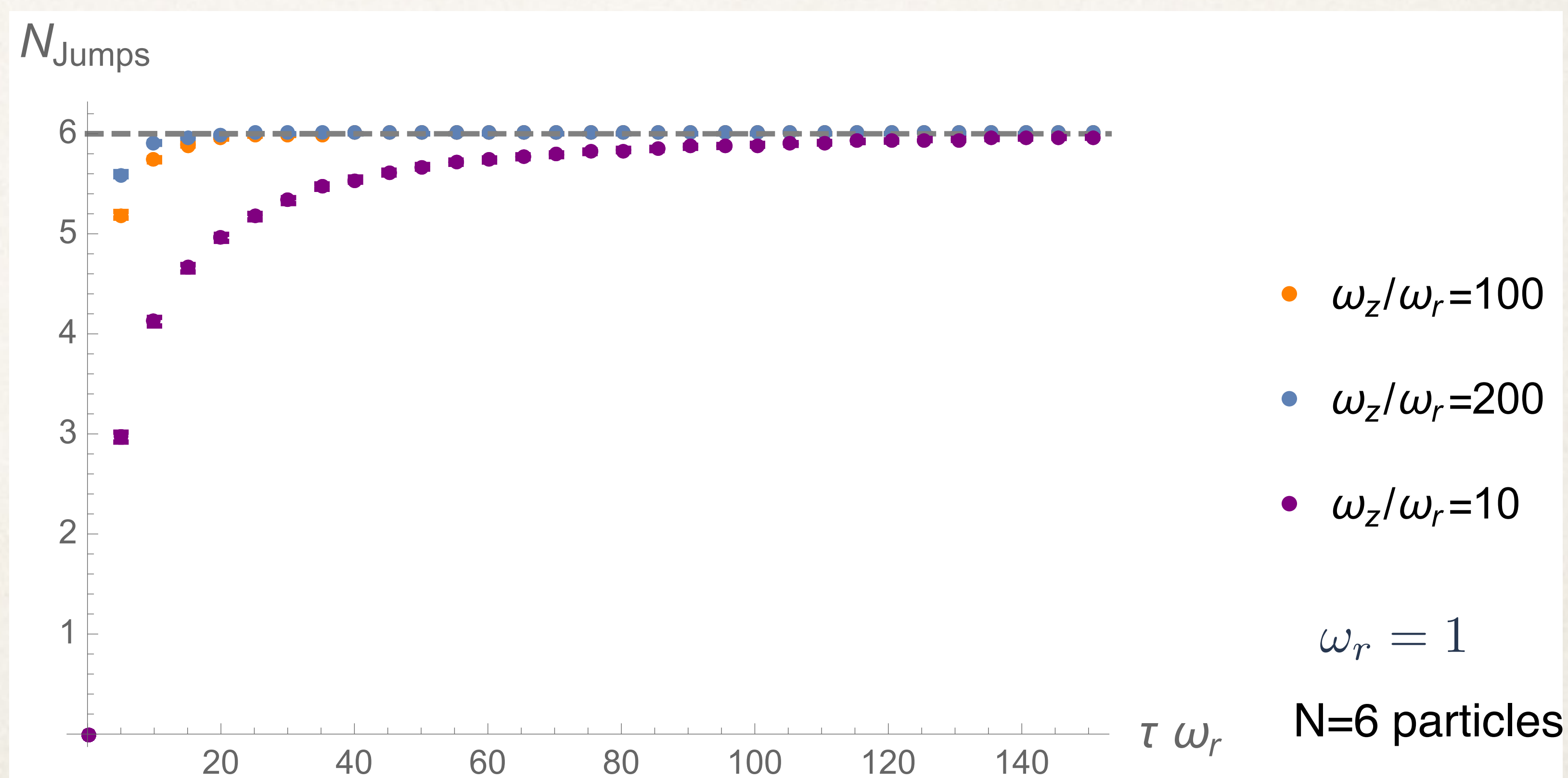
Fermi distribution $\bar{n}(\epsilon_n) = \dfrac{1}{\exp[\beta\epsilon_n - \mu] + 1} \in [0,1]$ $\qquad \epsilon_n = \hbar(\omega_r n_x + \omega_z n_z)$

Study of the dynamics with jump operators approach

$$H_{eff} = -\frac{i}{2}\sum_m \gamma_m \hat{c}_m^\dagger \hat{c}_m$$

Decay rate

$$\Gamma = \sum_m \gamma_m \longrightarrow e^{-\Gamma t}$$



Dynamics along the radial direction at zero temperature

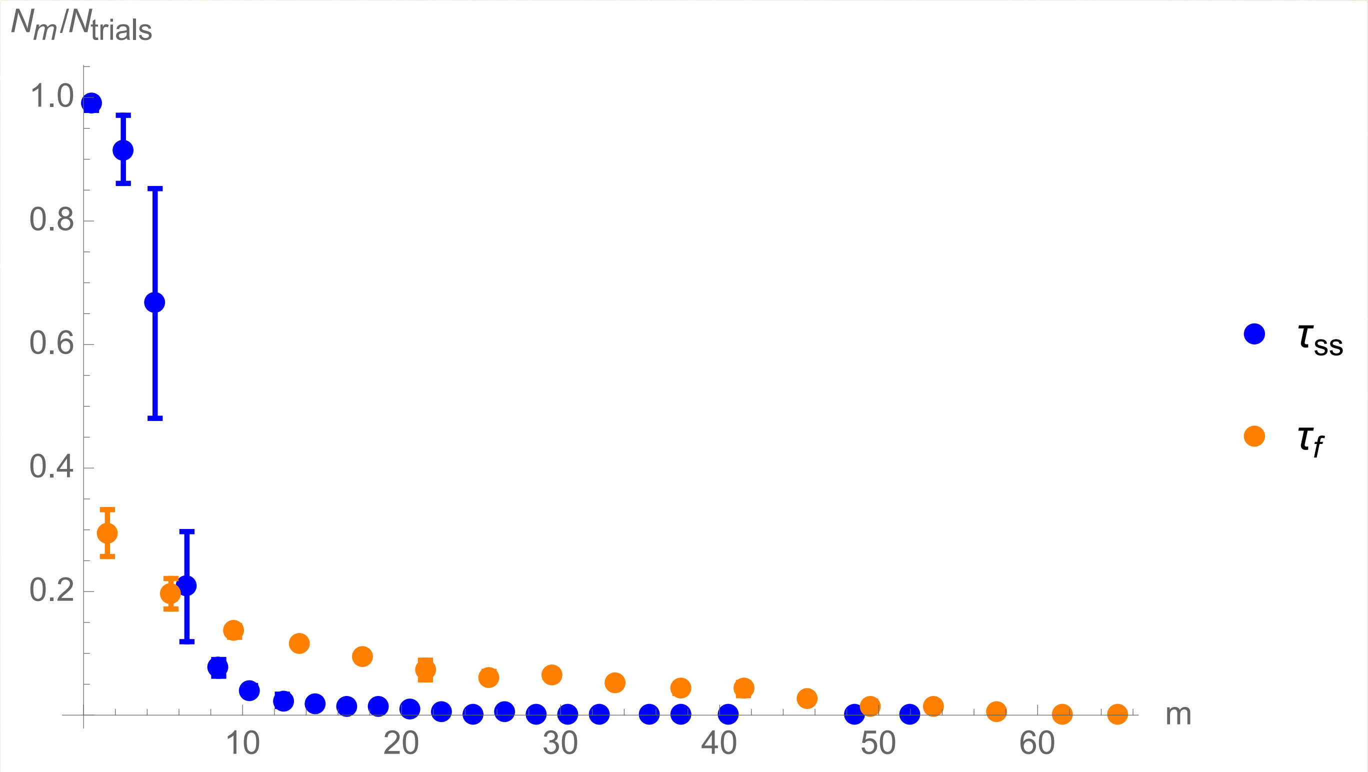
N=6 particles $\omega_z/\omega_r = 100$ $\omega_r = 1$

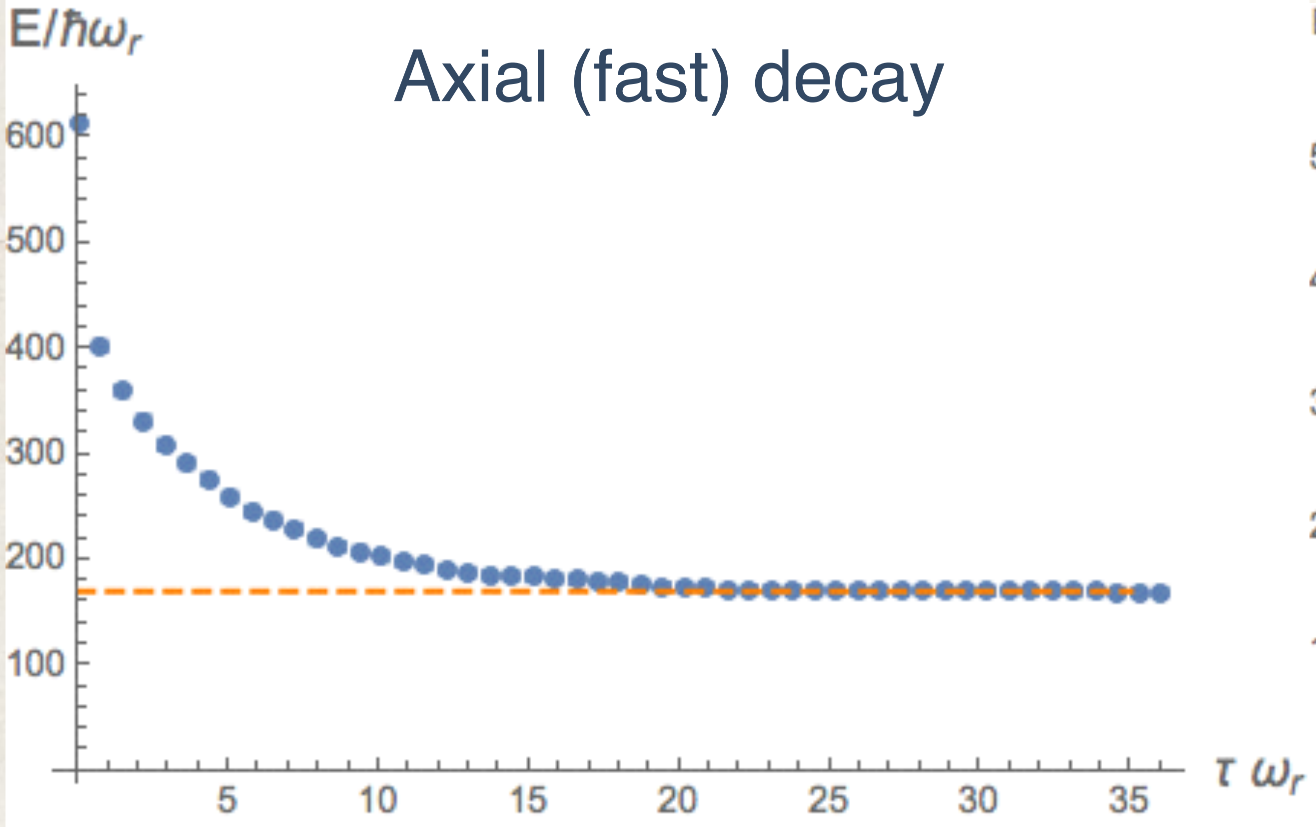
τ_f Time at which all the particles decayed from the excited state

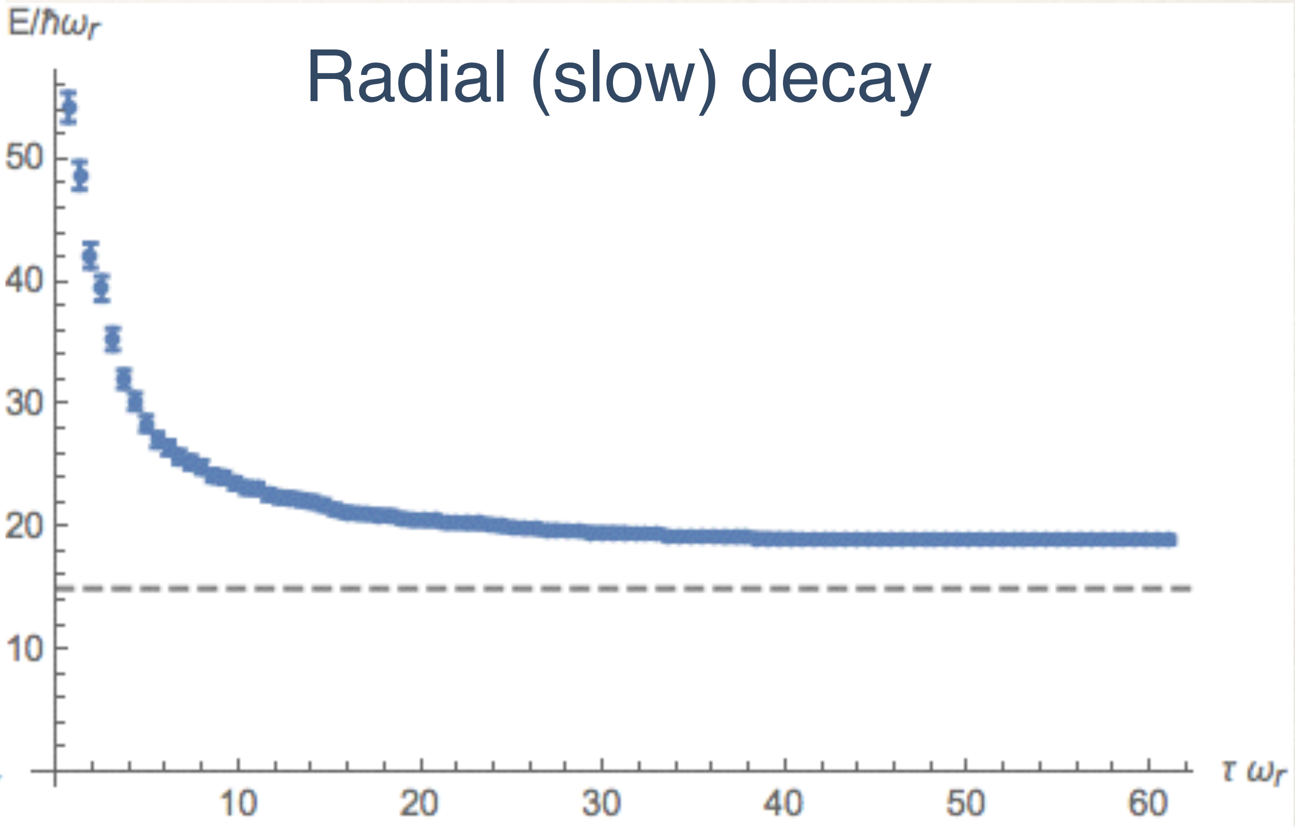
τ_{ss} Time at which the system approaches the steady state configuration

$\boxed{\text{No Pauli blocking}}$

$$E_f = 180\ \hbar\omega_r \to |30, 0\rangle$$





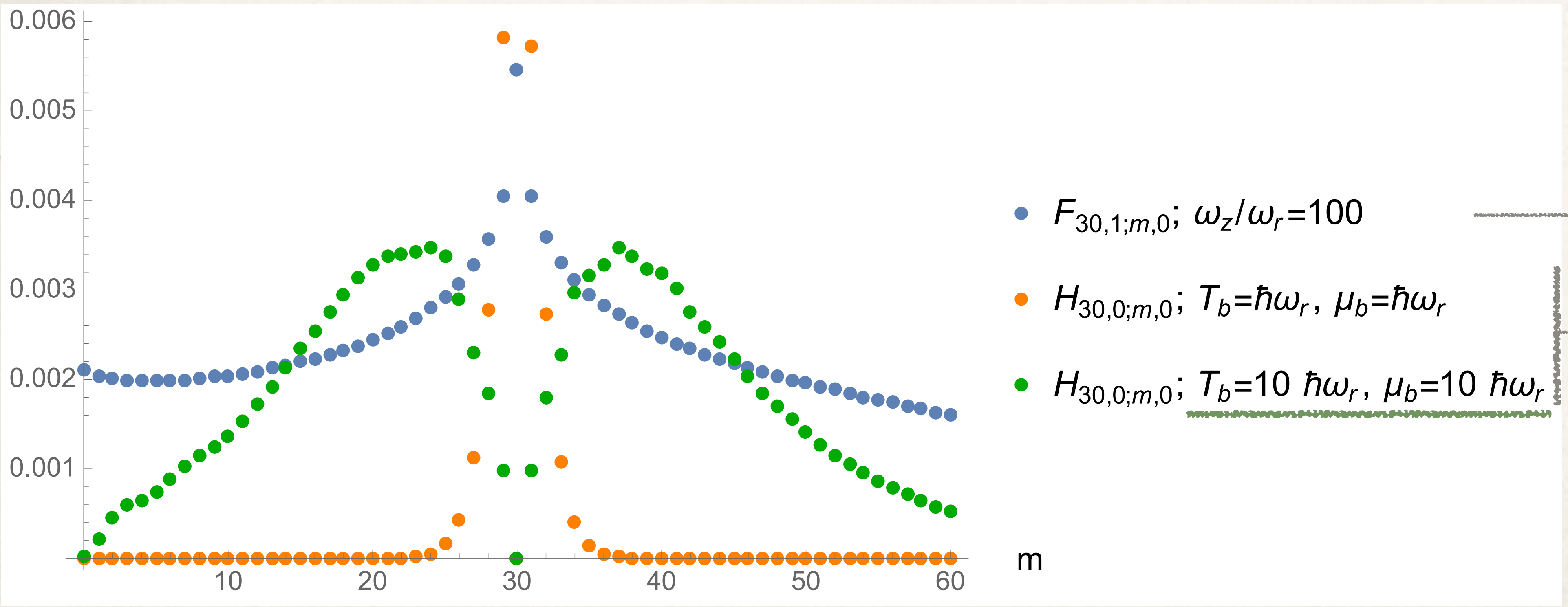


Environment at finite temperature: reheating effects

$$\dot{p}_m = \sum_{n>m} F_{n\to m} p_n - \sum_{n'<m} F_{m\to n'} p_m + \sum_n H_{n,m}(p_n - p_m)$$

Change parameters T_b and μ_b to see reheating effects in two regimes:

- $k_b T_b, \mu_b \lesssim \hbar\omega_r \ll \hbar\omega_z$ → Radial and axial reheating negligible
- $\hbar\omega_r \lesssim k_b T_b \lesssim \mu_b \ll \hbar\omega_z$ → Axial reheating negligible but radial reheating to be considered for some parameters



→ Decay transition coefficients

→ Reheating transition coefficients

Conclusion and future work

- Many particles dynamics for the decay in one site
  - Decay time
  - Quantum trajectories approach with jump operators in order to reconstruct the final distribution: **no Pauli blocking**
  - Reheating effects: we can neglect the axial contribution but the radial reheating contributes for some values of temperature and chemical potential
- Extension to the whole lattice to study the coherence properties
- Study the dynamics in the non-Markovian regime
- Experimental implementation