Emergent Pauli blocking in a weakly interacting Bose gas

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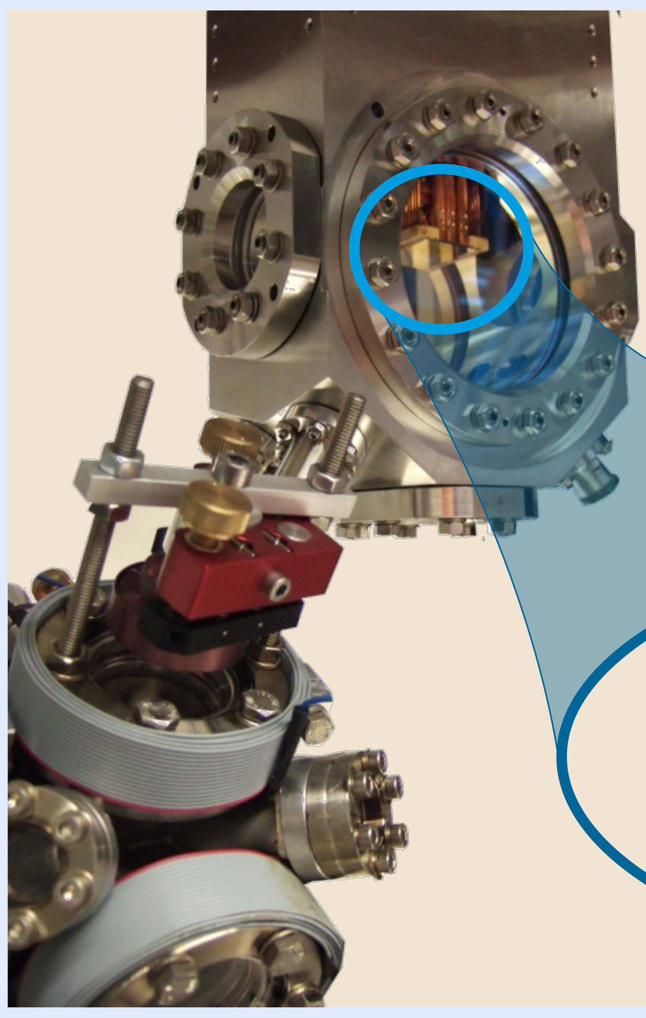
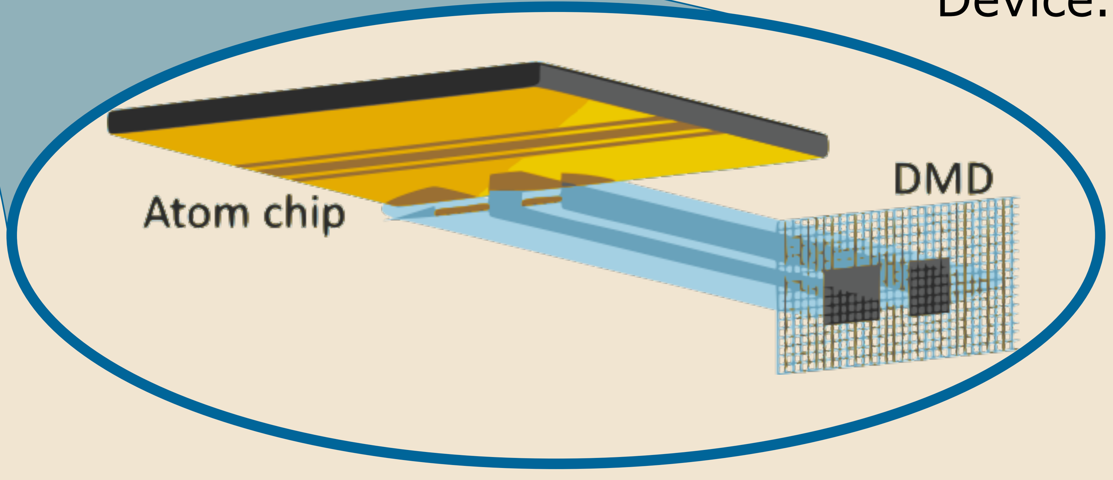
Emergent phenomena are a hallmark of interacting many-body quantum systems. Due to their reduced dimensionality, excitations of the 1D Bose gas are all collective of nature. They can be described as fermionic quasi-particles whose evolution follow hydrodynamic principles. We experimentally study the dynamics of a weakly interacting Bose gas in the dimensional crossover and observe 1D behaviour at energies far beyond conventional limits. Following the quasi-particle description, we interpret our observations as an emergent Pauli blocking of the 3D excitations.

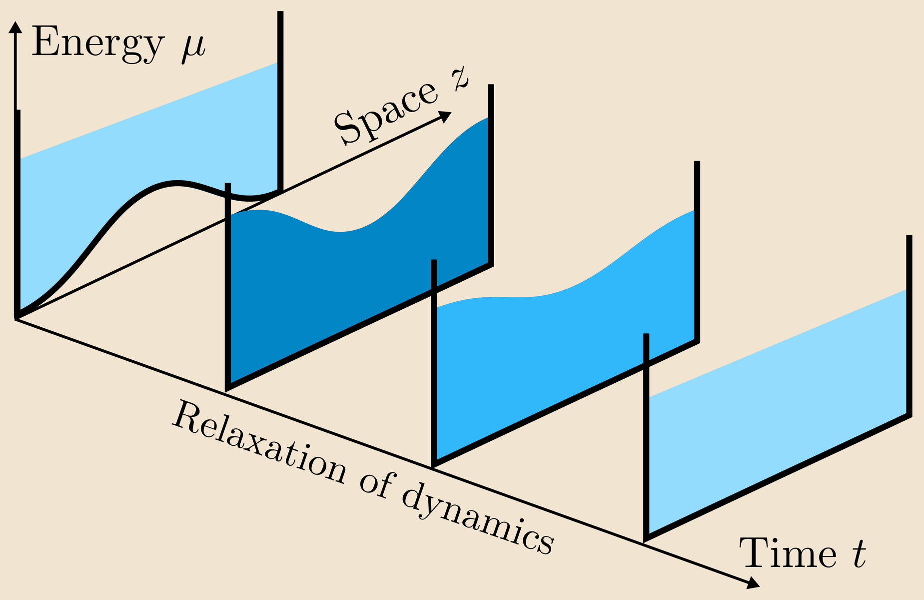
Experimental Setup



- Atom chip trap with tight transverse confinement $\omega_\perp = 2\pi \times 1.37\,\mathrm{kHz}$
- Measure density with absorption imaging.
  - Arbitrary 1D potential using Digital Micromirror Device.



Relaxation Dynamics

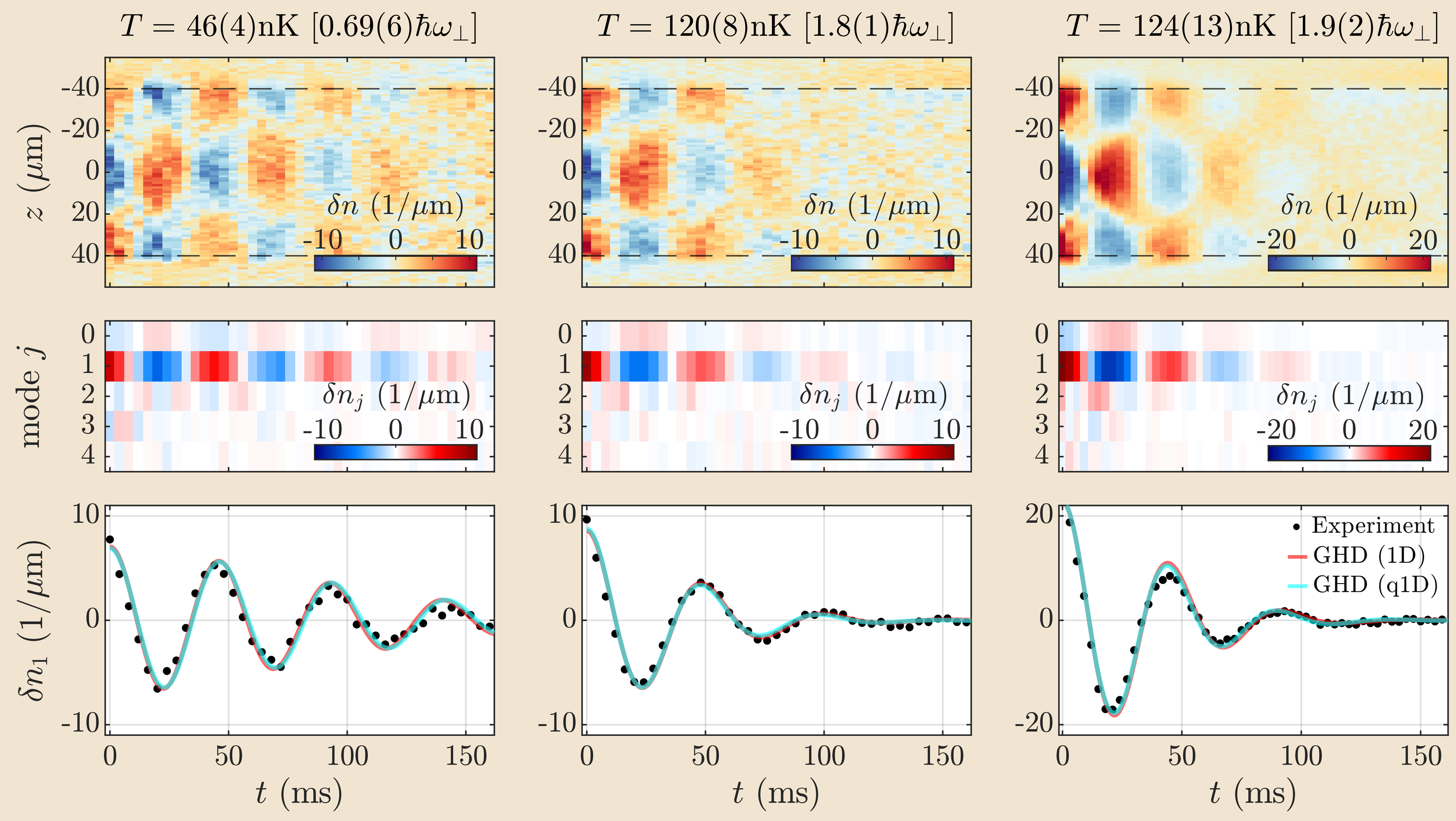


Quench protocol:

1. Imprint desity perturbation in the shape of a cosine mode.
2. Instigate dynamics by quenching to a flat box.

$$\delta n(z,t) = n(z,t) - \langle n(z,t) \rangle_t$$

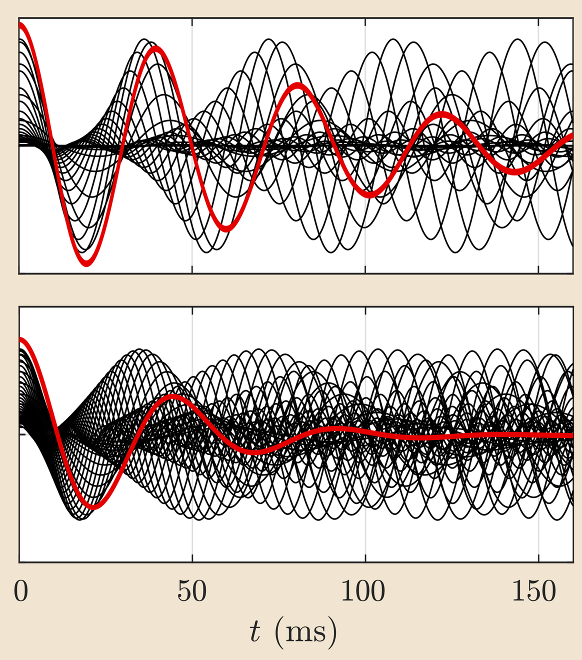
$$\delta n(z,t) = \sum_{j=0}^{\infty} \delta n_j(t) \cos(k_j z)$$



Dynamics are very accurately described by the (1D) integrable GHD.

The observed relaxation can therefore not be caused by thermalization.

Instead the relaxation of the density mode is via dephasing of its rapidities.

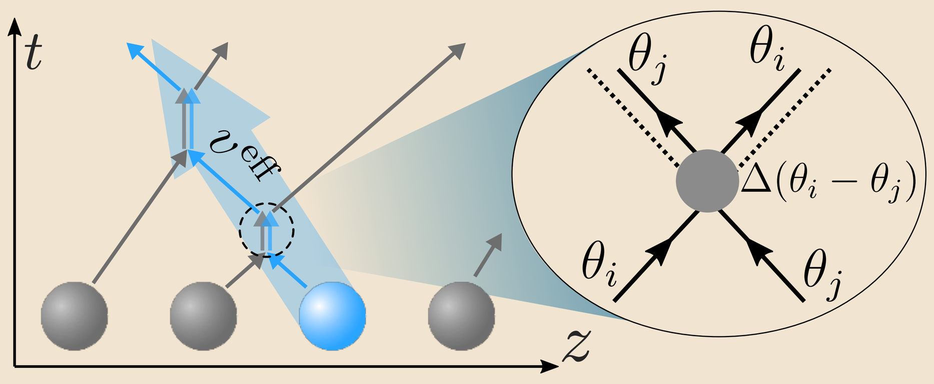


Emergence of Hydrodynamics (GHD)

1D Bose gas with contact interactions

$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{N} \partial_{z_i}^2 + g \sum_{i<j} \delta(z_i - z_j)$$

→ Thermodynamic macrostate fully determined by distribution of fermionic quasi-particles $\rho(\theta)$.



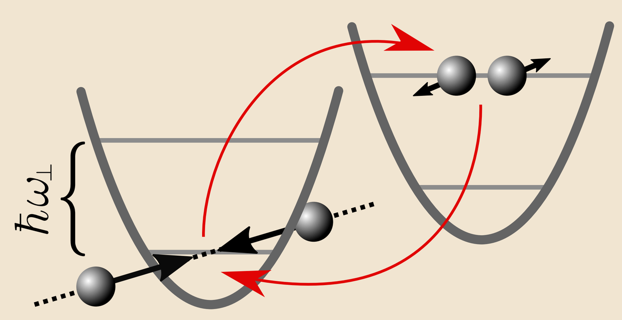
The sum of many microscopic interactions result in an effective propagation velocity for a quasi-particle with momentum θ.

$$v^{\mathrm{eff}}(\theta) = \frac{\hbar\theta}{m} - \frac{1}{2\pi}\int_{-\infty}^{\infty} d\theta'\, \Delta(\theta - \theta')\rho(\theta')\left[v^{\mathrm{eff}}(\theta') - v^{\mathrm{eff}}(\theta)\right]$$

Large-scale dynamics described by "simple" hydrodynamic evolution of the quasi-particles!

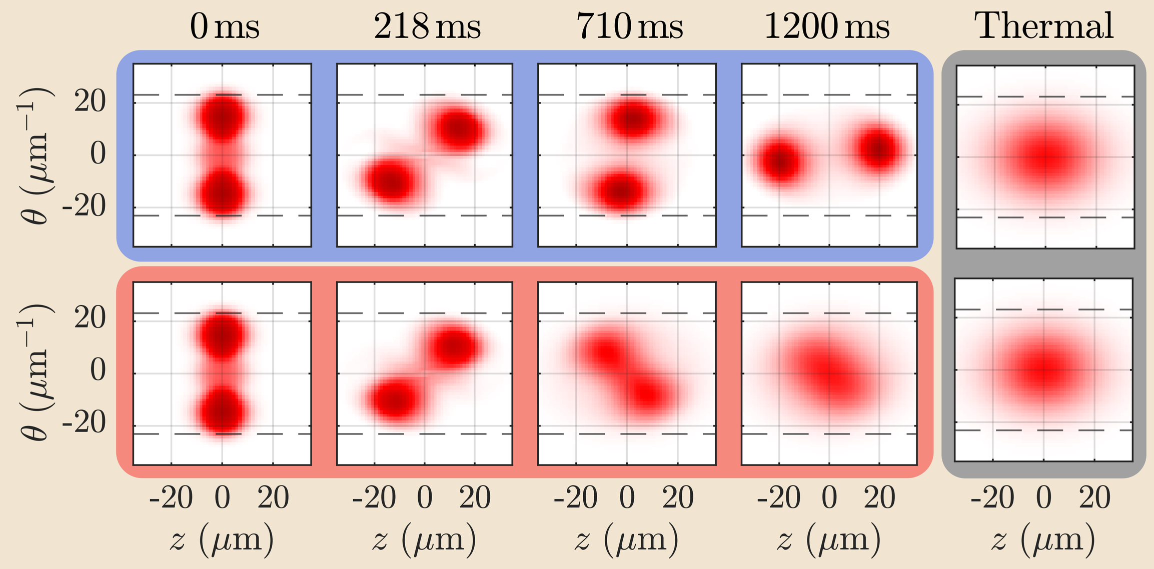
$$\partial_t \rho + \partial_z \left(v^{\mathrm{eff}} \rho\right) = \begin{cases} 0, & \text{1D (integrable)} \\ \mathcal{I}, & \text{quasi-1D} \end{cases}$$

Dimensional Crossover



$\mu,\, k_B T \ll \hbar\omega_\perp$ (standard 1D condition)

High energy collisions can excite atoms in the transverse confinement. This breaks integrability.



Example:

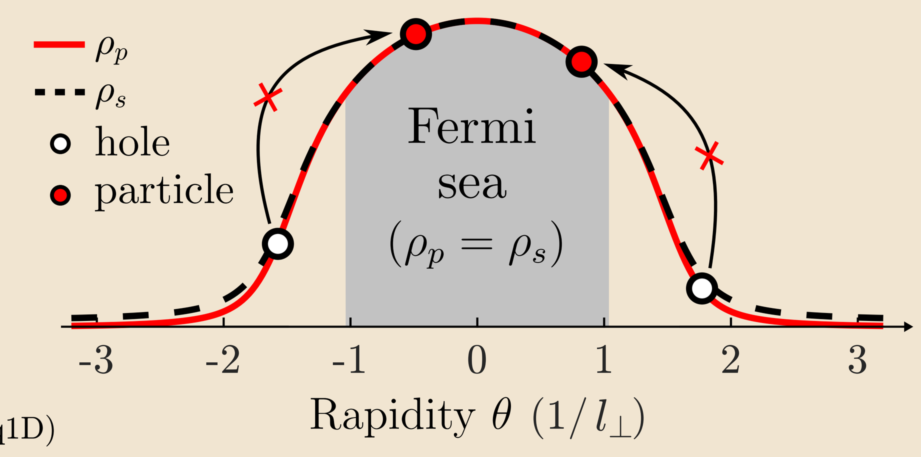
Evolution of ρ for 1D vs quasi-1D dynamics in quantum Newton's cradle.

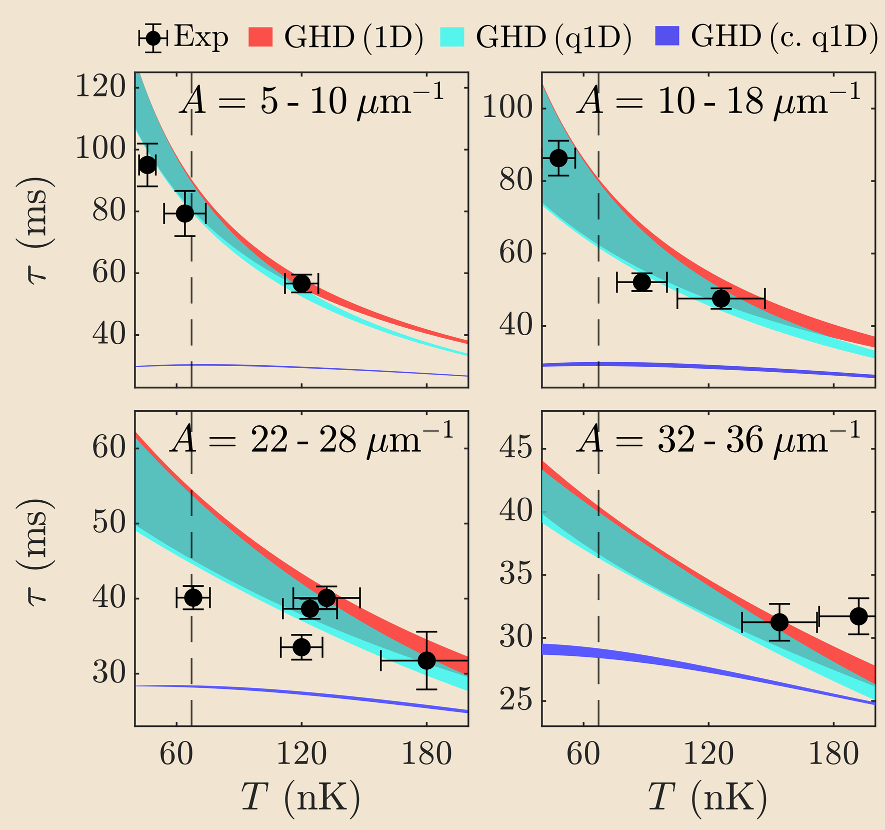
Transverse excitations break integrability and cause thermalization!

Pauli Blocking of Transverse Excitations

Near the ground state, or at high chemical potential, all states at low rapidity are fully occupied.

The fermionic statistics suppress the transverse excitations!





Extract relaxation time-scale for various quench amplitudes and temperatures.

$$\delta n_1(t) \sim A \exp\left(-(t/\tau)^{3/2}\right)\cos(\omega t)$$

Almost no difference between 1D and quasi-1D even at tempereature 3x the conventional limit for 1D !

Neglecting Fermi sea leads to rapid relaxation through thermalization.

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