Emergence of Hydrodynamics in Few Particle Systems

C. Heintze, S. Brandstetter, P. Lunt, K. Subramanian,
M. Holten and S. Jochim

Physikalisches Institut, Universität Heidelberg

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

ISOQUANT SFB1225

PHYSIKALISCHES INSTITUT

Center for Quantum Dynamics

Mesoscopic Fermi Gas

Fermionic Quantum Gases

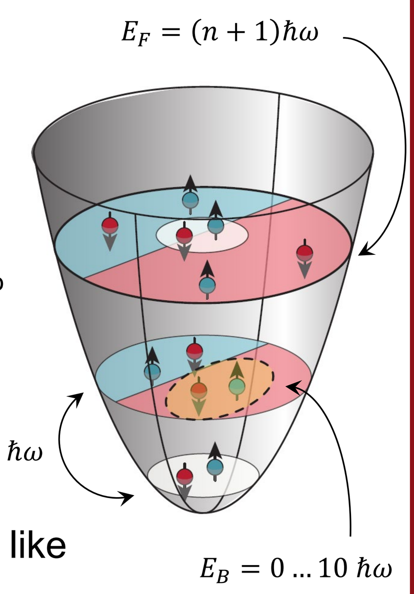
- Fermionic particles interacting via contact interactions

$$H = -\sum_i \frac{\hbar^2}{2m} + \sum_{i<j} g_0 \delta^2(r_i - r_j) + V_{ext}$$

- **Here:** Particles confined in external **harmonic** potential in **D=2.**

Energy Scales

- Attractive interactions characterized by binding energy E_B
- E_B competes with shell-structure E_{ho} and Fermi energy E_F



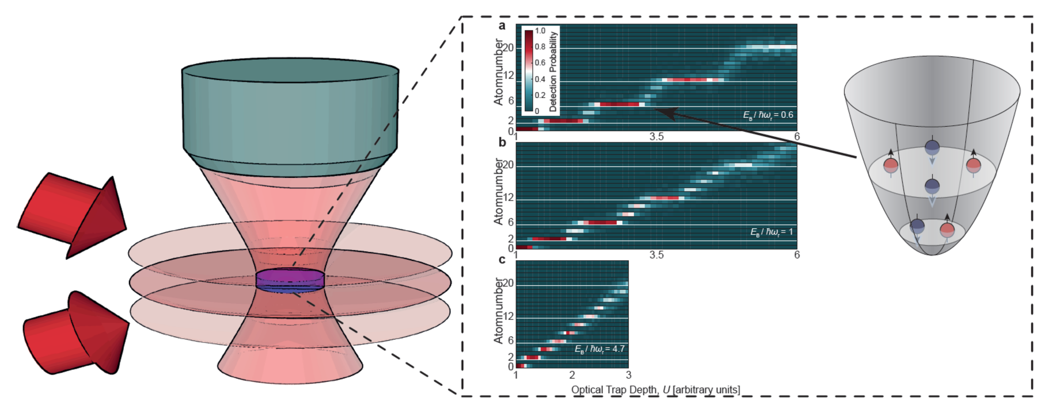
Few to Many

- How many particles are needed to observe collective effects like hydrodynamics?
- What are the few-body precursors of the phase transitions?

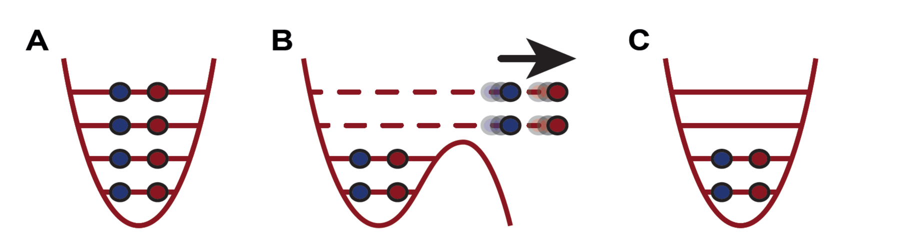
Few body

Deterministic Preparation

- Superposition of "pancake" trap and optical tweezer



- **Deterministic preparation** of ground states with a given atomnumber via spilling procedure

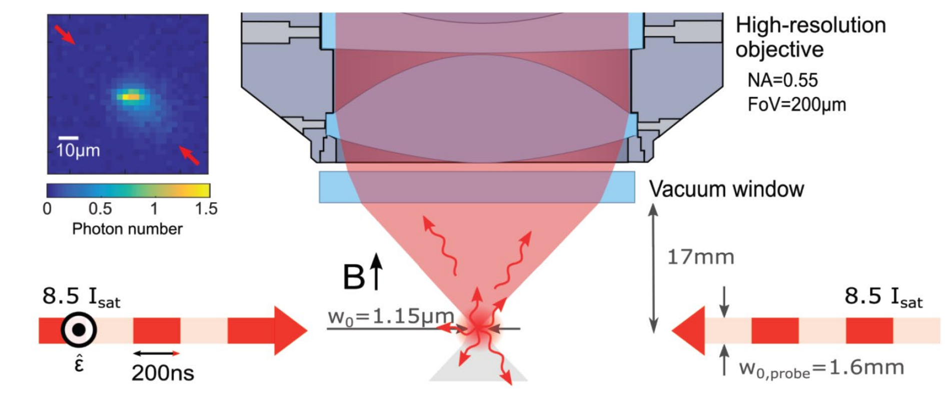


- **Tunable aspect ratio** from 1D ($\omega_z \ll \omega_r$) to 2D ($\omega_z \gg \omega_r$)
- **In 2D harmonic trap** closed shells with 2, 6, 12, … atoms

F.Serwane *et al.* Science **15**, 6027 (2011)
Bayha et al. Nature **587**, 583-587 (2020)

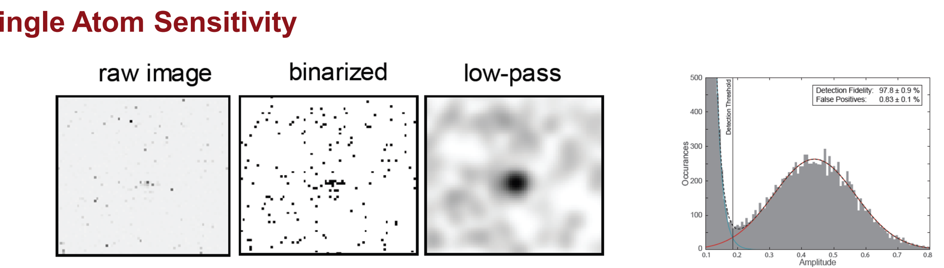
Imaging

Free-space fluorescence imaging



- Random walk of atoms due to photon recoil
  - Limit to ~ 300 photons / atom
  - Around 20 photons / atom on EMCCD
- No cooling scheme required
- Works in free space

Single Atom Sensitivity



- Detection fidelity ≥ 97%
- Resolution 4.0 μm

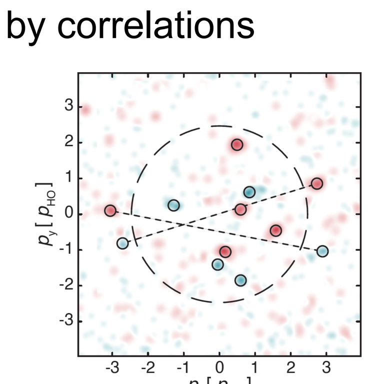
Bergschneider, Klinkhammer et al. PRA **97** (2018), 063613

Pairing correlations

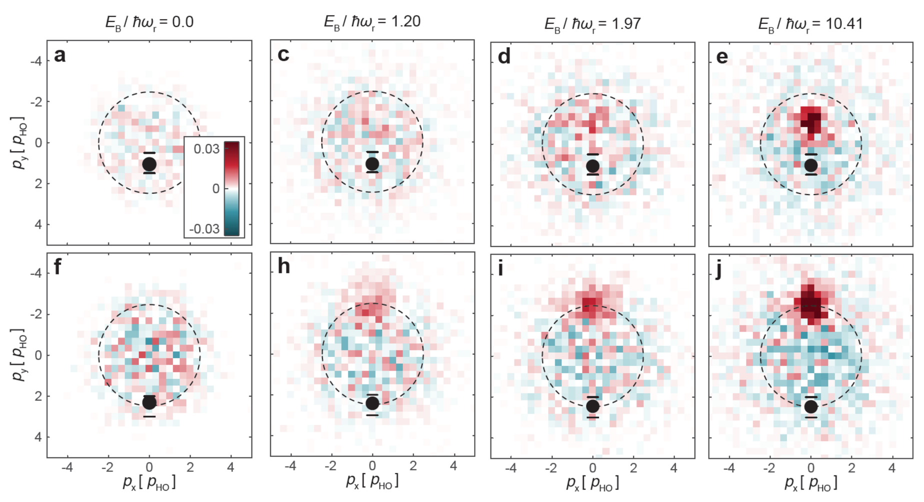
Fermionic Quantum Gases

- Quantum state can be characterized by correlations functions
- Natural choice for two component Fermi gas is the opposite spin density-density correlator:

$$C^{(2)}(\mathbf{p}_\uparrow, \mathbf{p}_\downarrow) = \langle n_\uparrow(\mathbf{p}_\uparrow) n_\downarrow(\mathbf{p}_\downarrow)\rangle - \langle n_\uparrow(\mathbf{p}_\uparrow)\rangle\langle n_\downarrow(\mathbf{p}_\downarrow)\rangle$$

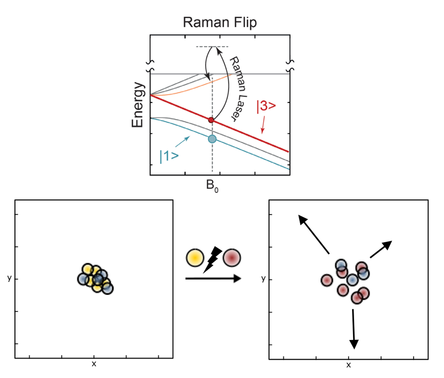


- **Cooper Pairing:** Find **strong correlations** between spin up and and down particles located at the **Fermi surface** in momentum space



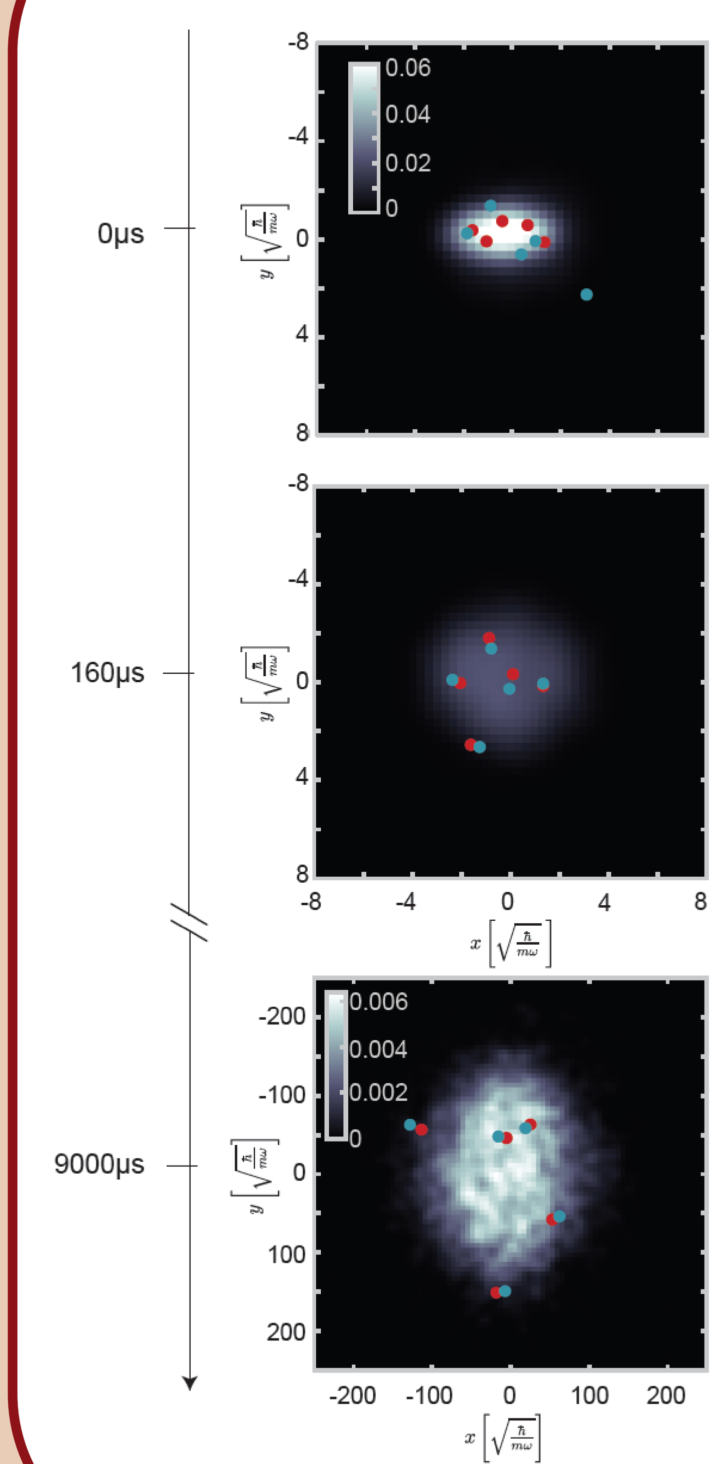
Quench interactions

- Flip state |3> to state |4>
- 2 photon Raman transition ~ 300ns



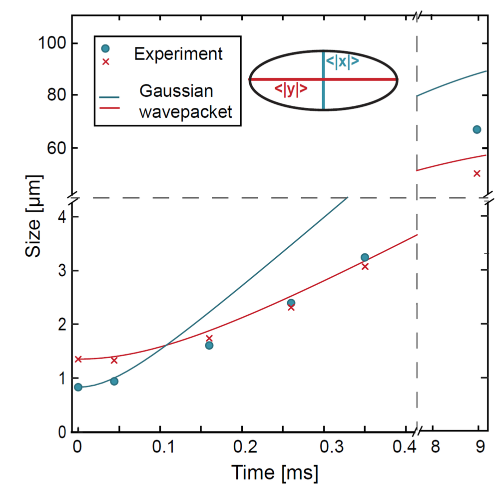
Holten et al. Nature **606**, 287-291 (2022)

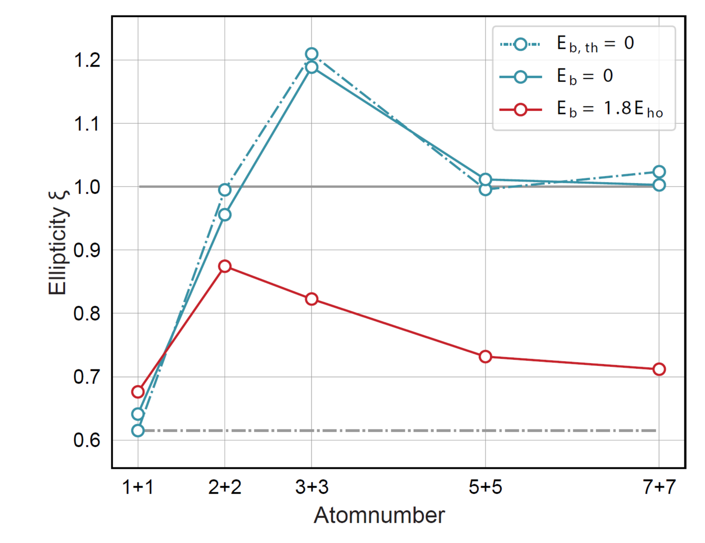
Hydrodynamics



Emergence of Hydrodynamics

- How many particles make a fluid?
- Do phase transitions in the initial system manifest in the expansion?
- Is the hydrodynamic behaviour linked to the formation of pairs?



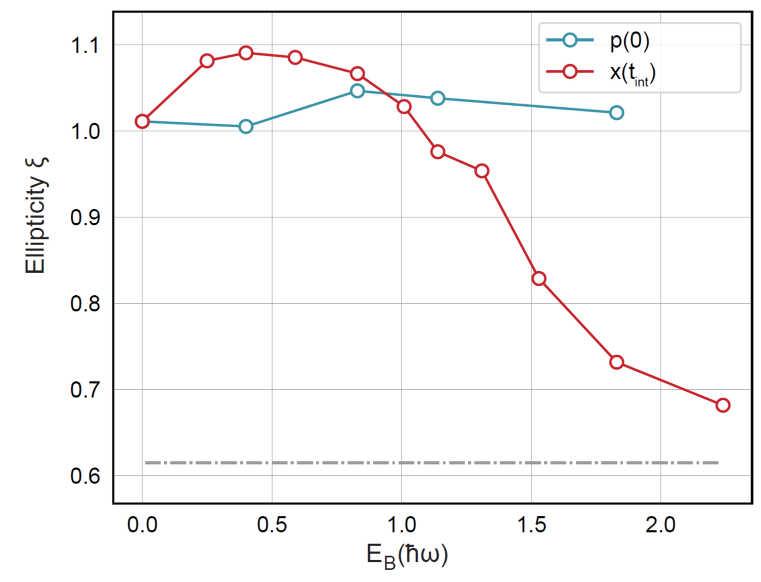


$E_B = 0.85\,\hbar\omega$, $l = 2.75\mu m$, $\sigma = 0.26\,\mu m$

$E_B = 2.28\,\hbar\omega$, $l = 0.9\,\mu m$, $\sigma = 0.8\,\mu m$

Measurement

- Prepare interacting particles in the harmonic oscillator ground state, finite ellipticity
- Switch off initial trap
- Interacting expansion
- Single atom and spin resolved imaging
  - ➢ momentum or position measurement of the particles at different times



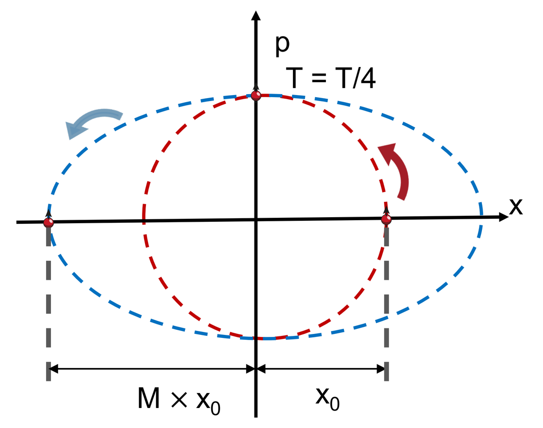
Real Space Imaging

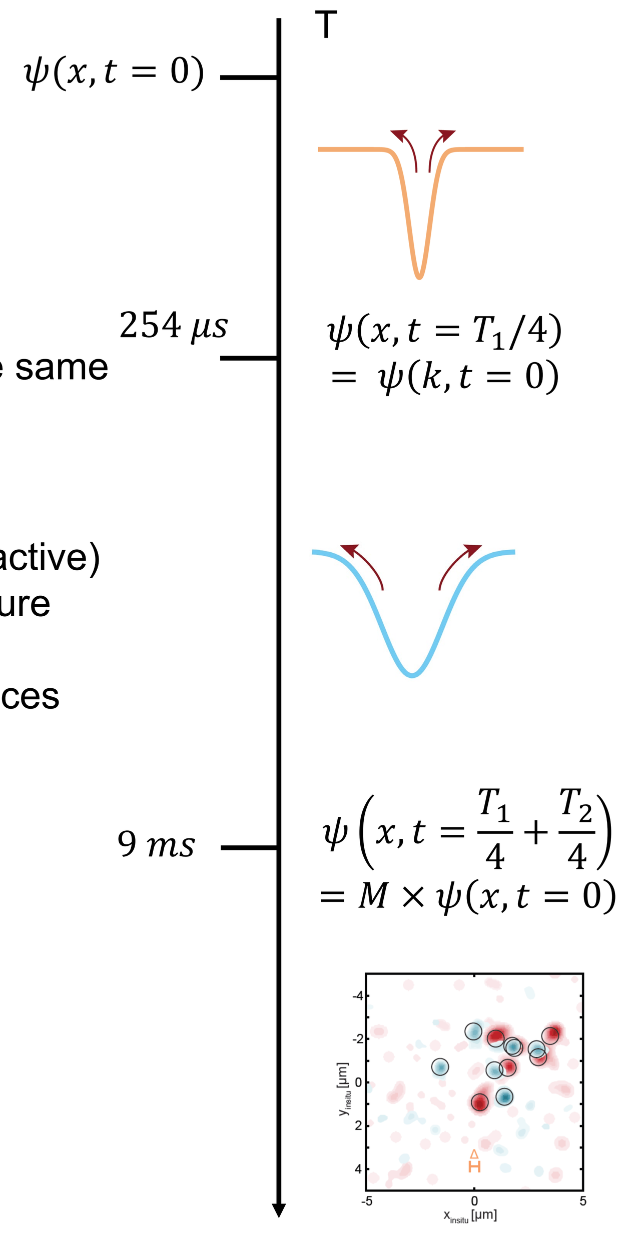
Why do we need a Matterwave Microscope?

- System size ~ 1μm
- Pair size Δ ~ 500 nm
- Imaging resolution ~ 4 μm
- Optical resolution ~ 1 μm
- Resolution of particles with the same spin ~ 10 μm

Setup

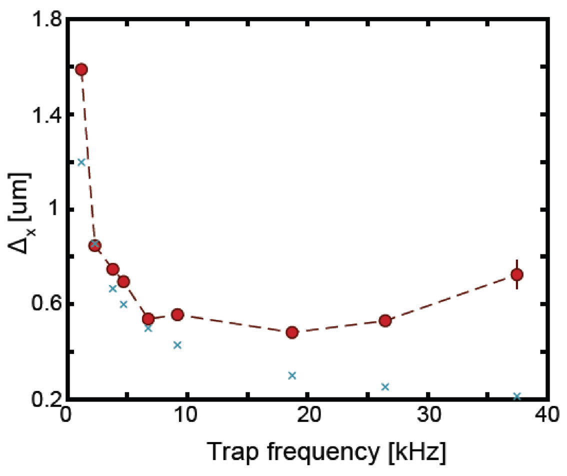
- Additional optical trap (1W, attractive)
- Deviation from harmonic curvature causes aberrations
- Large beam width (40 μm) reduces the problem





Characterization

- Magnification (30 - 65)
- Magnify test target (2 non-interacting particles in harmonic trap)
  - ➢ Tune trap frequency/size
- Resolution limit 500 nm



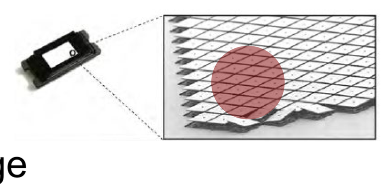
- Check field of view:
  - Create tightly bound pairs in a shallow trap
  - Does the pairsize depend on the position?

Murthy et al. Arxiv Preprint (2019). arXiv:2104.10089
Murthy et al. Phys. Rev. A **90** (2014), 043611
Weitenberg et al. Nature **599**, 571-575 (2021)

Box potentials

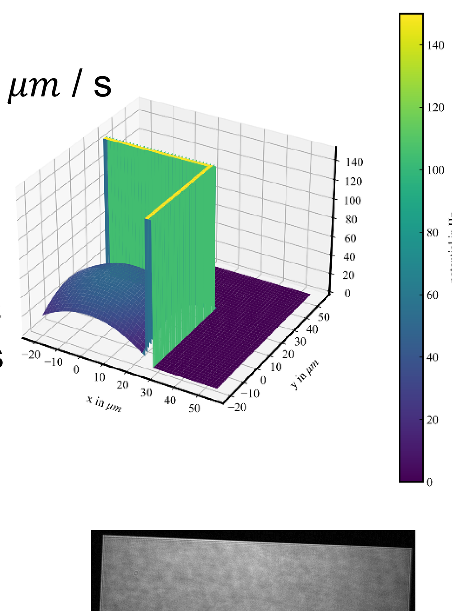
Digital Micromirror Device

- 1920 x 1080 mirrors, 10.8 μm each ~ 2 cm x 1.3 cm → 150 μm x 150 μm, demagnification ~ x 83

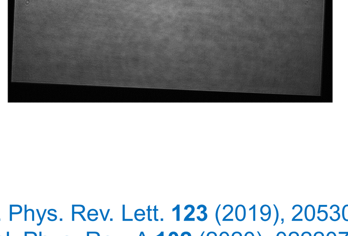


- Optical resolution ~ 1 μm, dynamical range ~ 50
- Pattern rate 16 kHz ~ 0.17 μm / s – 1 μm / s

Box potentials and finite reservoirs



- Binary and grey scaled potentials
  →Flatten harmonic confining beams
  →Imprint repulsive potential barriers
- Dynamic excitations (stirring, moving barriers)
- Measure transport phenomena and correlations
- Bulk properties in flat box potentials



Enss et al. Phys. Rev. Lett. **123** (2019), 205301
Amato et al. Phys. Rev. A **102** (2020), 022207