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Counterflow of impurities in harmonically confined optical lattices

Phys. Rev. Lett. 135, 023404 (2025)

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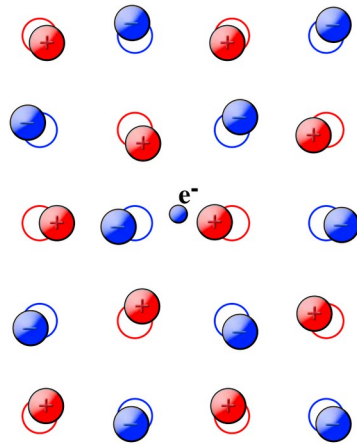
QUOST IX, Valparaíso, 7 November 2025

Collaborators

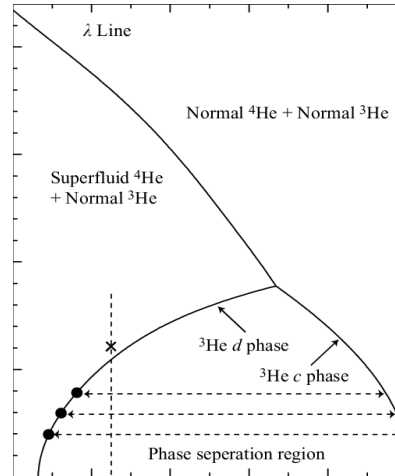
A. Rojo-Francàs, B. Juliá-Díaz
Universitat de Barcelona
L. Morales-Molina
PUC Chile

Impurities

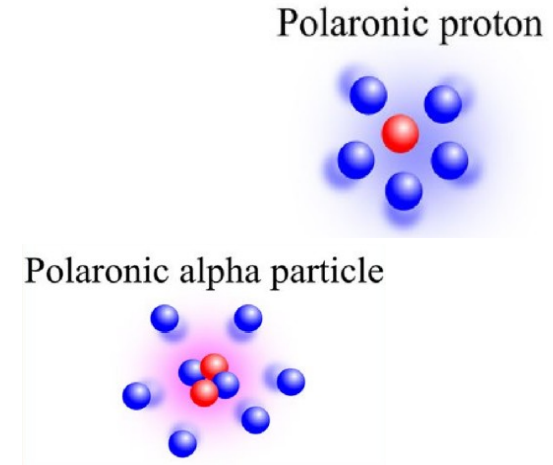
- The study of **impurities** immersed in a **quantum medium** has a **long history** and is **relevant** in **many fields** of physics.



Electrons in an ionic crystal
L. Landau and S. Pekar, Zh. Eksp. Teor.
Fiz 18, 419 (1948).



^3He impurities in ^4He
G. Baym and C. Pethick, "Landau Fermi-Liquid Theory:
Concepts and Application" (1991).



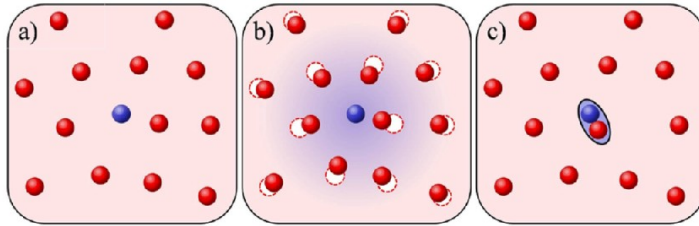
Impurities in nuclear systems
Tajima et al., AAPPS Bulletin, 34, 9 (2024).

Impurities in ultracold atomic gases

- The **study of impurities** has been **revitalised** thanks to their **experimental realisation in ultracold atomic mixtures** with a **high population imbalance**.

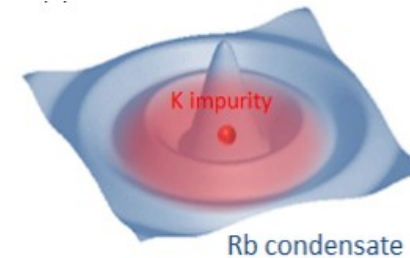
F. Grusdt *et al.* Rep. Prog. Phys. **88**, 066401 (2025). P. Massignan *et al.*, arXiv:2501.09618 (2025).

Fermi polaron



A. Schirotzek *et al.*, PRL **102**, 230402 (2009).

Bose polaron



M.-G. Hu *et al.*, PRL **117**, 055301 (2016).

- **Ultracold atoms** offer a high level of **controllability**, making them an **ideal platform** for studying **impurities**.

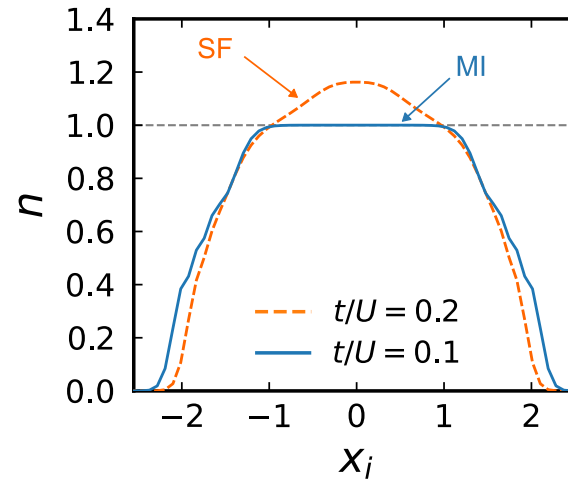
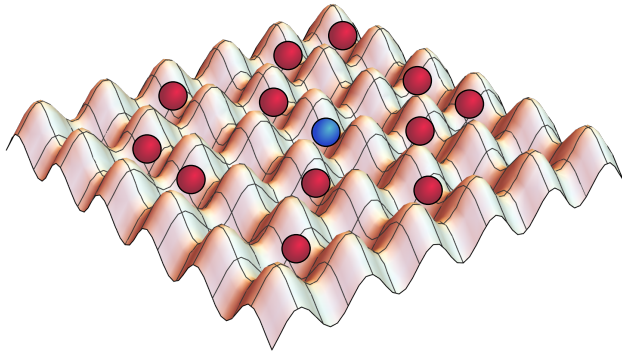
Impurities in optical lattices

- A **rich platform** for **studying** ultracold atomic **impurities** is tight **optical lattices**.

M. Lewenstein *et al.*, *Ultracold Atoms in Optical Lattices: Simulating Quantum Many-Body Systems* (Oxford, 2012).

- Bosons in optical lattices feature a **superfluid-to-Mott insulator** (SF-MI) transition.
- The study of **impurities across** this **SF-MI transition** has attracted increasing attention.

V. E. Colussi, F. Caleffi, C. Menotti, and A. Recati, *Phys. Rev. Lett* **130**, 17, 3002 (2023).

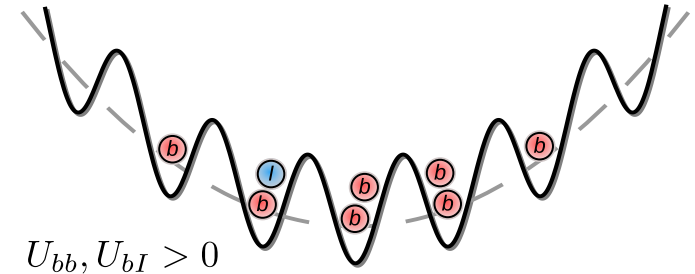


Density profiles of bosons in a one-dimensional optical lattice with harmonic confinement.

Impurities in harmonically confined optical lattices

- We studied a **single impurity** interacting with a **bosonic bath** in a **one-dimensional harmonically confined optical lattice**.

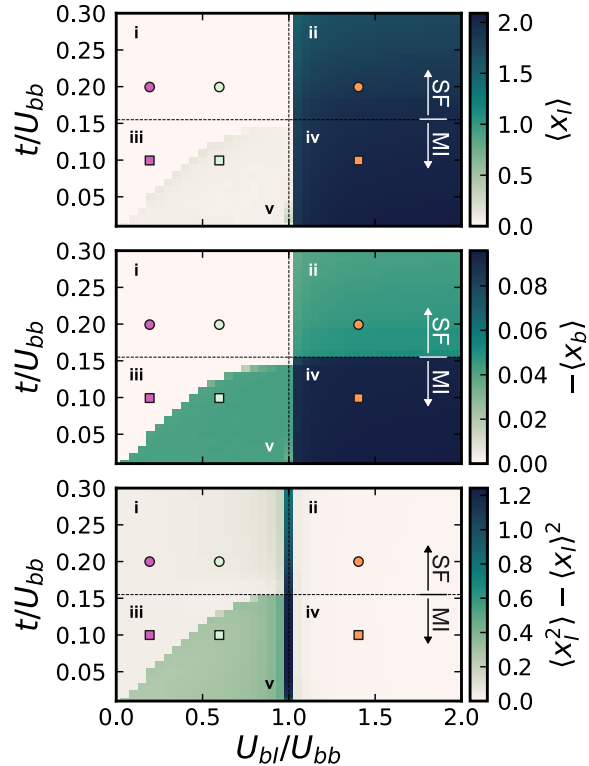
$$\hat{H} = \underbrace{-t \sum_{\sigma=b,I} \sum_i \left(\hat{a}_{i,\sigma}^\dagger \hat{a}_{i+1,\sigma} + \text{h.c.} \right)}_{\text{Tunnelling}} + \underbrace{V_{\text{ho}} \sum_i \sum_{\sigma=b,I} i^2 \hat{n}_{i,\sigma}}_{\text{Harmonic trap}} + \underbrace{\frac{U_{bb}}{2} \sum_i \hat{n}_{i,b} (\hat{n}_{i,b} - 1)}_{\text{Boson-boson repulsion}} + \underbrace{U_{bI} \sum_i \hat{n}_{i,b} \hat{n}_{i,I}}_{\text{Bath-impurity repulsion}}.$$



- We have investigated this system using the **density matrix renormalisation group (DMRG)** for **large lattices** with a **large number of particles**.

S. R. White, Phys. Rev. Lett. **69**, 2863 (1992). U. Schollwöck, Rev. Mod. Phys. **77**, 259 (2005).

Density profiles



Density profiles:

$$n_\sigma(i) = \langle \hat{n}_{i,\sigma} \rangle$$

Average position:

$$\langle x_\sigma \rangle = \frac{1}{N_\sigma} \sum_i x_i n_\sigma(i)$$

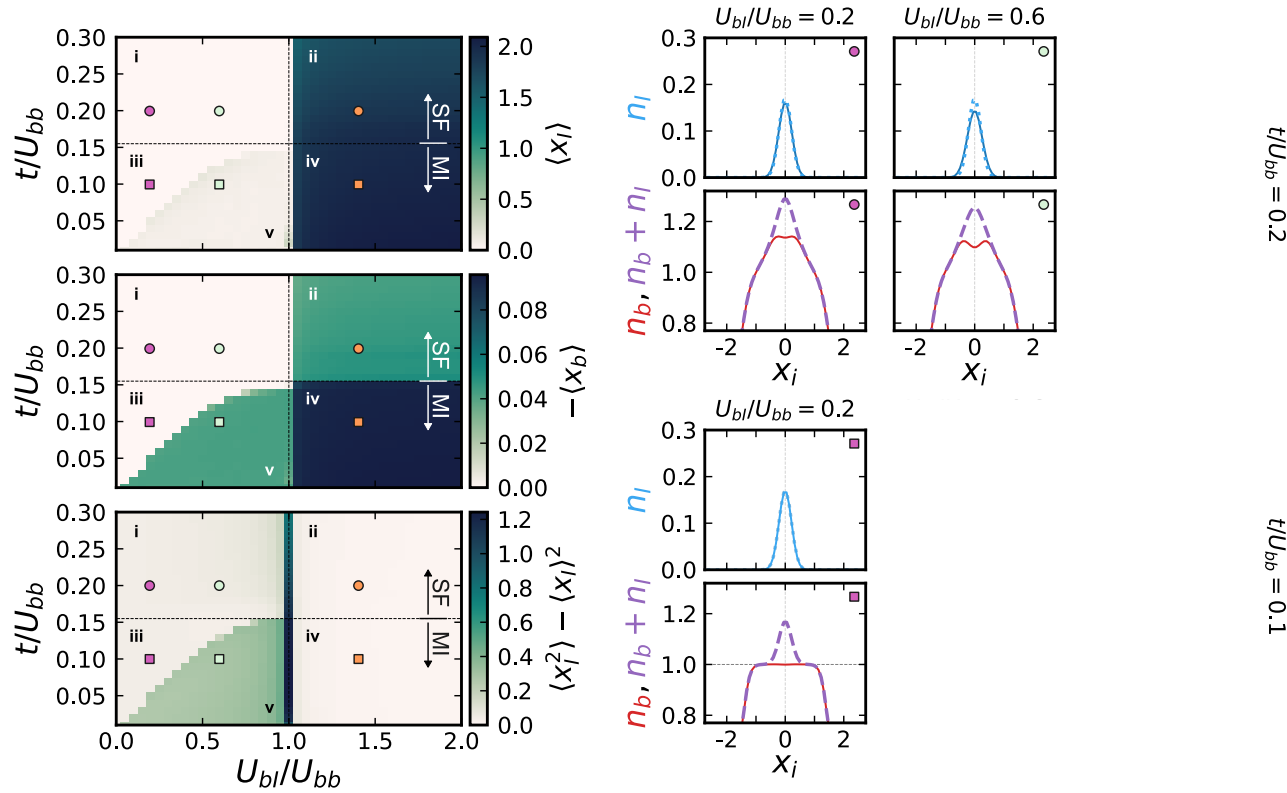
Impurity cloud:

$$\langle x_I^2 \rangle = \frac{1}{N_\sigma} \sum_i x_i^2 n_I(i)$$

$$x_i = i d / \xi, \quad \xi = d \sqrt{t / V_{\text{ho}}}.$$

- The system shows **well-defined phases**.

Density profiles



Density profiles:

$$n_\sigma(i) = \langle \hat{n}_{i,\sigma} \rangle$$

Average position:

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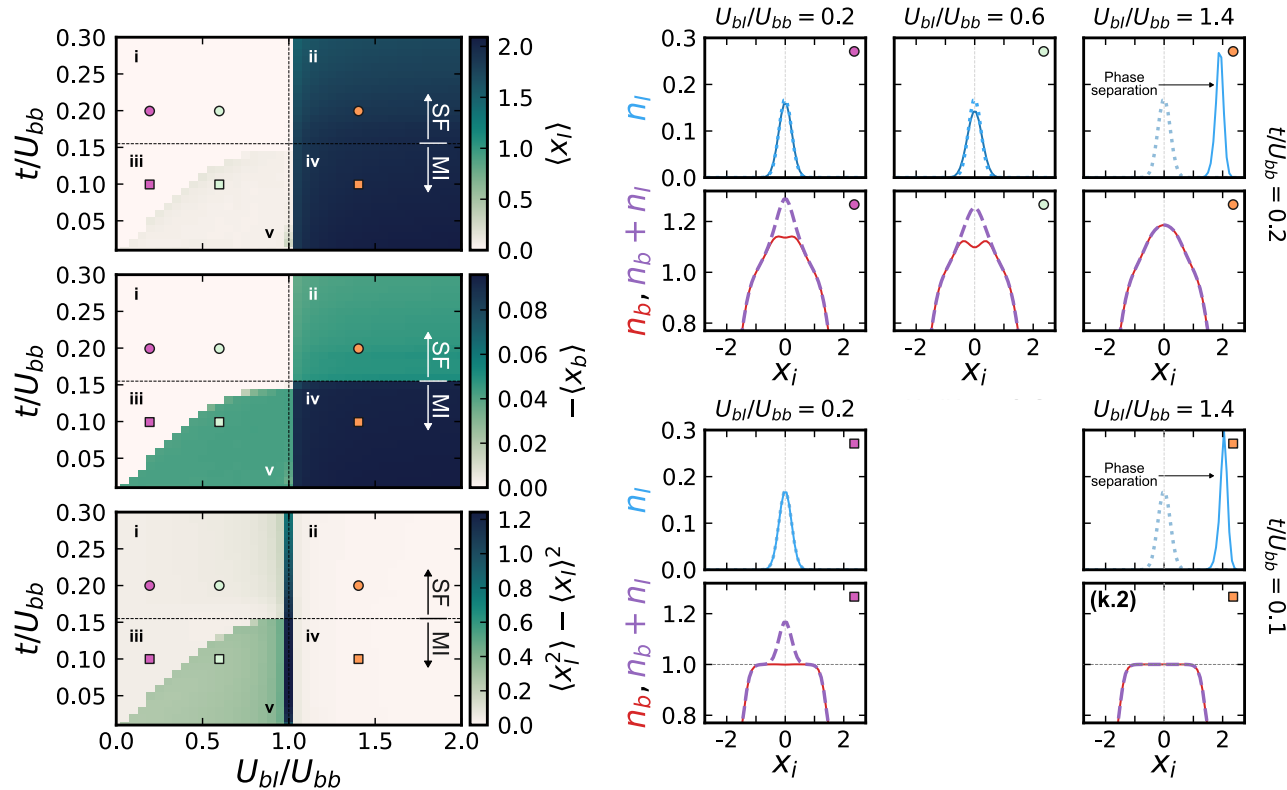
Impurity cloud:

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$$x_i = i d / \xi, \quad \xi = d \sqrt{t / V_{\text{ho}}}.$$

- Regions i and iii are miscible phases.

Density profiles



Density profiles:

$$n_{\sigma}(i) = \langle \hat{n}_{i,\sigma} \rangle$$

Average position:

$$\langle x_{\sigma} \rangle = \frac{1}{N_{\sigma}} \sum_i x_i n_{\sigma}(i)$$

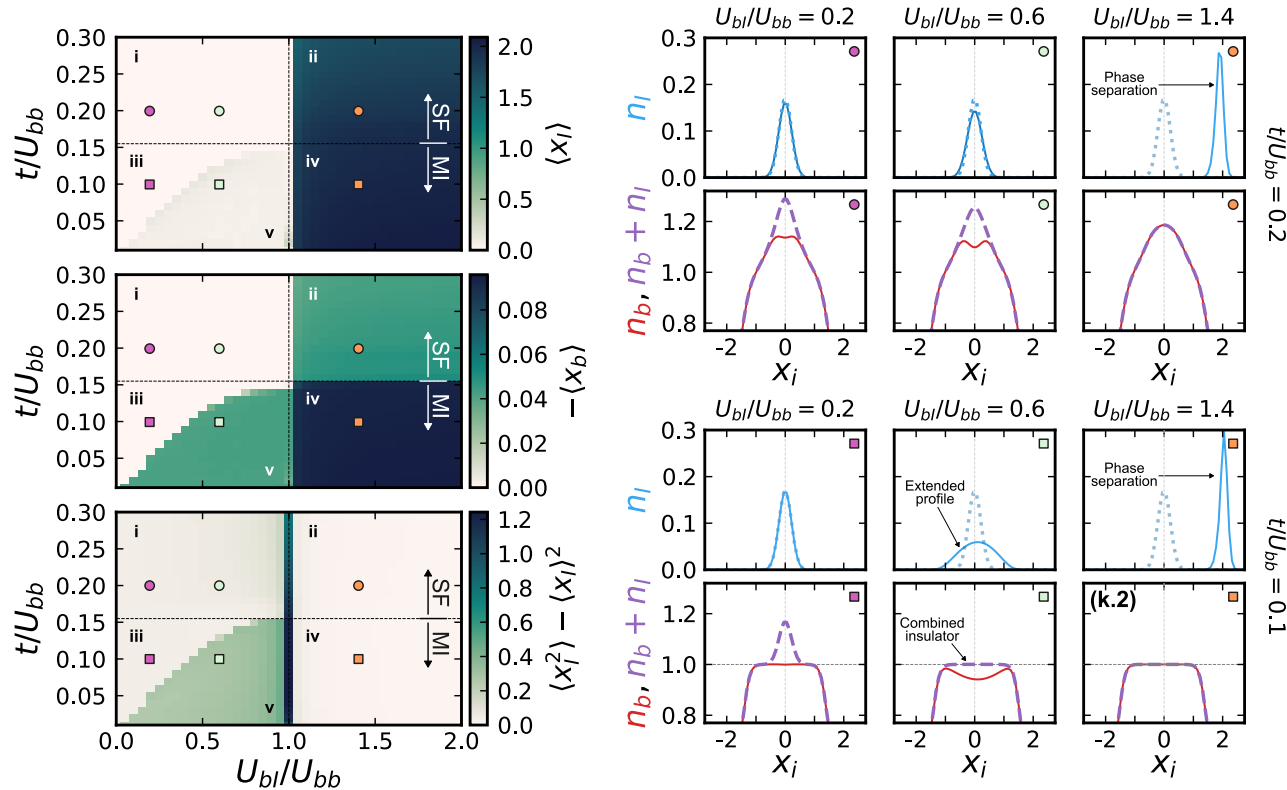
Impurity cloud:

$$\langle x_I^2 \rangle = \frac{1}{N_{\sigma}} \sum_i x_i^2 n_I(i)$$

$$x_i = i d / \xi, \quad \xi = d \sqrt{t / V_{\text{ho}}}.$$

- Regions ii and iv are phase-separated configurations.

Density profiles



Density profiles:

$$n_{\sigma}(i) = \langle \hat{n}_{i,\sigma} \rangle$$

Average position:

$$\langle x_{\sigma} \rangle = \frac{1}{N_{\sigma}} \sum_i x_i n_{\sigma}(i)$$

Impurity cloud:

$$\langle x_I^2 \rangle = \frac{1}{N_{\sigma}} \sum_i x_i^2 n_I(i)$$

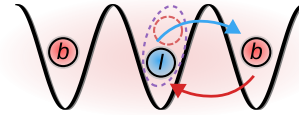
$$x_i = i d / \xi, \quad \xi = d \sqrt{t / V_{\text{ho}}}.$$

- **Region v** is a phase where the **impurity** shows an **extended profile**, and the **combined profile** of bath and impurity displays a domain of **unity filling**.

Counterflow

- The new state corresponds to a **counterflow phase** with **long-range anti-pair order**,

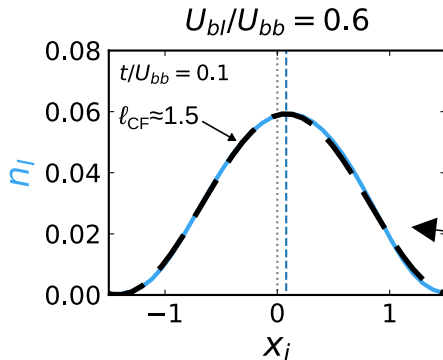
$$\mathcal{C}_{AP} = \langle \hat{a}_{0,I} \hat{a}_{0,b}^\dagger \hat{a}_{i,b}^\dagger \hat{a}_{i,I} \rangle.$$



- Supercounterflows** were realised experimentally very recently with **binary Mott insulators**.

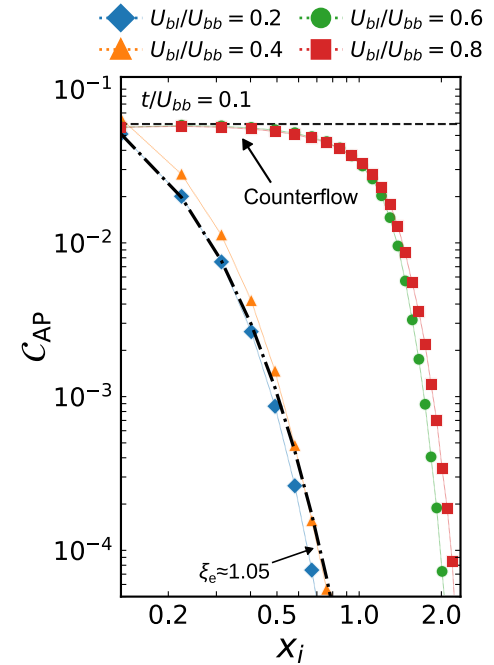
Y.-G. Zheng *et al.*, Nat. Phys. 21, 208 (2025).

- Our results show that **counterflows** appear for a **large population imbalance**.



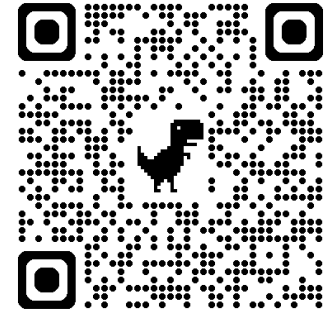
- The counterflow features an **orthogonality catastrophe**.
- The **impurity** behaves as a **free particle** in a **square well**,

$$n_I^{(CF)}(x_i) = n_i^{(0)} \cos^2(\pi(x_i - \langle x_I \rangle)/\ell_{CF}).$$



Conclusions

- An **impurity** can form a non-trivial **counterflow** state with a **bosonic bath** in harmonically confined **optical lattices**.
- This means that **counterflows** form in **mixtures** with **high population imbalances**.
- Future work:
 - Dynamics.
 - Multiple impurities.
 - Bose-Bose and Bose-Fermi mixtures.



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