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# Counterflow of impurities in harmonically confined optical lattices

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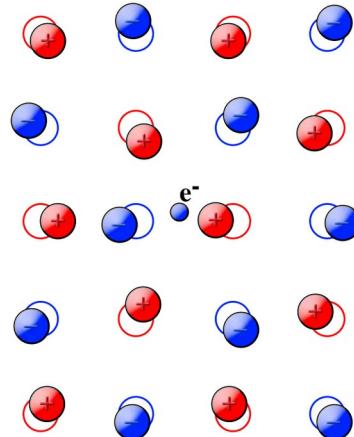
Universitat de Barcelona

L. Morales-Molina

PUC Chile

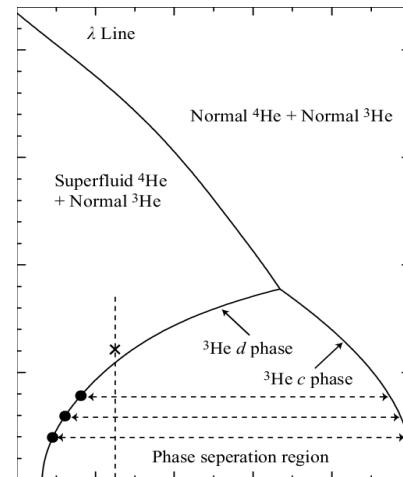
# Impurities

- 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

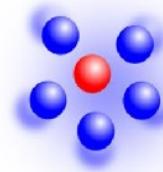
L. Landau and S. Pekar, Zh. Eksp. Teor. Fiz. **18**, 419 (1948).



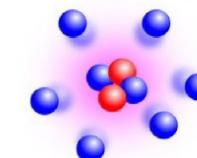
$^3\text{He}$  impurities in  $^4\text{He}$

G. Baym and C. Pethick, "Landau Fermi-Liquid Theory: Concepts and Application" (1991).

Polaronic proton



Polaronic alpha particle



Impurities in nuclear systems

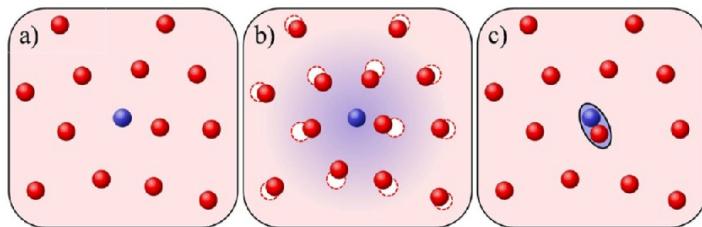
Tajima et al., AAPPS Bulletin, **34**, 9 (2024).

# 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**.

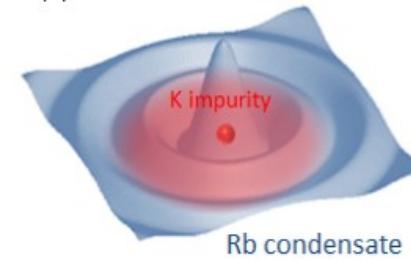
F. Grusdt *et al.* Rep. Prog. Phys. **88**, 066401 (2025). P. Massignan *et al.*, arXiv:2501.09618 (2025).

Fermi polaron



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

Bose polaron



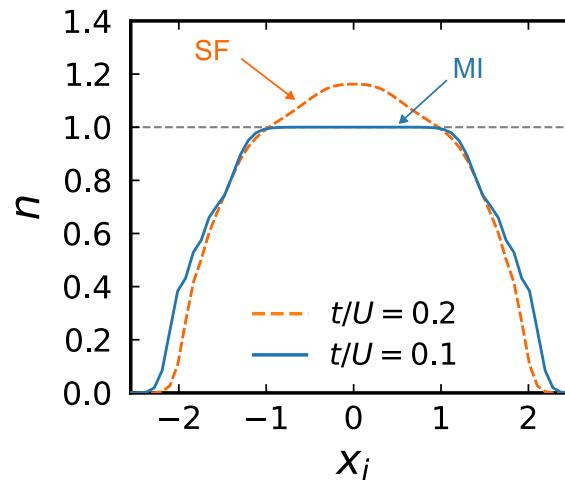
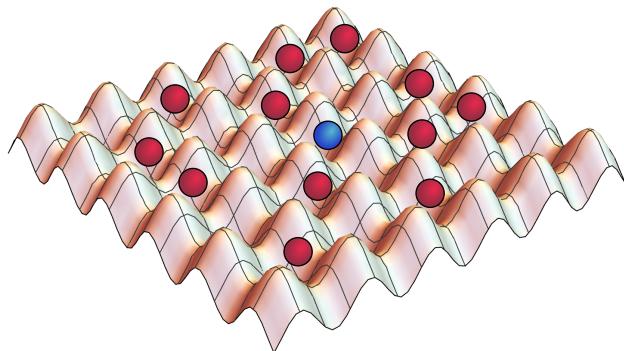
M.-G. Hu *et al.*, PRL **117**, 055301 (2016).

- 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**.

$$\hat{H} = -t \sum_{\sigma=b,I} \sum_i \left( \hat{a}_{i,\sigma}^\dagger \hat{a}_{i+1,\sigma} + \text{h.c.} \right) + V_{\text{ho}} \sum_i \sum_{\sigma=b,I} i^2 \hat{n}_{i,\sigma}$$

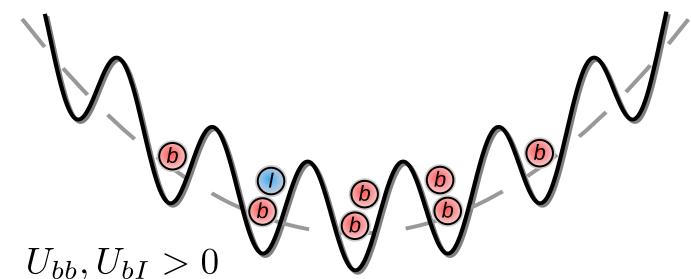
Tunnelling

Harmonic trap

$$+ \frac{U_{bb}}{2} \sum_i \hat{n}_{i,b} (\hat{n}_{i,b} - 1) + U_{bI} \sum_i \hat{n}_{i,b} \hat{n}_{i,I}.$$

Boson-boson repulsion

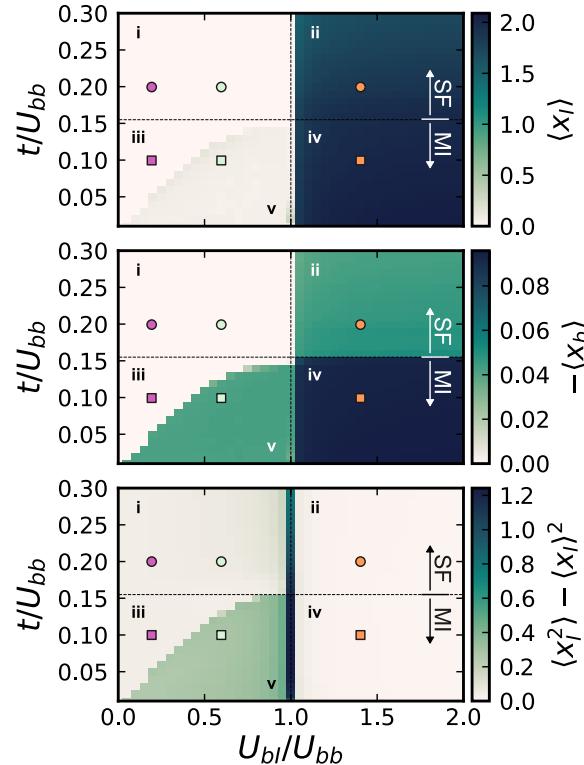
Bath-impurity repulsion



- 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



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

Density profiles:

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

Average position:

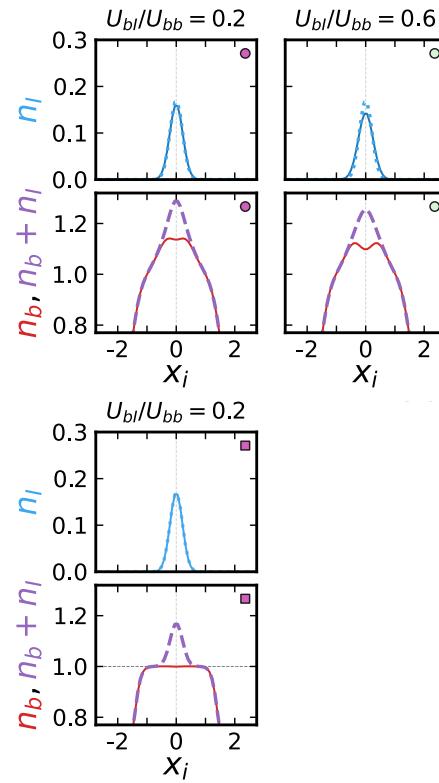
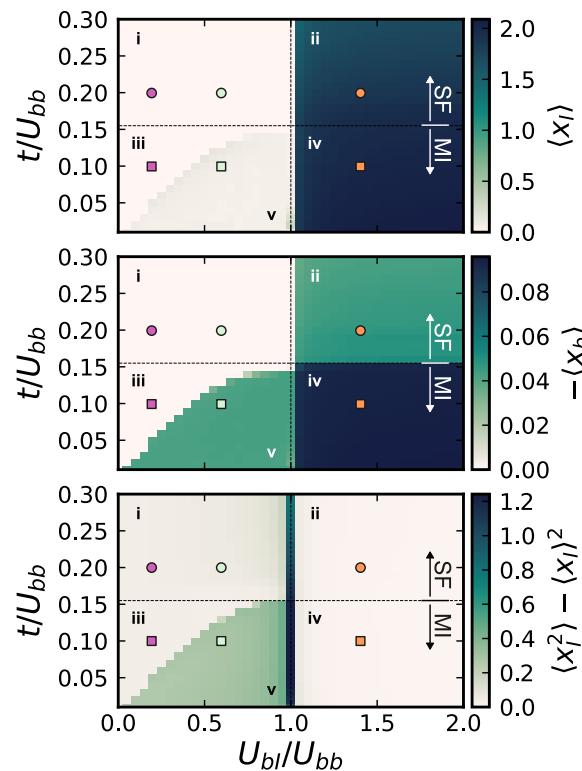
$$\langle x_\sigma \rangle = \frac{1}{N_\sigma} \sum_i x_i n_\sigma(i)$$

Impurity cloud:

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

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

# Density profiles



$t/U_{bb} = 0.2$

$t/U_{bb} = 0.1$

Density profiles:

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

Average position:

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

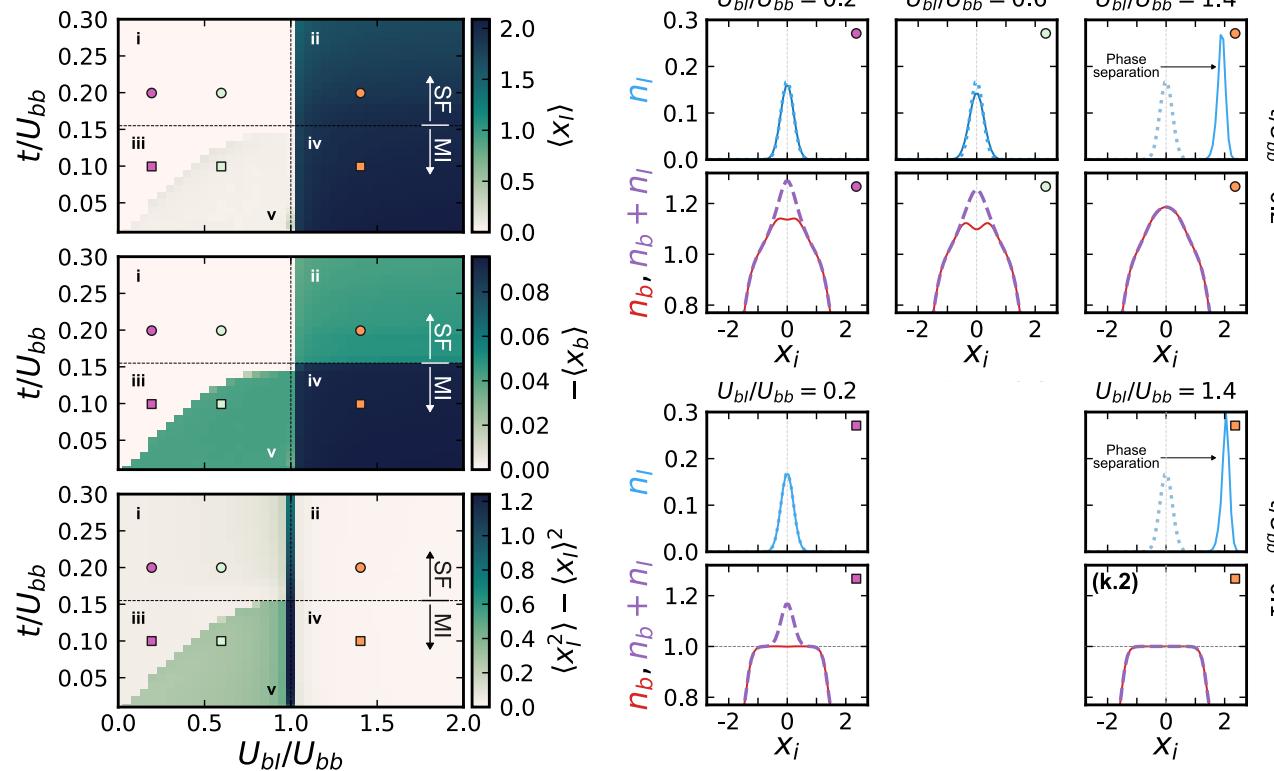
Impurity cloud:

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

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

- Regions i and iii are miscible phases.

# Density profiles



- Regions ii and iv are phase-separated configurations.

Density profiles:

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

Average position:

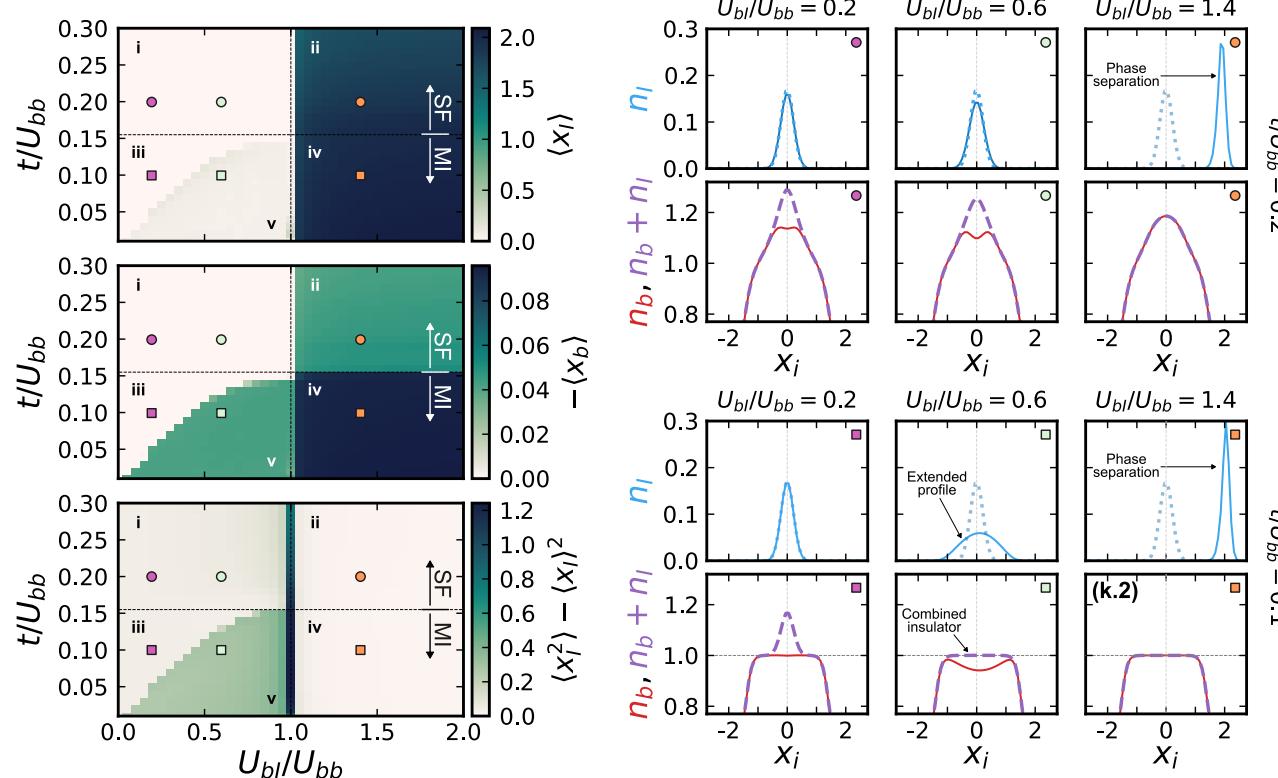
$$\langle x_\sigma \rangle = \frac{1}{N_\sigma} \sum_i x_i n_\sigma(i)$$

Impurity cloud:

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

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

# Density profiles



- 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**.

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:

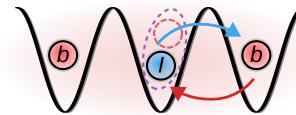
$$\langle x_I^2 \rangle = \frac{1}{N_\sigma} \sum_i x_i^2 n_I(i)$$

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

# Counterflow

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

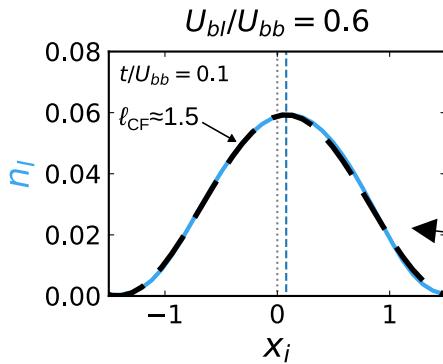
$$\mathcal{C}_{\text{AP}} = \langle \hat{a}_{0,I} \hat{a}_{0,b}^\dagger \hat{a}_{i,b}^\dagger \hat{a}_{i,I} \rangle.$$



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

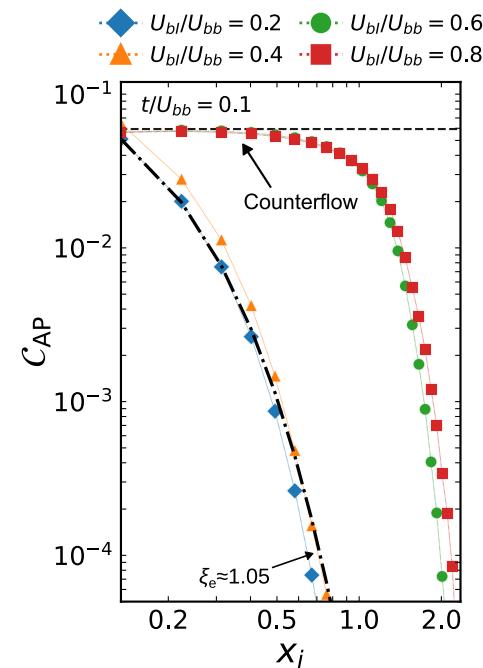
Y.-G. Zheng et al., Nat. Phys. **21**, 208 (2025).

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



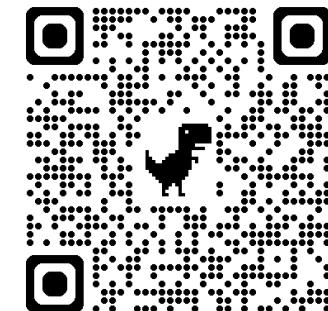
- The counterflow features an **orthogonality catastrophe**.
- The **impurity behaves as a free particle in a square well**,

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



# 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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