Counterflow of impurities in harmonically confined optical lattices

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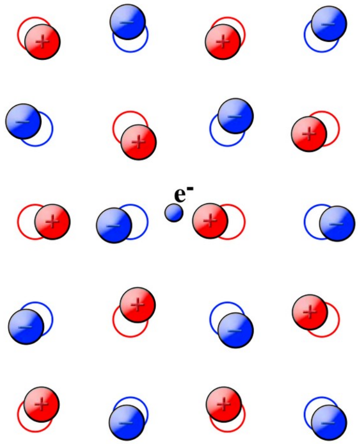
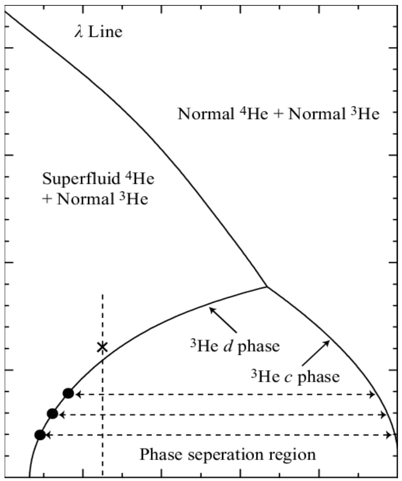
Impurities

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



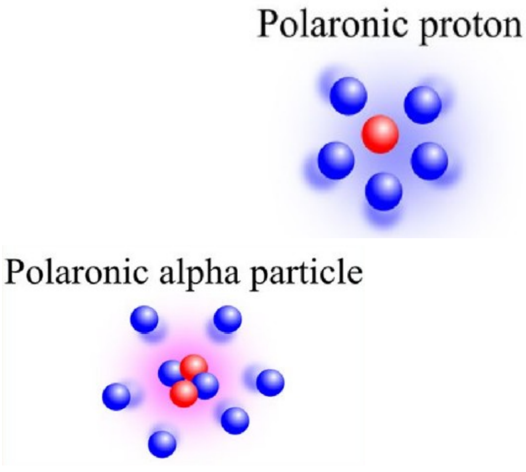
Electrons in an ionic crystal

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



^{3}He impurities in ^{4}He

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



Impurities in nuclear systems

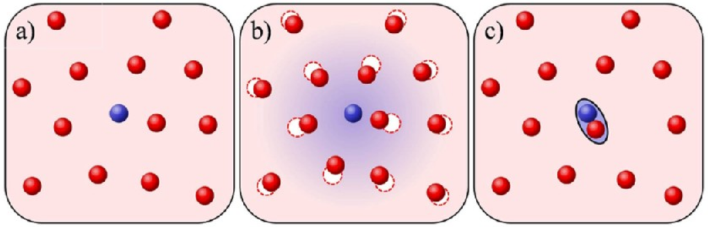
Tajima *et al*., AAPPS Bulletin, **34**, 9 (2024).

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**.

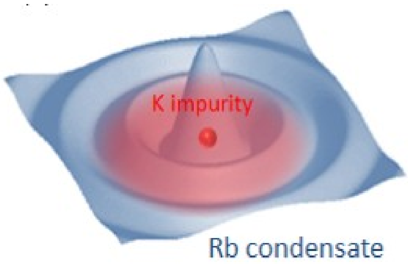
F. Grusdt *et al*. Rep. Prog. Phys. **88**, 066401 (2025). P. Massignan *et al*., arXiv:2501.09618 (2025),

Fermi polaron



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

Bose polaron



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

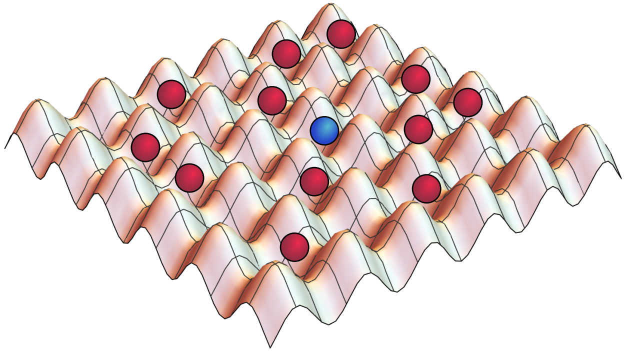
- **Ultracold atoms** offer a high level of **controllability**, making them an **ideal platform** for studying **impurities**.

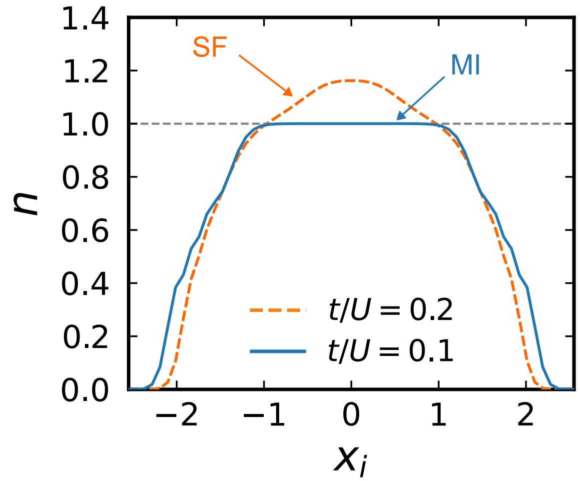
Impurities in optical lattices

- 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).





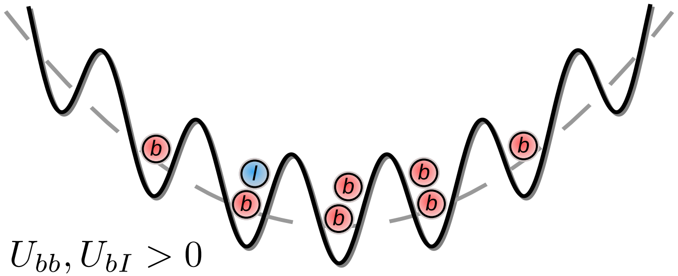
Density profiles of bosons in a one-dimensional optical lattice with harmonic confinement.

Impurities in harmonically confined optical lattices

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

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

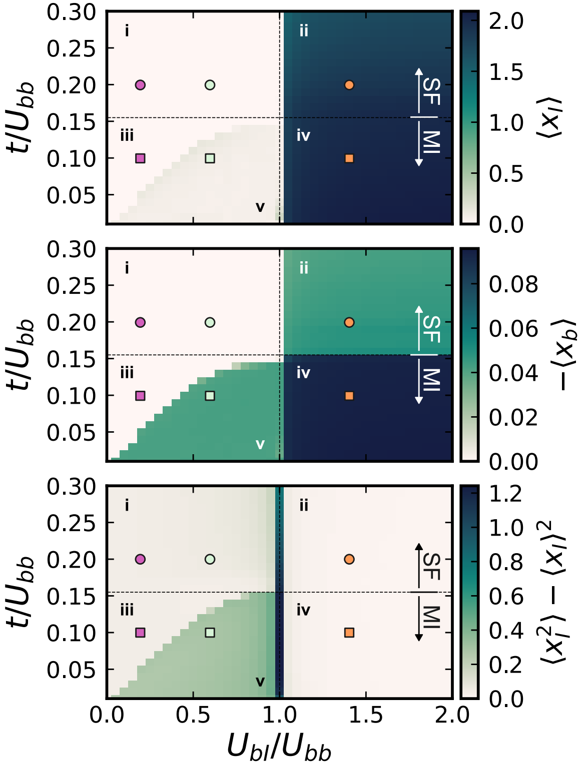
$$+ \underbrace{\frac{U_{bb}}{2} \sum_{i} \hat{n}_{i,b} \left(\hat{n}_{i,b} - 1 \right)}_{\text{Boson-boson repulsion}} + \underbrace{U_{bI} \sum_{i} \hat{n}_{i,b} \hat{n}_{i,I}}_{\text{Bath-impurity repulsion}}.$$



- 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:

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

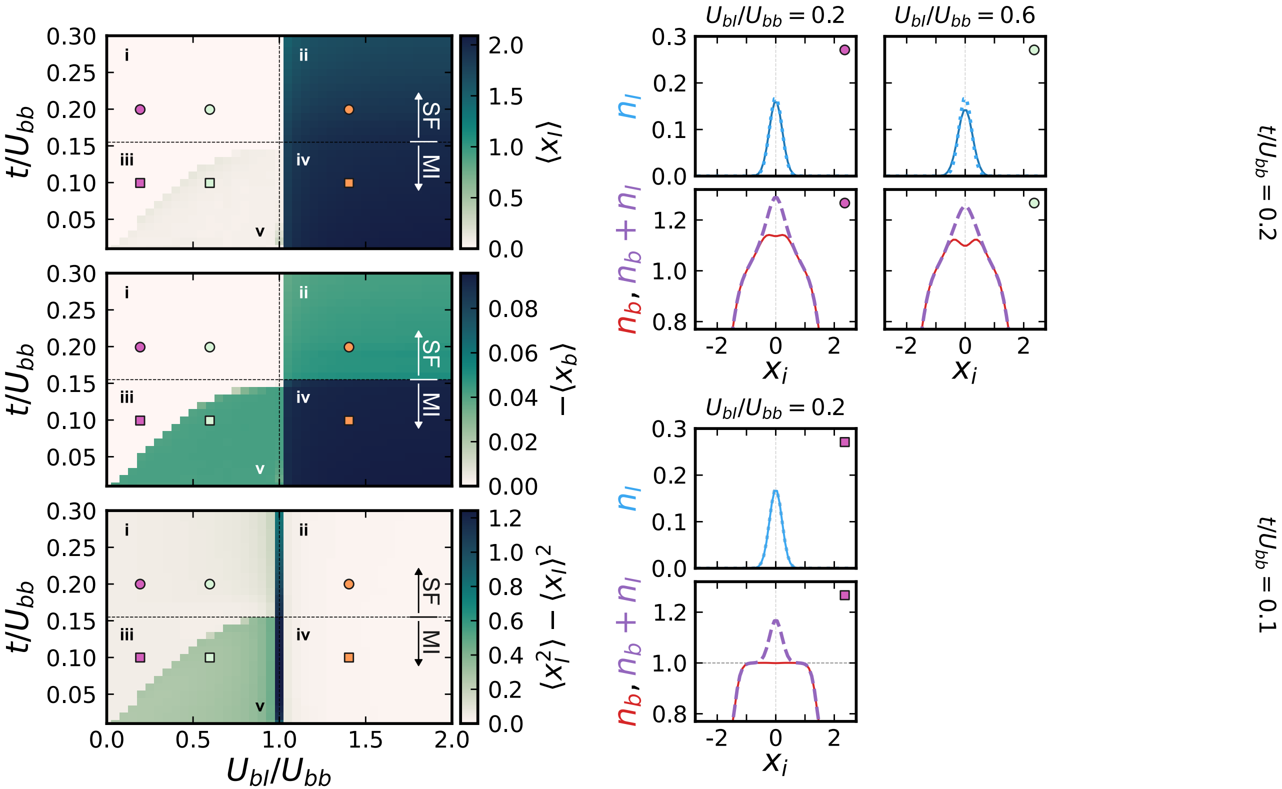
Impurity cloud:

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

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

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

Density profiles



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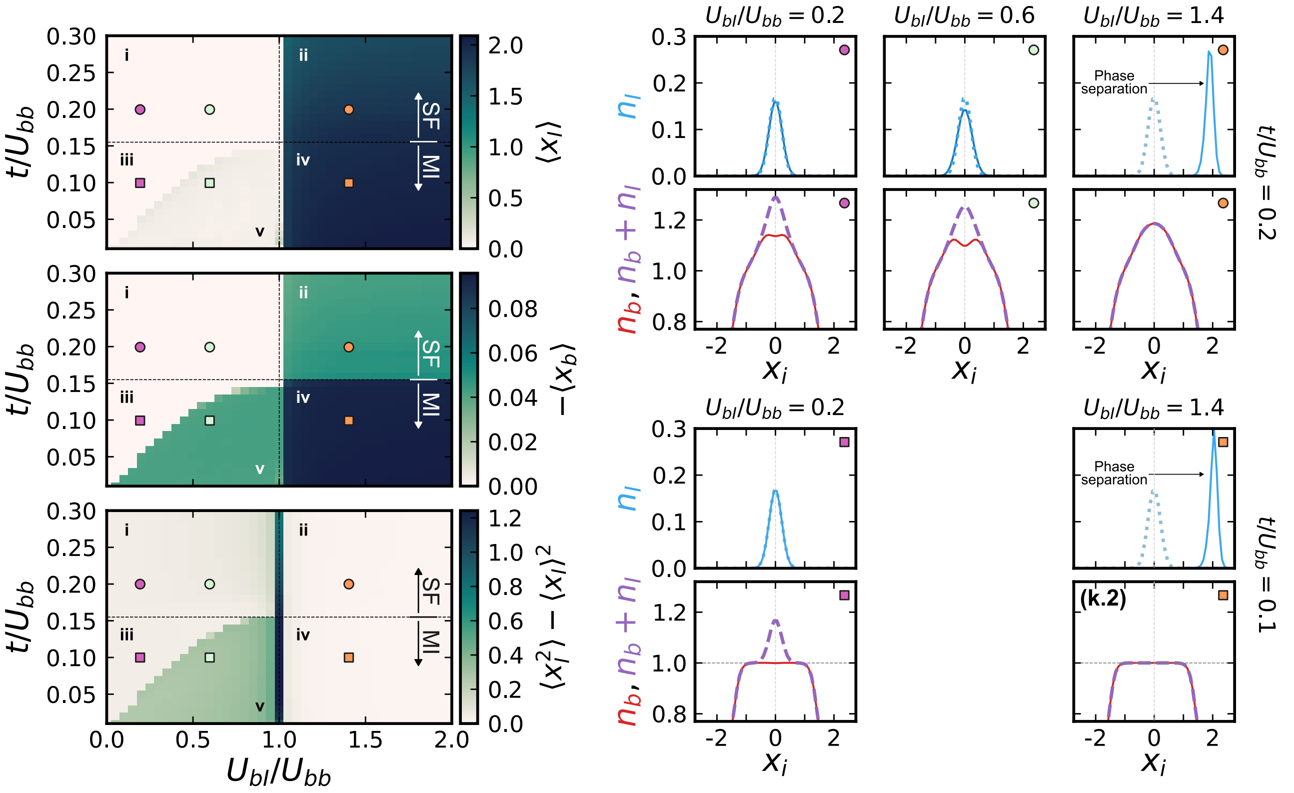
- **Regions i and iii** are **miscible** phases.

Density profiles



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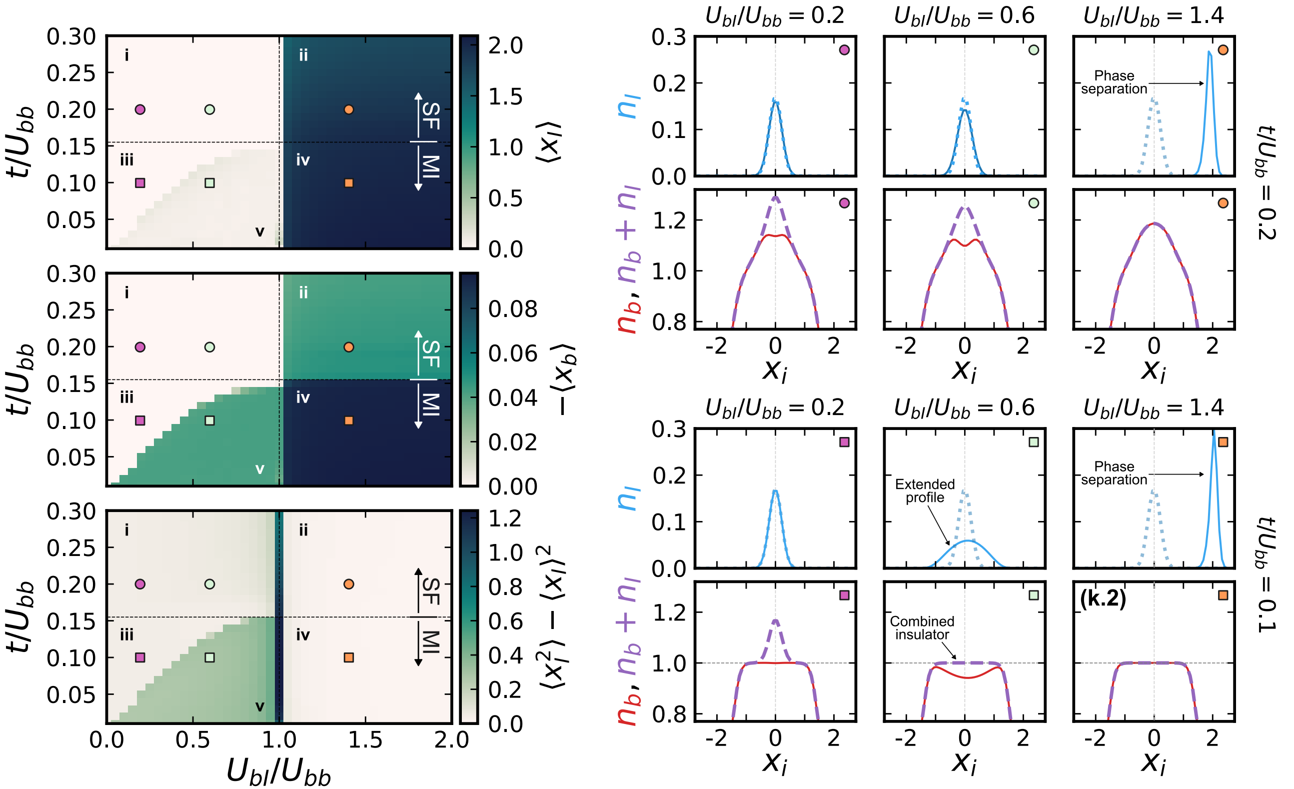
- **Regions ii and iv** are **phase-separated** configurations.

Density profiles



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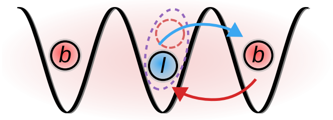
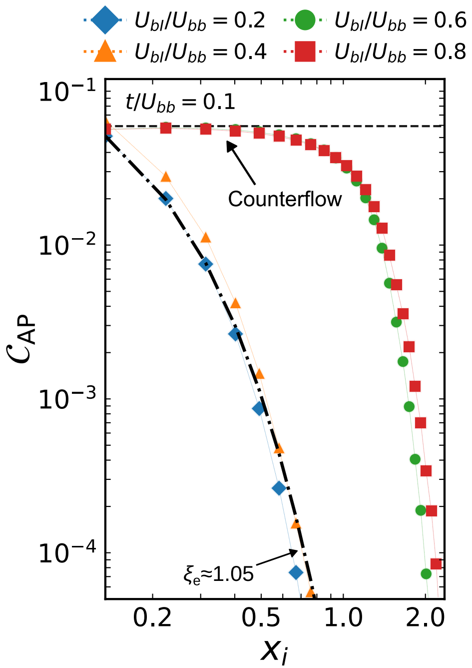
- **Region v** is a phase where the **impurity** shows an **extended profile**, and the **combined profile** of bath and impurity displays a domain of **unity filling**.

Counterflow

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

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

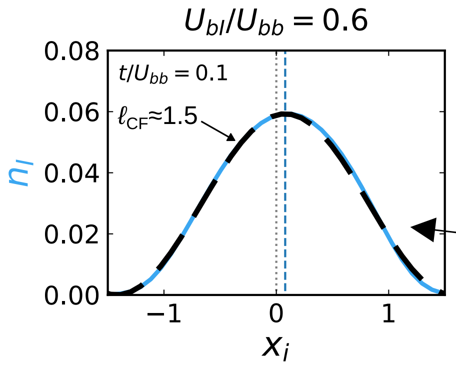




- **Supercounterflows** were **realised experimentally** very recently with **binary Mott insulators**.

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**,

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

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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