Tunable anisotropic superfluidity in optical Kagome superlattice

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Condensed matter systems with variable many-body interactions

OPTIMAS
TU Kaiserslautern

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1. Superfluid Density as Tensor

- **Linear response theory:**

$$p_i = VM\left(n_{\mathrm{n}ij}v_{\mathrm{n}j} + n_{\mathrm{s}ij}v_{\mathrm{s}j}\right) + \ldots$$

M. Ueda, *Fundamentals and New Frontiers of Bose-Einstein Condensation* (2010)

- **Dipolar interaction at finite temperature:**

Ghabour and Pelster, PRA **90**, 063636 (2014)

- **Dipolar interaction and isotropic disorder at zero temperature:**

Krumnow and Pelster, PRA **84**, 021608(R) (2011)

Nikolić, Balaž, and Pelster, PRA **88**, 013624 (2013)

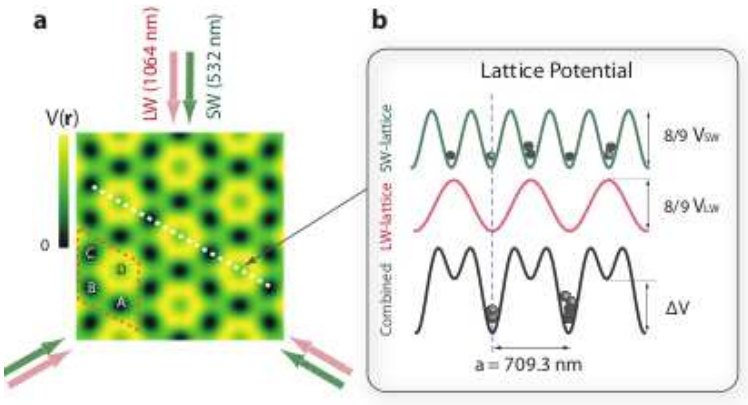
- **Spin-orbit coupling: elliptic vortices**

Devreese, Tempere, and Sá de Melo, PRL **113**, 165304 (2014)

- **Here: Tunable anisotropic superfluidity in Kagome superlattice**

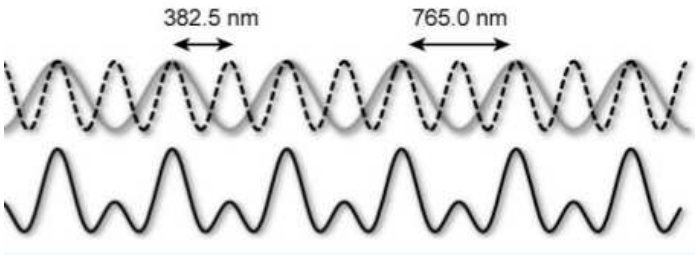
2. Physical Motivation

- **Frustrated lattices: e.g. Kagome**
  - **Candidates for spin liquid phase:**
    X.-G. Wen, *Quantum Field Theory of Many-Body Systems* (2004)
  - **Fractional charge edge states:**
    Zhang and Eggert, PRL **111**, 147201 (2013)



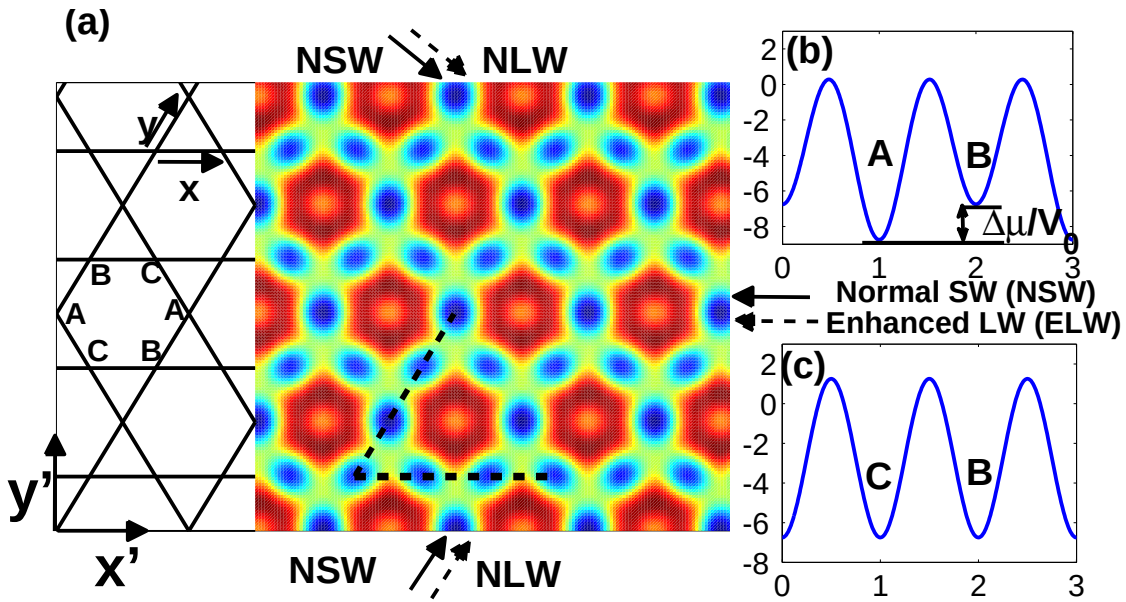
Jo, et al., PRL **108**, 045305 (2012)

- **Superlattices:**
  - **Insulating phases: fractional filling**
    Wang, Zhang, Eggert, Pelster, PRA **87**, 063615 (2013)
  - **Detection: single-site adressability**
    e.g. Bakr, et al., Nature **462**, 74 (2009)



Fölling, et al., Nature **448**, 1029 (2007)

3. Proposed Kagome Superlattice



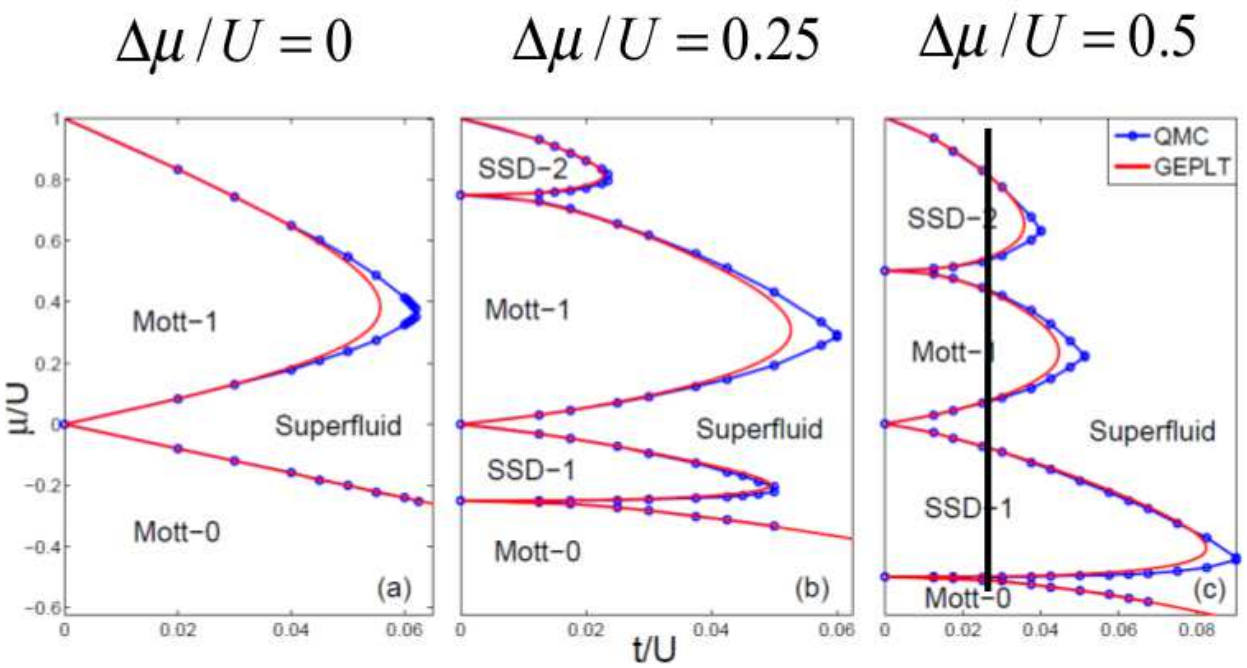
- **Optical potential** with $k = \sqrt{3}\pi/2\lambda_{\rm LW}$, $\lambda_{\rm LW} = 1064$ nm , $\gamma = V_{\rm E}/V_0$:

$$V_c/V_0 = \gamma^2 - 1 + 4\gamma\cos(\sqrt{3}kx)\cos(ky) + 2\cos(2ky) - 2\cos(4ky) - 4\cos(2\sqrt{3}kx)\cos(2ky)$$

- **Bose-Hubbard model** with $\Delta\mu = 4(\gamma - 1)V_0 > 0$:

$$\hat{H} = -t\sum_{\langle i,j\rangle}(\hat{a}_i^\dagger\hat{a}_j + \hat{a}_i\hat{a}_j^\dagger) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) - \mu\sum_i \hat{n}_i - \Delta\mu\sum_{i\in A}\hat{n}_i$$

4. Quantum Phase Diagram



- **QMC: stochastic cluster series expansion**

  Sandvik, PRB **59**, 14157(R) (1999)

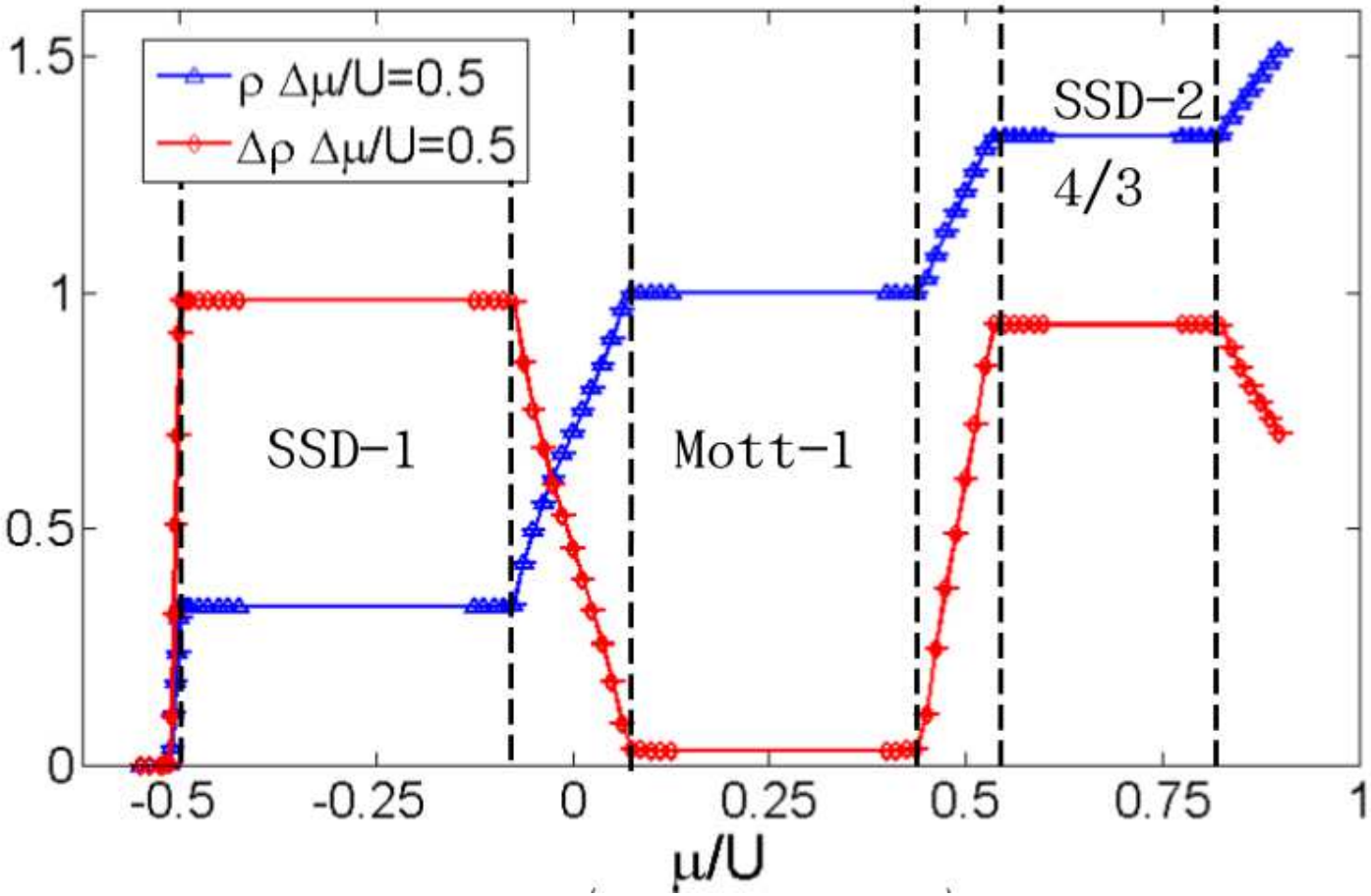
- **GEPLT: generalized effective potential Landau theory**

  Santos and Pelster, PRA **79**, 013614 (2009)

  Wang, Zhang, Eggert, Pelster, PRA **87**, 063615 (2013)

- **SSD (striped solid) phase:** fractional filling of 1/3 and 4/3

5. Insulating Phases



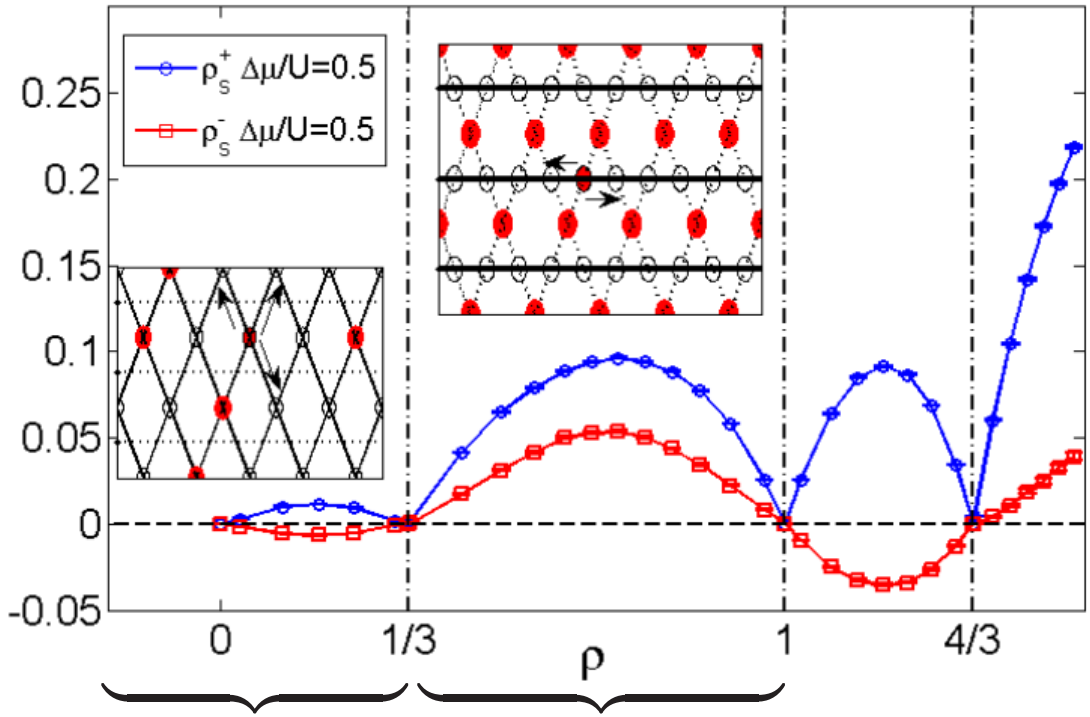
- **QMC:** $\beta U = 300$, $L = 9$, $t/U = 0.025$
- **Total density:** $\rho = (\rho_{\mathrm{A}} + \rho_{\mathrm{B}} + \rho_{\mathrm{C}})/3$
- **Density difference:** $\Delta\rho = \rho_{\mathrm{A}} - (\rho_{\mathrm{B}} + \rho_{\mathrm{C}})/2$

6. Anisotropic Superfluidity

- **Superfluid density via winding number**
  $\rho_s^{x/y} = \langle W_{x/y}^2 / 4\beta t \rangle$
  Pollock and Ceperley, PRB **36**, 8343 (1987)

- **Total superfluid density:**
  $\rho_s^+ = (\rho_s^x + \rho_s^y)/2$

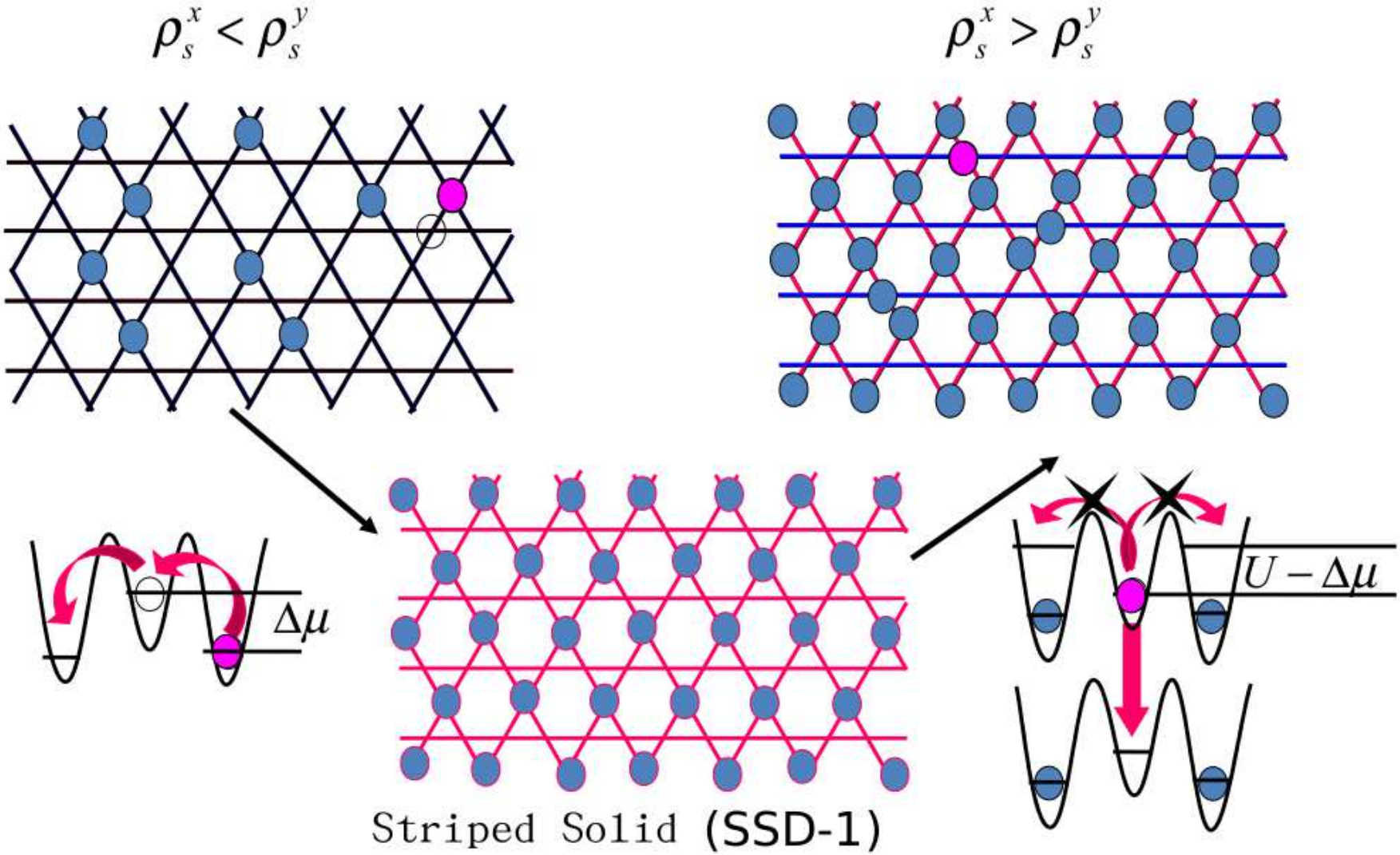
- **Superfluid density difference:**
  $\rho_s^- = \rho_s^x - \rho_s^y$



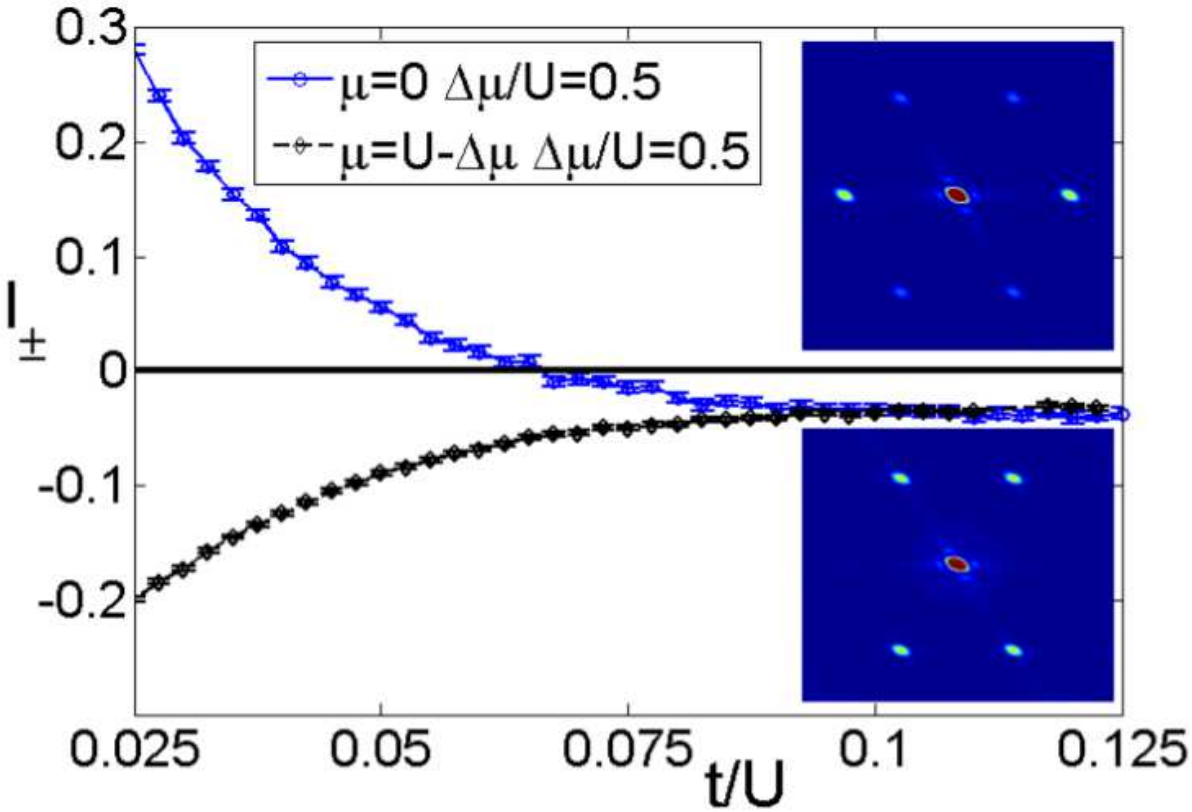
- $\rho_s^x < \rho_s^y$
- A preferred
- Effective square lattice

- $\rho_s^x > \rho_s^y$
- A full, B/C preferrred
- No supersolid due to artificial symmetry-breaking

7. Physical Explanation



8. Time-of-Flight Expansion



- **Anisotropic parameter:** $I_\pm = \dfrac{\rho_s^x - \rho_s^y}{\rho_s^x + \rho_s^y}$
- **Sign change indicates superfluid density is tensor**
- **Experimental detection by TOF absorption pictures**