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Polar molecules in one-dimensional optical lattices

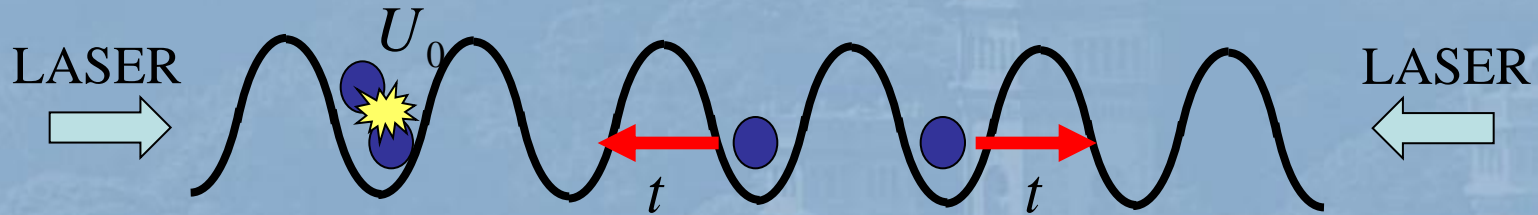
Luis Santos

Institute of Theoretical Physics and
Center of Excellence QUEST
Leibniz Universität Hannover



Santa Barbara, March 14 , 2013

Ultra-cold gases in optical lattices: lattice models

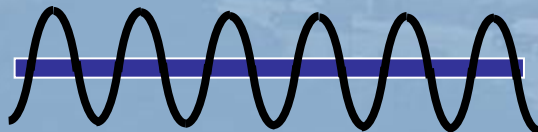


Bose-Hubbard Hamiltonian

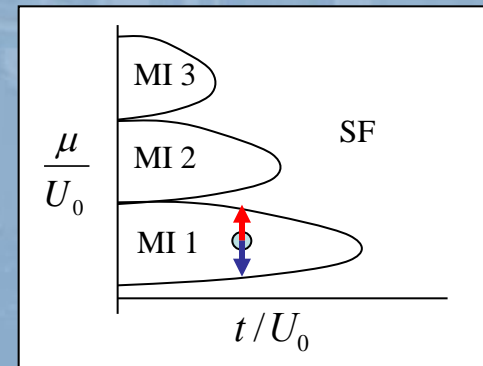
[Fisher *et al.*, PRB **40**, 546 (1989) ;
Jaksch *et al.*, PRL **81**, 3108 (1998)]

$$H = -t \sum_i \hat{a}_i^\dagger \hat{b}_i^+ \hat{b}_{i+1} + H.c. + \frac{U_0}{2} \sum_i \hat{a}_i n_i (n_i - 1)$$

Mott insulator (gapped incompressible insulator)

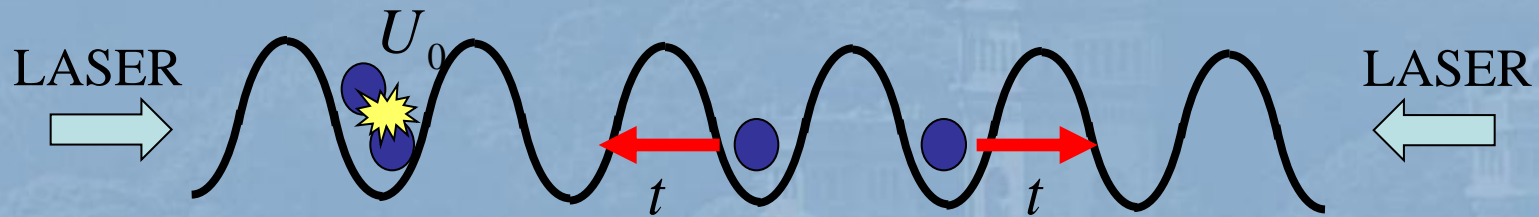


Superfluid



[M. Greiner *et al.*, Nature **415**, 39 (2002)]

Ultra-cold gases in optical lattices: lattice models



Bose-Hubbard Hamiltonian

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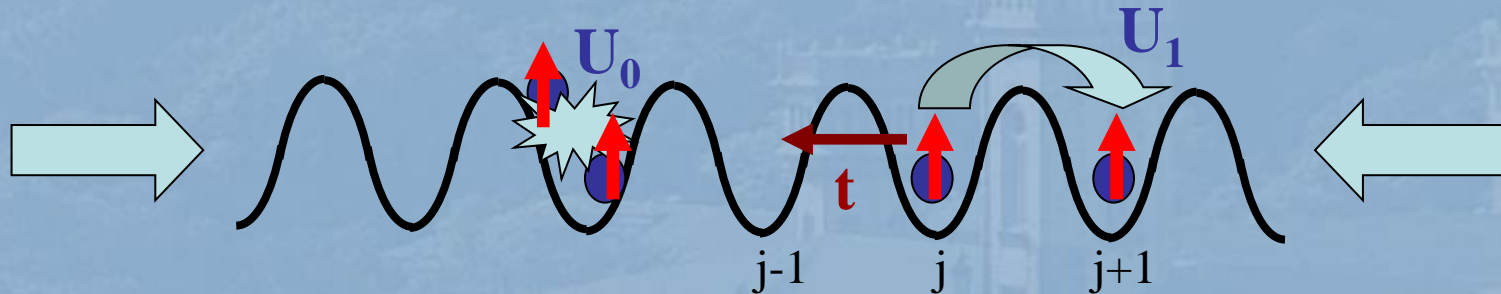
Resemble spin models,
e.g. hard-core bosons ($n=0,1$)



$$H_{XX} \gg -2t \sum_{\langle ij \rangle} \hat{a}_i (s_i^x s_j^x + s_i^y s_j^y)$$

Dipolar lattice gases: intersite effects

For a dipolar gas inter-site interactions become important



Extended Bose-Hubbard model

$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1}$$

Dipolar interactions have been shown already to play an important role in dipolar Chromium BECs in optical lattices (Stuttgart)

Inter-site destabilization

[Müller et al., PRA **84**, 053601 (2011)]

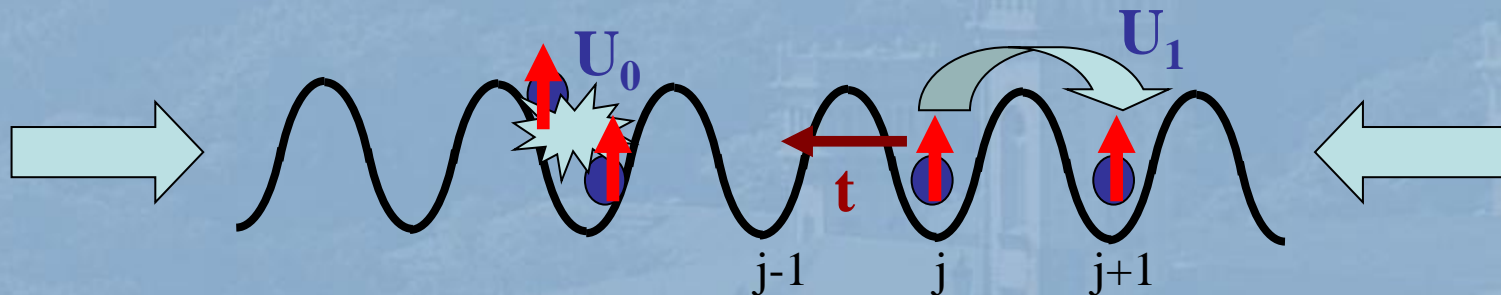
Time-of-flight-induced collapse of in-lattice stable BECs

[Billy et al., PRA **86**, 051603(R) (2012)]

Also in recent works on spin dynamics of Chromium in lattices (Talk of B. Laburthe)

Dipolar lattice gases: intersite effects

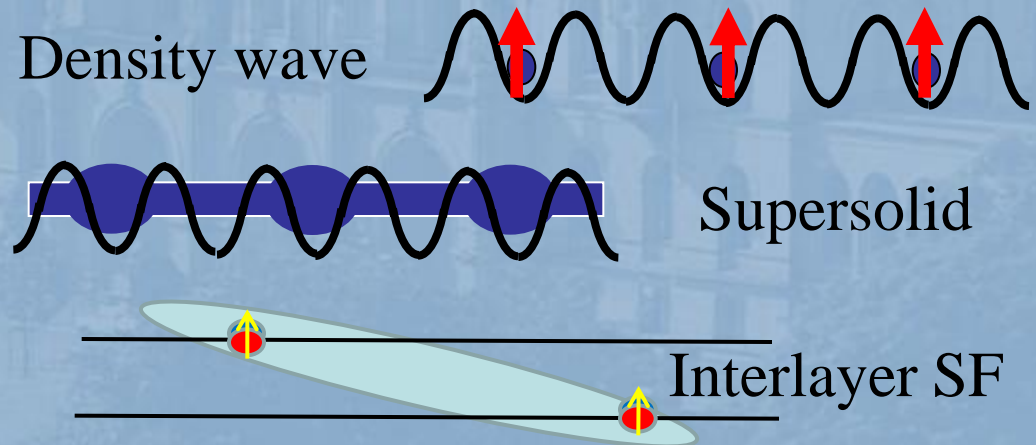
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Extended Bose-Hubbard model

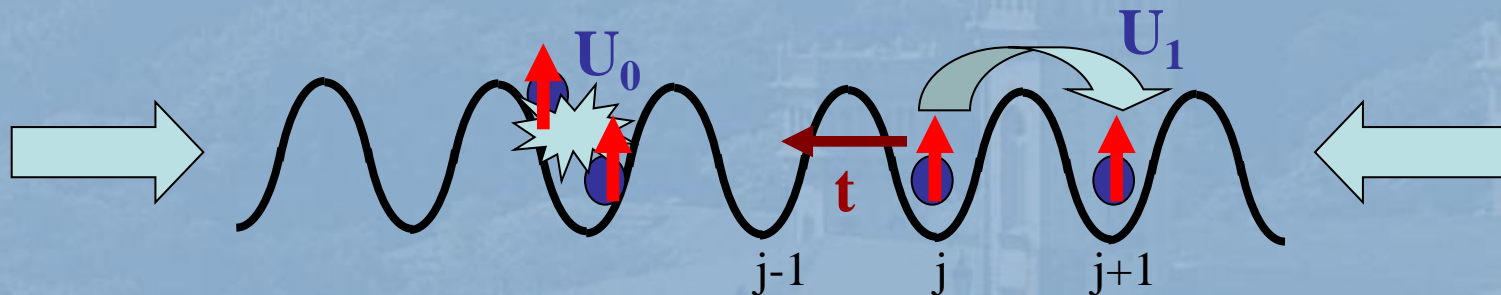
$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1}$$

Supersolid, density-waves, self-assembled crystals, metastable states, interlayer superfluids and more...



Dipolar lattice gases: intersite effects

For a dipolar gas inter-site interactions become important



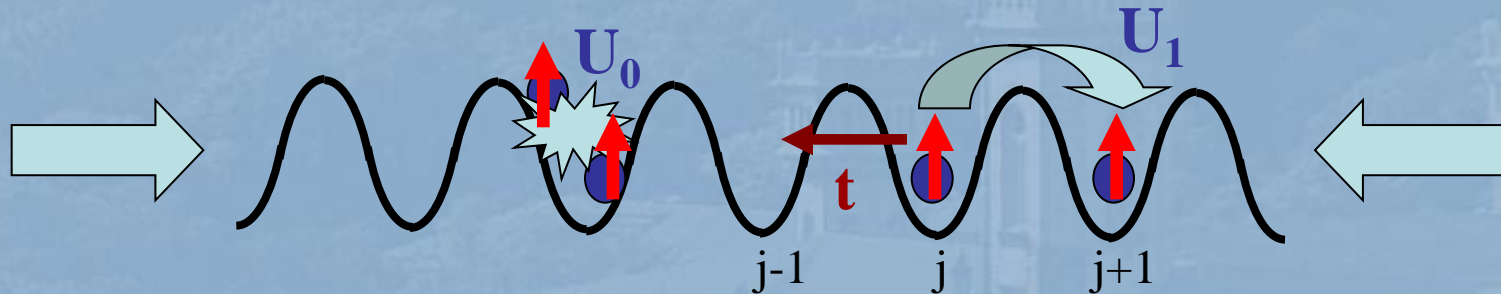
1D polar gases

The intersite interactions lead to a very rich physics for 1D chains and ladders

- Devil's staircase [Burnell et al., PRB 80, 174519 (2009)]
- Haldane insulator [Dalla Torre et al., PRL 97, 260401 (2006)]
- Disorder [Deng et al., arXiv (2012)]
- Simulation of spin-orbital models [Sun et al., PRB 86, 155159 (2012)]
- More... See. [Chemical Reviews 112, 5012 (2012)]

Dipolar lattice gases: intersite effects

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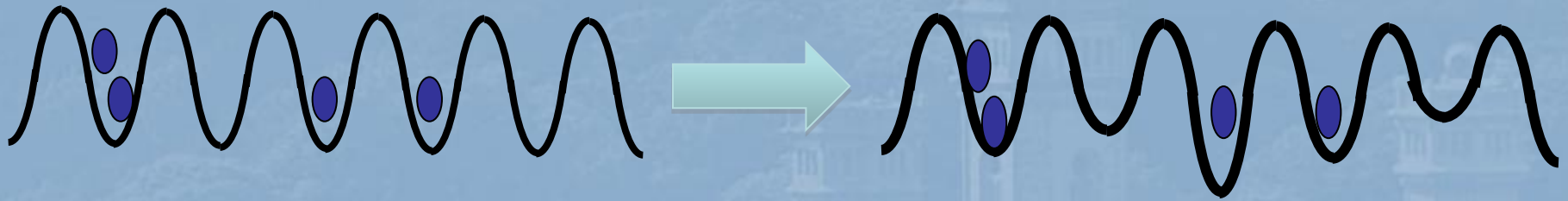


1D polar gases

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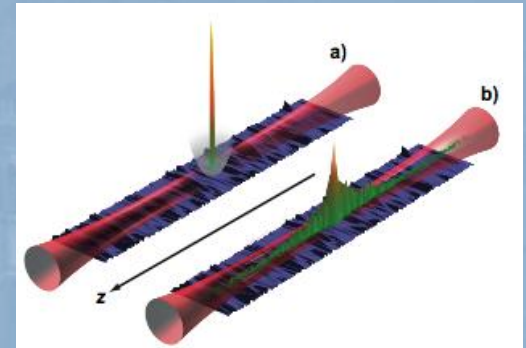
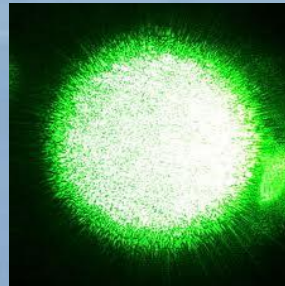
- **Devil's staircase** [Burnell et al., PRB 80, 174519 (2009)]
- **Haldane insulator** [Dalla Torre et al., PRL 97, 260401 (2006)]
- **Disorder** [Deng et al., arXiv (2012)]
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- **More... See.** [Chemical Reviews 112, 5012 (2012)]

Disorder in optical lattices



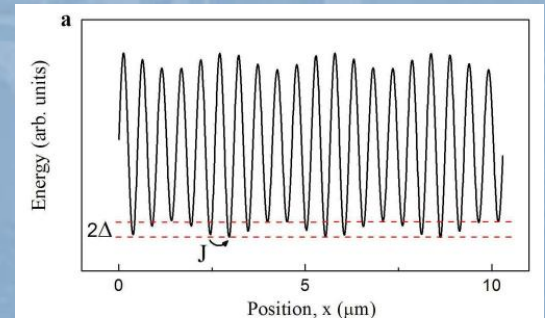
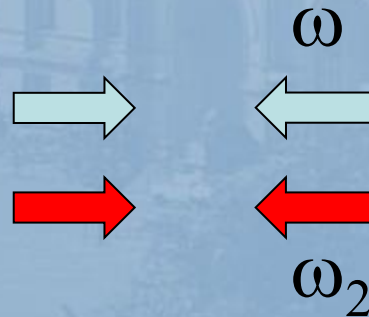
Speckle

[Billy et al., Nature **453**, 891 (2008)]



Bichromatic lattices

[Roati et al., Nature **453**, 895 (2008)]



Quasi-periodic

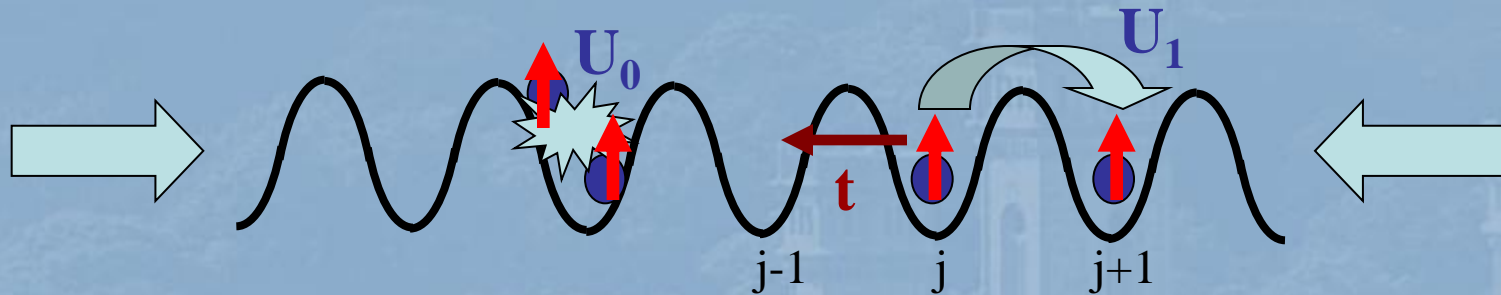
This talk

1D polar gases at unit filling

1D polar gases with uniform bound disorder

1D polar gases in a quasi-periodic lattice

1D polar bosons in optical lattices



Extended Bose-Hubbard model

$$H = -t \sum_i [b_i^+ b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1}$$

Average filling $\langle n \rangle = 1$

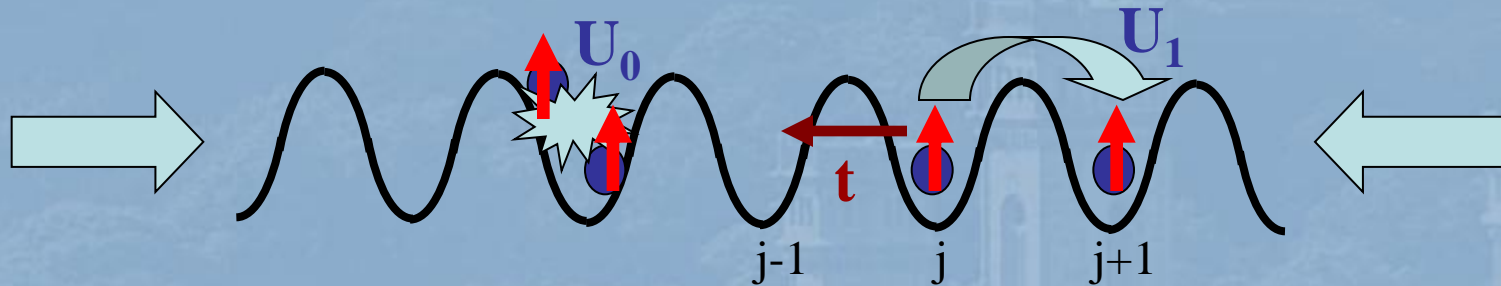
Holstein-Primakoff transformation maps occupation into spin-1

$$S_i^z = 1 - n_i \longrightarrow \begin{array}{l} \text{m=1} \\ \text{m=0} \\ \text{m=-1} \end{array}$$

$$S_i^+ = \sqrt{2 - n_i} b_i$$

$$S_i^- = b_i^+ \sqrt{2 - n_i}$$

1D polar bosons in optical lattices



Extended Bose-Hubbard model

$$H = -t \sum_i [b_i^+ b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1}$$

The system resembles to a large extent an AF spin-1 chain with uniaxial single-ion anisotropy

$$H = J \sum_i \left[S_i^x \cdot S_{i+1}^x + S_i^y \cdot S_{i+1}^y + \Delta S_i^z \cdot S_{i+1}^z + D (S_i^z)^2 \right]$$

$$J = 2t \quad D = U_0 / 4t$$

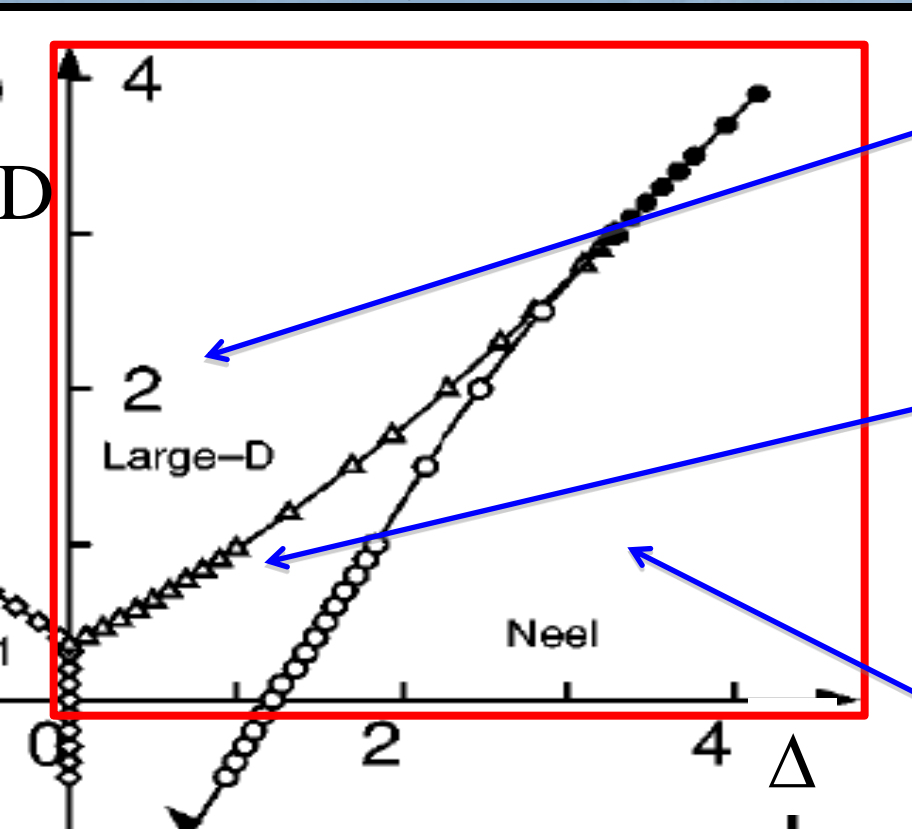
$$\Delta = U_1 / 2t$$

(imperfect mapping: due to $n > 2$ and extra terms $\sim S_i^- \cdot F(S_i^z + S_{i+1}^z) \cdot S_{i+1}^+$)

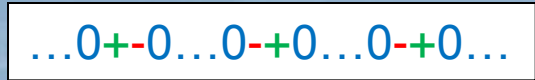
AF spin-1 chains

$$H = J \sum_i \left[S_i^x \cdot S_{i+1}^x + S_i^y \cdot S_{i+1}^y + \Delta S_i^z \cdot S_{i+1}^z + D (S_i^z)^2 \right]$$

[Chen, Hida and Sanctuary, PRB **67**, 104401 (2003)]



Large-D phase



Haldane phase



(„diluted AF order“)

Néel phase



1D polar gases in optical lattices: Haldane-insulator phase

$$H = -t \sum_i [b_i^+ b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1}$$

arXiv:1203.0505v1 [U₀/t 2 Mar 2012

Polar bosons in one-dimensional disordered optical lattices

^{1,2} Edmond Originaç,³ Anna Minguzzi,⁴ and Luis Santos¹

¹ Leibniz Universität Hannover, Appellstr. 2, D-30167 Hannover, Germany
² INFN and Spin-CNR, Università degli Studi di Salerno, Salerno, Italy
³ UMR 5076, CNRS, Université de Lyon, CNRS-UMR5072, 69634 Lyon Cedex 7, France
⁴ CNRS, Laboratoire de Physique et Modélisation, 93, Maison des Mathématiques, B.P. 166, 38042 Grenoble, France
 (Dated: March 5, 2012)

quasi-disorder on the ground-state properties of ultra-cold polar bosons
 overlap between disorder and inter-site interactions leads to rich physics
 Haldane-insulator phase with finite purity order, whereas a commensurate
 wave phase becomes a Bose-glass at very weak disorder. For quasi-disorder, the Haldane-insulator connects
 with a gapped generalized incommensurate density wave without an intermediate critical region.

Introduction. The interplay between disorder and interactions plays a crucial role in the physics of strongly-correlated systems [1]. Disorder in non-interacting systems leads to Anderson localization [2], which in one dimension occurs for vanishingly small disorder [3]. For the particular case of bosons in a lattice potential, interactions have been shown to stabilize a superfluid (SF) phase, a gapless localized incompressible phase known as Bose-Glass (BG), and a Mott-insulator (MI) occurring at commensurate lattice fillings. Ultra-cold atoms in optical lattices offer an extraordinarily controllable scenario for the detailed analysis of the competition between disorder and interactions. Disorder in the on-site energies may be implemented in various ways in these systems, including the use of speckle [10–13], binary mixtures [14–17], and bichromatic combinations of two mutually incommensurate lattices [18]. Recently, localization has been experimentally observed in non-interacting cold gases in 1D and 3D speckle [19, 20], and bichromatic potentials [21]. Bichromatic lattices constitute a peculiar type of disorder, rather a quasi-disorder, realizing the so-called Aubry-André model [22]. The effects of interactions in 1D lattices with quasi-disorder have been recently studied [23–25]. Particularly interesting is the existence of a gapped localized phase, the so-called incommensurate density wave (ICDW), which results from the quasi-periodicity of the potential.

Polar gases are attracting attention mostly motivated by experiments on atoms with large magnetic moments as Chromium [26] and Dysprosium [27], and especially by recent groundbreaking experiments on polar molecules [28]. Due to the dipole-dipole interaction, these gases present an exceedingly rich physics [29, 30]. Polar lattice gases are particularly interesting, mostly due to the qualitatively new features introduced by dipole-induced inter-site interactions [31]. In particular, intersite interactions may allow for the realization of the so-called Haldane-insulator (HI) phase [32], a gapped phase characterized by a nonlocal string order parameter.

In this Letter we show that the interplay between on-site and inter-site interactions and disorder leads to a rich physics for lattice bosons with nearest neighbor interactions. In par-

FIG. 1: Phase diagrams of bosons with nearest-neighbor interactions. (a) unperturbed case; (b) staggered on-site energy; (c) quasi-disorder; (d) quasi-disorder. Blue regions correspond to the HI phase. See text for details.

Mott-insulator

...1021...1201...1200...

Haldane-insulator

...101...121...101...121...

[Dalla-Torre, Berg and Altman, PRL **97**, 260401 (2006)]

Density wave

...0202020202020202...

U₁/t

$$H = -t \sum_i [b_i^+ b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} \quad (1)$$

String and parity order

„fluid of AF ordered defects“

$$dn_i = 1 - n_i$$

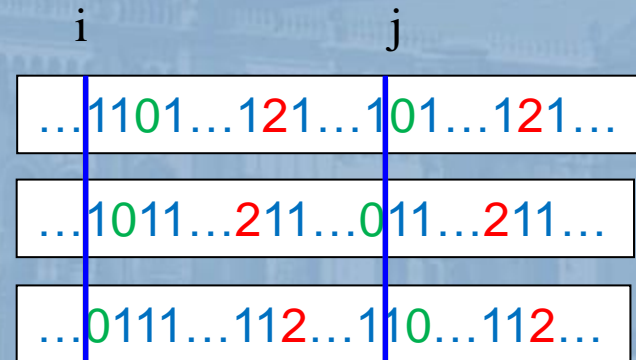


String order

$$O_S^2 \equiv \lim_{|i-j| \rightarrow \infty} \left\langle -dn_i \exp \left[i\rho \sum_{l=i+1}^{j-1} dn_l \right] dn_j \right\rangle \neq 0$$

Parity order

$$O_P^2 \equiv \lim_{|i-j| \rightarrow \infty} \left\langle \exp \left[i\rho \sum_{l=i+1}^{j-1} dn_l \right] \right\rangle = 0$$



For the Mott insulator $O_S^2 = 0$ $O_P^2 \neq 0$

[Endres et al.,
 Science **334**,
 200 (2011)]

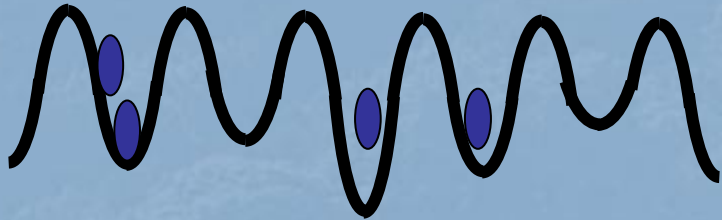
This talk

1D polar gases at unit filling

1D polar gases with uniform bound disorder

1D polar gases in a quasi-periodic lattice

1D gases in disordered optical lattices

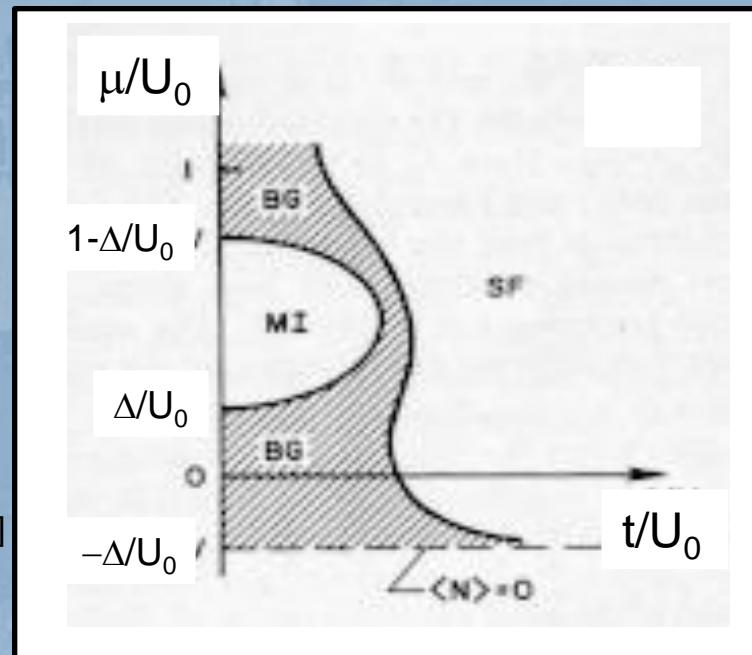


$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$
 (similar to speckle)

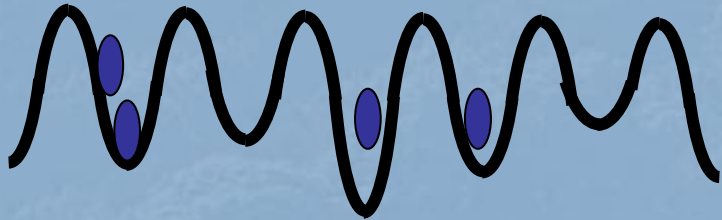
For non-polar bosons: Bose-Glass (gapless, compressible insulator)

[Giamarchi and Schulz, PRB **37**, 325 (1988);
 Fisher et al., PRB **40**, 546 (1989);
 Rapsch, Schollwöck and Zwerger, EPL **46**, 559 (1999)]



[From PRB **40**, 546 (1989)]

1D gases in disordered optical lattices

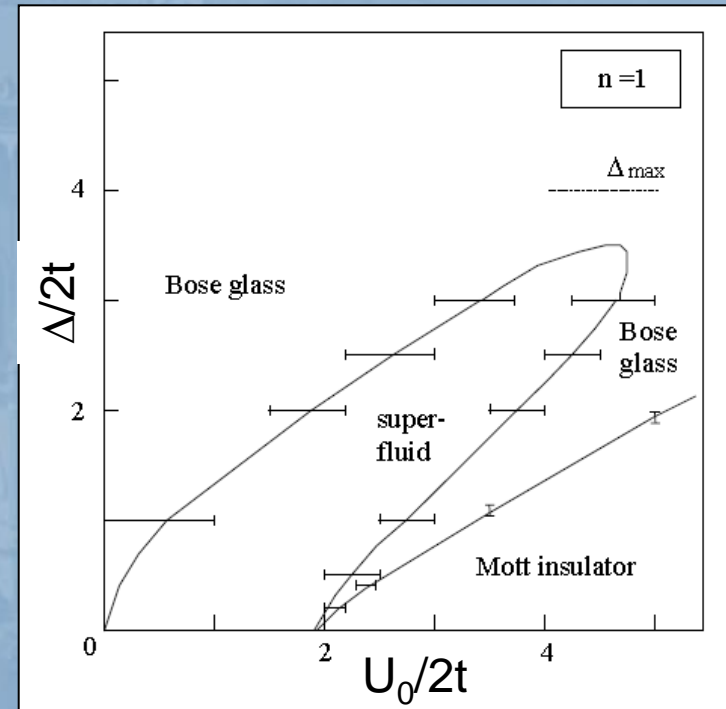


$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$

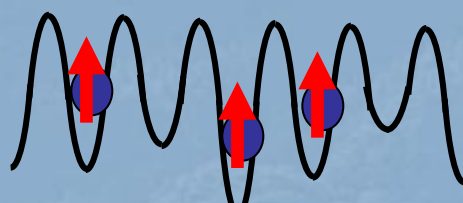
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$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i(n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$

Polar bosons in one-dimensional disordered optical lattices

D. Edmond Originaç,¹ Anna Minguzzi,² and Luis Santos³

¹ Leibniz Universität Hannover, Appellstr. 2, D-30167 Hannover, Germany
² INFN-CNR, Università degli Studi di Salerno, Salerno, Italy
³ Laboratoire de Physique et Modélisation, CNRS-UMR5072, BP164, F-38000 Grenoble, France

arXiv:1203.0505v1 [cond-mat.str-el] 2 Mar 2012

Introduction. The interplay between disorder and interactions plays a crucial role in the physics of strongly-correlated systems [1]. Disorder in non-interacting systems leads to Anderson localization [2], which in one dimension occurs for vanishingly small disorder [3]. For the particular case of bosons in a lattice potential, interactions have been shown, both in 1D [4–7] and higher dimensions [8, 9], to induce in the presence of disorder a phase diagram characterized by new phases: a superfluid (SF) phase, a gapless localized incompressible phase known as Bose-Glass (BG), and a Mott-insulator (MI) occurring at commensurate lattice fillings.

Ultra-cold atoms in optical lattices have an extraordinarily versatile scenario for the detailed analysis of the competition between disorder and interactions. Disorder in the on-site energies may be implemented in various ways in these systems, including the use of speckle [10–13], binary mixtures [14–17], and bichromatic combinations of two mutually incommensurate lattices [18]. Recently, localization has been experimentally observed in non-interacting cold gases in 1D and 3D speckle [19, 20], and bichromatic potentials [21]. Bichromatic lattices constitute a peculiar type of disorder, rather a quasi-disorder, realizing the so-called Aubry-André model [22]. The effects of interactions in 1D lattices with quasi-disorder have been recently studied [23–25]. Particularly interesting is the existence of a gapped localized phase, the so-called incommensurate density wave (ICDW), which results from the quasi-periodicity of the potential.

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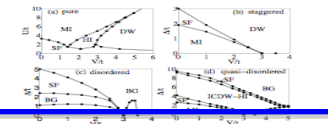
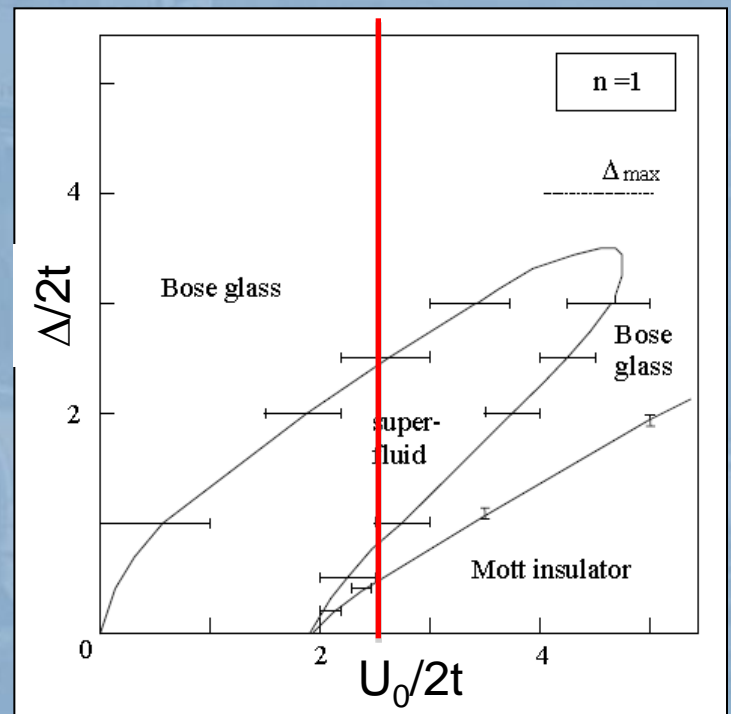


FIG. 1: Phase diagrams of bosons with nearest-neighbor interactions: (a) unperurbed case; (b) staggered on-site energy; (c) uniform disorder; (d) quasi-disorder. Figures (b)–(d) are obtained for $U_1/t = 2$. See text for details.



[From EPL 46, 559 (1989)]

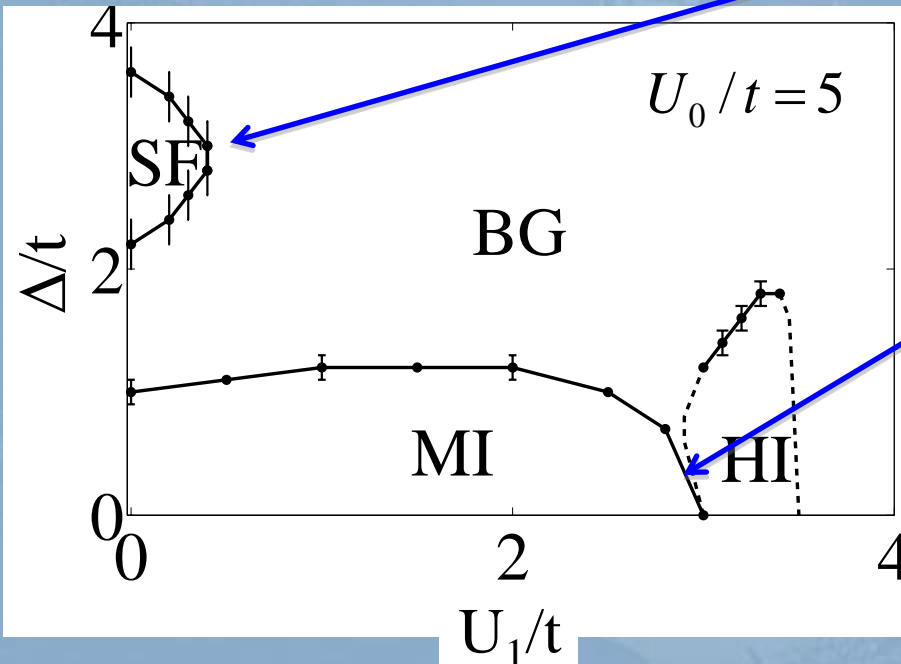
1D polar gases in disordered optical lattices

$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$

SF vanishes for growing NN interactions (SF-BG at $K=3/2$)

[Giamarchi and Schulz, EPL 3, 1287 (1987)]



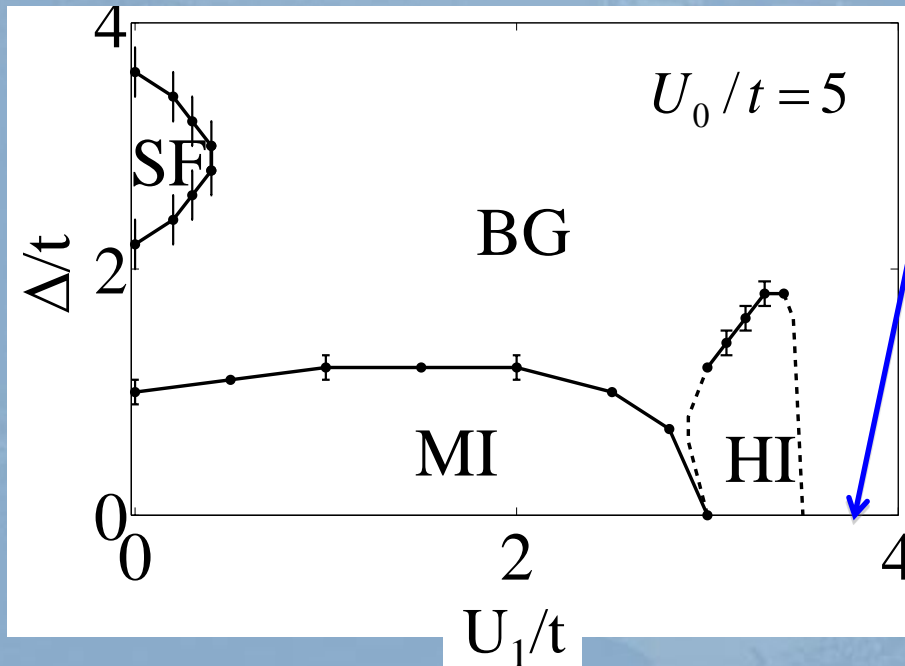
BG goes all the way to zero at the MI-HI for $K < 3/2$

[Deng et al., arXiv:1302.0528]

1D polar gases in disordered optical lattices

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Bounded box disorder: $-D < \varepsilon_i < D$



DW disappears even for very small disorder.

(Imry-Ma argument)

[Imry and Ma, PRL **35**, 1399 (1975)]

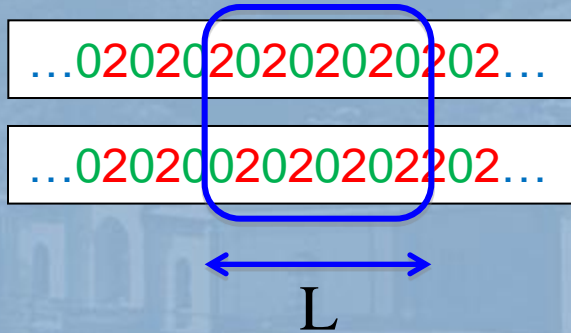
Imry-Ma argument

[Imry and Ma, PRL **35**, 1399 (1975)]

...0202020202020202...

$$\mathcal{O}_{DW} = \lim_{|i-j| \rightarrow \infty} \langle (-1)^{i-j} \delta n_i \delta n_j \rangle$$

Gap for flipping a spin



Energy of the domain

coming from the noise: $\langle \Delta \epsilon \rangle \sim \Delta L^{1/2}$

Energy of the domain walls $\sim V$

Formation of domains of size $L \sim (V/\Delta)^{1/2}$

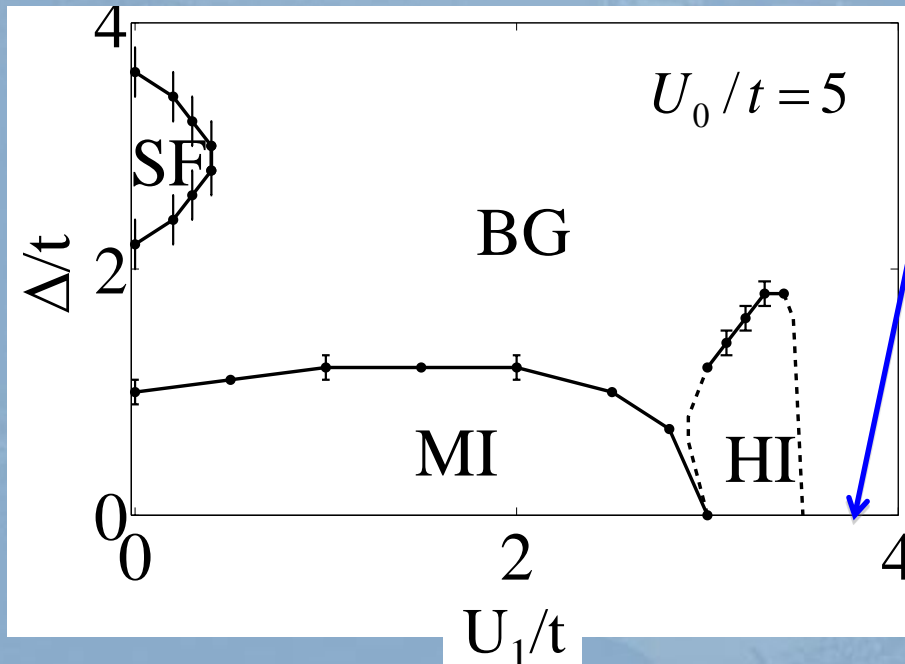
Domain formation destroys the order

The gap is destroyed because now the excitations are simply moving walls, not creating them

1D polar gases in disordered optical lattices

$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$



DW disappears even for very small disorder.

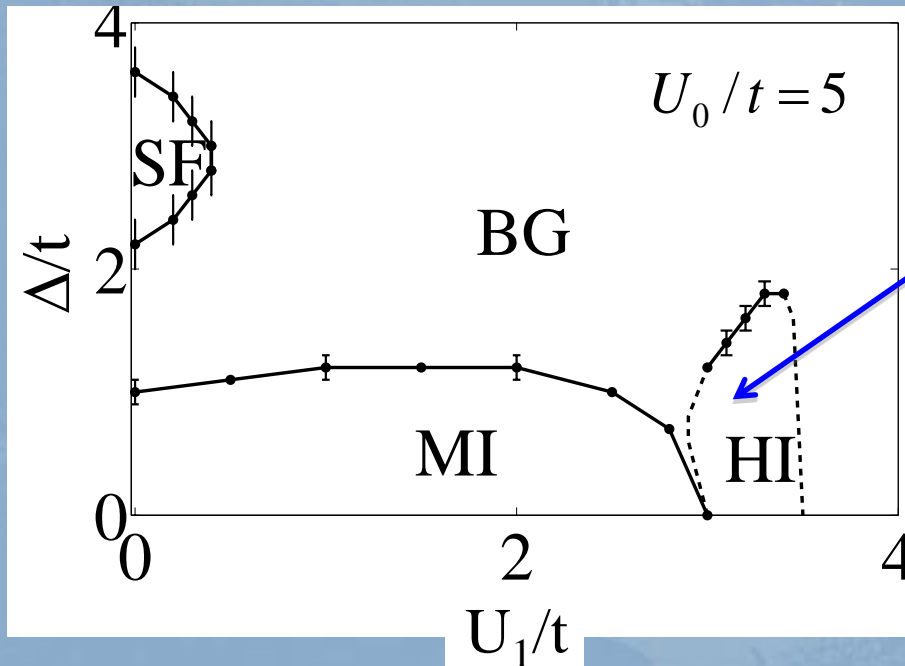
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1D polar gases in disordered optical lattices

$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$



The HI phase survives, but its character changes

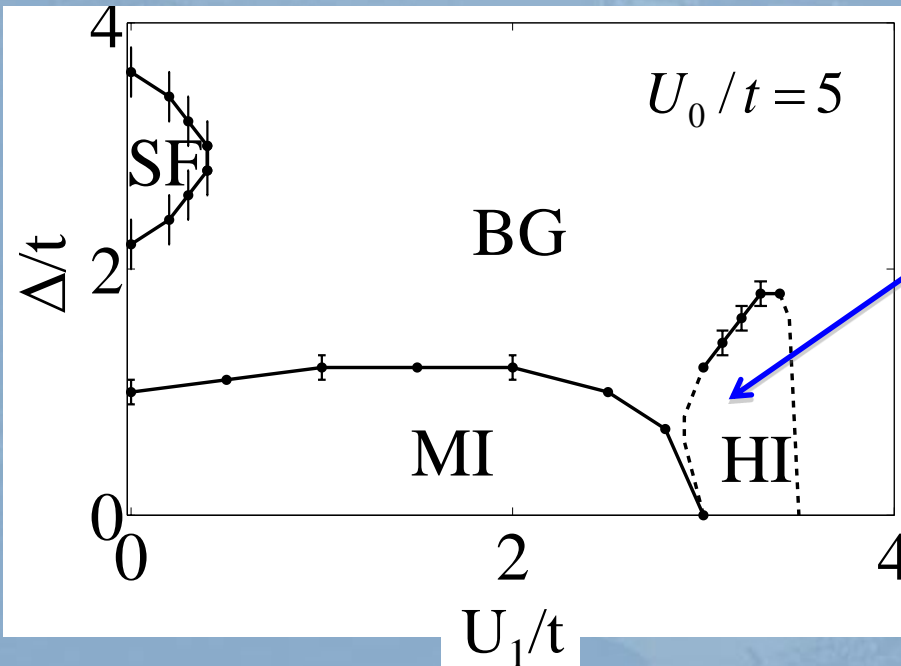
$$O_S^2 \quad 1 \quad 0$$

$$O_P^2 \quad 1 \quad 0$$

1D polar gases in disordered optical lattices

$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bounded box disorder: $-D < \varepsilon_i < D$



The HI phase survives, but its character changes

$$O_S^2 \quad 1 \quad 0$$

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This talk

1D polar gases at unit filling

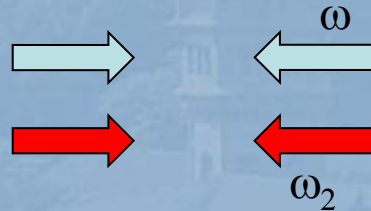
1D polar gases with uniform bound disorder

1D polar gases in a quasi-periodic lattice

1D gases in quasi-periodic optical lattices

$$H = -t \sum_i \hat{a}_i^\dagger \hat{b}_i^\dagger \hat{b}_{i+1} + H.c. + \frac{U_0}{2} \sum_i \hat{a}_i^\dagger n_i (n_i - 1) + \sum_i \hat{a}_i^\dagger e_i n_i$$

Bichromatic lattices

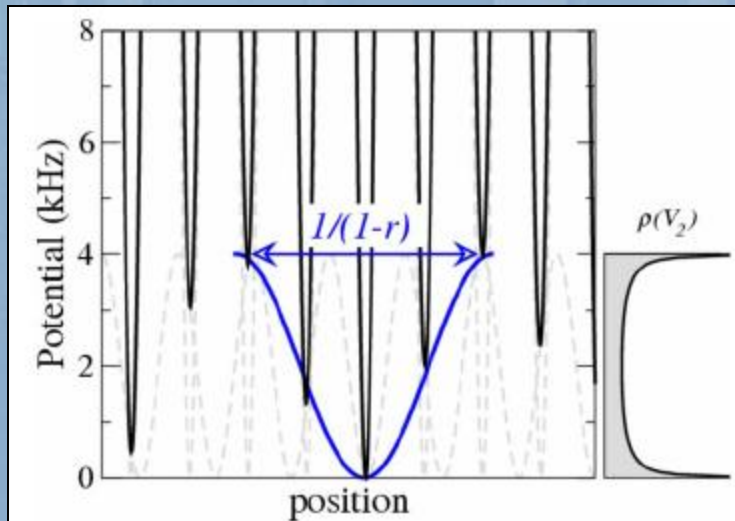


$$e_j = D \cos(2\pi r j + j)$$

$$r = q_2 / q_1$$

Extra phase: incommensurate density wave (ICDW)

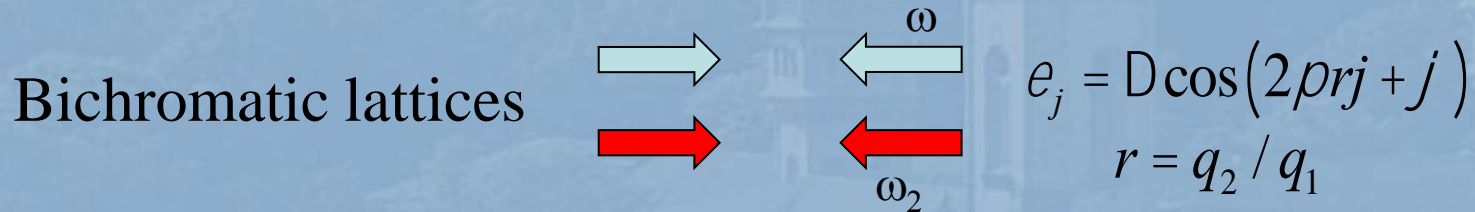
[Roskilde PRA **77**, 063605 (2008); Roux et al, PRA **78**, 023628 (2008)]



Super-wells develop over a characteristic length scale $1/(1-r)$ („super site“) due to the beating between the two periods of the two lattices.

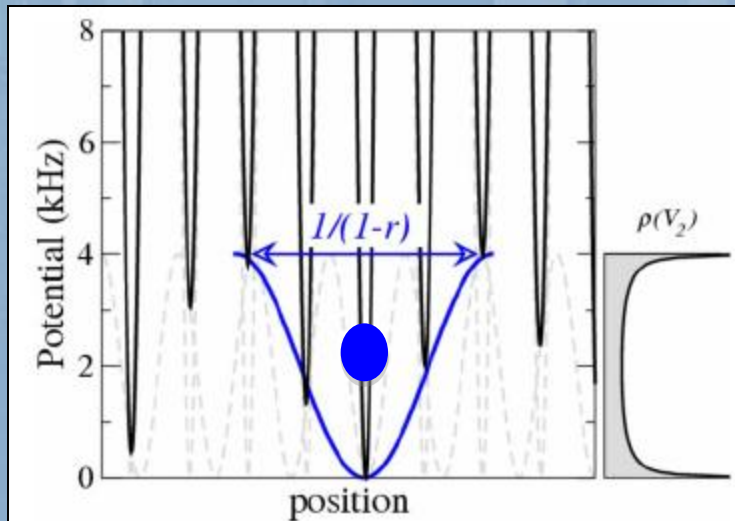
1D gases in quasi-periodic optical lattices

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Extra phase: incommensurate density wave (ICDW)

[Roskilde PRA **77**, 063605 (2008); Roux et al, PRA **78**, 023628 (2008)]



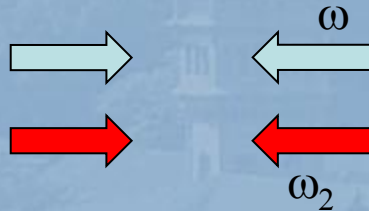
A ICDW phase for $\langle n \rangle = 1 - r$ may be interpreted as filling each „super-site“ with one particle.

For $n = r$ it is like having one hole sitting at each „super-site“

1D gases in quasi-periodic optical lattices

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Bichromatic lattices

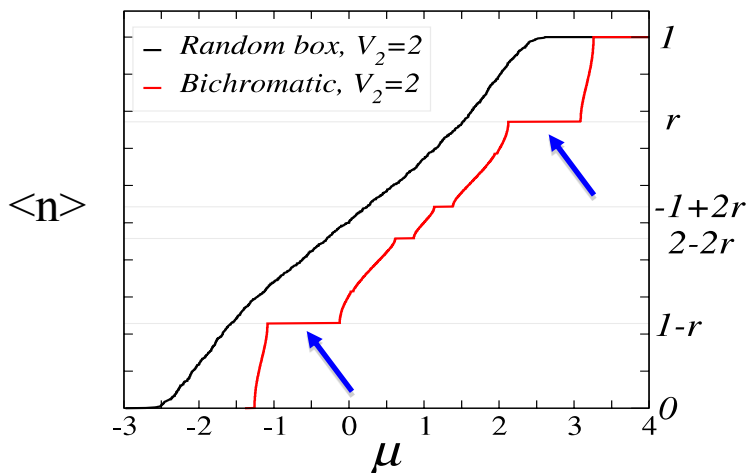


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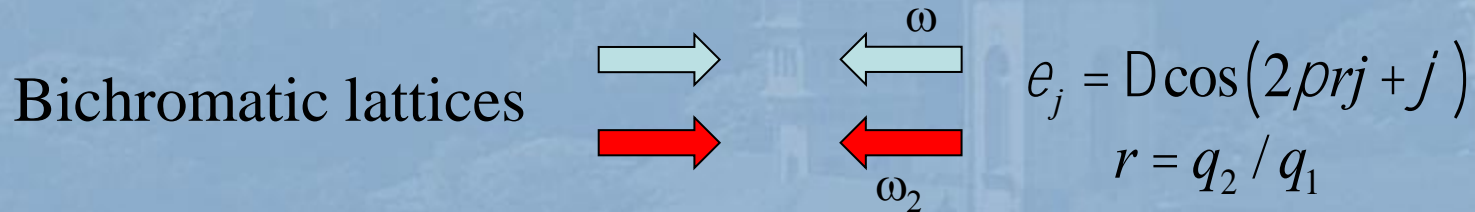


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1D gases in quasi-periodic optical lattices

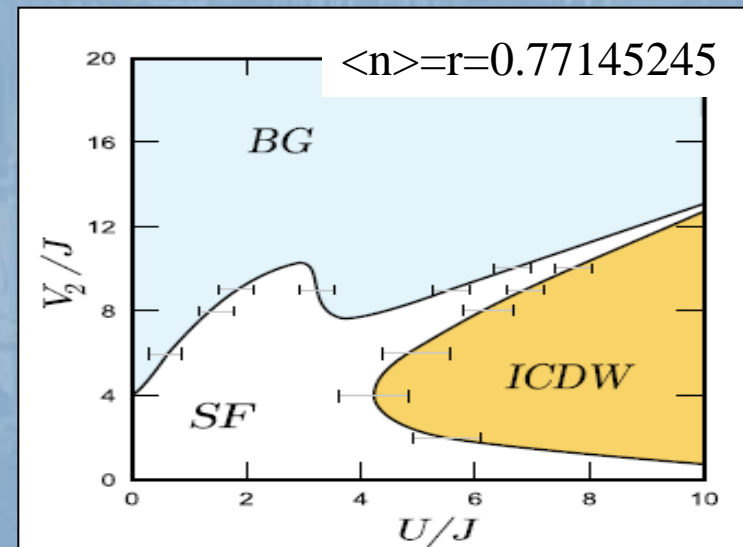
$$H = -t \sum_i \hat{a}_i^\dagger \hat{b}_i^\dagger \hat{b}_{i+1} + H.c. + \frac{U_0}{2} \sum_i \hat{a}_i^\dagger n_i (n_i - 1) + \sum_i \hat{a}_i^\dagger e_i n_i$$



Extra phase: incommensurate density wave (ICDW)

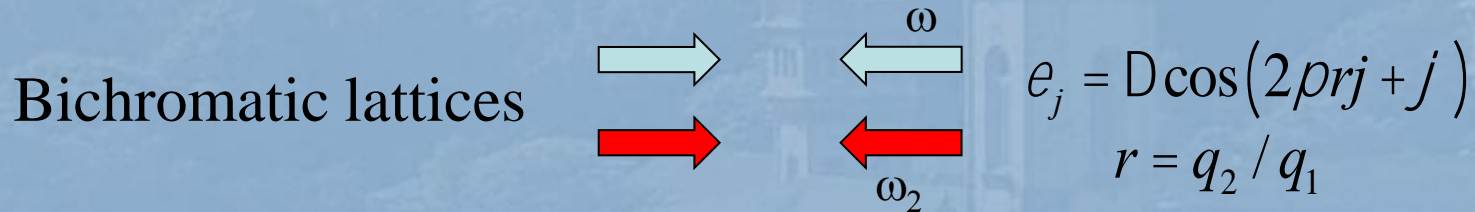
[Roskilde PRA **77**, 063605 (2008); Roux et al, PRA **78**, 023628 (2008)]

As a result a gapped ICDW appears with a structure factor peaking at the beating periodicity



1D gases in quasi-periodic optical lattices

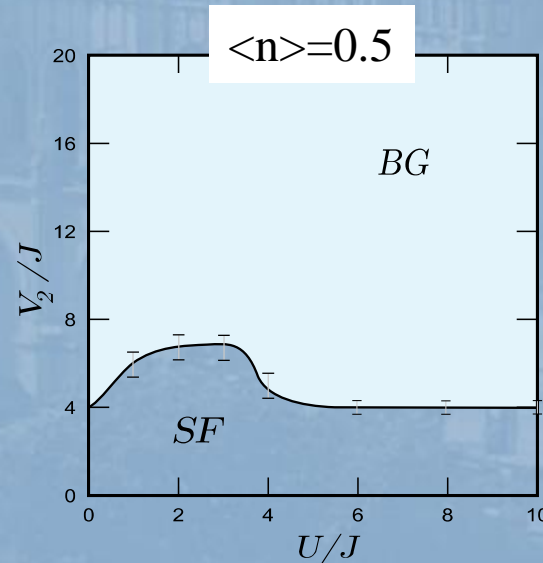
$$H = -t \sum_i \hat{a}_i^\dagger \hat{b}_i^\dagger \hat{b}_{i+1} + H.c. + \frac{U_0}{2} \sum_i \hat{a}_i^\dagger n_i (n_i - 1) + \sum_i \hat{a}_i^\dagger e_i n_i$$



Extra phase: incommensurate density wave (ICDW)

[Roskilde PRA **77**, 063605 (2008); Roux et al, PRA **78**, 023628 (2008)]

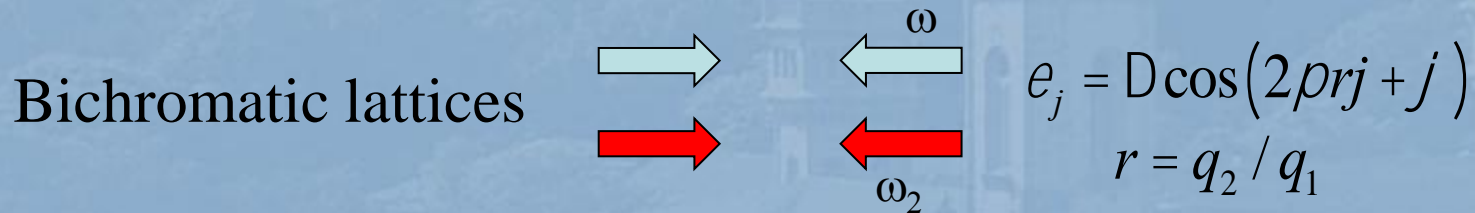
Away from these fillings
the ICDW disappears



[From PRA **78**, 023628 (2008)]

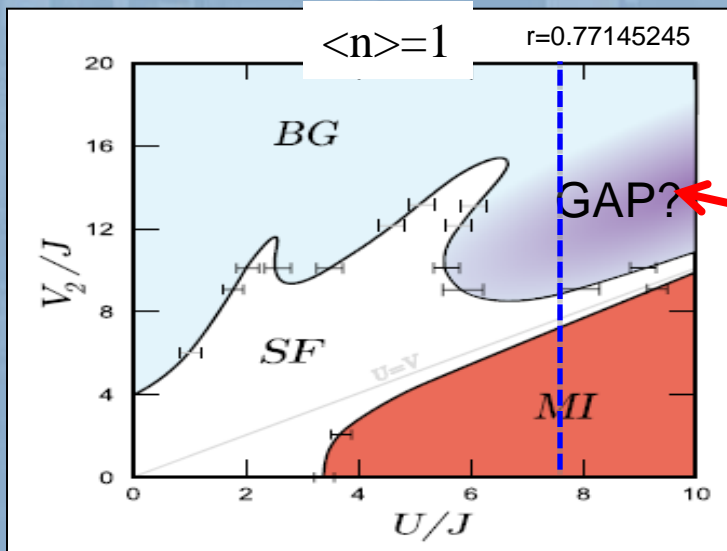
1D gases in quasi-periodic optical lattices

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Extra phase: incommensurate density wave (ICDW)

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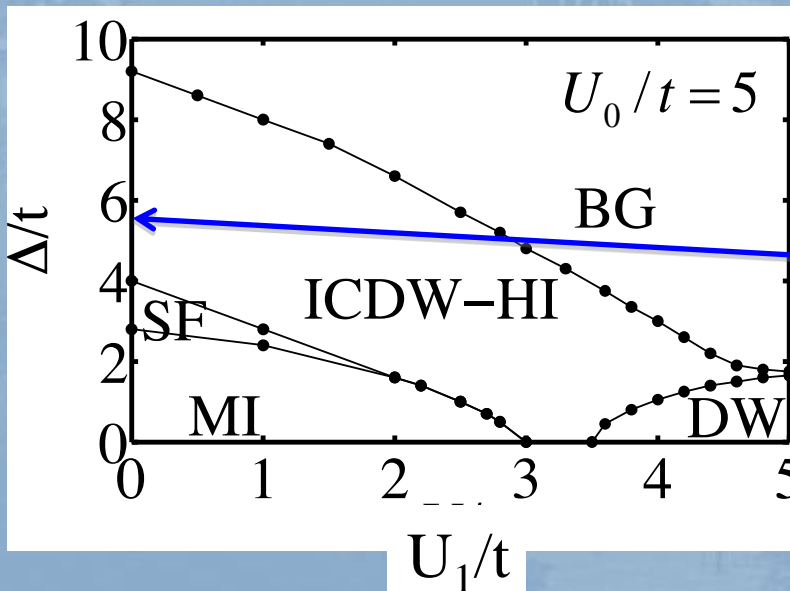
For a filling $\langle n \rangle = 1$ a possible gapped phase may occur as well (generalized ICDW)

1D polar gases in disordered optical lattices

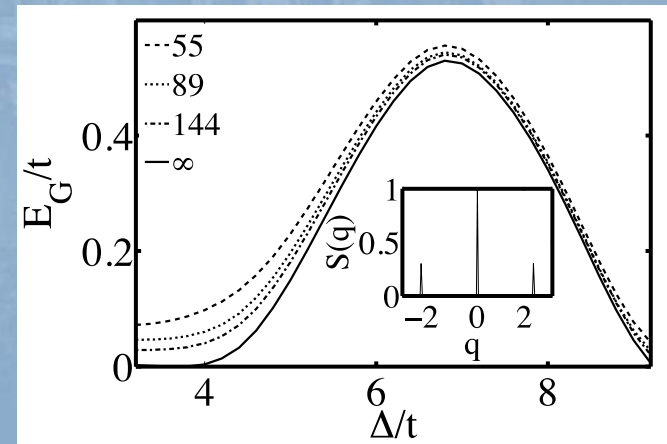
$$H = -t \sum_i [b_i^+ b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bichromatic lattices

$\xrightarrow{\omega}$ $\xleftarrow{\omega}$ $e_j = D \cos(2prj + j)$
 $\xrightarrow{\omega_2}$ $\xleftarrow{\omega_2}$ $r = q_2 / q_1 = (\sqrt{5} - 1) / 2$



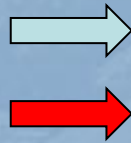
A generalized ICDW phase appears for $\langle n \rangle = 1$ for a sufficiently large 2nd lattice



1D polar gases in disordered optical lattices

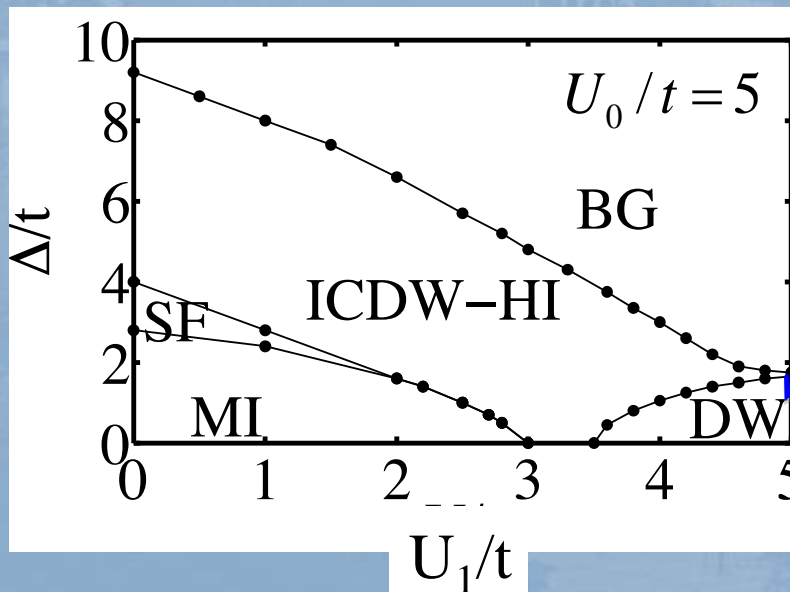
$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i (n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bichromatic lattices



$$e_j = D \cos(2prj + j)$$

$$r = q_2 / q_1 = (\sqrt{5} - 1) / 2$$

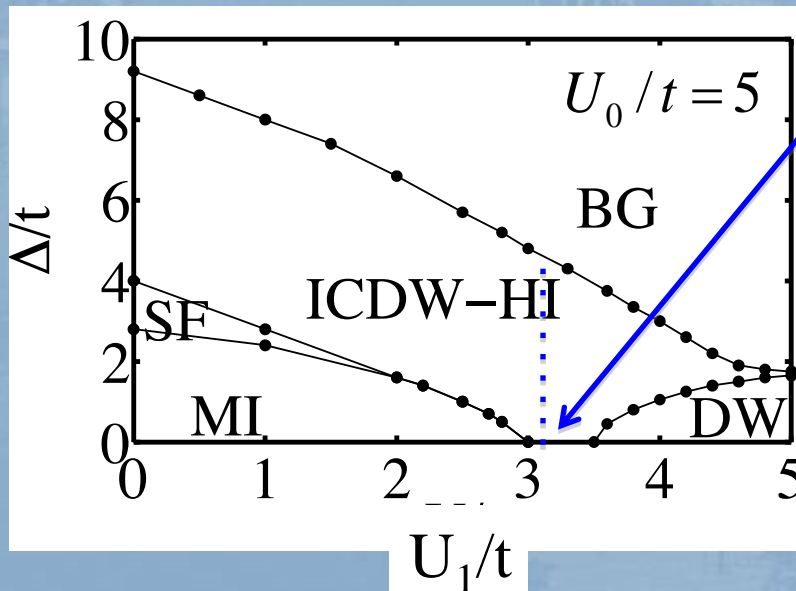
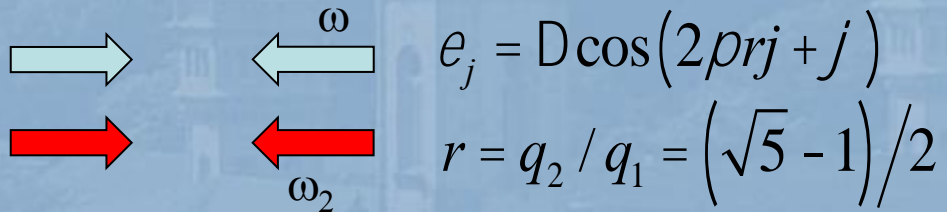


The DW phase survives for a small disorder (no Imry-Ma argument here)

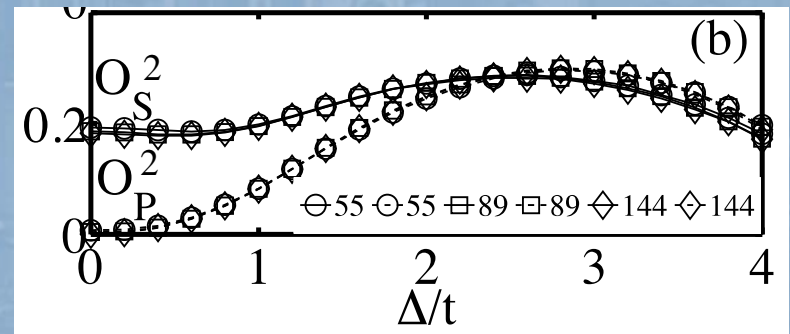
1D polar gases in disordered optical lattices

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Bichromatic lattices



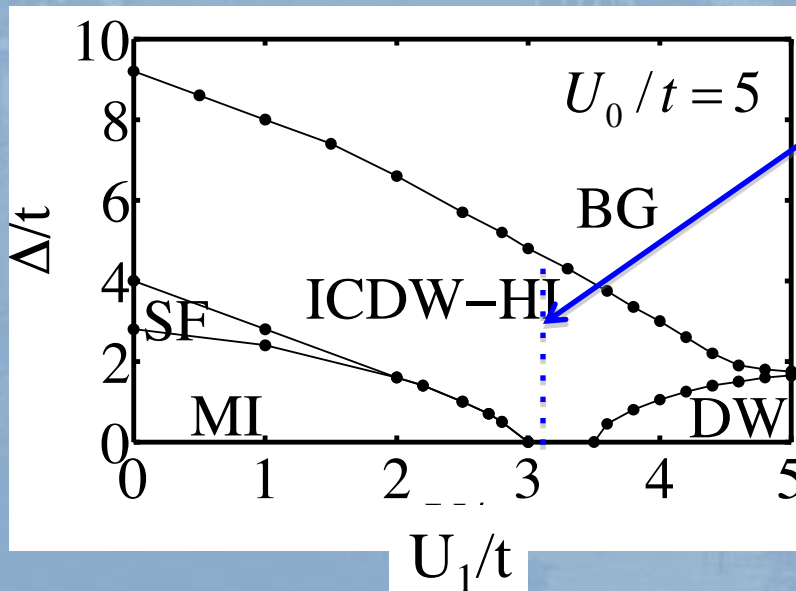
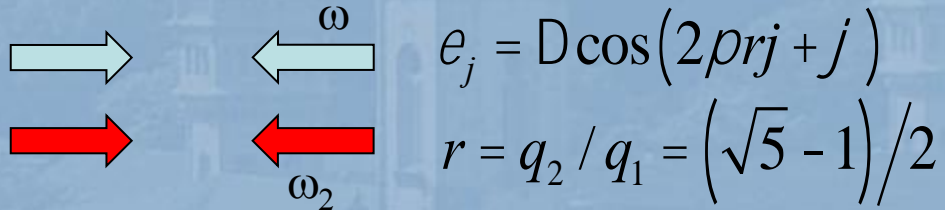
„Glassy“ HI phase due to the pinning of defects



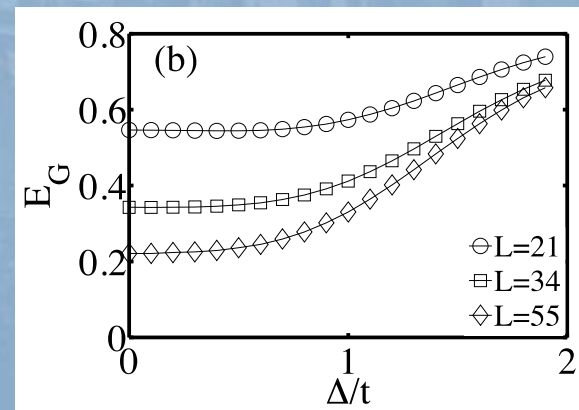
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Bichromatic lattices



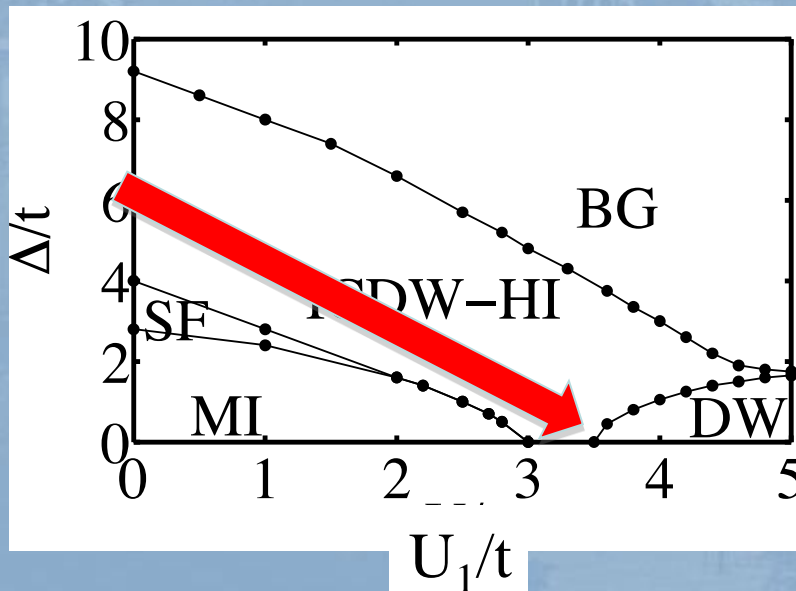
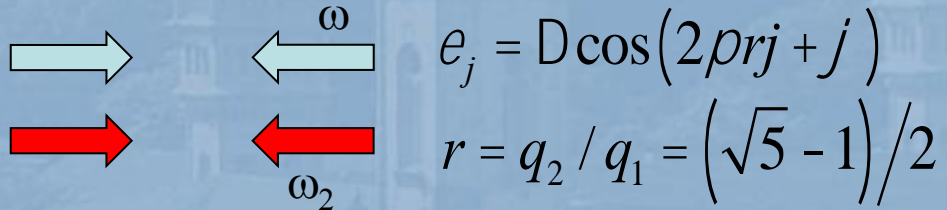
The „glassy“ HI phase connects adiabatically with the ICDW (which has also $O_S^2, O_P^2 > 0$)



1D polar gases in disordered optical lattices

$$H = -t \sum_i [b_i^\dagger b_{i+1} + H.c.] + \frac{U_0}{2} \sum_i n_i(n_i - 1) + U_1 \sum_i n_i n_{i+1} + \sum_i \varepsilon_i n_i$$

Bichromatic lattices



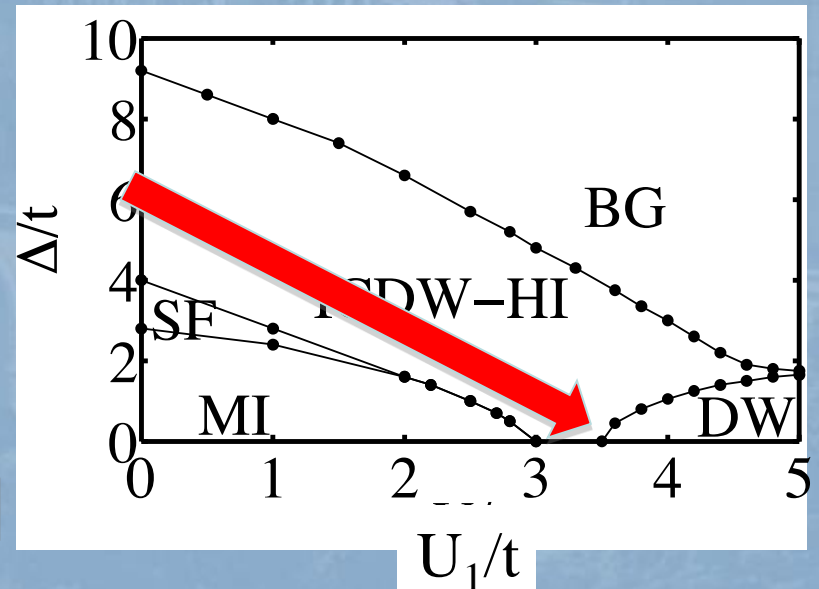
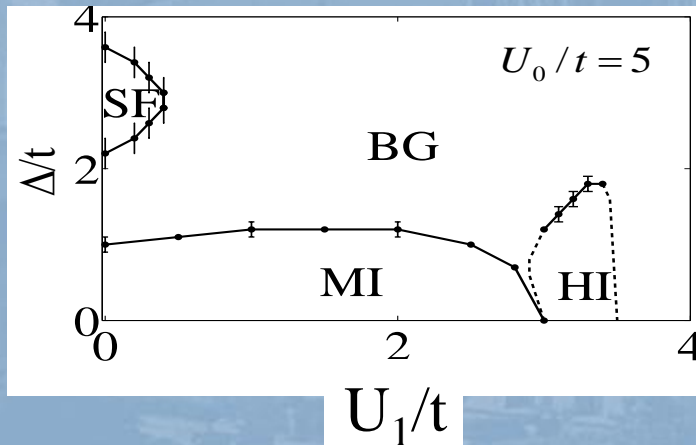
This may open an interesting route (protected by a gap) for the creation of the HI phase

Summary

Polar gases behave very differently in uniformly disordered lattices and quasi-periodic lattices

Uniform disorder: glassy HI (dissapearing into a BG) and rapidly vanishing DW

Quasi-disorder: finite DW, glassy-HI and ICDW adiabatically connected



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T. Vekua



G. Sun



+ G. Jackeli (MPI-FKP, Stuttgart)