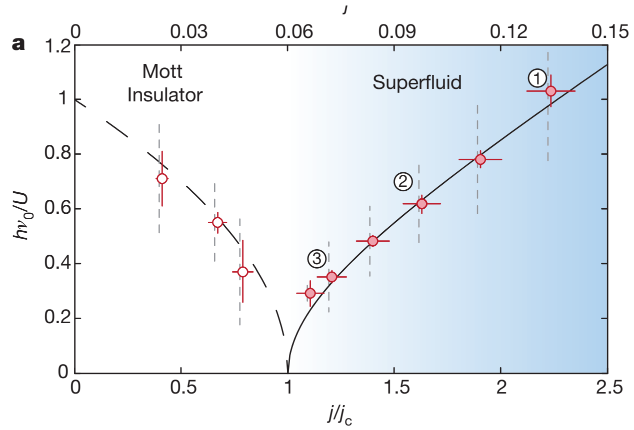
ETH zürich

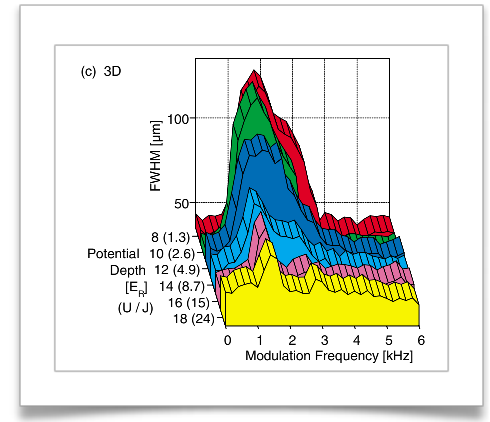
Amplitude modes and cold atoms

Sebastian Huber

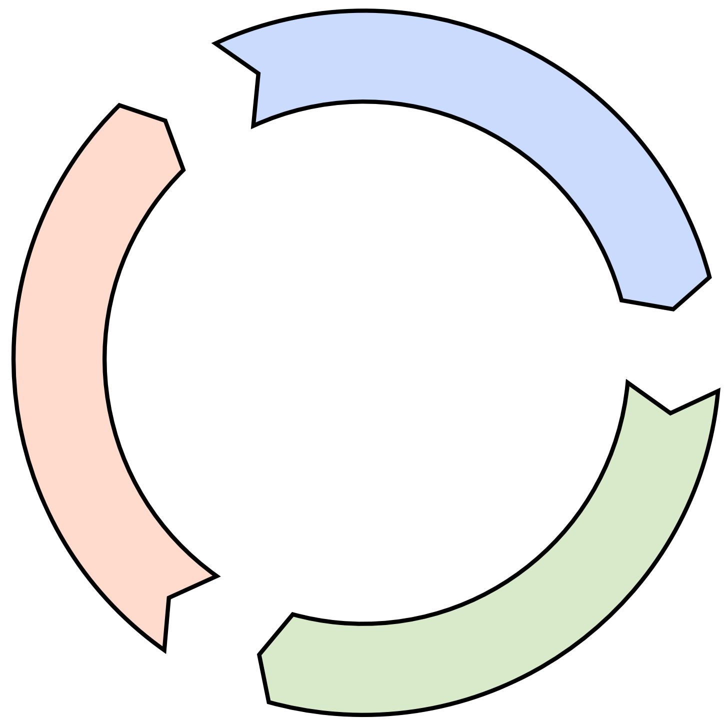
Endres Nature 2012



Experiments



Stöferle PRL 2004



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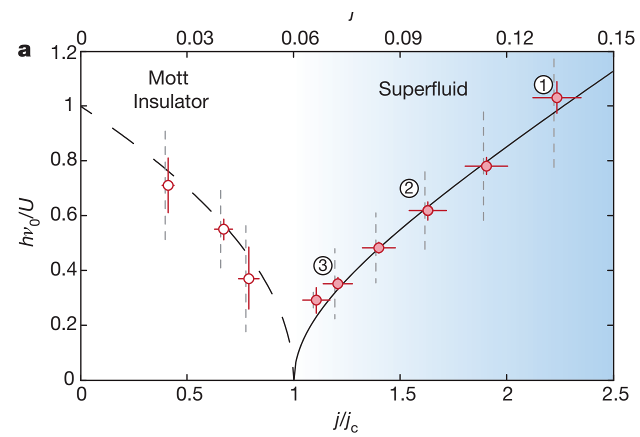
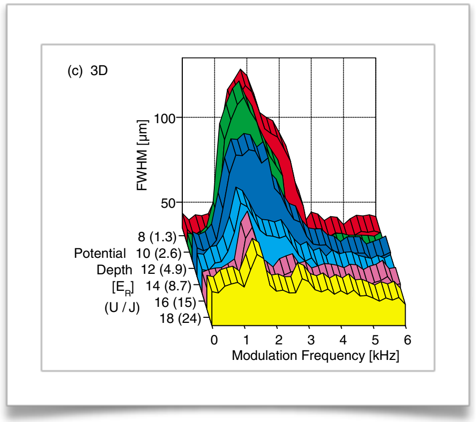


Experiments



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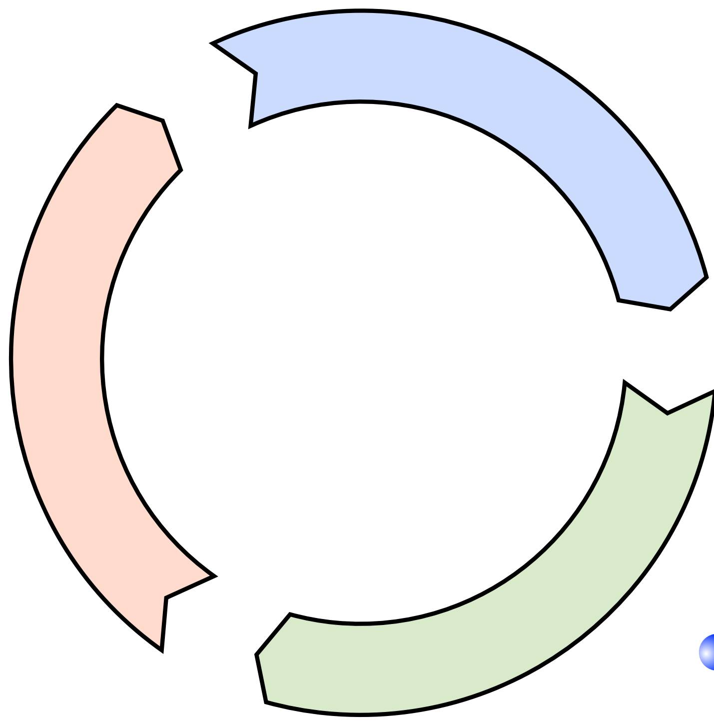
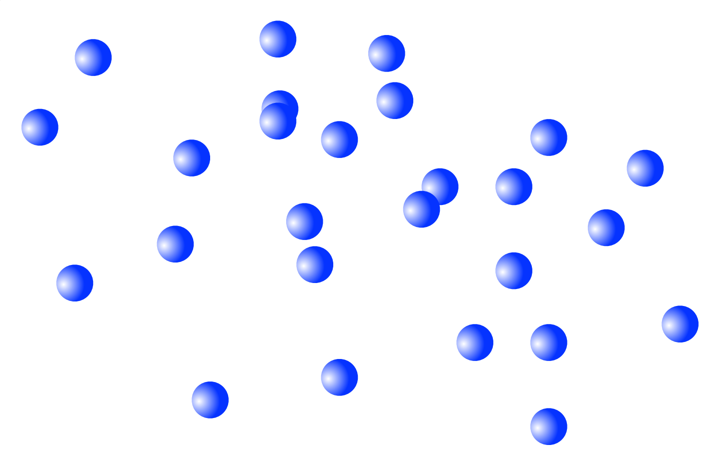
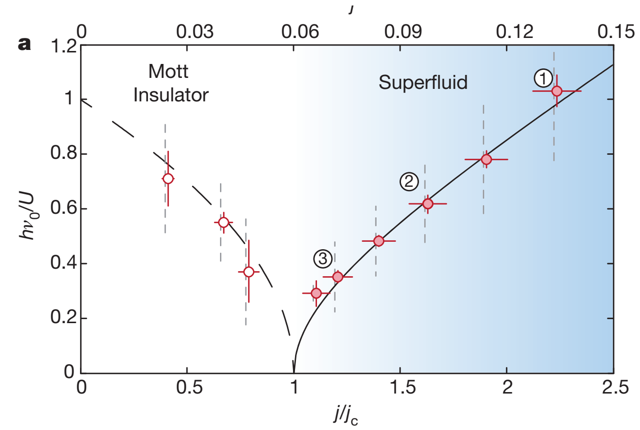


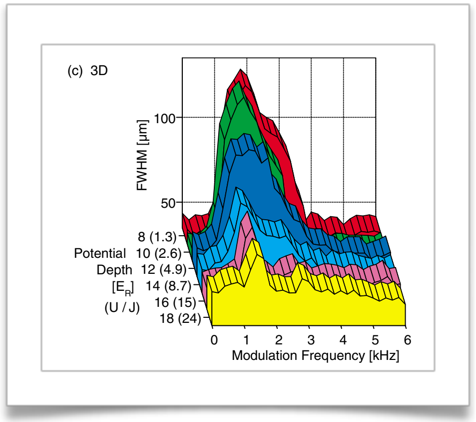


Microscopic description

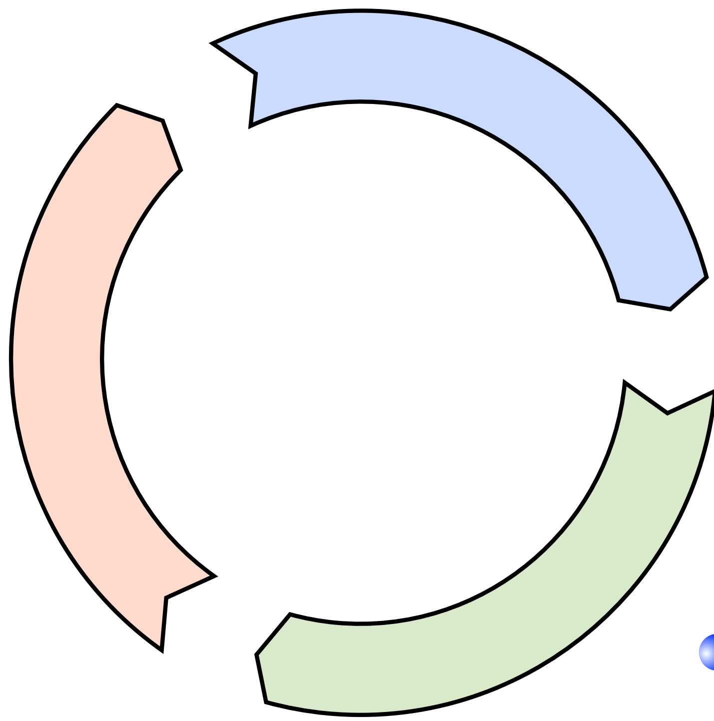
Endres Nature 2012

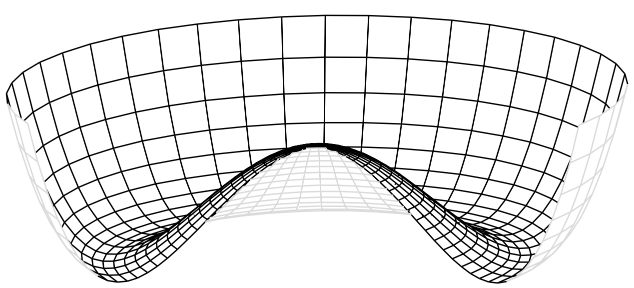


Experiments

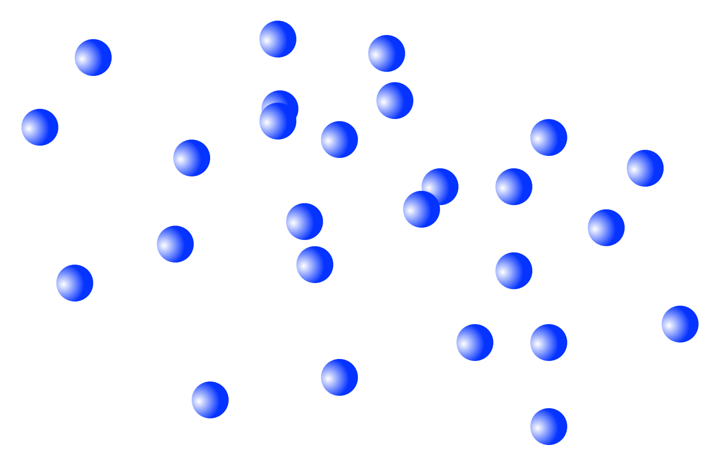


Stöferle PRL 2004



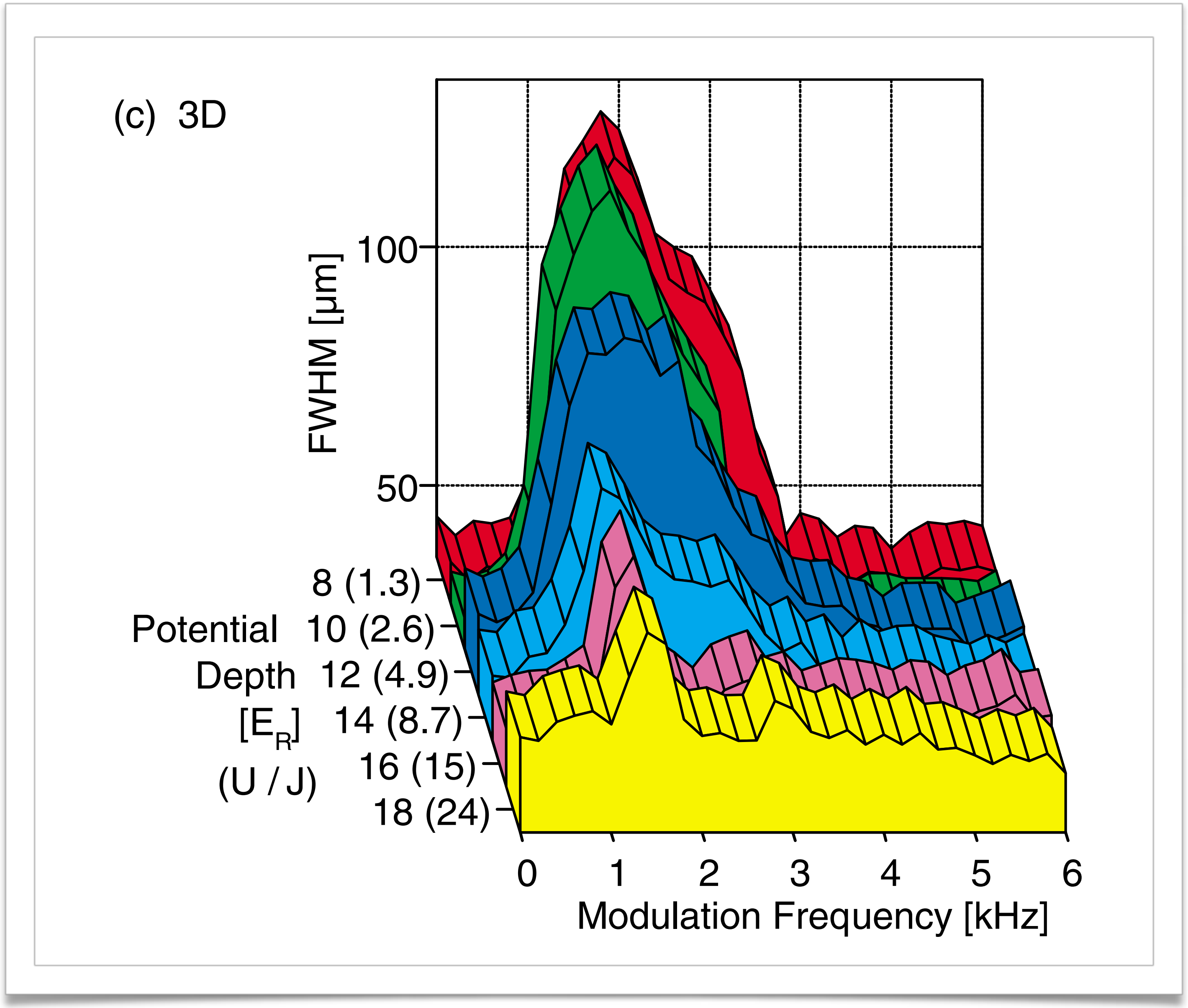


Interpretation in terms of a “Higgs” phenomena



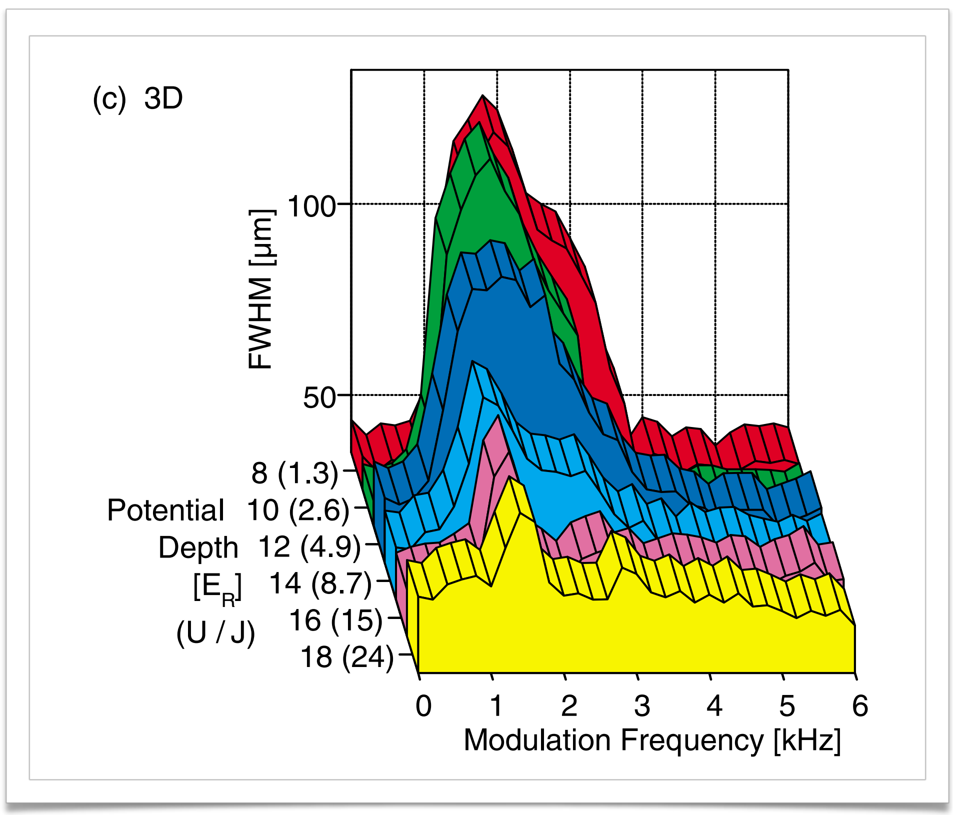
Microscopic description

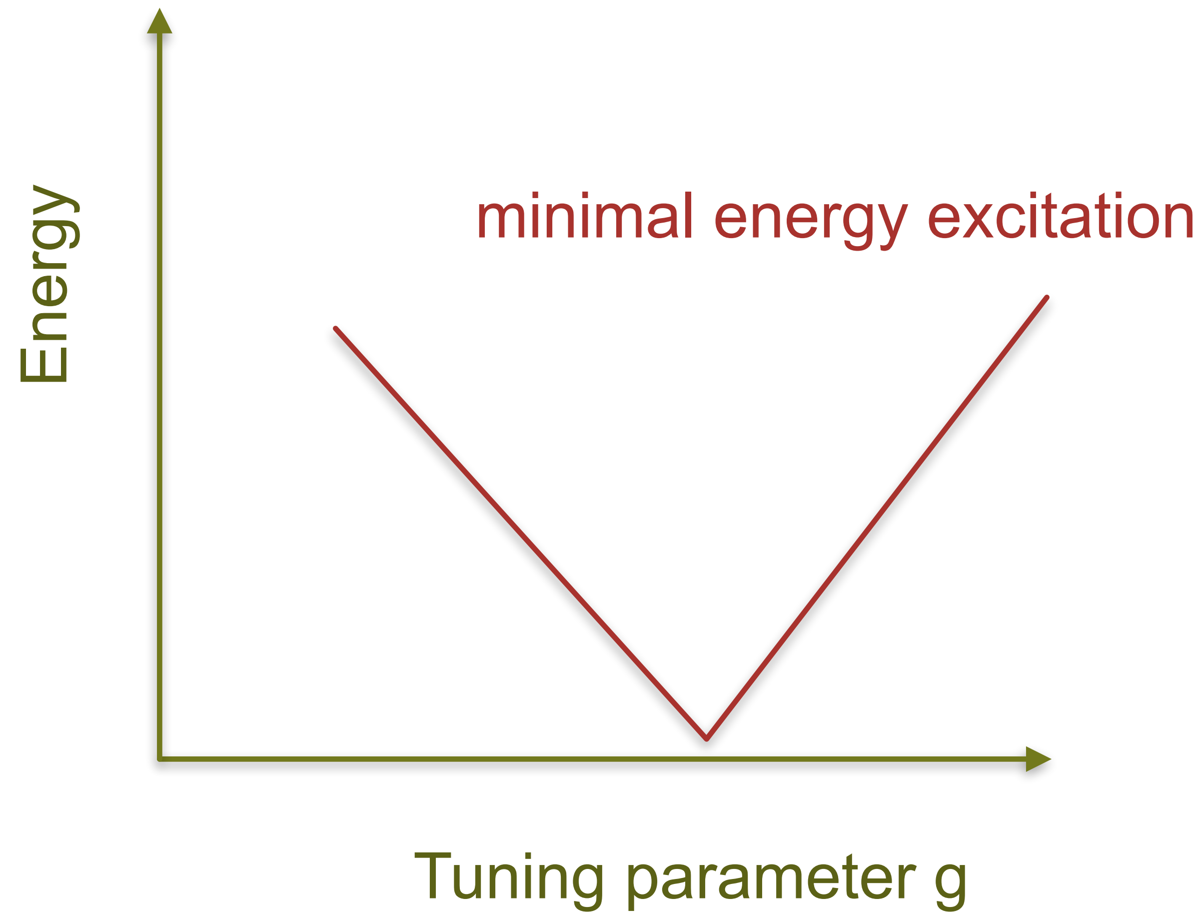
The starting point



Stöferle PRL 2004

The starting point



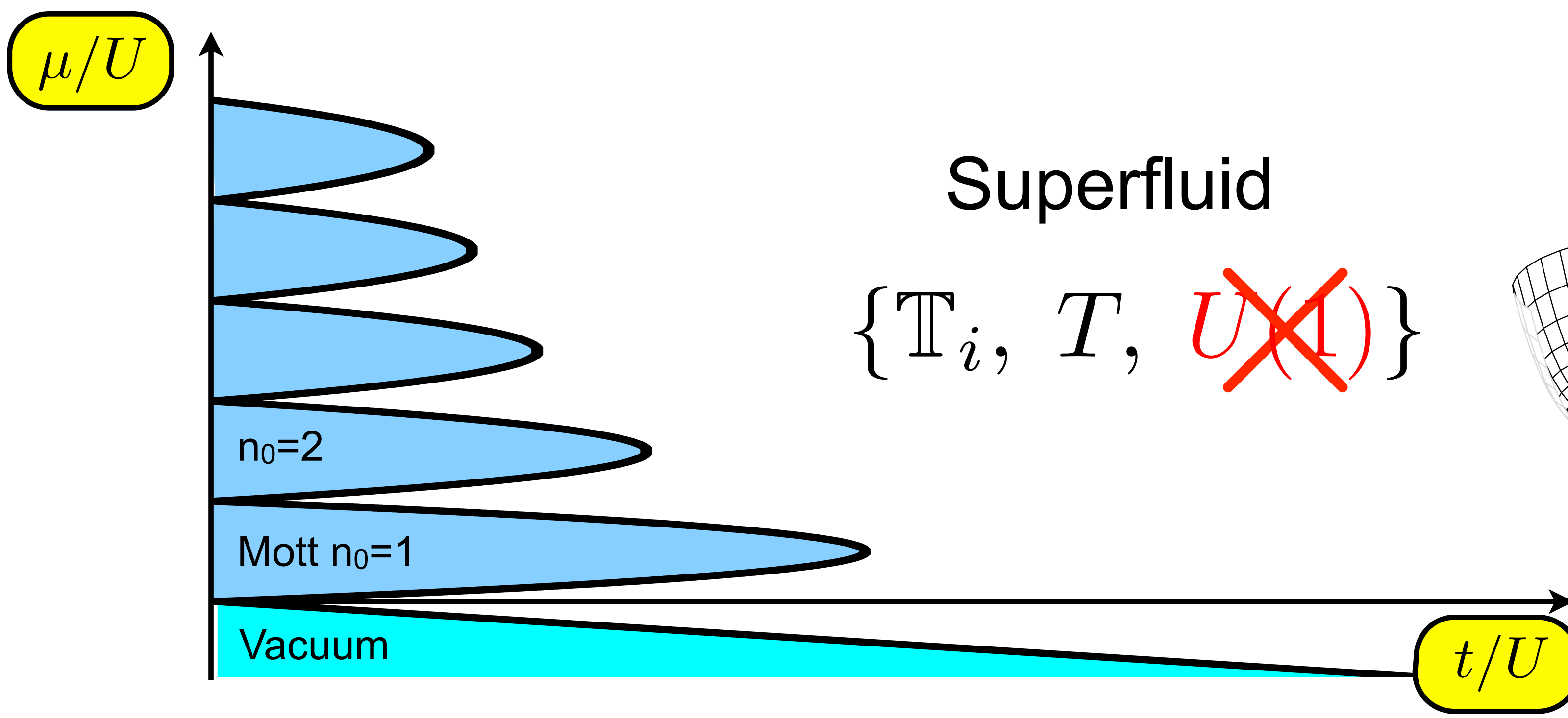


Stöferle PRL 2004

The system: the Bose Hubbard model

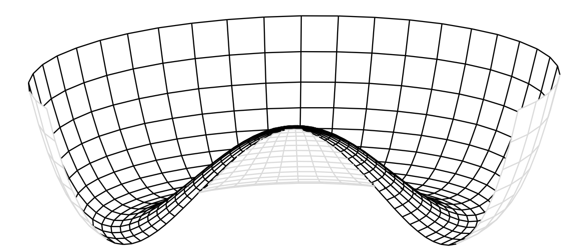
$$H_{\mathrm{BH}} = -t \sum_{\langle i,j \rangle} a_i^\dagger a_j + \frac{U}{2} \sum_i a_i^\dagger a_i (a_i^\dagger a_i - 1) - \mu \sum_i a_i^\dagger a_i$$

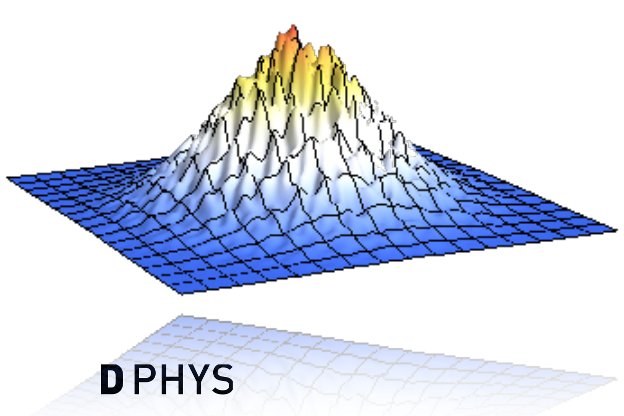
Symmetries: $\{\mathbb{T}_i,\ T,\ U(1)\}$



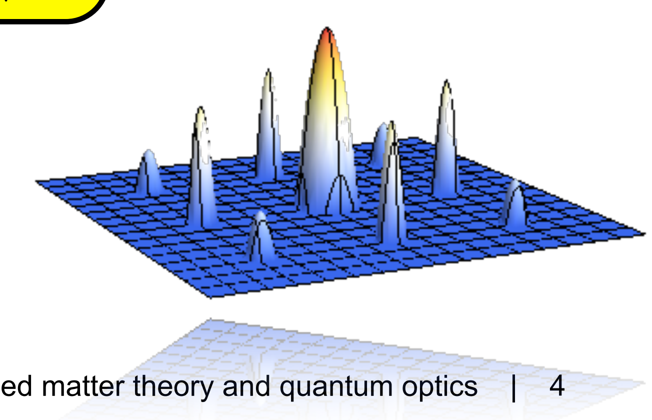
Superfluid

$\{\mathbb{T}_i,\ T,\ \cancel{U(1)}\}$

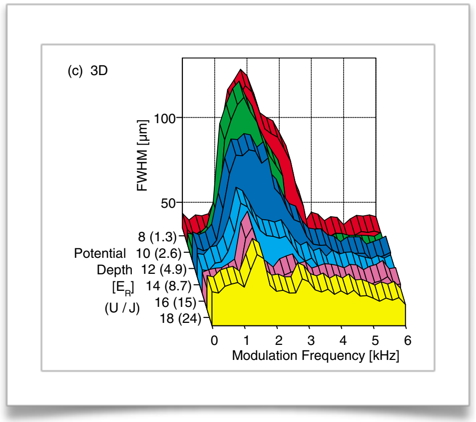




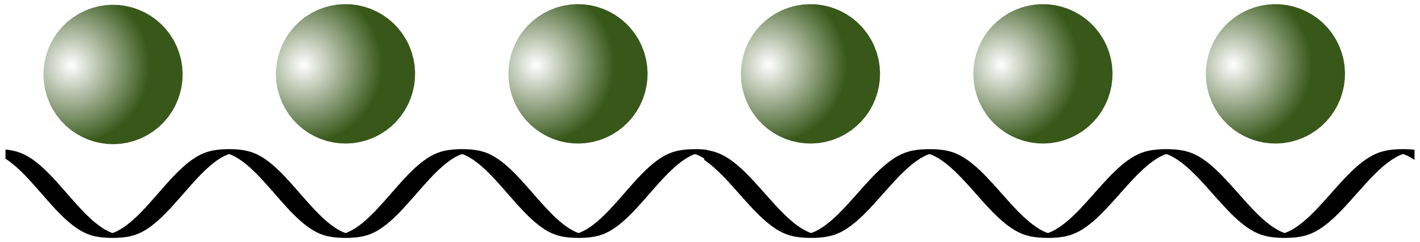
Fisher PRB 1989
Greiner Nature 2002



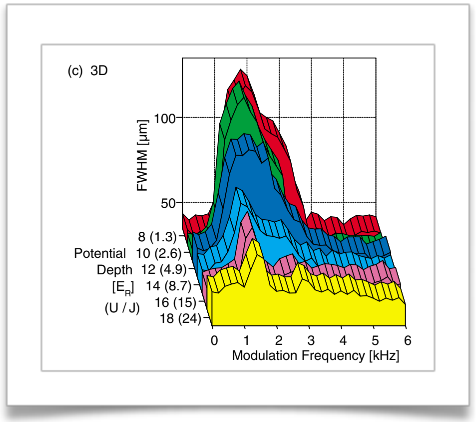
Excitations: Microscopic description I



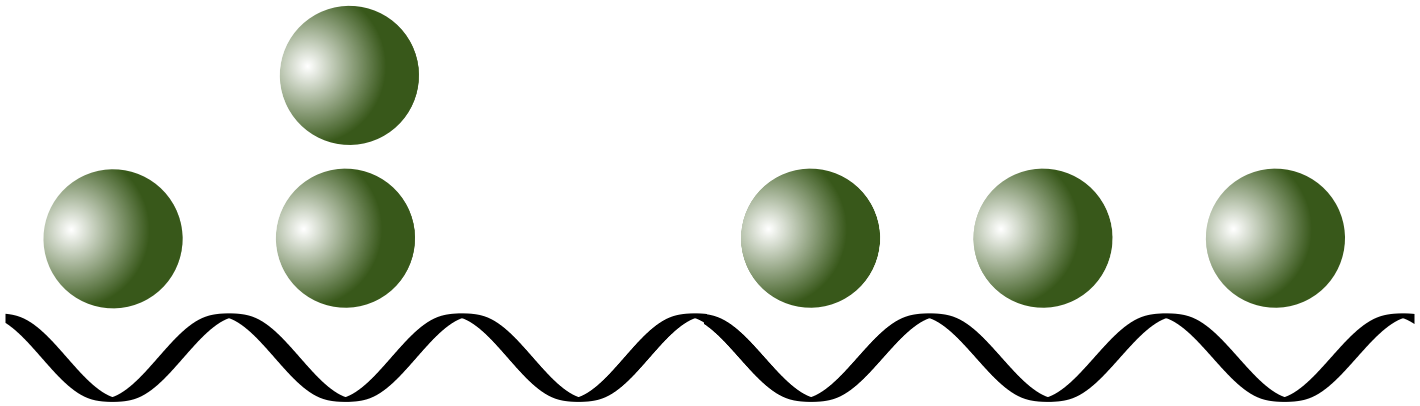
Stöferle PRL 2003



Excitations: Microscopic description I

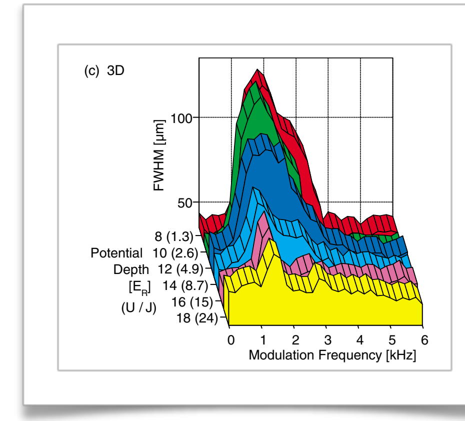


Stöferle PRL 2003



$$\hbar\omega(k) = \frac{U}{2}$$

Excitations: Microscopic description I



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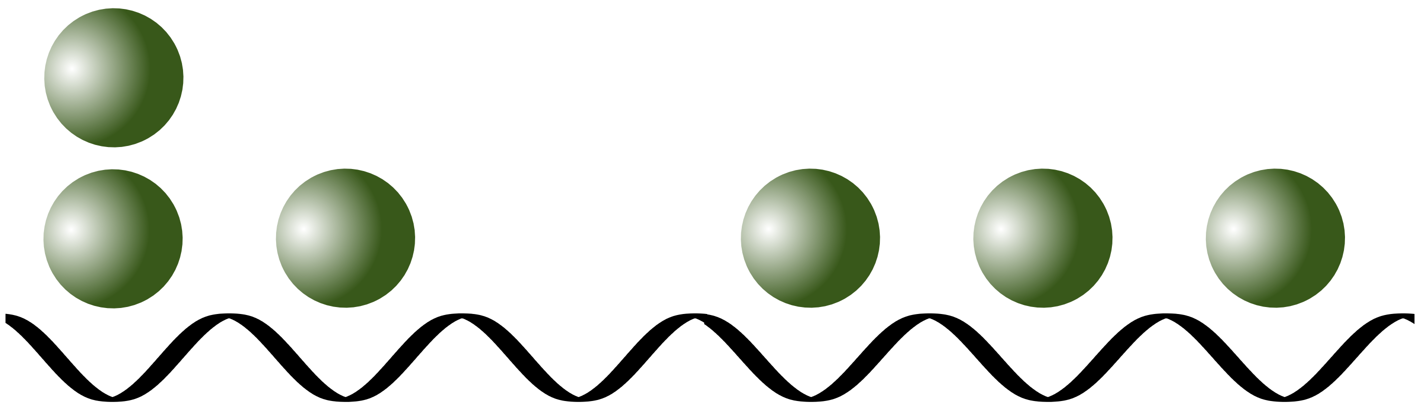
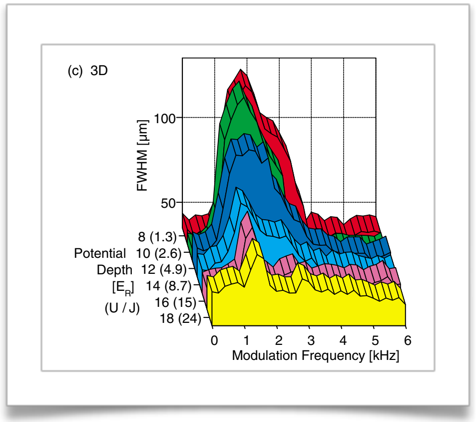
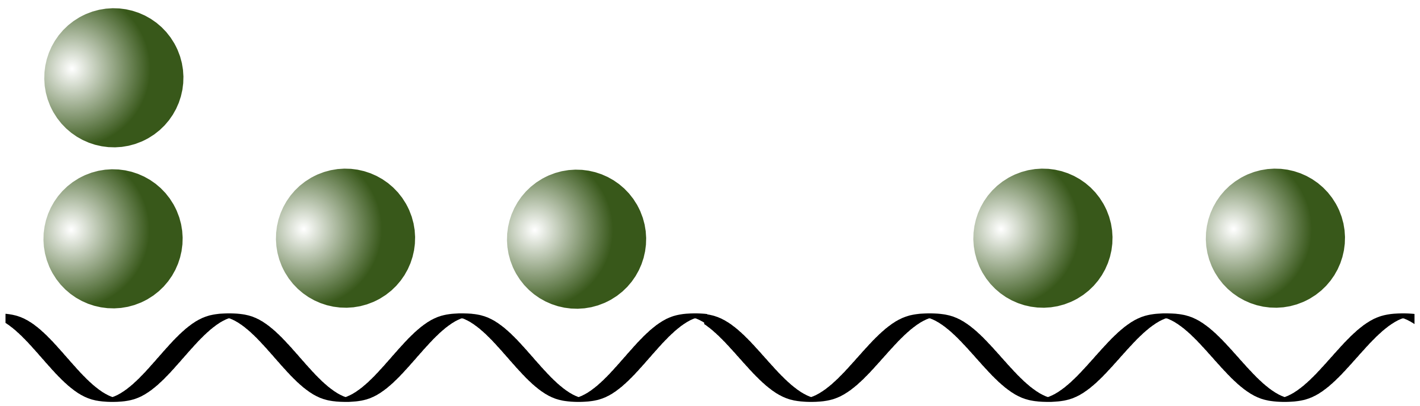


$$\hbar\omega(k) = \frac{U}{2} - 4t\cos(k)$$

Excitations: Microscopic description I



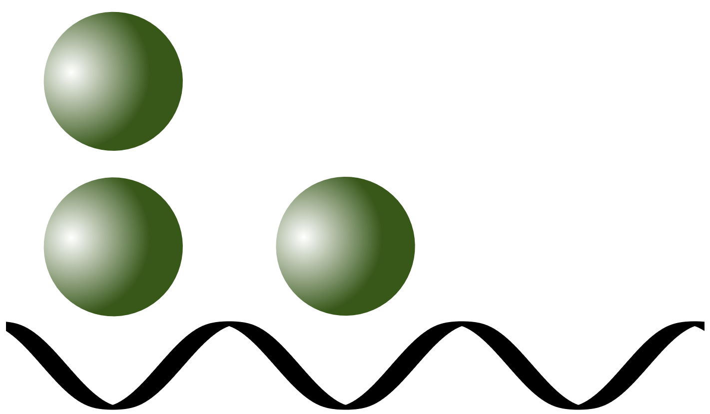
Stöferle PRL 2003



$$\hbar\omega(k) = \frac{U}{2} - 4t\cos(k)$$

$$\hbar\omega(k) = \frac{U}{2} - 2t\cos(k)$$

Excitations: Microscopic description II

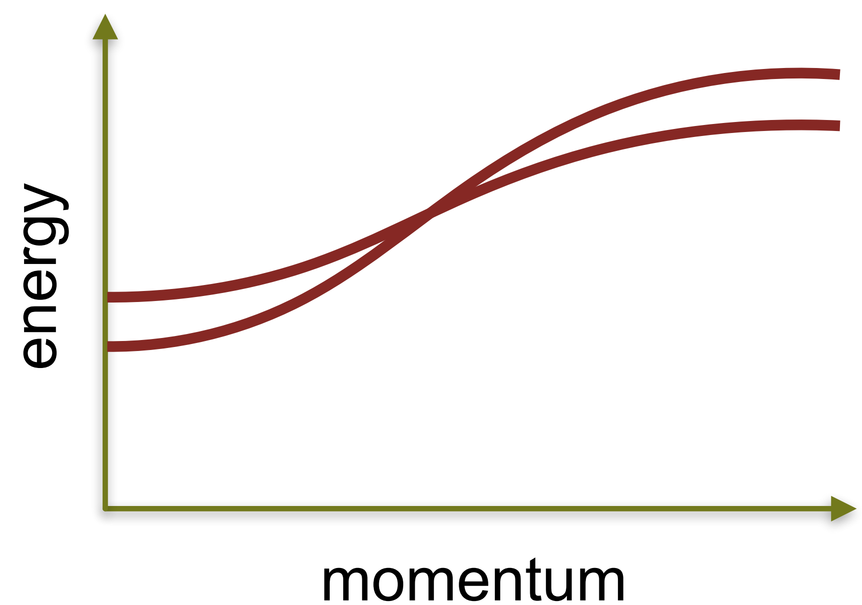


$$|+1\rangle \quad |0\rangle \quad |-1\rangle$$

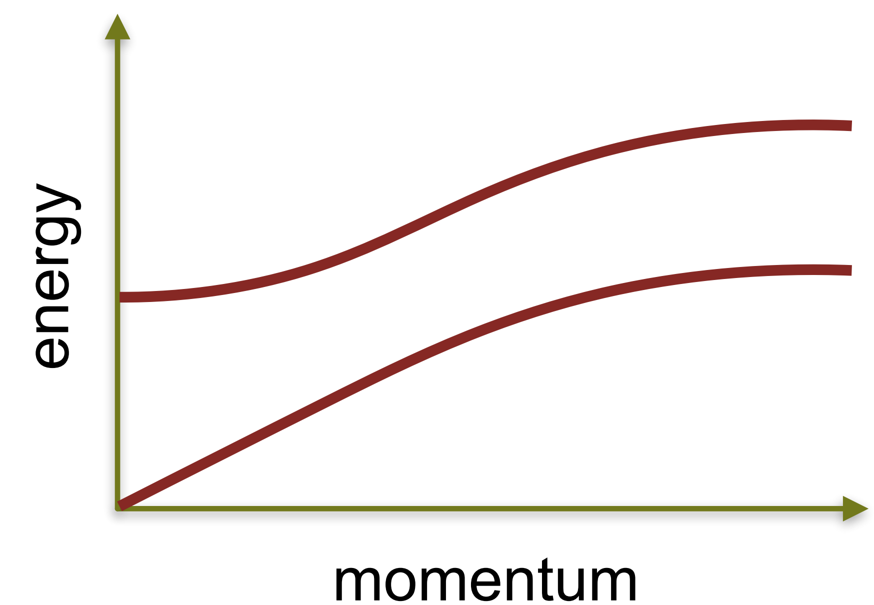
$$H_{\text{eff}} = -\frac{t}{2}\sum_{\langle i,j\rangle} S_i^+ S_j^- + \frac{U}{2}\sum_i (S_i^z)^2 - t\xi \sum_{\langle i,j\rangle} S_i^+ S_i S_j^- + \ldots$$

Altman PRL 2002
SDH PRB 2007

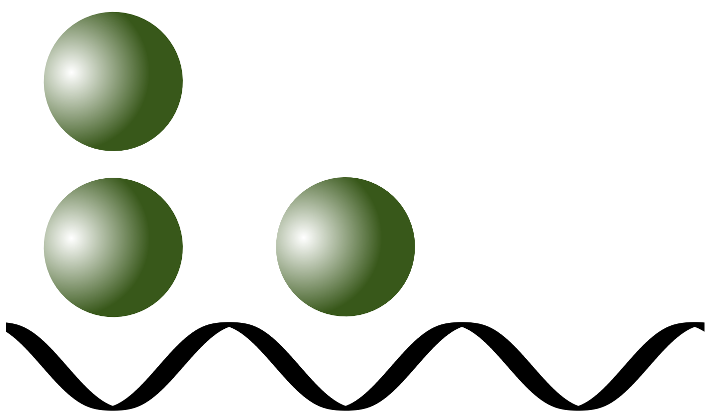
Mott insulator



Superfluid



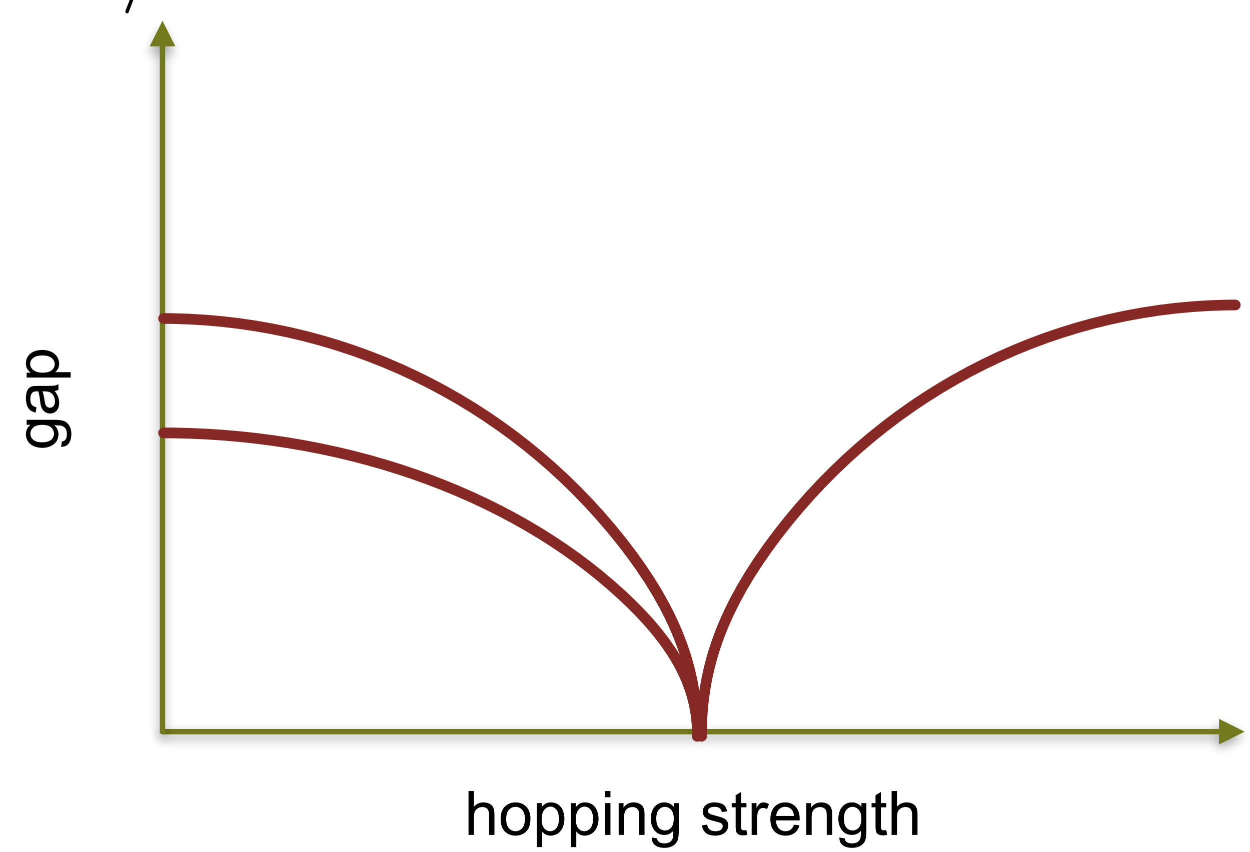
Excitations: Microscopic description III



$|+1\rangle \quad |0\rangle \quad |-1\rangle$

$$H_{\text{eff}} = -\frac{t}{2}\sum_{\langle i,j\rangle} S_i^+ S_j^- + \frac{U}{2}\sum_i (S_i^z)^2 - t\xi \sum_{\langle i,j\rangle} S_i^+ S_i S_j^- + \dots$$

SDH PRB 2007
SDH PRL 2008



Symmetries and energy scales

- Lorentz invariant
  - Electrodynamics
  - electrons and protons
- Galilei invariant
  - van der Waals & AC Stark shift
  - neutral atoms
- discrete symmetries
  - Single band Hubbard model
  - neutral atoms

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Symmetries and energy scales

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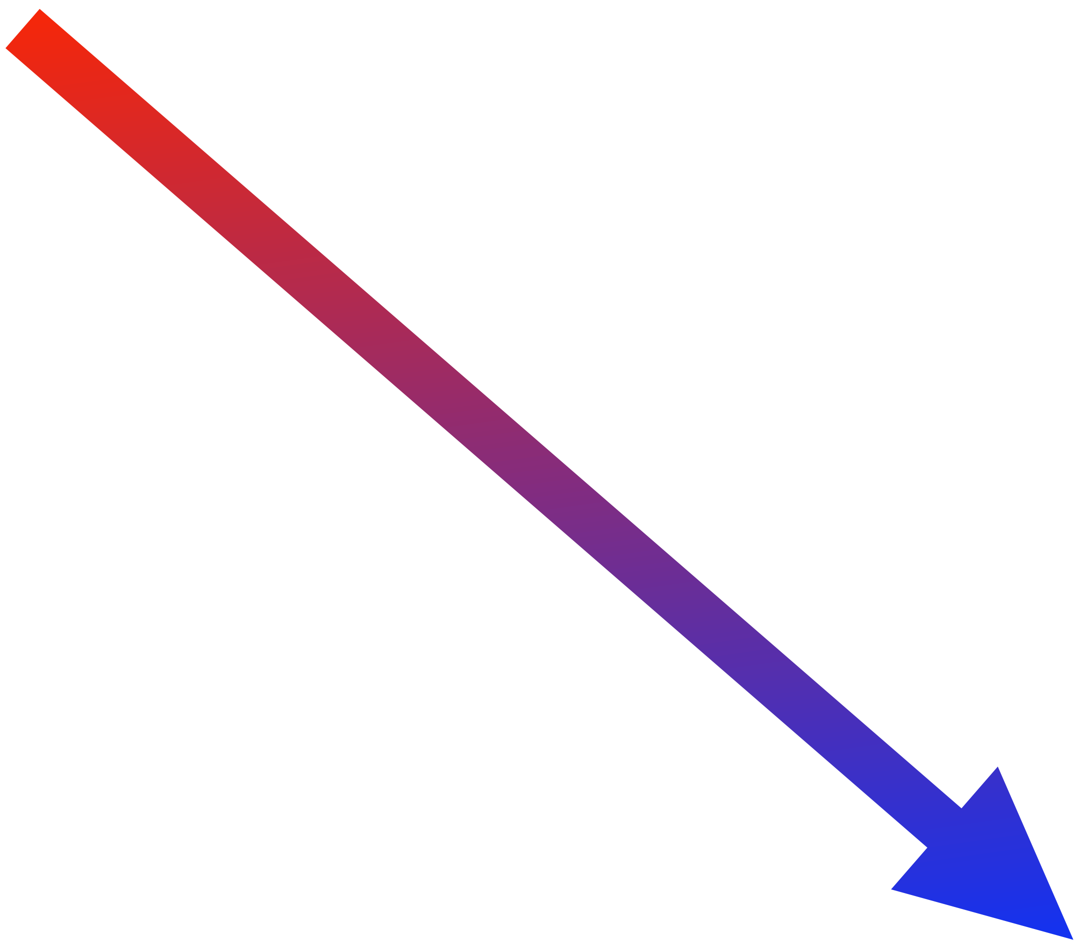
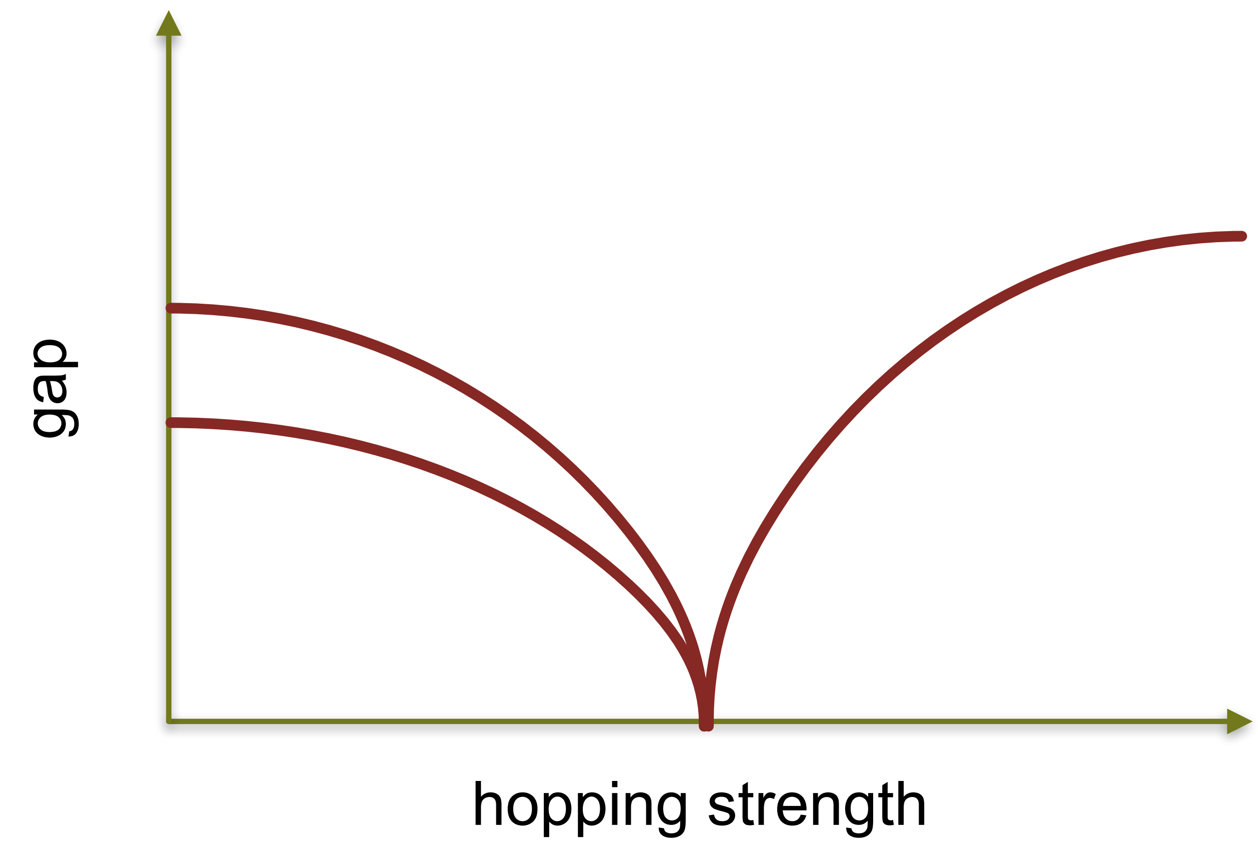
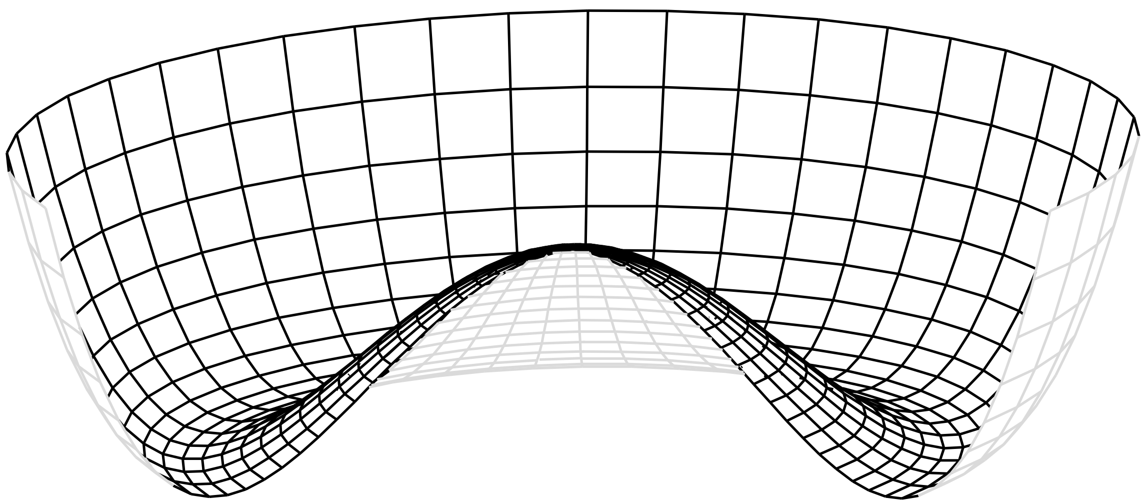




Excitation: Long-wavelength theory

$$\psi_i = \langle a_i \rangle$$

$$V(\psi_i) = r\psi_i^2 + \frac{u}{2}\psi_i^4$$

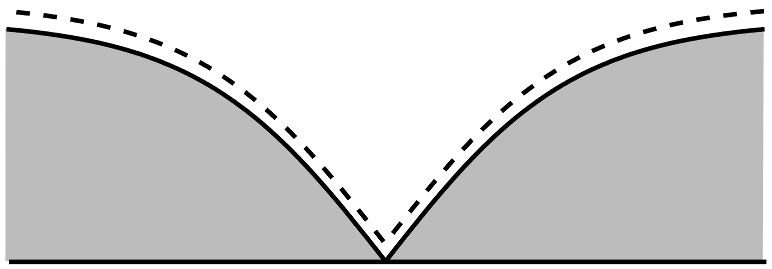


weakly interacting bosons: Gross-Pitaevskii

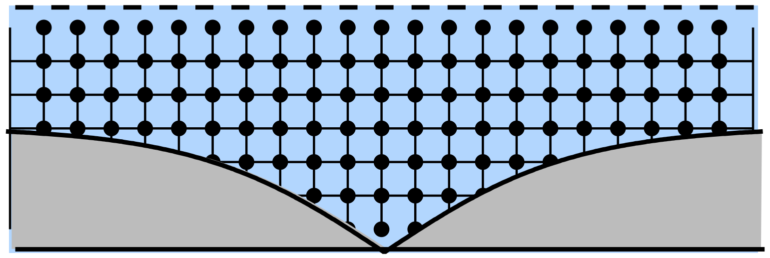
$$i\psi^*\partial_t\psi + (\nabla\psi)^2$$

Mott transition: relativistic critical theory

$$(\partial_t\psi)^2 + (\nabla\psi)^2$$

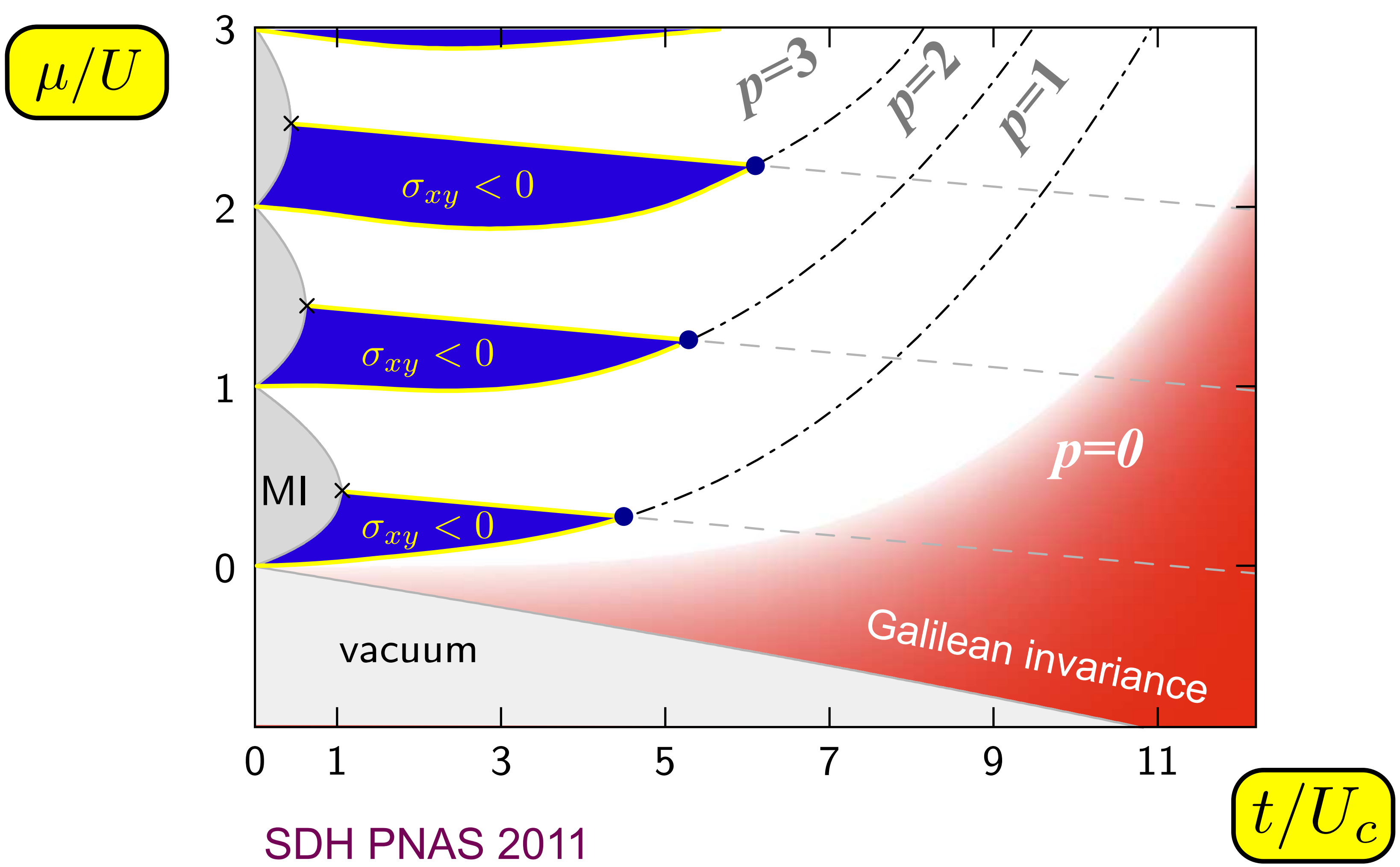


SDH PRL 2008
Polkovnikov PRA 2005
Varma J. Low Temp. Phys. 2002



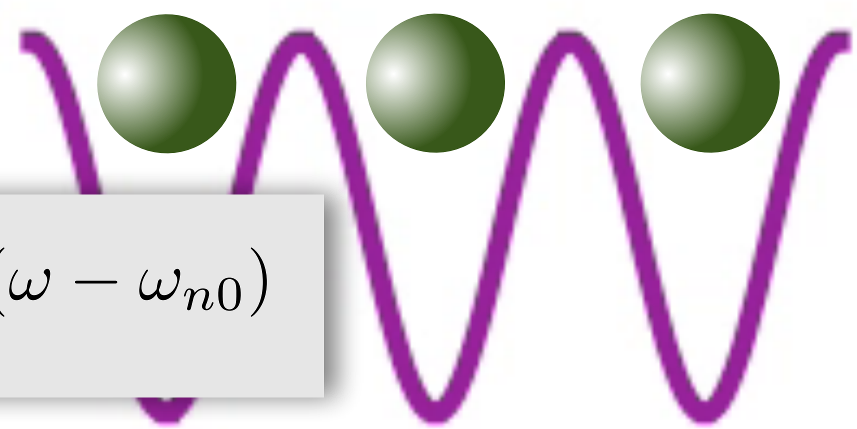
Where is the emergent physics relativistic?

$$\boxed{\sigma_{xy} = \rho + p}$$

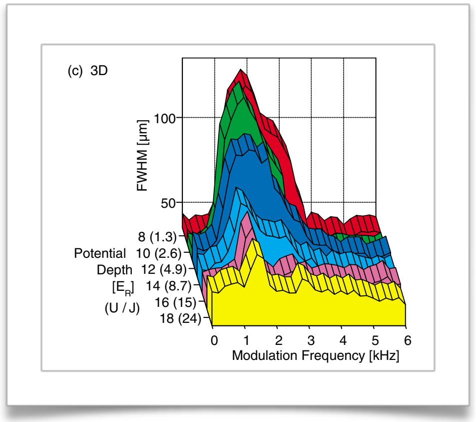


SDH PNAS 2011

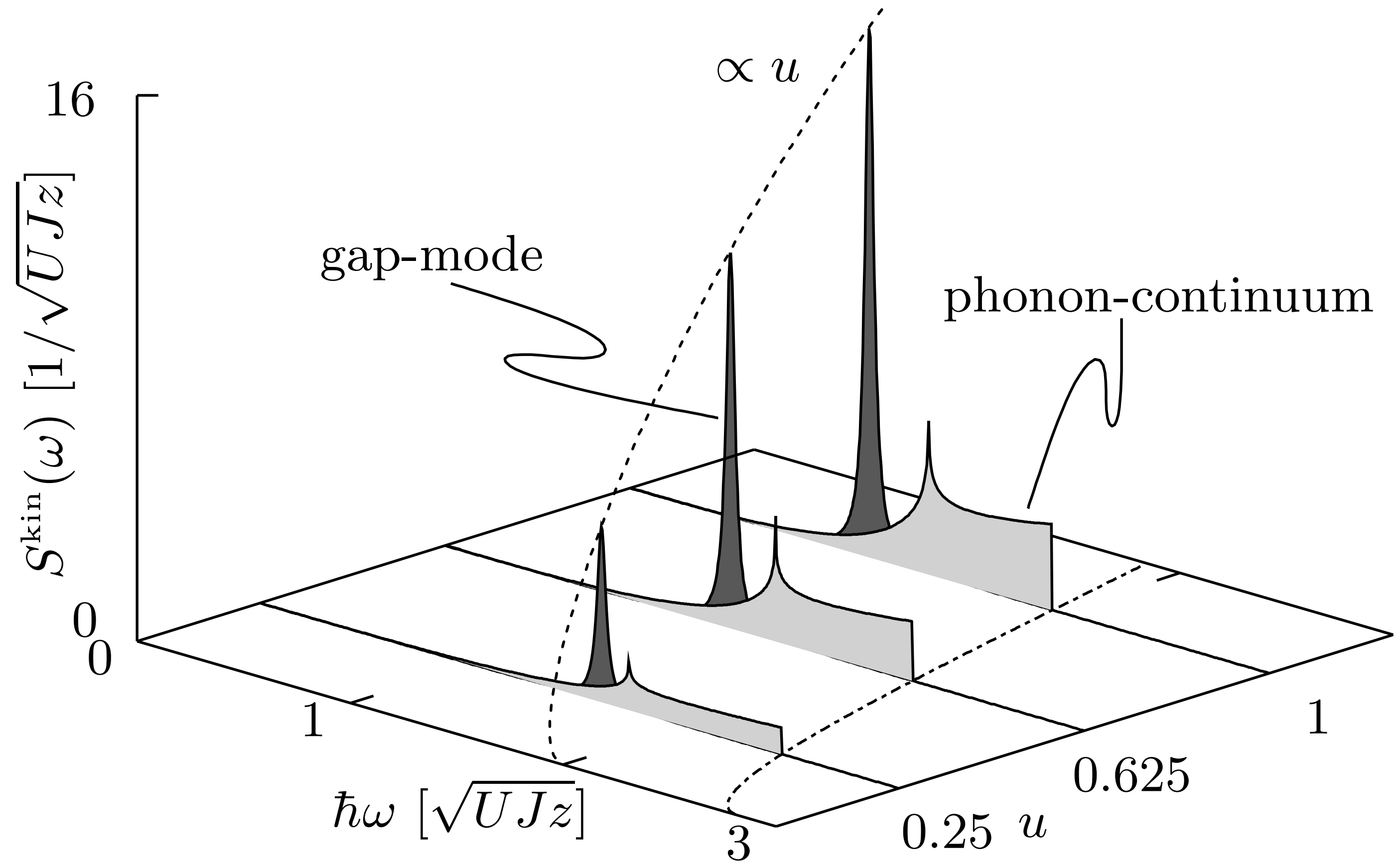
Experiments?



$$S^{\mathrm{kin}}_{(x)}(\omega) = \sum_n |\langle n|H^{\mathrm{kin}}_{(x)}|0\rangle|^2 \delta(\omega - \omega_{n0})$$



SDH PRB 2007
SDH PRL 2008



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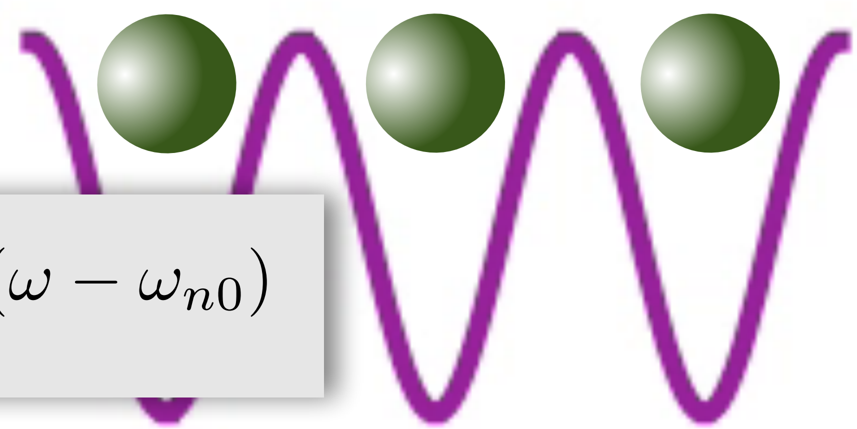

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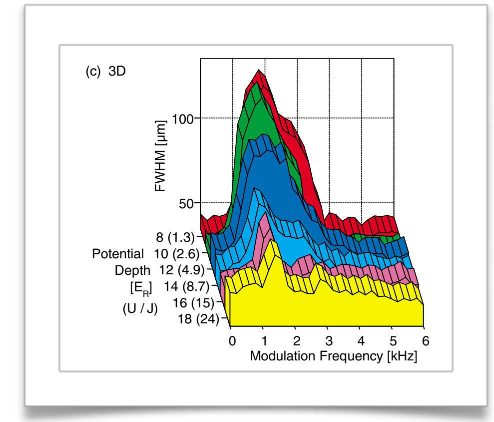

SDH PRB 2007
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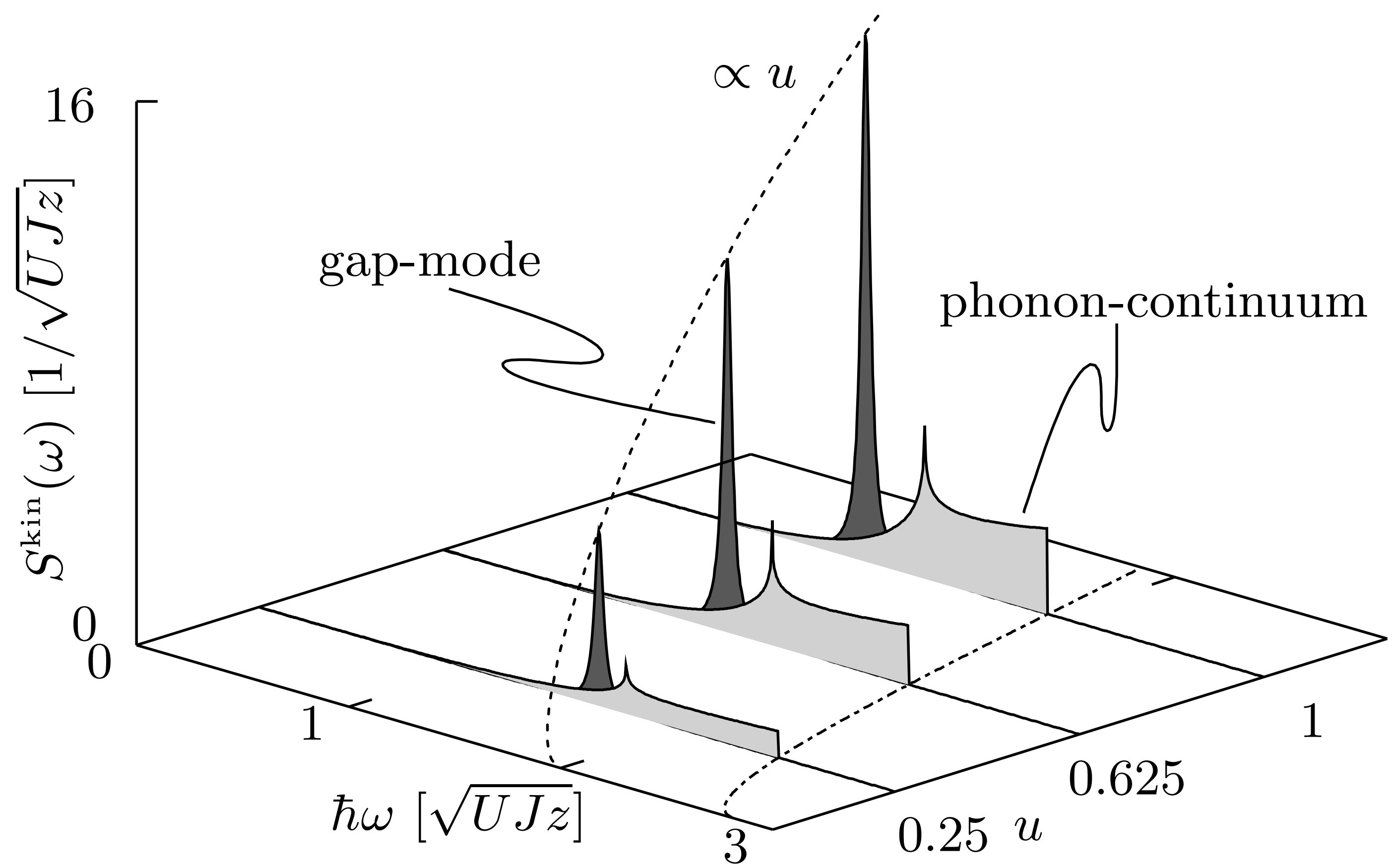

More models: more amplitude modes

$$\{\mathbb{T}_i,\, T,\, U(1)\} \;\Rightarrow\; \{\mathbb{T}_i,\, T,\, \cancel{U(1)}\}$$

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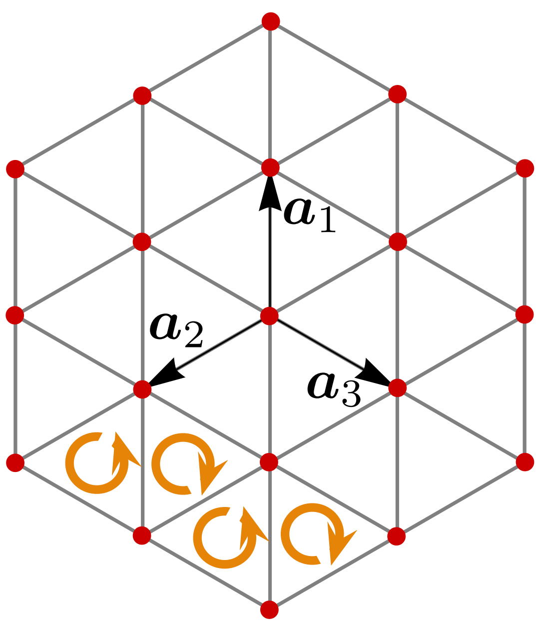
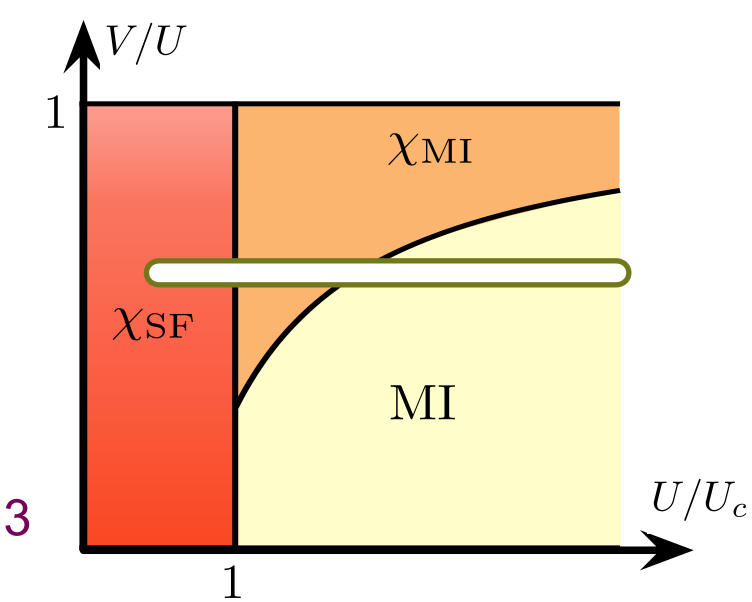
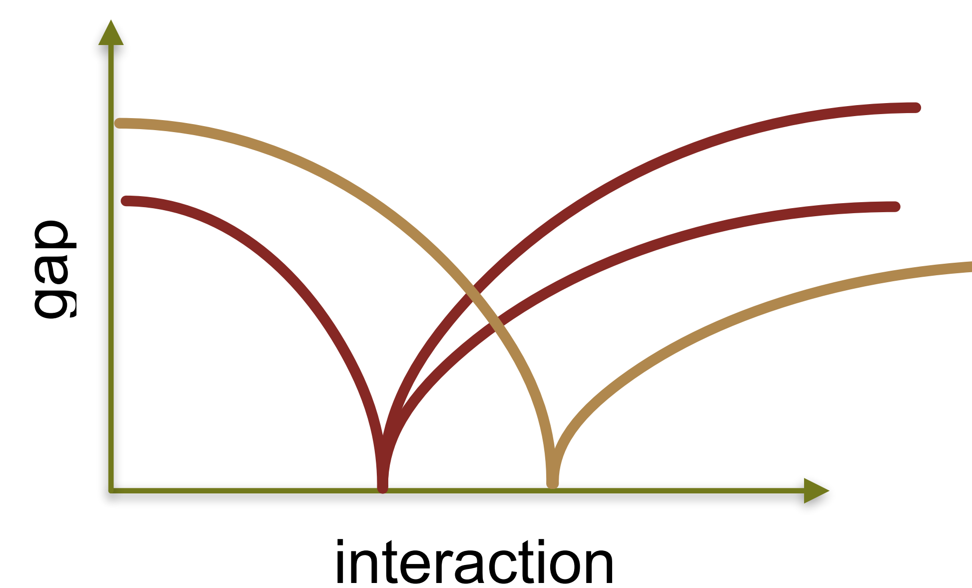


$$H = |t| \sum_{\langle i,j \rangle} a_i^\dagger a_j + \frac{U}{2} \sum_i (\delta n_i)^2 + V \sum_{\langle i,j \rangle} \delta n_i \delta n_j$$



Rüegg arXiv 2013



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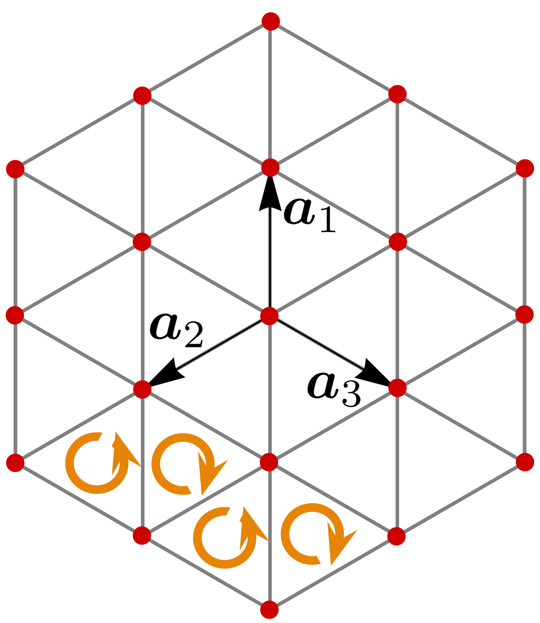

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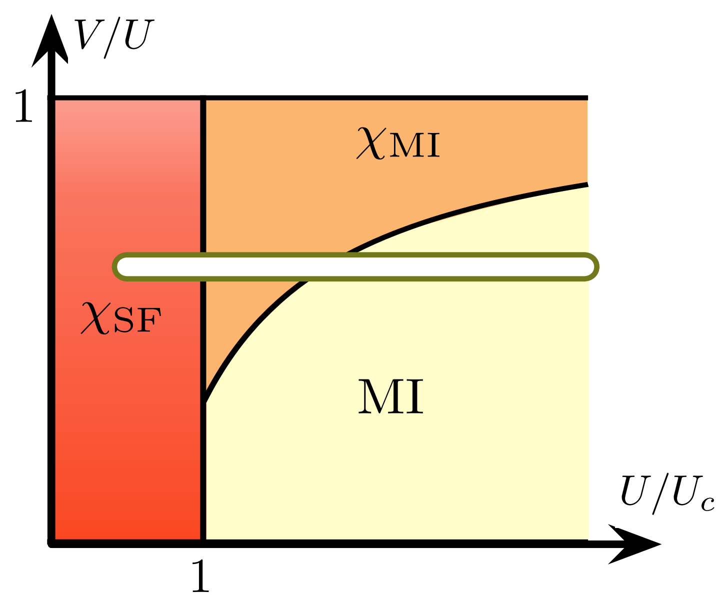
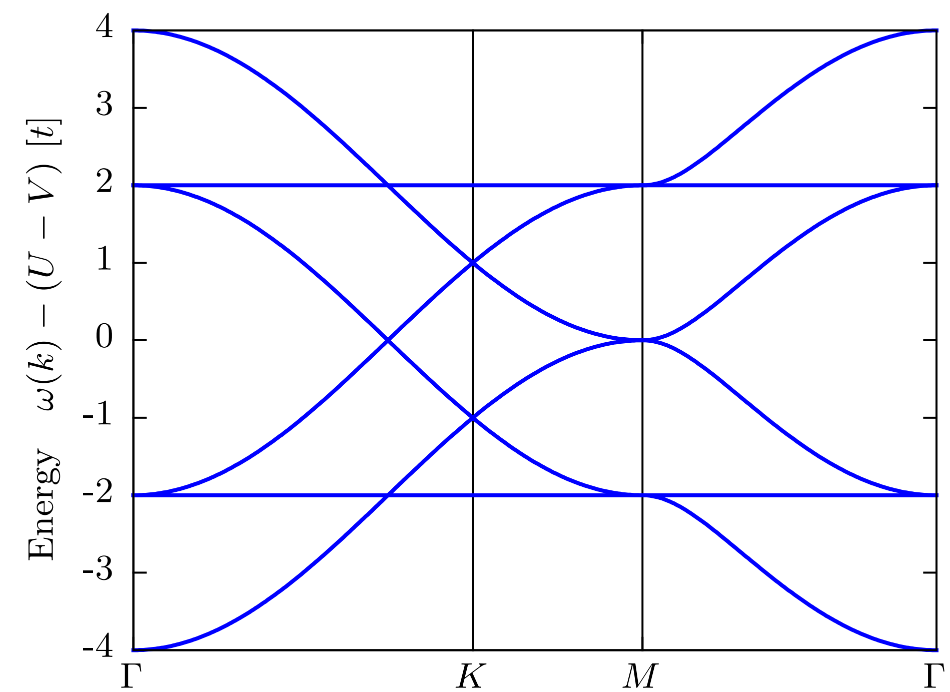
Rüegg arXiv 2013





Conclusions

- Cold atoms host and amplitude mode close to the superfluid to Mott transition.
- One can understand this mode in the framework of an emergent “Higgs” particle.
- By (time-) modulating the distance to the critical point one should be able to excite this mode.
- The emergent Lorentz invariance has a profound impact on the low energy behaviour of the system.

(Once) Open questions

- Stability of the cold-atoms Higgs mode
- Can one measure this mode unambiguously
- Hall conductivity in the presence of more broken symmetries: super-solids
- Chiral Mott insulator: good microscopic understanding of the mode softening