Observation of the Higgs amplitude mode in a two-dimensional superfluid

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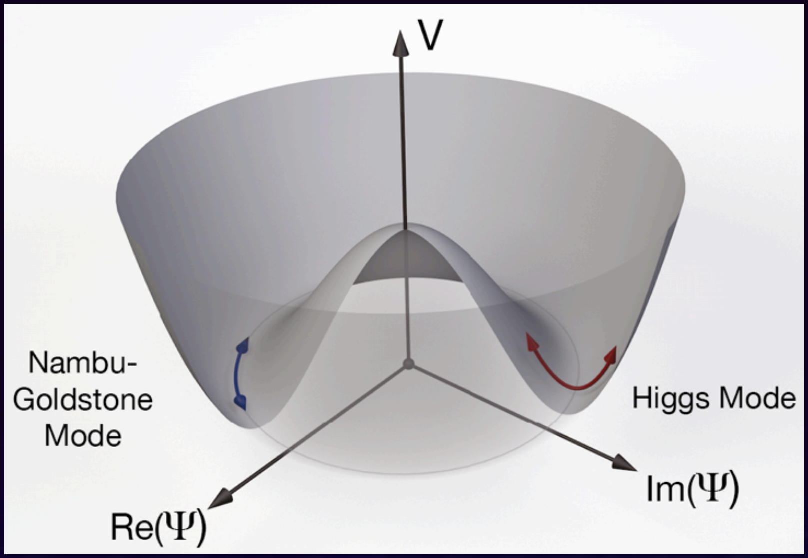
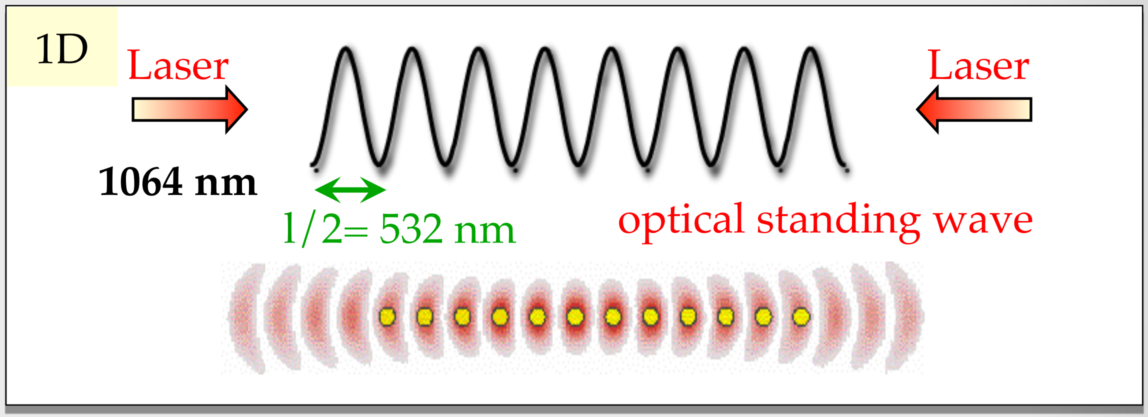
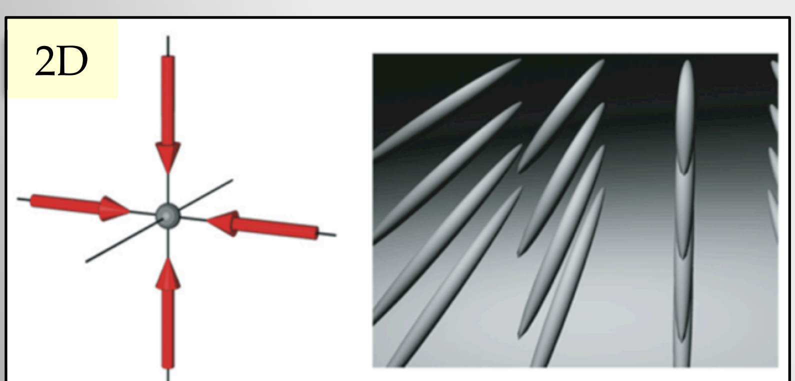


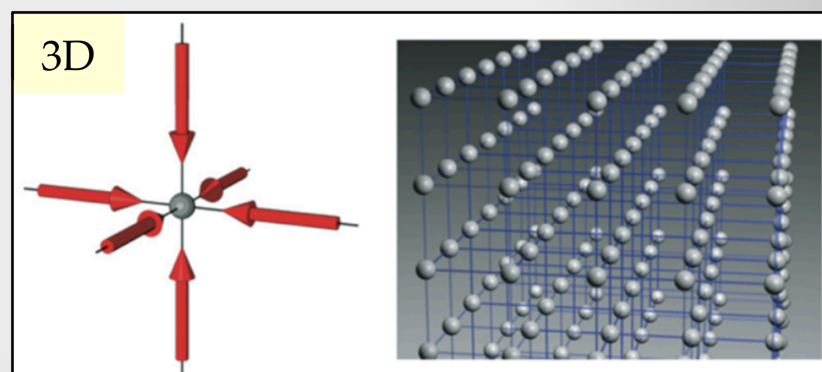
Ultracold Atoms in Optical Lattices

Optical lattice

Potential shift ∝ Light intensity







Bose-Hubbard Hamiltonian

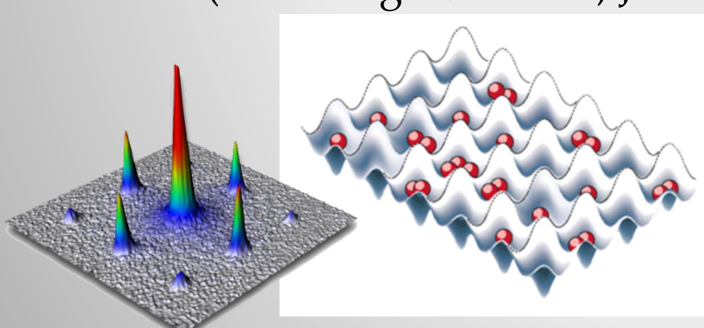
Bose-Hubbard Hamiltonian $$H = -J\sum_{\langle i,j\rangle}\hat{a}_i^\dagger\hat{a}_j + \frac{U}{2}\sum_i n_i(n_i-1) + \sum_i V_i n_i$$

J: tunneling *U*: on-site interaction

J/U can be tuned simply by varying the light intensity

Superfluid

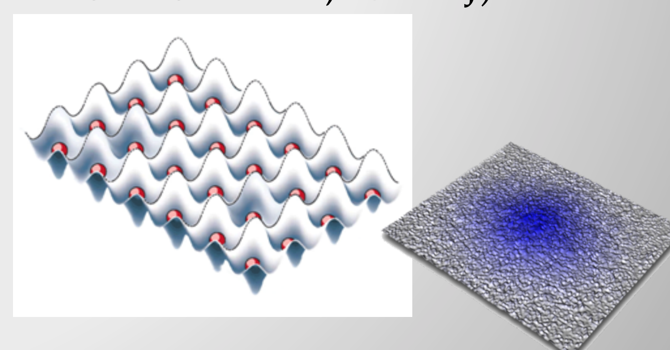
(tunneling dominant, J >> U)



- Poissonian atom number distribution
- Long range phase coherence

Mott insulator

(interaction dominant, U >> J)

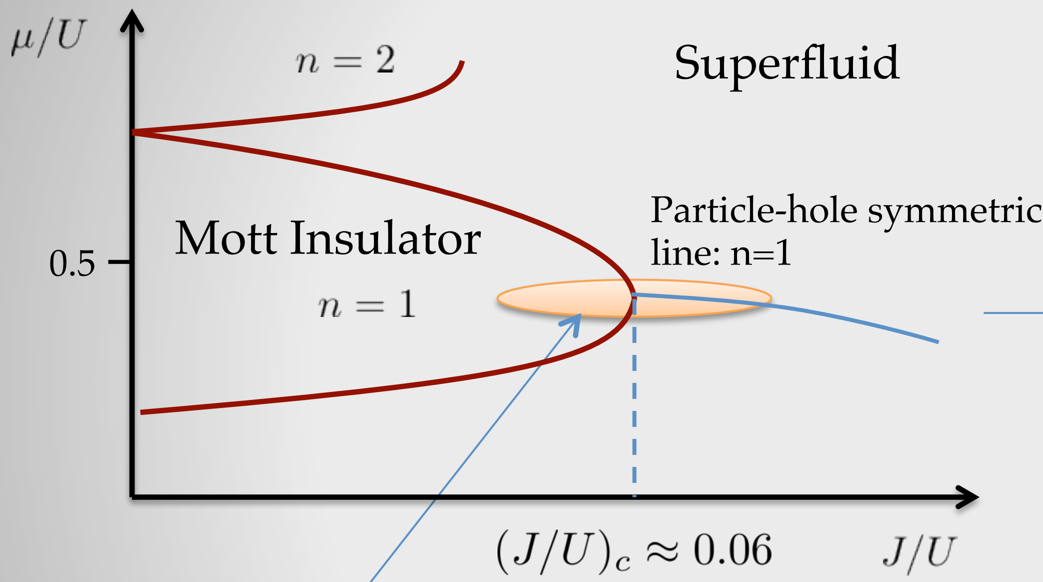


- Number squeezing
- No phase coherence

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

Low-energy effective theory

Bose-Hubbard phase diagram in 2d:



$J/U \to \infty$

Low-energy description

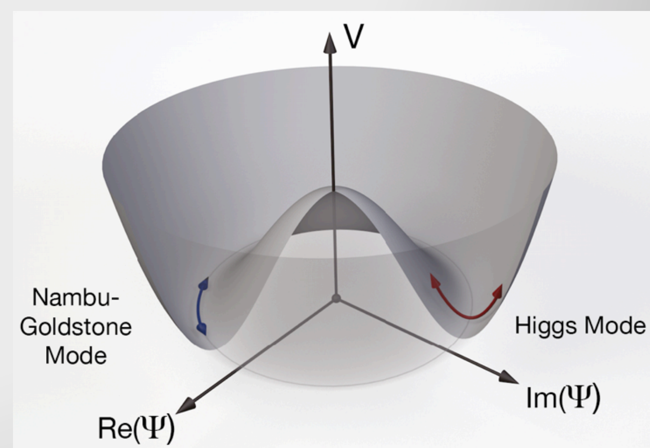
Gross-Pitaevskii

Bogoliubov mode only

Low-energy description:
"relativistic critical theory"

for $|\Psi| > 0$ $\quad \Psi$ = SF order parameter

$$\ddot{\Psi} = c^2 \nabla^2 \Psi + \frac{1}{2} \Delta_0^2 \Psi (1 - |\Psi|^2)$$



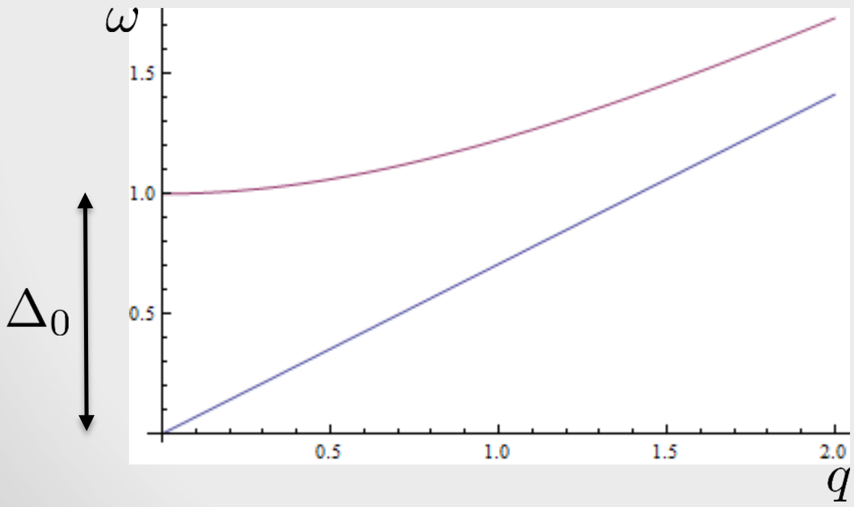
E. Altman and A. Auerbach, PRL 89, 250404 (2002)
Sachdev, "Quantum Phase Transitions"

Phase and Amplitude modes

$$\ddot{\Psi} = c^2 \nabla^2 \Psi + \frac{1}{2} \Delta_0^2 \Psi (1 - |\Psi|^2)$$

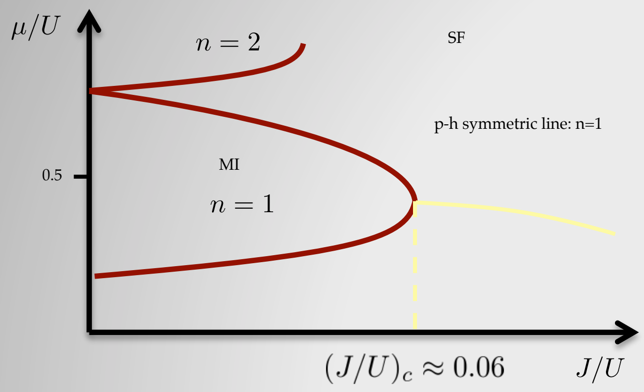
spectrum: two branches!

$$\omega^2 = \Delta_0^2 + (cq)^2$$



Additional gapped branch (Higgs amplitude mode)

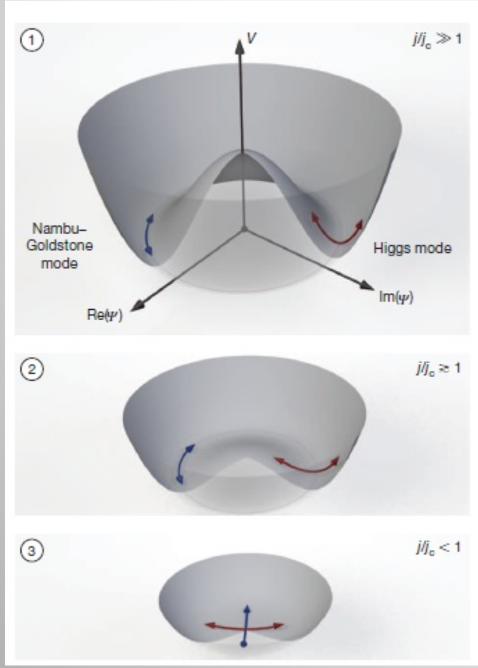
Softening



Coupling $j = J/U$

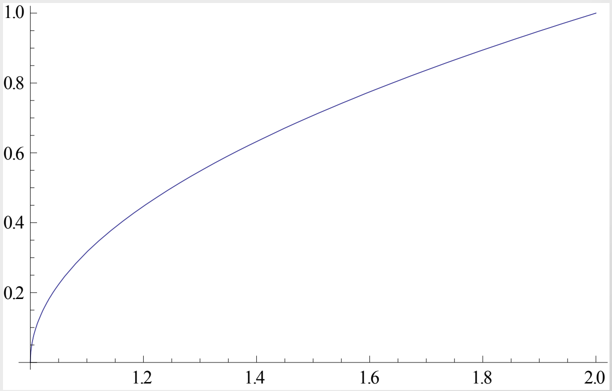
Distance to the critical point: $(j/j_c - 1)$

Minimum: $|\Psi_0| \propto (j/j_c - 1)^{1/2}$



$$\Delta_0 \propto (j/j_c - 1)^{1/2}$$

Mean field calculation



Higgs gap shows characteristic softening at critical point

Lattice modulation spectroscopy

Modulate lattice depth $\rightarrow \left(\frac{J}{U}\right)(t) = j(t)$

$\rightarrow$ modulate distance to critical point: $\left(\frac{j}{j_c} - 1\right)(t)$

$\rightarrow$ modulate mexican hat

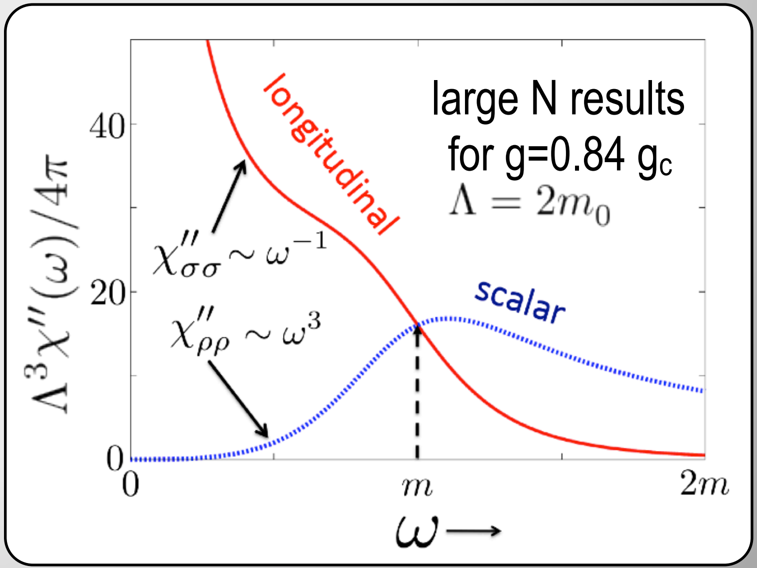
$$V(t) \propto \left(\frac{j}{j_c} - 1\right)(t)|\Psi|^2 + A|\Psi|^4$$

$$V \propto V_0 + \delta\cos(\omega t)|\Psi|^2$$

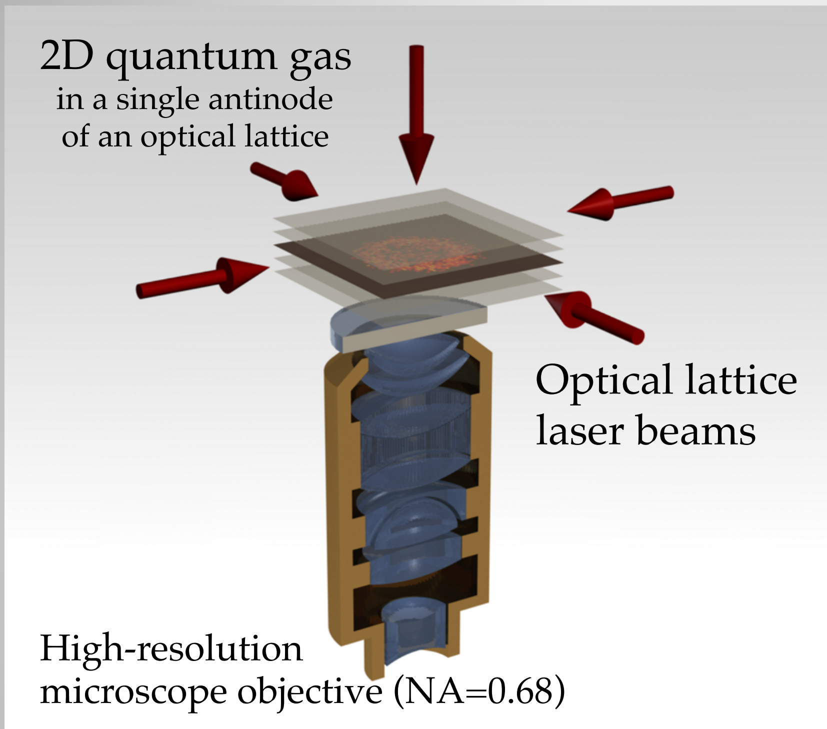
Coupling to $|\Psi|^2$ (amplitude modes) at q=0

scalar measurement

Daniel Podolsky



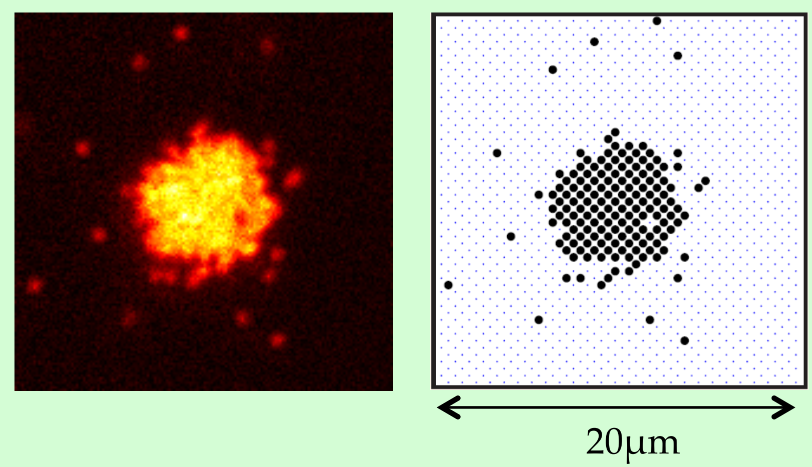
Experimental setup



$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i n_i (n_i - 1) + \sum_i V_i n_i$$

$$J/U \rightarrow 0$$

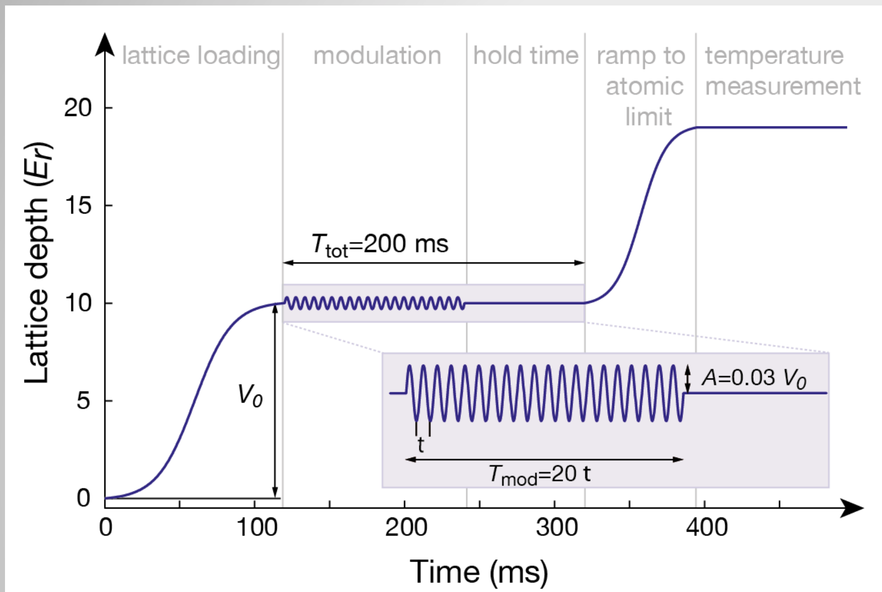
Atomic Mott Insulator in 2D

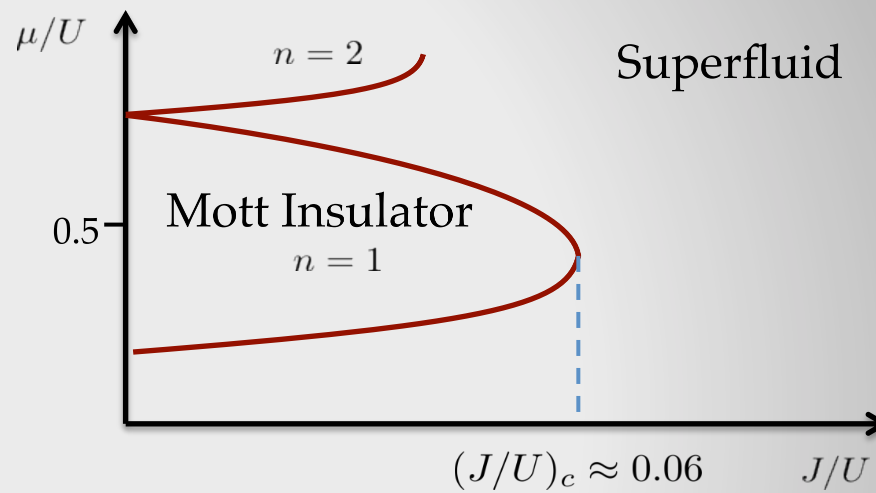


Atomic sample: ^{87}Rb atoms (bosons)
Imaging System:

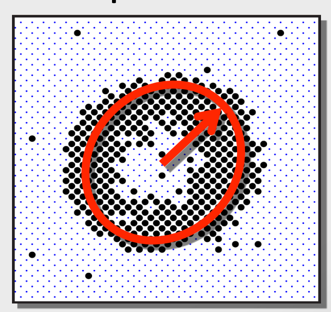
- NA = 0.68,
- 700 nm resolution
- Fluorescence detection
- Parity projection detection

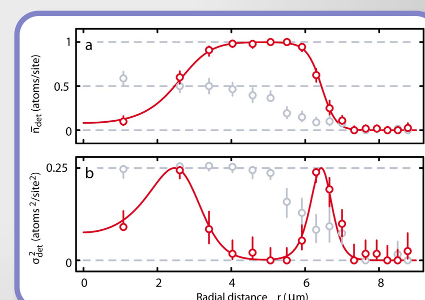
Experimental Sequence (detection)





Temperature measurement:

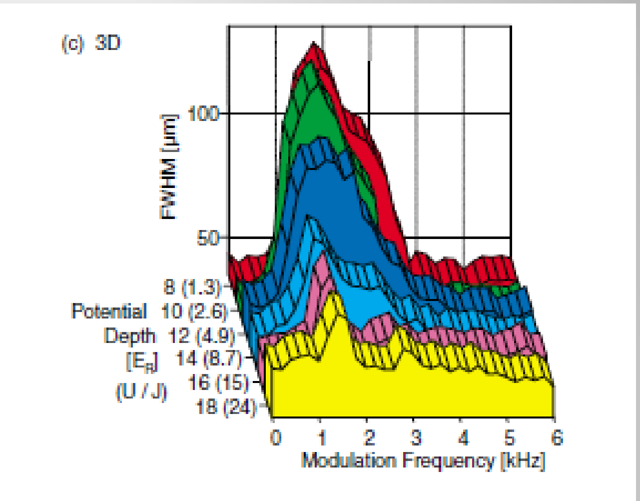




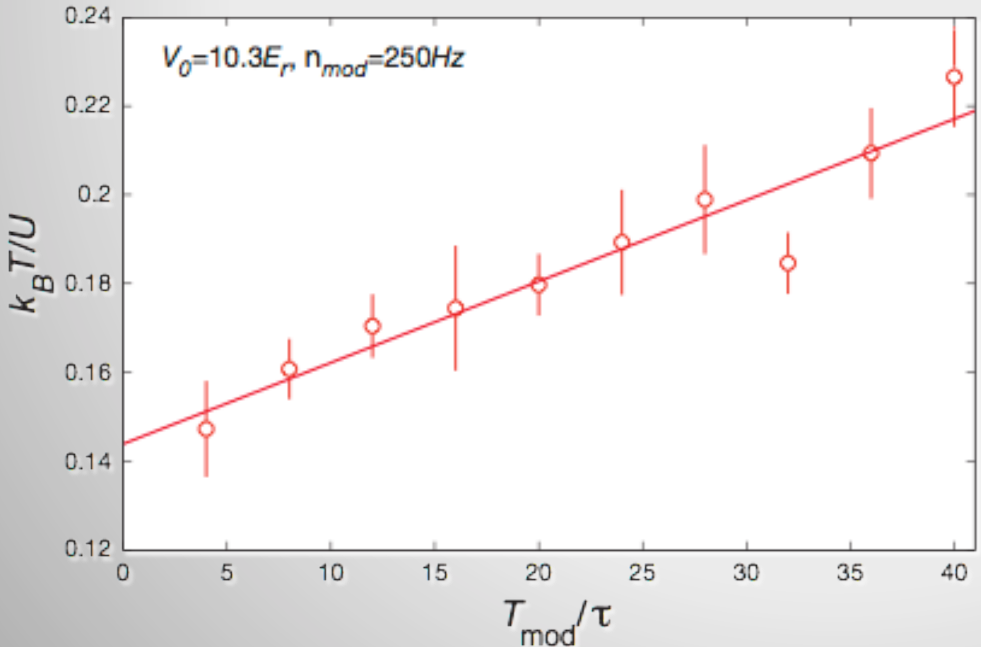
M. Endres, T. Fukuhara *et al.*, Nature **487**, 454 (2012).

Compare to previous work

- Fix modulation cycles, instead of mod. time
- gentle modulation (3%)

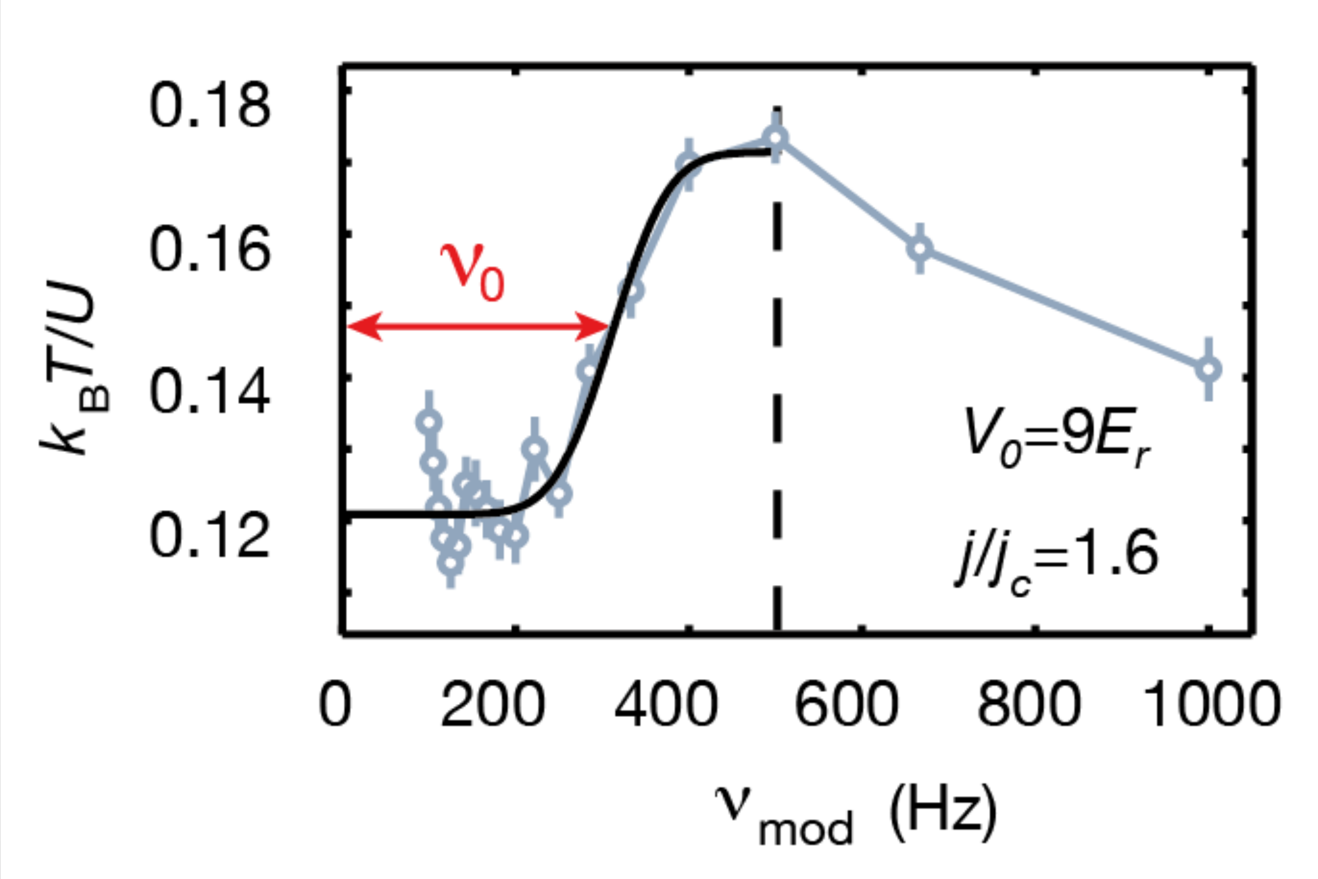


PRL 92, 130403 (2004), PRL 93, 240402 (2004).

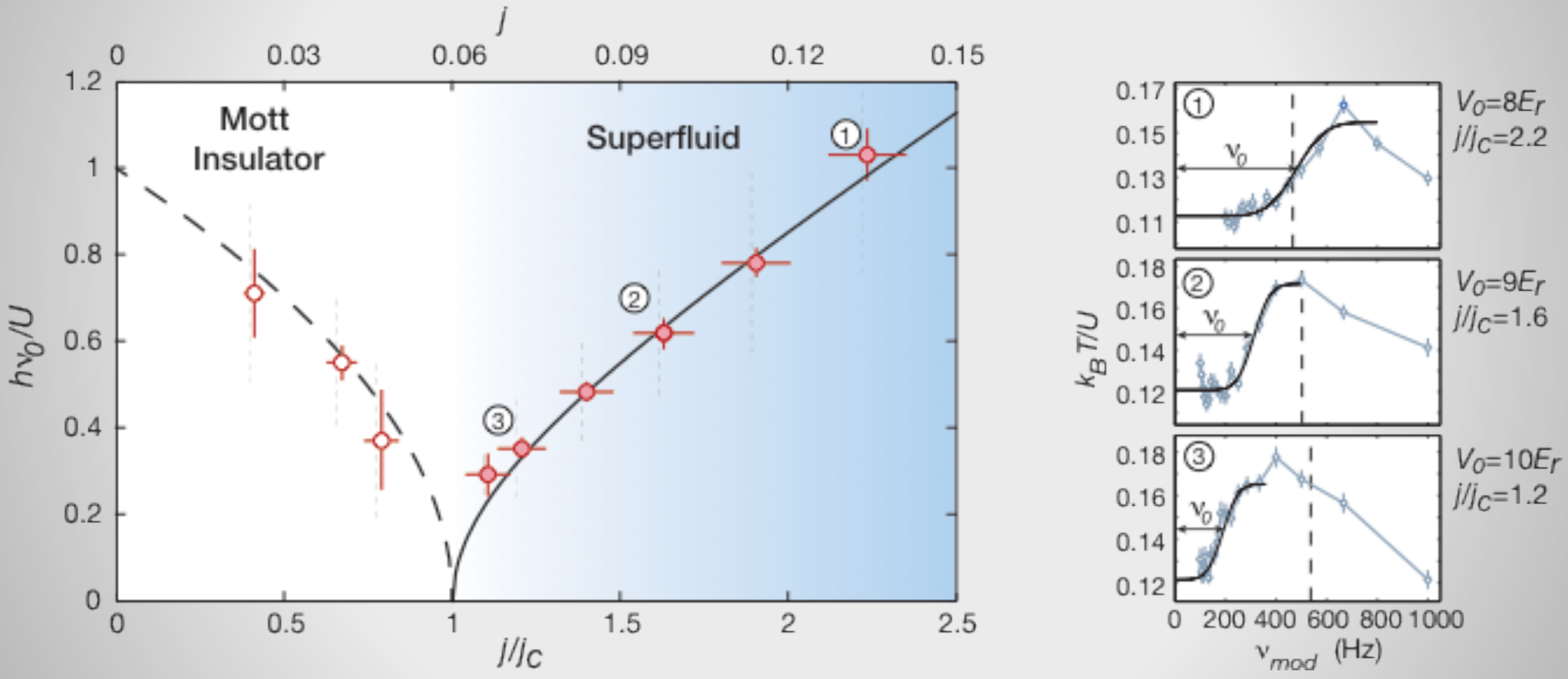


Strong modulation: amplitude 20%
Systems are highly excited.

Spectral Response

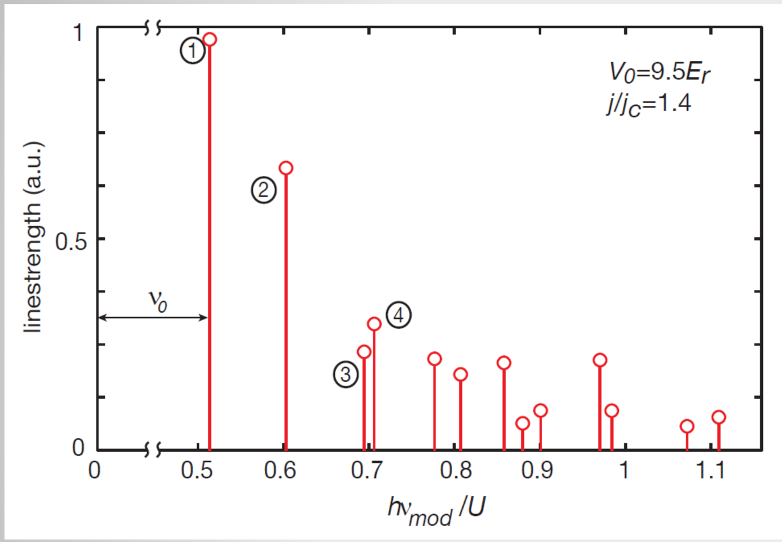


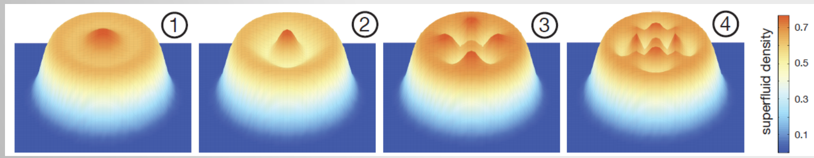
Softening of the Higgs mode

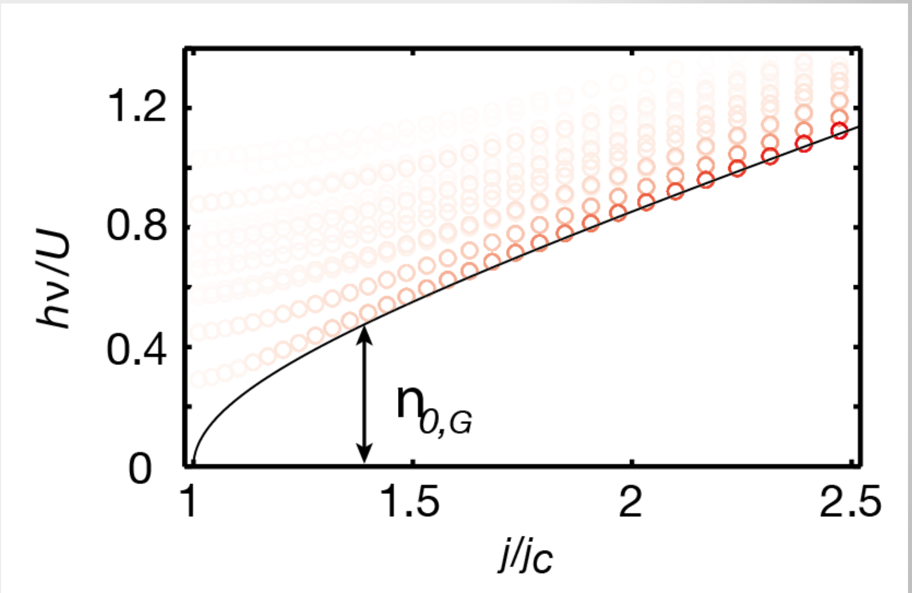


Role of the trap

Gutzwiller calculation using BH Hamiltonian

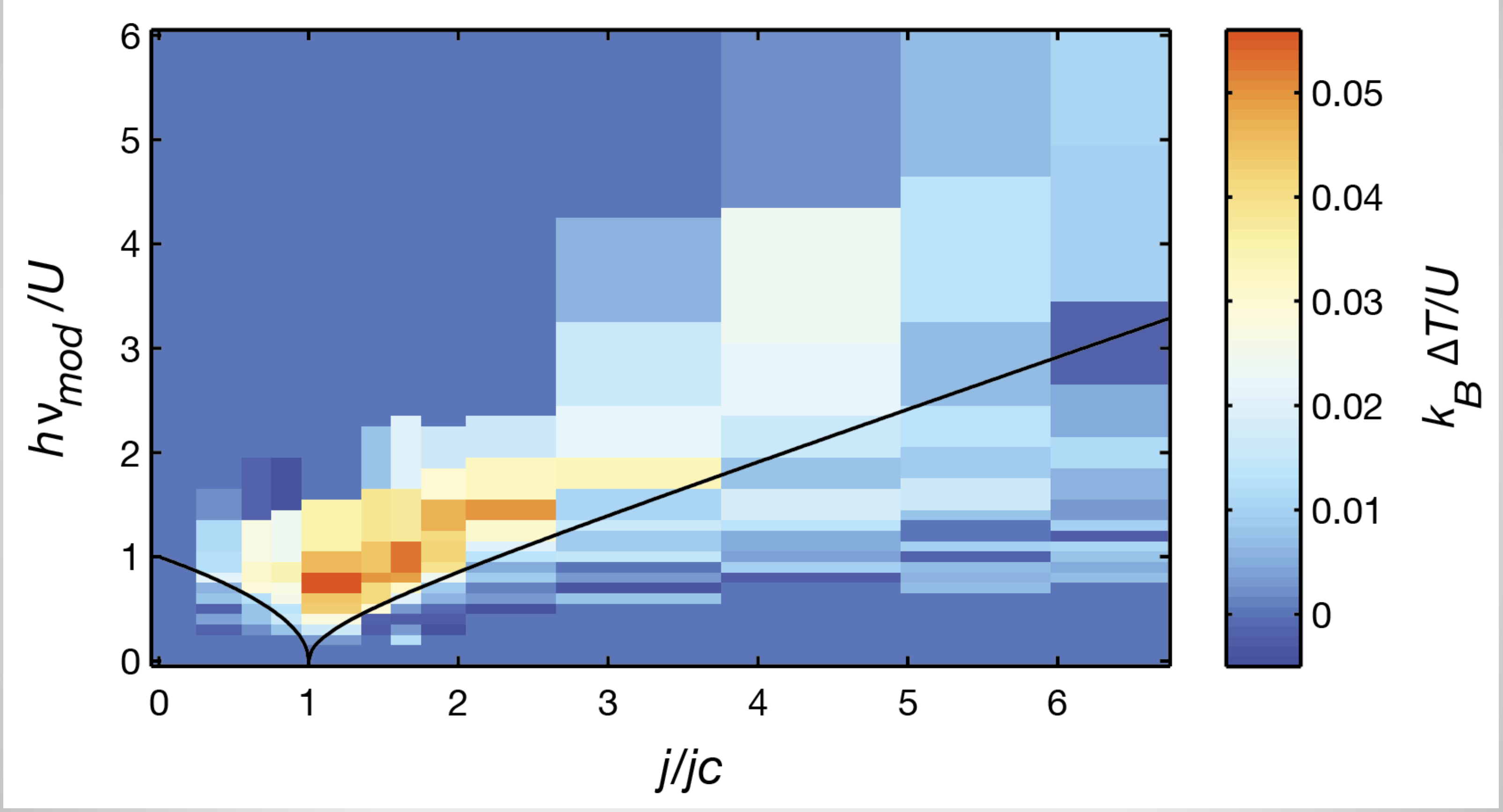




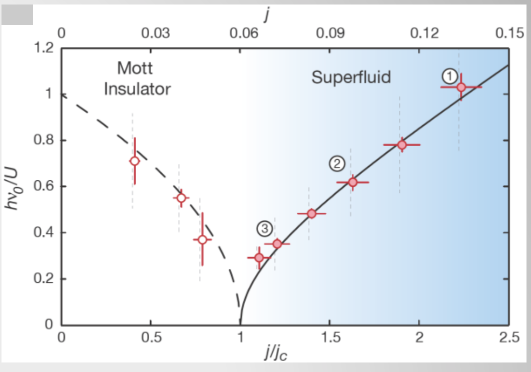


Superfluid acts like skin of a drum

Vanishing of the response

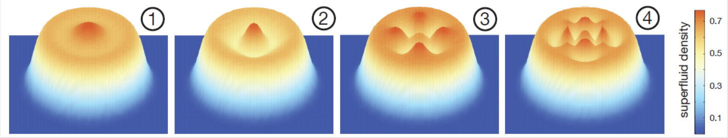


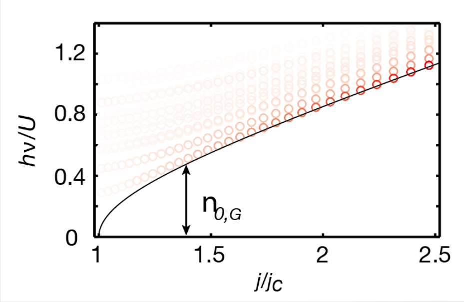
Summary



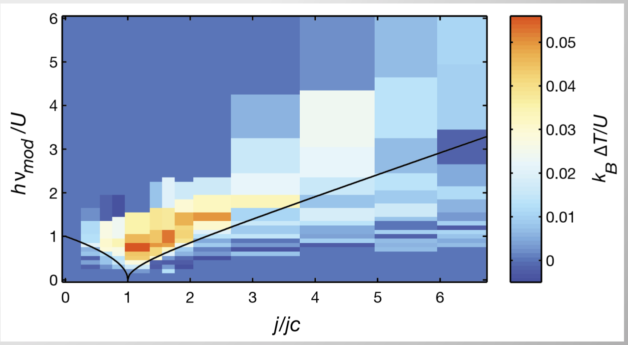
- Identify and study long-wavelength Higgs modes in a neutral 2d superfluid close to the transition
- Observe softening of Higgs mode

- Role of the trap: drum modes





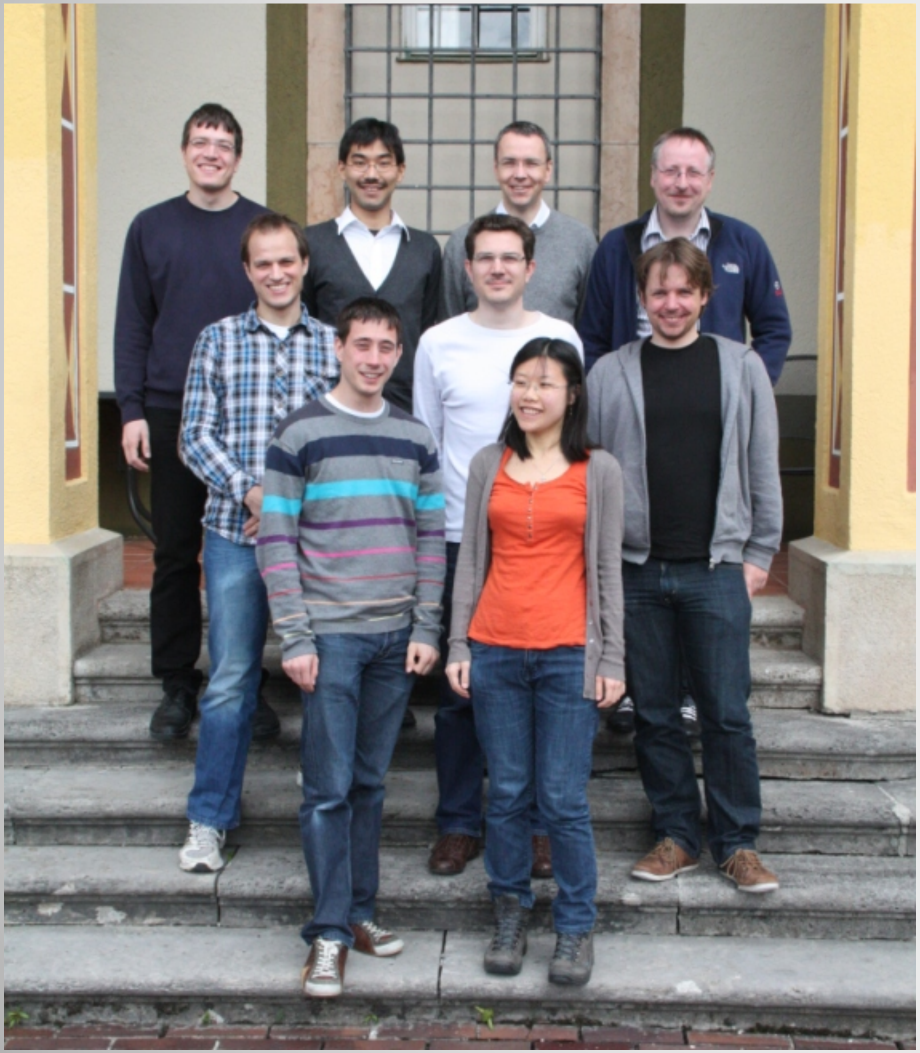
- Response vanishes in weakly interacting limit



Outlook

- Measure quantum critical behavior
  Larger system -> closer to the critical point
  (Avoid round-off due to finite size effect)
- Direct observation of Higgs drum modes

Thank you for your attention!



Peter Schauß, T F, Stefan Kuhr, Immanuel Bloch

Christian Groß, Marc Cheneau, Manuel Endres

Sebastian Hind, Amelia Wigianto

Theory (Harvard)

David Pekker

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