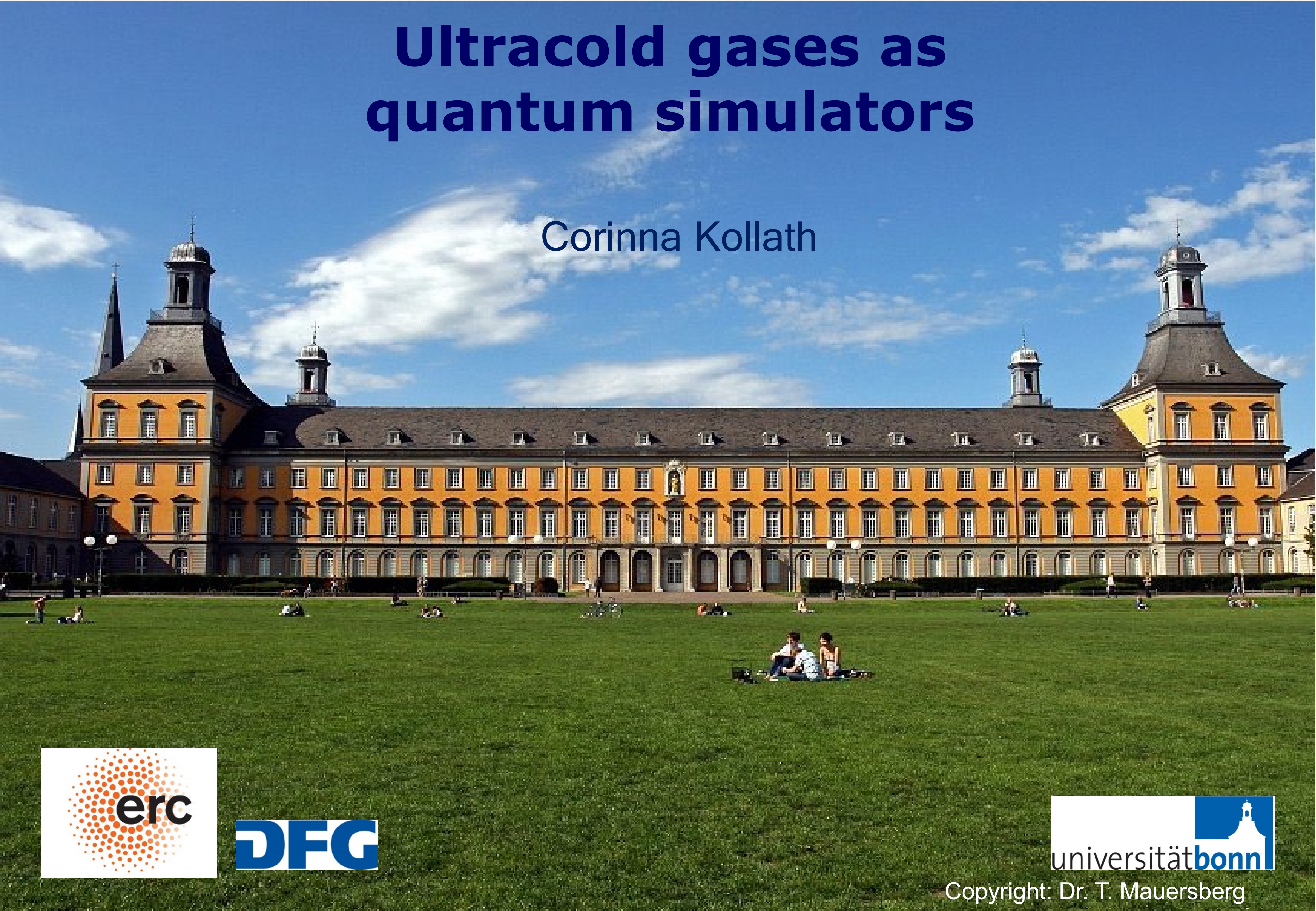
Ultracold gases as quantum simulators

Corinna Kollath



2007-2010 at CPHT

2007-2010 Junior chair at the Triangle de la Physique ‘

Unique environment:
CPHT, Institut d’Optique, Orsay, Saclay, ENS, College de France …

Exceptional for correlated systems and cold atoms:
A. Georges, A. Aspect, J. Dalibard, C. Salomon, S. Biermann, M. Ferrero,
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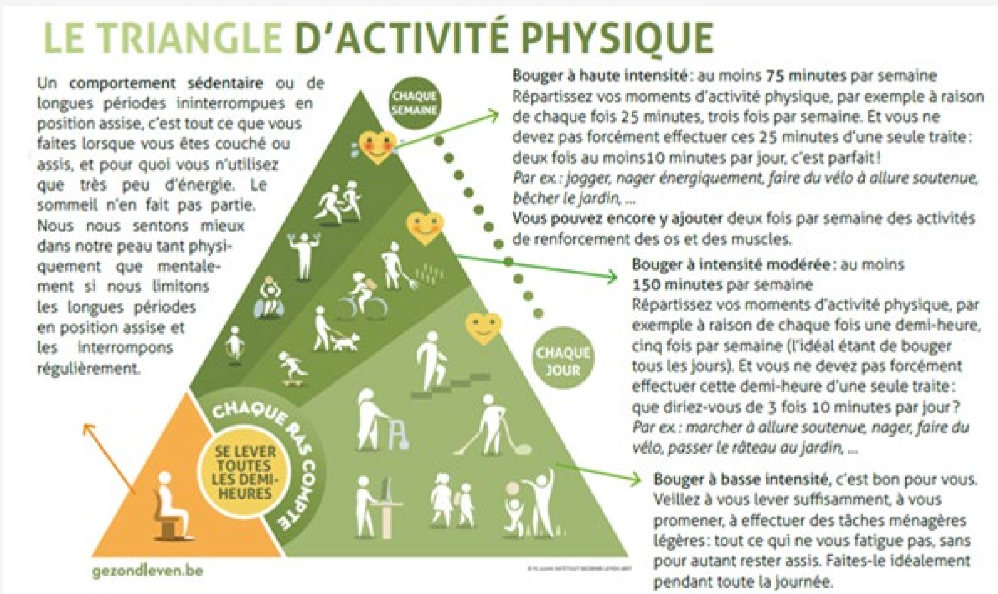

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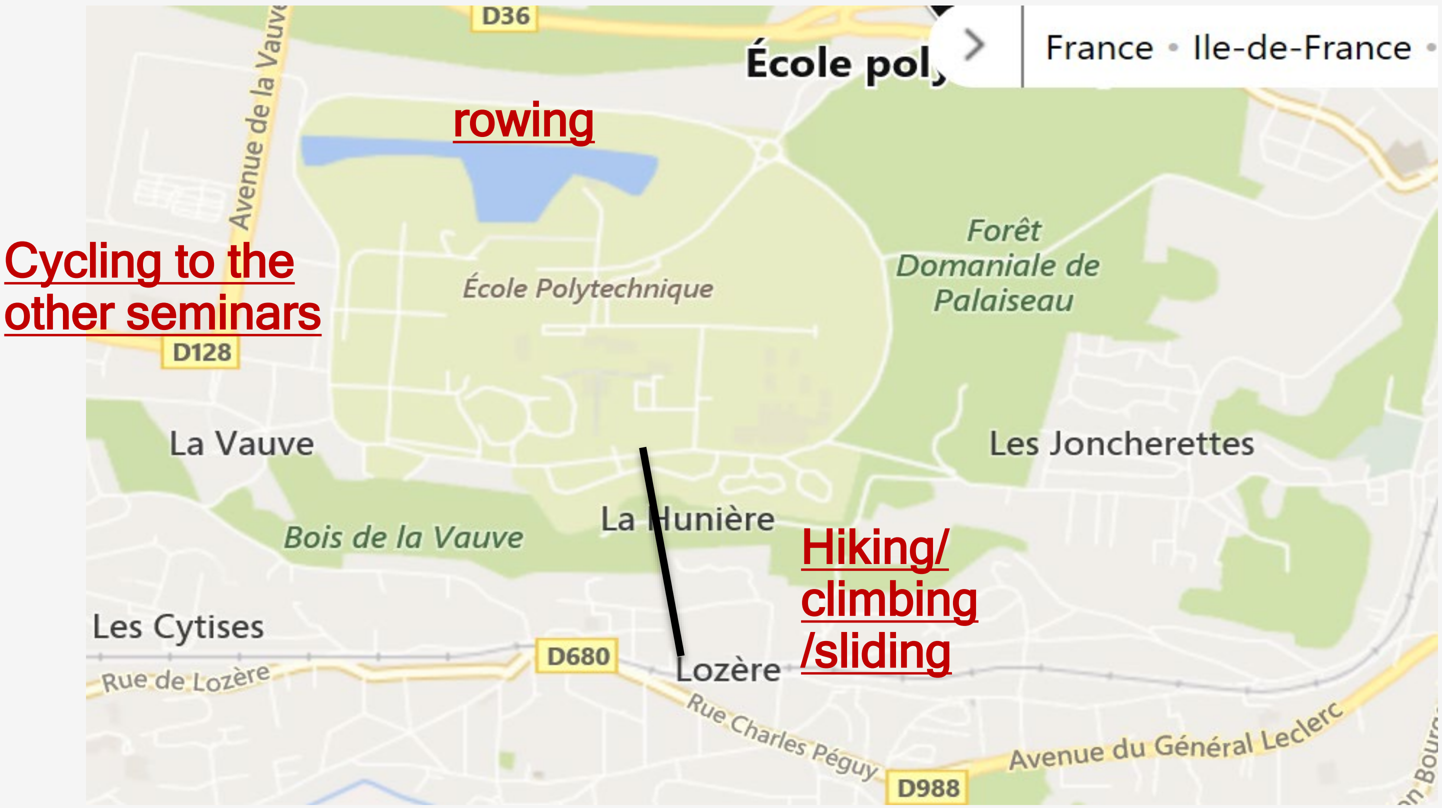

TRIANGLE DE LA PHYSIQUE

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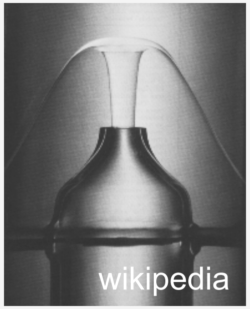
A minute change of the conditions triggers a dramatic effect

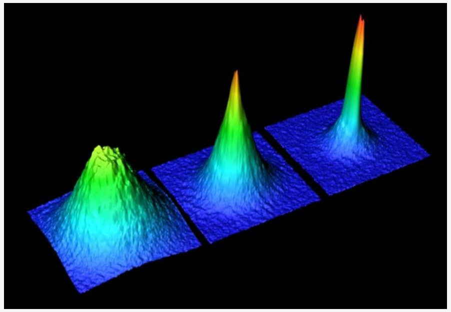
wikipedia

Phase Transitions

superconductor



superfluid He



Bose-Einstein condensation

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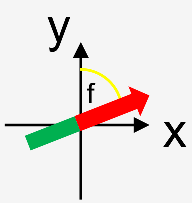
Long-range order

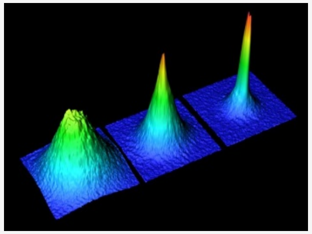
Emergence of long-range order „spontaneously“ breaks the symmetry of the Hamiltonian

Magnetism	Rotational symmetry of the spin
Bose-Einstein condensation	Phase of the wave function

Symmetries are important



Spin rotating in the xy-plane
characterized by angle ϕ



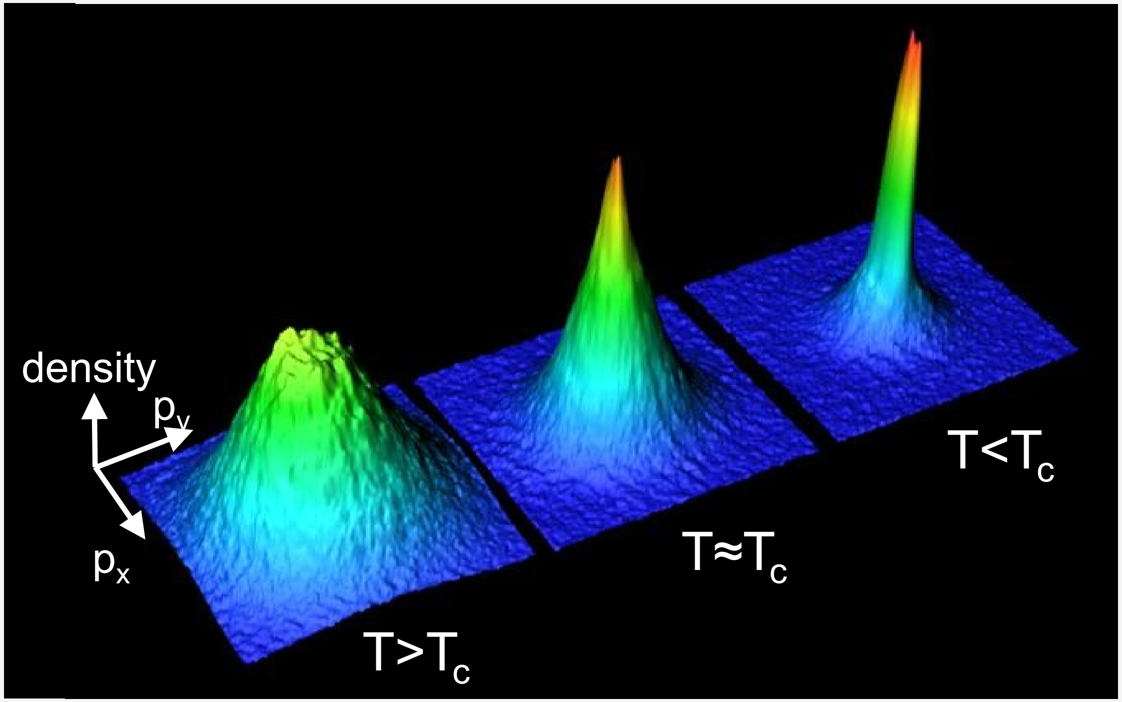
Condensate wave function

$$\Psi = |\Psi| e^{i\phi}$$

characterized by angle ϕ

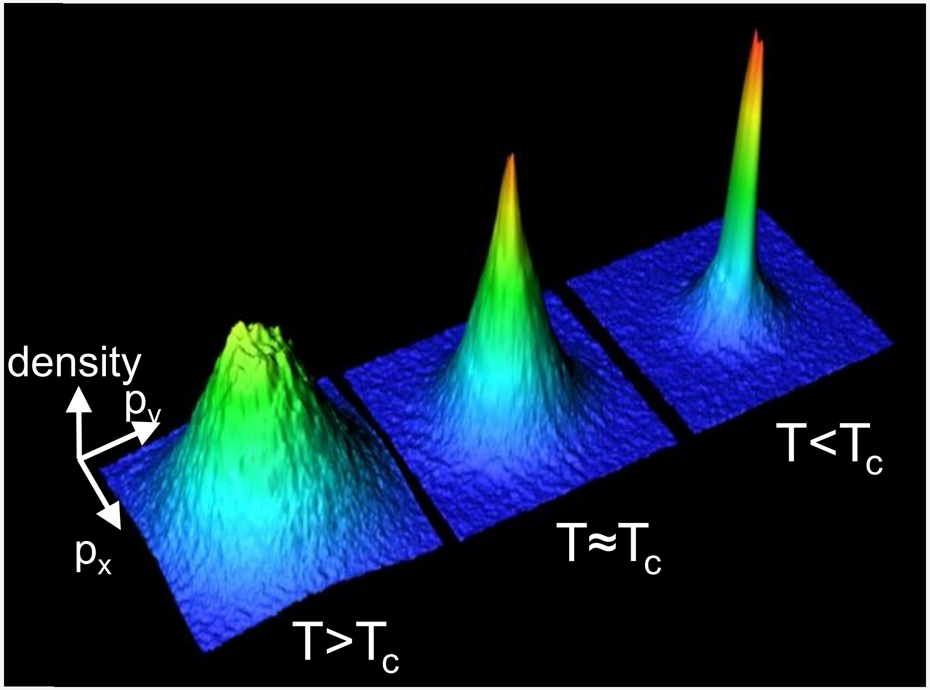
Same universality class => same critical behaviour

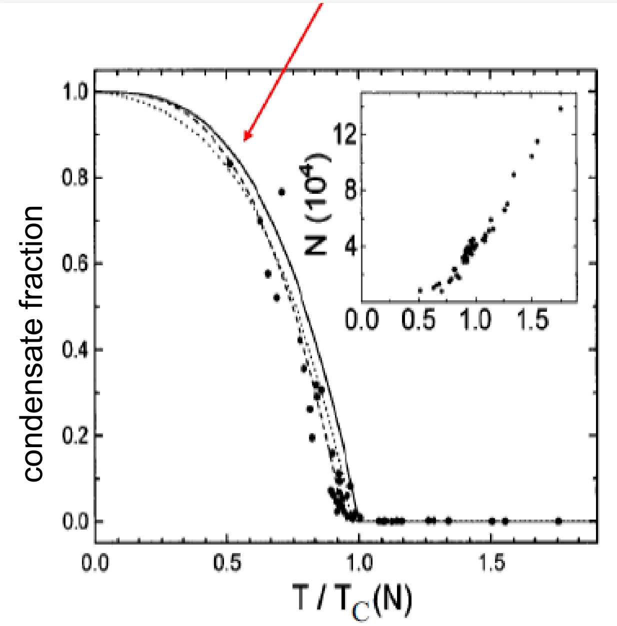
Bose-Einstein condensation



1. Observing the momentum distribution as the temperature is lowered.

Bose-Einstein condensation





Phys. Rev. Lett. **77**, 4984 (1996)

1. Observing the momentum distribution as the temperature is lowered.
2. Condensate fraction vs. temperature $\frac{N_0}{N} = 1 - \left(\frac{T}{T_c}\right)^3$
3. critical exponents agree approx. with mean-field and liquid He

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Universal phenomena

	m	n cm^{-3}	T_c
Nuclear matter	n	10^{38}	10^{12} K
Electron gas	m_e	10^{23}	50000 K
Superfluid He	^{4}He	10^{22}	5 K
Atomic gas	^{40}K	10^{13}	100 nK

very different orders of magnitude

universal phenomena are the same

Spontaneous symmetry breaking

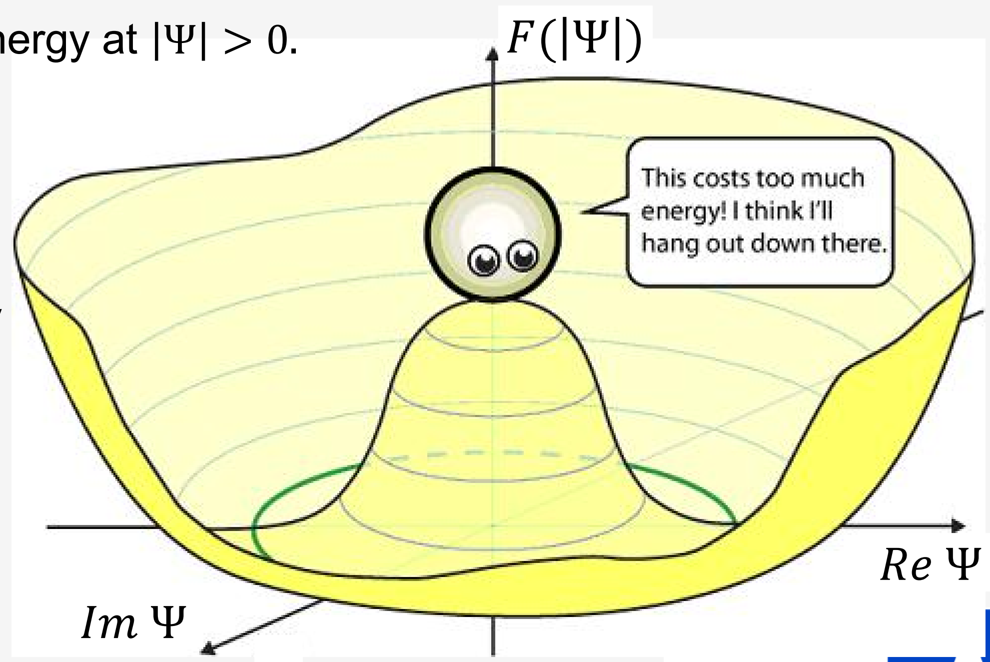
Gibbs free energy can be expanded in power series of order parameter (Landau)

$$F = \alpha|\Psi|^2 + \beta|\Psi|^4 + \ \dots$$

Temperature-dependent coefficients

High T: $\alpha > 0, \beta > 0$ => minimum of free energy at $|\Psi| = 0$.

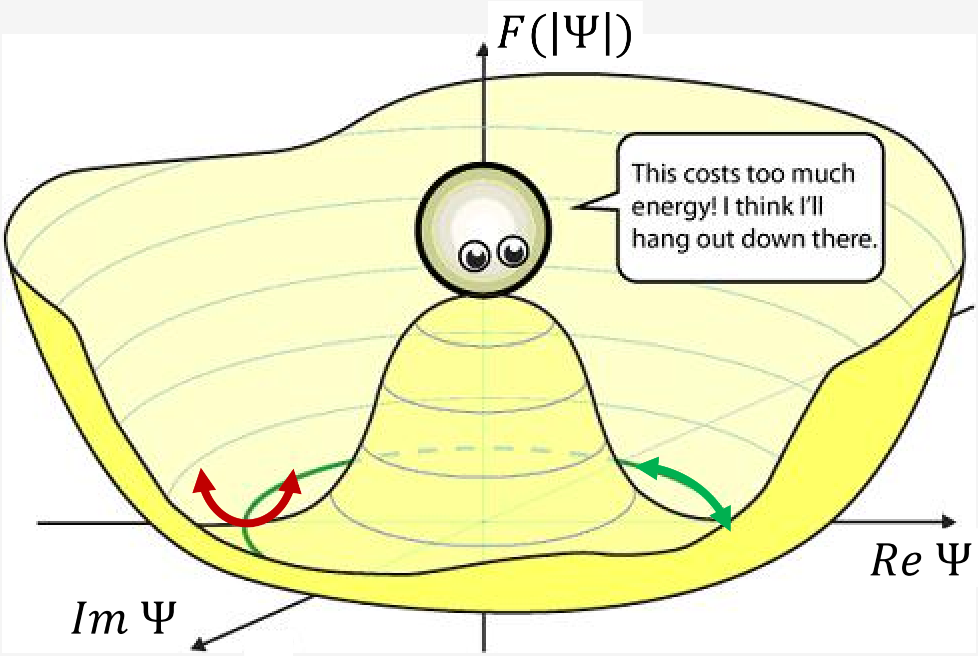
Low T: $\alpha < 0, \beta > 0$ => minimum of free energy at $|\Psi| > 0$.



Every phase angle ϕ has the same energy

=> system selects randomly a value of ϕ

Fluctuations of the order parameter



Amplitude fluctuations
„Anderson-Higgs mode“
(Nobel prize 2013)
Often unstable!

Phase fluctuations
„Nambu-Goldstone mode“
(Nobel prize 2008)
Always present!

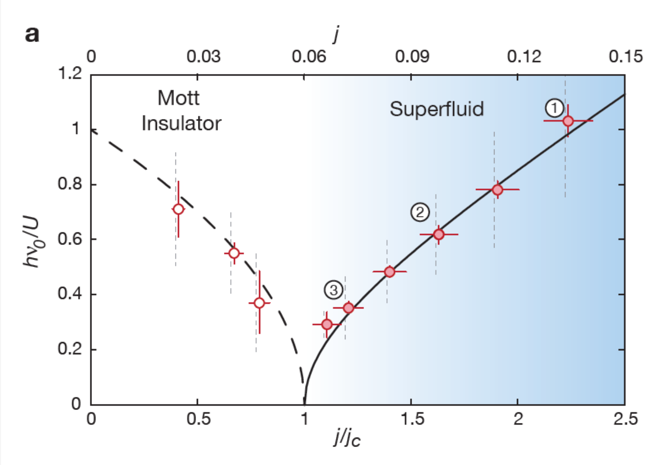
Magnet: spin waves
BEC: phonons
} for $k \to 0$

Higgs mode: Previous observations

Particle physics

ATLAS & CMS collaboration

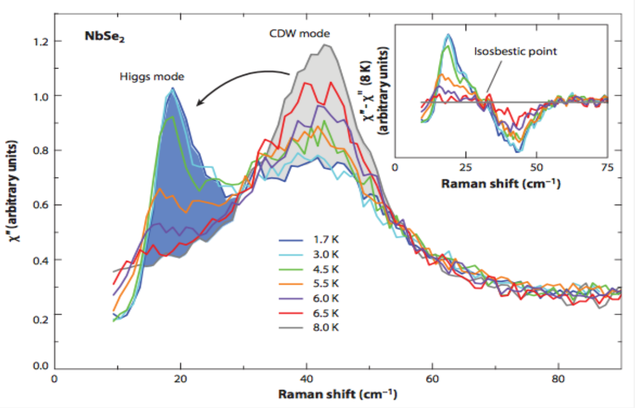
Cold atoms (bosons):



Stöferle et al., PRL 92 (2004)
Bissbort et al PRL 106 (2011)
Endres et al., Nature 487, 454 (2012)
Hoang et al., PNAS 113, 9475 (2016).
Leonard et al., arxiv (2017)

Condensed matter physics

no linear response coupling to normal probes



Raman spectra in NbSe2 indirect coupling via CDW
R. Sooryakumar, M.V. Klein, PRL 45, 8 (1980)
M.-A. Méasson et al, PRB 89, 060503 (2014)
in spin systems: Rüegg et al, PRL 100, 205701

in 3He: review by Halperin & Varoquax (1990)

weakly interacting

See also review by Pekker and Varma (2015)

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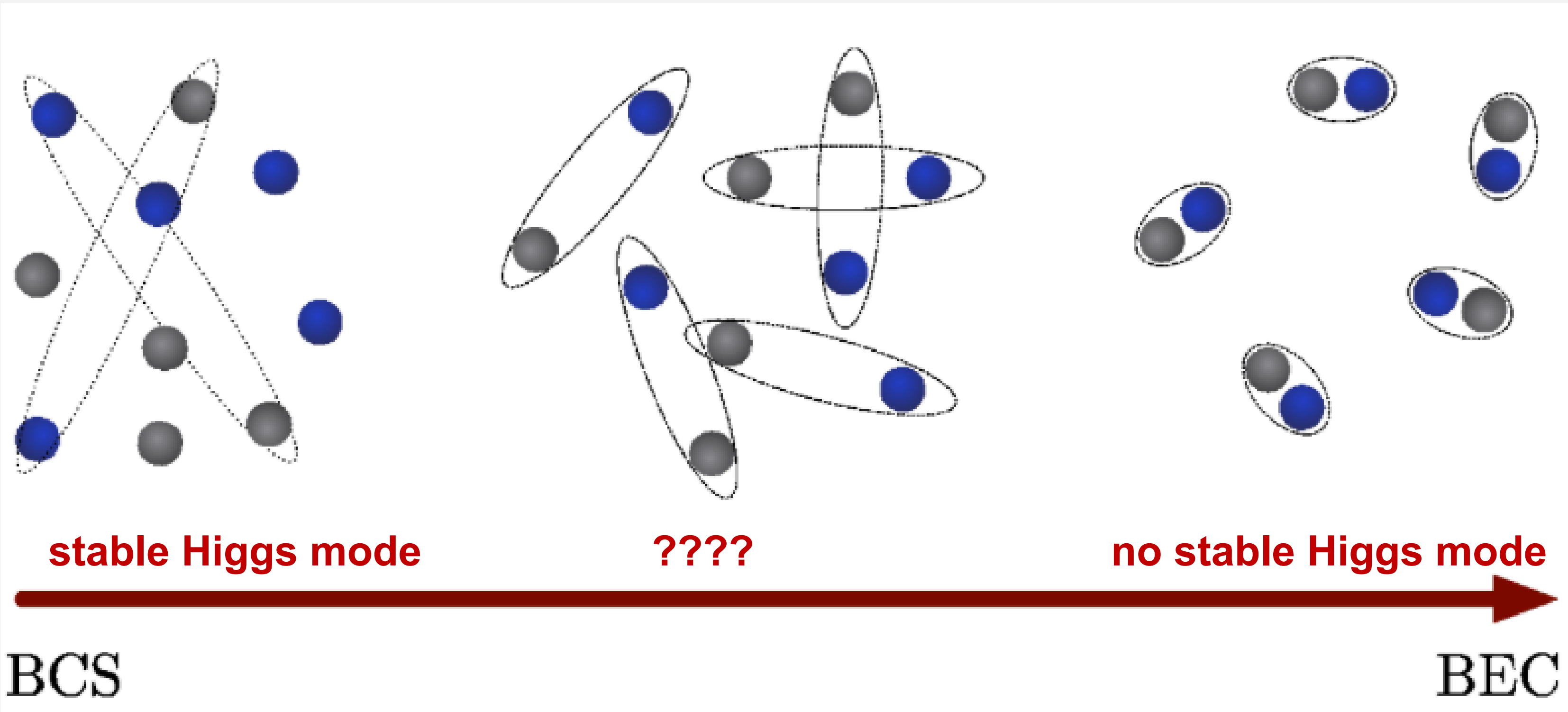
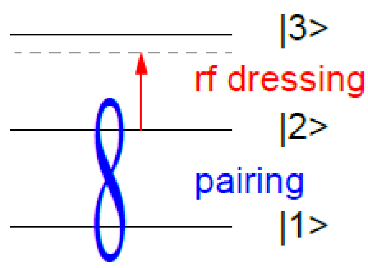
BCS-BEC crossover in fermionic quantum gases

BCS | strongly interacting | BEC of molecules



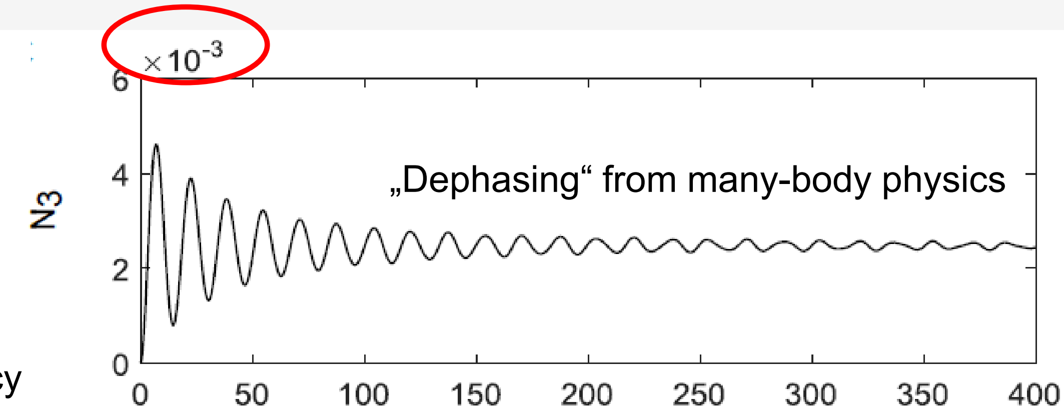
tuning of scattering length
via magnetic field

Excitation scheme

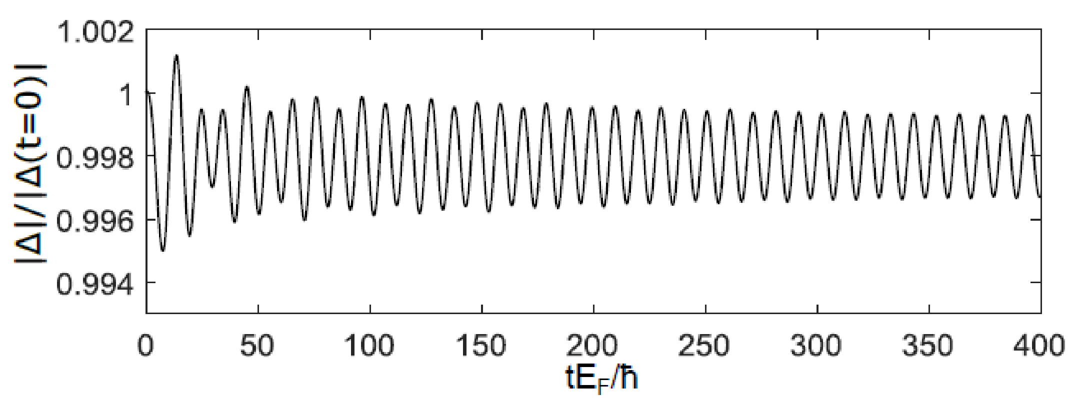


Time evolution at effective Rabi frequency

$$\Omega_R' = \sqrt{\Omega_R^2 + \delta^2}$$



Periodic drive leads to modulation of the superconducting gap



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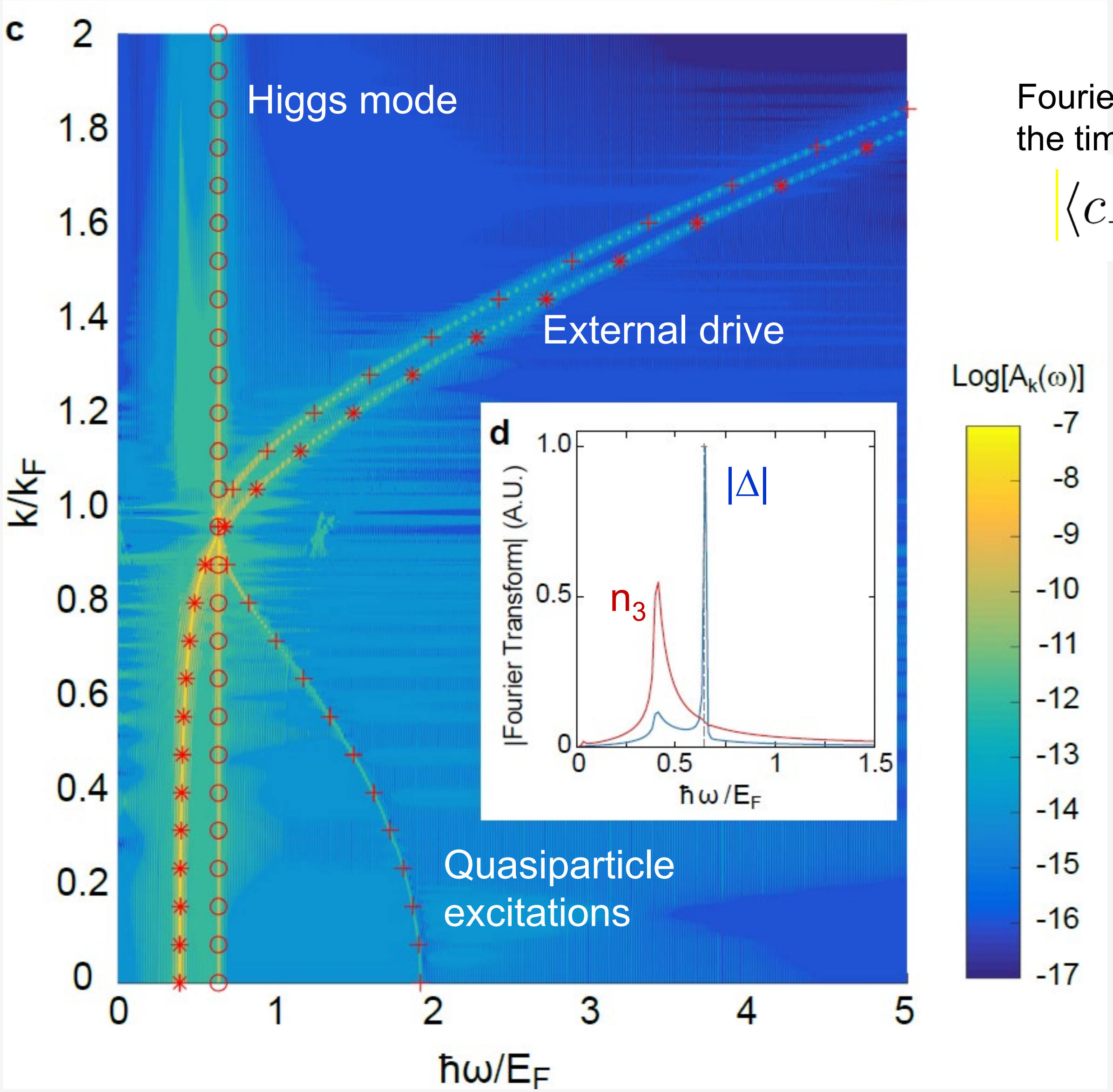
Alternative proposals: rapid quench of interaction strength (Volkov & Kogan, Stringari)

Numerical simulation



Fourier transform of the time evolution of

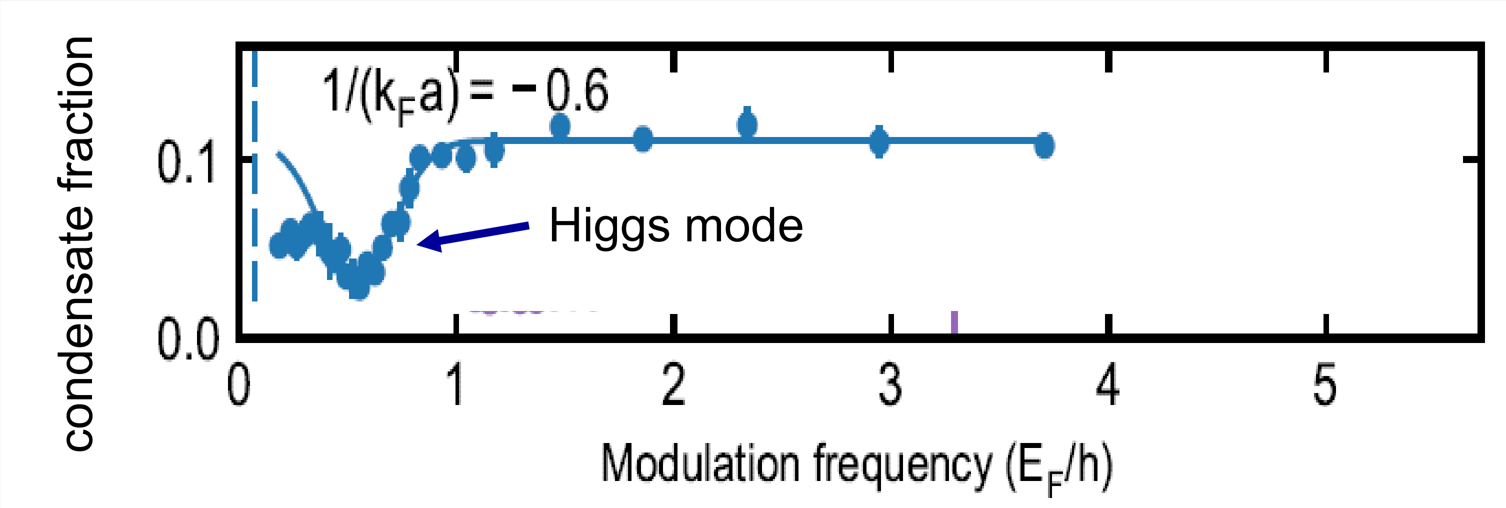
$$\left|\langle c_{-\boldsymbol{k},2} c_{\boldsymbol{k},1} \rangle\right|$$

Experimental results on BCS side

4×10^6 ^{6}Li atoms trapped in harmonic potential, $T/T_F \sim 0.07$

far red-detuned rf-excitation

observation of condensate fraction (by projection)

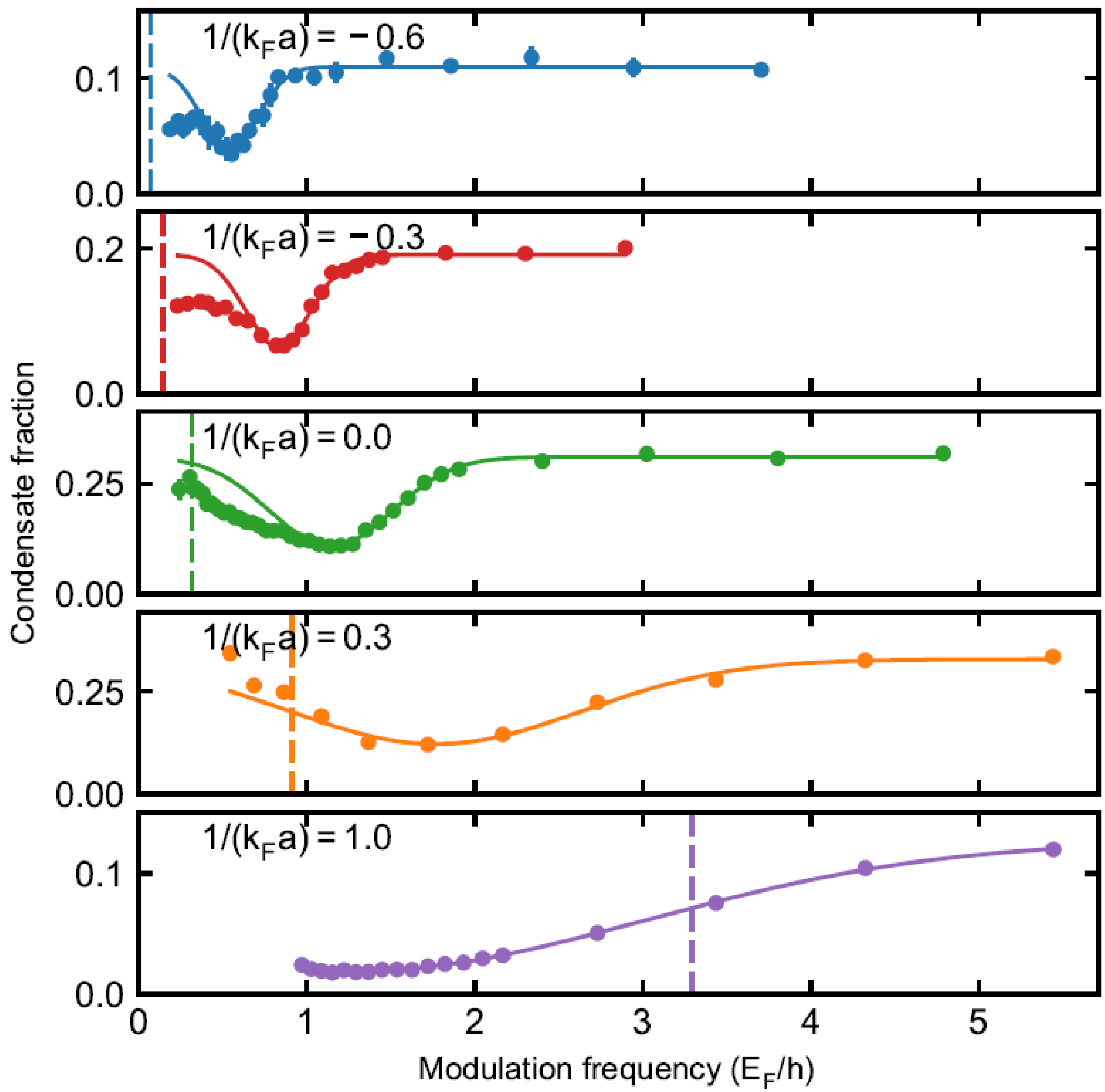


-> clear mode at $2\Delta \sim 0.6\, E_F$

Experimental results across crossover

BCS

BEC



clear mode at 2 Δ ~$0.6E_F$

still present at unitarity

washed out on BEC side

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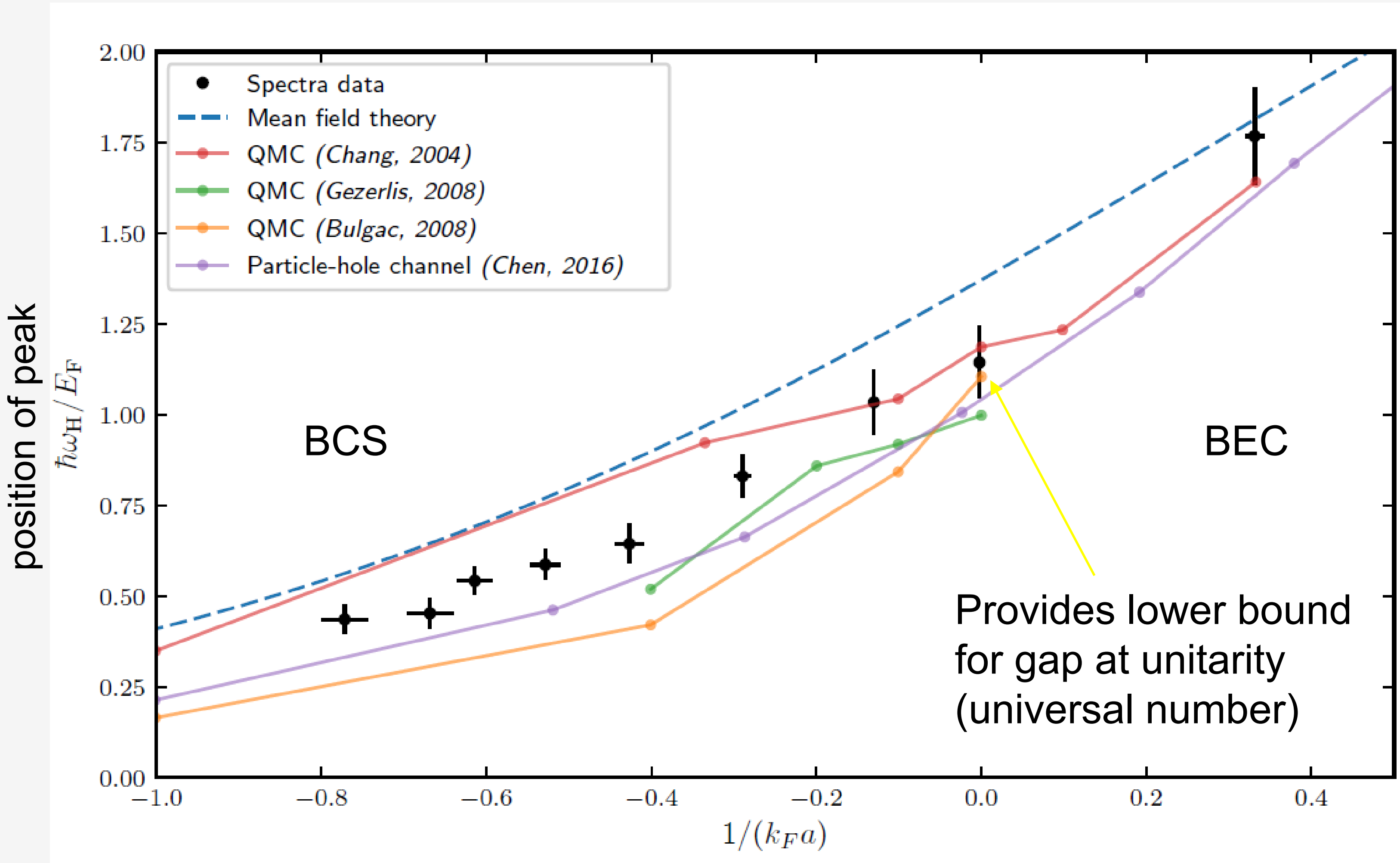
Frequency of the mode



Summary

- Quantum gases are models for tunable superconductors
- Equilibrium properties reveal 2nd order phase transition
- Non-equilibrium: collective Higgs mode

Thanks to
J. Kombe and J-S Bernier & experimental group M. Köhl

Summary

- Cold atomic gases are model system for tuneable superconductors
- Equilibrium properties reveal 2nd order phase transition
- Non-equilibrium: collective Goldstone and Higgs mode

Thanks to
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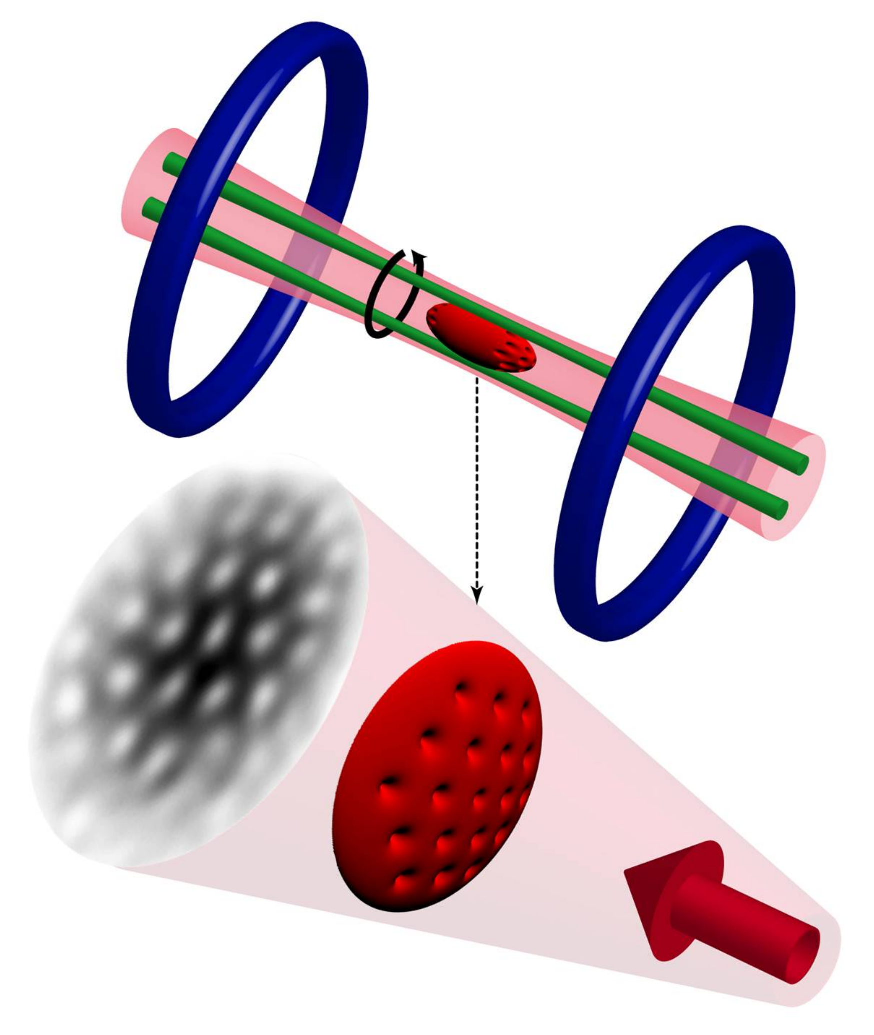
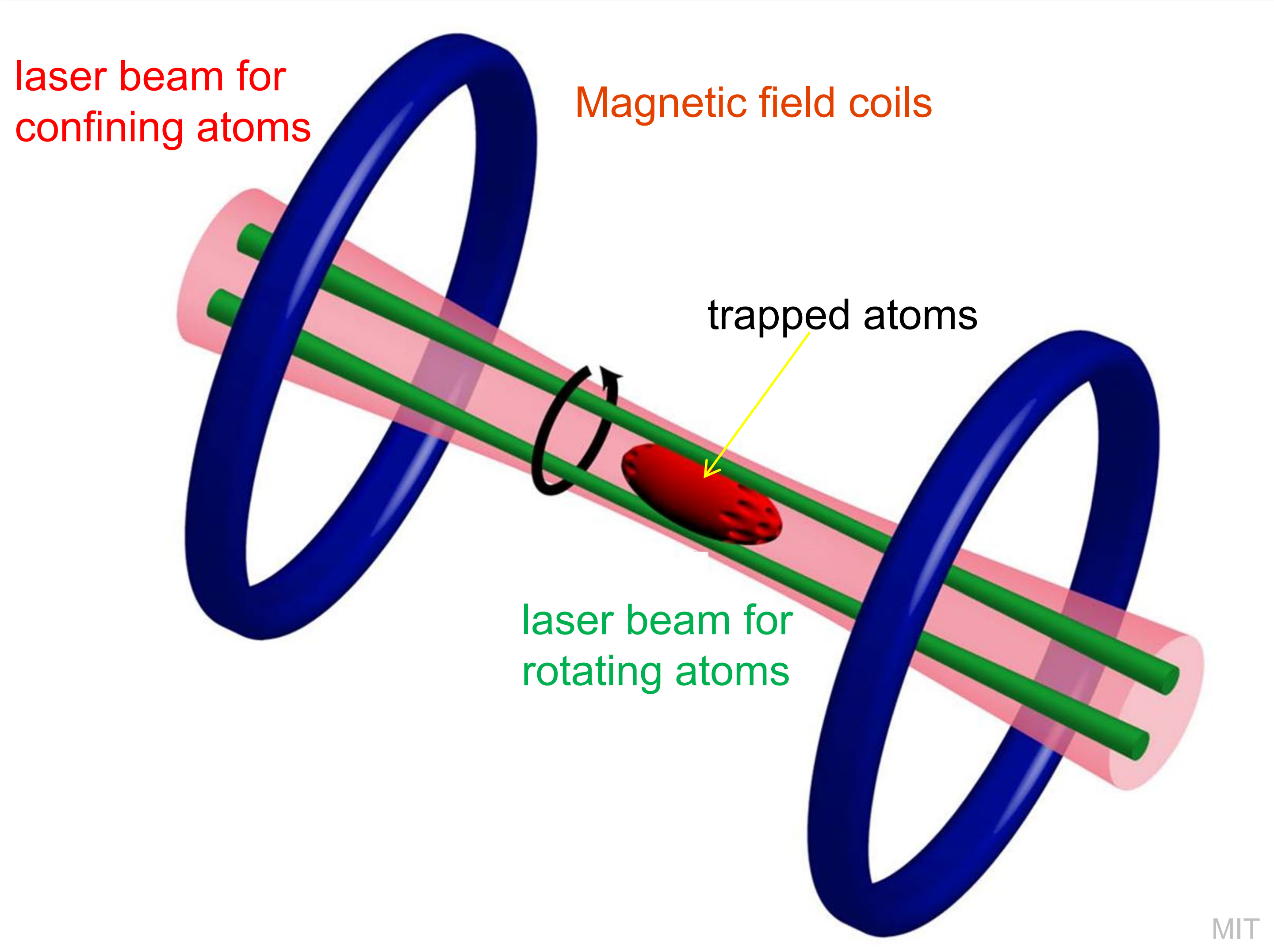
Spinning a strongly interacting Fermi gas

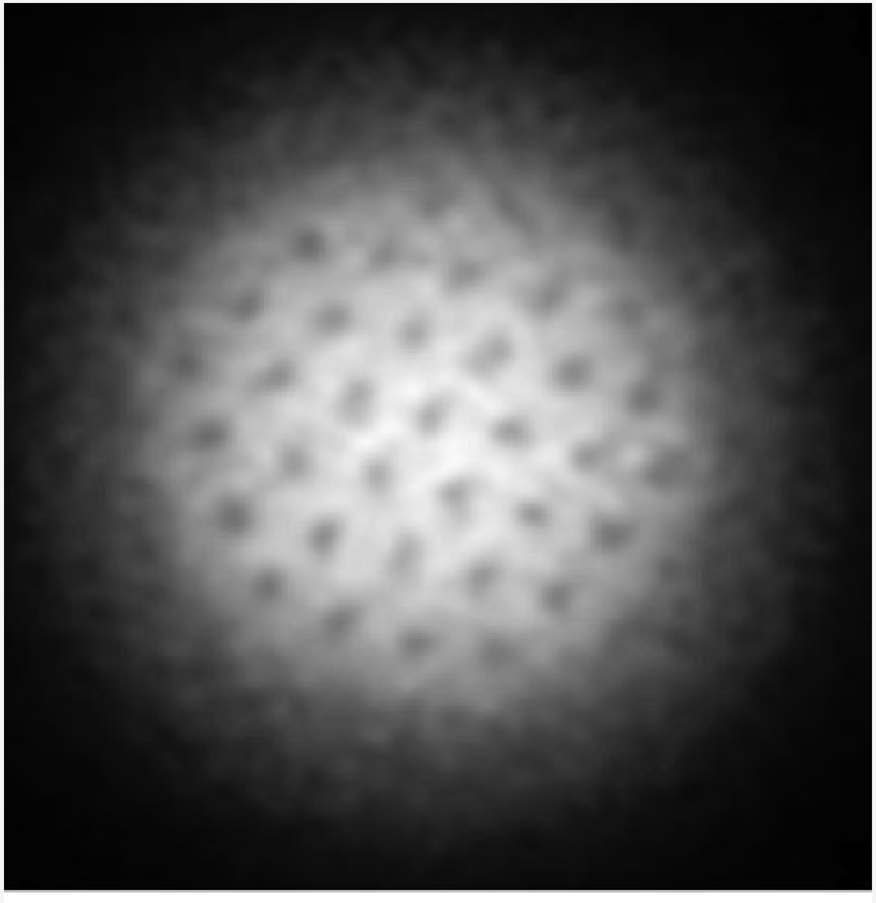


Observation of superfluidity

Spinning a strongly interacting Fermi gas



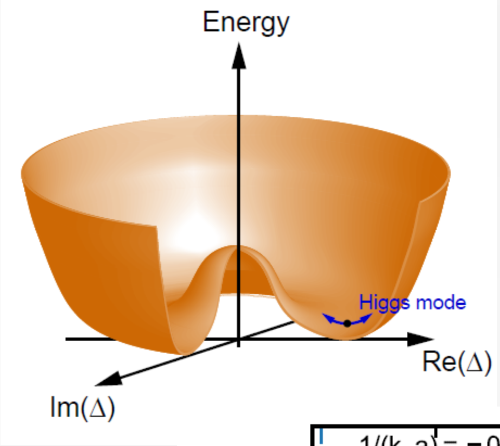
Vortex lattices: a sign of the superfluidity



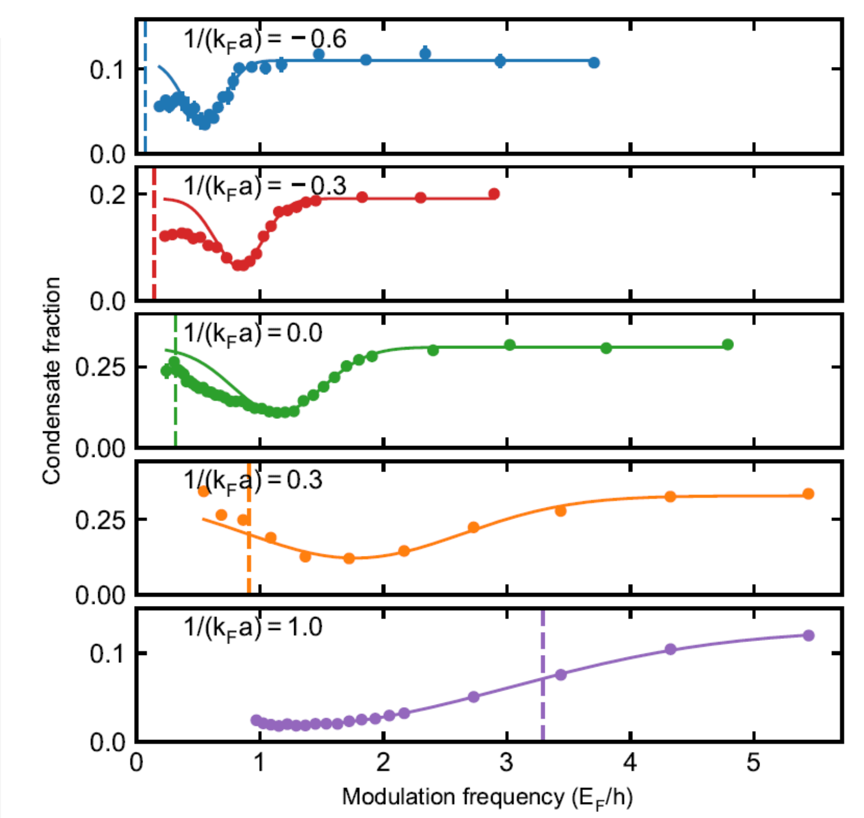
M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle,
Nature 435, 1047-1051 (2005)

Summary: Higgs mode in fermionic gases

red-detuned rf-excitation scheme
->direct coupling to Higgs mode



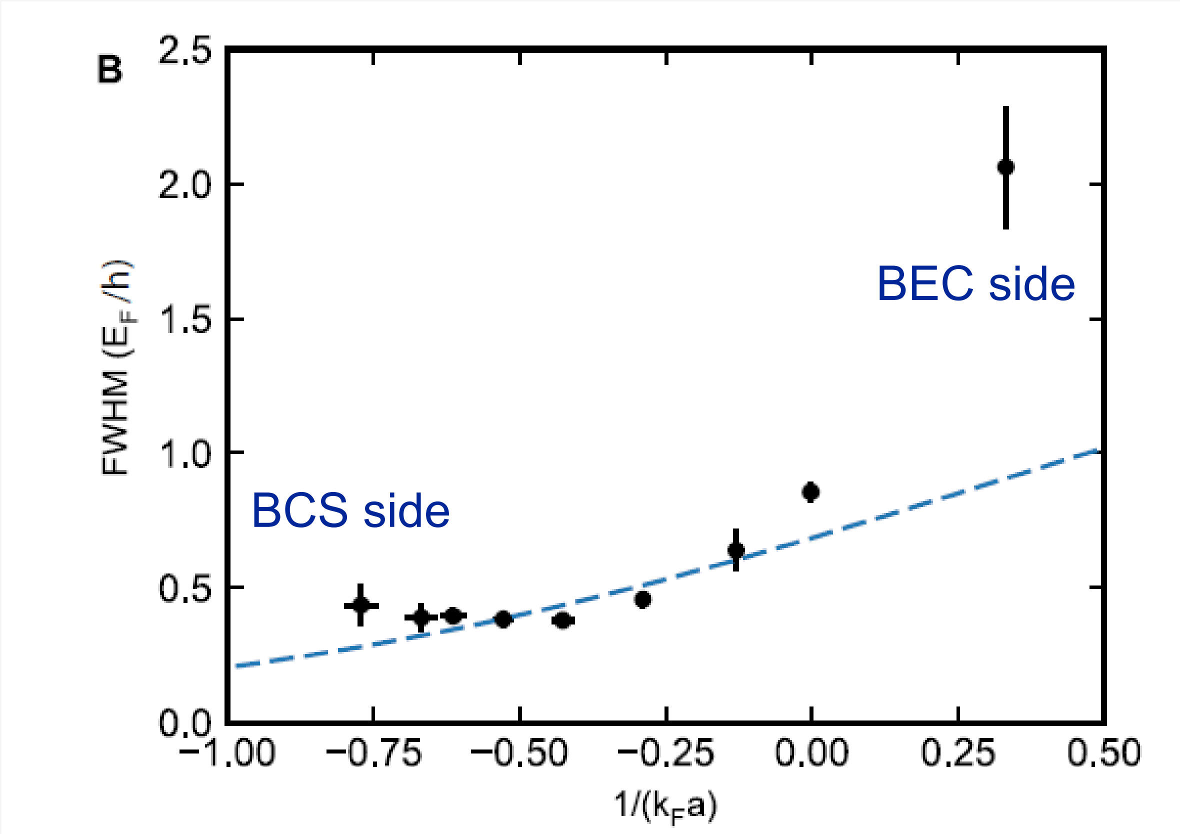
- stable Higgs mode at 2Δ on BCS side
- relatively narrow mode close to unitarity



Thanks to
J. Kombe and J-S Bernier
&
experimental group M. Köhl

Width of the mode

width of peak



~ expected broadening
from excitation scheme

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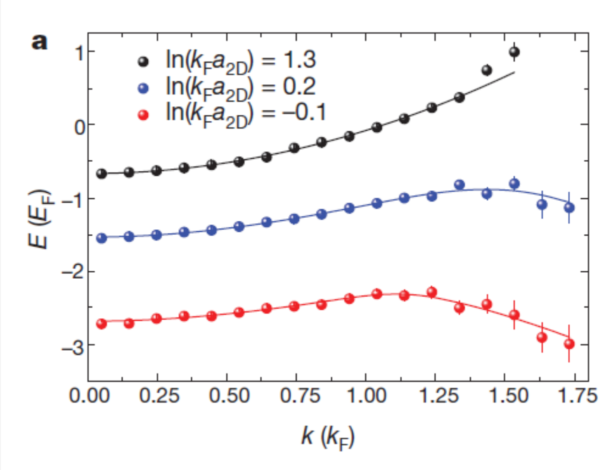
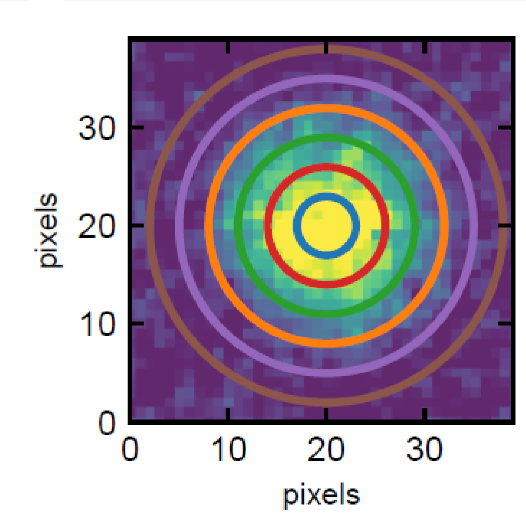
Is it a collective mode?

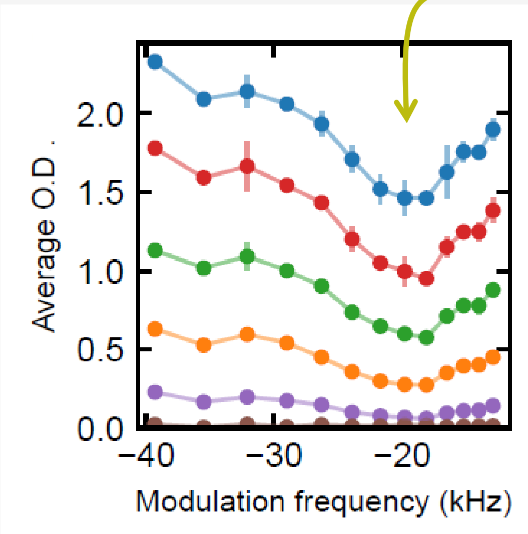
Combine spectroscopy with momentum resolution

Quasiparticles:
Pronounced dispersion
(Feld et al., Nature 2011)



Expand for quarter period in weak trap





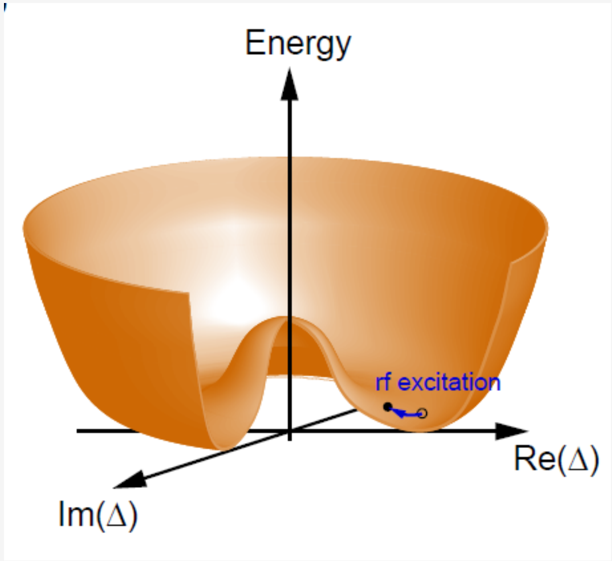
Higgs excitation:
Same resonance frequency for all momenta within condensate

BCS-equations of motion + 3rd state

change of order parameter

$$
\begin{aligned}
\hbar\frac{\partial}{\partial t}\langle c_{-k,2}c_{k,1}\rangle &= i\{-2\epsilon_k\langle c_{-k,2}c_{k,1}\rangle - \frac{\hbar\Omega_R}{2}\langle c_{-k,3}c_{k,1}\rangle + \Delta(n_{k,1}+n_{-k,2}-1)\} \\
\hbar\frac{\partial}{\partial t}\langle c_{-k,3}c_{k,1}\rangle &= i\{-\frac{\hbar\Omega_R}{2}\langle c_{-k,2}c_{k,1}\rangle - (2\epsilon_k - \hbar\delta)\langle c_{-k,3}c_{k,1}\rangle + \Delta\langle c^\dagger_{-k,2}c_{-k,3}\rangle\} \\
\hbar\frac{\partial}{\partial t}\langle c^\dagger_{-k,2}c_{-k,3}\rangle &= i\{\Delta^*\langle c_{-k,3}c_{k,1}\rangle + \hbar\delta\langle c^\dagger_{-k,2}c_{-k,3}\rangle - \frac{\hbar\Omega_R}{2}(n_{-k,2}-n_{-k,3})\} \\
\hbar\frac{\partial n_{k,1}}{\partial t} &= -2\mathrm{Im}(\Delta^*\langle c_{-k,2}c_{k,1}\rangle) \\
\hbar\frac{\partial n_{-k,2}}{\partial t} &= -2\mathrm{Im}(\Delta^*\langle c_{-k,2}c_{k,1}\rangle) + \hbar\Omega_R\mathrm{Im}(\langle c^\dagger_{-k,2}c_{-k,3}\rangle) \\
\hbar\frac{\partial n_{-k,3}}{\partial t} &= -\hbar\Omega_R\mathrm{Im}(\langle c^\dagger_{-k,2}c_{-k,3}\rangle)
\end{aligned}
$$

plus self-consistency condition
(no final state interaction)



Couples to the amplitude
of the order parameter

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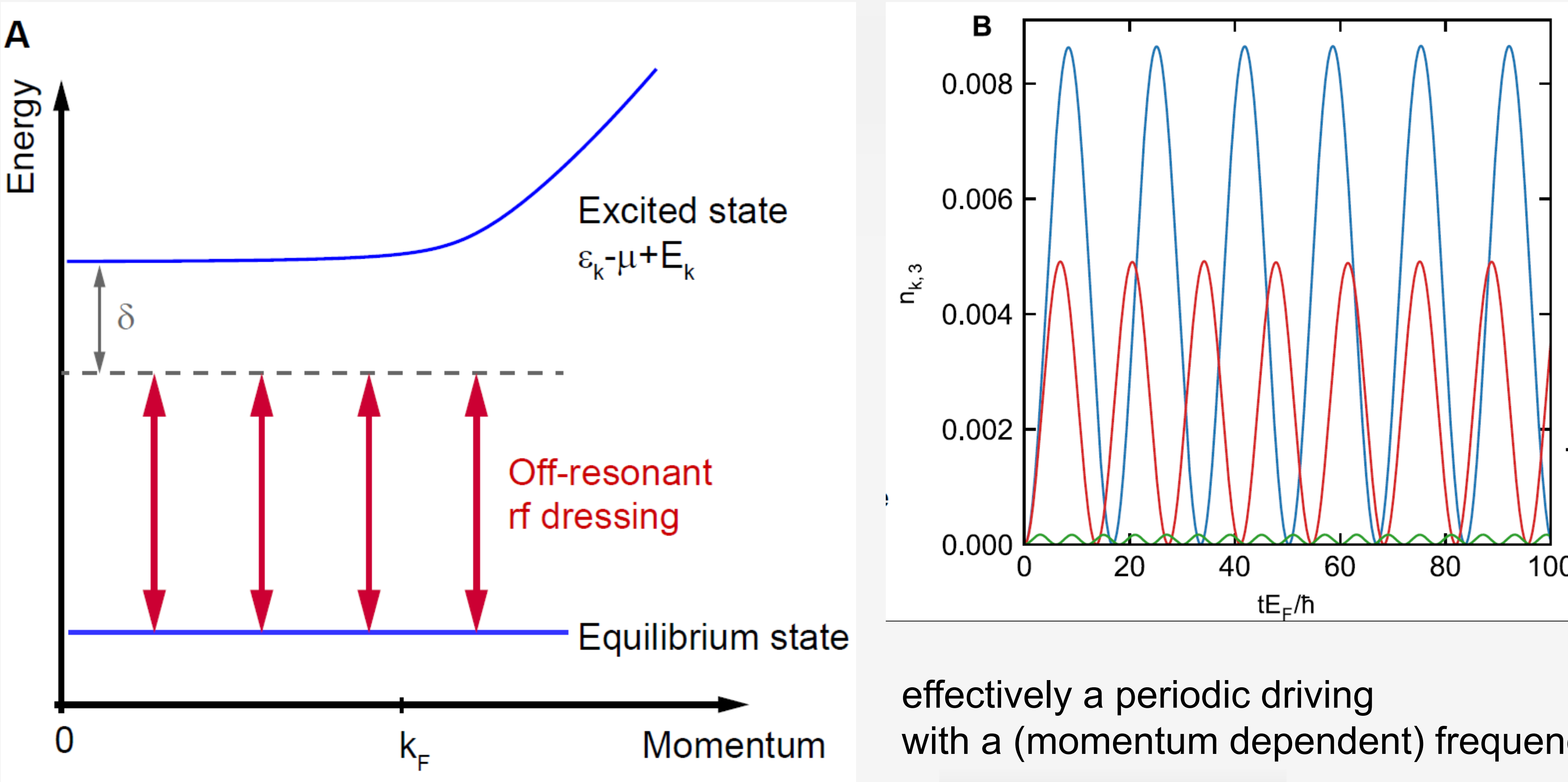
Far-off resonant rf-excitation scheme



effectively a periodic driving
with a (momentum dependent) frequency

$$\Omega_R' = \sqrt{\Omega_R^2 + \delta^2}$$

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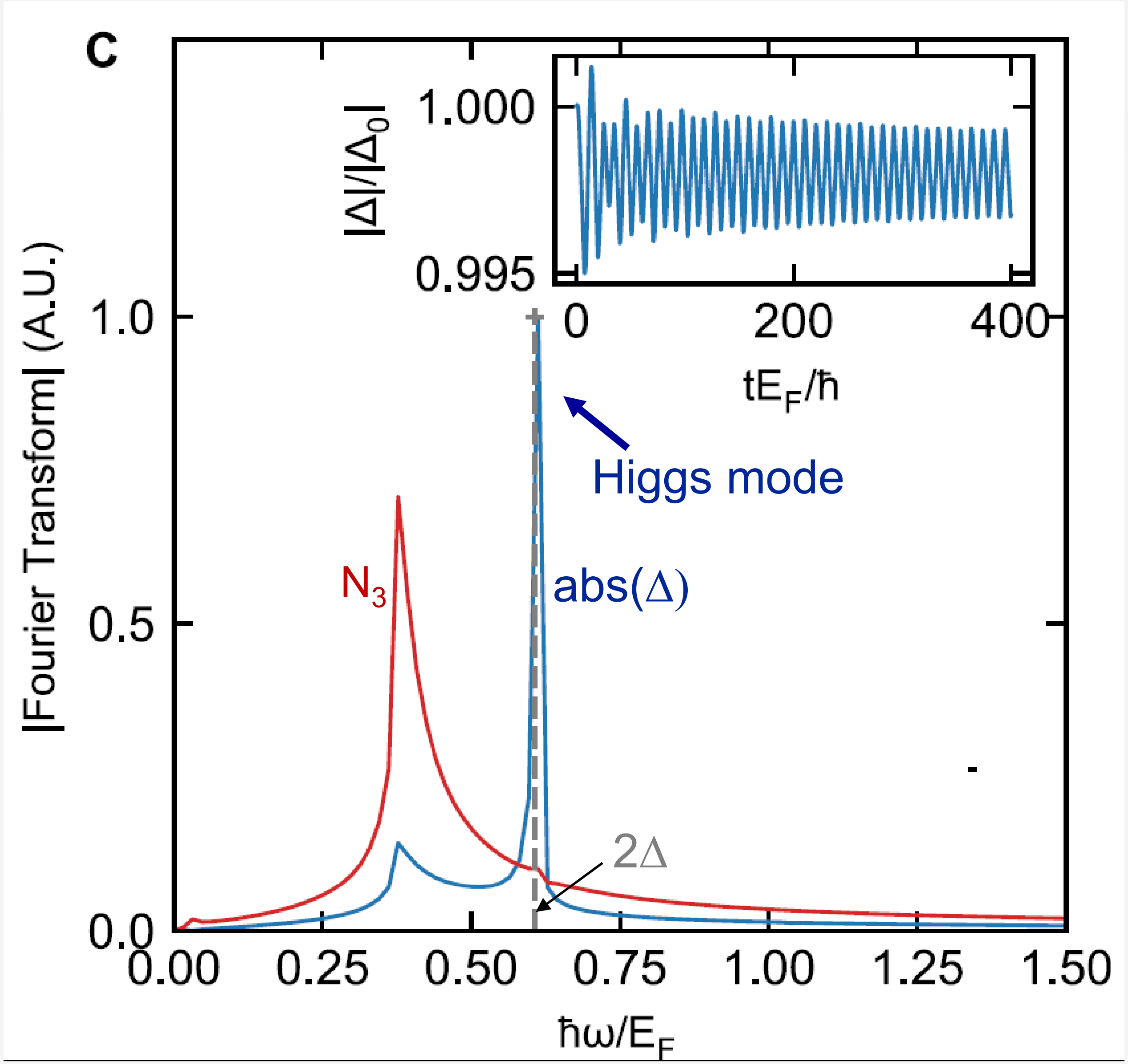
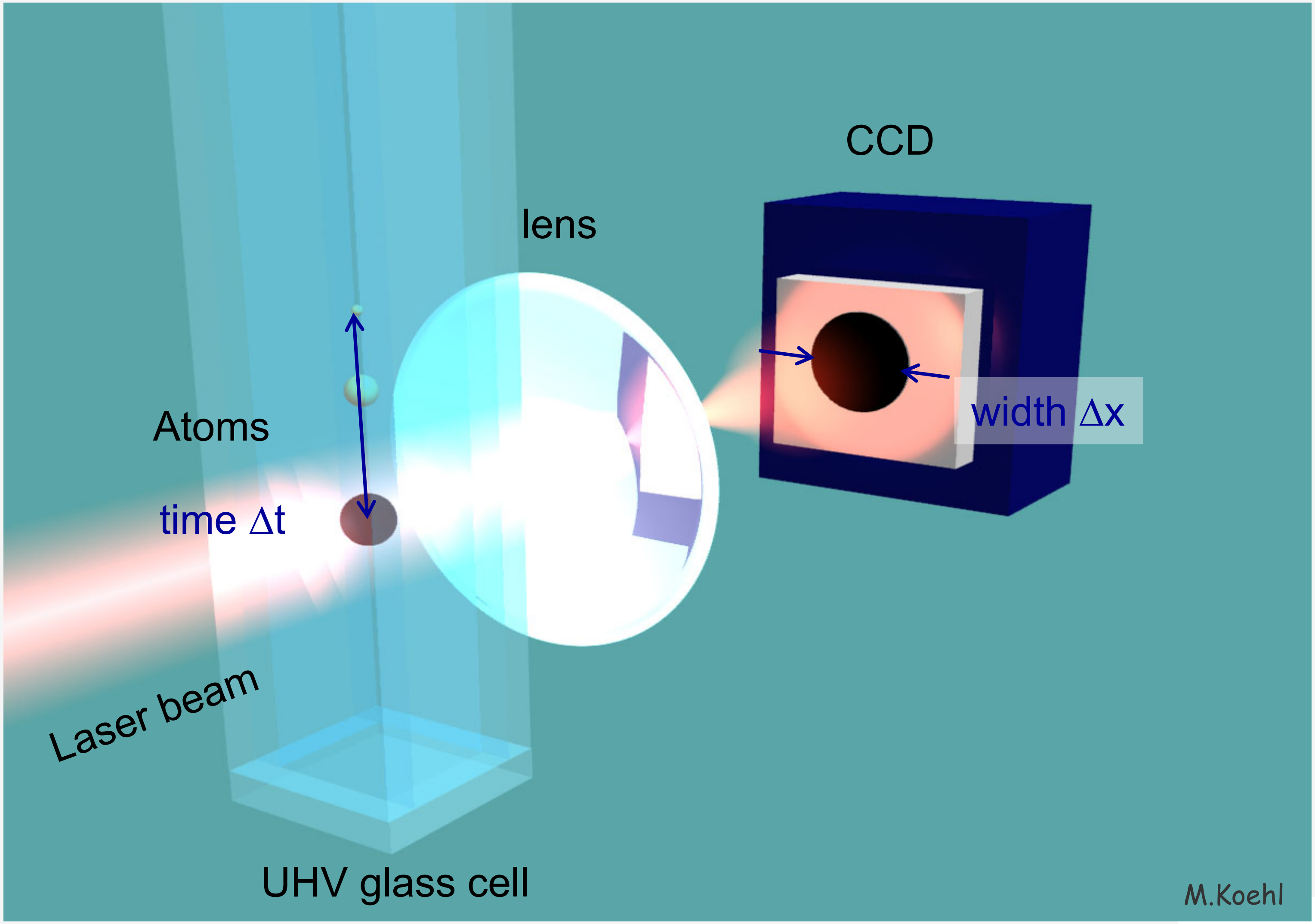
Dynamics within BCS theory



How to measure the Bose-Einstein condensate



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