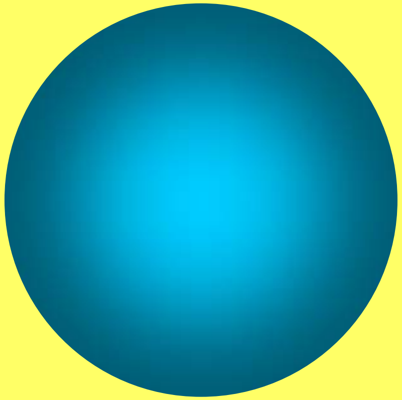
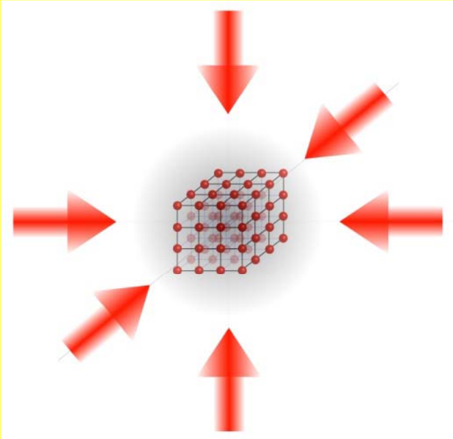
Optical Lattice and Quantum Information

OLAQUI

Tilman Esslinger
ETH Zürich

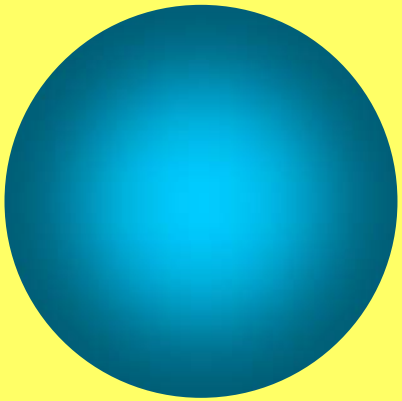


+



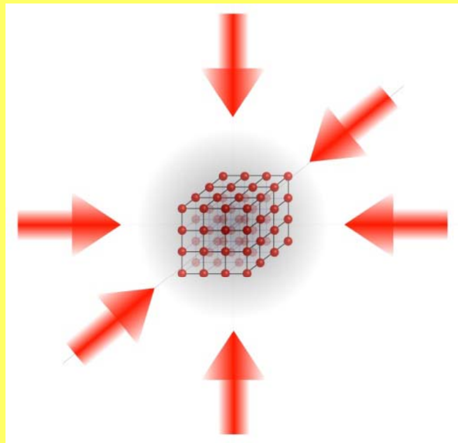
Quantum Gases

Optical Lattices



Quantum Gases

+



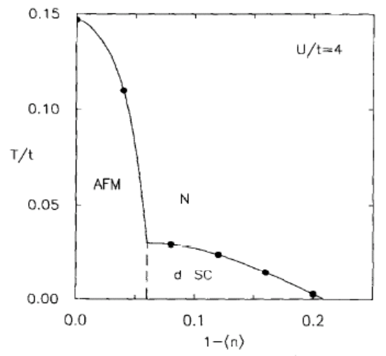
Optical Lattices

$$H = -J \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

Fermi-Hubbard

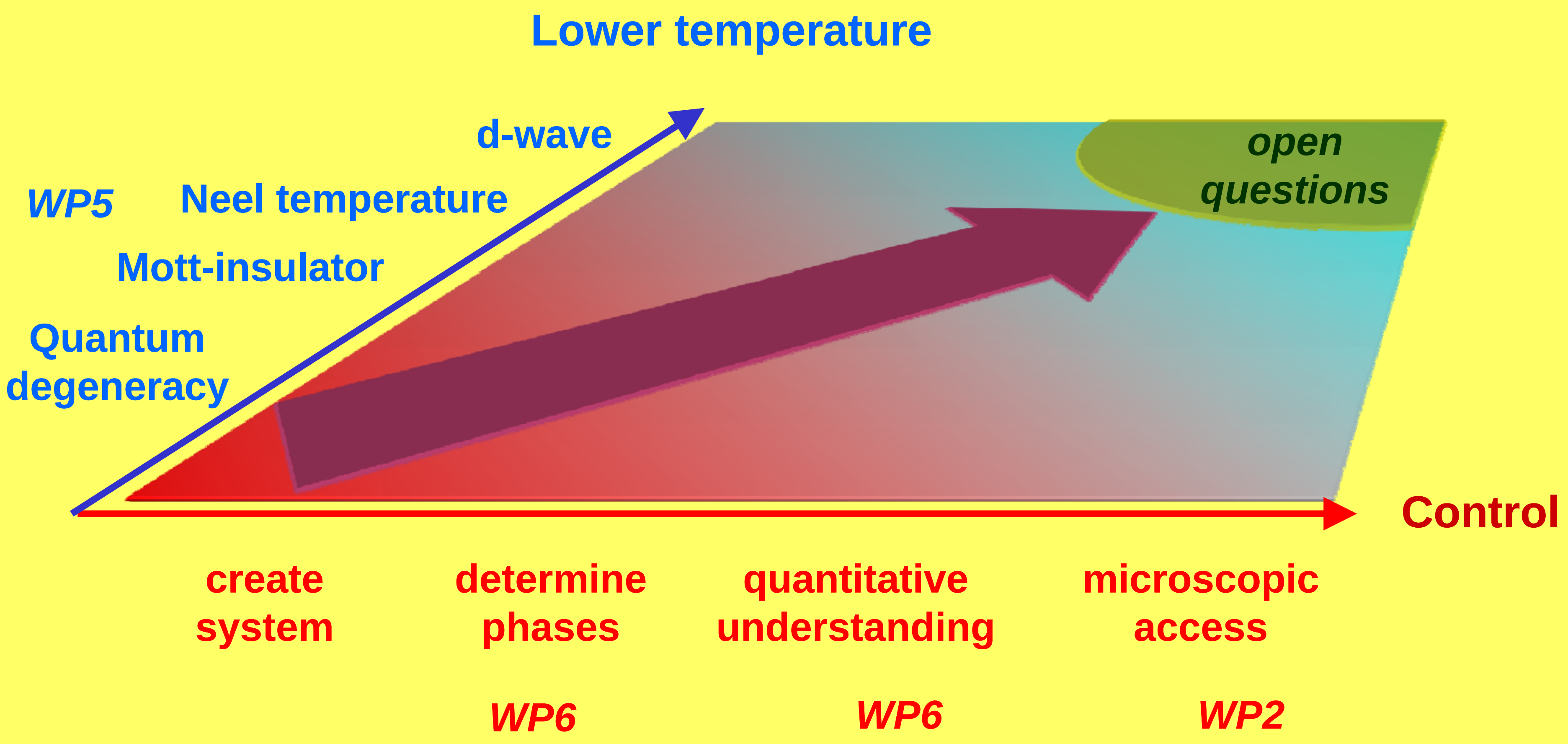
$$H = -J \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

d-wave superconductor



Scalapino, Phys. Rep. 250, 329 (1995)
Hofstetter et al., Phys. Rev. Lett. 89, 220407 (2002)

Quantum Simulation



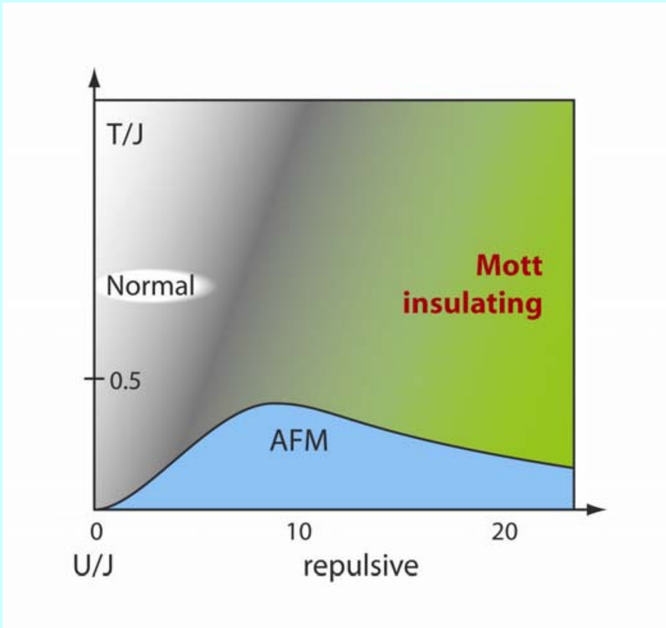
Outline

- **Determine phases (WP2, 5, 6)**:
  Mott insulator in a Fermi-Hubbard model

- **Microscopic access (WP2)**:
  Cavity QED with a BEC

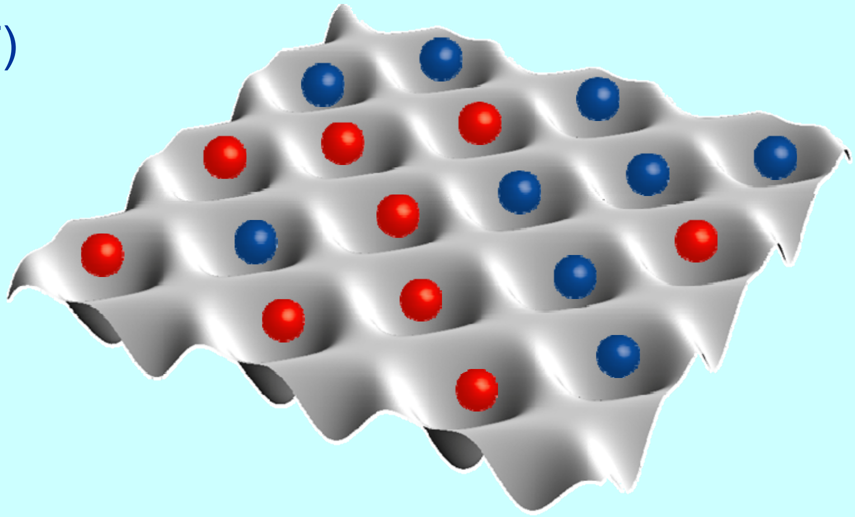
Mott insulator of fermions

Crossover from conductor to Mott-Insulator



What is a Mott insulator?

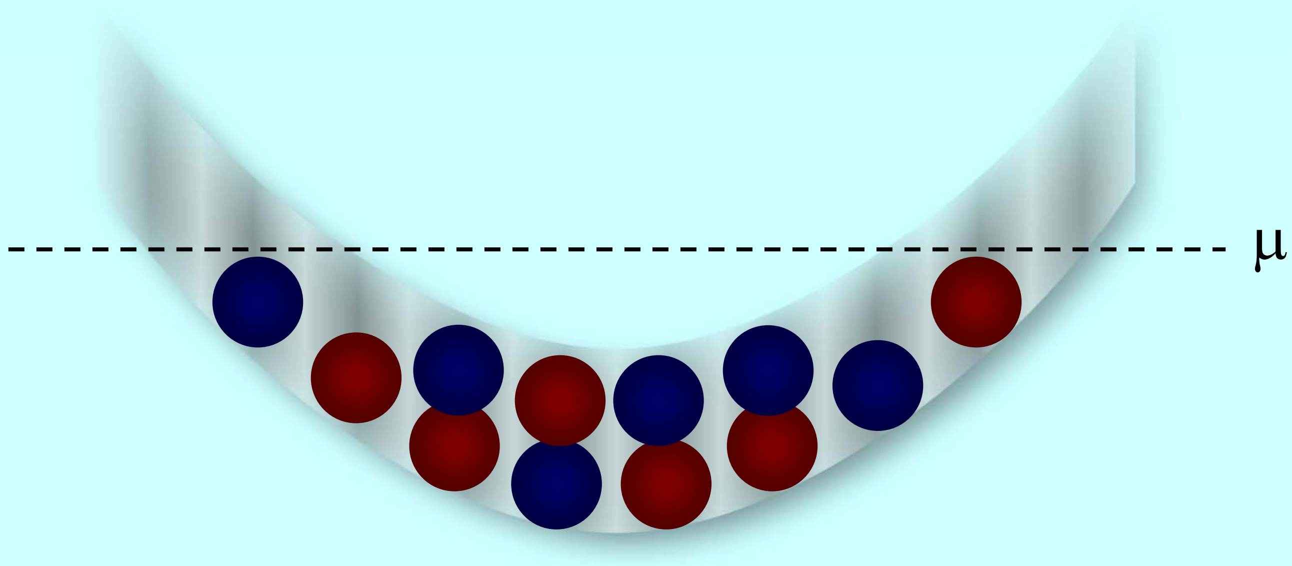
Interaction-induced localization (U>>T)



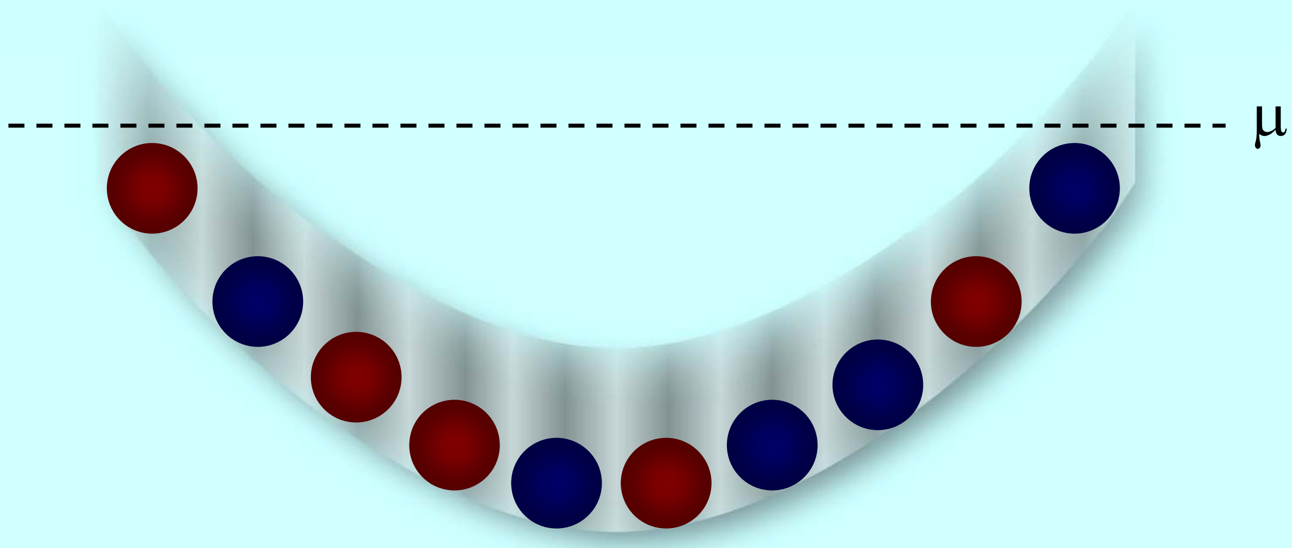
- insulator
- incompressible
- energy gap
- reduced number fluctuations

Measure double occupancy

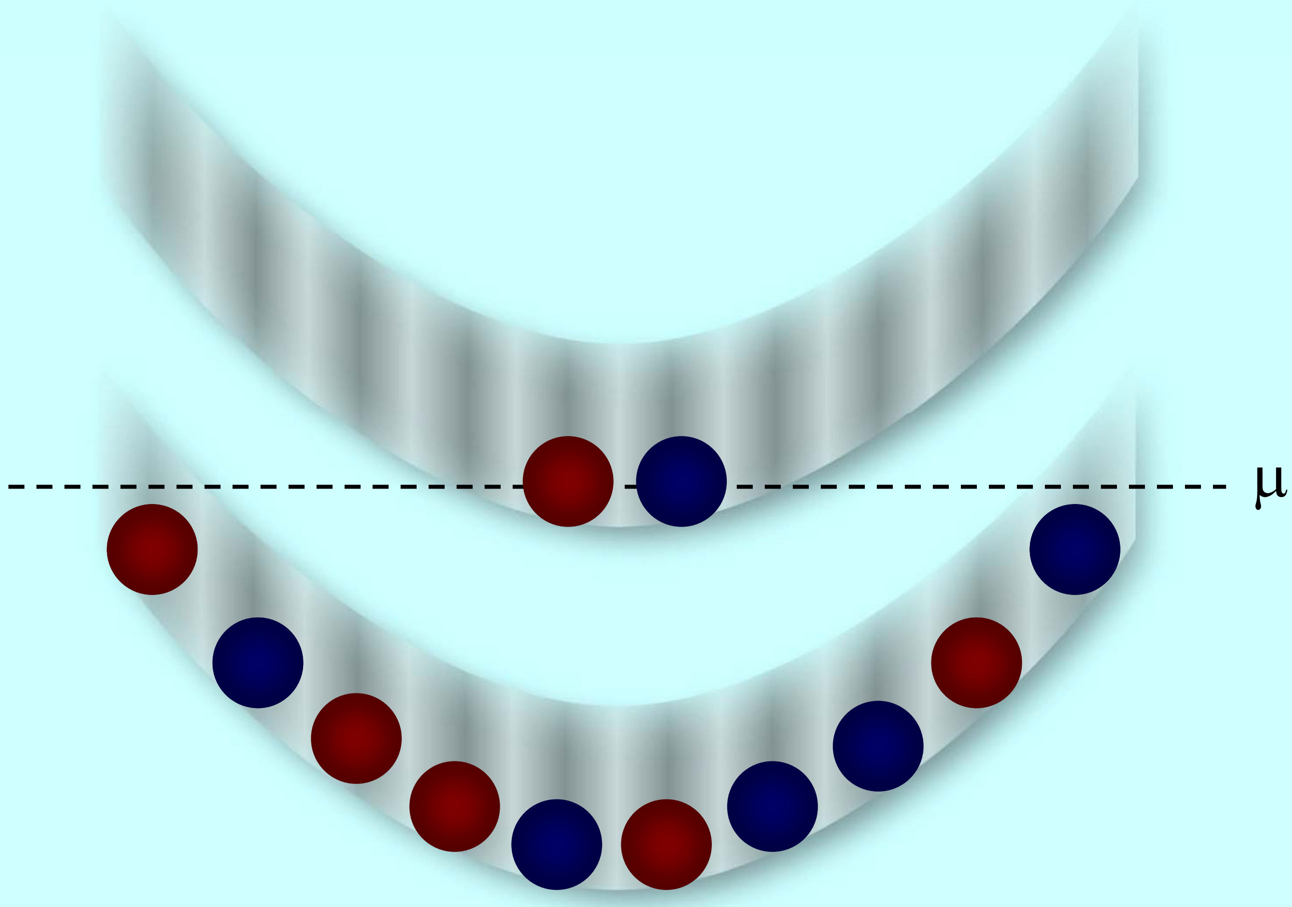
Energy spectrum



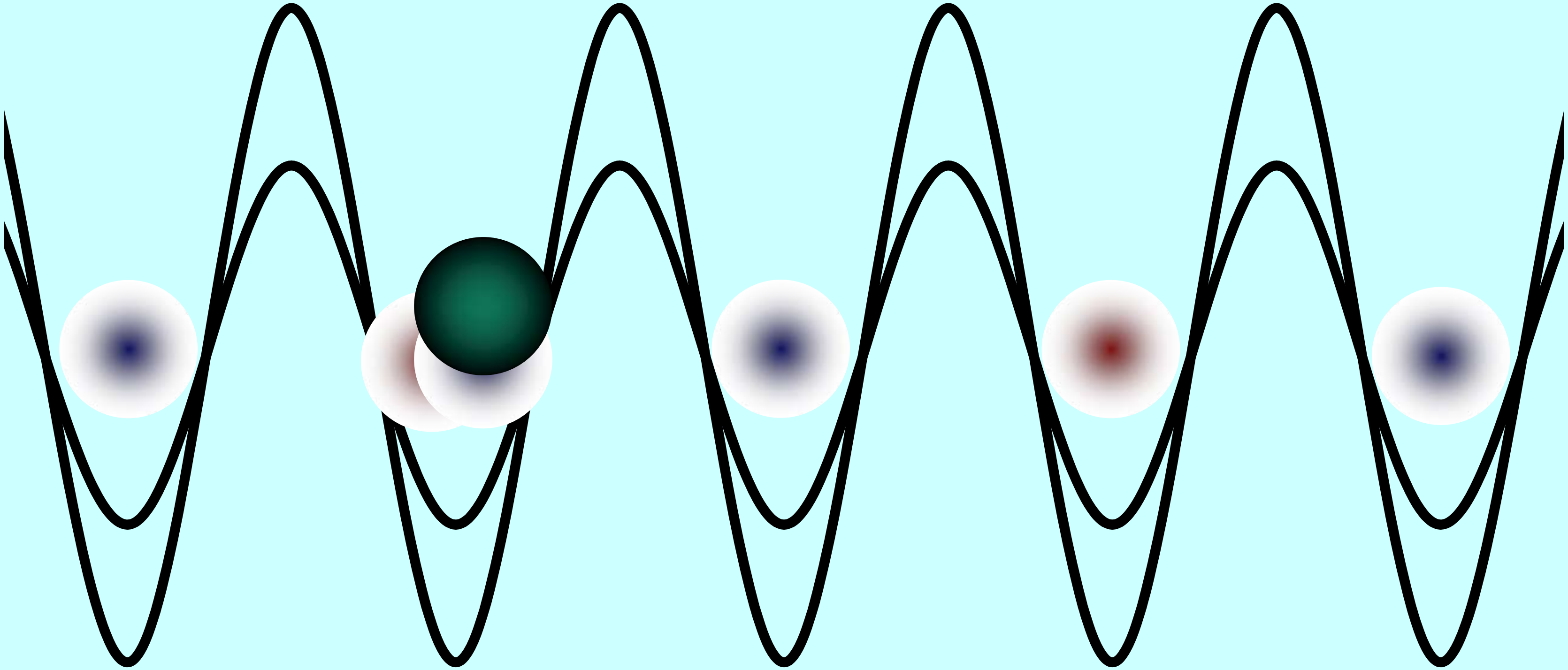
Energy spectrum



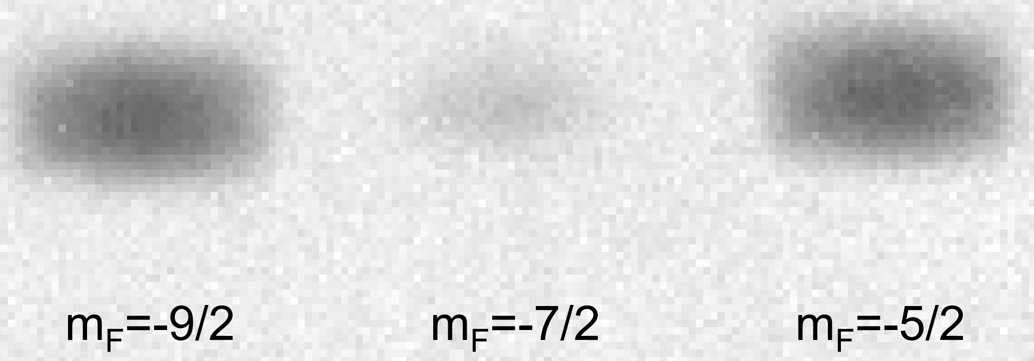
Energy spectrum



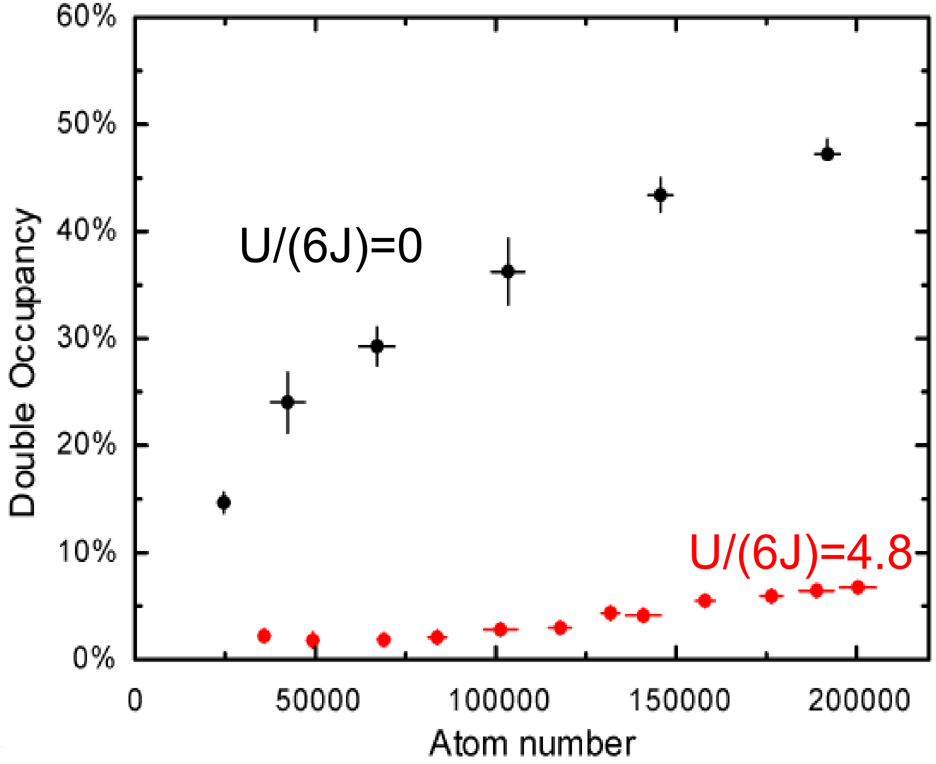
Measuring Double Occupancy (WP2)



Measuring Double Occupancy

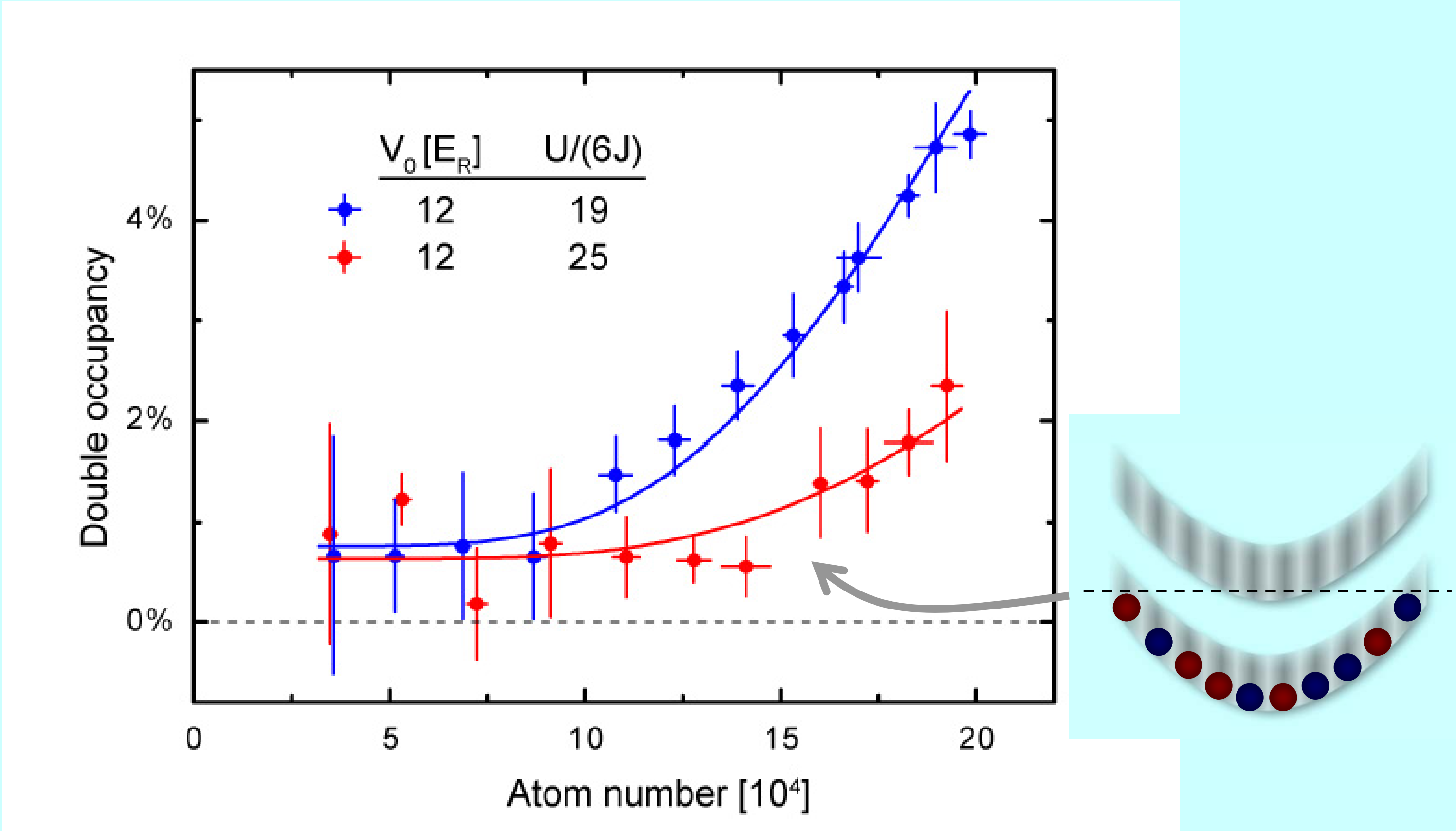


Suppression of double occupancy



R. Jördens, N. Strohmeier, K. Günter, H. Moritz, T. Esslinger, Nature 455, 204 (2008).

Occupation of upper Hubbard band (WP5, 6)



Fit: $T=0.2 \pm 0.1\ T_F$

Temperature

determine temperature in dipole trap:

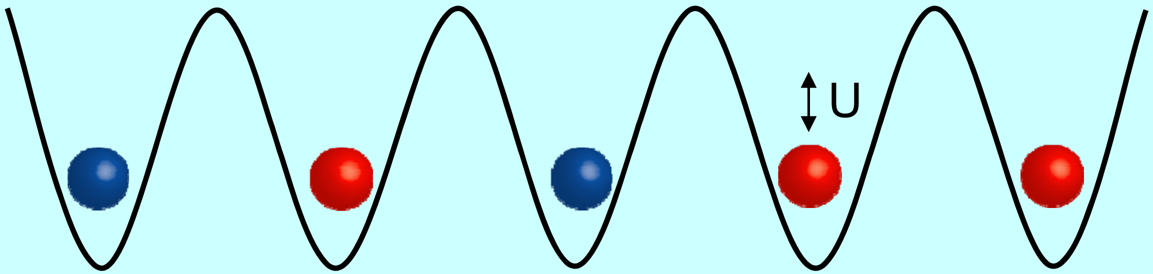
$T/T_F \sim 0.14$, $T_{rev}/T_F \sim 0.24 \Rightarrow$ use $T/T_F \sim 0.195$

constant entropy

→ 3 % vacancies in the center

$T/U = 0.1$

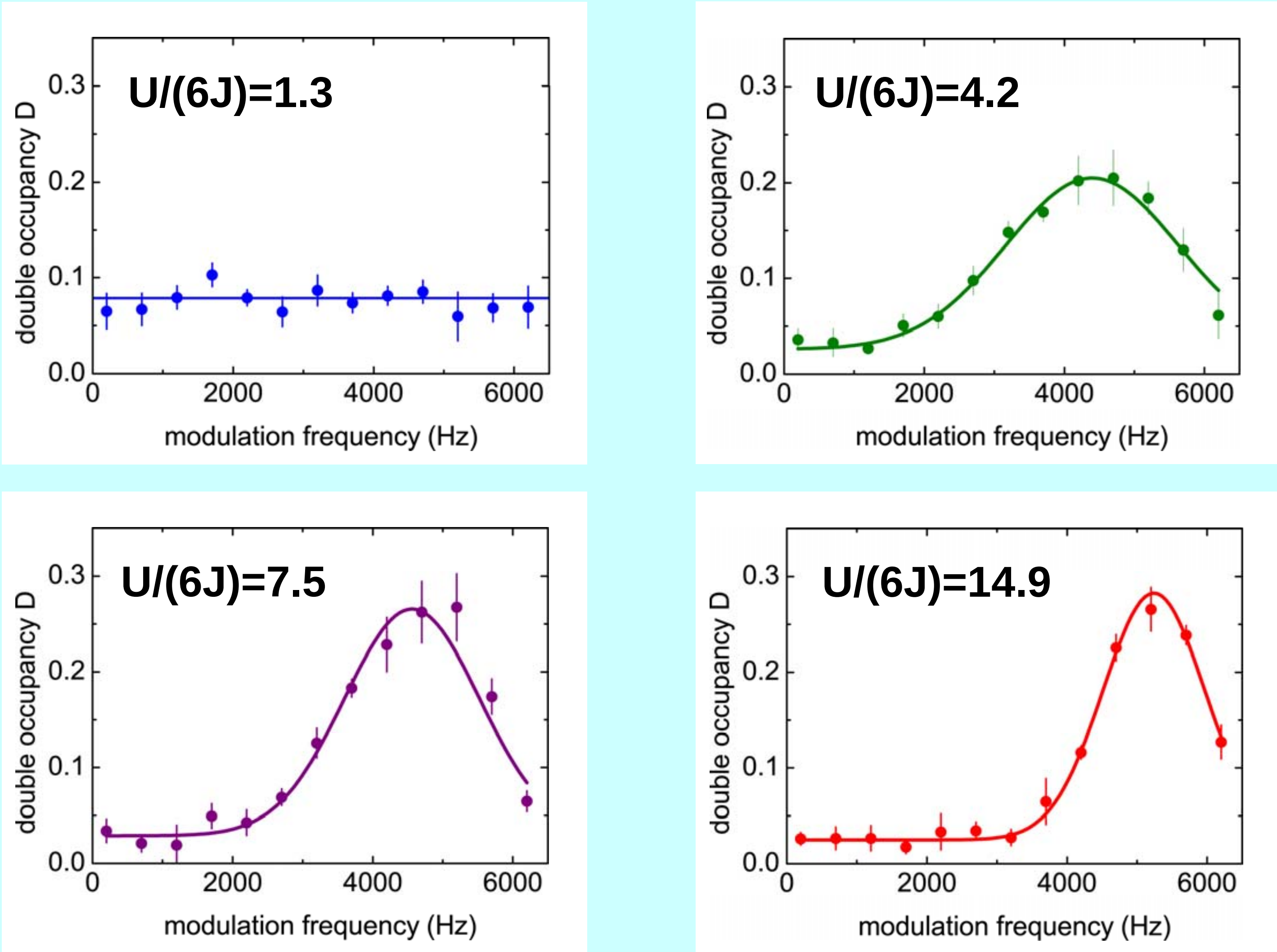
Gapped Mode



Modulation of the lattice amplitude with frequency U/h: Particle-hole excitation

C. Kollath et.al, Phys.Rev.A., 74, 041604 (2006)
T. Stöferle et.al., Phys.Rev.Lett., 92, 130403 (2004)

Gapped excitation mode



Mott-insulator

direct measurement

one atom per site

Temperature
+
Hubbard model

R. Jördens, N. Strohmeier, K. Günter, H. Moritz, T. Esslinger, Nature 455, 204 (2008).

Quantum Simulation

$$H = -J \sum_{\{i,j\},\sigma} (\hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + h.c.) + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow} + \sum_{i} \varepsilon_i \hat{n}_i$$

can be calculated for present experimental temperatures

(DMFT and HTE)

it should be possible to obtain very good agreement

between theory and experiment

Quantum Simulation

$$H = -J \sum_{\{i,j\},\sigma} (\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U\sum_{i} \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow} + \sum_{i} \varepsilon_i \hat{n}_i$$

If no agreement:

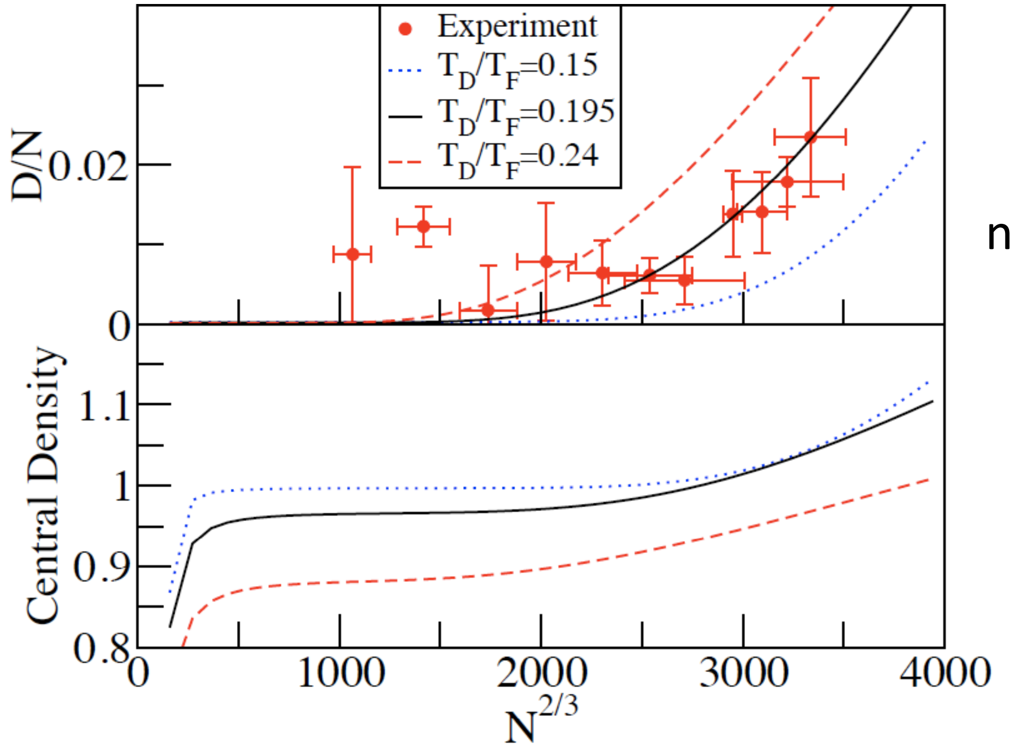
thermalization / adiabaticity

two-body scattering problem U

control of experimental parameters

Comparison with High Temperature Series Expansion of the Hubbard Model

V. Scarola Berkeley/ETH



no fitting parameters

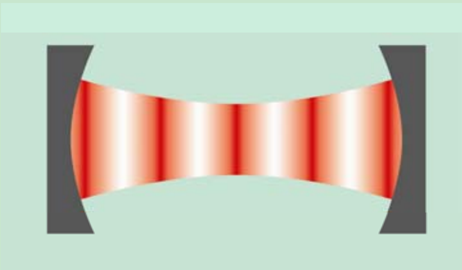
t=0.054 kHz
T_F=Fermi Temp.
U= 6.1 KHz

WP 2

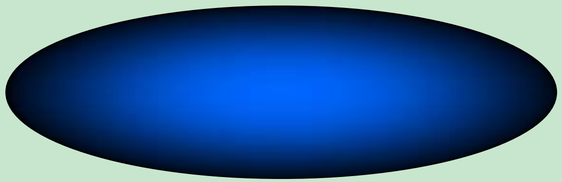
D3 - Detection of single atoms from Bose-Einstein condensates

D5 - Addressing single sites in an optical lattice

Cavity QED

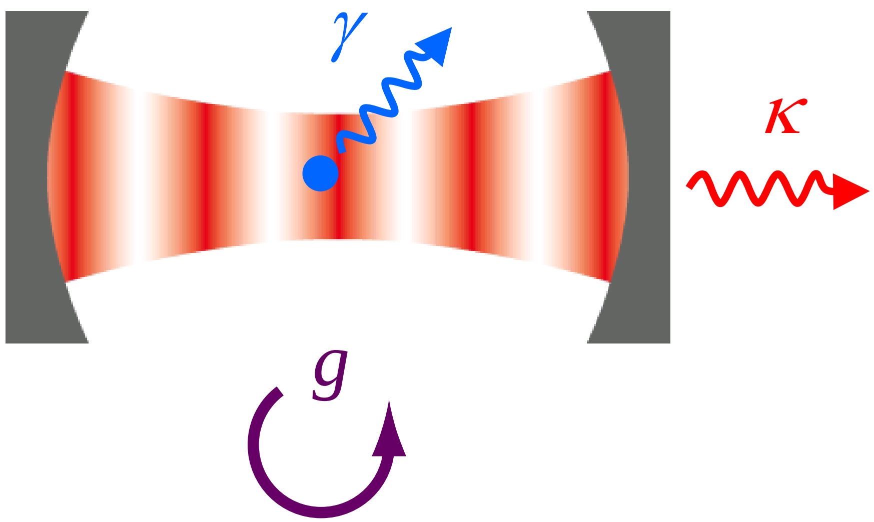


BEC



WP 2

Individual atoms in a high-finesse cavity

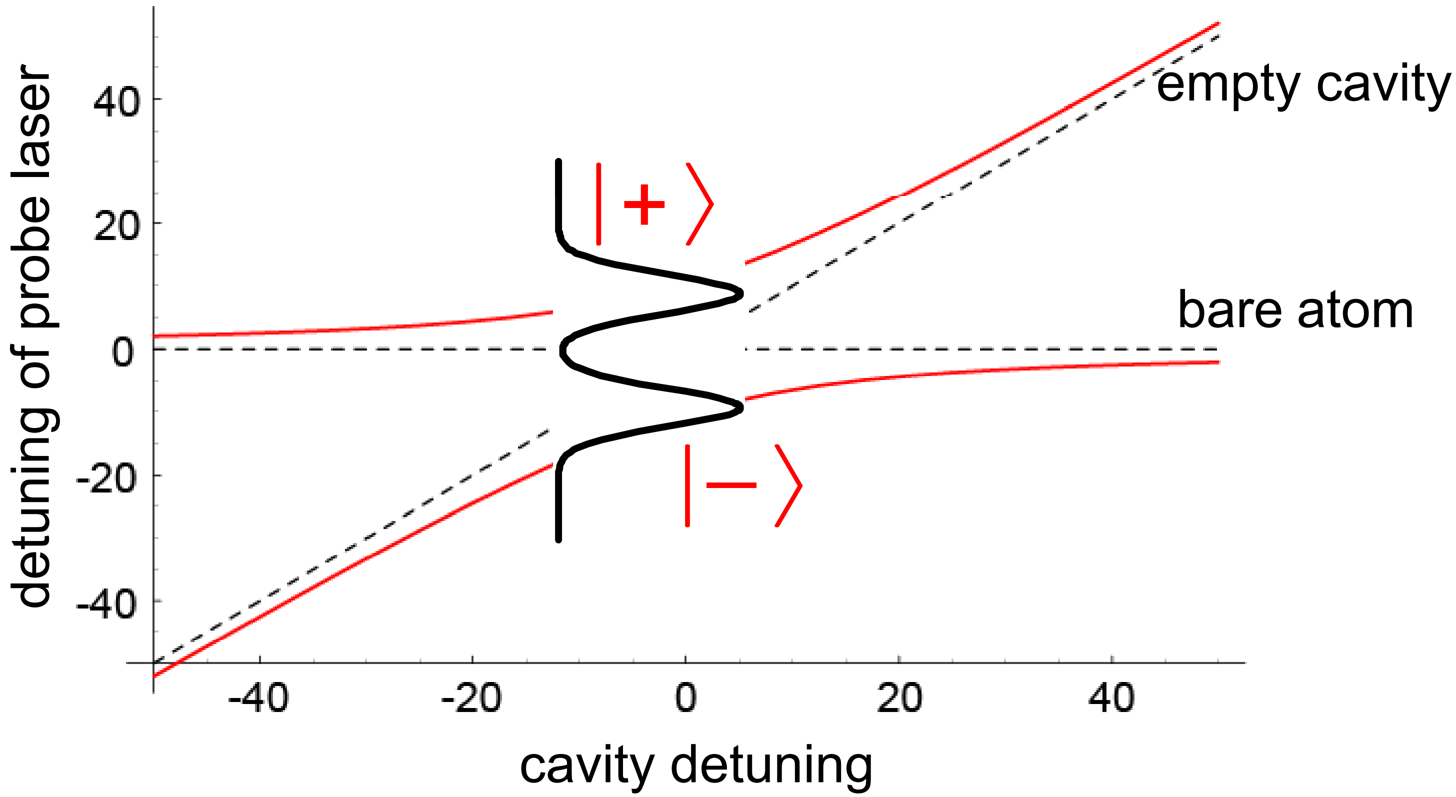


Strong coupling regime: $g > \gamma, \kappa$

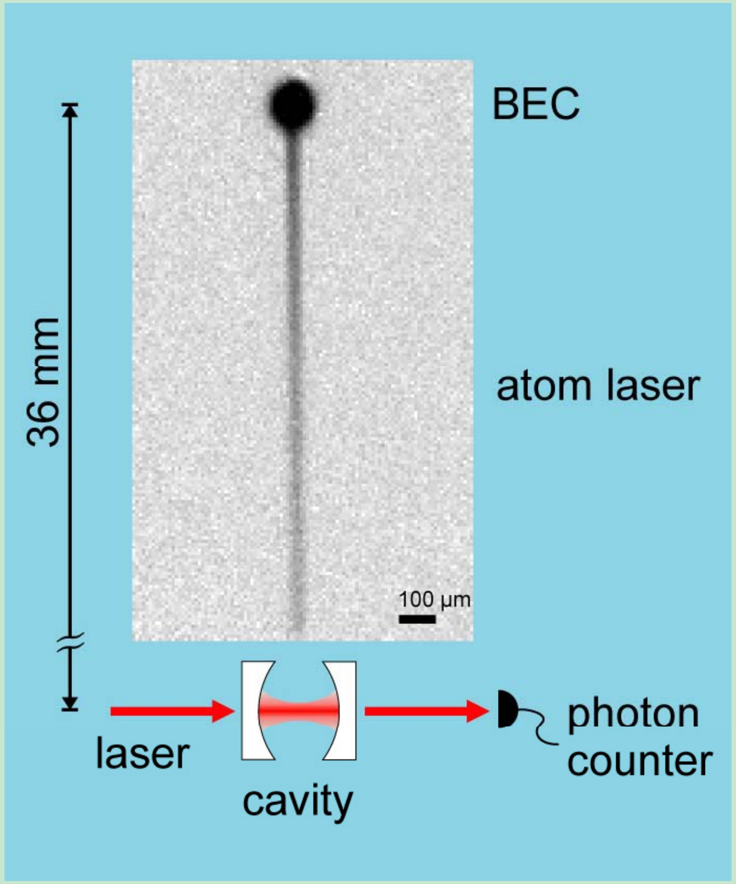
Optical cavity-QED: Kimble, Rempe, Chapman

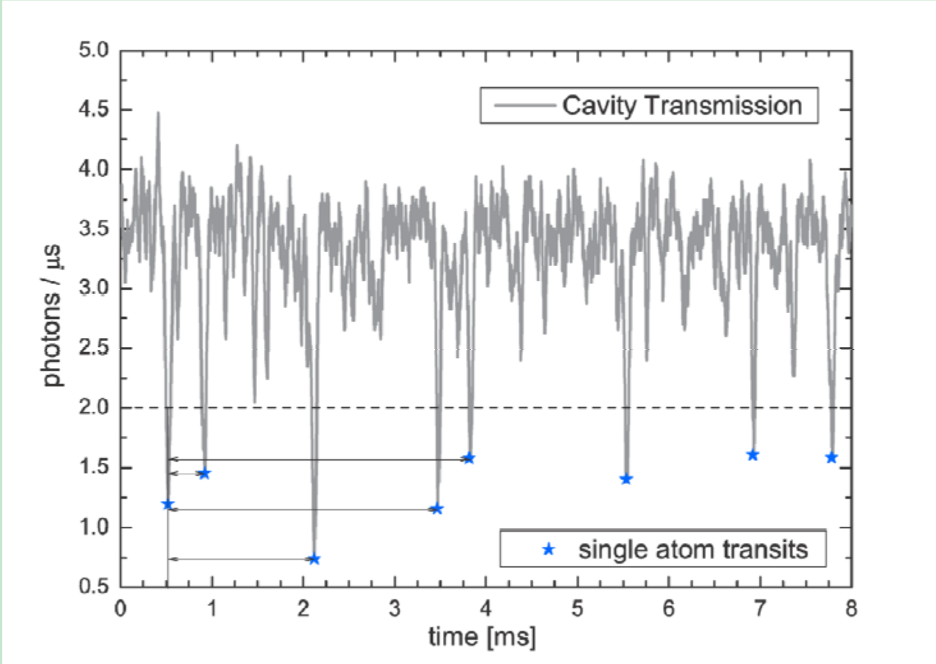
Microwave cavity-QED: Haroche, Walther

Jaynes-Cummings with detuning



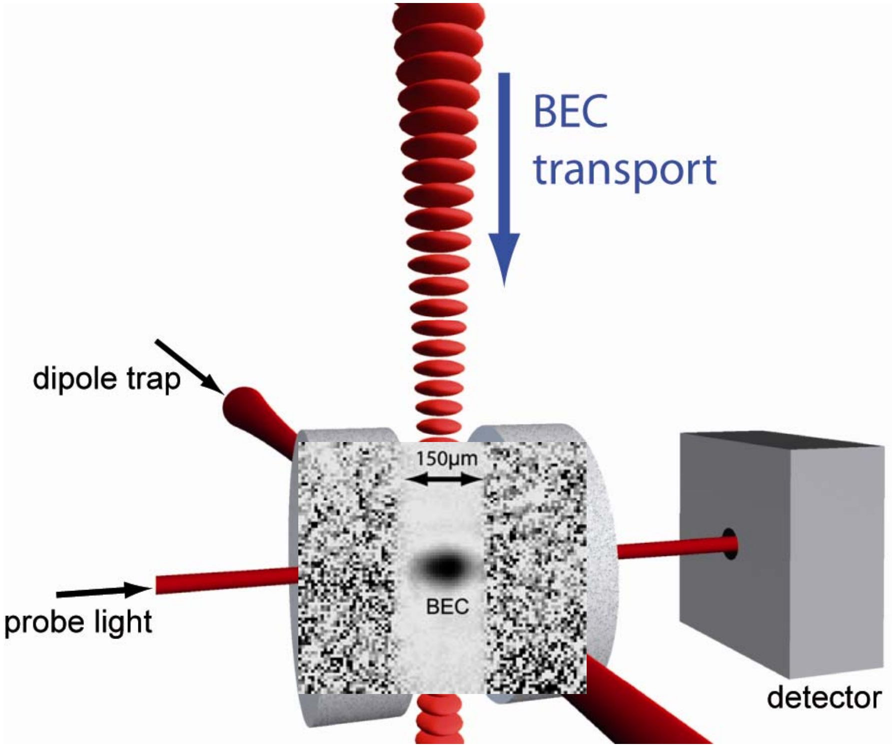
WP 2



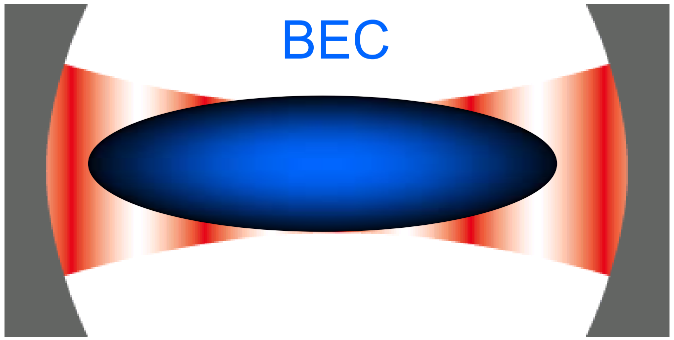


$$g^{(2)}(\tau) = P_c(t+\tau \mid t) = \frac{\langle I(t) I(t+\tau) \rangle}{\langle I \rangle^2}$$

Setup

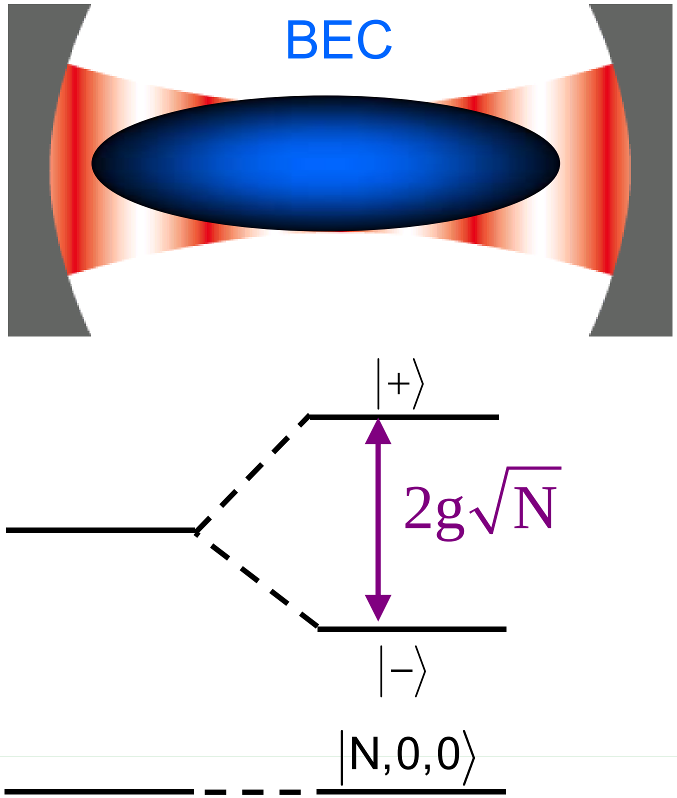


A BEC in a high-finesse cavity



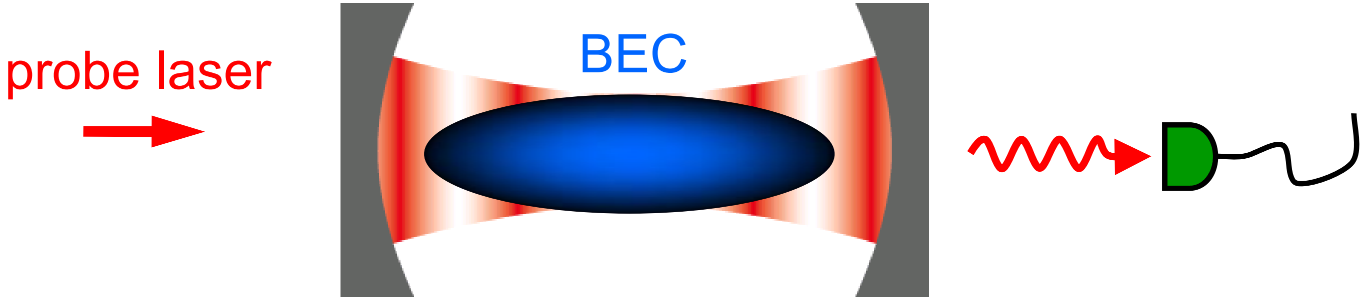
N atoms in delocalized wavefunction of BEC
coupling to the cavity

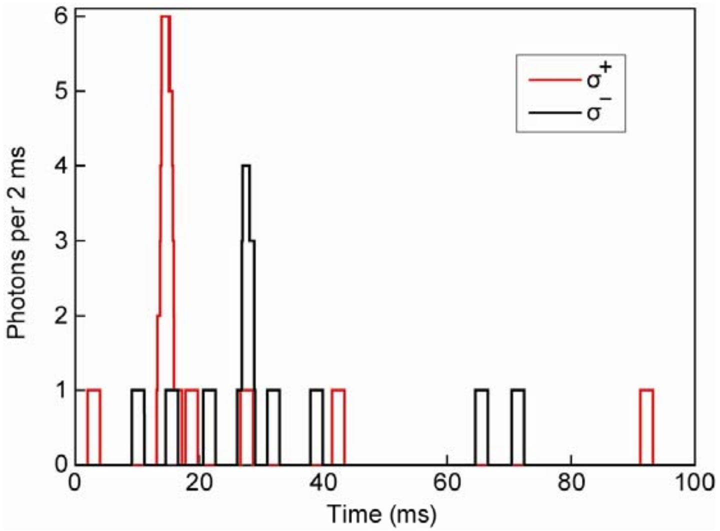
A BEC in a high-finesse cavity



Tavis-Cummings Hamiltonian

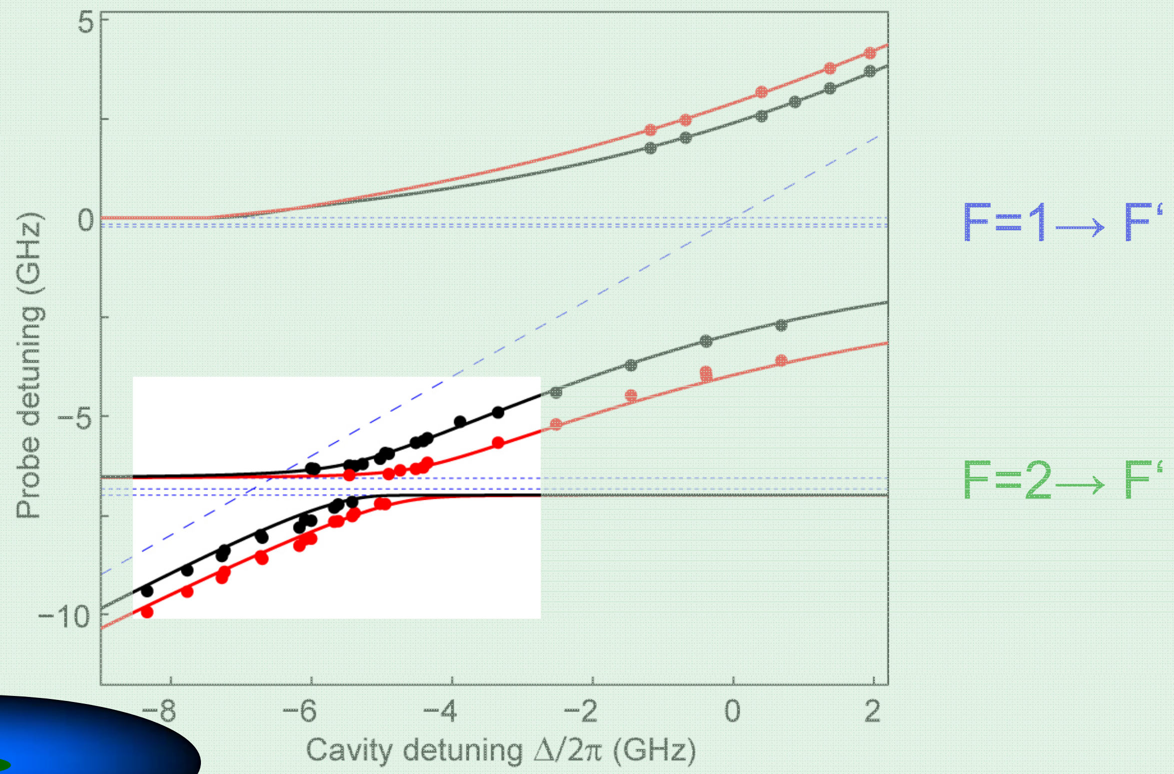
Spectroscopy of Cavity-BEC

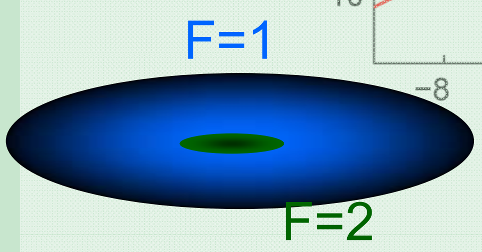




Probe frequency scan over 2.5 GHz at fixed cavity detuning

Cavity-BEC Energy Spectrum

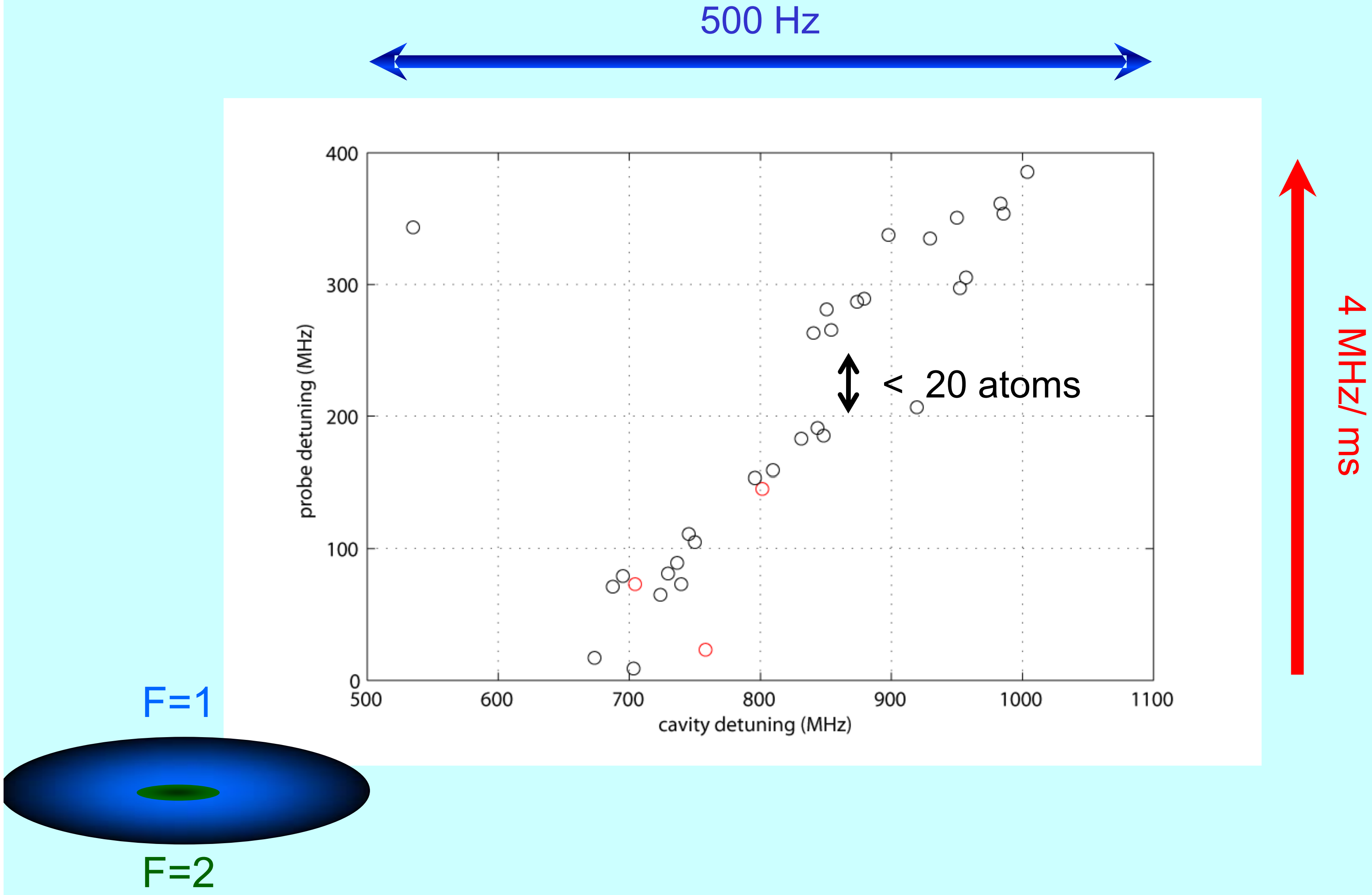




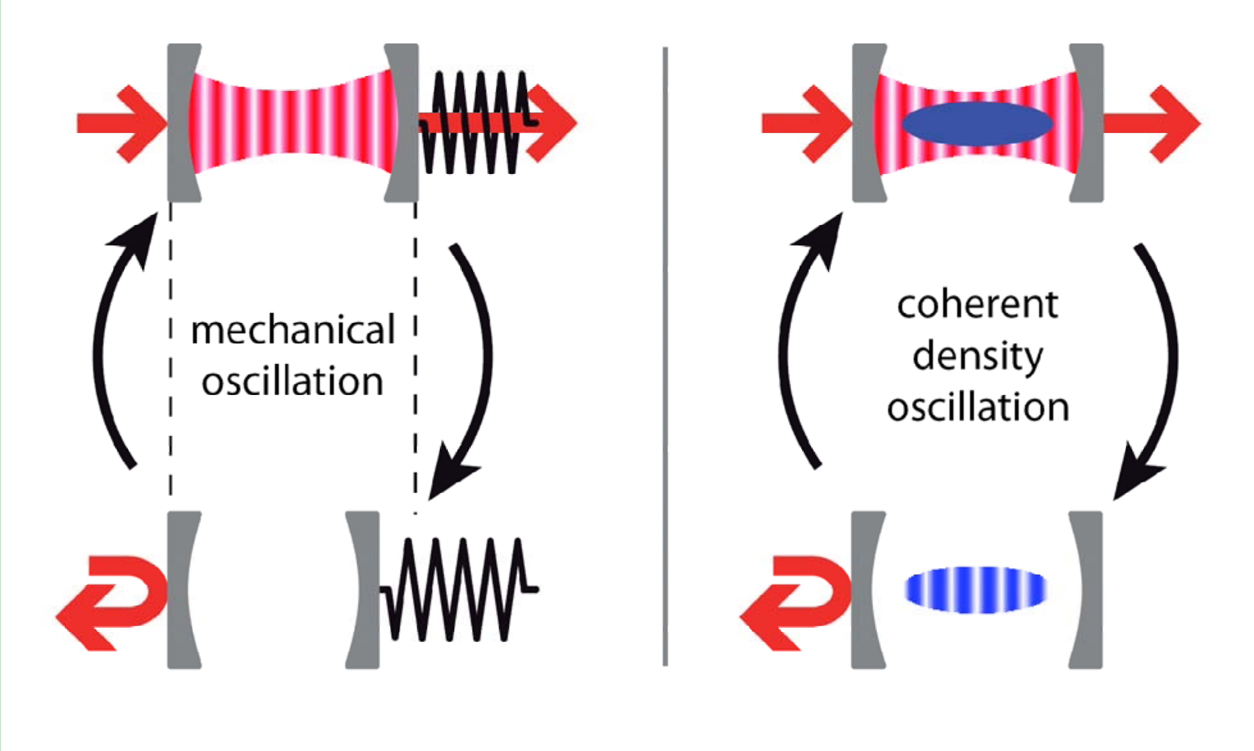
collective cooperativity: $Ng^2/(2\kappa\gamma)=1.6\text{x}10^6$

F. Brennecke, T. Donner, S.Ritter, T. Bourdel, M. Köhl, T. Esslinger, Nature 450, 268 (2007)

Monitoring few atoms



Cavity opto-mechanics with a BEC

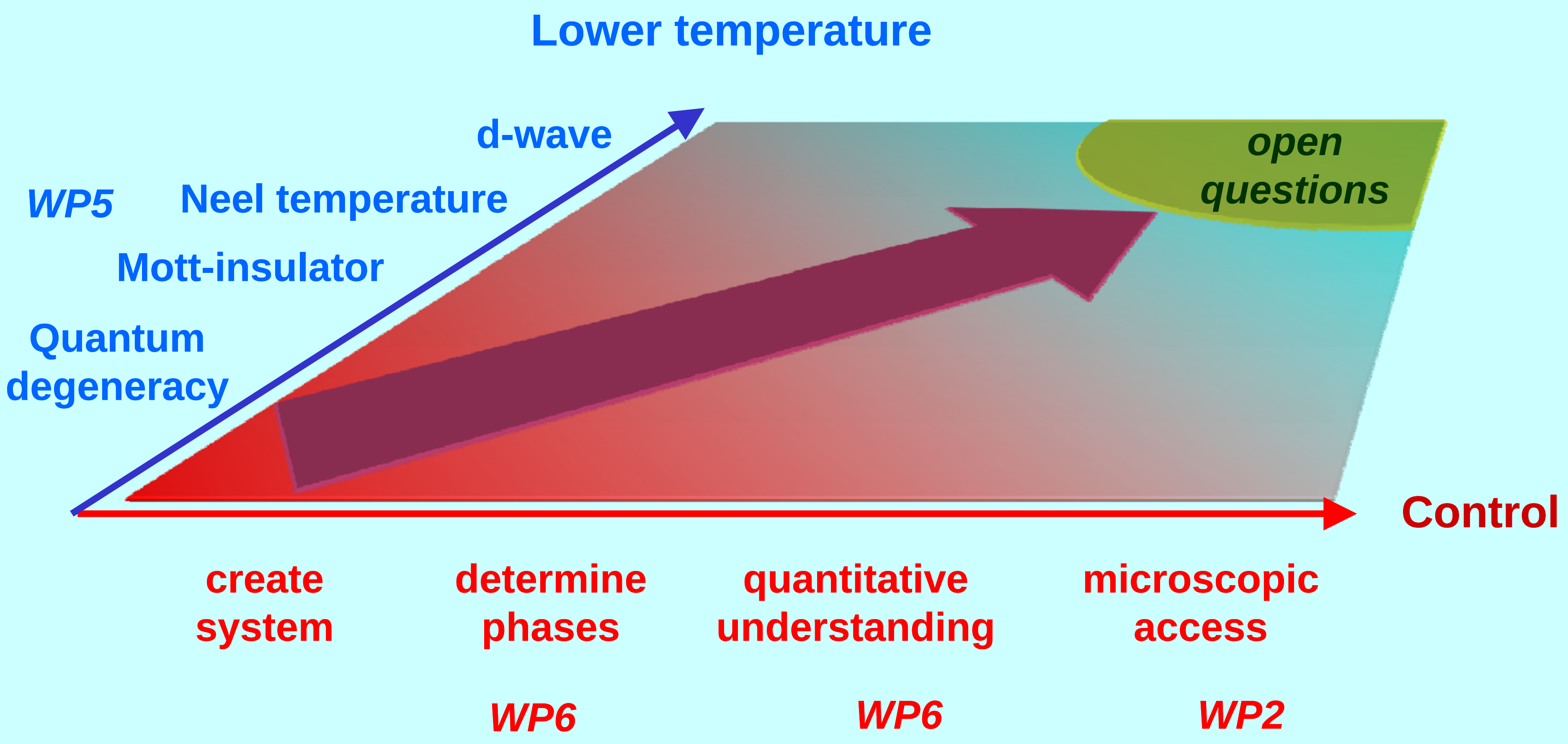


$$H = 4\hbar\omega_{rec}\hat{c}^{\dagger}\hat{c} - \Delta\hbar\hat{a}^{\dagger}\hat{a} + \hbar g\left(\hat{c} + \hat{c}^{\dagger}\right)\hat{a}^{\dagger}\hat{a} - i\hbar\eta\left(\hat{a} - \hat{a}^{\dagger}\right)$$

F. Brennecke, S. Ritter, T. Donner, T. Esslinger, Science 322, 235 (2008)

S. Ritter, F. Brennecke, C. Guerlin, K. Baumann, T. Donner, T. Esslinger, submitted

Quantum Simulation




Thanks !
Funding: ETH, EU (OLAQUI, SCALA), SNF, QSIT
Quantum Gases in Optical Lattices
Henning Moritz
Niels Strohmaier
Robert Jördens
Daniel Greif
Leticia Tarruell
Kenneth Günter (ENS, Paris)
Michael Köhl (now Cambridge, UK)
Thilo Stöferle (now IBM)
Yosuke Takasu (now U Kyoto)
Administration: Veronica Bürgisser
Lithium:
Bruno Zimmermann
Torben Müller
Henning Moritz
Jakob Meineke
BEC and Cavity
Ferdinand Brennecke
Christine Guerlin
Kristian Baumann
Stephan Ritter (now MPQ)
Tobias Donner (now Boulder)
Michael Köhl (now Cambrigde)
Thomas Bourdel (now Orsay)
Anton Öttl (now Berkeley)
Electronics: Alexander Frank