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A fermionic quantum gas in an optical lattice

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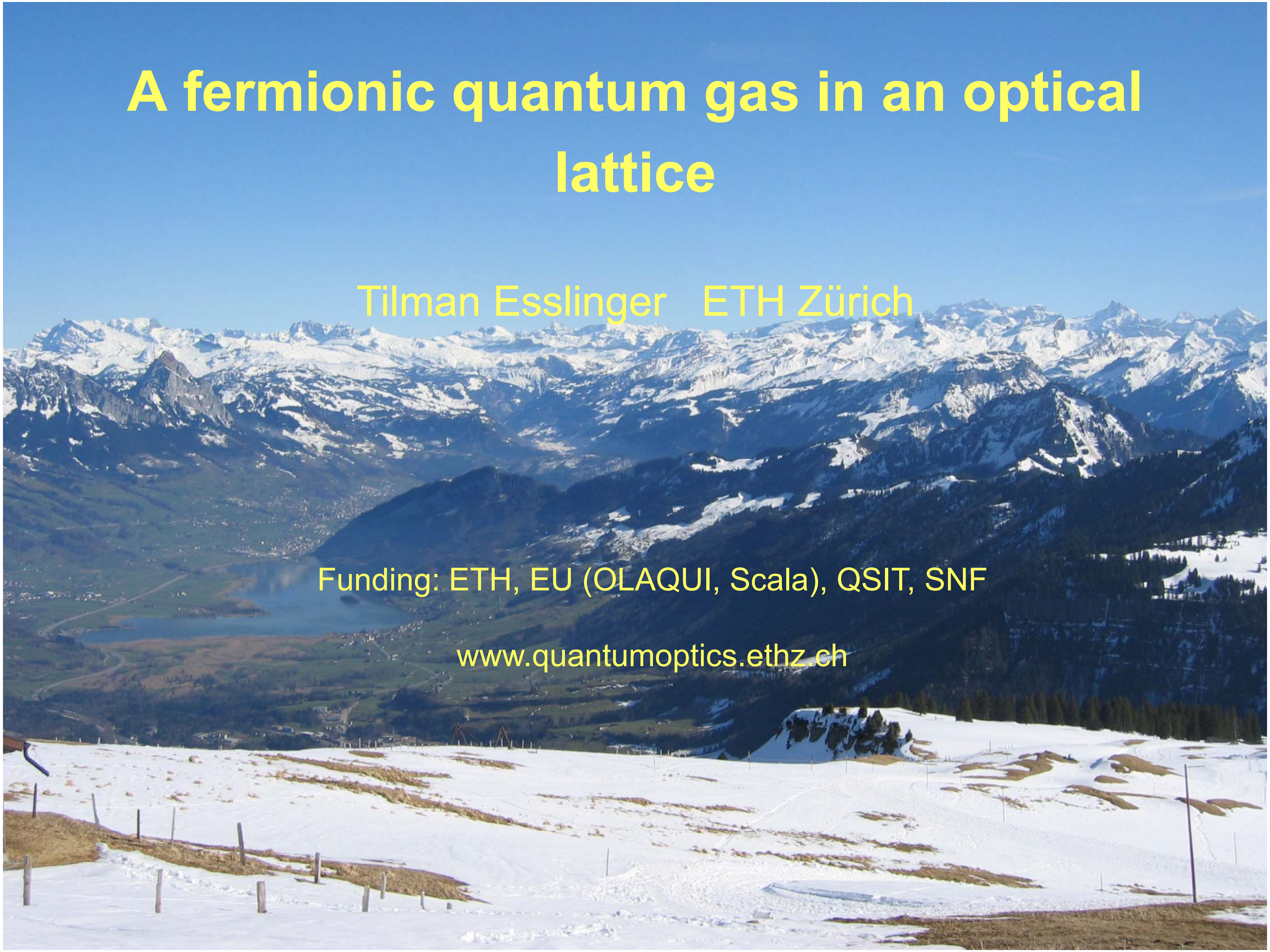
A fermionic quantum gas in an optical lattice

Tilman Esslinger ETH Zürich

Funding: ETH, EU (OLAQUI, Scala), QSIT, SNF

www.quantumoptics.ethz.ch



Superconductivity

↓

BCS-Theory

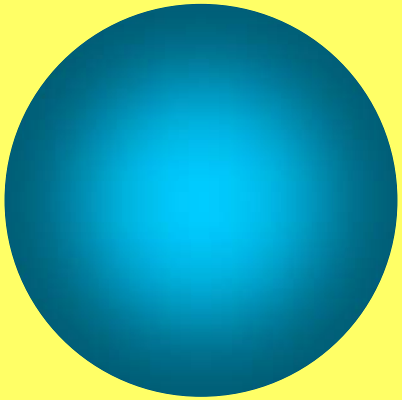
Model

↓

Experiment

Open Questions: $\mathbf{H} \rightarrow \Psi?$

Novel Models: **H= …**



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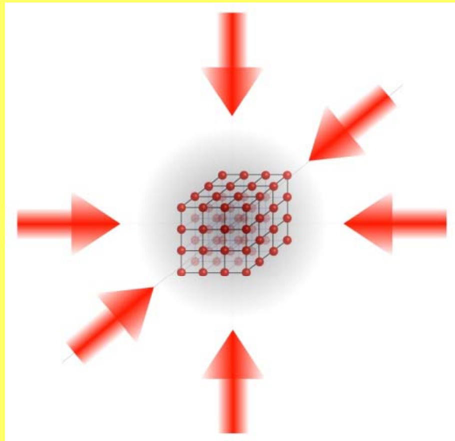


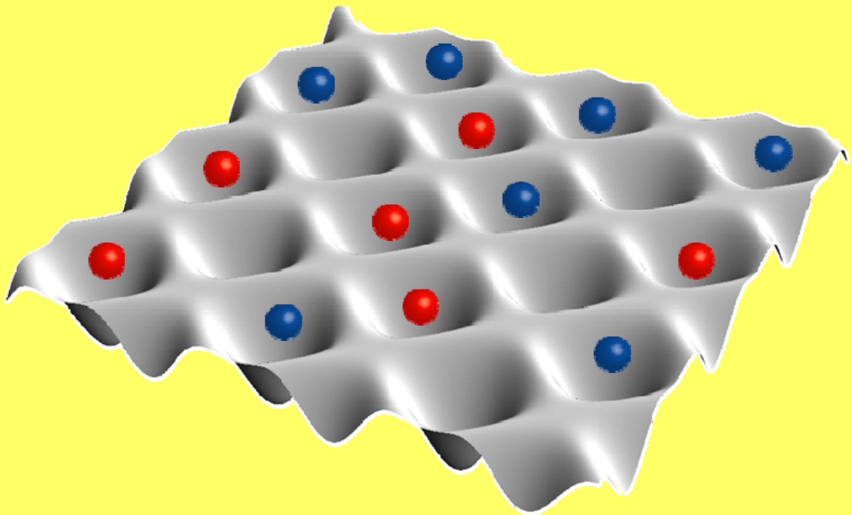
Quantum Gases Optical Lattices

3D OL: Munich, NIST, ETH, Mainz, Texas, Innsbruck, Florence, MIT, Hamburg, Pisa, Illinois, Kyoto, Chicago, …

Fermi-Hubbard

- Static potential
- Single band
- Local interactions

Fermi-Hubbard



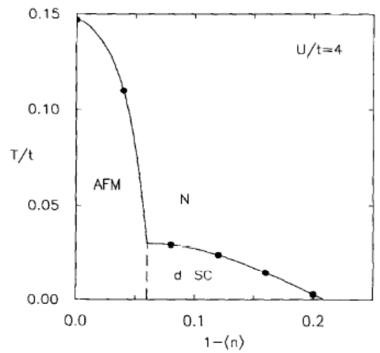
Fermi-Hubbard

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

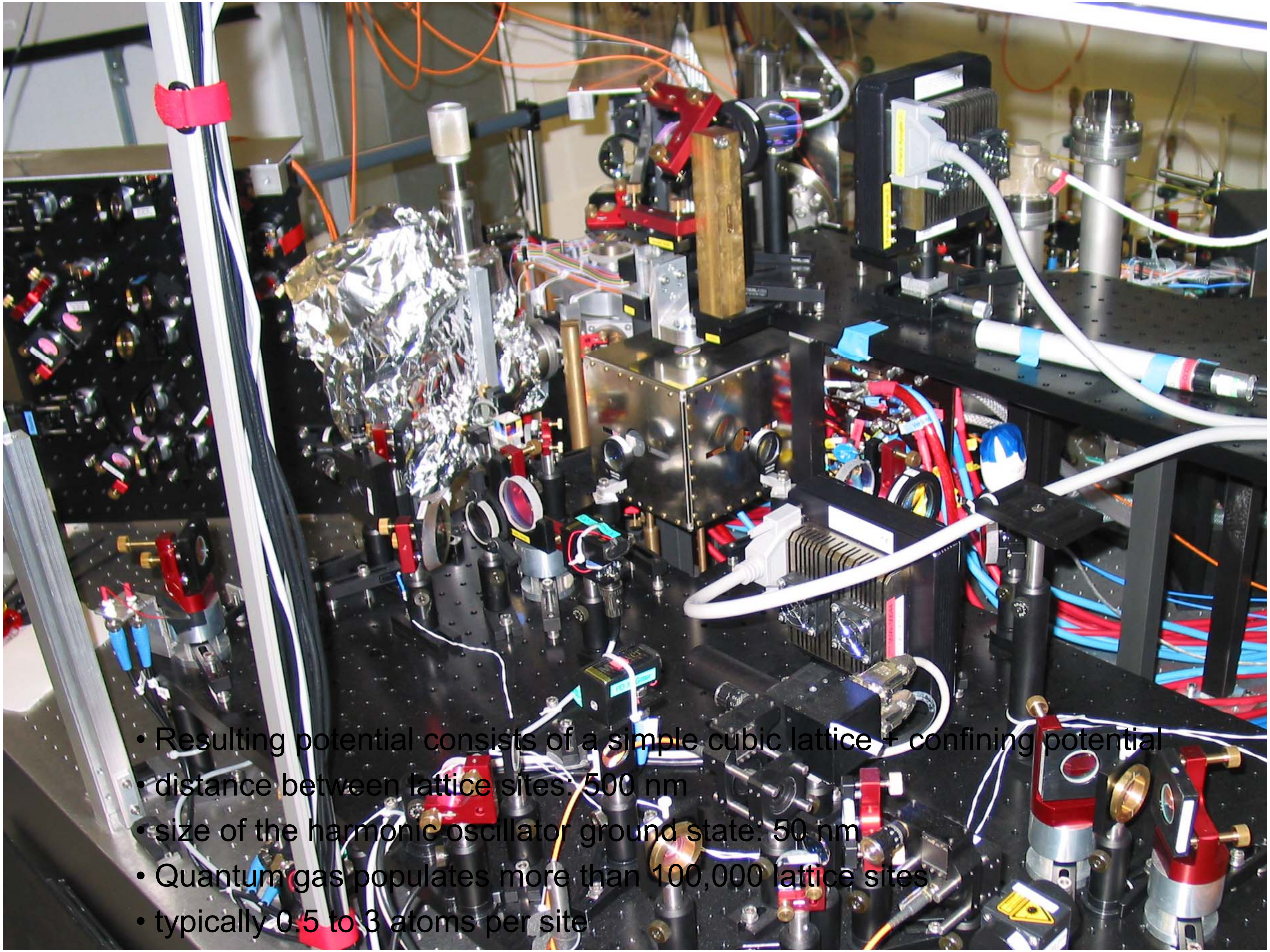
Fermi-Hubbard (U>0)

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

d-wave superconductor

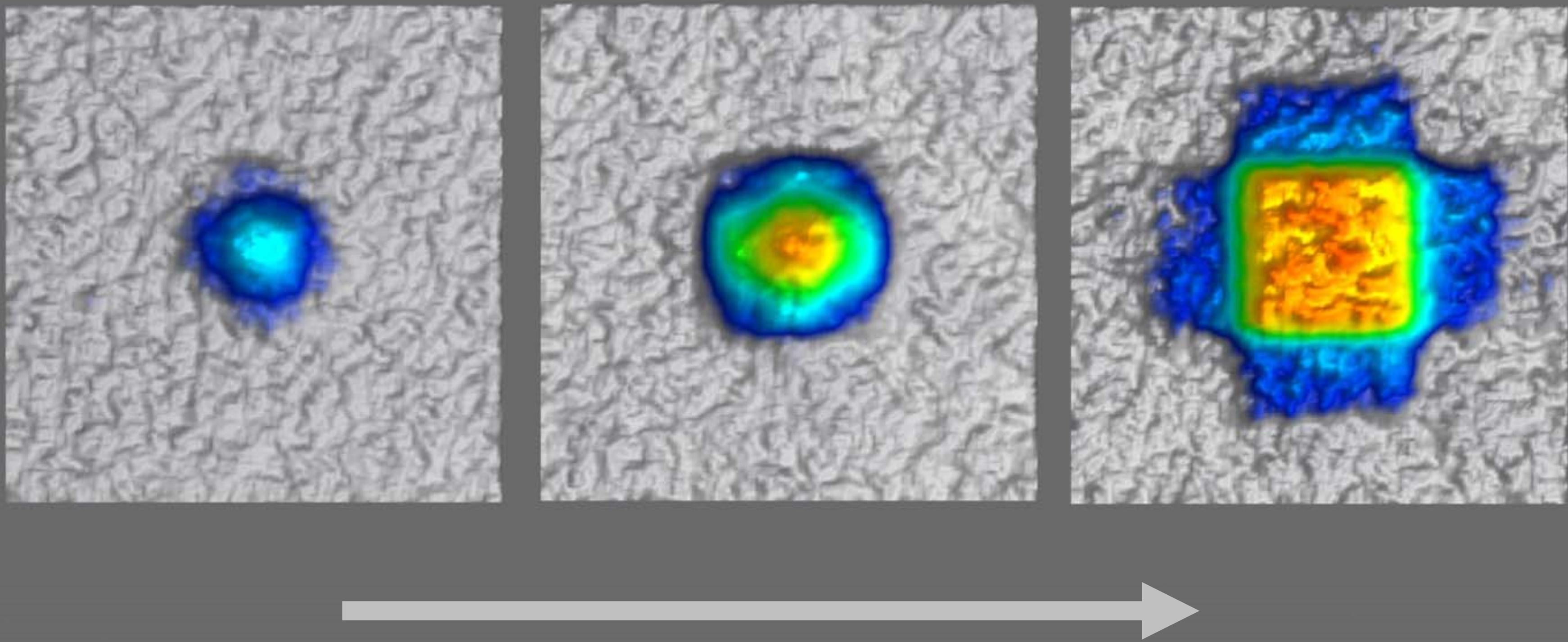


Scalapino, Phys. Rep. 250, 329 (1995)
Hofstetter et al., Phys. Rev. Lett. 89, 220407 (2002)



- Resulting potential consists of a simple cubic lattice + confining potential
- distance between lattice sites: 500 nm
- size of the harmonic oscillator ground state: 50 nm
- Quantum gas populates more than 100,000 lattice sites
- typically 0.5 to 3 atoms per site

Fermi Surfaces

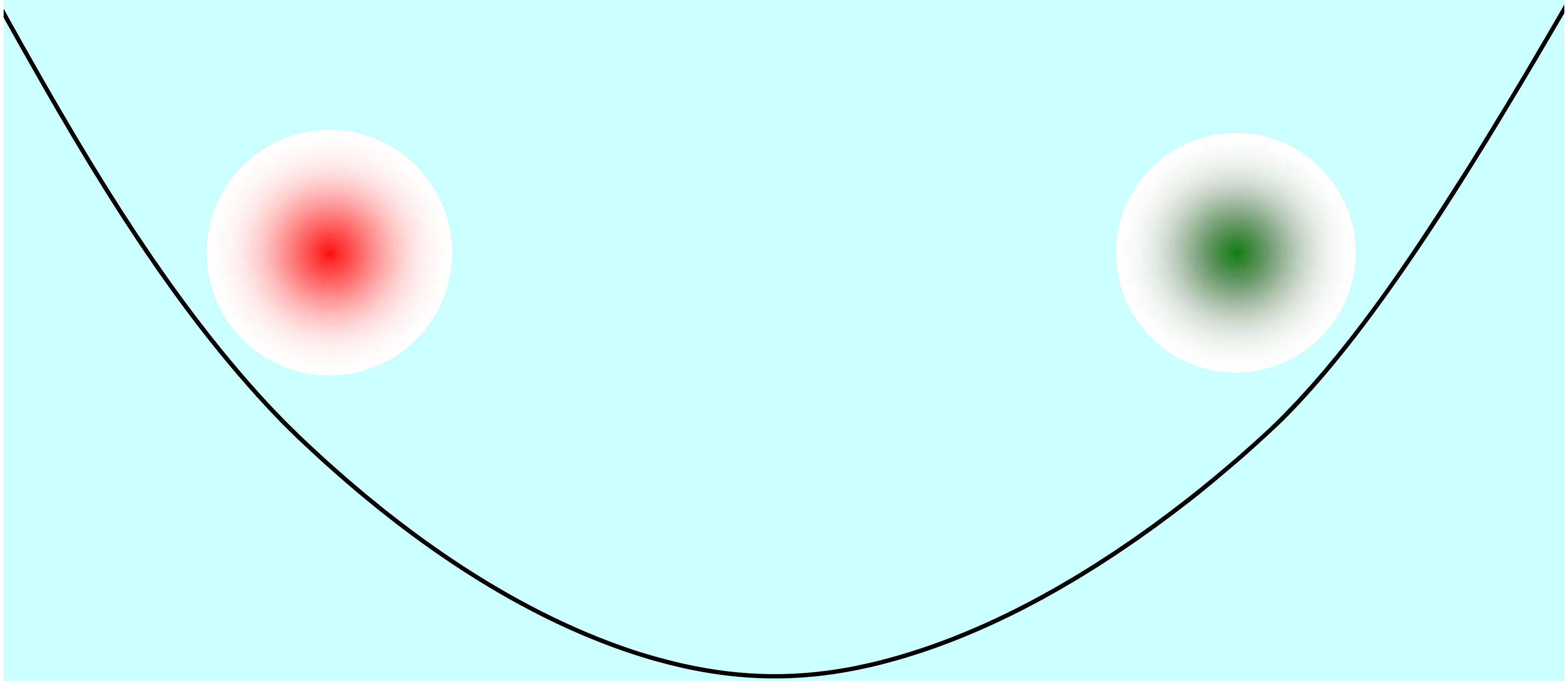


Increasing number of atoms in the lattice

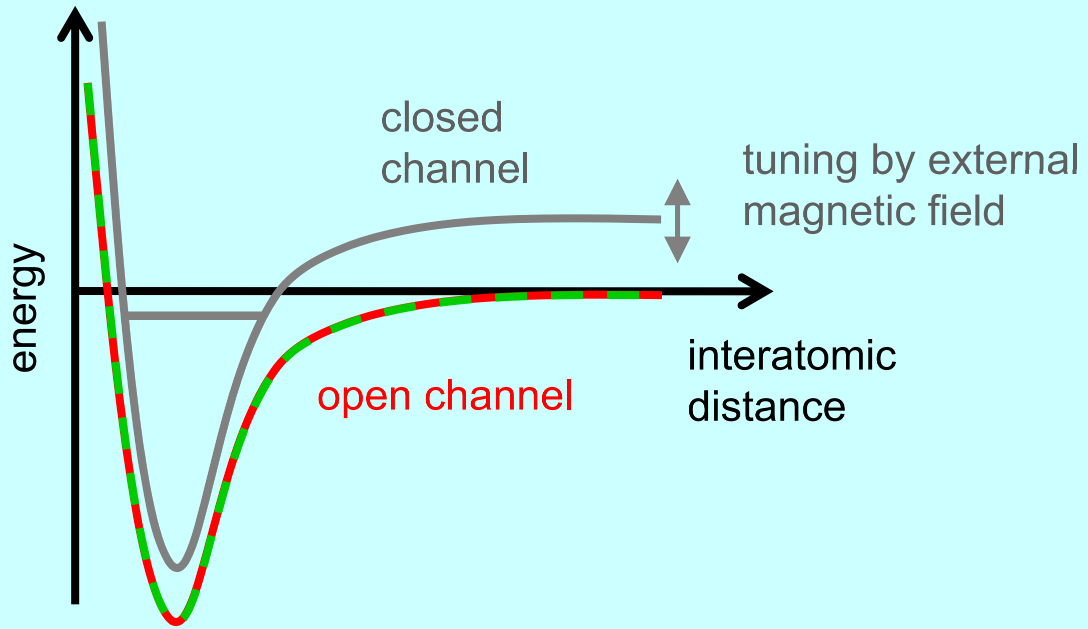
M. Köhl, H. Moritz, T. Stöferle, K. Günter and T. Esslinger, PRL 94, 080403 (2005).

See also: Chin, J. K. et al., Nature, 443, 961-964 (2006).
Rom, T. et al., Nature, 444, 733-736 (2006).

Repulsive Interactions



Tuning interactions: Feshbach Resonance



Tuning interactions: Feshbach Resonance

Weak interactions: ^{40}K: $|F=9/2, m_F=-9/2>$

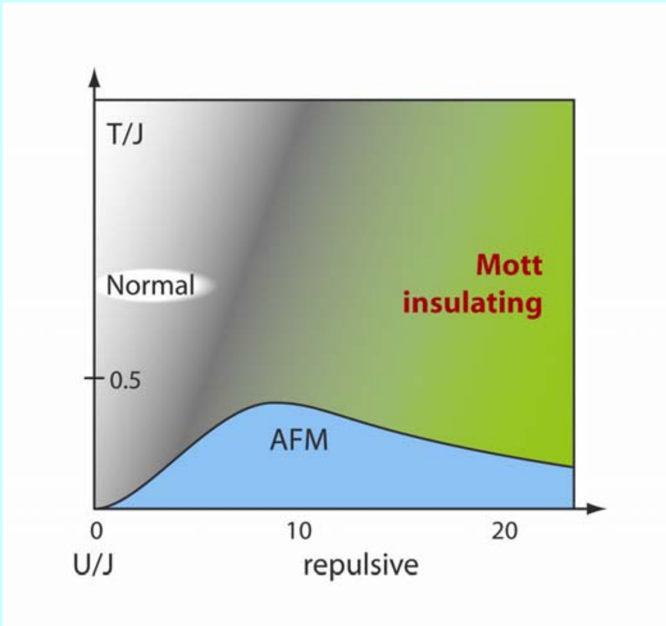
$|F=9/2, m_F=-7/2>$

Strong repulsive interactions: ^{40}K: $|F=9/2, m_F=-9/2>$

$|F=9/2, m_F=-5/2>$

See: C. Regal, D. Jin, PRL 90, 230404

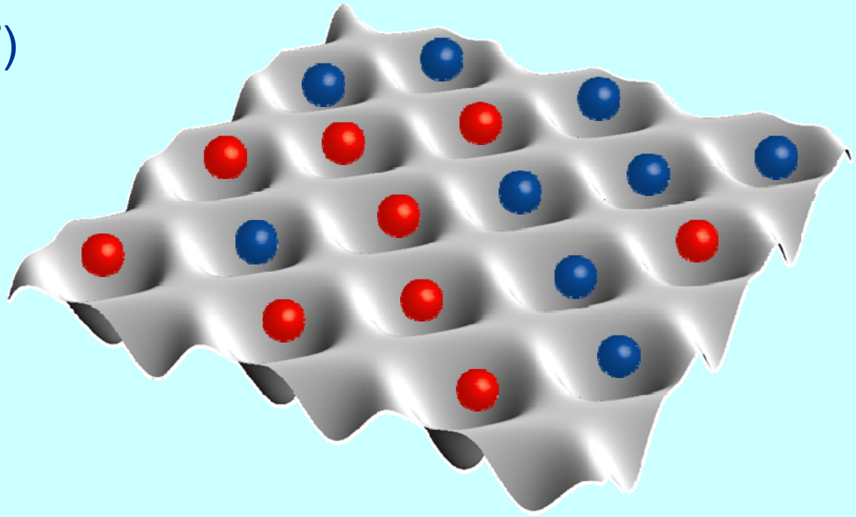
Conductor to Mott-Insulator crossover



Mott insulator

Interaction-induced localization (U>>T)

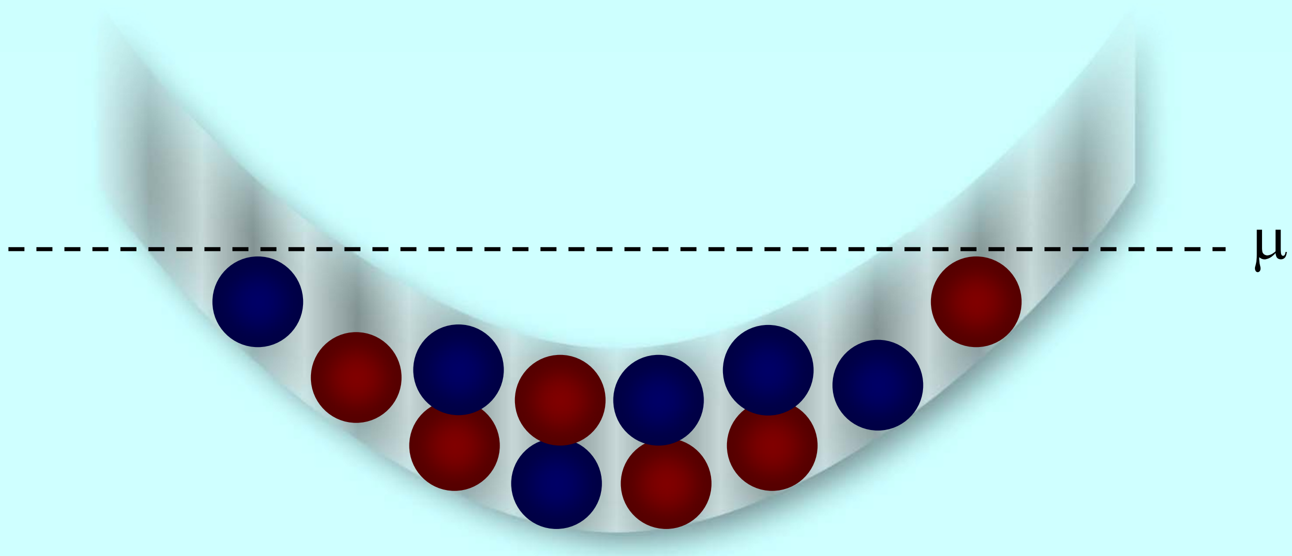
- insulator
- incompressible
- energy gap
- reduced number fluctuations



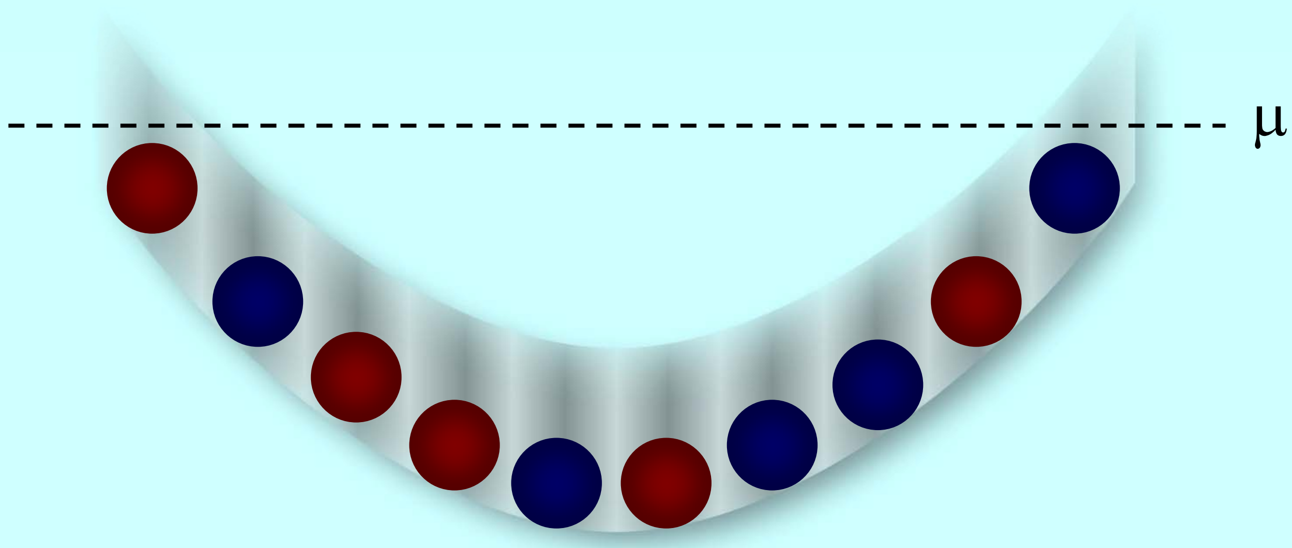

Incompressible core

Measure double occupancy

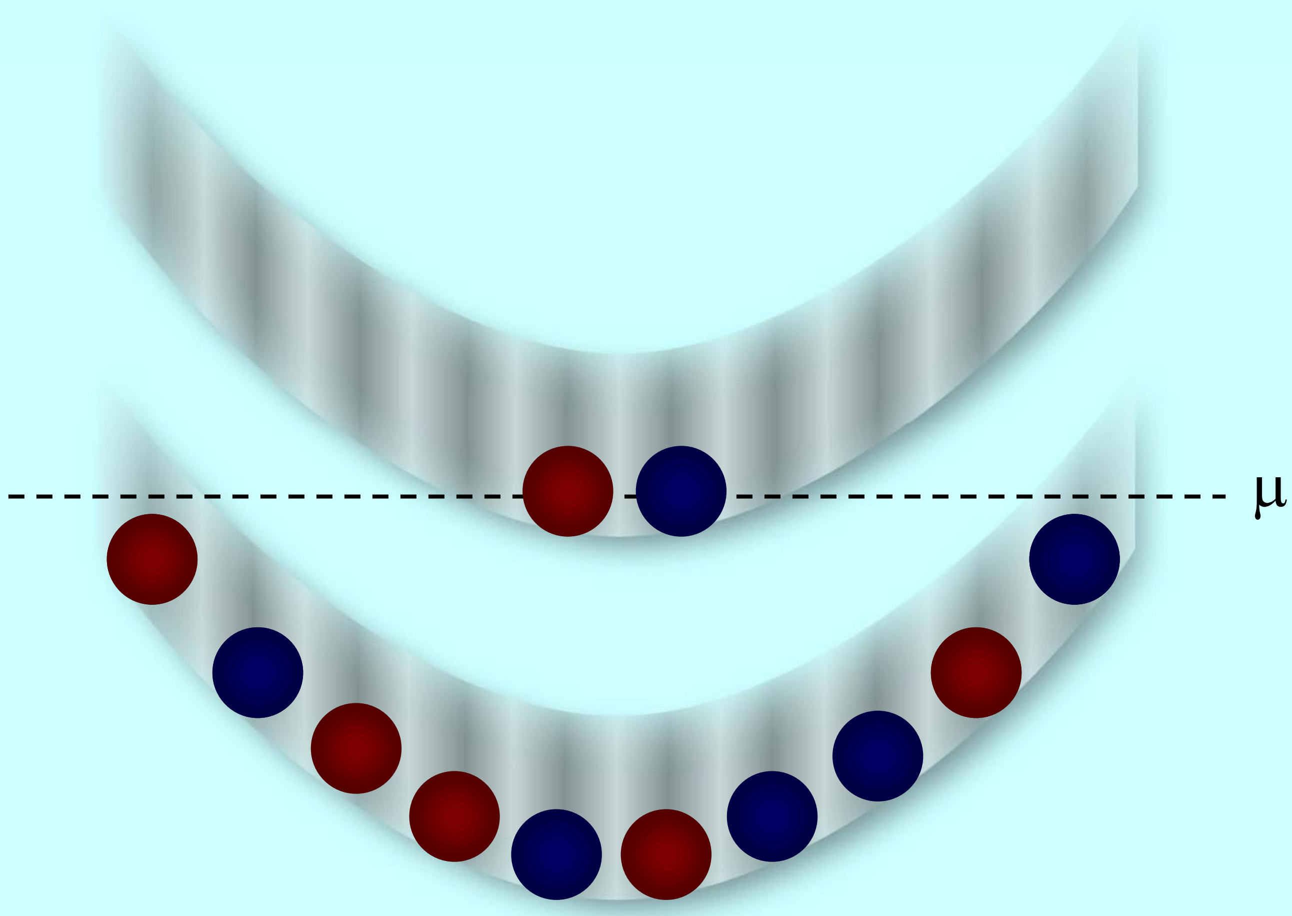
Energy spectrum



Energy spectrum

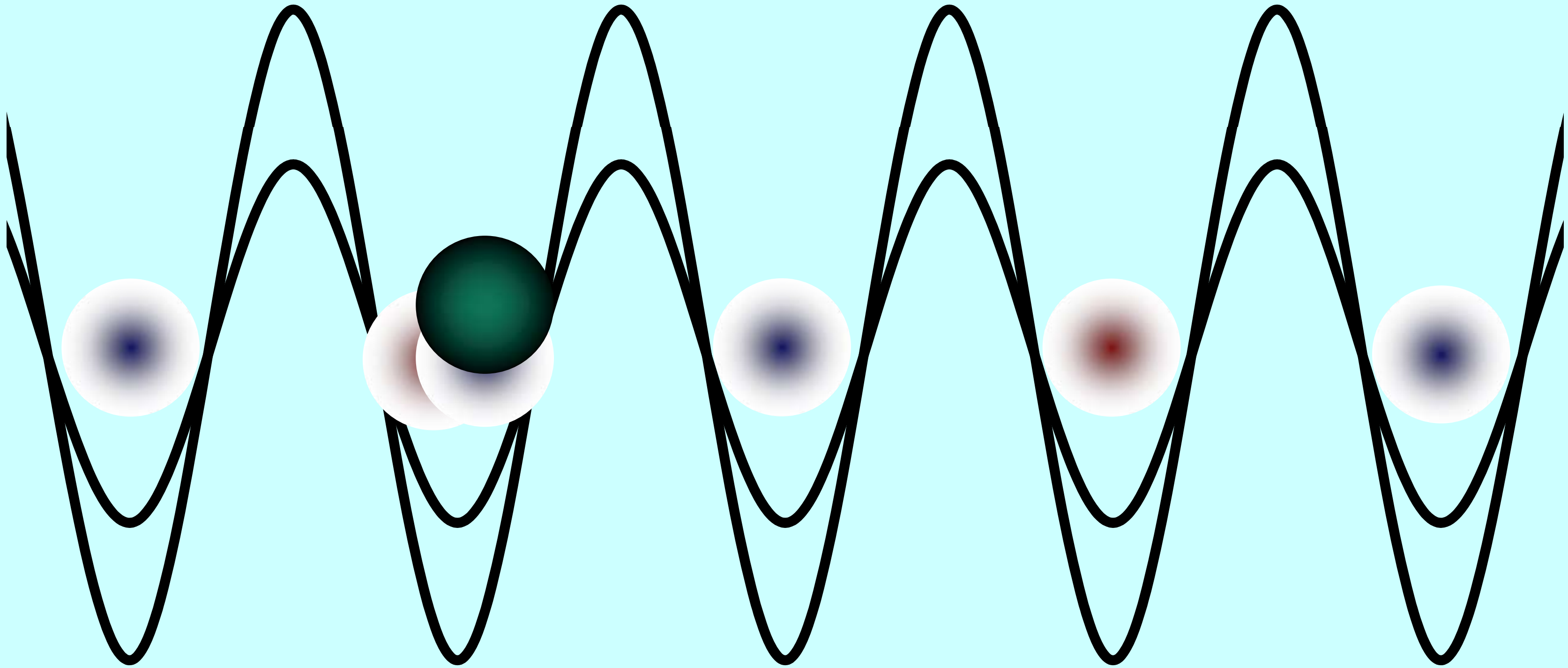


Energy spectrum

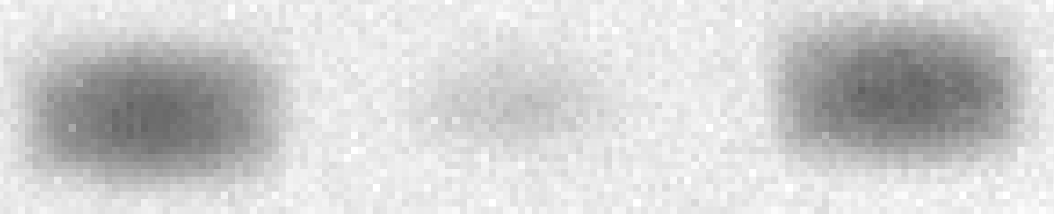


Measuring Double Occupancy

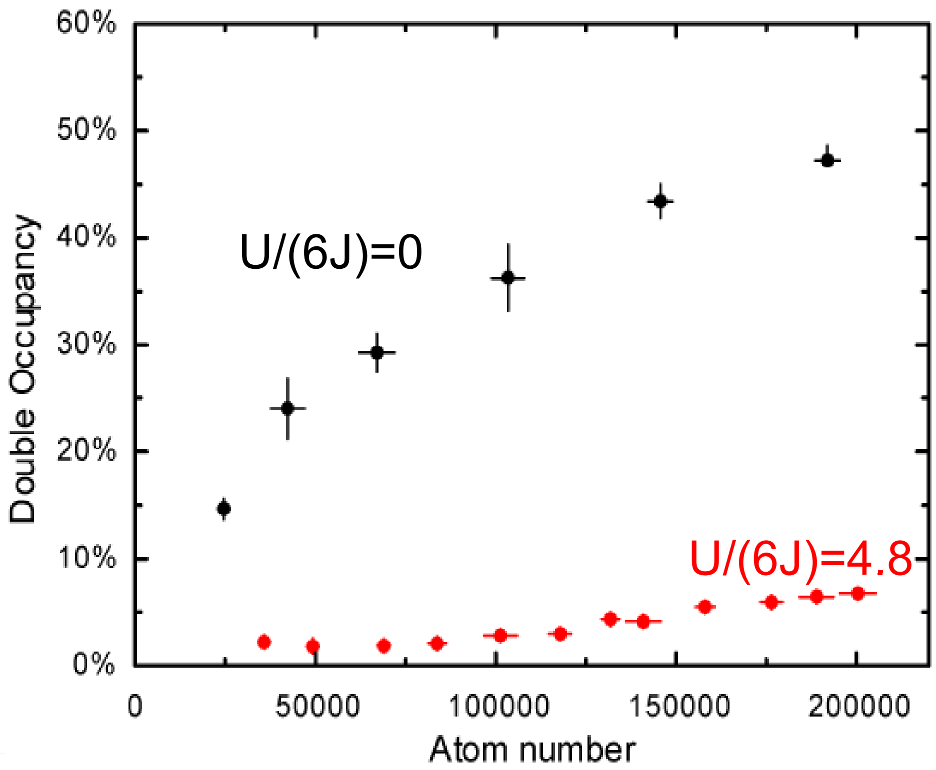
1. suppress tunneling
2. Feshbach induced energy shift
3. Rf transition
4. release and Stern-Gerlach separation



Measuring Double Occupancy



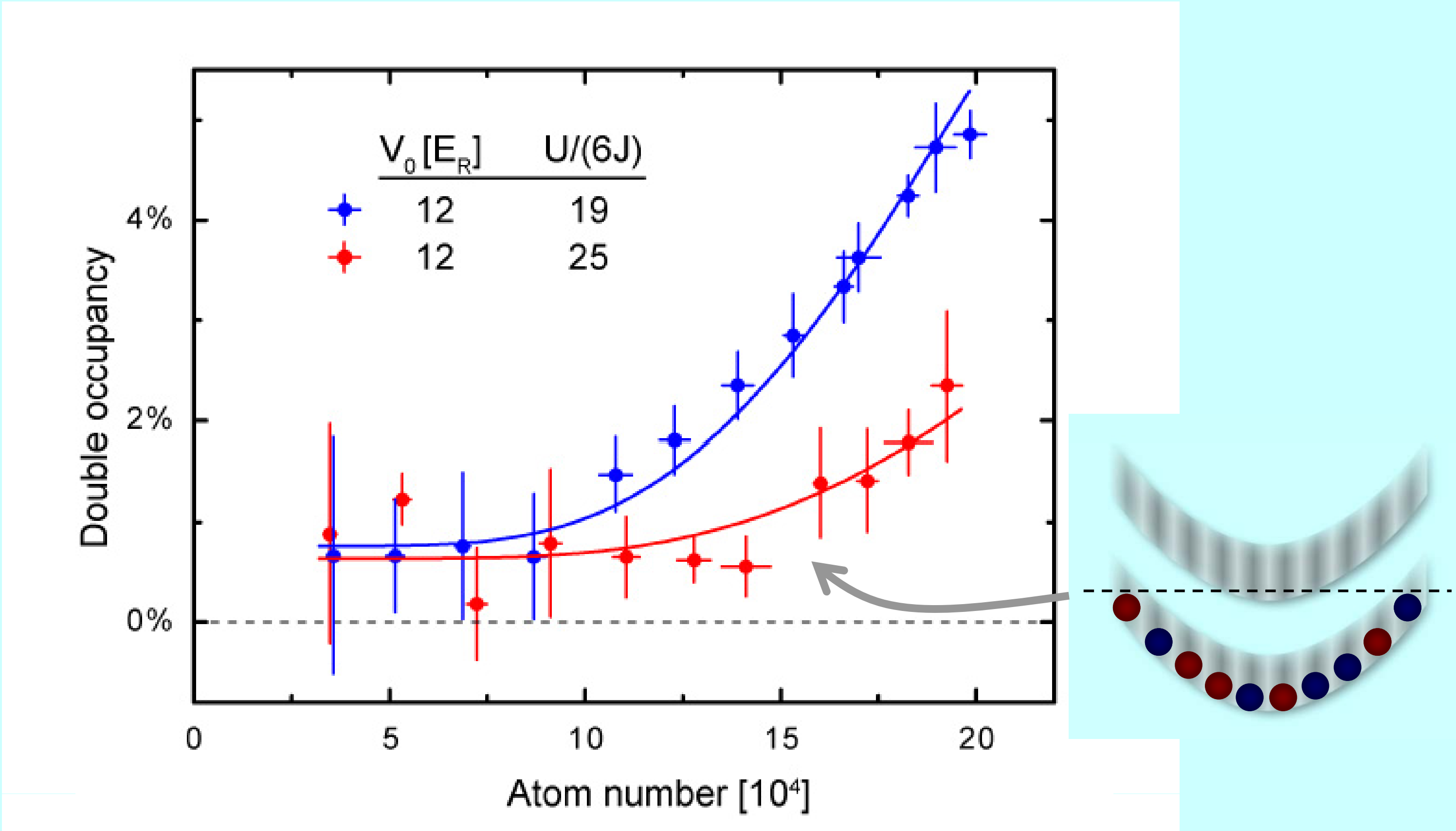
Suppression of double occupancy



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

See also: U. Schneider et al., Science 322, 1520 (2008).

Occupation of upper Hubbard band



Fit: T=0.2 ± 0.1 T_F

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

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

$\rightarrow$ 3 % vacancies in the center

$T/U=0.1$

Quantum Simulation

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

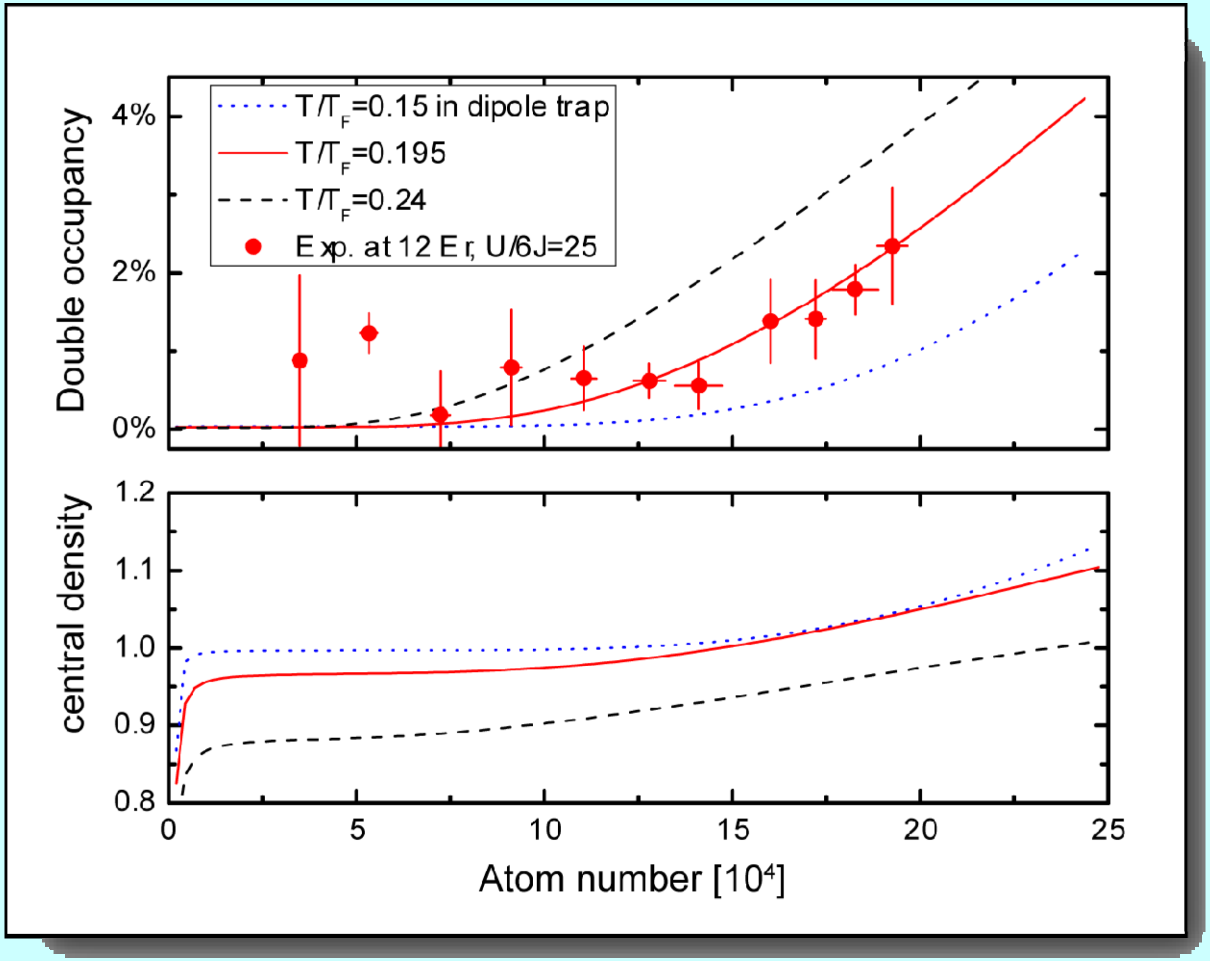
can be calculated for present experimental temperatures

(DMFT and HTE)

it should be possible to obtain very good agreement

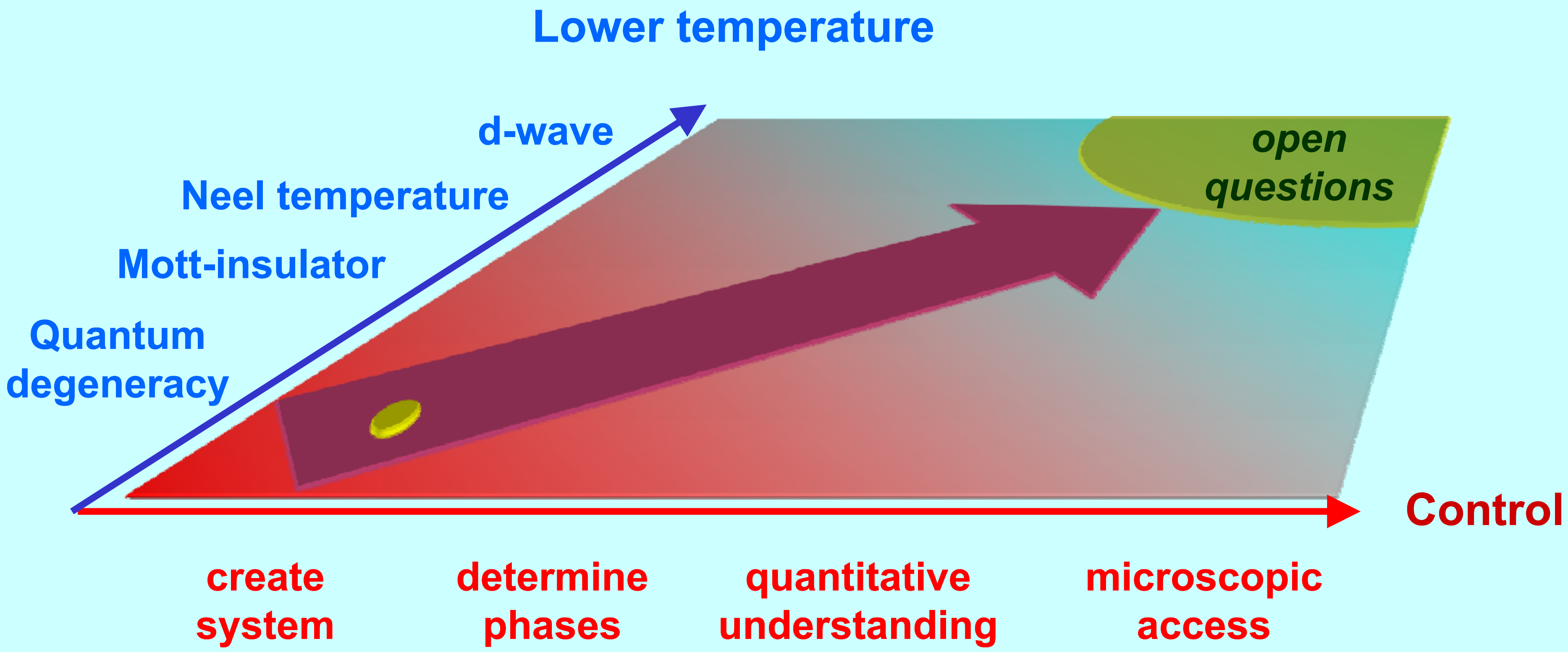
between theory and experiment

Comparison with theory



Theory: 10th order series expansion as in
V. Scarola, Pollet, Oitmaa, Troyer, cond-mat:0809.3239 (2008)

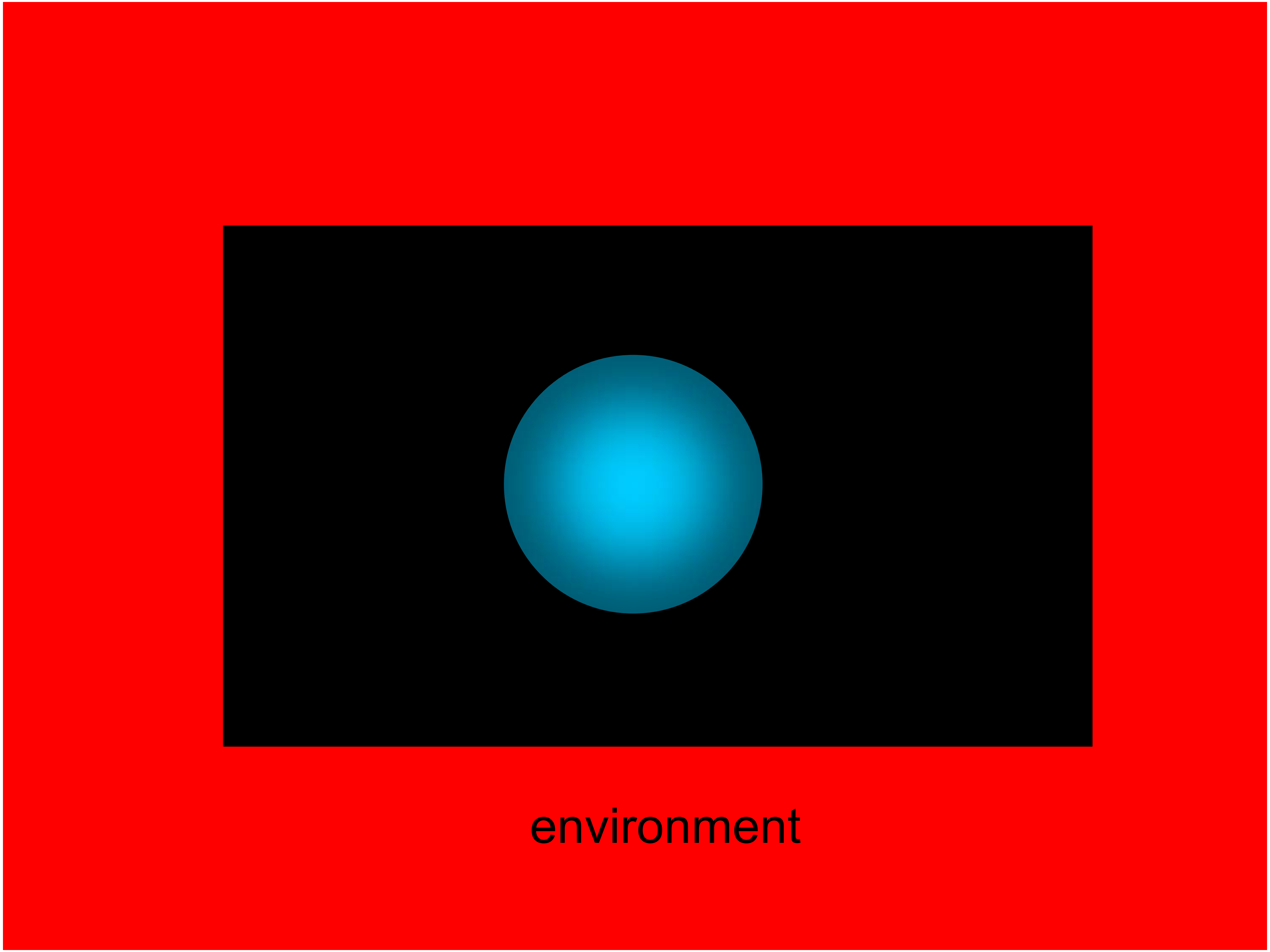
Quantum Simulation



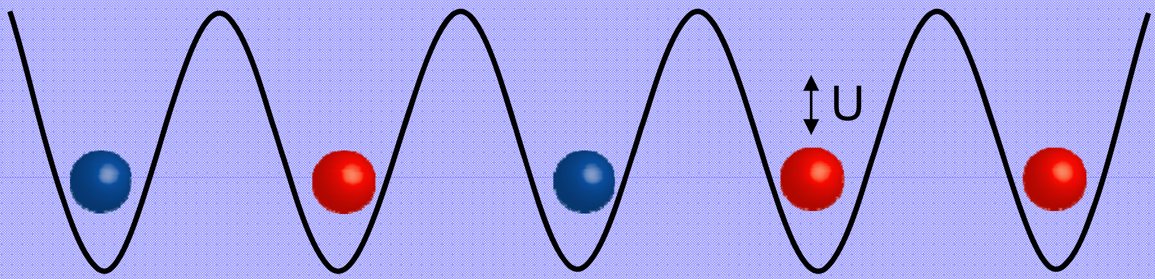
Excitations

Spectrum

Relaxation


environment

Gapped Mode

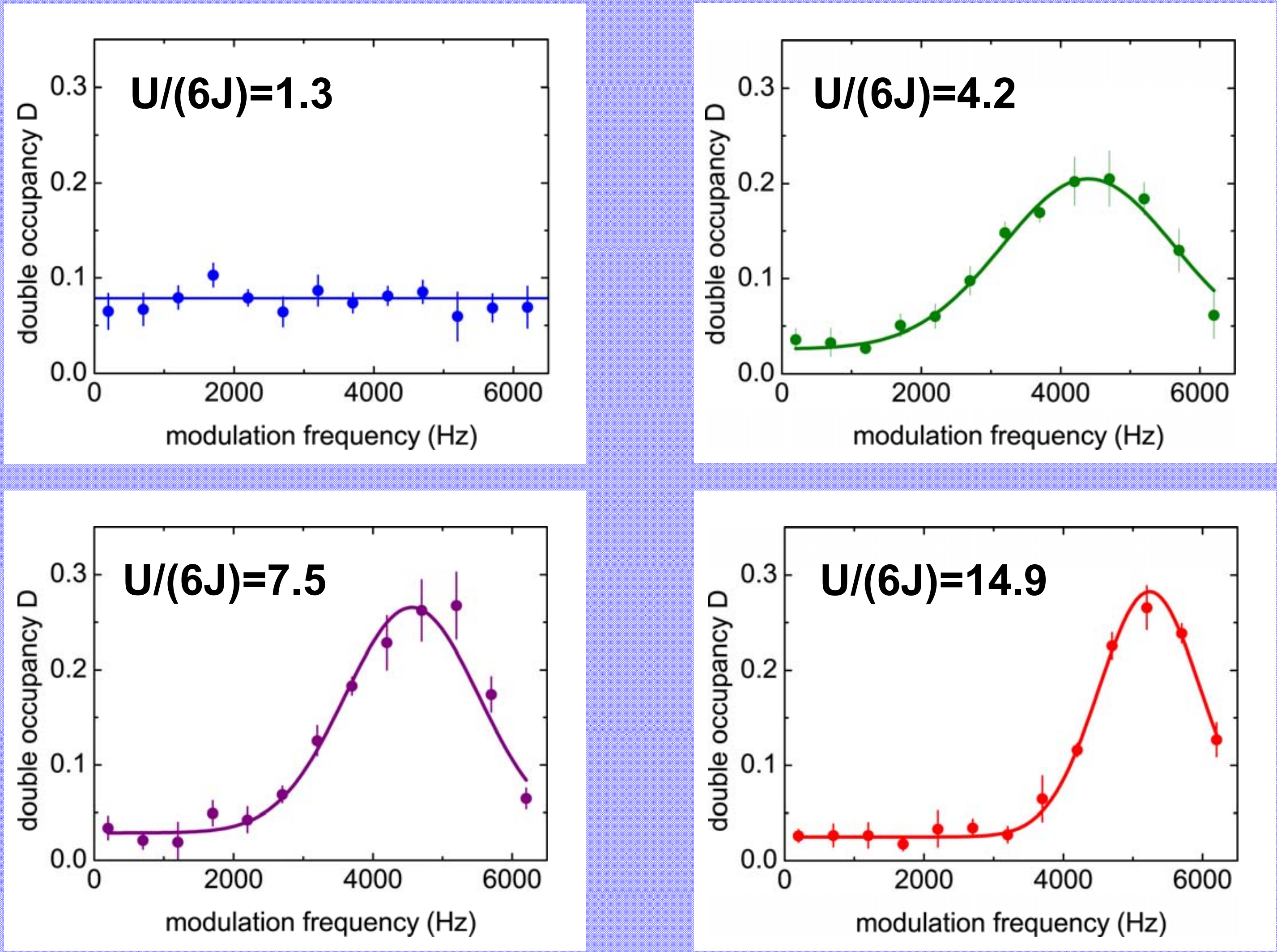


Modulation of the lattice amplitude with frequency U/h: Particle-hole excitation

C. Kollath et.al, Phys.Rev.A., 74, 041604 (2006)

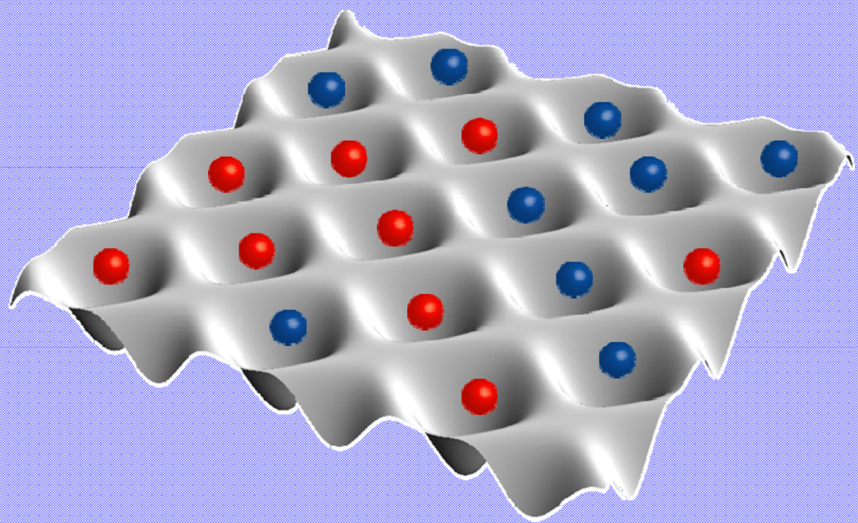
T. Stöferle et.al., Phys.Rev.Lett., 92, 130403 (2004)

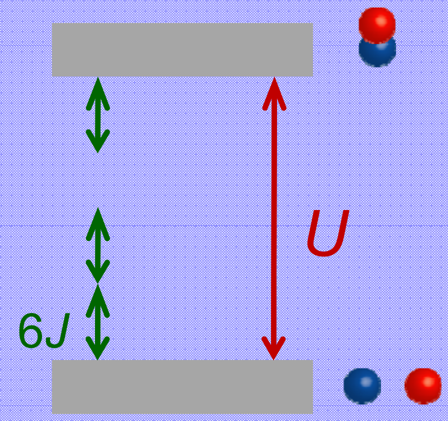
Gapped excitation mode



Fermi-Hubbard

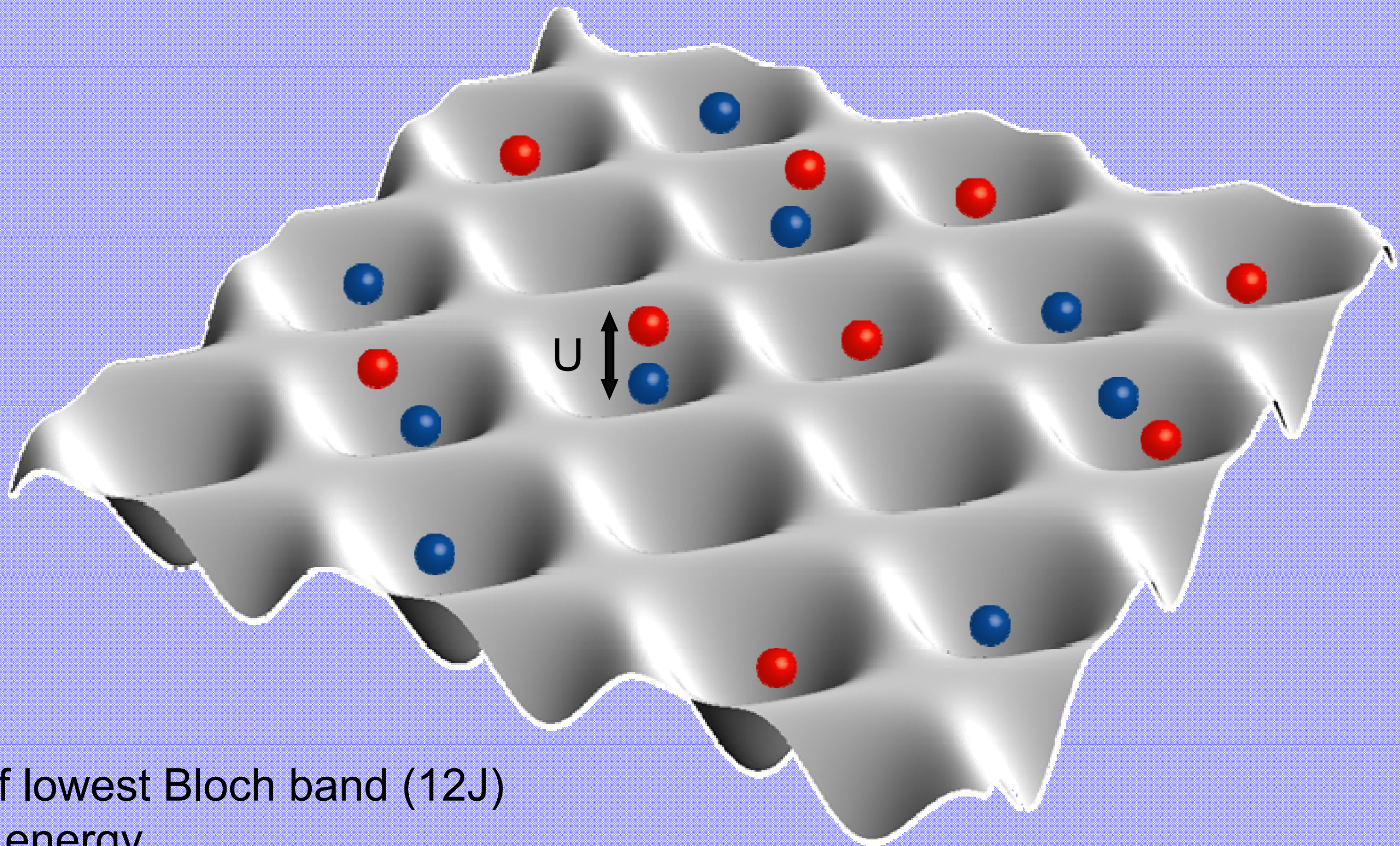
$$H = -t \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$





(collaboration with Demler group, Harvard)

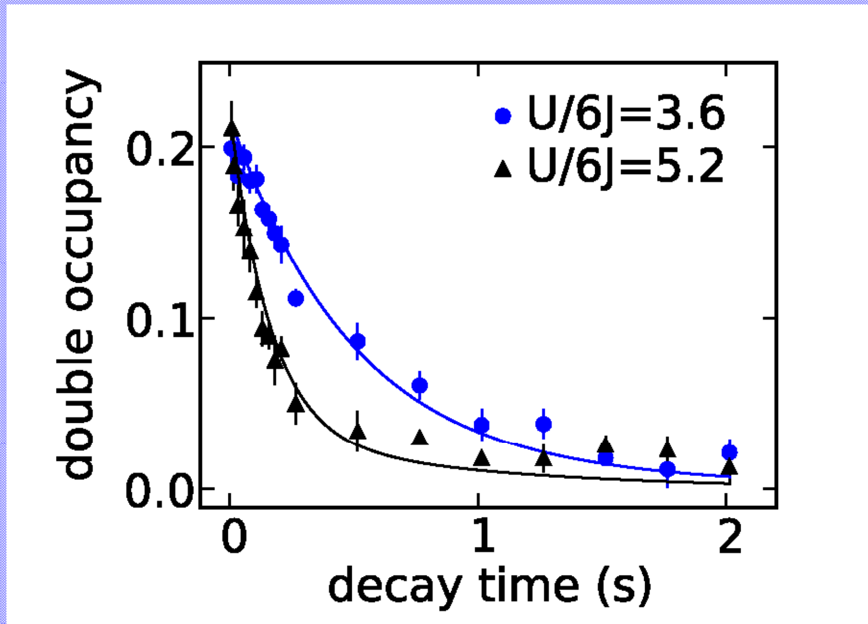
Doublons



Bandwidth of lowest Bloch band (12J)
limits kinetic energy
> Repulsively bound pair

Winkler et.al., Nature, 441 (2006)

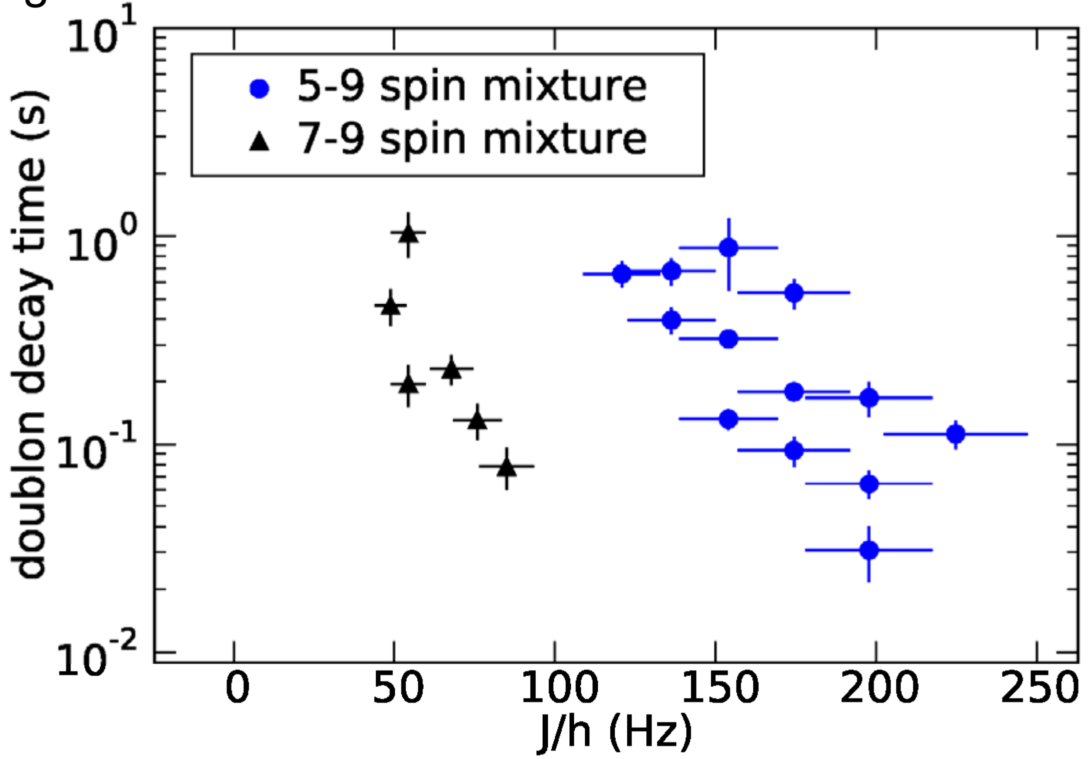
Doublon decay



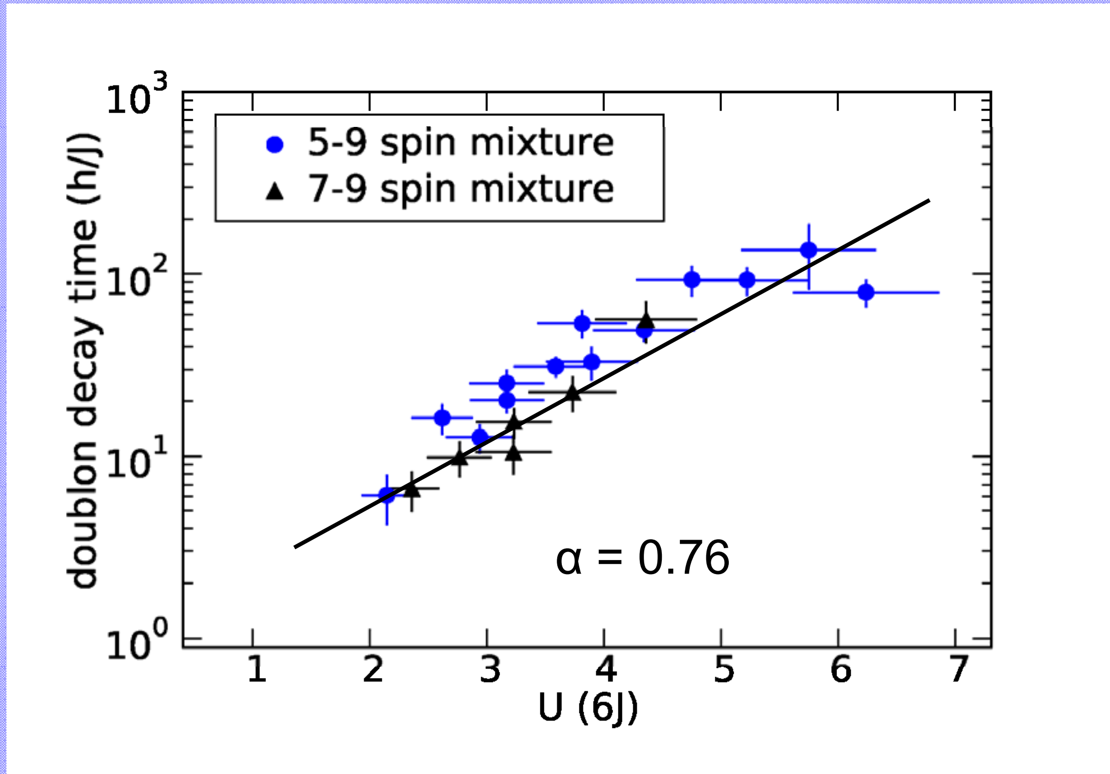
- decay of doublon into single particles
- lifetime depends on interaction and/or tunneling

Parameter space

tunneling time h/J



Scaling



- Lifetime of doublon $\tau/(h/J) \sim \exp(\alpha\, U/(6J))$
- multiple scattering
- Perturbation theory: α of order one

Theory collaboration: Rajdeep Sensarma, David Pekker, Eugene Demler

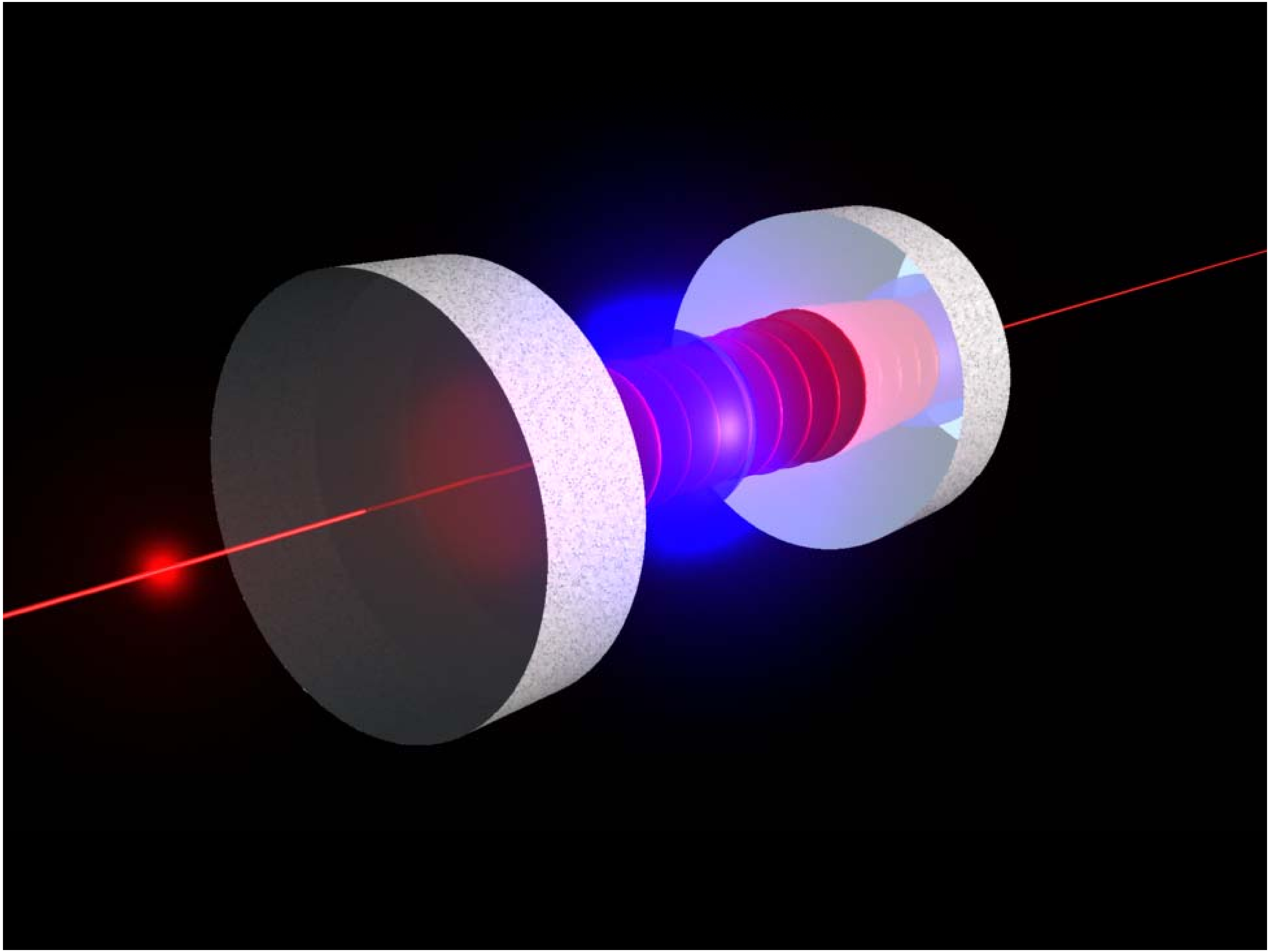
Novel Models?

long-range interactions

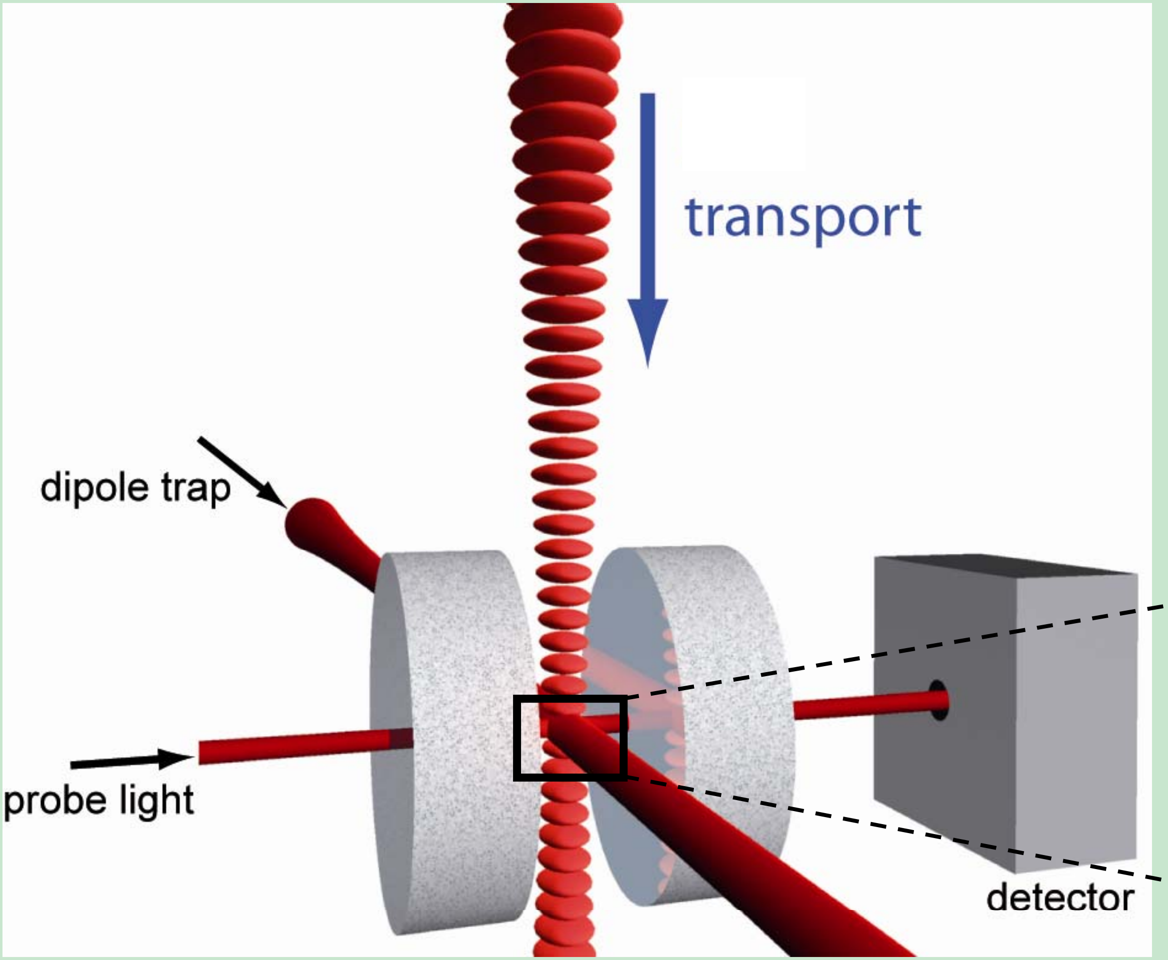
dipolar molecules

Rydberg atoms

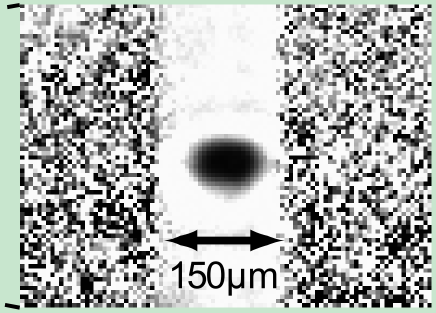
cavity mediated interactions



Experimental setup



$$\begin{aligned} g_0 &= 2\pi \times 10.6\,\mathrm{MHz} \\ \kappa &= 2\pi \times 1.3\,\mathrm{MHz} \\ \gamma &= 2\pi \times 3.0\,\mathrm{MHz} \\ \mathcal{F} &= 3 \times 10^5 \\ L &= 178\,\mu\mathrm{m} \end{aligned}$$



BEC after resonant probing and free expansion

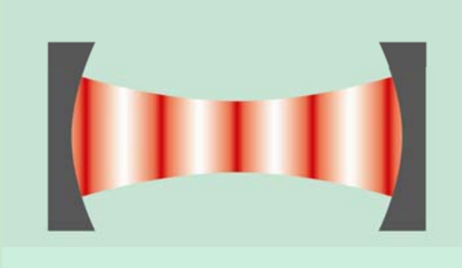
Related work: Stamper-Kurn (Berkeley), Reichel (ENS)

Single atoms, strong coupling: Kimble (Caltech), Rempe (MPQ)

Large volume cavities: Zimmermann (Tübingen), Hemmerich (Hamburg), Vuletic (MIT)

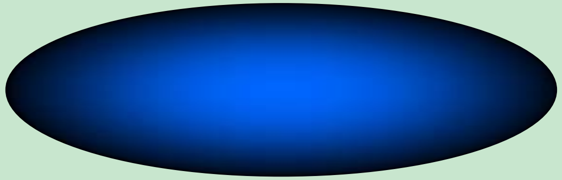
Cavity QED meets BEC

Cavity QED



Single mode of light field

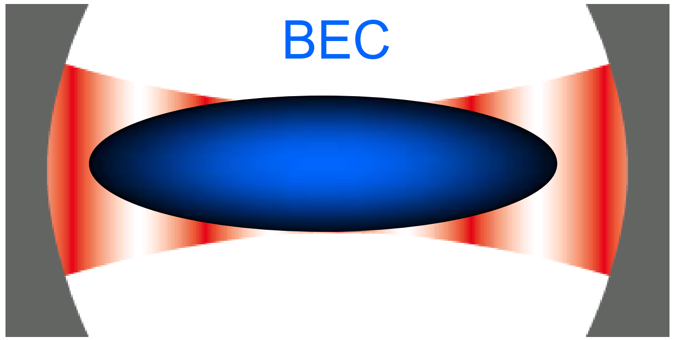
BEC



Single mode of matter field

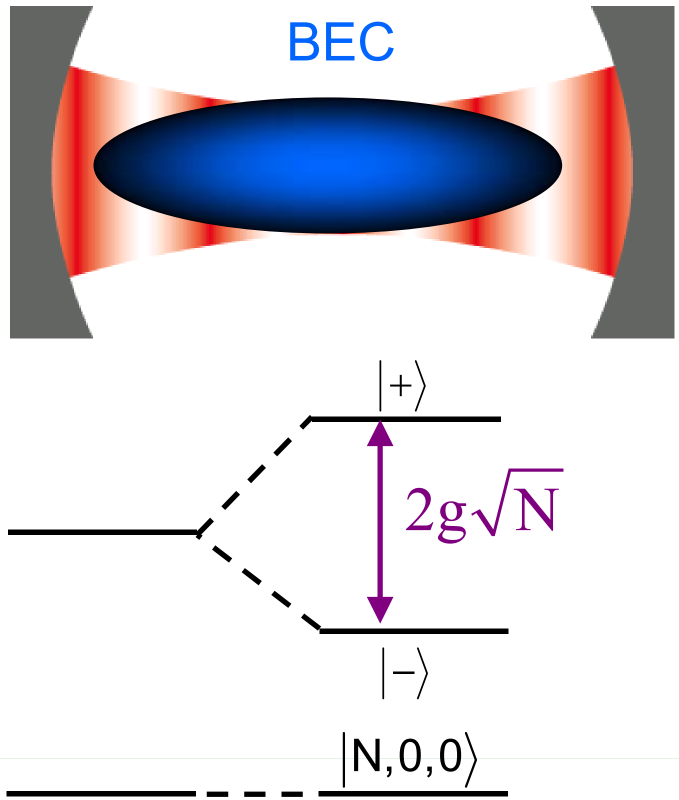
Theory, see e.g. Meystre, Ritsch, Lewenstein

A BEC in a high-finesse cavity



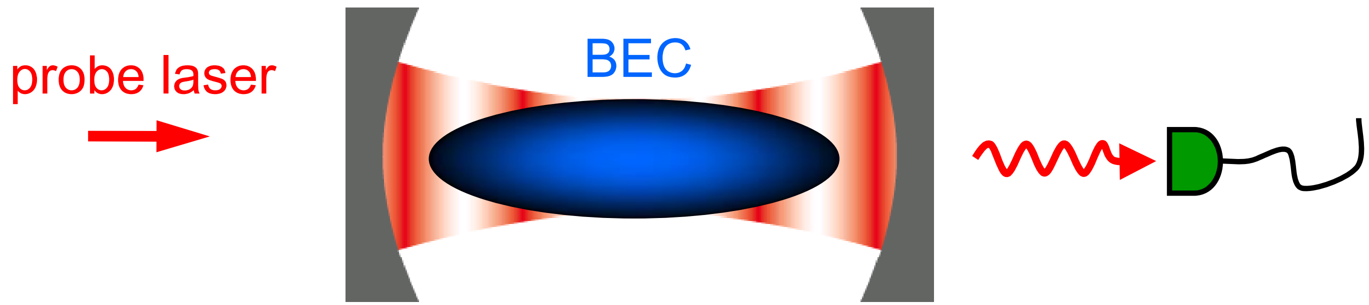
N atoms in delocalized wavefunction of BEC
coupling to the cavity

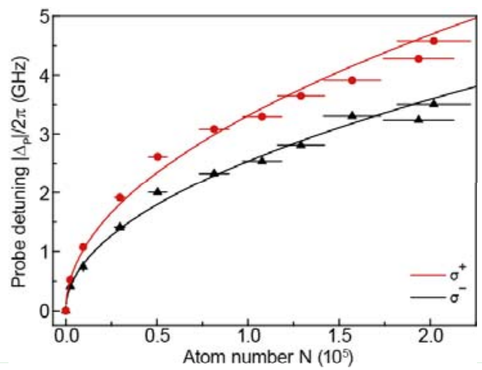
A BEC in a high-finesse cavity



Tavis-Cummings Hamiltonian

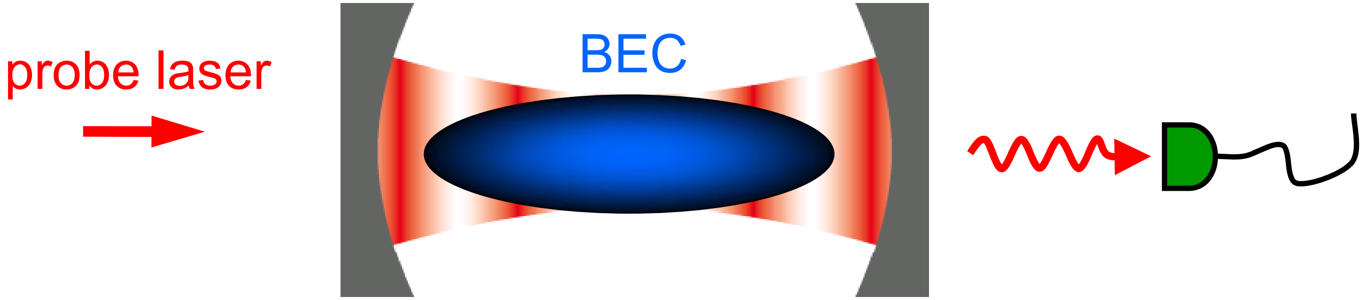
A BEC in a high-finesse cavity

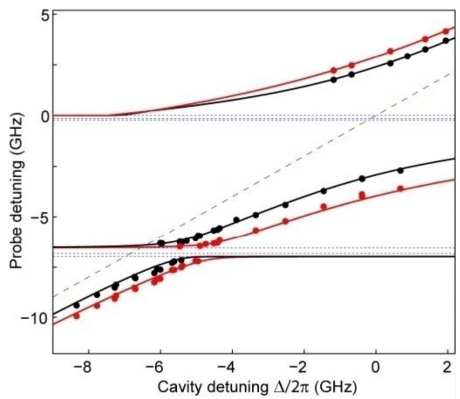




F. Brennecke, T. Donner, S.Ritter, T. Bourdel, M. Köhl, T. Esslinger, Nature 450, 268 (2007)

A BEC in a high-finesse cavity

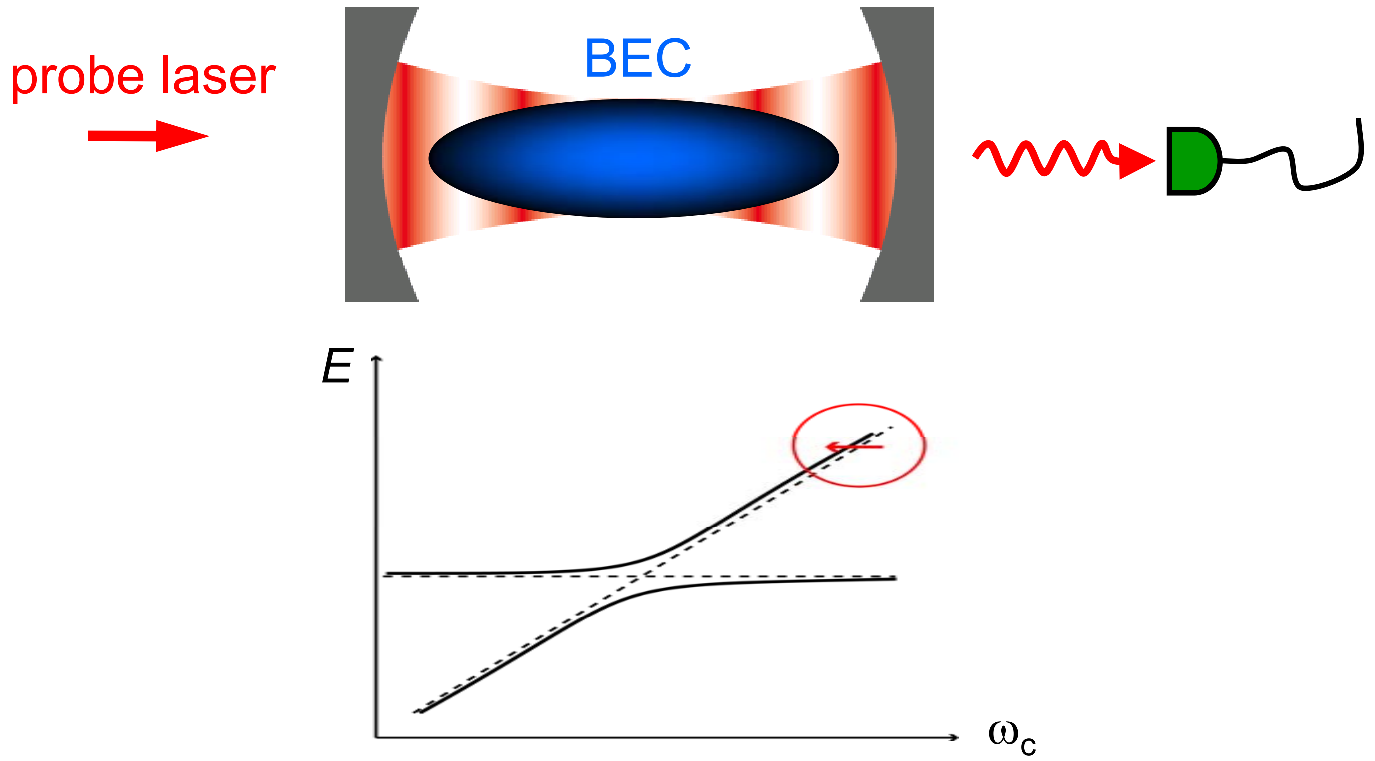




collective cooperativity: $Ng^2/(2\kappa\gamma)=1.6\text{x}10^6$

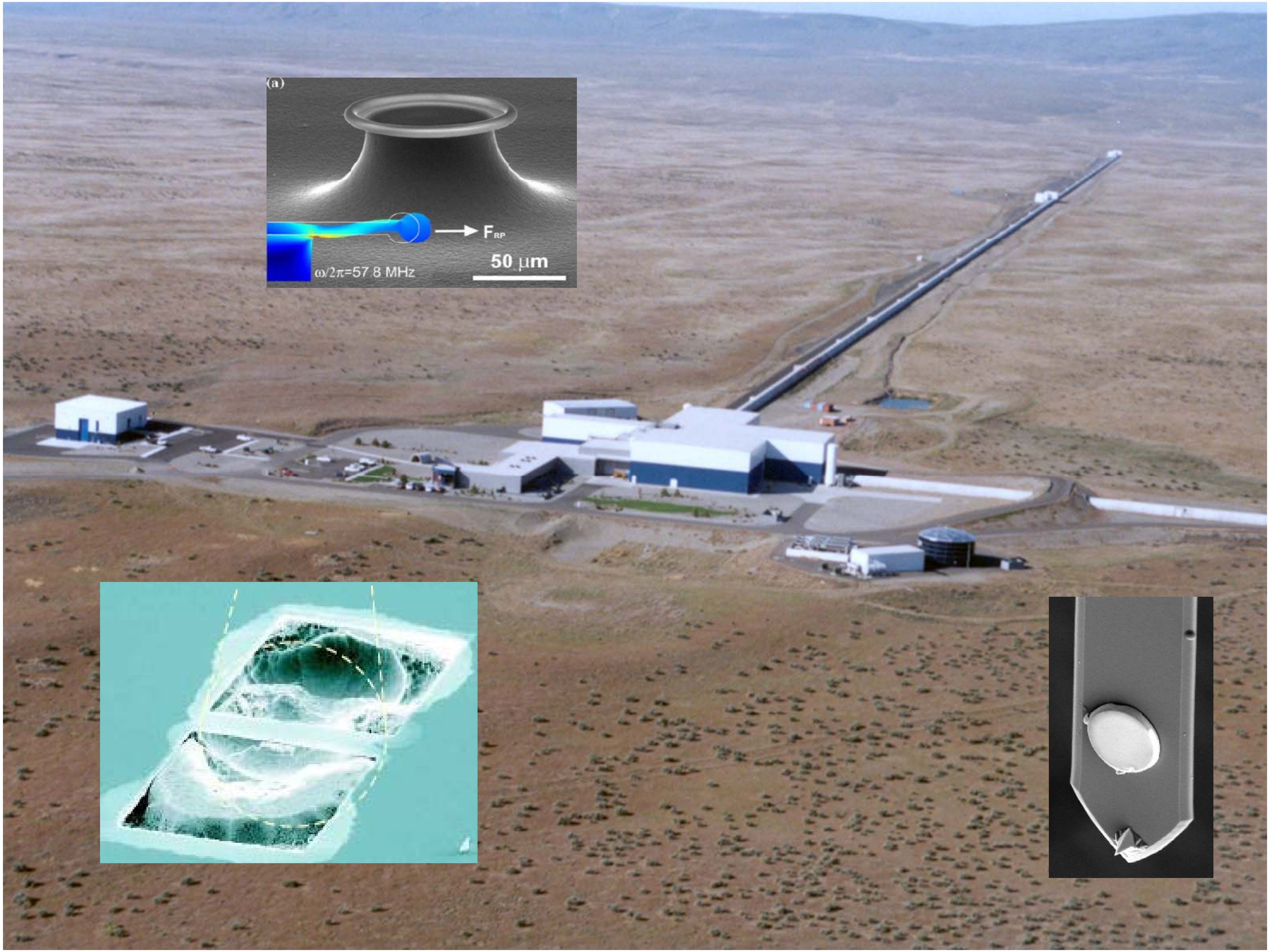
F. Brennecke, T. Donner, S.Ritter, T. Bourdel, M. Köhl, T. Esslinger, Nature 450, 268 (2007)

Dispersive regime



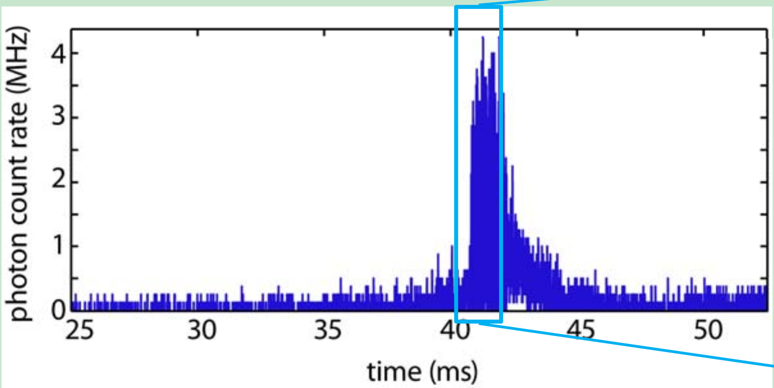
The bare cavity resonance frequency is refractively shifted by BEC

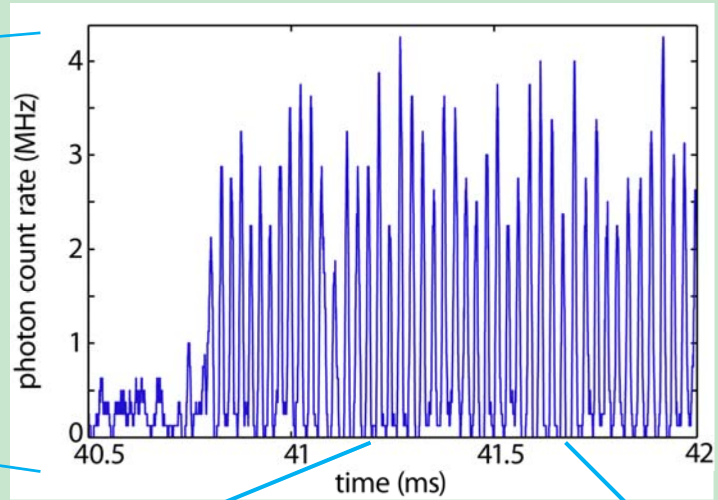
See also: D. Stamper-Kurn group: PRL 99, 213601 (2007), Nat. Phys. 4, 561 (2008)


(a)
F_RP
50 μm
ω/2π=57.8 MHz

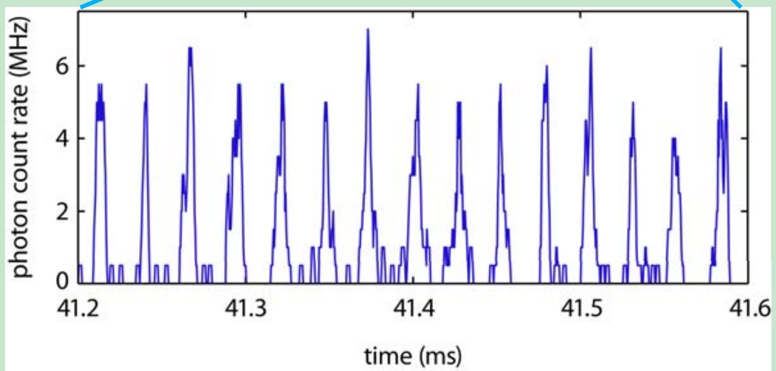
BEC Cavity Dynamics

BEC

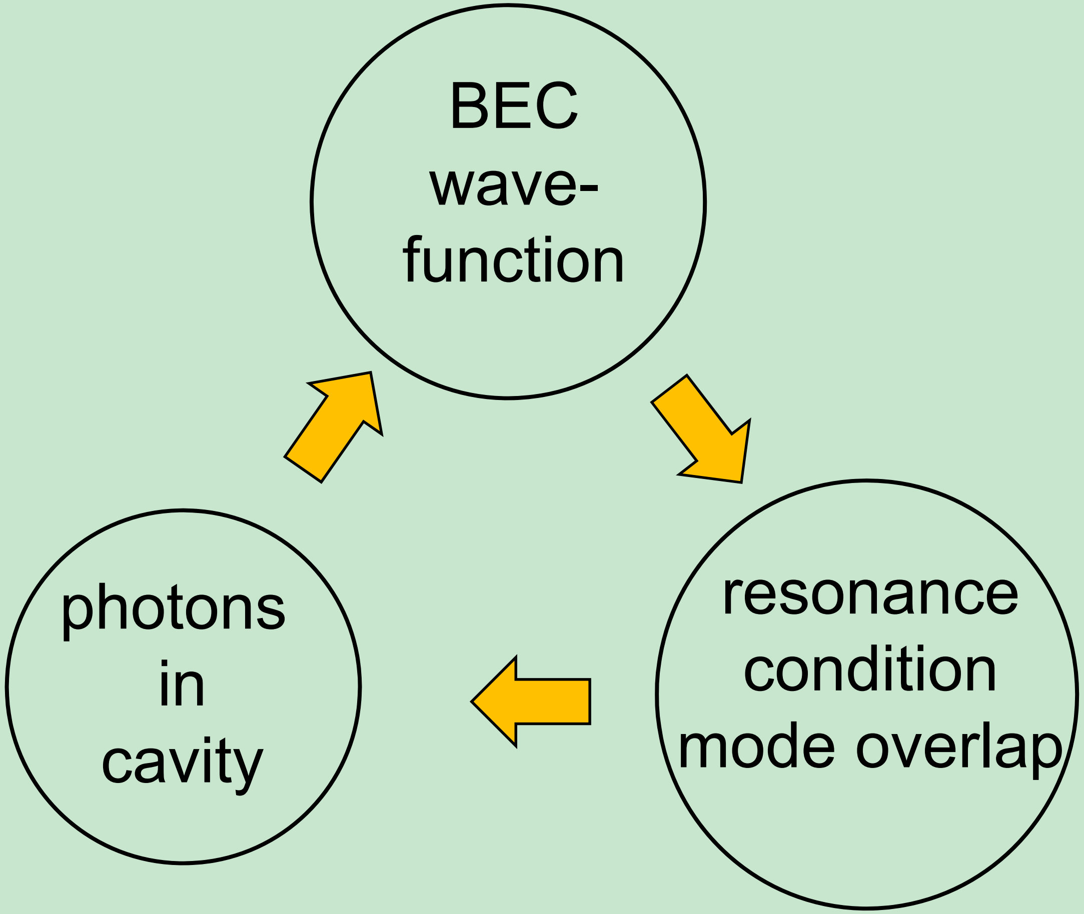




35 kHz – 25 kHz



BEC Cavity Dynamics



Equations of Motion

Mean field description

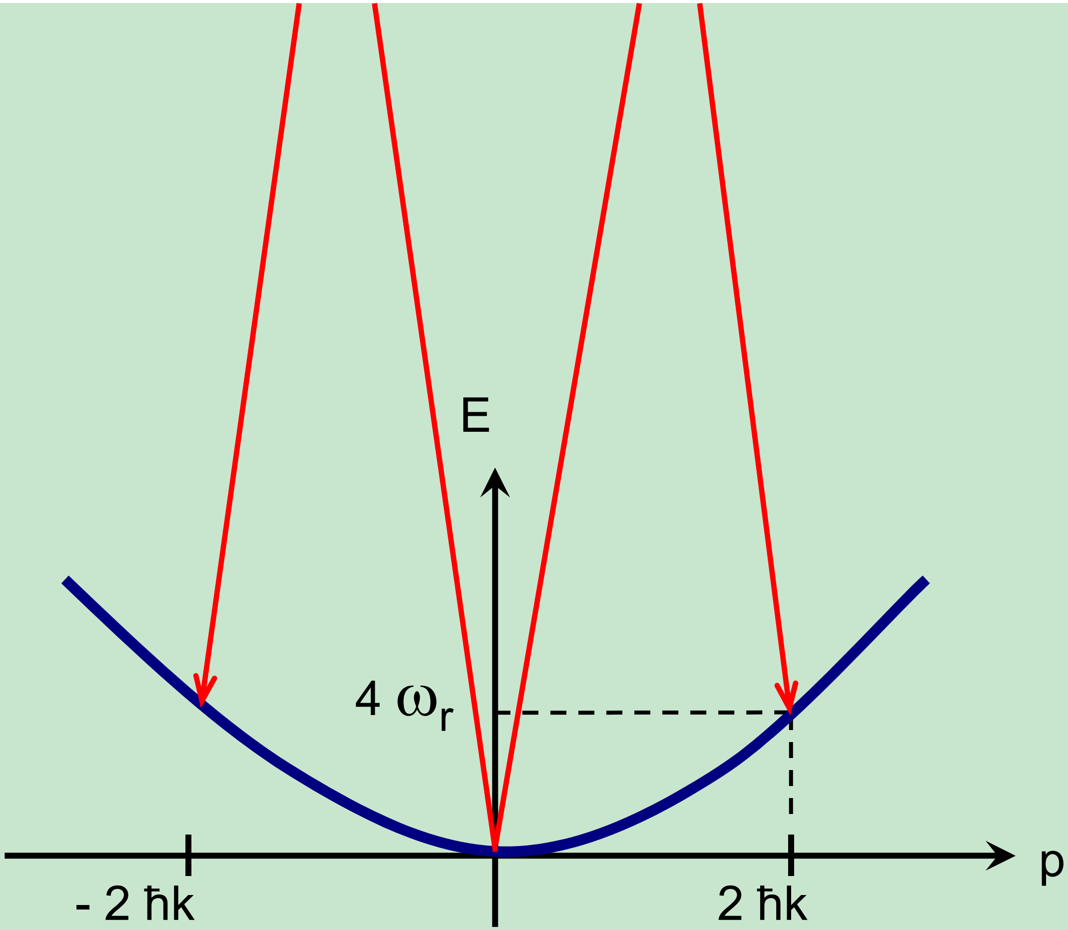
$$i\dot{\psi}(x,t) = \left(\frac{-\hbar}{2m}\frac{d^2}{dx^2} + |\alpha(t)|^2 U_0 \cos^2(kx)\right)\psi(x,t)$$

$$\alpha(t) = \frac{\eta}{\kappa - i(\Delta_c - NU_0\langle\cos^2(kx)\rangle)}.$$

non-local and non-linear coupling – overlap integral

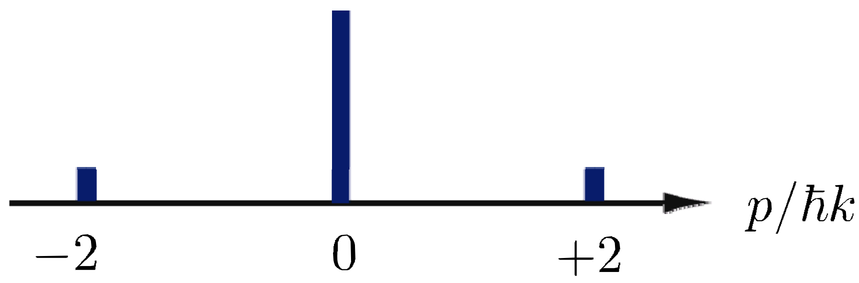
$$\langle\cos^2(kx)\rangle = \int |\psi(x,t)|^2 \cos^2(kx)dx$$

$|\alpha^2| \approx 5$



E
4 ω_r
p
- 2 ħk
2 ħk

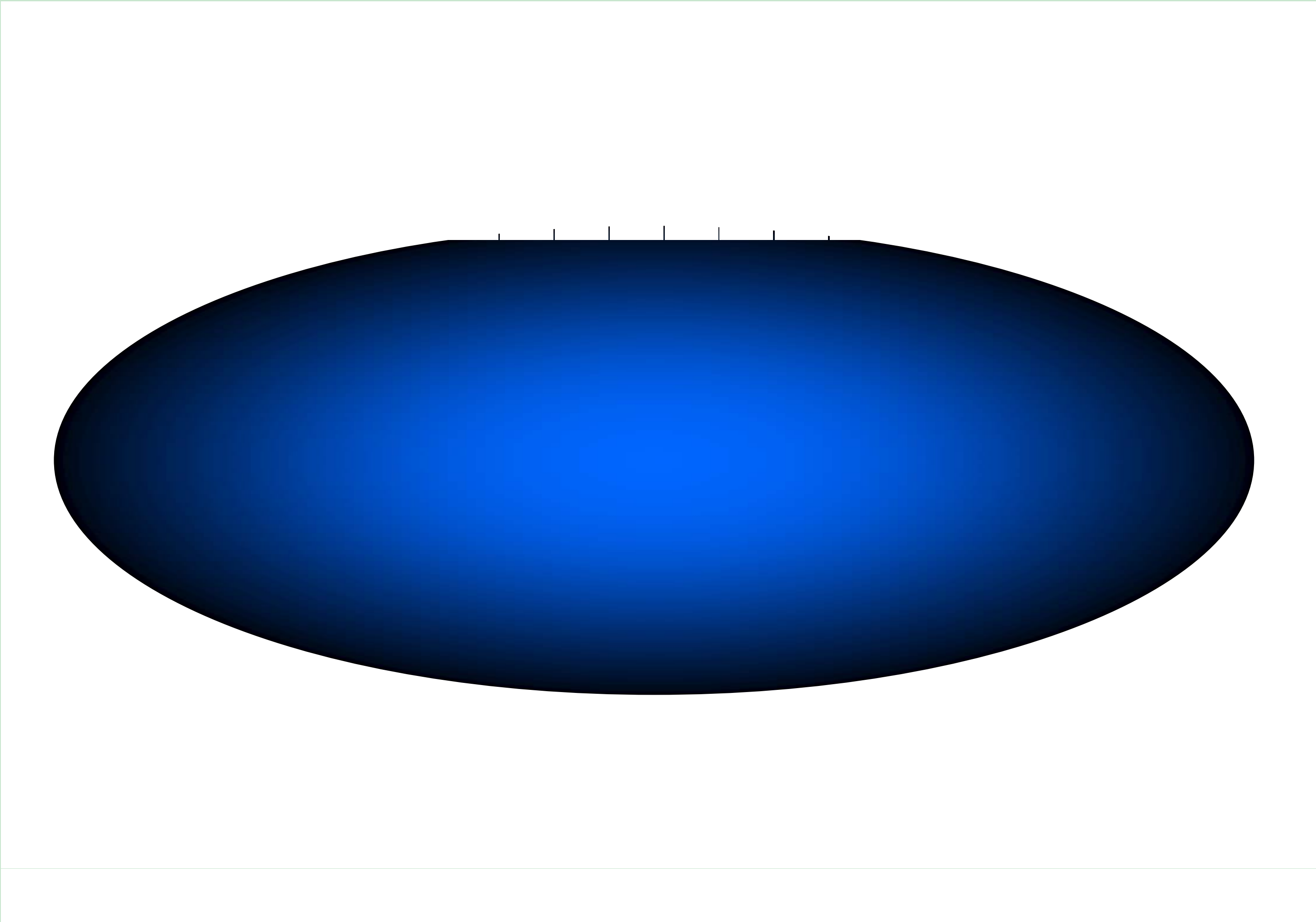
BEC as a mechanical oscillator



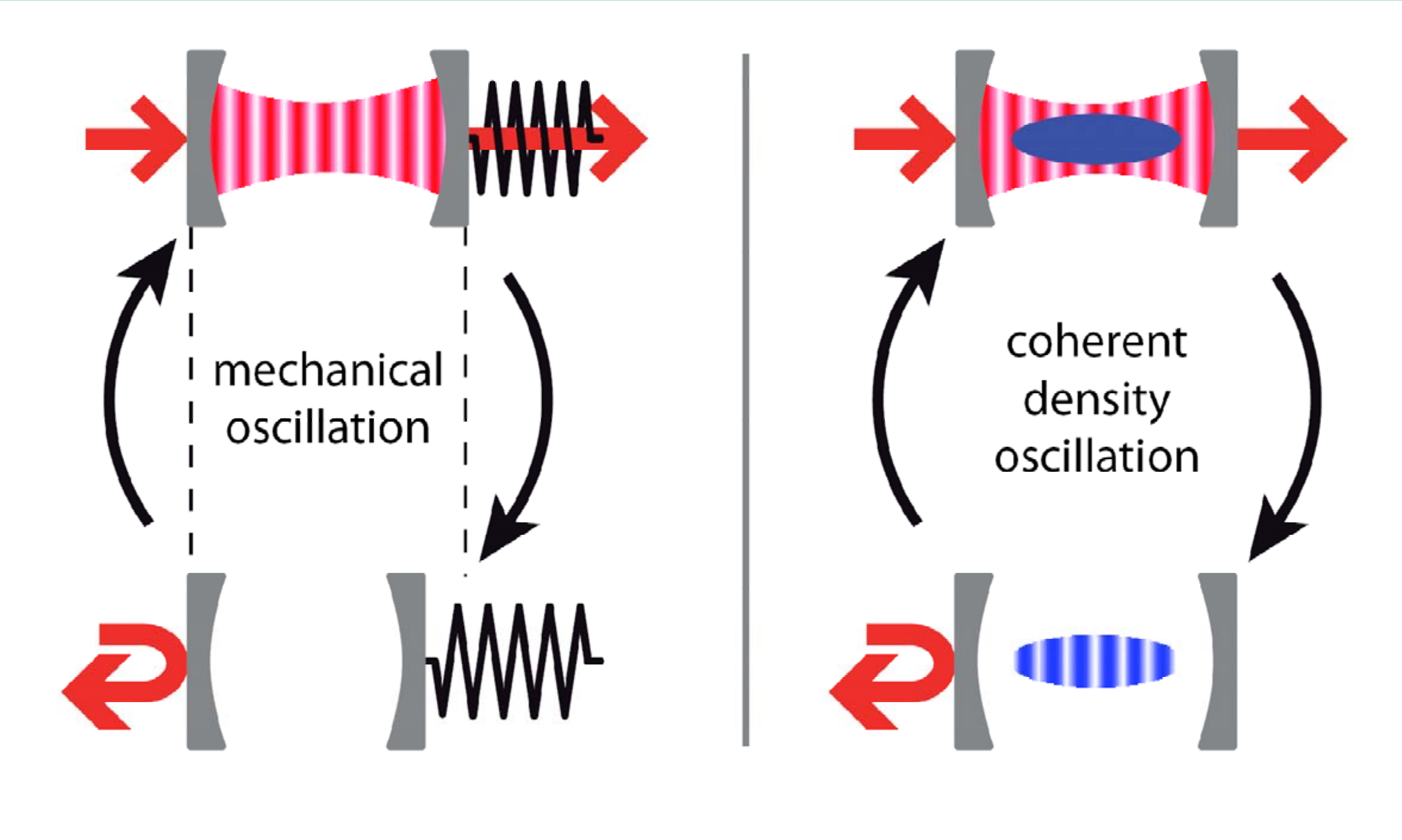
$$\Psi(x,t) = c_0(t)\left|p=0\right\rangle + c_2(t)\left|p=\pm 2\hbar k\right\rangle$$

$$\left|\Psi(x,t)\right|^2 \approx N + c_2\sqrt{N}\cos(2kx)\cos(4\omega_r t)$$

BEC as a mechanical oscillator



Cavity opto-mechanics with a BEC



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

See also: Stamper-Kurn (Berkeley), Nature Physics 2008

BEC mechanically coupled to cavity mode

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

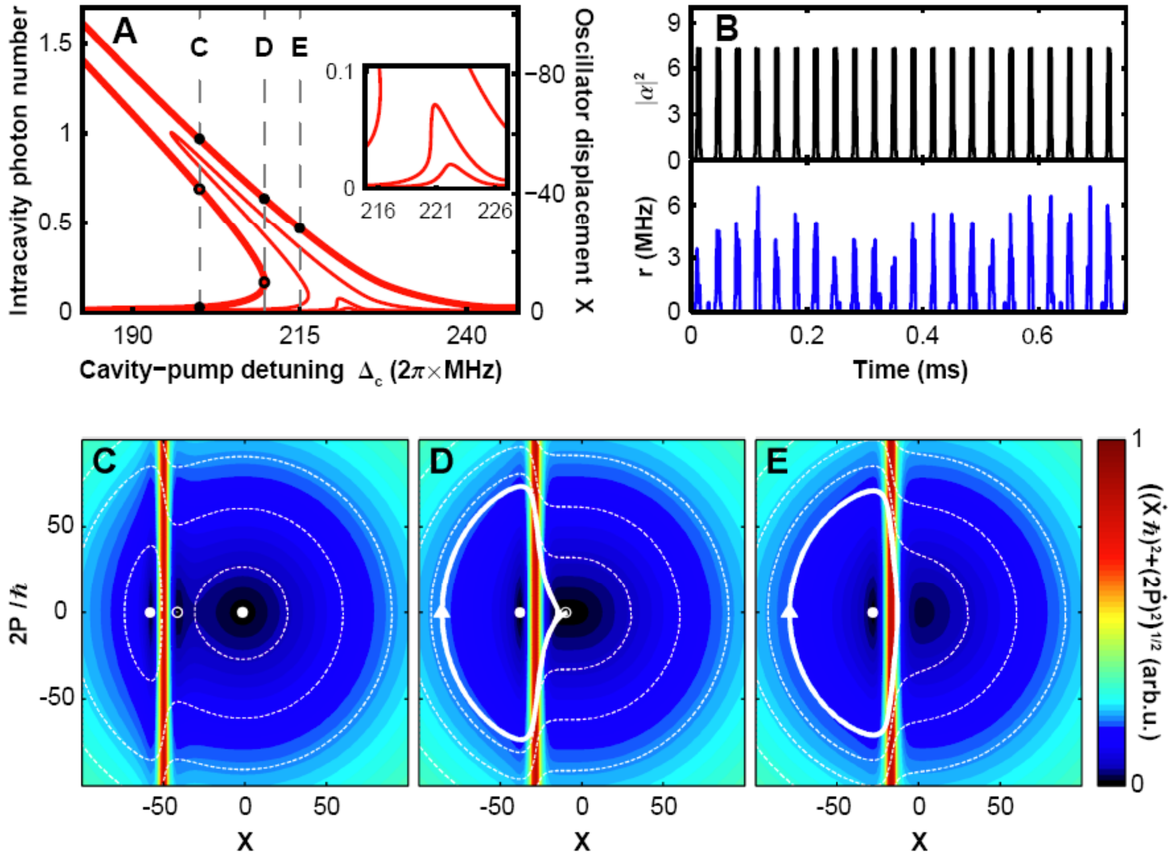
mechanical mode

optical mode

Strong coupling:
$g \approx 0.3\ \kappa$

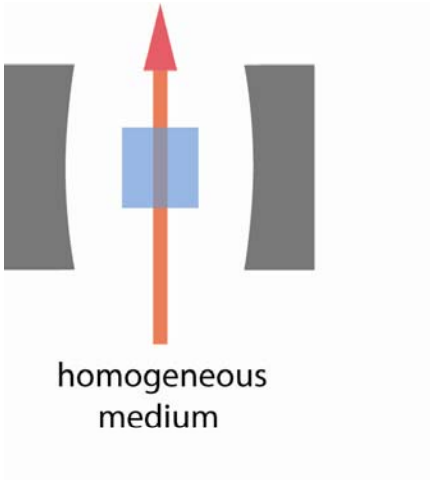
pump

Dynamics of of BEC cavity system



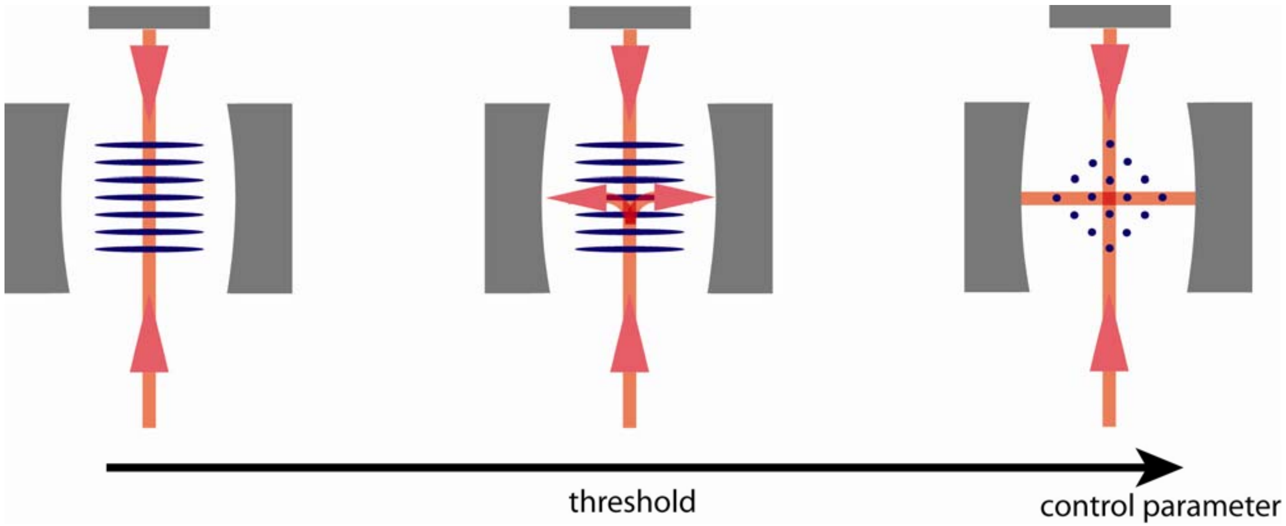
F. Brennecke, S. Ritter, T. Donner, T. Esslinger, Science 322, 235 (2008)

Cavity Detection



See: H. Ritsch, P. Domokos

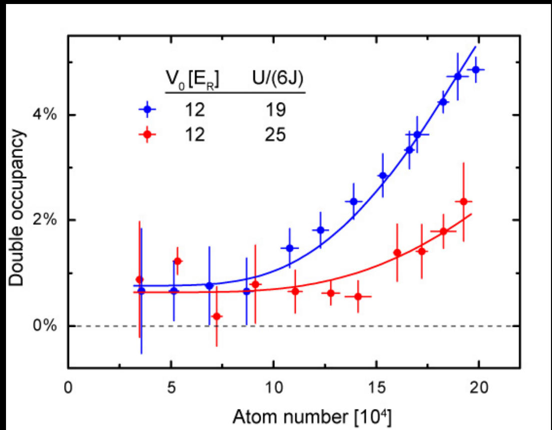
Cavity Controlled Quantum Gas

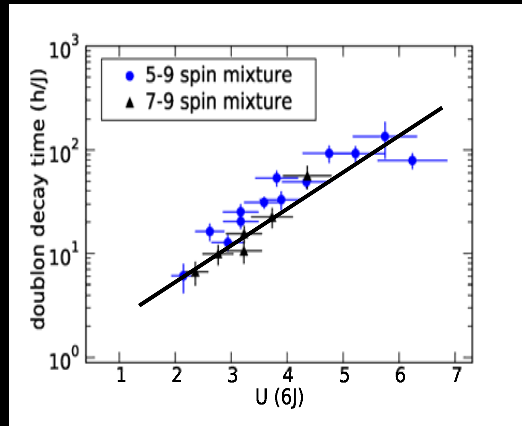


See: H. Ritsch, P. Domokos, M. Lewenstein, V. Vuletic

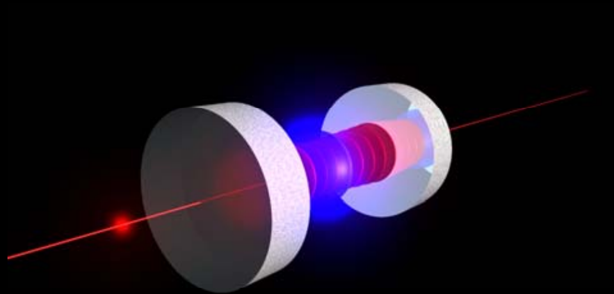
Conclusions and Outlook

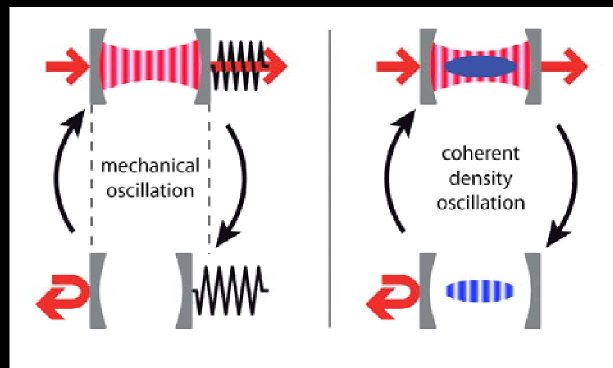
Fermi-Hubbard





Cavity opto-mechanics with a BEC



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