Wuhan Institute of Physics
and Mathematics
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Quantum Magnetism with Ultracold Fermions

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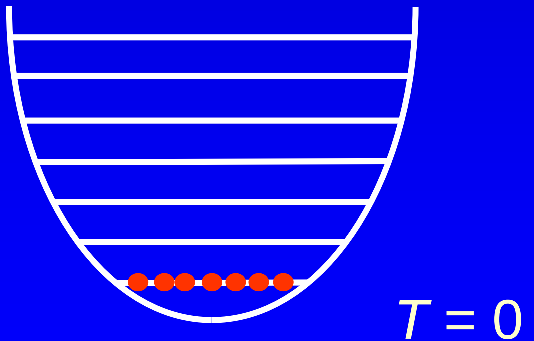
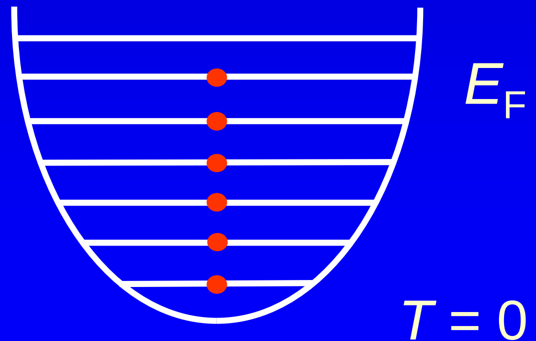
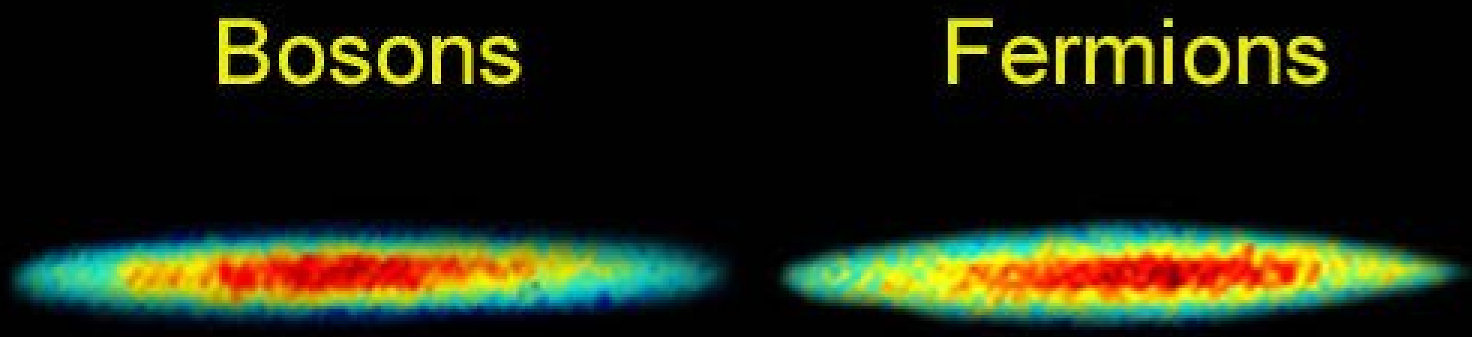
Lithium: Non-identical Twins

^7Li	^6Li
• 3 e's, 3 p's, 4 n's = 10 spin-½ particles ⇒ Boson	• 3 e's, 3 p's, 3 n's = 9 spin-½ particles ⇒ Fermion
• 94% abundance	• 6% abundance



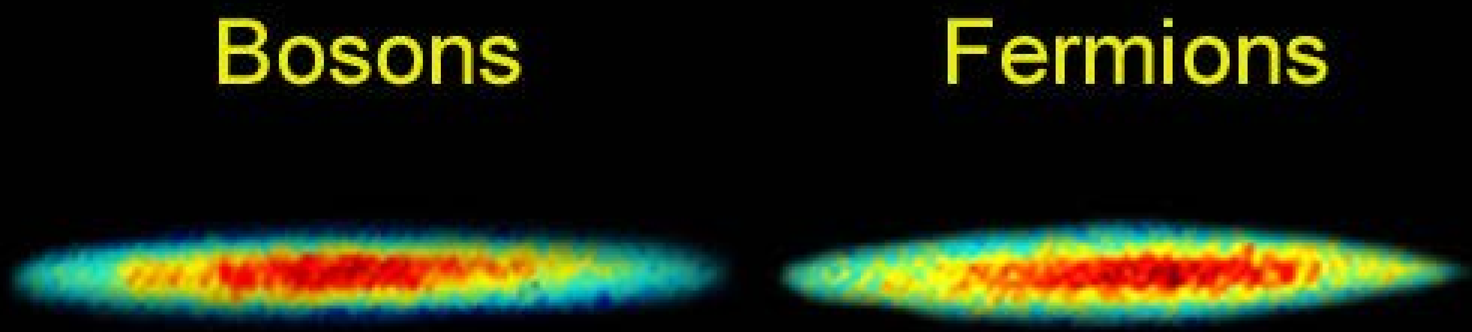




810 nK

$T/T_F = 1.0$

Truscott *et al.*, *Science* **291**, 2570 (2001)

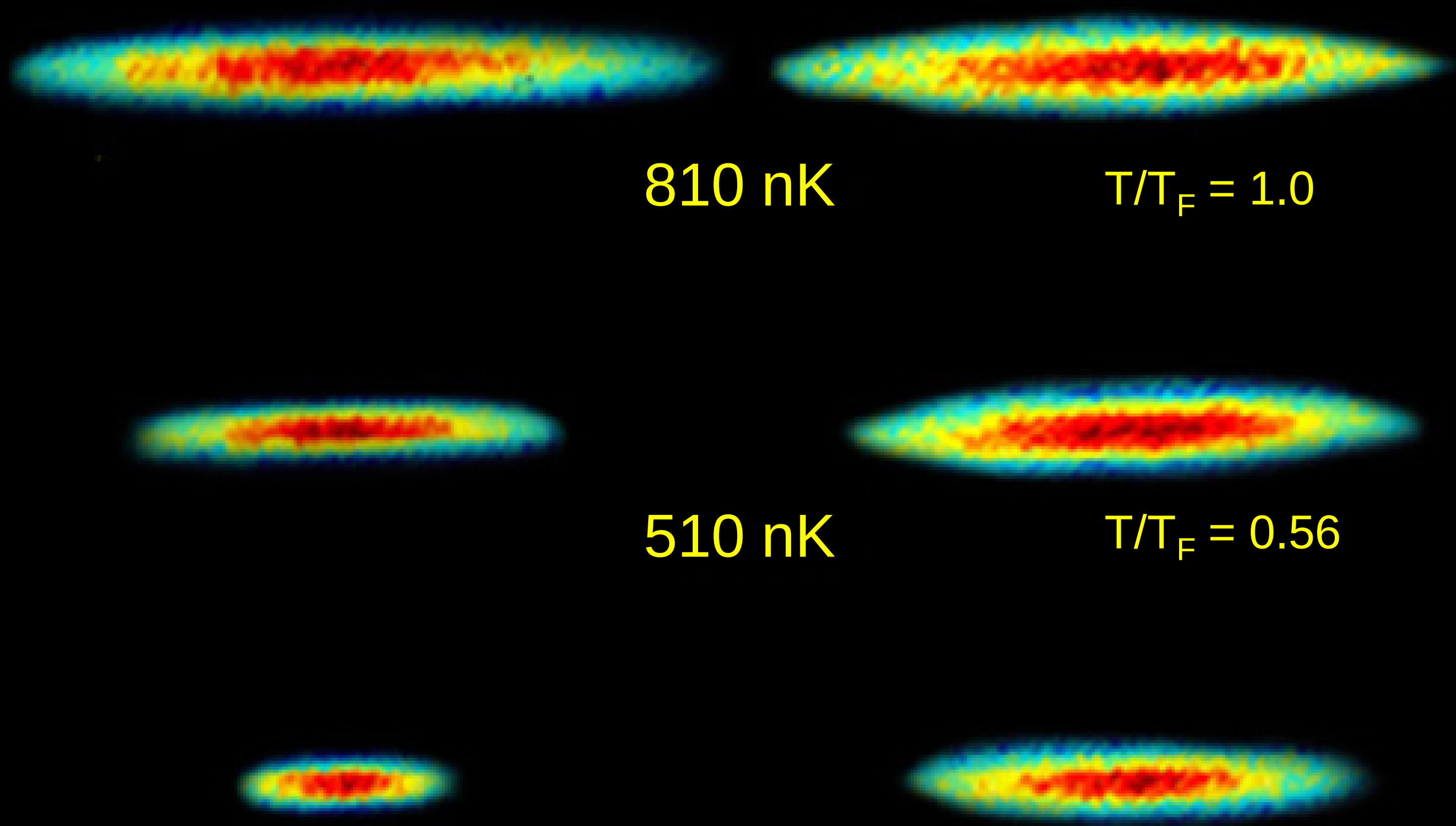


810 nK $T/T_F = 1.0$

510 nK $T/T_F = 0.56$

Truscott *et al.*, *Science* **291**, 2570 (2001)

Bosons | Fermions



810 nK — $T/T_F = 1.0$

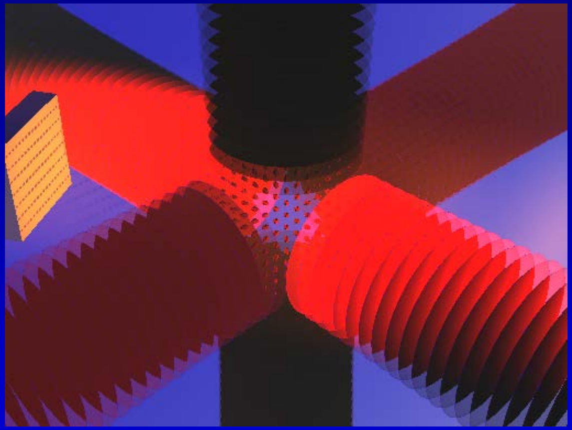
510 nK — $T/T_F = 0.56$

240 nK — $T/T_F = 0.25$

Truscott *et al.*, *Science* **291**, 2570 (2001)

Many-Body Physics with Ultracold Atoms

Ultracold atoms are being used to create strongly interacting many-body systems
Relevant to: condensed matter, nuclear, quark matter

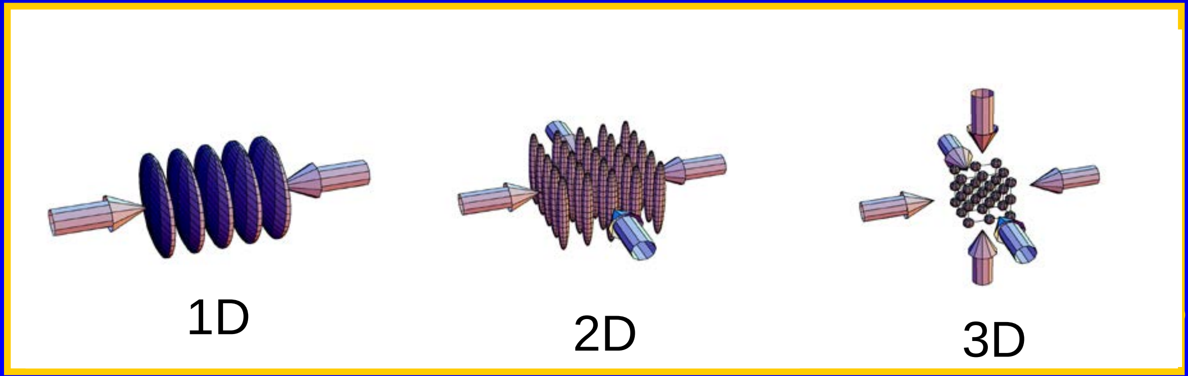


Examples underway:

- quantum magnetism ←
- exotic superconductors
- exactly solvable 1D systems ←
- quantum criticality
- disordered insulators
- topological matter

Tunable parameters:

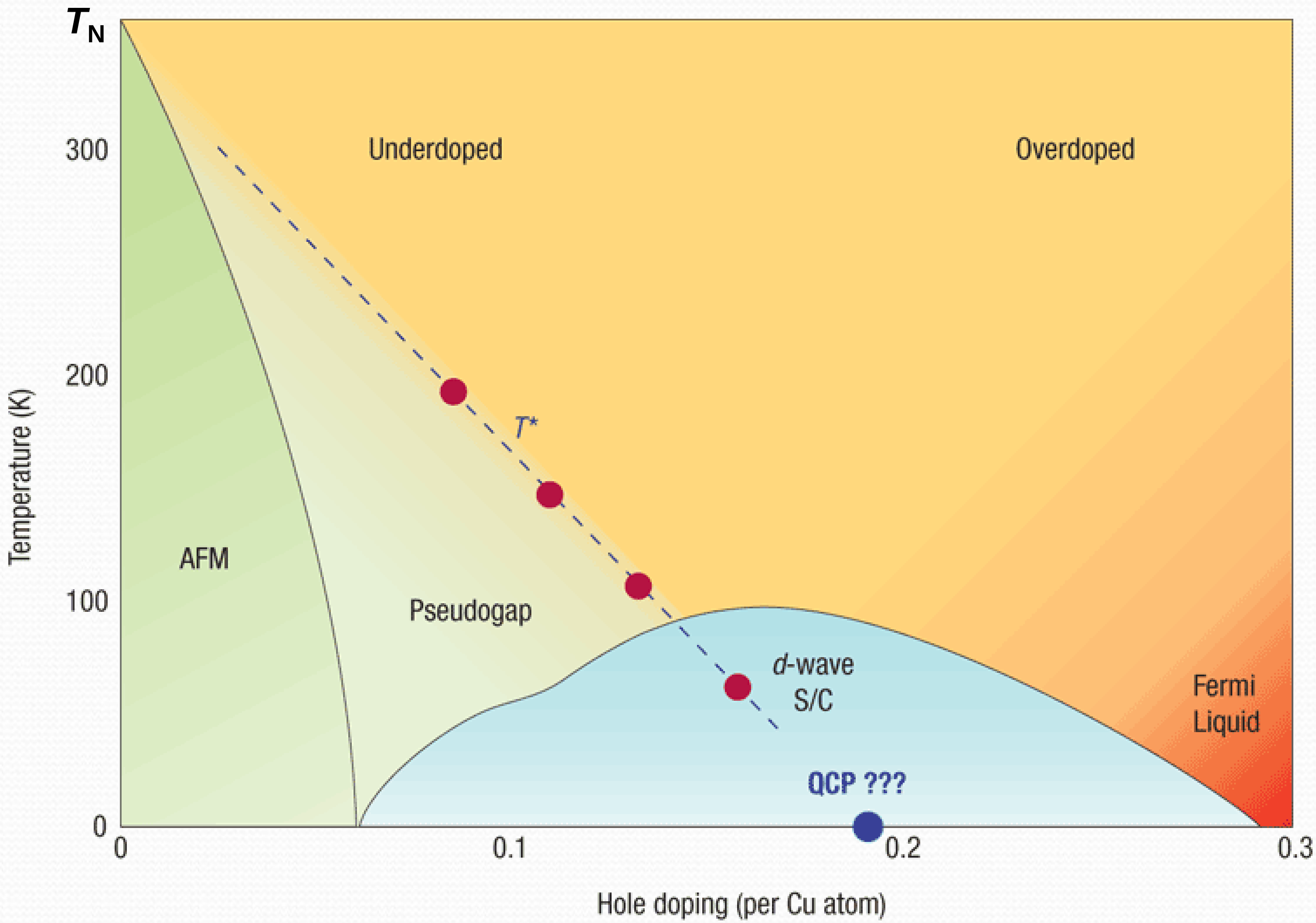
- interactions (*U*)
- lattice hopping (*t*)
- temperature (*T*)
- density (*n*)
- dimensionality
- geometry
- spin polarization
- spin-orbit interaction
- disorder



Optical lattice configurations

Phase Diagram of a High-T_c Superconductor

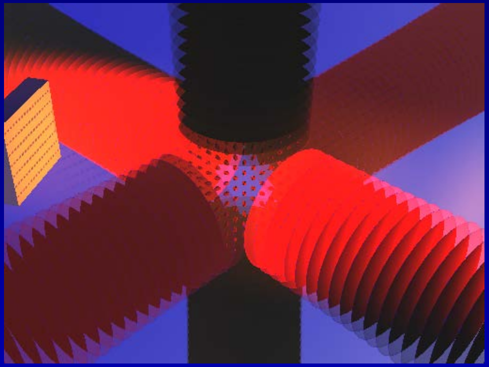
Example: cuprate superconductor
(also Fe pnictides, and heavy fermion superconductors)



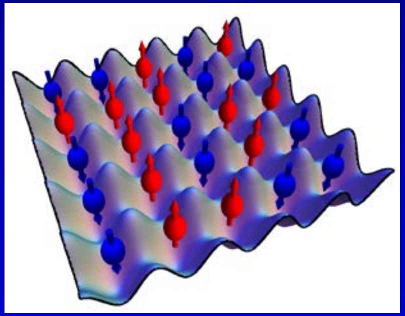
Broun *et al*, Nature Phys. **4**, 170 (2008)

Outline

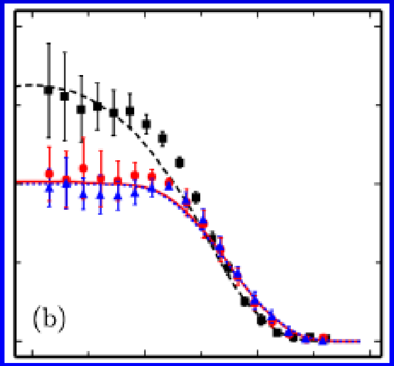
- **Optical lattices**



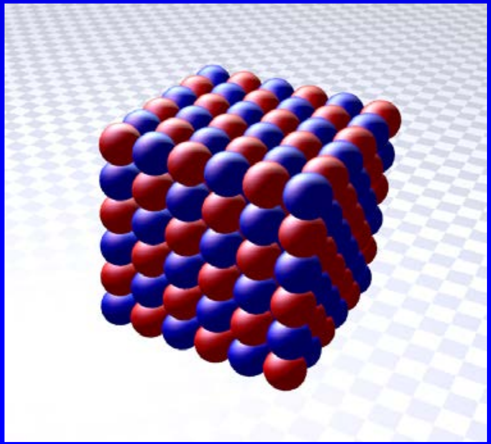
- **Hubbard model**



- **Compensated optical lattice**



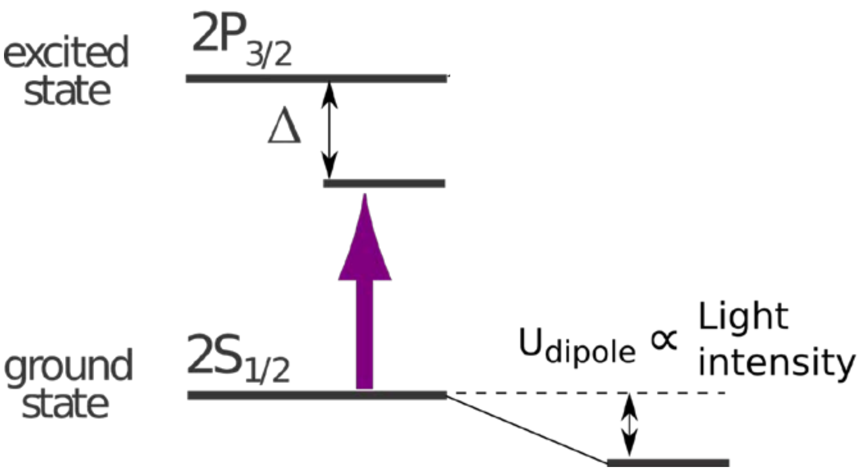
- **Mott insulator**



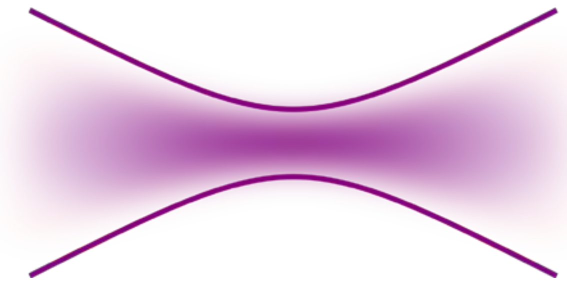
- **Detecting antiferromagnetic order**

Optical lattice

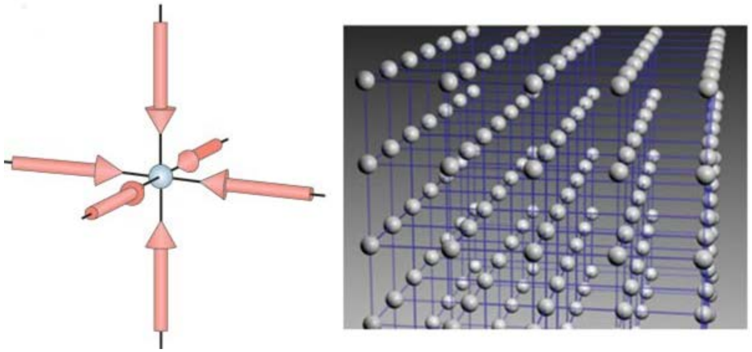
AC Stark shift



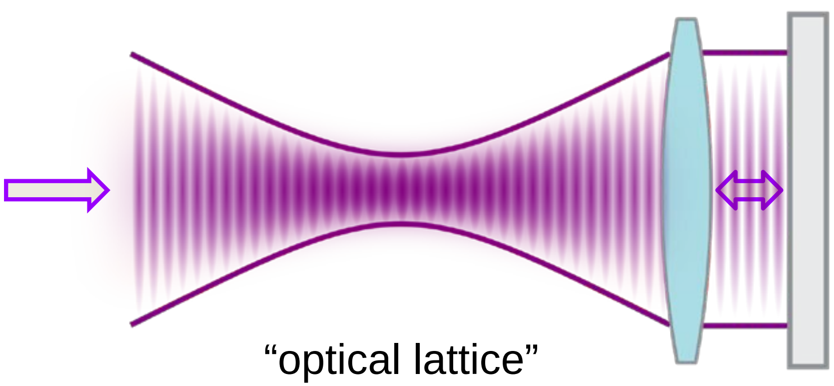
Tightly focused laser beam has an intensity maxima at the waist and can trap atoms there



“optical trap”

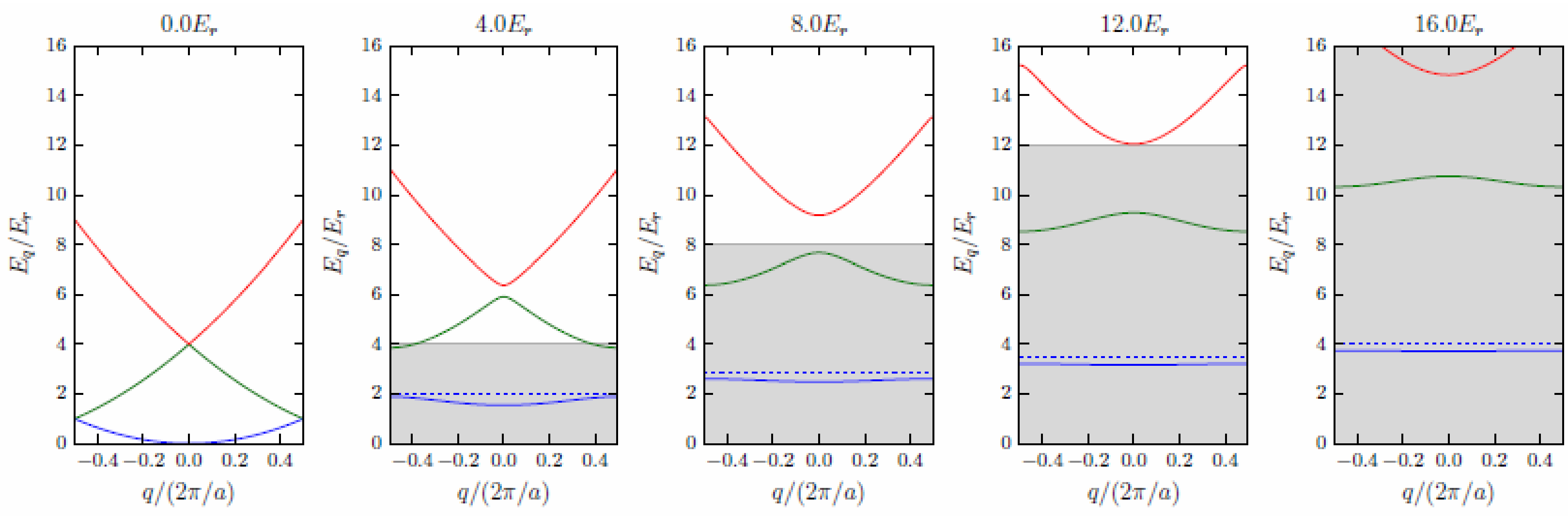


simple cubic lattice



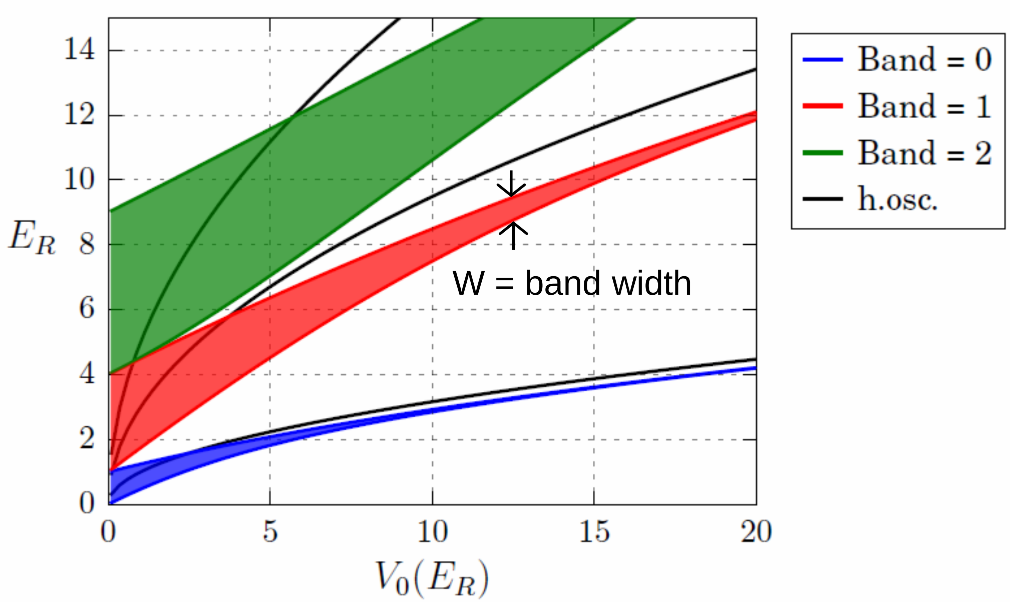
“optical lattice”

Band Structure

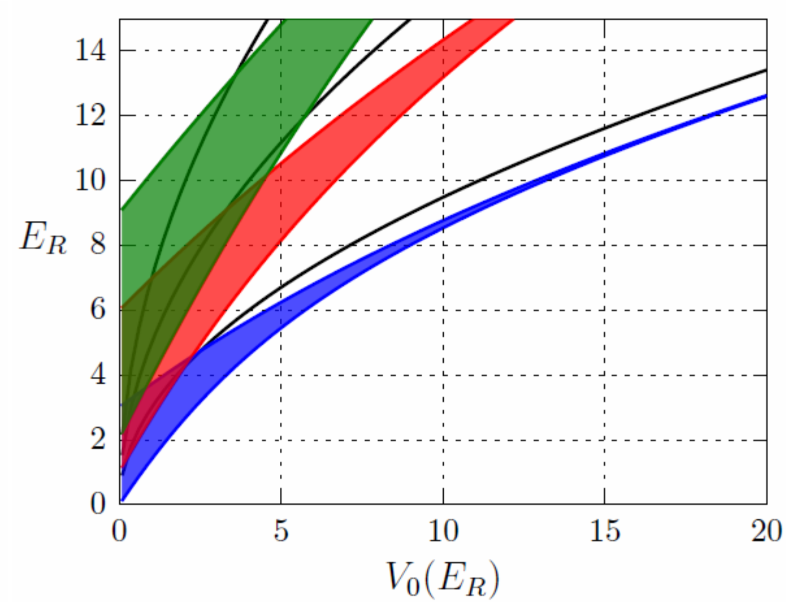


shaded area: lattice depth , dotted line: harmonic approximation $E_o \approx v_o^{1/2}$

1D



3D



Eigenstates

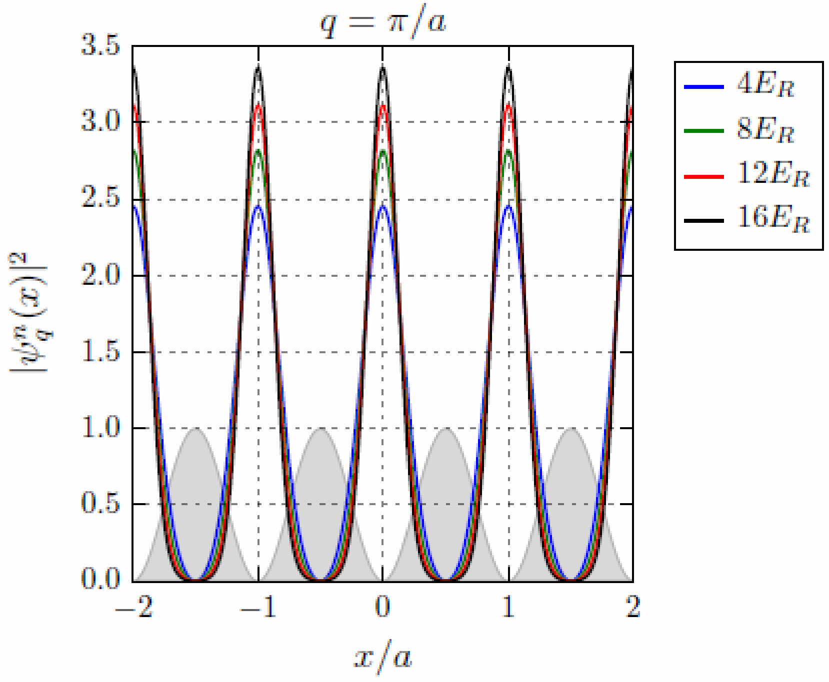
Tight binding limit:

For a deep lattice, $V_o >> E_r$, the eigenstates are harmonic oscillator functions

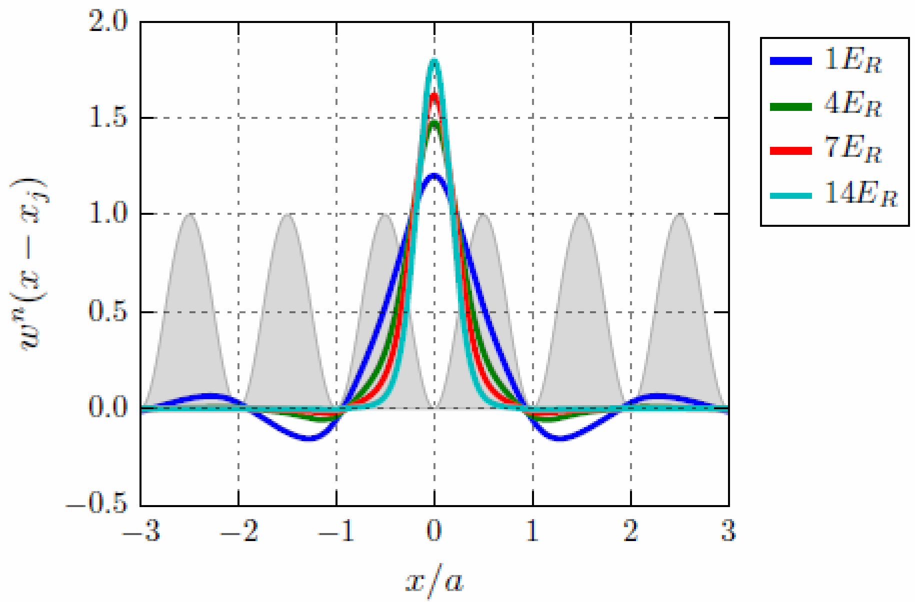
For a weaker lattice, the eigenstates are not tightly bound

A basis of states localized around a single site are known as *Wannier functions* $w(x)$

Eigenstates of H_{1D}

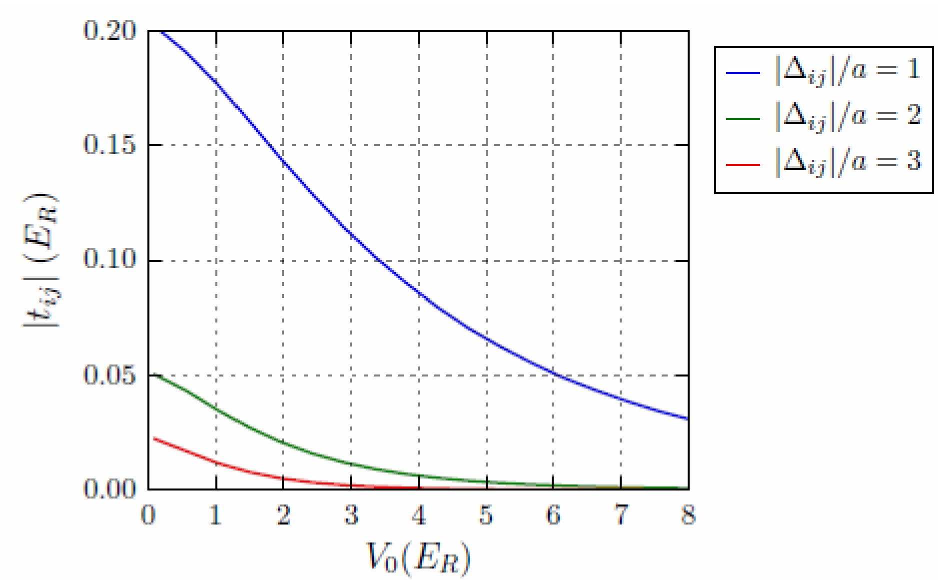


Wannier states



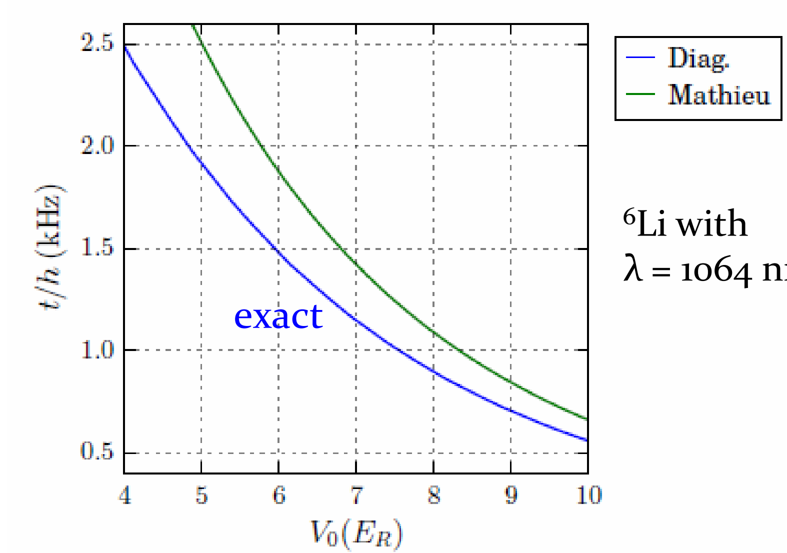
Tunneling

Atoms can tunnel from site to site, but for $V_0 > 5\ E_r$ only nearest neighbors contribute:



t can be approximated in the tight-binding limit:

$$t/E_r \simeq \frac{4}{\sqrt{\pi}} v_0^{3/4} \exp(-2\sqrt{v_0})$$



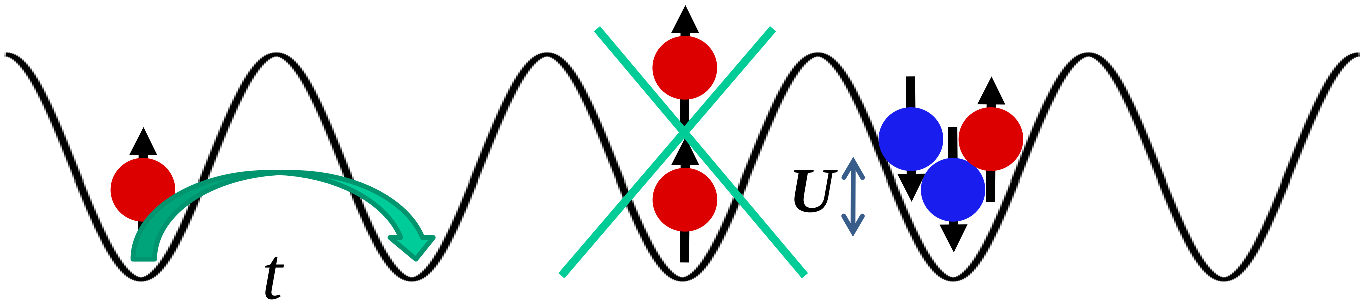
^{6}Li with
λ = 1064 nm

Hubbard Model
- the hydrogen atom of condensed matter

$$H = -t \sum_{<i,j>,\sigma} \left(c_{i,\sigma}^{\dagger} c_{j,\sigma} + \mathrm{h.c.} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

t = hopping energy

U = on-site interaction energy (repulsive)



single band: n = 0, 1, or 2

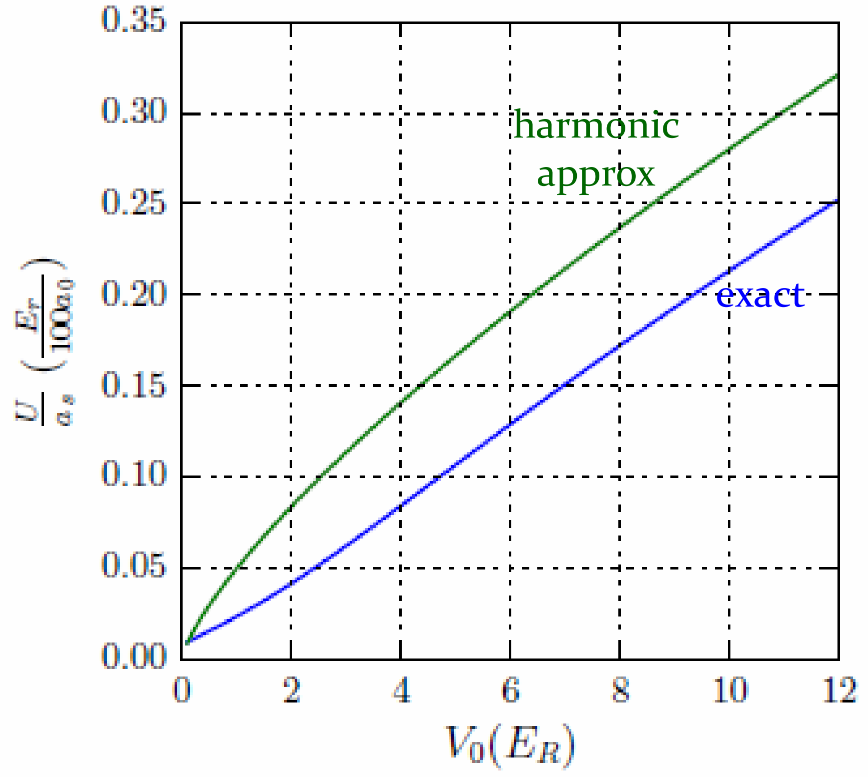
- Paradigm model of strongly correlated matter
- Proposed model for high-T_c superconductors
  - but we don't know for sure if it has *d*-wave pairing

Cannot be solved exactly: basis size = 2^N

On-Site Interactions

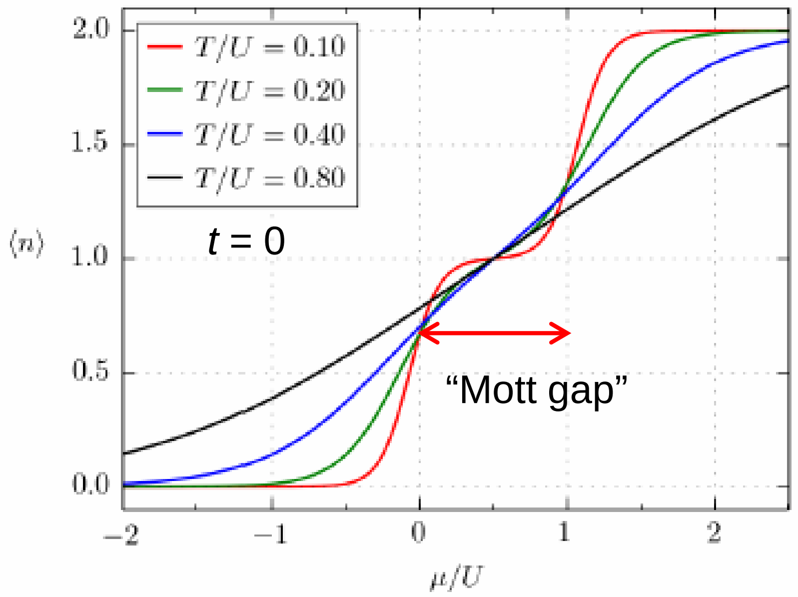
Harmonic approximation:

$U/E_r \approx (8\pi)^{1/2}\, a_s/a\, v_o^{3/4}$

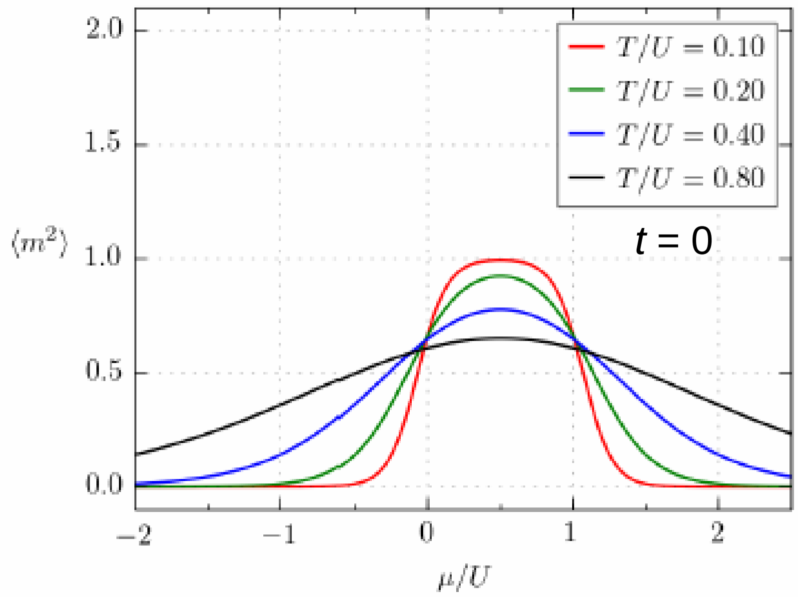


Mott Insulator Develops for $T \ll U$

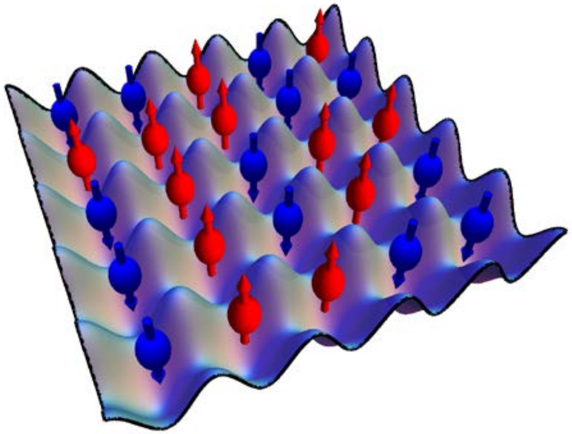
density



magnetization



A Mott insulator develops at $n = 1$ ("half-filling"):



Fermi-Hubbard Model

Special case: $n = 1$ "*half-filling*":

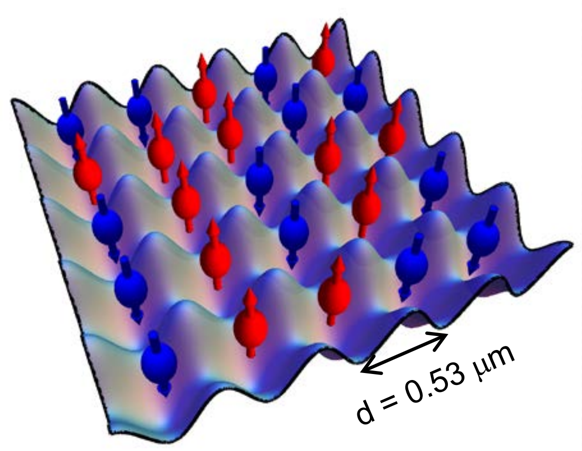
$$H_{\mathrm{AFM}} = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j ,$$

with $J = t^2 / U$ "*super-exchange*"

- Mott insulator for $T < U$, with $U/t >> 1$

R. Jördens *et al.* (ETH), Nature, 2008:
reduction of double occupancies

U. Schneider *et al.* (Munich), Science, 2008:
reduction of compressibility

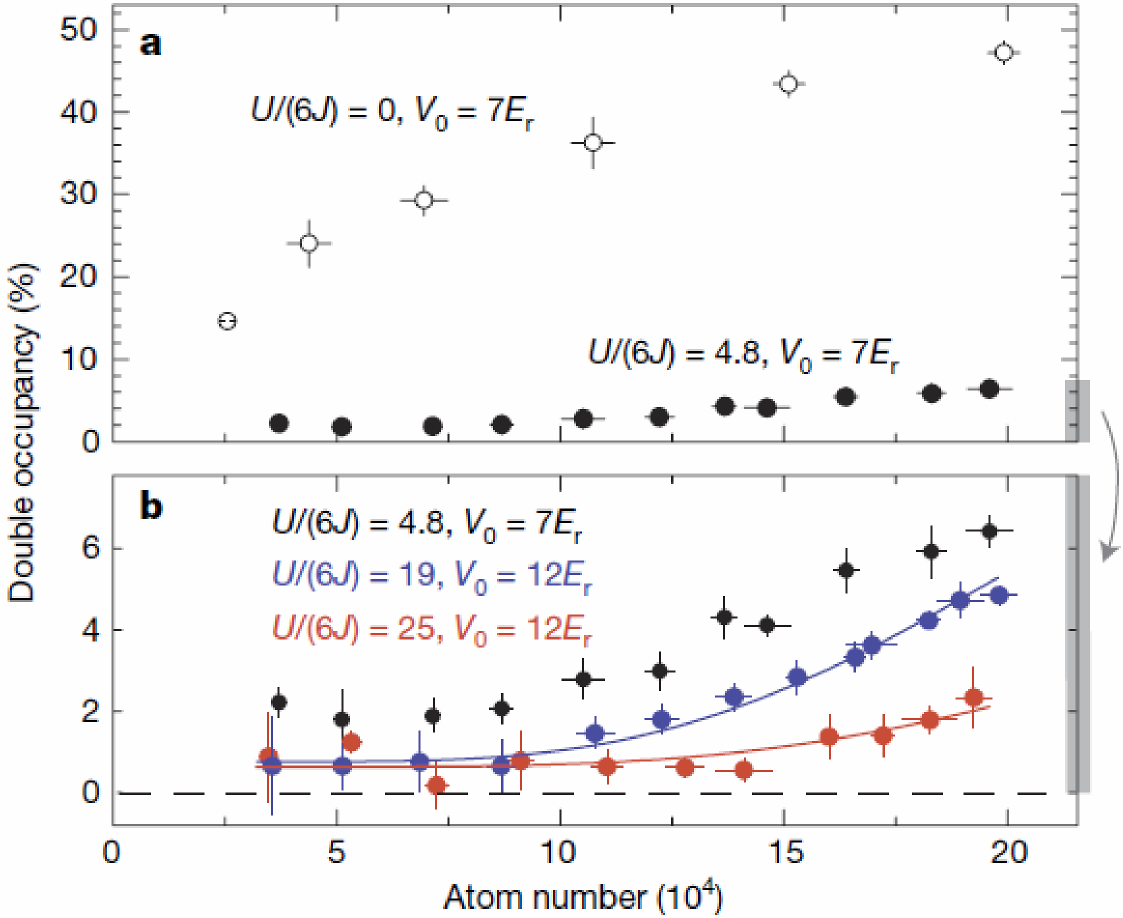


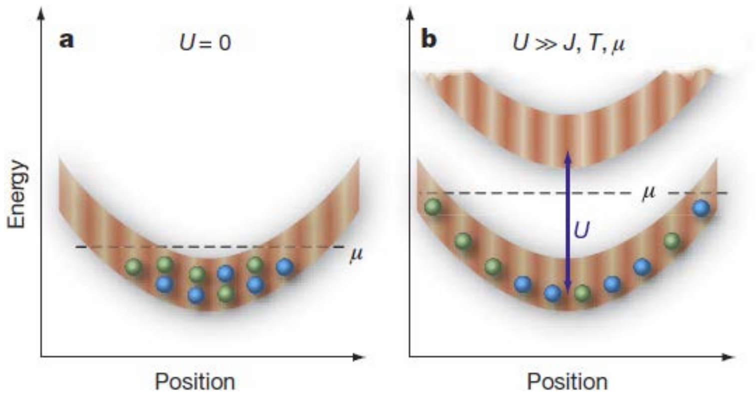
random spins

Fermion Mott Insulator – ETH, 2008

Double Occupancy

R. Jordans *et al, Nature* 455, 204, (2008)

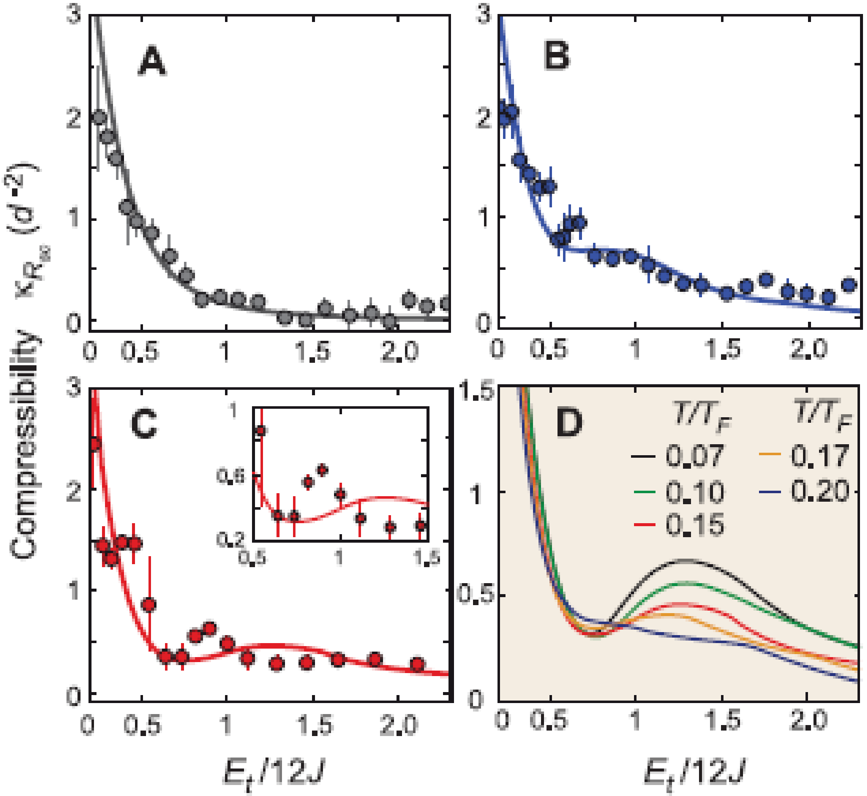


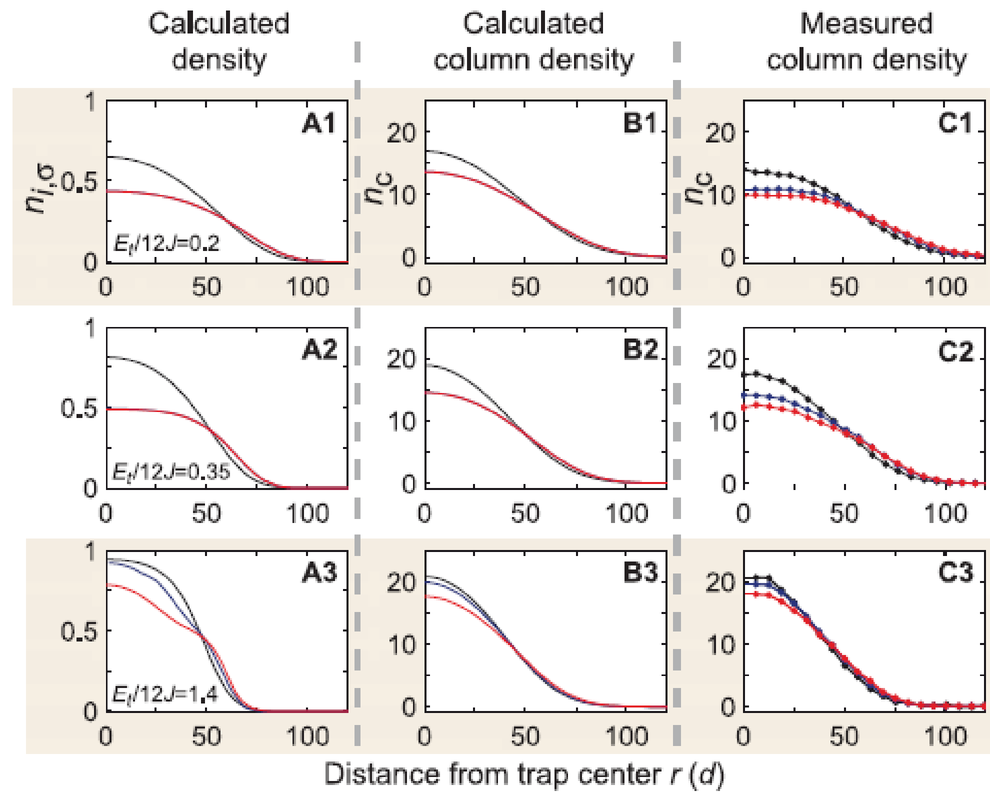


Fermion Mott Insulator – Munich, 2008

Incompressibility

U. Schneider *et al, Science* 322, 1520 (2008)





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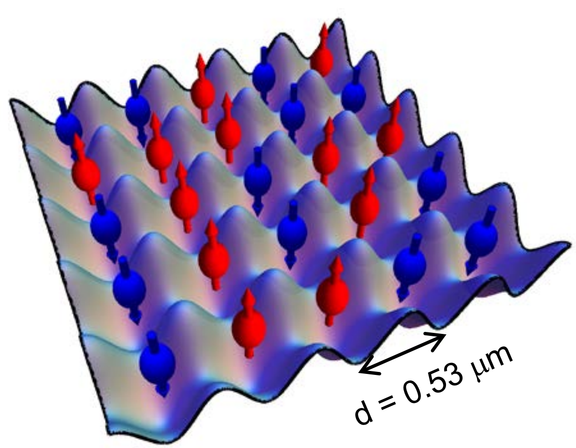
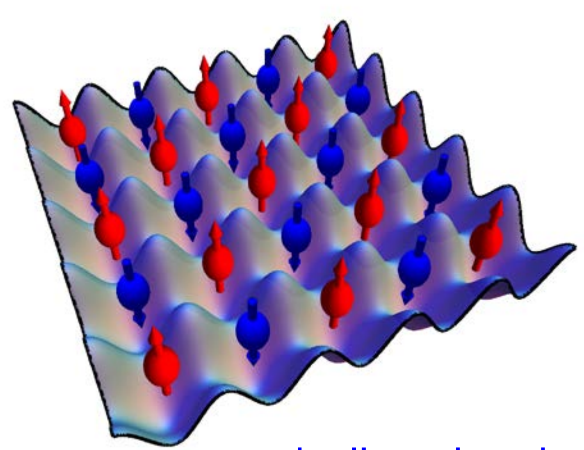


random spins

- Antiferromagnet for $T < T_{\text{Néel}} \sim 4t^2/U$

→ $S/N < k_B \ln(2) \sim 0.7\, k_B$

Fermions in an Optical Lattice:
Greif *et al* (ETH), Science 2013:
nearest neighbor singlet correlations along 1D chains



magnetically ordered

$T_{\text{Néel}}$ not yet achieved in a 3D optical lattice – Poses a major challenge for realizing novel quantum materials w/ cold atoms

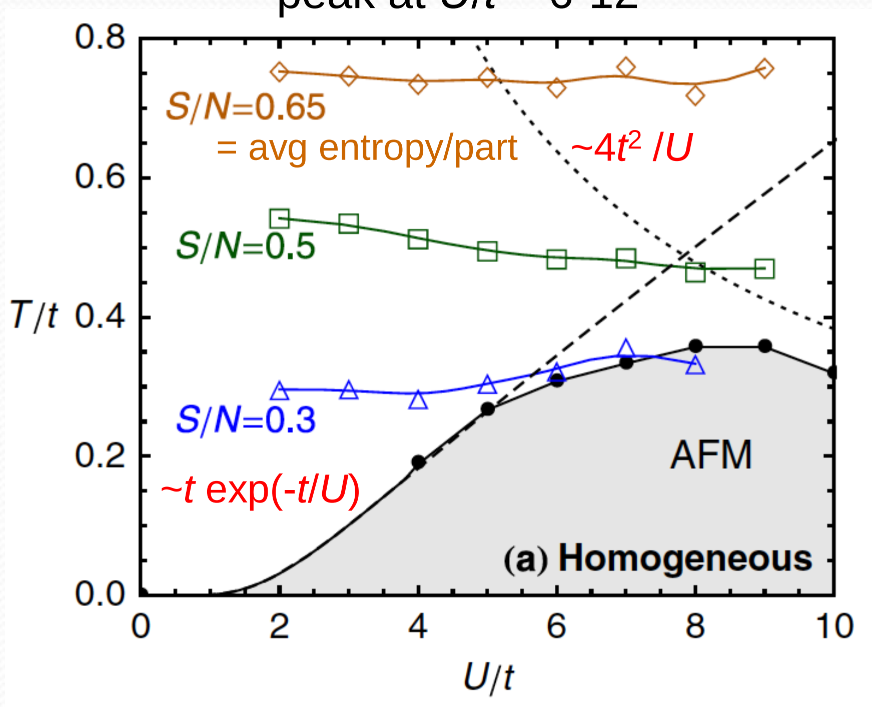
Néel Transition

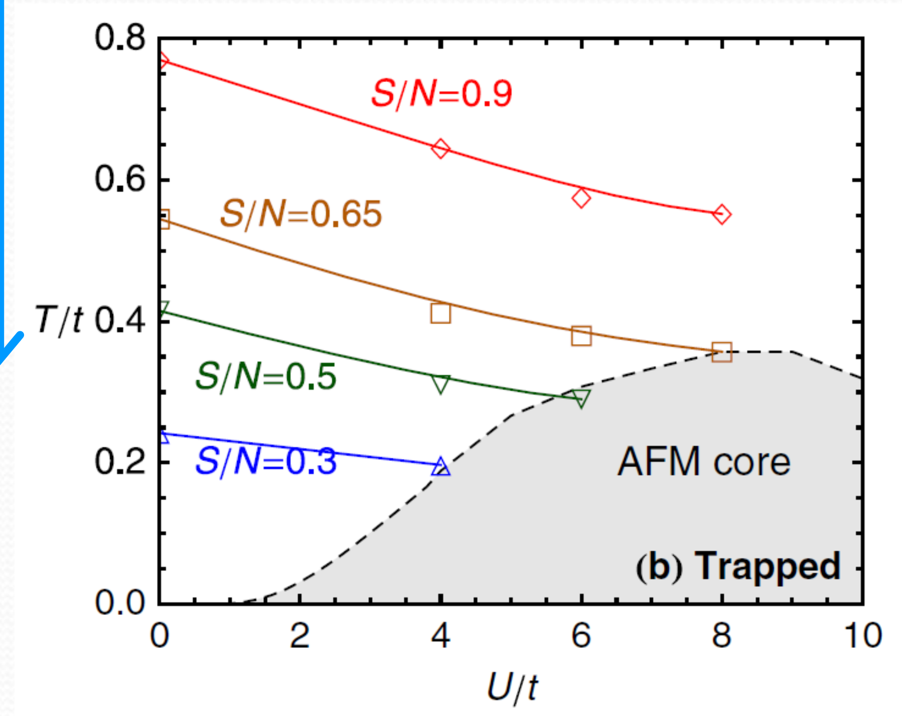
ETH Expt

***T/t* = 1.0** Imriska *et al*, PRL (2014)

***S/N* = 1.6 k_B**

T_N maximized in a broad peak at *U/t* ~ 6-12

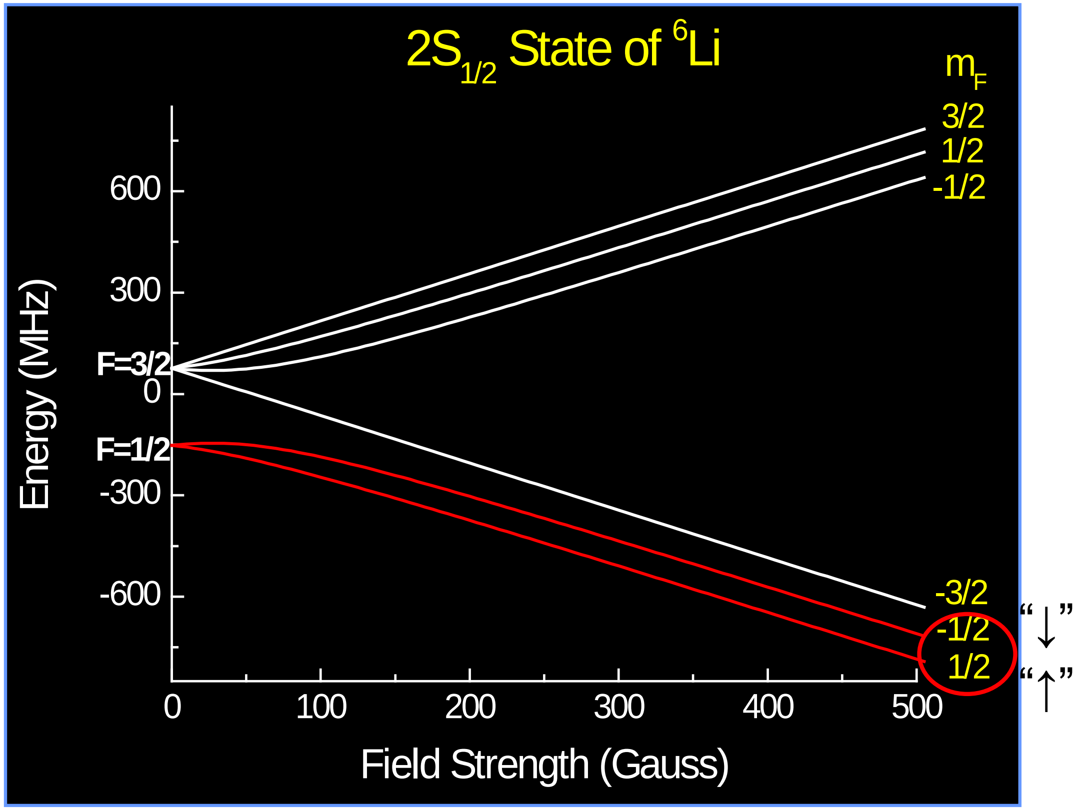




Quantum Monte Carlo

Paiva et al, PRL **107**, 086401 (2011)

"Spin" States in ^{6}Li



$m_s = ½$

Interactions tunable
by a Feshbach resonance

$m_s = -½$

Typical experimental parameters
for $N \approx 2 \times 10^5$ ^{6}Li atoms:

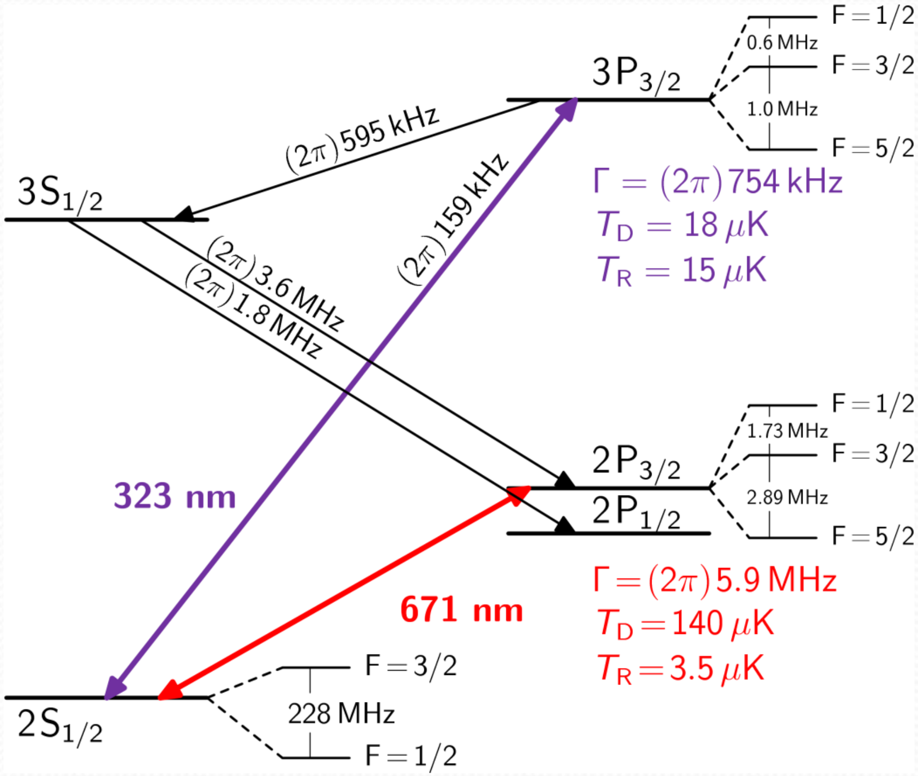
$V_L \approx 7\ E_R \quad (E_R = \hbar^2 k^2/2m = 1.4\ \mu K)$

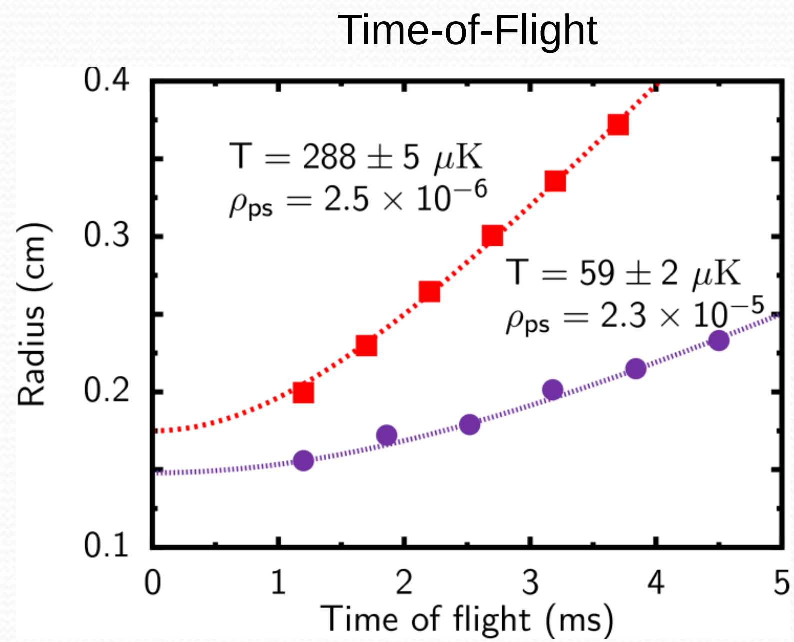
$t \approx 0.038\ E_R \approx 50$ nK ≈ 1 kHz

$U \approx 0.38\ E_R$ @ $250\ a_o$

$4t^2/U \approx 25$ nK $\approx 0.025\ T_F$

Narrow-Line Laser Cooling





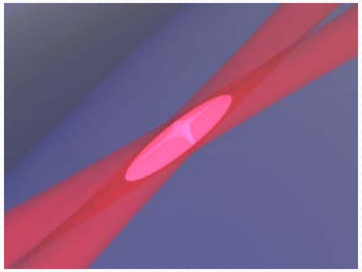
P. Duarte, R. Hart *et al.*, PRA 84, 061406 (2011)
Also, in ^{40}K: D. McKay (Toronto), PRA 84, 063420 (2011)

Red MOT	UV MOT
$N = 1 \times 10^9$	$N = 5 \times 10^8$
$T = 290\ \mu K$	$T = 59\ \mu K$
$n = 3 \times 10^{10}$ cm^{-3}	$n = 3 \times 10^{10}$ cm^{-3}
$\rho_{ps} = 2 \times 10^{-6}$	$\rho_{ps} = 2 \times 10^{-5}$ → ×10 increase

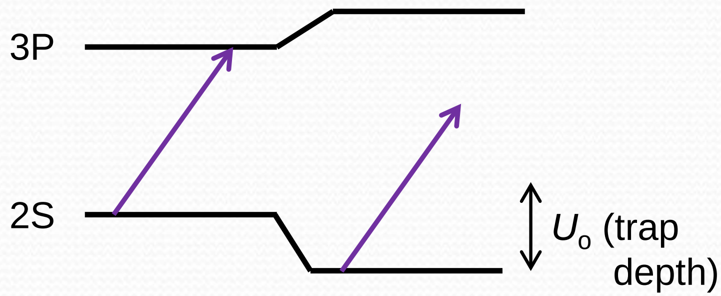
OLE OPTICAL LATTICE EMULATOR

RICE

Optical Trap - Magic Wavelength

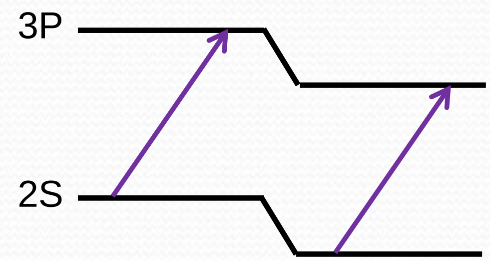


Crossed-beam trap at 1070 nm



Usual *non-magic* wavelength

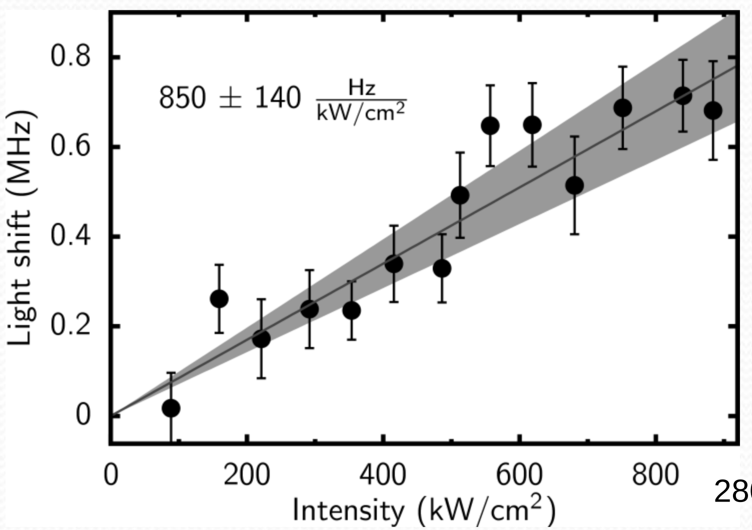
- Trap light shifts cooling transition out of resonance



Magic wavelength

- Light shifts of upper and lower levels are equal

Light shift measurement: Light shift □ γ at full trap depth



280 μK

After laser cooling in trap:

$N = 1 \times 10^7$

$T = 50\ \mu K$

$n_o = 4 \times 10^{13}\ cm^{-3}$

$T/T_F = 2.5$

$\rho_{ps} = 2 \times 10^{-2}$ → ×1000 increase

After 5 s of evaporation:

$N = 4 \times 10^6$ atoms

$T < 0.1\ T_F$

P. Duarte, R. Hart *et al.*, PRA 84, 061406 (2011)

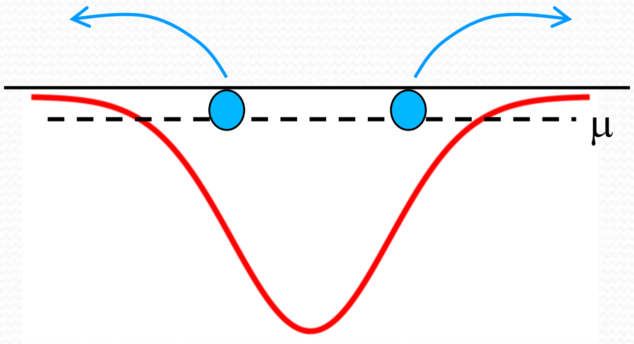
Light shift calculation: M. Safranova

OLE OPTICAL LATTICE EMULATOR

RICE

Evaporative Cooling – Trap vs Lattice

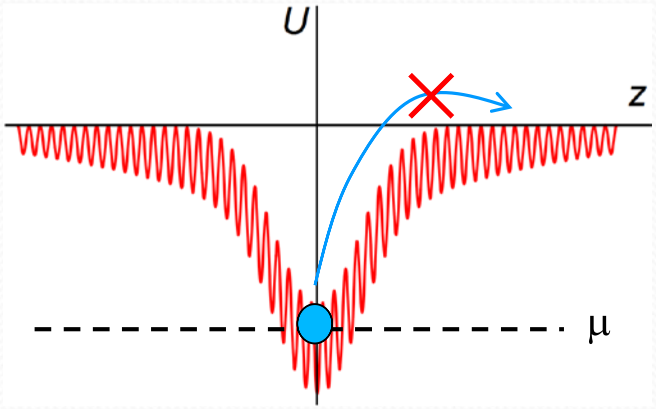
Evaporative cooling in a trap:



Very effective cooling: $T < 0.05\ T_F \rightarrow S < 0.7\ k_B$

In a red-detuned 3D lattice:

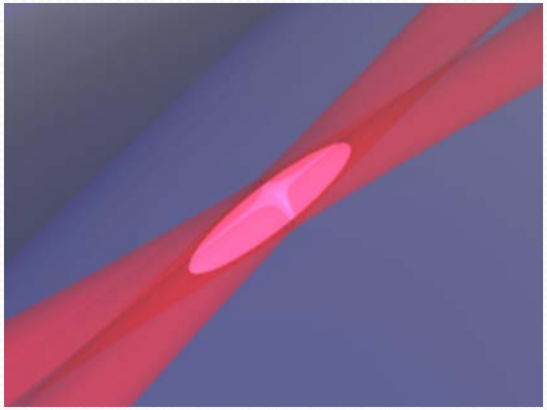
(looking along a lattice direction)



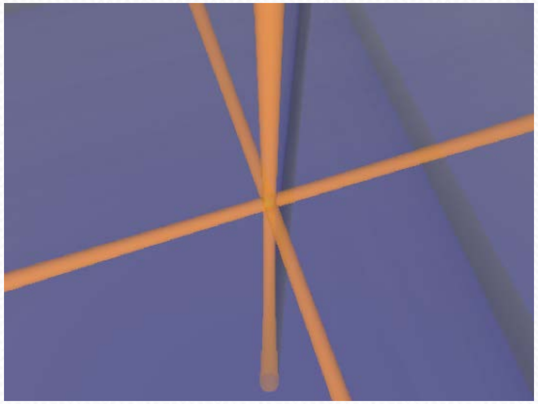
No cooling

(but there is heating)

Crossed Beam Trap



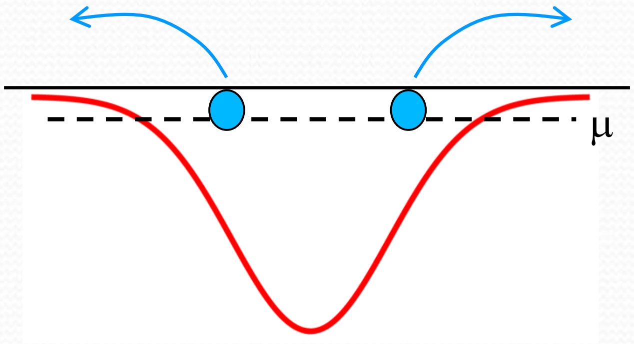
Optical Lattice



1064 nm

Compensated Lattice – How to get colder

Evaporative cooling in a trap:



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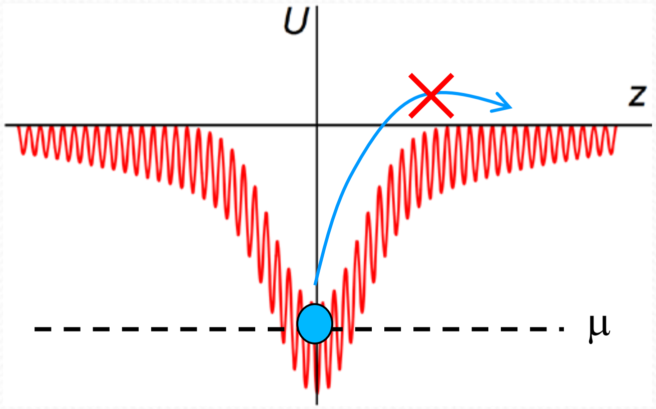
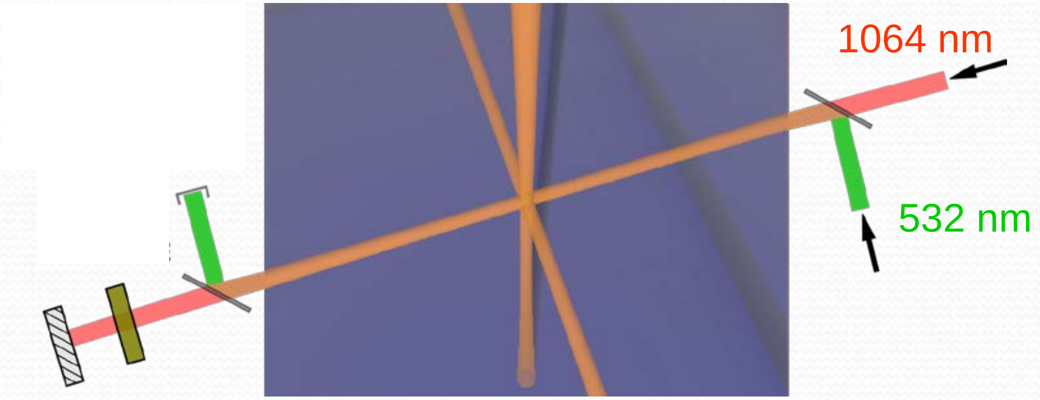
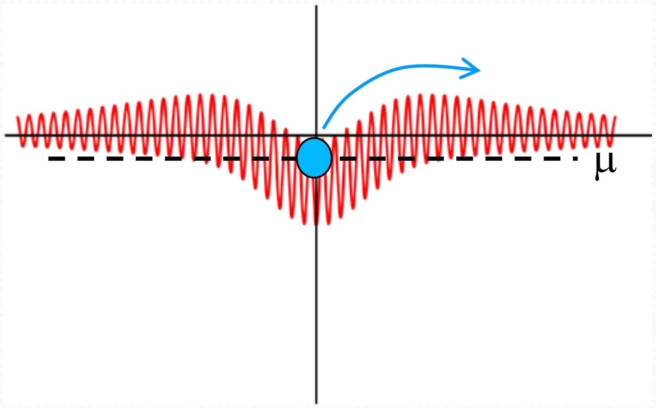


No cooling
(but there is heating)

Proposed solution: *compensated lattice*
with anti-confining green beams (not a lattice)



In a compensated lattice:



Three Functions of Compensated Lattice

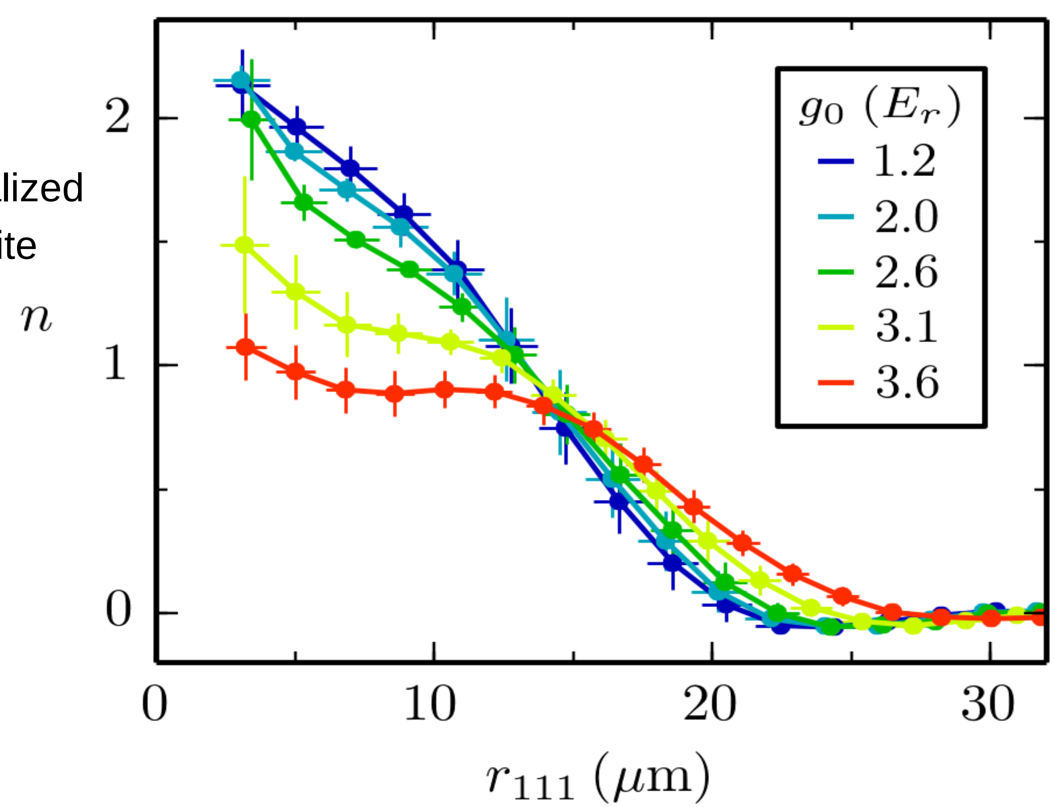
Mathy, Huse, Hulet, Phys. Rev. A **86**, 023606 (2012)

Compensation
1) density control knob
2) flatten band
3) provide cooling

3D densities from Abel transform

Central density plateaus as Mott core is formed

density normalized to 1 atom/site



V_L = 7 E_R

U/t = 15

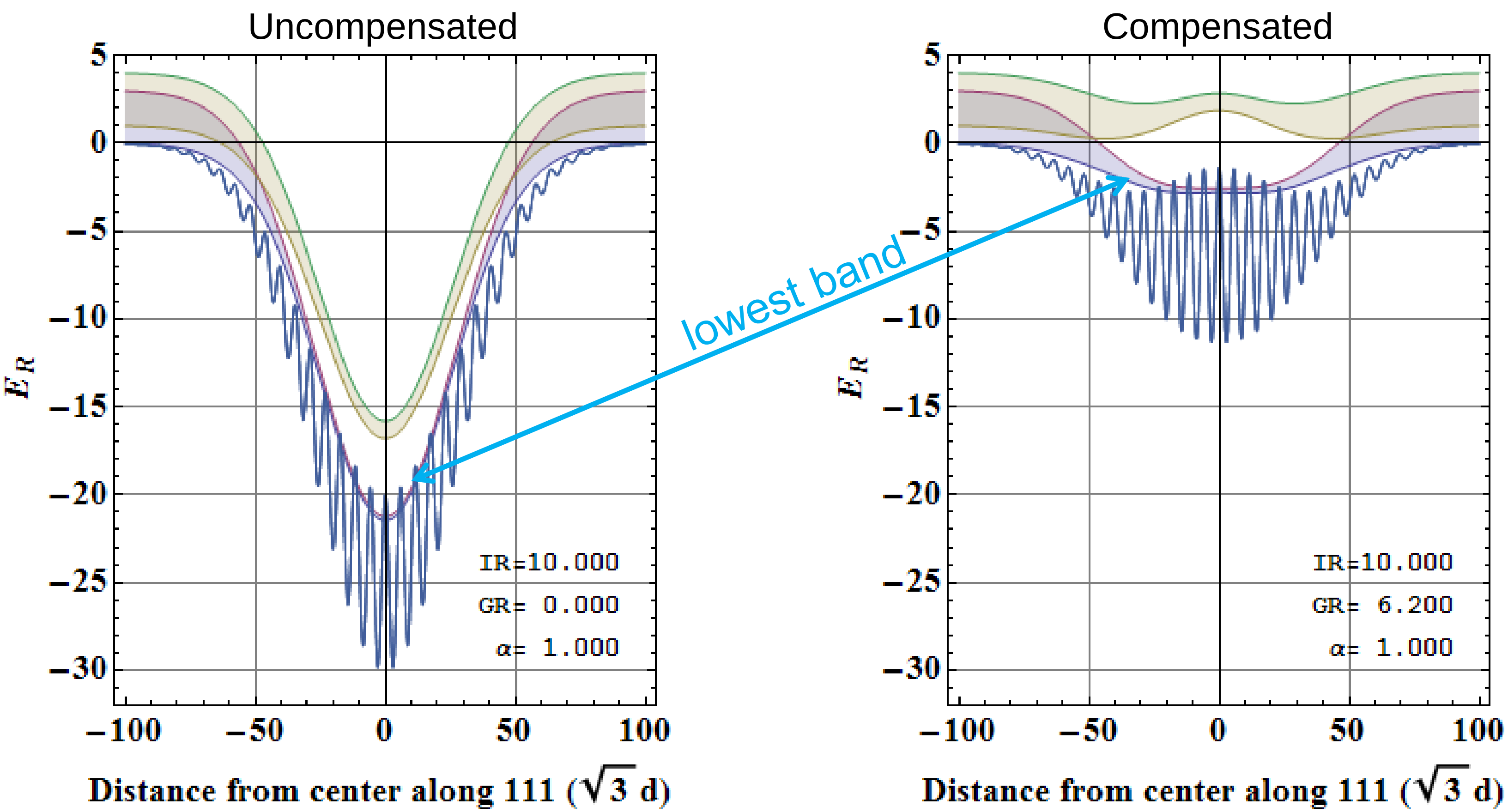
N = 1.8 × 10^5

Three Functions of Compensated Lattice

Mathy, Huse, Hulet, Phys. Rev. A **86**, 023606 (2012); also Ma *et al*, Phys. Rev. A **78**, 023605 (2008)

Compensation
- 1) density control knob
- 2) flatten band
- 3) provide cooling

Compensation beams have smaller waists than lattice beams in order to flatten potential

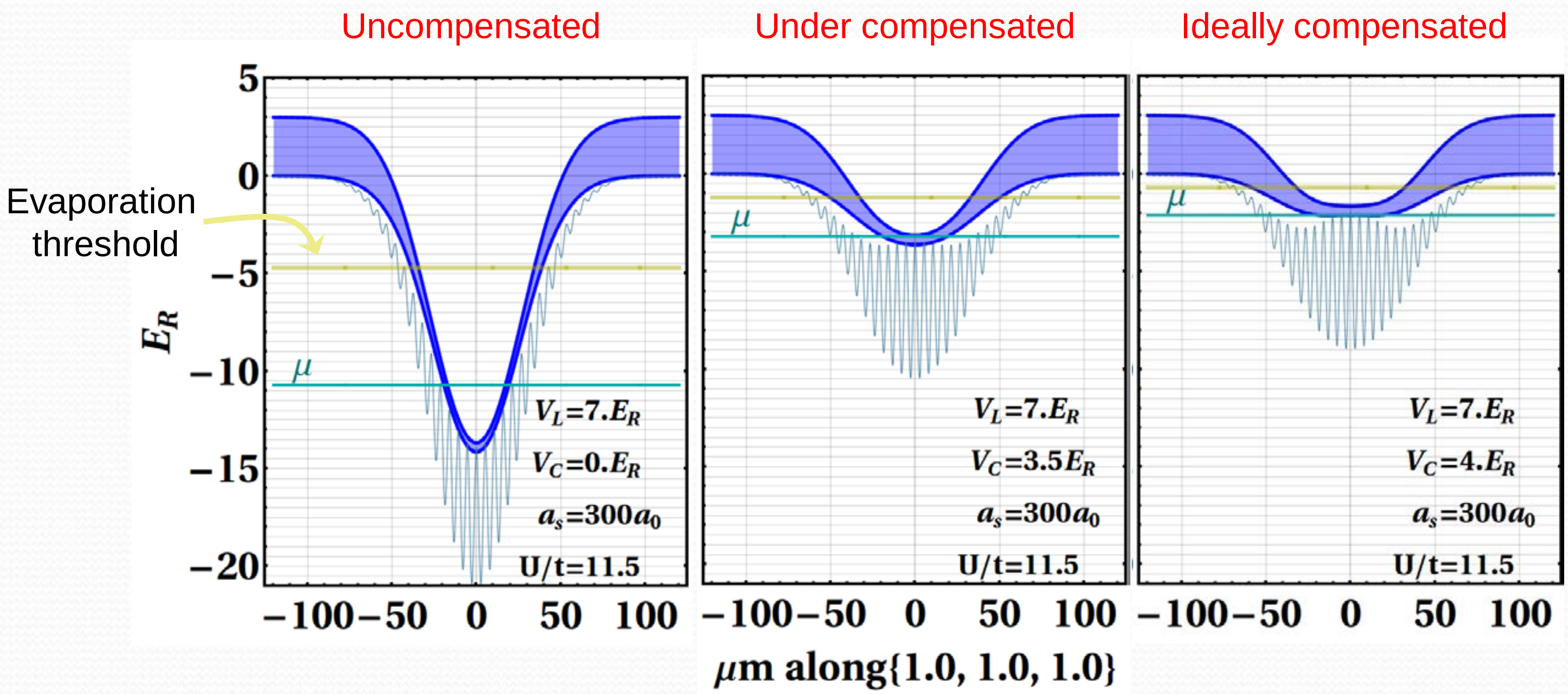


Evaporative Cooling in Compensated Lattice

Compensation

1) density control knob
2) flatten band
3) provide cooling

Compensation beams have smaller waists than lattice beams in order to flatten potential



Three Functions of Compensated Lattice

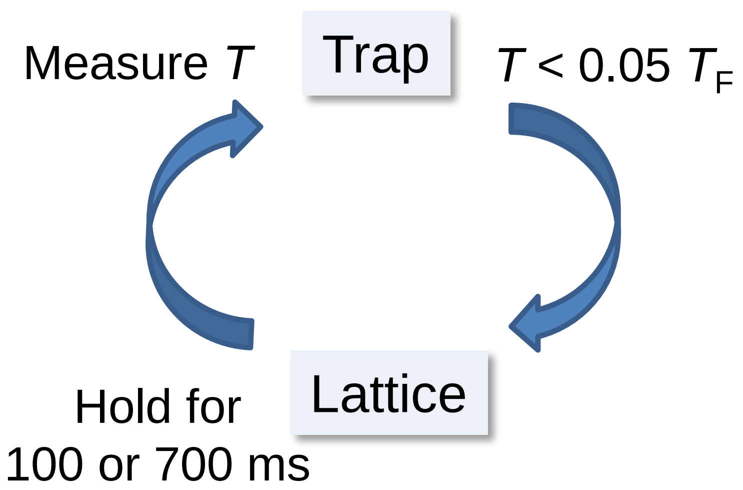
Mathy, Huse, Hulet, Phys. Rev. A **86**, 023606 (2012)

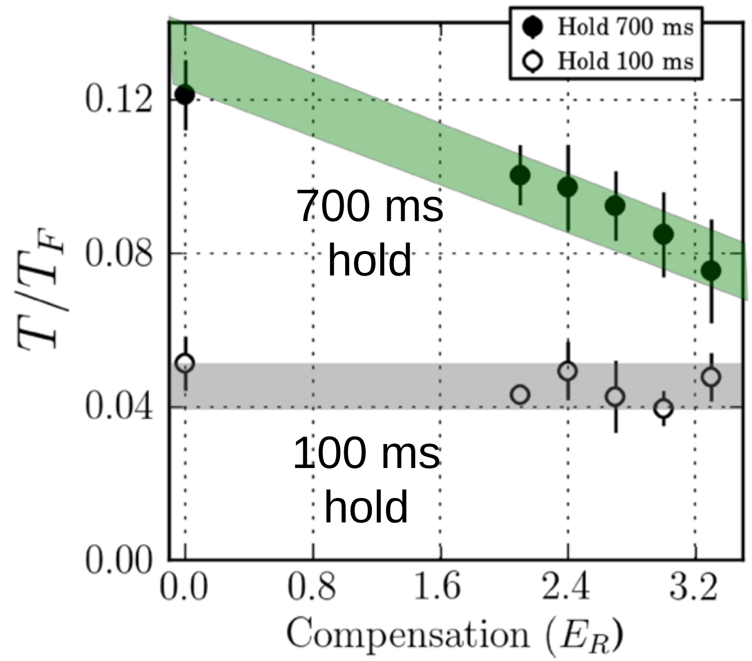
Compensation

1) density control knob
2) flatten band
3) provide cooling

Current setup is not optimized for evaporative cooling,

but we observe the suppression of heating:

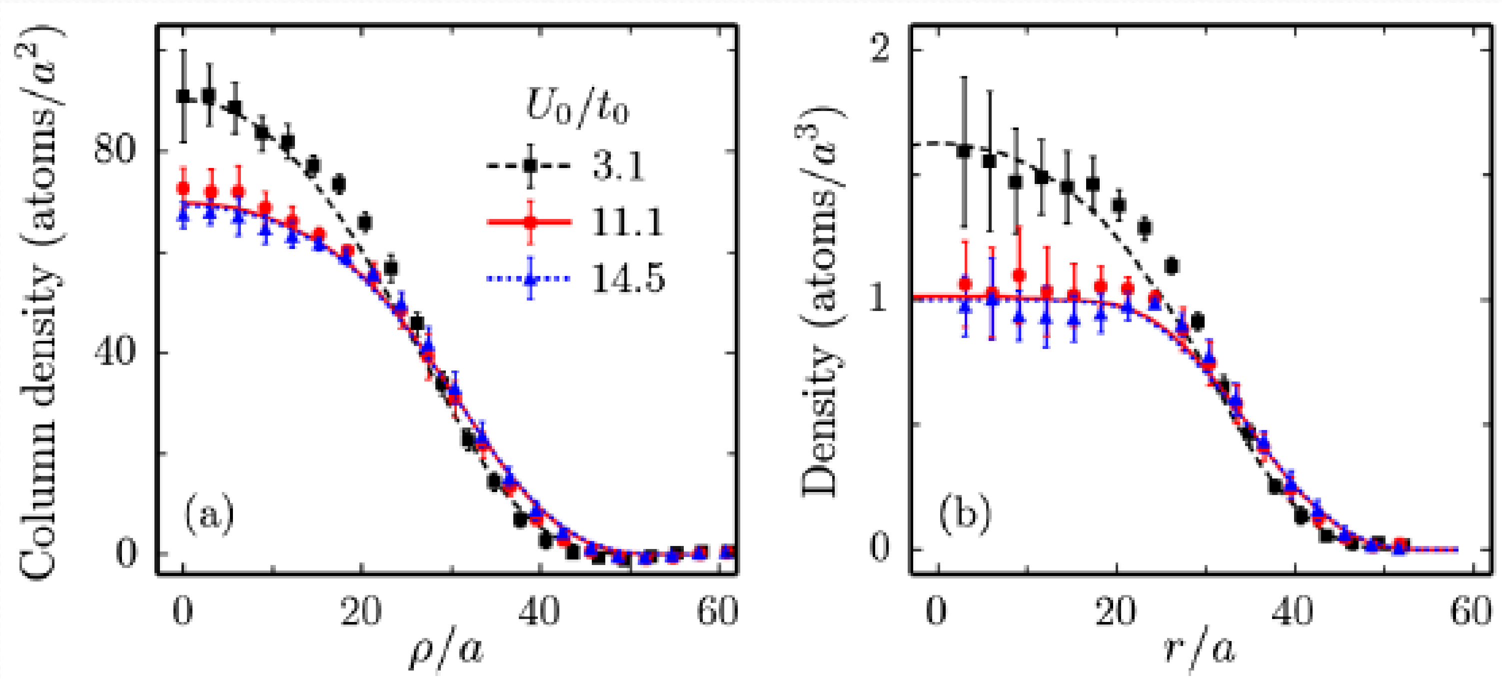




Mott Insulator Develops for Large *U/t*

Abel Transform

Column density images ⟷ 3D density distributions



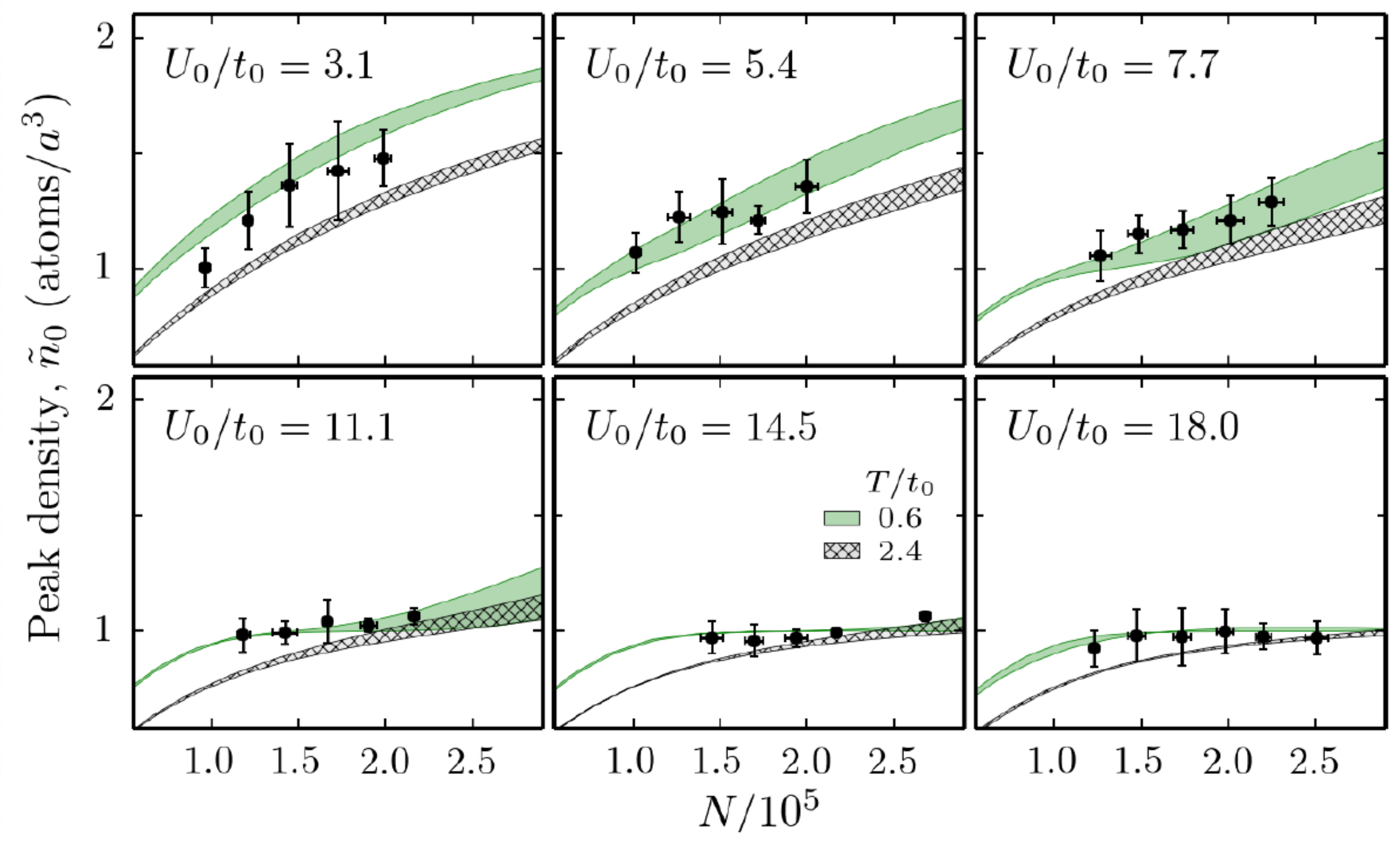
Band insulator

Mott insulator

P.M. Duarte *et al*, Phys Rev Lett (2015)

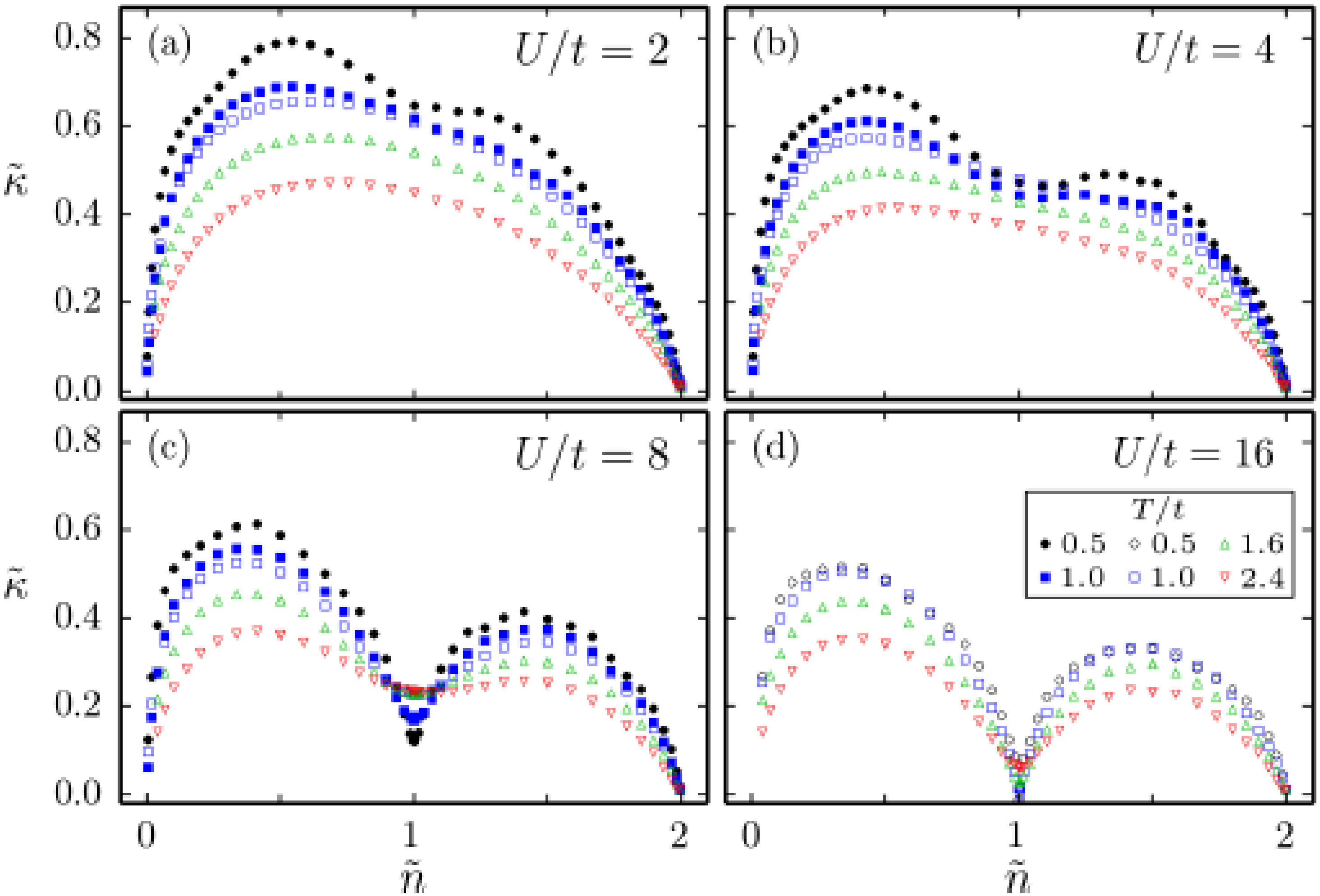
Solid lines are calculated using a numerical linked-cluster expansion

Incompressibility of Mott Phase



dn/dN is related to the compressibility: $\kappa = (1/n^2)\, dn/d\mu$

P. Duarte, Phys Rev Lett (2015)

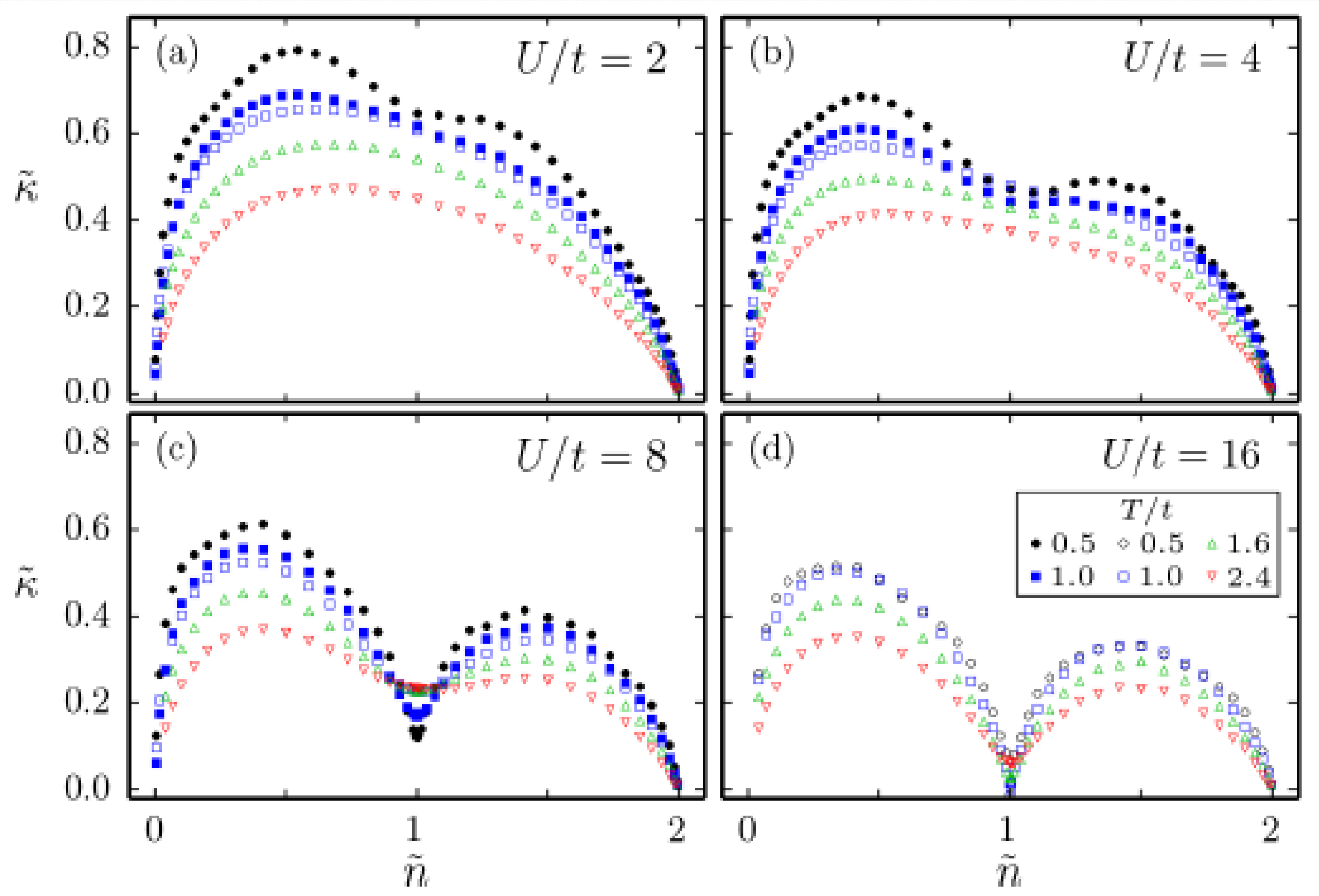


(a)
U/t = 2
(b)
U/t = 4
(c)
U/t = 8
(d)
U/t = 16
T/t
0.5
0.5
1.6
1.0
1.0
2.4
κ̃
κ̃
ñ
ñ
0.0
0.2
0.4
0.6
0.8
0
1
2

Local Compressibility

The compressibility vanishes in the Mott phase, due to the presence of a Mott gap:

$$\kappa = \frac{1}{n^2}\frac{\partial n}{\partial \mu}$$



P.M. Duarte *et al*,
Phys Rev Lett (2015)

Local Compressibility

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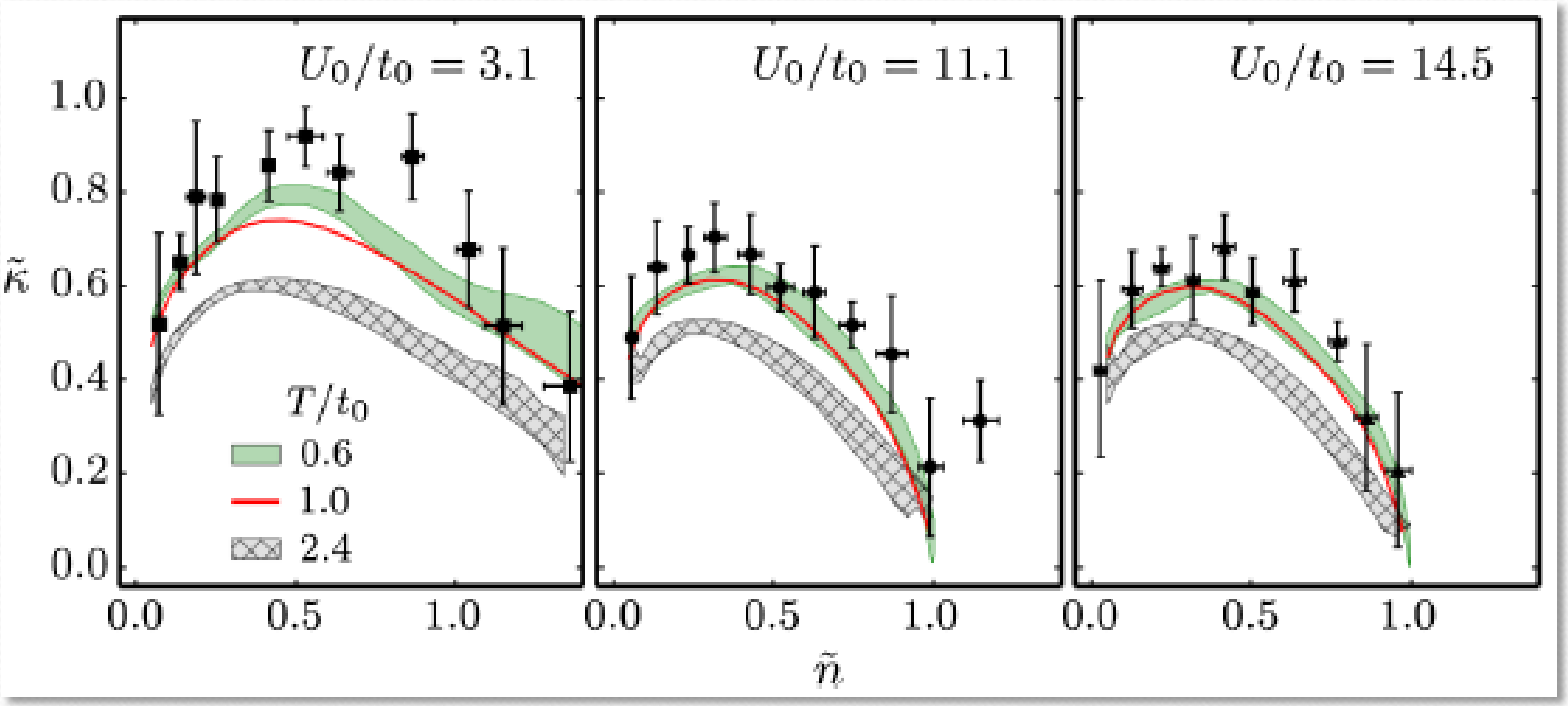
P.M. Duarte *et al*, Phys Rev Lett (2015)

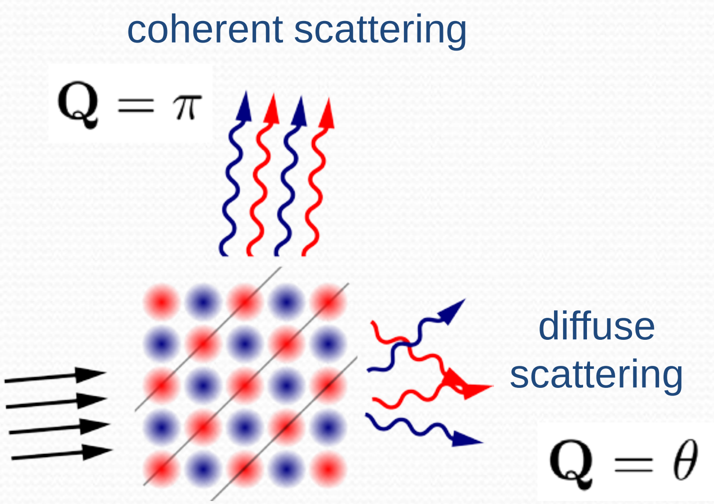


Normalized Density

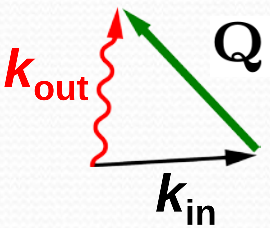
Lines and shaded regions: numerical calculations → $T/t \leq 1.0$

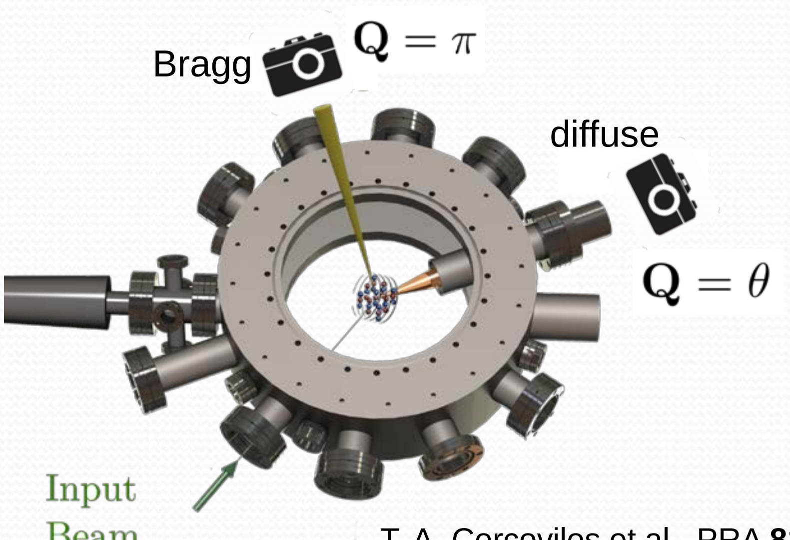
Detect Order by Bragg Scattering

Bragg scattering of near resonant light:



Bragg condition:





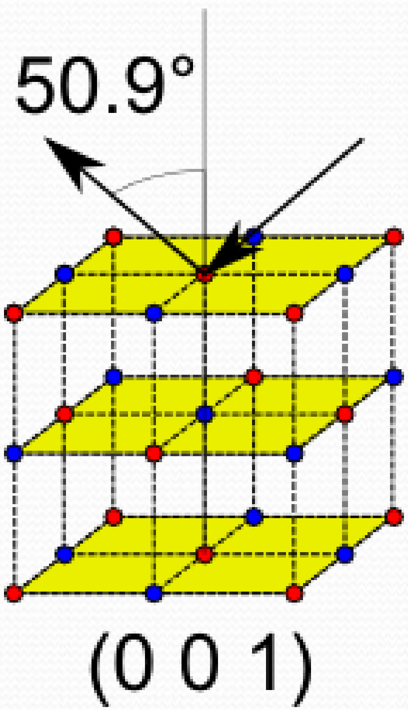
T. A. Corcovilos et al., PRA **81**, 013415 (2010)

Detect Order by Bragg Scattering

Bragg scattering of near resonant light:

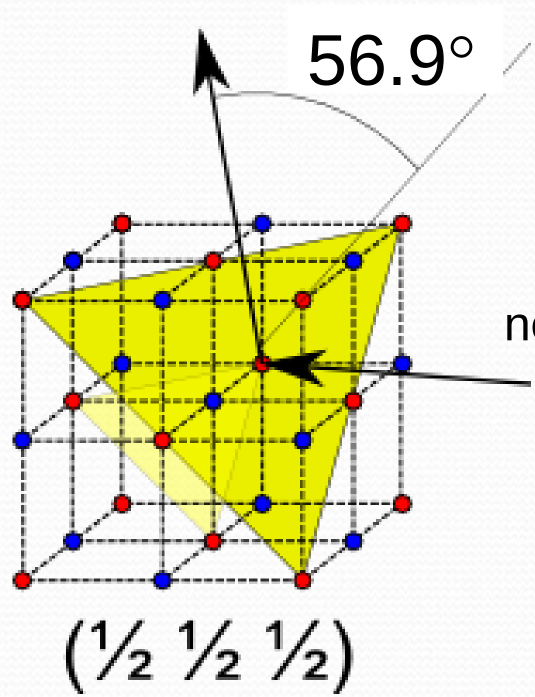
(0 0 1) peak indicates presence of cubic lattice structure

analogous to x-ray scattering

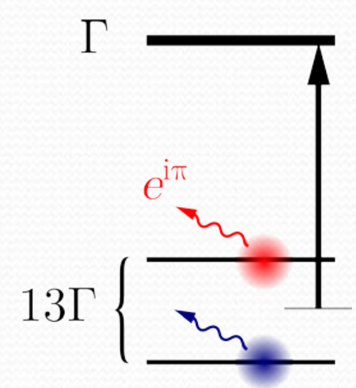


(½ ½ ½) peak unambiguously indicates presence of AFM order

analogous to neutron scattering



or $(\pi\ \pi\ \pi)$



T. A. Corcovilos et al., PRA **81**, 013415 (2010)

Bragg Scattering – Crystalline Order

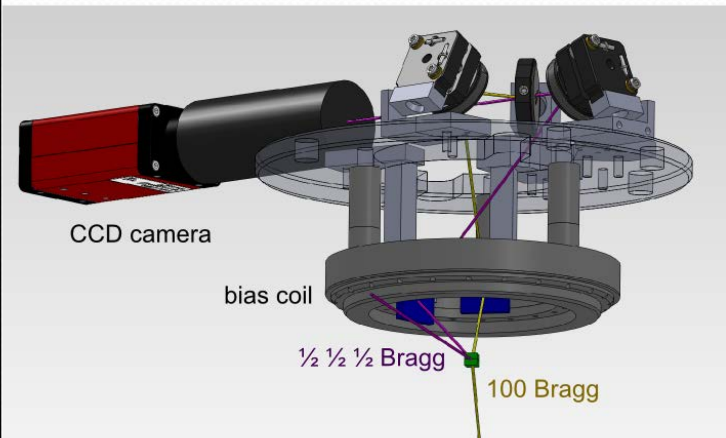
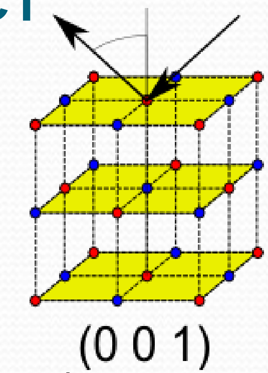


Image the scattered light onto a single pixel



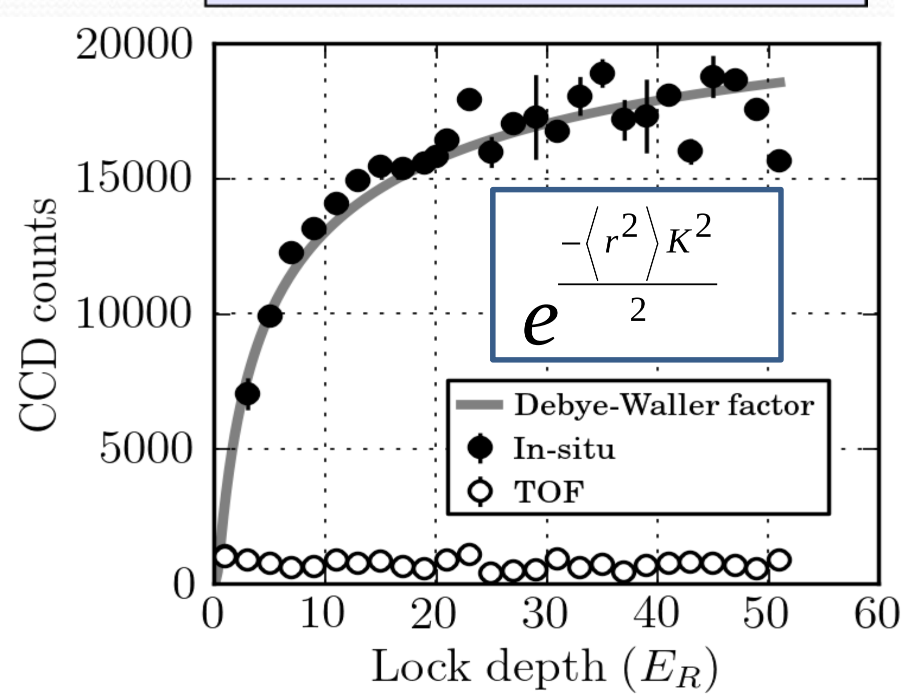
Also:

Birkl *et al* (NIST) PRL (1995)

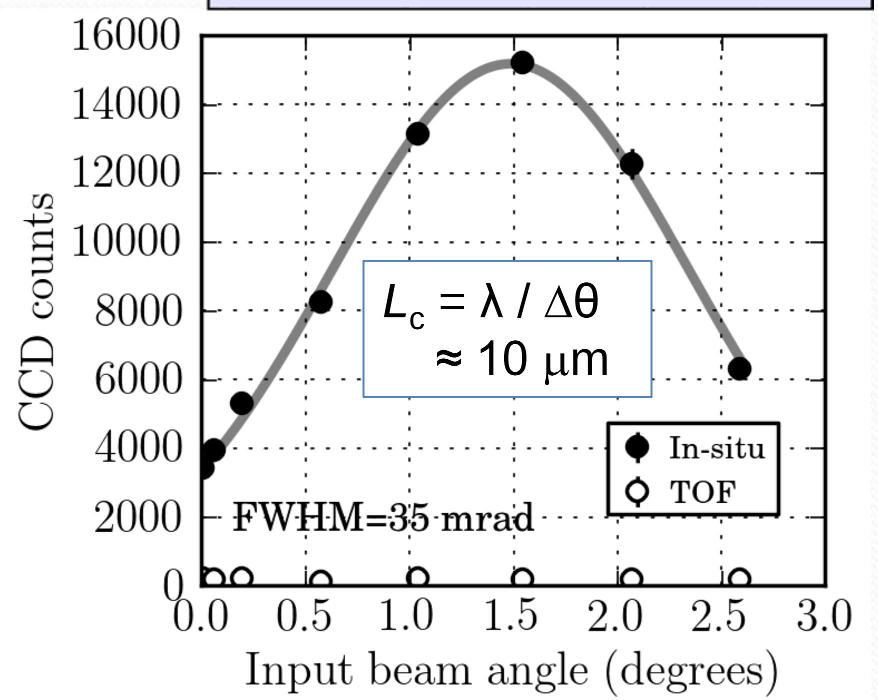
Weidemuller *et al* (MPQ), PRL (1995)

Miyake *et al* (MIT), PRL (2011)

Bragg signal vs lattice depth:



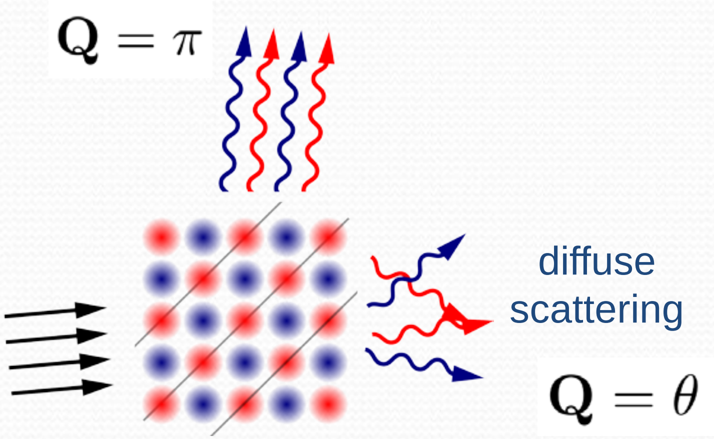
Bragg signal vs input angle:



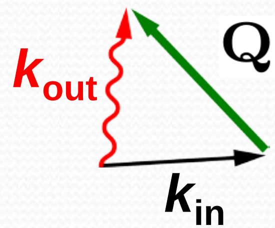
Detect AFM Order by Bragg Scattering

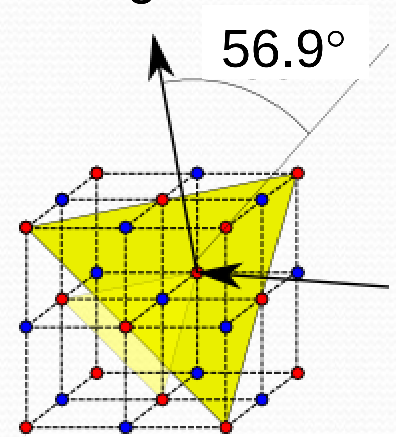
Spin-sensitive Bragg scattering of near resonant light:

coherent scattering



Bragg condition:

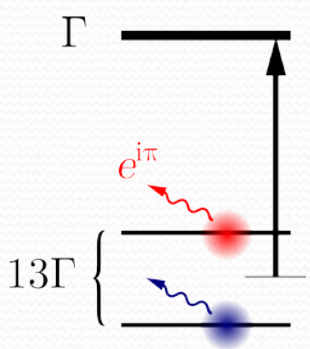




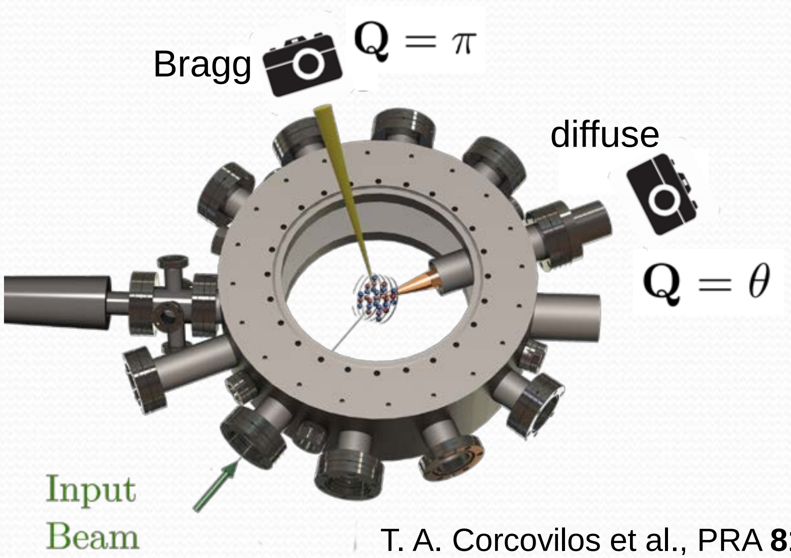
$\mathbf{Q} = (\pi\ \pi\ \pi)/a$ = "π"

(π π π) peak unambiguously indicates presence of AFM order

Spin-sensitive:



analogous to neutron scattering



T. A. Corcovilos et al., PRA **81**, 013415 (2010)

Bragg Signal / Spin-Structure Factor

$$S_{\boldsymbol{Q}} = \frac{4}{N}\sum_{mn} e^{i\boldsymbol{Q}(\boldsymbol{R}_m - \boldsymbol{R}_n)} S_{zm} S_{zn}$$ = spin structure factor = 1 to *N*

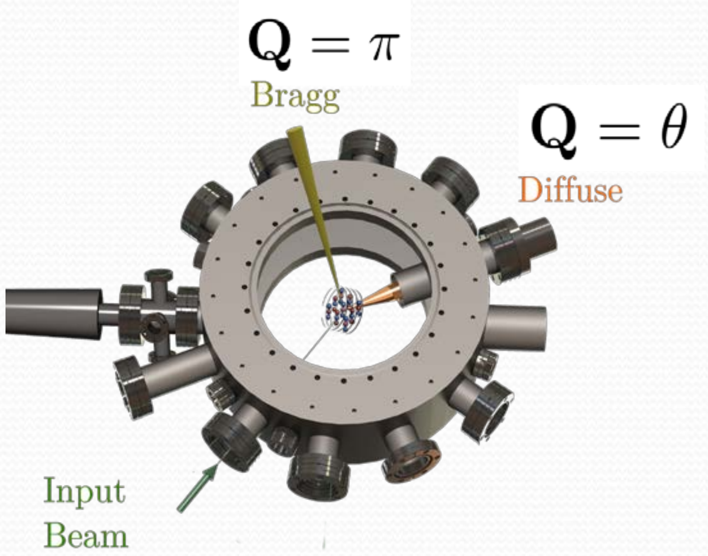
Bragg signal is proportional to S_Q:

$$I_Q \propto S_Q$$

Normalization:

Bragg signal is normalized by the signal after long TOF τ:

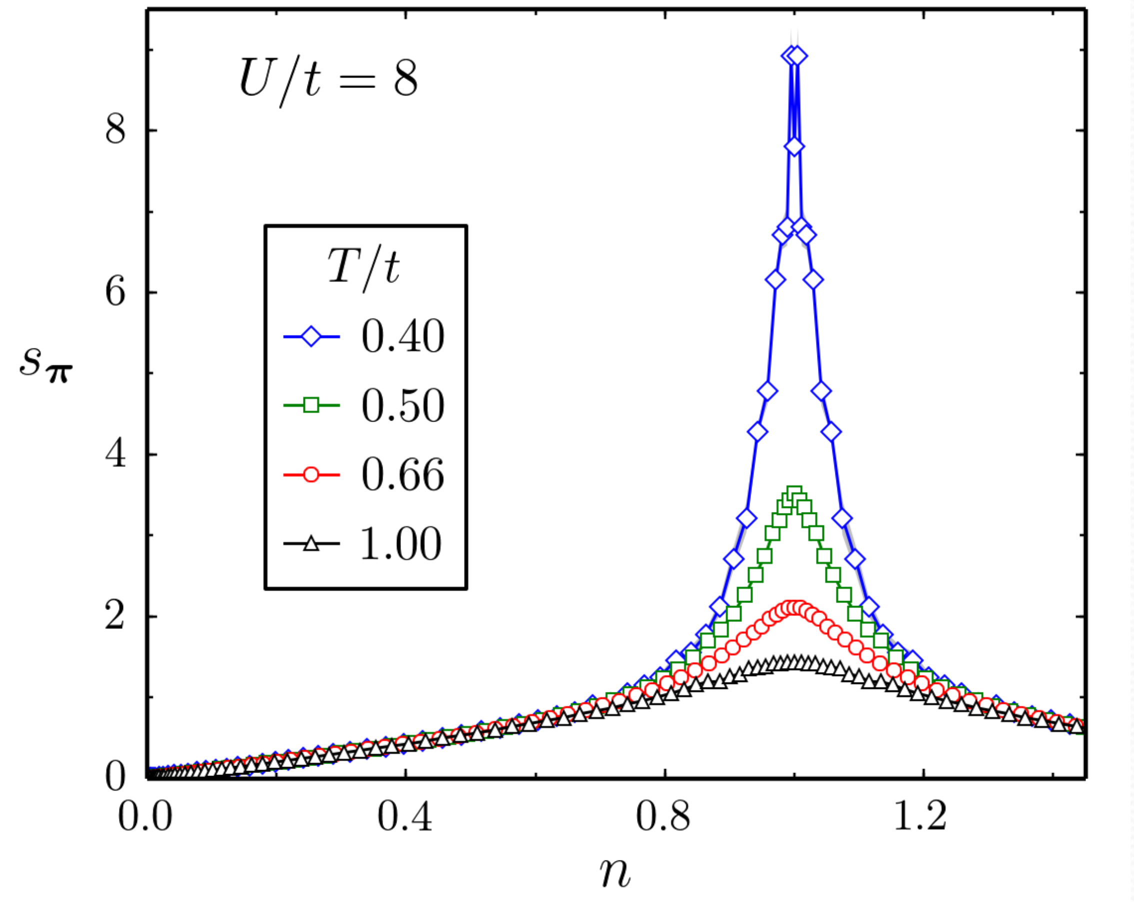
$$S_Q = I_Q\,(\tau=0)\;/\;I_Q\,(\tau=\infty)$$



Density Dependence - QMC

Bragg signal comes mainly from an $n = 1$ shell

QMC: $S(\pi)$ vs. n



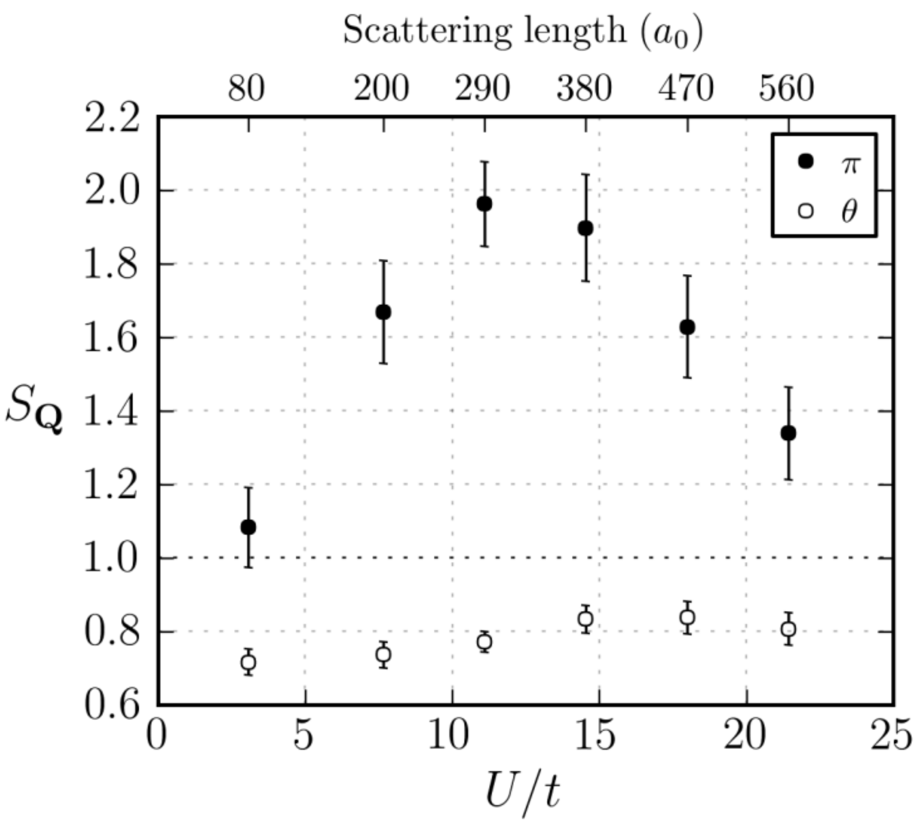
In the experiment, we vary N to maximize S_{π}

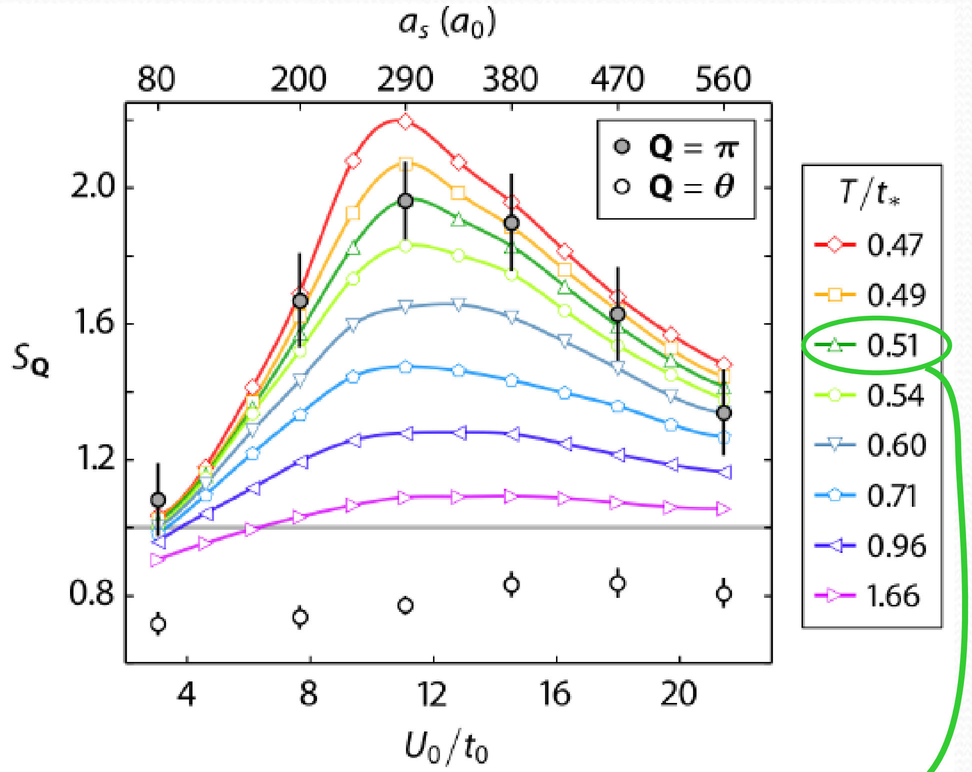
Interaction Dependence

Comparison with theory provides sensitive thermometry

Theory: Numerical Linked-Cluster Expansion and Quantum Monte Carlo

Theoretical S_Q is a trap average





Temperature fit: T/t = 0.50 (0.04) → T/T_N = 1.4 (0.1)

R. Hart, P.M. Duarte *et al*, Nature 2015

Detection of Magnetic Order

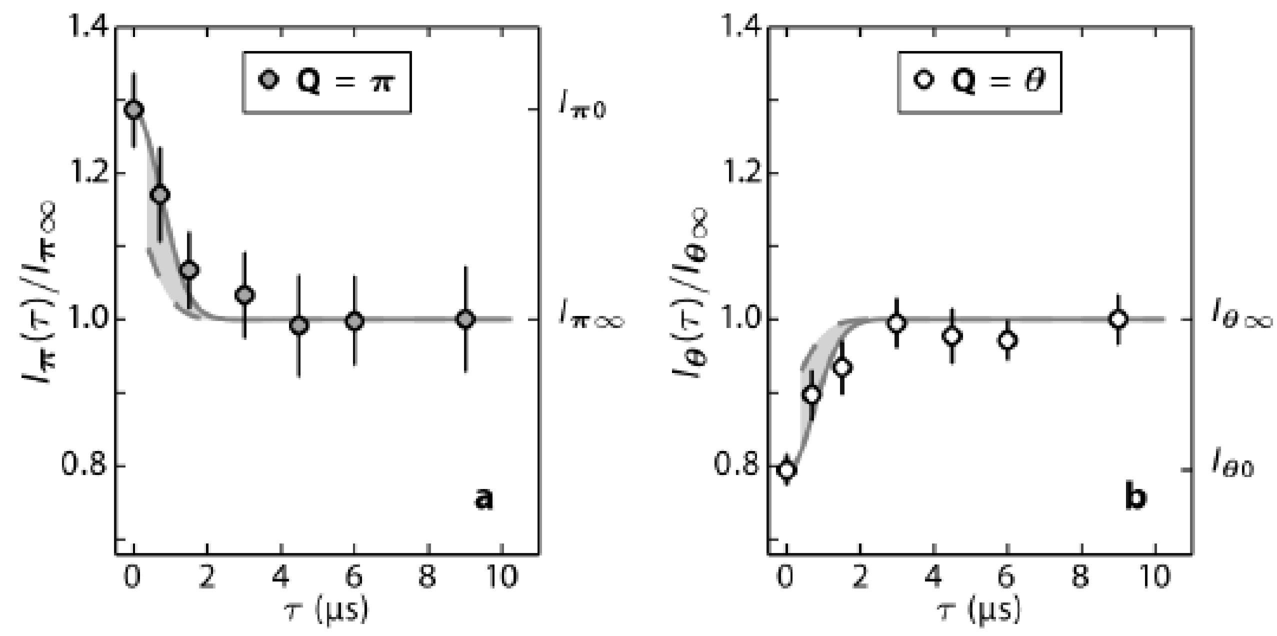
If the atoms are released from the lattice the Bragg signal decays due to loss of coherence:

Debye-Waller factor: $e^{\frac{-\langle r^2 \rangle K^2}{2}}$, where $\langle r^2 \rangle_t = \langle r^2 \rangle_0 + \frac{t^2}{m} \langle p^2 \rangle_0$

$S_Q = I_{Qo} / I_{Q\infty}$

7 *Er*, *U*/*t* = 13.4
a = 350 a_o

Shading indicates broadening by probe exposure time (1.7μs)

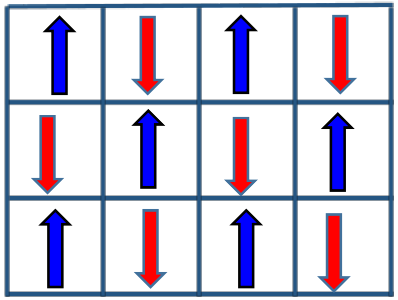


R. Hart, P.M. Duarte *et al*, Nature (2015)

Charge-Density Order for $U < 0$

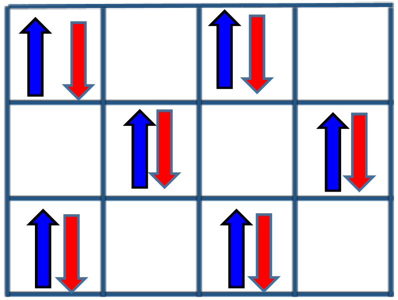
For $T < t^2/|U|$, the system will order according to the sign of U:

$U > 0$: magnetic order



or

$U < 0$: charge order



- Both types of order have symmetry planes in the π, π, π direction
  → detect by Bragg scattering

- Determine dynamical response of system to sudden change in U

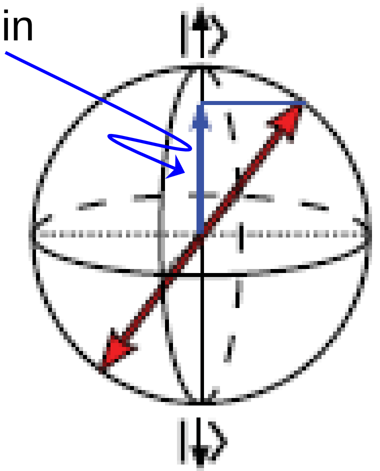
Canted Antiferromagnetism

Bragg signal only sensitive to magnetism along *z*

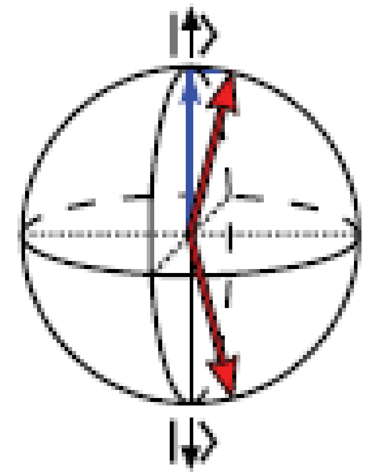
But small population imbalances favor AFM in the x-y plane:

Gottwald and van Dongen, PRA (2009) and E. Demler *et al*., PRA (2010)

z-component of staggered spin



Isotropic AFM

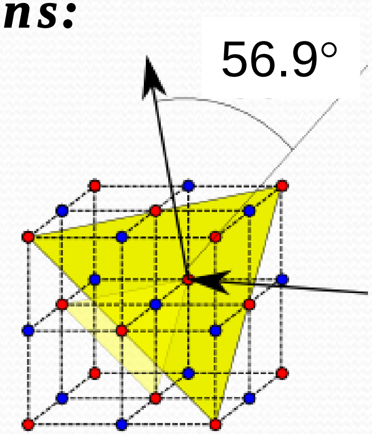


Canted AFM after $\pi/2$ pulse

Summary

- ***Detected short-range antiferromagnetic correlations:***
  - *Spin-dependent Bragg scattering*
  - *Thermometry by comparison with QMC*
  - *Temperature: $T = 1.4\ T_N$*

Limit of QMC!
(away from $n = 1$)



(½ ½ ½)

- ***Enabled by compensated lattice***
  - *Density control*
  - *Flatten band*
  - *Mitigation of heating by evaporation*
  - *Optimized compensation could lead to even lower T*

Opens new avenues for exploring other novels states of matter such as non-Fermi liquids


David Huse
Nandini Trivedi
Richard Scalettar
Thereza Paiva
Ehsan Khatami
COASTAL
REVOLUTION
Xinxing Liu
Russ Hart
Ernie Yang
Pedro Duarte