Quantum Simulation using Optical Lattices

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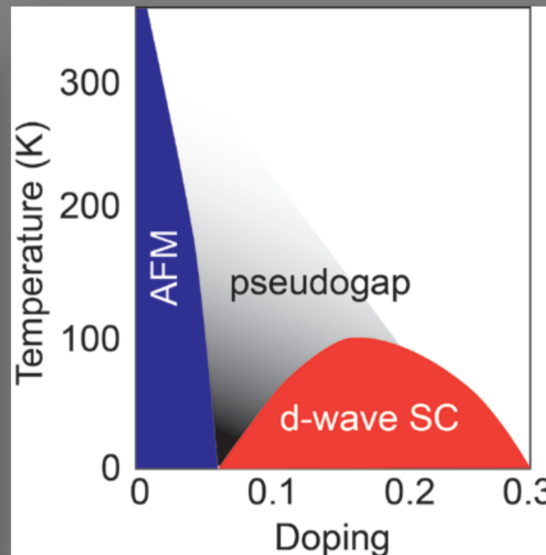
- **Hubbard model loose ends**
- **Thermometry and Cooling**

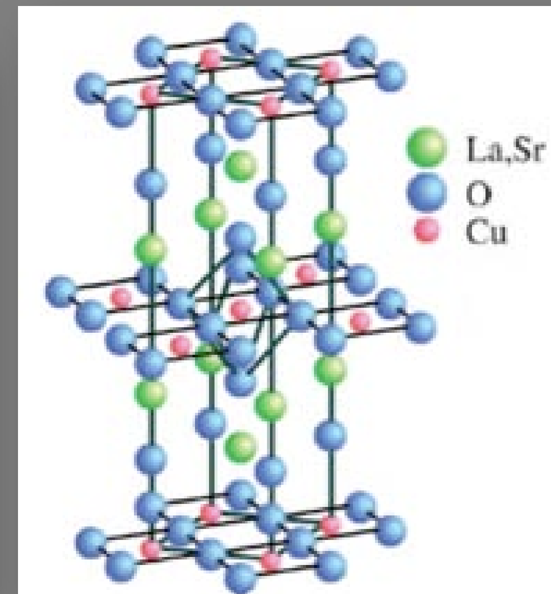
Agenda:

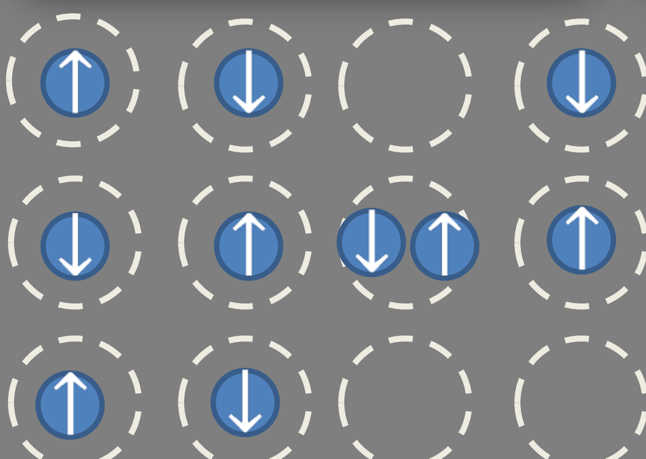
- Characteristic density; universal phase diagrams
- Challenges in cooling (and thermometry)
- Spin-dependent lattices: something we are doing about it (that won't work)

The Premise: an example

High temperature superconductivity / Hubbard model







$$H = -t \sum_{\langle ij \rangle, \sigma} c_{i,\sigma}^{\dagger} c_{j,\sigma} + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

tunneling interactions

- Can Hubbard model produce d-wave SC?
- Nature of pseudo-gap phase?

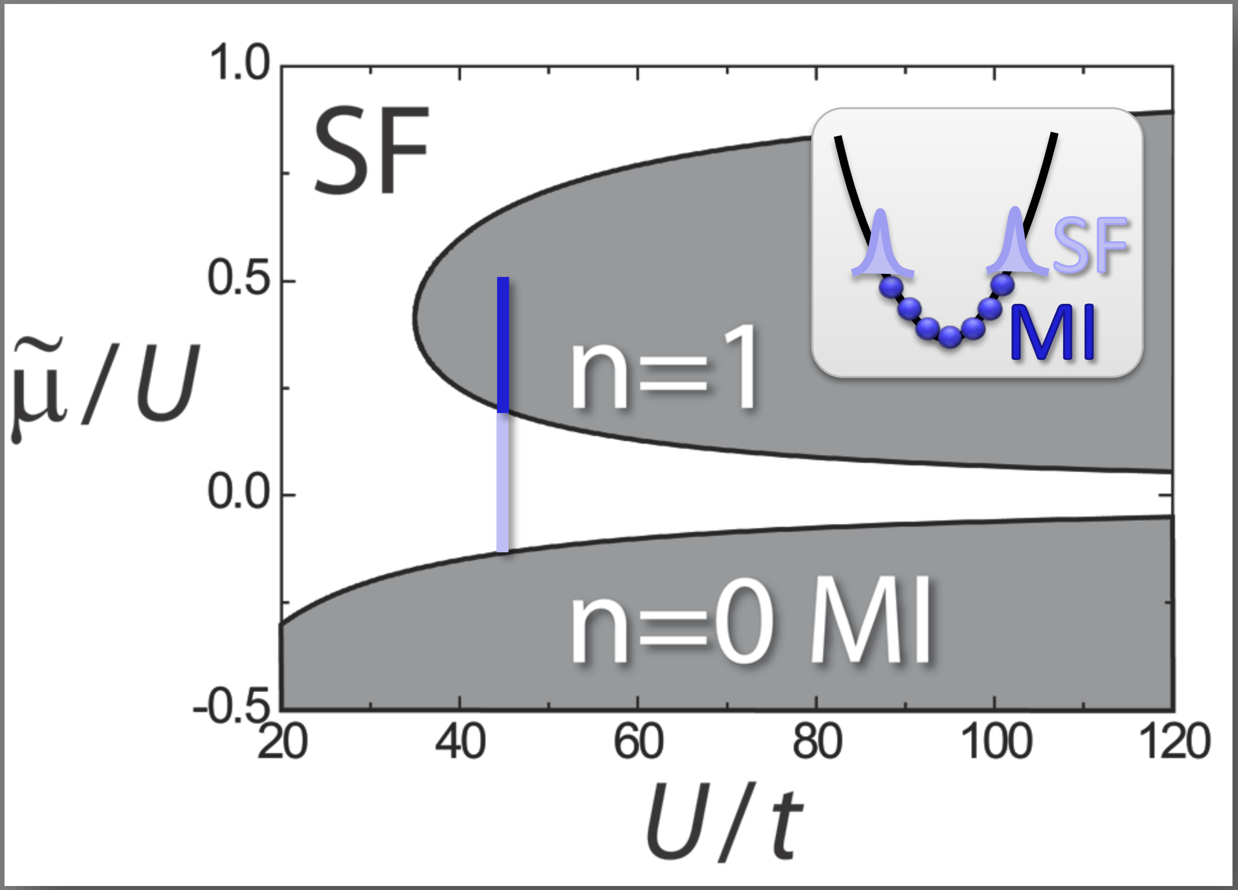
BH Phase Diagram

$$H = -t\sum_{\langle ij\rangle} b_i^\dagger b_j + \frac{U}{2}\sum_i n_i\left(n_i - 1\right) + \sum_i n_i \varepsilon_i$$

$$\epsilon_i = m\omega^2 r_i^2/2$$

Effective chemical potential:

$$\tilde{\mu} = \mu - m\omega^2 r_i^2/2$$

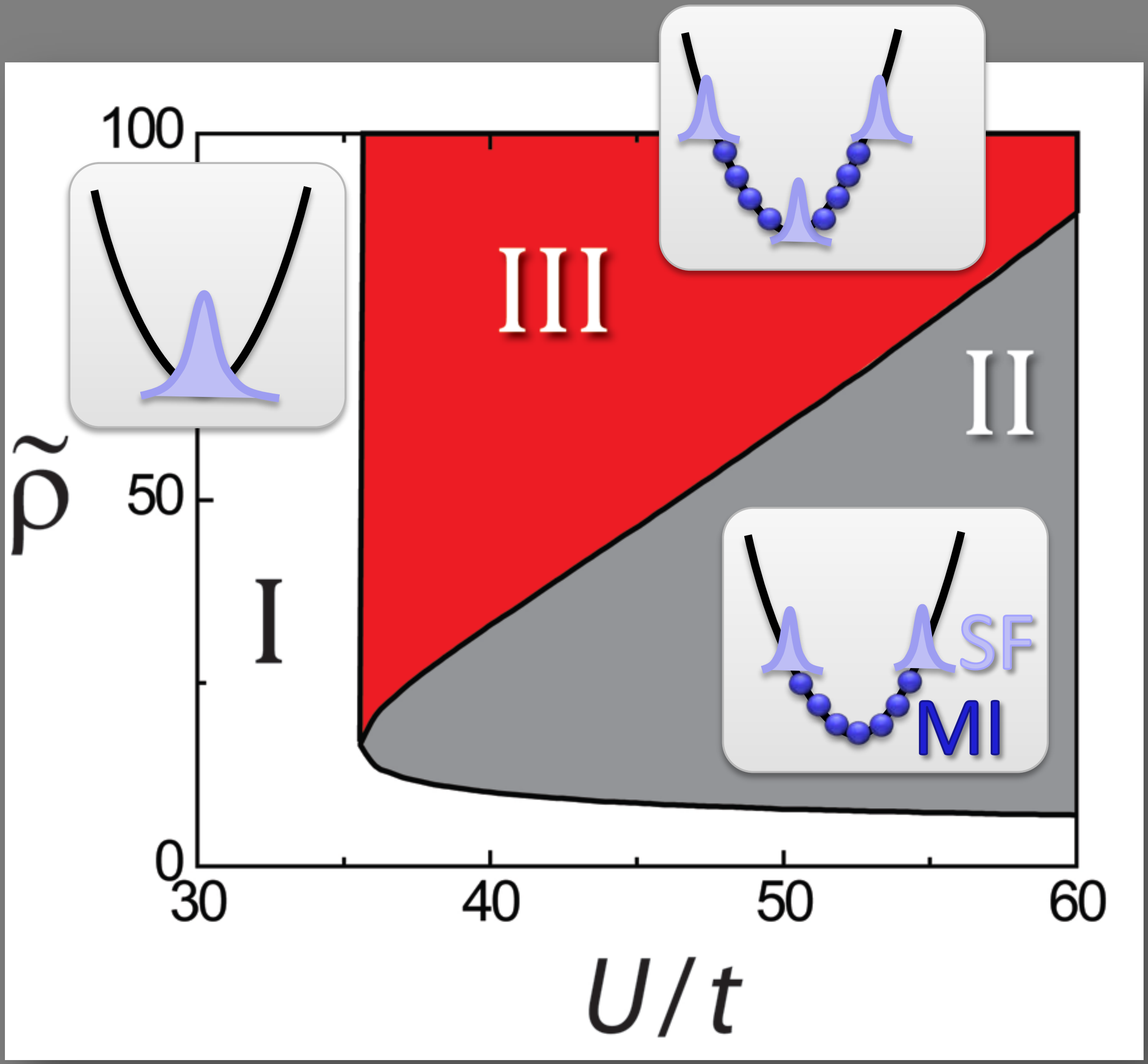


Universal phase diagram: bosons

Characteristic density

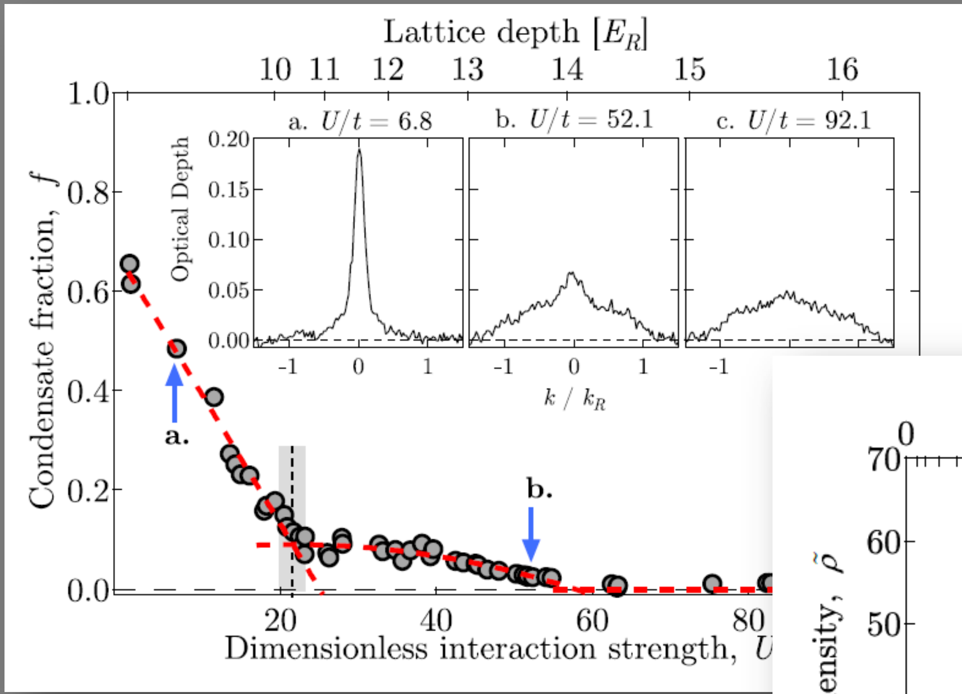
$$\tilde{\rho} = N\left(\frac{m\omega^2 d^2}{2jt}\right)^{j/2}$$

j: dimensionality

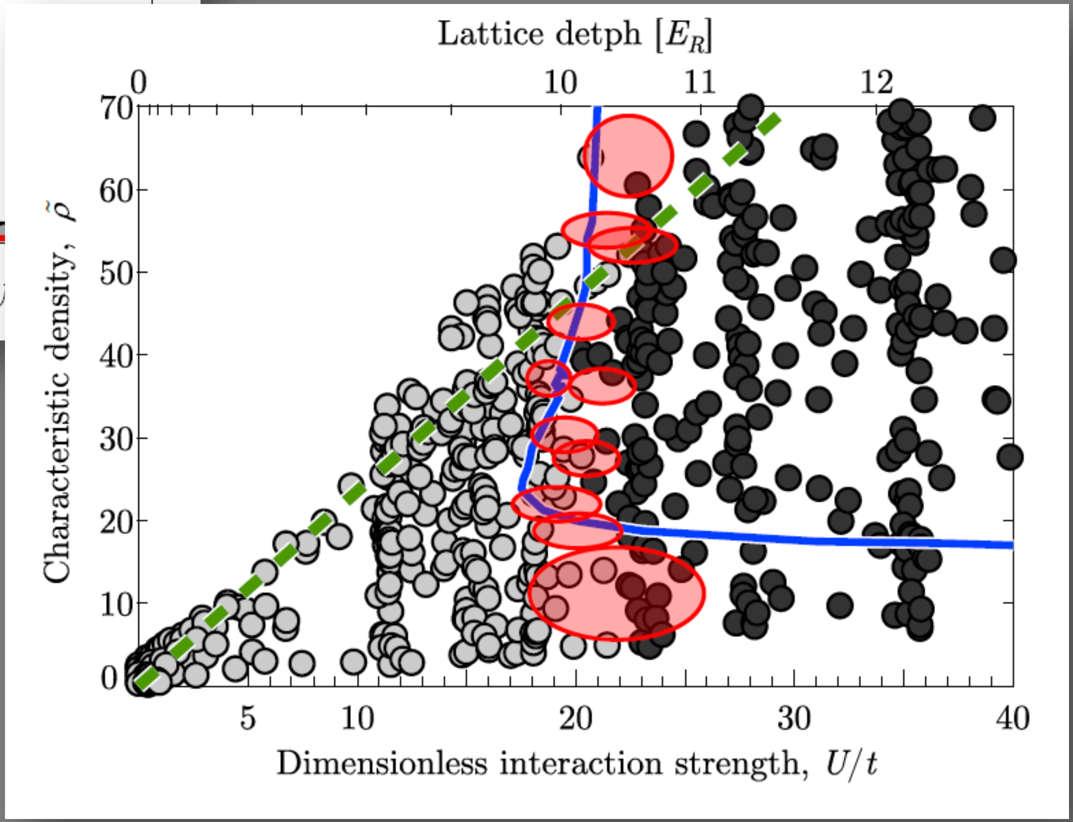


Rigol

Deviation from LDA



Spielman (JQI/NIST)
arXiv:1003.1541



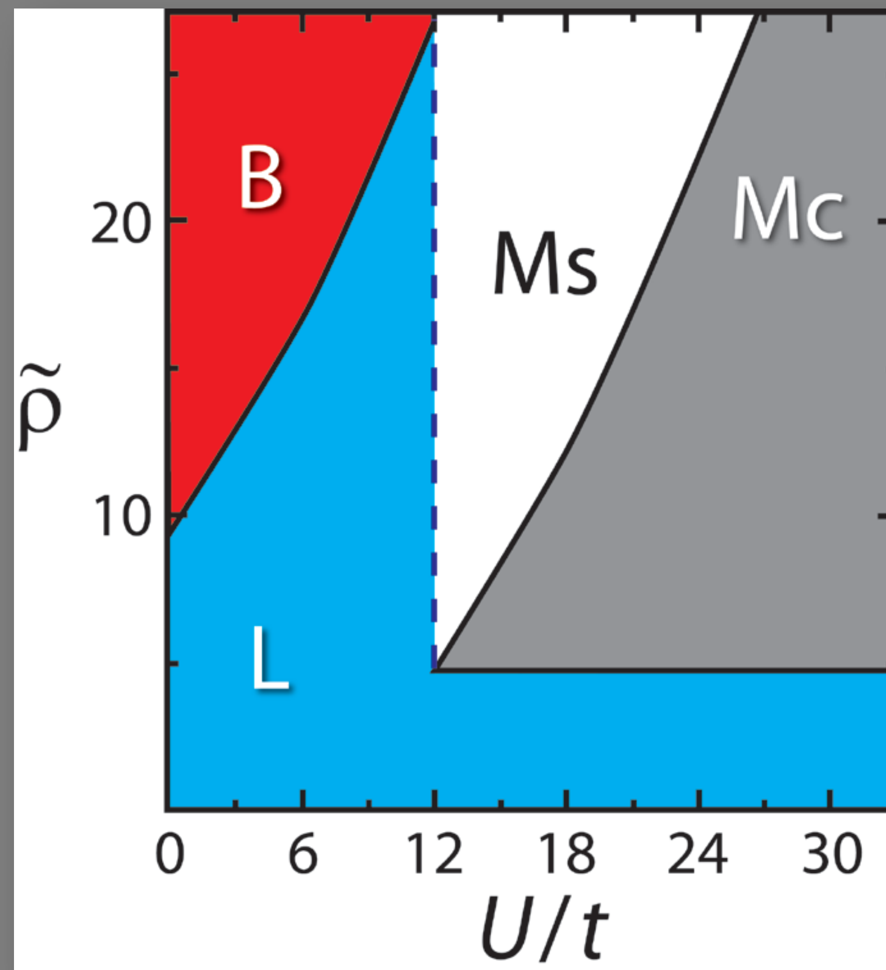
Universal phase diagram: fermions

De Leo, Kollath, Georges, Ferrero, and Olivier Parcollet

$$H = -t\sum_{\langle ij\rangle,\sigma} c^{\dagger}_{i,\sigma}c_{j,\sigma} + U\sum_{i} n_{i,\uparrow}n_{i,\downarrow} + \sum_{i,\sigma} n_{i,\sigma}\varepsilon_i$$

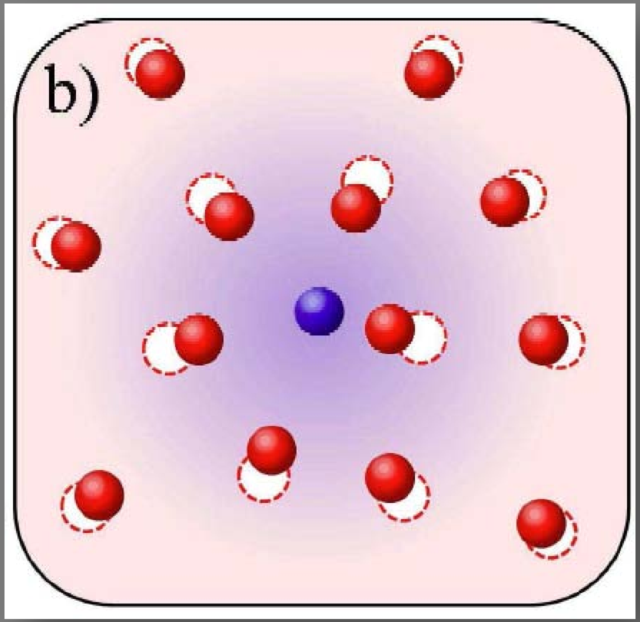
L: 

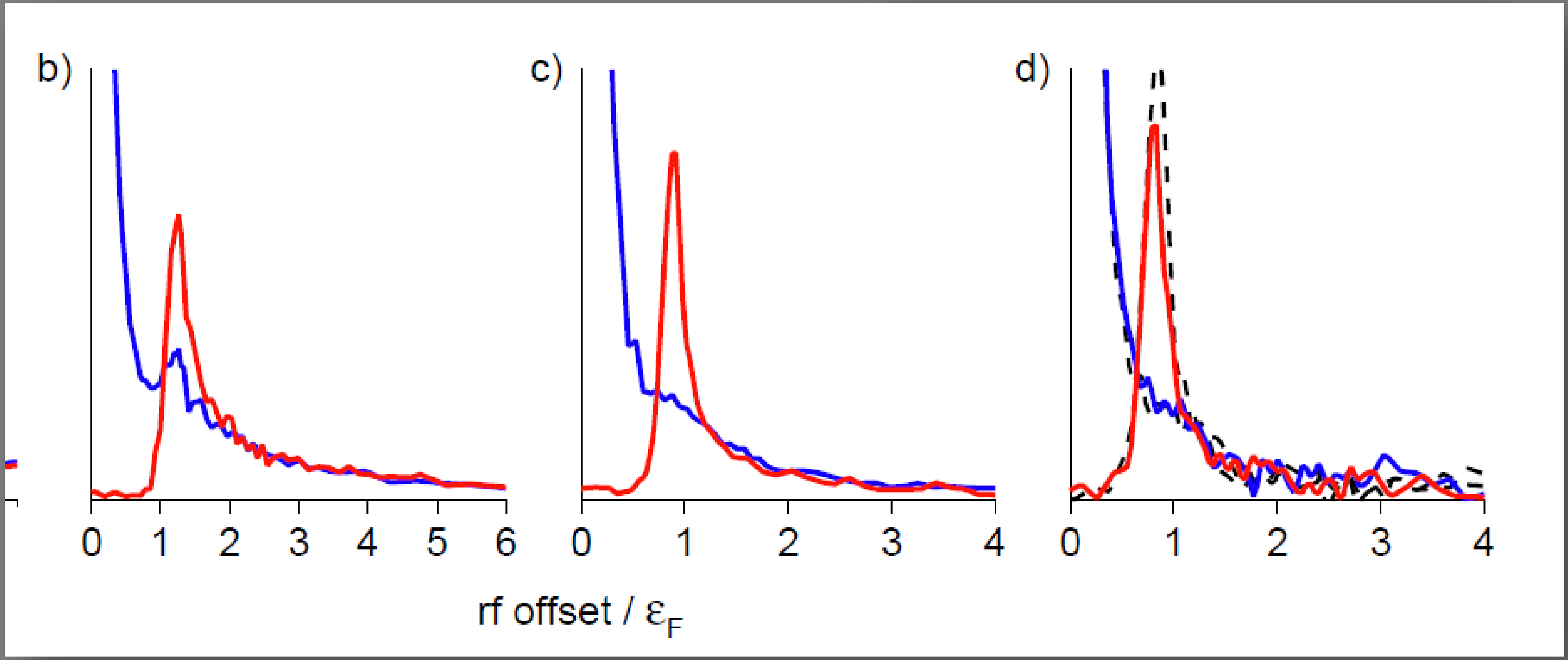
Fermi
Liquid



Fermi Liquid

(Zweirlein)





Universal phase diagram: fermions

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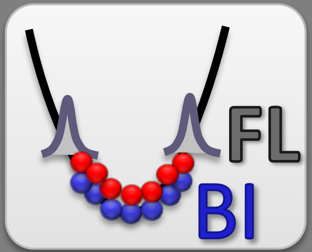
L:

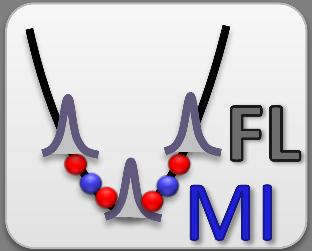
Fermi Liquid

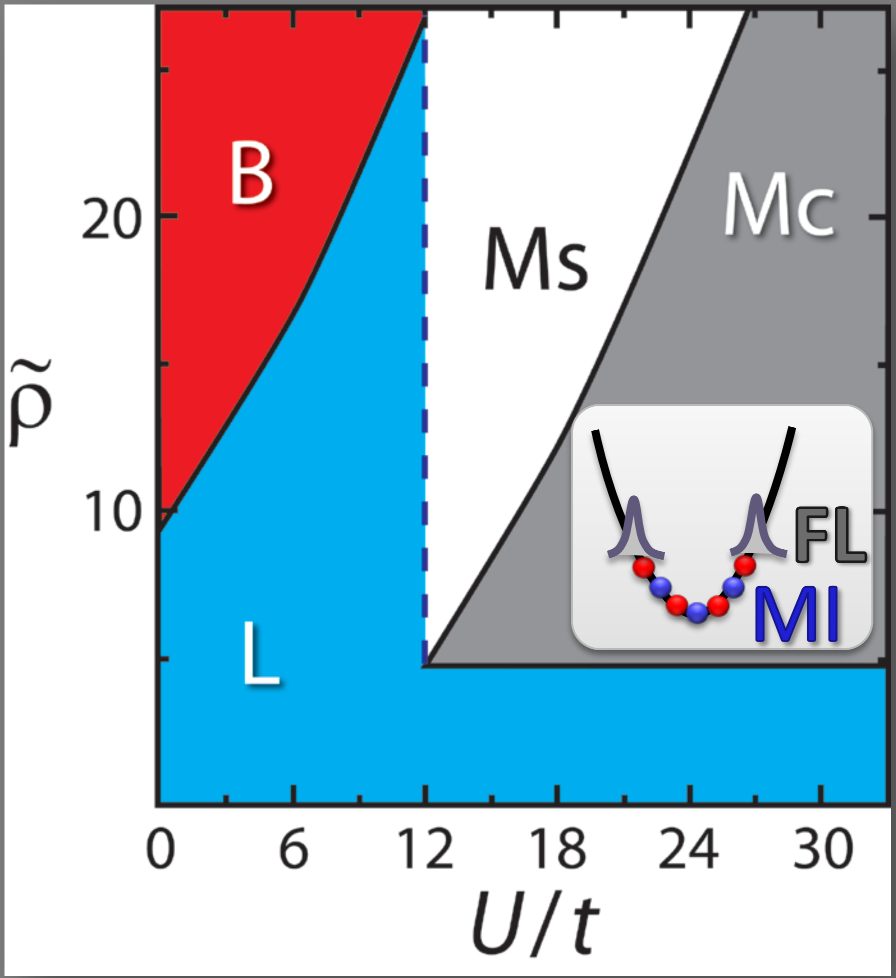
B:



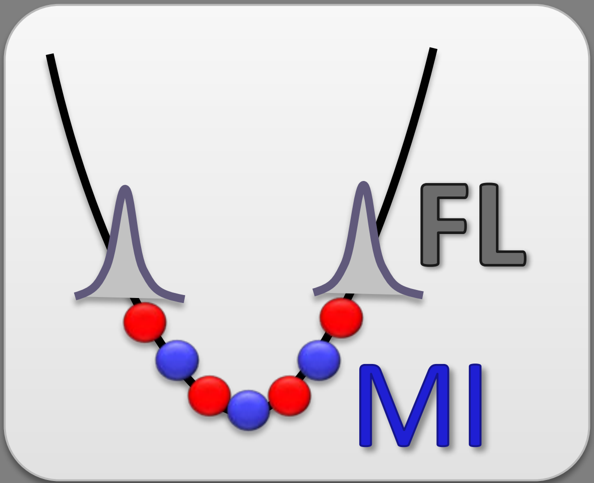
Band Insulator

Ms:





Anti-ferromagnetic (AFM) order



Effective $t/U \ll 1$ Hamiltonian:

$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j \qquad J = 4t^2/U$$

AFM achieved for $S/N = \frac{1}{2} k_B ln2 \approx 0.4\ k_B$

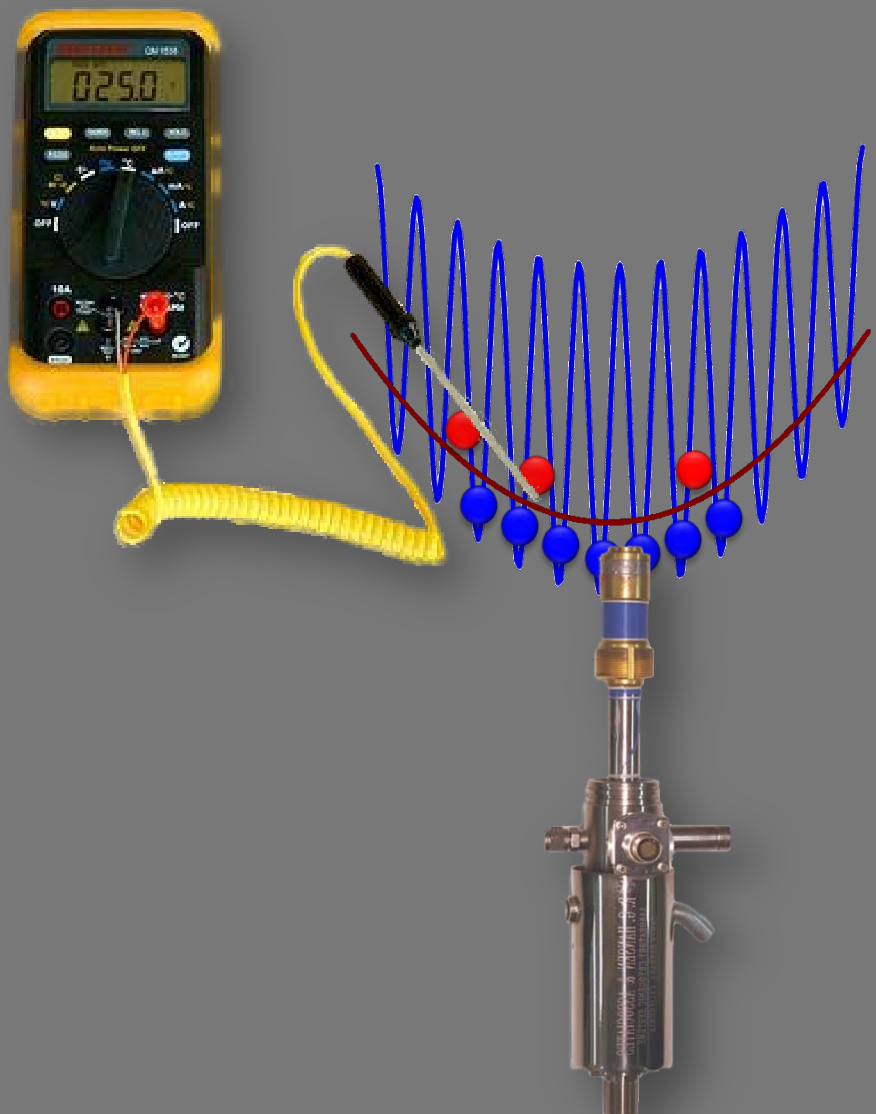
So far out of reach!

Requires $T/T_F = 0.03$ (ideal gas)...
...state-of-the-art in lattice: $T/T_F = 0.1$ (?)

A solution?

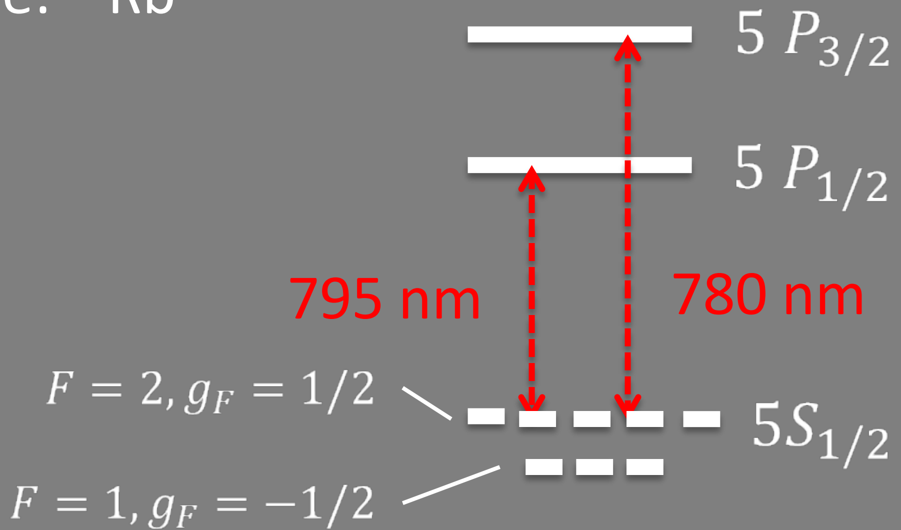
Species / spin-dependent lattice

- Two spin states
- Two atomic species ($^{40}K/^{87}Rb$, $^{133}Cs/^{40}K$)



Real Atoms

Example: ^{87}Rb



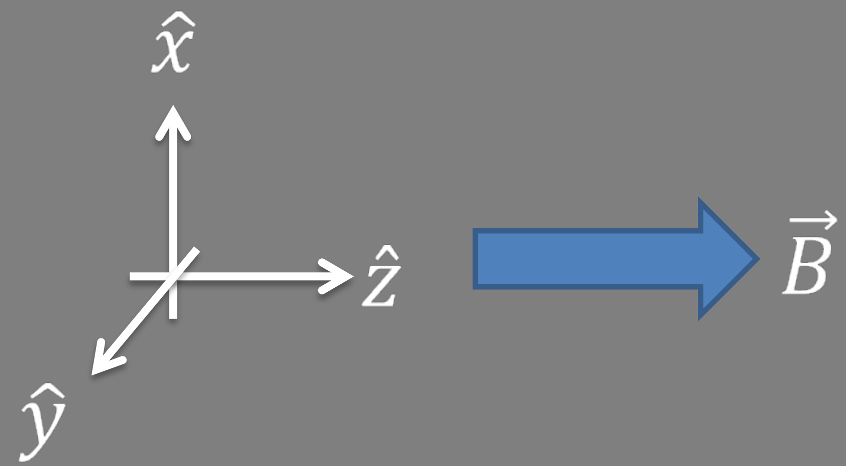
$$U_{dip} = \frac{\pi c^2 \Gamma}{2\omega_0}\left(\frac{2 + P g_F m_F}{\delta_{3/2}} + \frac{1 - P g_F m_F}{\delta_{1/2}}\right) I(\vec{r})$$

$P = -1\ (\sigma^-), 0\ (\pi), 1\ (\sigma^+)$ Polarization ***in the atomic basis***

$$\Gamma = \frac{\omega_0^3}{3\pi\epsilon_0 \hbar c^3} |\langle e|e\vec{r}|g\rangle|^2 = 1/\tau \approx 2\pi \times 6\ MHz$$

A note about polarization

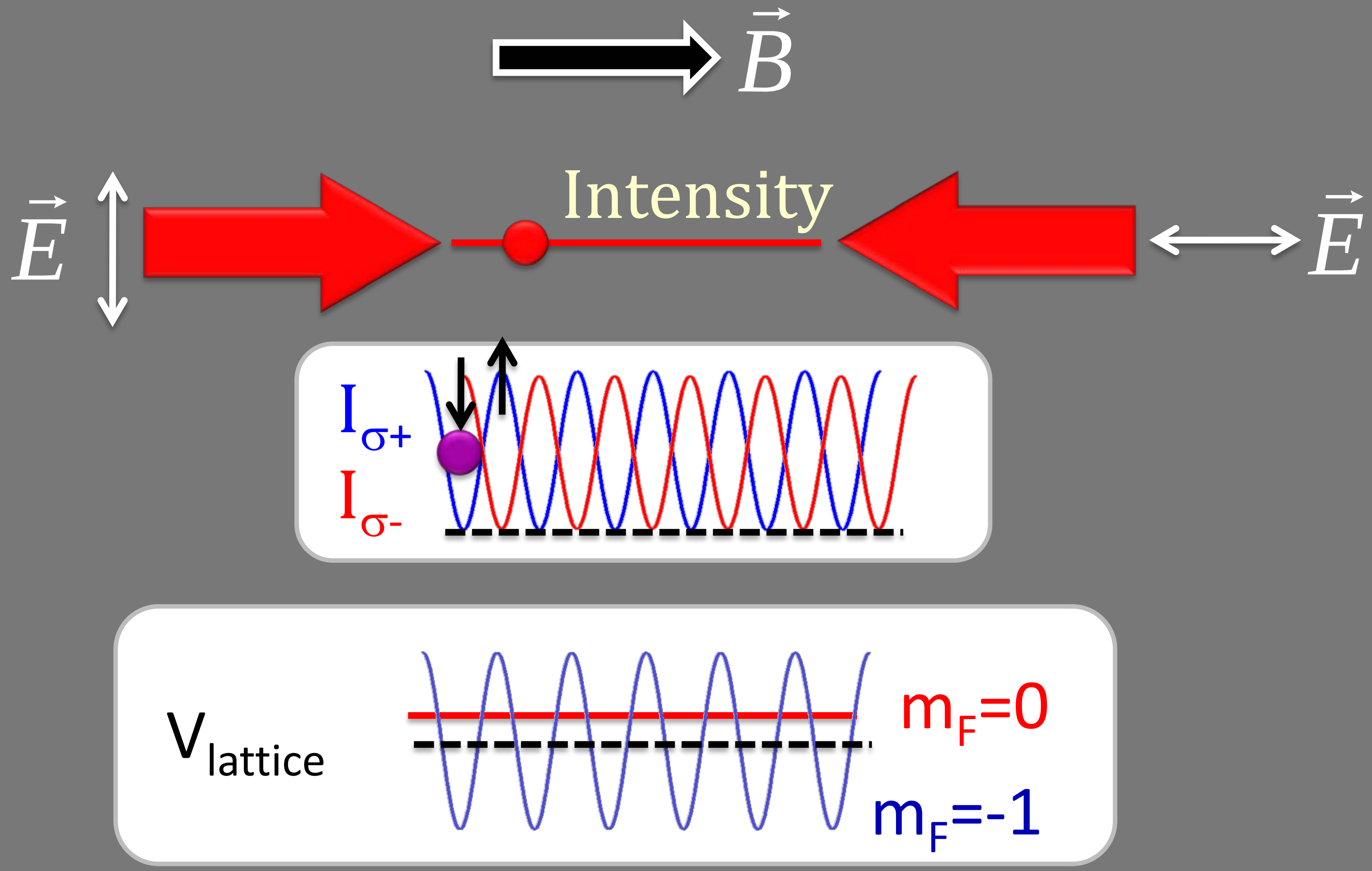
Polarization in the atomic basis



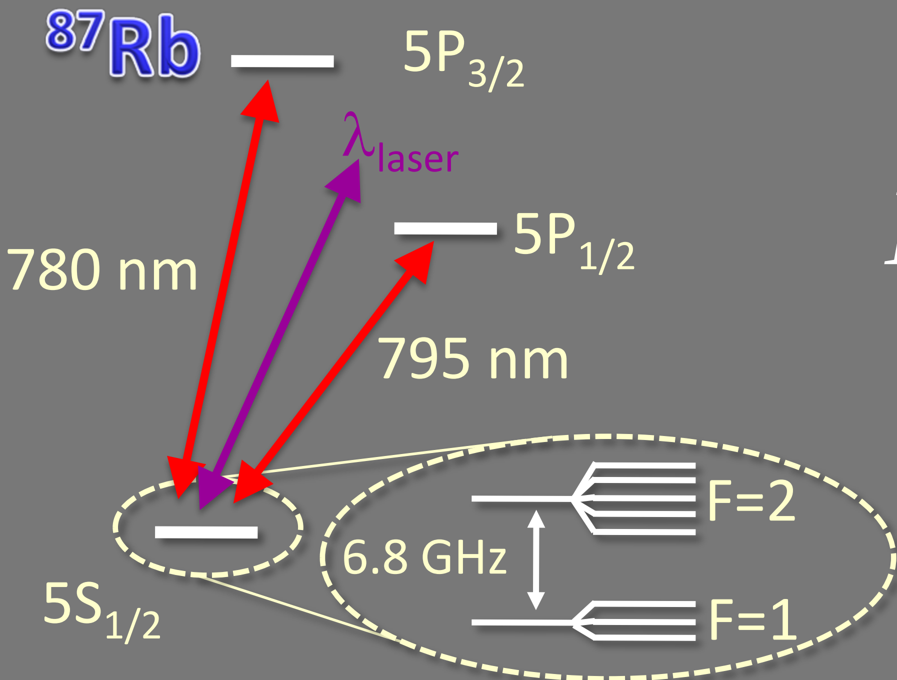
$$\hat{\pi} = \hat{z}$$
$$\hat{\sigma}^{+} = -(\hat{x} + i\,\hat{y})/\sqrt{2}$$
$$\hat{\sigma}^{-} = (\hat{x} - i\,\hat{y})/\sqrt{2}$$

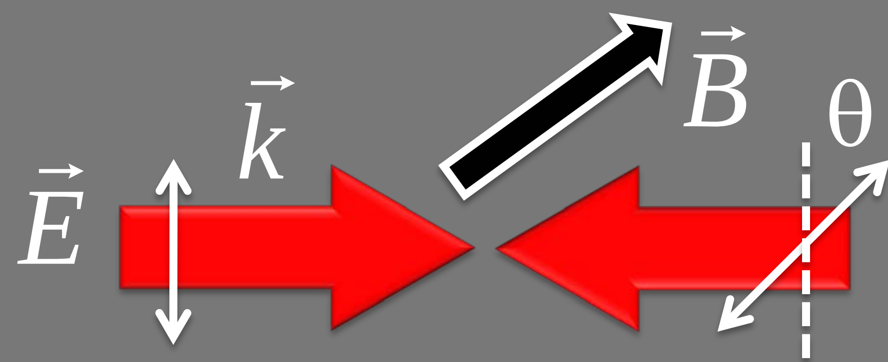
Polarization Gradient Lattices

Easiest to understand in 1D



3D Spin-Dependent Lattices





Standard ("Scalar") Lattice

$$V_{lattice} = 2\frac{\pi c^2 \Gamma^2 I_0}{2\omega_0^3}\left(\left(\frac{2}{\Delta_{3/2}} + \frac{1}{\Delta_{1/2}}\right)(1+\cos(\theta)\cos(2kr)) + g_F m_F \left(\frac{1}{\Delta_{3/2}} - \frac{1}{\Delta_{1/2}}\right)\vec{k}\cdot\vec{B}\sin(\theta)\sin(2kr)\right)$$

Spin-Dependent ("Tensor") Lattice

Spin-Dependent Lattices

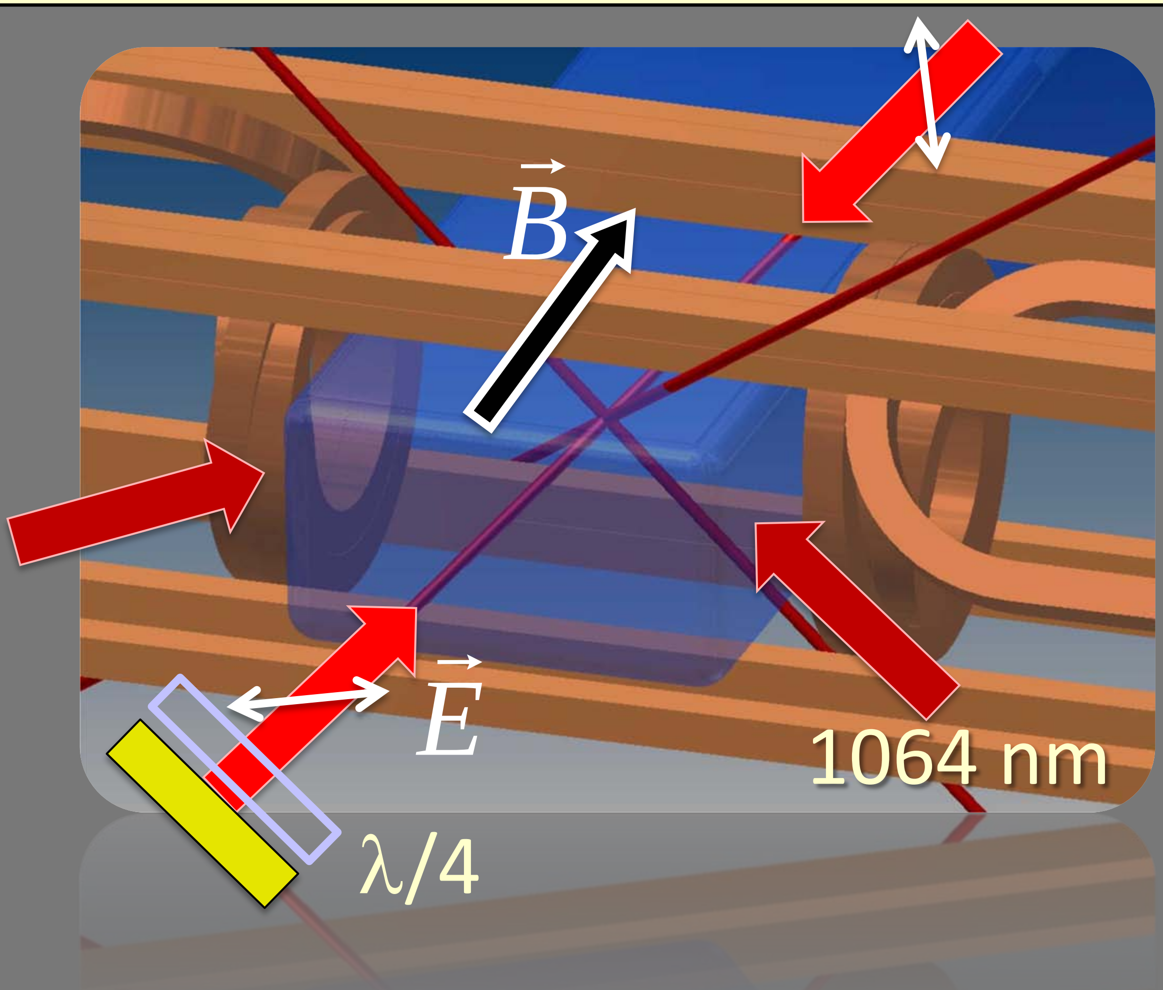
Standard Lattice

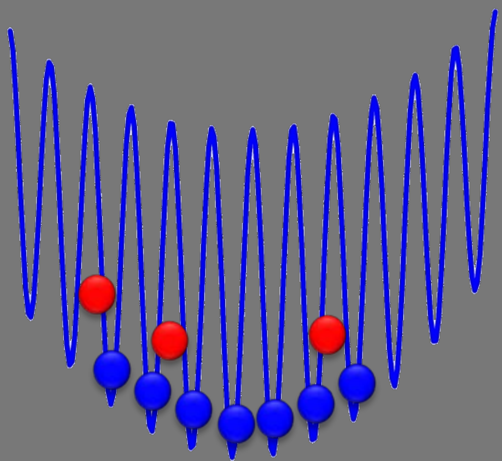
$$V_{\text{lattice}} = 2\frac{\pi c^2 \Gamma^2 I_0}{2\omega_0^3}\left(\left(\frac{2}{\Delta_{3/2}}+\frac{1}{\Delta_{1/2}}\right)(1+\cos(\theta)\cos(2kr))+ g_F m_F\left(\frac{1}{\Delta_{3/2}}-\frac{1}{\Delta_{1/2}}\right)\vec{k}\cdot\vec{B}\sin(\theta)\sin(2kr)\right)$$

Spin-Dependent Lattice

- No scalar lattice for θ=90° ("lin-perp-lin")
- Requires detuning comparable to fine structure splitting
- Lattice potential depth proportional to $g_F m_F$
- Lattice wavevector can not be perpendicular to magnetic field along any lattice direction
- Scalar lattice vanishes for "magic" wavelength (790 nm)

Spin-Dependent Lattice Thermometry

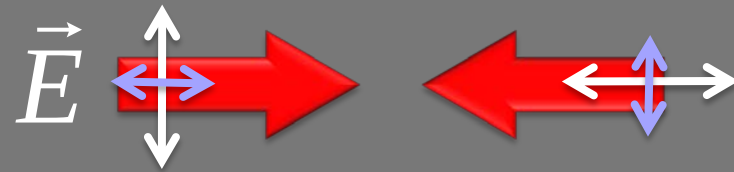




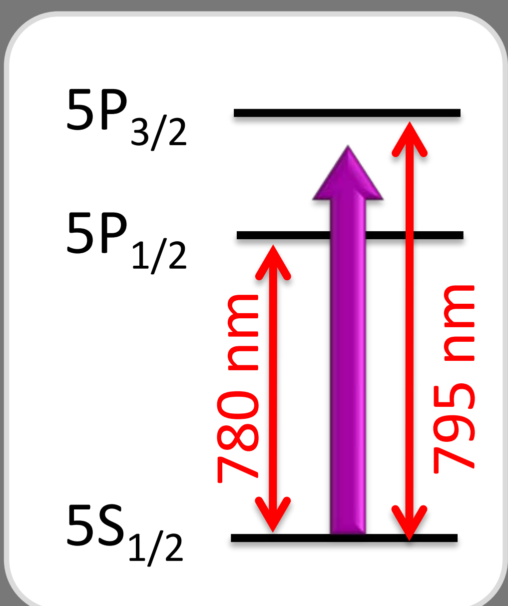
θ=90°: “lin-perp-lin”

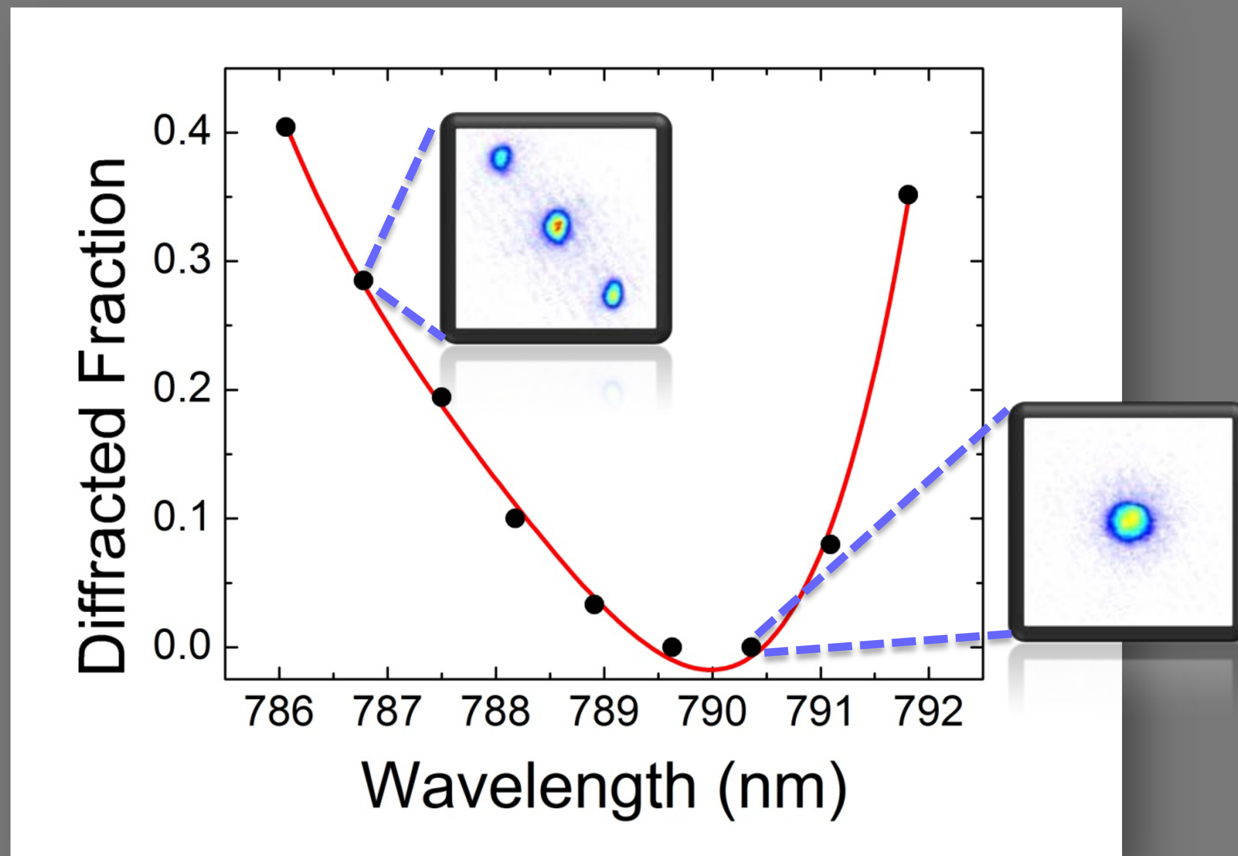
Lattice Technical Issues

Polarization Impurities



Create strong lattice for $m_F=0$ atoms

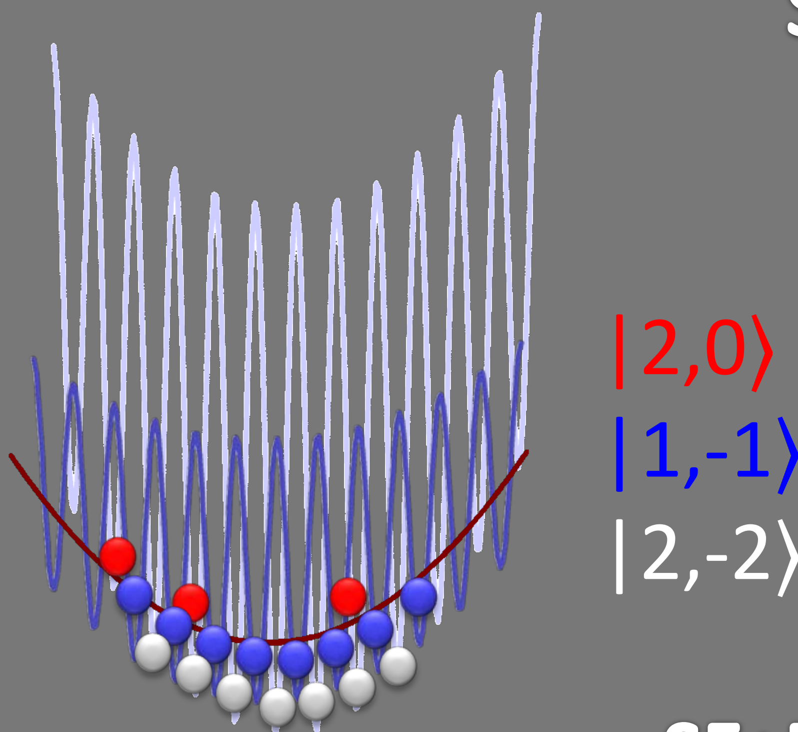




Solution: work at 790 nm

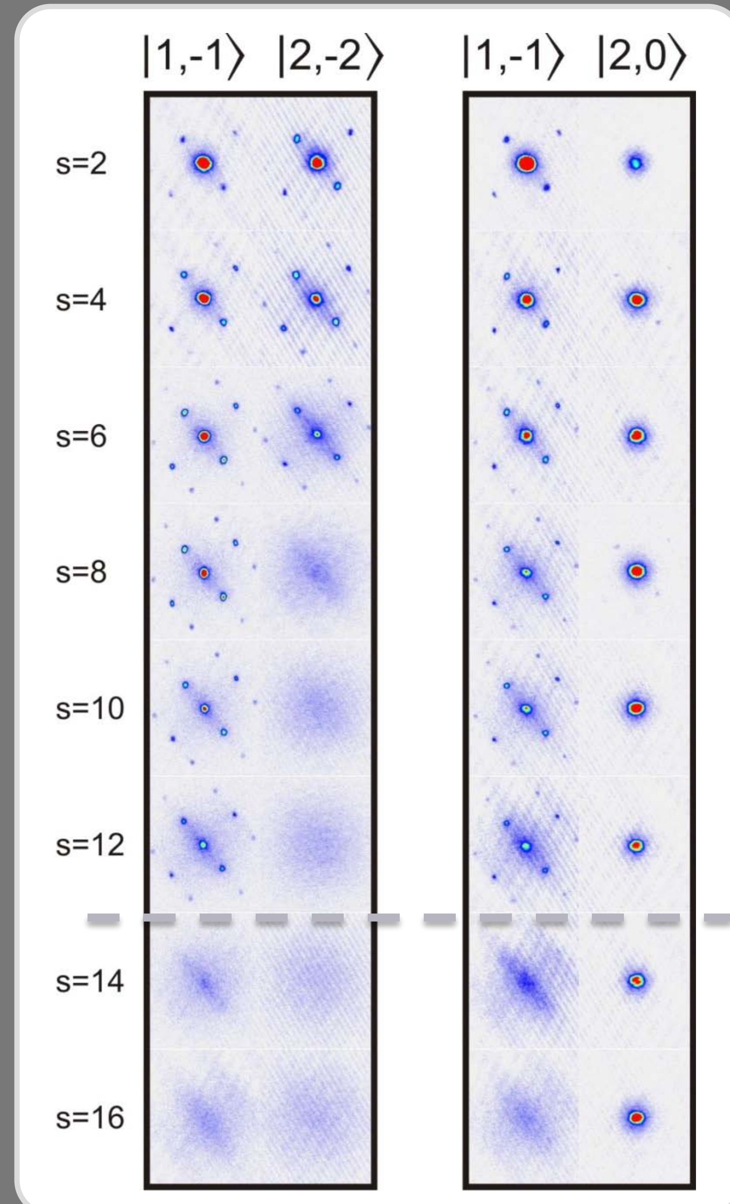
3D Spin-Dependent Lattice

θ=90°: lin-perp-lin



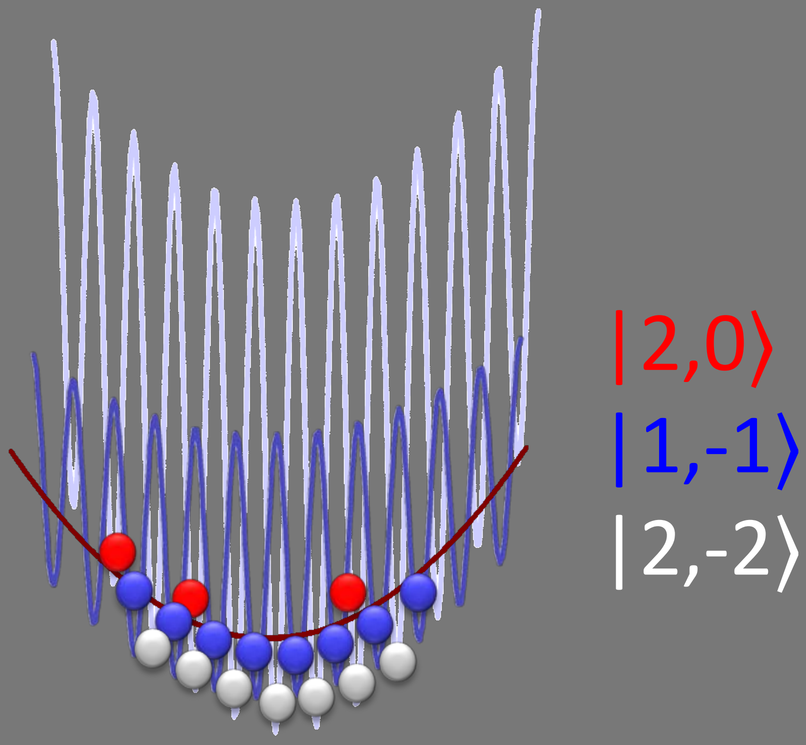
SF

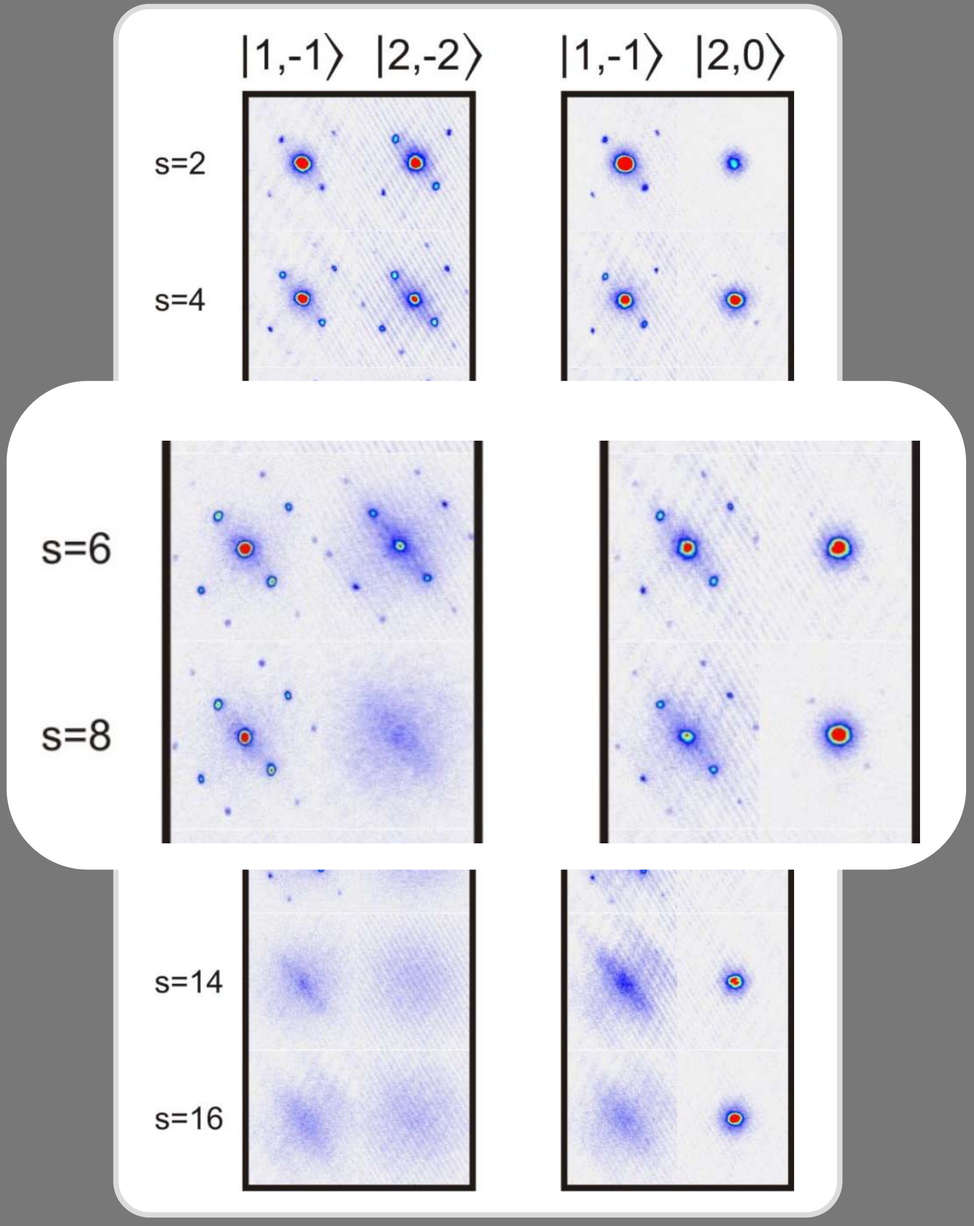
SF+MI



3D Spin-Dependent Lattice

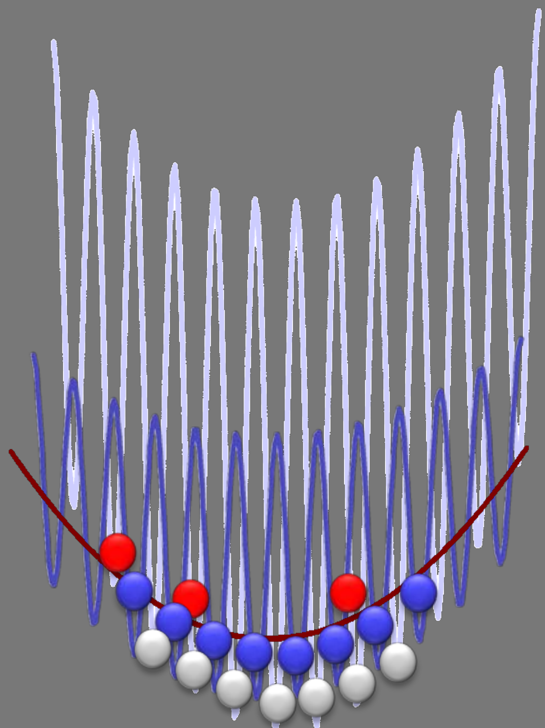
θ=90°: lin-perp-lin



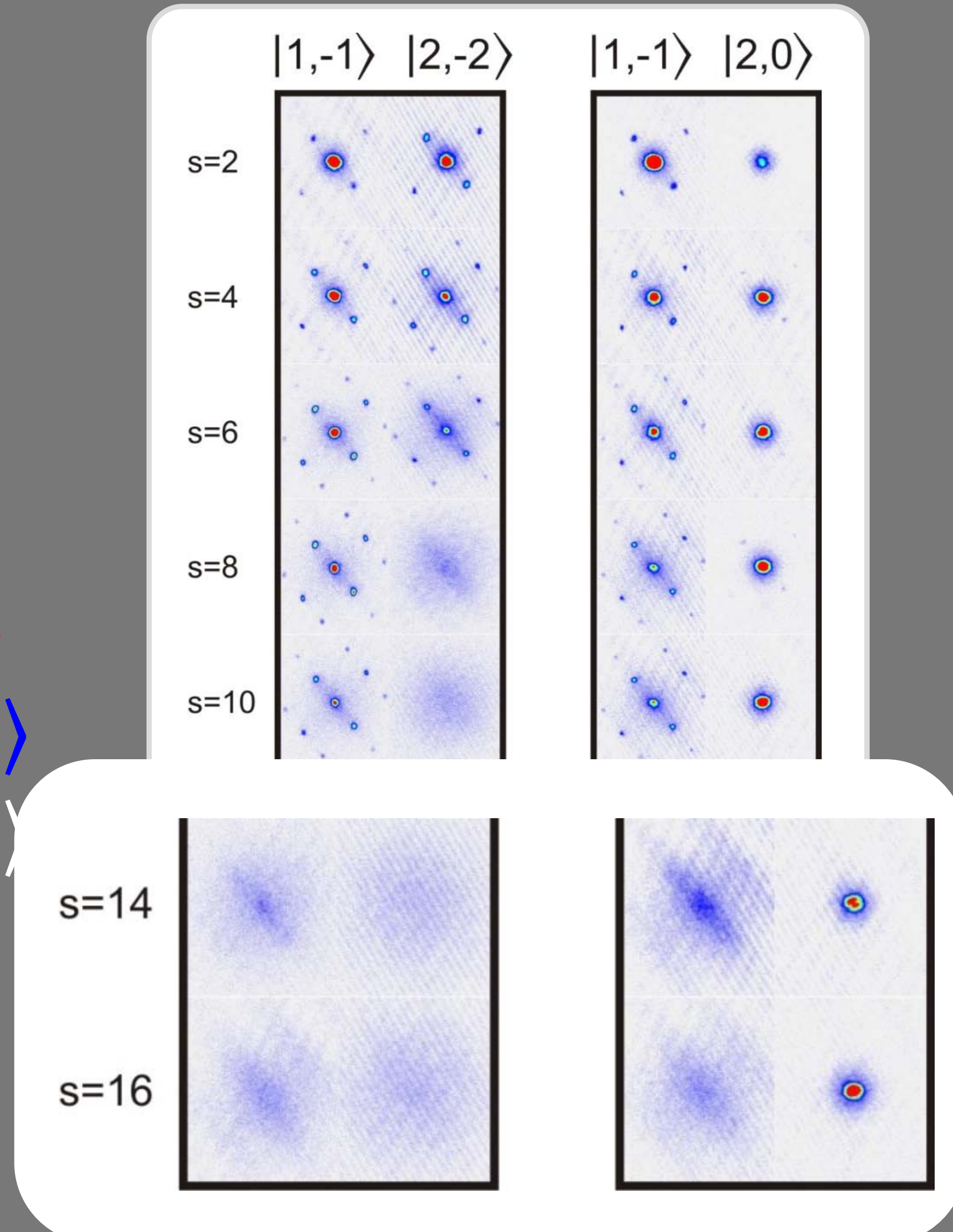


3D Spin-Dependent Lattice

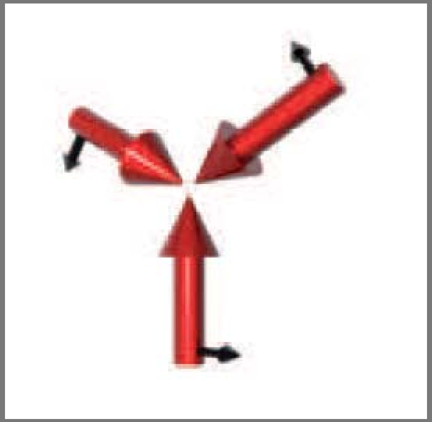
θ=90°: lin-perp-lin

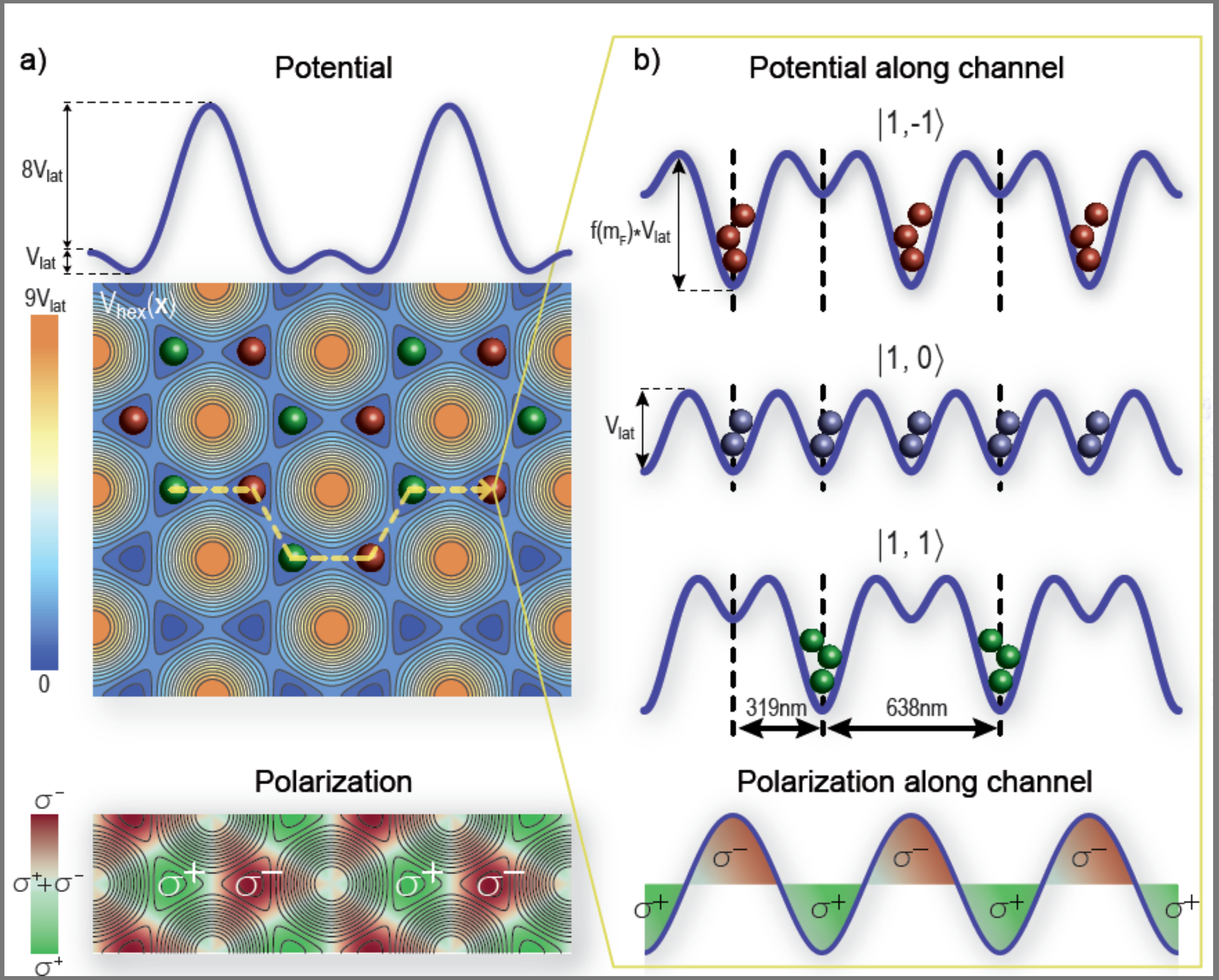


|2,0⟩
|1,-1⟩
|2,-2⟩



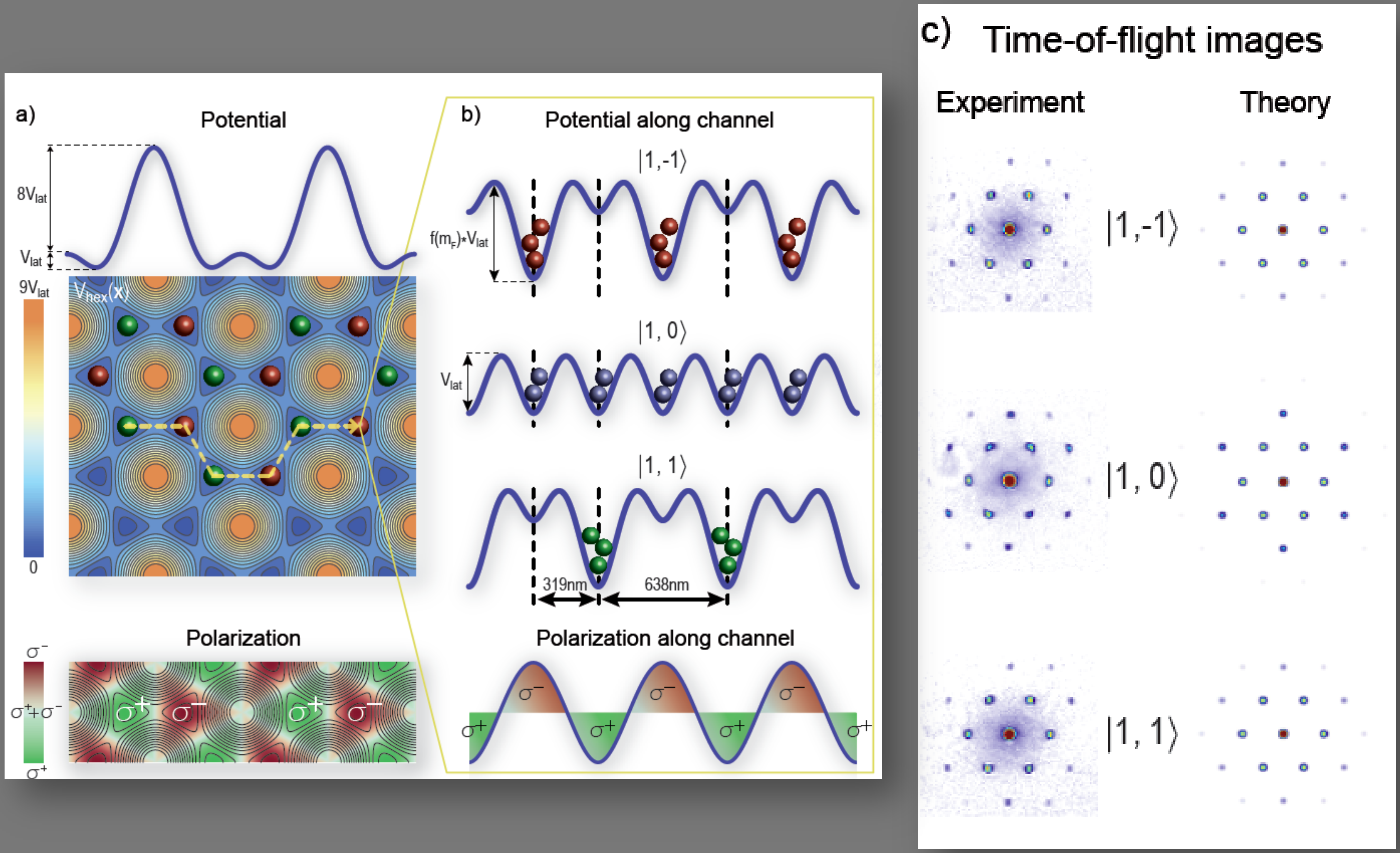
Hexagonal spin-dependent lattice





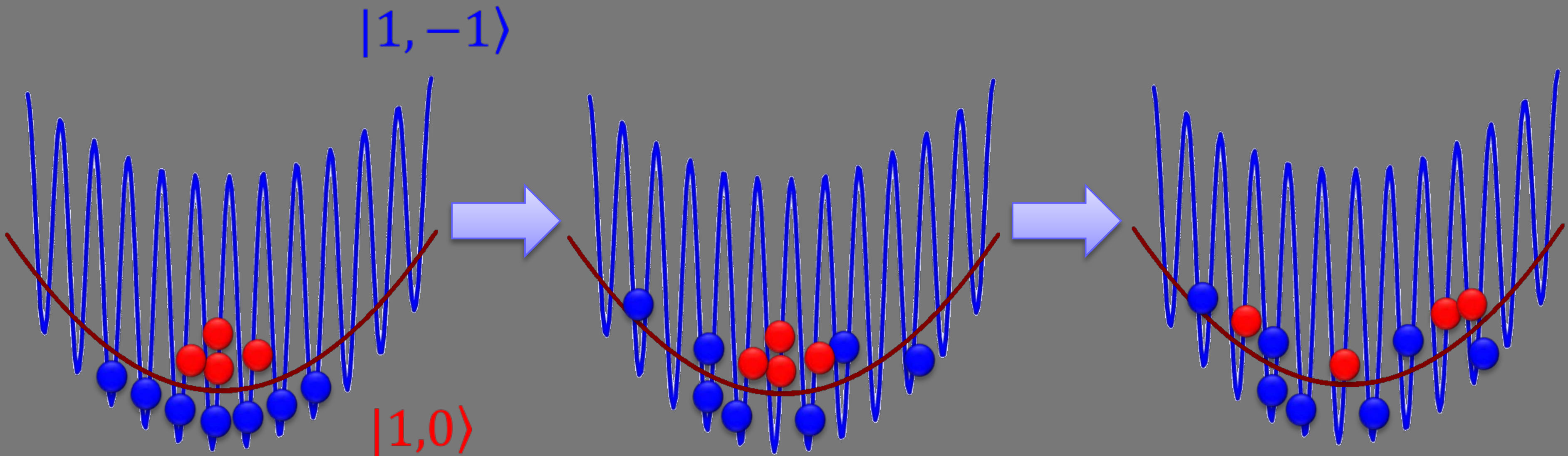
Sengstock

Hexagonal spin-dependent lattices



Controlled Heating

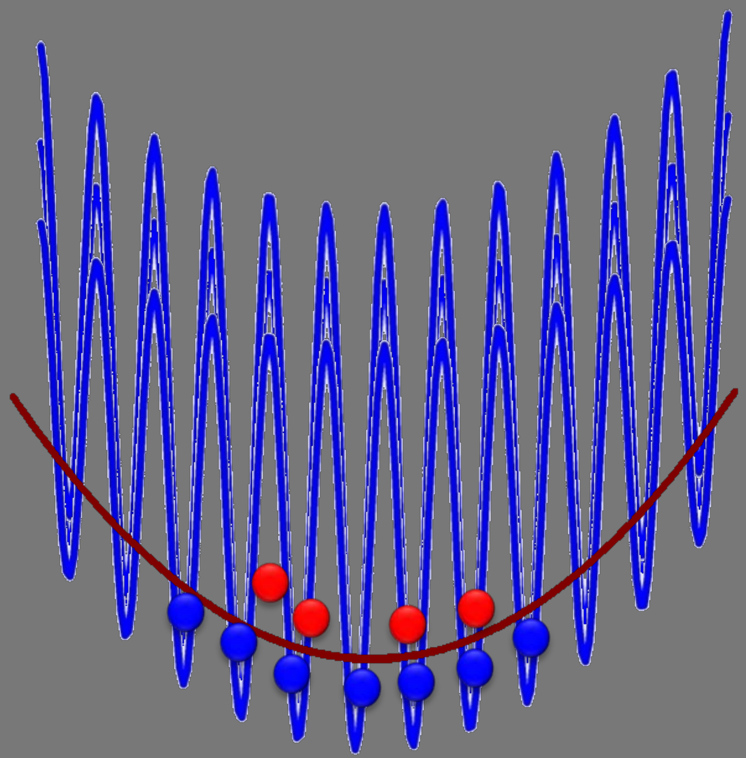
Thermalization?

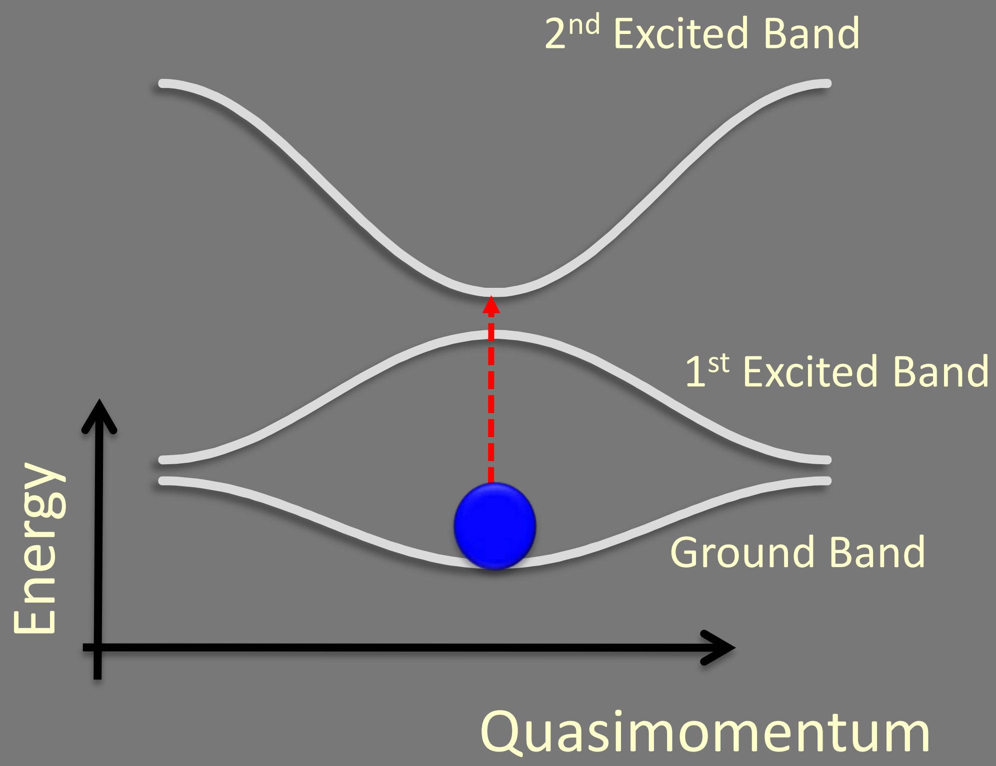


Invisible to |1,0>

Controlled Heating

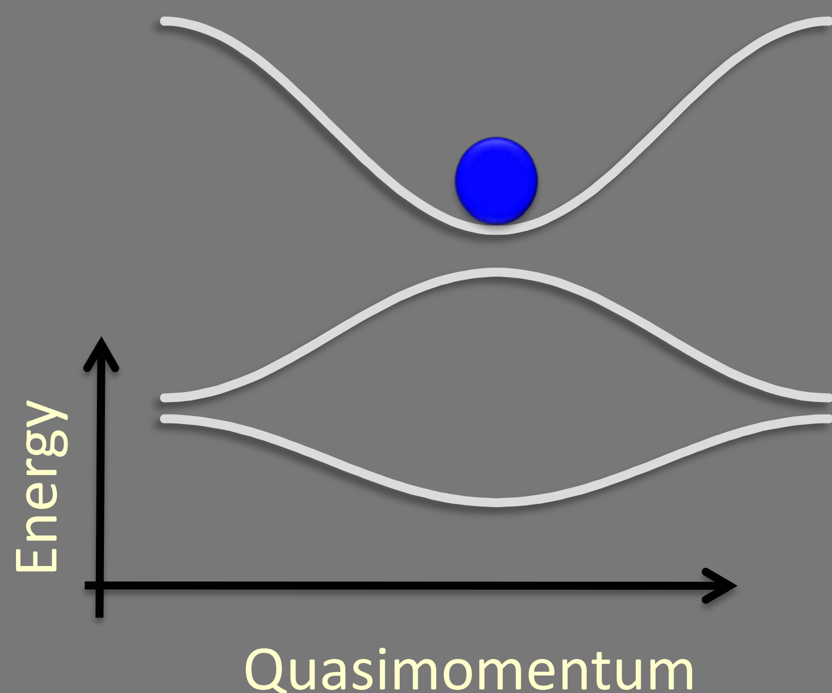
Parametric Oscillation of the Lattice

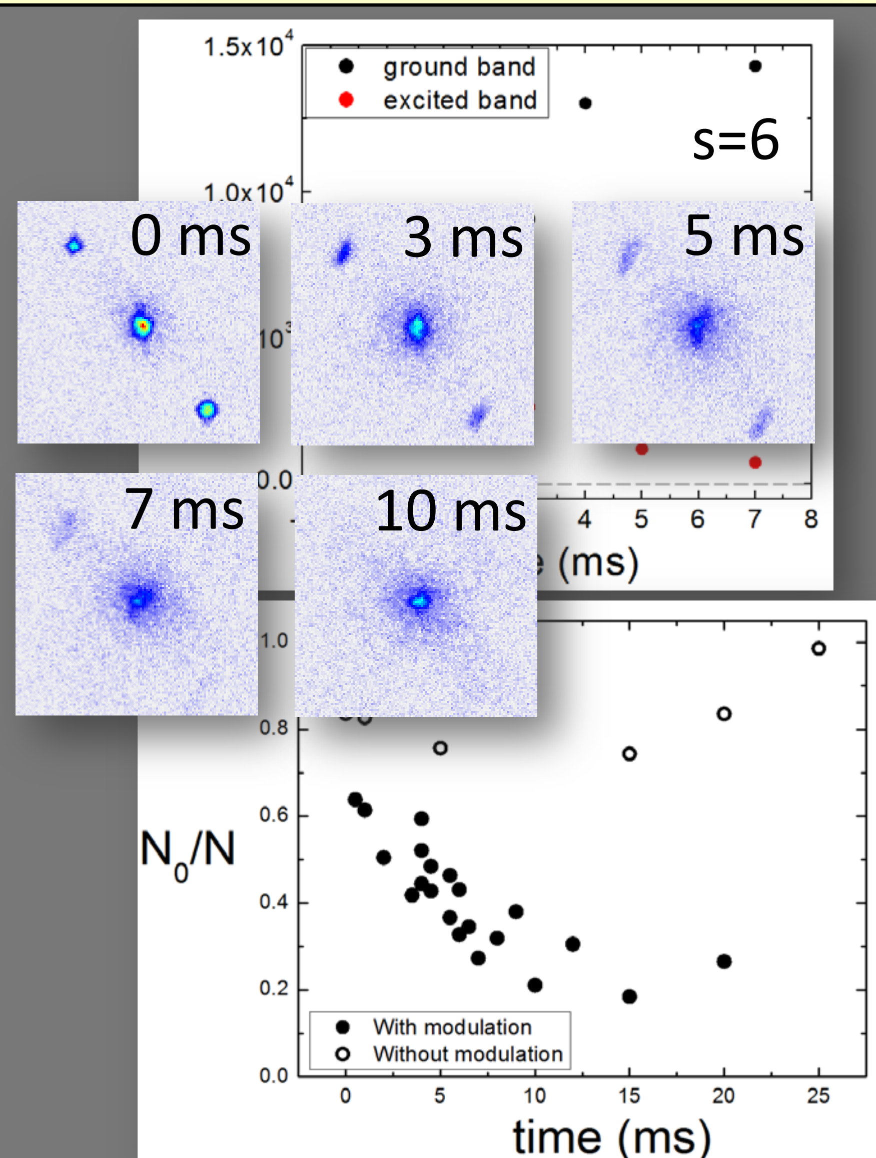




0,3,5,7,10

Band decay and thermalization



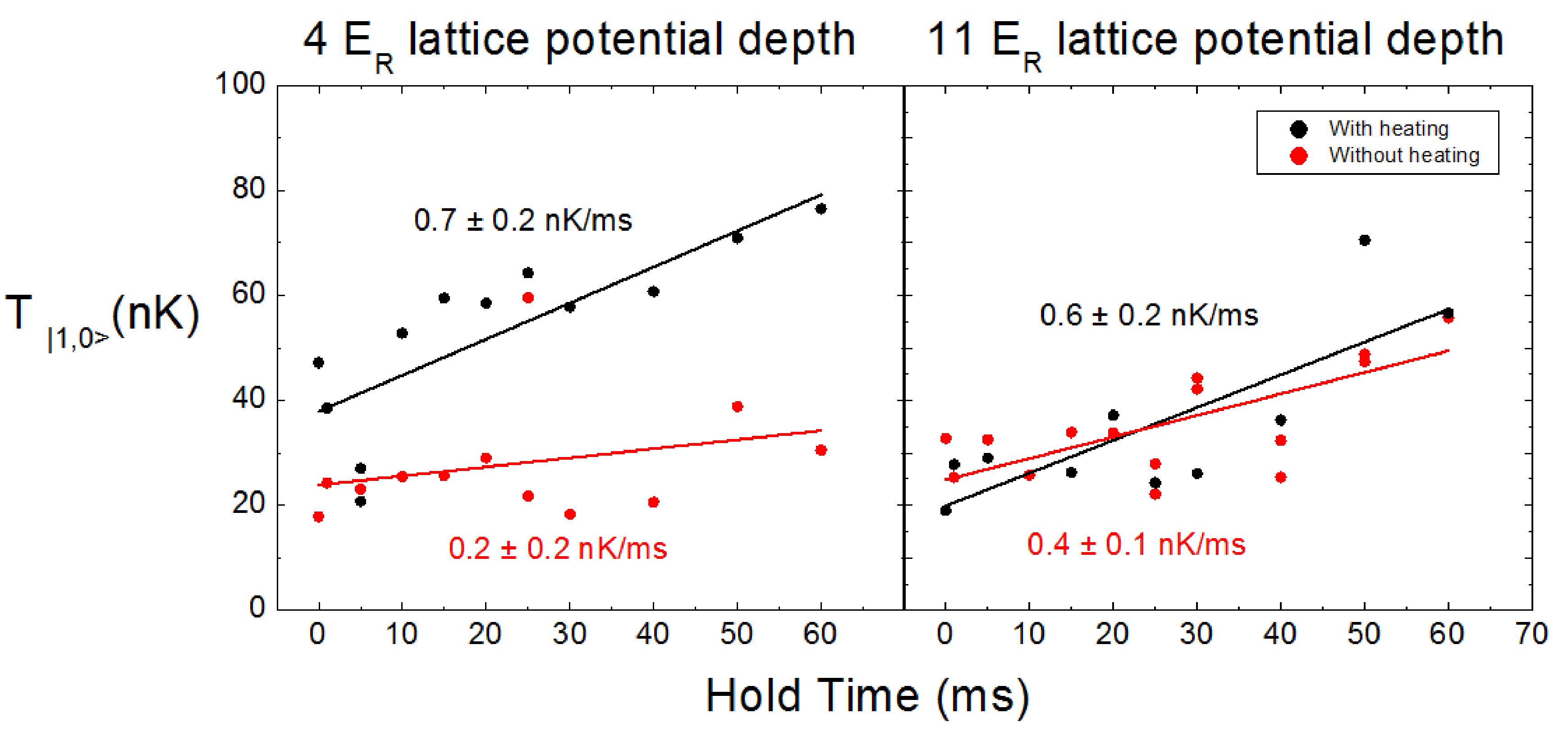


How fast is the Decay?

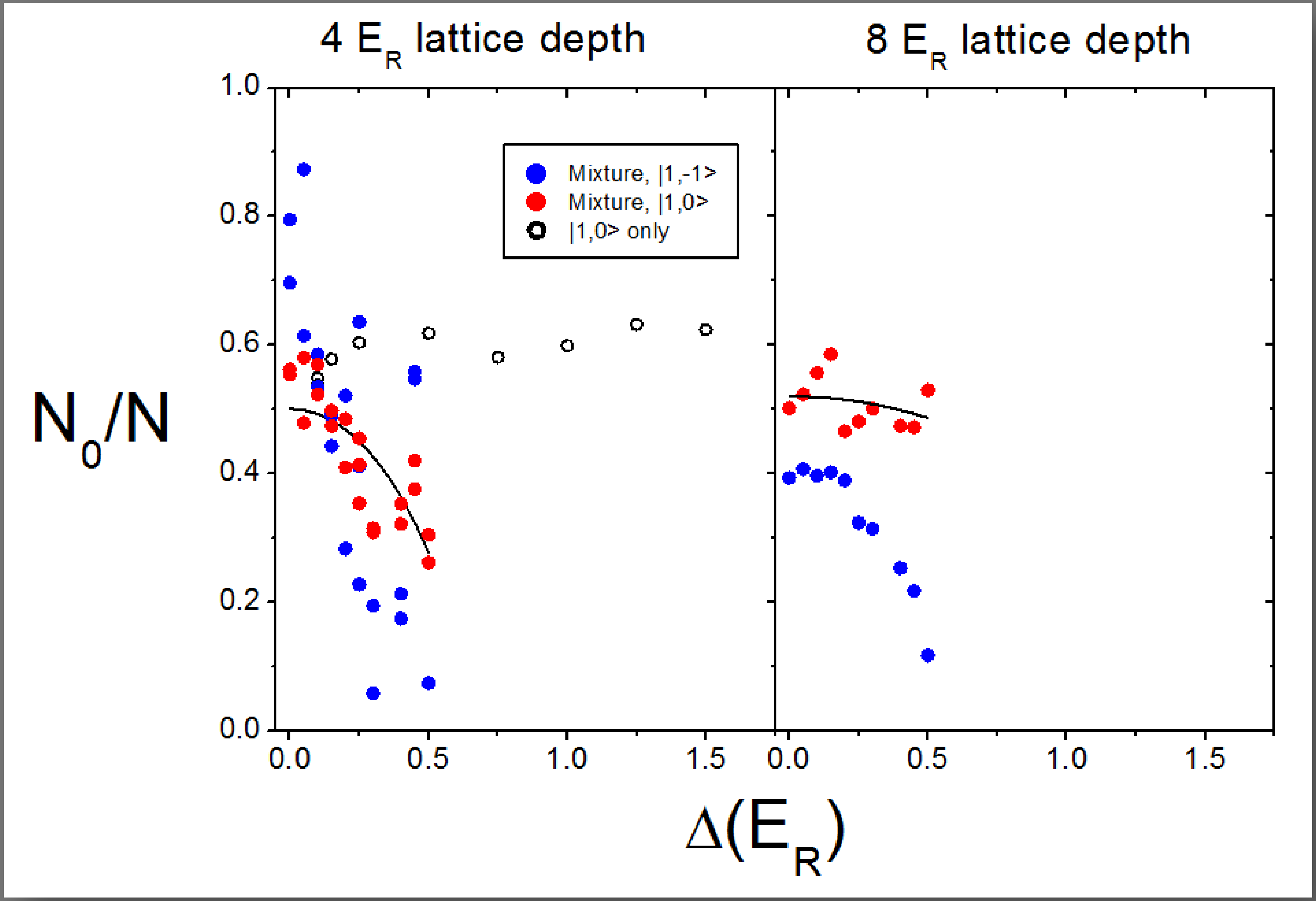
*thermalization timescale for lattice atoms= 5–7 ms from 6–11 ER

Thermalization after controlled heating

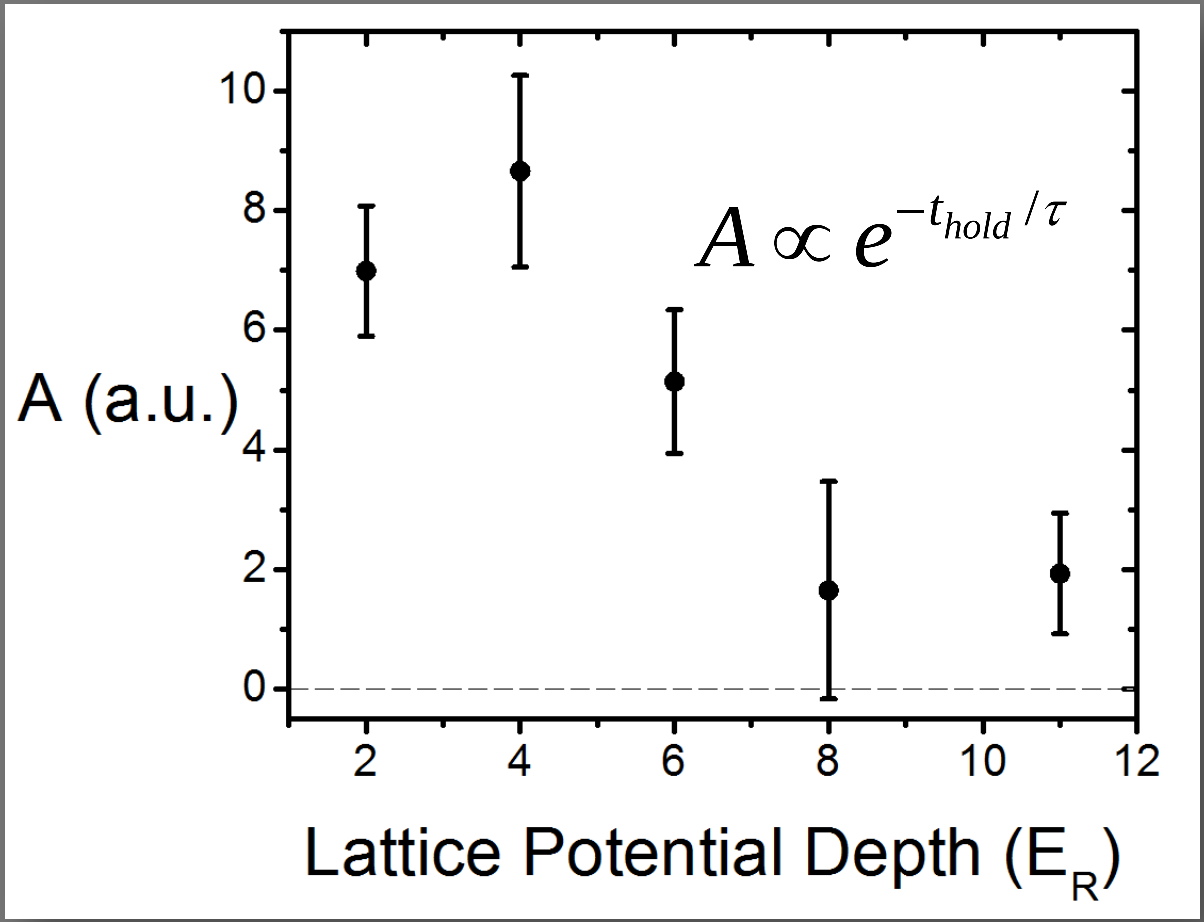
- In the harmonic trap (before loading the lattice), mixtures completely thermalize within 50 ms
- In the lattice, we cannot even observe relaxation!



Controlled heating – raw data



Controlled heating: results



Possible Explanation

Poor thermalization at higher lattice depth

Theory: need to consider effective mass, single-particle localized states, lattice dispersion (Kapitza resistance?), interaction-induced localization…