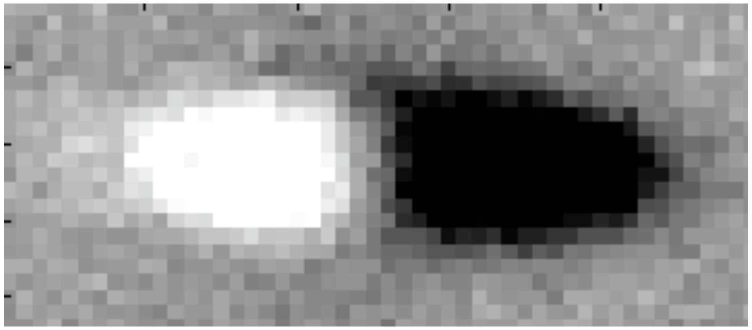
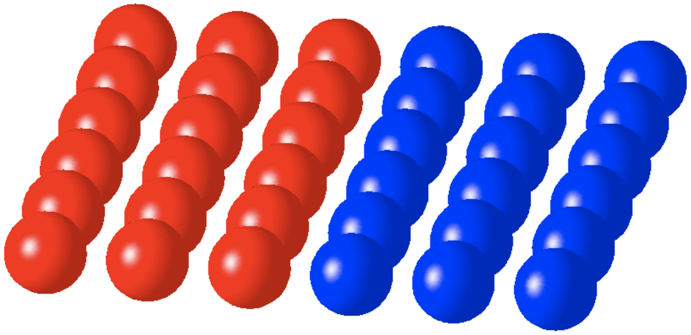
Thermometry and Cooling with Ultracold Spin Mixtures

Towards Quantum Simulation





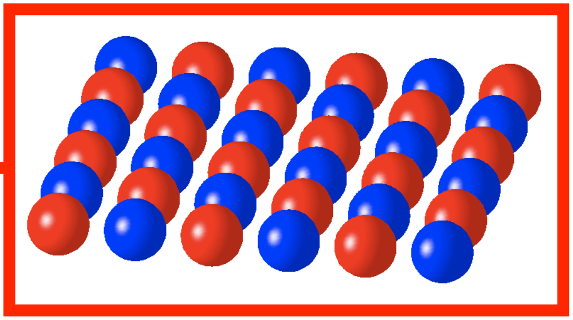
David Weld, MIT

“Beyond Standard Optical Lattices”
KITP, Santa Barbara
November 2010

Outline

- Motivation
- Thermometry
- Demagnetization Cooling
- Future Directions

Outline



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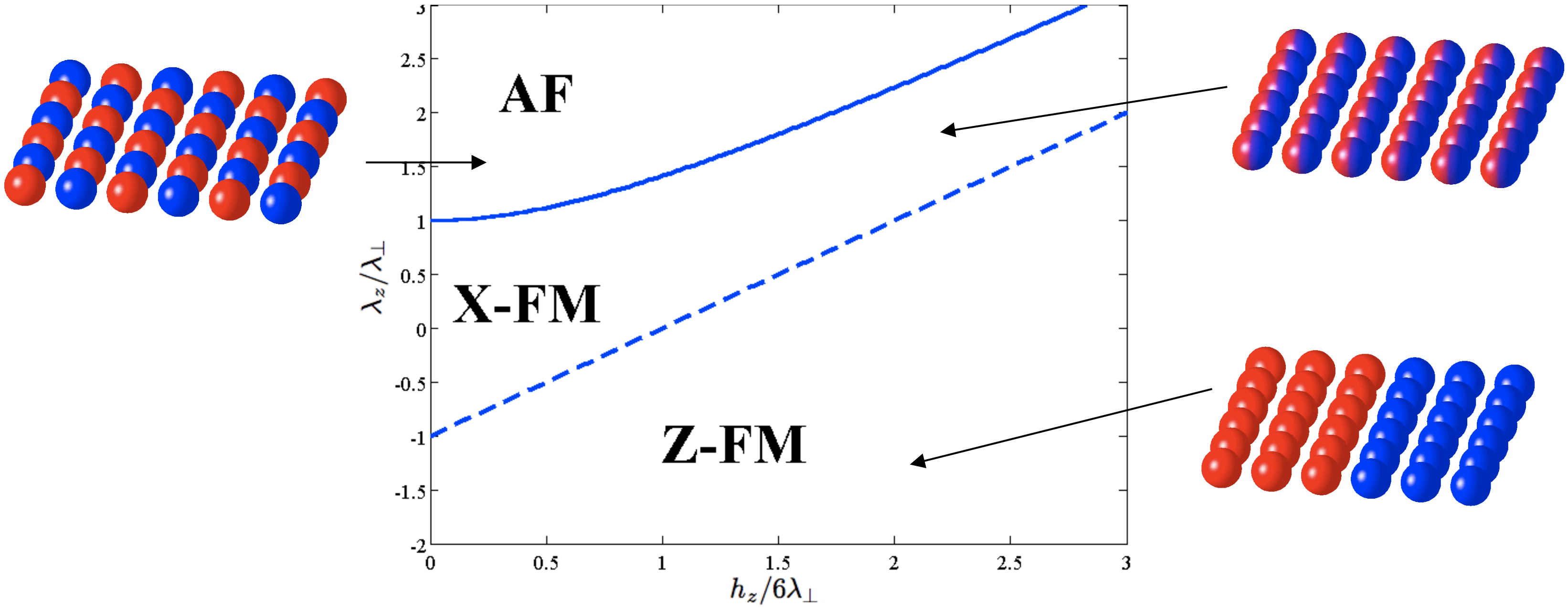
Goal: magnetic ordering of bosons

$$H = -\sum_{\langle ij\rangle\sigma}(t_{\mu\sigma}a^{t}_{i\sigma}a_{j\sigma} + H.c.) + \frac{1}{2}\sum_{i,\sigma}U_{\sigma}n_{i\sigma}(n_{i\sigma}-1) + U_{\uparrow\downarrow}\sum_{i}n_{i\uparrow}n_{i\downarrow}$$

$$H = \sum_{\langle i,j\rangle}\left[\lambda_z\sigma_i^z\sigma_j^z - \lambda_\perp\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)\right] - \sum_i h_z\sigma_i^z$$



A. Kuklov and B. Svistunov, Phys. Rev. Lett. **90**, 100401 (2003)

L.-M. Duan, E. Demler, and M. Lukin, Phys. Rev. Lett. **91**, 090402 (2003)

Relative Scales

	YBCO	Rb in YAG lattice
Lattice Constant	10^{-9} m	5×10^{-7} m
Site Density	10^{21} cm^{-3}	10^{13} cm^{-3}
Interaction U	600 THz	700 Hz
Tunneling J	100 THz	20 Hz
Exchange J^2/U	1500 K	5×10^{-11} K
Néel temperature	300 K	2×10^{-10} K

B. Capogrosso-Sansone, S. Soyler, N. Prokof'ev, and B. Svistunov, Phys. Rev. A **81**, 053622 (2010)

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Spin ordering temperature ~ **200 picokelvin**

➡ **Need new methods of thermometry & cooling**

B. Capogrosso-Sansone, S. Soyler, N. Prokof'ev, and B. Svistunov, Phys. Rev. A **81**, 053622 (2010)

Outline

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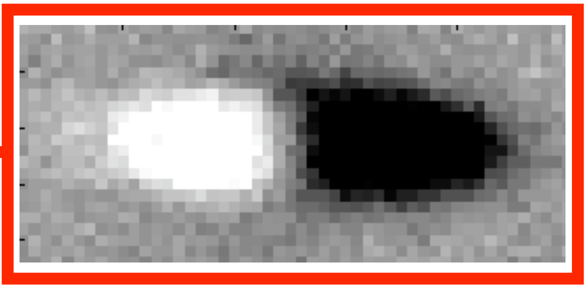
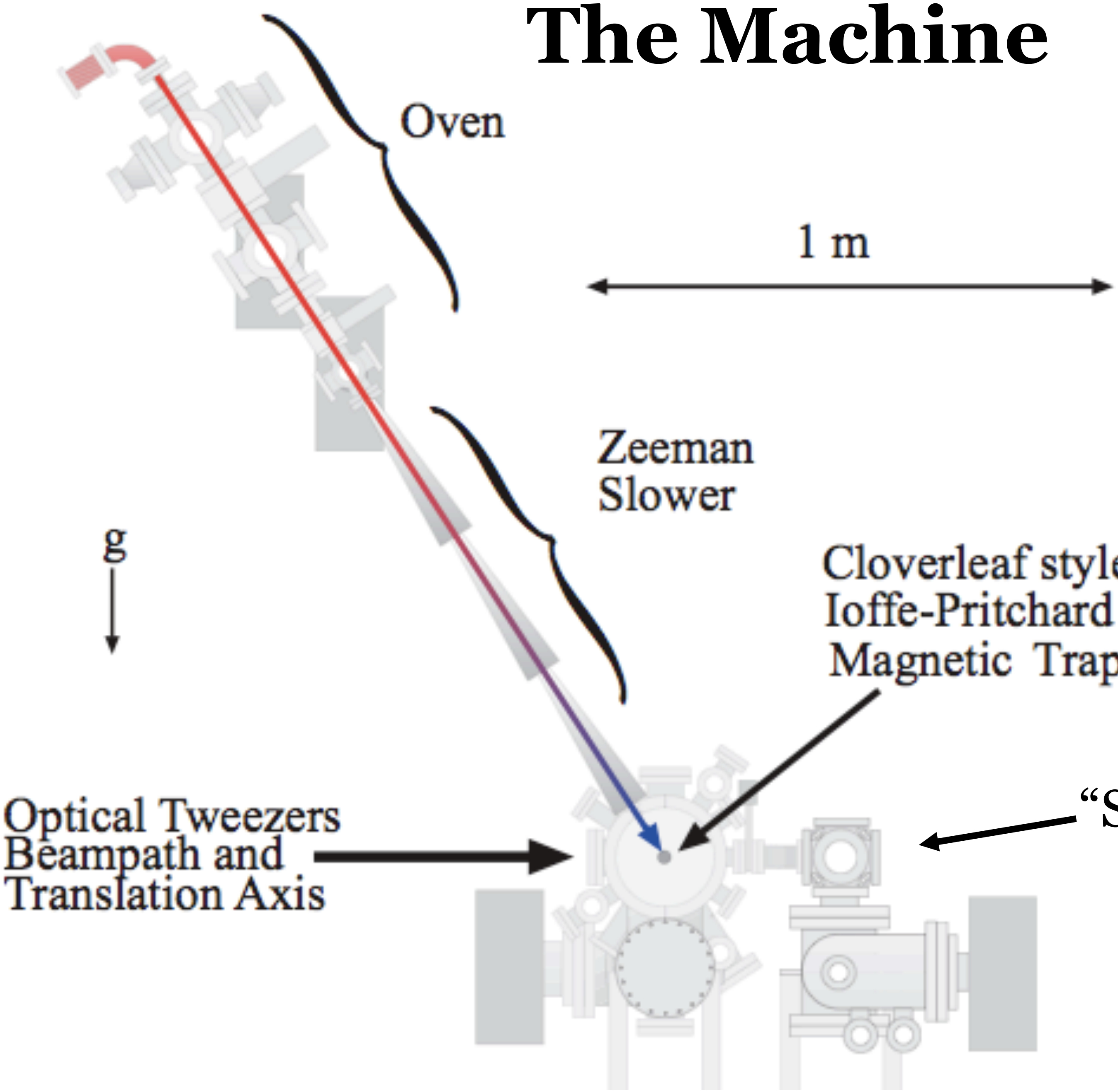
- Thermometry



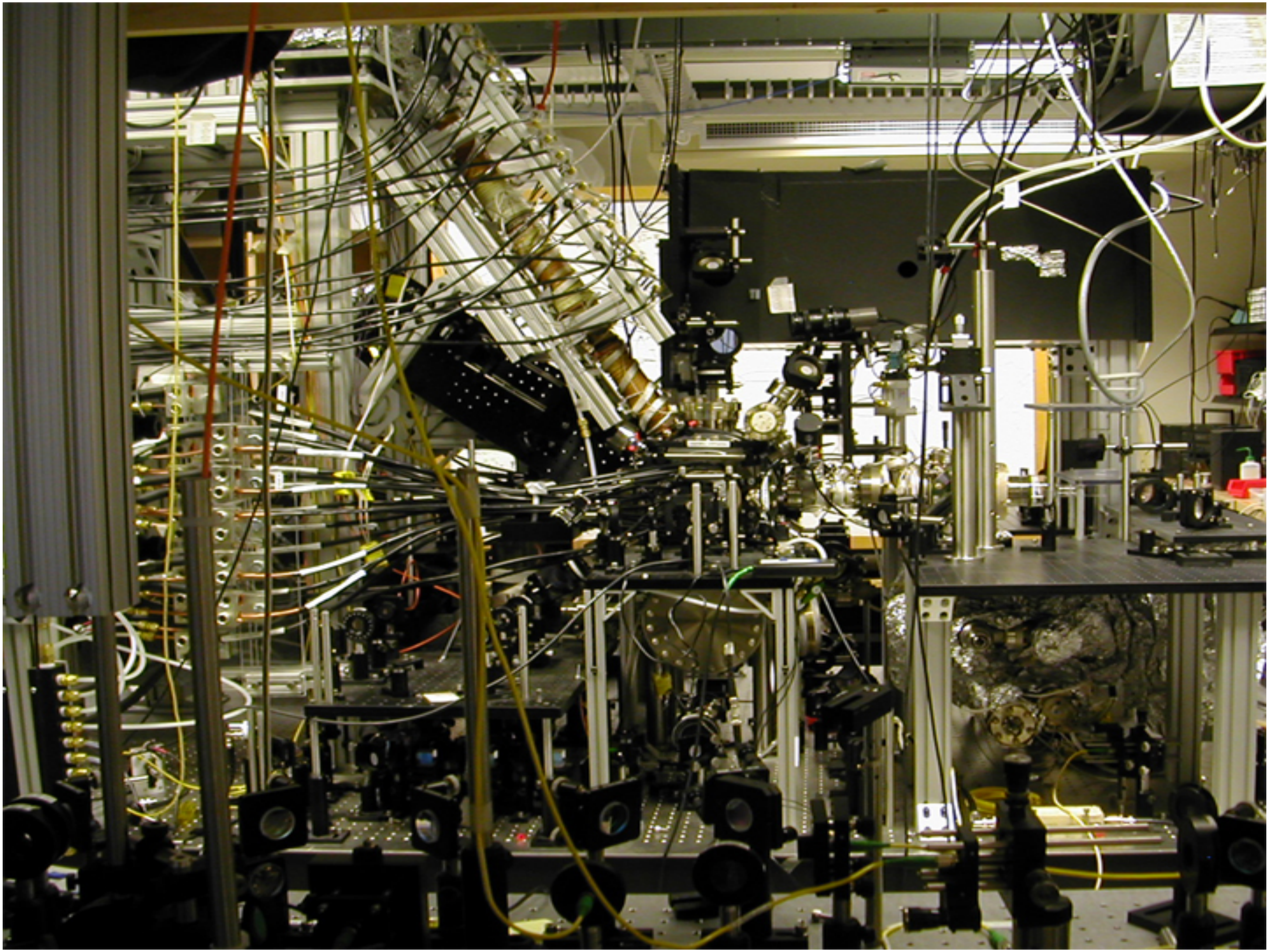
- Demagnetization Cooling
- Future Directions

The Machine



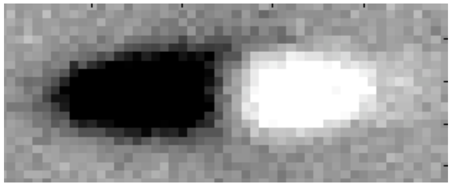
"Science Chamber"

E.W. Streed *et al*, Rev. Sci. Instrum. 77, 023106 (2006)

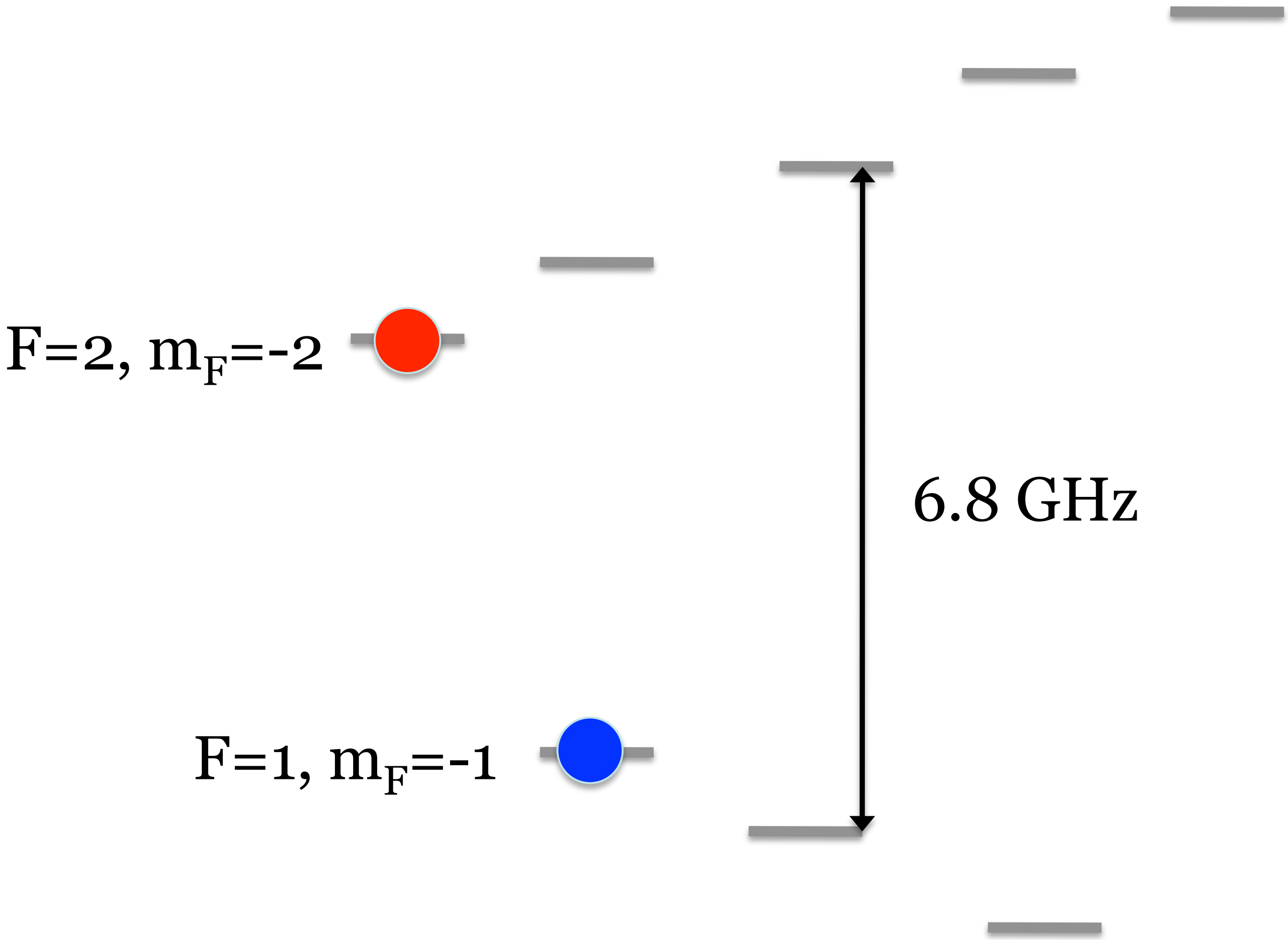


Typical Procedure

- Evaporate to BEC in optical trap
- Prepare spin mixture w/ nonadiabatic sweep
- Apply strong gradient & evaporate further
- Load into 3D optical lattice
- Image spin distribution:



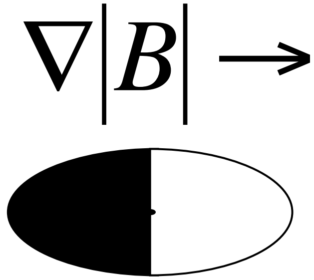
Experimental Realization

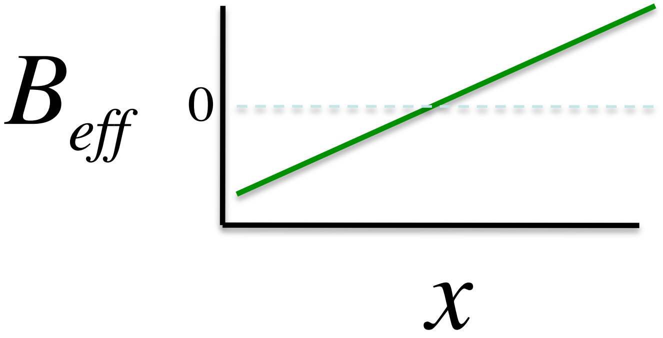


Experimental Realization

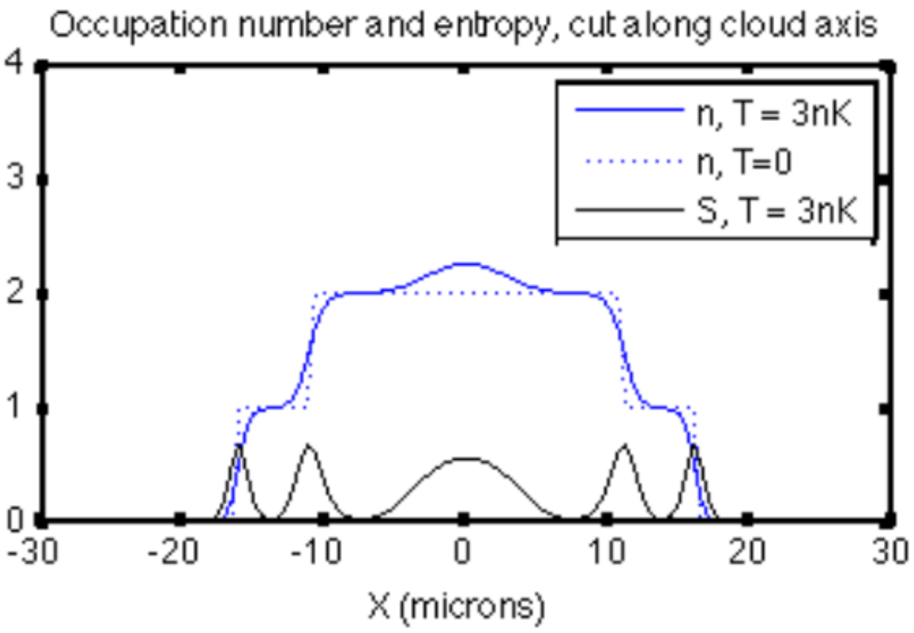
- A major difference between (most) cold atom systems and CM models: **fixed magnetization**.
- How can atoms respond to a field if magnetization is fixed?
- Solution: field gradient. Effective field varies across sample, atoms can rearrange in response.
- Can use DC field to prevent spin flips or for Feshbach purposes; it is cancelled in the spin Hamiltonian by a Lagrange multiplier

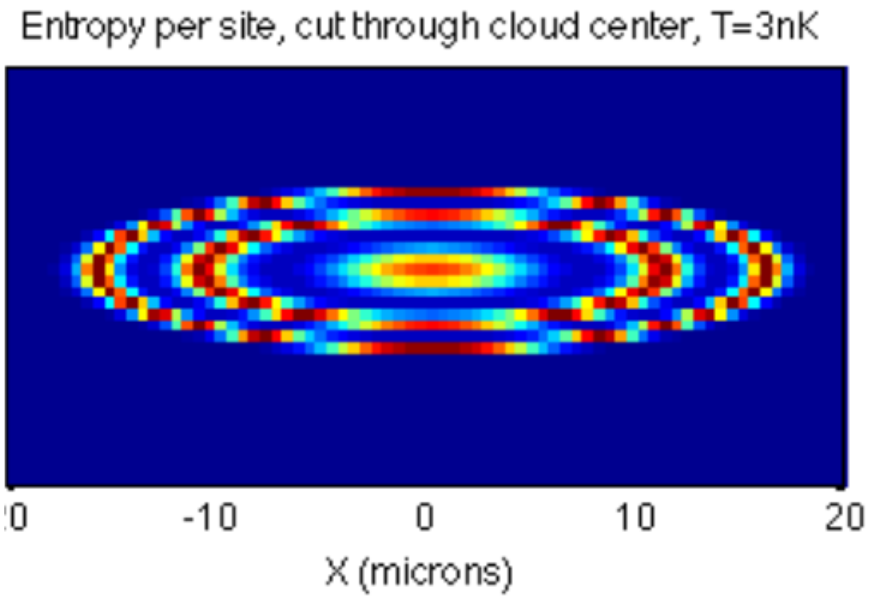
$$\boxed{B_{eff} = x \cdot \nabla|B|}$$





Excitations in the one-component MI





- "Wedding cake" particle distribution
- Particle-hole excitations localized at layers between Mott plateaux

N. Gemelke, X. Zhang, C.-L. Hung and C. Chin, *Nature*. **460**, 995 (2009)

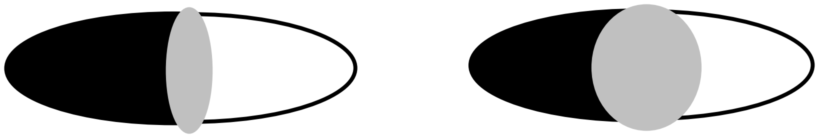
Excitations in the two-component MI

- 2CMI supports the same P-H excitations as 1CMI
- In addition, there is a spectrum of spin excitations whose energy is determined by the field gradient:
  - No spin excitations:

$\nabla|B| \rightarrow$

  - One spin excitation, with energy $E_0 = 2d \cdot \mu \cdot \nabla|B|$

- Thermal population of spin excitations will produce a region of mixed spin of width $w \approx k_B T/(\mu \cdot \nabla|B|)$



(Boundary layer looks like a single Mott shell, but with controllable width)

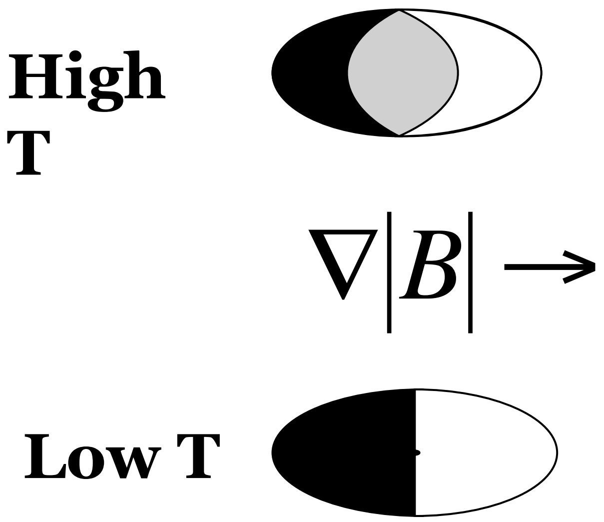
Spin Gradient Thermometry: Theory

- Spins separate in a field gradient

- At finite T, boundary region of mixed spin exists

- Mean local spin is a function of position, gradient, and temperature:

$$\langle s \rangle = 2\tanh\left(\beta\mu_B \frac{d|B|}{dx} x\right)$$



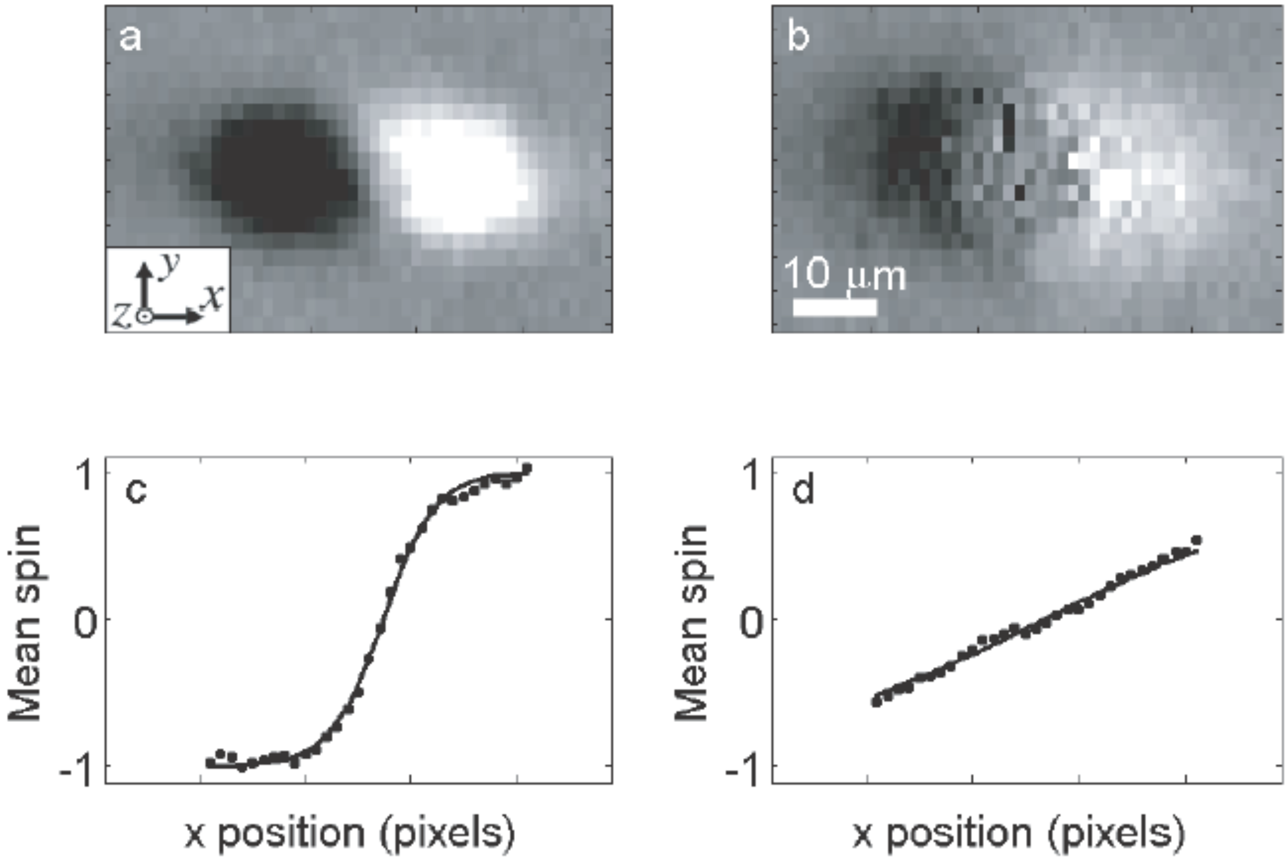
High T

$\nabla|B| \rightarrow$

Low T

Spin Gradient Thermometry: Results

Colder **Hotter**

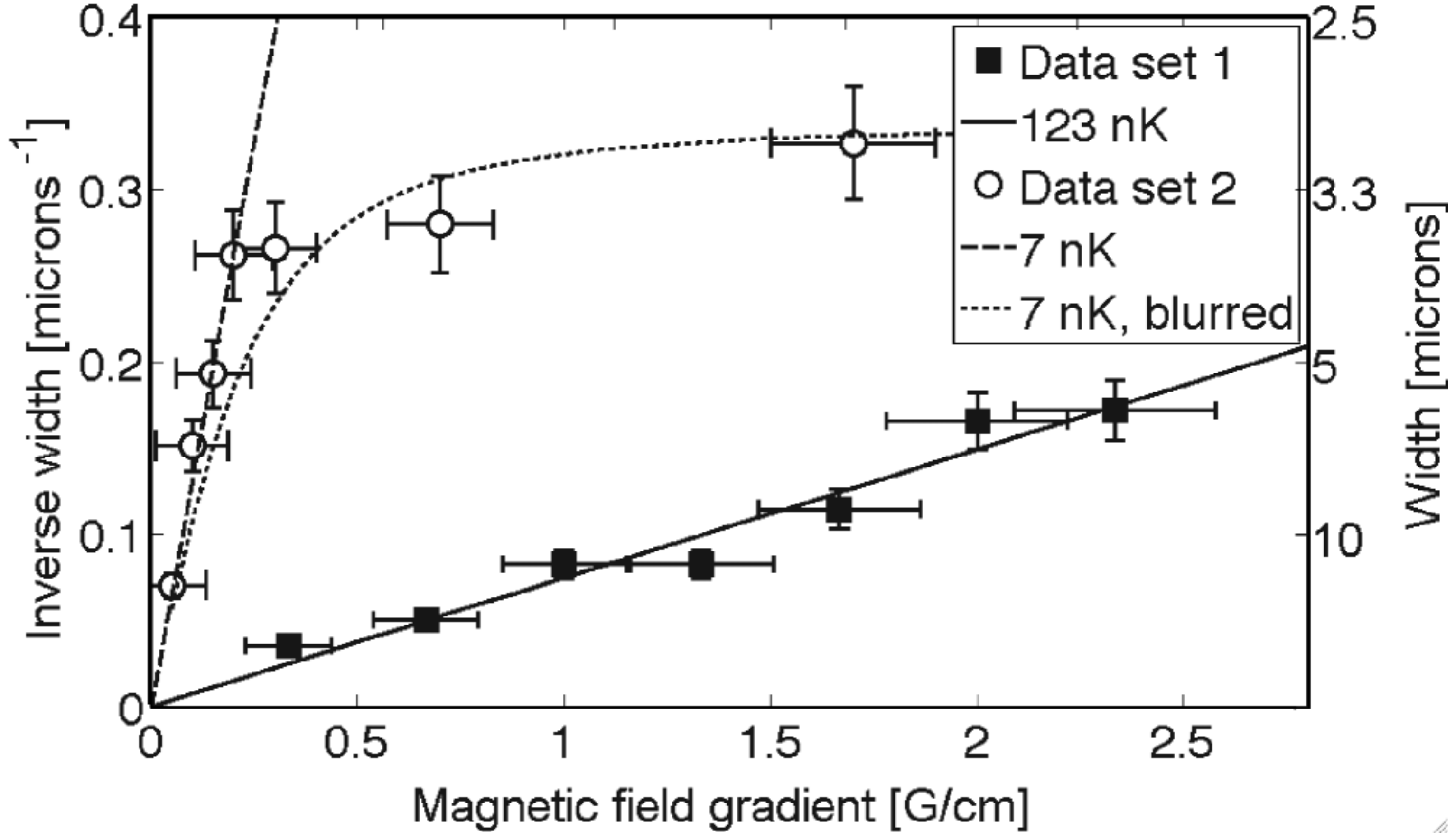


52 nK

296 nK

D.M. Weld *et al*, Phys. Rev. Lett. **103**, 245301 (2009)

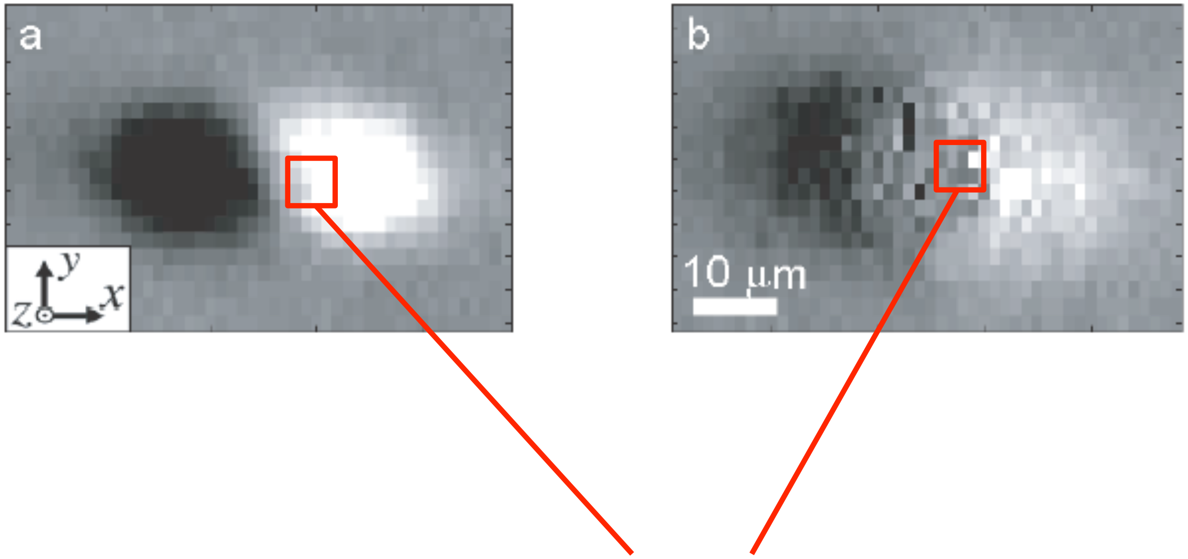
Spin Gradient Thermometry: Results



D.M. Weld *et al*, Phys. Rev. Lett. **103**, 245301 (2009)

Spin Gradient Thermometry

- Locally equivalent to paramagnetic thermometry (sample obeys Curie-Weiss law)



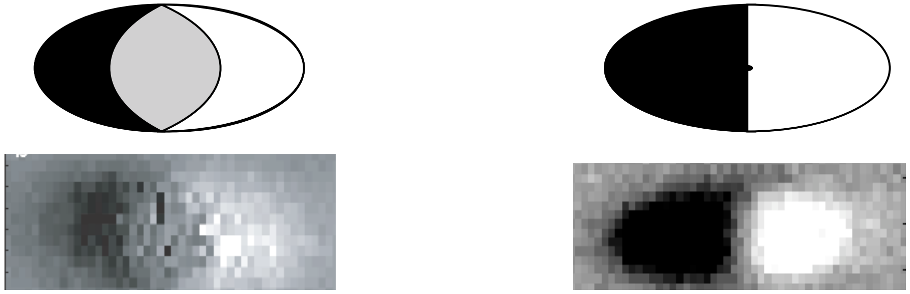
$$\chi \equiv \frac{M}{B_{eff}} \propto \frac{1}{(T - T_C)}$$

Spin Gradient Thermometry: Overview

- **Measures thermal population of spin excitations**

- **High dynamic range**
  - Adjustable energy scale
  - Works from above BEC critical temperature of 400 nK down to ~50 pK

- **Works in the Mott insulating state**
  - Simplest method which can be applied in this regime



Outline

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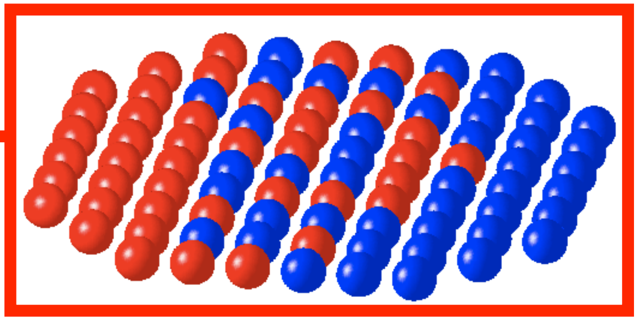
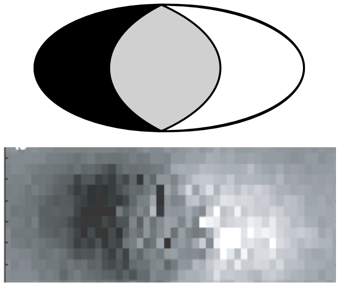
- Thermometry
- Demagnetization Cooling
- Future Directions



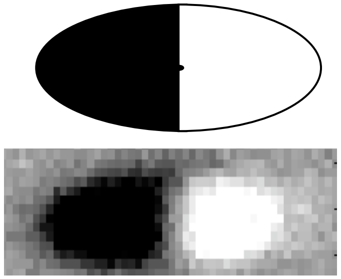
Beyond Thermometry

- SGT determines T by counting the number of spin excitations (i.e. width of boundary layer) in a fixed field gradient:

Hot:

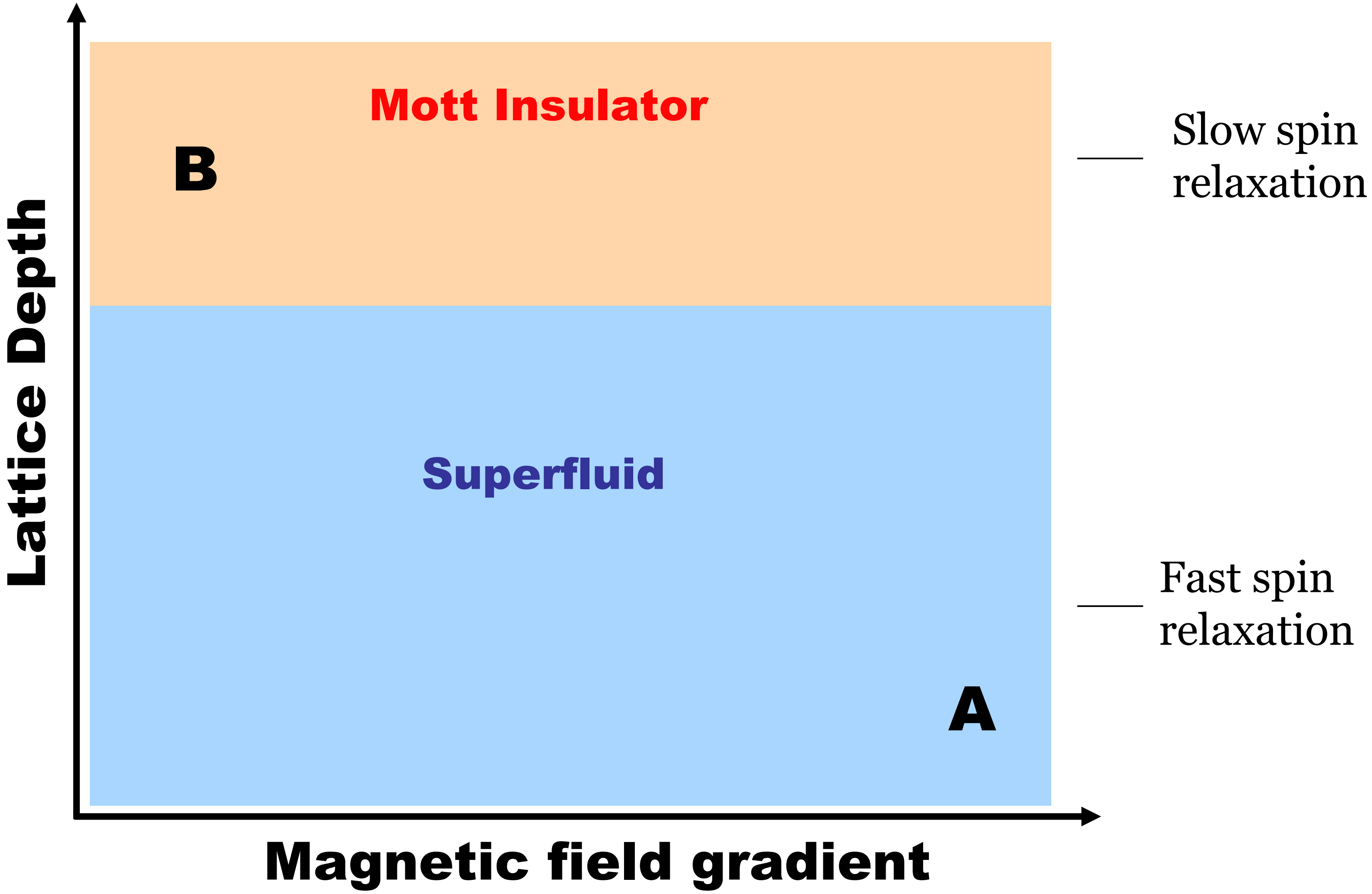


Cold:



- **What if the gradient is time-dependent?**
- Two regimes accessible: change gradient much faster or much slower than spin relaxation
- Possibilities:
  - Control spin temperature
  - Study spin dynamics
  - Refrigeration!

Experimental Phase Space



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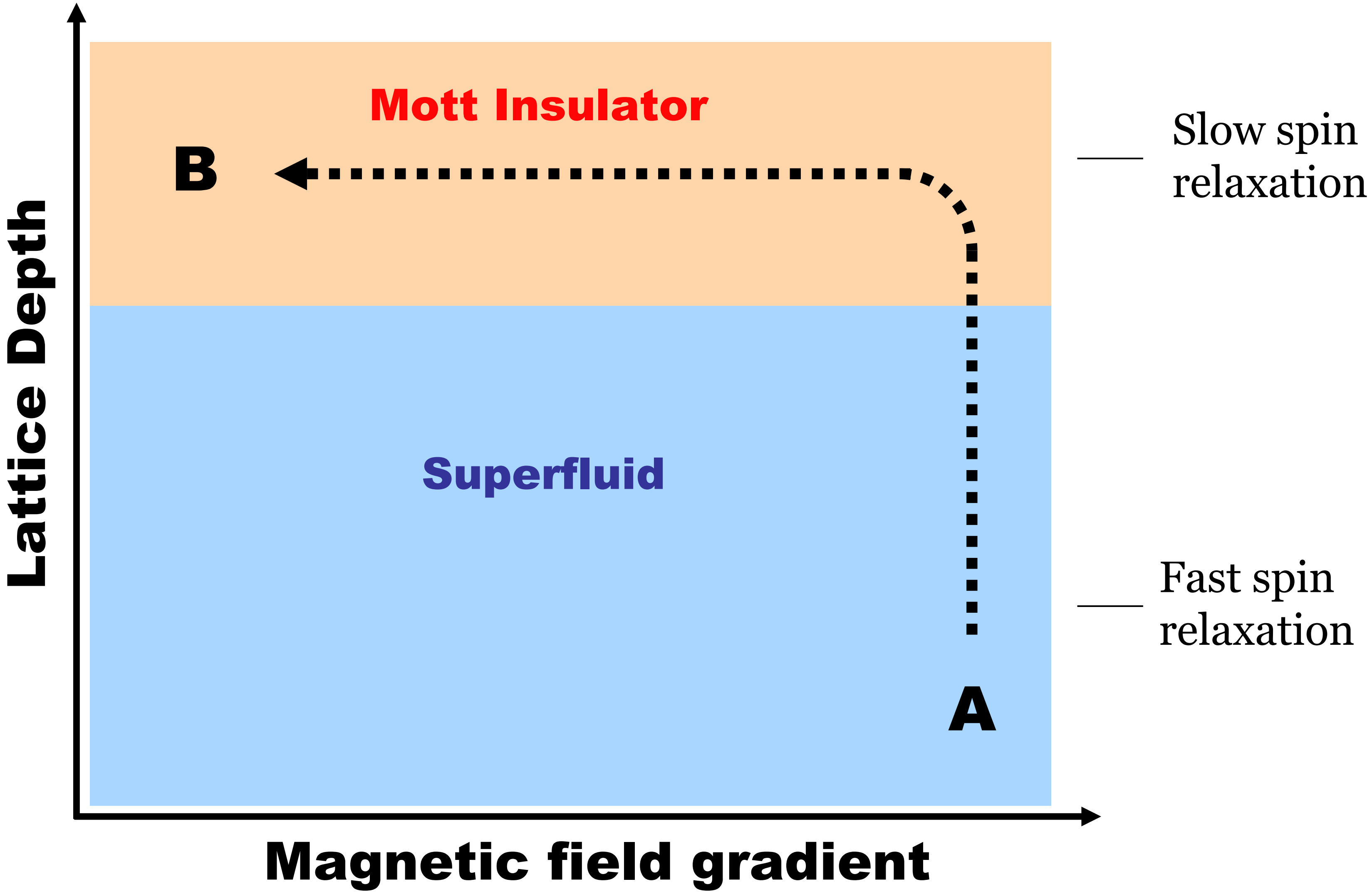
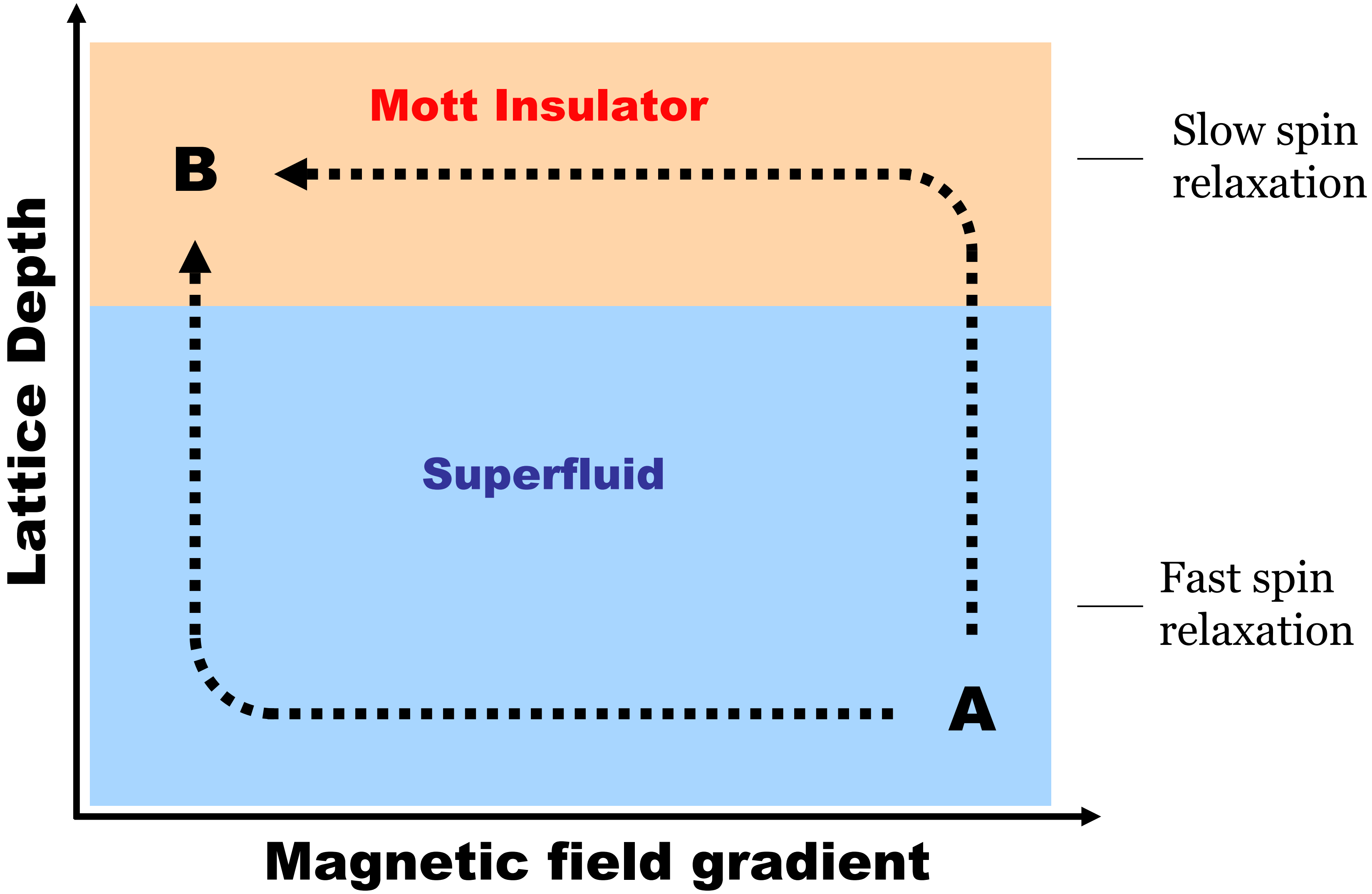


Slow spin relaxation

Fast spin relaxation

Experimental Phase Space



Mott Insulator

B

Superfluid

A

Slow spin relaxation

Fast spin relaxation

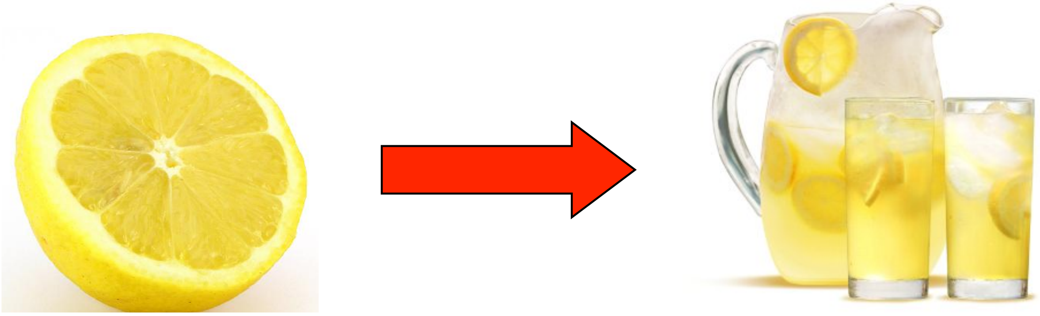
Lattice Depth

Magnetic field gradient

Controlling Spin Temperature

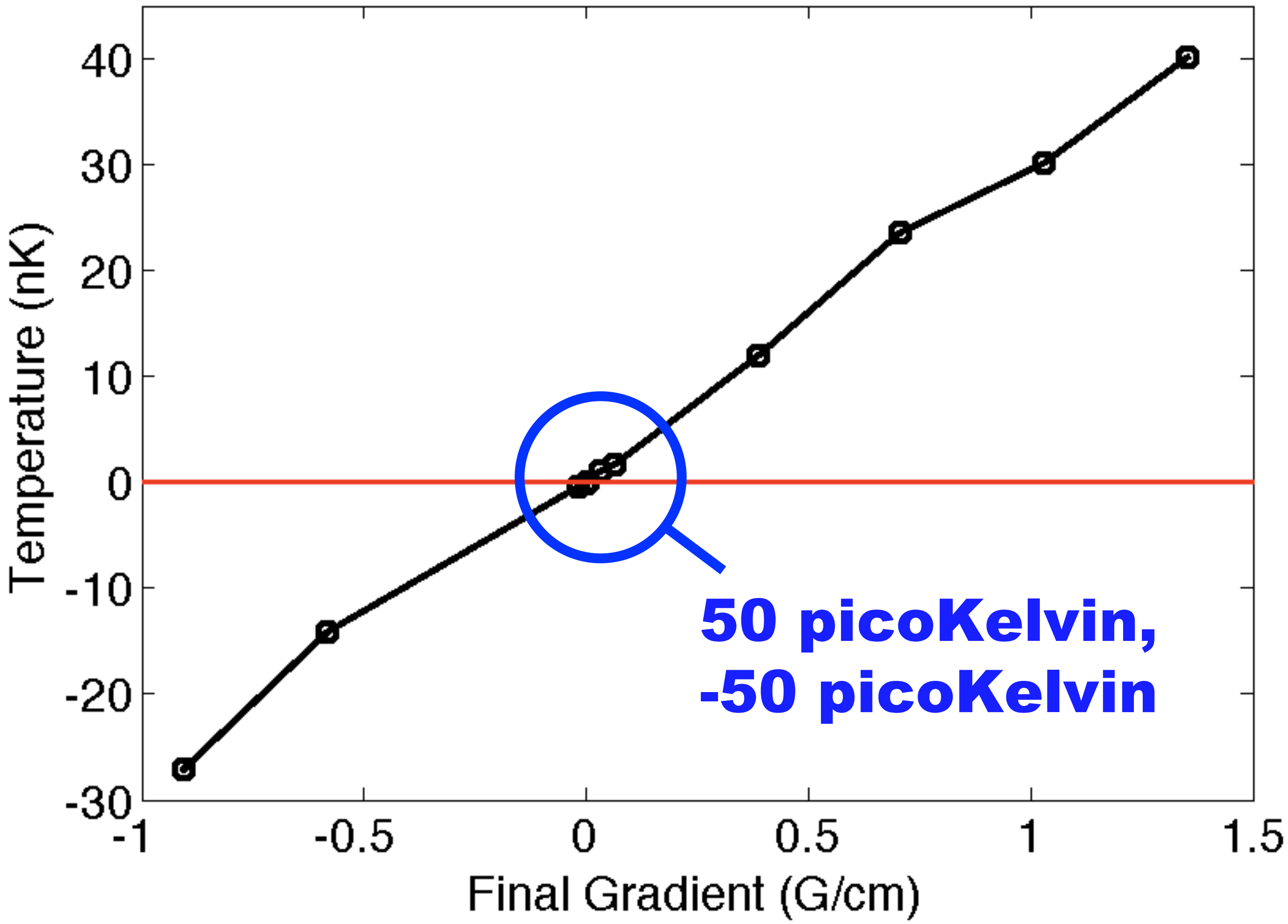
- When the lattice is raised **before** the gradient is changed, the system responds very slowly (~1 Hz).

- Slow response and finite heating rate makes it difficult to observe spin dynamics.



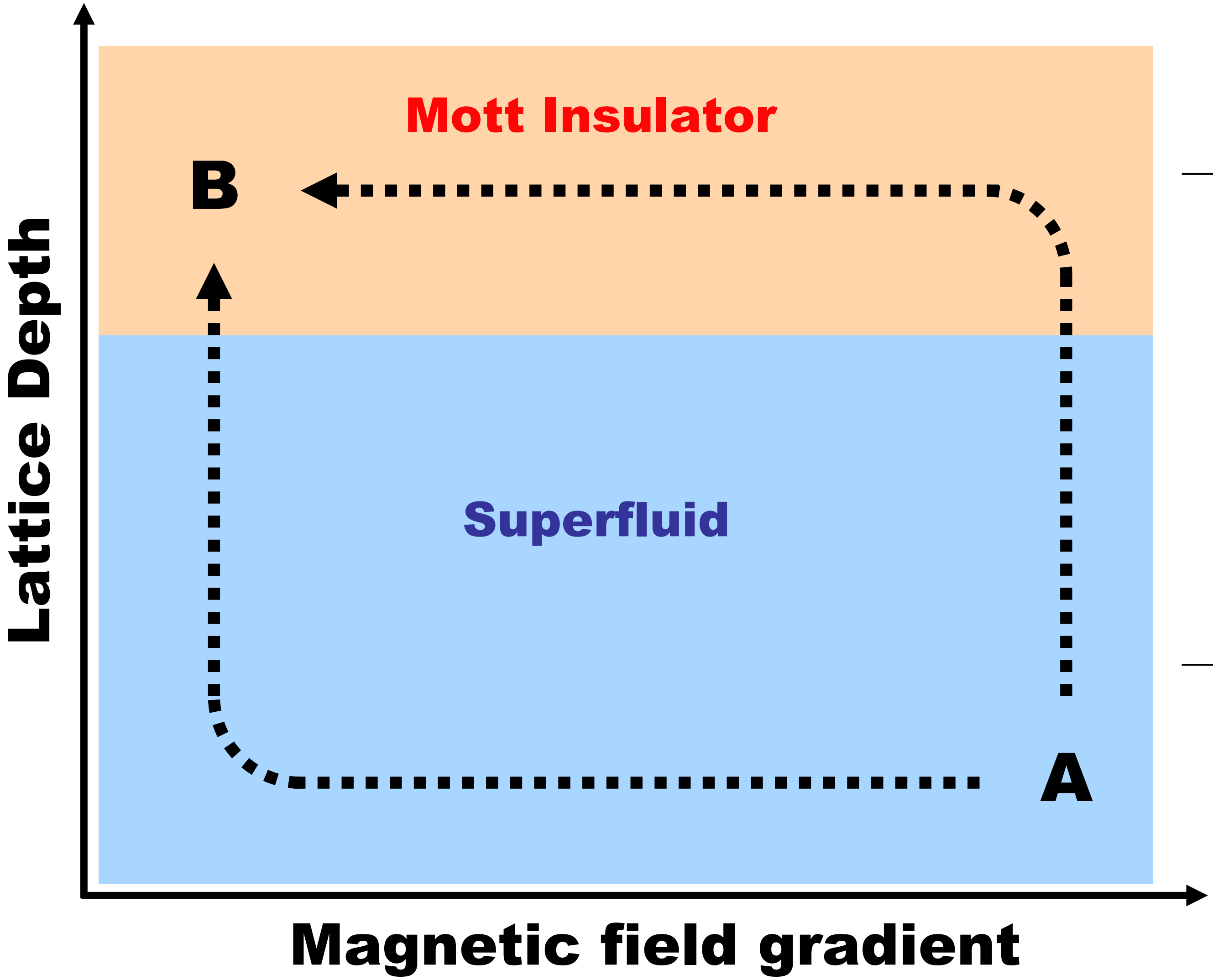
- This allows us to "dial in" any desired spin temperature.

Negative Spin Temperatures



- Takes advantage of long relaxation times in Mott insulator
- Not equilibrated with kinetic excitations

Experimental Phase Space



Slow spin relaxation

Fast spin relaxation

Demagnetization Cooling

- Magnetic field gradient is reduced adiabatically.

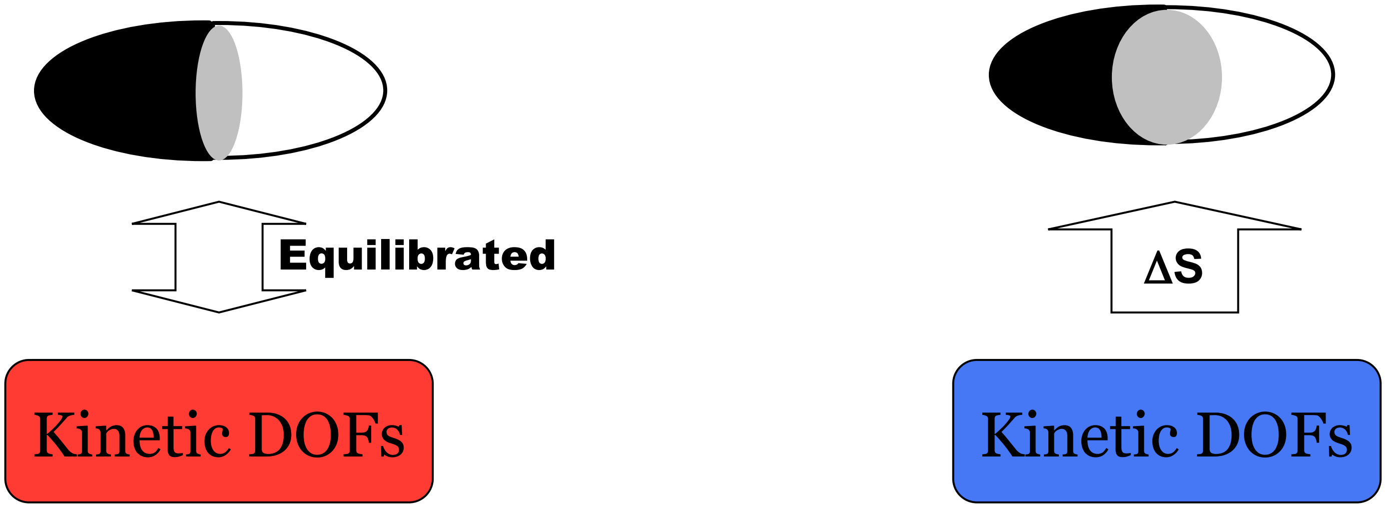
- Entropy has time to redistribute.

- This allows the spin degrees of freedom to **cool** the rest of the system.

- Analogous to **adiabatic demagnetization refrigeration** in condensed matter systems.

Gradient demagnetization cooling

Principle:



High gradient, $T_{initial}$

Low gradient, T_{final}

Equilibrated

ΔS

Kinetic DOFs

Kinetic DOFs

Principle of adiabatic cooling:

Compress energy spectrum of spin excitations.

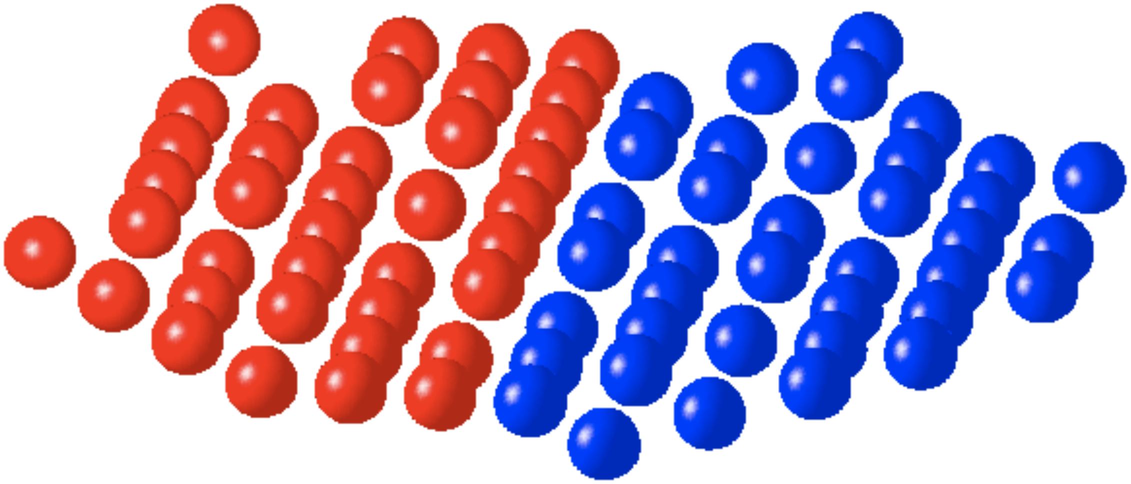
Entropy flows to the spin system.

Temperature drops.

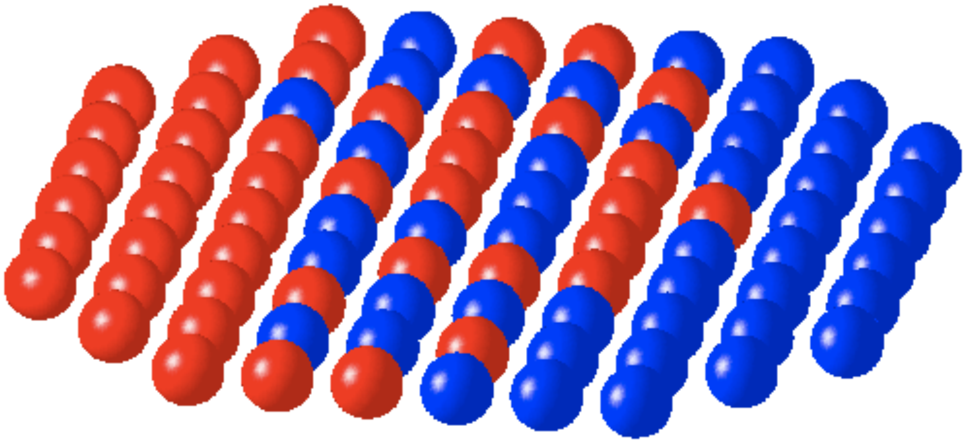
Gradient demagnetization cooling

Cartoon:

Initial State:



Final State:



Gradient demagnetization cooling

Calculations:

- Using LDA and neglecting tunneling, can calculate entropy at every lattice site
- Can thus plot how the distribution of entropy changes during adiabatic demagnetization
- Expect to see S pumped out of the P-H excitations and into the spin excitations

Gradient demagnetization cooling

Calculations:

$$\begin{aligned} E_i(n_\uparrow, n_\downarrow, \nabla\mathbf{B}) \;=\; & p \cdot \nabla\mathbf{B} \cdot x_i \cdot (n_\uparrow - n_\downarrow) \\ & + \frac{1}{2}\sum_\sigma U_{\sigma\sigma} n_\sigma (n_\sigma - 1) + U_{\uparrow\downarrow} n_\uparrow n_\downarrow \\ & + V_i(n_\uparrow + n_\downarrow) - \mu_\uparrow n_\uparrow - \mu_\downarrow n_\downarrow \end{aligned}$$

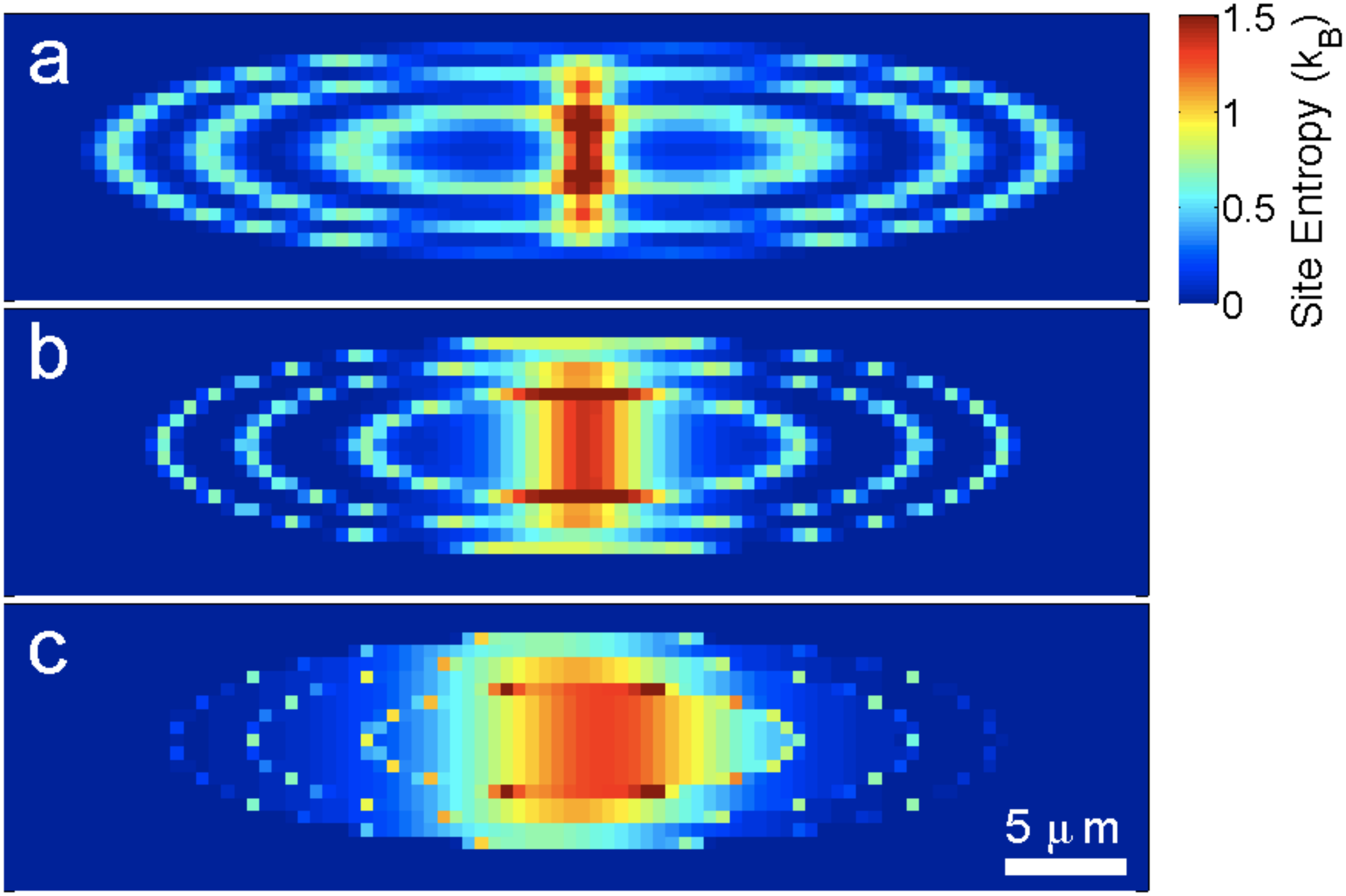
$$Z_i(\nabla\mathbf{B}) \;=\; \textstyle\sum_{\{n_\uparrow, n_\downarrow\}} \exp(-E_i(n_\uparrow, n_\downarrow, \nabla\mathbf{B})/k_B T)$$

$$p_i(n_\uparrow, n_\downarrow, \nabla\mathbf{B}, T) = \frac{\exp\left(-E_i(n_\uparrow, n_\downarrow, \nabla\mathbf{B})/k_B T\right)}{Z_i}$$

$$S_i(\nabla\mathbf{B}, T) = \sum_{\{n_\uparrow, n_\downarrow\}} -p_i \log p_i$$

Gradient demagnetization cooling

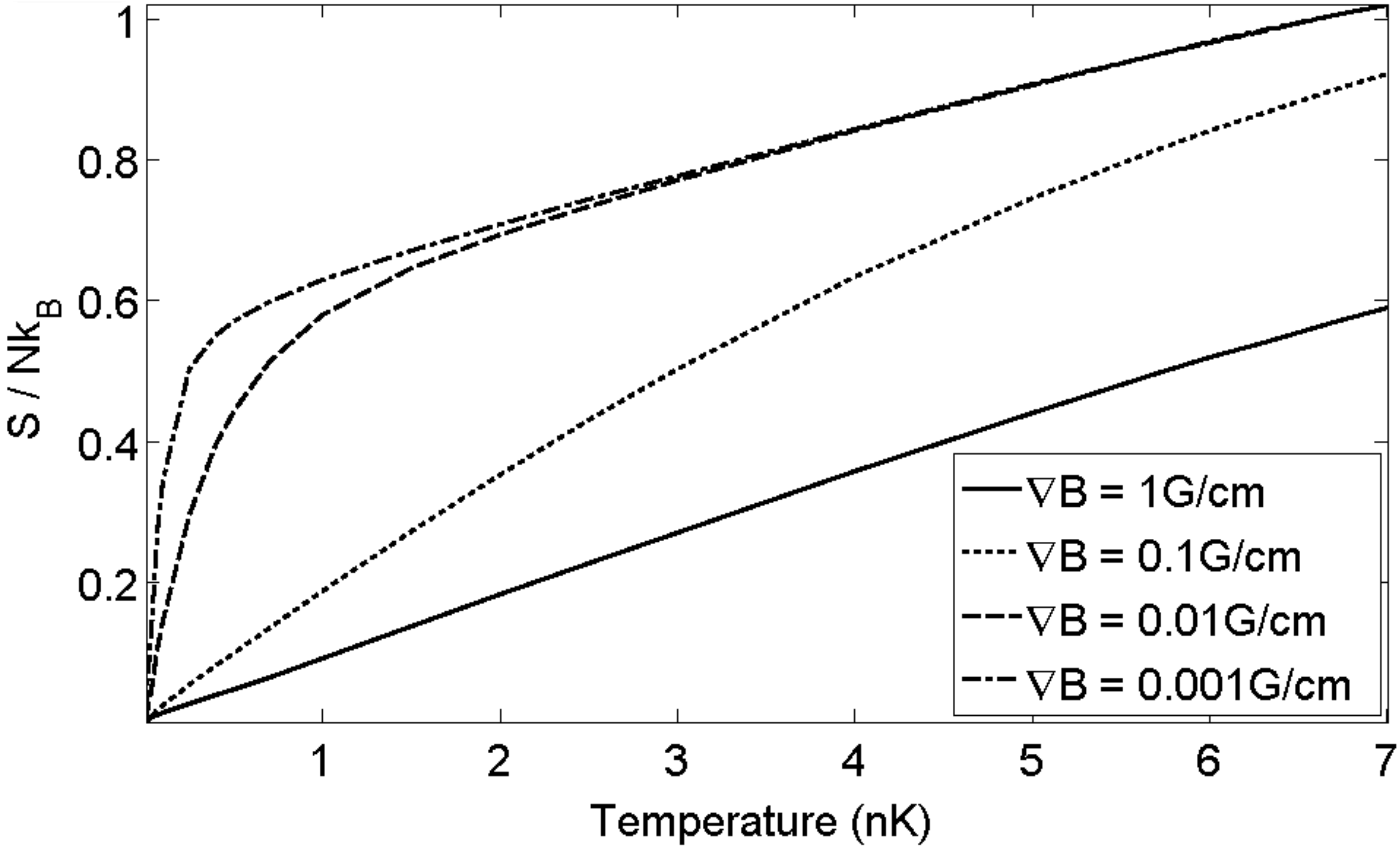
Calculations:



D. M. Weld, H. Miyake, P. Medley, D. E. Pritchard, and W. Ketterle, arXiv:1008.4610 (2010)

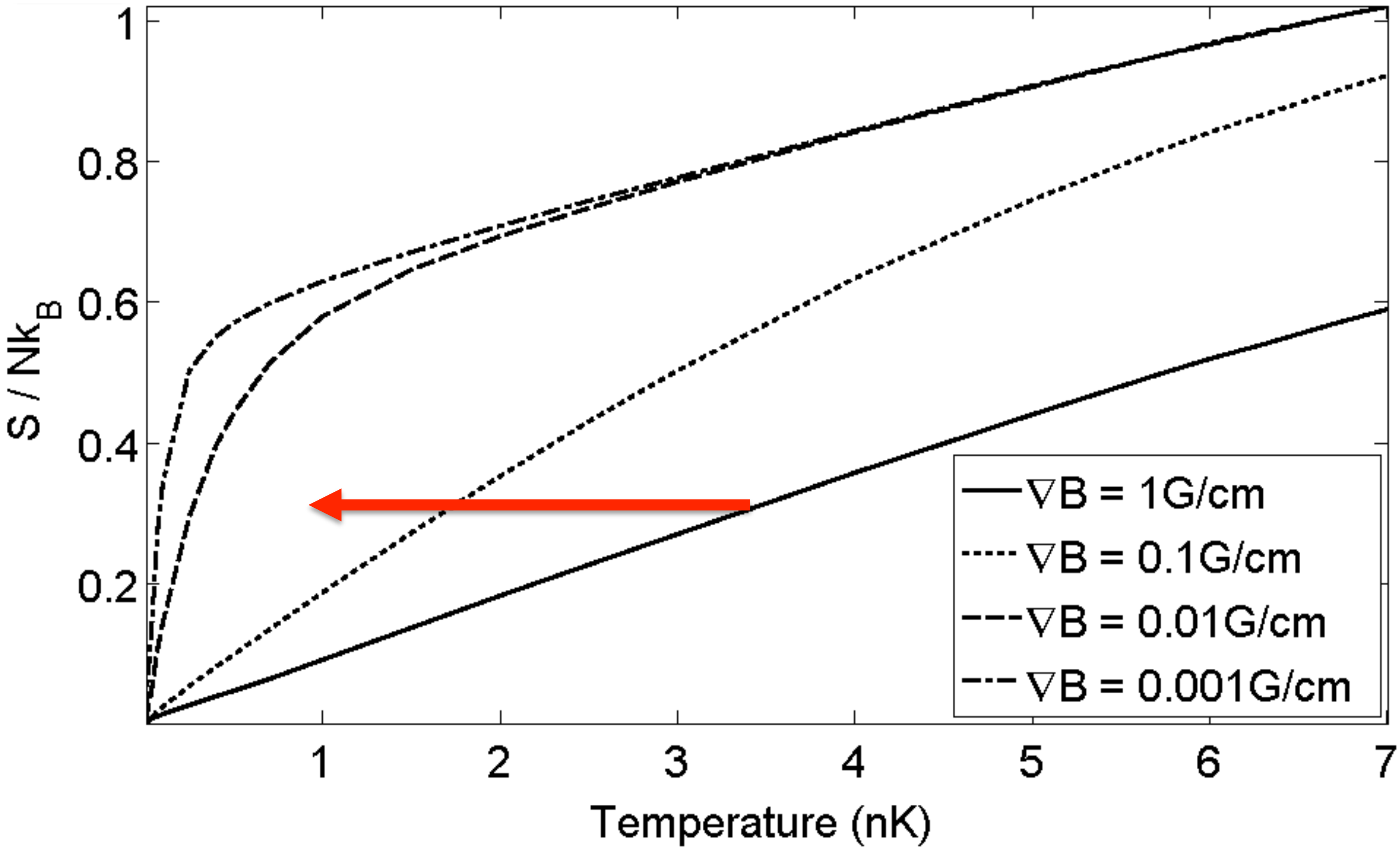
Gradient demagnetization cooling

Calculations:



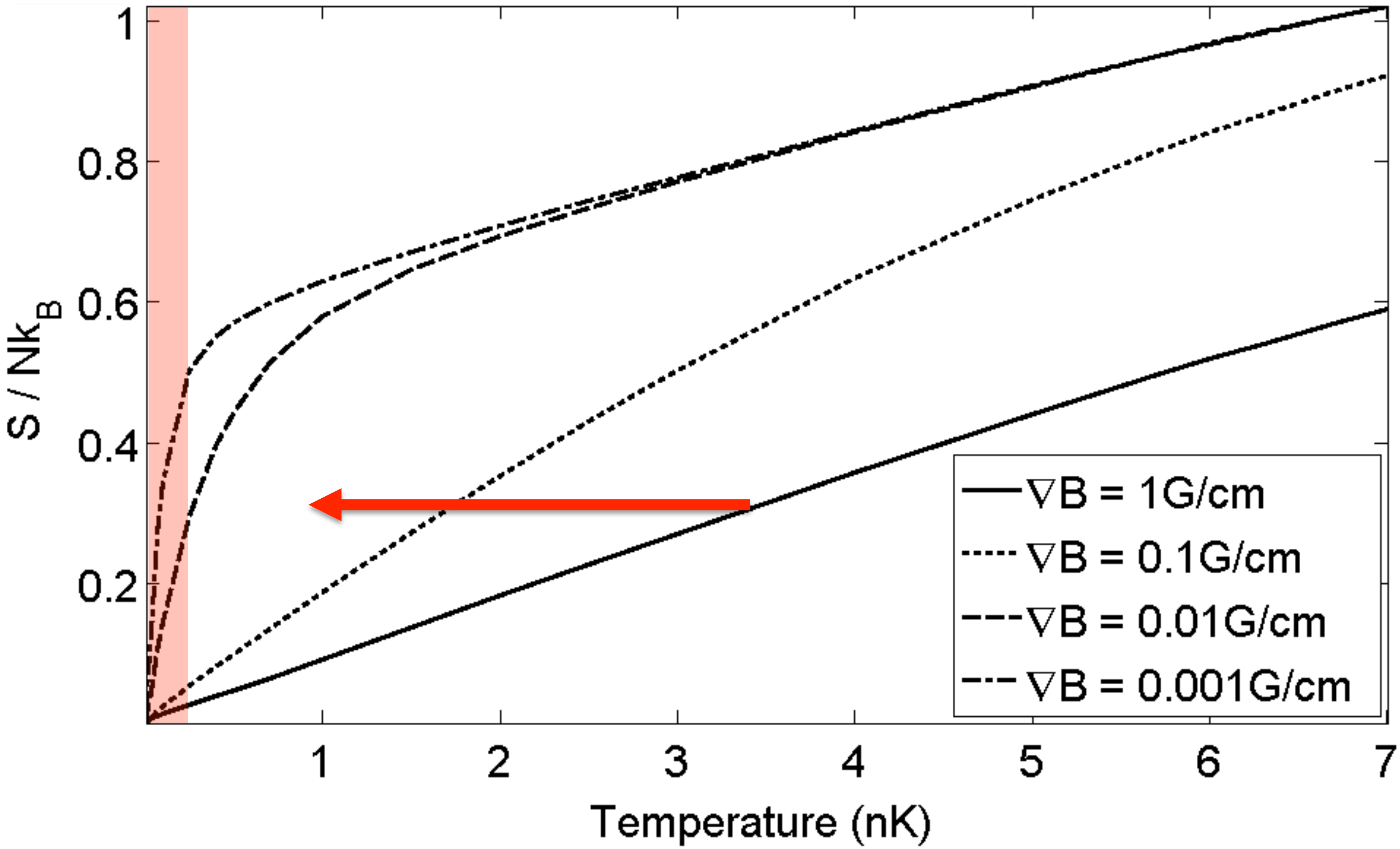
Gradient demagnetization cooling

Calculations:



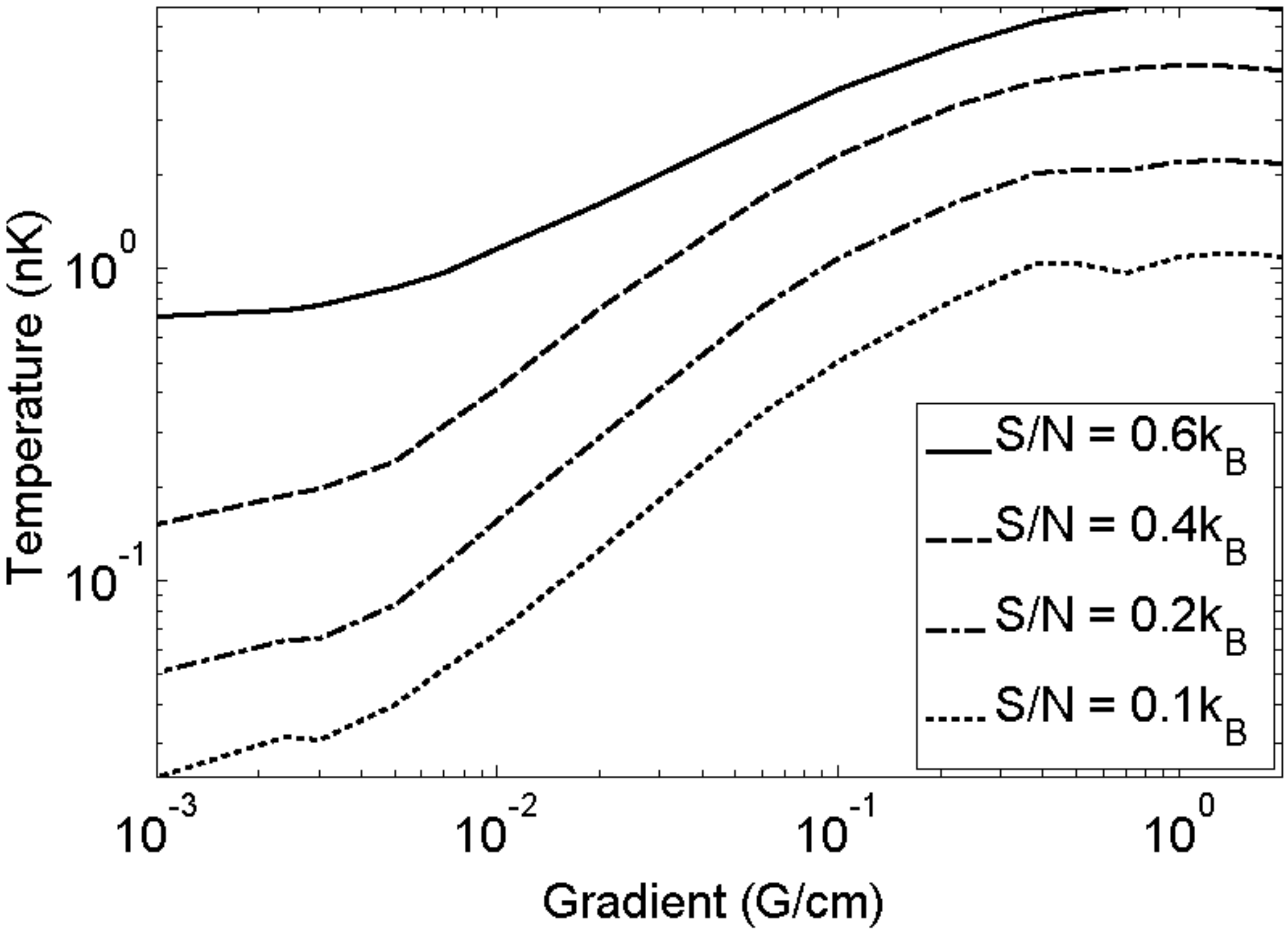
Gradient demagnetization cooling

Calculations:



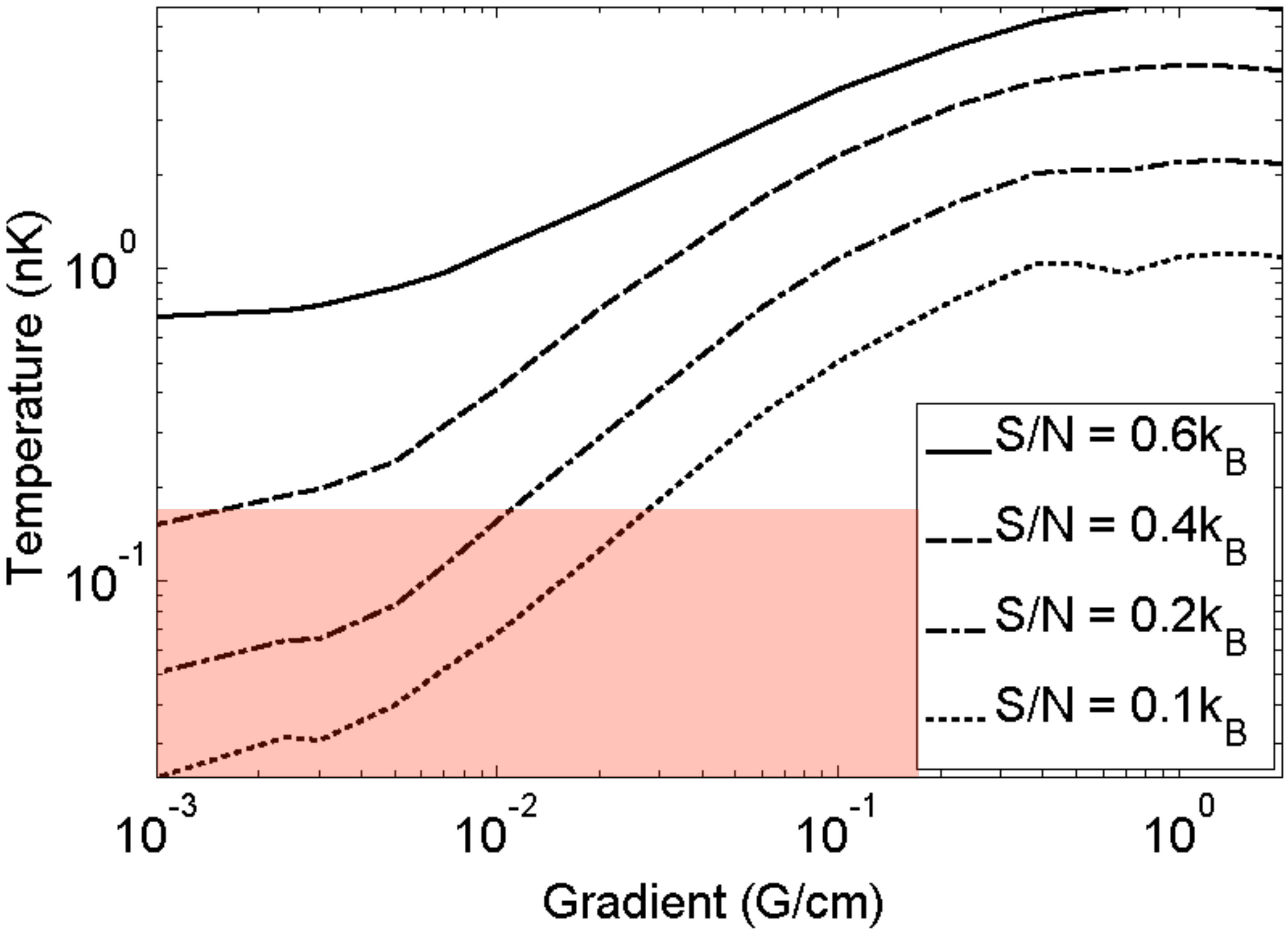
Gradient demagnetization cooling

Calculations:



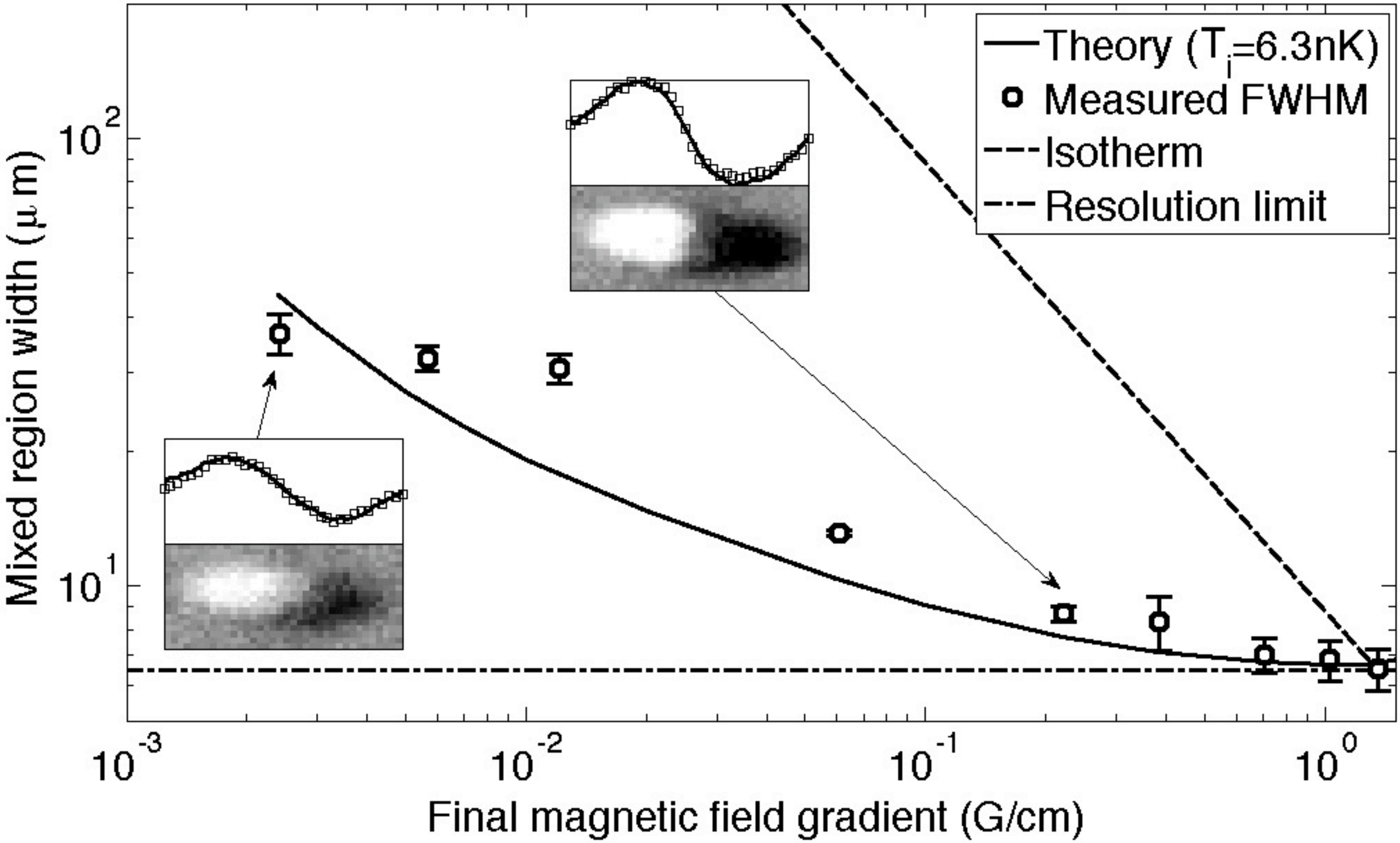
Gradient demagnetization cooling

Calculations:



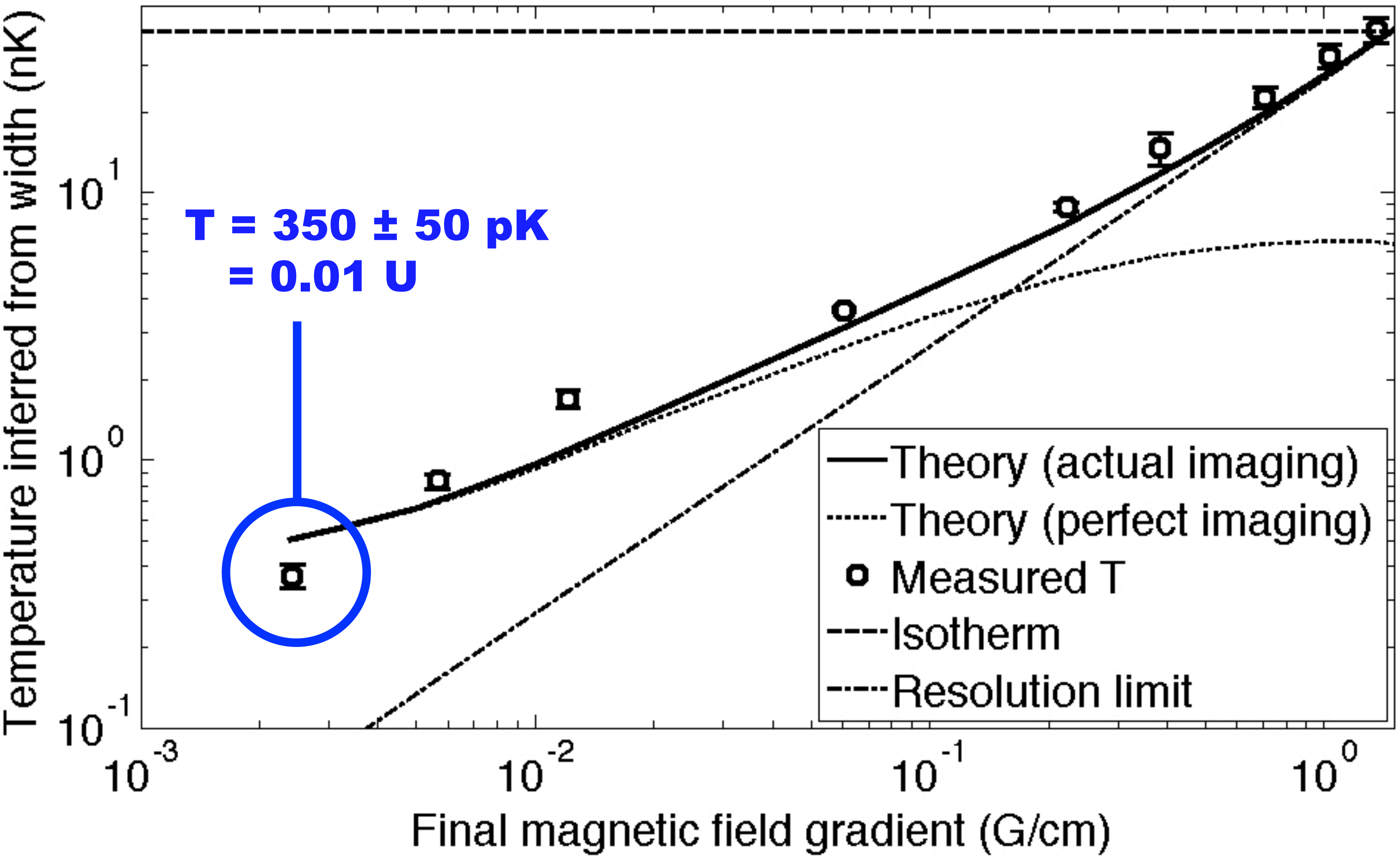
Gradient demagnetization cooling

Results:



Gradient demagnetization cooling

Results:



P. Medley, D. M. Weld, H. Miyake, D. E. Pritchard, and W. Ketterle, arXiv:1006.4674 (2010)

Demagnetization Cooling: Overview

- **Lower magnetic field gradient adiabatically**
- **Entropy redistributes; system is cooled**
  - Spin gradient thermometry measures final T of **350 pK**
  - Equilibration in deep lattice not guaranteed
  - But fit to tanh profile, fast response time of SF, reversibility of grad ramps, fit to cooling model, and thermometry check all point to good equilibration
- **If equilibrated, lowest temperatures ever measured**
  - Previous records:
    - Kinetic temperature in a gas: 450 pK (MIT, 2003)
    - Spin temperature: 100 pK, -750 pK (Helsinki, 1993-2000)

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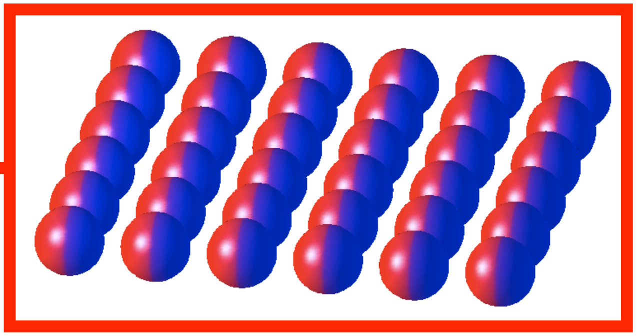
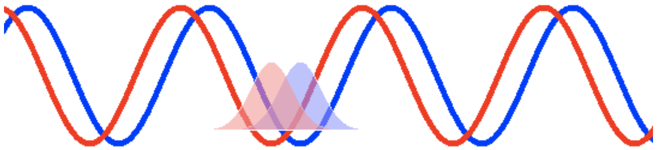
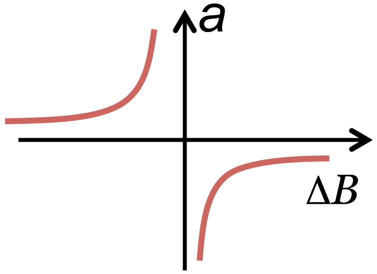


Future Directions: Magnetic Ordering

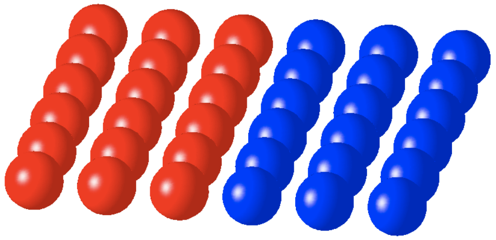
- Apply spin-dependent lattice or Feshbach resonance



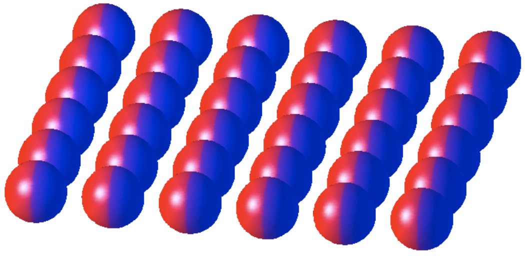
$$U_{\uparrow\downarrow} \neq U_{\uparrow\uparrow} \neq U_{\downarrow\downarrow},\quad t_{\uparrow} \neq t_{\downarrow}$$



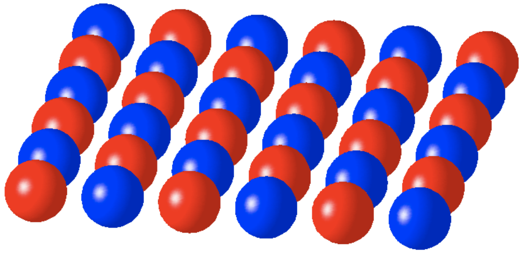
- Vary ground state
- Observe magnetic phase transitions:



Z-Ferromagnet

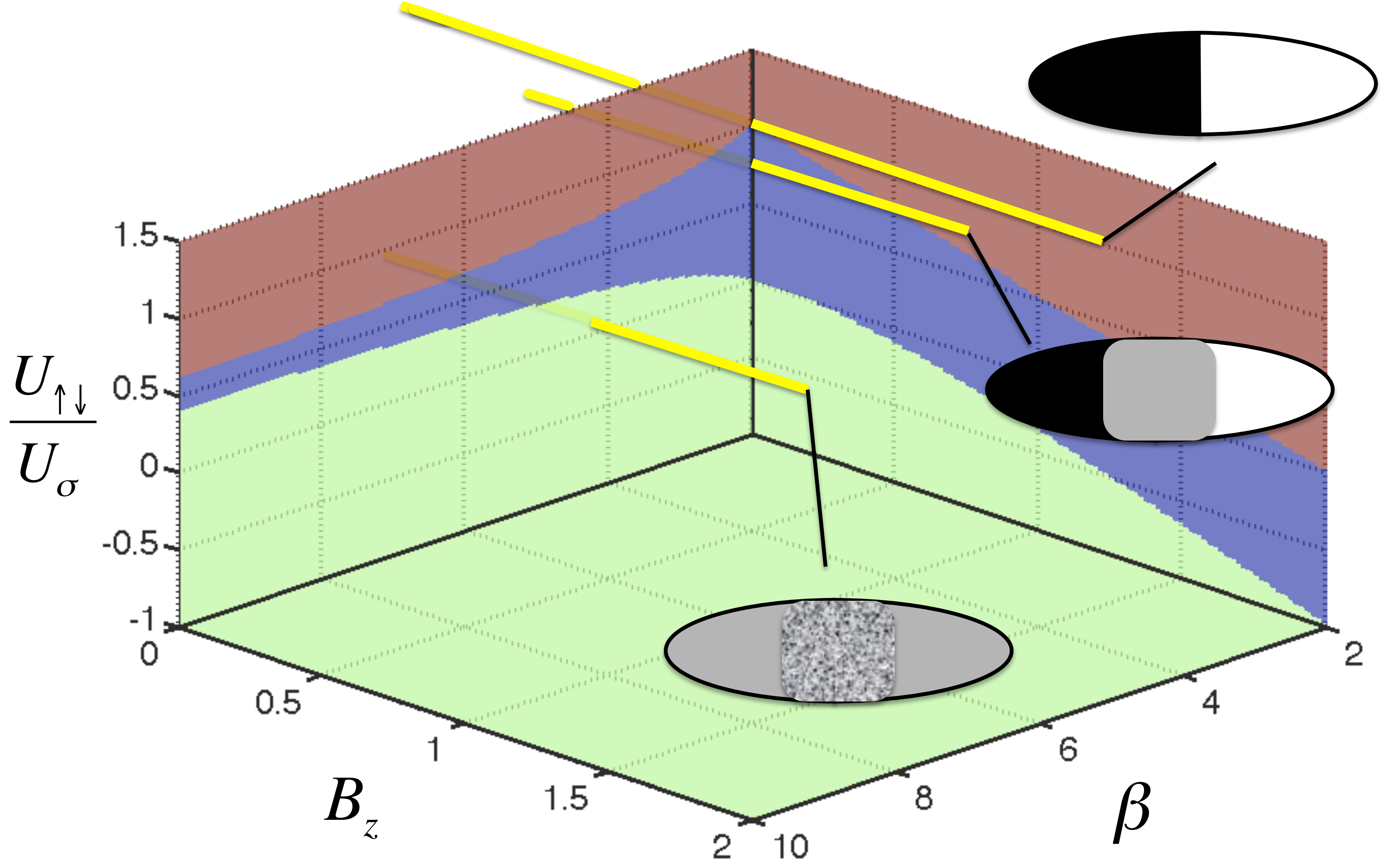


XY-Ferromagnet



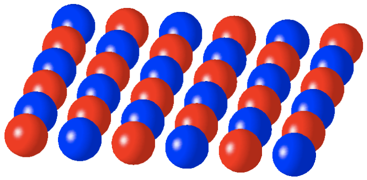
Antiferromagnet

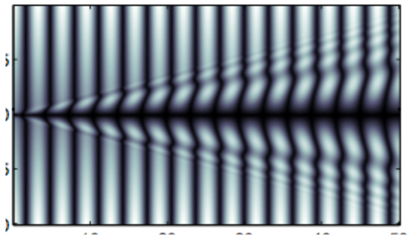
Experimental Realization

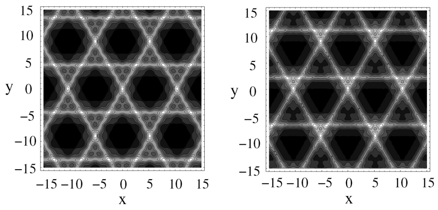


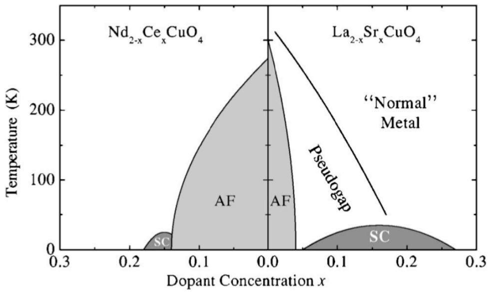
Future Directions

- Magnetic ordering
- Excitations
- Quantum criticality
- Dynamics & transport
- Frustration
- 3-component mixtures (color)
- Spin liquids, RVB states
- d-wave pairing in doped AF
- Etc…









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