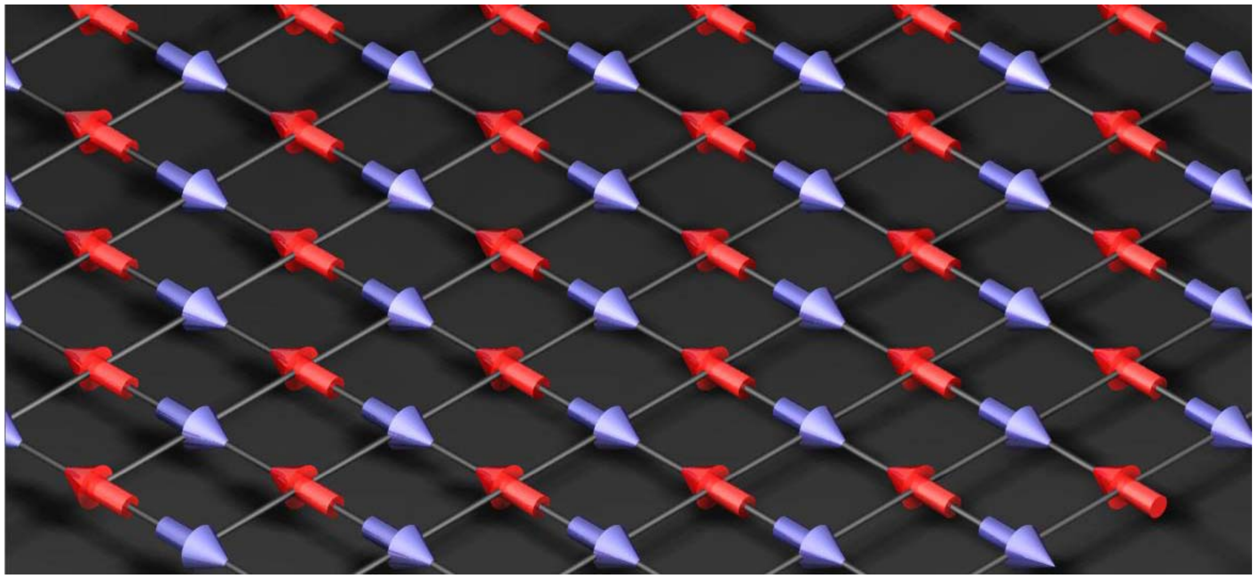
Quantum Simulations using Fermionic Atoms in Optical Lattices



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Fermi Gas Group at Penn State

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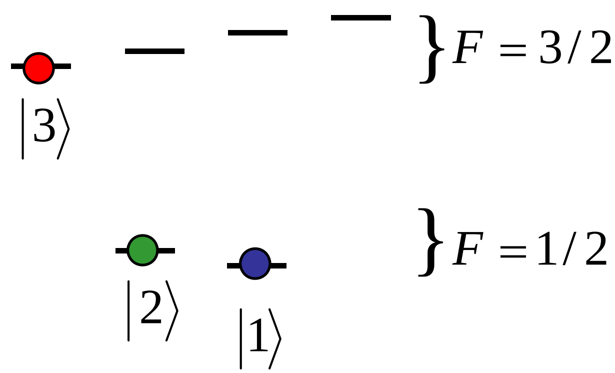
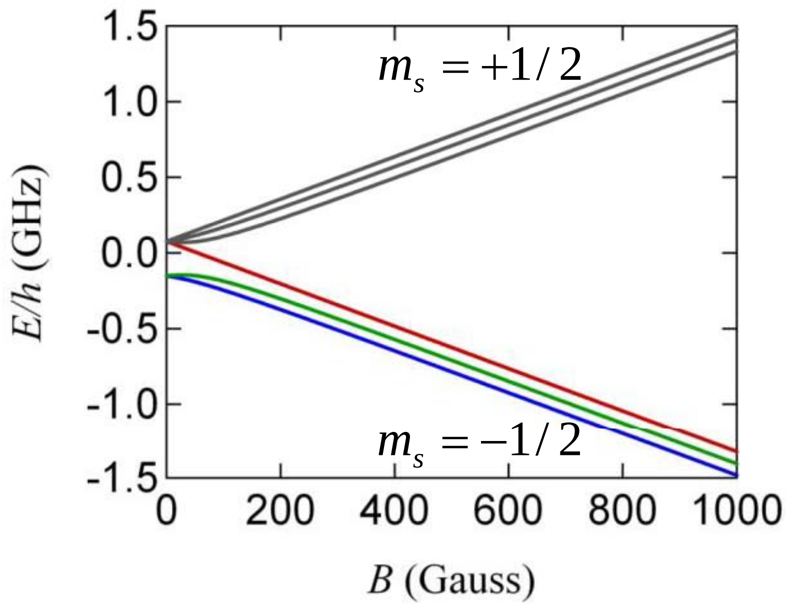
Outline

- Ultracold Fermionic Atoms
- The Hubbard Model
  - Quantum Magnetism
  - High-temperature superconductivity
- Reducing the Entropy of Atoms in a Lattice
- Three-Component Fermi Gases
  - The quantum 3-body problem
  - SU(3) Hubbard model: Color Superfluidity

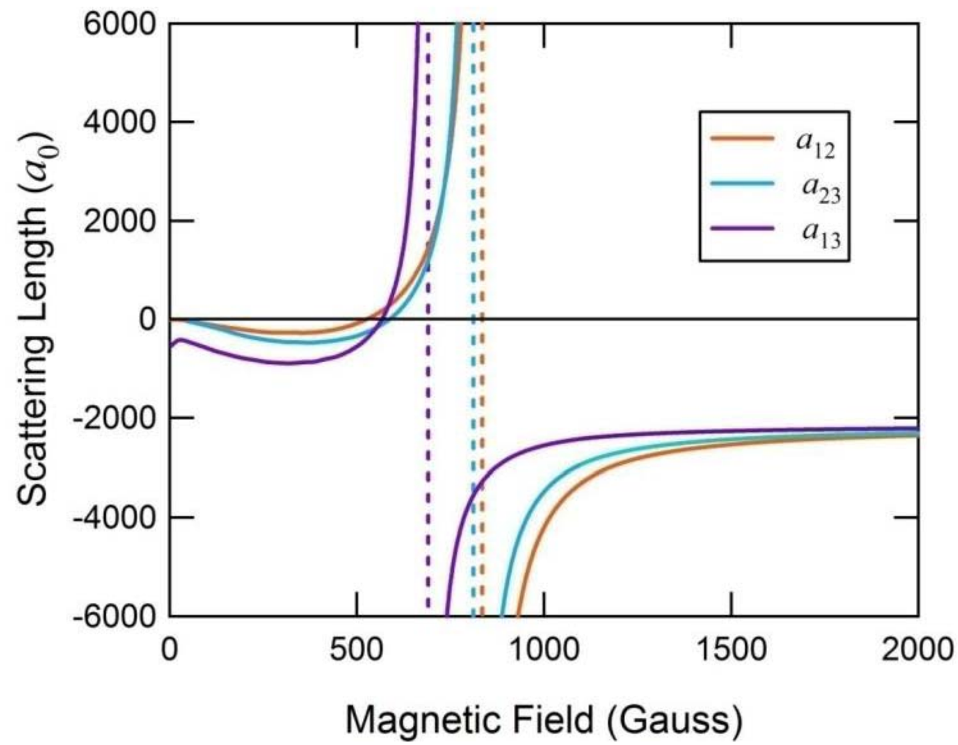
Two-State Mixtures in ^{6}Li

Hyperfine States





Feshbach Resonances

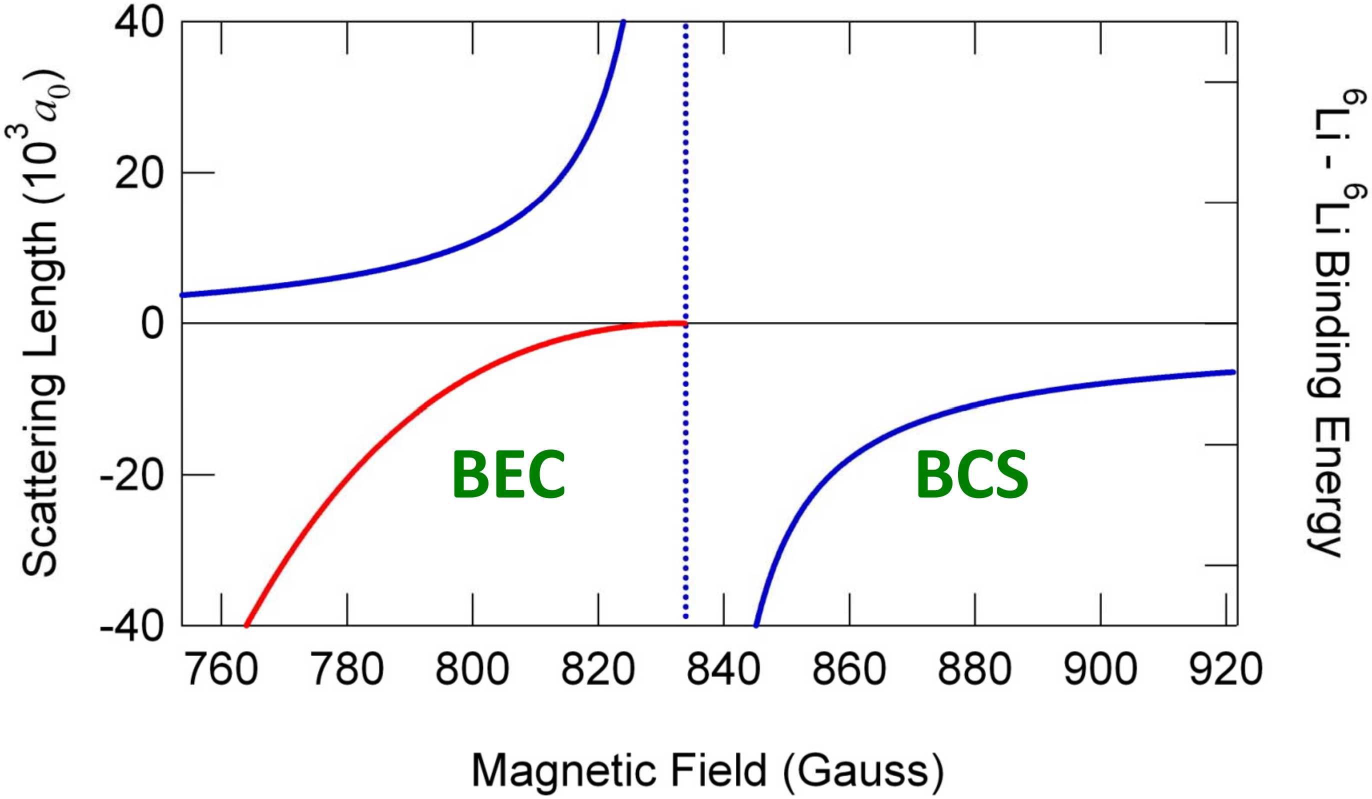


Interactions at High Field

$$a_{12}, a_{23}, a_{13} \rightarrow a_t \quad \text{as} \quad B \rightarrow \infty$$

$$a_t = -2140 a_0$$

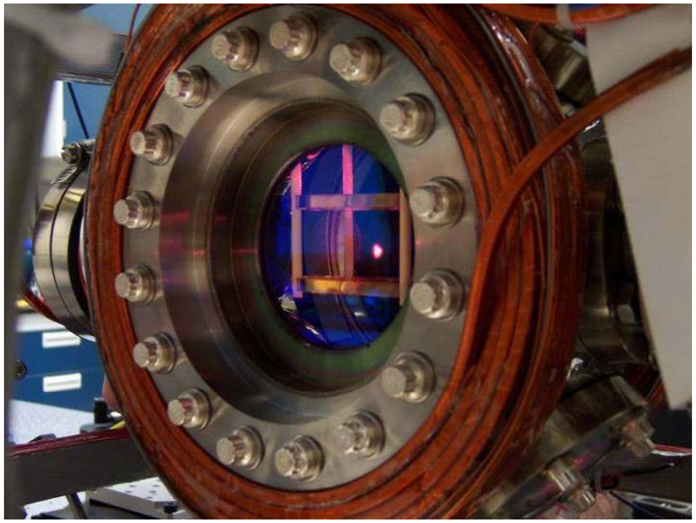
BEC-BCS Crossover with a Feshbach Resonance



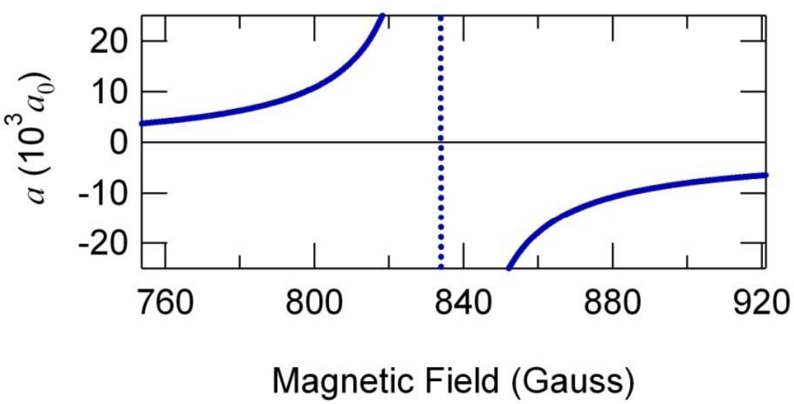
$$V(\mathbf{r}_1 - \mathbf{r}_2) = g\,\delta^{(3)}(\mathbf{r}_1 - \mathbf{r}_2)$$

$$g = \frac{4\pi\hbar^2 a}{m}$$

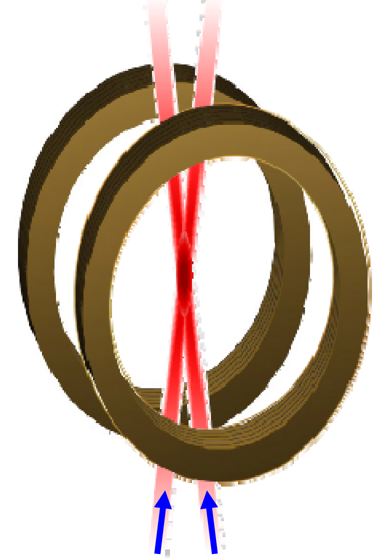
Making Degenerate Fermi Gases



- Magneto-Optical Trap
- Optical Trap
- Evaporative Cooling (at 760 Gauss)



Vertical crossed-dipole trap:
Two 80 Watt 1064 nm beams

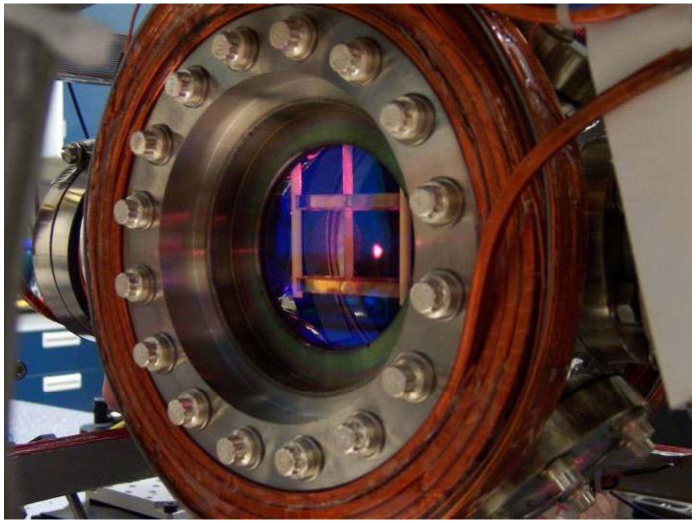


U_f = 38 μK/beam

ν_y = 106 Hz
ν_z = 965 Hz
ν_x = 3.84 kHz

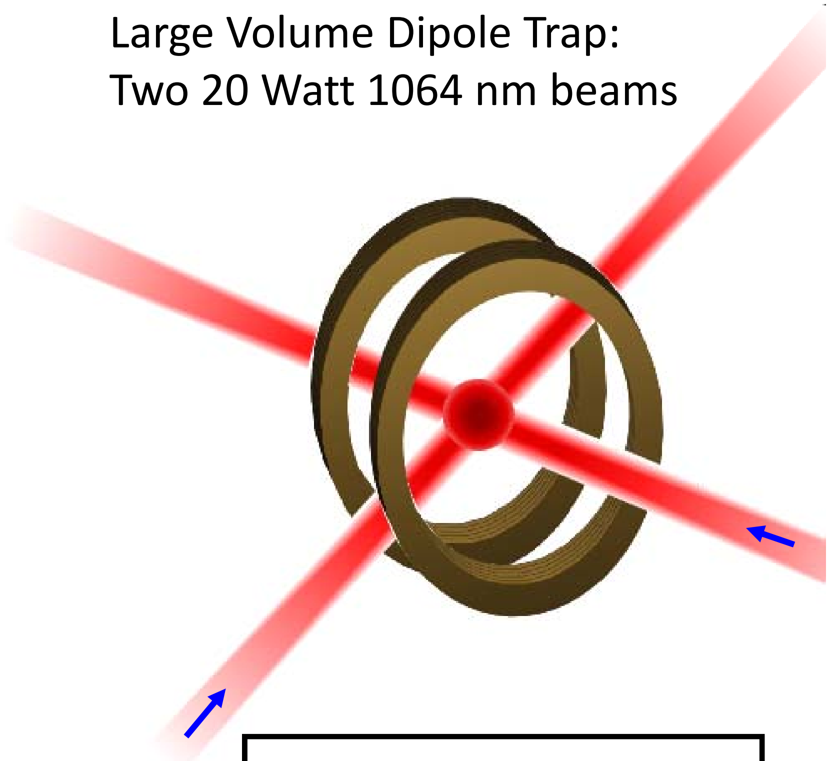
N = 2 x 10^5 atoms
T_F = 3 μK

Making Degenerate Fermi Gases



- Magneto-Optical Trap
- Optical Trap
- Evaporative Cooling (at 760 Gauss)
- Transfer to Large Volume Trap

Large Volume Dipole Trap:
Two 20 Watt 1064 nm beams



U_f = 2 μK/beam

ν_y = 21 Hz
ν_z = 35 Hz
ν_x = 92 Hz

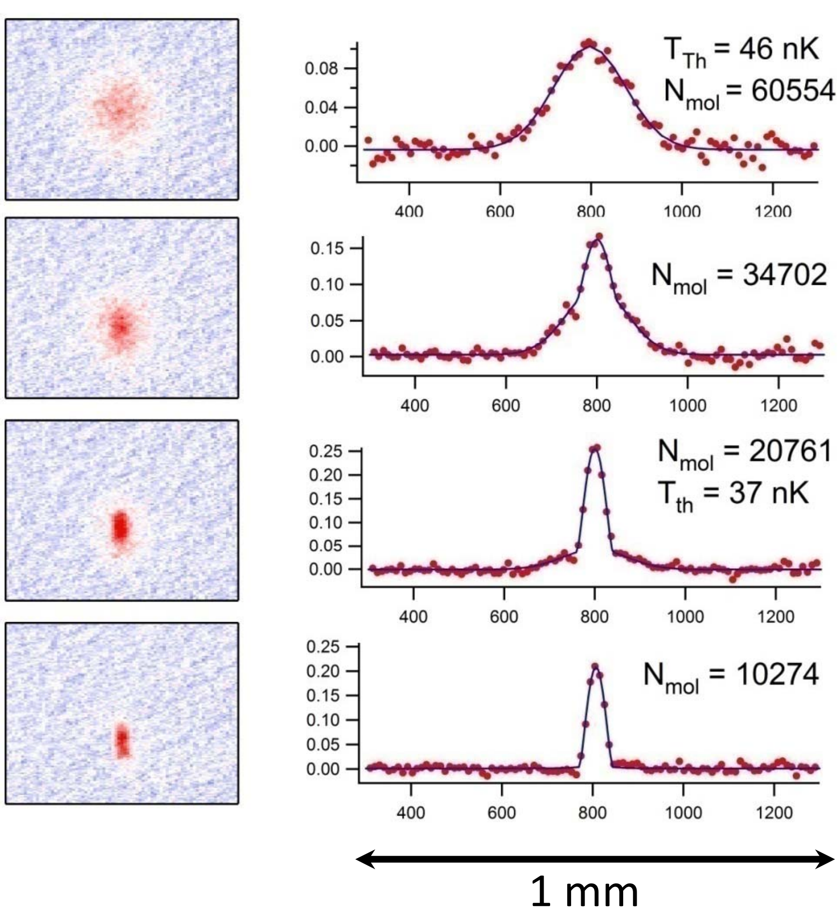
N = 2 x 10^5 atoms
T_F = 160 nK

BEC and DFG of ^{6}Li

BEC of Li_2 Molecules

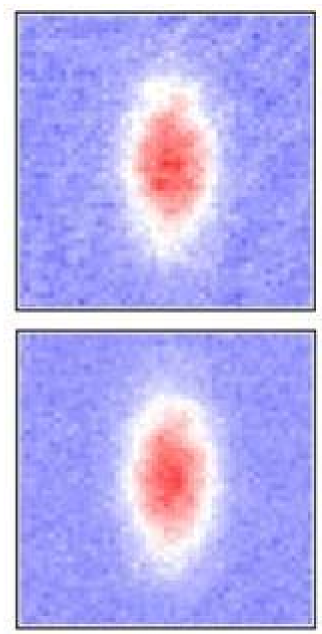
Absorption Image after Expansion

$$t_{\text{TOF}} = 10\text{ms}$$



2-State Degenerate Fermi Gas

Absorption Image after Expansion



$$|1\rangle$$

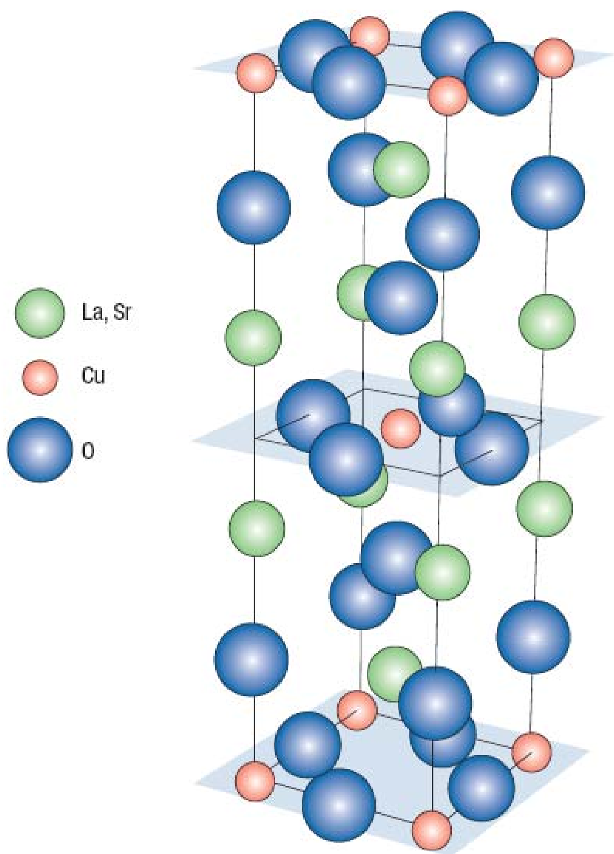
$$|2\rangle$$

$$N_\uparrow = N_\downarrow = 10^5 \qquad T \leq 0.1 T_F$$

$$T_F = 160\,\text{nK} \qquad T \leq 16\,\text{nK}$$

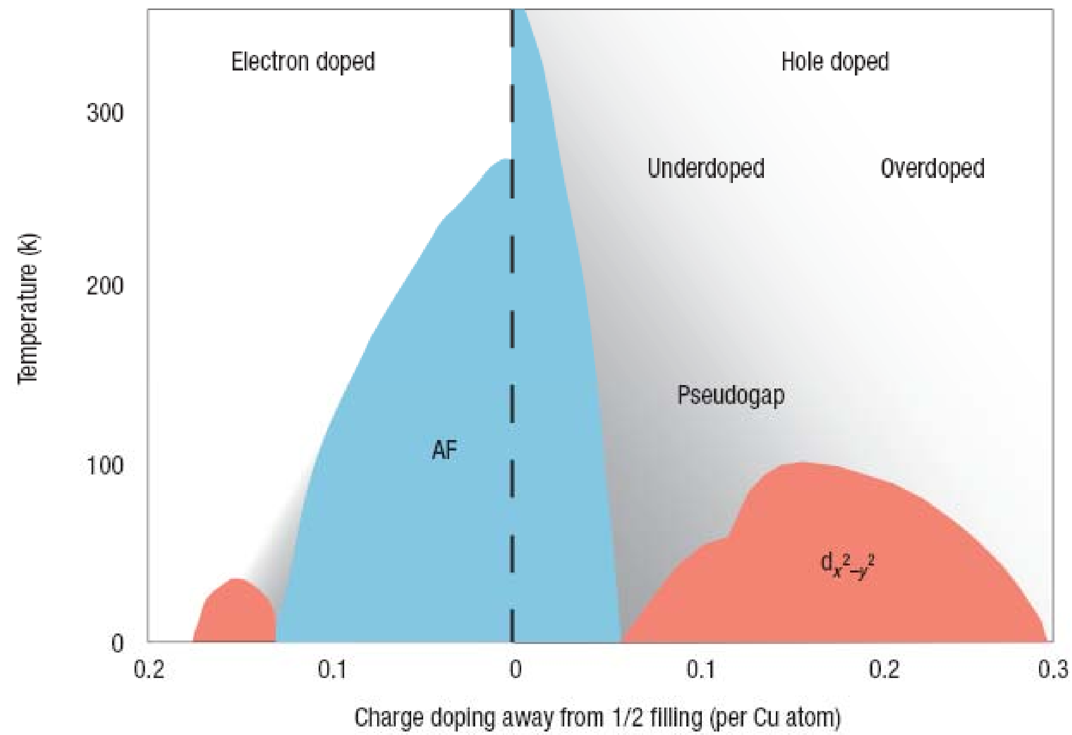
High-Temperature Superconductors

$La_{2-x}Sr_xCuO_4$
Crystalline Structure



Weakly Coupled
Square-Planar Sheets of CuO

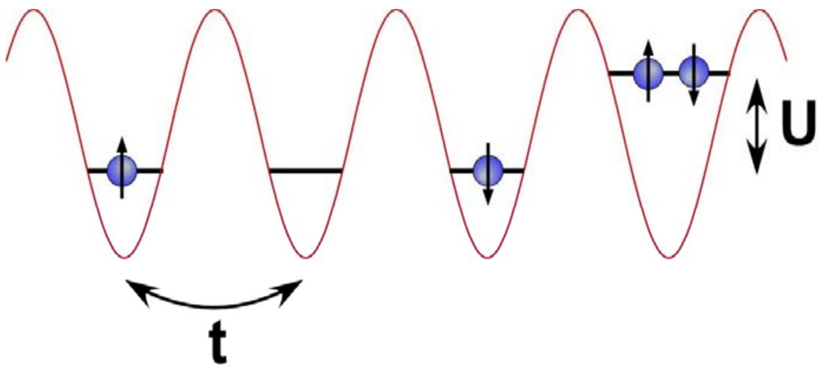
Typical Phase Diagram
of the Cuprates



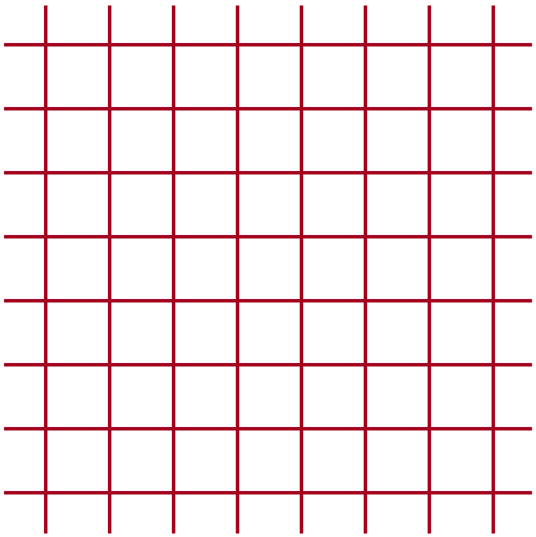
Antiferromagnetism
Adjacent to Superconductivity

The 2D Hubbard Model

- Simplest Model that includes Band Structure & Interactions



Square 2D Lattice



$$H = -t \sum_{\langle i,j \rangle,\sigma} (c^\dagger_{i,\sigma} c_{j,\sigma} + h.c.) + U \sum_j n_{j,\uparrow} n_{j,\downarrow}$$

t = hopping term, describes tunneling between lattice sites

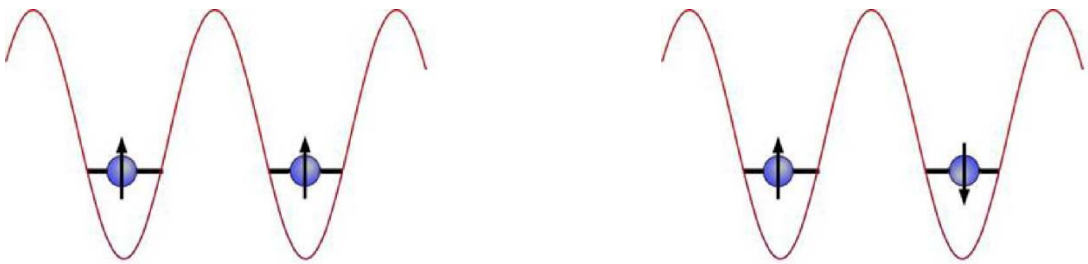
U = Interaction term, describes energy cost of filling doubly occupied sites

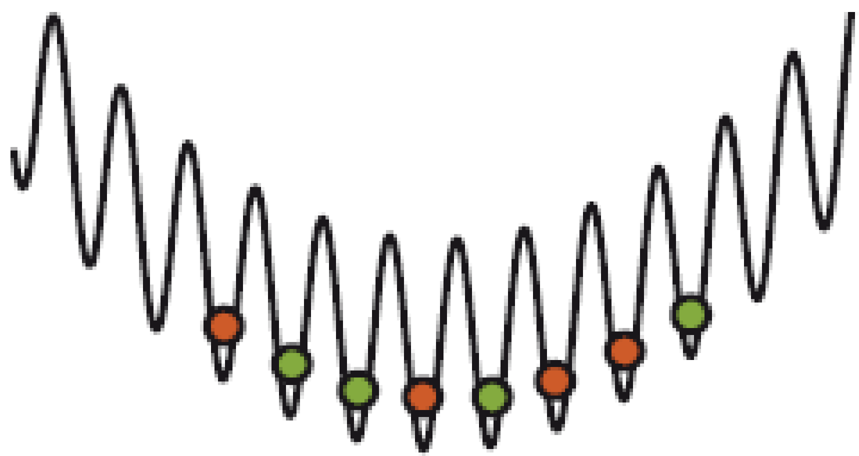
- Repulsive-*U* Hubbard Model

$U > 0$: Mimics Coulomb Repulsion between Electrons

Large U: Mott Insulator

- $U/t \to \infty$: Insulator
- Ground State: Mott Insulator



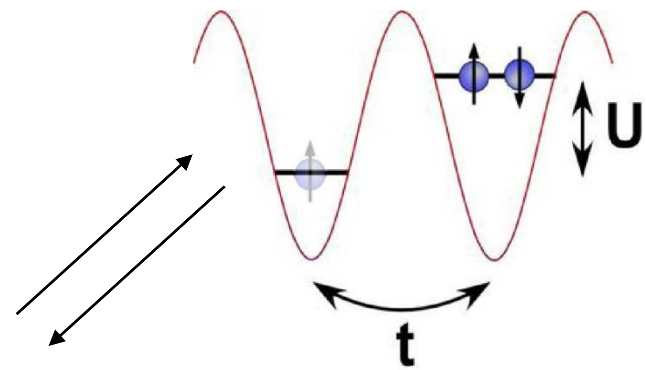


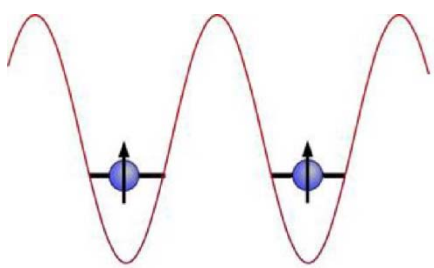
Non-zero *t*: Exchange Interactions

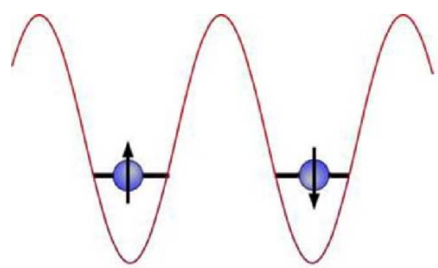
- Small, but nonzero *t*
- Matrix element *t* couples to doubly occupied sites

$$H_0 = U \sum_j n_{j,\uparrow} n_{j,\downarrow}$$

$$H_t = -t \sum_{\langle i,j \rangle, \sigma} \left(c_{i,\sigma}^{\dagger} c_{j,\sigma} + h.c. \right)$$





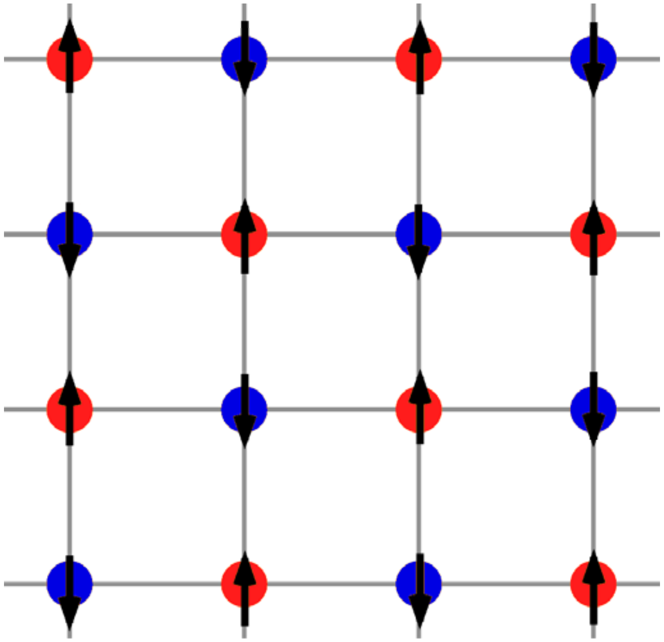


$$H^{(2)} = -\frac{\langle g | H_t | e \rangle \langle e | H_t | g \rangle}{\langle e | H_0 | e \rangle} = -\frac{t^2}{U}$$

$$H_{AF} = J \mathbf{S}_1 \cdot \mathbf{S}_2 \qquad J = \frac{4t^2}{U}$$

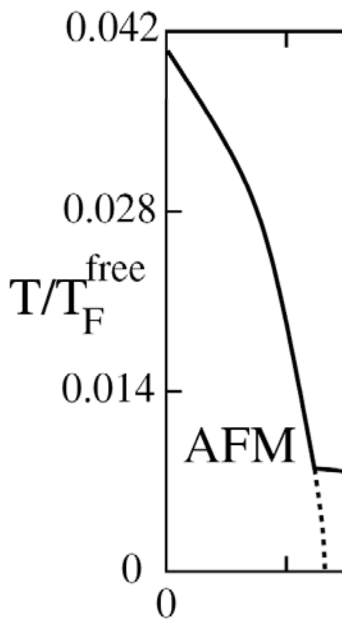
Anti-Ferromagnetic Mott Insulator

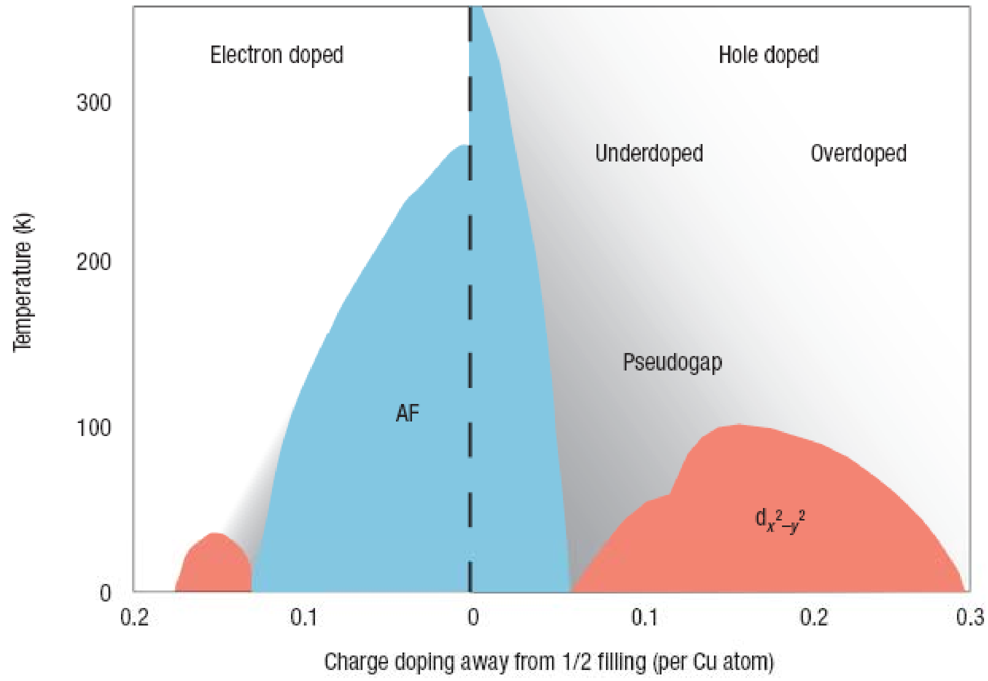
$$H_{AF} = J\mathbf{S}_1 \cdot \mathbf{S}_2 \qquad J = \frac{4t^2}{U}$$



Phase Diagram of the Hubbard Model

Phase Diagram in Fluctuation-Exchange Approximation





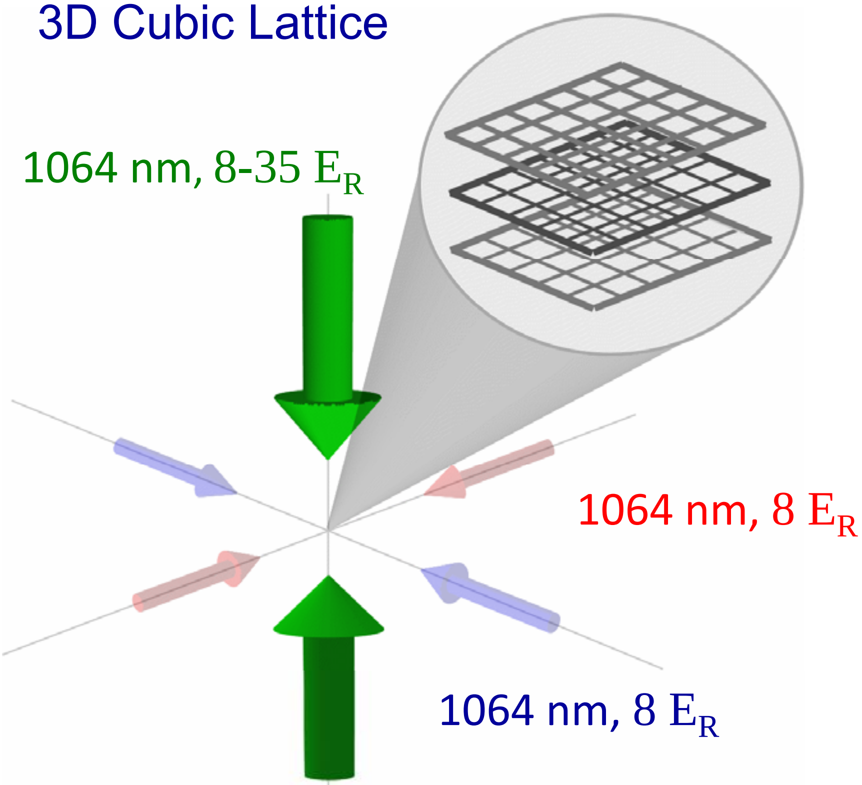
W. Hofstetter et al., PRL 89, 220407 (2002)

Realization of the Hubbard Model

Spin-1/2 Fermions:

$^{6}\mathrm{Li}$ in $F = 1/2,\ m_F = \pm 1/2$

3D Cubic Lattice



Tunneling Time (8 E_R): $\tau = \dfrac{h}{4t} = 455\ \mu s$

Experimental Parameters

Scattering Length: $a_s = 63 a_0$

$$\frac{t}{h} = 548\ \mathrm{Hz} \qquad \frac{U}{h} = 4.37\ \mathrm{kHz}$$

$$\frac{U}{t} = 8 \qquad \frac{E_{gap}}{U} = 29$$

Temperatures of Interest

Néel Temp: $\dfrac{4t^2}{U} \cong (275\mathrm{Hz})\, h$

$= 0.07\ k_B T_F$

$= 13\ \mathrm{nK}\ k_B$

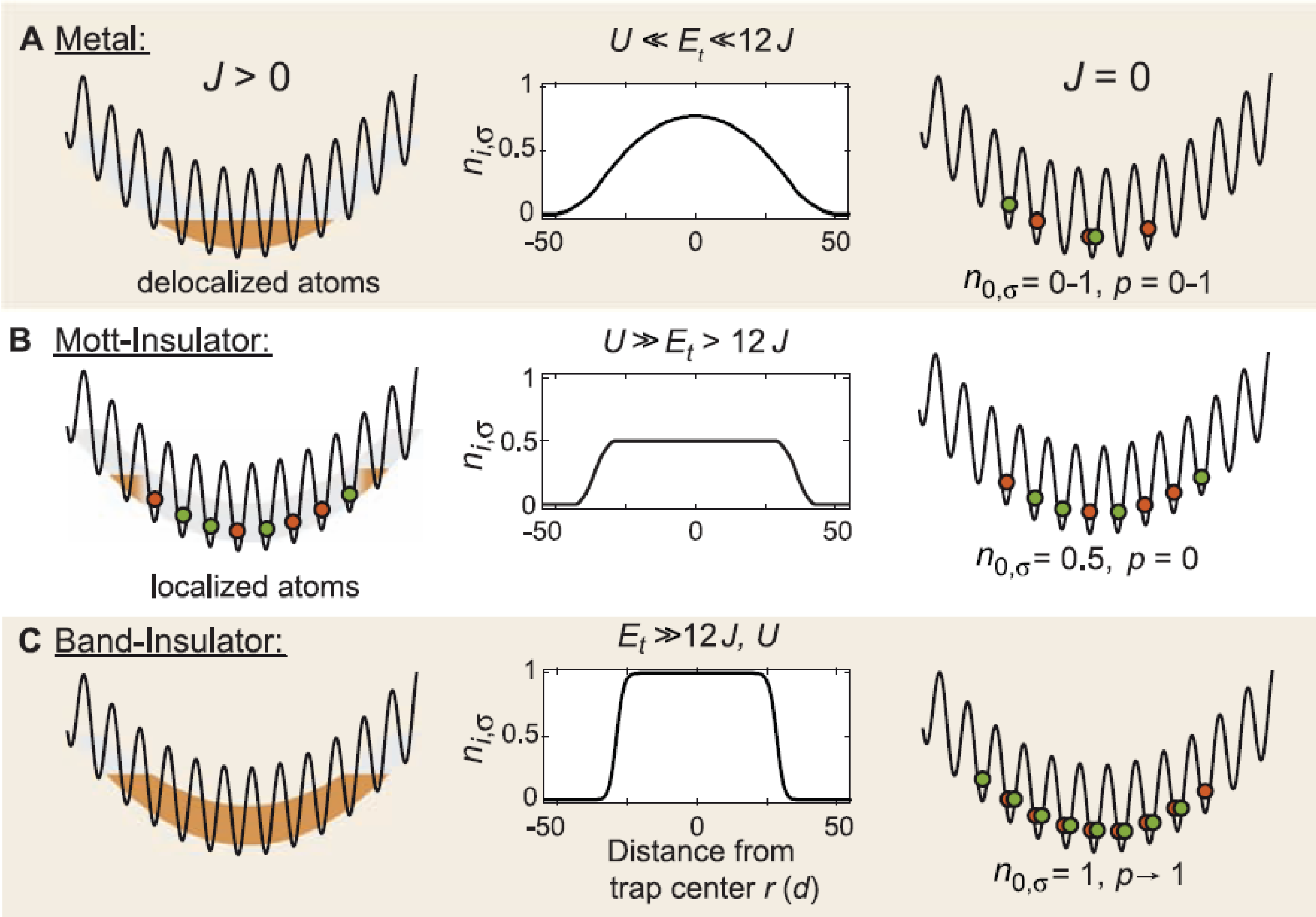
Superfluidity:

$$T_c \sim 0.01t \sim 0.002 k_B T_F$$

$= 350\ \mathrm{pK}\ k_B$

State of the Art: $T \approx 0.25 T_F$

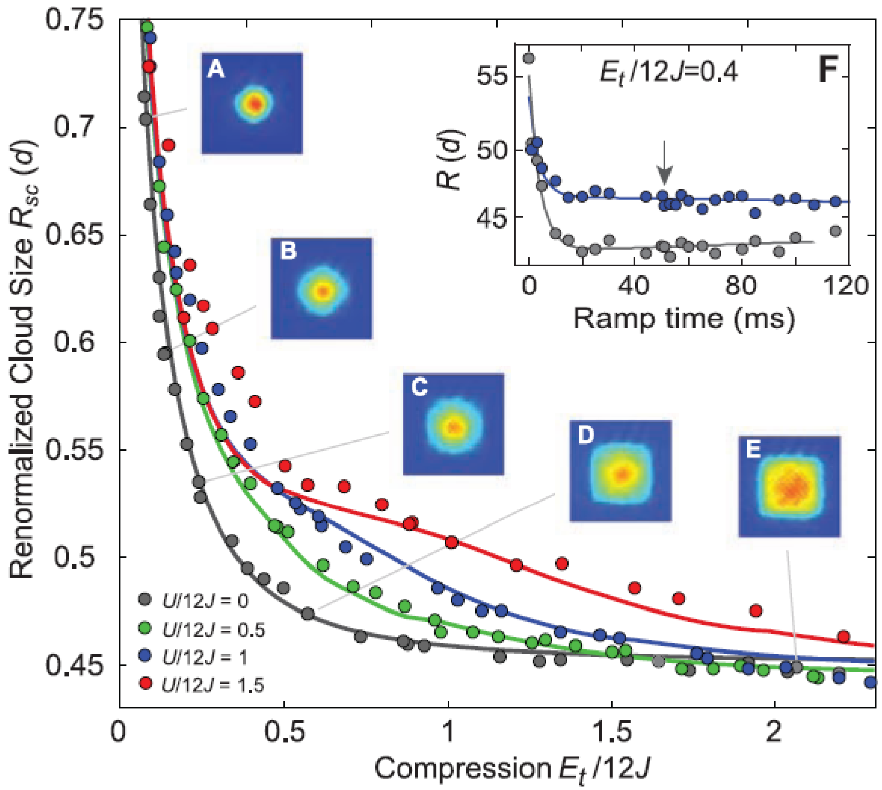
Observation of the Mott Insulator

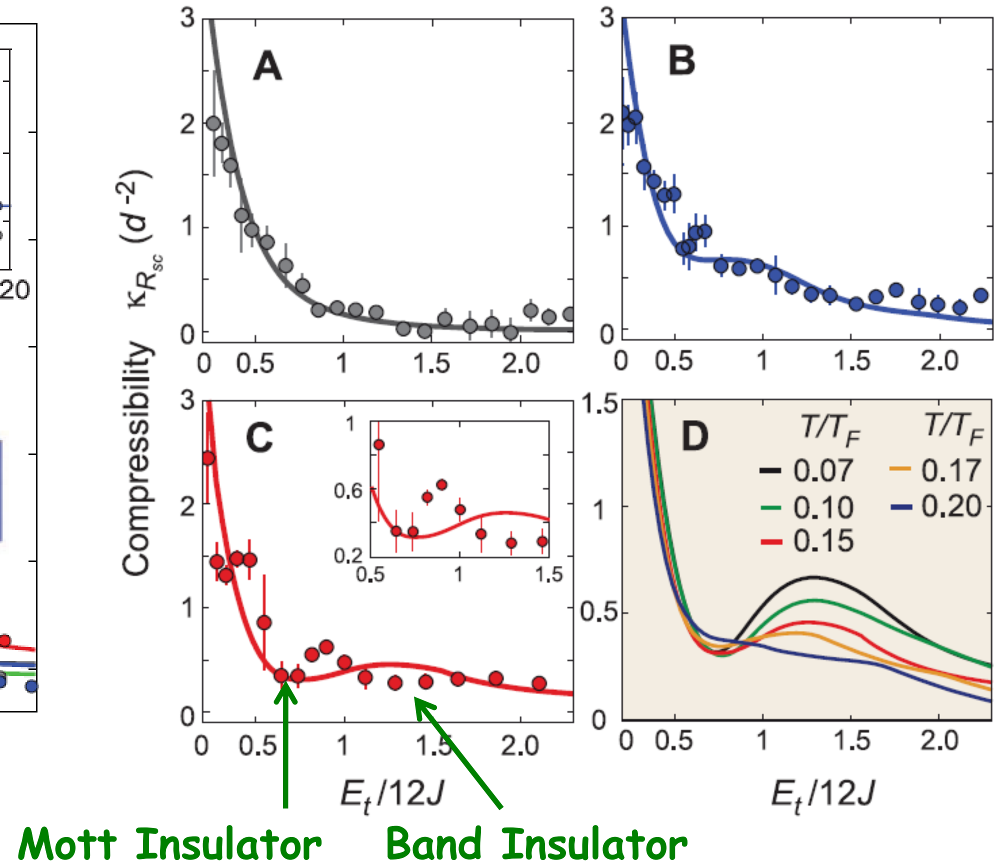


T. Esslinger *et al.*, Science **322**, 1520 (2008)

I. Bloch *et al.*, Nature **455**, 204 (2008)

Observation of the Mott Insulator



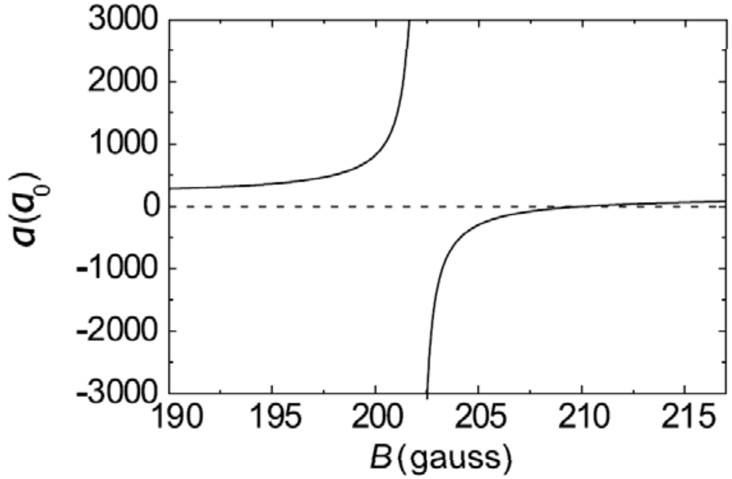


Requirement for Anti-Ferromagnet

Entropy of AF: $\frac{S}{N\,k_B} < \ln(2) = 0.69$

Entropy of Fermi Gas: $\frac{S}{N\,k_B} = \pi^2 \frac{T}{T_F}$

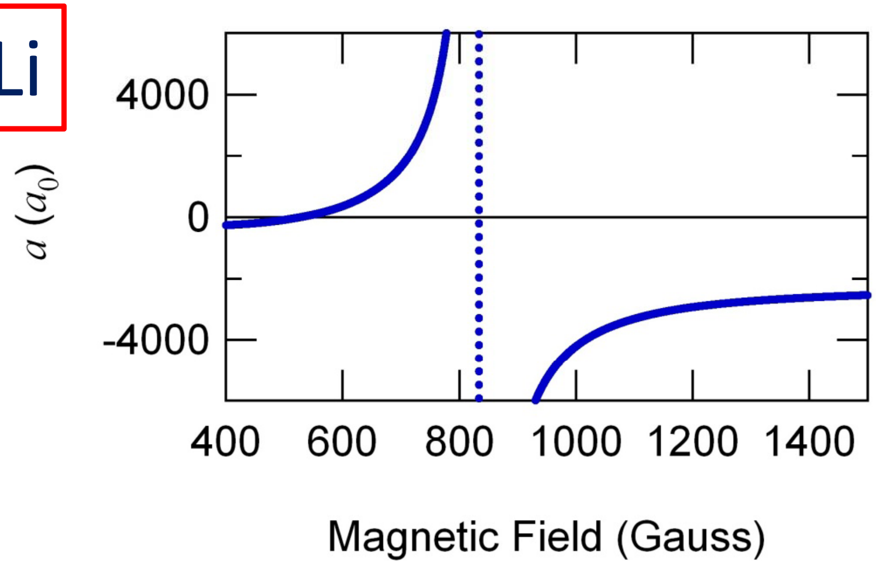
^{40}K



Large inelastic decay rates
3-body
p-wave resonance

$T/T_F \sim 0.15$ $\frac{S}{N\,k_B} = 1.48$

^{6}Li



Cooling near Feshbach Res.

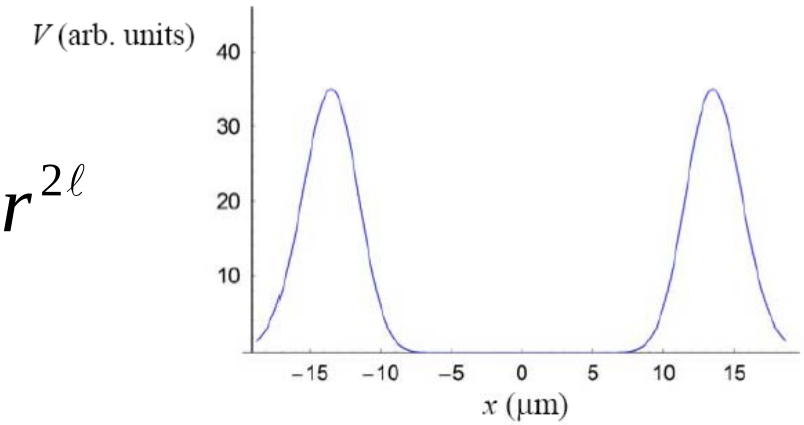
$T/T_F < 0.05$ $\frac{S}{N\,k_B} < 0.49$

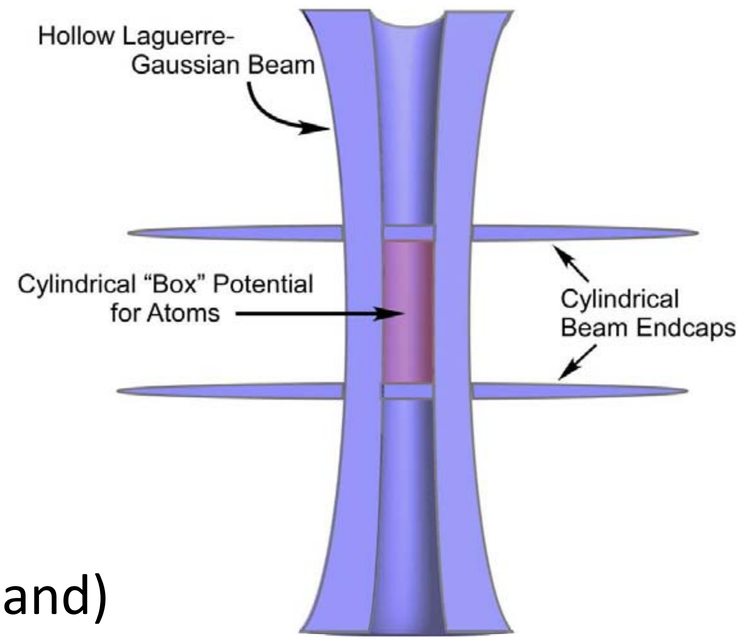
Cannot access weak repulsive interactions

Removing Entropy from the System

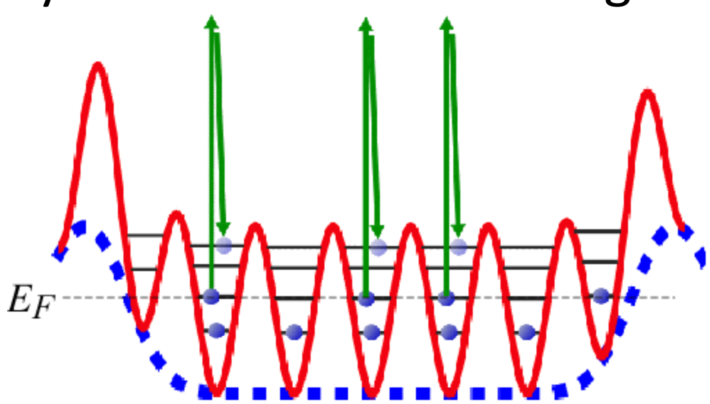
- External confinement: box-like potential

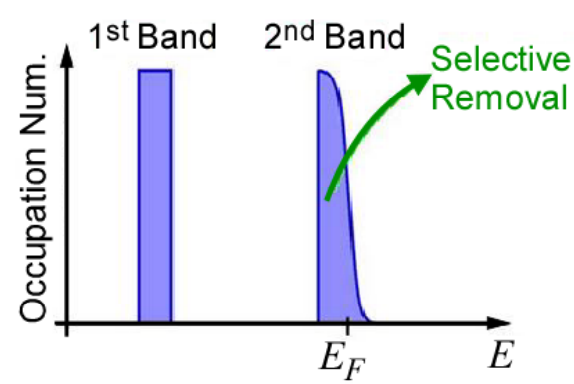
$$V \propto r^{2\ell}$$





- Load atoms at high density (partially fill 2nd band)
- Selectively remove atoms from higher bands

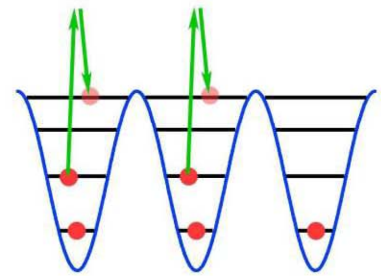


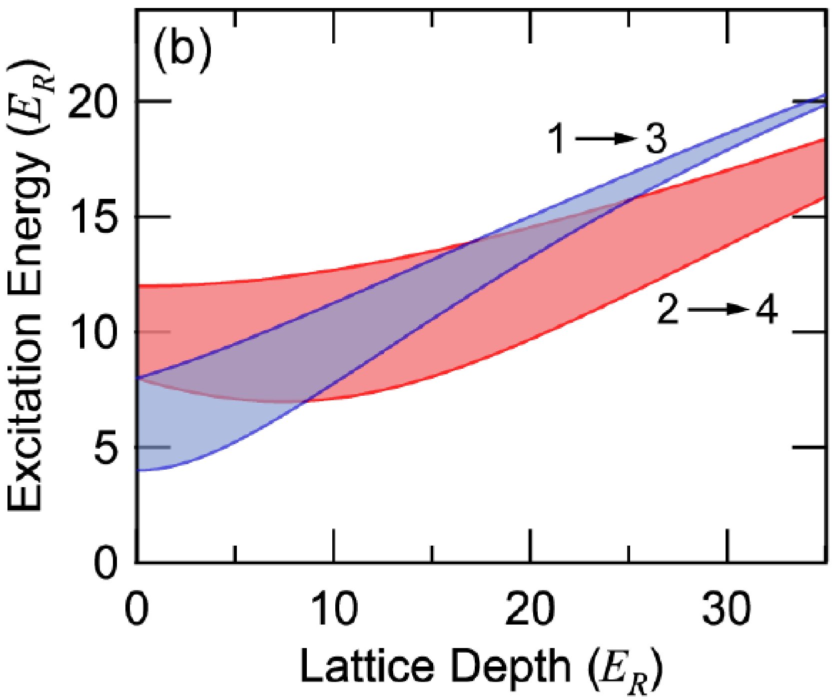


Filtering higher bands in 1D w/ harmonic confinement J. I. Cirac *et al.*, New J. Phys. **8**, 164 (2006).

Selective Removal from 2nd Band

- Amplitude Modulation
  - Selectively Excite 2nd → 4th Band

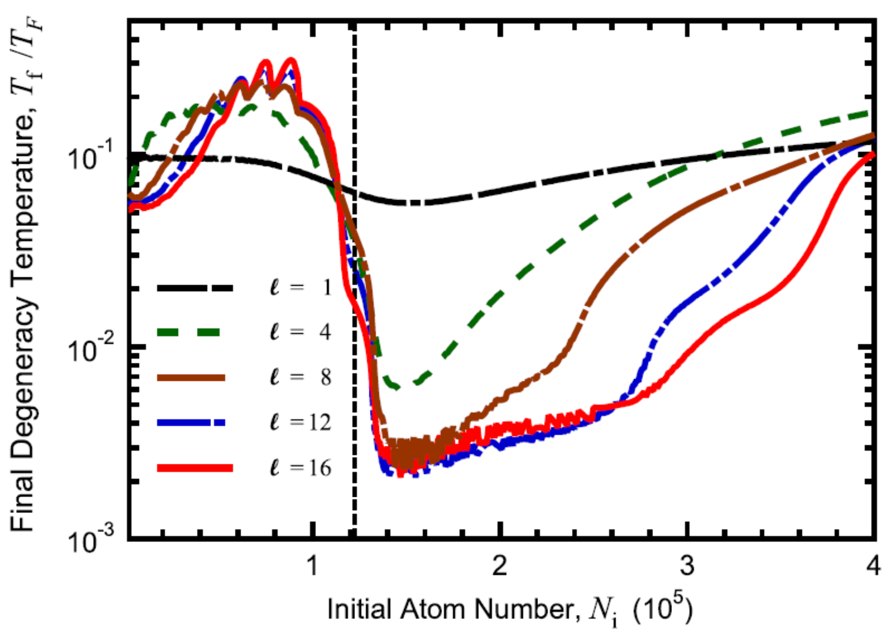


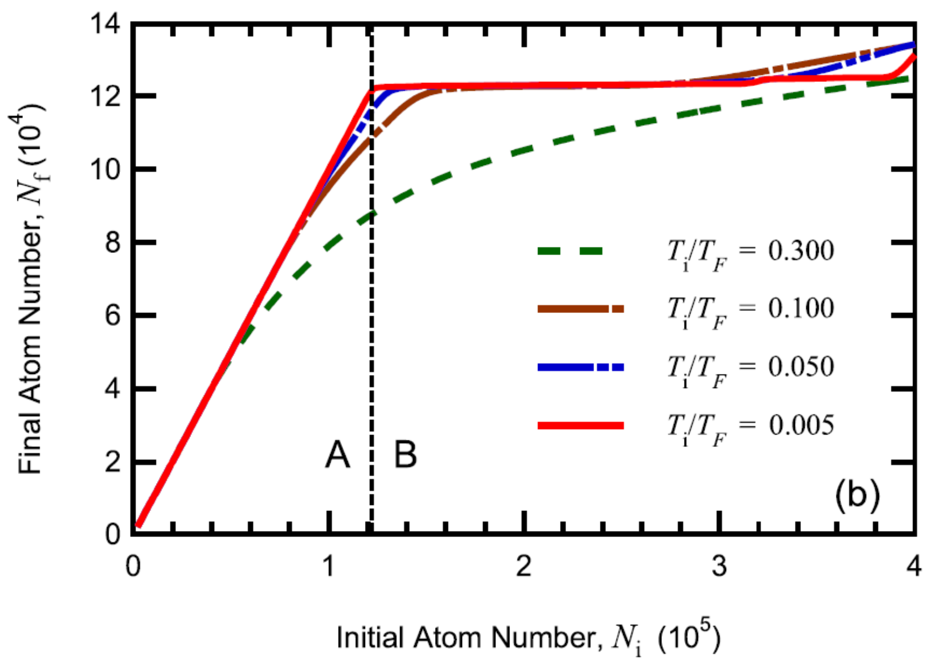


- Band Excitation by Rapid Adiabatic Passage
- Irreversible Removal of Atoms
- Reduction in Entropy

Projected Final Temperatures

- Numerical Results for Loading 35 E_R Lattice and Filtering





- Achieve $T = 0.003\ T_F$ with 13% atom loss
- Initial $S/N = 0.28\ k_B$, Final $S/N = 0.024\ k_B$
- Adiabatically Lowering Lattice to $5\ E_R$ gives $T < 0.001\ T_F$

J. R. Williams, J. H. Huckans, R. W. Stites, E. L. Hazlett, & K. M. O'Hara, arXiv:0804.2915

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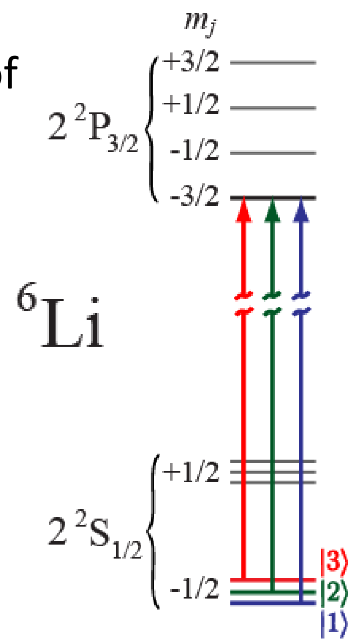
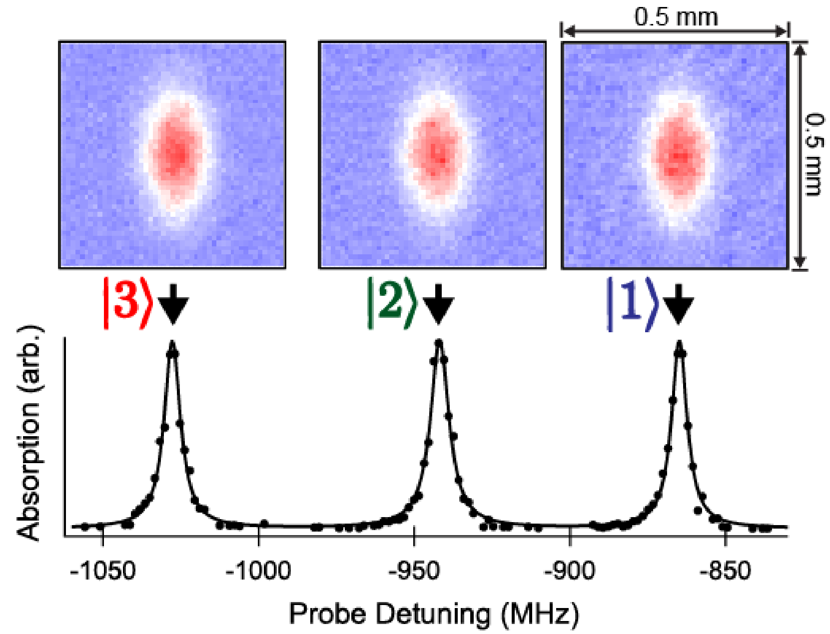
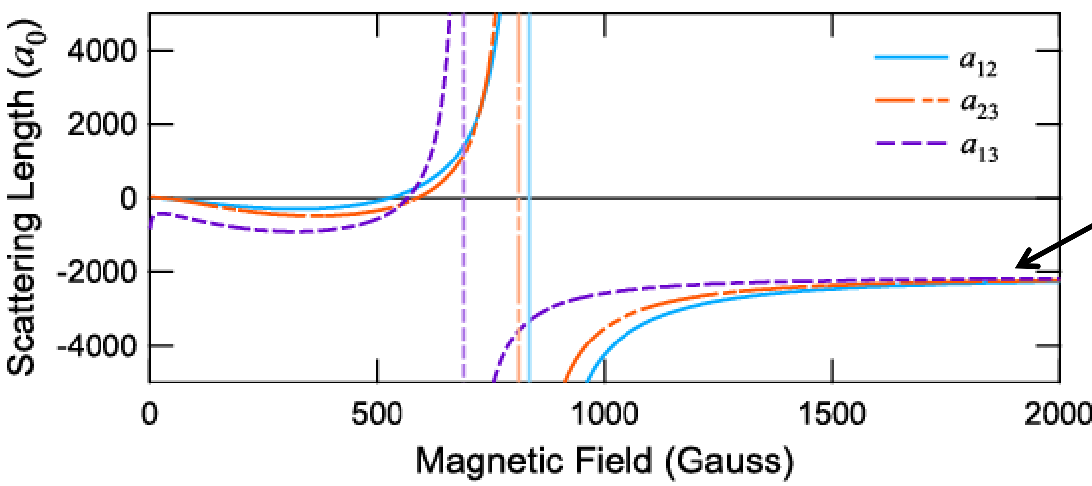
- o Ultracold Fermionic Atoms
- o The Hubbard Model
  - Quantum Magnetism
  - High-temperature superconductivity
- o Reducing the Entropy of Atoms in a Lattice
- o Three-Component Fermi Gases
  - SU(3) Hubbard model: Color Superfluidity
  - The quantum 3-body problem

A Three-Component Fermi Gas

- Three different internal states of ^6Li – labeled by color
- Mixture is stable against 2-body inelastic collisions
- Tunable interactions





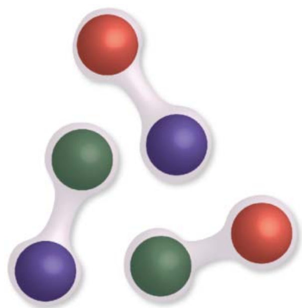


- Equal & strongly attractive interactions at high field (a_t = -2140 a_0)
- BCS Pairing with 3 types of Cooper pairing

Huckans, Williams, Hazlett, Stites & O'Hara, PRL **102**, 163502 (2009)

"Color" Superconductivity

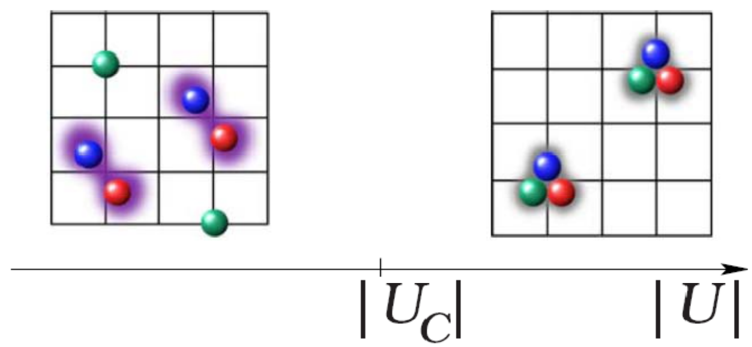
- BCS superfluid with three types of Cooper pairs

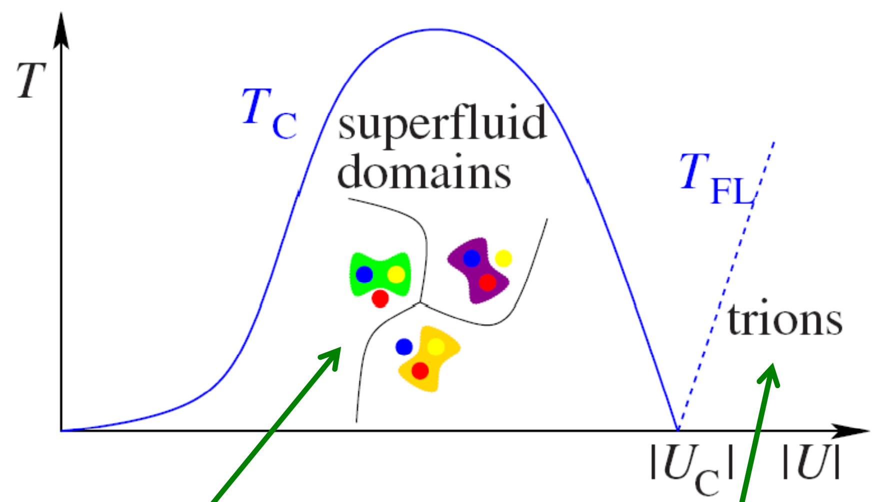


- Optical lattice: controls ratio of interaction energy to kinetic energy

- Quantum phase transition

  from "color superfluid" to "baryons" (RGB bound states) as interaction energy is increased





Rapp, Hofstetter & Zaránd, PRB **77**, 144520 (2008)

QUANTUM CHROMODYNAMICS

Lifestyles of the small and simple

Ultracold atoms in optical lattices are already used to simulate complex solid-state phenomena. But could the same platform also give us a better grasp of how quarks group together?

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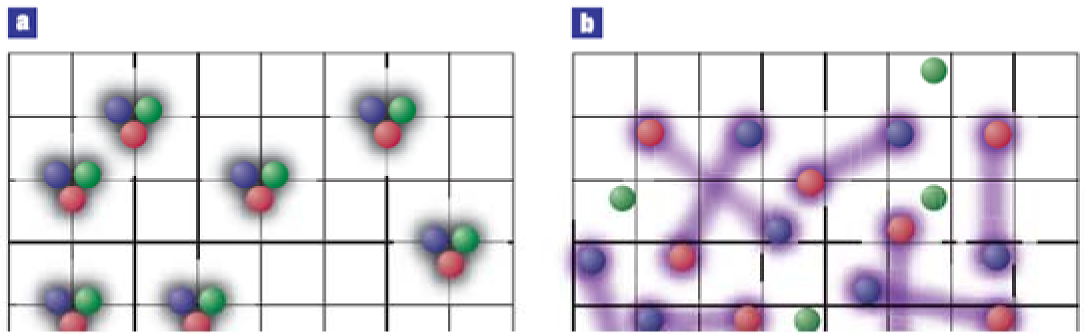
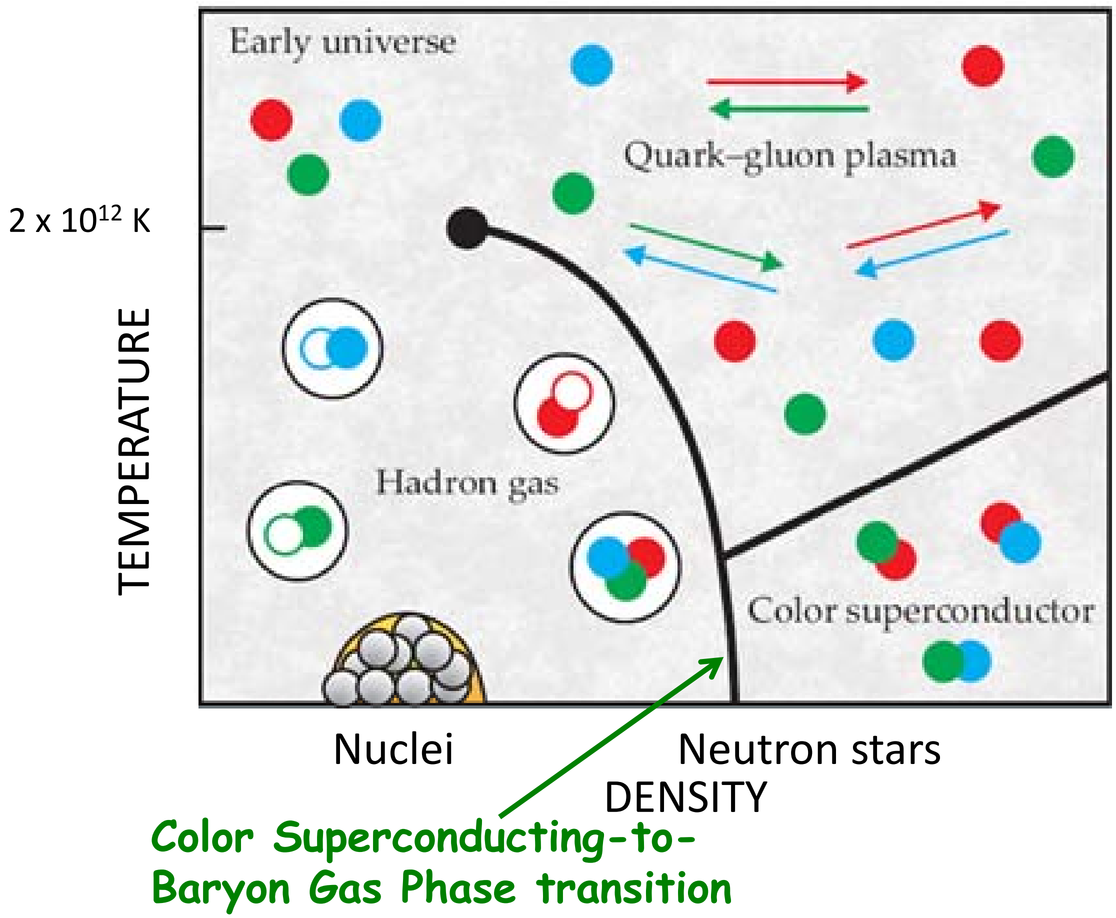
e-mail: wilczek@mit.edu



Quarks find other quarks — with different flavours and colours — attractive. They can choose either

QCD Phase Diagram

Conjectured phase diagram for QCD



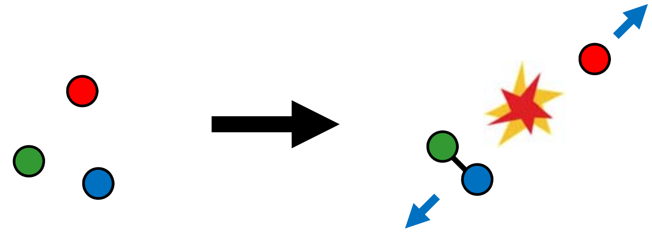
C. Sa de Melo, Physics Today, Oct. 2008

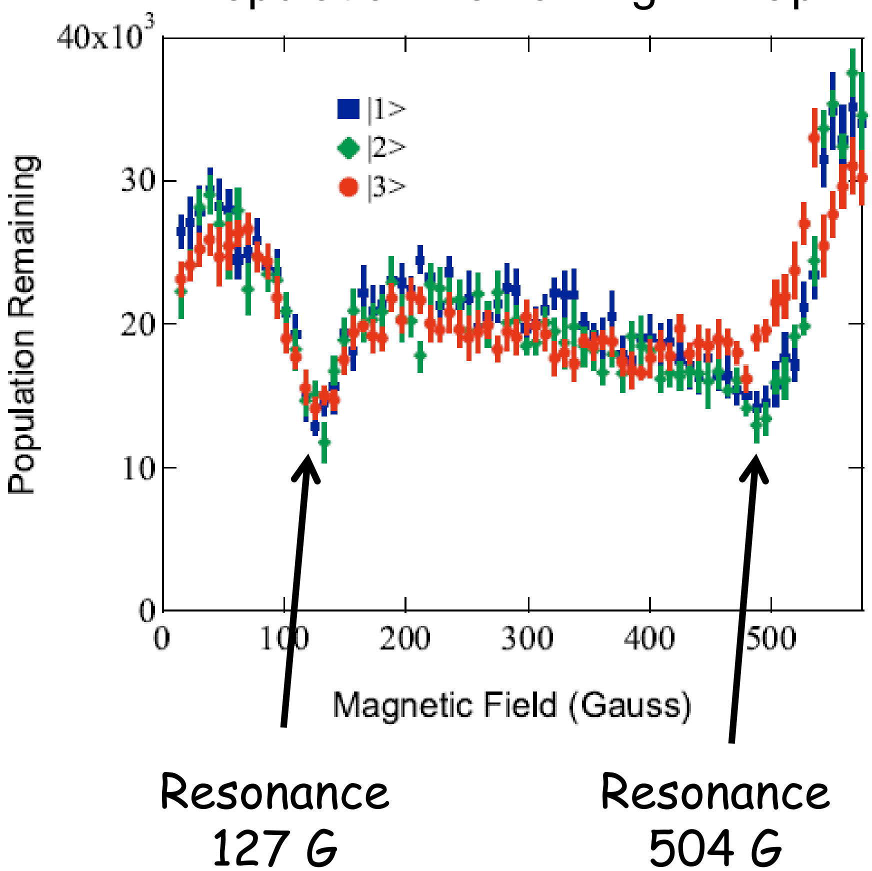
- Ultracold atoms can be used to simulate part of the QCD phase diagram
- Is the baryon-to-CSF phase transition first or second order?
- Does the color superfluid exhibit domain formation?
- What phases are possible in a spin-imbalanced 3-state Fermi gas?

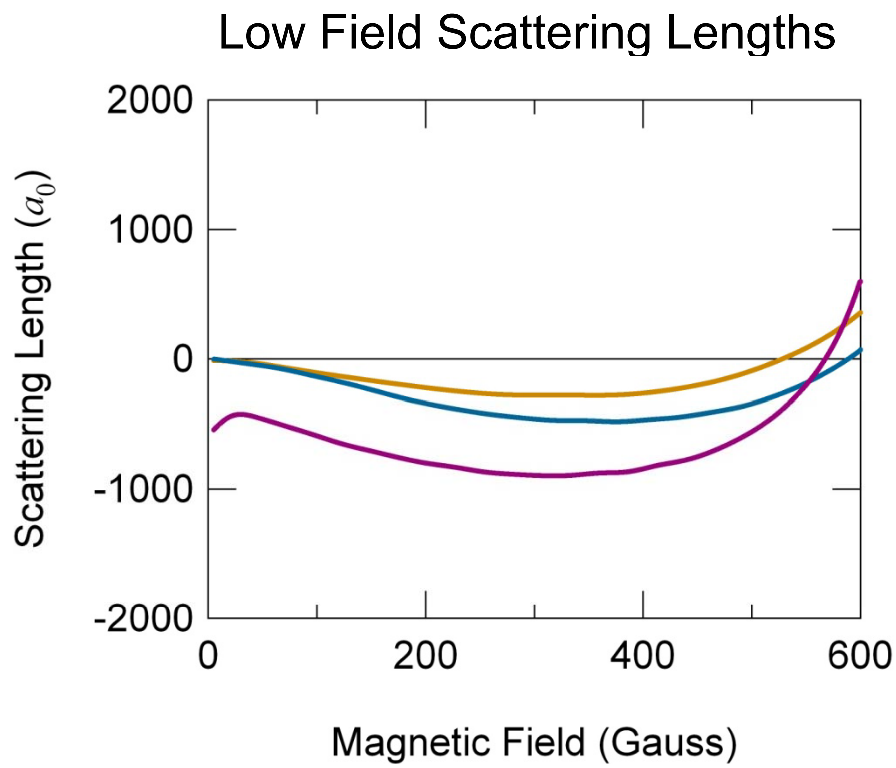
  (which mimics the higher mass of the strange quark)

Three-Body Recombination

Three-body recombination:





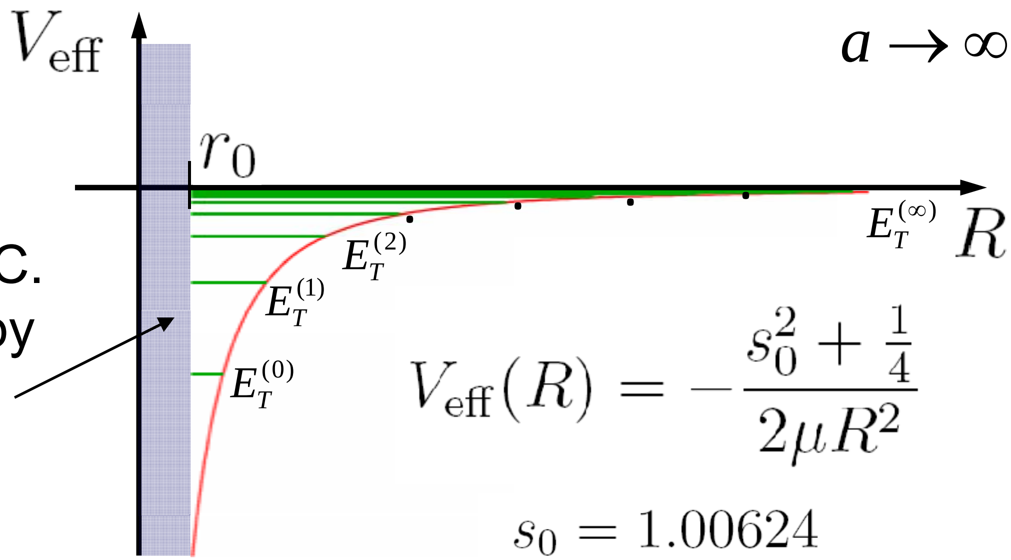


Resonances in the 3-Body Recombination Rate!

3-Body Problem: Efimov's Solution

(1970) Efimov: An infinite number of bound 3-body states

Inner wall B.C. determined by short-range interactions



Vitaly Efimov
circa 1970

Infinitely many 3-body bound states (universal scaling):

$$E_T^{(n+1)}/E_T^{(n)} \to 1/e^{2\pi/s_0} = 1/515.03$$

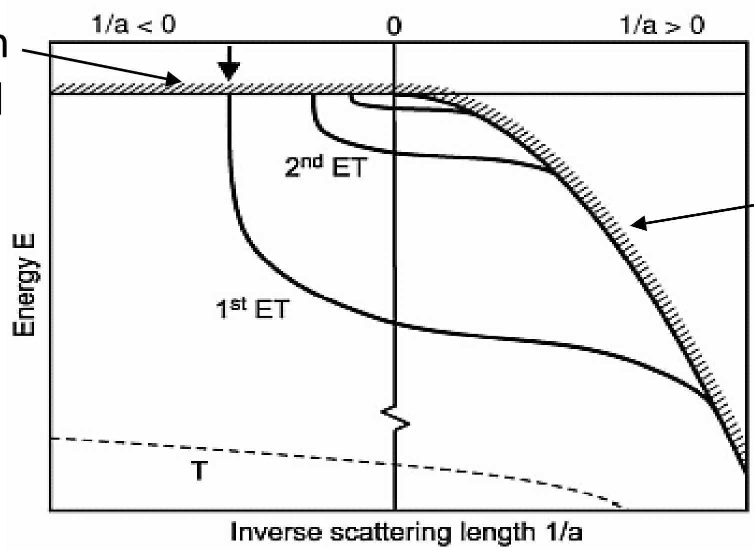
A single 3-body parameter: κ_*

$$E_T^{(n)} \to \left(\frac{1}{515.03}\right)^{n-n_*} \frac{\hbar^2 \kappa_*^2}{m}$$

3-Body QM Problem: Efimov's Solution

(**1970 & 1971**) Efimov: Identical Bosons in Universal Regime $a \gg r_0$

free atom threshold



atom-dimer threshold

$$E_d = \frac{\hbar^2}{ma^2}$$

Diagram from:
T. Kraemer *et al.*,
Nature **440** 315 (2006)

Note:
Only two free parameters:

κ* and η*

Observable:
Enhanced 3-body recombination ↓

$$K_3 = \frac{4677 \sinh(2\eta_*)}{\sin^2[s_0 \ln(0.6642|a|\kappa_*)] + \sinh^2 \eta_*} \frac{\hbar a^4}{m} \quad (a < 0)$$

Log-periodic scaling

$a < 0$ & $a > 0$

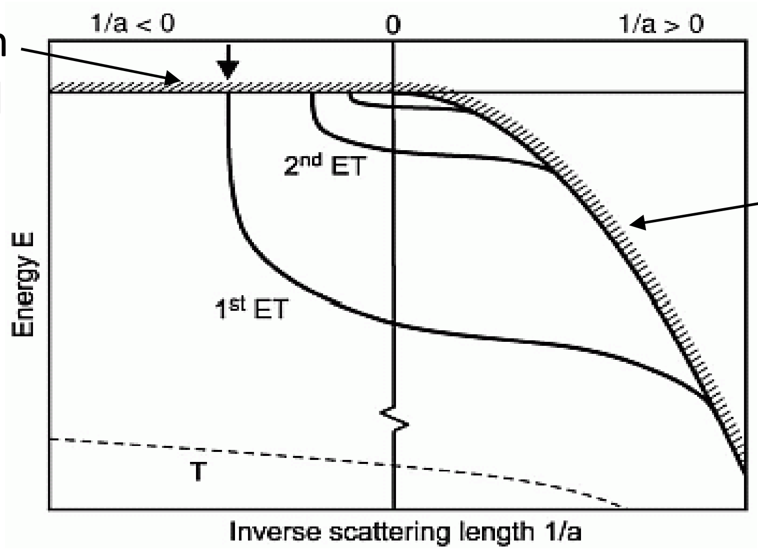
$a_*^{(n+1)} / a_*^{(n)} \to 22.7$

E. Braaten, H.-W. Hammer, D. Kang and L. Platter, arXiv:0811.3578

3-Body QM Problem: Efimov's Solution

(**1970 & 1971**) Efimov: Identical Bosons in Universal Regime

free atom threshold



atom-dimer threshold

$$E_d = \frac{\hbar^2}{ma^2}$$

Diagram from:
T. Kraemer *et al.*,
Nature **440** 315 (2006)

Observable:

Enhanced 3-body recombination ↓

$$K_3 = \frac{4677\sinh(2\eta_*)}{\sin^2[s_0 \ln(0.6642|a|\kappa_*)] + \sinh^2\eta_*} \frac{\hbar a^4}{m}$$

($a < 0$)

E. Braaten, H.-W. Hammer, D. Kang and L. Platter, arXiv:0811.3578

Observed Efimov Features: (ultracold Bosons)

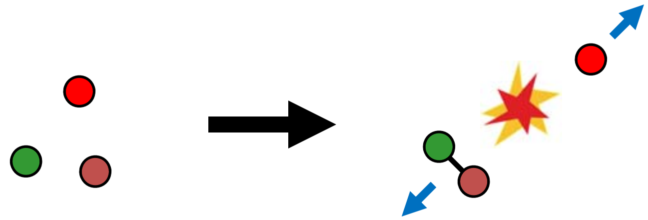
T. Kraemer *et al*. Nature **440** 315 (2006) [Cs]

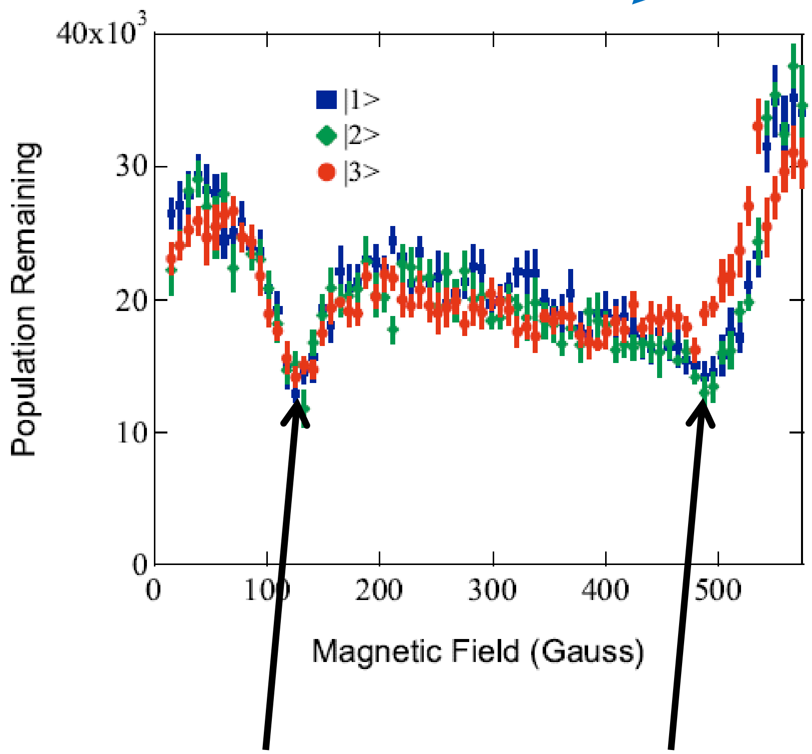
S. Knoop *et al*. Nature Physics **5** 227 (2009) [Cs]

G. Barontini *et al.* arXiv:0901.4584 [K, Rb]

M. Zaccanti *et al.* arXiv:0904.4453 [K]

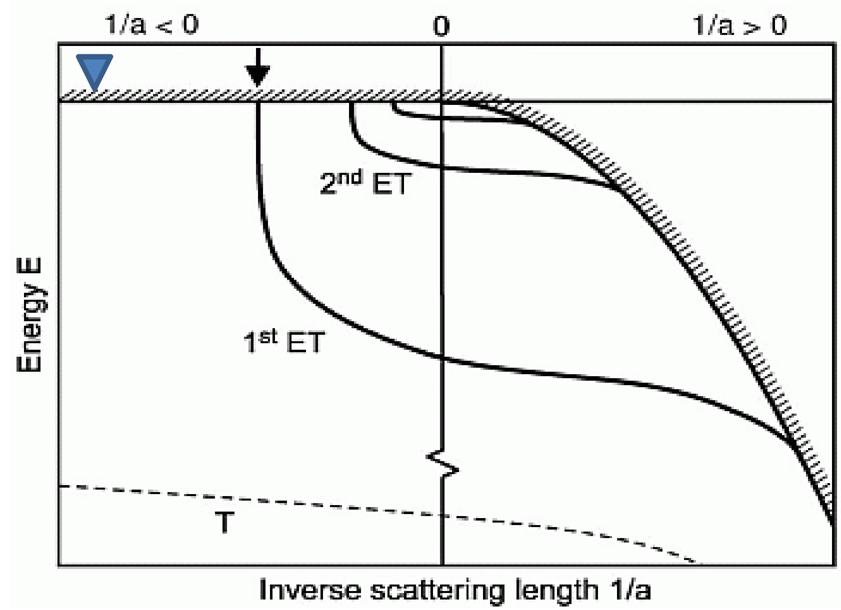
Resonant Loss Features



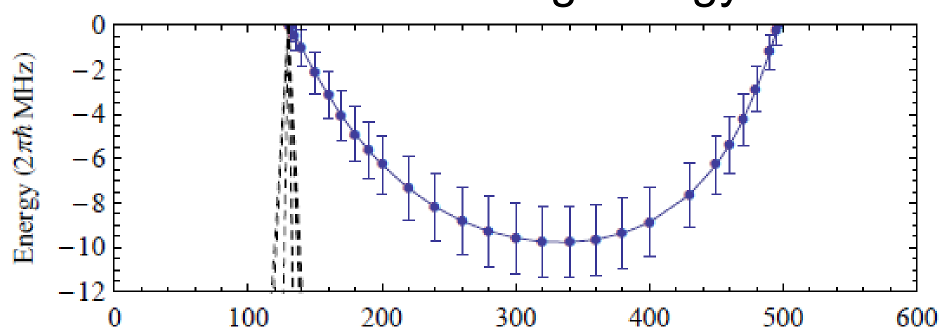


Resonance
127 G

Resonance
504 G



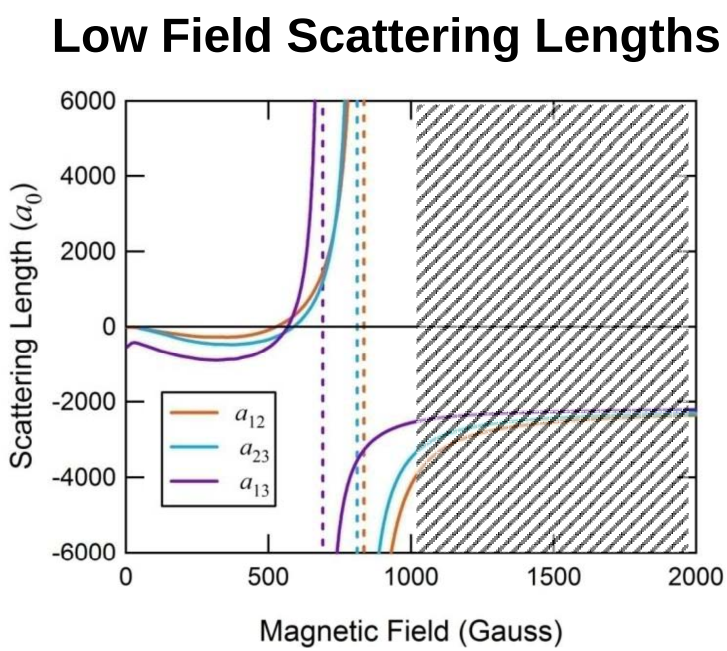
Trimer Binding Energy

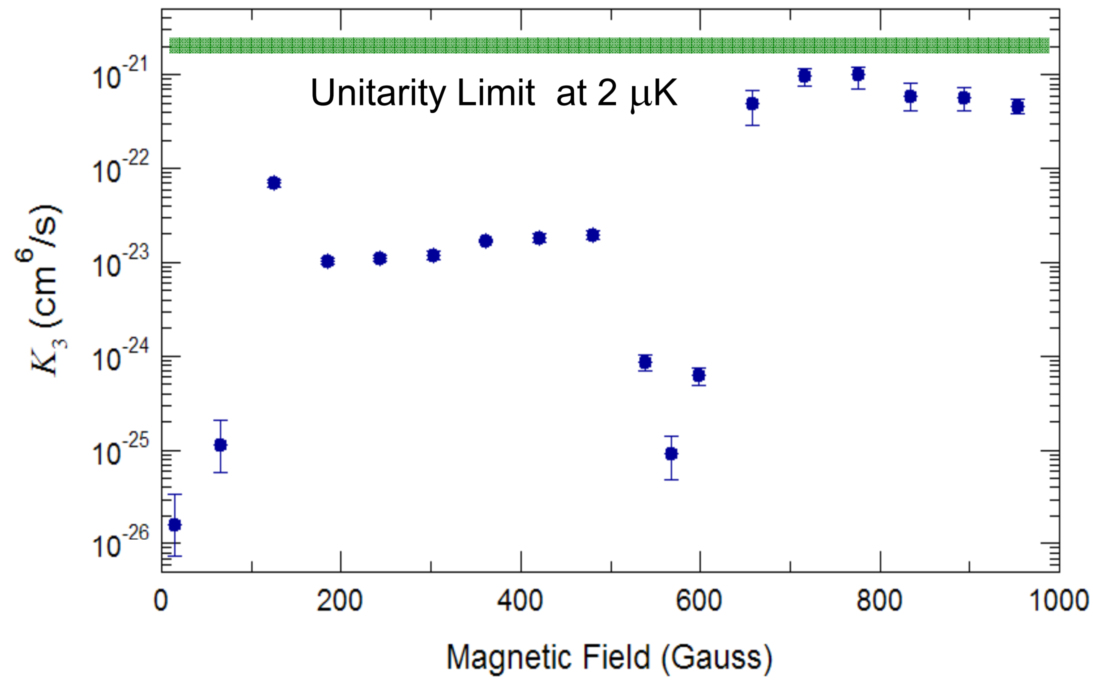


P. Naidon & M. Ueda, arXiv:0811.4086

Resonances in the 3-Body Recombination Rate!

Low-Field 3-Body Loss Data





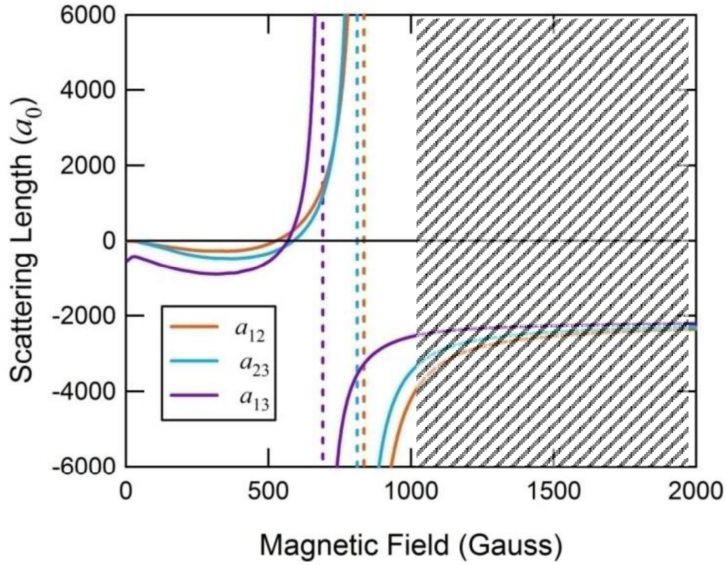
Low field 3-Body loss rate (K_3) over 10 G < B < 960 G

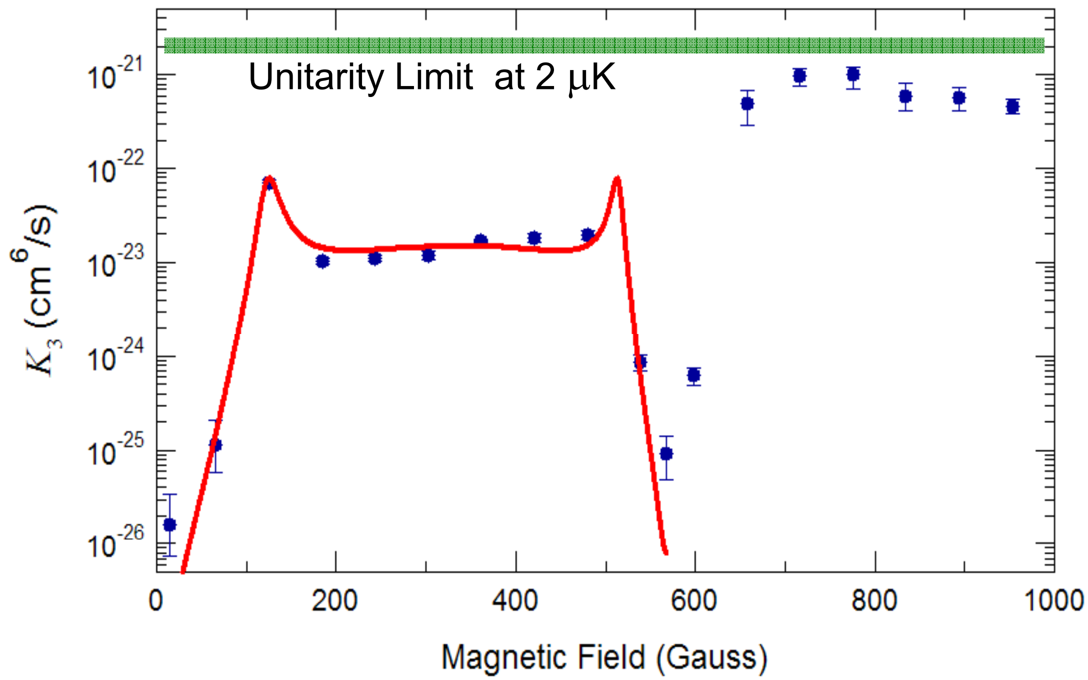
Huckans *et al.,* PRL **102**, 165302 (2009) (Penn State)

Ottenstein *et al.,* PRL **101**, 203202 (2008) (Heidelberg)

Low-Field 3-Body Loss Data

Low Field Scattering Lengths





$$K_3 = \frac{4677 \sinh(2\eta_*)}{\sin^2[s_0 \ln(0.6642|a|\kappa_*)] + \sinh^2 \eta_*} \frac{\hbar a^4}{m}$$

E. Braaten, *et al.*, arXiv:0811.3578

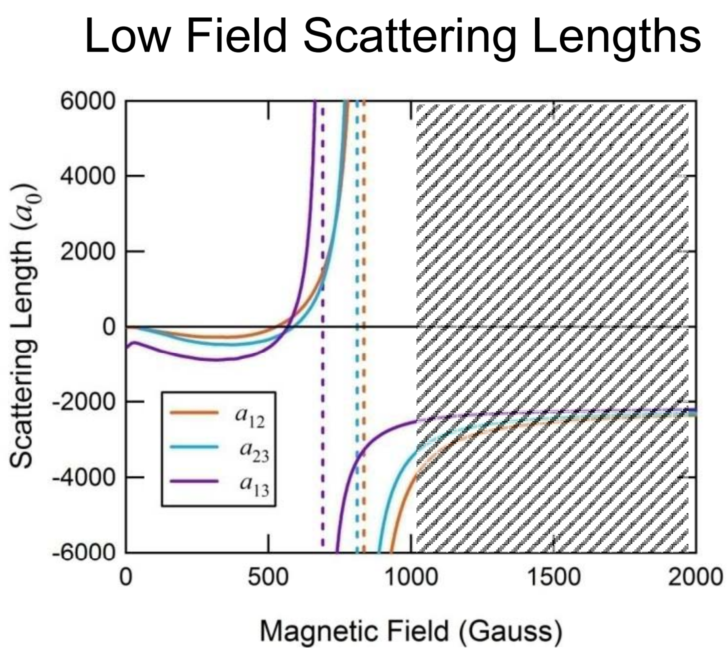
Fit with 2 free parameters:

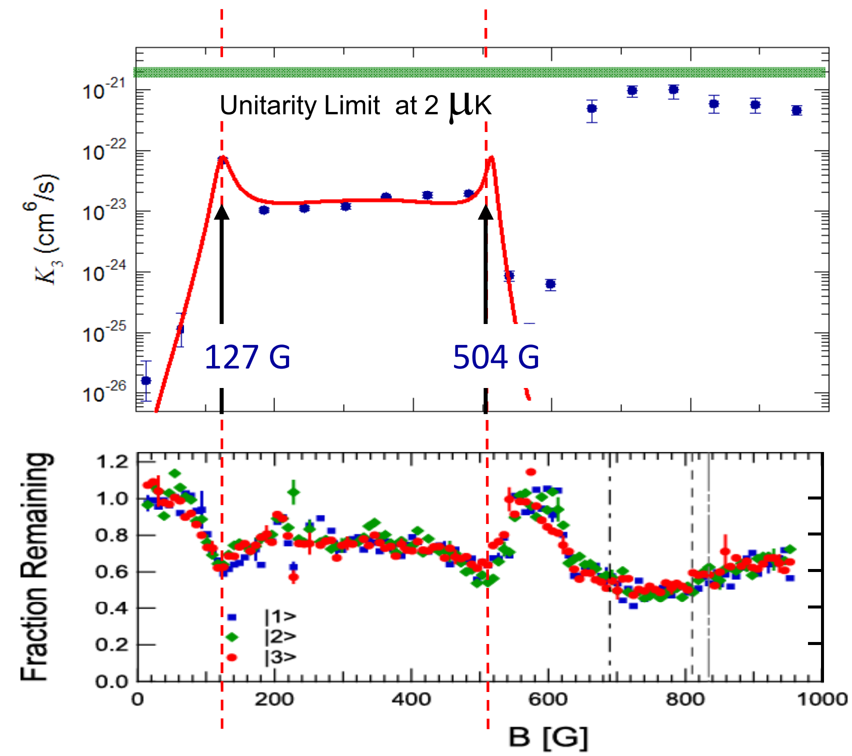
κ* and η*

$$a_{\mathrm{eff}} = \sqrt[4]{\frac{1}{3}\left(a_{12}^2 a_{23}^2 + a_{23}^2 a_{13}^2 + a_{12}^2 a_{13}^2\right)}$$

Andre Wenz, Diploma Thesis (2009)

Low-Field 3-Body Loss Data





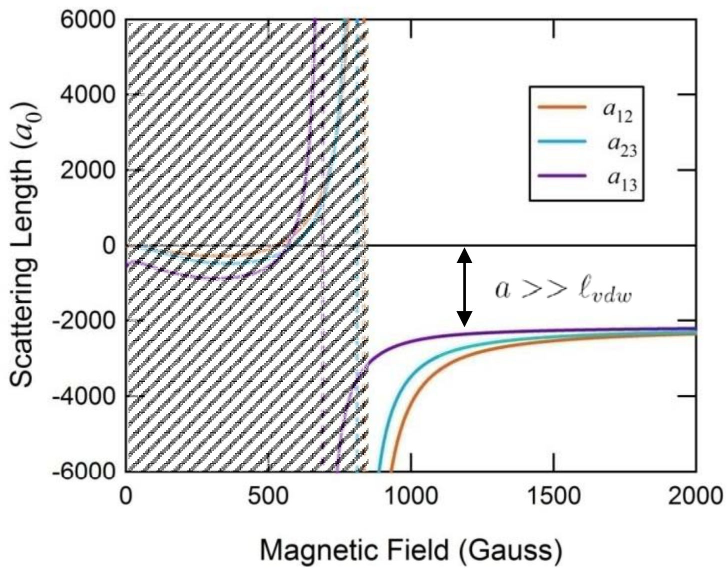
Resonant loss features at 127 and 504 Gauss

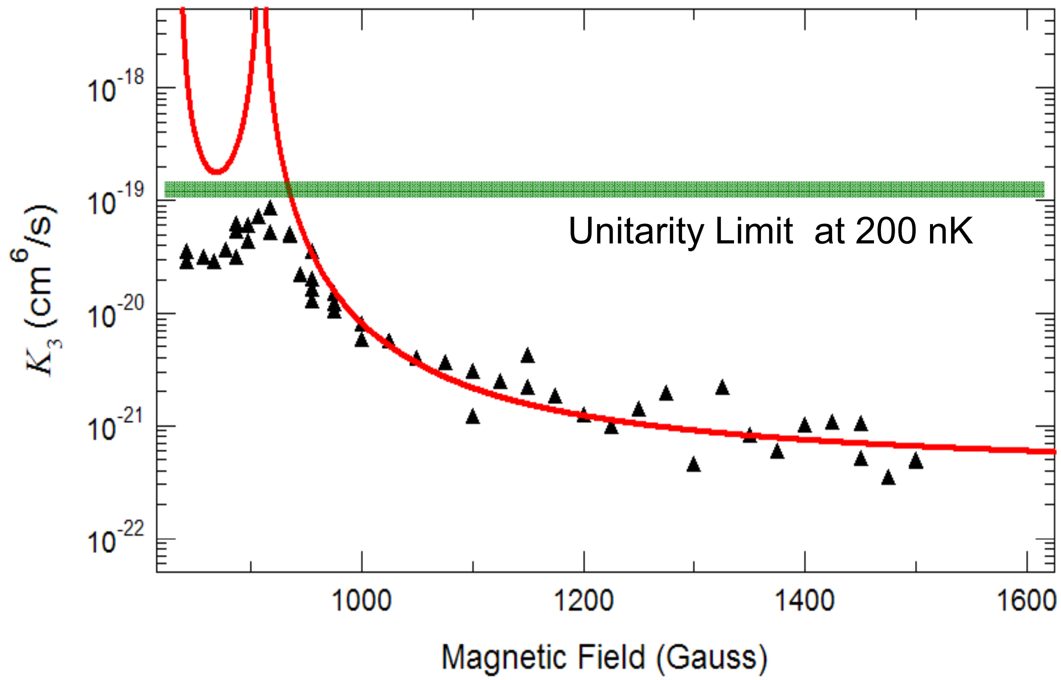
$$a_{\text{eff}}(127\text{ G}) \simeq a_{\text{eff}}(504\text{ G})$$

$$\kappa_* = 59.9\ a_0^{-1}\ , \qquad \eta_* = .075$$

High-Field 3-Body Loss Data

High Field Scattering Lengths





High field 3-Body loss rate (K_3) over 840 G < B < 1500 G

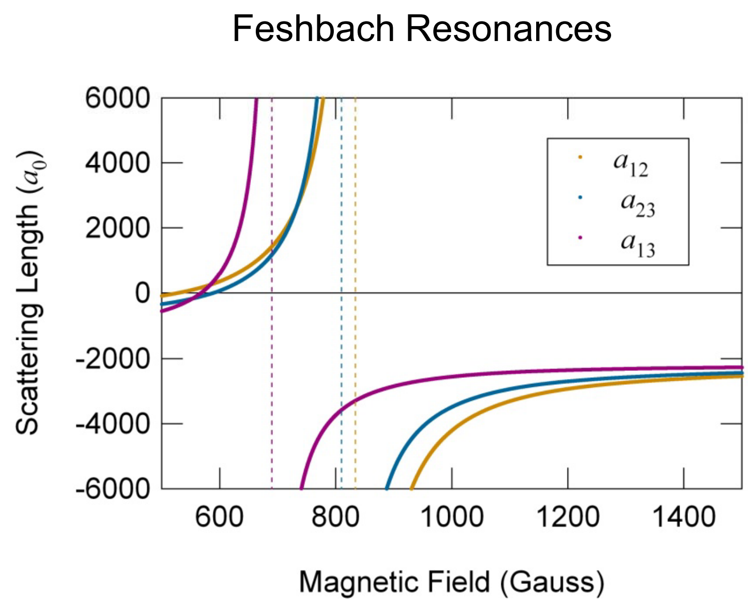
Resonant loss feature at 910 Gauss $a_{ij} > 35\, r_0$

$\kappa_* = 79.2\ a_0^{-1}$, $\eta_* = .01125$

Future Prospects

Efimov Physics with Overlapping Feshbach Resonances

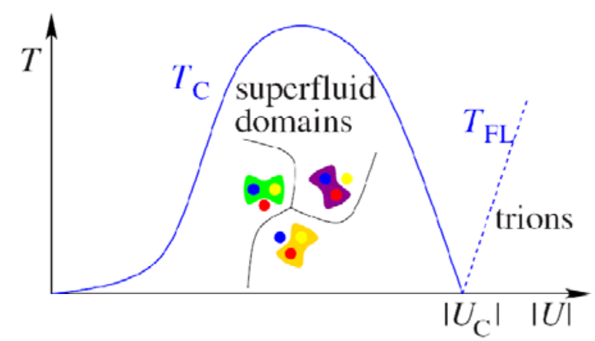
- Multiple scattering lengths: (a_{12}, a_{23}, a_{13})
  E. Braaten, *et al.,* arXiv:0811.3578 (2008)
  J. P. D'Incao and B. D. Esry, arXiv:0905.0772 (2009)
- Mutual attractive and repulsive interactions:
  (a_{12}, $a_{23} > 0$ & $a_{13} < 0$)



BCS Pairing in a 3-State Fermi Gas

- Pairing competition (attractive interactions)
- Unequal Fermi Surfaces (E_F)
- Superfluid Domain Formation
- Superfluid/Trion phase transition (3D Lattice)

- No condensed matter analog

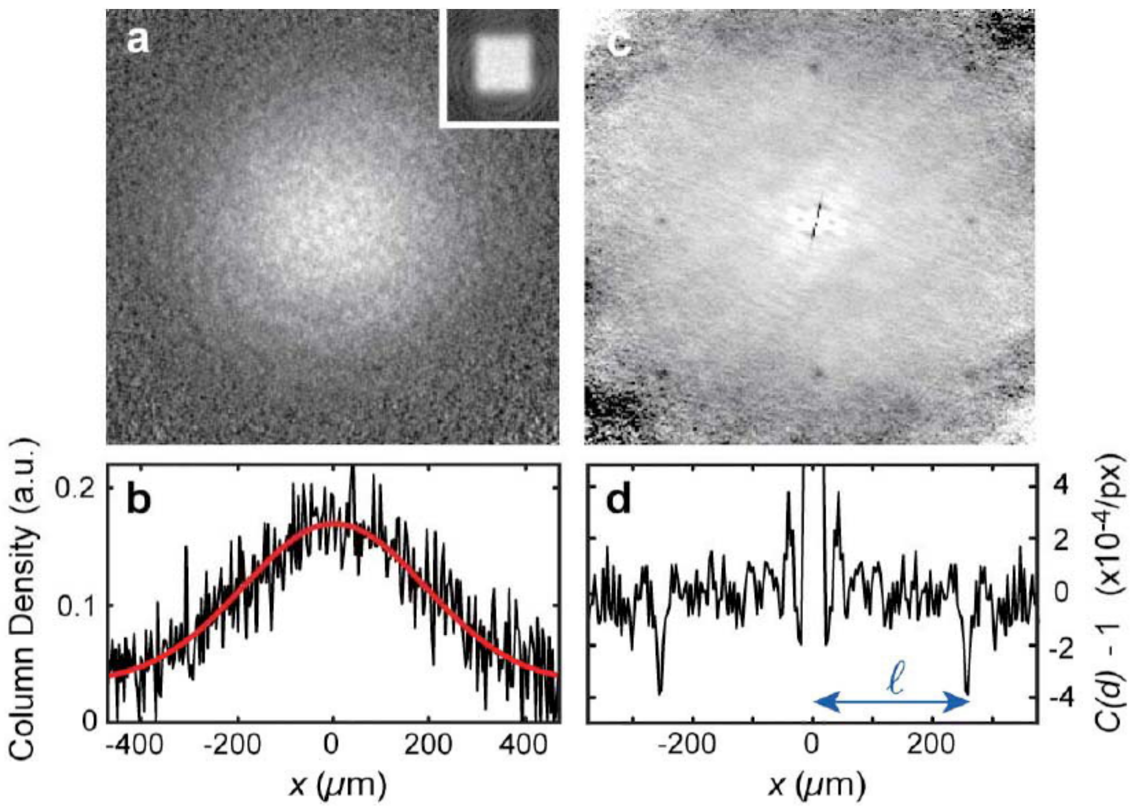


Rapp, Hofstetter & Zaránd,
PRB **77**, 144520 (2008)

Summary

- Hubbard model can be realized with ultracold atoms
- Mott insulator state has been observed in Zurich and Mainz
- Observation of AF will require reducing the entropy
- Entropy can be significantly reduced by filtering high entropy atoms
- Three-component Fermi gases in a lattice: Quant. Sim. of QCD
- Observation of Efimov resonances with unequal scattering lengths
  - Two low-field resonances with moderate scattering lengths (127 & 504 G)
  - Third high-field resonance at 910 G (well into universal regime)
- Agreement with Efimov theory $|a| >> r_0$ and $|a| \sim r_0$
  - Fits yield 3-body parameters for ^6Li at negative scattering lengths

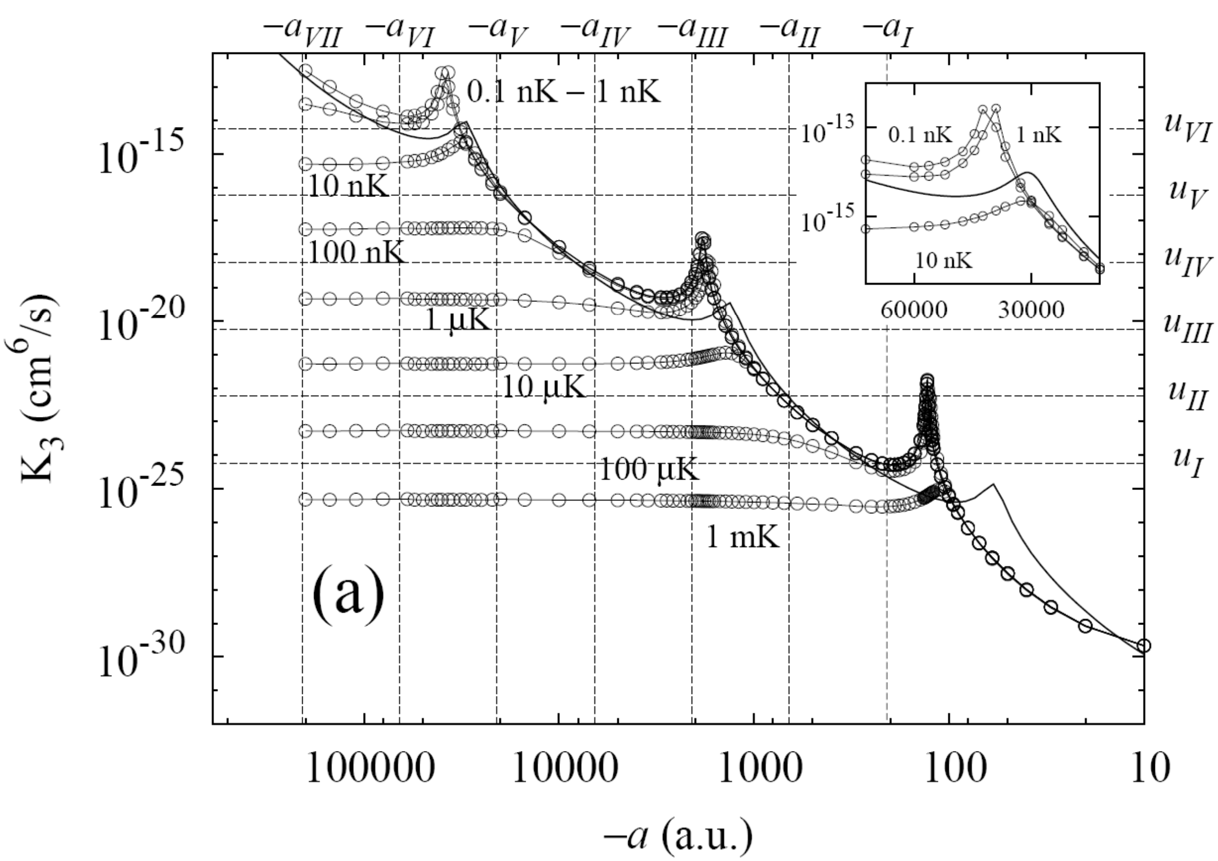
Density-Density Correlations



Nature, Vol 444, 733-736 (2006)

Density-density correlation function

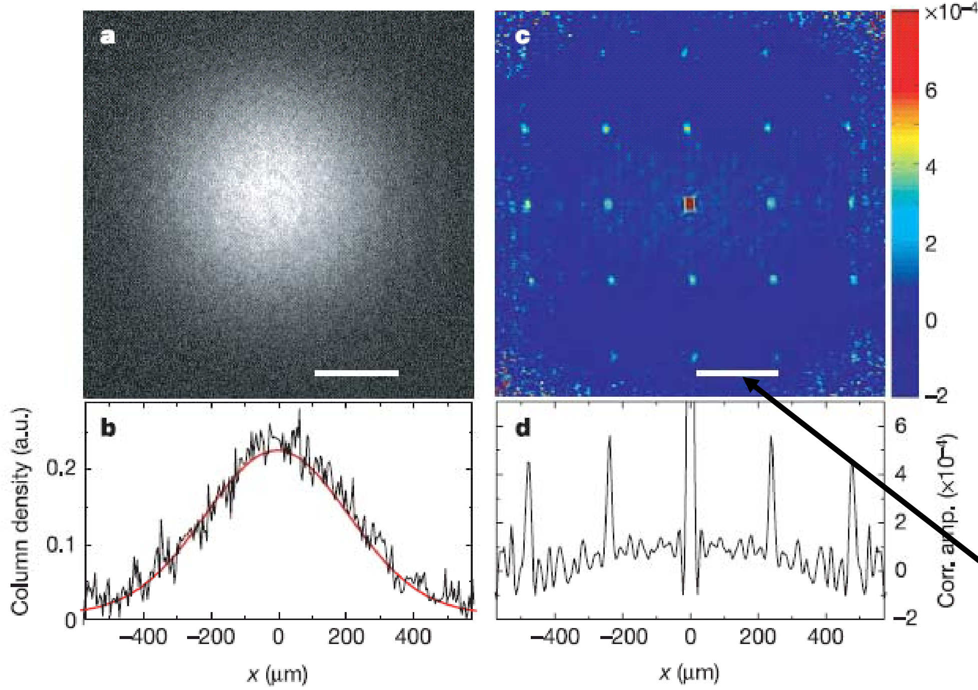
Limits on Universality



J. P. D'Incao, H. Suno & B. Esry, Phys. Rev. Lett. **93**, 123201 (2004)

Density-Density Correlations

- TOF Expansion and Image
- Density-Density Correlations in Expanded Cloud



$$\frac{ht_{\mathrm{TOF}}}{md}$$

(I. Bloch, 2005)

Density-Density Correlations

- State Selective Imaging of TOF Expansion
- Density-Density Correlations in Expanded Cloud