Hydrodynamics in a Degenerate, Resonantly Interacting Fermi Gas

Duke Physics
Atom Cooling and Trapping

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Outline

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- Strongly Interacting Fermi Gases
- All-Optical Cooling Method
- Hydrodynamic Expansion
- Hydrodynamic Excitation Spectra for Trapped Atoms
- Evidence for Superfluid Hydrodynamics
- Conclusions

Strongly-Interacting Fermi Gases Mimic Exotic Systems in Nature

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A BUNCH OF DEGENERATES

A degenerate gas of fermions occurs in diverse situations, as described below:

■ Superconductors: The electrons are degenerate and form loosely correlated Cooper pairs, which produce the superconductivity. Something similar must happen in high-temperature superconductors, but that process remains a mystery.

■ Neutron stars: The refusal of neutrons (which are fermions) to occupy identical quantum states generates a repulsion that prevents the star from collapsing under its own immense weight. A similar repulsion stabilizes the laboratory-made degenerate fermi gases against collapse.

– High-Temperature Superconductors
– Neutron Stars
– Strongly-Interacting Matter
– Quark-Gluon Plasma – Elliptic Flow

■ Quark-gluon plasma: As created at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, the exploding cloud of free quarks (which are fermions) and gluons has properties similar to a gas of fermionic atoms released from the confines of a trap.

26 SCIENTIFIC AMERICAN

Strongly-Interacting Fermi Gases Mimic Exotic Systems in Nature

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- Neutron Stars $U = \beta \varepsilon_F(x)$

  O'Hara et al., Science (2002)
  Heiselberg, PRA (2001)

  Carlson, et al., PRL (2003): $\beta = -0.56$

  Grimm: $\beta = -0.55$ — -0.75
  Salomon: $\beta = -0.55$

- Strongly-Interacting Matter (Steele)

  Effective Field Theory

  $$\beta_{calc} = \frac{5}{3}\frac{2}{3\pi}\frac{k_F a_S}{1-(2/\pi)k_F a_S}$$

- Condensed Matter

  Universal Thermodynamics (Ho)
  Super-High Temperature Superfluidity
  (Stoof/Hulet, Holland, Timmermans, Griffin)

- Quark-Gluon Plasma

  "Elliptic Flow," nearly perfect normal fluid hydrodynamics (Heinz)

Mixture of Spin Up/Down ^{6}Li Atoms

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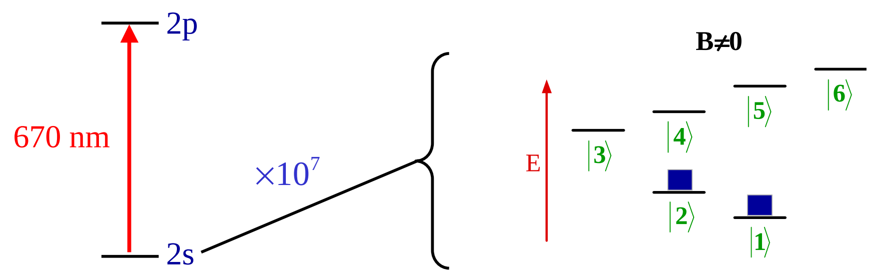
Ground State Hyperfine Structure in a Magnetic Field B



Ground State: $1s^2 2s^1$

Nuclear Spin: $I_N=1$

Level 1 Spin ½ Up $\quad |1\rangle = |\uparrow\rangle = \left|-\frac{1}{2},1\right\rangle$

Level 2 Spin ½ Down $\quad |2\rangle = |\downarrow\rangle = \left|-\frac{1}{2},0\right\rangle$

1,2 States High B-Field Seeking-Requires Optical Trap

Controlling Interactions with a Feshbach Resonance

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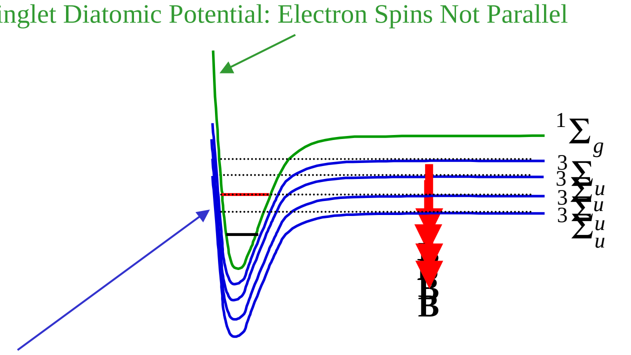
Resonant Coupling between Colliding Atom Pair – Bound Molecular State

Singlet Diatomic Potential: Electron Spins Not Parallel



Triplet Diatomic Potential: Electron Spins Parallel

Zero Energy Scattering Length $\quad a_S \rightarrow \pm\infty$

*Feshbach Resonance: Zero-Crossing

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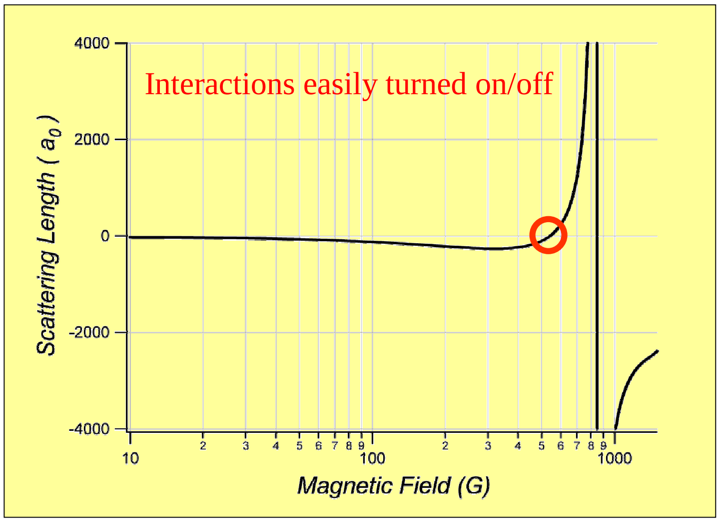

*M. Houbiers, *et al*., Phys. Rev. A **57**, 1497 (1998)

Cooling Fermi Gases in Optical Traps

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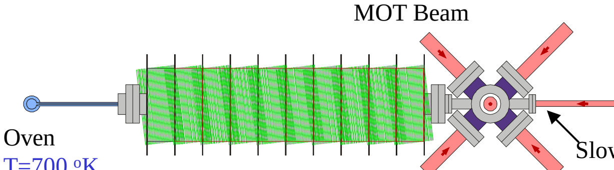
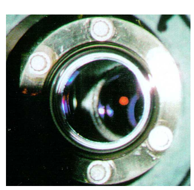
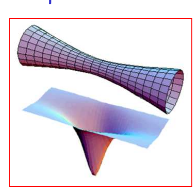


T=700 °K
$\rho = 10^{-9}$

T < 100 nK
$\rho = 1$

P = 10^{-11} Torr
T = 150 μK
$\rho = 10^{-5}$





Optical Trap

Optical Trap

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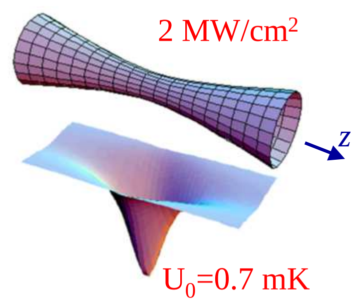
Focused Gaussian Laser Beam

$$U = -\frac{1}{2}\alpha \overline{E_0^2}\,\frac{1}{1+(z/z_0)^2}\,e^{-2r^2/w_0^2}$$



Ultrastable CO_2 Laser Trap

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- Stable Commercial Laser

- Typical Trap Parameters

$P = 65\text{ W}$ $\quad \omega_0 = 47\ \mu\text{m}$, $z_0 = 0.7\text{ mm}$

$I_0 = 2.0\text{ MW/cm}^2$ $\quad U_0 = 0.7\text{ mK}$

$\nu_r \cong 6.6\text{ kHz}$ $\quad \nu_z \cong 340\text{ Hz}$

- Negligible Optical Heating
  - Scattering Time: 1/2 hour
  - Optical Heating: 18 pK/s
- Extremely Low Noise
  - Intensity Noise Heating

$$\Gamma^{-1} \geq 2.3\times 10^4\text{ sec}$$

- Ultra-High Vacuum
  - Pressure: $< 10^{-11}$ Torr
  - Heating: < 5 nK/sec
  - Lifetime: 400 sec

Experimental Apparatus

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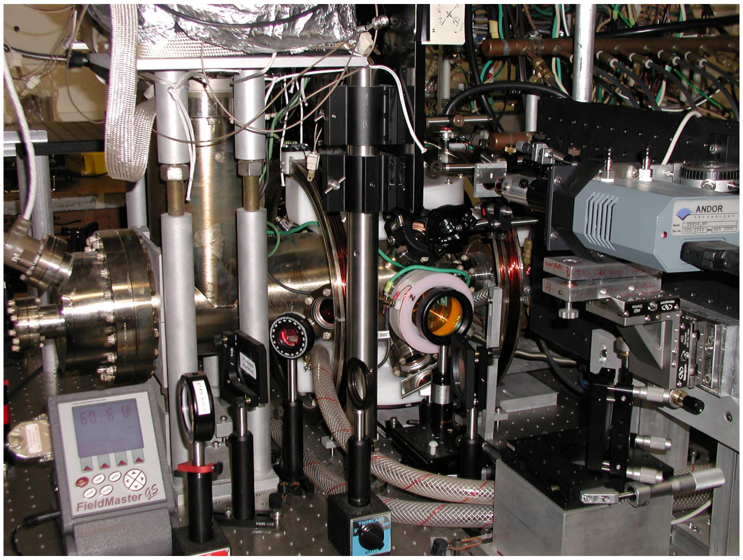

Optical Trap Loading

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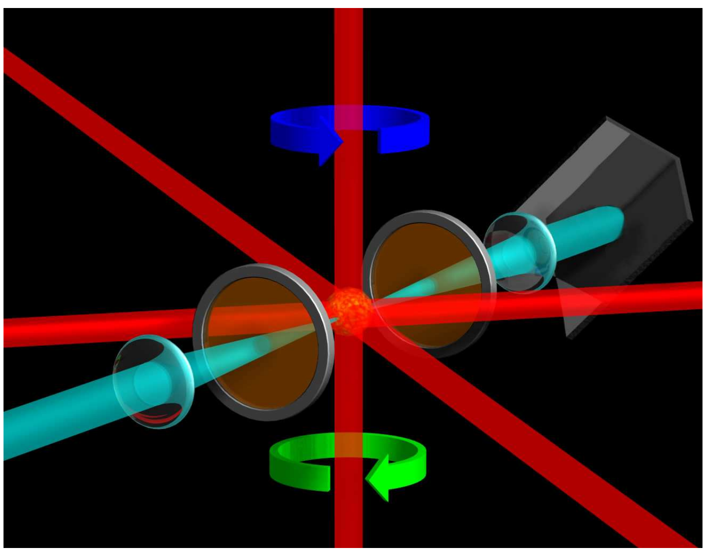

Forced Evaporation

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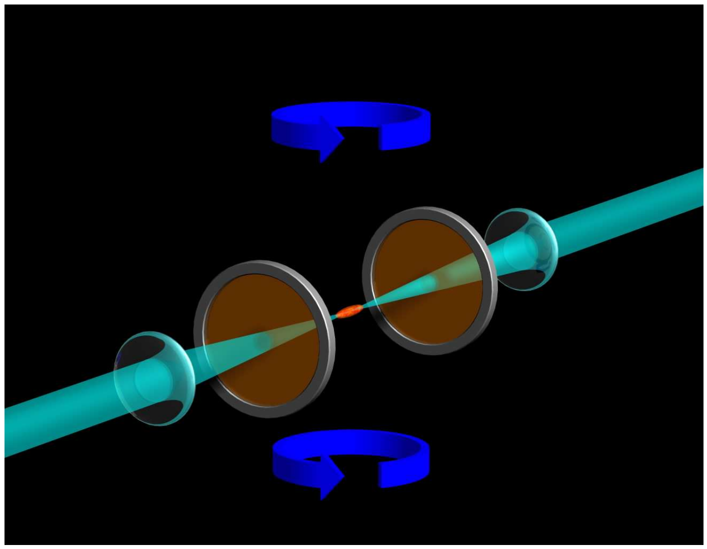

Timing Sequence for Evaporation

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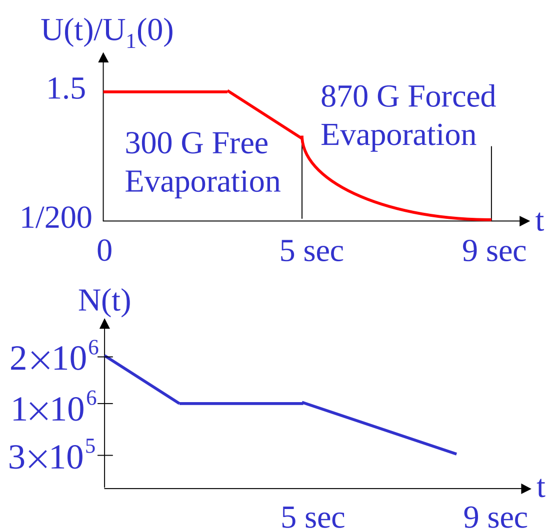

Scaling Laws:

$$\frac{\rho_f}{\rho_i} = \left(\frac{U_i}{U_f}\right)^{1.3} = 10^3$$

$$\frac{N_f}{N_i} = \left(\frac{U_f}{U_i}\right)^{\frac{3}{16}} = \frac{1}{2.7}$$

Cooling a Strongly-Interacting Fermi Gas

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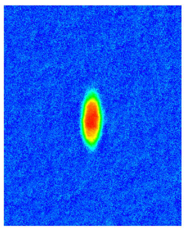
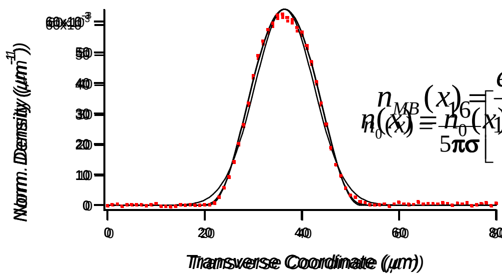
Evaporate for 3.5 s at 910 G:

t = 0.2 ms after release





$$n_{MB}(x)=\frac{e^{-x^2/\sigma^2}}{\sigma\sqrt{\pi}} \qquad n(x)=n_0(x)+\left(\frac{T}{T_F}\right)^2 n_2(x)$$

$T/T_F = 0.09$
T = 0.7 μK at full trap depth U_0
T = 50 nK at $U_0/200$

Superfluidity in Atomic Fermi Gases

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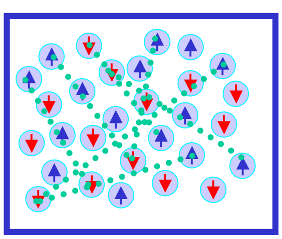
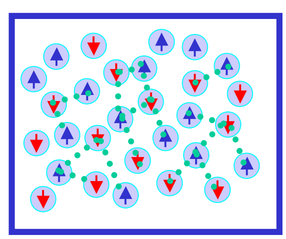
- Magnetically tunable interactions via Feshbach Resonance
- Theory BCS Pairing ^{6}Li: Houbiers, et al., PRA **56**, 4864 (1997).



$$T_C = \eta_C T_F$$



$$\eta_C \approx \exp\left(\frac{-L}{|a_S|}\right) << 1 \qquad \eta_C \approx 0.2-0.5$$

- On Resonance: Super-High T_C Superconductivity!

M. Holland, *et al.* Phys. Rev. Lett. **87**, 120406 (2001)
E. Timmermans, *et al.* Phys. Lett. A **285**, 228 (2001)
Y. Ohashi *et al.* cond-mat/0201262 (2002)

Prediction of Anisotropic Expansion*

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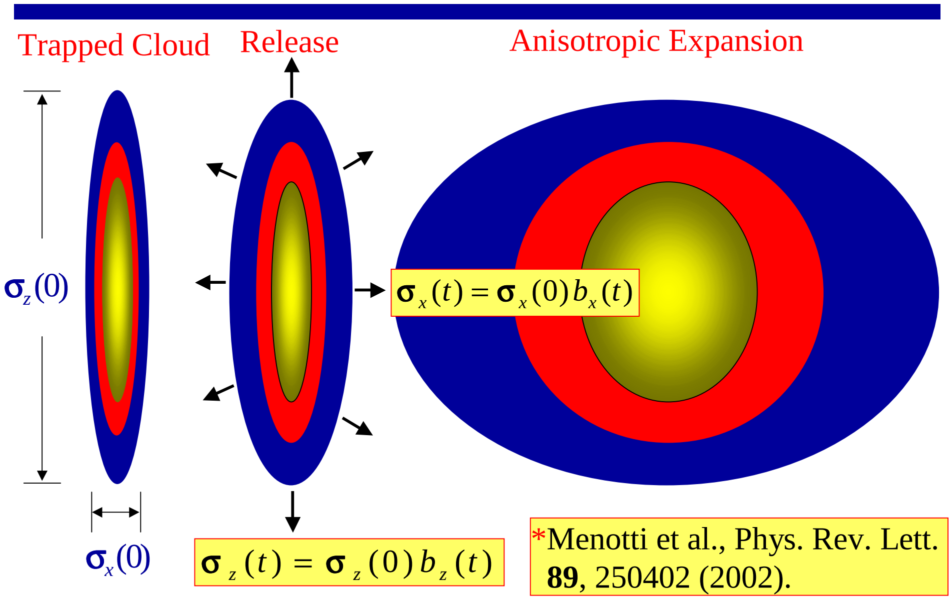

*Menotti et al., Phys. Rev. Lett. **89**, 250402 (2002).

Can Pauli Blocking Suppress Collisions?

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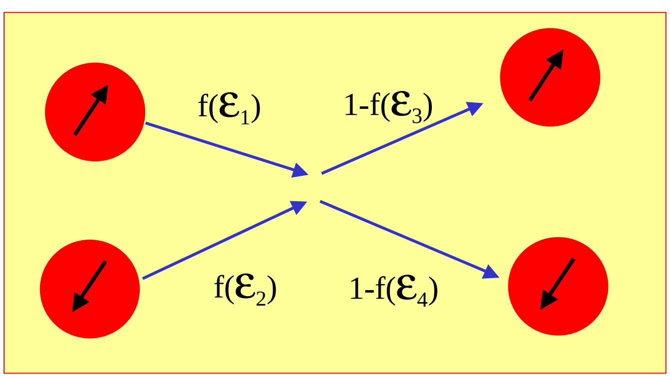
Collision cannot occur if the final state is occupied:



$$\Gamma_{coll} = \gamma \left(\frac{T}{T_F}\right)^2 \rightarrow 0$$

as $T \rightarrow 0$

$f(\varepsilon)$ is the occupation probability

Pauli Blocking in a Harmonic Trap

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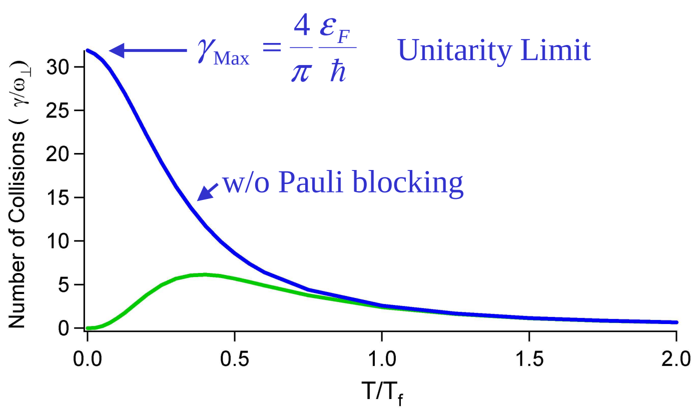
Depletion rate with and without Pauli Blocking:



Axial Expansion at 910 G

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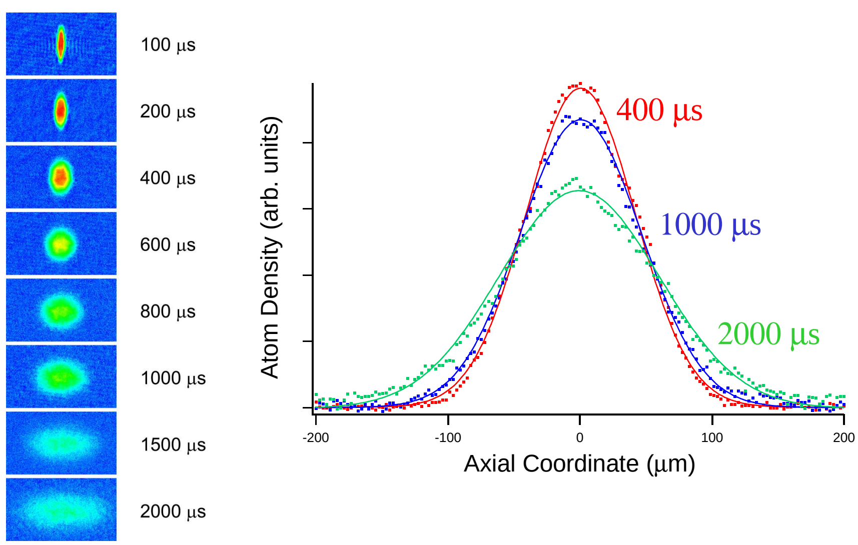

Transverse Expansion at 910 G

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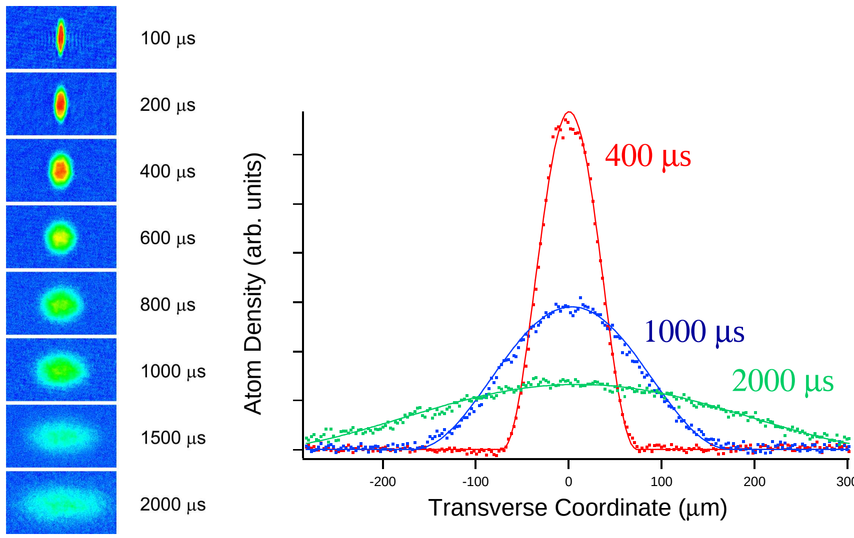

Transverse and Axial Widths vs Time

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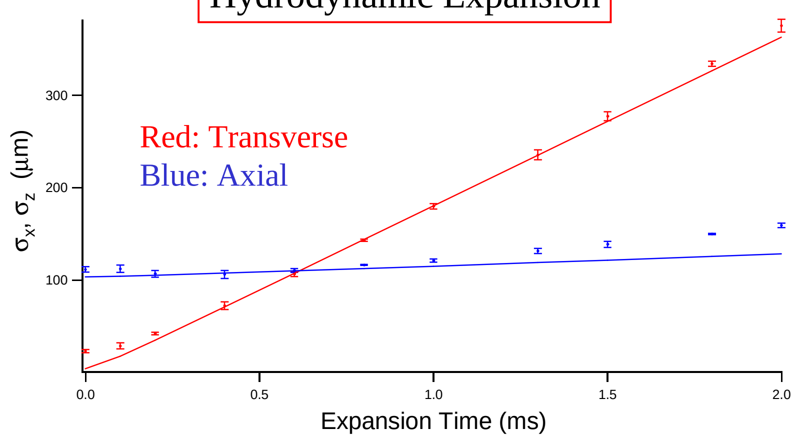
Hydrodynamic Expansion



Step-wise Model of Pauli-blocking

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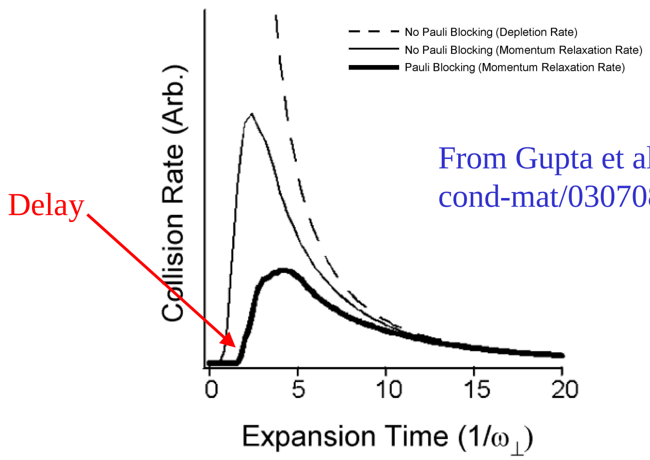

From Gupta et al., arXiv: cond-mat/0307088

Model: Ballistic expansion for time t_B followed by No Pauli Blocking

Relaxation Approximation

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Pedri et al., cond-mat/0305624 (2003); Guery-Odelin et al., PRA 60, 4851 (1999)

Ansatz: MB or Zero temp TF

$$W(\mathbf{x},\mathbf{p},t) = \frac{1}{\Pi_j (b_j \theta_j^{1/2})} W_0\left(\tilde{x}_i, \frac{p_i - M u_i}{\sqrt{\theta_i}}\right) \qquad \tilde{x}_i = \frac{x_i}{b_i}, \quad u_i = \tilde{x}_i \dot{b}_i$$

$$0 = \ddot{b}_i + \omega_i^2 b_i [1+\varepsilon(t)] - \frac{\theta_i}{b_i}\omega_i^2 + \frac{1}{M\langle \tilde{x}_i^2 \rangle}\left[\frac{1}{b_i}\left\langle \tilde{x}_i \frac{\partial U_{\mathrm{MF}}(\tilde{\mathbf{x}},t)}{\partial \tilde{x}_i}\right\rangle - \frac{\theta_i}{b_i}\left\langle \tilde{x}_i \frac{\partial U_{\mathrm{MF}}(\tilde{\mathbf{x}},0)}{\partial \tilde{x}_i}\right\rangle\right]$$

Trap Modulation

≈ 0 For hydrodynamic limit and $U_{\mathrm{MF}}(\mathbf{x}) = \frac{3}{5}\beta\varepsilon_{\mathrm{F}}(\mathbf{x})$

$$\dot{\theta}_i + 2\theta_i \frac{\dot{b}_i}{b_i} = -\frac{1}{\tau}(\theta_i - \bar{\theta}) \qquad \bar{\theta} = \tfrac{1}{3}\sum_j \theta_j$$

Momentum relaxation rate

Turn off for a time t_B

No Pauli Blocking:

$$\frac{1}{\tau} = \frac{1}{\Pi_j b_j \sqrt{\bar{\theta}}} \frac{8}{25}\left(\frac{4}{\pi}\frac{\varepsilon_{\mathrm{F}}}{\hbar}\right)$$

Collisional Expansion Dynamics

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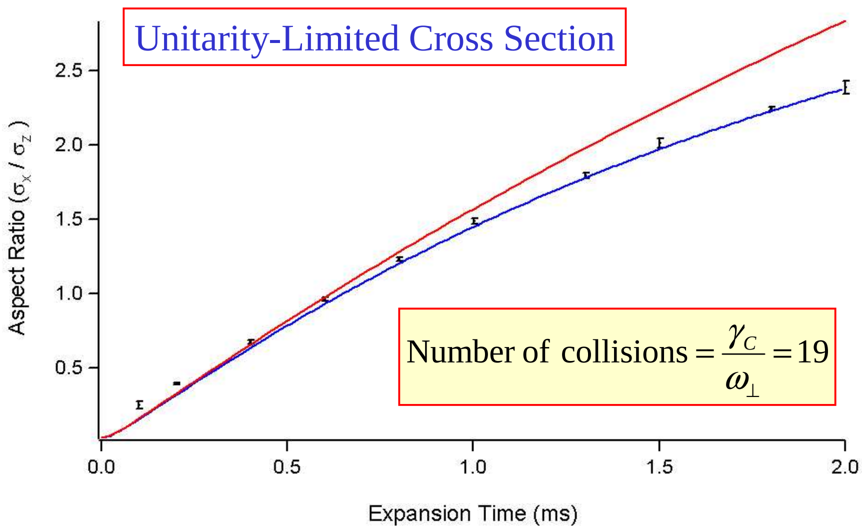

$$\text{Number of collisions} = \frac{\gamma_C}{\omega_\perp} = 19$$

Finite Time to Reinstate Collisions

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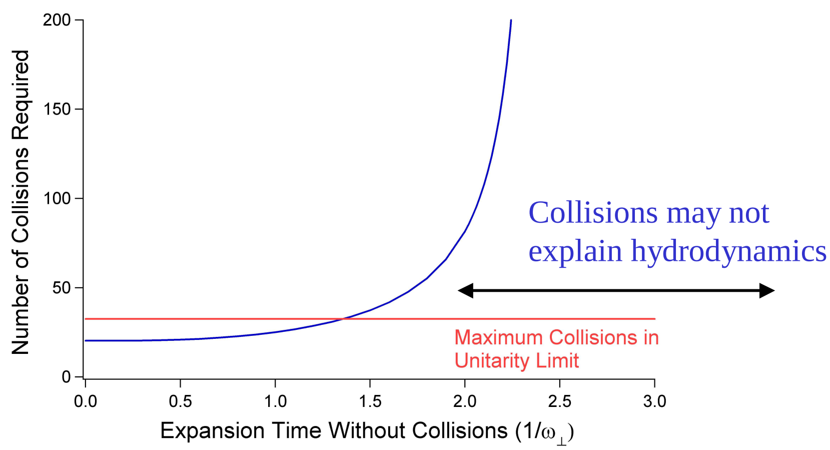
$$\text{Number of collisions to achieve our aspect ratio} = \frac{\gamma_C}{\omega_\perp}$$



"Shape-shifting" Fermi Gas

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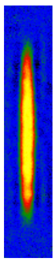
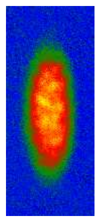
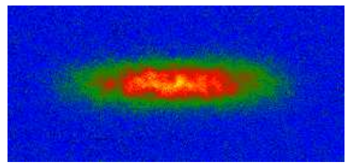
Trapped Gas: 0 ms



Released Gas: after 2.1 ms



Released Gas: 12 ms



Fermi energy 700 nK
$T/T_F < 0.1$

Anistropic Expansion (870 G)

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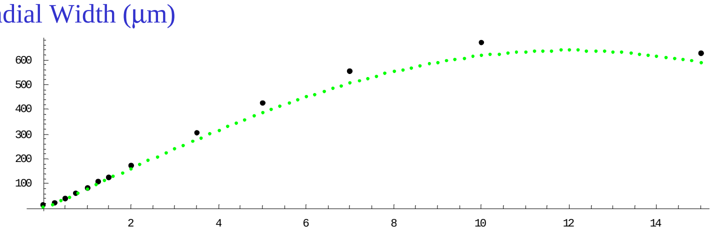
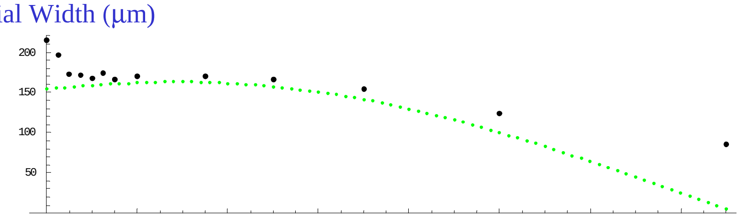
(4.6 % of maximum trap depth)





Hydrodynamics in a Trapped Fermi Gas

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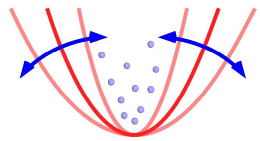
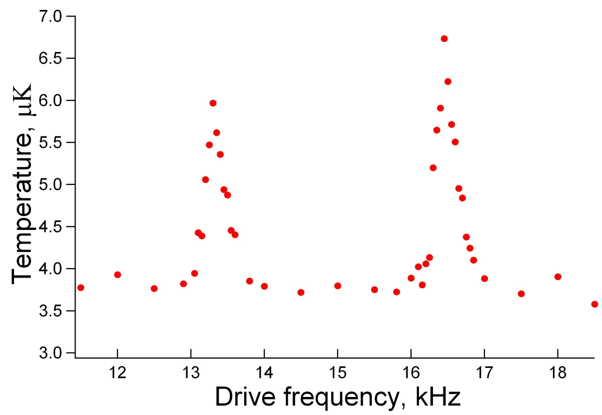
Parametric resonance



Modulate trap depth

Resonance at 2 ω

B = 300 G (few collisions)



Hydrodynamics in a Trapped Fermi Gas

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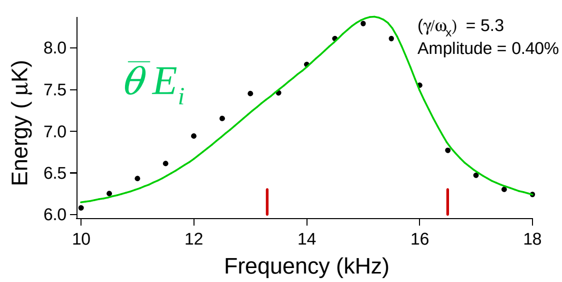
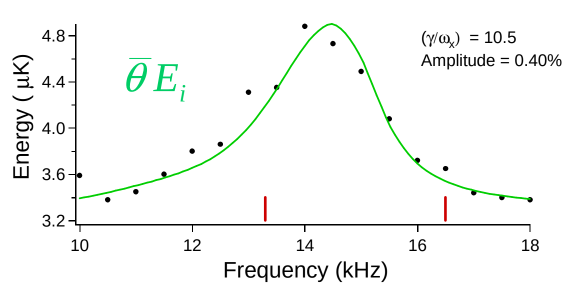
B = 910 G
(Strong Interactions)

$T = 0.6\ T_F$





Hydrodynamics in a Trapped Fermi Gas

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B = 910 G
(Strong Interactions)

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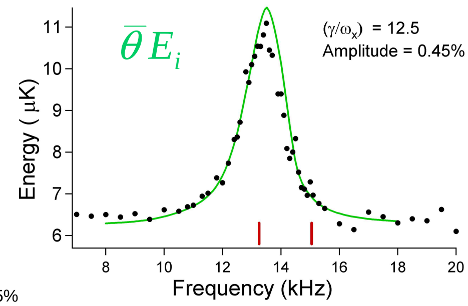

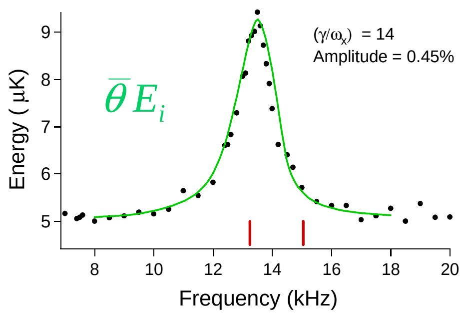

$T = 0.5\ T_F$

Breathing Mode in a Trapped Fermi Gas

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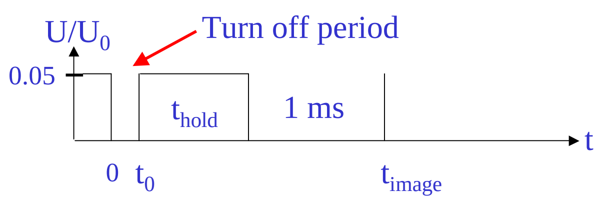

$$t_0 = \frac{1}{16}\frac{2\pi}{\omega} \qquad \frac{T_i}{T_F} \cong 0.1 - 0.15 \quad \Rightarrow \quad \frac{\Delta T}{T_F} \cong 0.05$$

Measure the Breathing Mode Oscillation Frequency and Damping Time versus Temperature

Collective Modes in a Trapped Fermi Gas

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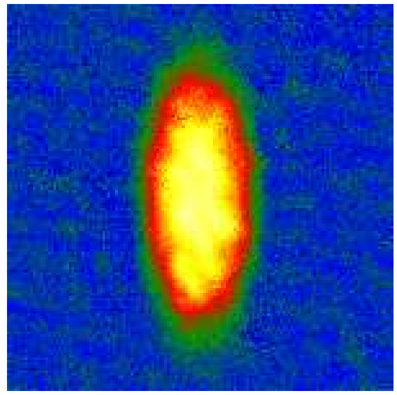
B = 870 G

$$\frac{T_i}{T_F} = 0.1 - 0.15$$



Breathing Mode in a Trapped Fermi Gas

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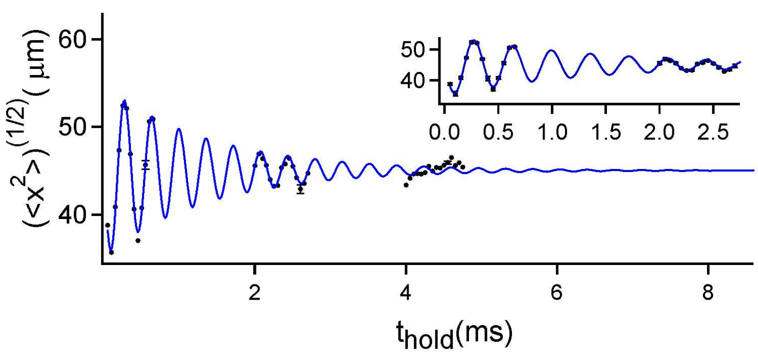
B = 870 G $\quad \frac{T_i}{T_F} = 0.50$



Breathing Mode in a Trapped Fermi Gas

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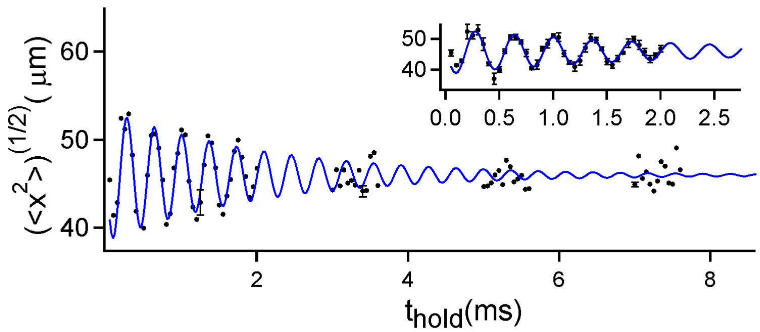
B = 870 G $\quad \frac{T_i}{T_F} = 0.33$



Breathing Mode in a Trapped Fermi Gas

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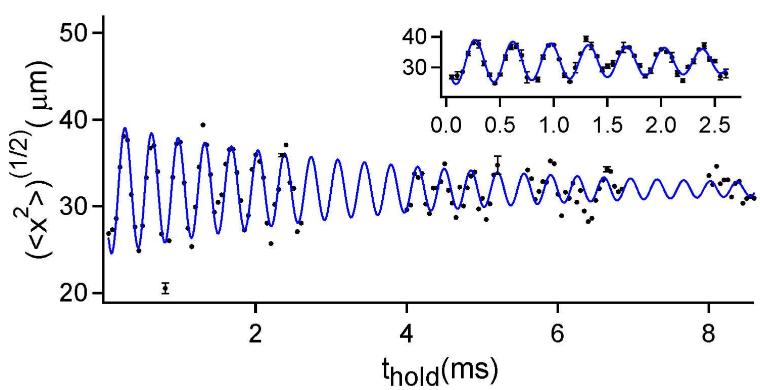
B = 870 G $\quad \frac{T_i}{T_F} = 0.17$



Breathing Mode Frequency

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Measured Oscillation Frequencies of Noninteracting Atoms:

$$\omega_x = 2\pi\times 1600\text{ Hz}$$
$$\omega_y = 2\pi\times 1500\text{ Hz}$$

Predicted Frequency for Hydrodynamic Fermi Gas:

$$\omega_{\text{Hydro}} = \sqrt{\frac{10}{3}\omega_x\omega_y} = 2\pi\times 2830\text{ Hz}$$

Measured Oscillation Frequency for Sinusoidal Fit:

$$\omega_{\text{Meas}} = 2\pi\times 2840\text{ Hz}$$

Breathing Mode Frequency vs B-Field

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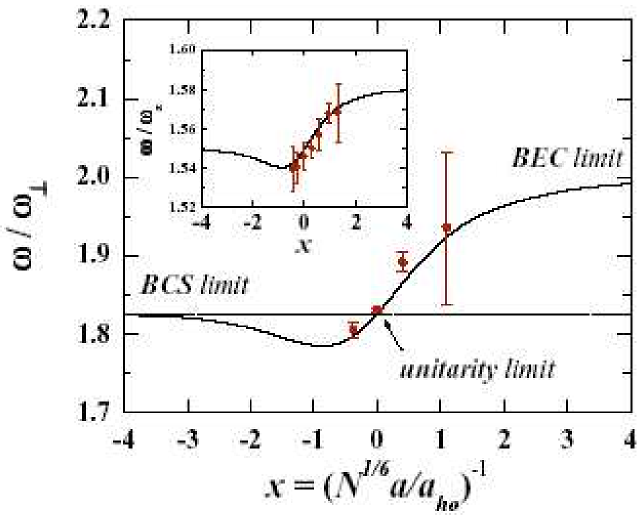
Hui Hu, A. Minguzzi, Xia-Ji Liu, and M. P. Tosi



Feshbach Resonance at 850 G

cond-mat/0404012 (Apr 2004)

Breathing Mode Frequency vs B-Field

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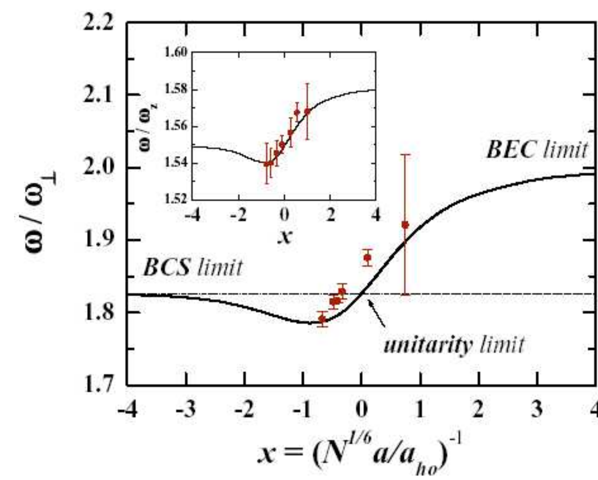
Hui Hu, A. Minguzzi, Xia-Ji Liu, and M. P. Tosi



Feshbach Resonance at 822 G

cond-mat/0404012 (Apr 2004)

Breathing Mode Frequency vs B-Field

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Atom Cooling and Trapping

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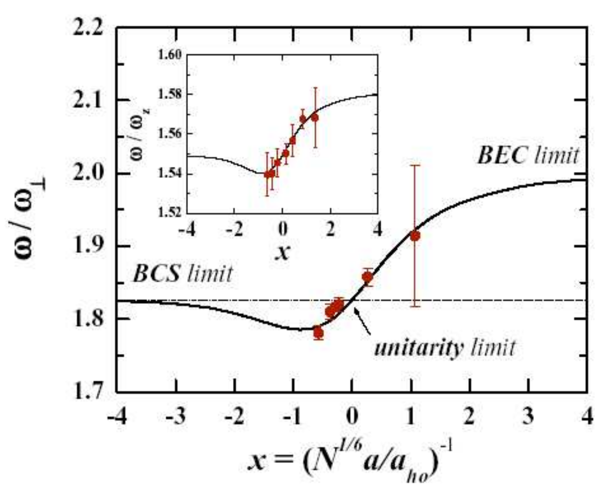

Feshbach Resonance at 838 G

cond-mat/0404012 (Apr 2004)

Damping Time of the Breathing Mode

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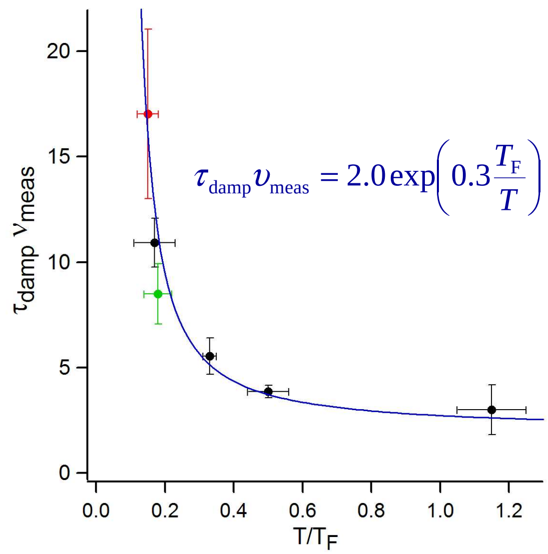

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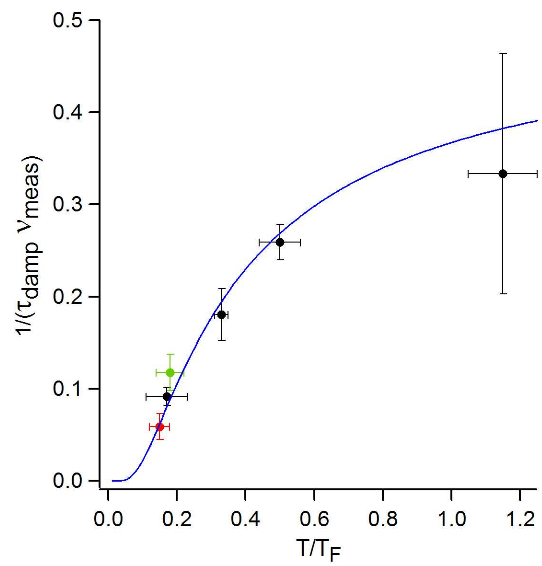


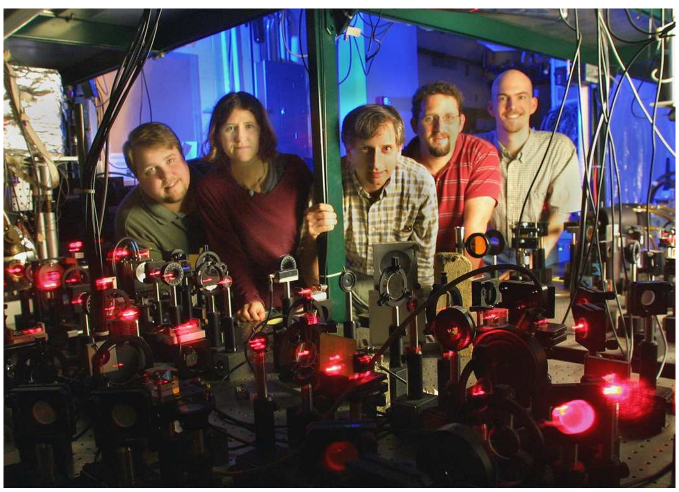
Summary

- All-Optical Production of Degenerate Fermi Gas
  - Efficient evaporation near Feshbach resonance
  - Very low T/T_F

Hydrodynamics of a Strongly-Interacting Fermi Gas

- Observation of Anisotropic Expansion
  - For low T, collisions may not explain hydrodynamics
- Trapped Atom Hydrodynamics
  - Collisionally-damped hydrodynamic spectra at high T
  - Hydrodynamic breathing modes weakly-damped as T is reduced
  - First evidence for superfluid hydrodynamics in a Fermi gas

The Team



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