Double-well geometries and species-selective environments

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Outline

- Species selective optical lattices
- Bose-fermi mixtures on a chip
- RF-dressed double well traps
- Direct observation of number squeezing?
- Other topics for discussion

Research Group

Postdocs

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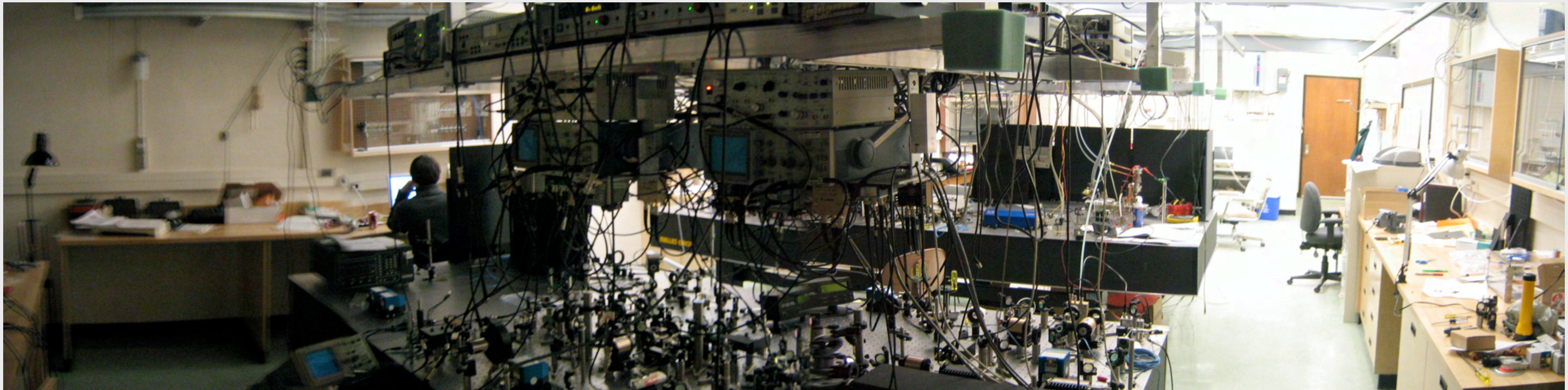
"Next gen:"

Brian Shuve → Harvard

Ian Leroux → MIT (Vuletic)

Dave McKay → DeMarco gp.

Dave Shirokoff → MIT



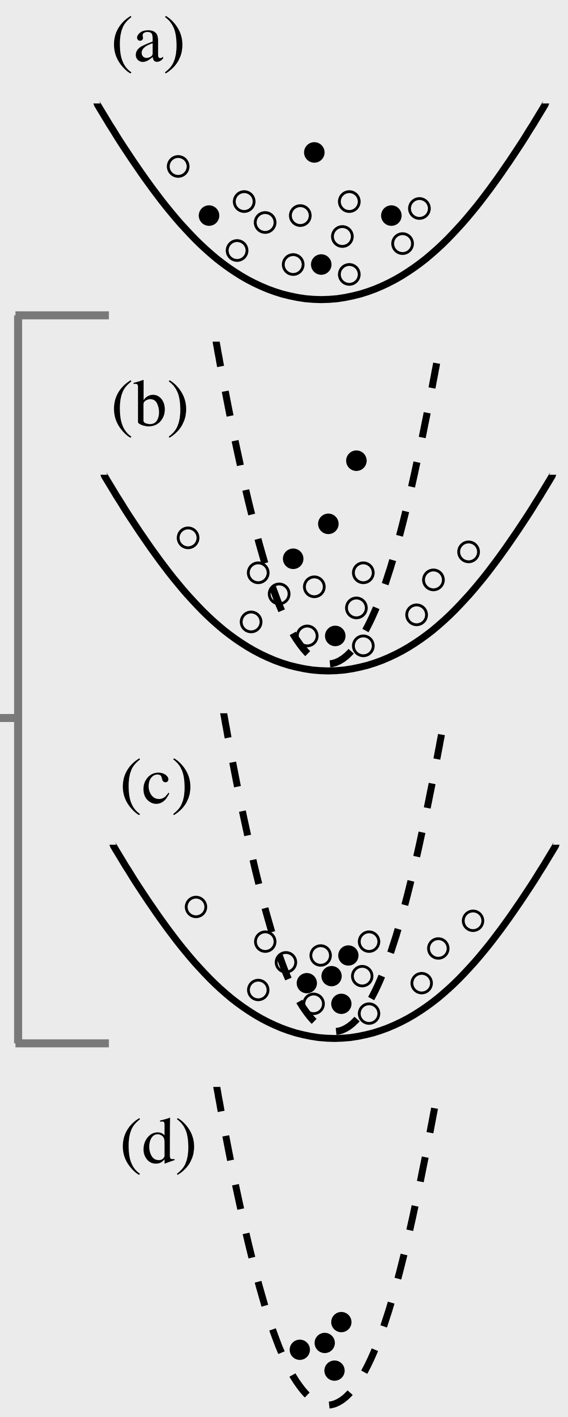
Species-selective optical lattices

L. J. LeBlanc and J. H. Thywissen
Species-specific optical lattices
c-m/0702034 and *Physical Reveiw A* (2007)

Wouldn't it be nice if...

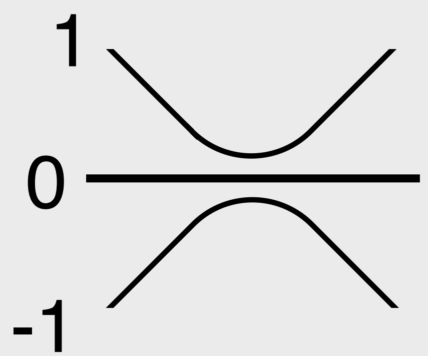
...we could choose trapping potential *independently* for different species?

- selective lattices
- isothermal compression
- single-species tweezers [Fei Zhou: dressing vortices]
- overlap engineering [equal TF radii for unequal μ]
- ...



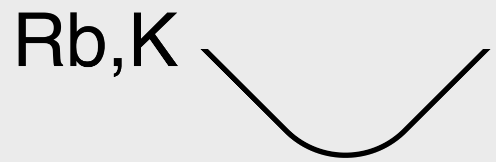
approaches

magnetic trap



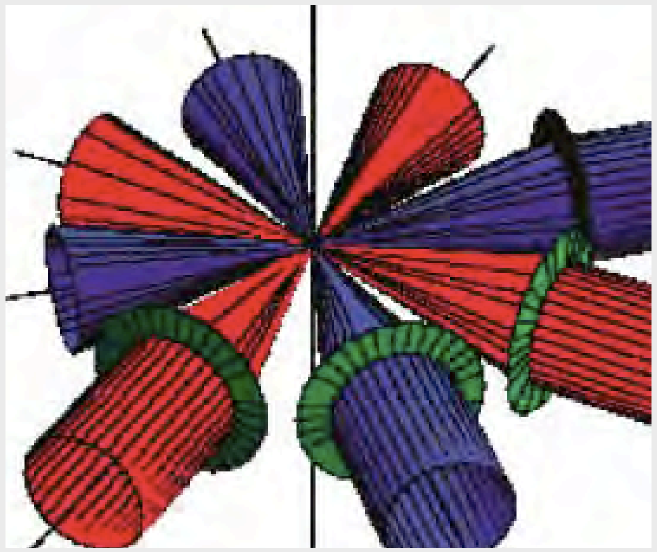
spin selectivity

FORT



small species selectivity

2-color trap

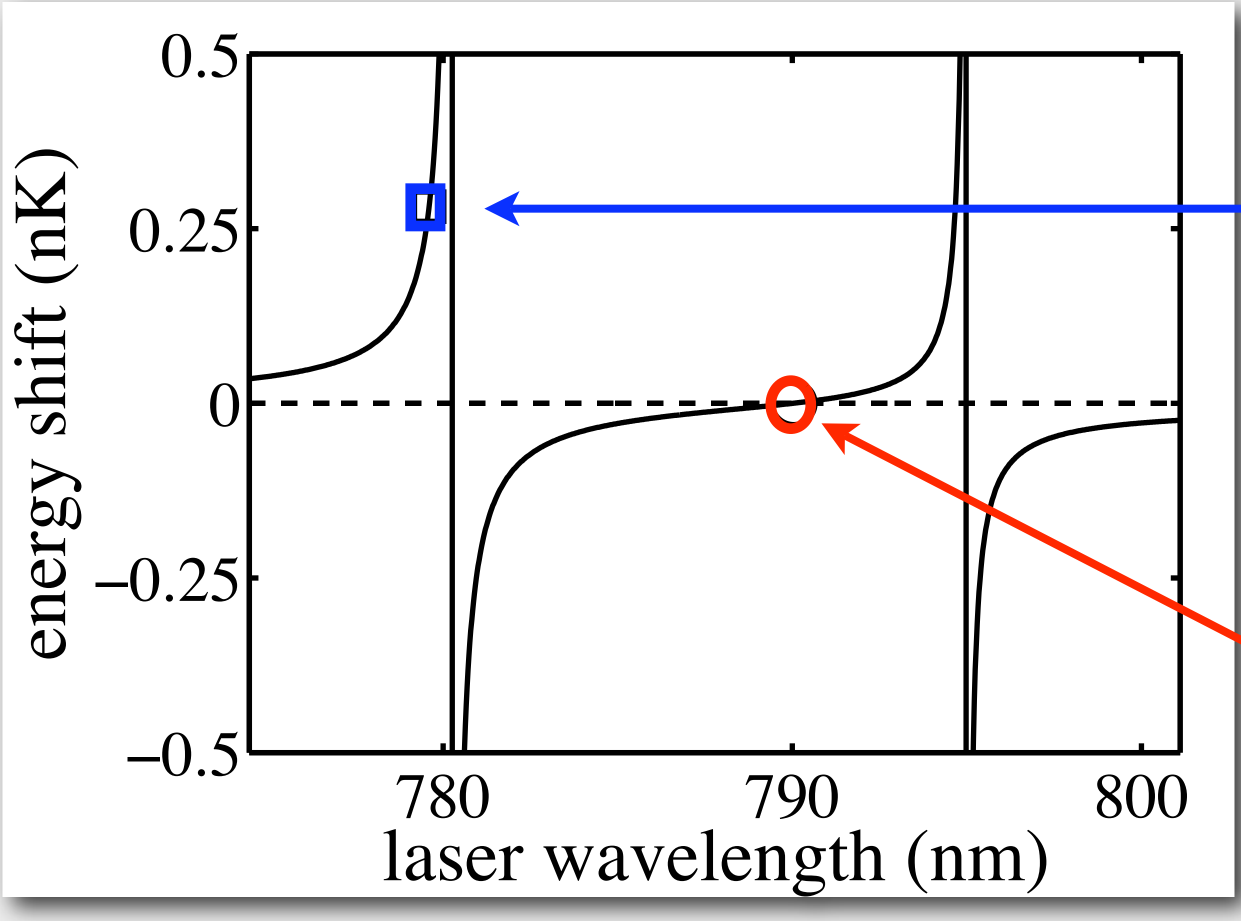


Onofrio et al. (2001,2002)

- None of these can create species-selective optical lattices
- We analyze two alternative optical approaches, that are *not* far-detuned

two selective detunings

Rb87



"Tune in"

Near resonance, much stronger shift on Rb than, eg, K

At crossover, no shift on Rb: so only K affected.

"Tune out"

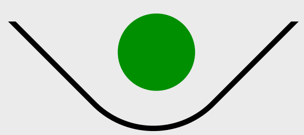
$$U_g = \frac{1}{2\epsilon_0 c}\sum_e \left[\frac{|\langle e|\mathbf{d}\cdot\hat{\epsilon}|g\rangle|^2}{\hbar(\omega_\mathrm{L}-\omega_\mathrm{eg})} - \frac{|\langle e|\mathbf{d}\cdot\hat{\epsilon}|g\rangle|^2}{\hbar(\omega_\mathrm{L}+\omega_\mathrm{eg})}\right] I$$

$$\gamma_g = \sum_e \frac{\Gamma_\mathrm{e}|\langle e|\mathbf{d}\cdot\hat{\epsilon}|g\rangle|^2}{\Delta_\mathrm{eg}^2} I$$

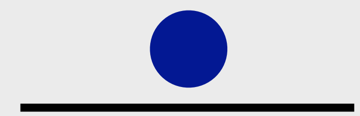
← problem: heating (light scattering).

Optimization

target



spectator



- Criterion 1: Selective

$$\rho = \left|\frac{U_{\mathrm{t}}}{U_{\mathrm{s}}}\right|$$ "selectivity"

U=shift
H=heating

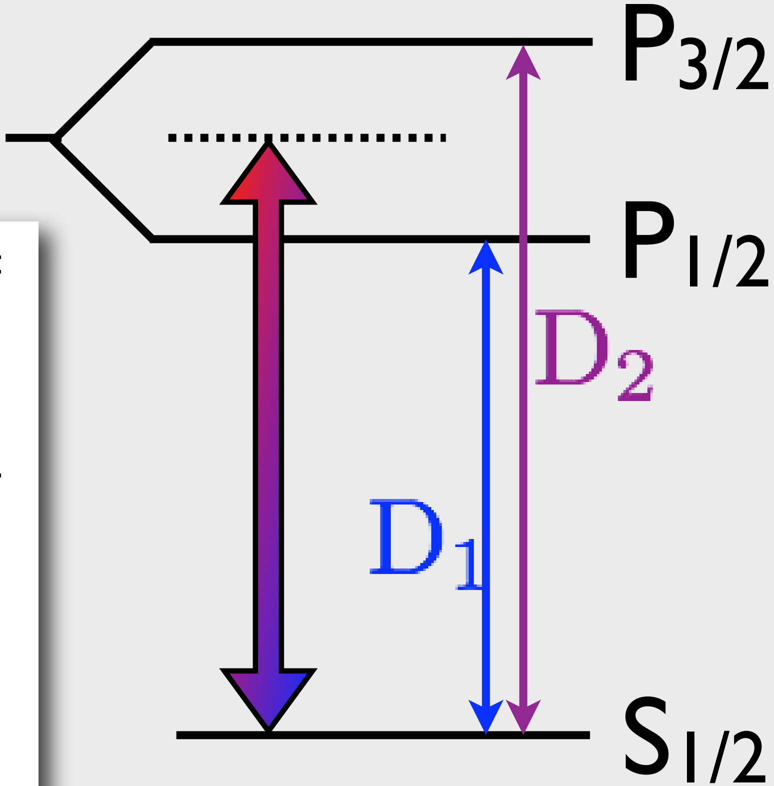
- Criterion 2: Low heating rate

$$\mathsf{s} = \frac{U_{\mathrm{t}}}{H_{\mathrm{t}} + H_{\mathrm{s}}}$$ "sustainability"

Question: what scheme maximizes both ρ and s ?

Tune out wavelengths

Element	$\lvert F, m_F \rangle$	λ_{TO} (nm) Eq. 1	Eq. 2	γ_{sc}/I (cm^2/mJ)
^{6}Li	$\lvert \frac{3}{2}, \frac{3}{2} \rangle$	670.99	670.99	2.8
^{7}Li	$\lvert 2, 2 \rangle$	670.97	670.97	2.4
^{23}Na	$\lvert 2, 2 \rangle$	589.56	589.56	2.0×10^{-3}
^{39}K	$\lvert 2, 2 \rangle$	768.95	768.95	1.4×10^{-4}
^{40}K	$\lvert \frac{9}{2}, \frac{9}{2} \rangle$	768.80	768.80	1.7×10^{-4}
^{87}Rb	$\lvert 2, 2 \rangle$	790.04	790.01	9.1×10^{-6}
^{133}Cs	$\lvert 4, 4 \rangle$	880.29	880.06	1.5×10^{-6}



- Heating rates low for elements with large fine splittings (Cs,Rb)
- Selectivity is infinite

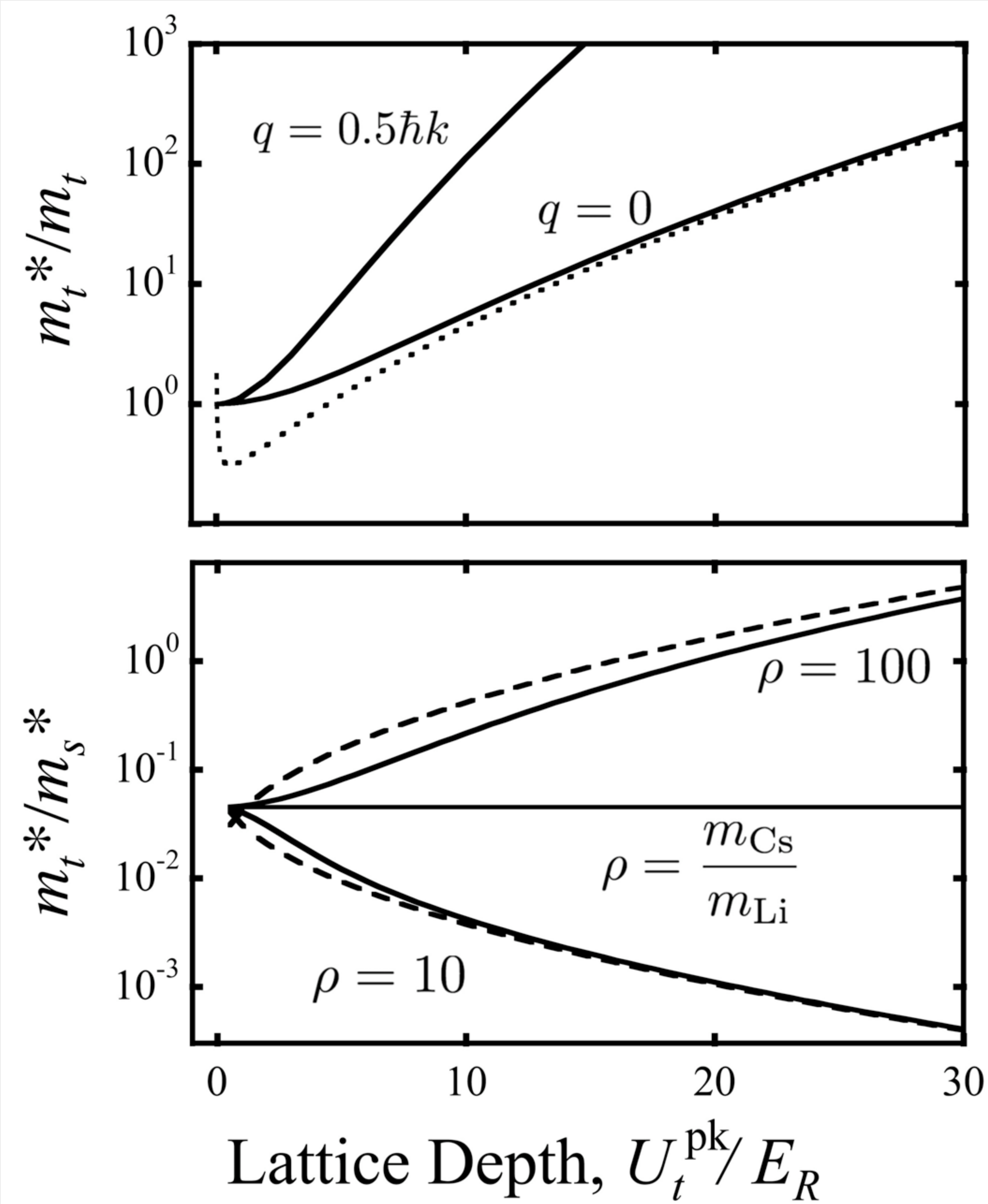
Sustainability of B-F mixtures for TO vs. TI

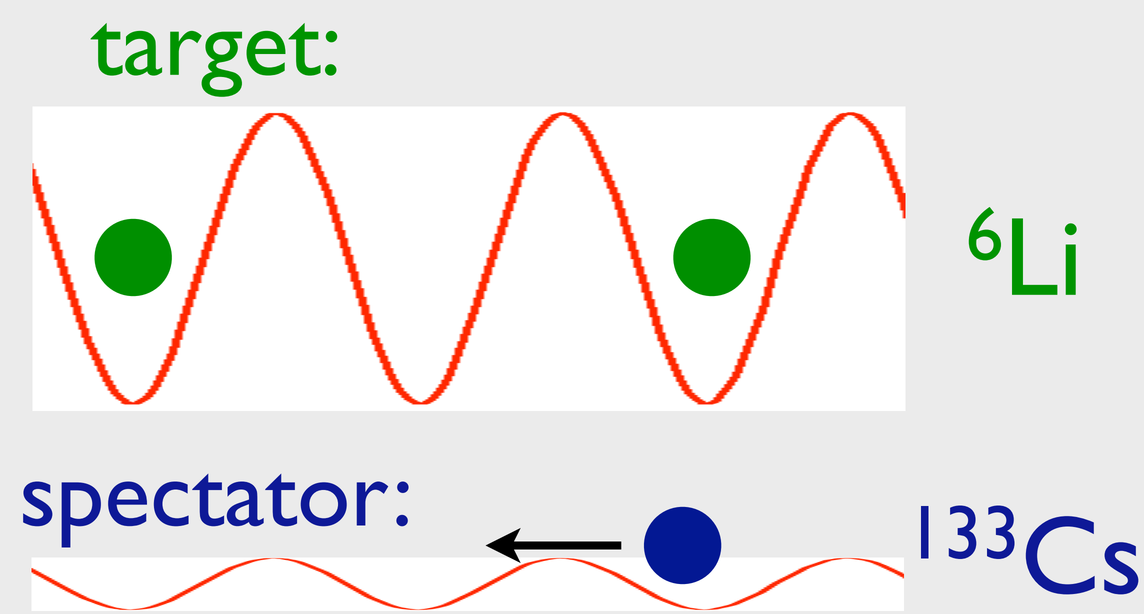
Target	ρ	Spectator ^{7}Li	^{23}Na	^{39}K	^{87}Rb	^{133}Cs
^{6}Li	∞	0.00134	7.77×10^{-4}	-0.0381	-1.20	-8.45
	100	2.66×10^{-5}	0.281	0.220	0.239	0.347
	10	3.92×10^{-6}	2.54	2.30	2.49	3.57
^{40}K	∞	4.28×10^{-7}	5.77×10^{-4}	0.188	-9.03	-25.8
	100	3.05	5.78	3.64×10^{-5}	0.251	1.39
	10	29.2	53.0	4.65×10^{-4}	3.27	18.8

units: seconds

- ☑ Optimal approach depends on mixture
- ☑ Several combinations have sustainability greater than 10s

application: Effective mass tuning

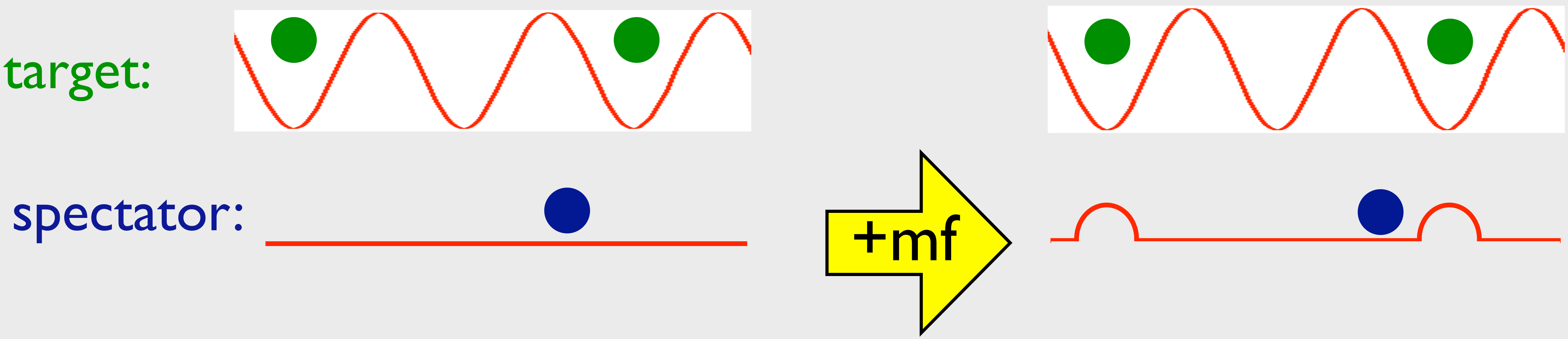




$$\frac{m_{\mathrm{t}}^*}{m_{\mathrm{s}}^*} \approx \frac{\exp\left\{2\sqrt{\eta_{\mathrm{t}}}\left(1-\sqrt{m_{\mathrm{s}}/\rho m_{\mathrm{t}}}\right)\right\}}{\rho^{3/4}}\left(\frac{m_{\mathrm{t}}}{m_{\mathrm{s}}}\right)^{1/4}$$

application: non-optical lattice

- Mean field of trapped target atoms create a lattice potential for spectator atoms



- Limits selectivity: $\rho_{\mathrm{max}} = \frac{\hbar \mu_{\mathrm{st}} \eta^{1/4}}{32\pi |a_{\mathrm{st}}| m_{\mathrm{t}}^{3/2} E_{\mathrm{R}}^{1/2}}$

- Also creates non-optical lattice: non-sinusoidal, and possibly dynamic.

Prospects

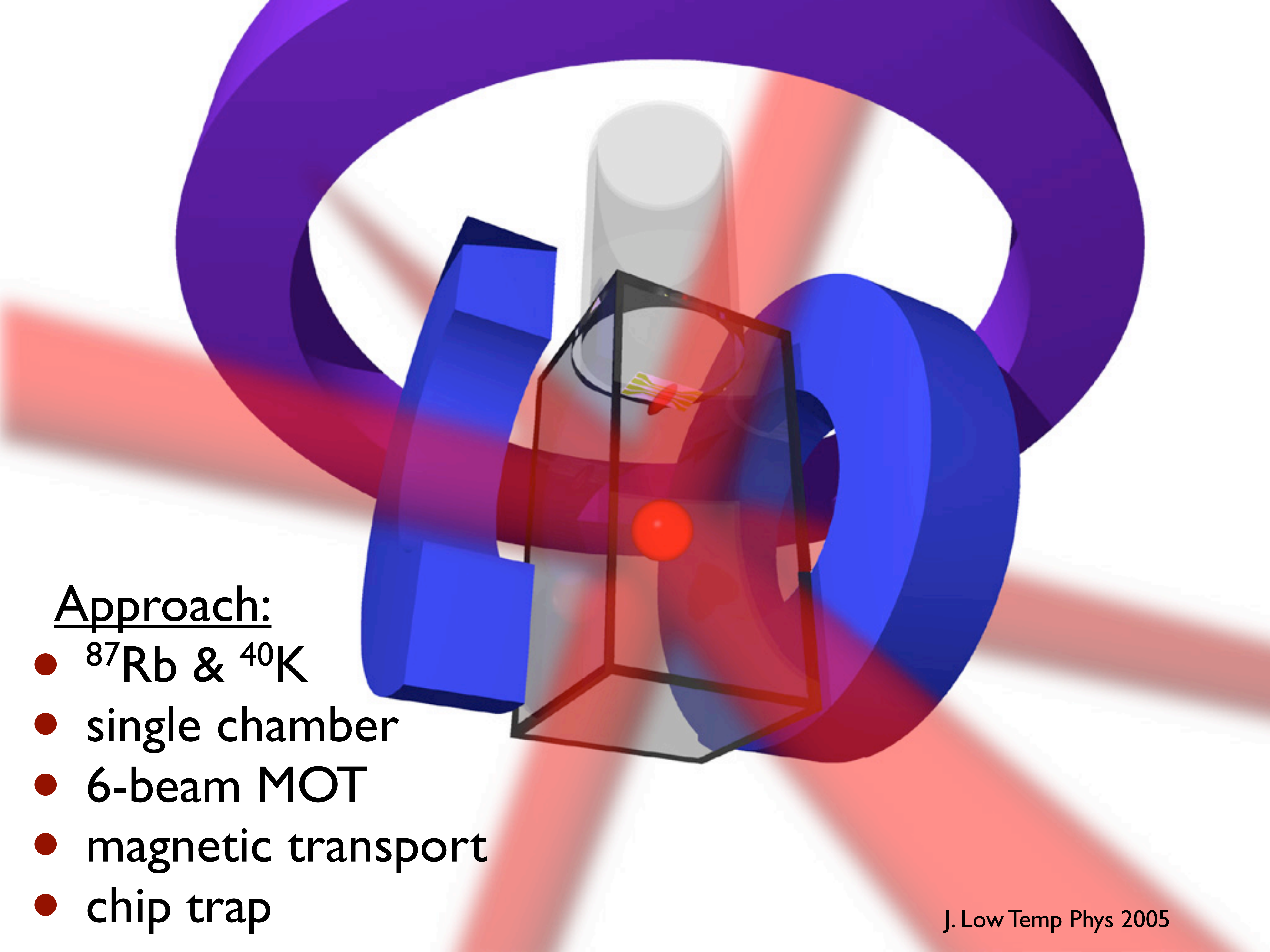
- mediated interactions between fermions
- effective mass engineering
- new kinds of lattices
- isothermal increase of phase space density

Issues

- Heating rates low enough?
- Selectivity limited by interactions
- Thermalization may be slow

Bose-Fermi mixtures on a chip

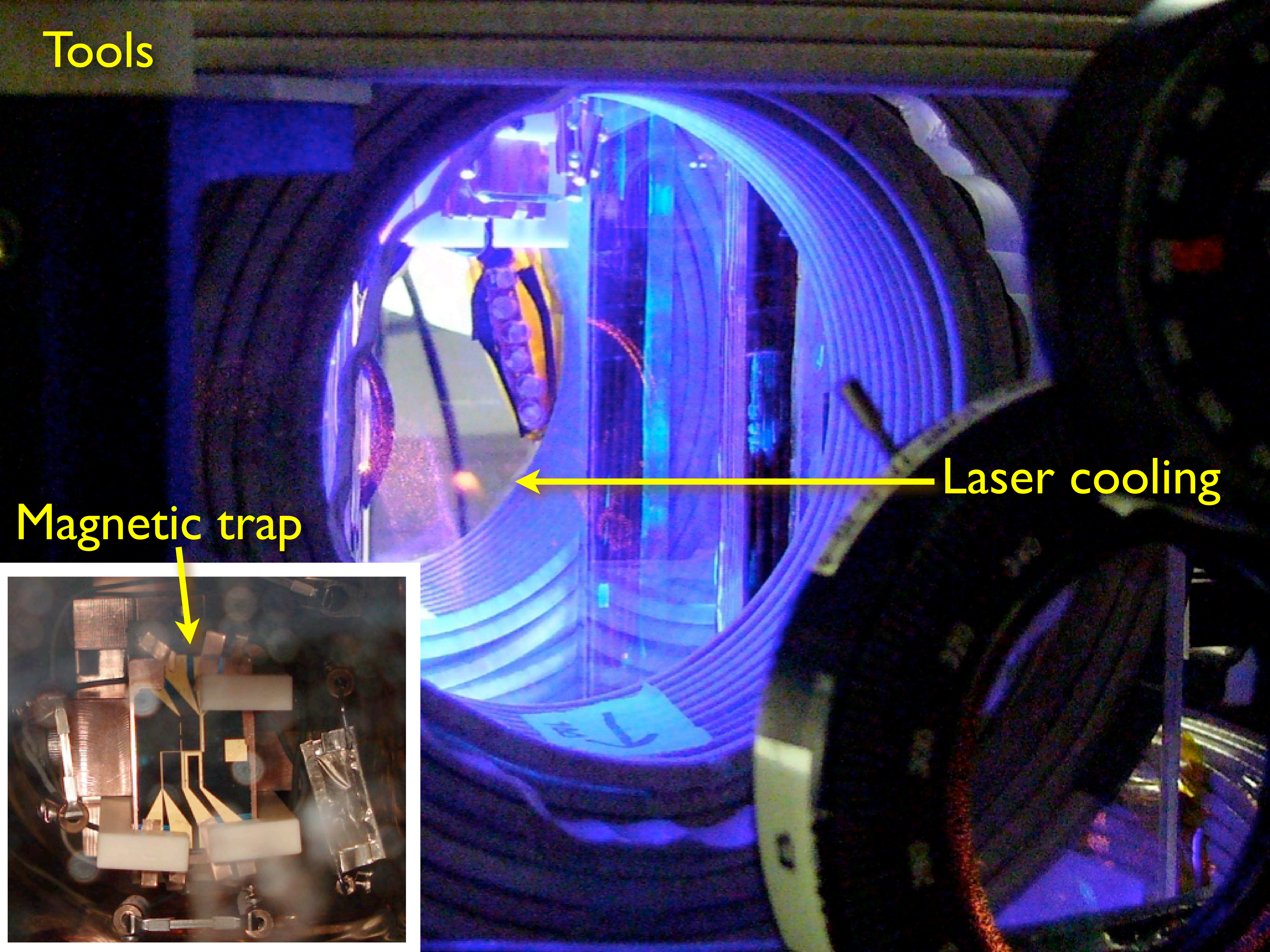
S. Aubin, S. Myrskog, M.H.T. Extavour, L. J. LeBlanc, D. McKay, A. Stummer, J. H. Thywissen
Rapid sympathetic cooling to Fermi degeneracy on a chip
Nature Physics **2**, 384-387 (2006)



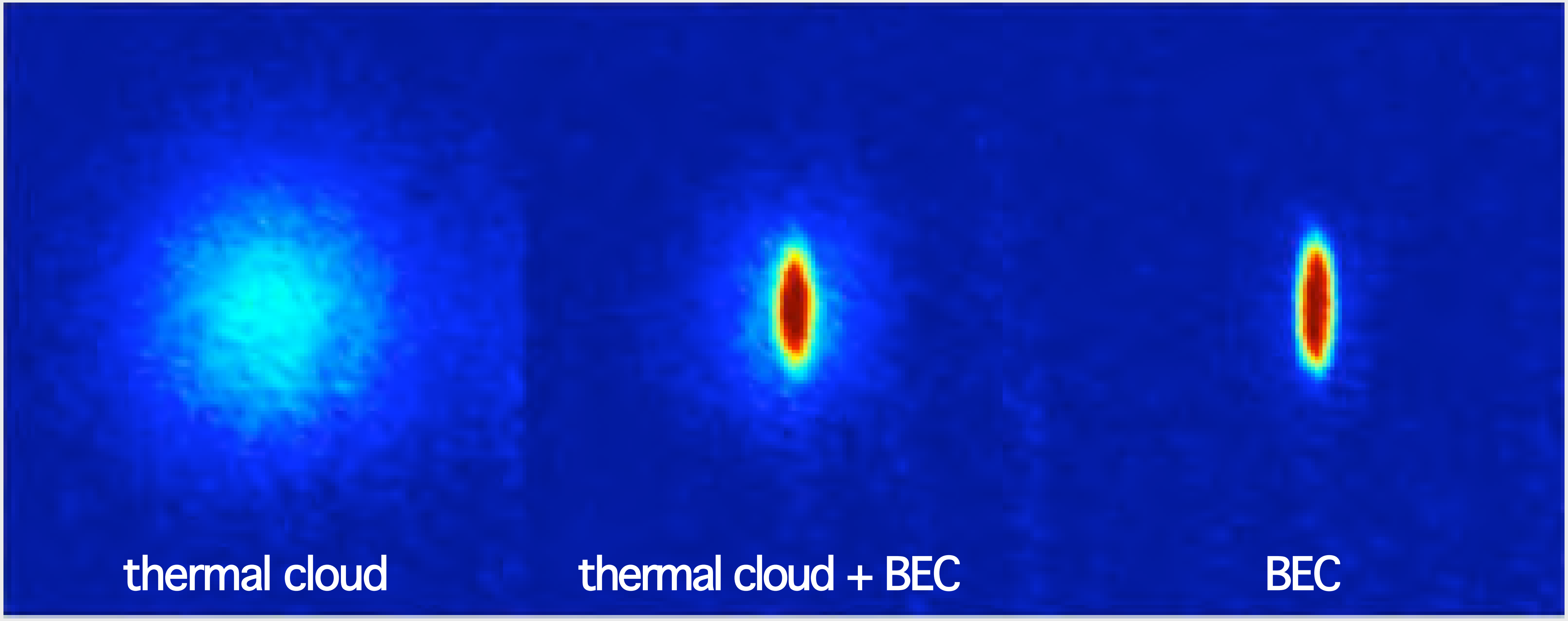
Approach:

- ^{87}Rb & ^{40}K
- single chamber
- 6-beam MOT
- magnetic transport
- chip trap

J. Low Temp Phys 2005

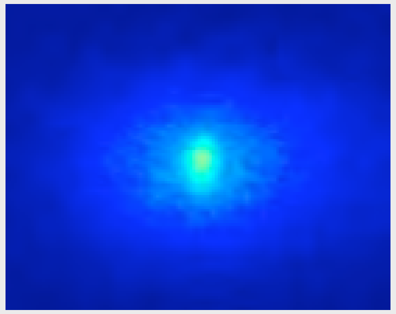

Tools
Laser cooling
Magnetic trap

Efficient evaporation



[April 2005]

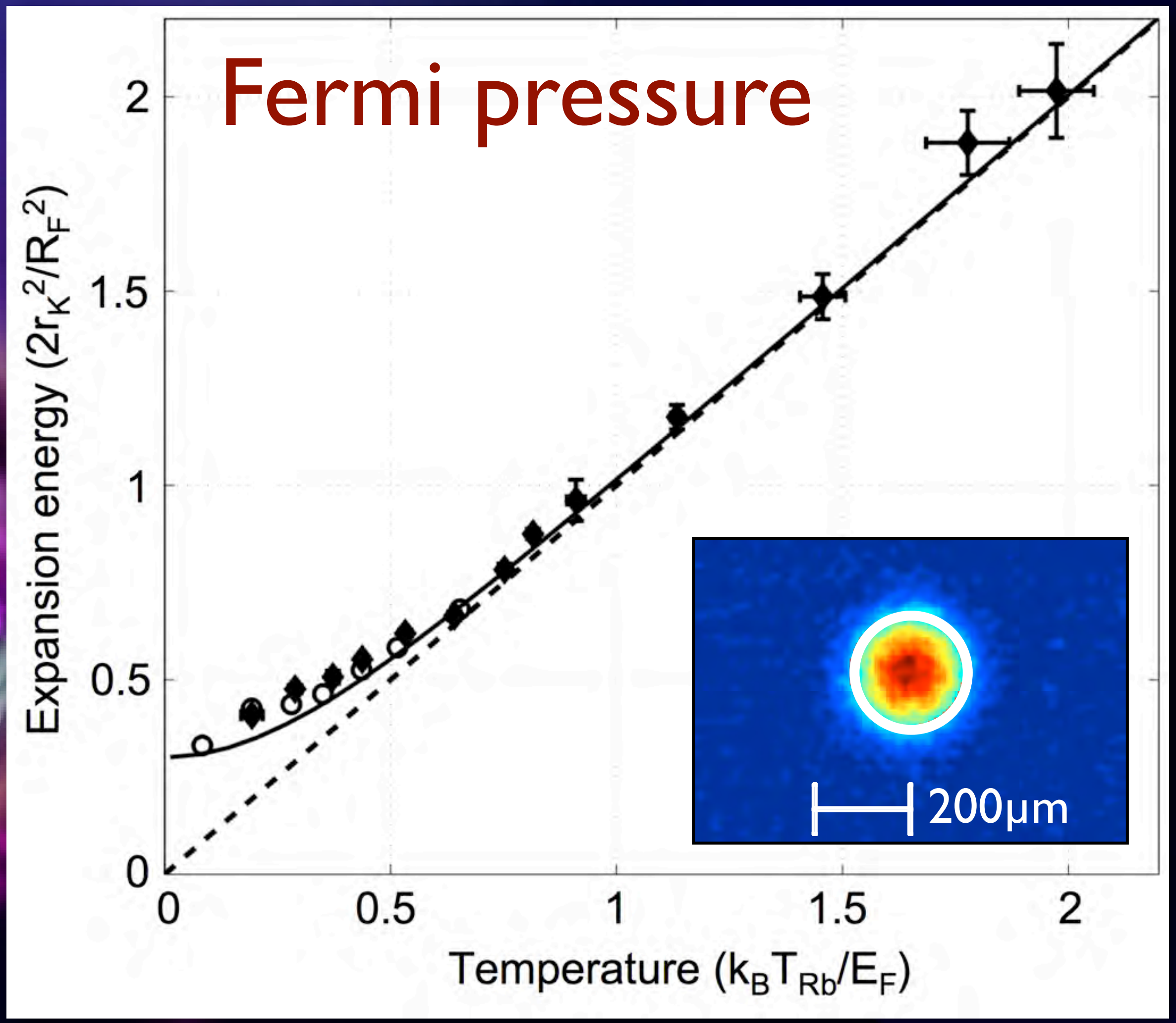
@1.725 MHz:
N = 6.4×10^5, T~T_c



Surprise! Reach BEC with only a 30x loss in atom number.

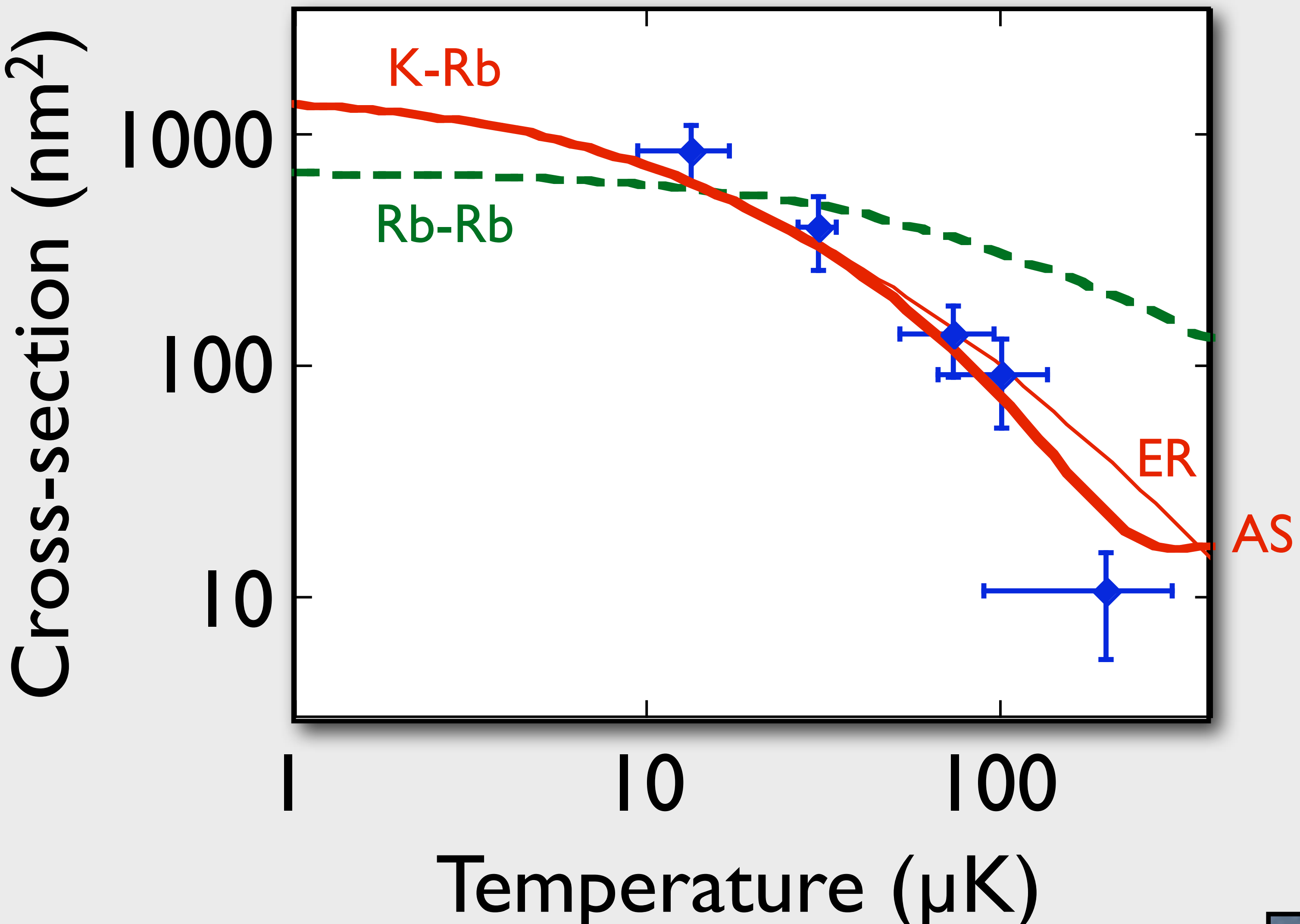
Compare to trap loaded with 2×10^7 atoms

sympathetic cooling on a chip



Aubin *et al*, Nature Phys. (2006)

Ramsauer-Townsend Effect



Both data & theory put K-Rb below Rb-Rb at T>20μK.

Aubin *et al*, Nature Phys. (2006)

Advantages of μfab traps

- Simple and robust approach: single cell
- High data rate:
  Sympathetic cooling in only 6s !
- New tools available:
  - single atom detection [eg, Reichel, Vuletic]
  - Strong rf manipulation
  - device integration

Double-well geometries for ^{87}Rb and ^{40}K

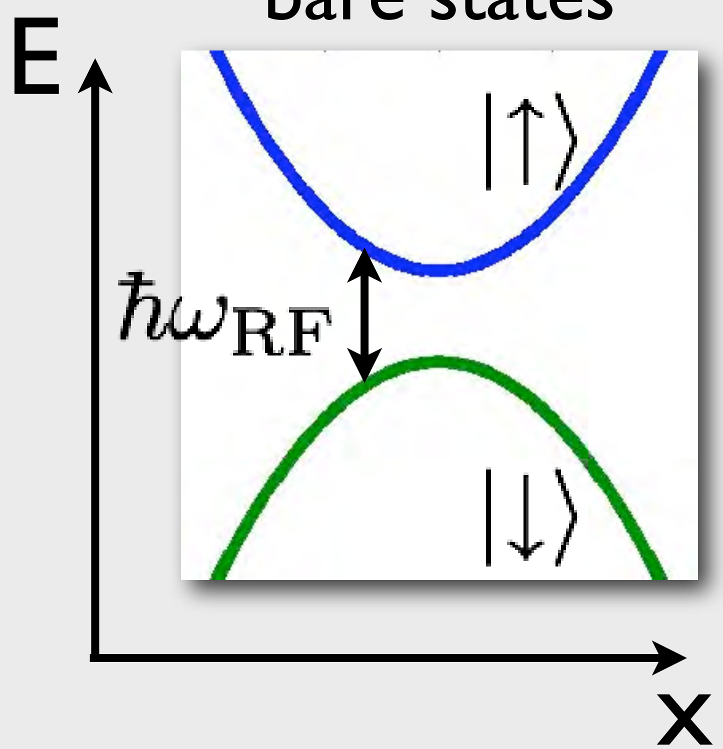
M. H. T. Extavour, L. J. LeBlanc, T. Schumm, B. Cieslak, S. Myrskog,
A. Stummer, S. Aubin, and J. H. Thywissen
Dual-species quantum degeneracy of 40K and 87Rb on an atom chip
Atomic Physics **20**, 241-249 (2006)

Double well formation

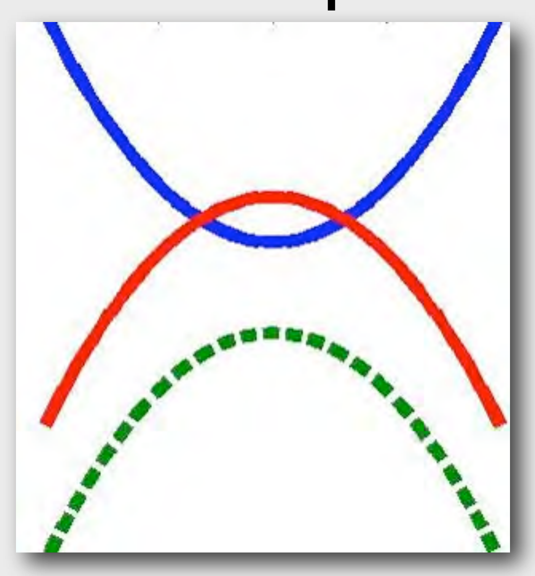
- Idea: combine static magnetic fields with (dressing) RF fields. This couples magnetic states:

[1D picture:]

bare states

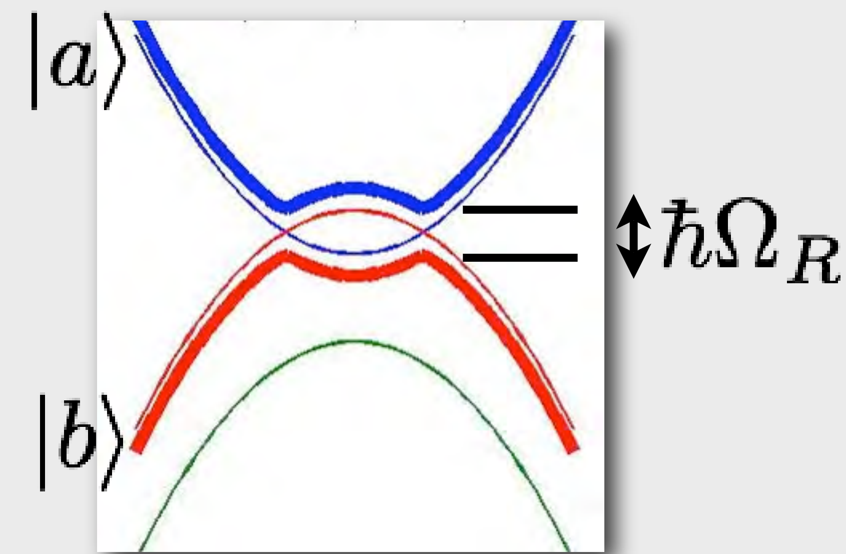


dress with photon



position controlled with RF frequency

adiabatic states



splitting controlled with RF amplitude

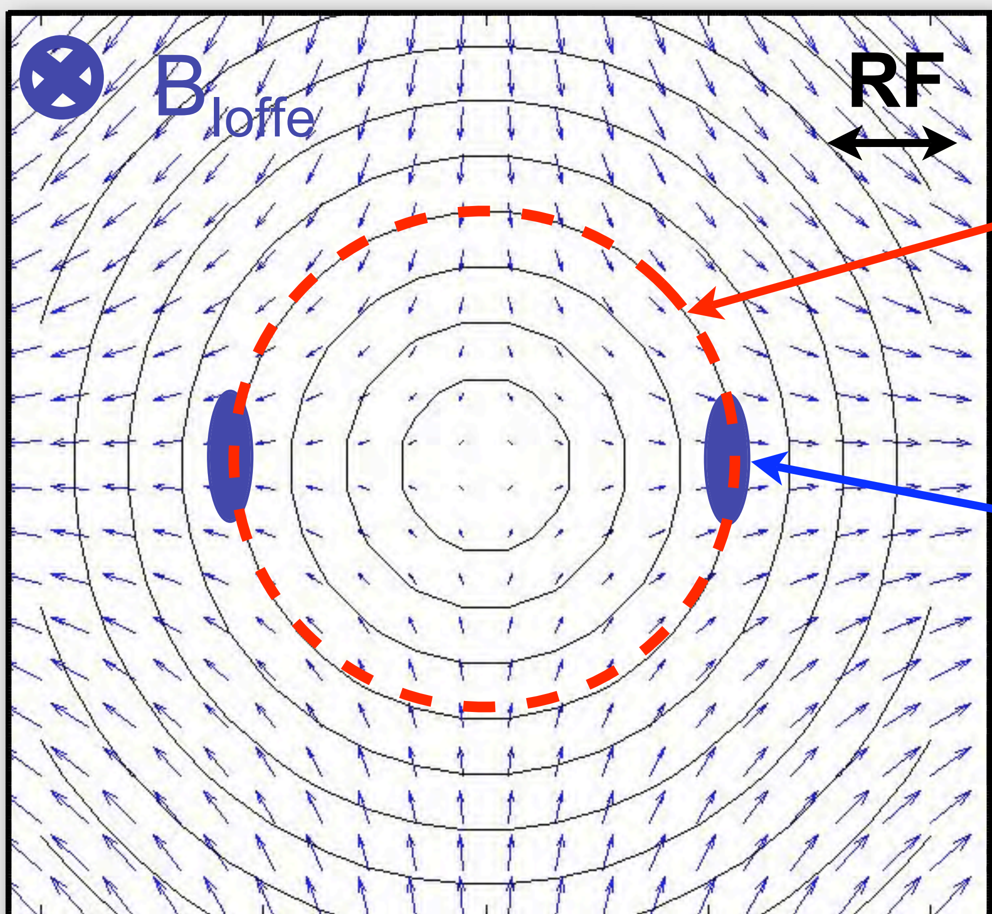
Refs:
Zobay&Garraway PRL (2001)
Colombe...Perrin, Europhys. Lett. (2004)
Schumm...Schmiedmayer, Nature Physics (2005)
DeMarco, PRA (2006)

[credit for this and next two slides: adapted from Schumm & Hoffelberth]

Adiabatic RF dressed potentials

- In 3D, the polarization of the RF field breaks rotational symmetry:

$$V = g_F m'_F \sqrt{\underline{[\mu_B B_{dc} - h\nu_{\rm rf}/g_F]}^2 + \underline{[\mu_B B_{\rm rf,\perp}/2]}^2}$$

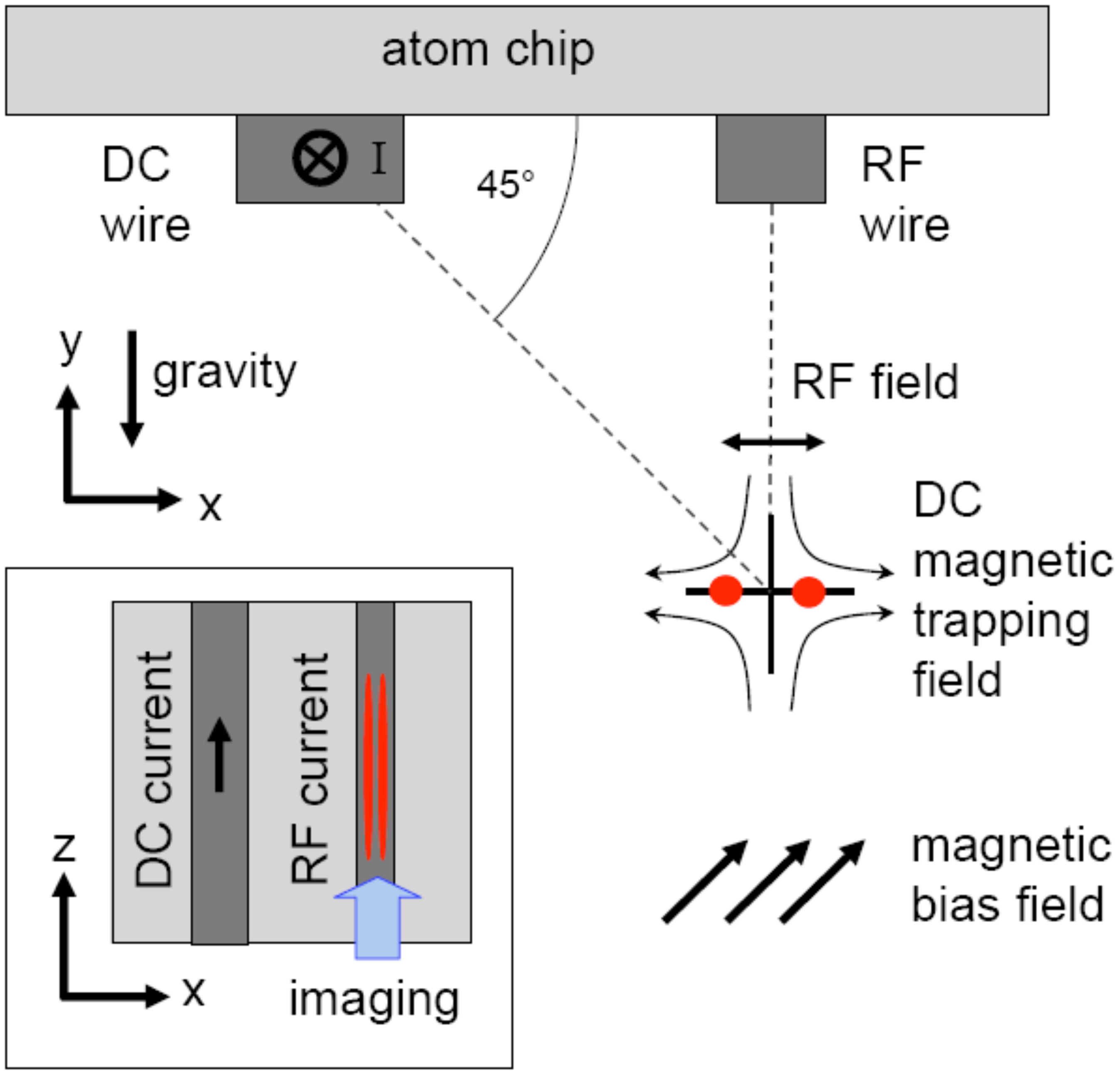


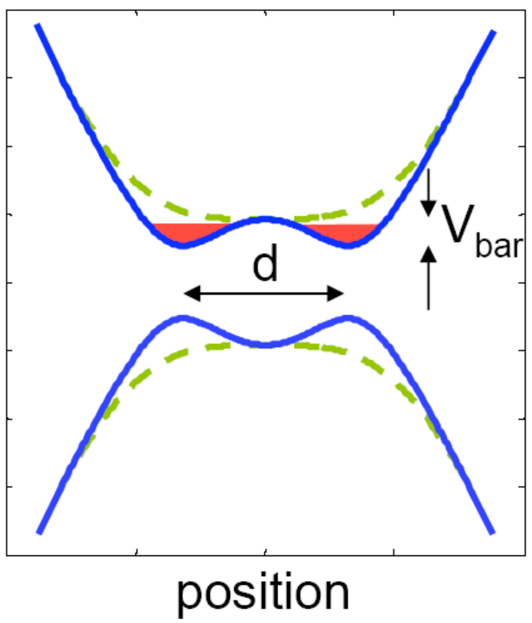
resonance condition forces the trap minimum on a circle

vector-dependent coupling term creates double well

Heidelberg experiment

RF beamsplitter: setup



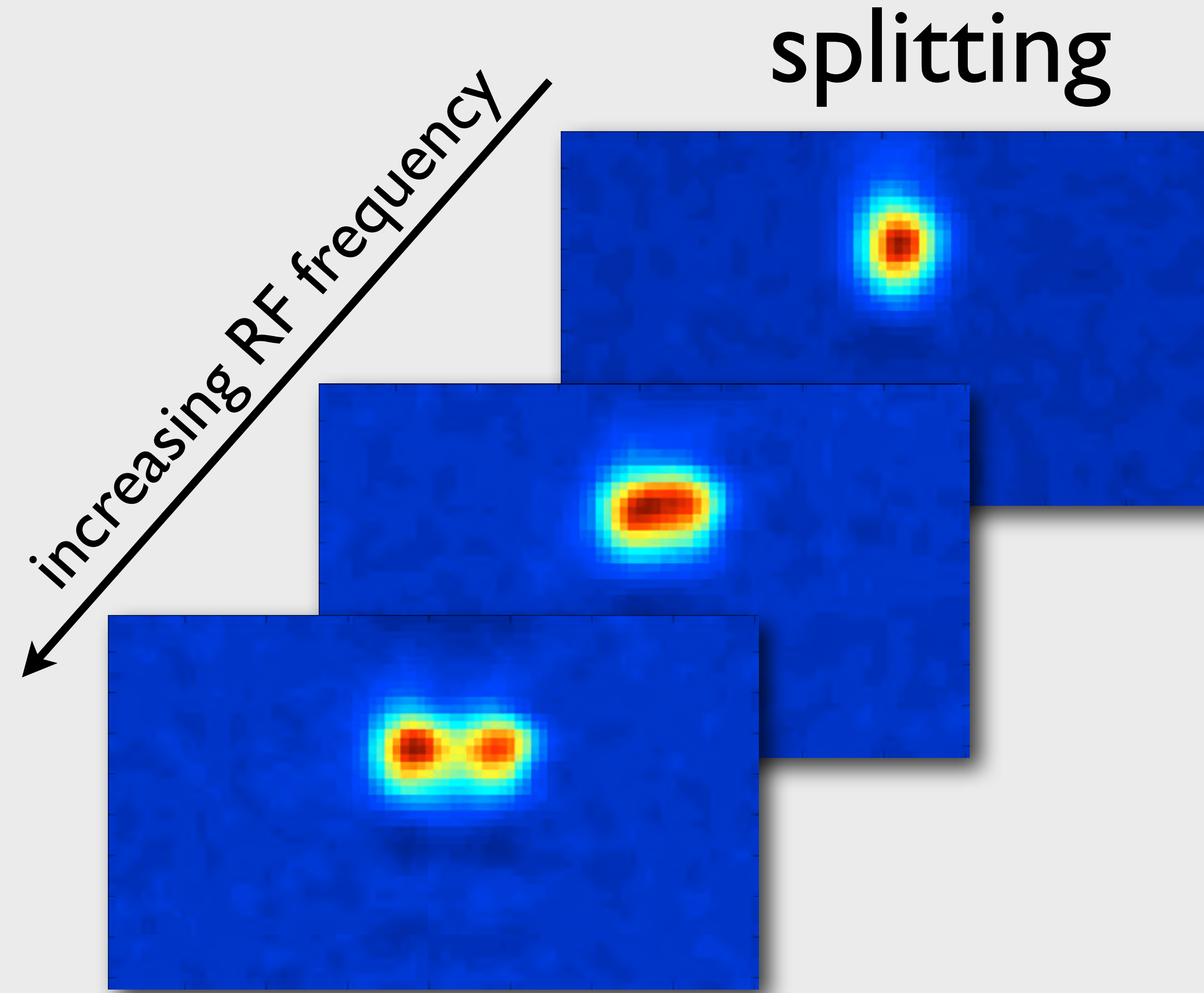


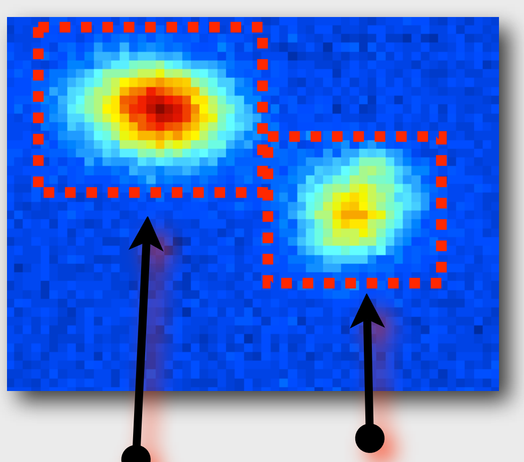
single linearly polarized RF field + static harmonic trap

→ Double well potential

Two types of measurement

- NUMBER:
  large initial separation & short TOF
  (clouds distinct)
  image to count N

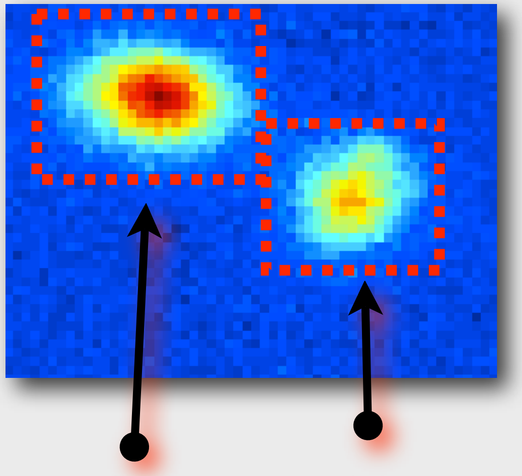




$$\Delta N = N_1 - N_2$$

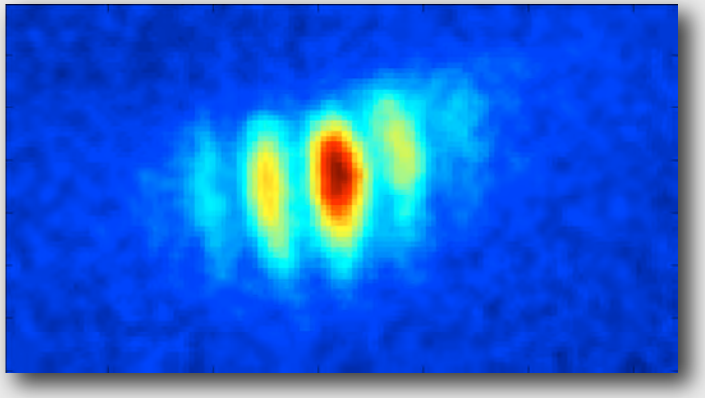
Two types of measurement

- NUMBER:
  large initial separation & short TOF
  (clouds distinct)
  image to count N



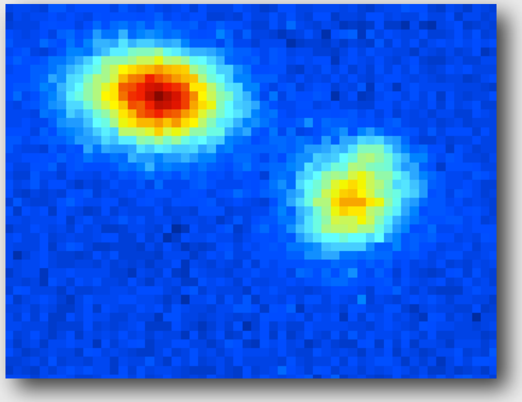
$$\Delta N = N_1 - N_2$$

- PHASE:
  small initial separation & long TOF
  (clouds interfere)
  image to measure phase

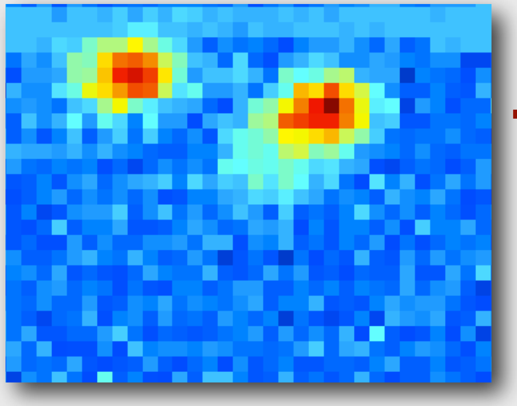


$$n(x) \sim 1 + a\cos(kx + \phi)$$

Bosons or Fermions

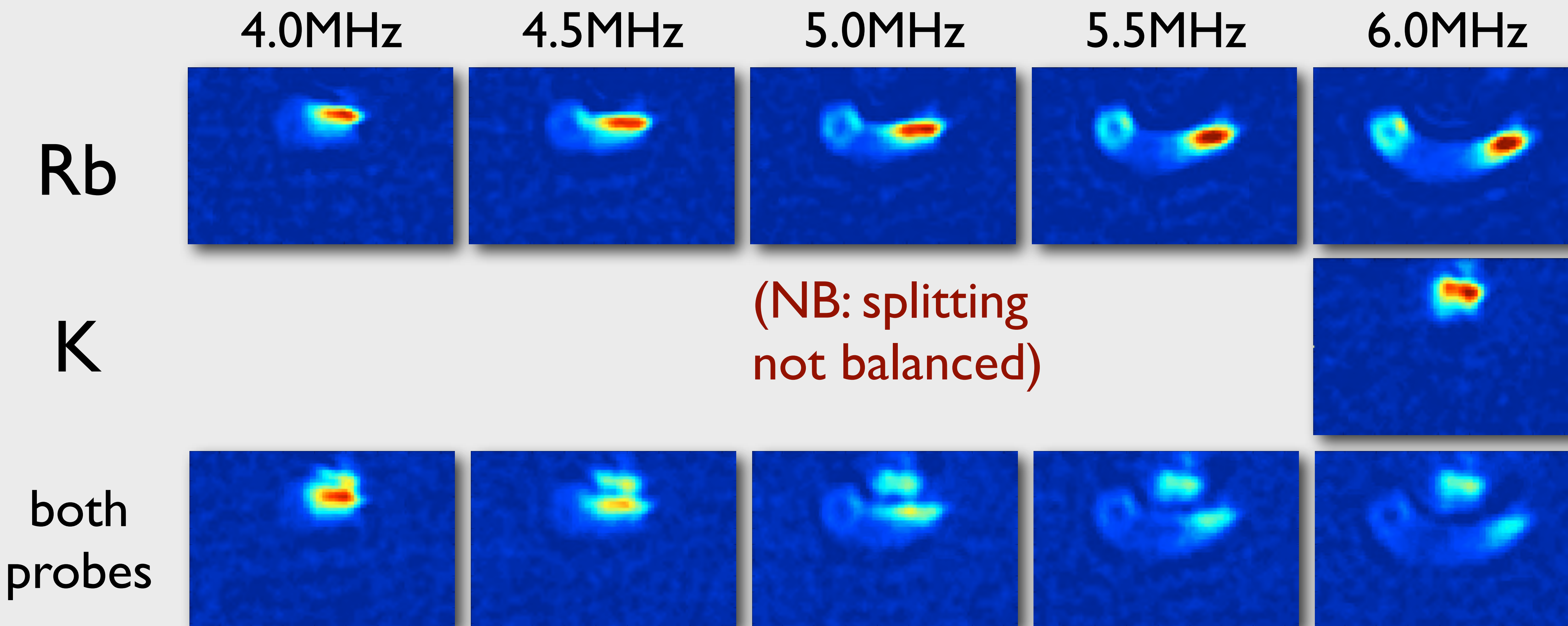


bosonic
^{87}Rb



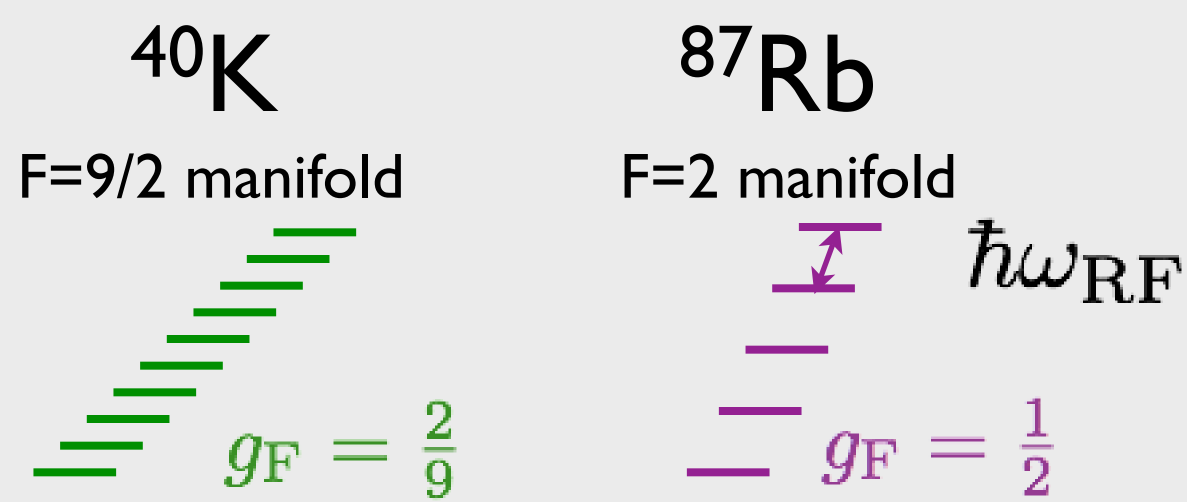
fermionic
^{40}K

Species-specific!



M. H. T. Extavour, *Atomic Physics* **20**, 241 (2006)

Why?
Zeeman shifts:
(& selection rules)



Towards a direct observation of number squeezing

Josephson effect: history

"external" effect:

- superconductors (Josephson 1962)
- 4He or 3He through a narrow channel (Anderson 1966, Avenel&Varoquaux 1988)
- Kasevich (1998); Oberthaler (2005)

"internal" effect:

- NMR in superfluid 3He (Leggett 1975)
- Cornell/Wieman (1998)

Model for double well

$$H = \frac{U}{2}M^2 + \frac{J}{2}\phi^2$$

where

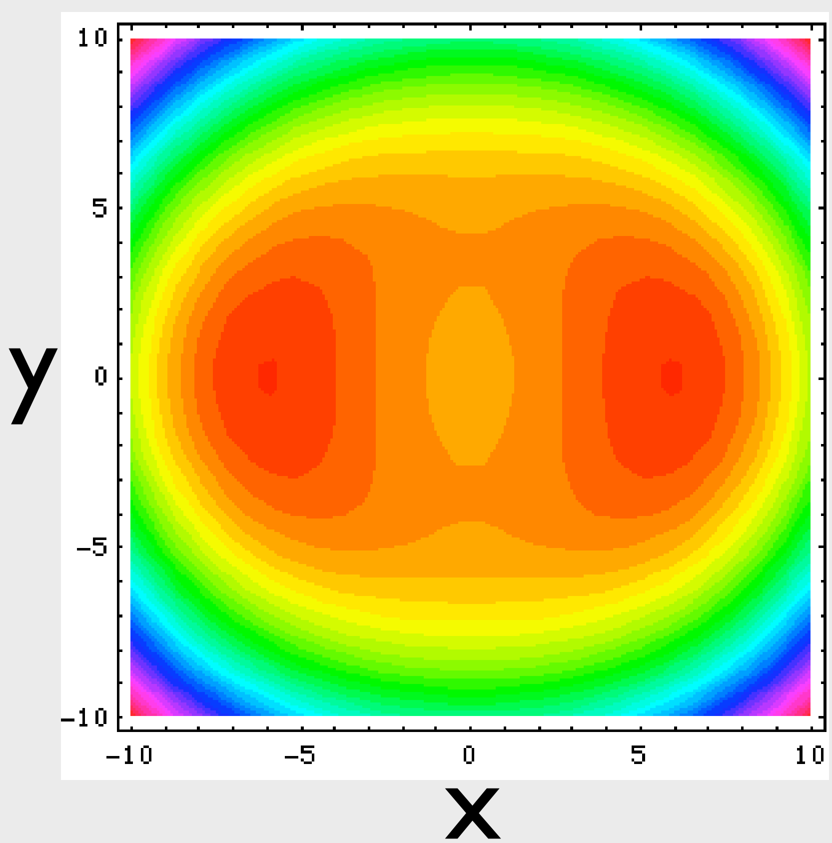
U =charging energy

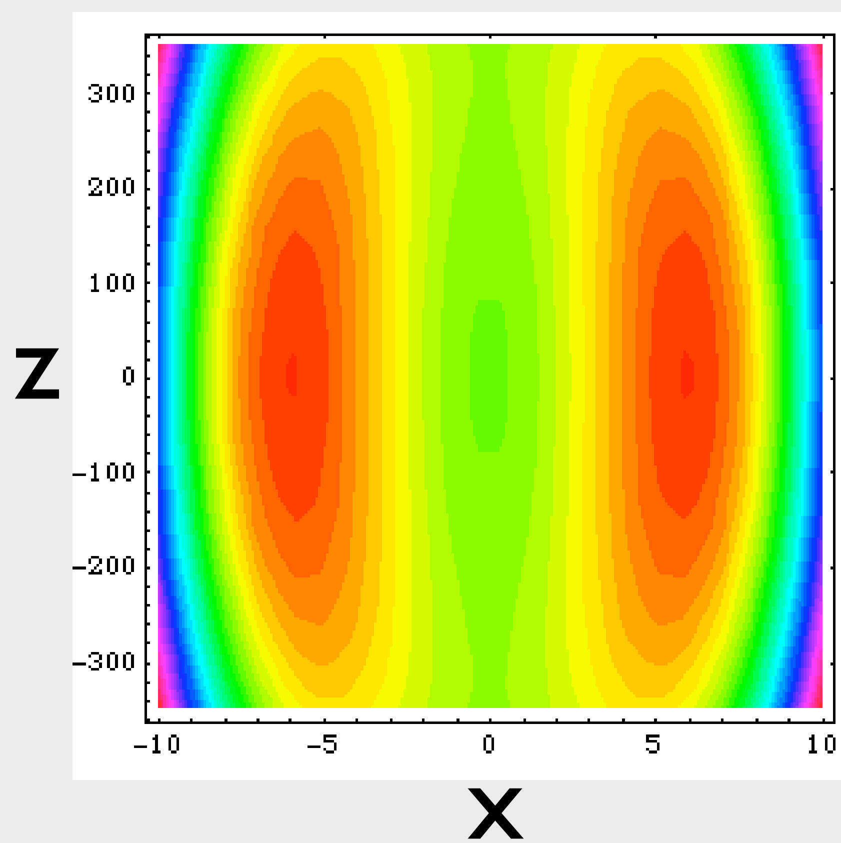
J =tunneling strength

M =number diff /2

ϕ =relative phase

potential:



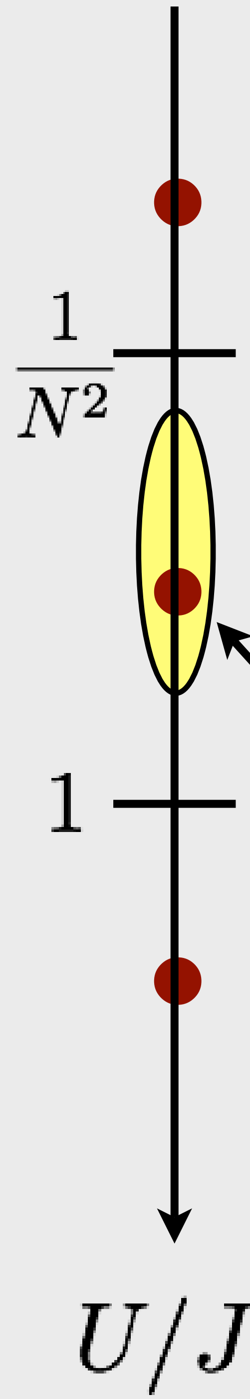


well separation:
0 to 200μm (here10μm)

junction area:
5μmx100μm

atom number:
10^3 to 10^4

regimes of U/J



Rabi regime: $U/J \ll N^{-2}$, $M_{\rm rms} \geq \sqrt{N}$

Josephson regime: $N^{-2} \ll U/J \ll 1$, $1 < M_{\rm rms} < \sqrt{N}$

Fock regime: $1 \ll U/J$, $M_{\rm rms} \ll 1$

our #s: $U/J \sim 10^{-5}$, $N^{-2} \sim 10^{-7}$

reminiscent of:

SF → Mott

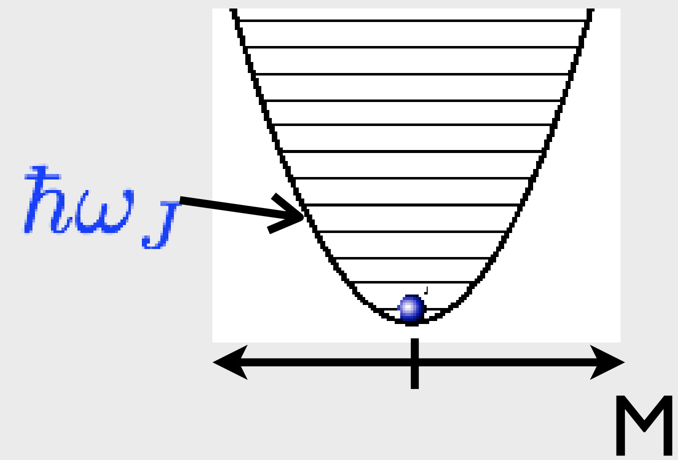
(when N~1)

Josephson physics

Classical oscillation frequency

$$\hbar\omega_J = \sqrt{UJ}$$

also the level spacing near ground state:

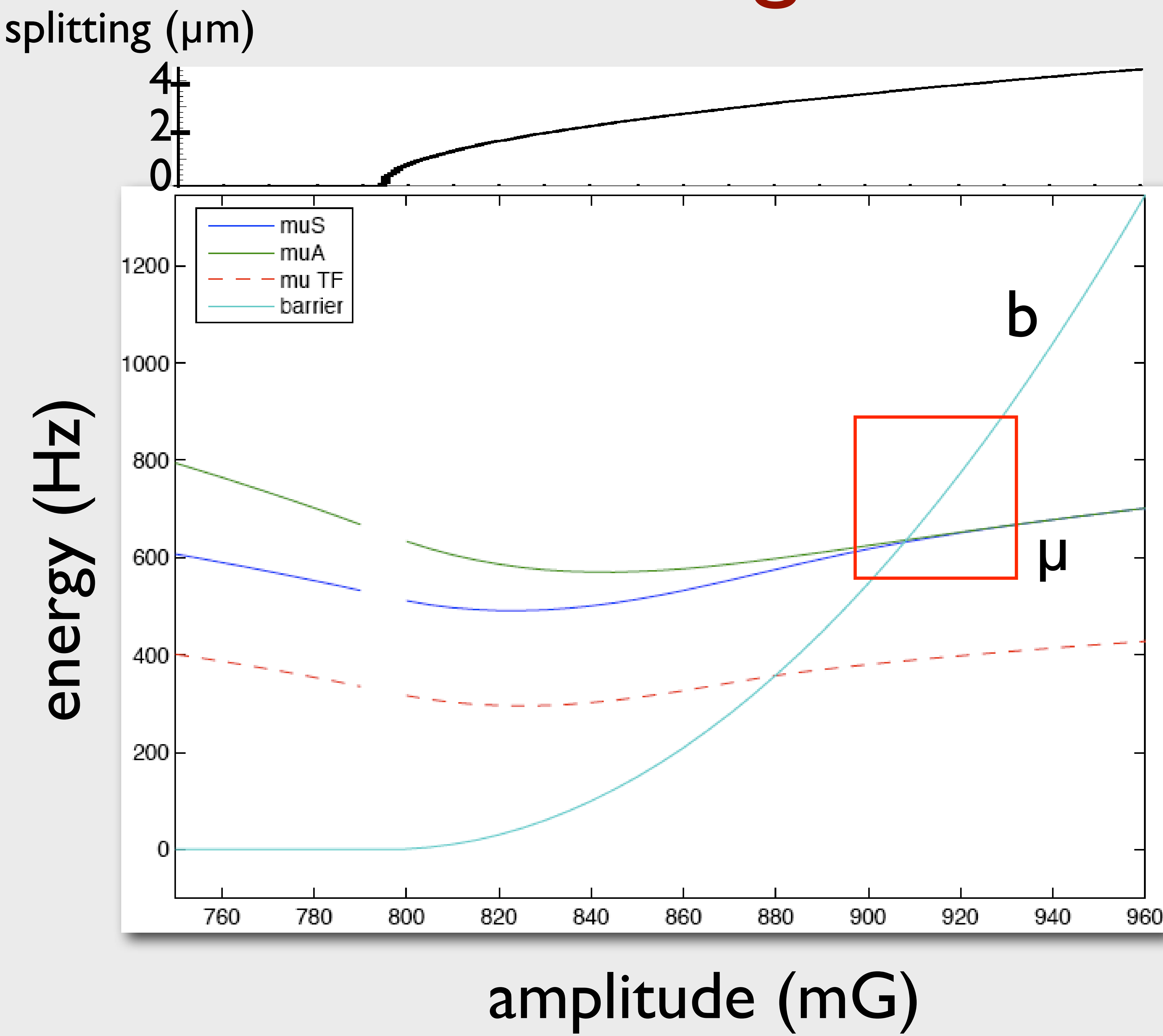


Ground state <M>=0 has width

$$M_{\rm rms} = (J/U)^{1/4}$$

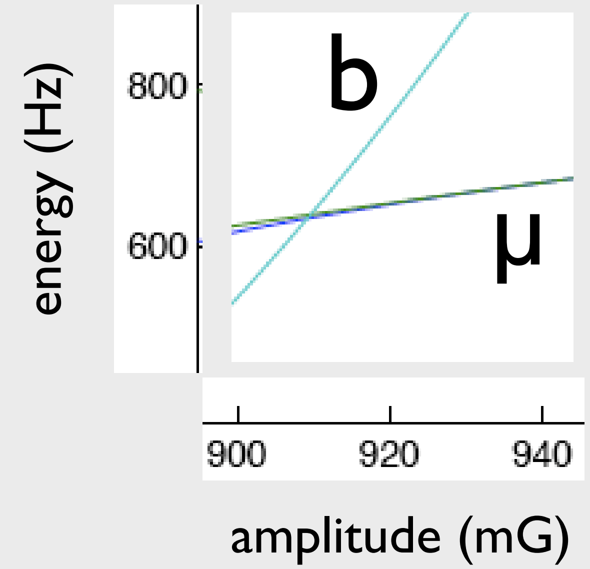
Basic idea: Tune **J** by increasing double-well separation. Look for reduced quantum fluctuation of ground state.

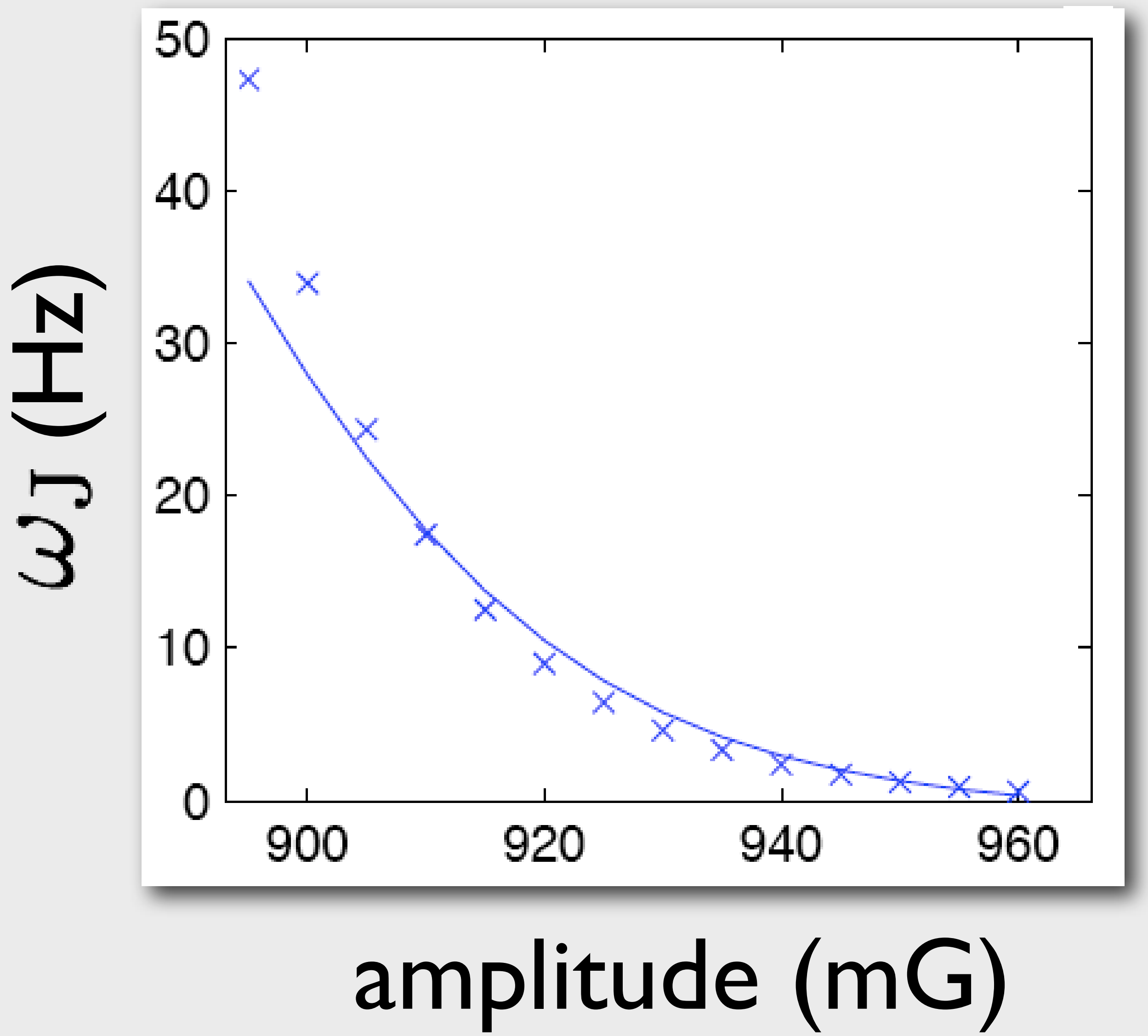
Tuning



splitting (μm)
4
2
0
muS
muA
mu TF
barrier
1200
1000
800
600
400
200
0
760
780
800
820
840
860
880
900
920
940
960
b
μ
energy (Hz)
amplitude (mG)

Splitting





U~0.1 Hz

J~5 kHz

x =simple exponential fit:
decreases 1/e in <u>15 mG</u>

Adiabatic-to-nonadiabatic evolution

- Ground state variance decreases so long as evolution adiabatic:

$$\dot{\omega}_J \ll \omega_J^2 \quad \text{adiabatic}$$

- Assume that M_{rms} "freezes" when $\dot{\omega}_J \sim \omega_J^2$
- If $\omega_J = \omega_J^o e^{-t/\tau}$ then this transition occurs when $\omega_J = 1/\tau$ or:

$$M_{\rm rms} = \sqrt{\frac{\hbar}{U\tau}}$$

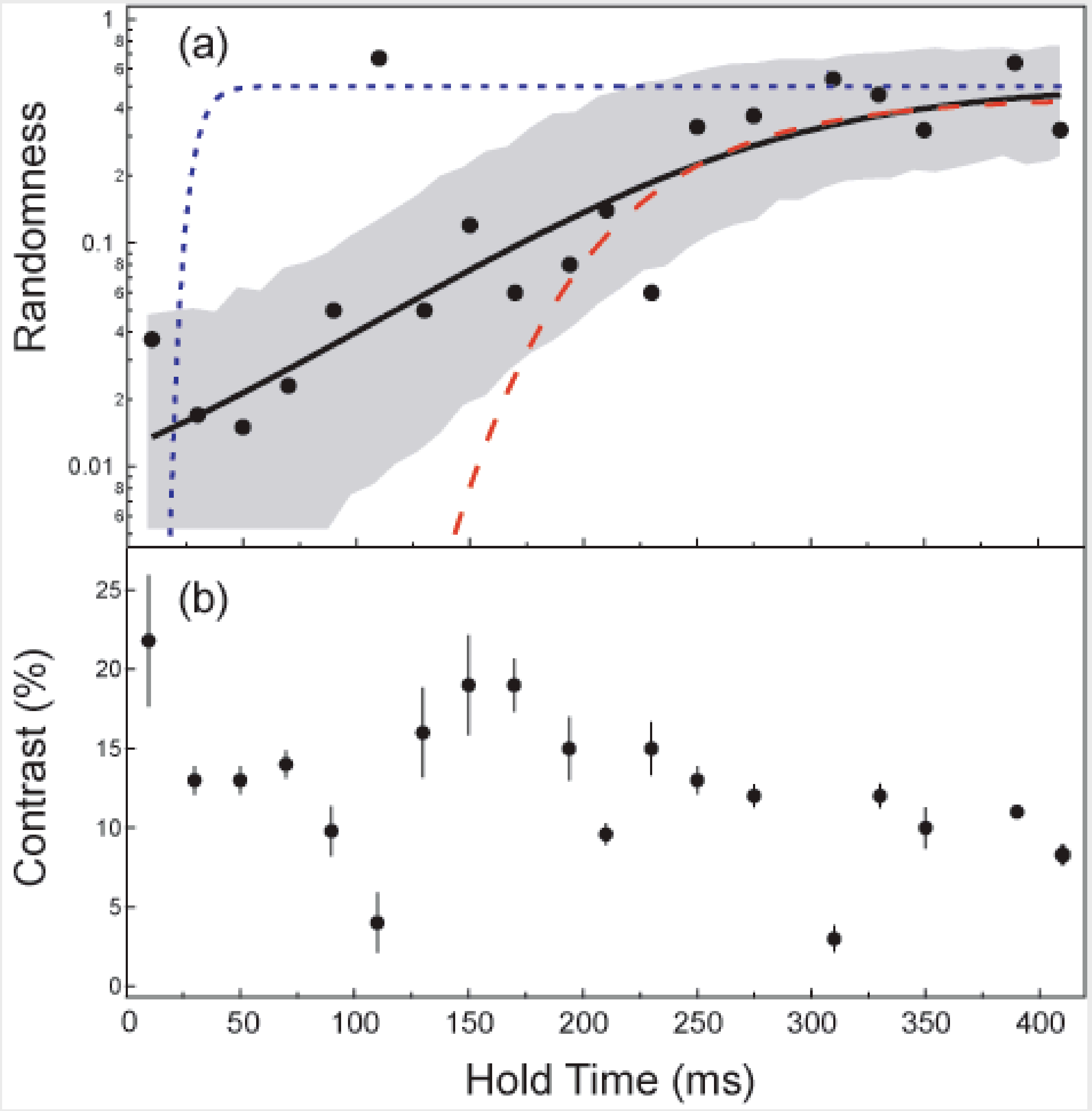
& thus

$$\frac{M_{\rm rms}}{\sqrt{N}} \sim \sqrt{\frac{\hbar}{\mu\tau}}$$

Argument explained to me by E. Demler and A. Burkov, but modestly attributed to A. Leggett (PRL comment with F. Sols, 1998)

Evidence of JJ number squeezing

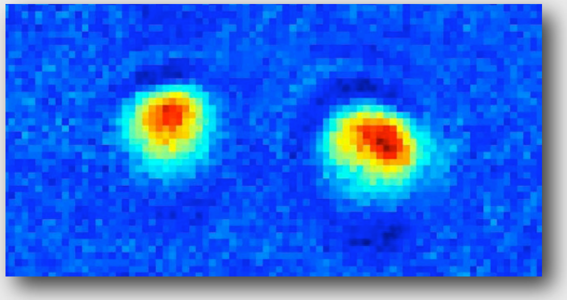
- measure width of phase distribution at various hold times
- Compare to expectation for coherent state
- Initial M spread leads to phase spread at long t
- Factor of 10 squeezing agrees with adiabatic est.



G. B. Jo ...W.Ketterle PRL **98**, 030207 (2007)
(see also: Kasevich, 2007)

Towards a direct measurement

- To date, measurements on coupled/split BEC systems have been exclusively on the phase
- We are developing sub-shot-noise *number* measurements



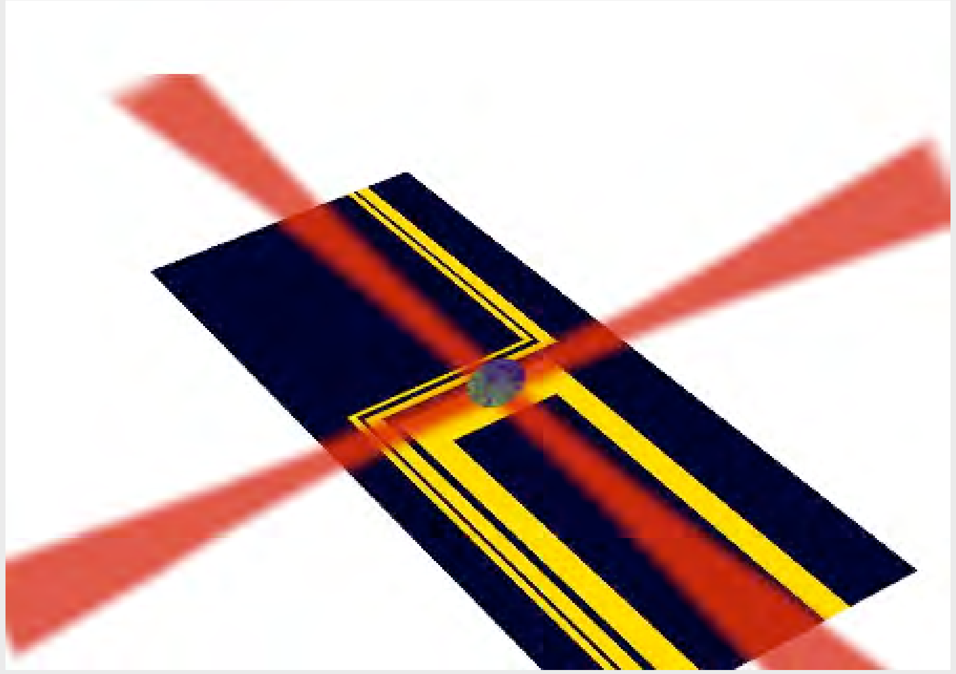
- Motivation:
  -direct, unambiguous signature
  -independent of dephasing physics
  -study role of adiabaticity
  -applicable to Fermions

status:

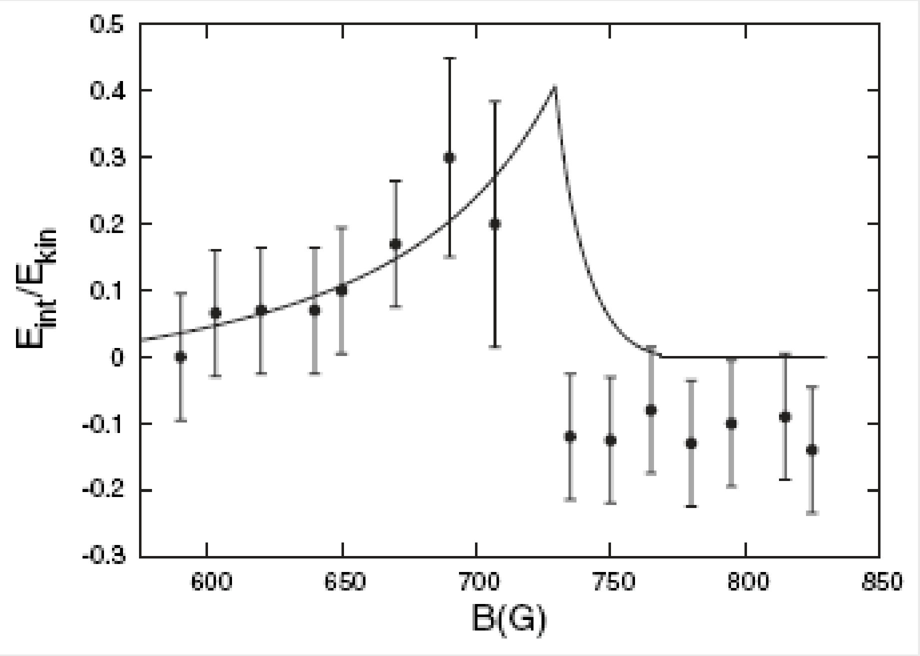
And just in case that wasn't enough to chat about...

Strongly interacting fermions

- Transfer 40K to crossed dipole trap
- go to Feshbach resonance (200G).
- Measure spin coherence time: "Itinerant magnetism?"

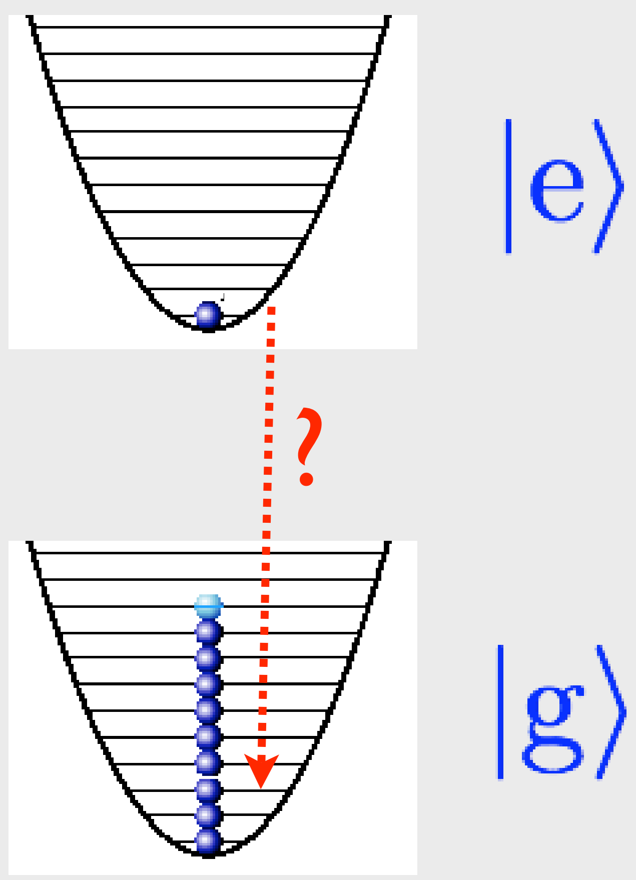


RA Duine, AH MacDonald, PRL **95**, 230403 (2005) →



Light scattering off Fermions

- New analytics: can now do calculation for full 3D problem without symmetries
- In the lab:
  -optical trapping holds all mF states
  -internal state tagging
  -high ER/EF possible

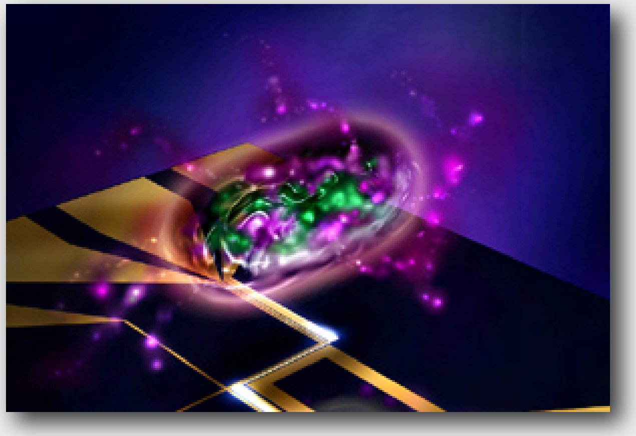


Th. Busch, J. R. Anglin, J. I. Cirac, P. Zoller, Europhys. Lett. **44** (1998)
B. DeMarco and D. S. Jin, Phys. Rev. A **58**, R4267 (1998)
K. Helmerson, M. Xiao, D. Pritchard, IQEC'90 book of abstracts, QTHH4 (1990)
J. Javanainen and J. Ruostekoski, Phys. Rev. A **52**, 2642 (1994)

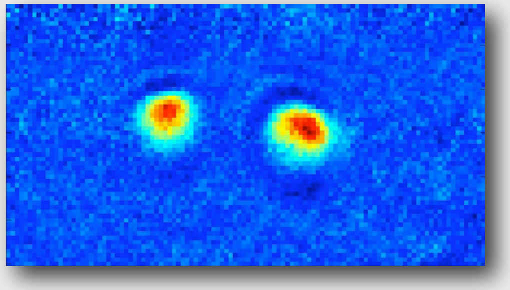
Summary

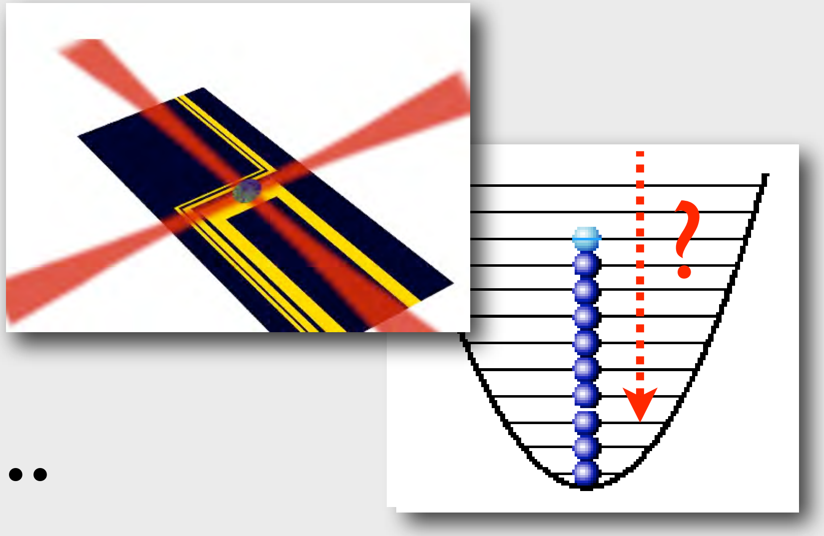
Species selective environments

DFG with μfab trap



Double well potentials & fluctuation statistics





etc...

Thank you!