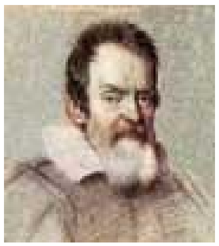
Cooling degenerate Fermi gases via frictionless control of a Bose species



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- Motivations
- Sympathetic cooling and heat capacity matching
- Four techniques for optimization of sympathetic cooling
- Focus on frictionless cooling

KITP, 2/19/2013

Collaborators (chronological order)

Carlo Presilla (Sapienza University, Rome)

Robin Cote` (University of Connecticut) &
Eddy Timmermans (Los Alamos National Laboratory)

Michael Brown-Hayes, Qun Wei & Woo-Joong Kim (Dartmouth)

Stephen Choi & Bala Sundaram (University of Massachusetts @ Boston)

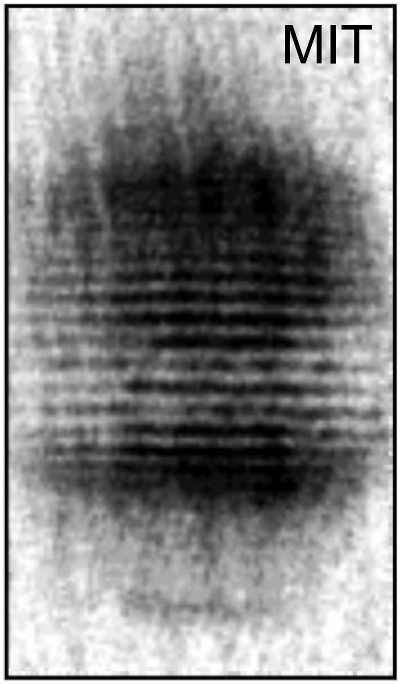
Condensed matter physics at low temperature and density

- Ultracold dilute atomic gases allow for a new window into quantum physics
  - Ultracold: ability to examine genuine quantum effects
  - Dilute:
    - Weak interactions, long scattering times, NE statistical mechanics
    - Often, if density is too great, quantum degeneracy is pre-empted by “normal” phase transitions to liquid or solid state
  - Exploit the precision offered by atomic spectroscopy

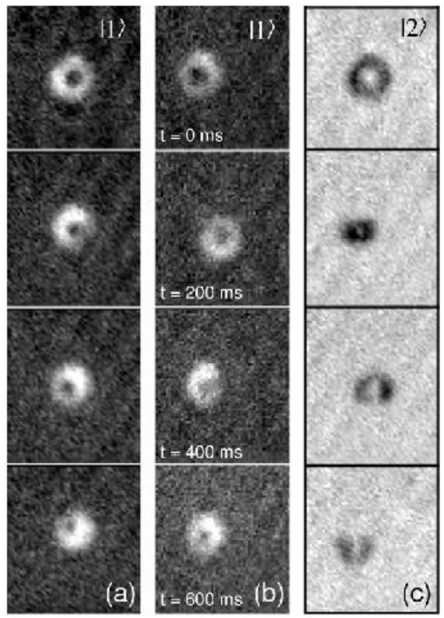
    (for internal degrees of freedom)

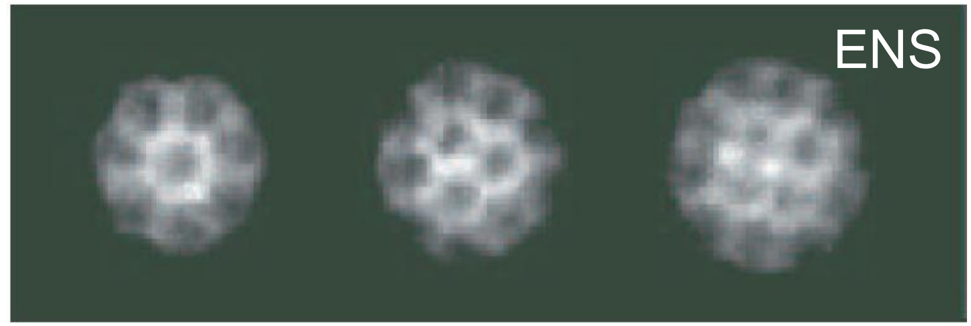
Goals: to extend quantum coherent phenomena at a more macroscopic scale and to understand at a more fundamental level (*i.e.* in a simpler way) several condensed matter physics phenomena

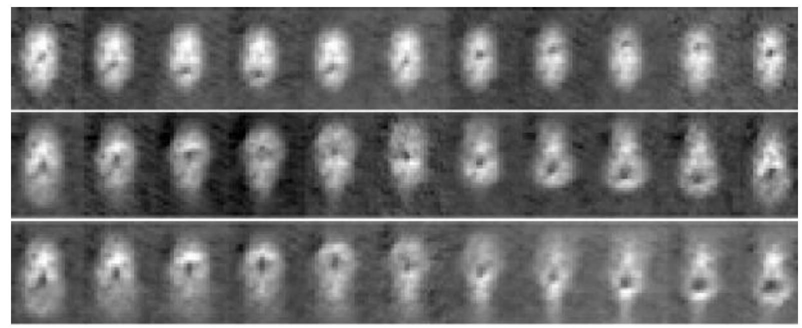
Macroscopic quantum coherence and superfluity in a Bose-condensed gas



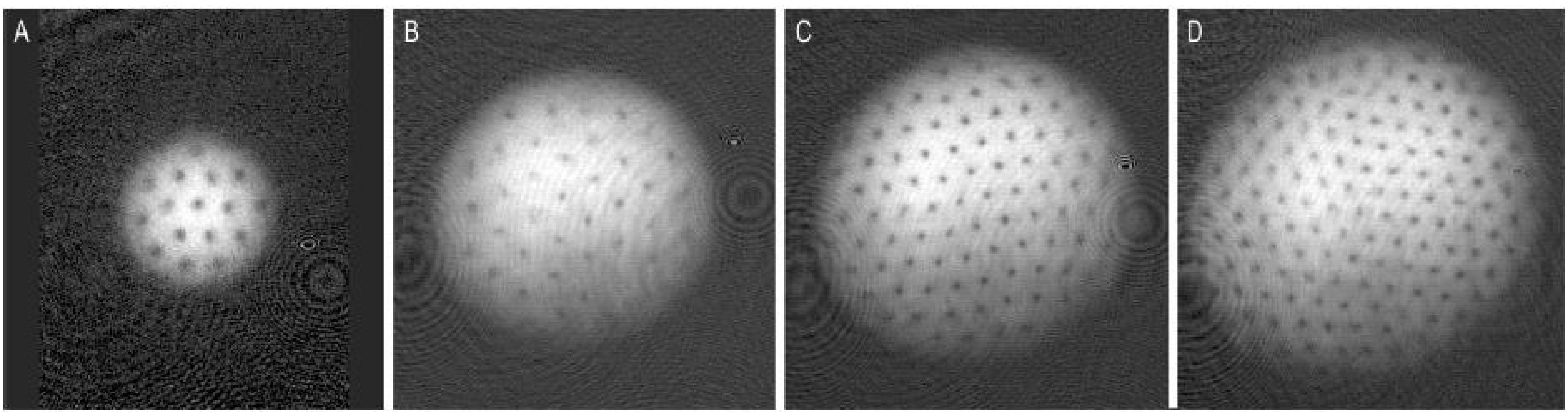
JILA







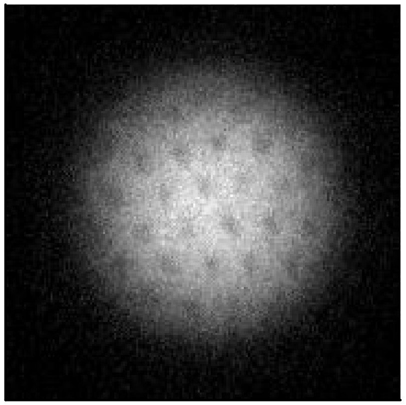
MIT

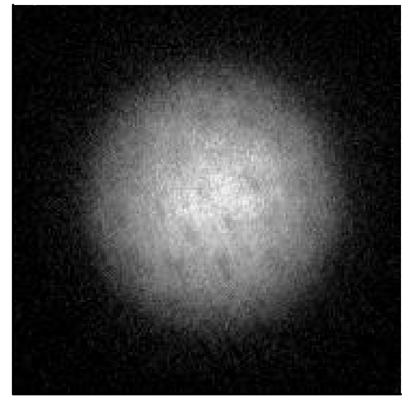


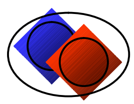
Fermi gases have to be considered as HT$_c$ superfluids

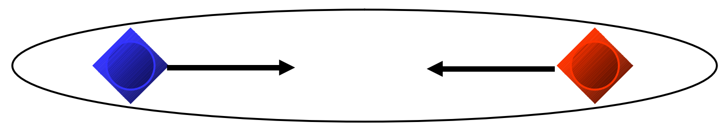
System	T_c	T_F	T_c / T_F
Li at ambient pressure	0.4 mK	55,000 K	10^{-8}
Metallic superconductors	1-10 K	10^5 K	10^{-5}-10^{-4}
^{3}He	2.6 mK	5 K	5 10^{-4}
HT$_c$ superconductors	35-140	2000-5000 K	10^{-2}
Atomic Fermi Gases	100 nK	1 μK	0.1

A strongly interacting Fermi gas in the BEC-BCS crossover is a superfluid









$B = 812$ G
$1/k_F a = 0.35$

$B_F = 834.15$ G

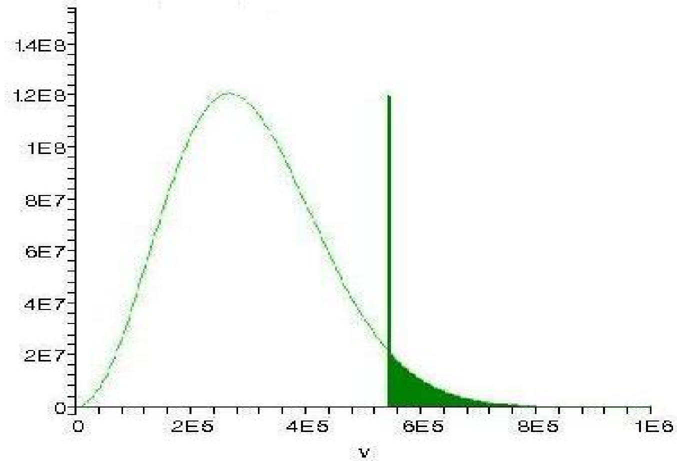
$B = 875$ G
$1/k_F\, a = -0.5$

BUT

quantum phase transitions in optical lattices, exotic superfluid states (LOFF, breached pairing),supersolid states, quantum simulations of model Hamiltonians,all typically require deeper Fermi degeneracy than the one currently available

- Intrinsic difficulties in cooling fermions

  Evaporative cooling relies on rethermalizing (elastic) collisions



  - No s-wave scattering allowed if in the same hyperfine state (Pauli principle)
  - At low temperatures, p-wave scattering is strongly suppressed
  - Pauli blocking effects manifest near $T=T_F$, inhibiting scattering of different states as well
  - Dual evaporative cooling decreases both N_F **AND** T_F

This issue is mitigated by using a Bose gas as a buffer/coolant (sympathetic cooling)

Fermi-Bose mixtures

- ^3He-^4He (Amsterdam)
- ^6Li-^7Li (Rice, ENS)
- ^6Li-^{23}Na (MIT)
- ^{40}K-^{39}K(^{41}K) (LENS)
- ^{40}K-^{87}Rb (LENS, JILA, ETH)
- ^6Li-^{87}Rb (Tübingen,Vancouver,Berkeley)
- ^6Li-^{133}Cs (Heidelberg)
- ^{84}Rb-^{87}Rb (LANL)
- ^6Li-^{174}Yb (Kyoto,Seattle)
- ^{171}Yb-^{87}Rb (Düsseldorf)
- ^{173}Yb-^{174}Yb (Kyoto)

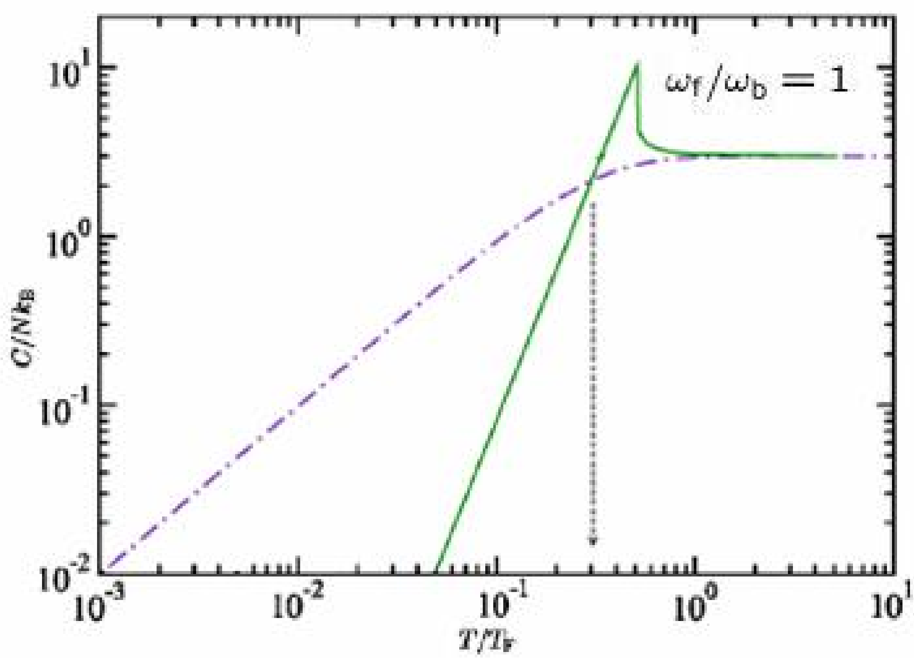
Fermi gases are sympathetically cooled at $T/T_F = 0.03–0.2$ since a decade, no further progress

(Ultimate) Limits of sympathetic cooling

Heat capacity matching between the Bose coolant and the Fermi gas

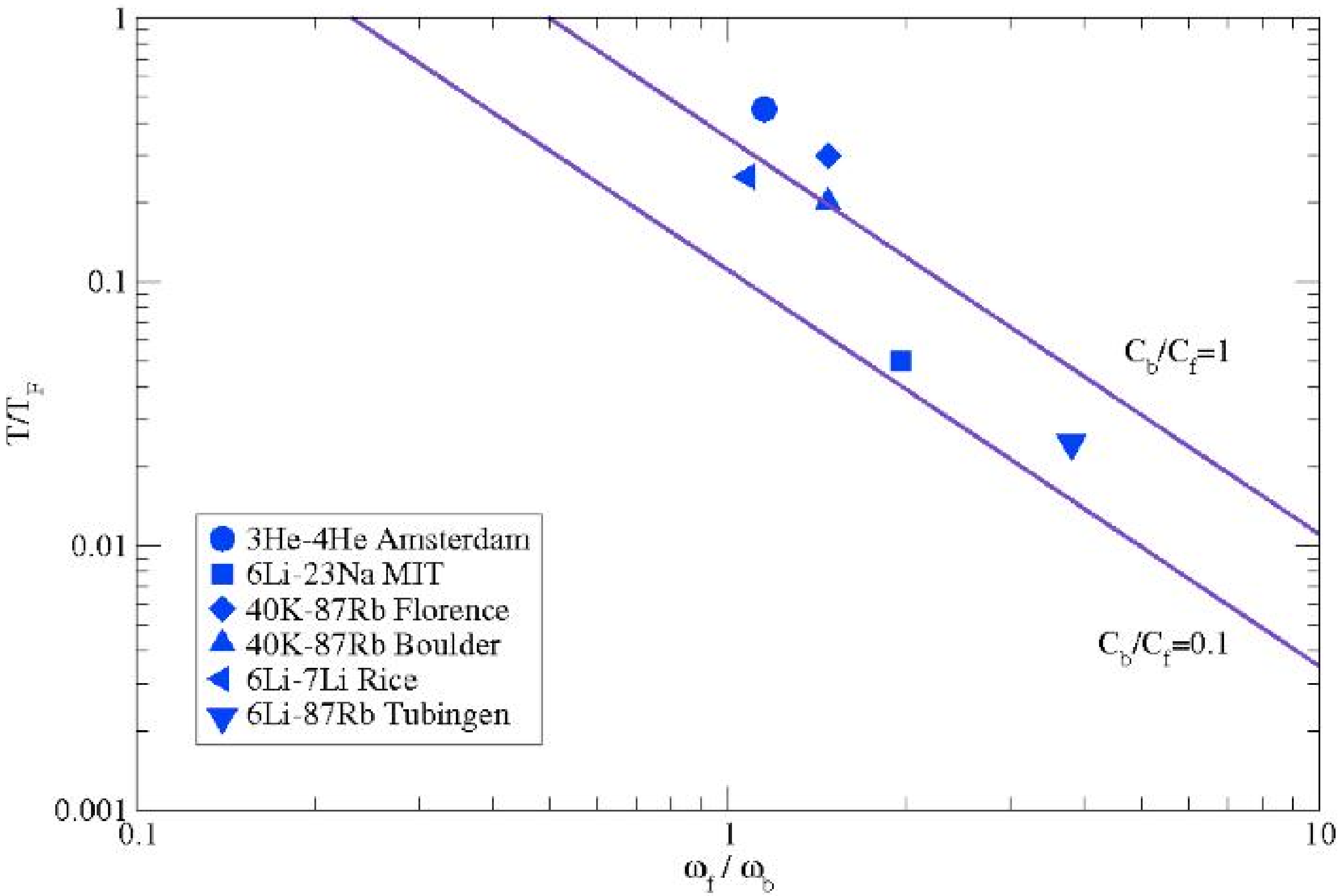
$$C_B \cong 10.8 k_B N_B \left(\frac{T}{T_C}\right)^3 \qquad C_F \cong \pi^2 k_B N_F \frac{T}{T_F}$$

$$T_C \cong 0.94 \hbar \omega_B N_B^{1/3} / k_B \qquad T_F \cong 1.82 \hbar \omega_F N_F^{1/3} / k_B$$



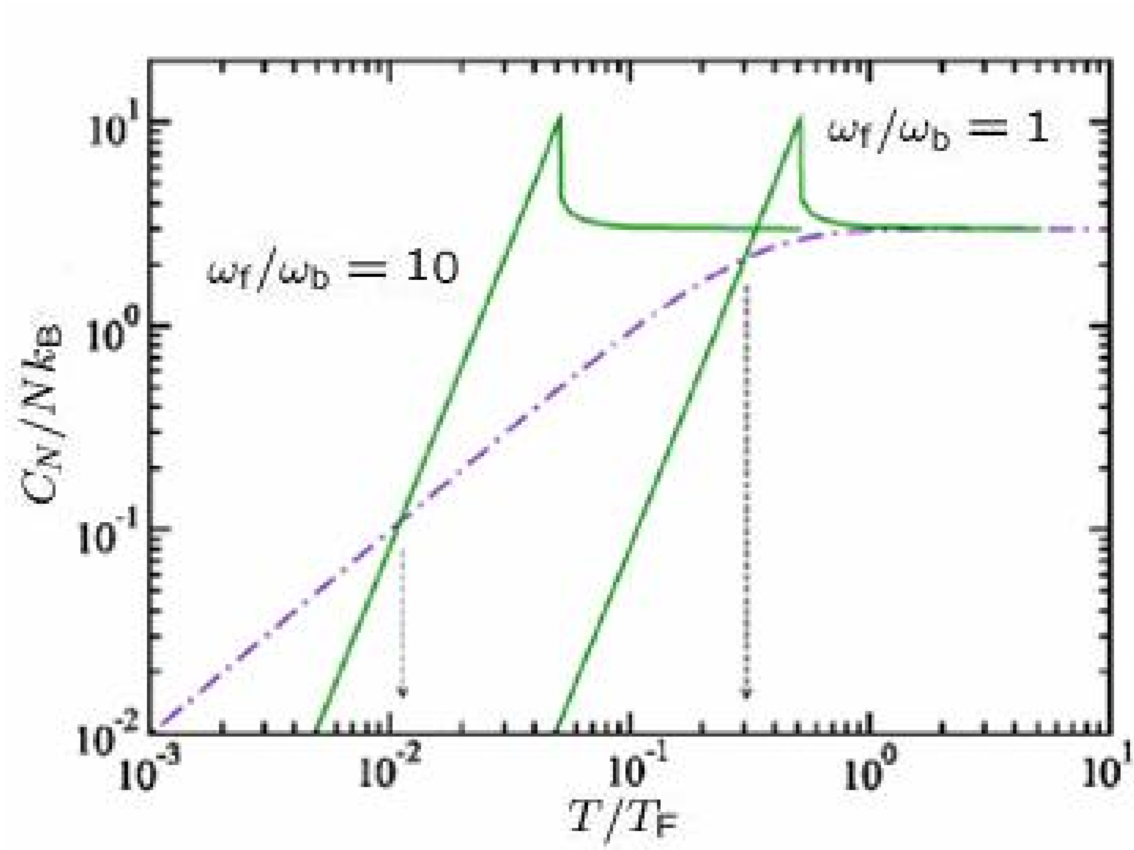
$$\frac{T}{T_F} \cong 0.35 \left(\frac{\omega_B}{\omega_F}\right)^{3/2} \left(\frac{C_B}{C_F}\right)^{1/2}$$

Efficient cooling if Bose gas more classical than the Fermi gas (less degenerate)



NB: in Li-Rb experiment at Tubingen not evident if the two species thermalize

This is a ***physical*** limitation, which can be mitigated with various tricks



The basic idea is to shift the crossover between fermionic and bosonic heat capacities as much as possible on the left side: increase Fermi temperature, decrease BEC temperature, and/or both

Trick # 1: proper choice of atomic species and hyperfine states

The trapping ratio can be made smaller by using a light Fermi species, and a heavy Bose species

$$\frac{\omega_F}{\omega_B} \propto \sqrt{\frac{\mathrm{mass_B}}{\mathrm{mass_F}}}$$

From this point of view the Li-Cs or Li-Yb mixtures seem optimal

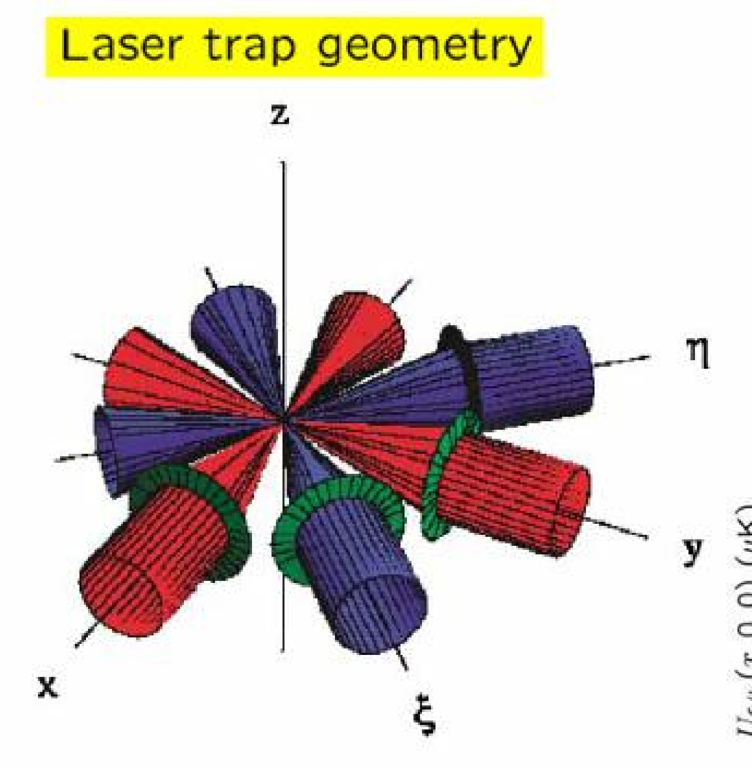
Even within the same species, different hyperfine states can make a difference

$$\frac{\omega_F}{\omega_B} = \sqrt{\frac{\mathrm{mass_B}}{\mathrm{mass_F}}}\sqrt{\frac{(m_F g_F)_B}{(m_F g_F)_F}}$$

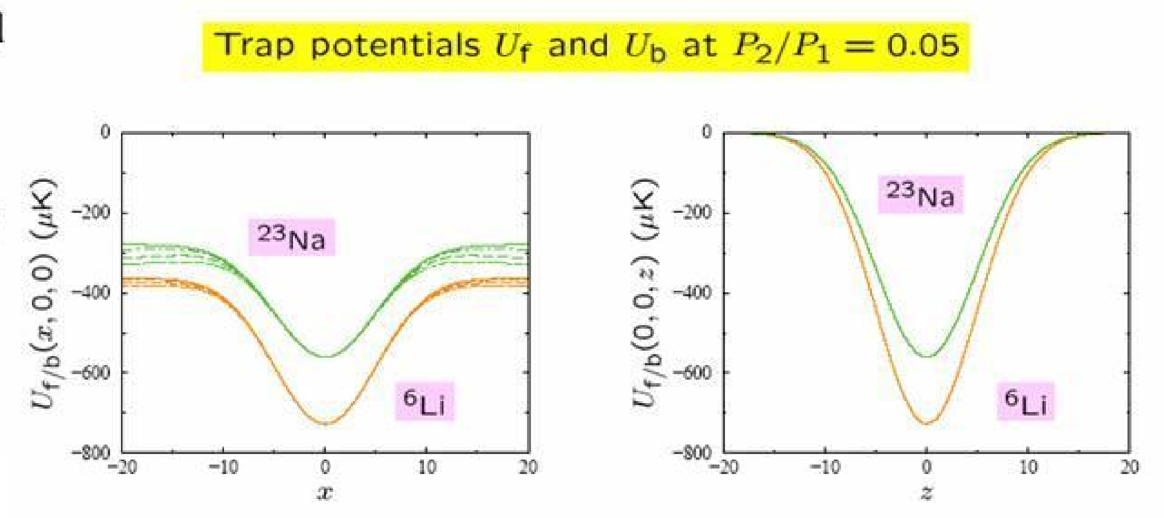
Fermi-Bose mixture	Hyperfine states	α	ω_F/ω_B
^{6}Li-^{23}Na	Li(1/2,−1/2)-Na(1,−1)	2/3	1.599
	Li(1/2,−1/2)-Na(2,2)	1/3	1.130
	Li(3/2,3/2)-Na(1,−1)	2	2.769
	Li(3/2,3/2)-Na(2,2)	1	1.958
^{6}Li-^{87}Rb	Li(1/2,−1/2)-Rb(1,−1)	2/3	3.109
	Li(1/2,−1/2)-Rb(2,2)	1/3	2.198
	Li(3/2,3/2)-Rb(1,−1)	2	5.385
	Li(3/2,3/2)-Rb(2,2)	1	3.808
^{6}Li-^{133}Cs	Li(1/2,−1/2)-Cs(3,−3)	4/9	3.138
	Li(1/2,−1/2)-Cs(4,4)	1/3	2.718
	Li(3/2,−3/2)-Cs(3,−3)	4/3	5.436
	Li(3/2,3/2)-Cs(4,4)	1	4.707

Trick # 2: independent trapping of the two atomic species

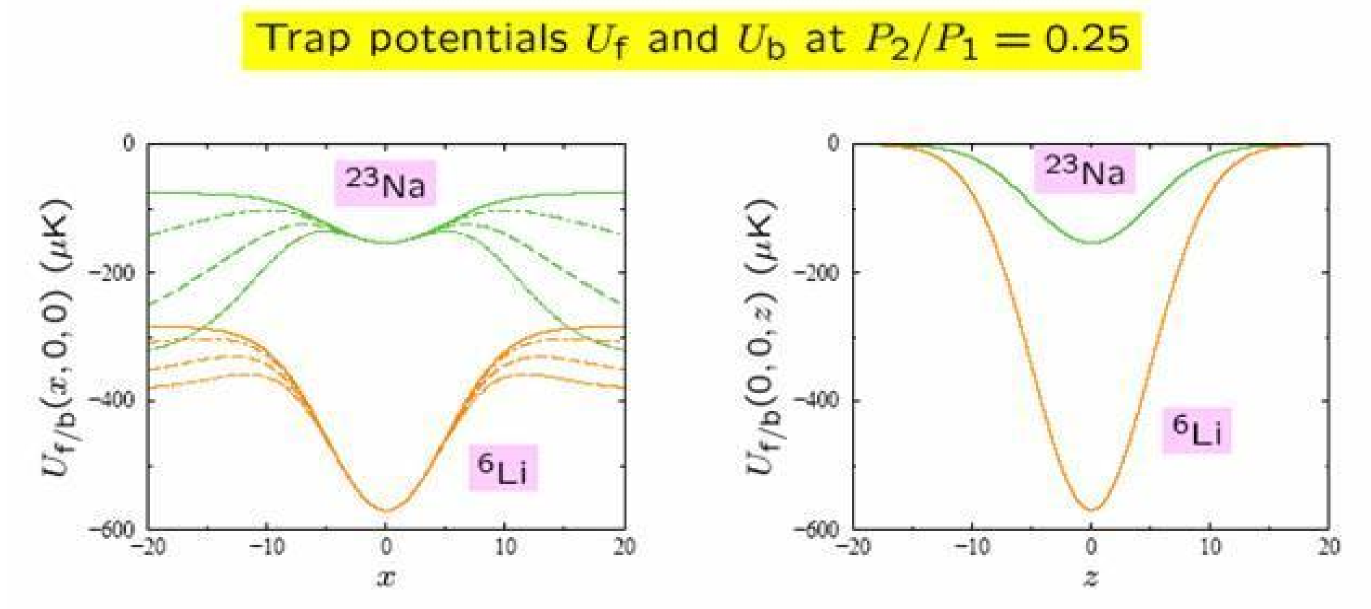
- Bichromatic trap, both single or crossed configuration
- One confining beam for both species (red-detuned)
- One beam deconfining for the bosonic species (blue-detuned)
- The alignment of the beams may be critical/challenging



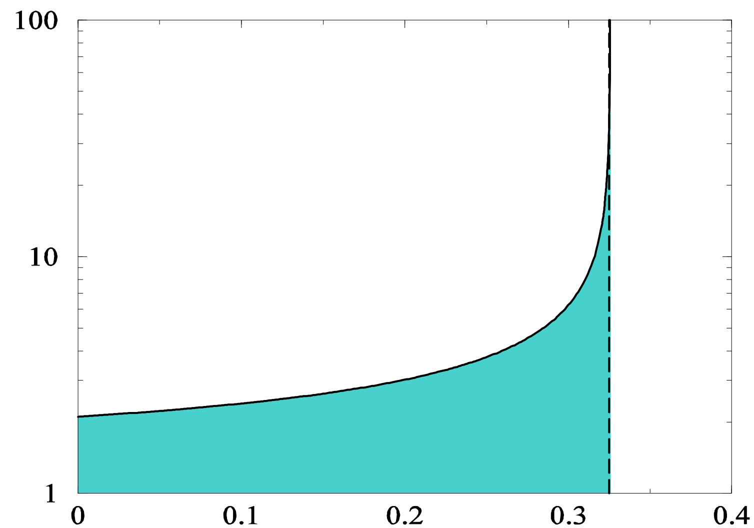
Li with D2 line at 671 nm,
Na with D2 line at 589 nm,
Confining laser at 1064 nm,
Deconfining laser at 532 nm



R.O. and C. Presilla, PRL 89, 100401 (2002); J. Stat. Phys. 115, 57 (2004)



Trapping frequency ratio



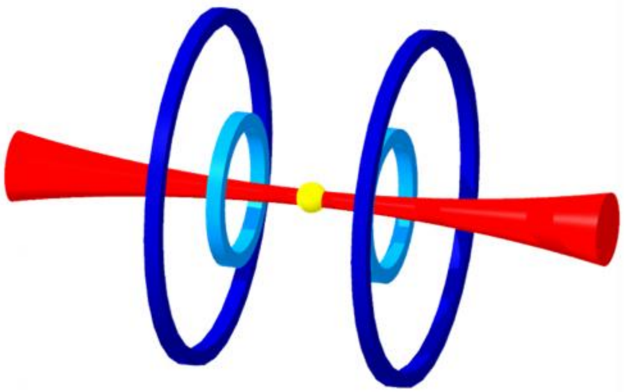
Laser power ratio

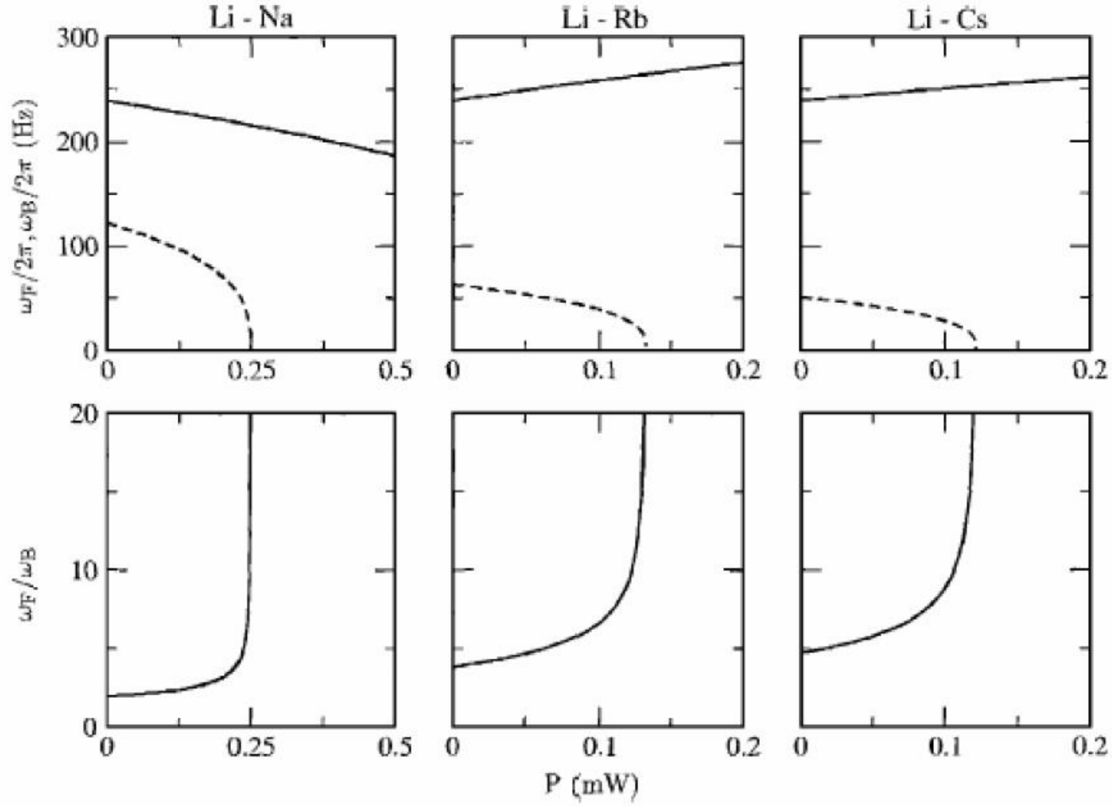
Trapping frequency ratios around 10 are feasible, higher values limited by laser power stability

Similar setting for Li (671 nm) Rb (780 nm) with a deconfining laser beam for Rb with intermediate wavelength

Feasible also in a magnetic trap by using a single focused beam

- Light-assisted magnetic traps





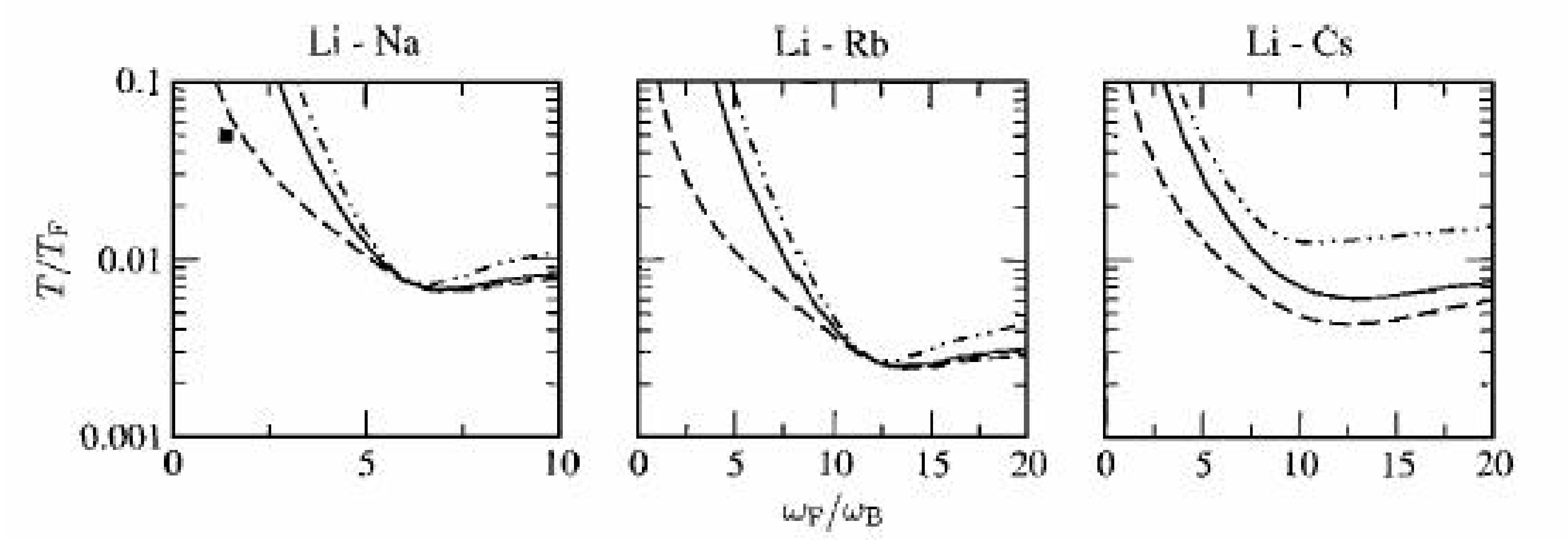
Case of a Joffe-Pritchard magnetic trap and a deconfining beam blue-detuned by 5 % with respect to the D2 line of the Bose species
(B_0=1 G, B′=170 G/cm, B″=125 G/cm^2, λ=560 nm, 741nm, 808 nm, w=8 μm)

Plugging a focused blue detuned beam in the center of a magnetic trap is a common practice since the earliest work on BEC, but use of Feshbach resonances may be precluded.

• Absolute elastic scattering of Bose specie large enough for evaporative cooling

• Interspecies scattering length large enough for sympathetic cooling

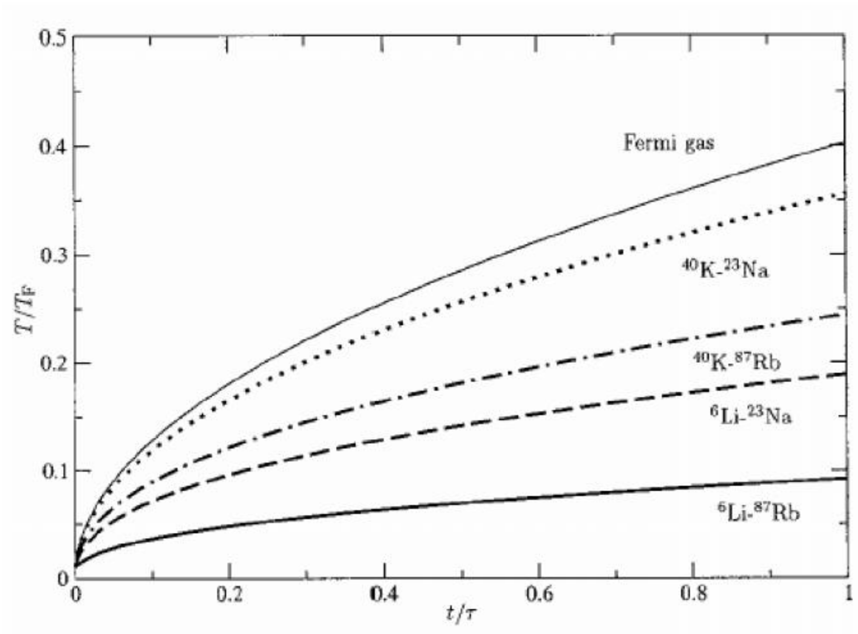
• For mixtures with large mass difference there is also an issue of relative gravity sagging at a finite trapping strength, poor spatial overlap will freeze cooling



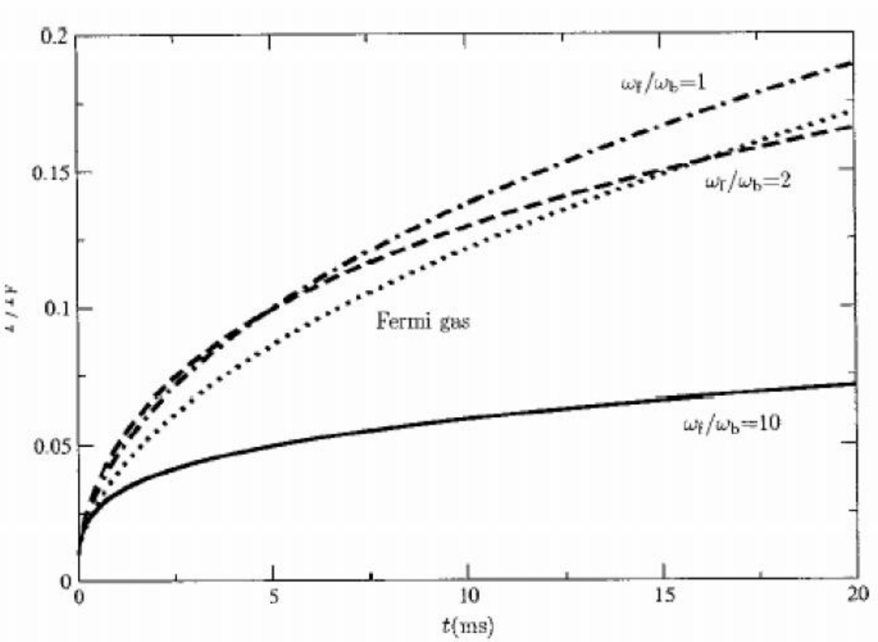
The three curves within each mixture are relative to different interspecies scattering lengths [-0.5 nm (dashed), 0.0 nm (continuous), 1.0 nm (dot-dashed)]

Rb is best balance of high mass ratio vs sagging/partial overlap
Gravity sagging quite evident for Cs
[M. Brown-Hayes and R.O., PRA 70, 063614 (2004)]

• Fermi hole heating discussed by Eddy Timmermans for a pure Fermi gas [PRL 87, 240403 (2001)]. It could quickly lead to a fast increase in the temperature of the sample (with initial rate inversely proportional to T / T_F)



In the case of a *homogeneous* Fermi-Bose mixture, the use of Bose coolers with large mass gives a slower dynamics for the heating rate

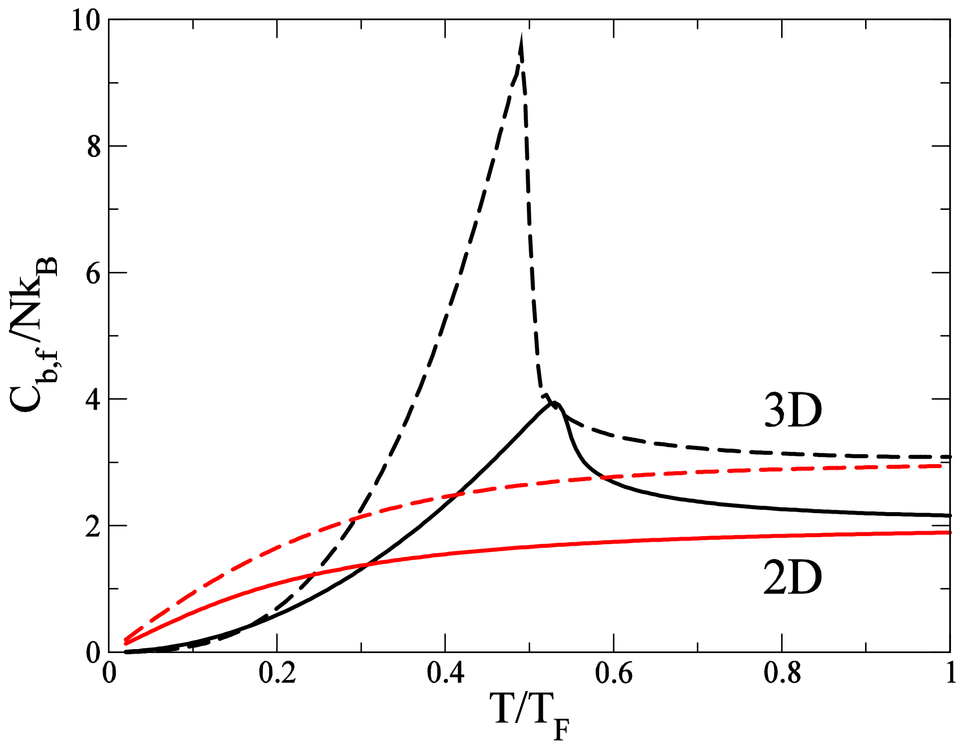


In the case of a *trapped Fermi-Bose mixture,* the use of an optimized trapping frequency ratio further mitigates the heating rate

The trade-off is that a larger Bose mass and a shallower confinement for the Bose gas can slow down too much the thermalization processes (evaporative+ sympathetic cooling) [R. Cote`, R.O., and E. Timmermans, PRA 72, 041605(R) (2005)]

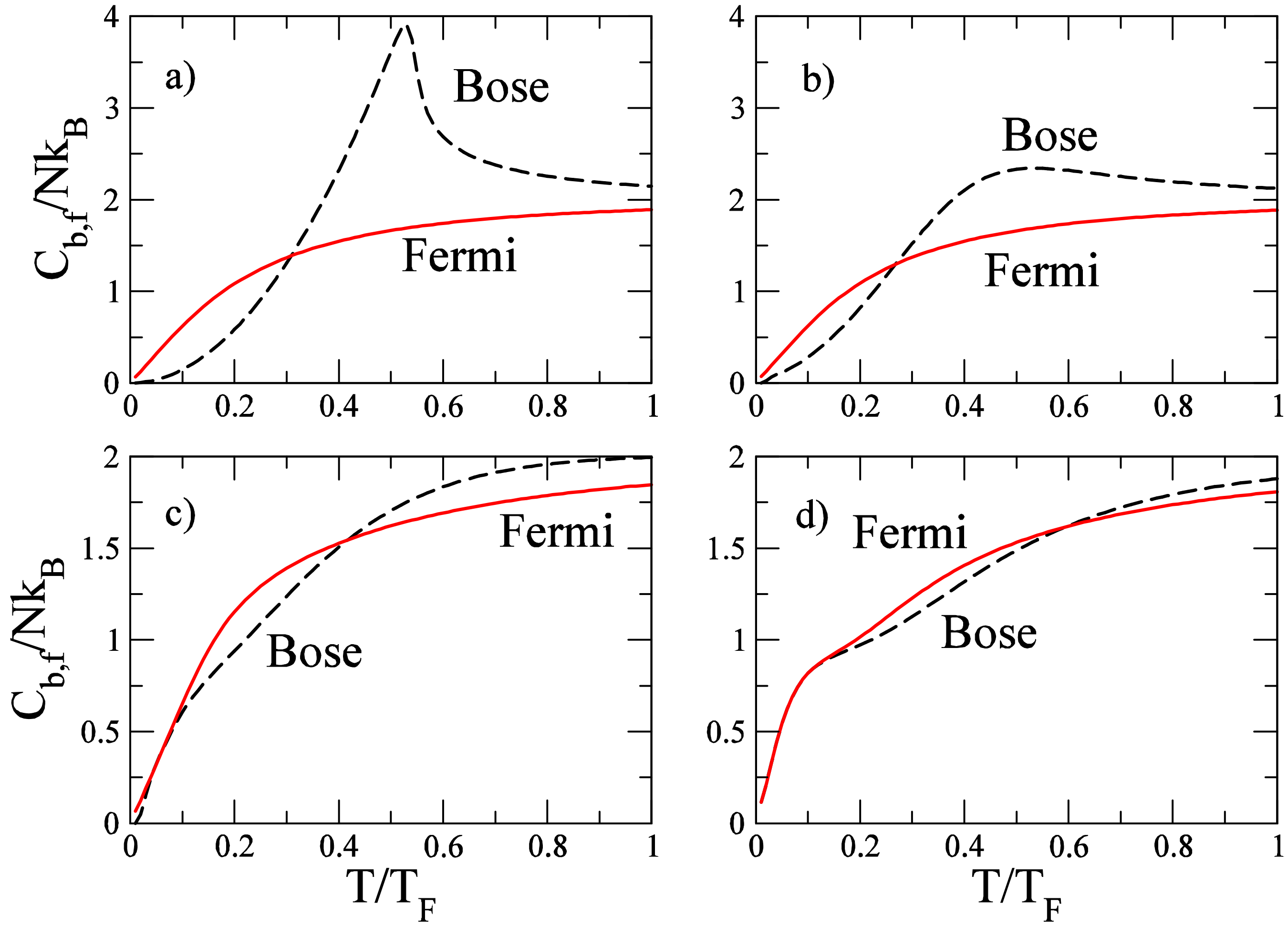
Trick # 3: lower dimensionality traps

The cubic dependence of the specific heat for bosons depend on their DOS



There is no gain in heat capacity matching going from 3D to 2D

Equal number of fermions and bosons, equal mass, 2D traps with frequency ratio 1, 2500, 20000, and 50000



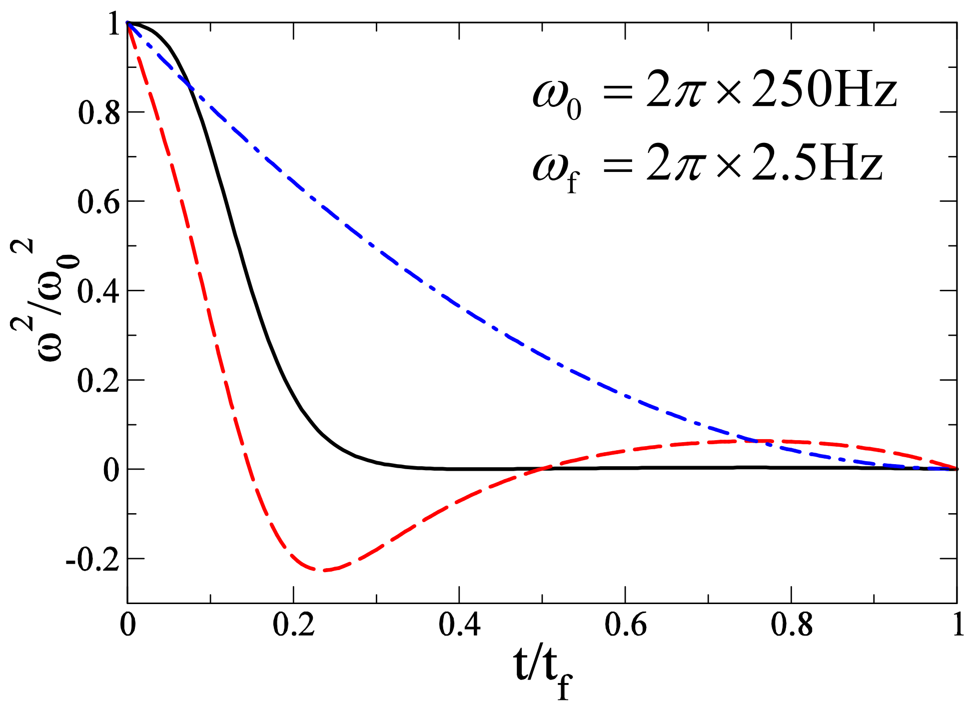
In 1 D ideal matching as the heat capacities have identical scaling
Reduced dimensionality cooling may be also viable for optical lattices
[M. Brown-Hayes *et al*., PRA 78, 013617 (2008)]

Trick # 4: proper control of the trapping frequency

'Fast' adiabatic/frictionless cooling [Chen *et al.*, PRL 104, 063002 (2010)]

Design the optimal frequency trajectory which reaches a targeted final frequency in a time much shorter than the corresponding (truly) adiabatic process

$$I(t) = \frac{\pi^2}{2m} + \frac{m\omega_0^2 q^2}{2b(t)^2}$$



Lewis-Riesenfeld invariant if

$$\ddot{b} + \omega(t)^2 b = \omega_0^2 / b^3$$

(Ermakov equation)

Boundary conditions on b and its first and second derivatives at initial and final times

Polynomial Ansatz for b(t)

$$\omega(t)^2 = \omega_0^2 / b^4 - \ddot{b}/b$$

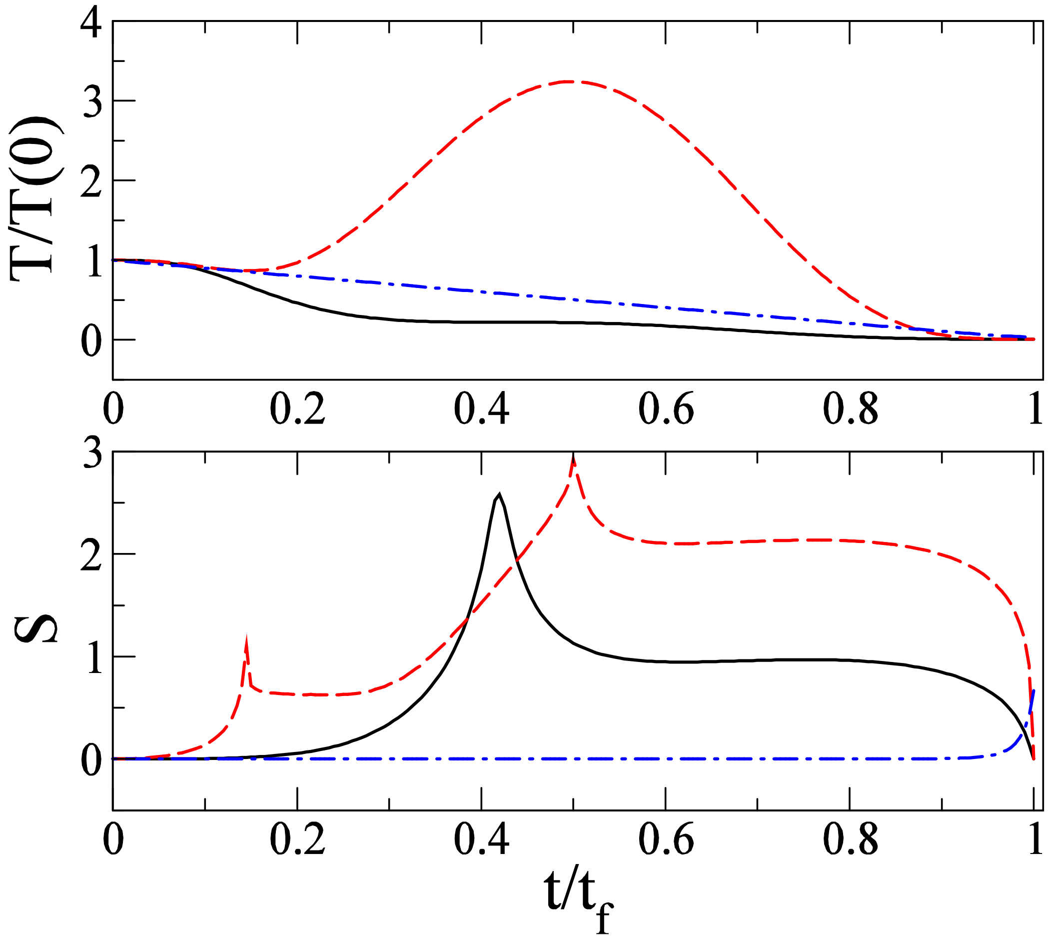
Dotted-dashed 'quasi-adiabatic' 400 ms

Continuous 'fast' 25 ms

Dashed 'fast' 6 ms

The role of frictionless cooling (or real adiabatic cooling) has been downplayed because it <u>does not allow for phase space density increase</u>, no route to degeneracy

In the framework of optimized sympathetic cooling this is precisely what we are looking for as an ideal coolant!

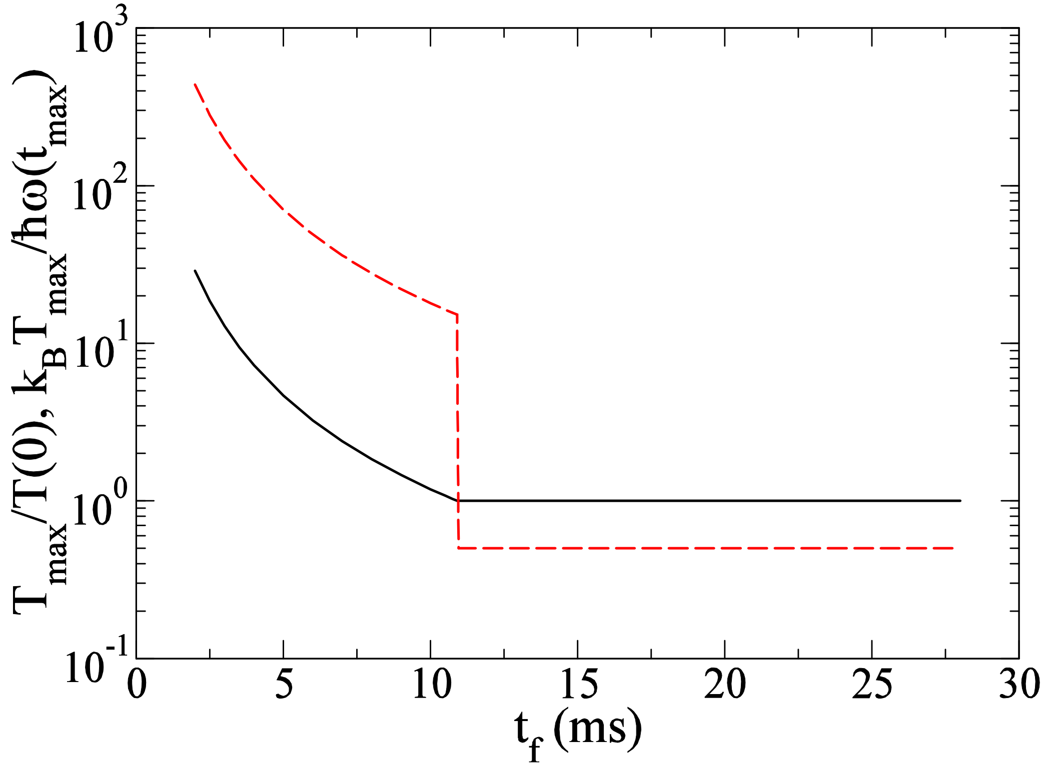


Important check: transient temperature increase, which exceeds the initial temperature for small times due to an antitrapping stage (available by using a bichromatic trap for instance)

This will limit the minimum time duration of the process

For 11 ms < t_f < 25 ms
T is always smaller than T(0)

Issues if instead t_f < 11 ms

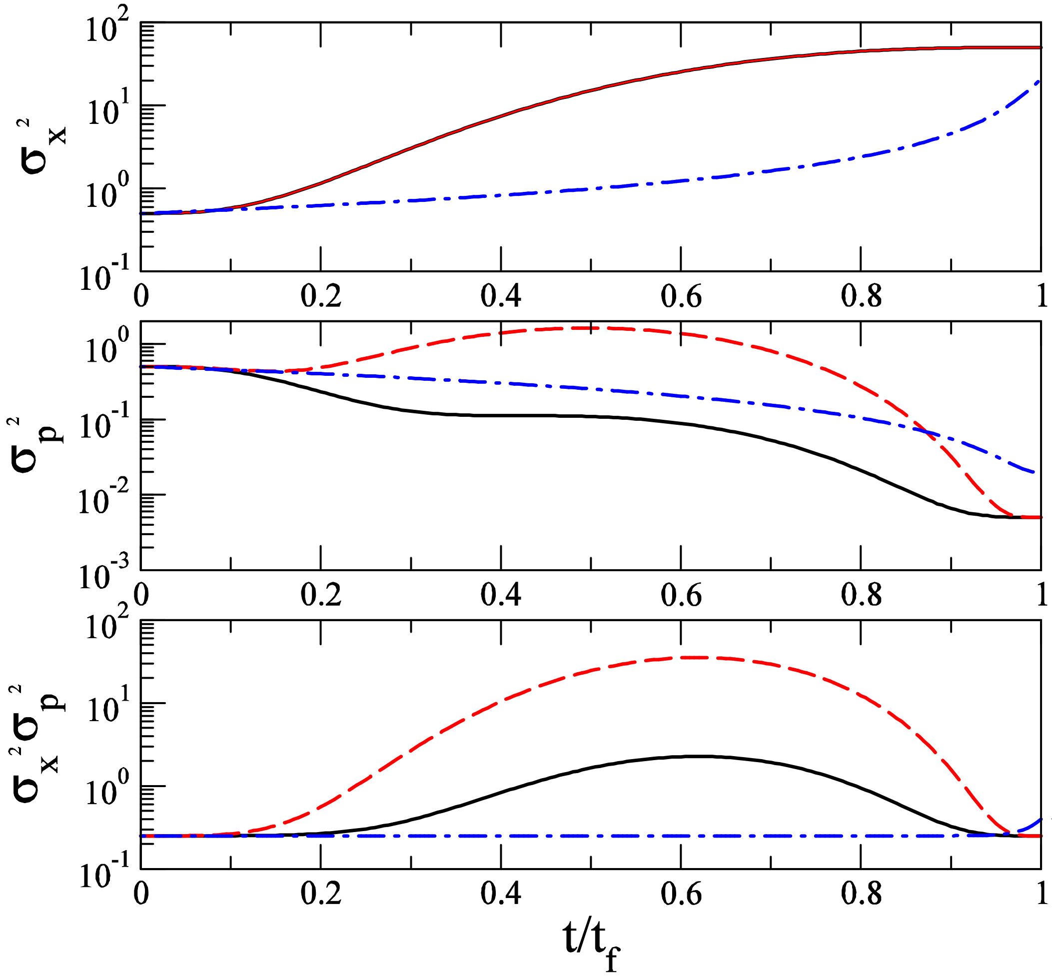


This analysis holds for a truly harmonic trap.
Realistic traps have a finite depth (e.g. ODTs)

Other limitations: overlap between the two species, elastic scattering rate during expansion of the coolant (to be studied in detail for each mixture)

S. Choi, R.O. & B. Sundaram, PRA 84, 051601(R) (2011)

It can be shown that frictionless cooling implies squeezed states with minimum uncertainty product [S. Choi, R.O. & B. Sundaram, PRA 86, 043436 (2012)]
A quasi-adiabatic trajectory does not preserve minimum uncertainty instead



Position variance increases

Momentum variance increases

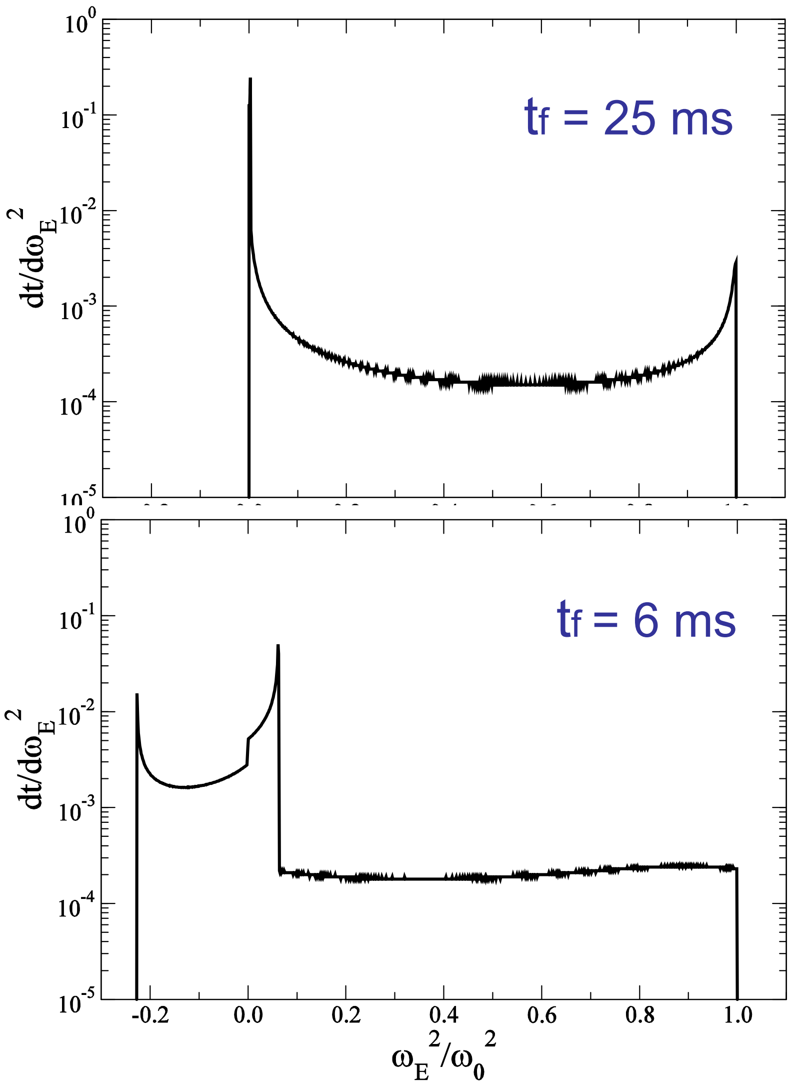
>0.25

=0.25

Uncertainty product may be used as a figure of merit of fidelity

Robustness of the protocol with respect to trap frequency jittering

This is an important check especially since for short times the trapping potential has a repulsive stage, in which the atoms spend a substantial portion of time.

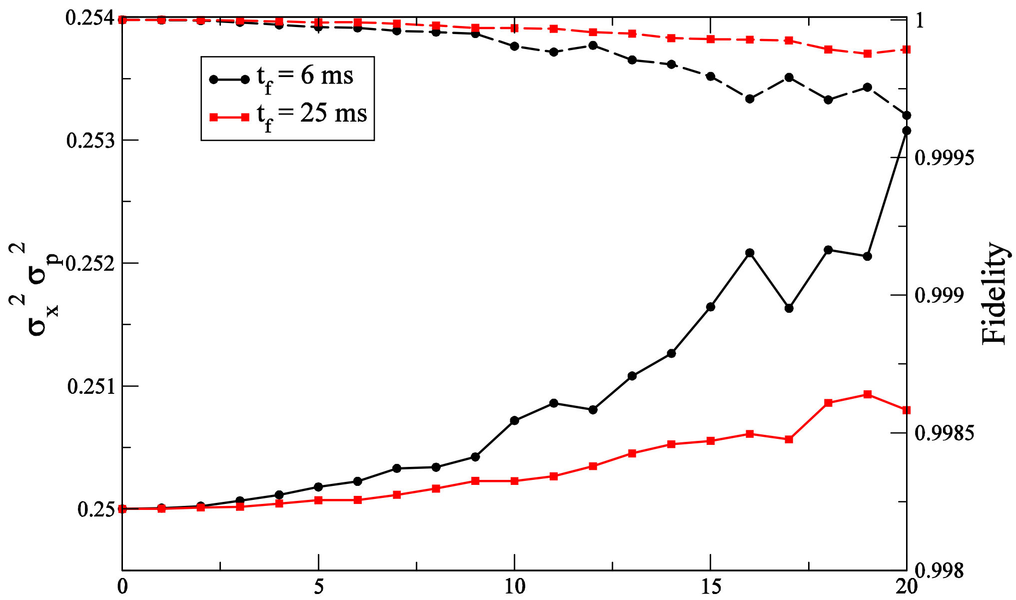


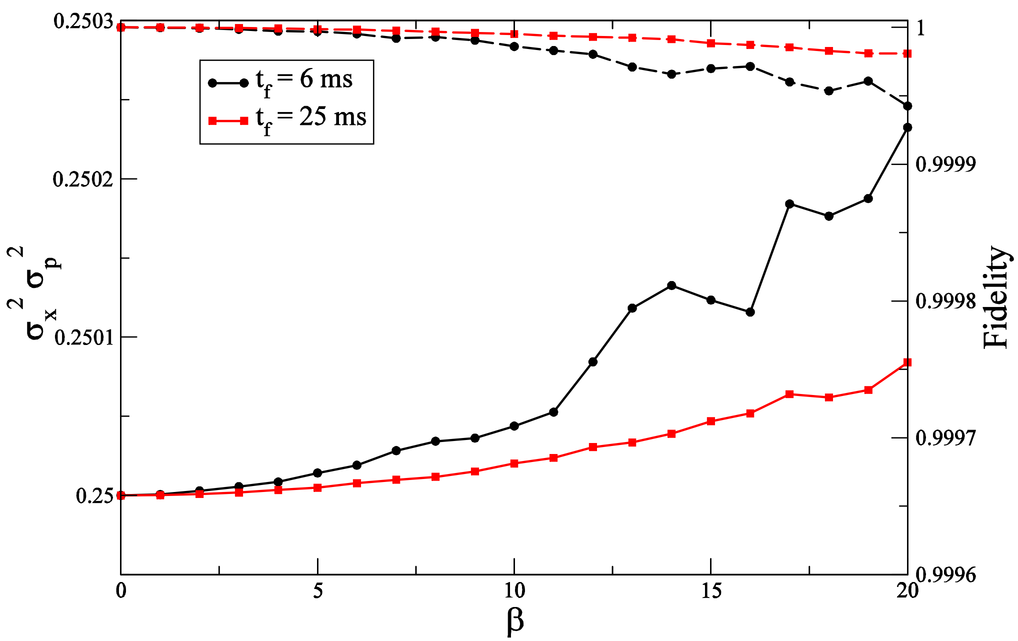
Define a 'temporal' density of states (TDOS) proportional to the time spent by the system in the frequency interval

$$[\omega_E^2, \omega_E^2 + d\omega_E^2]$$

where ω_E is the desired Ermakov trajectory at a given time

$$\text{TDOS} \propto [\mathrm{d}(\omega_E^2(t))/\mathrm{dt}]^{-1}$$





Solid lines: squeezing (left vert. axis)
Dashed lines: fidelity (right vert. axis)

Gaussian noise (SD $\beta \, |\, \omega_E^2(t) \,|$)

Fidelity defined as

$$|\langle \psi(\mathrm{t_f}) \,|\, \psi_{\mathrm{target}} \rangle|$$

Uniform noise (width $\beta \, |\, \omega_E^2(t) \,|$)

Experimental status

- Species-selective cooling demonstrated in Florence and Düsseldorf
- Frictionless cooling demonstrated in Nice

Florence: K-Rb (Bose-Bose) through adiabatic compression of K in the presence of Rb

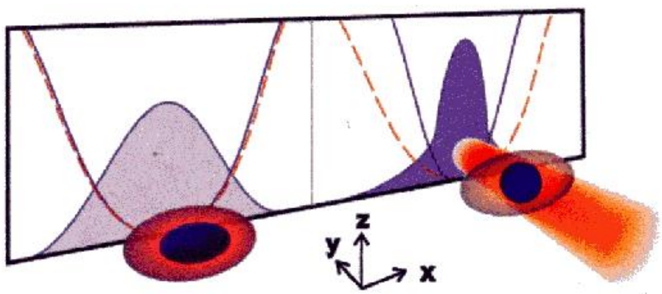
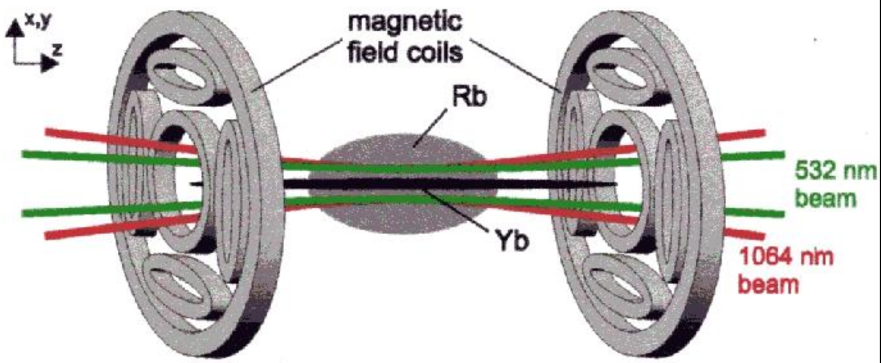


FIG. 1 (color online). Schematic of our experimental procedure. Left: the harmonic magnetic potential is common to both gases, auxiliary (red, larger) and target (blue, smaller). Right: the species-selective dipole beam compresses the target sample and drives it into the degenerate regime. Trapping potentials for the auxiliary Rb (dashed line) and the target K gas (solid line) are sketched on the background panels together with the K density distributions.

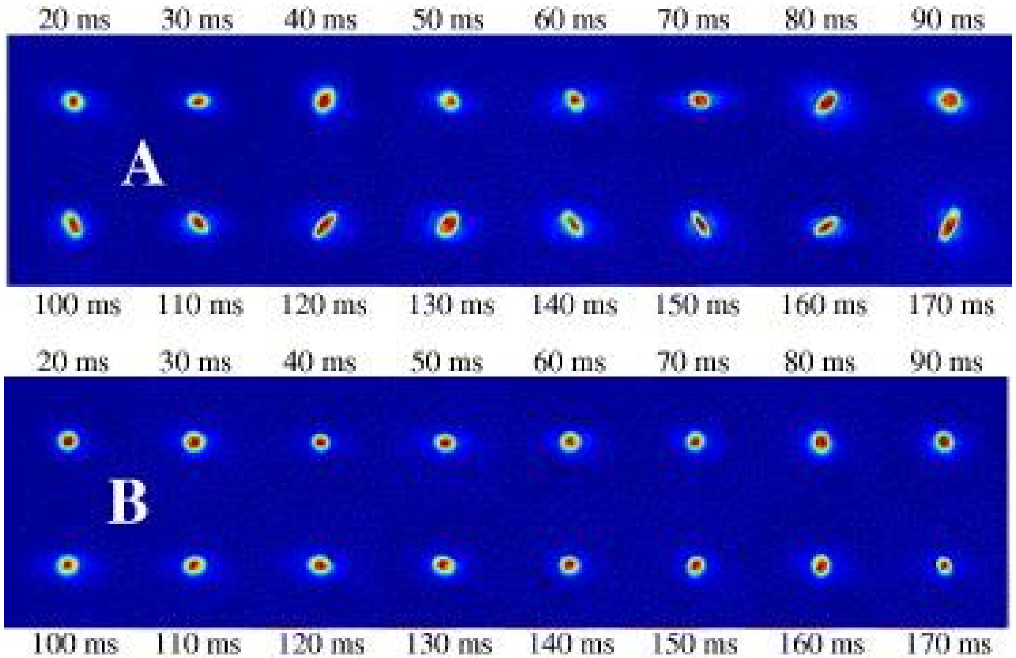
Catani *et al.*,
PRL 103, 140401 (2009)

Düsseldorf : Rb-Yb (Bose-Bose) with hybrid trap (magnetic+ODT)



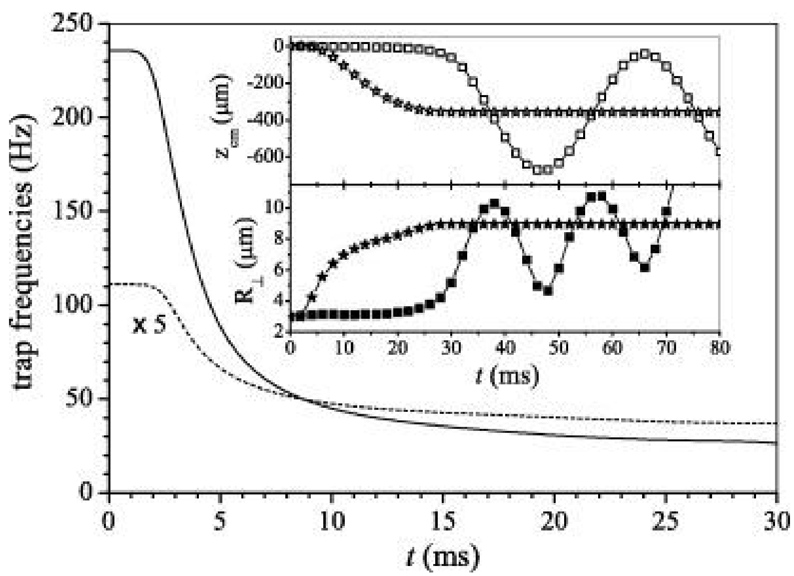
Yb dominant transition at 399 nm
Two-color optical trap used to change the Rb trapping frequency (including complete cancellation of the ODT potential)

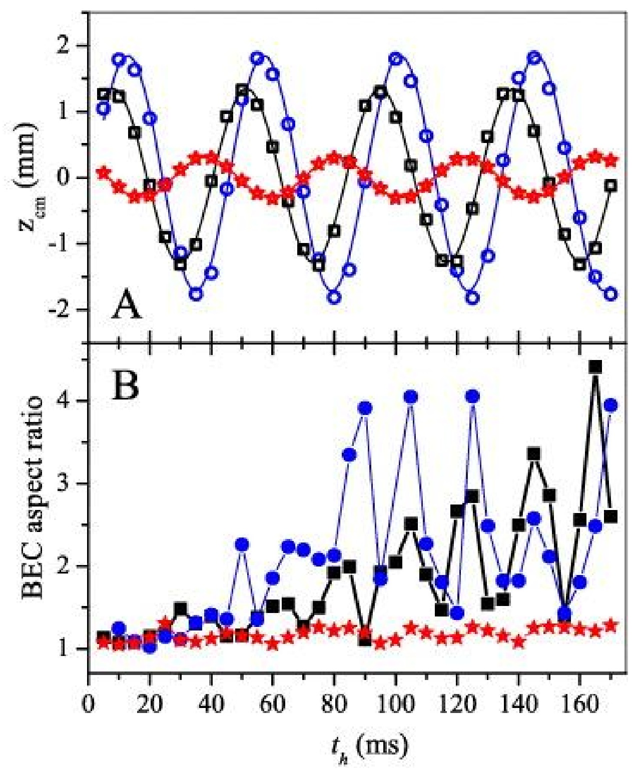
Baumer *et al.*,
PRA 83, 040702(R) (2011)



Nice-Sophia Antipolis:
Demonstration of shortcut
to adiabaticity in ultracold Rb
(thermal & BEC)

A: Linear ramp-down expansion
B: Shortcut to adiabaticity expansion
Both 30 ms duration





J.-F. Schaff *et al*., PRA 82, 033430 (2010); EPL 93, 23001 (2011)

Conclusions

- ✓ Discussion of the limits to sympathetic cooling in Fermi-Bose mixtures
- ✓ How to avoid morphing into symp(ly p)athetic cooling:
  intraspecies and interspecies elastic scattering rates,
  trap technical noise sources, <u>gravitational sagging</u>, <u>Fermi hole-heating</u>
- ✓ Four techniques to reach lower T/T_F
- ✓ Focus on frictionless cooling as the ideal strategy:
  'quantum control and reservoir engineering'
- ✓ Experimental demonstrations of various aspects already carried out separately in three different labs, necessary to have all in the same lab
- o Bonus of species selective traps: precision thermometry through a less degenerate (or non-degenerate) Bose gas
- o Issue of deeper Fermi degeneracy in optical lattices still open
  [see D.C. McKay and B. DeMarco, Rep. Prog. Phys. 74, 054401 (2011)]

For KITP people: I'm in room 2114 until 3/2
For the rest of the world: onofrior@gmail.com

Thank you!