Consiglio Nazionale delle Ricerche

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LENS

Università di Firenze

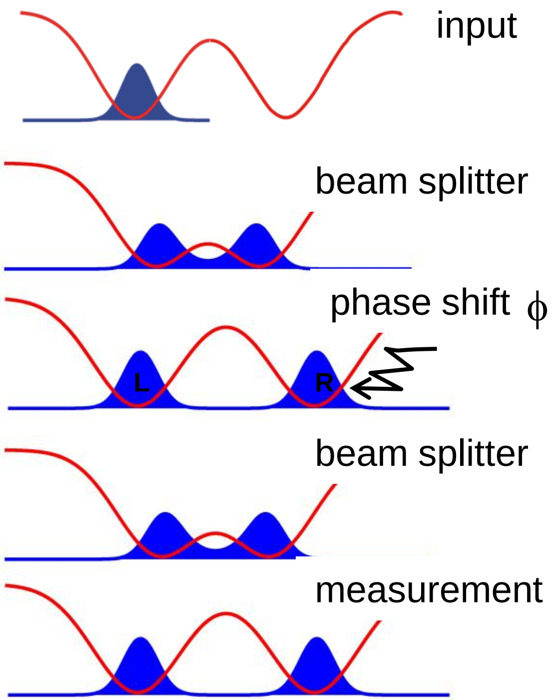
QIBEC

Quantum Interferometry with Bose Einstein Condensates

CNR-INO Experimental Unit

Kickoff meeting, 2-3 Febraury 2012, Firenze

Trapped Mach Zender Interferometry with BEC



Operation

- Sensitive to the difference in potential energy between the two wells
- Read-out phase $\phi \sim \Delta ET/h$
- Sensitive to gravity, accelerations, electomagnetic field gradient, etc…

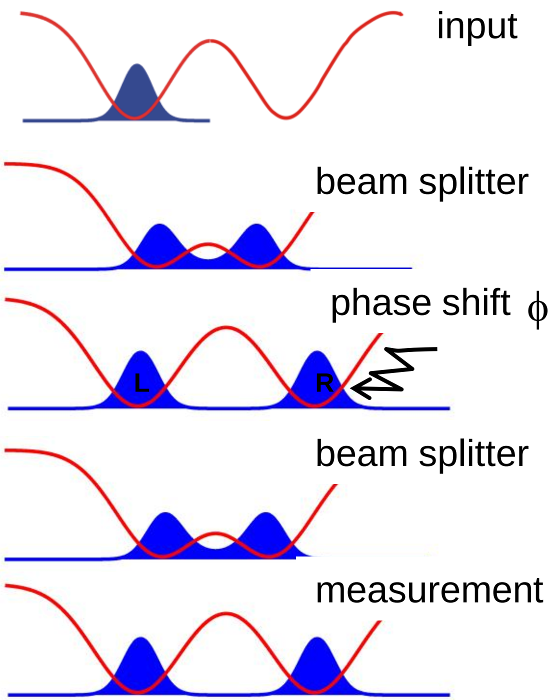
Main goals within the QIBEC project

- Operation of the interferometer with high sensitivity
- Exploitation of entanglement towards Heisenberg limited resolution

Target breakthrough

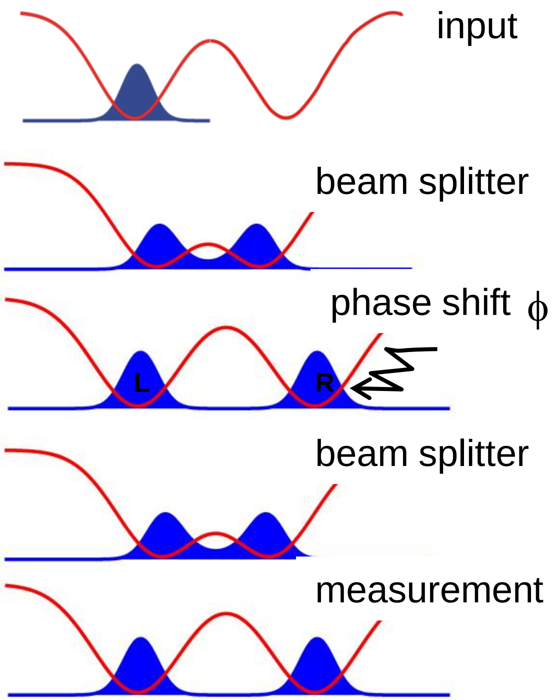
A new type of sensor with both high spatial resolution and high sensitivity

Trapped Mach Zender with BEC: main obstacles



- Interaction induced decoherence
- Heating and finite temperature
- Decoherence induced by the trapping potential or other external fields
- Losses
- Atom number counting with single atom resolution

Trapped Mach Zender with BEC: main obstacles



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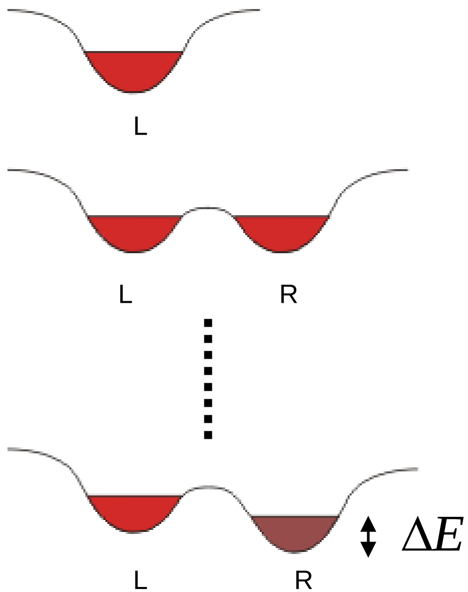
Interaction induced decoherence

Beam splitter

External force



$$|\Psi\rangle = \sum_{n=-N/2}^{N/2} c_n \left| \frac{N}{2}+n, \frac{N}{2}-n \right\rangle$$

$$|\Psi\rangle = \sum_{n=-N/2}^{N/2} c_n e^{i(2n\Delta E + E_i(n))T} \left| \frac{N}{2}+n, \frac{N}{2}-n \right\rangle$$

$$E_i(n) = U_C\left[\left(\tfrac{N}{2}+n\right)^2 + \left(\tfrac{N}{2}-n\right)^2\right] + U_D\left[\left(\tfrac{N}{2}+n\right)\left(\tfrac{N}{2}-n\right)\right]$$

J. Grond, U. Hohenester, J. Schmiedmayer, A. Smerzi, Phys. Rev. A 84, 023619 (2011)

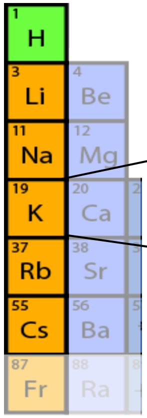
TU-Wien

CNR-INO-Th

If $U_C = U_D/2$

$$E_i(n) = U_C\left[\left(\tfrac{N}{2}+n+\tfrac{N}{2}-n\right)^2\right] = U_C N^2$$

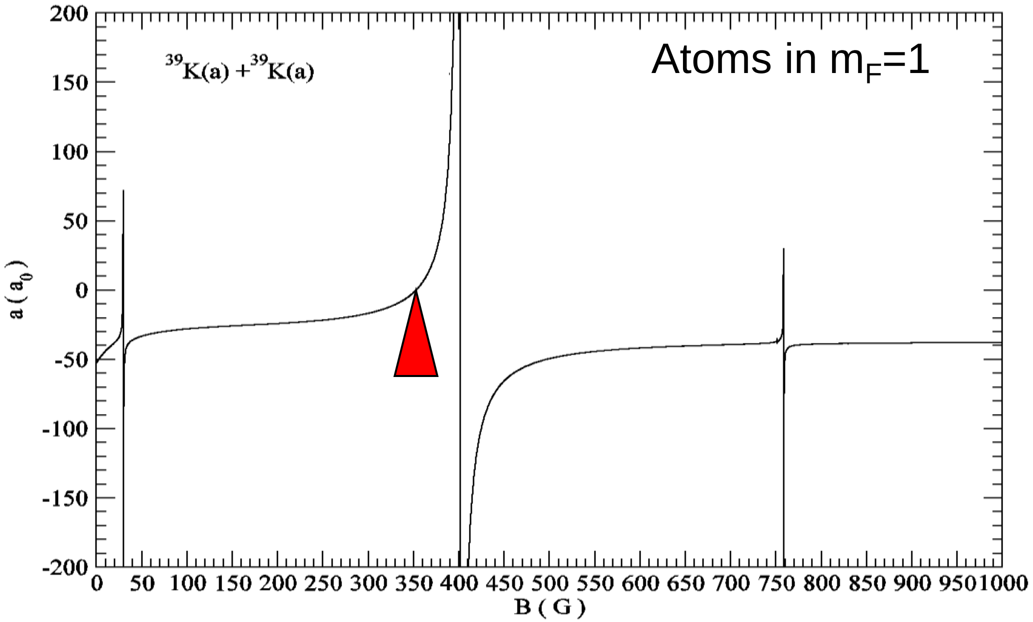
A weakly interacting condensate with a K isotope



^{41}K boson, condensed — G. Modugno et al, Science **294**, 1320 (2001)

^{40}K fermion — De Sarlo et al, PRA **75**, 022715 (2007)

^{39}K boson, a=-33a_0 — D'Errico et al. New J. Phys. **9**, 223 (2007); Roati et al. PRL **99**, 010403 (2007)



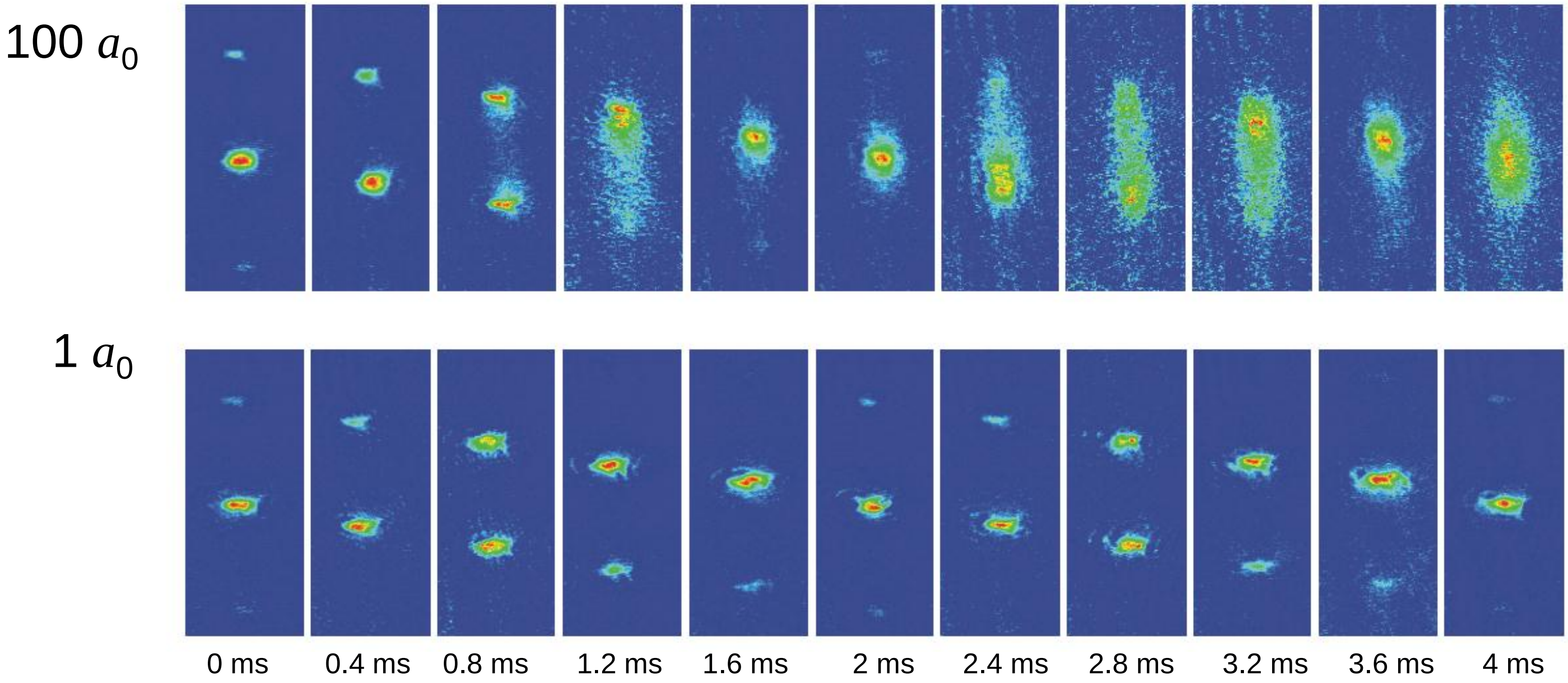
$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

$$a(B) \approx \frac{a_{bg}}{\Delta}(B - B_{ZC}) \longrightarrow \frac{\Delta a}{\Delta B} = 0.6\ a_0 / \mathrm{G}$$

Very high degree of tunability !!

Atom interferometry on the zero crossing of the broad Feshbach resonance

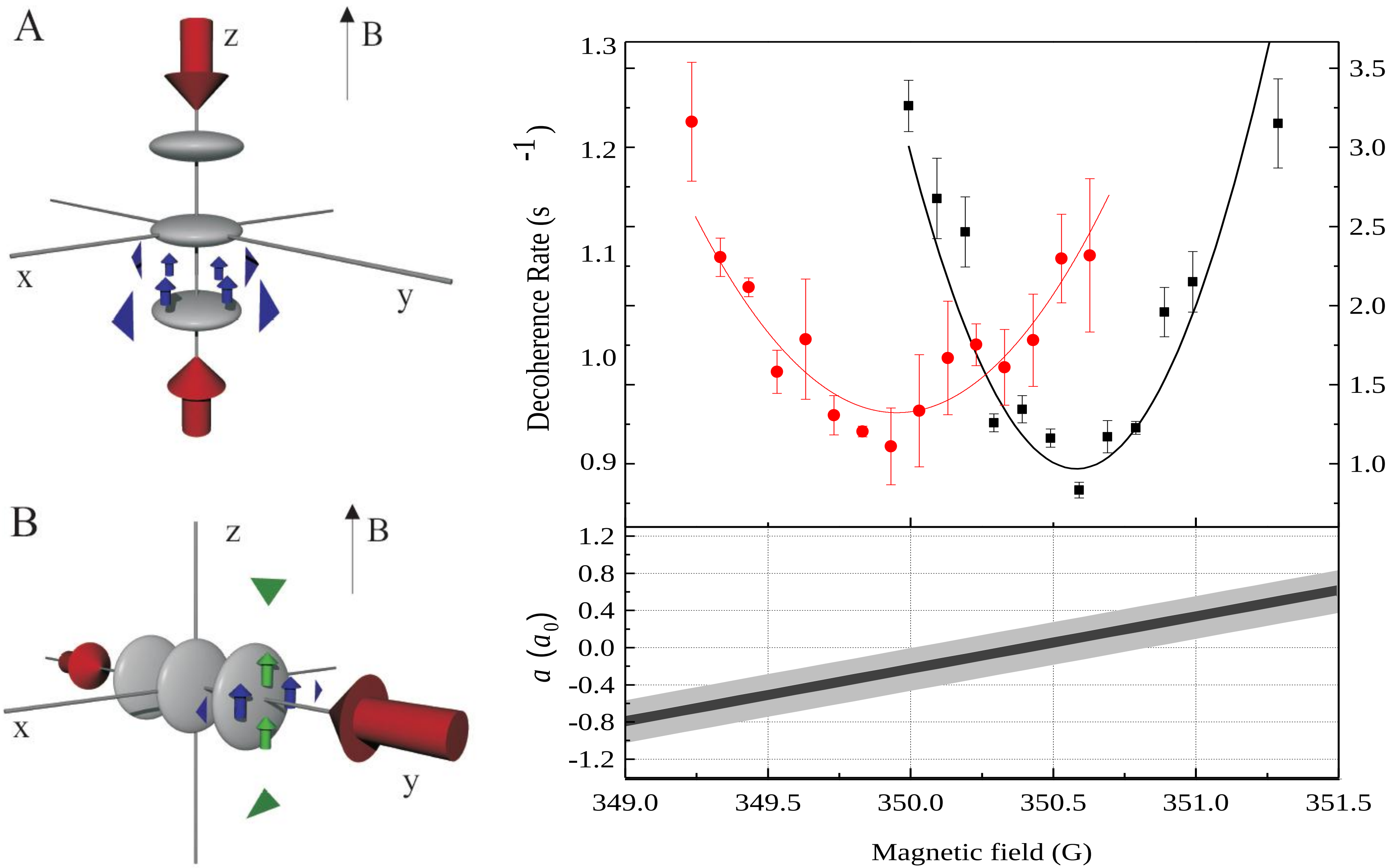
A weakly interacting condensate with a K isotope



M. Fattori, et al. Phys. Rev. Lett. PRL **100** 080405 (2008)

M. Gustavsson, et al, Phys. Rev. Lett. PRL **100** 080404 (2008)

Magnetic dipolar interaction



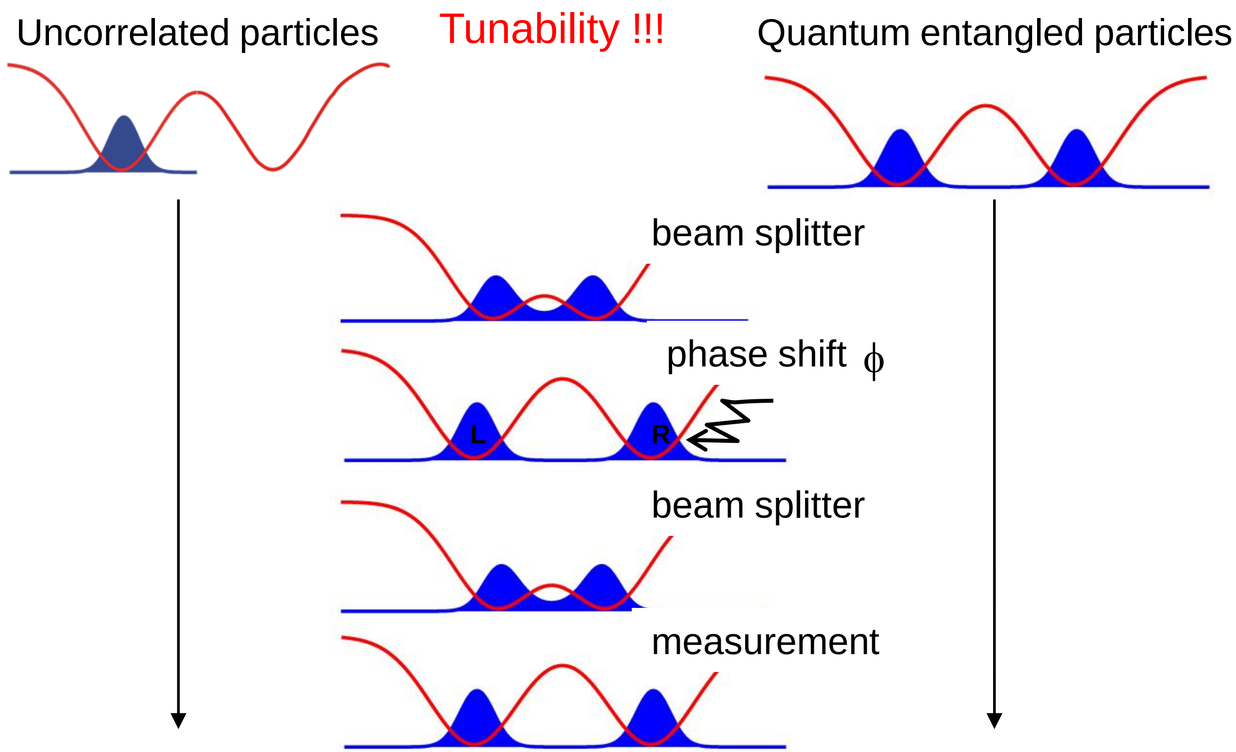
M. Fattori, G. Roati, M. J. Lasinio, L. Santos, M. Inguscio and G Modugno, PRL **101** 190405 (2008)

Quantum enhanced sensitivity

Tunability !!!

input

Spatial Mach Zender Interferometer



$\Delta\phi \sim 1/\sqrt{N}$ (Shot noise limit)

$\Delta\phi \sim 1/N$ (Heisenberg limit)

Test of linear vs non linear interferometer for different values of the scattering length

TU-WIEN

Appel, J. et al. Proc. Natl Acad. Sci. USA 106, 10960 (2009).

C. Gross, T. Zibold, E. Nicklas, J. Estève, M. K. Oberthaler, Nature 464, 1165 (2010)

Pezze´, L. & Smerzi, A., Phys. Rev. Lett. 102, 100401 (2009).

Interaction Induced decoherence

Some numbers

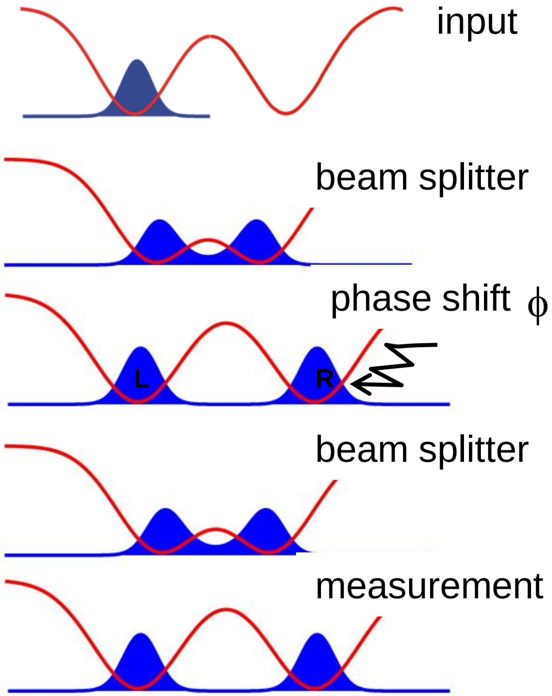
Coherence time for a residual interaction

$$t_c = \frac{1}{\sqrt{N}} \frac{h}{U_C}$$

for $a_S < 10^{-3}\ a_o$, N=10000, ω_{avg}=65 Hz → $t_c \sim 10000$ s

Single mode hypotesis fullfilled → $E_{int}/E_K < 10^{-1}$ for $a_{dipolar} \sim 0.3\ a_o$

Trapped Mach Zender with BEC: main obstacles



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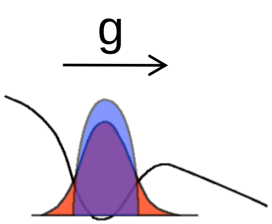
Heating and finite temperature

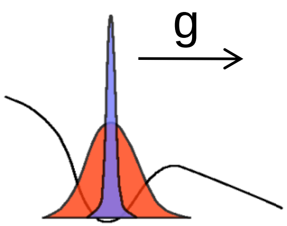
Two mode operation requires low temperature and low heating during the whole sequence

Ground state occupation, $|C_0|^2=1$ → $k_B T < \hbar\omega$, for T=3 nK, for 65 Hz

Interacting BEC

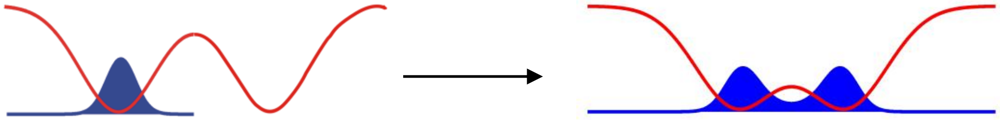


Non-Interacting BEC

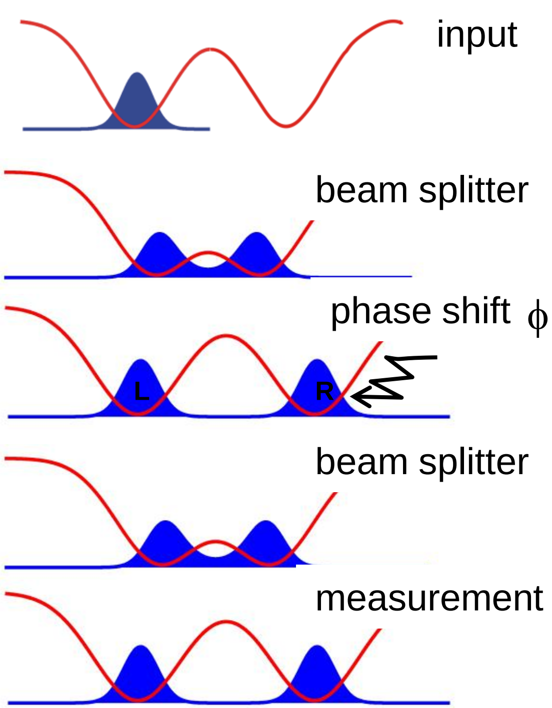


For λ = 1064 nm, Erec ~ 200 nK !! → Low light scattering rates with tightly focused beams

Fast splitting without excitations for the creation of strongly squeezed state and for beam splitter operation → Input from ULM, TU-WIEN and UHEI on application of OC theories (manipulation of the potential barrier and scattering length)



Trapped Mach Zender with BEC: main obstacles



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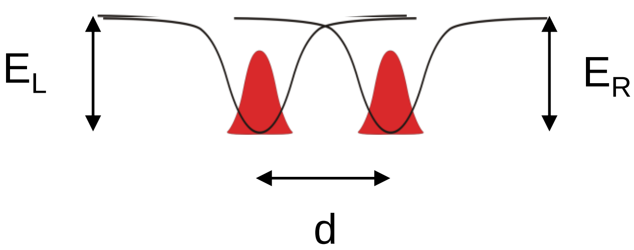
Decoherence induced by the trapping potential

$\Delta\phi \sim 1/N \sim 1$ mrad (for N=1000 atoms)

Uncontrolled energy shifts < 1 mHz (for 1 sec operation)

Using two indipendent dipole traps for the two wells



$E_{L,R} \sim 10$ kHz → 10^{-7} power stability !!!

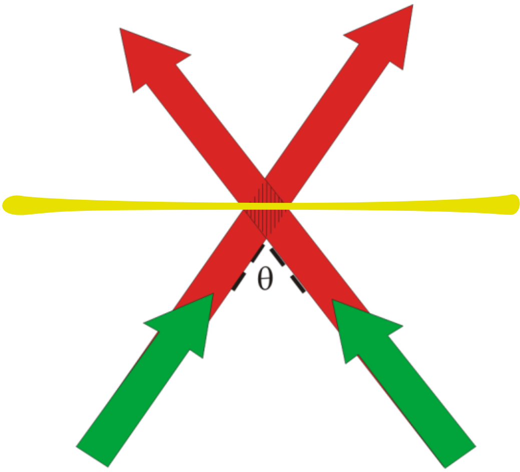
$\Delta E_g \sim 1$ kHz for $d \sim 1\ \mu$m → 1 pm pointing stability !!!

Way out:

- common mode trapping power fluctuations
- use of lattices to control the distance d

Decoherence induced by the trapping potential

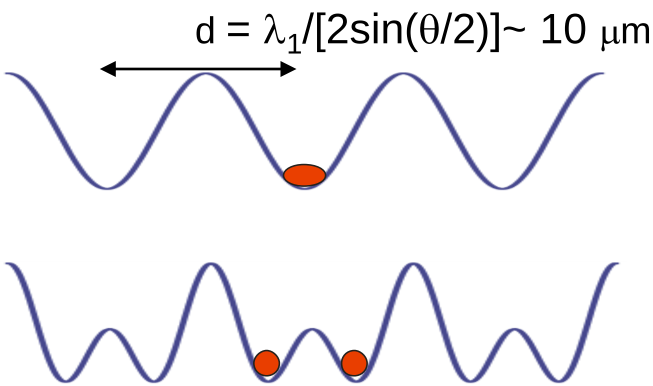
• Super-Lattice



λ_1=1064 nm

Radial confinement

λ_2=λ_1/2=532 nm



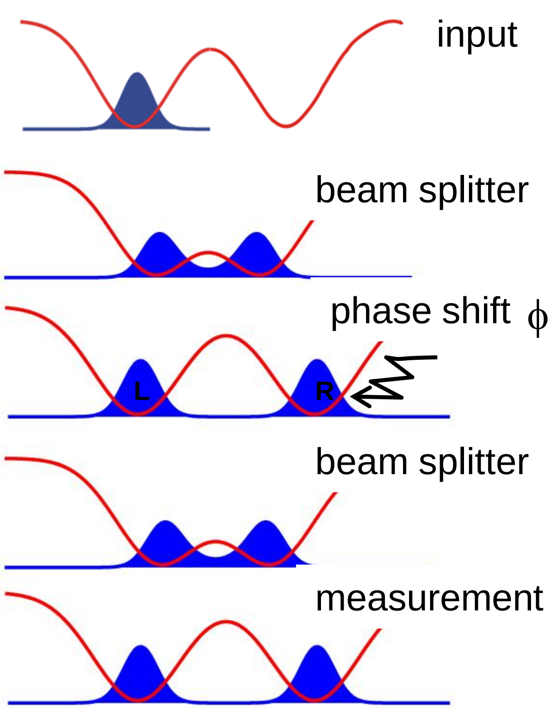
J. Sebby-Strabley, et al., Phys. Rev. A **73**, 033605 2006.

• Use of a lattice laeds to common mode rejection of light shifts in the two wells

• An array of interferometers allows rejection of uncontrolled spurious forces (vibrations, magnetic field gradients, etc…) → CNR-Th: Differential phase estimation protocol

• Increase of the sensitivity, full exploitation of the atom number (not possible in a single interferometer). $\sqrt{M}$ increase of the sensitivity with *M* the number of intererometers.

Trapped Mach Zender with BEC: main obstacles



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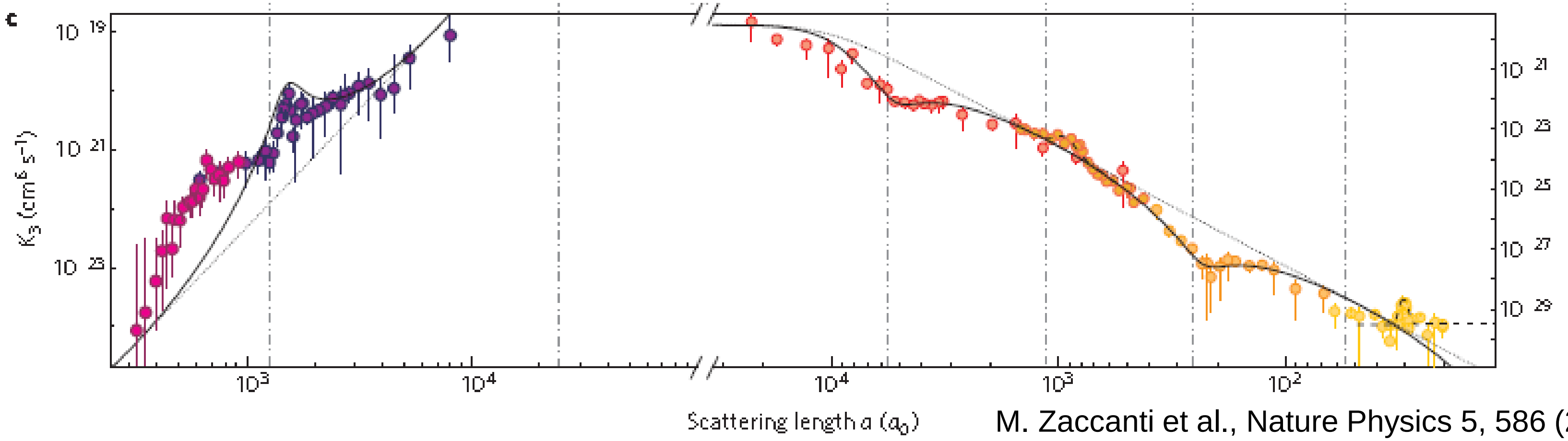
Losses



M. Zaccanti et al., Nature Physics 5, 586 (2009)

Effect of three body losses on the preparation of entangle states → CNRS-Th UHEI

C. Gross, T. Zibold, E. Nicklas, J. Estève, M. K. Oberthaler, Nature 464, 1165 (2010)

Y. Li, Y. Castin and A. Sinatra, PRL 100, 210401 (2008)

Three body losses rate on the zero crossing < 1 mHz for

N ~ 1000

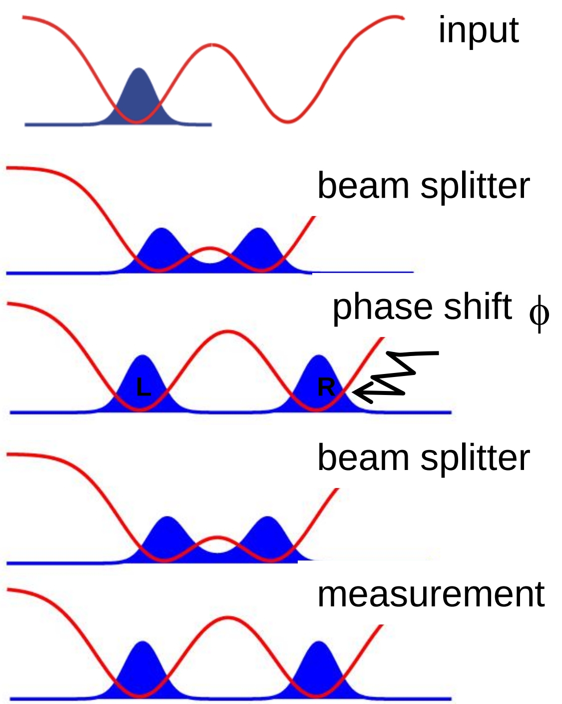
T ~ 1 s

ν_{trap}~ 100 Hz

→ Heisenberg limit

Other losses and decoherence sources: background losses and trapping light scattering

Trapped Mach Zender with BEC: main obstacles



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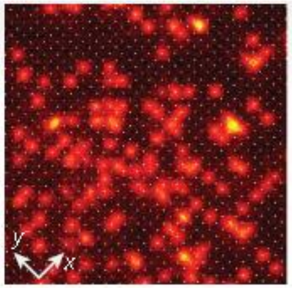
Atom number counting with single atom resolution

Input from the other units

R. Buecker et al. New J. Phys. 11 (2009) 103039

C. Gross, et al., Nature 464, 1165 (2010)



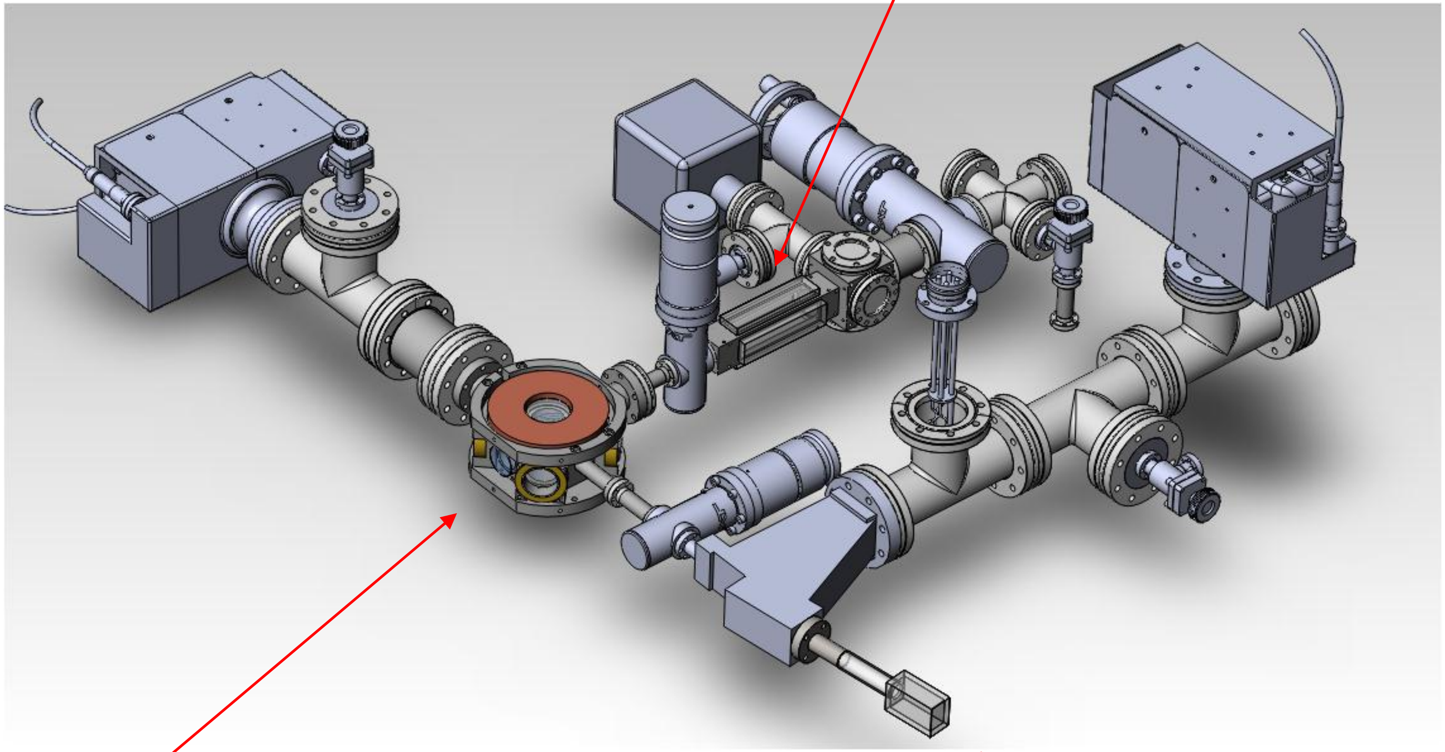
400 atoms with 99.5% efficiency

J. F. Sherson et al, *Nature* **467**, 68–72 (2010)

Possible route

- Fluorescence imaging of N atoms
- N_{ph} scattered by every atom and only βN_{ph} detected with $\beta \sim 0.1$
- Single atom resolution requires $\sqrt{N\beta N_{ph}} < \beta N_{ph} \longrightarrow \sqrt{N} < \sqrt{\beta N_{ph}} \longrightarrow \frac{N}{\beta} < N_{ph}$
- Distinguish between different atoms to keep N and N_{ph} low (beware of background noise)
- Trap and cool the atoms preventing radiative losses
- 3D lattice using Sub Doppler cooling now possible with K

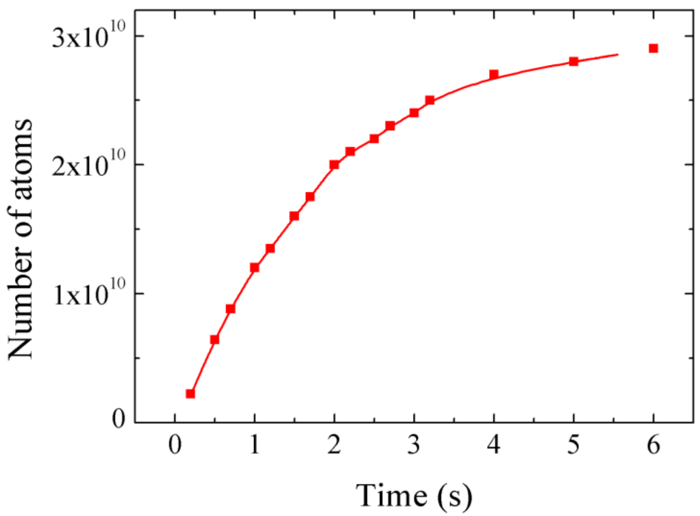
Experimental apparatus



Experimental sequence

- 2D MOT: 2×10^{10} atoms/s with a low average velocity of 25 m/s

- 3D MOT: 3×10^{10} atoms in 5 seconds



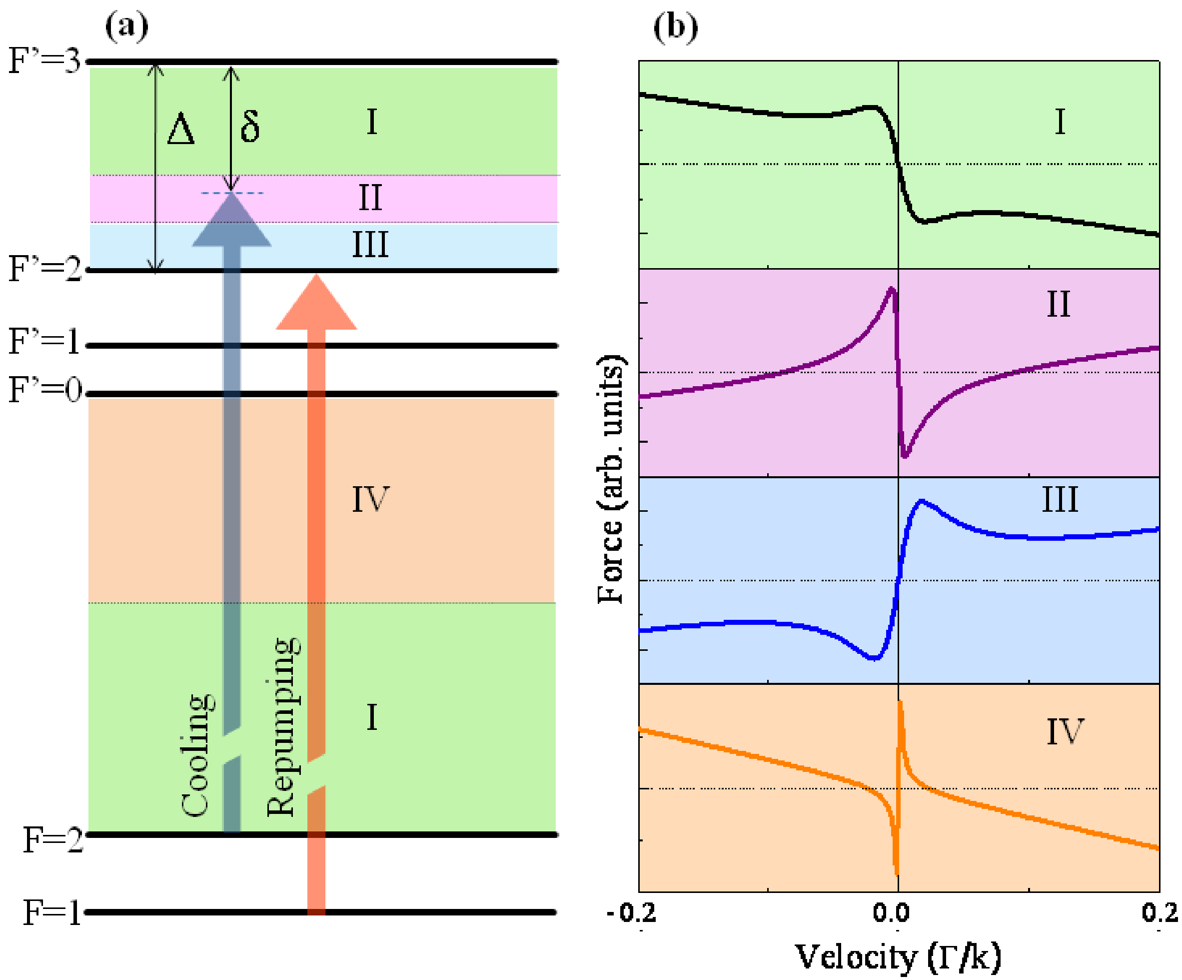
- C-MOT and Molasses

$N \sim 2 \times 10^{10}$, $T \sim 25\ \mu K$, $n \sim 10^{11} cm^{-3}$, $\rho \sim 10^{-5}$

Efficient Sub Doppler cooling

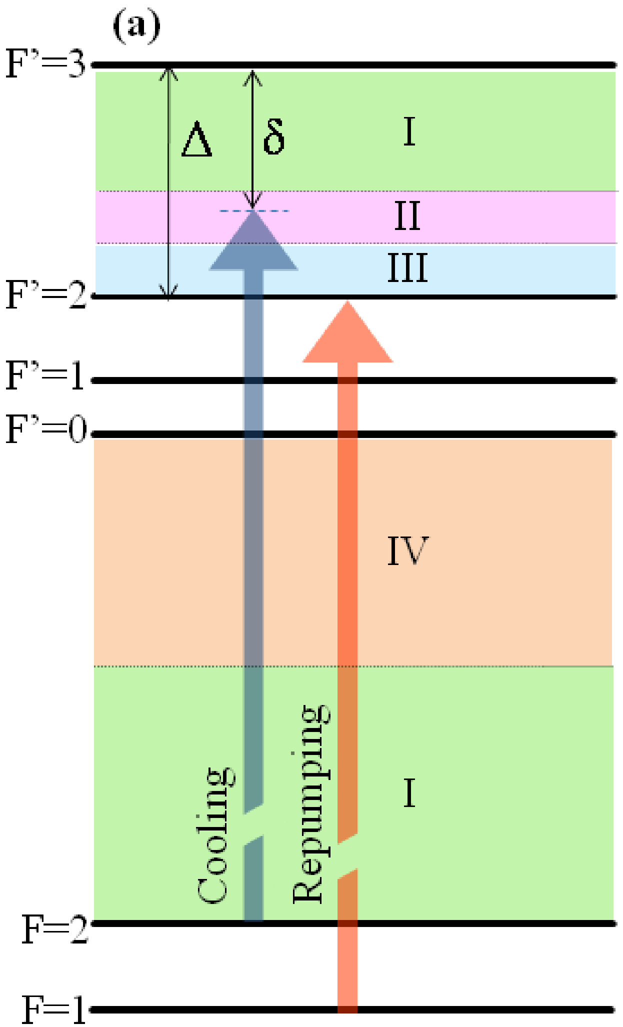
M. Landini, et al. PRA (2011)

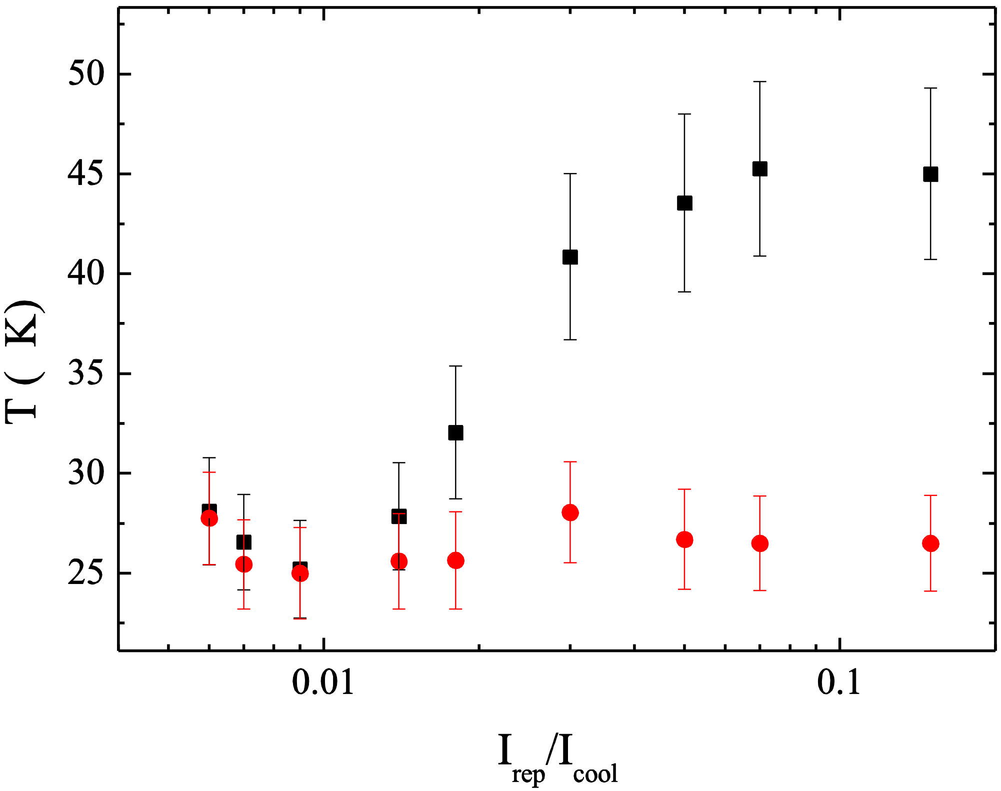
Sub Doppler cooling



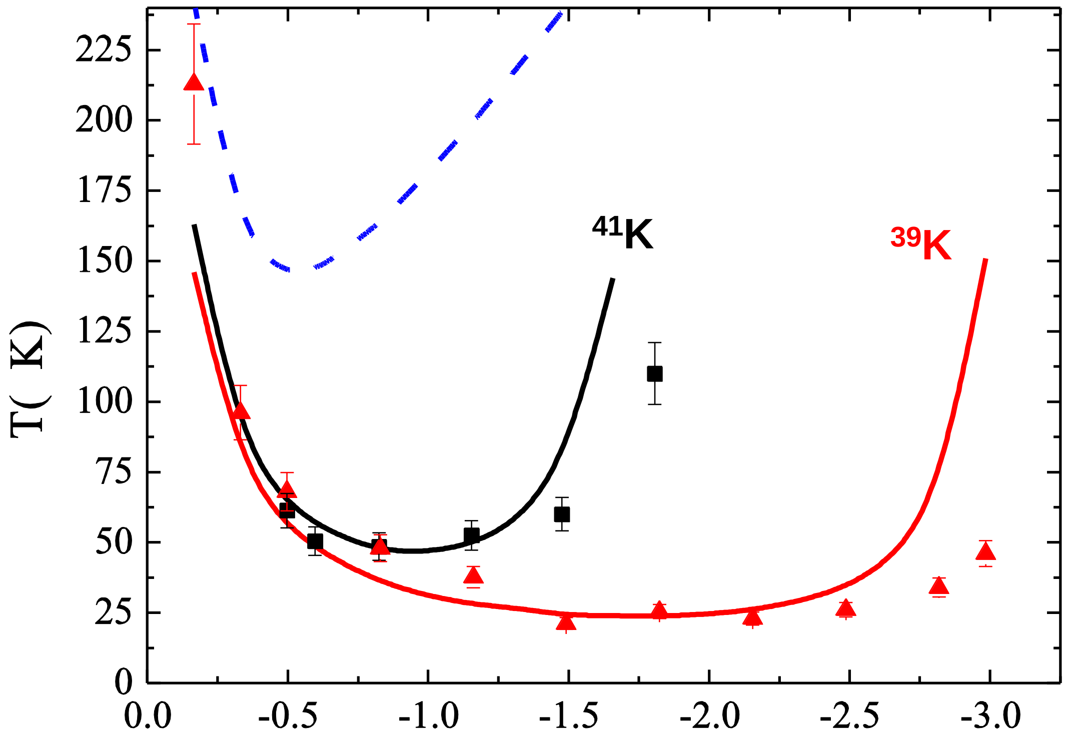
C. Fort, A. Bambini, L. Cacciapuoti, F. S. Cataliotti, M. Prevedelli, G.M. Tino, and M. Inguscio, Eur. Phys. J. D, **3,** 113 (1998)

Sub Doppler cooling





Sub Doppler cooling



Experimental sequence

• Magnetic transport to the science chamber with a movable magnetic field gradient and with atoms in the F=1, m_F=-1

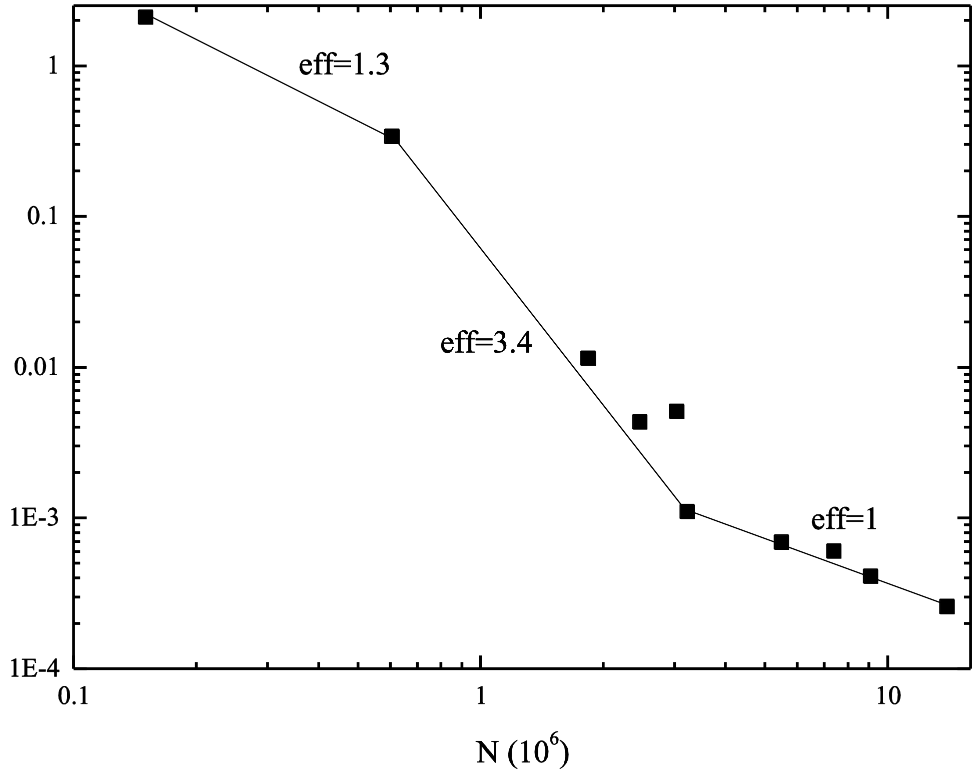
• Ramping up of a tightly focused laser (30 W, 25 μm waiste, 1064 nm) and switching off of the magnetic field gradient abruptly after 2 sec

N ~ 10^7, T ~ 220 μK, n ~ 5 x 10^{13} cm^{-3}, ρ ~ 10^{-4}

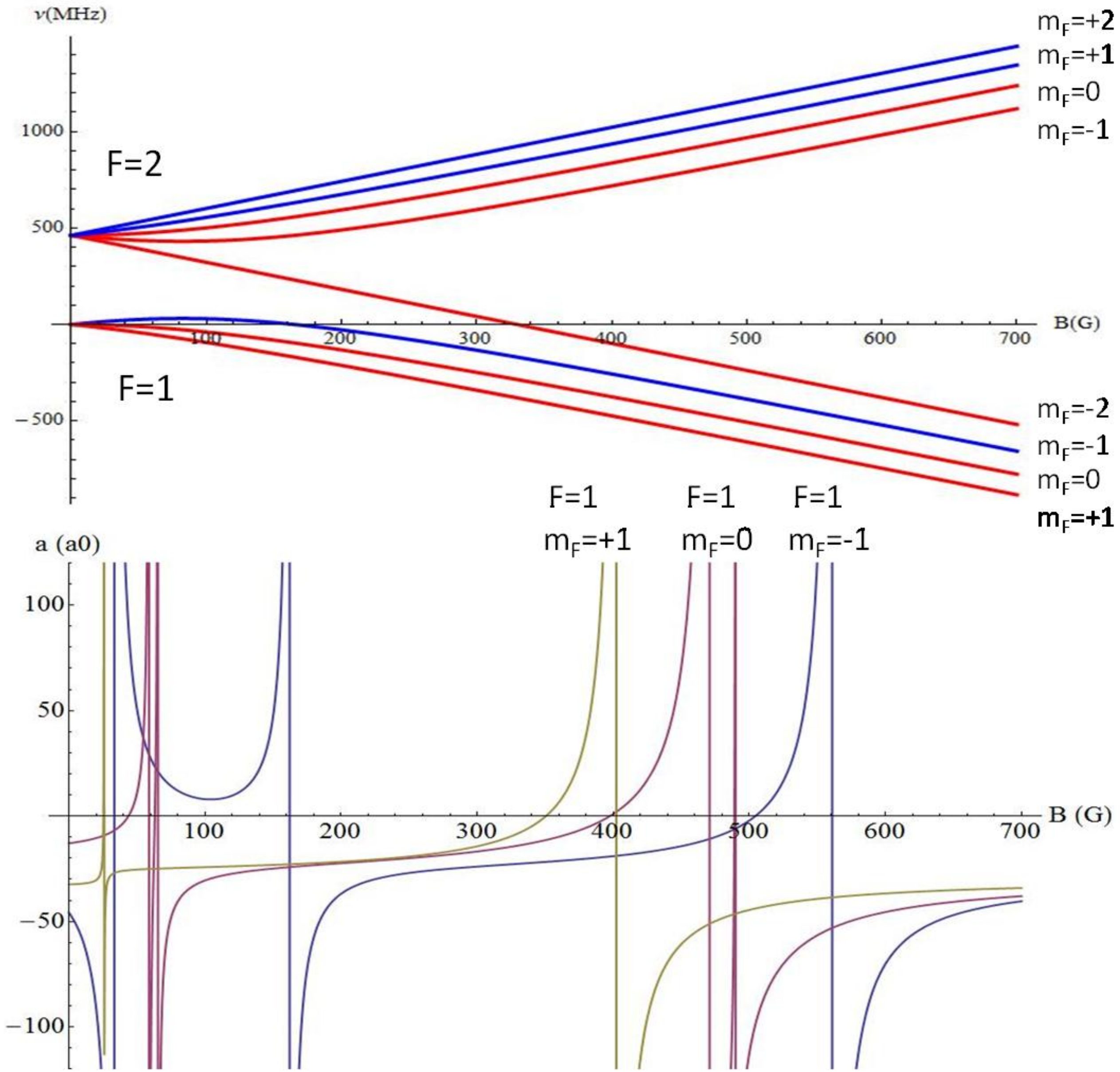
• Single beam evaporation at 40 G with 75 a_o

• Additional evaporation with a vertical dimple

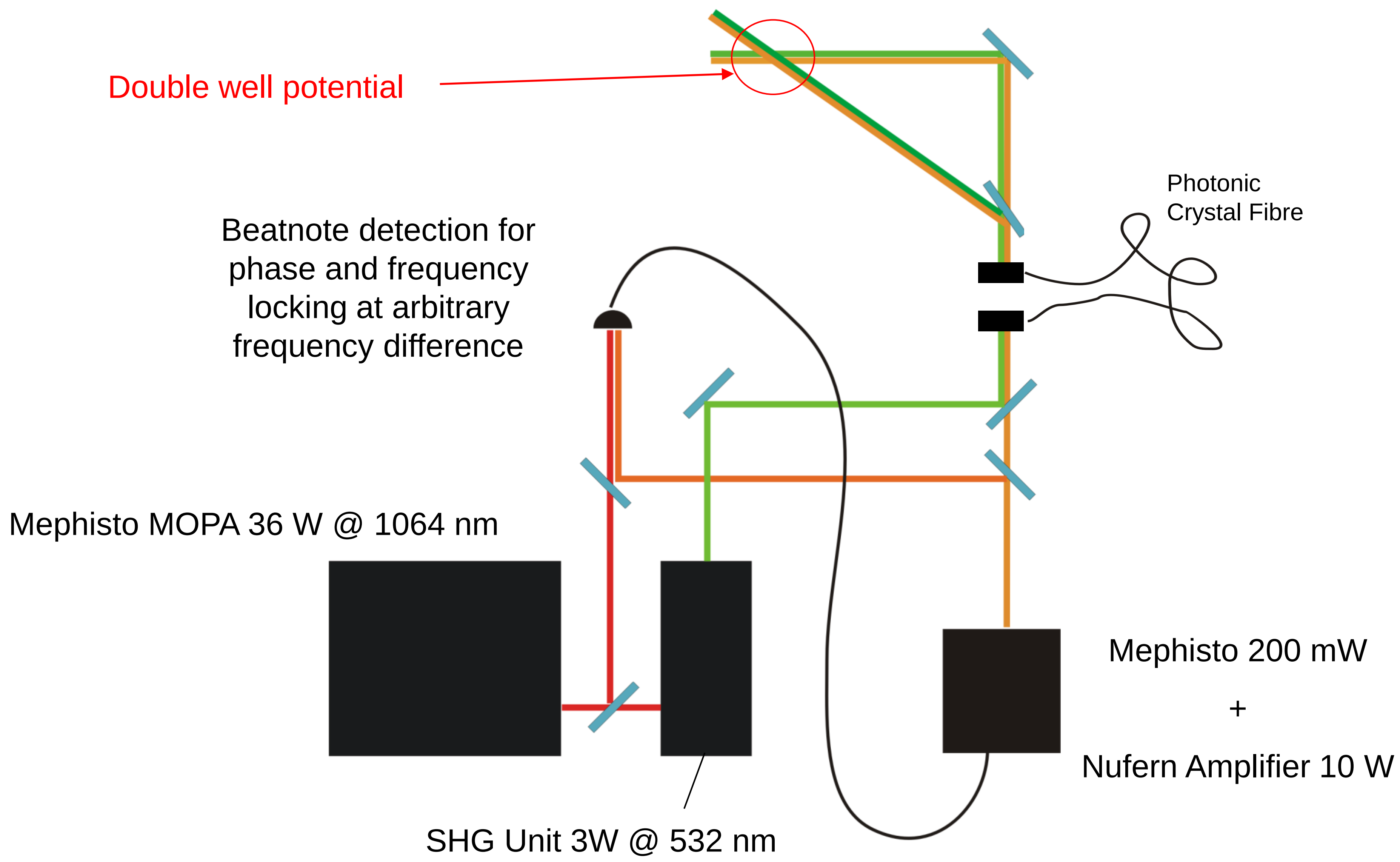
• BECs with 10^5 atoms in 20 sec



Experimental sequence



Double well potential laser system



Possible sinergies

TU-WIEN

- Fast creation of squeezing and operation of the interferometer with non null scattering length
- Single atom resolution

UHEI

- Creation of squeezed states
- Single atom reslution
- Large spacing optical lattices

CNRS

- Effect of losses on the entanglement formation
- Finite temperature effect

ULM

- Optimal control theory applied to our double well trap

People

PhD Manuele Landini

Post Doc Sanjukta Roy Chaudhuri

Dipl. Stud. Giacomo Spagnolli

Marco Fattori

Giovanni Modugno

Massimo Inguscio