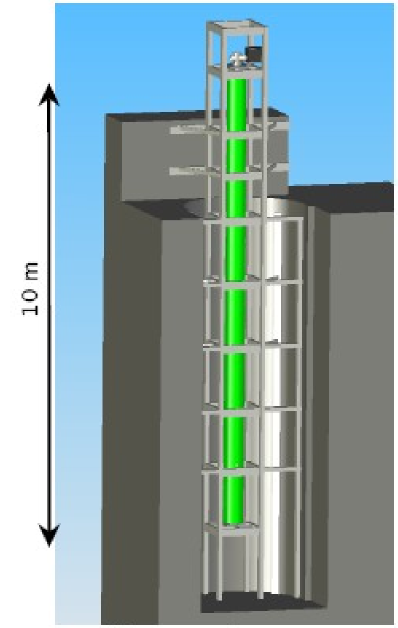
Towards compact transportable atom-interferometric inertial sensors

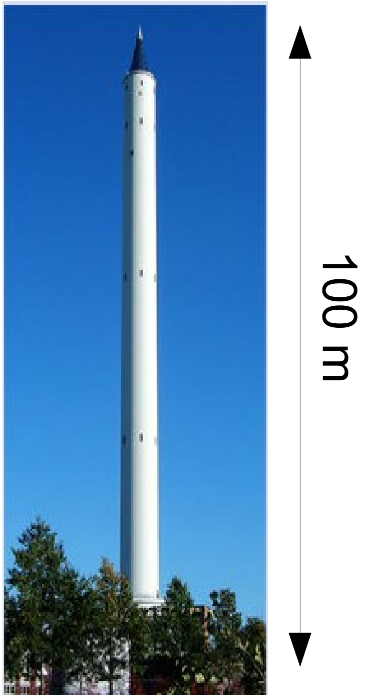
G. Stern (SYRTE/LCFIO)

Increasing the interrogation time



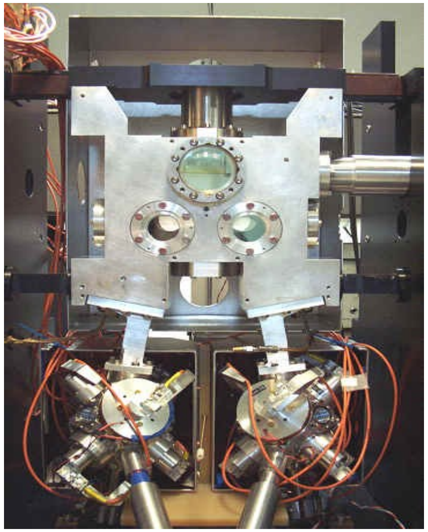
10 m atom drop tower.

- T is often the limiting parameter for the sensitivity.
- Different solutions:
  - Atomic fountain (T≈800 ms).
  - 10 meter high interferometer (Stanford): T≈1.4 s.
  - Parabolic flights (cf ICE): T≈ 20 s, 10^{-2} g.
  - 100 m drop tower in Bremen (cf QUANTUS): T≈ 5 s, 10^{-6} g.
  - Satellite (PHARAO): 10^{-6} g.



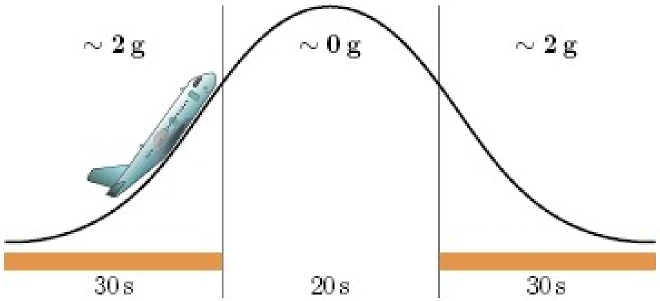
→ **Need for a compact and transportable interferometer**

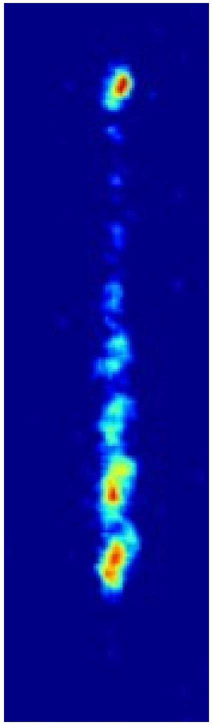
Outline



1. Inertial sensors with cold atoms @ SYRTE

2. Atomic interferometry in microgravity: the ICE project





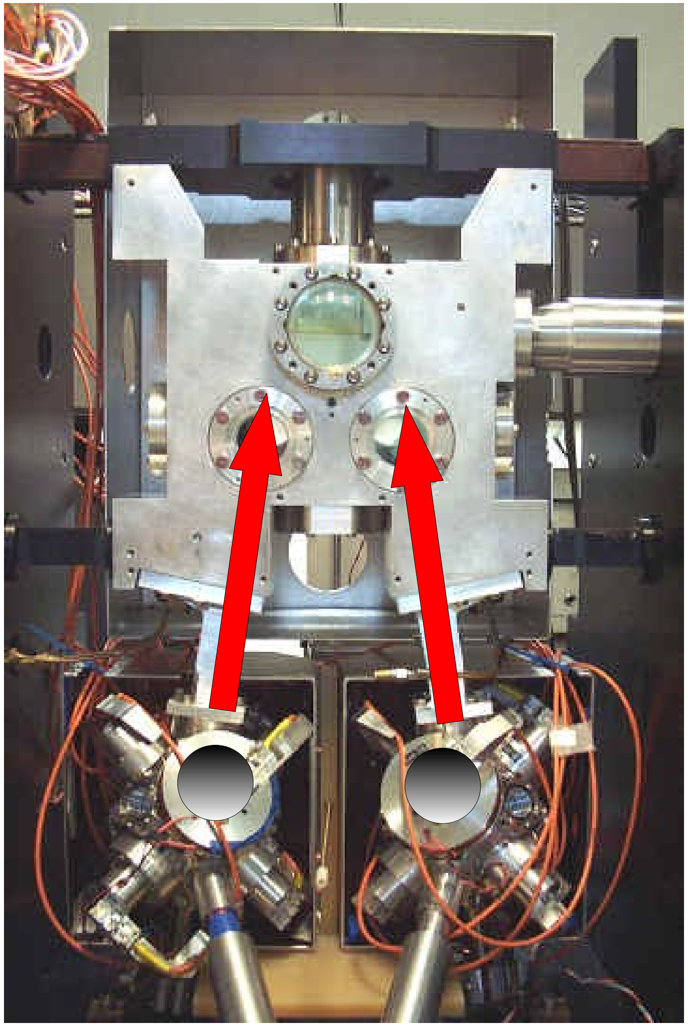
3. A matter-wave cavity for gravimetry

Inertial Sensors with cold atoms @ SYRTE: gravimeter and gyroscope

A. Landragin, F. Pereira Dos Santos, S. Merlet, T. Mehlstaubler, W. Chaibi,
N. Malossi, A. Gauguet, T. Lévêque, Q. Bodart, J. Le Gouët, C. Bordé

l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

Cold atoms gyroscope



MOT A **MOT B**

PARAMETERS

2 MOT of Cs

T_{atoms}~1 μK

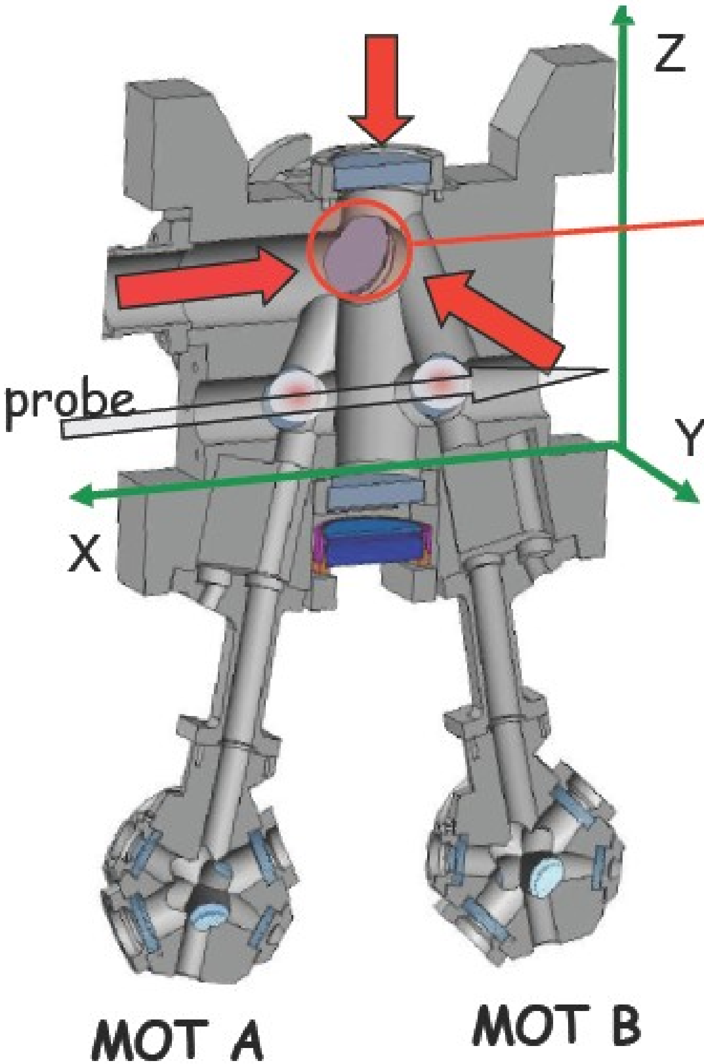
Launch velocity 2,4 m/s

Angle 8° ⇨ V_l=0,33 $m.s^{-1}$

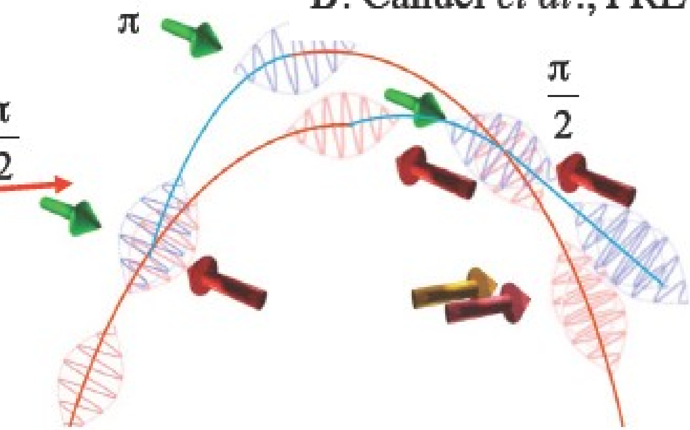
T_c = 0,58 s

Access to the six components of inertia

Retroreflected Raman beams



B. Canuel *et al.*, PRL **97**, 010402 (2006)

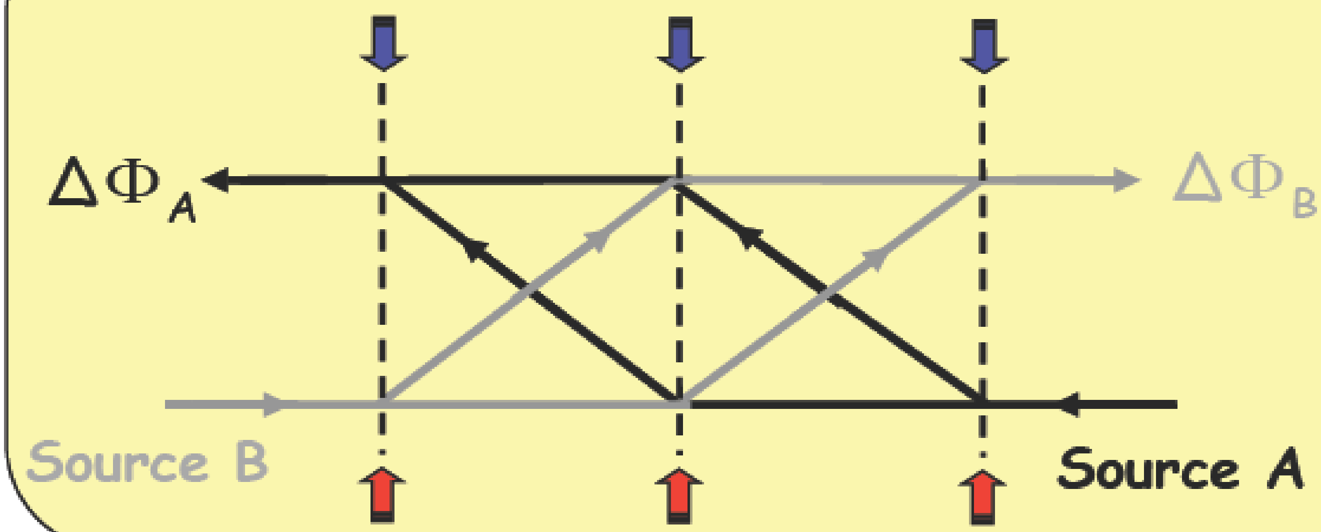


$$\Delta\Phi = \Delta\Phi_{acceleration} + \Delta\Phi_{rotation}$$

$$\vec{k}_{eff}.\vec{a}T^2 \qquad -2\vec{k}_{eff}.\vec{\Omega}\wedge\vec{V}\,T^2$$

(Sagnac effect)

Two atomic sources of opposite directions



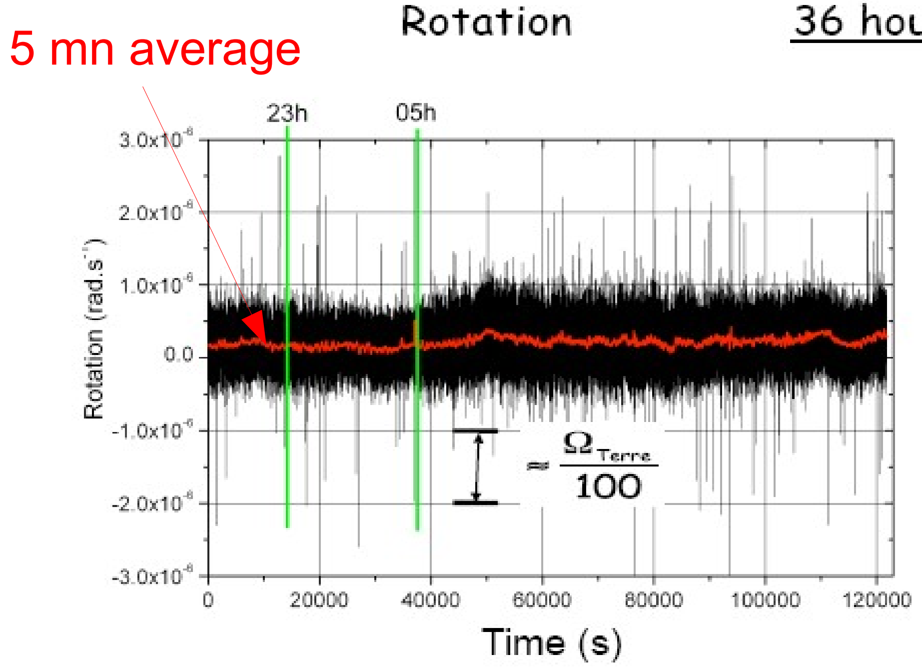
Sum: acceleration

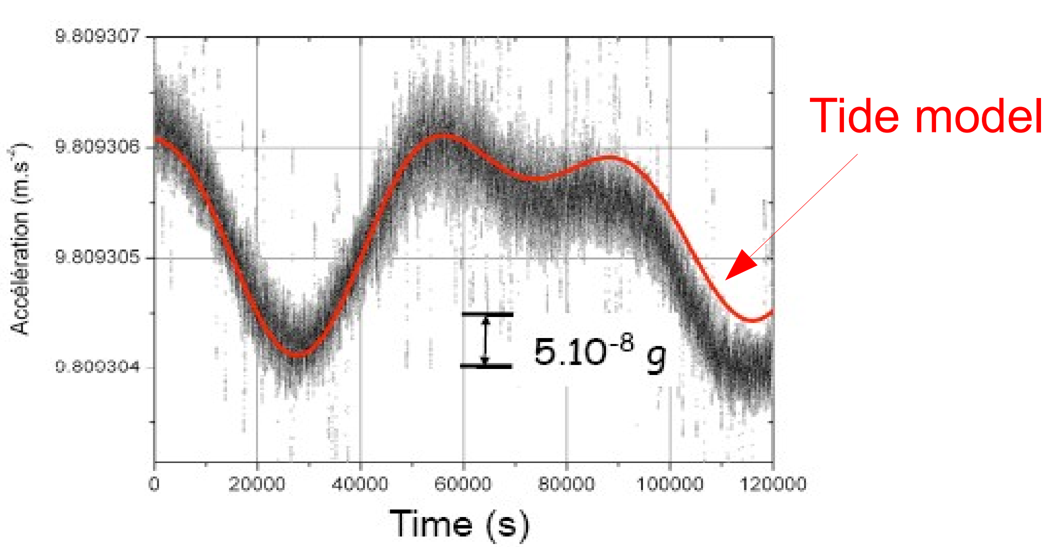
$$\Delta\Phi_{acc} = \frac{\Delta\Phi_A + \Delta\Phi_B}{2}$$

Difference: rotation

$$\Delta\Phi_{rot} = \frac{\Delta\Phi_A - \Delta\Phi_B}{2}$$

Rotation — 36 hours — Acceleration





Gyrometer performances

- Sensitivity to rotation:
  - ✓ short term: quantum projection noise $2.4\ 10^{-7}\ rad.s^{-1}/\sqrt{\tau}$
  - ✓ long term: wave front imperfections and fluctuations of the sources

- gyroscope accuracy:
  - ✓ bias : => wave front errors

Performances similar to the best FOG and to beam gyroscope (D. Durfee et al. PRL 97, 240801 (2006))

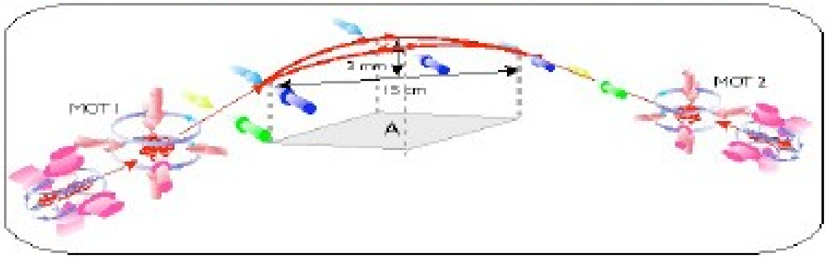
Prospects

Change of geometry => increase of the area

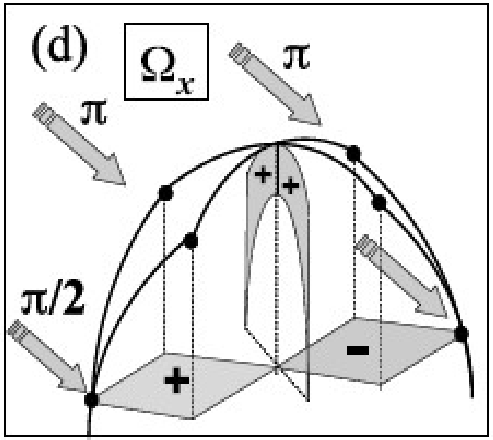
This first experiment: 4 mm^2

Split the Raman laser

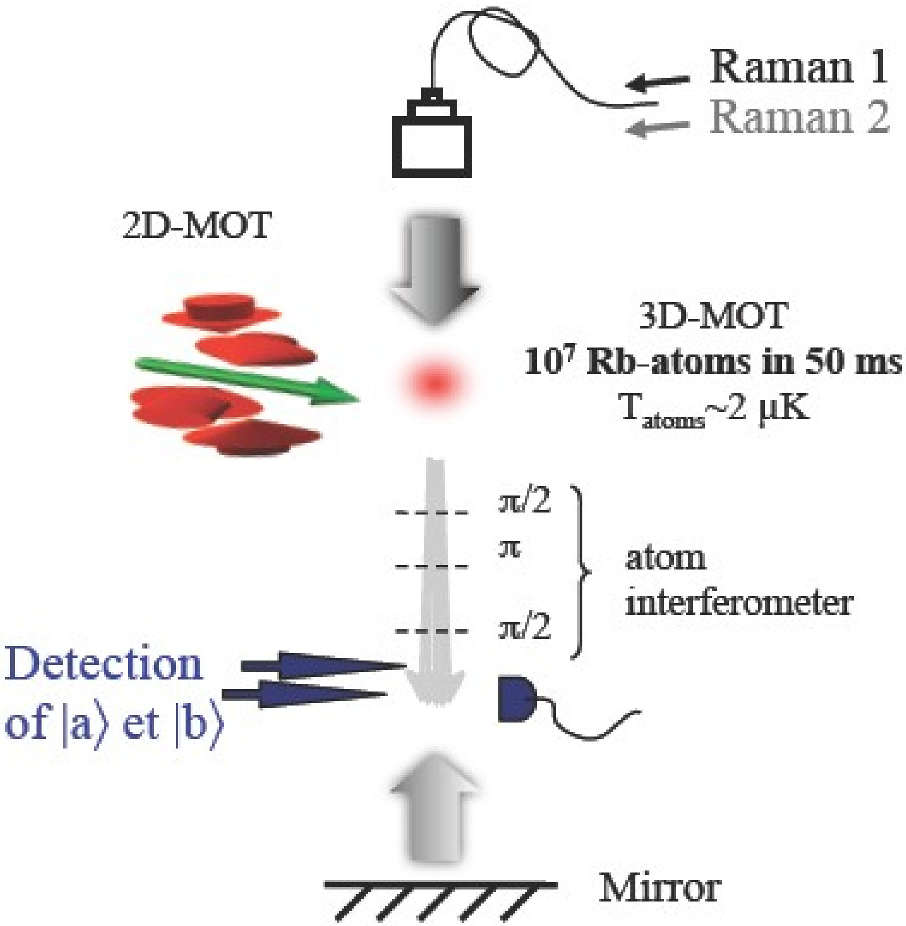
3 pulses straight trajectories (E. Rasel University of Hannover) (34 mm^2)



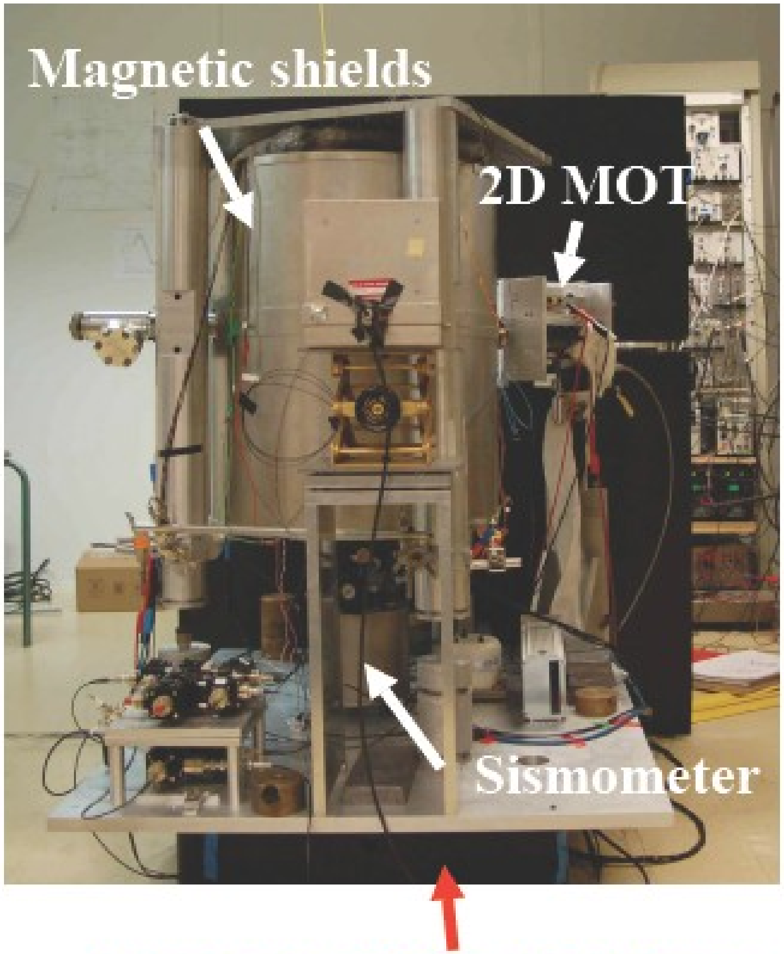
4 pulses sequences (future experiment) (up to 11 cm^2)



Cold atoms gravimeter

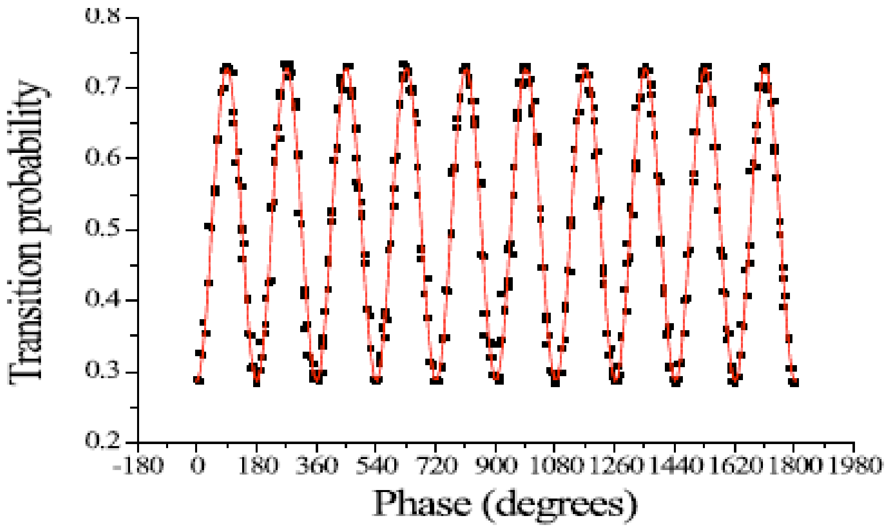


Measurement of the acceleration of the atoms compared to the referenced mirror



Passive isolation Plateform

Compact gravimeter results



Parameters

$2T = 100$ ms

$\tau = 6\ \mu s$

$\sigma_v \sim v_r$

$N_{det} = 10^6$

$T_c = 250$ ms

Contrast ~ 45 %

Typical sensitivity

$\sigma_g = 2\ 10^{-8}$ g at 1s => Resolution ~ 10^{-9}g after 500-1000 s

Best sensitivity (night, air cond OFF) => $\sigma_g = 1.4\ 10^{-8}$ g at 1s

Sources of noise

- mirror vibrations
- laser phase noise (2 extended cavity diode lasers phase locked on micro-wave reference: 3.5 mrad /shot => 4.10^{-9} g/s, can be reduce to 1 mrad/shot)

J. Le Gouët *et al*., Appl. Phys. B 92, 133–144 (2008)

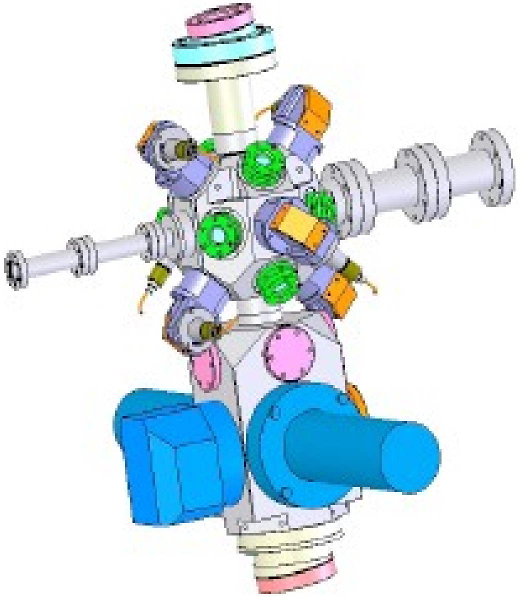
GRAVIMETER

- **Short term stability** $2\ 10^{-8}\ g/Hz^{1/2}$ (under noisy environment): better than the standard technology (same environment)

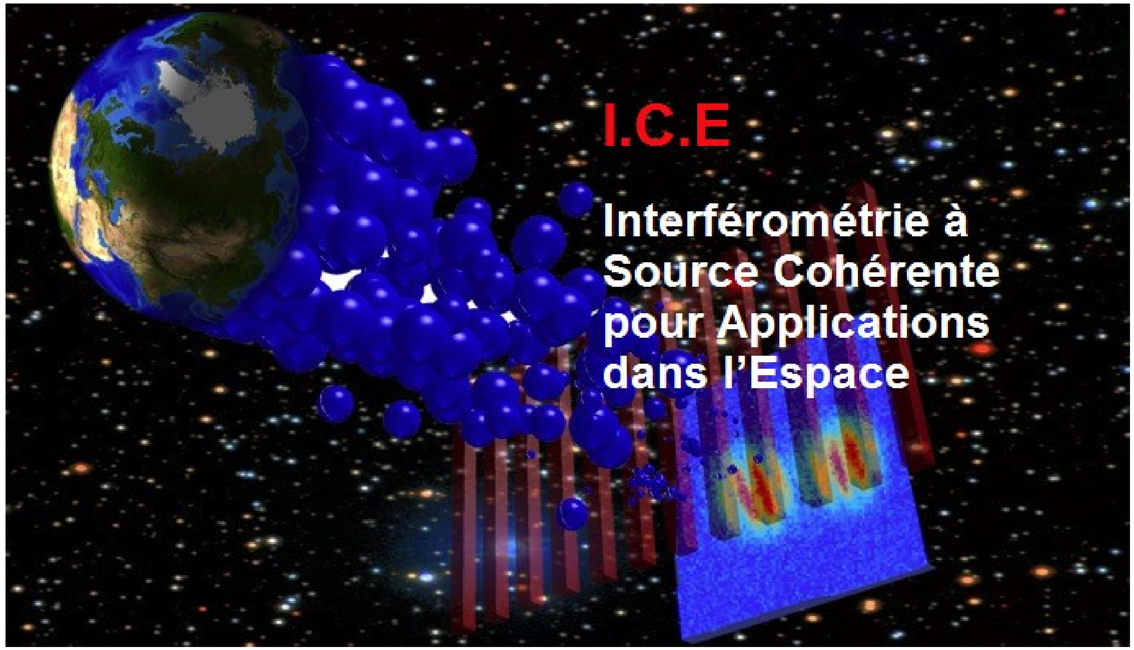
- **Systematic shifts**: many controlled at the 10^{-9} g level (magnetic and light shift...), Coriolis & aberrations remain a challenge
 (state of the art: 2-3 10^{-9}g)

  - **New vacuum chamber**
    More access, better optics

  - **Ultra-cold atoms**
    Dipole trapping
    Better control of transverse velocities



Atomic interferometry in microgravity: the ICE project



G. Stern[1,2], R. Geiger[1], B. Battelier[1], G. Varoquaux[1], T. Bourdel[1],
N. Zahzam[3], W. Chaïbi[2], J-F. Clément[1], O. Carraz[3], J-P. Brantut[1],
R. A. Nyman[1], F. Pereira[2], Y. Bidel[3], A. Bresson[3], A. Landragin[2], and P. Bouyer[1]

(1) INSTITUT d'OPTIQUE GRADUATE SCHOOL

(2) l'Observatoire de Paris – SYRTE – Systèmes de Référence Temps-Espace

(3) ONERA

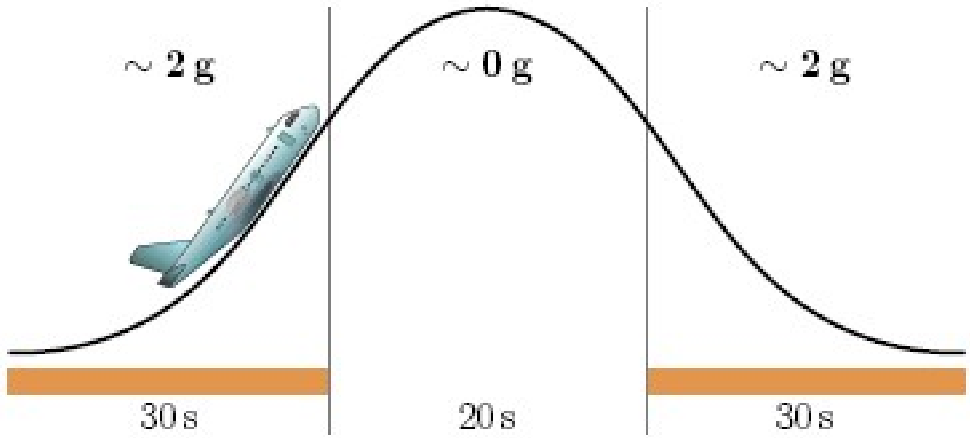
A microgravity environment

• The idea: reduced gravity for longer interrogation time

• Goal: making a differential accelerometer to test the UFF.

• Technologie developement (compactedness, design of new laser sources,...)

Ballistic flights for microgravity



Pull-up phase | **Micro-g phase** | **Pull-down phase**

• In the Novespace A300 ZERO-G Airbus (Bordeaux airport)

• 31 parabolas per day for 3 days

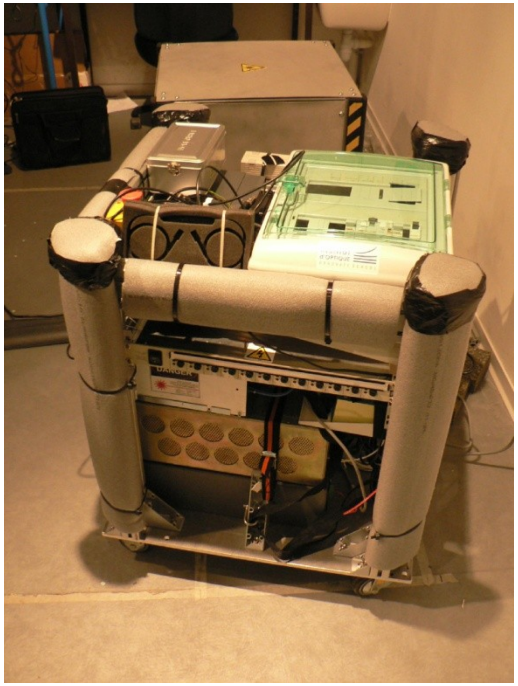
→ ≈ 30 minutes of micro-g (10^{-2} g)

• But noisy environment.

Need for a compact, transportable and robust apparatus

Setup

- ONERA: laser sources (MOT+ Raman)
- SYRTE: ultra-stable microwave reference source + control software
- IOGS: optical chamber, optics and control software

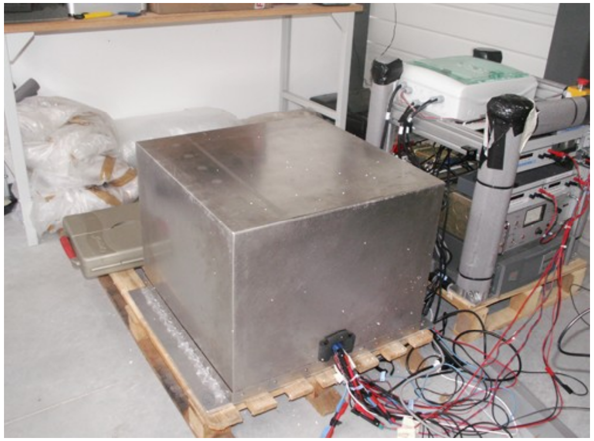


Electrical pannel
+
High laser power

A full cold atom experiment in 3 parts

(650 Kg, 1500 W)

μ-wave reference, laser sources, computer, etc...



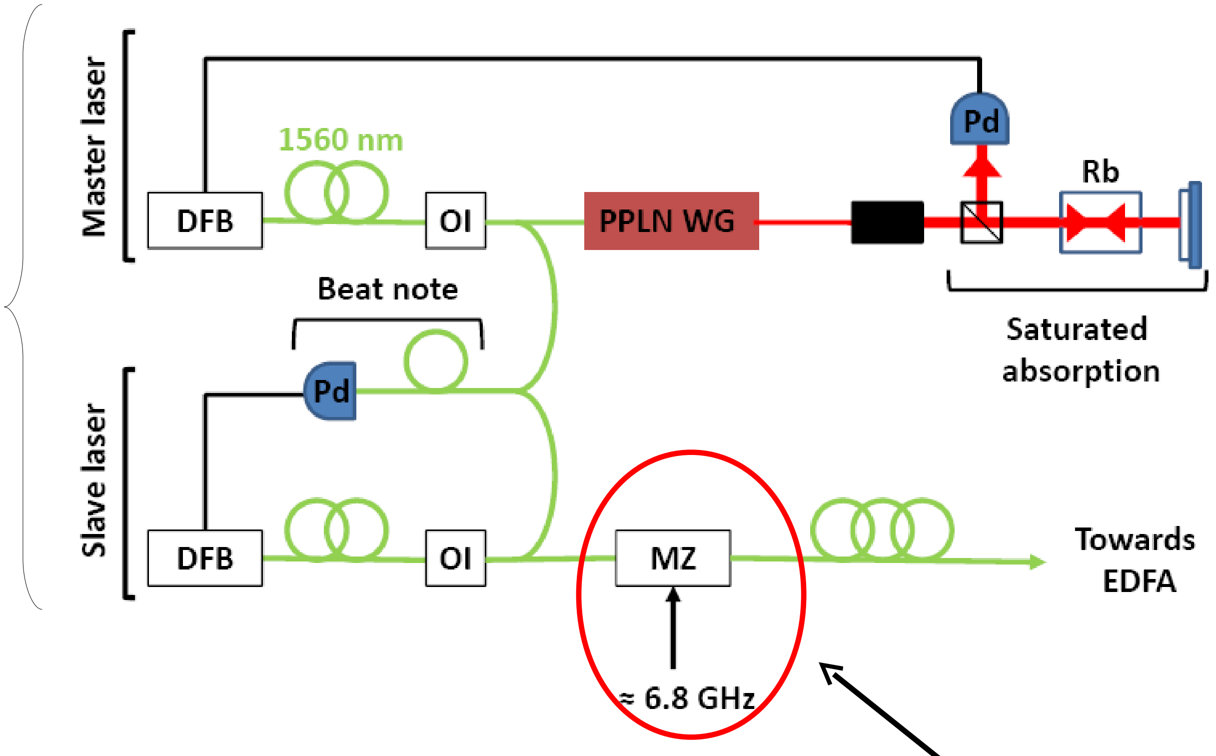
Science cell

(in its magnetic shield)

Laser sources for ^{87}Rb

Based on telecom technologies→ reliable, robust and compact system with fiber components.

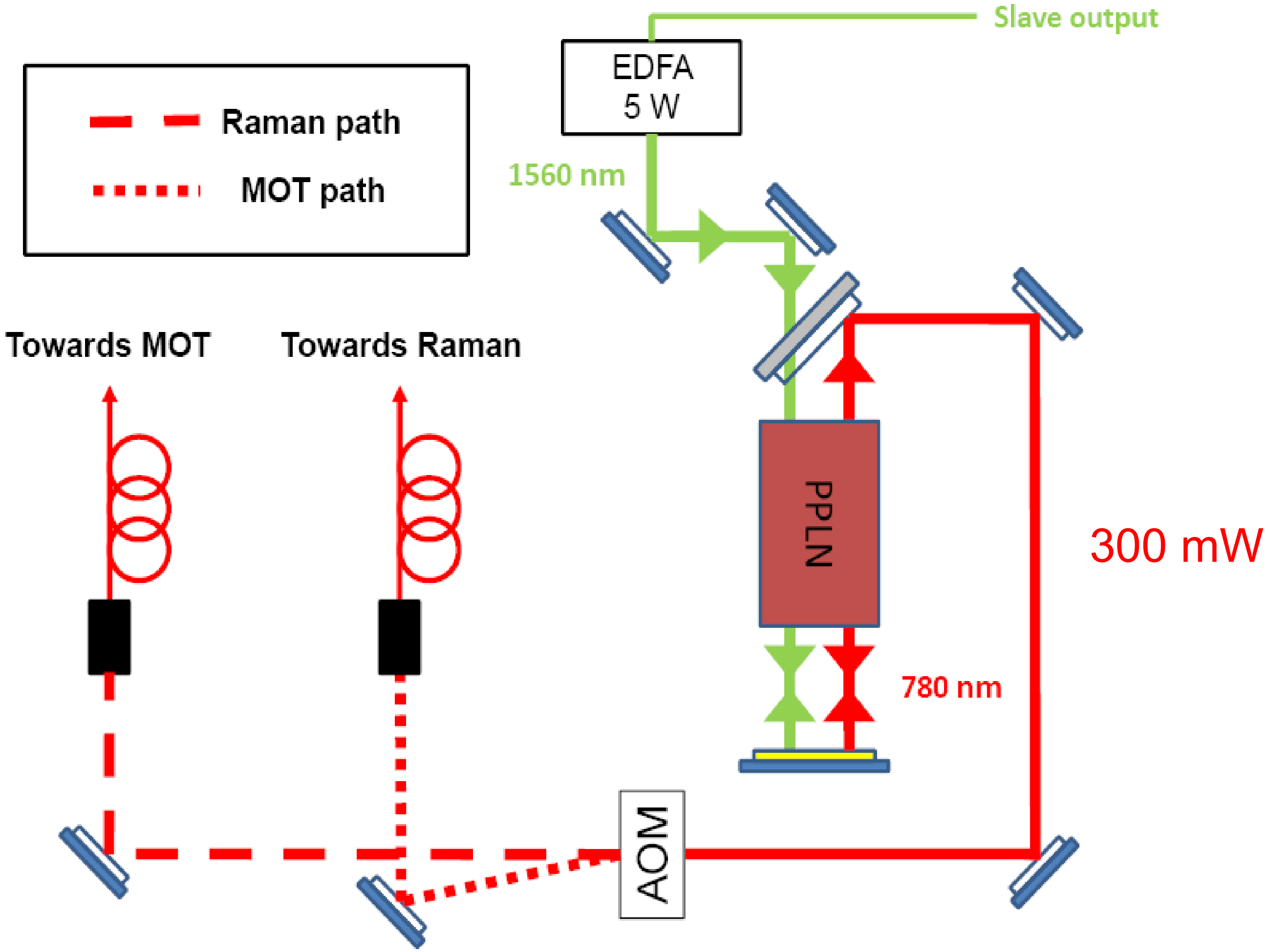
Frequency generation part



Sideband generation (MOT/Raman)

- Frequency-agile: switch from MOT to Raman detuning in 3-4 ms with the beat-note lock.
- Modulation frequency control for MOT or Raman

Free-space doubling part



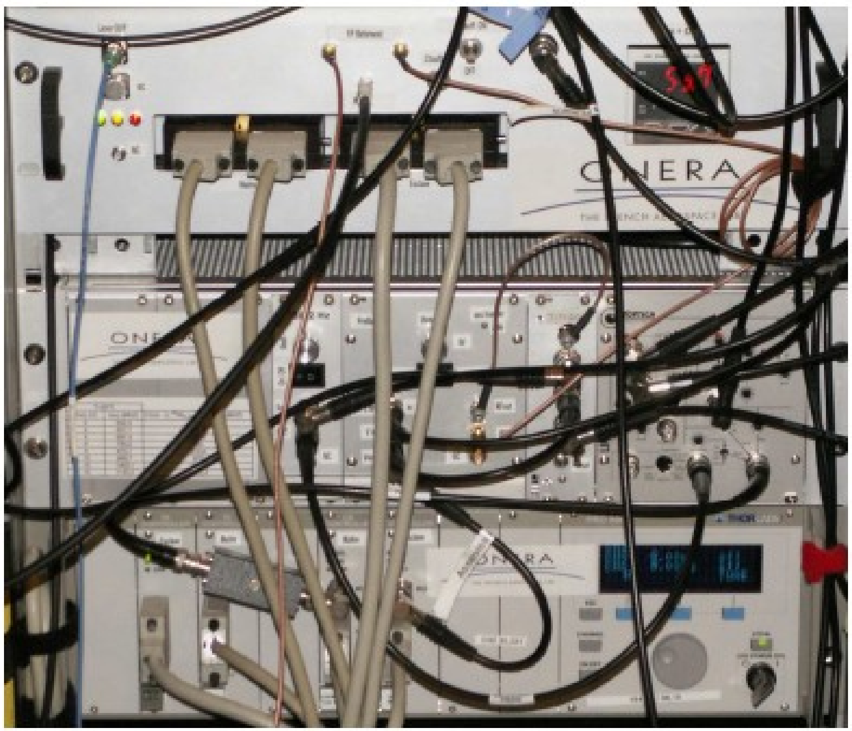
- ≈ 100 mW at each fiber ouptut

- AOM: optical switch for Raman

- MOT or Raman with the same beam → No relative misalignment and stable relative phase

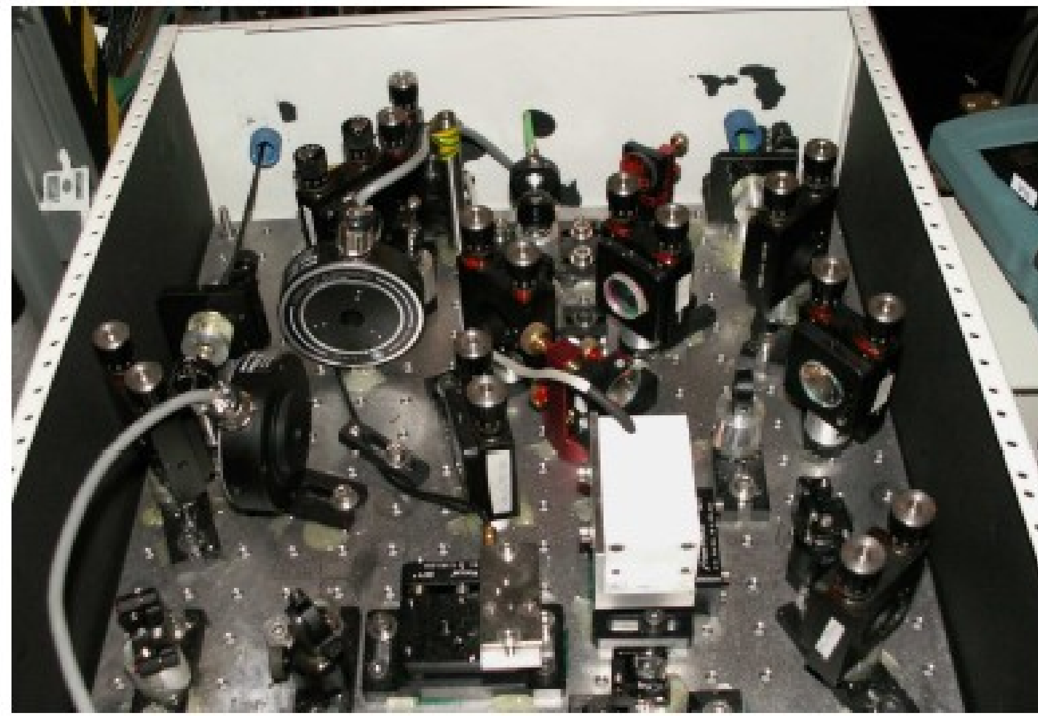
11 U

Generation frequency racks



19 "

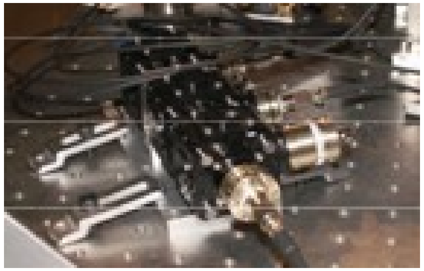
Free space doubling stage



19 "

The science cell

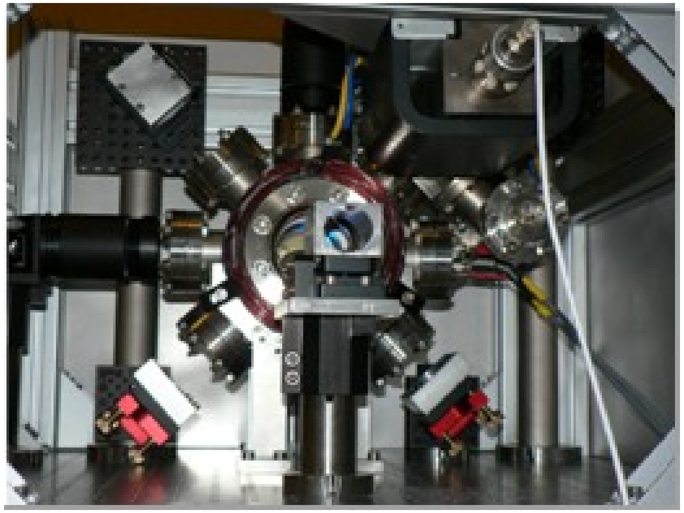
• MOT: 3 retro-reflected beams provided by a 1-3 Schäfter-Kirchoff splitter

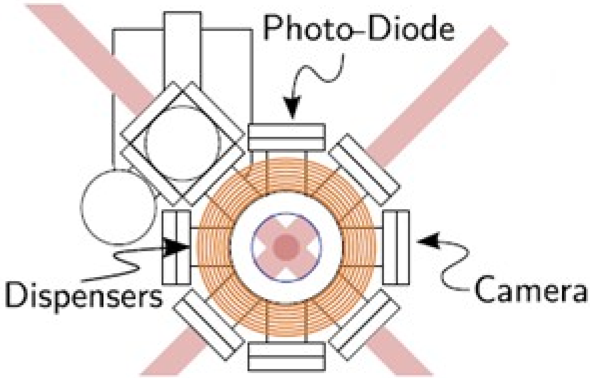


• Raman beams : <u>horizontal</u>

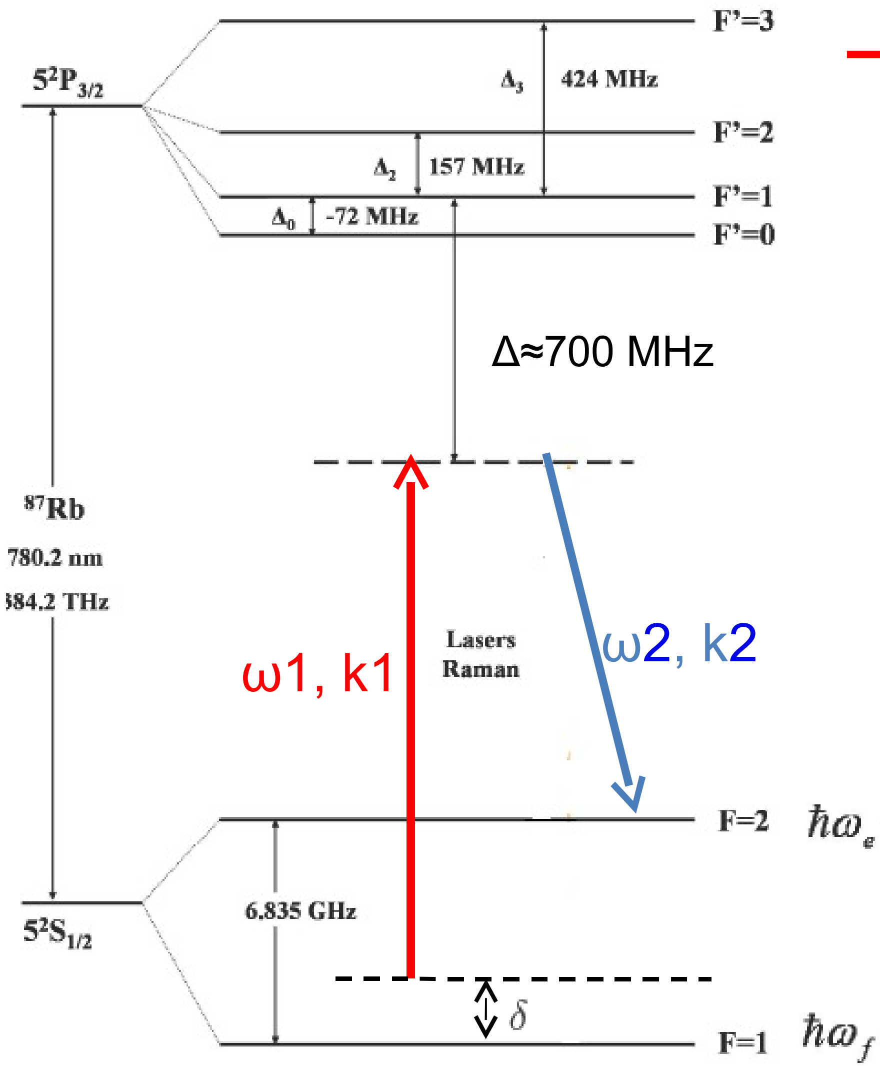
• Atom detection by fluorescence with the MOT beams

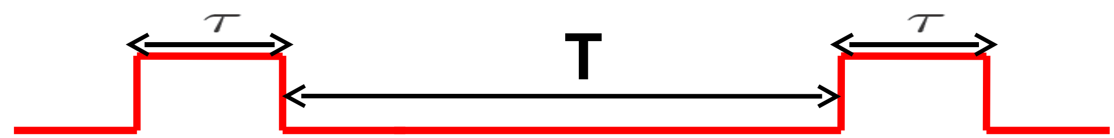
→ reduced T.O.F. (on Earth at least) but <u>compact interferometer</u>



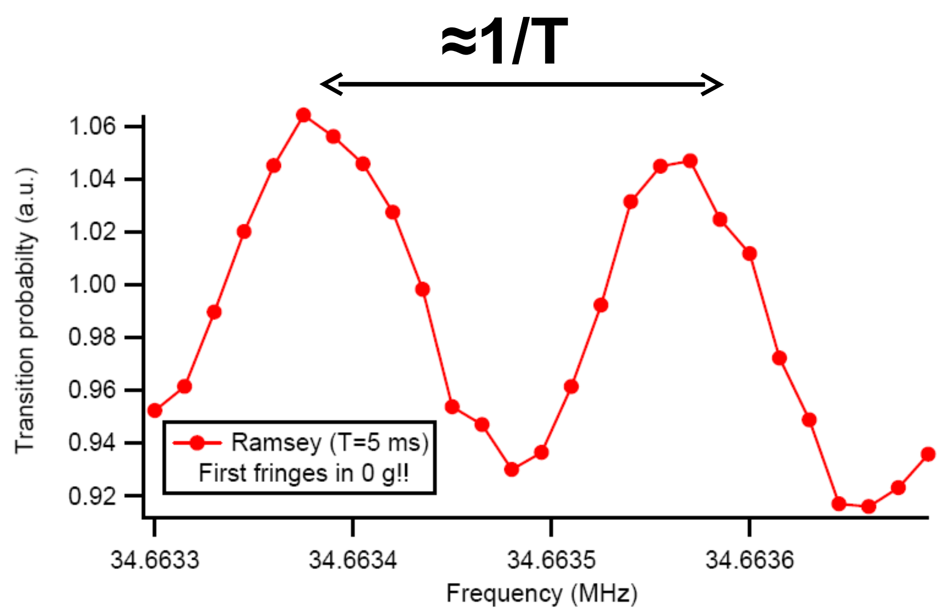


Ramsey fringes with copropagative Raman transitions





with $\Omega_{eff}\,\tau = \pi / 2$

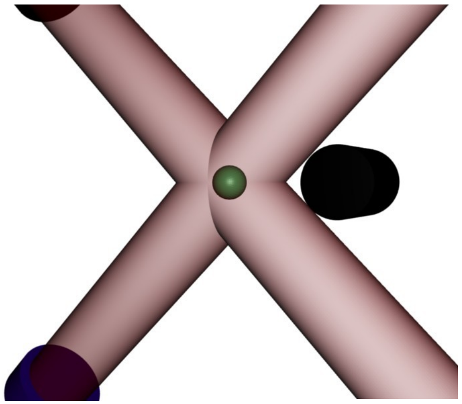


$\Omega_{eff} \approx 2\pi \times 12.5$ kHz

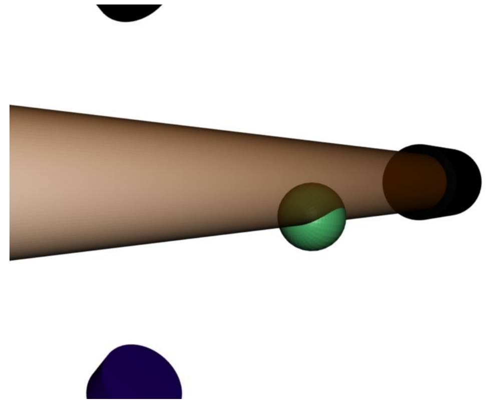
No more than T=25 ms on Earth for us

On Earth vs microgravity (T=40 ms)

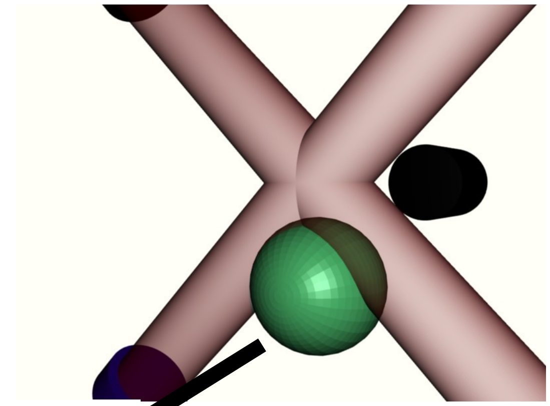
MOT



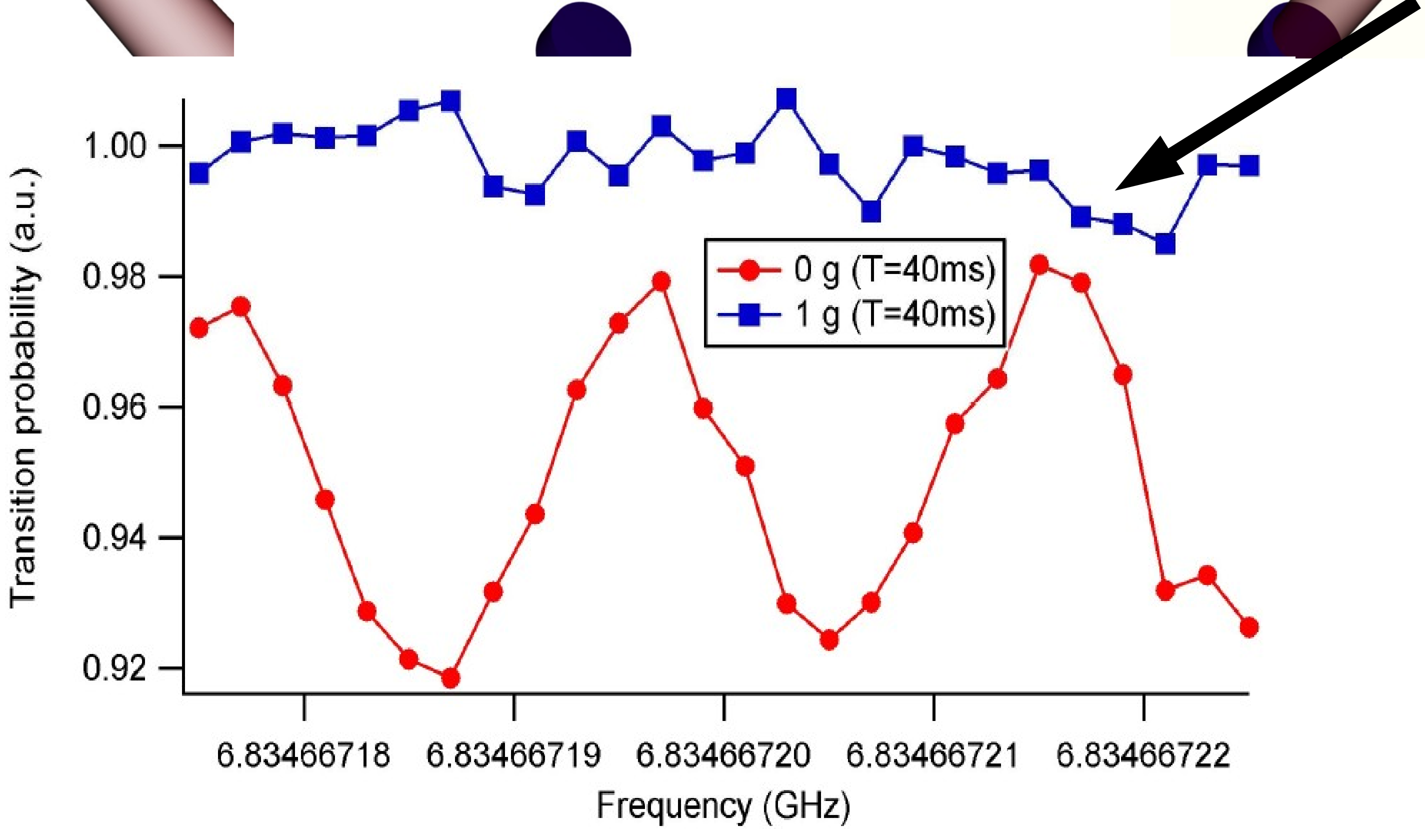
Raman sequence



Detection

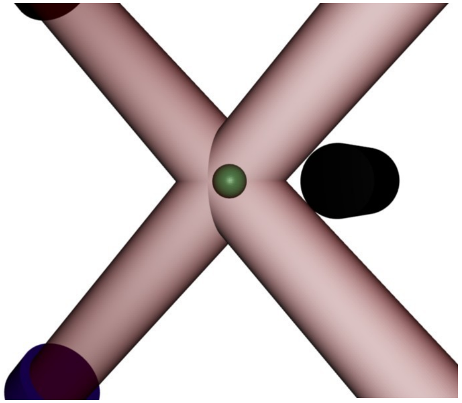


No normalization

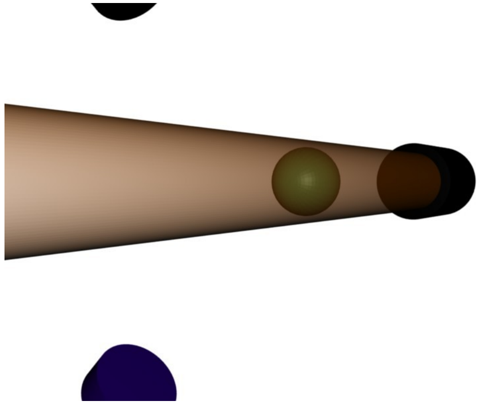


On Earth vs microgravity (T=40 ms)

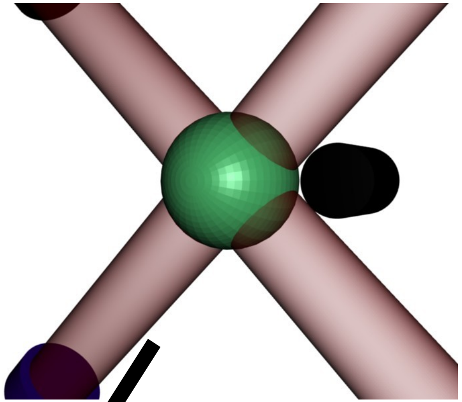
MOT



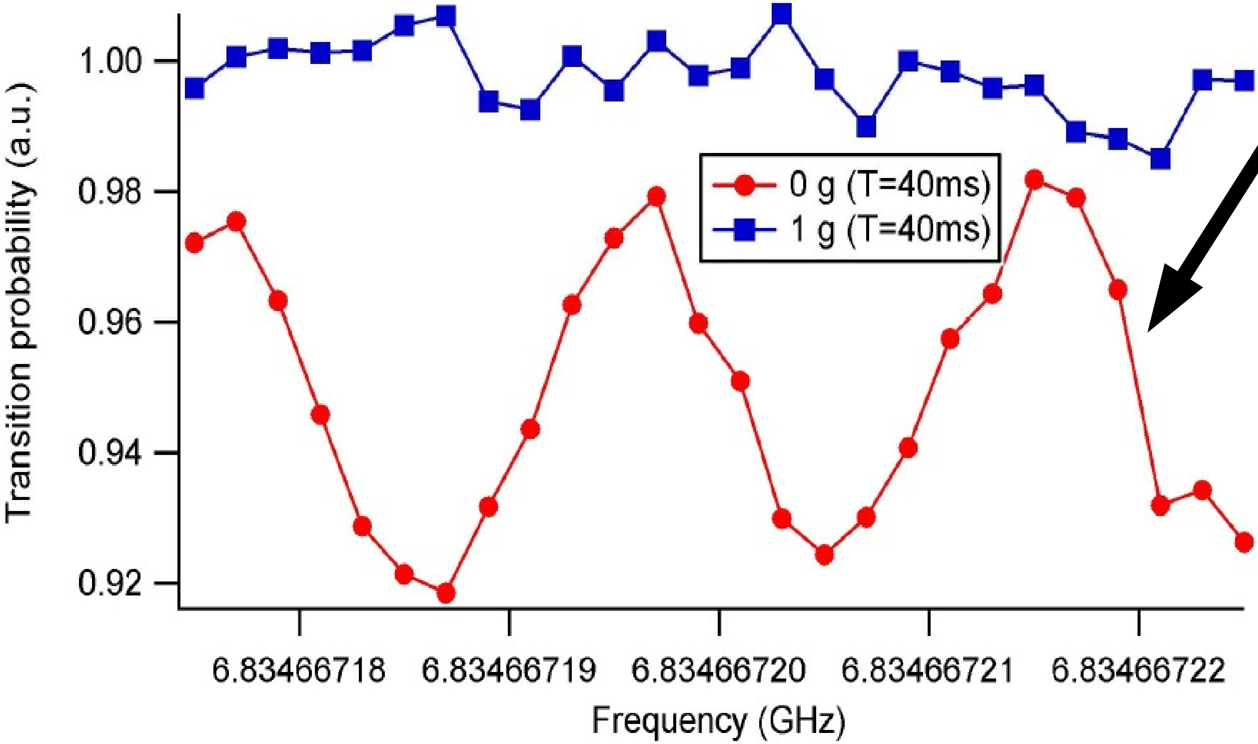
Raman sequence



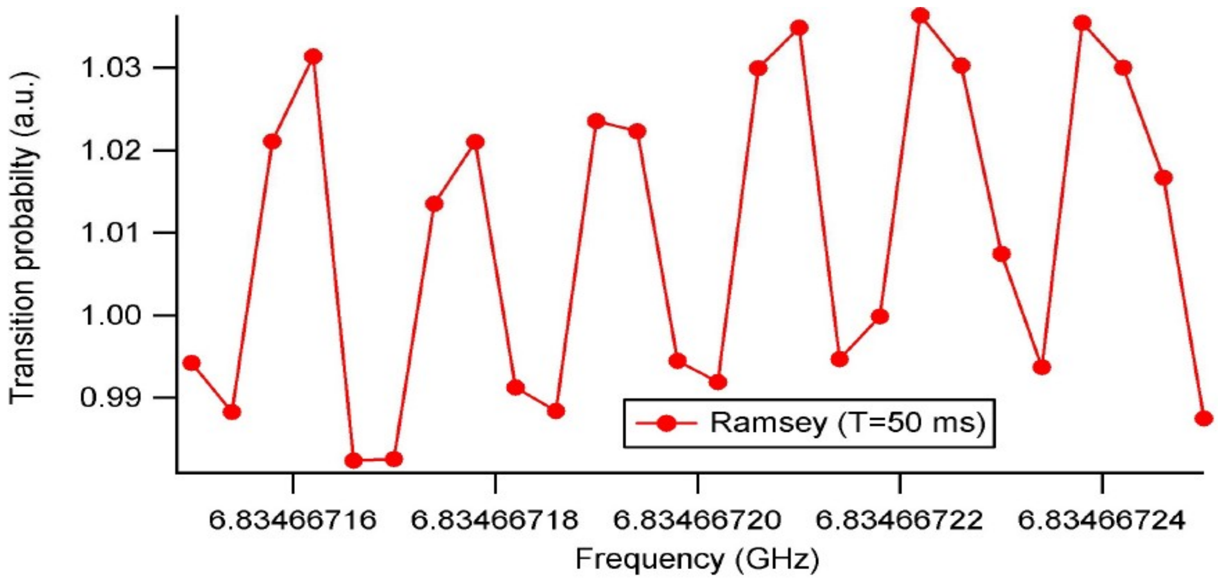
Detection

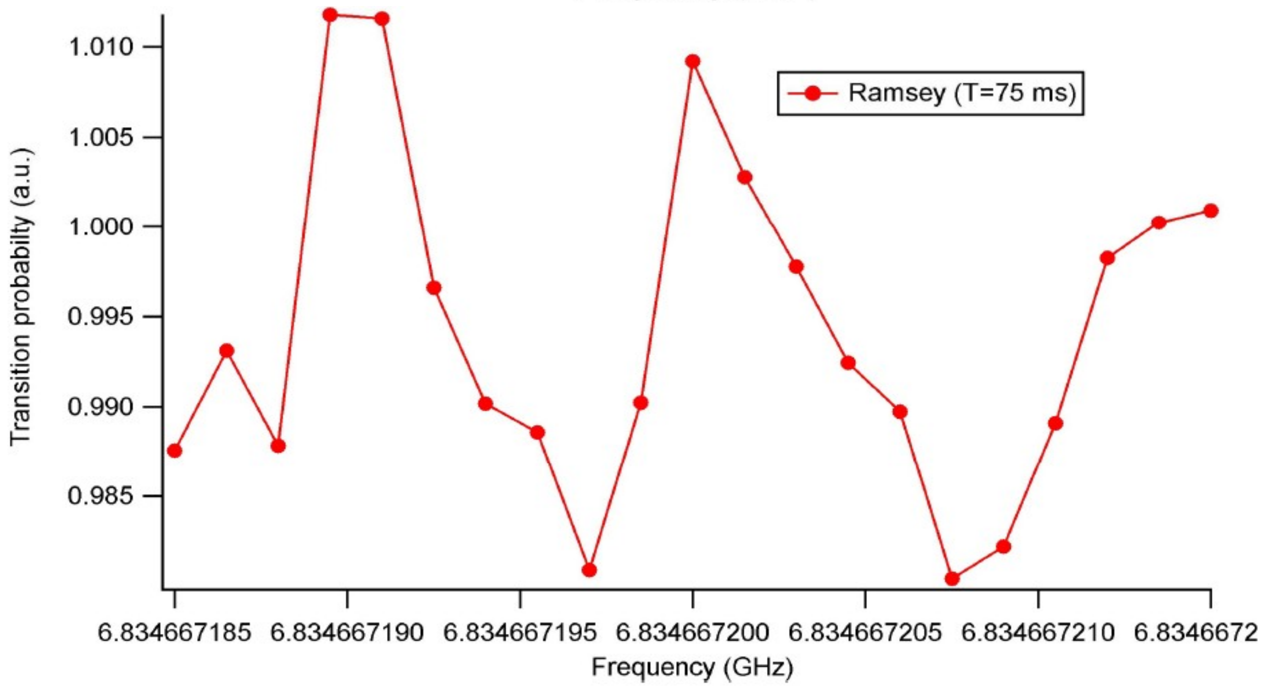


No normalization



Results in microgravity





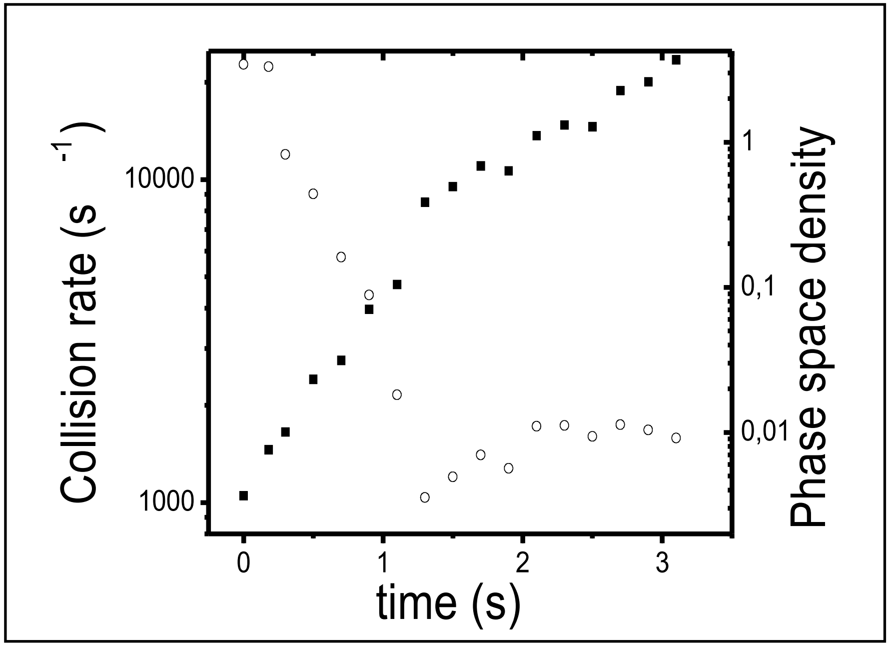
- One point = one shot
- One scan per parabola
- Limited by temperature

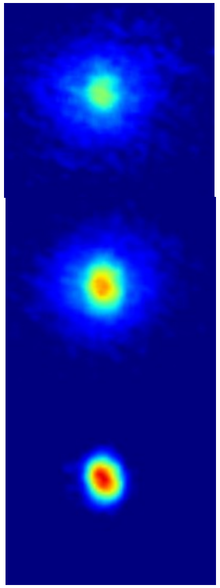
Conclusion/prospects

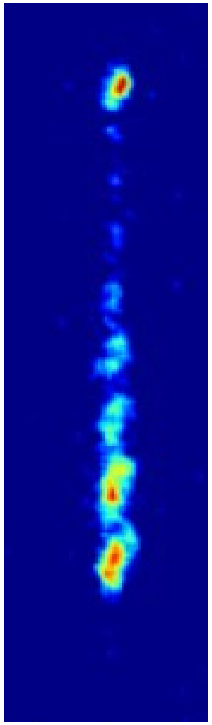
- Our laser sources can work in a µ-g environment.
- Counterpropagating configuration → sensitive to intertial effects.
- BUT problems with the acceleration noise → need for a vibration isolation.

- Double species interferometer fot the UFF test.
- ^{85}Rb or K (D_2 line=767 nm =1534nm /2).

A matter-wave cavity for gravimetry



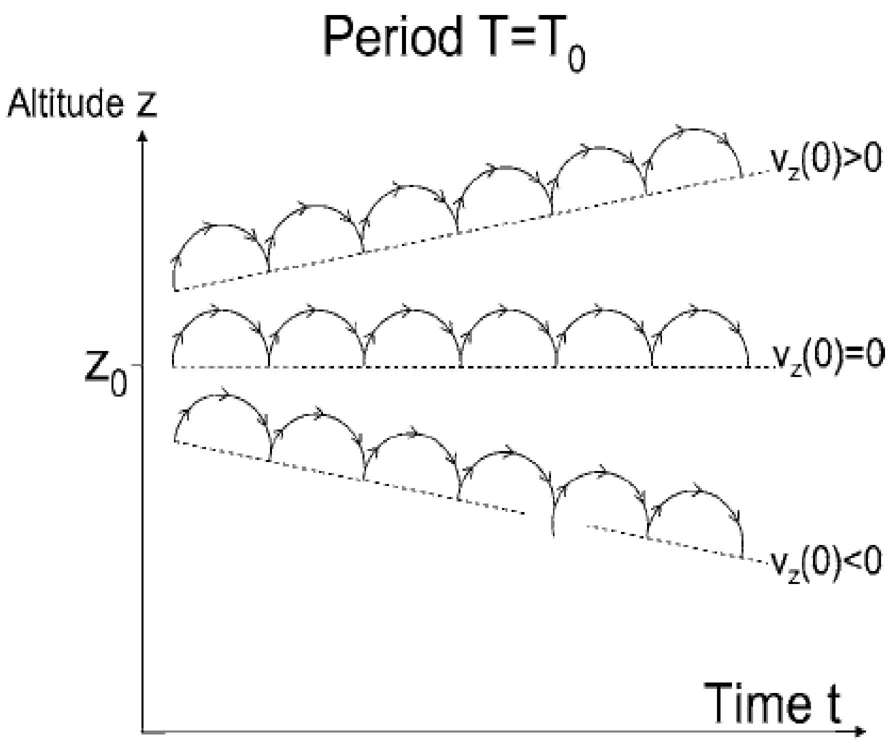




J-P. Brantut, RM. Robert de Saint Vincent, J -F. Clément,
G. Varoquaux, R. A. Nyman, T. Bourdel, P. Bouyer and A. Aspect

A matter-wave cavity for gravimetry

- Goal: demonstrating a new type of gravimeter permitting long interrogation time in a compact apparatus (F. Impens, *et al.*, Appl. Phys. B 84, 603)



$$\text{Period } T_0 = \frac{2\hbar k}{mg}$$

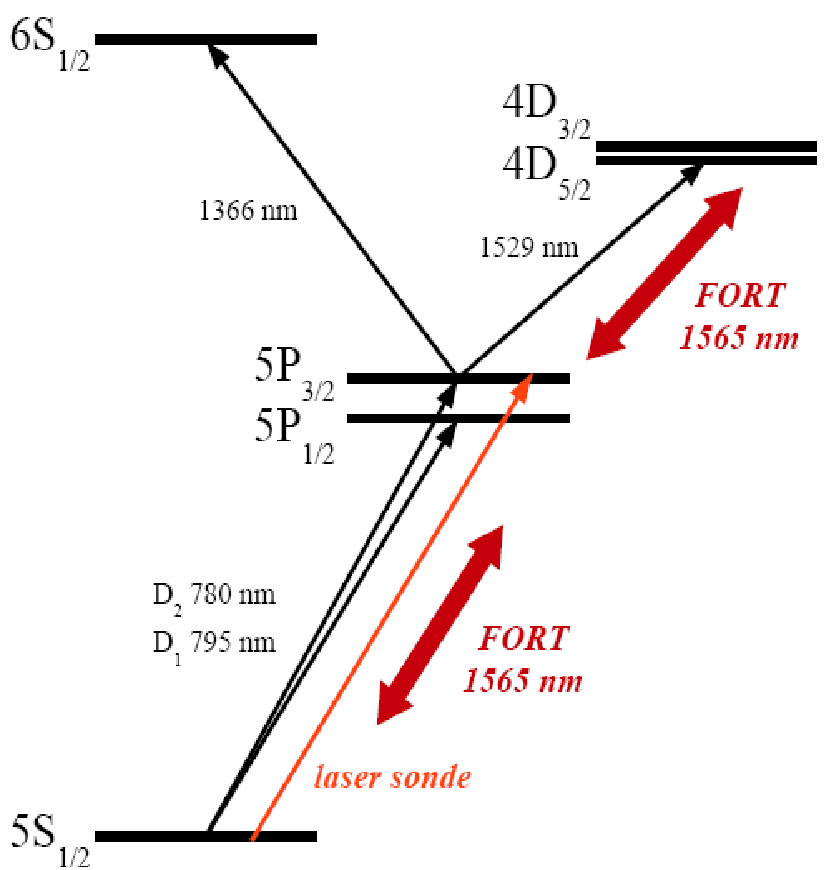
- Method: use periodic Bragg or Raman pulses to make the atoms bounce several times.

Wrong period
↓
Residual acceleration of the cloud
↓
Loss of atoms

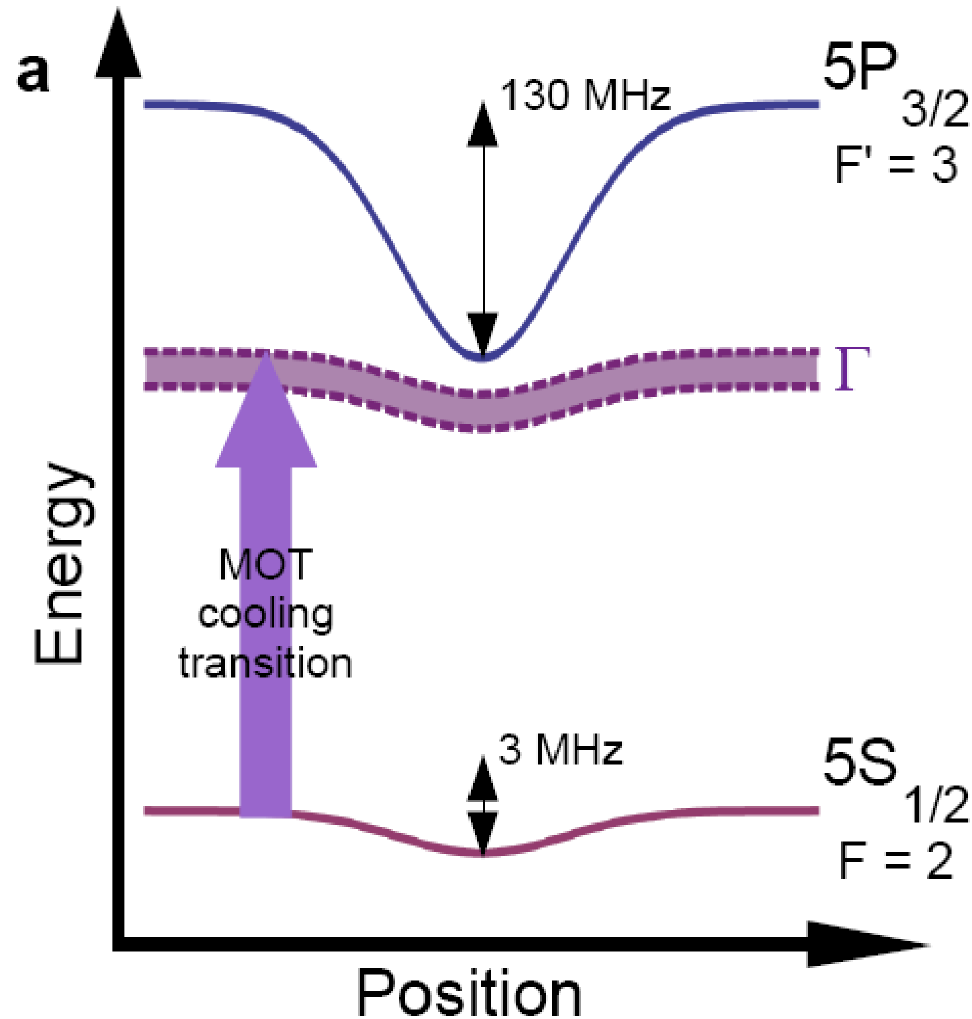
- Atoms don't fall ⟶ compactedness
- Sensitivity scales as $T^{3/2}$
- Recent estimation of g by Sackett with this kind of interferometer (K.J. Hughes *et al*, arXiv 09020109)

An all - optical BEC @ 1565 nm as an ultracold atom source

- Ultracold source→ narrow velocity distribution
- Strong light shifts for $5P_{3/2}$ hyperfine levels → possibility to cool and trap at he same time

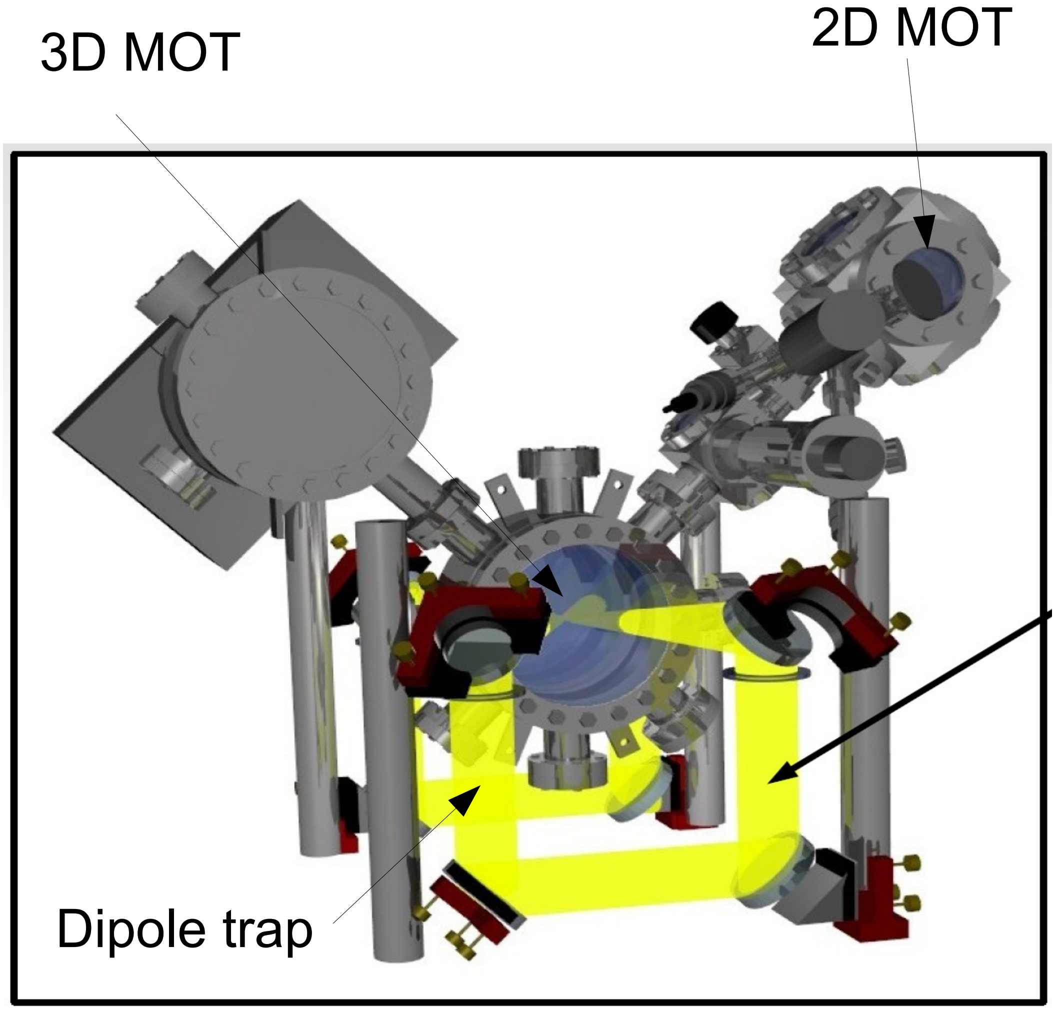


First energy levels of ^{87}Rb

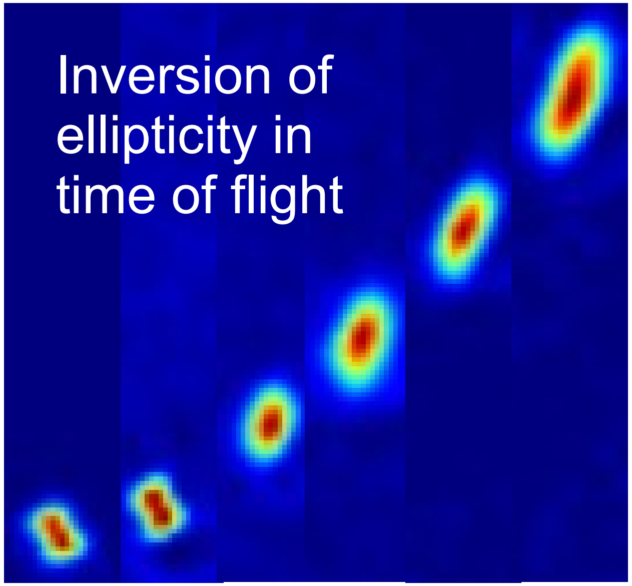


- First all-optical BEC at this wavelength.
- Laser souce: 50 W Erbium doped fiber laser

$3x10^5$ atoms at Tc
10^5 atoms in a pure BEC



Fastest evaporation to BEC: 650 ms

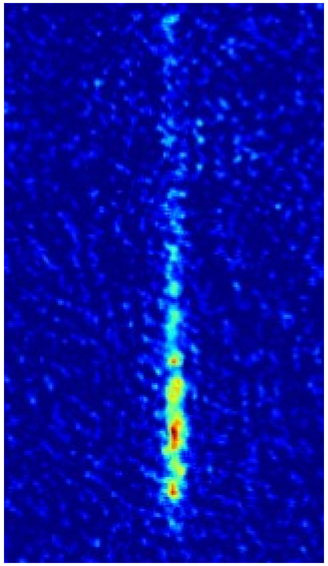


- 2-photons Bragg transitions in a *pulsed* 1D *static* lattice, 6.8 GHz detuned on the F = 2 -> F' = 3 transition (atoms in the F = 1 hyperfine state)

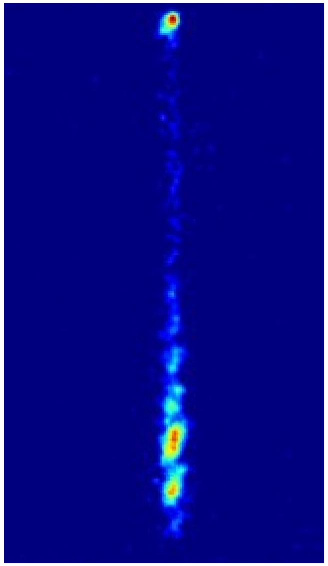
  ~ 6% of atoms diffusing one photon in 20 bounces

- Up to 20-30 bounces (~30 ms)

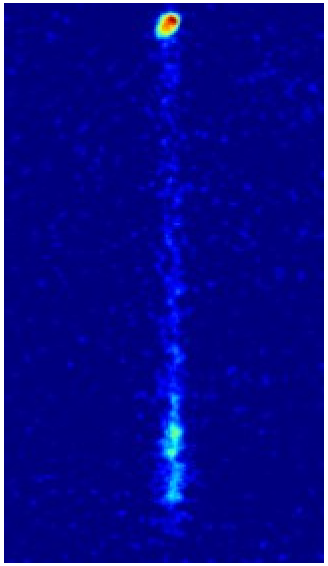
- Limited by the efficiency of a single (square) pulse (93%)



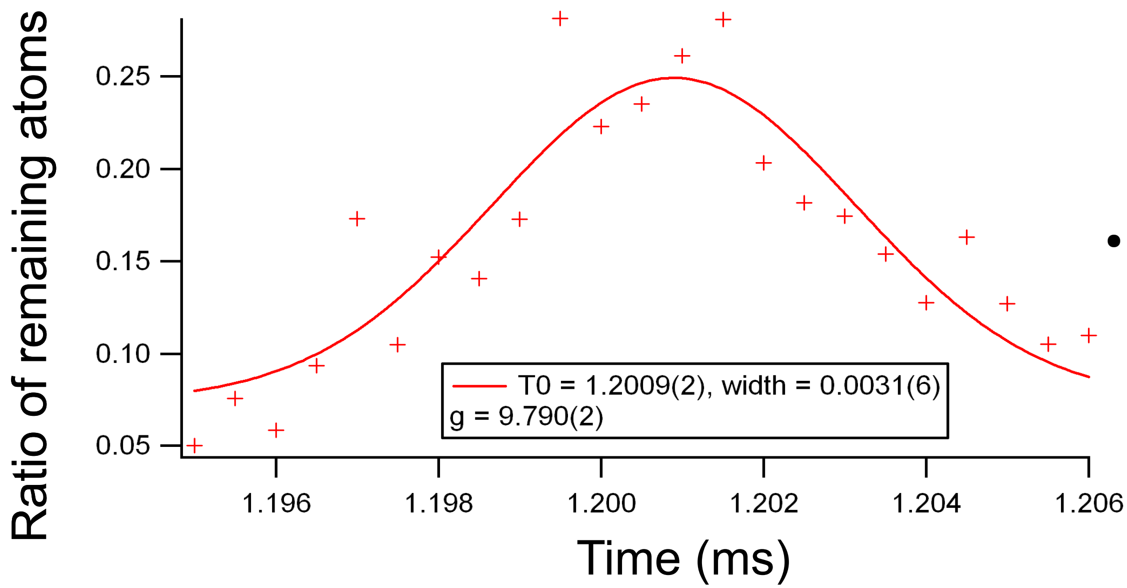
0.997 T0



0.999 T0



T0



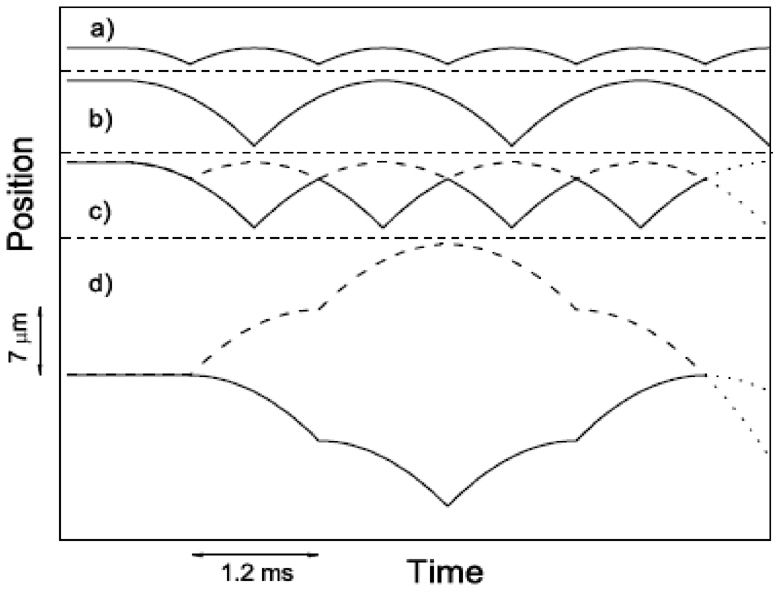
• We currently investigate for systematic bias (tilt, residual magnetic fields,...)

Conclusion

• A compact interferometer with an simple setup, as with Bloch oscillations (G. Ferrari *et al.*, PRL 97, 060402).

• Limited by pulse efficiency.

• Original interferometer configuration possible.



Thanks for your attention