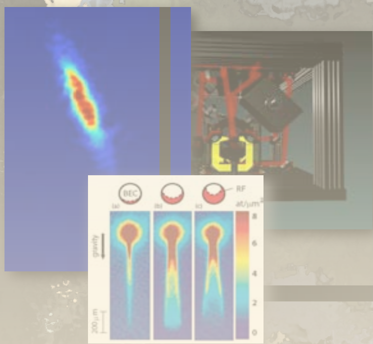


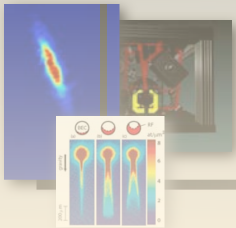
New transportable atom sensors and their applications to space experiments

P. Bouyer

Source Atomiques Cohérentes et Interférométrie Atomique

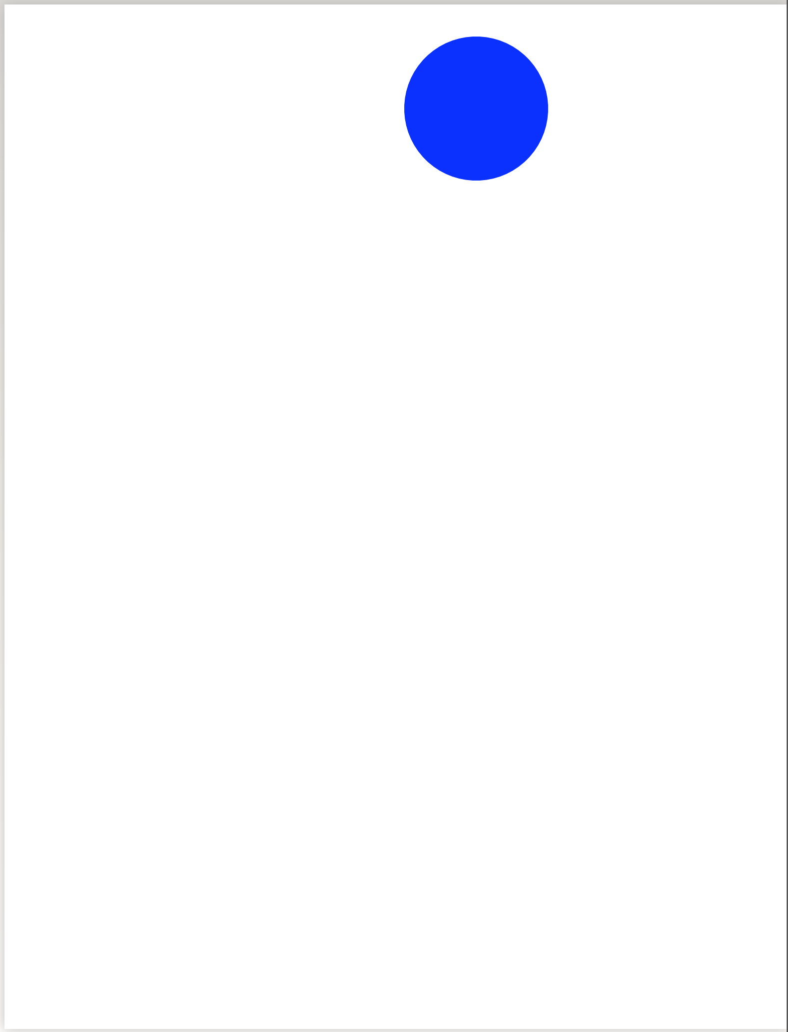
Groupe d'Optique Atomique
Laboratoire Charles Fabry de l'Institut d'Optique
Campus Polytechnique, France

- Atom Interferomtry : basic principle
- Atom Inertial Base (gyro + accelerometer)
- Coherent Atom Sensors
- I.C.E. : Tranportable Sensor for 0g tests
- Some possible space applications

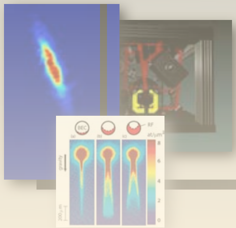


Atom accelerometer

- ❑ Based on Raman pulses atom optics
  - ➪ π/2−π−π/2 (Kasevich & Chu 1991) : interferometer
    - ➪π/2 : create a superposition of 2 different velocities : beam splitter
    - ➪π : exchanges velocities : mirror
- ❑ We use an (optical) ruler to precisely measure the (atomic) test mass position
  - ➪ Similar to falling corner cube gravimeter (FG5)
    - ➪FG 5 : Laser phase is read by optical interferometry
    - ➪Atom sensor : Laser phase is read by atom interferometry.
- ❑ An Atom Interferometer "reads" the position of an atom proof mass using some kind of "laser telemetry"
  - ➪Velocity measurement improves with time
  - ➪Acceleration measurement improves with time
  - ➪Absolute accuracy
    - ➪Example : watt balance for kg definition
  - ➪Performances Similar to best sensors
    - ➪Extension to low frequency



INSTITUT d'OPTIQUE GRADUATE SCHOOL



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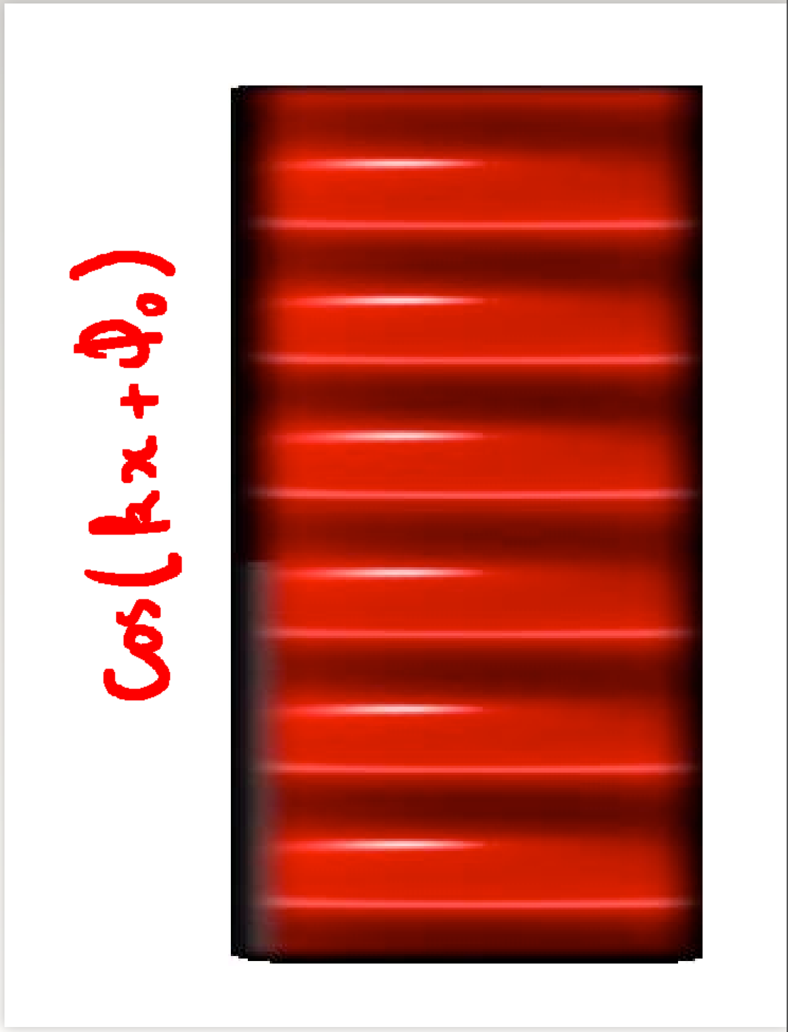
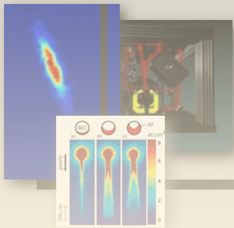
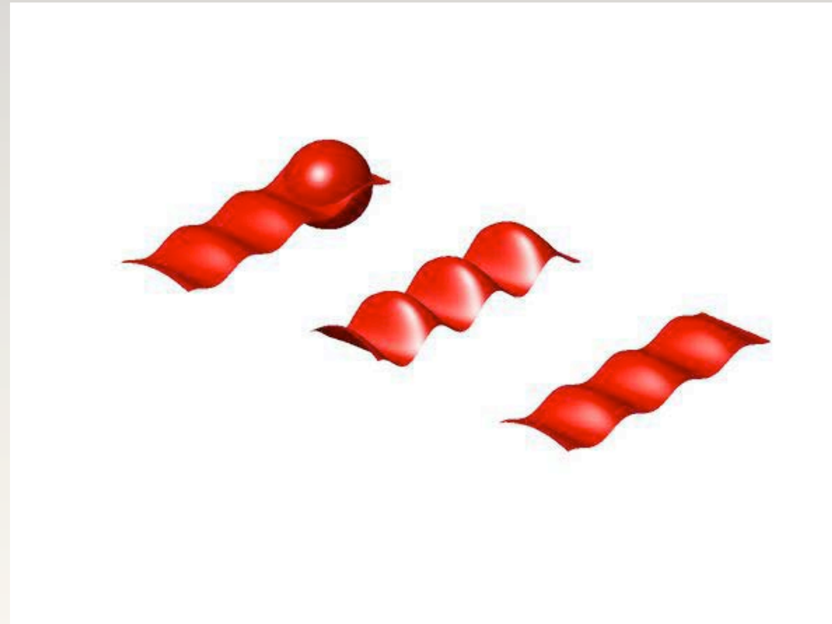




Atom Gyrometer

- 3 Raman pulses separated in time
  - ➾ Atoms with an initizal velcity perpendicular to lasers
    - ➾sensitivity to rotation = coriolis acceleration



$$\Delta\Omega_{min} = \frac{\Delta a_{cor.}}{2 v_y} = \frac{K}{m}\,\frac{1}{L v_R T \sqrt{N}}$$

- [x] Atom Interferomtry : basic principle
- [ ] Atom Inertial Base (gyro + accelerometer)
- [ ] Coherent Atom Sensors
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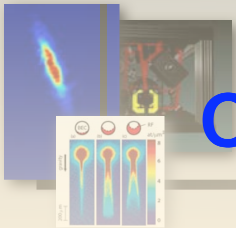
- [ ] Some possible space applications

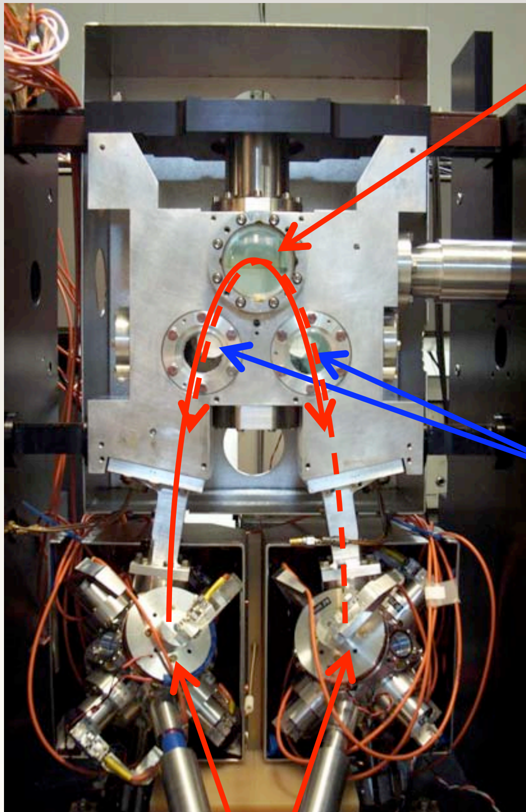
Cold Atom Inertial Base (SYRTE)



30 cm

50 cm

One pair of Raman lasers switched on 3 times



Detections

Magneto-Optical Traps

Launching velocity: 2.4 m.s^{-1}
Horizontal velocity: 0.33 m.s^{-1}

Six-Axis Inertial Sensor Using Cold-Atom Interferometry

B. Canuel, F. Leduc, D. Holleville, A. Gauguet, J. Fils, A. Virdis,* A. Clairon, N. Dimarcq, Ch. J. Bordé, and A. Landragin†
LNE-SYRTE, CNRS UMR 8630, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France

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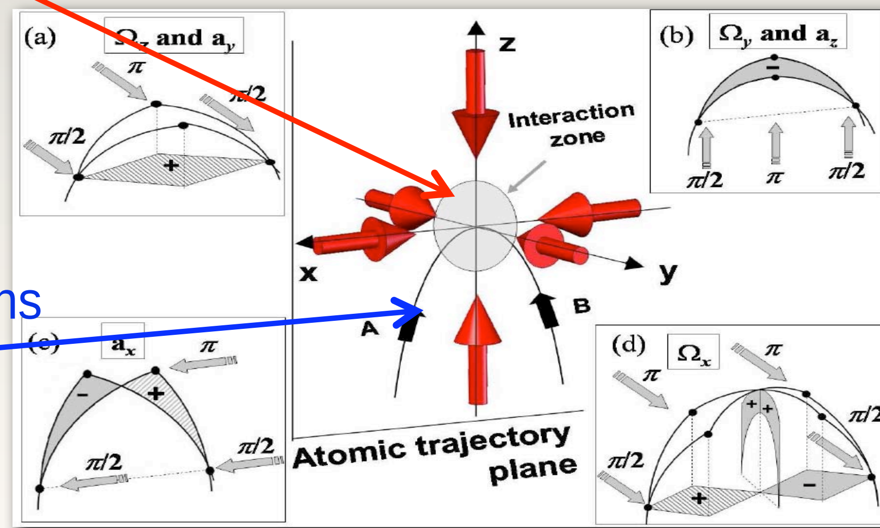
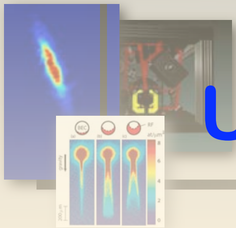
(Received 14 March 2006; published 7 July 2006)



Maximum interaction time : 80 ms
3 rotation axes, 2 acceleration axes
Cycling frequency 2Hz
Sensitivity (10^6 at):

- gyroscope : $3,5\ 10^{-7}$ rad.s^{-1}.Hz$^{-1/2}$
- accelerometer : $8\ 10^{-7}$ m.s^{-2}.Hz$^{-1/2}$



Ultimate limits for atom accelerometers ?

T_c (s)	$2T$ (s)	Source 1 $\sigma_\Phi(T_c)$ (mrad)	Source 2 $\sigma_\Phi(T_c)$ (mrad)	Source 3 σ_Φ (mrad)	Best Source $\sigma_a(T_c)$ ($m.s^{-2}$) / shot	Best Source $\sigma_a(1s)$ ($m.s^{-2}.Hz^{-1/2}$)
0.25	0.1	1.2	3.5	2.2	$3x10^{-8}$	$1.5x10^{-8}$
10	2	22	8.8	4.6	$1.1x10^{-9}$	$3.6x10^{-9}$
10	5	55	20	10	$9.9x10^{-11}$	$3.1x10^{-10}$
15	10	110	37	19	$4.7x10^{-11}$	$1.8x10^{-10}$

Table 1 Contribution of the 100 MHz source phase noise to the interferometric phase fluctuations (σ_Φ) and to the acceleration sensitivity (σ_a). The calculation has been performed for a ^{87}Rb interferometer, for each of the three different sources assuming pulse duration τ_R=10 μs. T_C is the cycle time for measurements, $2T$ is the total interrogation time. (Source 1: Premium; Source 2: BVA; Source 3: PHARAO)

Nyman et al., cond-mat/0605057 and App. Phys. B 84(4) 673

Metrology

➩ Accelerometer precision of a few 10^{-10} m/s^2 per shot (5 s interrogation time)
➩ Limit due to Raman-laser phase noise
  ➩ Noise comes from quartz oscillator

It is possible to go to a few seconds of interrogation time

➩ Well suited for space applications
➩ Best atom source ?

- [x] Atom Interferomtry : basic principle
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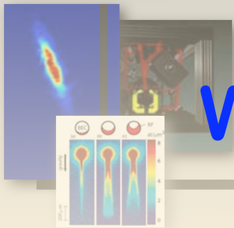
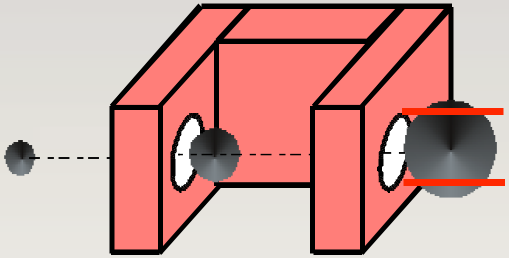
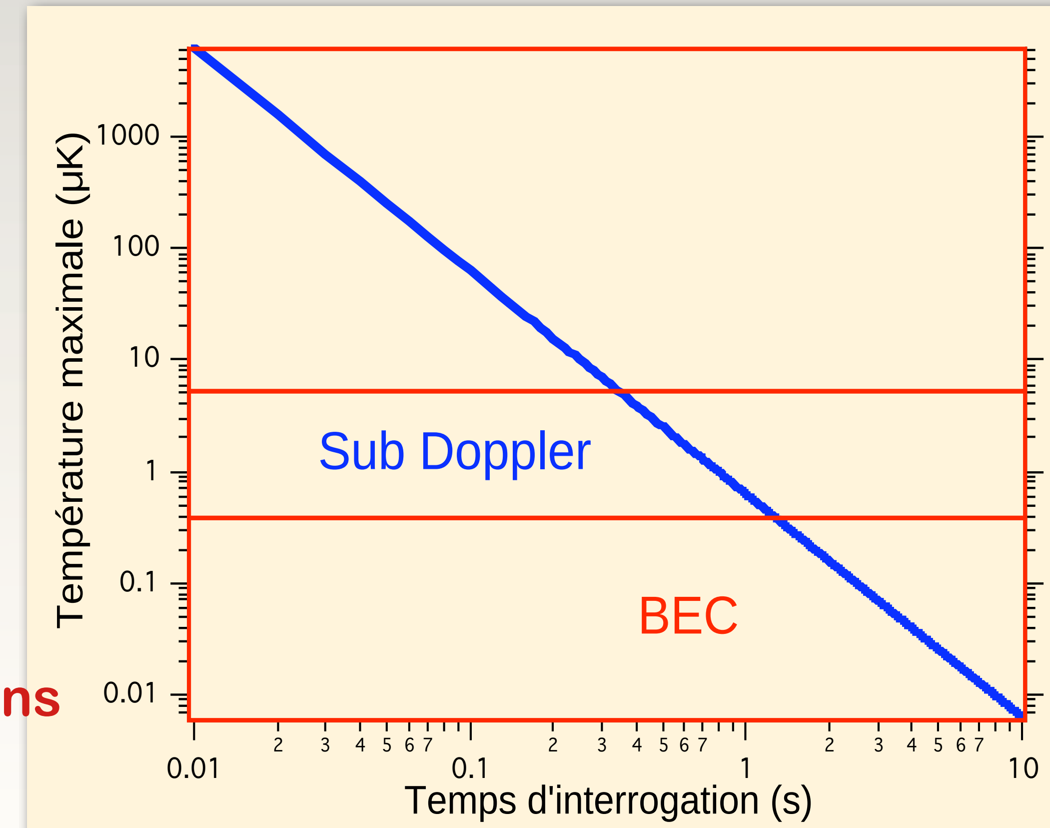


Why Coherent Source



- **Ultra cold**
  - **Longer interrogation**
  - **Better signal to noise**
    - *but lower flux !*
- **Atom Laser : space applications**
  - **Small source**
  - **«New» Physics**
    - *Correlation, condensed matter*

Le Coq et al., App. Phys. B 84(4)



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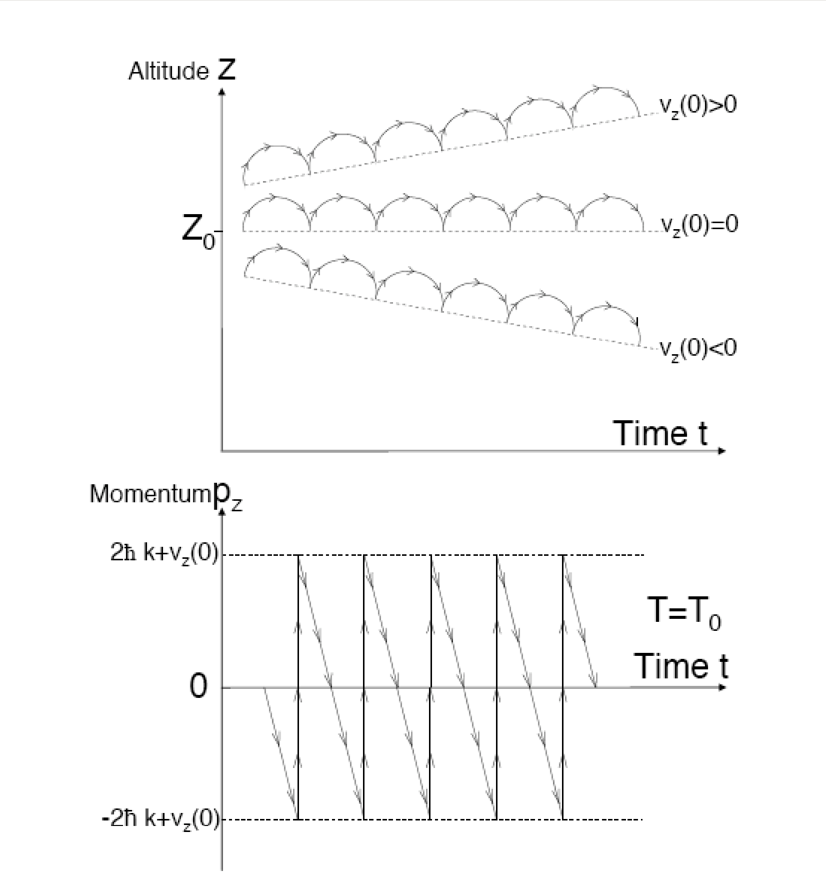
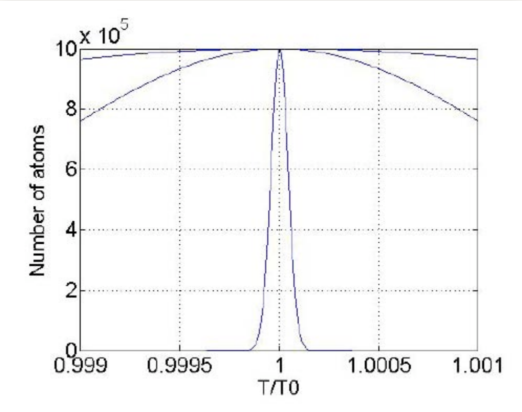
Gravitational "resonator" for BEC



2 resonance condition

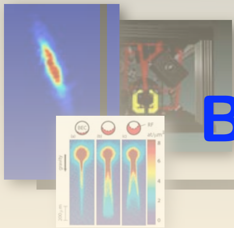
- ✱Bragg (or Raman) resonance
- ✱Oscillation resonance

$$T_0 = \frac{4\hbar k}{mg}$$



See C. Bordé's Talk

Impens, Bouyer, Bordé , App. Phys. B 84(4)



BEC : New generation of Interferometers

PHYSICAL REVIEW A VOLUME 56, NUMBER 2 AUGUST 1997

Heisenberg-limited spectroscopy with degenerate Bose-Einstein gases

P. Bouyer* and M. A. Kasevich
Department of Physics, Stanford University, Stanford, California 94035
(Received 14 March 1997)

We propose an experiment that exploits the quantum interference between two noninteracting ensembles of spatially degenerate Bose-Einstein atoms to measure phase shifts of atomic coherences at the Heisenberg limit. [S1050-2947(97)50207-1]

PACS number(s): 03.75.Dg, 03.75.Fi

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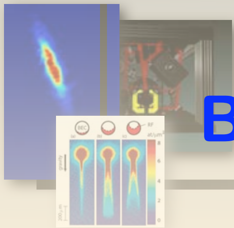

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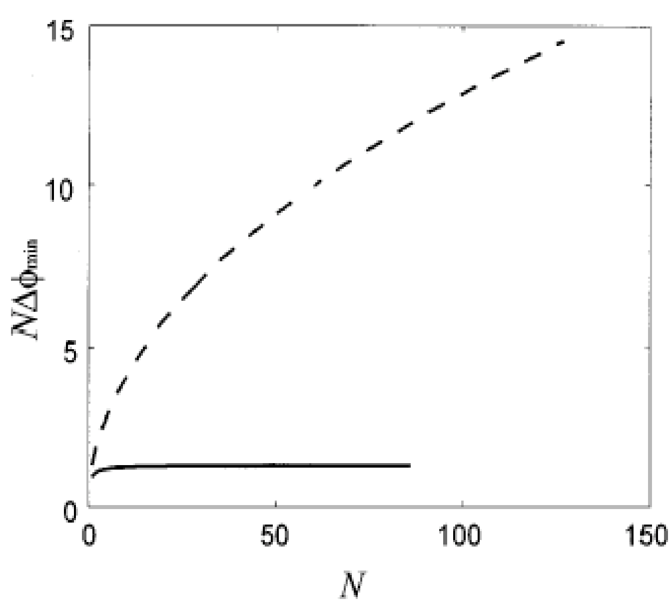

- **Heisenberg limited with number states**
  - Compensates low atom number S/N=10^6
- **Integrated interferometers**
  - ➩ BEC on chips
- **«active» interferometers**
  - ➩ Matter wave amplification

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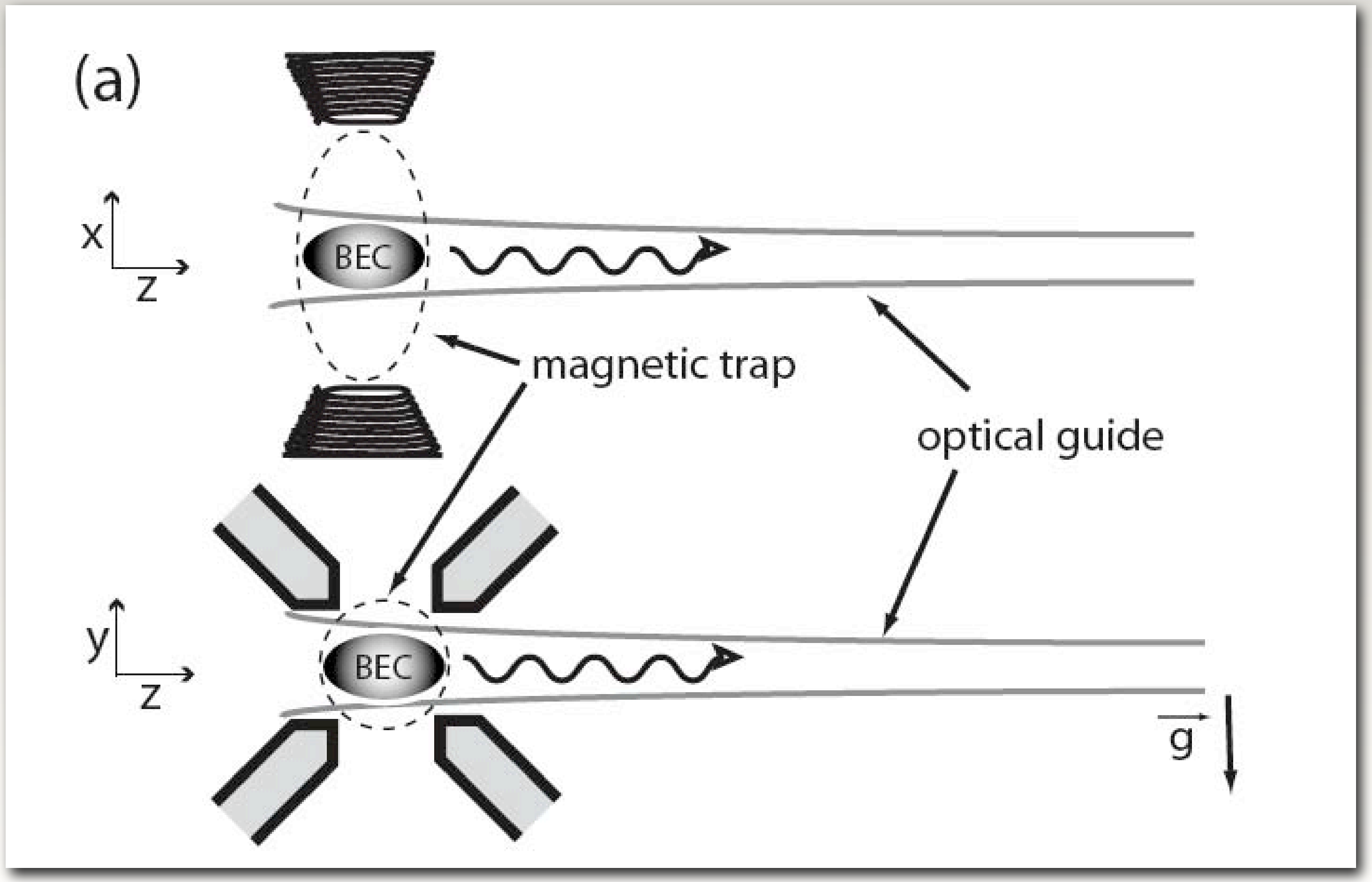
A Guided Atom Laser

W. Guerin et al., cond-mat/0607438

- So far, RF outcoupled lasers from a magnetic trap
  - ➾ Once atom lasers are extracted, they are subjected to gravity
  - ➾ λ becomes quickly very small

A Guided Atom Laser

W. Guerin et al., cond-mat/0607438



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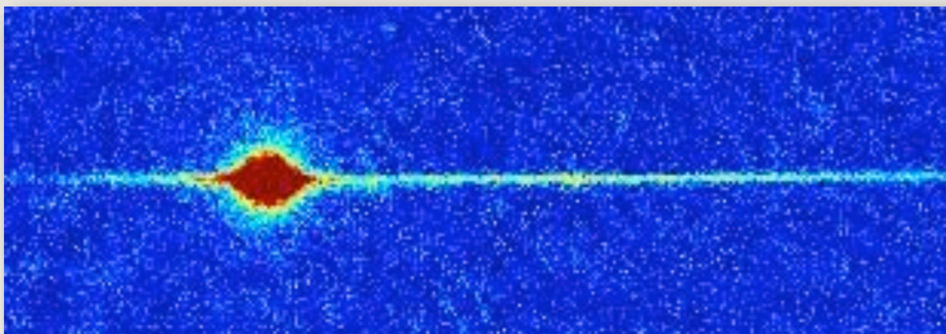
W. Guerin et al., cond-mat/0607438



❑BEC in hybrid (magnetic+optical) trap

- ➩Focused Nd:YAG laser (red detuned: 1064 nm)
- ➩Anisotrop: 2,5 Hz × 360 Hz (z_R= 2.7 mm)
- ➩Waist position chosen with translational stage

➩It is possible to use RF outcouplig

➩RF extracted matter wave is guided in the optical trap

➩Large de Broglie wavelength (1 µm)

- [x] Atom Interferomtry : basic principle
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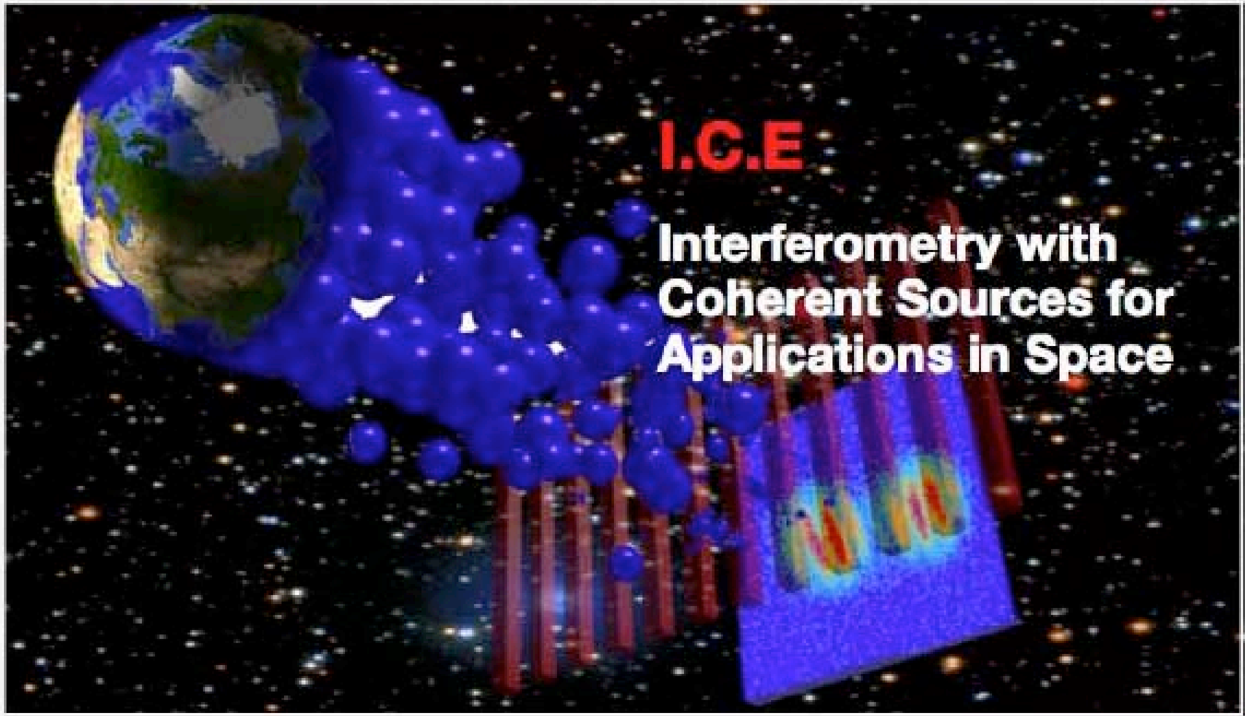
ICE | Concept | ICE Cube | The Lasers | News



Project members

Philippe BOUYER
Robert NYMAN
Gael VAROQUAUX
Jean-Francois CLEMENT
Jean-Philippe BRANTUT

Arnaud LANDRAGIN
Frank PEREIRA

Alexandre BRESSON
Yannick BIDEL
Pierre TOUBOUL

THE PROJECT

The objective of ICE is to produce an accelerometer for space with coherent atomic source. It uses a mixture of Bose-Einstein condensates with 2 species of atoms (Rb and K).

The major objective for 2007 is to carry out a first µg campaign, in parabolic flight for example, to test the various components together and to carry out a first comparison of accelerations measured by the 2 atomic species.

Partners

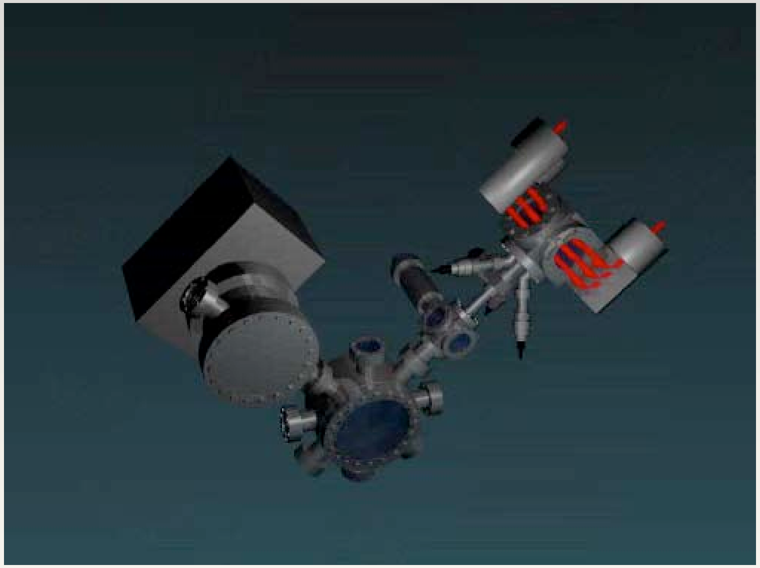
OPTIQUE ATOMIQUE

GROUPE ATOMES FROIDS

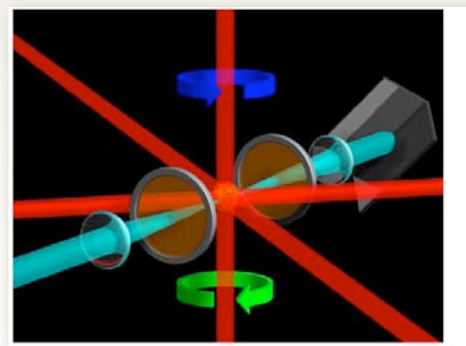
GROUPE SENSEURS INERTIELS

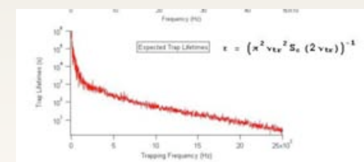
Internal Pages

ICE : Strategy



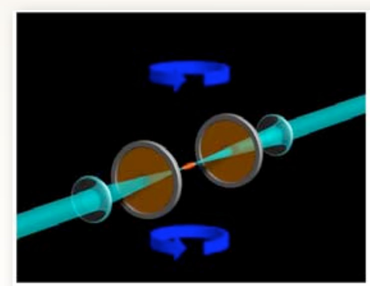
- ❑Use optical traps for “atom cavity”
- ❑Optical fields easilly switchable
  - ➾ No stray fields, only “diffusive effects”
  - ➾ Precision knowledge on position, velocity …



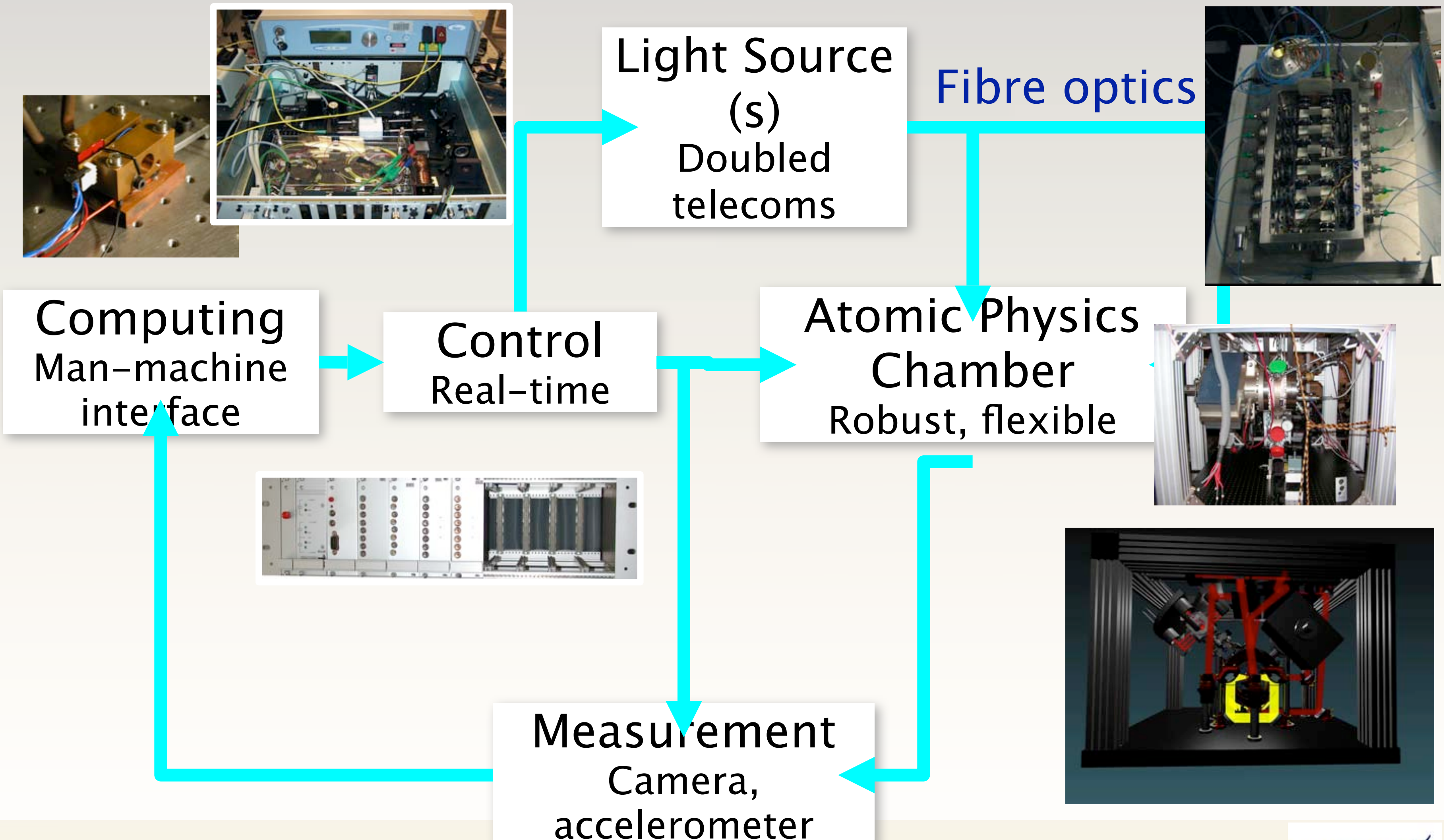


Compact BEC source :

- ➾ Crutial : efficient loading scheme into the optical trap
- ➾ Need powerfull laser



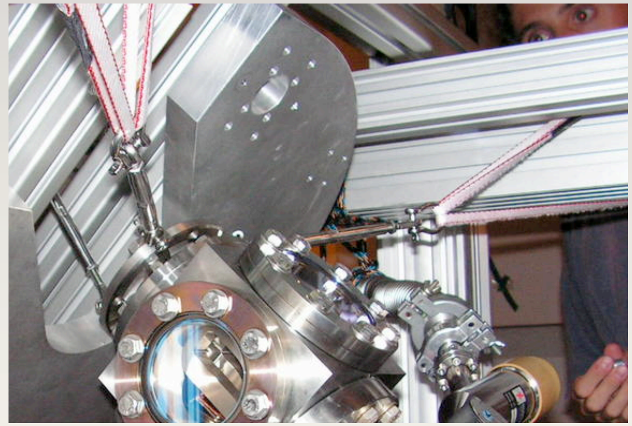
I. C. E. : structure



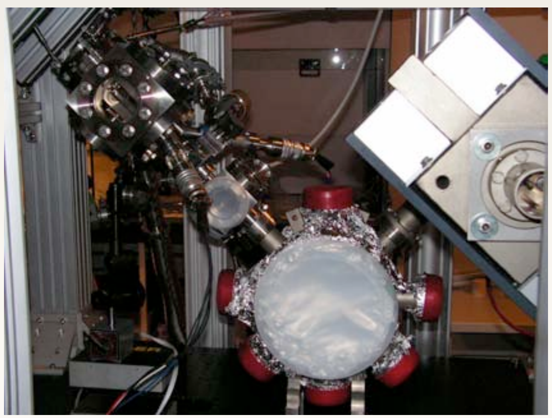
INSTITUT d'OPTIQUE GRADUATE SCHOOL

I. C. E. :Cube

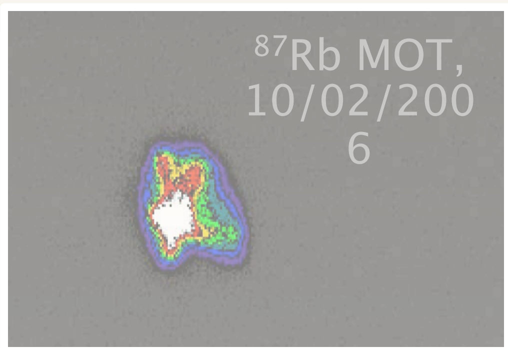
- Box superstructure
- Damped (foam filled)
- Grooves for adding optics anywhere in the volume
- Breadboard (low vibration)

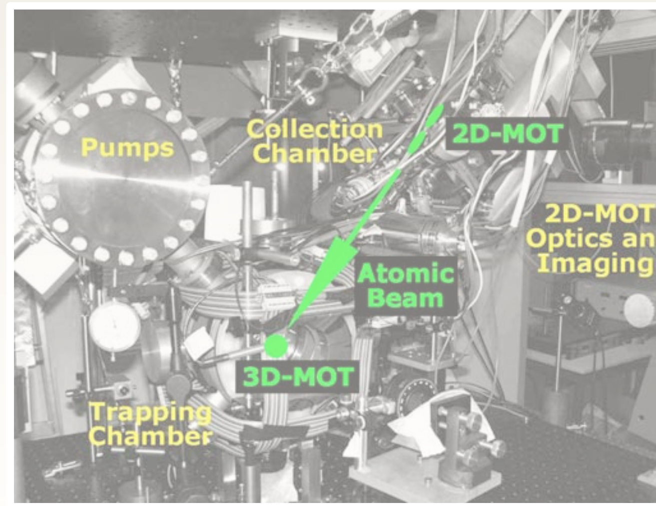


- Suspend vacuum chamber with ropes, slings, chains
- Adjust tension with turnbuckles



2×10^{8} at. in <5s

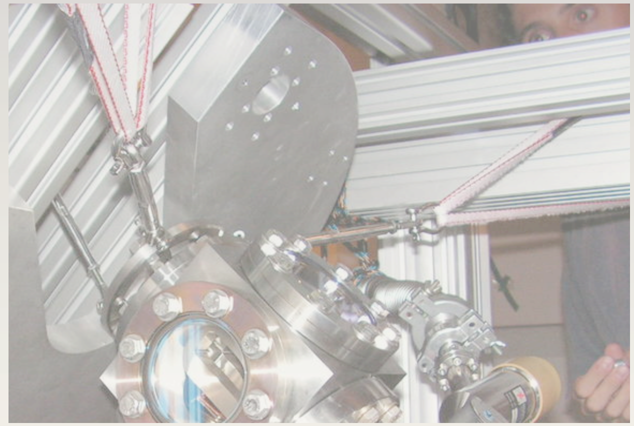




INSTITUT d'OPTIQUE GRADUATE SCHOOL

I. C. E. : Cubes (with atoms)

- Box superstructure
- Damped (foam filled)
- Grooves for adding optics anywhere in the volume
- Breadboard (low vibration)



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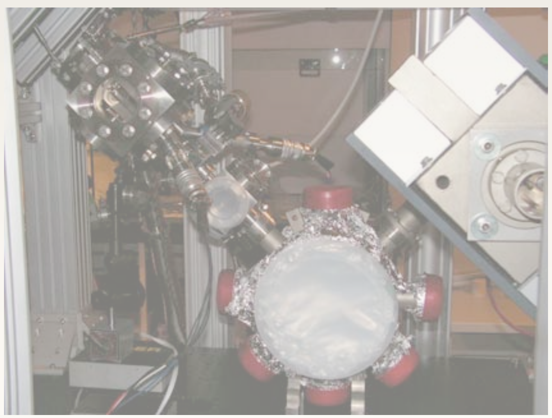

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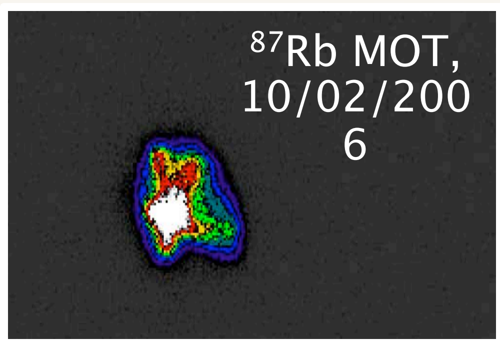

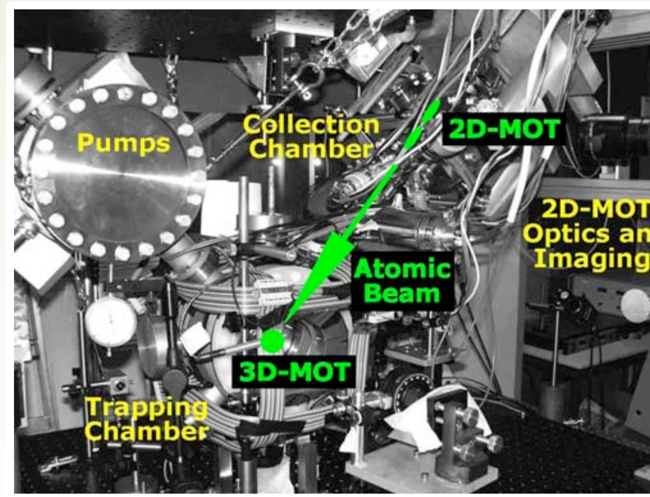

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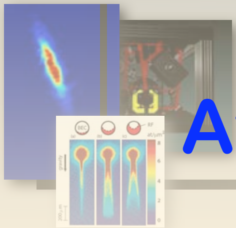
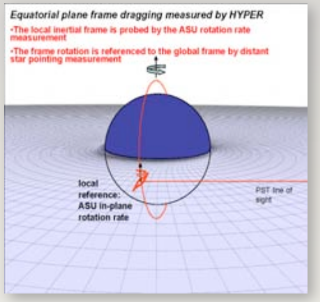
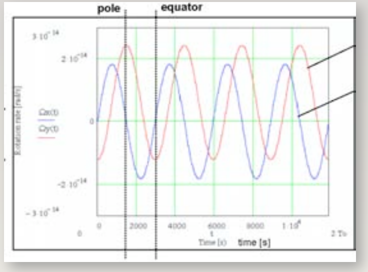


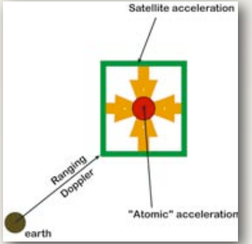
Atoms sensors in space : missions

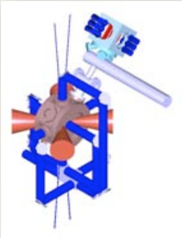
- **General Relativity**
  - Mapping the Lense-Thirring effect around the earth.
  - Equivalence Principle





- **Testing deviations of the gravitational law at short and long distances.**
  - Pioneer Anomaly
  - Beyond Casimir Effect





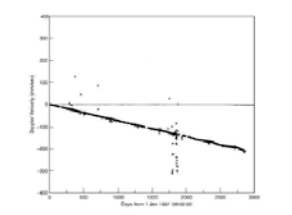
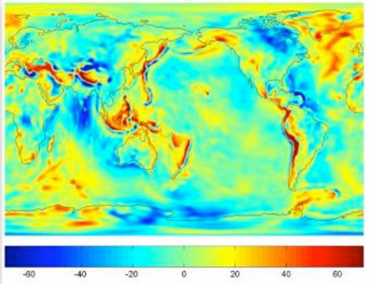
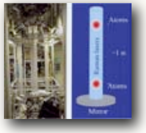
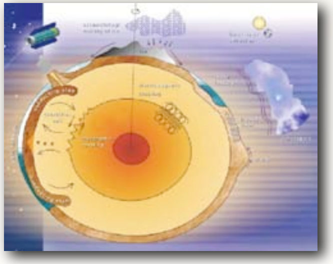


FIG. 8: CHASMP two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 vs. time. 1 Hz is equal to 65 mm/s range change per second. The model is fully-relativistic. The solar system's gravitational field is represented by the Sun and its planetary systems [49].

- **Mapping the gravitational potential with absolute gravity gradiometers**







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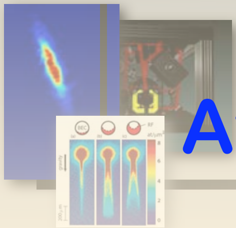
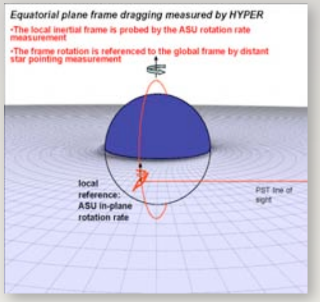
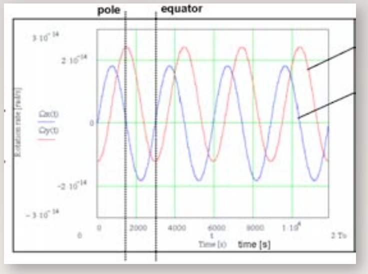


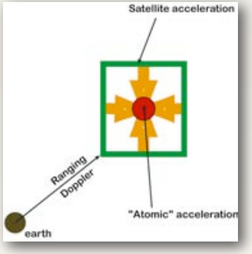
Atoms sensors in space : missions

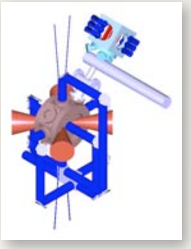
- **General Relativity**
  - Mapping the Lense-Thirring effect around the earth.
  - Equivalence Principle





- **Testing deviations of the gravitational law at short and long distances.**
  - Pioneer Anomaly
  - Beyond Casimir Effect





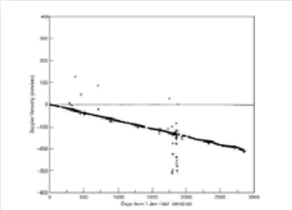
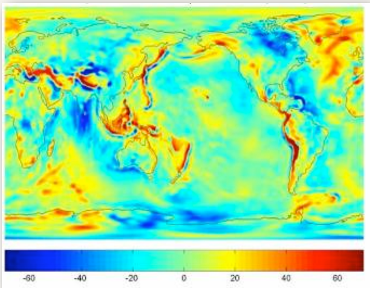
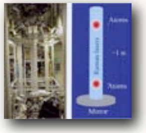
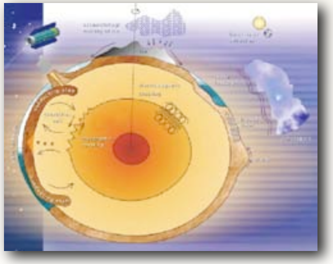


FIG. 8: CHASMP two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 vs. time. 1 Hz is equal to 65 mm/s range change per second. The model is fully-relativistic. The solar system's gravitational field is represented by the Sun and its planetary systems [49].

- **Mapping the gravitational potential with absolute gravity gradiometers**







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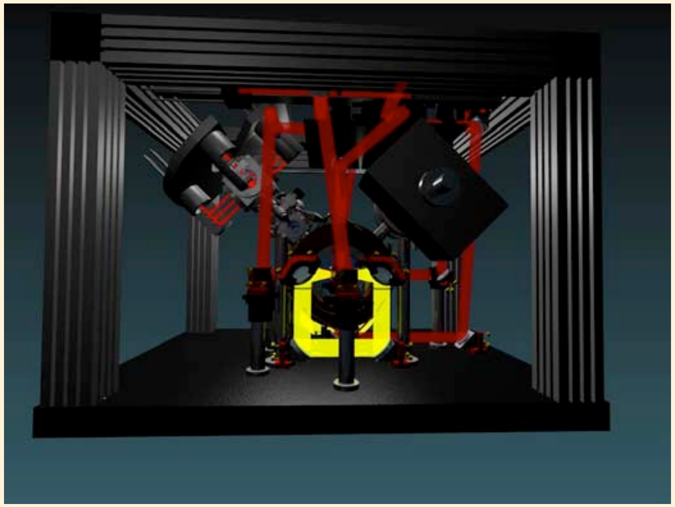

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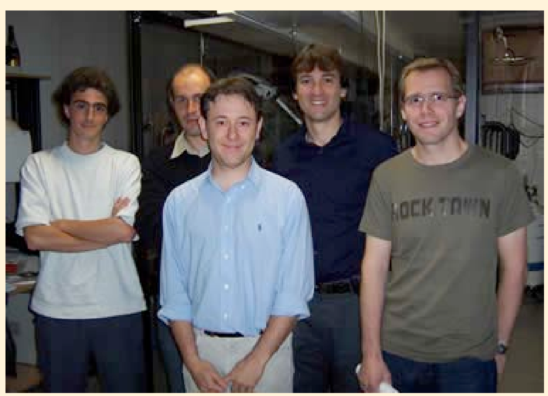

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