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Development of a Satellite-Based Cold Atom Clock

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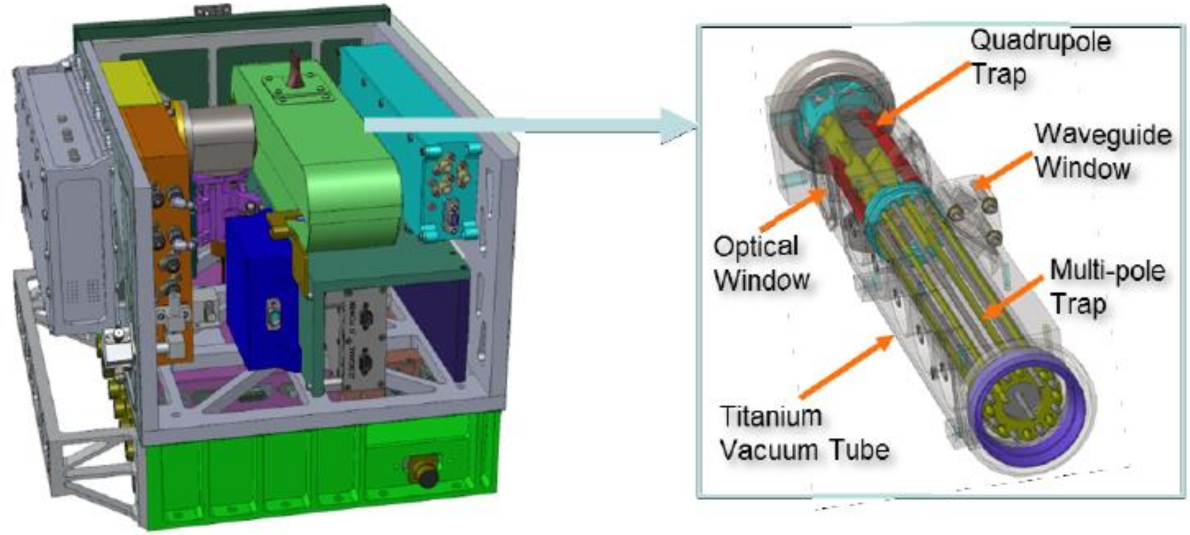
OUTLINE

1. Introduction
2. Laser cooling in diffuse light
4. Compact cold atom clock
5. Conclusions

OUTLINE

1. Introduction

JPL’s Deep Space Atomic Clock



DSAC DU with the mercury ion trap configuration
29x26x23 cm, 16 kg, 50W, 1E-15/d

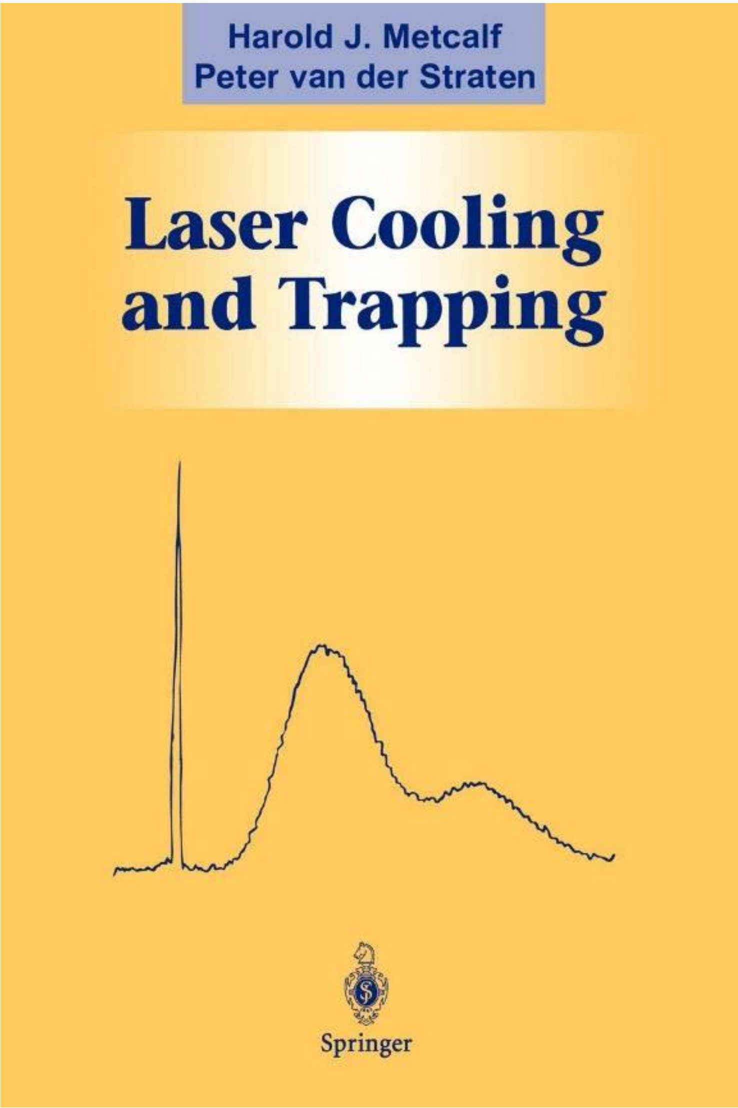
Satellite-based atomic clock

What we need for satellite-based atomic clock:

- ☐ Small size: <300x300x300 mm
- ☐ Light weight: <20kg
- ☐ Less power: <50W
- ☐ Good performance:
  - 1s: <2E-13
  - 1day: <1E-15
  - Drift: <1E-15
  - Uncertainty: <1E-15

Besides Mercury ion clock, an atomic clock with laser cooled atoms can reach the performance for next generation GNSS and deep space exploration.

Laser cooling of atoms

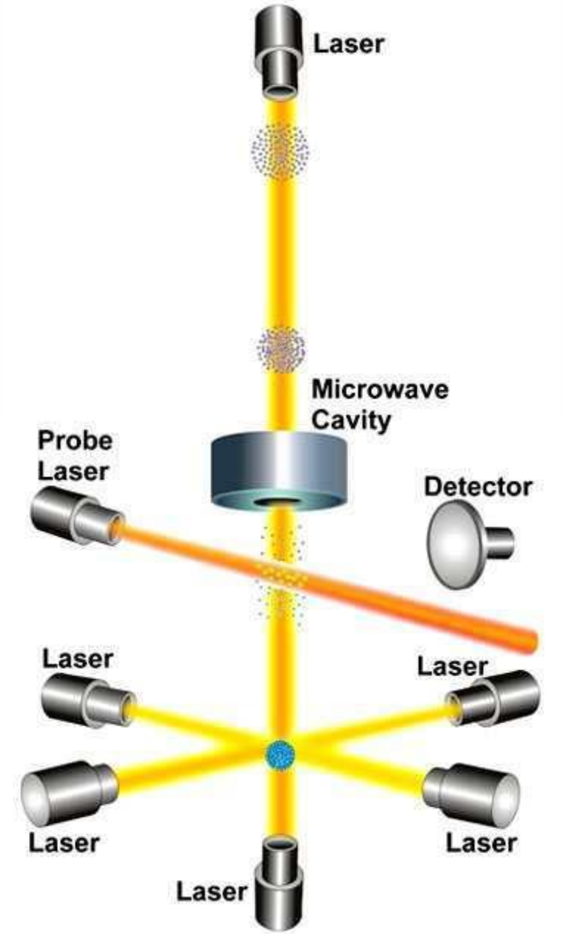


Harold J. Metcalf
Peter van der Straten

Laser Cooling
and Trapping

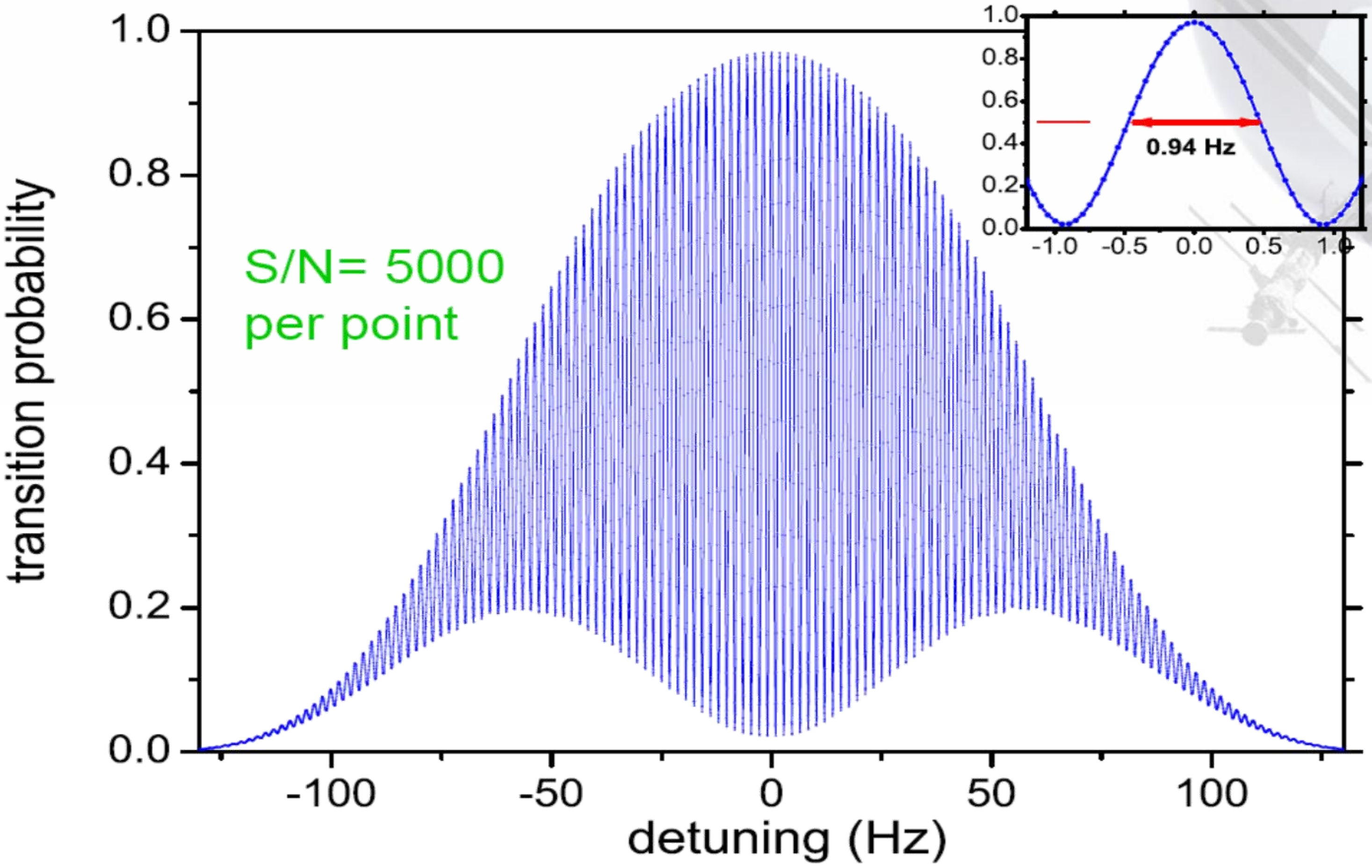
Springer

Atomic foutain



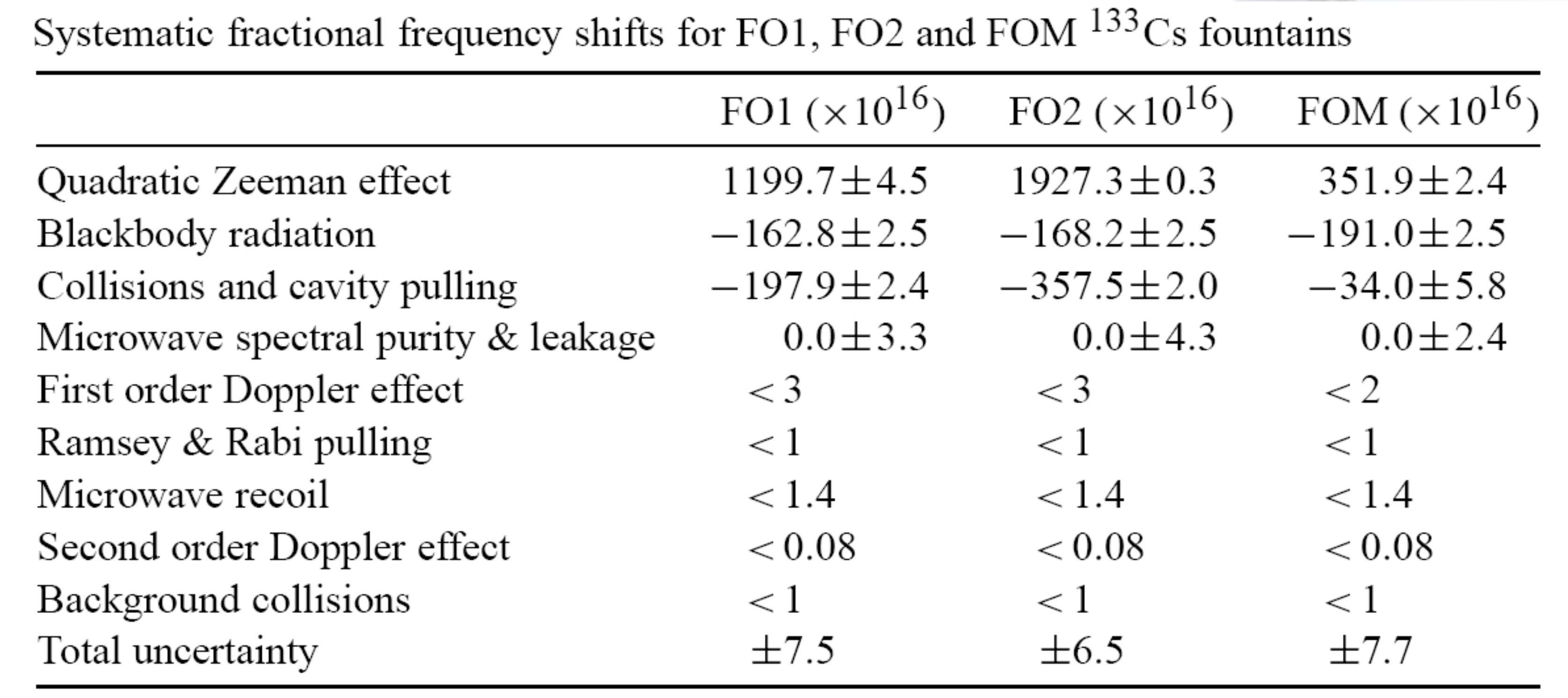
- ☐ Atoms are cooled at the bottom
- ☐ Cold atoms are launched upwards by lasers
- ☐ Cold atoms interact with microwave in the cavity
- ☐ Cold atoms drop after they reach the top
- ☐ Cold atoms interact with microwave again
- ☐ Cold atoms are detected by laser
- ☐ The signal feedback to microwave source

Atomic foutain



Typical Ramsey fringes, Paris

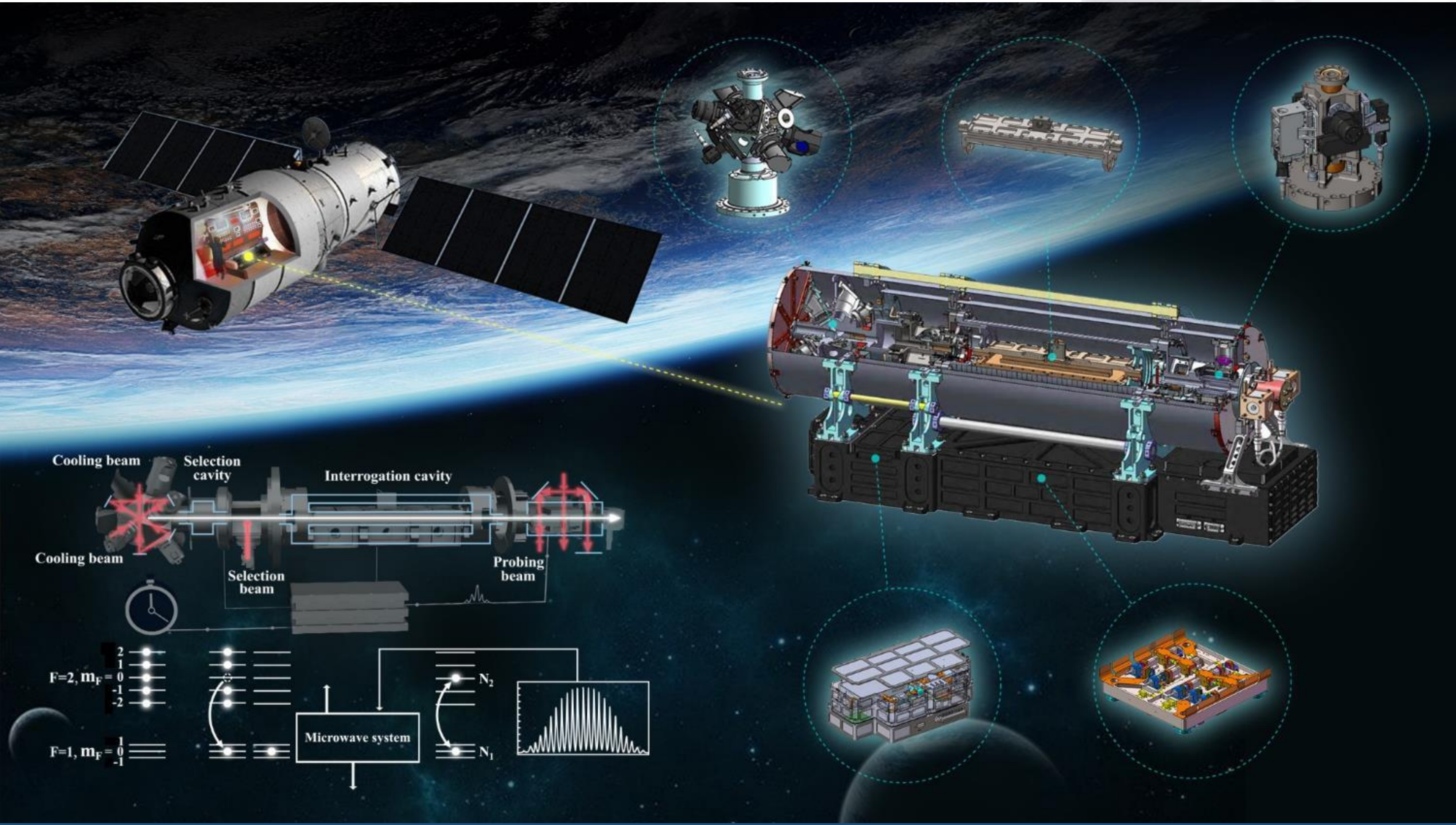
Atomic foutain



Systematic fractional frequency shifts for FO1, FO2 and FOM ^{133}Cs fountains

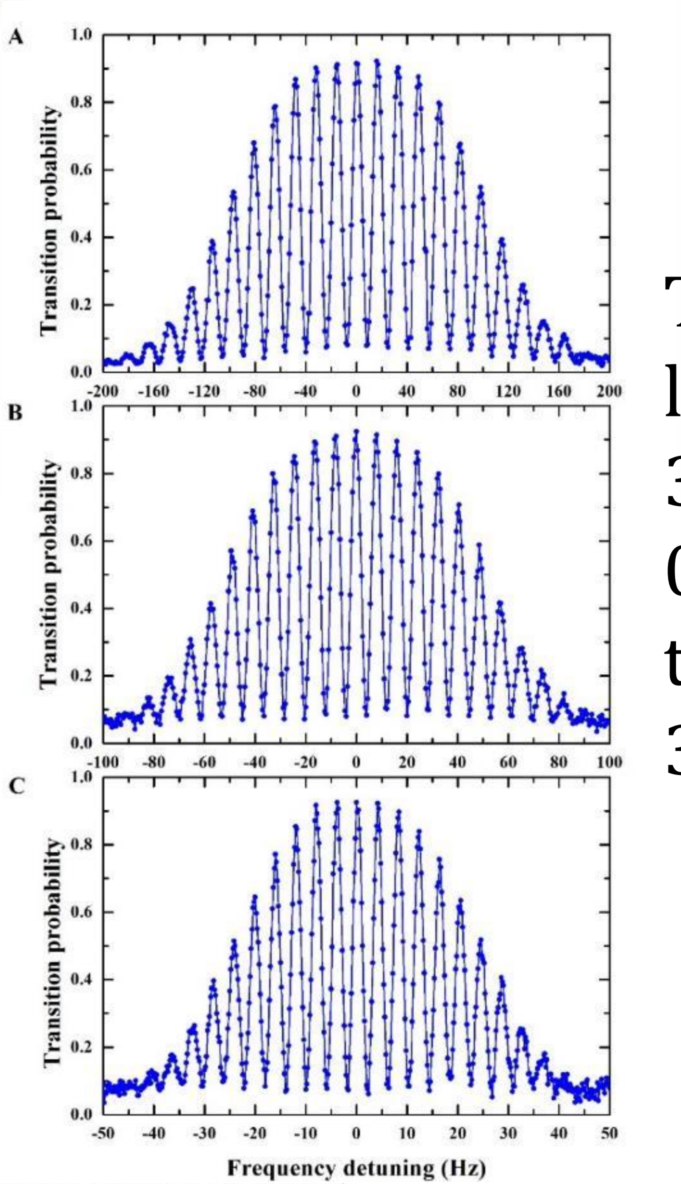
	FO1 ($\times 10^{16}$)	FO2 ($\times 10^{16}$)	FOM ($\times 10^{16}$)
Quadratic Zeeman effect	1199.7 ± 4.5	1927.3 ± 0.3	351.9 ± 2.4
Blackbody radiation	-162.8 ± 2.5	-168.2 ± 2.5	-191.0 ± 2.5
Collisions and cavity pulling	-197.9 ± 2.4	-357.5 ± 2.0	-34.0 ± 5.8
Microwave spectral purity & leakage	0.0 ± 3.3	0.0 ± 4.3	0.0 ± 2.4
First order Doppler effect	< 3	< 3	< 2
Ramsey & Rabi pulling	< 1	< 1	< 1
Microwave recoil	< 1.4	< 1.4	< 1.4
Second order Doppler effect	< 0.08	< 0.08	< 0.08
Background collisions	< 1	< 1	< 1
Total uncertainty	± 7.5	± 6.5	± 7.7

Cold atom clock in space



Cold Atom Clock Experiment in Space, CACES, with Tiangong-2

Cold atom clock in space



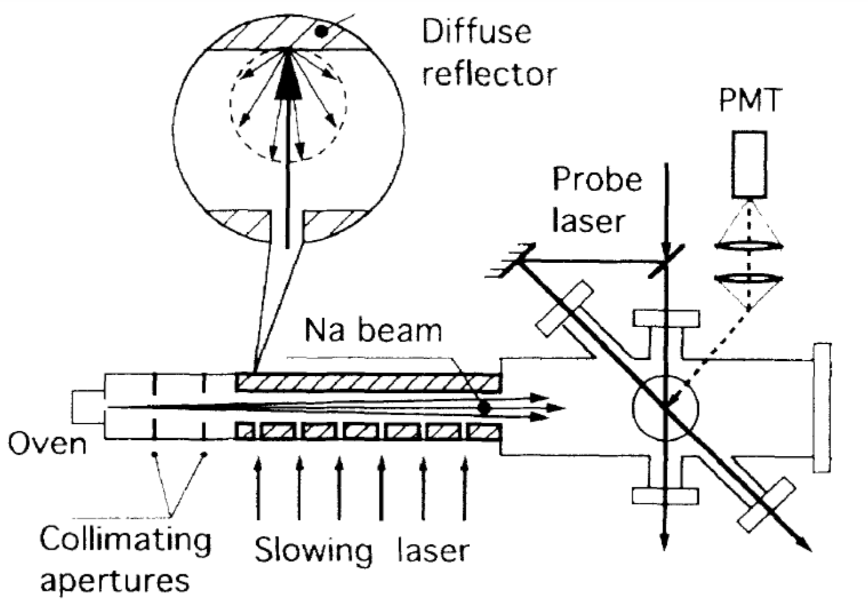
Typical Ramsey fringe. The launching velocity is (A) 3.15 m/s, (B) 1.69 m/s, (C) 0.78 m/s, corresponding to the width (A) 7.27 Hz, (B) 3.89 Hz, and (C) 1.80 Hz.

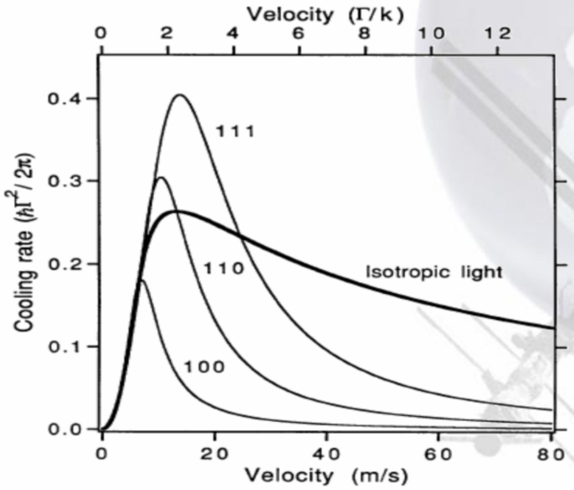
OUTLINE

2. Laser cooling in diffuse light

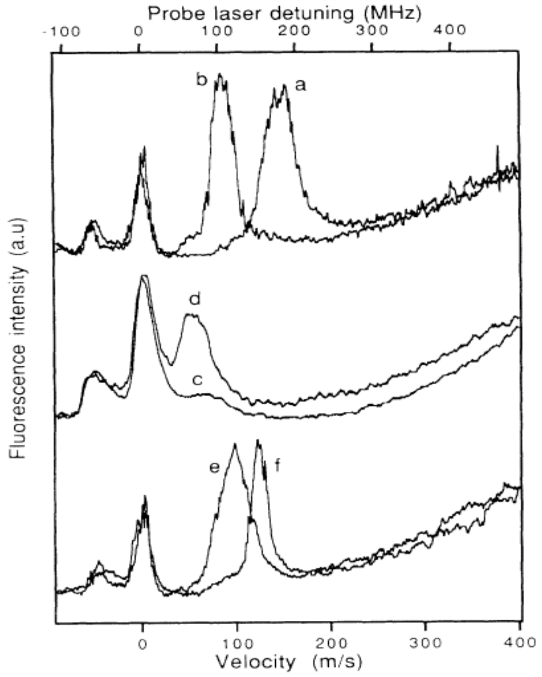
Diffuse deceleration of an atomic beam

$$\omega_a = \omega_1 + kv\cos\theta$$

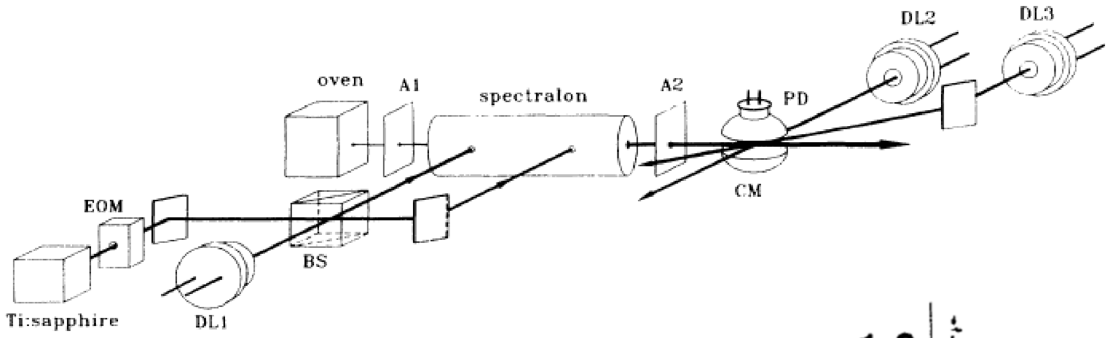


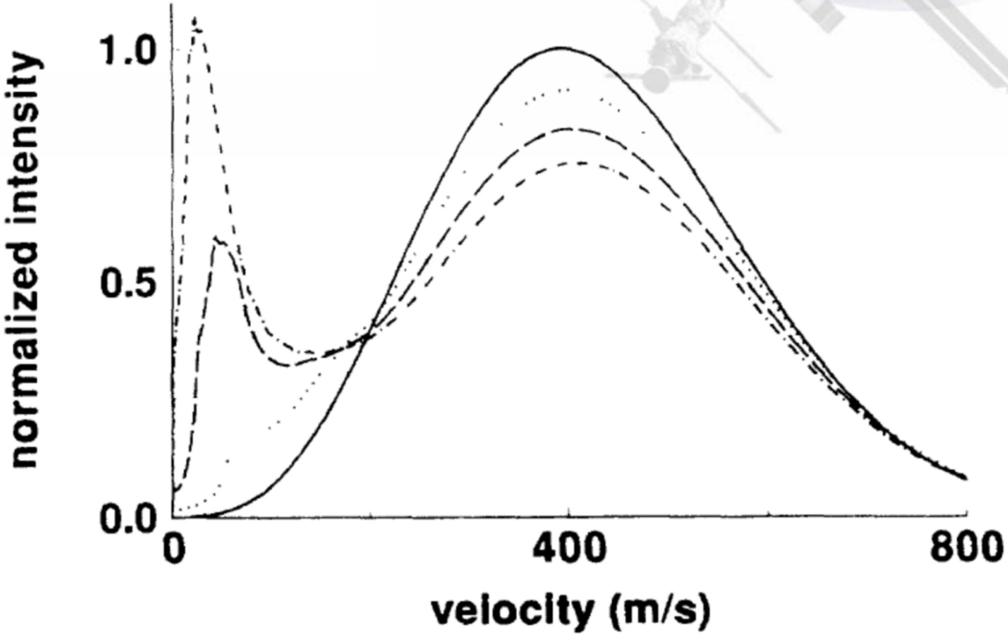


W. Ketterle, et. al., Phys. Rev. Lett. 69, 2483 (1992)



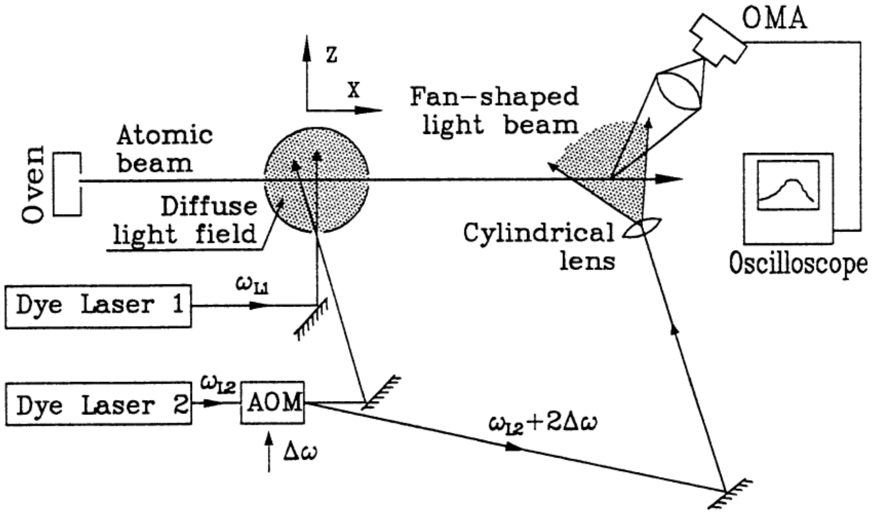
Diffuse deceleration of an atomic beam

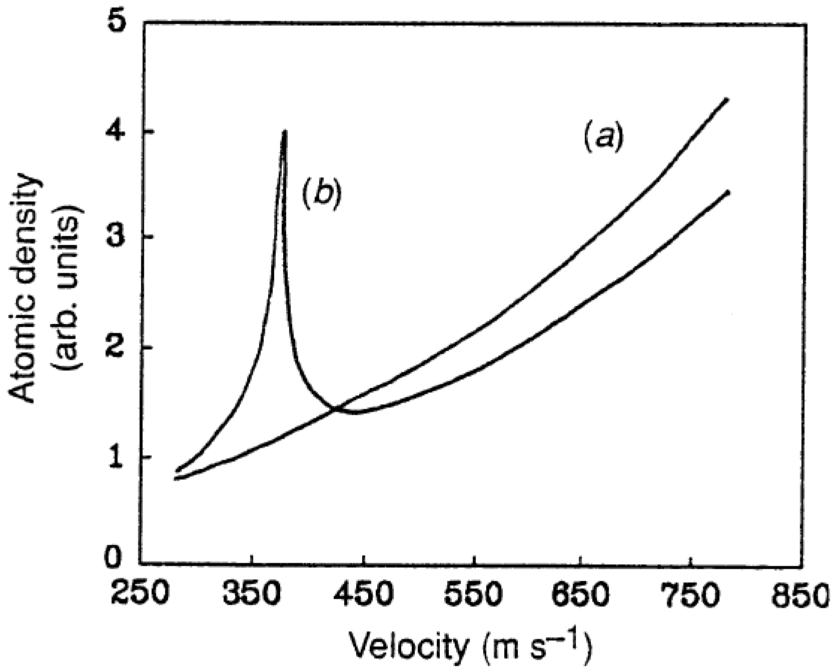




H. Batelaan, et.al., Phys. Rev. A 49, 2780 (1994)

Diffuse deceleration of an atomic beam



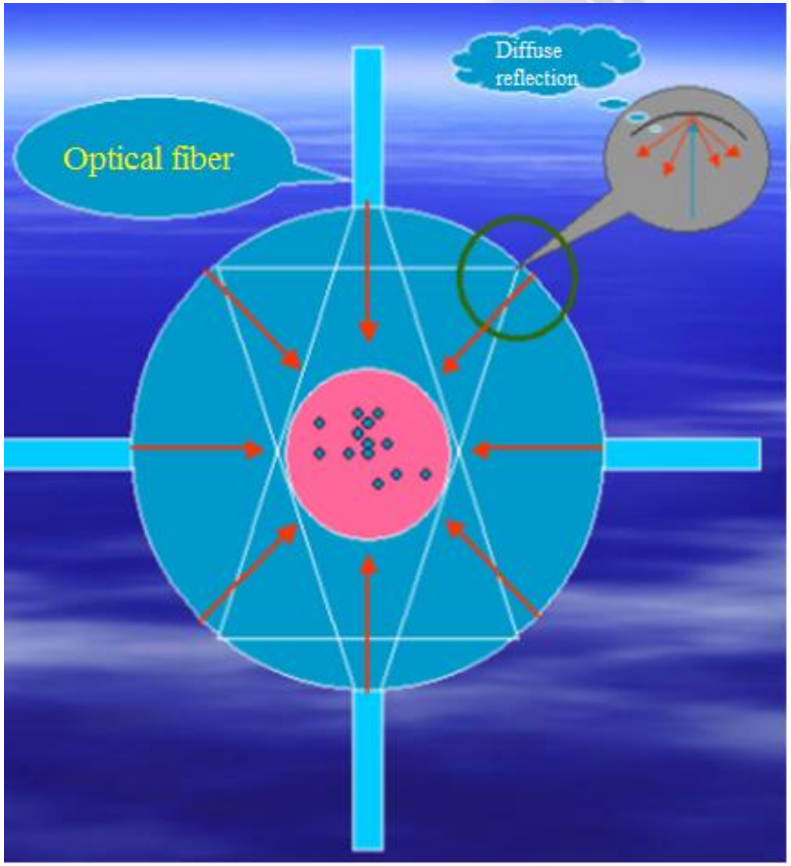


H.X. Chen, L. Liu and Y.Z. Wang, Acta Optica Sinica 14, 125 (1994)
Y.Z. Wang and L. Liu, Australian J. Phys. 48, 267 (1995)

Laser cooling in an integrating sphere

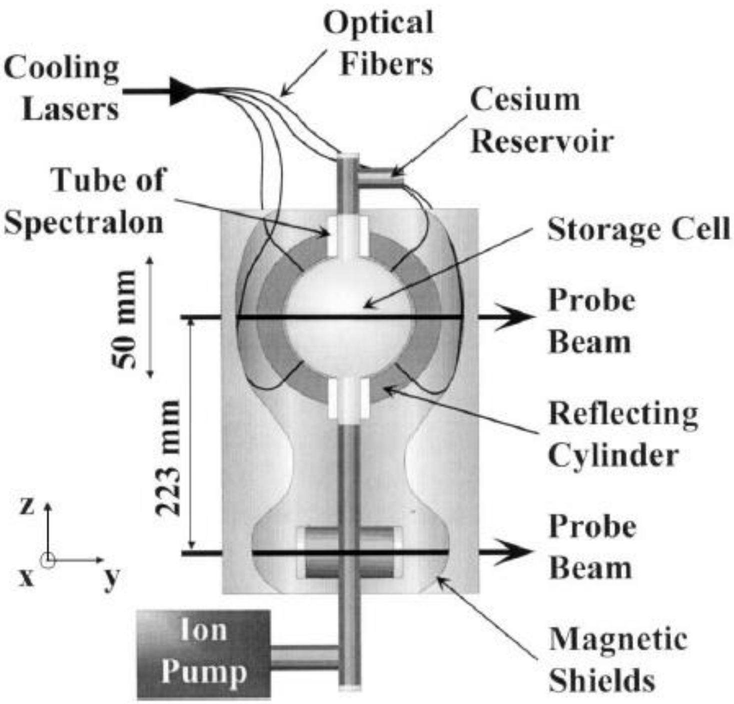
A new scheme of laser cooling is introduced in order to reduce the device size: diffuse laser cooling

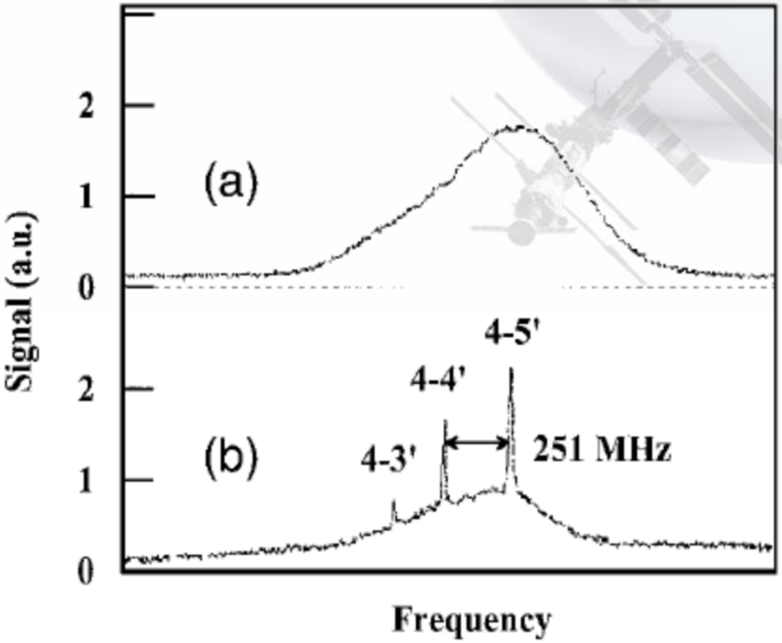
Typical integrating sphere



Principle of laser cooling in an integrating sphere

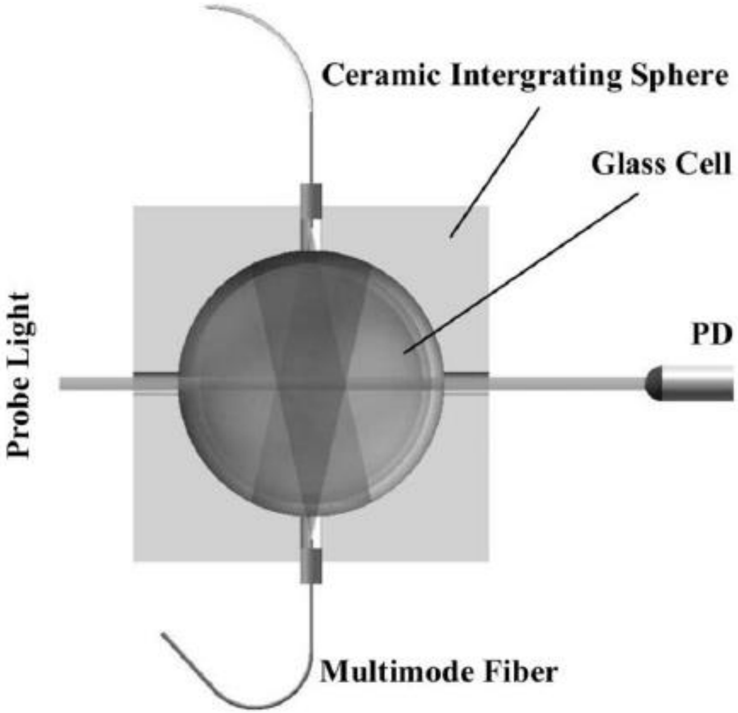
Laser cooling of atoms in diffuse light

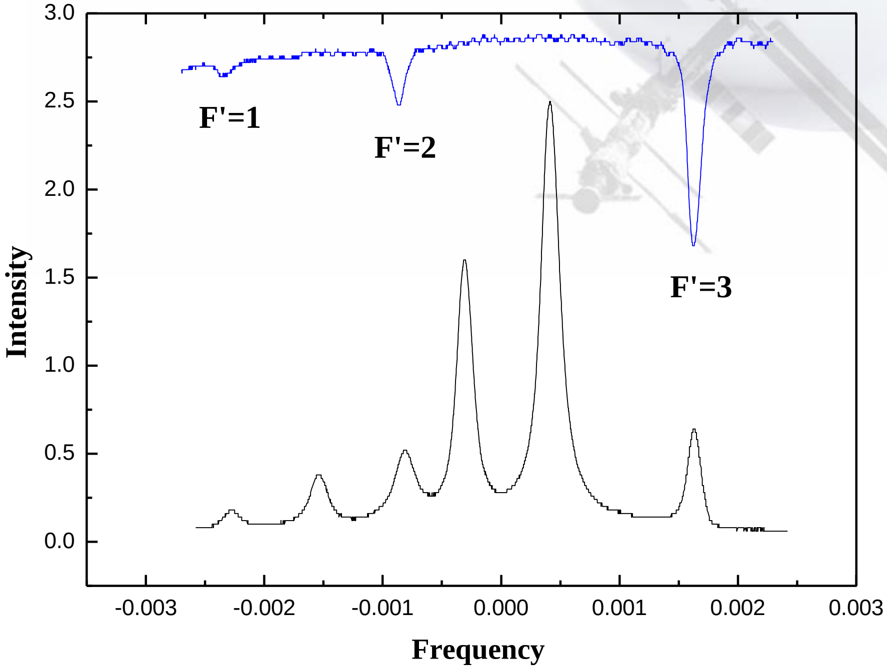




E. Guillot, *et al*., Opt. Lett. 26, 1639 (2001), Cs

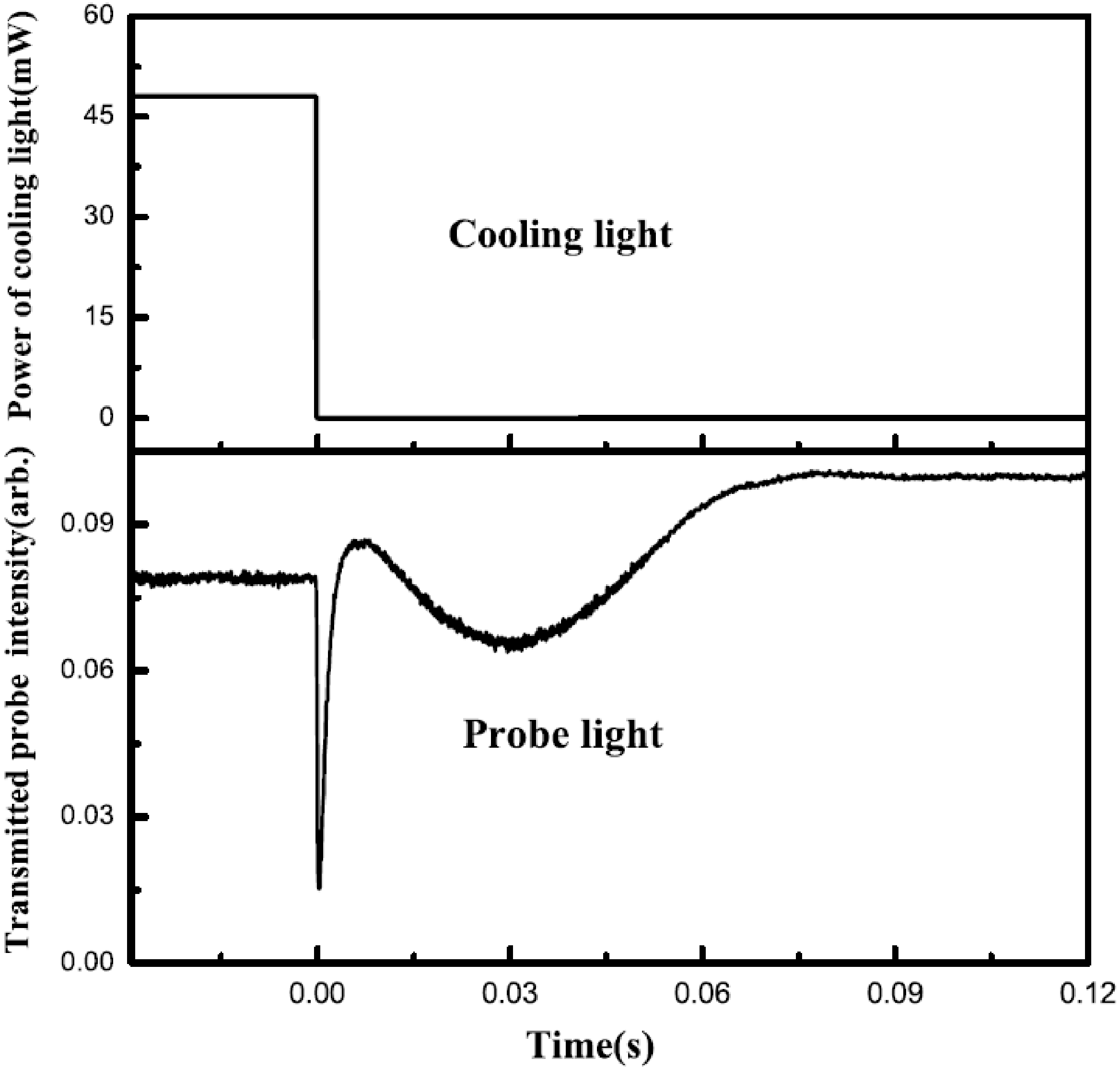
Laser cooling of atoms in diffuse light



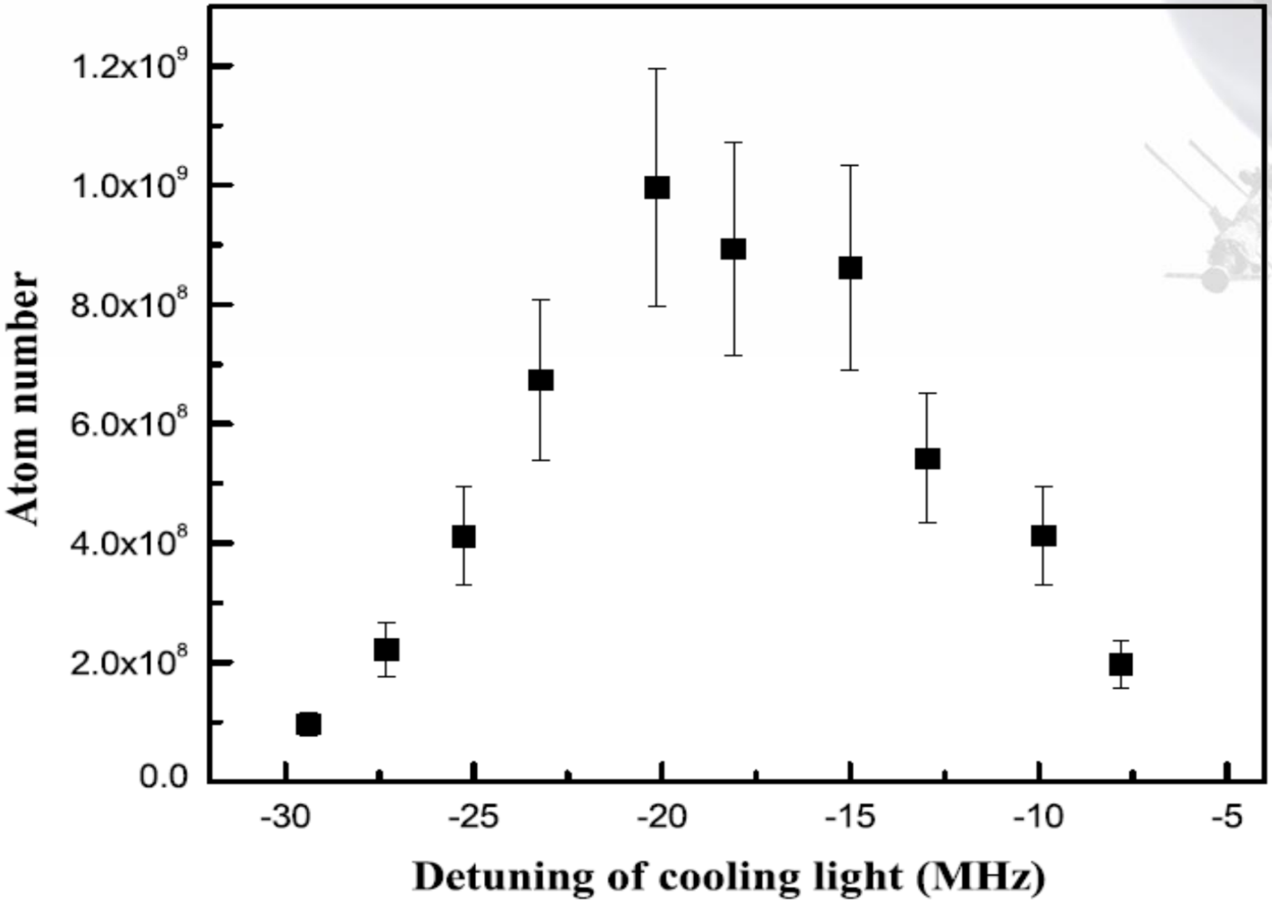


H.D. Cheng, *et al.*, Phys. Rev. A 79, 023407 (2009), Rb

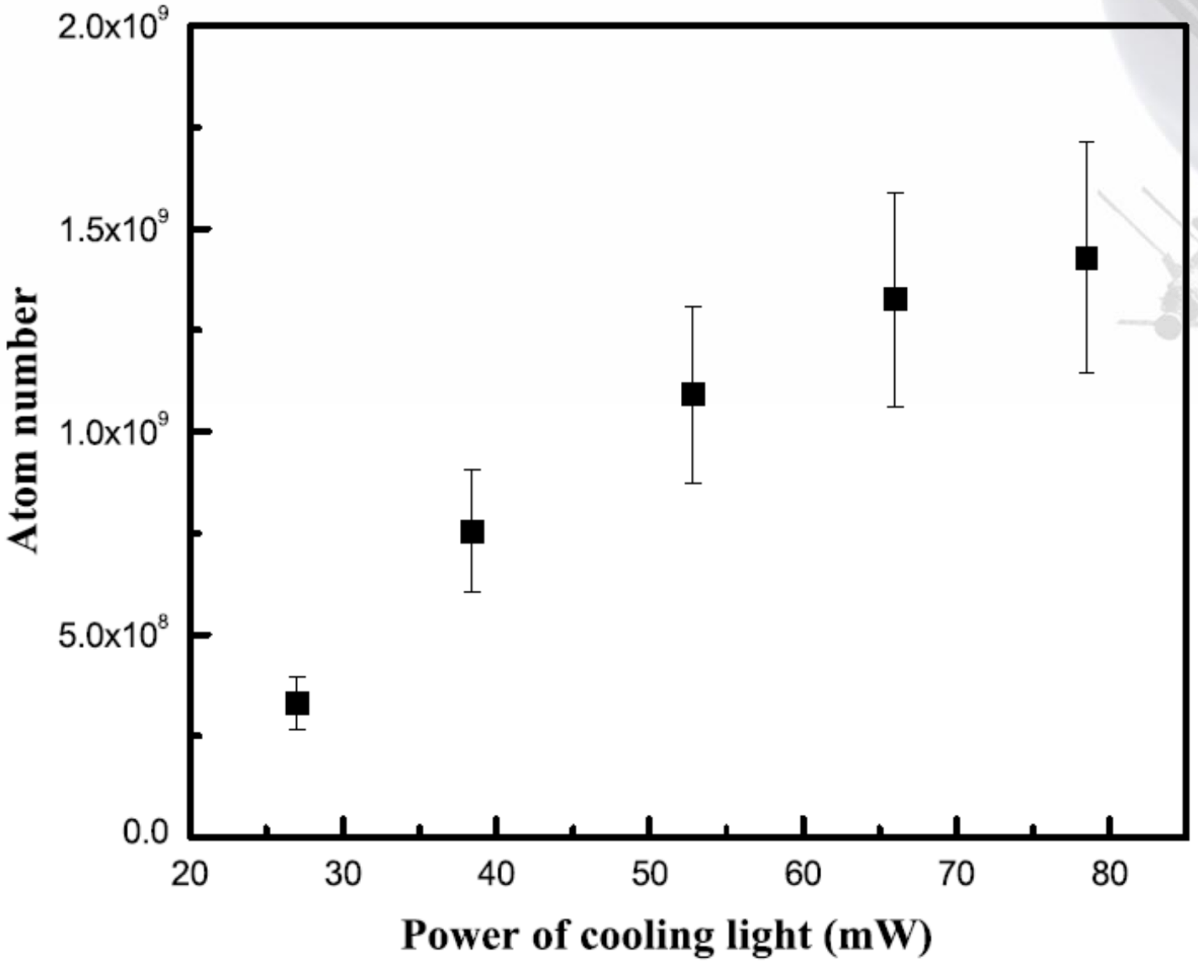
Laser cooling of atoms in diffuse light



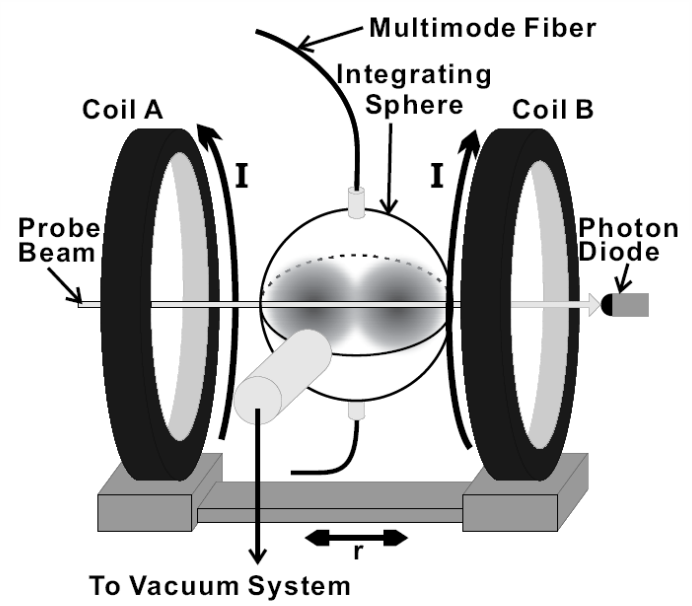
Laser cooling of atoms in diffuse light

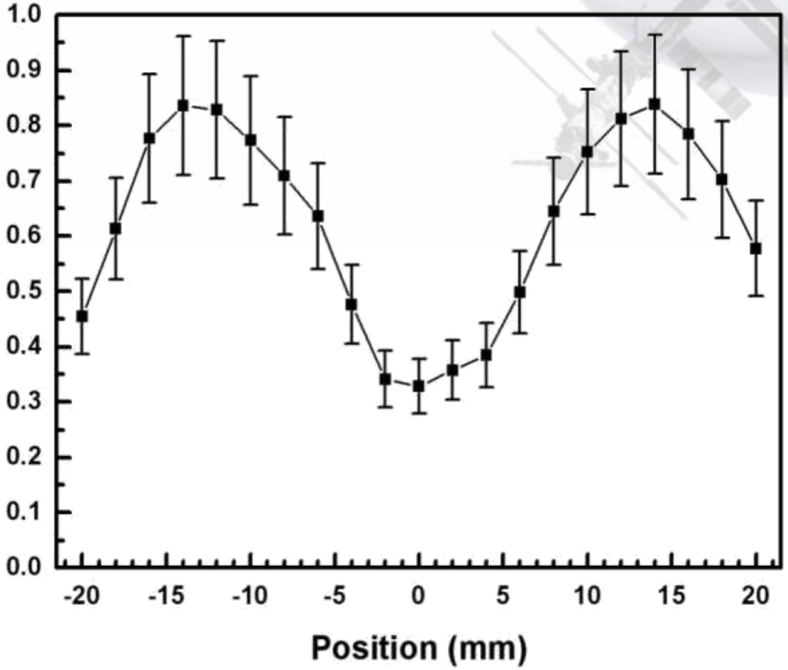


Laser cooling of atoms in diffuse light

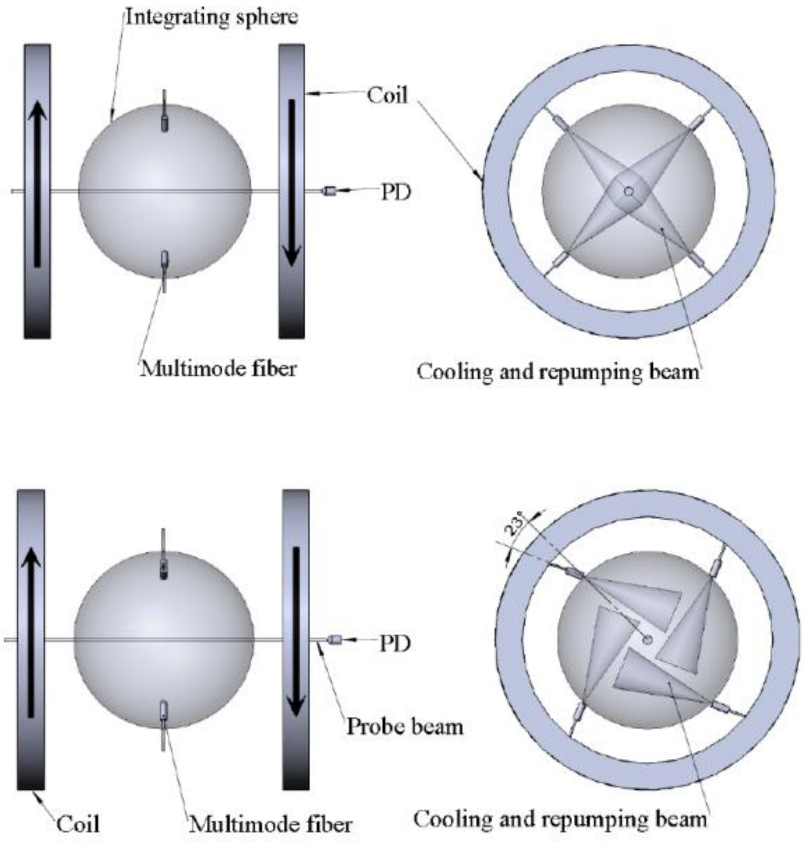


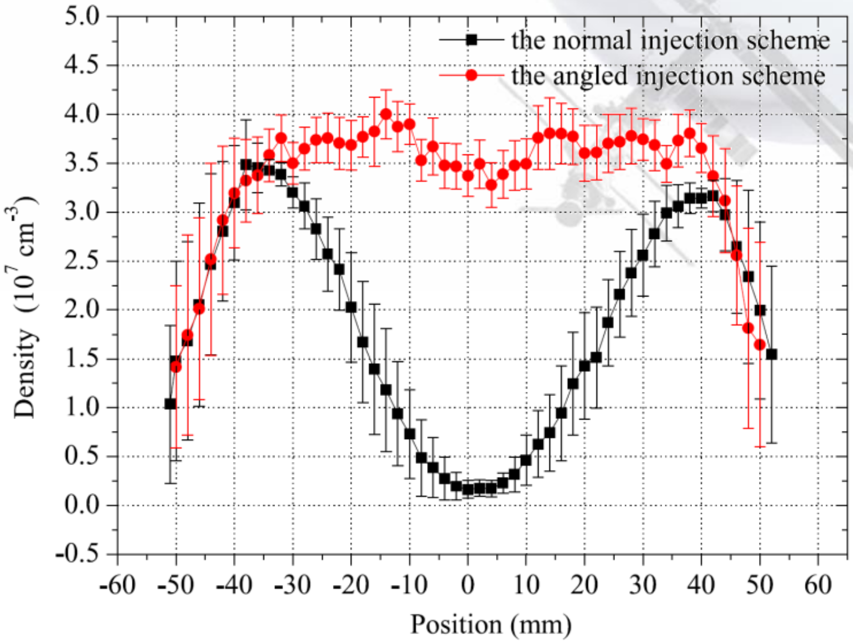
Controlling the distribution of atomic density





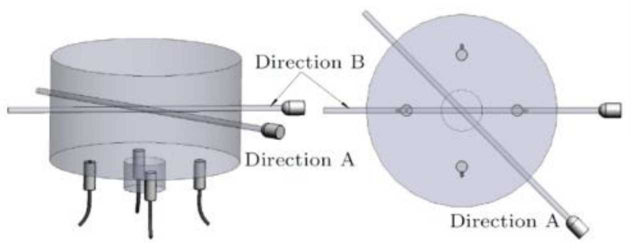
Controlling the distribution of atomic density

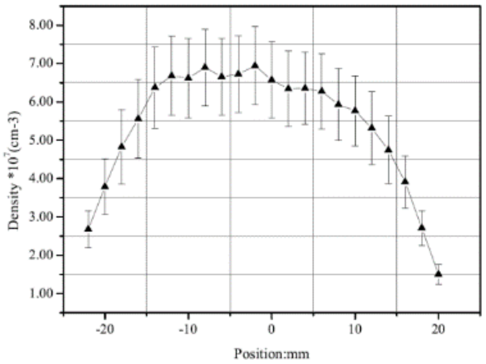




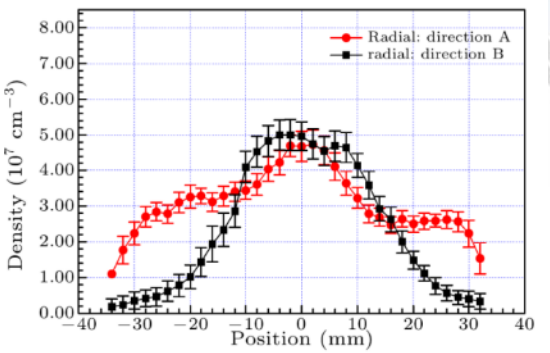
Controlling distribution of cold atom density in a spherical cavity

Controlling the distribution of atomic density





Axial



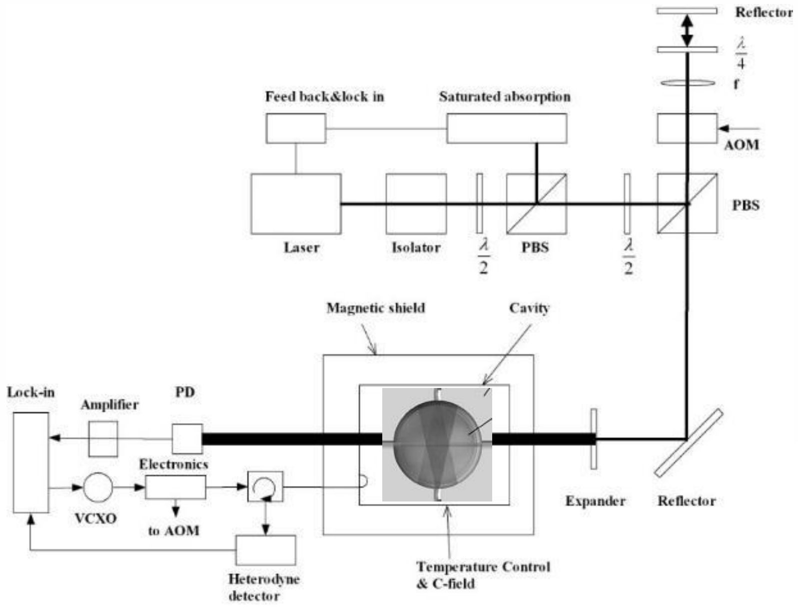
Radial

Controlling distribution of cold atom density in a cylindrical cavity

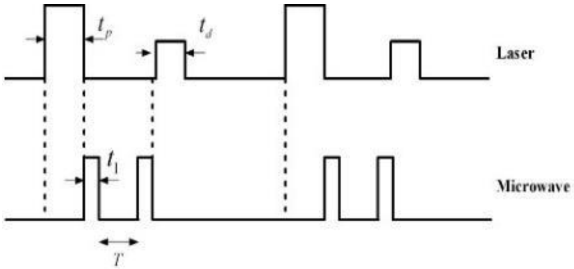
OUTLINE

3. Compact cold atom clock

Atomic clock with diffuse laser cooled atoms



A Pulsed Optically Pumped (POP) scheme: optical pumping, interrogation and detection are separate to avoid light shift.



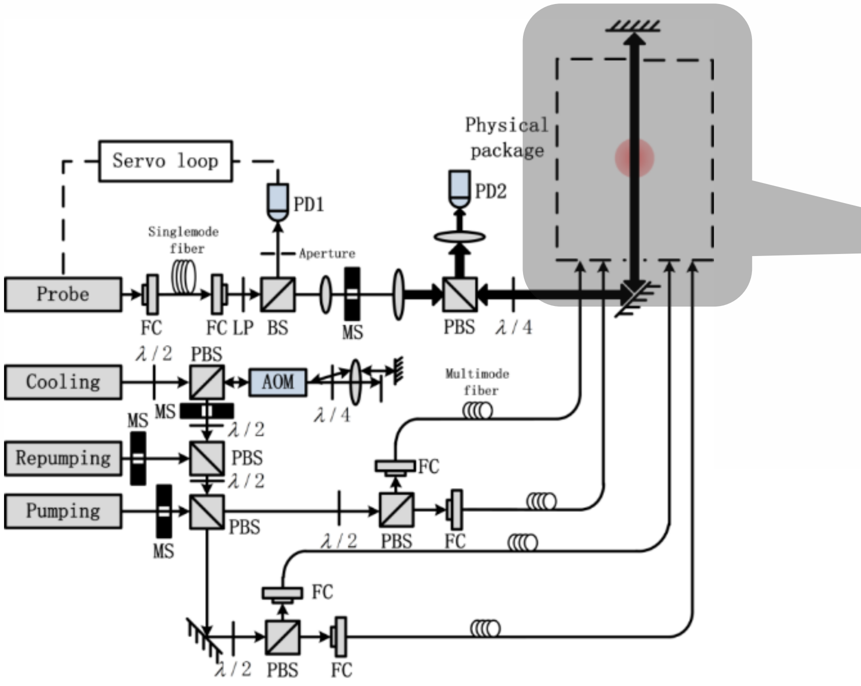
Optical detection time sequence

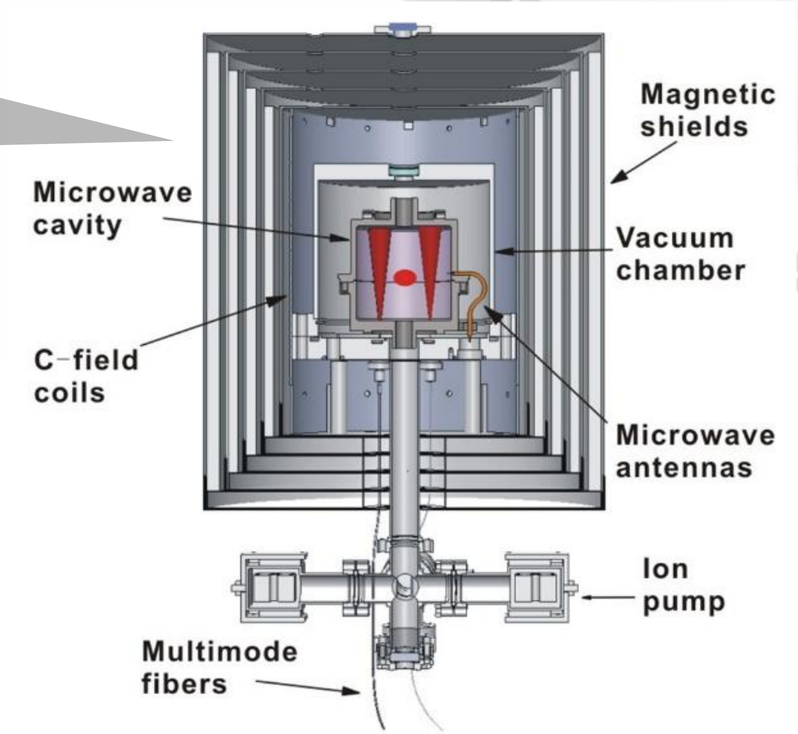
A Pulsed Optically Pumped (POP) scheme with diffuse laser cooled atoms in an integrating sphere (ISCAC)

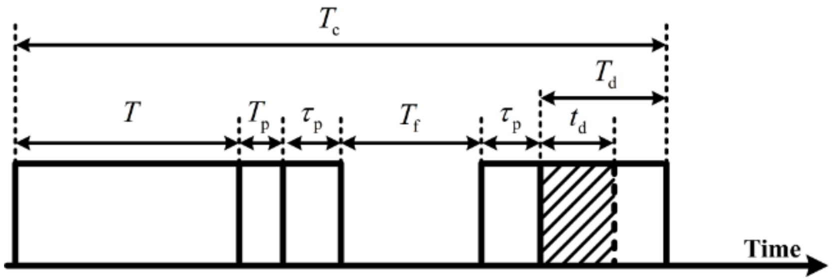
Atoms

	Cs	**Rb**
Atom	^{133}Cs	^{87}Rb
Microwave frequency	9.192632 GHz	6.834682 GHz
D2 line	F=2	F=1
Melting temperature	28.84 °C	38.89 °C
Cooling laser wavelength	852.356 nm	780.241 nm

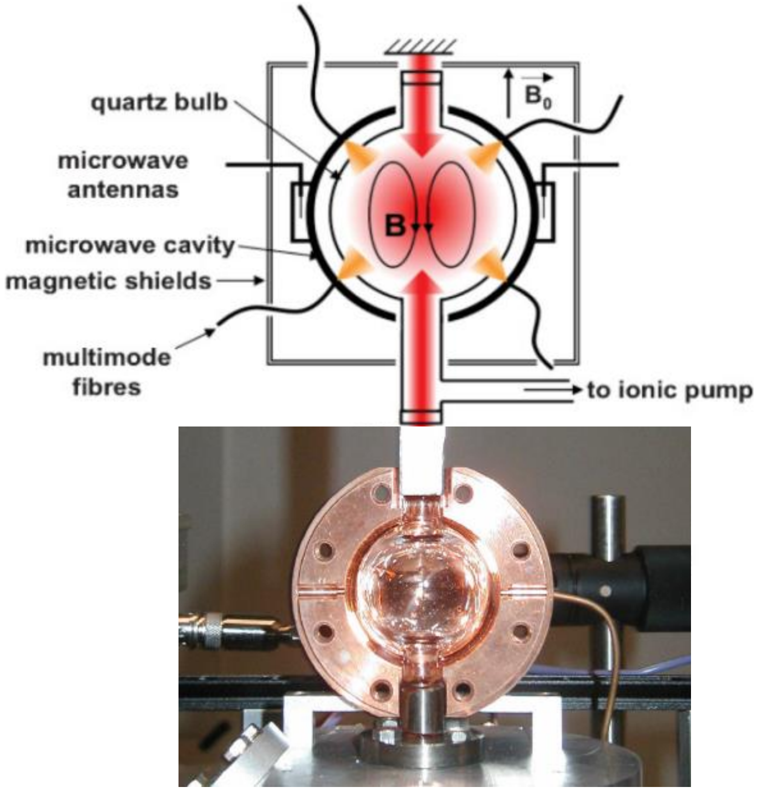
Atomic clock with diffuse laser cooled atoms

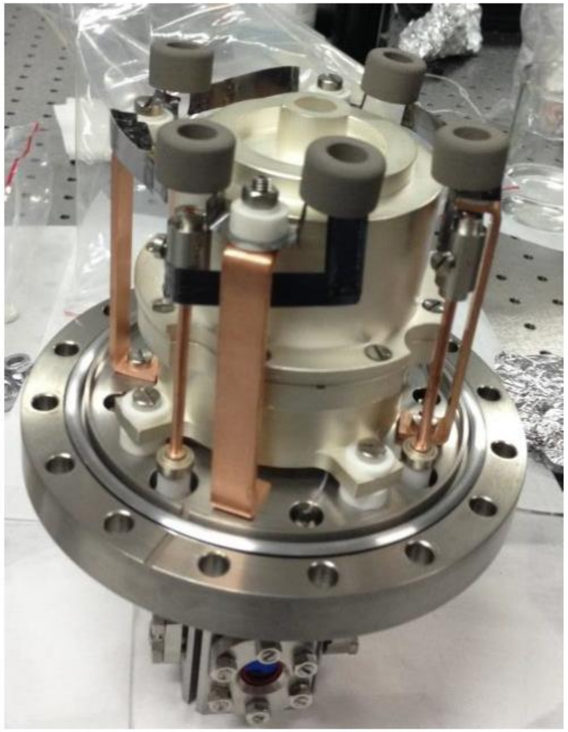






Microwave cavity

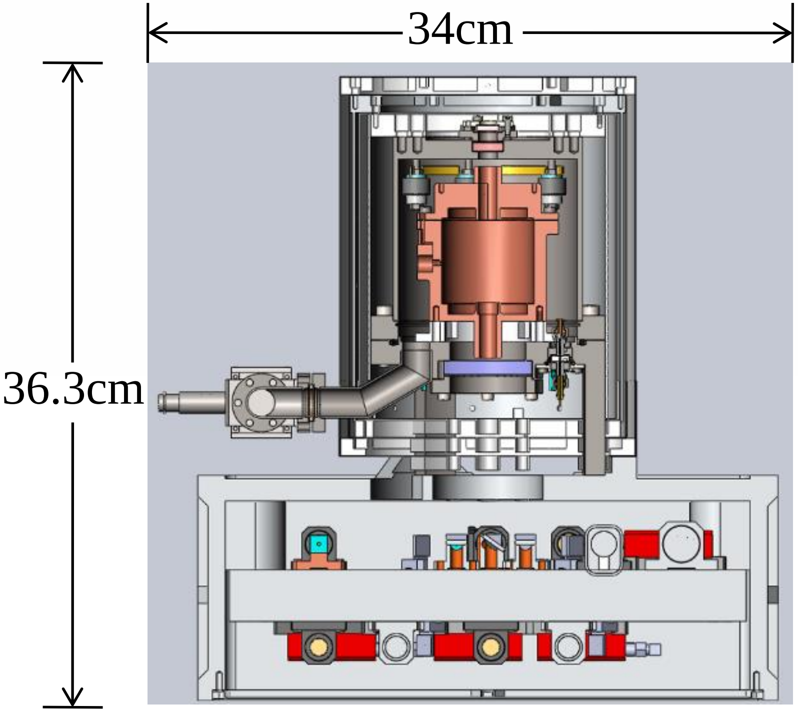


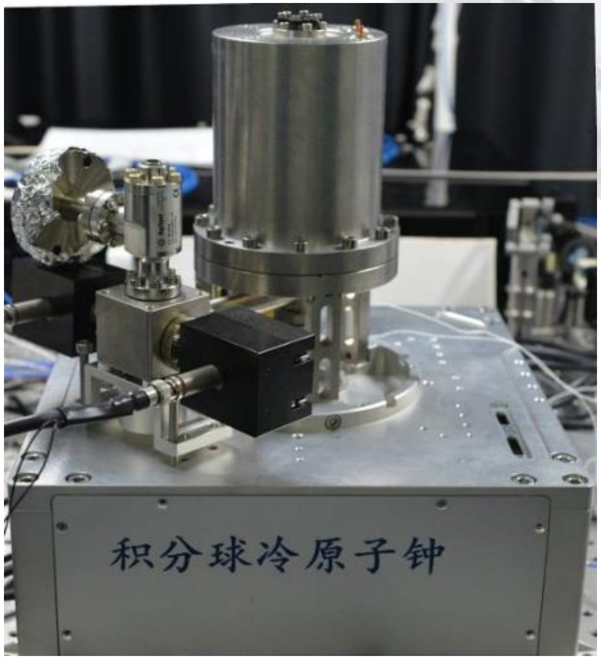


HORACE, Paris

ISCAC, Shanghai

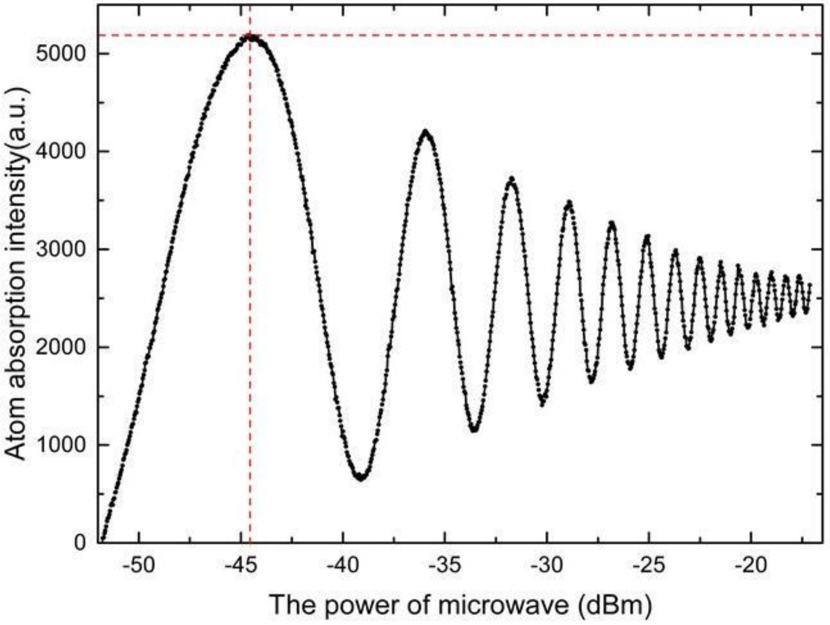
Atoms



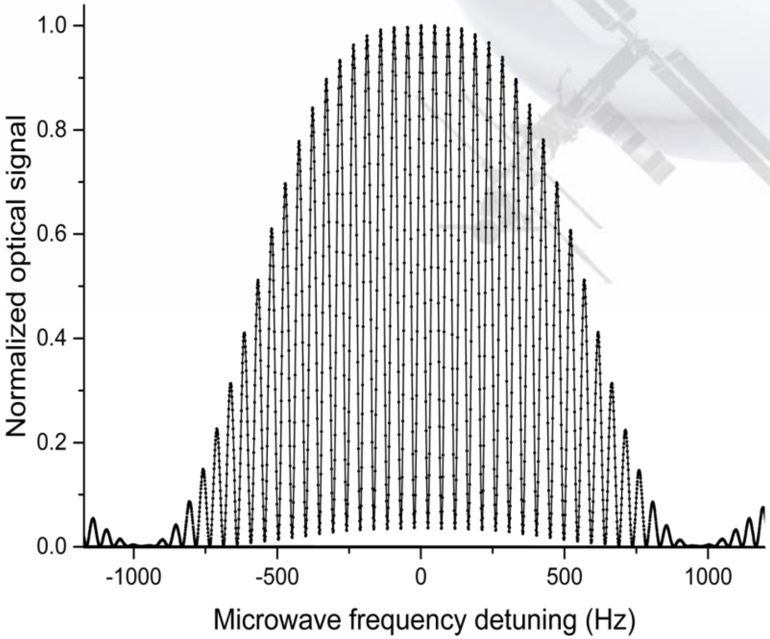


Engineering model

Clock signals

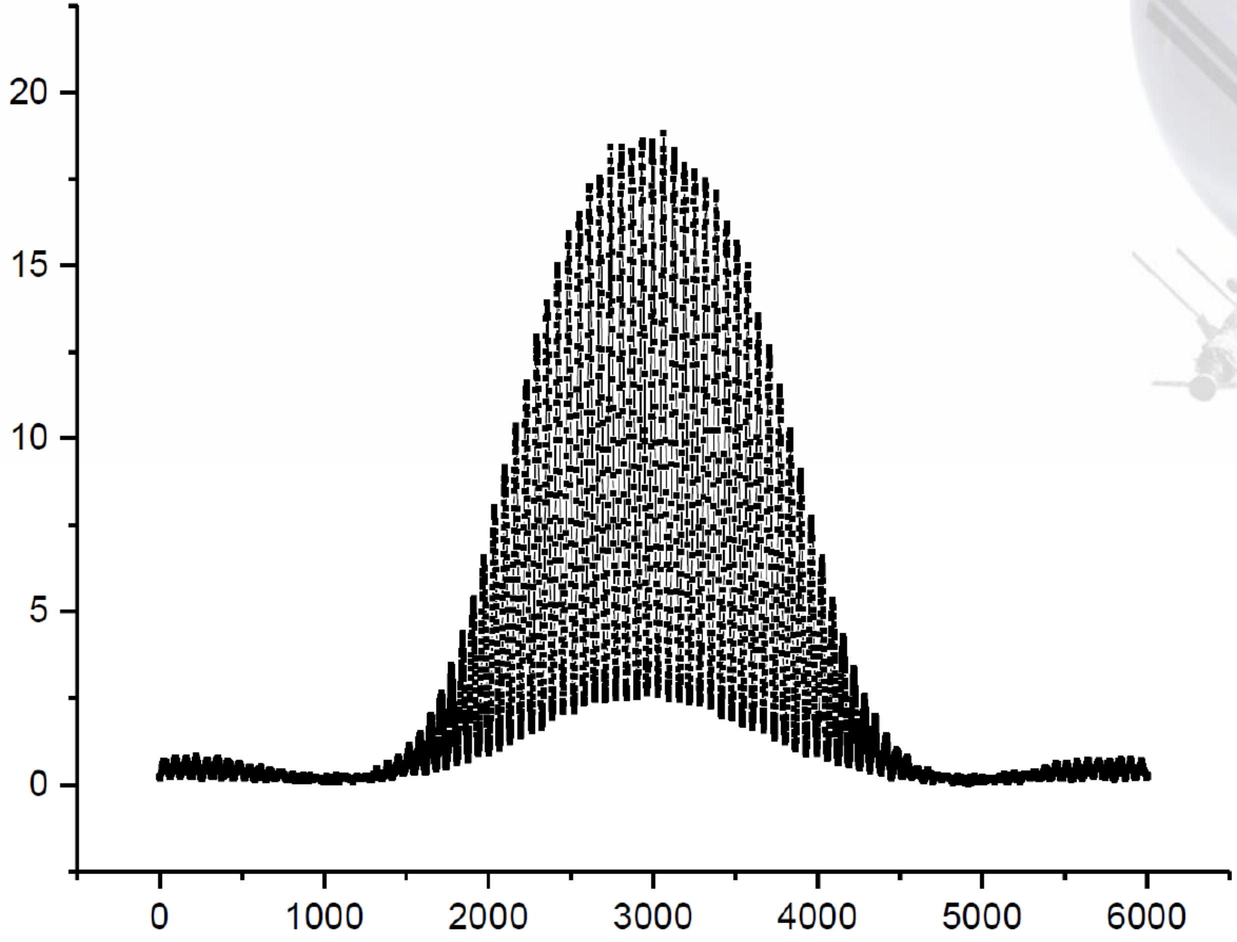


Rabi oscillation



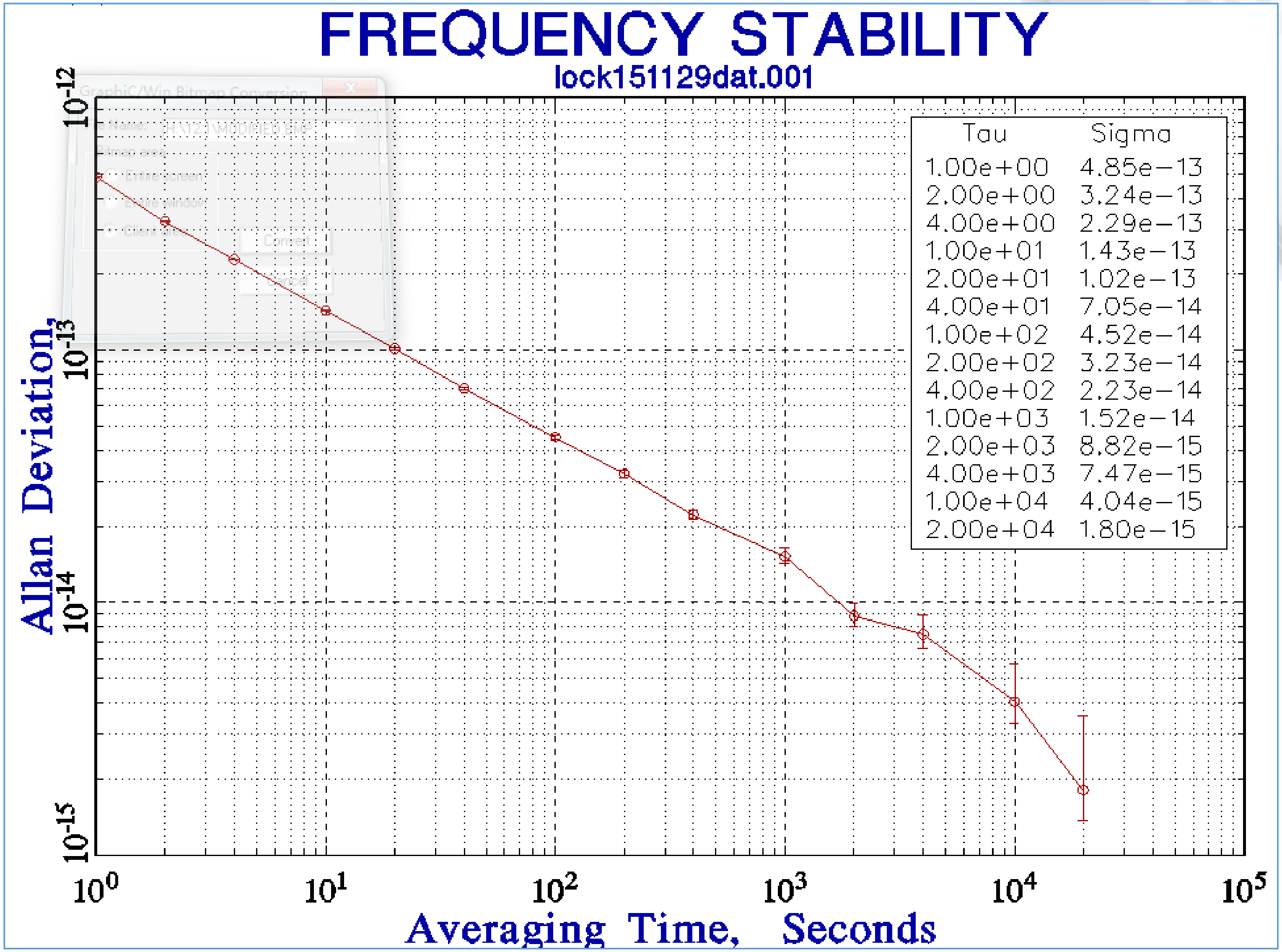
Ramsey fringe with linewidth 20 Hz

Clock signals



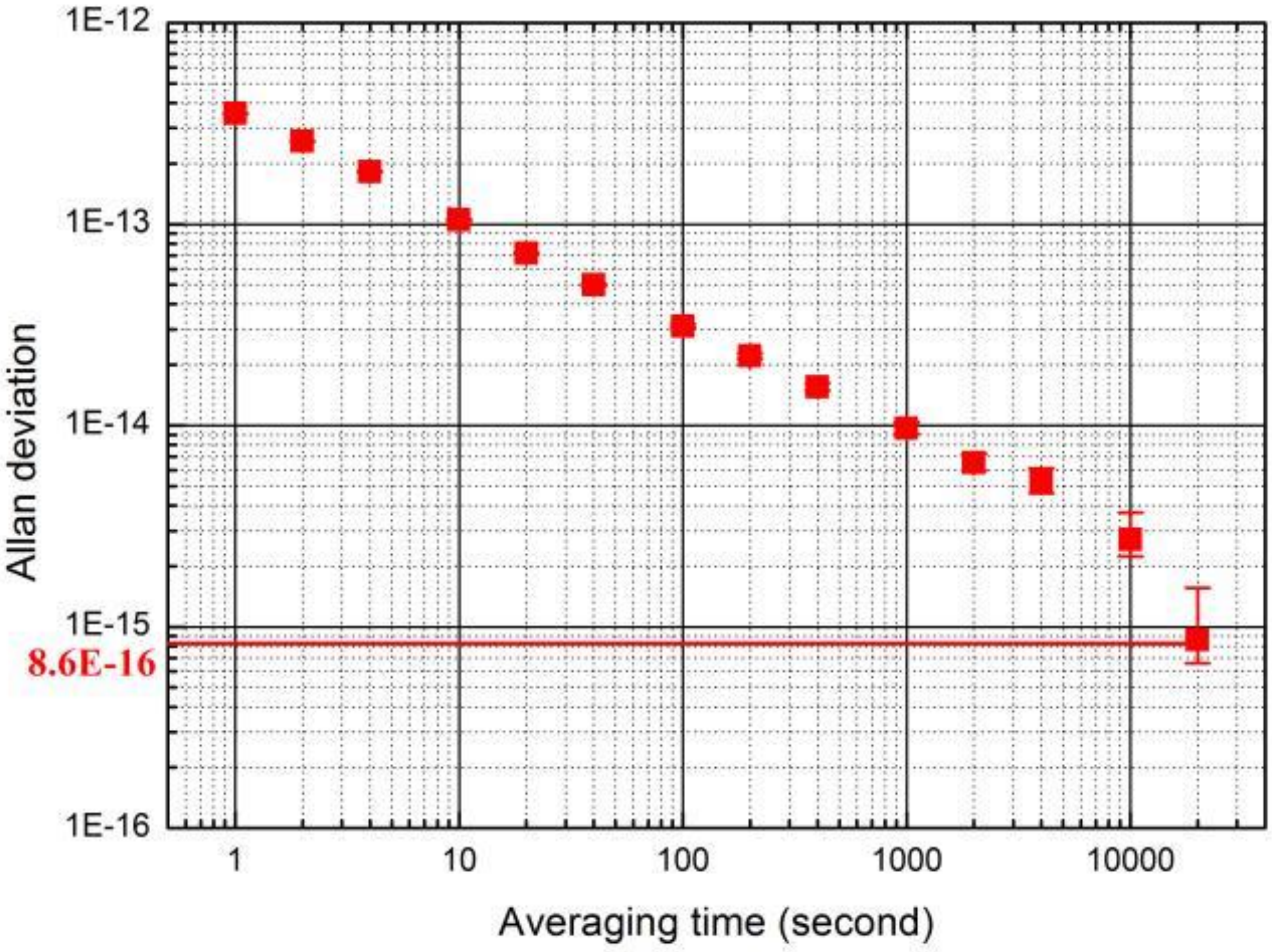
Ramsey fringe with linewidth 13.5 Hz

ISCAC stability



Tau	Sigma
1.00e+00	4.85e−13
2.00e+00	3.24e−13
4.00e+00	2.29e−13
1.00e+01	1.43e−13
2.00e+01	1.02e−13
4.00e+01	7.05e−14
1.00e+02	4.52e−14
2.00e+02	3.23e−14
4.00e+02	2.23e−14
1.00e+03	1.52e−14
2.00e+03	8.82e−15
4.00e+03	7.47e−15
1.00e+04	4.04e−15
2.00e+04	1.80e−15

ISCAC stability

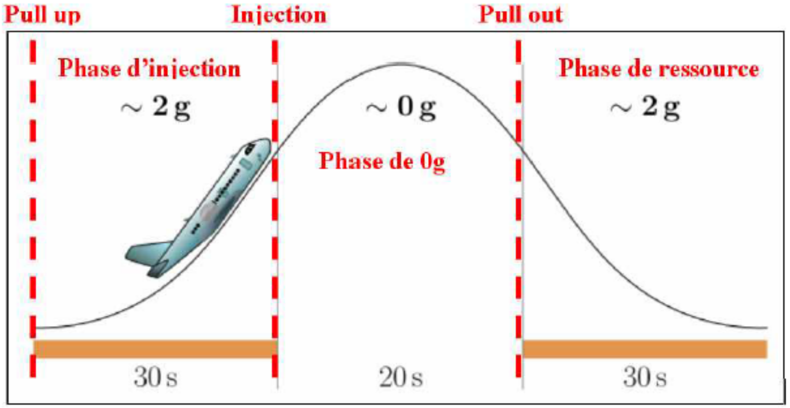


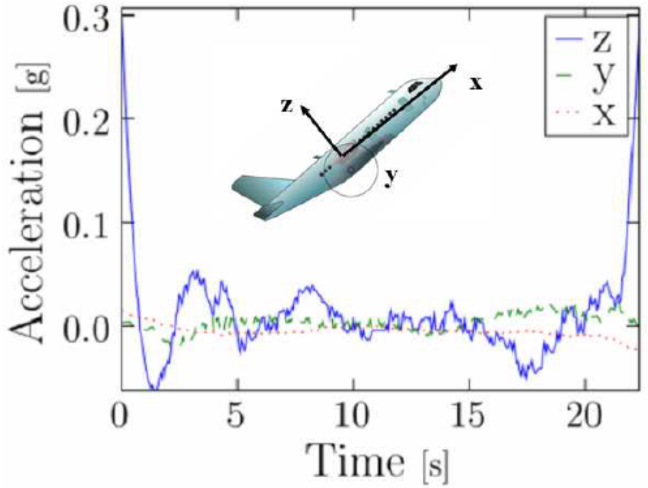
OUTLINE

4. Conclusions

Cold atom clock in microgravity

Possibilité de faire des mesures en « 0g », en « 1g » et en « 2g »



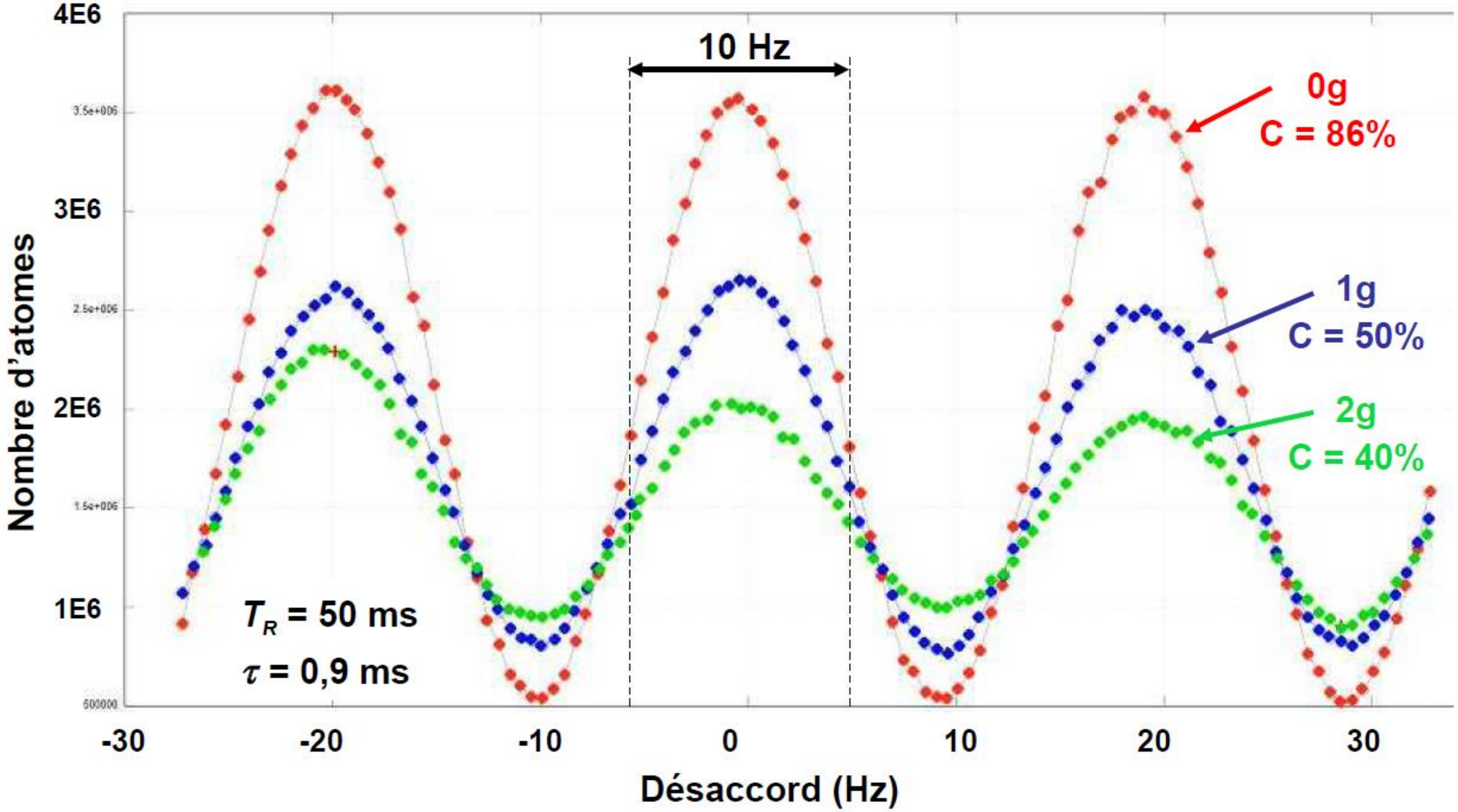


- Environnement accélérométrique relativement perturbé (~ 10^{-2} g suivant Z)
- Environnement magnétique très variable (jusqu'à 1G de variation entre l'entrée et la sortie de la parabole)

3 vols de 31 paraboles chacun – 20 secondes de microgravité par parabole
30 minutes de mesure, par tranche de 20s, en tout et pour tout !!

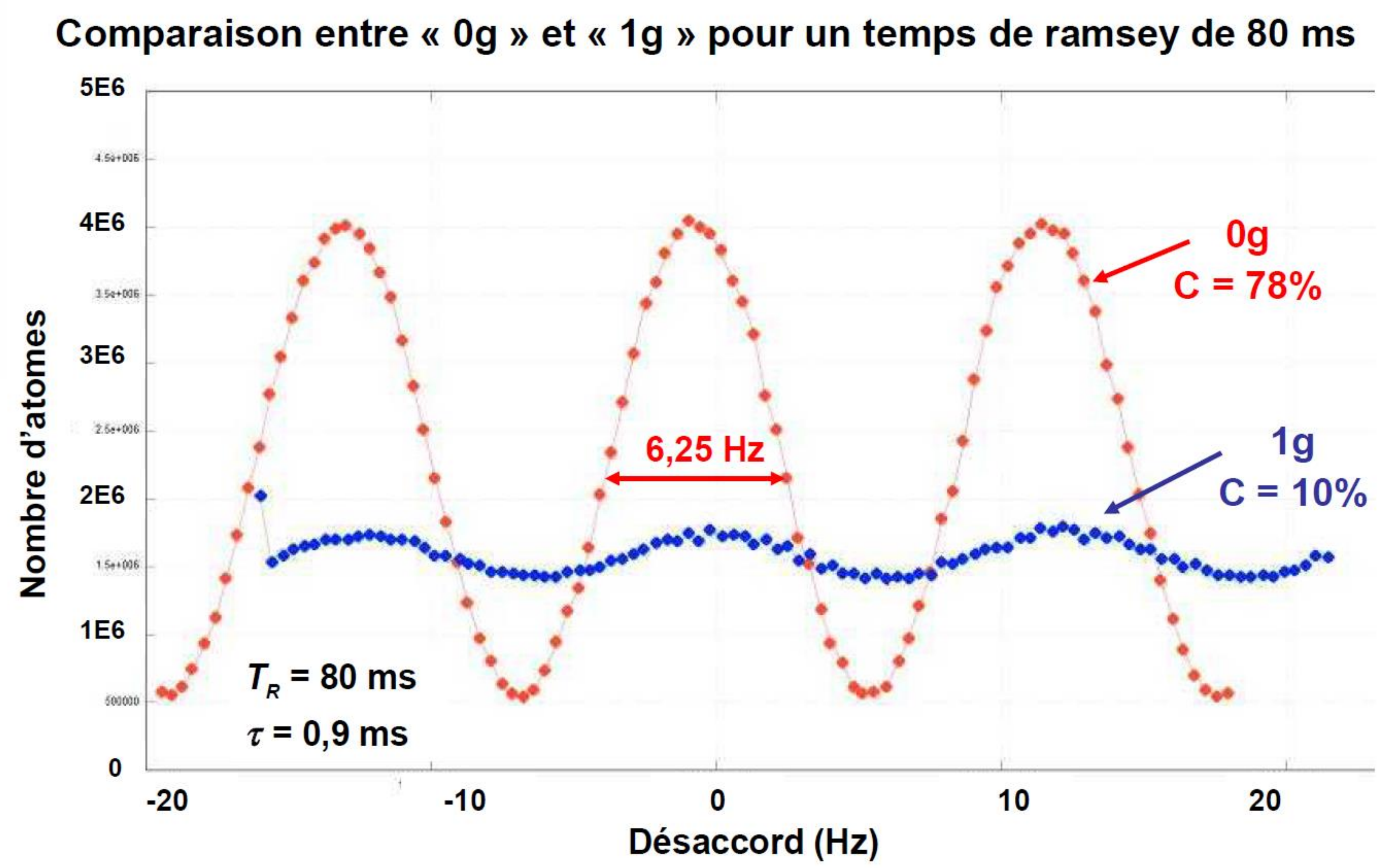
Cold atom clock in microgravity

Comparaison entre « 0g », « 1g » et « 2g » pour un temps de ramsey de 50 ms



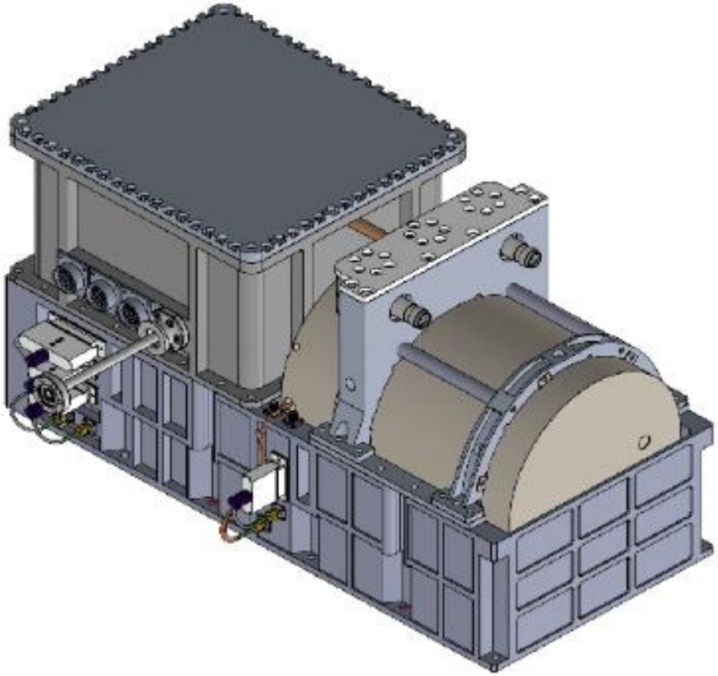
Gain d'un facteur 1,4 sur le nombre d'atomes et d'un facteur 1,7 sur le contraste pour T_R = 50 ms

Cold atom clock in microgravity



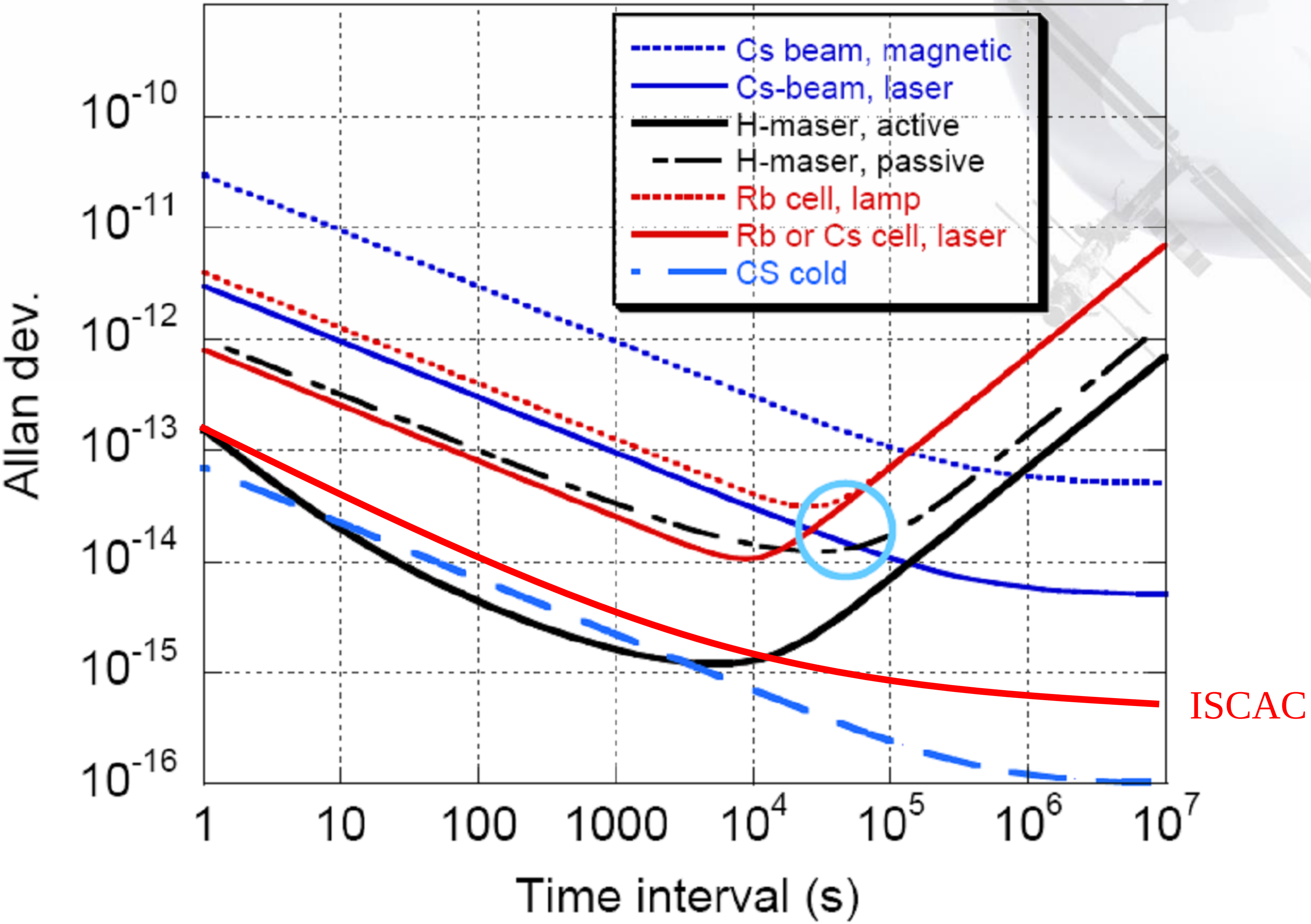
Comparaison entre « 0g » et « 1g » pour un temps de ramsey de 80 ms

Flight model



Flight model of ISCAC

Stability of atomic clocks



Thanks for attention