Non–destructive detection of lattice trapped ^{87}Sr atoms in an optical clock

ACES workshop 2019

B. Ximenez, W. Moreno, Y. Foucault, R. Le Targat, J. Lodewyck

Syrte

October 28, 2019

Outline:

- Overview of the Sr clocks at LNE–SYRTE
- Clock performance, accuracy budget, stability
- Detection scheme: Non-destructive detection

SORBONNE UNIVERSITÉ

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

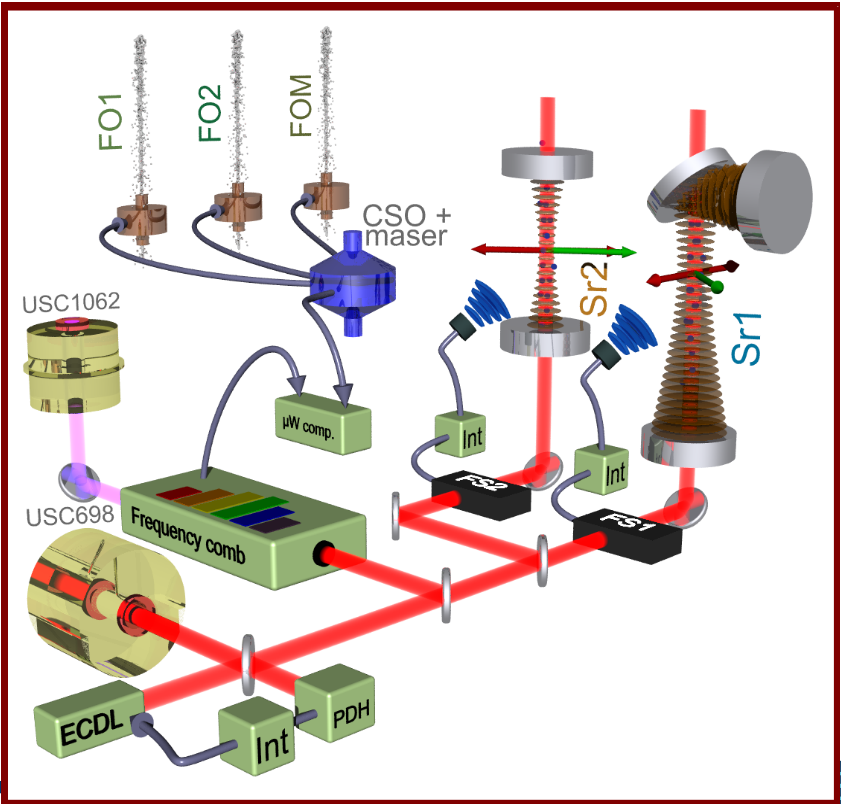
l'Observatoire de Paris SYRTE

Systèmes de Référence Temps-Espace

cnrs

^{87}Sr lattice clock at LNE-SYRTE

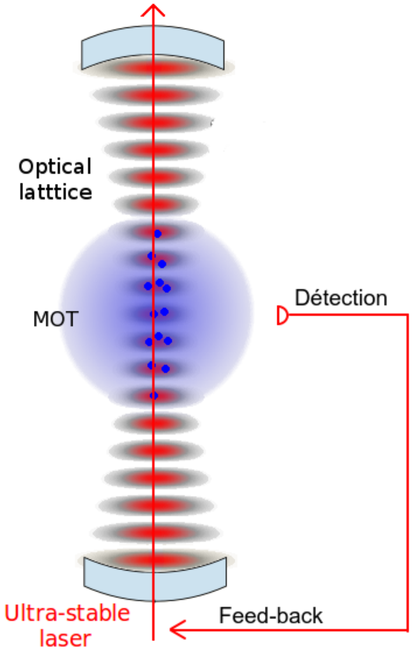
- Trap depth ranging from a few E_r to 1000's E_r
- Optical lattice cavity locked and intensity controled ($\omega_0 = 50\mu$m)
- Two ^{87}Sr clocks probed by a single US laser enabling studies of non-common mode systematics effect
- Comb linked to maser and atomic fountains primary standard



SORBONNE UNIVERSITÉ
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS
Systèmes de Référence Temps-Espace

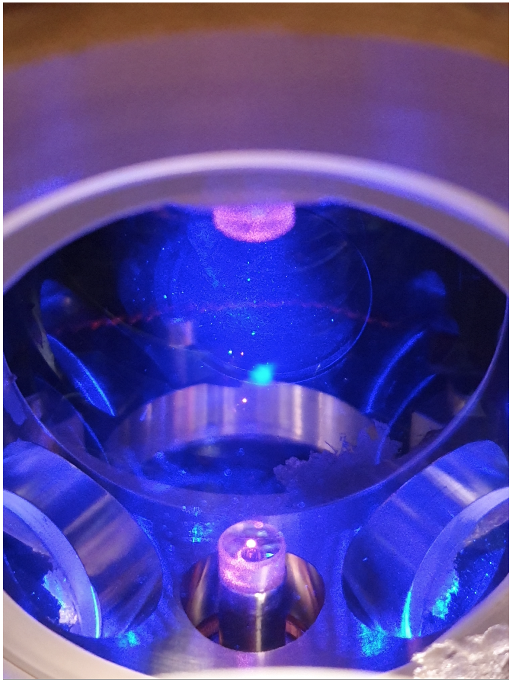
^{87}Sr lattice clock at LNE-SYRTE

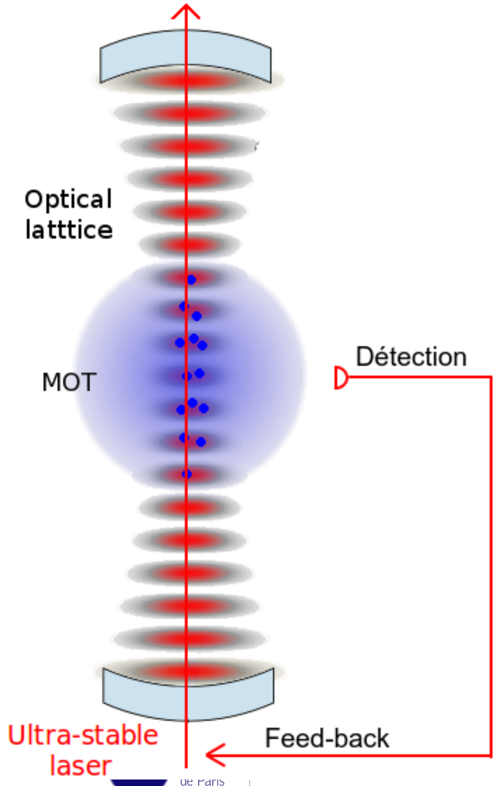
- Atoms loaded in a 3D MOT from Zeeman–slowed atomic flux
- From the MOT, cold atoms are loaded in a 1D lattice trap
- Further control of atomic motion and state preparation



SORBONNE UNIVERSITÉ
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE
l'Observatoire de Paris SYRTE
Systèmes de Référence Temps-Espace
cnrs

^{87}Sr lattice clock at LNE-SYRTE





SORBONNE UNIVERSITÉ

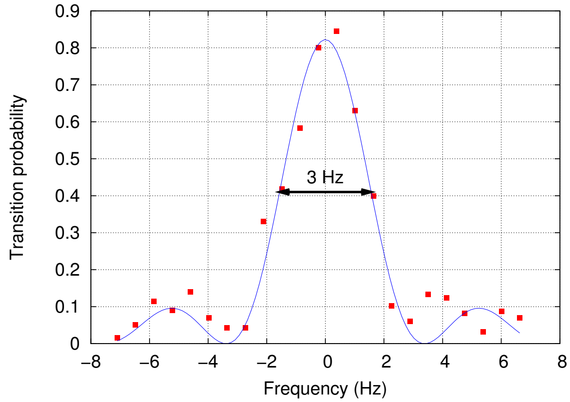
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

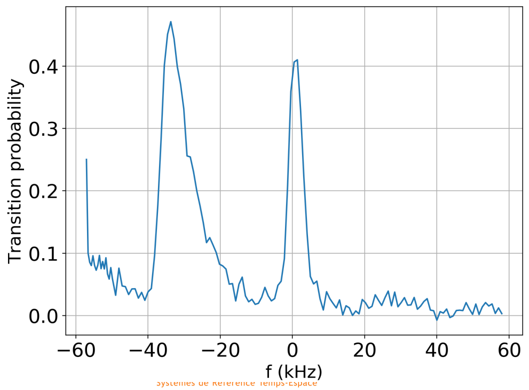
Systèmes de Référence Temps-Espace

cnrs

Clock performance

Effect	**Uncertainty** in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Density shift	8
Line pulling	6
Background collisions	5
Probe light	0.4
Total uncertainty	**1.7** $\times 10^{-17}$





- $T_r \approx 2\mu$K and $n_z \approx 0$
- Fourier limited linewidth
- $\sigma = 7 \times 10^{-16}/\sqrt{\tau}$
- Allows systematics study at the low of 10^{-17}

SORBONNE UNIVERSITÉ

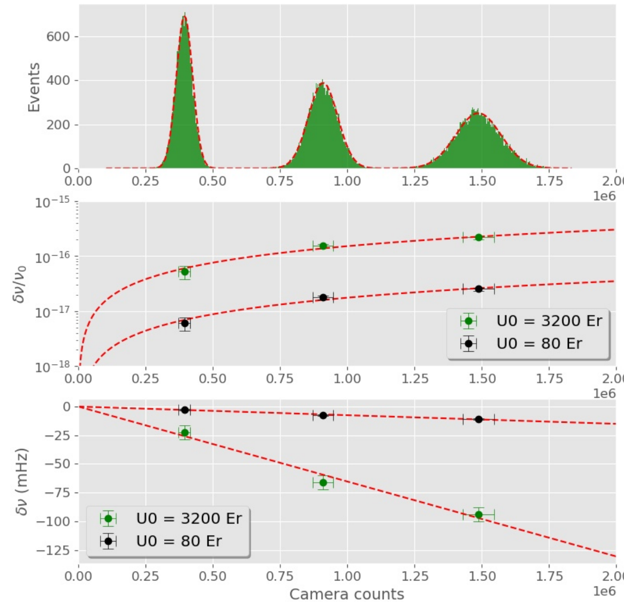
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Clock performance

Effect	**Uncertainty** in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Density shift	8
Line pulling	6
Background collisions	5
Probe light	0.4
Total uncertainty	**1.7** $\times 10^{-17}$

- $T_r \approx 2\mu$K and $n_z \approx 0$
- Fourier limited linewidth
- $\sigma = 7 \times 10^{-16}/\sqrt{\tau}$
- Allows systematics study at the low of 10^{-17}

Cold collision shift:

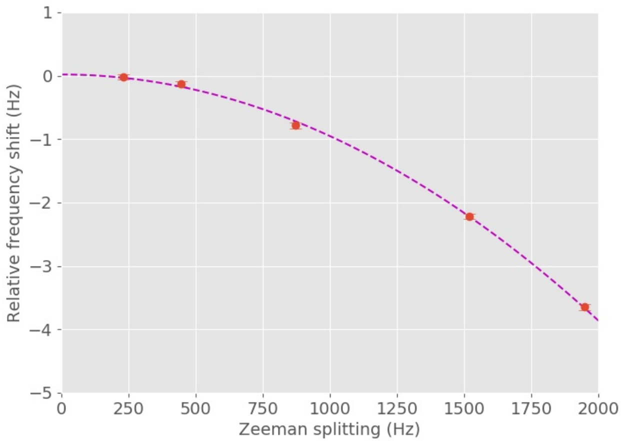


Clock performance

Effect	Uncertainty in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Density shift	8
Line pulling	6
Background collisions	5
Probe light	0.4
Total uncertainty	**1.7** $\times 10^{-17}$

- $T_r \approx 2\mu$K and $n_z \approx 0$
- Fourier limited linewidth
- $\sigma = 7 \times 10^{-16}/\sqrt{\tau}$
- Allows systematics study at the low of 10^{-17}

Quadratic Zeeman shift:



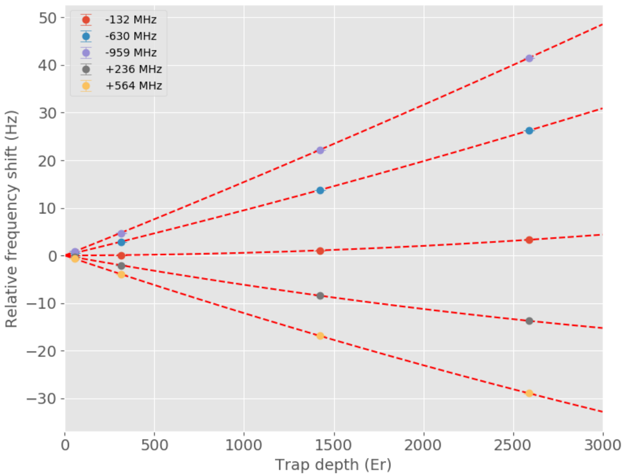
SORBONNE UNIVERSITÉ
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS
l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

Clock performance

Effect	**Uncertainty** in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Density shift	8
Line pulling	6
Background collisions	5
Probe light	0.4
Total uncertainty	**1.7** $\times 10^{-17}$

- $T_r \approx 2\mu$K and $n_z \approx 0$
- Fourier limited linewidth
- $\sigma = 7 \times 10^{-16}/\sqrt{\tau}$
- Allows systematics study at the low of 10^{-17}

Light shift:



SORBONNE UNIVERSITÉ

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

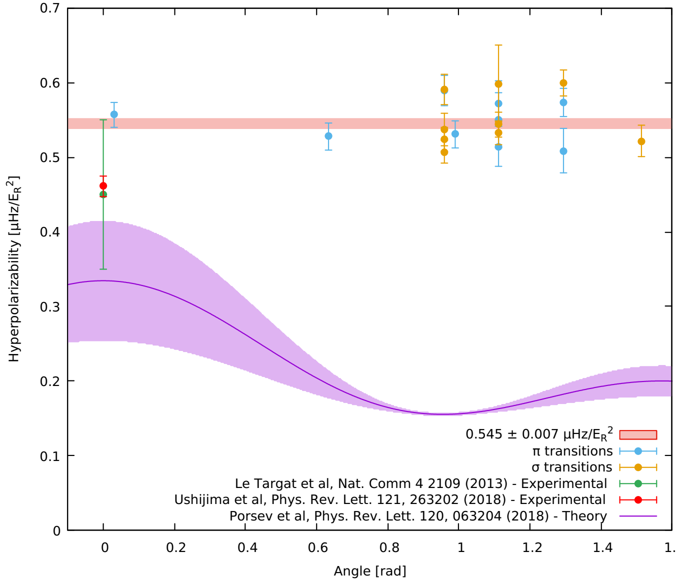
l'Observatoire de Paris | SYRTE
Systèmes de Référence Temps-Espace

Clock performance

Effect	Uncertainty in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Density shift	8
Line pulling	6
Background collisions	5
Probe light	0.4
Total uncertainty	**1.7** $\times 10^{-17}$

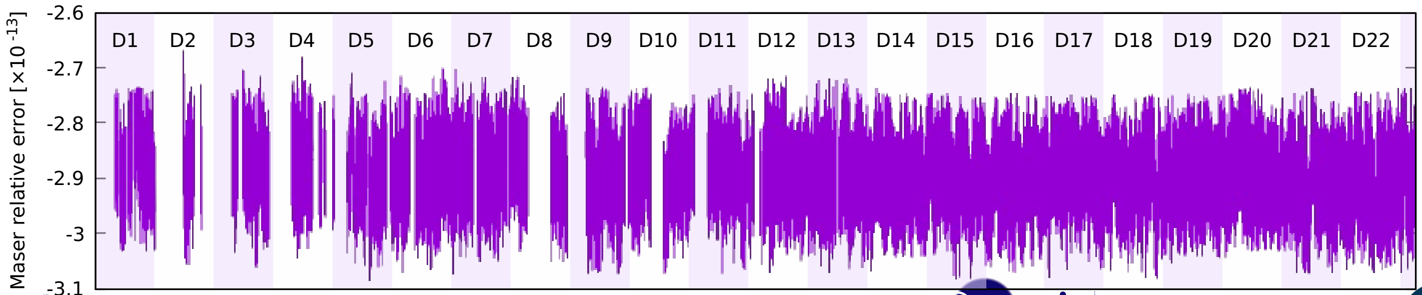
- $T_r \approx 2\mu\mathrm{K}$ and $n_z \approx 0$
- Fourier limited linewidth
- $\sigma = 7 \times 10^{-16}/\sqrt{\tau}$
- Allows systematics study at the low of 10^{-17}

Hyperpolarizability:



Clock performance – local and international comparisons

- Regularly comparing clocks with fairly automated instrumentation
- Enables fixing technical problems affecting the clock at the 10^{-17} range
- Robustness of instrumentation leading to high uptime $\approx 60 - 90\%$



SORBONNE UNIVERSITÉ LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace cnrs

TAI contribution

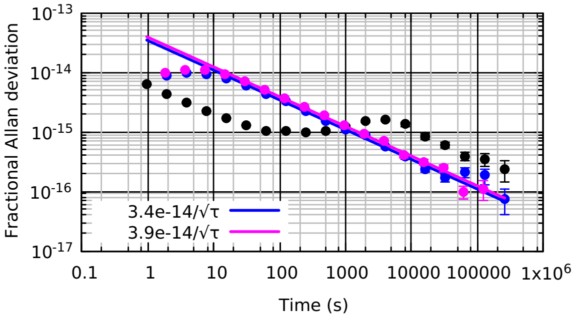
- First optical clock contribution to TAI (thanks, Michel Abgrall):

3 - Duration of the TAI scale interval d.

Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainties.
All values are expressed in 10**-15 and are valid only for the stated period of estimation.

Standard	Period of Estimation	d	uA	uB	ul/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Steer	Note
PTB-CS1	57784 57809	-18.71	6.00	8.00	0.00	0.15	10.00	PFS/NA		T148	8.	Y	(1)
PTB-CS2	57784 57809	-0.28	3.00	12.00	0.00	0.15	12.37	PFS/NA		T148	12.	Y	(1)
SYRTE-FO2	57784 57809	-1.30	0.40	0.32	0.11	0.32	0.61	PFS/NA		T301	0.23	Y	(2)
SYRTE-FORb	57784 57809	-0.91	0.20	0.29	0.11	0.32	0.49	0.7	[1]	T328	0.34	Y	(2)
SYRTE-SR2	56954 56964	0.81	0.20	0.04	0.10	0.53	0.57	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57179 57199	0.46	0.20	0.04	0.10	0.28	0.36	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57469 57479	-1.39	0.25	0.20	0.11	0.53	0.63	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57539 57554	-1.24	0.30	0.04	0.11	0.37	0.49	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SRB	57539 57554	-1.22	0.25	0.05	0.10	0.37	0.46	0.5	[1]	[2]	0.05	N	(3)
PTB-CSF2	57779 57809	-1.36	0.09	0.20	0.03	0.13	0.26	PFS/NA		T287	0.41	Y	(4)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 03 MAR. 2017 by LNE-SYRTE
(3) Report 16 AUG. 2016 by LNE-SYRTE
(4) Report 02 MAR. 2017 by PTB
[1] CIPM Recommendation 2 (CI-2015) : Updates to the list of standard frequencies in Proces-Verbaux des Seances du Comite International des Poids et Mesures, 104th meeting (2015), 2016, 47 p.
[2] Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock. Lodewyck J., Bilicki S., Bookjans E., Robyr J.L., Shi C., Vallet G., Le Targat R., Nicolodi D., Le Coq Y., Guéna J., Abgrall M., Rosenbusch P. and Bize S.. Metrologia 53(4), 1123, 2016.

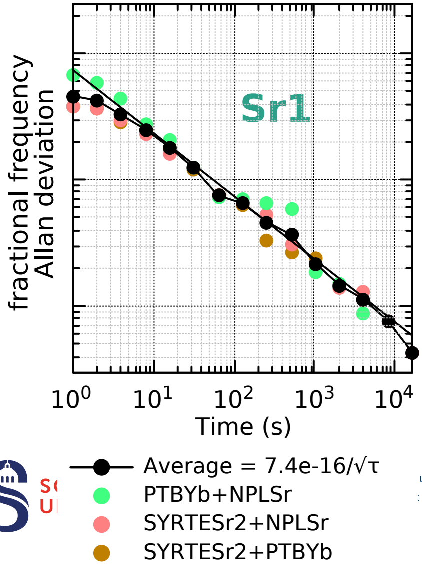


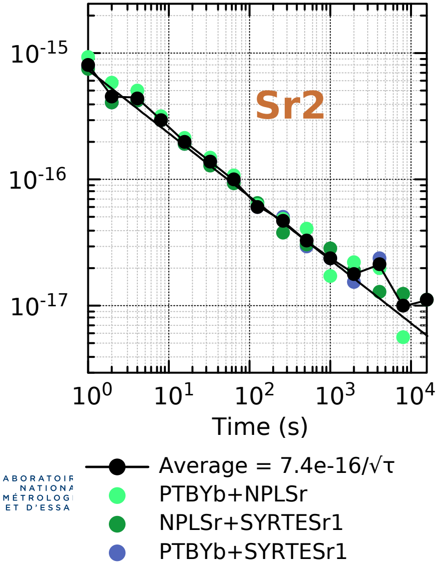
- First real time contribution Dec/2018: 10 days clock operation together with NICT
- SYRTE–Sr x NICT–Sr at 1^{-16} level via GPS-IPPP
- Other contributions for TAI: NIST–Sr, NIST–Yb

SORBONNE UNIVERSITÉ
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS
l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

Clock performance – local and international comparisons

- Fiber links between SYRTE, NPL and PTB: remote comparison of optical clocks
- Regular comparison campaigns since 2015

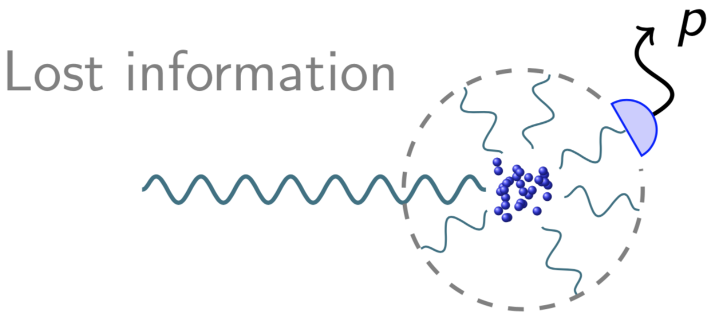




l'Observatoire de Paris SYRTE
Systèmes de Référence Temps-Espace

Detection scheme: non–destructive detection

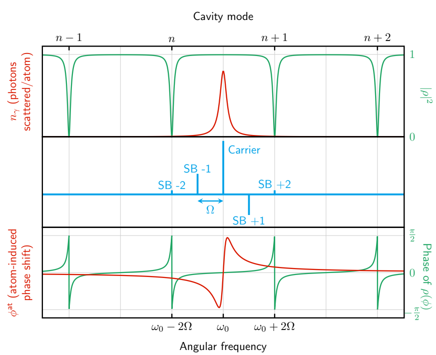
- Fluorescence–based detection
- Lost of atoms: need to reload the trap

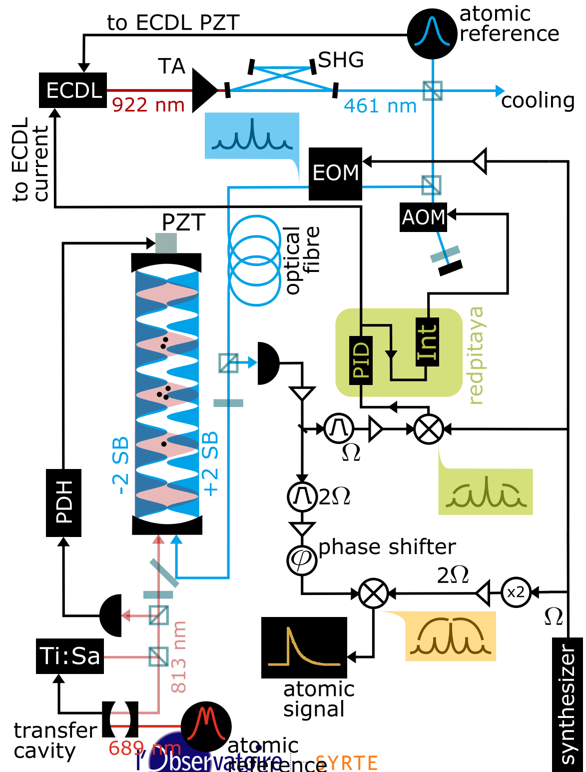


A phase-shift sensitive detection scheme can preserve the atoms in the trap!

Detection scheme: non–destructive detection

- Off resonance 461 nm blue probe phase modulated
- Coupled in the lattice cavity simultaneously with 813 nm
- Lock the cavity and measure the phase shift due to the atoms





SORBONNE UNIVERSITÉ

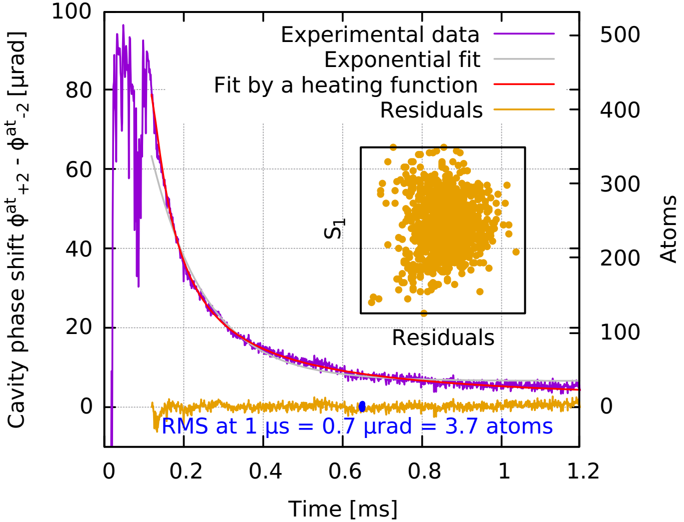
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

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

cnrs

Detection scheme: non–destructive detection

- Detection resolution: $\delta N = 3.7$ atoms
- Scattering of 38 photons per atom
- Shot noise limit: $\delta N \approx 0.7$
  Allows for recycling the atoms for the next interrogation



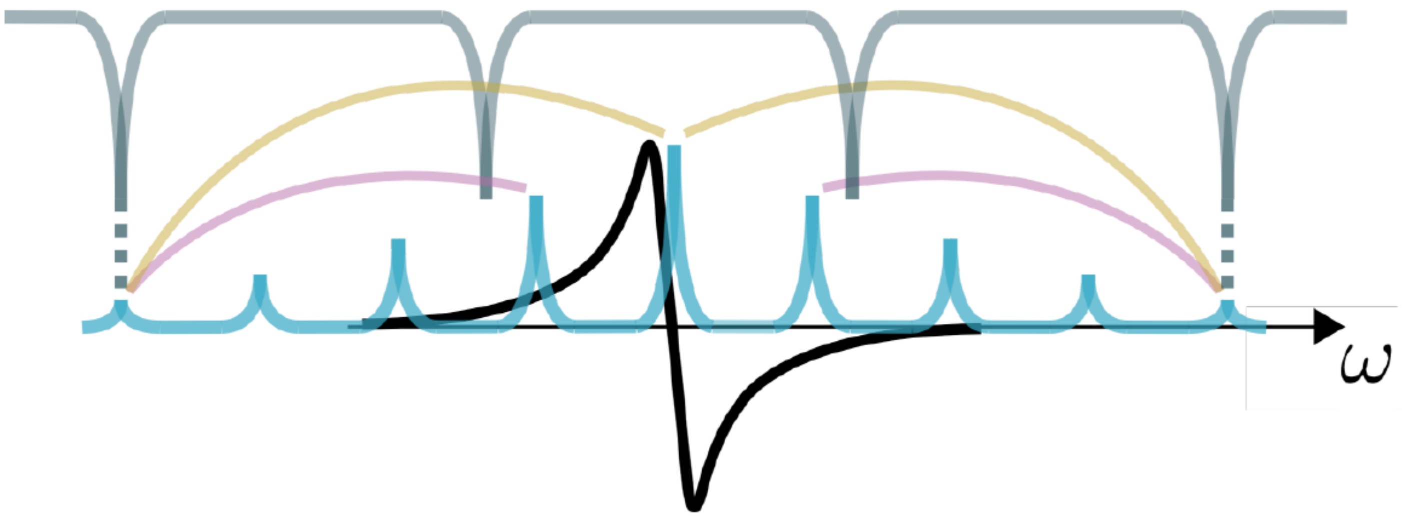
SORBONNE UNIVERSITÉ
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE
l'Observatoire de Paris SYRTE
Systèmes de Référence Temps-Espace
cnrs

Detection scheme: non–destructive detection, next steps

- Detection noise usually fundamentally limited by projection noise (projective measurements)

$$\delta \mathrm{N}_{QPN} \approx \sqrt{N}$$

- Overcome QPN: spin squeeze
- Reduced blue probe intensity by using 3rd and 4th side bands



Conclusions

- Robust clock operation: able to run the clock for weeks on demand
- Stability at the high 10^{-16} at 1 s, allowing for frequency resolution in the low 10^{-17} and systematics control at the same level
- Remote comparisons and TAI contributions
- Non–destructive detection, Dick effect reduction
- Moving towards quantum regime, spin squeeze to overcome QPN

SORBONNE UNIVERSITÉ
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE
l'Observatoire de Paris SYRTE
Systèmes de Référence Temps-Espace
cnrs

Acknowledgements:

- Sr clock team at SYRTE: J. Lodewyck, R. Le Targat, Y. Foucault, W. Moreno and (former member) G. Vallet
- Comb team at SYRTE: R. Le Targat, H. Alvarez–Martinez, C. Baerentsen
- Hg clock team at SYRTE: S. Bize, M. Andia, V. Cambier, C. G. Changlei

Thank you very much !

SORBONNE UNIVERSITÉ

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

l'Observatoire de Paris SYRTE

Systèmes de Référence Temps-Espace

cnrs