Métrologie quantique avec des horloges optiques

Jérôme Lodewyck, Haosen Shang, Miguel A. Cifuentes, R. Le Targat

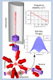
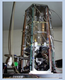
l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

Optical clocks: going to optical transitions

Microwave clocks	⇒	Optical clocks

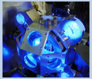
Cold atom clocks

- Cs and Rb atomic fountains

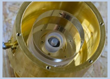
⇒

- Optical lattice cocks (Sr, Hg, Yb)



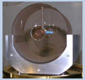

Ultra-stable oscillators

- Maser, CSO, Quartz

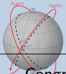
⇒

- Cavities, Spectral hole burning



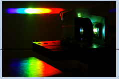

Comparison tools

- Satellites (GNSS)



⇒

- Optical fiber links, frequency combs

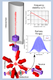
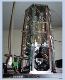



Optical clocks: going to optical transitions

Microwave clocks ⇒ **Optical clocks**

Cold atom clocks

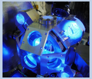
- Cs and Rb atomic fountains

10^{-16}

⇒

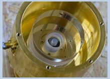
- Optical lattice cocks (Sr, Hg, Yb)




10^{-17} to 10^{-18}

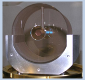
Ultra-stable oscillators

- Maser, CSO, Quartz

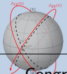
⇒

- Cavities, Spectral hole burning




Comparison tools

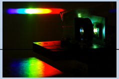
- Satellites (GNSS)



10^{-16} @ 1 week

⇒

- Optical fiber links, frequency combs

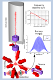
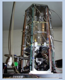
10^{-19} @ 3 hour

Optical clocks: going to optical transitions

Microwave clocks ⇒ **Optical clocks**

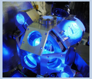
Cold atom clocks

- Cs and Rb atomic fountains

10^{-16} ⇒

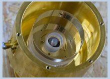
- Optical lattice cocks (Sr, Hg, Yb)




10^{-17} to 10^{-18}

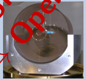
Ultra-stable oscillators

- Maser, CSO, Quartz

⇒

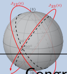
- Cavities, Spectral hole burning




Open questions
↗ Ultimate performances?
↗ Operational?

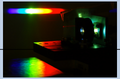
Comparison tools

- Satellites (GNSS)



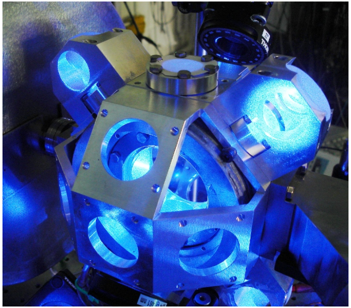
10^{-16} @ 1 week ⇒

- Optical fiber links, frequency combs

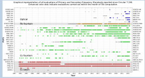
10^{-19} @ 3 hour

Sr optical lattice clocks at LNE-SYRTE



Metrology

- Clock comparisons (fiber links)
- Contributions to TAI

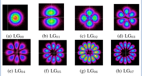


Fundamental physics

- Search for dark matter
- Lorentz invariance

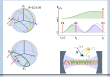
Ultimate accuracy

- Rydberg atoms (LAC)
- Laguerre-Gauß modes

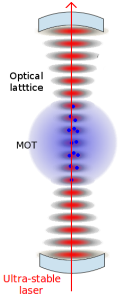


Ultimate stability

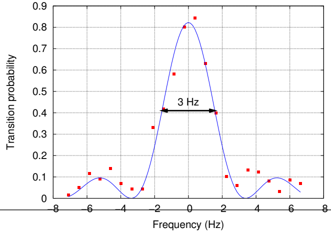
- Reduce the clock dead time
- **Use quantum entanglement**



Optical lattice clocks

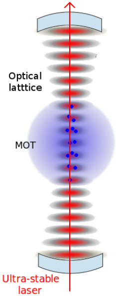


- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable "clock" laser
- Stabilize the clock laser on the narrow resonance



$$Q = 10^{14}$$

Optical lattice clocks

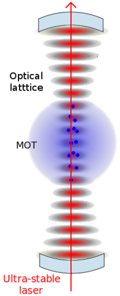


- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable "clock" laser
- Stabilize the clock laser on the narrow resonance

Combine several advantages:

- Optical clock
- Large number of atoms (10^4)

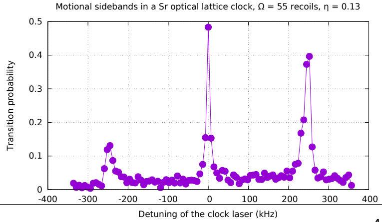
Optical lattice clocks



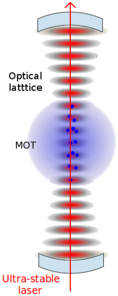
- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable "clock" laser
- Stabilize the clock laser on the narrow resonance

Combine several advantages:

- Optical clock
- Large number of atoms (10^4)
- Lamb-Dicke regime: insensitive to motional effects



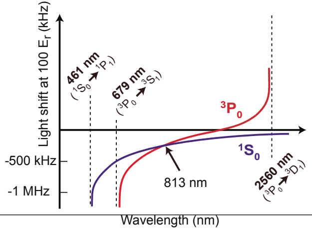
Optical lattice clocks



- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable "clock" laser
- Stabilize the clock laser on the narrow resonance

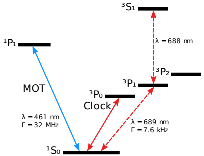
Combine several advantages:

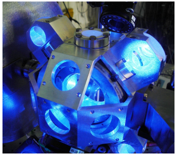
- Optical clock
- Large number of atoms (10^4)
- Lamb-Dicke regime: insensitive to motional effects
- Magic wavelength for unperturbed trapping



Strontium optical lattice clocks at SYRTE

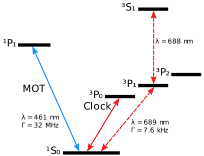
Sr1 

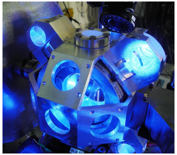


 Sr2

STRONTIUM OPTICAL LATTICE CLOCKS AT SYRTE

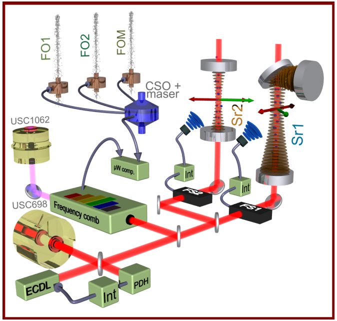
SR1





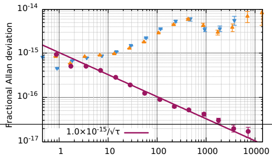
SR2

ACCURACY



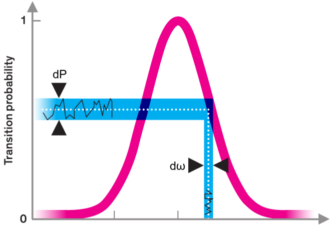
Effect	Uncertainty in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Lattice spectrum	1
Density shift	8
Line pulling	6
Background collisions	4
Static charges	1.5
Total	**17** $\times 10^{-18}$

STABILITY

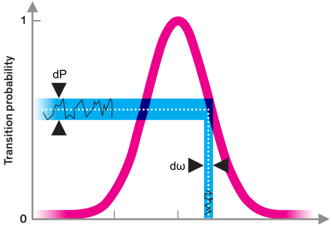


Frequency stability: noise sources

- Detection noise



- Detection noise
- Quantum projection noise



Quantum measurement of P_e with probabilistic outcome.

- 1 atom

$$|\psi\rangle_1 = \frac{1}{\sqrt{2}}(|f\rangle + |e\rangle)$$

result = 1 with proba 1/2, 0 with proba 1/2 $\Rightarrow \frac{1}{SNR} = 1$

- $N \gg 1$ **independent** atoms

$$|\psi\rangle_N = (|\psi\rangle_1)^{\otimes N}$$

result $\in [0..N]$, binomial distribution : $N/2 \pm \sqrt{N}/2 \Rightarrow \frac{1}{SNR} = \frac{1}{\sqrt{N}}$

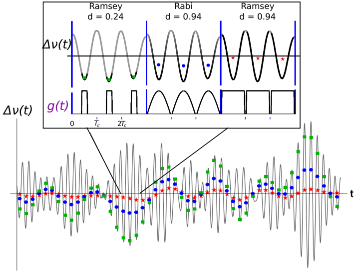
$$\sigma_y(\tau) \simeq \frac{1}{Q}\frac{1}{\sqrt{N}}\sqrt{\frac{T_c}{\tau}}$$

Magnitude

- Microwave clocks: $\simeq 10^{-14}$ @ $1s$
- Optical ion clocks: $\simeq 10^{-15}$ @ $1s$
- Optical lattice clocks: $\simeq 10^{-17}$ @ $1s$

Frequency stability: noise sources

- Detection noise
- Quantum projection noise
- Clock laser noise (Dick effect)



Frequency stability: noise sources

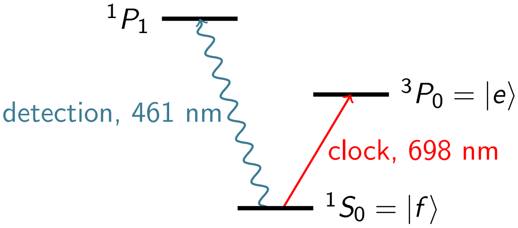
- Detection noise
- Quantum projection noise
- Clock laser noise (Dick effect)

Currently: Dick effect > Quantum Projection Noise > Detection noise.

- New laser sources (cryogenic cavities, spectral hole burning. . .)
- (Classical) non-destructive detections
- Synchronous interrogation
- Zero dead-time clocks

Explore ways to overcome the QPN

Measuring p with Sr atoms



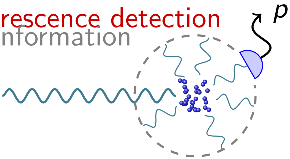
Probing the $^1S_0 \rightarrow {}^1P_1$ transition: measure of $N_{|f\rangle}$

$$p = 1 - \frac{N_{|f\rangle}}{N_{\text{total}}}$$

Detection methods

Usual scheme: fluorescence detection

- Fluorescence detection

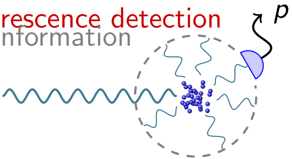


- Low efficiency ⇒ powerful probe beam
- Destructive detection: the atoms are scattered and lost ($n_\gamma \gg 1$)

Usual scheme: fluorescence detection

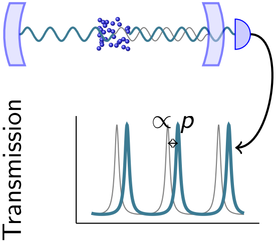
- Fluorescence detection

Lost information



- Low efficiency $\Rightarrow$ powerful probe beam
- Destructive detection: the atoms are scattered and lost ($n_\gamma \gg 1$)

Non-destructive dispersive detection

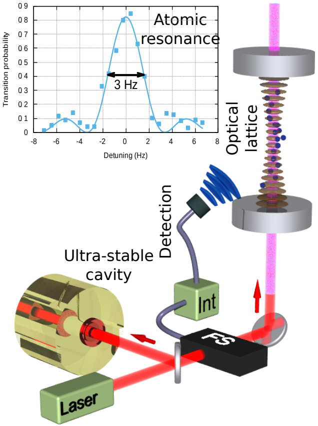


- Measure phase shift
- Cavity enhanced atom-light interaction

Cavity-assisted NDD: design goal

Objectives

- "Classical" non-destructivity
  ⇒ reduced Dick effect
- "Quantum" non-destructivity
  ⇒ Beyond QPN with Spin-squeezing



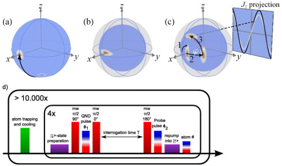
Cavity-assisted NDD: design goal

Objectives

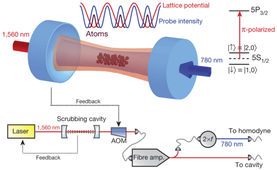
- "Classical" non-destructivity
  $\Rightarrow$ reduced Dick effect
- "Quantum" non-destructivity
  $\Rightarrow$ Beyond QPN with Spin-squeezing

Weak measurements for microwave clocks

- dipole trap based or cavity based
- differential measurement on the two clocks states



A. Louchet-Chauvet, New J. Phys. **12** 065032 (2010)



O. Hosten, Nature **529** 505 (2016)

Cavity-assisted NDD: design goal

Objectives

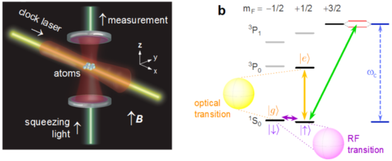
- "Classical" non-destructivity
  ⇒ reduced Dick effect
- "Quantum" non-destructivity
  ⇒ Beyond QPN with Spin-squeezing

Weak measurements for microwave clocks

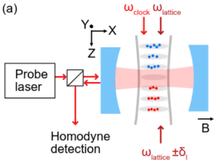
- dipole trap based or cavity based
- differential measurement on the two clocks states

Challenges

- Optical transition
- Moderate number of atoms
- Actual clock system

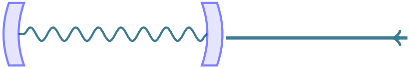


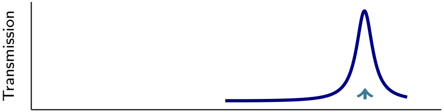
E. Pedrozo-Peñafiel, Nature **588** 414 (2020)



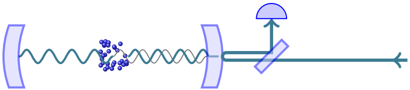
John M Robinson arXiv:2211.08621

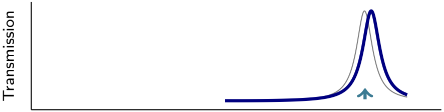
Cavity-assisted NDD: detection principle





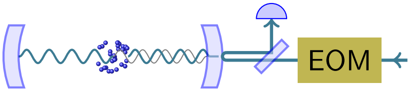
Cavity-assisted NDD: detection principle

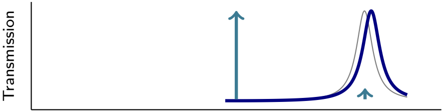




- Phase shift $= \mathcal{F}\phi_{\text{at}}$

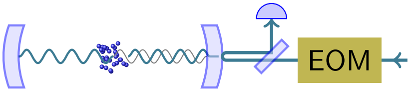
Cavity-assisted NDD: detection principle

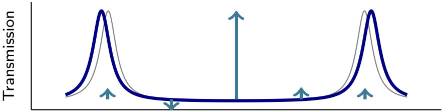




- Phase shift $= \mathcal{F}\phi_{\text{at}}$
- Measured by a local oscillator (PDH-like)

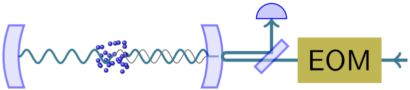
Cavity-assisted NDD: detection principle

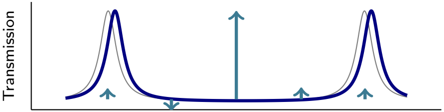




- Phase shift $= \mathcal{F}\phi_{\text{at}}$
- Measured by a local oscillator (PDH-like)
- Differential measurement $\phi_{\text{at},+2} - \phi_{\text{at,-2}} = 2\phi_{\text{at}}$
  (resonance centered on the carrier $\phi_{\text{at},+2} = -\phi_{\text{at,-2}}$)

Cavity-assisted NDD: detection principle



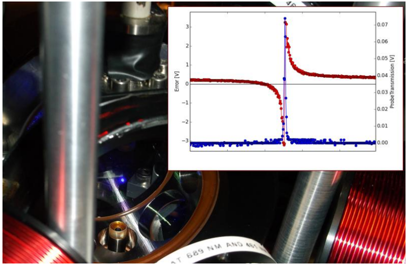


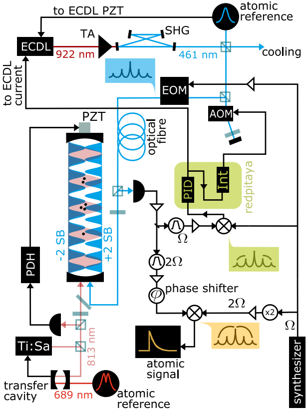
- Phase shift $= \mathcal{F}\phi_{\text{at}}$
- Measured by a local oscillator (PDH-like)
- Differential measurement $\phi_{\text{at},+2} - \phi_{\text{at,-2}} = 2\phi_{\text{at}}$
  (resonance centered on the carrier $\phi_{\text{at},+2} = -\phi_{\text{at,-2}}$)
- Technical noise $\phi_{\text{tech.},+2} - \phi_{\text{tech.,-2}} = 0$

Detection immune to technical noise

Cavity-assisted NDD: experimental setup

In practice

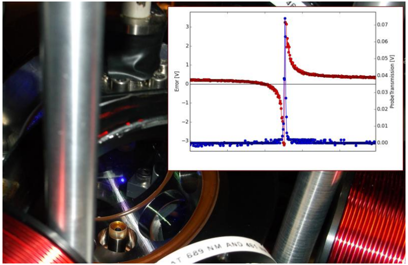


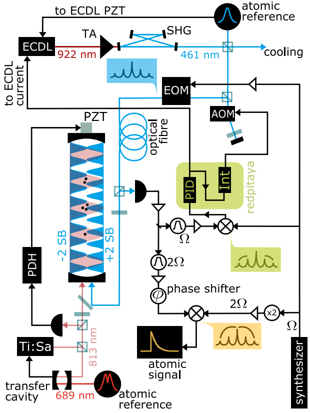


- Bi-chromatic cavity (lattice 813 nm + detection 461 nm)
- High finesse (16 000) at 461 nm
  $\Rightarrow$ 100 fold increase of the SNR

G. Vallet *et al.* New J. Phys. **19** 083002 (2017)

IN PRACTICE

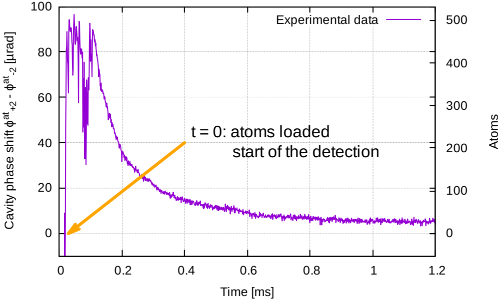




- Bi-chromatic cavity (lattice 813 nm + detection 461 nm)
- High finesse (16 000) at 461 nm
  $\Rightarrow$ 100 fold increase of the SNR
- Heterodyne dual-mode detection
  $\Rightarrow$ Homogeneous atom-cavity coupling

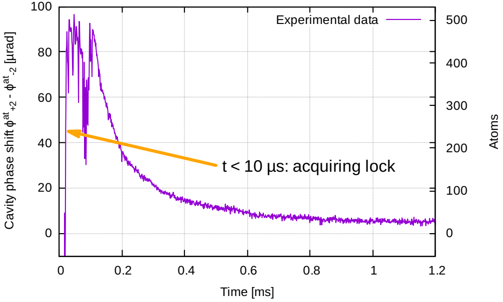
G. Vallet *et al.* New J. Phys. **19** 083002 (2017)

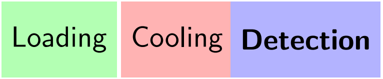
Cavity-assisted NDD: experimental results



Loading	Cooling	**Detection**

Cavity-assisted NDD: experimental results

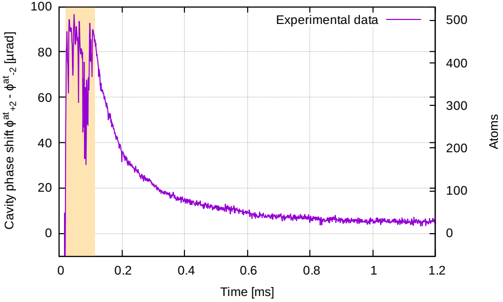


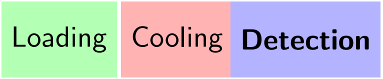


- Lock laser on cavity

- Digital, TTL switchable lock (Redpitaya)

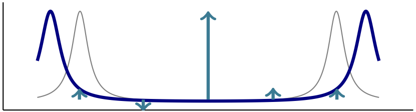
Cavity-assisted NDD: experimental results



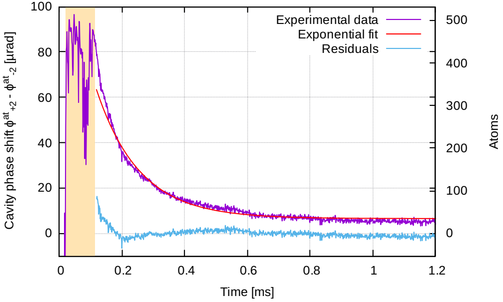


- Lock laser on cavity
- 500 atoms dynamic range

- Digital, TTL switchable lock (Redpitaya)

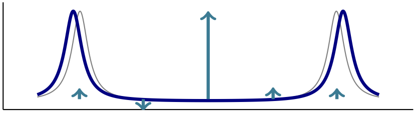


Cavity-assisted NDD: experimental results



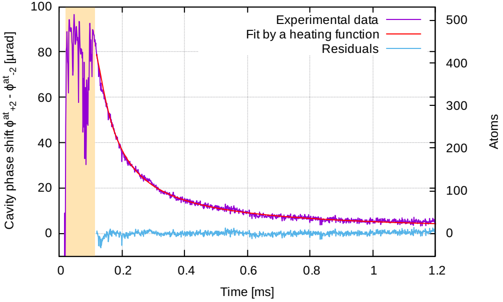
Loading | Cooling | **Detection**

- Lock laser on cavity
- 500 atoms dynamic range



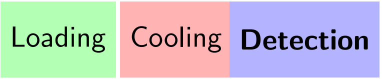
- Noise immune detection of the atom decay

Cavity-assisted NDD: experimental results



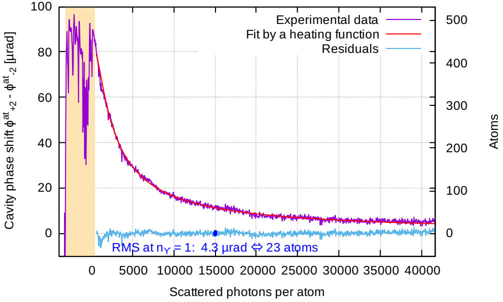
- $N(t) = N_0 \left(1 - e^{-3U/n_\gamma}\right)$
- $n_\gamma / t = 40$ photons$/\mu$s

(fit and measurement)



- Lock laser on cavity
- 500 atoms dynamic range
- n_γ photons scatt./atom

Cavity-assisted NDD: experimental results



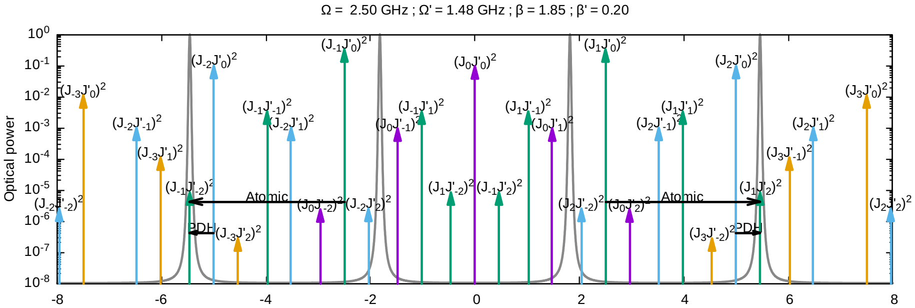
Loading | Cooling | **Detection**

- Lock laser on cavity
- 500 atoms dynamic range
- n_γ photons scatt./atom
- Noise $= 23/\sqrt{n_\gamma}$ atoms

- Destructive regime (full integration) $\Rightarrow$ high resolution: $\delta N \ll 1$ atom
- Classical non-destructive regime $\Rightarrow$ high resolution: $\delta N < 4$ atoms
- Quantum non-destructive regime for $n_\gamma < 1$ photon, $\delta N > 23$ atoms $\Rightarrow \delta N < \sqrt{N}$ for $N > 500$

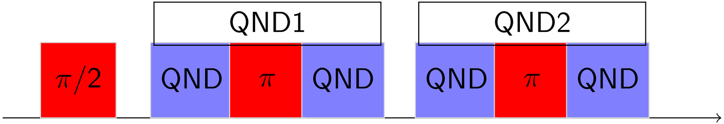
- new system with two independent modulation frequencies
- large detuning (5.7 GHz) + decoupling of cavity lock and QND signal
  $\Rightarrow$ low scattering rate achieved
- improved dynamical range by tracking cavity resonances

(R. Hobson, Optics Express **27** 37099 (2019))



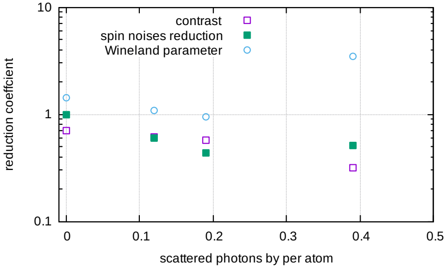
QND measurements

Sequence



Observing quatum correlation

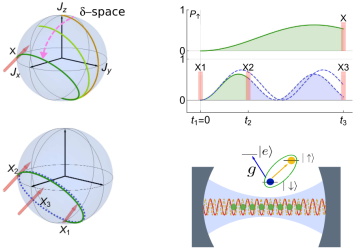
- Observing correlations between QND measurements
- Coherence preserved during the QND measurements
- Wineland parameter $\xi = 0.95$



Outlook: integrating QND measurements in the clock sequence

Protocol: adapted Rabi interrogation with 3 QND pulses (ICFO)

- Integrated evaluation of $N_{|e\rangle}$ and $N_{|g\rangle}$
- Evaluation of the sub-QPN stability with Gaussian estimators
- Numerical optimization of QND pulse timing and power



D. Benedicto Orenes *et al.*
Phys. Rev. Lett. **128**, 153201 (2022)

Acknowledgments

Questions ?

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Contributing to TAI with an optical clock

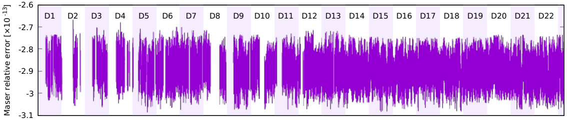
TAI = Temps Atomique International

- Long, quasi-continuous, operations of optical clocks (slots of 5 days)
- Calibration of a H-maser connected to UTC
- Calibration of TAI submitted to BIPM, included in Circular T 350 (Feb. 2017) as a non-steering contribution,

3 - Duration of the TAI scale interval d.

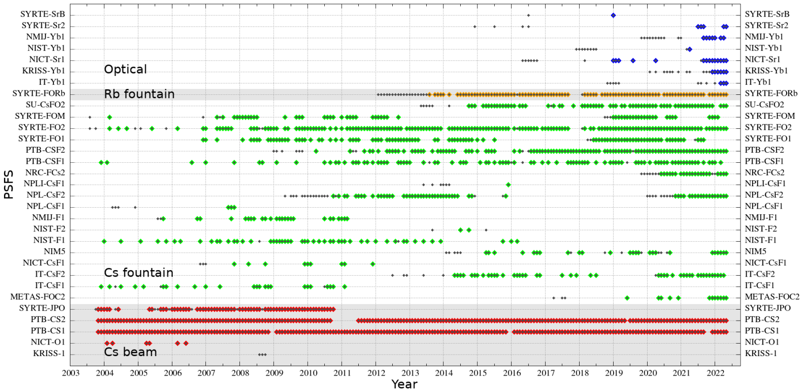
Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainties.
All values are expressed in 10**-15 and are valid only for the stated period of estimation.

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)



Contributing to TAI with an optical clock

Graphical representation of all evaluations of Primary and Secondary Frequency Standards reported since Circular T 190.
Enhanced color dots indicate evaluations carried out within the month of TAI computation.

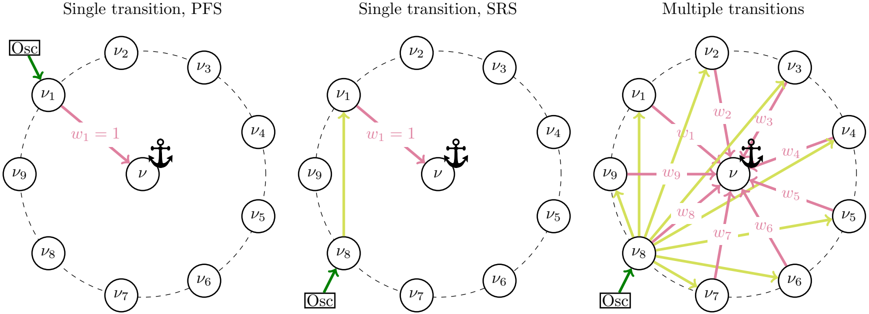


https://webtai.bipm.org/ftp/pub/tai/other-products/taipsfs/psfs.png

Redefinition of the SI second: How and when?

Under consideration at the BIPM/CCTF working groups:

1. Option 1: Replacing Cs with an optical transition
   → which one ? Sr, Yb, Yb^+, Sr^+, Ca^+, Th, ...
2. Option 2: **Defining the second with multiple transitions**



$$\prod_i \nu_i^{w_i} \equiv N\,\text{Hz}$$

- Optimal generalisation of PFS / SRS
- Update of the unit possible without drift

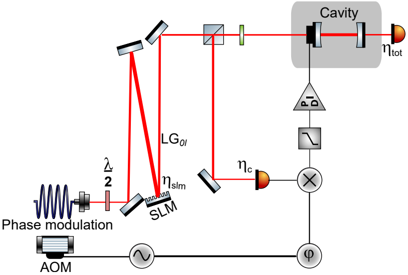
Metrologia **56** 055009 (2019)

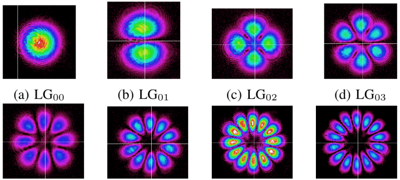
Laguerre-Gauss modes for the lattice

Aim: trapping atoms in high order transverse modes

- Lower density shift (single occupancy)
- "3D"-like lattice in a 1D cavity
- Test lattice model

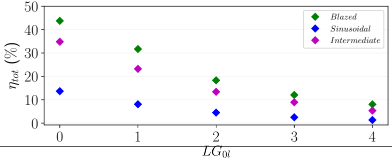
Injecting LG modes in the lattice cavity

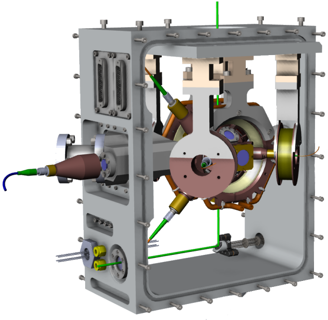




(a) LG_{00} (b) LG_{01} (c) LG_{02} (d) LG_{03}

(e) LG_{04} (f) LG_{05} (g) LG_{06} (h) LG_{07}





Design goal

- Improved mechanical stability
  - Long term operation
  - Non-destructive detection
- Improved BBR evaluation (sub 10^{-18})
  - Passive control of temperature inhomogeneities