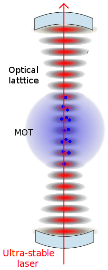
Non-destructive detection for strontium optical lattice clocks: towards a lattice clock in the quantum regime

G. Vallet, S. Bilicki, E. Bookjans, R. Le Targat, and Jérôme Lodewyck

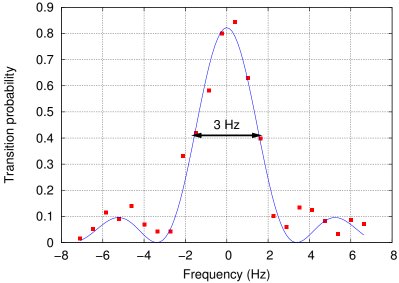
Systèmes de Référence Temps-Espace

Content

Optical lattice clocks

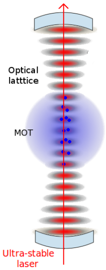


- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable "clock" laser
- Stabilize the clock laser on the narrow resonance



$$Q = 10^{14}$$

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

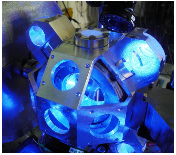
Combine several advantages:

- Optical clock
- Large number of atoms (10^4)
- Lamb-Dicke regime
  insensitive to motional effects
- Magic wavelength for unperturbed trapping
- Developed in many laboratories (Sr)
- ⇒ good candidates for a new SI second

Strontium optical lattice clocks at SYRTE

Sr1

Sr2



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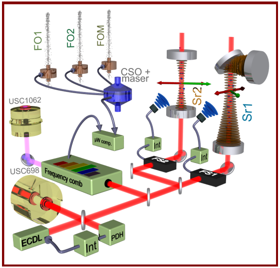

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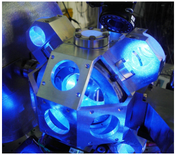

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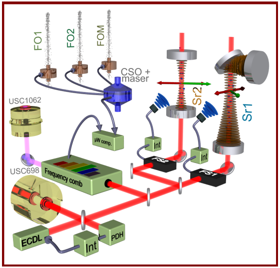
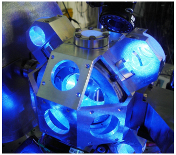
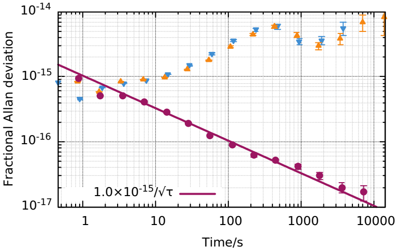


Sr2



Stability

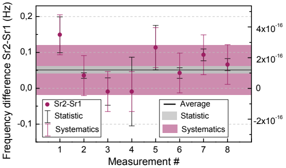


Accuracy (in 10^{-18})

Effect	Correction	Uncertainty
Black-body radiation shift	5208	20
Quadratic Zeeman shift	1317	12
Lattice light-shift	−30	20
Lattice spectrum	0	1
Density shift	0	8
Line Pulling	0	20
Probe light-shift	0.4	0.4
AOM phase chirp	−8	8
Servo error	0	3
Static charges	0	1.5
Black-body radiation oven	0	10
Background collisions	0	8
Total	**6487.4**	**41**

Results

- First agreement between two OLCs with an uncertainty beyond the accuracy of microwave clocks



Sr_2 - Sr_1 =

$$1.1 \times 10^{-16} \pm 2 \times 10^{-17}(\text{stat}) \pm 1.6 \times 10^{-16}(\text{sys})$$

Repeated agreement:

Sr_2 - Sr_1 = $(2.3 \pm 7.1) \times 10^{-17}$

P. Delva *et al.*, Phys. Rev. Lett. **118**, 221102 (2017)
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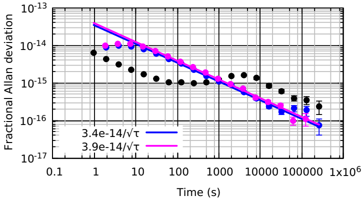

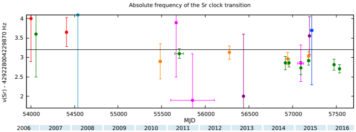

SYRTE, PTB, JILA, Tokyo University, NICT, NMIJ, NIM

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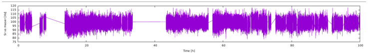

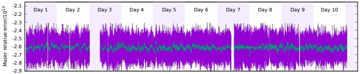

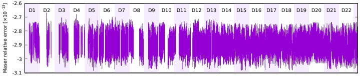

67% to 92% uptime

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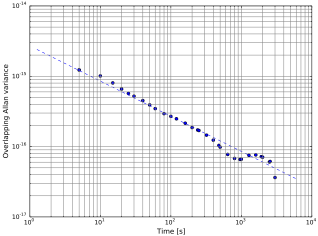

$$\text{Hg/Sr} = 2.62931420989890915$$
$$\pm 5 \times 10^{-17}(\text{stat}) \pm 1.7 \times 10^{-16}(\text{sys})$$

Best reproduced frequency ratio (with RIKEN, Tokyo)

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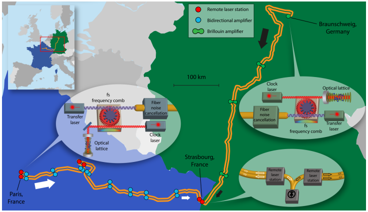

PTB, LPL and SYRTE established a 1415 km long optical fibre link and performed in 2015 the first direct comparison of optical clocks at continental scale

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Statistical uncertainty 2×10^{-17} after $\simeq 1$ hour
150 hours of data
$\mathrm{Sr_{PTB}/Sr_{SYRTE}} - 1 = (4.7 \pm 5.0) \times 10^{-17}$

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- Bounds on tests of Local Lorentz Invariance with remote clock comparisons (with LPL, PTB and NPL)

correction to relativity: $|\alpha| < 10^{-8}$

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- Bounds on tests of Local Lorentz Invariance with remote clock comparisons (with LPL, PTB and NPL)
- First contribution to TAI with optical clocks

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.

Included in Circular T 350 (Feb. 2017) as a non-steering contribution

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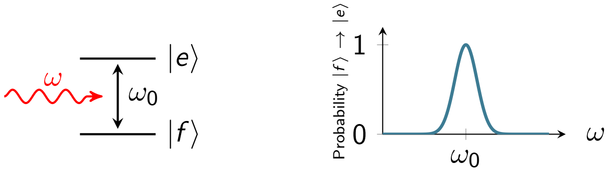
Content

Quantum projection noise: statistical model

Atomic resonance

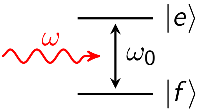


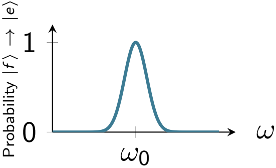
Each atom answers $|f\rangle$ or $|e\rangle$ (projection of the wave packet)

$$\Rightarrow \text{SNR} \simeq 1$$

Quantum projection noise: statistical model

Atomic resonance





Each atom answers $|f\rangle$ or $|e\rangle$ (projection of the wave packet)

$$\Rightarrow \text{SNR} \simeq 1$$

Solutions:

- Increase the number of particles $N \Rightarrow \sqrt{N}$ improvement
- Increase the integration time $\tau \Rightarrow \sqrt{\tau / T_c}$ improvement

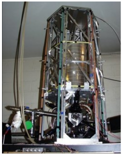
Quantum projection noise limited frequency instability

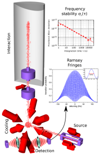
$$\sigma_y(\tau) \simeq \frac{1}{\pi Q} \frac{1}{\sqrt{N}} \sqrt{\frac{T_c}{\tau}},$$

Q = quality factor

Quantum projection noise in clocks

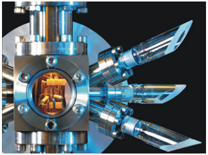
Microwave atomic fountains





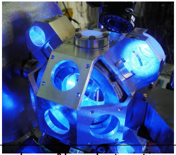
- $Q = 10^{10}$, $N =$ a few 10^6
- QPN limit: $\sigma_y(\tau) =$ a few $10^{-14}/\sqrt{\tau}$
- Experimentally realized

Optical ion clocks



- $Q =$ a few 10^{14}, $N = 1$
- QPN limit: $\sigma_y(\tau) = 10^{-15}/\sqrt{\tau}$
- Experimentally realized

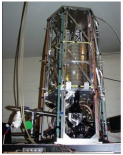
Optical lattice clocks

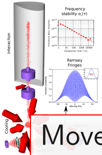


- $Q =$ a few 10^{14}, $N = 10^4$
- QPN limit: $\sigma_y(\tau) = 10^{-17}/\sqrt{\tau}$
- Experiments limited at $\sigma_y(\tau) = 10^{-16}/\sqrt{\tau}$ by technical noise (Dick effect)

Quantum projection noise in clocks

Microwave atomic fountains



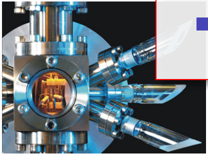


- $Q = 10^{10}$, $N =$ a few 10^6
- QPN limit: $\sigma_y(\tau) =$ a few $10^{-14}/\sqrt{\tau}$
- Experimentally realized

Move to lower instabilities

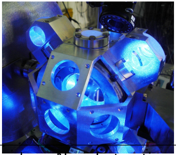
- Achieve the QPN limit in OLCs
- Develop quantum protocols to overcome the QPN

Optical ion clocks



- $Q =$ a few $10^{1?}$, $N = 1$
- QPN limit: $\sigma_y(\tau) = 10^{-15}/\sqrt{\tau}$
- Experimentally realized

Optical lattice clocks



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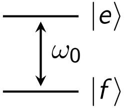
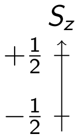
Quantum projection noise: a spin model



$\Leftrightarrow$

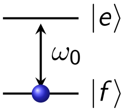


Two level atom

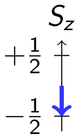
$\frac{1}{2}$-spin

$\Leftrightarrow$

Quantum projection noise: a spin model



$\Longleftrightarrow$



Two level atom

$\frac{1}{2}$-spin

- $|f\rangle$

- $|-\rangle_z$

$\Longleftrightarrow$

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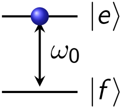

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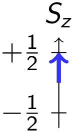


Two level atom

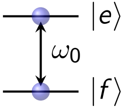
$\frac{1}{2}$-spin

- $|f\rangle$
- $|e\rangle$

$\Leftrightarrow$

- $|-\rangle_z$
- $|+\rangle_z$

Quantum projection noise: a spin model



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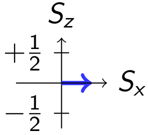


Two level atom

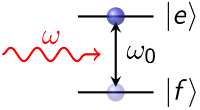
$\frac{1}{2}$-spin

- $|f\rangle$
- $|e\rangle$
- $\frac{1}{\sqrt{2}}\left(|f\rangle + |e\rangle\right)$

$\Leftrightarrow$

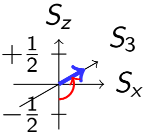
- $|-\rangle_z$
- $|+\rangle_z$
- $\frac{1}{\sqrt{2}}\left(|-\rangle_z + |+\rangle_z\right) = |+\rangle_x$

Quantum projection noise: a spin model



Two level atom

$\Leftrightarrow$



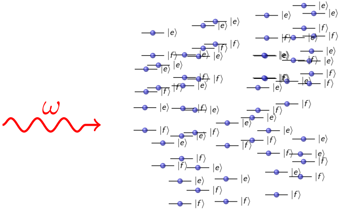
$\frac{1}{2}$-spin

- $|f\rangle$
- $|e\rangle$
- $\frac{1}{\sqrt{2}}\left(|f\rangle + |e\rangle\right)$
- $\alpha|f\rangle + \beta|e\rangle, \quad |\beta|^2 = p_{|f\rangle\rightarrow|e\rangle}$

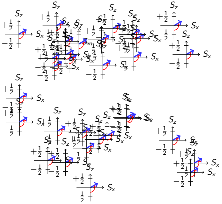
$\Leftrightarrow$

- $|-\rangle_z$
- $|+\rangle_z$
- $\frac{1}{\sqrt{2}}\left(|-\rangle_z + |+\rangle_z\right) = |+\rangle_x$
- $|+\rangle_3$

Quantum projection noise: a spin model



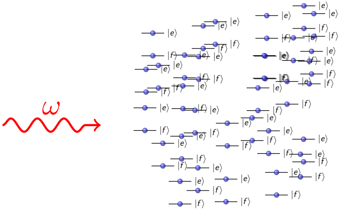
$\Longleftrightarrow$



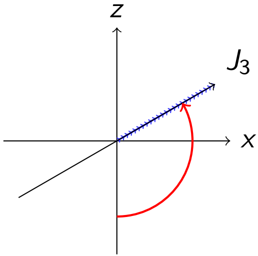
N two level atoms

N $\frac{1}{2}$-spins

Quantum projection noise: a spin model



$\Leftrightarrow$

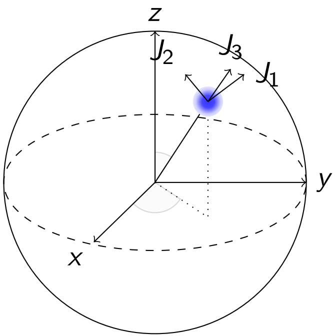


N two level atoms

N $\frac{1}{2}$-spins

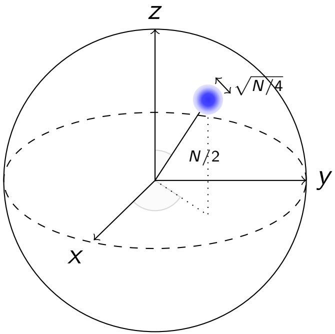
- $\vec{J} = \sum_{i=1}^{N} \vec{S}^{(i)}$
- $J_3 \simeq \frac{N}{2}$

Spin squeezing



- $[J_1, J_2] = iJ_3 \simeq i\frac{N}{2}$
- $\Rightarrow \Delta J_1 \, \Delta J_2 \geq \frac{N}{4}$
- Similar to $[X, P] = i\hbar$ systems
  - Quantum harmonic oscillator
  - Quantum optics

Spin squeezing



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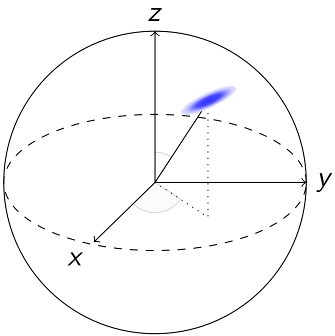
Quantum projection noise

- Symmetric uncertainty area
- $\Delta J_1 = \Delta J_2 = \sqrt{\frac{N}{4}}$
- $\mathrm{SNR} = \frac{N/2}{\sqrt{N/4}} = \sqrt{N}$ (QPN)

Spin squeezing



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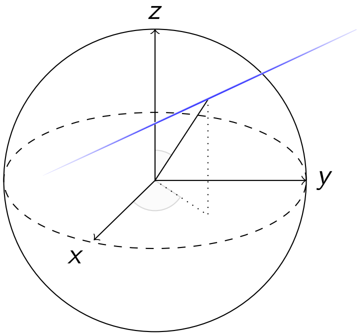

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Spin squeezing

- Asymmetric uncertainty area
- $\Delta J_2 < \Delta J_1$
- Limit: $\Delta J_1 \simeq N \rightarrow \Delta J_2 \simeq 1$
  $\Rightarrow \mathrm{SNR} \simeq N$
  (Heisenberg limit)

Spin-squeezing: requirements

How to achieve spin squeezing

- Non-linear evolution (cavity back-action, interactions,. . .)
- Weak QND measurement

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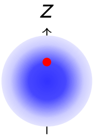

1. QPN limited measurement

Spin-squeezing: requirements

How to achieve spin squeezing

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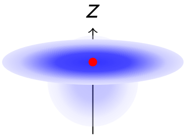

1. QPN limited measurement
2. Subsequent measurement correlated

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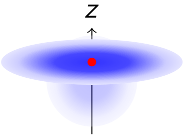

1. QPN limited measurement
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3. Design a protocol to acheive a sub-QPN resolution

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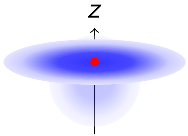

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Requirements

- low detection noise ($SNR \ll \sqrt{N}$)
- low information loss ($n_\gamma \ll 1$)

$\Rightarrow$ high resolution non-destructive detection

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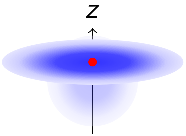

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Requirements

- low detection noise ($SNR \ll \sqrt{N}$)
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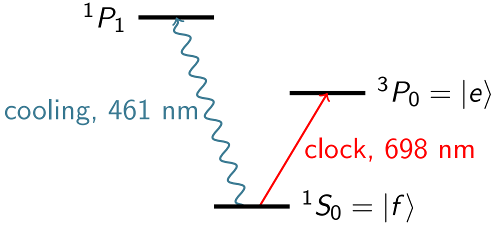
$\Rightarrow$ high resolution non-destructive detection

Classical non-destructivity

- Low photon scattering $\Rightarrow$ atoms stay trapped
- Atoms recycle $\Rightarrow$ less dead time in the clock cycle
  $\Rightarrow$ reduced Dick effect

Content

Measuring p with Sr atoms



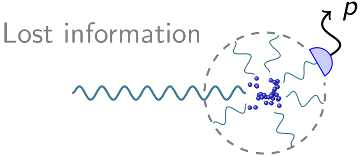
Probing the $^1S_0 \rightarrow ^1 P_1$ transition: measure of $N_{|f\rangle}$

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

Detection methods

Usual scheme: fluorescence detection

- Fluorescence detection



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

Detection methods

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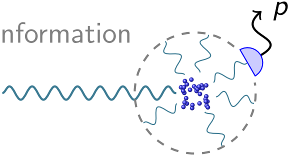
Lost information



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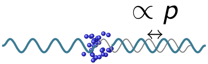
Non-destructive dispersive detection



- Phase shift ⇒ low power probe beam
- SNR fundamentally limited by the light shot noise

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Usual scheme: fluorescence detection

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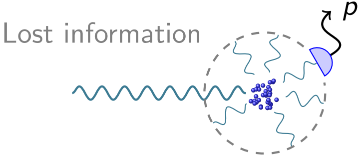

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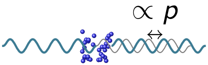
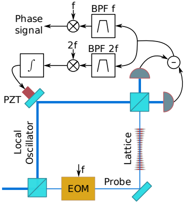
Non-destructive dispersive detection

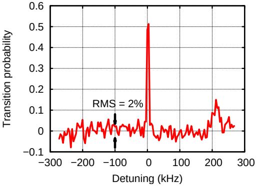


- Phase shift ⇒ low power probe beam
- SNR fundamentally limited by the light shot noise
- Classical non-destructivity
- Quantum non-destructivity: no information loss

Non-destructive detection

Interferometer with heterodyne detection

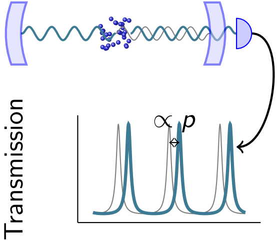




- Shot noise limited SNR
- Classical non-destructivity

J. Lodewyck et al. Phys. Rev. A **79** 061401(R) (2009)

Cavity



- Longer interaction
  $\Rightarrow$ improved SNR $(\times\sqrt{\mathcal{F}})$
- Self-alignment
- Long term mechanical stability

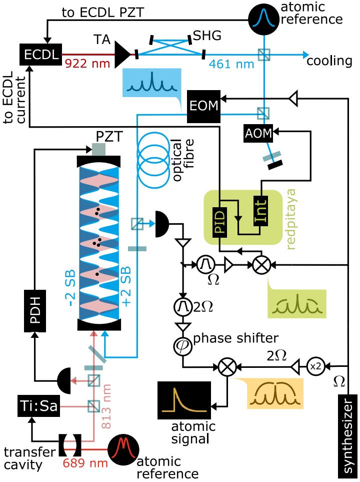
Experimental setup

Challenge

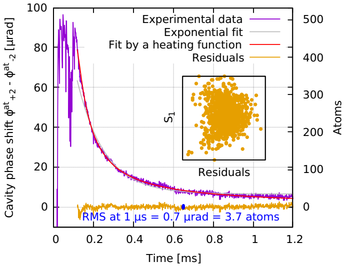
- discriminate technical noises from the atomic signal

Design

- Bi-chromatic cavity 813 nm + 461 nm
  ⇒ lattice and detection aligned
- High finesse (16 000) at 461 nm
  ⇒ 100 fold increase of the SNR
- Dual mode injection
  ⇒ Immune to technical fluctuations (cavity, laser)
  ⇒ Homogeneous atom-cavity coupling
- Heterodyne, PDH-like, detection ⇒ close to the shot noise limit

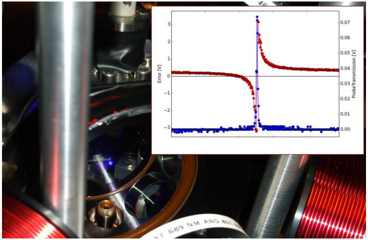


Experimental results



Detection signal

- Dynamic range of $\simeq$ 500 atoms
- Scattering rate well modeled
- Immunity to technical noises demonstrated



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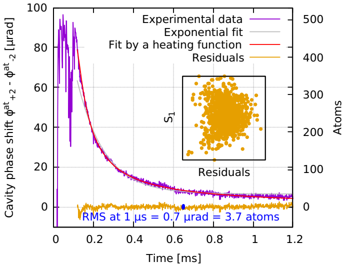

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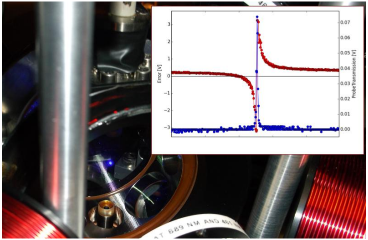
Detection noise δN

- $\delta N = 23$ atoms$/\sqrt{n_\gamma}$
- Classical non-destructive regime
  $\delta N = 3.7$ atoms for $n_\gamma = 38$ photons
  $\Rightarrow$ high resolution
- Quantum non-destructive regime
  $\delta N > 23$ atoms for $n_\gamma < 1$ photon
  $\Rightarrow \delta N < \sqrt{N}$ for $N > 530$ atoms.



Conclusion and prospects

Requirements for a clock detection in the quantum regime

- High SNR (cavity assisted)
- Low destructivity
- Homogeneous coupling
- Robust for operating in a state-of-the-art optical clock

Prospects

- Classical non-destructivity for an improved frequency stability
- Demonstrate quantum correlations
  (technical issues for a low scattering)
- Overcome the QPN limit for the frequency stability

Post-doc position available