Quantum metrology with optical lattice clocks

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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)

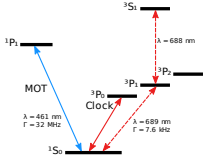
10^{-16} @ 1 week ⇒

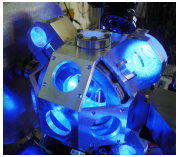
- Optical fiber links, frequency combs


10^{-19} @ 3 hour

Strontium optical lattice clocks at LNE-SYRTE

Sr1

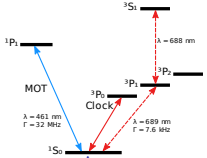


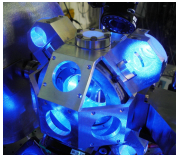


Sr2

Strontium optical lattice clocks at LNE-SYRTE

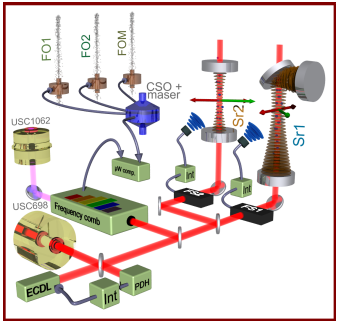
Sr1





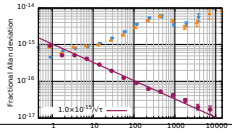
Sr2

Accuracy

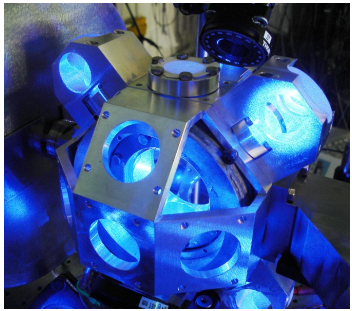


Effect	Uncertainty in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Lattice spectrum	1
Density shift	8
Line pulling	6
Background collisions	4
Static charges	1.5
Total	**17** $\times 10^{-18}$

Stability



Strontium optical lattice clocks at LNE-SYRTE



Metrology

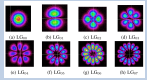
- Clock comparisons (fiber links)
- Contributions to TAI

Fundamental physics

- Search for dark matter
- Lorentz invariance

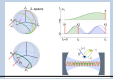
Ultimate accuracy

- Rydberg atoms (LAC)
- Laguerre-Gaussian modes



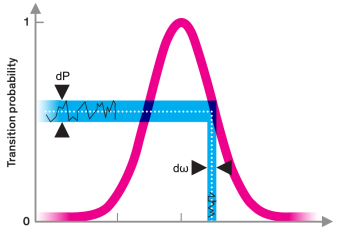
Ultimate stability

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



Frequency stability: noise sources

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



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

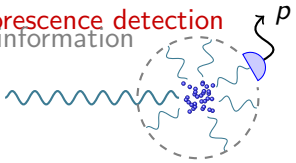
- New laser sources (cryogenic cavities, spectral hole burning...)
- (Classical) non-destructive detections
- Synchronous interrogation
- Zero dead-time clocks

Explore ways to overcome the QPN

Detection methods

Usual scheme: fluorescence detection

- Fluorescence detection
  Lost information



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

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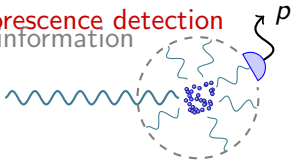

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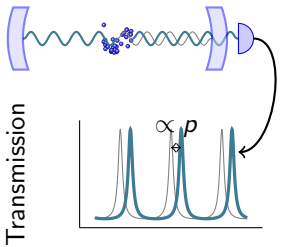
Non-destructive dispersive detection

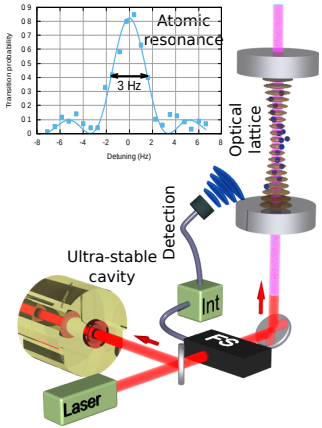


- Measure phase shift
- Cavity enhanced atom-light interaction

Cavity-assisted NDD: design goal

Objectives

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



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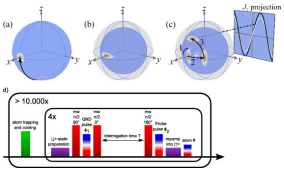
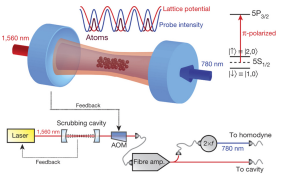
Weak measurements for microwave clocks

- 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)

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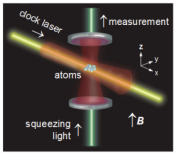

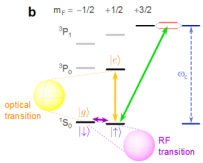

Weak measurements for microwave clocks

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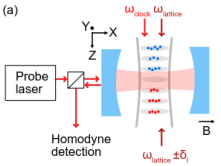
- differential measurement on the two clocks states

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

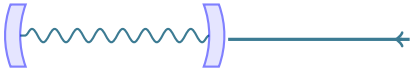


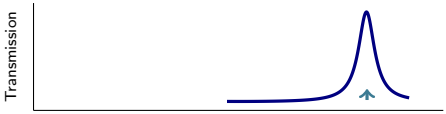
Challenges

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

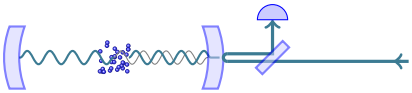
John M Robinson arXiv:2211.08621

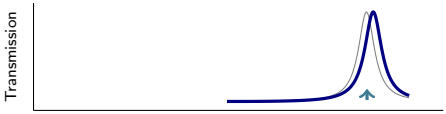
Cavity-assisted NDD: detection principle





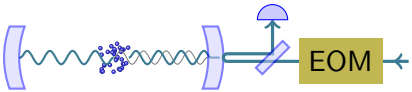
Cavity-assisted NDD: detection principle

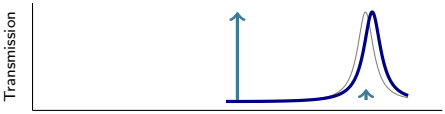




- Phase shift $= \mathcal{F}\phi_{\mathsf{at}}$

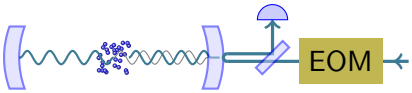
Cavity-assisted NDD: detection principle

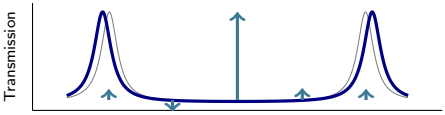




- Phase shift $= \mathcal{F}\phi_{\mathsf{at}}$
- Measured by a local oscillator (PDH-like)

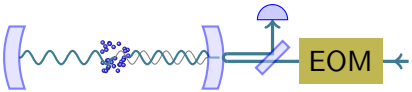
Cavity-assisted NDD: detection principle

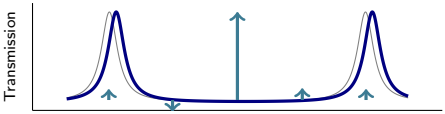




- Phase shift $= \mathcal{F}\phi_{\mathrm{at}}$
- Measured by a local oscillator (PDH-like)
- Differential measurement $\phi_{\mathrm{at},+2} - \phi_{\mathrm{at},-2} = 2\phi_{\mathrm{at}}$
  (atomic resonance centered on the carrier $\phi_{\mathrm{at},+2} = -\phi_{\mathrm{at},-2}$)

Cavity-assisted NDD: detection principle





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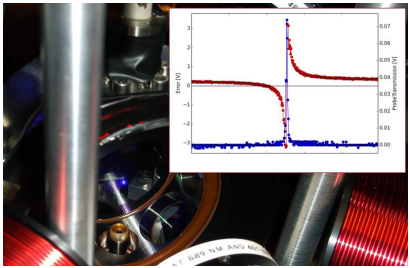
  (atomic resonance centered on the carrier $\phi_{\text{at},+2} = -\phi_{\text{at},-2}$)
- Technical noise $\phi_{\text{tech.},+2} - \phi_{\text{tech.},-2} = 0$

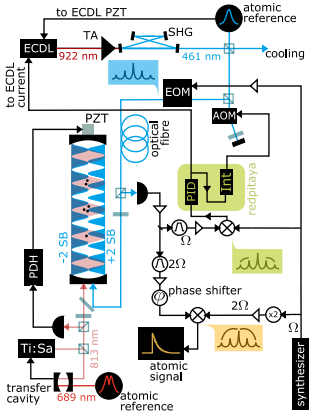
Detection immune to technical noise

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)

Cavity-assisted NDD: experimental setup

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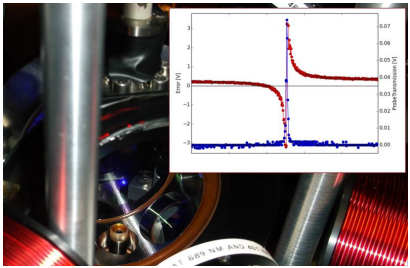
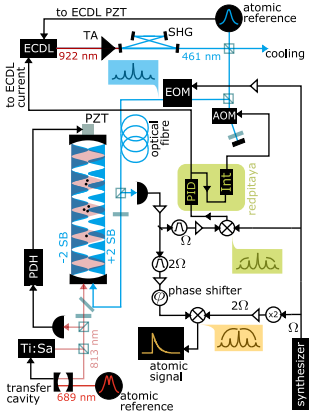
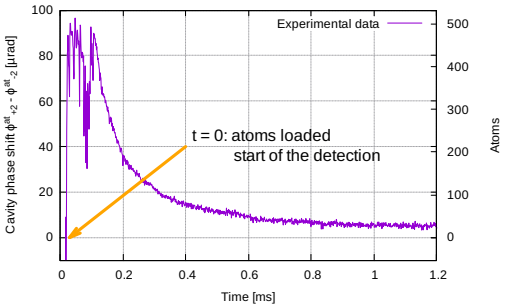




- Bi-chromatic cavity (lattice 813 nm + detection 461 nm)
- High finesse (16 000) at 461 nm
  ⇒ 100 fold increase of the SNR
- Heterodyne dual-mode detection
  ⇒ Homogeneous atom-cavity coupling

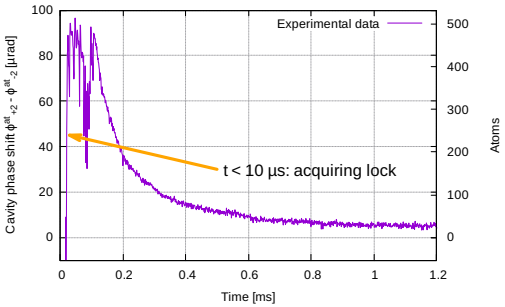
G. Vallet *et al.* New J. Phys. **19** 083002 (2017)

Cavity-assisted NDD: experimental results



Loading | Cooling | **Detection**

Cavity-assisted NDD: experimental results



- Digital, TTL switchable lock (Redpitaya)

- Lock laser on cavity

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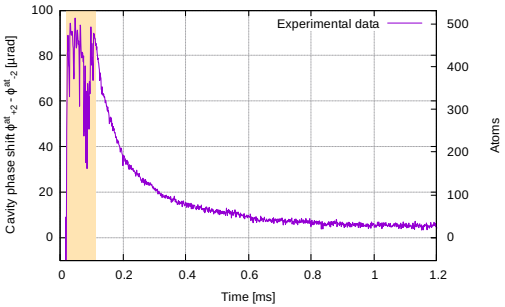
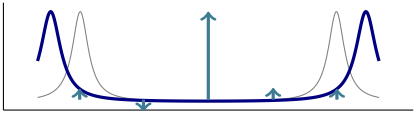


- Digital, TTL switchable lock (Redpitaya)

- Lock laser on cavity
- 500 atoms dynamic range



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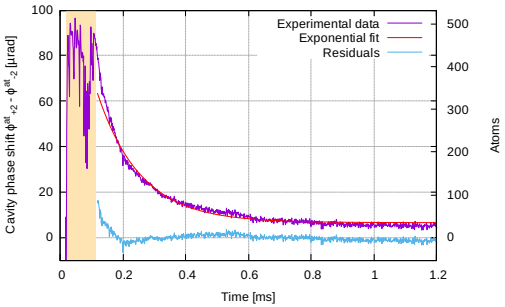
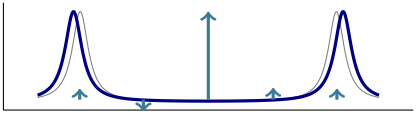


- Noise immune detection of the atom decay

- Lock laser on cavity
- 500 atoms dynamic range



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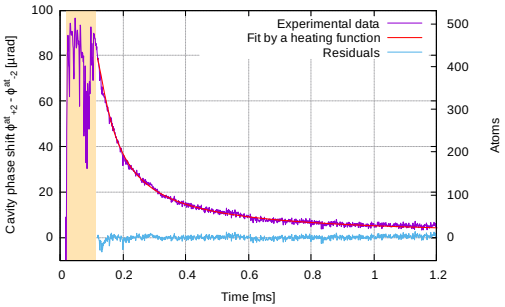


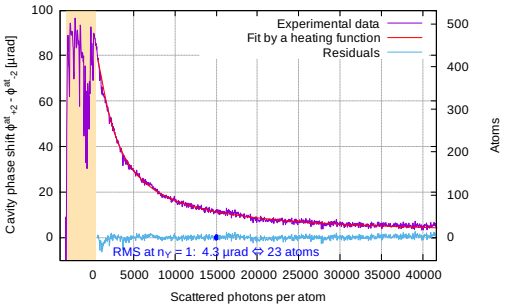
- $N(t) = N_0 \left(1 - e^{-3U/n_\gamma}\right)$
- $n_\gamma/t = 40$ photons/μs

(fit and measurement)

Loading | Cooling | **Detection**

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

Cavity-assisted NDD: experimental results

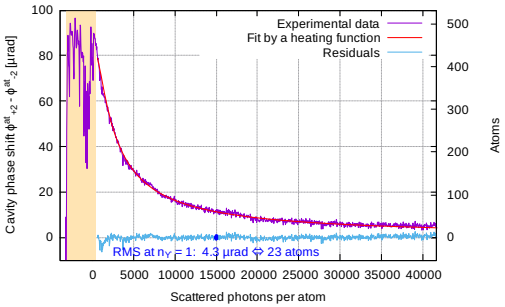


- Destructive regime (full integration)
  $\Rightarrow$ high resolution: $\delta N \ll 1$ atom
- Classical non-destructive regime
  $\Rightarrow$ high resolution: $\delta N < 4$ atoms
- Quantum non-destructive regime for $n_\gamma < 1$ photon, $\delta N > 23$ atoms $\Rightarrow \delta N < \sqrt{N}$ for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

Loading	Cooling	**Detection**

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

Cavity-assisted NDD: experimental results



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Loading | Cooling | **Detection**

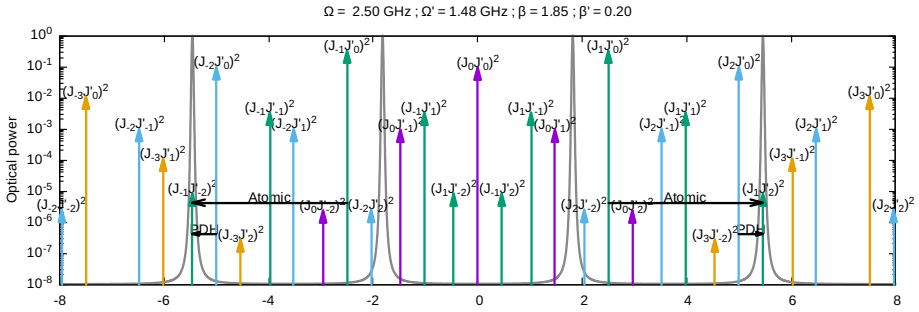
- Lock laser on cavity
- 500 atoms dynamic range
- n_γ photons scatt./atom
- Noise $= 23/\sqrt{n_\gamma}$ atoms

$T_{\text{probe}} < 25$ ns !!

High frequency version

- new system with two independent modulation frequencies
- large detuning (5.5 GHz) + decoupling of cavity lock and QND signal
  $\Rightarrow$ low scattering rate achieved
- improved dynamical range by tracking cavity resonances

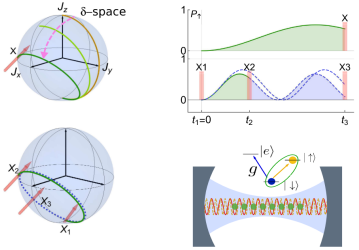
(R. Hobson, Optics Express **27** 37099 (2019))



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