Systèmes de Référence Temps-Espace

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Developments to improve the stability of optical lattice clocks

S. Bize, B. Fang, Y. Le Coq, R. Le Targat, J. Lodewyck, P.-E. Pottie
and members of the FOP team
Miguel Angel Cifuentes Marin, Michael Hartman, Ahmad Hasan, Xiuji Lin, Maxime Mazouth, Benjamin Pointard, Haosen Shang, Nemanja Lucic, Changlei Guo, William Moreno, Manuel Andia, Mads Tonnes, Shuo Zhang, Clara Zyskind

SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE

Symposium on Frequency Standards and Metrology
2023/10/17
Kingscliff, NSW, Australia

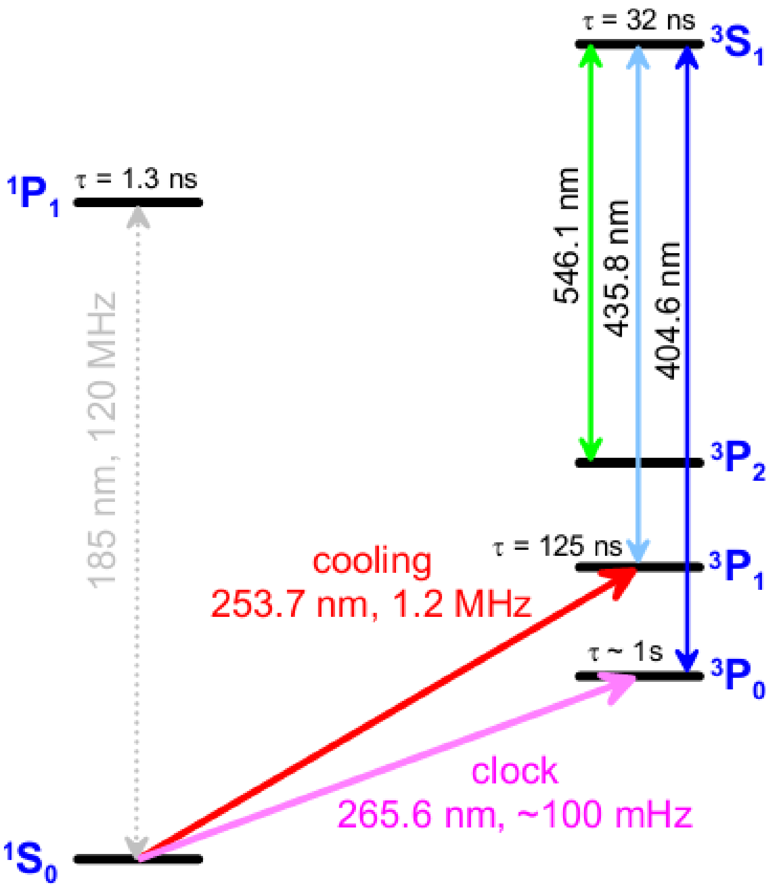
Outline

- **Progress in the development of a Hg lattice clock**
- **Two developments to improve the stability of optical lattice clocks**
  - Non-destructive detection for Sr lattice clocks
  - Laser stabilization using spectral hole burning

Properties of neutral mercury

Hg, Z= 80

Isotope	Abundance (%)	Spin
196	0.15	0
198	10.1	0
199	17.0	1/2
200	23.1	0
201	13.2	3/2
202	29.6	0
204	6.85	0



- **Low sensibility to BBR and static electric fields**

  At 300 K: -1.6×10^{-16} (~Sr/30, Yb/15)

- **7 isotopes, 6 of them >6% abundant (2 fermions, 4 bosons)**
- **^{199}Hg is a fermion with nuclear spin ½**
- **High sensitivity to α variations**

  Phys. Rev. A ***70****, 014102 (2004)*

$$\frac{\delta\nu}{\nu} = 0.81\frac{\delta\alpha}{\alpha}$$

- **High vapor pressure**

  No oven, 2D-MOT possible

- **Mostly unexplored in the ultra-cold regime**
- **Challenge: deep UV laser sources**

Status in 2015

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❑ Uncertainty of 1.7E-16 with 199Hg

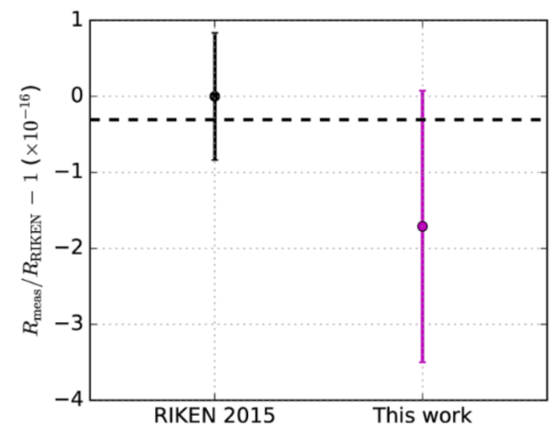
- Limited by
  - Level of control of the lattice frequency
  - The maximum trap depth achievable (56 E_R)
  - The stability >1.2E-15 @1s
  - Reliability / measurement time cumulated

❑ Frequency ratio against Cs, Rb and 87Sr

- From local comparisons
- Frac. uncertainty for Hg/Sr: 1.8E-16
- In agreement with RIKEN

Yamanaka et al., PRL114,230801 (2015)

Ratio	Measured value
ν_{Hg}/ν_{Cs}	122 769.55 729 311 011 (45)
ν_{Hg}/ν_{Rb}	165 124.754 879 997 258 (62)
ν_{Hg}/ν_{Sr}	2.629 314 209 898 909 15 (46)



❑ 199Hg in the CCTF-2015 LoR

- And SRS since CCTF-2017

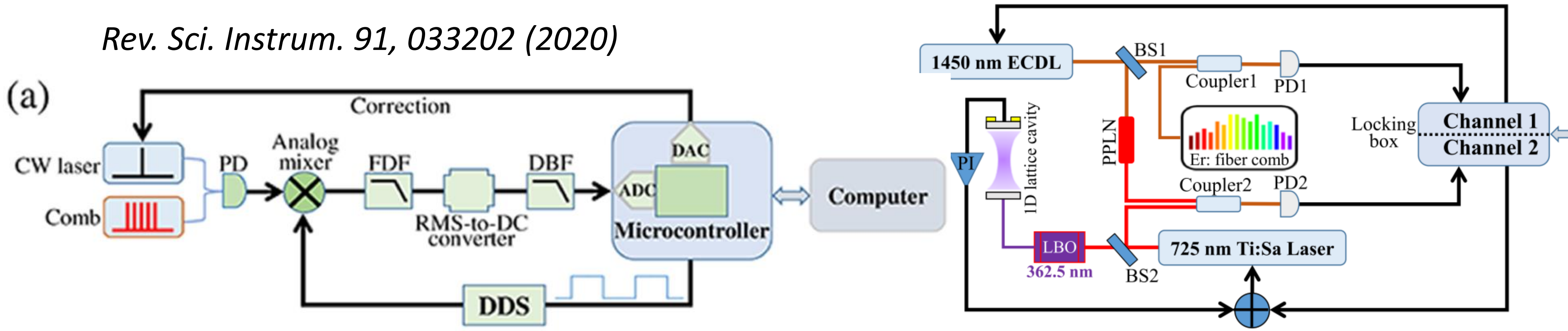
Tyumenev et al., New J. Phys. 18, 113002 (2016)

Some improvements: lattice frequency lock

❑ Accurate control of the lattice frequency

- Scalar shift ~1.1E-17/MHz at a depth of 100 E_R → control at the 10 kHz needed
- → a frequency doubled ECDL at 1450 nm to connect the comb to the TiSa of the lattice trap
- → an accurate locking scheme that can tolerate relatively broad laser linewidth and poor signal to noise ratio to avoid adding constrain to the existing comb

Rev. Sci. Instrum. 91, 033202 (2020)



❑ Lock accuracy in our application: 1 kHz

- → Hg clock average nicely to 1E-17, where it used to flicker at a few 1E-17

❑ The scheme can find application on other cases

- Accurate frequency control of lasers with broad linewidth
- Tolerates extremely poor signal to noise ratio → can considerably extend the usable wavelength range of a given frequency comb in certain applications.

Some improvements: 2DMOT

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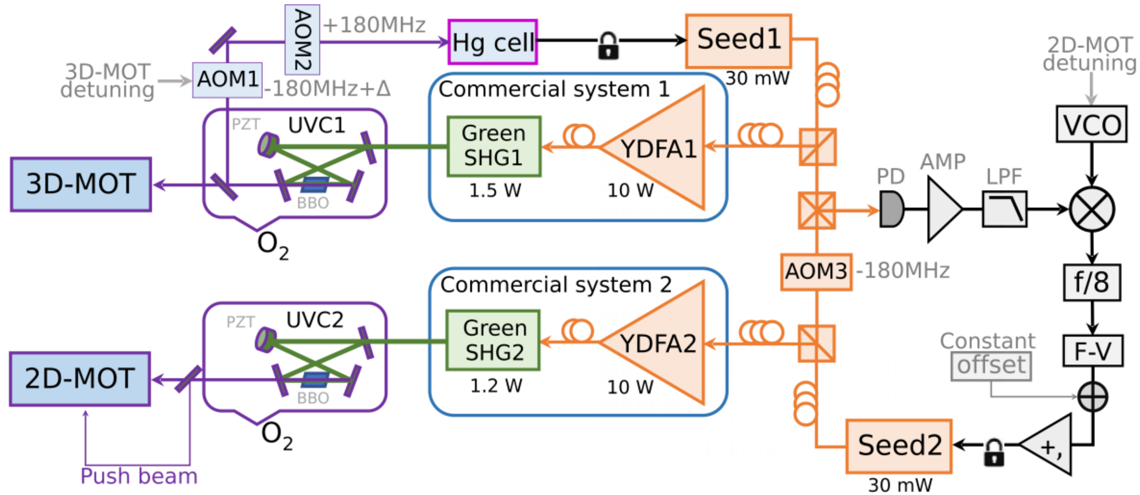
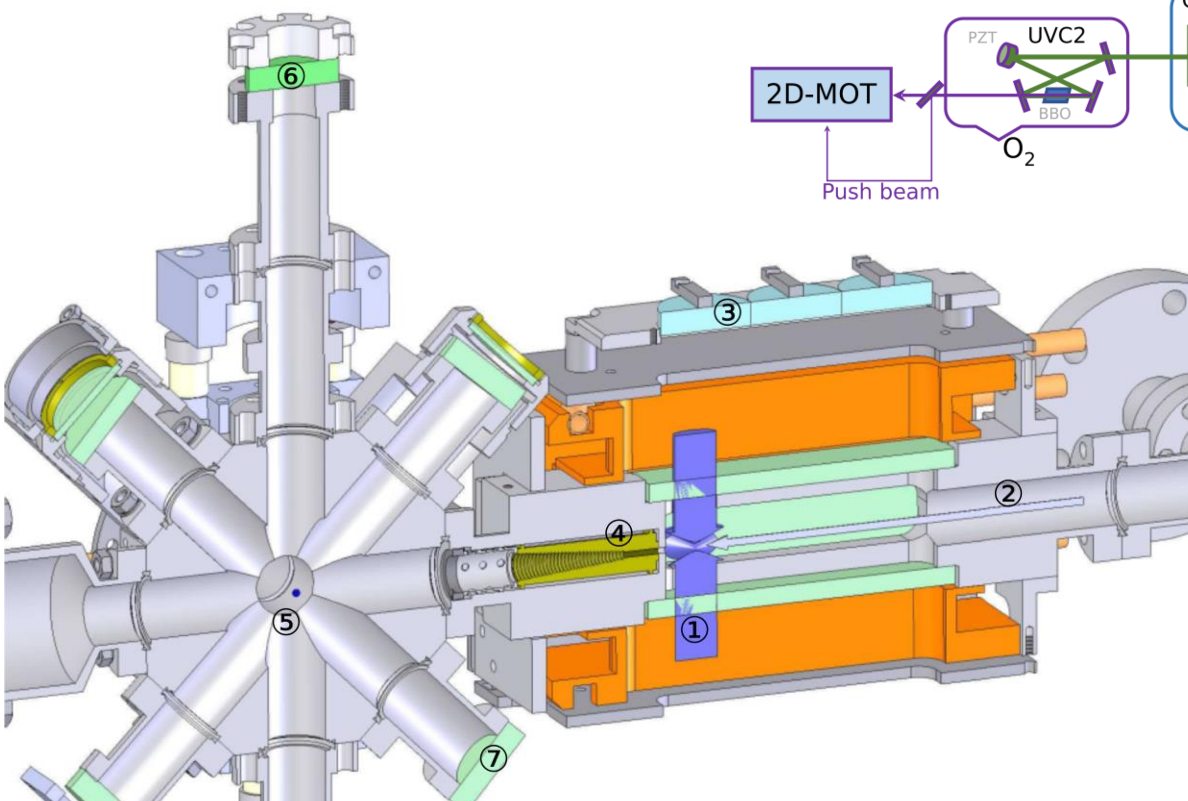
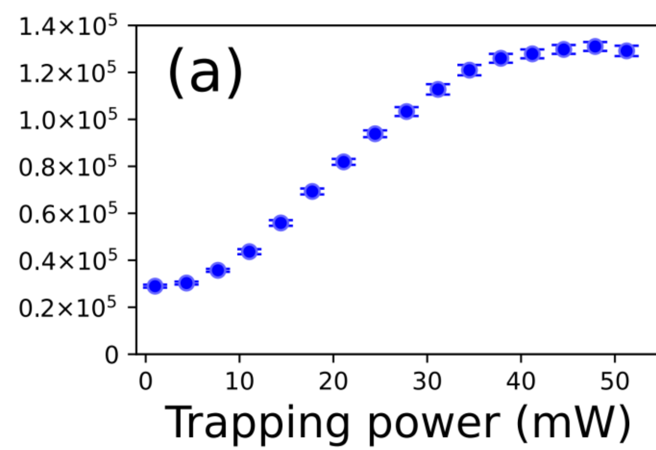
- **Laser system based on a commercial YDFA + SHG system**
  - 1.2 W in the VIS, 50 mW in UV, linewidth ~100 kHz (natural linewidth 1.3 MHz)
- **2DMOT limited to 1 zone**
  - 3mmx9mm beams + push





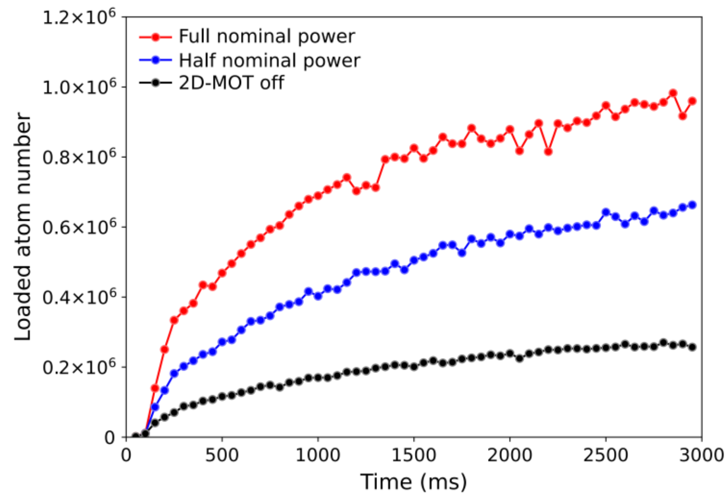


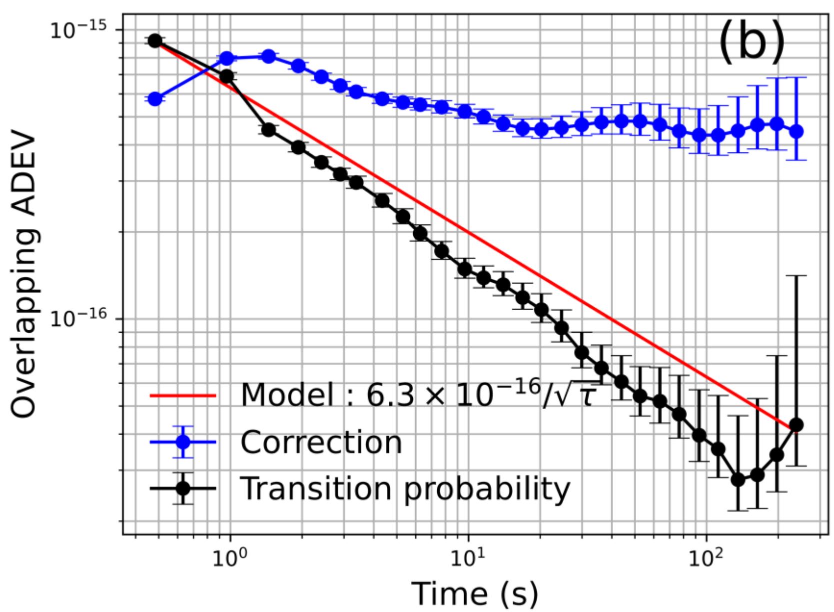
Phys. Rev. A 107, 033116 (2023)

Stability with 2DMOT

- **2DMOT improve loading rate by up to 4.5**

- **Stability of 6.3E-16 at 1 s**
  - With a clock cycle of 482 ms with 160 ms probe (duty cycle of 0.33, instead of <0.1 before)
  - With a 4E-16 laser (10cm cavity)



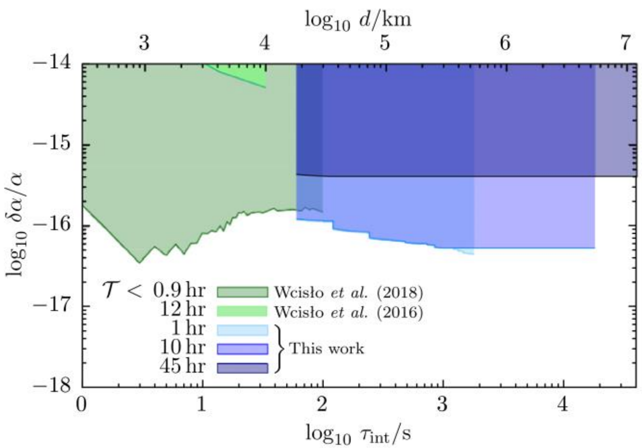


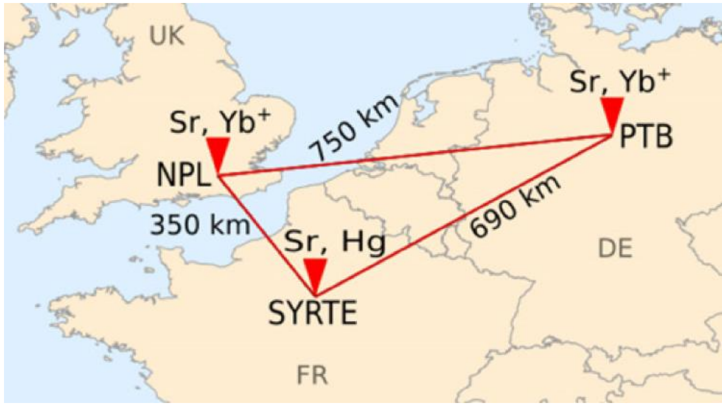
- **Limits**
  - Reliability: SHG 508 → 254 nm is the weak point (3DMOT and 2DMOT)
  - Significant improvement should be possible with optimized geometry
  - With more power too.

Comparisons

- **Improved reliability**
  - Capability to participate in coordinated fiber link comparisons, to cumulate many hours of measurements over a campaign (ex: 100h during 2023 campaign)
  - Still requiring the presence of an operator
- **Contribution to search for α variation and dark matter**
  - Search for topological dark matter exploits the spatial distribution of clock connected by links

Roberts *et al*, *New J. Phys.* 22, 093010 (2020)





Fiber link collaborations
INRIM, PTB, NPL, SYRTE
LPL, RENATER
(REFIMEVE infrastructure)
EURAMET projects

Comparisons

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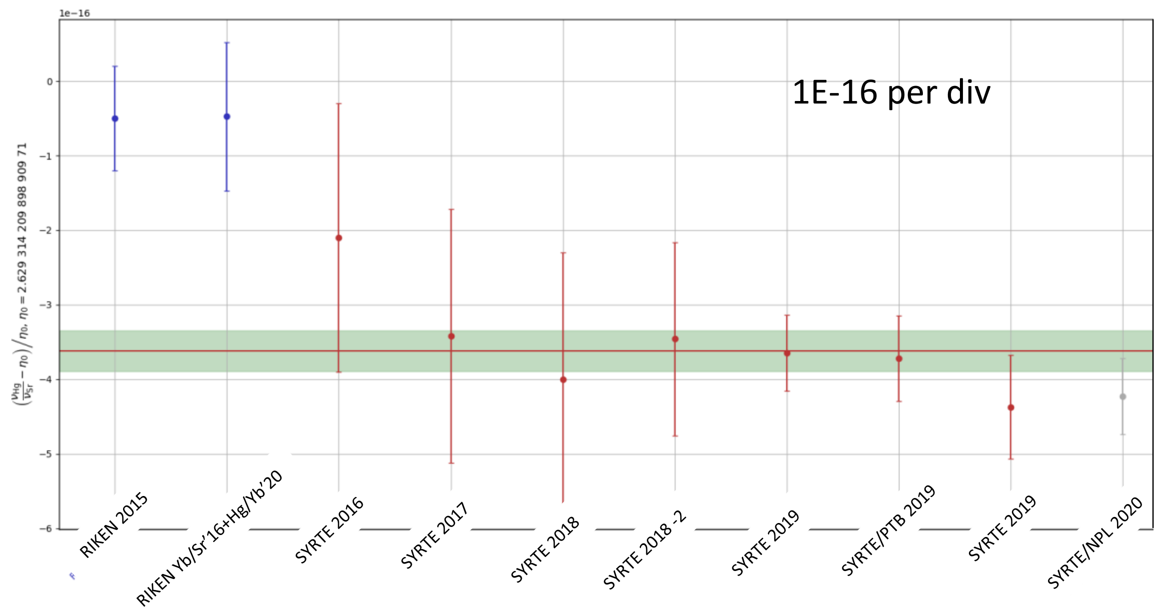
	Correction	Uncertainty
Cold collisional shift	2.6	1.5
Linear lattice light shift	-3	2.1
Nonlinear lattice light shift	-3	3
Quadratic Zeeman effect	1.3	0.2
Black-body radiation	15.1	2
Background gas collisions	0	2
Probe light shift	0	0.1
Probe laser AOM phase transient	0.2	0.4
TOTAL	14.2	4.8

❑ Uncertainties Hg (x1E-17)

- Improved thanks to lattice control, improved stability
- Limited by stability/reliability, coupling between lattice depth and collision shift, lattice lifetime

❑ 199Hg/Sr comparisons

- Uncertainties dominated by Hg



❑ Other comparisons with Yb+(E3), Yb+(E2), Yb

- Including the March/April 2023 campaign still under analysis

Toward using bosonic isotopes

❑ 199Hg 3P0 state has a relatively short lifetime

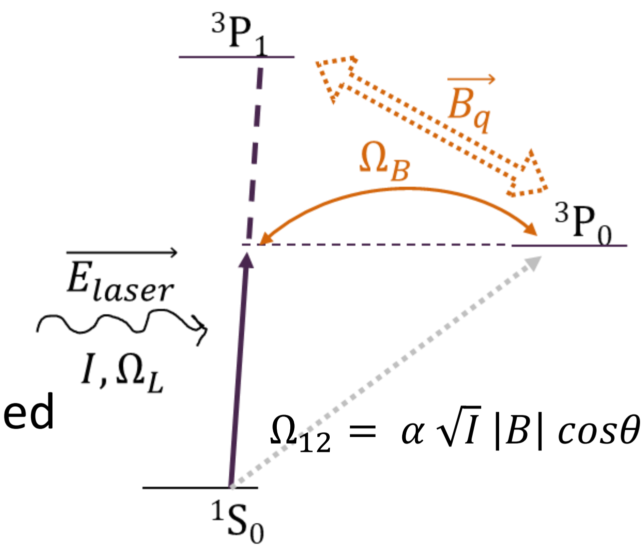
- ~1.5 s → will be a limit for the next generation of ultra-stable lasers

❑ Bosonic isotope can be used with a quenching scheme

- Lifetime unlimited, probing time adaptable to laser characteristics
- Done successfully in 174Yb and 88Sr *Taichenachev et al., Phys. Rev. Lett., 96, 3,(2006)*

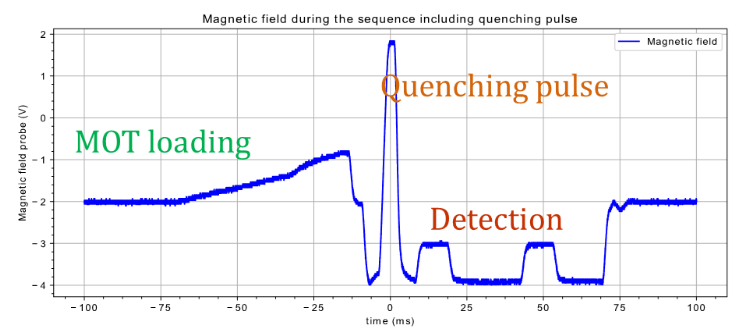
❑ Modification to implement this scheme

- Broadly tunable ultra-stable probe to address any of the isotopes while preserving 4E-16 stability
- Pulse magnetic field to quench the transition up to 15.5 mT
- Used 199Hg to maximize coupling of light to trapped atoms. (Rabi frequency of 2 kHz)
- →inferred Rabi frequency for bosons >50 Hz



❑ Search for the transition in 198Hg

- Current uncertainty is 10.3 MHz
- →not easy but feasible



Non-destructive detection for Sr lattice clocks

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Quantum non-destructive measurements to improve clocks

- uW transition, trapped Cs, dispersive measurement
  New J. Phys. 12 065032 (2010)
- uW transition, trapped Rb, -18.5 dB below SQL, cavity enhanced-dispersive measurement, bichromatic cavity
  Nature 529 505 (2016)
- Optical transition, Yb lattice, cavity in strong coupling
  Nature 588, 414 (2020)
- Optical transition, Sr lattice, transverse cavity in strong coupling *arXiv:2211.08621*

Goals of this work

- A practical implementation in optical lattice clock that goes beyond proof-of-principle
- Possible benefit for a transportable clock of both classical and quantum non-destructivity
  - →to relax the constrain on transportable ultra-stable cavities

    By reducing the impact of the Dick effect

    By extending the probe time beyond the laser coherence time using e.g. the atomic phase lock scheme

R. Kohlhaas, et al., Phys. Rev. X 5, 021011 (2015)

Detection method

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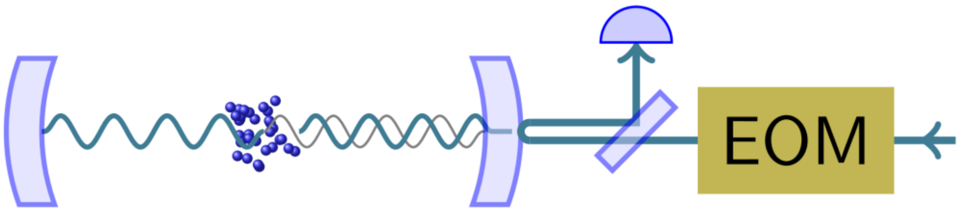
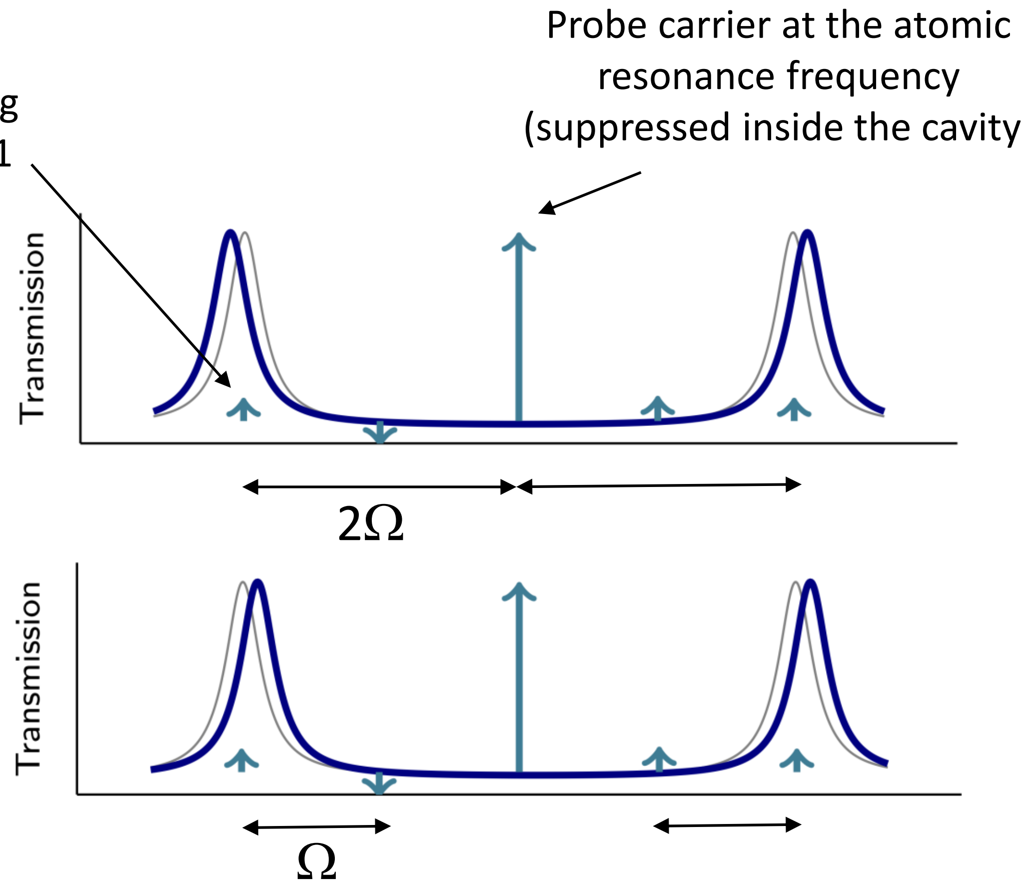
- **PDH like detection immune to technical noise**



$$\phi^{at} = \frac{N}{S}\frac{3\lambda^2}{2\pi}\frac{\Delta/\Gamma}{s + 4\Delta^2/\Gamma^2}$$

Amplified by the cavity finesse → $\mathcal{F}\phi_{at}$



- At 2Ω
  Atomic signal immune to technical noise
- At Ω
  PDH-like signal to lock the laser to the cavity

1^{st} generation experimental setup

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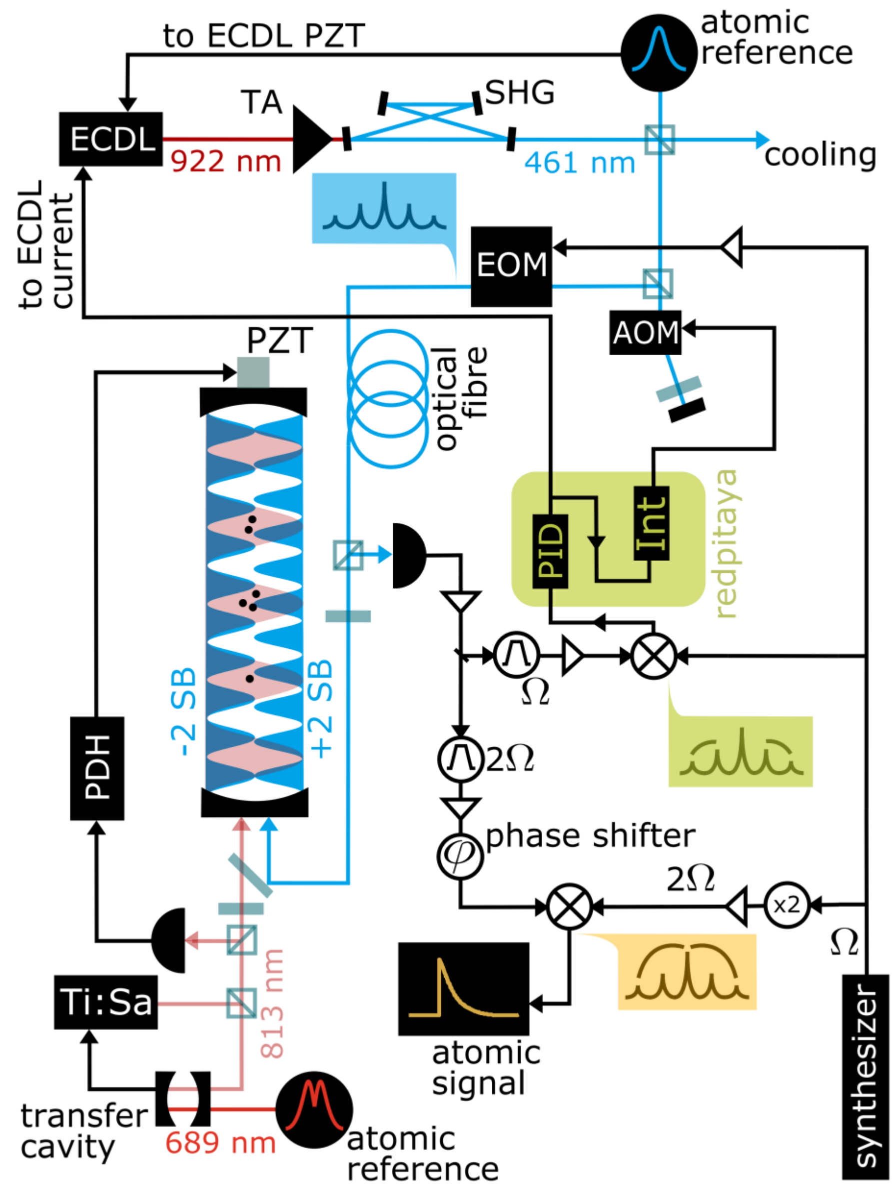
❑ Features of the setup

- Bi-chromatic cavity (lattice 813 nm + detection 461 nm)
  →self-aligned
- High-finesse at 461 nm (16000)
  →100 fold increase of the SNR
- Heterodyne dual-mode detection
  →homogeneous atom-cavity coupling
- Fast digital servo system
  →possibility of pulsed operation



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

Experimental results and limits

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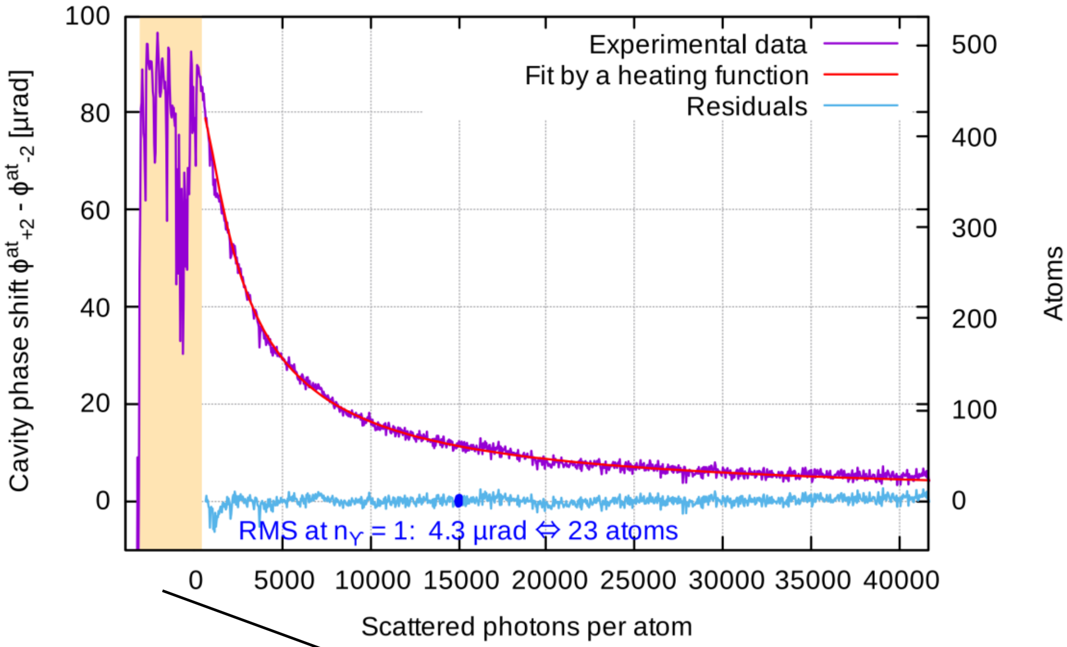
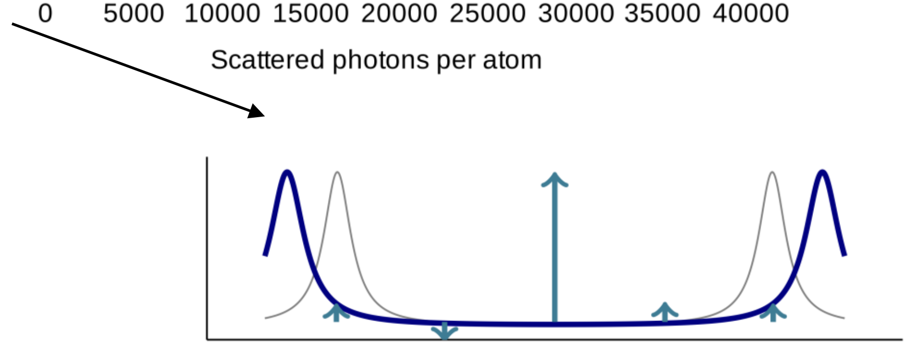
- Detection continuously on
- Dynamic range
  - 500 atoms
- Scattering rate
  - $n_\gamma / t = 40$ photons$/\mu s$
- Noise level
  - $23/\sqrt{n_\gamma}$ atoms
- 3 regimes of optimization
  - Destructive (long, $n_\gamma >> 1$)
    $\delta N \ll 1$ atom
  - Classically non-destructive
    $\delta N < 4$ atoms
  - Quantum non-destructive: $n_\gamma < 1$
    $\delta N > 23$ atoms $\Rightarrow \delta N < \sqrt{N}$ for $N > 500$





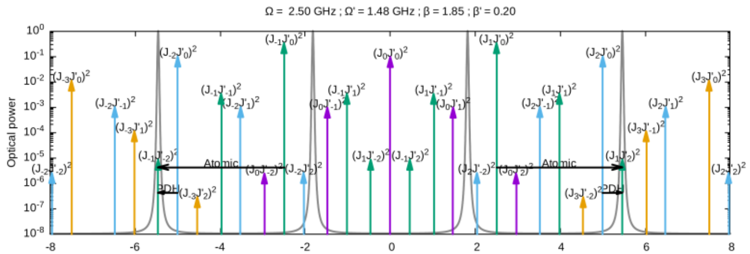
- →Need to improve dynamic range and noise/destructivity tradeoff

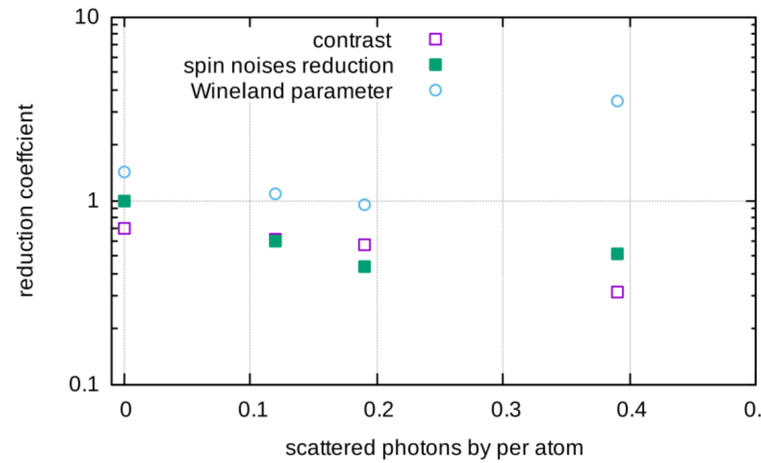
2nd experimental setup and prospects

❑ New system with two independent modulation frequencies

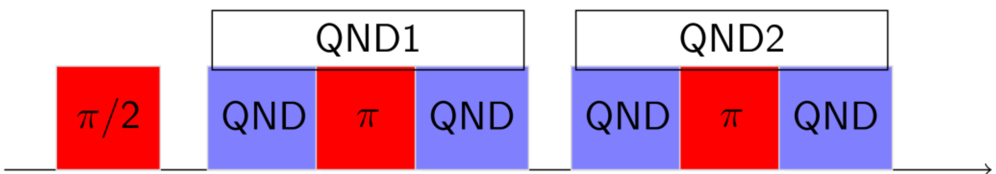
- Large detuning (5.7 GHz) →low scattering rate
- Tracking of the cavity resonances →improved dynamic range
- Pulsed operation

As in Hobson et al., Optics Express 27 37099 (2019)





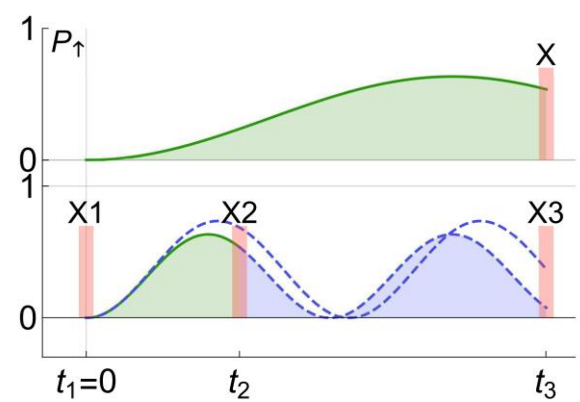
❑ QND measurements



- Observation of correlations between QND meas.
- Wineland parameter ξ = 0.95

❑ Protocol to exploit this detection (with ICFO)

- Rabi interrogation with 3 QND measurements
- Optimization accounting imperfections
- →significant gain possible (7.9 dB for 2E4 atoms)



Phys. Rev. Lett. 128, 153201 (2022)

Spectral hole burning for lasers <1E-17

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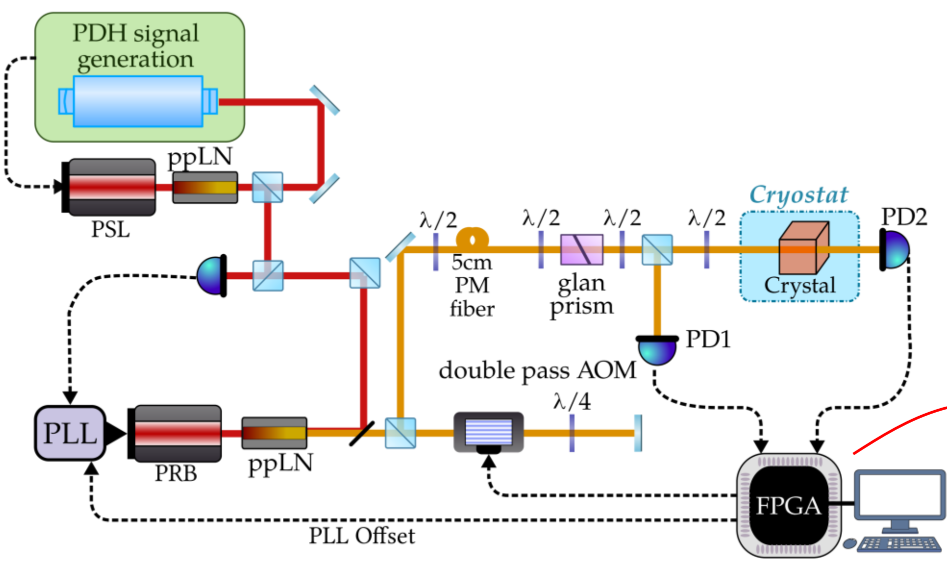
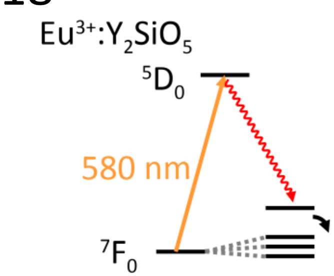
❑ Laser stabilization to spectral features obtained by spectral hole burning (SHB)

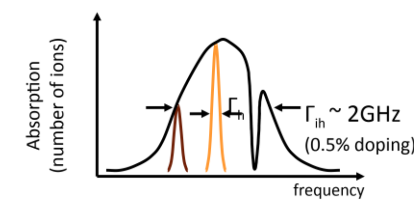
- Have extremely low fundamental limits.
- One possibility to beat the thermal noise limit of room temperature cavities.
- Was investigated at NIST, HHU *Nat. Photon. 5, 688 (2011)* *Phys. Rev. Lett.107, 223202 (2011)*

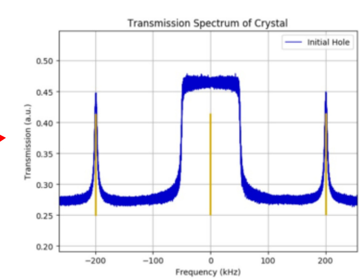
❑ Eu3+ ions doped into Y_2SiO_5 matrix at cryogenic temperature

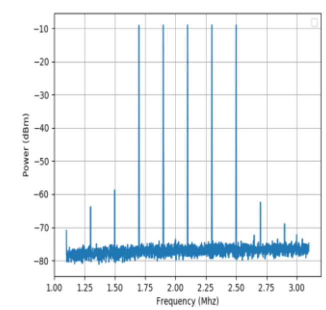
- Long-lived spectral holes can be burned in the optical absorption spectrum.
- T_2 = 2.6 ms (1.4 K) -> Γ_h= 122 Hz expected. 1 - 2 kHz routinely observed.
- Fundamental limits inc. thermal noise <1E-18











N. Galland, et al., Opt. Lett. 45, 1930-1933 (2020).
S. Zhang, et al., Phys. Rev. A 107, 013518 (2023).
S. Zhang, et al., Appl. Phys. Lett. 117, 221102 (2020).
N. Galland, et al., Phys. Rev. Applied 13, 044022 (2020).
S. Zhang, et al., Phys. Rev. Research 2, 013306 (2020).

Spectral hole burning at 3.2K & dilution temperature

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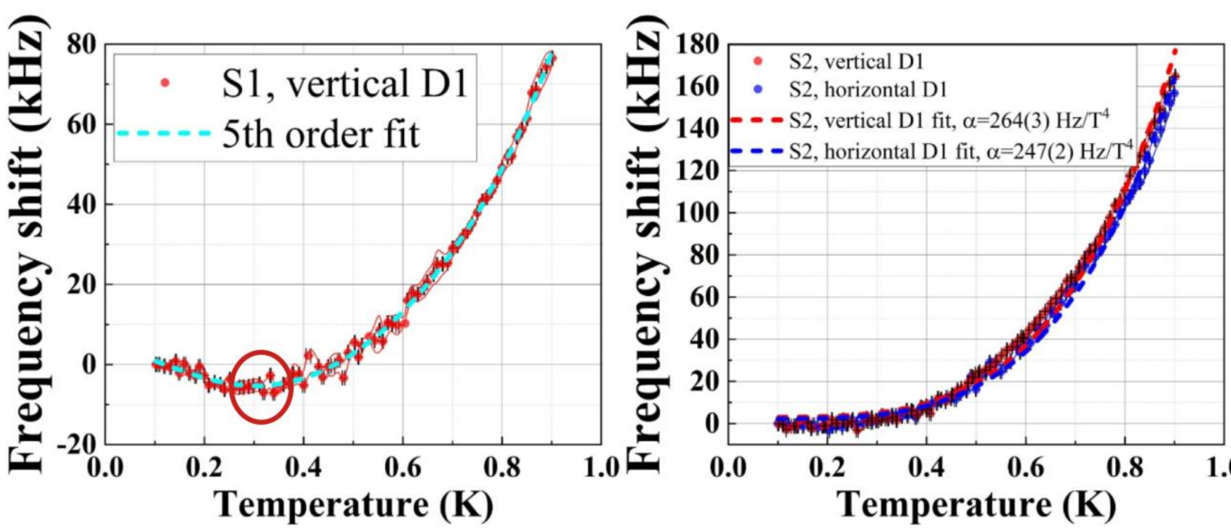
❑ At 3.2K, several studies of sensitivities

- Stark, strain/acceleration, magnetic field, temperature
- →sensitivities and perturbations present in the environment compatible with <1E-17, except for the temperature
- Probing schemes setup and stability of 1.7E-15 @1s for 1 hole.

❑ At <1K, measurement of the temperature sensitivity

- Drastically reduced sensitivity and a turning point



@320mK (magic point), $\Delta T \sim 100\mu K$ implies $\Delta\nu/\nu \sim 10^{-21}$

@100mK, $\Delta\nu/\nu < 10^{-17}$ implies $\Delta T < 5mK$