Laboratoire Temps Espace

An optical lattice clock with a bosonic isotope of mercury

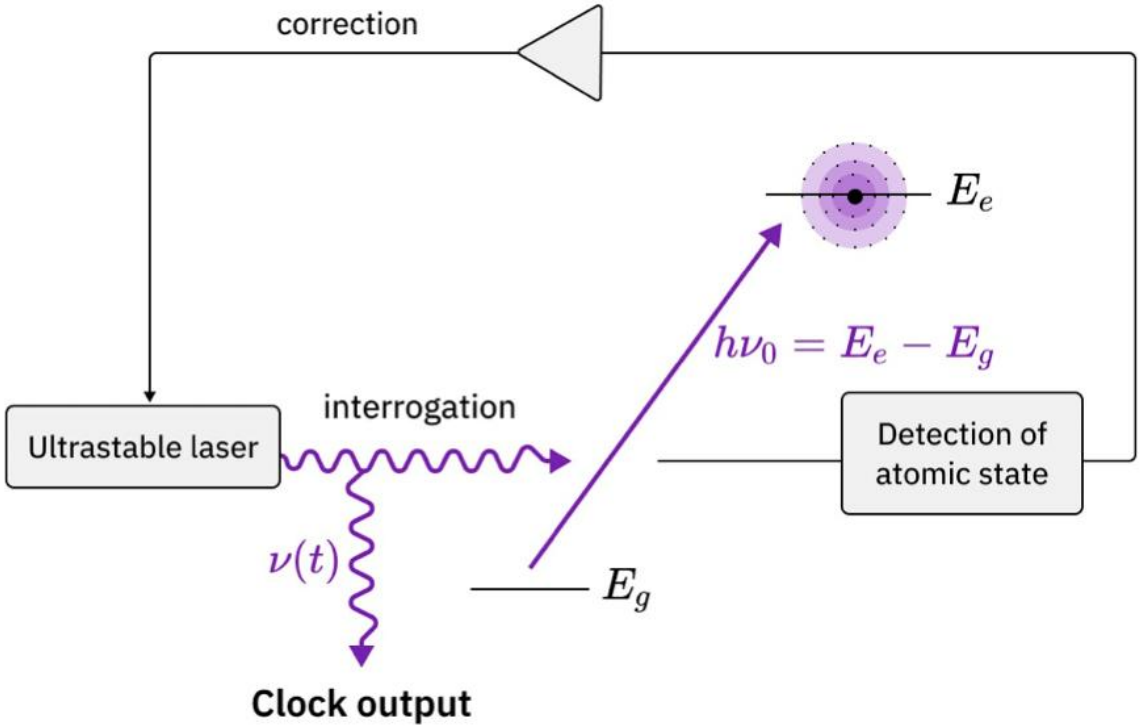
International Conference on Precision Physics of Simple Atomic Systems, Vienna

May, 21st 2026

Ashley Béguin

Context

Clock principle



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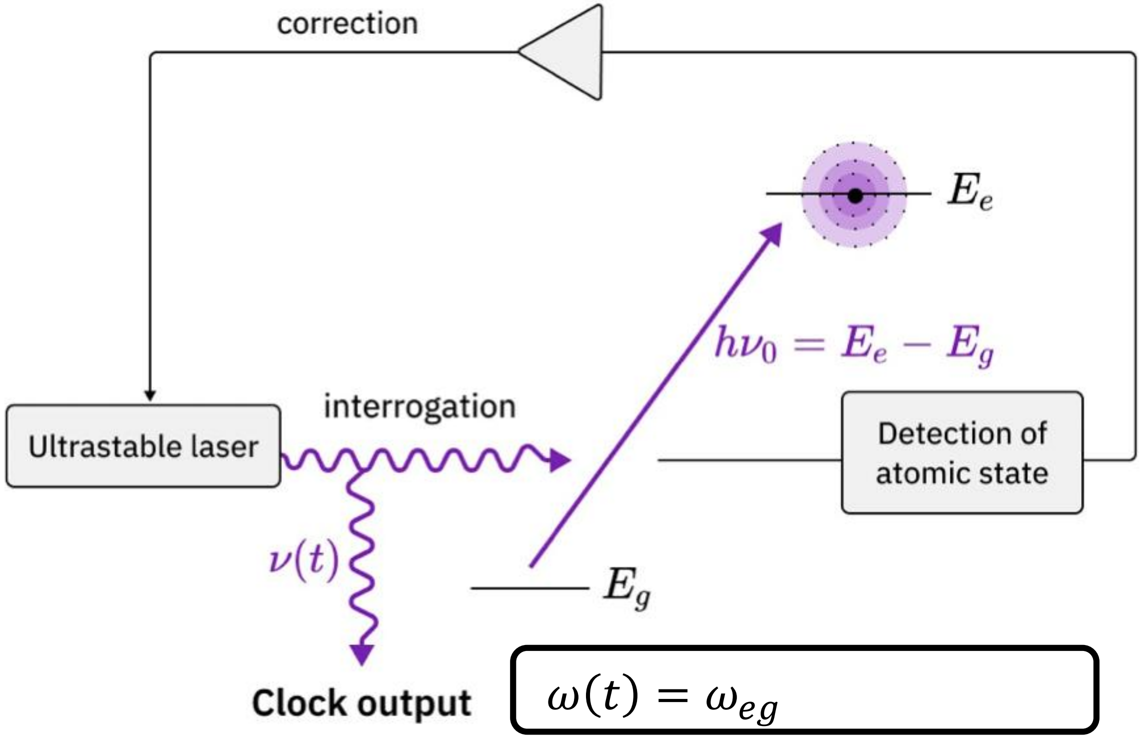

$$\omega(t) = \omega_{eg}$$

Context

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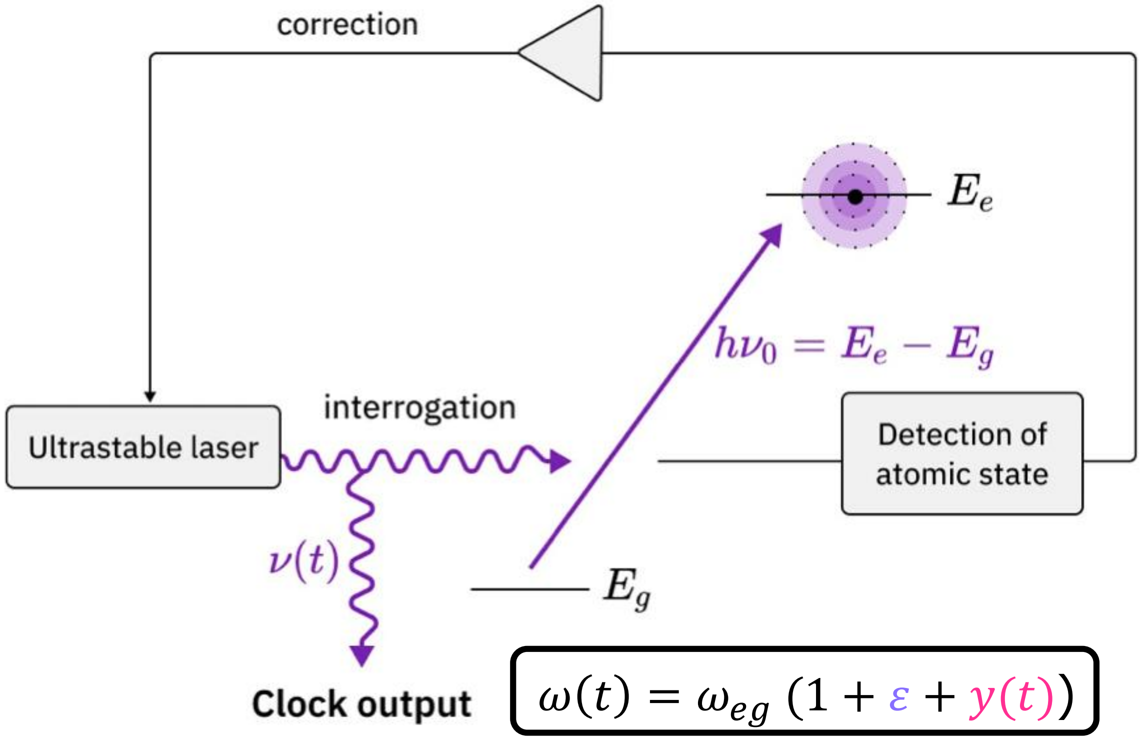

$$\omega(t) = \omega_{eg}\,(1 + \varepsilon + y(t))$$

Context

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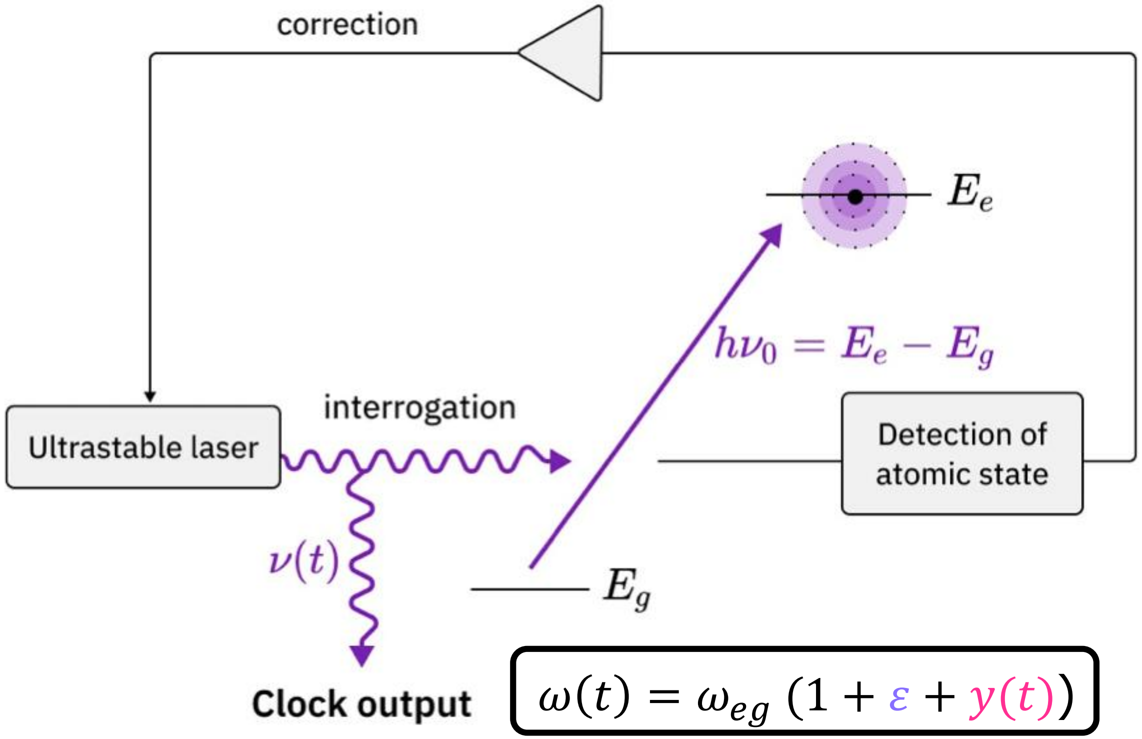

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- High accuracy: overall uncertainty on ε
- High stability: statistical properties of $y(t)$
- Low sensitivity to external perturbations
- Reproducible

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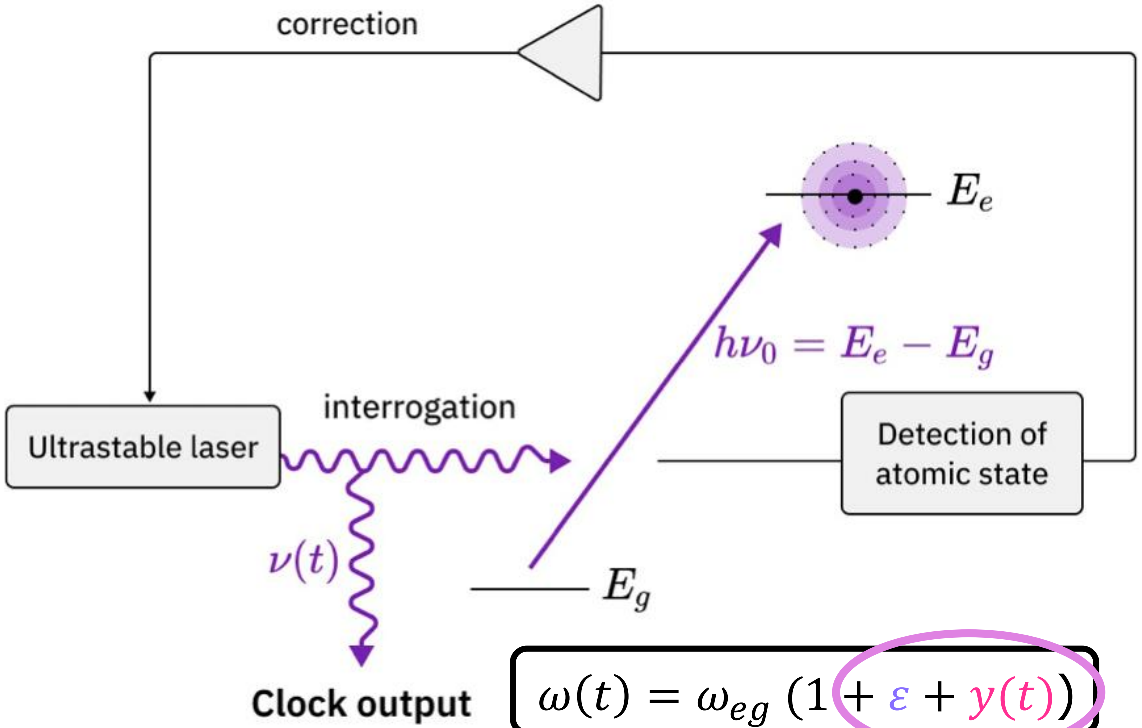

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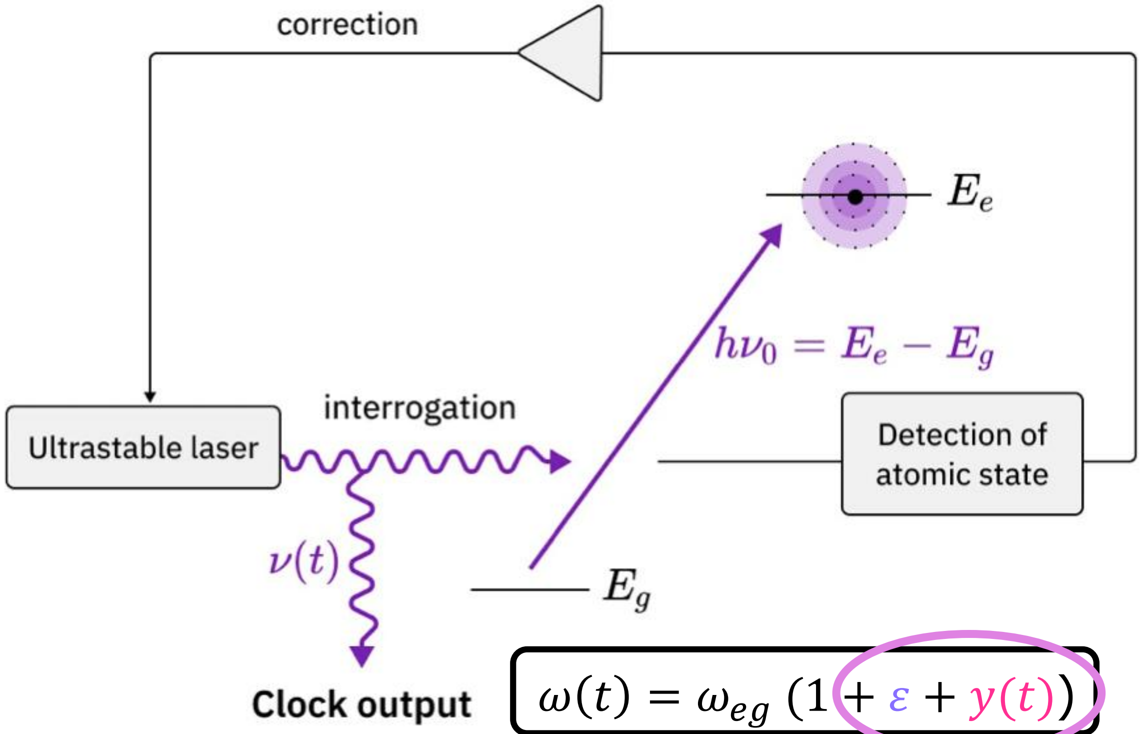

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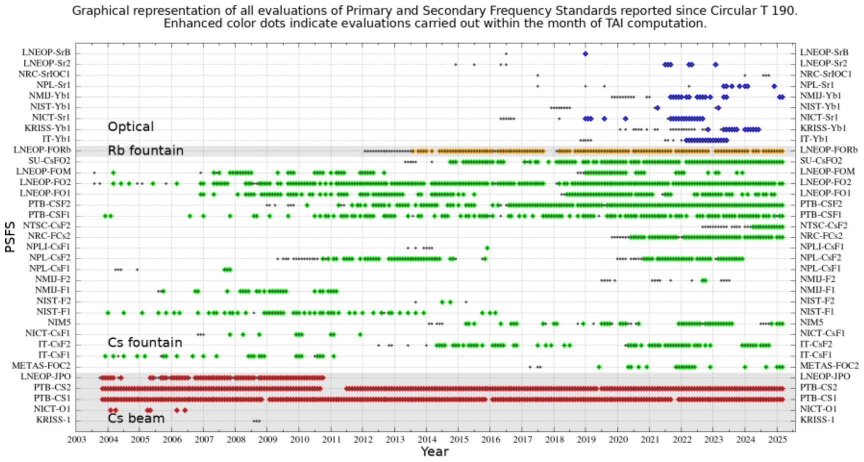
Physical effects inducing noise and shifts:

- ❑ Main sources of noise
  - Laser
  - Detection
- ❑ Effects of trapping
- ❑ Effects of thermal radiation
- ❑ Interactions between atoms
- ❑ Many other physical and technical effects

Context

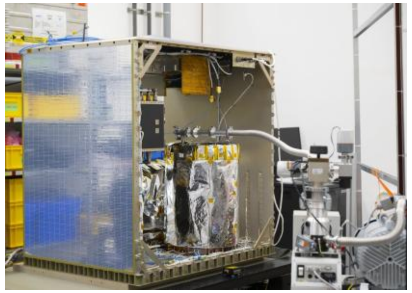
Applications



Optica 13, 143 (2026)

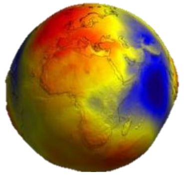
- **Metrology**
  - Better time & frequency references
  - Redefinition of the SI second

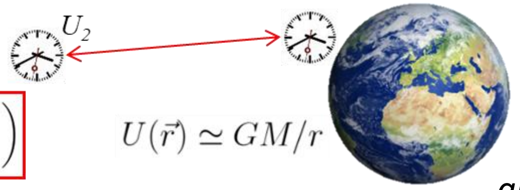
- **Tests of fundamental laws**
  - Test of GR *Living Rev. Relativ. 17, 4 (2014)*
  - Stability of fundamental constants *Rev. Mod. Phys. 90, 025008 (2018)*
  - Search for dark matter *Living Rev Relativ 28, 6 (2025)*
  - Probe nuclear properties via isotope shifts *Nat Rev Phys 7, 119 (2025)*



ACES

- **Chronometric geodesy**
  - Transportable optical clocks
  - Optical fiber and free-space links





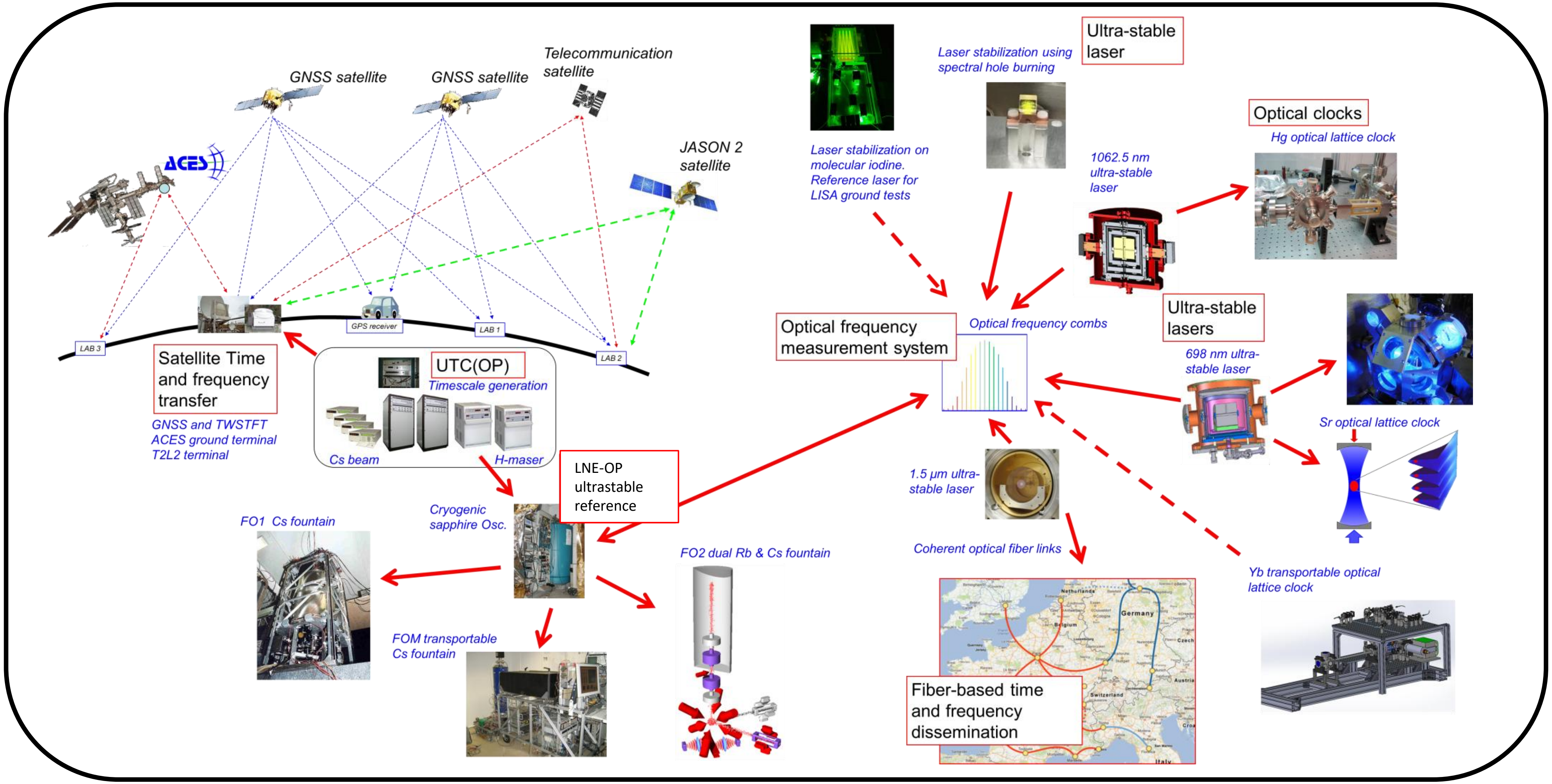
$$\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)$$

$$U(\vec{r}) \simeq GM/r$$

arXiv:1804.09506

Context

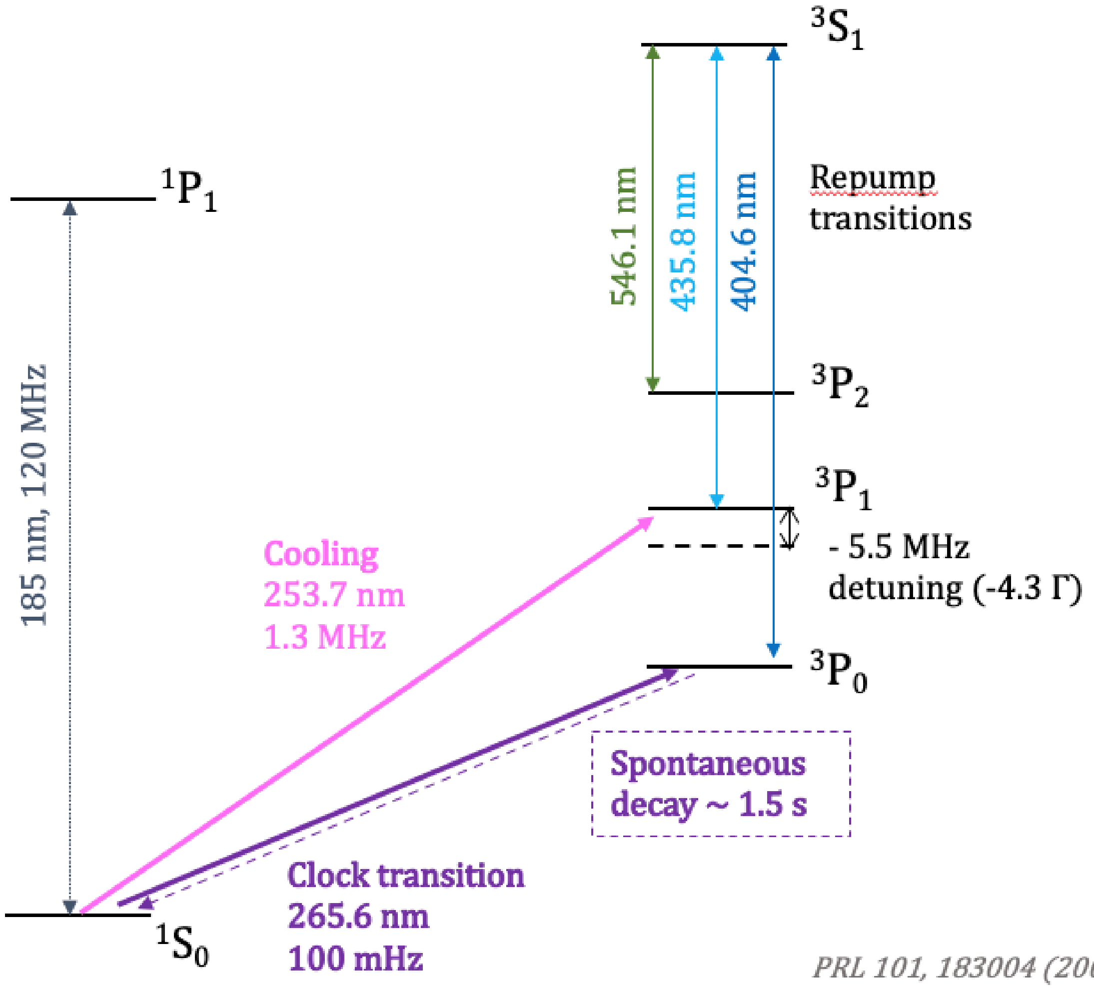
Laboratoire Temps Espace (LTE) clock ensemble



Hg optical clock

Why using mercury (Hg) for an optical clock?

- ❑ Low sensitivity to black body radiation (Yb/16, Sr/30)
- ❑ High vapour pressure (no oven)
- ❑ Simple transition structure (7 stable isotopes)
- ❑ High sensitivity to possible variations of constant α



PRL 101, 183004 (2008)

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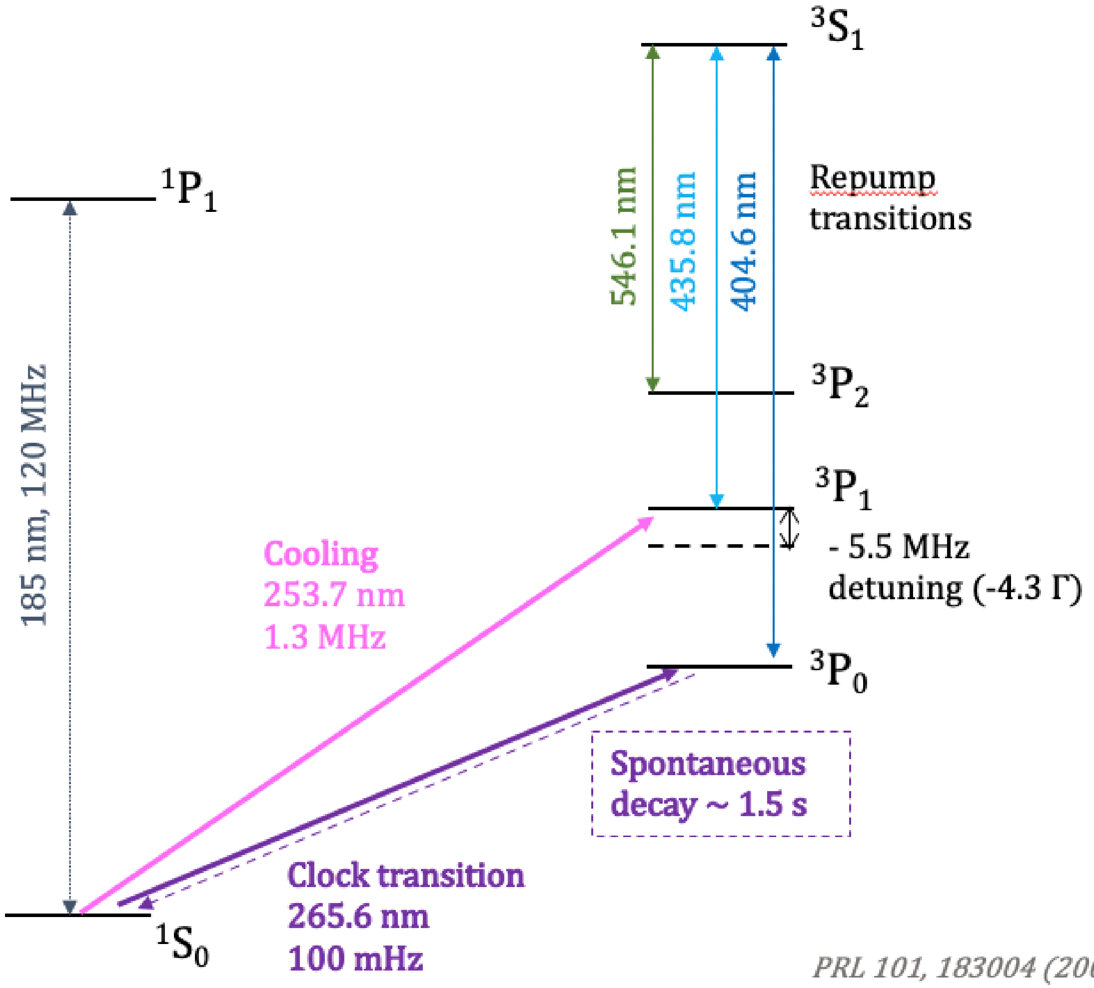

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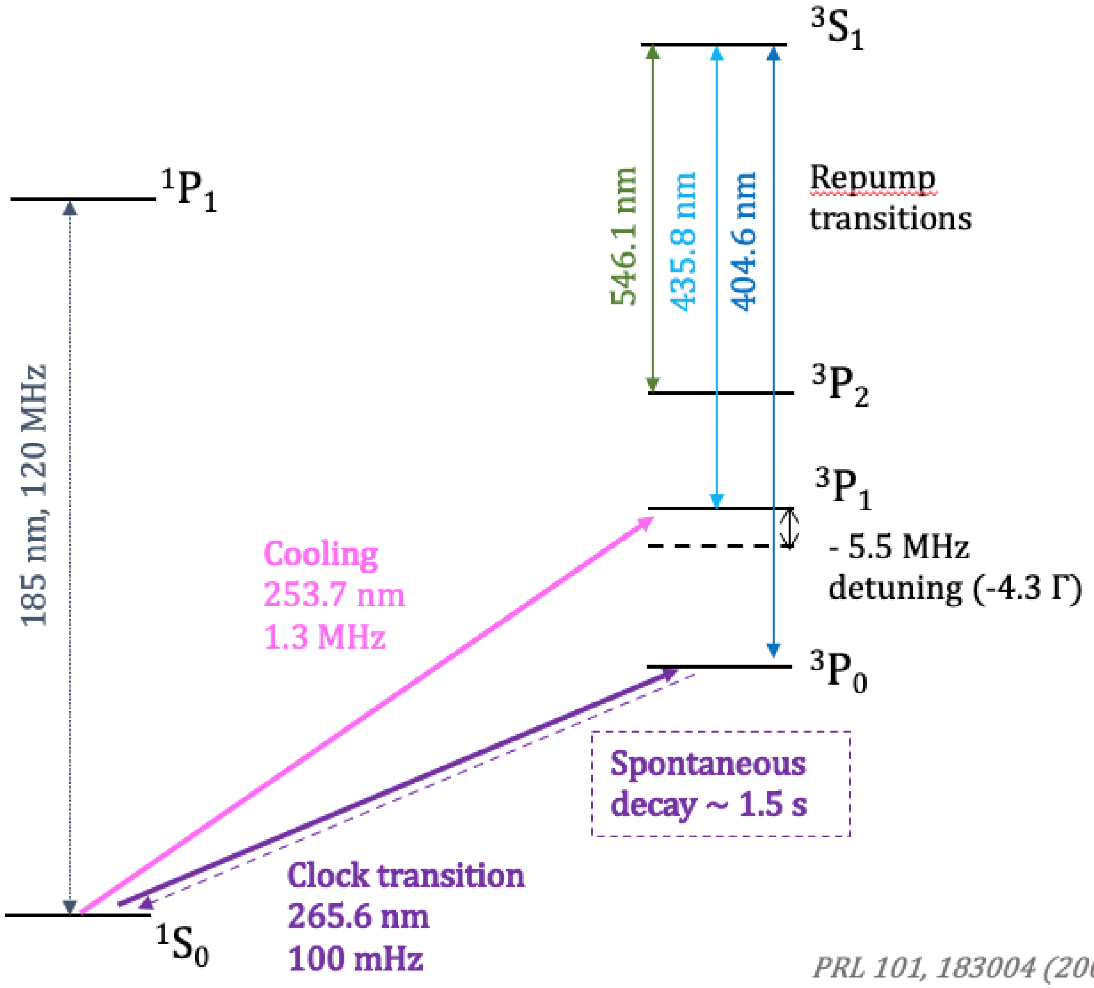
So far only ^{199}Hg isotope:
- ❑ Secondary representation of the second
- ❑ Performances reached @ LTE:
  - Systematic effects uncertainty : ~ 5 x 10^{-17} [1]
  - Stability : 8-9 x 10^{-16} @ 1s [2][3]



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[1] 2024, Zyskind, PhD Thesis
[2] 2016, Tyumenev, NJP18, 113002
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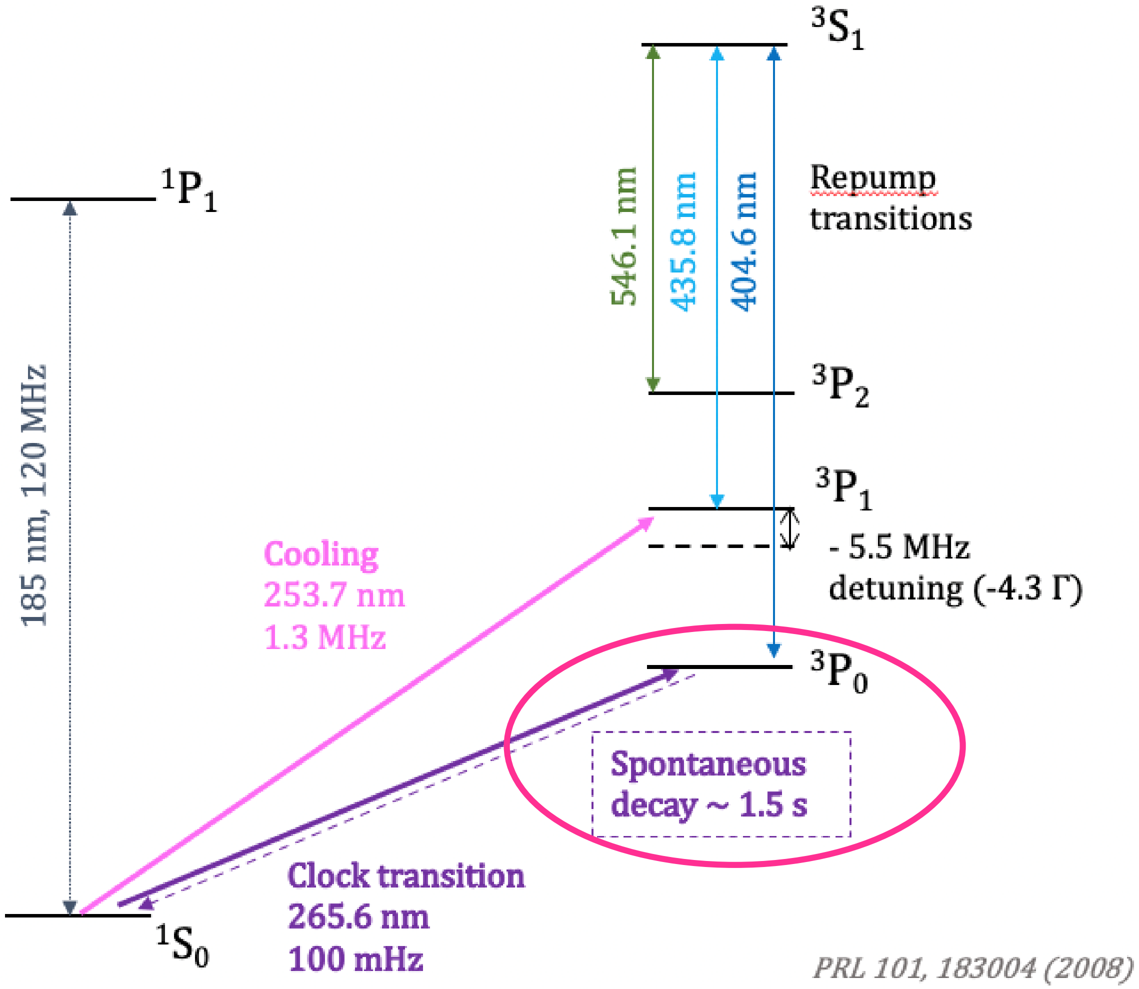
Transition width soon a limitation vs new generation of ultrastable lasers



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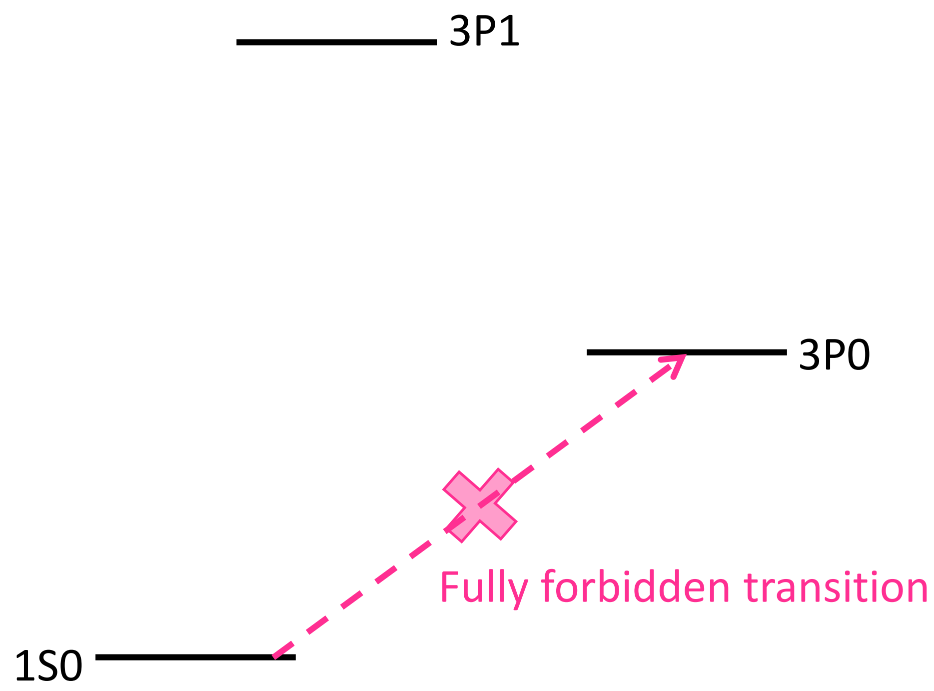
Towards Hg bosonic isotopes

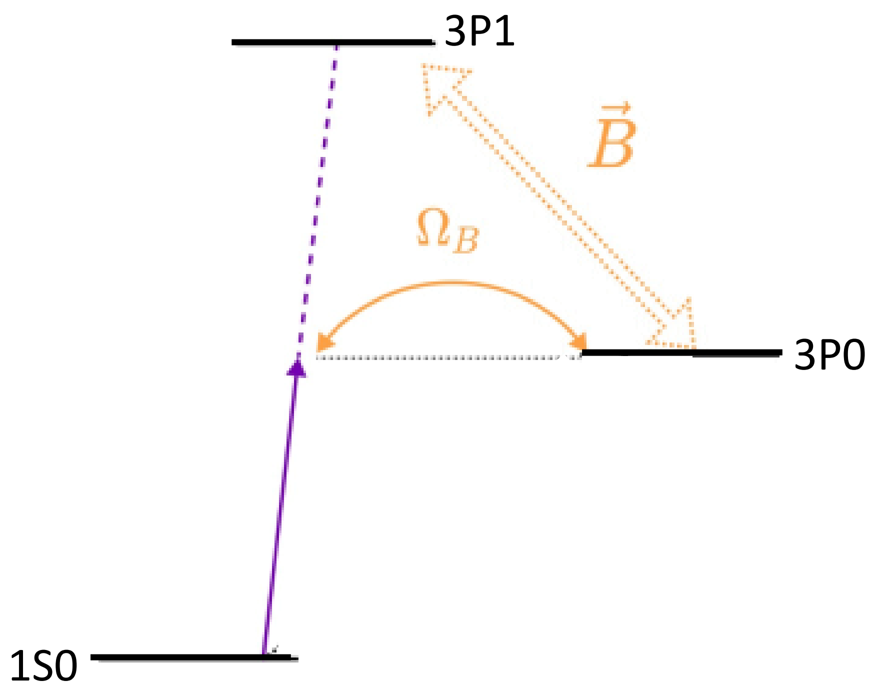
Bosonic isotopes: no nuclear spin



Towards Hg bosonic isotopes

Quenching scheme

Bosonic isotopes: no nuclear spin



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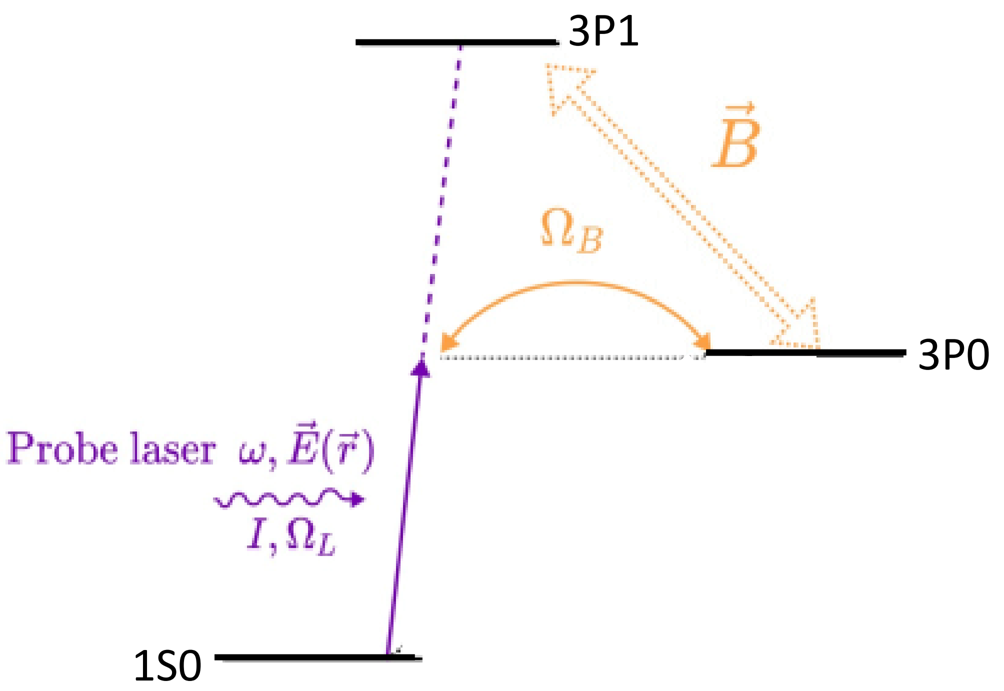

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Bosonic isotopes: no nuclear spin

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- Already demonstrated in ^{88}Sr and ^{174}Yb

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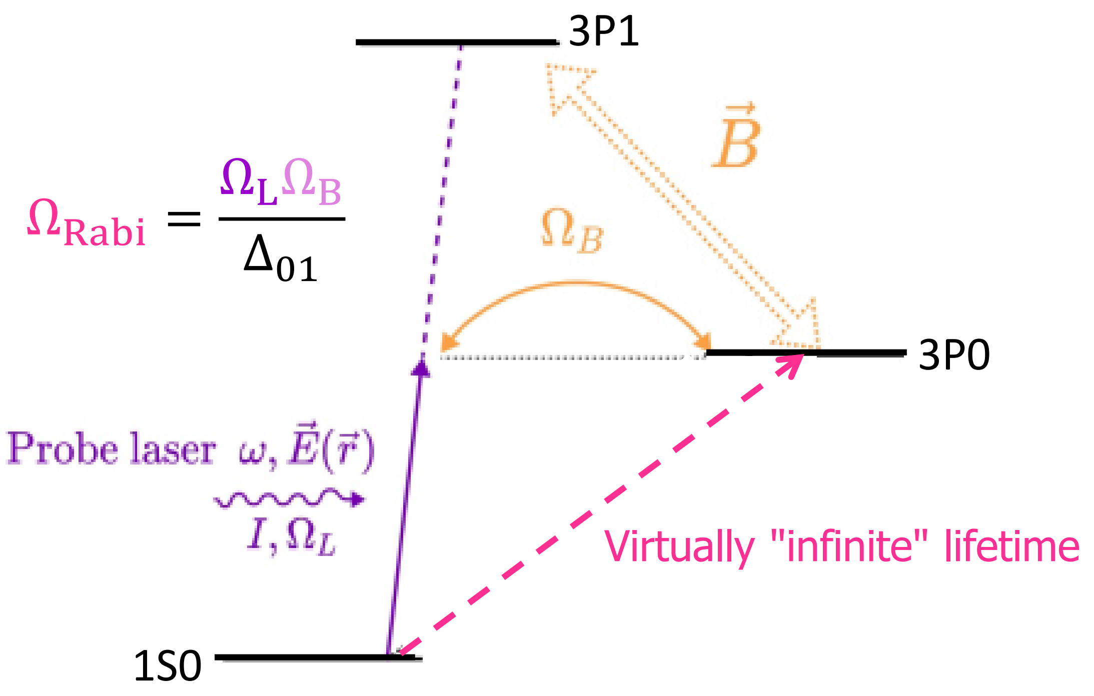

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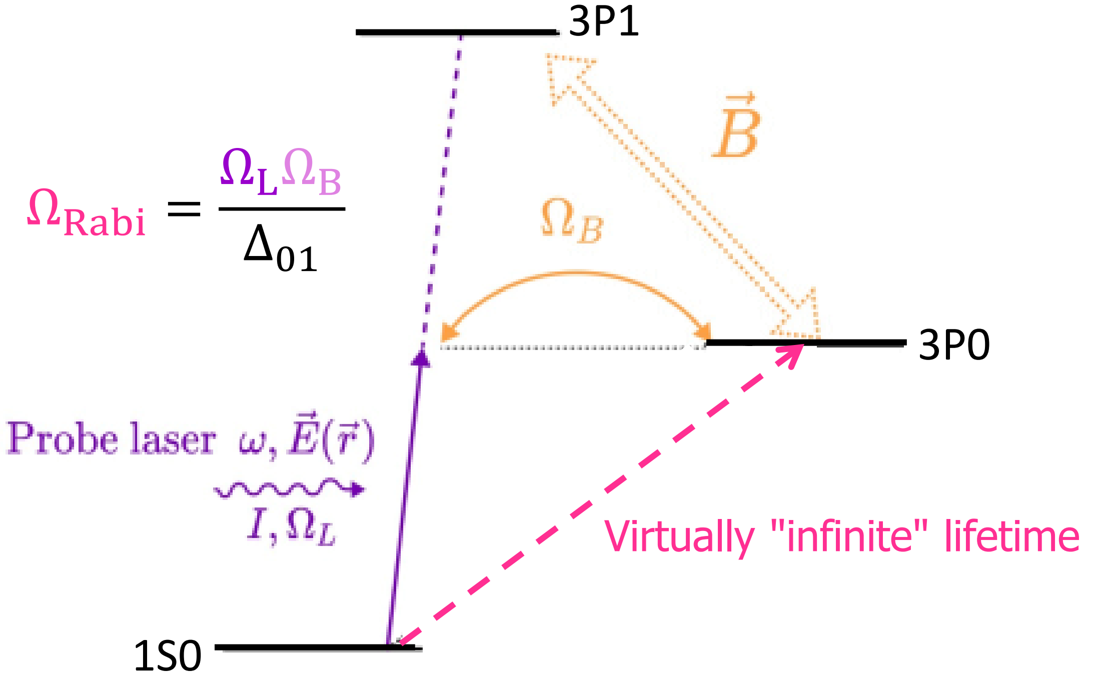
Weak coupling:

- ❑ Strong magnetic field ➡ Quadratic Zeeman Shift
- ❑ Strong probe power ➡ Probe Light Shift

Quenching scheme



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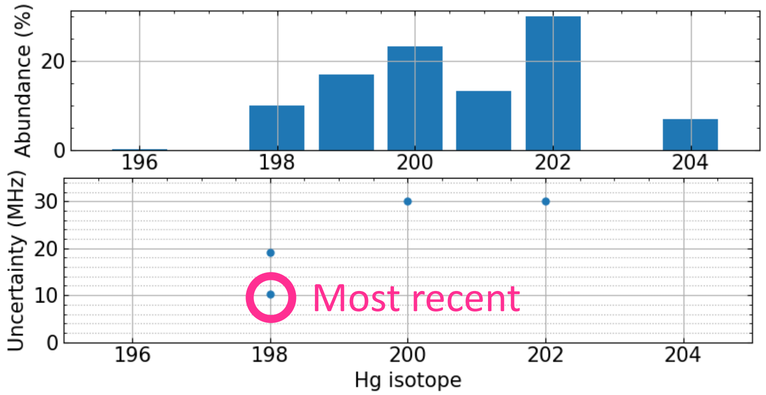
198Hg bosonic isotope

Isotope choice:



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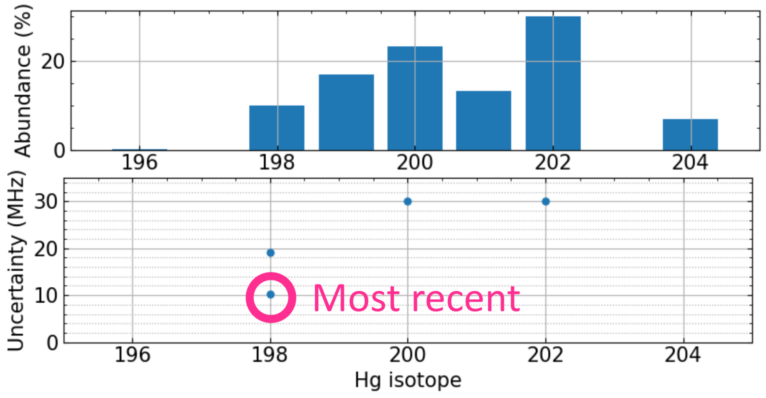
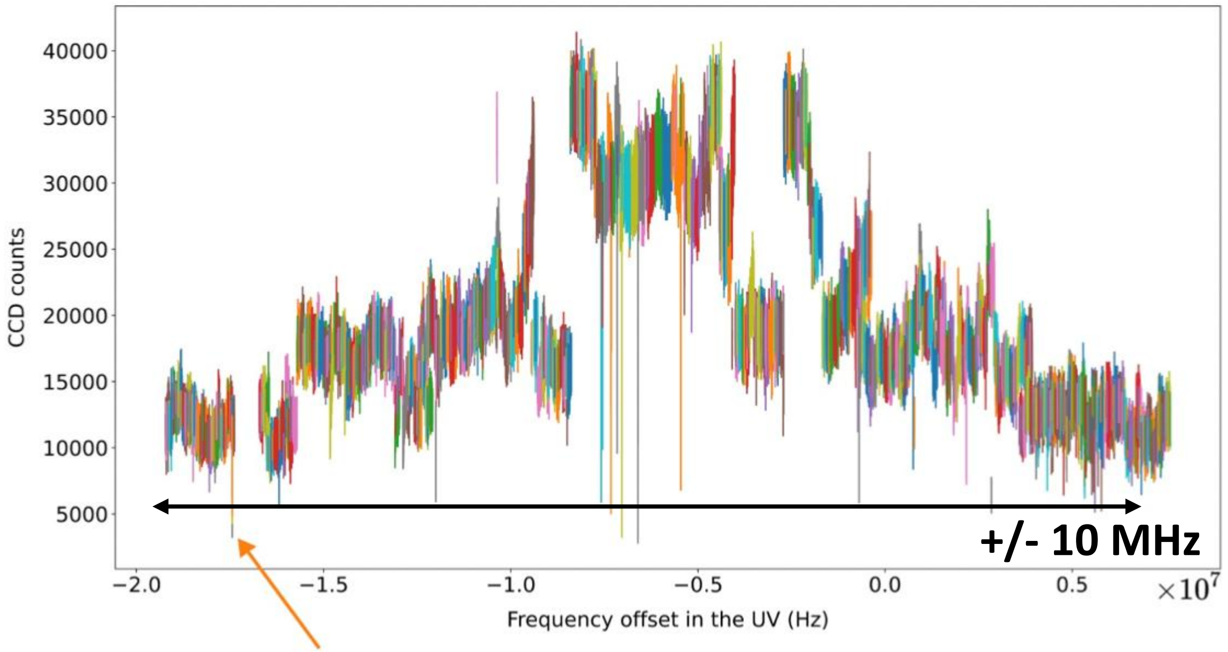


Probing the transition: Transition width of ~ Hz over +/- 10 MHz range!



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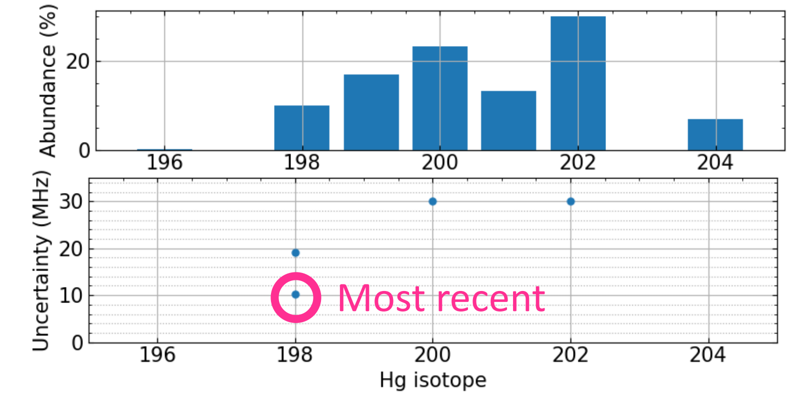

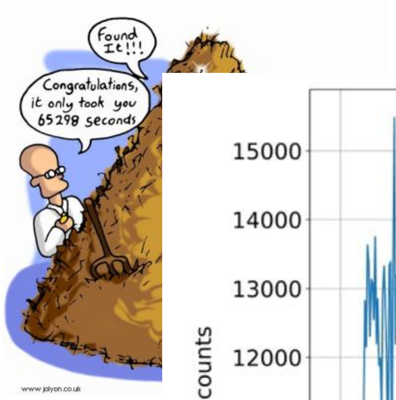

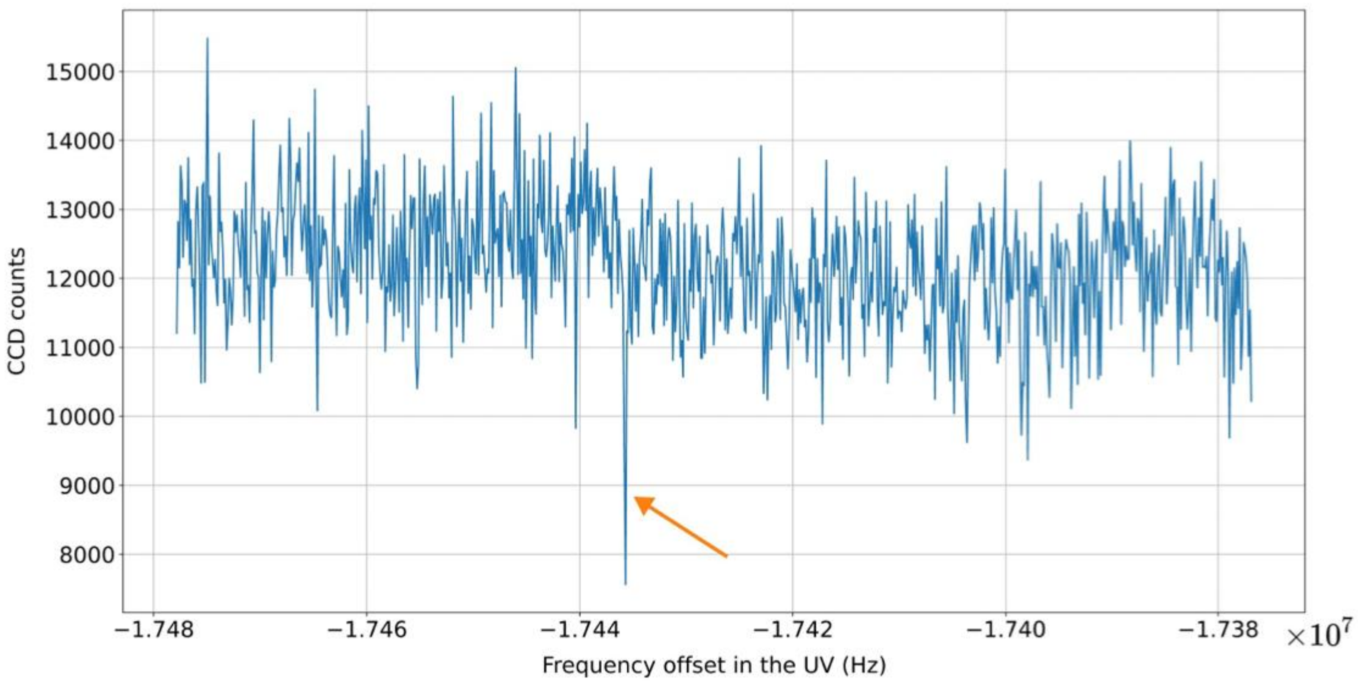

Transition found in 2024! [1]

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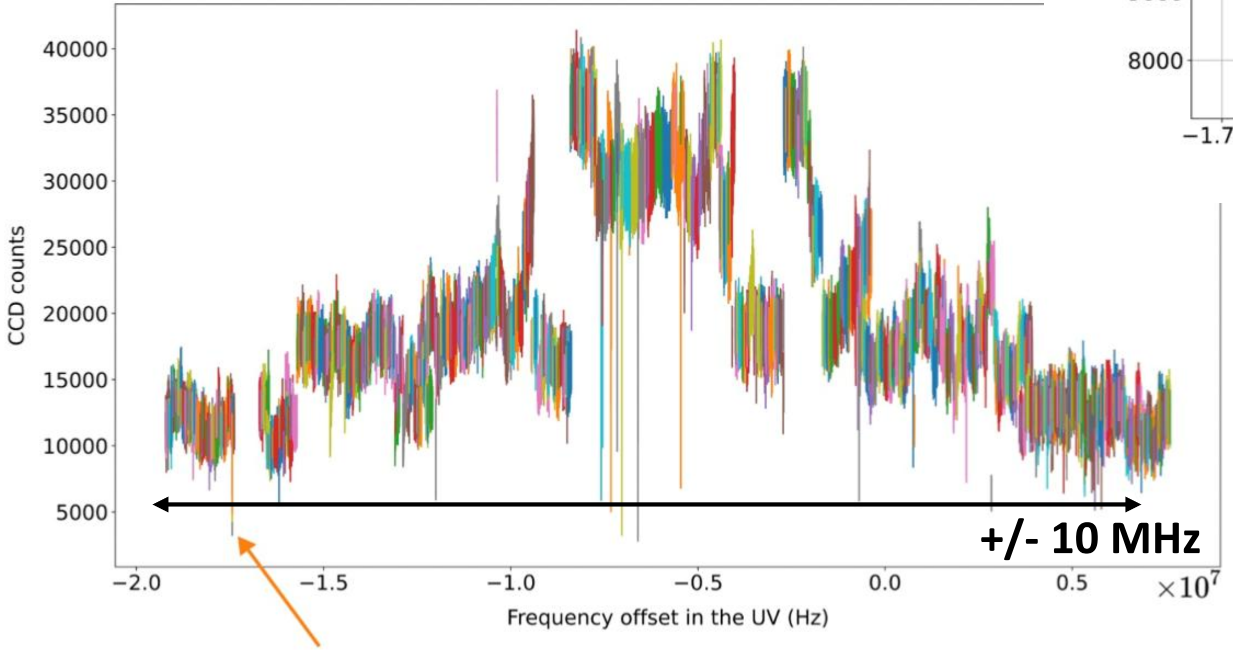

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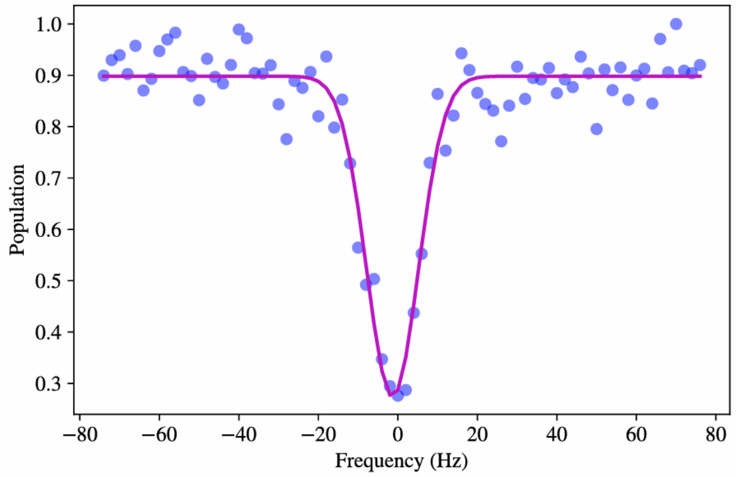
198Hg bosonic isotope clock

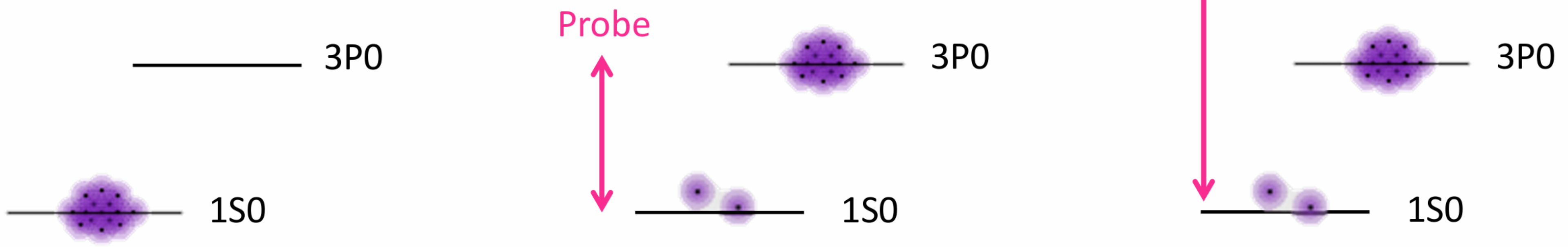


Lattice:
Trapping depth ~ 92.4 Er
Waist ~ 69 μm

Ultrastable laser:
Linewidth ~ 200 mHz
Mean drift rate ~ -16.9 mHz/s

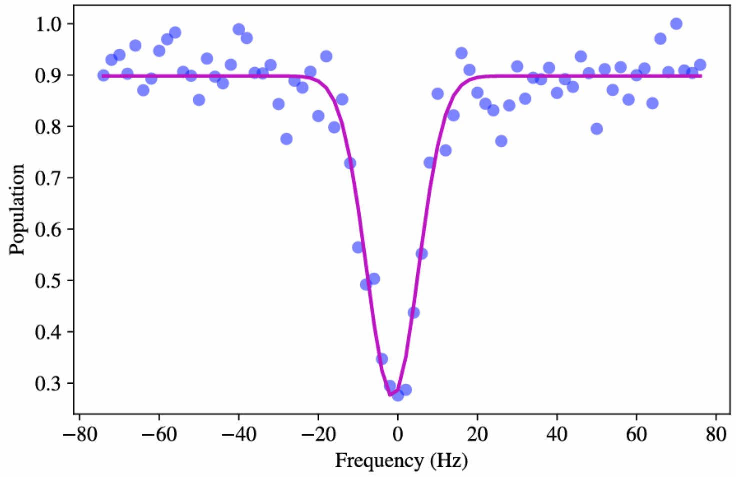
Cooling → **Lattice trapping** → **Clock interrogation** → **Detection**

2D MOT
3D MOT



198Hg bosonic isotope clock

<u>How to get a reliable clock?</u>



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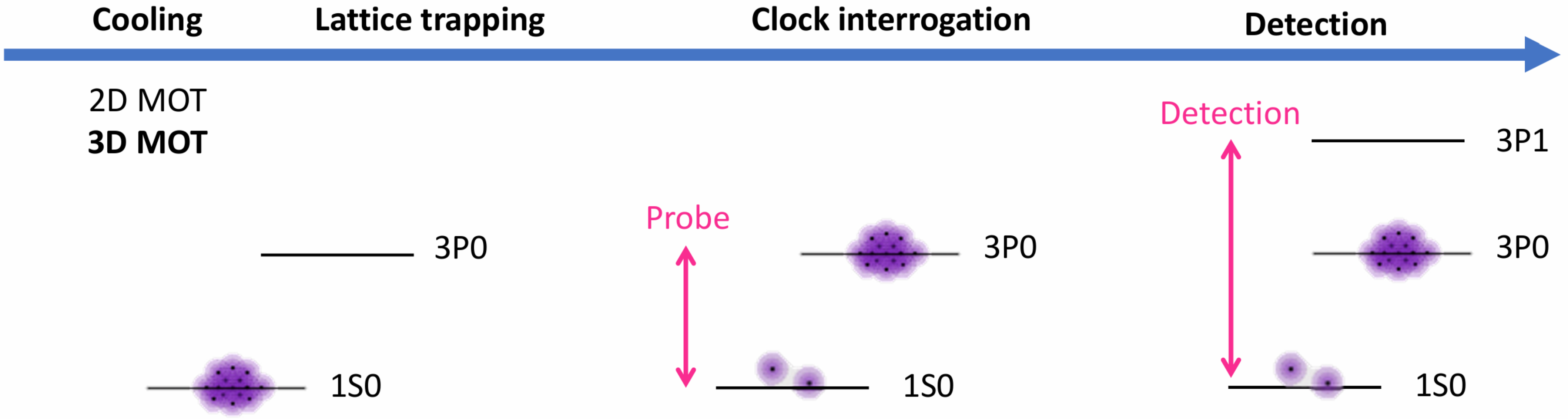
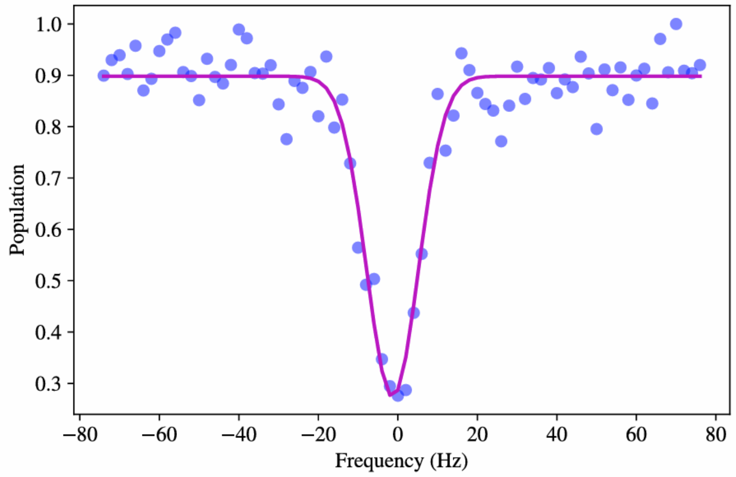


198Hg bosonic isotope clock

How to get a reliable clock?

- ❑ High stability ➡ Statistics
- ❑ High accuracy ➡ Systematics



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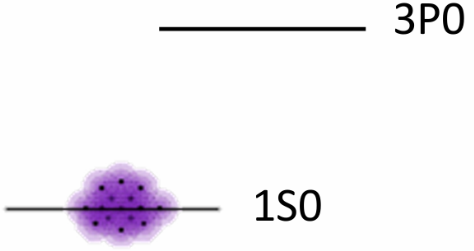

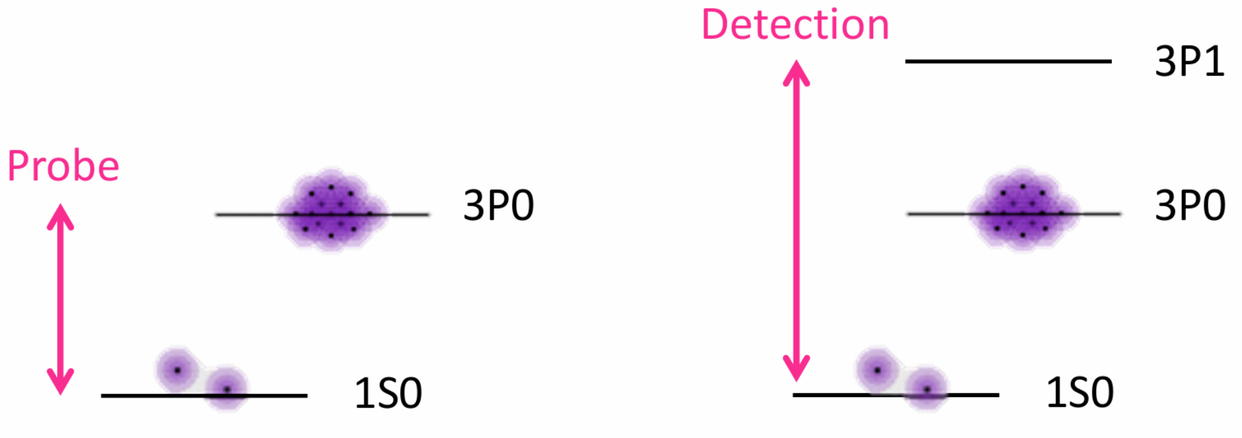

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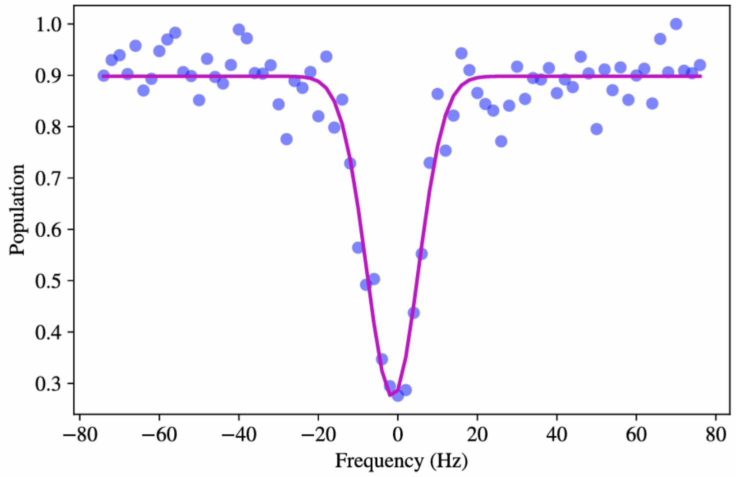

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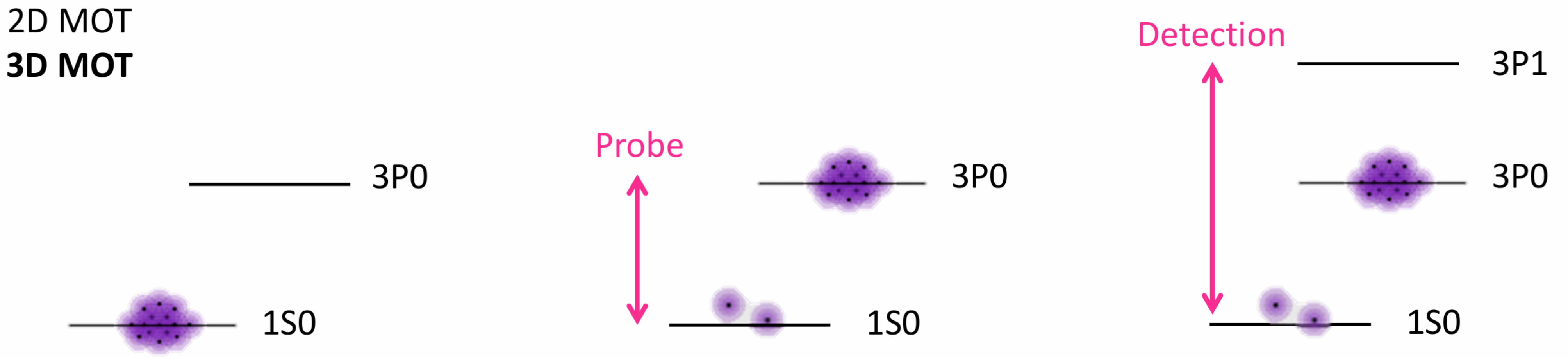

198Hg systematics characterization

Lattice linear lightshift

- Total shift on atomic clock transition: $\Delta\nu = \left(\alpha_{1S_0}(\nu) - \alpha_{3P_0}(\nu)\right) \frac{|E_L|^2}{8\pi\hbar}$

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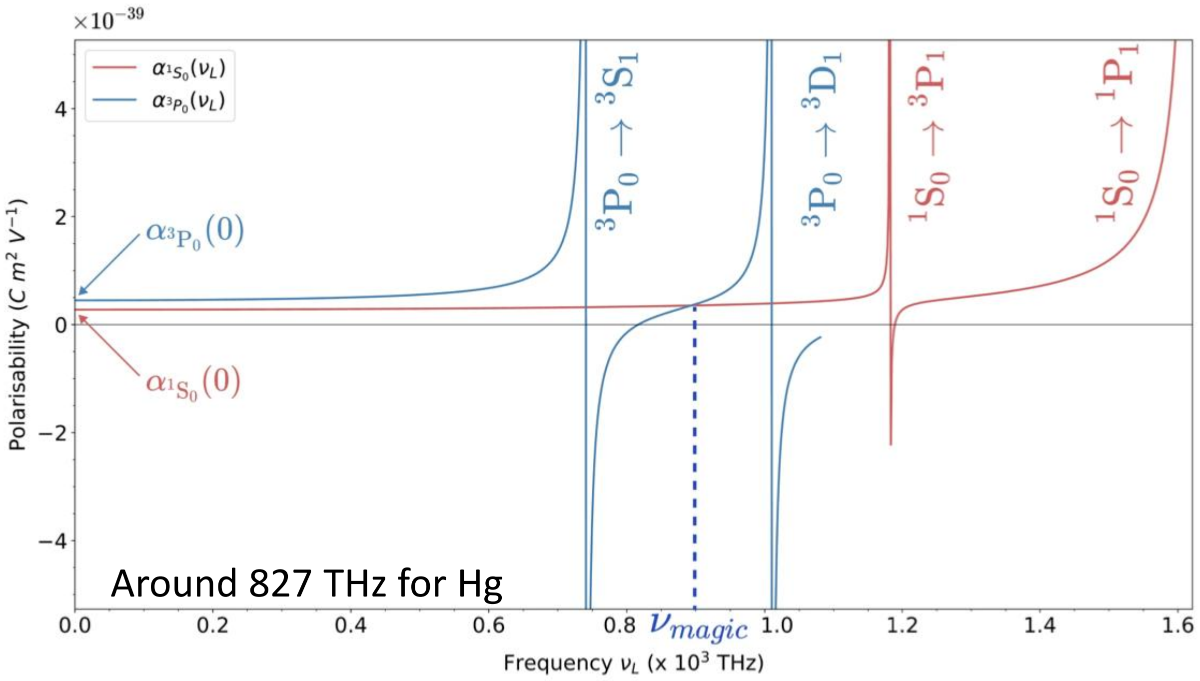

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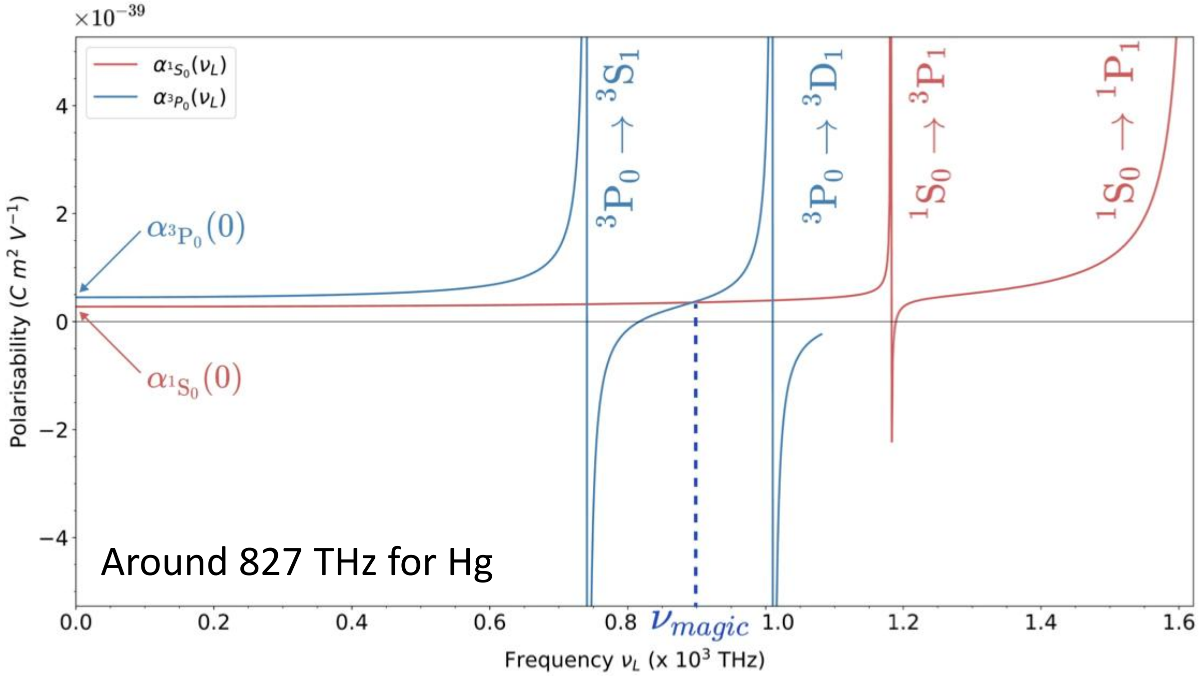
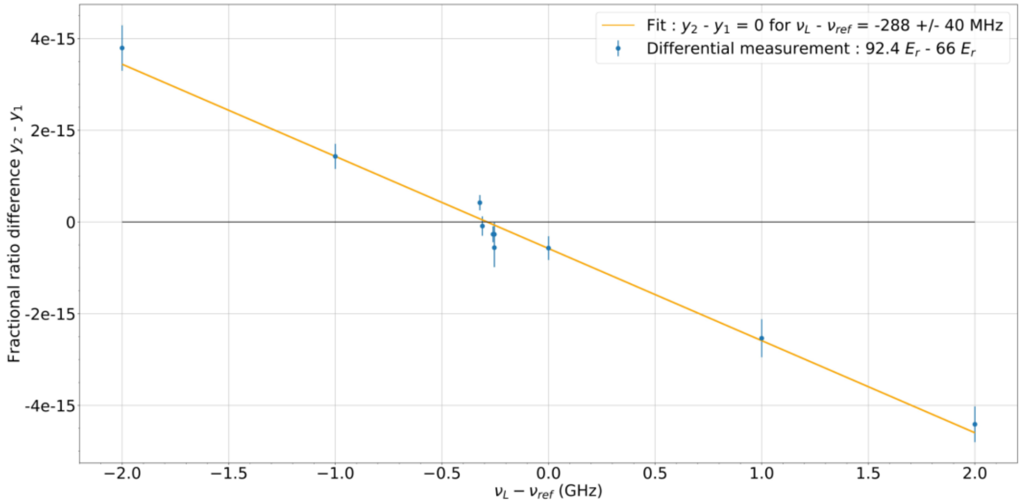


Magic Wavelength calibration

$$\Delta_{\text{magic}} = \kappa\nu_L(\nu_L\text{-}\nu_{\text{magic}})U_{\text{L}}$$

- ❑ Differential measurements using different lattice depths



$$\nu_{\text{magic}} = 826.855\ 228(28)\ \text{THz}$$

$$\frac{\sigma\Delta}{\nu_0} = \text{+/-}\ 3.2 \times 10^{-16}$$

198Hg systematics characterization

Systematics calibration of clock transition

Cold collisional shift

- Induced by interactions between cold atoms

$$\Delta_{\mathrm{CCS}} = K_{\mathrm{CCS}}\, N_{\mathrm{atom}}$$

- Differential measurements with different atom number

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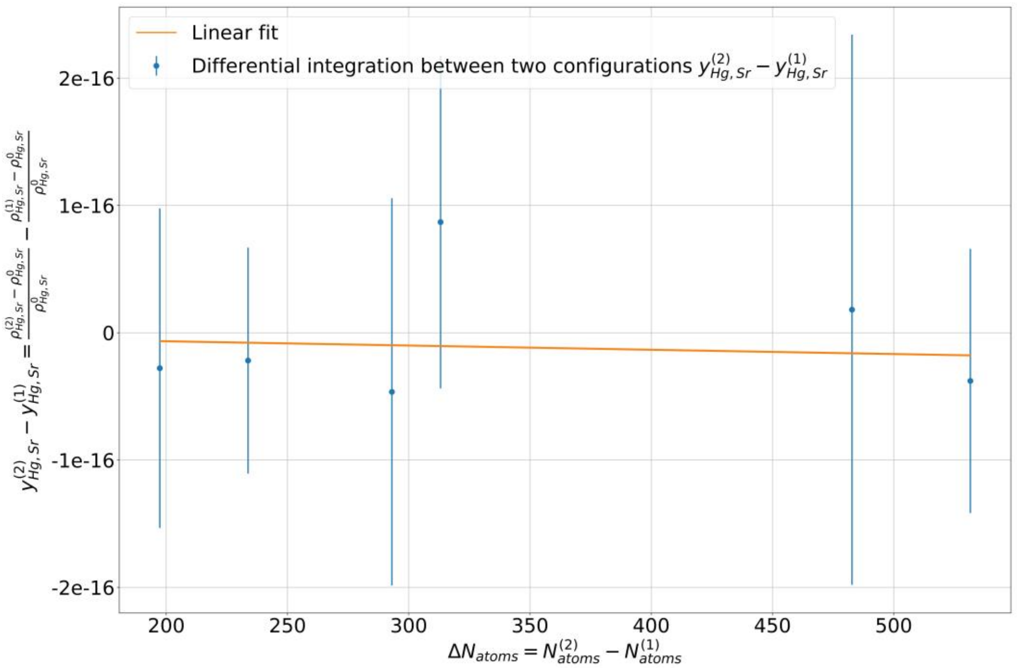

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Our experiment: ~ 500-1000 atoms

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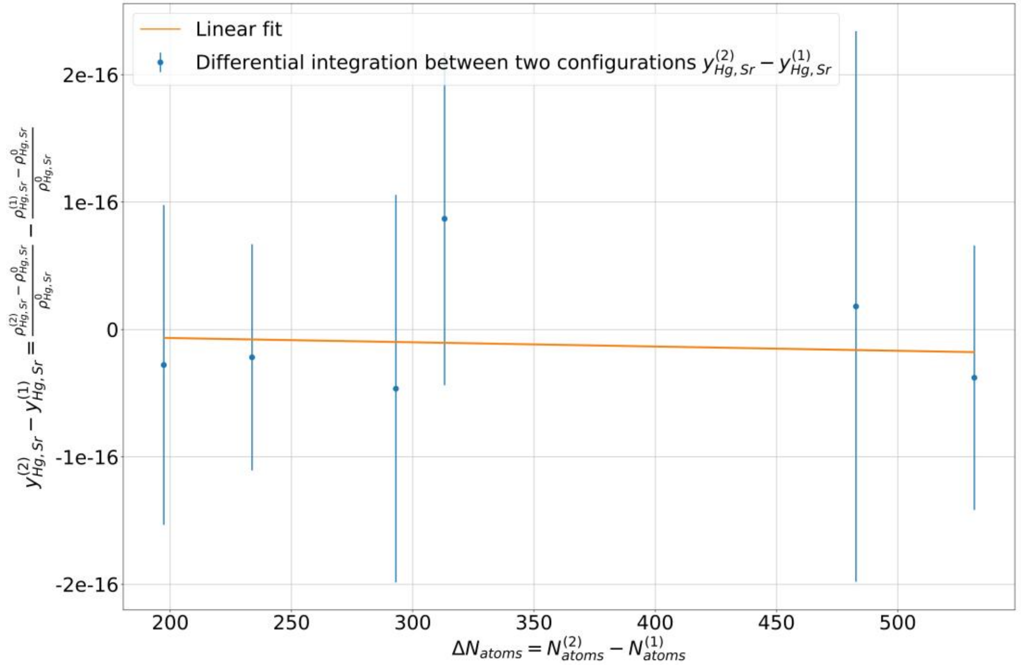

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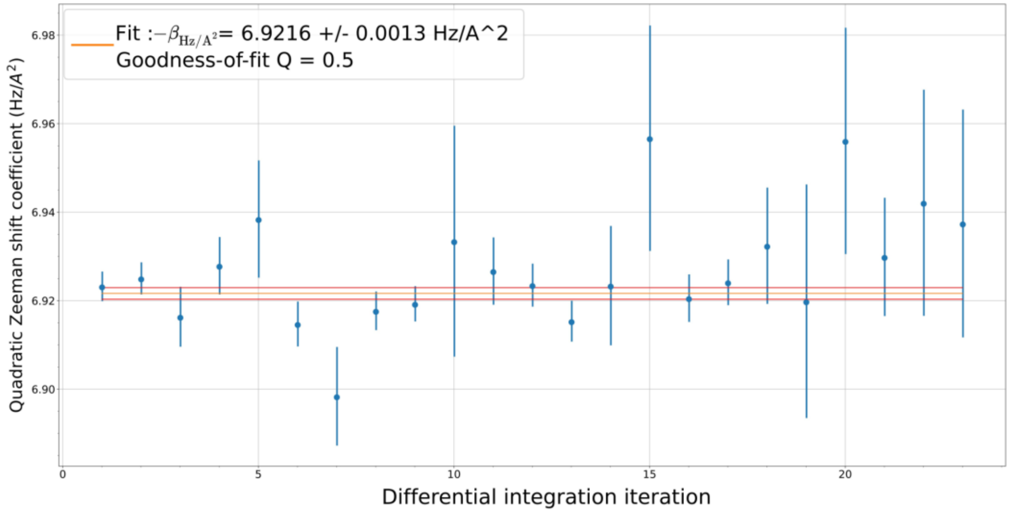
Systematics calibration of clock transition

Quadratic Zeeman Shift (QZS)

- ❑ $\Delta_{QZS} = \beta \left\| \vec{B} \right\|^2$
- ❑ Differential measurements with different values of B



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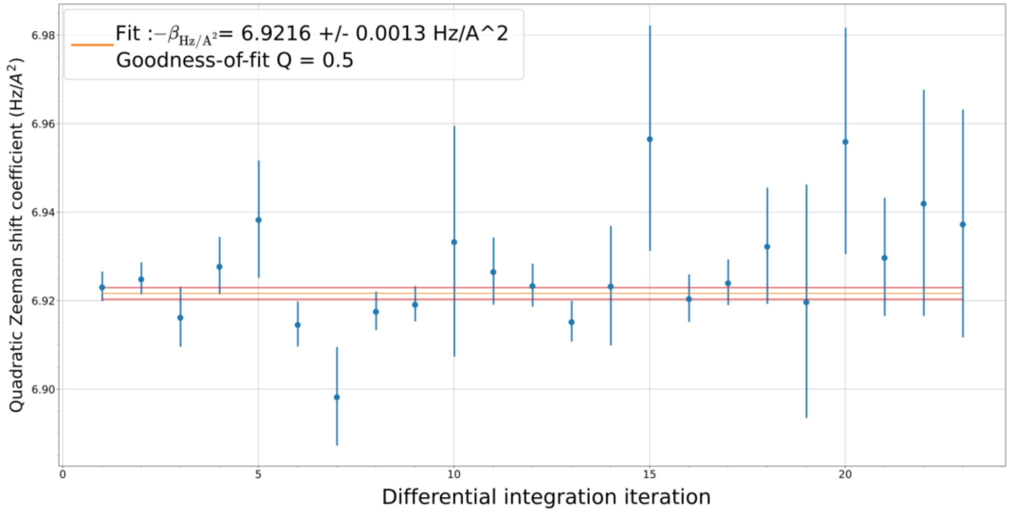

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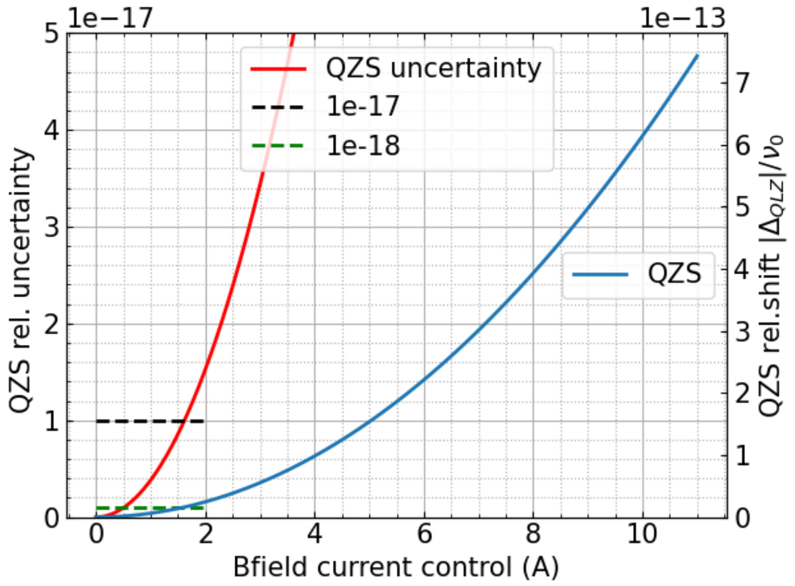

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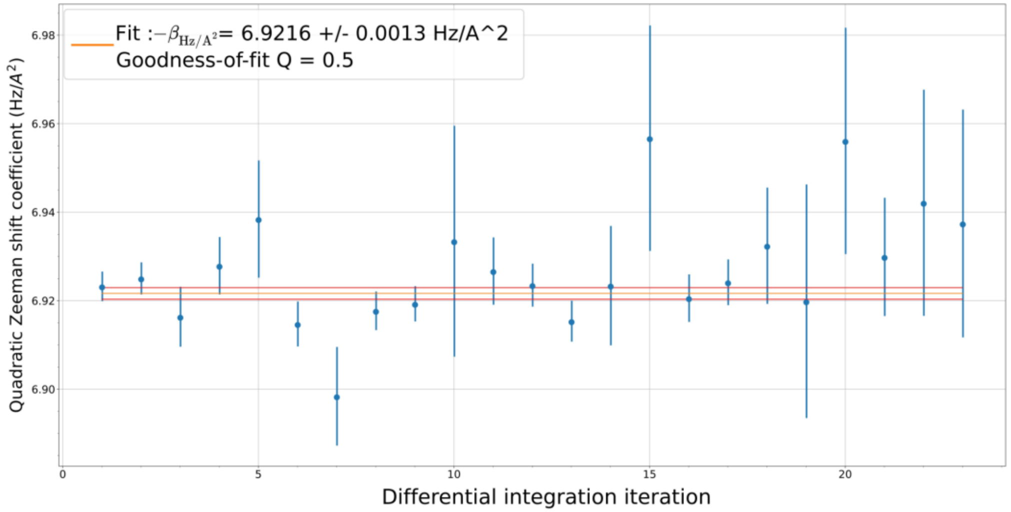

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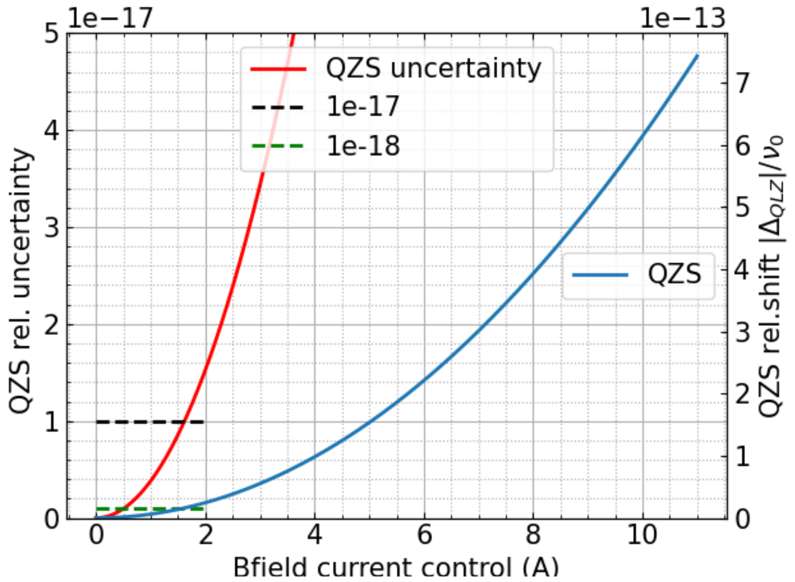

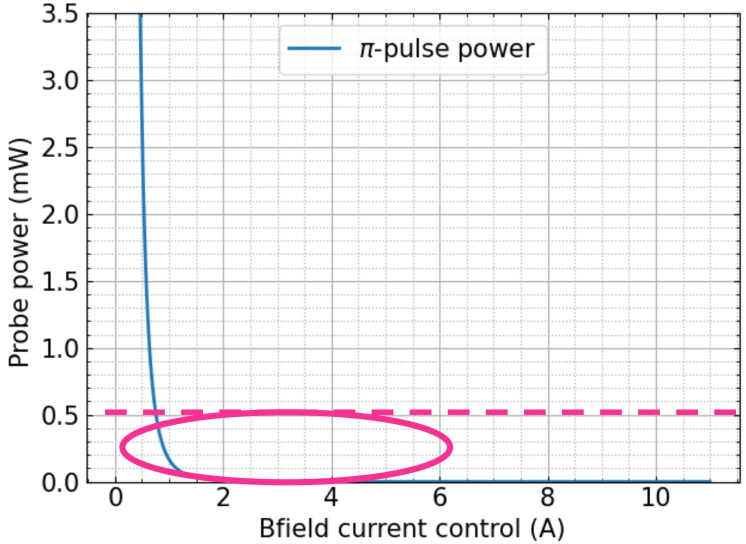

maximum power ~ 500 µW

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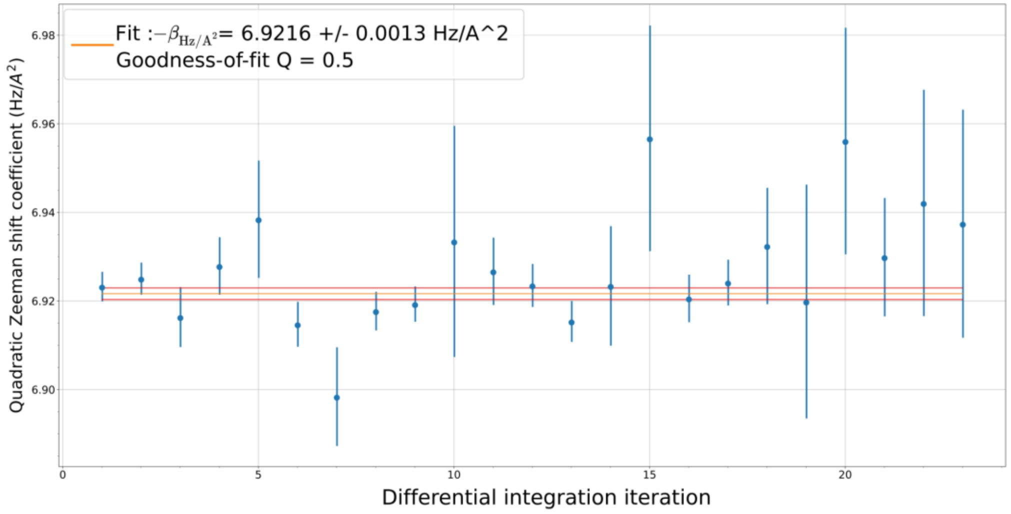

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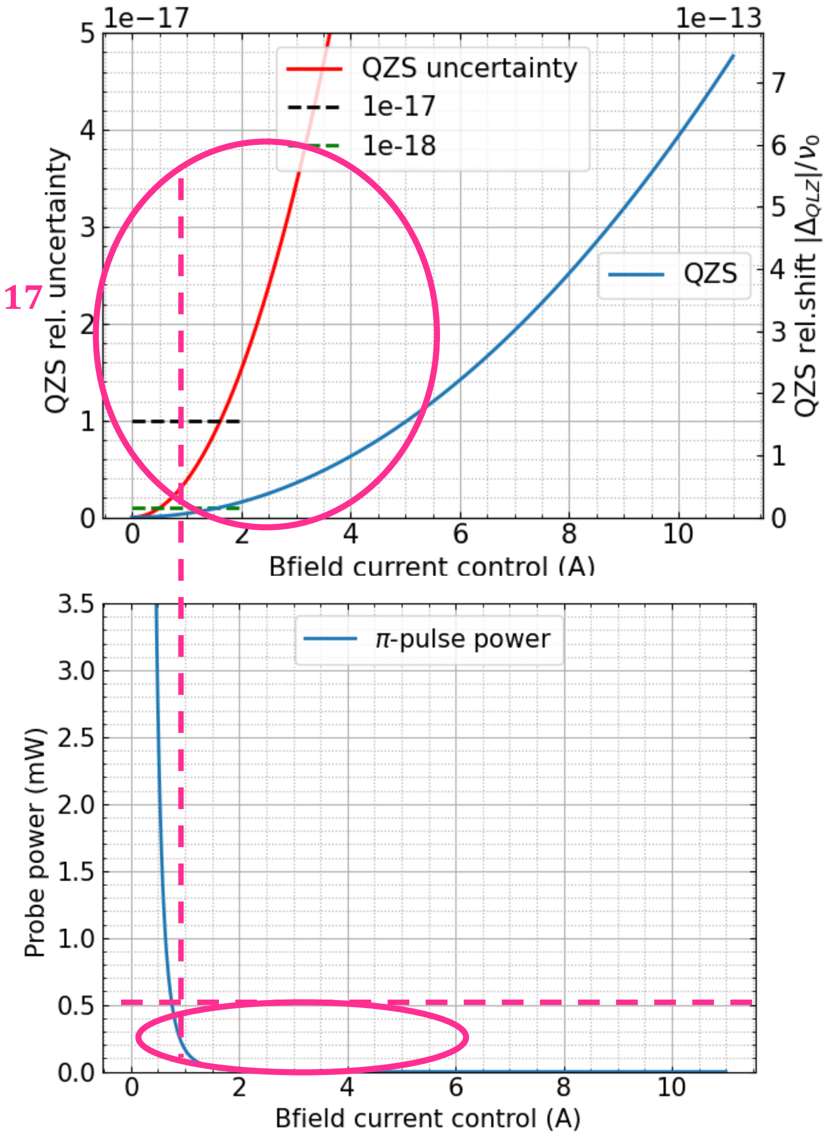
$\frac{\sigma\Delta}{\nu_0}$ =+/- 1-4 $\times\ 10^{-17}$



maximum power ~ 500 µW

198Hg systematics characterization

Systematics calibration of clock transition

Probe Light Shift (PLS)

- ❑ Δ_{PLS} =αP

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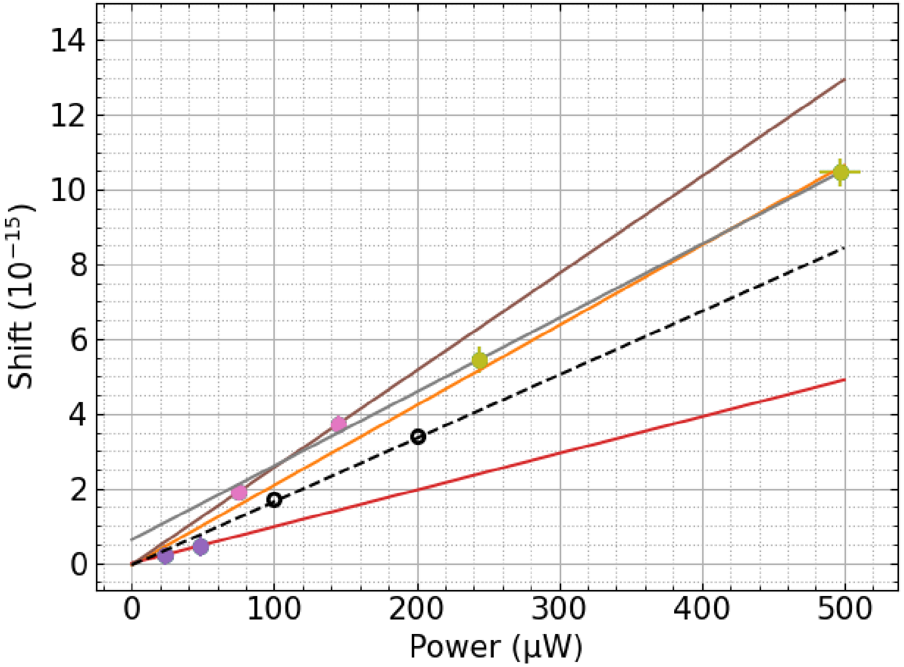

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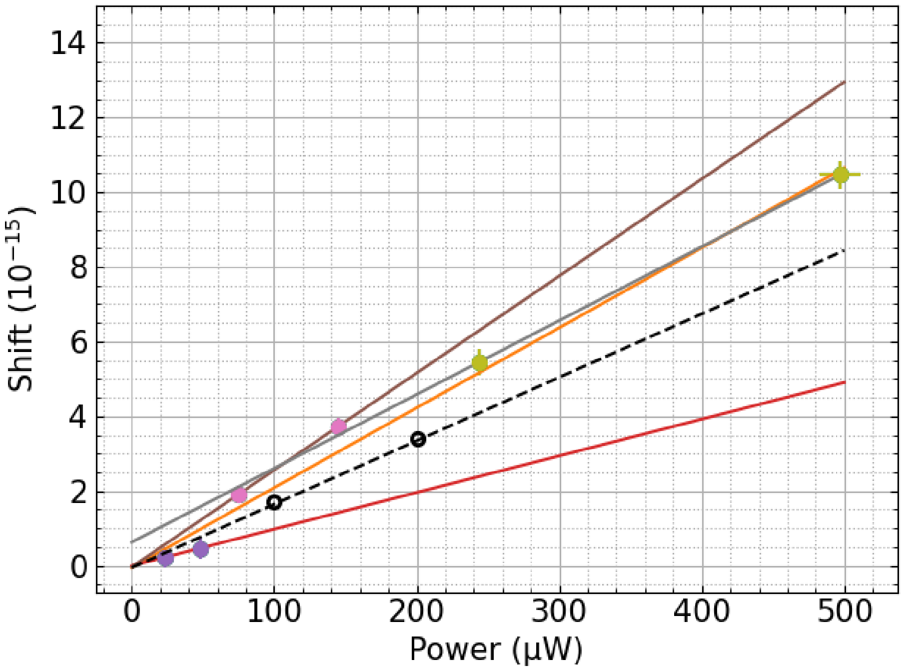
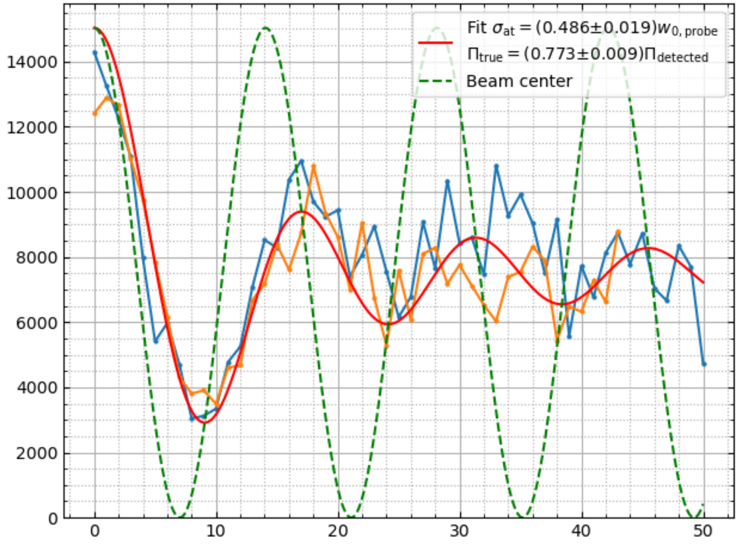


Maximum power ~ 500 μW:

- Waist of ~ 63.5 μm
- σ_{at} ~ 50 μm

➡ Strong spatial inhomogeneities



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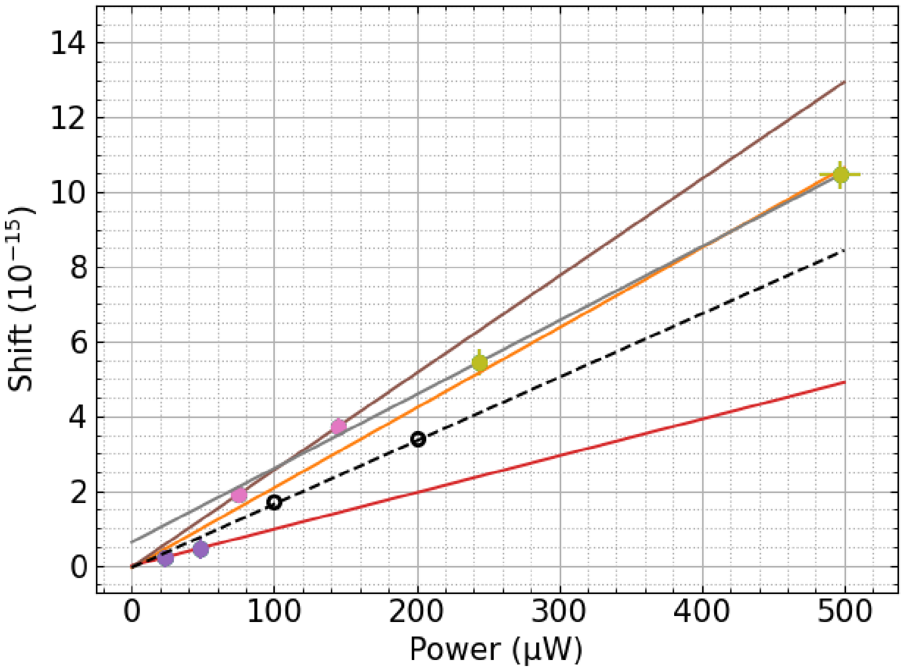

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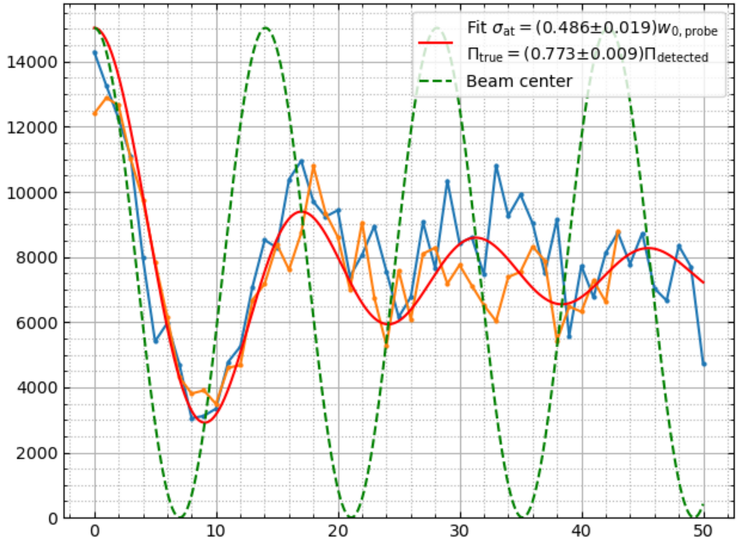

➡ Biases on PLS estimation

$\frac{\Delta_\nu}{\nu_0}$ =+/- 5.8× 10^{-18}/μW

198Hg / 87Sr Comparison

2 month local comparison campaign:

- Total relative systematic uncertainty: 6.9×10^{-16}
- Statistics $< 3 \times 10^{-17}$
- ^{87}Sr: 4.6×10^{-17}

$$\frac{\nu_{^{198}Hg}}{\nu_{^{87}Sr}} = 2.629\ 315\ 734\ 684\ 118\ 1\ (18)$$

$$\nu_{^{198}Hg} = 1\ 128\ 575\ 945\ 288\ 666.3\ \pm 0.78\ \text{Hz}$$

Zyskind et al., arXiv:2512.04920

Effect	Correction ($\times 10^{-17}$)	Uncertainty ($\times 10^{-17}$)
Quadratic Zeeman effect	7868.7	4.9
Magnetic field fluctuations	0	2.9
Residual magnetic field	0	4.3
Cold collisional shift	4.1	17.3
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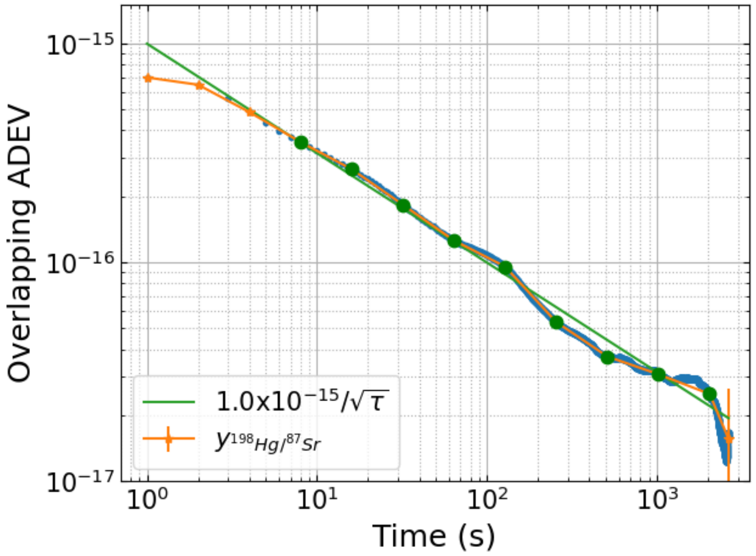
With ~**1s cycle/200ms probe**:

$$\sigma_{198\text{Hg}}(\tau) \sim 6 - 7 \times 10^{-16}/\sqrt{\tau}$$

- ❑ Already better than fermionic isotope
- ❑ Limited by **Dick contribution**



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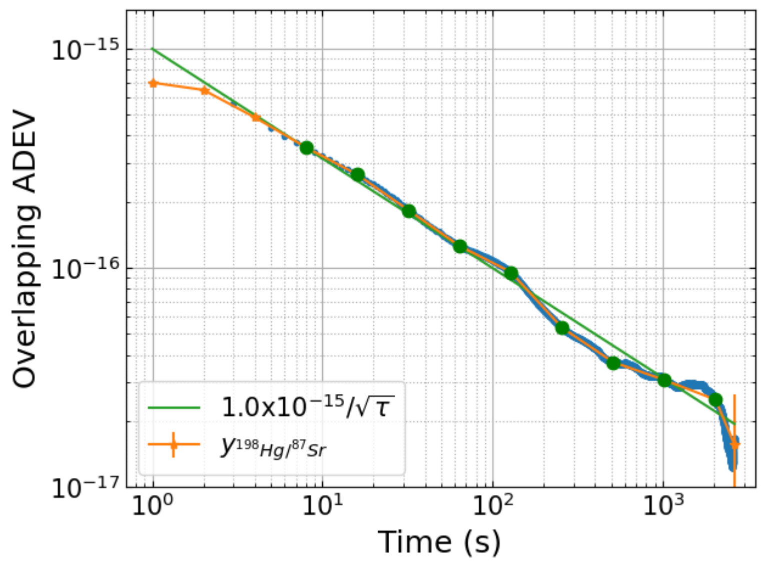
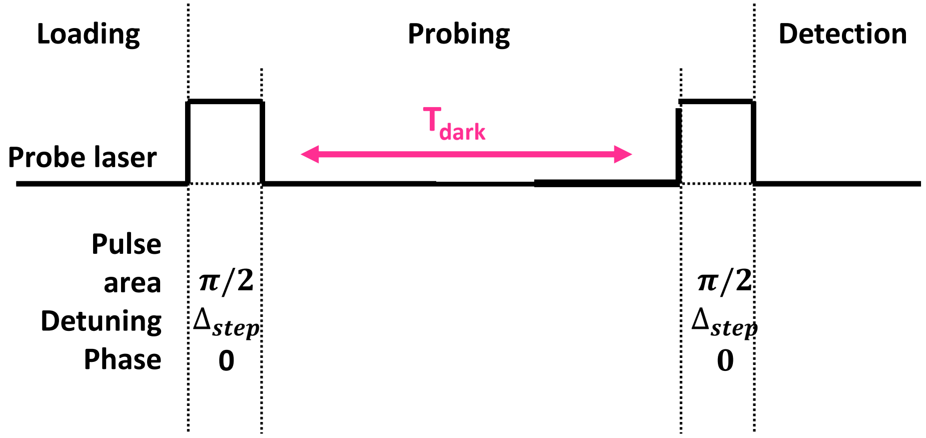


Hyper-Ramsey Spectroscopy

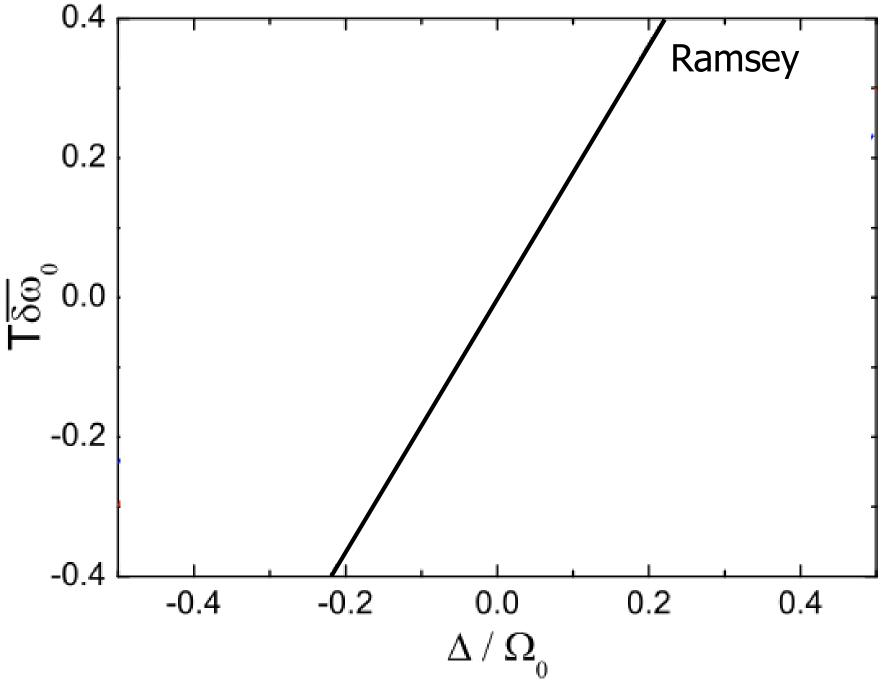
Ramsey Interferometer:



$$\phi = -\delta T_{\text{dark}} + \Delta\tau$$

Sensitive to light shift errors:

- Shift $\delta_{\omega 0}$
- Broadening



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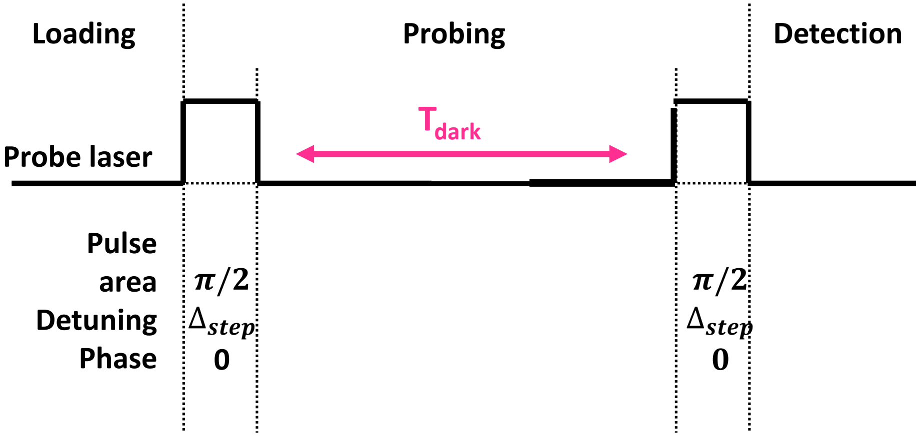

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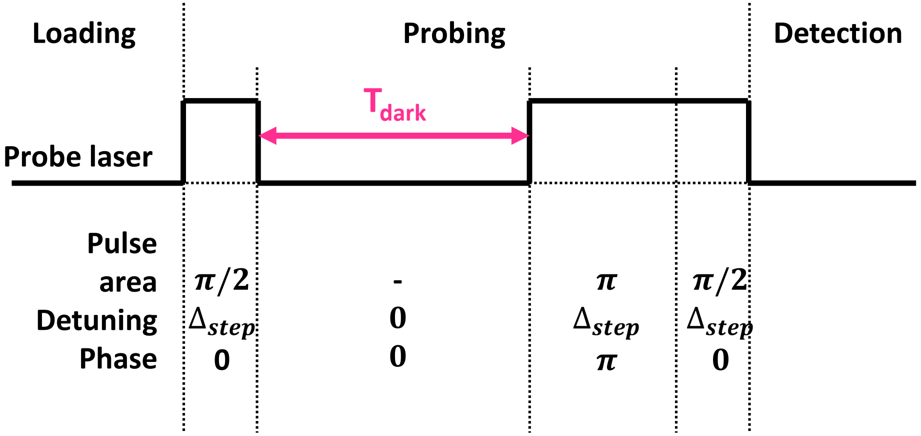

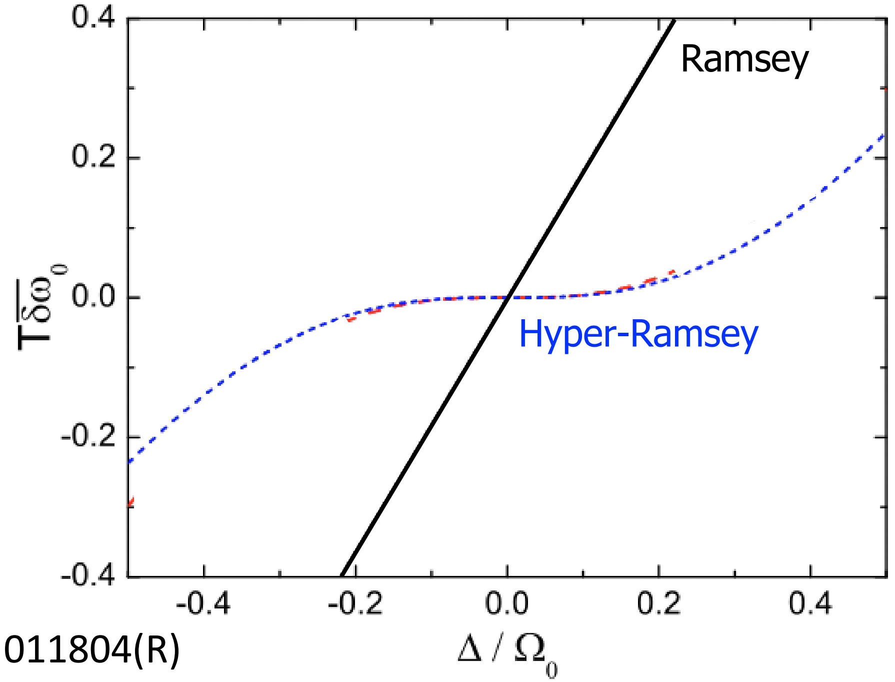

Phys. Rev. A **82**, 011804(R)

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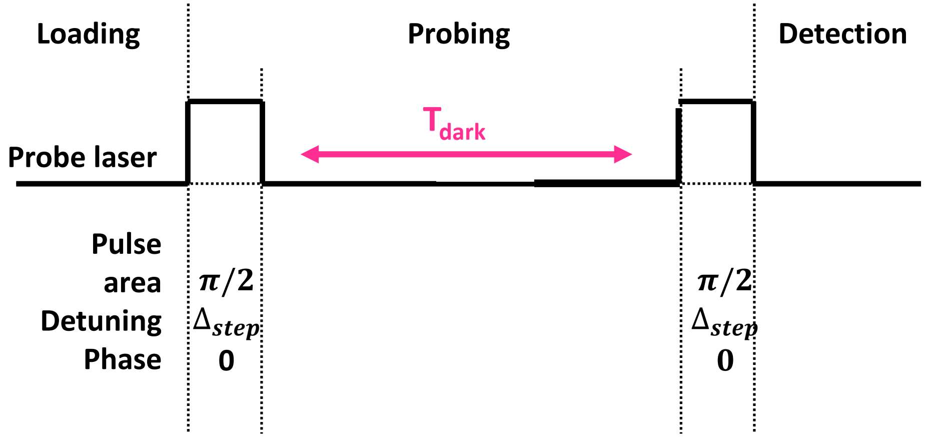

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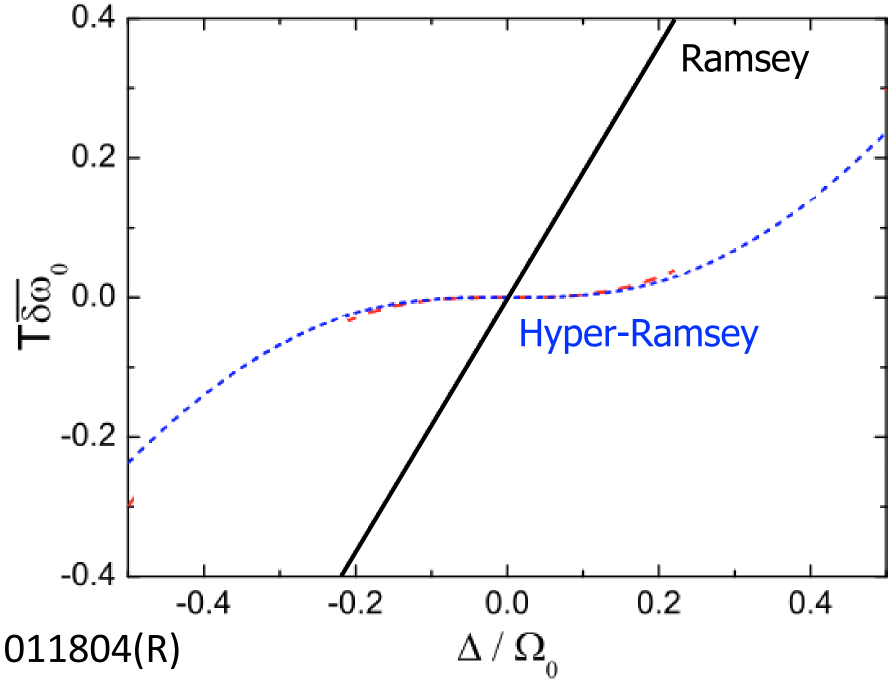

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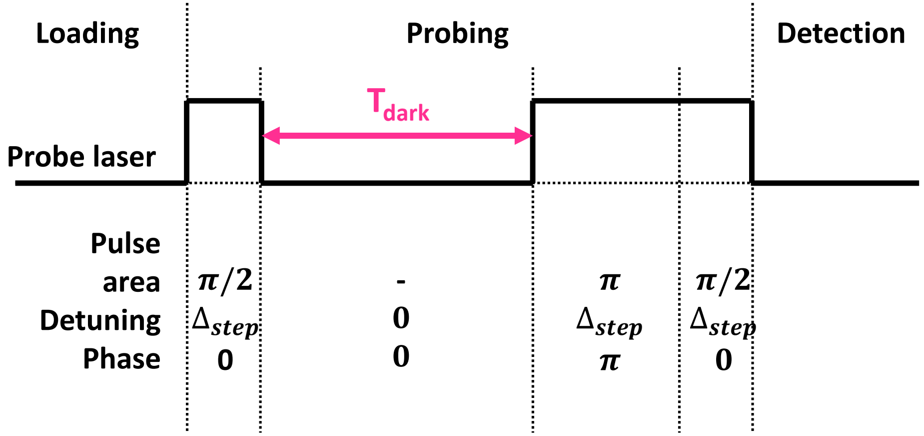

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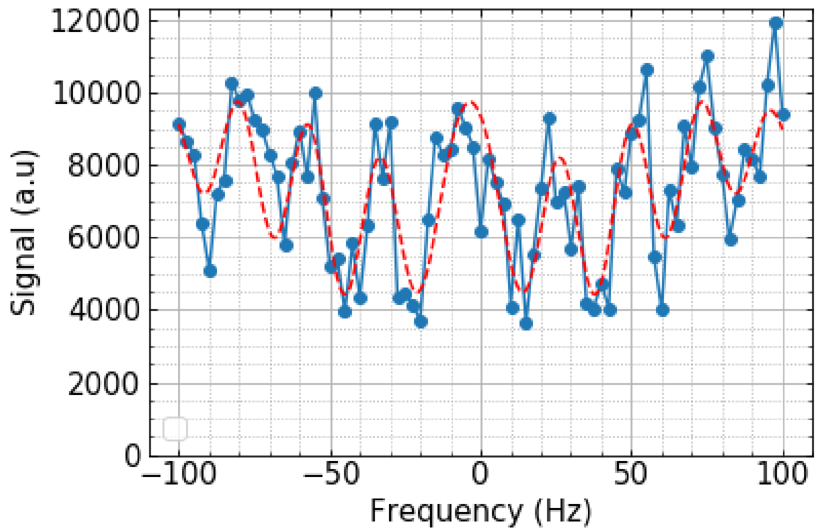
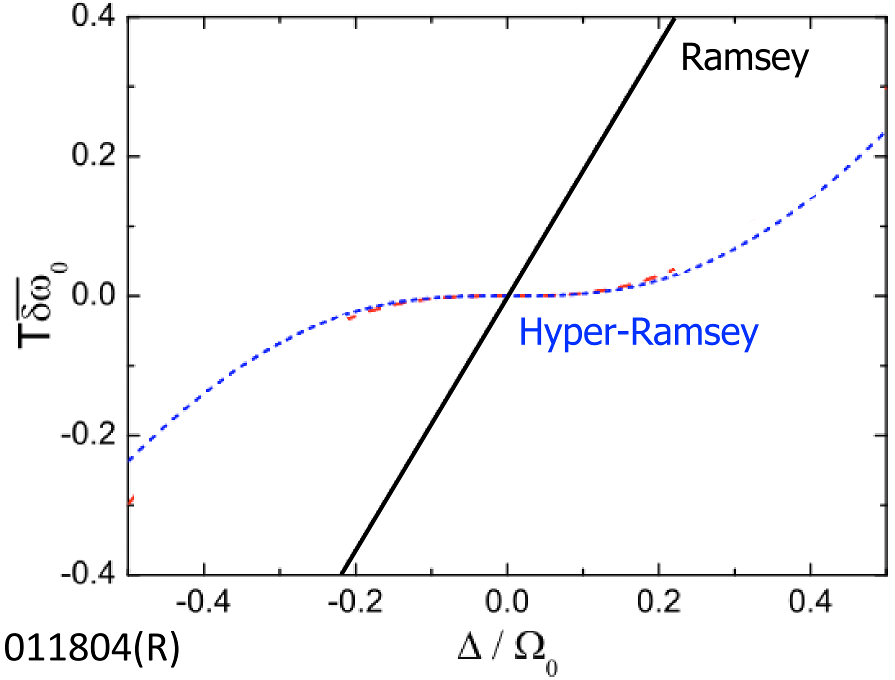


<u>Successful implementation</u>

1st integration tests on-going



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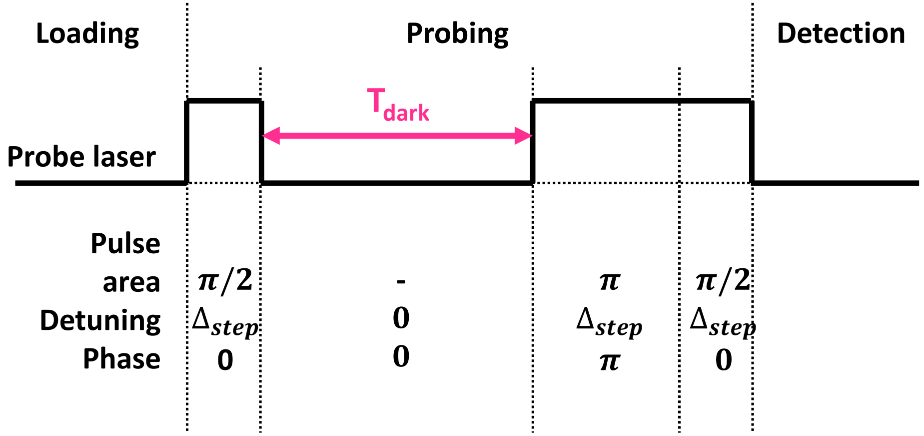

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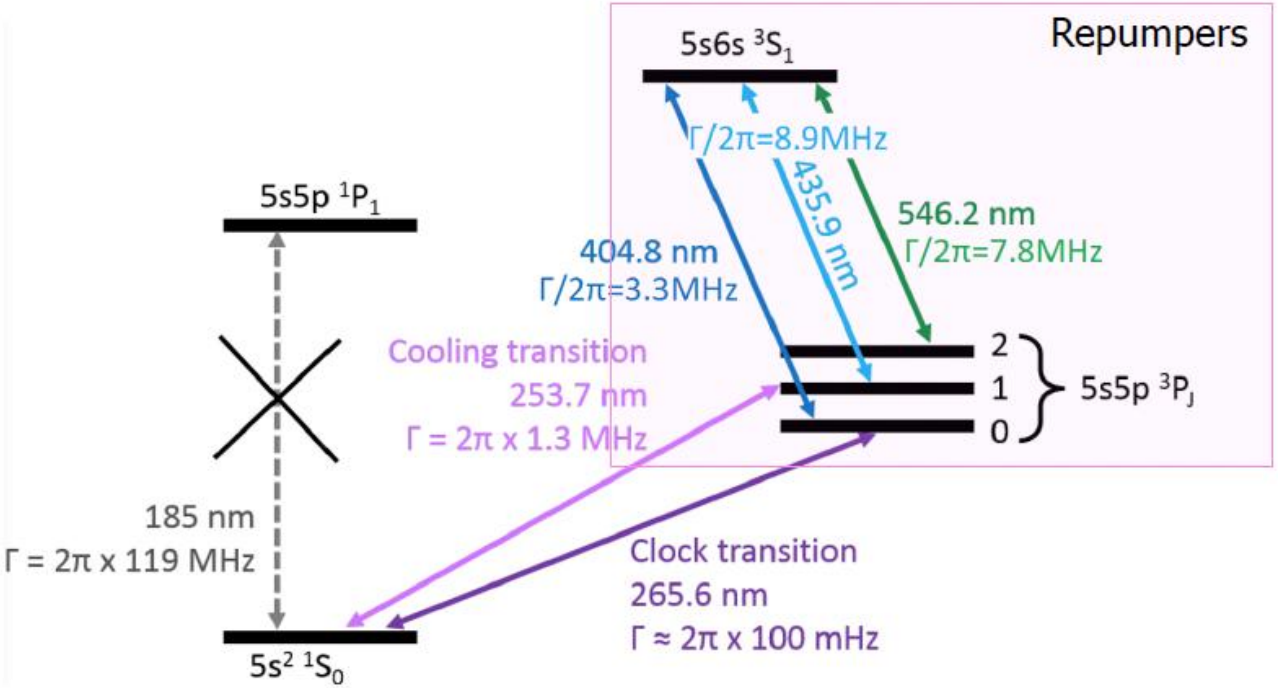
Using of Repumpers



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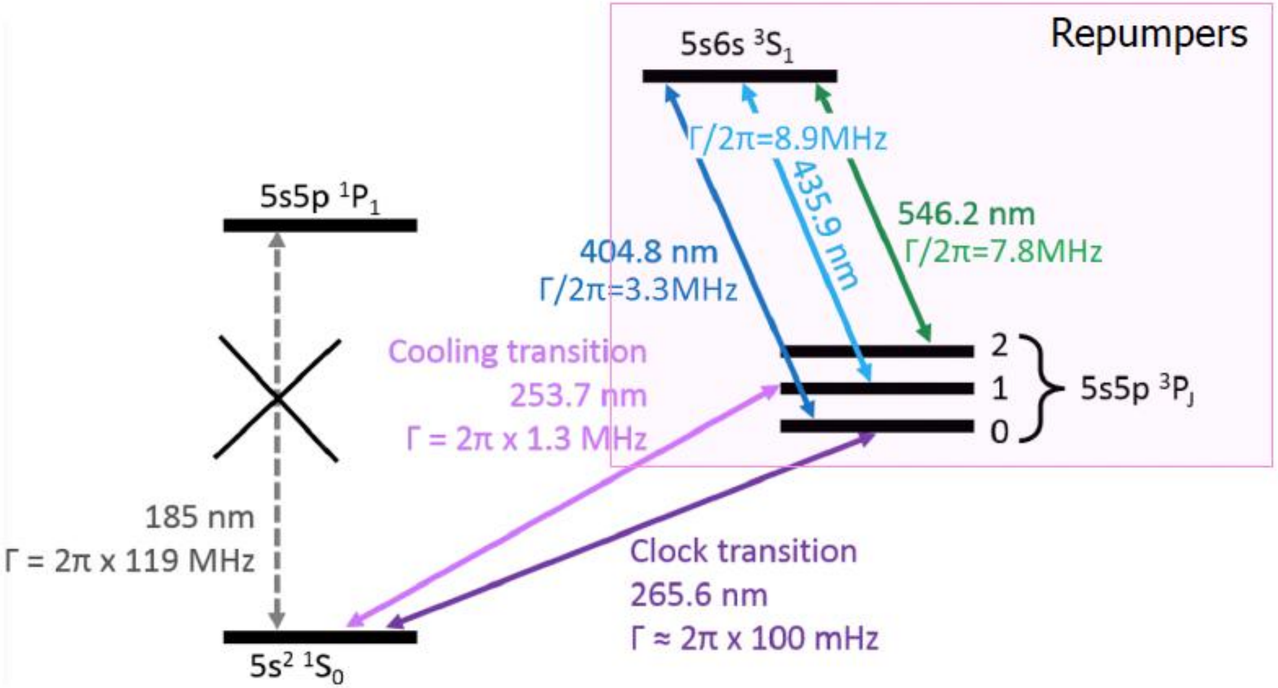
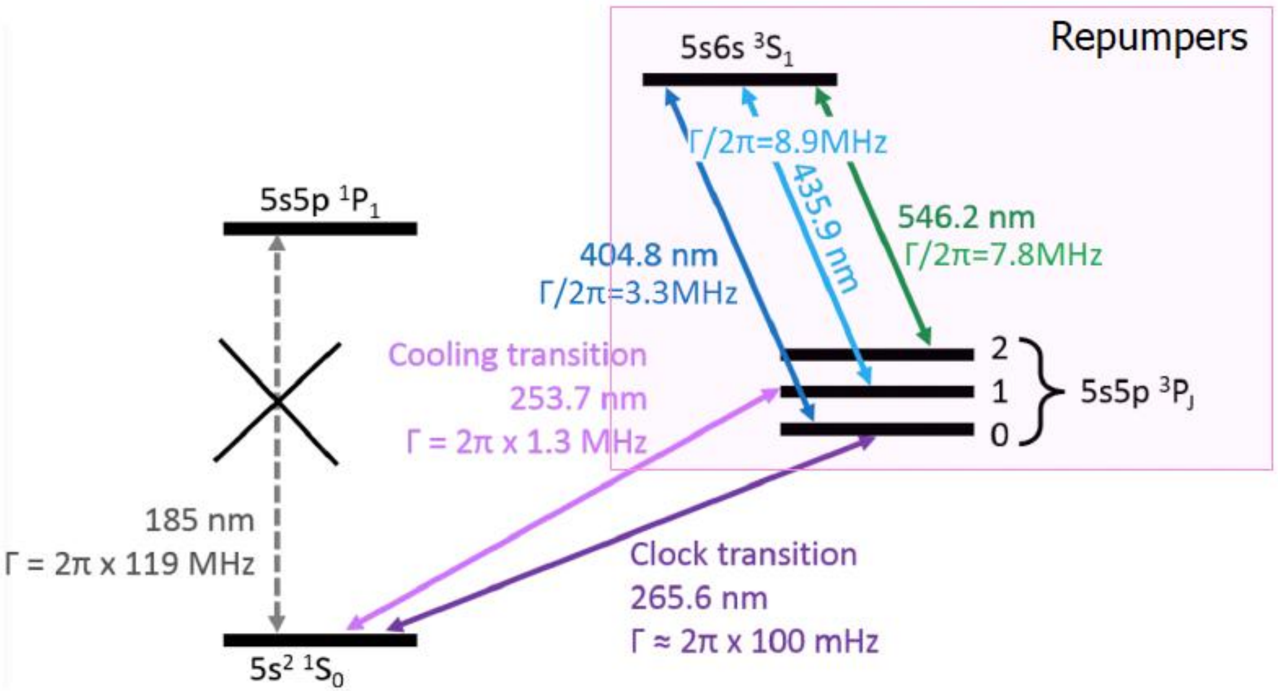


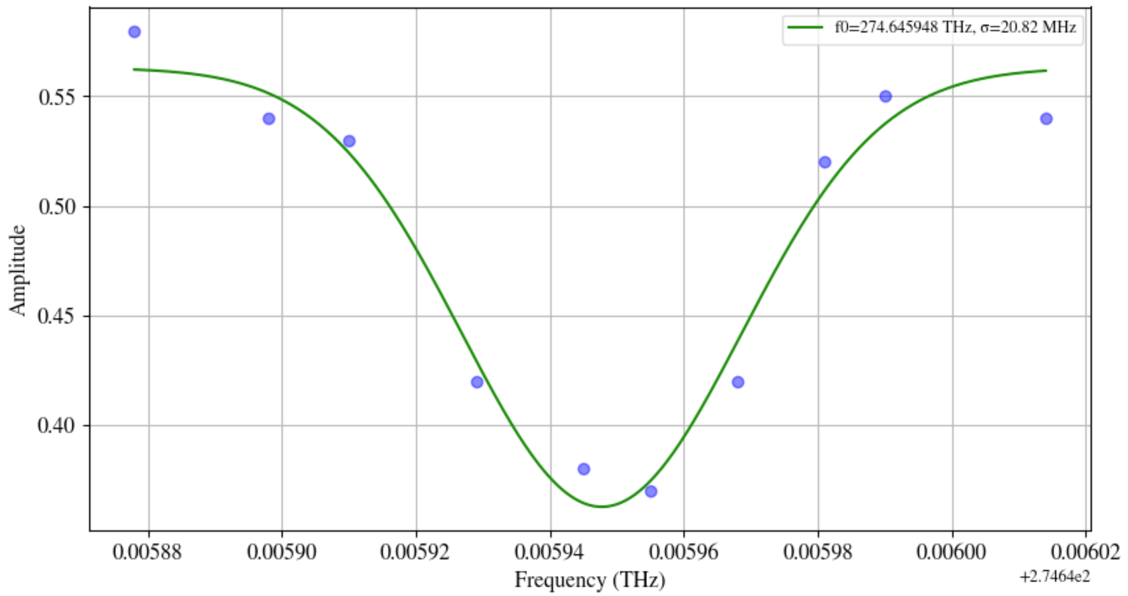
<u>198Hg repumpers:</u>

- ❑ Sideband cooling
  - ➢ Decrease atomic cloud size
- ❑ Normalized detection

Using of Repumpers



- 405 transition



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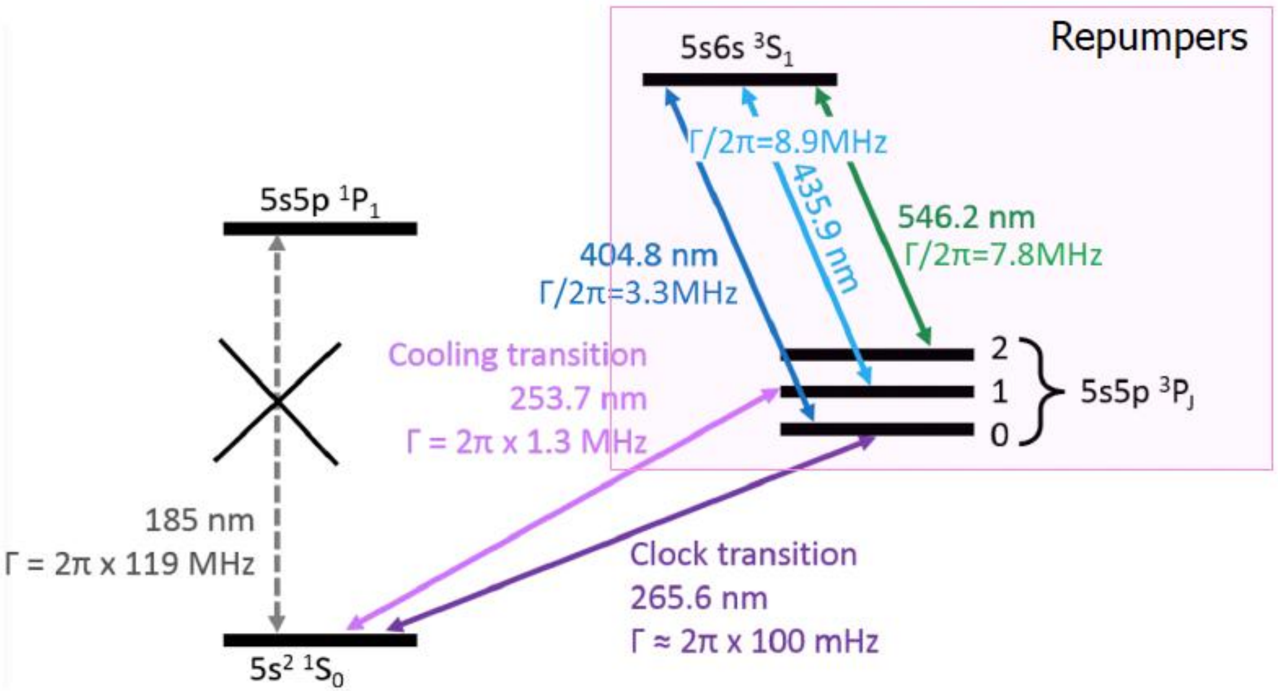

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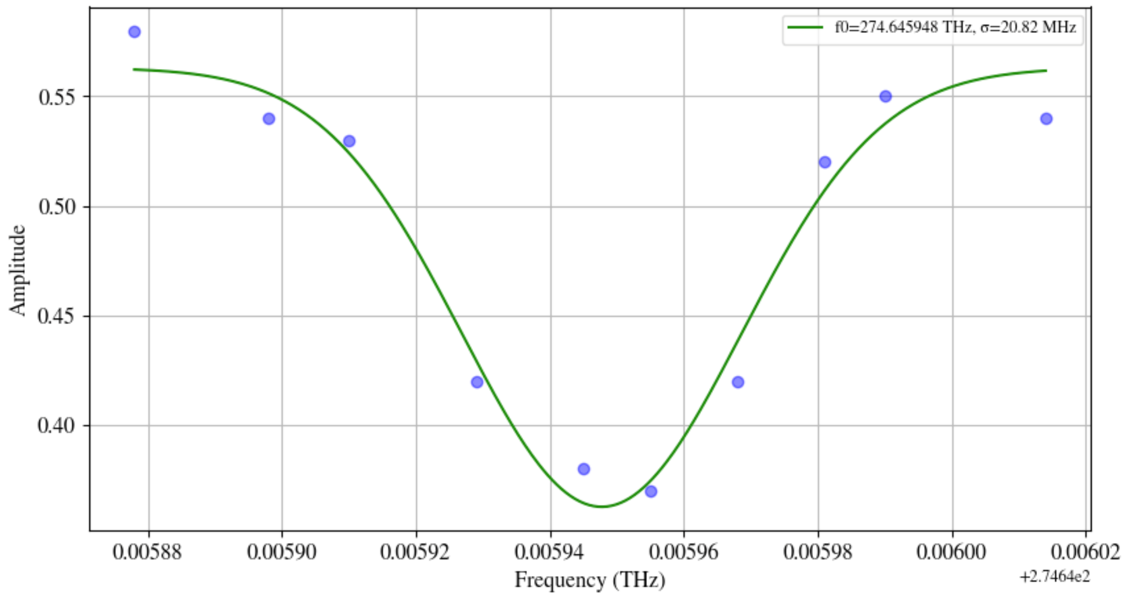

❑ No signal of 546 transition so far

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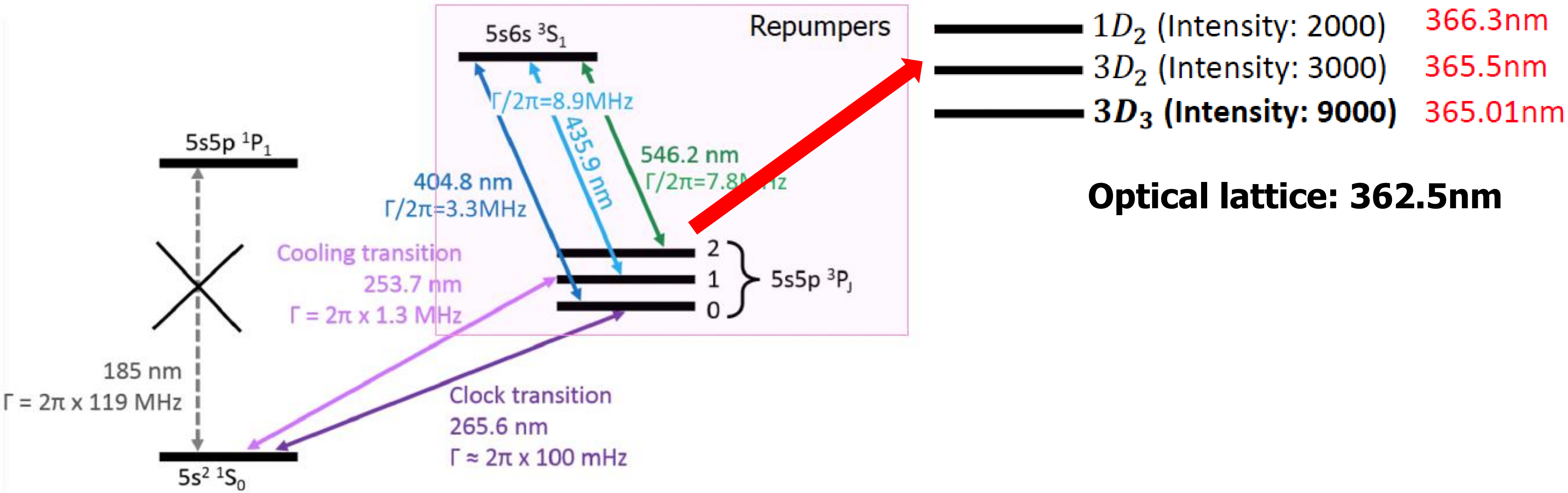

Optical lattice: 362.5nm

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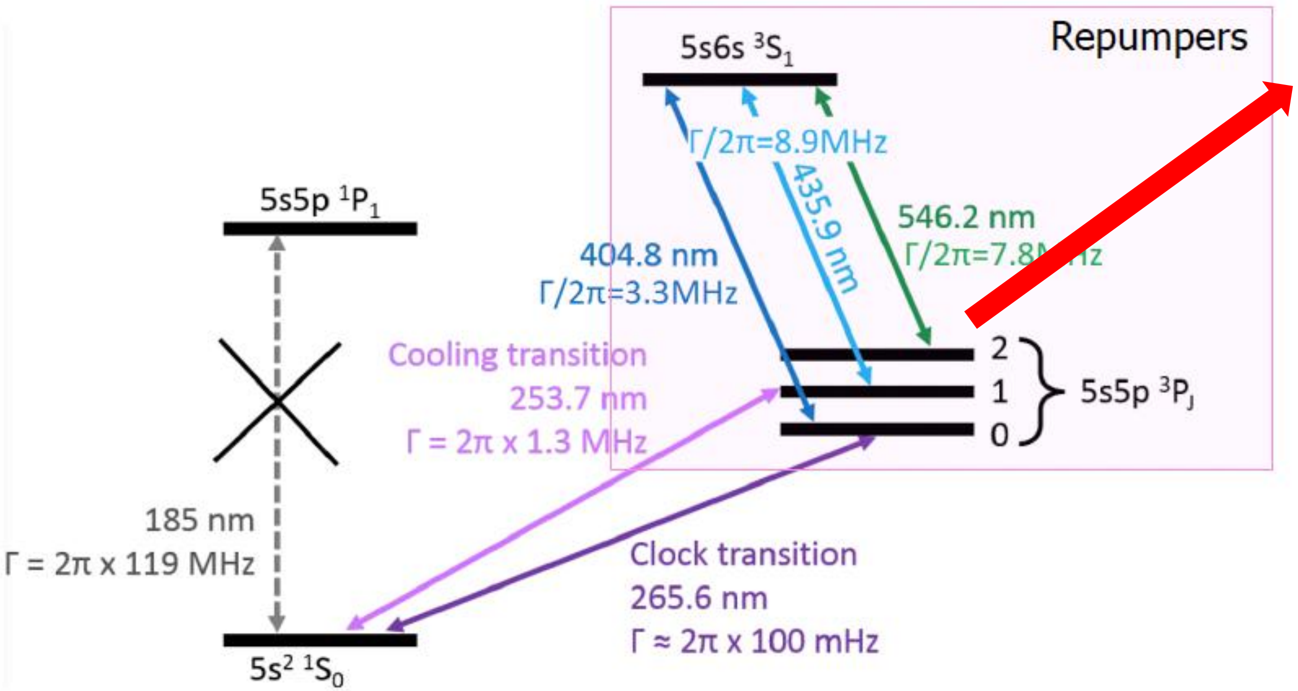

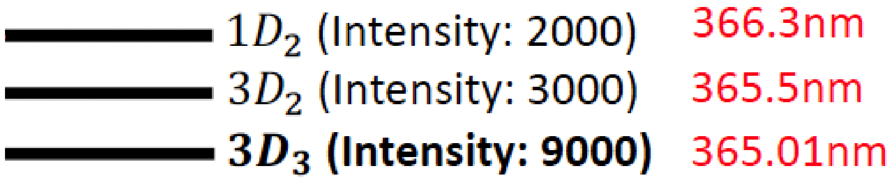

Optical lattice: 362.5nm

- ❑ Blue detuned lattice w/ dipole force ~ 100x larger
- ❑ Should loose atoms in 3P2 in a few ms

➡ Very short pulses of 546nm: need more power

<u>198Hg repumpers:</u>

- ❑ Sideband cooling
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- ❑ Normalized detection

- ❑ <u>No signal of 546 transition so far</u>

Conclusion

❑ 1st experimental measurement of the clock transition in a bosonic isotope of Hg:

$$\frac{\nu_{^{198}Hg}}{\nu_{^{87}Sr}} = 2.629\ 315\ 734\ 684\ 118\ 1 \quad \text{w/} \sim 7 \times 10^{-16} \text{ uncertainty}$$

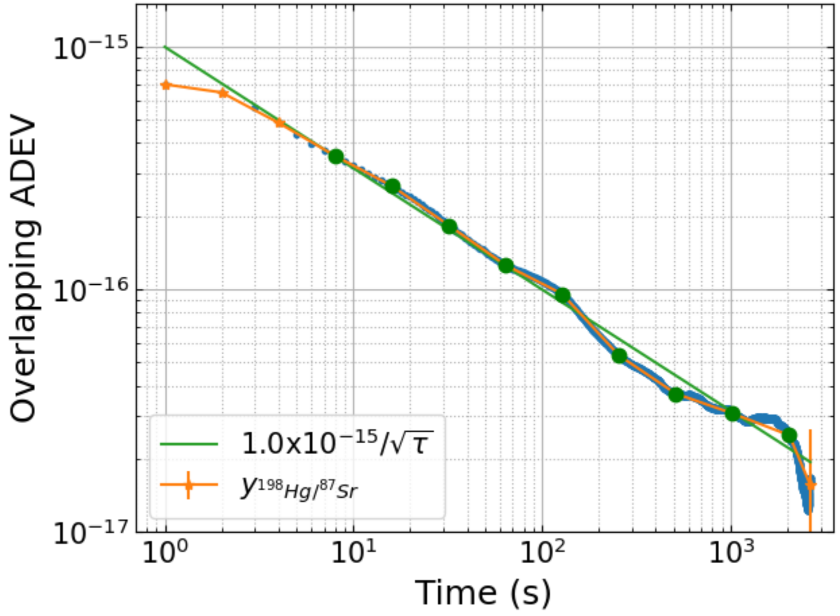
❑ Stability $6 - 7 \times 10^{-16}/\sqrt{\tau}$

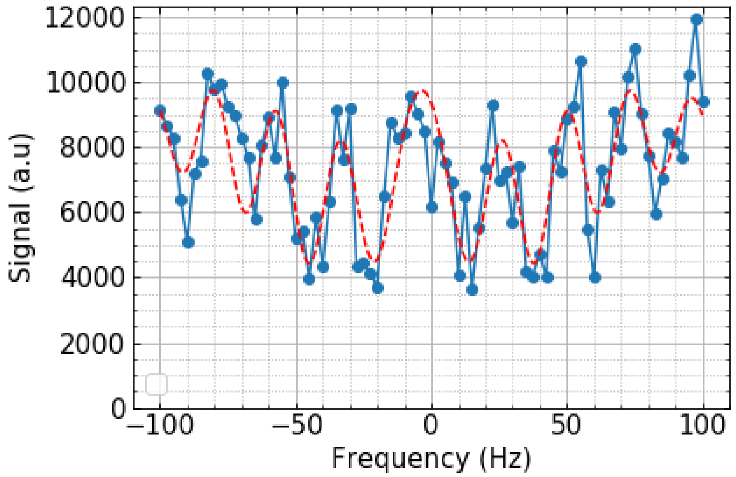
(Paper submitted on PRL)

❑ Uncertainty dominated by probe light shift uncertainty

Insensitive hyper-Ramsey interrogation

❑ Setting up repumpers





Perspectives

- ❑Investigating purity transfer and synchronization of Hg/Sr clocks

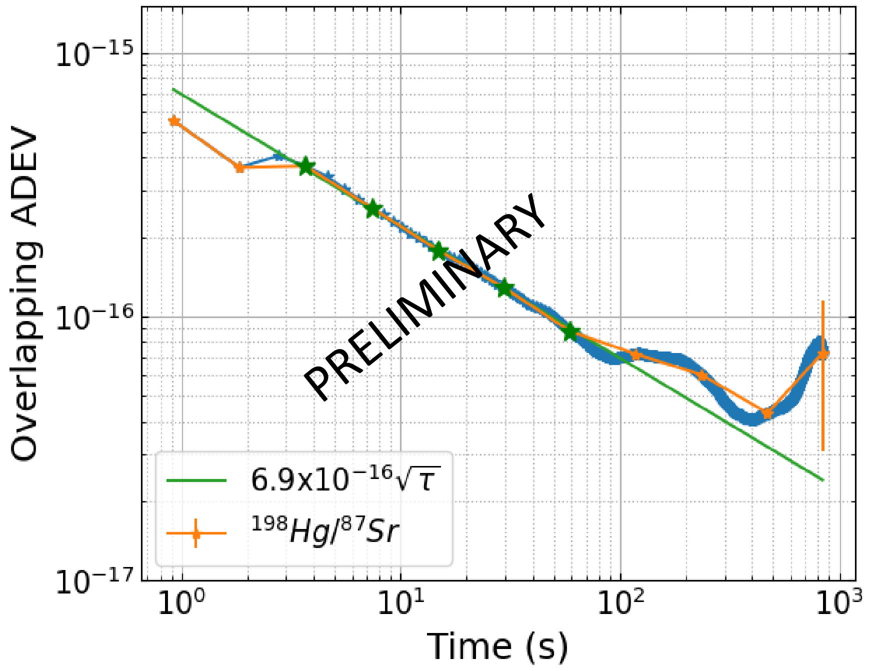
(cancelling Dick contribution)

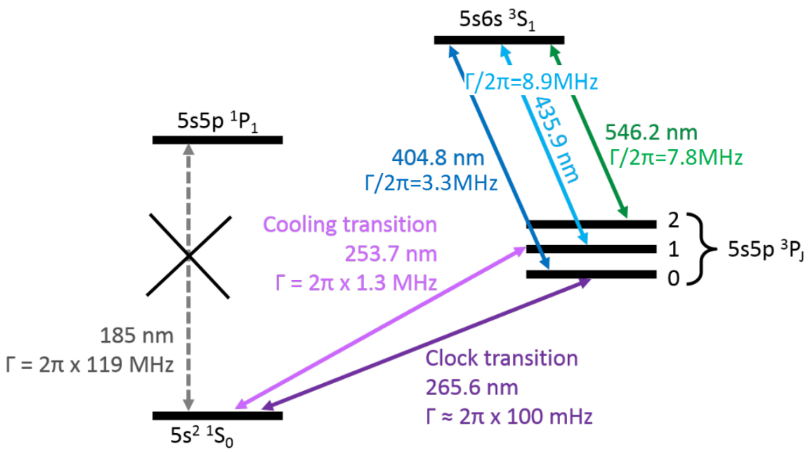
- ❑Continue working on implementing repumping

- ❑New campaign of systematics calibration

(lattice light shift, cold collision calibration…)

- ❑New vacuum chamber for improved lifetime (~ 600ms)





Thanks!

Mercury Lab

Sébastien Bize
Thomas Lauprêtre
Carla Zyskind

Srontium Lab

Jérôme Lodewyck

Frequency Comb Lab

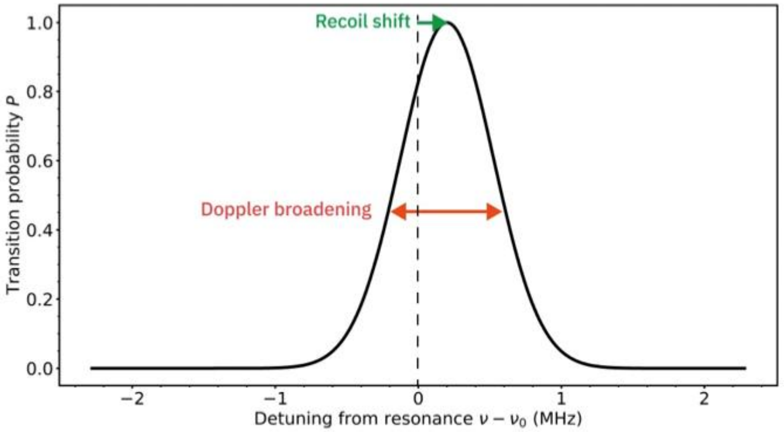
Benjamin Pointard
Rodolphe Le Targat

Laboratoire Temps Espace

198Hg systematics characterization

Lattice linear lightshift

- ❑ Unbound atoms: Doppler broadening + recoil shift



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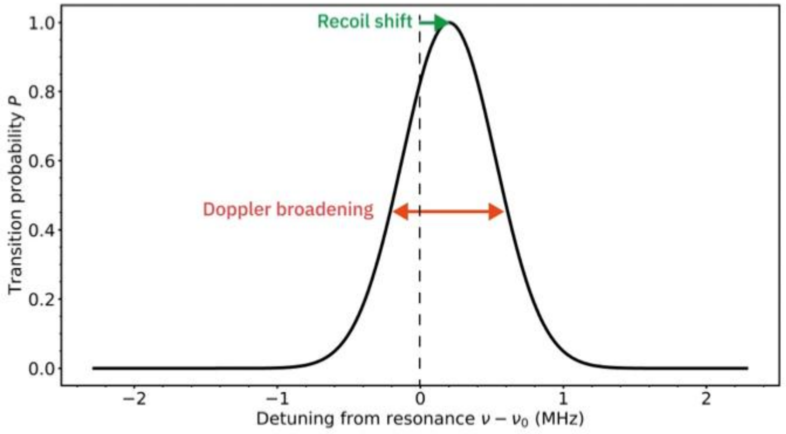

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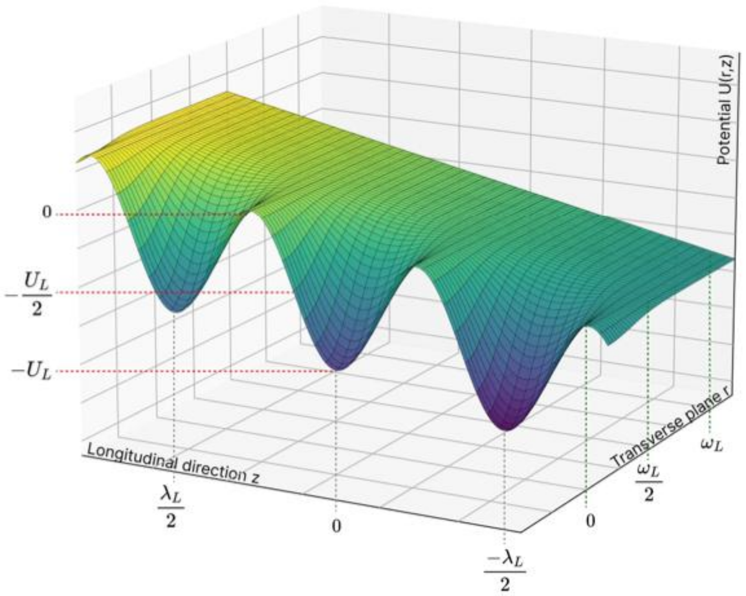

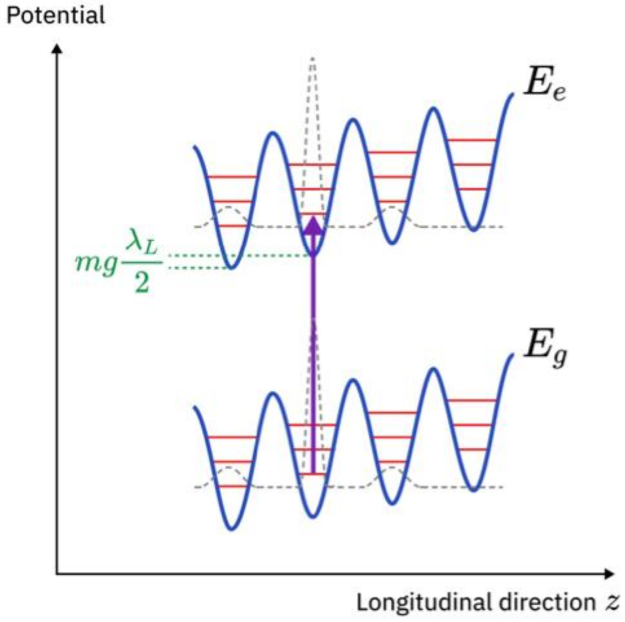

Confinement in Lamb-Dicke regime:

- ❑ Intracavity power ~ 9W
- ❑ Waist ~ 69 μm

➡ **Strong Stark shifts on the two clock levels**