Zero-dead-time Differential Spectroscopy Beyond the Laser Coherence Limit

WILL MCGREW

NIST-BOULDER

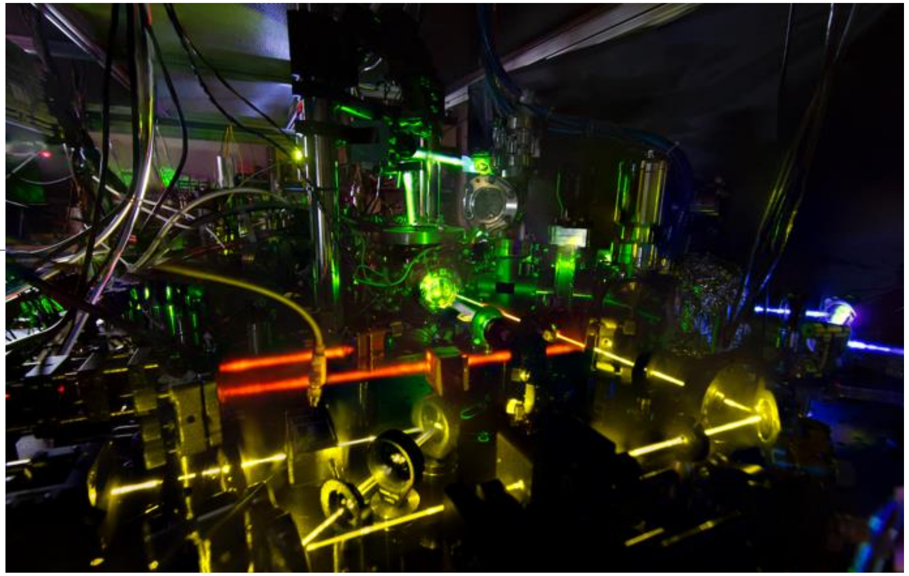


Image credit: Nate Phillips

Outline

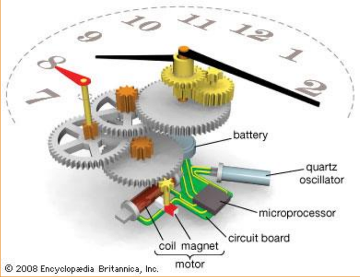
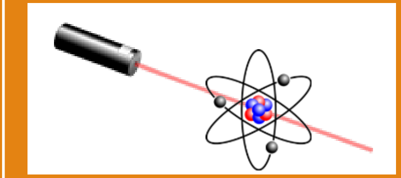
I - Clocks and tests of fundamental physics

II - Differential spectroscopy

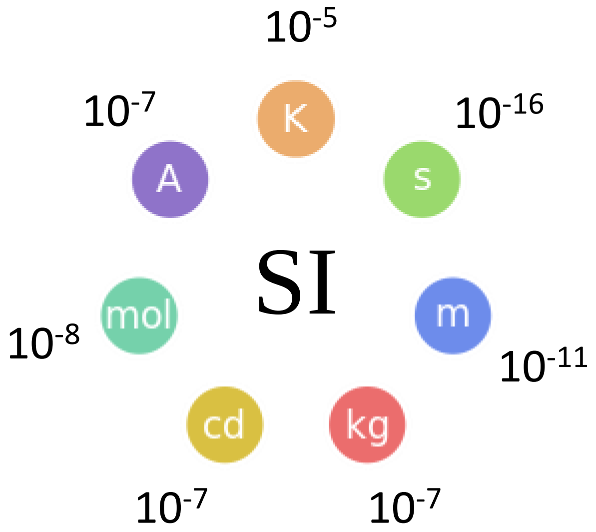
III - Zero-dead-time differential spectroscopy

Part I – Clocks and tests of fundamental physics

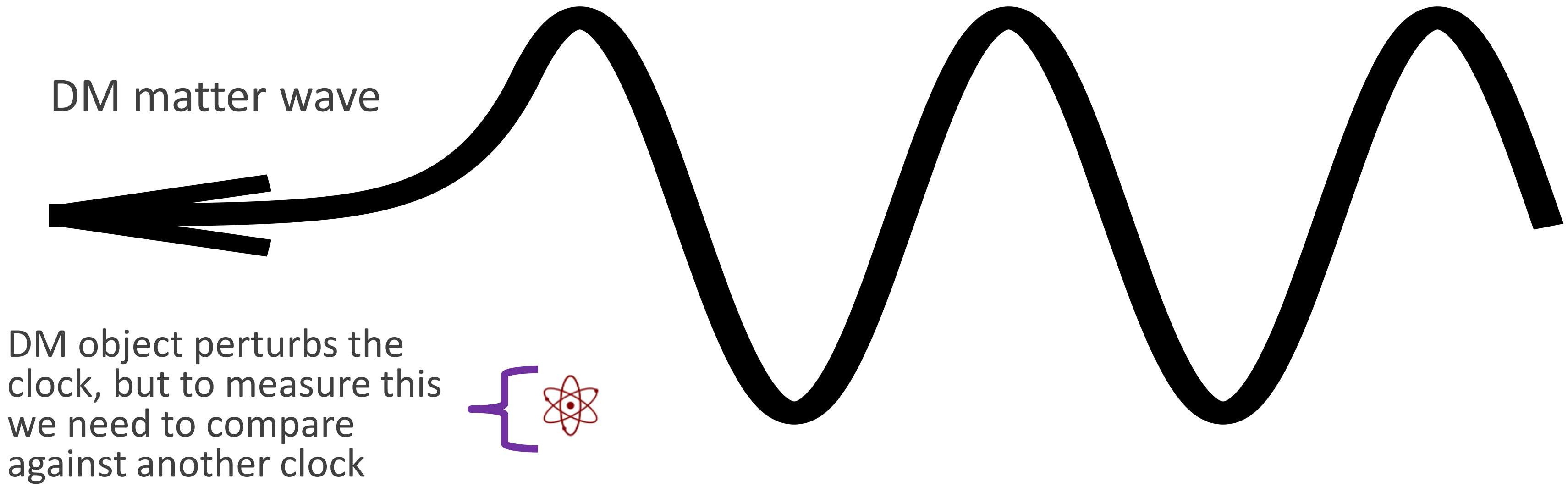
Clocks

				
Ticking rate (Hz)	10^0	10^7	10^{10}	10^{15}
Instability (s/day)	10^0	10^{-7}	10^{-10}	10^{-13}

Do we need better?



Tests of ultralight dark matter



Arvanitaki, A., Huang, J., & Van Tilburg, K. (2015). Searching for dilaton dark matter with atomic clocks. *Physical Review D*, *91*(1), 015015. https://doi.org/10.1103/PhysRevD.91.015015

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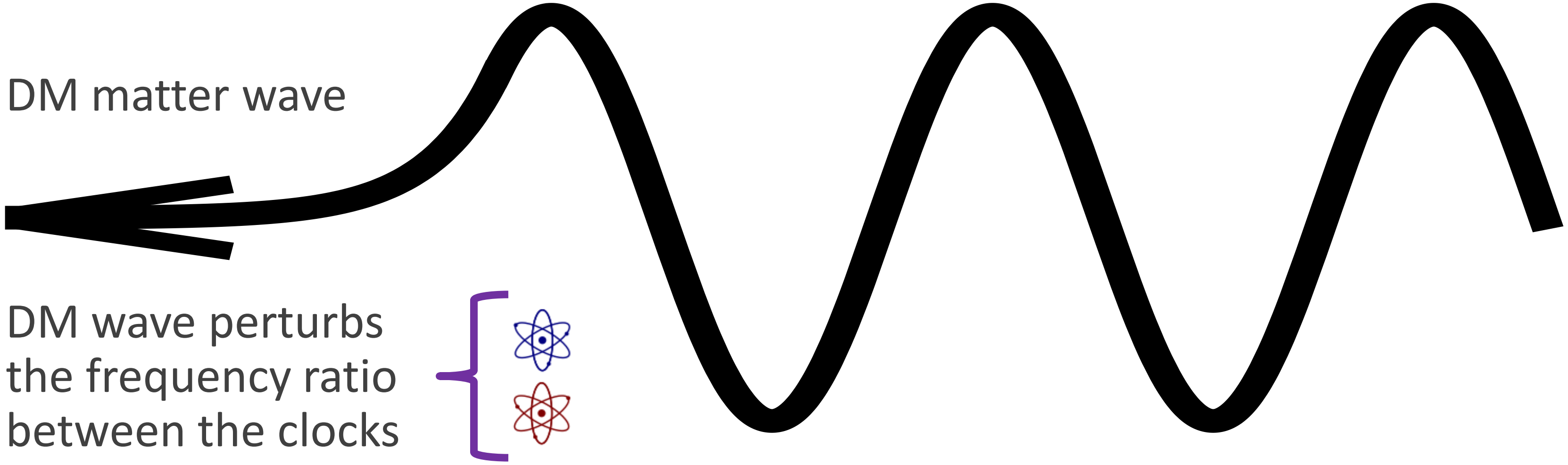

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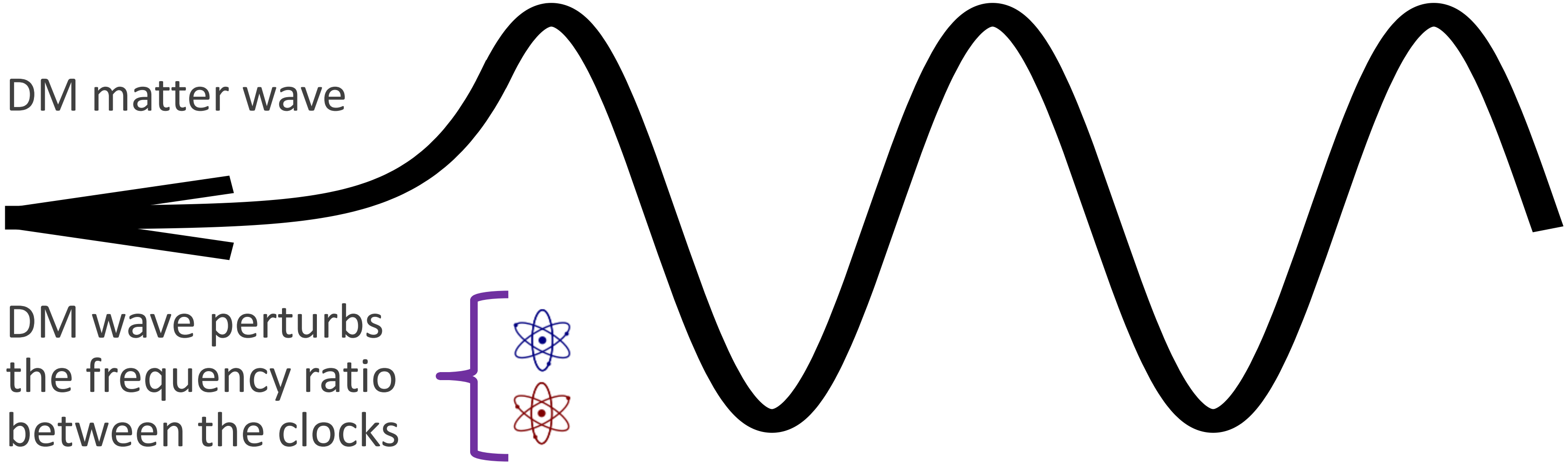

- Highly local
- Extraordinary precision (better than 10^{-16} in fractional frequency)
- Bandwidth of ~Hz and below (~10^{-15} eV and below)

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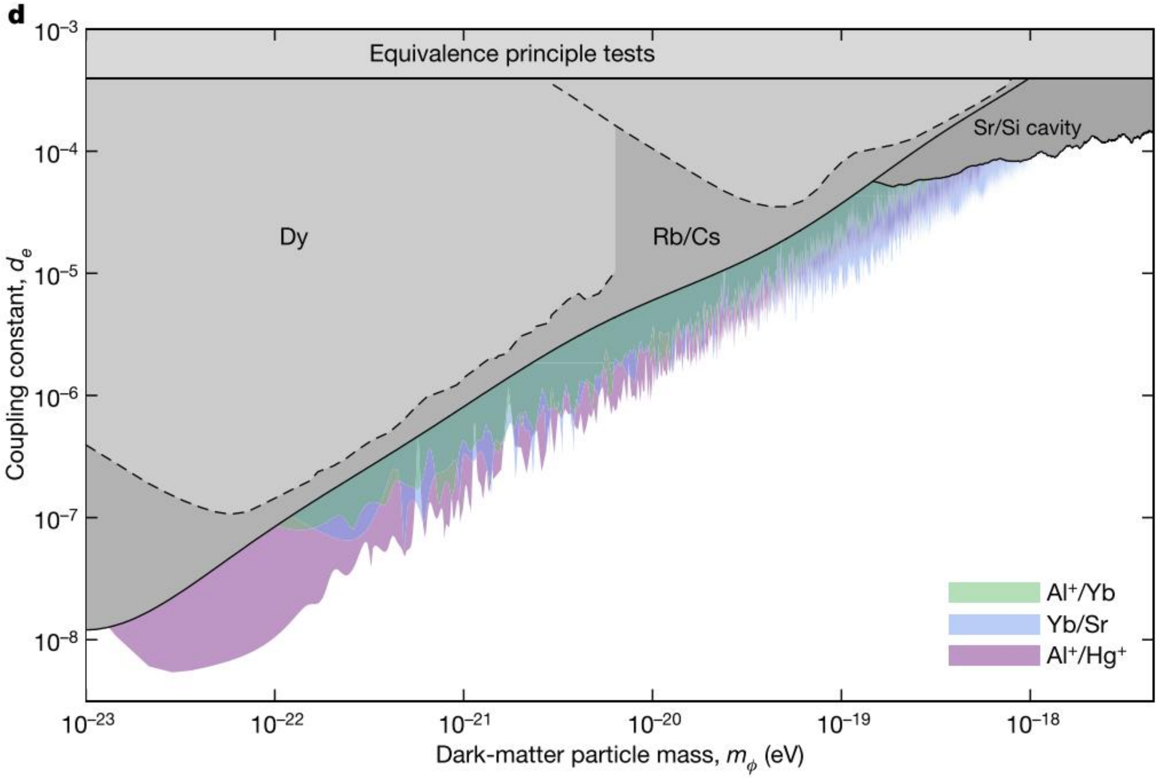
Constraints on ultralight dark matter



BACON Collaboration. (2021). Frequency ratio measurements at 18-digit accuracy using an optical clock network. *Nature*, *591*, 564–569. https://doi.org/10.1038/s41586-021-03253-4

Clock instability

Dick effect: technical biasing phenomenon related to the OLO noise properties

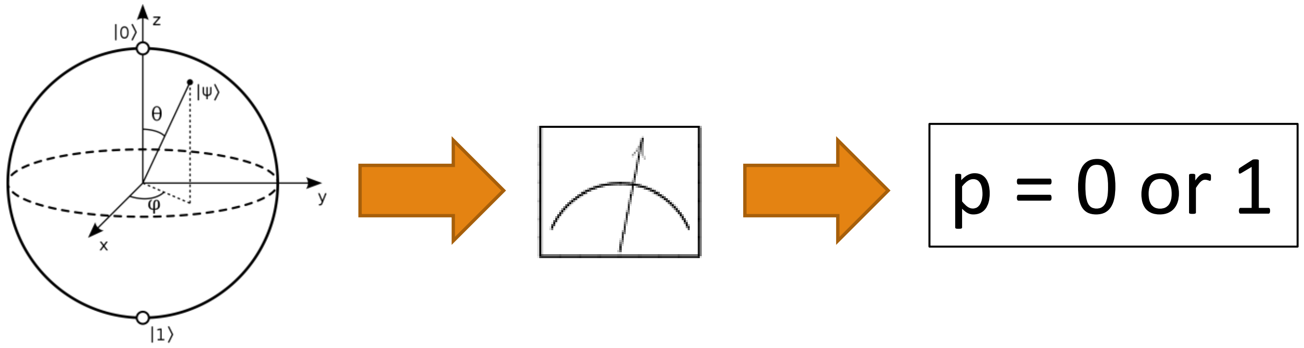
Other sources of noise:

$$\sigma_y(\tau) = \left(\frac{S}{N}\right)^{-1} n_{meas}^{-1/2}$$

Contributions: technical detection noise, photon shot noise, quantum projection noise (QPN)

QPN is fundamental (for uncorrelated quantum systems). Other sources are subject to technical reduction.

Quantum projection noise



$(\phi, \psi) \in \mathfrak{R} \times \mathfrak{R}$

$p \in \mathfrak{B}$

$\left(\frac{S}{N}\right)^{-1} = \frac{\Delta f}{f_0} = \frac{\left(\frac{df}{dp}\right)\Delta p}{f_0}$, but due to projection noise, $\Delta p \approx \frac{1}{2}$. For Ramsey spectroscopy, $\frac{df}{dp} \approx \frac{1}{\pi T_i}$

$\left(\frac{S}{N}\right)^{-1} = \frac{1}{2\pi T_i f_0}$ for a single quantum oscillator. For N oscillators, $\left(\frac{S}{N}\right)^{-1} = \frac{1}{2\pi T_i f_0 \sqrt{N}}$.

Quantum projection noise

$$\sigma_y(\tau) = \left(\frac{S}{N}\right)^{-1} n_{meas}^{-1/2}$$

The number of measurements we have is $n_{meas} = \frac{\tau}{T_c}$, where τ is the measurement time and T_c is the cycle time.

$$\sigma_y(\tau) = \frac{1}{2\pi T_i f_0}\sqrt{\frac{T_c}{N\tau}} \approx \frac{1}{2\pi f_0\sqrt{NT_i\tau}}$$

How to decrease QPN?

$$\sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{N T_i \tau}}$$

Increase τ

Increase f_0

Increase N

Increase T_i

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$$\sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{N T_i \tau}}$$

Increase τ

Increase f_0

Increase N

Increase T_i

Pity the grad student!

$$\tau \approx \frac{1}{(2\pi f_0\, \sigma_y)^2 N T_i}$$

PHD length (lower bound) → τ

Target instability → σ_y

How to decrease QPN?

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Increase τ

Increase f_0

Increase N

Increase T_i

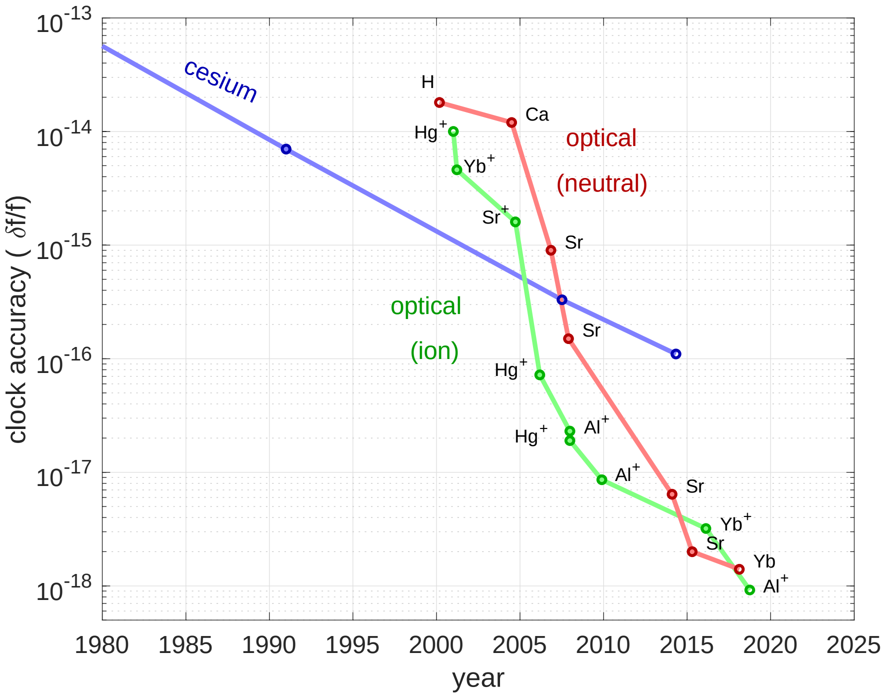


Image credit: May Kim

How to decrease QPN?

$$\sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{N T_i \tau}}$$

Increase τ

Increase f_0

Increase N

Increase T_i

Can we increase N?

Two major types of optical clocks: ion clocks and neutral atom clocks

- Lattice clocks can operate with $N \approx 10^4$
- Coupling between ions have so far constrained ion clocks to $N = 1$

However, exemplary systematic uncertainties have been attained by ion clocks

Also, some ion clocks have high sensitivity for tests of fundamental physics

TABLE I. Fractional frequency shifts ($\Delta\nu/\nu$) and associated systematic uncertainties for the $^{27}Al^+$ quantum-logic clock.

Effect	Shift (10^{-19})	Uncertainty (10^{-19})
Excess micromotion	−45.8	5.9
Blackbody radiation	−30.5	4.2
Quadratic Zeeman	−9241.8	3.7
Secular motion	−17.3	2.9
Background gas collisions	−0.6	2.4
First-order Doppler	0	2.2
Clock laser Stark	0	2.0
AOM phase chirp	0	<1
Electric quadrupole	0	<1
Total	−9336.0	9.4

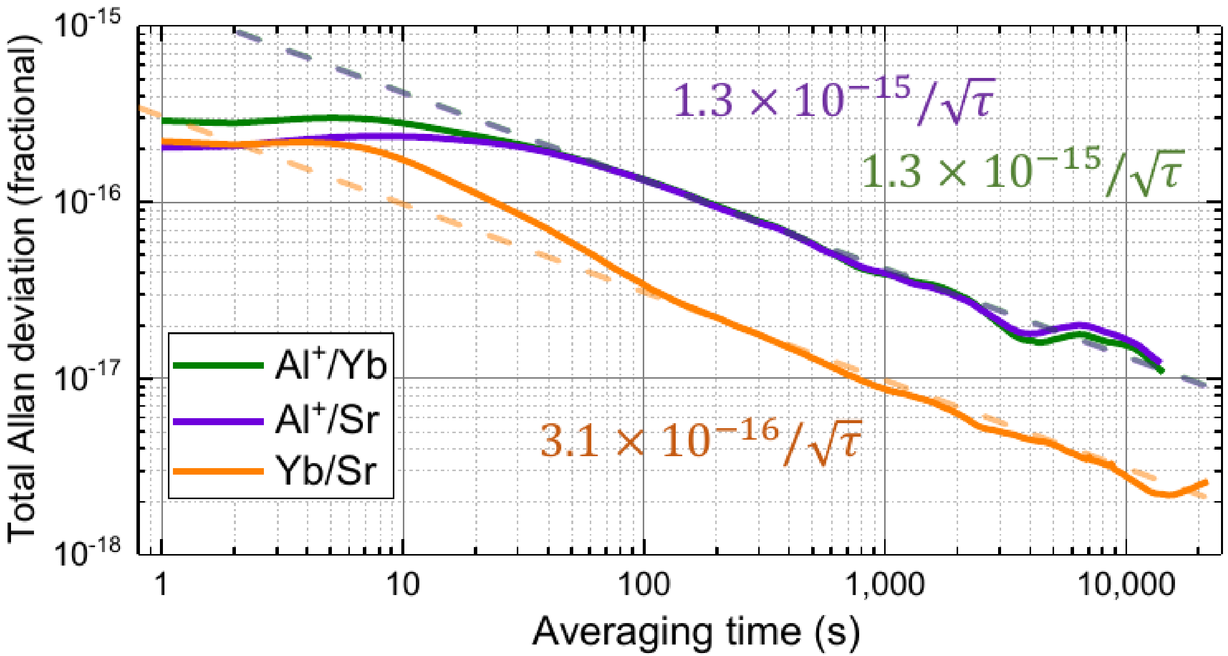
Brewer, S. M., Chen, J. S., Hankin, A. M., Clements, E. R., Chou, C. W., Wineland, D. J., … Leibrandt, D. R. (2019). Al+ 27 Quantum-Logic Clock with a Systematic Uncertainty below 10-18. *Physical Review Letters*, *123*(3), 033201.

Our previous comparisons

Sr lattice clock at JILA

Al^+ ion clock and Yb lattice clock at NIST

20 days of continuous comparison to reach 1×10^{-18} instability for Al^+/Yb or Al^+/Sr



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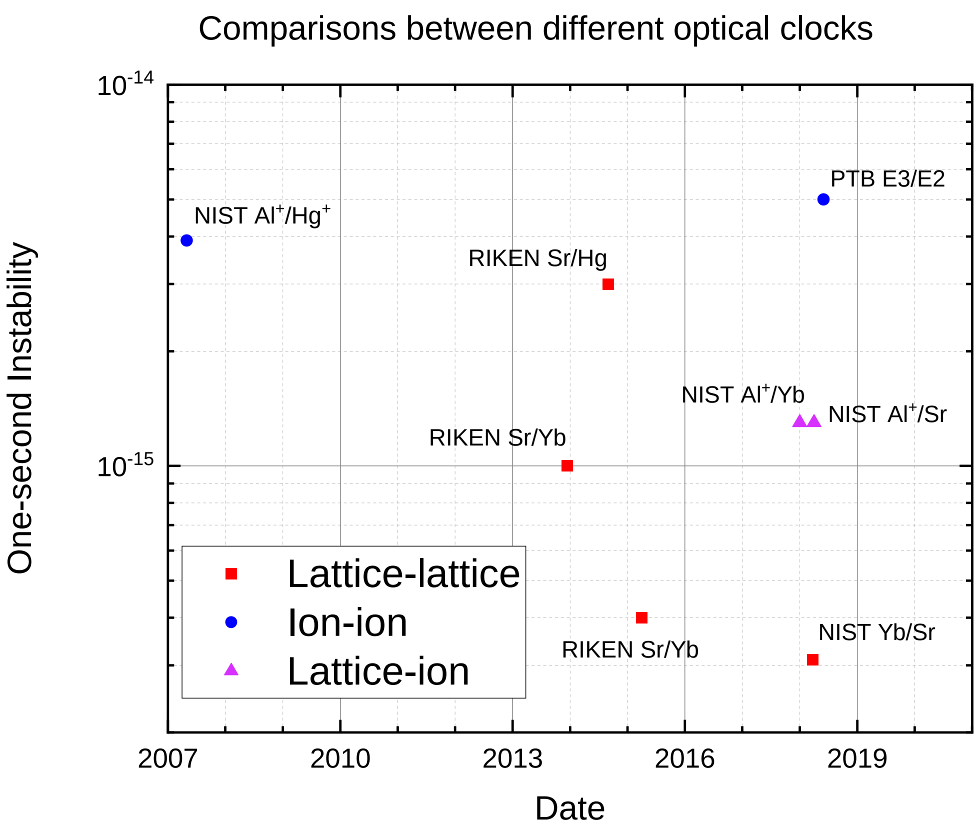
Interspecies comparisons



How to decrease QPN?

$$\sigma_y(\tau) \approx \frac{1}{2\pi f_0 \sqrt{N T_i \tau}}$$

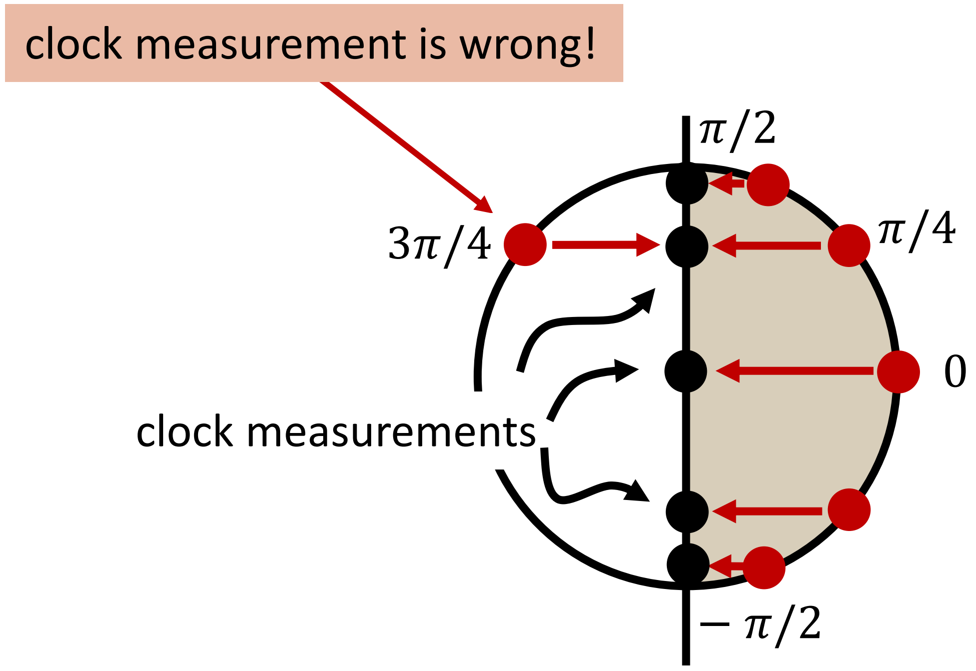
Increase τ

Increase f_0

Increase N

Increase T_i

The coherence limit to interrogation



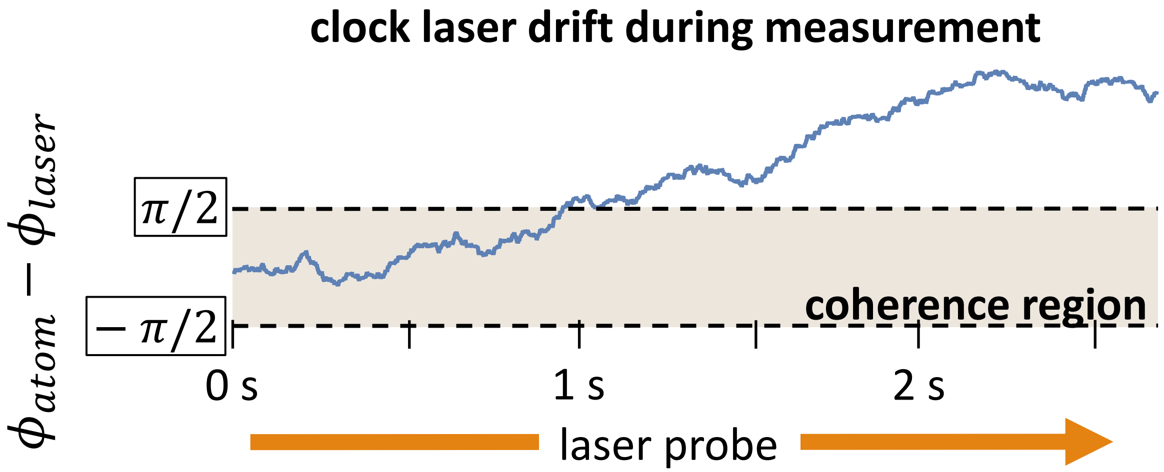
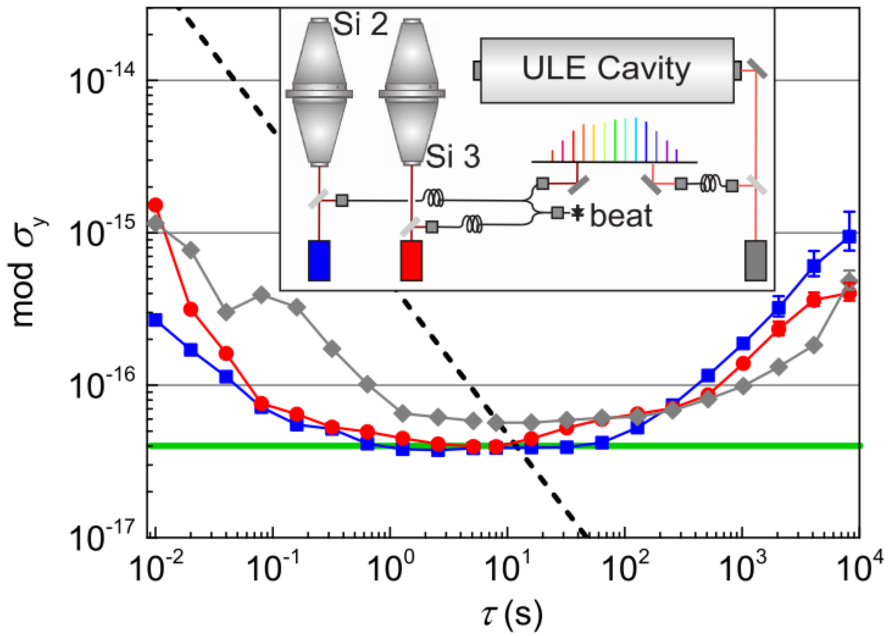


Image credit: Nick Nardelli

Increase the stability of the OLO?



Matei, D. G., Legero, T., Häfner, S., Grebing, C., Weyrich, R., Zhang, W., … Sterr, U. (2017). 1.5 µm Lasers with Sub-10 mHz Linewidth. *Physical Review Letters*, *118*(26), 263202.

Part II – Differential spectroscopy

Novel interrogation schemes

Use one or several systems to prestabilize another

- Borregaard, J., & Sørensen, A. S. (2013). Efficient atomic clocks operated with several atomic ensembles. *Physical Review Letters*, *111*(9), 090802.
- Schioppo, M., Brown, R. C., McGrew, W. F., Hinkley, N., Fasano, R. J., Beloy, K., … Ludlow, A. D. (2017). Ultrastable optical clock with two cold-atom ensembles. *Nature Photonics*, *11*, 48–52.

Dynamical decoupling

- Dörscher, S., Al-Masoudi, A., Bober, M., Schwarz, R., Hobson, R., Sterr, U., & Lisdat, C. (2020). Dynamical decoupling of laser phase noise in compound atomic clocks. *Communications Physics*, *3*, 185.

Novel interrogation schemes

Nondestructive measurements to achieve a phase lock

- Kohlhaas, R., Bertoldi, A., Cantin, E., Aspect, A., Landragin, A., & Bouyer, P. (2015). Phase locking a clock oscillator to a coherent atomic ensemble. *Physical Review X*, *5*(2), 021011.
- Bowden, W., Vianello, A., Hill, I. R., Schioppo, M., & Hobson, R. (2020). Improving the Q Factor of an Optical Atomic Clock Using Quantum Nondemolition Measurement. *Physical Review X*, *10*(4), 041052.

Correlation spectroscopy

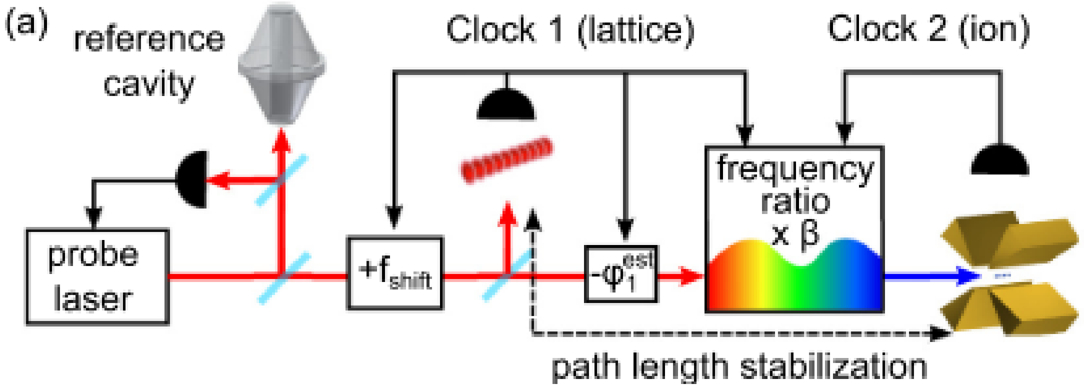
- Chwalla, M., Kim, K., Monz, T., Schindler, P., Riebe, M., Roos, C. F., & Blatt, R. (2007). Precision spectroscopy with two correlated atoms. *Applied Physics B: Lasers and Optics*, *89*, 483–488.
- Clements, E. R., Kim, M. E., Cui, K., Hankin, A. M., Brewer, S. M., Valencia, J., … Hume, D. B. (2020). Lifetime-Limited Interrogation of Two Independent Al+ 27 Clocks Using Correlation Spectroscopy. *Physical Review Letters*, *125*(6), 243602.

Differential spectroscopy – a proposal

Phase lock OLOs to each other

Interrogate synchronously

Phase corrections from Yb



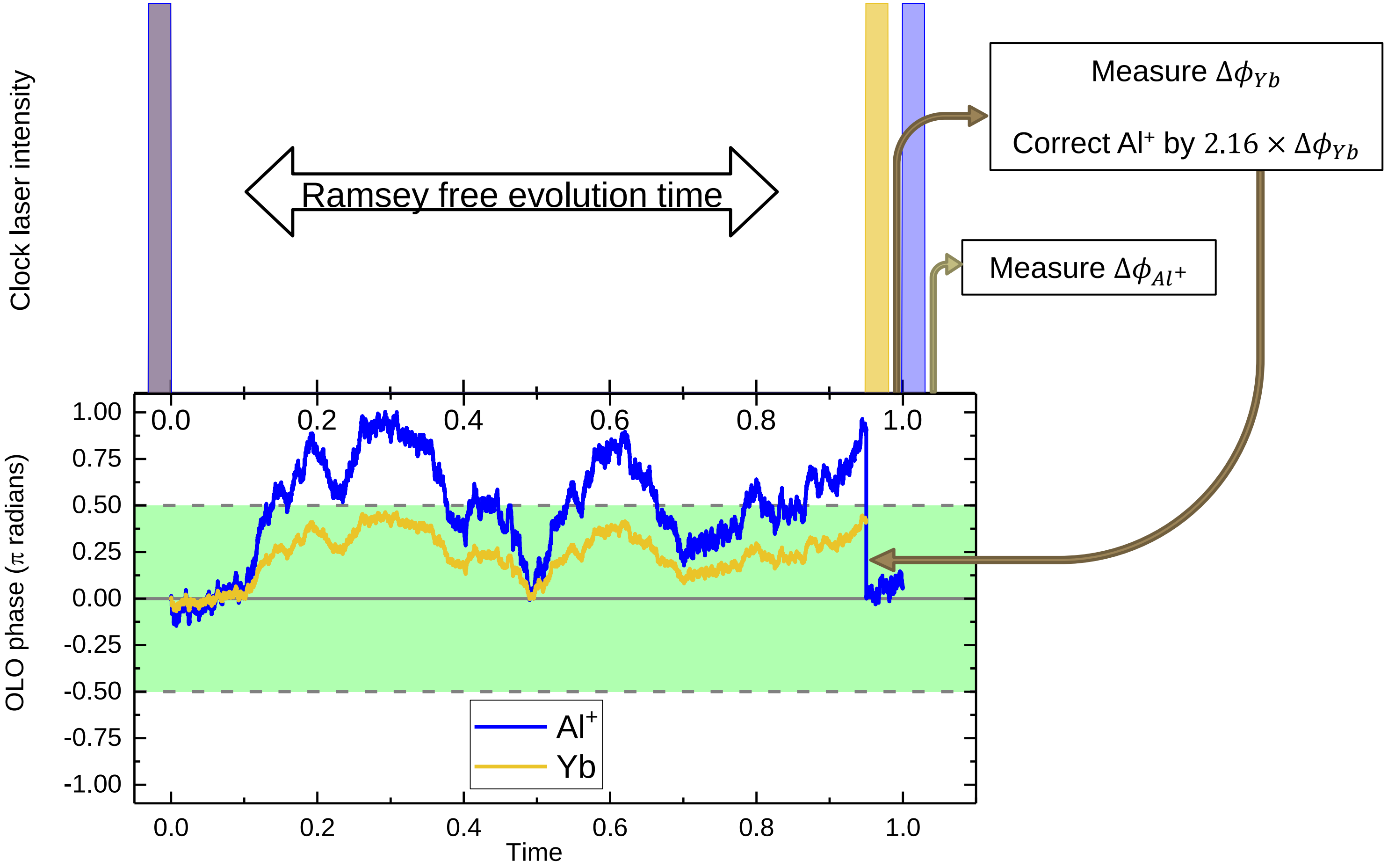
Hume, D. B., & Leibrandt, D. R. (2016). Probing beyond the laser coherence time in optical clock comparisons. *Physical Review A*, *93*(3), 032138.

Differential spectroscopy – implementation

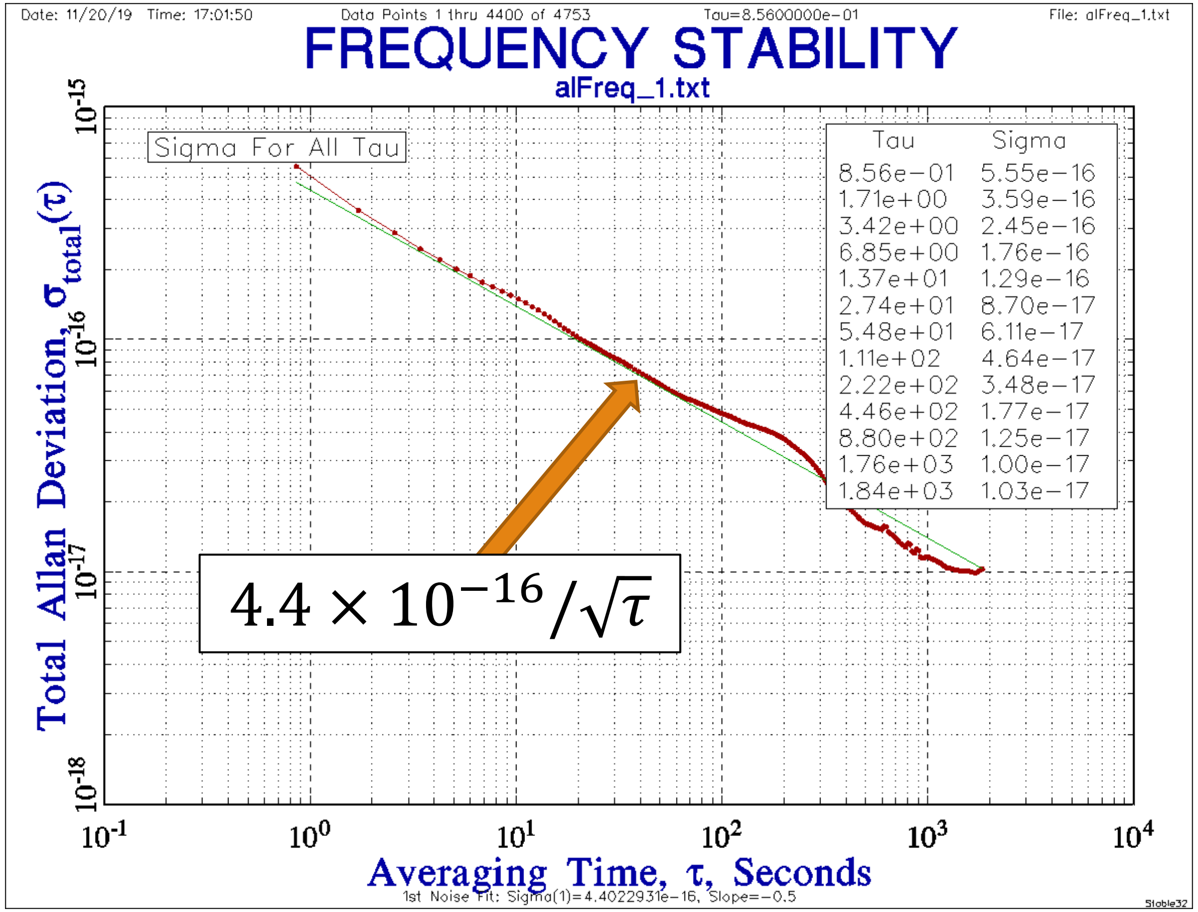
Provide phase corrections from a high-(S/n), lower-frequency clock

The high frequency clock can operate outside of its inversion regime

Increase interrogation time by the frequency ratio (2.16 for Al^+/Yb)



Differential spectroscopy – results with 500 ms spectroscopy

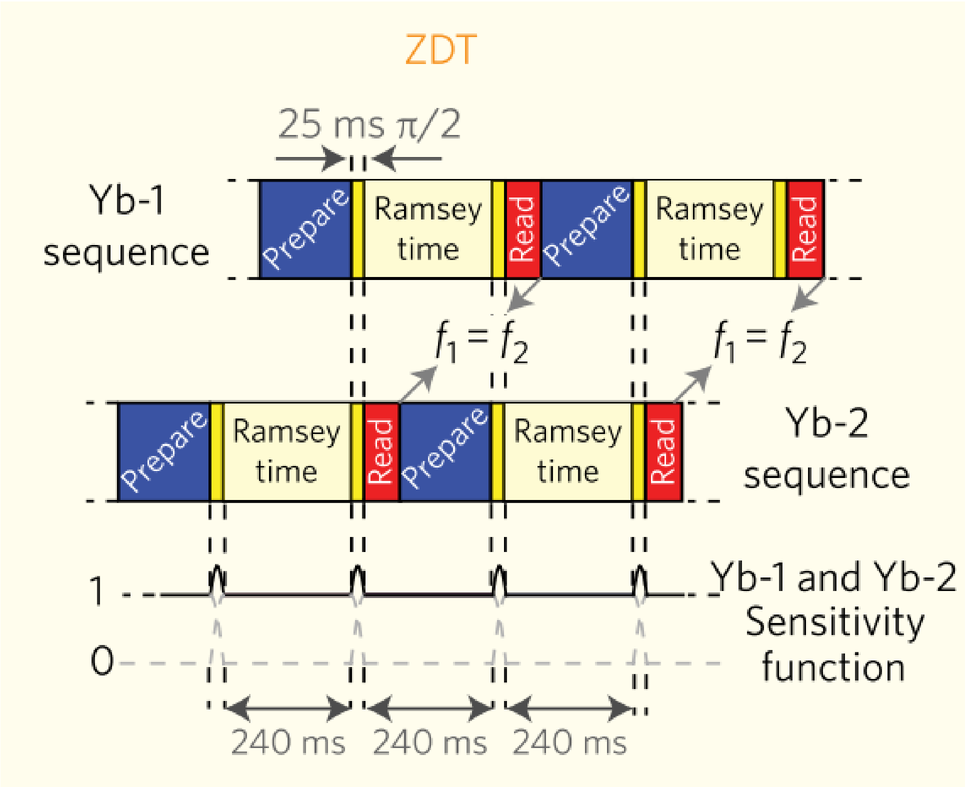


Part III – ZDT differential spectroscopy

Zero-dead-time spectroscopy

Originally demonstrated to suppress the Dick effect

Can be naturally paired with differential spectroscopy



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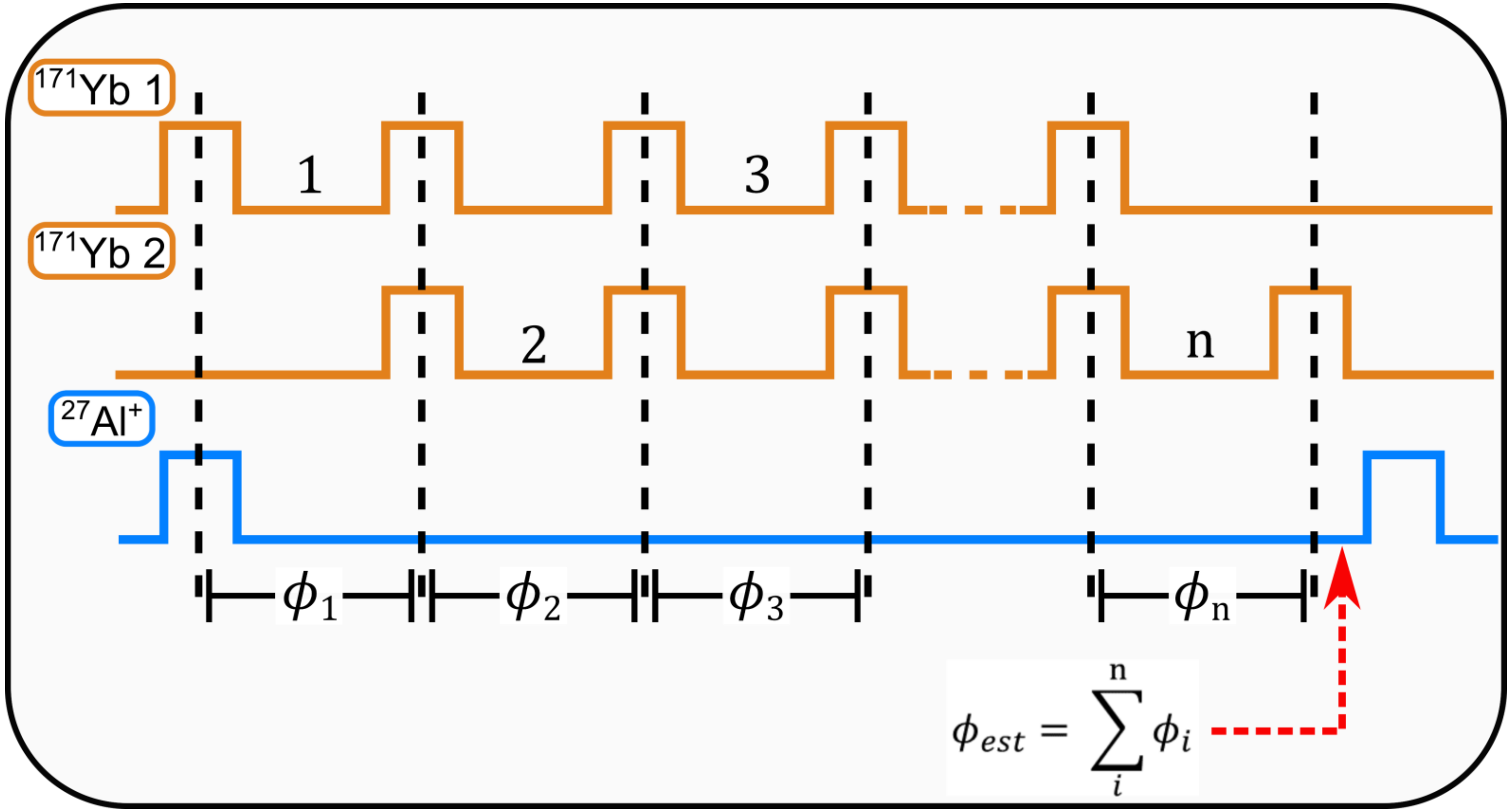
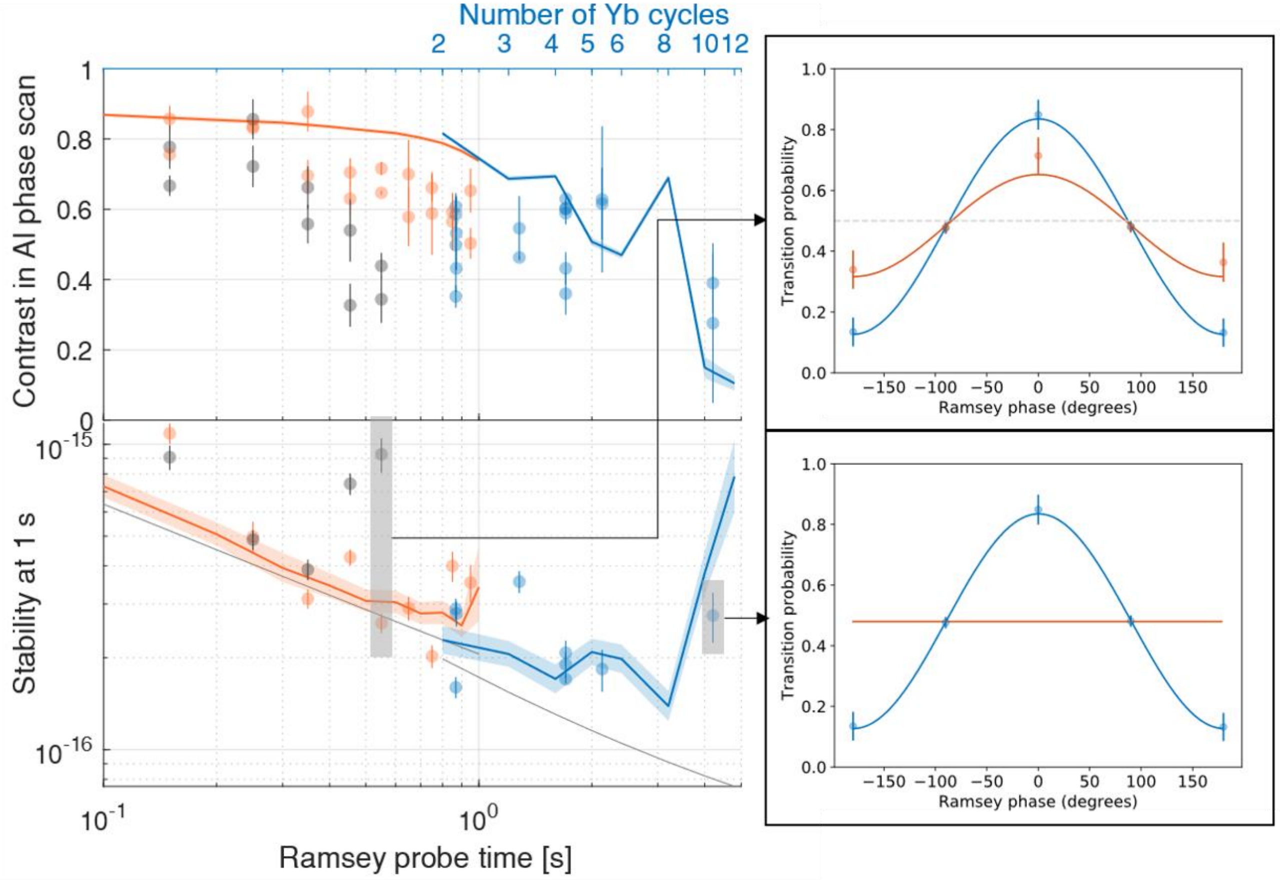
Combining differential spectroscopy with zero-dead-time spectroscopy



Differential spectroscopy results



No phase corrections from Yb

Single-clock differential spectroscopy

ZDT differential spectroscopy

Four cycles, 1.7 s spectroscopy time

Lifetime limit for QPN:

$6 \times 10^{-17}/\sqrt{\tau}$

Previously, 20 days to reach 1×10^{-18}

Now, 7 hours

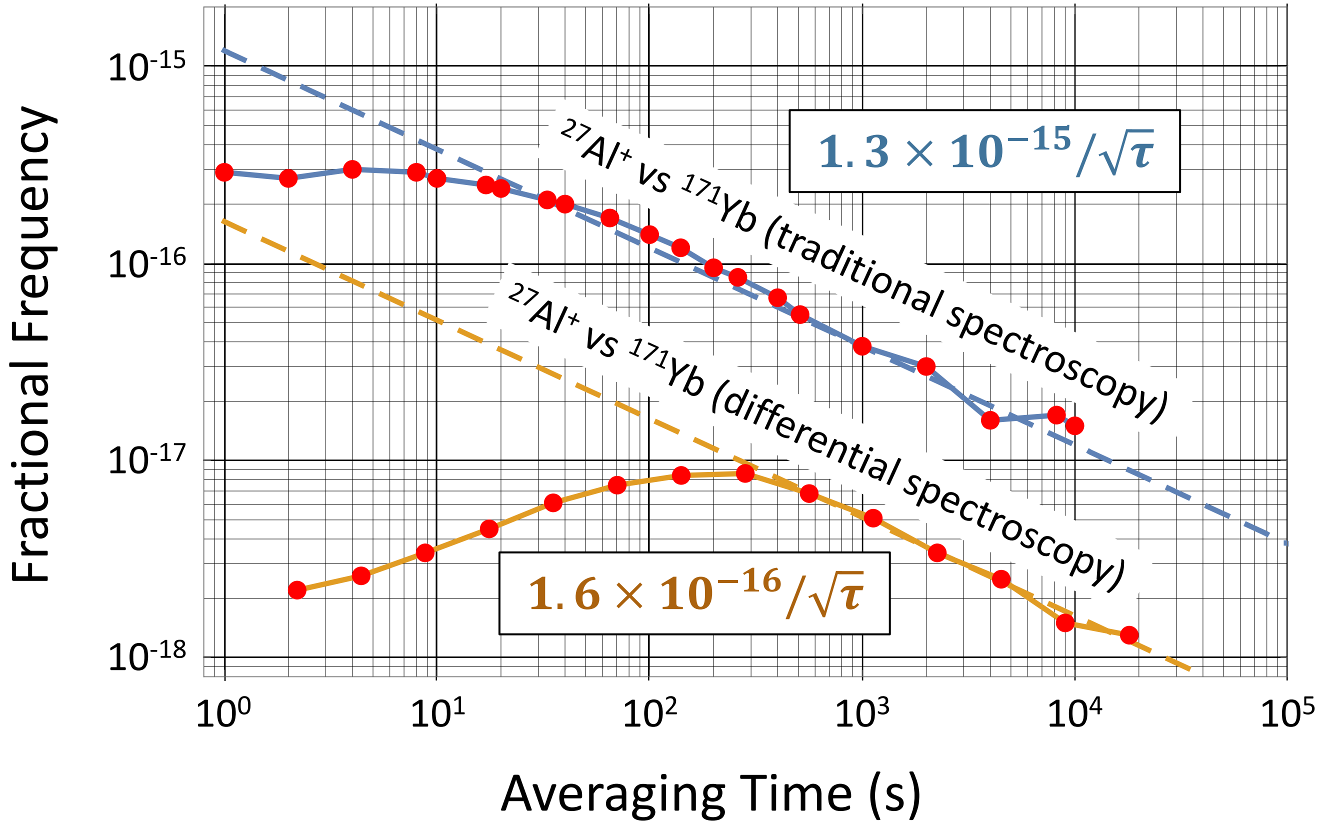


Image credit: Nick Nardelli

What continues to limit the instability?

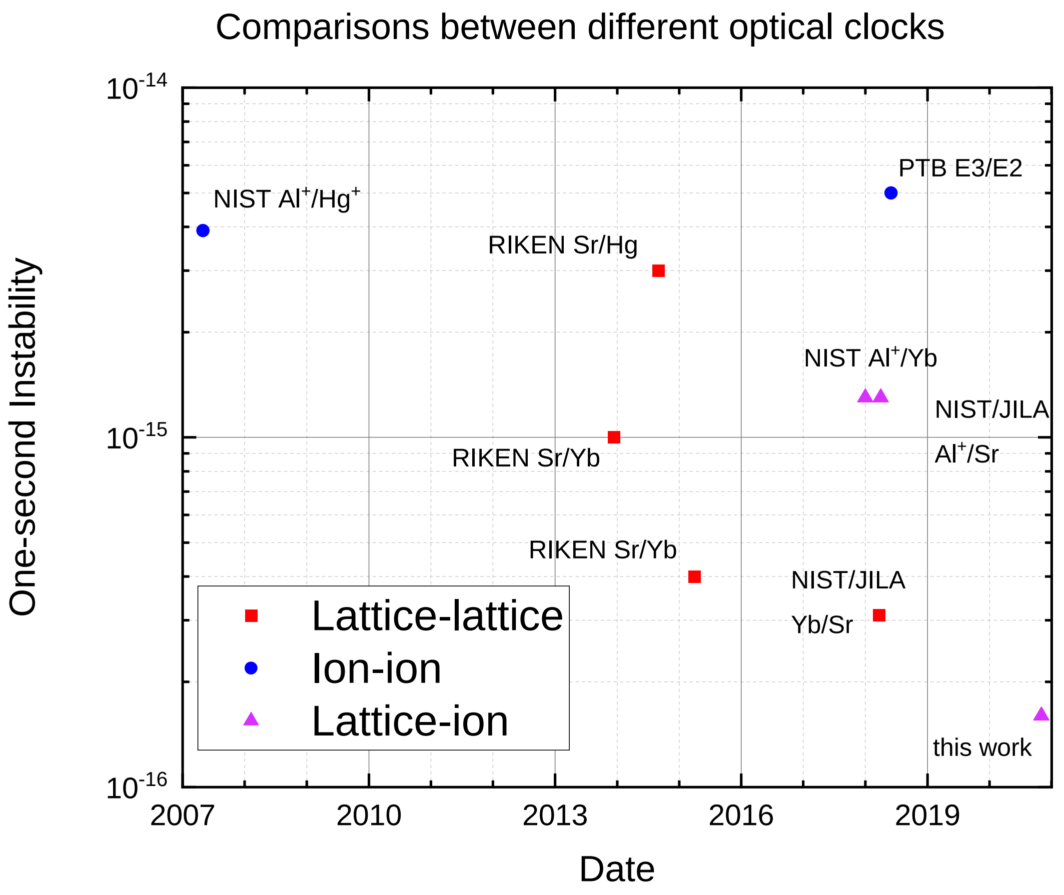
Magnetic field fluctuations on both clocks

Phase-noise-cancellation instability

Frequency transfer uncertainty through the comb

All these are technical and subject to reduction

Interspecies clock comparisons



Perspectives: improvement to DM constraints

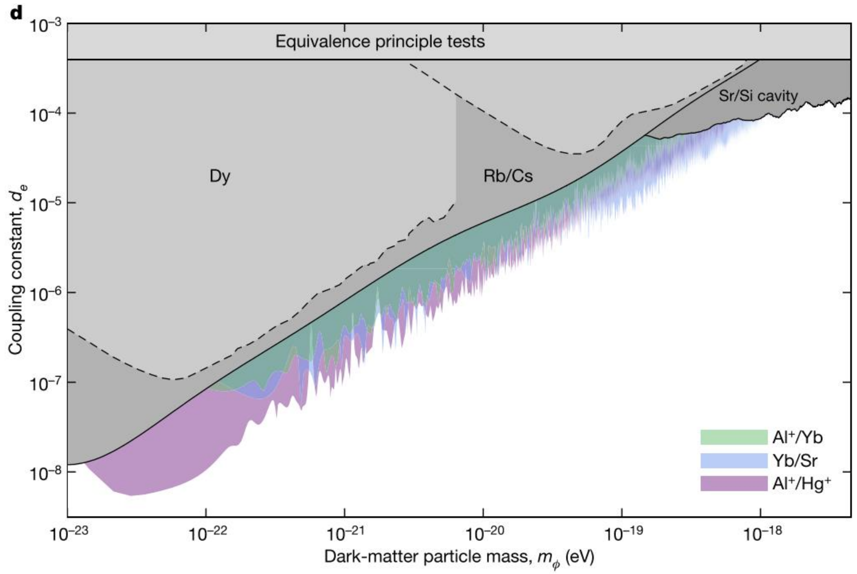
Improved interspecies instability affords improved constraint of DM coupling

ZDT differential spectroscopy can improve any interspecies comparison

$$K_{Yb} = 0.31$$
$$K_{Al^+} = 0.008$$

$K_{Yb^+E3} = -5.95$ (Ekkehard Peik's talk)

HCIs, Th nuclear clock, etc. offer even better improvements (Marianna Safronova's and Steven King's talks)



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David Leibrandt

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