Differential Spectroscopy of Atomic Clocks

Tara Fortier….. and many others!

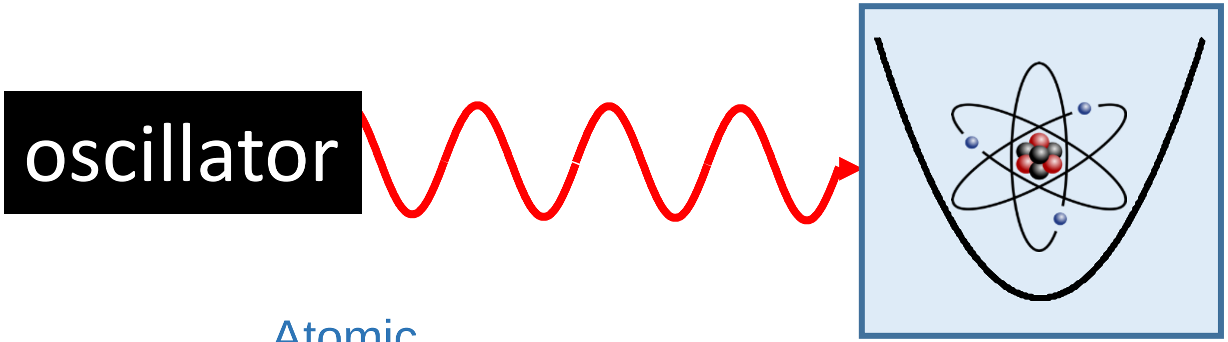
Time and Frequency Division
National Institute of Standards and Technology

That's me holding a koala! →

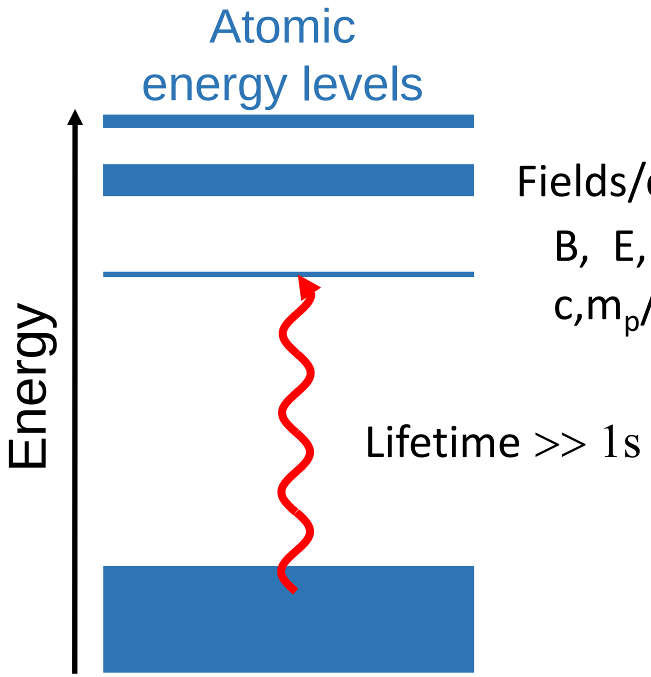
NIST

9FSM: Oct 16 2023

Atomic clock basics



Isolate, trap, cool,
control, probe….

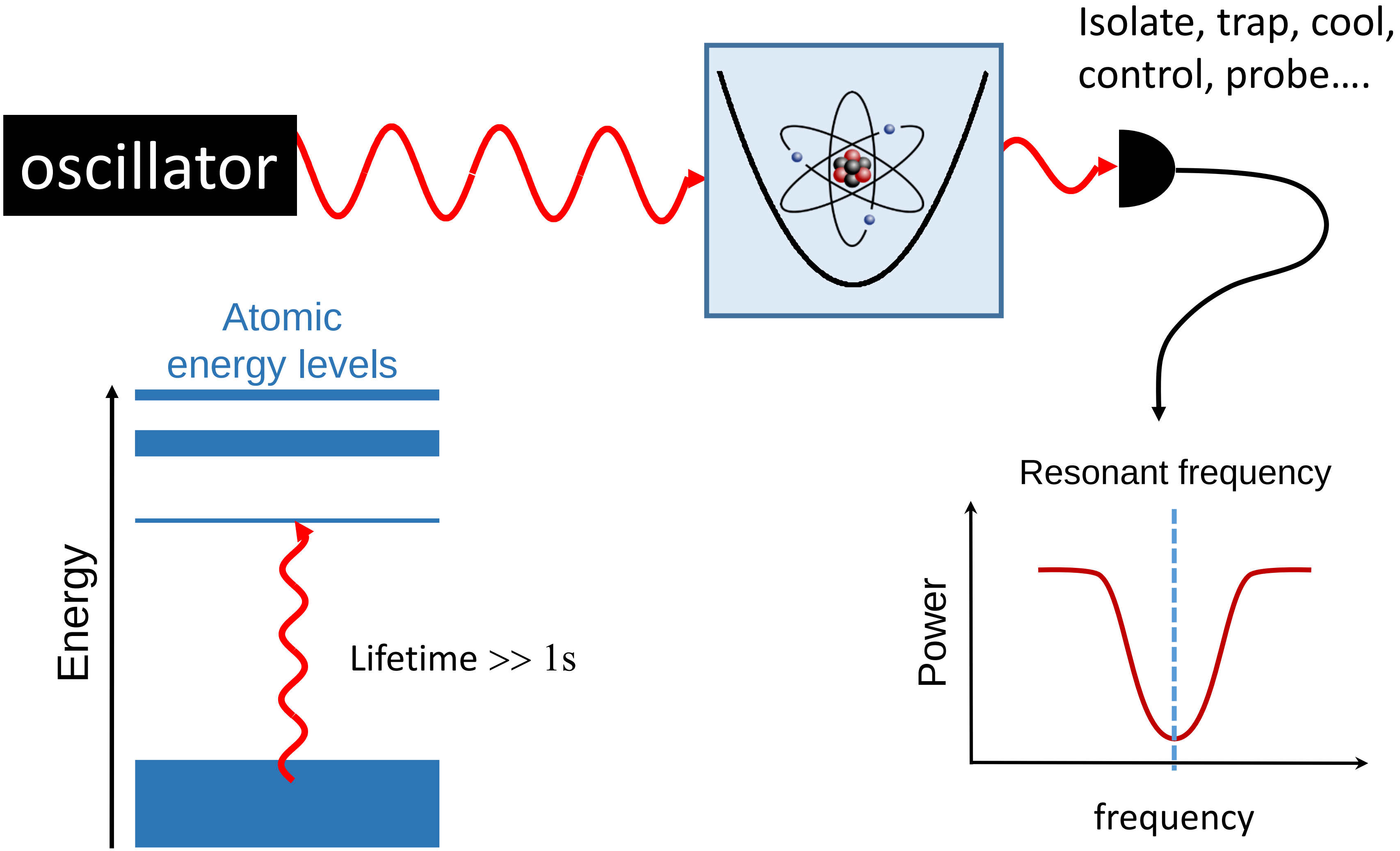


Fields/constants:

B, E, T, U….

$c, m_p/m_e, \alpha$…

Atomic clock basics



oscillator

Isolate, trap, cool, control, probe....

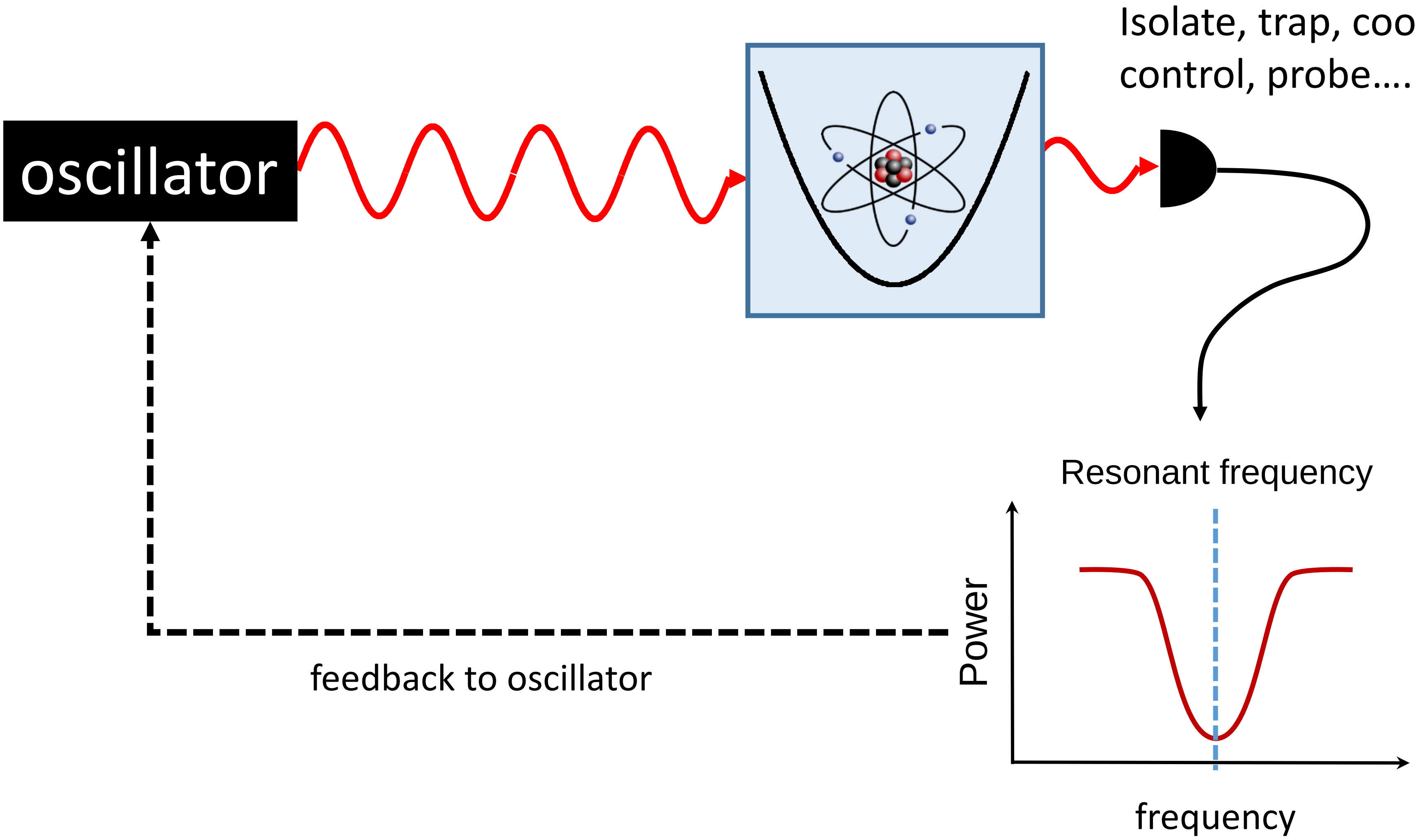
Atomic energy levels

Lifetime >> 1s

Resonant frequency

Atomic clock basics

Cycles of an electromagnetic field are stabilized to an atomic transition



Isolate, trap, cool,
control, probe….

oscillator

Resonant frequency

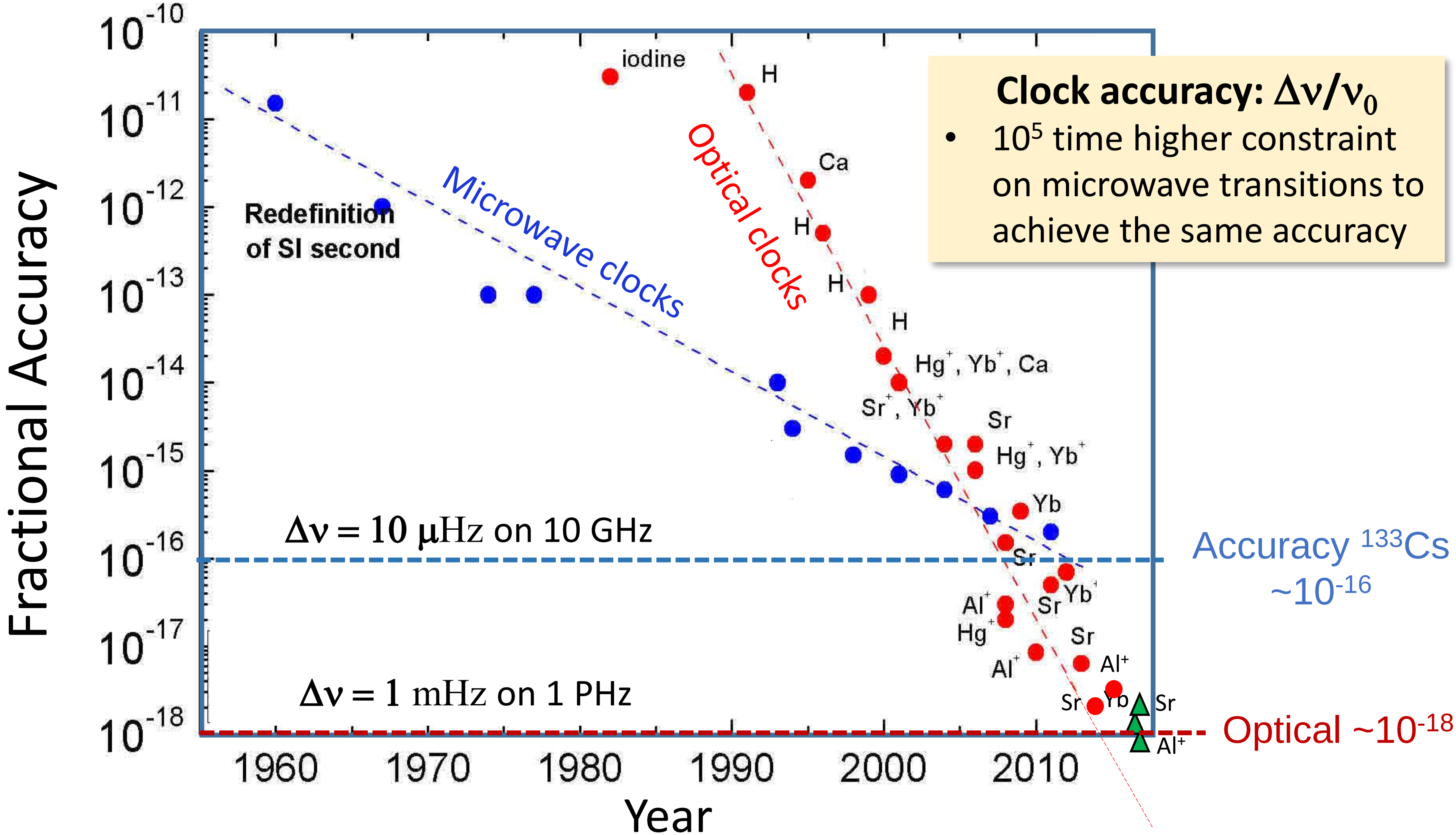
Power

frequency

feedback to oscillator

Historical Performance of Atomic Clocks

*N. Poli et al, Rivista del Nuovo Cimento, **36** (2013)*
A. Ludlow et al. Rev. Mod. Phys. 87, 637 (2015)



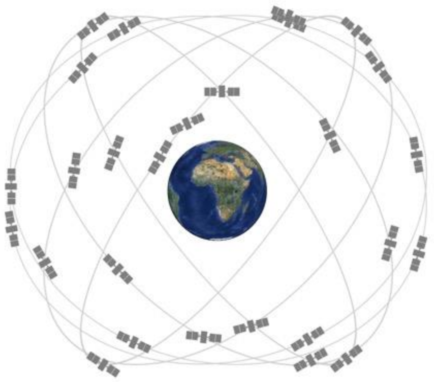
Clock accuracy: $\Delta\nu/\nu_0$

- 10^5 time higher constraint on microwave transitions to achieve the same accuracy

Is it time to redefine the SI second?

Atomic Clock Applications

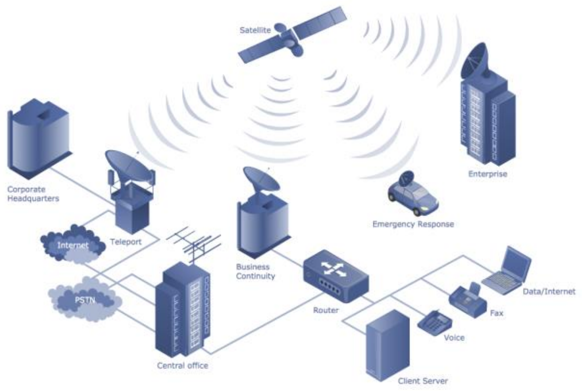
GPS and Navigation

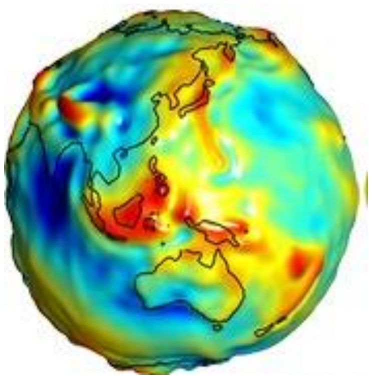


F. Riehle, et. al., *Metrologia* 55.2 188 (2018).
T. E. Mehlstäubler et. al., *Rep. Prog. Phys.* 81 (2018)
C. Grebing, et. al.,, *Optica, 3(6) (2016).*

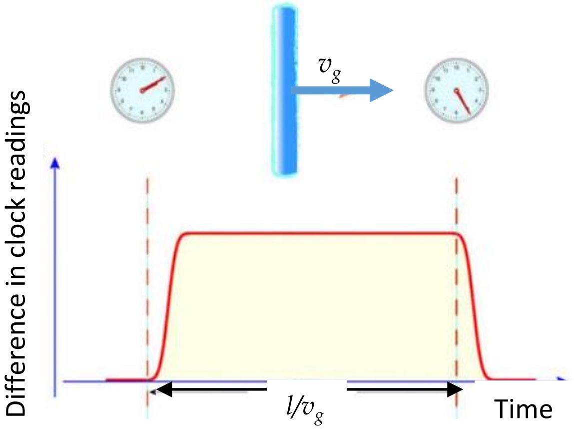
Defining the SI second

Synchronization in communications networks





Improve local geodesic measurements



Credit: A. Derevianko

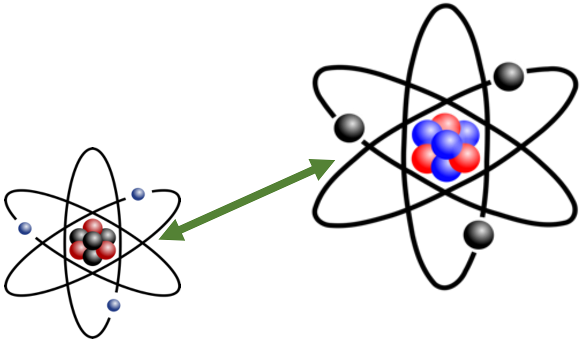
Dark matter detection

Variation of fundamental constants

Applications requiring comparison of two dissimilar clocks

Fundamental physics

Atomic Clock	Resolution $\times 10^{-18}$	Accuracy $\times 10^{-18}$	α– Sensitivity
^{171}Yb	1	1	+0.06
^{87}Sr	1	1	+0.31
^{199}Hg^{+}	40	30	-3.0
^{27}Al^{+}	4	1	+0.0079



Hees et al, Phys. Rev. D. (2018)
T.Rosenband et al. Science (2008)

Roadmap for redefining the SI second

Demonstrate robustness of optical systems, consistency between the new and current SI, and 100 improved accuracy

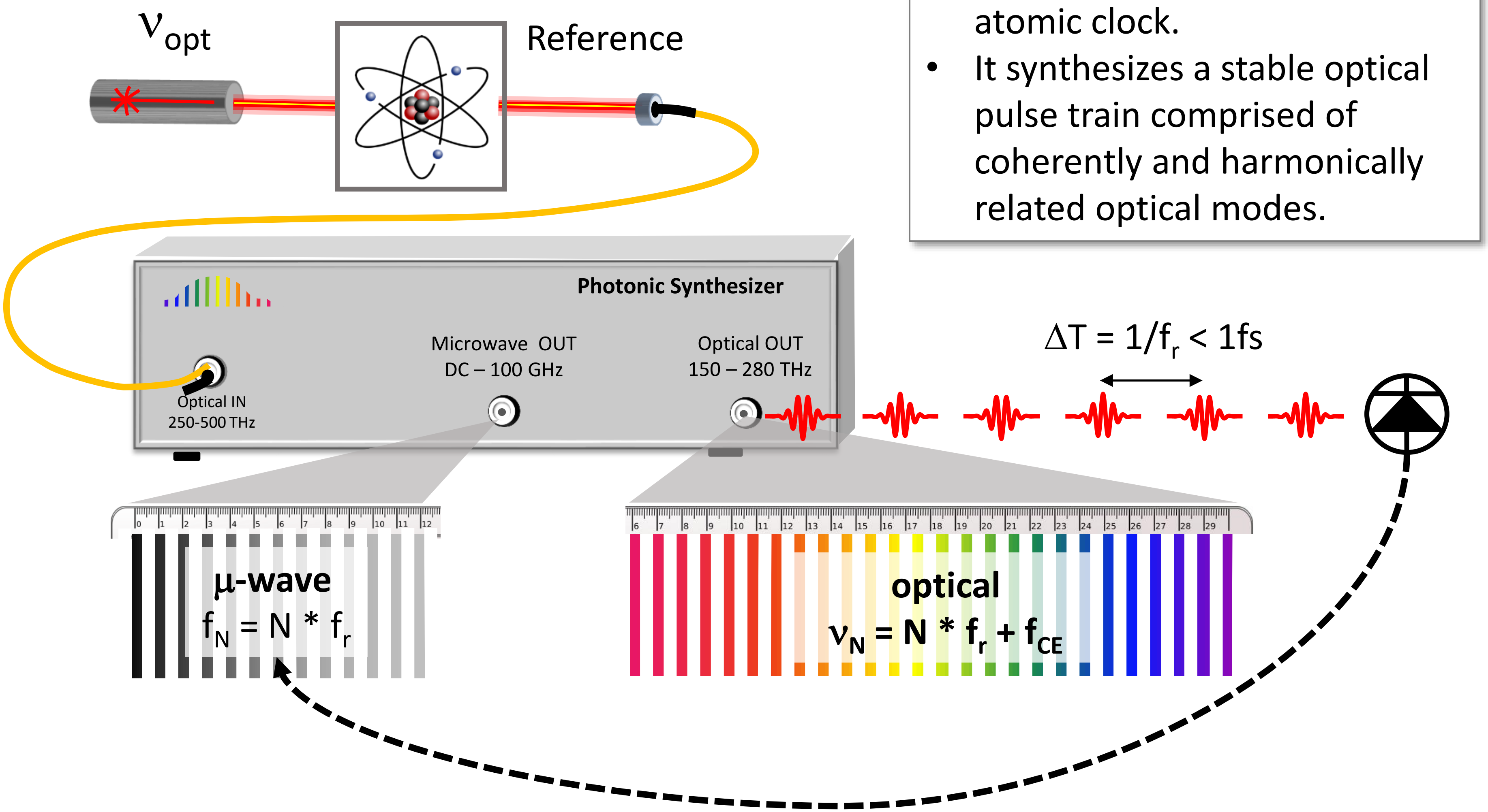
- ➢ Demonstrating comparison between different atomic clock species at 5 x 10^{-18}

How do you compare optical clocks when they operate at different optical frequencies?

Skeptical bush stone-curlew:
Currumbin Wildlife Sanctuary

Frequency comb: a pulsed harmonic synthesizer

- The OFC is referenced using an atomic clock.
- It synthesizes a stable optical pulse train comprised of coherently and harmonically related optical modes.

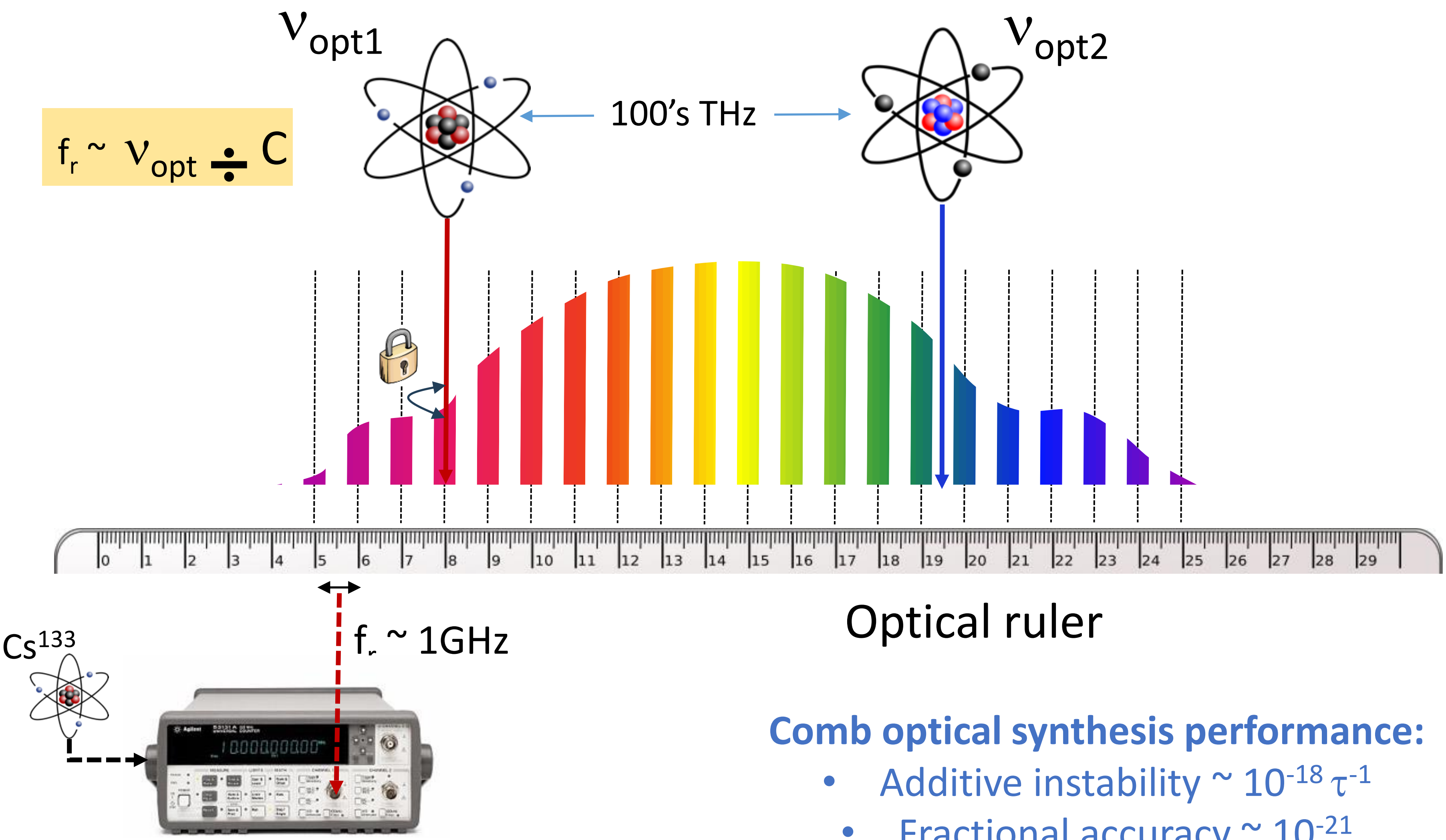


$f_r \sim \nu_{opt} \div C$ ← C ~ 500,000 (non-integer)

Review: Fortier and Baumann, Communications Physics (2019)

Combs for clock comparisons

Frequency ratios are unitless: relative measurement of optical atomic clocks allow for measurements independent of the 10^{-16} accuracy limitations of PSFS (Hz).



$f_r \sim \nu_{opt} \div C$

Optical ruler

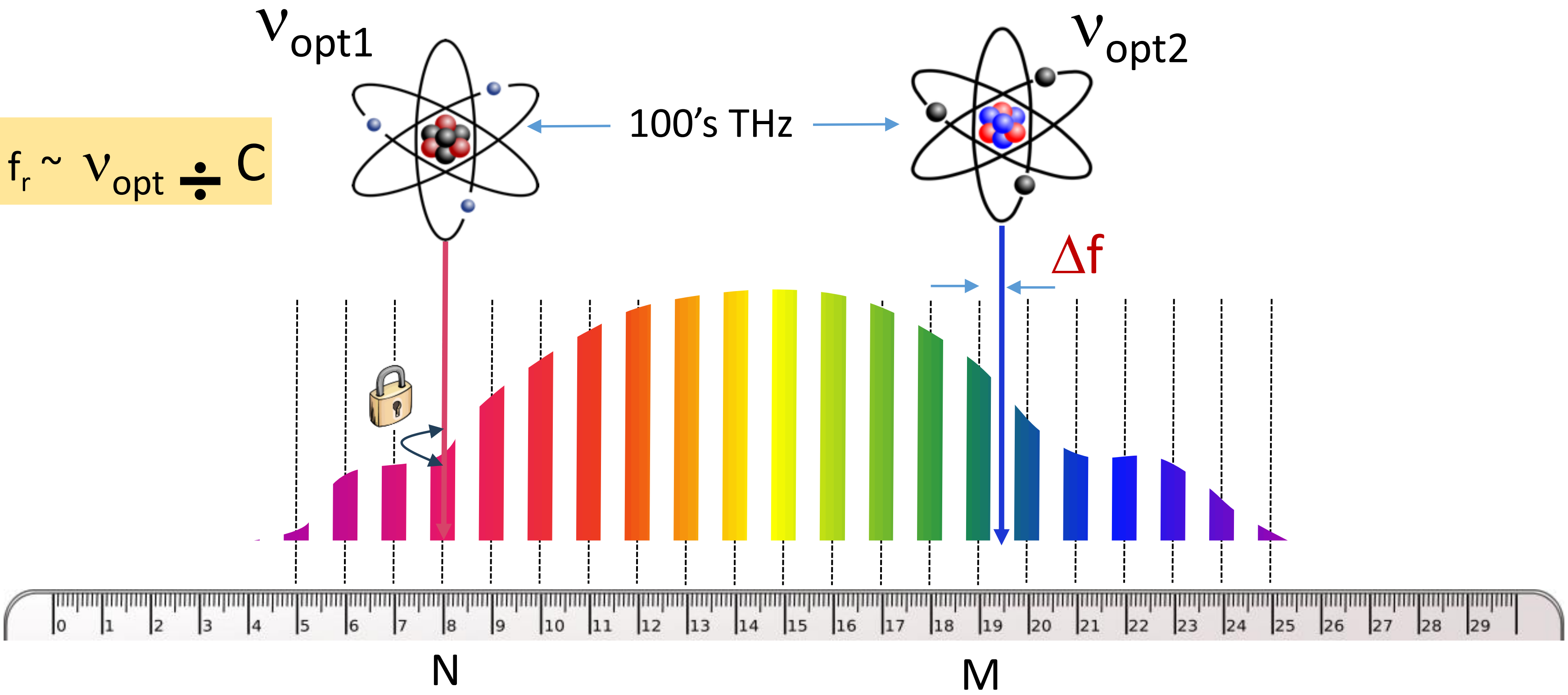
Comb optical synthesis performance:

- Additive instability ~ $10^{-18}\ \tau^{-1}$
- Fractional accuracy ~ 10^{-21}

Optical-to-optical clock comparisons

Frequency ratios are unitless: relative measurement of optical atomic clocks allow for measurements independent of the 10^{-16} accuracy limitations of PSFS (Hz).

$f_r \sim \nu_{opt} \div C$

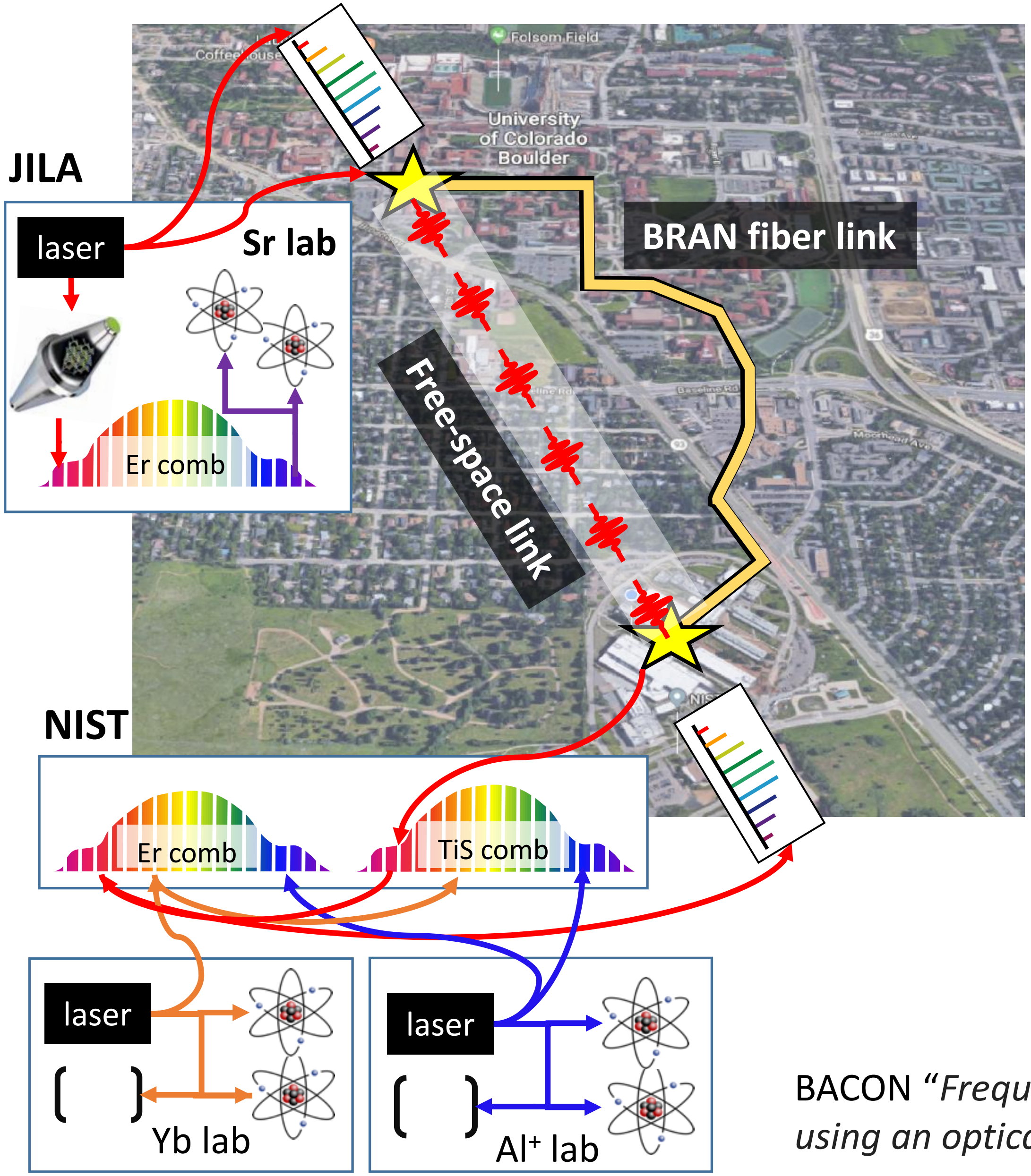


$$\frac{\nu_{opt2}\ \cancel{(\text{“Hz”})}}{\nu_{opt1}\ \cancel{(\text{“Hz”})}} = \boxed{\frac{M}{N}} + \frac{\Delta f}{\nu_{opt1}}$$

fractional offset < 1e-9

Dominant term

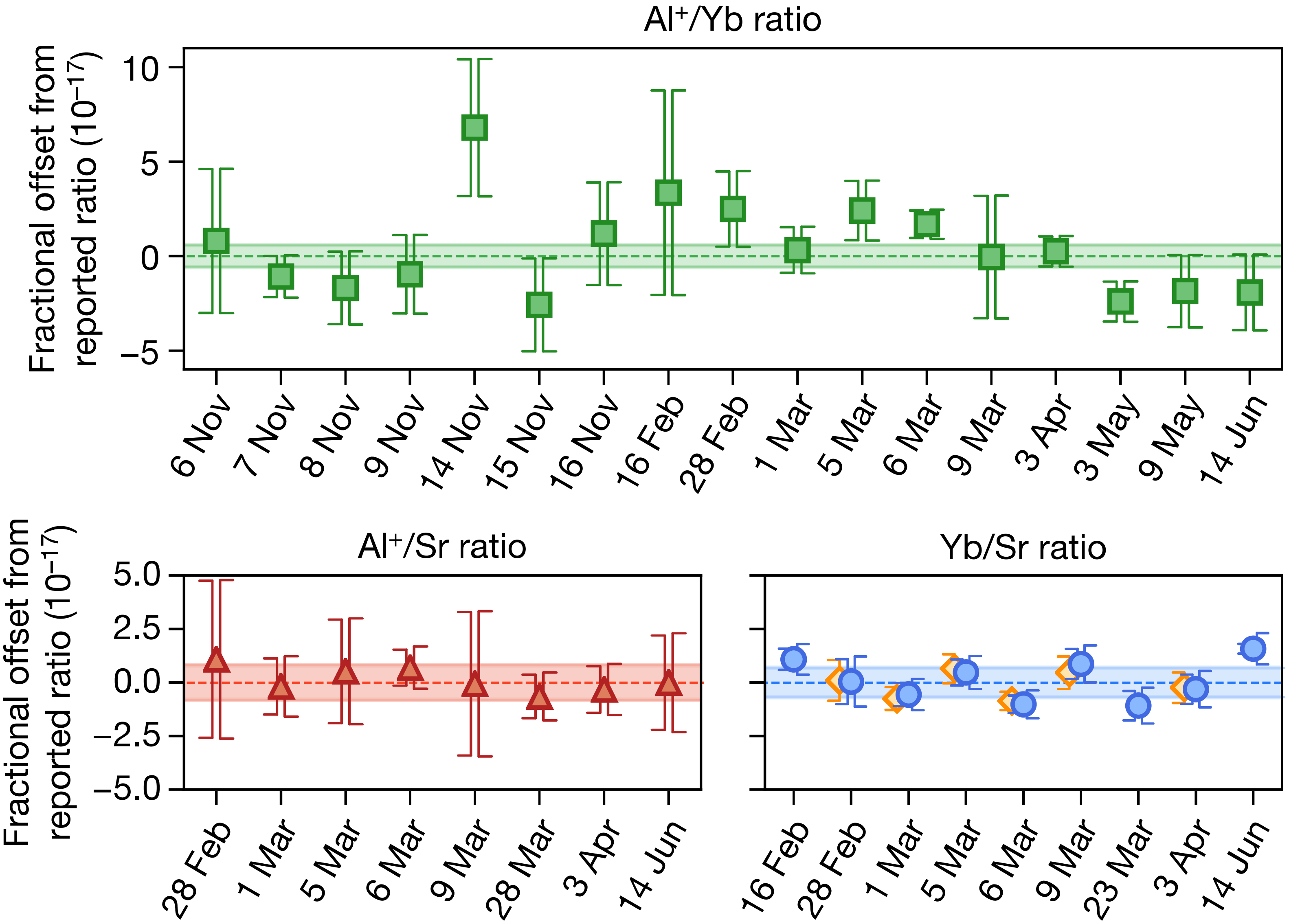
Boulder Atomic Clock Optical Network (2018)



- Frequency combs used for: 1) ratio and absolute clock measurements, 2) free-space time/frequency dissemination, 3) optical synthesis and 4) microwave generation for absolute frequency measurements.
- Record measurement of 3 optical atomic clocks ratios, all near 10^{-18} using an inter-city optical fiber network (BRAN).
- First comparison of optical atomic clocks across a free-space optical link, with measurement accuracy near 10^{-18}
- New constraints on the coupling of ultralight dark matter to normal matter via the fine structure constant.

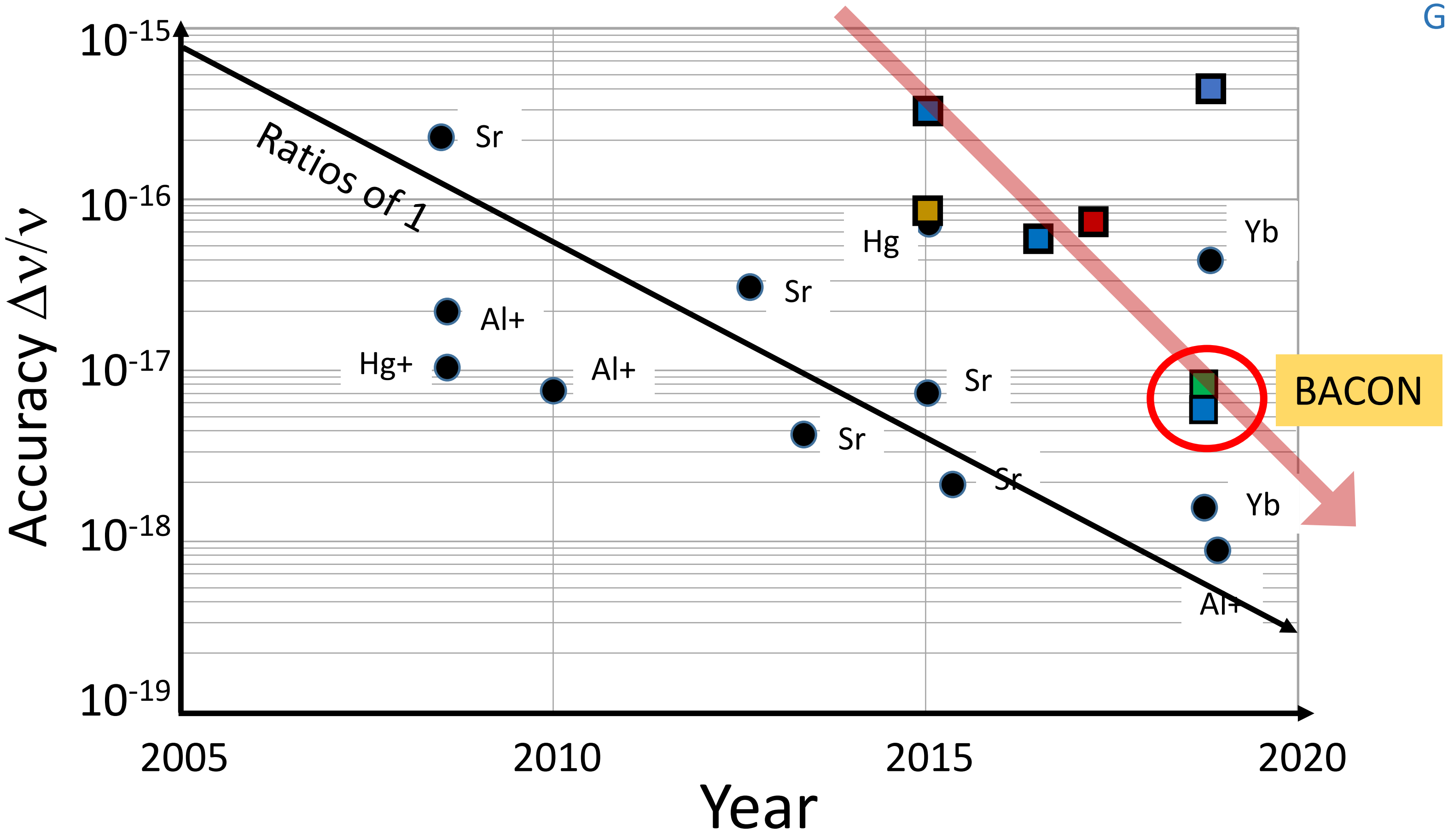
BACON “*Frequency ratio measurements at 18-digit accuracy using an optical clock network,*” Nature **591** (2021).

Ratios Day by Day



Comparison with world and past results

Clocks will be competitive with LIGO : 10^{-21}



Relativistic Sensitivity

Comparisons at 10^{-19} will require knowledge of relative clock height difference at the mm-level…..

Clocks and tests of fundamental physics

One theory of dark matter (DM) suggests that our galaxy is pervaded by a DM halo composed of Bosonic, ultralight particles.

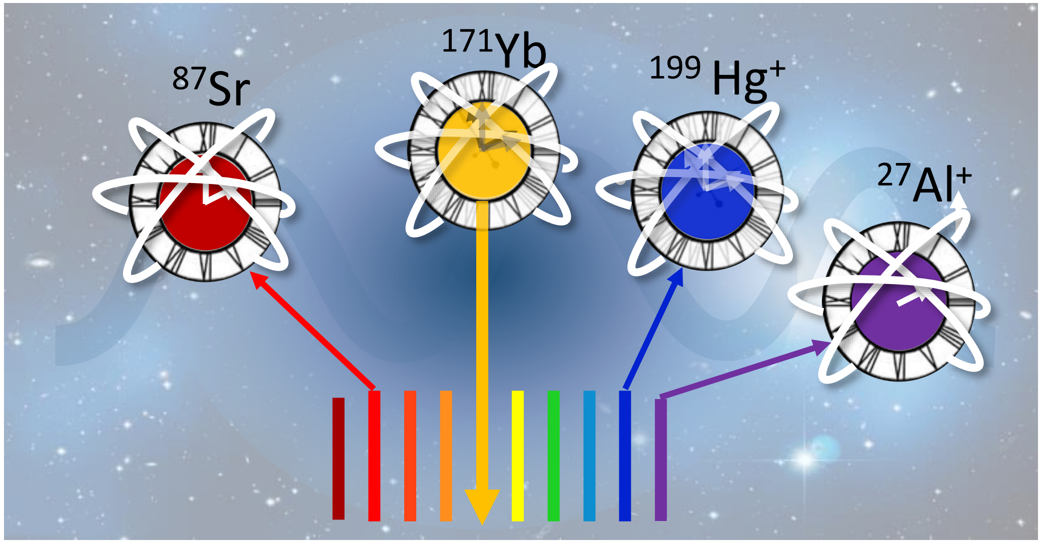
DM is predicted to couple transitions will couple to a DM field via α–fine structure constant

Coupling will result in a periodic time-variation in α,

$$\alpha(t) \propto \frac{d_e^* \cos(\omega_{DM}\, t)}{\omega_{DM}}$$

DM coupling strength

Compton frequency $\propto$ DM mass



Atomic Clock	Resolution $\times 10^{-18}$	Accuracy $\times 10^{-18}$	α– Sensitivity
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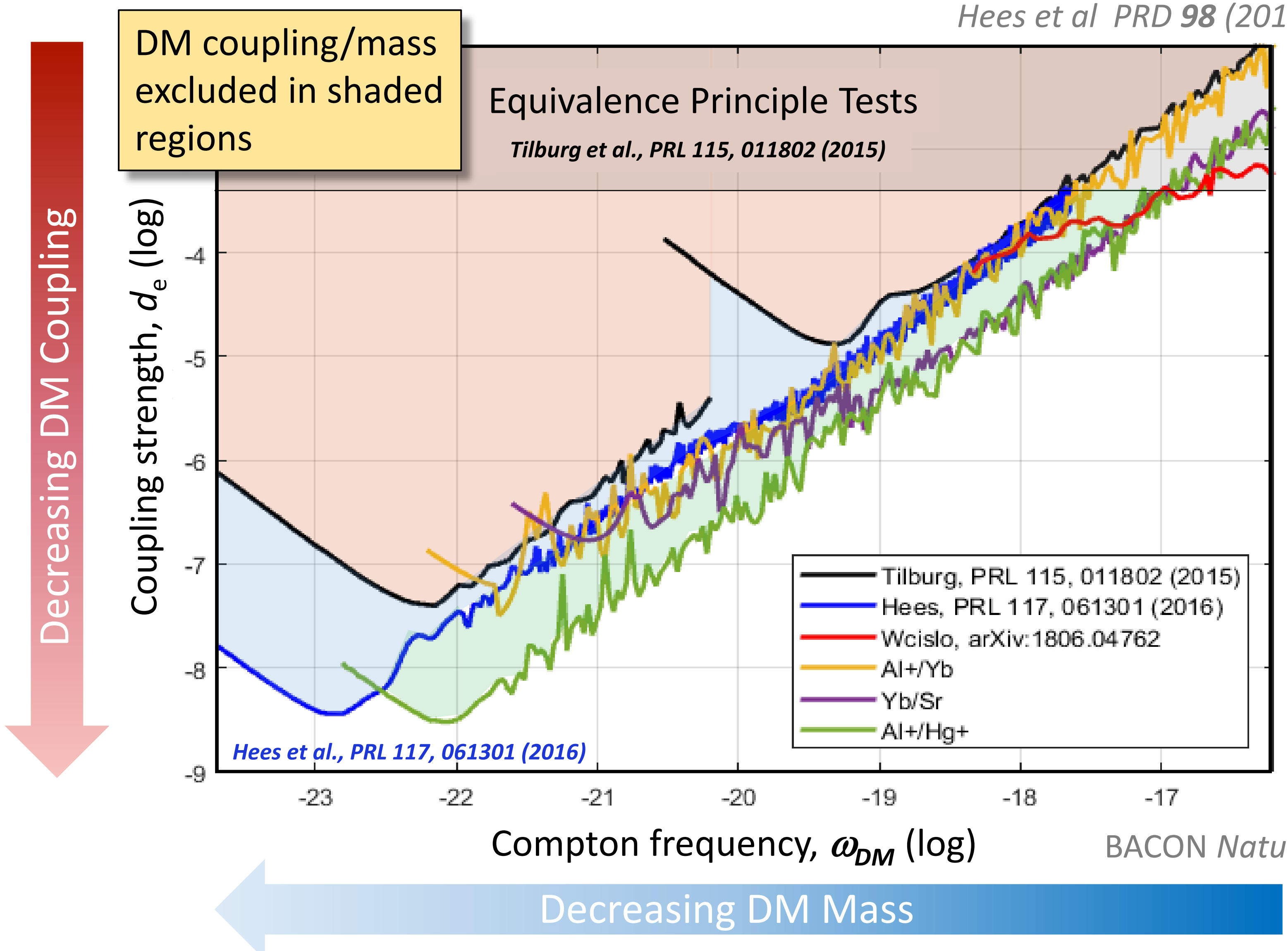
A. Arvanataki et al.,Phys. Rev. D **91**, 015015 (2015)
Y. V. Stadnik and V. V. Flambaum, Phys. Rev. Lett. **115**, 201301 (2015)
A. Derevianko and M. Pospelov., Nature Phys. **10**, 933 (2014)
Y. V. Stadnik and V. V. Flambaum, PRA **93**, 063630 (2016)

Clocks and tests of fundamental physics

Improve coupling constraint over 6 decades in DM mass.

Hees et al PRD ***98*** *(2018)*

DM coupling/mass excluded in shaded regions



BACON *Nature* **591** (2021)

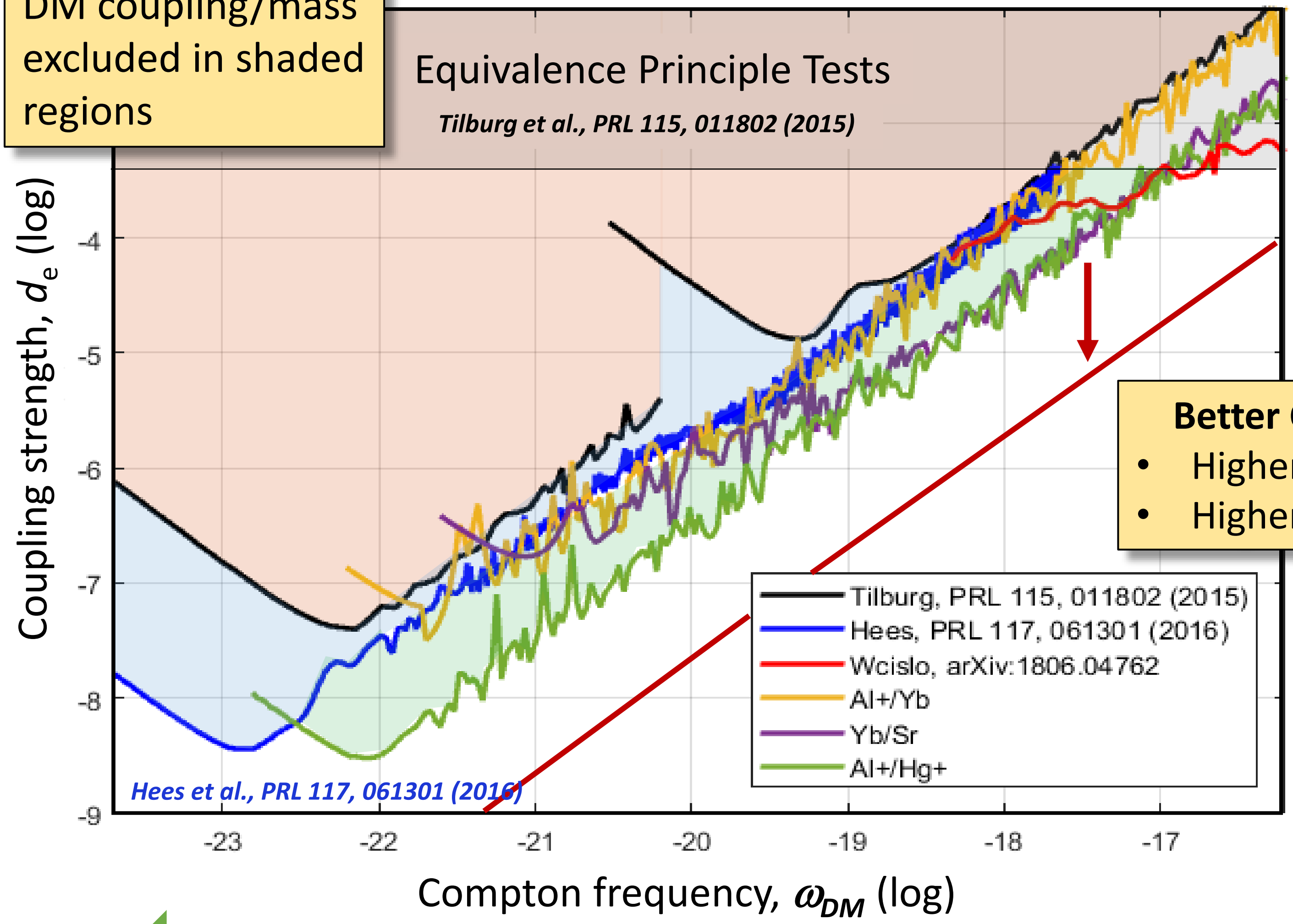
Clocks and tests of fundamental physics

Improve coupling constraint over 6 decades in DM mass.

Hees et al, arXiv:1807.04512v3 (2018)

DM coupling/mass excluded in shaded regions

Improved measurement resolution



Better Constraints

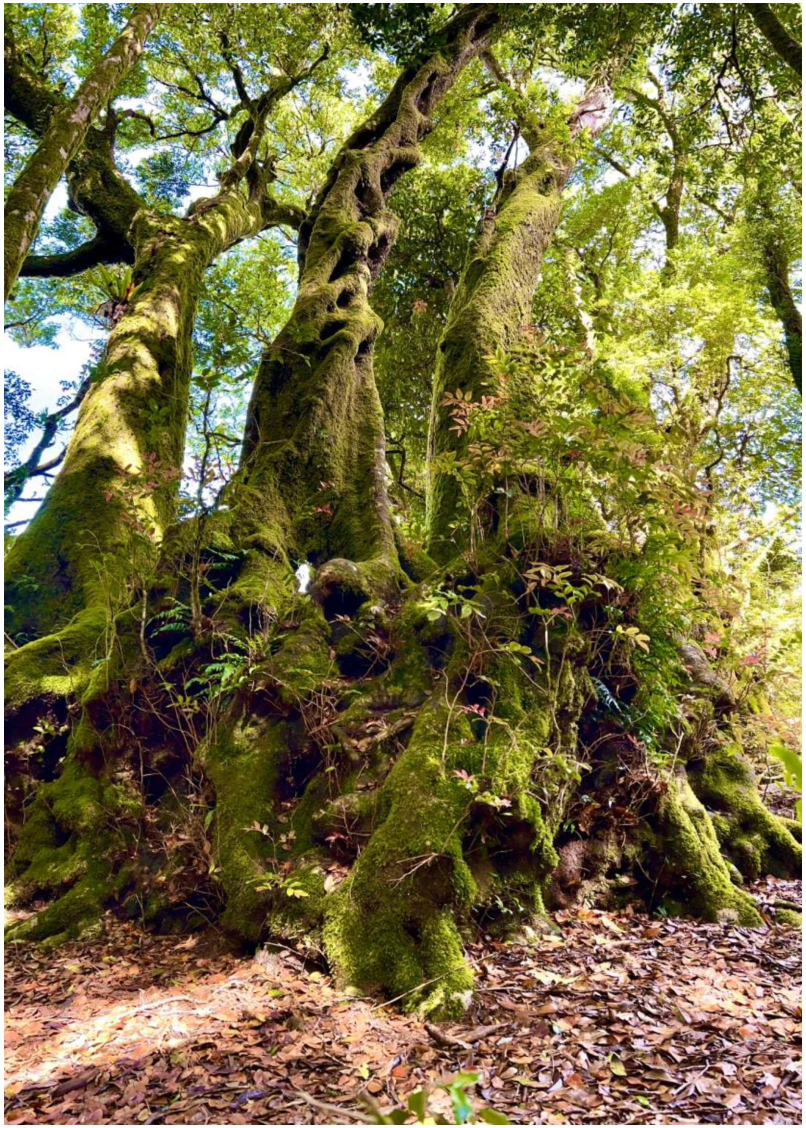
- Higher α sensitivity
- Higher stability

Longer time interval

Quick aside.....

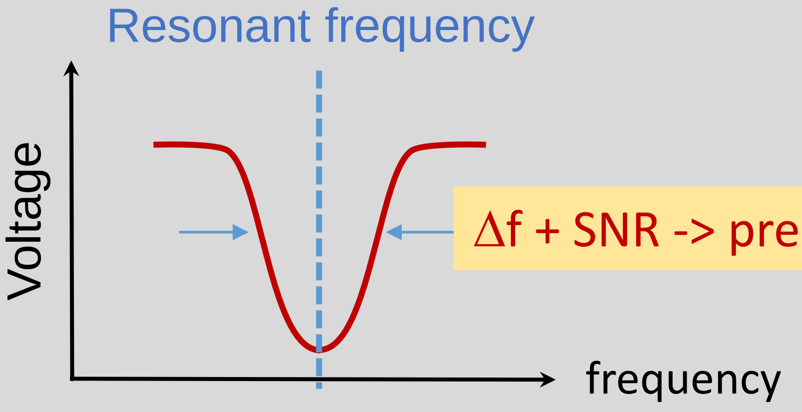
Enthusiastic scientist at Currumbin Wildlife Sanctuary

Best tree(s) ever!....... Antarctic beech trees in Springbrook National Park



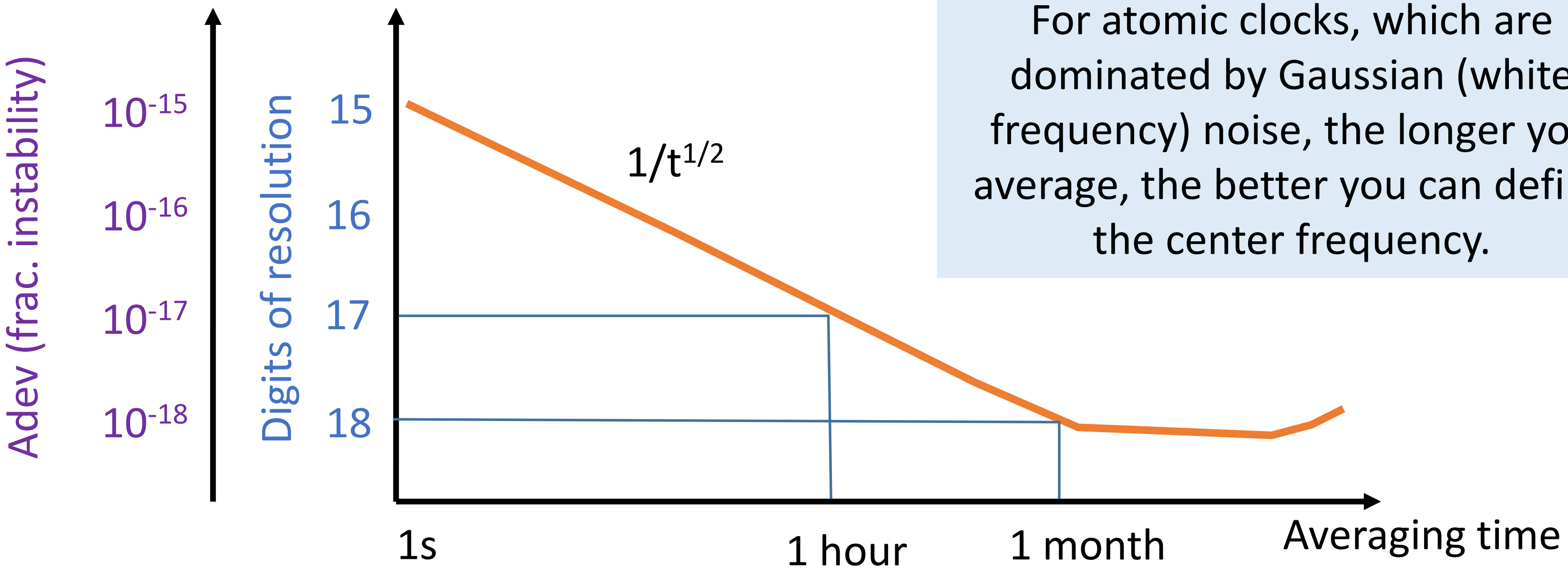
Stability vs accuracy in clocks

Accurate and precise!



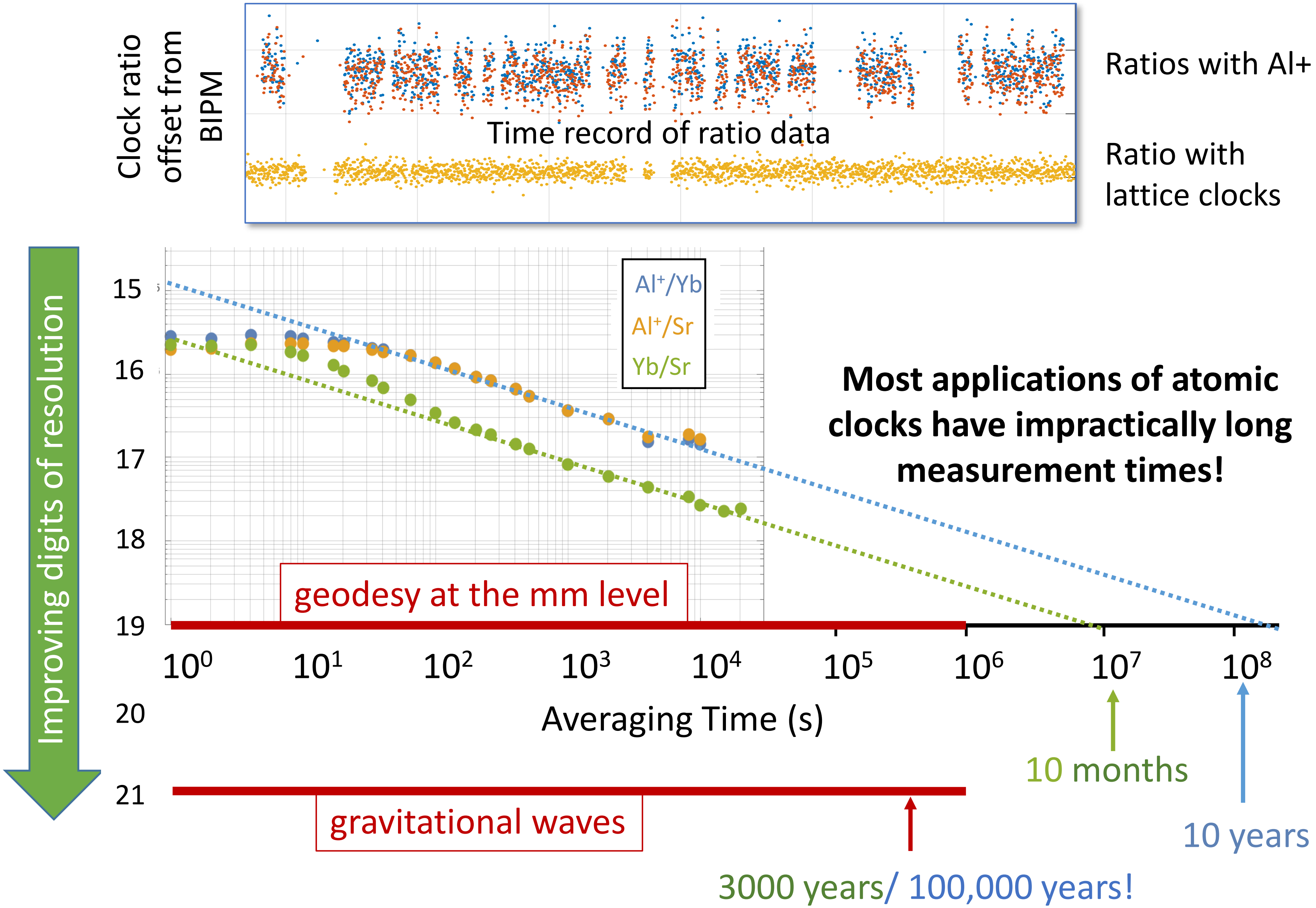
Δf + SNR -> precision

Δf_c -> accuracy



For atomic clocks, which are dominated by Gaussian (white frequency) noise, the longer you average, the better you can define the center frequency.

Clock stability impact on applications

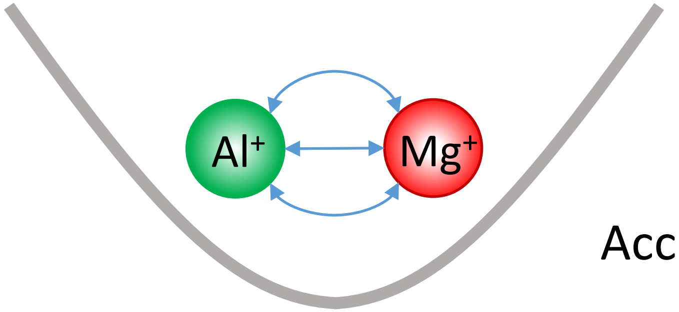


Most applications of atomic clocks have impractically long measurement times!

NIST Boulder Atomic Clocks

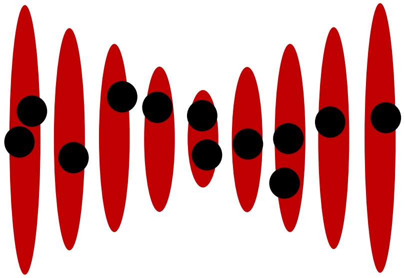
^{27}Al+ quantum logic clock

S. Brewer et al. PRL ***123*** *(2019)*



^{171}Yb & ^{87}Sr lattice clocks

W. McGrew et. al. Nature ***564*** *(2018)*
T. Bothwell et al Metrologia ***56*** *(2019)*



Accuracies ~ 10^{-18}

ν_o = 1.12 PHz
N = 1
$\sigma = 1.5 \times 10^{-15}\ \tau^{-1/2}$
T_p = 150 ms

ν_o = 0.518 PHz
$N \sim 10^4$
$\sigma = 2\text{-}3 \times 10^{-16}\ \tau^{-1/2}$
T_p = 500 ms

$$\text{Stability} = 1/\sigma \propto \upsilon_0\sqrt{N T_p \tau}$$

Averaging time

Atomic probe time

Transition frequency

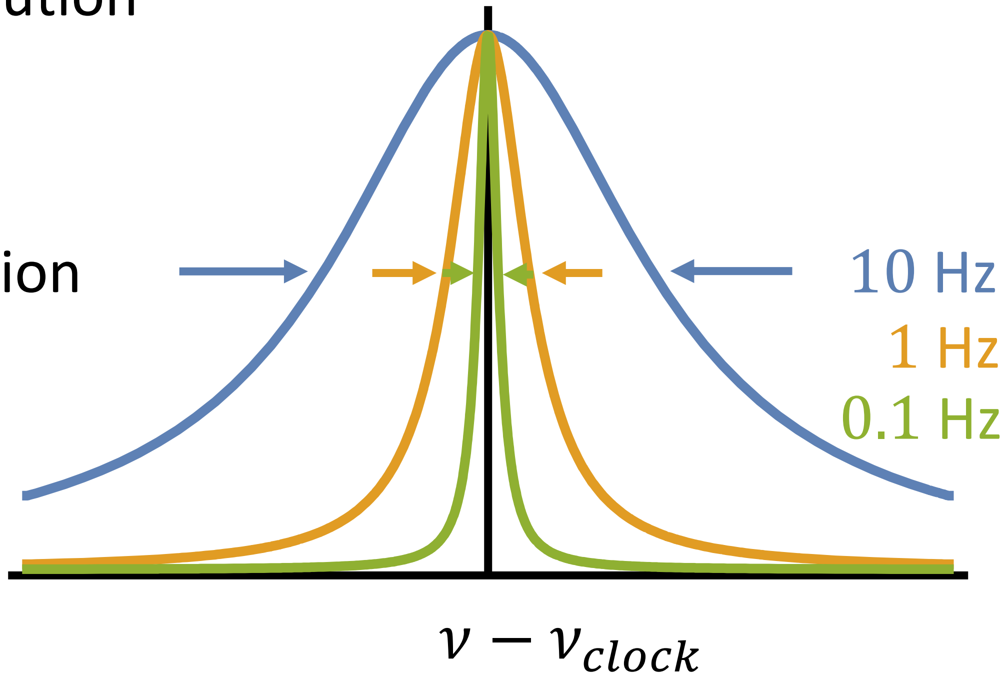
 # Atoms

Probe time and frequency resolution

longer probe, T_p (free evolution time)

➔ better frequency resolution

Resolvable clock transition



Stability = 1/σ ∝ $\upsilon_0\sqrt{N T_p \tau}$

Averaging time

Atomic probe time

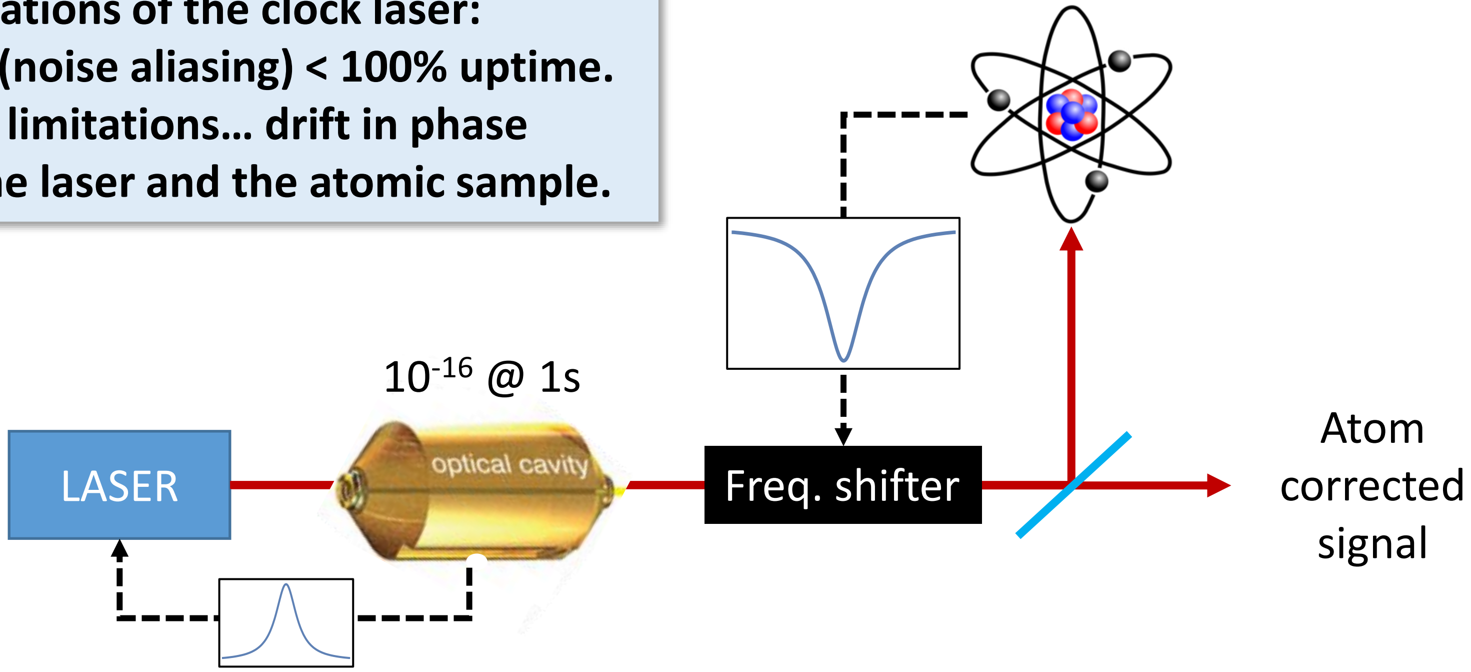
Transition frequency

 # Atoms

Atomic clocks and laser atom decoherence

Technical limitations of the clock laser:

- **Dick effect (noise aliasing) < 100% uptime.**
- **Probe time limitations… drift in phase between the laser and the atomic sample.**



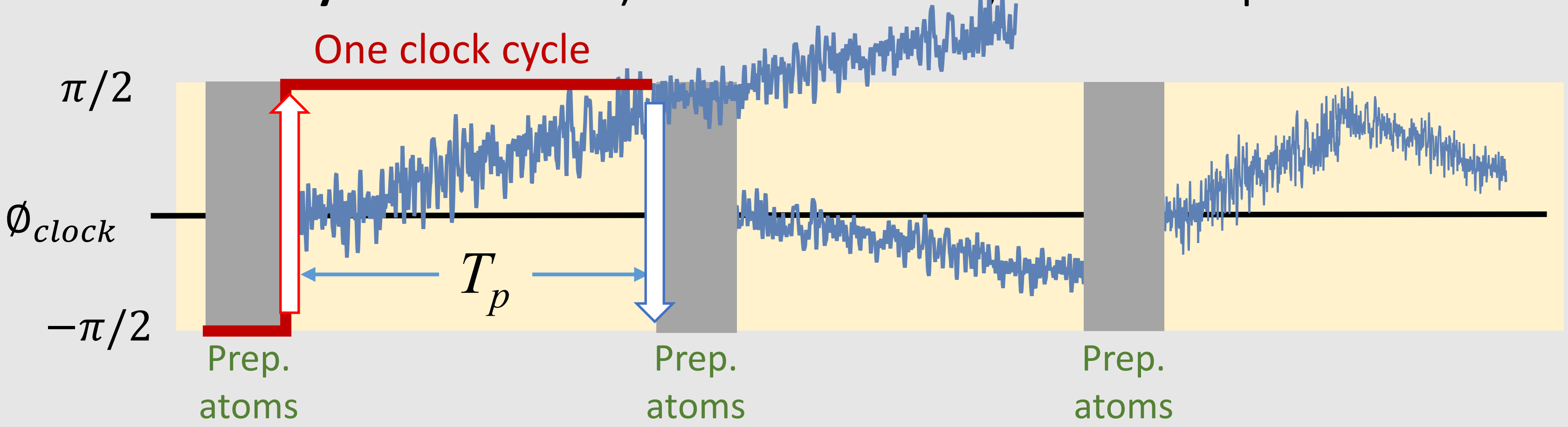
10^{-16} @ 1s

LASER

Freq. shifter

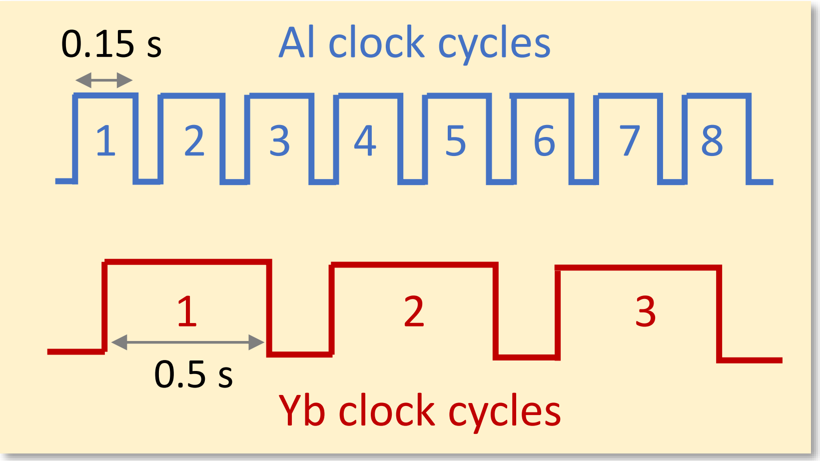
Atom
corrected
signal

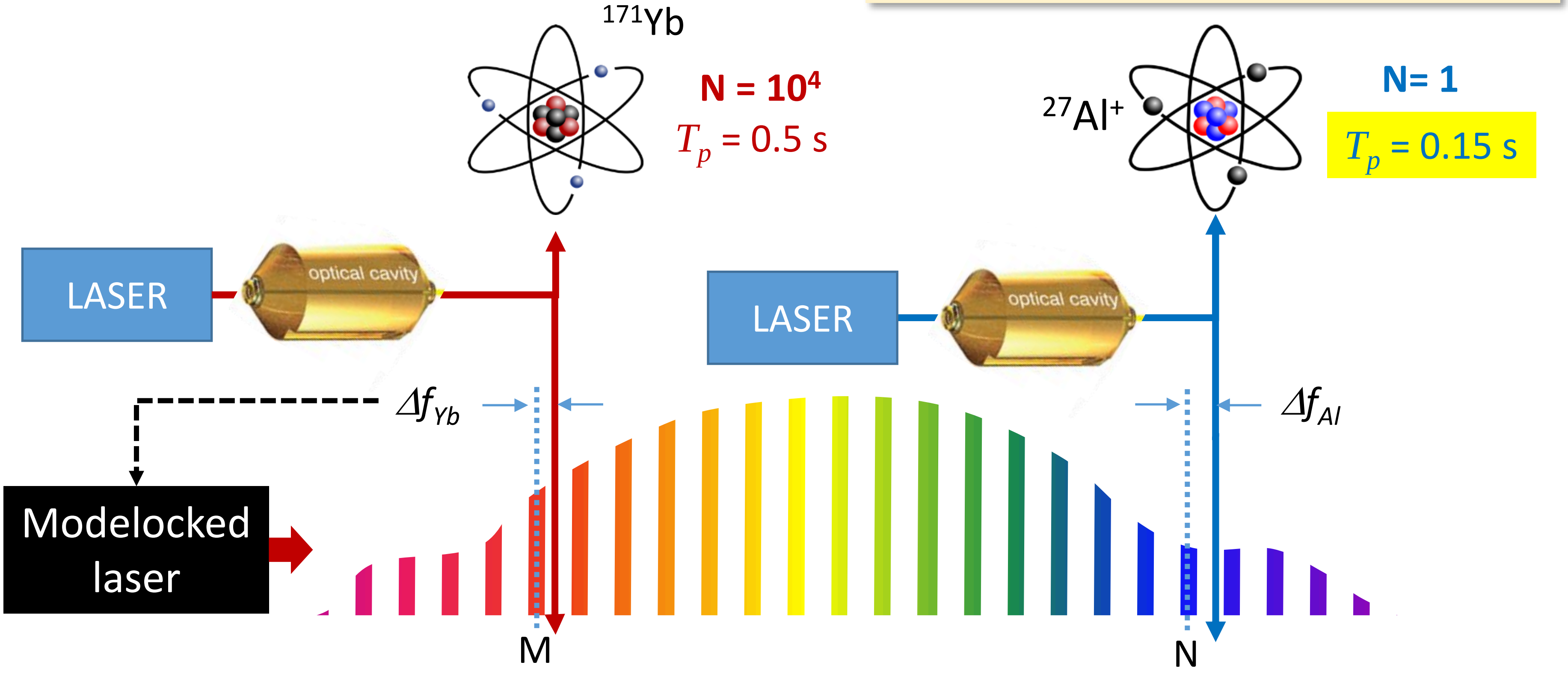
Clock stability limitations: 1) laser noise and 2) atom-laser phase drift



Traditional clock comparison

Atom stabilized light from each clock is sent to the frequency comb….
clocks are operated independently and asynchronously.

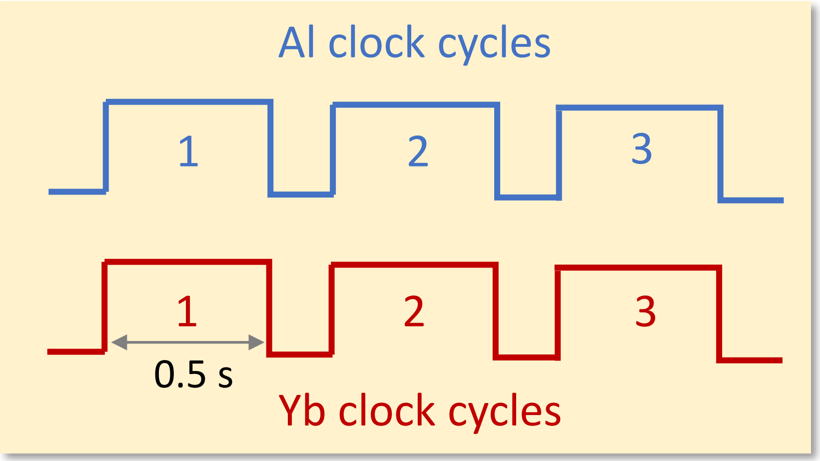




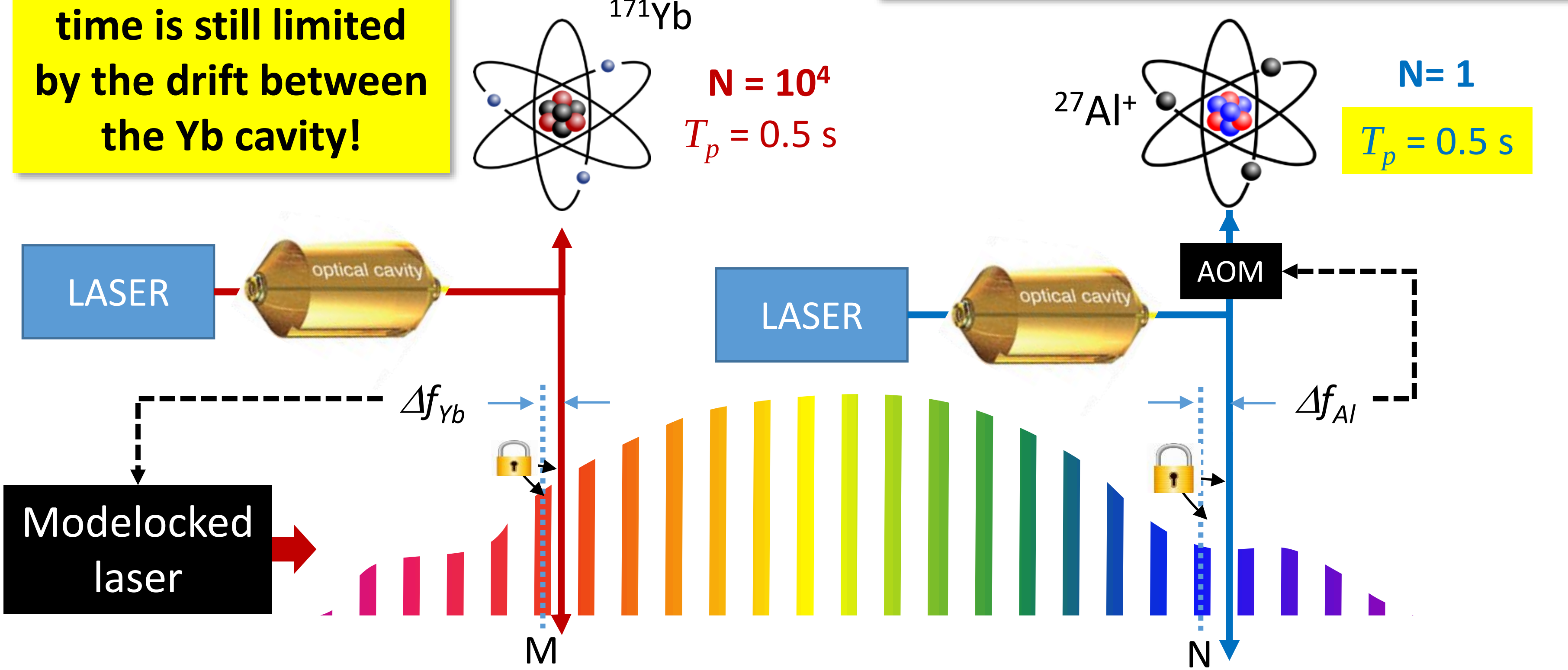
Differential Spectroscopy

1) The comb is stabilized to the Yb clock
2) Al+ laser is locked to the com
3) Clocks are operated synchronously

Al and Yb clocks share phase information and are synchronous.



But… the Al+ probe time is still limited by the drift between the Yb cavity!

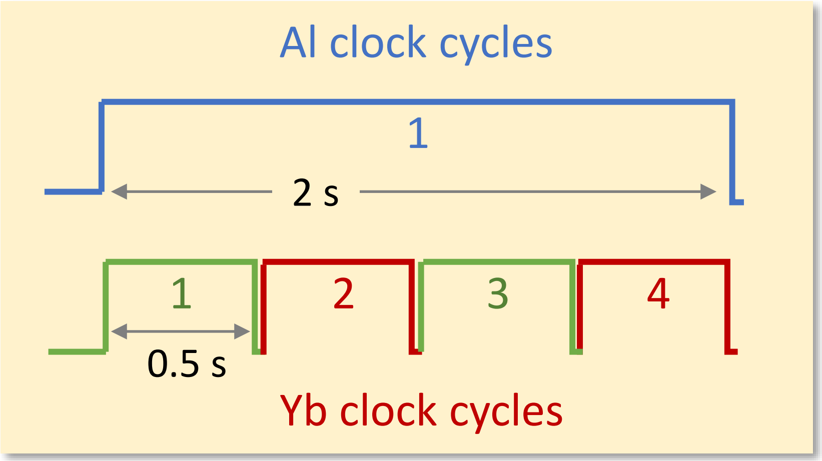


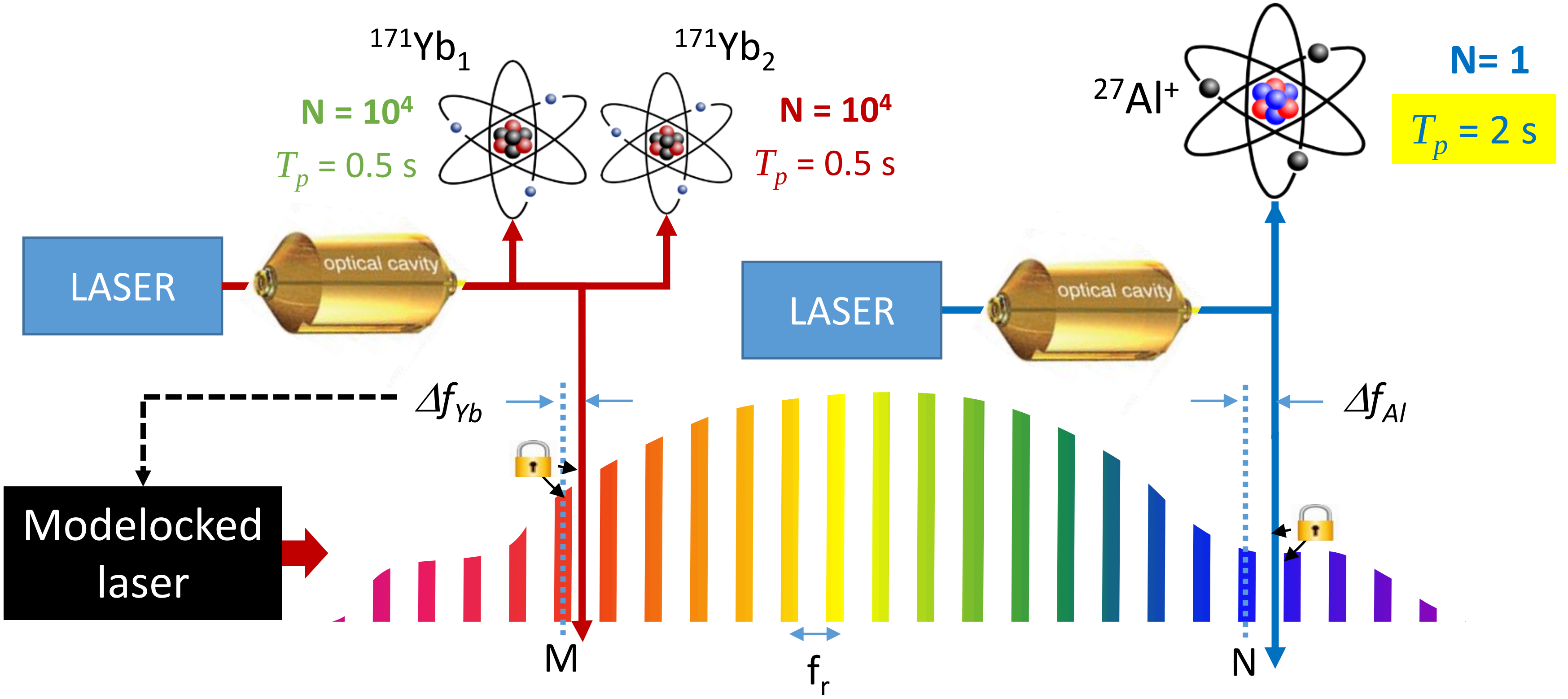
D. Hume and D. Leibrandt, Phys. Rev. A, 93, 032138 (2016)

Zero-Dead Time Differential Spectroscopy

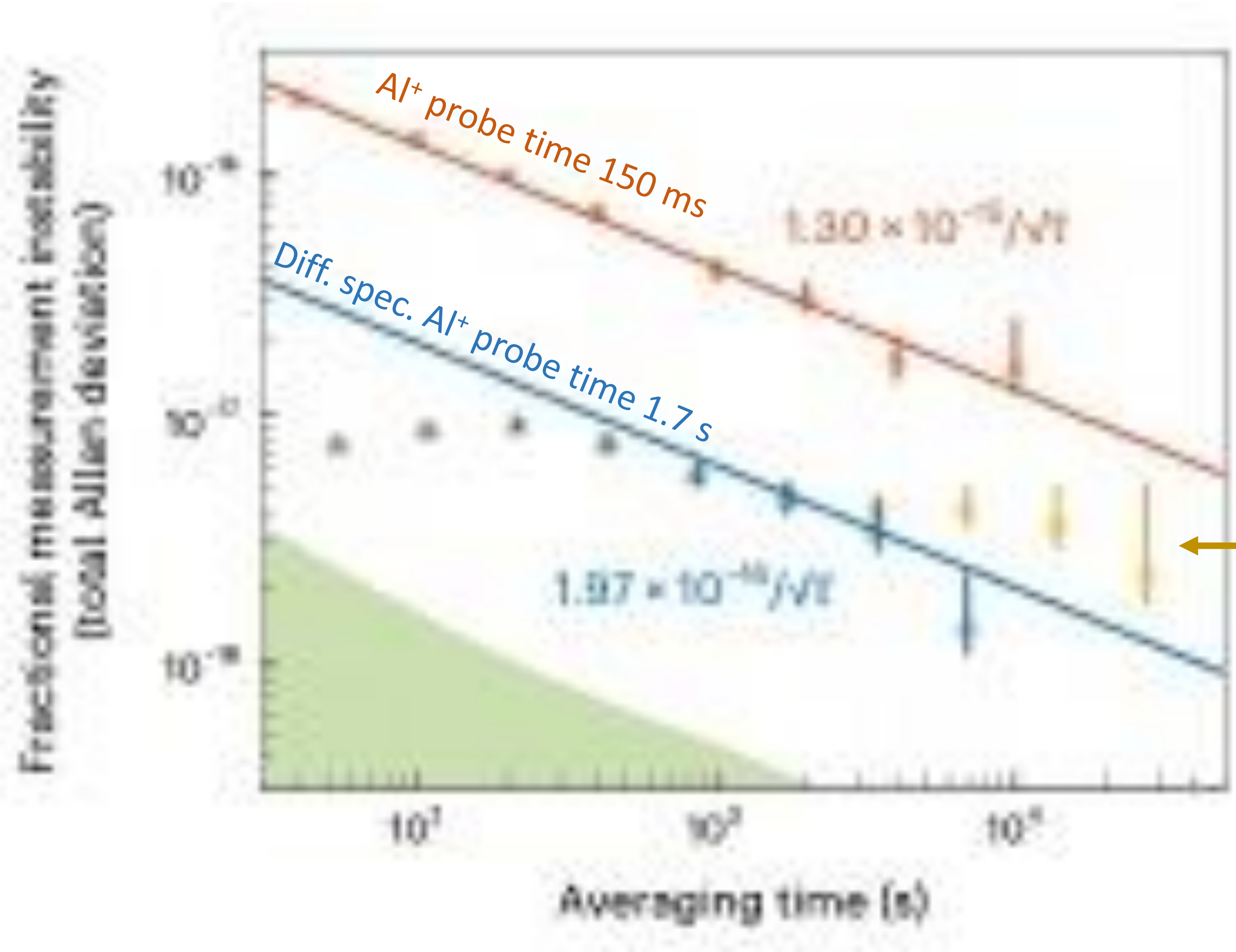
1) The comb is stabilized to interleaved Yb clocks
2) Al+ laser is locked to the comb
3) The Al clock is probed synchronously over multiple Yb/Yb clock cycles.

We can extend the Al probe time to multiple seconds!



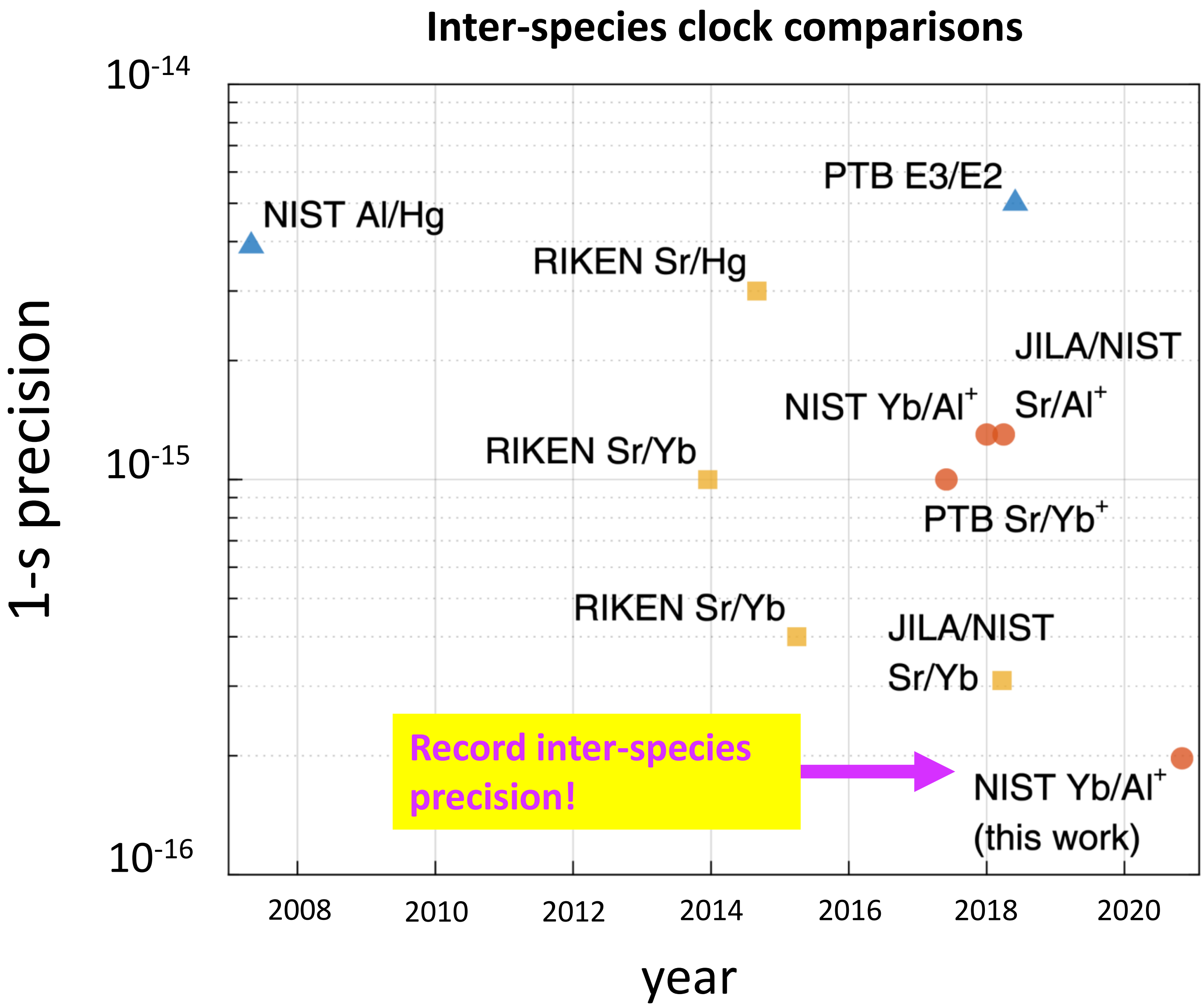


Improved clock measurement resolution



Clocks were not run in high accuracy mode.

Comparison with previous results

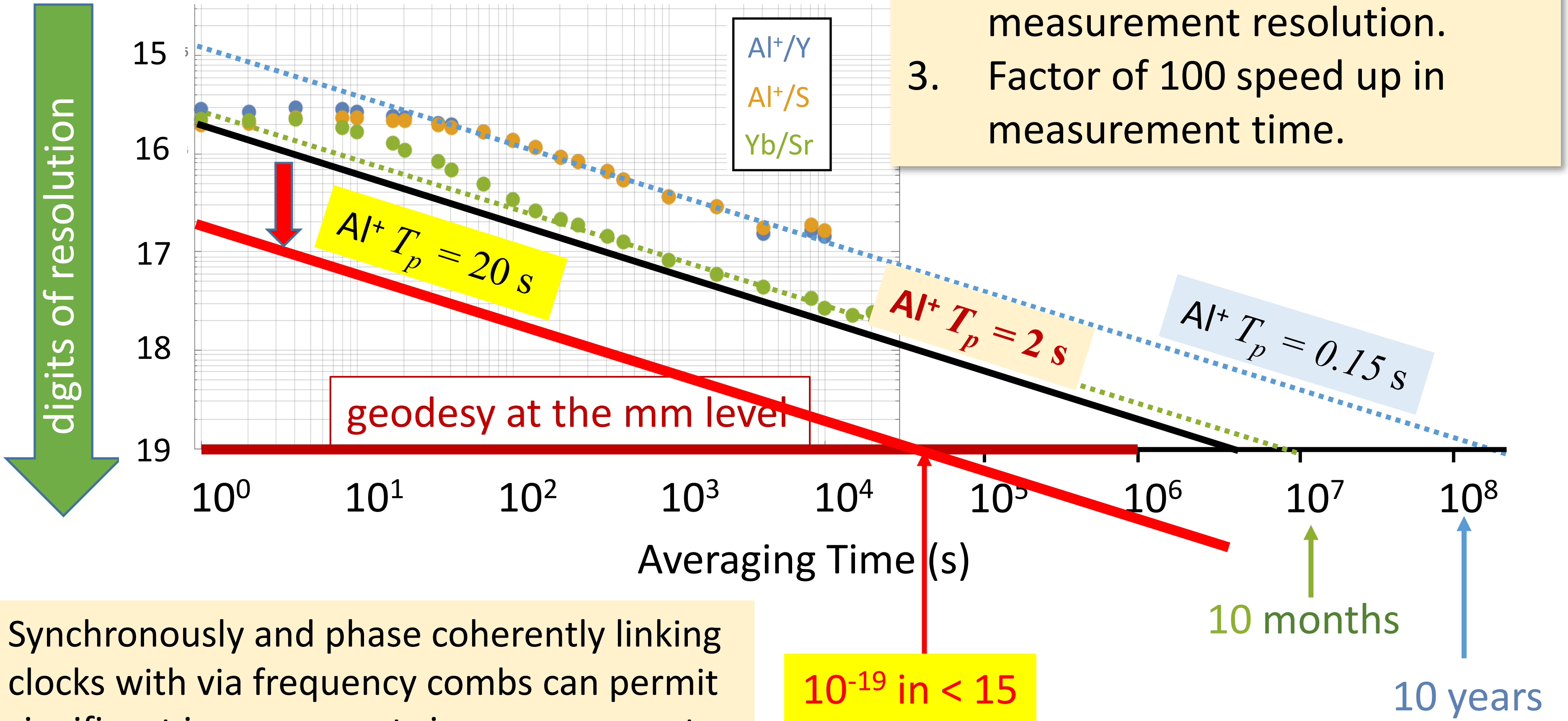


Record inter-species precision!

What does this have to do with time?

Improved clock measurement resolution

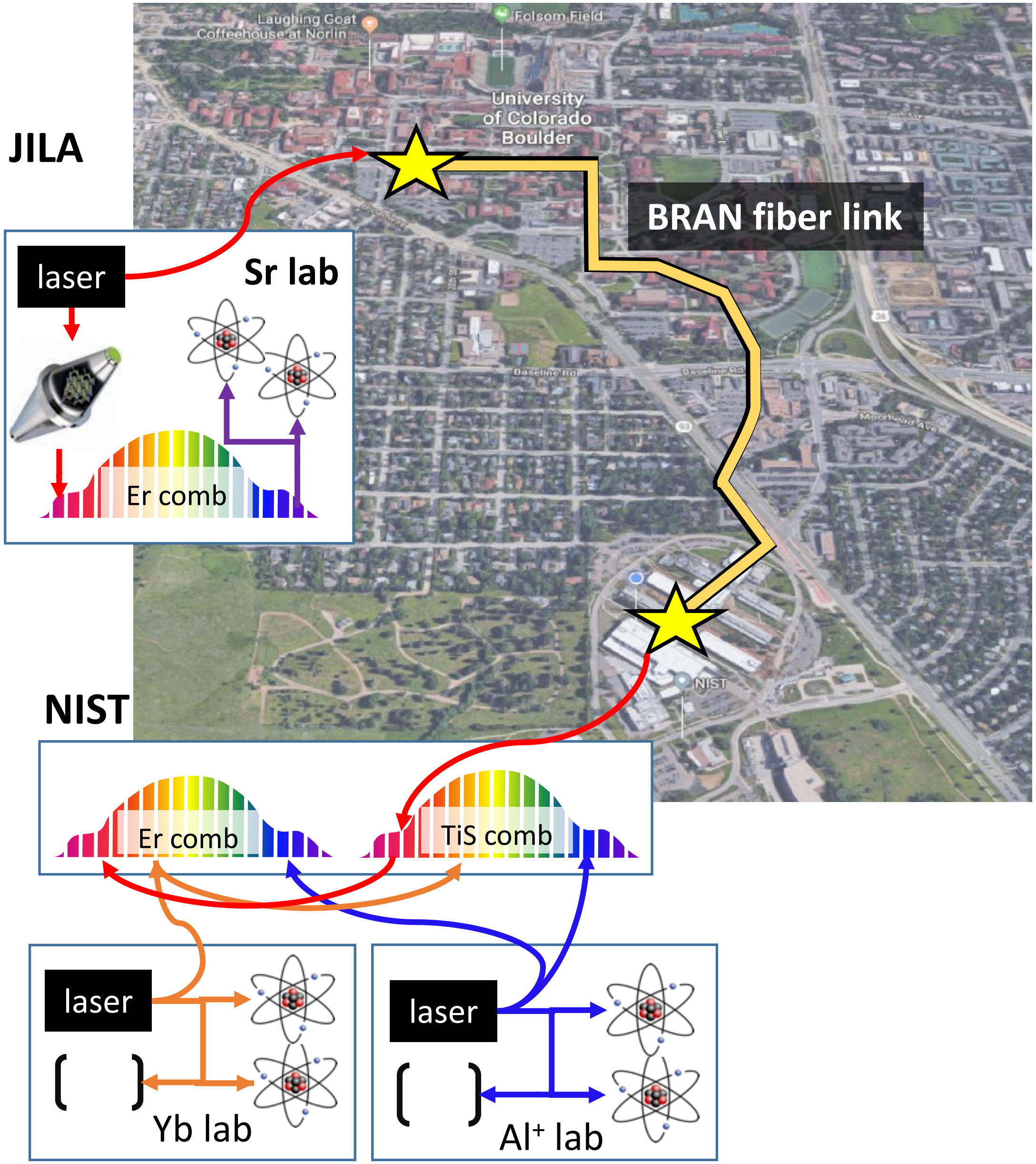
1. Highest measurement for any interspecies clock comparison
2. Factor of 10 improvement in measurement resolution.
3. Factor of 100 speed up in measurement time.



10^{-19} in < 15 hours!

Synchronously and phase coherently linking clocks with via frequency combs can permit significant improvements in measurement resolution… bringing next generation applications closer to reality.

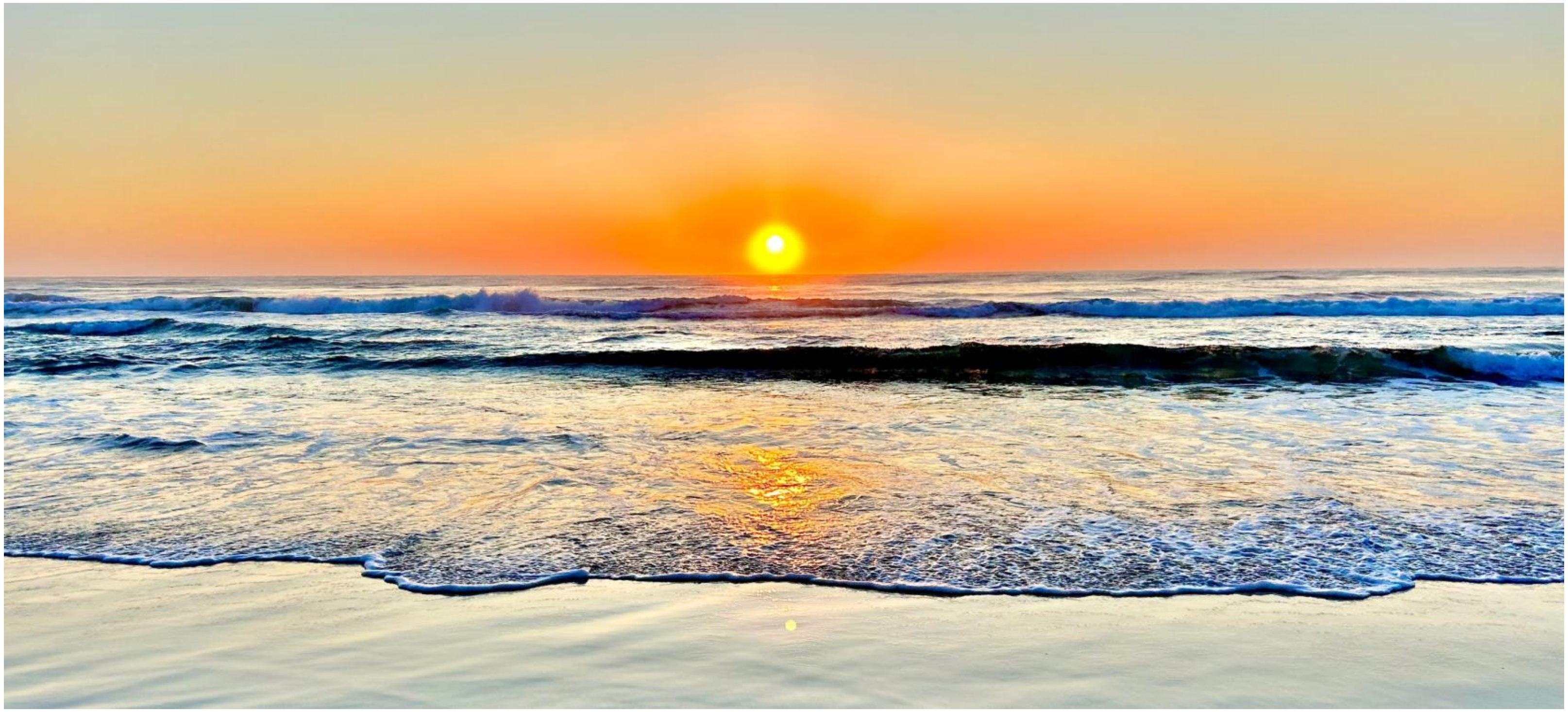
Boulder Atomic Clock Optical Network 2.0 (2024...?)



Distribute the Sr clock LO (Si cavity) to the Al and Yb clocks:

- ➢ Probe all 3 clocks synchronously
- reduce measurement induced laser noise and
- improve the QPN of the Al and Yb clocks, whose probe time is limited by atom-laser decoherence.

Boulder Atomic Clock Network Collaboration



Al Ion Clock
May Kim
Ethan Clements
David Hume
Sam Brewer
Jwo-Sy Chen
David Leibrandt

Yb Lattice Clock
Xiaogang Zhang
Will McGrew
Robbie Fasano
Stefan Schäffer
Daniele Nicolodi
Kyle Beloy
Andrew Ludlow

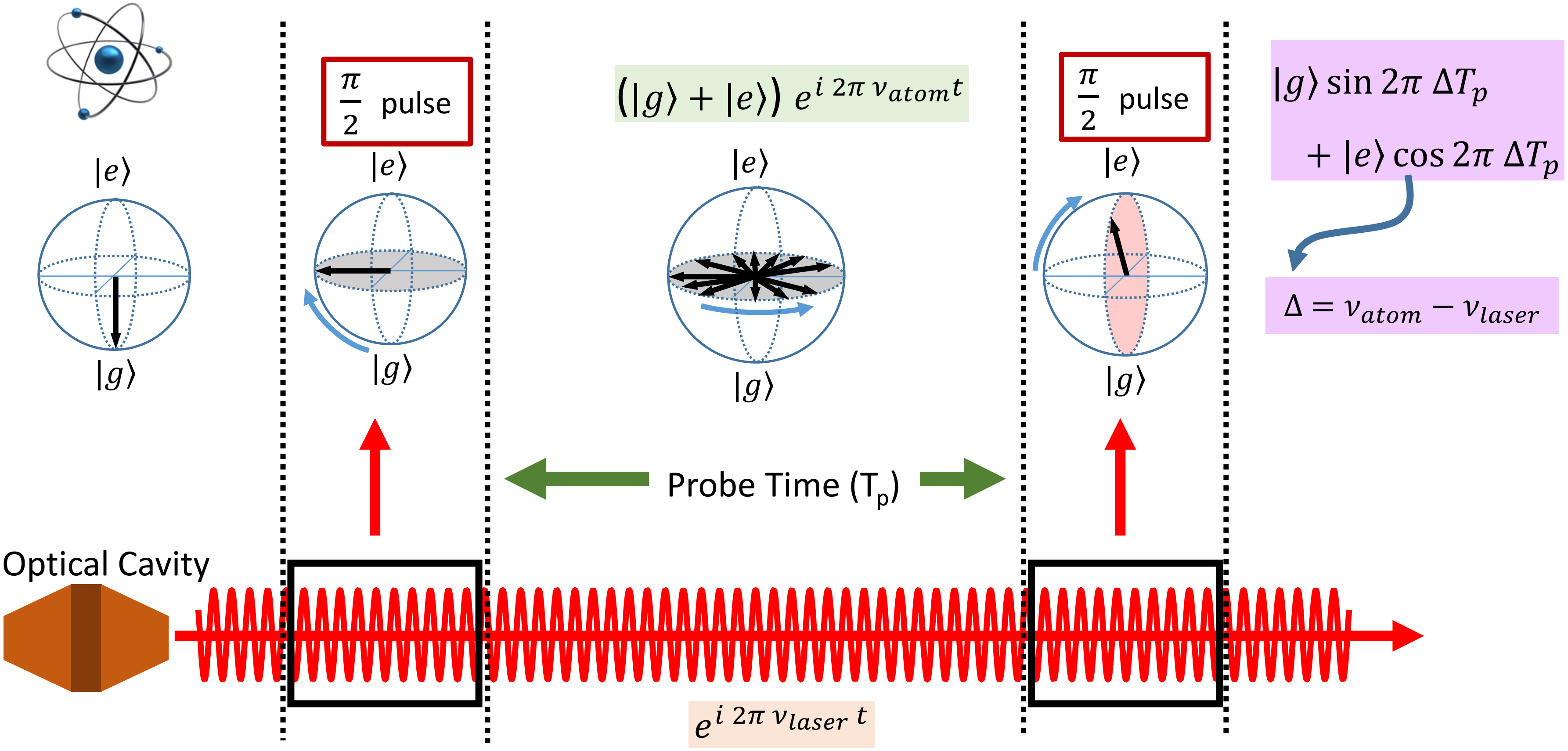
Sr Lattice Clock
Dhruv Kedar
Colin Kennedy
Toby Bothwell
John Robinson
Eric Oelker
Sarah Bromley
Jun Ye

Optical Frequency Measurement Group
Scott Diddams
Holly Leopardi
Nick Nardelli
Tara Fortier

Free-Space Time Transfer
Martha Bodine
Issac Khader
Laura Sinclair
JD Deschenes
Nate Newbury

FIN

Ramsey Spectroscopy



$|e\rangle$

$|g\rangle$

$\frac{\pi}{2}$ pulse

$|e\rangle$

$|g\rangle$

$(|g\rangle + |e\rangle)\; e^{i\,2\pi\,\nu_{atom} t}$

$|e\rangle$

$|g\rangle$

$\frac{\pi}{2}$ pulse

$|e\rangle$

$|g\rangle$

$|g\rangle \sin 2\pi\;\Delta T_p$

$+\;|e\rangle \cos 2\pi\;\Delta T_p$

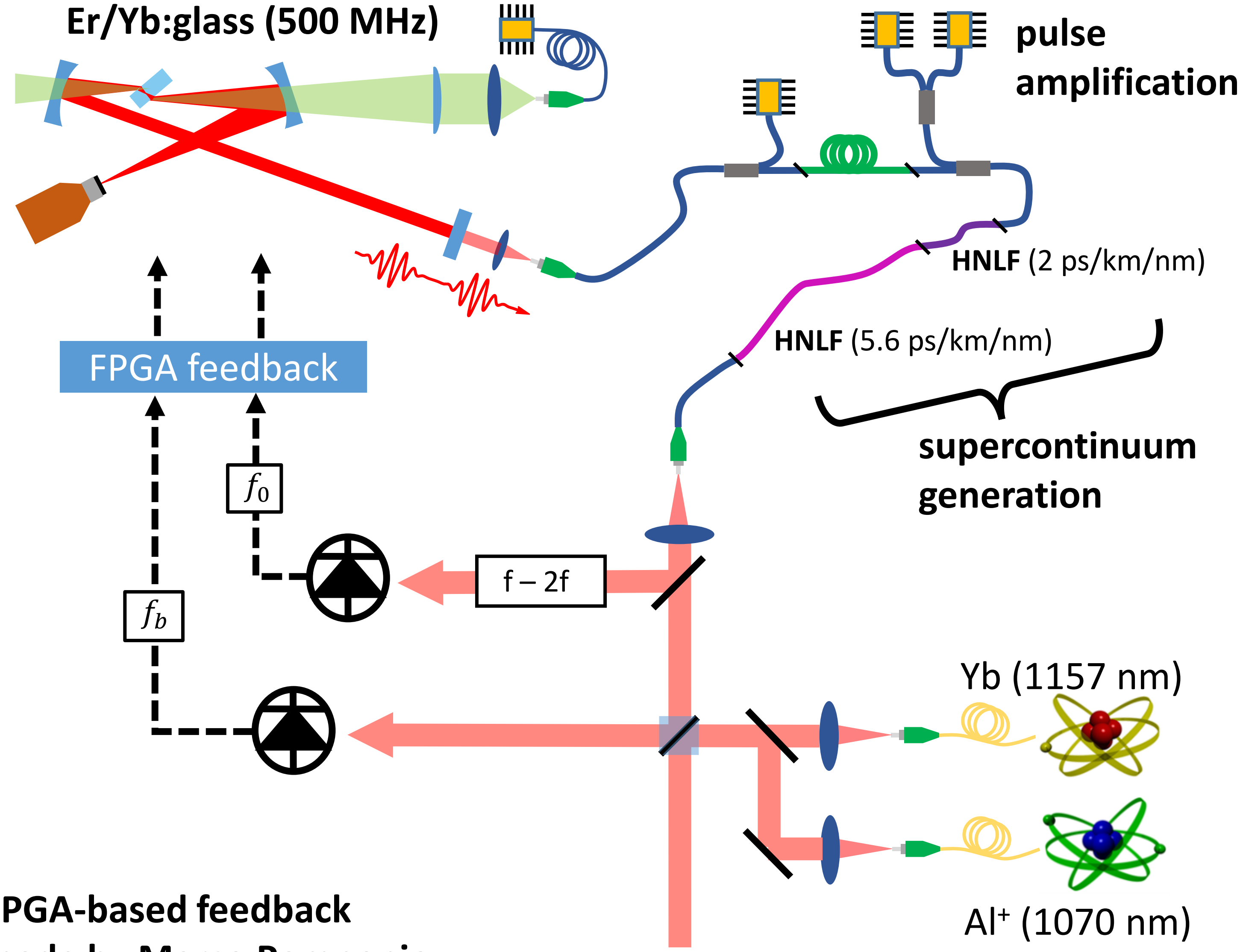
$\Delta = \nu_{atom} - \nu_{laser}$

Probe Time (T_p)

Optical Cavity

$e^{i\,2\pi\,\nu_{laser}\,t}$

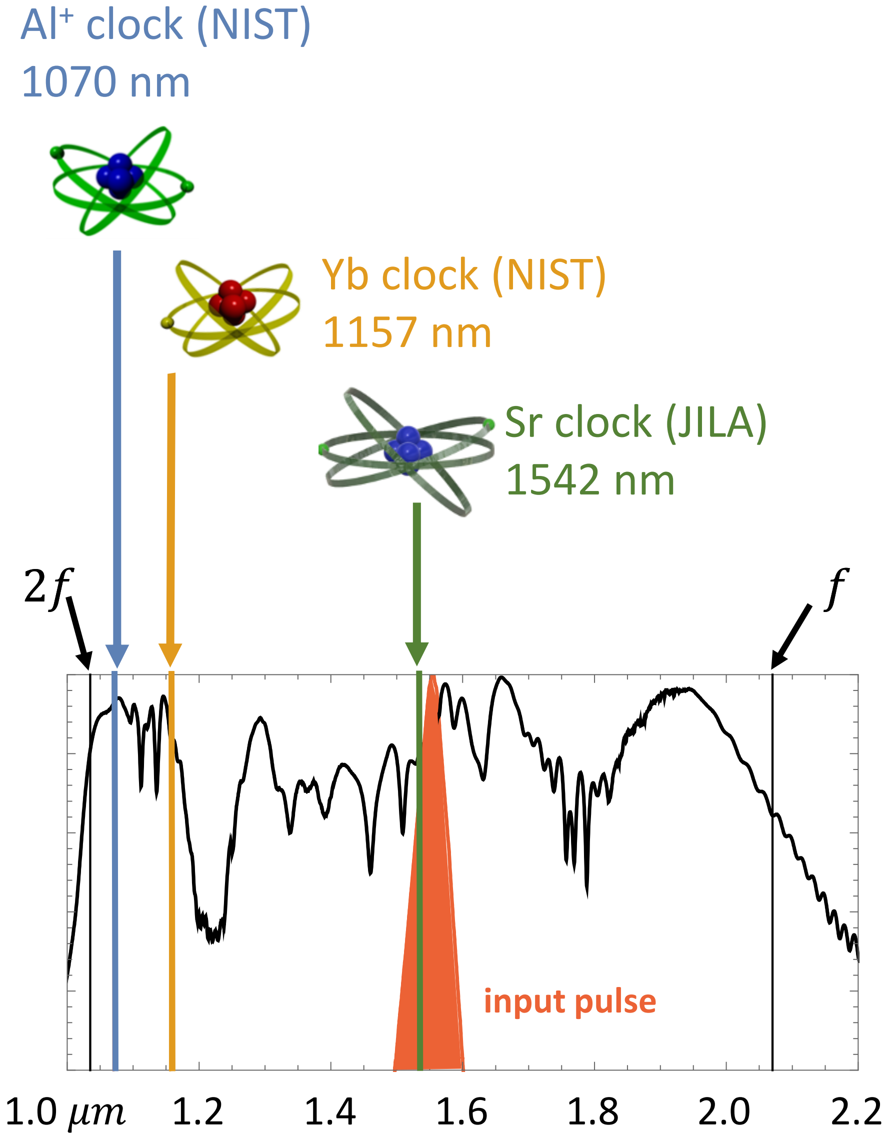
The Er/Yb:glass Frequency Comb



FPGA-based feedback made by Marco Pomponio

The Er/Yb:glass Frequency Comb

N. V. Nardelli et al., ***Optical and microwave metrology at the 10^{-18} level with an Er/Yb:glass frequency comb***, *Laser & Photonics Reviews (2023).*



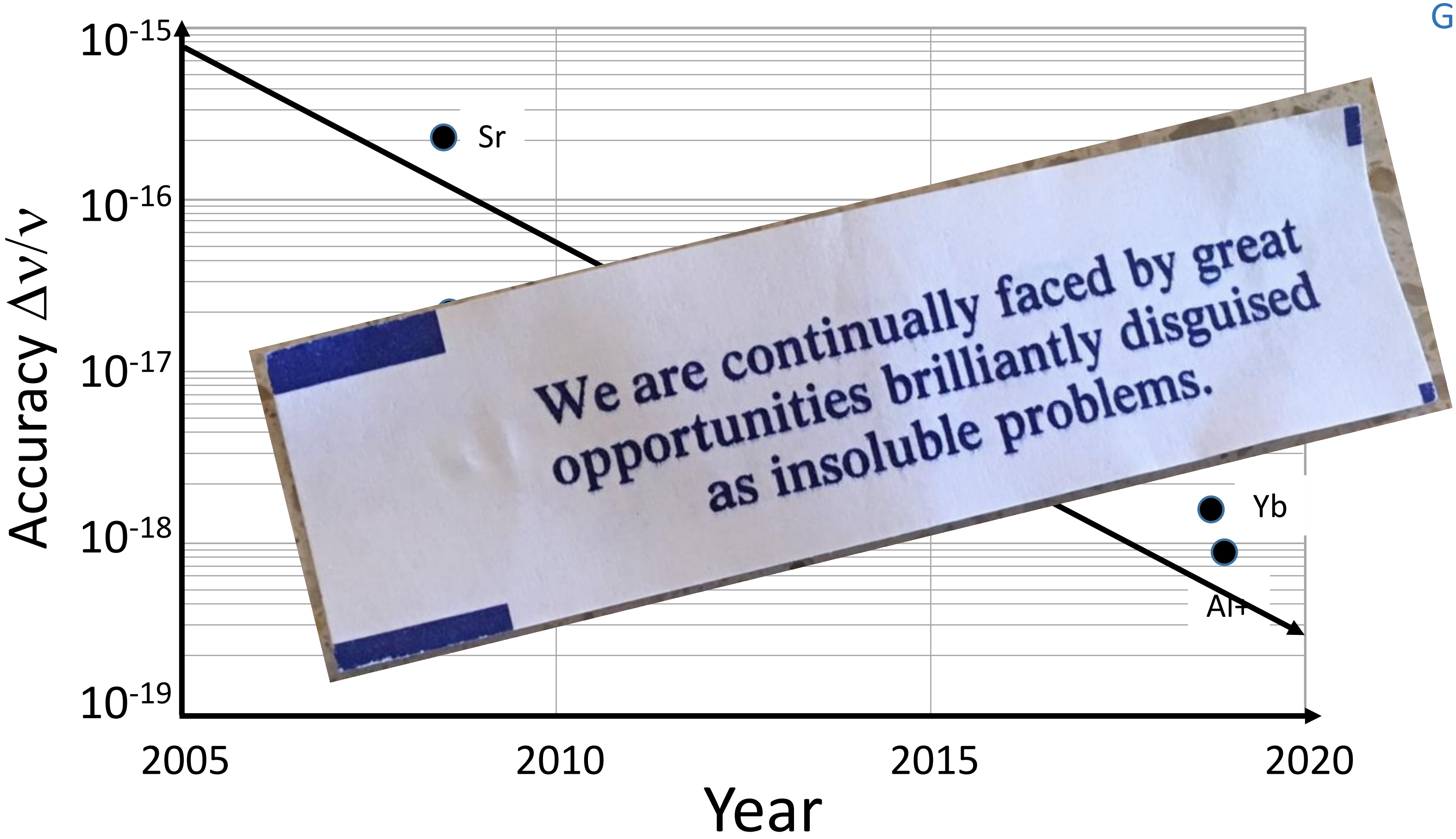
Al^+ clock (NIST)
1070 nm

Yb clock (NIST)
1157 nm

Sr clock (JILA)
1542 nm

Comparison against previous results

Clocks will be competitive with LIGO : 10^{-21}



We are continually faced by great opportunities brilliantly disguised as insoluble problems.

Relativistic Sensitivity

Gravitational
redshift
m^2/s^2
(altitude)

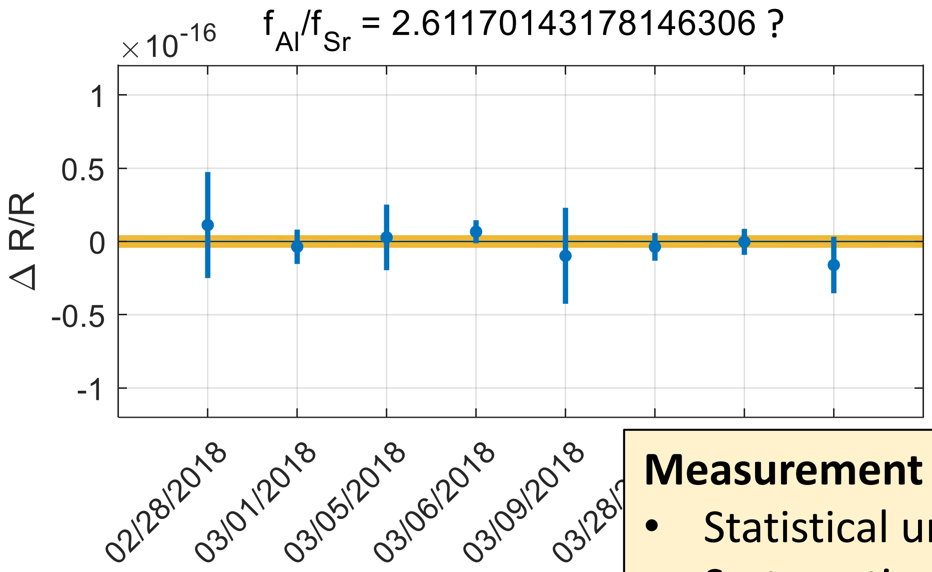
10 cm

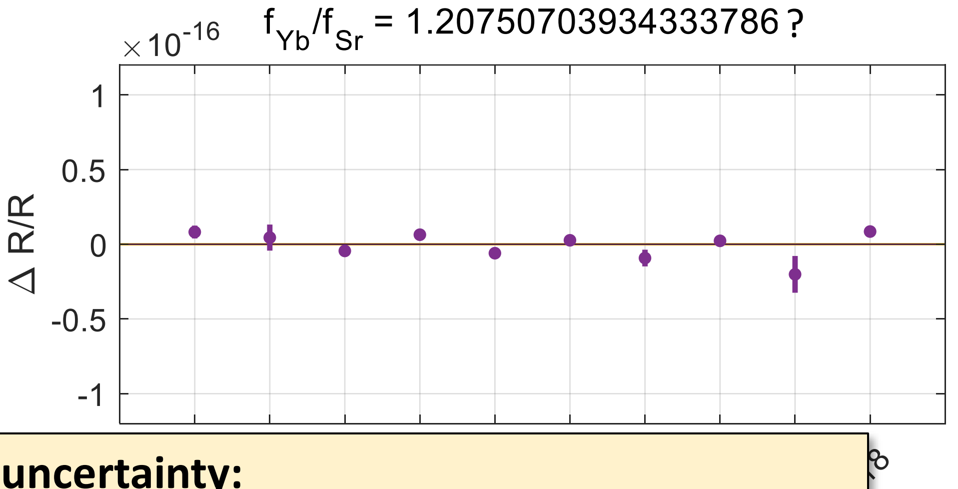
1cm

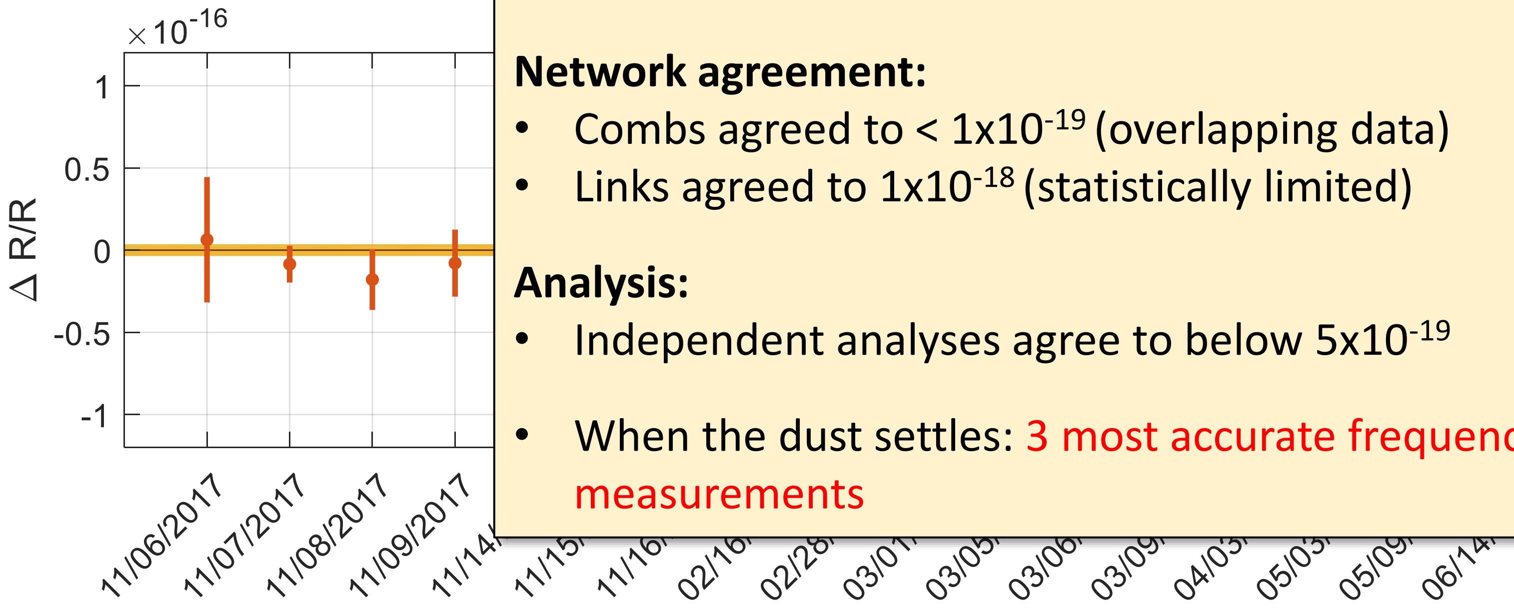
1 mm

Comparisons at 10^{-19} will require knowledge of a relative height difference at the mm-level!

Ratios Day by Day


f_{Al}/f_{Sr} = 2.61170143178146306 ?


f_{Yb}/f_{Sr} = 1.20750703934333786 ?



Measurement uncertainty:

- Statistical uncertainties averaged below 5×10^{-18}
- Systematic uncertainties evaluated below 5×10^{-18}

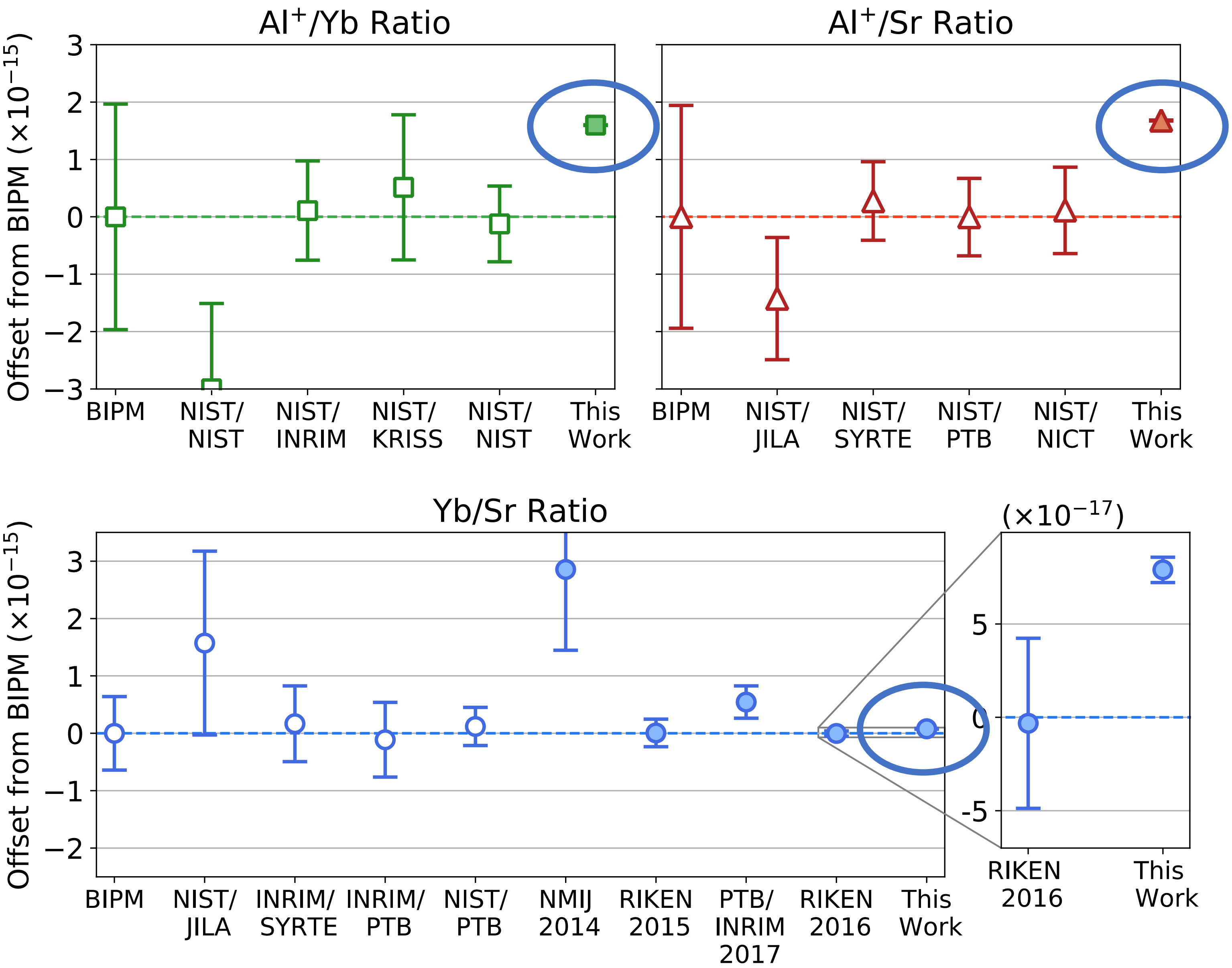
Network agreement:

- Combs agreed to < 1×10^{-19} (overlapping data)
- Links agreed to 1×10^{-18} (statistically limited)

Analysis:

- Independent analyses agree to below 5×10^{-19}
- When the dust settles: 3 most accurate frequency ratio measurements

Comparison with previous results

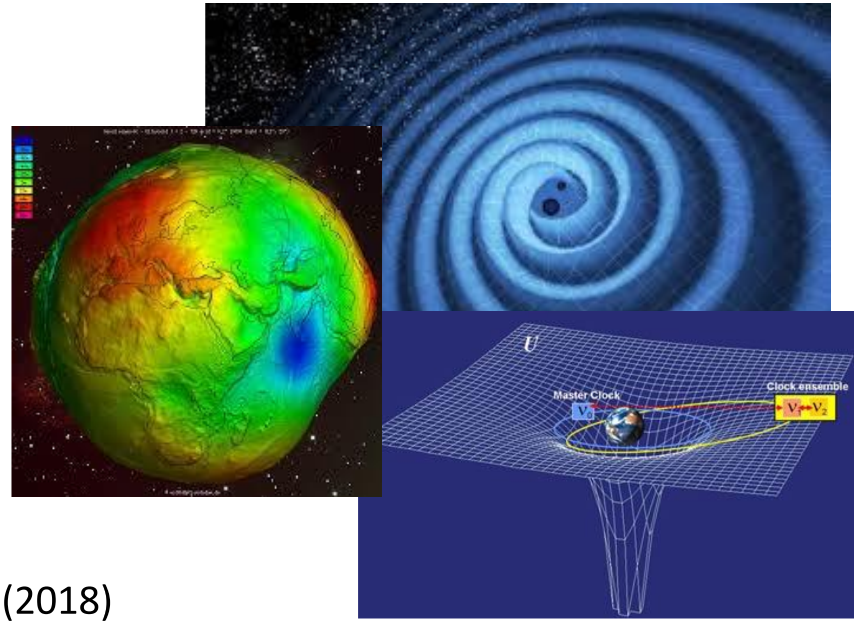


Clocks as Sensors!

Atomic clock transitions are sensitive to relativistic time-dilation shifts:

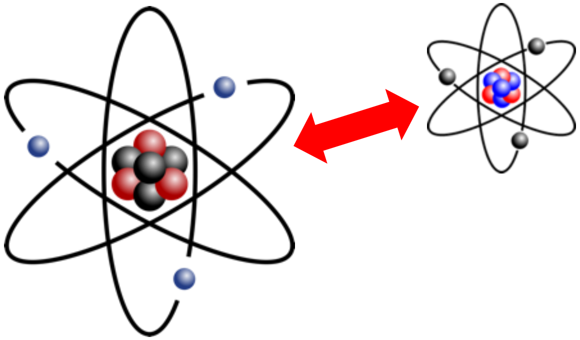
- Relativistic geodesy
- gravitational wave detection
- Violation of LPI

J. Grotti et al. Nature (2018)
*N. Ashby Nat. Physics **14** (2018)*
*P. Delva PRL **118** (2017),*



Review: T. Mehlstäubler, Reports on Scientific Progress (2018)

An extremely fine tool for probing the laws of Physics



Atomic transitions are defined by fundamental constants (m_e, m_p, α)

- Time variation of fundamental constants

  T.Rosenband et al. Science 2008
  N. Huntemann et al PRL (2014)
  R. M. Godun et al PRL (2014)

- Searches for dark matter

Clocks and tests of fundamental physics

One theory of dark matter (DM) suggests that our galaxy is pervaded by a DM halo composed of Bosonic, ultralight particles.

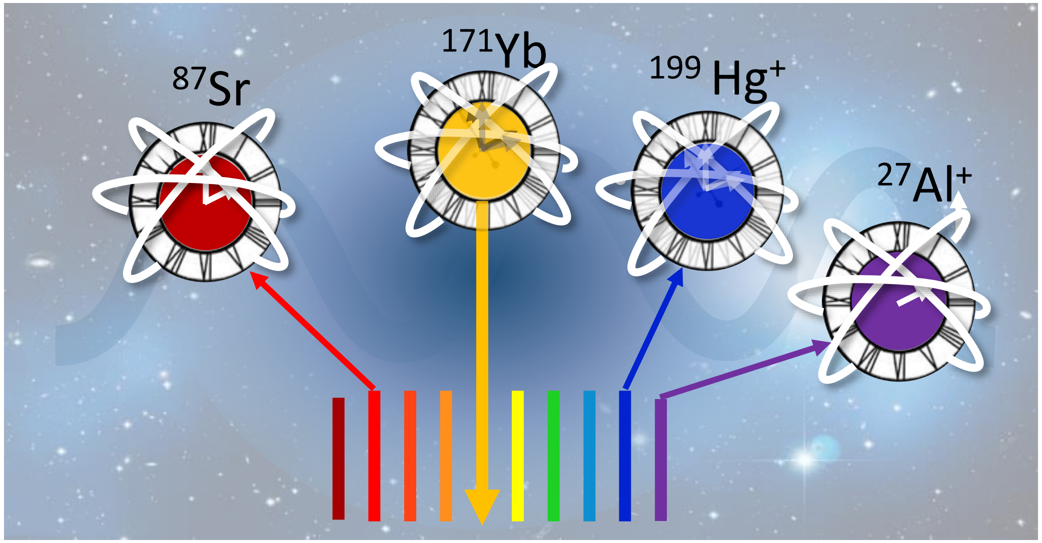
DM is predicted to couple transitions will couple to a DM field via α–fine structure constant

Coupling will result in a periodic time-variation in α,

$$\alpha(t) \propto \frac{d_e^{*} \cos(\omega_{DM}\, t)}{\omega_{DM}}$$

DM coupling strength

Compton frequency ∝ DM mass



Atomic Clock	Resolution $\times 10^{-18}$	Accuracy $\times 10^{-18}$	α– Sensitivity
^{171}Yb	1	1	+0.06
^{87}Sr	1	1	+0.31
^{199}Hg$^+$	40	30	-3.0
^{27}Al$^+$	4	1	+0.0079

A. Arvanataki et al.,Phys. Rev. D **91**, 015015 (2015)
Y. V. Stadnik and V. V. Flambaum, Phys. Rev. Lett. **115**, 201301 (2015)
A. Derevianko and M. Pospelov., Nature Phys. **10**, 933 (2014)
Y. V. Stadnik and V. V. Flambaum, PRA **93**, 063630 (2016)

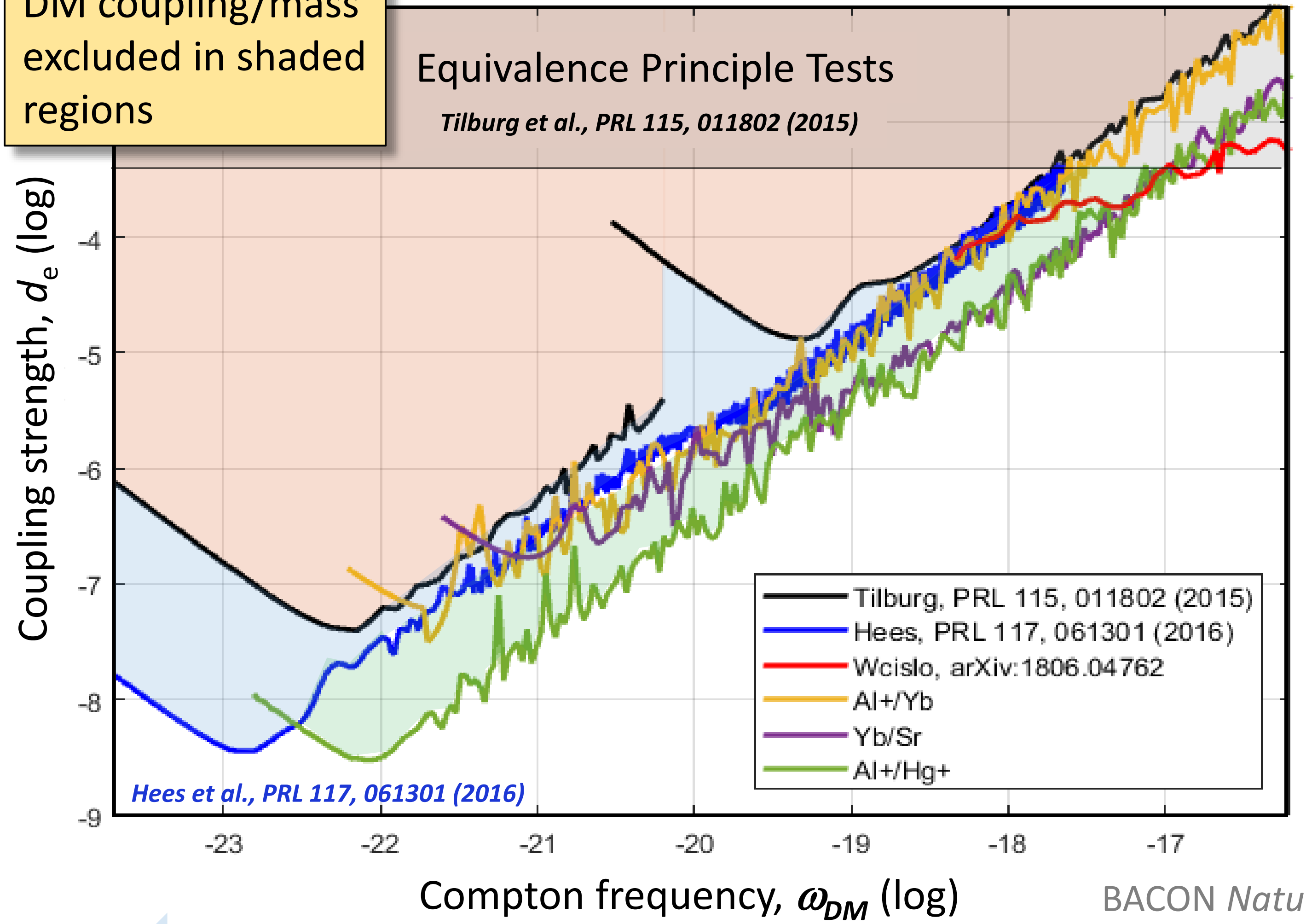
Exclusion plot for dark matter coupling

Improve coupling constraint over 6 decades in DM mass.

*Hees et al PRD **98** (2018)*

DM coupling/mass excluded in shaded regions

Decreasing DM Coupling



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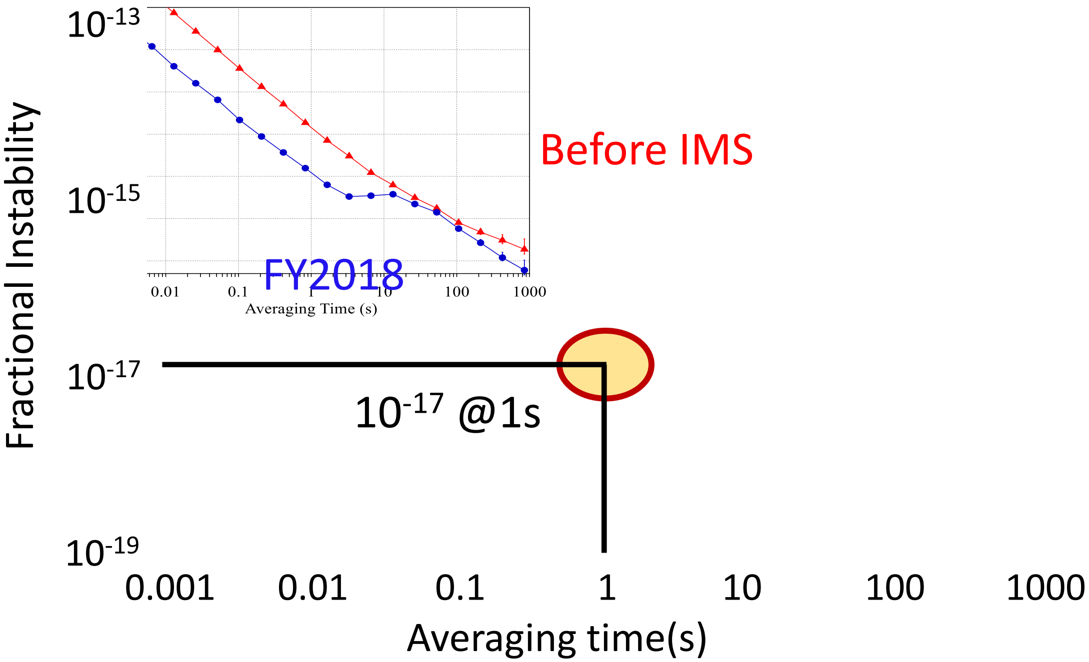
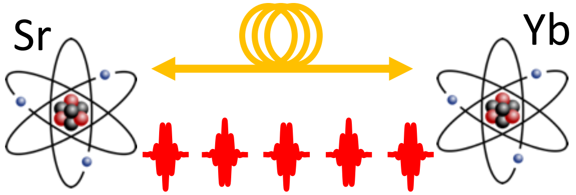
Decreasing DM Mass

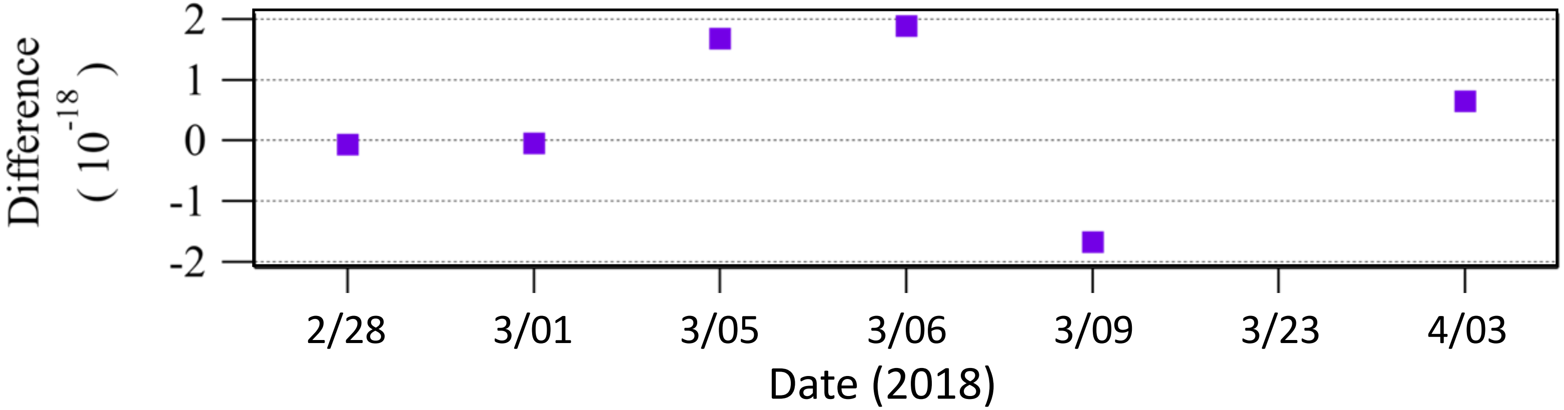
Free-space optical link


Fidelity of free-space link



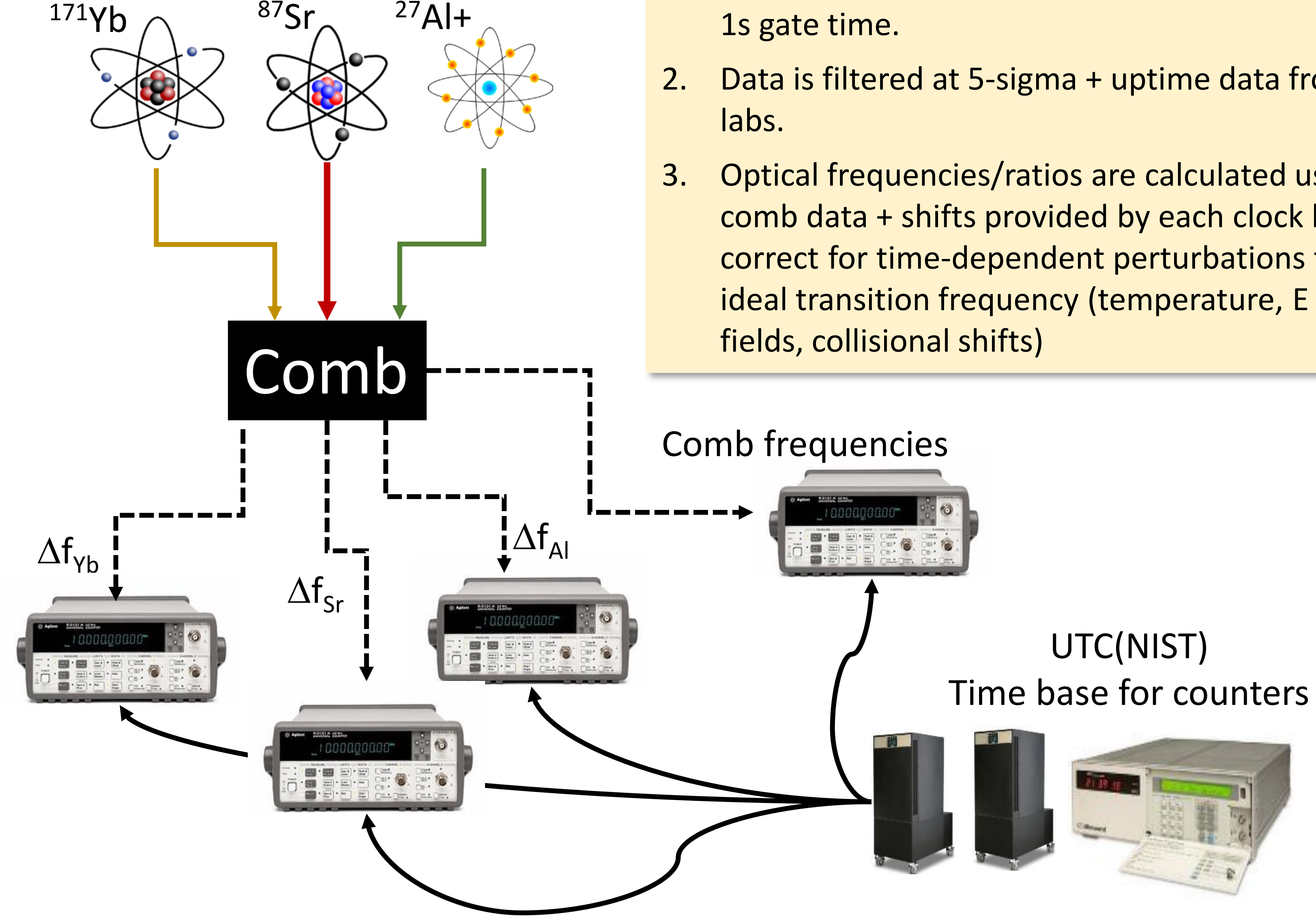
- Residual link noise at 10^{-17} @1s
- Free-space and BRAN link agreement near 10^{-18} (consistent with statistics)

Link agreement in optical clock ratio measurement



Counting optical frequencies for comparisons

1. Counter data is recorded on a computer as multiple columns of microwave frequencies, averaged over a 1s gate time.
2. Data is filtered at 5-sigma + uptime data from clock labs.
3. Optical frequencies/ratios are calculated using the comb data + shifts provided by each clock lab that correct for time-dependent perturbations to the ideal transition frequency (temperature, E + B fields, collisional shifts)



^{171}Yb

^{87}Sr

^{27}Al+

Comb

Δf_{Yb}

Δf_{Sr}

Δf_{Al}

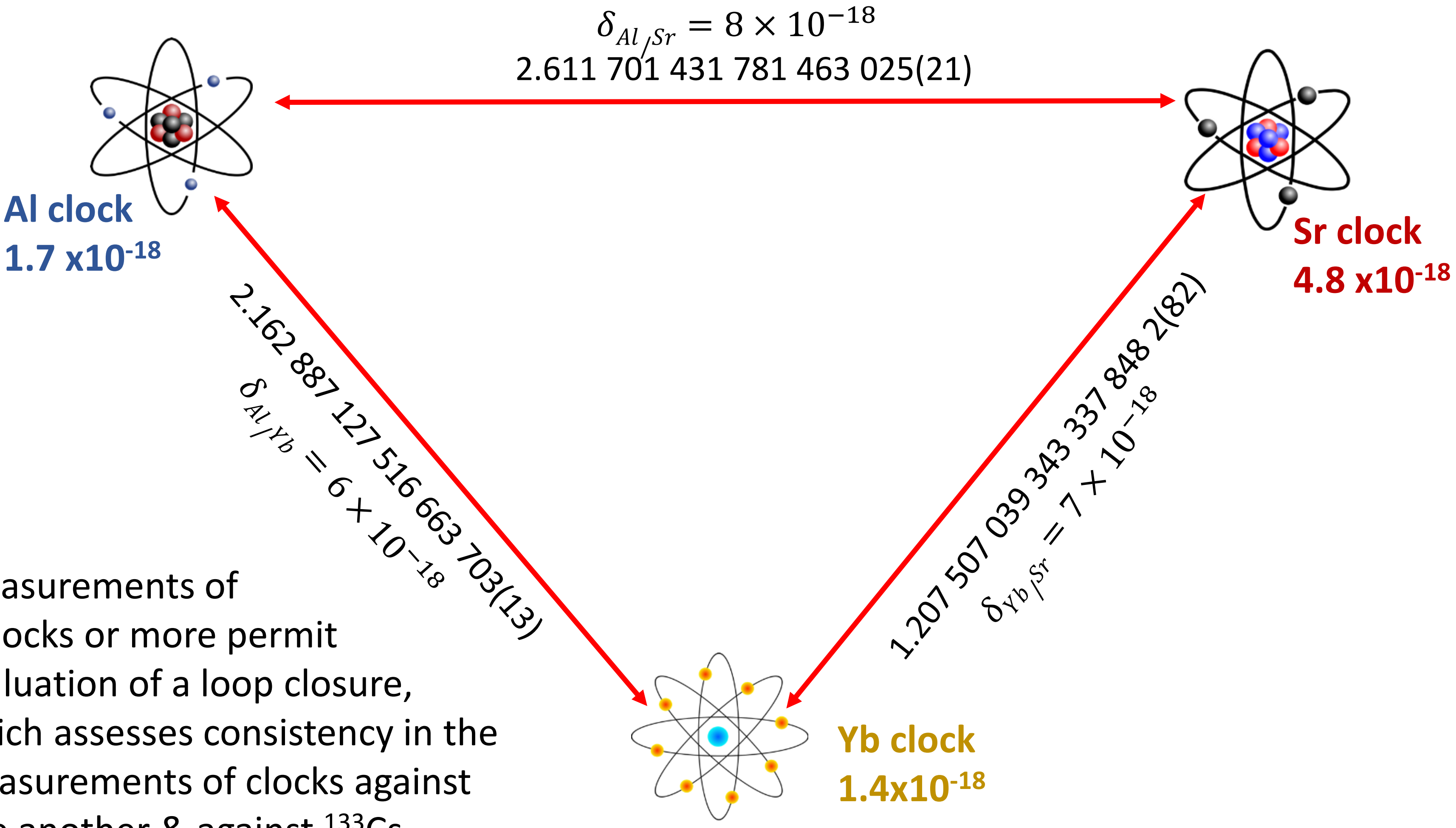
Comb frequencies

UTC(NIST)
Time base for counters

Ratios for loop closures

Loop Closure:

$$1-\frac{\upsilon_{Al}}{\upsilon_{Yb}}\times\frac{\upsilon_{Sr}}{\upsilon_{Al}}\times\frac{\upsilon_{Yb}}{\upsilon_{Sr}}=0.06\pm 2\times 10^{-17}$$



$\delta_{Al/Sr} = 8 \times 10^{-18}$

2.611 701 431 781 463 025(21)

Al clock

1.7 x10^{-18}

Sr clock

4.8 x10^{-18}

2.162 887 127 516 663 703(13)

$\delta_{Al/Yb} = 6 \times 10^{-18}$

1.207 507 039 343 337 848 2(82)

$\delta_{Yb/Sr} = 7 \times 10^{-18}$

Yb clock

1.4x10^{-18}

Measurements of
3 clocks or more permit
evaluation of a loop closure,
which assesses consistency in the
measurements of clocks against
one another & against ^{133}Cs.

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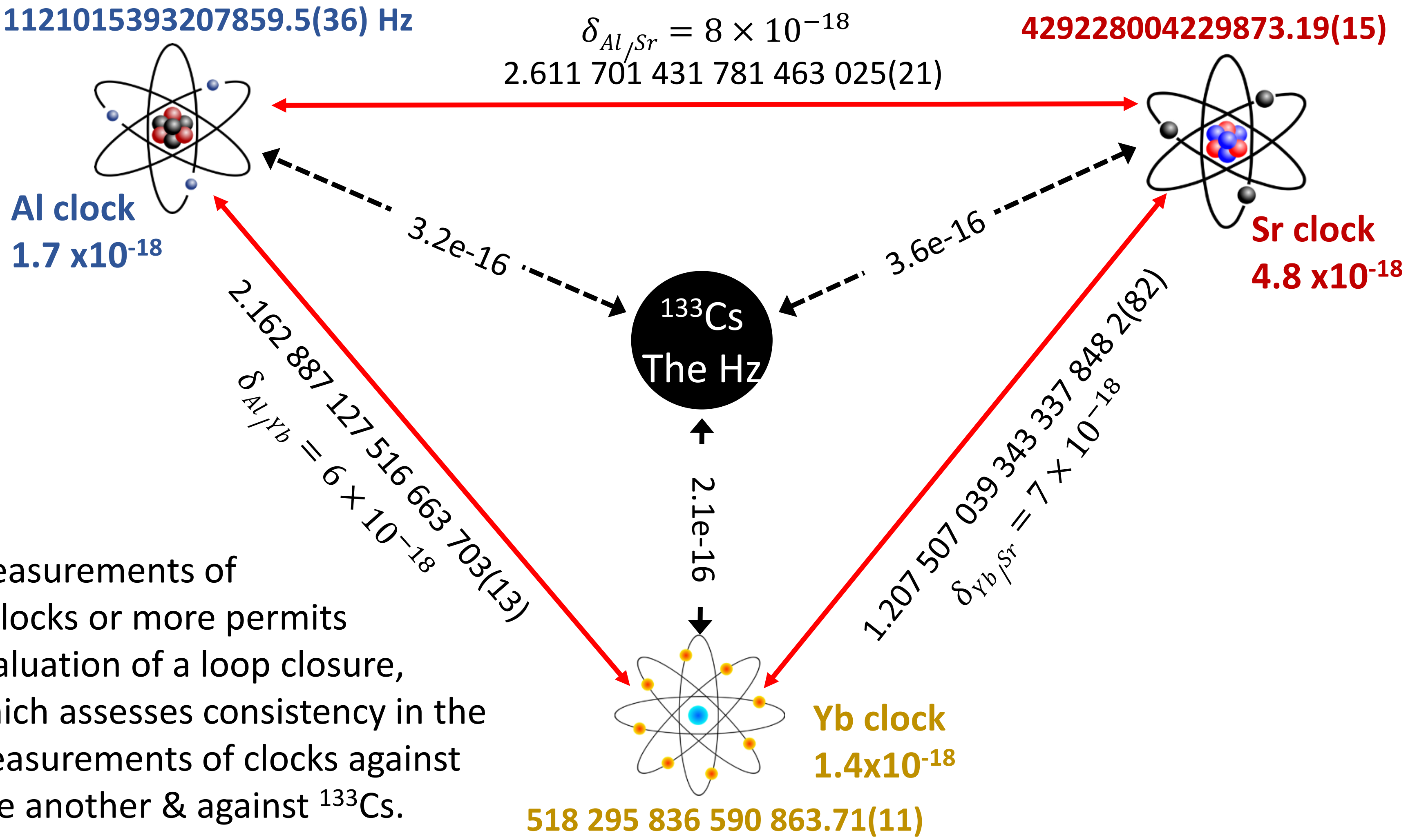

1121015393207859.5(36) Hz

Al clock
1.7 x10^{-18}

$\delta_{Al/Sr}=8\times10^{-18}$
2.611 701 431 781 463 025(21)

429228004229873.19(15)

Sr clock
4.8 x10^{-18}

3.2e-16

3.6e-16

^{133}Cs
The Hz

2.1e-16

2.162 887 127 516 663 703(13)
$\delta_{Al/Yb}=6\times10^{-18}$

1.207 507 039 343 337 848 2(82)
$\delta_{Yb/Sr}=7\times10^{-18}$

Yb clock
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518 295 836 590 863.71(11)

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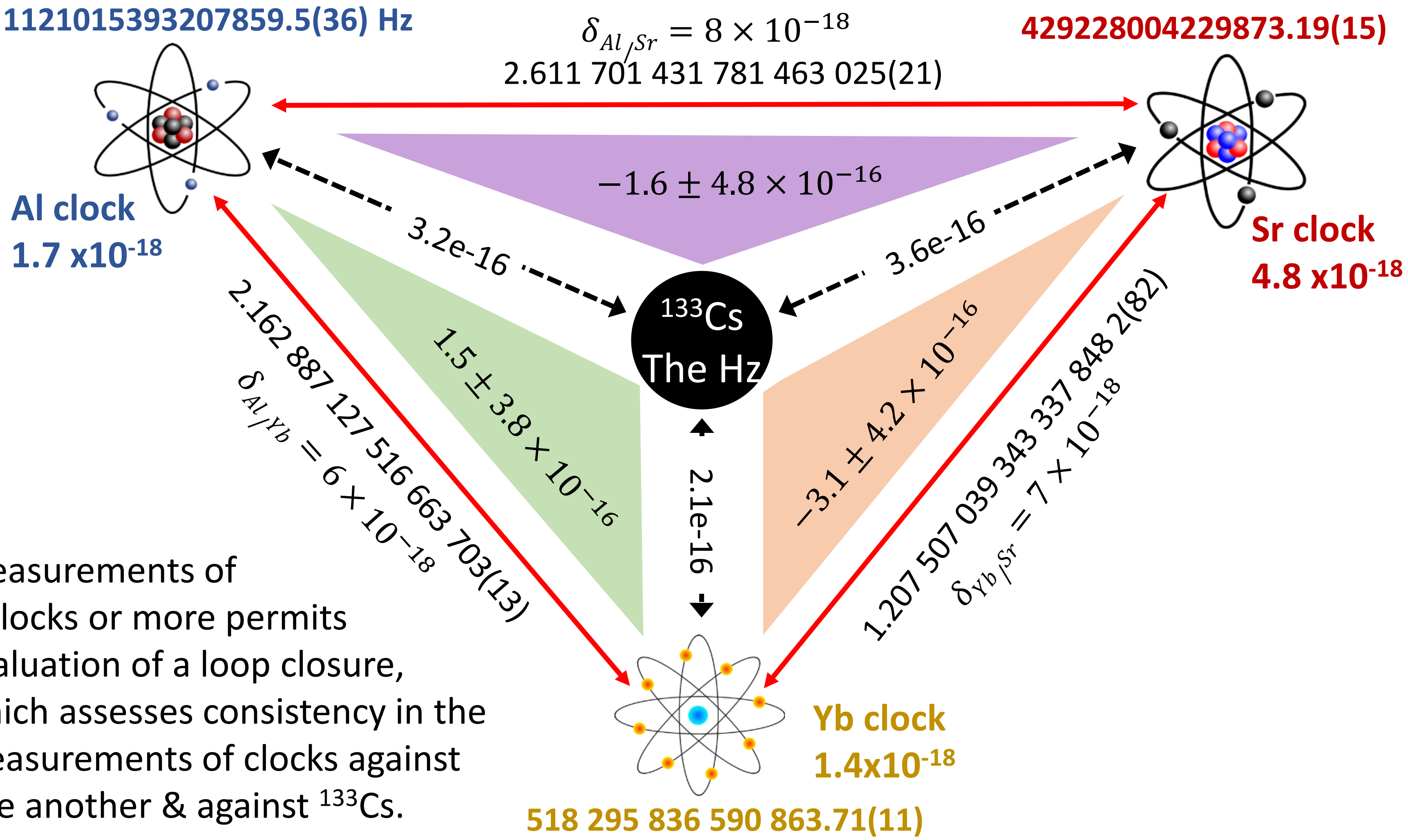

1121015393207859.5(36) Hz

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2.611 701 431 781 463 025(21)

429228004229873.19(15)

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4.8 x10^{-18}

$-1.6 \pm 4.8 \times 10^{-16}$

3.2e-16

3.6e-16

^{133}Cs
The Hz

2.162 887 127 516 663 703(13)
$\delta_{Al/Yb} = 6 \times 10^{-18}$

$1.5 \pm 3.8 \times 10^{-16}$

2.1e-16

$-3.1 \pm 4.2 \times 10^{-16}$

1.207 507 039 343 337 848 2(82)
$\delta_{Yb/Sr} = 7 \times 10^{-18}$

Yb clock
1.4x10^{-18}

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Measurements of
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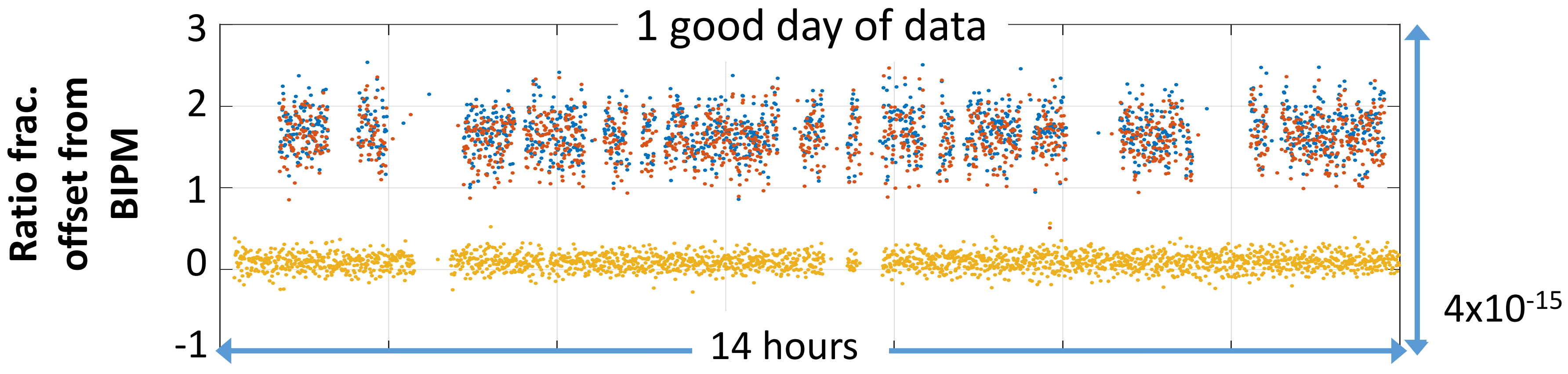
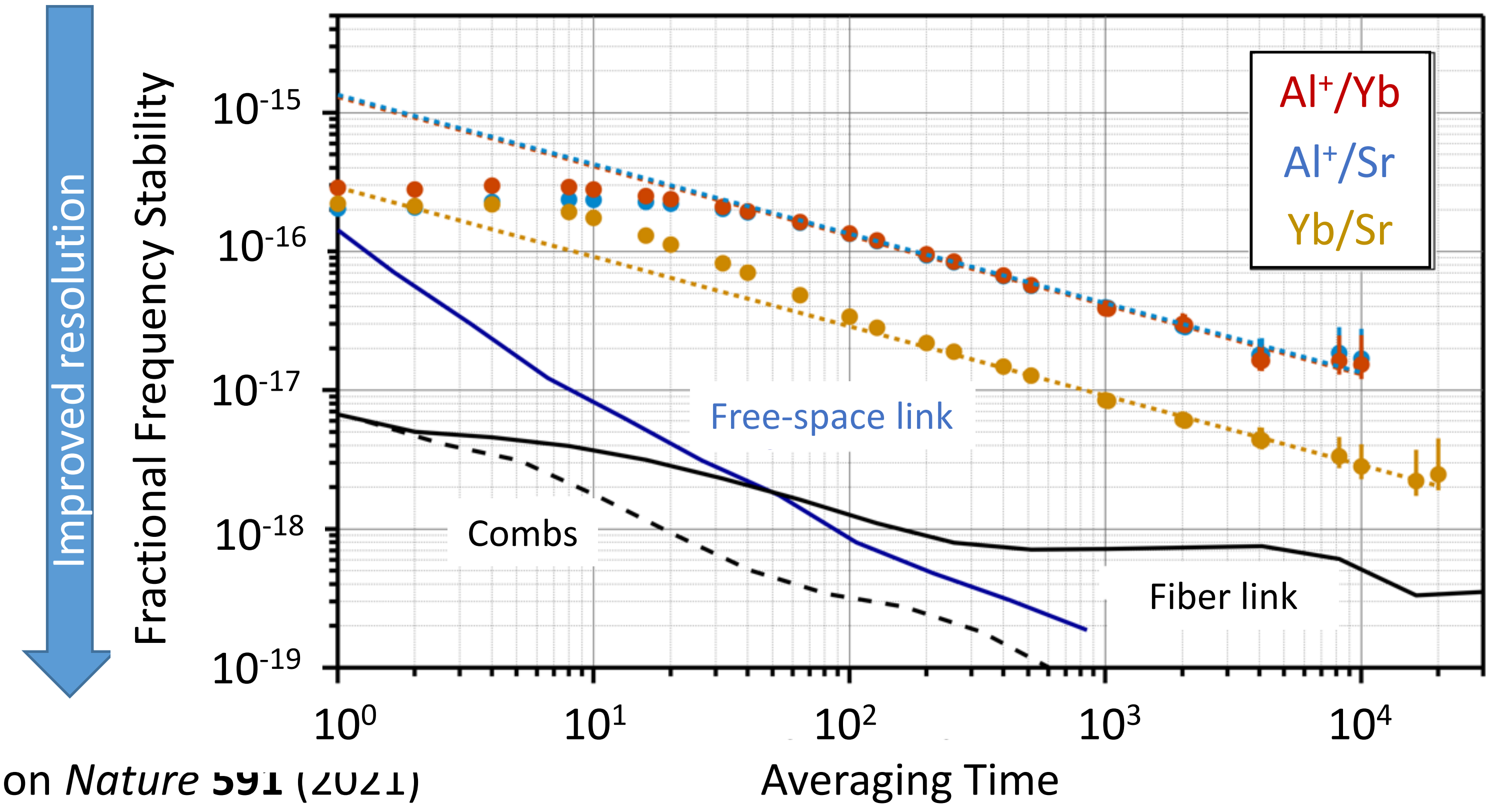
2018 Clock ratio data



Optical network performance better than clocks so does not add measurement errors/instability



BACON collaboration *Nature* **591** (2021)