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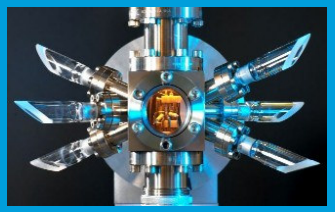
When should we change the definition of the second?

Patrick Gill



The new SI:
units of measurement based on fundamental constants

National Measurement System

Discussion meeting, The Royal Society,
London, 24-25 January 2011

Outline

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- Evolution of quantum-based definition of the second
- Current Cs fountain realisation – a constant of nature
- Alternative paradigms for a new definition:
  (fundamental constants base, optical constant of nature, frequency ratios, matrix idea, VUV / XUV transitions)
- A definition based on an optical transition
  candidate choices, status, comparison
- How to compare such standards: combs and remote comparison
- Outlook, timescales and perspectives

Evolution of atomic clocks

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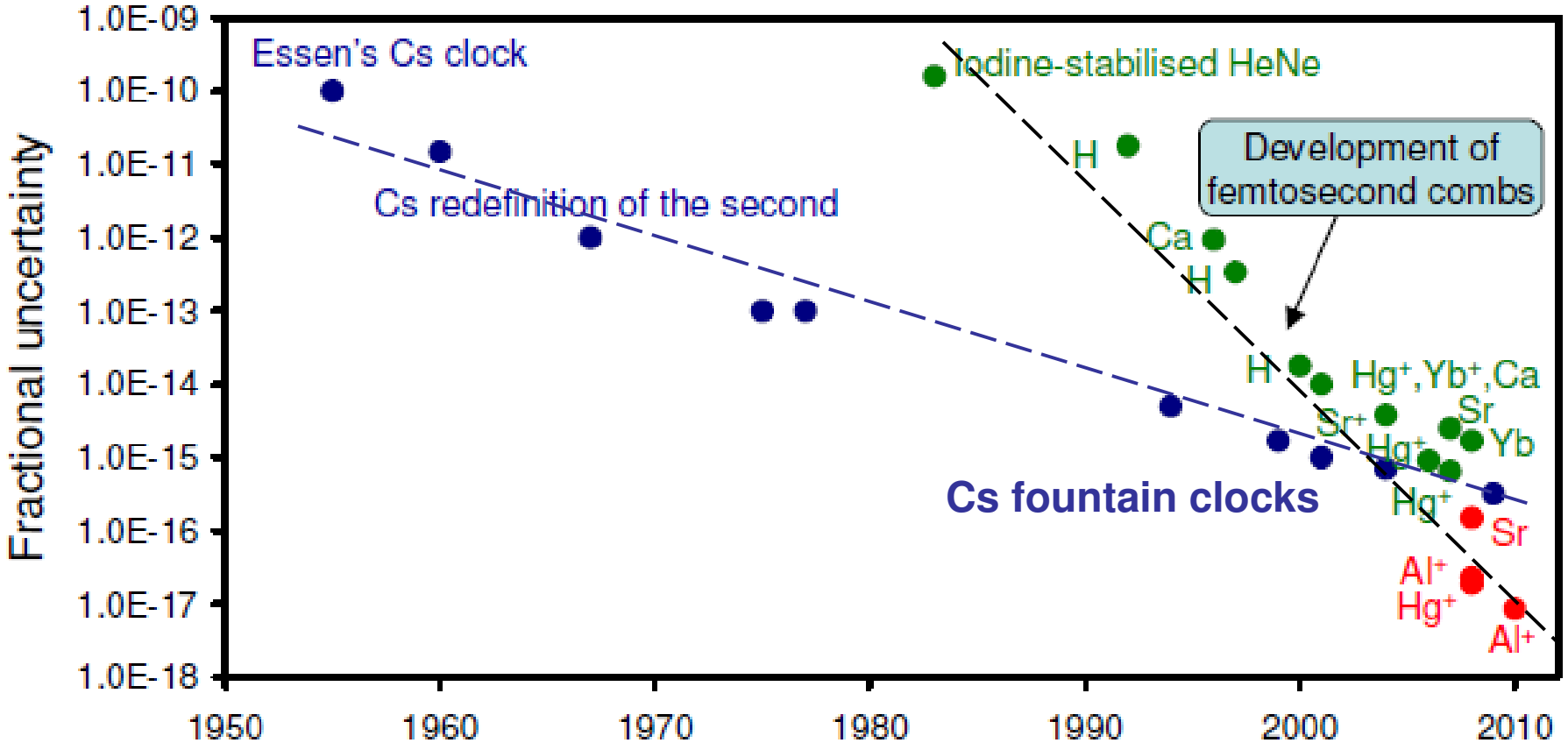

In the future a new optical definition for the second will be needed:
When?: - optical progress slowed
- candidate systems fully evaluated
- remote clock comparisons

Definition and Realization of the Second

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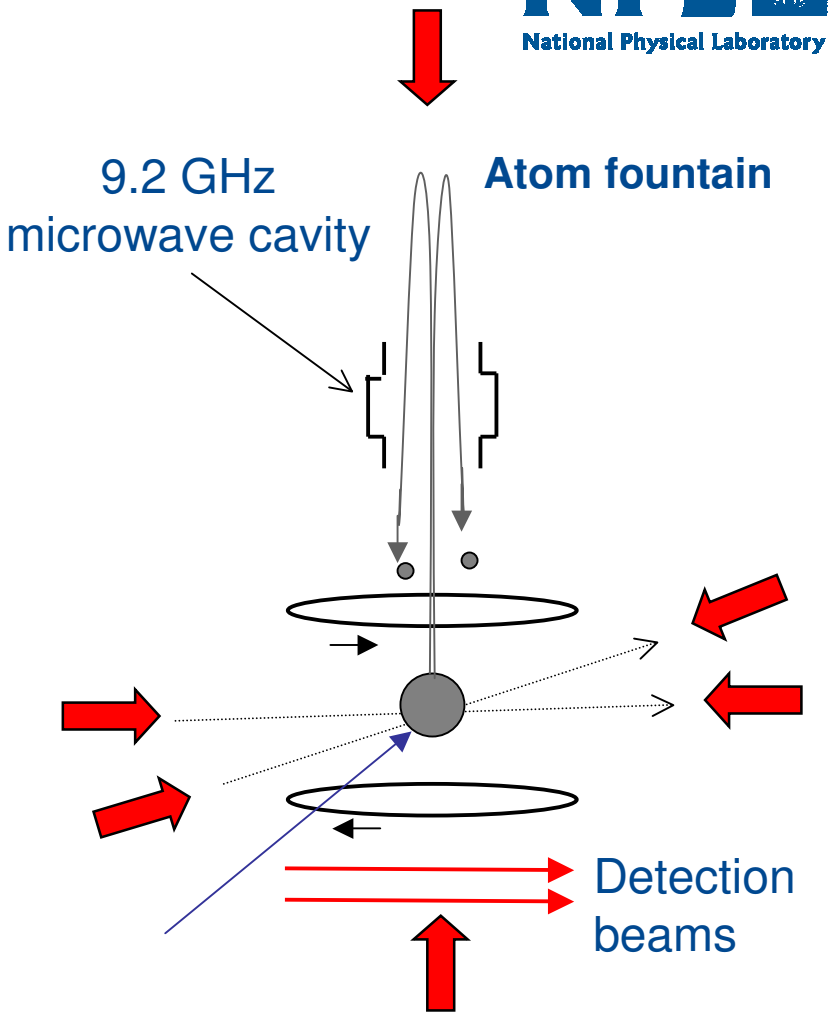
Today's best realization

cloud of Cs atoms
laser cooled to few μK
in magneto-optic trap

cold atoms are then launched
vertically by laser light

atoms undergo Ramsey excitation
in microwave cavity

fraction of excited atoms are
detected by laser beams



- < 5×10^{-16} systematic uncertainty
- < 50 ps per day
- contribute to TAI
- several fountains worldwide
- Underpins optical freq meas.

Cs cold collisional shift cancellation: Szymaniec et.al. Phys Rev Lett 2007 (NPL / NIST / PTB)

Advantage of optical clocks

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Clock frequency stability:

instability $\sigma \propto \frac{\Delta f}{f}\frac{1}{(S/N)}$

$$\sigma(\tau) = \frac{1}{2\pi f\sqrt{NT_{\text{int}}\tau}}$$

Where f and Δf are frequency and width of atomic reference transition

Optical clocks

- Based on forbidden optical transitions in ions or atoms
- Frequencies $f \sim 10^{15}$ Hz, natural linewidth Δf typically 1 Hz
  ie Q-factor ~ 10^{15} (or even higher)
- Better stabilities than microwave clocks
- Better clock stability facilitates evaluation of lower uncertainties
- Better time resolution (clock "ticks" faster)

Single ion N = 1

Atoms in a lattice N = 10^4-10^6

Possibilities for a Redefinition of the second

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- Fixed value of the Rydberg constant?

$$R_\infty = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c} = \frac{m_e c \alpha^2}{2h}$$

- Choose a single optical transition: a constant of nature

  Optical analogue of Cs microwave standard but with frequency 10^5 higher, uncertainty x100 – x1000 lower

- An optical transition plus a set of frequency ratios

  Optical frequency ratio measurements using combs are accurate and efficient

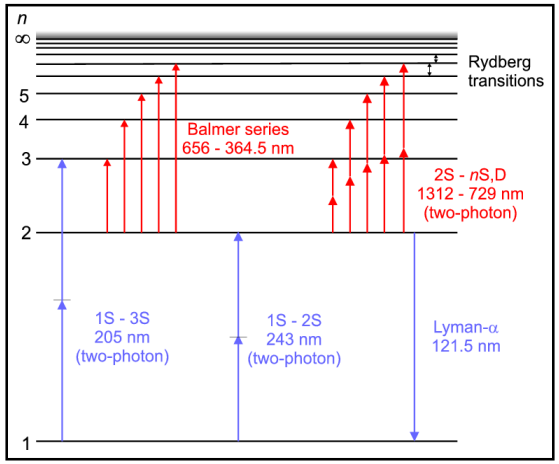
- A “virtual” frequency based on a matrix of “best” optical transitions (or secondary representations of the s),

  where the value is weighted mean of the matrix values

- Very high frequency transitions in VUV, XUV:

  eg Thorium nuclear transition, Mossbauer transitions in solids

Definition based on the Rydberg constant?



Hydrogen energy levels:

$$E_n \approx -\frac{R_\infty ch}{n^2}$$

where **Rydberg constant**

$$R_\infty = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c} = \frac{m_e c\alpha^2}{2h}$$

Laser spectroscopy → H(1S-2S) frequency to 1.4 parts in 10^{14}

With meas. of other hydrogen transitions, → **Rydberg** to 6 parts in 10^{12}

Why not fix Rydberg at measured value, & compute H(1S-2S) frequency or another transition: $\nu(\text{1S-2S}) = -R_\infty c\,(1/n_2^2 - 1/n_1^2)$

Problem: QED theory corrections and proton size uncertainty

Hydrogen is only viable possibility for this approach – but even then

- Uncertainty of realisation limited by QED corrections
- Would need to trap and cool hydrogen
- Frequency shifts large (eg 2nd order Doppler shift)
- Not competitive with cold atom and ion clock uncertainties

Comment on definition possibilities (continued)

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Optical clock definition:

- How to choose the best transition
  (lowest uncertainty? system investigated by most NMIs?)
- There will likely be a number of candidates with uncertainties within a factor of a few of each other
- There would be no problem with 1 cold ion / atom primary standard plus several other secondary representations
- Comb transfer would provide primary-secondary linkage with no loss of accuracy

Most likely option at this time

Set of comb-measured frequency ratios:

- In effect, similar to above, if anchored to an optical transition
- More problematical if Cs retained, as there would be a disconnect between data derived via ratios and Cs-related measurements

Comment on definition possibilities (continued)

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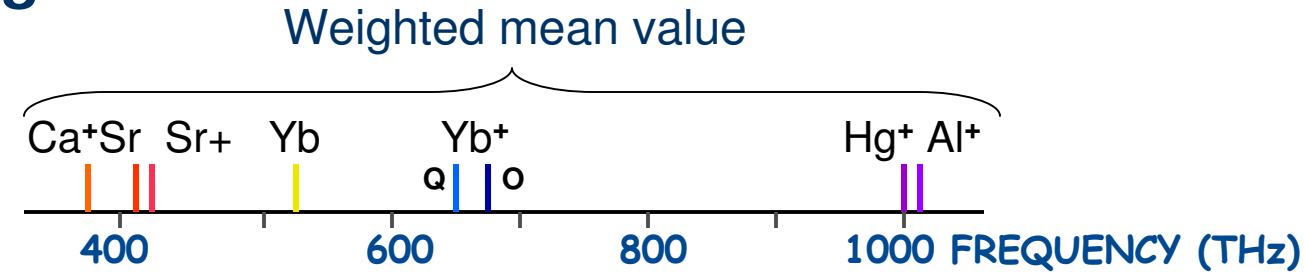
Matrix value suggestion:

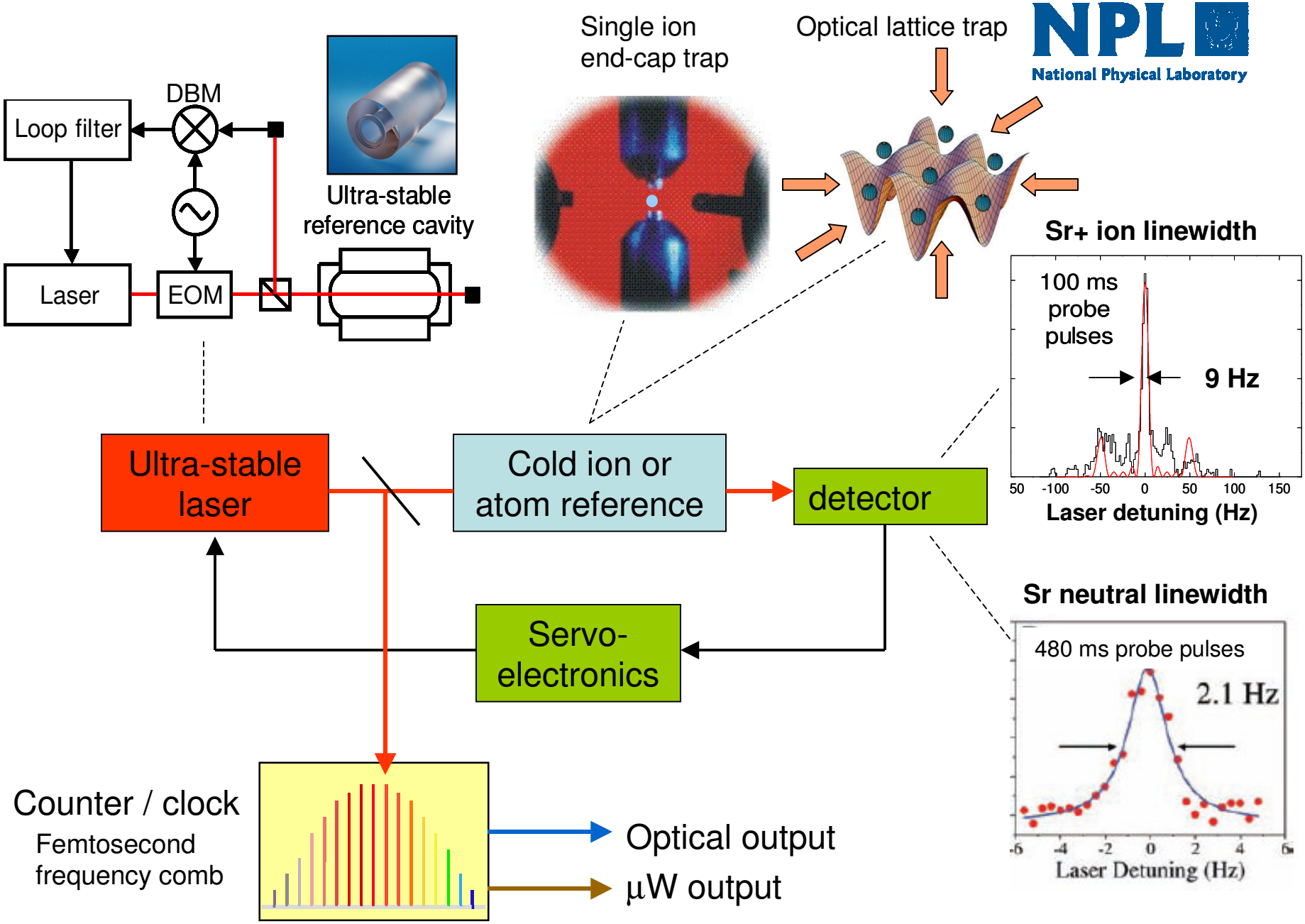


- Best individual values at redefinition adopted
- Individual values updated for bias corrections & improved uncertainty as appropriate
- BUT matrix value would have no physical significance

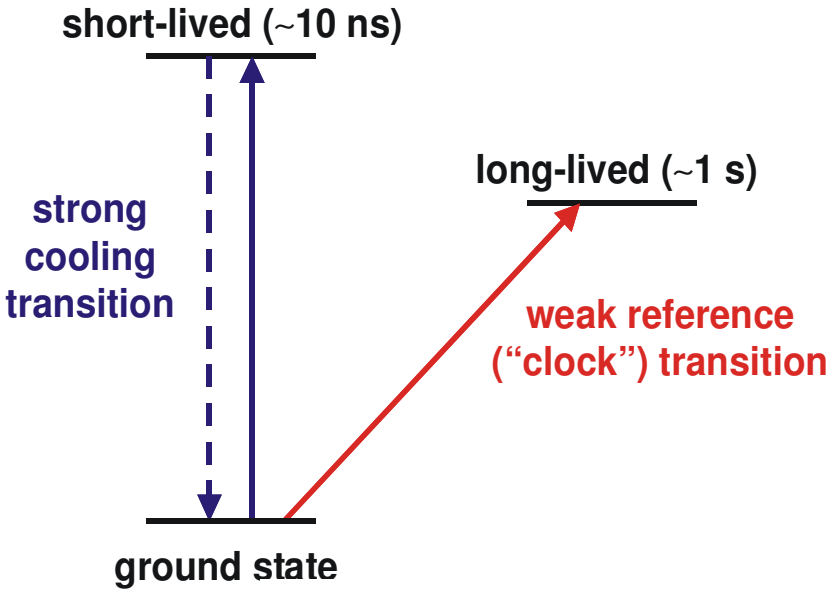
Nuclear transitions:

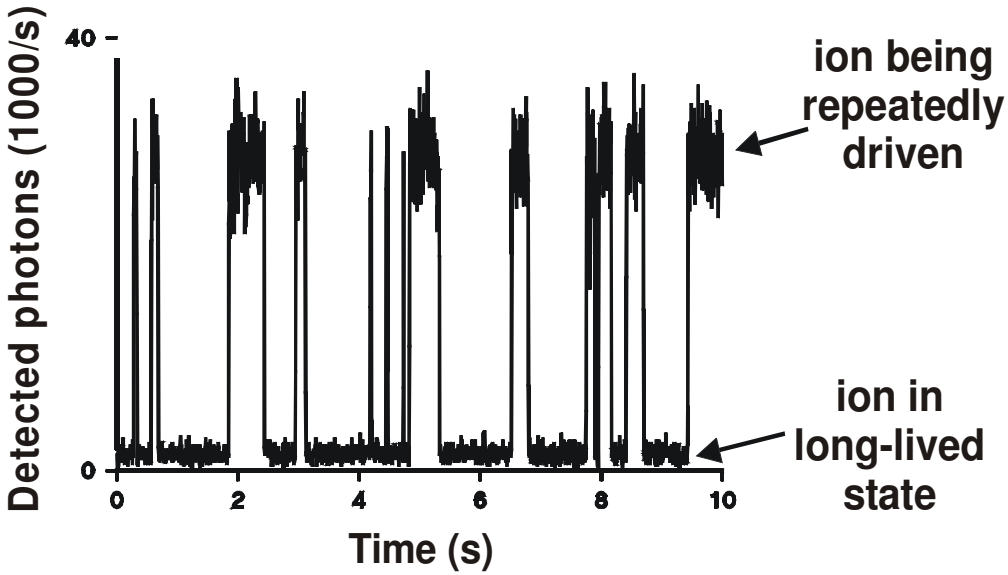
- Nuclear transitions so should be less sensitive to environmental fields, but if using solid state arrangement, then strong local field perturbation?
- Large uncertainty over precise location of VUV & XUV clock frequencies
- Technology difficulty in generating clock and cooling transitions – need for high harmonic generation

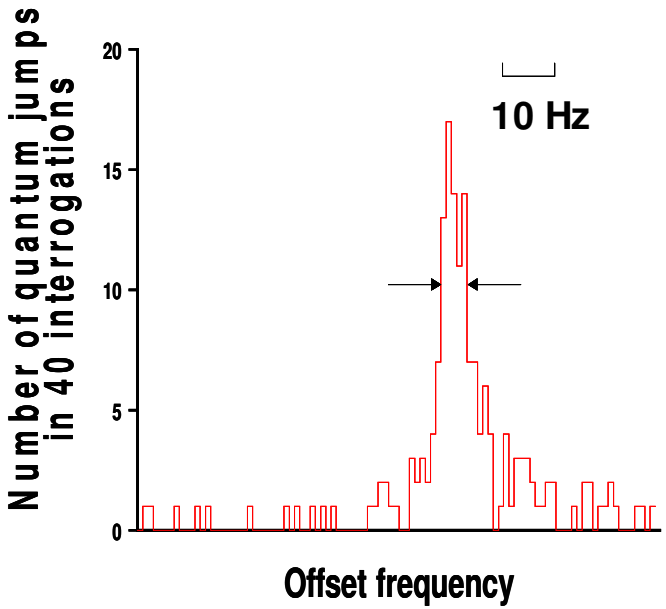
Optical clock architecture



Quantum jumps for servo-locking to a clock transition in a single ion







Locking the "clock" probe laser to the ion clock transition

- Laser hops to either side of centre.
- Imbalance in jumps indicates that laser has drifted.
- Correction made to laser frequency

Optical redefinition of the second: Which atom or ion?

Optical clock candidates:

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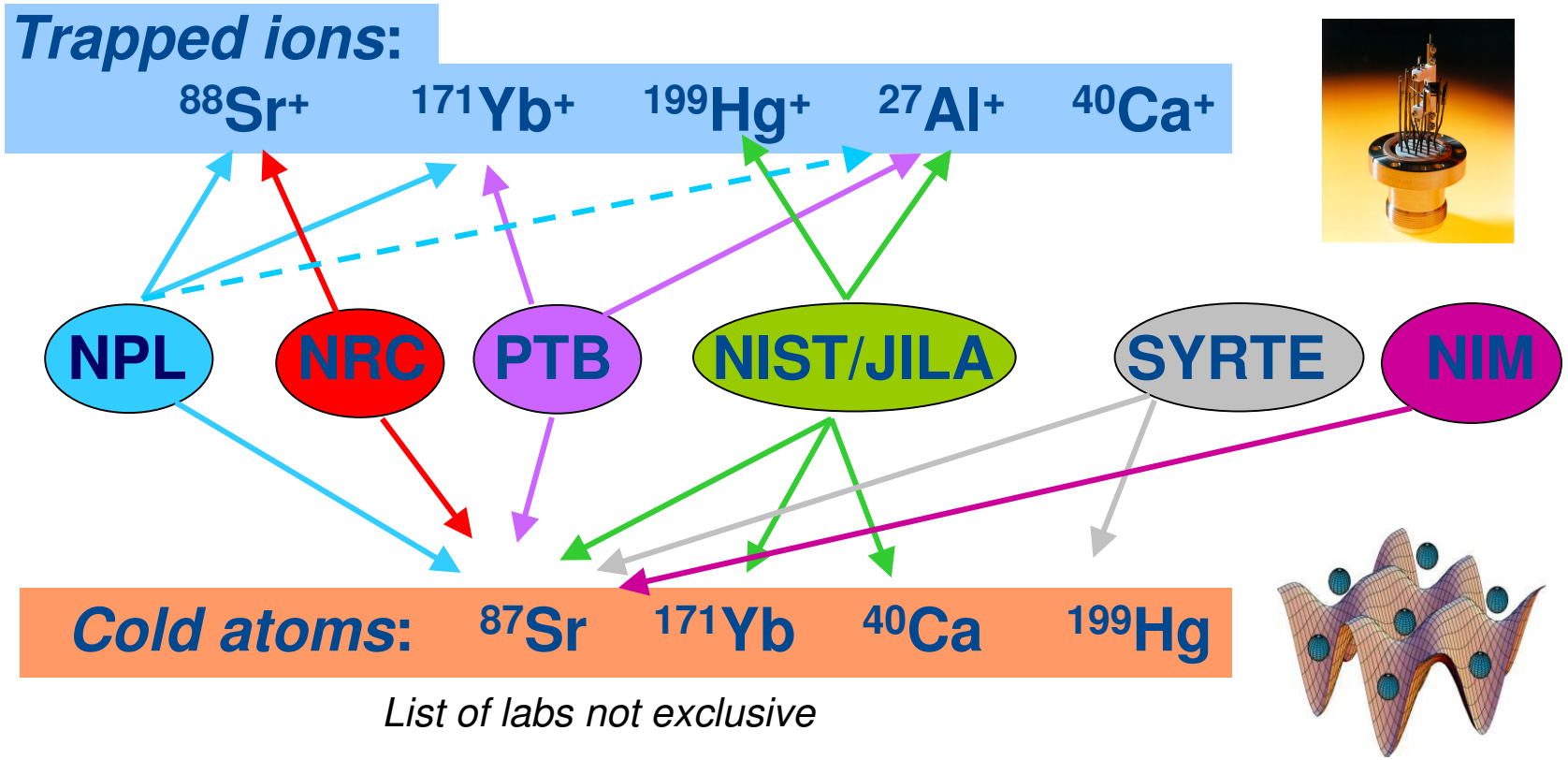


List of labs not exclusive

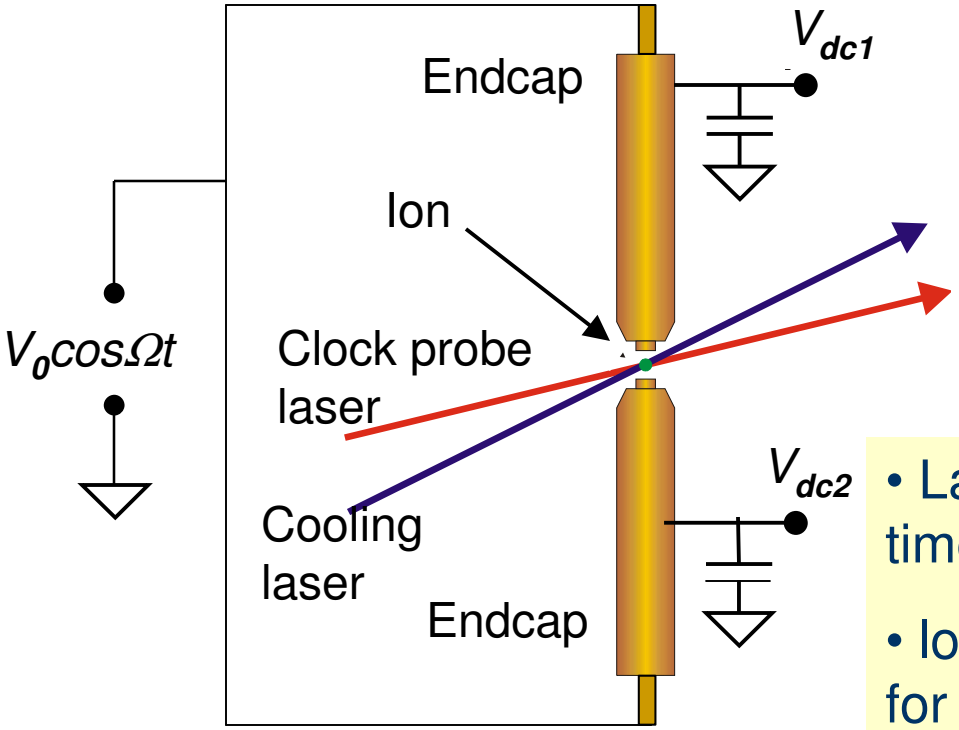
Opportunities (better than Cs)

Some systems now have estimated uncertainties below Cs

Absolute accuracy limitations

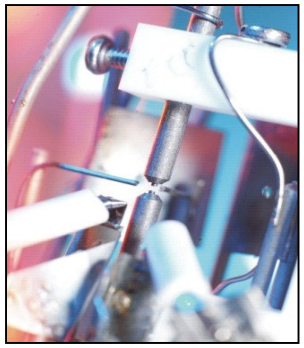
Can be no better than Cs value until redefinition

Trapped single ion frequency standards



End-cap trap

Rf "saddle" potential
Ω drive frequency ~ 15 MHz
V_{rf} ~ few 100 volts
V_{dc} ~ few volts
Electrode separation ~ 1 mm



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$^{88}Sr^{+}$ end-cap trap (NPL)

- Laser-cooled single ion trapped in rf time-averaged potential minimum
- long interrogation times possible (> 1 s) for high-Q optical clock transitions
- low perturbation environment:
  - no 1st order Doppler shift
  - minimised 2nd order Doppler shift
  - E-field perturbation minimised at trap centre
  - low background collision rate

→ Isolated, unperturbed particle, virtually at rest

Other rf trap designs

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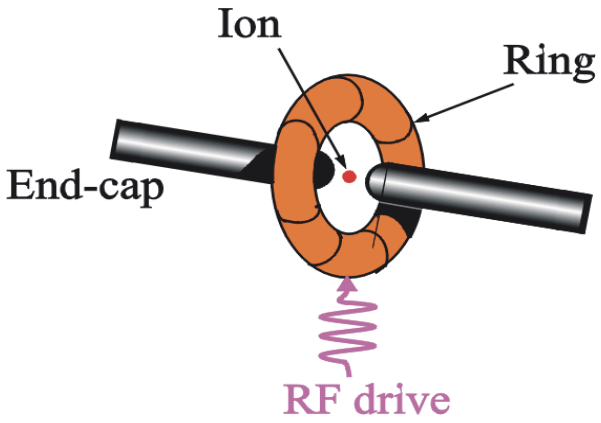
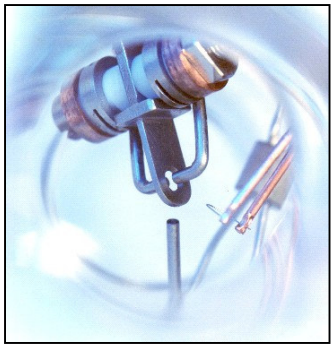
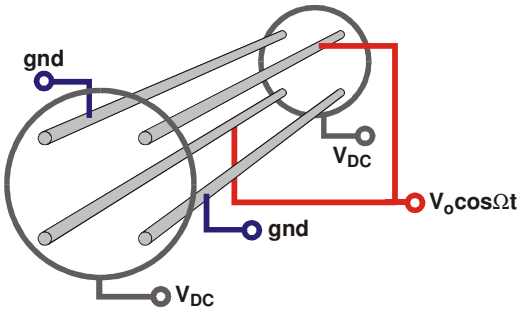
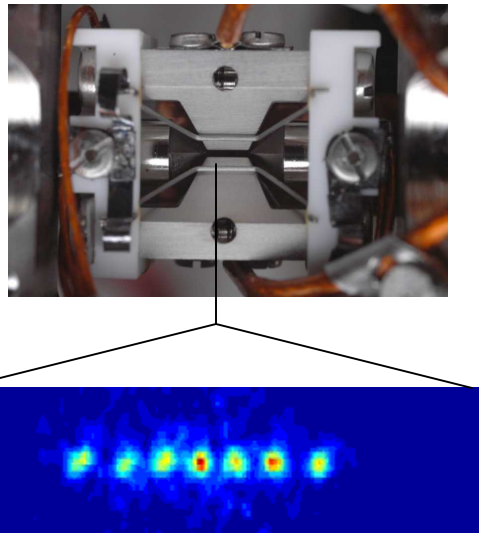




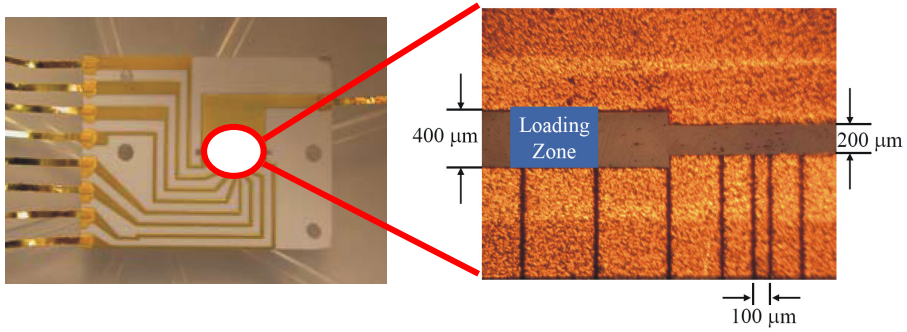
$^{171}Yb^{+}$ ring trap (PTB)



$^{40}Ca^{+}$ linear blade trap (eg Innsbruck)



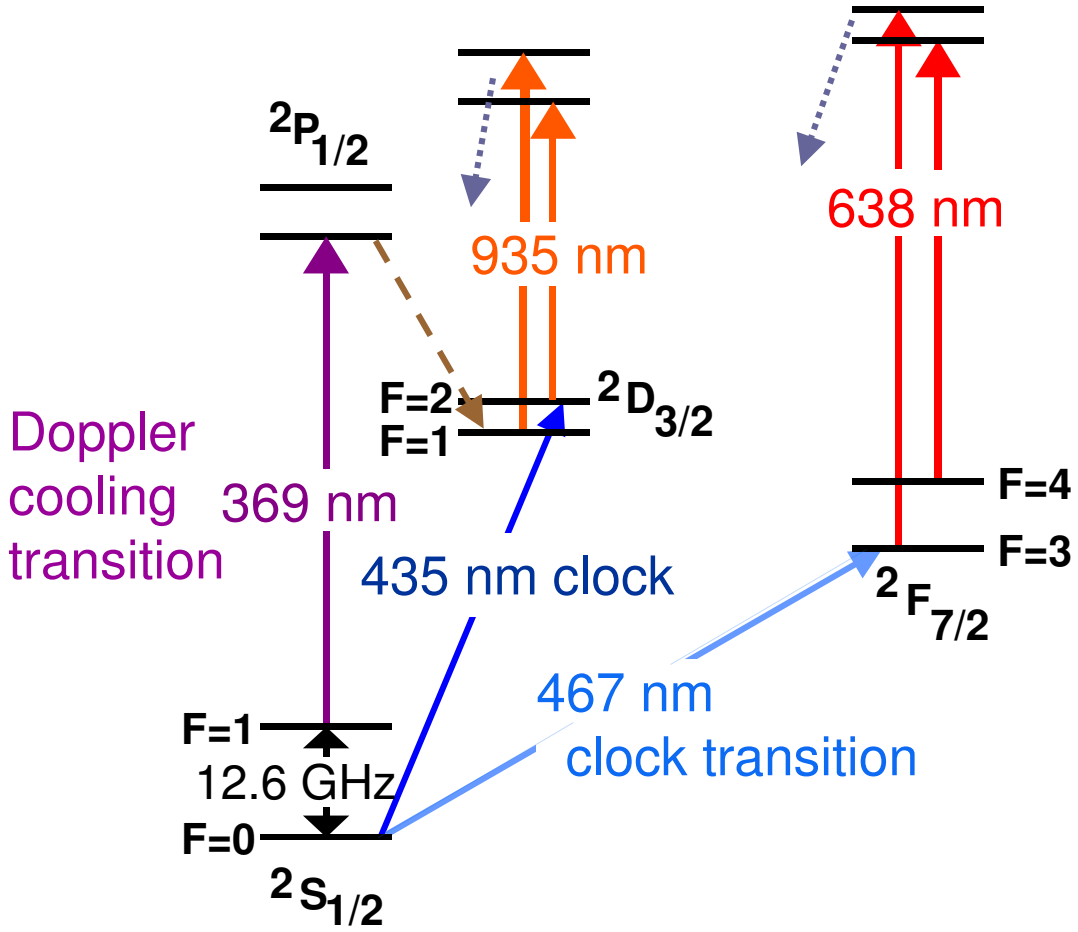
Courtesy: R Blatt



NIST micro-fabricated (wafer) linear segmented trap

$^{171}Yb^{+}$ Single ion octupole and quadrupole clock transitions

- **Electric octupole transition**
  Very weak transition at 467 nm
- **Natural linewidth ~ nHz**
  Limited by probe laser linewidth
- **Odd isotope**
  → hyperfine levels, but
- **$m_F = 0 \rightarrow m_F = 0$ transition**
  Free from linear Zeeman shift
  Small quadratic Zeeman shift
- **AC Stark shift**
  High intensity needed, but shift small with sub-Hz lasers
- **Small quadrupole shift**
  x15 smaller than $^{88}Sr^{+}$



- **Electric quadrupole transition at 435 nm**
  3 Hz natural linewidth

PTB & NPL

$^{171}Yb^{+}$ Quadrupole / Octupole Frequency ratio for search for time variation in fine structure constant

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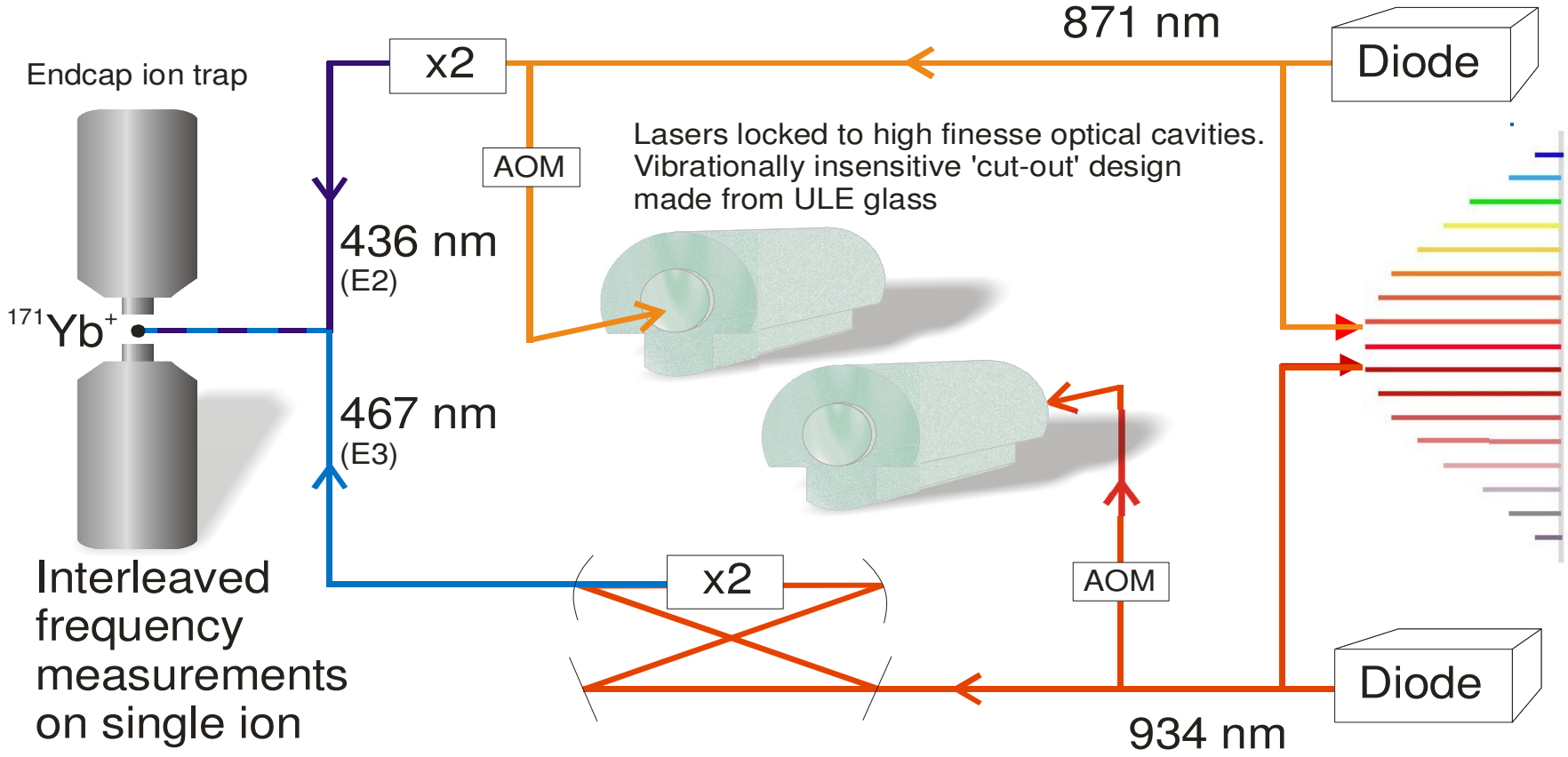
Ratio of 435 nm quadrupole to 467 nm octupole clock frequency has highest sensitivity factor (6.8) for search for possible time variation in α



$\nu_{435} / \nu_{467} \sim 10^{-17} \rightarrow d\alpha/dt \sim 2\times10^{-18}$ per year

$^{27}Al^{+}$ species as a single ion clock

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√	Clock transition:	267 nm (SHG + SHG of 1070 nm)
√√	Clock linewidth:	8 mHz
√√	Frequency shift:	smallest known blackbody shift,
√√	sensitivities	negligible electric quadrupole shift,
√		no linear Zeeman shift (m_F=0 → m_F=0),
√		small quadratic Zeeman shift
X	Cooling transition:	167 nm, not accessible, deep UV

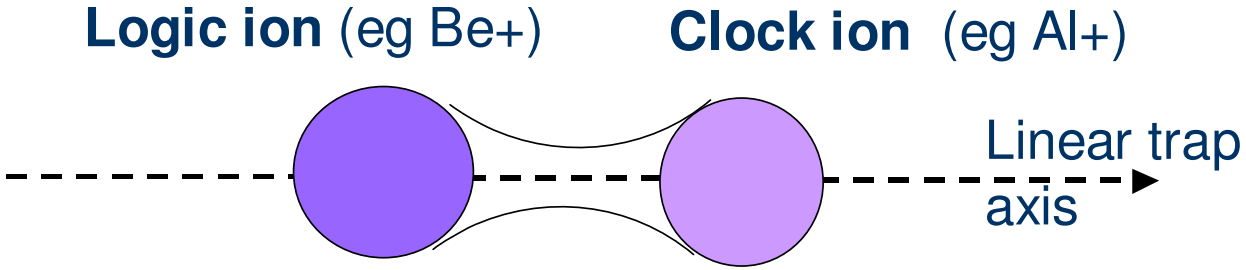
So, how to overcome cooling transition problem?

Quantum Logic Clock proposal: *Wineland et al: 6th Symp Freq Stds & Met 2001*

Separate clock functionality from cooling functionality

→ 2 different ion species held in linear ion trap

Cooling of and communication with Al+ via coulomb interaction of ions



Driving the actual Al^+ $^1S_0$ – $^3P_0$ clock transition with quantum logic

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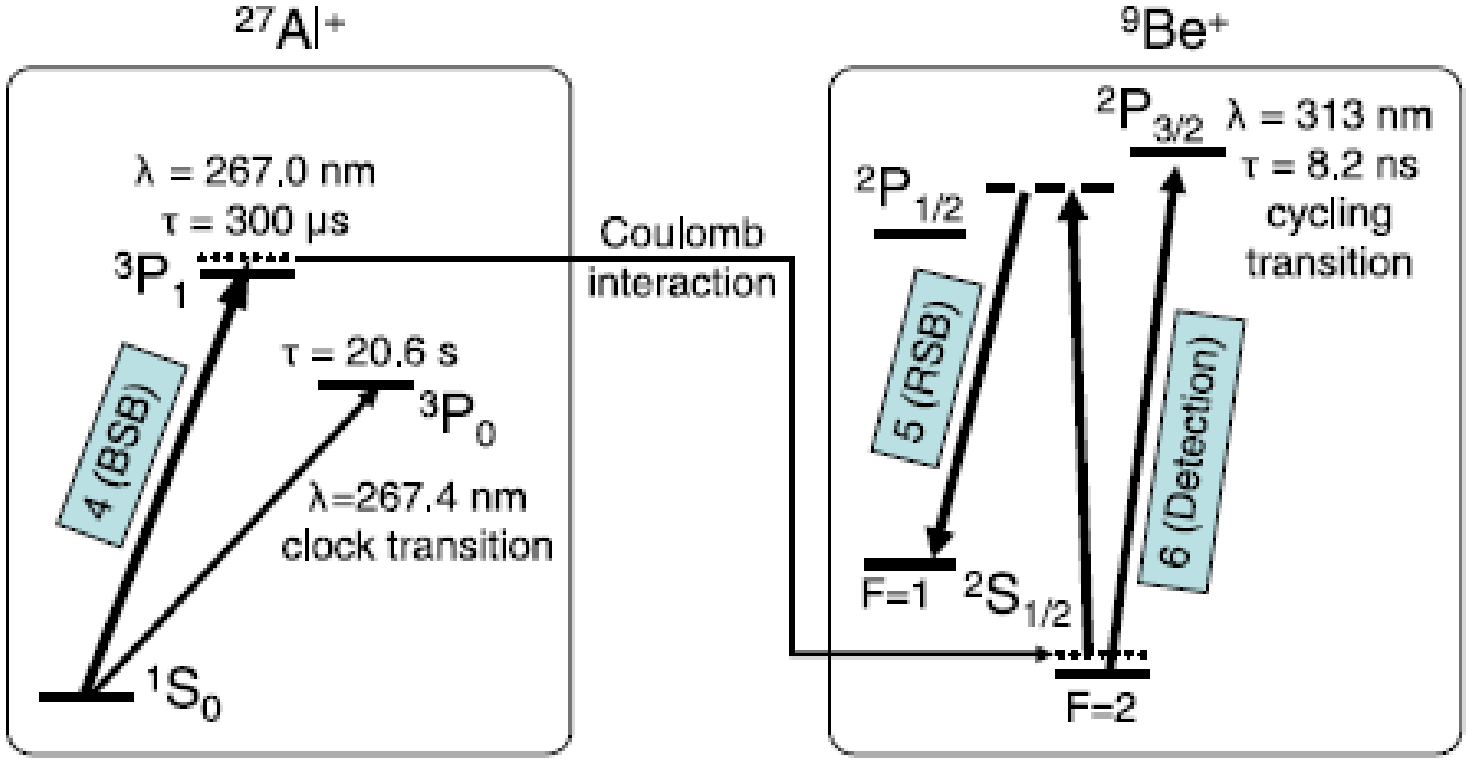

Read-out of the Al^+ clock state by mapping back onto Be^+ ion via entanglement

*Rosenband et al. Phys Rev Lett **98** 220801 (2007)*

NIST comparison of 2 quantum logic Al^+ clocks

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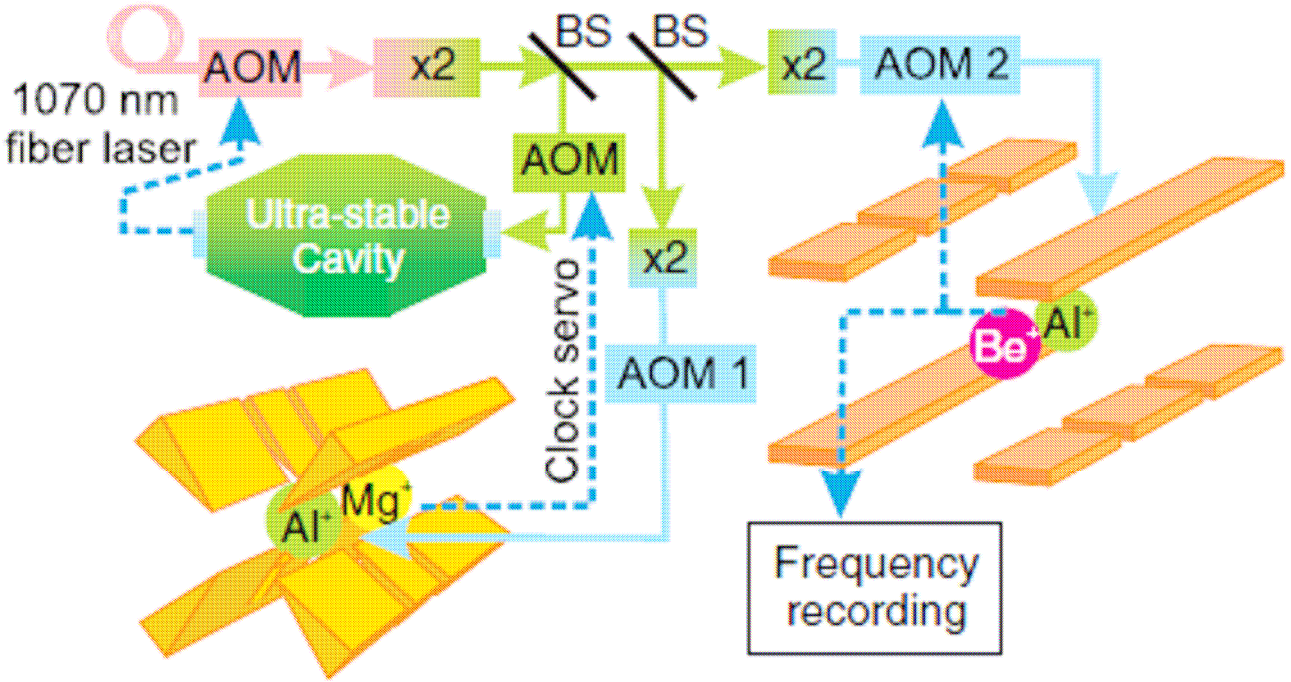
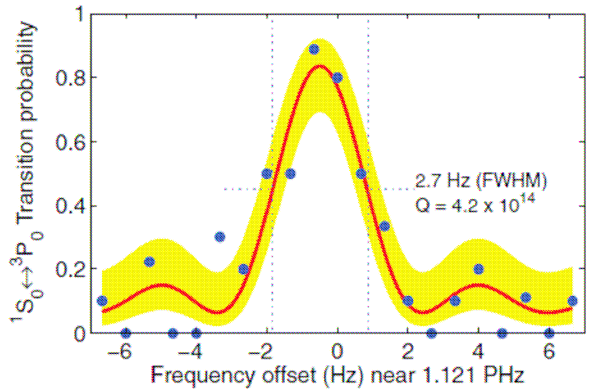


Frequency inaccuracy:	8.6×10^{-18}
Frequency instability:	$2.8 \times 10^{-15}\ \tau^{-1/2}$
Measurement uncertainty:	7×10^{-18}
Frequency difference between Al^+ clocks:	-1.8×10^{-17}



Chou et al. Phys. Rev. Lett ***104*** *(2010)*

Al^+ $^1S_0 - {}^3P_0$ clock transition linewidth
Chou et al. Science 2010

Current optical clock status

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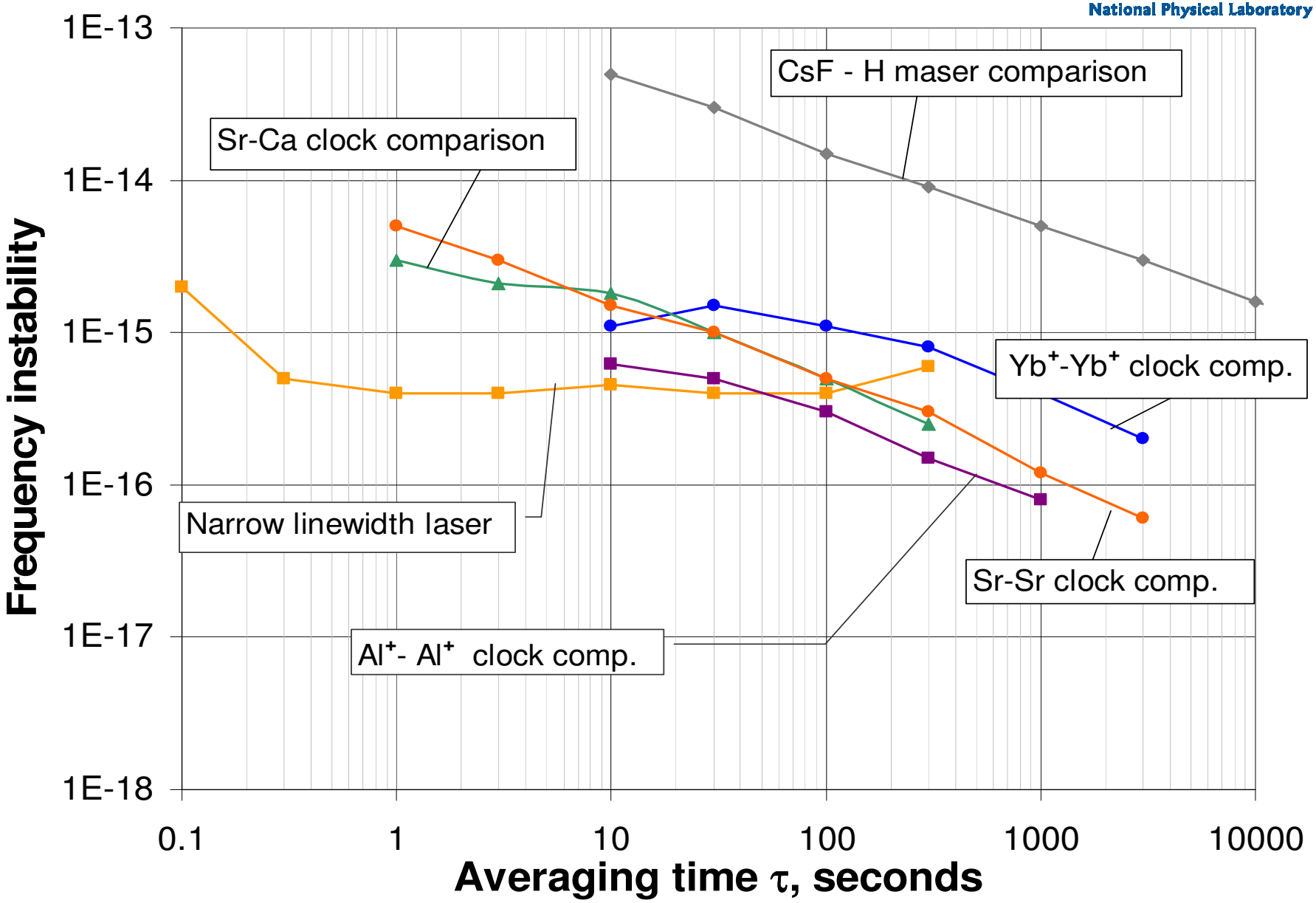
Ion / Atom	Clock transition	λ nm	Estimated sys. Freq. uncert.	Freq instability @ 10 s	Laboratory	Other labs contributing
$^{27}Al^+$ ion	$^1S_0 - {}^3P_0$	267	9×10^{-18}	6×10^{-16}	NIST	
$^{199}Hg^+$ ion	$^2S_{1/2} - {}^2D_{5/2}$	282	2×10^{-17}		NIST	
^{87}Sr in lattice	$^1S_0 - {}^3P_0$	698	1.6×10^{-16}	1.5×10^{-15}	JILA	SYRTE, Tokyo, PTB, NPL, NIM, Florence
^{171}Yb in lattice	$^1S_0 - {}^3P_0$	578	3.4×10^{-16}	1.5×10^{-15}	NIST	NMIJ, KRISS, INRIM, Duesseldorf
$^{171}Yb^+$ ion	$^2S_{1/2} - {}^2D_{3/2}$	436	4.5×10^{-16}	1.1×10^{-15}	PTB	NPL
$^{40}Ca^+$ ion	$^2S_{1/2} - {}^2D_{5/2}$	729	2.4×10^{-15}		Innsbruck	NICT
$^{88}Sr^+$ ion	$^2S_{1/2} - {}^2D_{5/2}$	674	3.8×10^{-15}		NPL	NRC
^{40}Ca atom	$^1S_0 - {}^3P_1$	657	7.5×10^{-15}		NIST	PTB
$^{171}Yb^+$ ion	$^2S_{1/2} - {}^2F_{7/2}$	467	1.8×10^{-14}		NPL	PTB
$^{115}In^+$ ion	$^1S_0 - {}^3P_0$	237	1.8×10^{-13}		MPQ	
$^{199,201}Hg$ in lattice	$^1S_0 - {}^3P_0$	266			SYRTE	Tokyo

Optical clock frequency instability comparisons



How close to quantum–limited performance?

$$\sigma(\tau) = \frac{1}{2\pi f \sqrt{N T_{\text{int}} \tau}}$$

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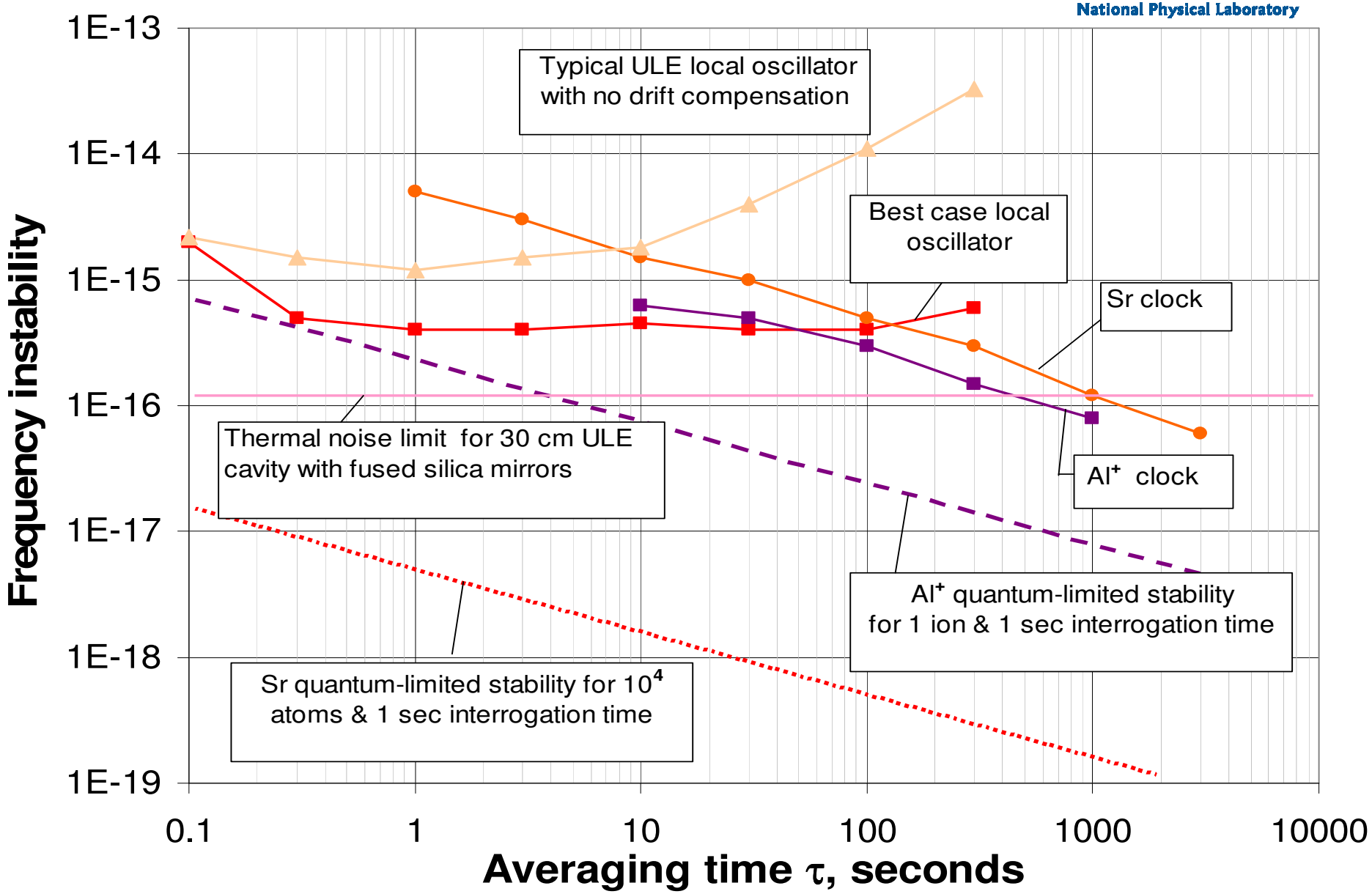

Optical clock shift comparison data

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Ion / atom	Blackbody shift @ 300 K (10^{-16})	Electric quad moment (e_0a^2)	1st order Zeeman shift Ions ~ Hz $(nT)^{-1}$ Atoms ~ Hz $(\mu T)^{-1}$	2nd order Zeeman shift (mHz / μT^2)
$^{199}Hg^+$	NA	-0.51	Ist order insensitive	- 19
$^{27}Al^+$	-0.08	0	2-comp av + shield	-0.007
$^{115}In^+$	0.38	0	2-comp av + shield	
$^{171}Yb^+$ O	-2.4	-0.22	Ist order insensitive	-1.72
$^{171}Yb^+$ Q	-5.4	2.08	Ist order insensitive	-60
$^{88}Sr^+$	7.4	2.6	2-comp av + shield	0.006
$^{40}Ca^+$	9.3	1.83	2-comp av + shield	0.026
^{199}Hg	-1.6	-	2-comp av	-0.024
^{171}Yb	-26	-	2-comp av	-0.006
^{87}Sr	-54.9	-	2-comp av	-0.025

How well can we compare optical frequencies?

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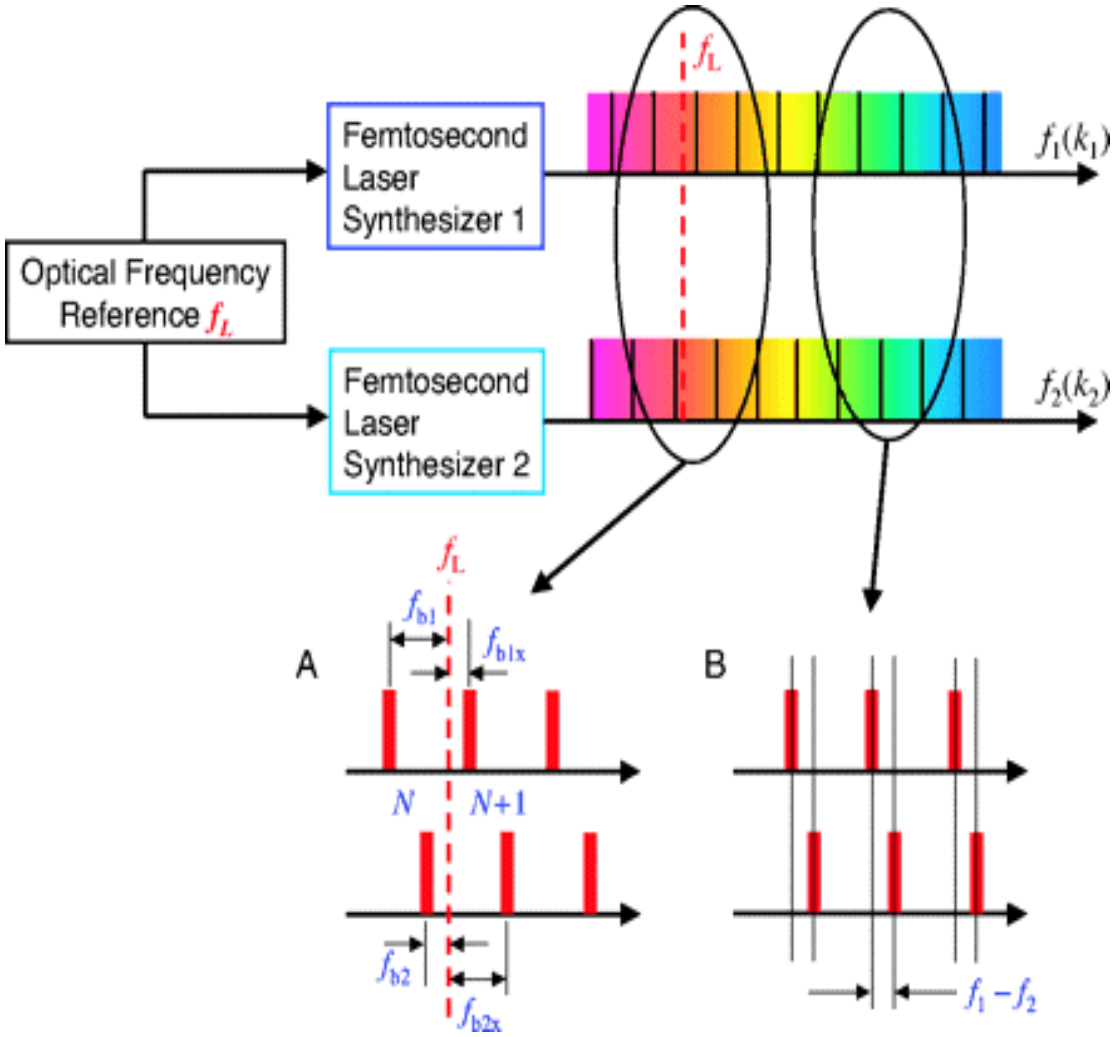

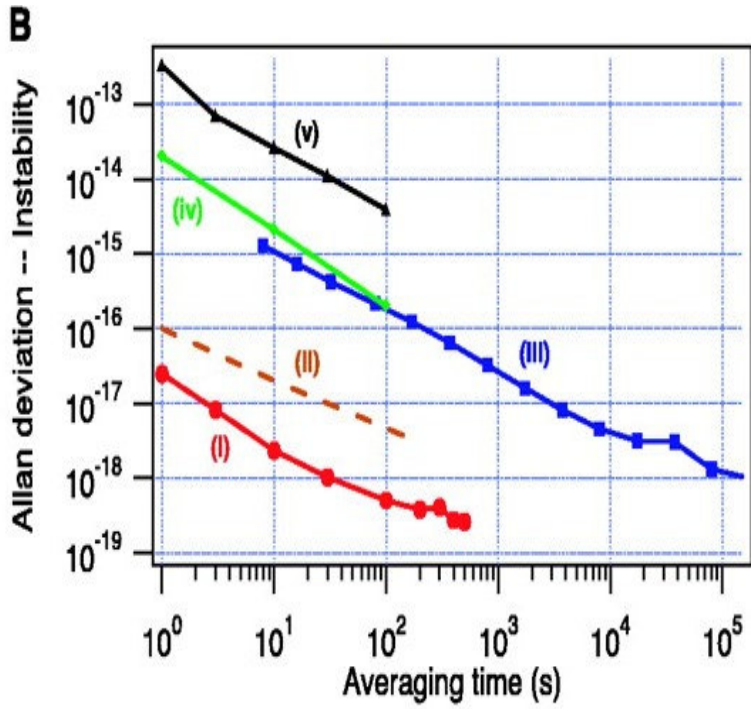

Femto-second comb comparison
L-S Ma et al, Science 2004

Uncertainty between combs locked to the same optical reference:

1.4×10^{-19}

Remote comparison of optical clocks more difficult

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Need: high accuracy (10^{-18}) frequency comparison of remote optical clocks in different NMIs with no loss of clock accuracy

Essential for optical clock evaluation prior to optical redefinition of second

Possible remote frequency comparison techniques:

- Standard two-way satellite microwave comparison:
  Limited to 10^{-15} per day at best
  ACES on ISS microwave link (maybe) → 10^{-17} but 10 days averaging
- Satellite-satellite optical links + ground-satellite time-transfer by laser-link (T2L2): very preliminary demo; target 10^{-16} per day
- Portable optical clocks (trade-off of accuracy for portability)
- Optical carrier frequency transfer by optical fibre (Best results to date)
  coverage issue, but target specific NMI links
- Optical master clock in space in geostationary orbit

Long distance dark fibre links between European NMIs?

Opt carrier transfer over eg 251 km fibre link show link instabilities < 10^{-18} @ 100 s

→ no compromise of clock stability

Newbury et al (NIST), Opt. Lett 2007

NPL – SYRTE: 470 km
NPL – PTB: 880 km
PTB – MPQ: 900 km
NPL – INRIM: 1250 km

Problems:

- Fibre phase noise (fibre optical path length changes) due to vibrations/thermal effects
- Phase noise cancellation by comparing optical signal before / after fibre

→ round-trip time limit to servo bandwidth

Optical carrier transmission feasible over 1000 km with phase-coherent EDFA repeater stages every few 100 kms to address attenuation and bandwidth limits

Optical clocks in Europe

900 km dark fibre link between PTB and MPQ

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- A pair of 900 km dark fibers
- Attenuation > -200dB
- 8 Container stations for
  1. Amplification
  2. Fiber Stabilization
- An optical communication channel allows for remote access to the EDFAs

LPL-SYRTE frequency transfer demo on internet fibre

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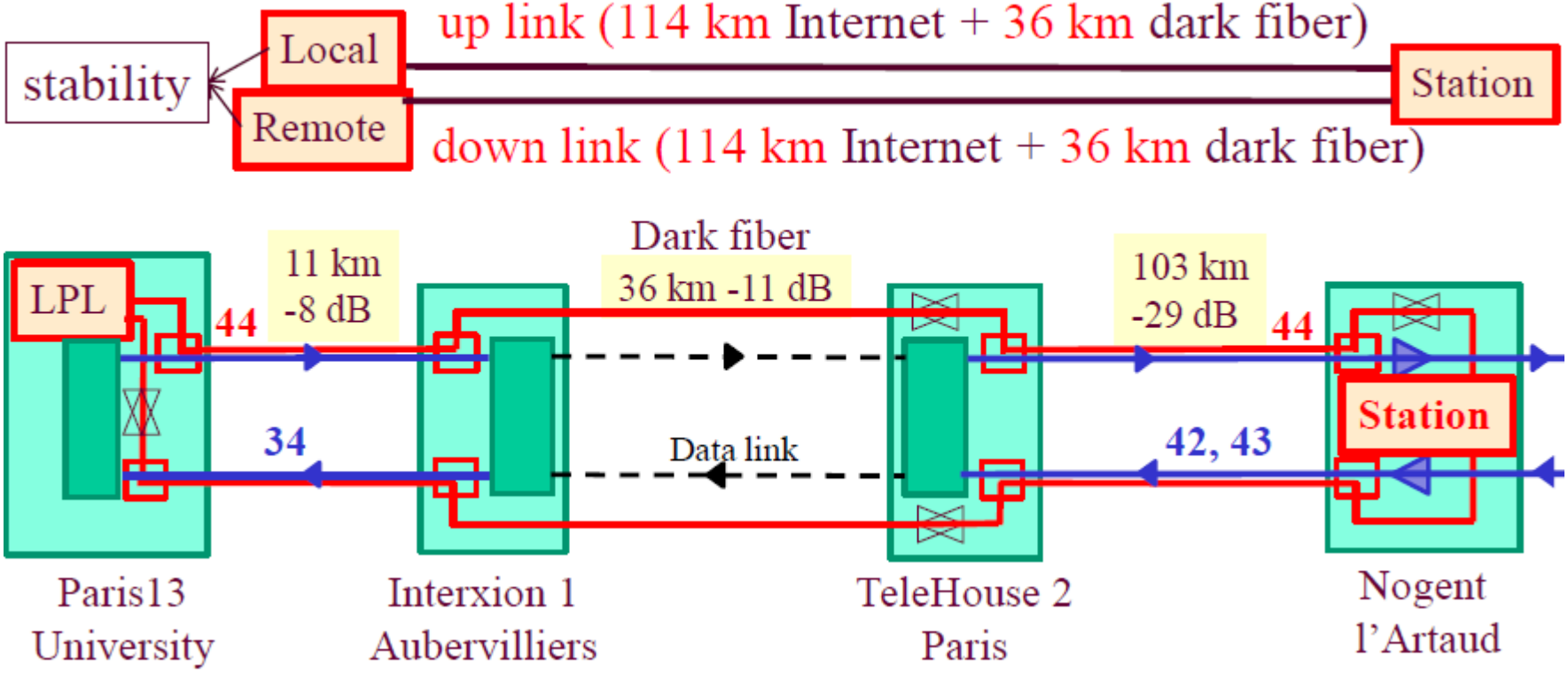
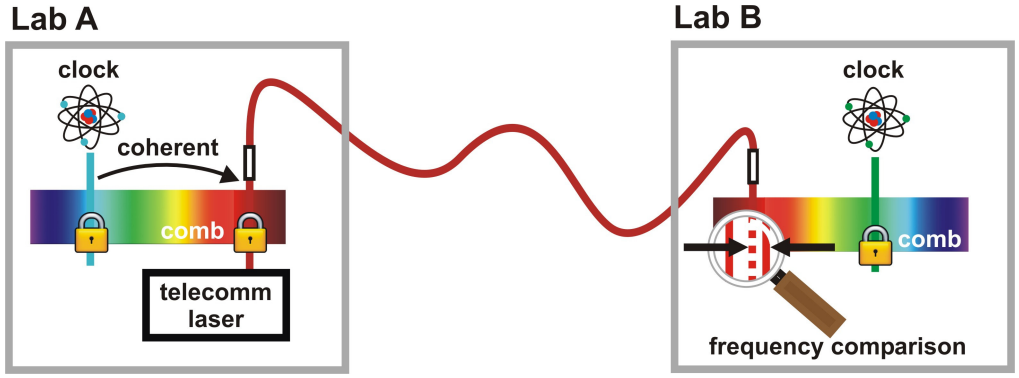


Target:
Link from Paris to Strasbourg

	σ_y@1 s	σ_y@10^4 s
86 km (urban dark fiber)	2×10^{-16}	8×10^{-20}
108km with Internet Data	4×10^{-16}	8×10^{-20}
2x150km with fiber spools	4×10^{-16}	$\sim6\times10^{-20}$
2 x150km multiplex link (urban+backbone)	3×10^{-15}	4×10^{-19}

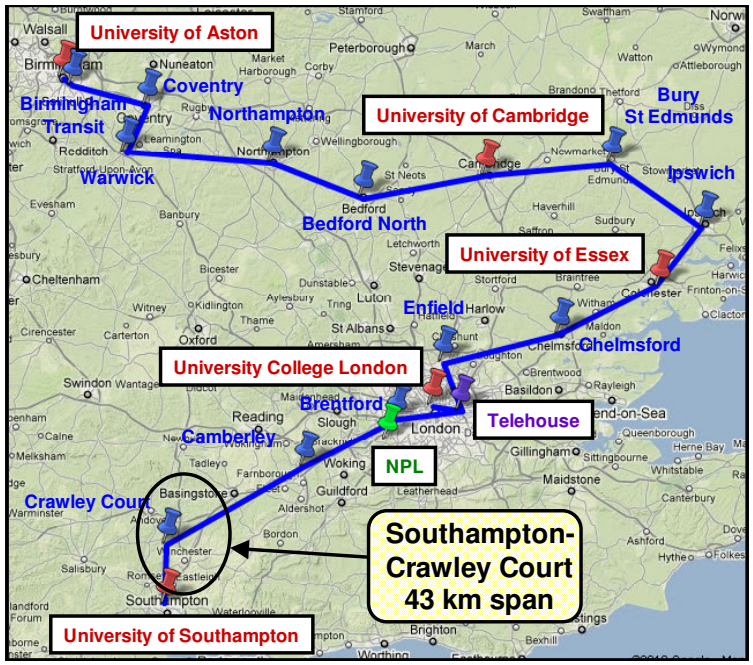
Remote frequency comparison over UK fibre network

Optical carrier transfer



- 1.5 μm ultrastable laser under development for test expts on the JANET Aurora network
- Access to international routes is being explored (eg Geant)

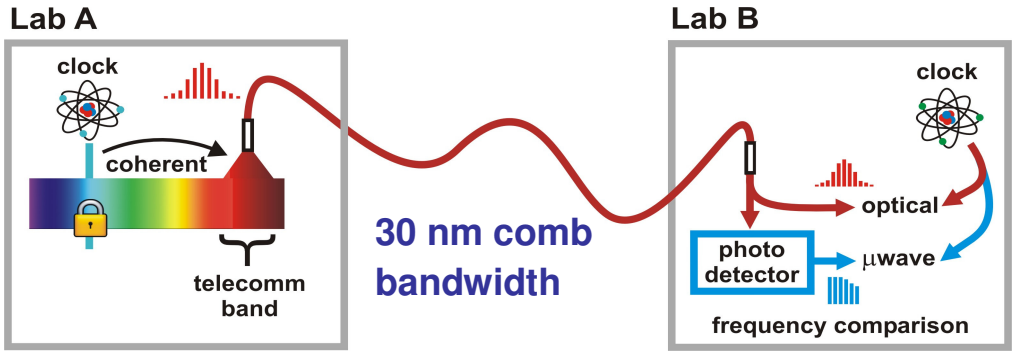
Collab with UCL, London



JANET Aurora dark fibre network

Transfer of an optical frequency comb (simultaneous optical + microwave)

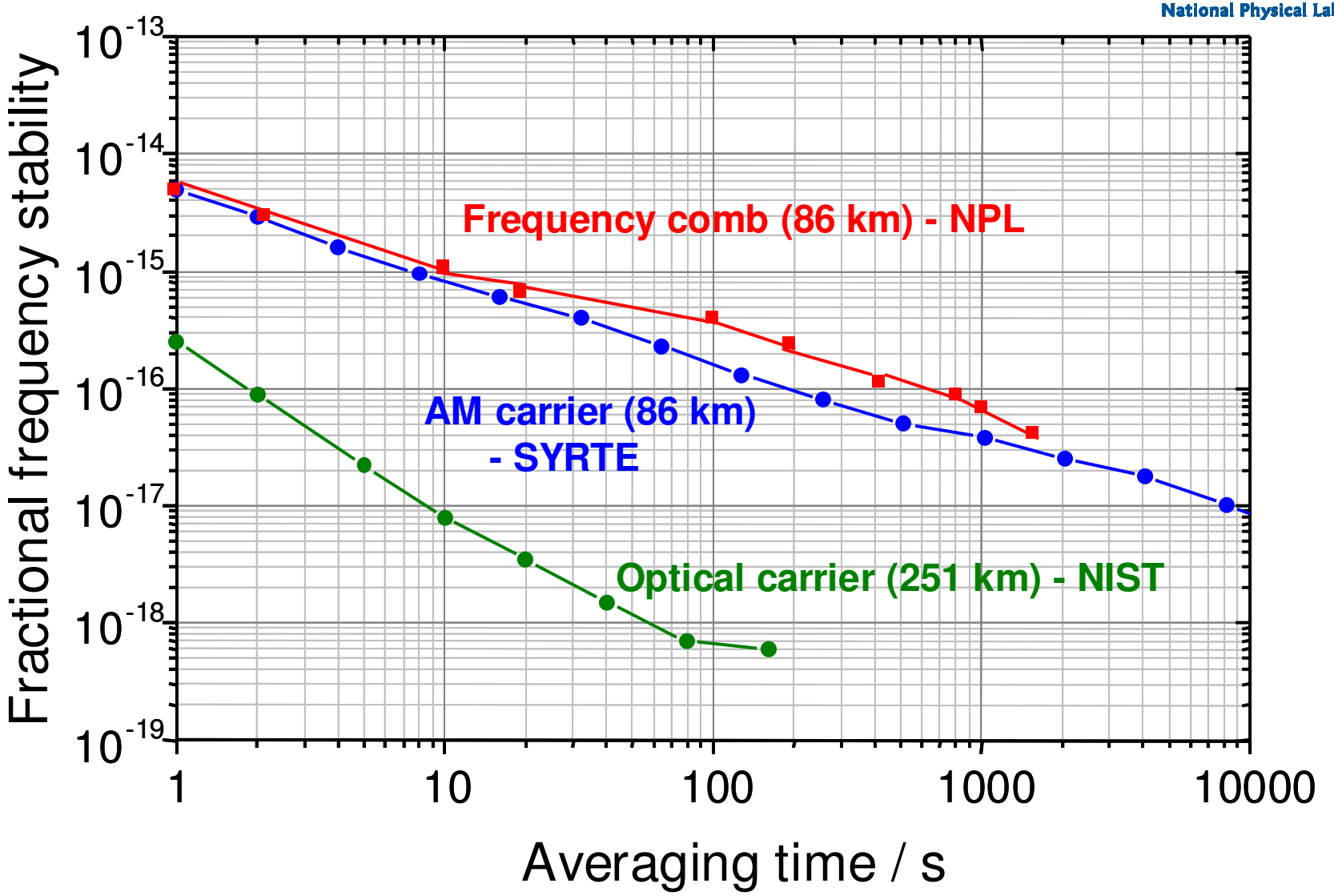
Marra et al. Opt Lett. 2011



Simultaneous transfer of 10^4 equally-spaced optical frequencies + μwave freq. (rep-rate)

Collab.with ORC, University of Southampton

Clock comparison by fibre: state of the art



Challenge: comparison over longer distances.

Timescale for a redefinition of the s

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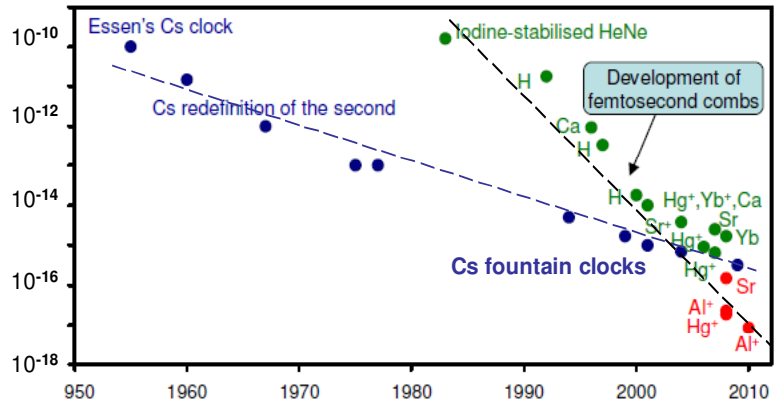
Requirements:

- Improved optical clock reliability
- Option systematics fully evaluated
- Regular optical clock contribution to TAI
- Remote optical clock comparison



Timing:

- Cs OK for time being for current industrial timing requirements
- Science requirements will become limited by Cs-referenced optical sec. representations of s
- High science applications should drive optical clock reliability improvement (eg through space mission technology development)
- Still an open question over "best" choice (eg ion or atoms?, species?)

Once different candidates fully evaluated, rate of improvement will slow down

- Not before high-accuracy remote free-space and fibre comparison available
- Not before 2019 CGPM

Optical “master” clock(s) in space

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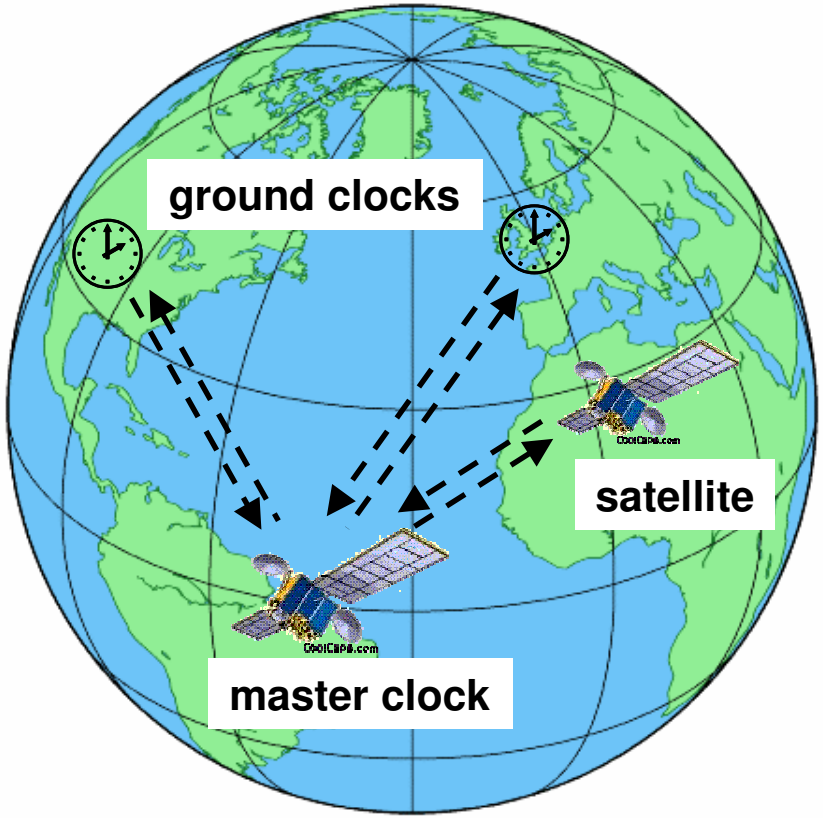
- Could meet requirement for high accuracy (10^{-18} level) intercomparison of remote (trans-atlantic) ground-based optical clocks
- ACES target of 10^{-16} @ 1 day not sufficient



Globe from www.mapAbility.com

- Common-view comparison via optical master clock(s)
- Geostationary orbit(s)
- Gets over the geoid problem: 10^{-18} gravitational redshift for 1 cm height difference on the ground
- Altitude determination to 40 cm required for 10^{-18} accuracy
- Also available for other applications

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Thank you

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&

Many other NMI and CCTF colleagues

National
Measurement
System