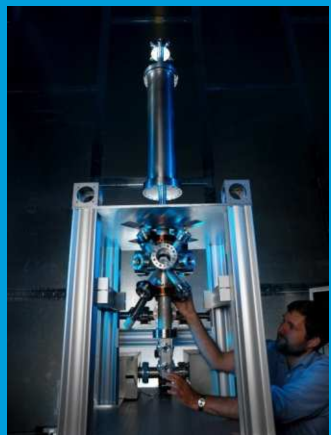
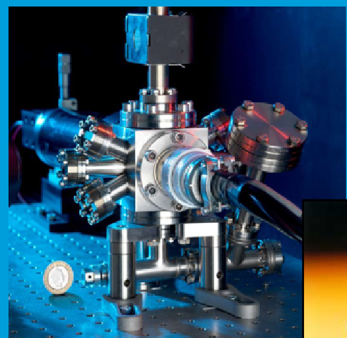
NPL

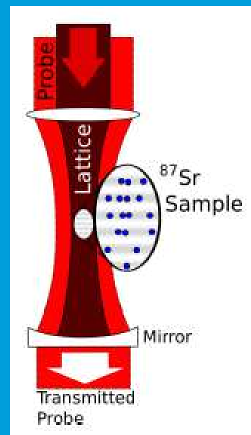
Microwave and Optical Atomic Clocks

Patrick Gill

National Physical Laboratory







National Measurement System

Optical networks for Accurate Time & Frequency Transfer, Amsterdam, 20th November 2012

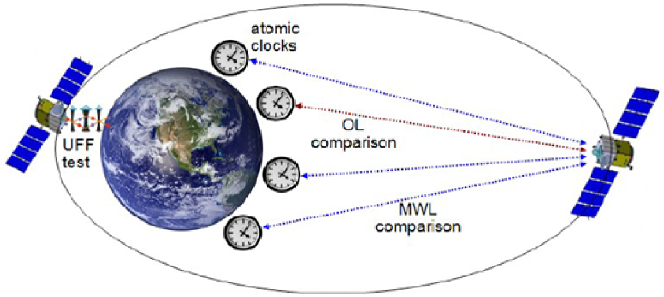
Outline

- Cs Fountain Microwave clocks realising the SI second
- Evolution of atomic clocks → redefinition of the second
- Architecture of optical clocks
- Performance of optical clocks
- Science & technology applications of optical atomic clocks
- Comparison of remote high-accuracy optical clocks

Applications of atomic clocks

- **Realisation of SI units**

  Time (UTC and TAI) and Length



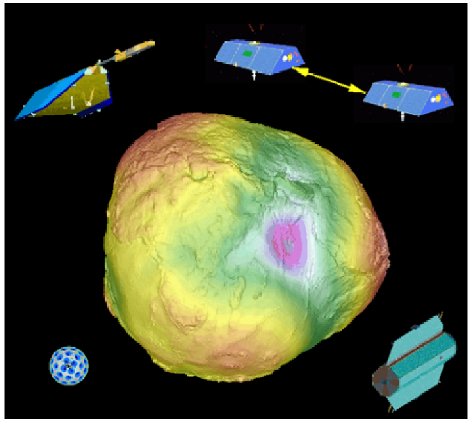
- **Fundamental physics**

  Tests of QED, general relativity

  Measurements of fundamental constants

  Searches for time-variation of fundamental constants

  - Earth Observation – Geoscience



Direct measurement of earth's geoid
with high resolution (cf GRACE, GOCE, NGGM)

- **Satellite navigation and ranging**

  GPS, Galileo and deep space missions

- **Telecommunications**

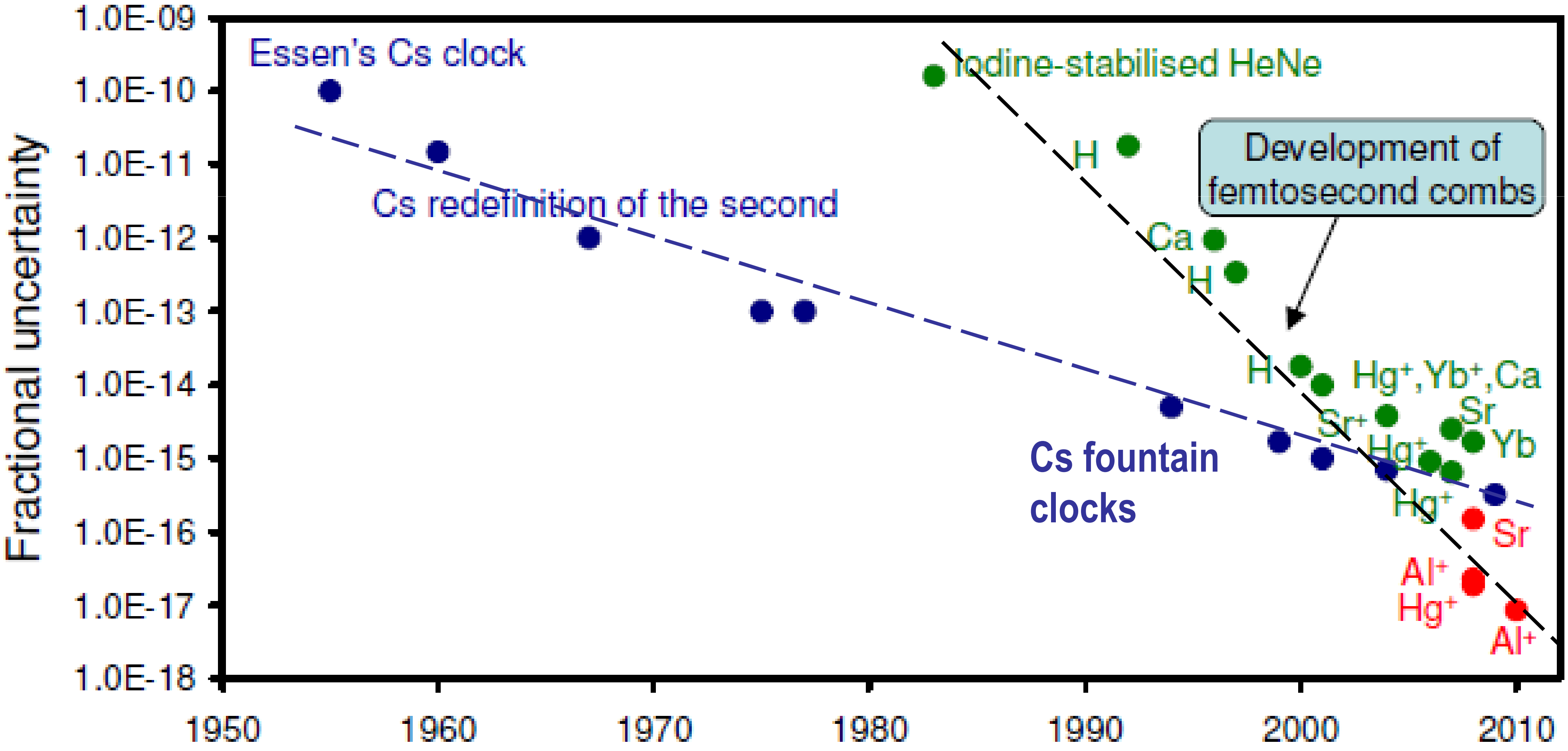
  internet synchronisation

- **Astronomy and survey**

  Star and planetary survey using VLBI

  Distributed antenna array synchronisation

Evolution of atomic clocks



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

Today's best realization

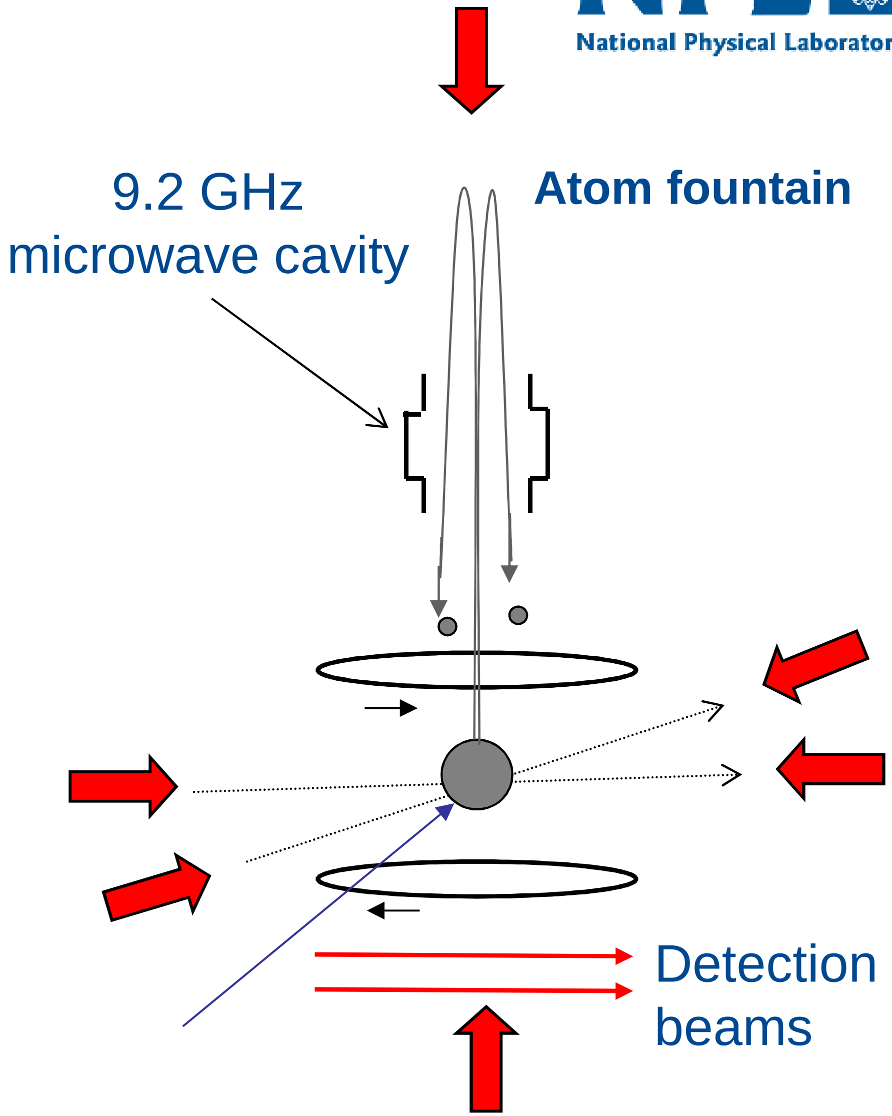
cloud of Cs atoms
laser cooled to few μK
in magneto-optic trap

cold atoms are then launched
vertically by laser light

atoms undergo Ramsey excitation
in microwave cavity

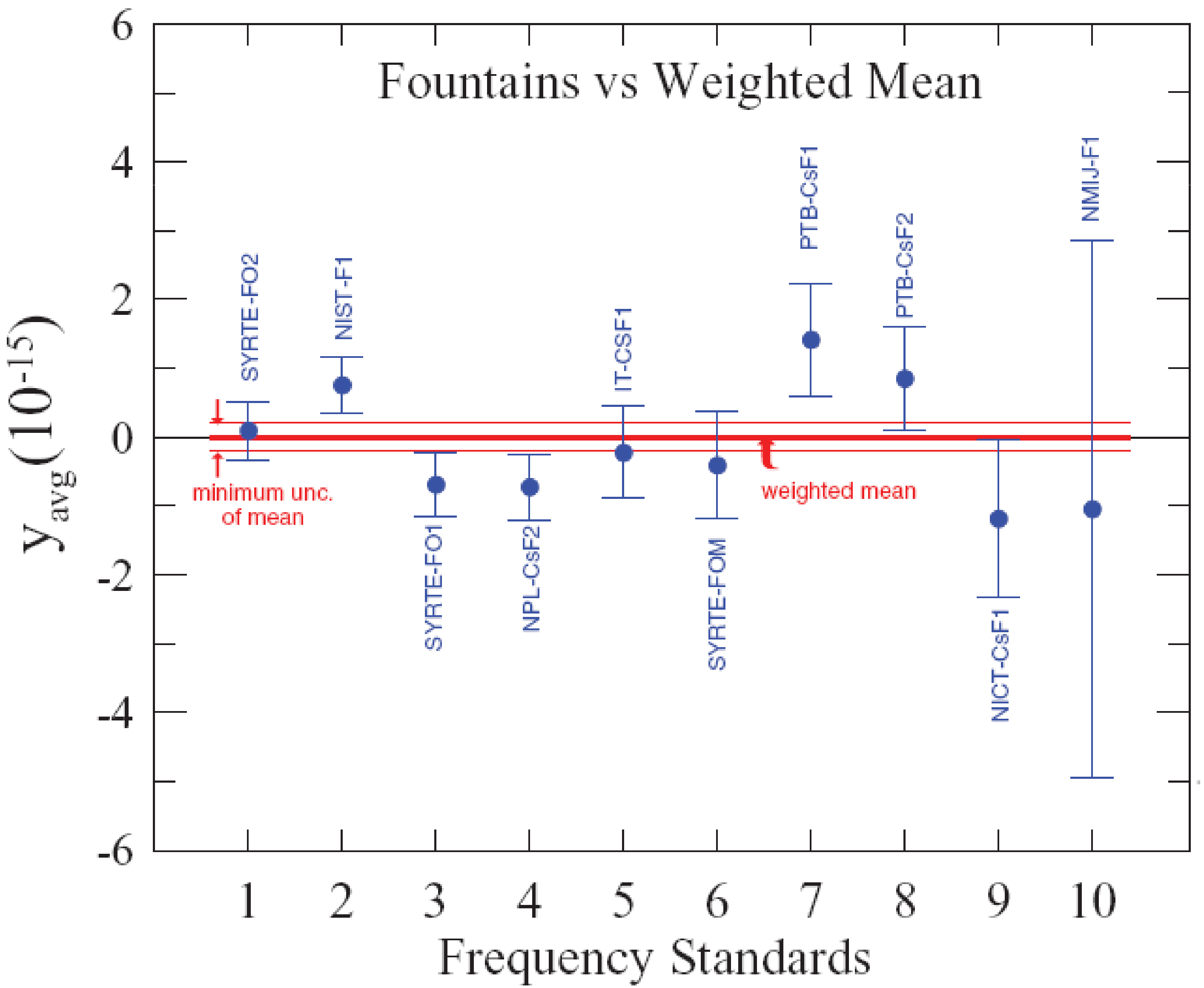
fraction of excited atoms are
detected by laser beams

- < 5x10^{-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)

Comparison of Cs fountains



Compiled from all data published in Circular T during the period March 2008 – May 2011

T. E. Parker, Rev. Sci. Instrum. 83, 021102 (2012)

Advantage of optical clocks

Clock frequency stability:

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

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

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 = 10^3-10^6

Comment on possibilities for a redefinition of the second

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Optical clock definition based on a cold atom or ion:

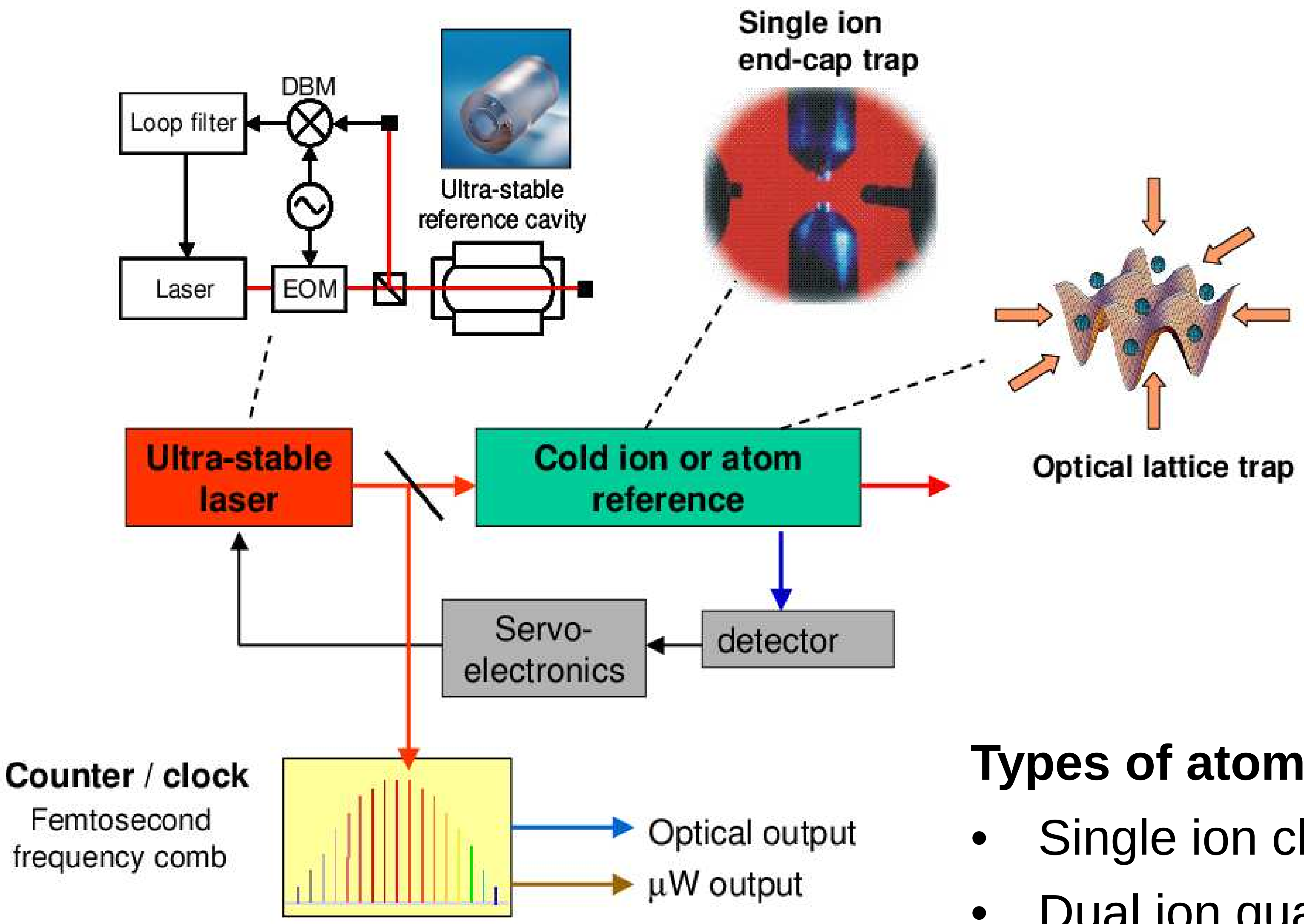
- How to choose the best transition
  (lowest uncertainty? system investigated by most NMIs?)
- There will likely be a number of candidates with uncertainties within a factor of a few of each other
- One could operate with 1 cold ion / atom primary standard plus several other secondary representations
- 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
- Need to ensure consistency between data derived via ratios and Cs-related measurements to avoid disconnects.

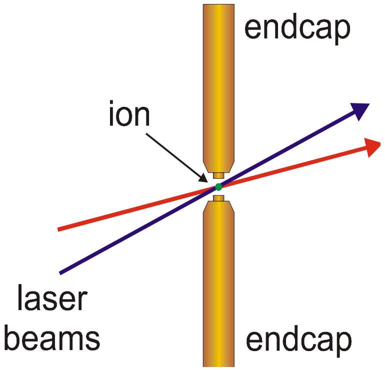
Optical clock architecture

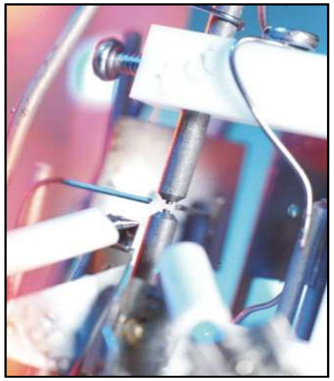


Types of atomic reference:

- Single ion clock
- Dual ion quantum logic clock
- Neutral atoms on optical lattice

Single ion clock





NPL end-cap trap:

"Single ion virtually at rest & isolated from environment"

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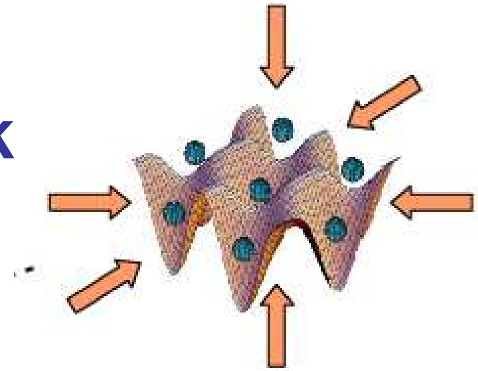
Neutral atom lattice clock

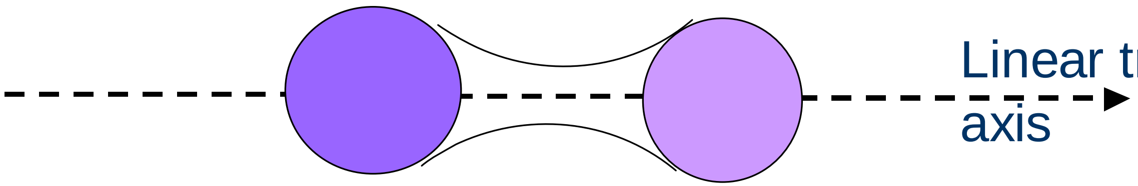
N atoms → stability ∝ √N and controllable systematics

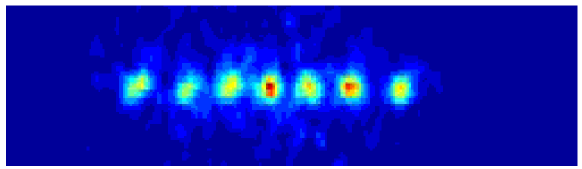


Optical lattice trap

Dual ion quantum logic clock

Logic ion (eg Be+) **Clock ion** (eg Al+)

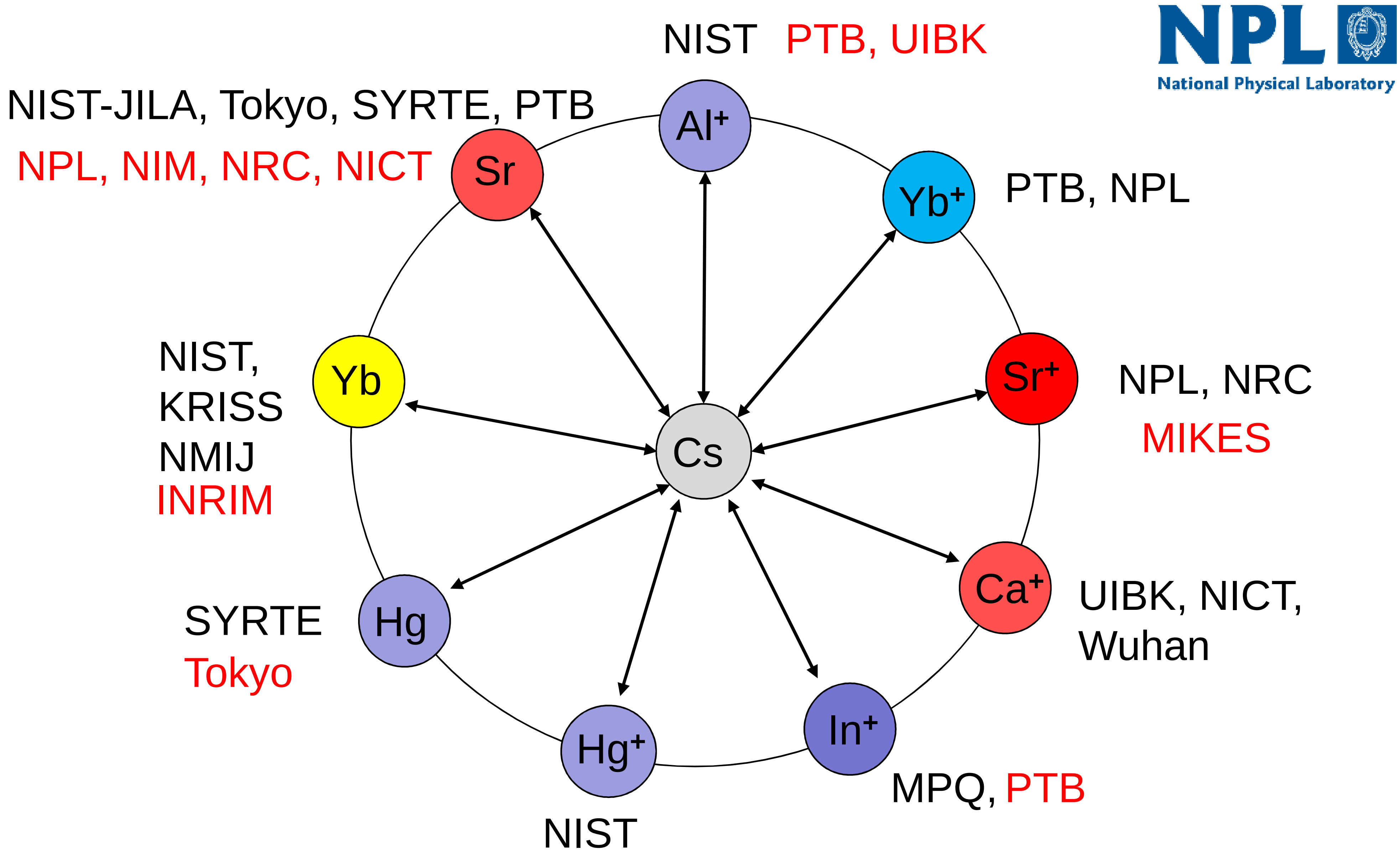




Clock ion sympathetically cooled by logic ion

Clock data read out by logic ion using entanglement

Redefinition candidates: Which ion or atom?



- Some systems now have estimated uncertainties below Cs
- Absolute accuracy – No better than Cs value until redefinition

Single ion quadrupole clocks:

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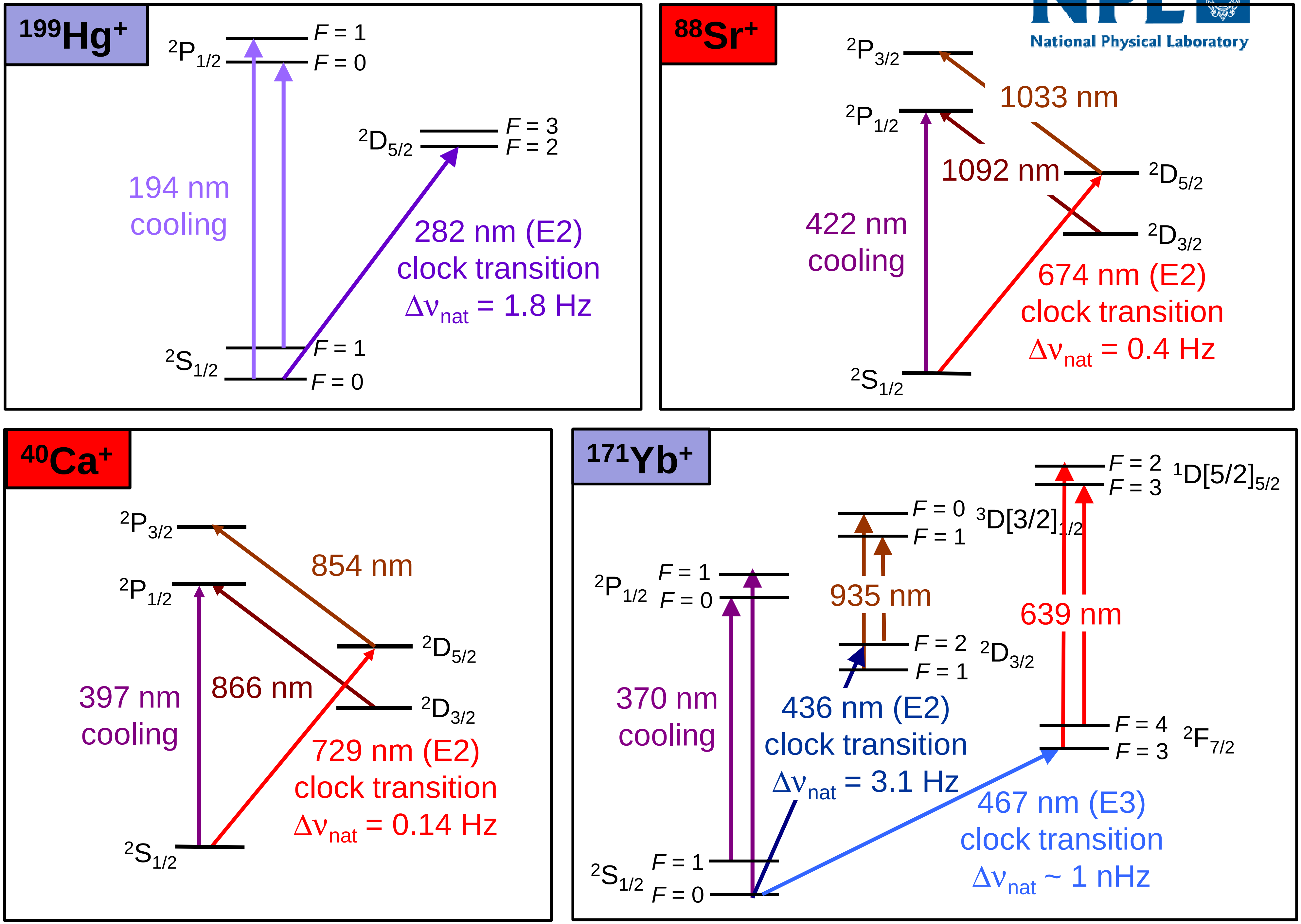
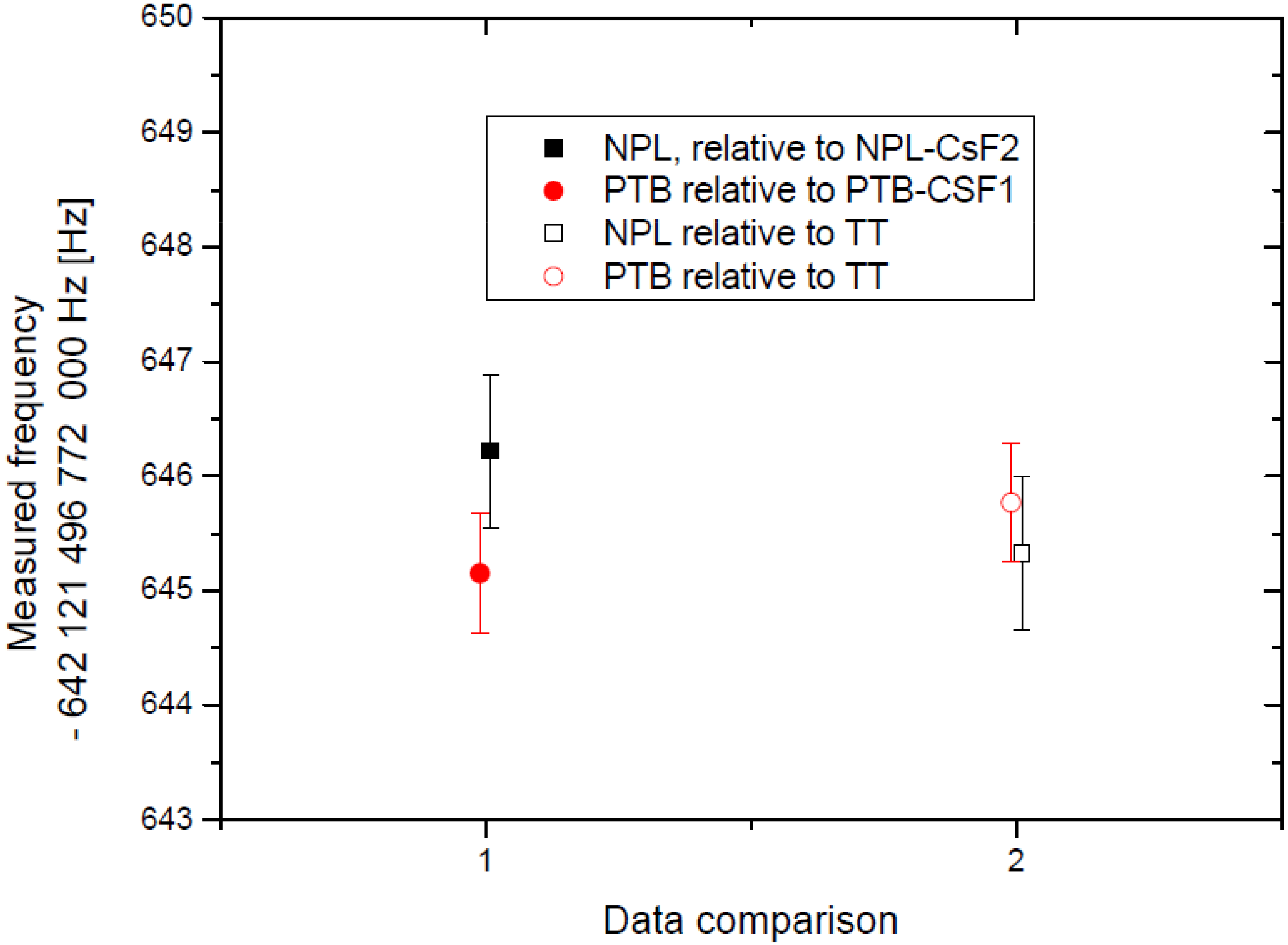


Comparison of PTB & NPL measurements



Excellent agreement between 2 separate expts in different labs

NPL: King et al. New J. Phys 2012

PTB: Huntemann et al.: Phys. Rev Lett 2012

$^{27}Al^+$ 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
√ small quadratic Zeeman shift

X Cooling transition: 167 nm, not accessible, deep UV

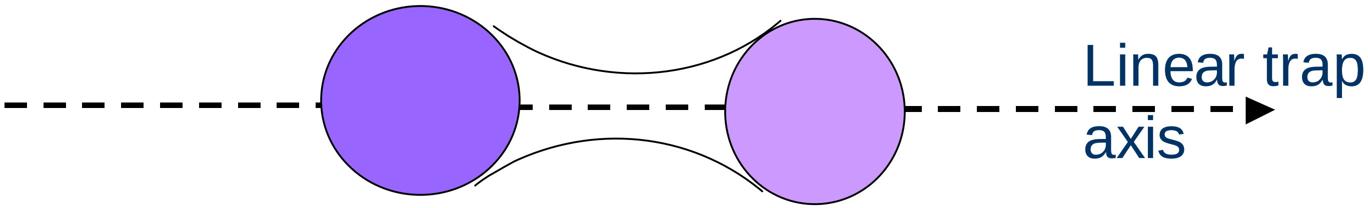
So, how to overcome cooling transition problem?

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

Logic ion (eg Be+) **Clock ion** (eg Al+)



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

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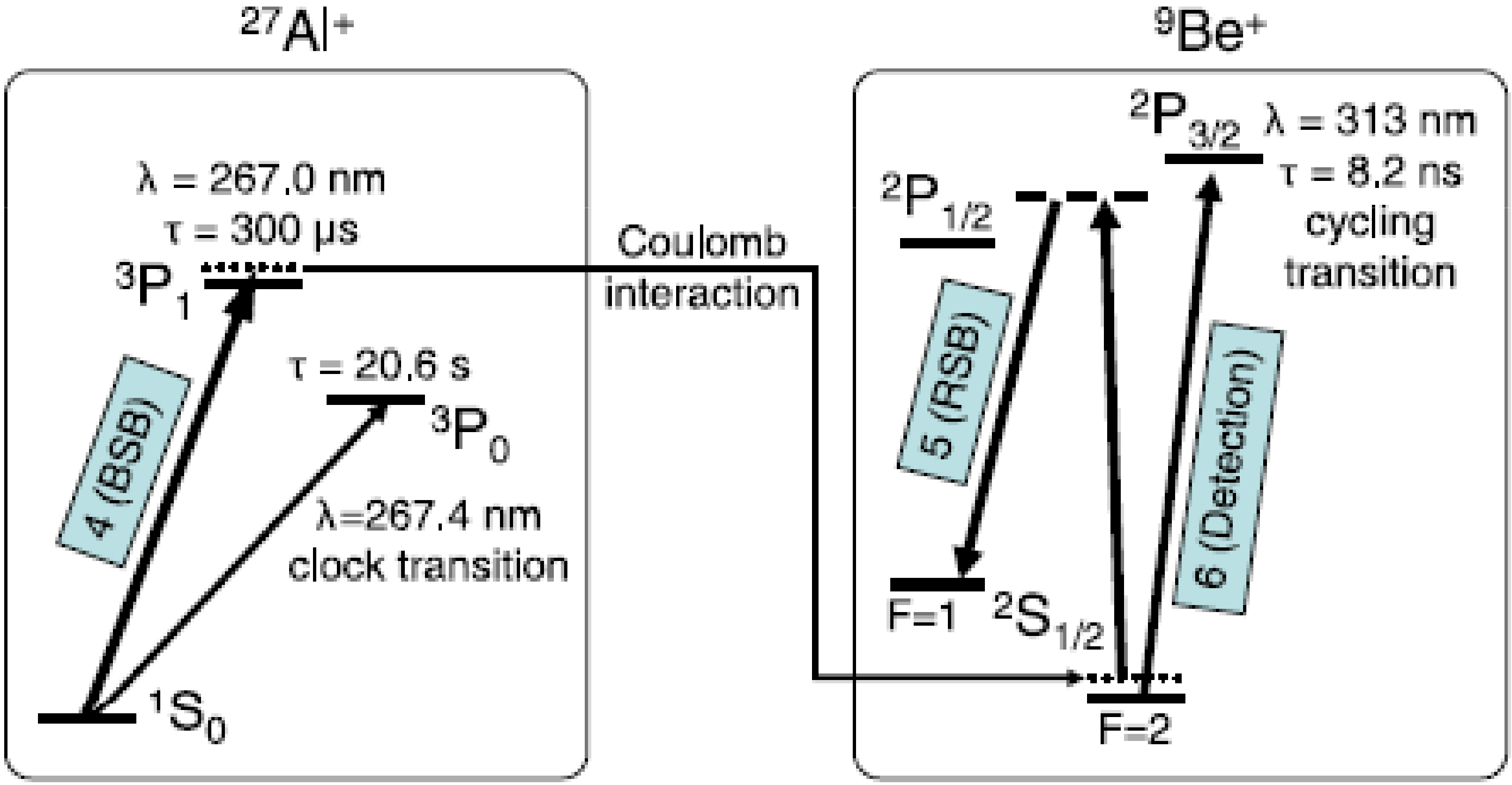
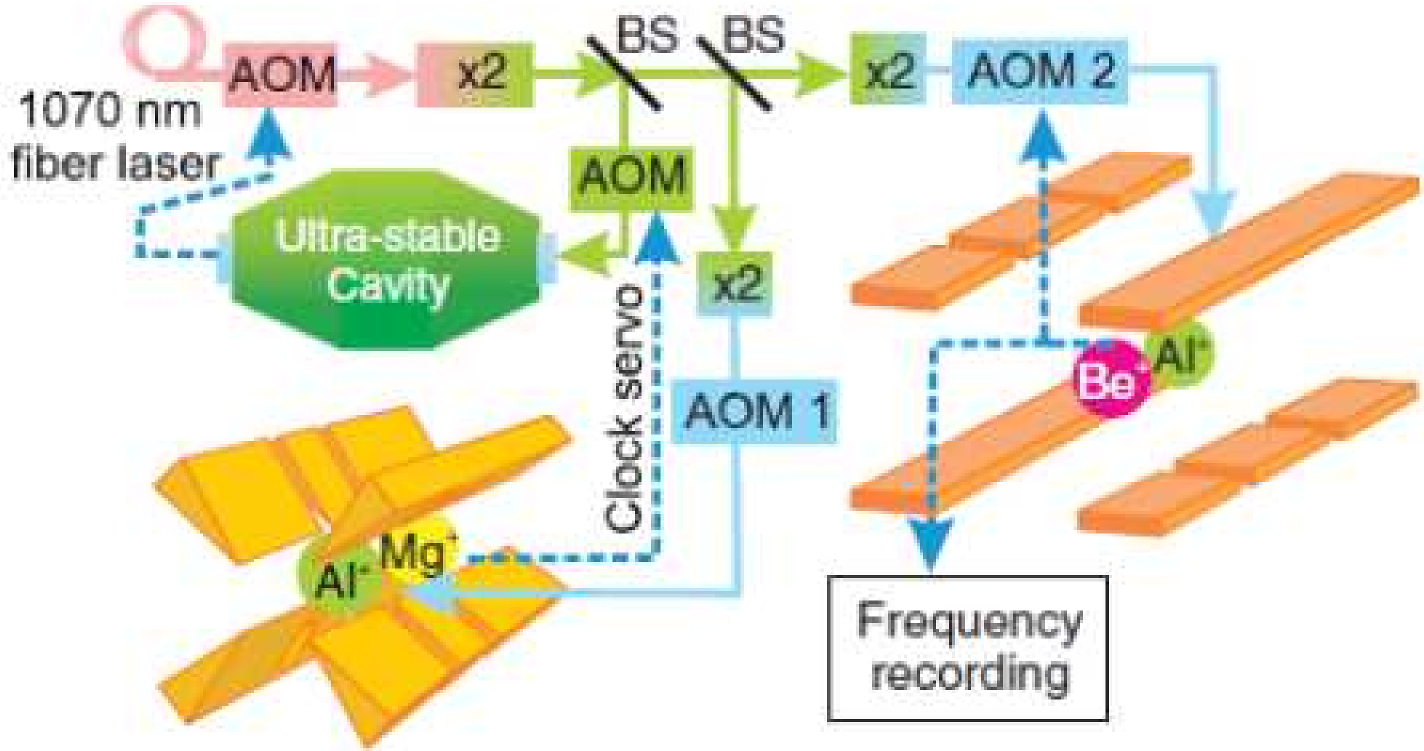
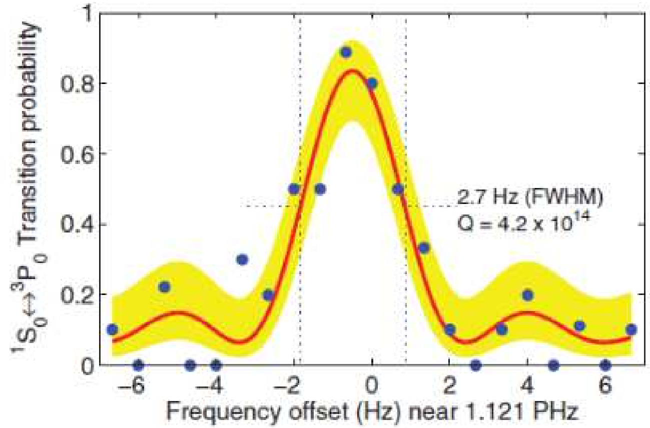


Read-out of the Al^+ clock state by mapping back onto Be^+ ion via entanglement

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

NIST comparison of 2 quantum logic Al^+ clocks





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}

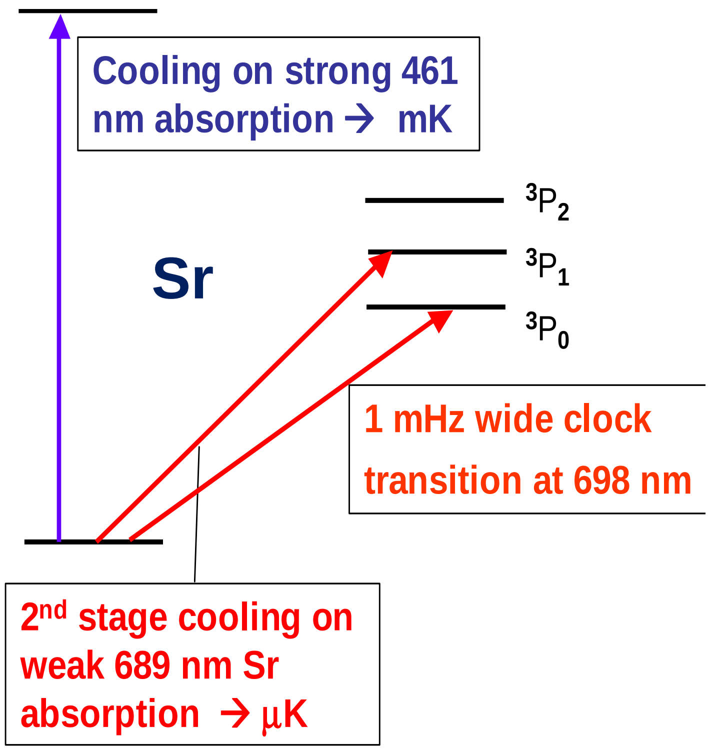
Chou et al. Phys. Rev. Lett ***104*** *(2010)*

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

Neutral atom optical lattice clock (eg Sr, Yb, Hg)

Sr $^1S_0 - {}^3P_0$ clock transition

1 mHz wide natural linewidth



<u>**Optical Lattice to hold the atoms**</u>

Off-resonant standing wave laser field

→Light-shift generated trapping sites with sub-λ spacing

But weak lattice light trapping potential, so

- 2-stage pre-cooling in magneto-optical trap to get to low enough temperatures
- Higher laser powers needed for the trapping, cooling & lattice beams

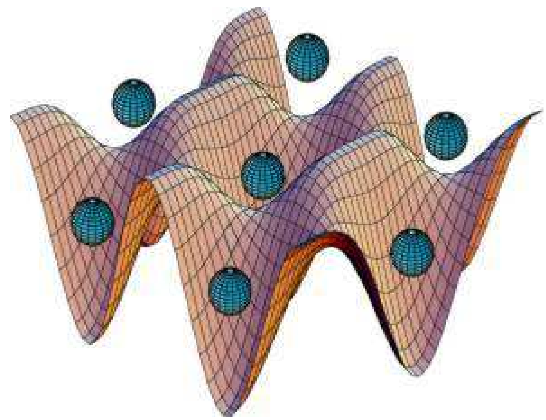
→Storage/interaction times of seconds

→many atoms, good for stability

→No 1st order Doppler effect (Lamb-Dicke regime)

→Collisional shifts small if 1 atom per site

BUT How to deal with AC stark shift (light shift)?



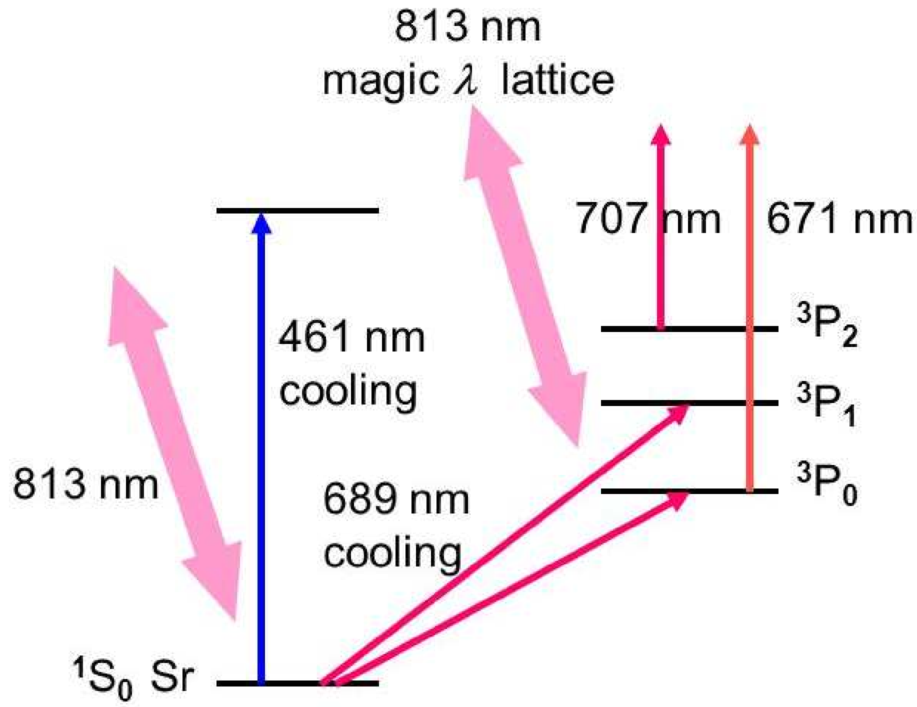
Optical lattice trapping sites

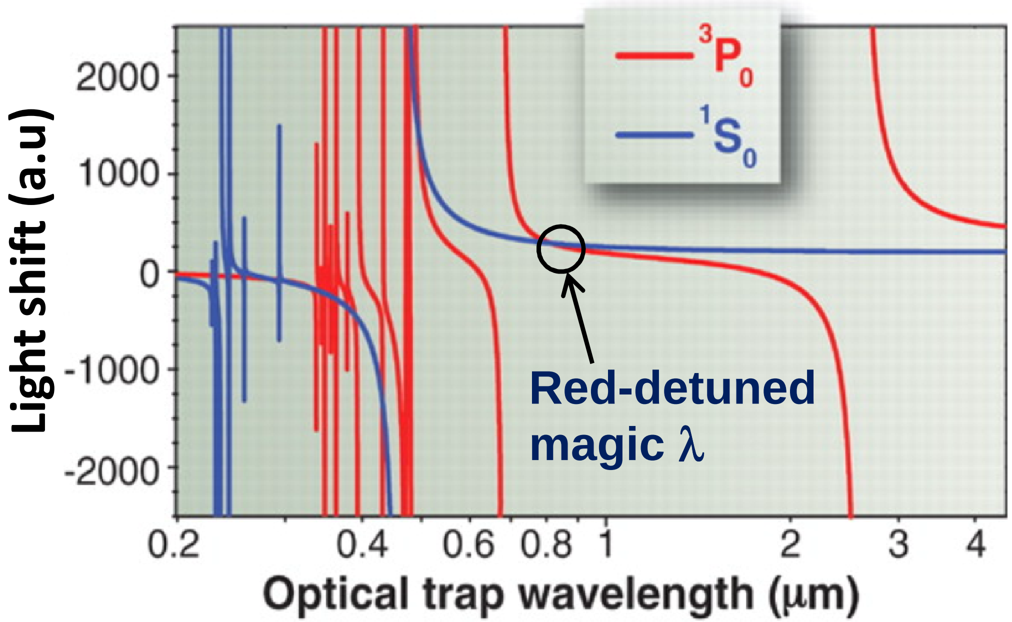
Optical lattice confinement without light shifts

- Sr $^1S_0$-$^3P_0$ clock has ~ 1 mHz natural linewidth but have to avoid broadening and shifts
- Light shift magnitude results from the difference in AC Stark shift caused by off-resonant lattice trapping beam on $^1S_0$ and $^3P_0$ levels
- Minimise overall light shift by tuning to "magic λ" where $^1S_0$ and $^3P_0$ contributions cancel out

→ N atoms with stability ∝ $N^{1/2}$ and controllable systematics

→ But need better LO performance & more data on frequency shifts





Source: Andrew Ludlow

Sr lattice clock:
Absolute frequency measurements

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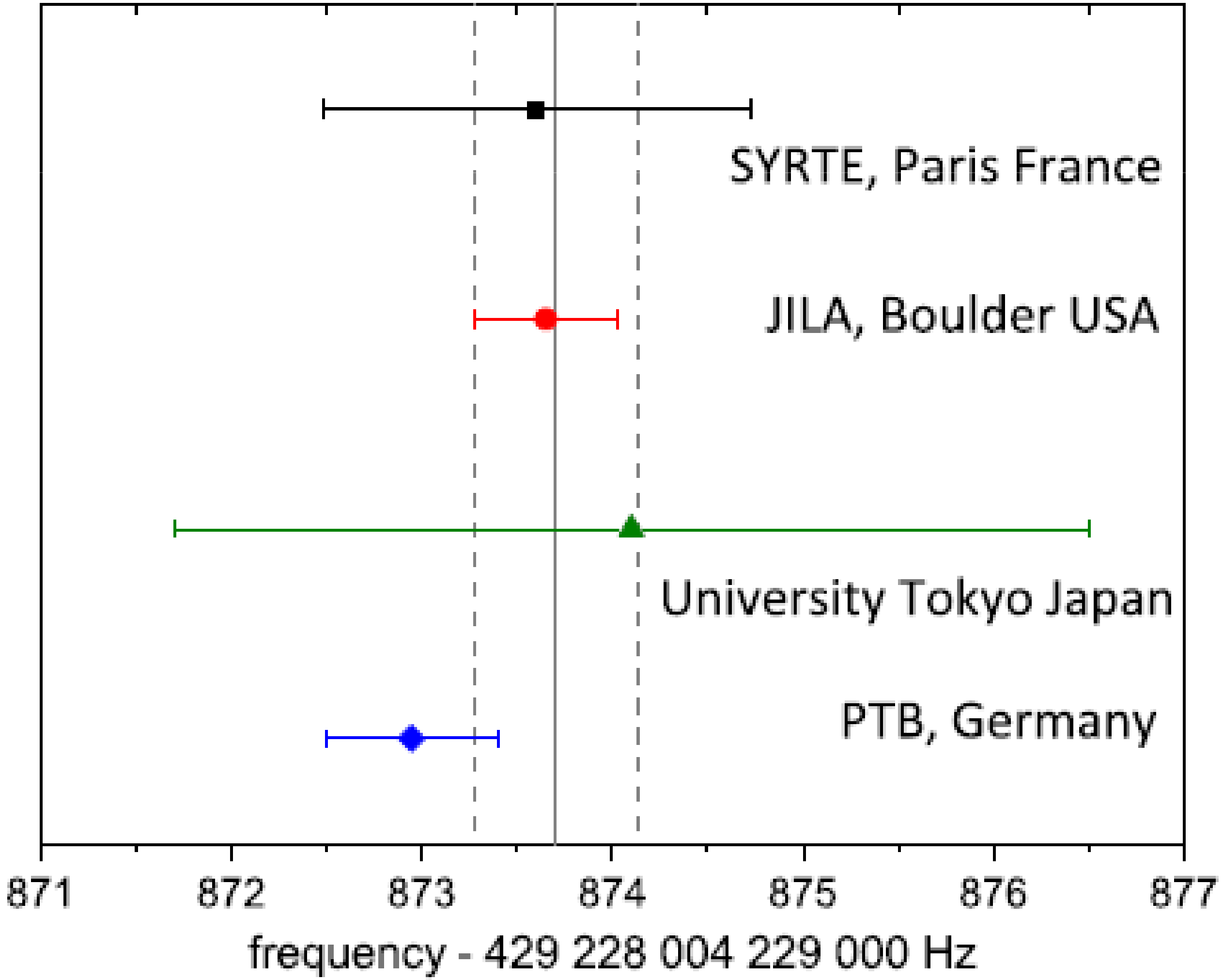

Falke et al, Metrologia 2011

Black-body shifts (Mitroy et al 2010)

Row 2: Relative Black-body shift ($x10^{-16}$) at 300 K

Row 3: Black-body shift at 300 K ($x10^{-18}$) for 1 K change

Ion / atom	$^{199}Hg^+$	$^{27}Al^+$	^{199}Hg	$^{171}Yb^+$ octupole	$^{115}In^+$	$^{171}Yb^+$ quad	$^{88}Sr^+$	$^{40}Ca^+$	^{171}Yb	^{87}Sr
$x10^{-16}$	-	0.07	1.6	1.6	2.0	5.3	5.6	9.2	26	55
$x10^{-18}$	-	0.1	2.1	2	2.7	7	7.4	12.2	35	73

	Logic Clock	UV ion /atom & octupole clocks	visible ion quadrupole clocks	visible atom clocks
Unc. for 1 K	$\sim 10^{-19}$	Low $x10^{-18}$	High 10^{-18}	Mid $x\ 10^{-17}$

Issues (Ions): Temperature shielding, low rf drive power for avoidance hot-spots

(atoms): Temperature shielding, hot oven and thermal beam, mag field coils

So how good are optical clocks right now?

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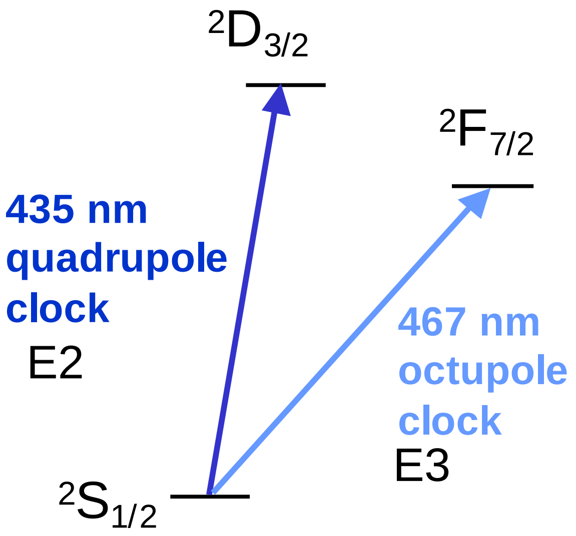
	Reported uncertainty
Al+ ion quantum logic clock:	$9x10^{-18}$
Hg+ ion cryogenic ion clock:	$2x10^{-17}$
Sr+ ion quadrupole clock:	$2.1x10^{-17}$
Yb+ ion octupole clock:	$7x10^{-17}$
Sr neutral lattice clock:	$1.5x10^{-16}$
Yb neutral lattice clock:	$3.4x10^{-16}$
Cs fountain clock systematic unc:	$2x10^{-16}$ (best)

But its work in progress & other systems under evaluation……..

Search for time variations in fundamental constants: eg Fine structure constant (α)



$$\frac{\dot{\nu}}{\nu} = S\,\frac{\dot{\alpha}}{\alpha}$$

- Currently, $\nu\,(_{Al+}) / \nu\,(_{Hg+})$ ratio = 5.2×10^{-17} → $(-1.6 \pm 2.3)\times10^{-17}$
- E2 and E3 transitions in Yb+ ion clocks have large and opposite sensitivities to any time variation of α (sensitivity factor ~ x7)
- **Two clocks in the same ion probed at the same time**
- Some systematic shifts (e.g. gravitational redshift, second-order Doppler shift) cancel exactly when ratio is measured in the same, single ion
- Black body correction not necessary

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

Demonstration of relativistic time dilation in the lab

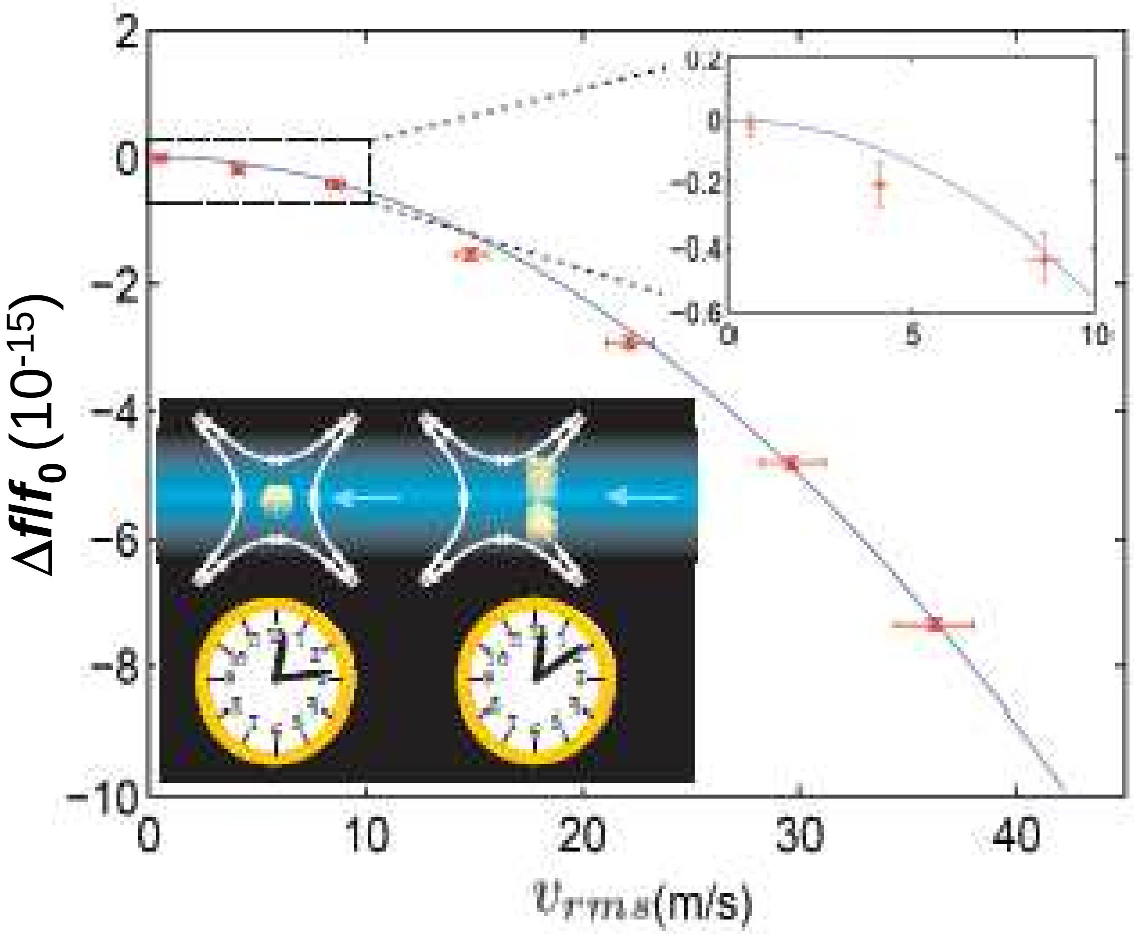
Typically needed large velocities approaching *c*

$$\Delta f/f_0 \sim - \langle v^2 \rangle / 2c^2$$

With optical clocks, can now observe this with slow velocities in the lab:

$$\langle v^2 \rangle = (\beta f_{RF} \lambda)^2/2$$

DC offset voltage applied to trap increases ion's micro-motion and modulation index



Chou et al, Science 2011

Demonstration of gravitational red-shift in the lab

Chou et al, Science 2011

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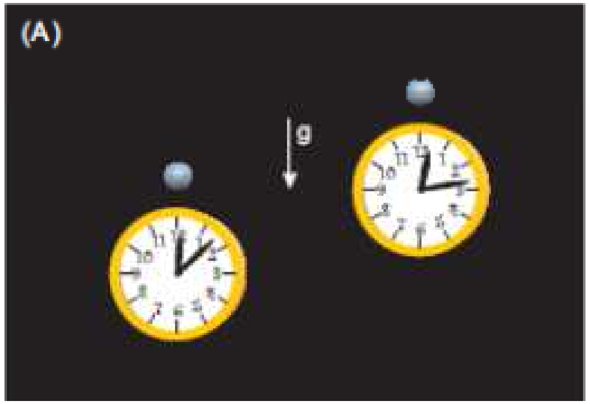


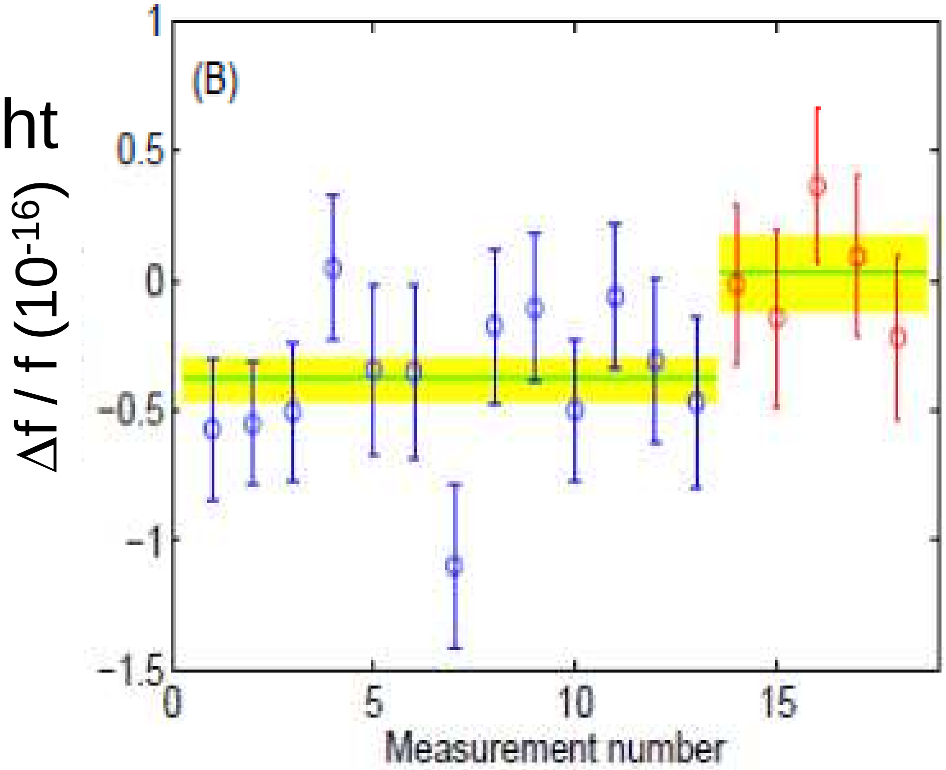
Red-shift between 2 clocks separated in height close to Earth surface:

$$\Delta f / f_0 = g.\Delta h \, / \, c^2 \sim 10^{-16} \text{ per metre}$$

Previous demos required large height differences (10 – 10^4 km)

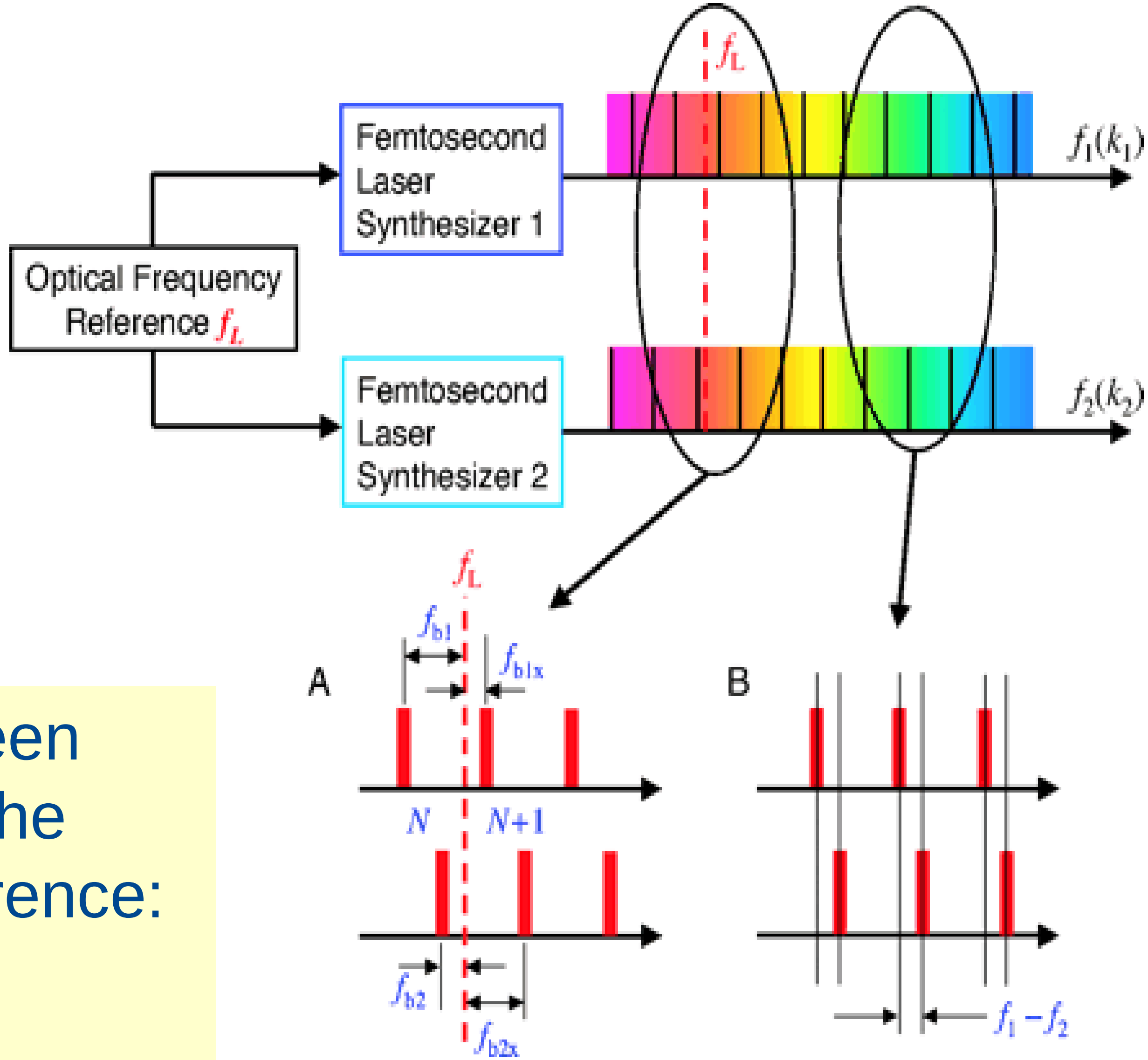
Raising one Al^+ ion clock by 33 cm relative to 2nd clock:

$$\rightarrow \Delta f / f_0 = (4.1 \pm 1.6) \times 10^{-17}$$



→ Implications for future geodesy with optical clocks at the cm – mm level

How well can we compare optical frequencies?



Uncertainty between combs locked to the same optical reference:

1.4×10^{-19}

Direct comparison of remote clocks

Highly desirable prior to any redefinition, but how?

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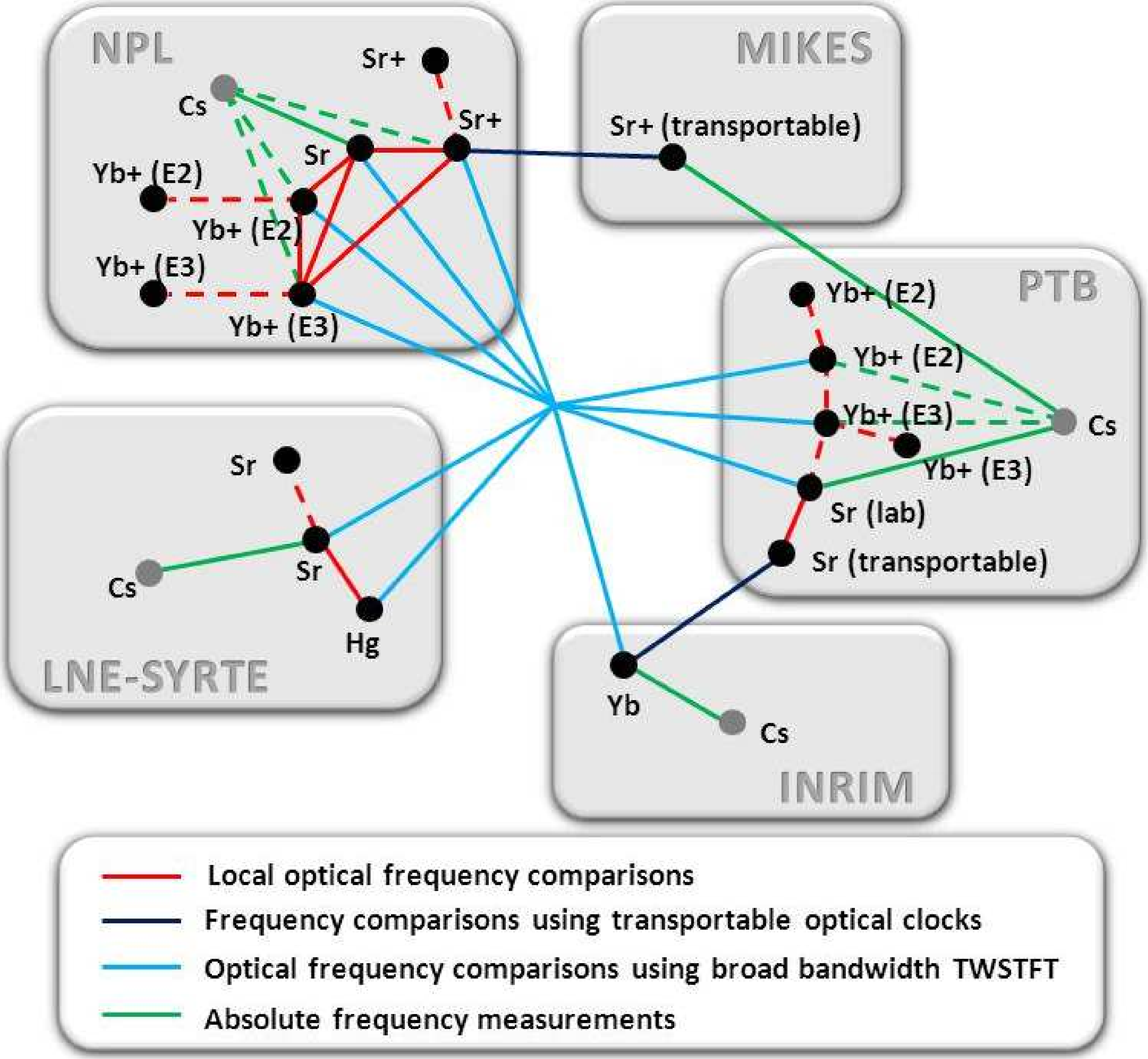
- 2-way satellite frequency transfer
  10^{-15} per day,
  ACES should do better

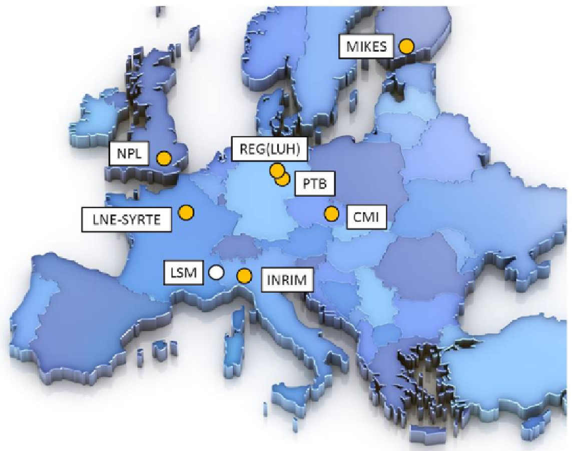
- Optical ground → satellite & satellite → satellite
  In its infancy, some proving expts
  targetting 10^{-16} per day

- Portable clocks
  trade-off accuracy v compactness
  but ESA looking to space clocks

- Optical frequency transfer by fibre
  10^{-18} in minutes demonstrated,
  but coverage issues



EMRP
European
Metrology
Research
Programme
proposal



So where are the fibre links?

900 km dark fibre link between PTB and MPQ

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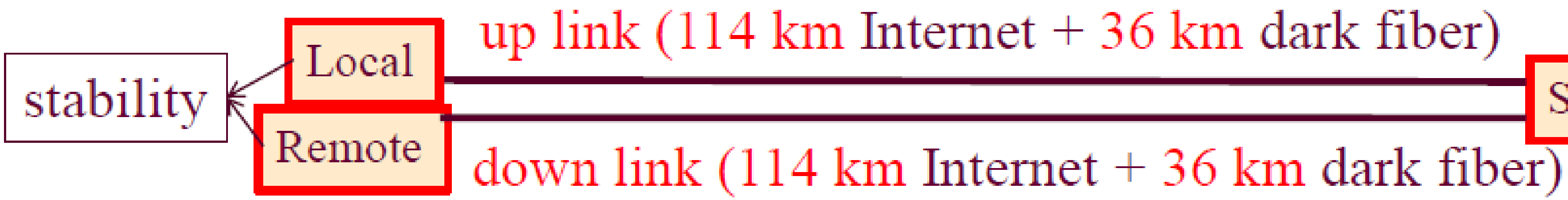
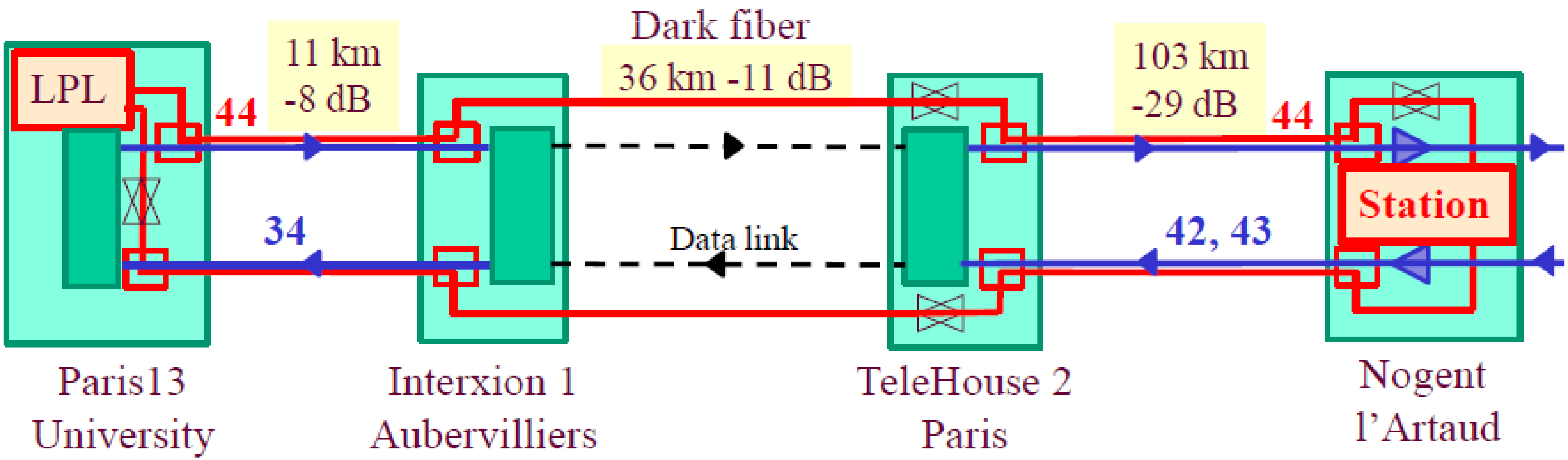
- A pair of 900 km dark fibers
- Attenuation > -200dB
- 8 Container stations for
    1. Amplification
    2. Fiber Stabilization
- An optical communication channel allows for remote access to the EDFAs

LPL-SYRTE frequency transfer demo on internet fibre





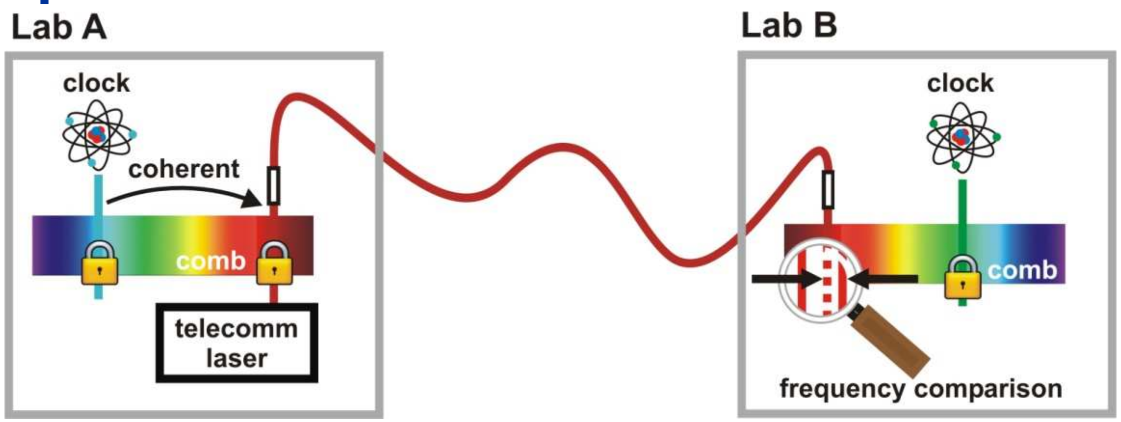
<u>Target:</u>

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}

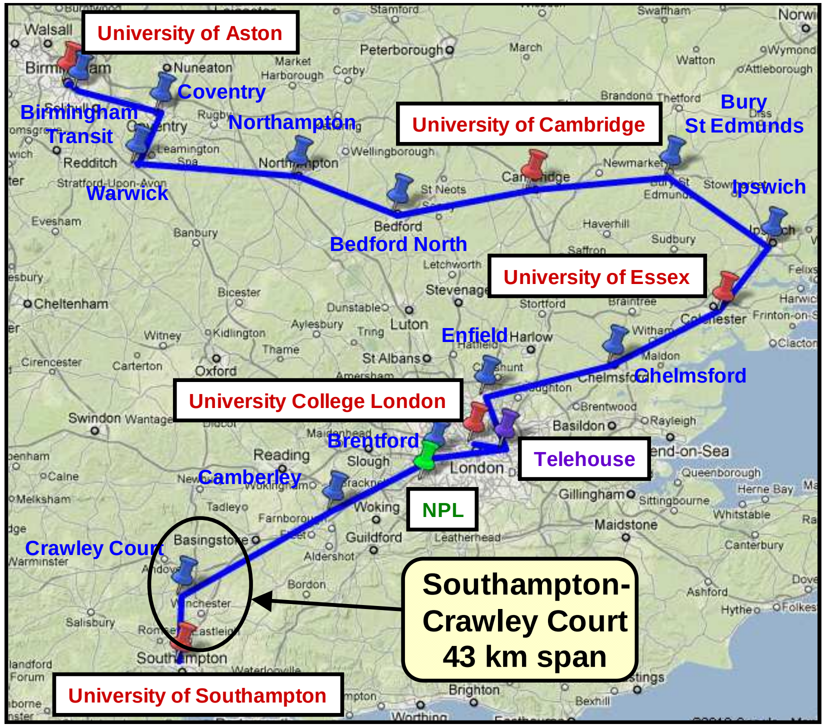
Remote frequency comparison over UK fibre network

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)

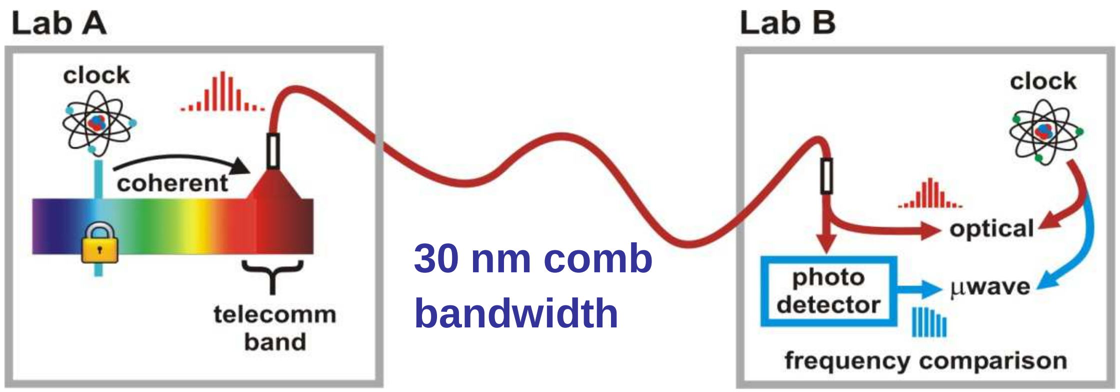
Collab with UCL, London



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

NPL Dark fibre links coming on line early 2013

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Possibilities for a London (NPL) to Paris (SYRTE) link via Geant

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Frequency transfer comparison of ACES Microwave Link with Optical Fibre links?

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ACES due for launch to ISS 2014/15

- On-board Cs and maser clocks
- MWL link allowing remote clock comparison of European high-accuracy clocks in common view
- Projected comparison accuracy at $\leq 10^{-16}$

Potential for direct comparison of frequency transfer via ACES MWL and via upcoming optical fibre links between TAI labs

Euro-Fibre network evolving for high-accuracy frequency transfer

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

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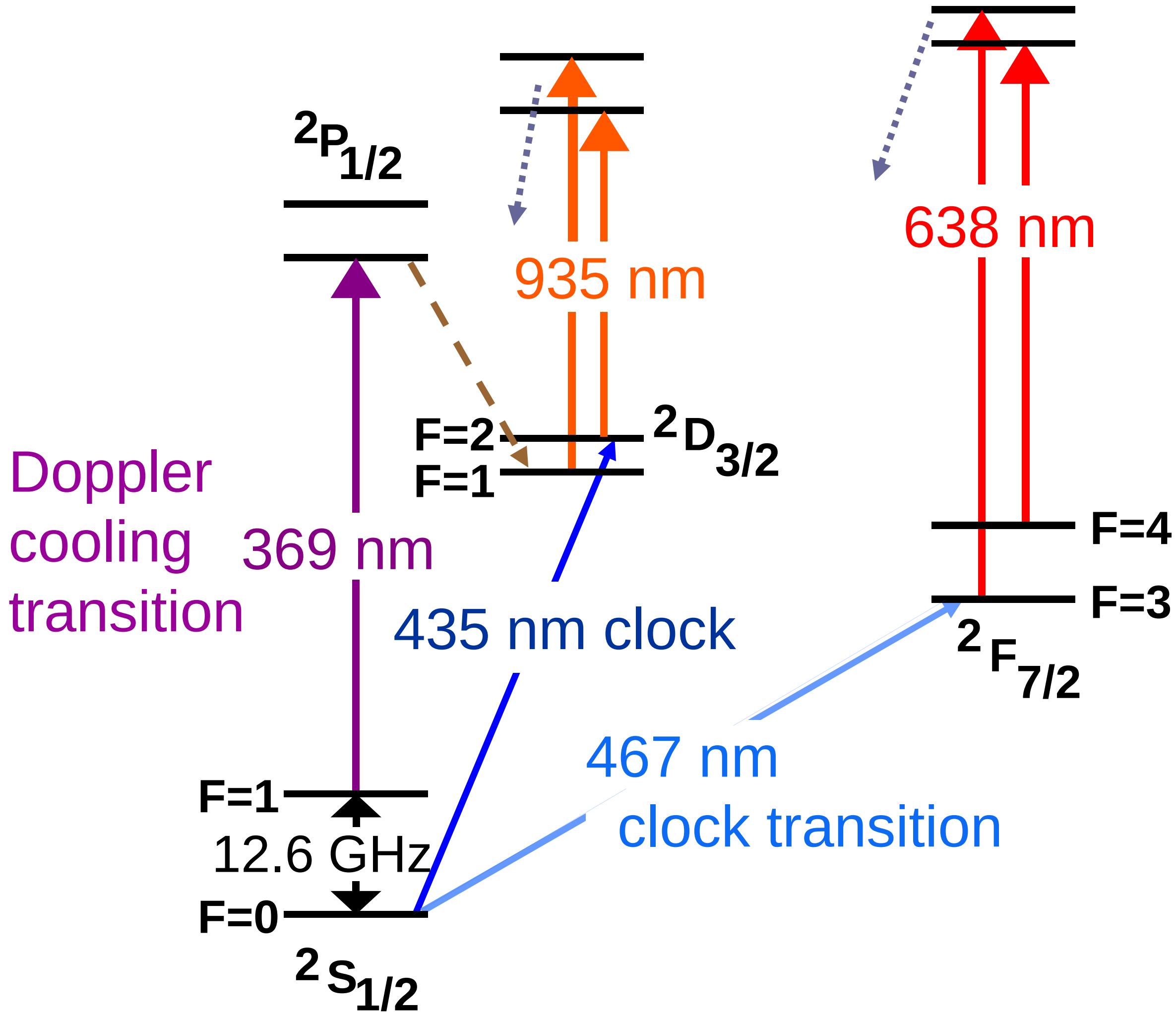
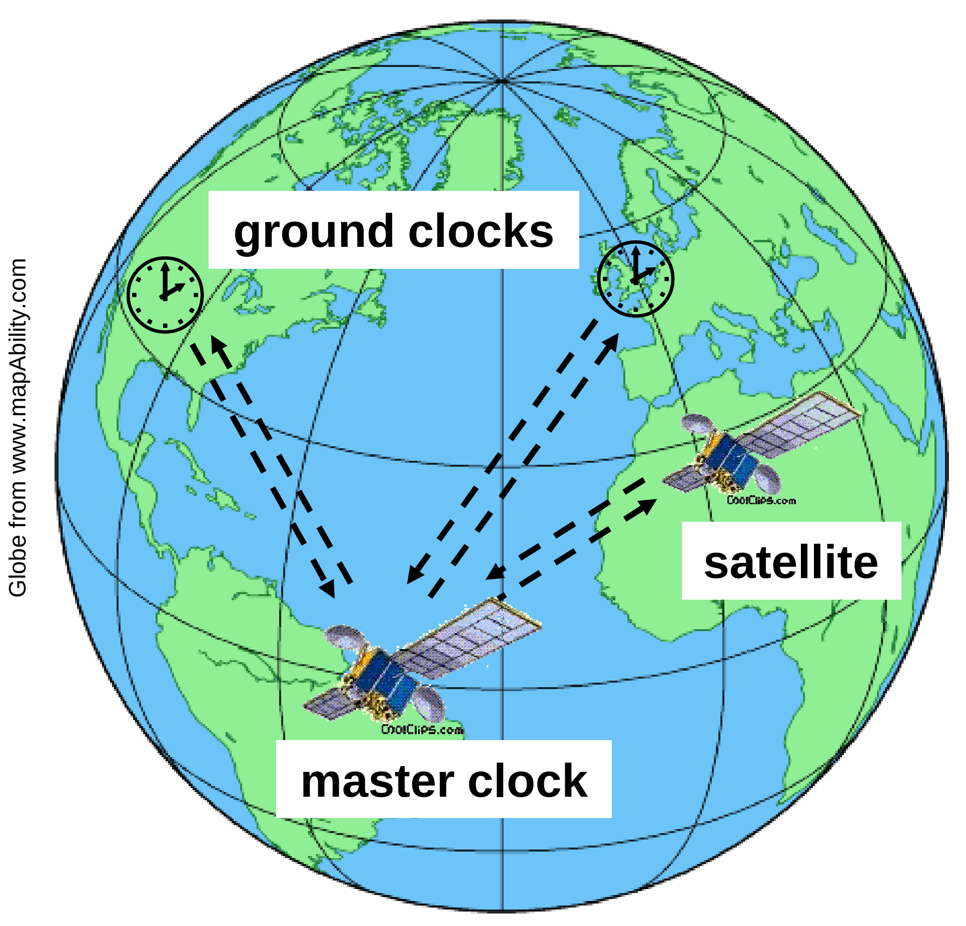
- **Electric octupole transition**
  Very weak transition at 467 nm
- **Natural linewidth ~ nHz**
  Limited by probe laser linewidth
- **Odd isotope**
  → hyperfine levels, but
- **$m_F = 0 \rightarrow m_F = 0$ transition**
  Free from linear Zeeman shift
  Small quadratic Zeeman shift
- **AC Stark shift**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



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

Optical “master” clock(s) in space

- 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



- Common-view comparison via optical master clock(s)
- Geostationary orbit(s)
- Gets over the geoid problem: $\mathbf{10^{-18}}$ 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