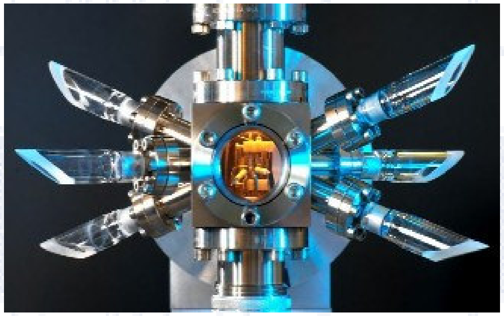
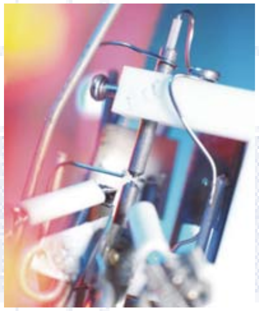
Recent Advances in Optical Frequency Standards & Precision Measurements





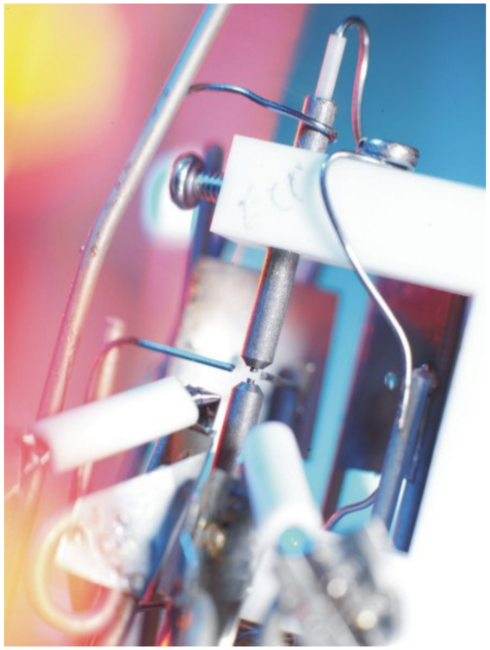
Patrick Gill

Geoff Barwood, Hugh Klein, Kazu Hosaka, Guilong Huang,
Stephen Lea, Helen Margolis, Krzysztof Szymaniec, Stephen Webster,
Adrian Stannard & Barney Walton

National Physical Laboratory, UK

Advances in Precision Tests & Experimental Gravitatition in Space
Galileo Galilei Institute, Arcetri, Firenze 28th Sept 2006

Outline



- Introduction to optical frequency standards
- Different approaches
- Recent trapped ion advances
- Cold atom lattice clocks
- Opportunities, problems
- Summary & future

The optical advantage

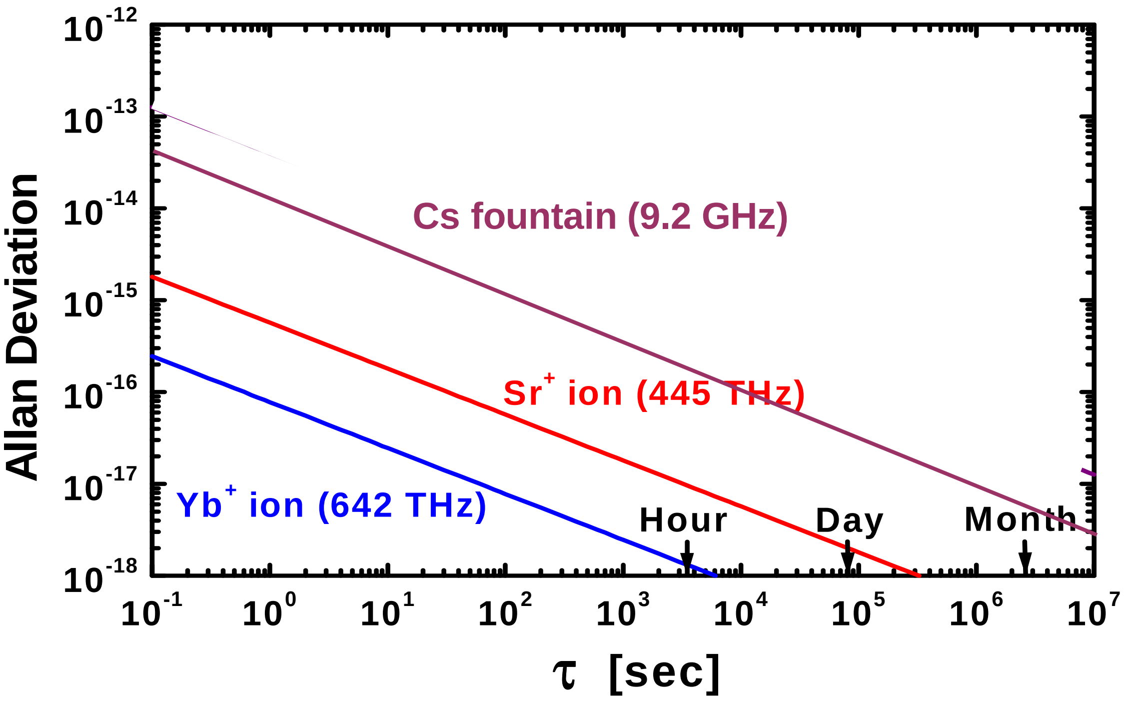
Frequency Instability:

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

- **Frequency ~ 10^5 times higher**

- **Linewidth determined by interrogation time (limited either by natural decay or probe interaction time)**

→ better stability in optical



Assuming: Cs fountain: $T_{\text{int}} = 1$ sec

Sr^+ ion: $T_{\text{int}} = 0.4$ sec

Yb^+ ion: $T_{\text{int}} = 10$ sec

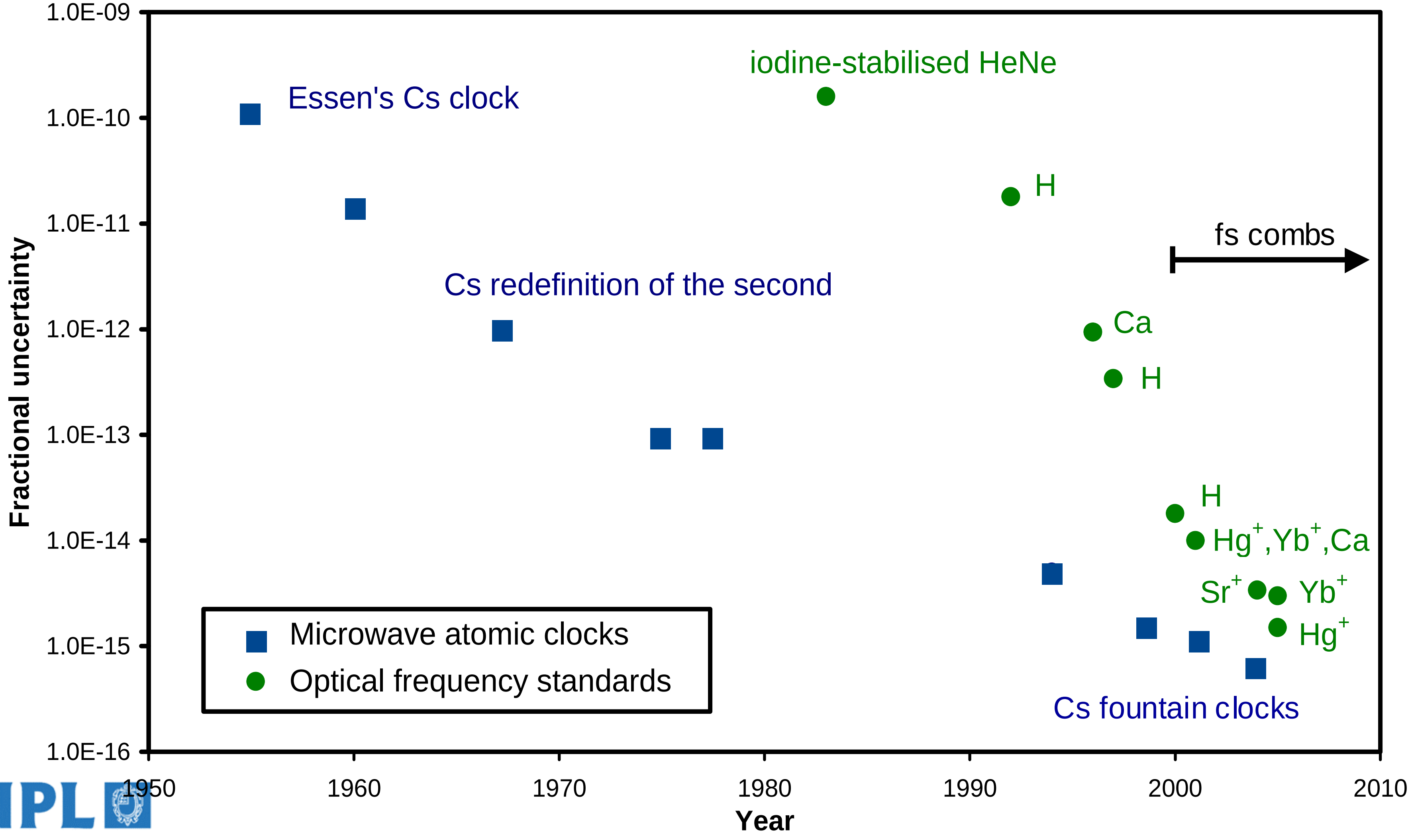
ν : Frequency of clock transition

N : Number of atoms / ions

T_{int} : Ramsey interrogation time

τ : Sampling time

Improvements in optical frequency standards

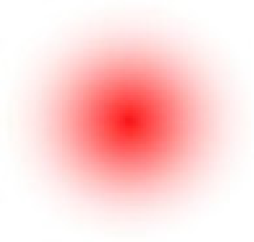


The Field!

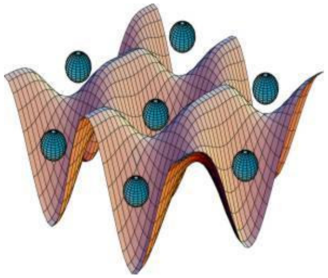
optical systems:

trapped ions: $^{199}Hg^+$, $^{88}Sr^+$, $^{171}Yb^+$, $^{26}Al^+$, In^+ Ca^+

cold atoms: Ca, Mg,



→ Sr, Yb, Hg

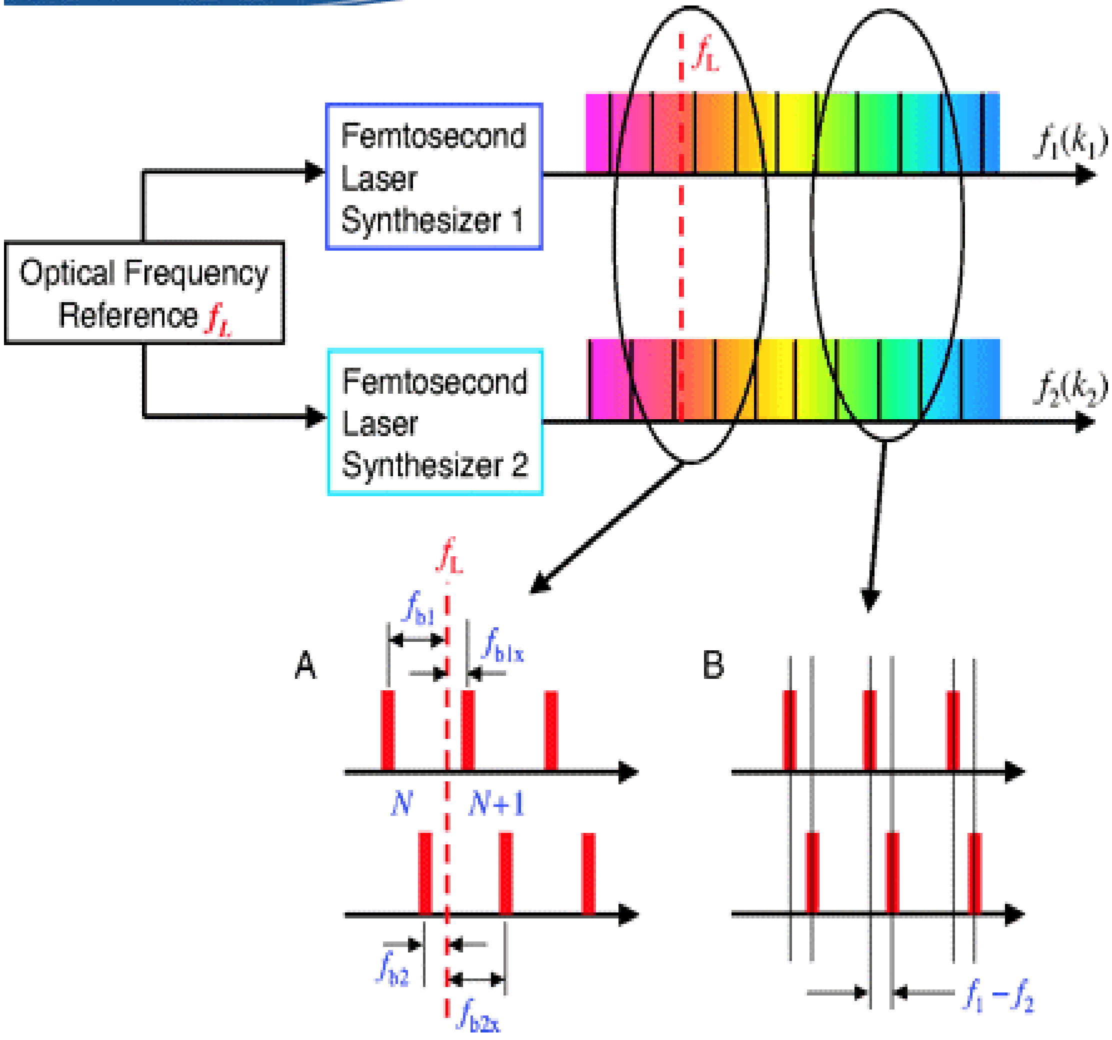


Opportunities (better than Cs)

Limitations (no better than Cs value)

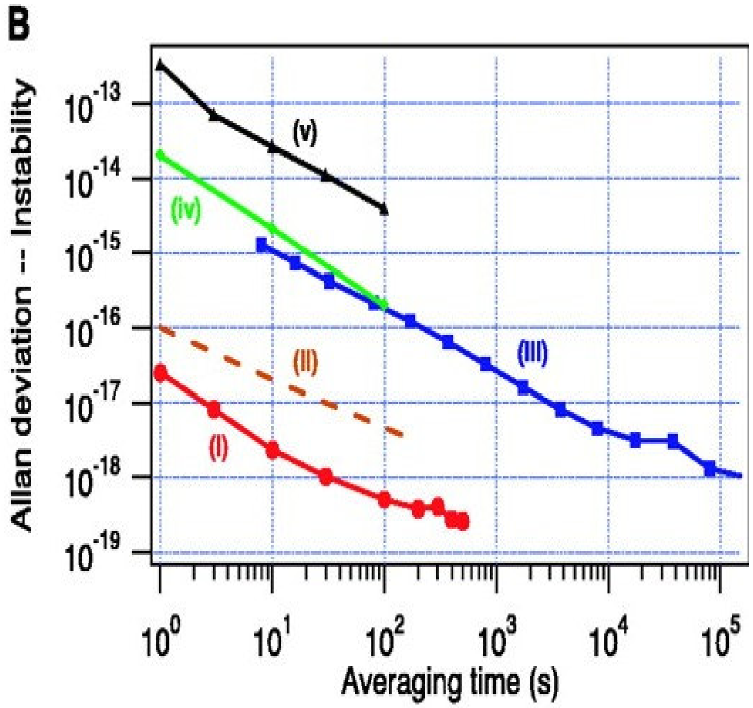
Femto-second Comb comparison

L-S Ma et al, Science 2004



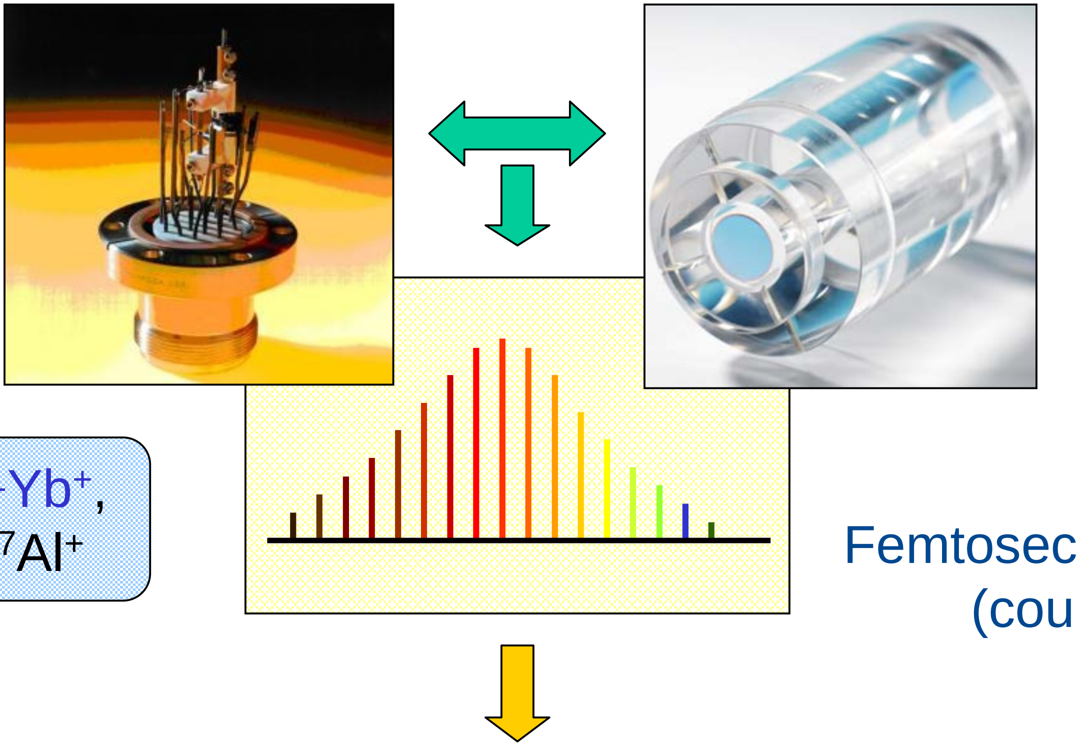
Uncertainty between combs locked to the same optical reference:

1.4×10^{-19}



Trapped ion optical frequency standards

Single cold
trapped ion
(atomic reference)



Ultra-stable
probe laser
(local oscillator)

$^{191}\text{Hg}^+$, $^{88}\text{Sr}^+$, $^{171}\text{Yb}^+$,
$^{40}\text{Ca}^+$, $^{115}\text{In}^+$, $^{27}\text{Al}^+$

Femtosecond comb
(counter)

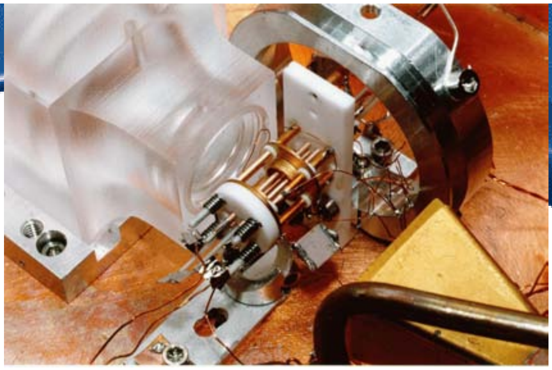
Optical clocks – future redefinition of the second?
Fundamental constants and tests of physics
Satellite ground station clocks?
Future satellite navigation and ranging??

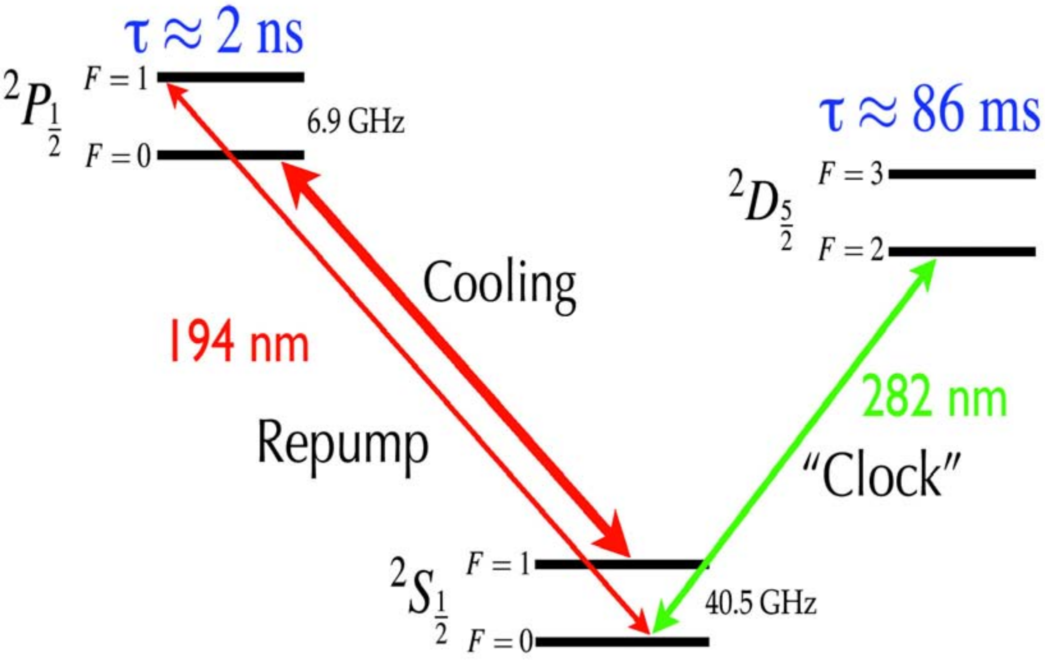
Trapped ion optical clock candidates

Trapped ion optical clock natural linewidths & frequency uncertainties

Ion	λ	Transition	Theory	Expt	Freq uncert.	Laboratory
$^{199}\mathrm{Hg}^+$	282 nm	$^2S_{1/2}$ - $^2D_{5/2}$	1.7 Hz	7 Hz	0.9 Hz	NIST
$^{88}\mathrm{Sr}^+$	674 nm	$^2S_{1/2}$ - $^2D_{5/2}$	0.4 Hz	9 Hz, 5Hz	1.7 Hz	NPL, NRC
$^{171}\mathrm{Yb}^+$	435 nm	$^2S_{1/2}$ - $^2D_{3/2}$	3 Hz	10 Hz	2.1 Hz	PTB
$^{40}\mathrm{Ca}^+$	729 nm	$^2S_{1/2}$ - $^2D_{5/2}$	0.14 Hz	1 kHz	-	UIBK, CRL
$^{115}\mathrm{In}^+$	236 nm	$^1S_0$ - $^3P_0$	1 Hz	170 Hz	230 Hz	MPQ/Erlangen
$^{171}\mathrm{Yb}^+$	467 nm	$^2S_{1/2}$ - $^2F_{5/2}$	0.5 nHz	180 Hz	600 Hz	NPL
$^{27}\mathrm{Al}^+$	266 nm	$^1S_0$ – $^3P_0$	8 mHz	20 Hz	-	NIST

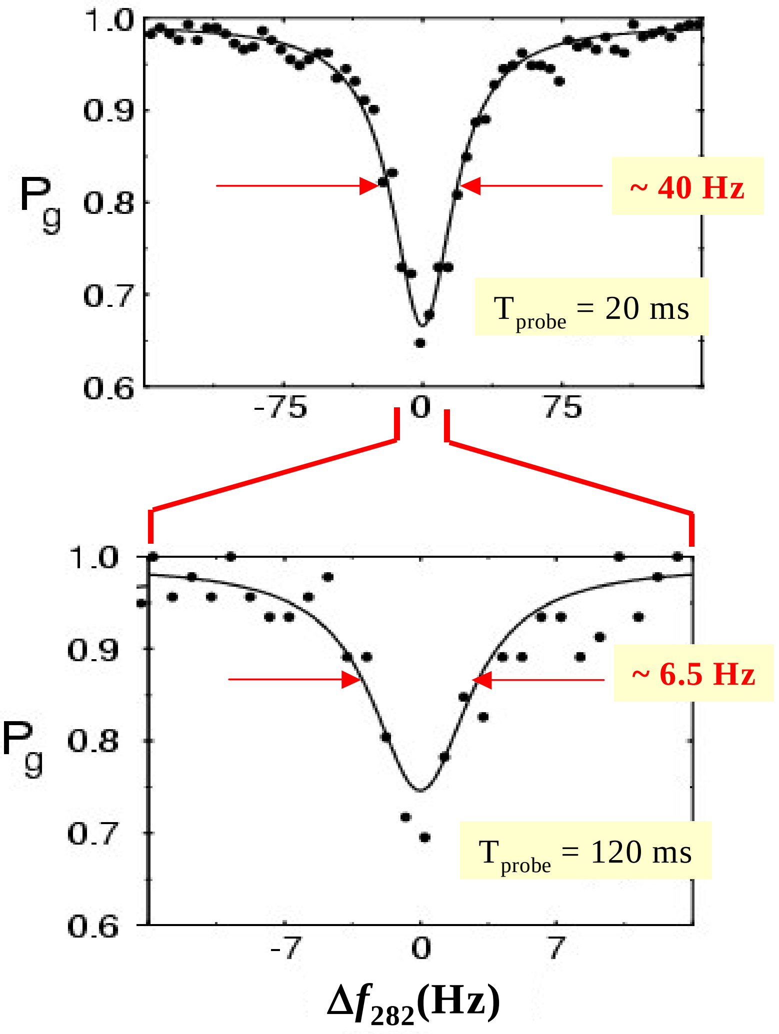
^{199}Hg$^+$ 282 nm quadrupole transition (Bergquist et al, NIST)



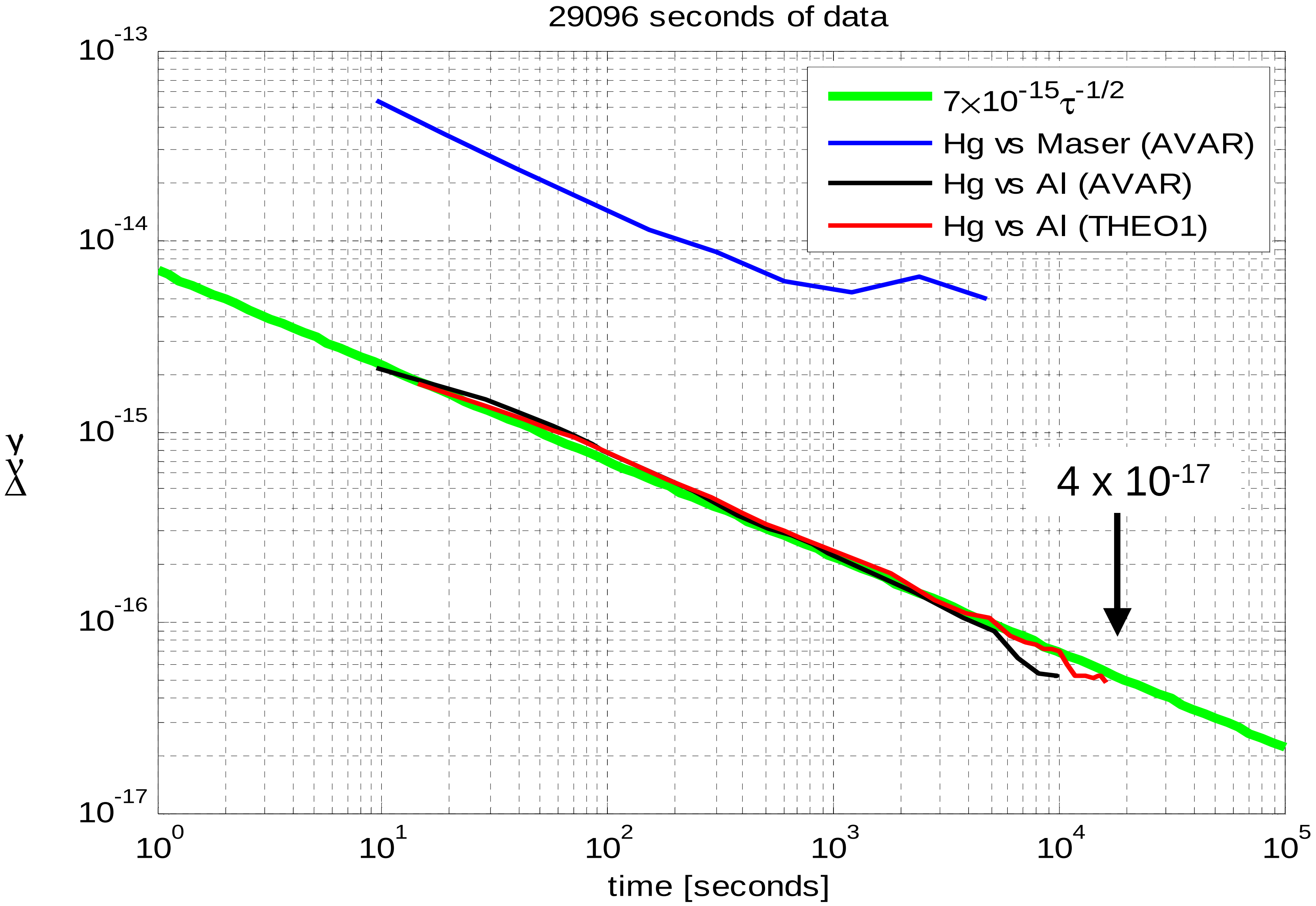


$$Q \approx 5 \times 10^{14}$$

- Atomic line ~ 1.8 Hz
- State detection by electron shelving
- Small blackbody shift
- static quadrupole shift can be minimized



Al+/Hg+ Comparison
courtesy J C Bergquist



29096 seconds of data

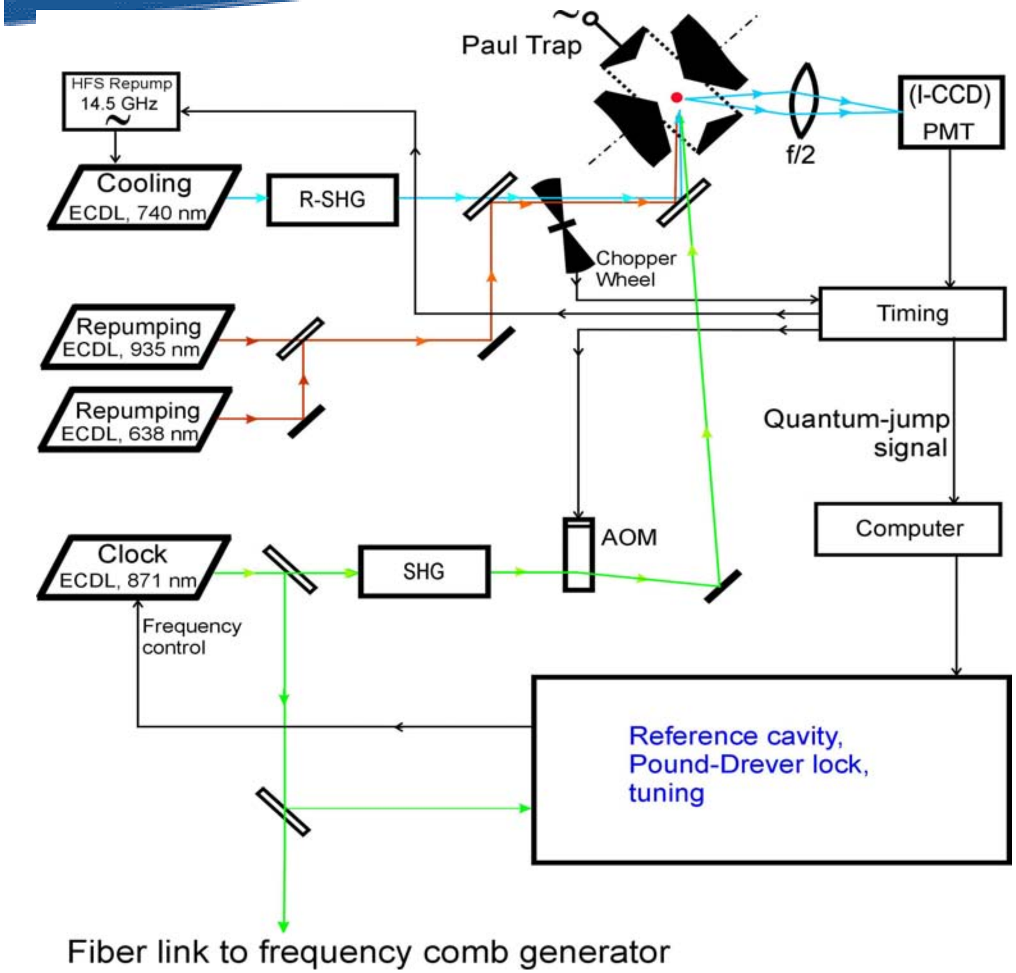
$^{199}Hg^+$ clock transition uncertainty budget

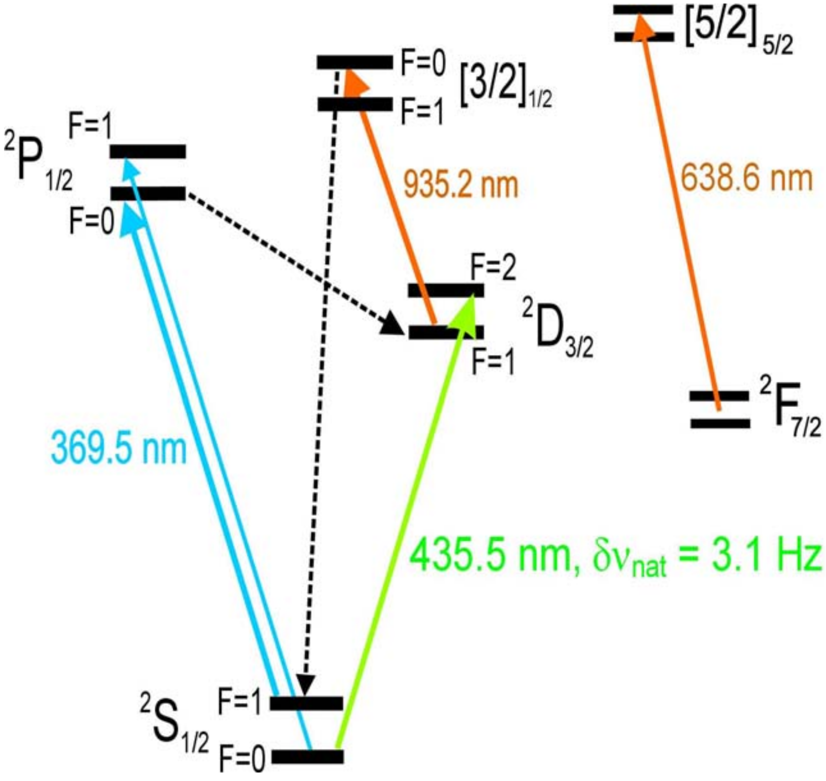
Effect	**Parameter**	**Hg^+ shift** *[x 10^{-17}]*	**Hg^+ Uncert** *[x 10^{-17}]*
Blackbody shift	Operating temperature	negligible	Negligible
Micromotion 2nd order Doppler	RF field	-0.3	0.3
Micromotion AC Stark	RF field	0.3	0.3
Secular 2nd order Doppler	Secular temperature	-0.3	0.3
2nd order Zeeman	magnetic field	-120.3	0.1
AC Zeeman	RMS field	0	3.0
AOM phase chirp	Drive power	0	0.03
Background gas collisions	Collision period	0	0.4
Total		**-120.6**	**3.0**

Total meas uncertainty

0.91×10^{-15}

Yb⁺ single-ion standard at 436 nm (PTB)

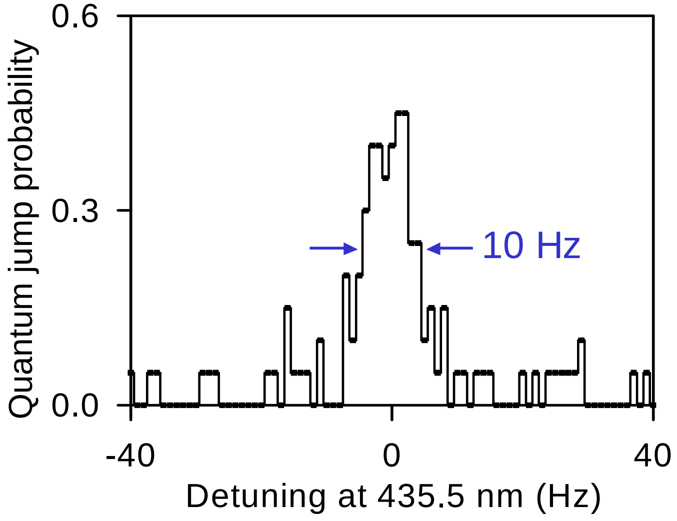




Chr. Tamm, D. Engelke, V. Bühner,
Phys. Rev. A **61**, 053405 (2000)

^{171}Yb^{+} quadrupole clock transition: Linewidth and stability

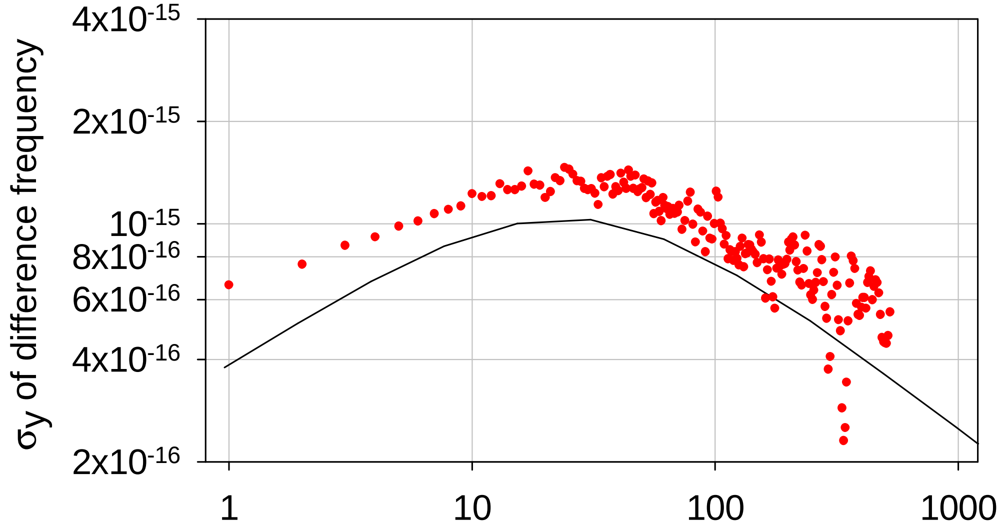
Approaching the resolution limit:
τ(pulse) = 90 ms ≈ $2 \cdot \tau(\mathrm{Yb}^{+})$



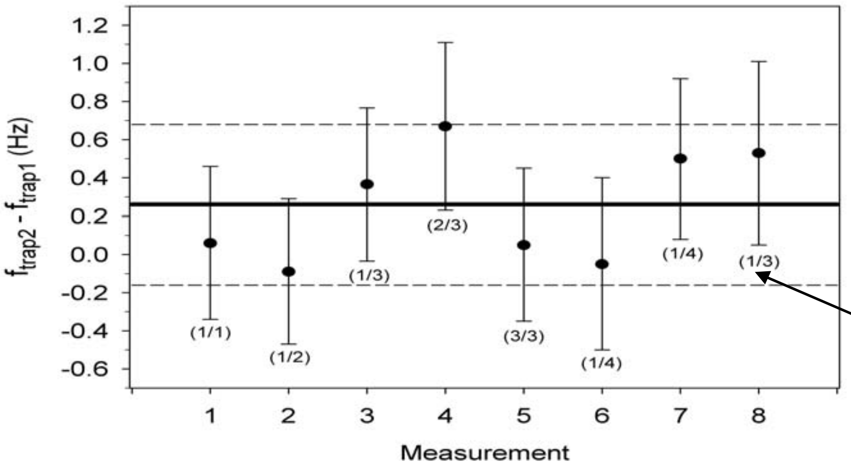
signal linewidth → Fourier limited
laser linewidth <10 Hz

Two-ion stability

90 ms probe time



E. Peik, T. Schneider, Chr. Tamm,
J. Phys. B: At. Mol. Opt. Phys **39**,145 (2006)

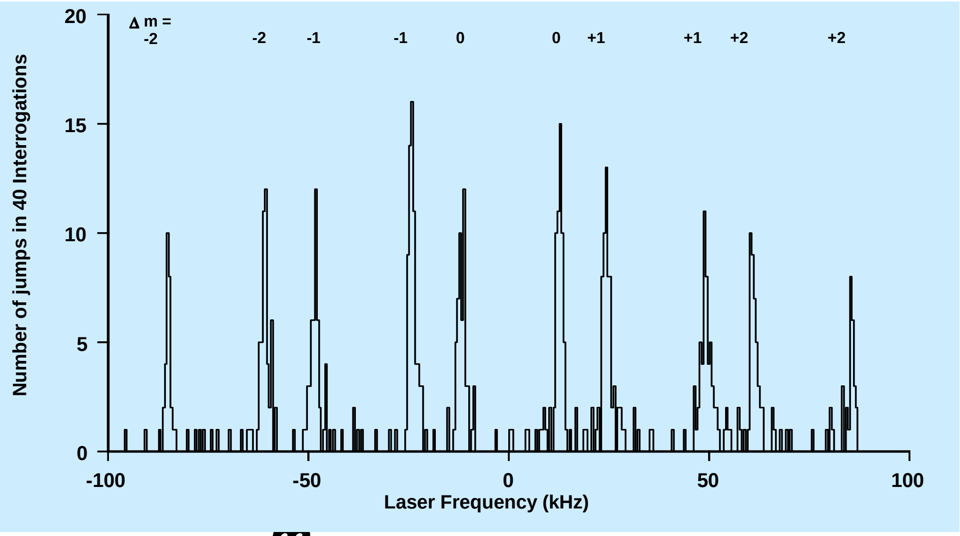


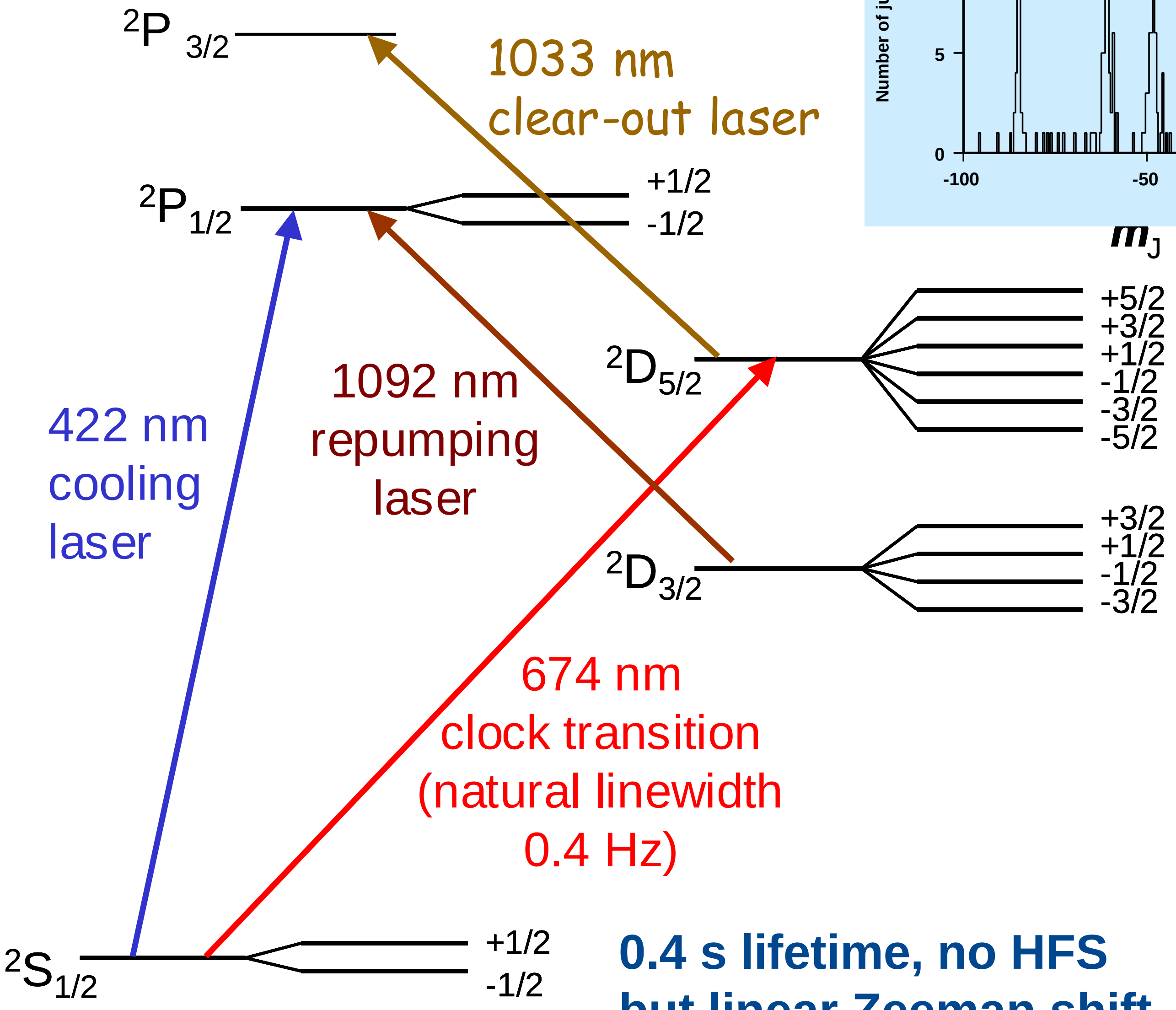
Two-trap freq.difference.

⇕ 6x10^{-16}

1,2,3: systems of orthogonal axes

$^{88}Sr^{+}$ optical frequency standard





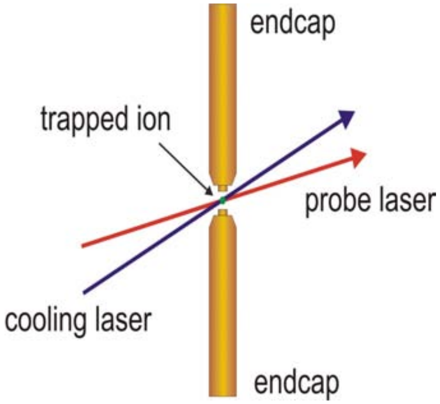
1033 nm
clear-out laser

422 nm
cooling
laser

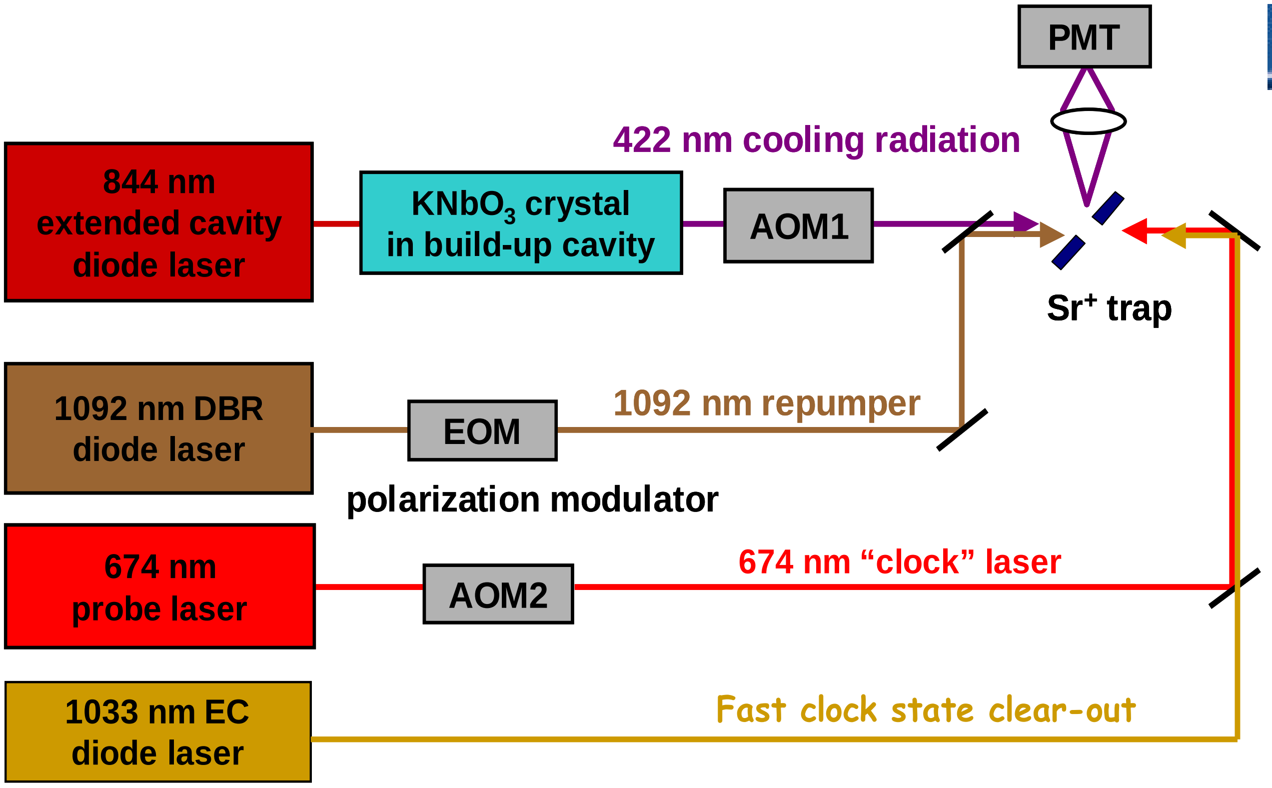
1092 nm
repumping
laser

674 nm
clock transition
(natural linewidth
0.4 Hz)

0.4 s lifetime, no HFS
but linear Zeeman shift



experimental hardware



844 nm extended cavity diode laser

KNbO$_3$ crystal in build-up cavity

AOM1

422 nm cooling radiation

PMT

Sr$^+$ trap

1092 nm DBR diode laser

EOM

1092 nm repumper

polarization modulator

674 nm probe laser

AOM2

674 nm “clock” laser

1033 nm EC diode laser

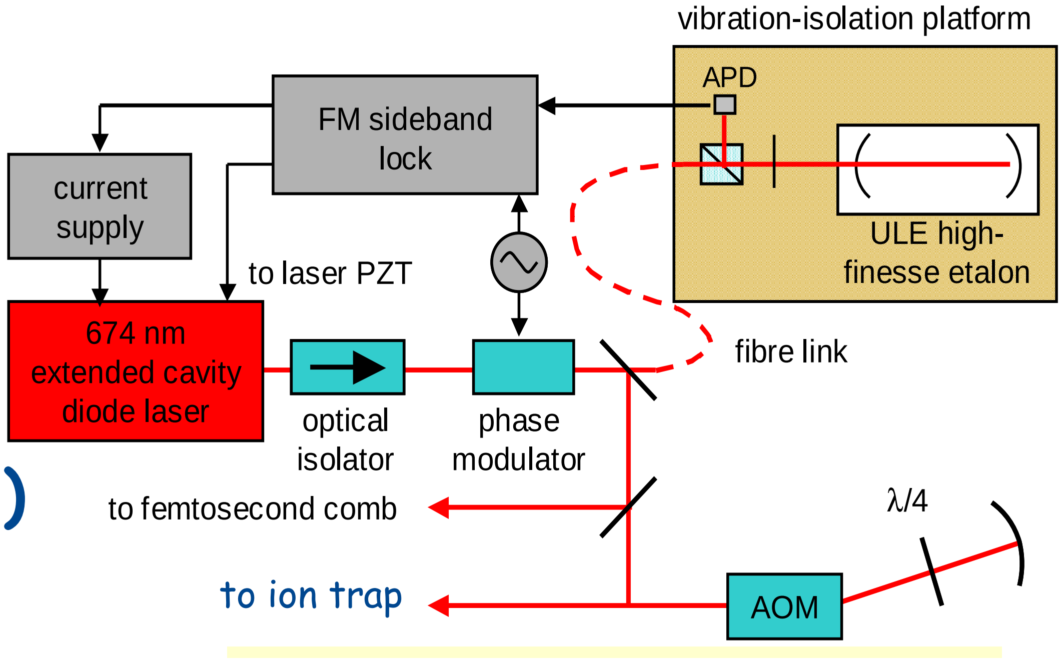
Fast clock state clear-out

674 nm probe laser

Probe linewidth:

~ 1 Hz (1-s timescale)

~ 5 Hz (30 s cycle time)



vibration-isolation platform

APD

ULE high-finesse etalon

FM sideband lock

current supply

to laser PZT

674 nm extended cavity diode laser

optical isolator

phase modulator

fibre link

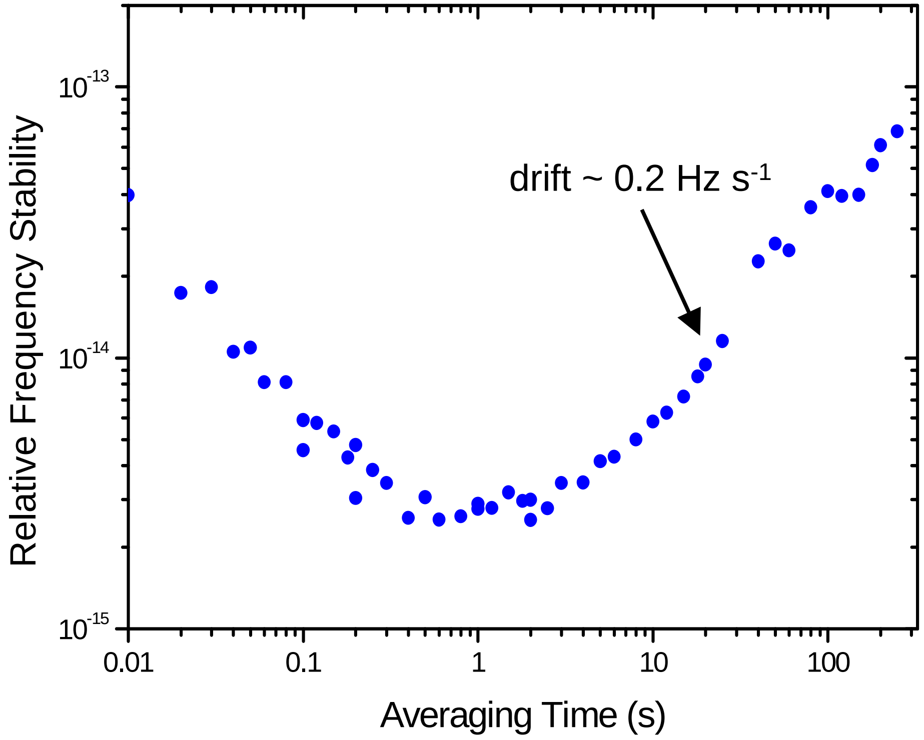
to femtosecond comb

to ion trap

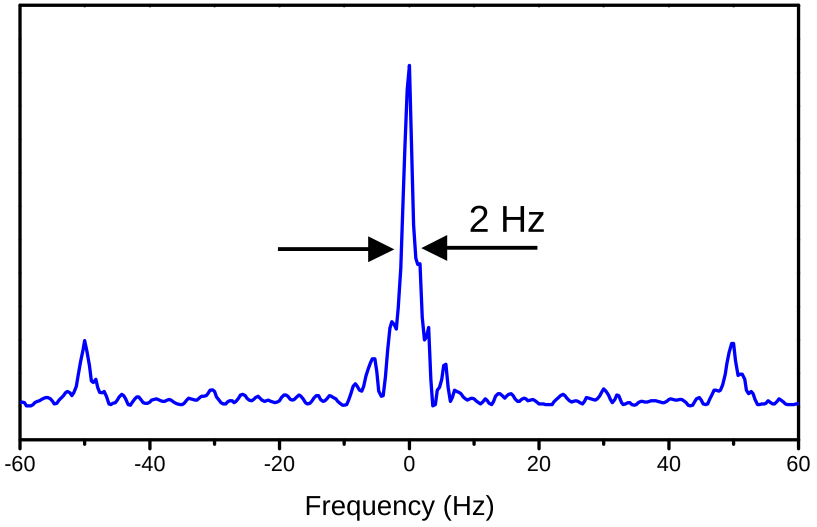
AOM

λ/4

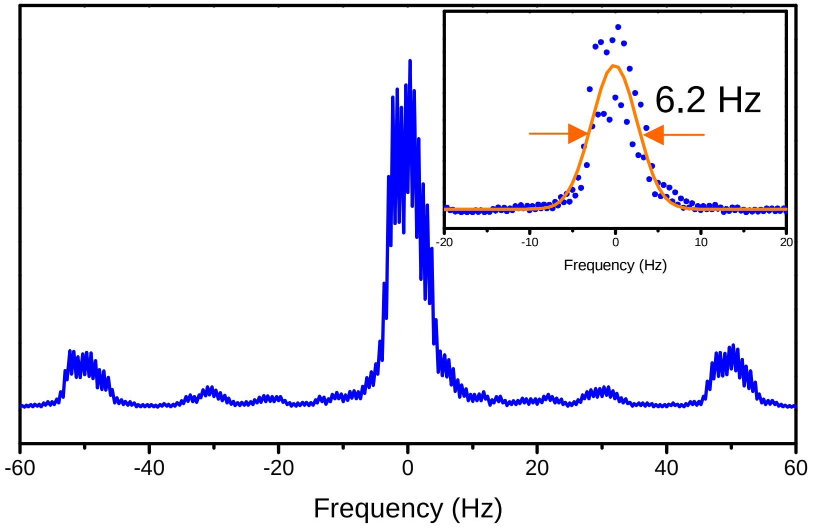
Beat between two independent 674 nm probe lasers



3s averaging time



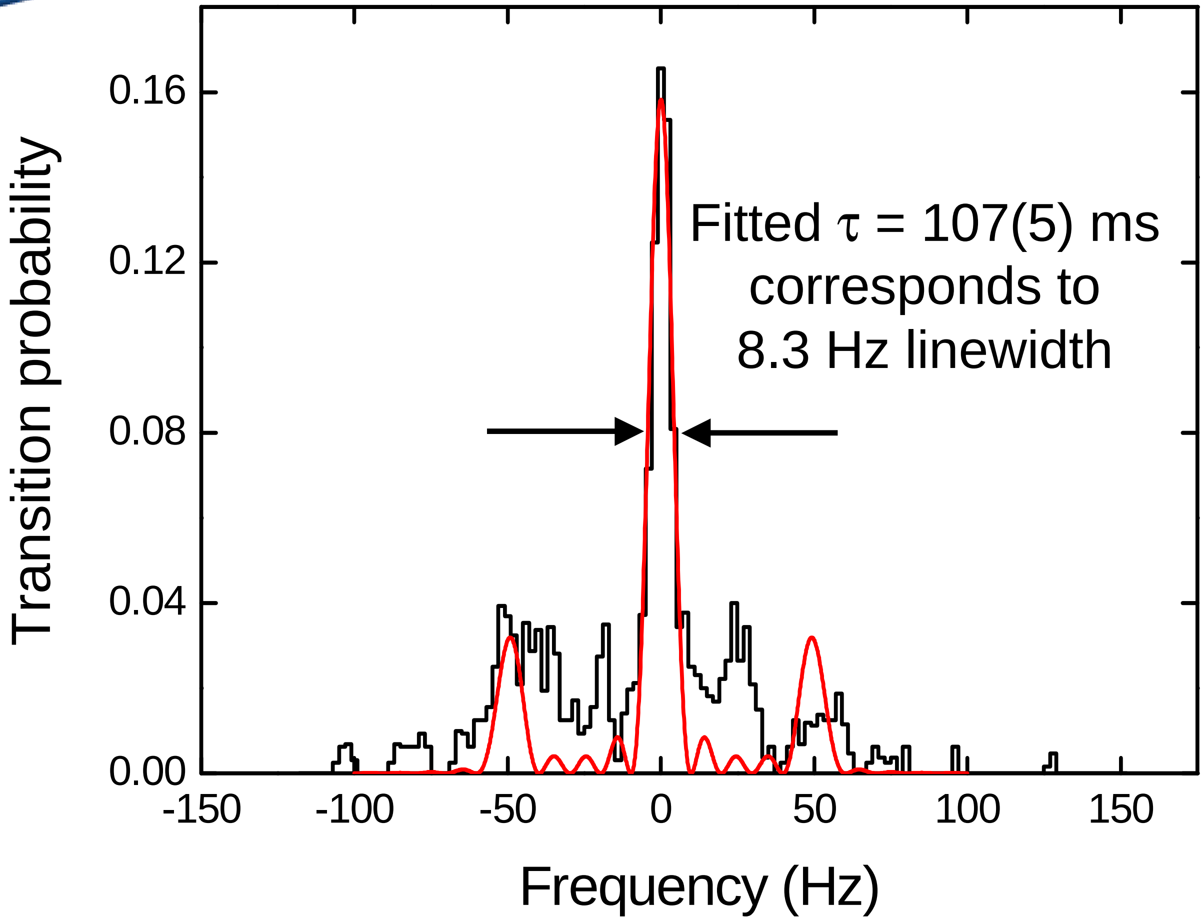
30 s averaging time, drift compensation 0.2 Hz s^{-1}



Linewidth probably limited by vertical vibrations

$^{88}Sr^{+}$ 674 nm cold ion clock transition linewidth

- ***m_J*** = 1/2 → ***m'_J*** = 1/2 Zeeman component
- Probe pulse length: 100ms
- Frequency step width: 2 Hz
- 0.2 Hz s^{-1} drift compensated
- 4 separate scans combined



Fitted τ = 107(5) ms corresponds to 8.3 Hz linewidth

Consistent with Fourier-transform-limited linewidth of 9 Hz.

Nulling the $^{88}Sr^+$ electric quadrupole shift: & absolute freq measurement

Due to interaction between electric quadrupole moment of 4d $^2D_{5/2}$ state and residual electric field gradient at position of ion

Frequency shift of 4d $^2D_{5/2}$ state with magnetic quantum number ***m**_j_* is:

$$\Delta\nu = \left(\frac{3}{10h}\right) Q_{\mathrm{dc}}\,\Theta(D,5/2)\left(\frac{35}{12}-m_j^2\right)\left(3\cos^2\beta-1\right)$$

quadrupole field gradient

quadrupole moment of 4d $^2D_{5/2}$ state

angle between quadrupole field axis & magnetic field

Measure frequencies of pair of Zeeman components in 3 orthogonal magnetic field directions → Average EQS = 0 (NIST)

Measure frequencies of 3 pairs of Zeeman components $|m_j|$ = 1/2, 3/2, & 5/2 → Average EQS = 0 independent of field direction (NRC)

f_{Sr+} = 444 779 044 095 484.6 (1.5) Hz

Margolis ***et al.***, ***Science*** **306**, 1355 (2004)

Projections for $^{88}Sr^+$ systematic frequency shifts

Second order Doppler shifts:

due to residual thermal motion ($\omega/2\pi$ ~ 1-2 MHz) and micromotion ($\Omega/2\pi$ ~ 15 MHz)

- $\Delta\nu_T \sim (\omega x_a / 2c)^2$ → 10^{-18} for T ~ 1 mK
- $\Delta\nu_M \sim (\Omega x_a / 2c)^2$ → 10^{-18} for micromotion well-minimised in 3D

Zeeman Shifts:

- Linear Zeeman $\Delta\nu_z \sim \pm 5.6$ Hz nT^{-1} for $\Delta m = 0$ components
  need symmetrical component averaging and mu-metal shielding for typical 1 μT field and few nT noise
- Quadratic Zeeman $\Delta\nu_z \sim 5.6$ μHz μT^{-2} (for $\Delta m = 0$) → 6 μHz
- Blackbody shift $\Delta\nu_{BBz} \sim$ 40 μHz for BB room temp field of 7 μT^2

Projections for Sr+ systematic frequency shifts II

Stark shifts:

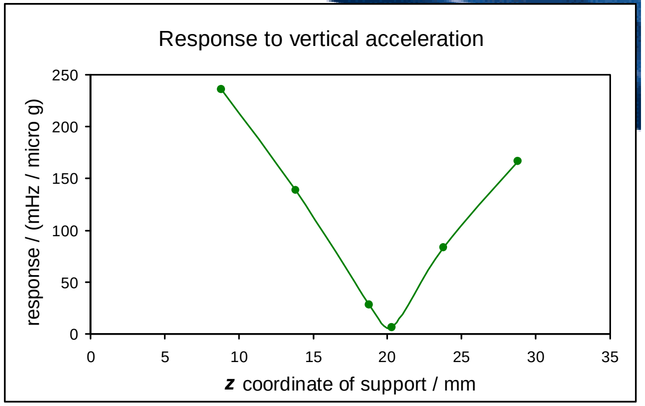
- **Micromotion- and thermal-induced** interaction with time-averaged fields
  (eg patch fields) → ~ few mHz (10^{-17}) with well-minimised micromotion

- **Blackbody Stark shift** (relative to 0 K) due to room temp apparatus
  → ~ 300 mHz (6×10^{-16})
  large due to T^4 temp dependence, but essentially constant
  1 K reproducibility of T(apparatus) → 10 mHz (2×10^{-17})
  also large uncertainty (+30 %) for Stark coefficients – need better values

- **AC Stark shifts**: off-resonant interactions of probe (and other cooling / clear-out) light with coupled transitions out of upper & lower levels of clock transition
  422 nm cooling & 1092 nm clear-out not a problem if fully switched off from ion during probe interrogation period
  674 nm probe light Stark coefficient: ~ 0.5 mHz (Wm^{-2})
  → ~ 0.15 mHz ($<10^{-18}$) for 30 nW in 300 μm

NPL

Near term future



$^{88}Sr^{+}$ 674 nm quadrupole optical clock:

- CCTF secondary representation of second (along with $^{199}Hg^{+}$, $^{171}Yb^{+}$ quadrupole and ^{87}Sr)
- Extension of probe time → 0.4 s natural lifetime with sub-Hz transform limited probe lasers
- Improve insensitivity to vibrations
- Cs-limited comb measurement of clock transition
- 2-trap comparisons for stability & systematics evaluation
- Possibilities for a portable frequency standard

$^{88}Sr^{+}$ Ion Optical Clock

What looks possible?

- Quantum limited stability for probe times ~ 0.4 s natural decay
  → $6 \times 10^{-16}\ \tau^{-1/2}$
- Feed-forward compensation of 0.2 Hz s^{-1} ($5 \times 10^{-16}\ s^{-1}$) ULE cavity drift
- Black-body Stark shift uncertainty for 1K temp rise → 2×10^{-17}
- Long single ion storage times possible
- All-diode-laser driven

1092 nm repumper:	DFB now
1033 nm fast clear-out 844 nm cooling	ECDL now, DFB?

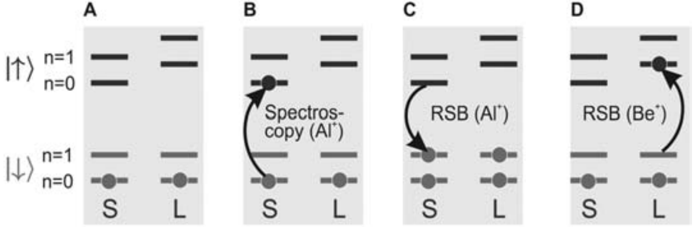
→ Ground station clock (near → mid term)

→ Space clock (Cosmic vision 2015-2025?)

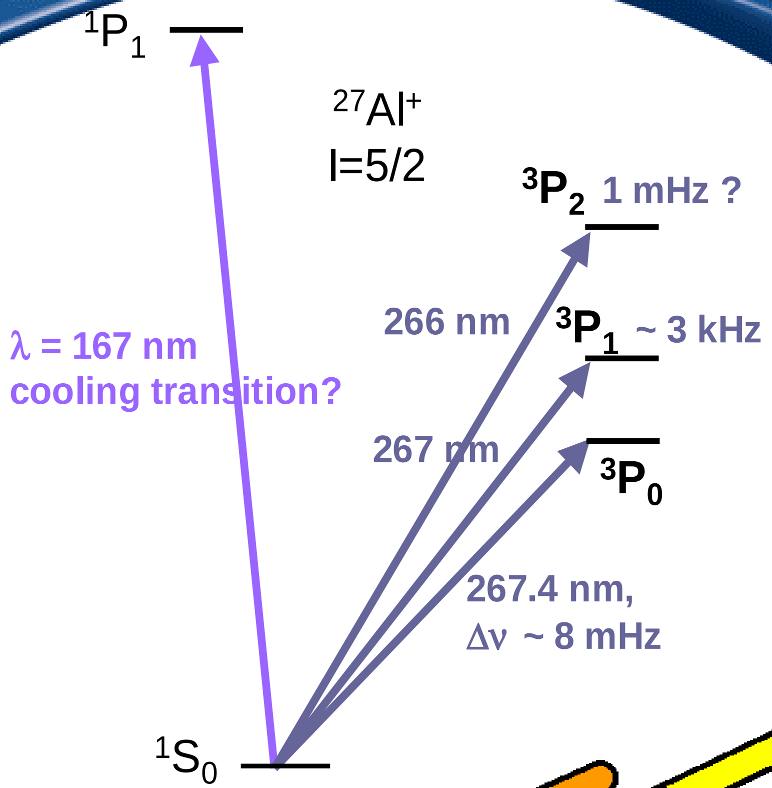
Spectroscopy of $^{27}Al^+$

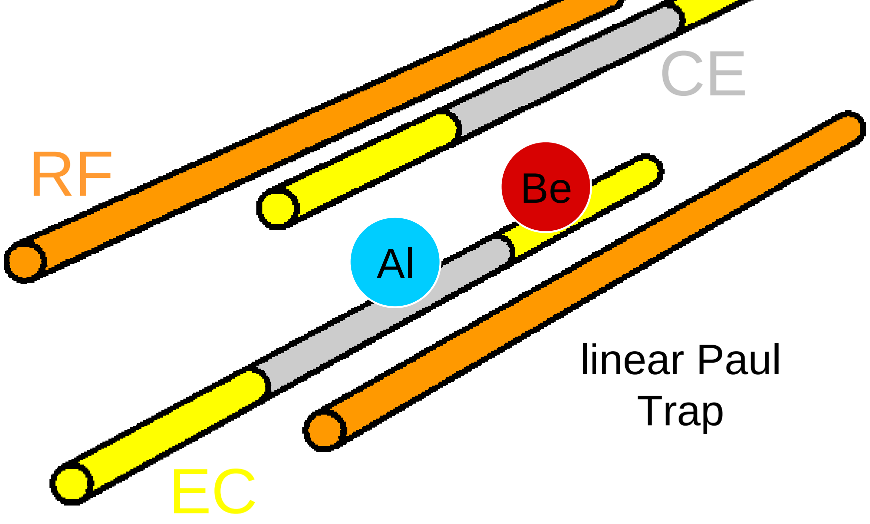
- 8 mHz linewidth clock transition
- minimal static quadrupole shift
- smallest known room temperature blackbody shift
- no accessible strong transition

→ use $^9Be^+$ for cooling, state preparation & readout



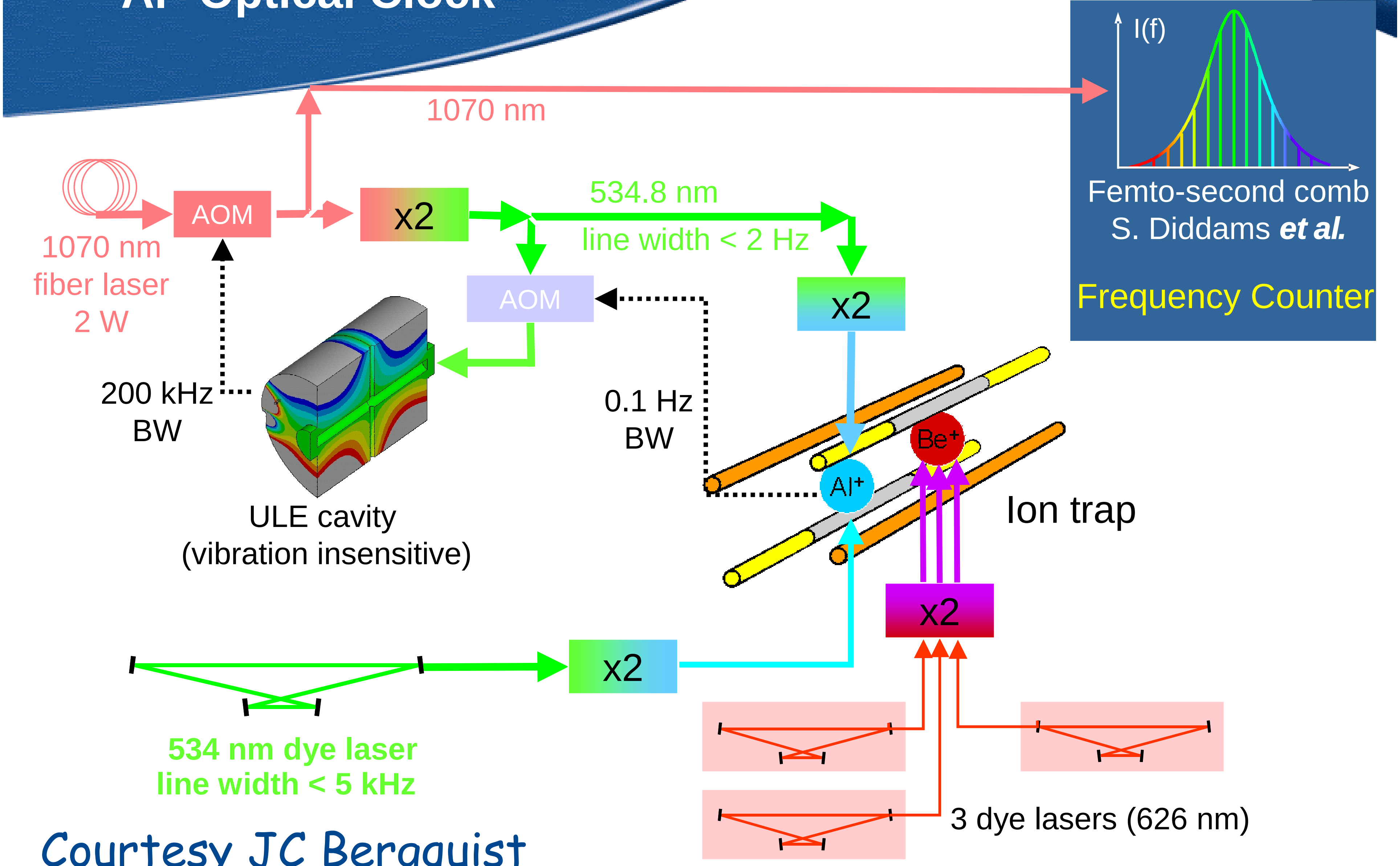
D.J. Wineland ***et. al.***,Proc. 6th Symp. on Freq Stds and Metrology, 2001.





linear Paul Trap

$^{27}Al^{+}$ Optical Clock

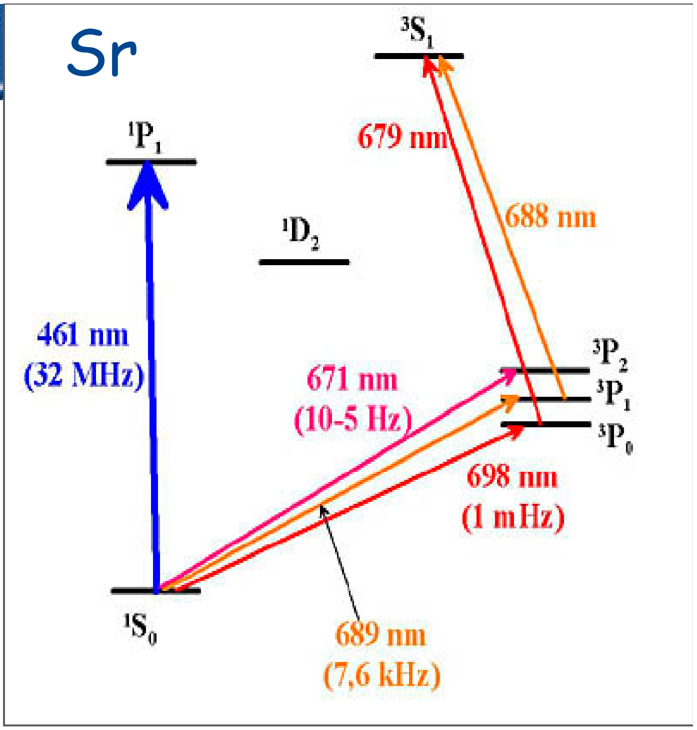


Courtesy JC Bergquist

Neutral Atom
Optical Lattice Clock

mHz-wide $^1S_0$ – $^3P_{0,2}$ clock transitions available, much narrower than the $^1S_0$ – $^3P_1$ intercombination transitions in Ca (370 Hz) and Mg (30 Hz)

→Long interrogation times → better stability, but how to hold the atoms?



Fountains or ballistic expansion not so good!

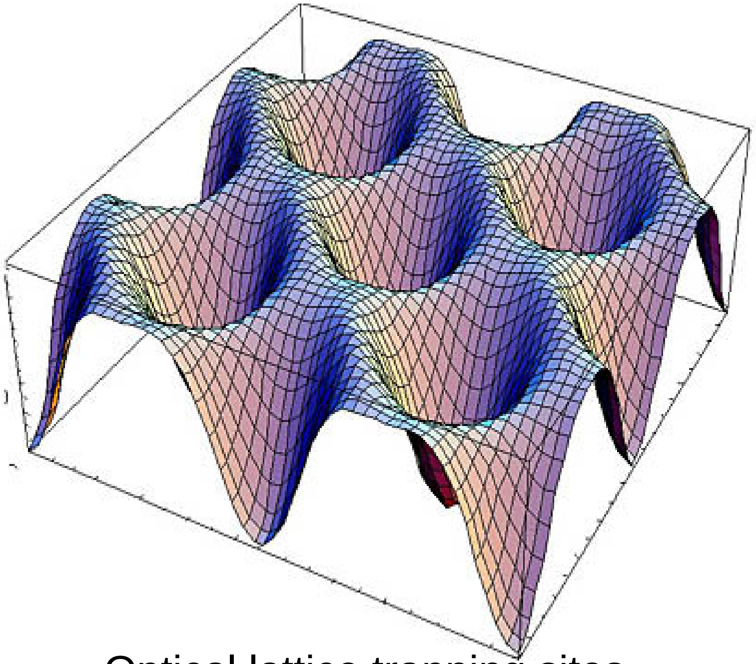
Problems still remain with residual Doppler shifts, cold collisional shifts and < 1 sec interrogation times

Optical Lattice idea (Katori 2001)

3D off-resonant standing wave laser field

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

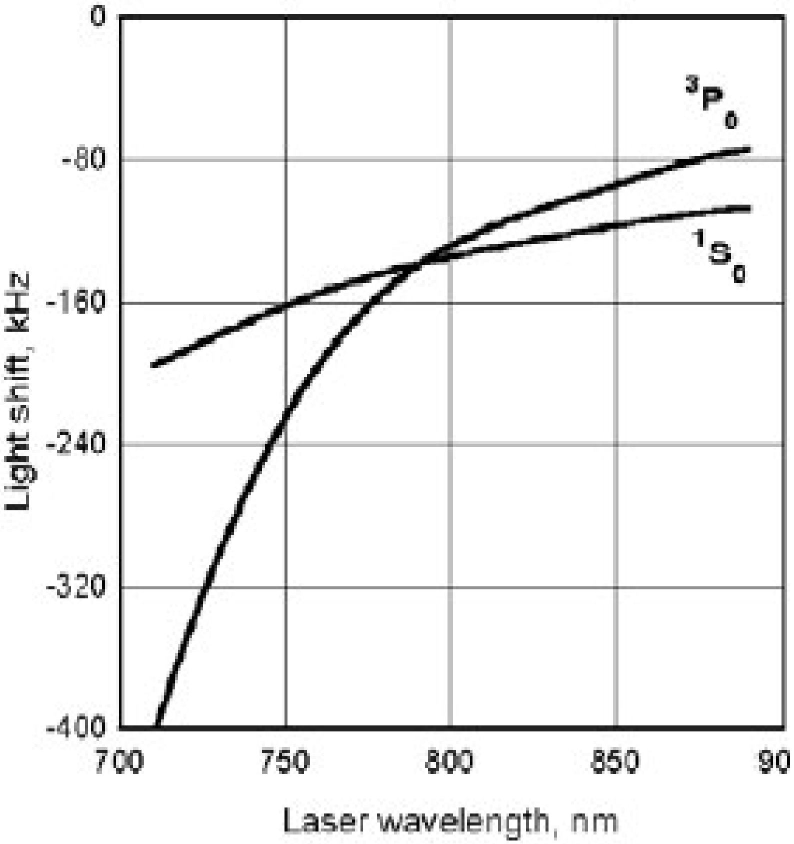
- Long interaction times, many atoms
- 1st order Doppler effect eliminated (Lamb-Dicke regime)
- Collisional shifts small if 1 atom per site
- How to deal with AC stark shift (light shift)



Optical lattice trapping sites

Neutral Atom Optical Lattice Clock (Sr or Yb or Hg or Ca)

- eg Sr $^1S_0$-$^3P_0$ has ~ 1 mHz natural linewidth
- Mott insulator transition from BEC to effect single atom only in each filled lattice site
- Light shift magnitude results from the difference in AC Stark shift caused by off-resonant lattice trapping beams 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

NPL

Cold Atom Optical Frequency Standard Candidates:

Cold atom optical clock linewidths ($\Delta\nu$) & uncertainties

Atom	λ nm	Transition	$\Delta\nu$ (Hz)		Absol. Freq	Laboratory
			Theory	Expt	Uncert. (Hz)	
Mg	457 nm	$^1S_0 - {}^3P_1$	30	--	--	Hannover
Ca	657 nm	$^1S_0 - {}^3P_1$	370	700	5-8 Hz	PTB, NIST
Sr	698 nm	$^1S_0 - {}^3P_0$	0.001	2	5 Hz	JILA, Tokyo, SYRTE, PTB Firenze
Yb	551 nm	$^1S_0 - {}^3P_0$	---	20		NIST, KRISS Duesseldorf

Secondary representations of the second: CCTF 2006 Recommendations

System	Studied at	Value / Hz	Relative uncertainty
^{199}Hg^{+}	**NIST**	**1 064 721 609 899 145**	**3×10^{-15}**
^{88}Sr^{+}	**NPL, NRC**	**444 779 044 095 484**	**7×10^{-15}**
^{171}Yb^{+}	**PTB**	**688 358 979 309 308**	**9×10^{-15}**
^{87}Sr	**NMIJ / Toyko,** **JILA, LNE-SYRTE,** PTB, Firenze, (NPL, NRC)	**429 228 004 229 877**	**1.5×10^{-14} ***

* included:

429 228 004 229 875 (4) Hz Tokyo
429 228 004 229 879 (5.3) Hz SYRTE
429 228 004 229 876 (4.5) Hz JILA

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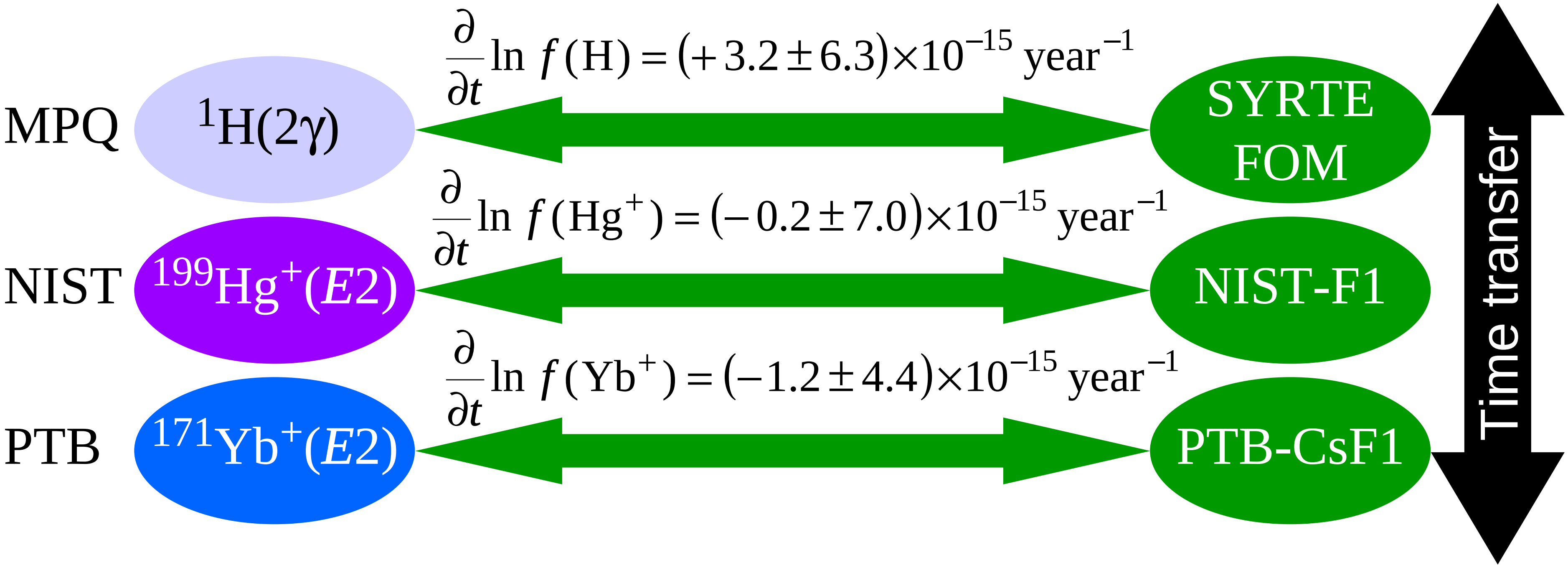
Comparisons of optical standards for fine structure constant variation with time

optical **caesium**



MPQ $^{1}\mathrm{H}(2\gamma)$

$$\frac{\partial}{\partial t}\ln f(\mathrm{H}) = (+3.2 \pm 6.3)\times 10^{-15}\ \mathrm{year}^{-1}$$

SYRTE FOM

NIST $^{199}\mathrm{Hg}^{+}(E2)$

$$\frac{\partial}{\partial t}\ln f(\mathrm{Hg}^{+}) = (-0.2 \pm 7.0)\times 10^{-15}\ \mathrm{year}^{-1}$$

NIST-F1

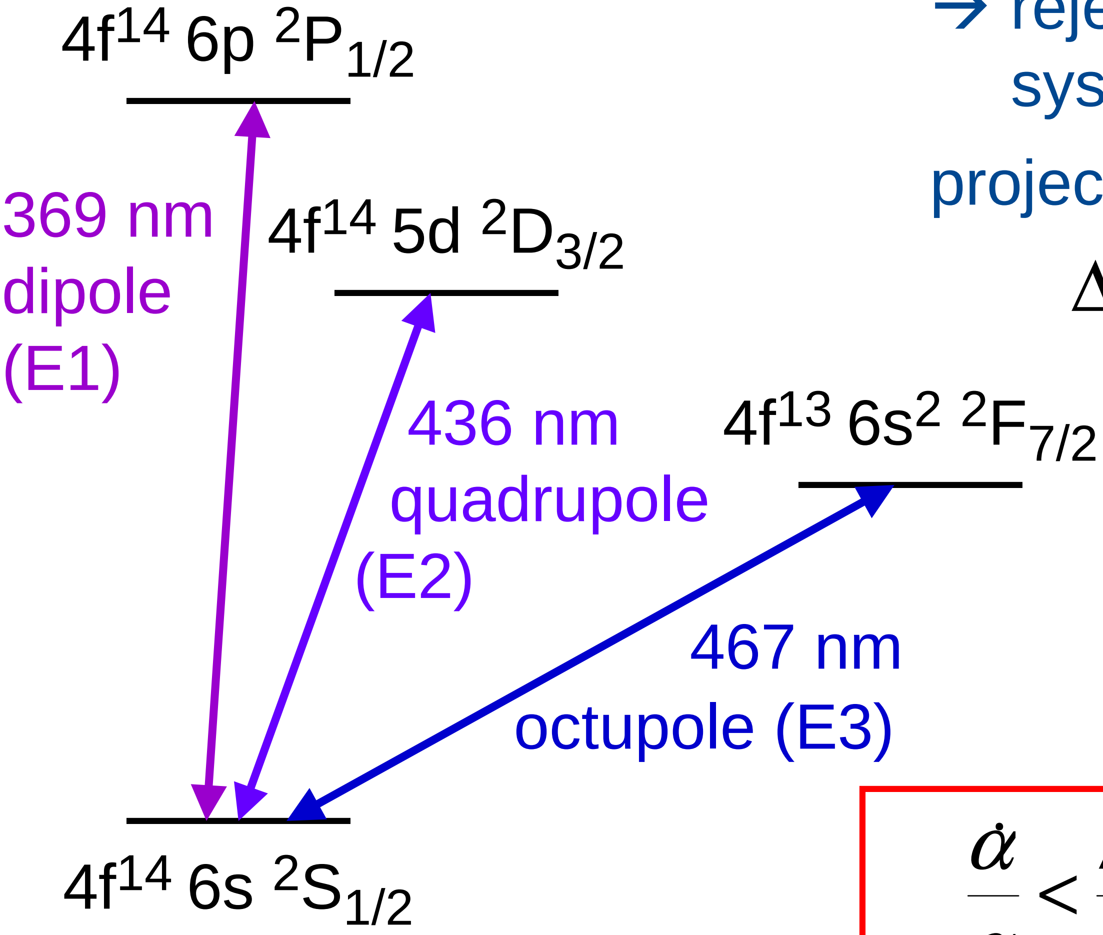
PTB $^{171}\mathrm{Yb}^{+}(E2)$

$$\frac{\partial}{\partial t}\ln f(\mathrm{Yb}^{+}) = (-1.2 \pm 4.4)\times 10^{-15}\ \mathrm{year}^{-1}$$

PTB-CsF1

Time transfer

$^{171}\mathrm{Yb}^{+}$: quadrupole-to-octupole frequency ratio for α-dot measurement



$4f^{14}\,6p\;^{2}P_{1/2}$

369 nm dipole (E1)

$4f^{14}\,5d\;^{2}D_{3/2}$

436 nm quadrupole (E2)

$4f^{13}\,6s^{2}\;^{2}F_{7/2}$

467 nm octupole (E3)

$4f^{14}\,6s\;^{2}S_{1/2}$

Two optical frequency standards in one ion

→ rejection of common mode systematic uncertainties

projected uncertainty:

$$\Delta\nu/\nu \sim 1 \times 10^{-17}$$

after 1 year:

$$\boxed{\frac{\dot{\alpha}}{\alpha} < \frac{\Delta\nu}{\nu} \sim 2\times10^{-18}\,\mathrm{year}^{-1}}$$

The way ahead

- Best trapped ion results are reaching into 10^{-17} region for stability and uncertainty, & can go further
- Neutral atom lattice clocks catching up fast
- Environmental field perturbations probably likely to make life difficult below 10^{-18}
- Gravitational red shift most significant in this respect for comparing remote standards
  → 10^{-17} corresponds to 10 cm height difference
  → geoid fluctuations may drive this

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So how do we compare high accuracy remote frequency standards?

- Improved microwave links? (eg ACES MWL?), but
  still need long averaging times for better than 10^{-16}
- Optical fibre dissemination
  Good results between SYRTE–LPL link with 10^{-17} resn
  Similar with NIST & JILA, offering local linkage for Cs, Hg+, Al+, Sr and Yb
  Desirability of access to European dark fibre routes
- Portable optical standards?
  10^{-15} probably Ok, but how big an investment to go beyond this level?
- Inter-satellite optical links?

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Thank you!