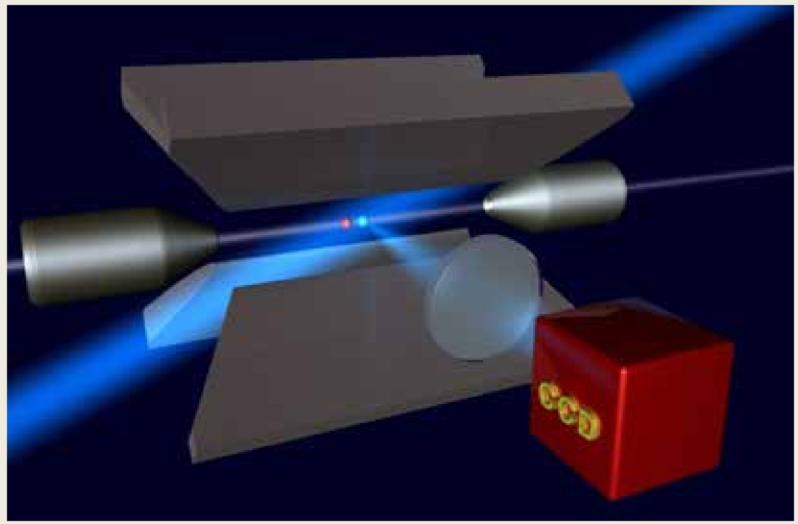
Optical Clocks III



Piet O. Schmidt

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Physikalisch-Technische Bundesanstalt, Braunschweig
& Leibniz Universität Hannover

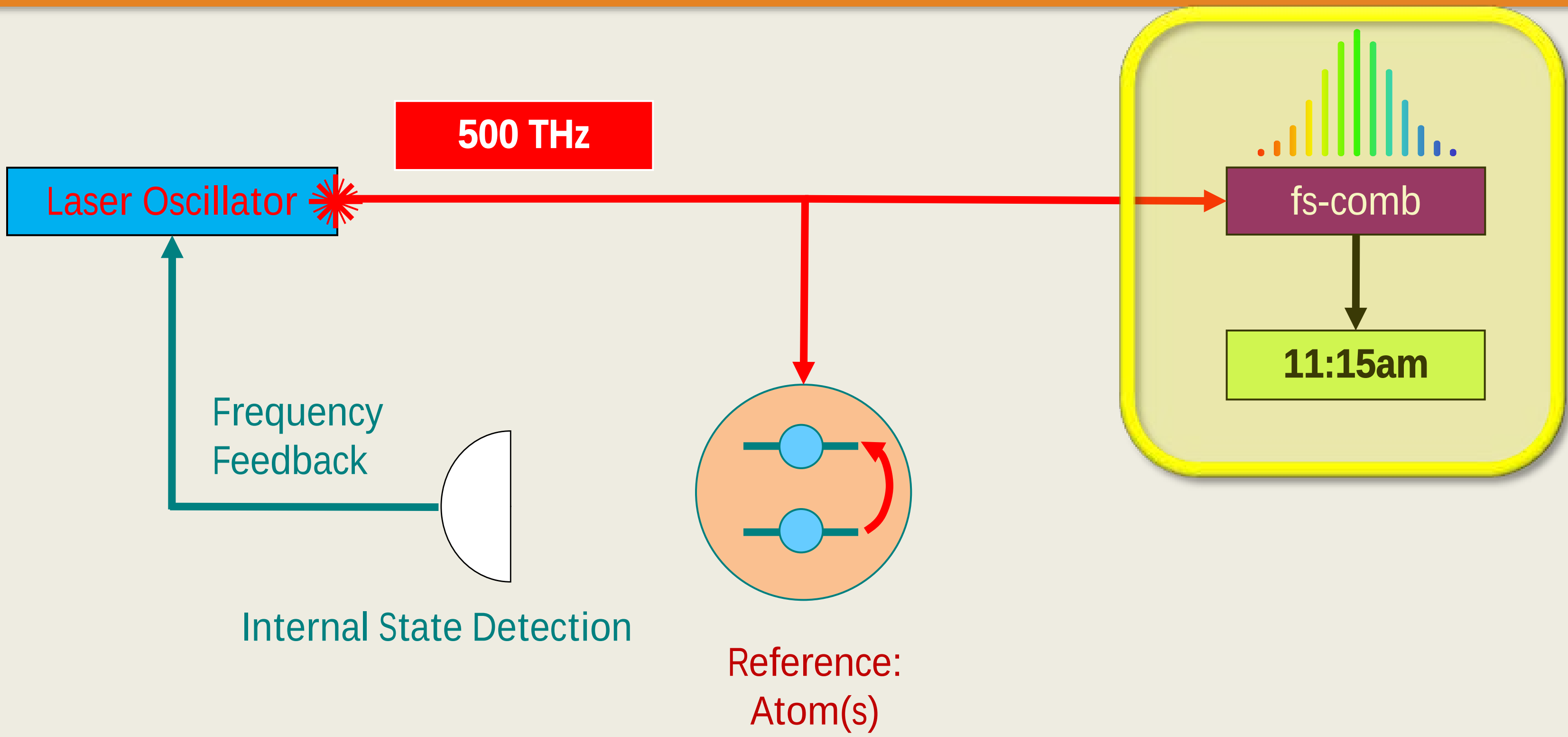
Les Houches Winter School, 19.-30.01.2015

Overview Optical Clocks I+II

- Introduction
  - brief history of time (keeping)
  - principle & characterization of clocks
- The atomic reference
  - ions & neutrals
  - frequency shifts
- The clock laser
  - Requirements or “Mission impossible”
  - Important design aspects

Overview Optical Clocks III

- Frequency comb and dissemination
  - counting optical cycles
  - getting the light somewhere useful
- Results from selected ion clocks
- Applications
  - relativistic geodesy
  - fundamental physics
- Future trends
  - improving the instability of ion clocks



FREQUENCY COMB AND DISSEMINATION

Optical Frequency Combs

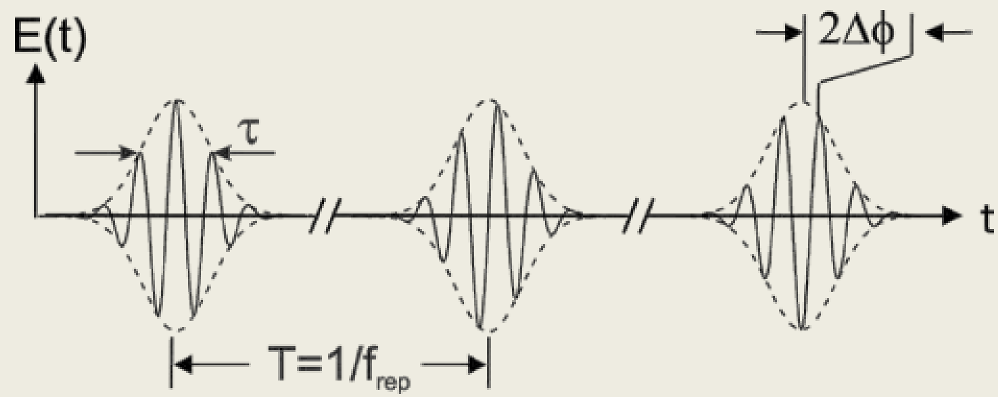
- time regime: fs pulses with pulse width τ & repetition rate f_{rep}=1/T
- bandwidth of spectrum: $1/\tau$
- frequency regime: frequency comb with „teeth“ fully defined by

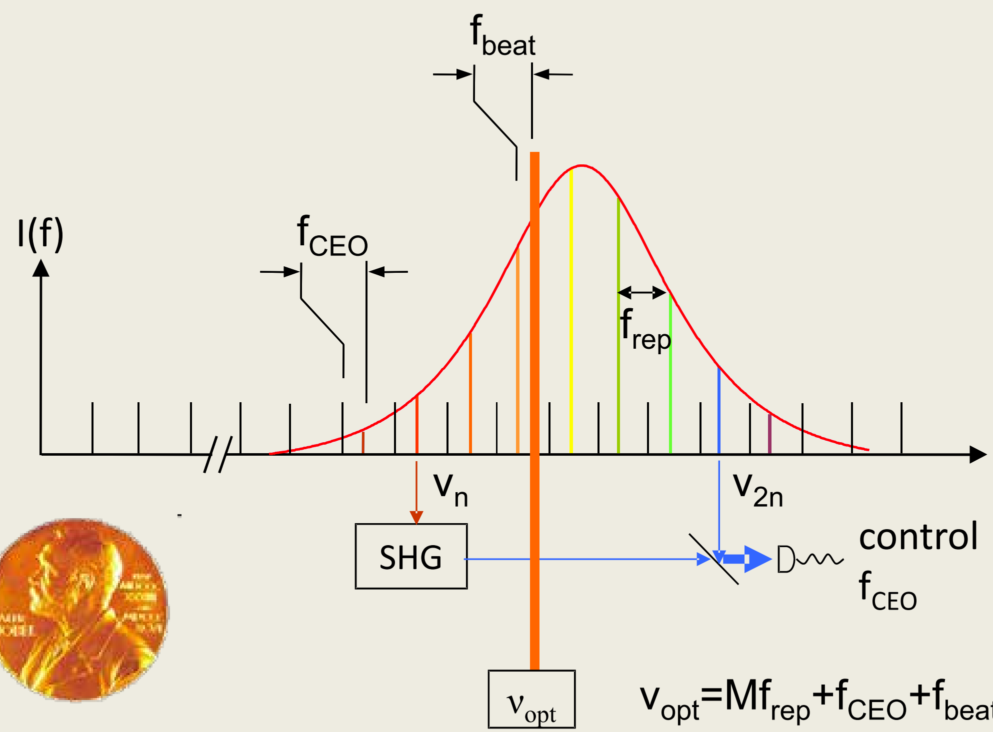
$$f_n = M f_{rep} + f_{CEO}$$

- Origin of f_{CEO}?

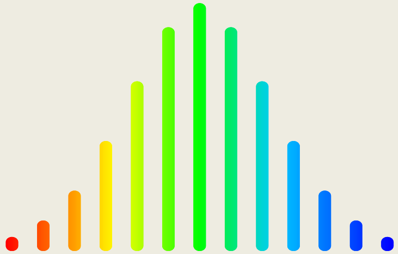
è Difference between phase and group velocity: $f_{CEO} = \Delta\phi f_{rep}/2\pi$

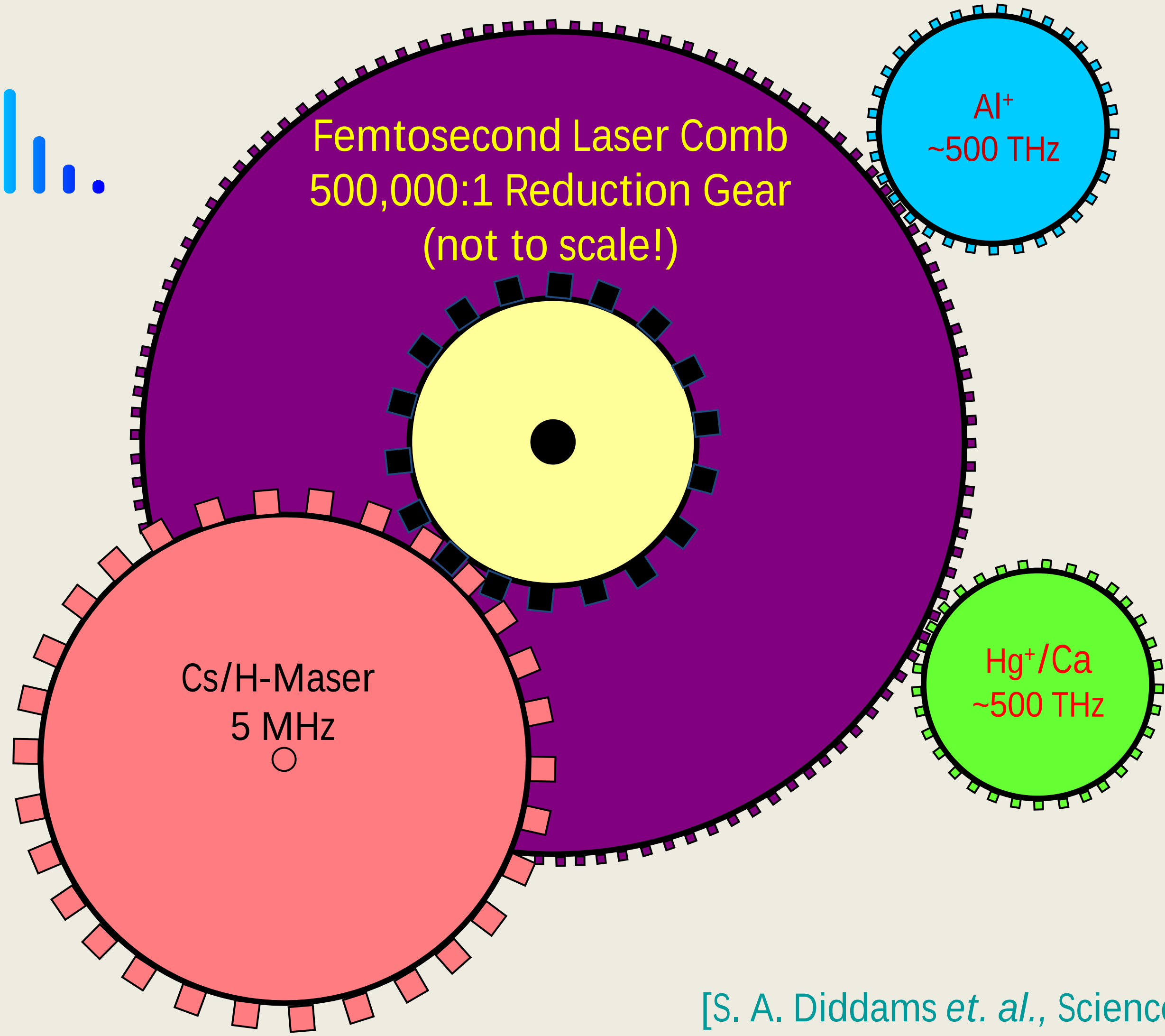
- Locking f_{CEO}: f-2f intererometer





RF to Optical Clockwork with a Femtosecond Laser Comb





[S. A. Diddams *et. al.*, Science **293**, 825 (2001)]

Comb choices

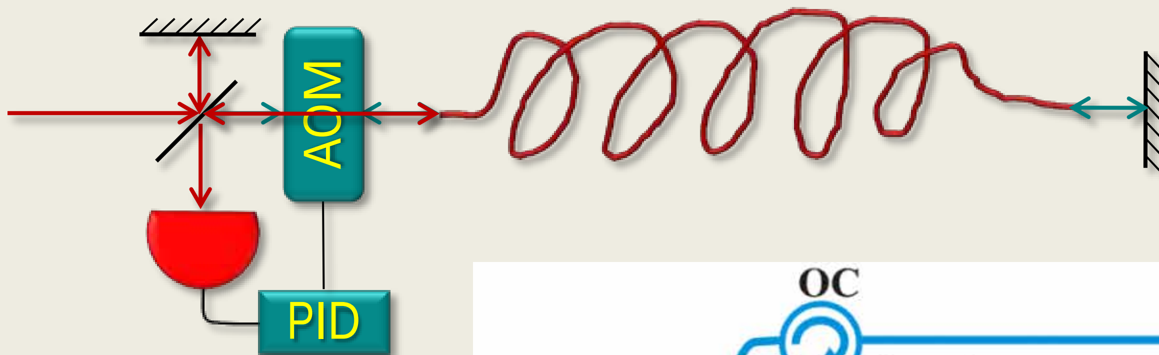
- Ti:Sa combs
  - high repetition rate (>1 GHz)
  - high spectral purity of comb lines
  - more difficult to operate
  - spectrum centered around 800 nm
- fiber-based combs
  - medium repetition rate (250 MHz)
  - high phase noise (~ 200 kHz comb tooth width)
  - 24/7 operation
  - spectrum centered around 1.5 µm

  è non-linear fibers & crystals allow tailoring of center frequency

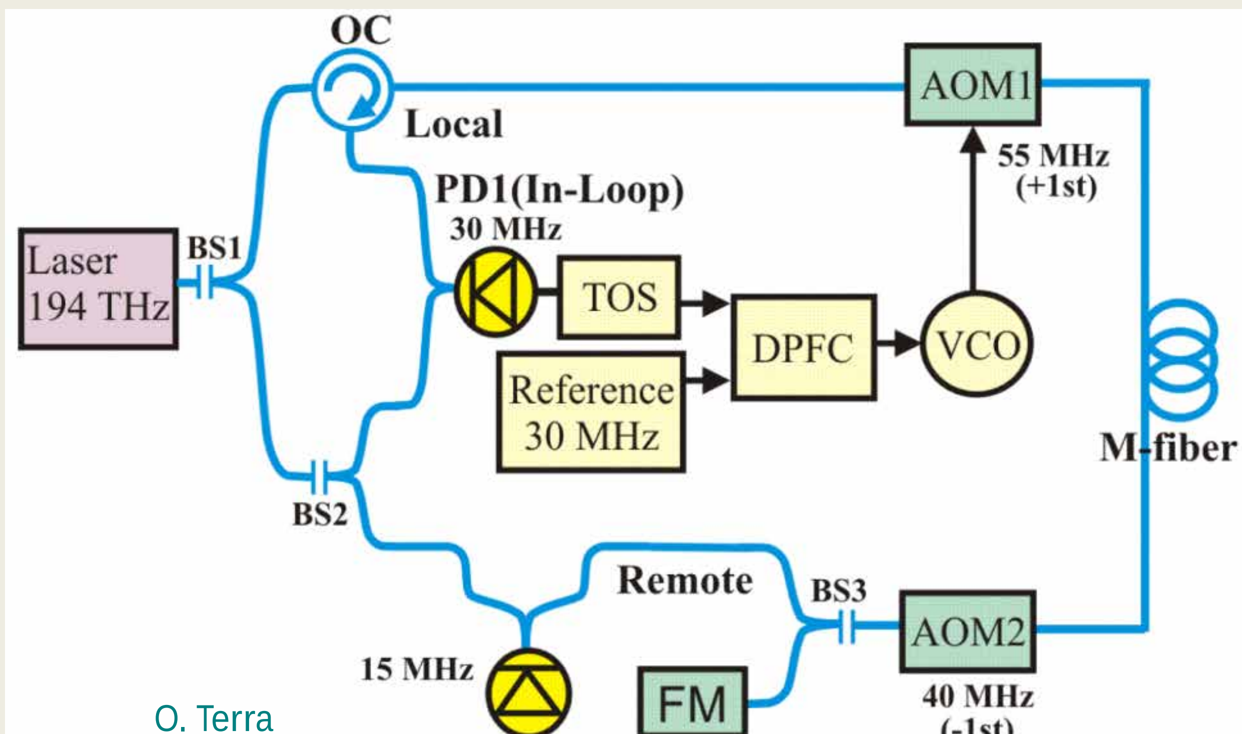
  è telecom compatible!

Fiber Length Stabilisation

- Length stabilization via Michelsen Interferometer



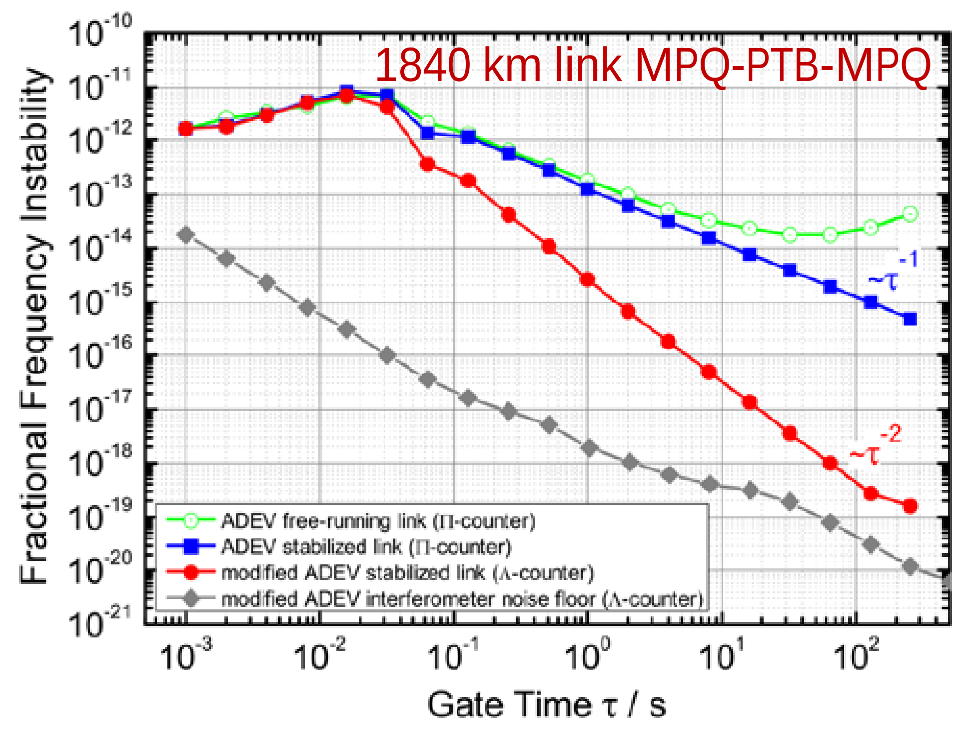
- BS: beam splitter
- OC: optical circulator
- TOS: tracking oscillator
- DPFC: digital phase-frequency comparator
- VCO: voltage controlled oscillator
- FM: Faraday mirror
- AOM: acousto-optical modulator
- PD: photo diode



O. Terra
PhD Thesis 2010

Performance Fiber Links

- Optical carrier 900 km: 5´ 10^{-18} in 10^{4} s
- fundamental stability limit: time delay in feedback
  è residual PSD: $S_D(f) \approx (2\pi f\tau)^3 S_{fiber}(f)/3$
- non-reciprocal noise



è Group of Harald Schnatz @ PTB

[Droste *et al.*,PRL **111**, 110801 (2013)]

EXAMPLES OF CLOCKS

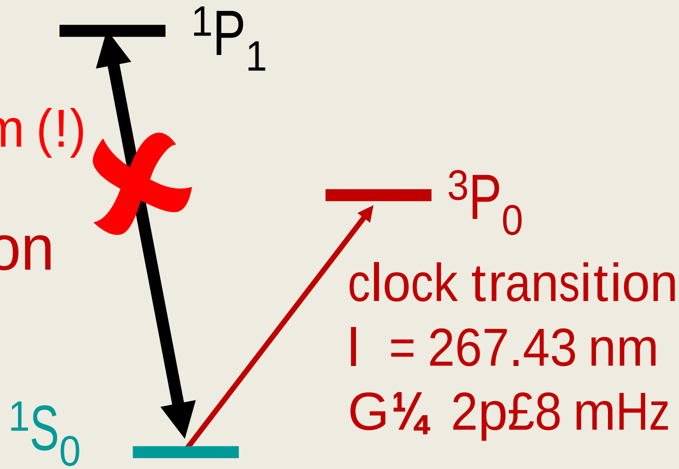
Aluminum as Optical Clock Atom

- **Hans Dehmelt 1992 (NP 1989)**
- **Al⁺ Features:**
  - no electric quadrupole shift
  - small black-body shift
  - small Zeeman shift
  - narrow optical transition

  (high accuracy: no electric quadrupole shift, small black-body shift, small Zeeman shift)

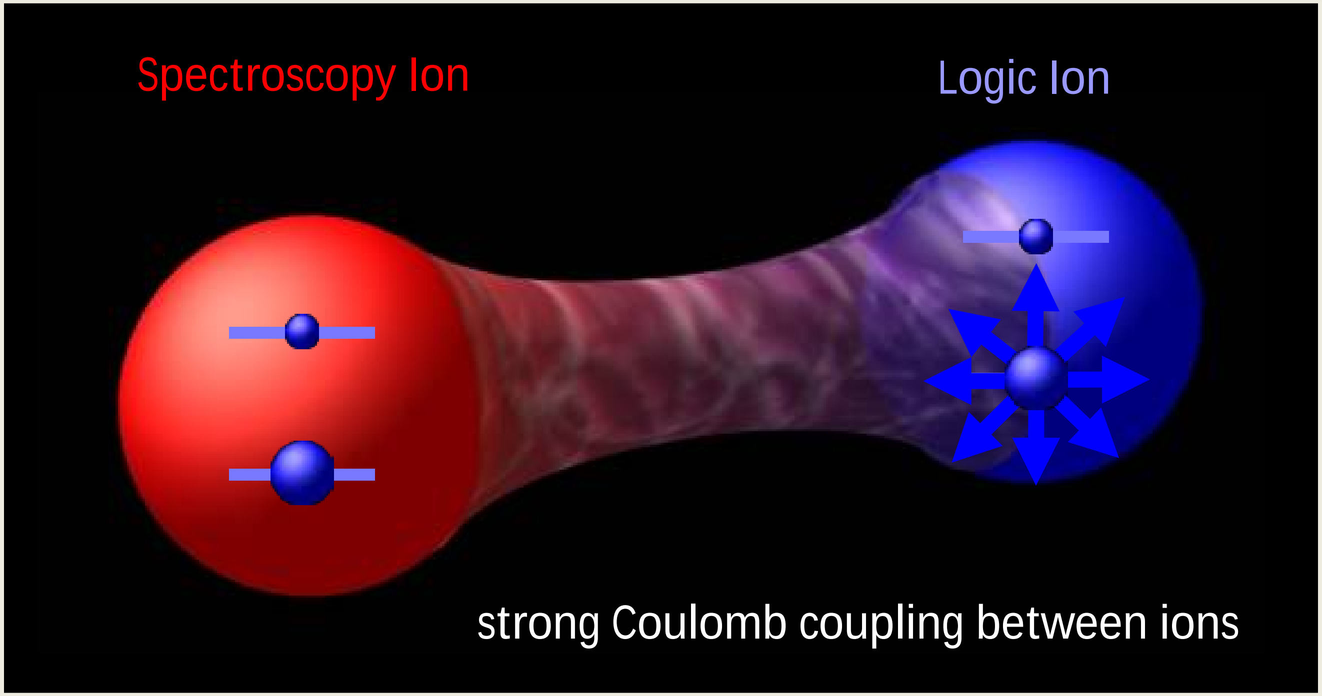
  è high stability
  - But: no accessible cooling transition

è quantum logic spectroscopy



$^{27}Al^+$ (I=5/2) partial level scheme

Quantum Logic Spectroscopy



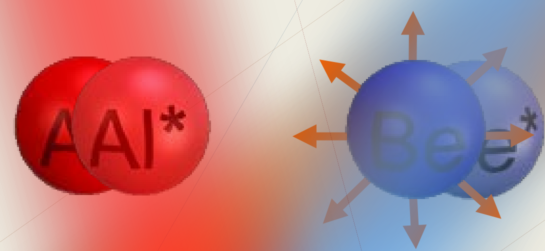
- logic ion is a sensor for spectroscopy ion
- spectroscopy ion controlled through logic ion
- combine advantages of atomic species

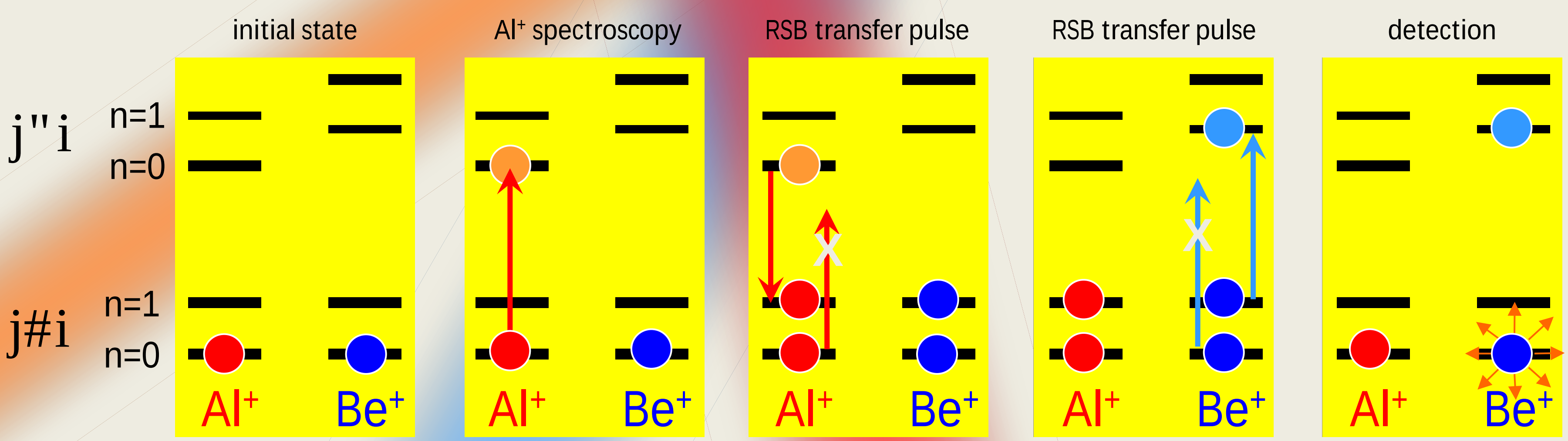
è requires long-lived spectroscopy states

D.J. Wineland *et. al.*, Proc. 6th Symposium on Frequency Standards and Metrology, 361 (2001)

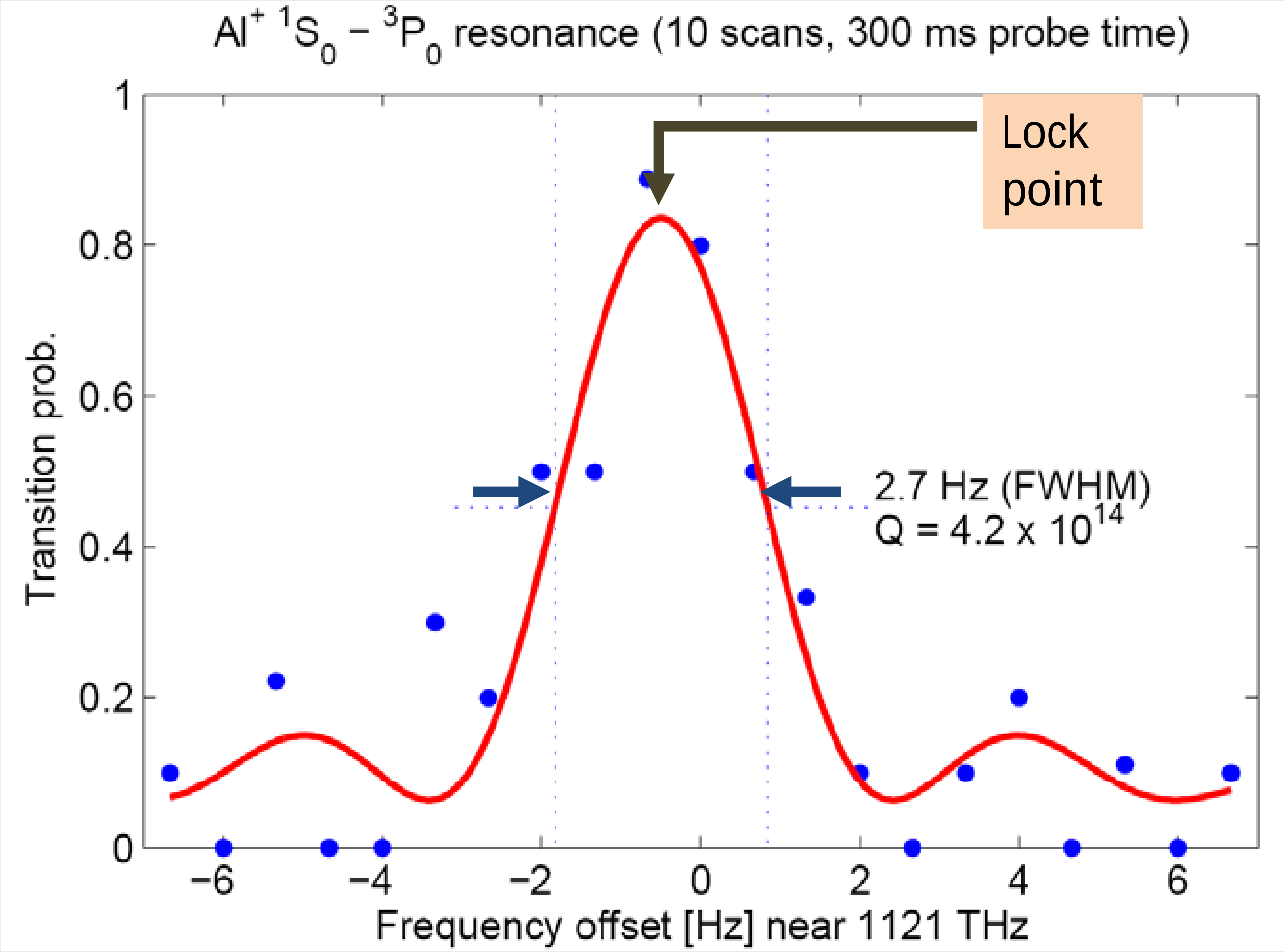
P.O. Schmidt et al., Science **309**, 749 (2005)

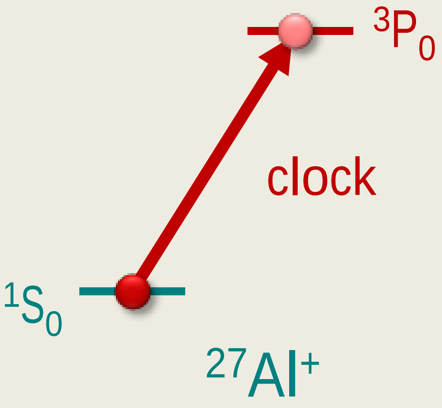
Quantum Logic State Transfer





Al^+ Clock Transition

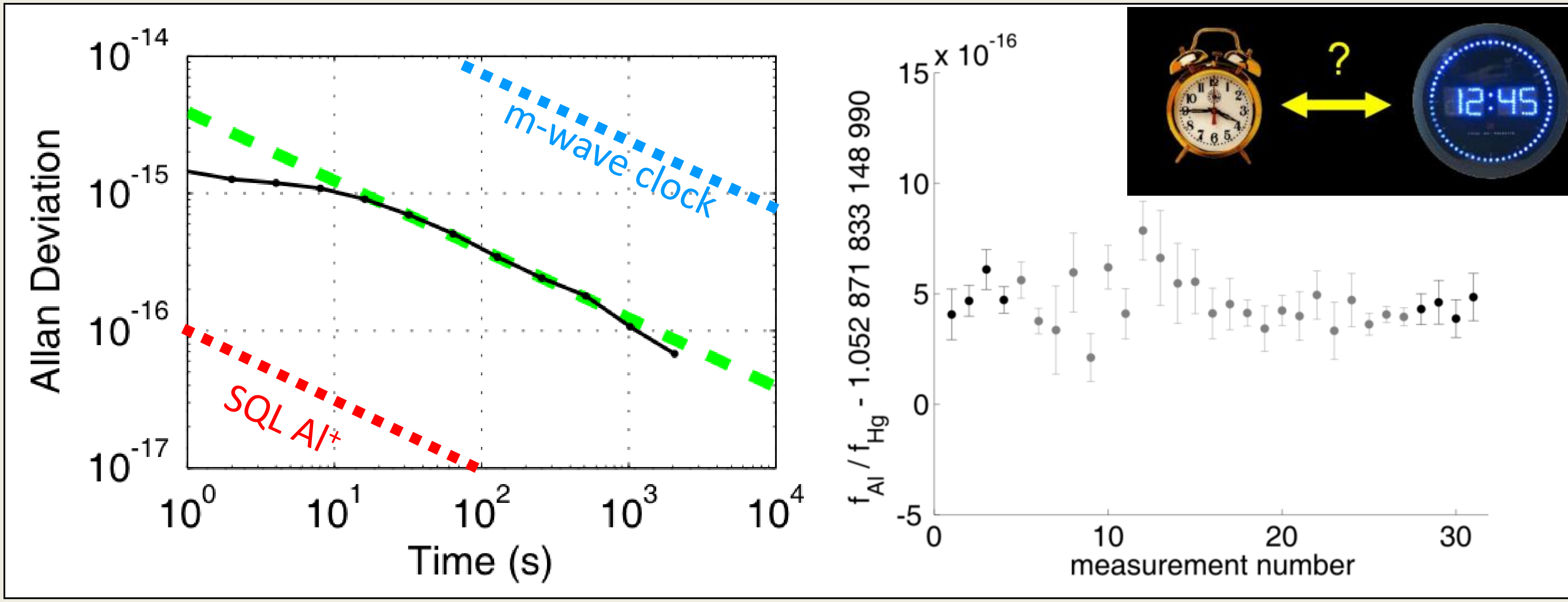




C.W. Chou, *et al.*
Science **329**, 1630 (2010)

NIST

NIST Al^+-1/Hg^+ Comparison



Al^+: 2.3×10^{-17} systematic uncertainty

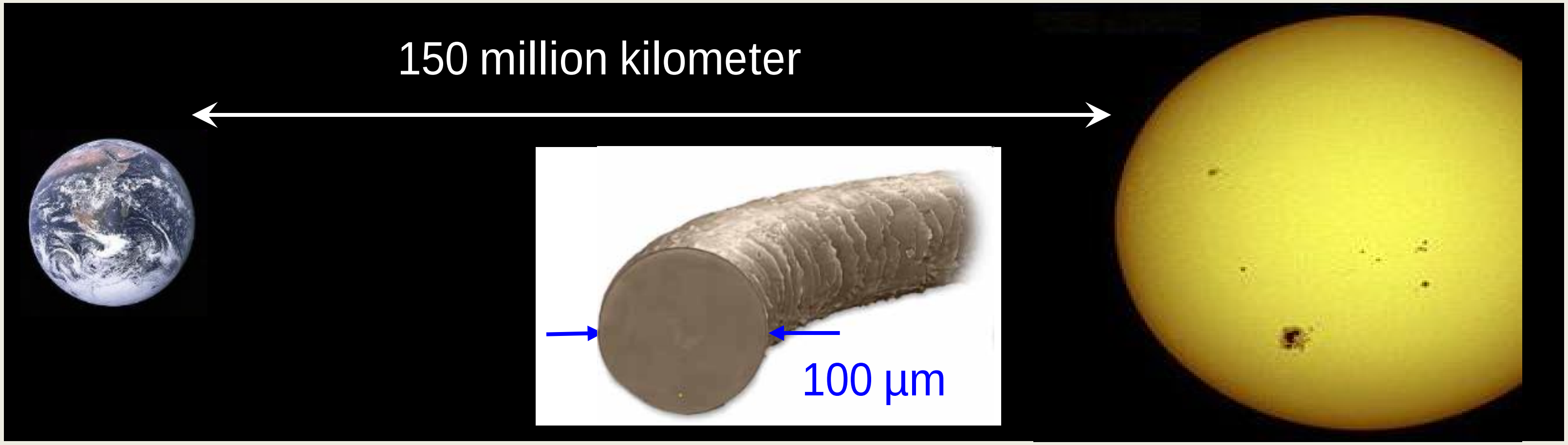
Hg^+: 1.9×10^{-17} systematic uncertainty

First comparison of frequency standards at the 17th digit

T. Rosenband *et al.*, Science **319**, 1808 (2008)

What does 10^{-17} mean?

- 10x more accurate than Cs fountain clocks
- 1 s deviation in 3 billion years
- 1st order Doppler shift: 3 nm/s or 300 µm/year
- Gravitational red shift of 10 cm
- Distance measurement earth-sun to 1/100 of the diameter of a hair



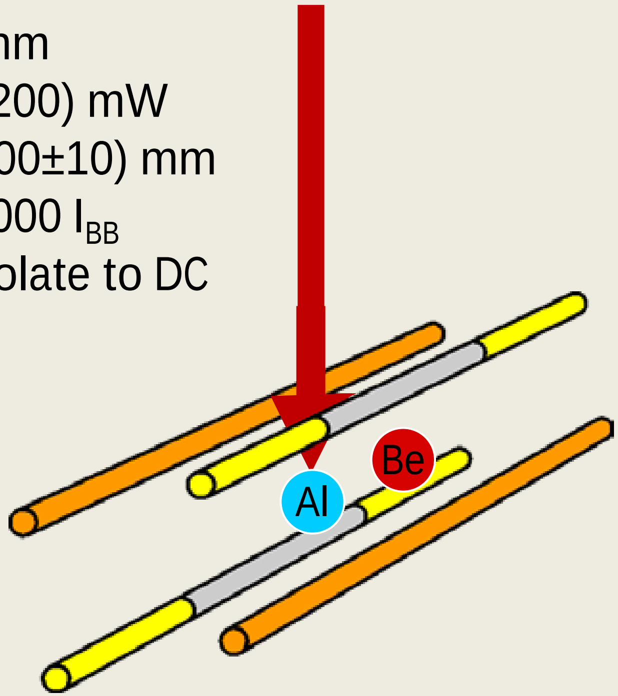
NIST Al-2 error budget

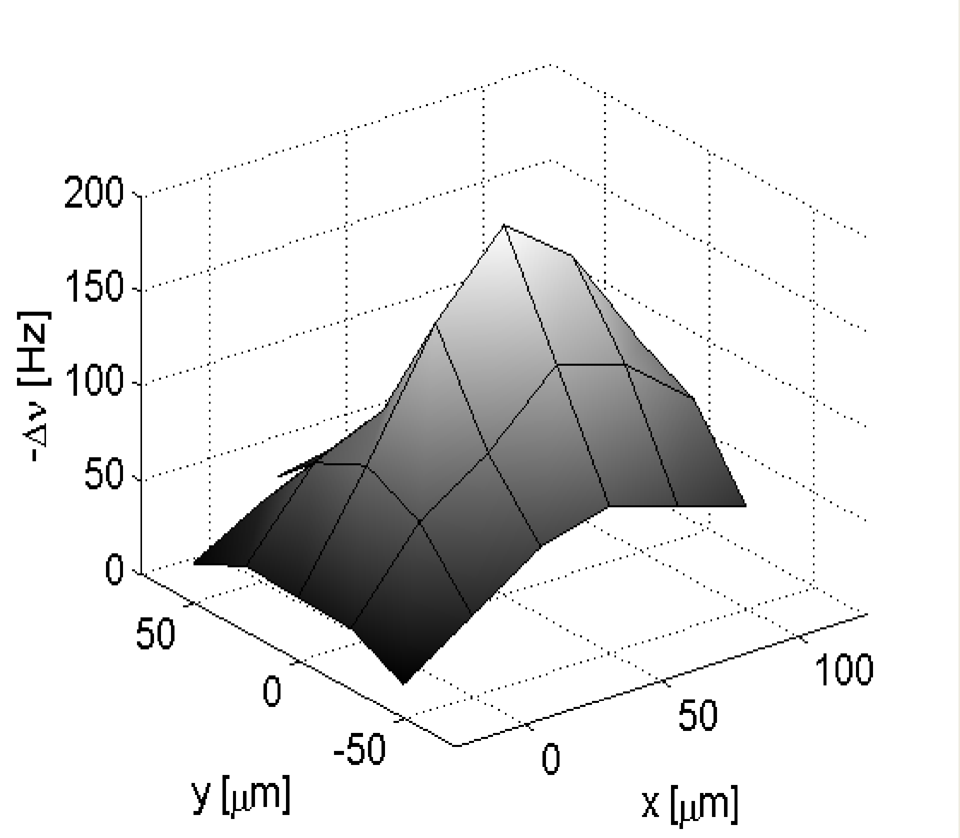
Effect	Parameter	Shift [x 10^{-18}]	Uncertainty [x 10^{-18}]
Blackbody shift	Operating temperature	-9	3 è 0.6*
Micromotion 2^{nd} order Doppler	Radial static field	-9	6
Secular 2^{nd} order Doppler	Radial temperature	-16.1	5
2^{nd} order Zeeman	RMS magnetic field	-1079.9	0.7
Cooling laser Stark shift	I / I_{sat}	-3.6	1.5
Linear Doppler shift, clock laser Stark shift, background gas collisions shift, AOM frequency error		0	0.6
Total		**-1117.6**	**8.6 è 8.0**

C.-W. Chou, et al.
PRL 104, 070802 (2010)
* C.-W. Chou, priv. com. (2014)

Polarizability Measurement

l = 1126 nm
P = (600±200) mW
waist = (100±10) mm
I_{1126} = 21 000 I_{BB}
è extrapolate to DC





map out laser intensity profile

New measurement with 976 nm laser:

è $\Delta\alpha_S = 4\pi\epsilon_0 \cdot 6.31(85) \cdot 10^{-32}\ \mathrm{m}^3$

è agrees well with theory value

è $\Delta f / f = 3.8(4) \times 10^{-18}$

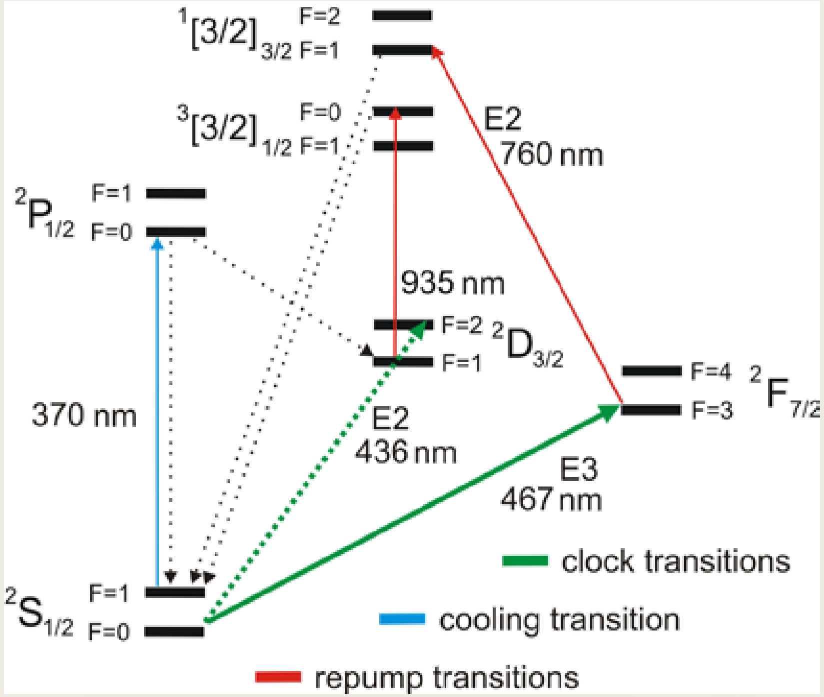
[C.-W. Chou, priv. com. (2014)]

[T. Rosenband et al. in *Proceedings of the 20th EFTF* 289–291 (2006)]

$^{171}Yb^+$

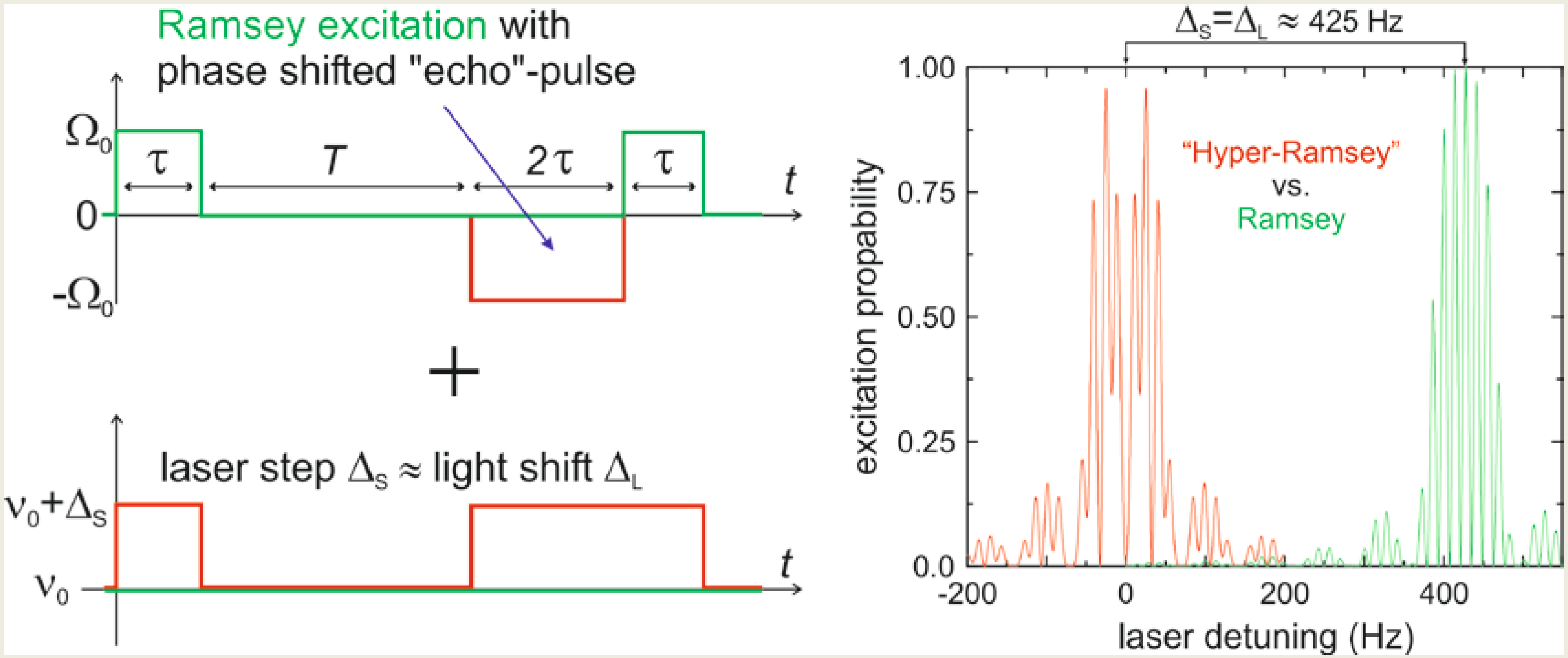
- 2 clock transitions:
  - quadrupole (E2): 3.1 Hz
  - octupole (E3): 10^{-9} Hz
- high sensitivity to $\dot{\alpha}/\alpha$
- but: E3 has huge AC Stark shift from clock laser!

è Hyper-Ramsey spectroscopy



E2: Tamm *et al.*, Phys. Rev. A **80**, 043403 (2009)
E3: Huntemann *et al.*, Phys. Rev. Lett. **108**, 090801 (2012)

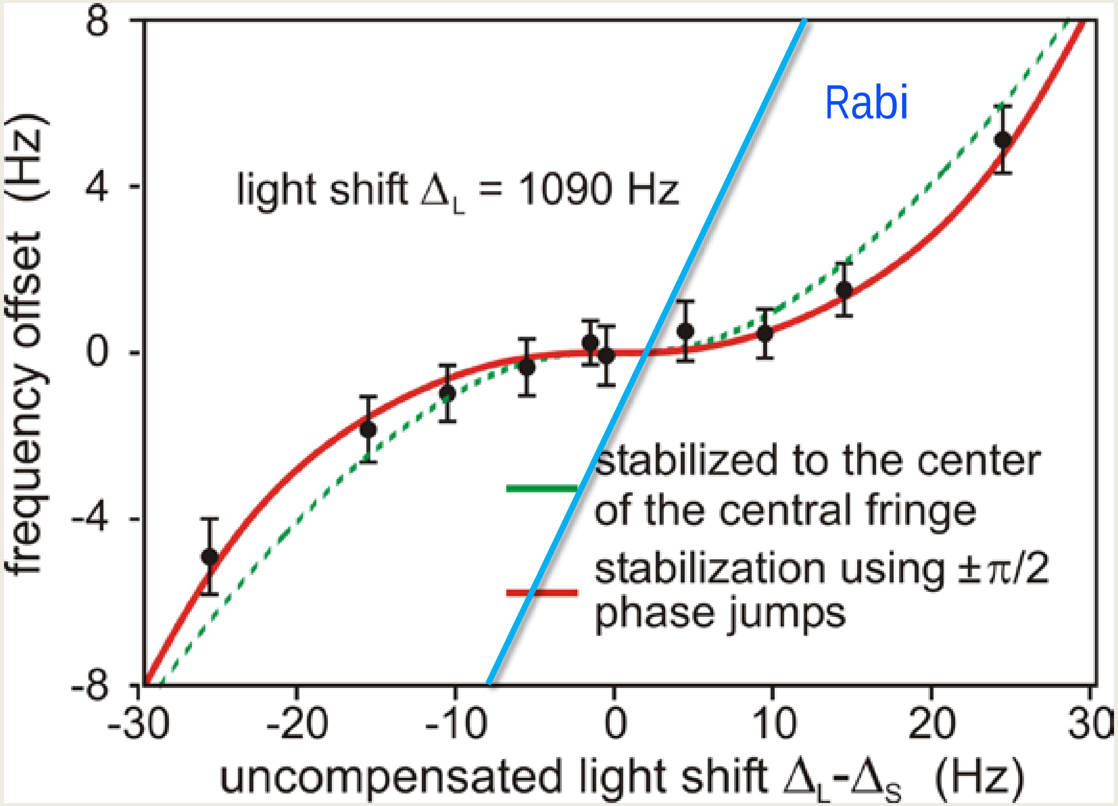
Hyper-Ramsey Spectroscopy



- frequency of probe laser is adjusted to match light shift during pulses: $\Delta_S = \Delta_L$
- additional p-pulse cancels the linear dependence on Δ_L
  è strong suppression of light shift
- Discriminator signal is generated by ±p/2 phase steps

Yudin *et al.*, Phys. Rev. A **82** 011804(R) (2010)
Huntemann *et al.*, Phys. Rev. Lett. **109** 213002 (2012)

Hyper-Ramsey Spectroscopy



• interleaved stabilization on $(\Delta_L - \Delta_S) = 0$ and $(\Delta_L - \Delta_S) \neq 0$
è cubic dependence of the resonance centered on $(\Delta_L - \Delta_S)$

Huntemann *et al.*, Phys. Rev. Lett. **109** 213002 (2012)

Compare to: Sr lattice clock

Effect	Shift ($\times 10^{-18}$)	Uncertainty ($\times 10^{-18}$)
Lattice Stark	-1.3	1.1
BBR static	-4562.1	0.3
BBR dynamic	-305.3	1.4
dc Stark	0.0	0.1
Probe Stark	0.0	0.0
1st-order Zeeman	-0.2	0.2
2nd-order Zeeman	-51.7	0.3
Density	-3.5	0.4
Line pulling + tunneling	0.0	<0.1
2nd-order Doppler	0.0	<0.1
Background gas	0.0	<0.6
Servo offset	-0.5	0.4
AOM phase chirp	0.6	0.4
Total	-4924.0	2.1

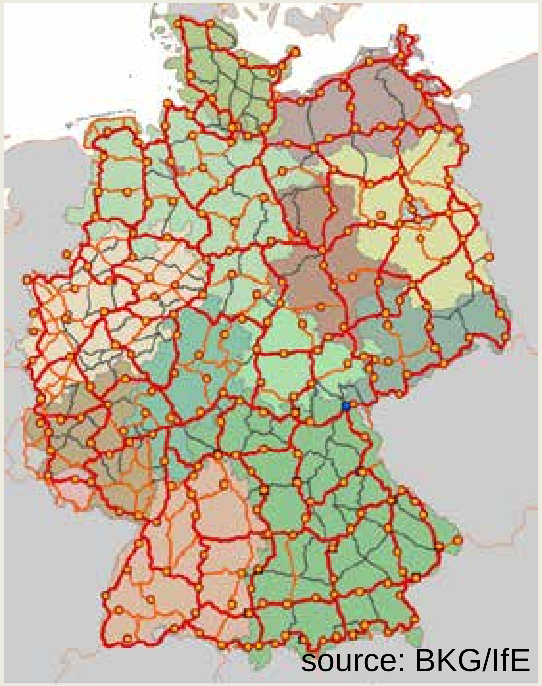
lowest estimated uncertainty for a lattice clock

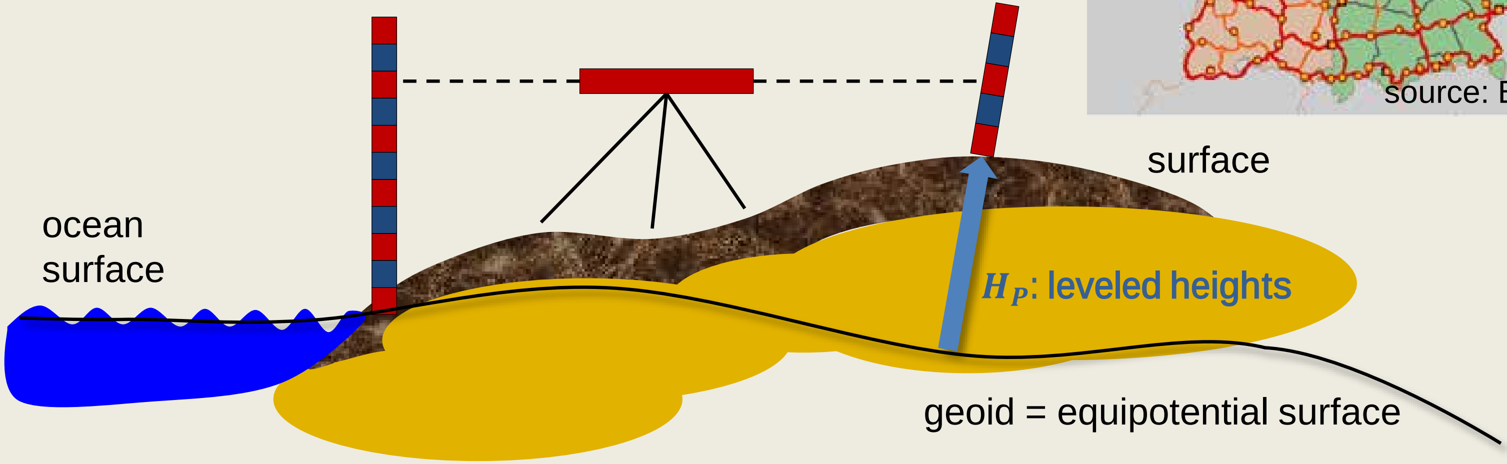
[T. L. Nicholson *et al.*, arXiv:1412.8261]

APPLICATIONS

Leveling and Height Systems

- Establishing a height system:
  leveling + terrestrial gravimetry
- In Germany:
  - 30 908 km leveling lines
  - 287 loops, 469 nodes
  - renewed every ~10 years





- remark: GPS measures height above ellipsoid

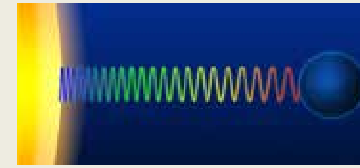
New Era: Relativistic Geodesy

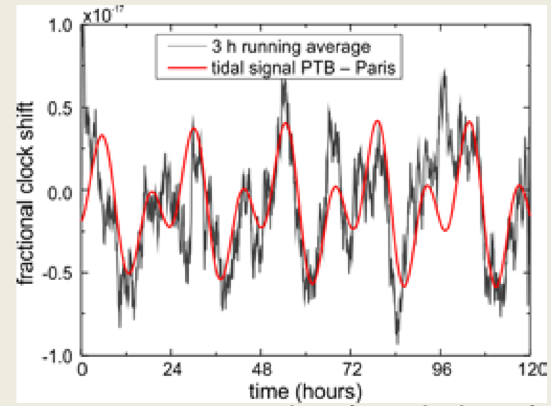
- relativistic frequency change: $\frac{\Delta f}{f} = \frac{W_0 - W_P}{c^2}$
- gravity potential W: Newtonian + centrifugal terms
- height: $H_P = \frac{W_0 - W_P}{\bar{g}} = \frac{c^2}{\bar{g}} \frac{\Delta f}{f}$

è chronometric leveling over long distances

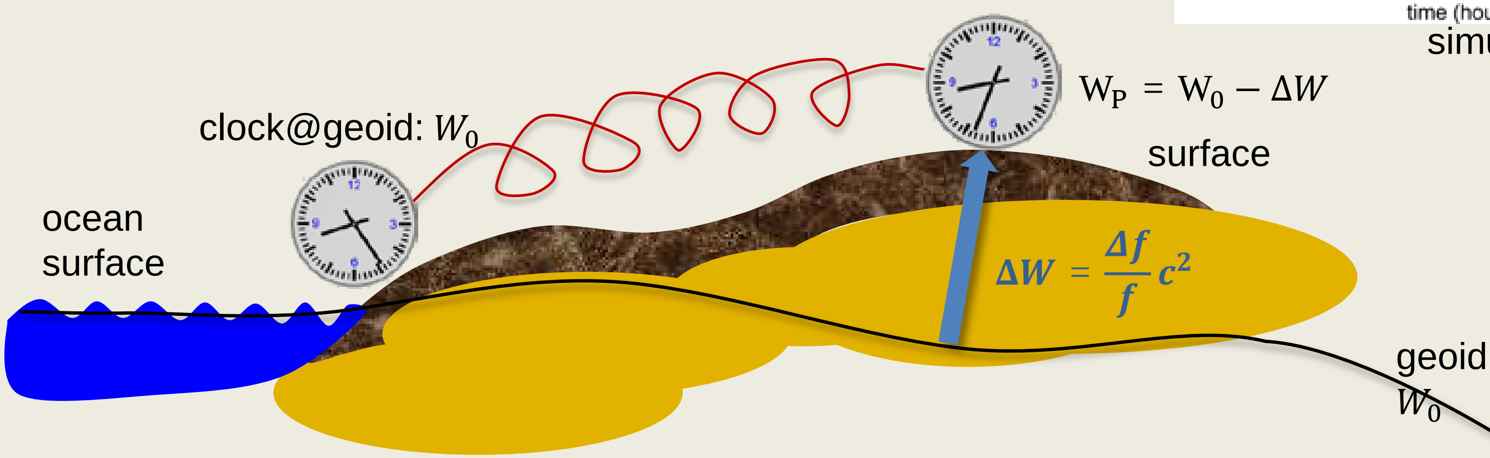
è clock-based height system

è Required for redefinition of the SI second





simulated signal



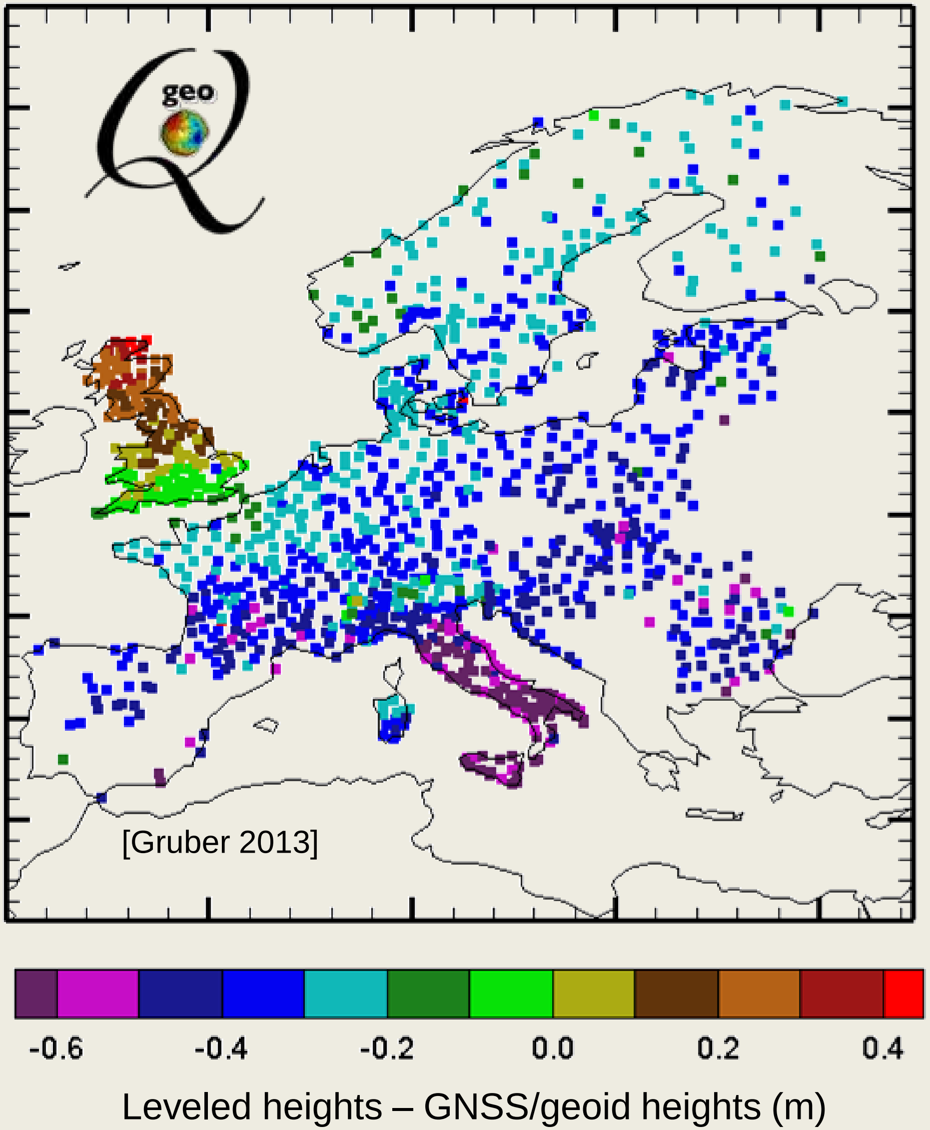
Vermeer, Reports of the Finnish Geodetic Institute **83(2)**, 1(1983); Bjerhammar, Bull. Geodesique **59**, 207 (1985).

Resolve Height Inconsistencies?

- decimeter inconsistencies hamper combination of tide gauges

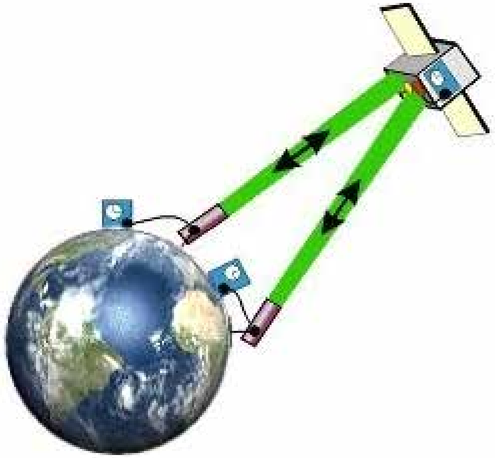
è efforts for **height system modernization**

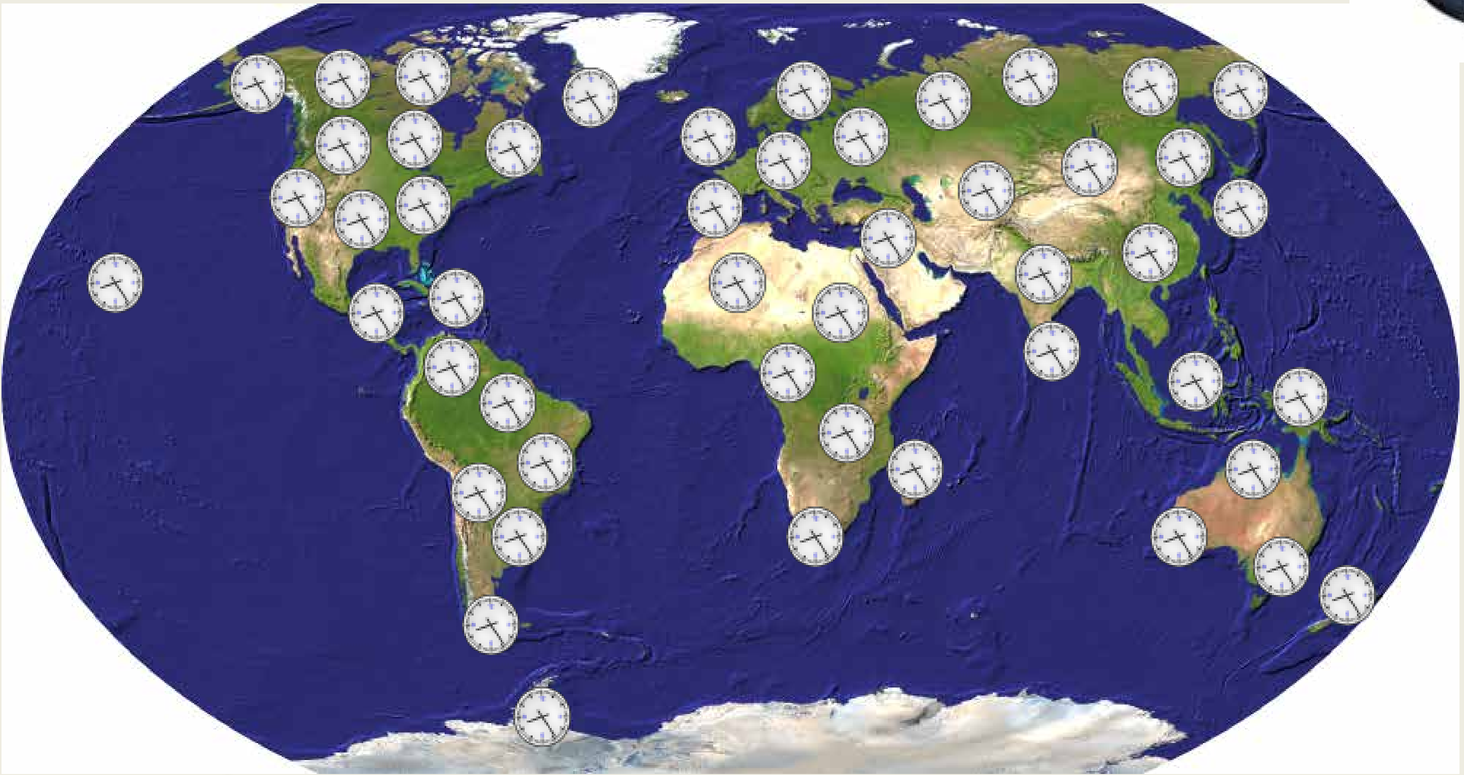
è **clocks** could provide **in-situ cm** accuracy referenced to **well-defined W_0**



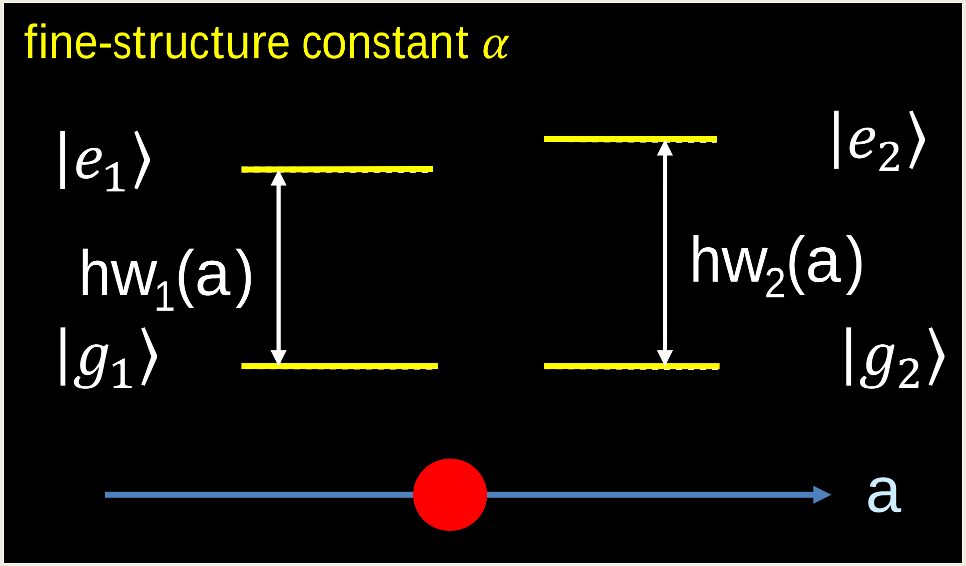
Vision

optical frequency comparison
via satellites
è clock-based consistent
reference frame

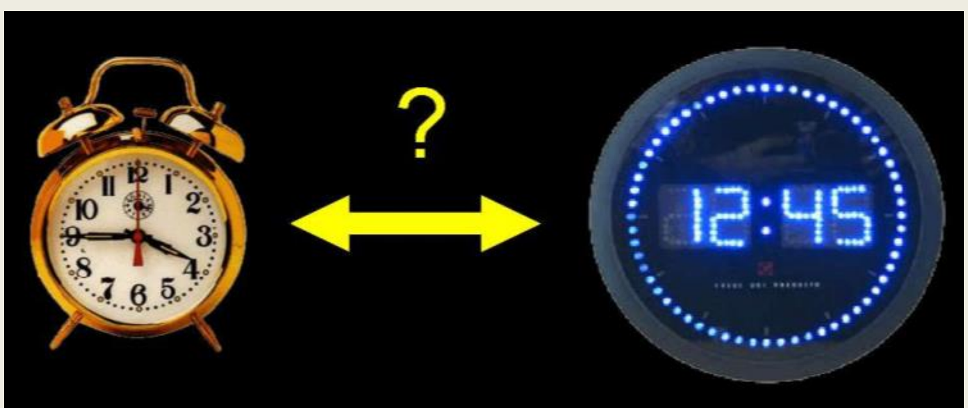




Variation of Fundamental Constants

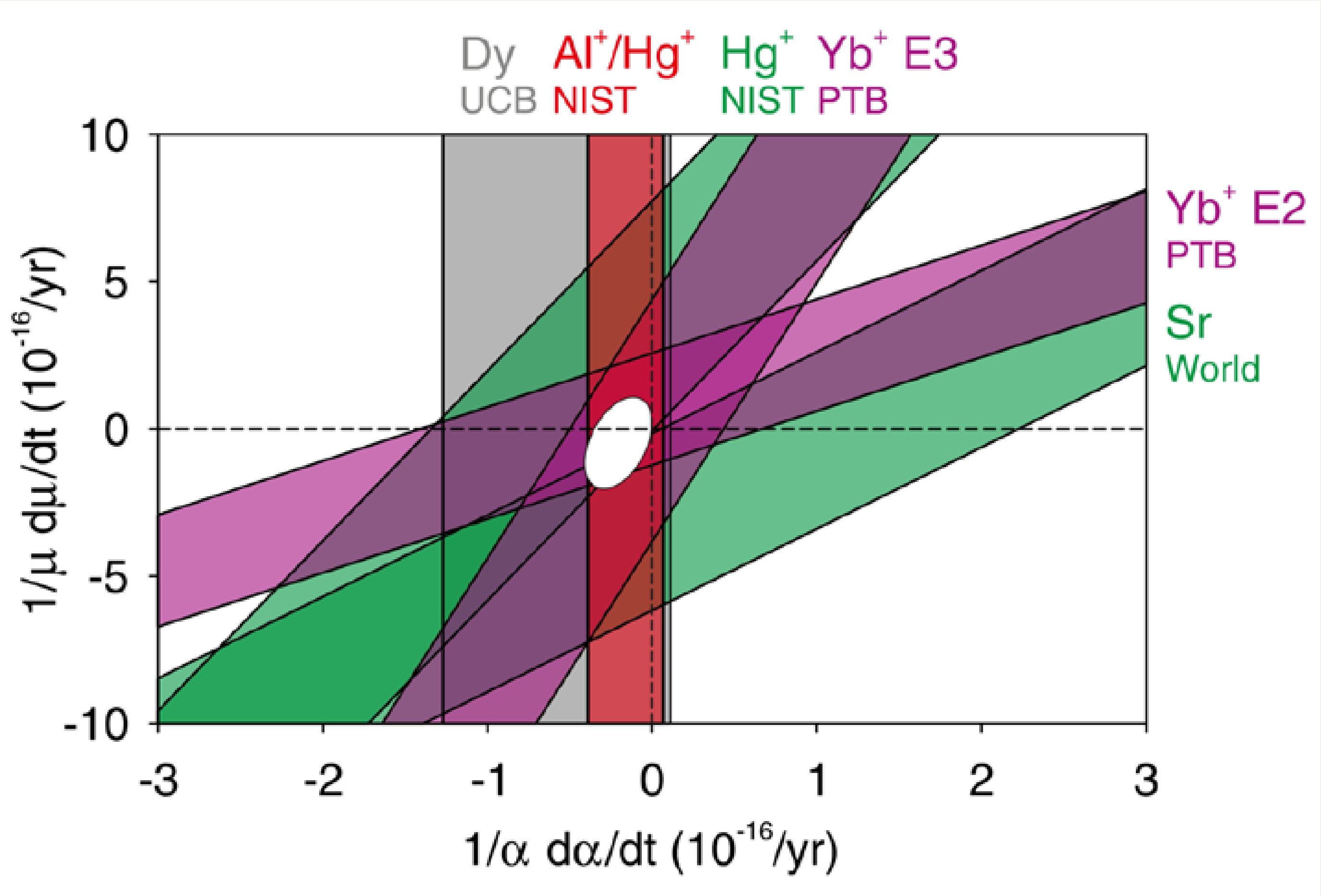


$$\omega_k(\alpha) \approx \omega_k + 2q_k \frac{\Delta\alpha}{\alpha}$$



system	q (cm^{-1})
Sr	443
Dy	-24000, 6000
Yb^+ E2	10397
Yb^+ E3	-63752
Hg^+	-52200
Al^+	146
Ho^{14+}	-186000
Ir^{17+}	-385367, 367161
Cf^{16+}*	-370928, 465293
Th* nuclear	2.5×10^8

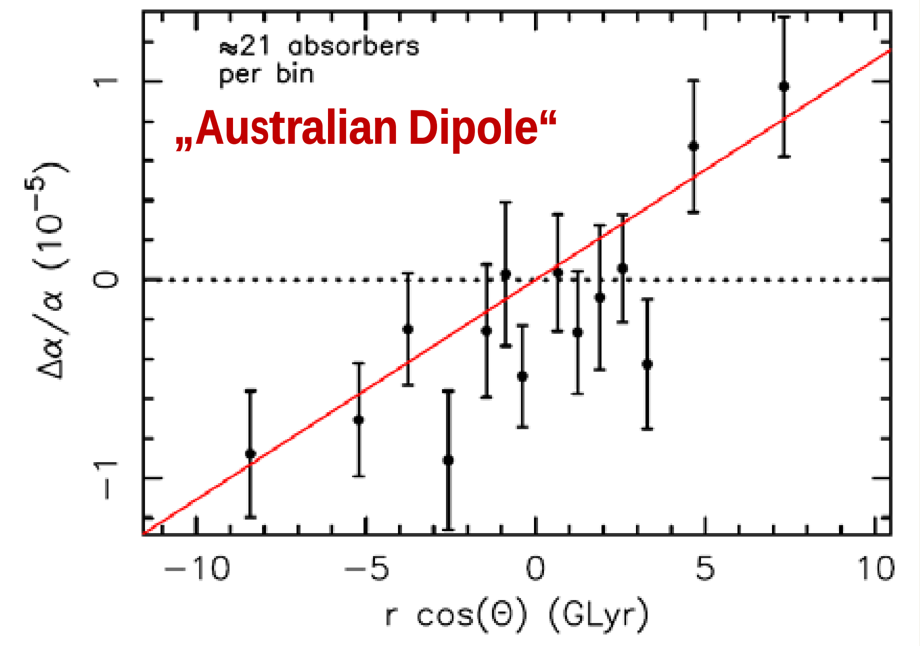
Combined data from clocks



$$\dot{\alpha}/\alpha = -0.20(20) \times 10^{-16}/\mathrm{year}$$
$$\dot{\mu}/\mu = -0.5(1.6) \times 10^{-16}/\mathrm{year}$$

Huntemann *et al.*, PRL **113**, 210802 (2014)
also: Godun *et al.*, **113**, 210801 (2014)

Latest Astronomy Result: Spatial Variation of a?



J.K. Webb *et al.*, Phys. Rev. Lett. **107**, 191101 (2011)

è a changes with position: $\Delta\alpha/\alpha = 1.10(25) \times 10^{-6} \cos\Theta$

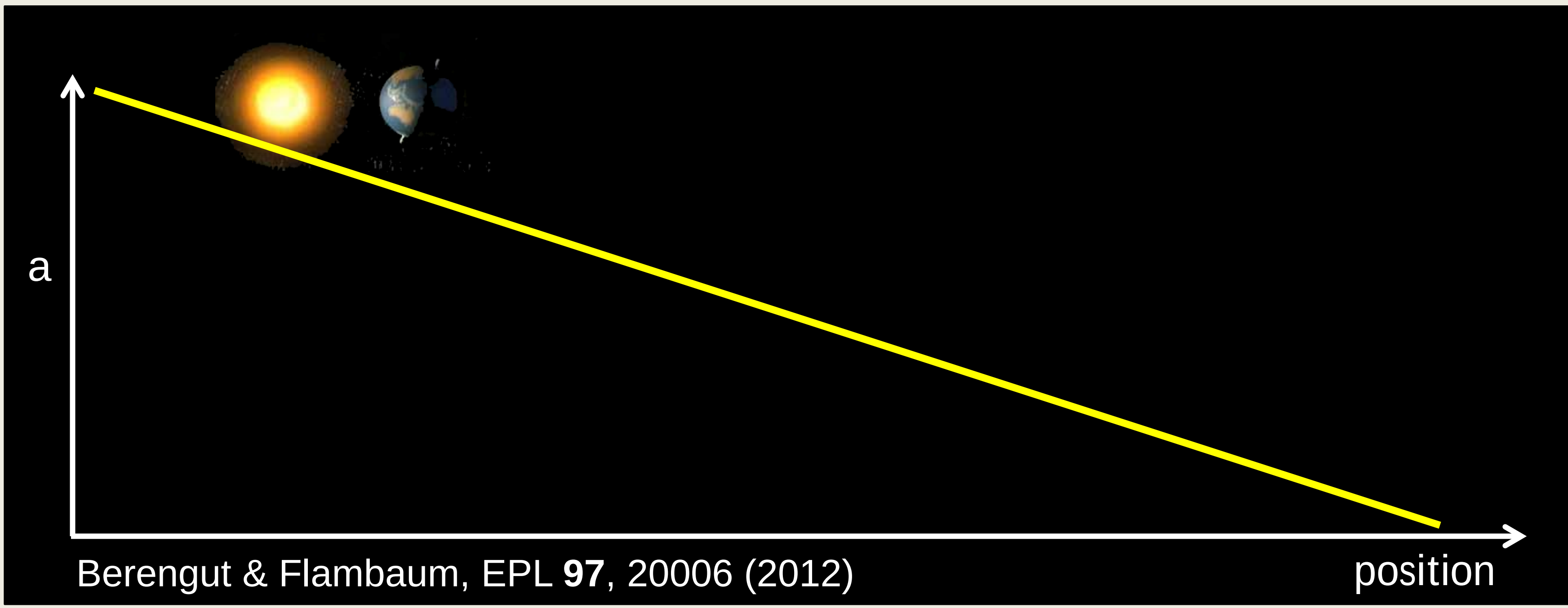
Limited by knowledge of isotope shifts of broad transitions!

M. G. Kozlov et al. Phys. Rev. A **70**, 062108 (2004); Murphy & Berengut, MNRAS **438**, 388–411 (2014)

Future Challenges

- „Australian Dipole“ suggests spatial variation of a
- solar system is moving with respect to CMB background

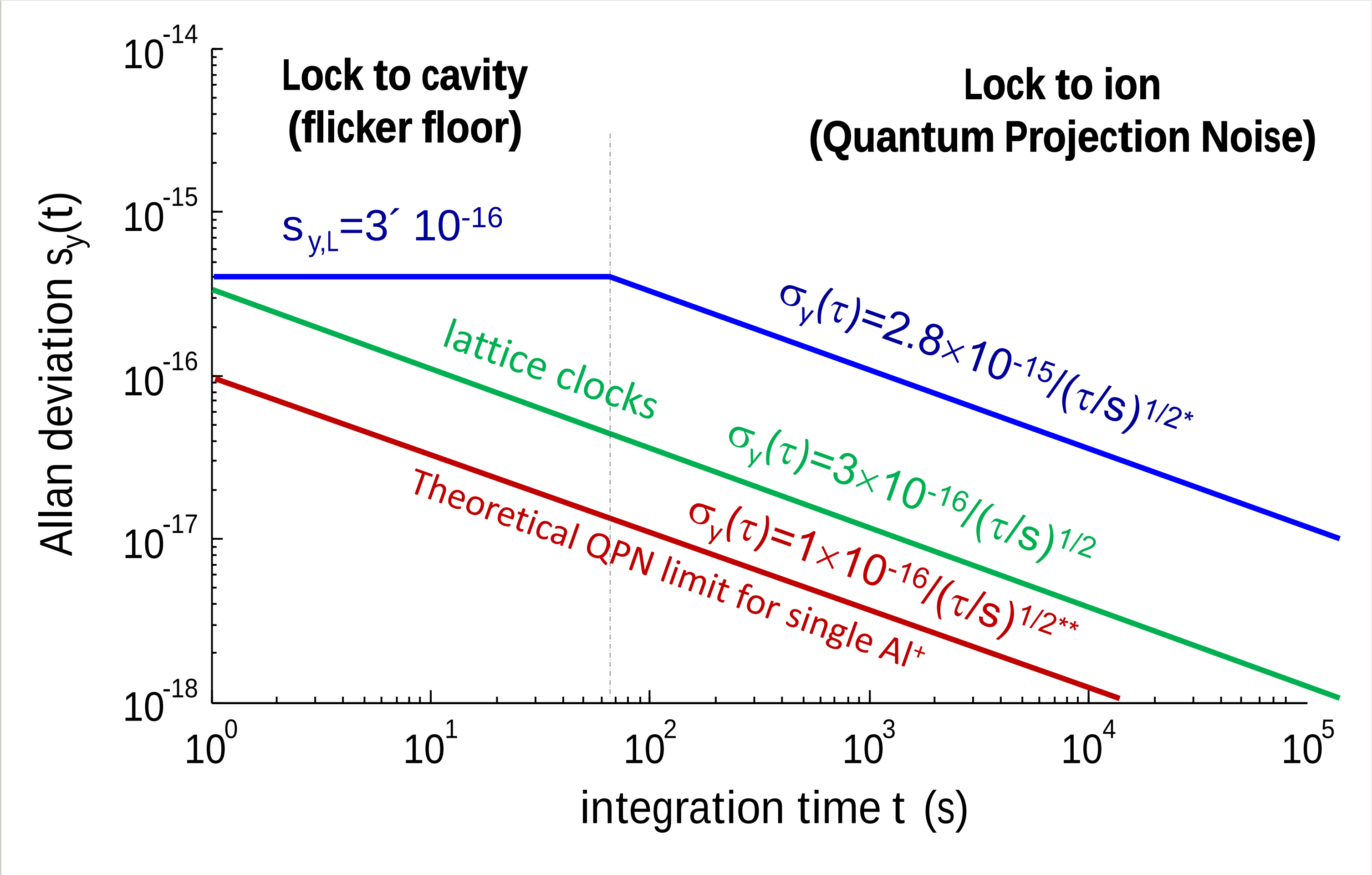
  è variation in a: $\frac{\Delta\alpha}{\alpha} \approx 10^{-19}/year$



- dark matter searches, gravitational waves,...

FUTURE TRENDS

Improved Stability?



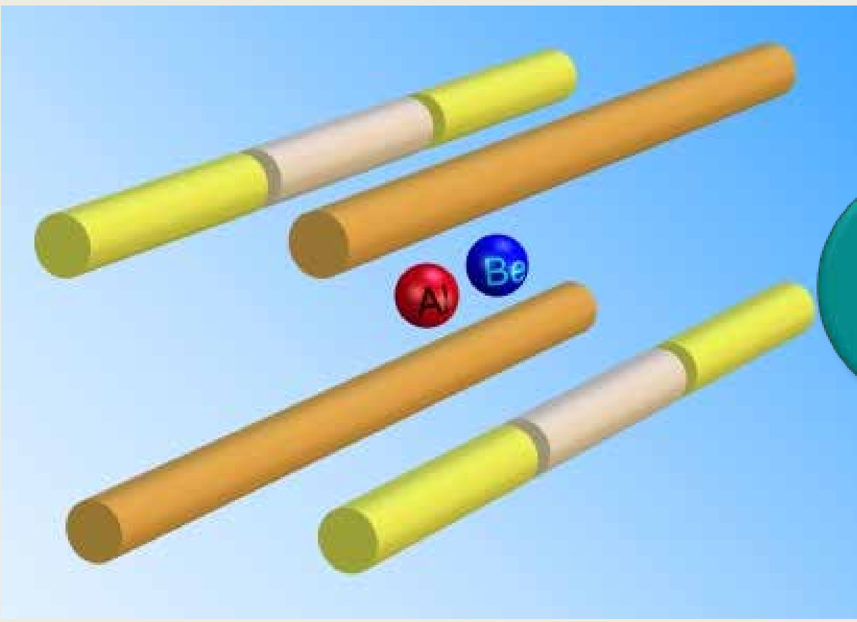
Several interrogations required for lock to ion!

* Chou *et al*. PRL, vol. 104, Issue 7 (2011)

E. Peik *et al.* J. Phys. B: At. Mol. Opt. Phys. **39 (2006) 145–158

Ultimate Stability Boost?

è precision spectroscopy with multiple ions?



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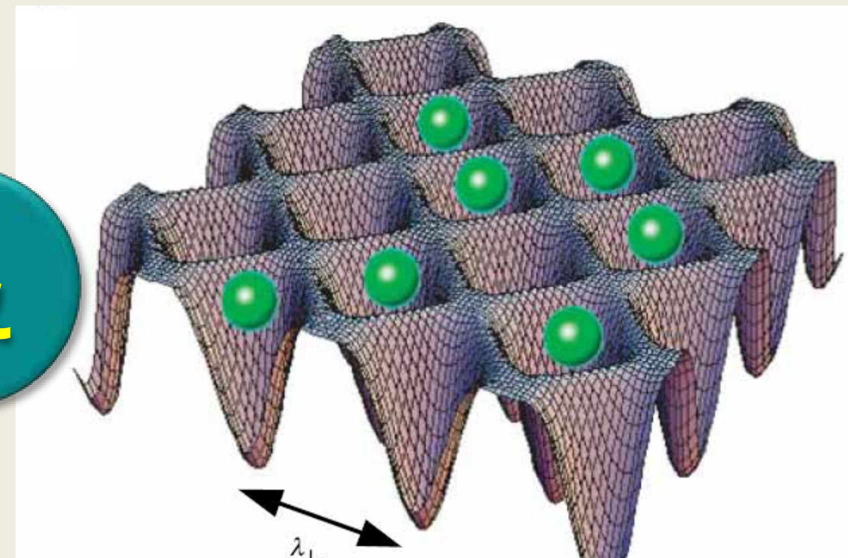
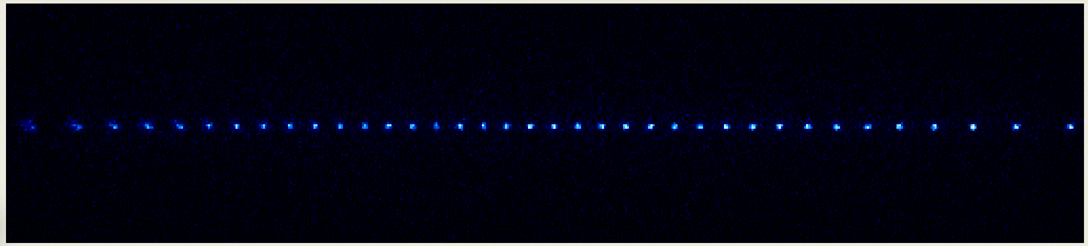


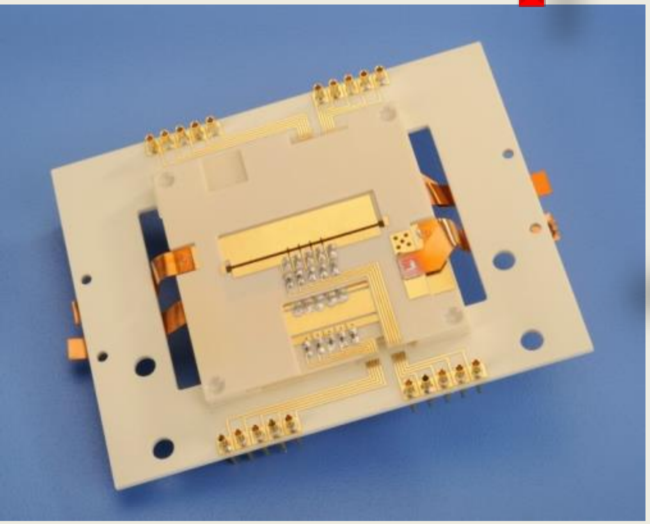
Takamoto *et al.*, Nature **435**, 321 (2005)

Multi-Ion Traps

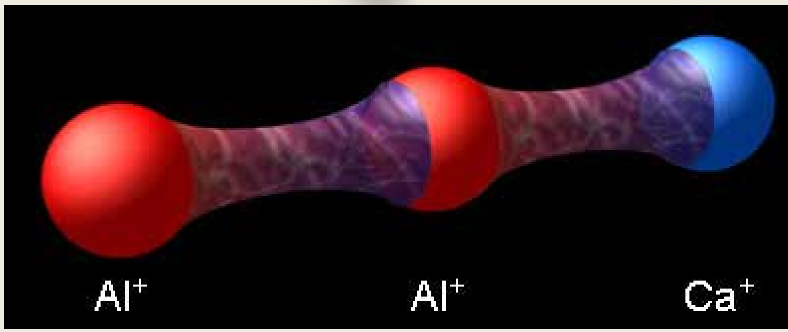
T.E.Mehlstäubler



- Multi-ion clocks
- Entangled ion clocks (Heisenberg limit)
- Scalable ion traps!



Herschbach *et al.*, Appl. Phys. B **107**, 891 (2012)
Pyka *et al.*, Appl. Phys. B **114**, 231–241 (2014)

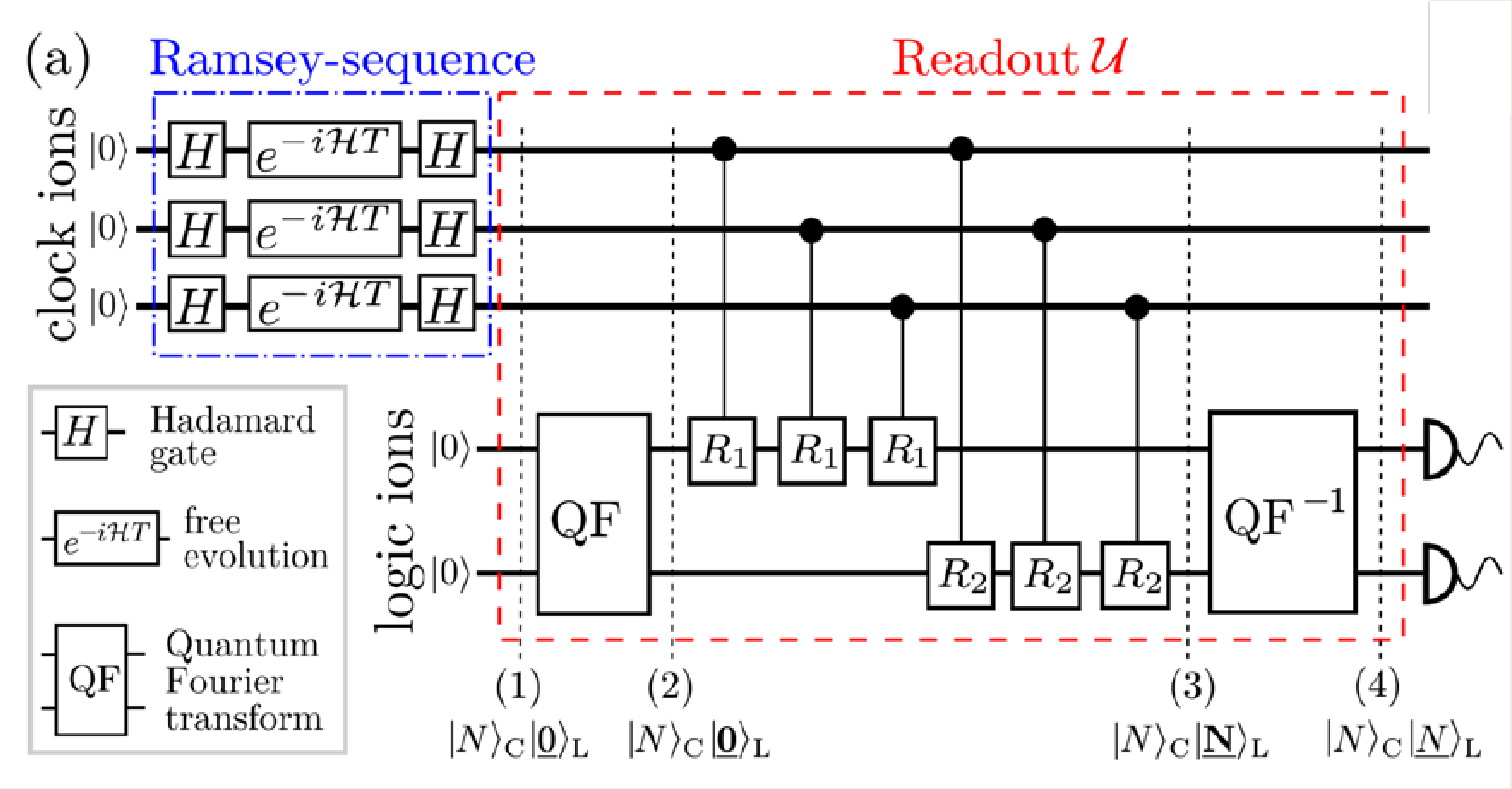


works only for ions with $\Theta_{el} \sim 0$: Al^+, In^+

Quantum algorithmic clock readout

- problem: multi-ion readout for quantum logic clock

è map # of excited clock ions in binary code onto logic ions

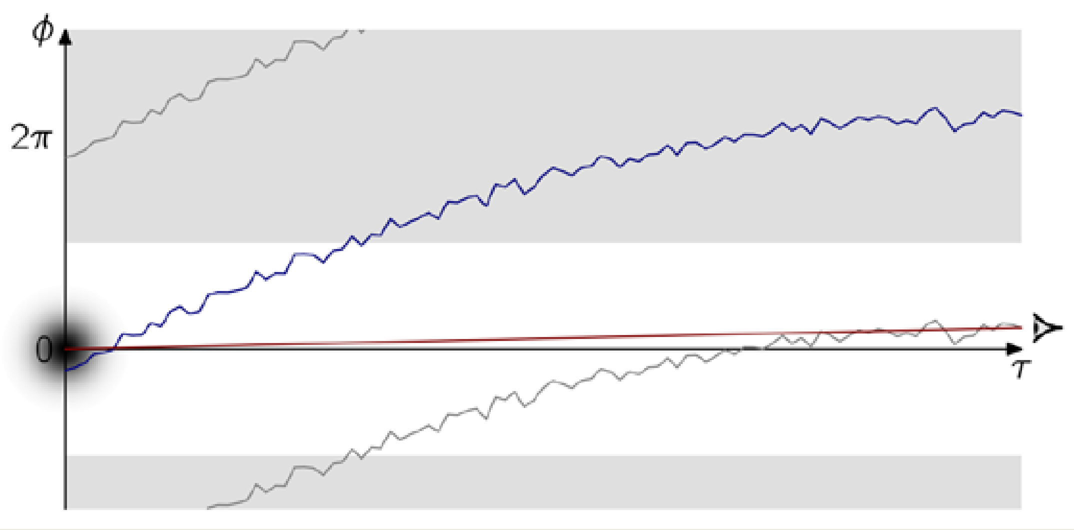


[Schulte *et al.*, arXiv:1501.06453]

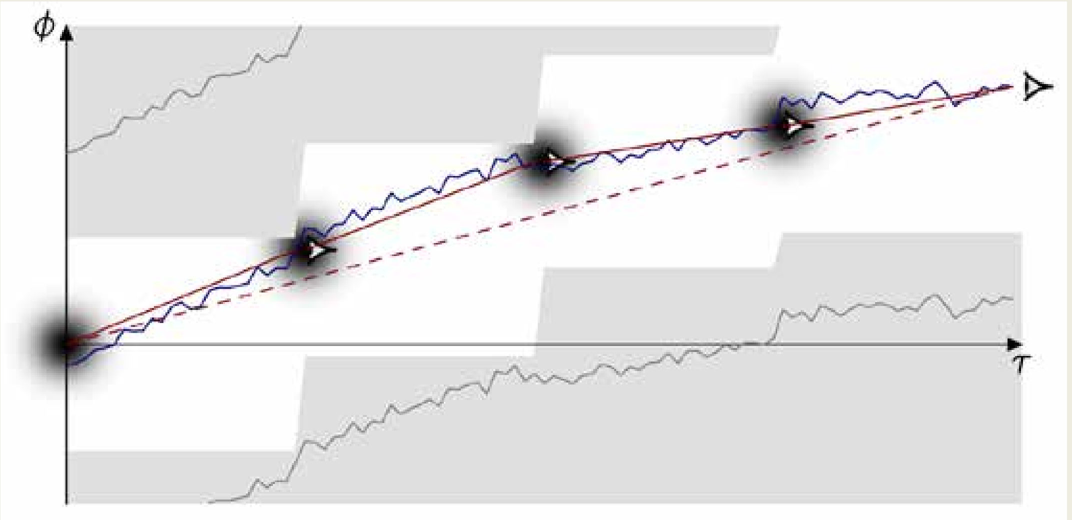
Cascaded clocks

- problem: flicker frequency noise of laser
  è limits probe time T_c

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

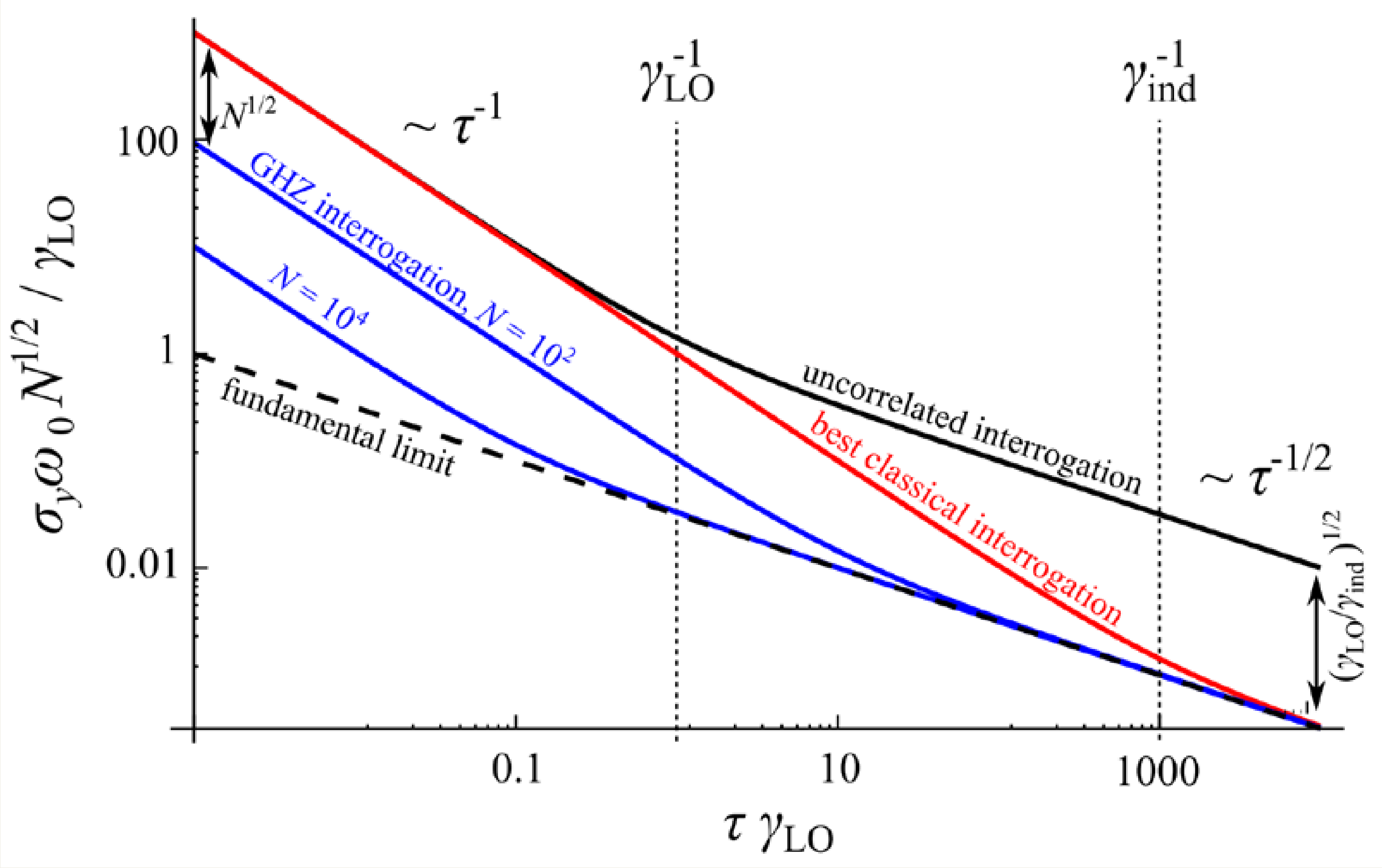


- idea: use cascaded ensembles of clocks operating at different interrogation times
  è extend maximum probe time to $T_C^* \gg T_C$



Borregaard & Sørensen, PRL **111**, 090802 (2013)
Rosenband & Leibrandt, arXiv:1303.6357 (2013)

Entanglement for improved stability?

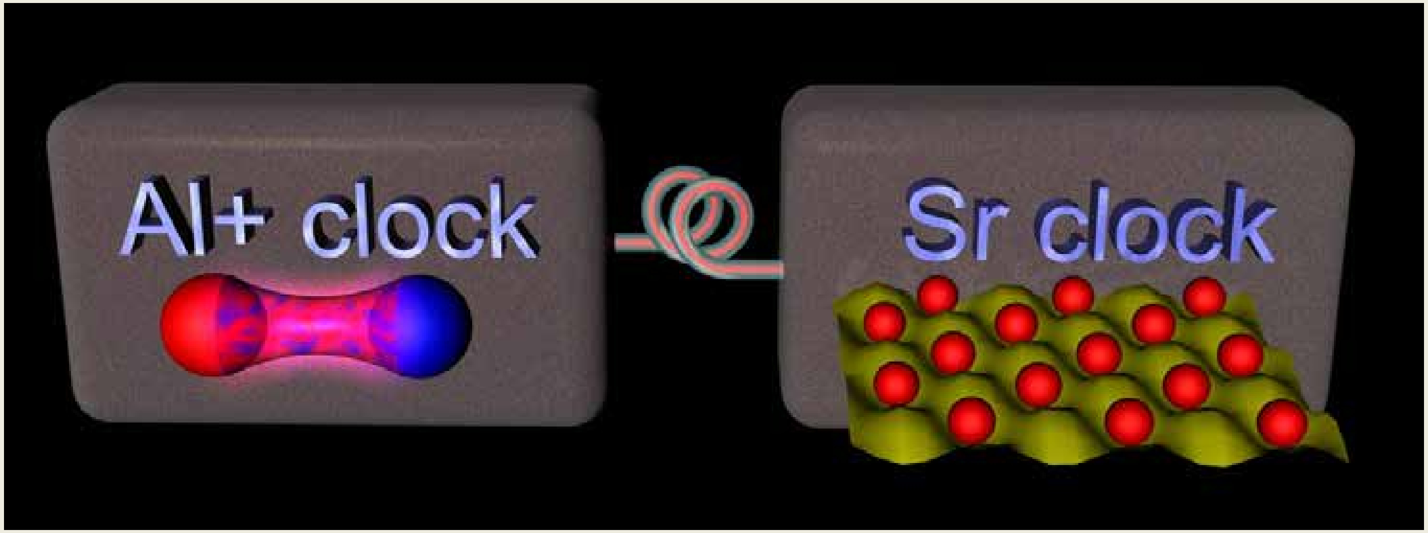


Kessler et al.,PRL **112**, 190403 (2014)

Hybrid Clock

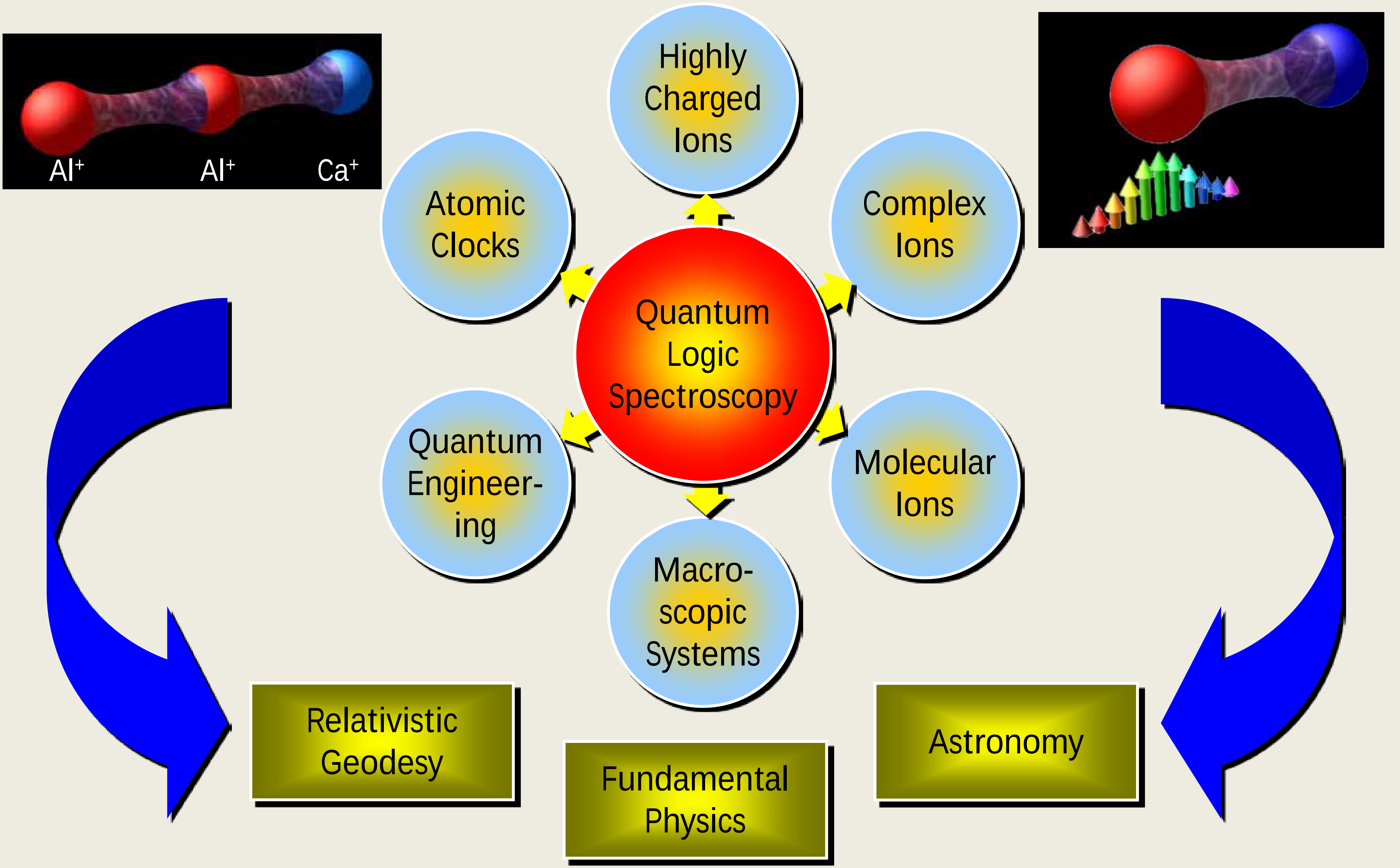
- Al^+-slaved Sr lattice clock

è accuracy of Al^+ + stability of Sr lattice



- approach for clocks with the same species:
  correlation spectroscopy
  è local oscillator noise acts the same on both atoms
  è common mode rejected

Quantum Logic Spectroscopy



The End