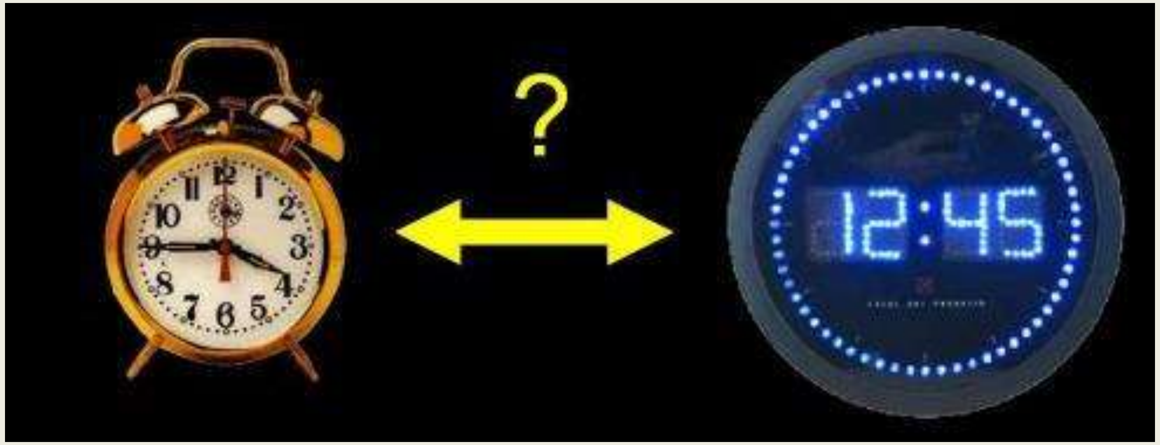
Search for new physics with clocks



P. O. Schmidt
QUEST Institute for Experimental Quantum Metrology
PTB Braunschweig and Leibniz Universität Hannover

International Conference on Quantum Technology for High-Energy Physics, CERN, 01.11.2022

The measurement with the most significant digits ever performed:

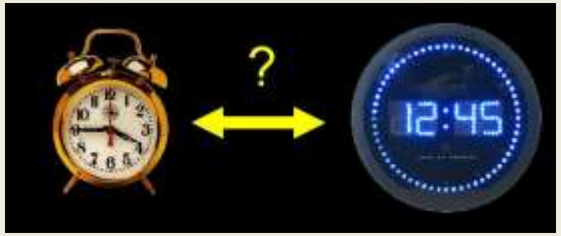
$$2.16288712751666370 3(13)$$

(Quantum) Metrology with optical clocks

The measurement with the most significant digits ever performed:

$$\frac{f_{\mathrm{Al}^+}}{f_{\mathrm{Yb}}} = 2.162887127516663703(13)$$

[BACON collaboration, Nature **591**, 564 (2021)]



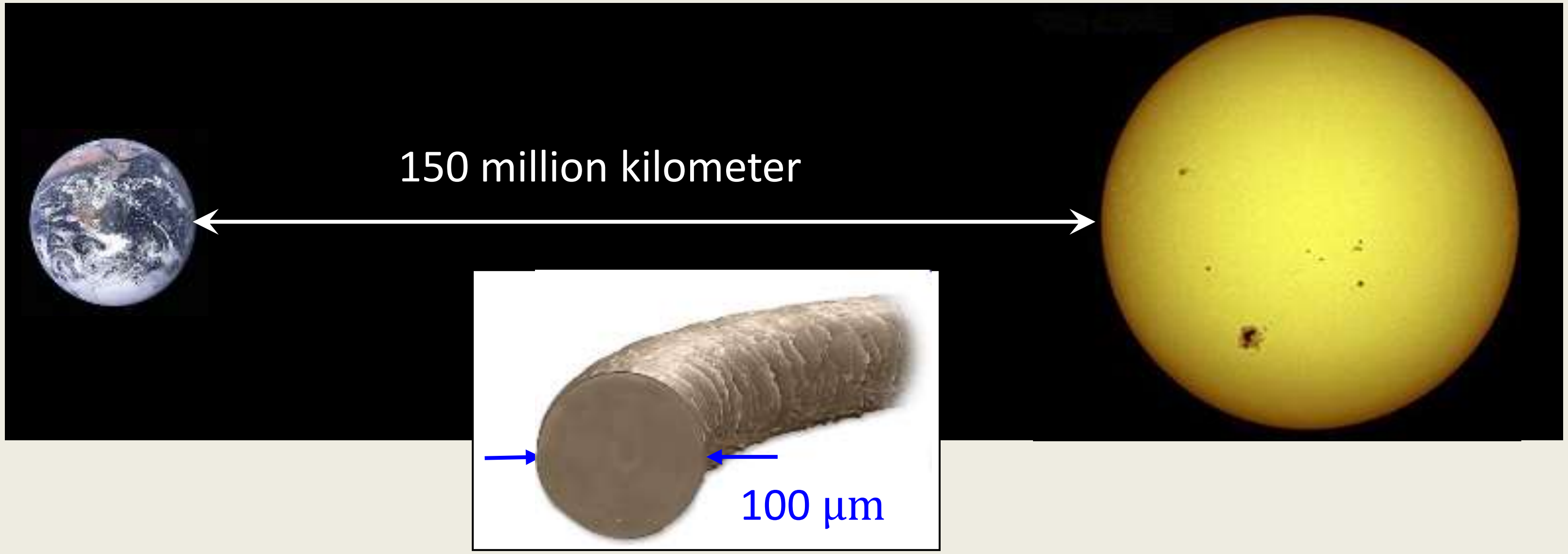
optical clock comparison with 18 digits

…no fundamental limit for improvement in sight

What does 10^{-18} mean?

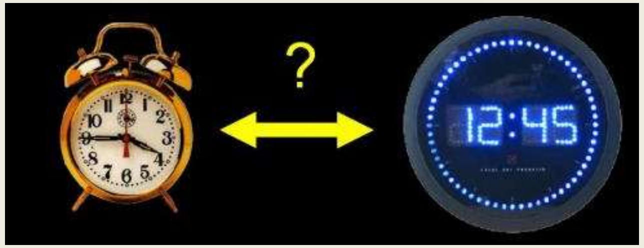
- 1 : 1,000,000,000,000,000,000
- 300x better than Cs fountain clocks
- 1 s deviation in 30 billion years
- 1^{st} order Doppler shift: 0.3 nm/s or 30 mm/Jahr
- Distance measurement earth-sun to 1/1000 of the diameter of a hair

Who needs clocks this good?



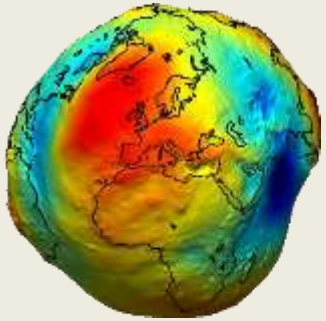
Who Needs Better Clocks?

- Clocks have many applications:
  - Tests of fundamental physics
  - Geodesy
  - Synchronization of large networks
  - Navigation
  - …



DQmat

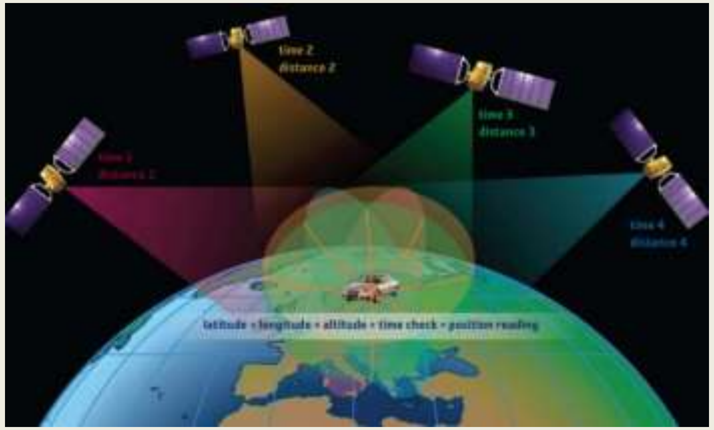
CRC 1227



Terra

CRC 1464

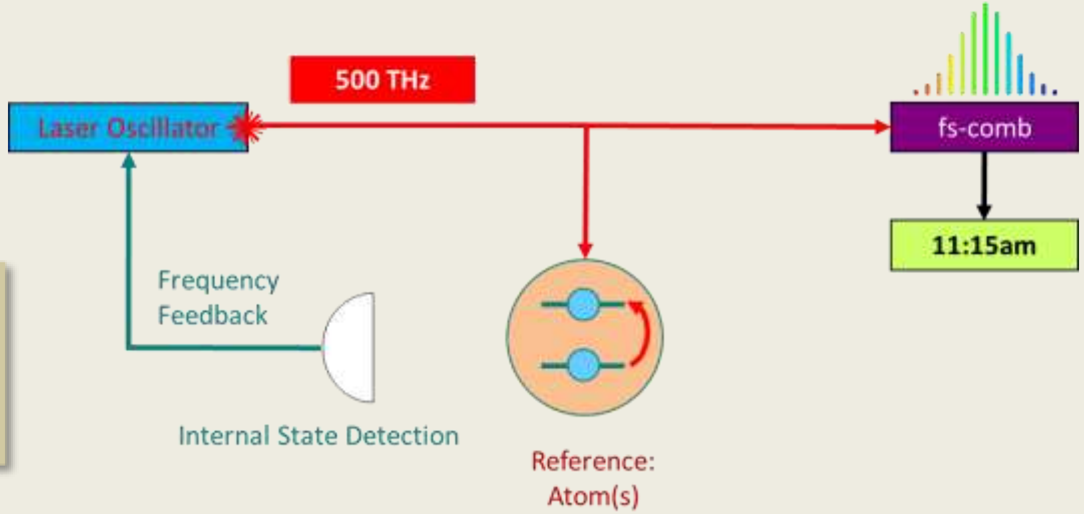
opticlock

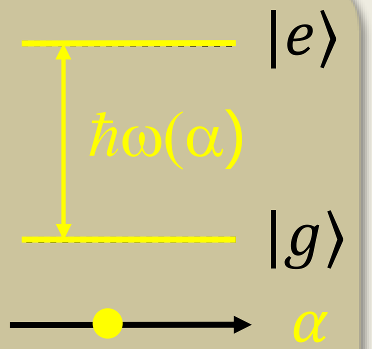


Overview

- Introduction to clocks
- New physics with clocks
  - variation of fundamental constants
  - searches for dark matter
  - tests of relativity: LPI, LLI tests
  - searches for 5th forces
- Summary & future

Many more examples!

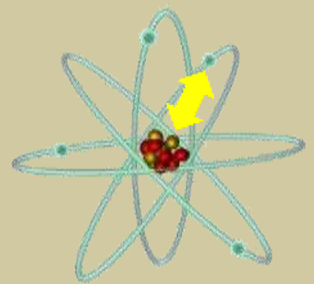




Changing constants

Dark matter

Lorentz invariance

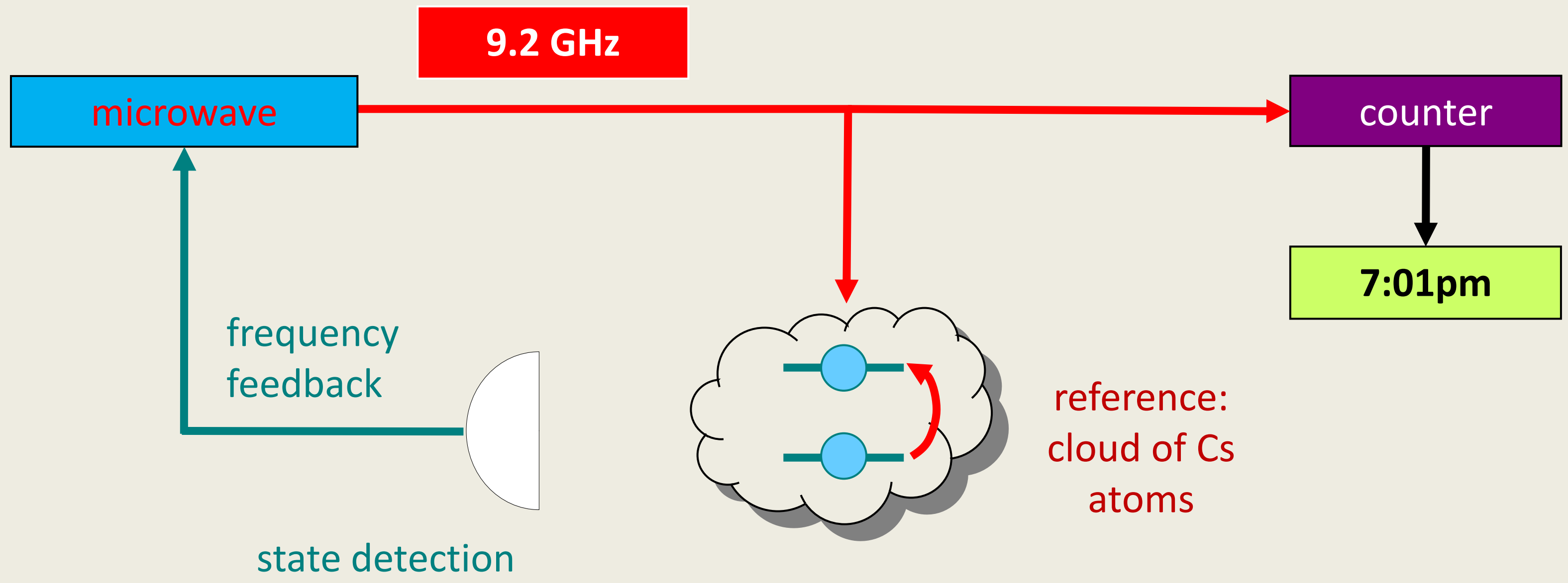


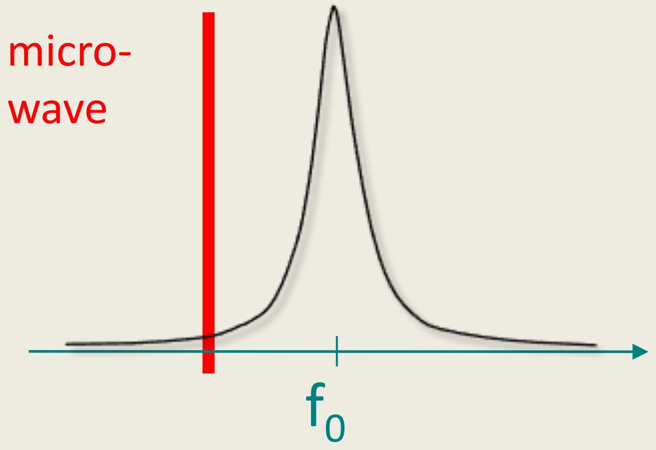
5^{th} forces

[Safronova *et al.* Rev. Mod. Phys. **90**, 025008 (2018)]

INTRODUCTION TO CLOCKS

Principle of microwave atomic clocks





Since 1967:

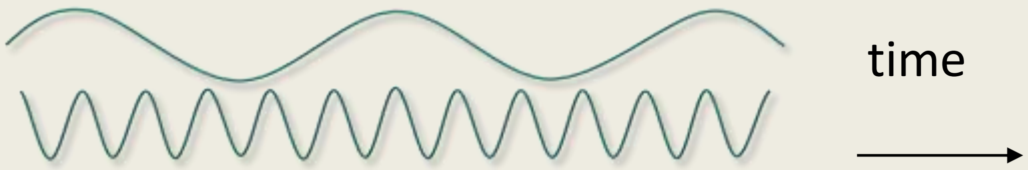
The second is defined as being equal to the time duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental **unperturbed** ground-state of the caesium-133 atom.

Why optical clocks?

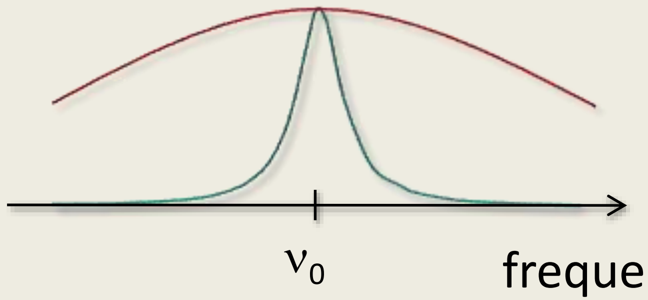
statistical uncertainty

- microwave vs. optical clocks

low frequency (mw)
$\downarrow \times 10^5$
high frequency (optical)



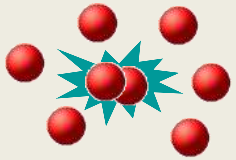
- line width $\Delta\nu$



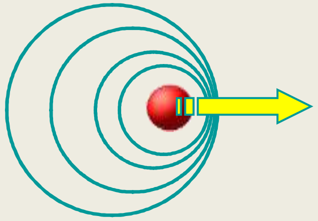
relevant quantity: $\frac{\Delta\nu}{\nu_0}$

systematic uncertainty

- small frequency shift $\delta\nu$ (species dependent)
  → even smaller relative shift $\delta\nu/\nu_0$

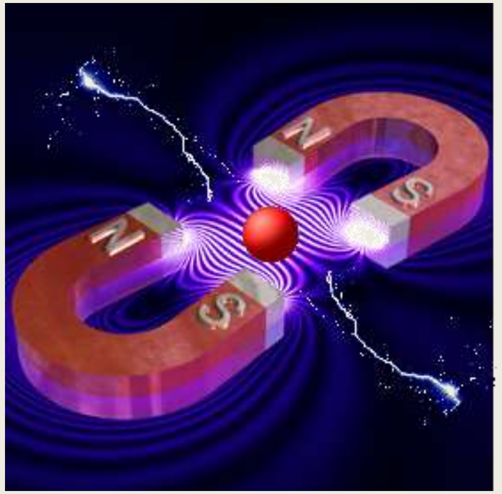


collisions

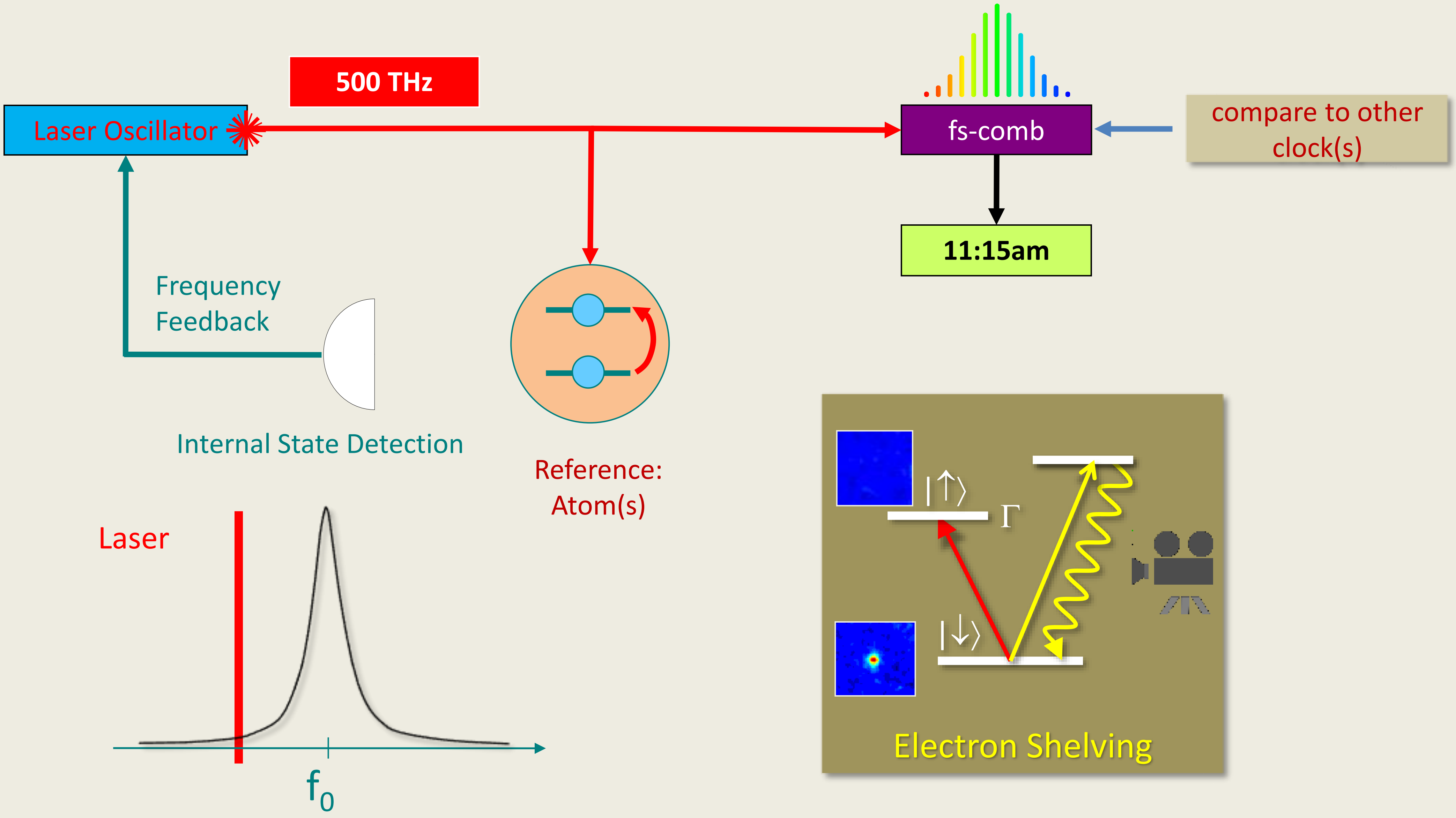


Doppler shift

electric and magnetic fields



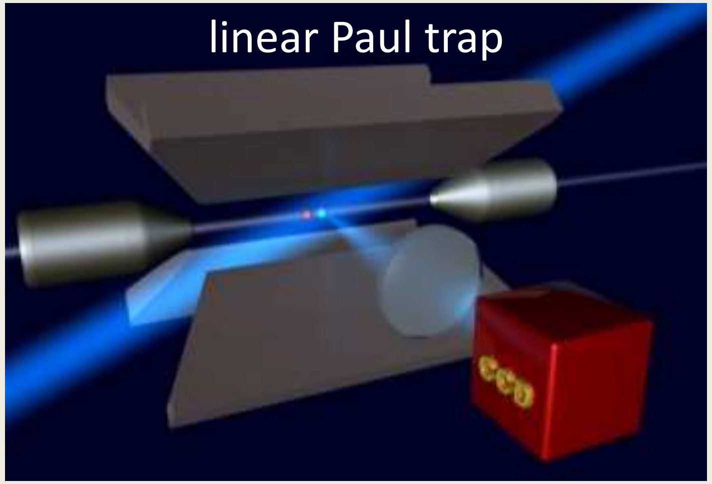
Principle of Optical Clocks

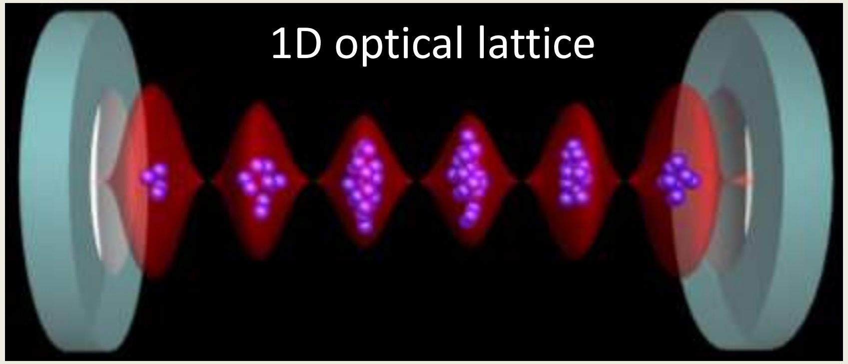


Ion clocks and neutral atom lattice clocks

- We want:
  - good statistical uncertainty → long probe times
  - good systematic uncertainty → small systematic shifts

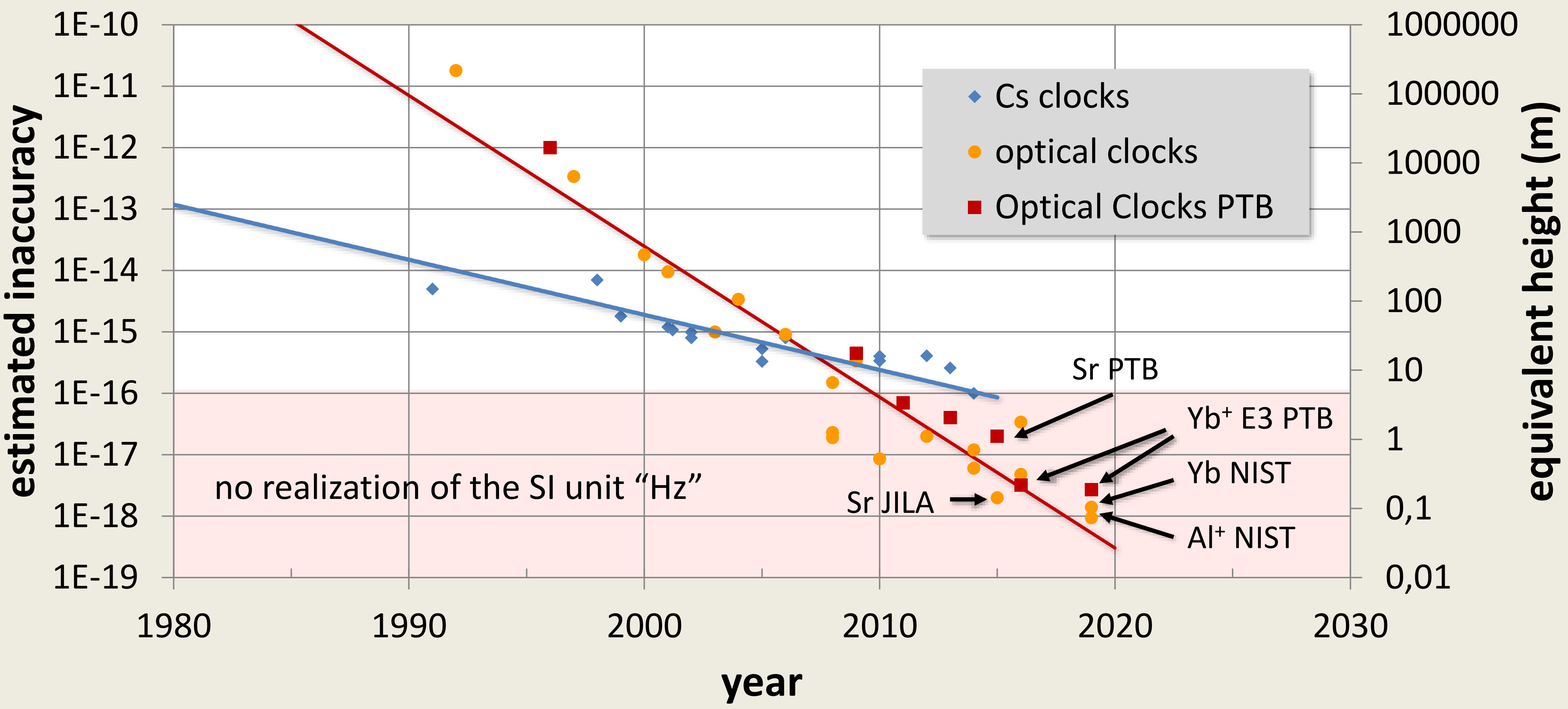
need to trap & laser cool the atoms → full quantum control





- Trapping: 3d harmonic confinement
- Cooling: localisation and quantum control over motional degrees

Evolution of (estimated) clock accuracy

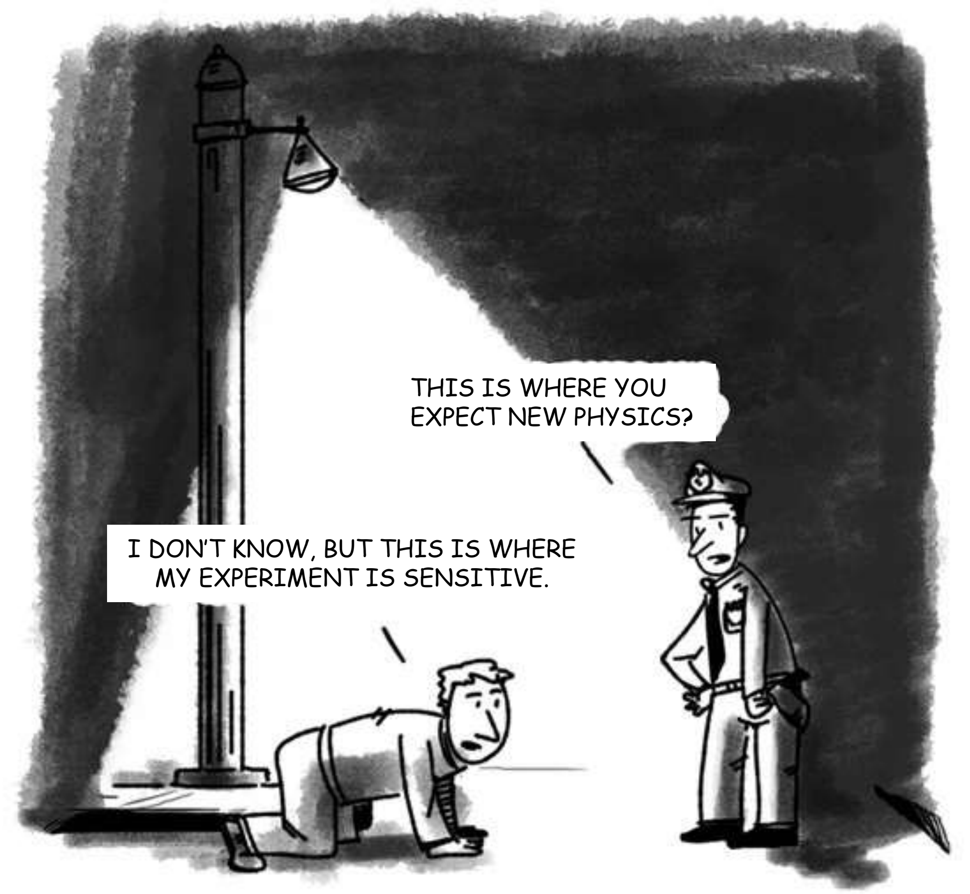


NEW PHYSICS WITH CLOCKS

General considerations

- transition energy of clocks can not be calculated with 18 digits accuracy
  - → no direct comparison with theory
  - → search for changes in frequency ratio measurements
  - → isotope shift measurements (many digits common mode)
- no predictions what to search for
  - → null measurements
  - → exclusion plots of phenomenological models
  - → often "dual use" of data

need models to motivate searches



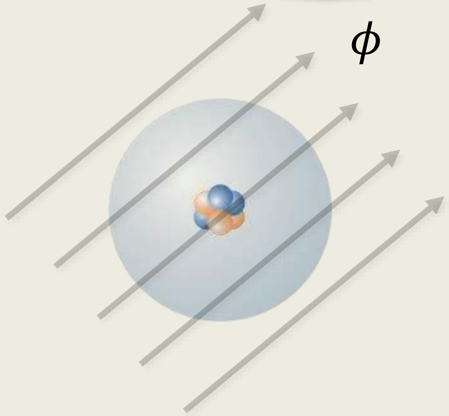
pranarora.com/streetlight-effect-of-human-behaviour/

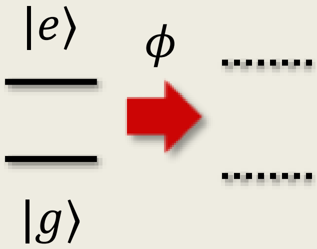
Variation of fundamental constants

- Motivated by theories beyond the SM:
  - string theory & other theories with extra dimensions: dilaton field
  - Discrete & loop quantum gravity
  - Dark energy theories: chameleon & quintessence model
  - …
- typically: cosmological evolution towards a minimum of the field
- spatial as well as temporal variation possible
- if one constant varies, all of them do (equivalence principle)

[J.-P. Uzan, Living Rev. Relativity **14**, 2 (2011); J.-P. Uzan, Comptes Rendus Physique **16**, 576 (2015)]

Dark matter searches & variation of constants





- dark matter candidate: e.g. ultralight scalar field ϕ
  - oscillating field: $\phi(t) = \phi_0 \cos(m_\phi t)$
  - topological field (forming „clumps“)
  - …
- weak (non-gravitational) linear coupling to matter:

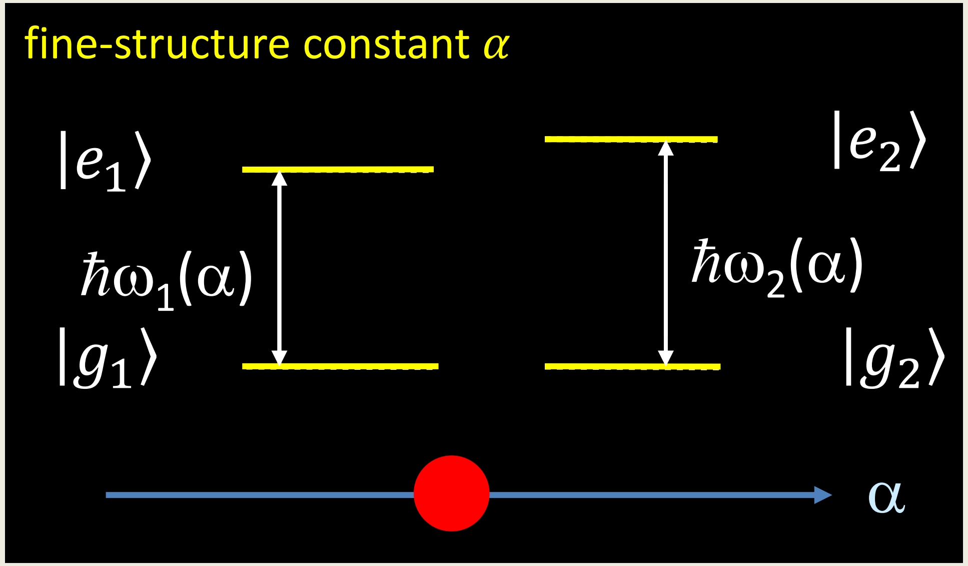
photons — electrons — gluons — quarks

$$\mathcal{L}_\phi = \frac{4\pi\phi}{M_{Pl}}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{e}e - \frac{d_g \beta_3}{2g_3} G^A_{\mu\nu}G^{A\mu\nu} - \sum_{i=u,d}\left(d_{m_i} + \gamma_{m_i} d_g\right) m_i \bar{\Psi}_i \Psi_i\right]$$

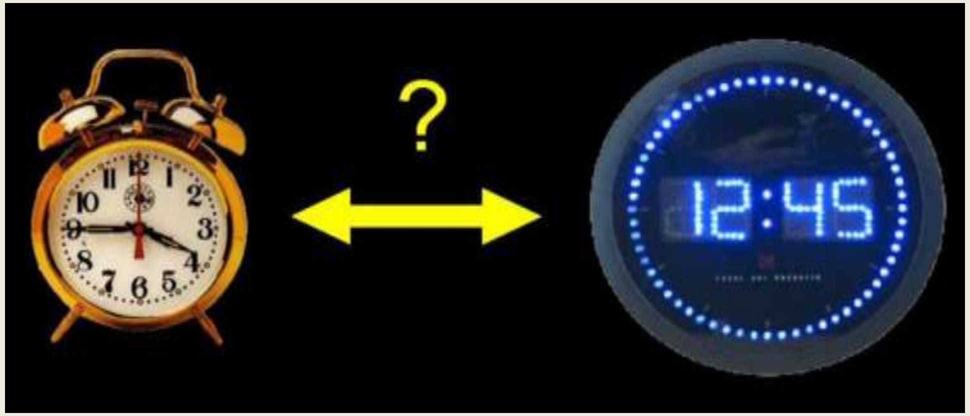
➔ apparent variation of fundamental constants (α, fermionic masses, …)

[Arvanitaki *et al.*, Phys. Rev. D **91**, 015015 (2015); review: Safronova *et al.*, RMP **90**, 025008 (2018)]

Variation of Fundamental Constants



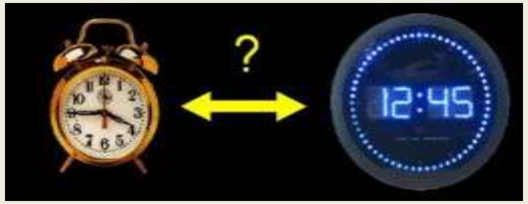
$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

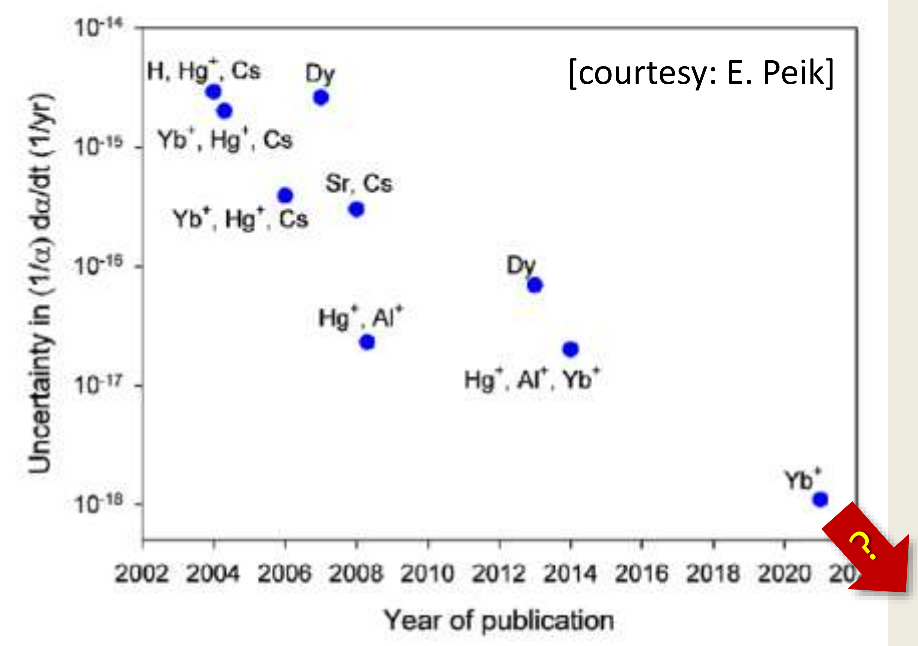


$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

System	K	λ (nm)
Sr	0.06	699
Yb^+ E2	0.91	436
Yb^+ E3	-6	467
Hg^+	-2.9	281.5
Al^+	0.01	267

Drifting constants: Combined data from clocks





$$\dot{\alpha}/\alpha = 1.0(1.1) \times 10^{-18}/\text{year}$$

[Lange *et al.* PRL **126**, 011102 (2021)]

$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

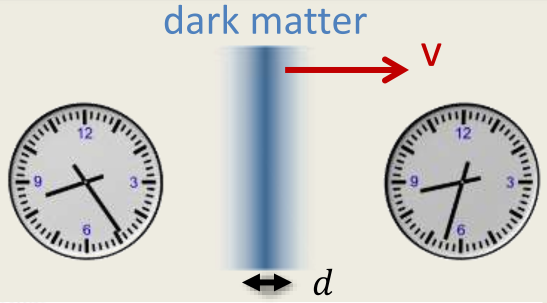
System	K	λ (nm)
Sr	0.06	699
Yb^+ E2	0.91	436
Yb^+ E3	-6	467
Hg^+	-2.9	281.5
Al^+	0.01	267
Ir^{17+} T1	-22	ca. 280
Ir^{17+} T2	145	ca. 1980
Cf^{16+}* T1	59	ca. 775
Cf^{17+}*	-48	ca. 535
Th* nuclear	8000	ca. 150

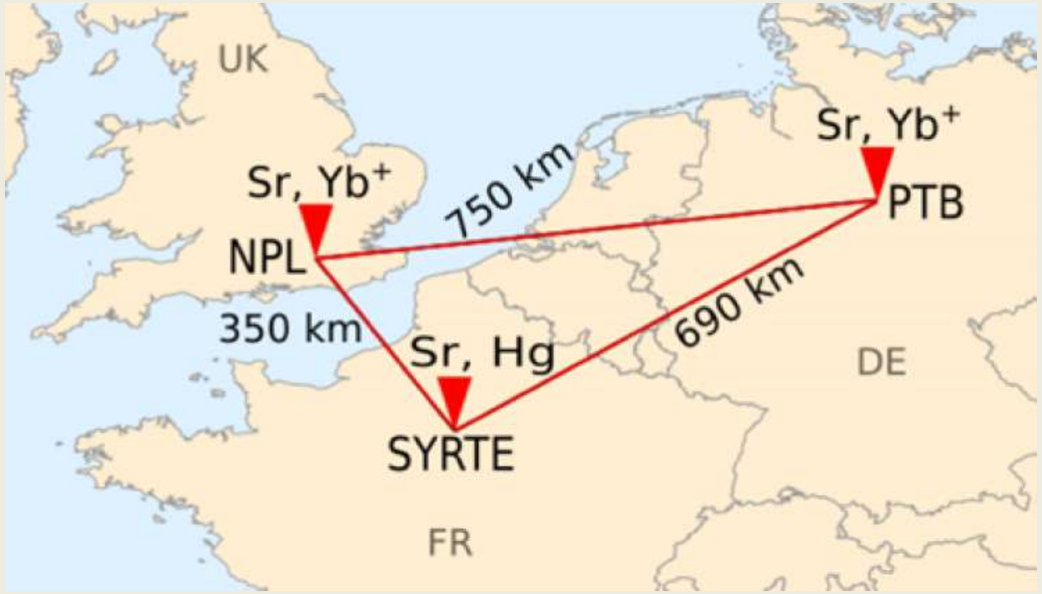
highest sensitivity of all known atomic systems

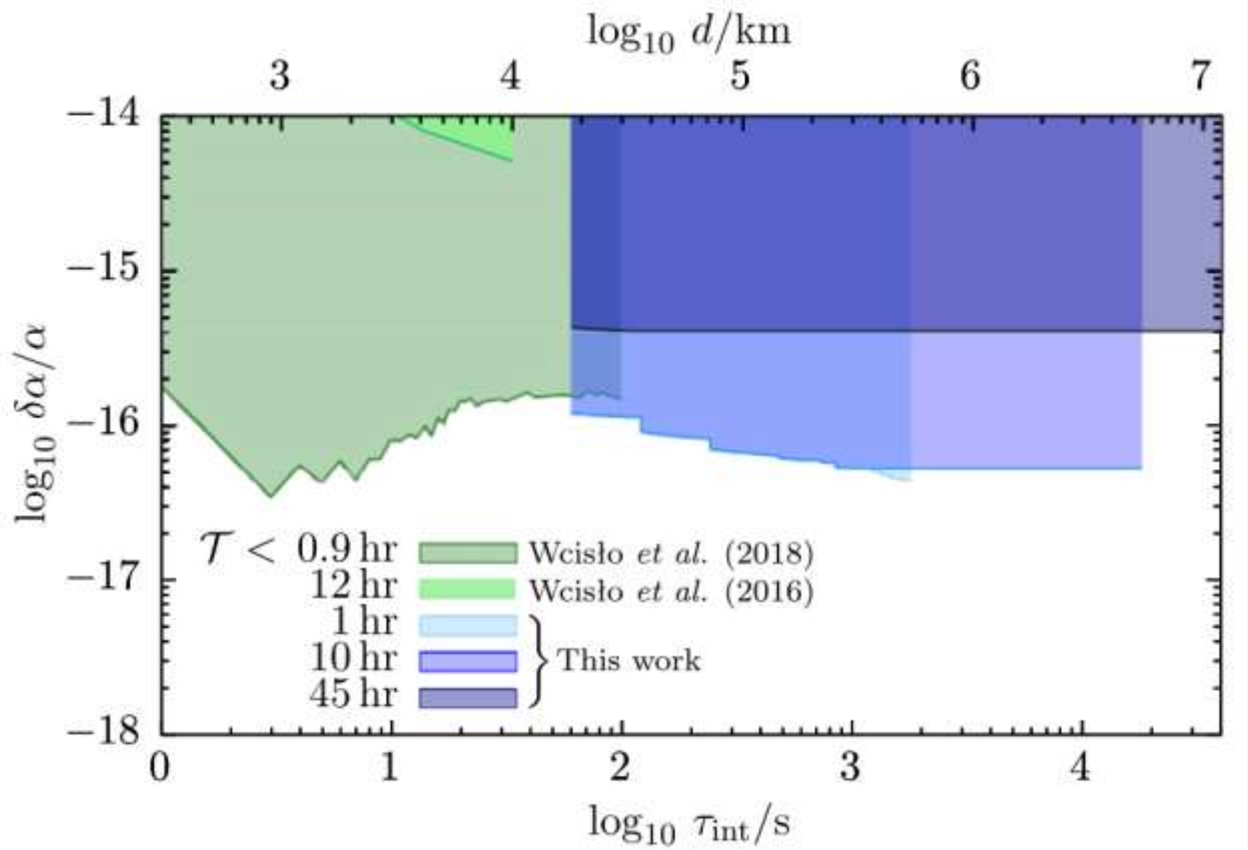
→ level-crossing transitions

Transient variations: network of clocks

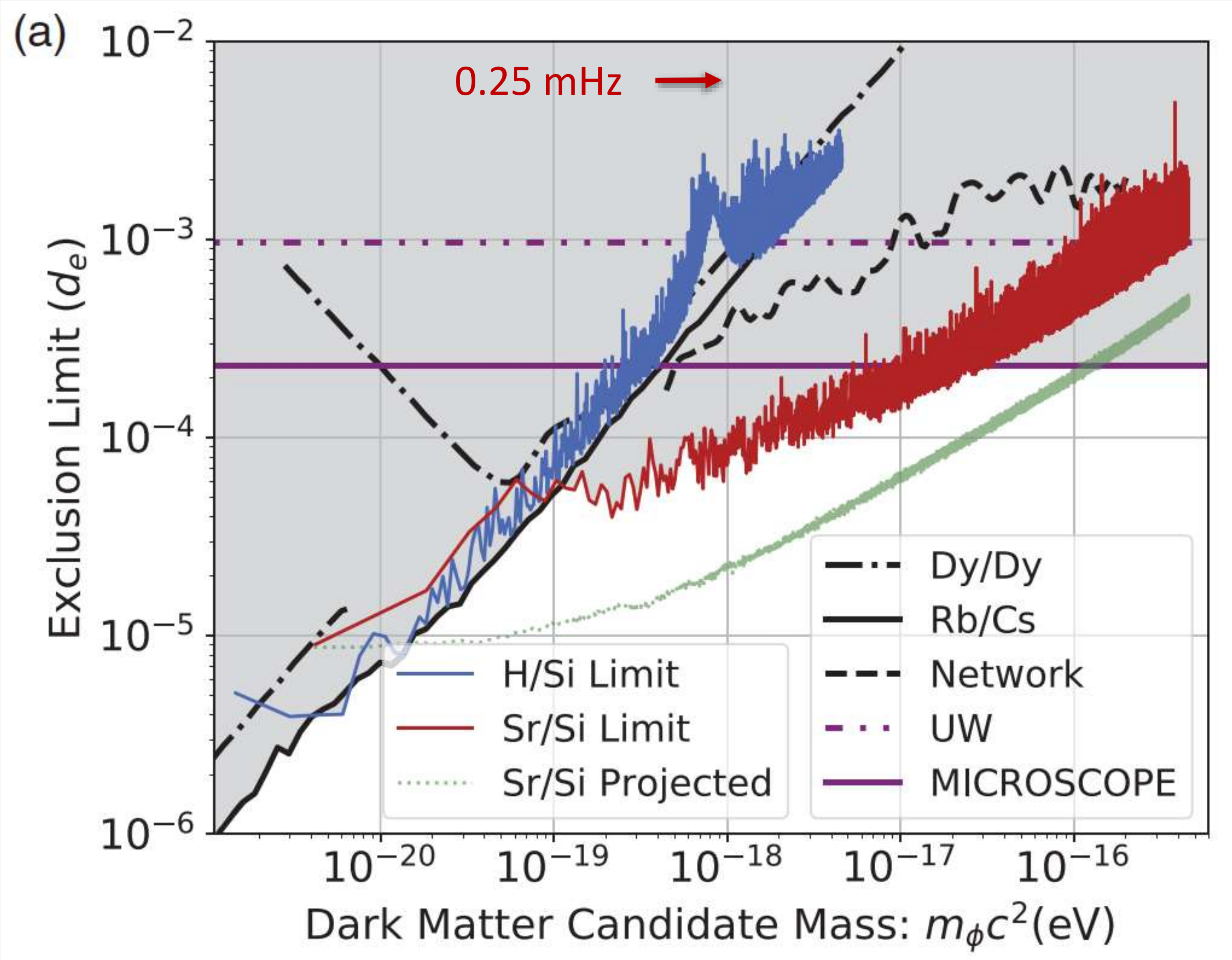
- comparison of clock frequency ratios via fibre network
  [Derevianko & Pospelov, Nat Phys **10**, 933 (2014); Roberts *et al.*, New J. Phys. **22**, 093010 (2020)]
- transient duration: τ_{int}
- time between consecutive transitions: $\mathcal{T}$







Oscillating constants: clock/clock/cavity comparisons



[Kennedy et al., PRL **125**, 201302 (2020)]

Dy/Dy: K. Van Tilburg *et al.*,
PRL **115**, 011802 (2015)
Rb/Cs: A. Hees *et al.*,
PRL **117**, 061301 (2016)
Network: P. Wcislo *et al.*,
Sci. Adv. 4, 4869 (2018)
UW: Schlamminger *et al.*,
PRL **100**, 041101 (2008)
MICROSCOPE: Bergé *et al.*,
PRL **120**, 141101 (2018)

Coupling of fundamental constants to gravity

- motivation: local position invariance test
- fundamental constant η couples to solar gravity potential $\Delta U(t)$:

$$\frac{\delta\eta}{\eta} = k_\eta \frac{\Delta U(t)}{c^2}$$

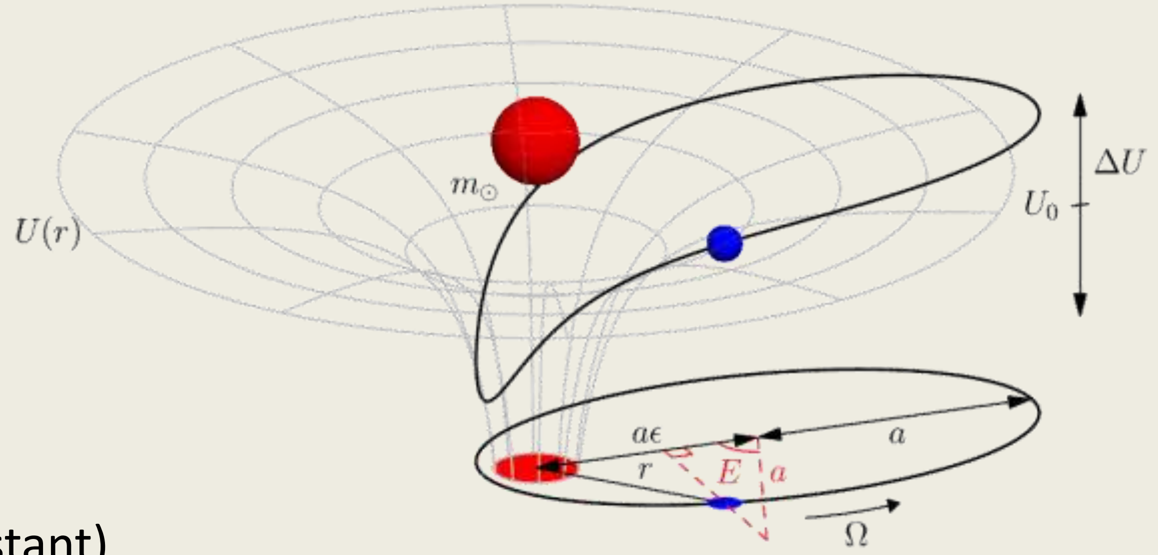
- combine measurements of several years:

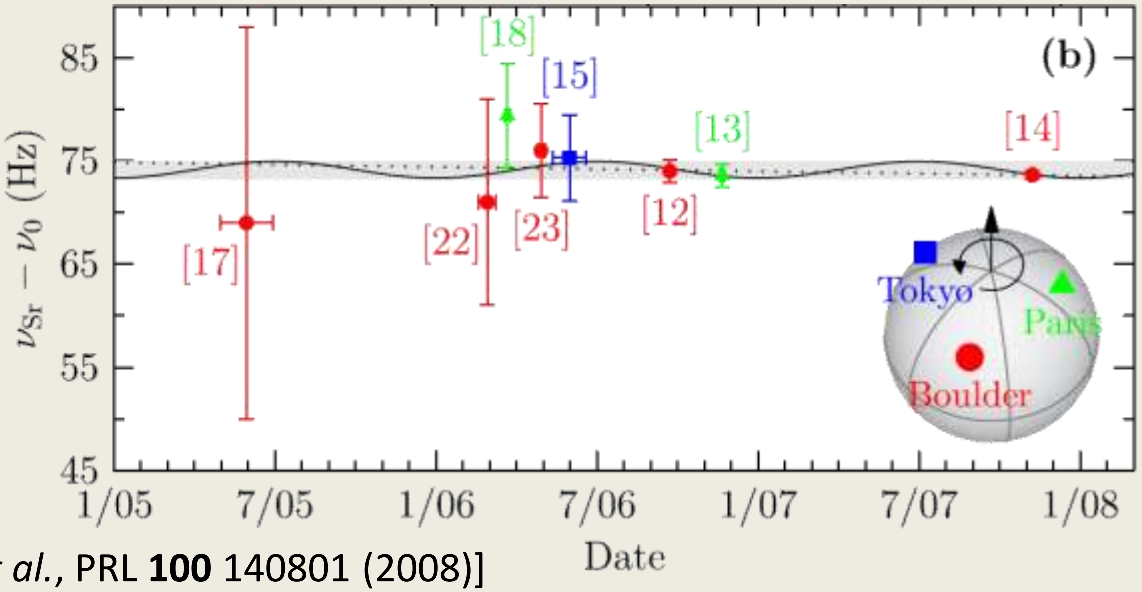
→ $k_\alpha = (-5.5 \pm 5.2) \times 10^{-7}$ (fine-structure constant)

→ $k_\mu = (-2.5 \pm 5.4) \times 10^{-6}$ (m_e/m_p)

→ $k_q = (3.8 \pm 4.9) \times 10^{-6}$ (light quark mass)

[Leefer *et al.*, PRL **111**, 060801 (2013);
Peil *et al.*, PRA **87**, 010102 (2013)]



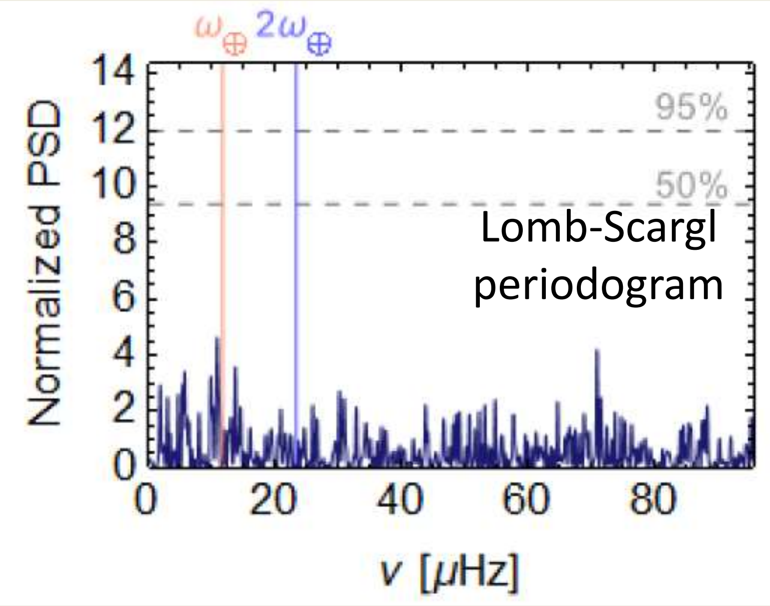


[S. Blatt *et al.*, PRL **100** 140801 (2008)]

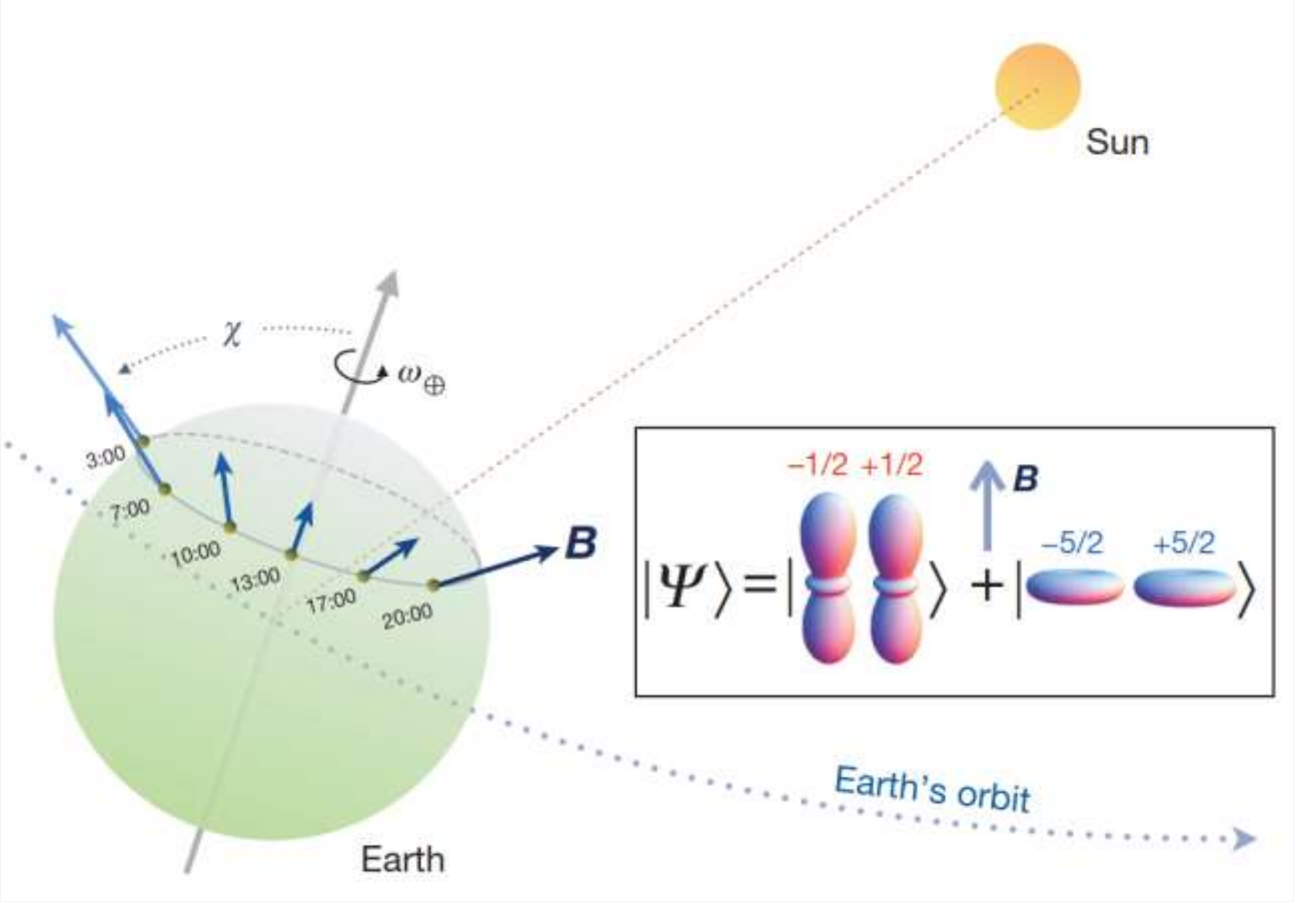
Testing local Lorentz invariance with clocks

- probe for LLI violation in electron-photon sector
- idea: electron orbitals have directionality → measure sidereal energy oscillations
- Yb^+ $^2F_{7/2}$ state is very sensitive

c_{X-Y}	$(-5.2 \pm 7.8) \times 10^{-21}$
c_{XY}	$(4.4 \pm 3.9) \times 10^{-21}$
c_{XZ}	$(-5.0 \pm 9.3) \times 10^{-21}$
c_{YZ}	$(6.3 \pm 8.9) \times 10^{-21}$



[Dreissen *et al.*, arXiv:2206.00570]



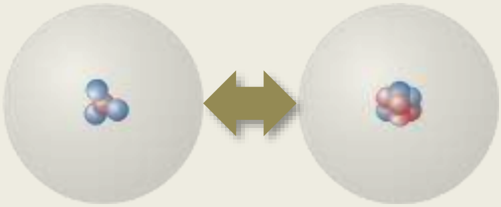
[Pruttivarasin et al., Nature **517**, 592 (2015)]

Search for 5th forces

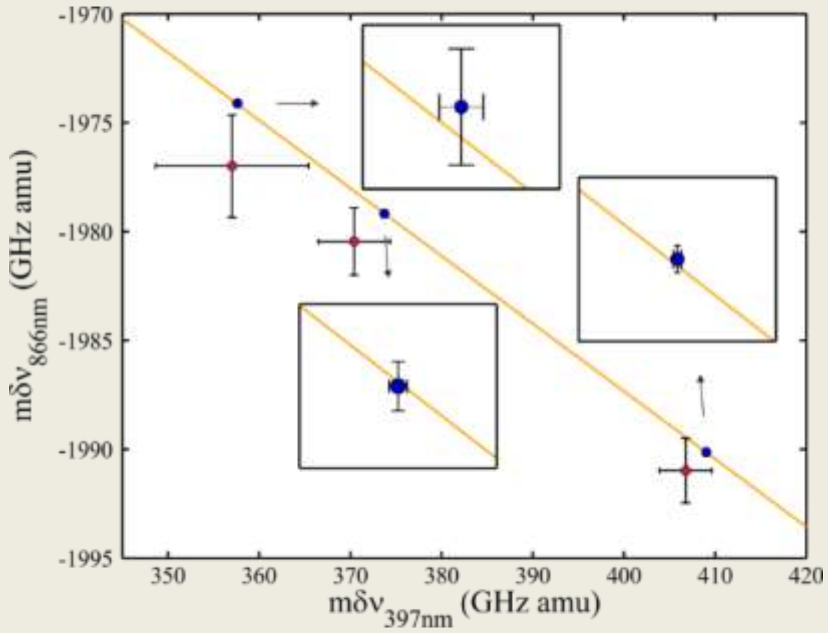
Isotope shift spectroscopy: King's plot

- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2 \rangle_{A,A'} + k_i \frac{A-A'}{AA'}$

field shift   recoil shift

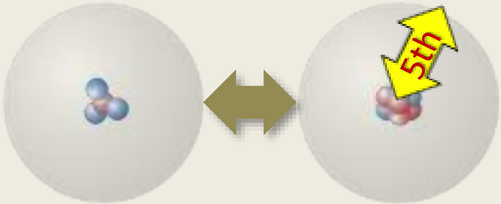


- use 2 transitions i, j → eliminate $\delta\langle r^2 \rangle_{A,A'}$



Additional hypothetical 5th force (relaxion, DM, …)

- new force mediated through scalar field with mass $m_\phi \rightarrow X_i$
- coupling constant: α_{NP}



→ nonlinearity in King's plot:

$$\delta\nu_i^{A,A'} = F_i \delta\langle r^2 \rangle_{A,A'} + k_i \frac{A-A'}{AA'} + \alpha_{NP} X_i (\mathrm{A} - \mathrm{A}')$$

[Stadnik, PRL **120**, 223202 (2018); Berengut *et al.*, PRL **120**, 091801 (2018); Frugiuele *et al.*, Phys. Rev. D **96**, 015011 (2017); Delaunay *et al.*, Phys. Rev. D **96**, 093001 (2017); Delaunay *et al.*, Phys. Rev. D **96**, 115002 (2017)]

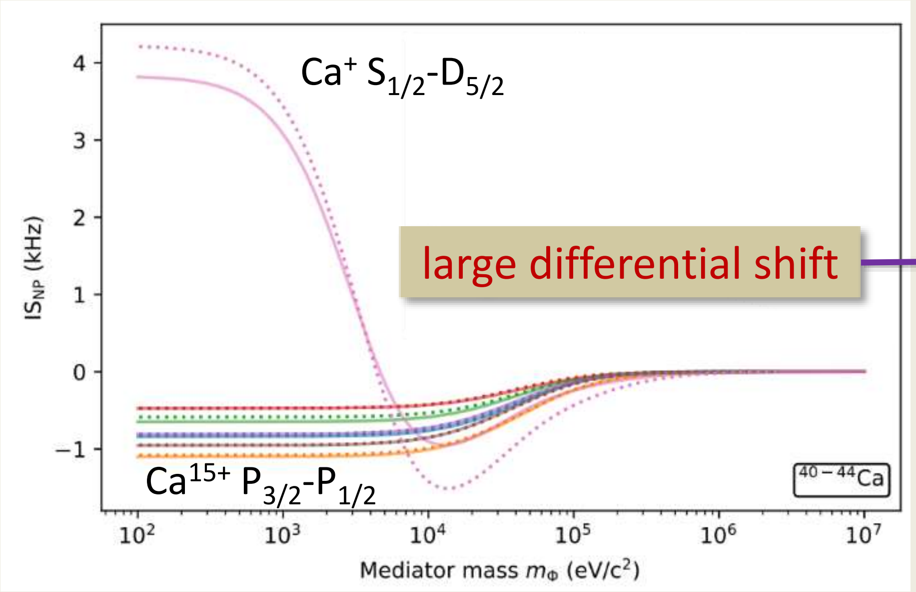
Isotope shift spectroscopy of $^{40,42,44,46,48}Ca^{+/14+/15+}$

- need transitions of different character

→ promising approach:

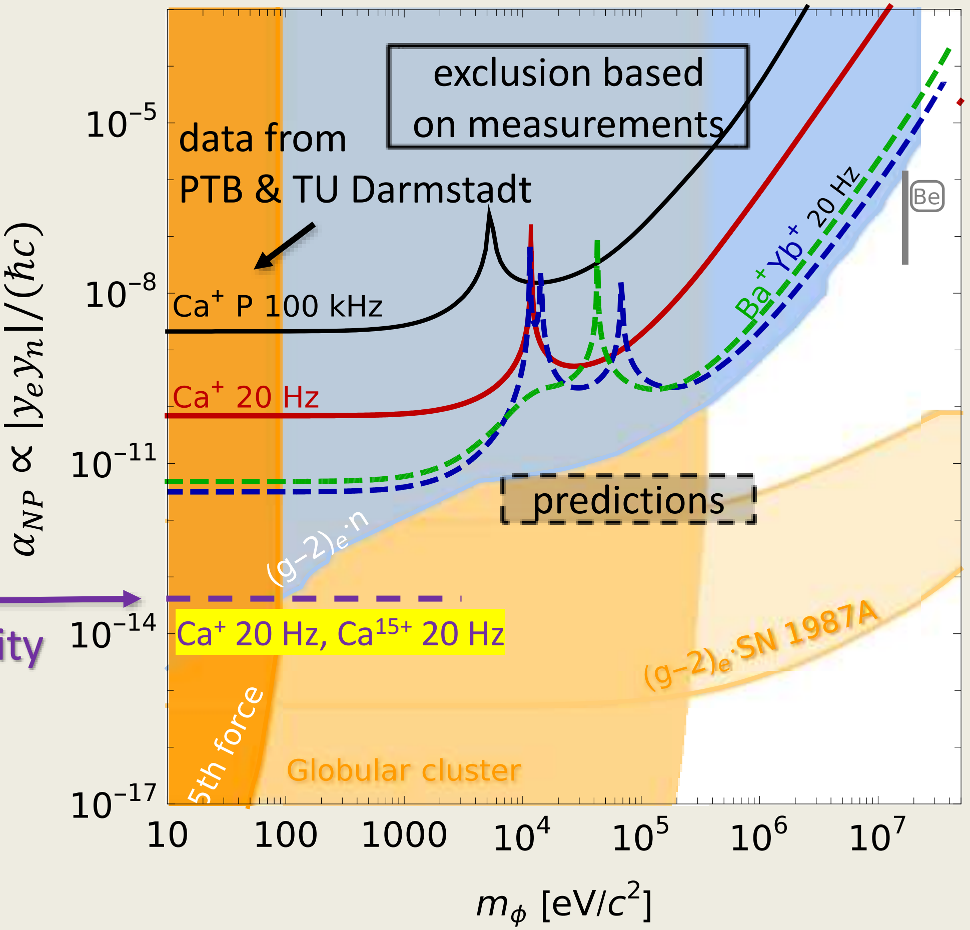
isotope shifts of clock transitions in Ca^{+} & **$Ca^{14+/15+}$**

(with Surzhykov, Berengut, Fuchs & Crespo)



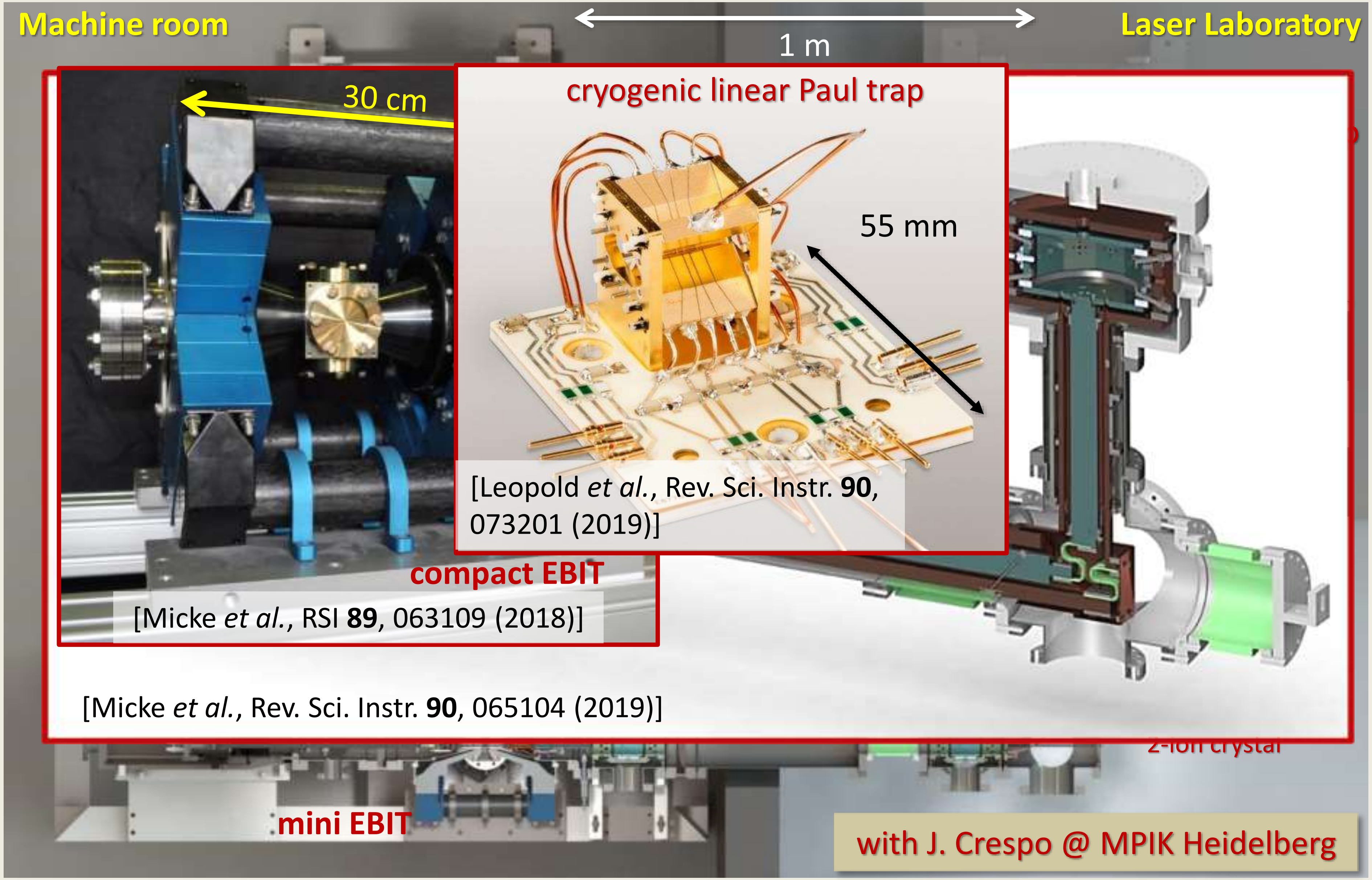
[Rehbehn, *et al.*, PRA **103**, L040801 (2021)]

×100 higher sensitivity



[adapted from: Solaro *et al.*, PRL **125**, 123003 (2020)]

Approach to precision HCI spectroscopy: CryPTEx-PTB



Specs vacuum system:

- Vacuum: $< 10^{-14}$ mbar
  → HCI lifetime: ~ 100 min
- Temperature: < 5 K
- Vibrations: < 20 nm
- Magnetic field: < 200 pT

Specs EBIT:

- Magnetic field: 0.86 T (72 permanent magnets)
- Acceleration voltage: 10 kV
- Current: > 80 mA

Specs ion trap:

- 5 segments, Au-coated Al_2O_3, 0.7 mm ion-electrode distance
- Trapping frequencies: > 1 MHz
- Heating rates: ~ 1 1/s
- f/# ~ 1 imaging with bi-aspheric lens

Systematic shifts for Ar^{13+}

Shift source	Mitigation	Shift (10^{-18})	Uncertainty (10^{-18})
Micromotion	Real-time measurement	-443	22
AC Zeeman shift	Calibration at much higher powers and extrapolation	0	2
First-order Doppler	Counter-propagating beams	0	< 1
Electric quadrupole	Small coefficient, averaging over multiple Zeeman components	0	< 1
Linear Zeeman	Averaging over multiple Zeeman components	0	< 1
Quadratic Zeeman	Small coefficient, small field	< 1	$\ll 1$
2nd order Doppler	Algorithmic cooling	-1	< 1

no fundamental limitations

$^{40}Ar^{13+}$ clock with 2.2×10^{-17} systematic uncertainty

$^{40/36}Ar^{13+}$ isotope shift: confirm QED nuclear recoil effect

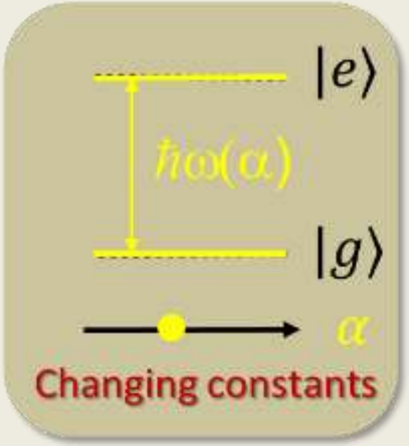
atomic data from: [Y-M. Yu and B.K. Sahoo, PRA **99**, 022513 (2019)]

[King, Spieß *et al.*, arXiv:2205.13053, Nature, in print]

Summary

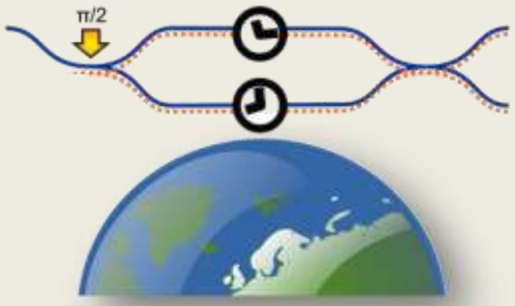
Summary

- optical clocks offer 18 significant digits in frequency comparisons
- searches for new physics at the high-precision, low-energy frontier
  - variation of fundamental constants
  - searches for dark matter
  - tests of relativity: LPI, LLI tests
  - searches for 5^{th} forces
- need theory input for interpretation & models



Future

- optical clocks will furter improve
- new types of clocks: Th, HCI
- quantum clock interferometry?
- entangled states in gravity?
- improved redshift tests?



Quantum Logic Spectroscopy Group

€

M. Schwarz, L. Schmöger & J. Crespo

A. Wilzewski, S. Chen, L. Spieß,
M. Wehrheim, P. Micke, S. King, T. Leopold

PhD/PostDoc openings

Collaborators:

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- N. Huntemann, R. Lange, E. Benkler (PTB)
- A. Surzhykov (PTB & TU Braunschweig)
- K. Hammerer (LUH, Hannover)
- J. Berengut (U. of New South Wales)
- M. Safronova (U. of Delaware)

European Research Council – ERC Adv. Grant „FunClocks"

Quantum Valley Lower Saxony

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THE END