Atomic Clocks - from Optical Clocks and Novel Quantum Concepts

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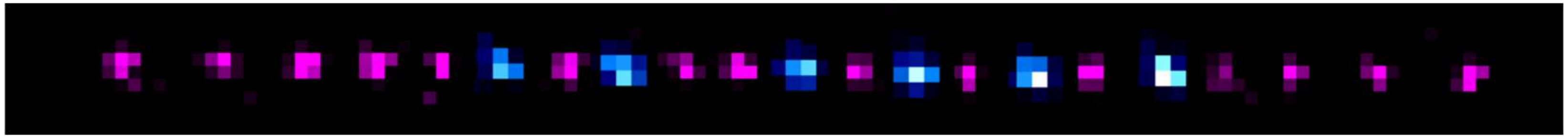


3. September 2025 – 841. Heraeus Semina: Quantum Technologies – Origins and Applications

1. Time – Clocks – Metrology

1707: Δx >> 100 km
(Scilly naval disaster)

1714: British parlament:
longitude act
20,000 £

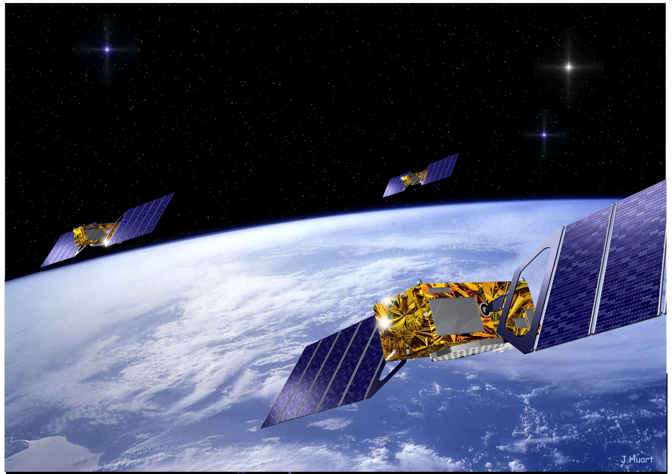
1762: $\Delta x \sim 20$ km
- John Harrison

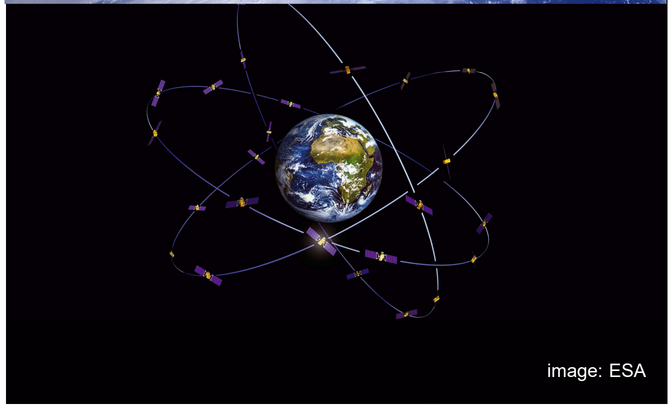
Harrison's chronometer

See book by Dava Sobel:
"Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time" (2007)

1. Time – Clocks – Metrology

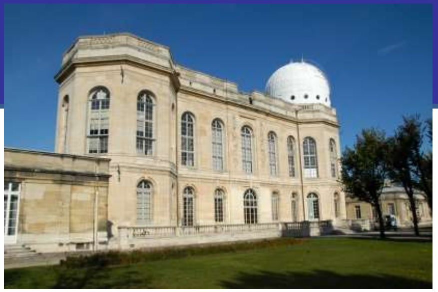
1762: 20 km





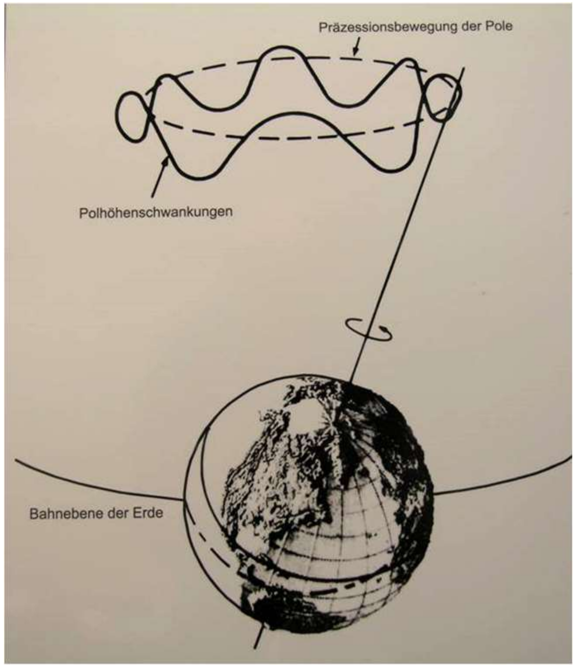
2009: 10 cm

Clocks & Definition of Time



- **Greenwich Mean Time (1884)**

1s = 1/86400 of the mean solar day



Mechanical Clocks

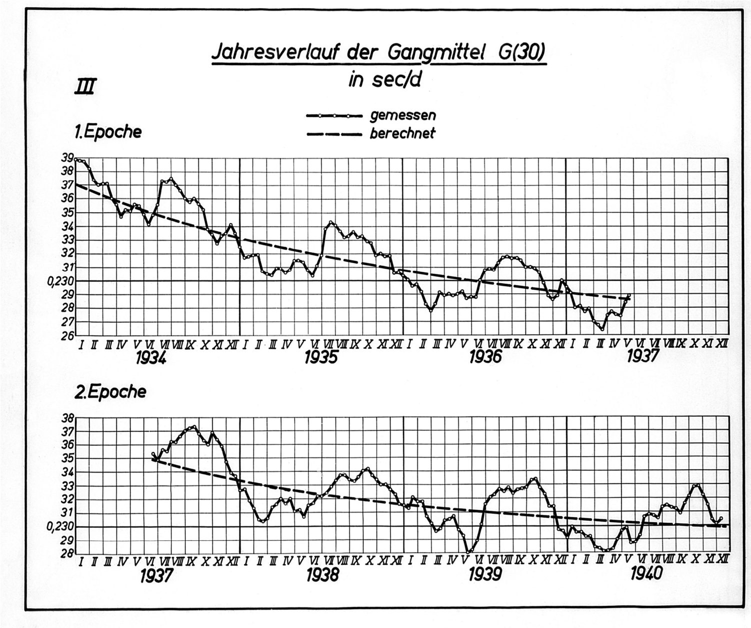
$f_{osc} \approx 1$ Hz
daily uncertainty ≈ 1 s/d

Harrison‘s chronometer

Clocks & Definition of Time

- **Greenwich Mean Time (1884)**

1s = 1/86400 of the mean solar day



Mechanical Clocks

$f_{osc} \approx 1$ Hz
daily uncertainty ≈ 1 s/d

Quartz Clocks (1930s)

$f_{osc} \approx 60$ kHz,
daily uncertainty ≈ 1 ms/d

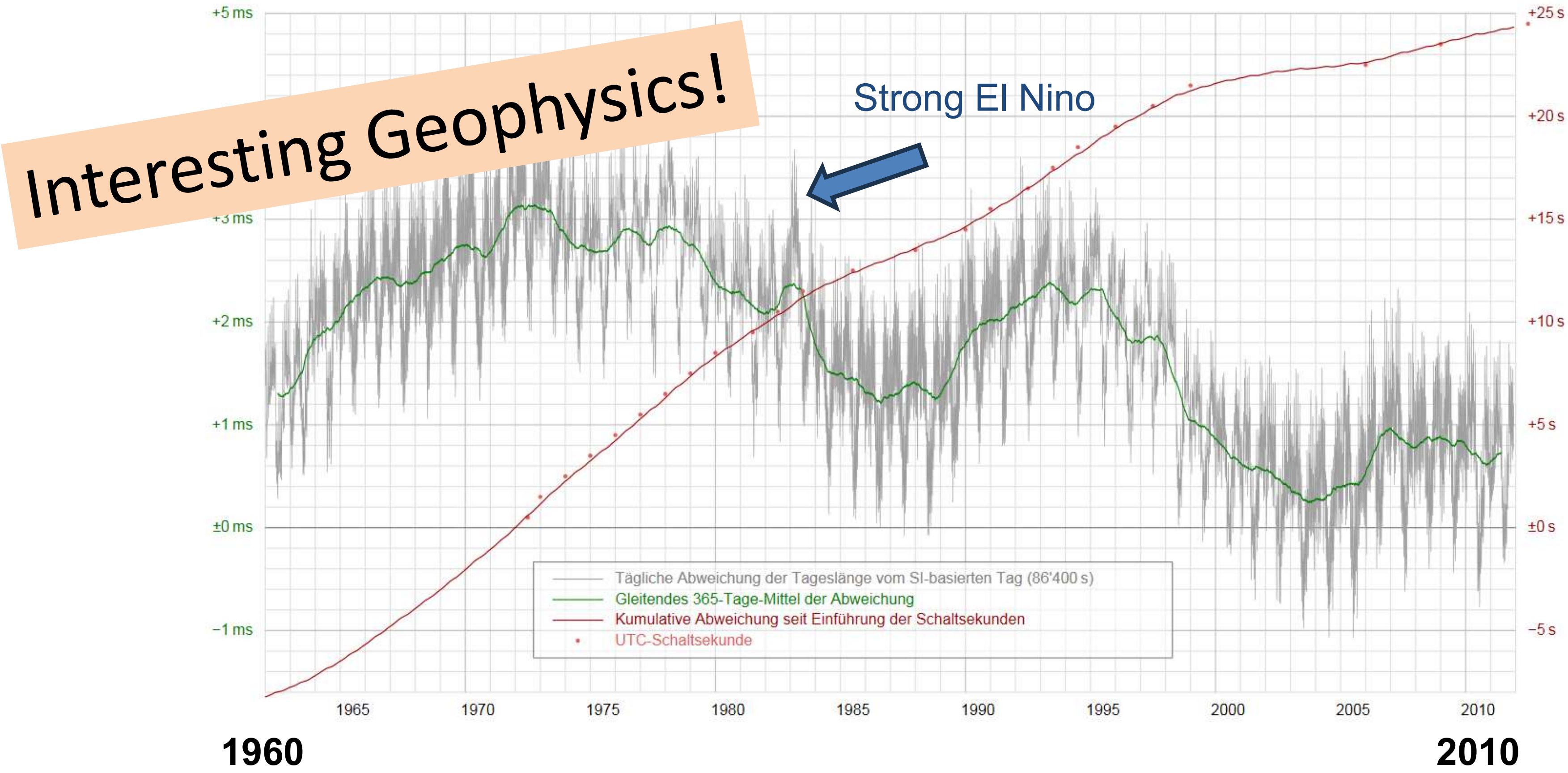
Measurement of mean solar day with first Quartz clocks

→ **Physikalisch-Technische Reichsanstalt**: A. Scheibe und U. Adelsberger, Z. f. Phys. Bd. 127, S. 416 - 428 (1950)

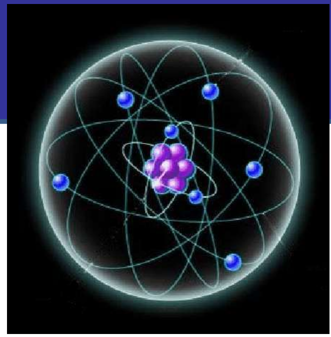
Rotation of our Earth!

length of day increases by 17 µs per year

(= +23 µs tides - 6 µs post-glacial uplift !)



Clocks & Definition of Time



- **Greenwich Mean Time (1884)**

1s = 1/86400 of the mean solar day

Mechanical Clocks

f_{osc} ≈ 1 Hz
daily uncertainty ≈ 1 s/d

New Definitions:

- **Ephemeris Time (1960-1967)**

1 s = 1 / 31,556,925.9747 of the tropical year of
0. January 1900 at 12^h UT

Quartz Clocks (1930s)

f_{osc} ≈ 60 kHz,
daily uncertainty ≈ 1 ms/d

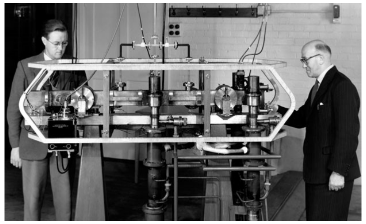
- **Temps Atomique International (1967)**

„Duration of 9 192 631 770 periods of
the radiation corresponding to the transition between the
two hyperfine levels of the ground state of the ^{133}Cs atom"

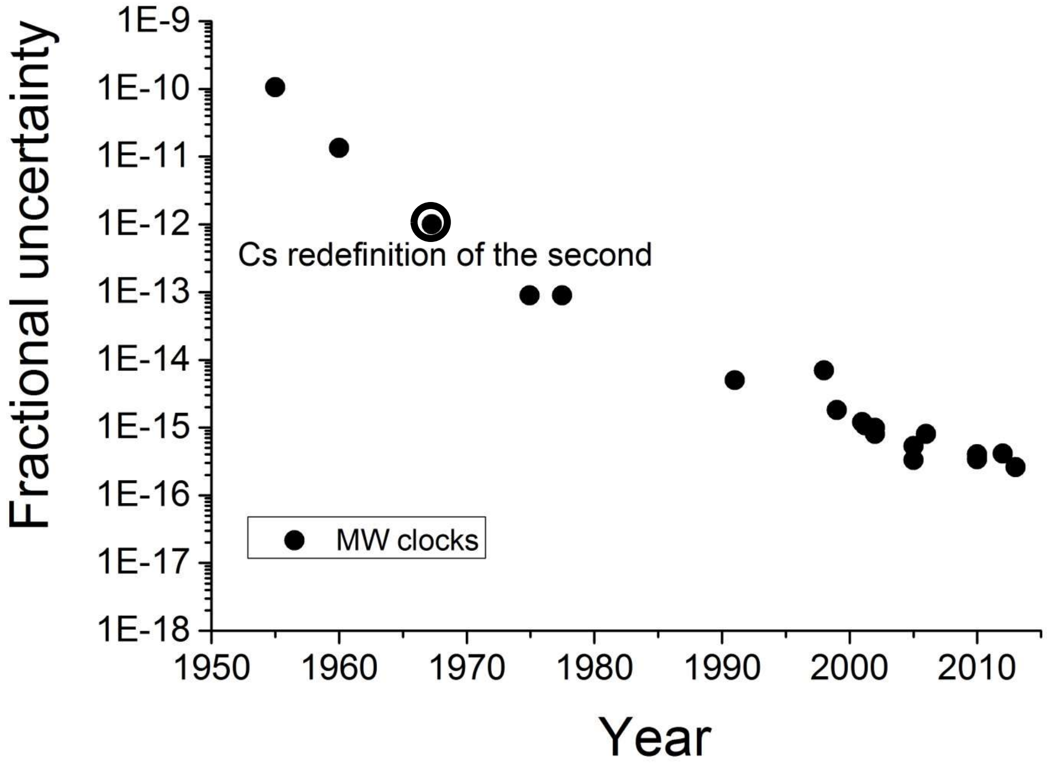
Atomic Cesium Clocks

f_{osc} ≈ 9.2 GHz (**MW**)
1955 Essen's clock: $\Delta t \sim 10\ \mu s$ /d
daily uncertainty < 1 ns/d

Uncertainty of MW Clocks

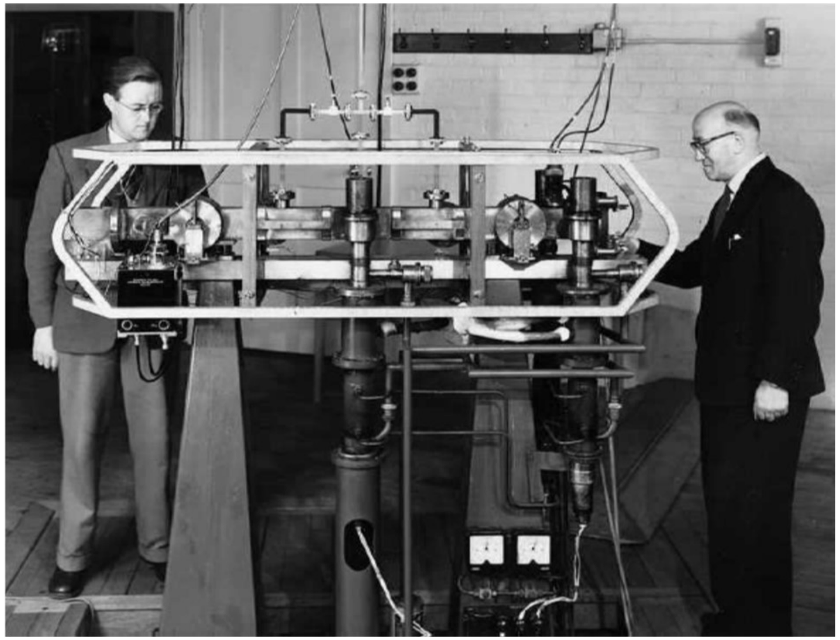


0.1 ns per day! →

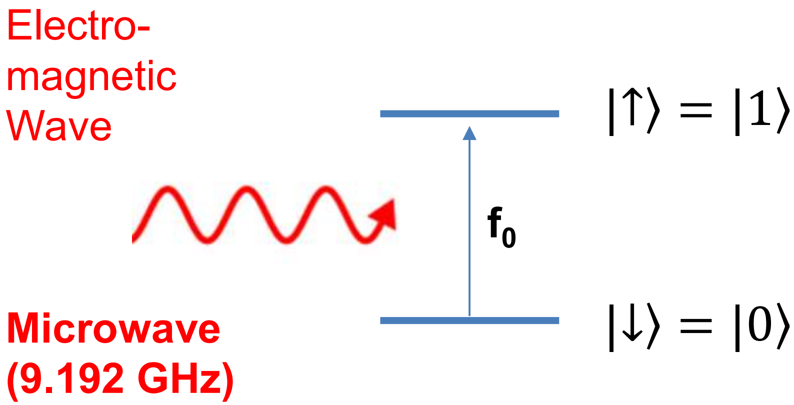


1955: Atomic Clocks

Use atomic states that are highly insensitive to environment, $f_0 \approx$ const.



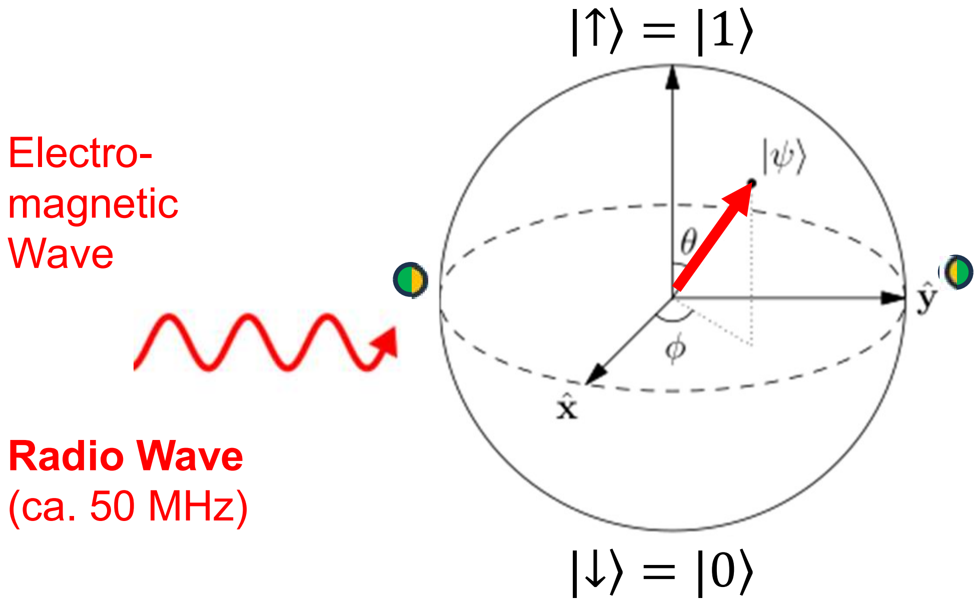
1955: first cesium atomic clock- Essen & Parry (London)



→ **Nuclear spin of cesium (^{133}Cs) atom** is flipped at 9.192.. GHz

Nuclear Magnetic Resonance (NMR, MRI, KST)

Magnetic field dependent resonances, $f_0(B)$; $B \approx 1$ T

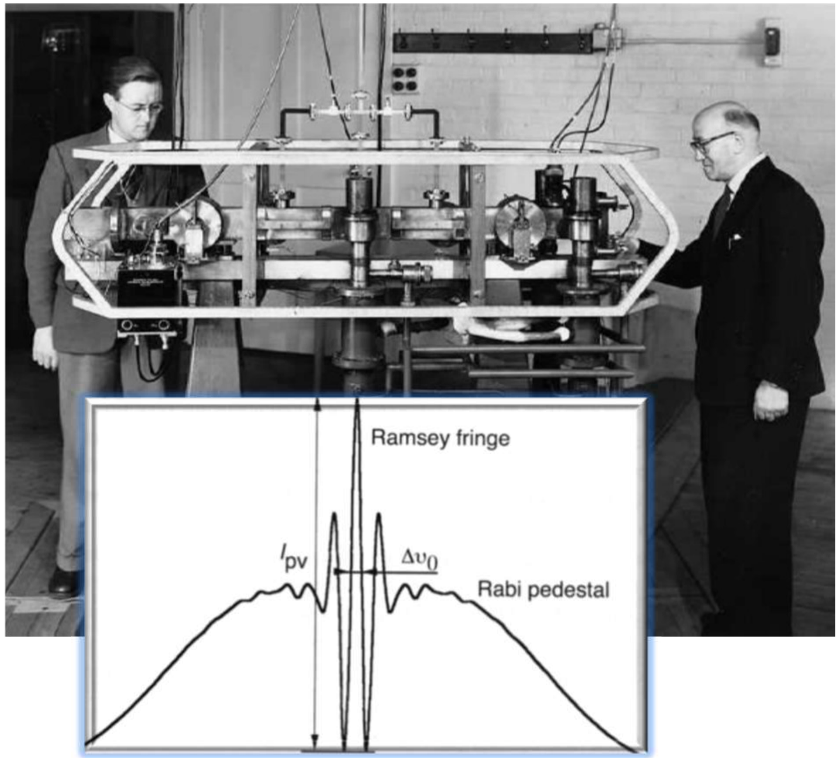


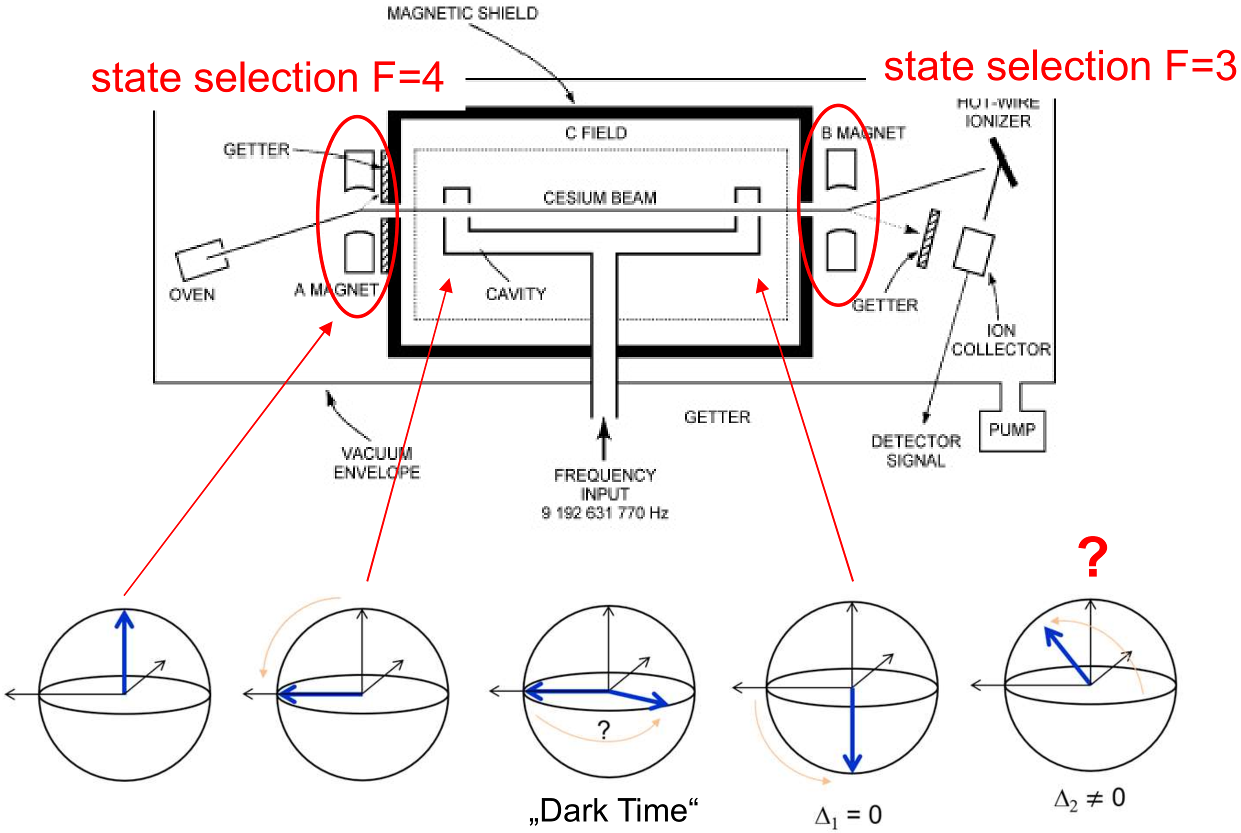
QM-state is represented on **Bloch-sphere***

$$|\Psi\rangle = a(t)\,|\uparrow\rangle + b(t)\,e^{-i\phi}\,|\downarrow\rangle$$

* Feynman, Vernon, Hellwarth „*Geometrical Representation of the Schrödinger Equation for Solving Maser Problems*", J. Appl. Phys. **28**, 49 (1957)

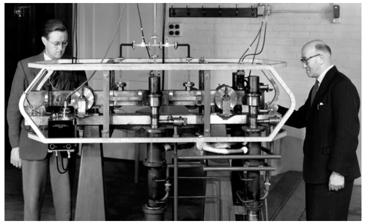
Atomic Clocks – Ramsey Spectroscopy



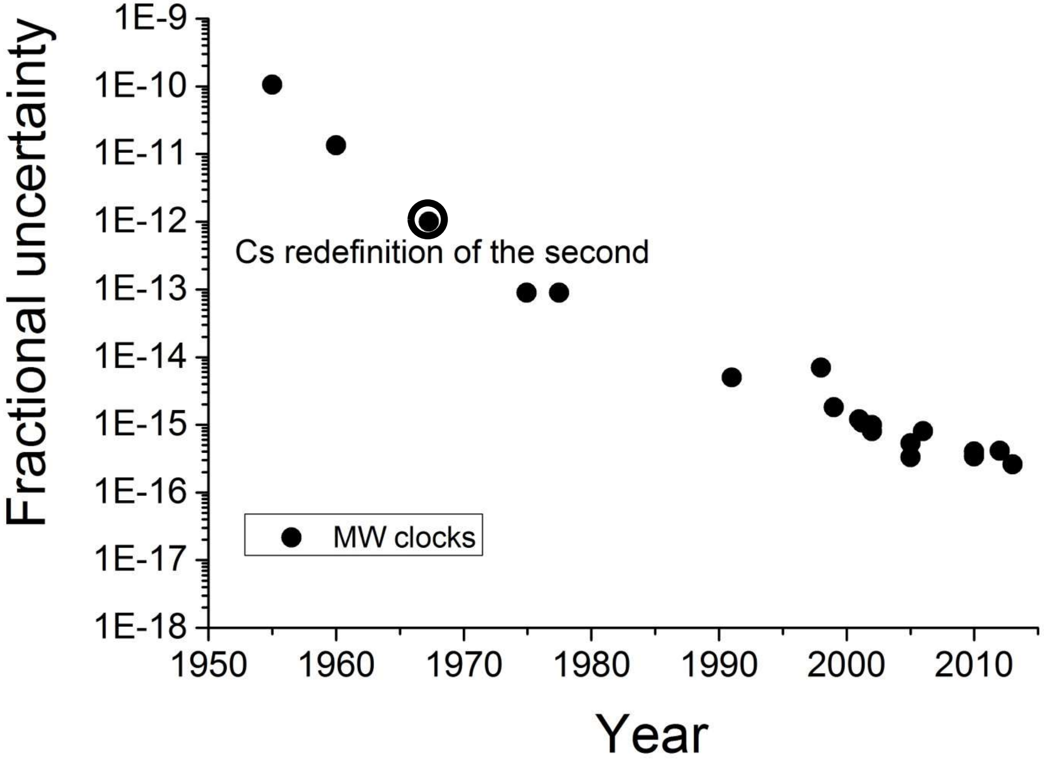


State Preparation | MW-pulse: Excitation to Superposition (½ , ½) | MW-pulse: Excitation to Final State

Uncertainty of MW Clocks

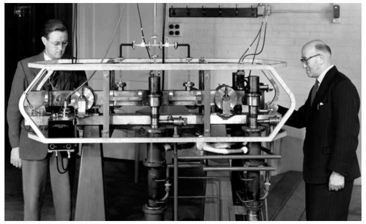


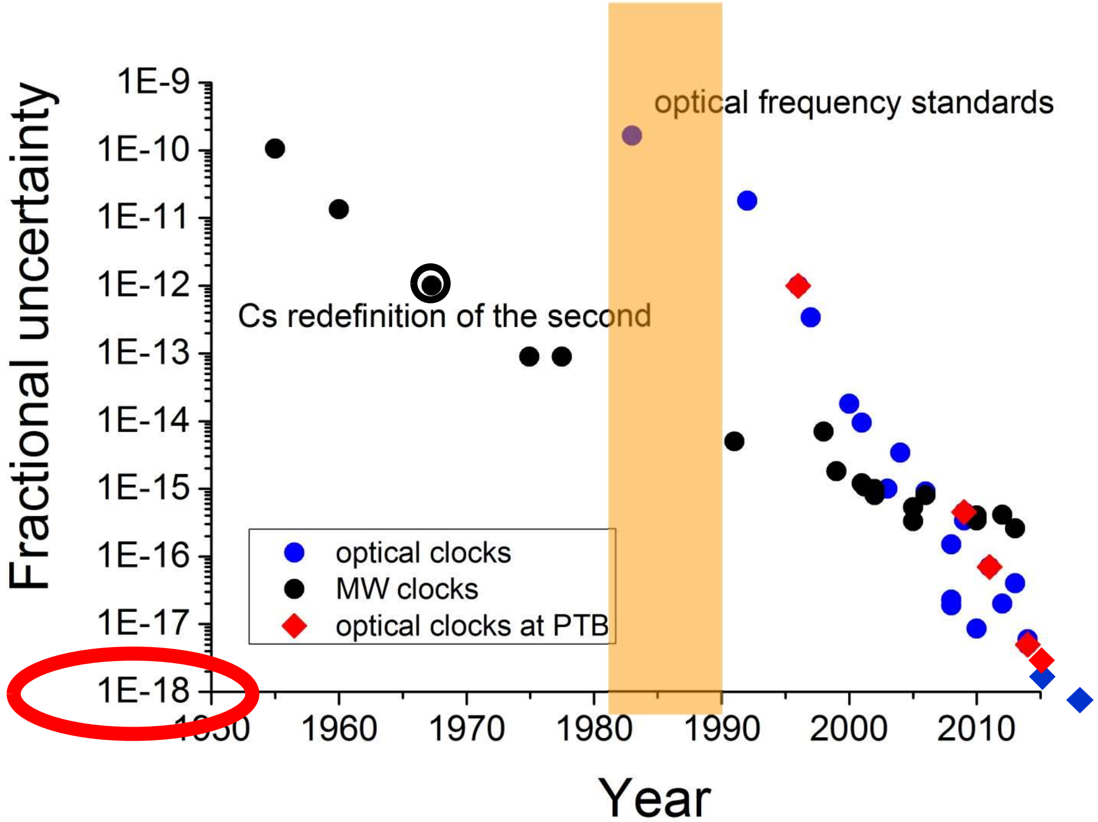
0.1 ns per day! →



Cs- fountains → UTC

Uncertainty of MW Clocks – Optical Clocks





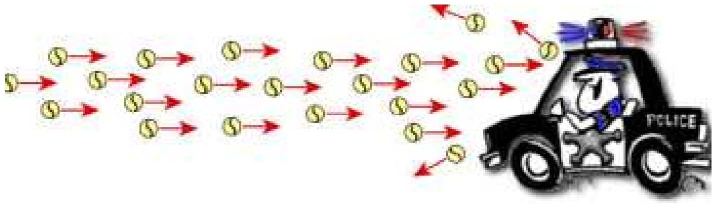
Cs- fountains → UTC

Laser Cooling and Trapping of Atoms

Some first laboratory clocks are close to 10^{-18} now… and demonstrate potential for low 10^{-19}

Laser Cooling of Atoms

$$\Delta p = \frac{h}{\lambda}$$



Nobel prize **1997**

"for development of methods to cool and trap atoms with laser light"

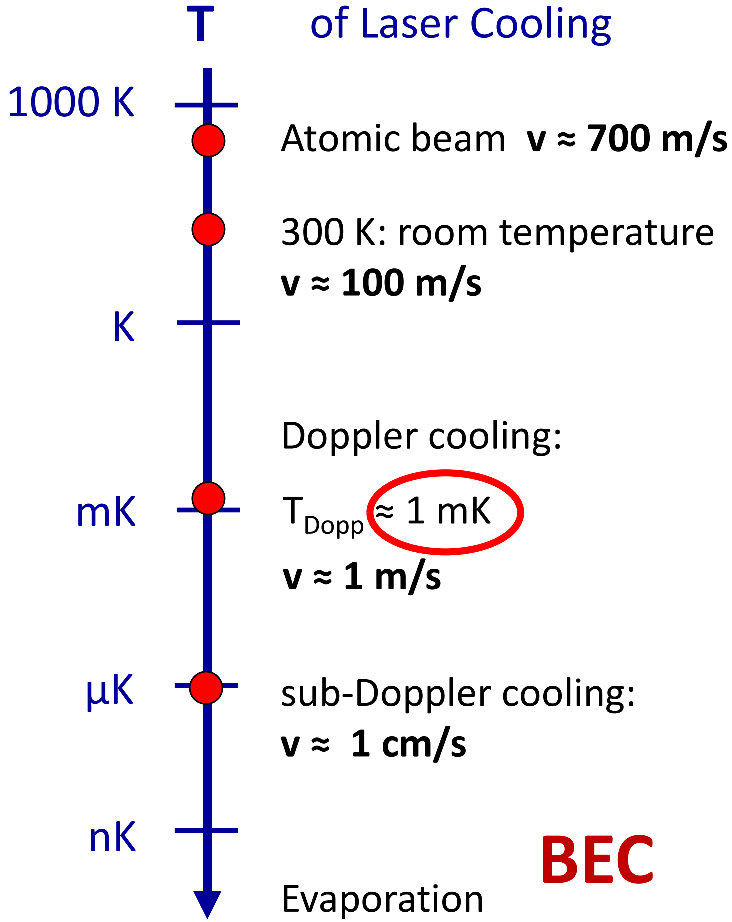
Steven Chu

C. Cohen-Tannoudji

William D. Phillips

→ **Trap and localize atoms & minimize time dilation shifts!**

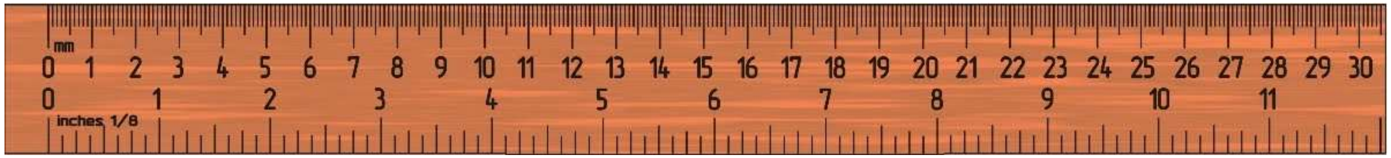
Temperature Scale
of Laser Cooling



MW clock – optical clocks

higher frequency: 10^{15} Hz ↔ 10^{10} Hz

(1) finer scale: shorter averaging times



(2) smaller relative uncertainties: $\Delta\nu/\nu$!

Stability versus Accuracy

$$\frac{\delta\nu(t)}{\nu} = \boxed{\epsilon} + y(t)$$

Systematic uncertainty (u_B)

Types of shifts

1. **Field shifts** e.g. Zeeman shift and black body radiation shift
2. **Relativistic shifts** e.g. time dilation
3. **Collision shifts** e.g. background gas
4. **Technical shifts** e.g. AOM phase chirp

Inspired by Dave Hume

Stability versus Accuracy

$$\frac{\delta\nu(t)}{\nu} = \epsilon + y(t)$$

Systematic uncertainty (u_B)

Statistical uncertainty (u_A)

Types of shifts

1. **Field shifts** e.g. Zeeman shift and black body radiation shift
2. **Relativistic shifts** e.g. time dilation
3. **Collision shifts** e.g. background gas
4. **Technical shifts** e.g. AOM phase chirp

$\Delta\nu$ = 0.1 mHz → $\left(\frac{\Delta\nu}{\nu}\right)_{MW} = 10^{-14}$ *and* $\left(\frac{\Delta\nu}{\nu}\right)_{optical} = 10^{-19}$

Gain with higher frequencies

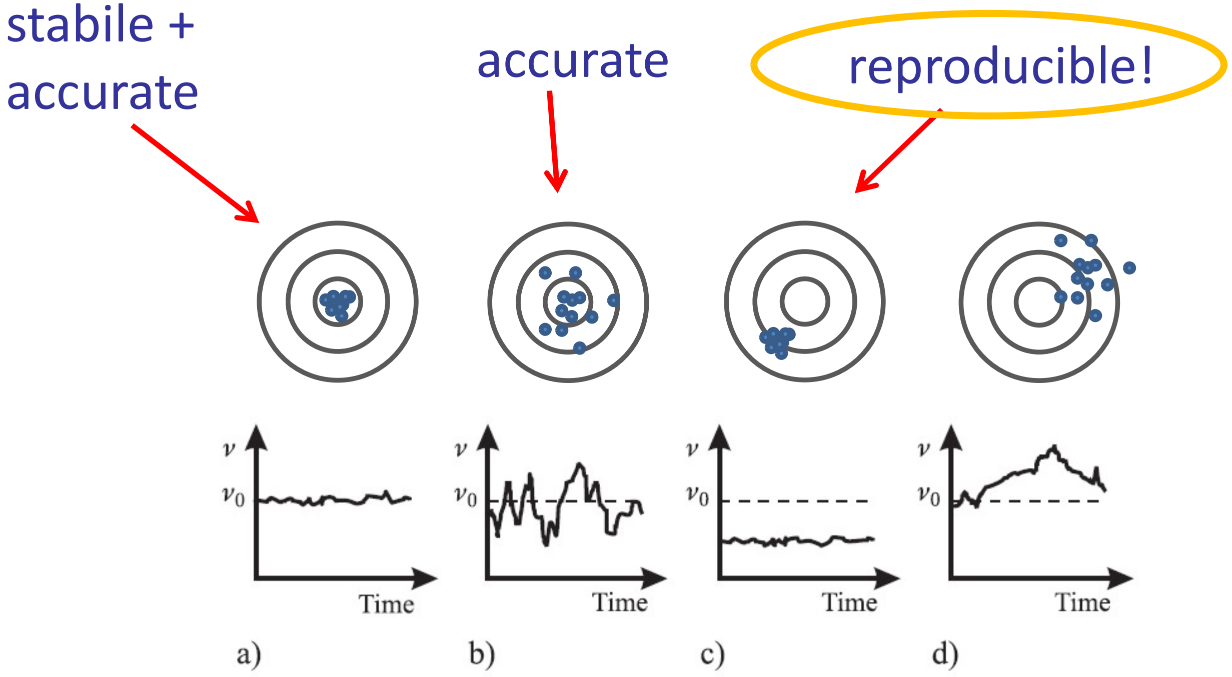
Shift independent of transition, also relevant for HCIs, nuclear ion clocks, etc..

Inspired by Dave Hume

Stability versus Accuracy

Accuracy = deviation of the frequency from its true value

i.e. **the undisturbed eigen-frequency of** atomic transition (atom at rest, T = 0 K)



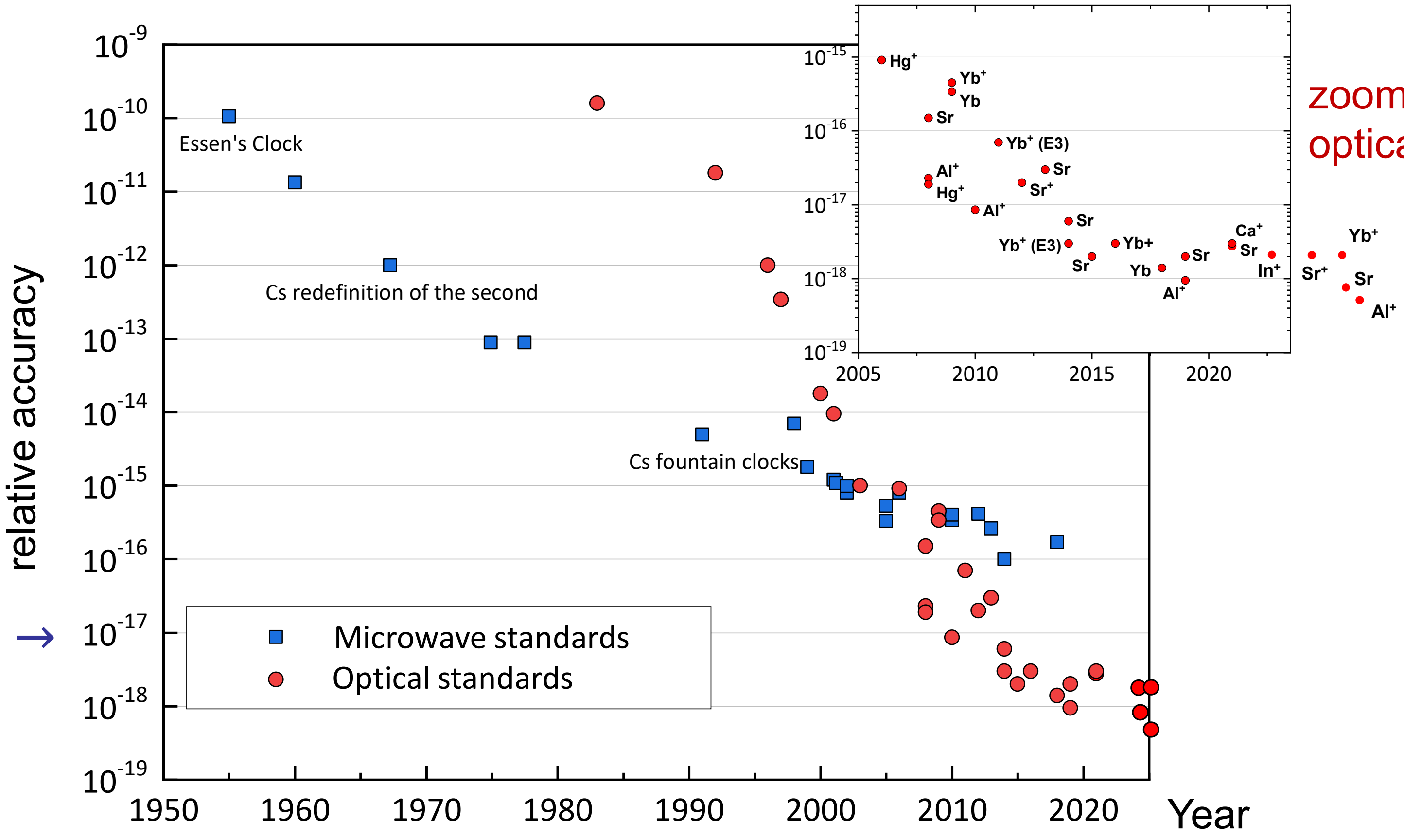
Sufficient for atomic sensors or search for new physics

(e.g. portable devices for relative comparisons**)**

Riehle, Frequency Standards, Wiley VCH 2004

Atomic Clocks – Status Quo

Temporal evolution of relative systematic uncertainties of MW and optical clocks



1 ps per day! →

Types of Optical Clocks

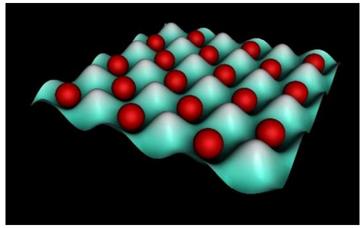
-

Atomic References

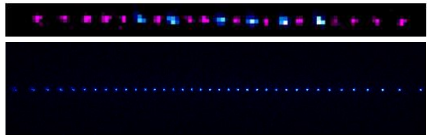
Types of optical clocks

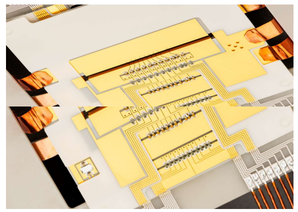
I. Optical clocks with single clock-ions in rf-trap

II. Optical lattice clocks with neutral atoms or molecules



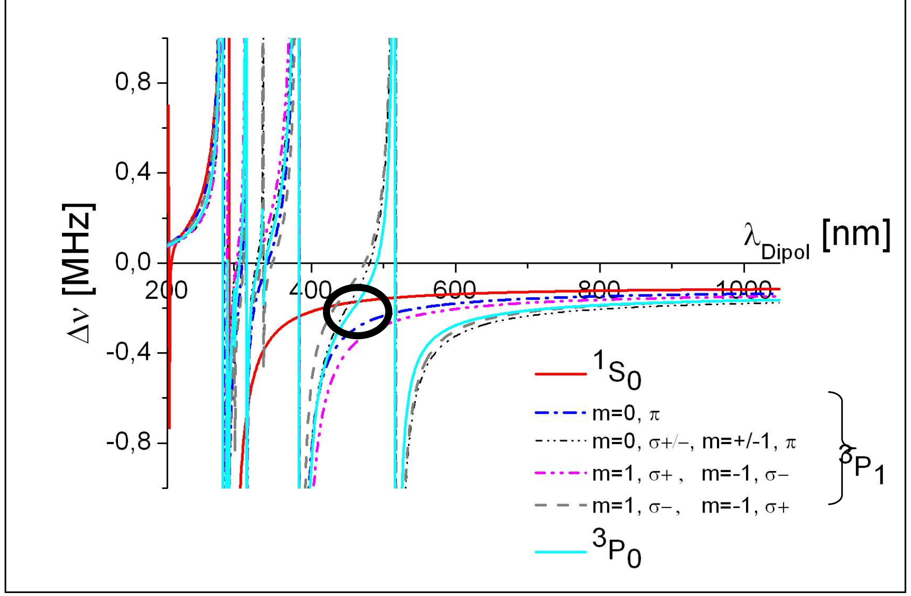
III. Multi-ion clocks and quantum-logic clocks



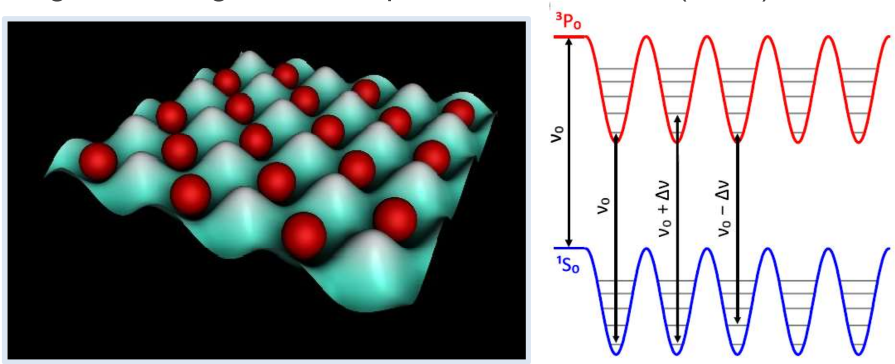


Optical Lattice Clocks with Neutral Atoms

Stark-Shifts of $^1S_0$ and $^3P_{1,0}$ levels



H. Katori *et al.*, „Ultrastable Optical Clock with Neutral Atoms in an Engineered Light Shift Trap", PRL **91**, 173005 (**2003**)



Trapping atoms at the „**magic wavelength**"
leaves clock transition unperturbed

→ to store atoms in optical lattice $\mathbf{T_{atoms} \approx \mu K}$ **needed** !

optical lattice clocks are the <u>most stable frequency standards</u> with $10^3 - 10^4$ atoms in lattice

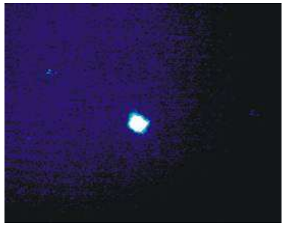
$\boldsymbol{\sigma_y = 5 \times 10^{-17}}$ **in 1 s**

T. E. Mehlstäubler, *Novel cooling methods for an optical Mg frequency standard,* PhD thesis (2005)

Bothwell et al., Metrologia 56, 065004 (2019)

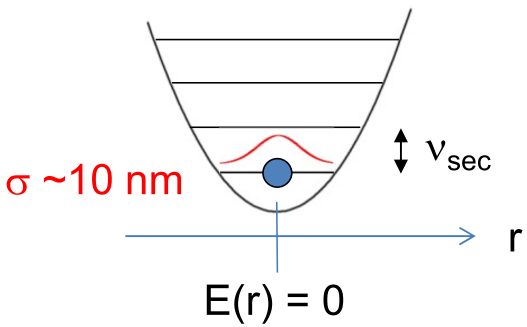
Accuracy of Single Ion Clocks

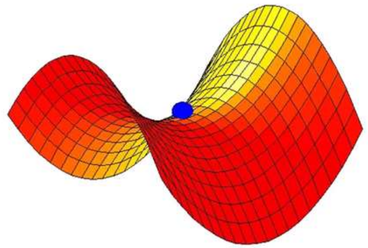
3D-Paul trap



single Yb^{+}-ion

Trap Depth ~ 10^4 K





ponderomotive potential

$$\Psi = \frac{e^2|E|^2}{4m\Omega^2}$$

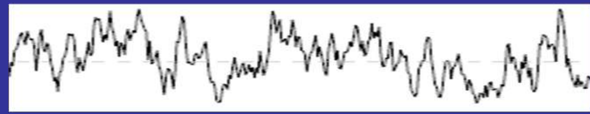
- deep traps → **long trapping times** for single ion (up to months)
- ions are trapped at **E = 0** → no systematic shifts to 1^{st} order
- strong trapping potentials → **strong localization (≈ nm)**
- high level control of internal & external degrees of freedom
- physics package **can be very compact and robust**

<u>most accurate frequency standard</u> **$\Delta\nu/\nu$ = 5 x 10^{-19}**

Marshall et al., PRL 135, 033201 ***(2025)***

Multi-Ion Approach

Instability: statistical error



How well can we resolve the atomic frequency?

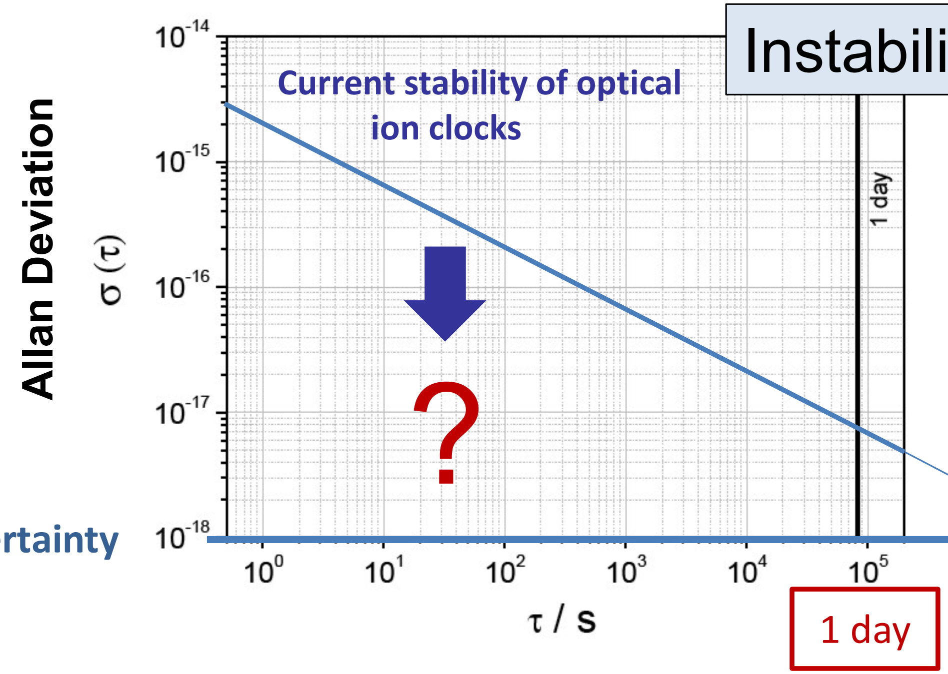
$$\sigma_y \approx \frac{1}{Q} \cdot \frac{1}{\sqrt{N_A}} \cdot \sqrt{\frac{T_c}{\tau}}, \qquad \text{mit} \qquad Q = \frac{f}{\Delta f}$$

Frequency

Number of atoms

Resolved linewidth (laser, atom)

Instability limits uncertainty of clock!



system. uncertainty

10s - 100 days !

Ion clocks: stability limited by quantum projection noise; high duty cycle

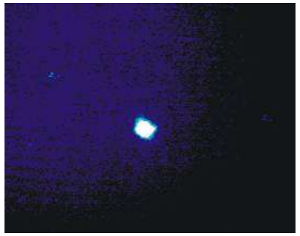
Multi-Ion Clocks ?

<u>needed</u>: „experimental methods, that allow to manipulate and measure many-body quantum systems.”

- Lower **instability** with N_{ions}
- Less stringent requirements for **clock laser**
- Basis for **entangled clocks** → 1/N scaling
- Basis for **multi-ensemble clocks** → $1/\tau$ scaling

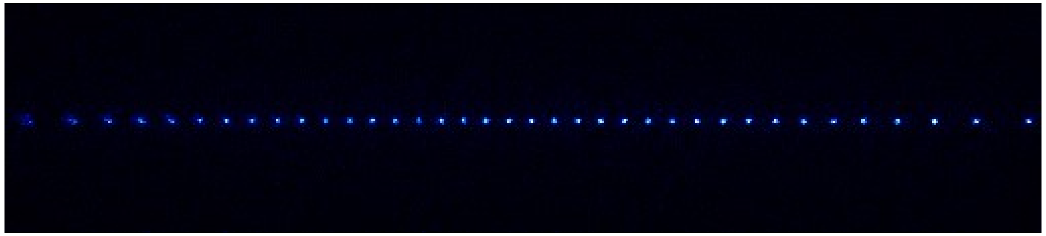
Averaging time

37 days averaging



single Yb^{+} ion

1 day averaging



Coulomb crystal of 37 Yb^{+} ions

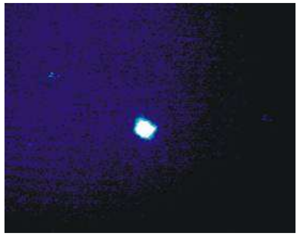
Quantum Metrology ↔ Quantum Simulation & Information

PTB: Herschbach et al., *Appl. Phys. B* 107, 891 (**2012**)

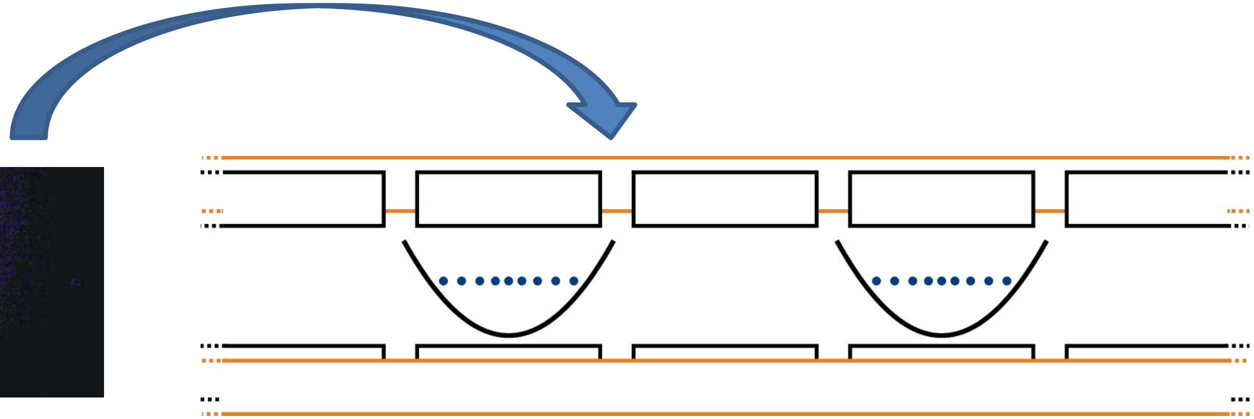
Scaling up the number of ions for metrology

- Basis for **multi-ensemble clocks** and new **interrogation protocols** in one system

our approach: bottom up, scalable ion traps



single Yb^+-ion



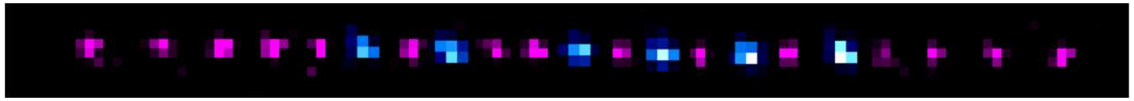
Linear array of Coulomb crystals

→ **Cascaded clock operation with simpler local oscillator**

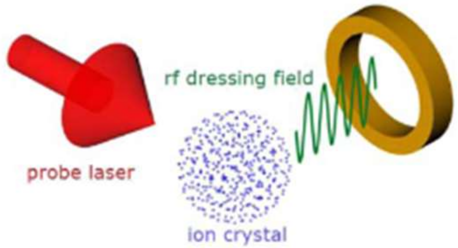
Rosenband and Leibrandt, *arXiv:1303.6357* (**2013**), Borregaard and Sorensen, *PRL 111*, 090802 (**2013**), Kessler et al., *PRL* 112 (**2014**), Lebedev et al., *PRA* 89 (**2014**)

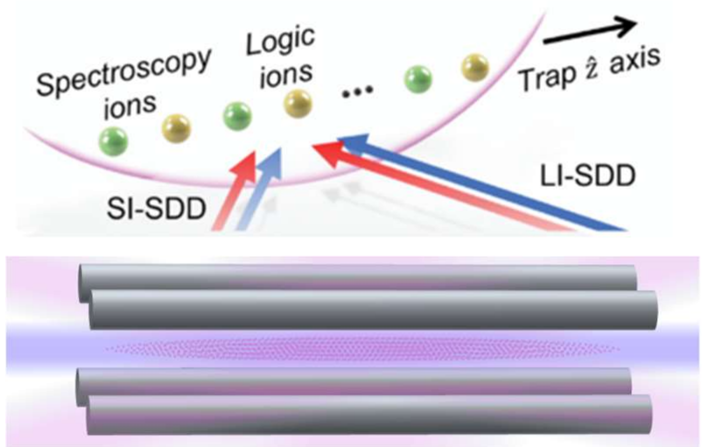
Other Multi-Ion Clocks

In⁺: Herschbach *et al.*, Appl. Phys. B **107**, 891 (**2012**)



Lu⁺: Arnold *et al.*, PRA **92**, 032108 **(2015)**
Ca⁺: Aharon *et al.*, NJP **21**, 083040 (**2019**)
Al⁺: Cui *et al.*, PRL **129**, 193603 (**2022**)
Sn²⁺: Leibrandt *et al.*, arXiv:2205.15484 (**2022**)
Sr⁺: Steinel et al., PRL ……. (**2022**)



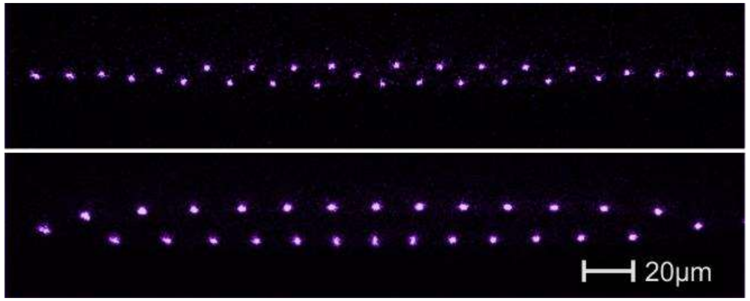


Challenge: controlling a complex many-body system…

Creation of **Topological Defects** – 2nd order Phase Transitions

- Pyka *et al.*, ***Topological defect formation and spontaneous symmetry breaking in ion Coulomb crystals,*** Nat. Commun. 4, 2291 (2013)
- Partner *et al.*, NJP (2013), Physica A (2015)
- Puebla *et al.*, ***Fokker-Planck formalism approach to Kibble-Zurek scaling laws and nonequilibrium dynamics***, PRB (2017)

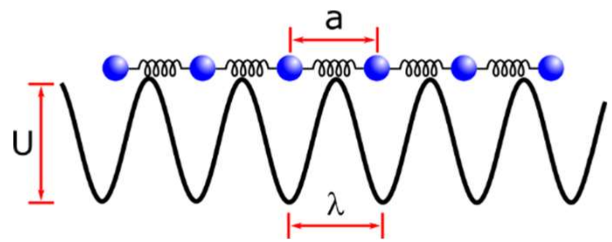
Localized Defect

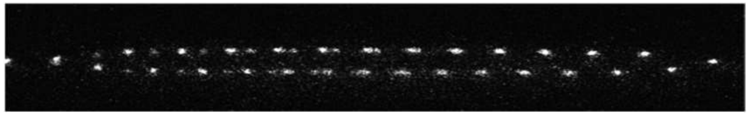


Extended Defect

Nanofriction in a Self-Organized System with Back-Action

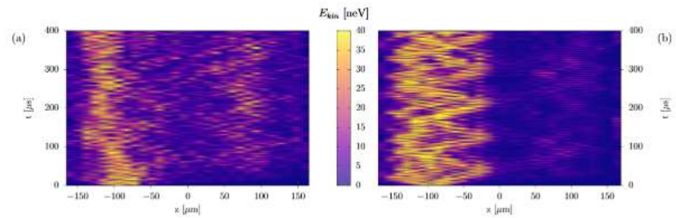
- Kiethe *et al.*, ***Probing Nanofriction and Aubry-type Signatures in a Finite Self-Organized System,*** Nat. Communs. (2017)
- Kiethe *et al.*, ***Nanofriction and Motion of Topological Defects in Coulomb Crystals,*** NJP (2018)
- Kiethe *et al.*, ***Finite-temperature spectrum at the symmetry-breaking linear to zigzag transition,*** PRB (2021)





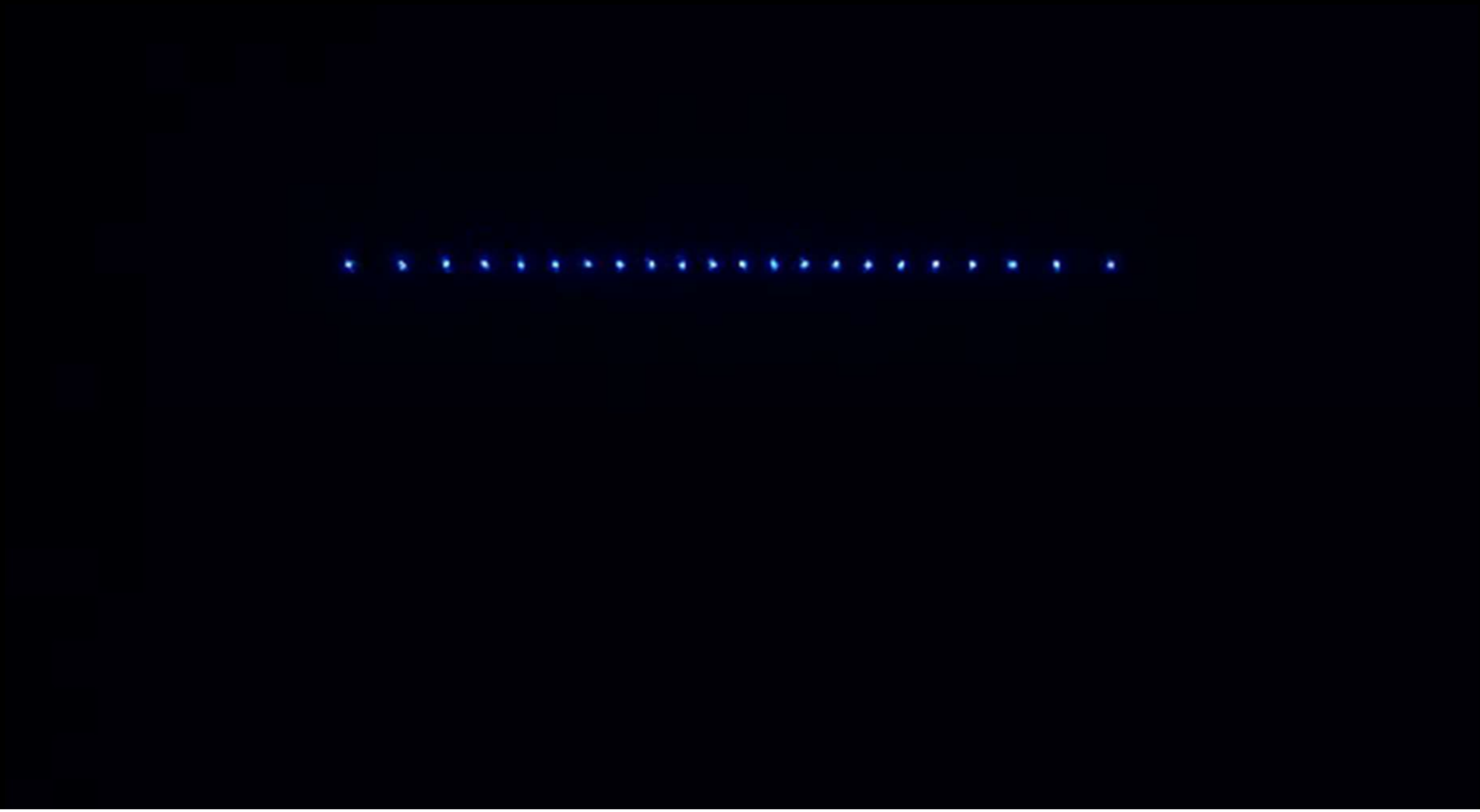
Energy transport and Quantum Friction

- Timm *et al.*, ***Energy localization in an atomic chain with a topological soliton,*** Phys. Rev. Research (2020)
- Timm *et al.*, ***Quantum nanofriction in trapped ion chains with a topological defect,*** Phys. Rev. Research (2021)
- Timm *et al.*, ***Heat transport in a Coulomb ion crystal with a topological defect,*** arXiv:2306.05845 *(2023)*



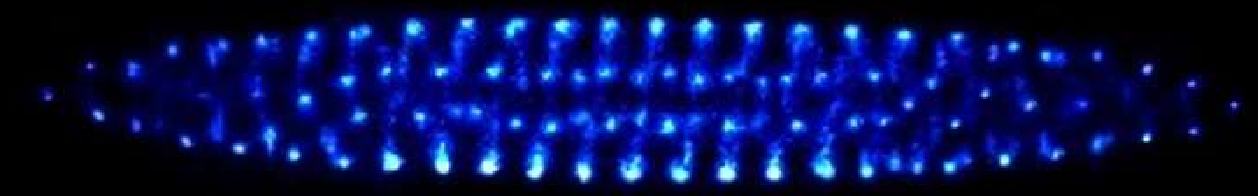
Trapped and Laser cooled $^{172}Yb^{+}$ Ions

Video of Ion Fluorescence taken with EMCCD Camera



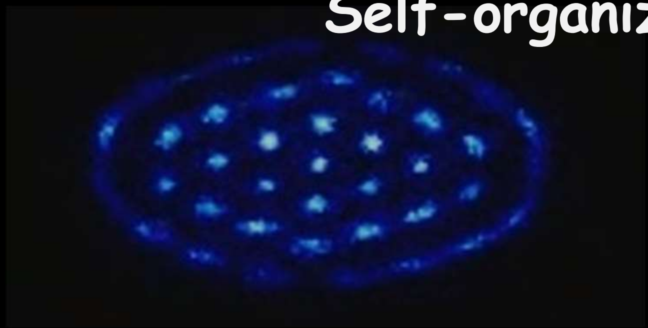
Ion Coulomb Crystals, $E_{pot} > E_{kin}$

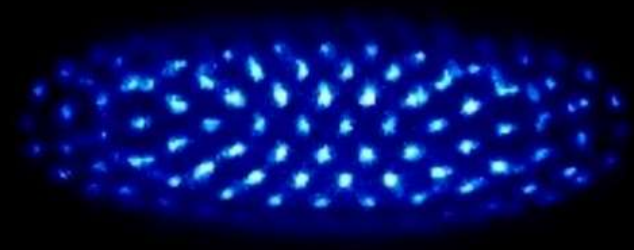
T < 20 mK

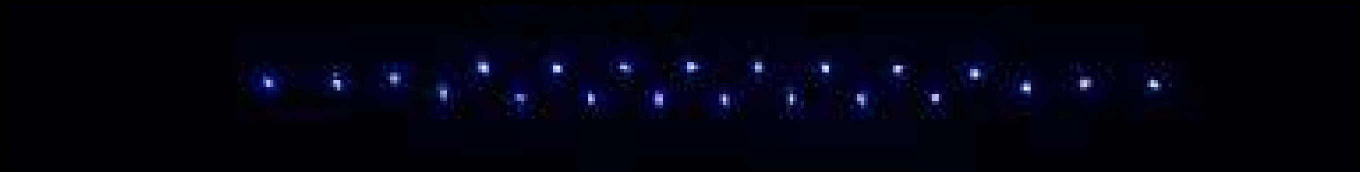


3D

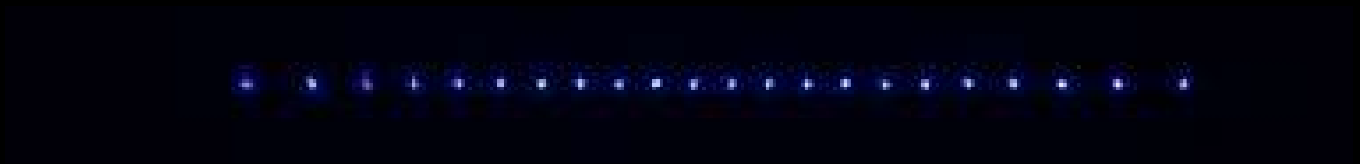
Self-organized system with back-action







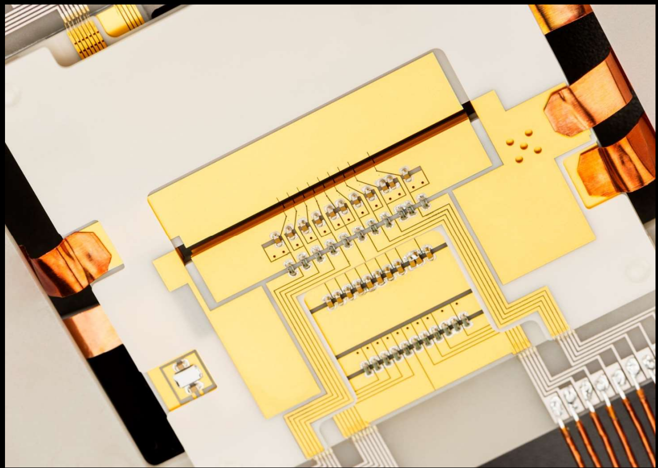
2D

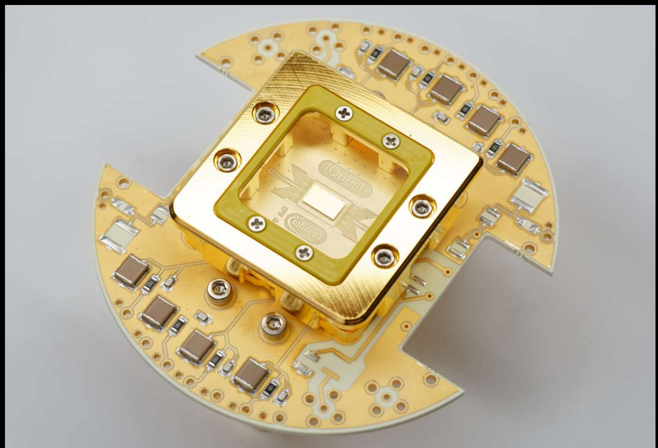


1D

Technological Challenge: Scaling trapped Ions

Scalable Ion Traps





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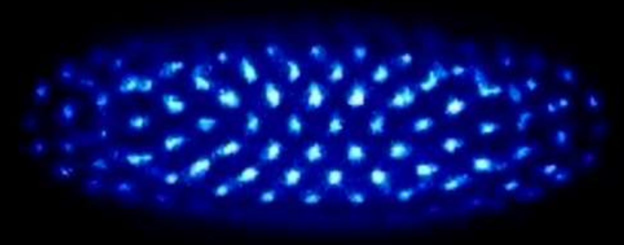
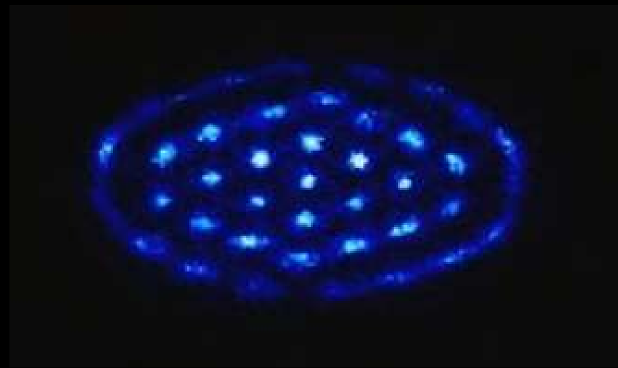
Braunschweig und Berlin

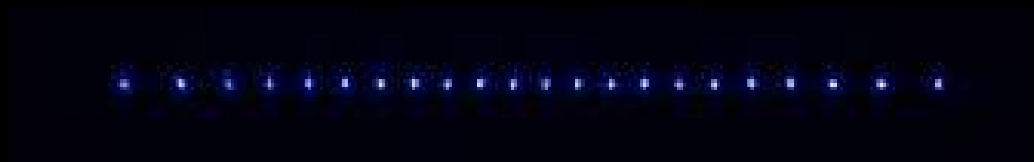
infineon

Yb^{+} Ion Crystals: 1D, 2D, 3D

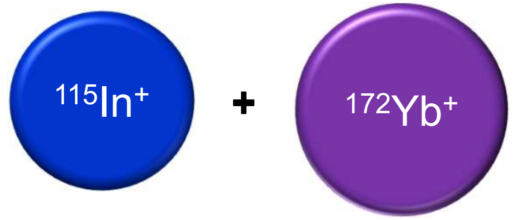


T = 1 mK

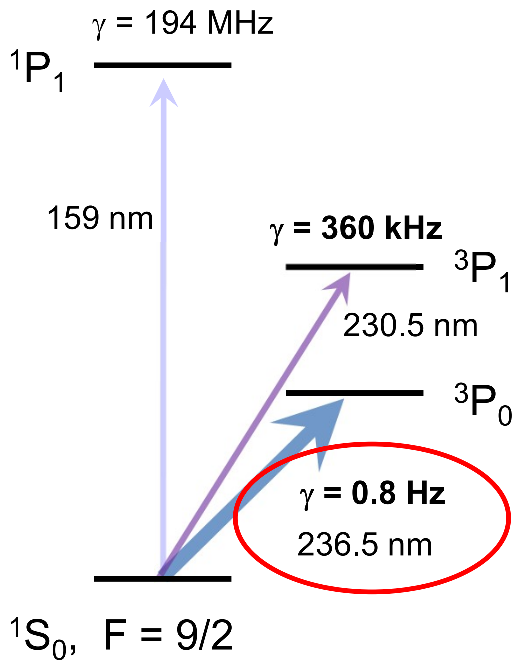




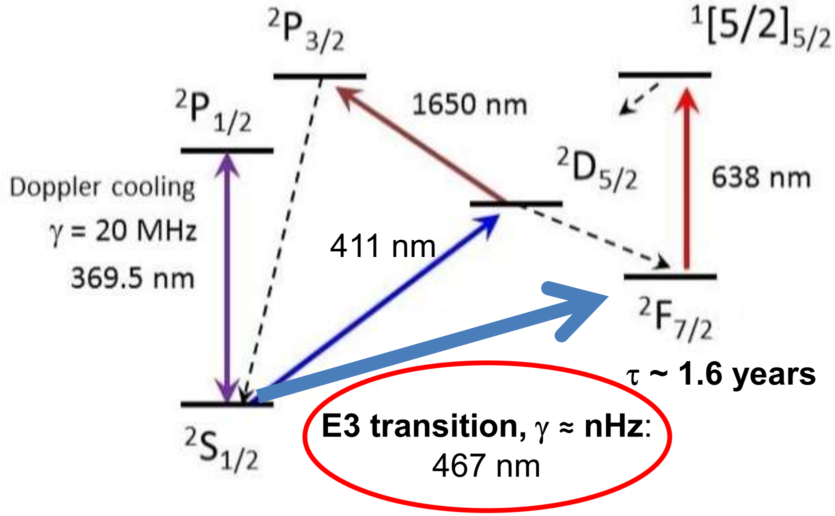
Our atomic candidates: In^+ (clock) sympathetically cooled with Yb^+



$^{115}In^+$ …heavy ion, potential for 10^{-19}



$^{172}Yb^+$ … heavy ion + 2 clock transitions

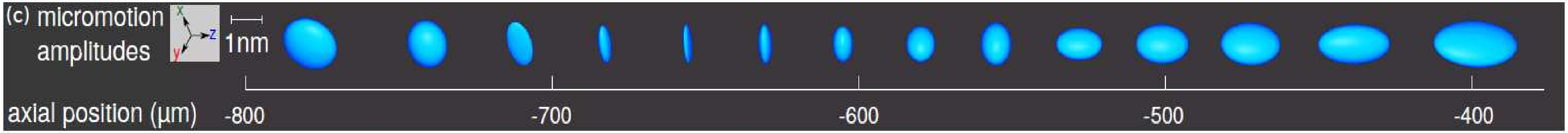


Both clock states have very low quadrupole moment

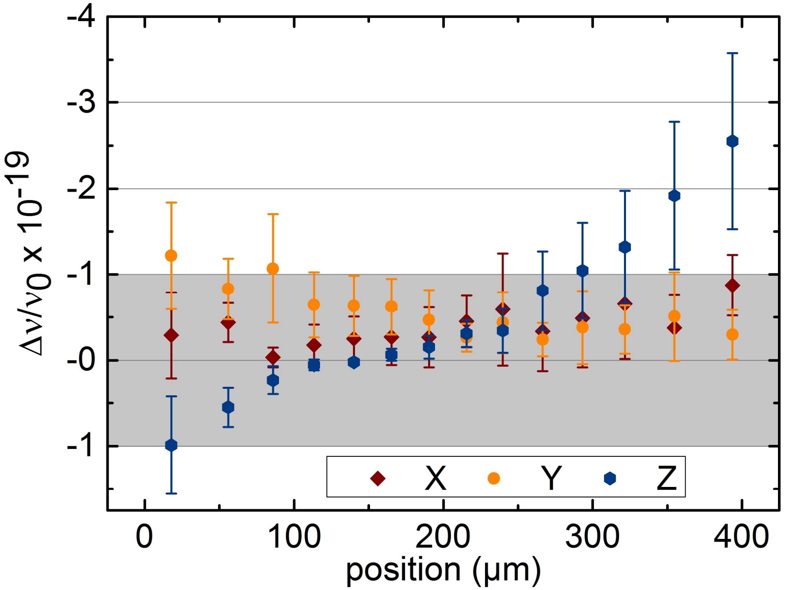
→ low sensitivity to electric field gradients → BUT also other ion species will work!

Challenge: spatial time gradients due to inhomogeneities

Atomically resolved micromotion of individual ions



atomic resolution: **nm** micromotion amplitudes   &   temporal resolution: **ns**

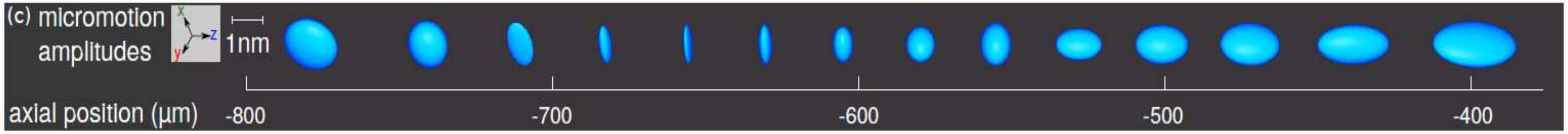


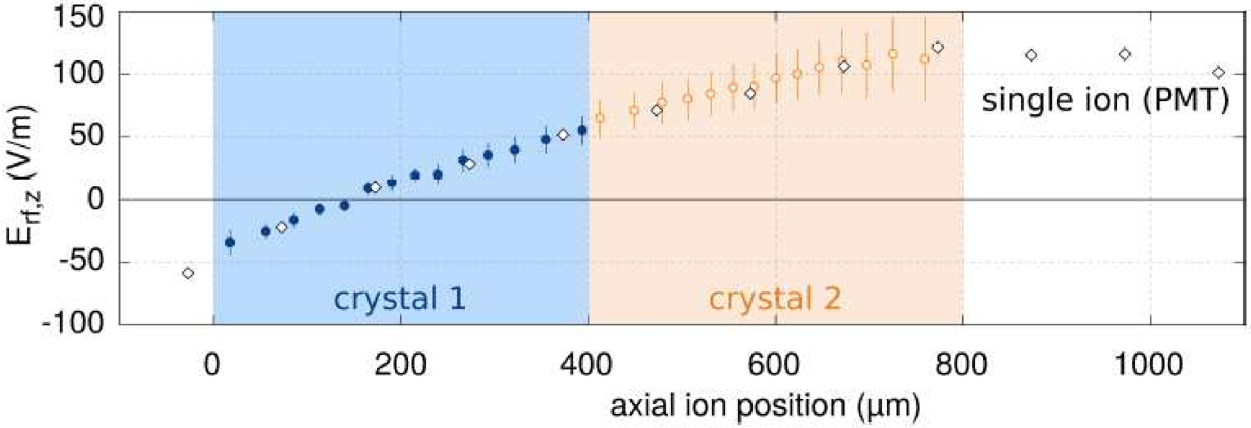
Gradient of Time Dilation of individual ions inside crystal:

$|\Delta\nu/\nu|_{D2} < 1 \times 10^{-19}$ over 300 µm

Keller *et al.*,   "**Probing Time Dilation in Coulomb Crystals in a high-precision Ion Trap**",   Phys. Rev. Appl. (**2019**)

Atomically resolved micromotion of individual ions

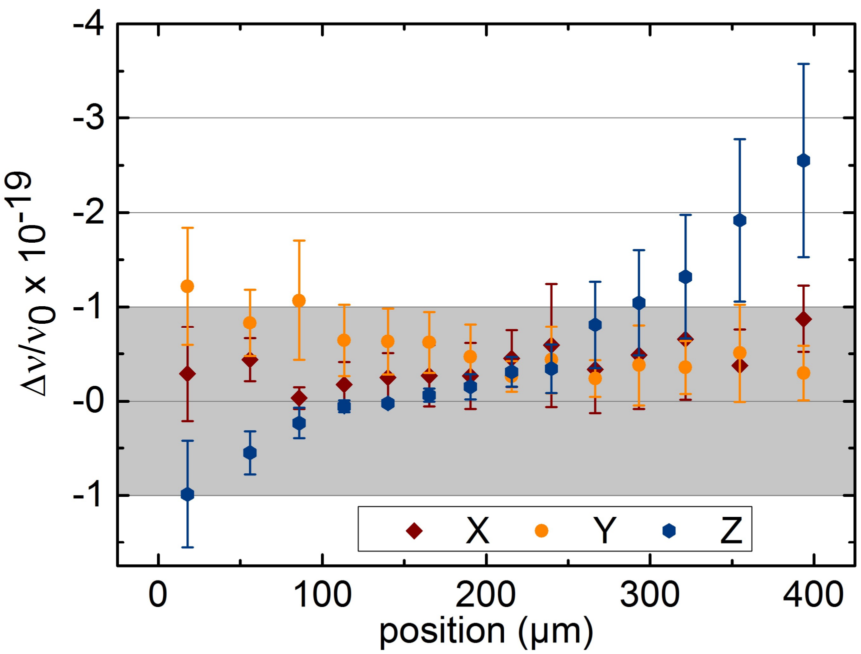




Time dilation shift due to rf motion : $|\Delta\nu/\nu|_{D2}$ **< 1 × 10^{-19} over 300 µm**

"**Probing Time Dilation in Coulomb Crystals in a high-precision Ion Trap**", Keller et al., Phys. Rev. Appl. 11 (**2019**)

micromotion of individual ions

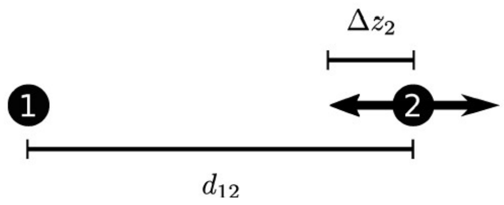


- **Time dilation shift of individual ions** due to rf motion:

  $|\Delta\nu/\nu|_{D2} < 1 \times 10^{-19}$ over 300 μm

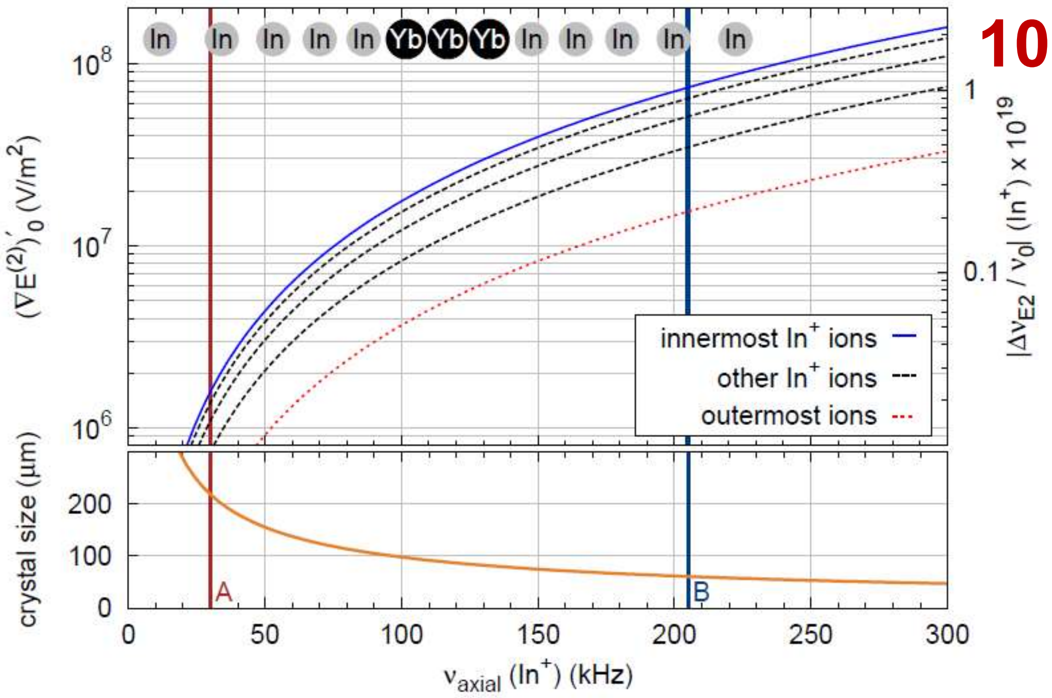
- **Dipolar Coupling between ions:** **$|E_{2\to1}/E_{rf,2}| < 10^{-3}$**

$$\frac{E_{2\to1}}{E_{\mathrm{rf},2}} = \frac{e^2}{2\pi\varepsilon_0}\frac{1}{m\Omega_{\mathrm{rf}}^2(lu_{12})^3} = \frac{2}{u_{12}^3}\left(\frac{\omega_{\mathrm{ax}}}{\Omega_{\mathrm{rf}}}\right)^2$$



"Probing Time Dilation in Coulomb Crystals in a high-precision Ion Trap", *Keller et al., Phys. Rev. Appl.* 11, 011002 (**2019**)

Quadrupole Shift: electron wavefunction interacts with electric field gradients



10^{-19}

$$H_{E2} = \nabla E^{(2)} \Theta^{(2)}$$

Tensorial quadrupole shift
→ can be zeroed at $\boldsymbol{\beta \approx 54.7}$ °

Axial secular frequency

$$\kappa = -2\pi \cdot \frac{1}{4h} \cdot \frac{J(1+J) - 3m_J^2}{J(2J-1)} \cdot \frac{dE_z}{dz} \cdot \Theta \cdot (3\cos^2\beta - 1)$$ [1]

Quadrupole moment

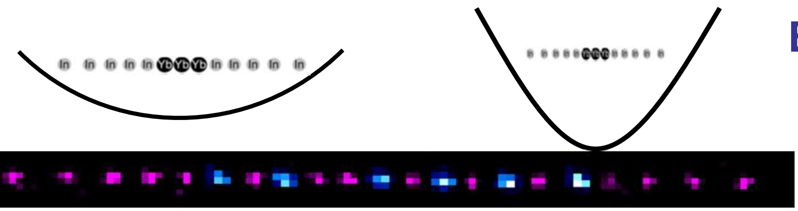
Angle between B-field and trap axis

Beloy et al. PRA (2017), Keller et al. PRA 99, 1 (2019)

2019: Measurement based multi-ion uncertainty budget (trap based)

Yes, we can! ☺

Confinement A   Confinement B



B) Sympathetic cooling

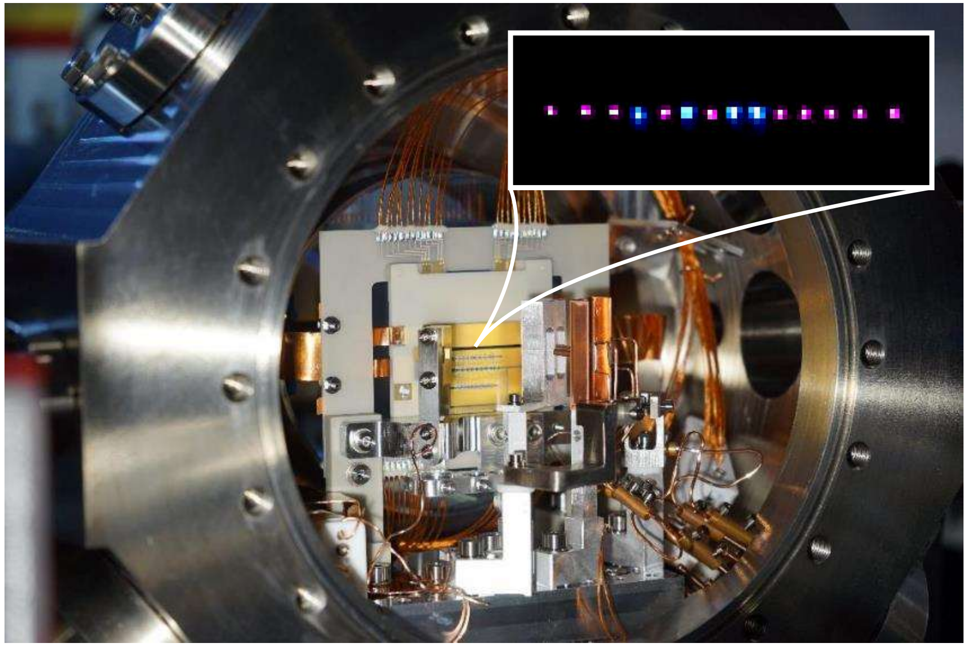
Effect	Max shift $\Delta\nu/\nu_0$	$u(\Delta\nu/\nu_0)$	Max shift $\Delta\nu/\nu_0$	$u(\Delta\nu/\nu_0)$
Time dilation (thermal)	-2	0.4	-19	4
Heating (per second)	-3.1	0.2	-0.6	0.02
Time dilation (EMM)	-1.8	0.8	-1.3	0.6
AC Stark (thermal MM)	-0.003		-0.03	
AC Stark (EMM)	-0.2	0.1	-0.2	0.1
El. quadrupole shift	-0.02	<0.01	-1.1	0.02
BBR at 300 K temperature uncertainty	-137	0.15	-137	0.54
Total	-141.3	0.9	-158.7	4.1

Units: 10^{-19}

Keller et al., “**Controlling systematic frequency uncertainties at the 10^{-19} level in linear Coulomb crystals**“, PRA 99, 1 **(2019)**

Dedicated In^+ Clock Setup

In^+ Clock Measurement (**2021 – 2022**)
… and evaluation (**2022 – 2025**)

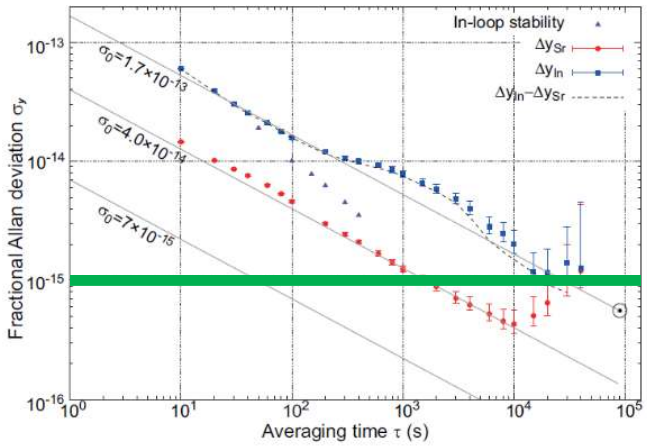


ARTIQ
SINARA

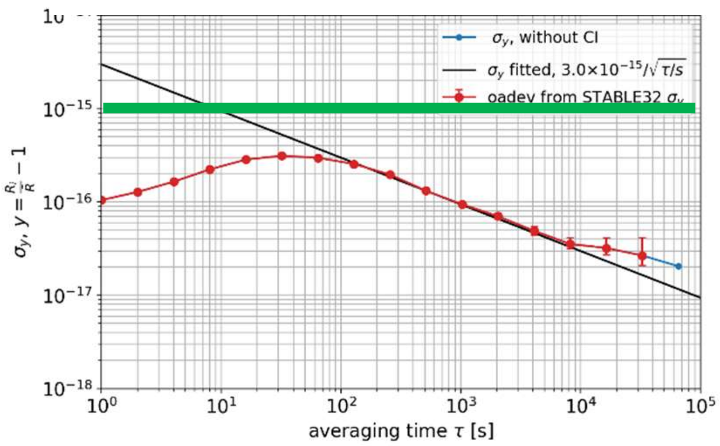
Summer 2021: First frequency ratio $^{115}In^+$ - ^{87}Sr - $^{171}Yb^+$

In^+ Yb^+

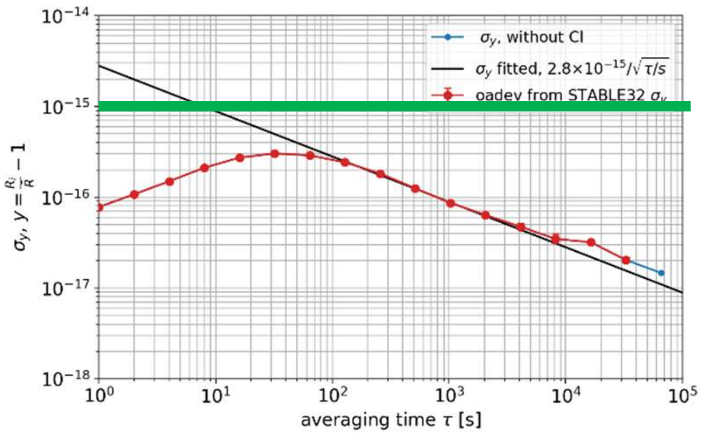
Frequency ratio measurement of $^{115}In^+$ versus ^{87}Sr at NICT in Japan 2020[1]



$^{115}In^+/^{172}Yb^+$ clock versus ^{87}Sr lattice clock[2]



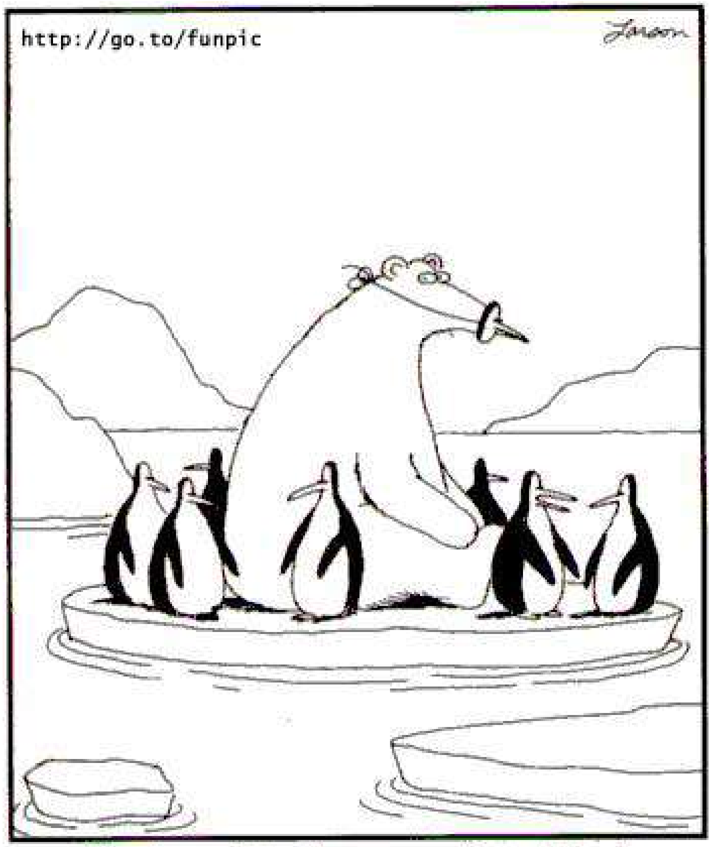
$^{115}In^+/^{172}Yb^+$ clock versus $^{171}Yb^+$ (E3) single ion clock[3]



[1] Ohtsubo et al., *Opt. Lett.* **45**, 5950 (2020)
[2] Dörscher et al., *Metrologia* **58** 015005 (2021)
[3] Huntemann et al., *Phys. Rev. Lett.* **116**, 063001

→ 2 orders of magnitude improvement

2. Conclusion - Theory



"And now Edgar's gone. ... Something's going on around here."

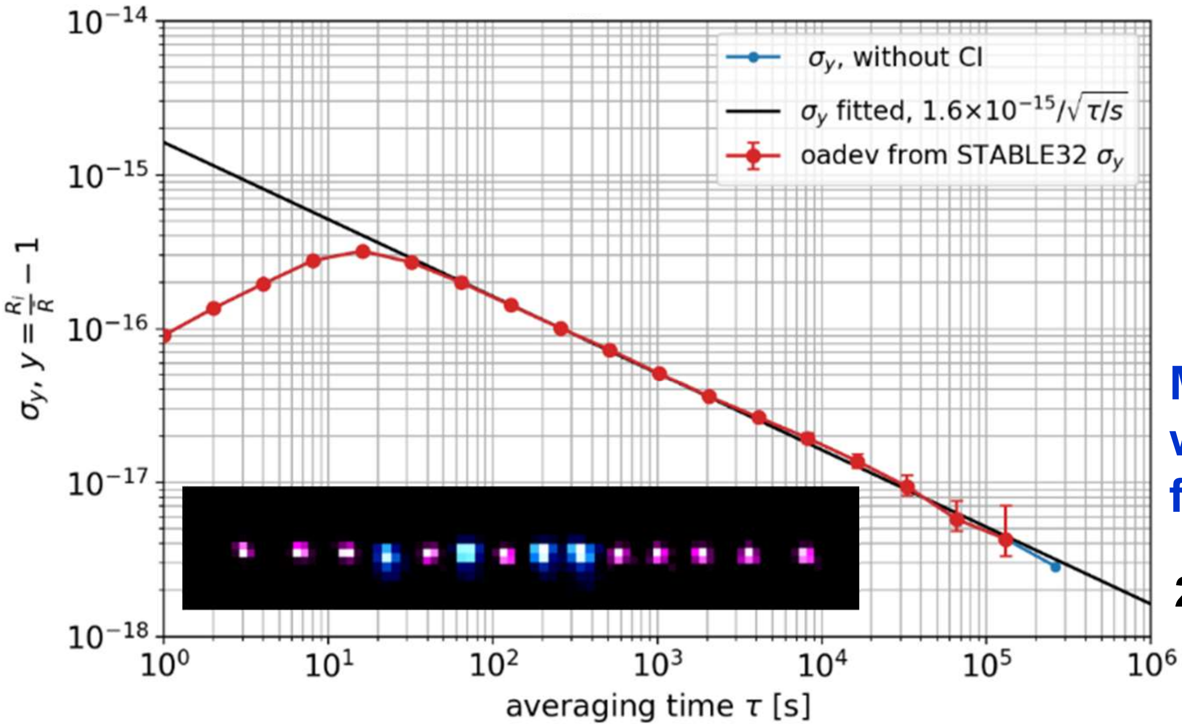
2024: first In^+ Ion Crystal Clock

unit: 10^{-18}

Clocks	u_A	u_B	u_{RRS}	u_C	Ratio
$^{115}In^+/^{171}Yb^+$ (E3)	2.4	3.7	0.5	4.4	1.973 773 591 557 215 789(9)

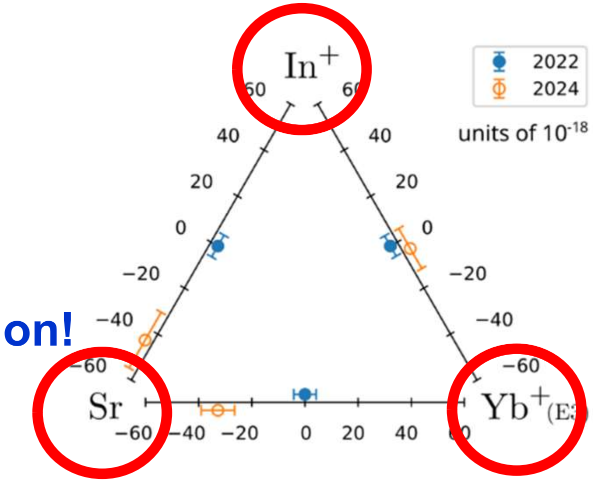
In^+ / Yb^+ frequency ratio:
World record in clock comparison
→ a mandatory criterion for re-definition of second is fulfilled for the first time!

Frequency measurement of In^+ crystal clock vs Sr lattice clock



Measurement with mHz frequency resolution!

2.4×10^{-18}



Hausser et al., Phys. Rev. Lett. 134, 023201 (***2025***)

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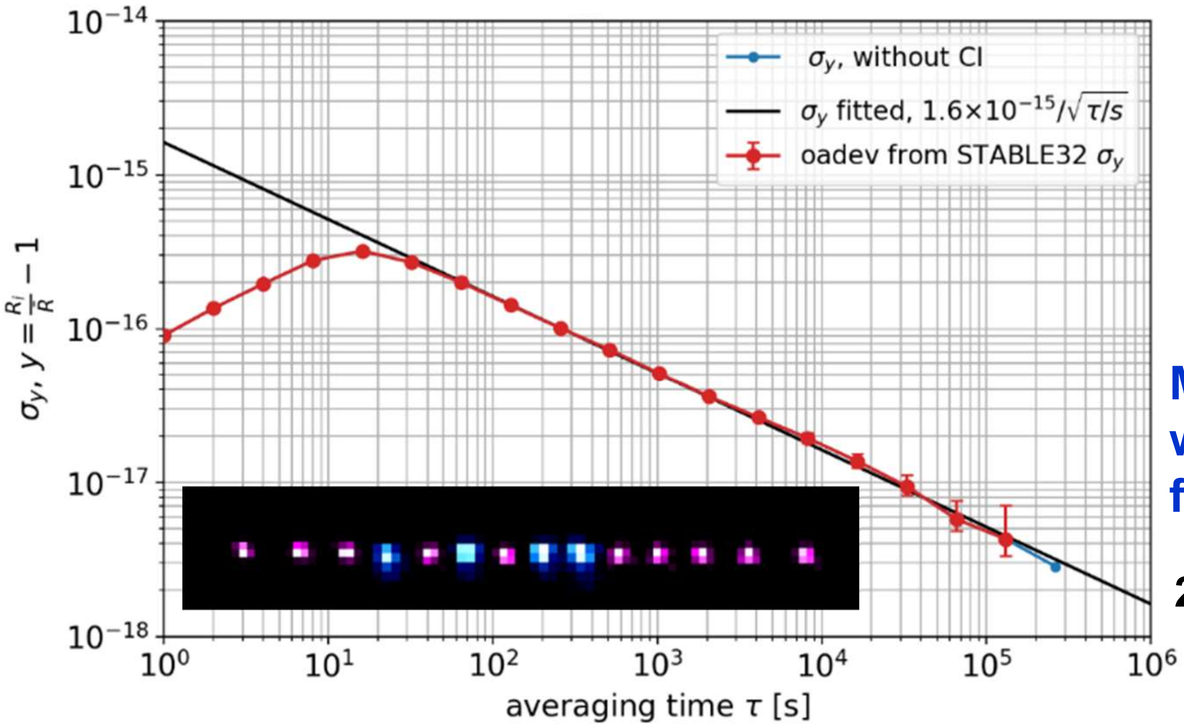

Measurement with mHz frequency resolution!

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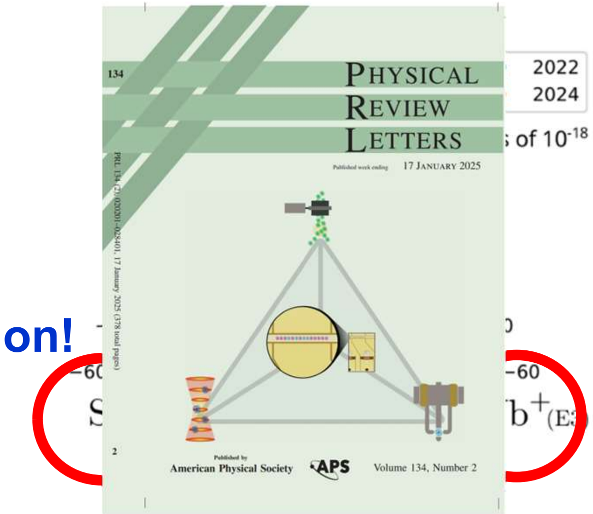
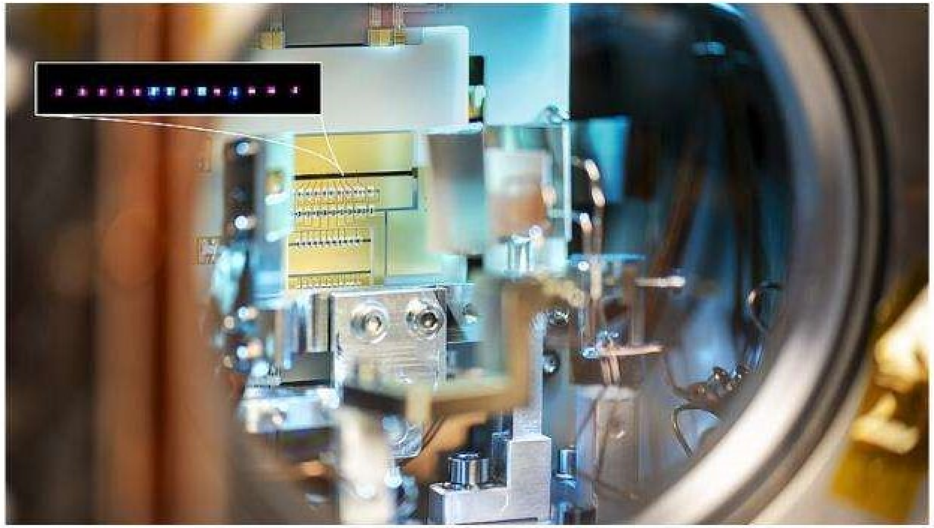


Hausser et al., Phys. Rev. Lett. 134, 023201 (***2025***)

Auf dem Weg zur „neuen“ Sekunde

27.01.2025



Die Ionenfalle der neuartigen In+/Yb+-Kristalluhr in ihrer Vakuumkammer.

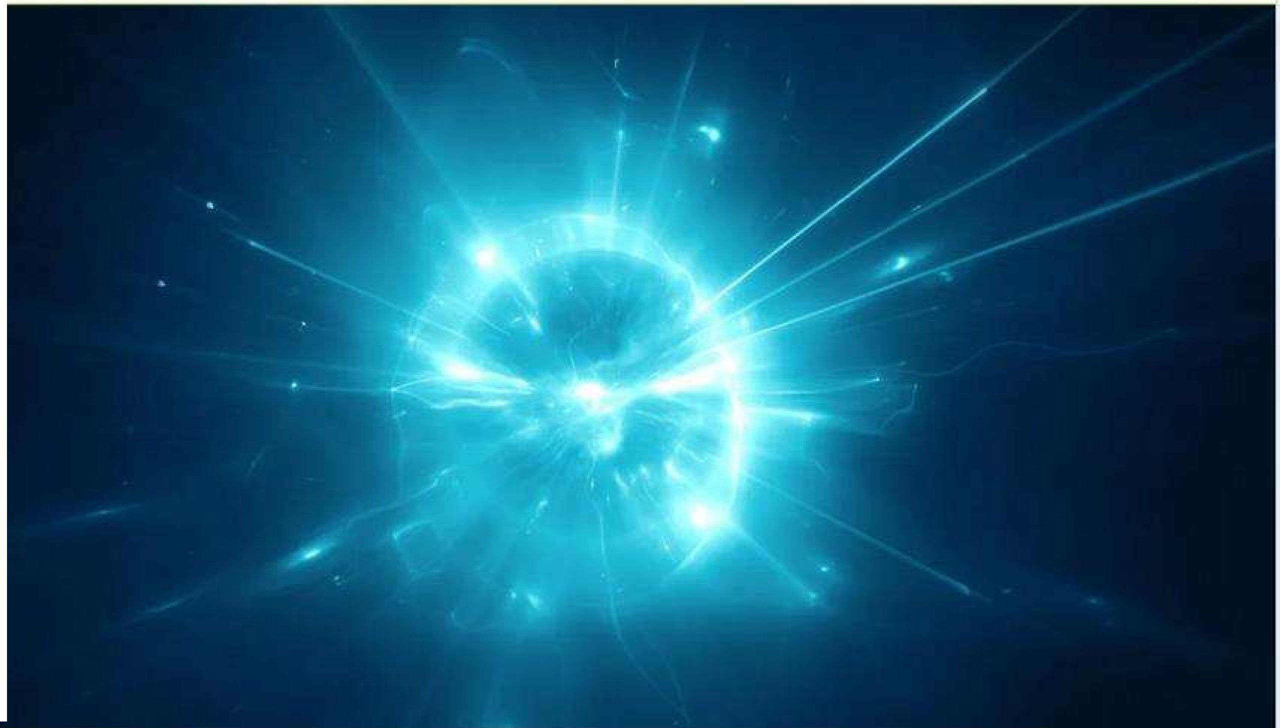
Neuartige optische Atomuhr erreicht in Vergleich Rekordgenauigkeit auf dem Weg zur Neudefinition der Sekunde

Multi-Ion Optical Atomic Clock Takes A Step Towards Changing The Definition Of A Second

The breakthrough has applications from metrology to dealing with the consequences of climate change.

DR. ALFREDO CARPINETI
Senior Staff Writer & Space Correspondent

| by Maddy Chapman



A second might be redefined in the coming years, thanks to technological breakthroughs. Image Credit: pixelparticle/Shutterstock.com

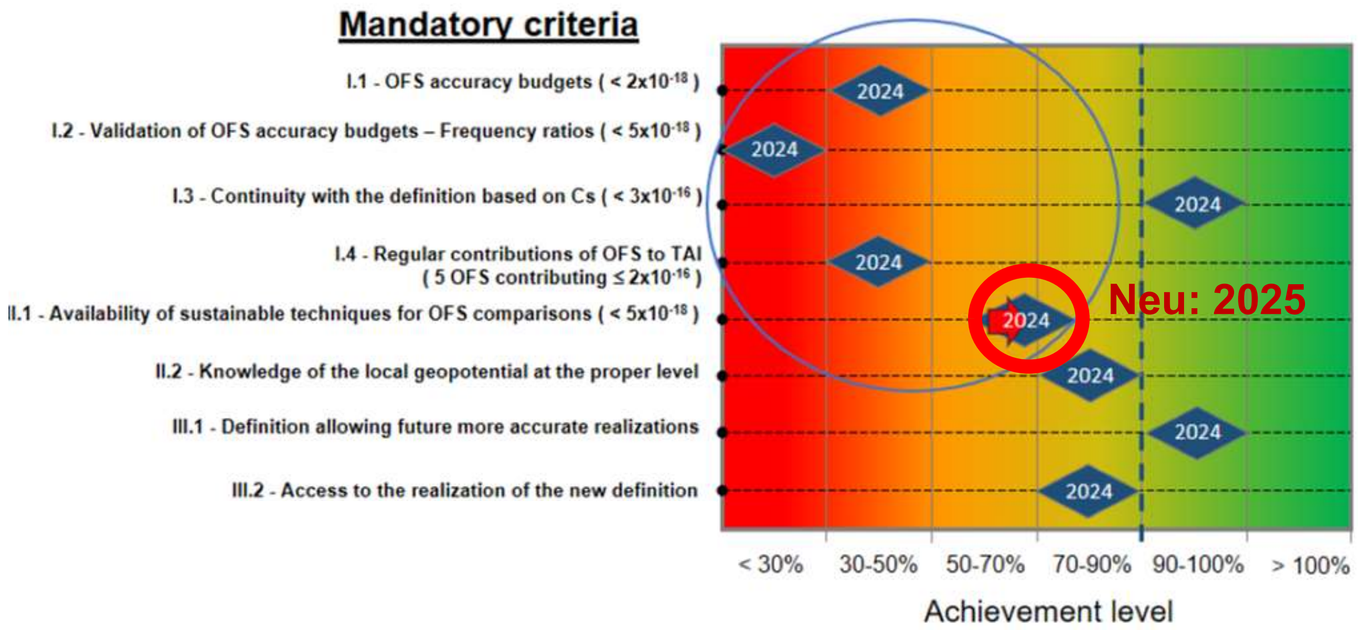
New Definition of Second by Optical Clocks ?

Neudefinition der Sekunde: Kriterien und ihr Erfüllungsgrad

PTB

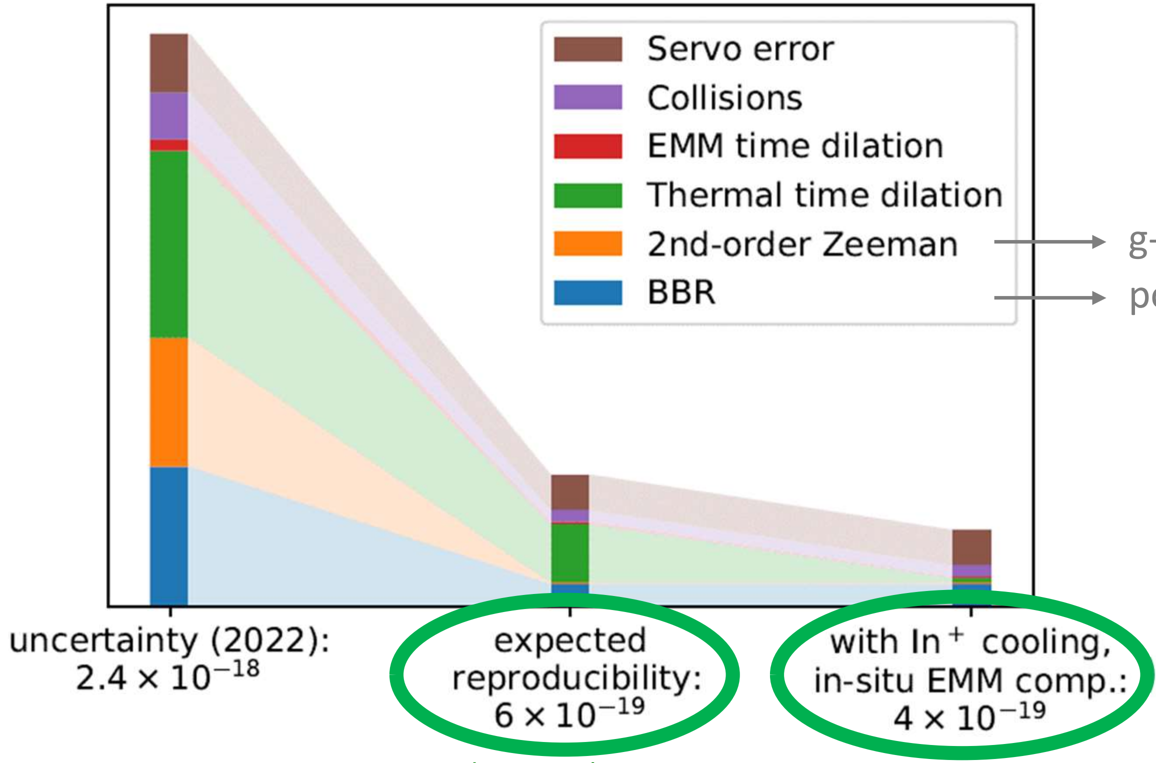
Task Force SG2 „Criteria“:

N Dimarcq et al 2024 Metrologia 61 012001 → 8 “Mandatory Criteria” & 6 “Ancillary Conditions”



Slide: Stefan Weyers (PTB)

Evaluation of In^+/Yb^+ Crystal Clock

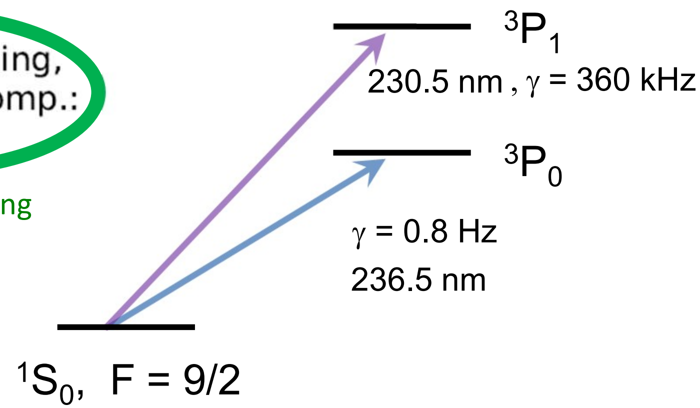


g-factor needs to be measured

polarizability needs to be measured

u_B due to unknown natural constants (g and polarizability)

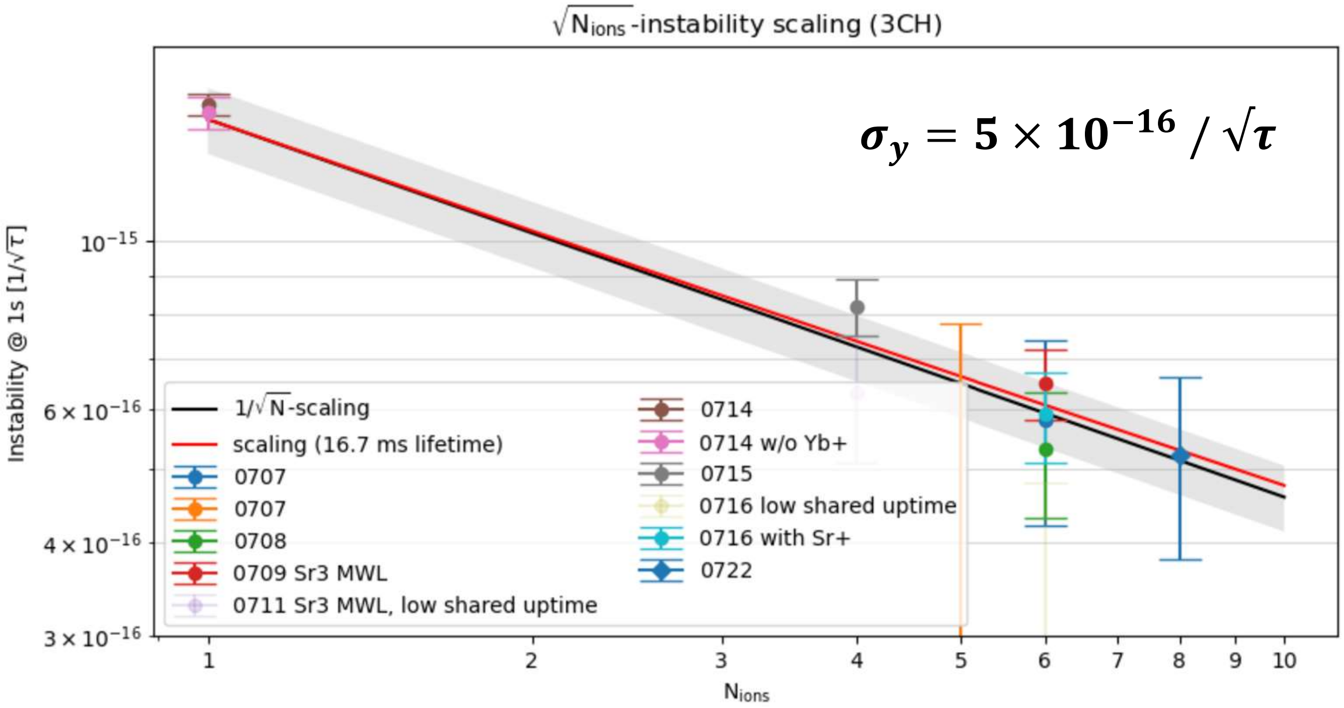
2nd stage cooling



*Hausser et al., arXiv 2402.16807 (**2024**), sub. to PRL*

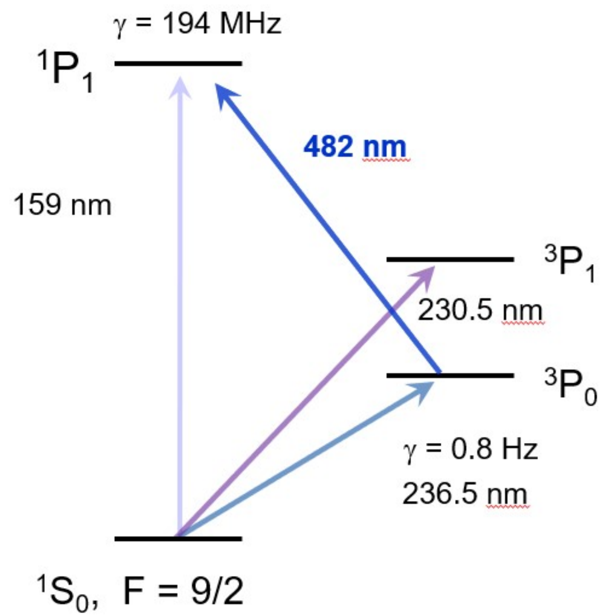
QPN limited sqrt(N) Scaling of Short-Term Stability !

First Quantum Projection Noise limited scaling observed:



Solution: quenching clock state

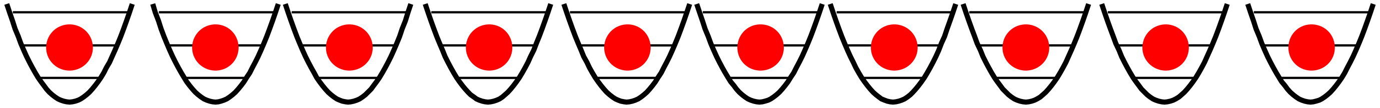
$$\Gamma_{eff} = \Gamma_{3P0} + \frac{\Omega_{482}^2}{\Gamma_{1P1}} \propto \frac{\Gamma_{1P1-3P0}}{\Gamma_{1P1}}$$



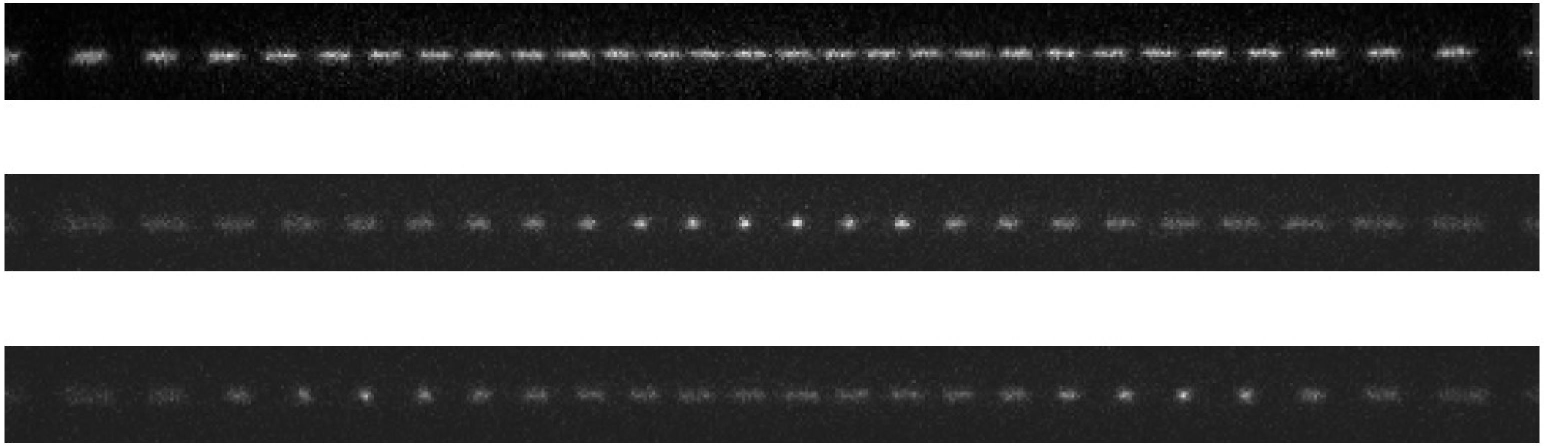
Quench transition: Priv. comm. Marianna Safronova
Mehlstäubler et al., Journal of Optics B 5, 183 (2003)

Thermal Time Dilation Shifts

Coupled Many-Body System:

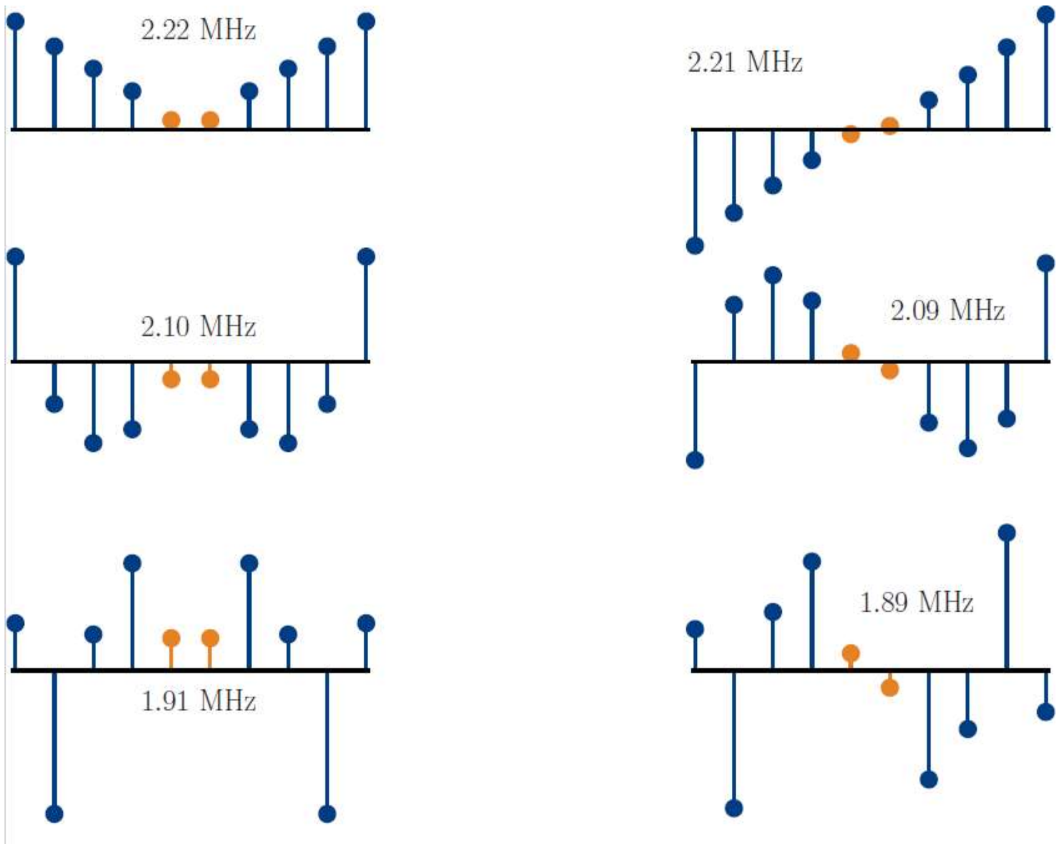


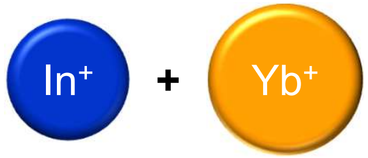
Example: **photos** of first **3 collective modes of linear crystal**



→ We need to control the motional states of all phonons

Thermal Motion - Eigenmode Vectors



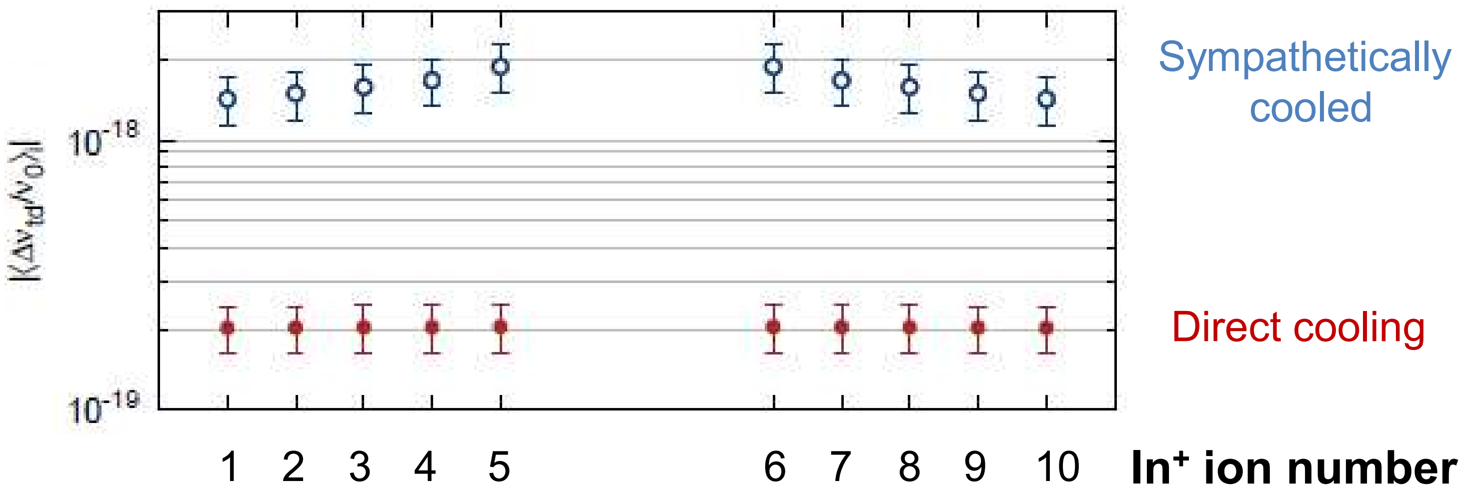


Composite system:

Some modes cannot be cooled well sympathetically in given time

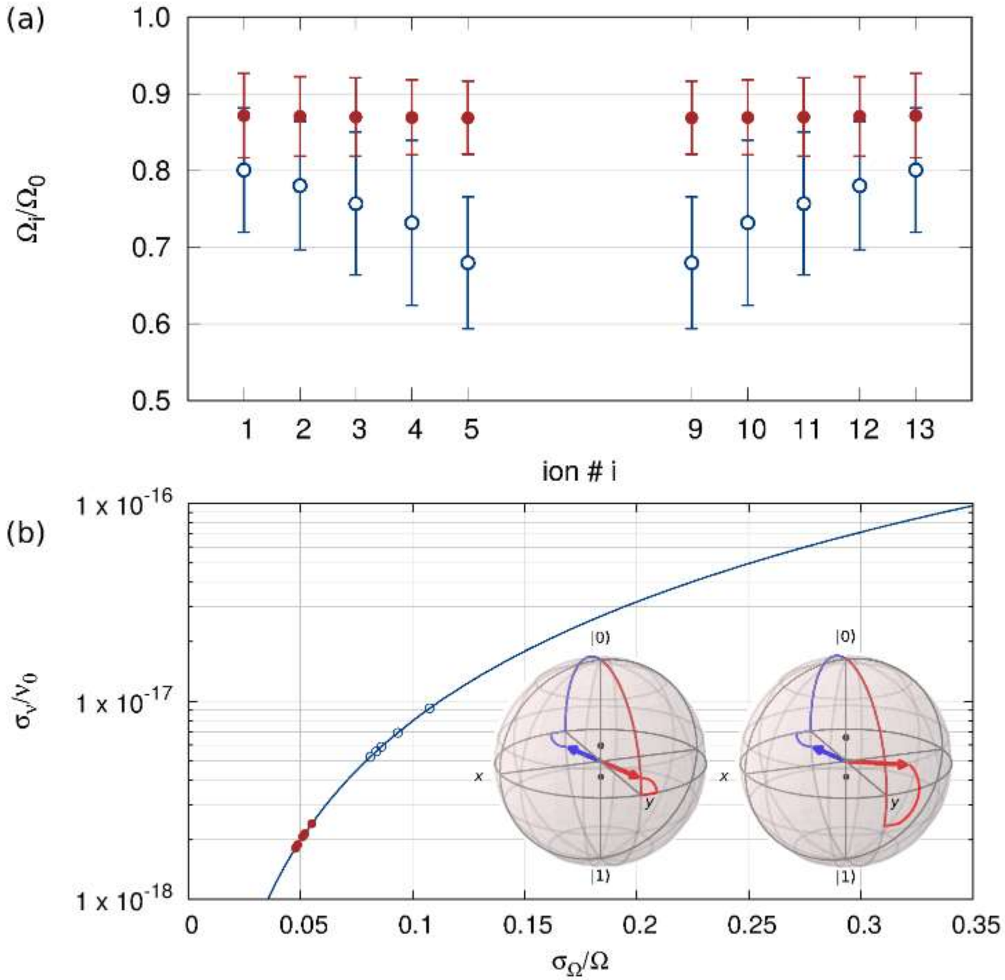
Time Dilation due to Thermal Motion

Time Dilation Shift



Example configuration

Reduced Stability due to Thermal Motion



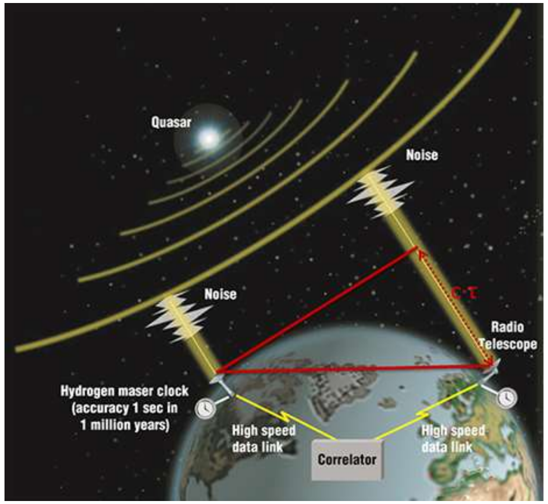
Debey-Waller effect:

$$\frac{\sigma_{\Omega,i}}{\Omega_i} = \sqrt{\left[\prod_\alpha I_0\left(2\eta_{\alpha,i}^2\sqrt{\bar{n}_\alpha(\bar{n}_\alpha+1)}\right)\right] - 1}$$

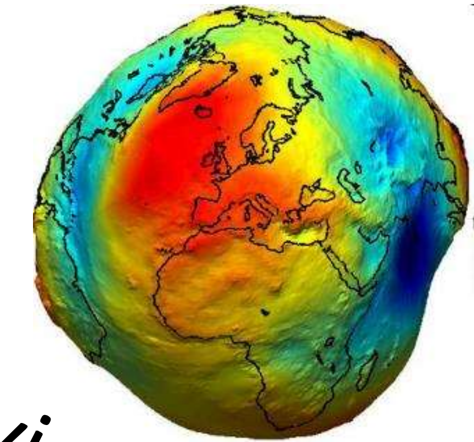
$$\eta_{\alpha,i} = k_\alpha \beta'_{\alpha,i}\sqrt{\frac{\hbar}{2m_i\omega_\alpha}}$$

Wineland et al., J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998); Keller et al., PRA 99, 1 (2019)

Applications of Today's Clocks



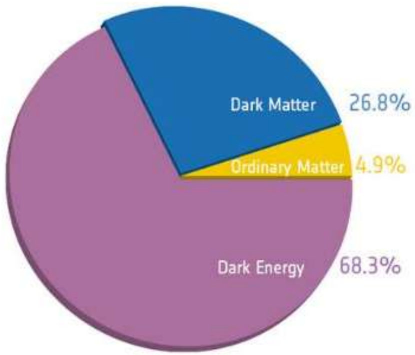
https://space-geodesy.nasa.gov/techniques/VLBI.html



Timing & Navigation,

autonomous driving...

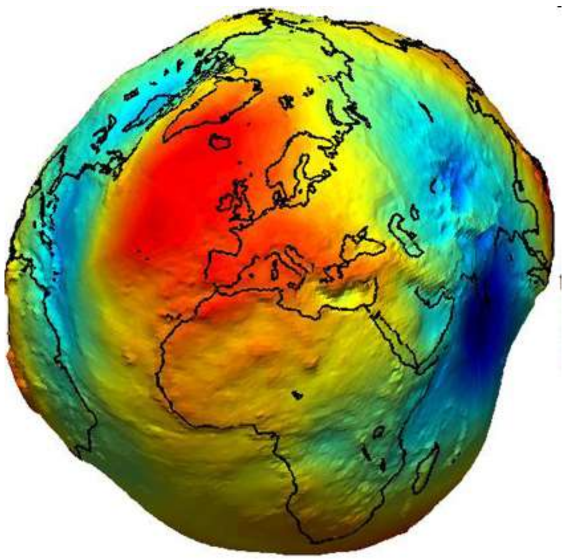
Relativistic Geodesy



Test of Fundamental Physics

The Earth‘s Geoid

- Carl Friedrich Gauß describes „**die Erdfigur**“ **= equipotential surface,** shape water would take at rest under Earth‘s gravity and rotation



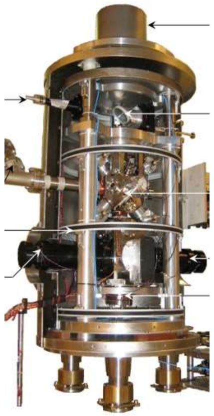
Gauß statue in Braunschweig

Clocks as Quantum Sensors for Geodesy

Gravity red-shift

$$Z \equiv \frac{\Delta\upsilon}{\upsilon} = (1+\alpha)\frac{\Delta U}{c^2} \quad = \mathbf{10^{-18}}$$

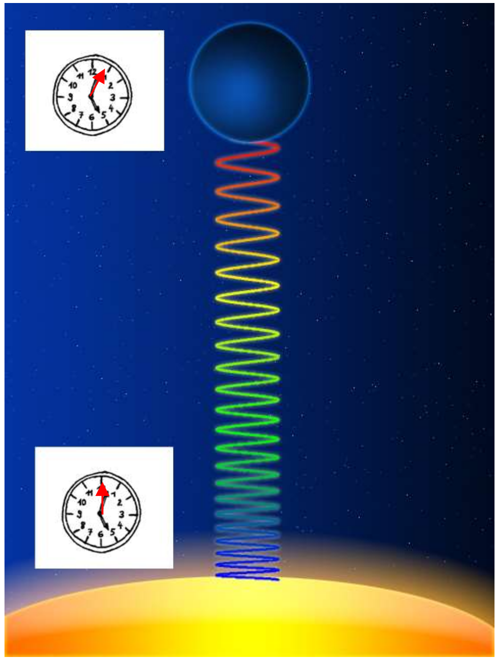
$\Delta\nu/\nu = \mathbf{10^{-18}}$ → **1 cm** height resolution

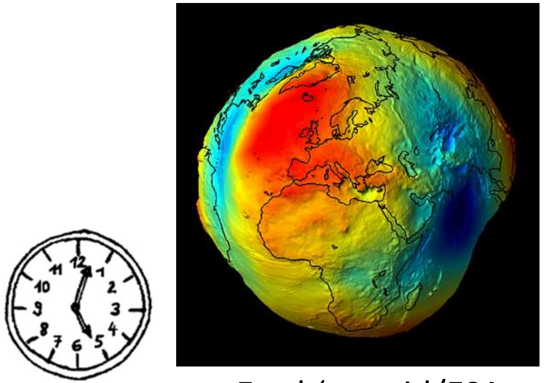


gravimeter

→ **measures acceleration g**

= local gradient of potential





Earth's geoid/ESA

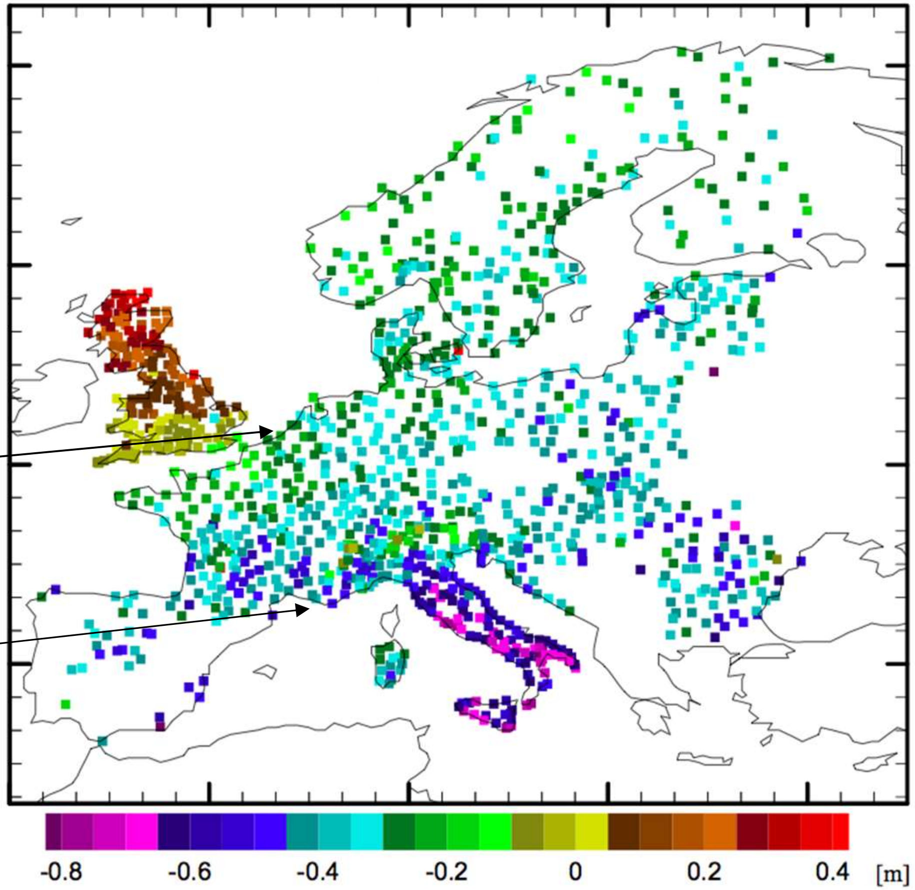
clocks

→ **measure difference in potential**

Height inconsistencies

Tide gauge in Amsterdam

Tide gauge in Marseilles



Gravity satellite data
→ ca. > 100 km spatial resolution

→ Clocks can serve as height references !

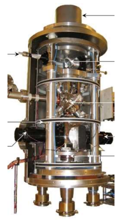
Bjerhammar, Boll. di Geodesia e Scienze Affini 185 (1975)
Vermeer, Rep. Finnish Geodetic Inst., 83 (1983)

Differences **European leveling network** (EUVN-DA) vs. Heights from GPS + **GOCE geoid**

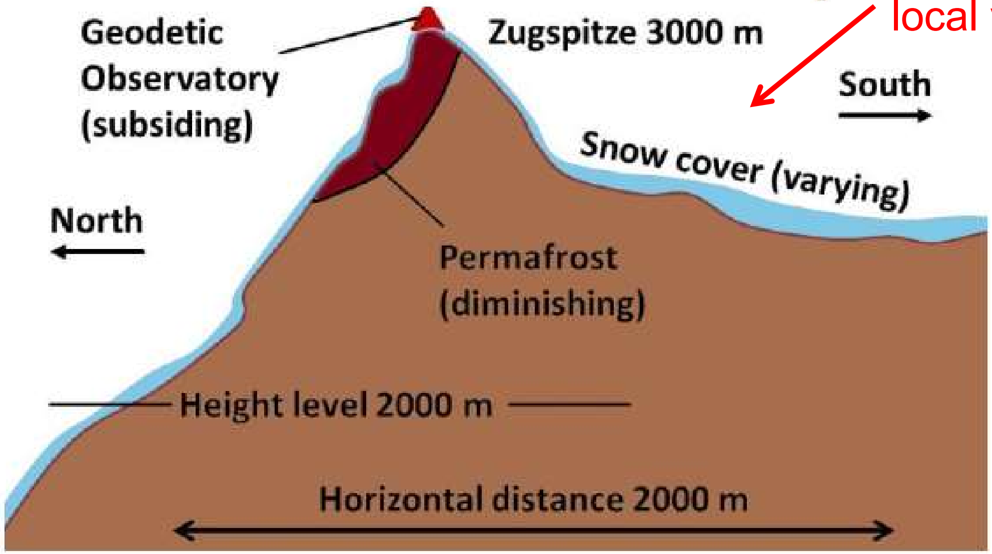
Gruber et al 2011
(GOCEplus study)

Examples for Geodetic Observations

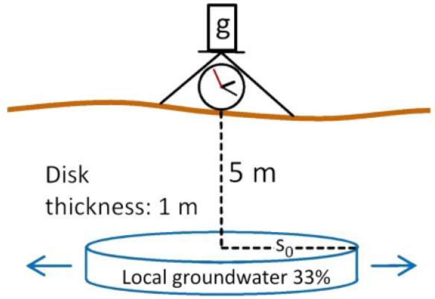
Clock: long-range 1/r :
height changes



Gravimeter: short-range $1/r^2$
local variations



Example: impact of groundwater body on gravity acceleration δg and gravitational potential δN

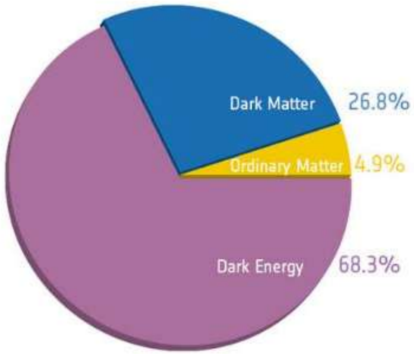


S_0 [m]	δg [nm/s²]	δN [mm]
10	77.1	0.0001
100	131.5	0.0014
1 000	137.7	0.0141
10 000	138.3	0.1400
100 000	138.3	1.3650
1 000 000	138.3	10.7170

Resolution of FG5 gravimeter: **10 nm/s² ≈ 10^{-9} g**

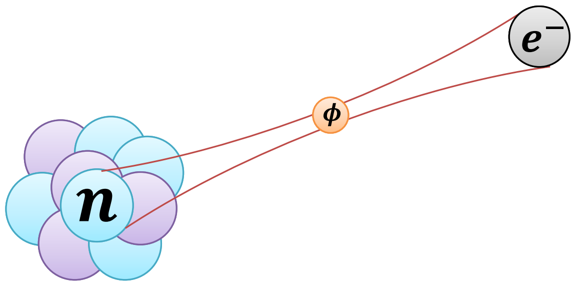
Signal due to height loss: **$\Delta g = 3 \times 10^{-9}$ g** per year
Signal due to snow cover changes: **$\Delta g = 50 \times 10^{-9}$ g** per year

Mehlstäubler *et al.*, „Atomic Clocks for Geodesy“, Rep. Prog. Phys. 81, 6 (2018)



Test of Fundamental Physics

$$V_{\mathrm{ne}}(r) = \hbar c \cdot \alpha_{\mathrm{NP}} \cdot \exp(-r m_\phi c/\hbar)/r$$



Isotope shift measurement in search for new boson

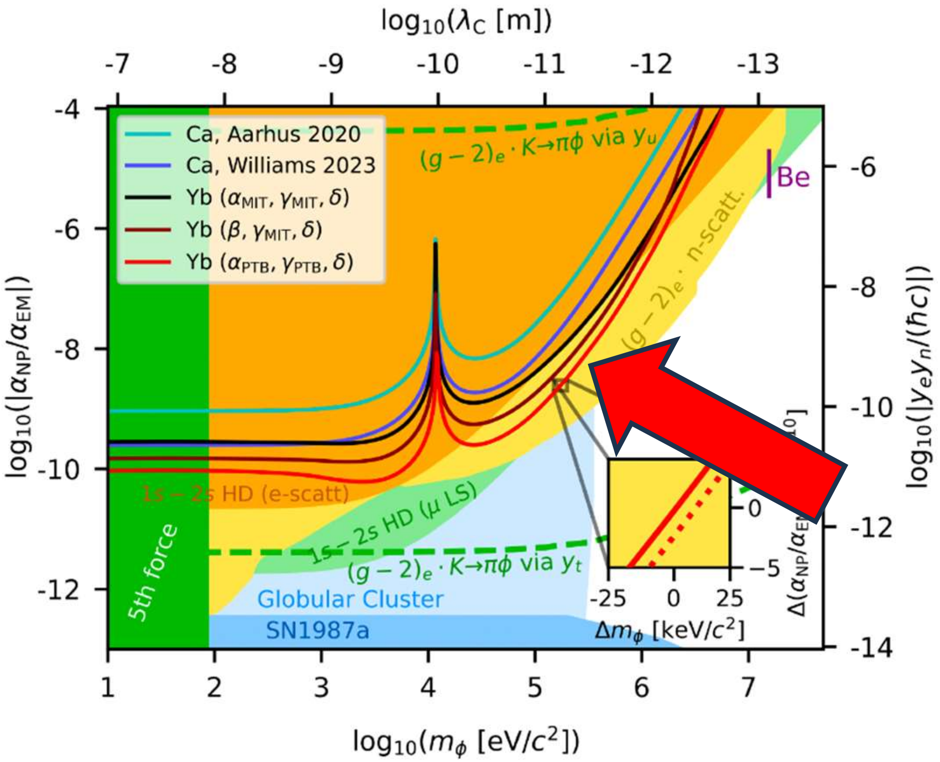
→ Search for 5th forces

5 stable even isotopes: Yb-168, Yb-170, Yb-172, Yb-174, Yb-176

Berengut *et al.,* Phys. Rev. Lett. 120.9 (2018)

New Bounds on Existence of a new Boson

Exclusion Plot with New Bound:



IS: linear in μ

Possible SM nonlinearities

$$\bar{\nu}_{\gamma}^{AA'} = f_{\gamma\tau} + K_{\gamma\tau}\bar{\mu}^{AA'} + G^{(4)}_{\gamma\tau}\overline{\delta\langle r^4\rangle}^{AA'} + G^{(2)}_{\gamma\tau}\overline{[\delta\langle r^2\rangle^2]}^{AA'}$$
$$+ v_{ne}D_{\gamma\tau}\bar{a}^{AA'},$$

Assuming that contribution of New Boson is smaller than observed 2nd source (of 23 σ)

$$\alpha_{\mathrm{NP}} = (-1)^{s+1} y_n y_e / (4\pi\hbar c)$$

is the product of the coupling constants y_n and y_e of the new boson (with mass m_ϕ and spin s)

$$V_{\mathrm{ne}}(r) = \hbar c \cdot \alpha_{\mathrm{NP}} \cdot \exp(-r m_\phi c/\hbar)/r$$

Door *et al.*, Phys. Rev. Lett., 134, 063002 **(2025)**

New Window into Nuclear Physics

Ab initio computations of the fourth-order charge density moments of ^{48}Ca and ^{208}Pb

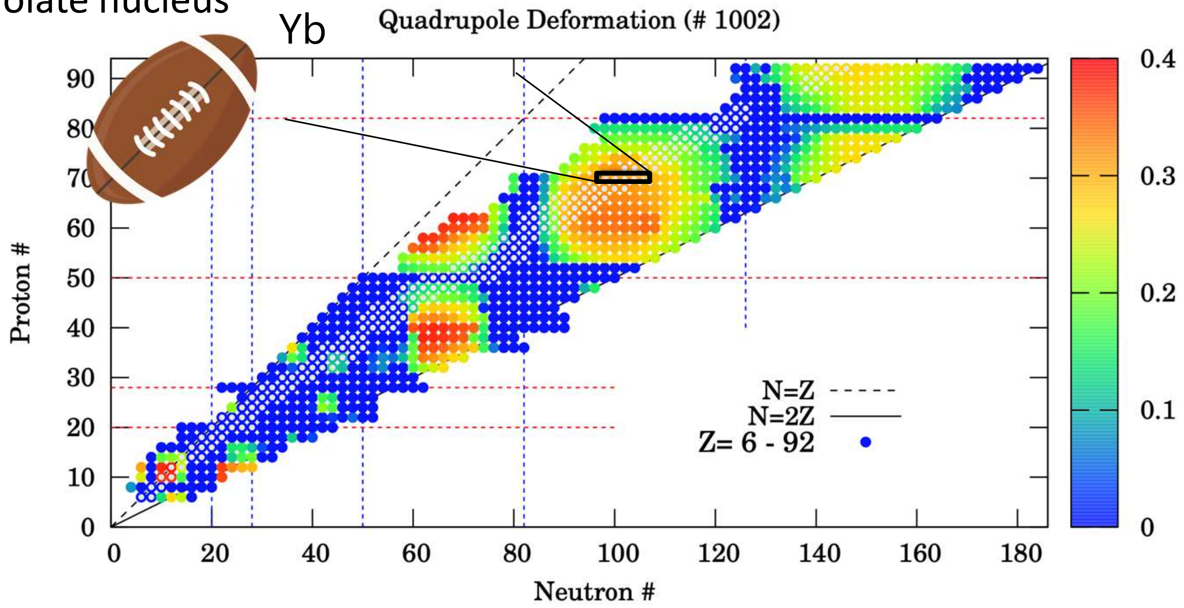
T. Miyagi[a], M. Heinz[b,c], A. Schwenk[d,e,f]

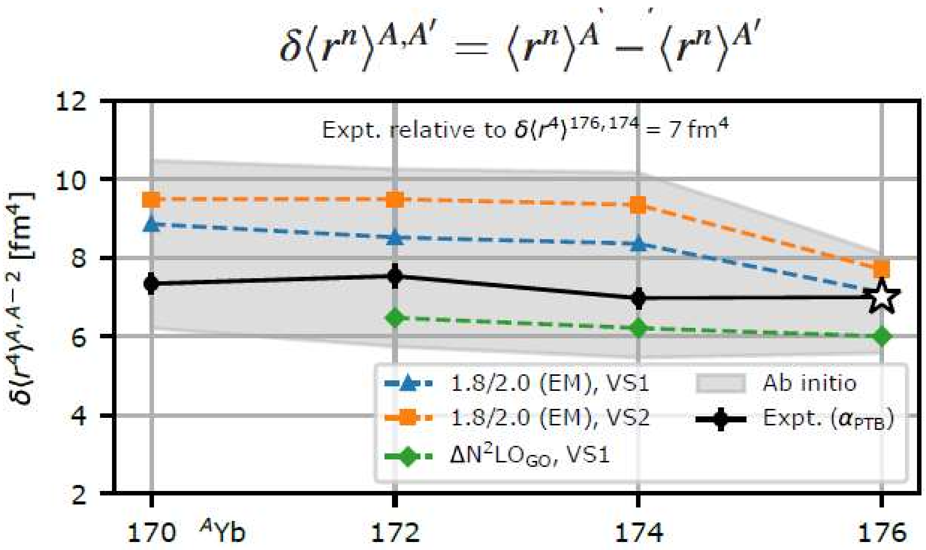
arXiv:2508.10767

[a]Center for Computational Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8577, Japan
[b]National Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

→ Neutron skins of neutron-rich nuclei provide crucial insights into the properties of neutron-rich nucleonic matter, constraining the equation of state of neutron star matter around saturation density.

Prolate nucleus





→ **Nuclear Theory:**

microscopic description of Yb nuclei starting from chiral effective field theory interactions based on Q-chromodynamics

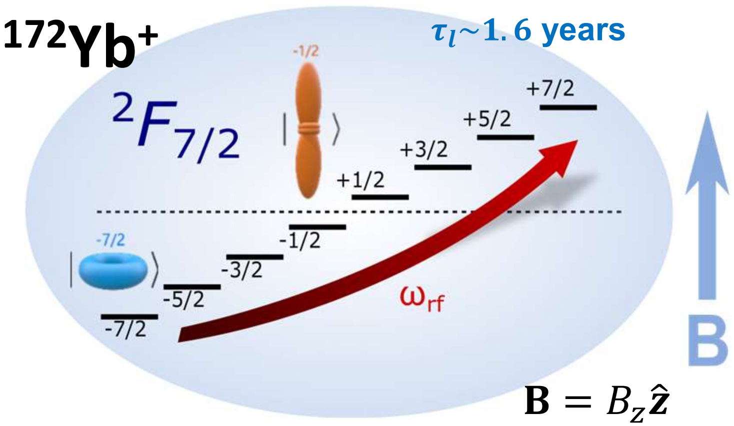
Testing local Lorentz invariance with an $^{172}Yb^{+}$ ion

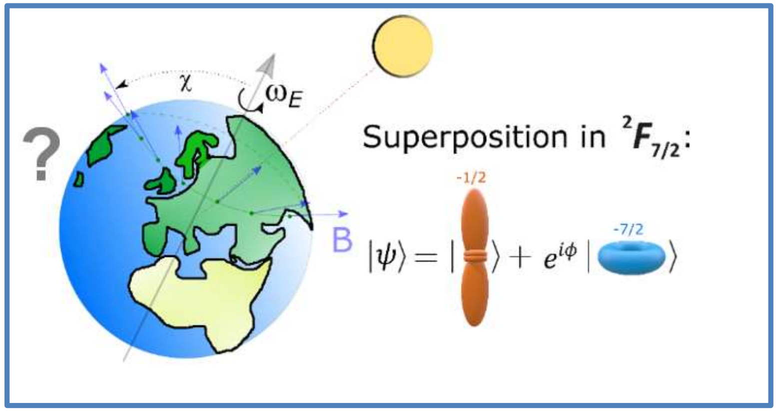
Laura S. Dreissen, Chih-Han Yeh, Henning A. Fürst, Kai C. Grensemann and Tanja E. Mehlstäubler

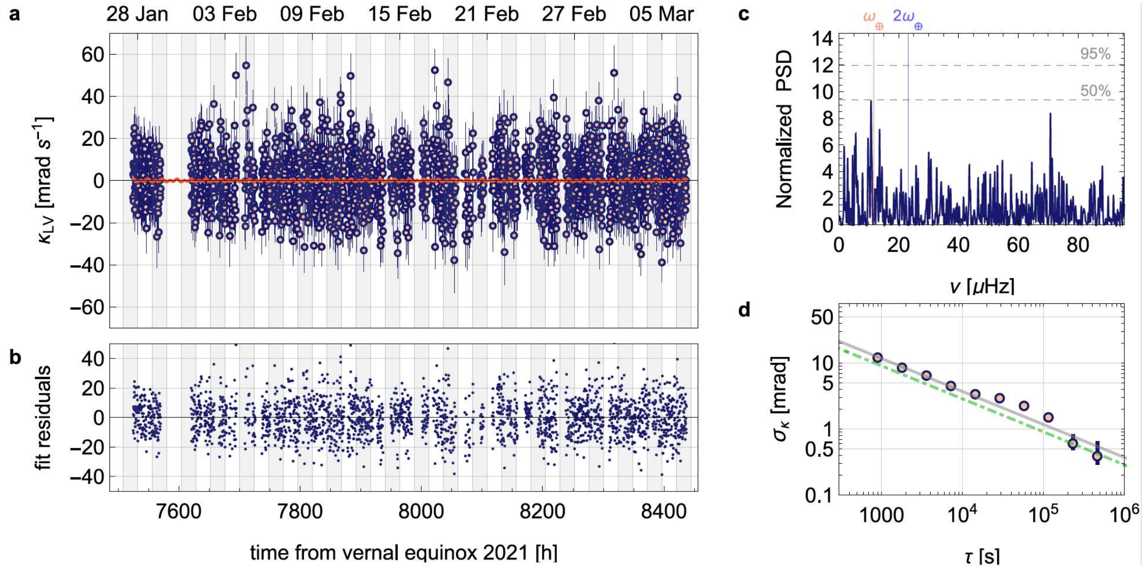
<u>New limit in electron-photon sector at 10^{-21} level</u>

Nat. Commun. 13 (Nov. 2022)

Testing local Lorentz invariance (LLI) with $^{172}Yb^+$ at 10^{-21}







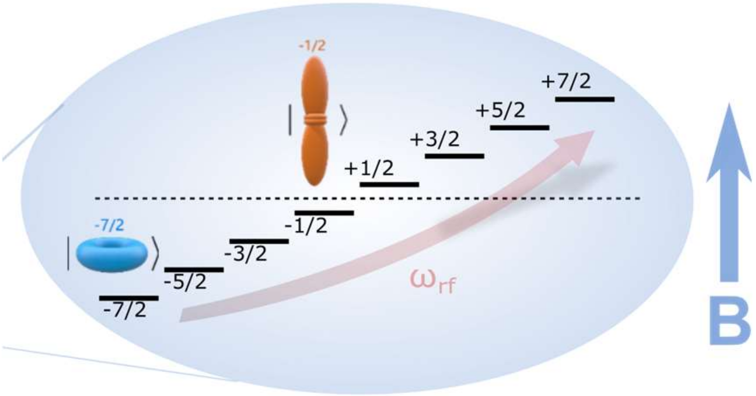
Correlated LV parameters	Measurement time: 2.2×10^6 s
c_{X-Y}	$(-5.2 \pm 7.8) \times 10^{-21}$
c_{XY}	$(4.4 \pm 3.9) \times 10^{-21}$
c_{XZ}	$(-5.0 \pm 9.3) \times 10^{-21}$
c_{YZ}	$(6.3 \pm 8.9) \times 10^{-21}$

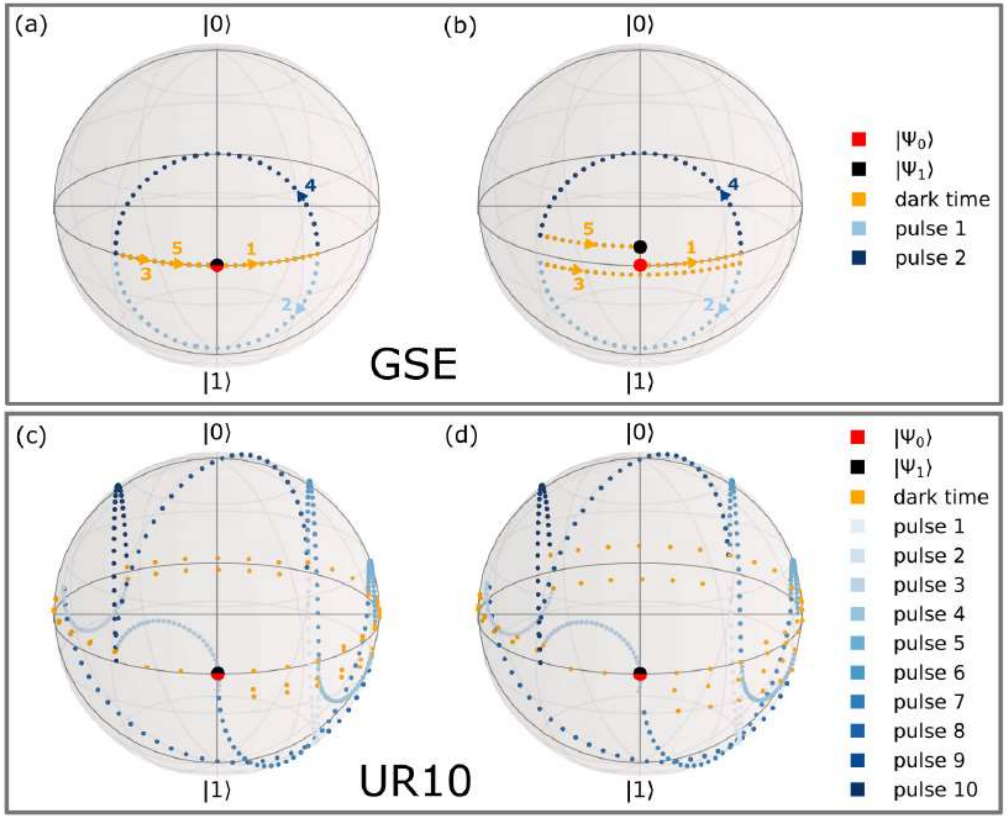
World leading Bound

Dreissen, Yeh, Fürst . *et al. Nat Commun* **13**, 7314 (2022)
Yeh *et al., New J. Phys.* **25** 093054 (2023)

Ramsey spectroscopy

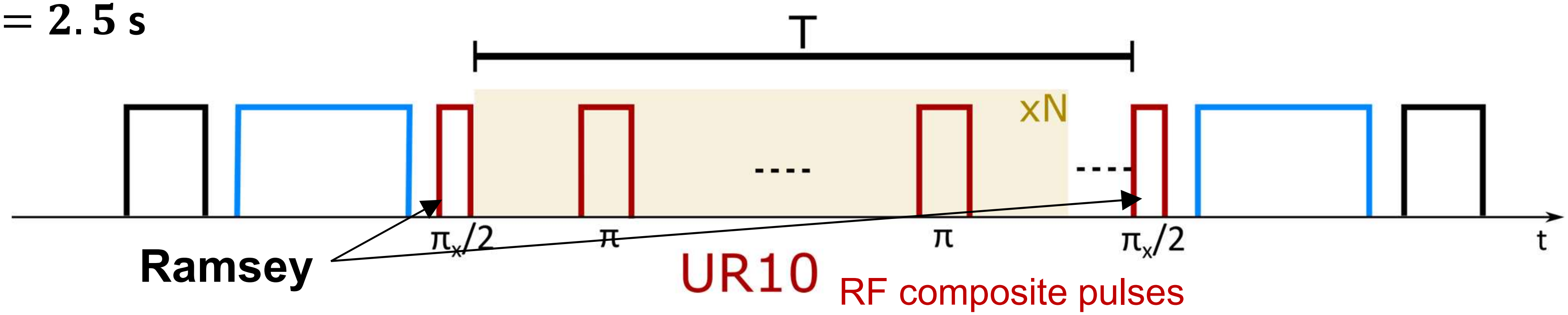
Composite pulse sequence to suppress B-field noise
(1st oder Zeeman sensitivity)





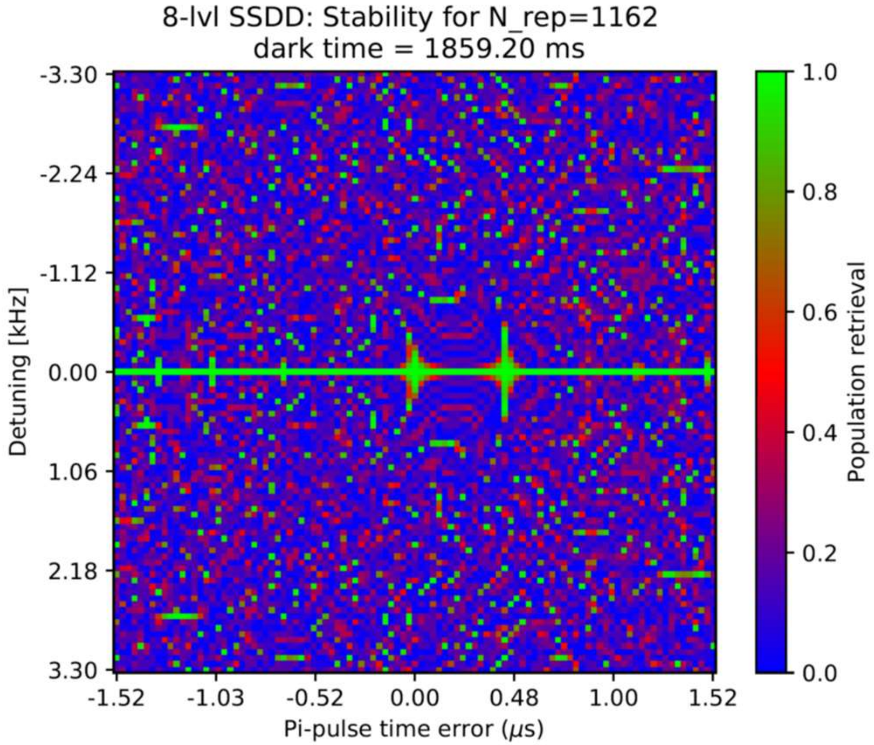
Gain a factor 10,000 in coherence time

$\rightarrow \boldsymbol{T_{Dark} = 2.5}$ **s**

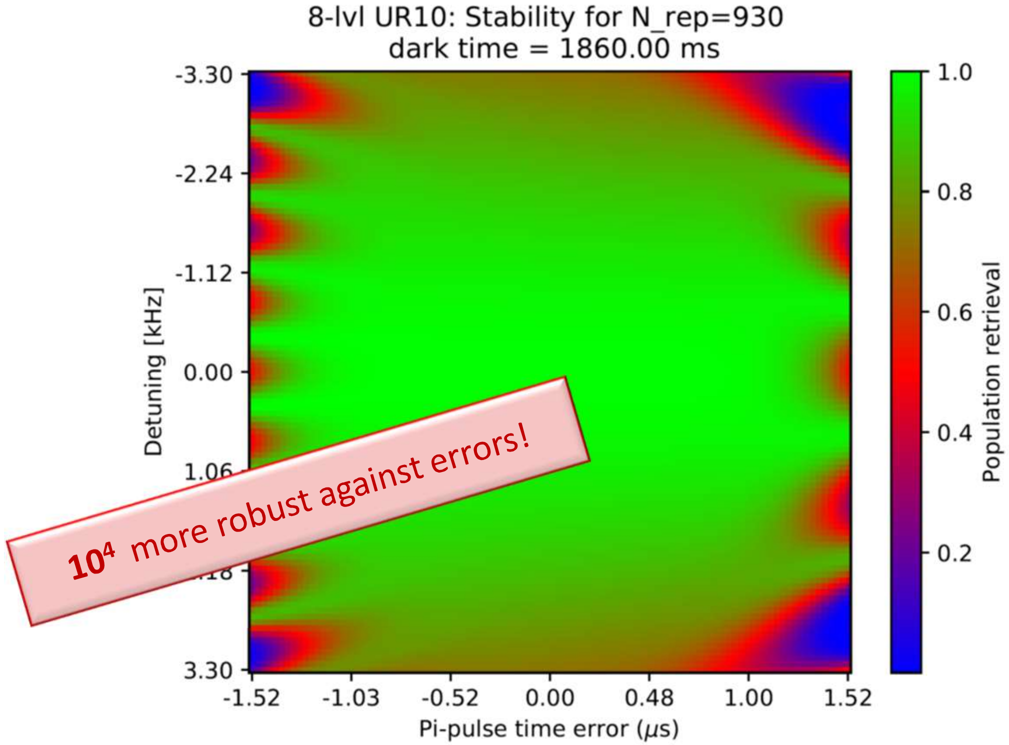


Stability diagram UR10

Simple spin-echo scheme



UR 10 sequence:
$(\mathbf{0,4,2,4,0,0,4,2,4,0})\mathbf{4\pi/5}$



F > 0.85 is reached for |ηω| < 0.03 for a fixed pulse duration error |ηt | = 0.004

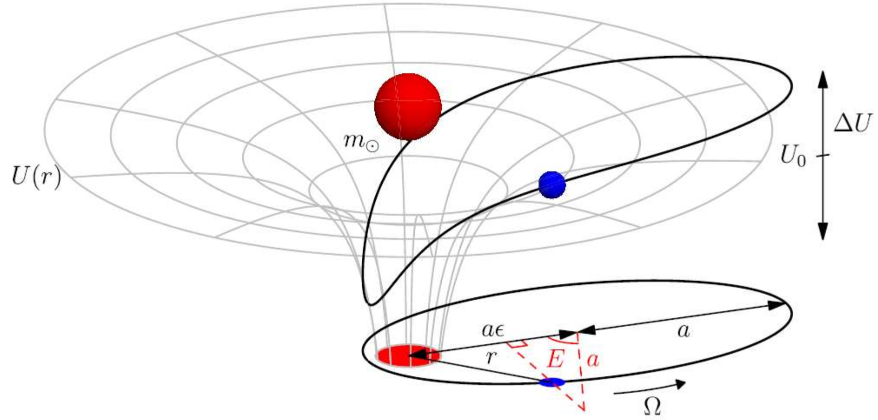
G. T. Genov *et al.,* Phys. Rev. Lett. 118, 133202 (2017)

Ch.-H. Yeh *et al.,* NJP (**2023**)

Test of General Relativity with Atomic Clocks in the Lab

Local Position Invariance (LPI)

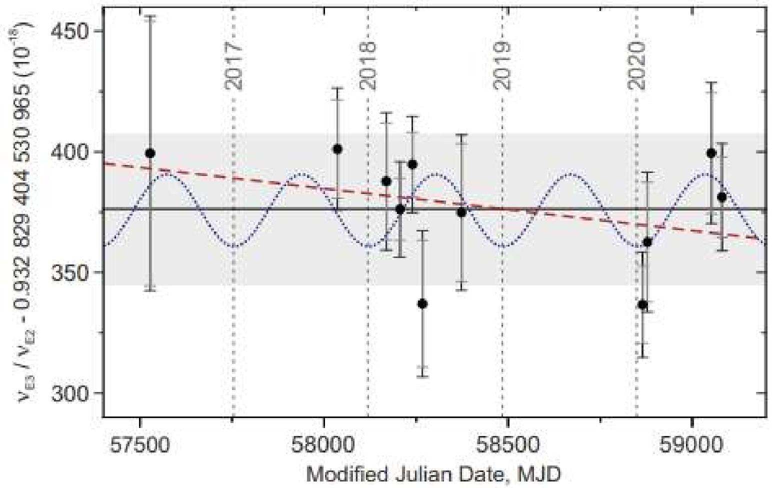
Do natural constants depend on the gravitational field of the Sun?



Annual Orbit of Earth through Gravitational Potential of Sun:
$\Delta U/c^2 \approx 10^{-10}$

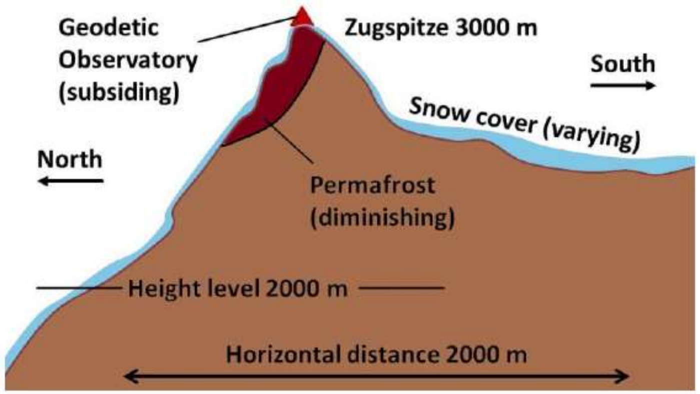
$$c^2/\alpha\left(\frac{d\alpha}{d\Phi}\right) = 14(11) \times 10^{-9}$$

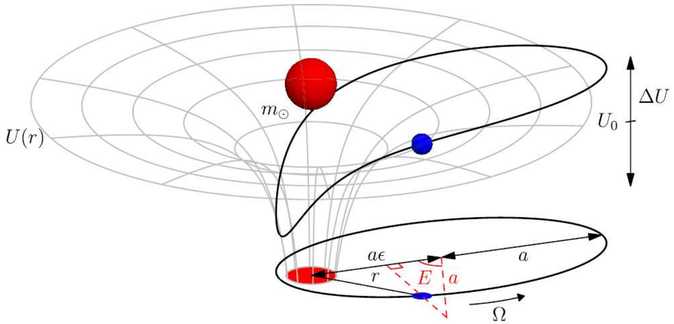
$$c^2/\mu\left(\frac{d\mu}{d\Phi}\right) = 7(45) \times 10^{-8}$$

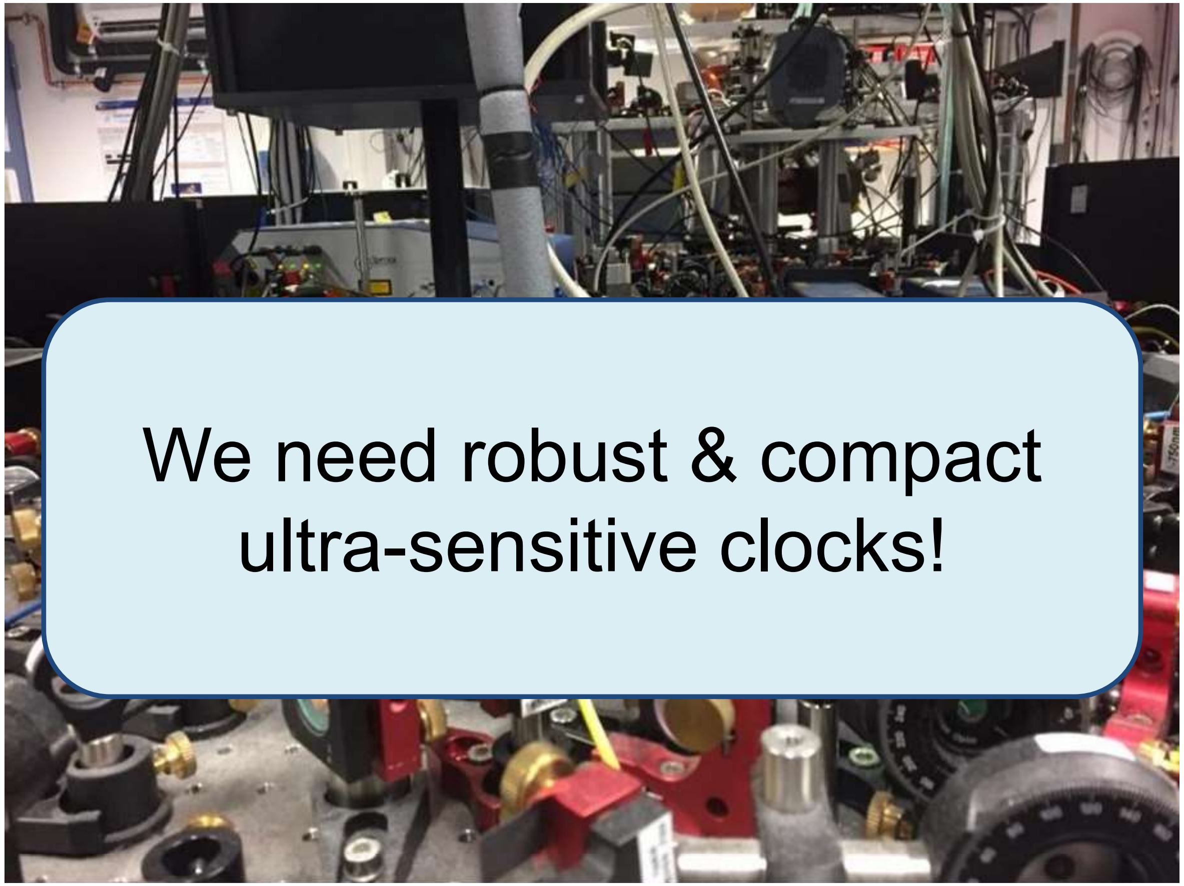


V. V. Flambaum and A. F. Tedesco, Phys. Rev. C 73 (2006)
S. Blatt et al., Phys. Rev. Lett. 100, 140801 (2008)
R. Lange et al., Phys. Rev. Lett 126, 011102 (2021)

Typical Clock Setup in Laboratory

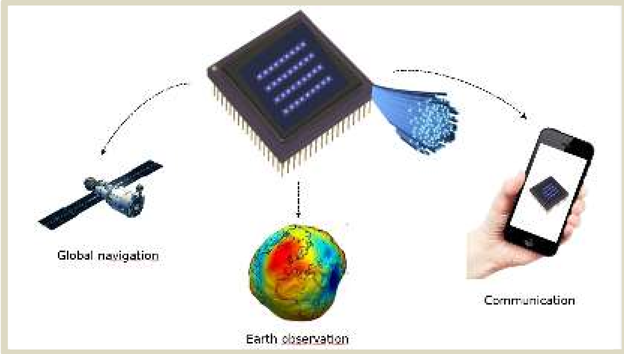




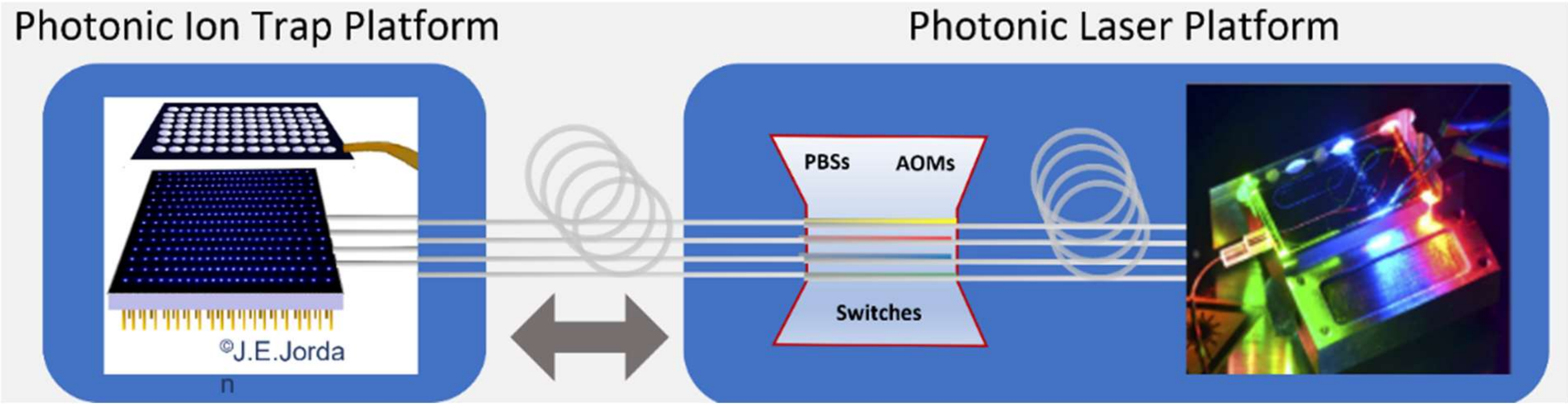


We need robust & compact ultra-sensitive clocks!

Photonic Integrated Systems – „Clock on a Chip“



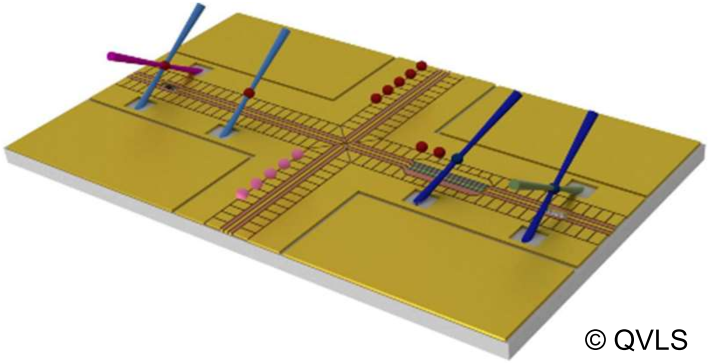
Our Vision



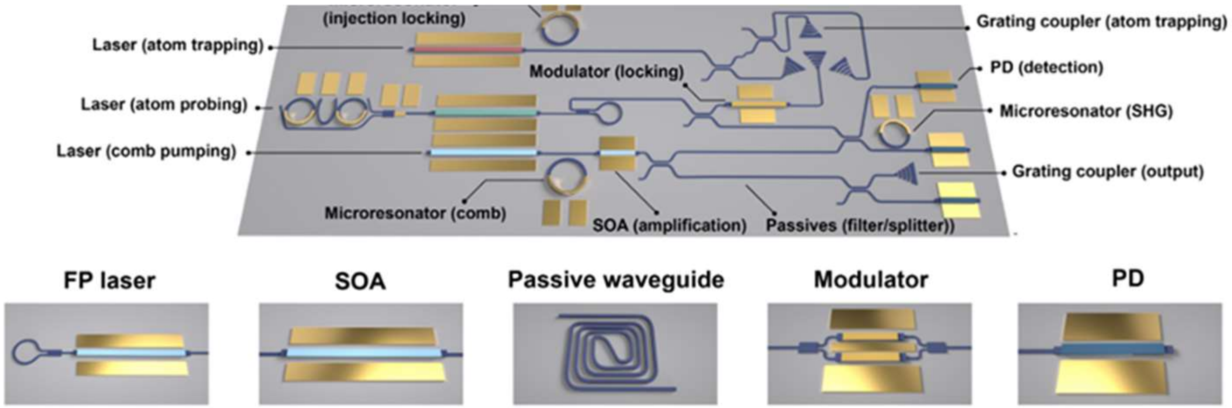
1000 ions in 2D array

Requirements for scalable trapped ion clock & quantum computer

- **Integrated ion traps**



- **Integrated active and passive nanooptics elements**

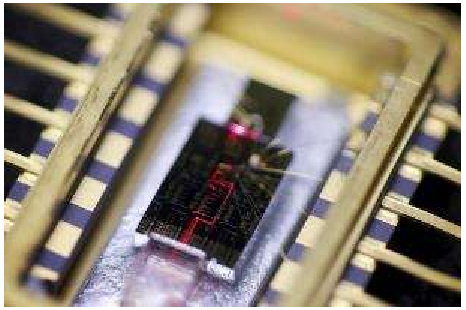


Tran, M. A., et al., "Extending the spectrum of fully integrated photonics," arXiv:2112.02923 (2021)

PhoeniX D
Photonics · Optics · Engineering
Innovation Across Disciplines

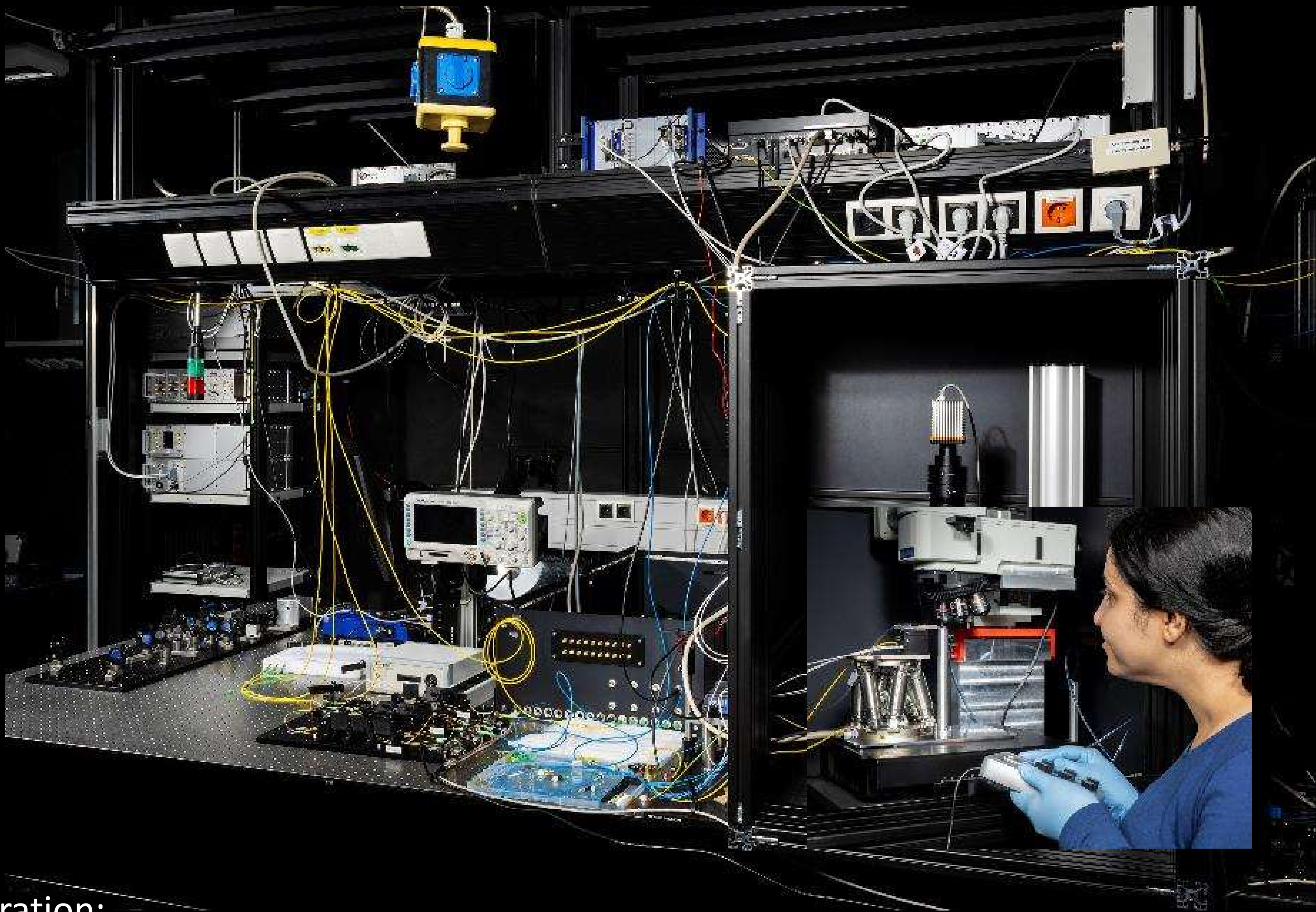
Qu-PIC

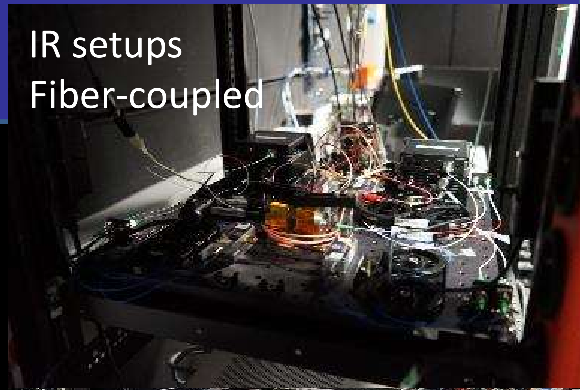
CHAMP-ION
The European Ion Trap Pilot Line

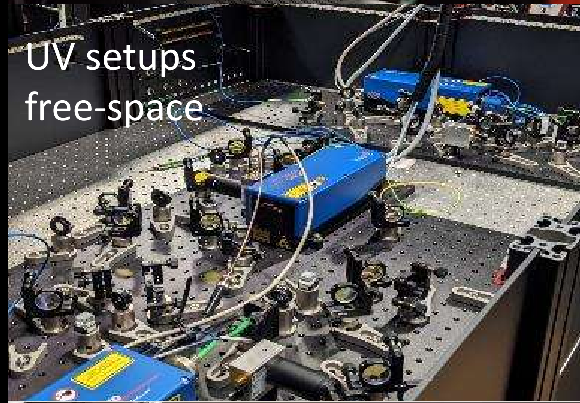


picmagazine.net/article/113573/
Chilas_to_reveal_new_external_cavity_laser

Setup for Characterization of PICs (370-1650nm)



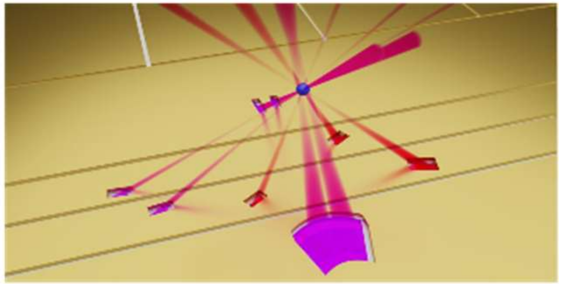


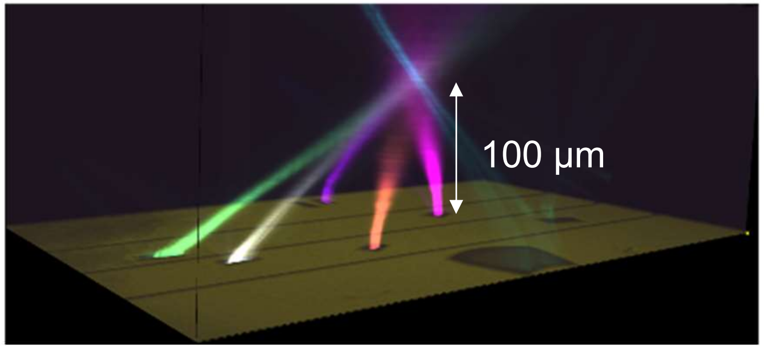


Collaboration:
K. Mehta (Cornell), S. Garcia Blanco (Twente), AMO, Aluvia, Infineon, Toptica, …

First ion trap with all integrated laser paths, 370 – 1650 nm

a) 

b) 

c) 

Measurement →

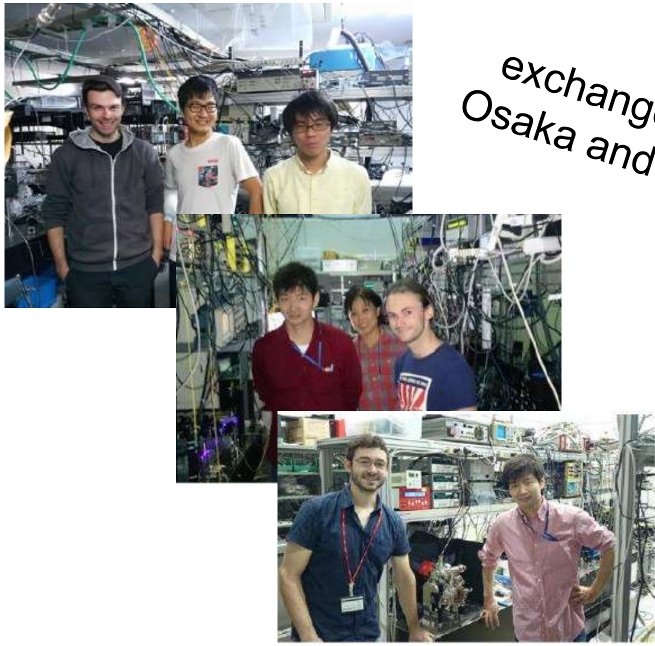
Measurement setup

a) Photonic integrated ion trap chip (PIC) for Yb^+ ions (made by LioniX).
b) Scheme of surface trap with waveguides and Bragg grating couplers made of Si_3N_4 (170 nm) and Al_2O_3 (120 nm) for UV to IR wavelength
c) measured 3D-beam-tomography of laser beams from 370 nm to 1650 nm

LioniX INTERNATIONAL

Collaboration: K. Mehta (Cornell), G. Beck (ETH)

The Team “Quantum Clocks and Complex Systems”



exchange with Osaka and Tokyo

Int. Collaborations:
NICT Toyko (J)
University of Osaka (J)
CMI (Prag, Cz)
W. Zurek (Los Alamos NL)
Julian Berengut (Uni Sydney, Au)
Jacinda Ginges (Brisbane, Au)
…

Visiting scientists:
V. Yadav, R. Pal (Tirupati, IN)
R. Singh (Sekim, IN)
N. Ohtsubo (NICT, Tokyo)
M. Kitao (Osaka University)
M. Doležal (CMI, Prag)
…

Industry Partners:
Grintech (Jena)
Naneo (Lindau)
D&G (Stuttgart)
Toptica (München)
Allectra (Berlin)
Infineon (Munich)
…

TRIAC

International Joint Laboratory for Trapped-Ion Integrated Atomic-Photonic Circuits

DFG

EURAMET
European Association of National Metrology Institutes

TC FS

Bundesministerium für Bildung und Forschung

mat

QF

PhoeniXD
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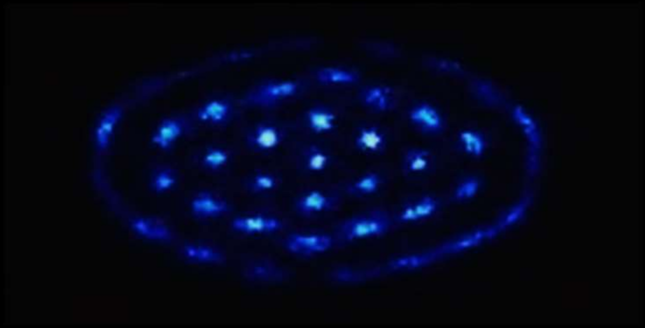
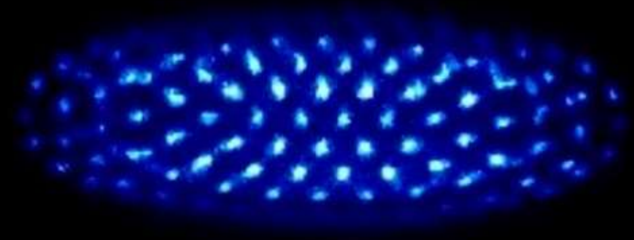
Innovation Across Disciplines





Thank you for your attention

Acknowledged support and cooperation regarding clock campaigns:

- Stefan Weyers, Johannes Rahm, Erik Benkler, Burghard Lippardt, Thomas Legero (**PTB**)
- Miroslav Dolezal and Petr Balling (**CMI**)
- **Sr-lattice clock and $^{171}Yb^{+}$-single ion team at PTB**