Atomic Clocks for Geodesy & Test of LLI

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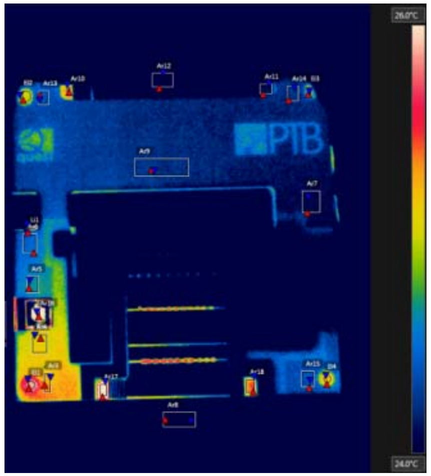


Fundamental Physics in Space – Bremen
October 25th, 2017

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Why better and better clocks?

- Tests of Fundamental Physics:
  LPI, LLI, constancy of natural constants, ...
- Applications such as navigation & geodesy

Overview of this Talk

- Geodesy with Atomic Clocks
- Development of Multi-Ion Clocks
- Testing Local Lorentz Invariance with Ions

I. Geodesy with Atomic Clocks

Carl Friedrich Gauß

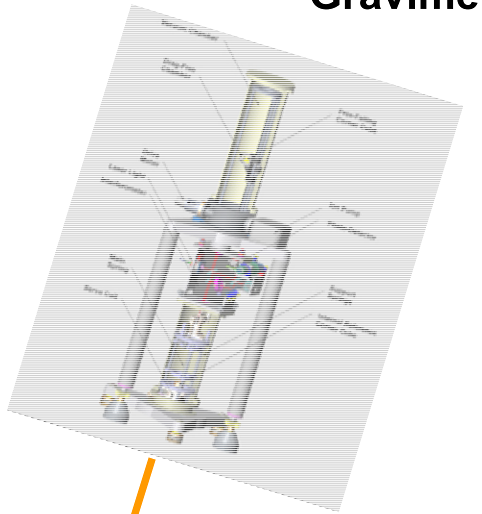
describes first the “Erdfigur” (geoid)

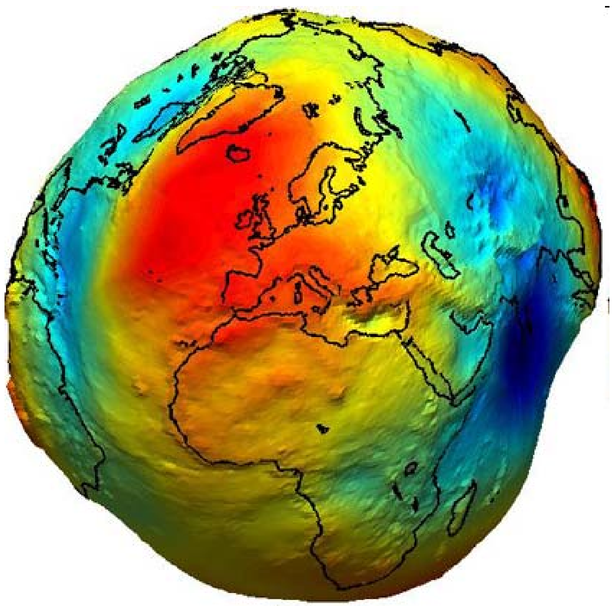
Foto: Braunschweig Stadtmarketing GmbH/Gerald Grote

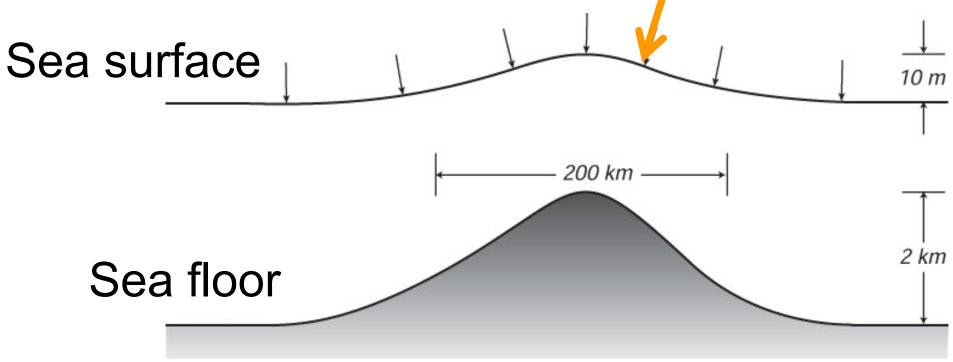
The Earth‘s Geoid

- equipotential surface, shape water would take at rest under Earth‘s gravity and rotation
- deduced from extensive gravitational force measurements and calculations
- uncertainty of geoid before GRACE: 30 – 50 cm

Falling Corner Cube Gravimeter







The Earth's Geoid

- equipotential surface, shape water would take at rest under Earth's gravity and rotation
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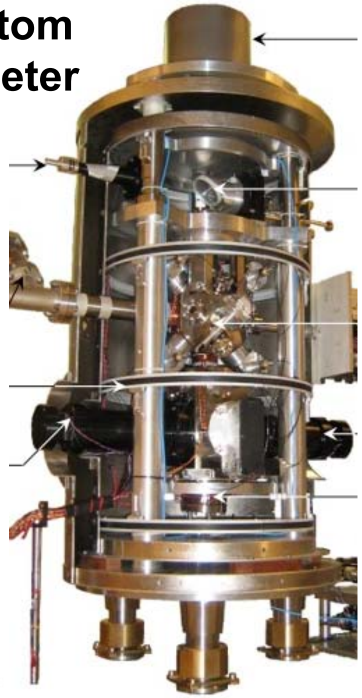
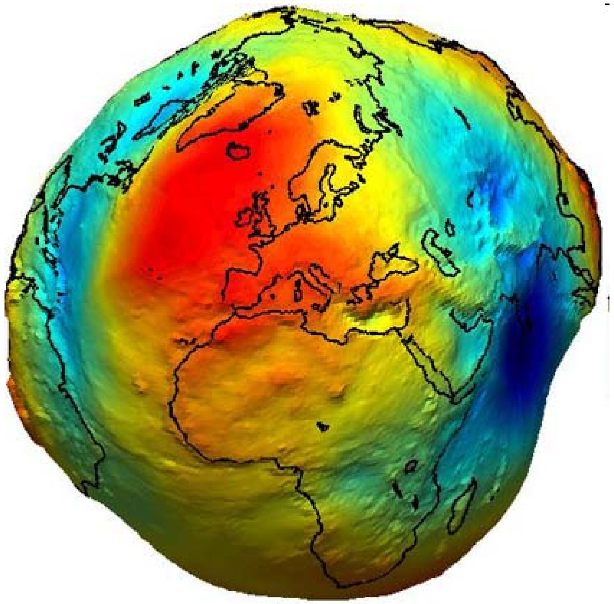
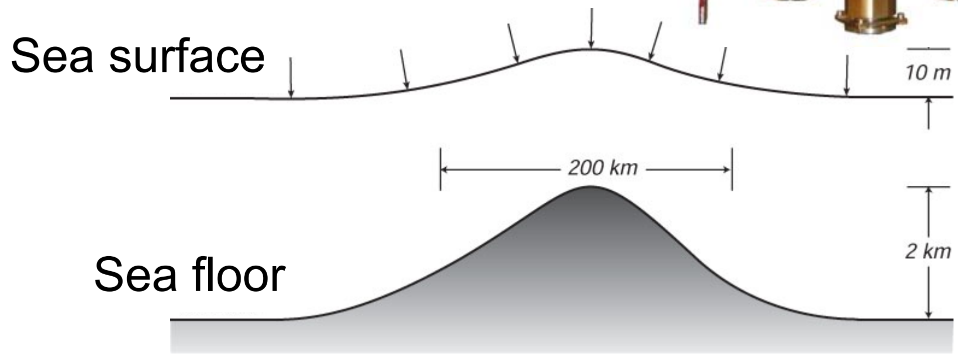
Cold Atom Gravimeter

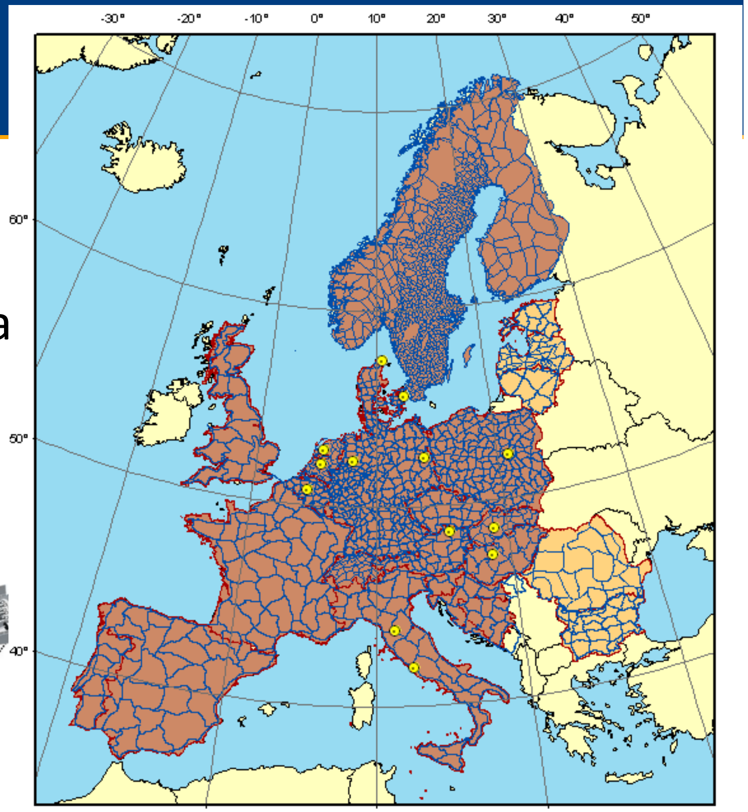




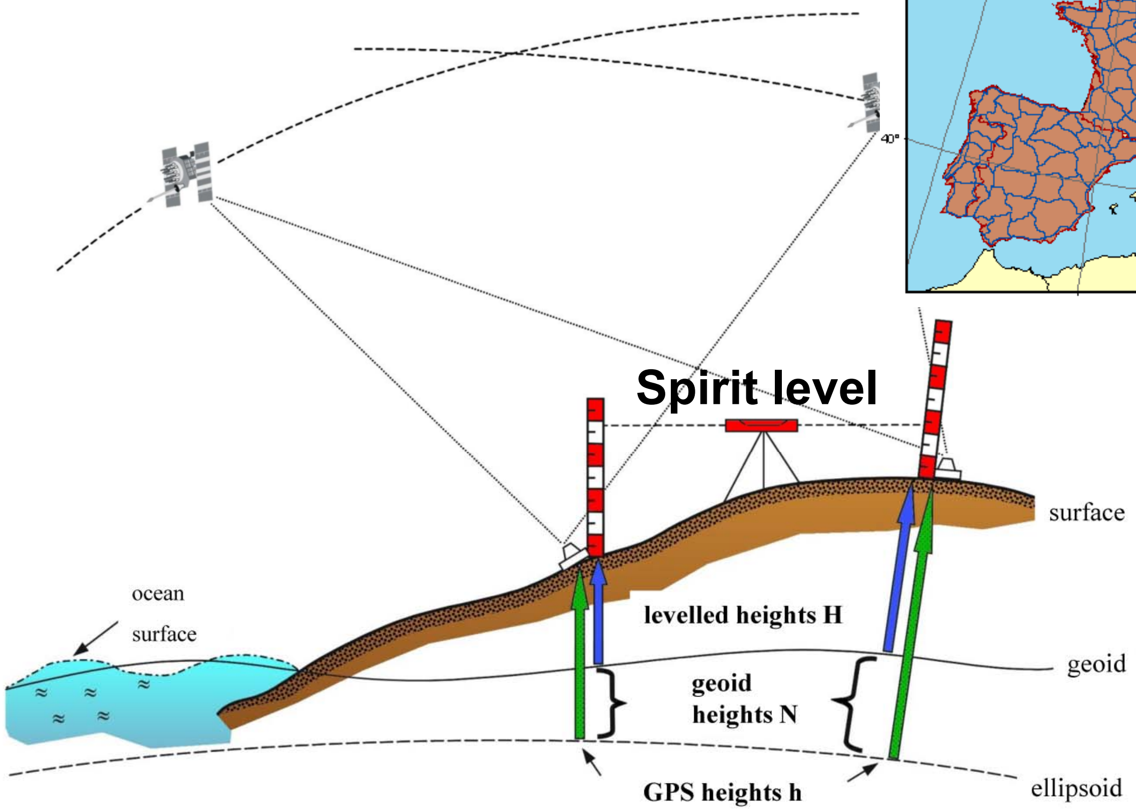


Classical Levelling & Heights

- < 1 mm accuracy at distances < 1 km !
- **accumulation of errors** (10s cm) over large dista
- **tide gauges** as rather **arbitrary reference**

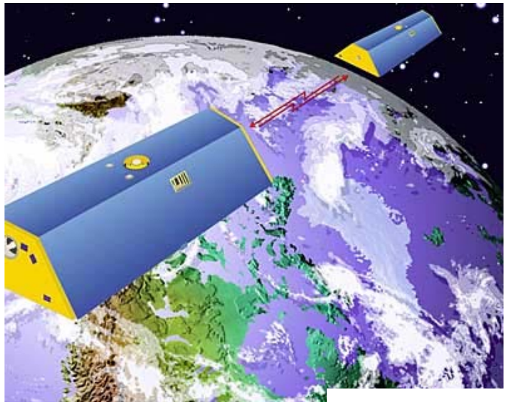


UELN 2008, source: BKG

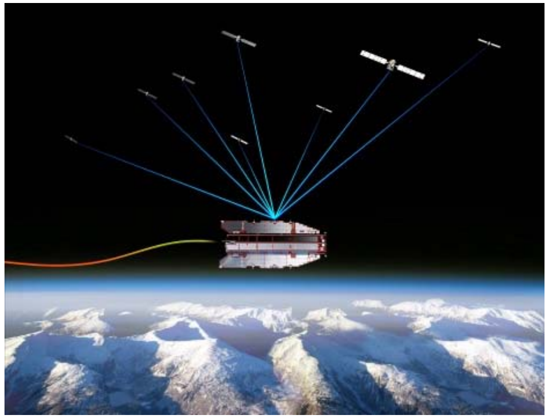


Satellite Gravimetry

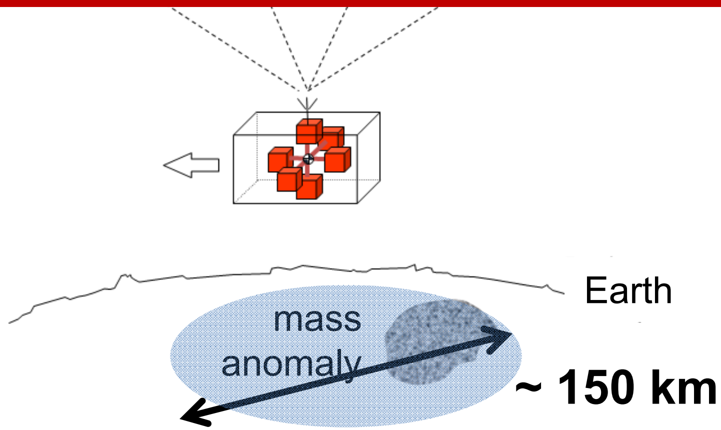
GRACE: MW inter-satellite ranging, since 2002



GOCE: gradiometry with electrostatic accelerometers, 2009 – 2013



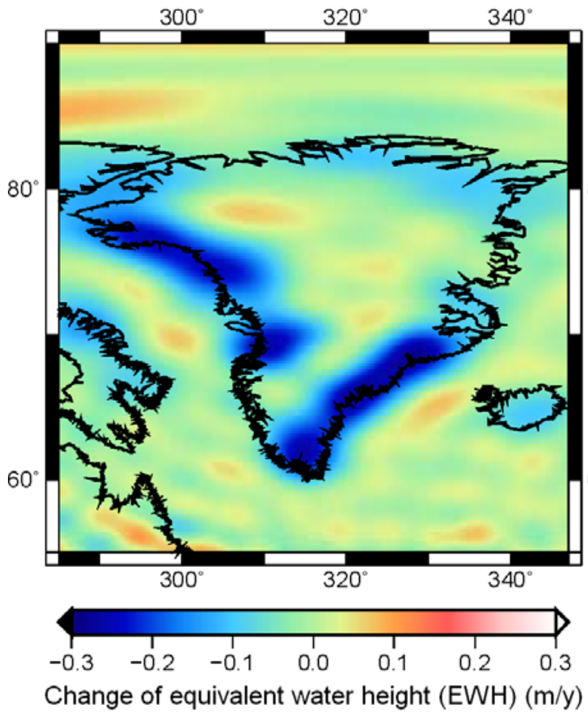
Challenges: modelling, different filtering, references,...

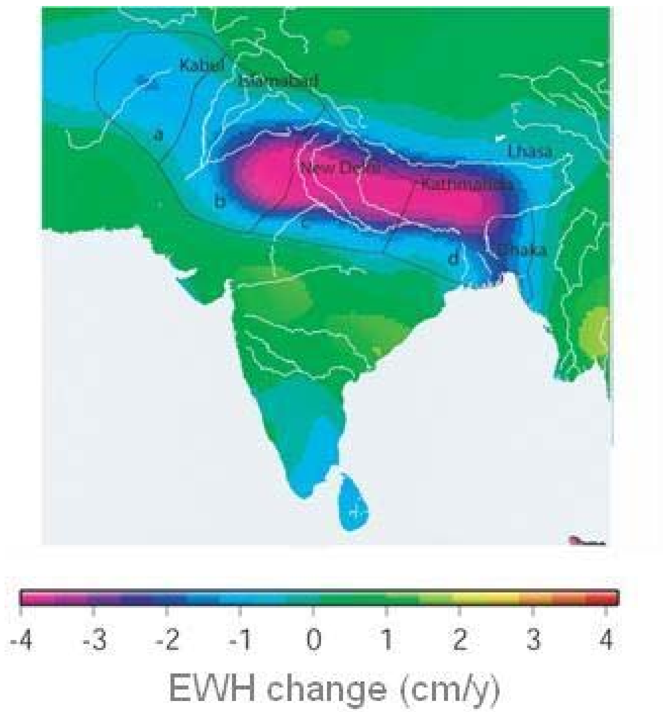


The Earth‘s Geoid

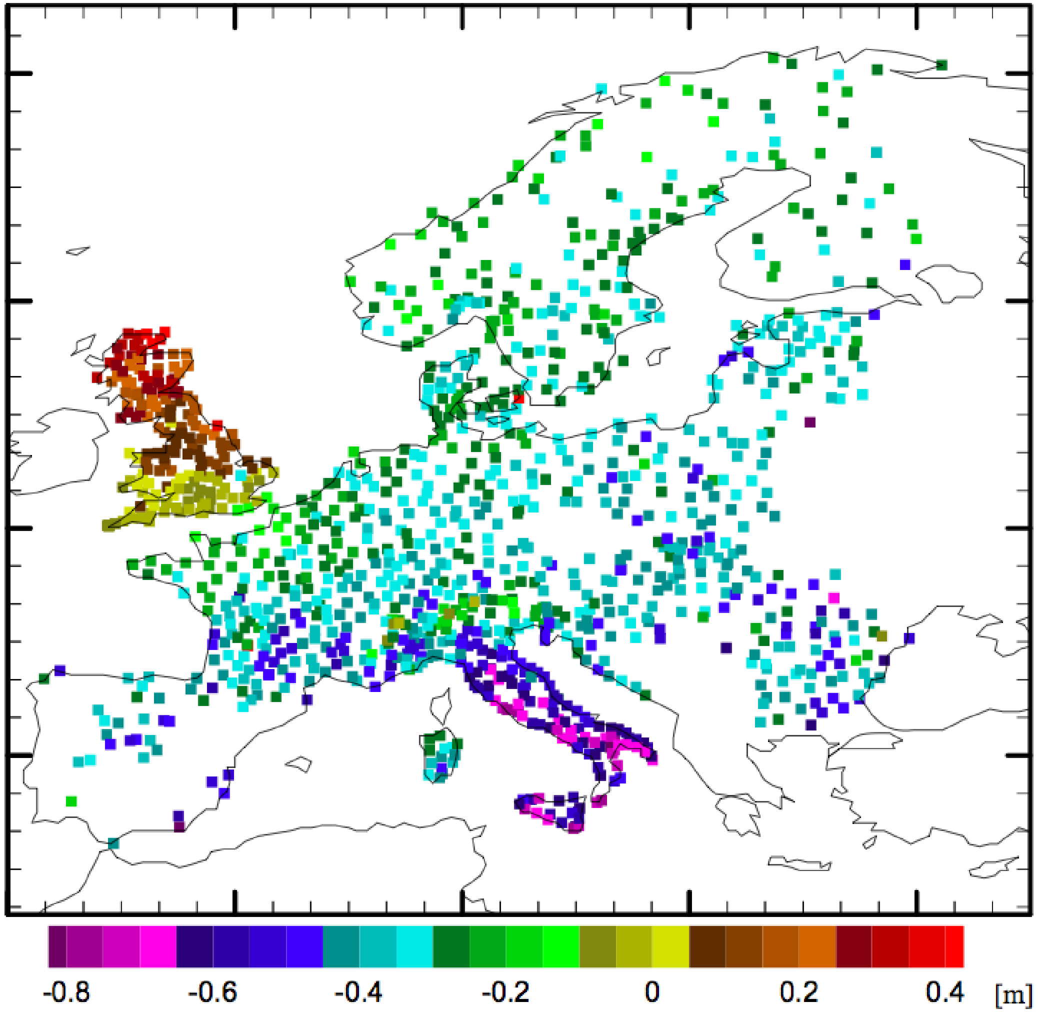
Precise knowledge of Geoid is necessary to determine:

- Change of ocean currents
- Convection in mantle – drives continental drifts
- Global & local mass variations
  (e.g. ground water level, melting of glaciers, post-glacial uplift,..)





Height inconsistencies



Today: 2 - 3 cm ?

Gruber et al 2011
(GOCEplus study)

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

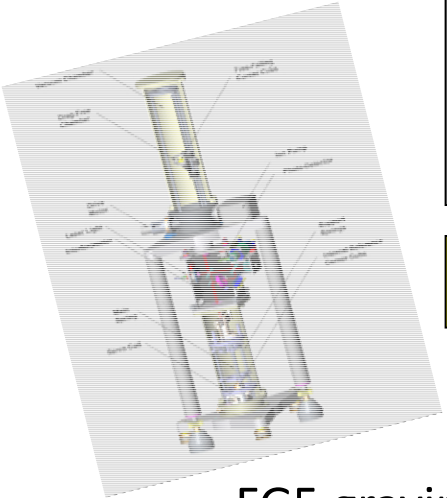
Clocks as Quantum Sensors for Geodesy

$= 0 \pm 10^{-4}$

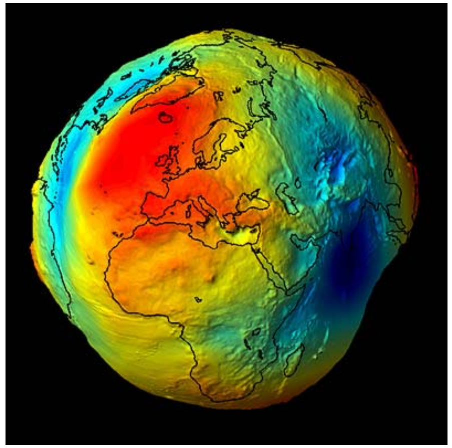
Gravity red-shift

$$Z \equiv \frac{\Delta\upsilon}{\upsilon} = (1+\alpha)\frac{\Delta U}{c^2}$$

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



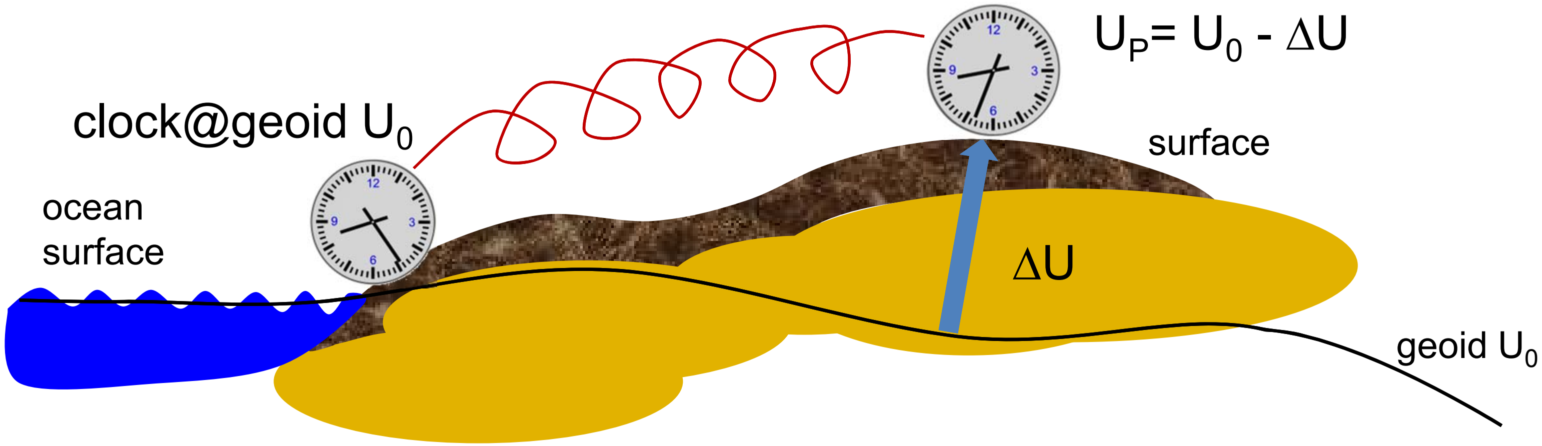
FG5 gravimeter



Earth's geoid/ESA

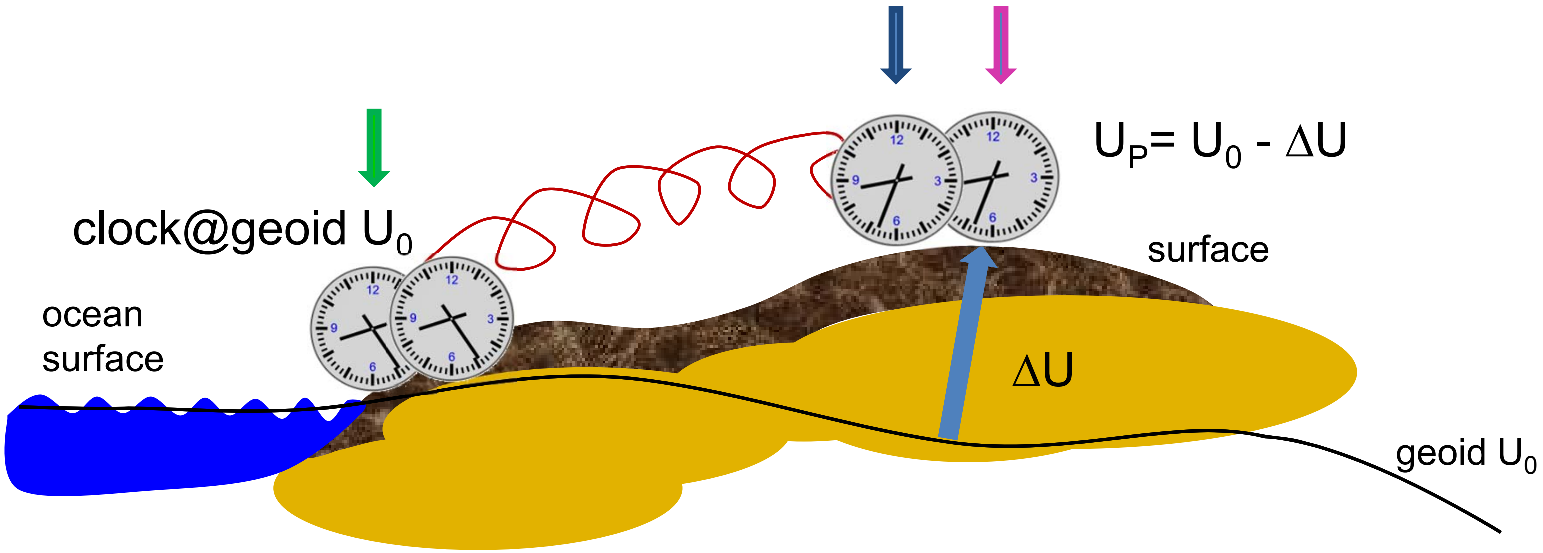
Vermeer, Reports of the Finnish Geodetic Institute **83(2)**, 1(1983); Bjerhammar, Bull. Geodesique **59**, 207 (1985)

Chronometric Levelling



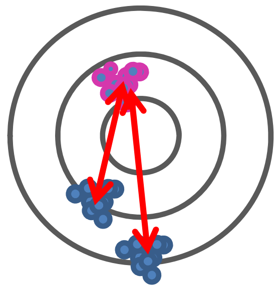
- relativistic frequency change: $Z \equiv \frac{\Delta \upsilon}{\upsilon} = \frac{U_O - U_P}{c^2}$
- gravity potential U : Newtonian + centrifugal terms
- height: $H_P = \frac{U_O - U_P}{\bar{g}} = \frac{c^2}{\bar{g}} \frac{\Delta \nu}{\nu}$
- curvature of **space-time** now relevant at the **cm level** on Earth surface (corresponding to $\Delta\nu/\nu$= **10^{-18}**)

→ Portable clocks are needed!



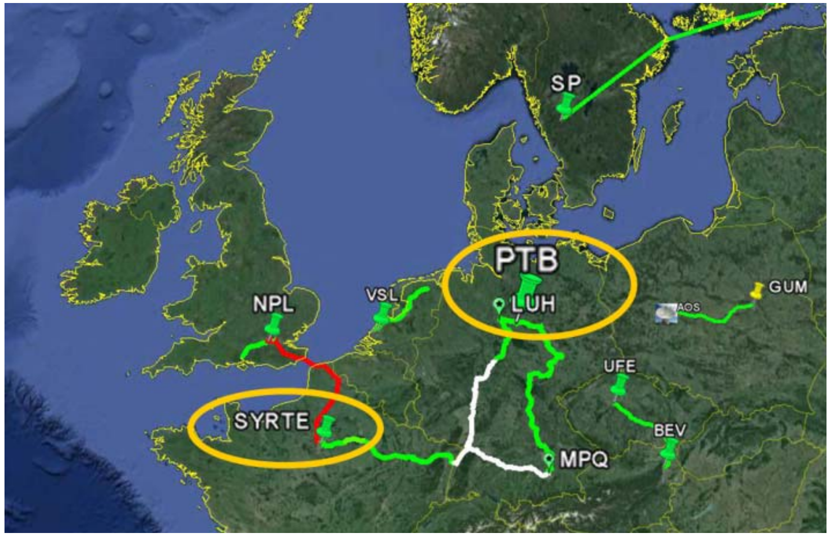
- Portable clocks require reproducability, not accuracy!

→ calibrate against stationary clock!



What is needed to contribute to geodesy?

- High stability links for frequency transfer $\sigma_y/f < 10^{-18}$ ✓
- Portable optical clocks
- Optical satellite links !
- Clocks with reproducability of 10^{-18} and better!
- Clocks with short averaging times
- From theory side: practical models for a relativistic geoid



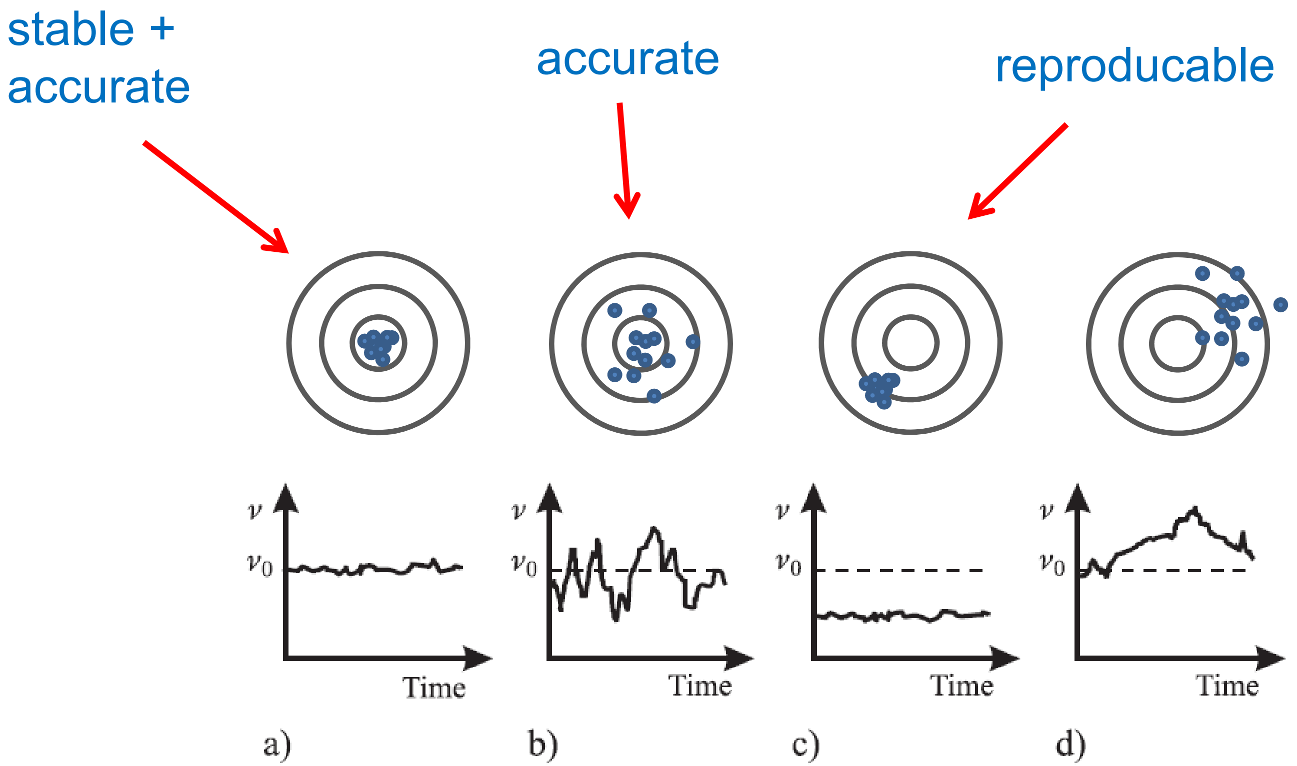
What do present clocks need to reach the 10^{-18}

... and beyond?

Terminlogy: Stability versus Accuracy

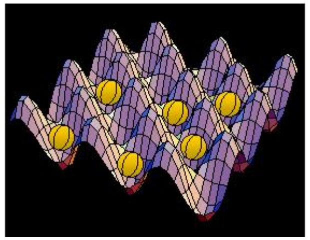
accuracy = the frequency deviation from its true value

i.e. **the unperturbed center** of the atomic transition (atom at rest, T = 0 K)



Riehle, Frequency Standards, Wiley VCH 2004

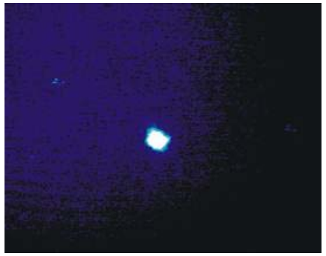
Neutral atoms & single ion clocks



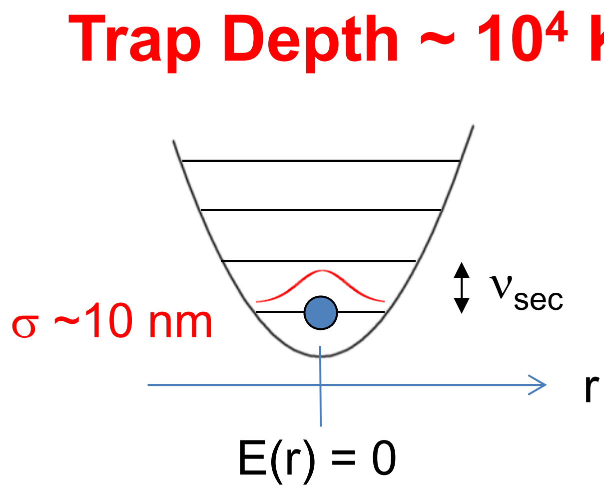
	Optical ion clocks		Optical lattice clocks	
Number of atoms	$N = 1$		$N = 10^3 – 10^4$	
Advantages	**High level of control** + Low polarizability		**High stability**	
Systematic effects	Motional Shifts 2/3 of uncertainty budget of best clocks!		Residual lattice light shift Collisions Black body radiation shift $\sigma_{Temperature}$ = **mK** needed!	
BBR shift $\Delta\nu/\nu$ @ 300 K	Al^+: -3×10^{-18}	In^+: -1×10^{-17}	Sr: -5×10^{-15}	Hg: $-1{,}6\times10^{-16}$

High Accuracy of Single Ion Clocks:

3D-Paul trap



single Yb^+-ion



- ions are trapped in minimum of EM-field !
- high level control of single ion
- low collision shift
- storage times up to days/months !
- relative simple and compact setup

Huntemann et al., PRL 2016: Yb^+ ion clock: $\Delta\nu/\nu$ = **3.2 x 10^{-18}**

Stability: how well can we resolve a frequency

$$\sigma_y \approx \frac{1}{Q} \cdot \frac{1}{\sqrt{N_A}} \cdot \sqrt{\frac{T_c}{\tau}}, \quad with \quad Q = \frac{f}{\Delta f}$$

frequency

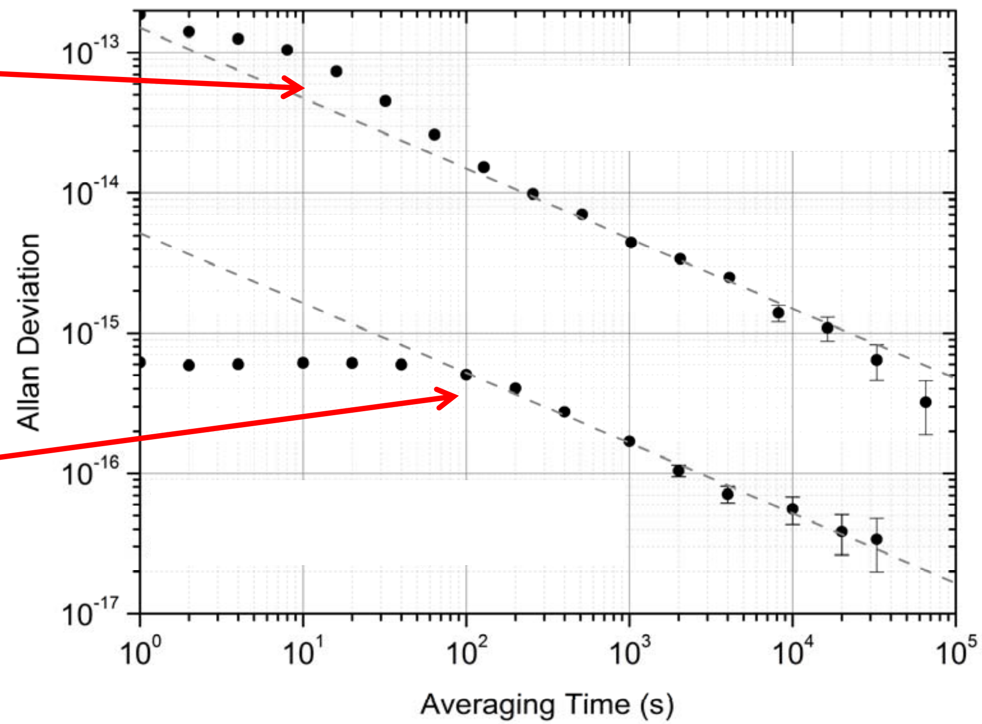
resonance line width (laser, atom)

no. of atoms

Relative frequency instability σ_y/f :

Yb$^+$ single ion vs Cs fountain
optical - MW

Yb$^+$ single ion vs Sr lattice clock
optical - optical



Single ion clock limited by $N_A = 1$

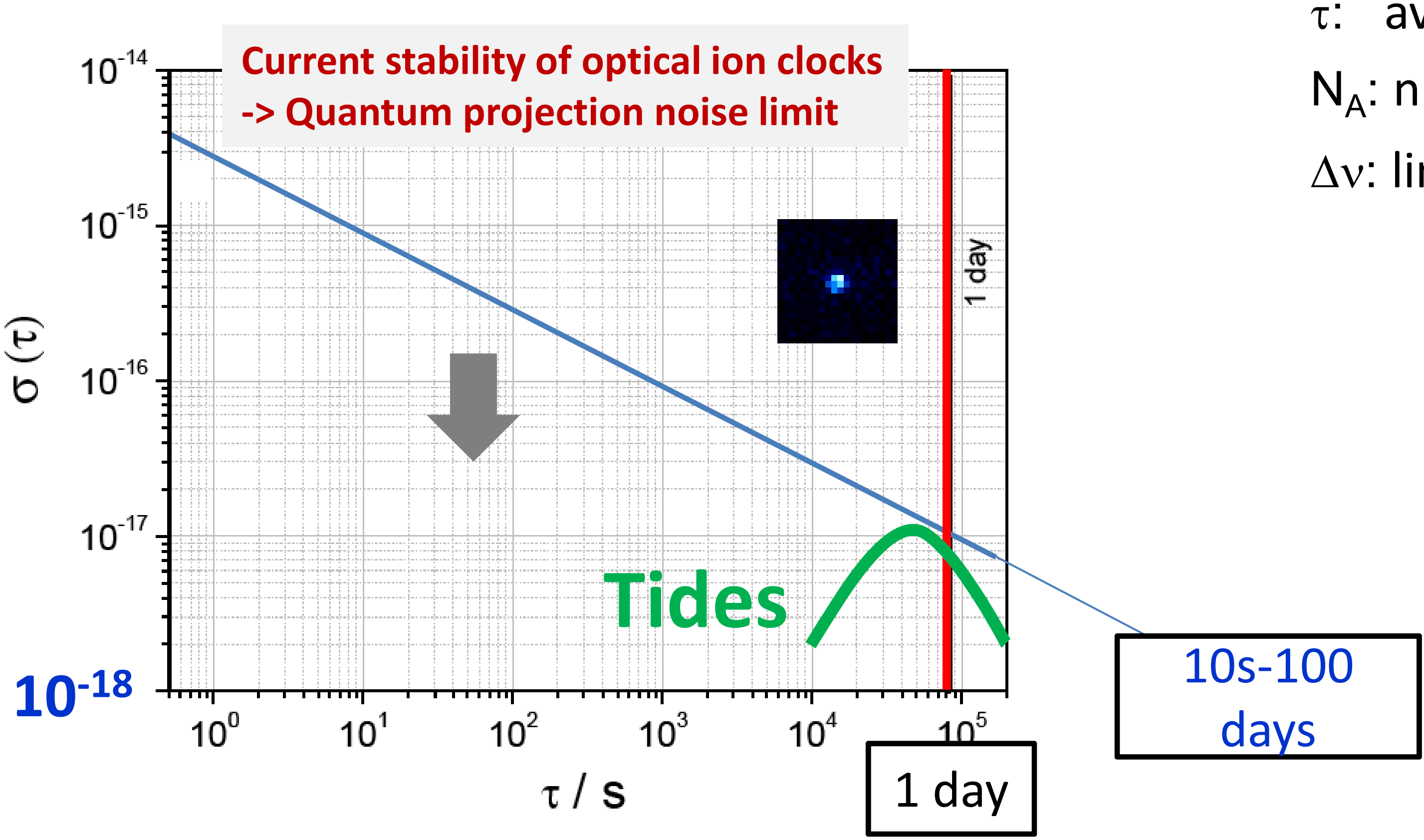
Instability of the frequency standard:

$$\sigma \approx \frac{1}{Q} \cdot \frac{1}{\sqrt{N_A}} \cdot \sqrt{\frac{T_c}{\tau}} \quad \text{with } Q = \frac{\upsilon}{\Delta \upsilon} \rightarrow T_c$$

τ: averaging time

N_A: number of atoms

$\Delta\nu$: linewidth



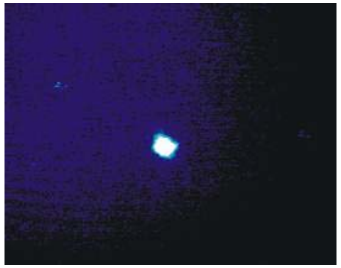
II. Development of Multi-Ion Clocks

Scaling up the number of ions for metrology

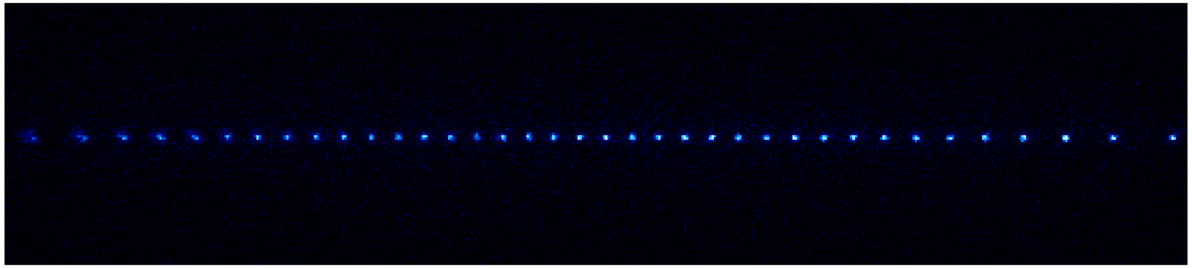
Multi-ion clocks
Multi-ensemble clocks
Entangled ion clocks

?

37 days **1day**



single Yb^+-ion



Coulomb crystal of 37 Yb^+-ions

Quantum Metrology ↔ Quantum Simulation & Information

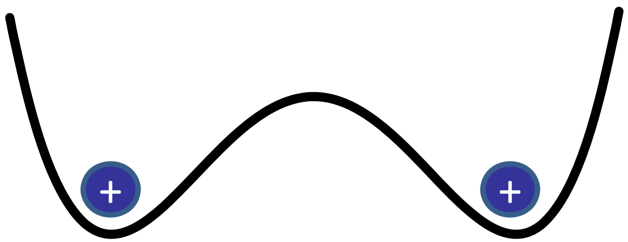
Herschbach et al., *Appl. Phys. B* 107, 891 (2012)

Why did nobody do it before?

Electric Quadrupole Moment

Problem: asymmetry in electron shell !

N $\geq$ 2 ions: E = 0 but $\langle \nabla E \rangle \neq 0$!



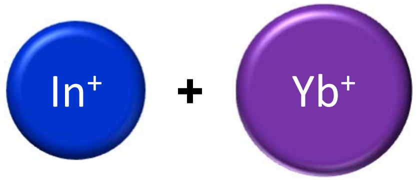
Quadrupole moment θ let's ions interact with electric field gradients.
Find candidates with low θ

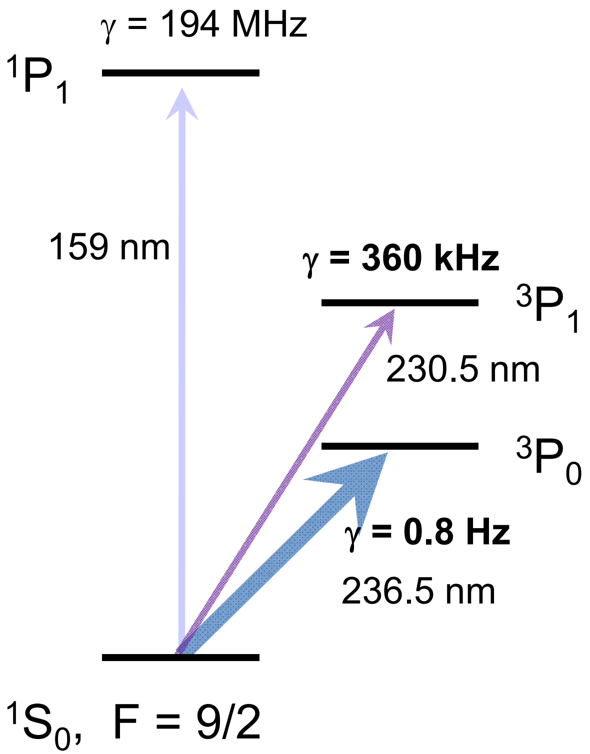
	Al^+	In^+	Yb^+ (F-state)
$\Theta(ea_B^2)$	-0.17×10^{-5}	-1.59×10^{-5}	-4.1×10^{-2}
$\Delta\nu/\nu_0$ max shift for 10 ions with ν_{axial}=82 kHz	-0.0005×10^{-18}	-0.02×10^{-18}	-77×10^{-18}

Beloy et al., Phys. Rev. A ***95****, 043405 (2017), Huntemann et al., PRL* ***108,*** *090801 (2012)*

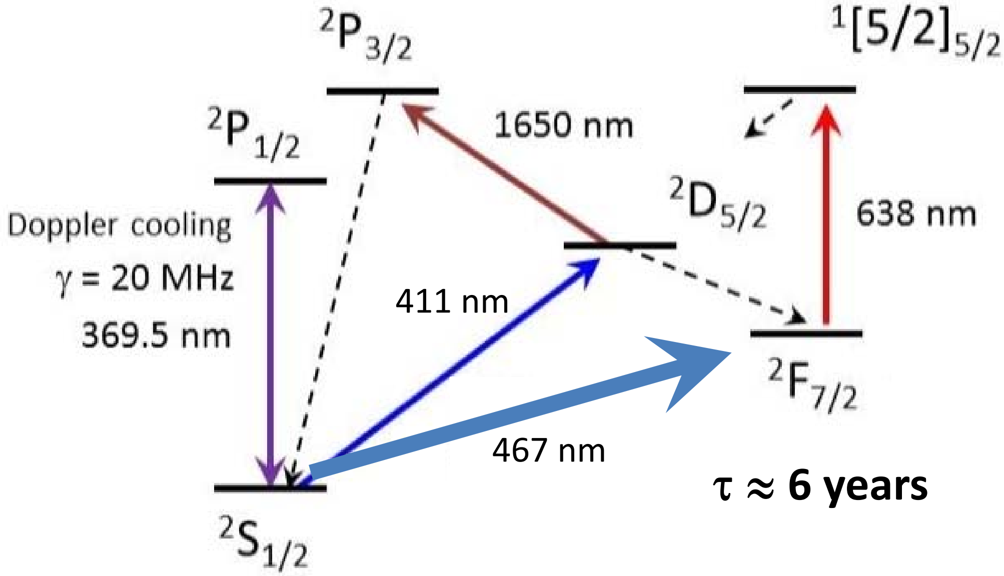
Our ion species

^{115}In^{+} J = 0 → 0 intercombination line





^{172}Yb^{+} quadrupole + octupole transition



T ~ 100 μK

T ~ 1 mK

Challenges

- Motional control of a many-body system with strong coupling

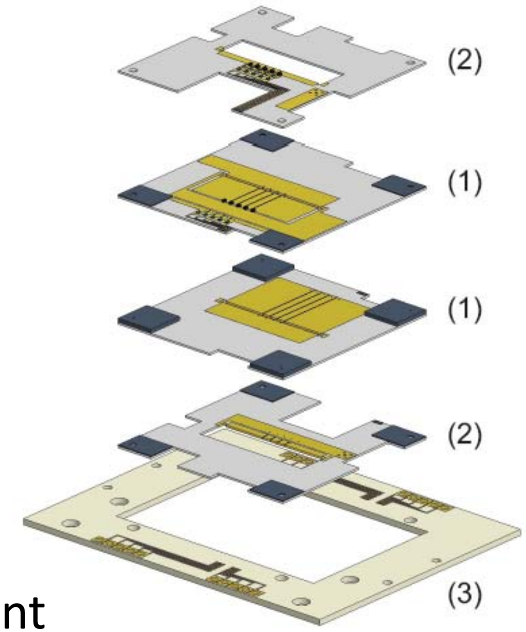
- Ion Trap properties

Warming of trap → Black Body Radiation

Heating rate
Micromotion } → Time dilation

B-field gradients

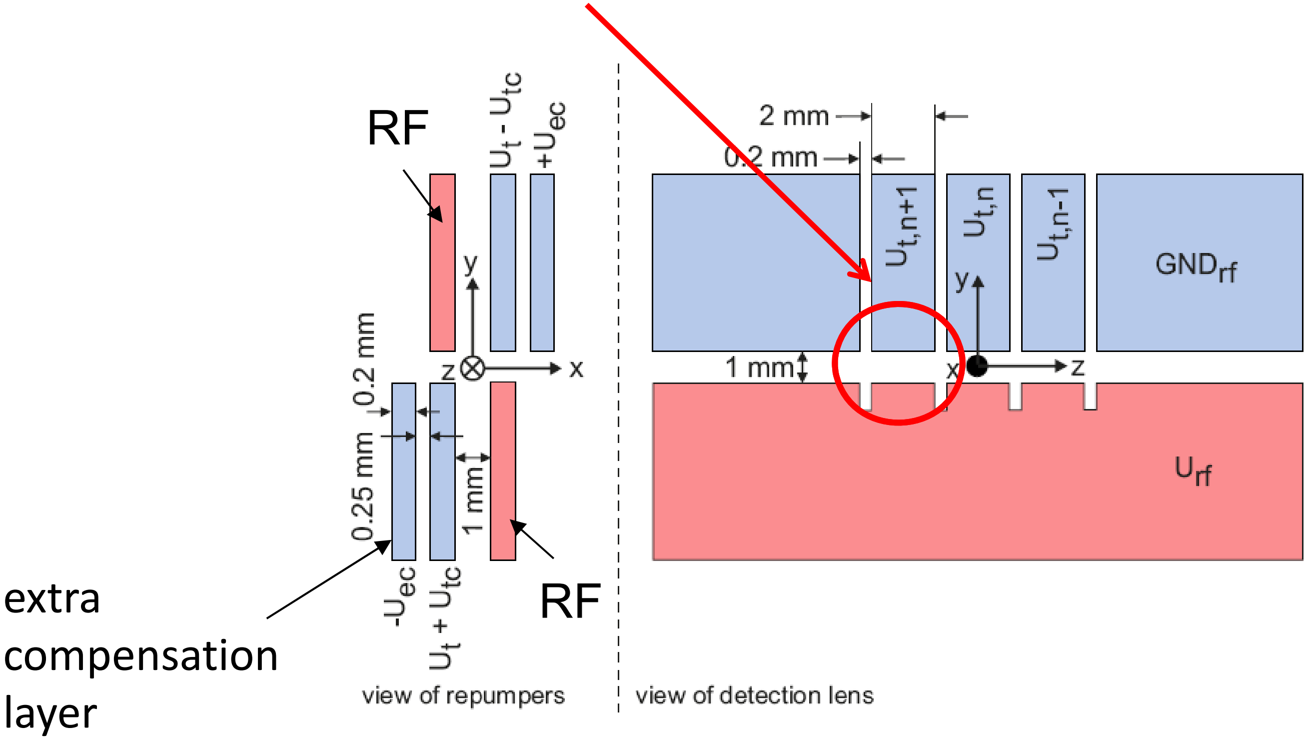
2/3 of uncertainty



scalable linear trap: 4 years development

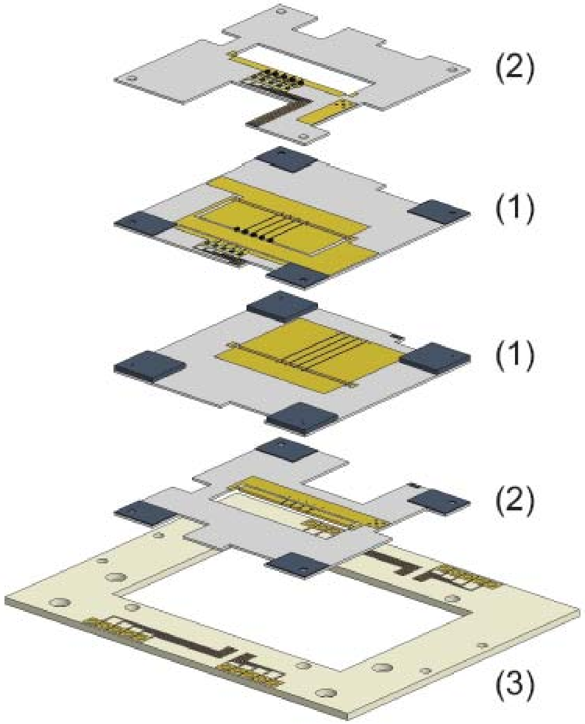
Scalable Ion Trap Design for Clock Operation

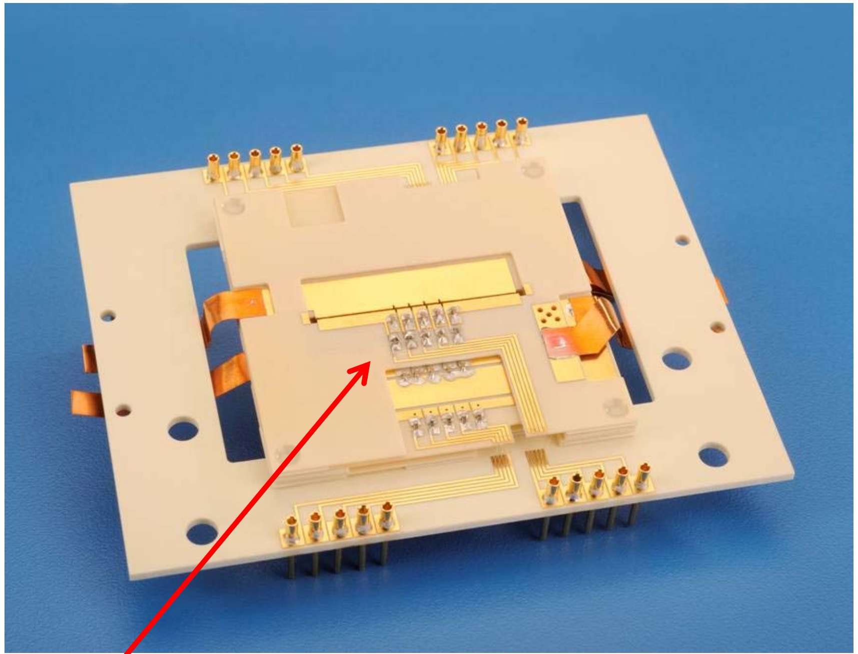
- Low axial micromotion (optimized by FEM simulations)
- 3D micromotion compensation + laser access
- Separated loading and spectroscopy segment



N. Herschbach et al., Appl. Phys. B 107, 891 (2012)

Trap Prototype (Rogers 4350B)





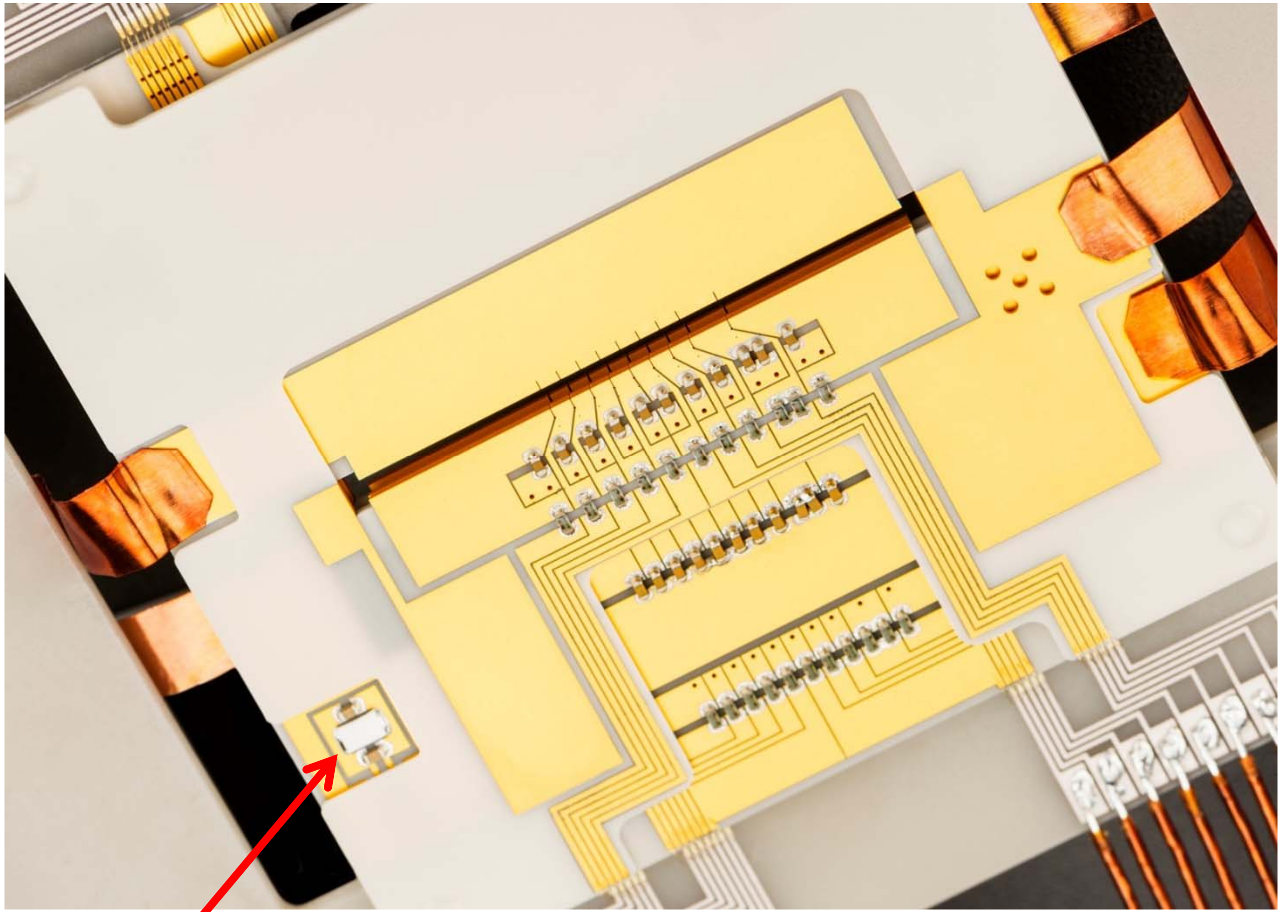
Trap stack with OFHC Cu Foil
aligned under Zeiss microscope $\Delta < 20\mu m$
Optocast 3410 Gen2: UV+heat cured

on-board low pass filters

Pyka et al., Appl. Phys. B 114, 231 (2014)

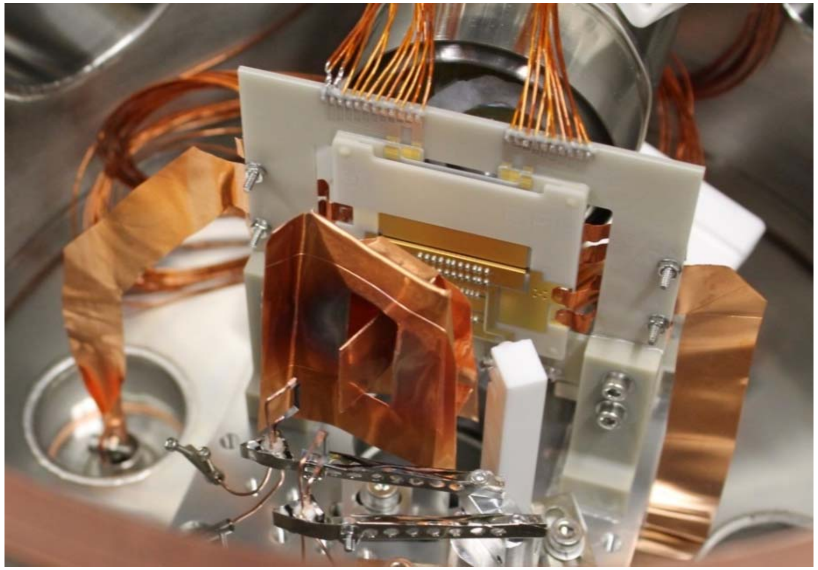
Ion Trap Fab at PTB - AlN Ceramics Trap 2016

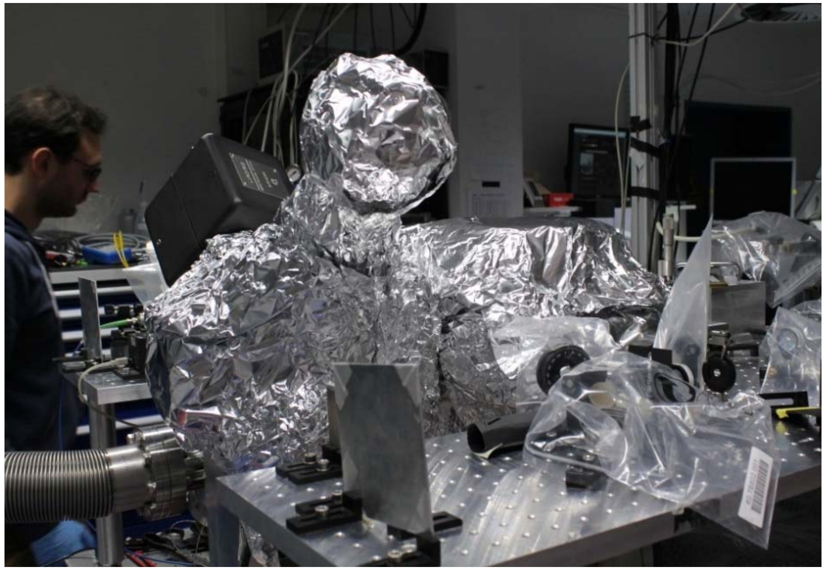
Precision laser machined AlN ceramics



PT100 sensors, σ_T = 30 mK

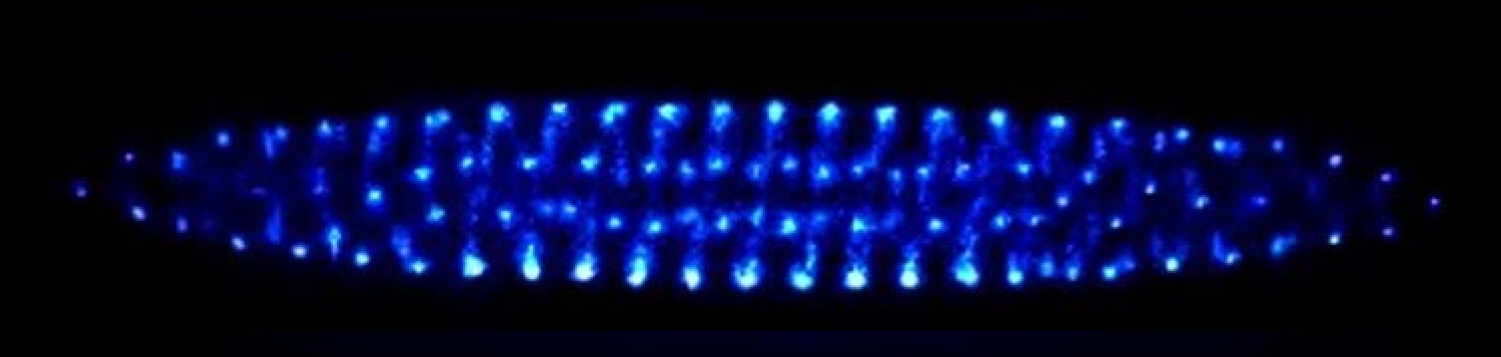
Pictures from the lab: installation of a new trap

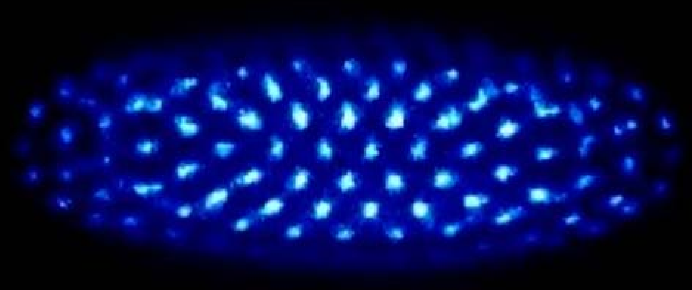


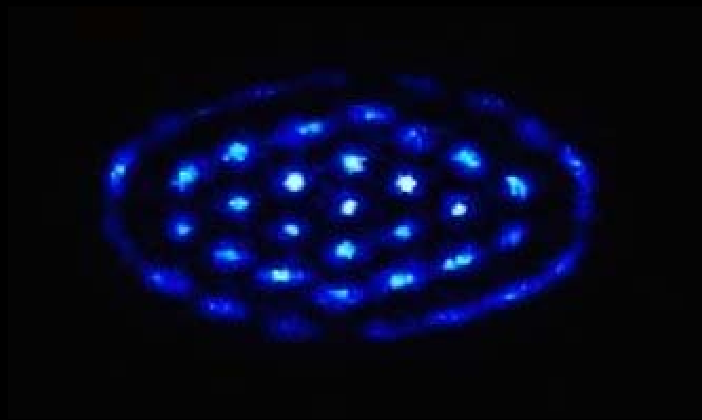


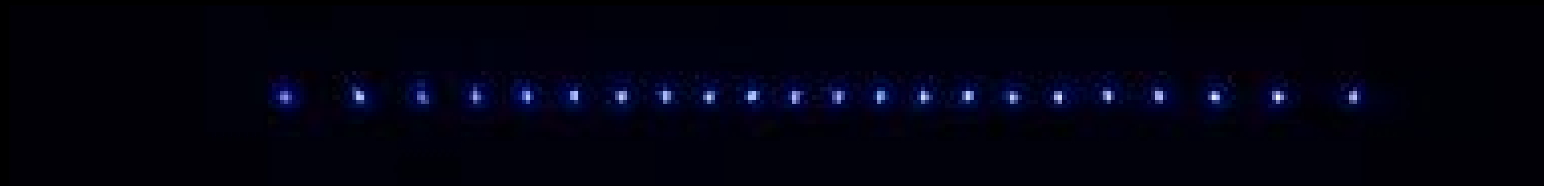
Ion Coulomb Crystals

$E_{kin} < E_{pot}$!









Characterization of the trap

RF driven micromotion, heating rate,
blackbody radiation, background collisions, ...

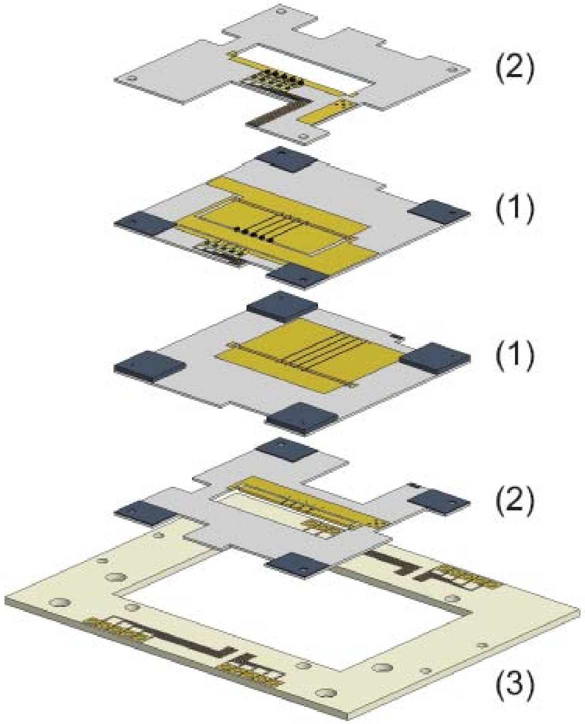
Here: one example (black-body radiation)

Blackbody Shift

-

Warming of the trap

Ion trap operates at $U_{RF} \approx 1000$ V !

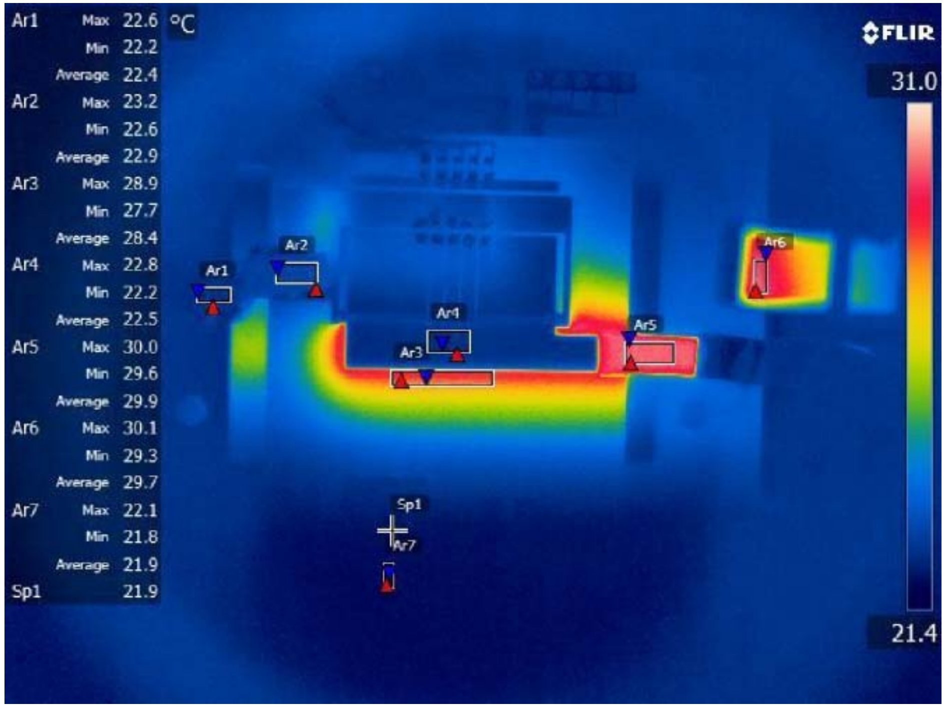


In ion traps temperatures up to 150°C were observed

Lot‘s of dielectric material !

Temperature studies @ CMI / Prague

IR-image (7-14 µm) of a single Rogers chip:

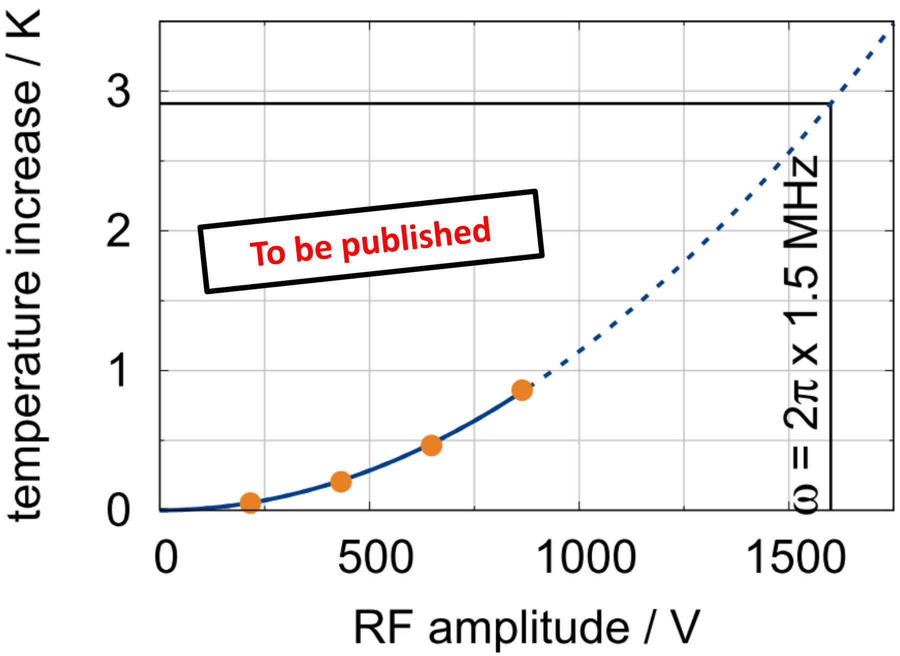


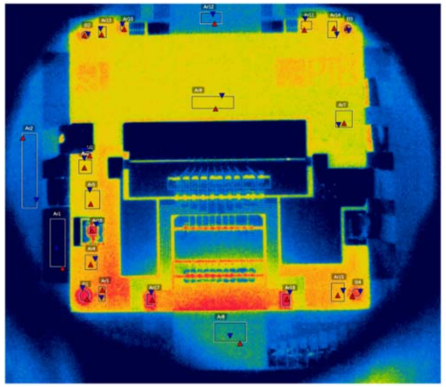
T=31°C

T=21°C

Method + FEM evaluation: Dolezal *et al.*, Metrologia **52**, 842 (2015)

Temperature of the operational AlN trap:





Example for $^{115}In^+$: U_{RF} = 1.5 kV
max. temp. rise seen by ion $\Delta T < 1$ K

➔ Power dissipation **180 mW**

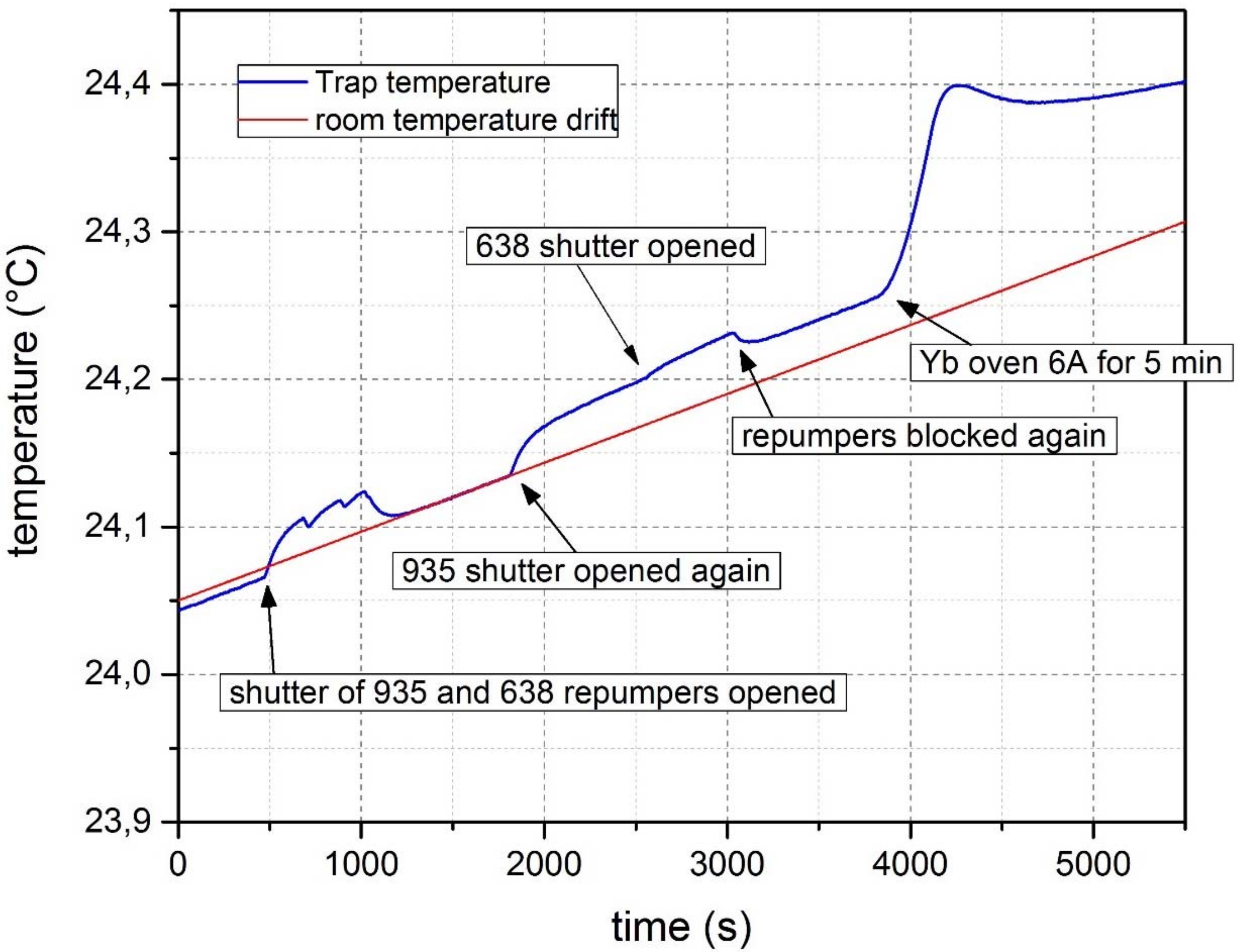
➔ Absolute BBR shift (from ΔT)*

$\Delta\nu/\nu_0 \approx 1.6 \times 10^{-19}$

$\delta(\Delta\nu/\nu_0) < 2 \times 10^{-20}$

* Safronova et al., Phys. Rev. Lett. **107**, 143006 (2011)

Influence of lasers and oven on trap temperature



Estimated uncertainty budget

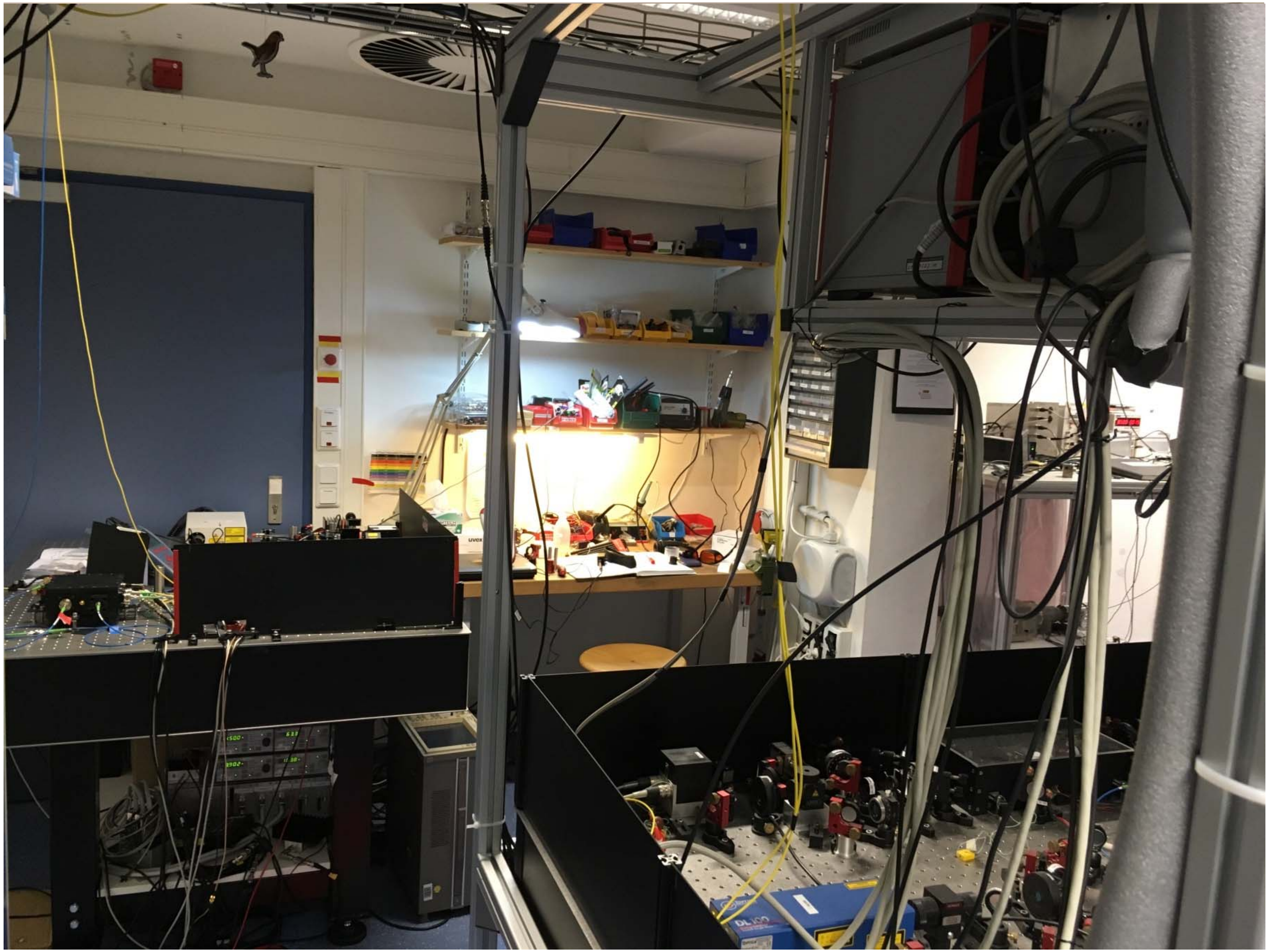
Estimated uncertainty budget in 10^{-19}

$\Delta\nu/\nu$ in 10^{-19}	Sympathetic cooling to $T_{Doppler}$		Direct cooling to 100 µK on In^{+}	
	shift	**uncertainty**	**shift**	**uncertainty**
Time dilation (thermal)	- 25	5	- 2	0.2
Time dilation (excess µ-motion)	> - 1	< 0.1	> - 1	< 0.1
BBR	136	0.2 (trap)	136	0.2 (trap)
2^{nd} Zeeman	< 0.7	< 0.7	< 0.7	< 0.7
Collisions (Langevin)	0.94	0.94	0.94	0.94
Quadrupole (to m = ± 7/2)	- 1.1 ν_{ax}=205kHz	0.9 (theory)	- 0.02 ν_{ax}=30 kHz	0.02 (theory)
Total:	**111**	**< 5.1**	**135**	**< 1.3**

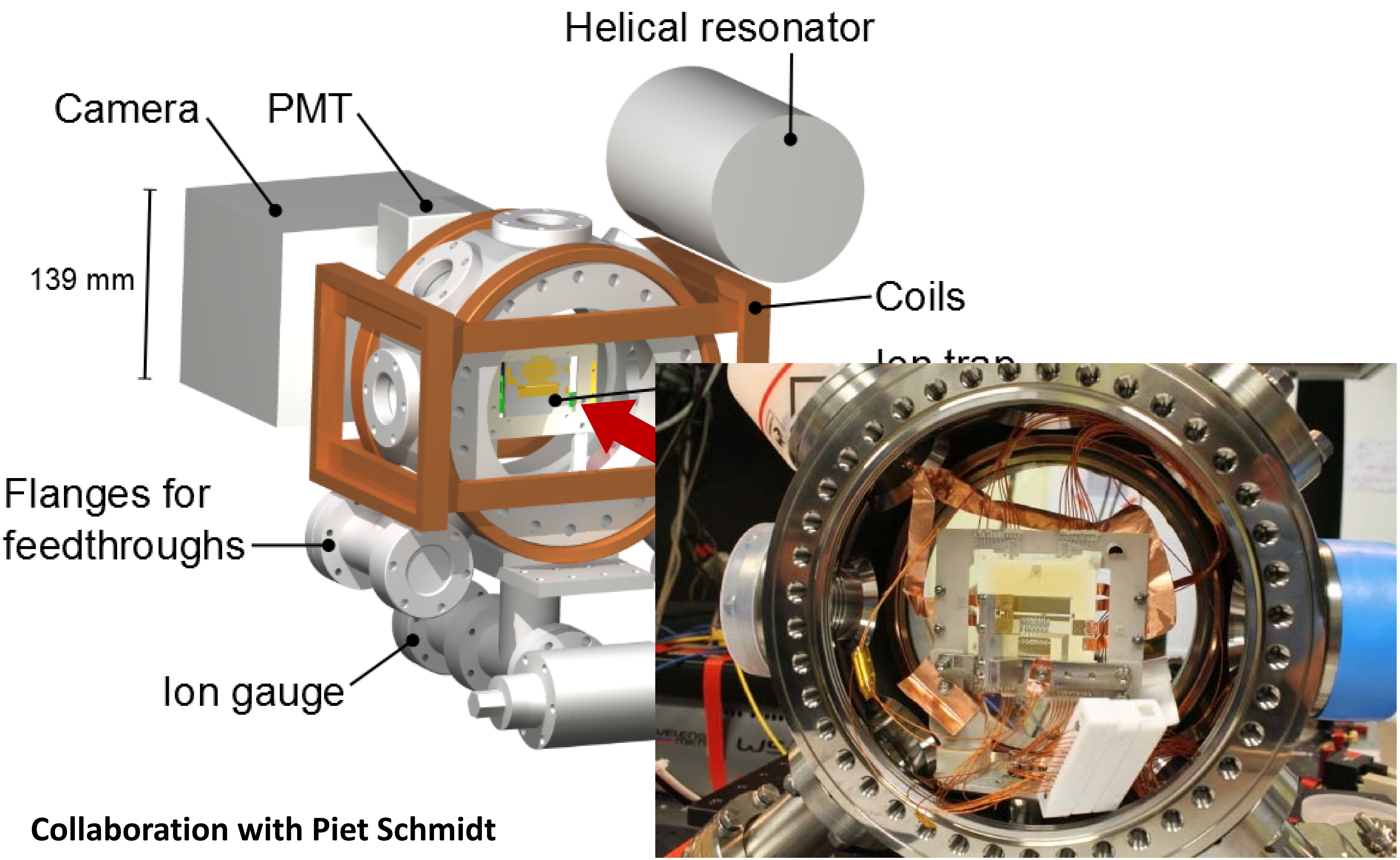
Paper submitted..

Is it now a clock for geodesy?

Photos from the lab...

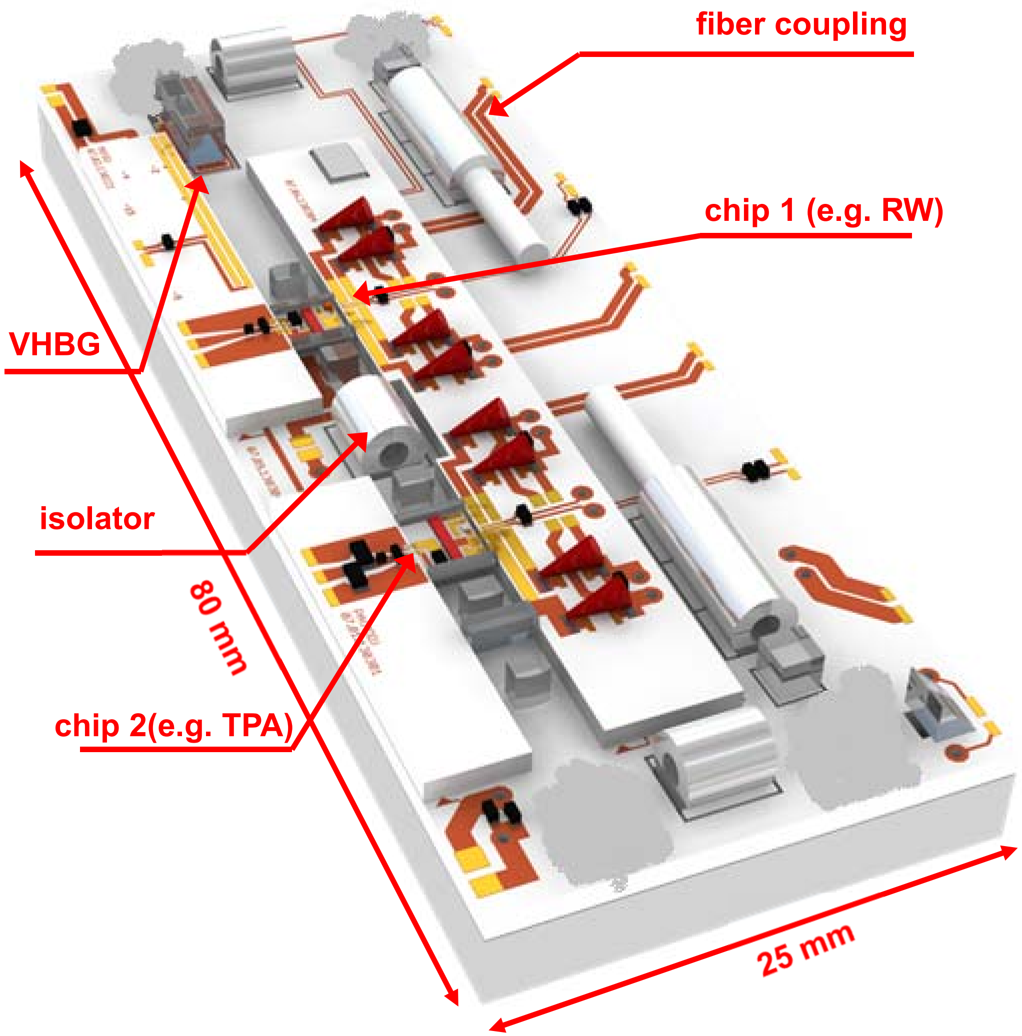


Future: Transportable Al^+ System (SFB GeoQ)



Collaboration with Piet Schmidt

Highly Integrated Al^+ clock laser @ 267 nm

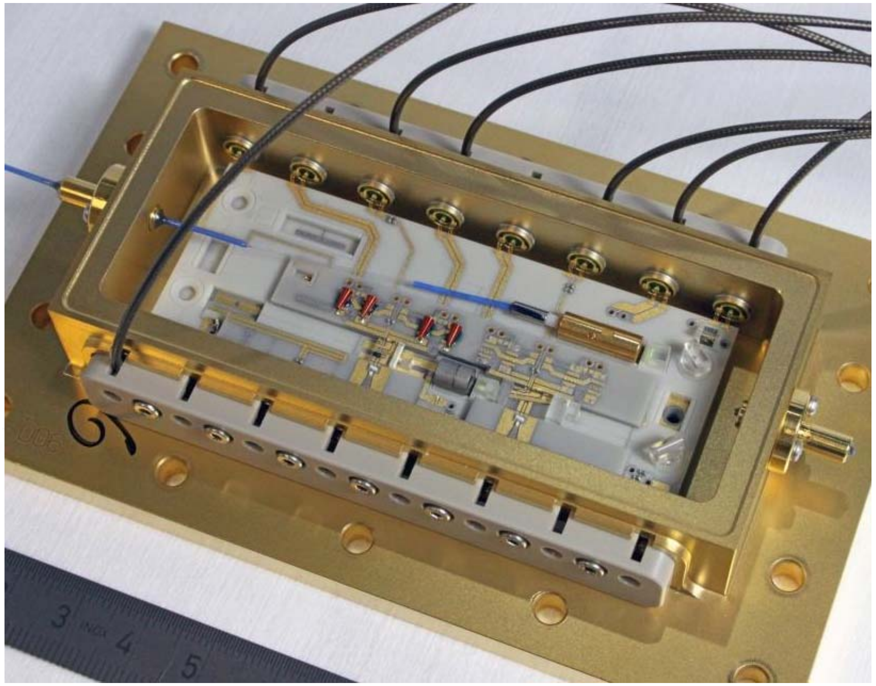


1068 nm ECDL + PA

NTT waveguide doubler → 534 nm

integrated BBO doubling module → 267 nm

space qualifiable



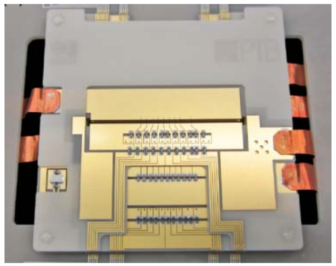
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

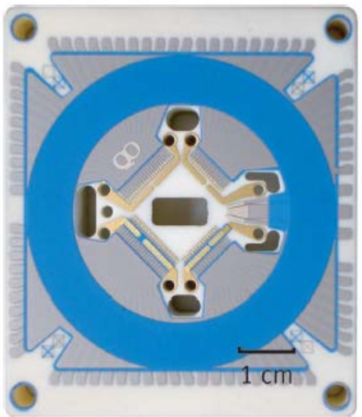
opticlock

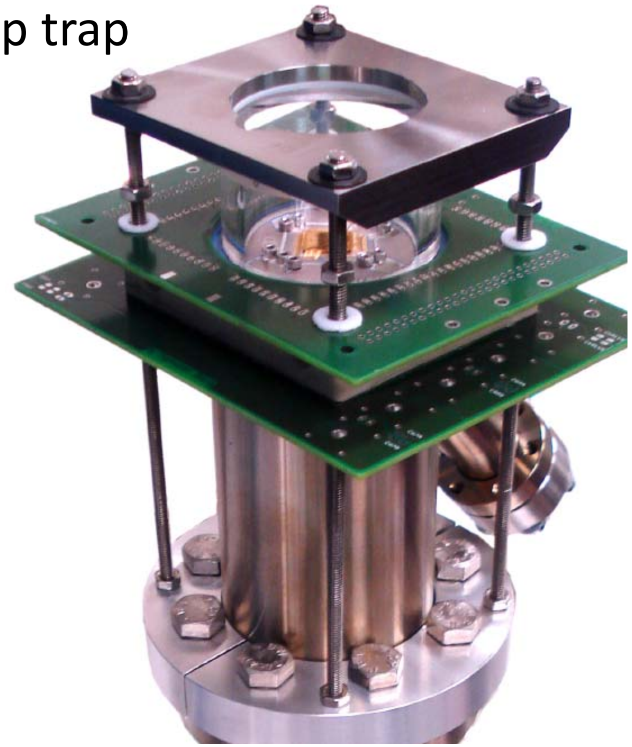
QUTEGA
Quantentechnologie – Grundlagen und Anwendungen

Since May 2017:

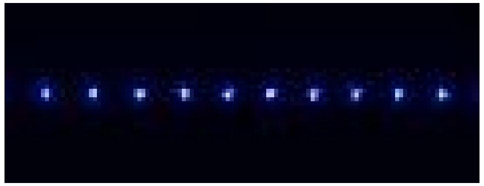
- together with Uni Siegen, Uni Bonn & German industry
- Demonstrator for first commercial optical clock
- Performance: better than H-maser
- one Workpackage: integration of scalable linear chip trap



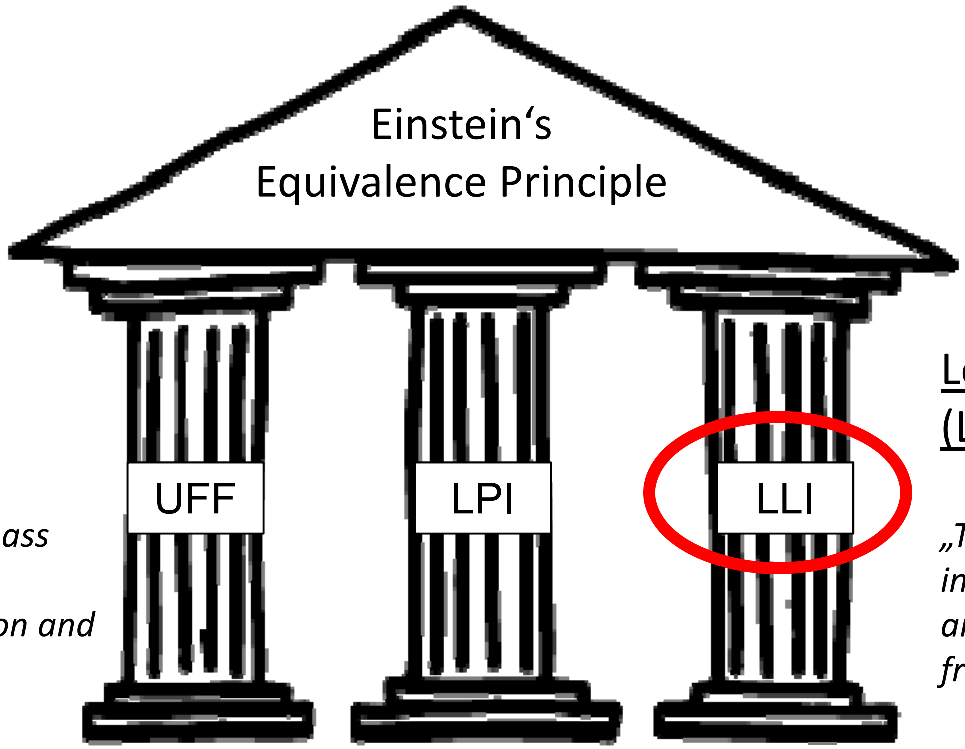




III. Testing Local Lorentz Invariance with Ions



General relativity



Universality
of Free Fall (UFF)

„The trajectory of a point mass in a gravitational field only depends on its initial position and velocity.“

Local Lorentz Invariance
(LLI)

„The result of your experiment is independent of the orientation and velocity of the laboratory frame.“

Local Position Invariance (LPI)

„The result of your experiment is independent of its location in space and time.“

First Tests of Local Lorentz Invariance

The Michelson-Morley light interferometer:

Albert Michelson: 1881 Telegraphenberg in Potsdam

Is there a preferred direction in the Universe?

First Tests of Local Lorentz Invariance

Tests of the electron-photon sector:

Michelson and Morely, “Influence of Motion of the Medium on the Velocity of Light” Am. J. Science 34, 427 (1887)

S. Herrmann et al., „Rotating optical cavity experiment testing Lorentz invariance at the $\mathbf{10^{-17}}$ level” PRD 80, 105011 (2009)

Eisele et al. “Laboratory Test of the Isotropy of Light Propagation at the $\mathbf{10^{-17}}$ level” PRL 103, 090401 (2009)

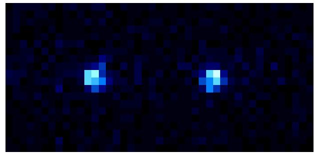
With atoms:

Hohensee et al. “Limits on Violations of Lorentz Symmetry and the Einstein Equivalence Principle using Radio-Frequency Spectroscopy of Atomic Dysprosium “ PRL 111, 050401 (2013) **->** $\mathbf{10^{-16}}$

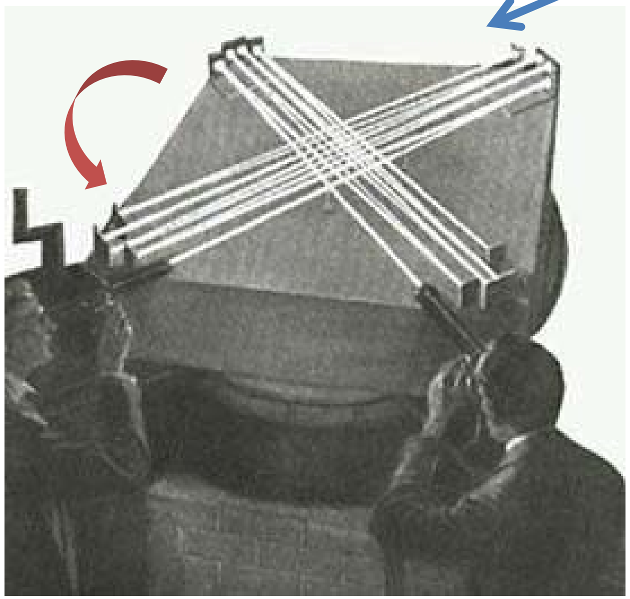
T. Pruttivarasin et al. „A Michelson-Morley Test of Lorentz Symmetry for Electrons“ Nature 517, 592 (2015) **->** $\mathbf{10^{-18}}$

Test of Local Lorentz Invariance with two Yb^+ ions

Build a Michelson-Morley atom interferometer:

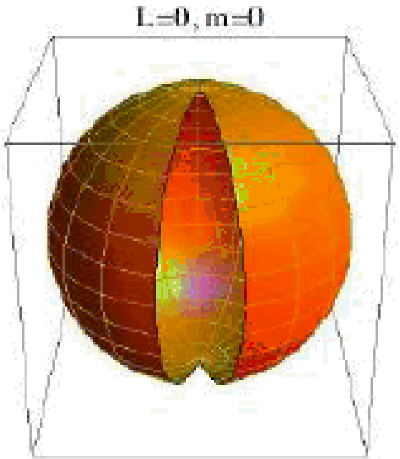


(1) (2)



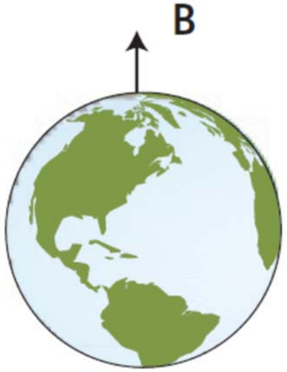
What does this mean concrete?

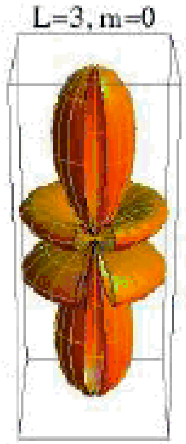
s-orbital

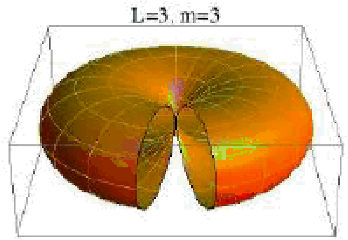


→ Spherical symmetry!
→ useless....

LLI test with atomic states



$|\psi\rangle =$ $|$ 

$\rangle + e^{i\phi}$ $|$ 

$\rangle$

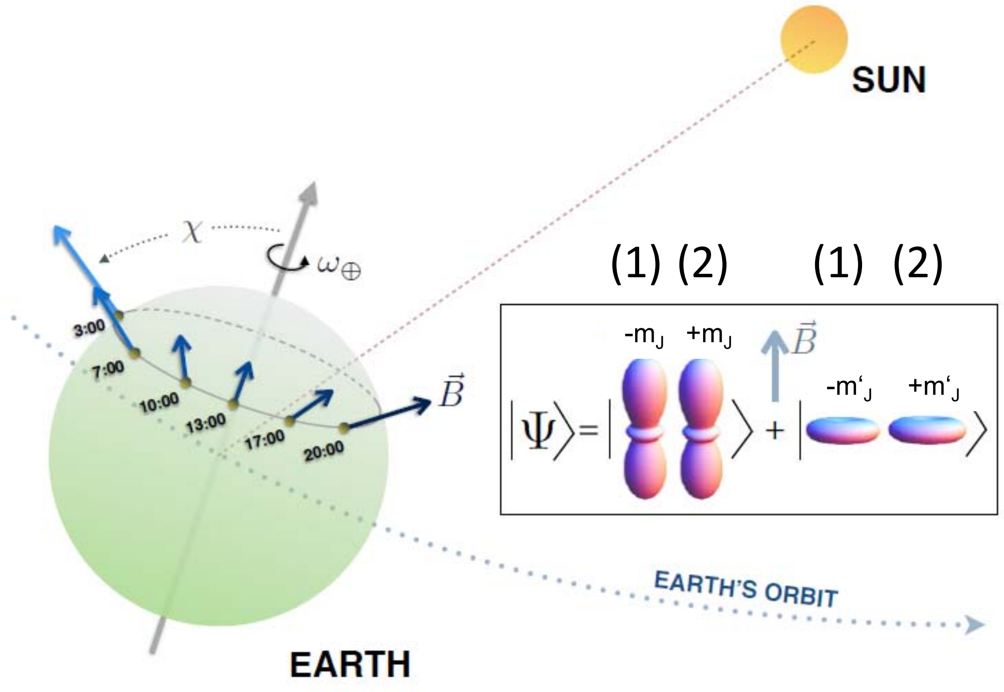
The decoherence-free subspace

BUT: For a single atom/ion ΔE depends linearly on magnetic fields!

→ Any electronic equipment in the lab creates randomly fluctuating magnetic fields that will quickly dephase the above superposition

→ Use two entangled atoms/ions with states that have the same energy dependence!

Michelson-Morely with two Yb^+ ions



(A) Use different directions in the wavefunctions of the electron orbitals

(B) Measure energy difference between these states:

$\rightarrow$ improvement by factor **10^3** expected !

Pruttivarasin et al., Nature 517, 592 (2015)

Dzuba et al., Nature Phys. (2016)

Why 1000 better?

TABLE 1: Reduced matrix elements of $T^{(2)}$ operator in Ca^+, Ba^+, Yb^+ ions in atomic units. Ca^+ values are from Ref. [7].

Ion	State	$\langle J \| T^{(2)} \| J \rangle$
Ca^+	$3d\,^2D_{3/2}$	7.09(12)
	$3d\,^2D_{5/2}$	9.25(15)
Ba^+	$5d\,^2D_{3/2}$	6.83
	$5d\,^2D_{5/2}$	8.65
Yb^+	$4f^{14}5d\,^2D_{3/2}$	9.96
	$4f^{14}5d\,^2D_{5/2}$	12.08
	$4f^{13}6s^2\,^2F_{7/2}$	-135.2

$$T_0^{(2)} = \mathbf{p}^2 - 3p_z^2$$

Yb^+ has higher mass than Ca^+ and has deeply localized 4*f* shell

→ larger electron momentum → **x 40**

in $^{40}Ca^+$ Ramsey time limited by:

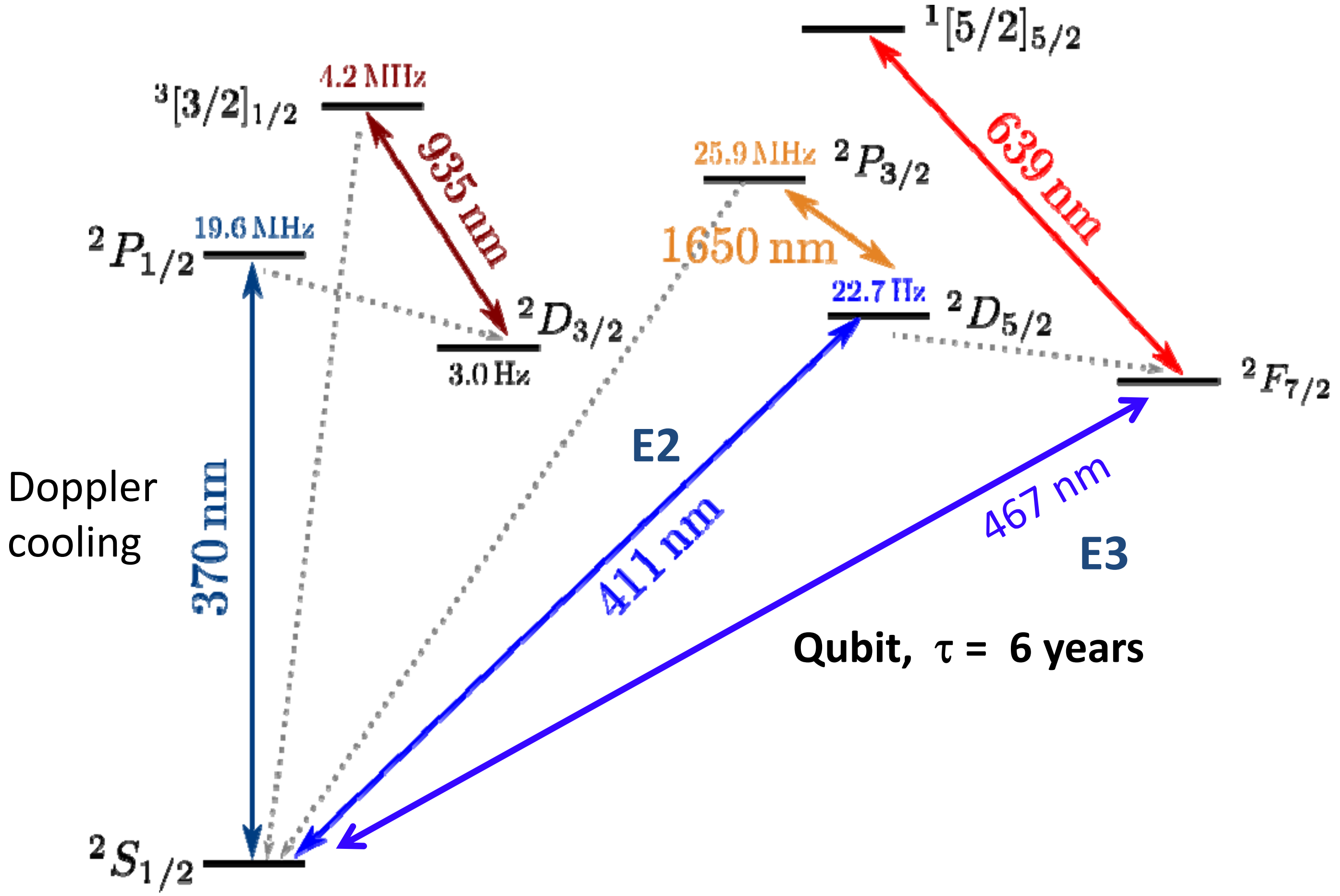
- $^2D_{5/2}$ state lifetime of **1.2s**
- Heating rate: **400 – 1000 phonons/s**

in $^{172}Yb^+$:

- lifetime of $^2F_{7/2}$ state ~ **several years**
- our heating rate: **1 phonon/s**

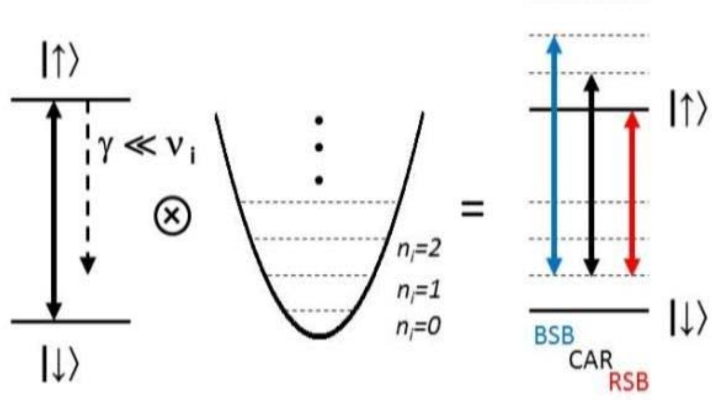
V. A. Dzuba et al., *Nature Physics* **12**, 465 (2016)

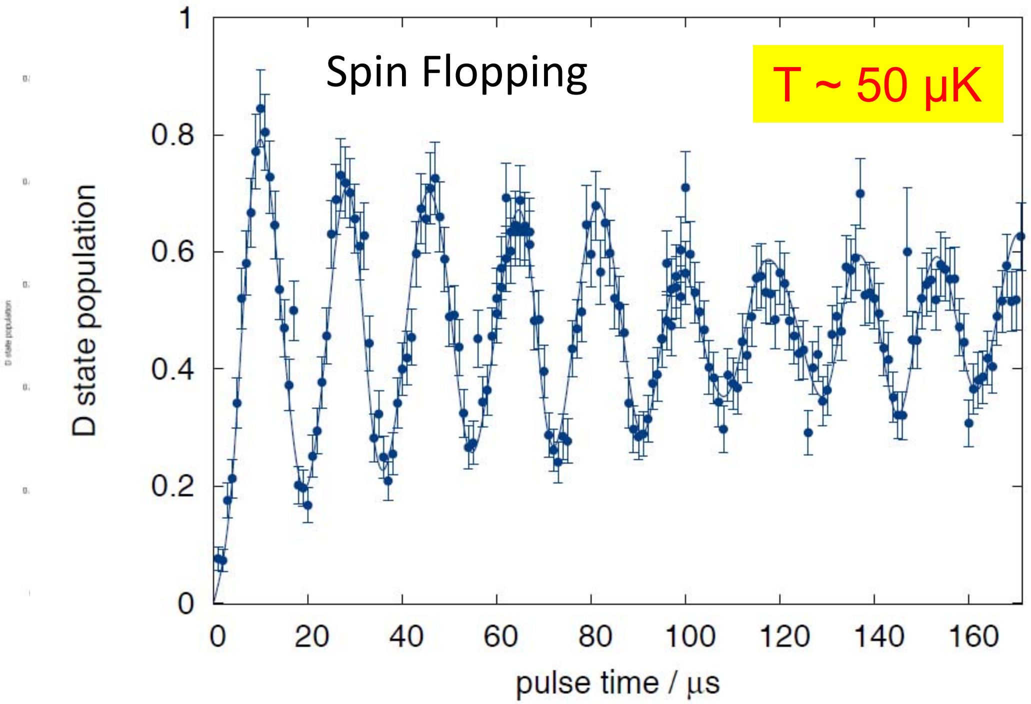
Level scheme of $^{172}Yb^+$



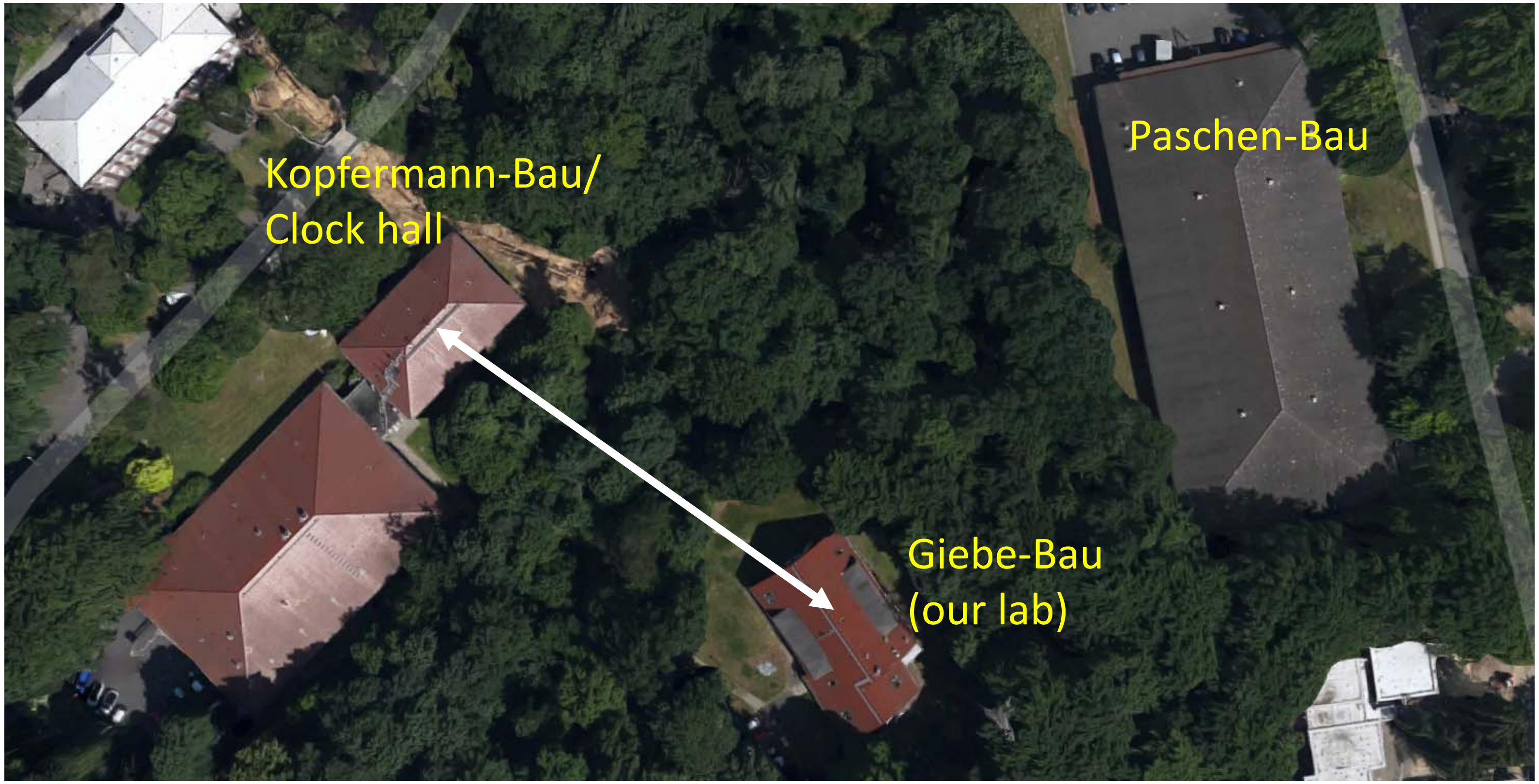
Coherent Quantum State Manipulation

- Sideband spectroscopy on E2
- Ground state preparation





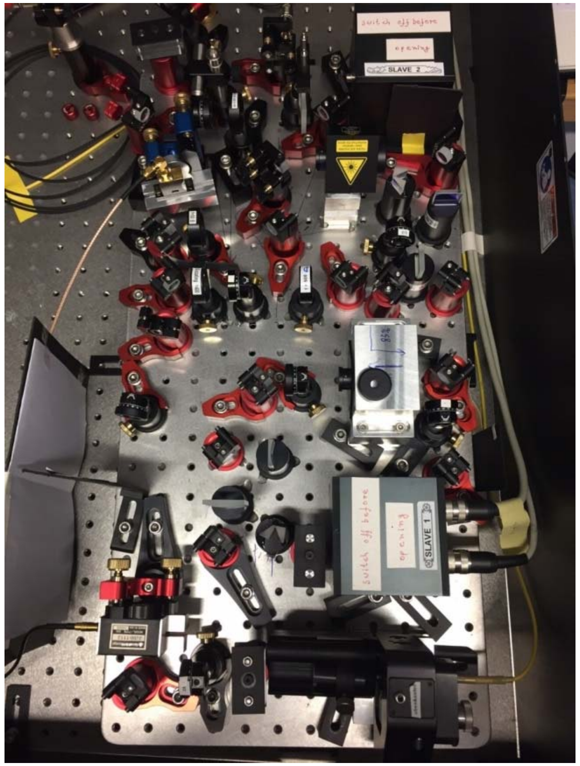
Left to do... Setting up the E3 laser



Cooperation with E. Peik's group

→ frequency-stable octupole laser light for $^{171}Yb^+$

Left to do… Setting up the E3 laser

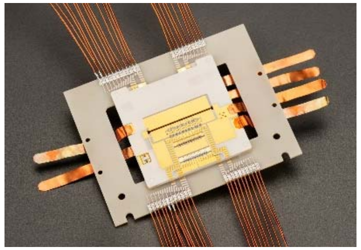


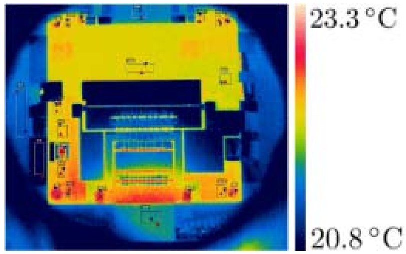
Octupole amplifier system

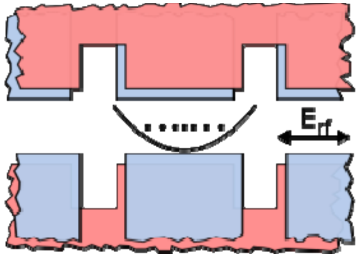
- Bridge isotope shift between $^{171}Yb^{+}$ and $^{172}Yb^{+}$ (~ 4.8 GHz)
- Slave lasers for high power
- Fiber-coupled SHG waveguide → 467nm

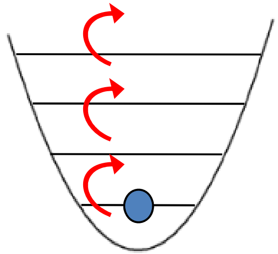
Summary

Summary



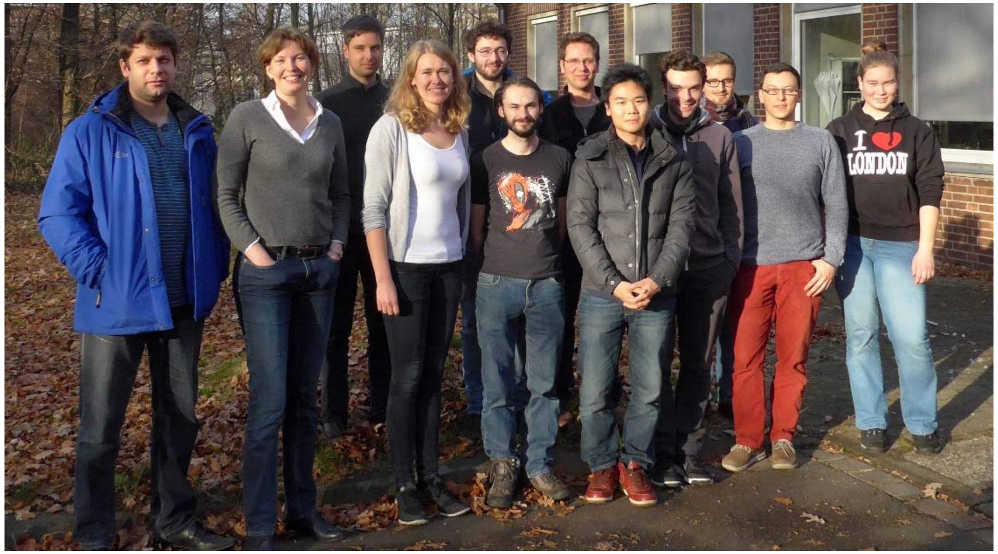




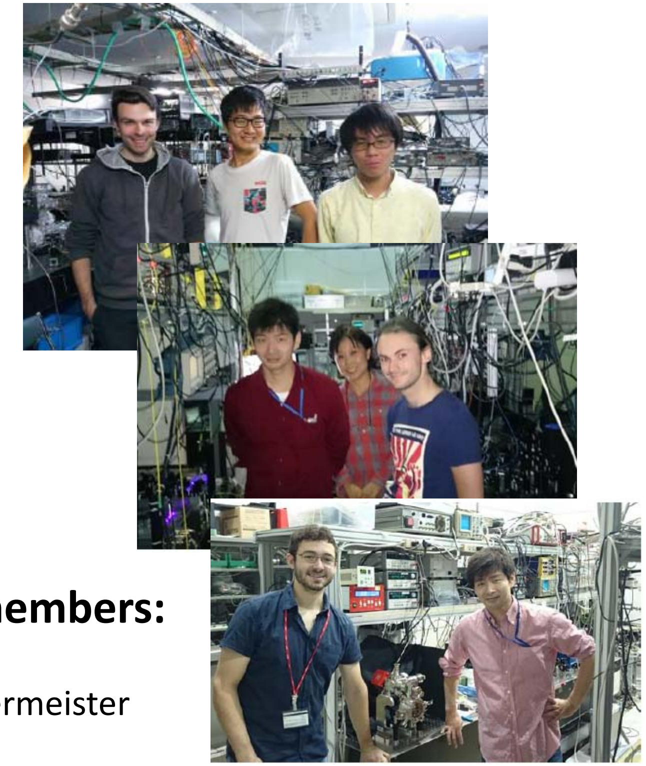


- First trap for multi-ion clock in operation & characterized
- Trap enables systematic uncertainties in the low 10^{-19}
- New compact setups are in progress
- In running experiment: test of LLI with entangled ions

Thank you for your Attention !



Back: J. Keller, A. Didier, A. Kulosa, M. Senn
Front: S. Ignatovitch, T. Mehlstäubler, T. Nordmann, J. Kiethe, M. Kitao, T. Schmirander, D. Kalincev, K. Dudde



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R. Nigmatullin (Univ. Sydney)
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Visiting scientists:

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Keshav Thirumalai

www.quantummetrology.de

EURAMET European Association of National Metrology Institutes

DFG Deutsche Forschungsgemeinschaft

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

mat