Optical Clocks

Tanja E. Mehlstäubler

Physikalisch-Technische Bundesanstalt
&
Center for Quantum Engineering and Space Time Research

QUEST at PTB

„Experimental Quantum Metrology“
Head of Group: Piet O. Schmidt

„Quantum Sensors with Cold Ions“
Head of Group: Tanja E. Mehlstäubler

“Sub-Hz lasers and high performance cavities”
Project Leader: Thomas Kessler

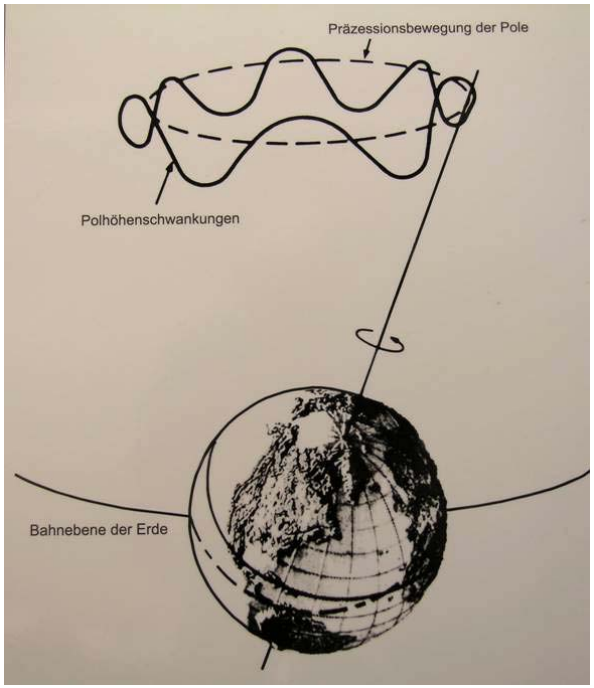
Task Groups:
„Variations of Fundamental Constants“, „Transportable Ultra-Stable Clocks“

Outline

- Definition and Measurement of Time
- Time and Frequency Metrology
- Ingredients of an Optical Clock - Today‘s State of the Art
  - Natural Reference - Candidates
  - Atom/Ion Traps
  - Local Oscillator
  - Frequency Comb
- Applications and Future Developments

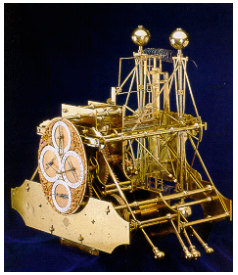
Definition and Measurement of Time

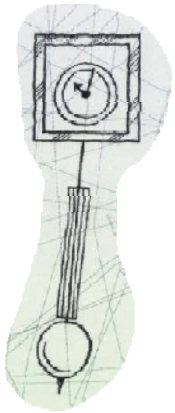
- **Greenwich Mean Time**
  - global standard since 1884
  - 1 s = 1 / 86400 of the mean solar day



- **Mechanical Clocks**

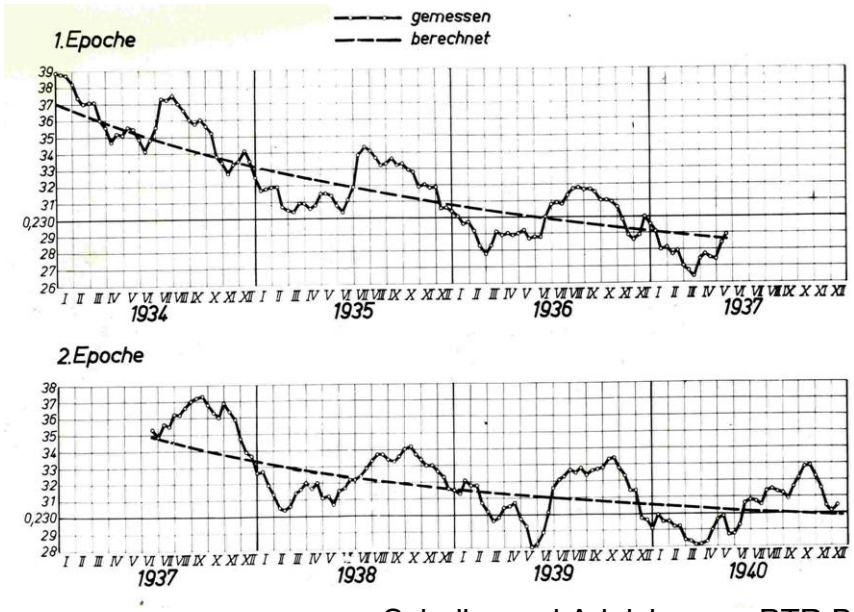
  $\Delta t \sim 1$ s/d





Definition and Measurement of Time

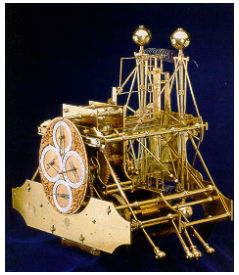
- **Greenwich Mean Time**
  - global standard since 1884
  - 1 s = 1 / 86400 of the mean solar day



Scheibe and Adelsberger, PTR Berlin

- **Mechanical Clocks**

  $\Delta t \sim 1$ s/d



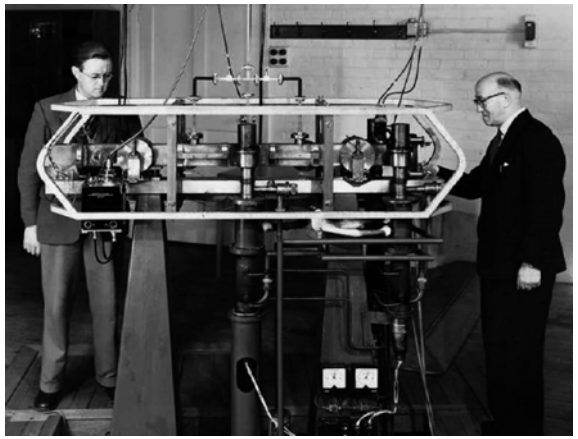
- **Quartz Clocks** ($f_{res} \sim$ MHz)

  1930-40s: $\Delta t \sim 1$ ms /d

Definition and Measurement of Time

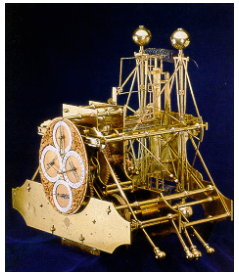
- **Greenwich Mean Time**
  - global standard since 1884
  - 1 s = 1 / 86400 of the mean solar day

- **Ephemeris Time**
  - adopted by the CGPM in 1960
  - 1 s = 1 / 31,556,925.9747 of the tropical year of 0. January 1900 at 12^h UT



- **Mechanical Clocks**

  $\Delta t \sim 1$ s/d



- **Quartz Clocks** ($f_{res} \sim$ MHz)

  1930-40s: $\Delta t \sim 1$ ms /d

- **Atomic Cs-Clocks** (f_{res}= 9.2 GHz)

  <u>1955</u> Essen‘s clock: $\Delta t \sim 10$ µs /d

  today: $\Delta t < 1$ ns /d

Definition and Measurement of Time

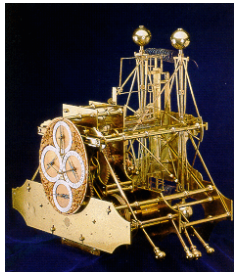
- **Greenwich Mean Time**
  - global standard since 1884
  - 1 s = 1 / 86400 of the mean solar day

- **Ephemeris Time**
  - adopted by the CGPM in 1960
  - 1 s = 1 / 31,556,925.9747 of the tropical year of 0. January 1900 at 12^h UT

- **TAI (Temps Atomique International)**
  - since 1967

- **Mechanical Clocks**

  $\Delta t \sim 1$ s/d



- **Quartz Clocks** ($f_{res} \sim$ MHz)

  1930-40s: $\Delta t \sim 1$ ms /d

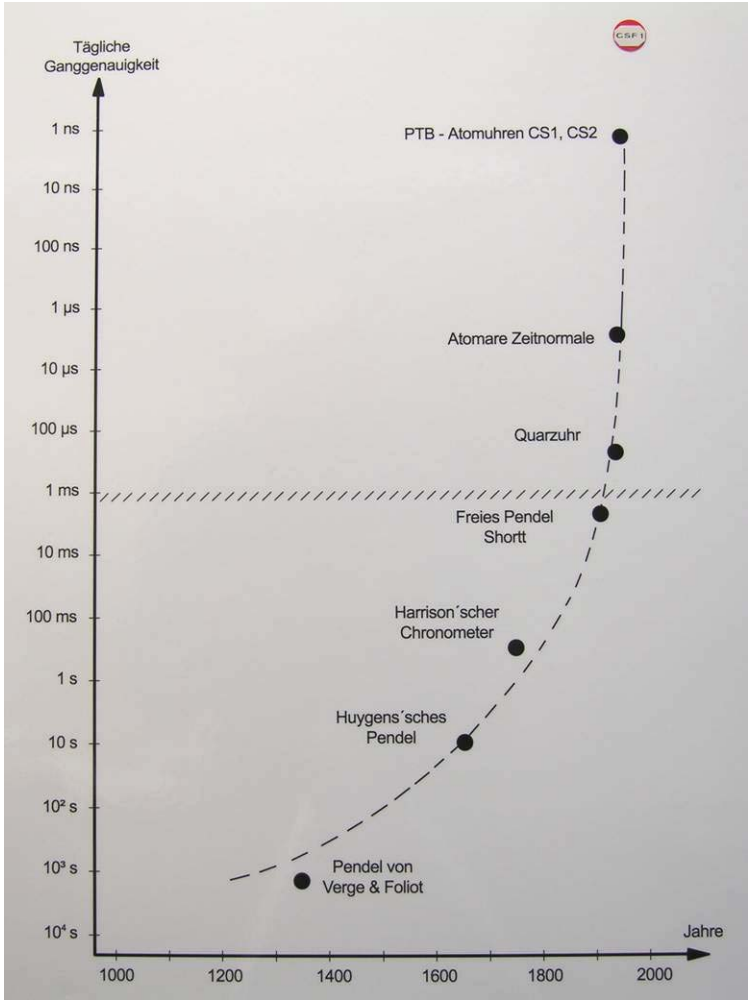
- **Atomic Cs-Clocks** (f_{res}= 9.2 GHz)

  <u>1955</u> Essen‘s clock: $\Delta t \sim 10$ µs /d

  today: $\Delta t < 1$ ns /d

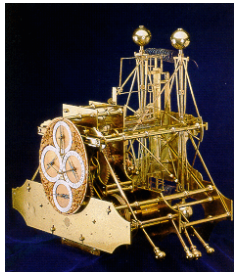
„Duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom“

Definition and Measurement of Time



- **Mechanical Clocks**

  $\Delta t \sim 1$ s/d



- **Quartz Clocks** ($f_{res} \sim$ MHz)

  1930-40s: $\Delta t \sim 1$ ms /d

- **Atomic Cs-Clocks** (f_{res}= 9.2 GHz)

  1955 Essen‘s clock: $\Delta t \sim 10$ µs /d

  today: $\Delta t < 1$ ns /d

- **Optical Clocks (f_{res}~ 1000 THz)**

Clock Operation (optical)

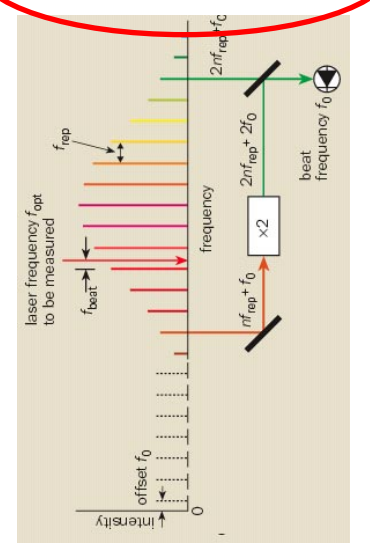
to Cs-fountain or 2nd optical clock

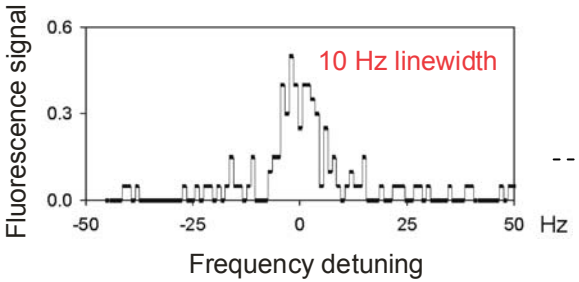
Trapped ion or atoms
(long term reference)

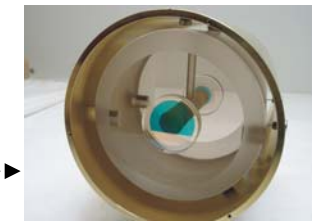
Local Oscillator

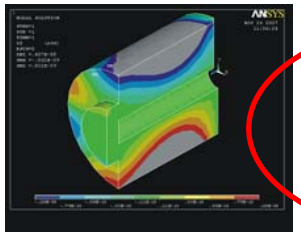
f ~ 1000 THz
Laser

Frequency Comb





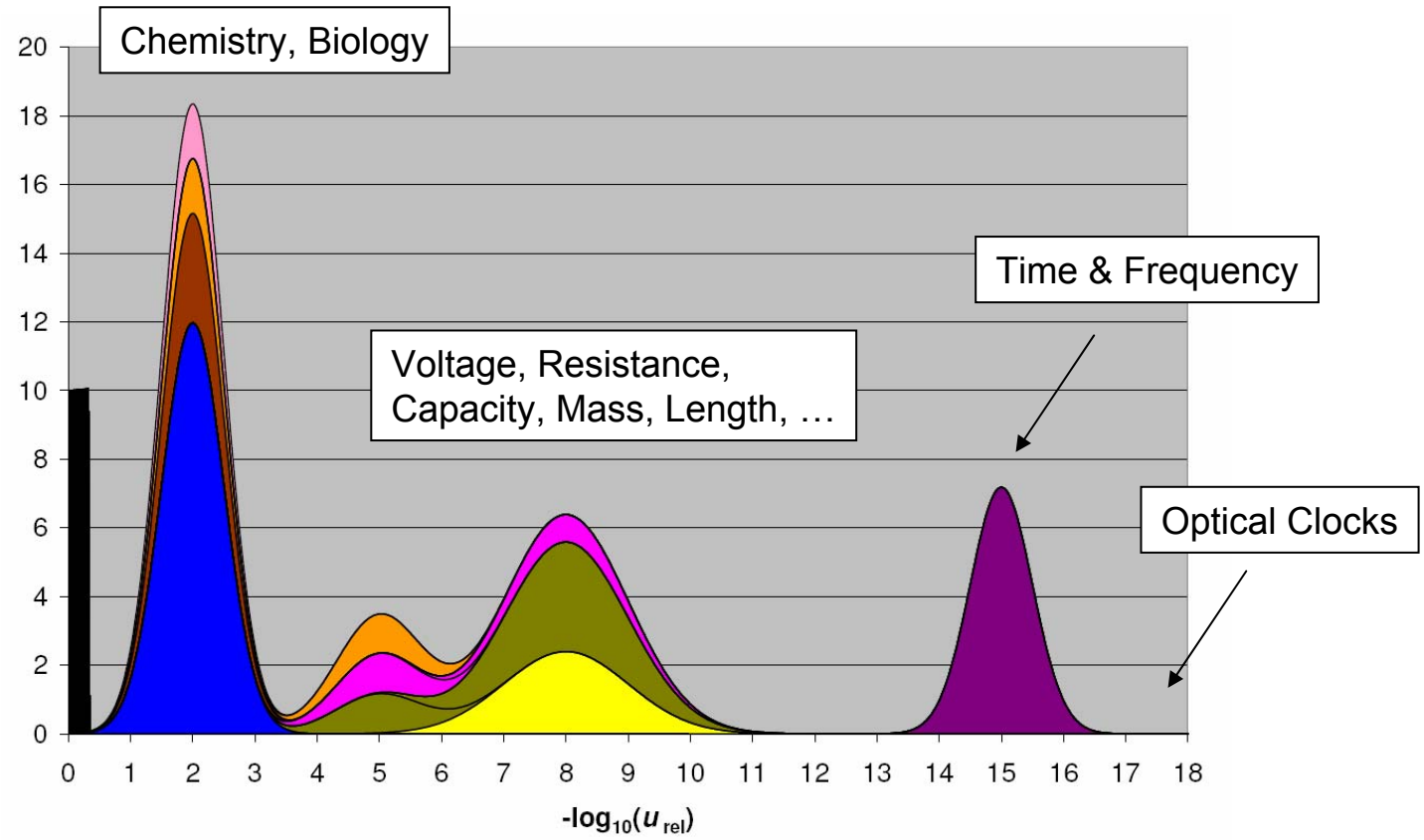




ULE cavity
(Flywheel)

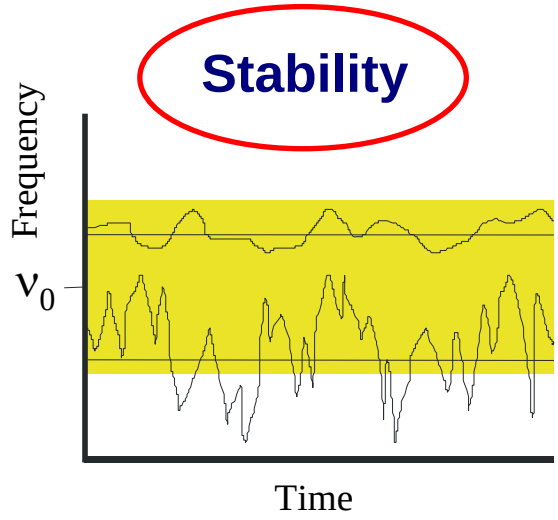
Time & Frequency Metrology

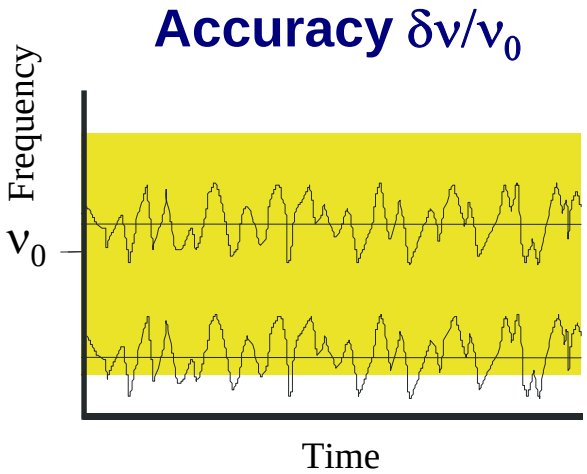
Uncertainty of Quantities in today‘s Metrology



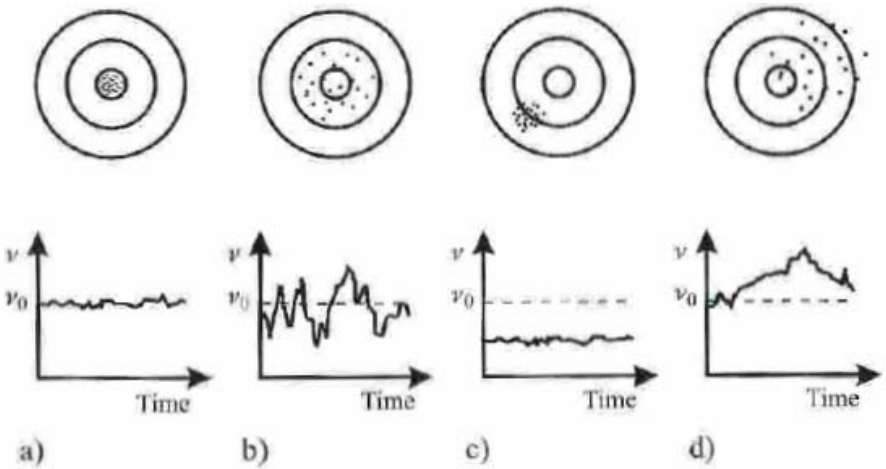
from BIPM Summer School of Metrology 2007

Time and Frequency Metrology





Example:



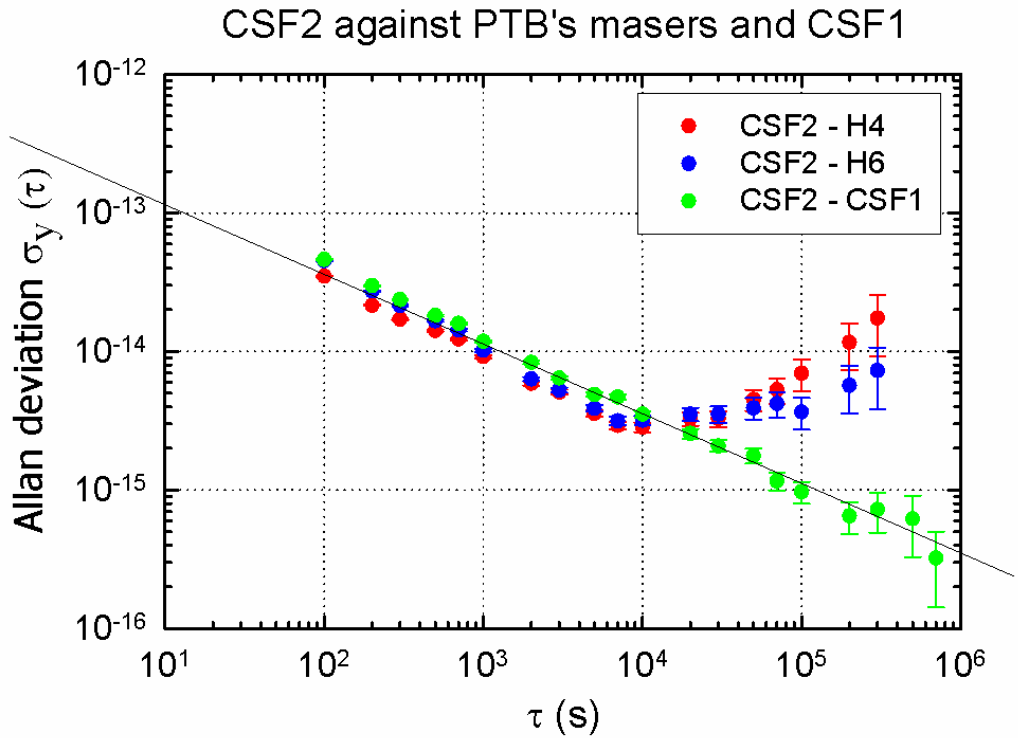
Riehle: Frequency Measurements (2004)

Allan variance

Fractional frequency instability as a function of averaging time

Fractional frequency:

$$y = \frac{f(t) - f_0}{f_0}$$



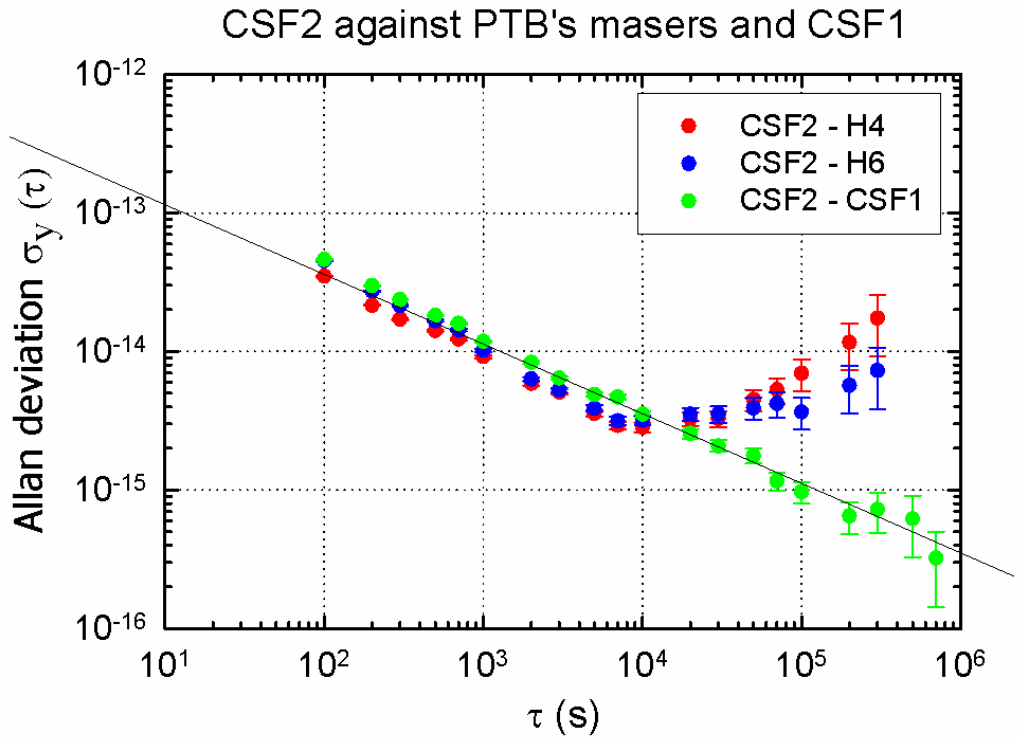
$$\sigma_y^2(\tau) = \left\langle \frac{1}{2}\left(\bar{y}_{i-1} - \bar{y}_i\right)^2 \right\rangle \quad \text{where} \quad \bar{y}_i = \frac{1}{\tau}\int_{t_i}^{t_i+\tau} y(t)\,dt$$

Allan variance

Fractional frequency instability as a function of averaging time

Fractional frequency:

$$y = \frac{f(t) - f_0}{f_0}$$



$$\sigma_y(\tau) = \frac{1}{K \cdot Q \cdot \frac{S}{N}} \left(\frac{T_c}{\tau}\right)^{1/2}$$

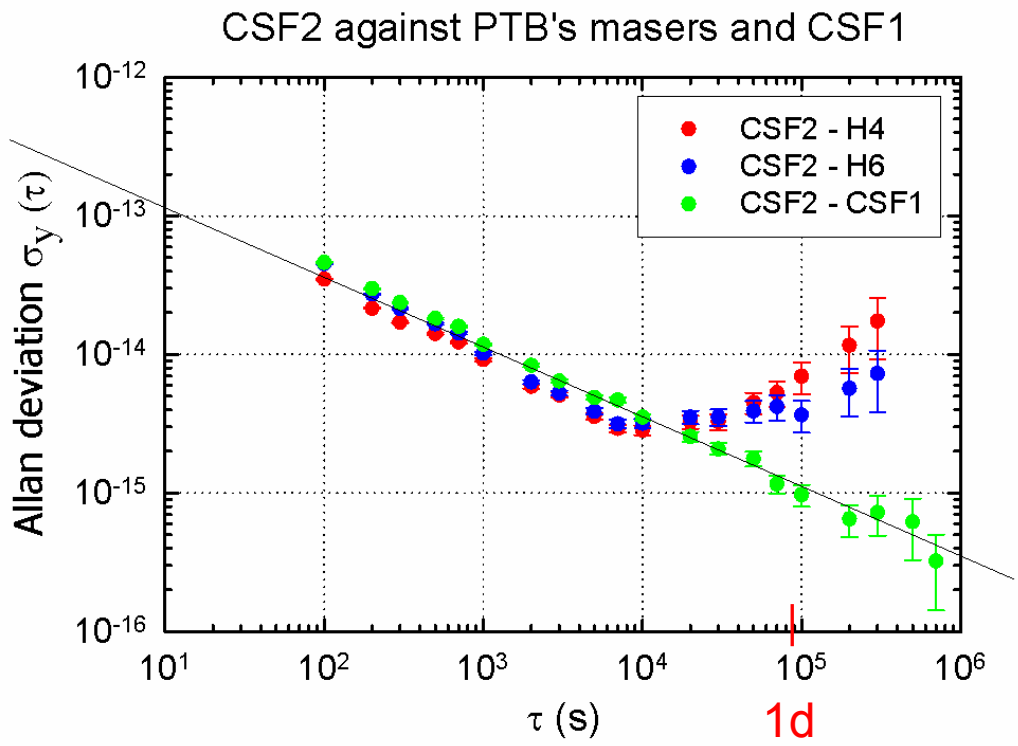
quality factor: $Q = \frac{\nu_0}{\Delta \nu}$

Allan variance

Fractional frequency instability as a function of averaging time

Fractional frequency:

$$y = \frac{f(t) - f_0}{f_0}$$



Stability needed to measure ν_0 with this precision

BUT:
Is it accurate?

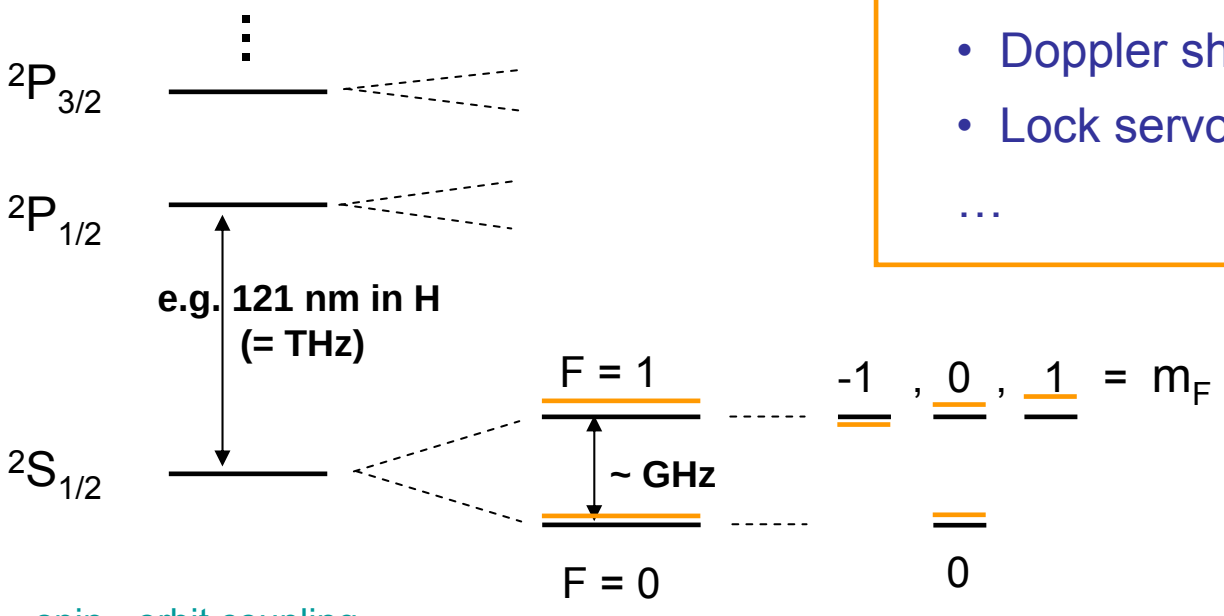
Accuracy / Systematic Errors

Sytematic Shifts can be due to:

- Magnetic Fields
- Electric Fields / Blackbody radiation
- Collisions
- Doppler shifts
- Lock servo errors

…

Example
1e$^-$ atom: S = 1/2
nuclear spin: I = 1/2



spin - orbit coupling
(fine-structure)
$J = |L \pm S|$

HF-structure
$F = |I \pm J|$

magnetic sublevels

Improvement through Optical Clocks

Accuracy $\Delta\nu/\nu_0$

Systematic shifts proportional to ν_0: 1st and 2nd order Doppler shift

Systematic shifts with absolute order of magnitude: 1st and 2nd order Zeemann shift, Stark shifts (blackbody, light shift, etc…)

Stability

Allan Standard Deviation:

$$\sigma = \frac{1}{\pi \cdot S/N} \frac{1}{Q} \sqrt{\frac{T_c}{\tau}} \quad \text{with} \quad Q = \frac{\nu_0}{\Delta\nu}$$

quality factor of transition

$\nu_0 = 9.19 \times 10^9$ Hz $\rightarrow$ $\nu_0 \sim 10^{15}$ Hz

Ingredients of an Optical Clock

(A) Suitable Atoms

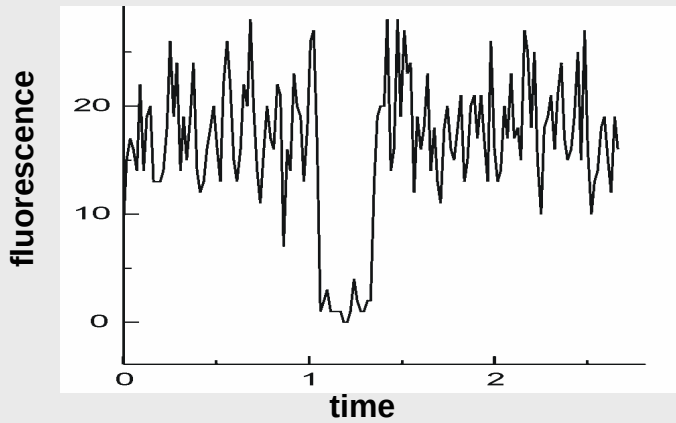
Atomic Transitions

$$\gamma(e \rightarrow g) = \frac{4(2\pi\upsilon_0)^3}{3c^3}\,\alpha\left|\langle e\|d\|g\rangle\right|$$

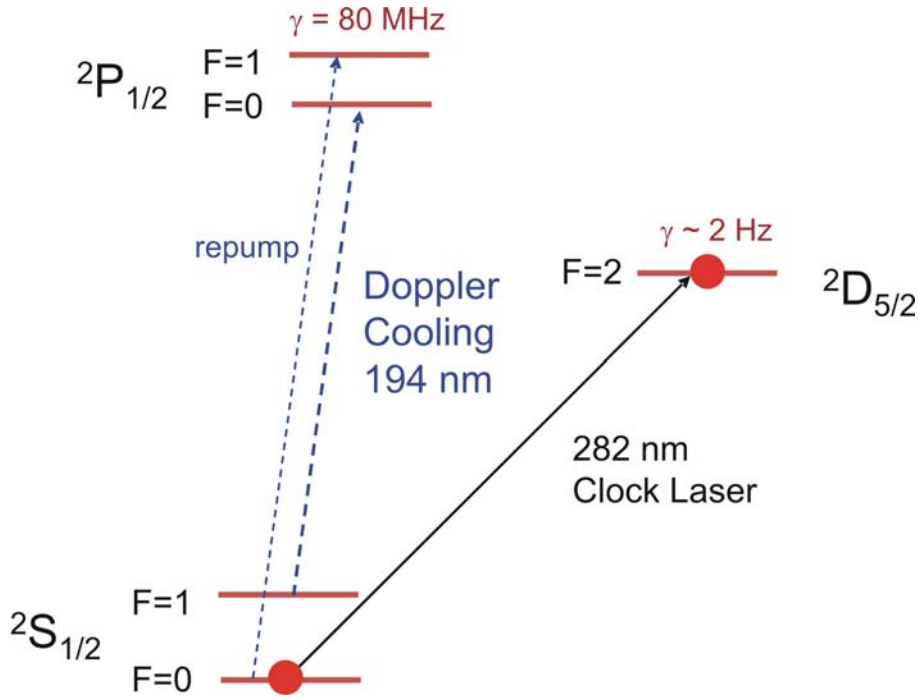
→ forbidden transitions

But how to detect…

Quantum Jumps
(e^- - shelving)



Example $^{199}Hg^+$



Atomic Transitions

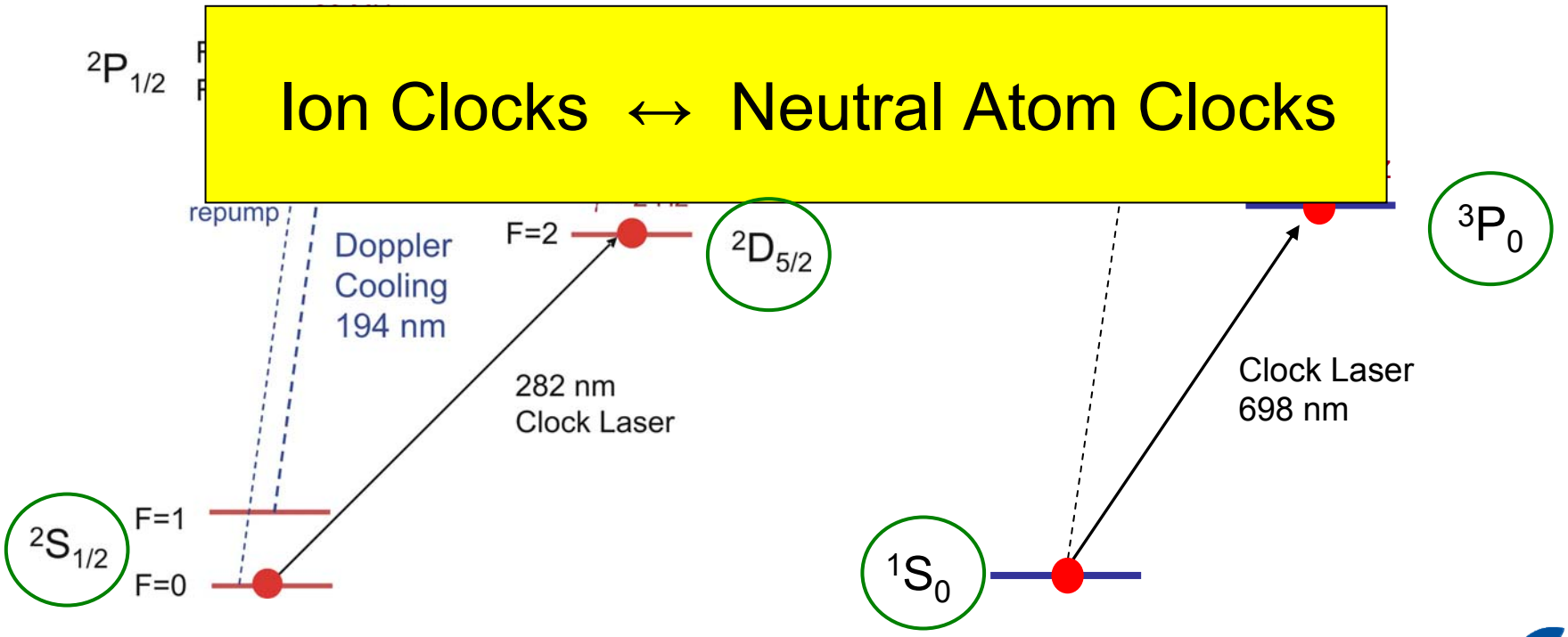
$1e^-$ Systems

$^{199}Hg^+$, $^{171}Yb^+$, etc…

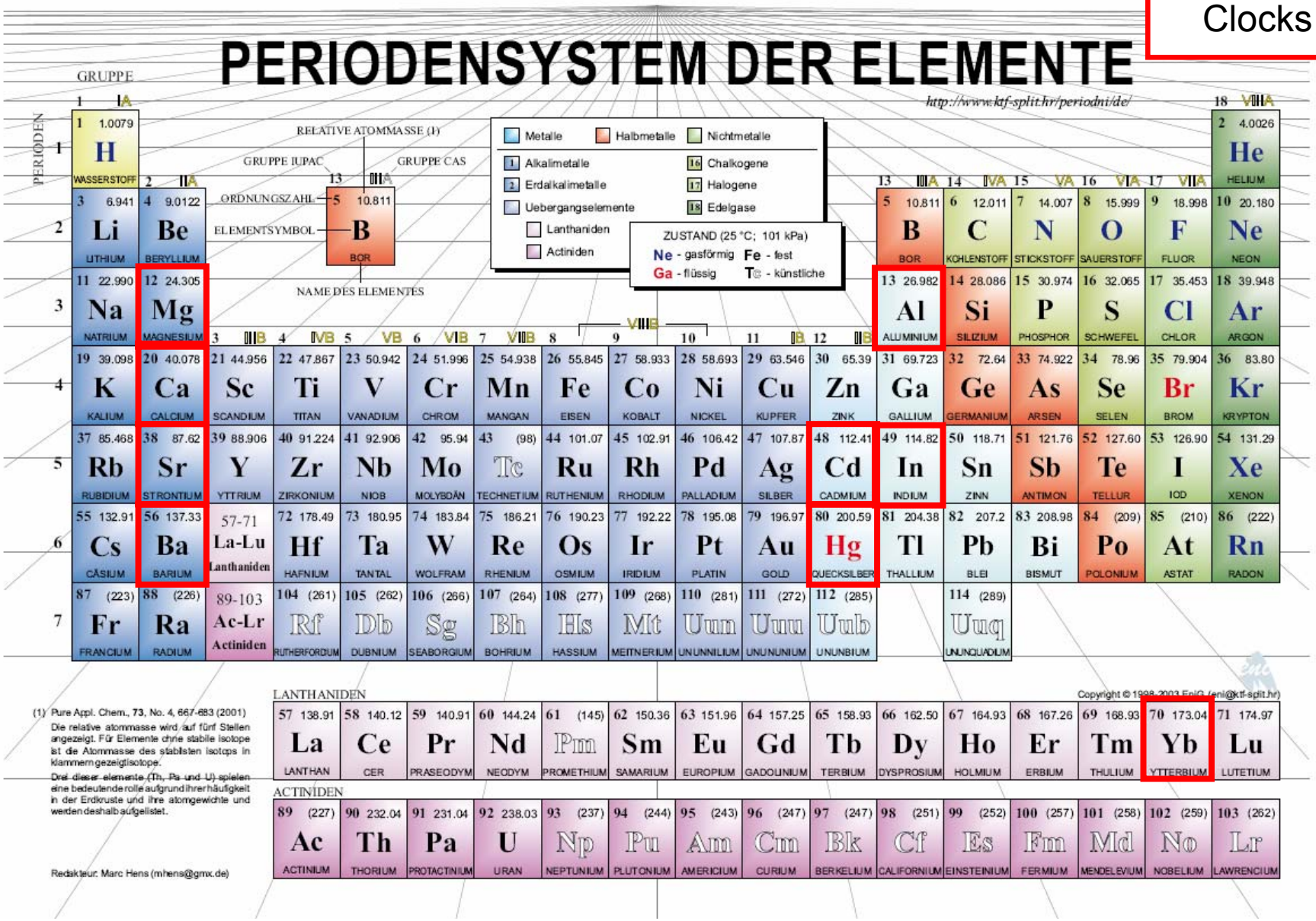
$2e^-$ Systems

^{87}Sr, $^{27}Al^+$, $^{115}In^+$…

Ion Clocks ↔ Neutral Atom Clocks



Clocks

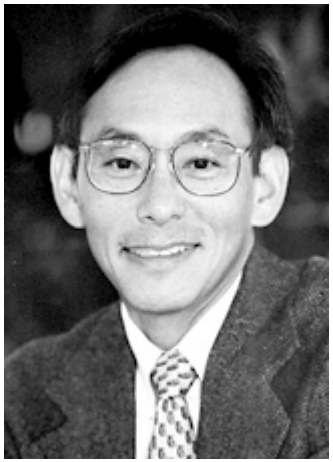

PERIODENSYSTEM DER ELEMENTE
http://www.ktf-split.hr/periodni/de/
GRUPPE
PERIODEN
RELATIVE ATOMMASSE (1)
GRUPPE IUPAC
GRUPPE CAS
ORDNUNGSZAHL
ELEMENTSYMBOL
NAME DES ELEMENTES
Metalle
Halbmetalle
Nichtmetalle
Alkalimetalle
Erdalkalimetalle
Uebergangselemente
Lanthaniden
Actiniden
Chalkogene
Halogene
Edelgase
ZUSTAND (25 °C; 101 kPa)
Ne - gasförmig
Fe - fest
Ga - flüssig
Tc - künstliche
LANTHANIDEN
ACTINIDEN
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Die relative atommasse wird auf fünf Stellen angezeigt. Für Elemente ohne stabile Isotope ist die Atommasse des stabilsten Isotops in klammern gezeigt Isotope.
Drei dieser elemente (Th, Pa und U) spielen eine bedeutende rolle aufgrund ihrer häufigkeit in der Erdkruste und ihre atomgewichte und werden deshalb aufgelistet.
Redakteur: Marc Hens (mhens@gmx.de)
Copyright © 1998-2003 EniG. (eni@ktf-split.hr)

(B) Atom / Ion Traps

Laser Cooling of Atoms

Nobel price 1997

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



Steven Chu

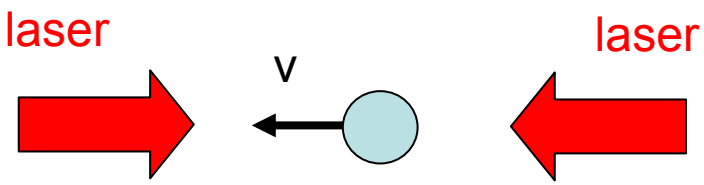
Claude Cohen-Tannoudji

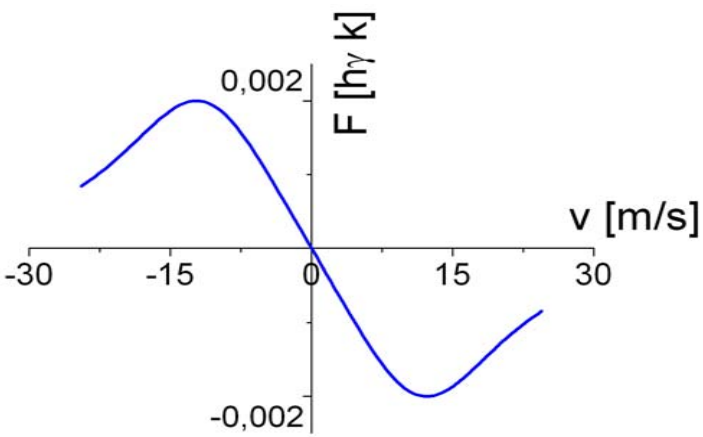
William D. Phillips

Laser Cooling of Atoms

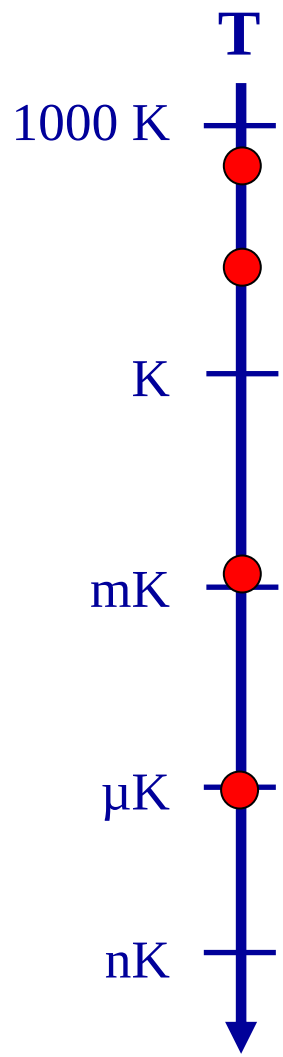
Doppler cooling:

red detuned laser beams
on strong transition γ ~ 1 - 80 MHz





temperature scale
of laser cooling



atomic beam v ~ 700 m/s

300 K: room temperature
v ~ some 100 m/s

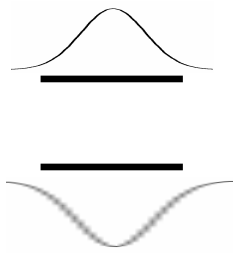
Doppler cooling:

T_{Dopp} ~ 1 mK
v ~ 1 m/s

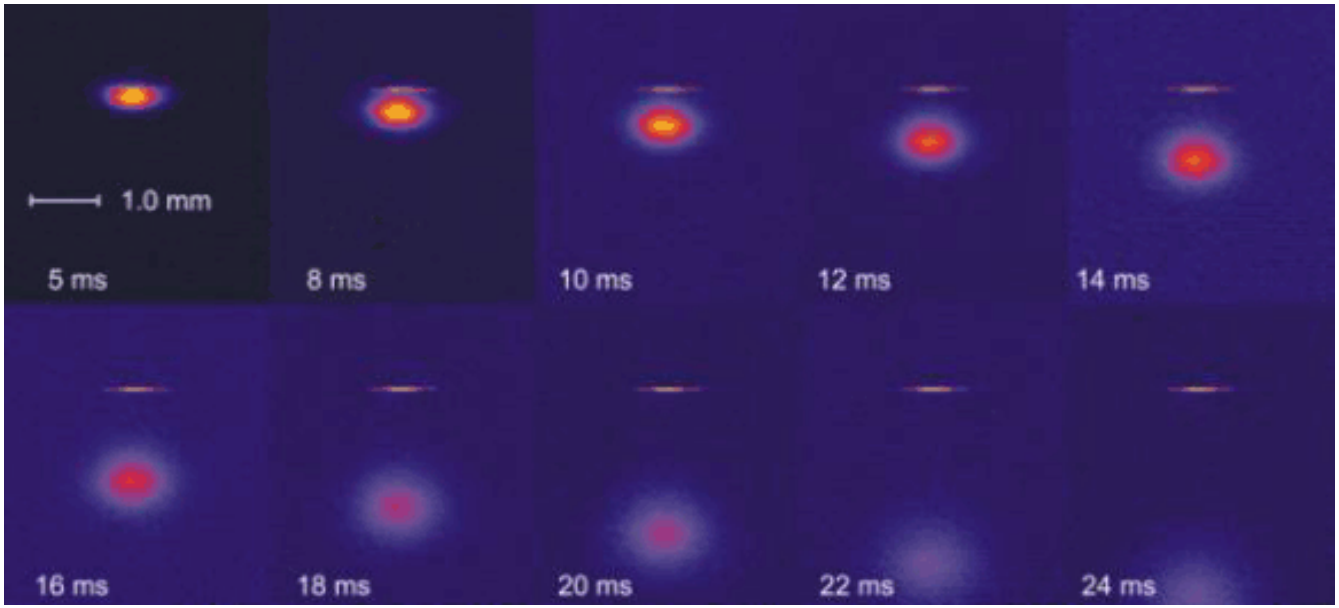
sub-Doppler-cooling:
v ~ 1 cm/s

Evaporation

Optical Dipole Traps for Neutral Atoms



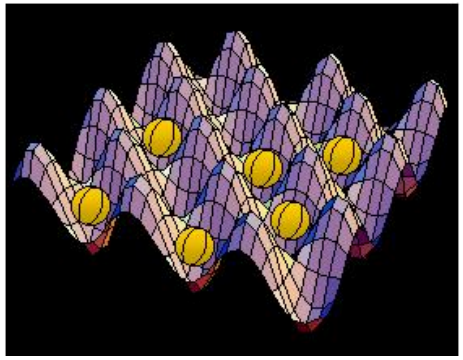
Laser light distorts atomic energy levels

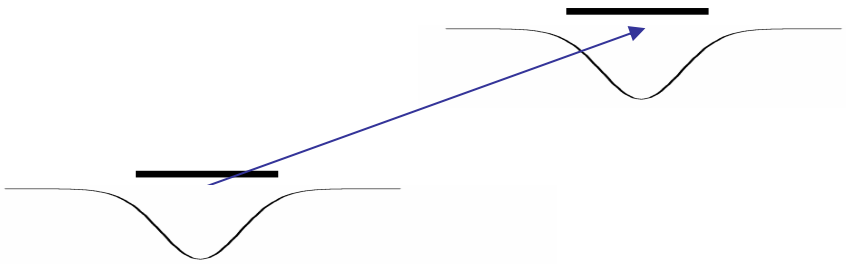


loading of Sr atoms into 1D lattice

Trap Depth ~ 50 µK

The Optical Lattice Clock



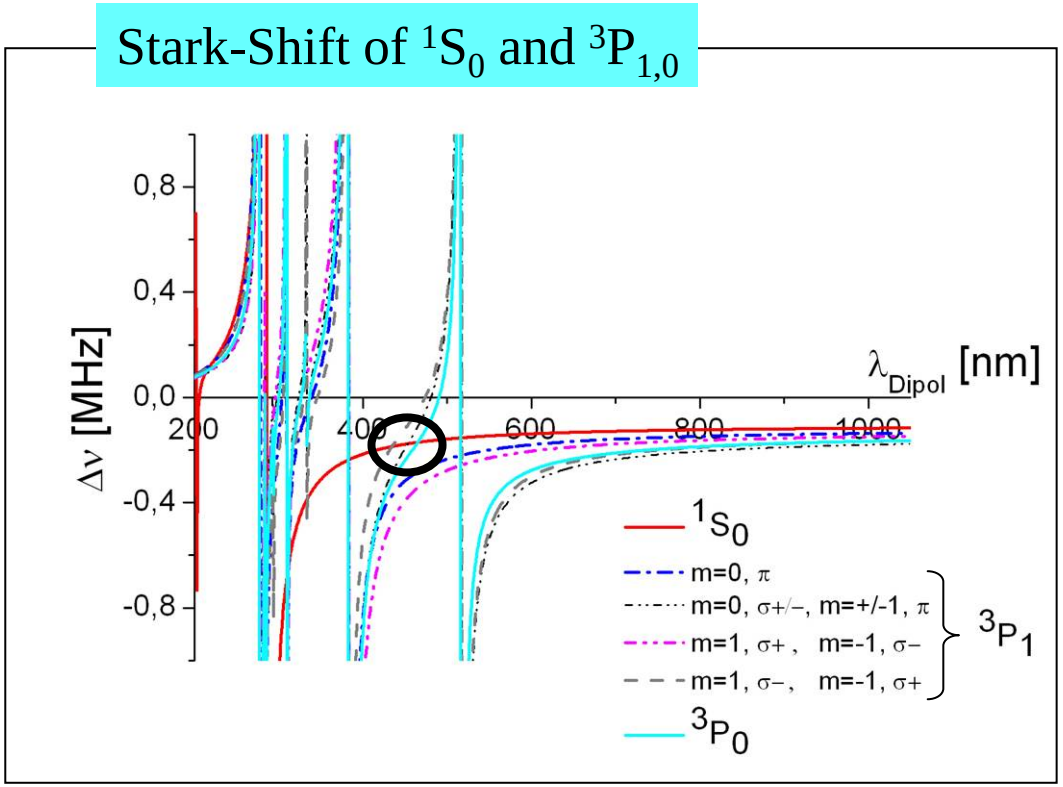


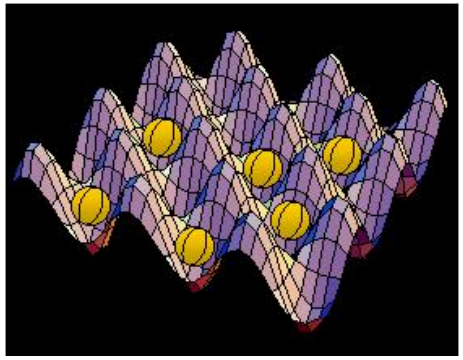
"magic wavelength"(*)

ground and excited state
experience same Stark shift

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

The Optical Lattice Clock





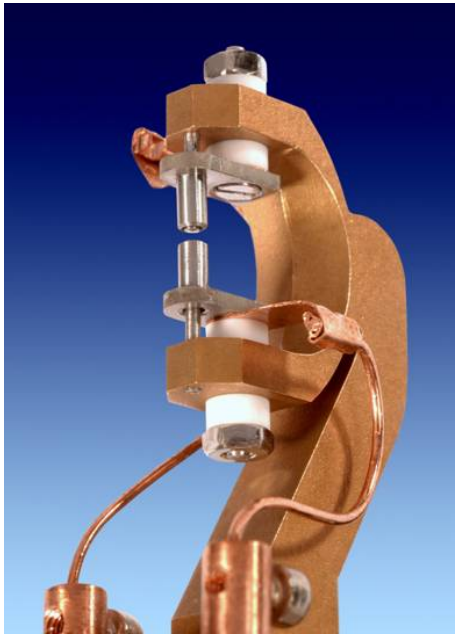
"magic wavelength"(*)

ground and excited state experience same Stark shift

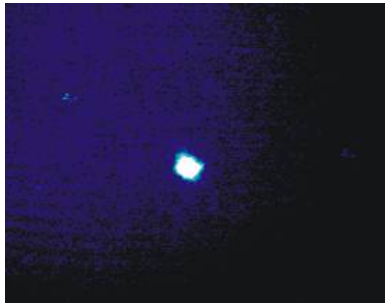
(*) Takamoto *et al.*, Nature **435**, 321 (2005)

Ion Traps

Paul trap



endcap trap



single Yb^+-ion

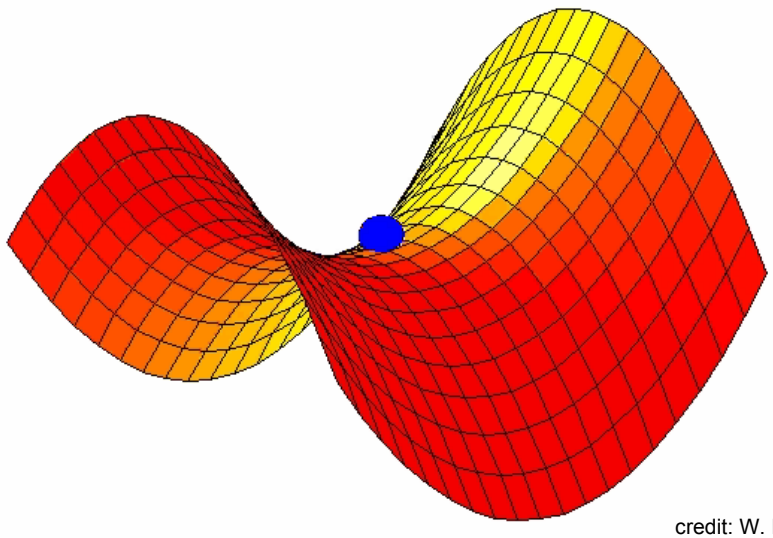
Ion Traps

Charged ions interact strongly with environment → trap with electric fields ?

$$\nabla \phi = \vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} = 0$$

BUT: Non-Trapping Theorem

Trap Depth ~ 10^4 K

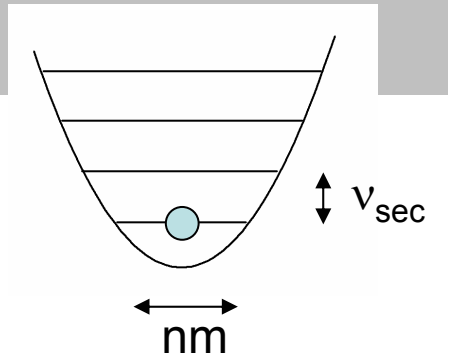


credit: W. Lange

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

Ponderomotive Potential

Ion versus Neutral Atom Clocks



Optical Lattice Clocks with Neutrals

- 10^4 – 10^5 atoms: high S/N
- short servo times
- high stability

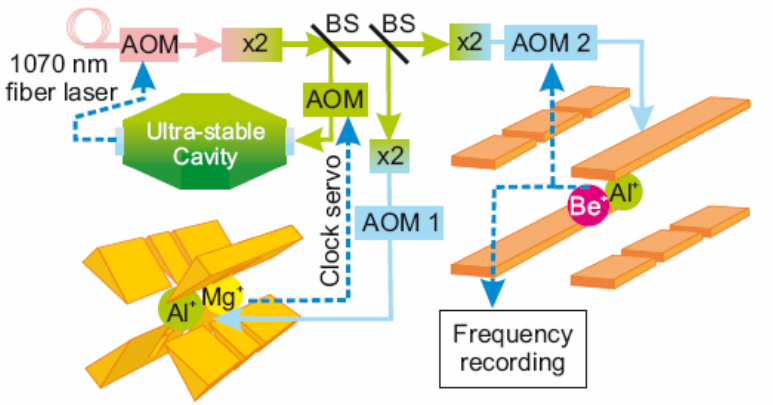
- collisions
- higher order effects in lattice
- polarization dependence of lattice

Single Ion Optical Clocks

- ions are trapped in minimum of EM-field
- high level control of single ion
- no collisions
- storage times up to days/months

- limited short term stability
- higher need for ultra-stable laser

Today‘s State of the Art



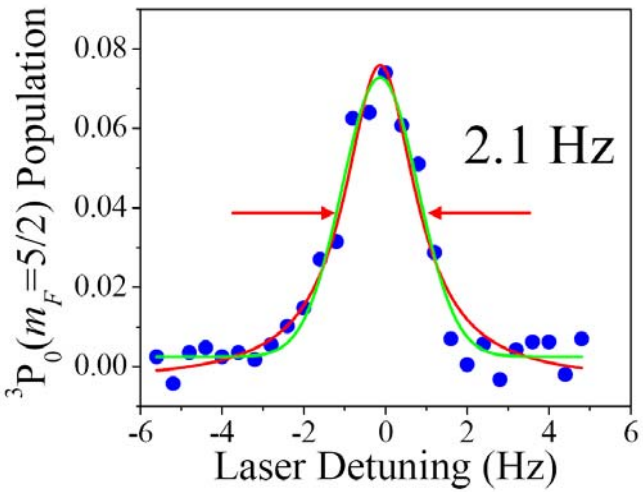
Comparison of 2 ion clocks ($^{27}Al^+/^{27}Al^+$):

- inaccuracy = 7.0×10^{-18}
- stability $\sigma \sim 2.0\times10^{-15}$ in 1s

Chou et al., PRL **104**, 070802 (2010)

NIST and now at PTB (see P. Schmidt‘s talk)

Best resolved atomic resonance (^{87}Sr):



Sr/Ca comparison (JILA/NIST):

- inaccuracy = 1.5×10^{-16}
- stability $\sim 3\times10^{-15}$ in 1s

Paris, Boulder, Tokyo, Braunschweig, London, Florence, Moscow, …

A. Ludlow et al. Science **319**, 1805 (2008)

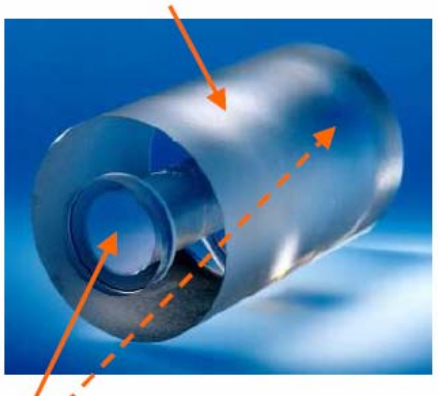
(C) Local Oscillator

The Reference Cavity

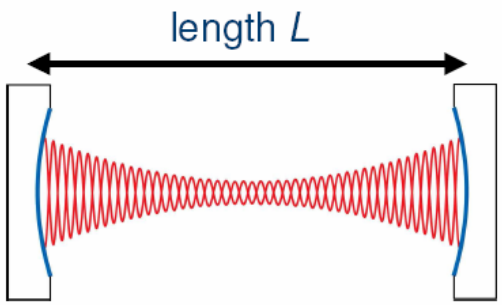
Ultra-low expansion (ULE) glass:

- Coefficient of thermal expansion < 20 ppb/K
- Zero crossing close to room temperature

Spacer: 10 cm length



Optically contacted mirrors
with Finesse F > 100,000



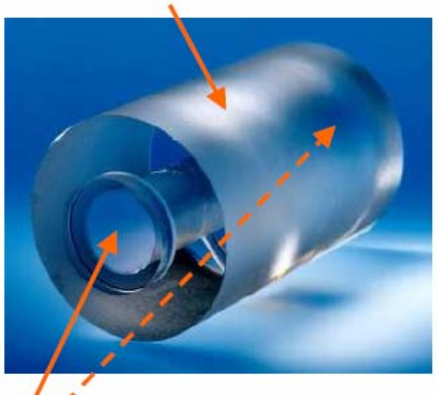
Linewidth:
$\Delta f = FSR/ F \sim 15$ kHz

The Reference Cavity

Ultra-low expansion (ULE) glass:

- Coefficient of thermal expansion < 20 ppb/K
- Zero crossing close to room temperature

Spacer: 10 cm length



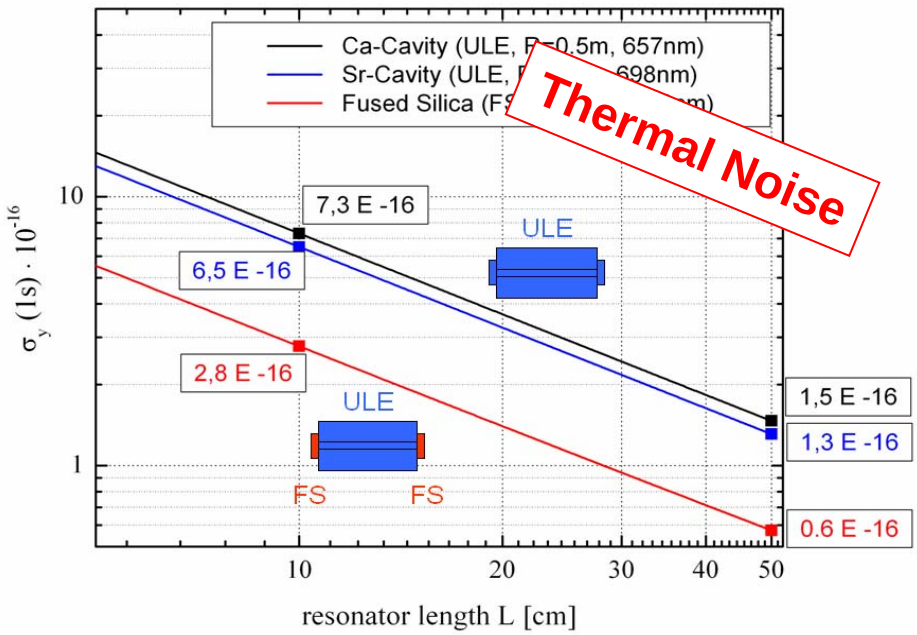
Optically contacted mirrors
with Finesse F > 100,000

1 Hz laser width:

$\sigma_\nu/\nu_0 = 3\times10^{-15}$

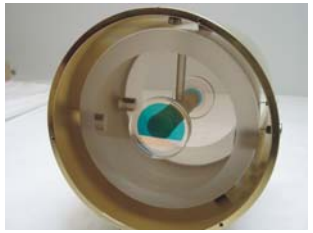
$\sigma_L = 3\times10^{-16}$ m

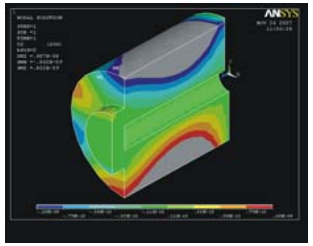
Cavity Designs

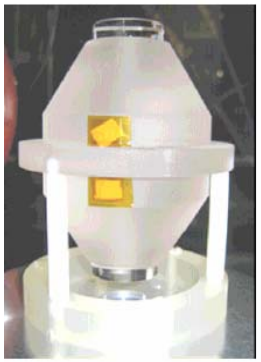


calculation Th. Legero, PTB

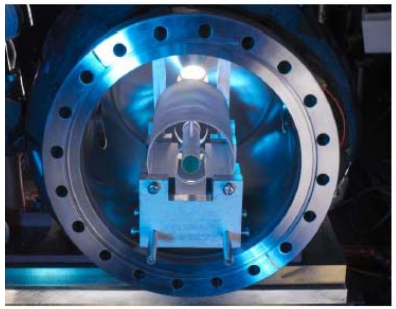
PTB horizontally mounted cavity
Nazarova *et al.*
„Vibration-insensitive reference cavity for an ultra-narrow-linewidth laser“
Appl. Phys. B 83, 531 (2006)







JILA vertical cavity
Notcutt *et al.*
„Compact, thermal-noise-limited optical cavity for diode laser stabilization at 1x10^{-15}“
Optics Lett. 32, 641 (2007)



NPL cut-out cavity
Webster *et al.*
„Vibration insensitive optical cavity“
PRA 75, 011801 (R) (2007)

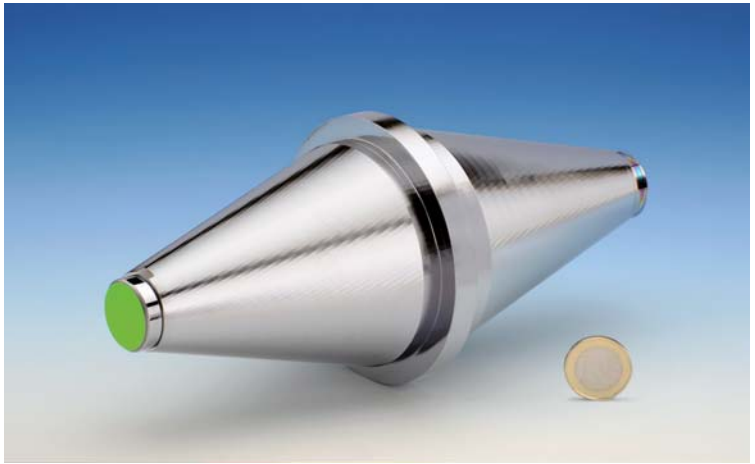
Sub-Hz Lasers?

QUEST RP

Reduction of thermal noise in high performance optical reference cavities

Silicon as resonator material

Alternative mirror concepts



Material	Q	T_0 (K)	$d\alpha/dT$ (K^{-2})	Opt. transp
Si	5×10^7	120	$2.3\ 10^{-8}$	IR
Si		17	$1.2\ 10^{-9}$	
ULE	6×10^4	293	$2.4\ 10^{-9}$	VIS

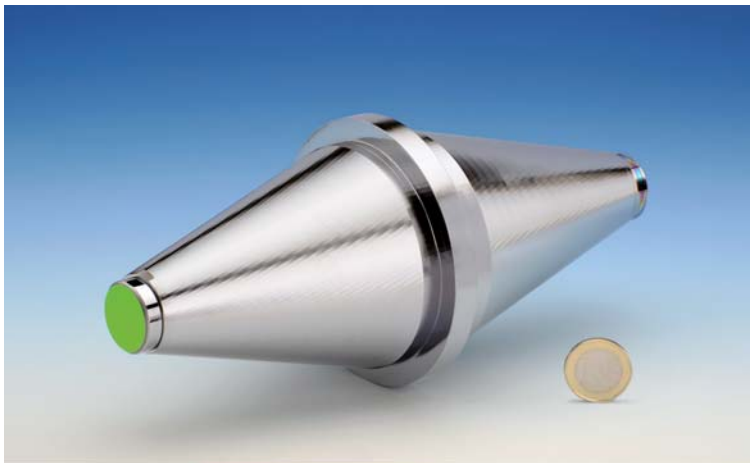
Sub-Hz Lasers?

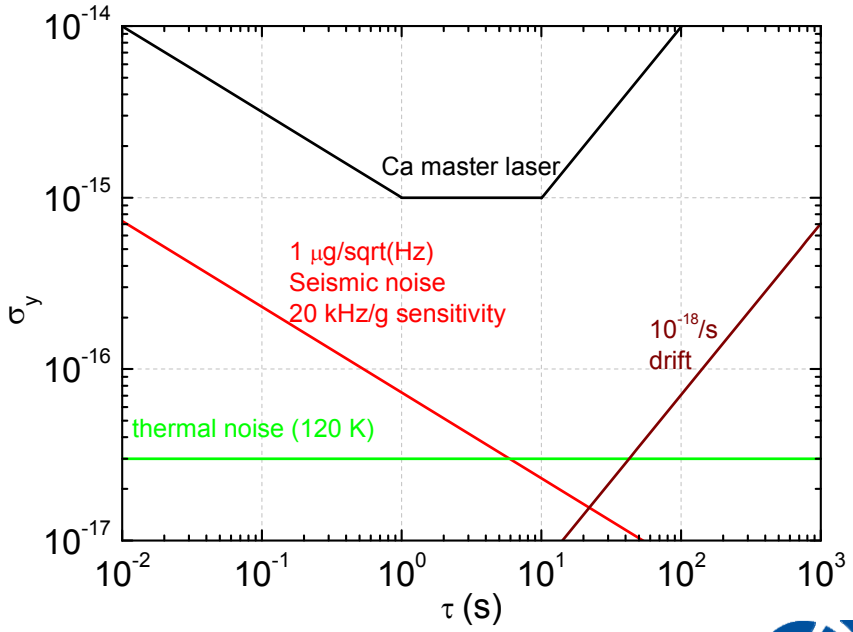
QUEST RP

Reduction of thermal noise in high performance optical reference cavities

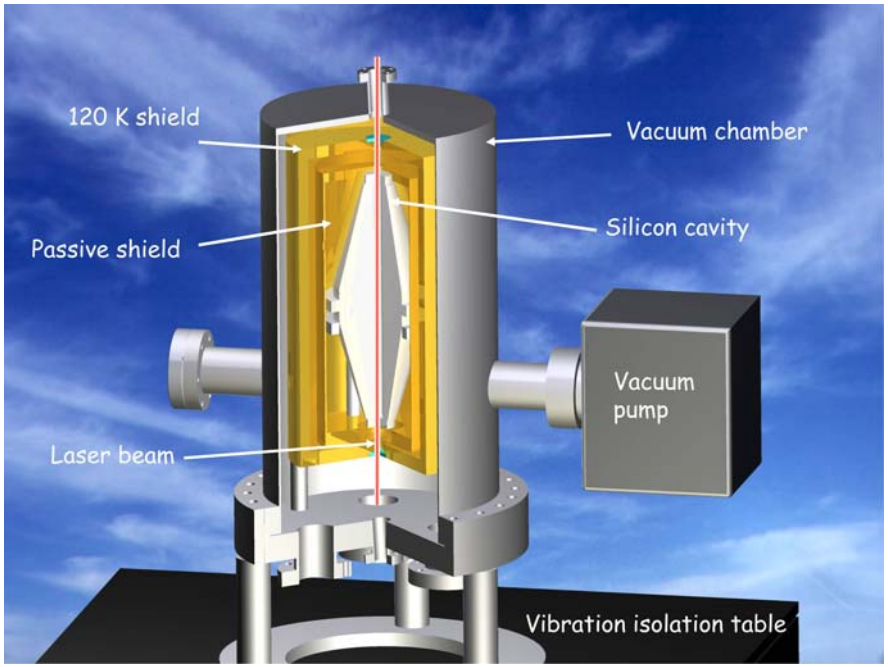
Silicon as resonator material

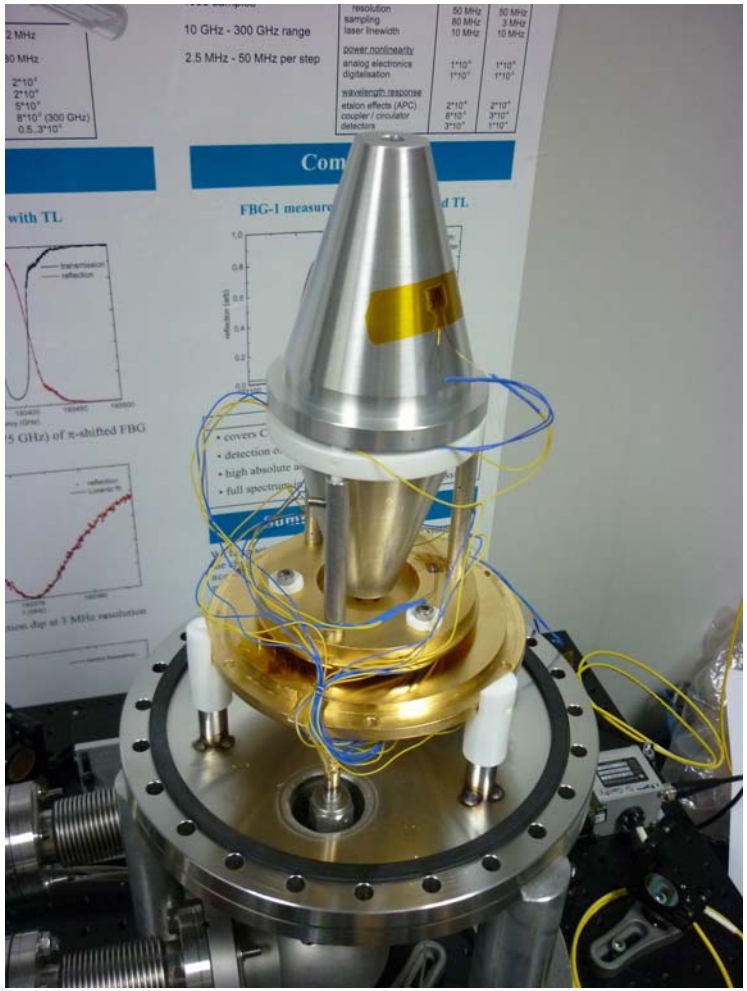
Alternative mirror concepts





Experimental Setup





(D) Frequency Combs

Optical Frequency Combs

Nobel price 2005

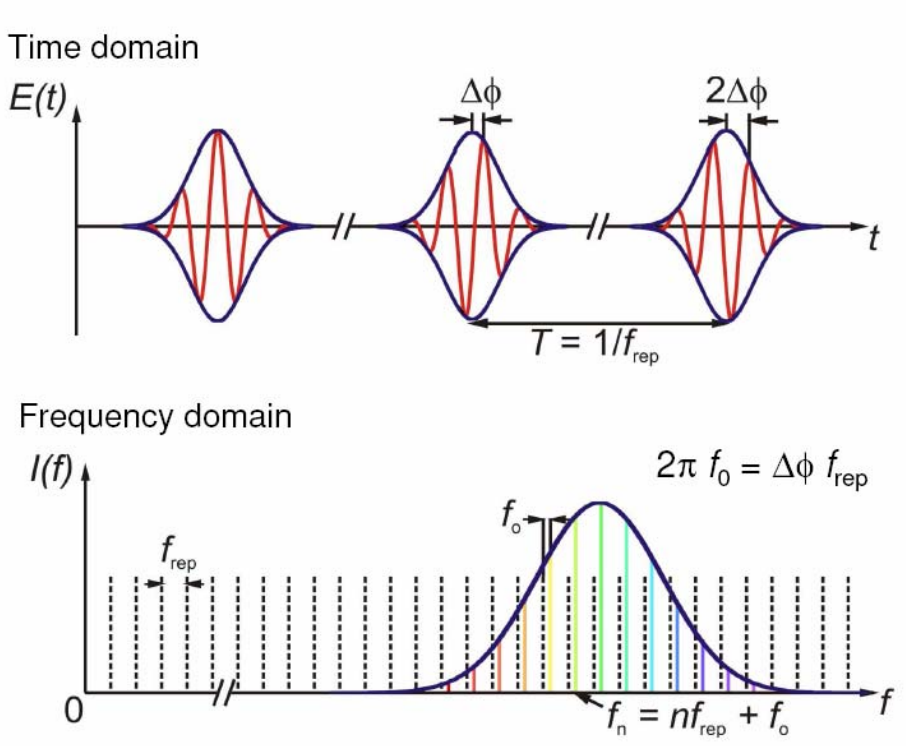
"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

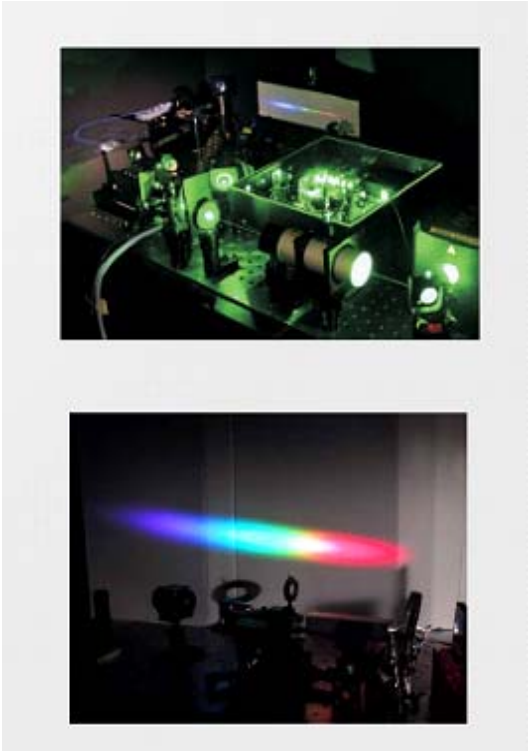
John L. Hall

Theodor W. Hänsch

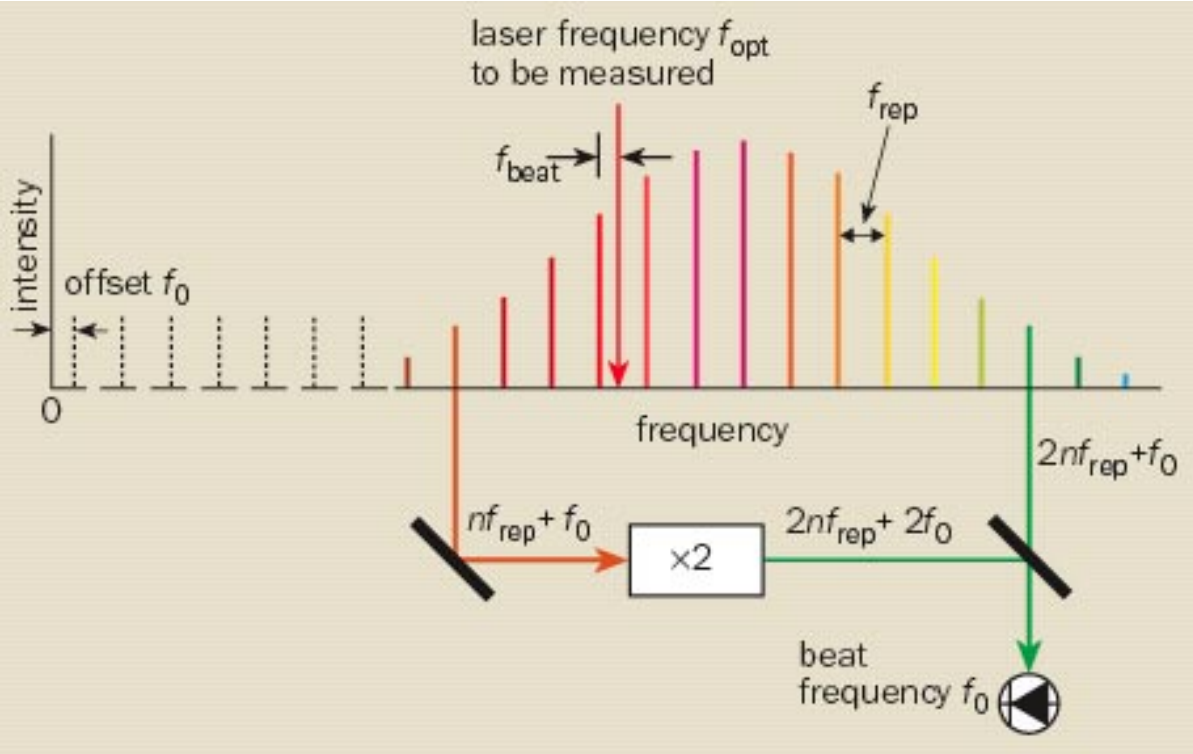
Optical Frequency Combs

- Mode locked Ti:Sapphire or Er-Fiber Lasers
- pulse duration 1 - 10 fs → f_{rep}= 100 MHz – 1 GHz





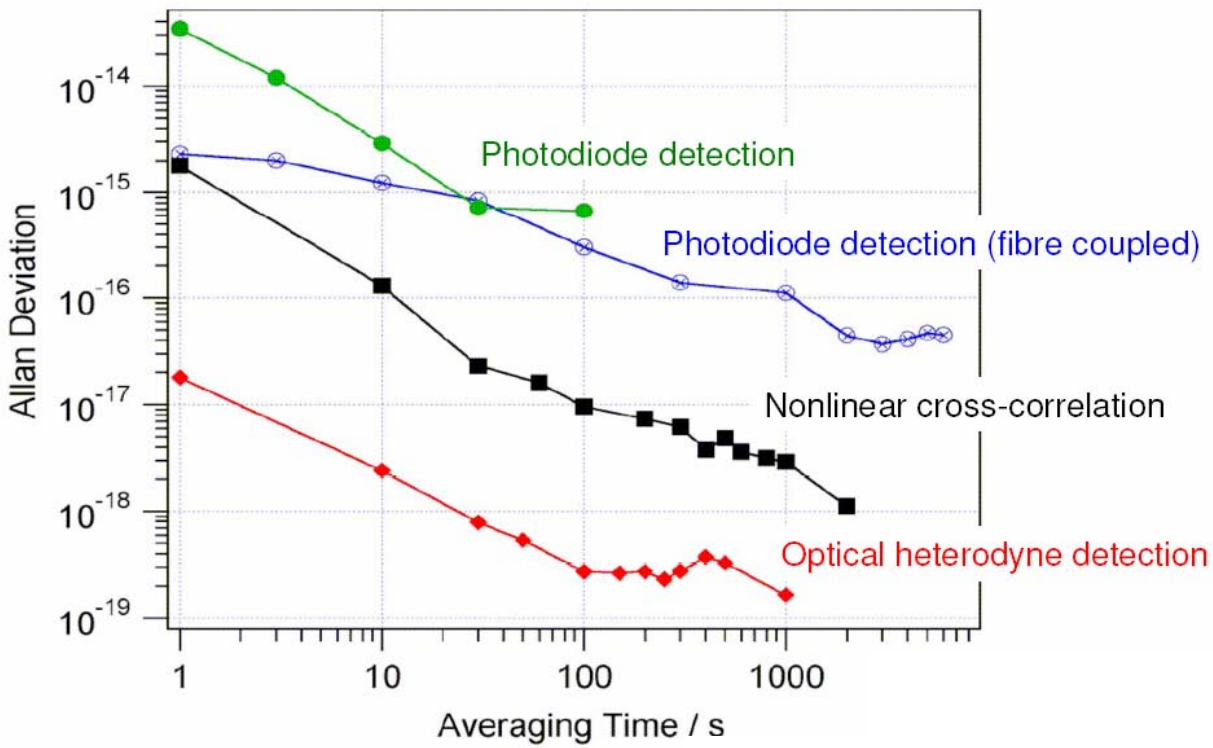
Optical Frequency Combs



$$f_{probe} = m\, f_{rep} \pm f_0 \pm f_{beat}$$

- ✓ m measured with wavemeter
- ✓ f_{rep} locked to Cs-fountain
- ✓ f_0 by beating ground & 2nd harmonic

Optical Frequency Combs



→ Required accuracy and stability for optical clock comparison has been demonstrated!

Ma et al., IEEE J. Quant. Electron. 43, 139 (2007)

Optical Frequency Combs

Applications and Future Developments

Clocks and Navigation

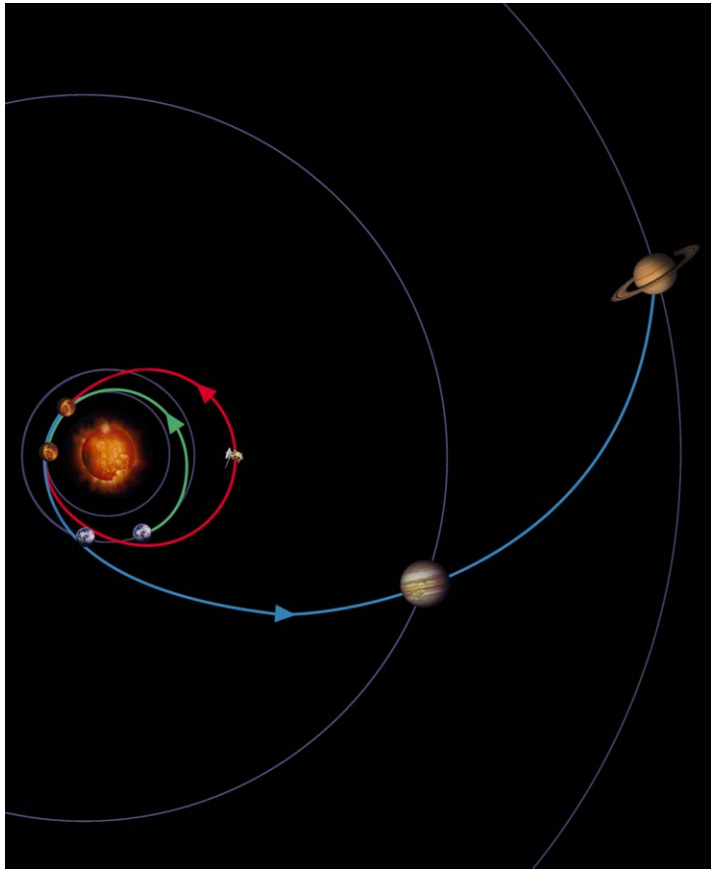
- Optical Clock in Ground Stations: Deep space missions
- Master Clock in Space: GNSS
  - improved location resolution
  - integrity of space segment, smaller prediction errors

Scenario	Satellite time	System time	Theoretical error over 2 hours / ns
I	Rubidium clock	Optical clock	0.59
II	Passive maser	Optical clock	0.11
III	Optical clock	Active maser	0.014
IV	Optical clock	Optical clock	0.002

Simulations by Institute of Communications & Navigation (DLR)

ESA study contract 19837/06/F/VS

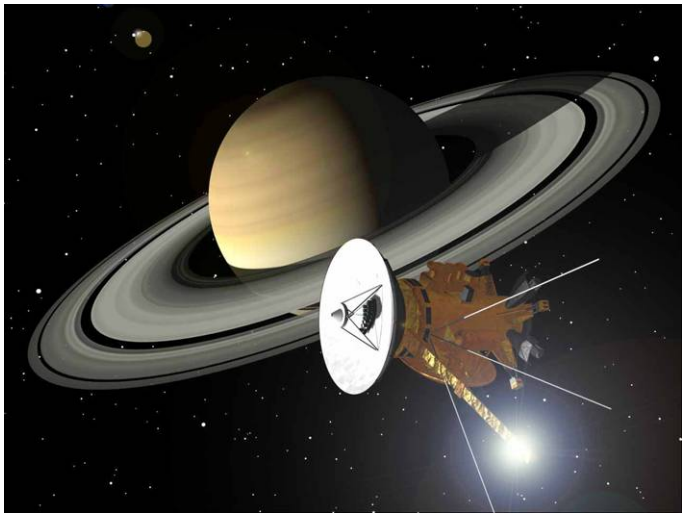
Clocks and Navigation



1997: Lift-off of Cassini - Huygens probe → Saturn (2004)

4 Swingbys near Venus,
Jupiter, Earth at 300 km distance

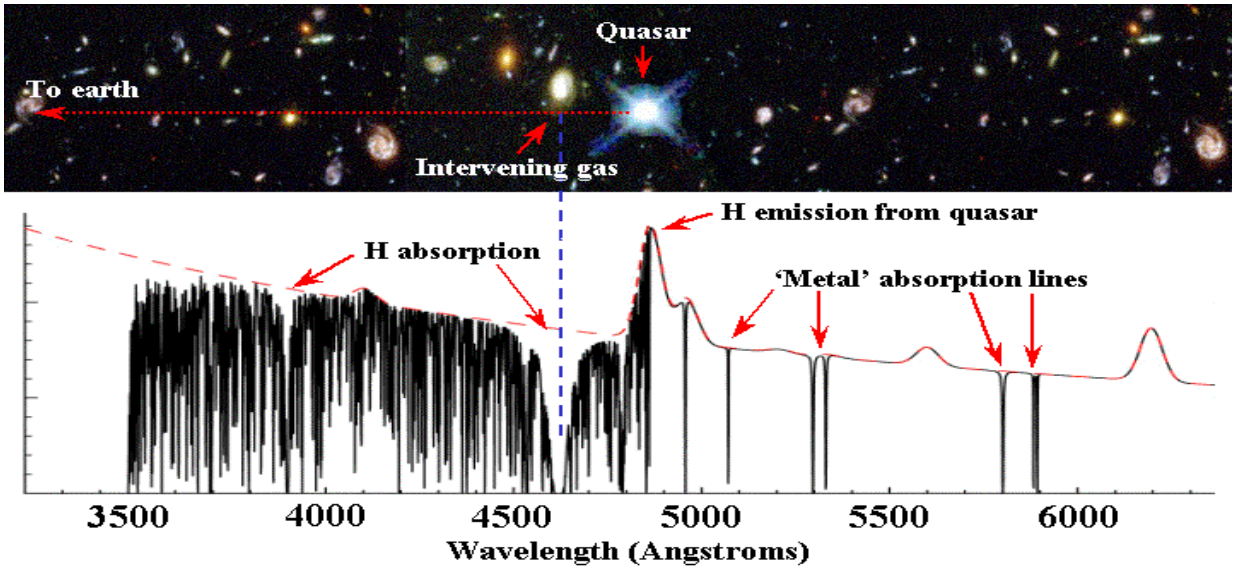
Required accuracy: ±25 km



Are fundamental constants really constant?

TG 4

Equivalence Principle: fundamental constants need to be constant in time



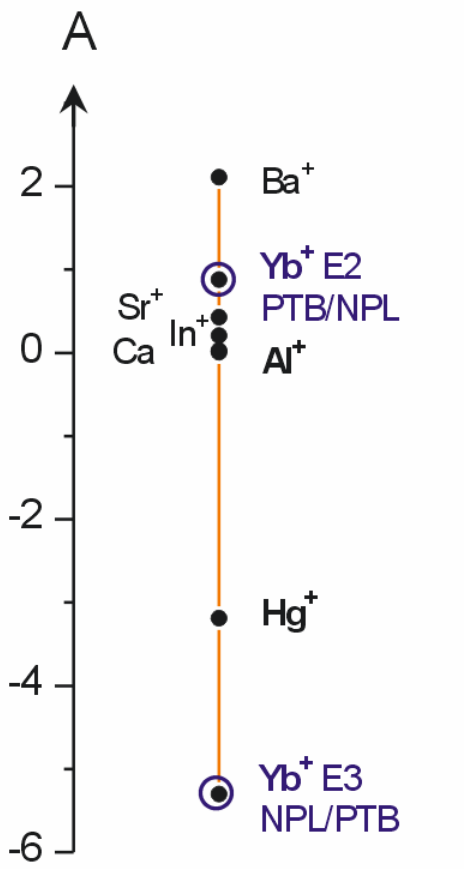
$$\Delta\alpha/\alpha \qquad \left(-5.4 \pm 1.2\right) \times 10^{-6}$$

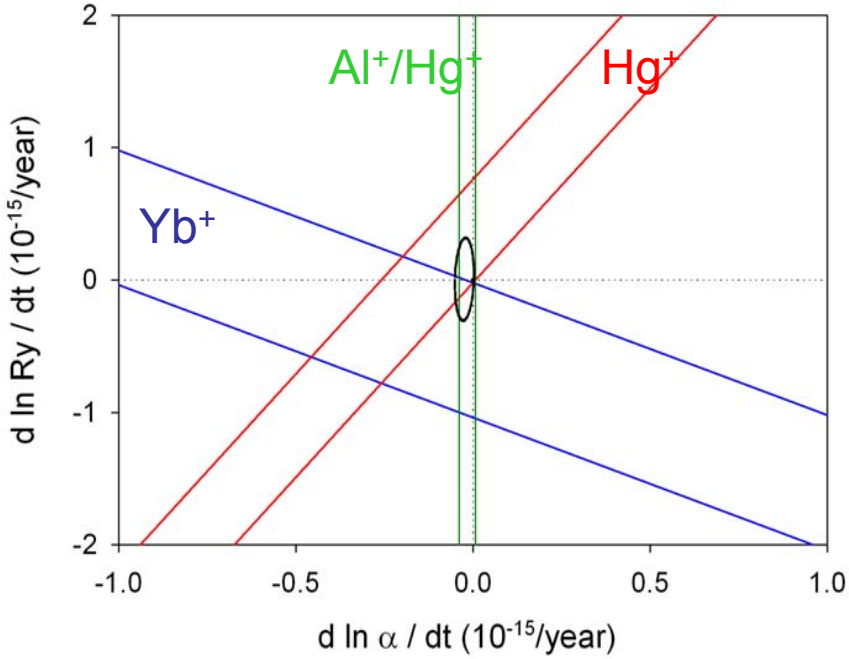
$$\Delta\mu/\mu \qquad \left(2.6 \pm 0.6\right) \times 10^{-5}$$

Reinhold *et al.*, PRL **96**, 151101 (2006)
Murphy *et al.*, Mon. Not. R. Astron. Soc. **345**, 609 (2003)

Laboratory Tests

TG 4





Present status:

$$\frac{\partial \ln \alpha}{\partial t} = (-2.4 \pm 2.7) \cdot 10^{-17}\ \mathrm{yr}^{-1}$$

$$\frac{\partial \ln Ry}{\partial t} = (0.0 \pm 3.2) \cdot 10^{-16}\ \mathrm{yr}^{-1}$$

Dzuba *et al.* PRL **82** (1999)

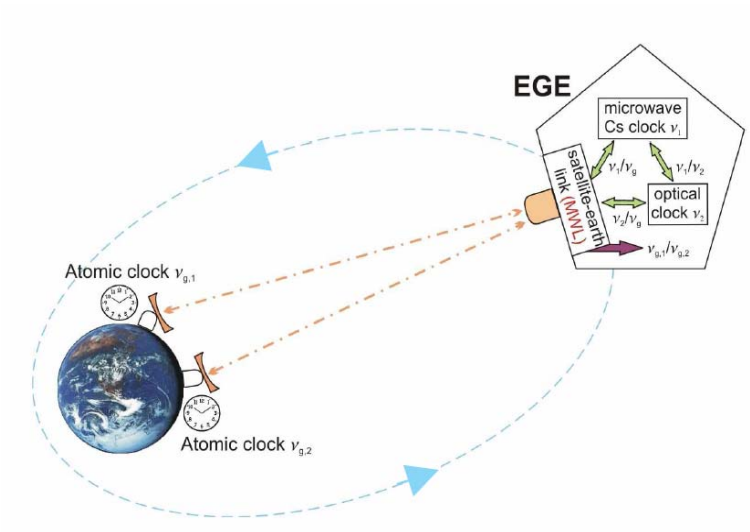
Al+/Hg+: T. Rosenband *et al.*, Science **319**, 1808 (2008)

Gravitational Redshift

Shift of clock transition: $$Z \equiv \frac{\Delta \upsilon}{\upsilon} = (1+\varepsilon)\frac{\Delta U}{c^2}$$

non-zero if local position invariance doesn't hold

ε tested to be < 7×10^{-5}



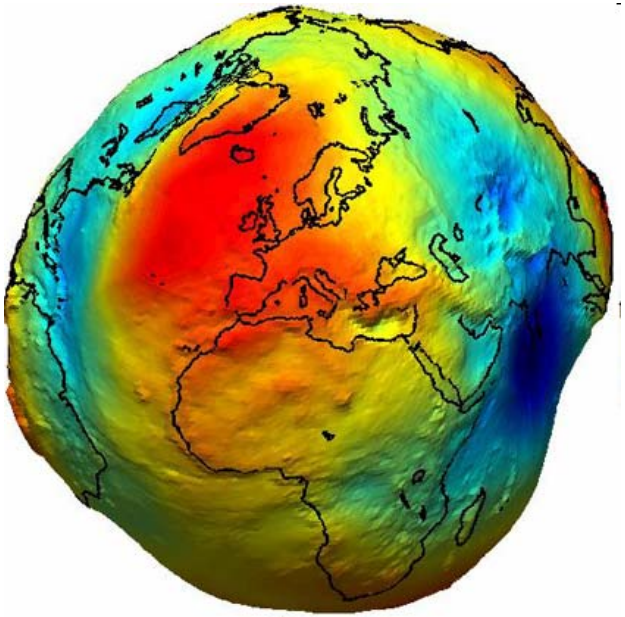
Einstein Gravity Explorer (EGE)

could provide test at the 2×10^{-8} level

Schiller, Tino, Gill, Salomon et al. (2007)

Geodesy at 10^{-18}

- Direct measurement of earth's geopotential
- Current uncertainty: 30 - 50 cm



→ resolve height difference

of 1 cm

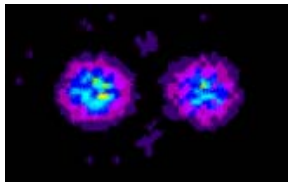
- Tracking tectonic plate movement 2-20 cm/yr

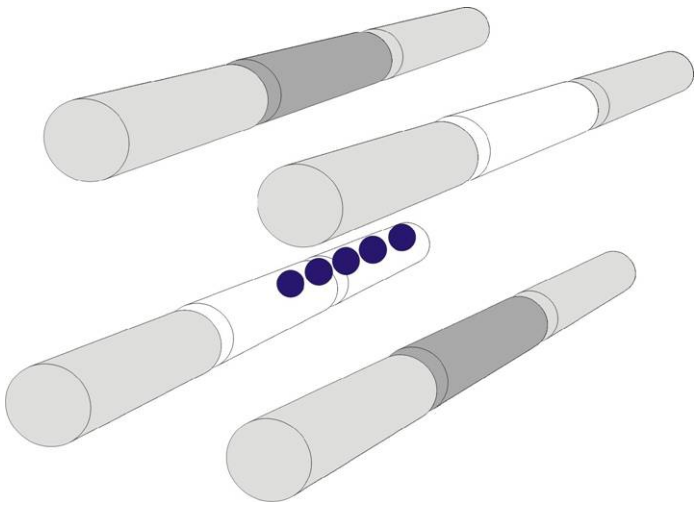
→ $\Delta v \sim 1$ cm/yr

Future Challenges

- Reliability (compact, portable clocks)
- Non destructive detection in optical lattice
- Can we use more than one ion? – new ion trap designs
- Entangled atoms / ions?
- Quantum logic clocks

$$\Delta \upsilon_{Quad} \propto \nabla E \cdot \Theta = 0$$

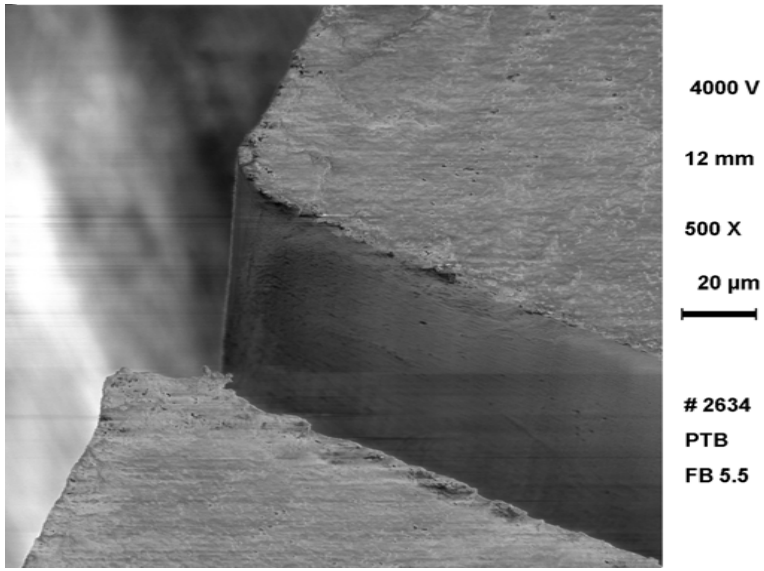




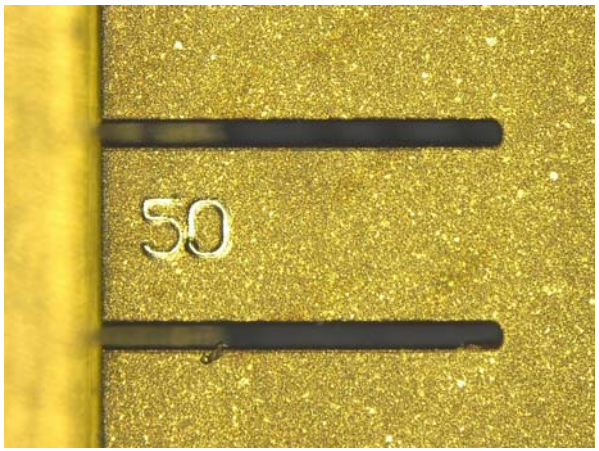
linear trap

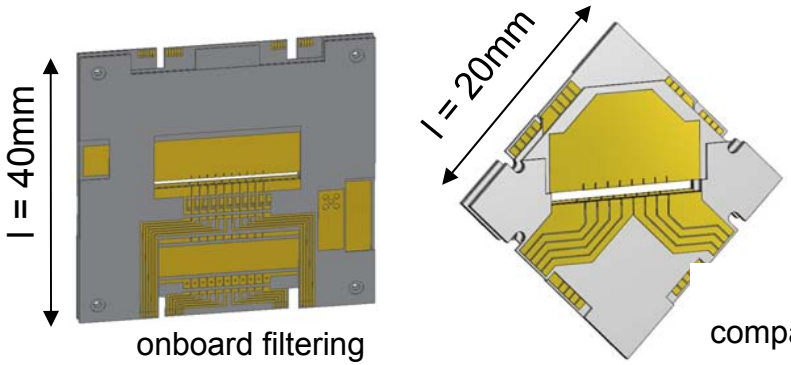
Scalable Chip Traps

- Laser cutting with pulsed 10ns tripled YAG at 355nm
- Low RF-loss AlN / sapphire wafer
- Au, Nb, Mo metalization



First test with ns-pulsed YAG-laser at PTB

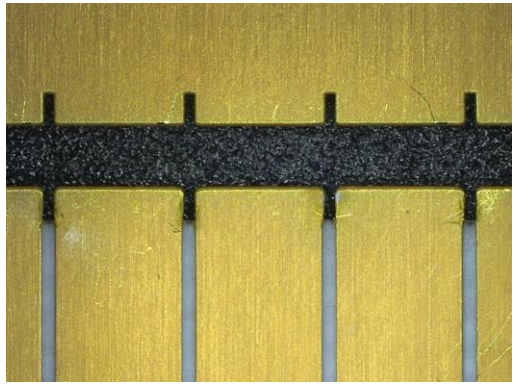




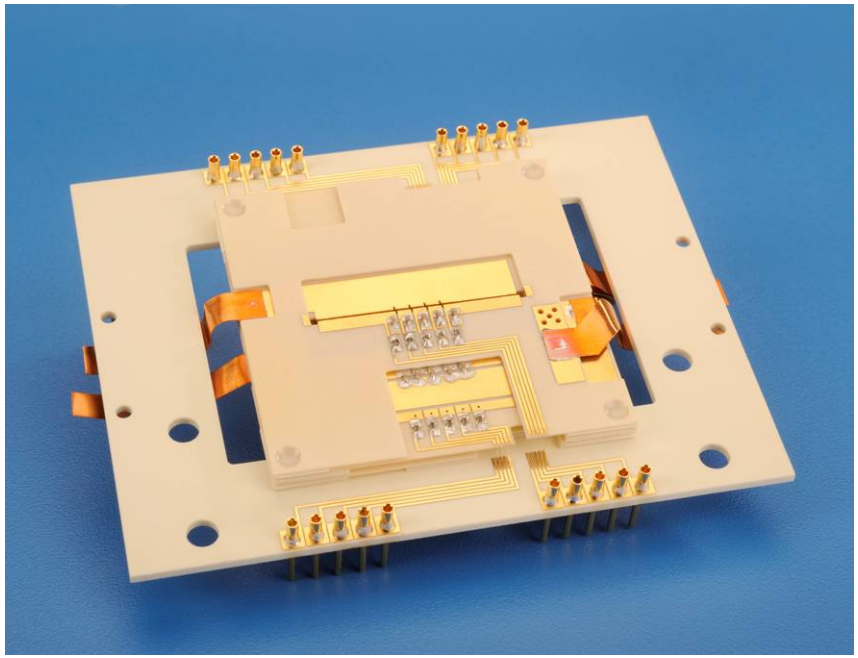
onboard filtering

mounted on compact chip carrier

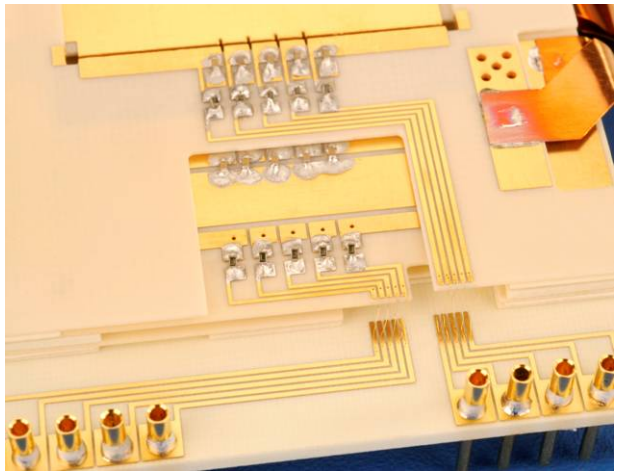
First Prototype (Rogers 4350B)



laser cut electrodes



stack of glued PC boards with
laser cut electrodes

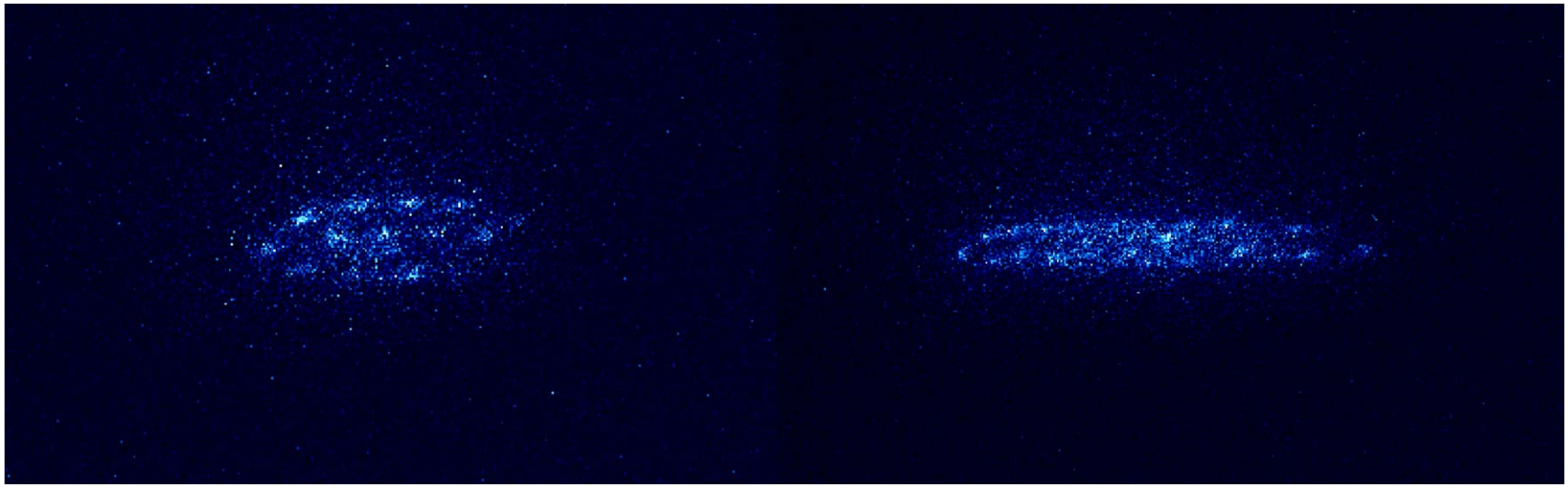


low pass 110 Hz

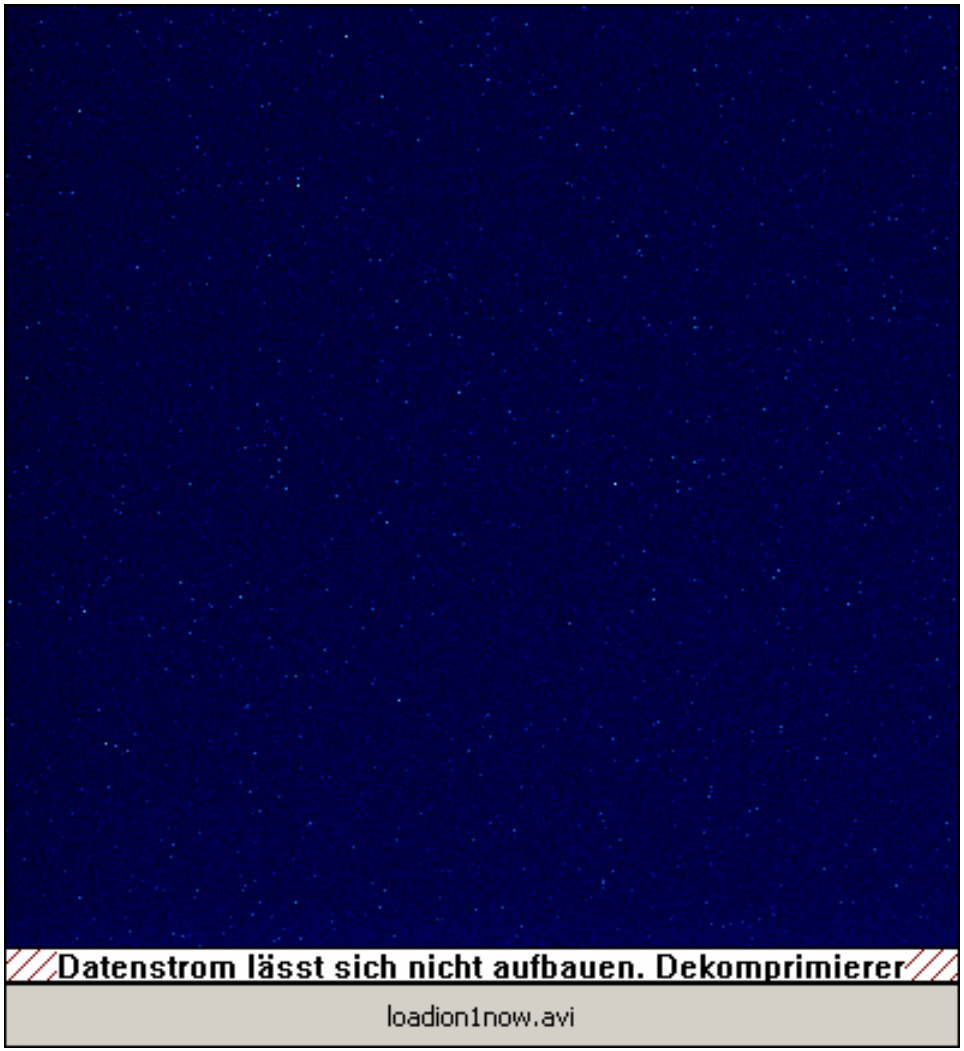
onboard RF-filtering with soldered SMD parts, connection of DC-electrodes via bonding of 30µm Au wire

Ions in Chip Trap

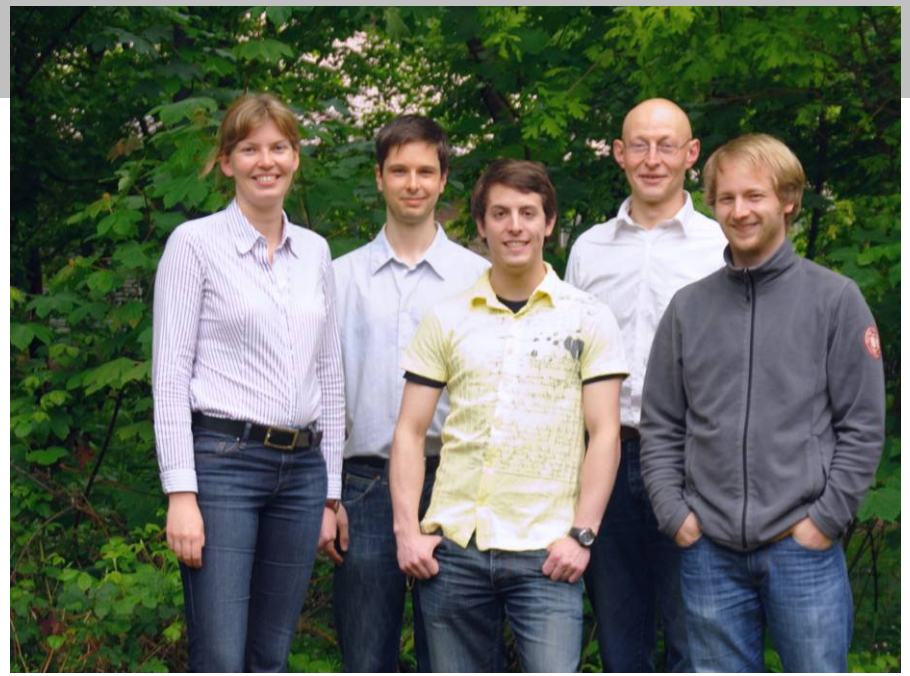
Coulomb crystals of ytterbium-172 ions:



Ions in Chip Trap



Optical Clock Groups at PTB:



T.E.M. Jonas Keller Norbert Herschbach
David Meier Karsten Pyka

Uwe Sterr

Christian Tamm

Piet Schmidt

Ekkehard Peik