Optical Clocks at PTB

Outline

Introduction to optical clocks

An optical frequency standard
with Ca atoms

Improved reference cavity

Yb^+ Ion Clock

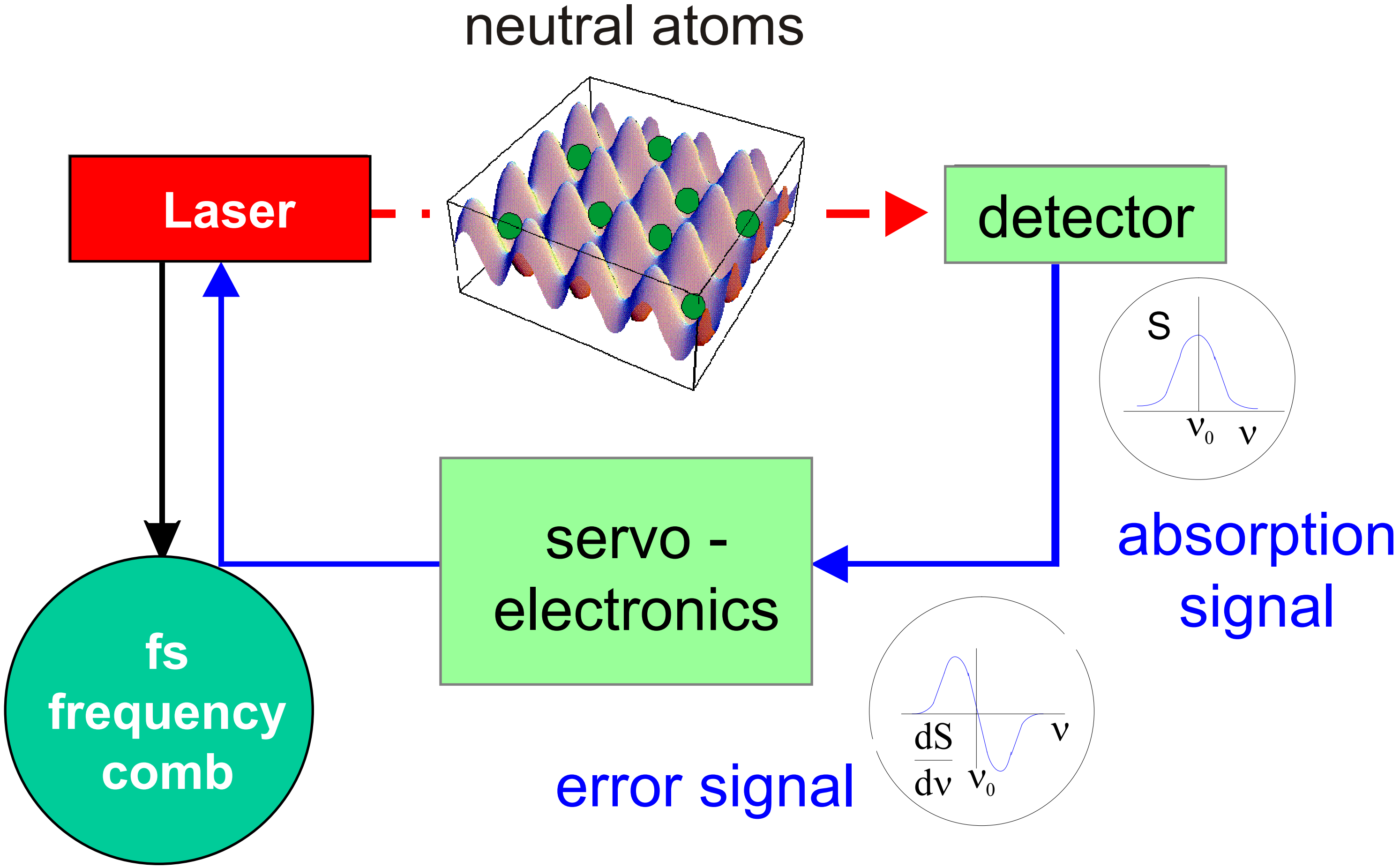
Sr optical lattice clock

Optical frequency measurements

European–Australian Workshop on Quantum-Atom Optics,
February 2006

Physikalisch-Technische Bundesanstalt

Principle of Clocks



neutral atoms

Laser

detector

servo - electronics

fs frequency comb

absorption signal

error signal

Why better clocks ?

Generation of more stable time scales

  secondary representations of the second

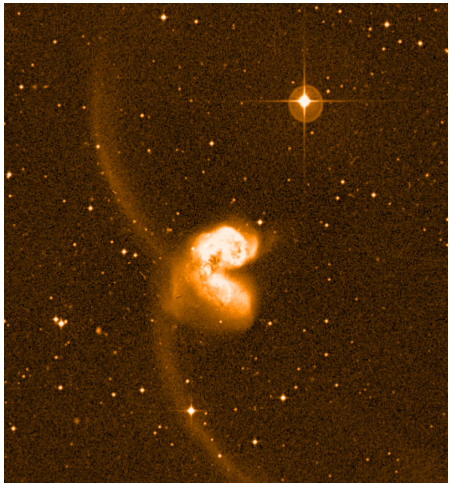
  future better definition of the second

Tests of fundamental theories:

  General Relativity

  Cosmology

  Constance of fundamental constants

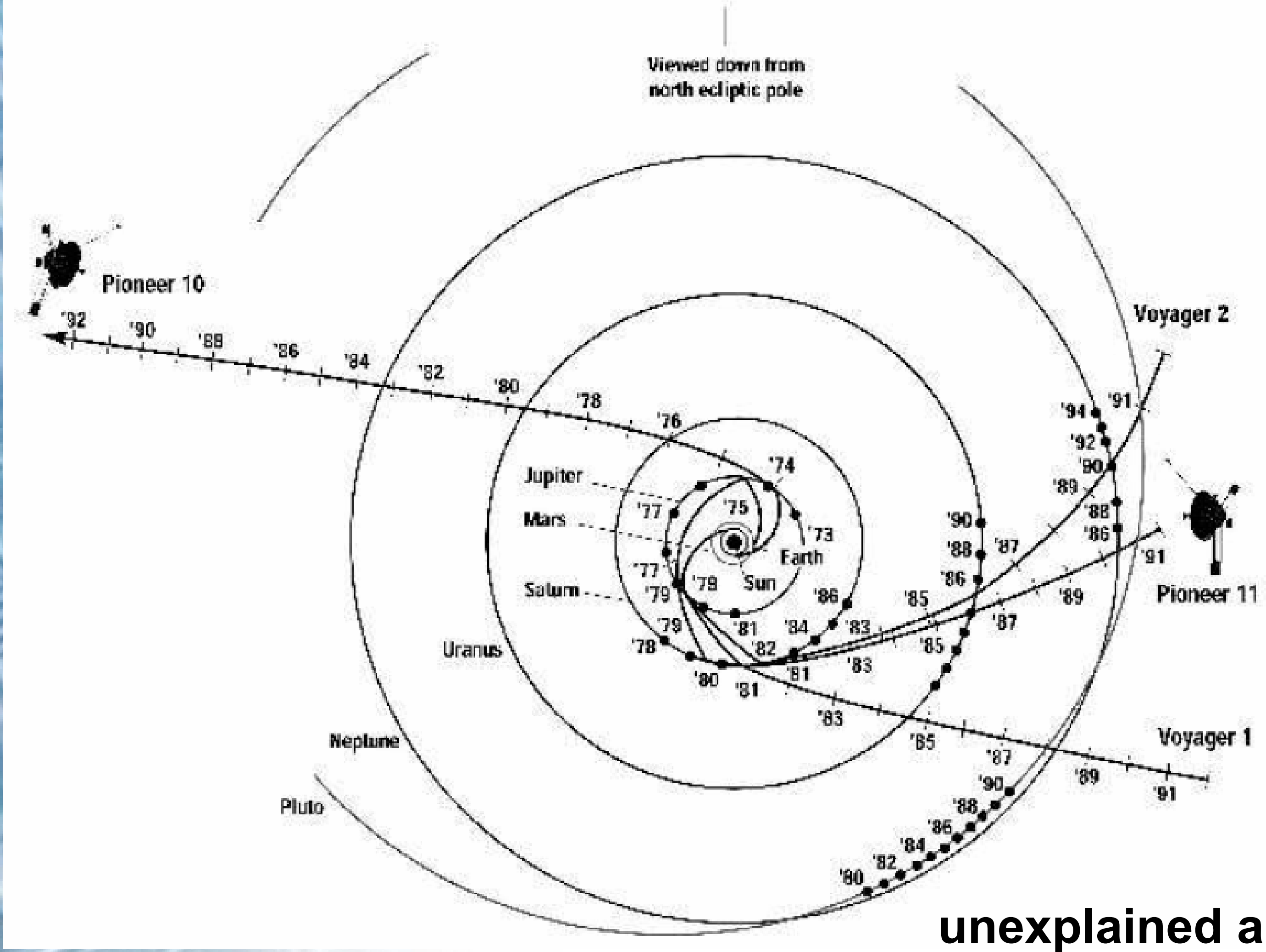


Navigation

  Deep-space navigation

  Pioneer anomaly

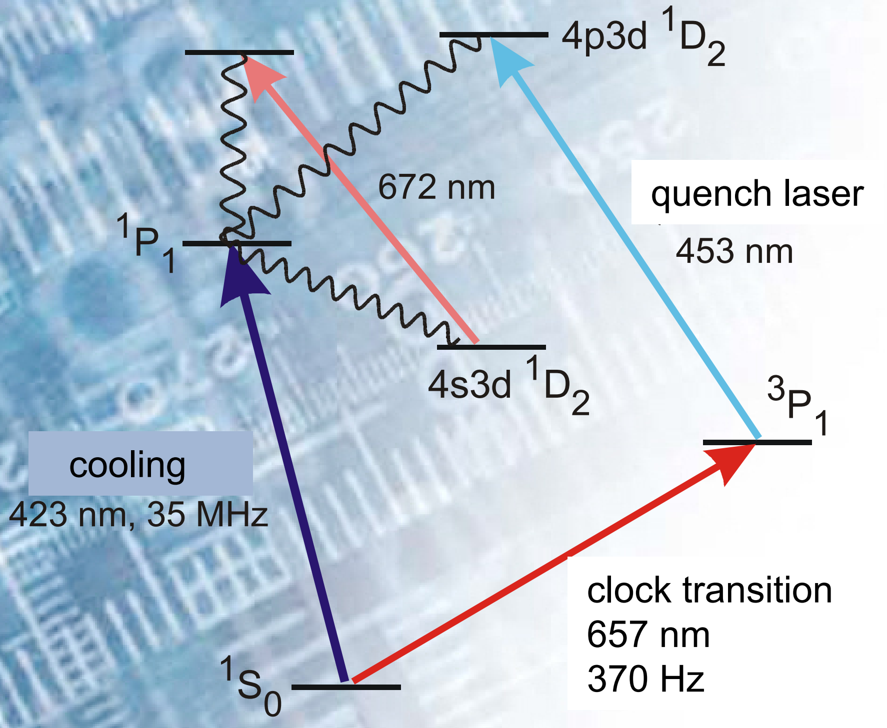
Pioneer Anomaly



unexplained acceleration

$$\alpha_{Pioneer} = -(8.74 \pm 1.33) \cdot 10^{-10}\ \mathrm{m/s^2}$$

Laser Cooling of Calcium



4p3d $^1D_2$

$^1P_1$

672 nm

quench laser

453 nm

4s3d $^1D_2$

$^3P_1$

cooling

423 nm, 35 MHz

$^1S_0$

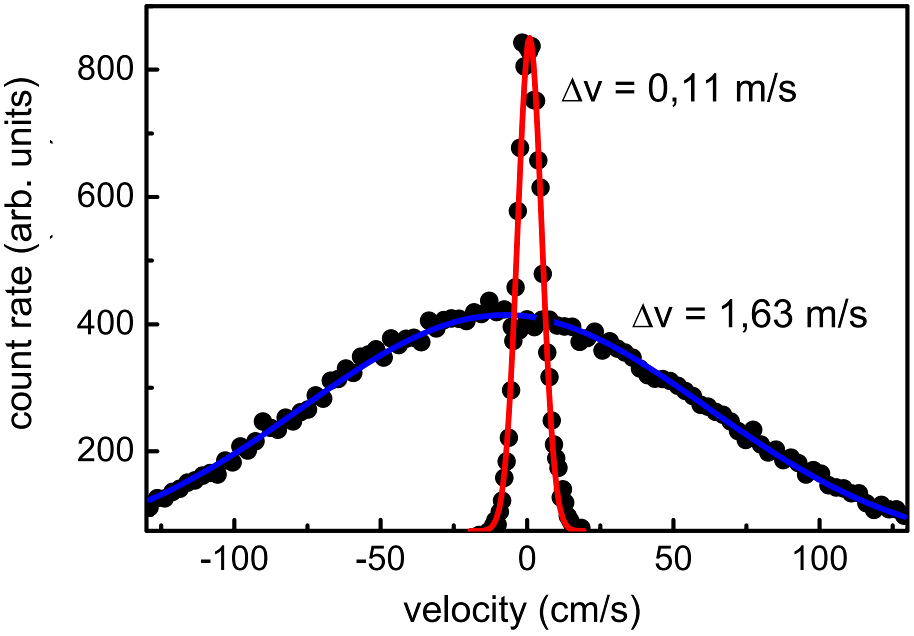
clock transition
657 nm
370 Hz

first stage:

- T ≈ 3 mK

second stage: quench-cooling:

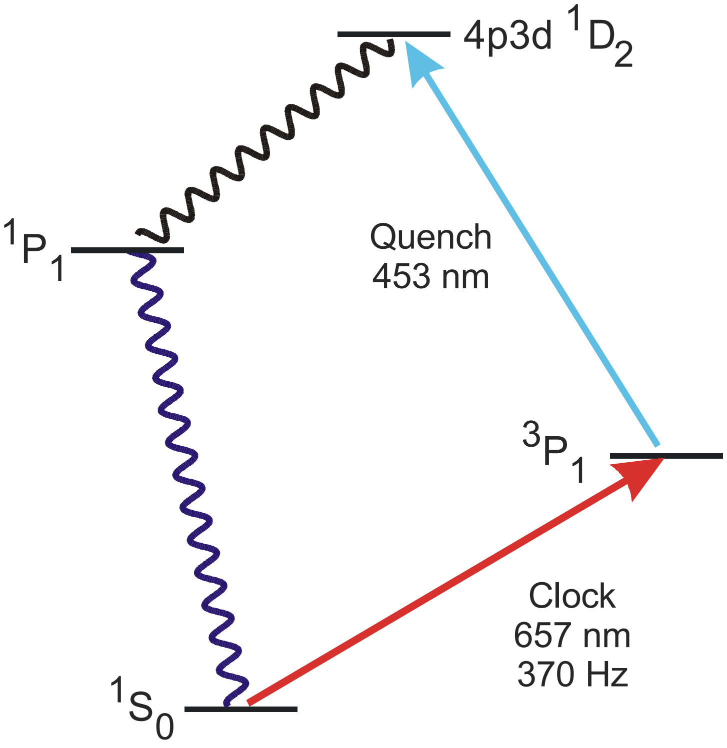
- T ≈ 10 μK

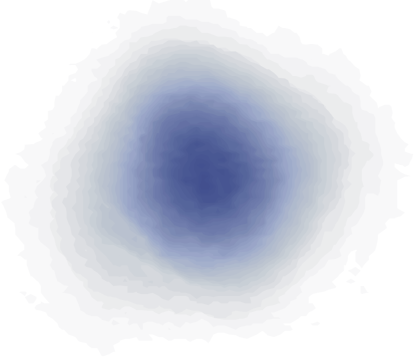


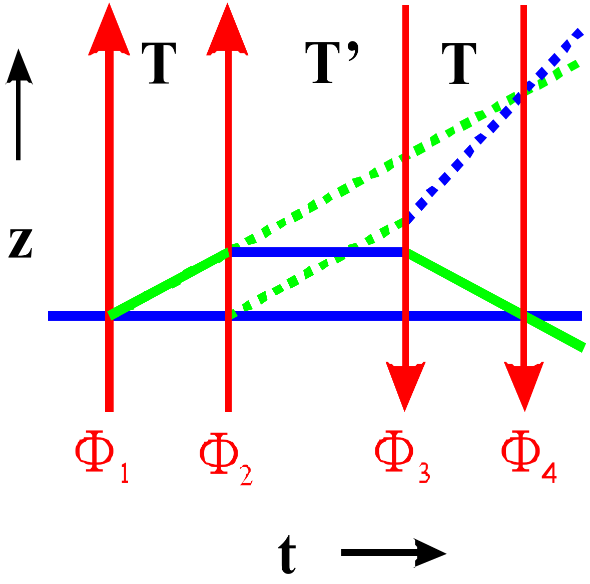
T. Binnewies et al., PRL **87**, 123002-1 (2001)

Ca: Clock transition and cooling

second stage cooling

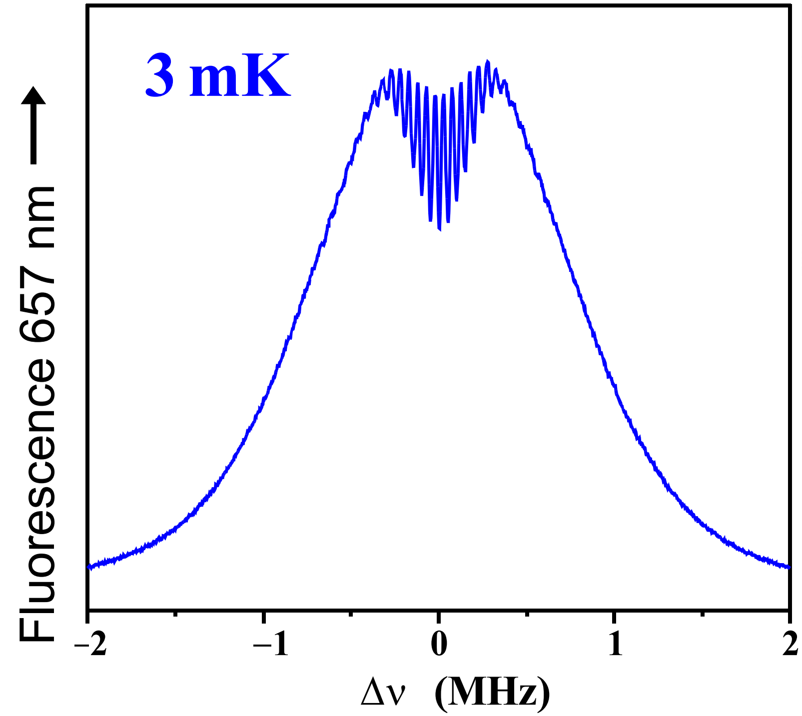


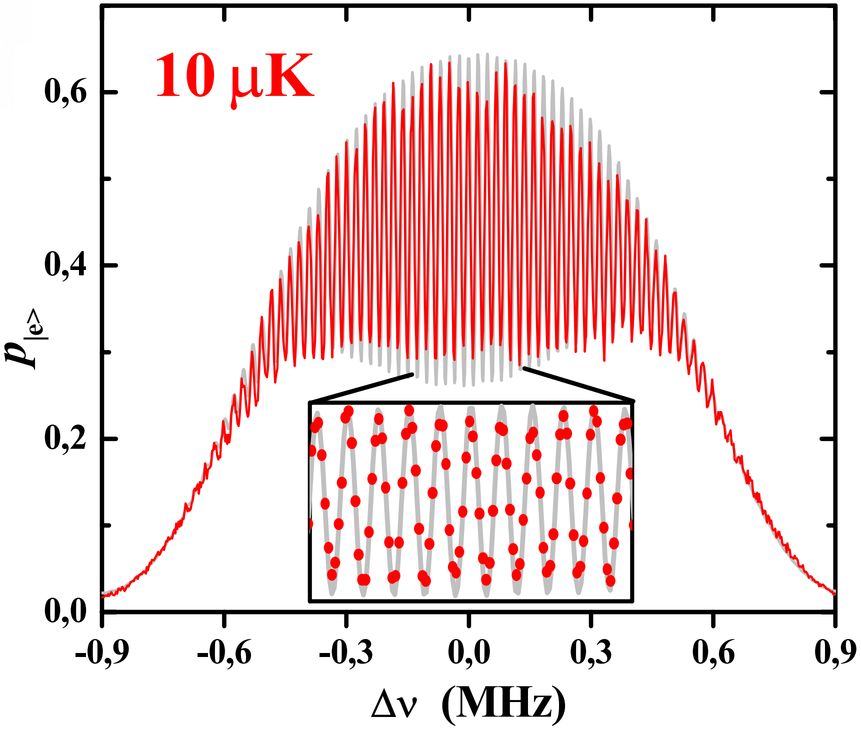




T. Binnewies et al., PRL **87**, 123002-1 (2001)

Cold and Ultracold Atom Interferences





Doppler width
3 MHz

\>

Fourier width
1 MHz

\>

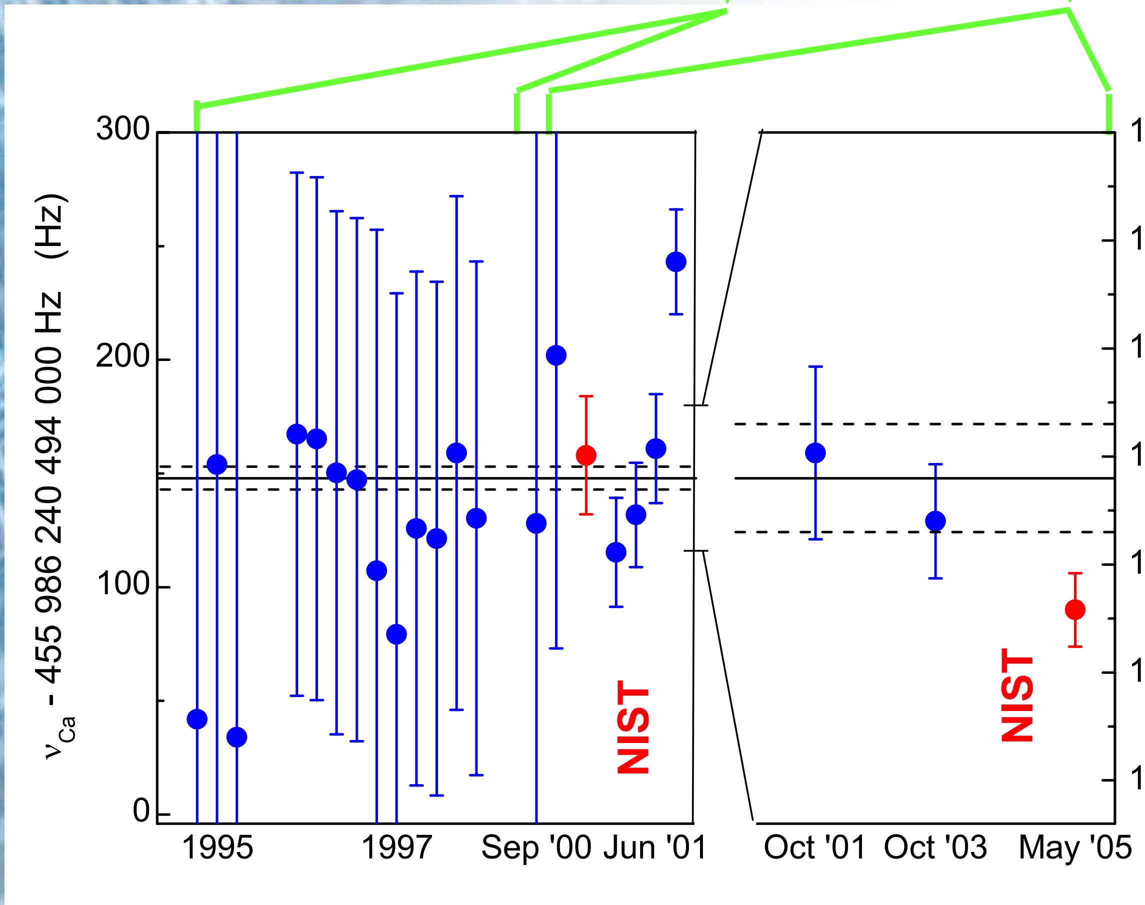
Doppler width
0.2 MHz

Optical frequency measurement of calcium

Ca-Frequency-standard
456 THz

Comparison
frequency chain / frequency comb

Primary Standard
Cs-Fountain
9.2 GHz



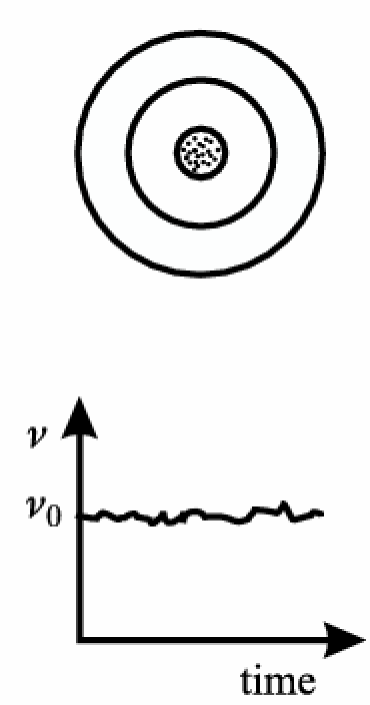
PTB
October 2003
ν_{Ca} = **455 986 240 494 143 Hz**
± **5.5 Hz**

$u_y = 1.2 \cdot 10^{-14}$

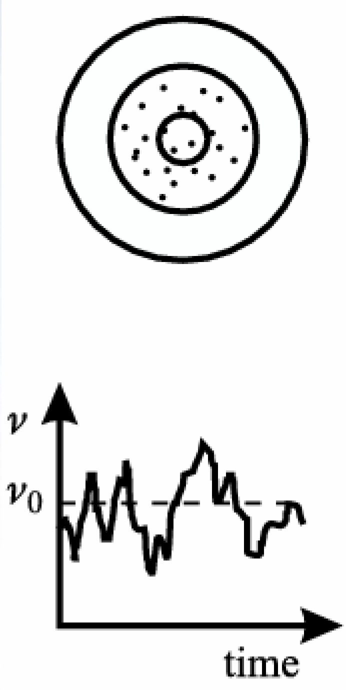
Calcium is still the best neutral atom clock

$u_y \sim 10^{-15}$ **is possible but motion sets a limit**

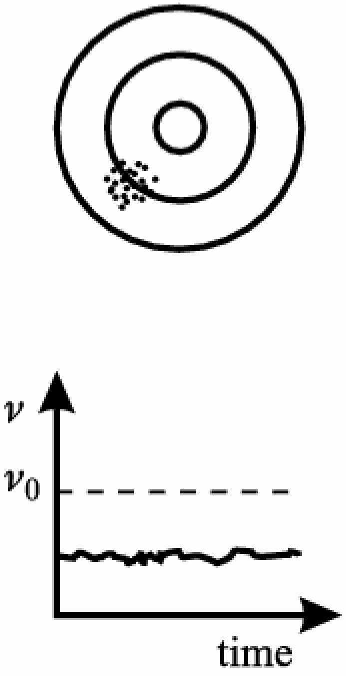
Uncertainty - Stability



good clock:
small uncertainty
high stability



small uncertainty
low stability



high stability
low uncertainty

Allan Variance: $\sigma_y(\tau)^2 = \frac{1}{\nu_0^{\,2}}\left\langle\left(\overline{\nu_i}-\overline{\nu_{i+1}}\right)^2\right\rangle$ with $\overline{\nu_i} = \frac{1}{\tau}\int_{t_i}^{t_i+\tau}\nu(t)\,dt$

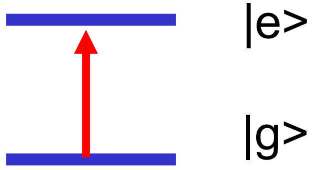
Stability

Quantum Projection Noise Limit:

After the interrogation the number of excited atoms N_e is measured i.e. the quantum state

$$\left|\psi\right\rangle = c_g\left|g\right\rangle + c_e\left|e\right\rangle$$

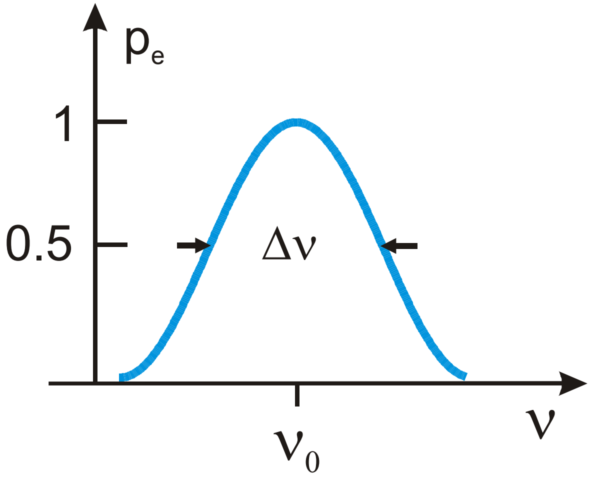
is projected to either the state $|e>$ or $|g>$.



$$\left\langle N_e\right\rangle = N_0 p_e \qquad \sigma^2{}_{N_e} = N_0 p_e (1-p_e)$$

$$\sigma_y(\tau) \propto \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_C}{N_0\tau}}$$

T_C : cycle time



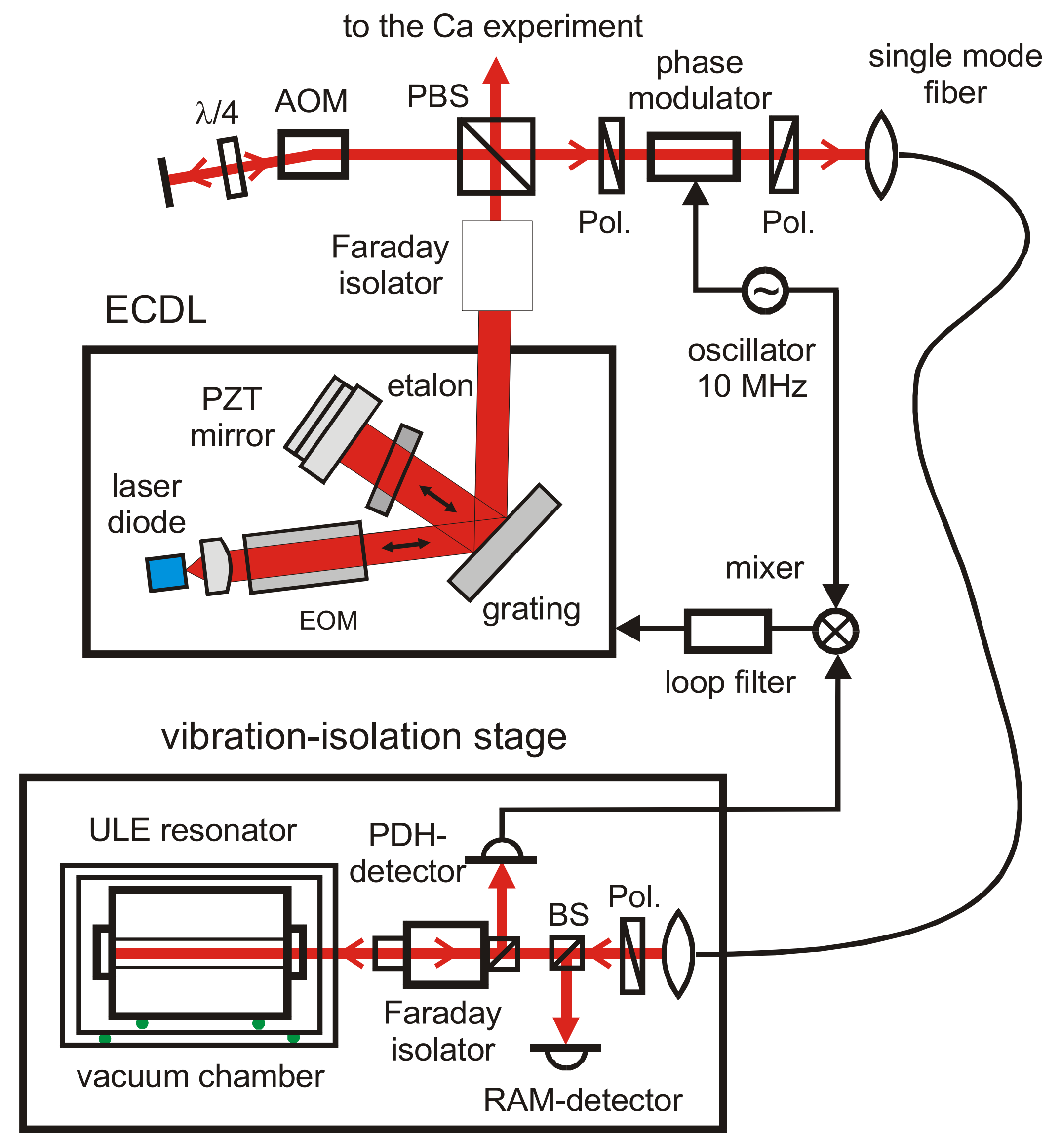
Itano et al., PRA **47**,3554 (1993)

$6\cdot10^5$ Cs atoms, ν = 9.2 GHz, $\Delta\nu$ = 1 Hz : $\sigma_y(\tau) \sim 4\cdot10^{-14}\ \tau^{-1/2}$

Single Yb ion, λ = 436 nm, $\Delta\nu$ = 3.1 Hz: $\sigma_y(\tau) \sim 5\cdot10^{-15}\ \tau^{-1/2}$

10^7 Ca atoms, λ = 657 nm, $\Delta\nu$ = 400 Hz: $\sigma_y(\tau) \sim 6\cdot10^{-17}\ \tau^{-1/2}$

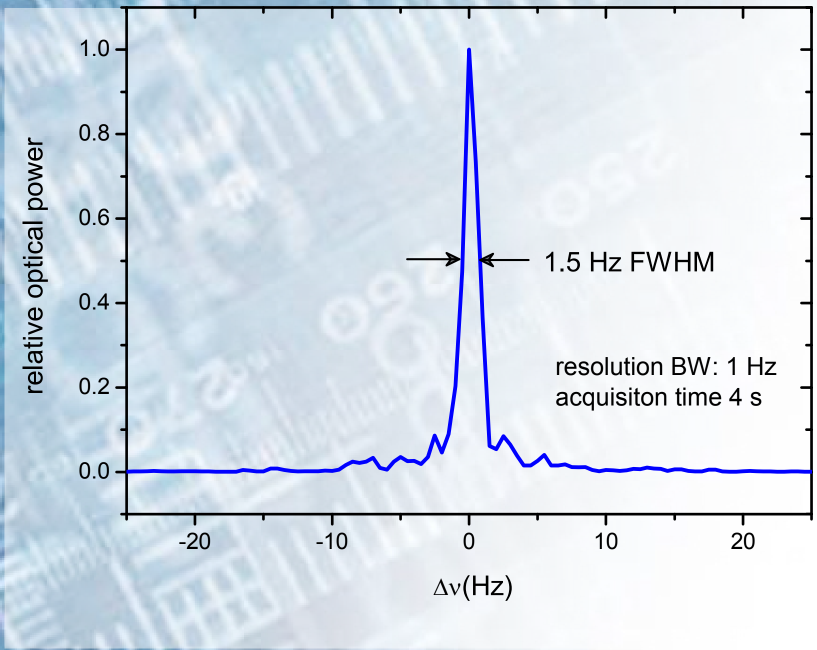
Interrogation Laser



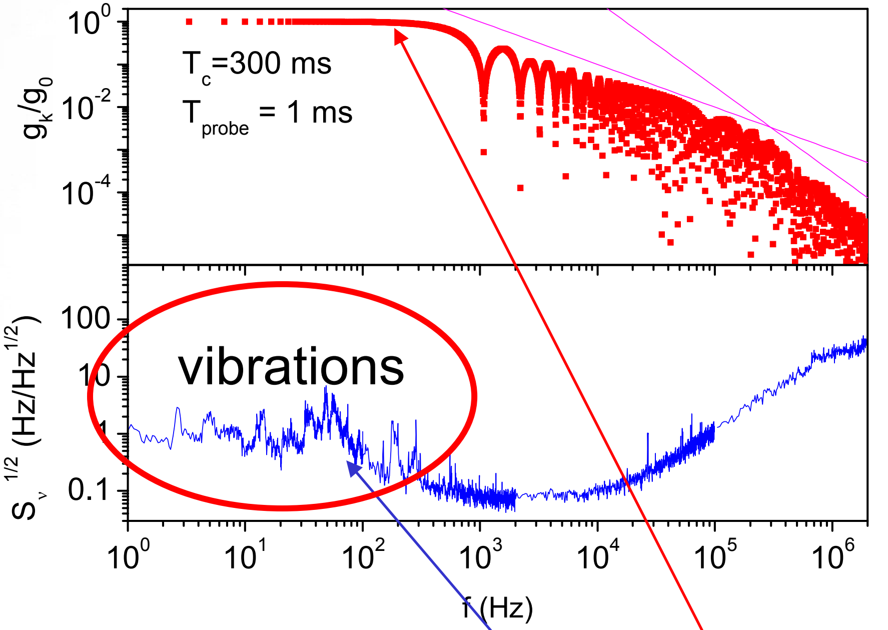
Resonance frequencies:
0.7 Hz vertical, 0.6 Hz horizontal

H. Stoehr, F. Mensing, J, Helmcke, U. Sterr,
Opt. Lett. March 2003

Laser Linewidth



power spectrum of the beat



spectral density of frequency noise

weighting function

laser linewidth ≈ 1 Hz, drift 0.06 Hz/s

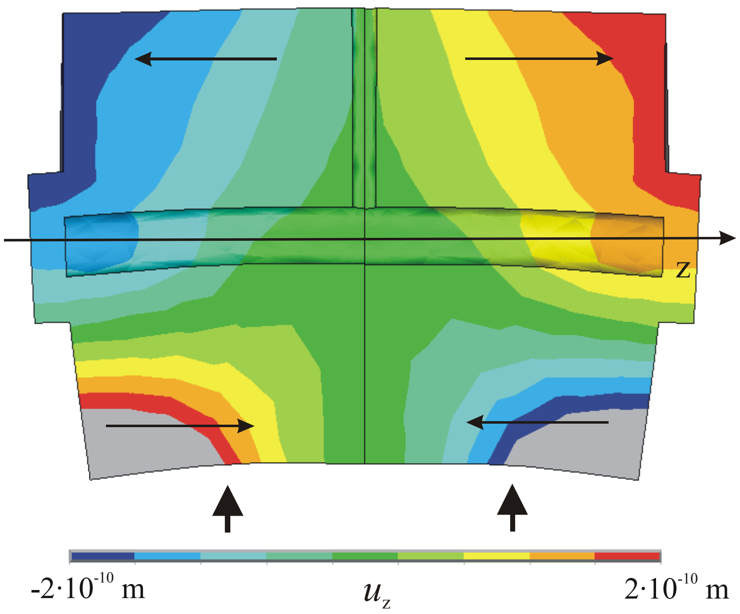
Dick effect:

$$\sigma^2_y(\tau) = \frac{2}{\tau}\sum_{k=1}^{\infty} S_y(kf_c)\left|\frac{g_k}{g_0}\right|^2$$

Present stability is imited by Dick effect because of the poor duty cycle to $\sigma(\tau) = 2\cdot 10^{-14}\,\tau^{-1/2}$

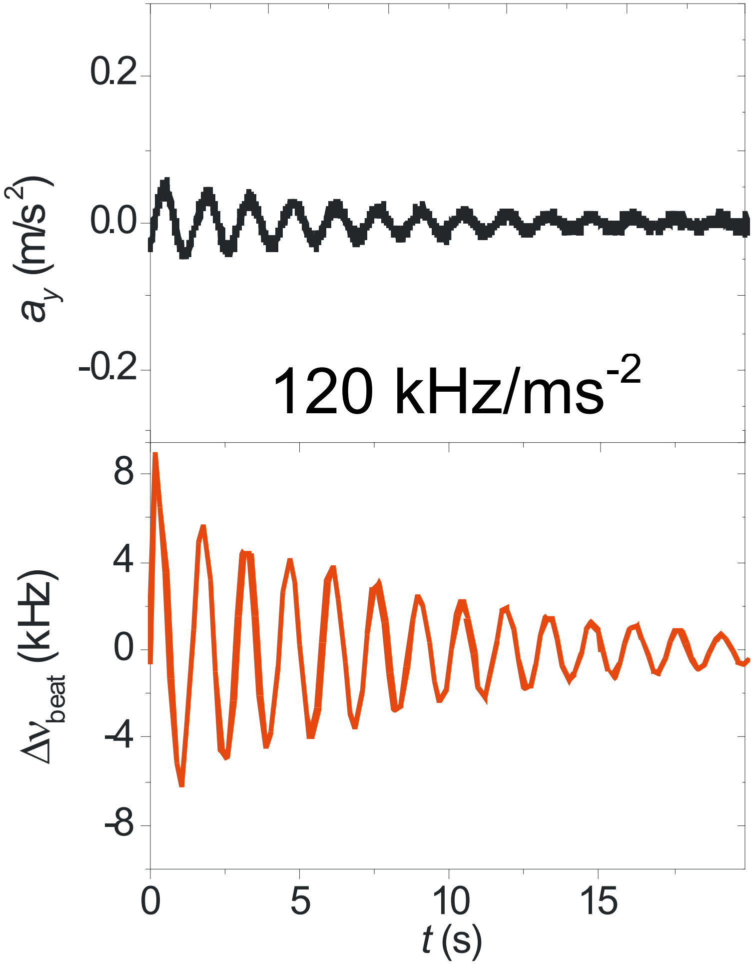
previous cavity mount

Finite-Element calculations:

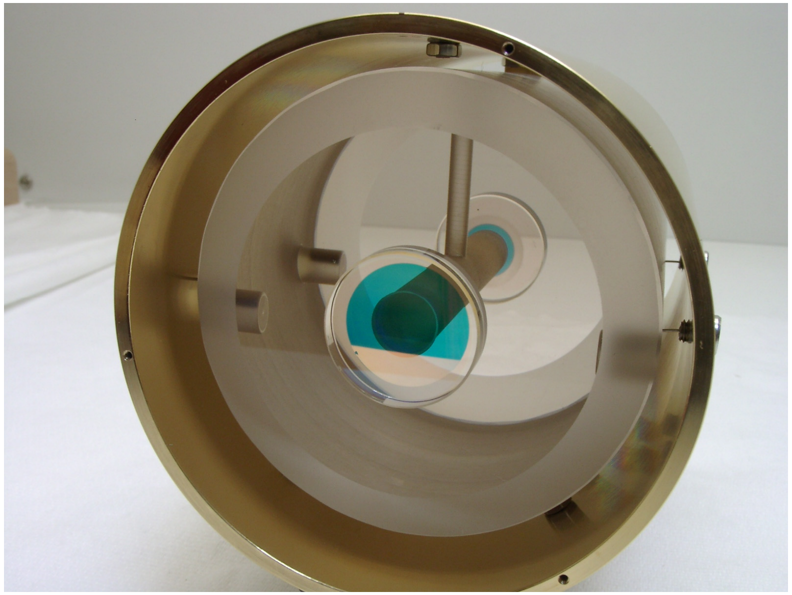


$a = 10\ \mathrm{m/s^2}$

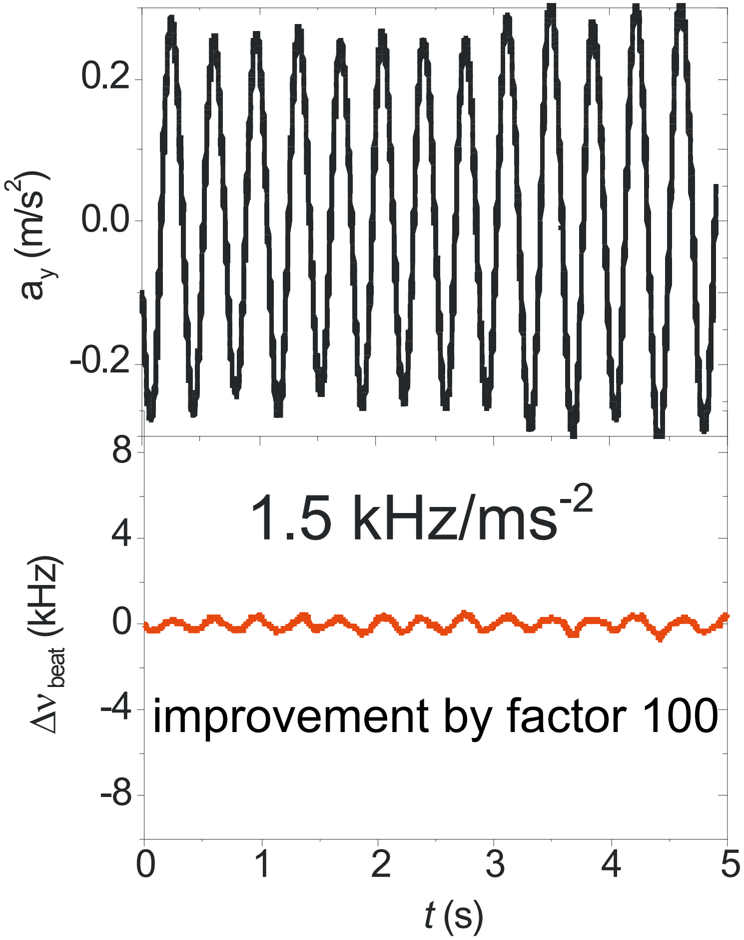
deformations magnified by 10^7



new cavity mount

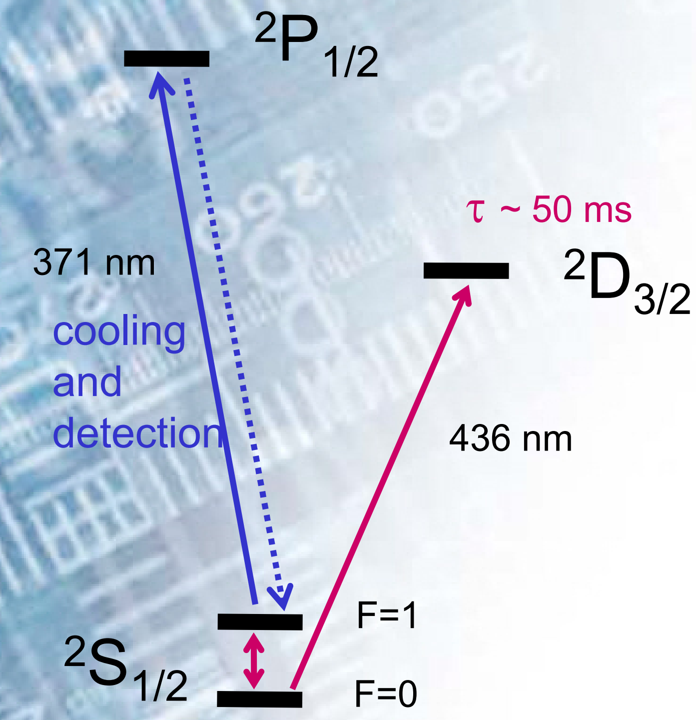


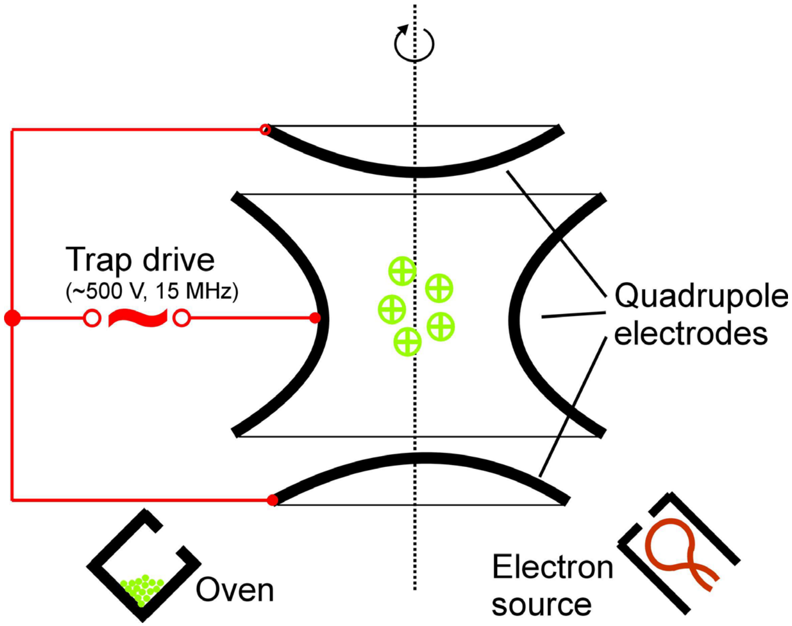
see poster by Tatiana Nazarova

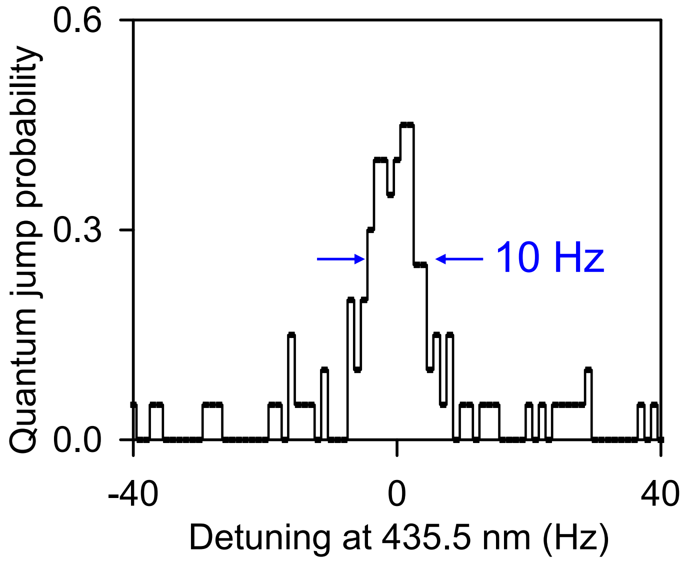


^{171}Yb^{+} Single-Ion Frequency Standard

Ekkehard Peik, Christian Tamm





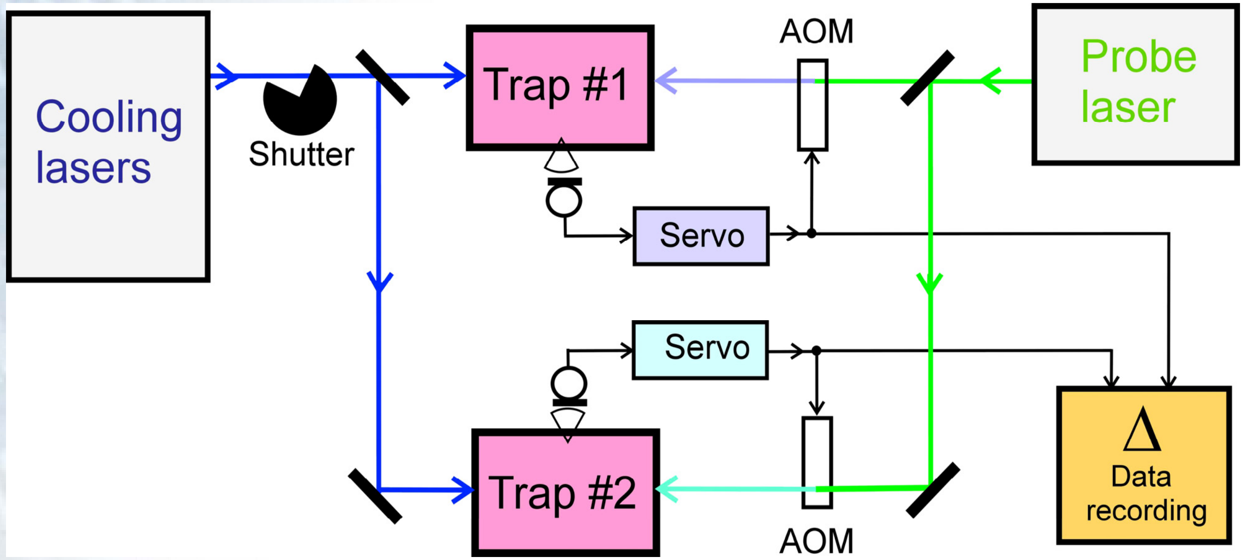


clock transition: $^2S_{1/2}$ - $^2D_{3/2}$

λ = 436 nm, $\Delta\nu$ = 3.1 Hz

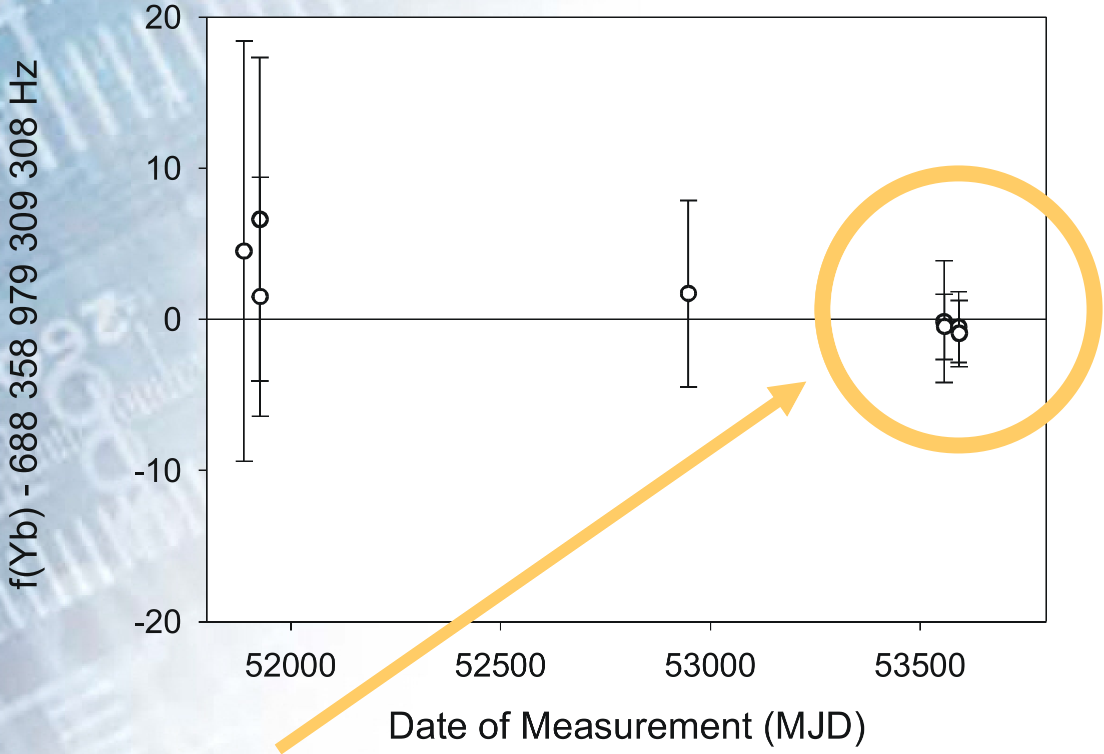
$\sigma_y(\mathrm{min}) \sim 5\cdot10^{-15}\ \mathrm{s}^{-1/2}$

Frequency comparison between two ions



- Frequencies agree to 3.8(6.1)ﬁ10^{-16}
  (similar to best results of Cs-clocks)
  T. Schneider, E. Peik, Chr. Tamm,
  Phys. Rev. Lett. ***94****, 230801 (2005)*
- Instability of difference frequency: $v_y(100\ \mathrm{s})=9\circ 10^{-16}$
  (similar to best results of cold atoms)
  E. Peik, T. Schneider, Chr. Tamm,
  J. Phys. B. ***39****, 145 (2006)*

Frequency Messurement of the Yb$^+$-clock



ν(Yb$^+$)=688 358 979 309 307.7 (2.2) Hz

Cotributions to uncertainty budget of the measurements in 2005:

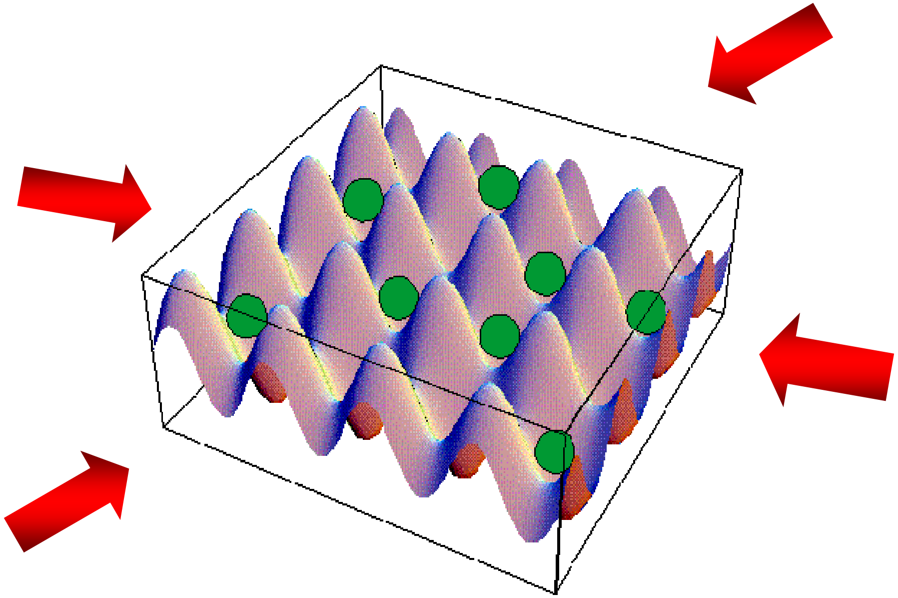
u_A=0.40 Hz	(continuous measurement time of up to 36 h)
u_B(Cs)=1.82 Hz	(„$\pi/3\pi$"-problem)
u_B(Yb$^+$)=1.05 Hz	(Quadrupole-, Black-body-Stark-shift, line profile, influence of the trap fields)

Optical Lattice Clock

Earth alkali elements Mg, Ca, Sr

and Yb, Hg have metastable $^3P_0$ state

- accessible by 1 photon transition
  in isotopes with nuclear spin $I \neq 0$
  $\Delta\nu \sim$ mHz
- in most abundant isotopes with I = 0
  transitions get allowed in magnetic field
  $\Delta\nu \sim \mu$Hz with B ~ 1 mT
- "magic wavelengths" dipole traps
- efficient cooling possible



"Magic Wavelength"

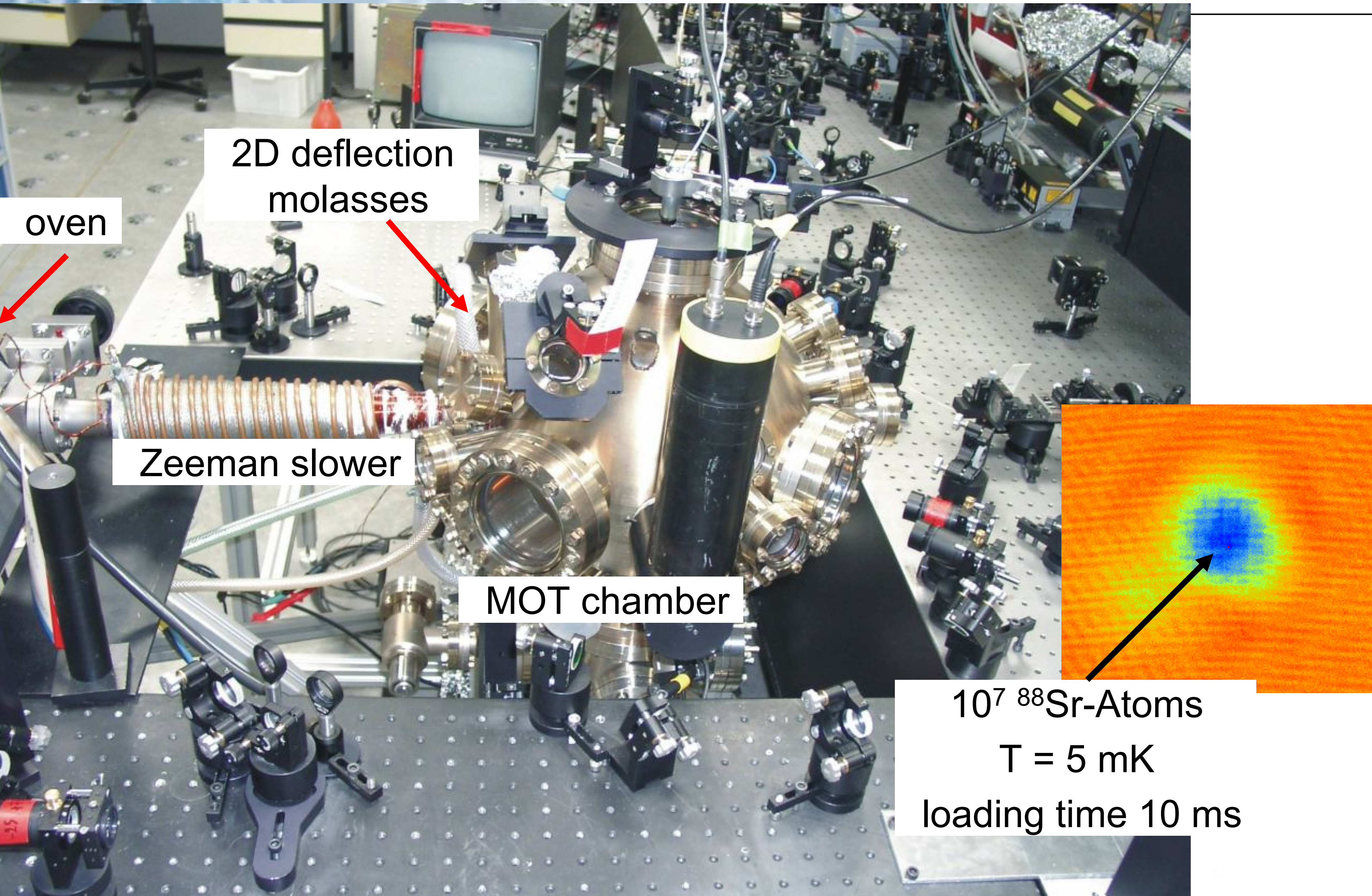
- no net light shift

10^7 neutral atoms

estimated uncertainty

$u_y < 10^{-16}$

Strontium Setup



oven

2D deflection molasses

Zeeman slower

MOT chamber

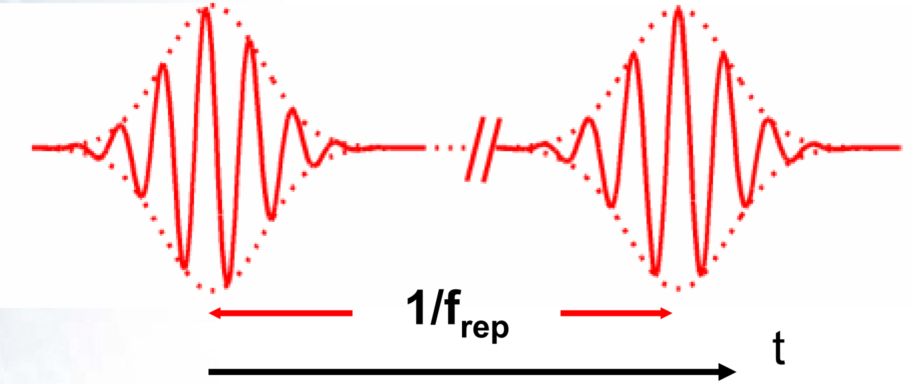
10^7 ^{88}Sr-Atoms

T = 5 mK

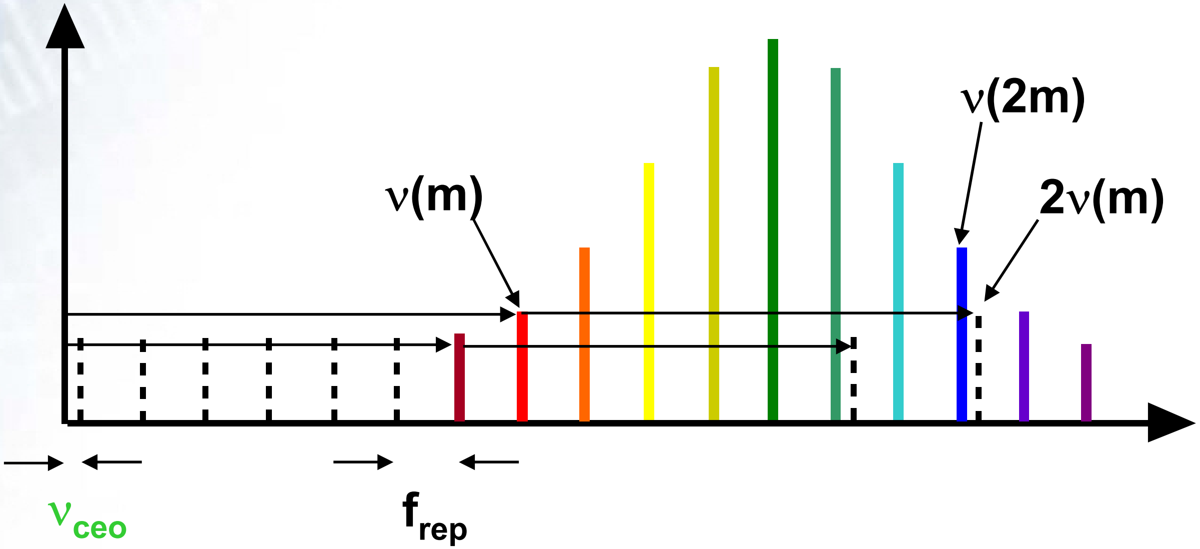
loading time 10 ms

Optical Frequency Comb

time domain:
fs-laser with repetition frequency f_{rep}



frequency domain:
comb of frequencies



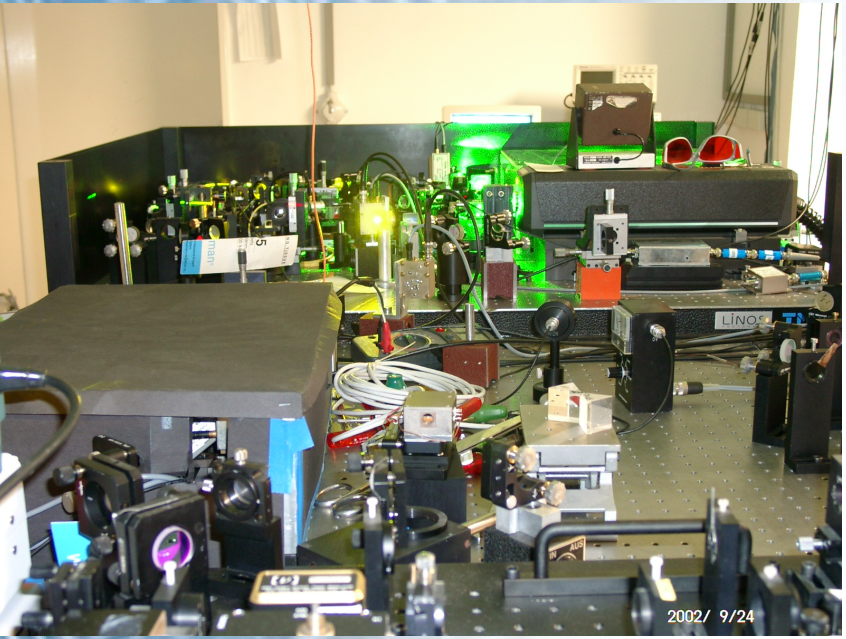
$\nu(m) = \nu_{ceo} + m f_{rep}$

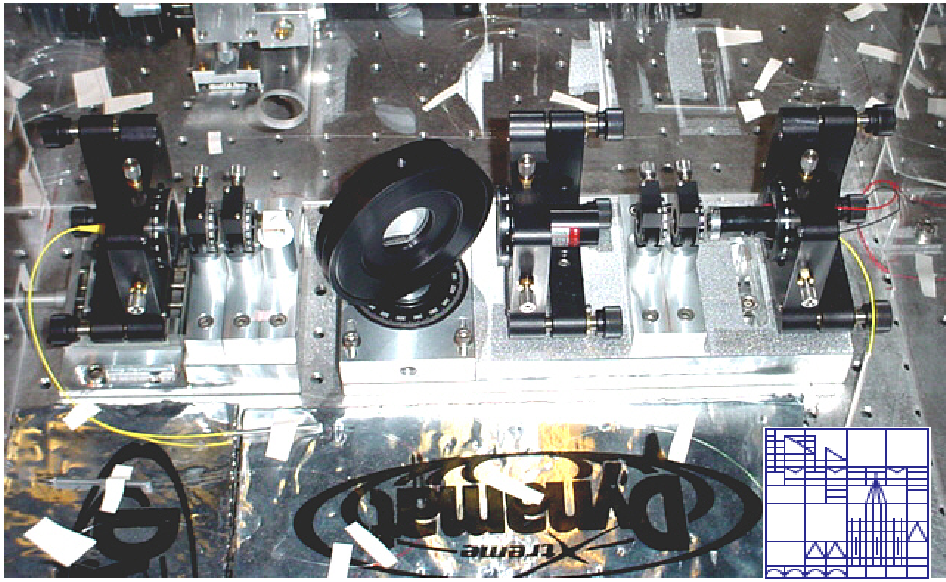
$\nu(2m) = \nu_{ceo} + 2m f_{rep}$

self-referencing
to measure ν_{ceo}

$\nu_{ceo} = 2\nu(m) - \nu(2m)$

fs Frequency Combs


2002/ 9/24



Universität
Konstanz
Fachbereich
Physik

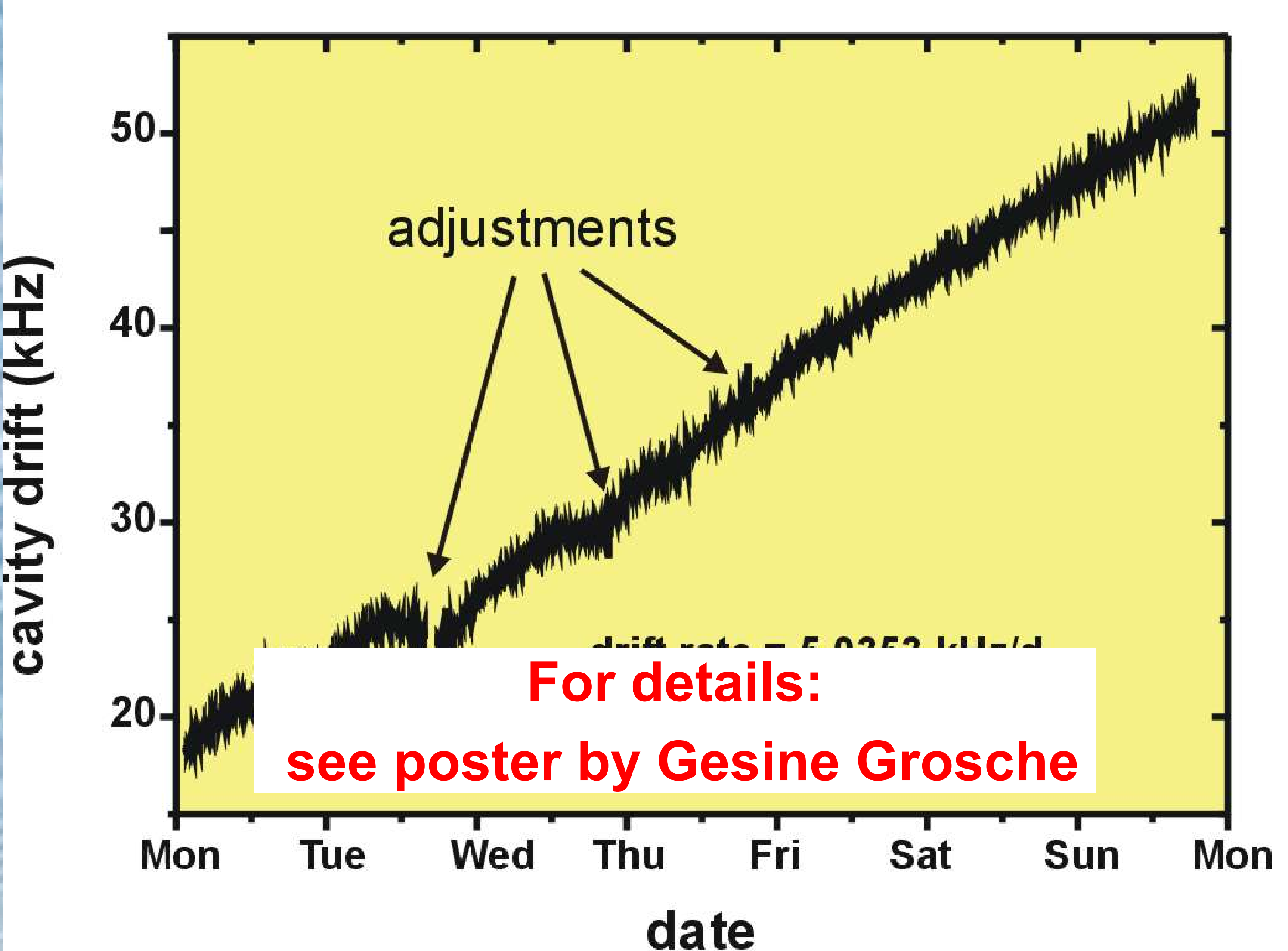
Ti:sapphire comb

broad-band for calibration of lasers
633 nm, 532 nm ..

Er:fiber comb

frequency devider for optical clock
comparison of Yb$^+$ – Ca – Sr

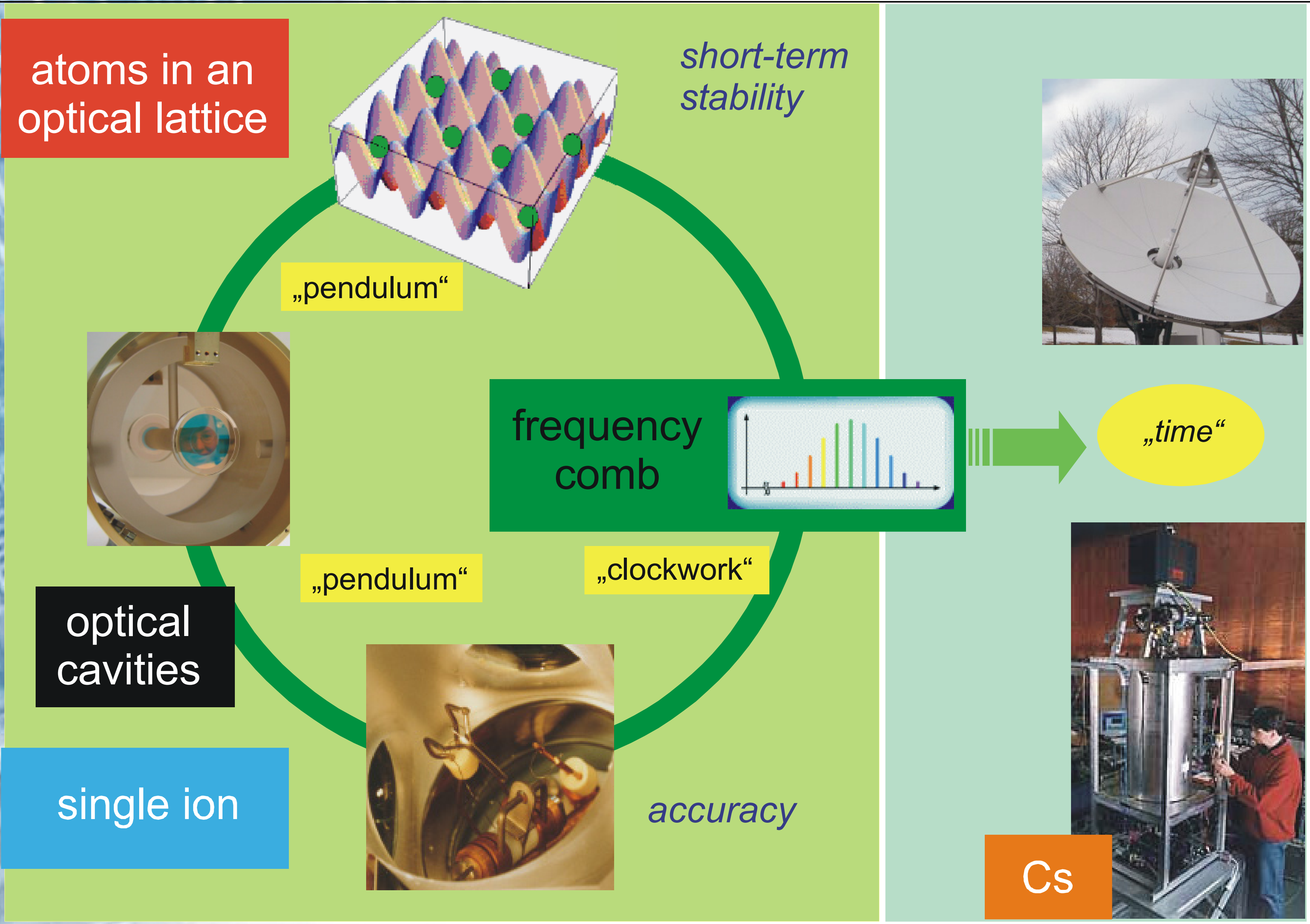
drift of an optical cavity



For details:

see poster by Gesine Grosche

optical clock ensemble



atoms in an optical lattice

short-term stability

„pendulum“

optical cavities

„pendulum“

frequency comb

„clockwork“

„time“

single ion

accuracy

Cs

Conclusion

- Calcium clock
  - vibrationally insensitive reference cavity
  - relative frequency uncertainty $1.2 \cdot 10^{-14}$
- Yb clock
  - relative uncertainty $1.2 \cdot 10^{-15}$
- Strontium lattice clock
- Reliable fiber based femtosecond comb

Future:

- Uncertainty $\approx 10^{-17}$ with ions and atoms in lattice
- Clock with instability $< 10^{-16}$ in one second
- New area at $<10^{-16}$: Gravitational red shift,
  Constancy of constants
  Thermal noise

Thanks to:

Ca standard:
Tatiana Nazarova
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Christophe Grain
Carsten Degenhard (now Aachen)
Hardo Stoehr (now Lübeck)

Sr standard:
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Sundar Raaj
Paul-Eric Pottie (now Paris)

Fritz Riehle
U.S.

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Harald Schnatz
Burghardt Lipphardt

Yb^+ single ion:
Christian Tamm
Ekkehard Peik
Tobias Schneider

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EU CAUAC
SFB 407

Research
Training Networks

SFB 407:
Quantum-limited measurements with photons, atoms and molecules