Towards Optical Atomic Clocks

Outline

Introduction to optical clocks

Accuracy and stability of an optical
frequency standard with Ca atoms

Optical frequency measurement

Future prospects: optical lattice clock
Measurement of the “magic wavelength”

Physikalisch-
Technische
Bundesanstalt
Braunschweig,
Germany

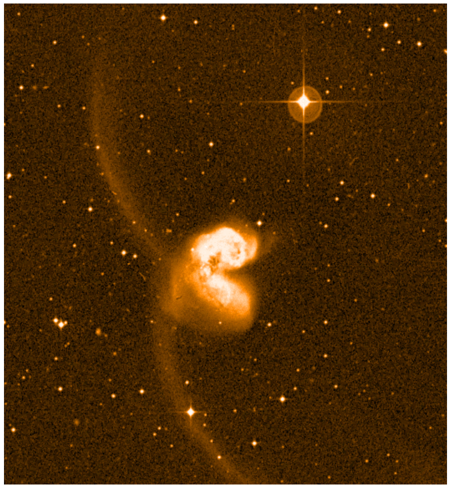
Quantum Engineering with Photons, Atoms, and Molecules, Les Houches, 17. 02. 2005

Applications that require better atomic clocks

Generation of more stable time scales

Tests of fundamental theories:

- General Relativity
- Quantum Electrodynamics
- Cosmology
- Constance of fundamental constants



Navigation

- Deep-space navigation
- Pioneer anomaly

Deep Space Network

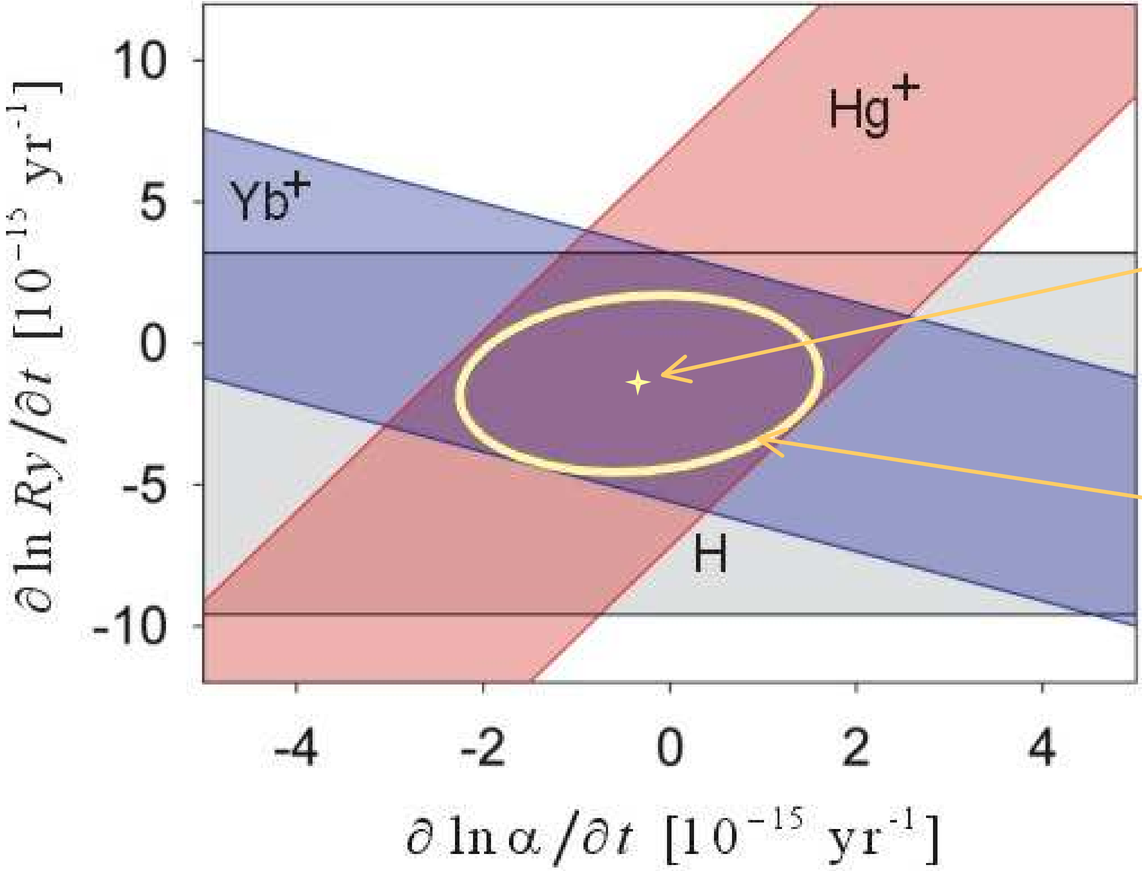
1997: Lift-off of Cassini - Huygens probe -> Saturn (2004)

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

Required accuracy: +/- 25 km

Telemetry using 3 antennas on earth only works with the best clocks available.

Temporal Variation of Fundamental Constants



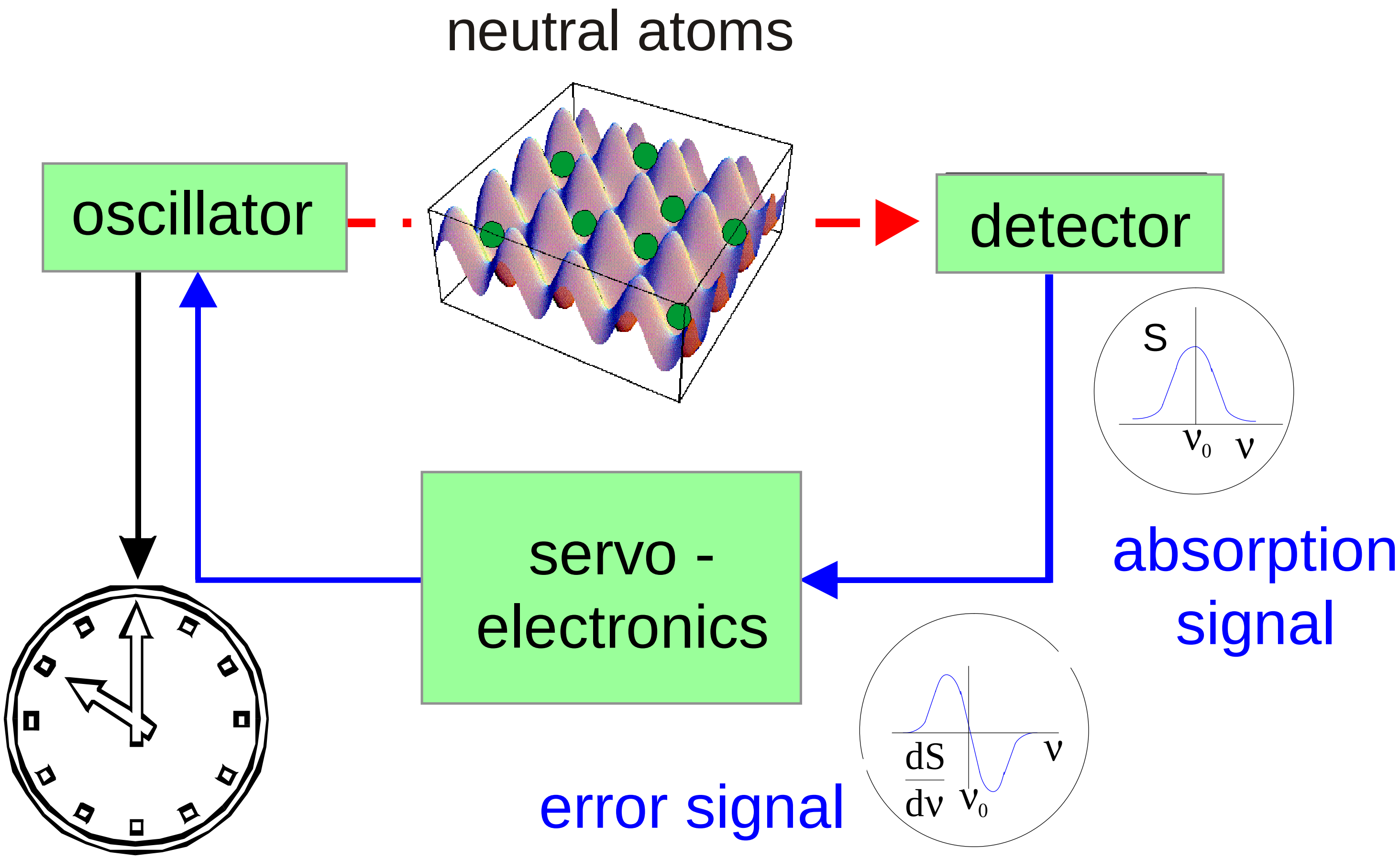
$$\frac{\partial \ln f}{\partial t} = \frac{\partial \ln Ry}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t}$$

$\partial\alpha/\partial t$ and $\partial Ry/\partial t$ estimate (weighted mean of present Yb$^+$, Hg$^+$, H data)

1σ confidence range

Peik et al. PRL 2004

Principle of Clocks



neutral atoms

oscillator

detector

servo - electronics

absorption signal

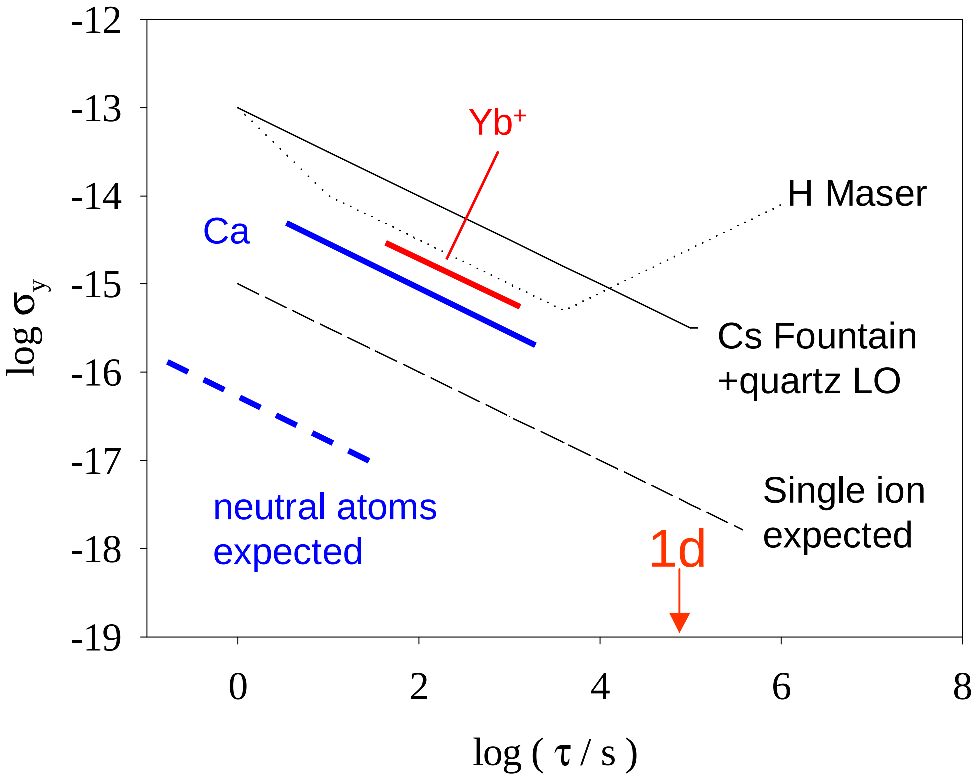
error signal

Stability of Atomic Clocks

Stability:
necessary averaging time,
to detect a certain effect ?

depends on relative line width $\Delta\nu/\nu_0$
atom number *N* and cycle time T_c

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_c}{N\tau}}$$



goal: small instability

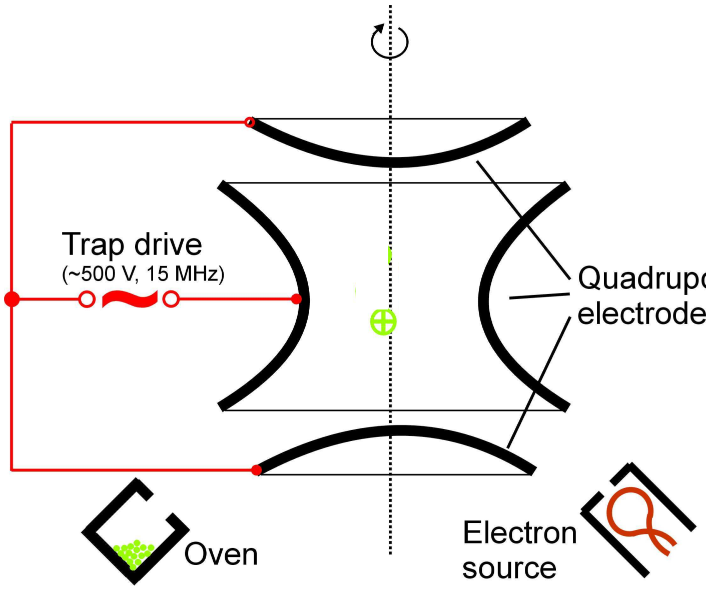
reduction of $\Delta\nu$ with cold trapped atoms;
increase ν_o (optical frequencies instead of microwaves)

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

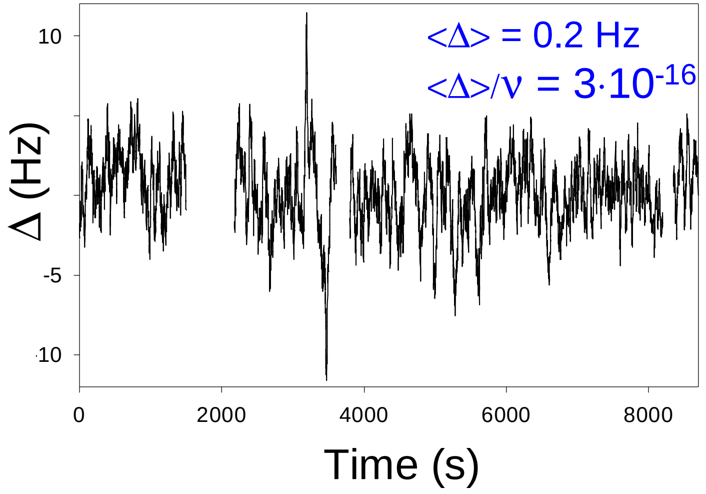
transition: $^{2}S_{1/2}$ - $^{2}D_{3/2}$

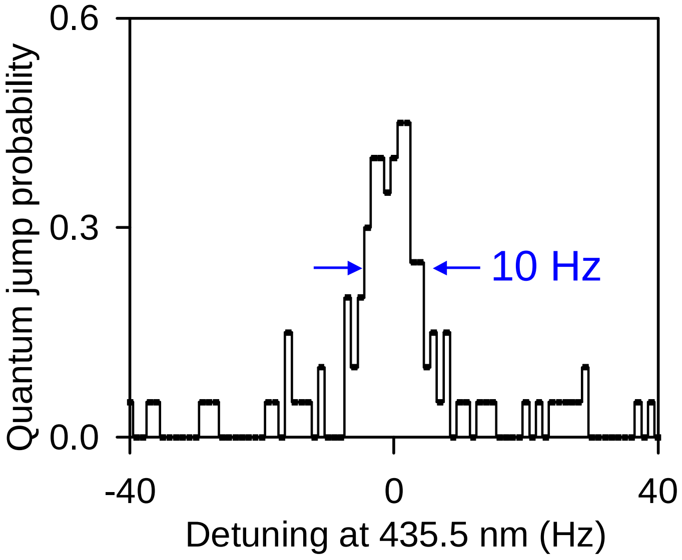
λ = 436 nm, $\Delta\nu$ = 3.1 Hz
$\sigma_y(\text{min}) \sim 5\cdot10^{-15}\ s^{-1/2}$

- two traps agree within a few Hz
- shift due to stray fields

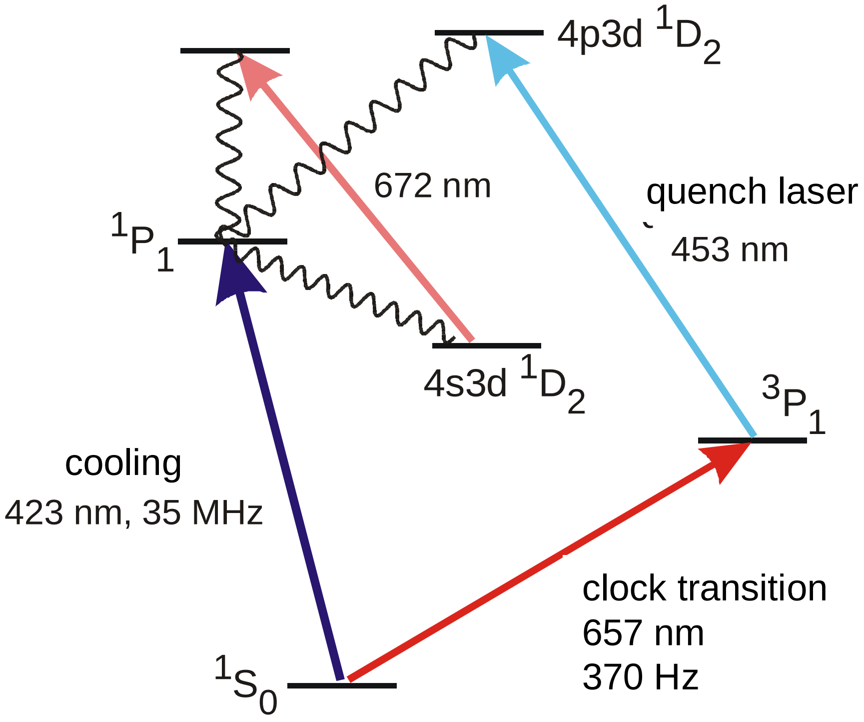


frequency comparison of two traps
(same conditions)





Sub-Doppler Cooling of Calcium

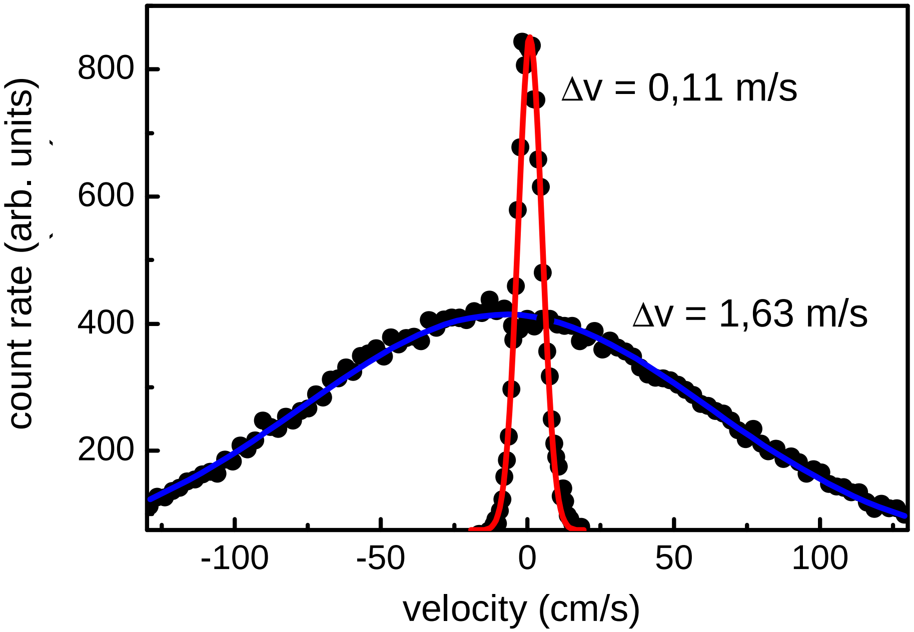


first stage:

- T ≈ 3 mK

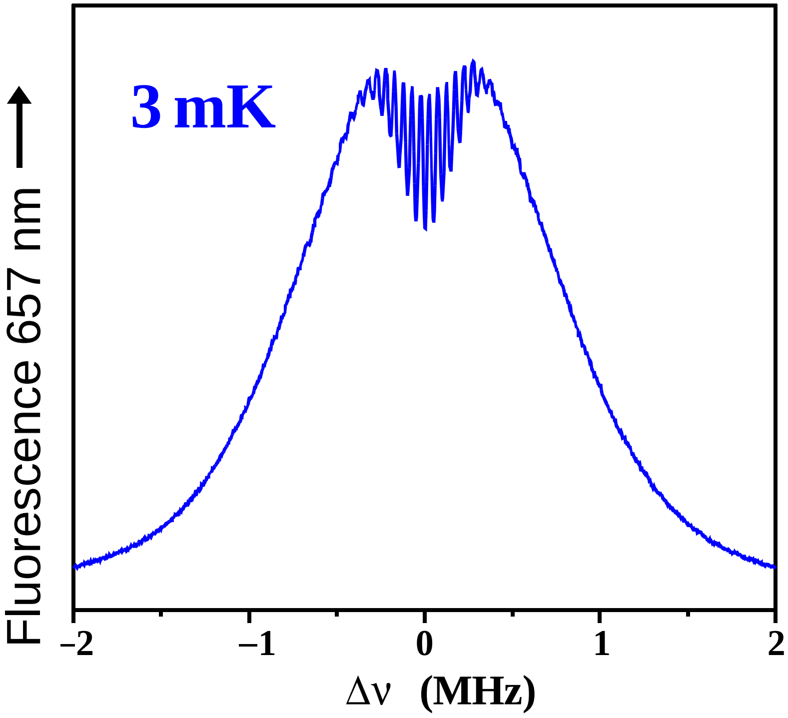
second stage: quench-cooling:

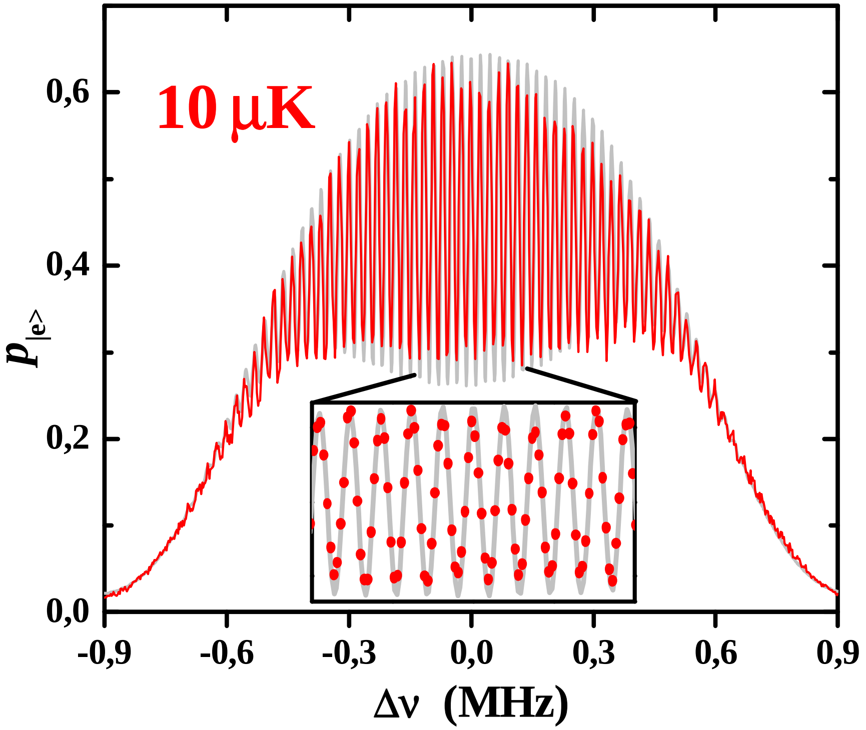
- T ≈ 10 µK



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

Cold and Ultracold Atom Interferences





Doppler width
3 MHz

\>

Fourier width
1 MHz

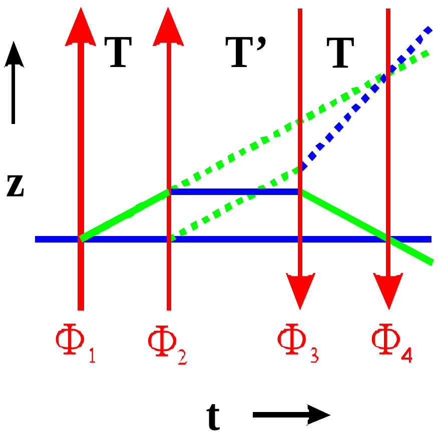
\>

Doppler width
0.2 MHz

ultracold atoms →

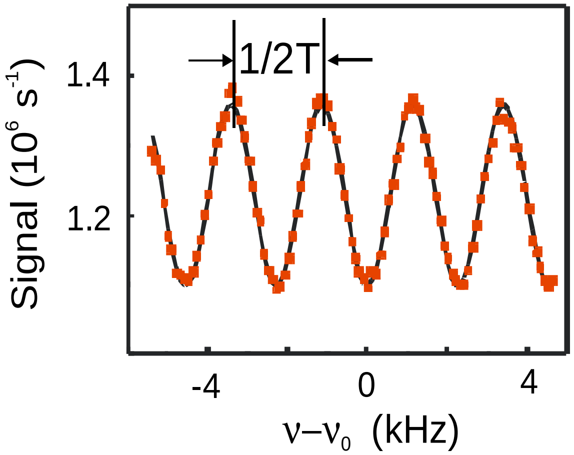
- optimum contrast of the atom interferences
- higher S/N (all atoms contribute to the signal)
- better known line shape
- novel detection scheme applicable

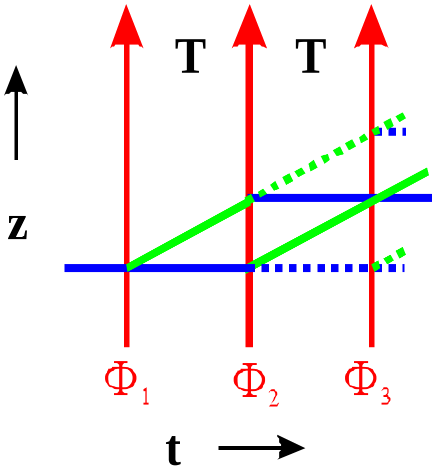
Time-Domain Atom Interferometers



asymmetric atom interferometer

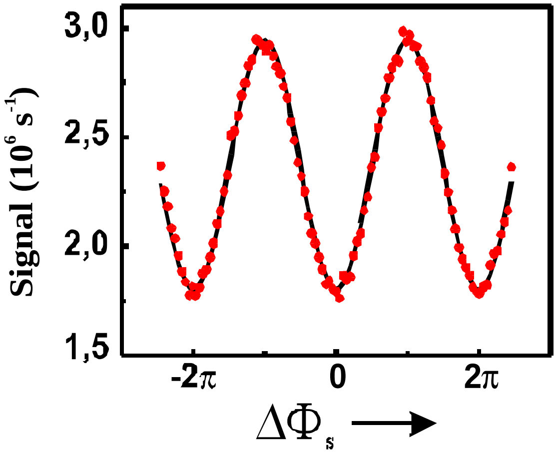
$$\Delta\Phi_a = [2\pi(\nu-\nu_0)+\delta]\cdot 2T + \Phi_2 - \Phi_1 + \Phi_3 - \Phi_4$$



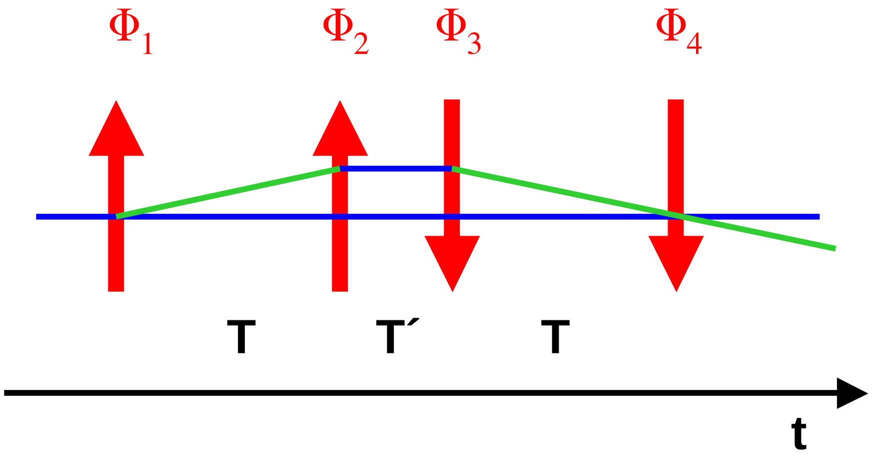


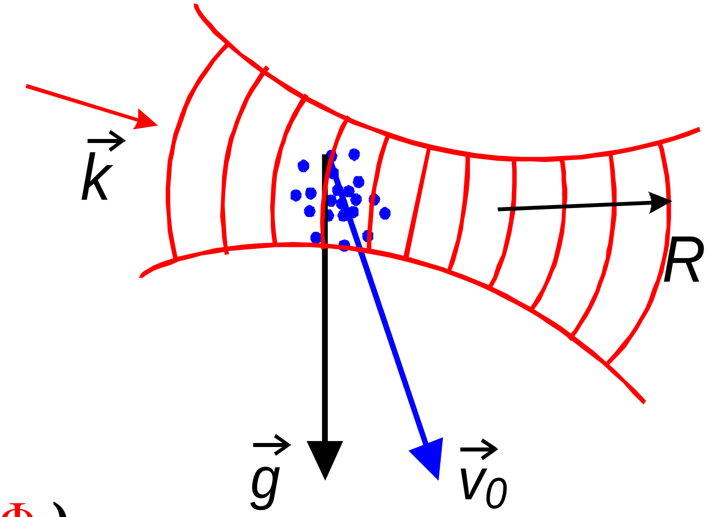
symmetric atom interferometer

$$\Delta\Phi_s = 2\Phi_2 - \Phi_1 - \Phi_3$$



Spurious Phase Shifts in an Optical Clock





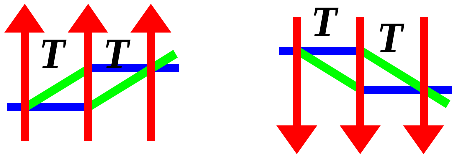
$$I(\nu-\nu_0) \sim \cos\left([2\pi(\nu-\nu_0)+\delta]\cdot 2T + \Phi_2 - \Phi_1 + \Phi_3 - \Phi_4\right)$$

$$\Phi(\vec{r}(t_i)) = \vec{k}\cdot(\vec{r}_0 + \vec{v}_0\cdot t_i + \frac{1}{2}\vec{g}\cdot t_i^2) + k\frac{r_\perp(t_i)^2}{2R}$$

velocity gravity wavefront curvature

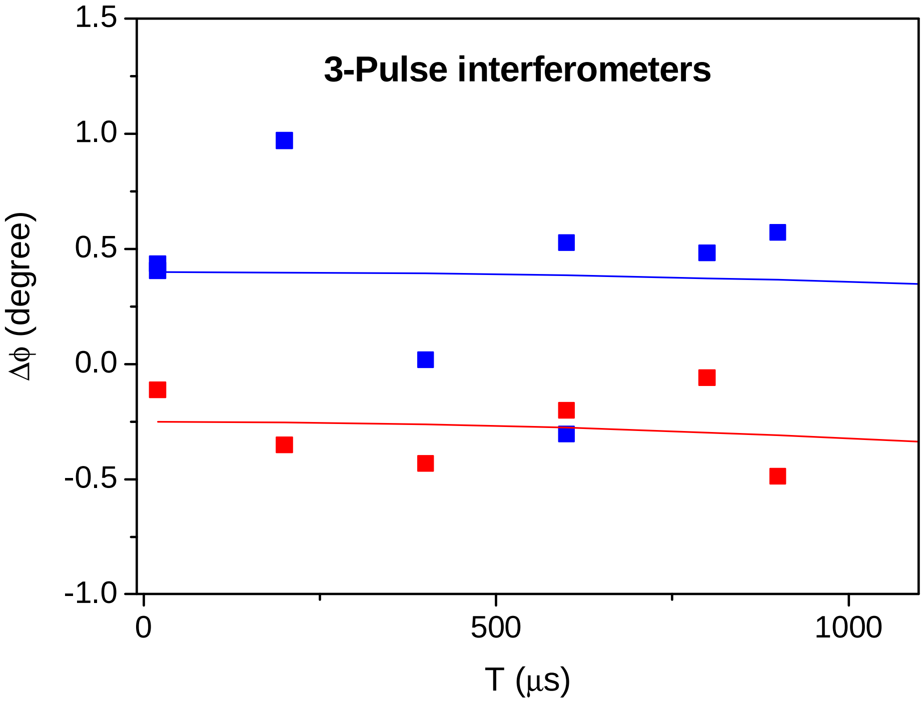
G. Wilpers et al.: Appl. Phys. B 76, 149 (2003)

Correction of Spatial Phase Errors



$$\Delta\Phi = \text{const} \cdot T^2$$

The **const** depends on horizontal allignment and wavefront curvature.

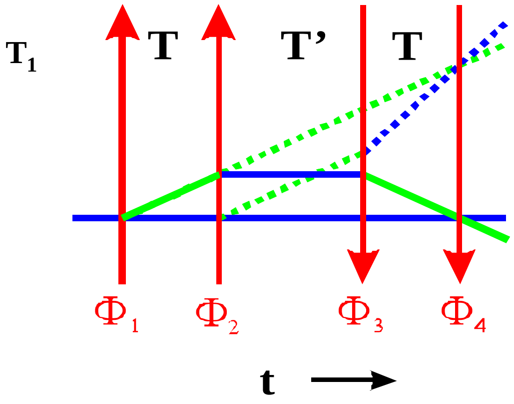


With ultracold atoms the residual shifts due to spatial phases contribute
less than 1 Hz (2 x 10^{-15})

horizontal alignment:
< 100 µrad (0.3 ')

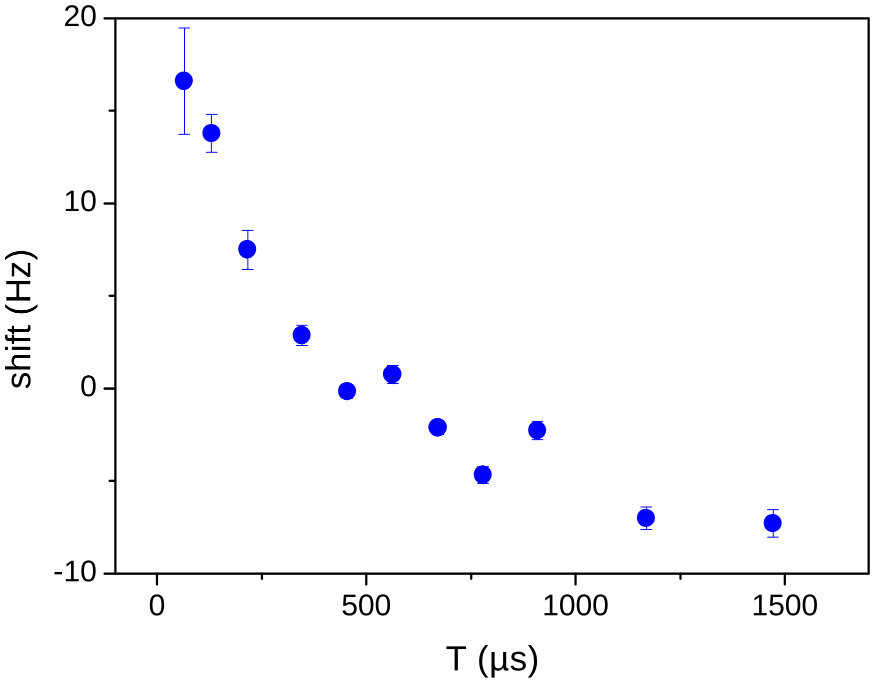
radius of curvature: R > 6 m
(small sensitivity at T=10 µK)

Correction of Spatial Phase Errors

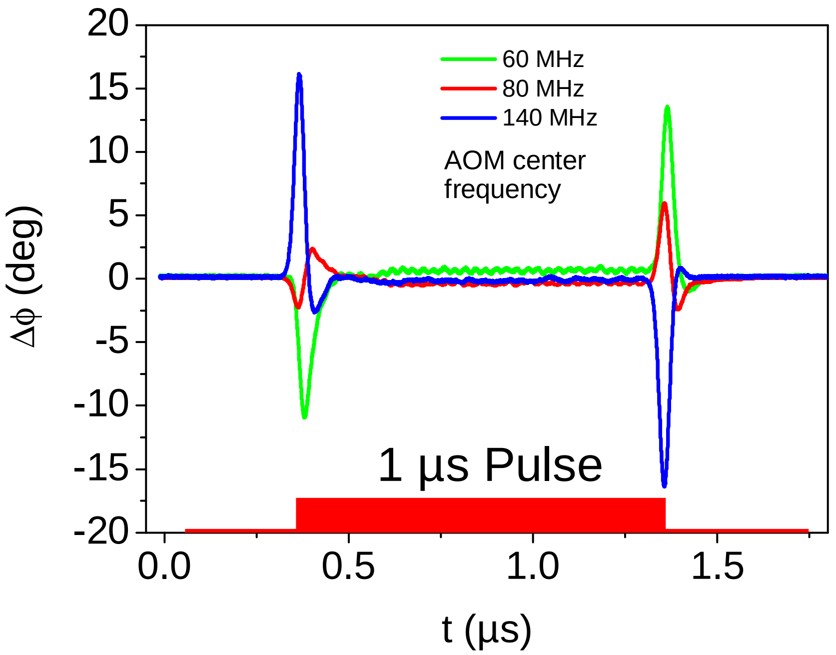


frequency shift as a function
of the pulse separation time T

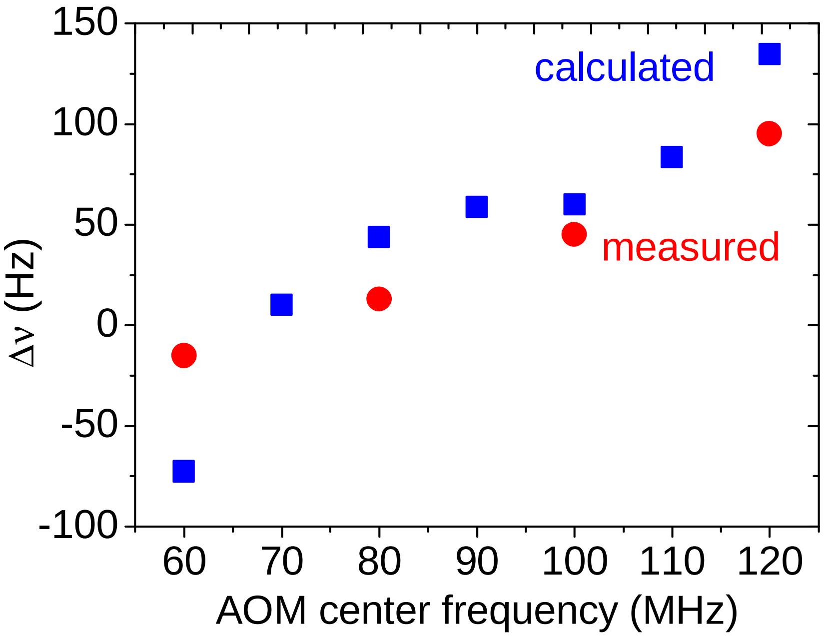
resolution dependence



Temporal Phase Errors: AOM Chirp

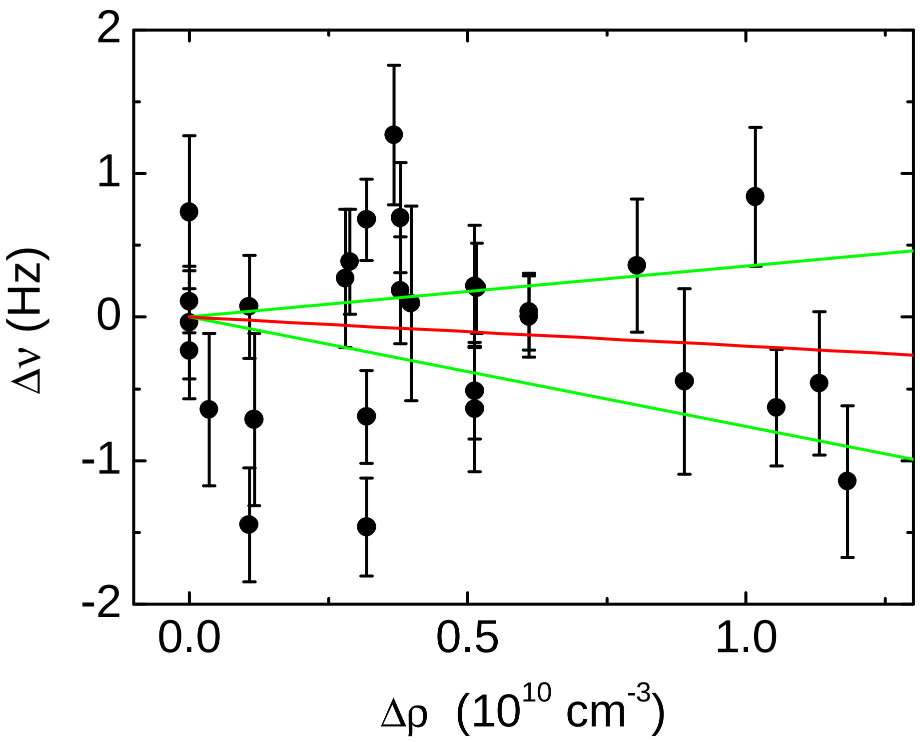


instantaneous optical phase during a laser pulse for different AOM center frequencies



measured and calculated shift using optical Bloch equations with measured temporal laser phase

Collisional Frequency Shift at T = 20 µK



Density-dependent shift at
T ≈ 20 µK:

$$\Delta\nu = A \cdot \langle\rho\rangle$$

$$A = (-2 \pm 6) \cdot 10^{-11}\ \text{Hz cm}^3$$

frequency uncertainty

$$u(\nu) = 0.06\ \text{Hz}$$

Atom	A/ν (10^{-24} cm^3)
Cs (F = 3)	-600 ± 60
Rb (F = 1)	-6.4 ± 16.4
Ca	-0.04 ± 0.12

mean-field energy:

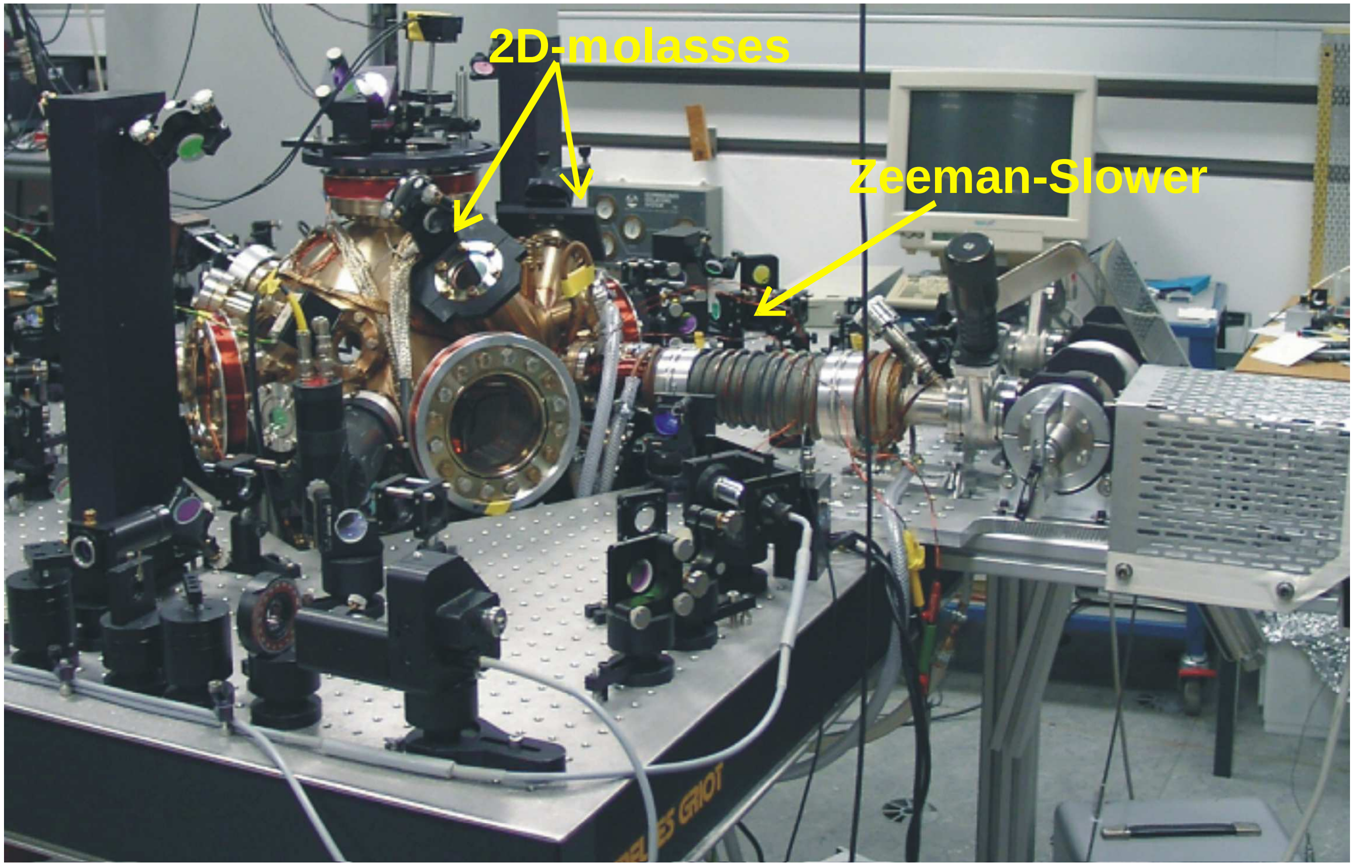
$$E_{MF} = \frac{4\pi\hbar^2 a}{m} n < 0.1\,\text{Hz} \cdot h$$

s-wave scattering length (50 a_0 – 300 a_0)

Uncertainty budget

Effect	T = 12 µK (2003)	T = 12 µK near future
spatial phases - Doppler effect	1.0 Hz	150 mHz
temporal phase contributions	1.6 Hz	200 mHz
asymmetry of line shape	0.05 Hz	50 mHz
magnetic field (64 Hz/mT^2)	0.2 Hz	200 mHz
quadratic Stark effect ($\lvert E \rvert$ < 2 V/cm)	0.1 Hz	100 mHz
black body radiation		
oven	3.9 Hz	
walls	0.07 Hz	70 mHz
laser frequency drift	0.1 Hz	100 mHz
influence of cold atom collisions	0.06 Hz	60 mHz
statistical uncertainty of the frequency meas.	3.0 Hz	5 mHz
Cs clock ($1 \cdot 10^{-15}$)	0.5 Hz	
total uncertainty $\delta\nu$	**5.5 Hz**	**370 mHz**
total relative uncertainty $\delta\nu/\nu$	**$1.2 \cdot 10^{-14}$**	**$8 \cdot 10^{-16}$**

New Setup

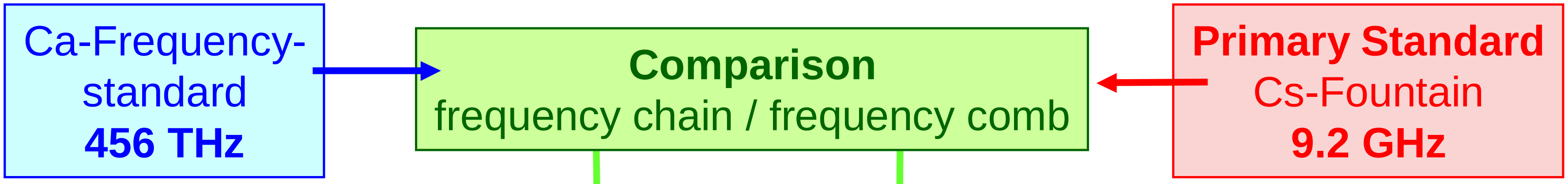


direct loading from thermal atomic beam is replaced by:

- Zeeman slower
- 2-D molasses to deflect slow atoms to MOT region
- better loading rate: 10^9 trapped atoms within 1 s

no black body shift from the oven

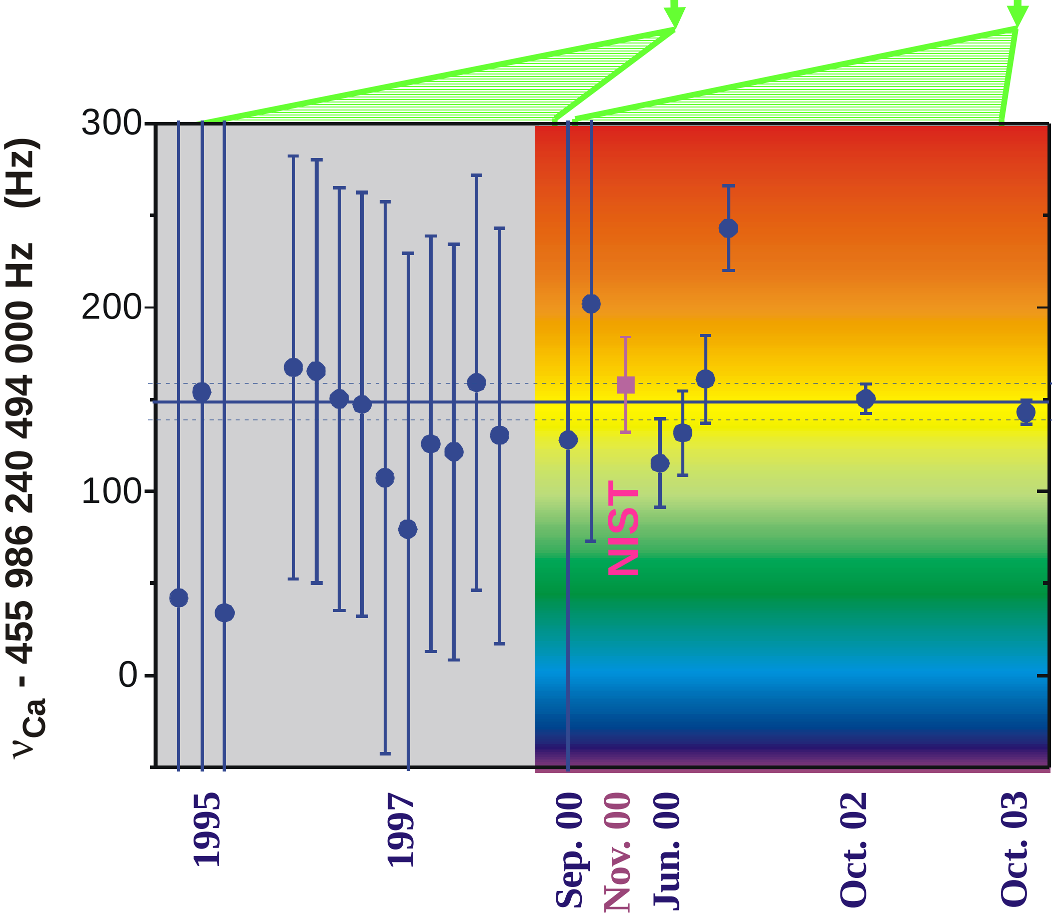
Optical frequency measurement of calcium



Ca-Frequency-standard
456 THz

Comparison
frequency chain / frequency comb

Primary Standard
Cs-Fountain
9.2 GHz

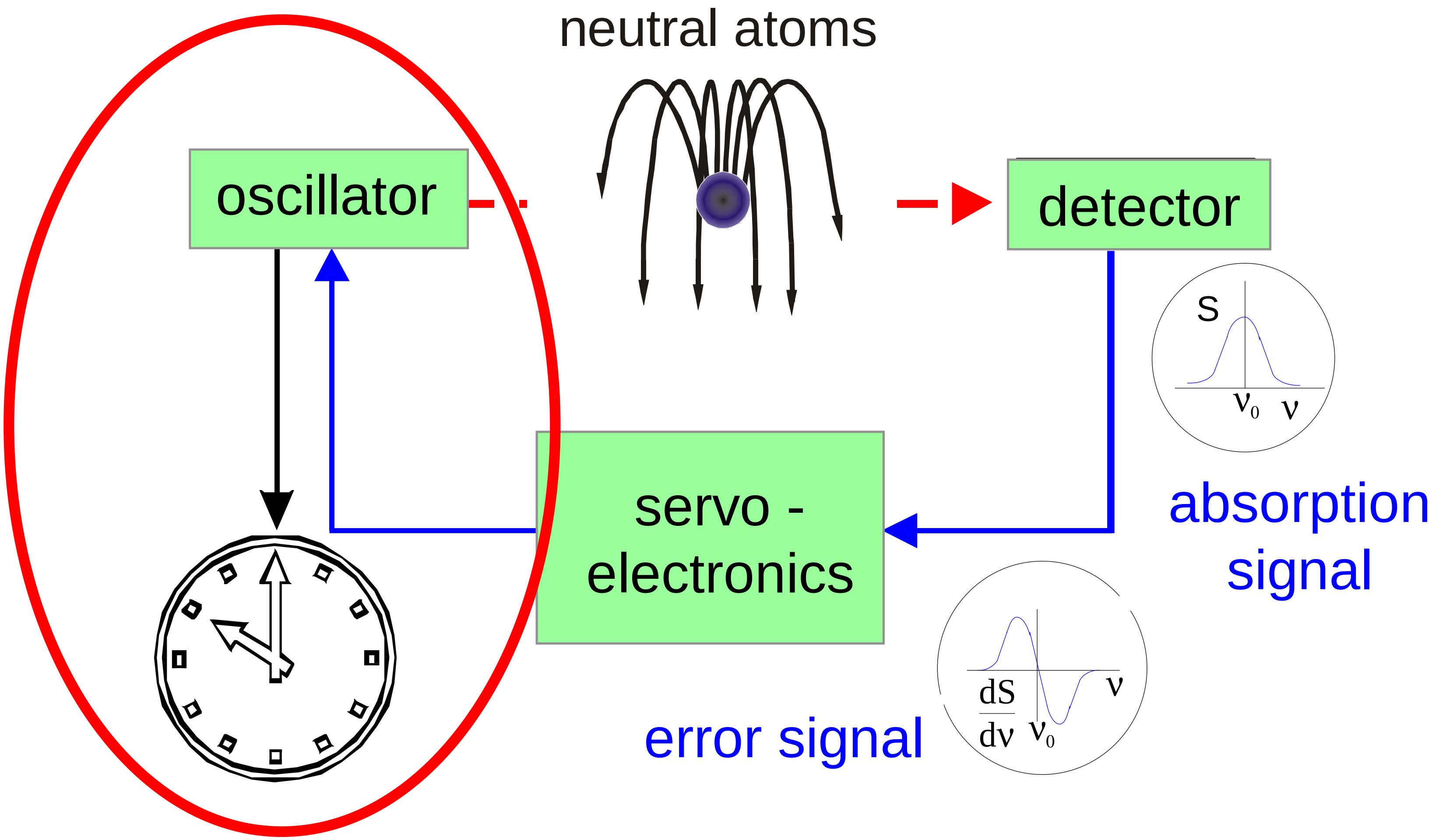


October 2003

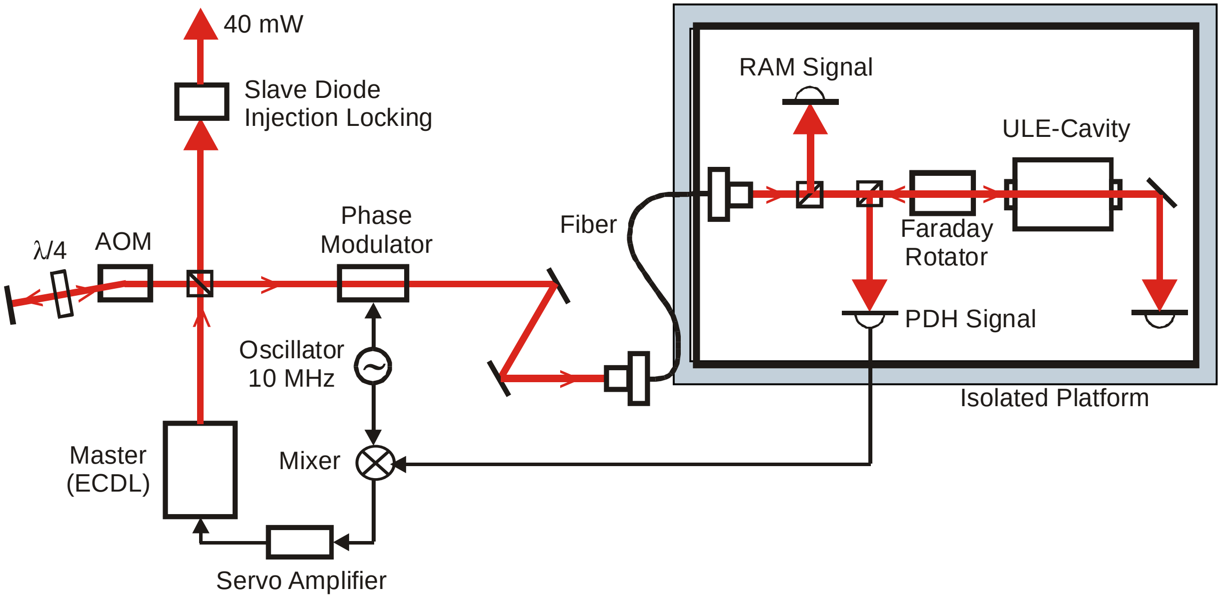
$$\nu_{Ca} = 455\,986\,240\,494\,143 \text{ Hz} \pm 5.5 \text{ Hz}$$

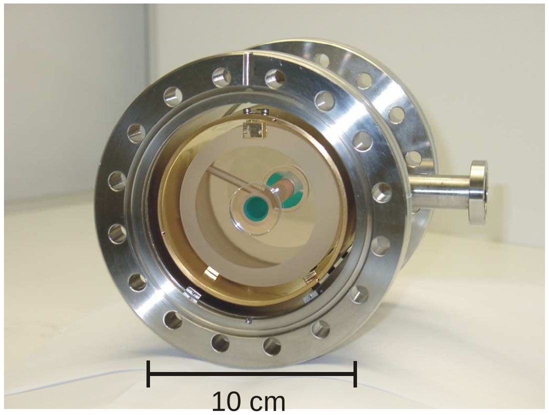
$$\frac{u(\nu_{Ca})}{\nu_{Ca}} = 1.2 \cdot 10^{-14}$$

Principle of Clocks



Interrogation Laser

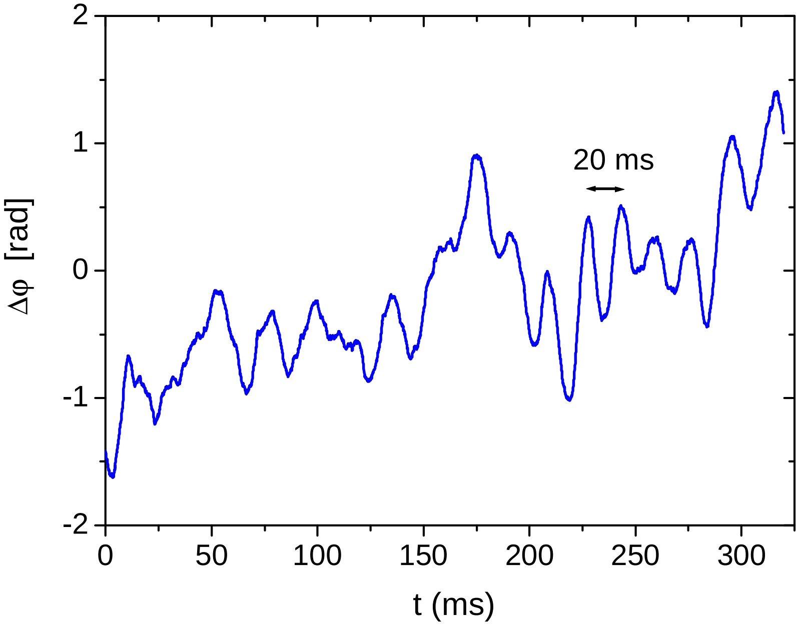


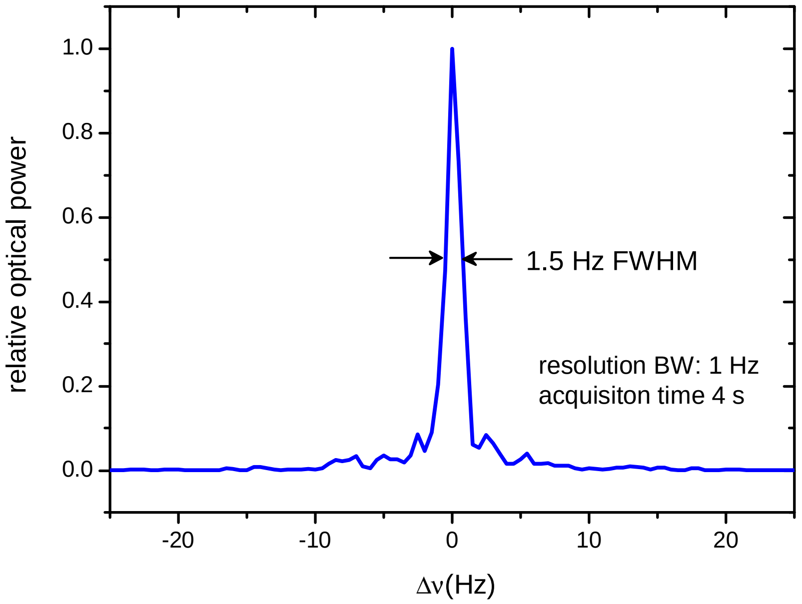


finesse: 79 000
linewidth (FWHM): 19 kHz

Resonance frequencies:
0.7 Hz vertical, 0.6 Hz horizontal

Beat between Two Independent Lasers



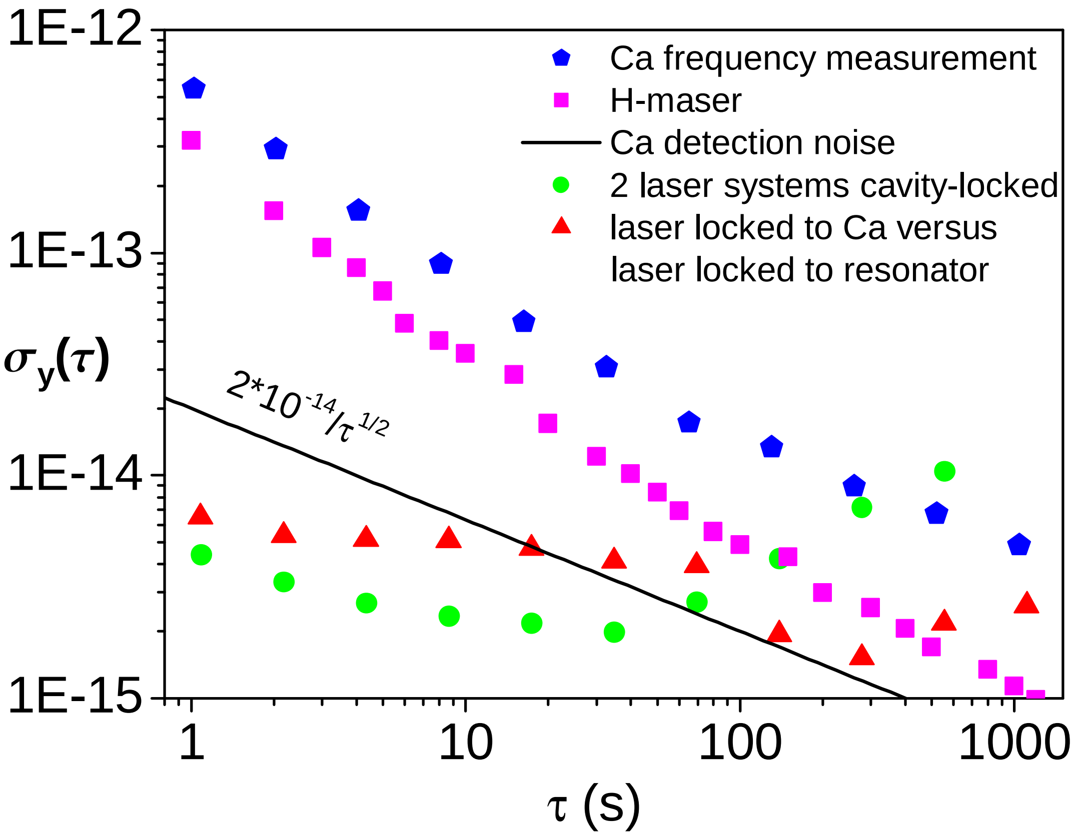


optical phase difference
between two lasers

power spectrum
of the beat

laser linewidth ~ 1 Hz
drift 0.06 Hz/s

Measured Stability



Allan standard deviation $\sigma_y(\tau)$ limited by technical and laser noise of Ca-standard

Quantum-Projection noise limit

$\sigma_y(1s) = 5 \cdot 10^{-17}$

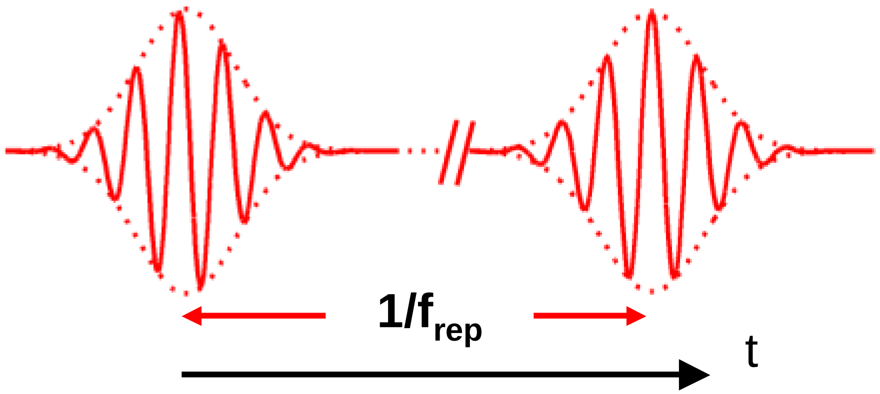
($N_0 = 3 \cdot 10^7$ atoms

$T_{cycl} = 30$ ms)

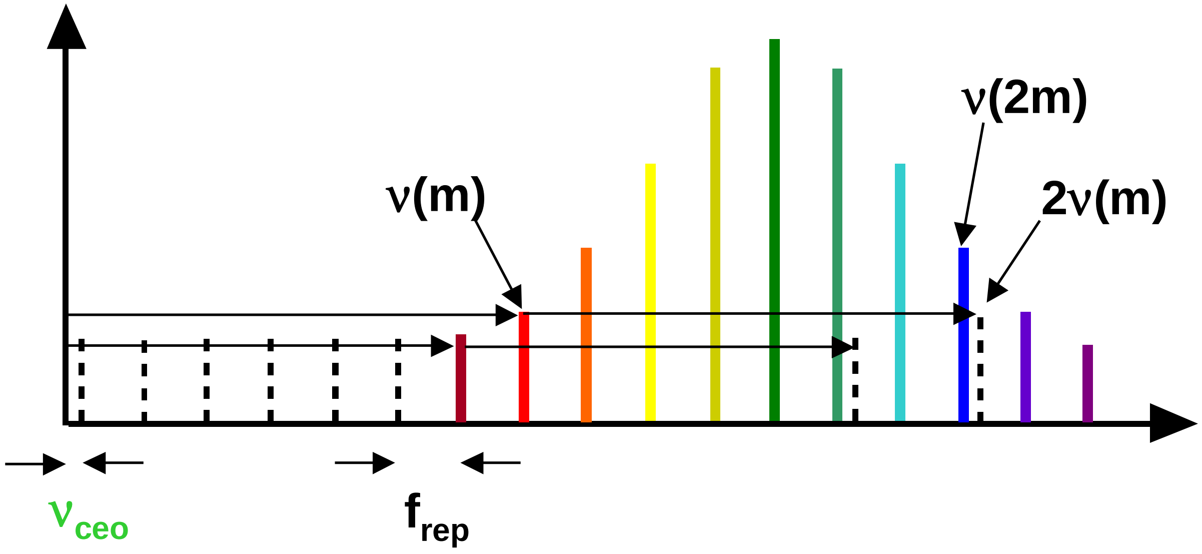
$$\sigma_y(\tau) = \frac{1}{\pi} \cdot \frac{1}{4T\nu_0} \sqrt{\frac{1-\overline{p}}{N_0 K^2 \overline{p}}} \cdot \sqrt{\frac{T_{cycl}}{\tau}}$$

Optical Frequency Comb

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



frequency domain:
comb of frequencies

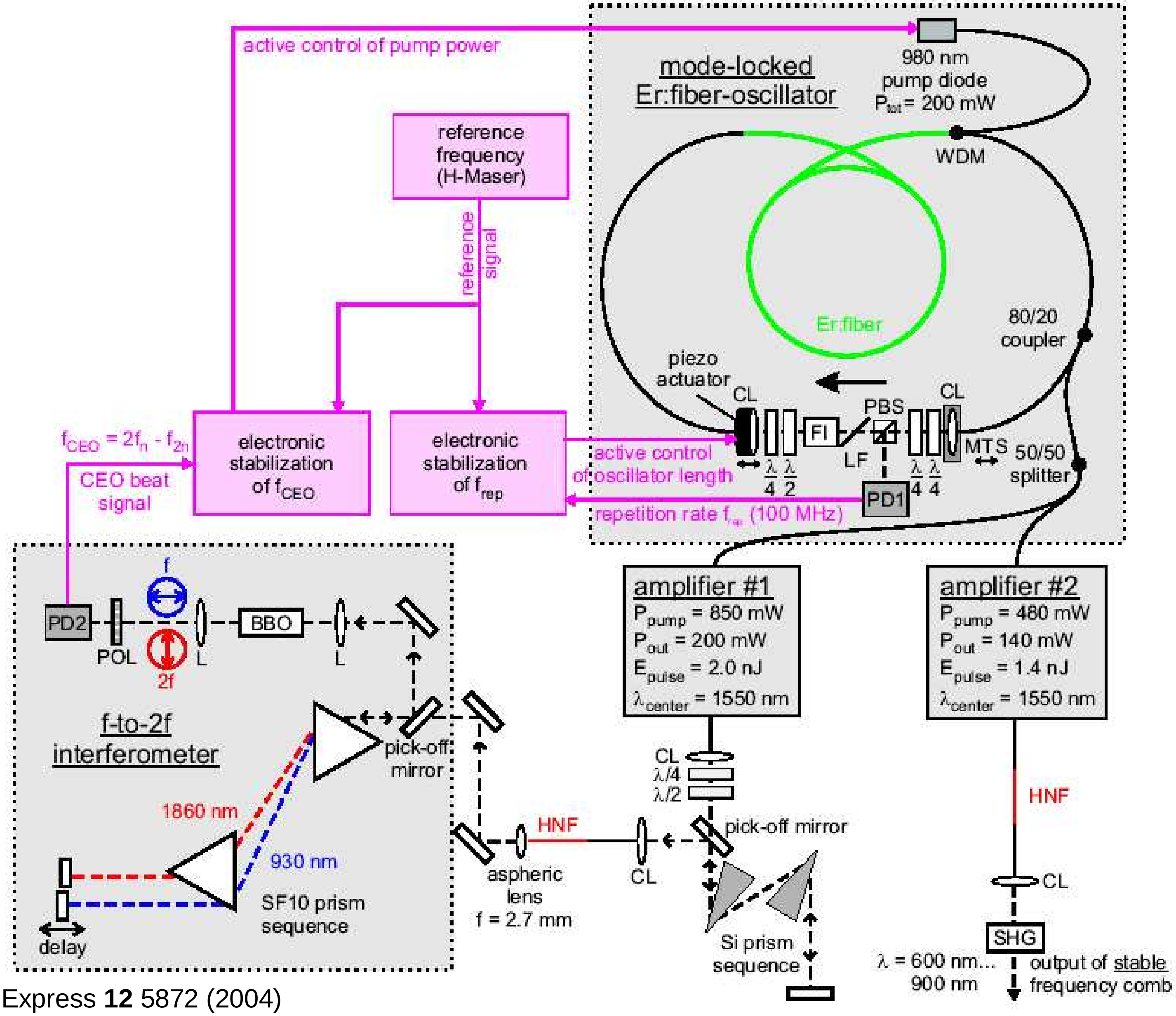


self-referencing
to measure ν_{ceo}

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

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

Fiber Laser fs Frequency Comb

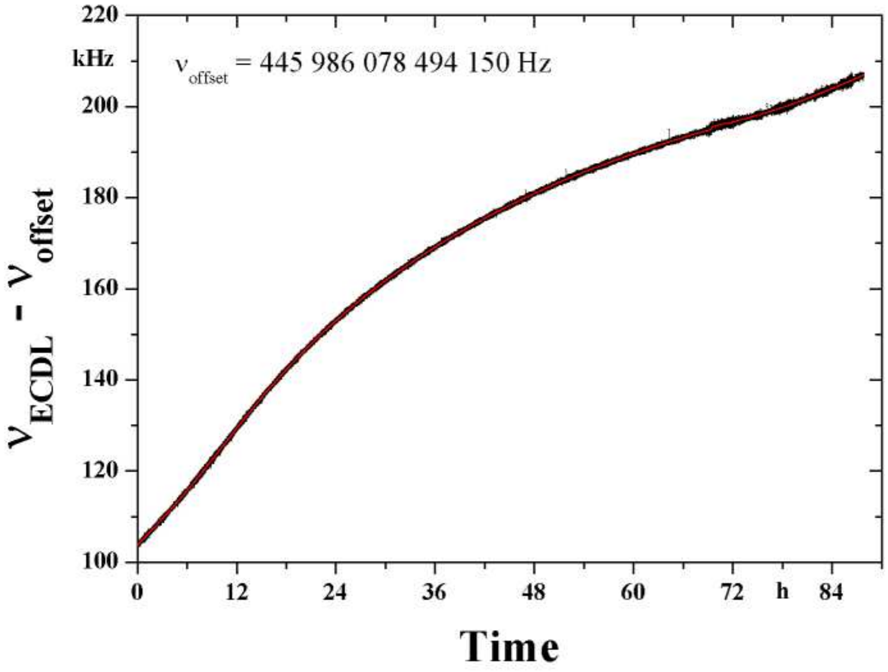


Adler et al., Opt. Express **12** 5872 (2004)

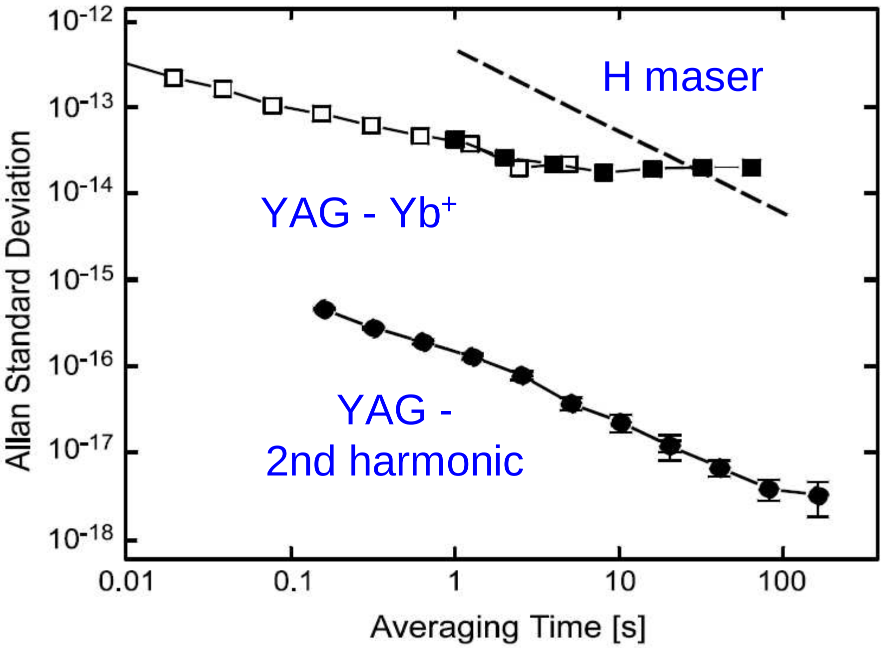
reliability and accuracy

Er$^+$-doped fs-fiber laser, λ ~1550 nm

- long term operation:
  88 h without interruption
  $3 \cdot 10^{21}$ counts



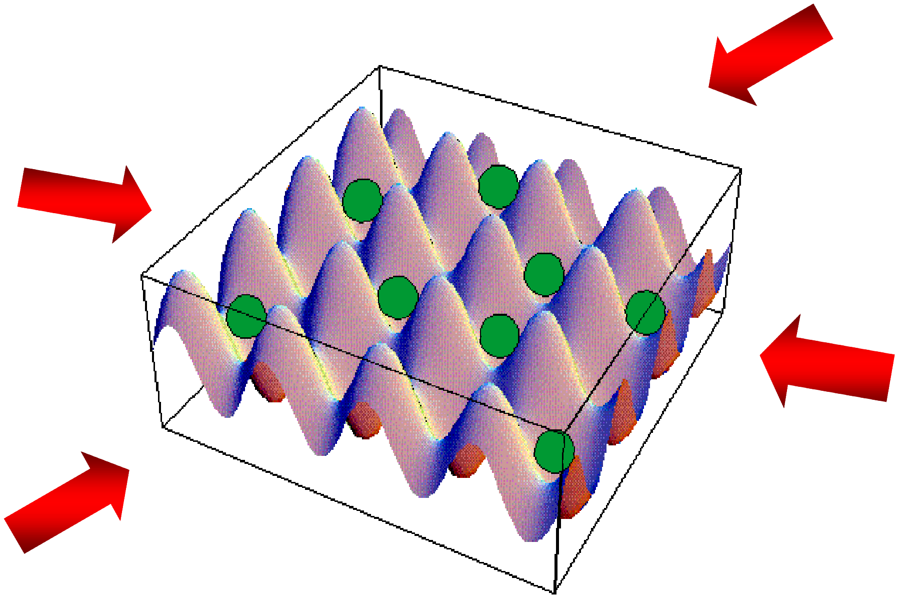
frequency measurement of a cavity-stabilized diode laser



performance of a Ti:Saphire comb

Stenger et al., PRL **88** 073601 (2002)

Concept of an optical lattice clock



“Magic Wavelength”

- no net light shift

10^7 neutral atoms

H. Katori: Spectroscopy of Strontium Atoms in the Lamb-Dicke Confinement. In: Proc. of 6th Symposium on Frequency Standards and Metrology, (P. Gill ed., World Scientific), p. 323 - 330, (2002).

Advantages

- Very long interaction time
  small line width
- Confinement to the Lamb-Dicke regime $\Delta x < \lambda$
  no first-order Doppler effect
- Large number of atoms
  High signal-to-noise-ratio
  $S/N \sim N^{1/2}$
- Prospects to surpass this quantum limit with entangled states

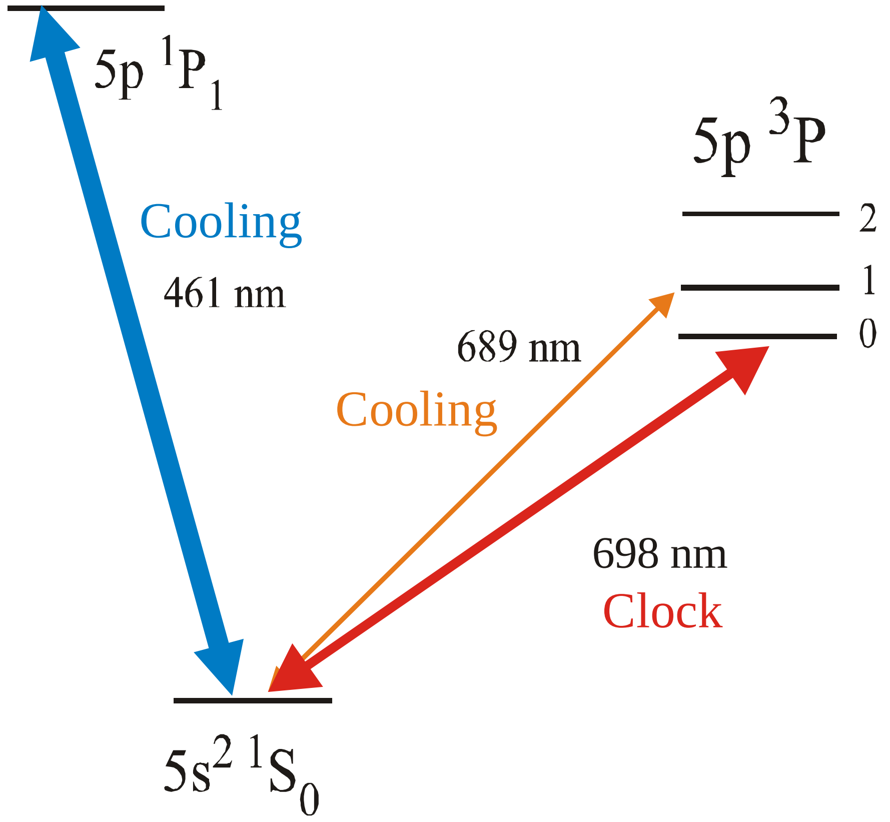
Optical Lattice Clock

Earth alkali elements Mg, Ca, Sr

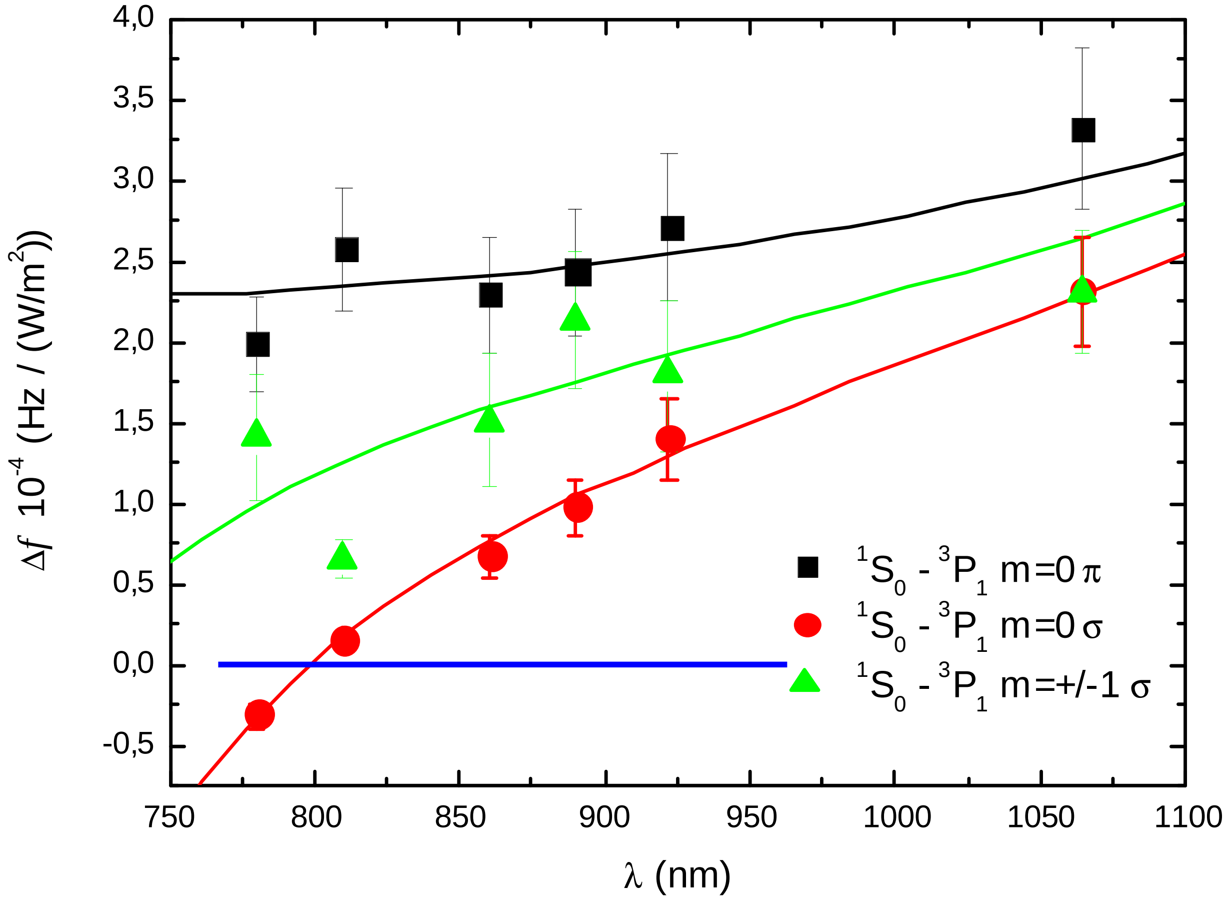
and Yb, Hg have metastable $^3P_0$ state

- accessible by 1 photon transition in fermionic isotopes, Δν ~ mHz
- or by 2 and 3 photon Raman transitions also in bosonic isotopes
- “magic wavelengths”
- efficient cooling possible

Strontium



Measurement of Ca - “Magic Wavelength”



Theory:

using available atomic data and adjusting line strength of the 2 most important transitions

magic wavelengths:

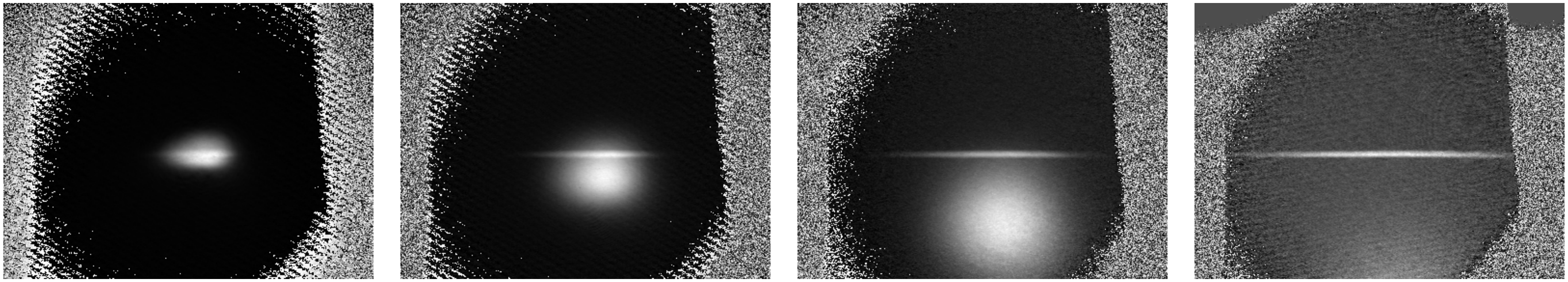
$^3P_1$: (800.8 ± 2.2) nm

$^3P_0$: (735.5 ± 20) nm

Degenhardt et al. PRA **70**, 023414 (2004)

Optical dipole trap

- Conservative light forces in focused laser beam to trap atoms
- Trap depth: 8 W @ 514 nm, $w_0 = 50\ \mu\text{m} \Rightarrow U_{dip} = 40\ \mu\text{K}$
- Loading of dipole trap: overlap with MOT ~ 2 % transfer
- Quench-cooling is compatible with trap operation as long as the light-shifts are right ! (poster Felix Vogt)



0 ms 10 ms 20 ms 30 ms

expansion after turning off the MOT

- how close will laser cooling lead towards quantum degeneracy ?

Conclusion

- Calcium clock at present
  - frequency uncertainty $1.2 \cdot 10^{-14}$
  - negligible collisional frequency shift
- Reliable fiber based femtosecond comb
- Measurement of “magic wavelength”
- Optical dipole trap for calcium

Future:

- Uncertainty $\approx 10^{-15}$ with ballistic atoms
- Clock with instability $< 10^{-16}$ in one second
- Optical lattice clock with low uncertainty
- Quantum degeneracy

The People

Ca and Sr standards:

Tatiana Nazarova
Felix Vogt

Christian Lisdat (U. Hannover)
Paul-Eric Pottie
Christophe Grain

Fritz Riehle
U.S.

former members:

Hardo Stoehr
Guido Wilpers (NIST)
Tomas Binnewies
Carsten Degenhardt
Jürgen Helmcke

Frequency measurements:

Harald Schnatz
Burghardt Lippard
Harald Telle
Nils Haverkamp
Stefan Weyers

Yb single ion:

Christian Tamm
Ekkehard Peik
Tobias Schneider

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DFG
EU CAUAC
SFB 407

Research
Training Networks

DFG

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