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Systèmes de Référence Temps-Espace

Sr optical lattice clock: hyperpolarizability effects and preliminary accuracy evaluation

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Le progrès, une passion à partager

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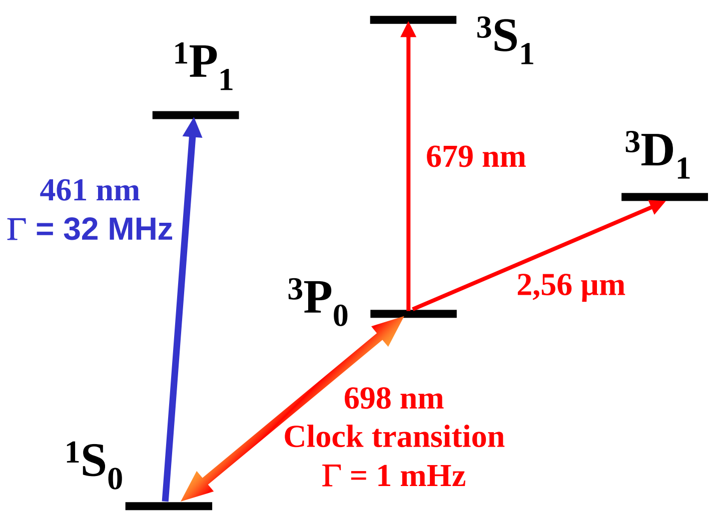
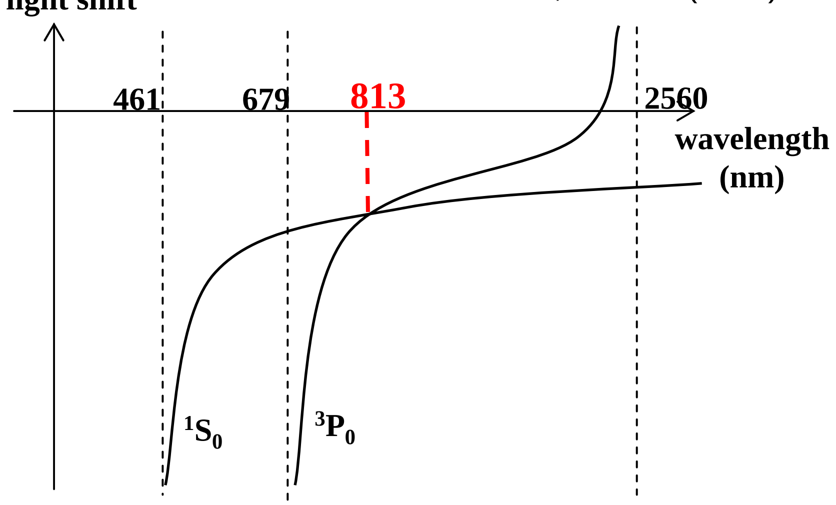
^{87}Sr Optical lattice clock

- Optical lattice clock with atoms confined in an optical lattice
- Expected ultimate fractional accuracy: 10^{-18}
- Lattice @ “magic wavelength” => cancellation of first order differential light shift



Katori et al. PRL 91, 173005 (2003)



Differential light shift cancellation ?

- ❑ U_0=10 E_r (36 kHz) is enough to cancel motional frequency shift

P. Lemonde, P. Wolf, Phys. Rev. A, **72** 033409 (2005)

Accuracy of 10^{-18} ⇔ Control at a level of 10^{-8} x Light shift

- ❑ Neutral atoms in an optical lattice :

$$\hbar\nu = \hbar\nu^{(0)} - \frac{1}{4}\Delta\alpha(\mathbf{e},\omega)E^2 - \frac{1}{64}\Delta\gamma(\mathbf{e},\omega)E^4 - \ldots$$

- ❑ At the magic wavelength, the first order term cancels

- ❑ Higher order terms : Hyperpolarizability => Scale as $E^4 \propto U_0^2$

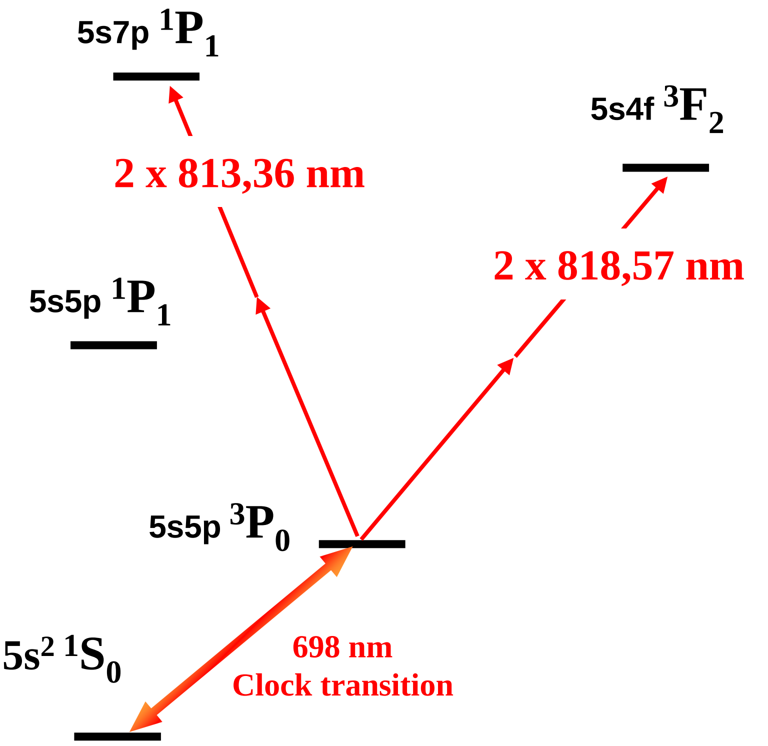
⇒ Feasibility is conditioned by the magnitude of higher order effects

Hyperpolarizability effects on the clock frequency

- Theoretical prediction of -2 µHz/E_r^2,
  @ the theoretical magic wavelength: 800 nm

  H Katori, M. Takamoto, V.G. Pal'chikov, and V.D. Ovsiannikov, Phys. Rev. Lett., **91**, 173005 (2003)

λ_m = 813,428 nm



- Second order light shift: magic wavelength close to two two-photon transitions
  - 5s5p $^3P_0$ -> 5s7p $^1P_1$

    fortunately forbidden: J=0 -> J=1

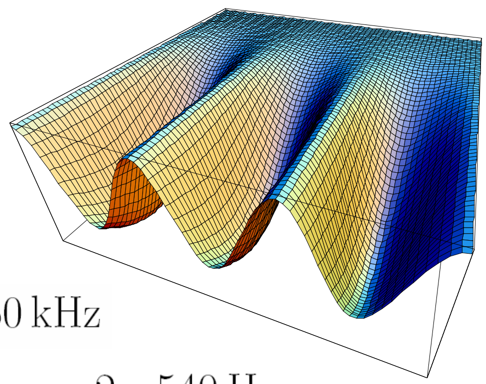
    G. Grynberg, B. Cagnac, Rep. Prog. Phys. **40,** 791 (1977)
  - 5s5p $^3P_0$ -> 5s4f $^3F_2$

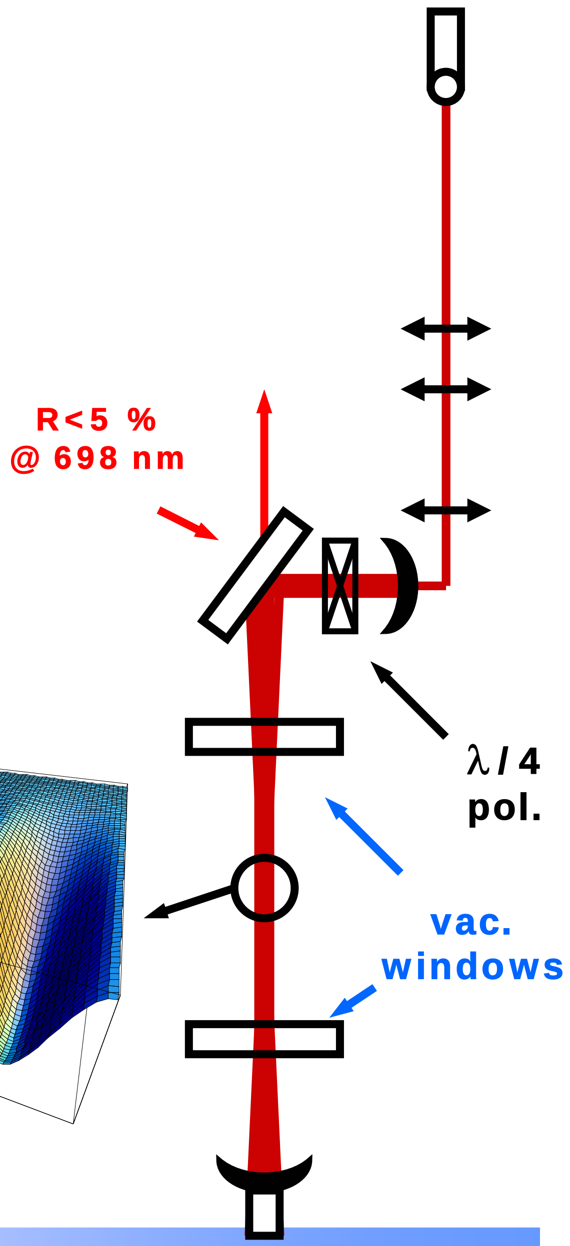
Need for an experimental evaluation of the effect

Optical lattice

Need for high peak intensity > 100 kW/cm²

- Laser Ti:sapph ~ 7-800 mW @ 813 nm
- Linear build-up cavity
  - Finesse ~ 100
  - Waist 89µm
  - Peak intensity ~ 400 kW/cm²
- Linear polarization (to within ~ 10^{-4})
- probe transmission @ 698 nm





Max trapping depth
1400 E_R ~ 4,5 MHz
~ 200 µK

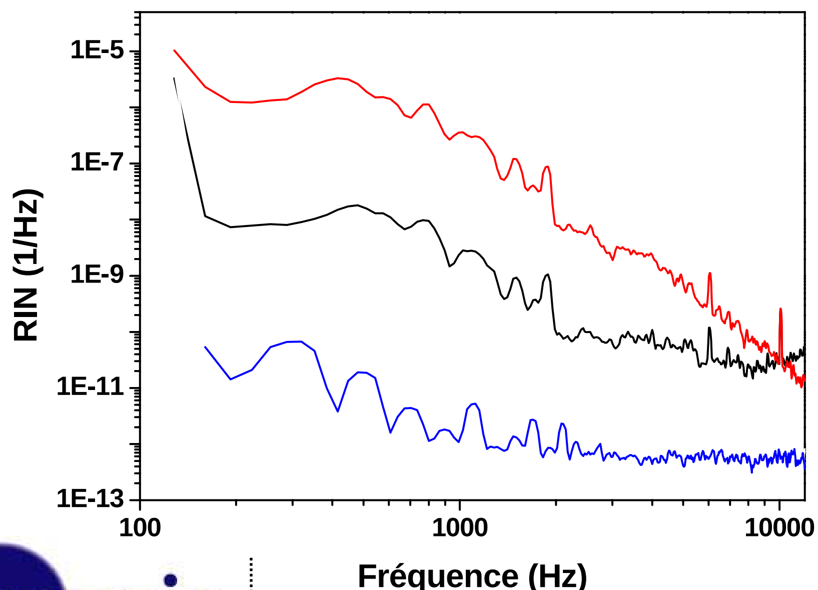
$$\omega_{trap,z} = 2\pi.250\,\mathrm{kHz}$$

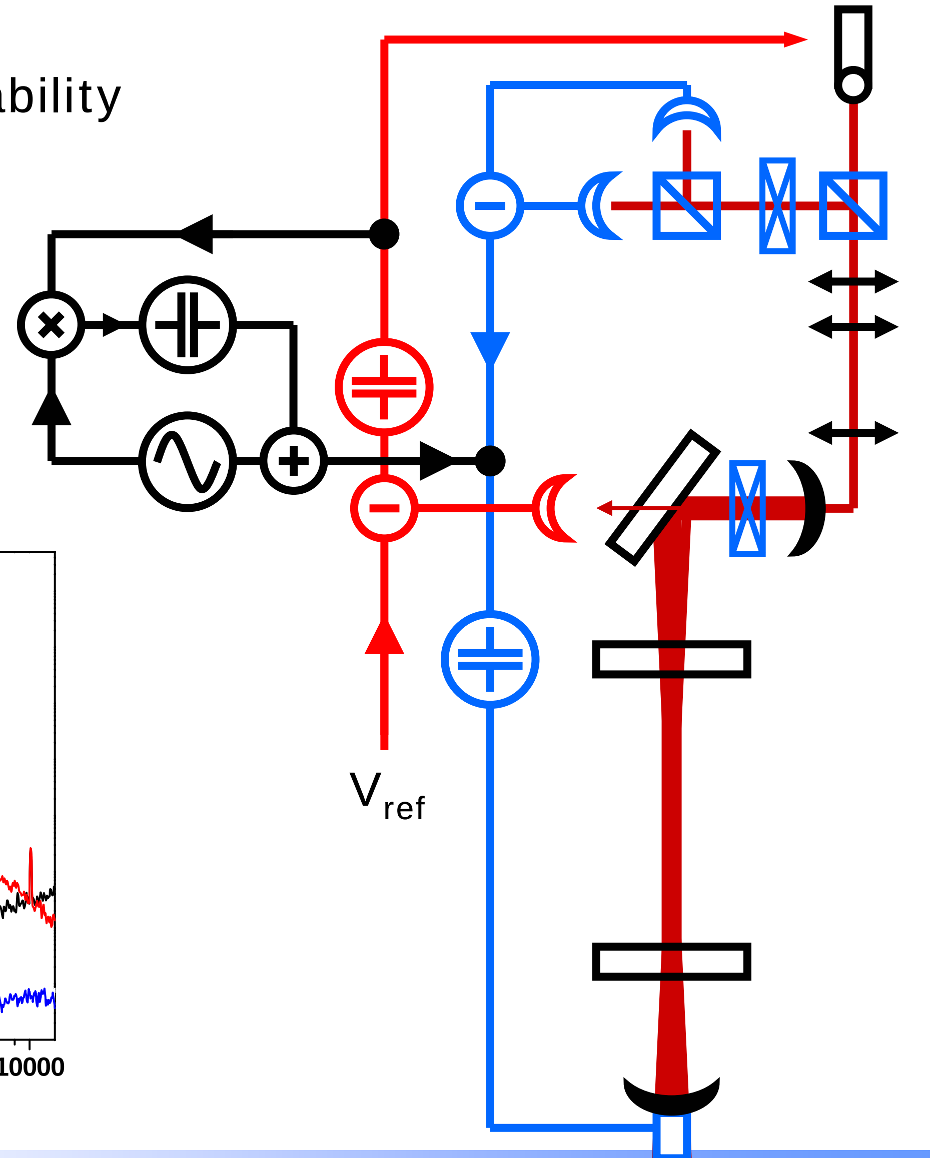
$$\omega_{trap,x} = \omega_{trap,y} = 2\pi.540\,\mathrm{Hz}$$

Servo-loop system

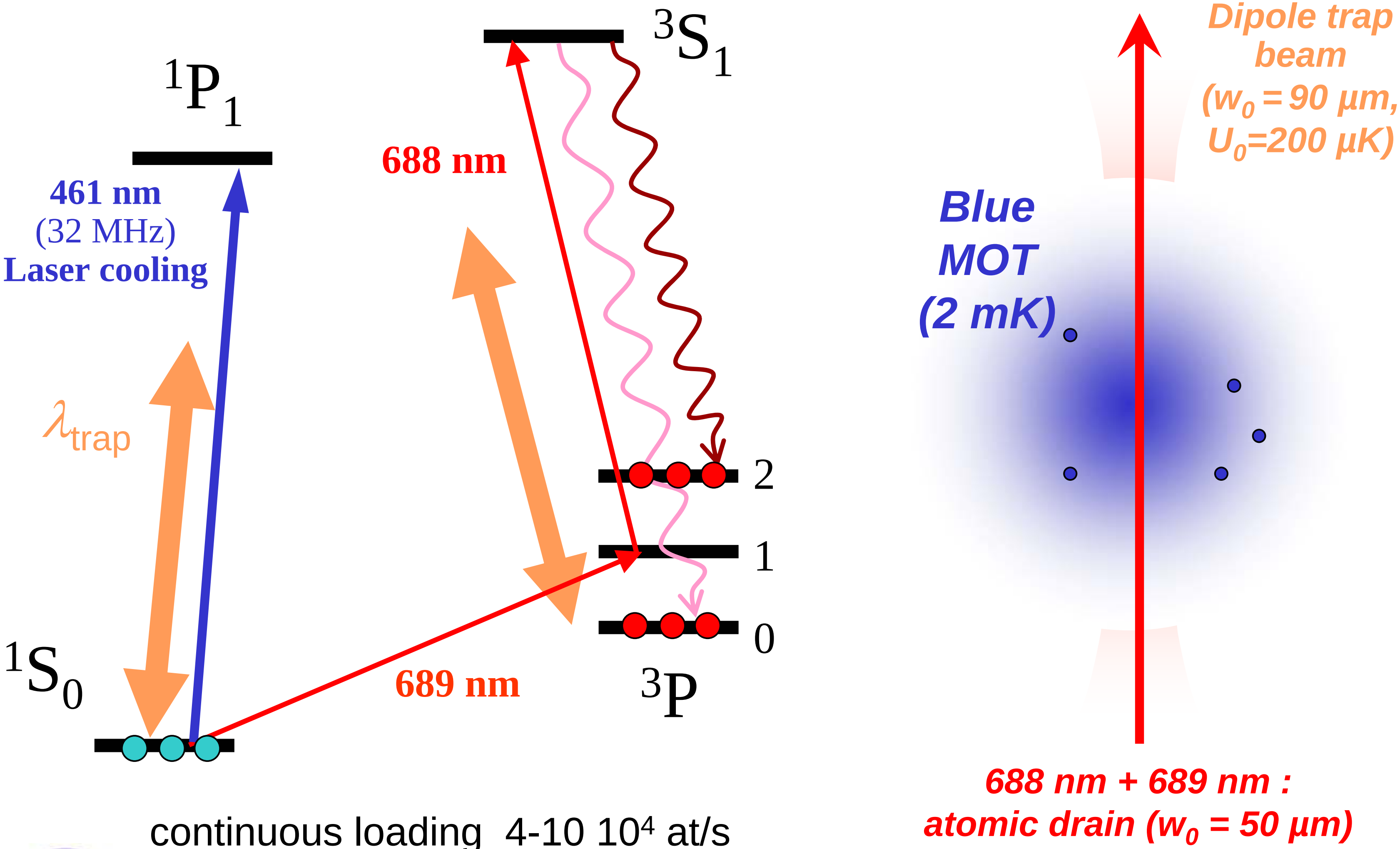
3 servos to ensure optimal stability

1. Hänsch-Couillaud
2. Intracavity power control
3. offset HC



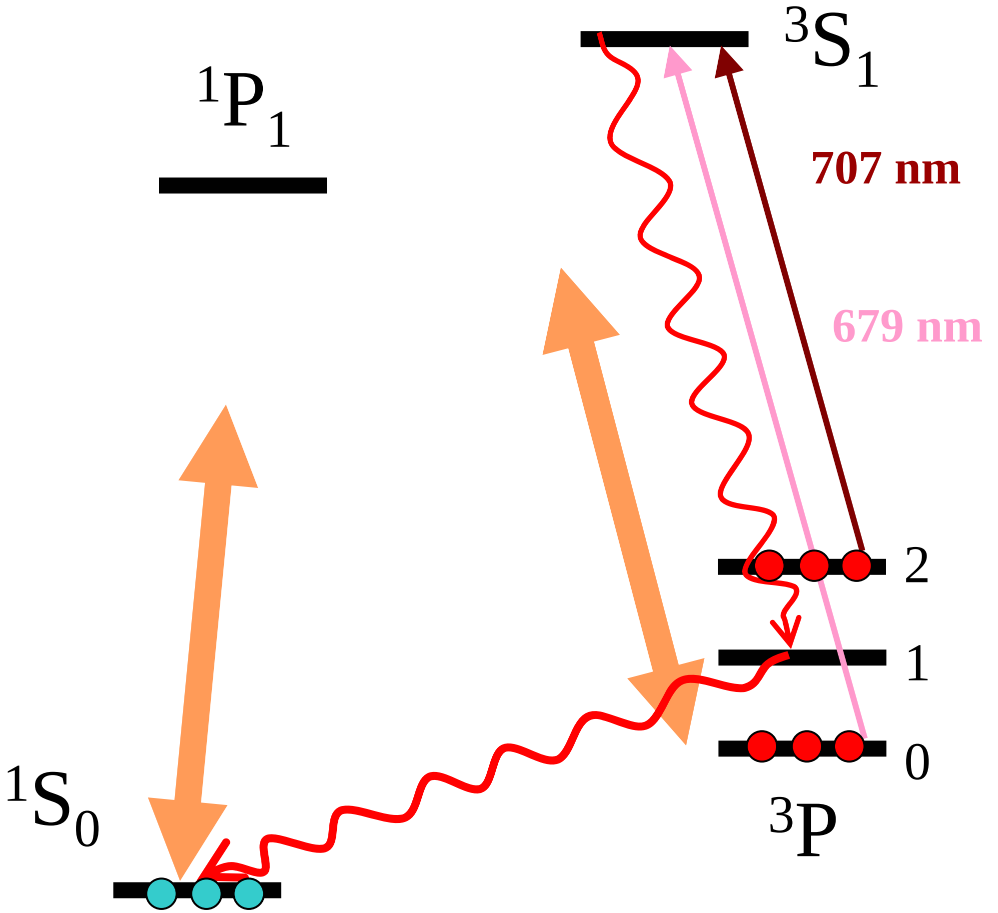


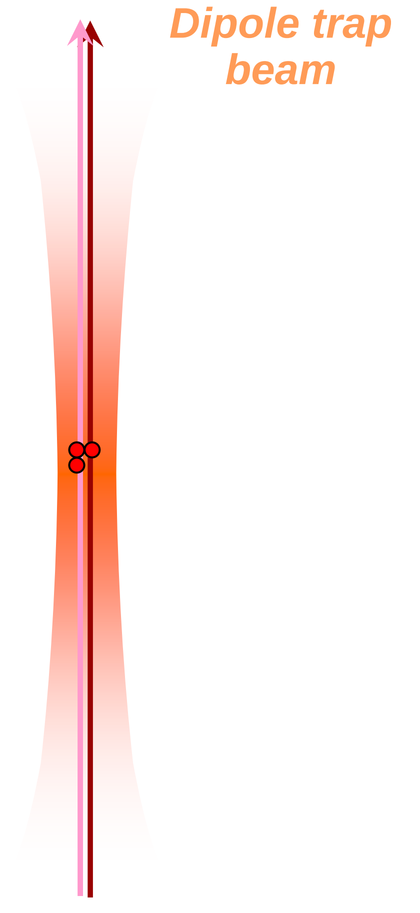
loading the dipole trap



continuous loading 4-10 10^4 at/s

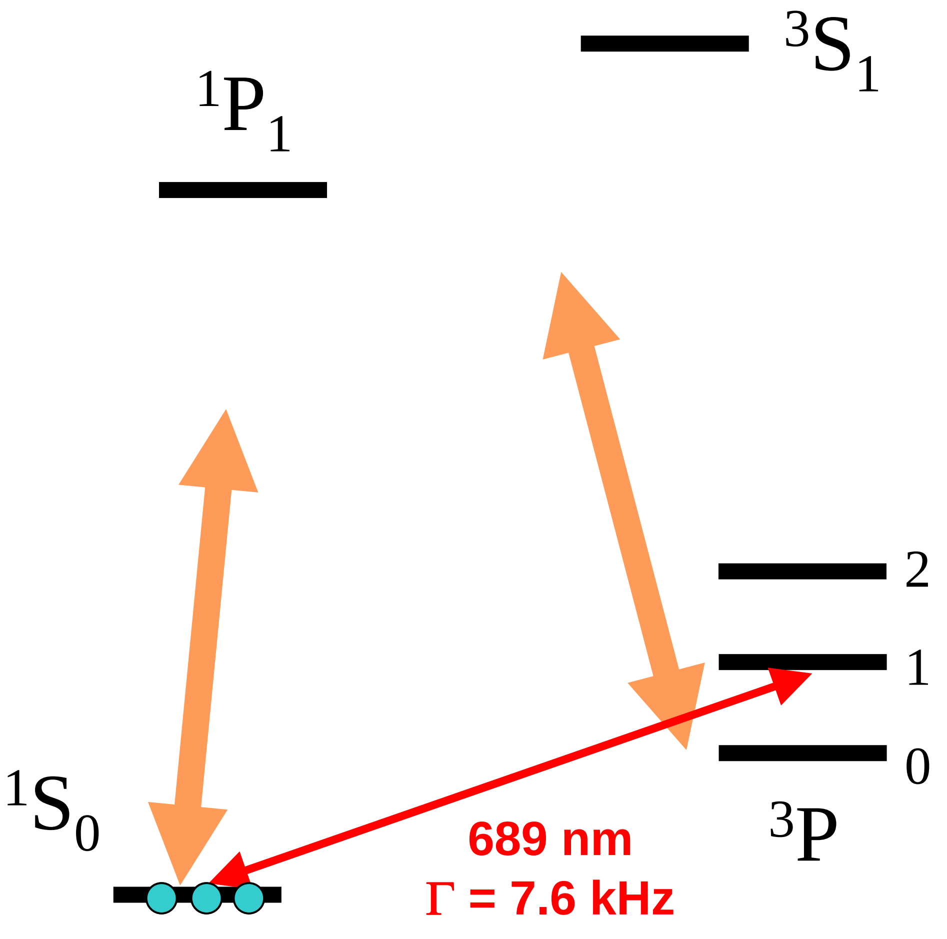
loading the dipole trap

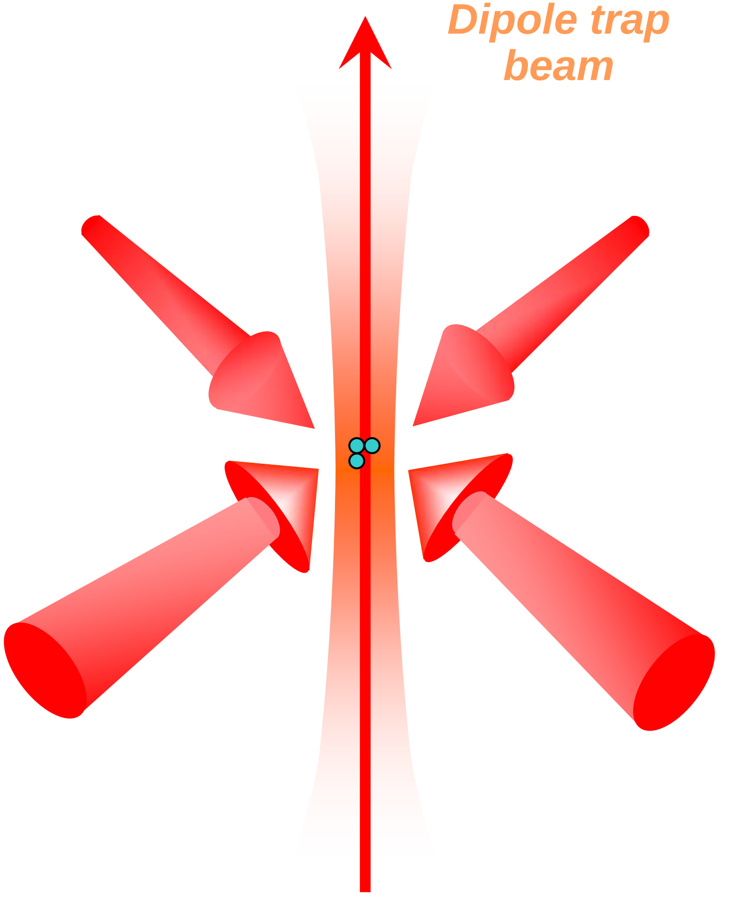




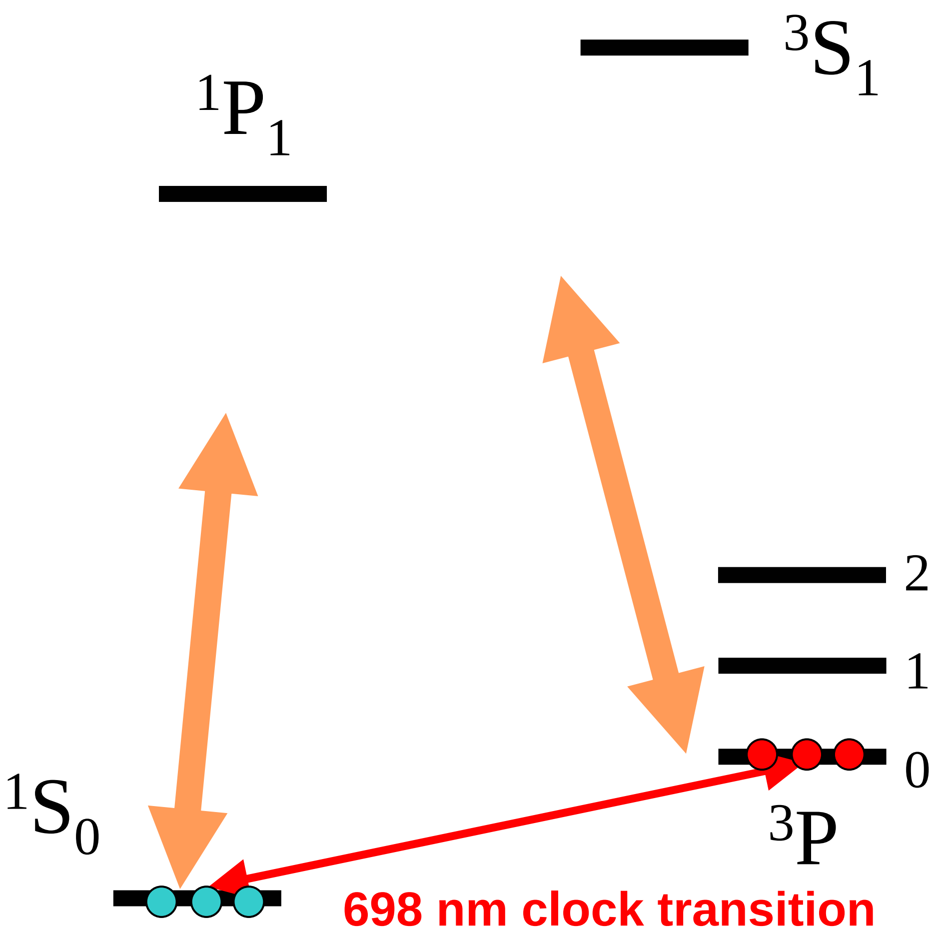
707 nm + 679 nm :
repumpers (w_0 = 200 µm)

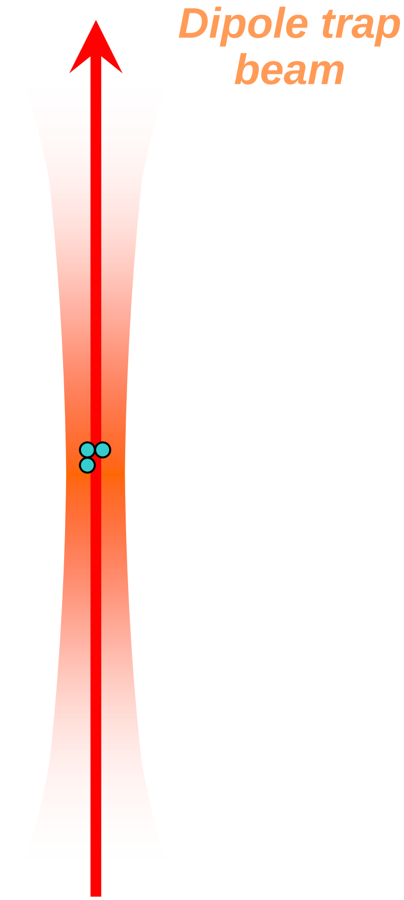
Narrow line cooling in the dipole trap





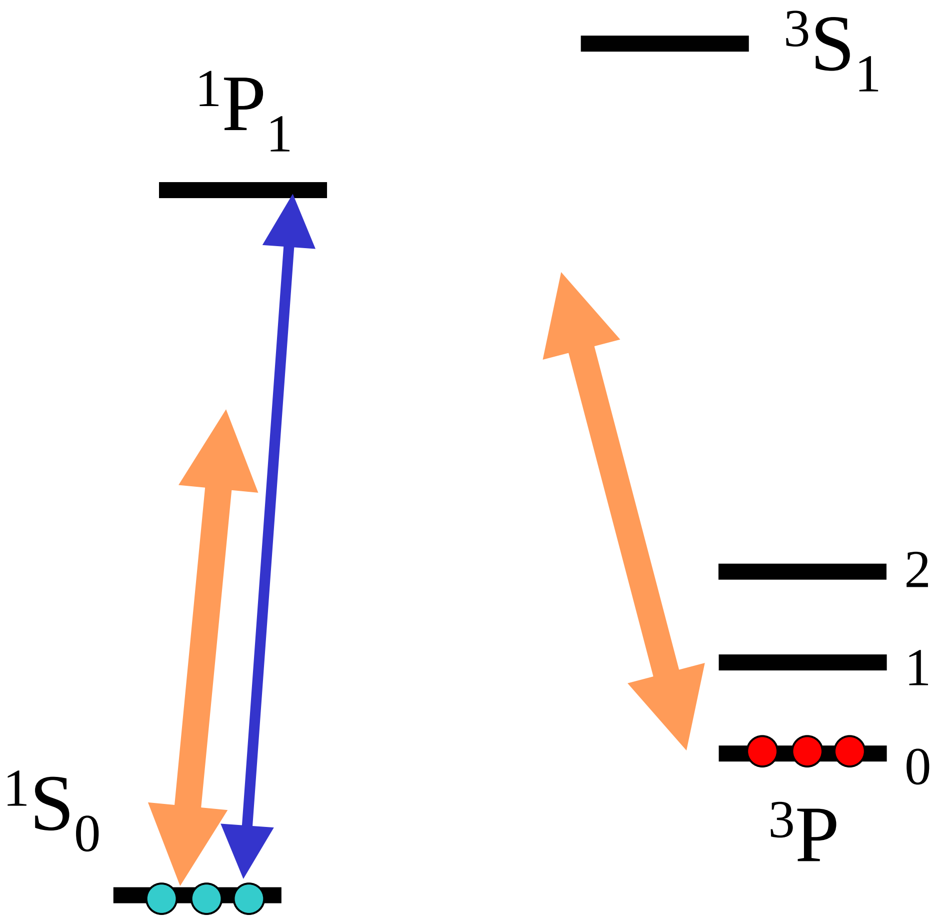
Clock transition spectroscopy

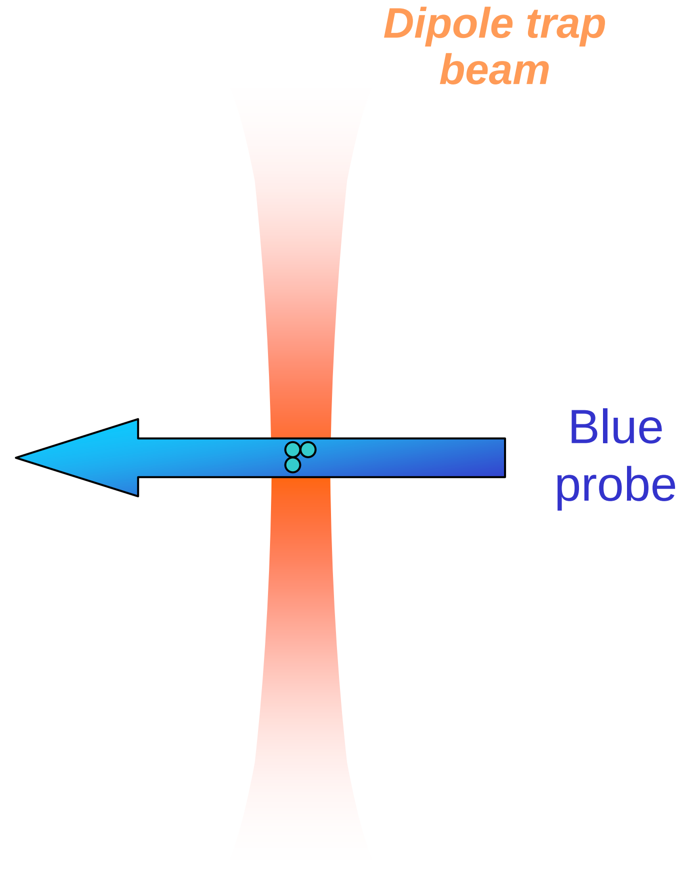




698 nm laser referenced to an ultrastable cavity
w_0=200 µm

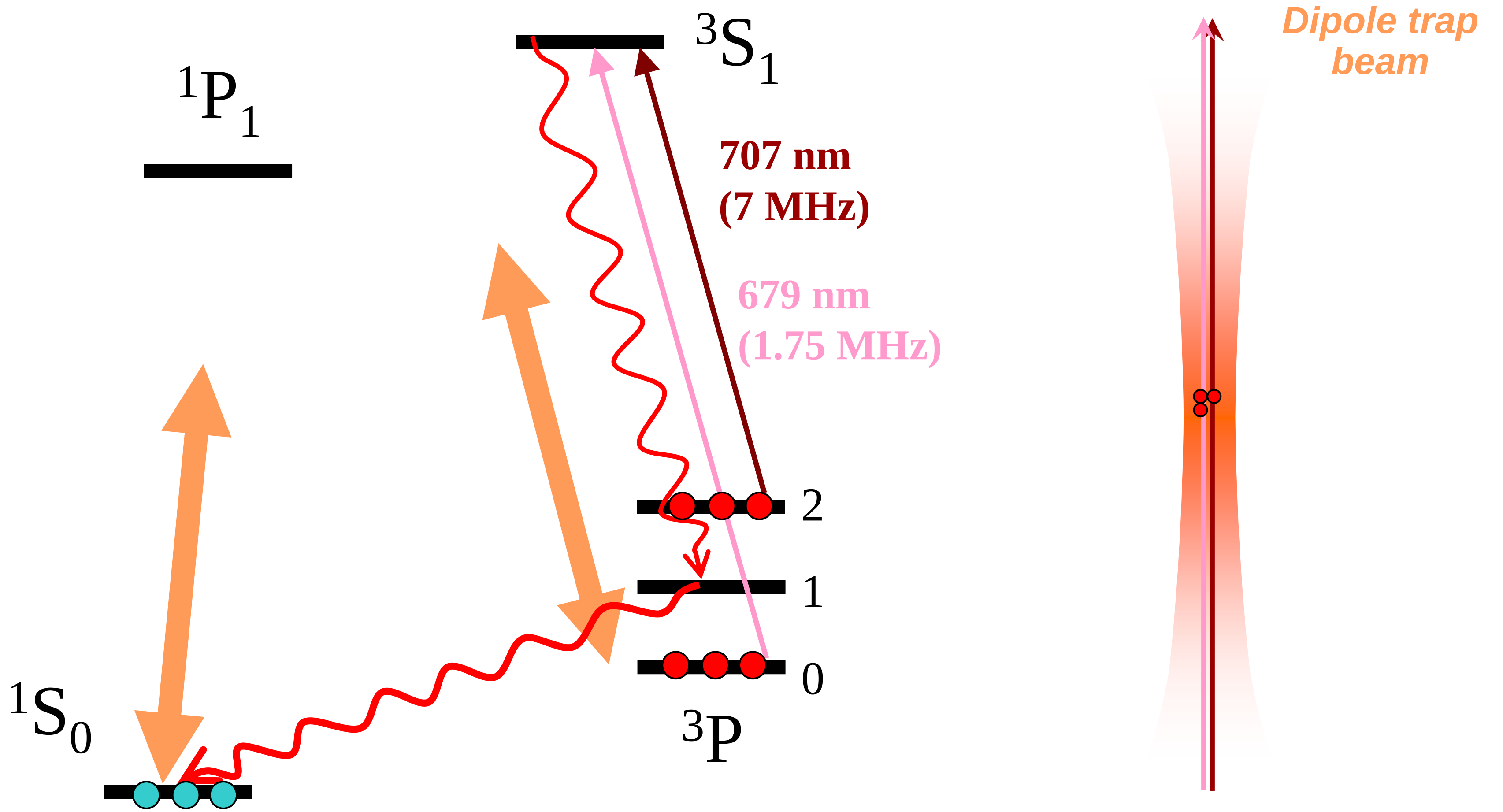
Detection





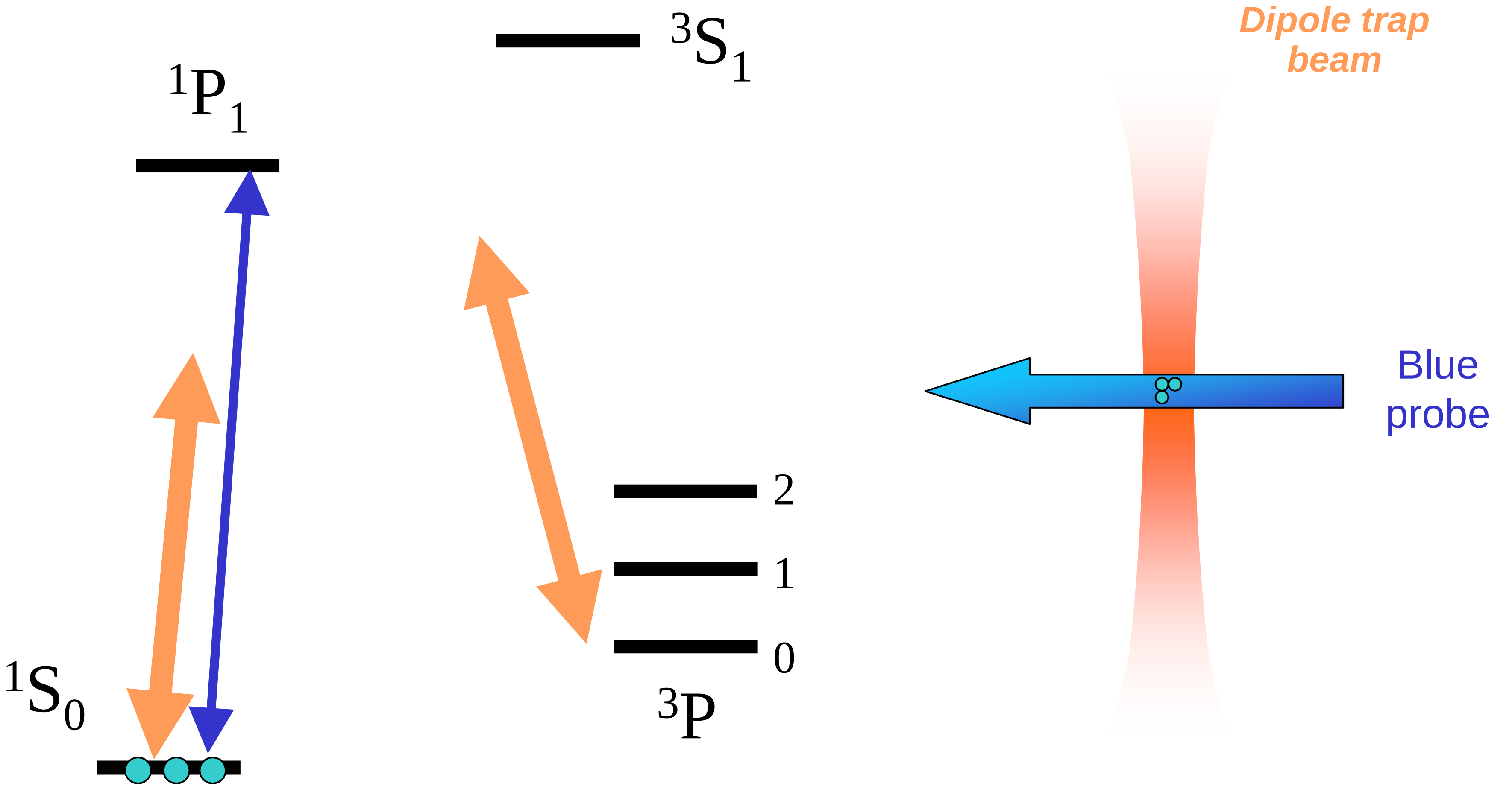
Fluorescence detection

Detection

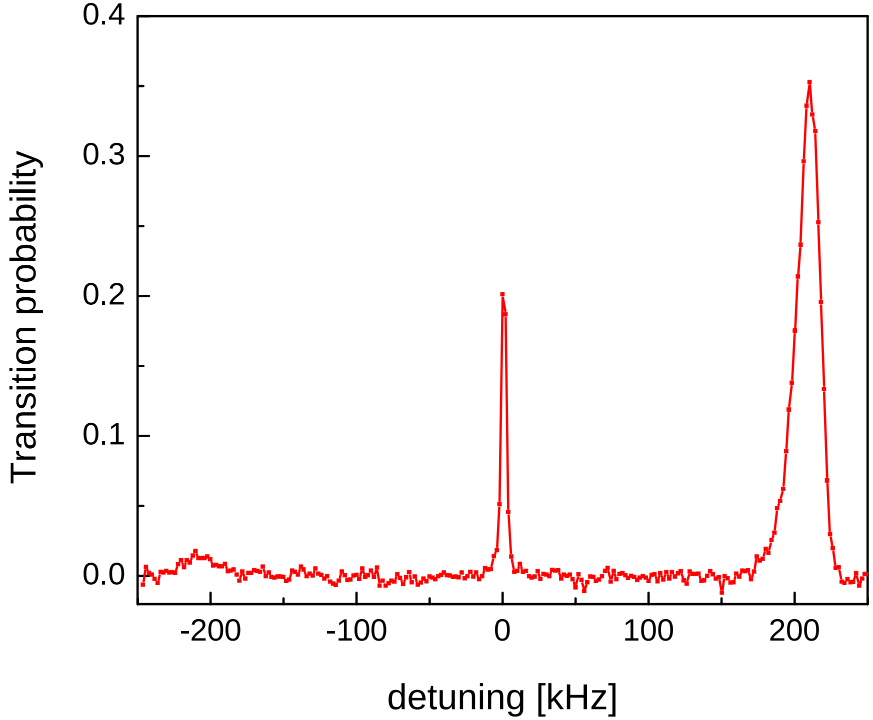


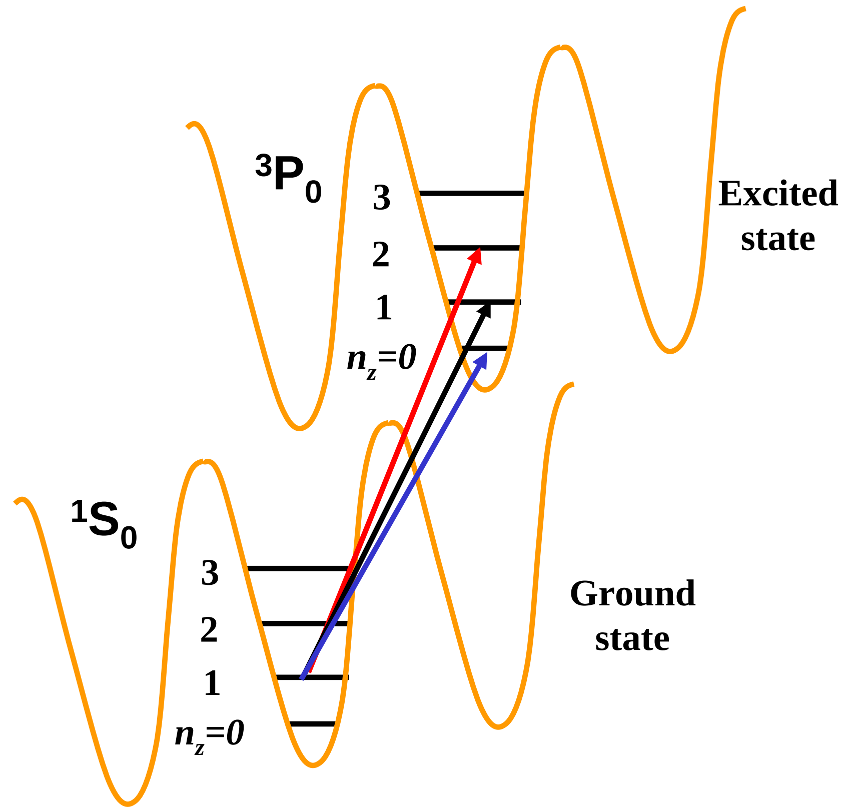
707 nm + 679 nm :
repumpers (w_0 = 200 µm)

Detection



Sideband spectrum

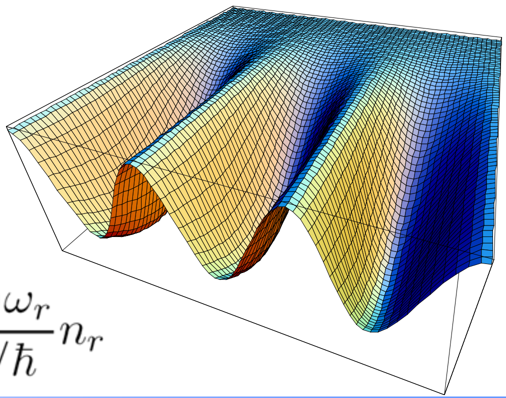




Longitudinal temperature given by sidebands ratio

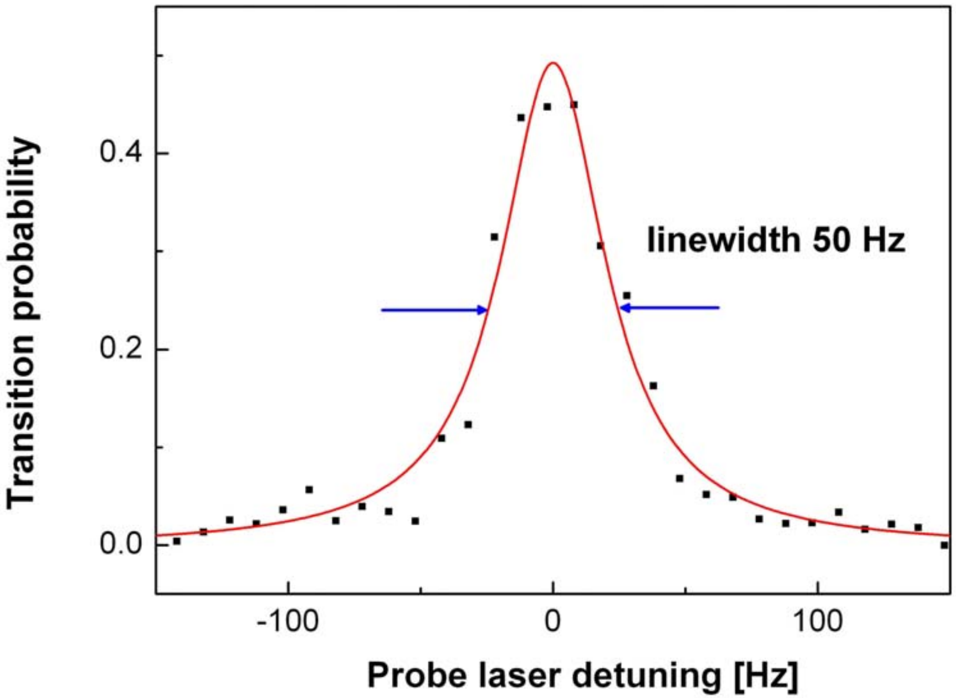
T_z = 2 µK, 95 % of the atoms in |n_z=0>

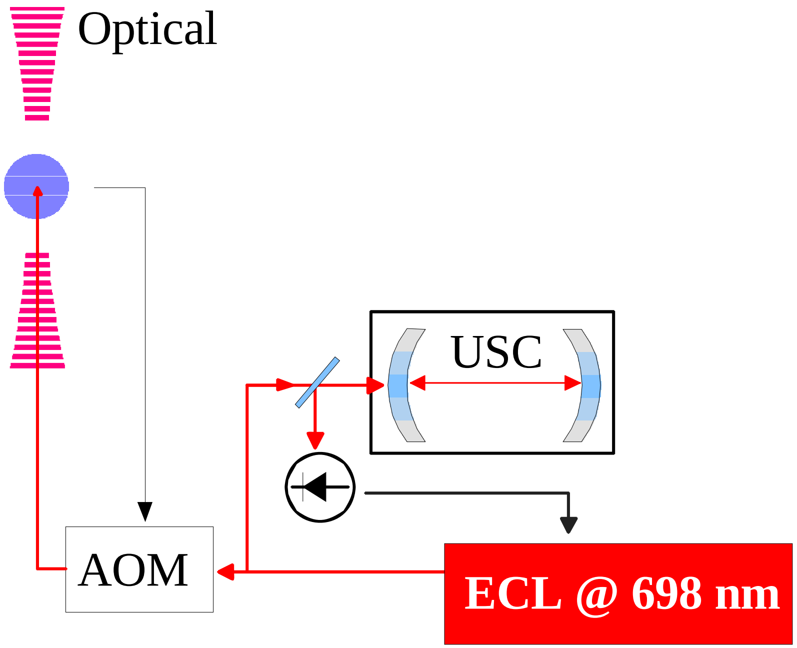
Longitudinal sidebands frequency depends on the transverse excitation. Shape of sidebands gives the transverse temperature. **T_r = 10 µK**



$$\omega_z(n_r) = \omega_z(0) - \frac{\omega_z(0)\omega_r}{4U_0/\hbar} n_r$$

Atomic carrier resonance





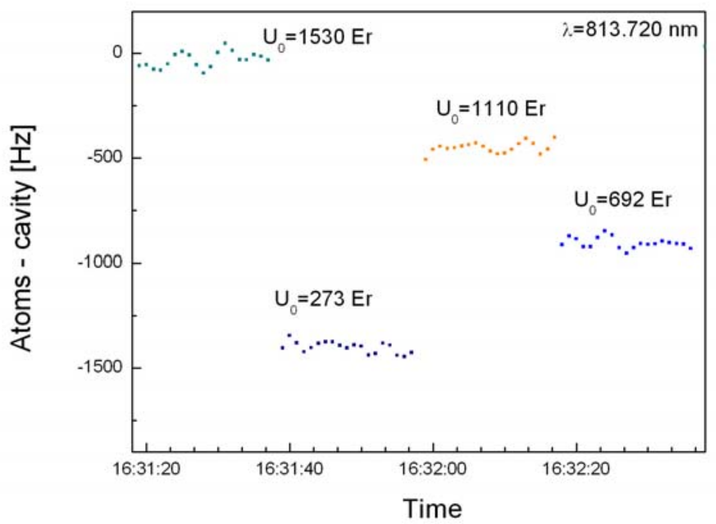
698 nm probe :

15 ms, 3 μW

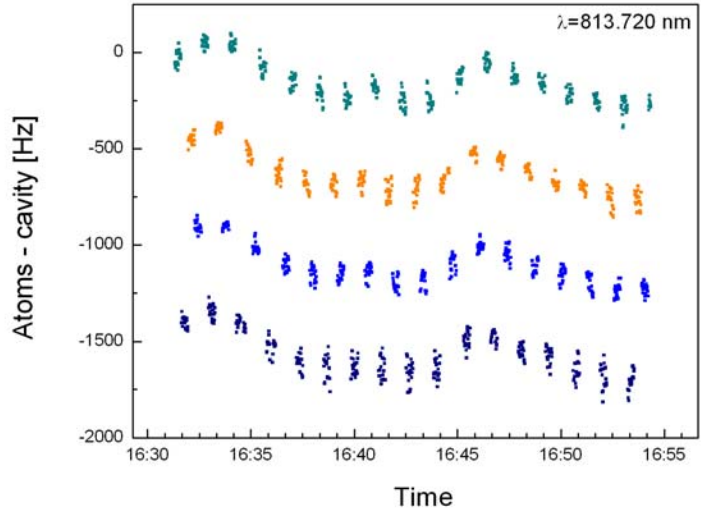
Laser frequency is locked to the atomic resonance via an AOM

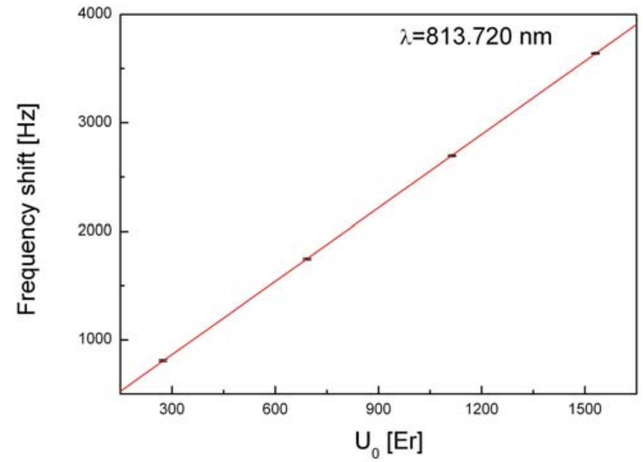
Measurement of the frequency shift due to the trap

-Differential measurement atoms-cavity vs trapping depth



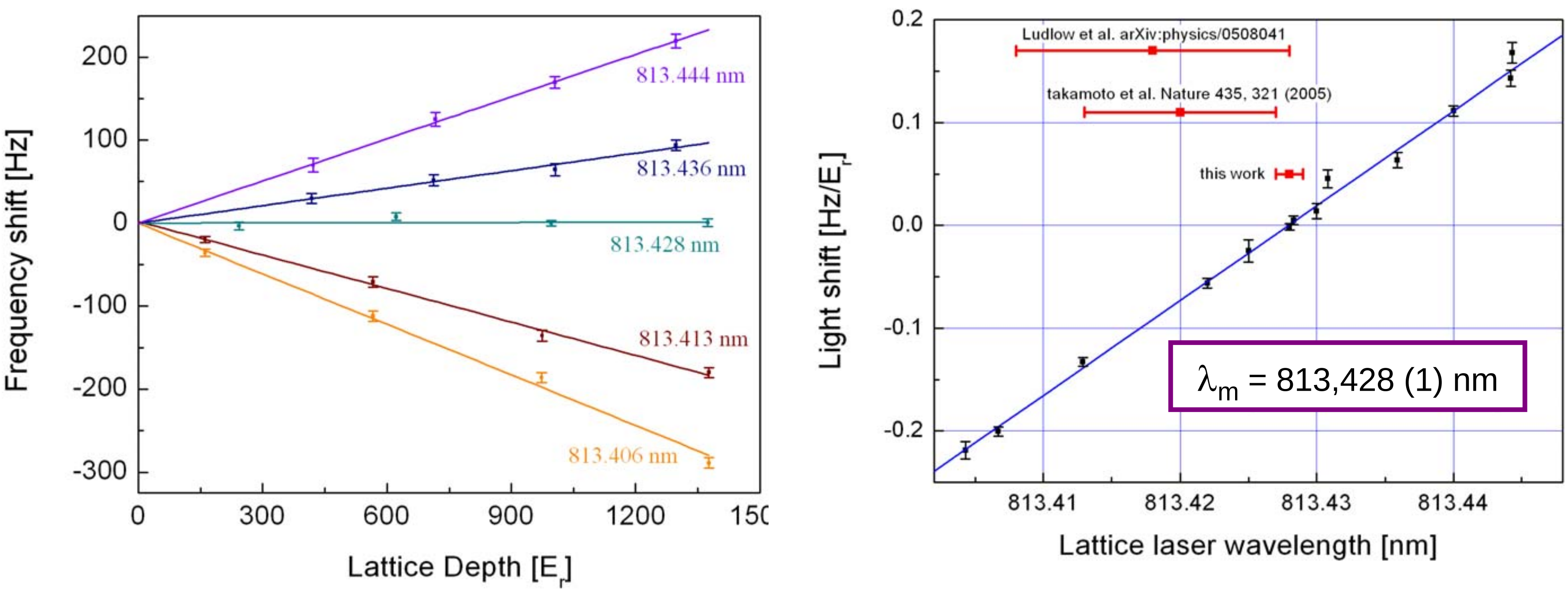
repeated N times =>





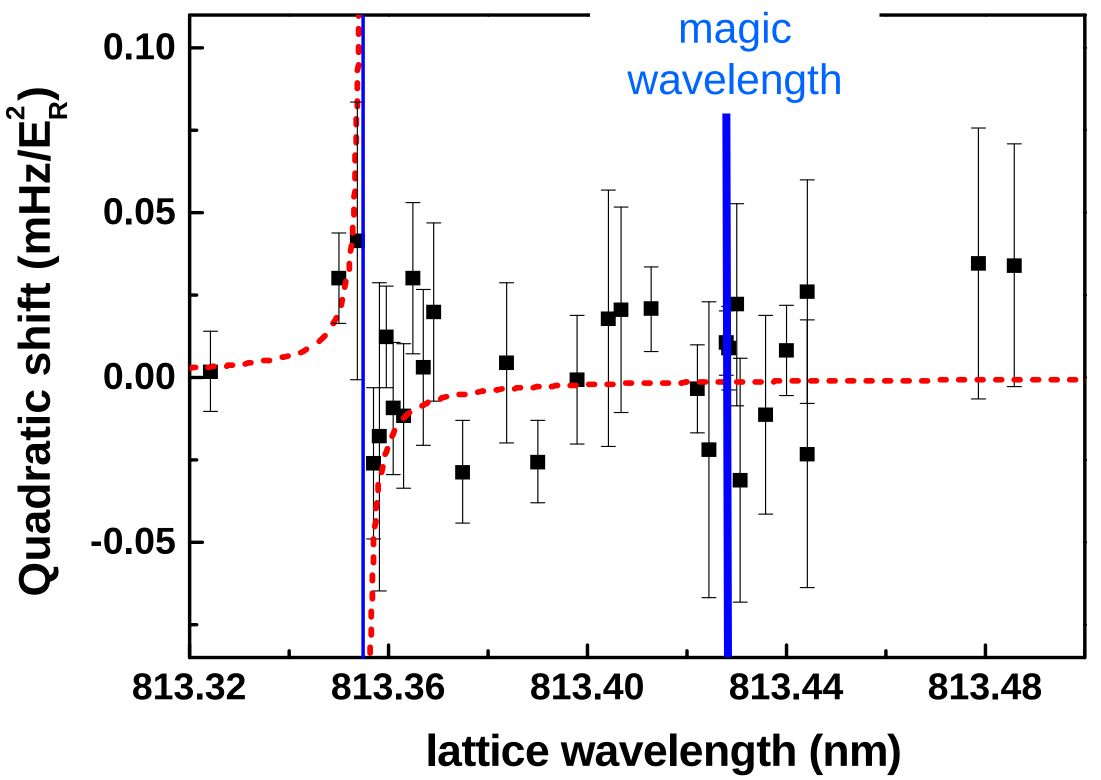
-The cavity frequency fluctuations are filtered by a polynomial fit

First order light shift



- Measurements done at different wavelengths and different depths

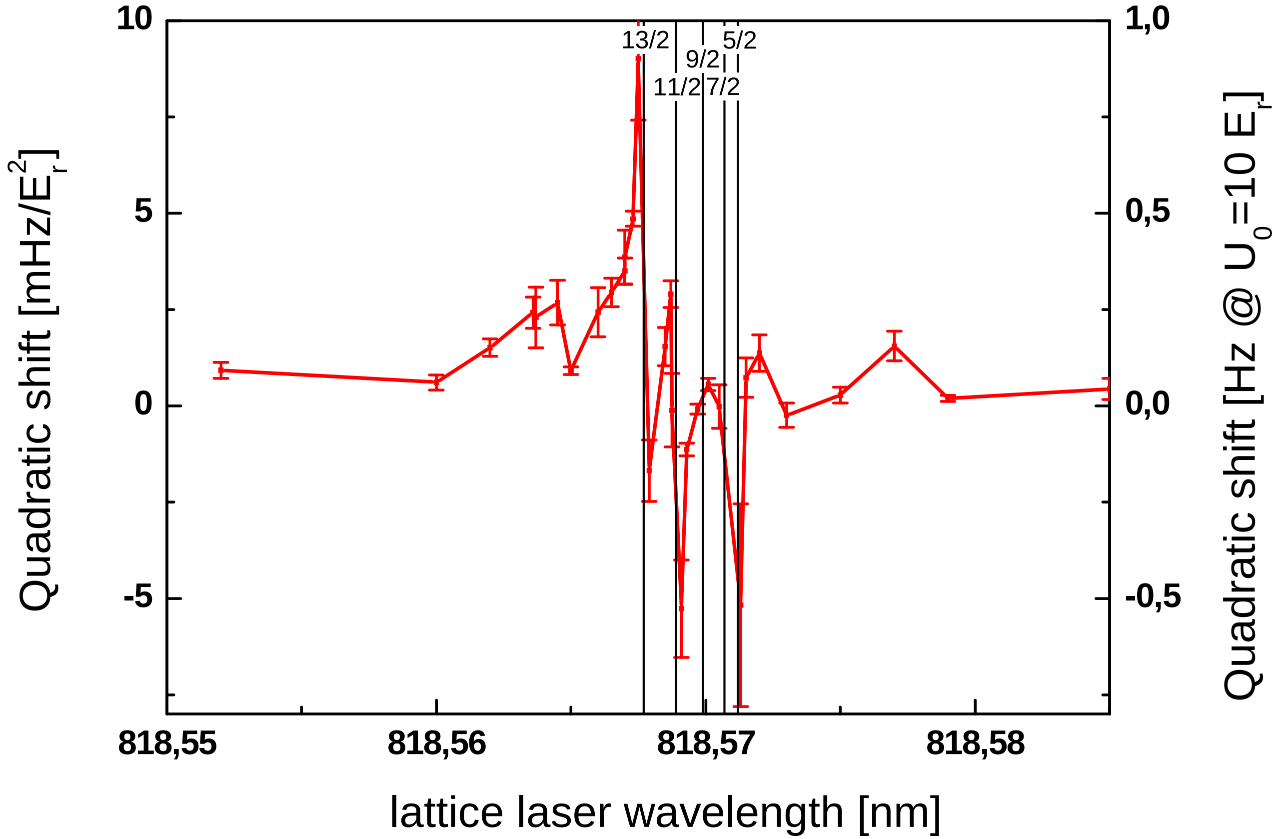
Second order light shift near the $^3P_0$-$^1P_1$ transition



No visible effect around the $^3P_0$ – $^1P_1$ transition

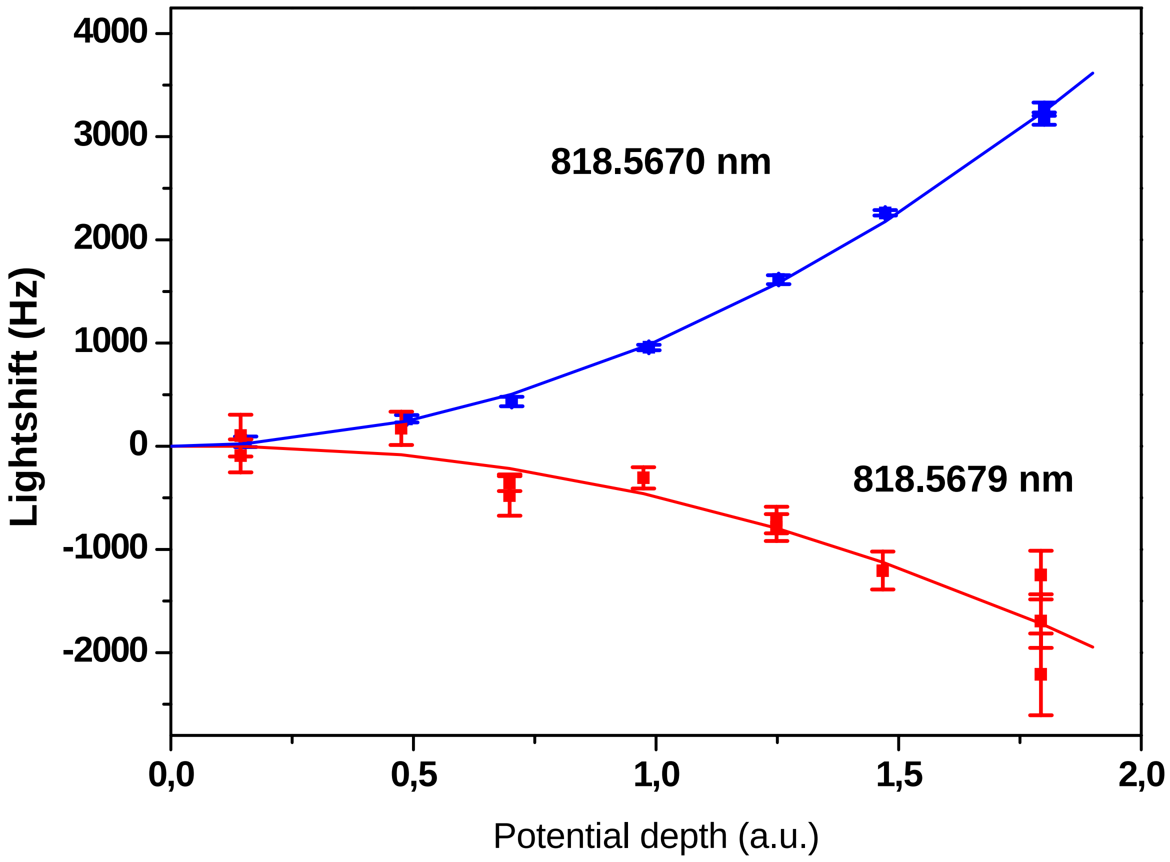
contribution <1 µHz/E_r^2 at λ_m (0,1 mHz @ 10 E_r)

Second order light shift near the $^3P_0$-$^3F_2$ transition



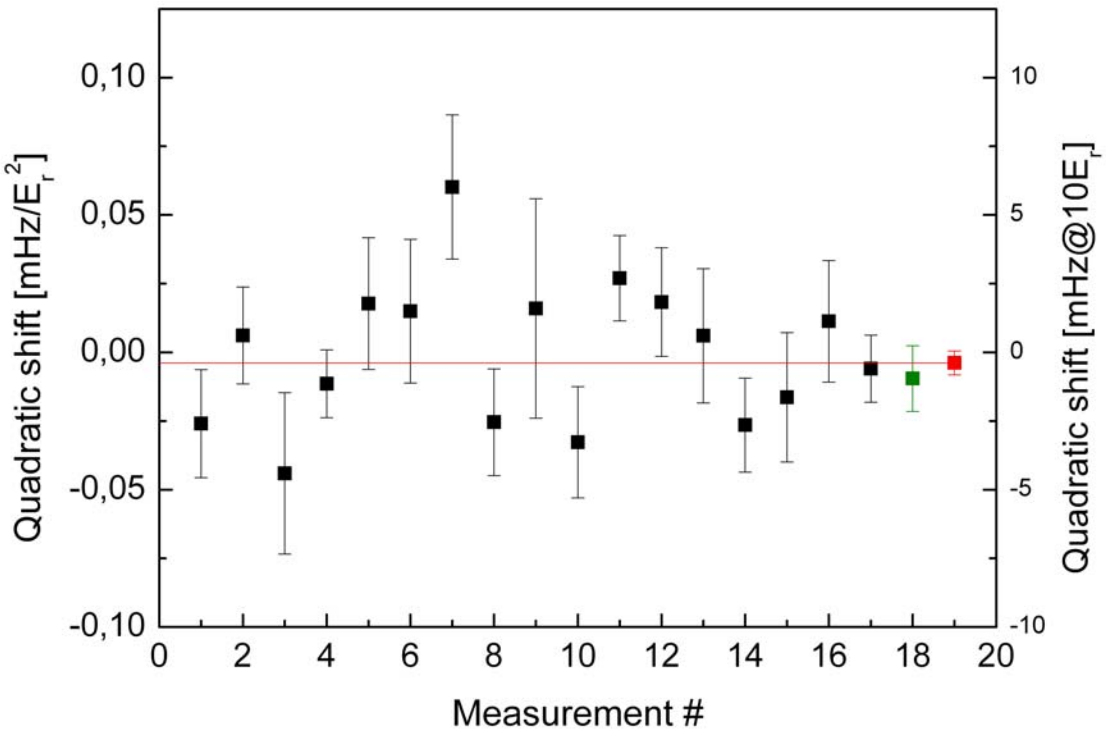
Contribution of this resonance @ λ_m < 2 µHz/ E_R^2 (0,2 mHz @ 10 E_r)

Second order light shift near the $^3P_0$-$^3F_2$ transition



Quadratic shift clearly visible once the first order term has been removed

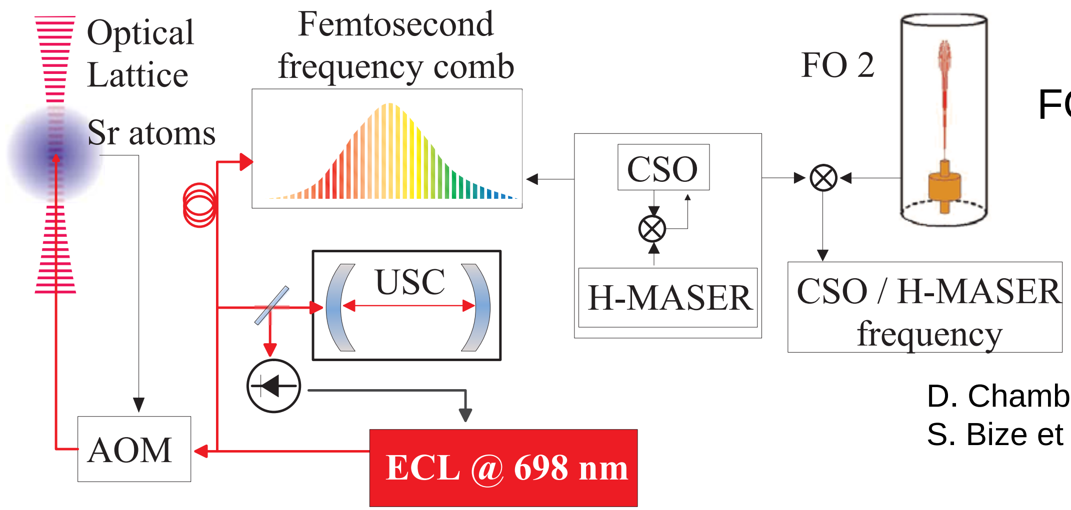
Hyperpolarizability effects at λ_m



- Hyperpolarizability shift of -4 (4) µHz/E_r^2 (-0.4(4) mHz @ 10 E_r), corresponding to a -1(1).10^{-18} relative frequency shift @ 10 E_r
- This effect will not limit the clock accuracy down to the 10^{-18} level

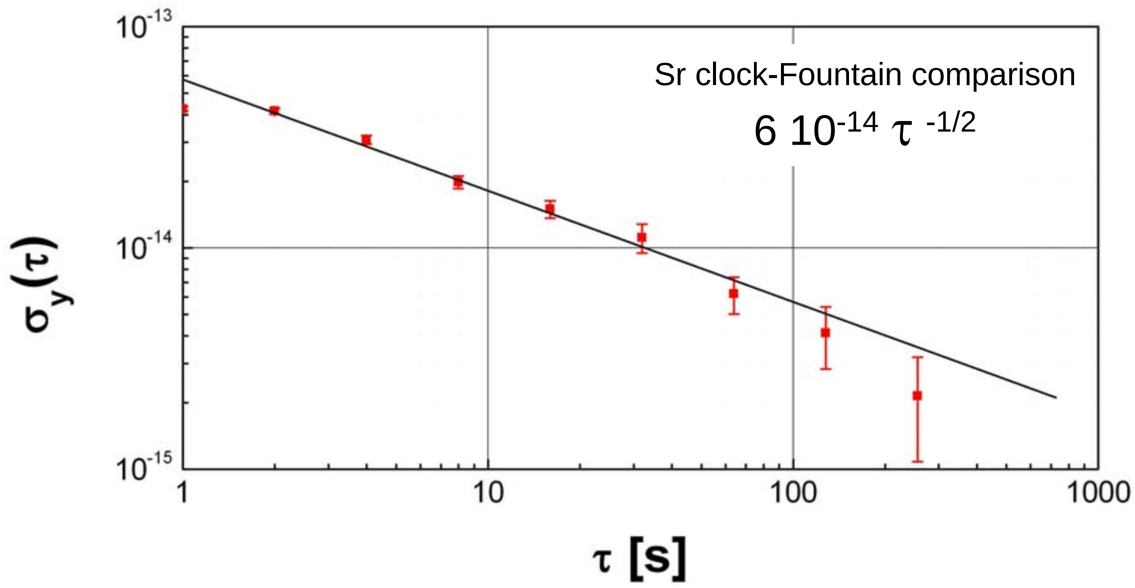
A. Brusch et al. PRL **96**, 103003, 2006

Frequency chain



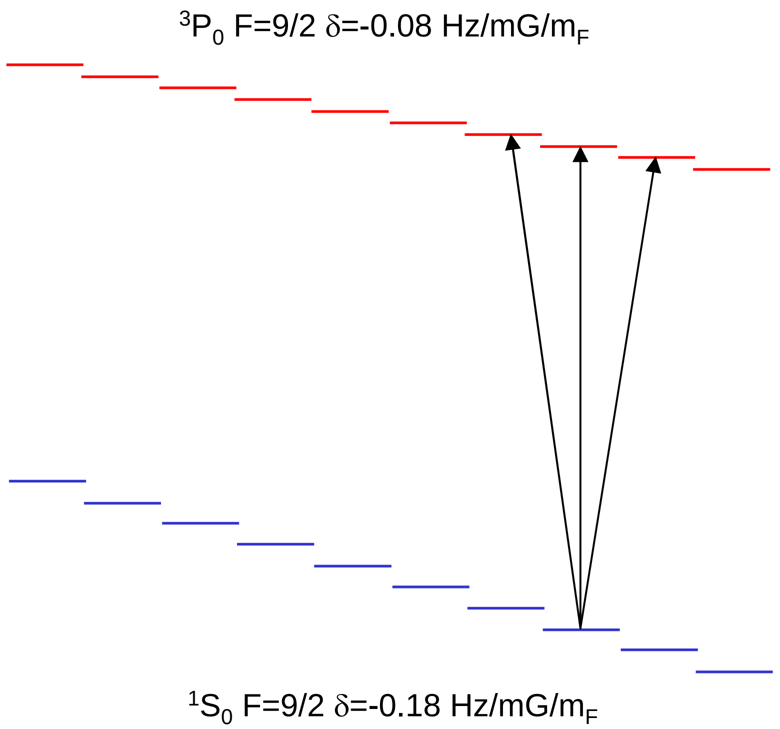
FO2 frequency accuracy ~ 4 10^{-16}
stability ~ 1.6 10^{-14} $\tau^{-1/2}$

D. Chambon et al. Rev. Sci. Inst. **76**, 094704, 2005
S. Bize et al. C. R. Physique **5**, 829, 2004.

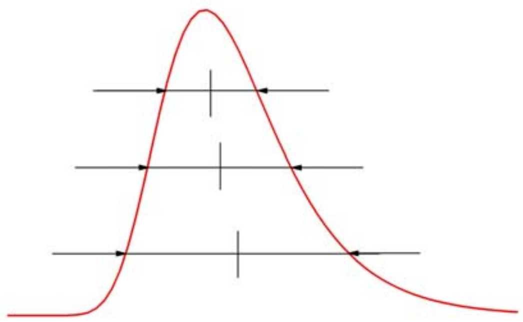


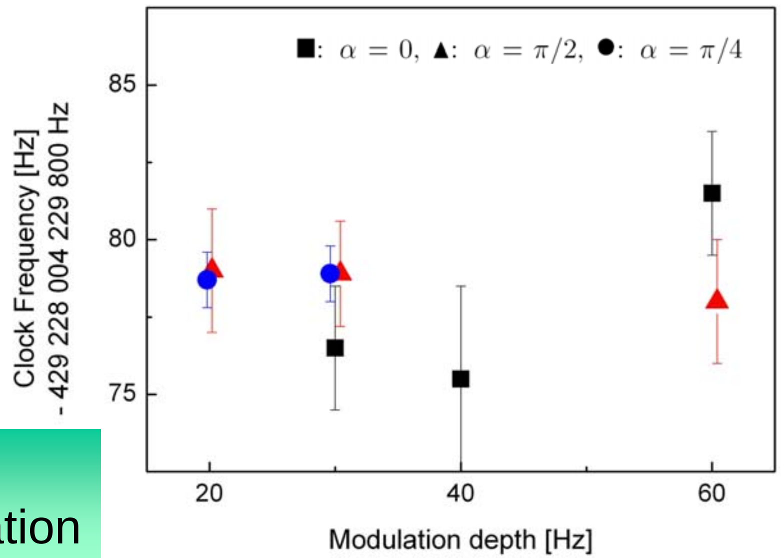
Frequency resolution: ~1 Hz @ 600 s

1st order Zeeman effect



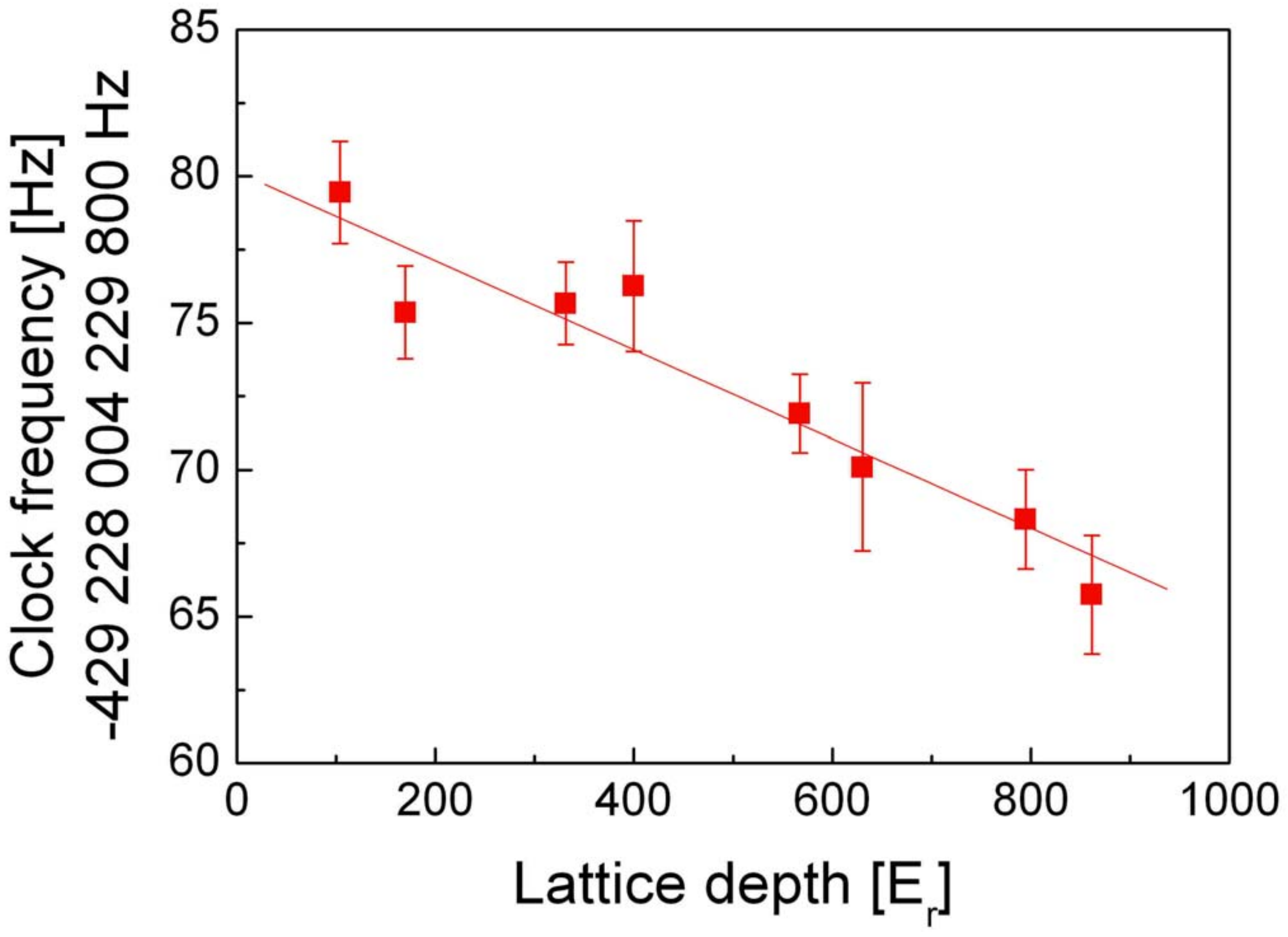
Frequency shift due to residual field, asymetry in Zeeman population and depending on probe polarization





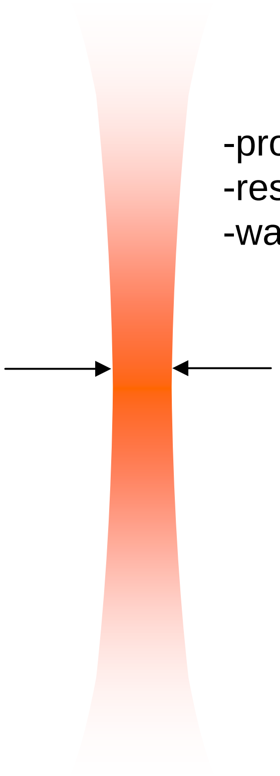
Assigned uncertainty 5 Hz
future improvement by bias field+state preparation

Residual light shift

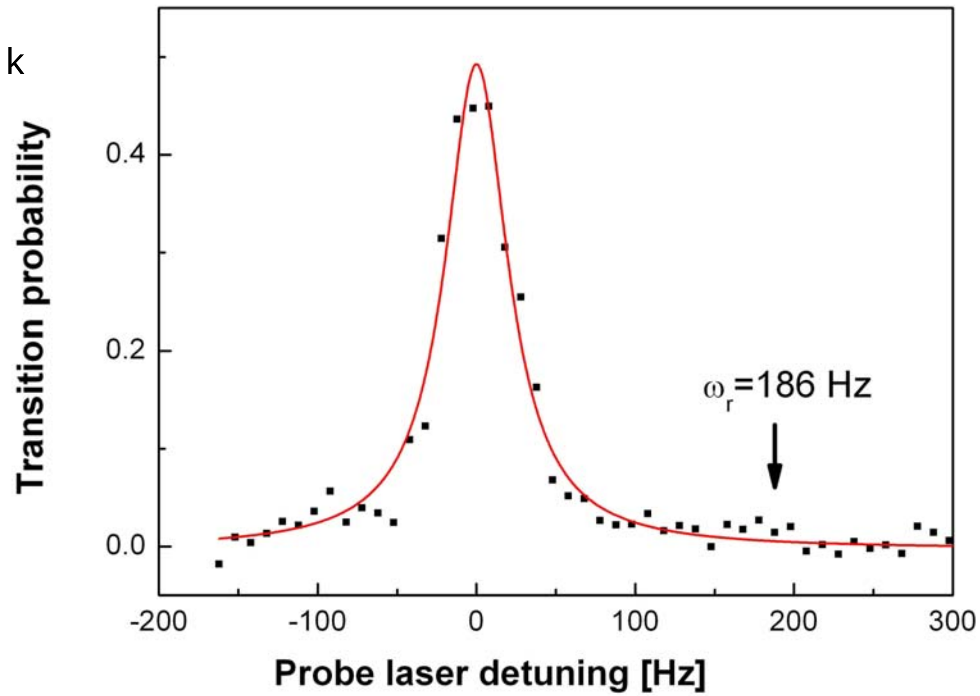


1 Hz uncertainty @ 400 E_r (1.4 MHz).
Control of the light shift at a level of 7 10^{-7}

Pulling by transverse sidebands

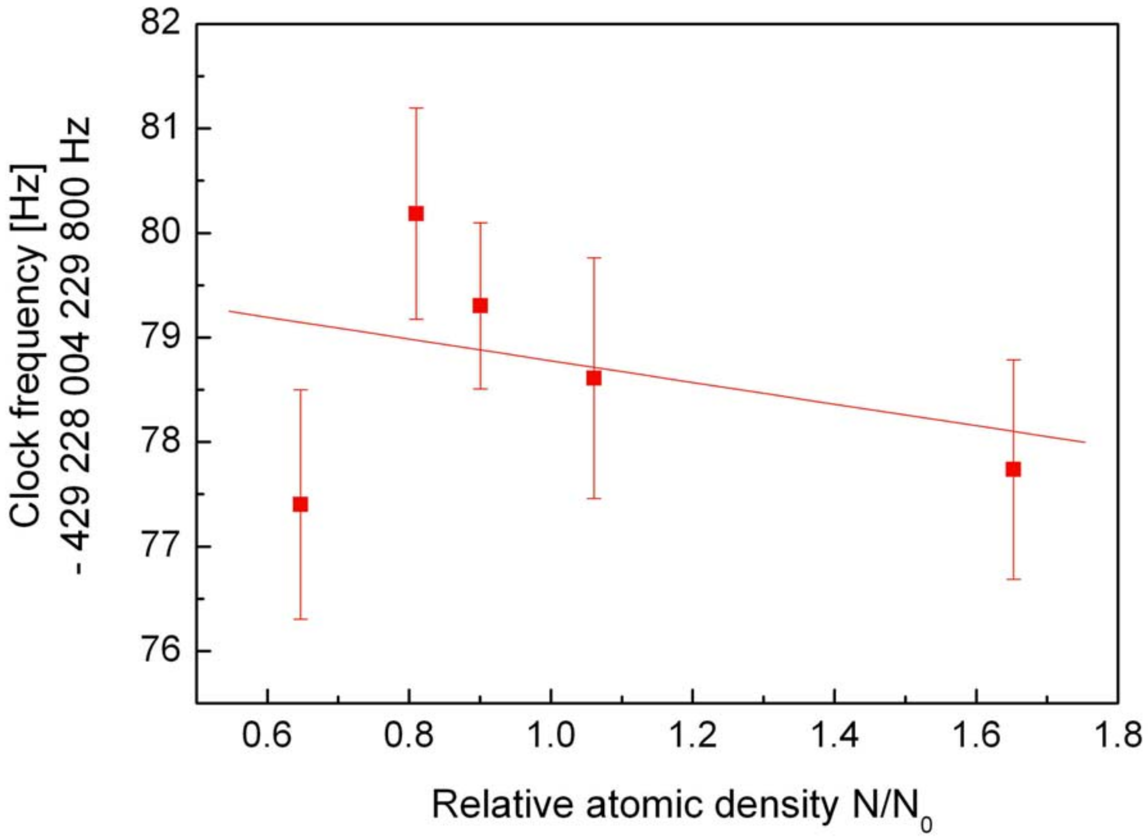


- -probe 2 w_0=400 µm => k_r~10^{-3} k
- -residual probe-lattice angle
- -wavefront distortion



Line pulling < 1 Hz

Cold collisions



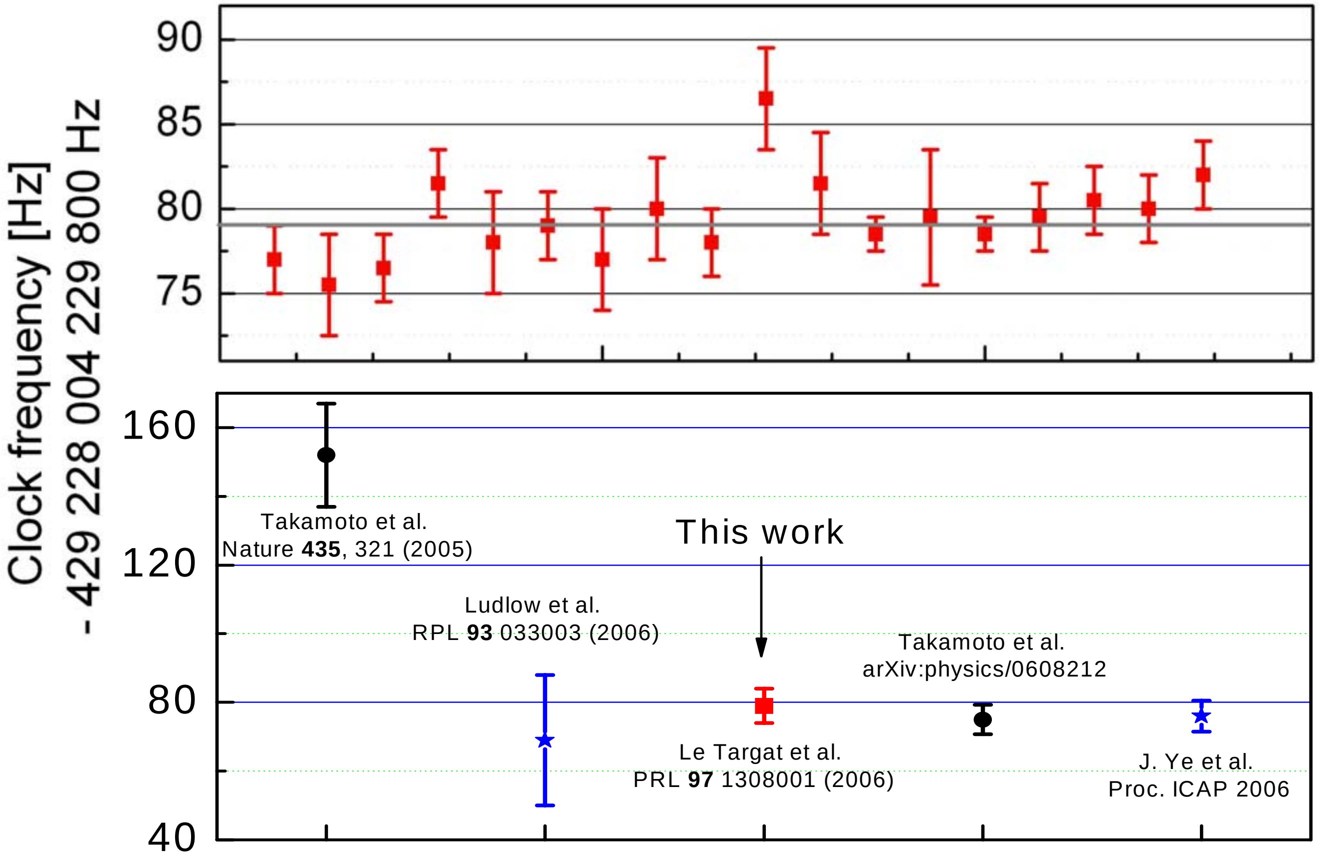
a few 10 atoms per lattice site : $N_0 \sim 10^{11}$ at/cm^3

No resolved shift: -1(1) Hz @ N_0

Accuracy budget

Effect	Correction (Hz)	Uncertainty (Hz)	Fractional Uncertainty (10^{-14})
First order Zeeman	0	5	1.2
Lattice AC Stark shift (400 Er)	4.5	0.9	0.2
Lattice 2nd order Stark shift (400 Er)	0.6	0.6	0.1
Line pulling (transverse sidebands)	0	1	0.2
Cold collisions	1	1	0.2
BBR shift	2.4	<1	<0.1
Total	**8.5 Hz**	**5.3 Hz**	**1.2 10^{-14}**

Frequency measurements



$\nu_{^1S_0-^3P_0}$=429 228 004 229 879 (5) Hz


€: LNE, CNES,ESA, DGA