Atomic clocks with cold atoms

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Quantum engineering with photons, atoms and molecules
Les Houches, February 2005

Atomic Fountains

10 fountains in operation (SYRTE, PTB, NIST, USNO, PENN state, ON, IEN, NPL) with an accuracy of ~10^{-15}. Several projects (NIJM, NIM, KRIISS, VNIIFTRI...)

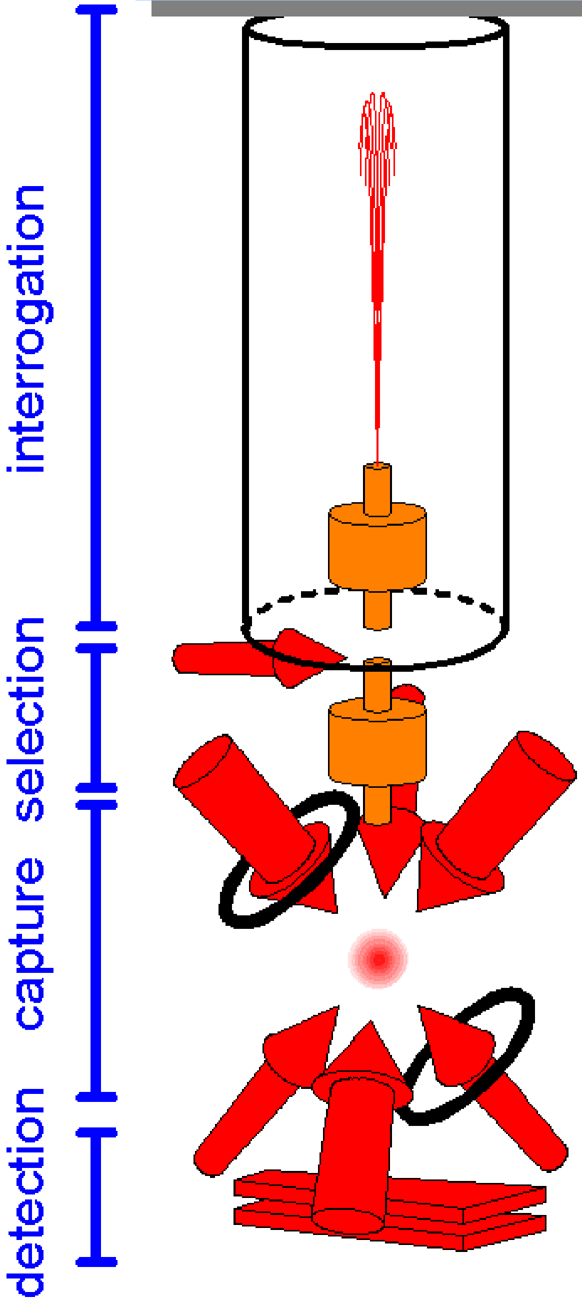
See e.g. Proc. 6th Symp. Freq. Standards and Metrology (World Scientific 2002)

BNM-SYRTE (F)

PTB (D)

NIST (USA)

Atomic fountains: Principle of operation



N_{at} ~2×10⁹

σ_r ~1.5–3mm

T ~1µK

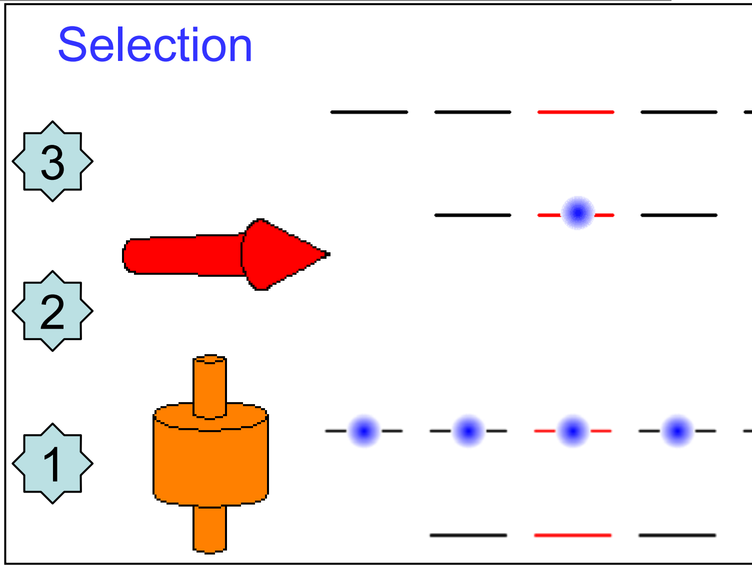
ΔV ~2 cm.s^{-1}

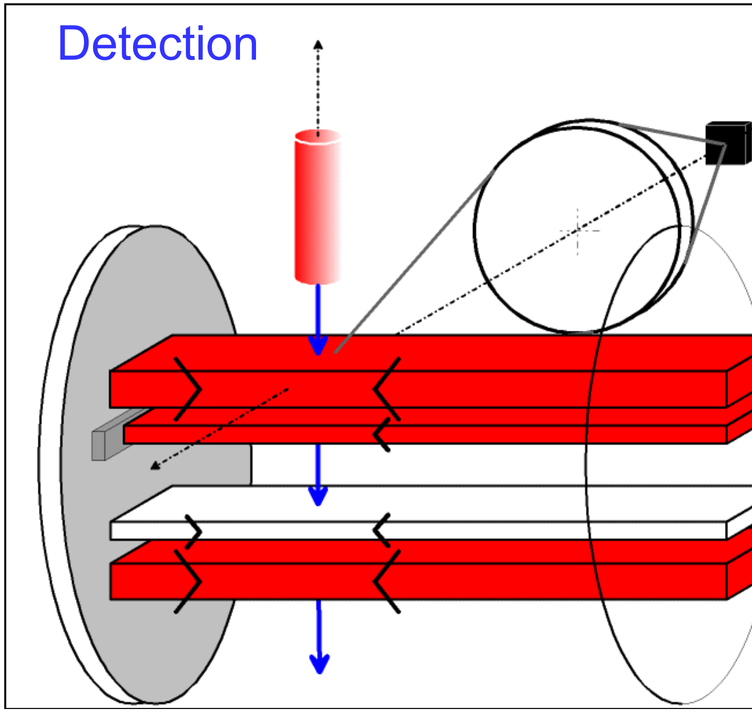
V_{launch} ~ 4m.s^{-1}

H ~1m

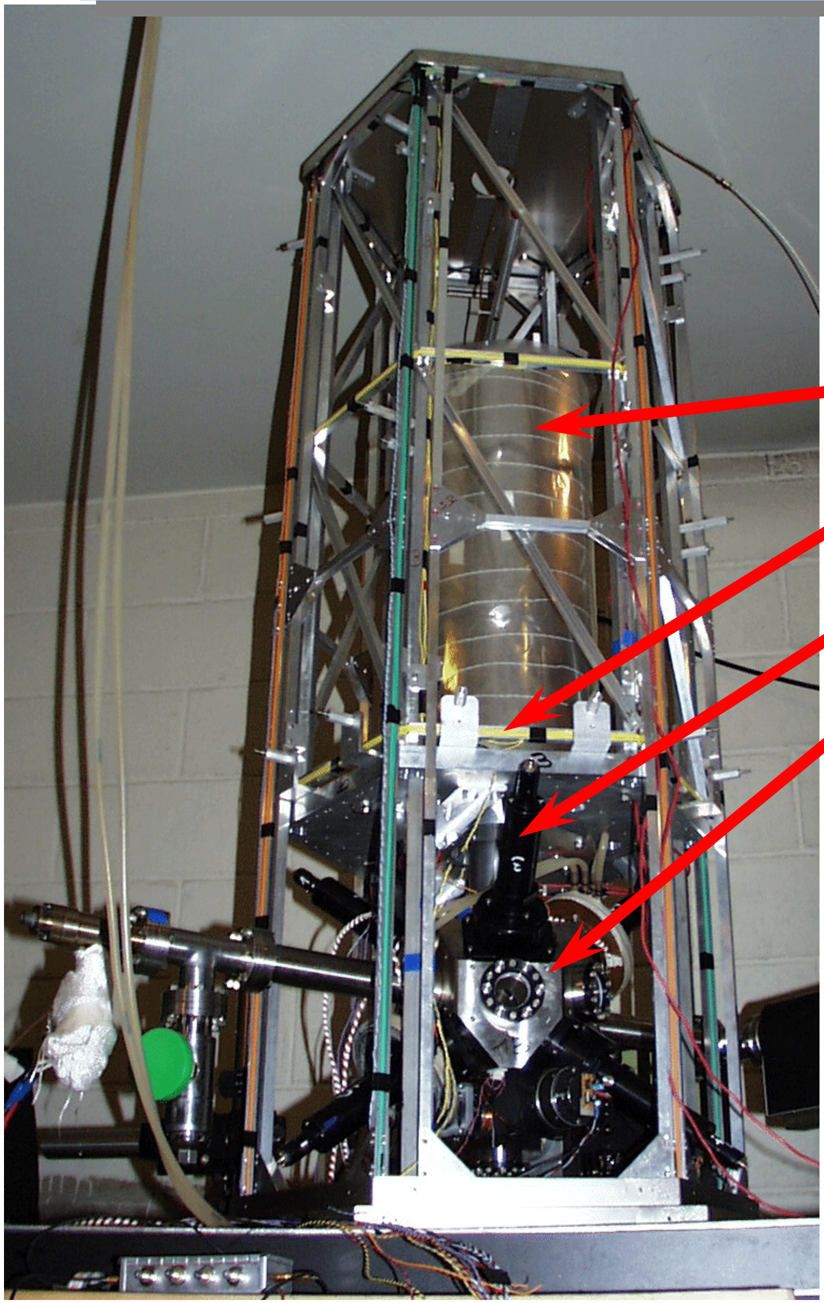
T ~500ms

T_c ~0.8-2s





vacuum chamber and cavity



The 2 outermost shields are removed

Interrogation region with magnetic and thermal shields

Compensation coils

Collimator for molasses beams

Optical molasses

optical bench

Laser diode based system, can be made compact and reliable

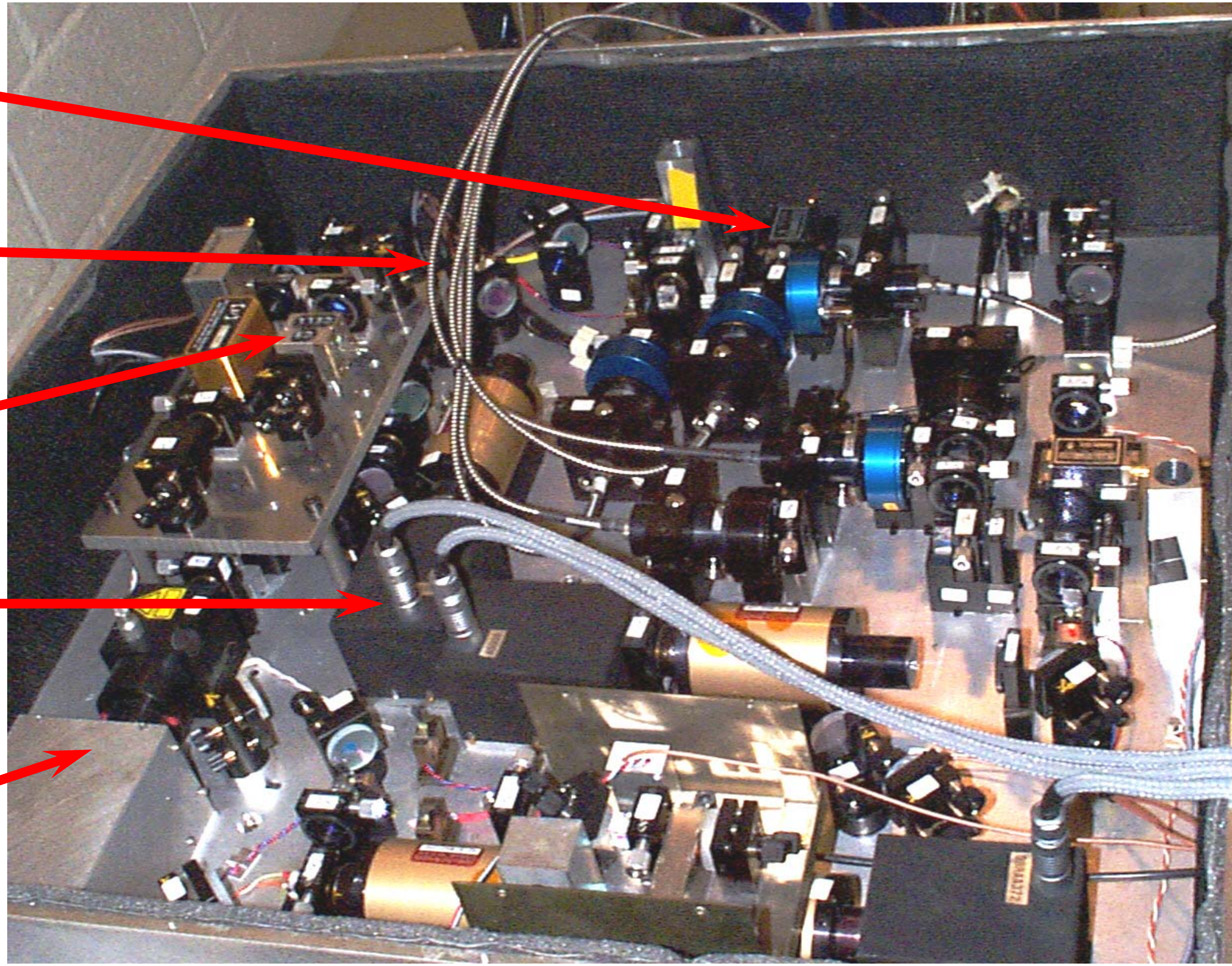
Acousto-optic modulator

Optical fibers

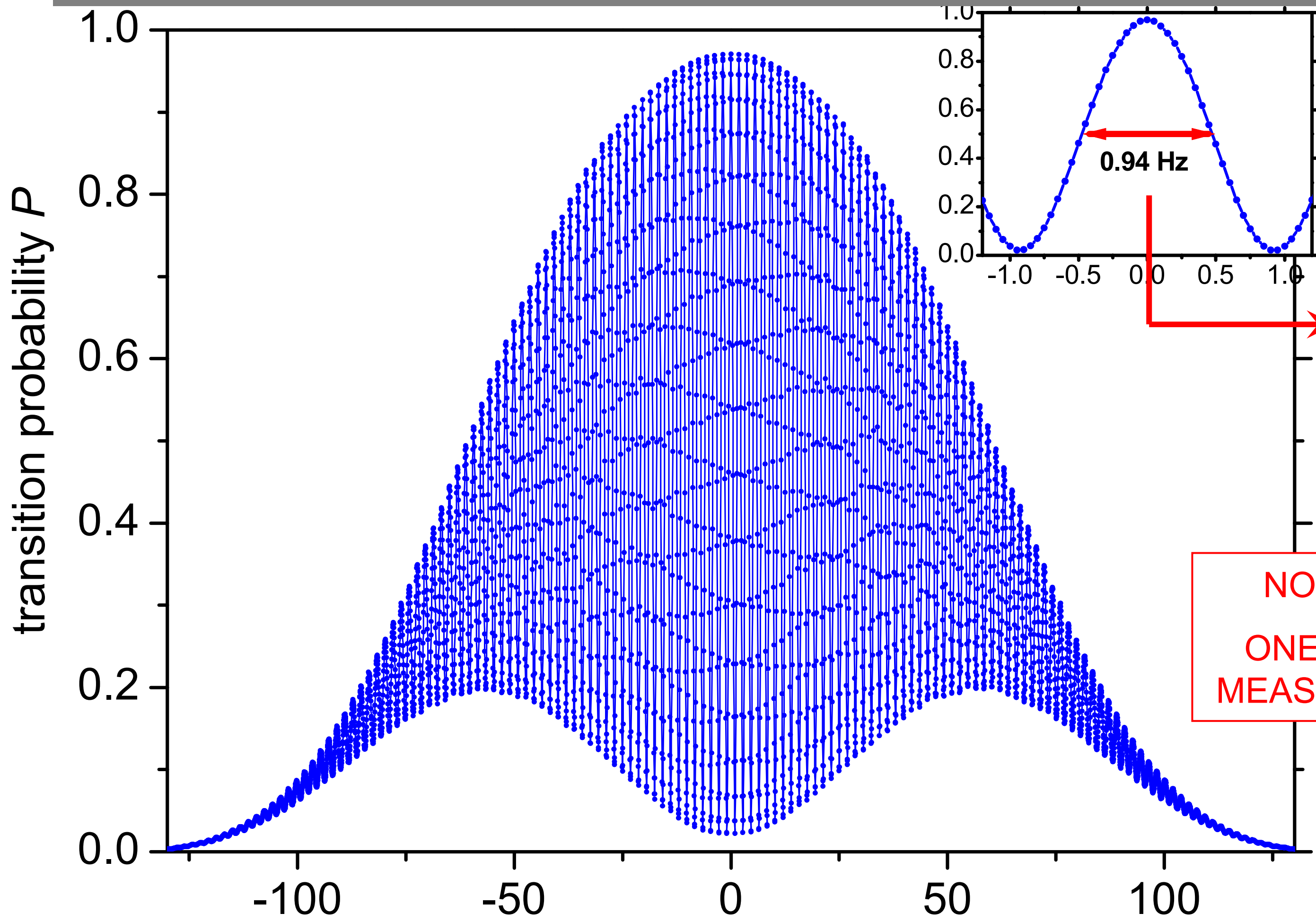
Cs vapor cell

Injection locked diode laser

External cavity diode laser



Ramsey fringes in atomic fountain



$\delta/2\pi$

$$\frac{\Delta}{2\pi} = \frac{1}{2T}$$

$T \sim 500\ \mathrm{ms}$

NO AVERAGING

ONE POINT = ONE MEASUREMENT OF P

We alternate measurements on bothe sides of the central fringe to generate an error signal, whi is used to servo-control the microwave source

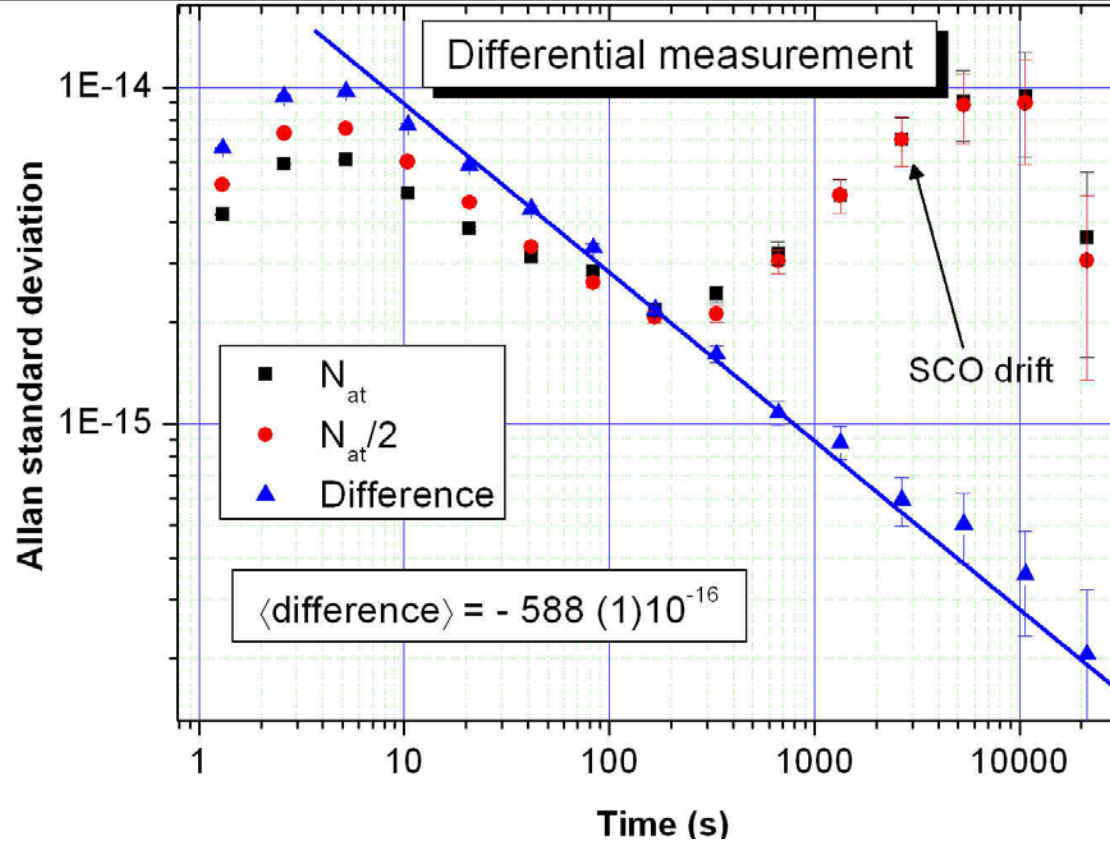
Fluctuations of the transition probability: $\sigma_{\delta P} \simeq 2 \times 10^{-4}$

Frequency stability with a cryogenic Oscillator

With a cryogenic sapphire oscillator, low noise microwave synthesis (~ 3×10^{-15} @ 1s)

FO2 frequency stability

$$\sigma_y(\tau) = 1.6 \times 10^{-14}\tau^{-1/2}$$



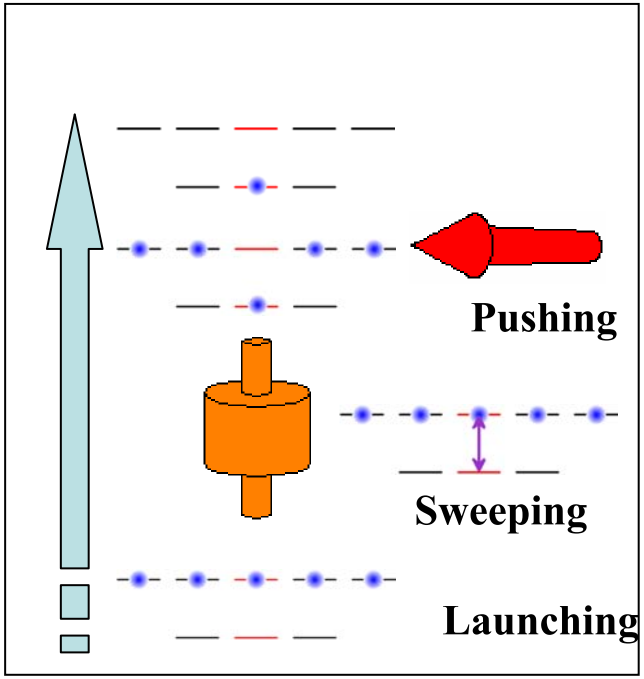
This stability is close to the quantum limit. A resolution of **10^{-16}** is obtained after 6 hours of integration. With Cs the frequency shift is then close to 10^{-13}!

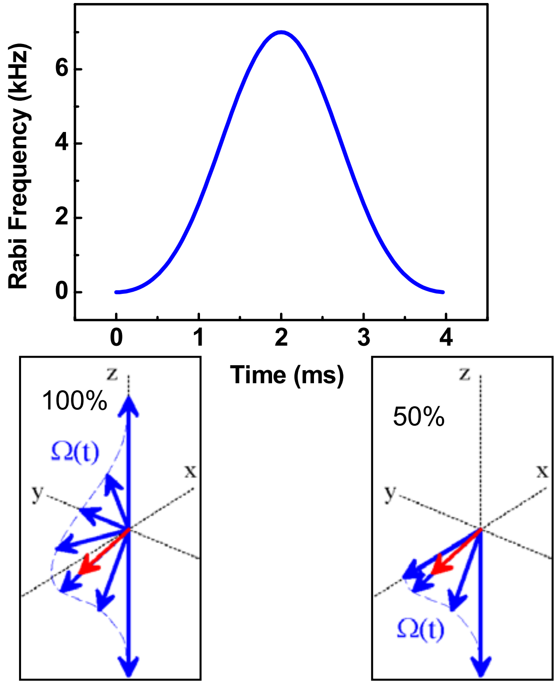
Fountain Accuracy

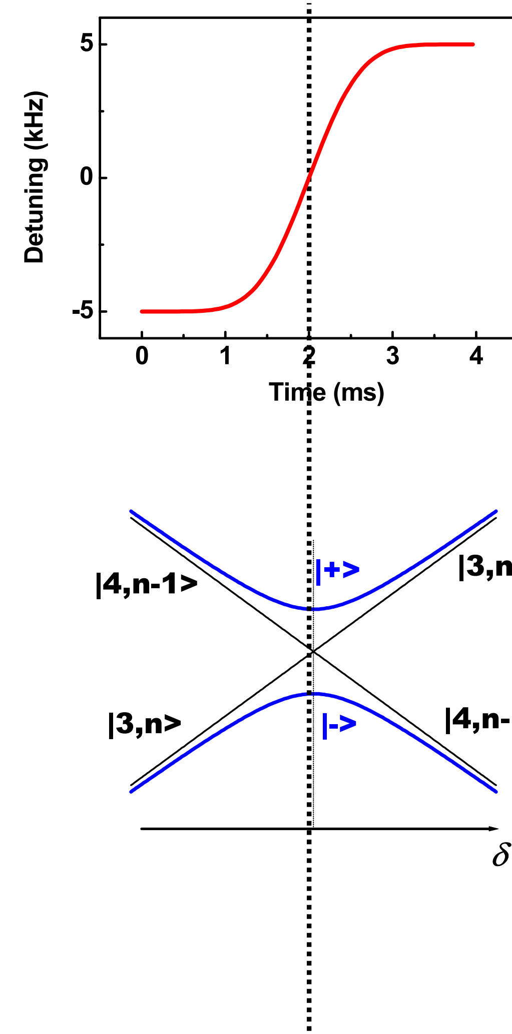
Fountain (BNM-SYRTE)	FO2(Cs)	FO2(Rb)	FO1
Effect	Shift and uncertainty (10^{-16})		
second order Zeeman	1927.3(.3)	3207.0(4.7)	1199.7(4.5)
Blackbody radiation	-168.2(2.5)	-127.0(2.1)	-162.8(2.5)
Collisions + cavity pulling	-357.5(2)	0.0(1.0)	-197.9(2.4)
Residual Doppler effect	0.0(3.0)	0.0(3.0)	0.0(3.0)
Recoil	0.0(1.4)	0.0(1.4)	0.0(1.4)
Neighbouring transitions.	0.0(1.0)	0.0(1.0)	0.0(1.0)
Microwave leaks, spectral purity, synchronous perturbations.	-4.3(3.3)	0.0(2.0)	-3.3(3.3)
Collisions with residual gaz.	0.0(1.0)	0.0(1.0)	0.0(1.0)
Total	6.5	7	7.5

Frequency difference between FO1 and FO2: 3 10^{-16}

Collisional shift measurement







By performing the internal state selection with adiabatic passage, we vary the atomic density by a factor of 2 without changing velocity and position distribution

- **Cold collisions then only depend on the atomic number**

To measure the cold collision shift in quasi real time

- **We alternate measurements with full or interrupted adiabatic passage (produces n or n/2)**

F. Pereira Dos Santos *et al.*, PRL 89,233004 (2002)

The “adiabatic passage method”: Experiments

The value and the stability of the ratio between 50% and 100% configurations is monitored during each measurement. We find:

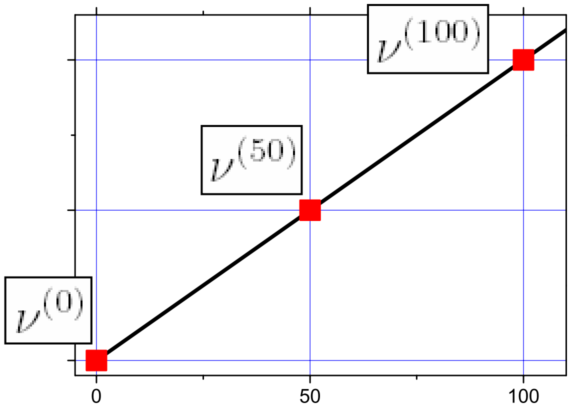
$$\frac{A_e^{(50)}}{A_e^{(100)}} = \frac{1}{2} \times \left(1 + 10^{-3}\right)$$

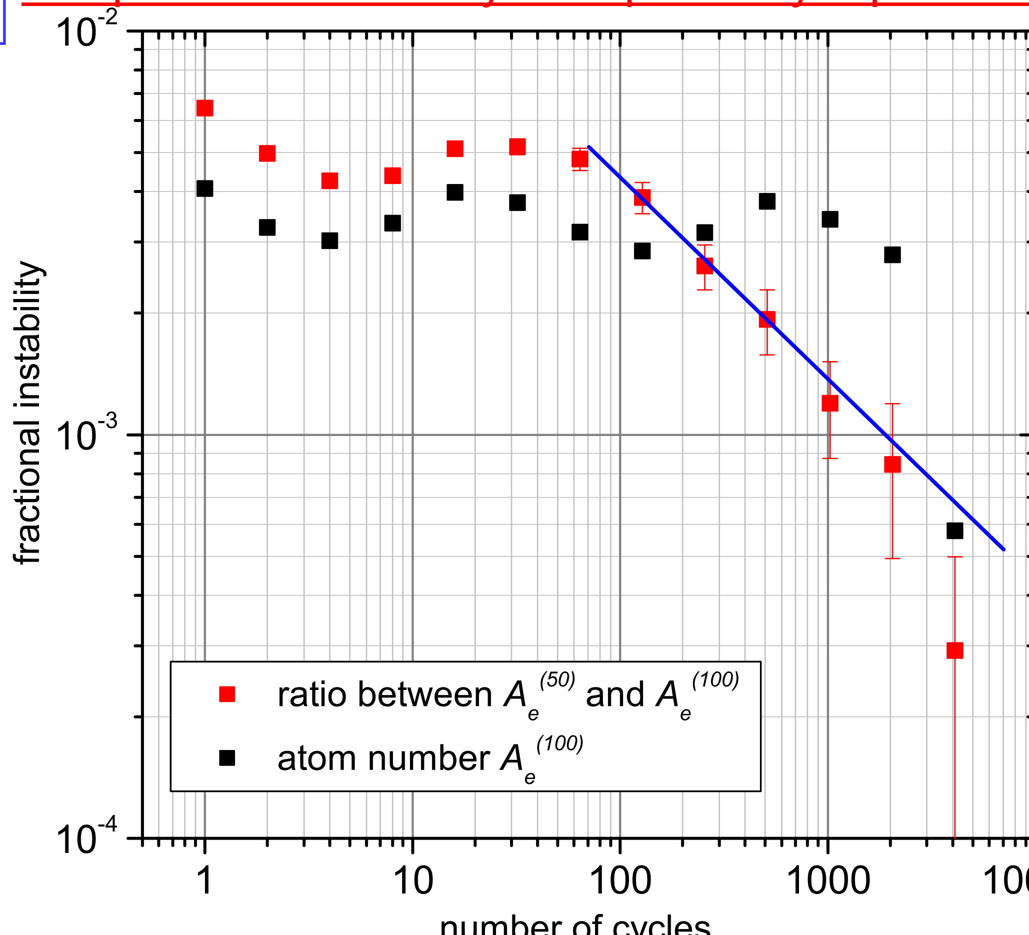
MEASURED

We have a practical realization of two atomic samples with a density ratio precisely equal to 1

Extrapolation of the collisional shift:

$$\nu^{(0)} = \nu^{(50)} - \left(\nu^{(100)} - \nu^{(50)}\right)$$
$$= 2 \times \nu^{(50)} - \nu^{(100)}$$





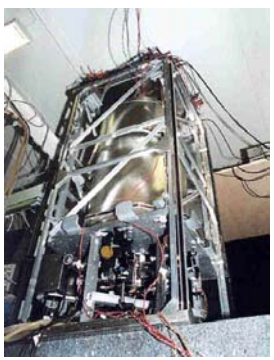
BNM-SYRTE fountain ensemble

atomic timescales

100 MHz hydrogen maser

phase-lock loop
at 100 MHz
τ ~ 1-1000 s

INTERROGATION OSCILLATOR
BVA quartz oscillator at 5 MHz
or
sapphire resonator cryogenic oscillator
~12 GHz



synthesis
9.192... GHz

atomic fountain FO1

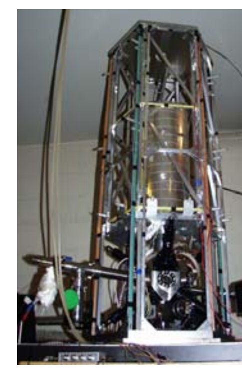
synthesis
9.192... GHz

transportable fountain FOM

synthesis
6.834... GHz

synthesis
9.192... GHz

dual fountain DF Rb-Cs



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Systèmes de Référence Temps-Espace

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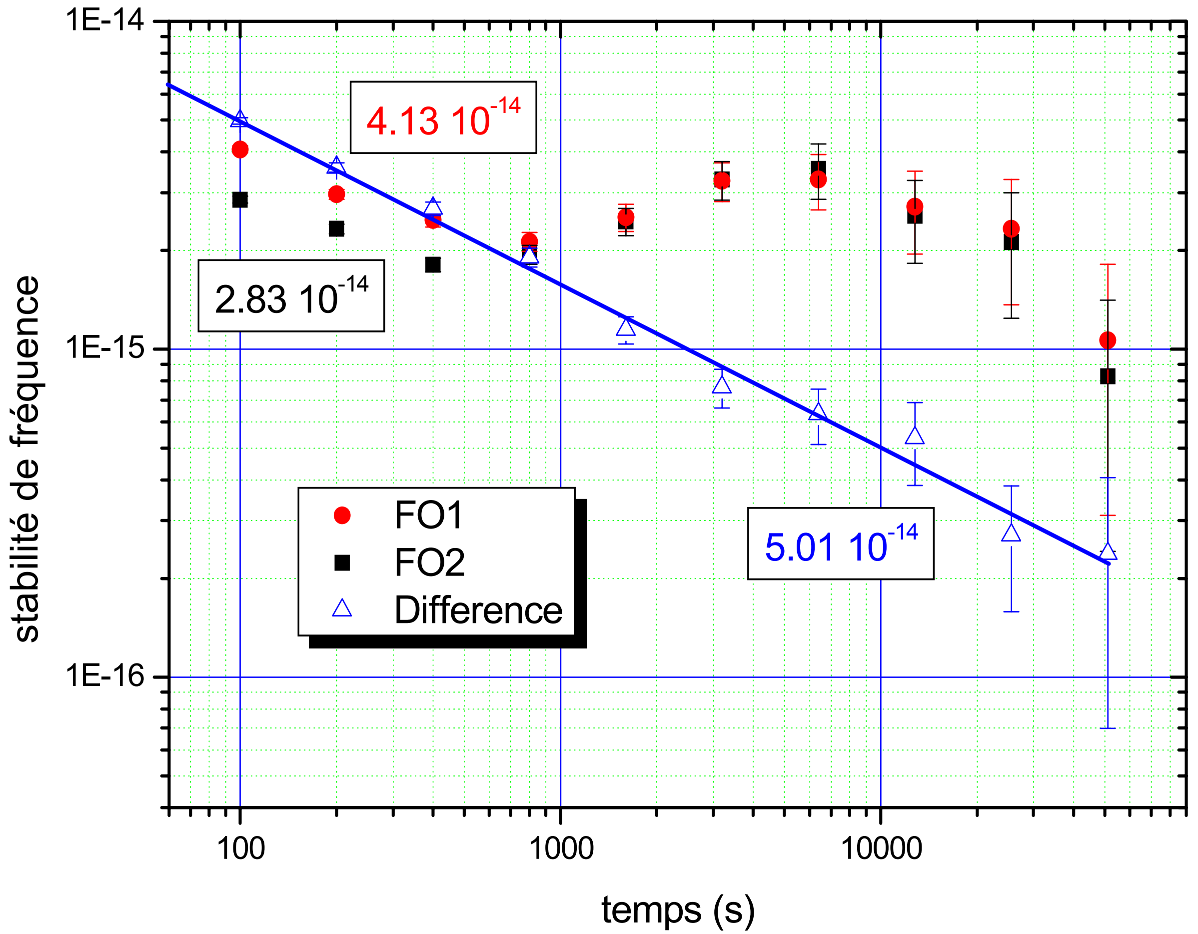
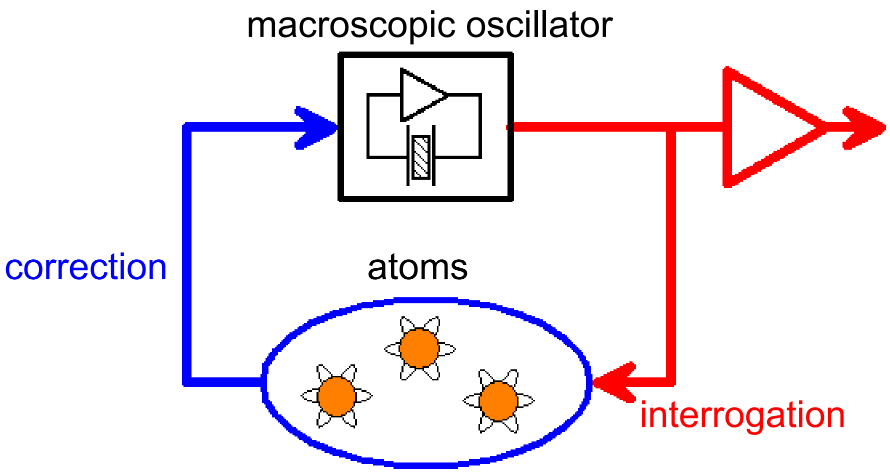
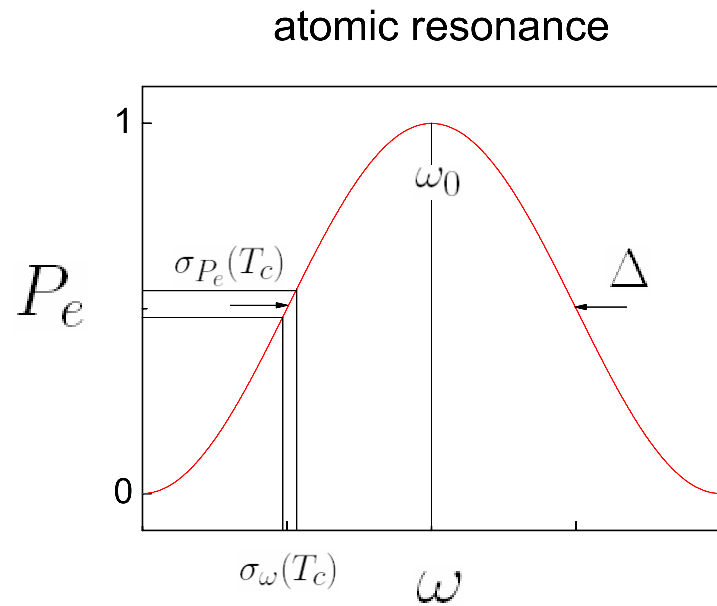
Frequency comparisons between fountains



Below 10^{-16}: Two possible ways





$$\sigma_y(\tau) \sim \frac{1}{\omega_0}\sigma_\omega(T_c)\sqrt{\frac{T_c}{\tau}} \sim \frac{\Delta}{\omega_0}\sigma_{P_e}(T_c)\sqrt{\frac{T_c}{\tau}}$$

atomic quality factor $Q_{\mathrm{at}} = \frac{\omega_0}{\Delta}$

ω_0 -as high as possible

Δ
- -low natural width
- -Fourier limit, long interaction time
- -low oscillator spectral width

$\sigma_{P_e}(T_c)$
- -Large atom number
- -low noise detection scheme
- -low noise oscillator

+ transition should be insensitive to external perturbations

Atomic transition in the optical doma

A clock in space

Optical frequency standards ?

Frequency stability :

$$\sigma_y(\tau) = \frac{\Delta}{\pi\omega_0\sqrt{N_{\mathrm{det}}}}\sqrt{\frac{T_c}{\tau}}$$

Increase ω_0 (x 10^5)

Optical fountain at the quantum limit $\sigma_y(\tau) \sim 10^{-18}\tau^{-1/2}$!!!!!!!!!

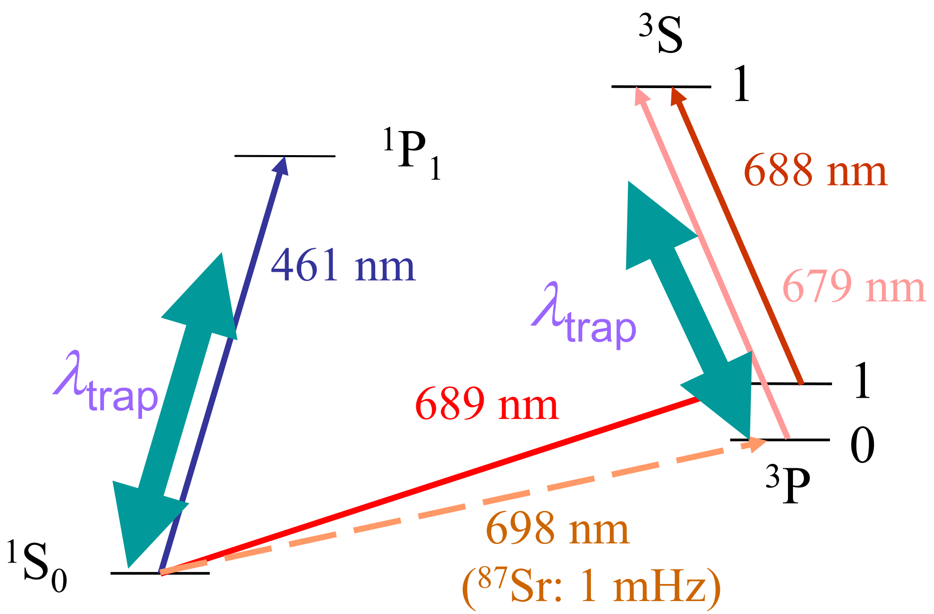
Frequency accuracy: most of the shifts (expressed in absolute values) don't depend on the frequency of the transition (Collisions, Zeeman...).

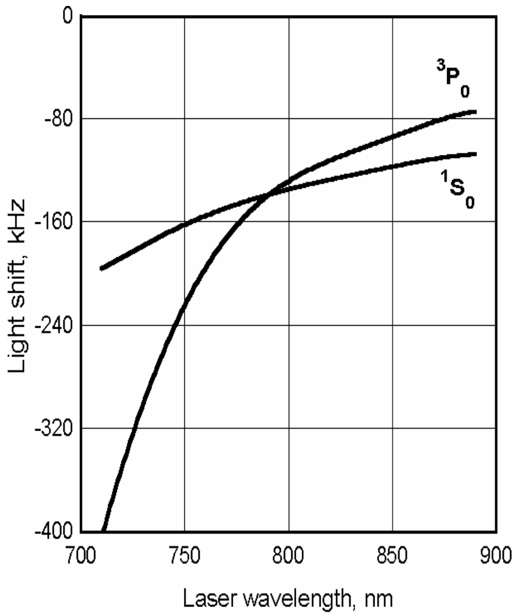
Three major difficulties

- -Ability to compare frequencies (now solved with femto)
- -Recoil and first order Doppler effect (trapped ion clocks)
- -Interrogation oscillator noise conversion (Dick effect).

The best optical clocks so far exhibit frequency stabilities in the $10^{-15}\,\tau^{-1/2}$ range together with an accuracy around 10^{-14}.

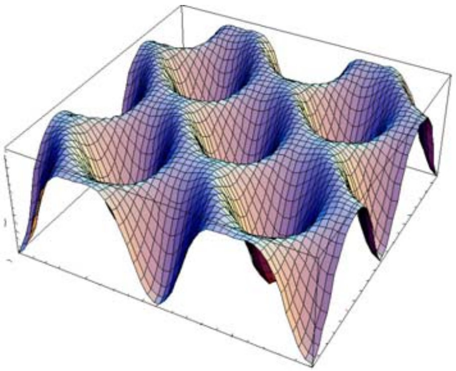
Optical lattice clock





Clock transition $^1S_0$-$^3P_0$ transition

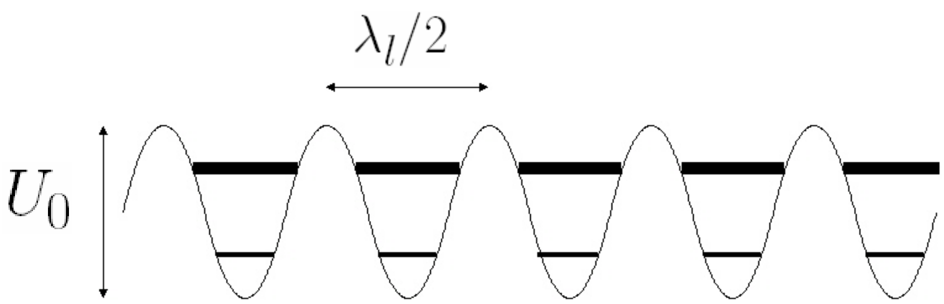
Katori, Proc. 6th Symp. Freq. Standards and Metrology (2002)
Pal'chikov, Domnin and Novoselov J. Opt. B. **5** (2003) S131
Katori et al. PRL 91, 173005 (2003)



Combine advantages of single trapped ion and
Free fall neutral atoms optical standards

Other possible atoms: Hg, Yb, Ca, Mg
What is the required depth of the lattice (hyperpolarisability, available power...) ?

Periodic Potential

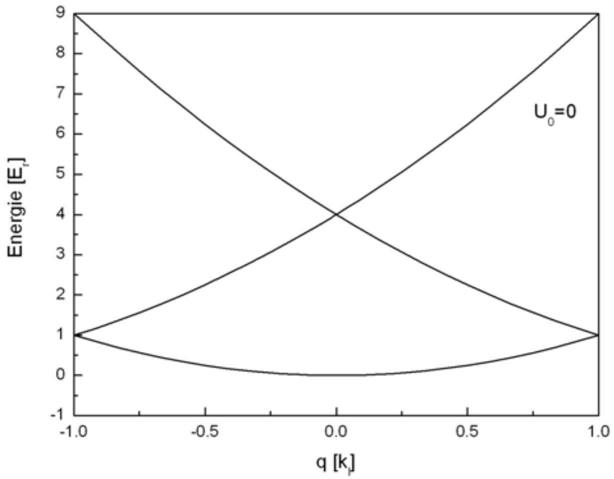


$$H_{ext} = \frac{\hbar^2\alpha^2}{2m_a} + \frac{U_0}{2}(1 - \cos(2k_l x))$$

Eigenstates organize in bands and write $|n, q\rangle$, with n the band number and q the quasi-momentu

$|n, q + 2k_l\rangle = |n, q\rangle$ one restricts to the first Brillouin zone]-k_l,k_l]

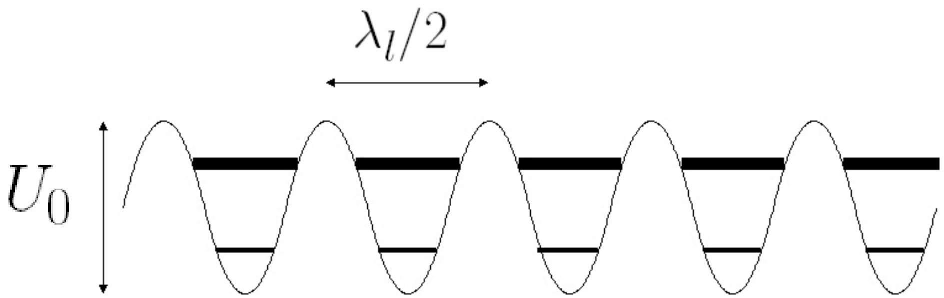
$\langle z + \lambda_l/2|n, q\rangle = e^{iq\lambda_l/2}\langle z|n, q\rangle$ Eigenstates are delocalized over the whole lattice



U_0=0 Eigenstates are plane waves $|n, q\rangle = |\kappa_{n,q}\rangle$

$$\kappa_{n,q} = q + 2nk_l$$

Periodic Potential



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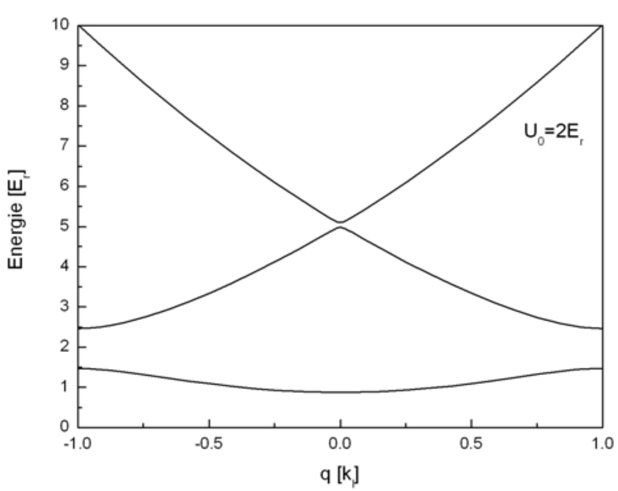
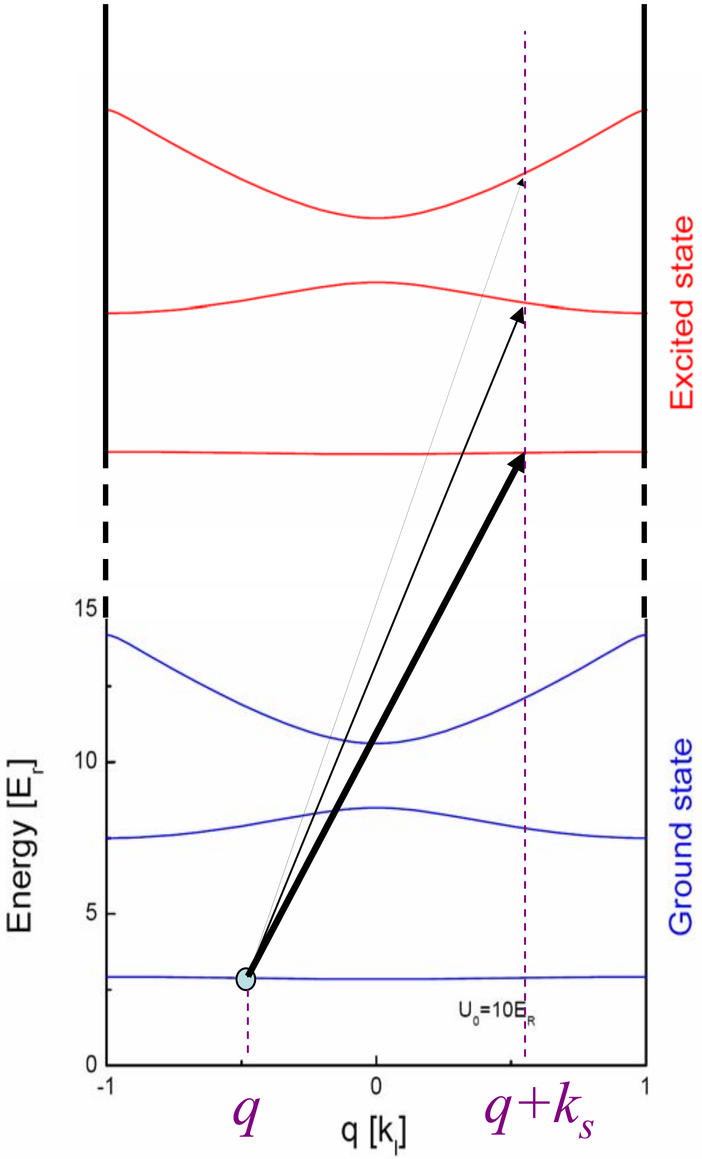


$U_0 \neq 0$ plane waves separated by $2k_l$ are coupled by H_{ext}

$$|n, q\rangle = \sum_j c_j^{n,q}|\kappa_{j,q}\rangle \qquad \kappa_{n,q} = q + 2nk_l$$

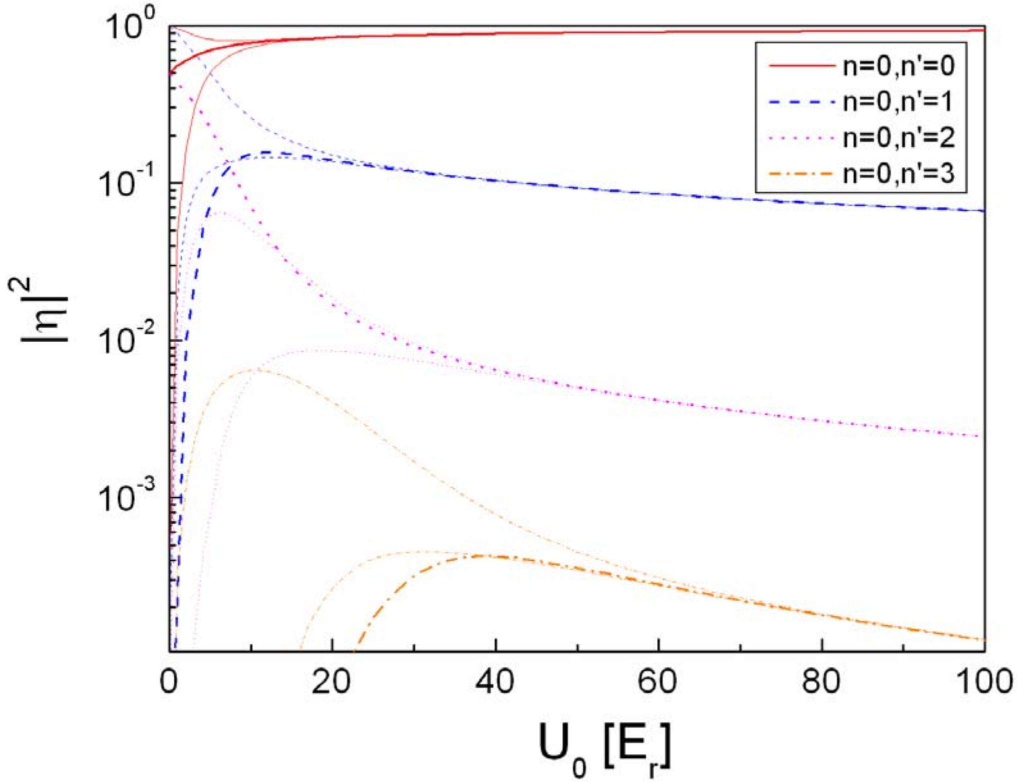
Energy scale (Sr) $E_r = \frac{\hbar^2 k_l^2}{2m_a} \sim 3.5\,\mathrm{kHz}$

Spectroscopy in a lattice



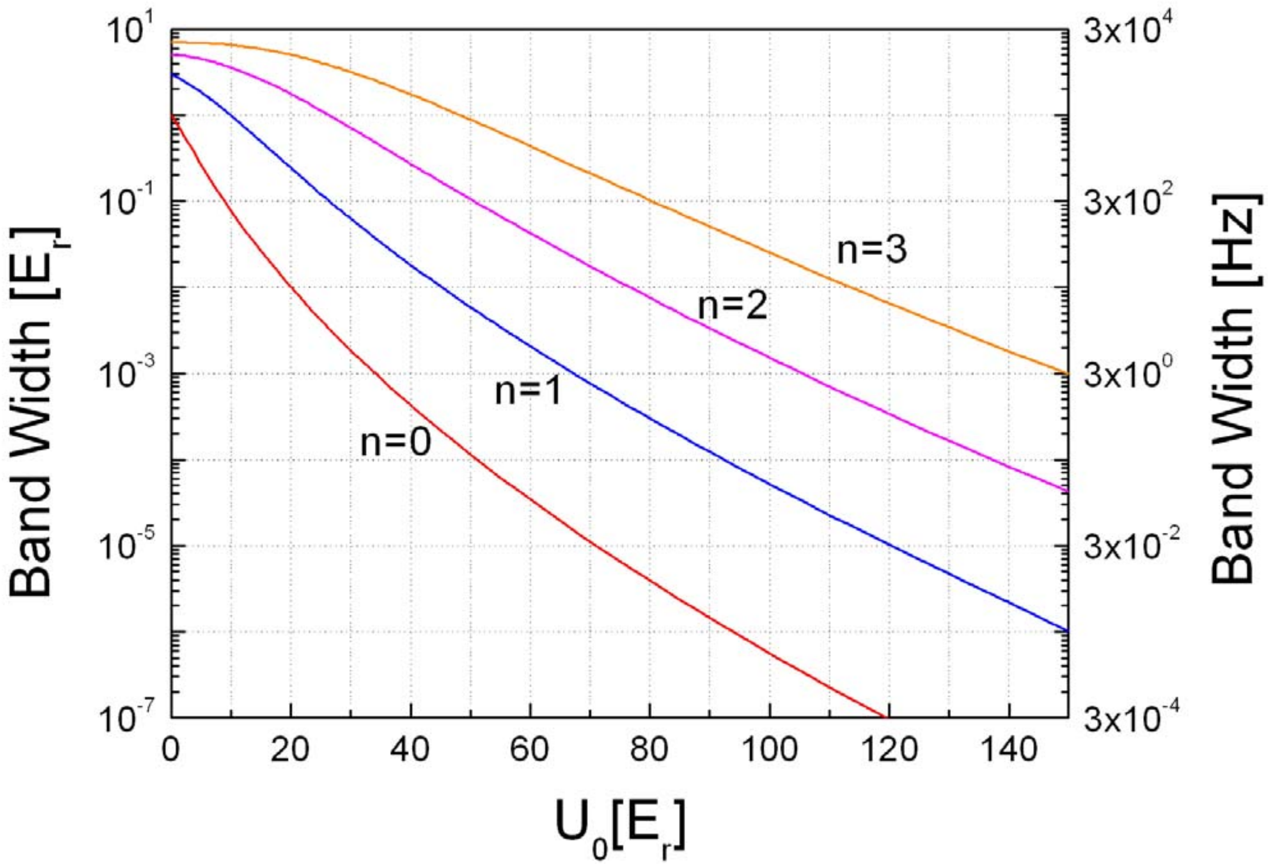
Absorption of a photon: translation of the atomic momentum by ħk_s

$$e^{ik_s x}|n,q\rangle = \sum_j c_{n,\kappa_{j,q}}|\kappa_{j,q}+k_s\rangle$$
$$= \sum_{n'} \eta_{n,n',q}|n',q+k_s\rangle$$



Spectroscopy in a lattice

Transitions are shifted by ~ width of the band: Residual Doppler/recoil)

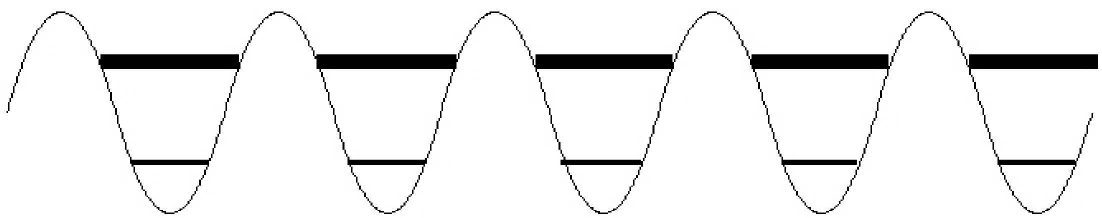


Atoms have to be prepared in the ground band

U_0 has to be high : 50-100 E_r High order effects, Hg, can we do better ?

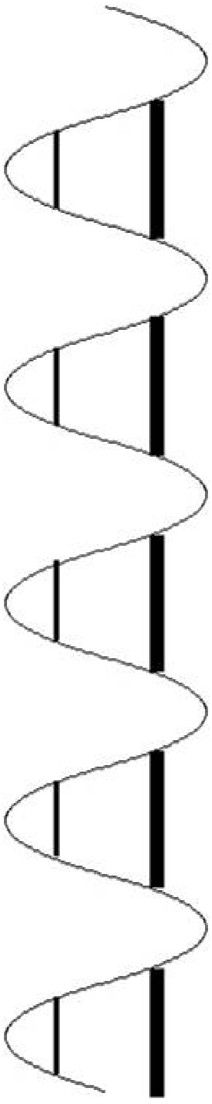
A deep lattice is needed...

Problem



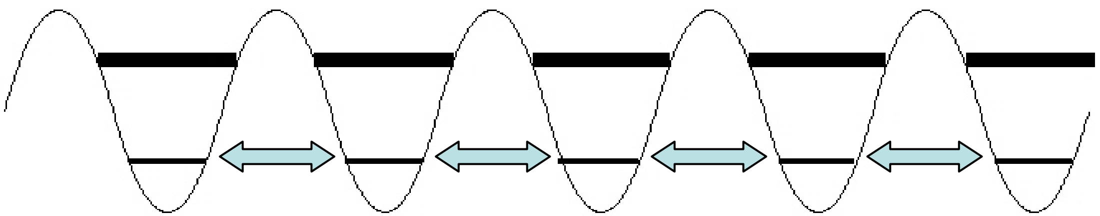
Though...

Solution



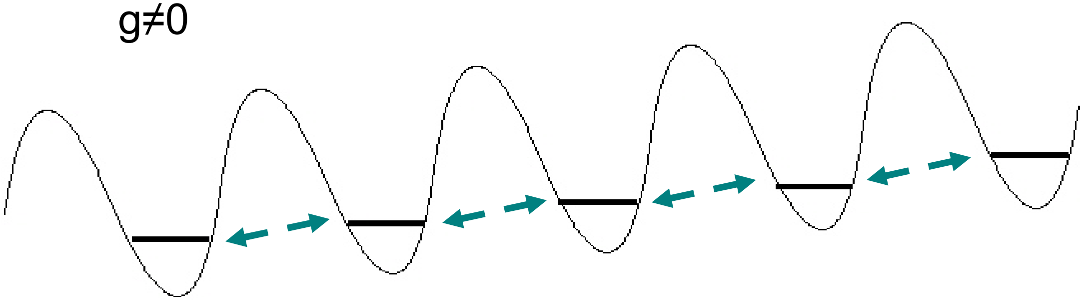
Effect of gravity

g=0



Resonant tunnel effect ⇒ delocalizatio

g≠0

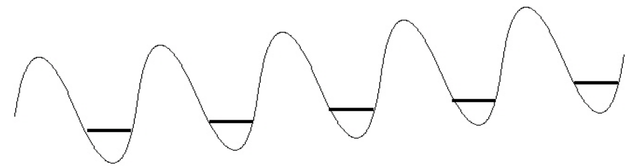


Non-resonant tunnel effect ⇒localizatio

For Sr: Δ_g~1 kHz

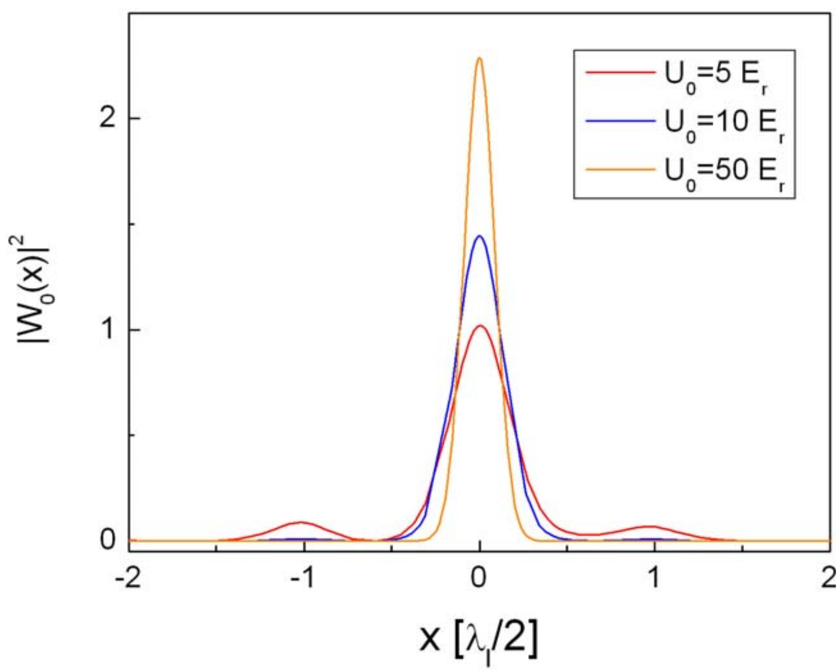
Wannier-Stark states

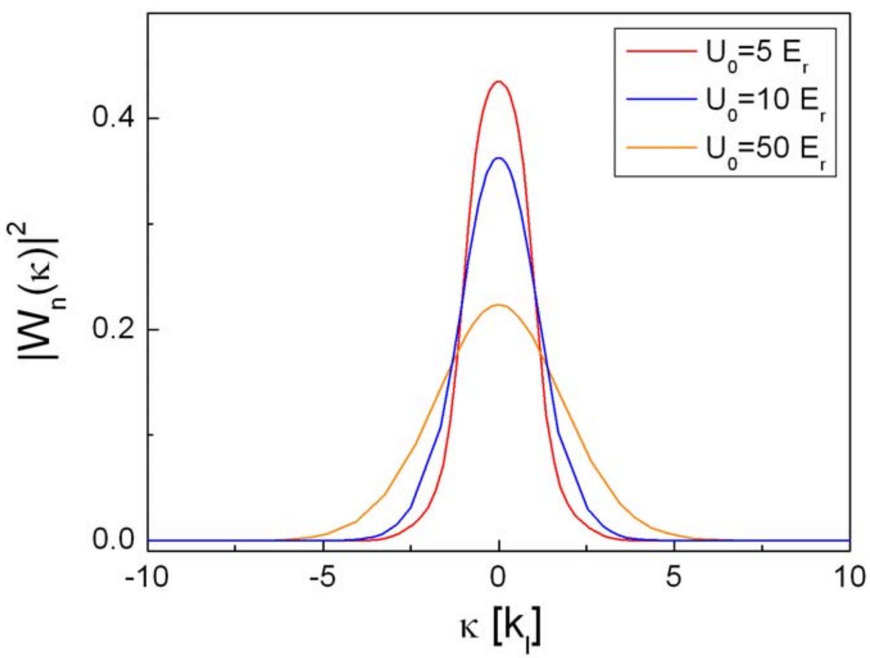
$$H_{ext} = \frac{\hbar^2\alpha^2}{2m_a} + \frac{U_0}{2}(1-\cos(2k_l x)) + m_a g x$$



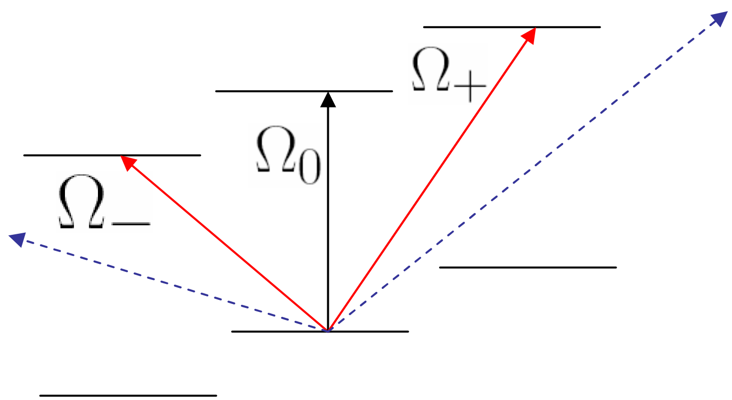
$m_a g x$ couples |*q*> states with each other (Bloch oscillations)

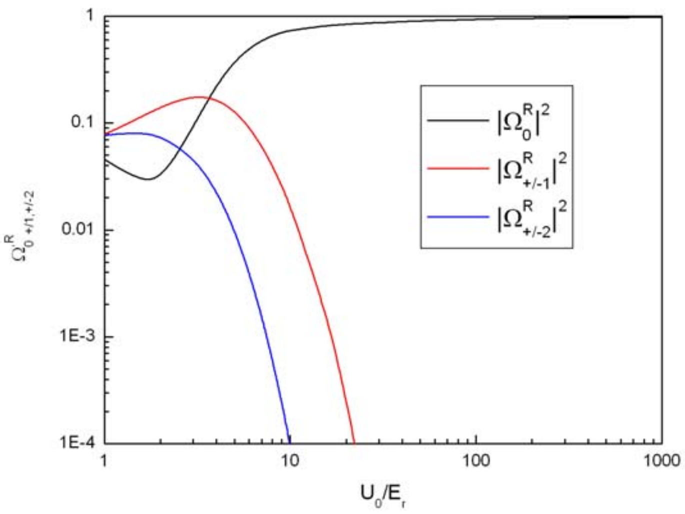
Long-lived metastable states separated by $mg\frac{\lambda_l}{2}$ $\quad |W_n\rangle = \int_{-k_l}^{k_l} dq\, b_n(q)|q\rangle$

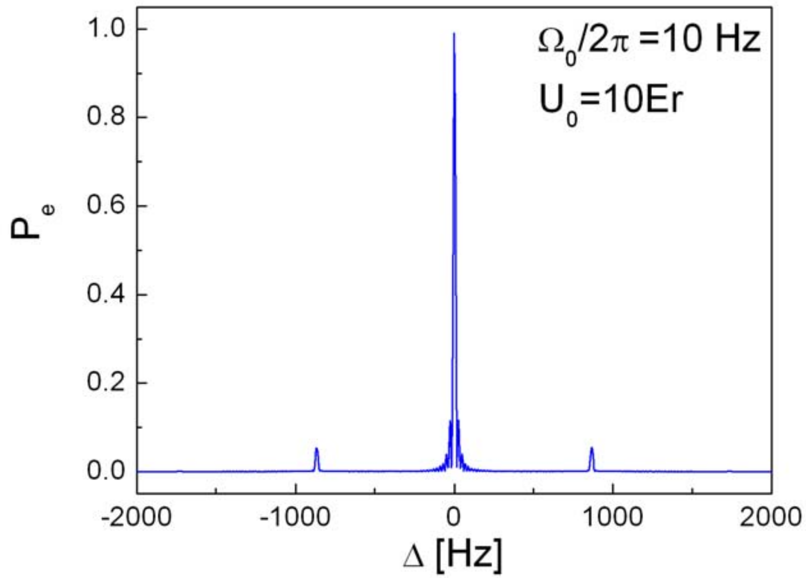


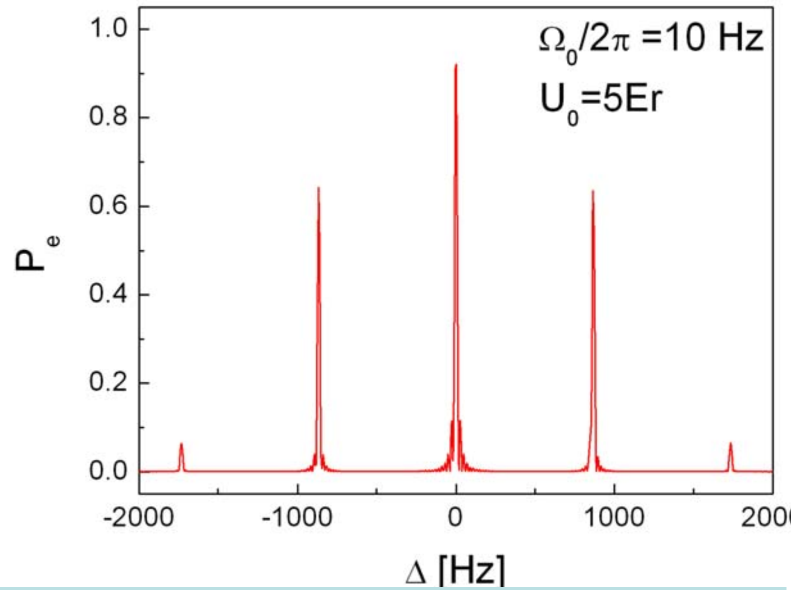


Spectroscopy of W-S states









unshifted carrier
symmetric sidebands: possibility to use a much shallower traps (~10 E_r)