Accélération d'atomes ultra-froids : vers une mesure de h/M et de α

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Determination of the fine structure constant

$h/M_A \Rightarrow \alpha$

Hydrogen atom

$$chR_\infty = \frac{1}{2} m_e c^2 \alpha^2$$

$$\alpha^2 = \frac{2R_\infty}{c} \times \frac{M_A}{m_p} \times \frac{m_p}{m_e} \times \frac{h}{M_A}$$

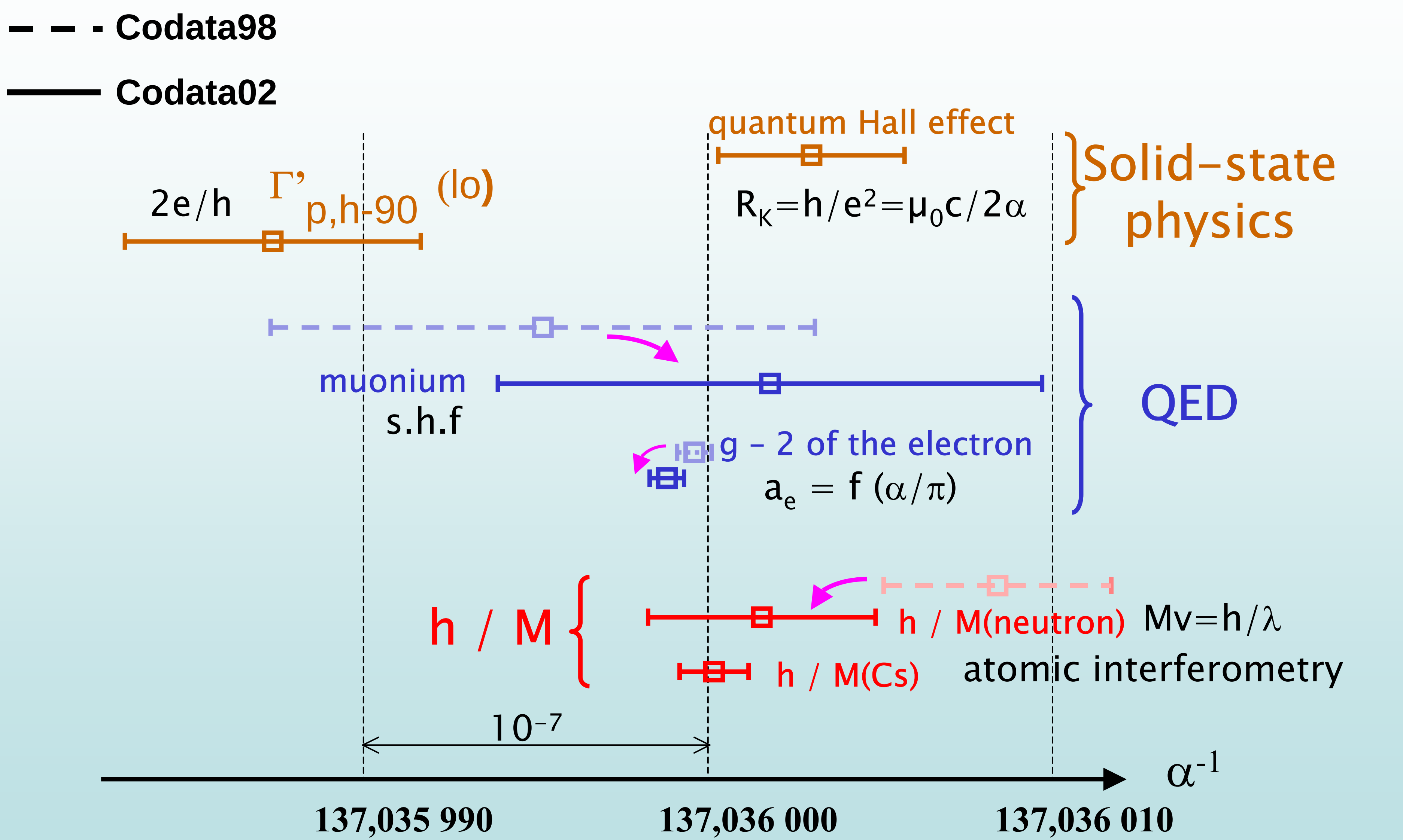
- Rydberg constant (7×10^{-12})
- $\frac{\text{atomic mass}}{\text{proton mass}}$ (2×10^{-10})
- $\frac{\text{proton mass}}{\text{electron mass}}$ (4.6×10^{-10})

• measurement of h/M_A at 6×10^{-8}

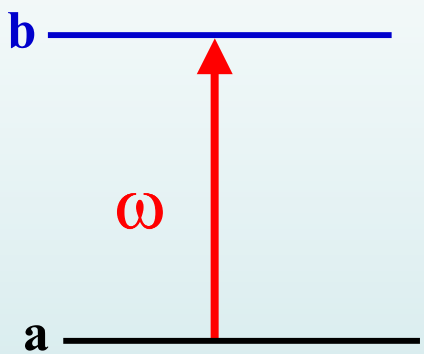
➡ determination of α at 3×10^{-8}

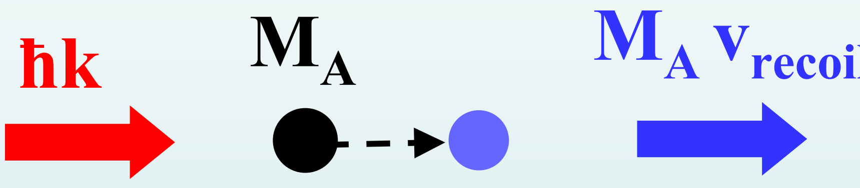
• total dispersion of α measurements: 2.4×10^{-7} (CODATA 1998)

Measurements of α



The principle of the experiment : measurement of the atomic recoil velocity



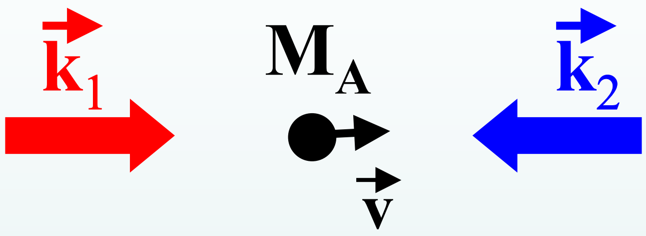


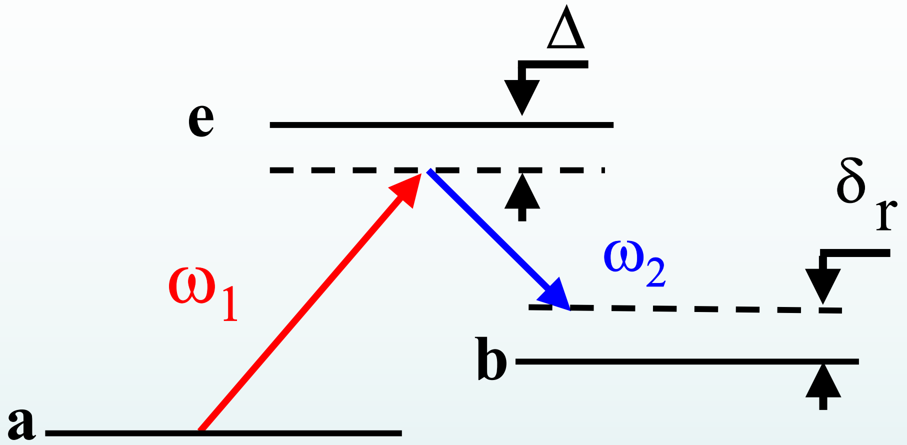
$$v_{recoil} = \frac{\hbar k}{M_A}$$

$$v_{recoil}^{^{87}Rb} \approx 6 mm \cdot s^{-1}$$

measurement of v_{recoil} and $k \Rightarrow h/M_A$

Raman transitions (1) : velocity selection





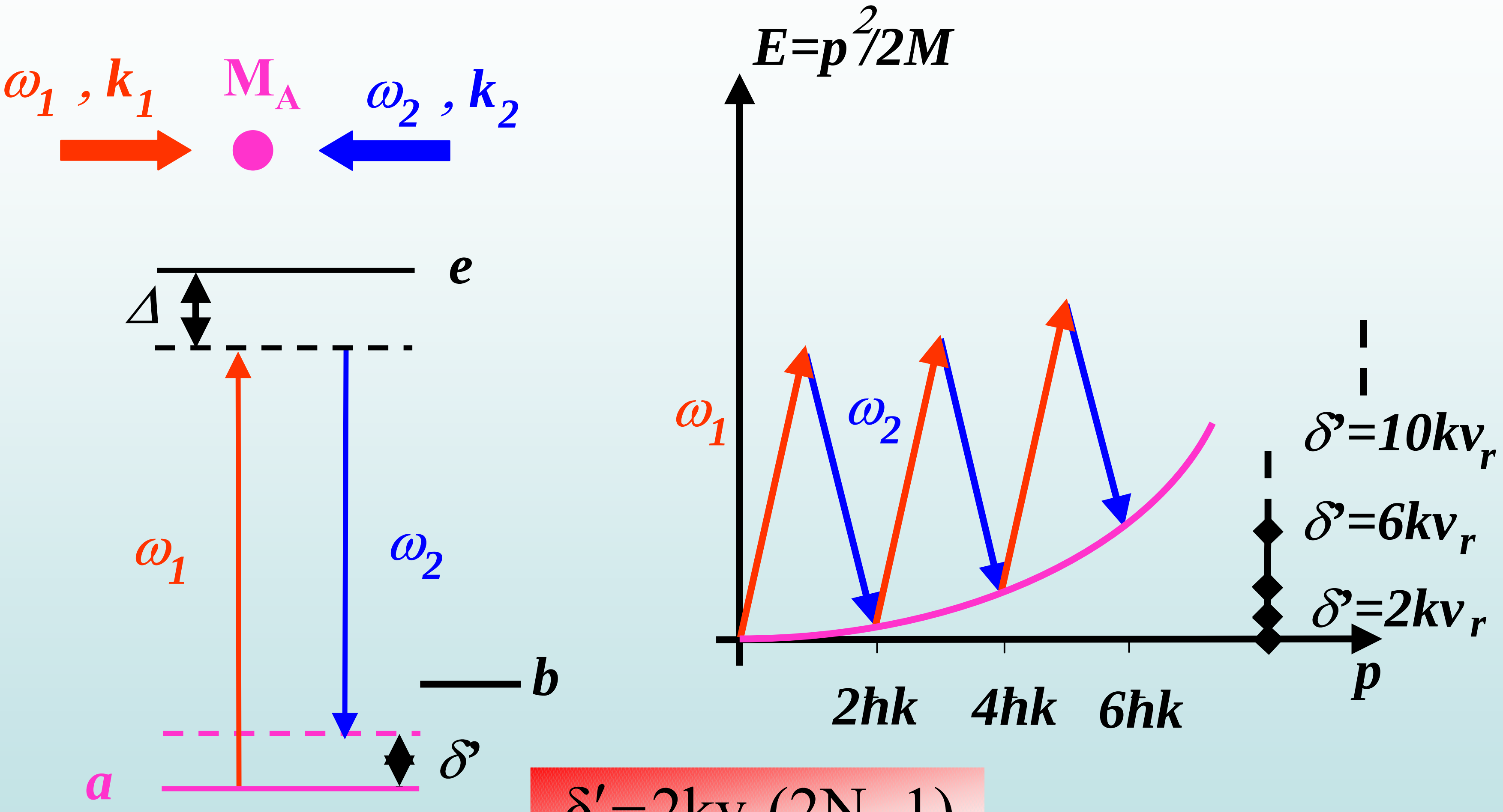
$$M_A \Delta\vec{v} = \hbar\left(\vec{k}_1 - \vec{k}_2\right)$$

$$2\pi\,\delta_r = \omega_1 - \omega_2 - \omega_{ab} - \vec{v}\cdot\left(\vec{k}_1 - \vec{k}_2\right) - \hbar\frac{\left(\vec{k}_1 - \vec{k}_2\right)^2}{2M_A}$$

$$\delta_r = 0 \text{ and } \vec{k} = \vec{k}_1 \approx -\vec{k}_2 \Rightarrow \omega_1 - \omega_2 \approx \omega_{ab} + 2k\left(v + v_r\right)$$

- coherent momentum transfert
- control of δ_r ⇨ control of v
- two hyperfine levels involved ⇨ velocity selection and measurement

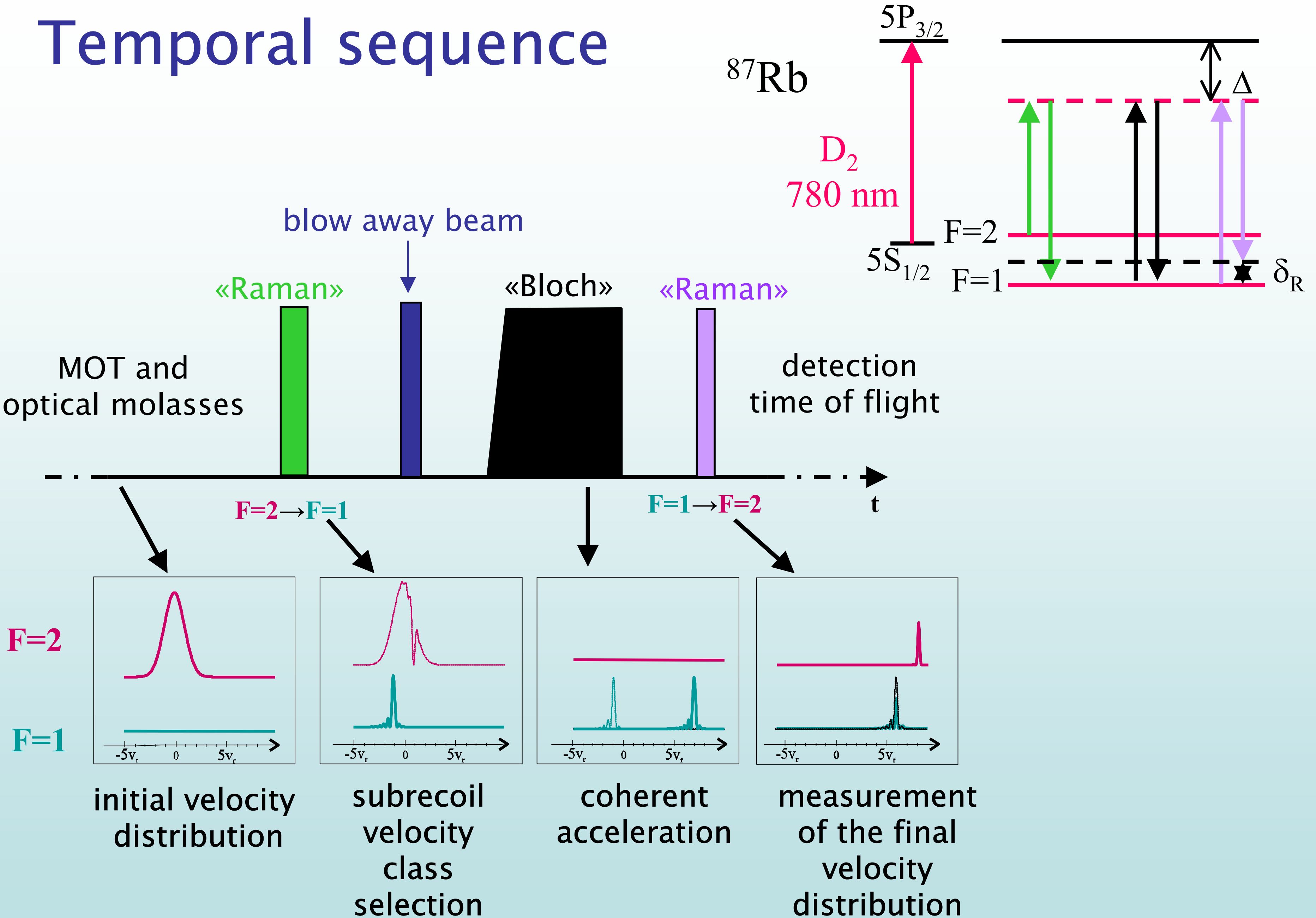
Raman transitions (2) : acceleration of atoms



$$\delta' = 2kv_r(2N-1)$$

Acceleration ⇔ Bloch oscillations

Temporal sequence

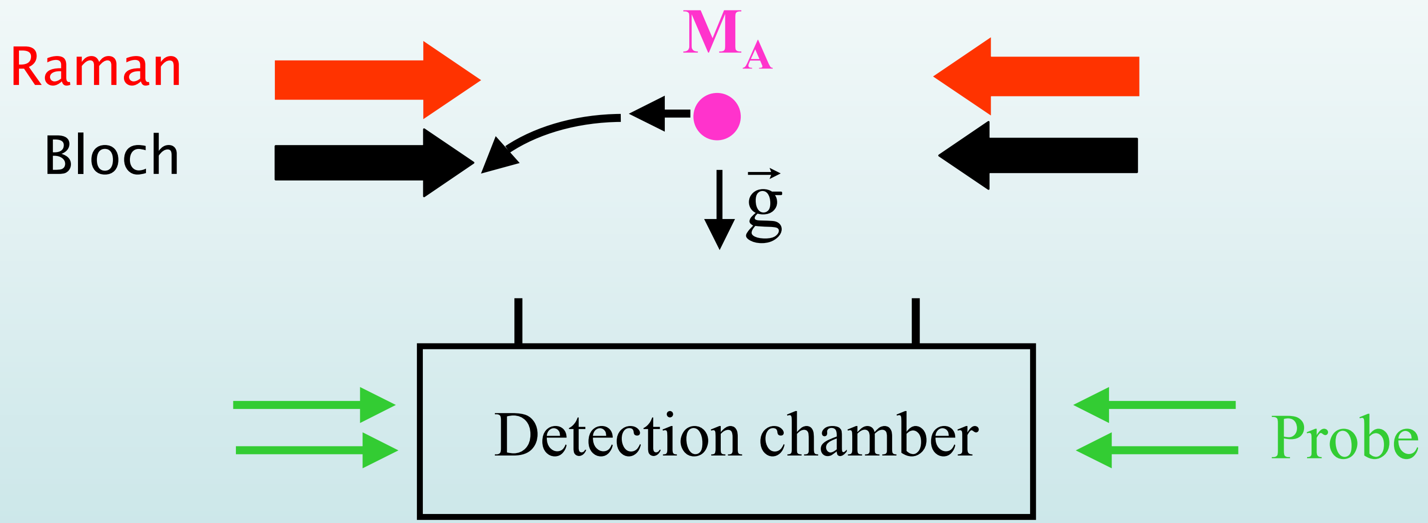


$\nu_{sel} = \nu_2 - \nu_1$ fixed

$\nu_{meas} = \nu_2 - \nu_1'$ tuned

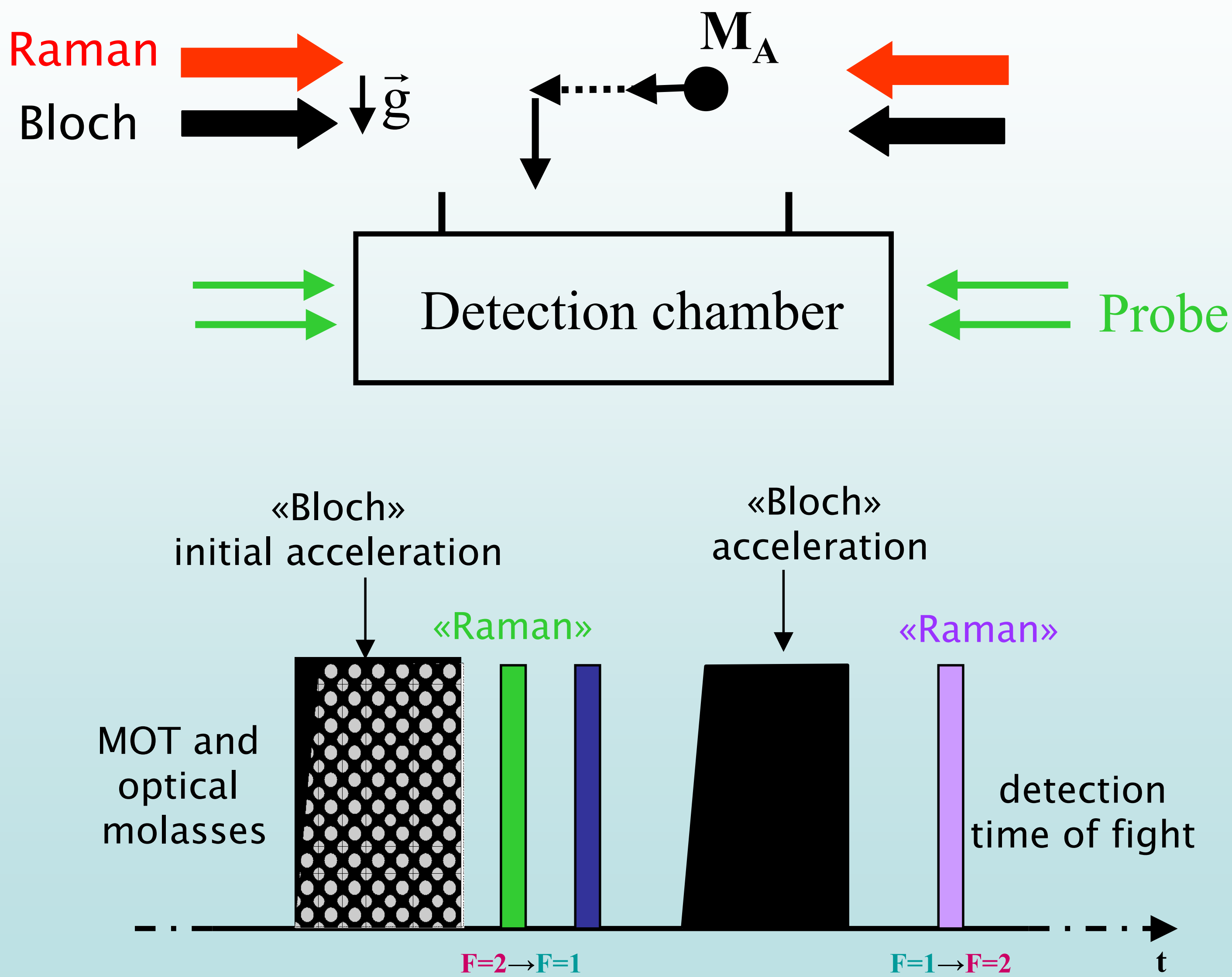
Horizontal acceleration of atoms (1)

$$\nu_{sel} - \nu_{meas} = \frac{1}{2\pi} 2N(\vec{k}_1 - \vec{k}_2).\vec{k}_{Bloch} \frac{\hbar}{M_A} = 2N \frac{h\nu_B \overline{\nu}_R}{M_A c^2}$$



Problem ! For $N \geq 4$, atoms miss the detection area.

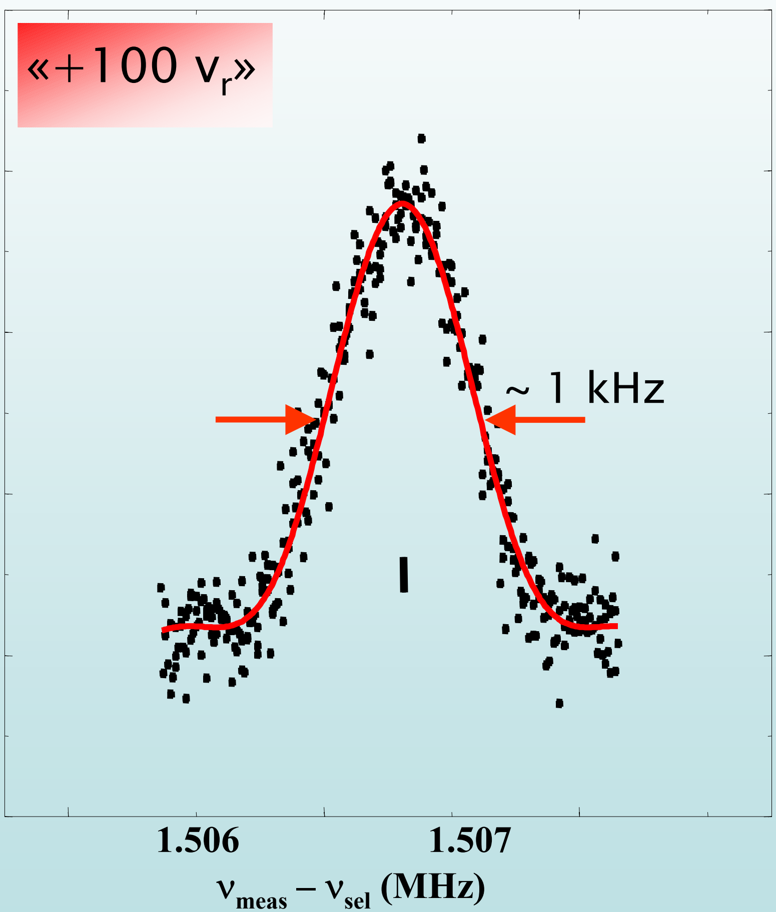
Horizontal acceleration of atoms (2)



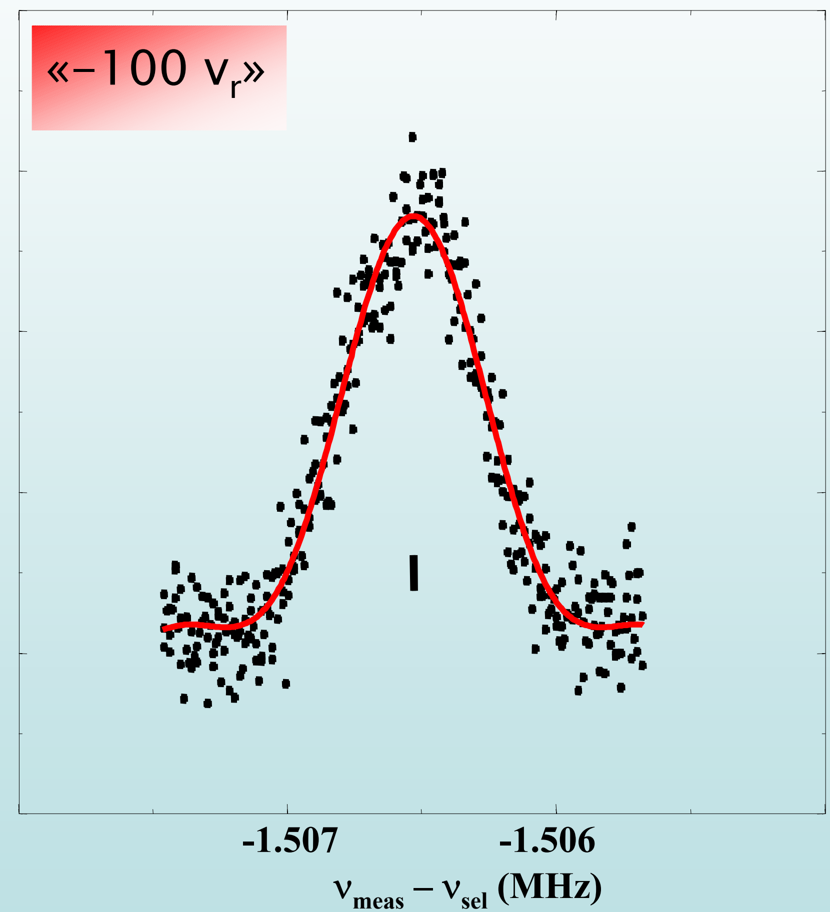
Experimental curves (50 oscillations)

to reduce systematic errors ⇨ alternate and symmetric accelerations in horizontal opposite directions

$\delta_0 = +\,(1\,506\,799{,}5 \pm 3{,}1)$ Hz



$\delta_0 = -\,(1\,506\,531{,}2 \pm 3{,}1)$ Hz



deduced recoil : 15 066, 690 (23) Hz

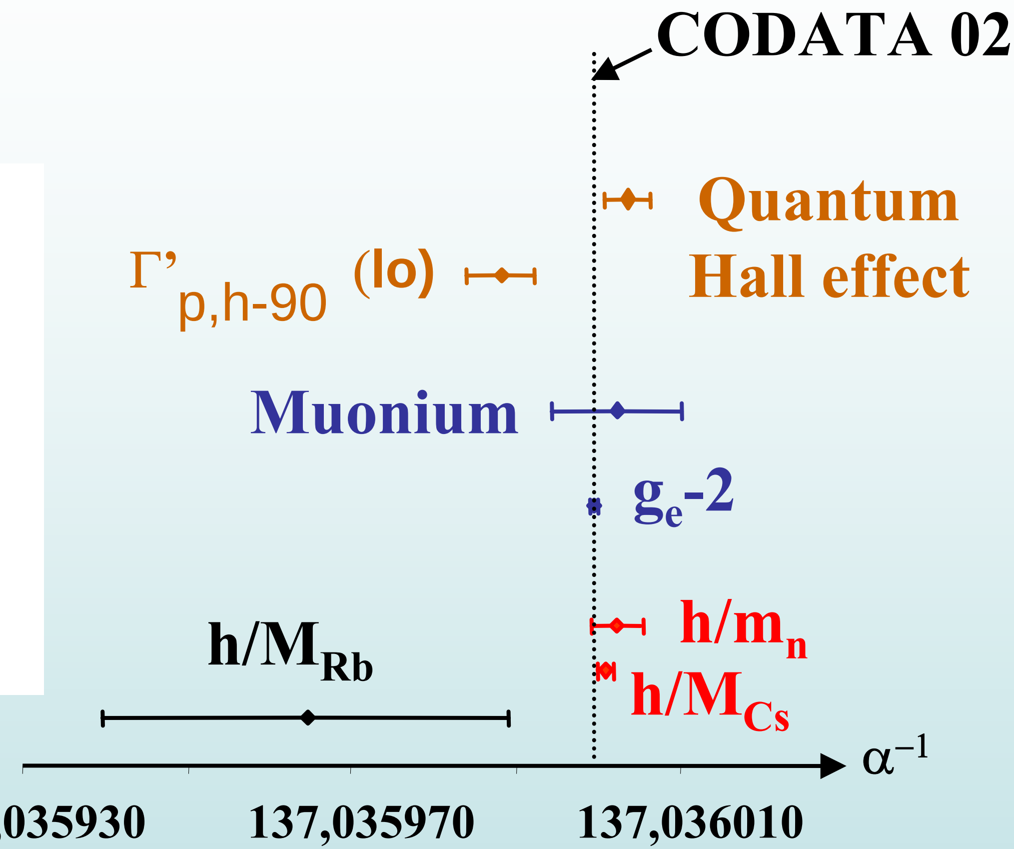
uncertainty: $1{,}5 \times 10^{-6}$

Horizontal geometry : results

h/M_{Rb} relative uncertainty : **4.2×10^{-7}**

Gap between our value
and the expected one : **6.1×10^{-7}**

$\chi^2 = 99$ for 43 measurements.



η (per Bloch oscillation) = **99.5%**

R.Battesti et al, Phys. Rev. Lett. **92**, 253001 (2004)

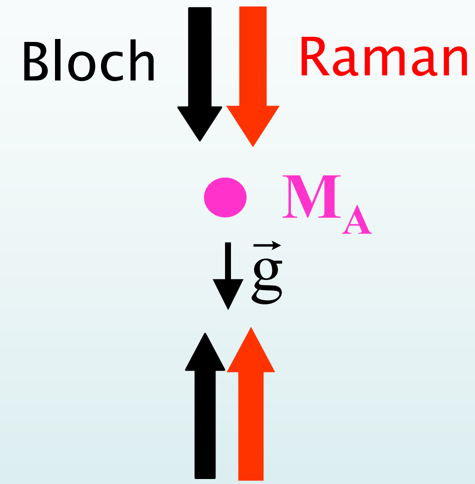
Vertical configurations (1)

➡ Vertical acceleration with Bloch oscillations

$$M_A \Delta \mathrm{v} = M_A g t - N \times \frac{2h\nu}{c}$$

⇓

$$\frac{h}{M_A} = \frac{(gt - \Delta \mathrm{v})}{N} \frac{c}{2\nu}$$

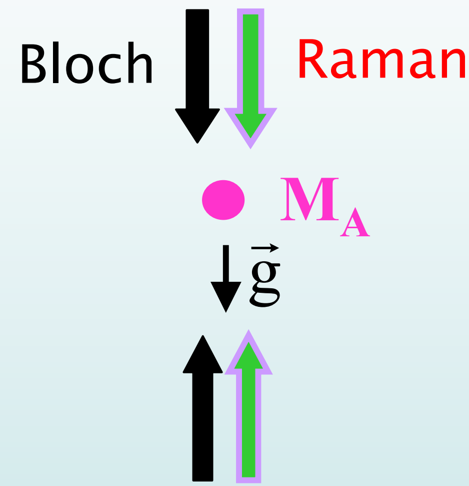


differential measurement («up» and «down» accelerations)

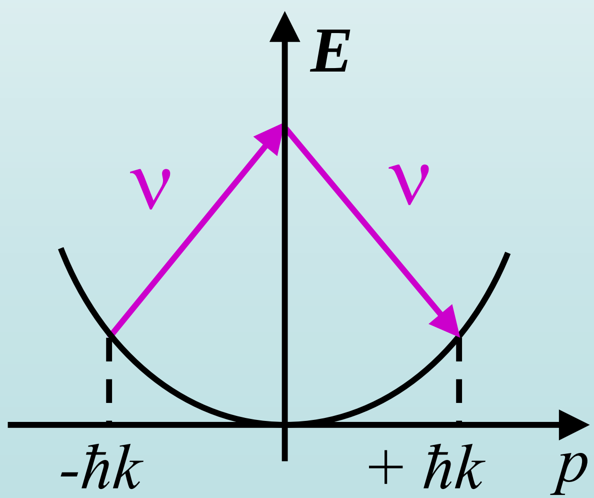
⇒ independent of *g*

Vertical configurations (2)

➡ Vertical beams so that the force due to the Raman transitions exactly compensates gravity



atoms submitted to a vertical standing wave



In the standing wave, the atom oscillates at the same place with the frequency:

$$\nu_B = \frac{M_A g}{2\hbar k}$$

Present work: vertical geometry

⇨ vertical acceleration of the atoms

- 80 recoil transfers

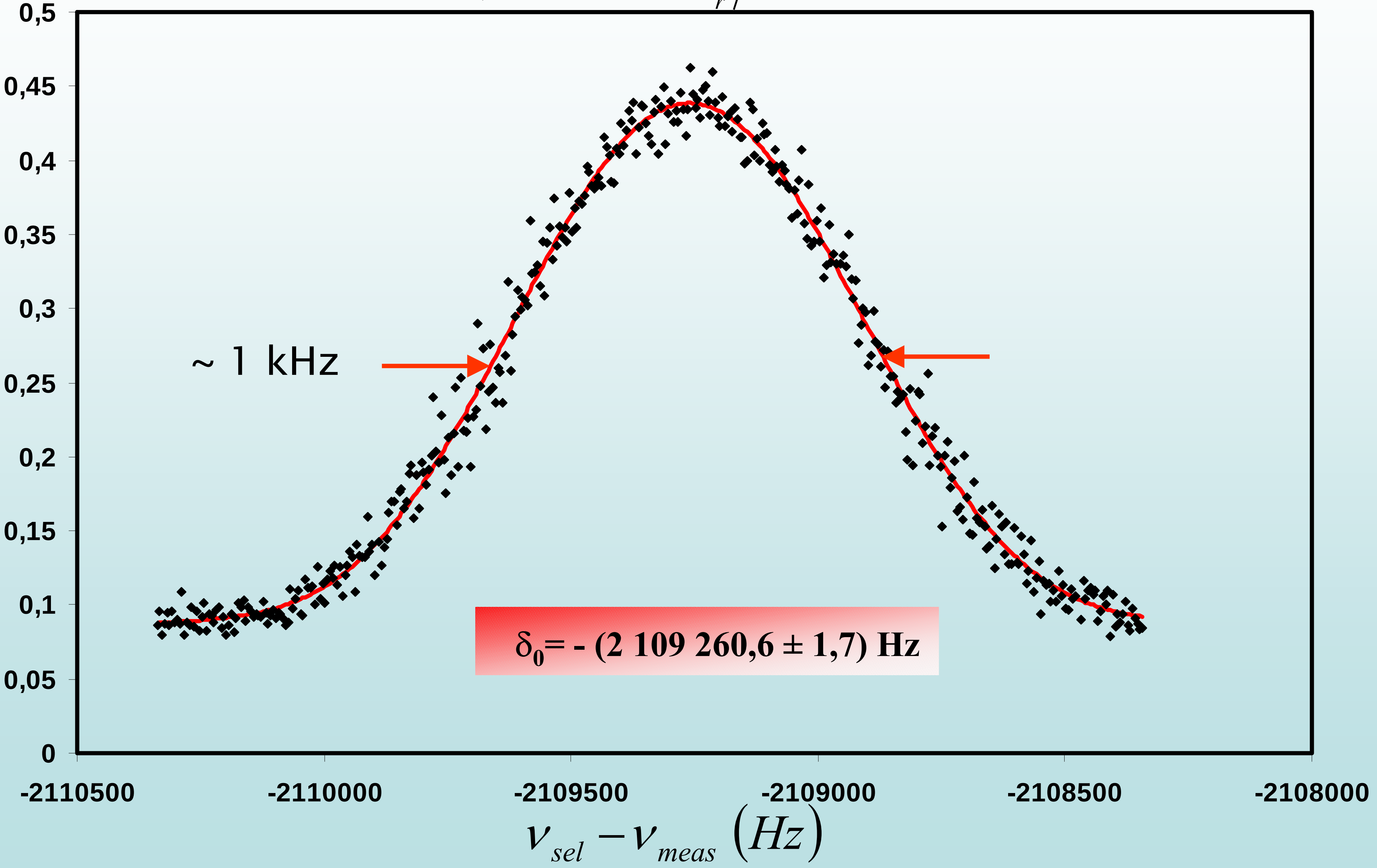
- careful investigations of experimental limiting factors and systematic effects

⇨ observation of Bloch oscillations in the vertical standing wave

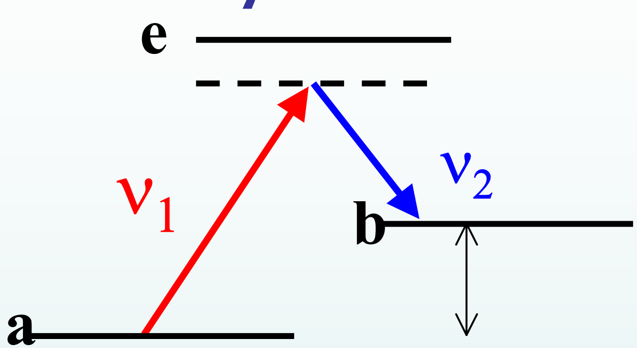
Experimental curves in vertical geometry

80 oscillations

center of the curve: 1,7 Hz ⇨ $\nu_r/9000$ in 10 minutes



Inverting the sens of photons: a way to reduce systematic effects



$$\frac{E_b - E_a}{h} = \nu_{HFS} + \Delta(x,t)$$

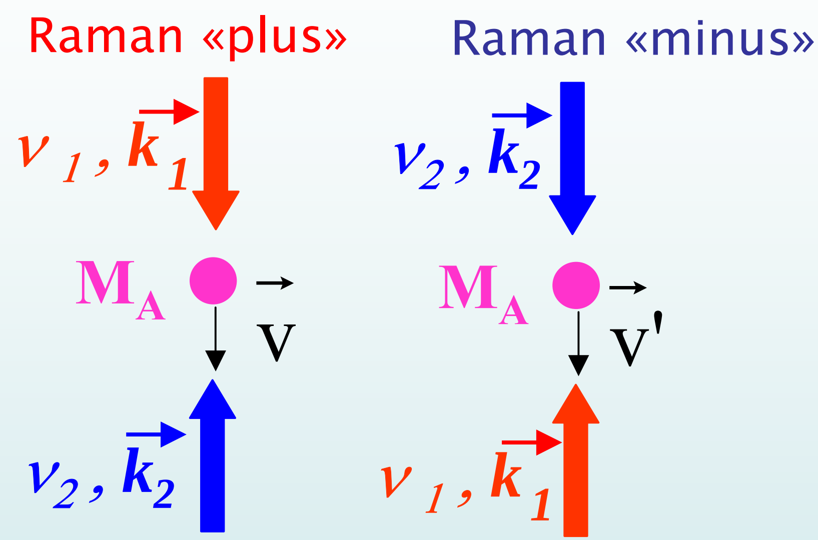
with $\Delta(x,t)$ a systematic effect (light shift, quadratic Zeeman effect ($m_F=0$)..)

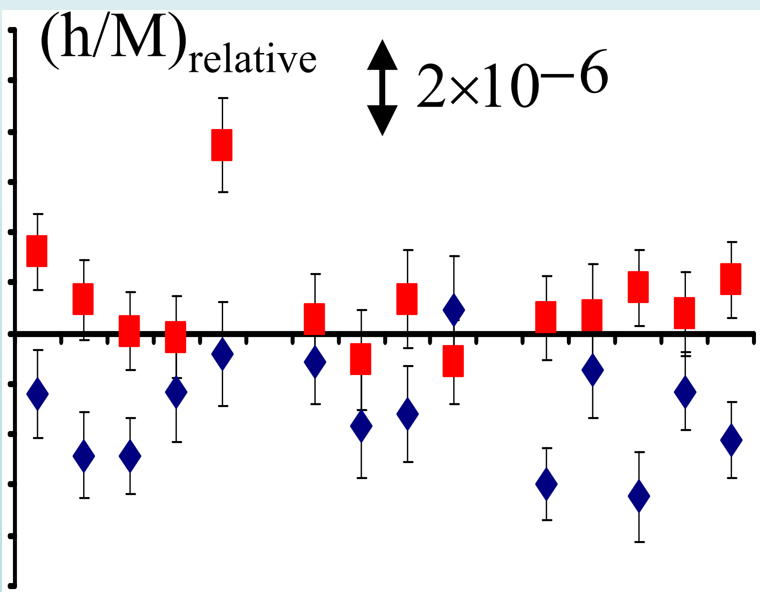
$$\left(\vec{k}_2 - \vec{k}_1\right)\cdot \vec{\mathrm{v}}_{\mathrm{meas}} = 2\pi\left[\delta - (\nu_{HFS} + \Delta(x,t))\right]$$

$$\left(\vec{k}_1 - \vec{k}_2\right)\cdot \vec{\mathrm{v}'}_{\mathrm{meas}} = 2\pi\left[\delta' - (\nu_{HFS} + \Delta(x,t))\right]$$

$$\overline{\mathrm{v}}_{\mathrm{meas}} = \frac{\pi}{2k}\left(\delta' - \delta\right)$$ independent of $\Delta(x,t)$

$$k_1 \approx k_2 = k$$

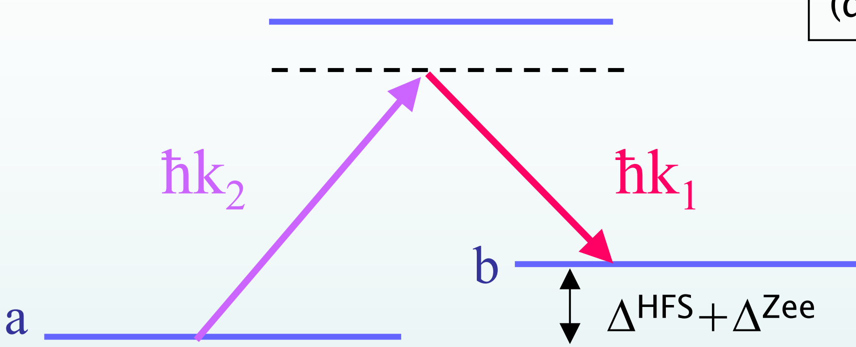


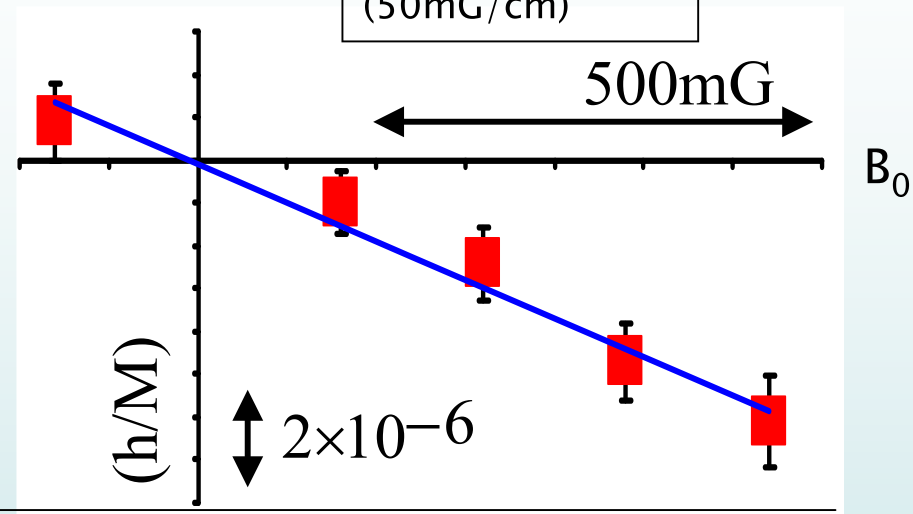


Zeeman effect

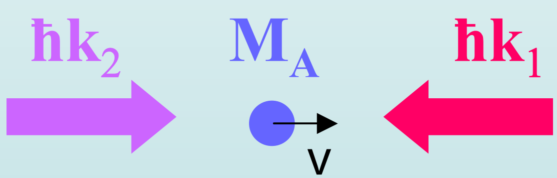
$\Delta^{Zee}(z_{selec}) - \Delta^{Zee}(z_{mes}) \sim B_0 \nabla B \Delta z$

- B_0: Applied magnetic field (quantification axis)
- ∇B: Residual gradiant (50mG/cm)
- Δz: Vertical motion (~1cm)

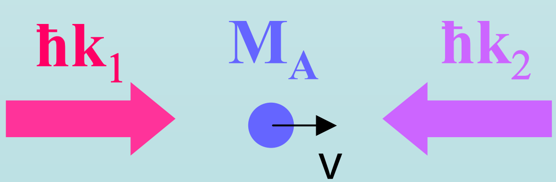




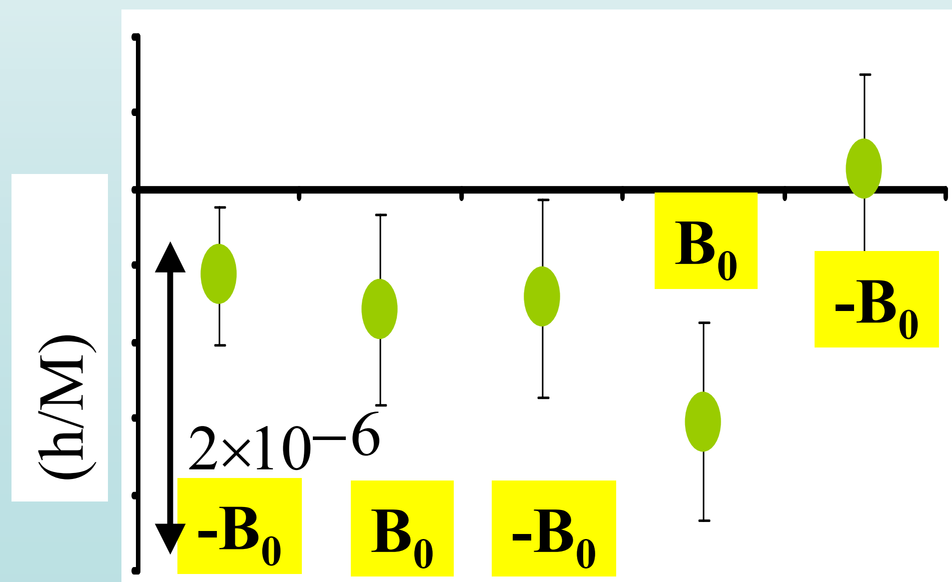
$\Delta^{Zee} = K^{(2)} B^2 \ ; \ K^{(2)} \sim 514 \ \text{Hz/G}^2$



$(\vec{k}_2 - \vec{k}_1) \cdot \boldsymbol{\delta}\vec{\mathbf{v}} = \Delta^{Zee}$



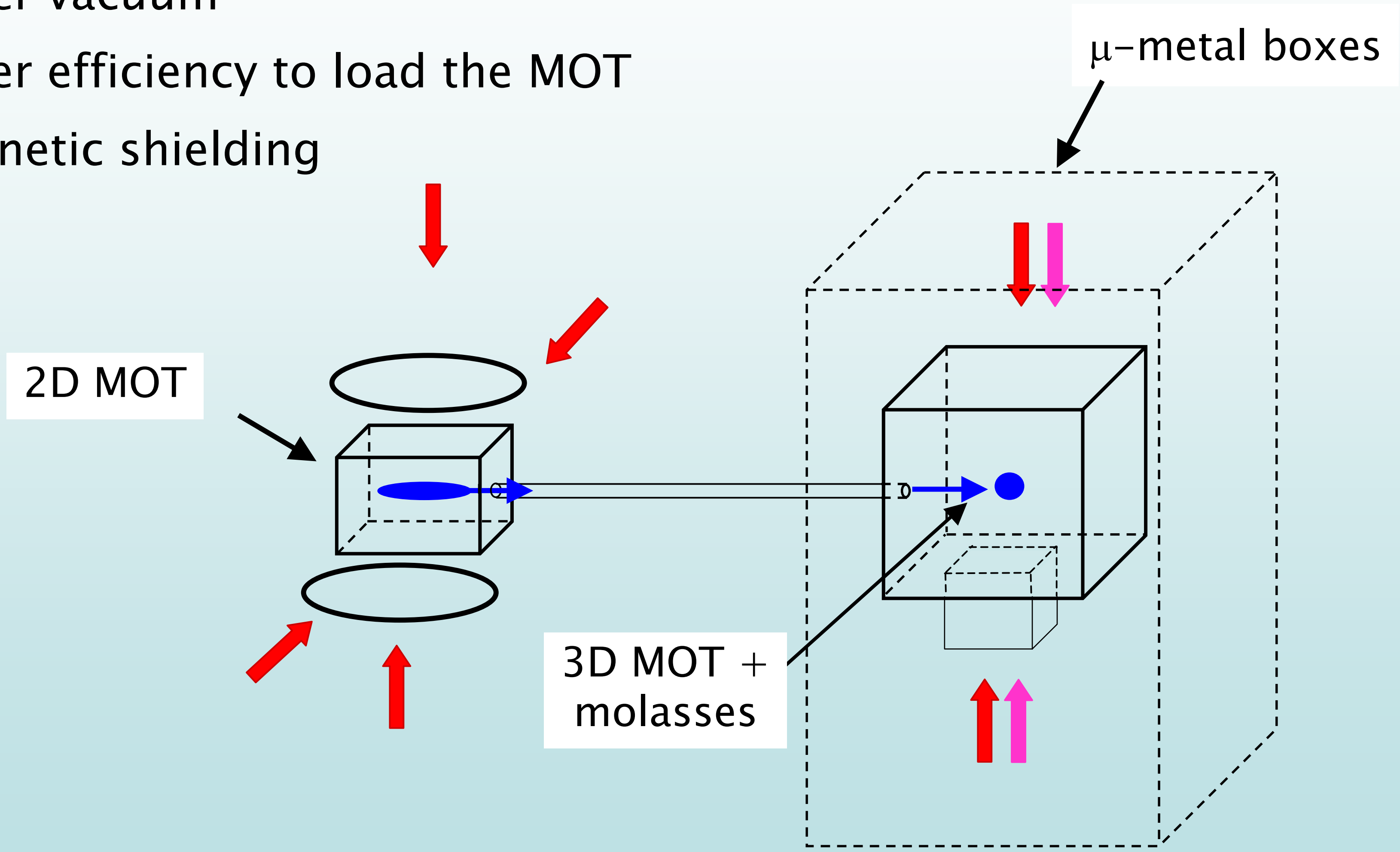
$(\vec{k}_1 - \vec{k}_2) \cdot \boldsymbol{\delta}\vec{\mathbf{v}} = \Delta^{Zee}$



Prospects

Future : new cell + slow atoms source

- better vacuum
- better efficiency to load the MOT
- magnetic shielding



Uncertainties (1)

Lasers wavelenghts

uncertainty of 10 MHz on the Raman and Bloch laser frequencies

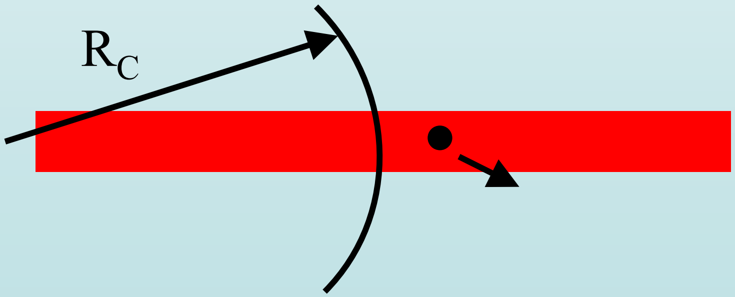
→ 5.2×10^{-8}

Angle between the different laser beams

estimation based on the fiber diameter (5 μm)
and the focal lenghts (40 mm) $\rightarrow$ 63 μrd

→ 2×10^{-9}

Wave fronts curvature

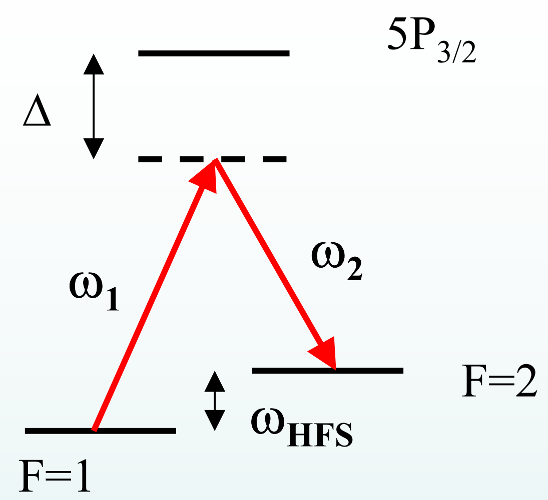


radius of curvature $R_C > 20$ m

vertical motion in 20 ms ~ 2 mm $\rightarrow \theta \sim 10^{-4}$ rd

→ 5×10^{-9}

Uncertainties (2)



Light shifts

$$\delta(\boldsymbol{F}=1)=\frac{1}{2\pi}\frac{\Gamma^2}{8\boldsymbol{I}_s}\left(\frac{\boldsymbol{I}_1}{\Delta}+\frac{\boldsymbol{I}_2}{\Delta+\omega_{HFS}}\right)$$

differential effect ($I_1 = I_2$ and π pulse):

$$\delta(F=2)-\delta(F=1)=-\frac{2}{\tau}\frac{\omega_{HFS}}{\Delta}$$

$\tau \sim 1.6$ ms $\quad \Delta \sim 340$ GHz $\rightarrow$ 26 Hz (N=50) → 8×10^{-6}

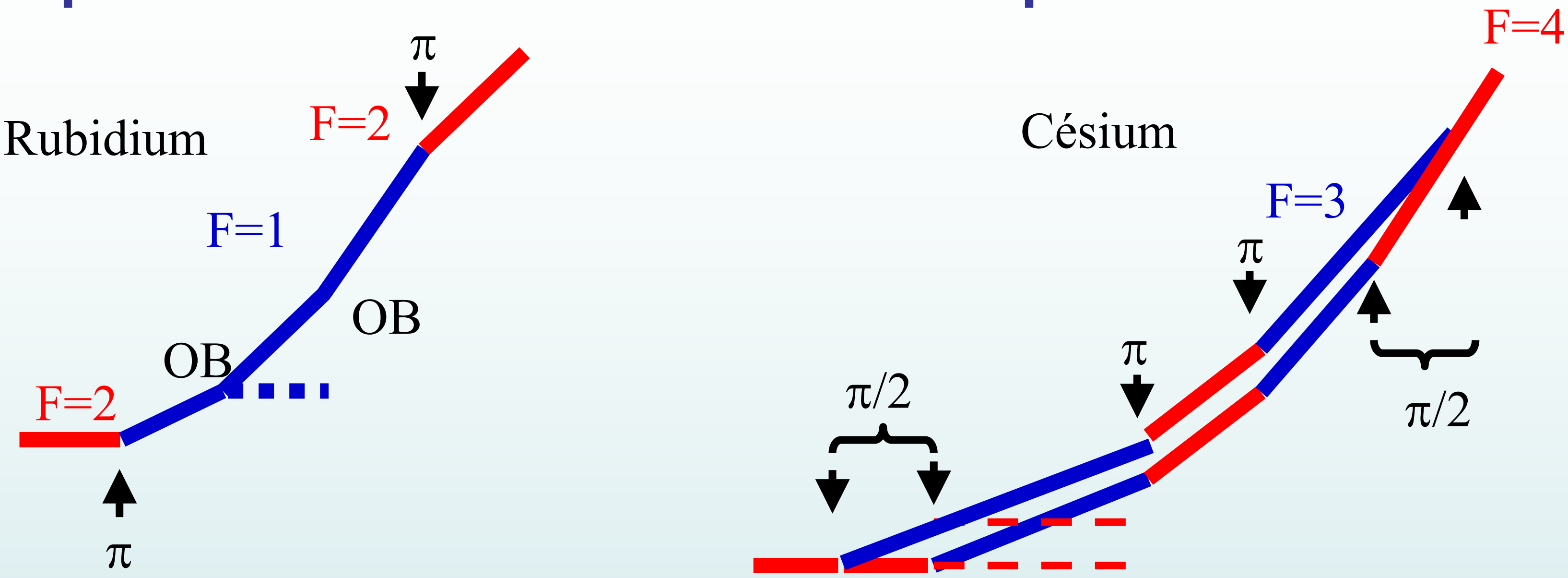
differential effect between the measurements +/- 50 oscillations → 8×10^{-8}

Magnetic fields fluctuations

transition between $m_F = 0$ sub-levels
magnetic field of 150 mG $\rightarrow$ 9,6 Hz
Fluctuations $[(B_{sel} - B_{mes})_{+50} - (B_{sel} - B_{mes})_{-50}] \sim 1$mG $\rightarrow$ 0,13 Hz

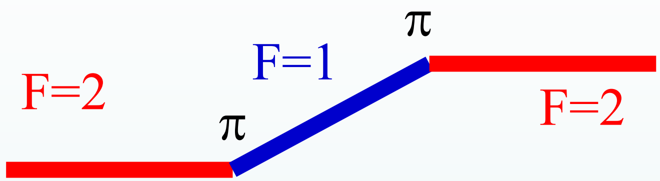
→ 4×10^{-8}

Comparison with S. Chu's experiment



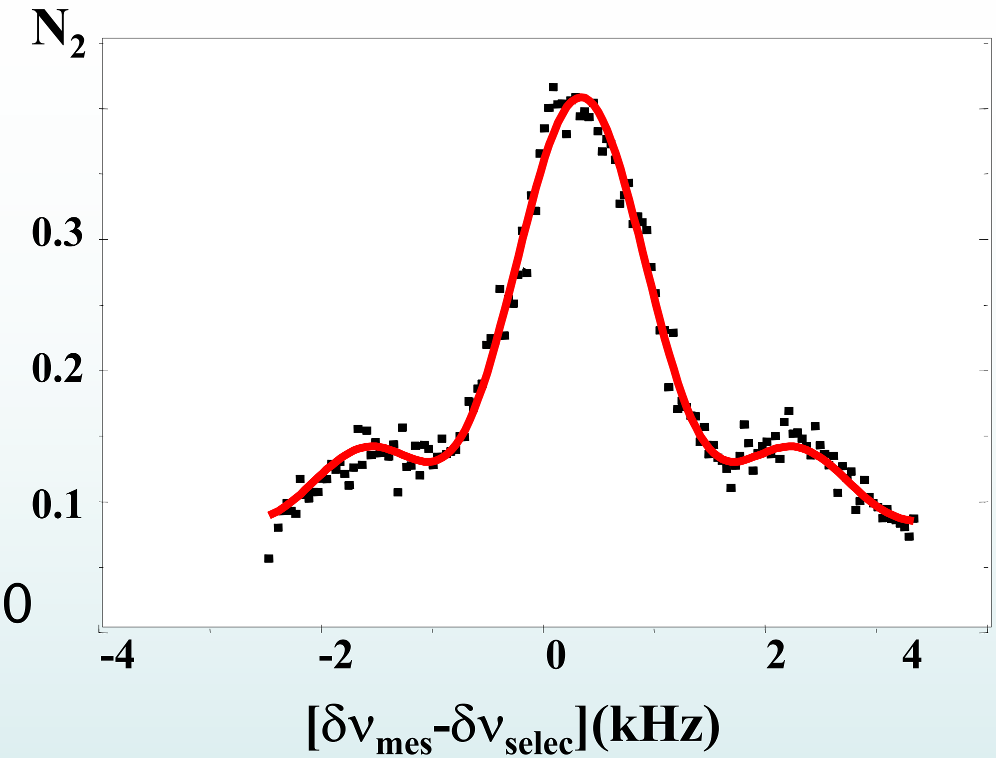
- vertical geometry
- atomic interferometry : fringes width of 8 Hz (500 Hz in our experiment)
- transfert by resonant adiabatic passages between the F=3 and F=4 levels: efficiency 94% (99,5 % in our experiment)
- interferometry: sensitivity to gradients (magnetic fields, intensity...) Bloch oscillation in the gravity field: sensitivity to gravity fluctuations

π pulse



caracteristic width ~ 1 kHz
(v_{recoil} / 15)

sub-recoil velocity class → v_{recoil}/30



Ramsey fringes