Laboratoire Kastler Brossel
Physique quantique et applications

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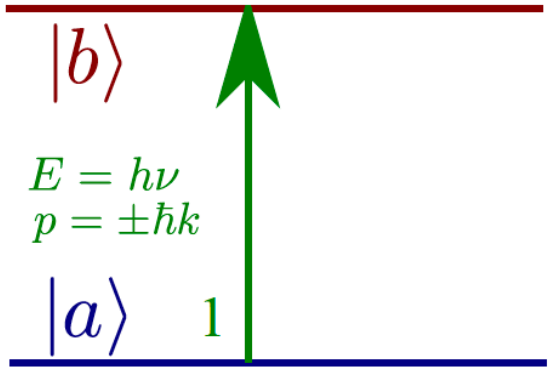
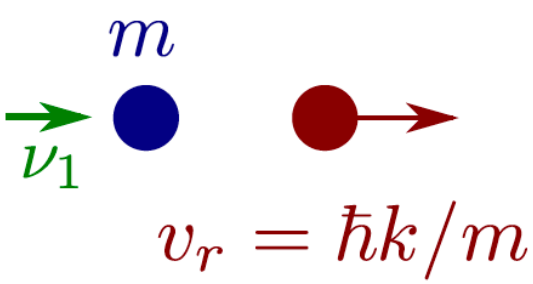
ENS

Measurement of the fine structure constant using atom interferometry: status of Paris experiment

Saïda Guellati-Khelifa

Recoil velocity





- $v_r = 6\ \mathrm{mm/s}$ for *Rb* atoms

Accurate measurement of the ratio h/m_X

Plane wave: $$v_r = \frac{h}{m_X}\frac{1}{\lambda}$$

- Relative atomic mass $A_r(X)$, the relative electron mass $A_r(e)$ and the Rydberg constant are measured with high accuracy.

Quantity	relative uncertainty
Rydberg constant	5.9×10^{-12}
$A_r(e)$	2.9×10^{-11}
$A_r(^{87}Rb)$	7.5×10^{-11}
$A_r(^{133}Cs)$	6.5×10^{-11}

- G. Audi et al., 2014 Nuclear Data Sheets 120, 1-5 (2014)
- S. Sturm et al. Nature 506, 476-470 (2014),
- P. J. Mohr et al. Rev. Mod. Phys. 88, 035009 (2016).

The fine-structure constant

$$hcR_\infty = \frac{1}{2}m_e\alpha^2c^2 \quad \Rightarrow \quad \alpha^2 = \frac{2R_\infty}{c}\frac{m_p}{m_e}\frac{m_X}{m_p}\frac{h}{m_X}$$

The unified atomic mass constant $$\frac{h}{m_u} = \frac{h}{m_X}A_r(X)$$

The fine-structure constant α , h/m_u and the new SI

- The fine-structure constant plays an important role in the adjustment of fundamental physical constants: in the new SI *c*, *h* and *e* are now fixed, the numerical values of ε_0 et μ_0 will depend on α.

$$\mu_0 = \frac{2\alpha h}{e^2 c} = 1.00000000\text{xxx} \times 4\pi \times 10^{-7}\ \mathrm{m \cdot kg \cdot s^{-2} \cdot A^{-2}}$$

- The Avogadro constant N_A is also fixed for new definition of the mole, molar mass of carbon-12 will no longer be exactly defined

$$M\left({}^{12}\mathrm{C}\right) = N_A \times m\left({}^{12}\mathrm{C}\right) = \frac{12 N_A h}{h/m_\mathrm{u}} = 12.00000000\text{xxx}\ g/mol$$

Determinations of the fine structure constant: the state of the art

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \sim \frac{1}{137}$$

Electron magnetic-moment anomaly measurement and QED calculations

$$a_e = a_e(\mathrm{QED}) + a_e(\mathrm{weak}) + a_e(\mathrm{hadron})$$

Gabrielse (Harvard), Dehmelt (UWash), Kinoshita and Nio (Riken)

Electrical measurements

$$R_K = \frac{h}{e^2} = \frac{\mu_0 c}{2\alpha}$$

LNE, NIST, NPL, NMI

Recoil measurement

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{At}}{m_e}\frac{h}{m_{At}}$$

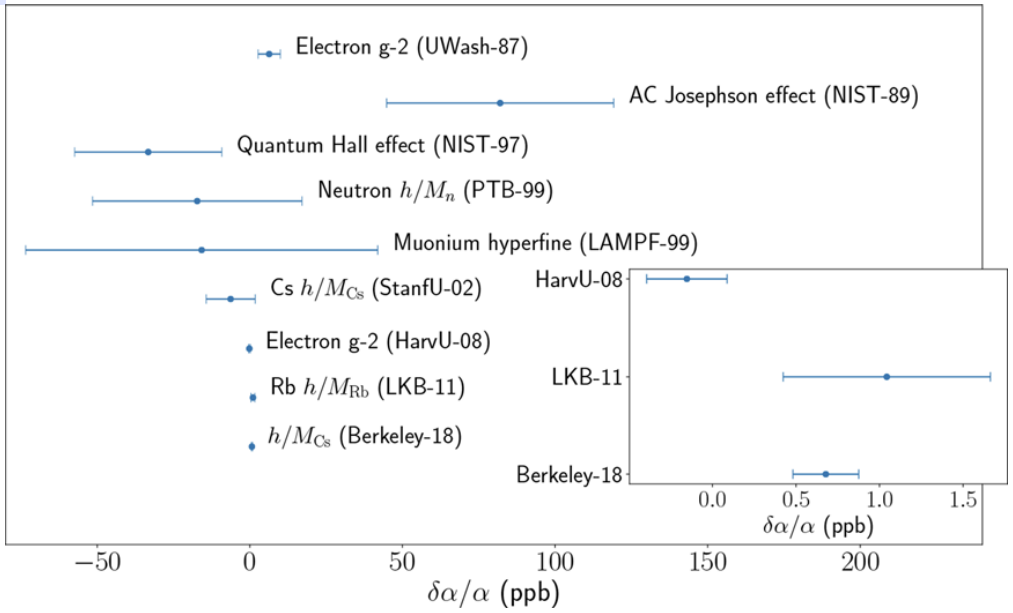
Paris, Berkeley

Transition frequencies measurement

Muonium ground-state hyperfine splitting

$$\Delta\nu_{Mu}(\mathrm{th}) = \Delta\nu_F \times \mathcal{F}(\alpha, m_e/m_\mu)$$

$$\Delta\nu_F = \frac{16}{3} c R_\infty Z^3 \alpha^2 \frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$



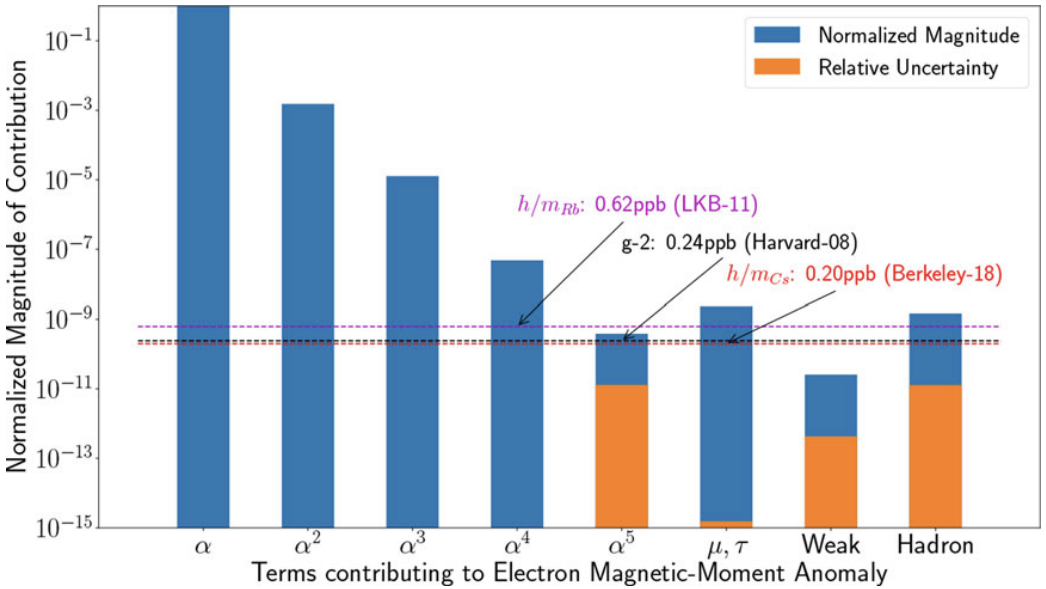
Yu, C., Zhong, W., Estey, B., Kwan, J., Parker, R. H., Müller, H., *ANNALEN DER PHYSIK* 2019, 531, 1800346.

Test of QED calculations

$$a_e(\mathrm{QED}) = \sum_{n=1}^{\infty} A_e^{(2n)} \left(\frac{\alpha}{\pi}\right)^n + \sum_{n=1}^{\infty} A_{\mu,\tau}^{(2n)} \left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}\right) \left(\frac{\alpha}{\pi}\right)^n$$

- The mass-independent terms are known accurately until 6th order and recent numerical evaluations have yielded values for the 8th and 10th orders
- The mass-dependent terms have been calculated up to the 5th order and contribute only a negligible uncertainty

(T. Aoyama et al., Phys. Rev. D (2015), 91,033006 and Phys. Rev. D (2017), 96,019901)



The recent measurement of the Berkely University team

$$a_e(\alpha) = 0.00115965218161(23)$$

$$\delta a_e = a_{e,\mathrm{meas}} - a_e(\alpha) = -0.88(0.36) \times 10^{-12}$$

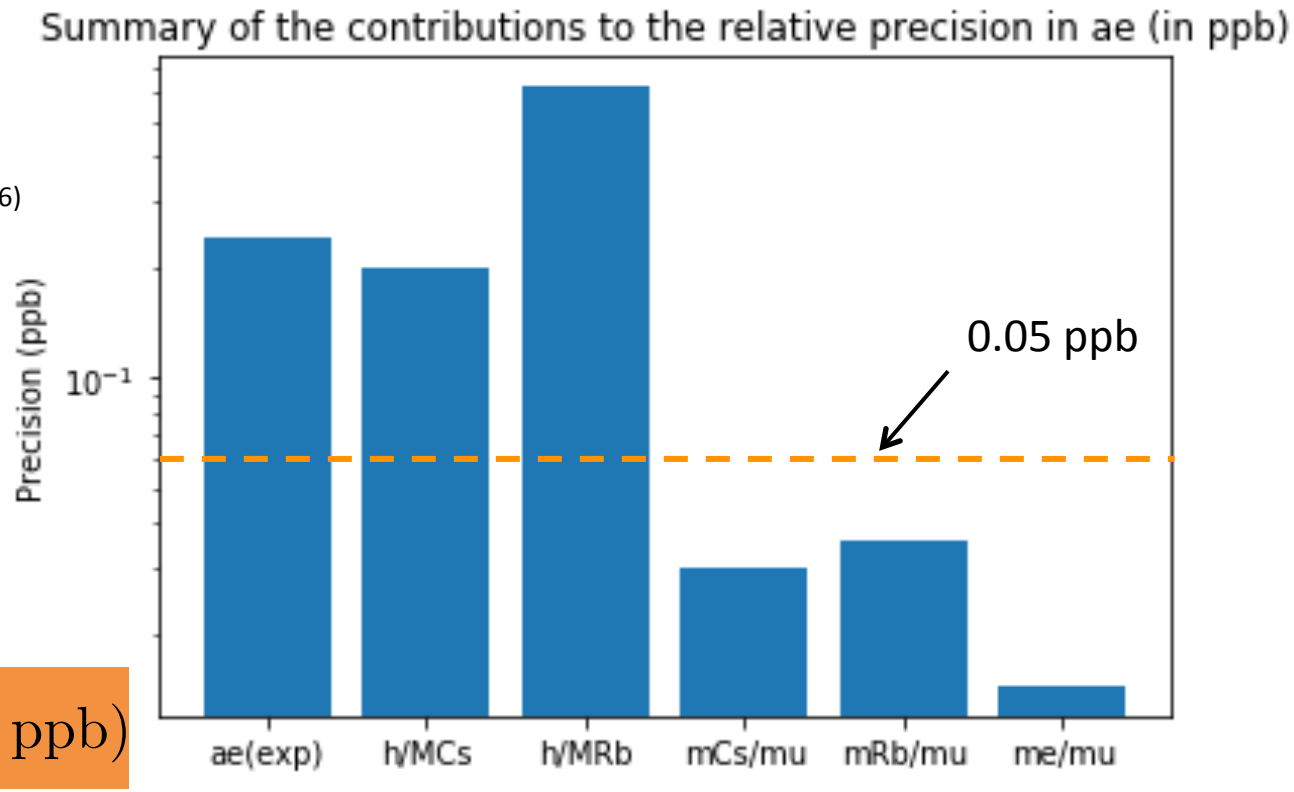
- For the first time the error bar is below the contribution of the 5th order QED.
- It shows a 2.5 σ discrepancy with the experimental value of a_e.

Testing the muon anomaly in the electron sector through a recoil measurement

$$\delta a_e = a_e(\mathrm{exp}) - a_e(\mathrm{th}) = -0.88(0.36) \times 10^{-12}$$

$$\delta a_\mu = a_\mu(\mathrm{exp}) - a_\mu(\mathrm{th}) = 250(86) \times 10^{-11}$$

CODATA 2014,P. J. Mohr, D. B. Newell and B. N. Taylor, J. Phys. Chem. Ref. Data, 45, 043102 (2016)



Assuming a "Naive scaling" hypothesis

$$\left|\frac{\delta a_e}{\delta a_\mu}\right| = \left(\frac{m_e}{m_\mu}\right)^2$$

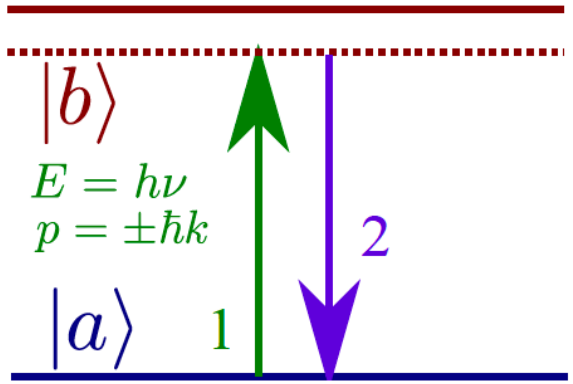
$$\sigma_{a_e} = 2.5 \times 10^{-9} \times \left(\frac{m_e}{m_\mu}\right)^2 = 5.8 \times 10^{-14}\ (0.05\ \mathrm{ppb})$$

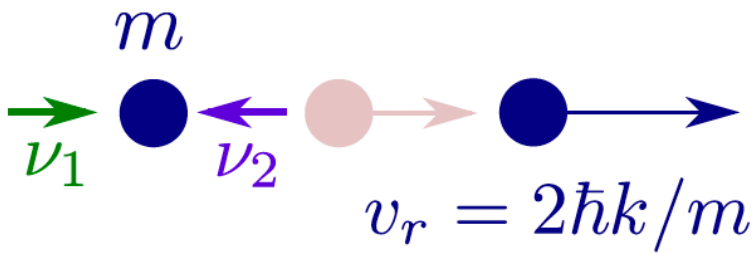
F. Terranova and G. M. Tino, Phys. Rev. A 89, 052118 (2014)

This test requires an uncertainty on h/m less than 10^{-10}

Recoil measurement: principle of Paris experiment

$$\alpha^2 = 2R_\infty \frac{m_{\mathrm{Rb}}}{m_{\mathrm{e}}} \frac{h}{m_{\mathrm{Rb}}}$$

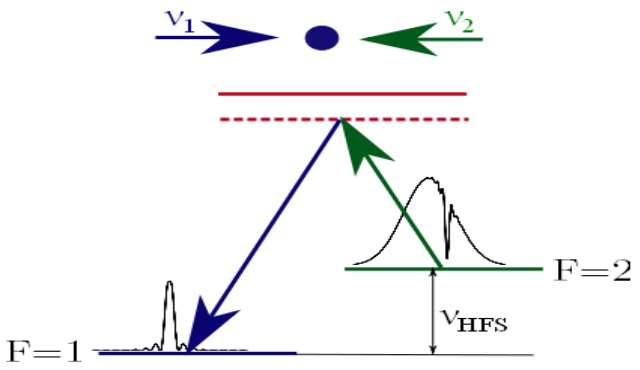




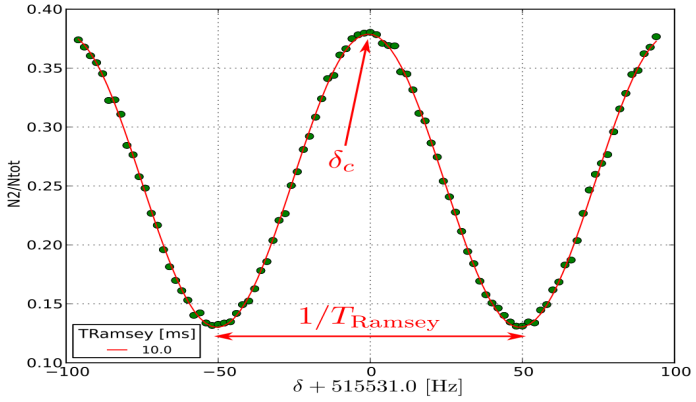
- Velocity sensor based on atom interferometer $\longrightarrow \sigma_v$
- Bloch oscillations technique to transfert to the atoms a large number of photon momenta

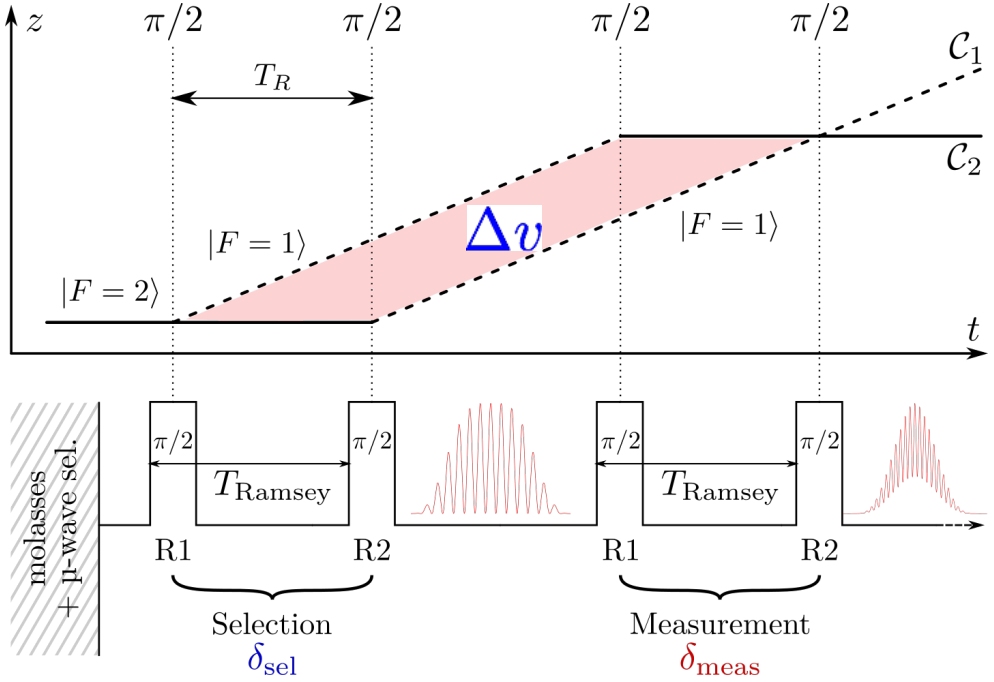
$$2Nv_r \longrightarrow \frac{\sigma_v}{2N}$$

Ramsey Bordé atom interferometer: velocity sensor

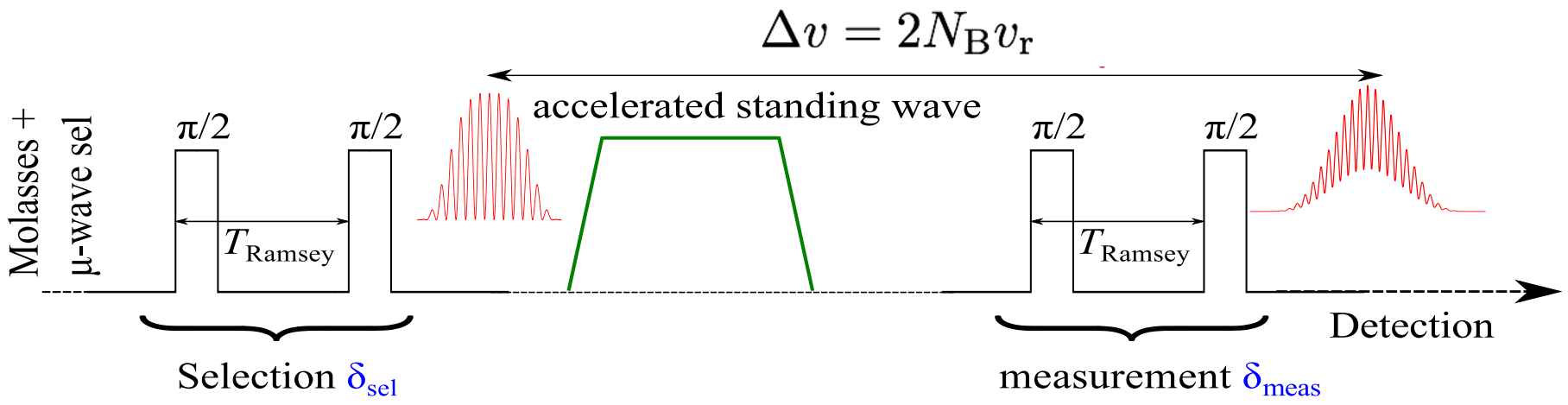


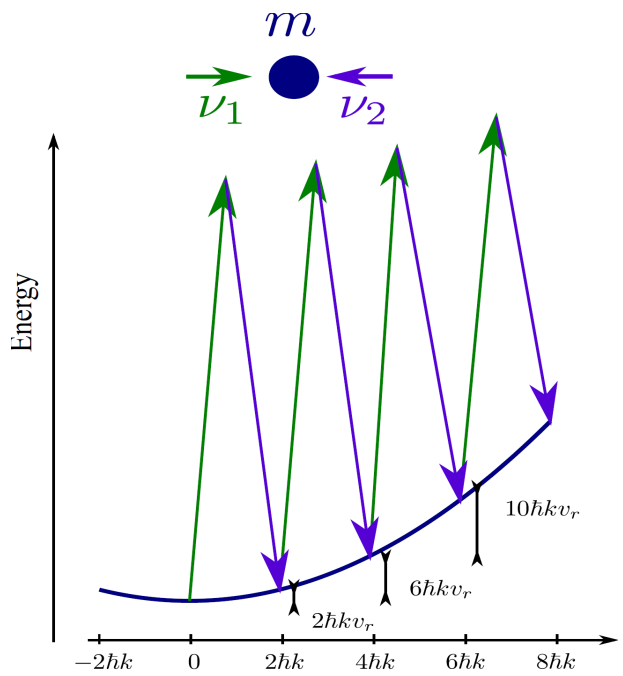
- Velocity sensitive Raman transitions
- Measurement of Doppler shift due to Δv





Coherent acceleration: Bloch oscillations technique



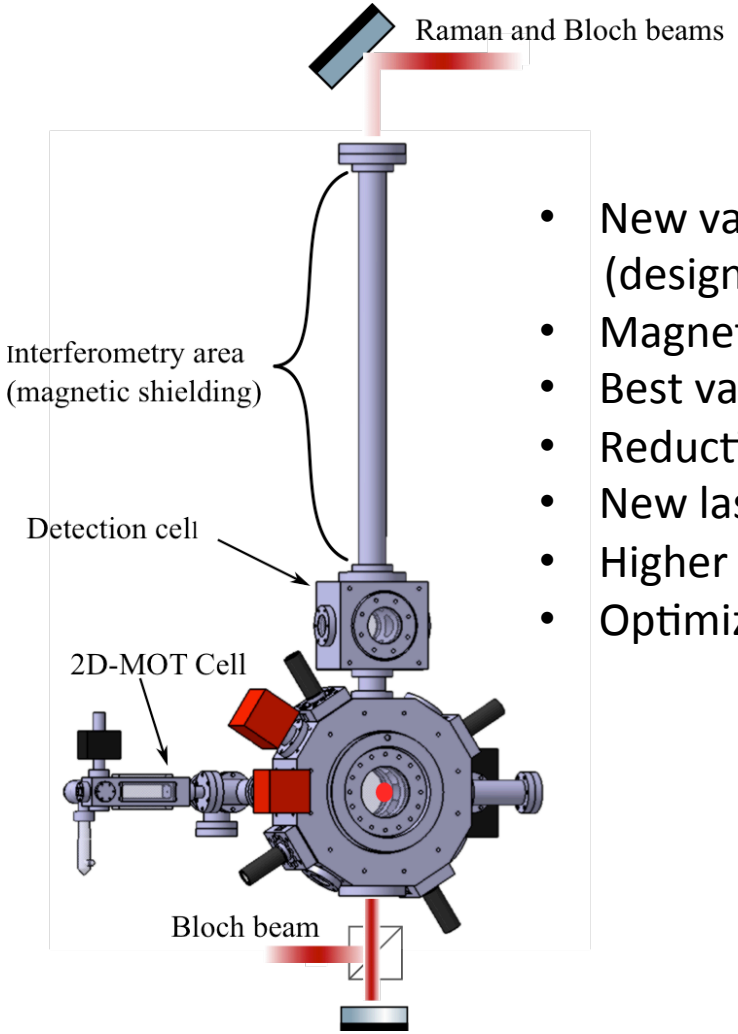


$$\nu_2 - \nu_1 = at$$

High transfer efficiency per recoil

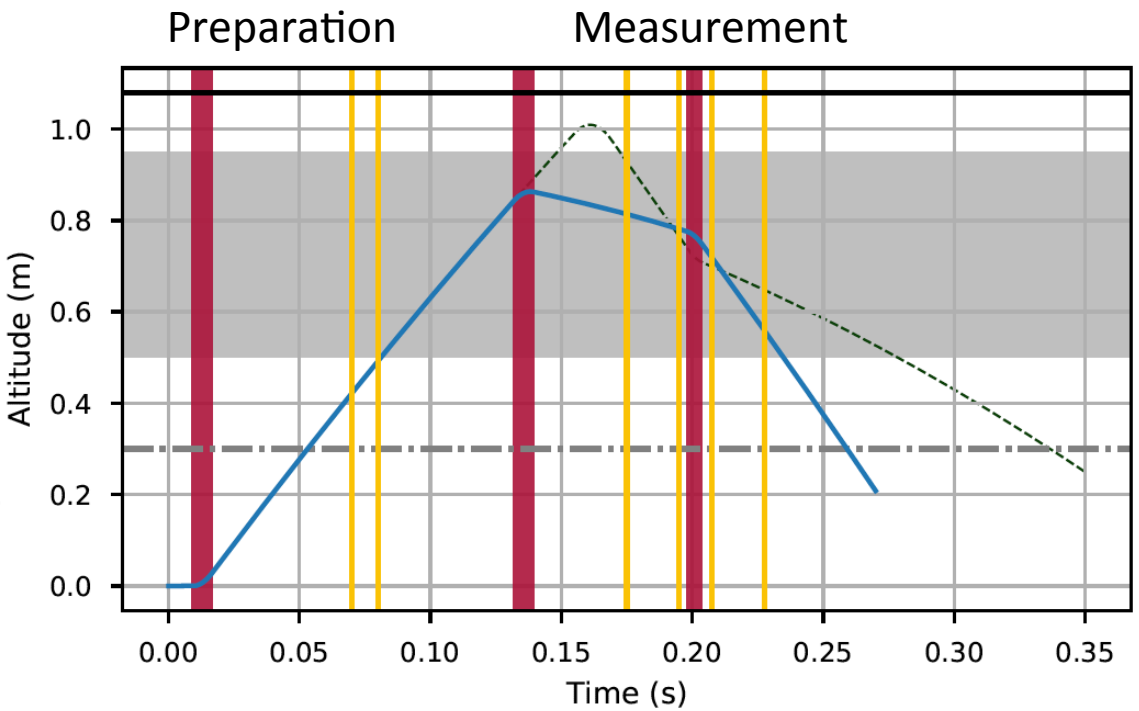
$$\eta = 99.95\% \implies \Delta v = 1000 v_{\mathrm{r}}$$

New experimental setup

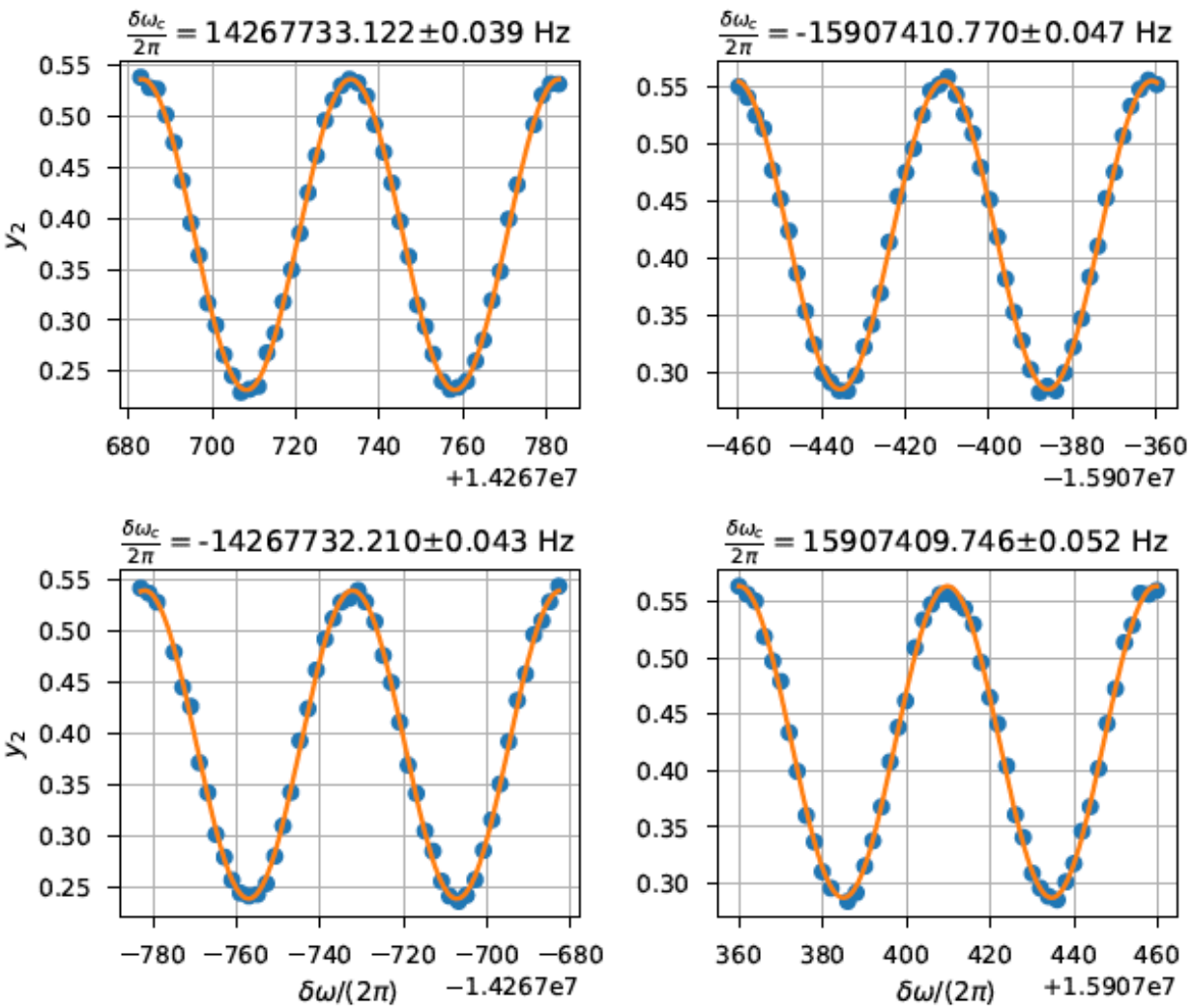


- New vacuum chamber (design and residual vacuum)
- Magnetic shielding
- Best vacuum
- Reduction of vibration noise
- New laser sources
- Higher atomic density
- Optimization of the time sequence

Trajectory of the atoms and light-pulses sequence



Measurement protocol



$$0 = T_{\text{Ramsey}}\left(\epsilon_R k_R\left(\epsilon_B 2N_B\frac{\hbar}{m}k_B - gT_{\text{delay}}\right) - \delta\omega_c\left(\epsilon_R,\epsilon_B\right)\right) + \delta\phi\left(\epsilon_B\right)$$

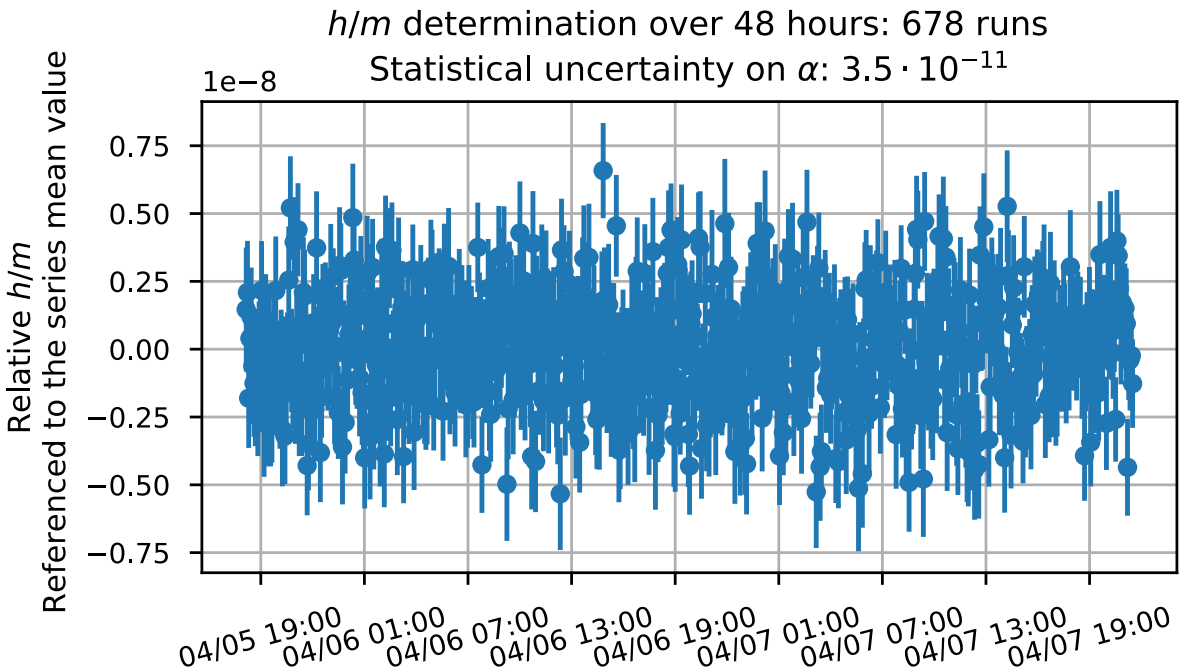
for $\epsilon_R = \pm 1$, $\epsilon_B = \pm 1$.

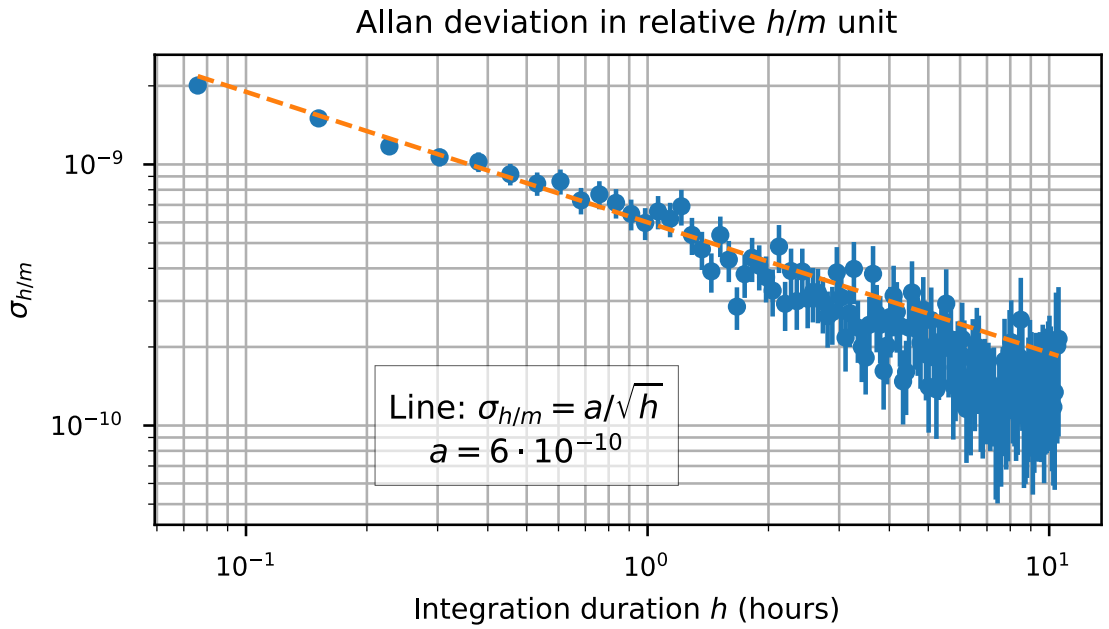
$$\frac{h}{m} = \frac{\pi}{4N_B k_B k_R}\sum_{\epsilon_R,\epsilon_B}\epsilon_R\epsilon_B\delta\omega_c\left(\epsilon_R,\epsilon_B\right)$$

→ Frequency measurements

Uncertainty on h/m of 1.5×10^{-9} in 5 min

Statistical uncertainty





Statistical uncertainty on α of 3.5×10^{-11}:
Improvement by a factor of 5 in comparison to Berkeley's measurement.

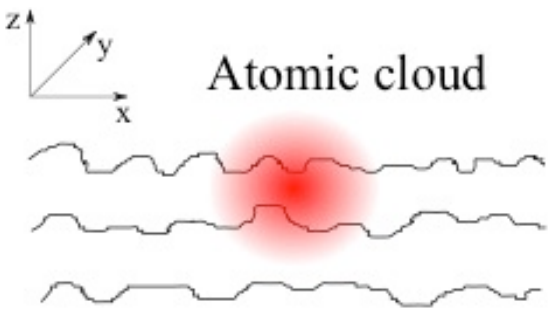
Preliminary error budget

Source	$\delta\alpha/\alpha(2011)$ (In part per 10^{10})	$\delta\alpha/\alpha(20119$ (In part per 10^{10})
Laser frequencies	0 ± 1.3	0 ± 0.26
Raman frequency chain	N	0 ± 0.33
Beams alignment	-3.3 ± 3.3	0.05 ± 0.05
Wavefront curvature and Gouy phase	-25.1 ± 3.0	$+10.0 \pm 1.0$
2nd order Zeeman effect	4.0 ± 3.0	0 ± 0.005
Gravity gradient	-2.0 ± 0.2	0 ± 0.0005
Earth rotation	N	0 ± 0.2
Light shift (one photon transition)	0 ± 0.1	0 ± 0.65
Light shift (two photon transition)	0 ± 0.01	$+0.35 \pm 0.02$
Light shift (Bloch oscillation)	0 ± 0.5	0 ± 0.02
Index of refraction atomic cloud and atom interactions	0 ± 2.0	0 ± 0.3
Global systematic effects	-26.4 ± 5.9	10.4 ± 1.3
Statistical uncertainty	2.0	0.35 (48h)

→ Main effect : wavefront distorsions of the Raman and Bloch laser beams

Recoil velocity of atom in a distorted wavefront

S. Bade et al., Phys. Rev. Lett. 121, 073603 (2018)



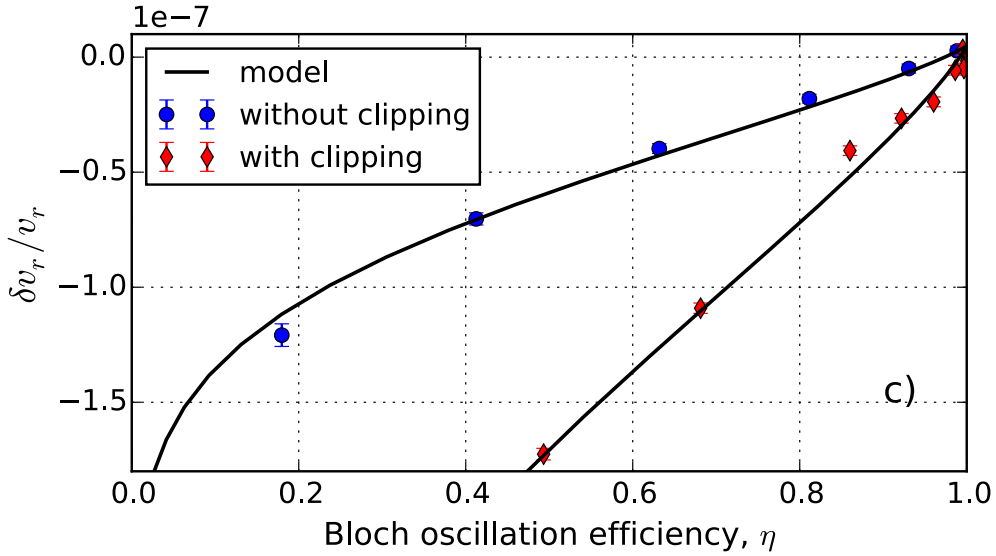
- Plane wave, photon momentum: $p = \hbar k = \frac{h\nu}{c}$
- Quality of optics: atoms experiment distorted Optical Field: $E(x,y,z) = A(x,y,z)\ \mathrm{e}^{i\Phi(x,y,z)}$

Local amplitude fluctuations induces momentum correction (in paraxial approximation):

$$p_z = \hbar k(1 + \delta k_{\mathrm{rel}}) \quad \text{where} \quad \delta k_{\mathrm{rel}} = -\frac{1}{2}\left|\left|\frac{\vec{\nabla}_\perp \phi}{k}\right|\right|^2 + \frac{1}{2k^2}\frac{\Delta_\perp A}{A}$$

The probability $P(I)$ to transfer light momentum is governed by Landau-Zener losses and depends on the laser intensity, the average correction is:

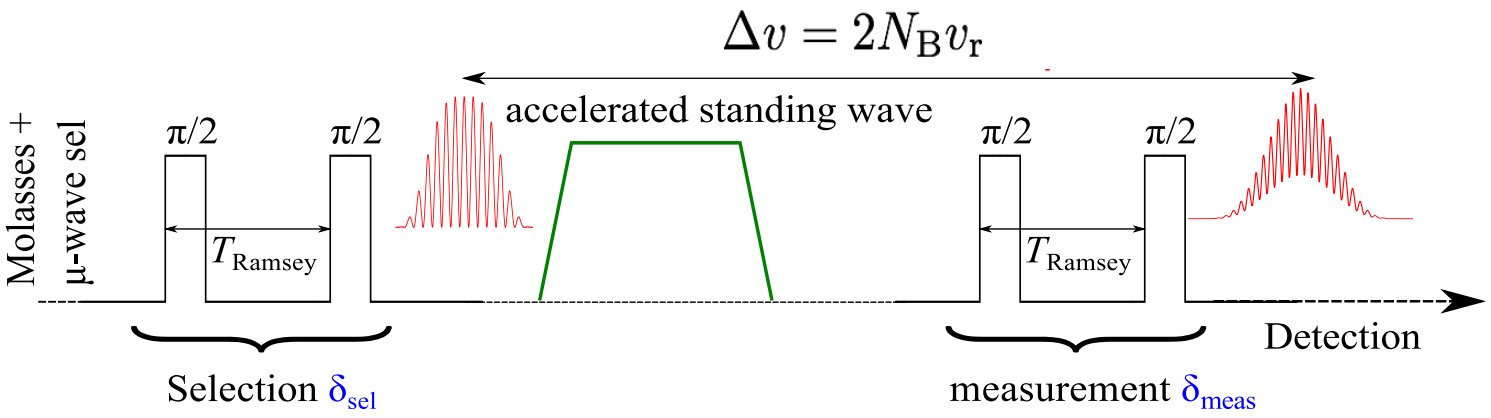
$$\langle \delta k_{\mathrm{rel}} \rangle = \frac{\langle \delta k_{\mathrm{rel}} P(I) \rangle}{\langle P(I) \rangle}$$

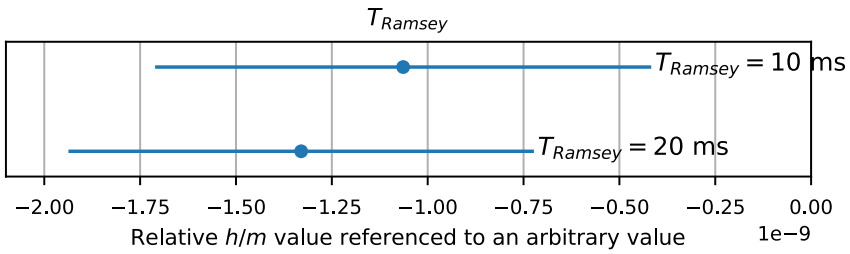


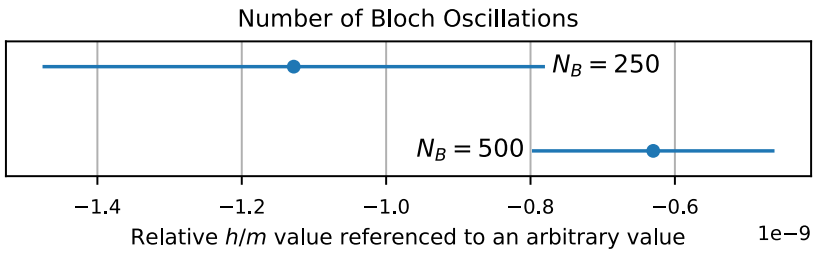
The precise numerical evaluation of δk_{rel} requires: precise measurements of beam profiles, temperature and atomic cloud size.....

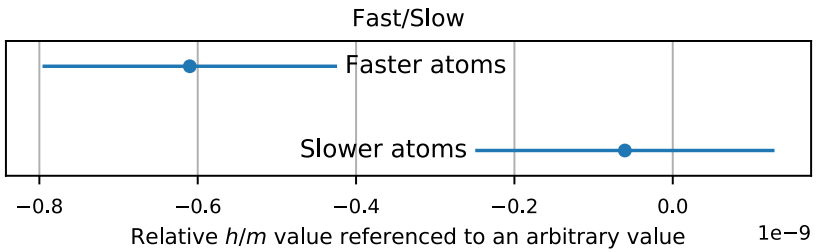
Work in progress

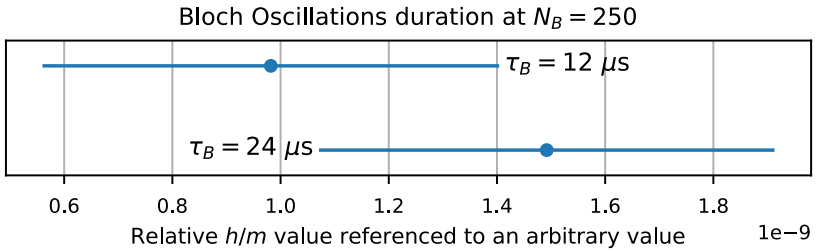
Investigation for hidden systematic effects



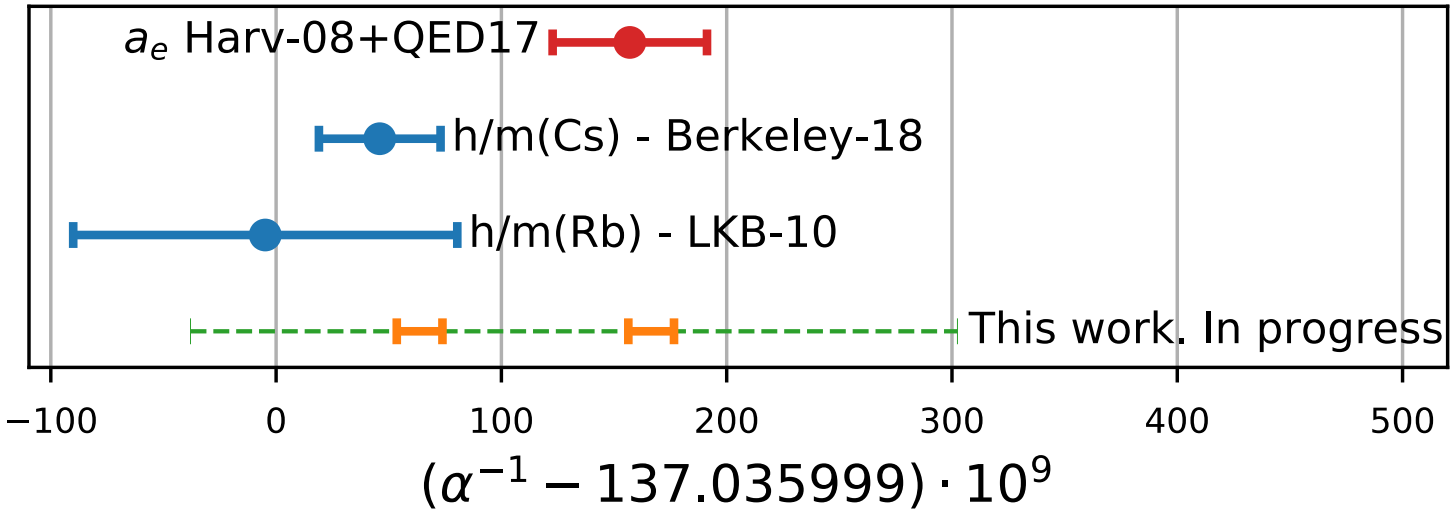








Study of systematic effects in progress !



New measurement of the ratio h/m_{Rb85} using the old experimental set-up.
the ratio $\frac{m_{\mathrm{Rb87}}}{m_{\mathrm{Rb87}}}$ is known with uncertainty less than 10^{-10}

- Permanent staff:
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