Measuring the fine-structure constant to refine the Standard Model predictions

Saïda Guellati-Khélifa

Short story of the fine-structure contant

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

- Sommerfeld-Bohr model: Naive model to explain the splitting of Balmer lines in hydrogen spectrum

A. Sommerfeld, Annalen der Physik 51, 1-94, 125-167 (1916)

1928, Dirac equation

- Energy levels of hydrogen atom: $E(n,j) \simeq m_e c^2 \left[1 - \frac{\alpha^2}{2n^2} - \frac{\alpha^4}{2n^4}\left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4}\right) + ...\right]$

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

- Electron magnetic moment: $\vec{\mu}_e = -g_e \frac{e}{2m_e}\vec{S}, \quad g_e = 2$

Test of Quantum electrodynamics and Standard model

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Physique quantique et applications

α : coupling constant of electromagnetic interaction

Transition frequencies measurement

Muonium ground-state hyperfine splitting

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

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

Anomalous Magnetic Moment of the Electron

$$a_e(\mathrm{theo}) \equiv a_e(\exp)$$

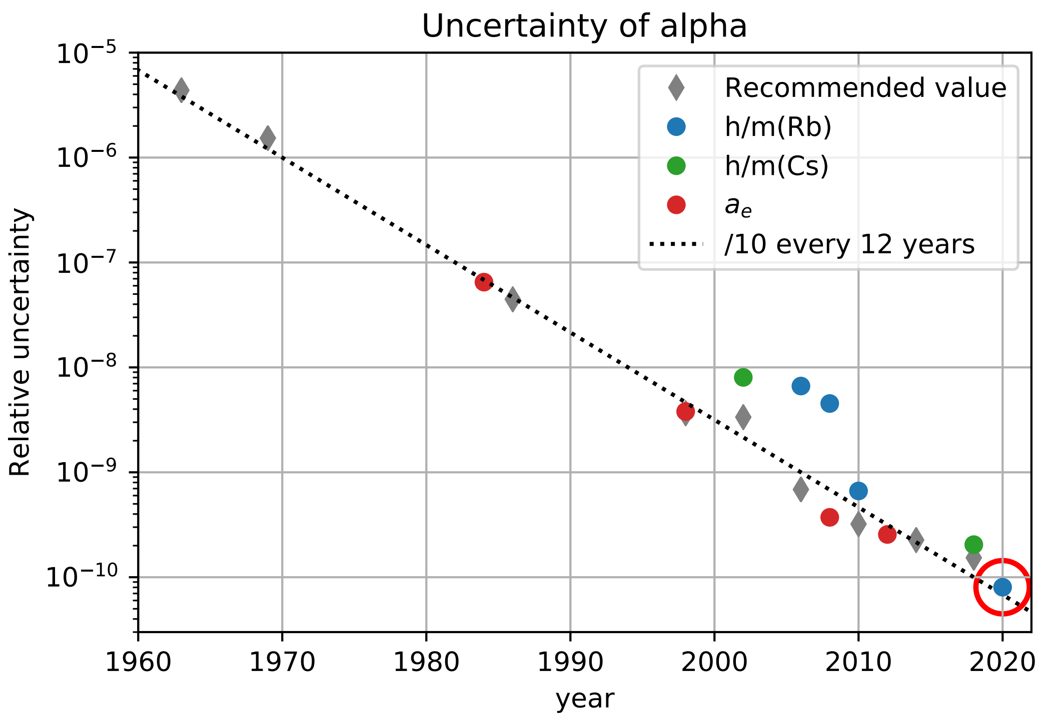
Quantum Hall effect

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

Recoil measurement

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

Paris, Berkeley



Physics beyond Standard Model ?

$$a_e(\mathrm{theo}) - a_e(\exp) \overset{?}{=} \delta a_e(\mathrm{BSM})$$

Anomalous Magnetic Moment of the Electron

$$a_\mathrm{e} = \frac{g_\mathrm{e} - 2}{2}$$

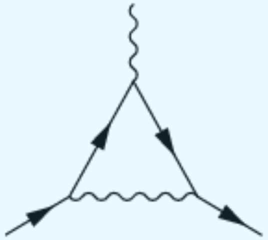
- Measurement of *g*-factors of Ga, In and Na: $\Longrightarrow g_\mathrm{e} = 2.00229 \pm 0.00008$

P. Kush and H. M. Foley, Phys. Rev. 72, 1256 (1947)

- Vacuum fluctuations and polarization modify the interaction of the electron with the magnetic field,

$$a_e = \frac{g_e - 2}{2} \simeq \frac{1}{2}\frac{\alpha}{\pi}$$

Schwinger, Phys. Rev. 73, 416 (1948); Phys. Rev. 75, 898 (1949)



Feynman diagram for the one photon-loop correction for the free electron

$\longrightarrow$ Birth of quantum electrodynamics

Anomalous Magnetic Moment of the Electron (SM) prediction

- Higher order corrections:
  perturbative series of $\alpha = 1/137.036 \approx 0.007$

J. Schwinger, R. Feynman, E. Stueckelberg, S. Tomonaga....

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

$$a_e(\mathrm{theo}) = a_e(\mathrm{QED}) + a_e(\mathrm{Hadron}) + a_e(\mathrm{Weak})$$

- Each coefficient is calculated by the Feynman diagrams technique

Coefficient $A_i^{(2n)}$	Value (Error)	References	
$A_1^{(2)}$	0.5	Schwinger 1948	
$A_1^{(4)}$	$-0.328\,478\,965\,579\,193\cdots$	Petermann 1957, Sommerfield 1958	
$A_2^{(4)}(m_e/m_\mu)$	$0.519\,738\,676\,(24)\times 10^{-6}$	Elend 1966	
$A_2^{(4)}(m_e/m_\tau)$	$0.183\,790\,(25)\times 10^{-8}$	Elend 1966	
$A_1^{(6)}$	$1.181\,241\,456\,587\cdots$	Laporta-Remiddi 1996, Kinoshita 1995	
$A_2^{(6)}(m_e/m_\mu)$	$-0.737\,394\,164\,(24)\times 10^{-5}$	Samuel-Li, Laporta-Remiddi, Laporta	
$A_2^{(6)}(m_e/m_\tau)$	$-0.658\,273\,(79)\times 10^{-7}$	Samuel-Li, Laporta-Remiddi, Laporta	
$A_3^{(6)}(m_e/m_\mu, m_e/m_\tau)$	$0.1909\,(1)\times 10^{-12}$	Passera 2007	72 diagrams
$A_1^{(8)}$	$-1.912\,245\,764\cdots$	Laporta 2017, AHKN 2015	
$A_2^{(8)}(m_e/m_\mu)$	$0.916\,197\,070\,(37)\times 10^{-3}$	Kurz et al 2014, AHKN 2012	
$A_2^{(8)}(m_e/m_\tau)$	$0.742\,92\,(12)\times 10^{-5}$	Kurz et al 2014, AHKN 2012	891 diagrams
$A_3^{(8)}(m_e/m_\mu, m_e/m_\tau)$	$0.746\,87\,(28)\times 10^{-6}$	Kurz et al 2014, AHKN 2012	
$A_1^{(10)}$	$6.737\,(159)$	AKN 2018,2019	
$A_2^{(10)}(m_e/m_\mu)$	$-0.003\,82\,(39)$	AHKN 2012,2015	12671 diagrams
$A_2^{(10)}(m_e/m_\tau)$	$\mathcal{O}(10^{-5})$		
$A_3^{(10)}(m_e/m_\mu, m_e/m_\tau)$	$\mathcal{O}(10^{-5})$		

$$a_e(\mathrm{theory}:\alpha(\mathrm{Rb})) = 1159652182.037\,(720)\,(11)\,(12)\times 10^{-12}$$
$$a_e(\mathrm{theory}:\alpha(\mathrm{Cs})) = 1159652181.606\,(229)\,(11)\,(12)\times 10^{-12}$$

- (720), (229): Fine-structure constant
- (11): Numerical evaluation of the tenth-order QED
- (12): hadronic contribution

- T. Aoyama, T. Kinoshita, M. Nio, Phys. Rev. D 2018, 97, 036001.
- S. Laporta, Phys. Lett. B 2017, 772, 232–238.
- T. Aoyama, T. Kinoshita and M. Nio, Atoms 2019, 7, 28
- R. Bouchendira et al., Phys. Rev. Lett. 2011, 106, 080801.
- R.H. Parker et al, Science 2018, 360, 191–195.

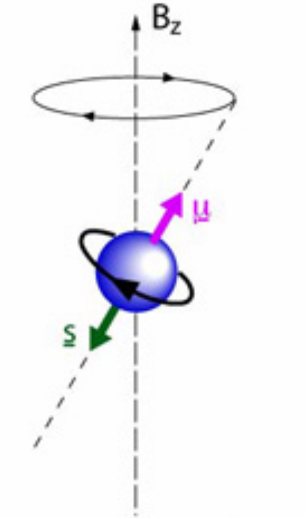
Measurement of the anomalous magnetic moment of the electron

R. S. Van Dyck., P. B. Schwinberg and H. G. Dehmelt. Phys. Rev. D 34, 722 (1986) and Phys. Rev. Lett. 59, 26 (1987)

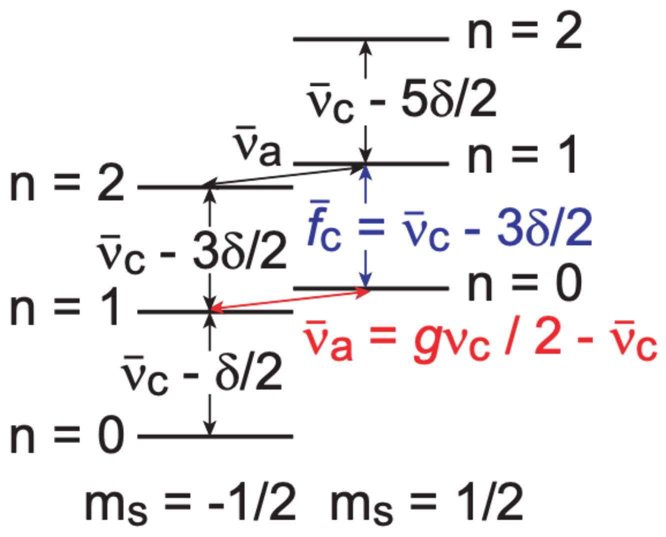
- Electron in a magnetic field

$$\frac{g_\mathrm{e}}{2} = \left|\frac{\mu_\mathrm{e}}{\mu_\mathrm{B}}\right| = \frac{\nu_\mathrm{s}}{\nu_\mathrm{c}} = 1 + \frac{\nu_\mathrm{s} - \nu_\mathrm{c}}{\nu_\mathrm{c}} = 1 + \frac{\nu_\mathrm{a}}{\nu_\mathrm{c}}$$

$$\mu_\mathrm{B} = \frac{e}{2 m_\mathrm{e} \hbar} : \text{Bohr magneton}$$



$$E_{n,m_\mathrm{s}} = m_s h \nu_\mathrm{s} + \left(n + \frac{1}{2}\right) h \nu_\mathrm{c}$$



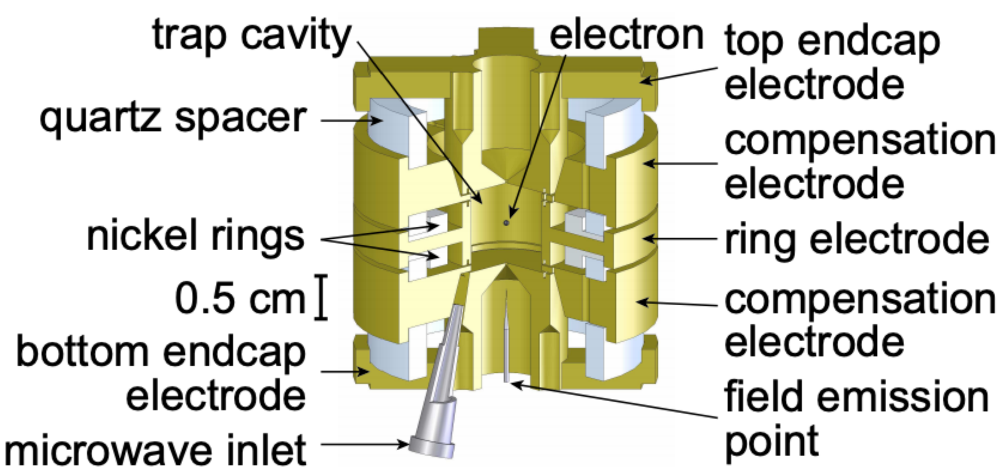
Advantages

- The magnetic field dependence drops out of the ratio.
- ν_c and ν_s differs by 10^{-3}, measuring frequencies to $10^{-10} \longrightarrow g_e$ to 10^{-13}

Measurement of the electron magnetic moment: Harvard experiment

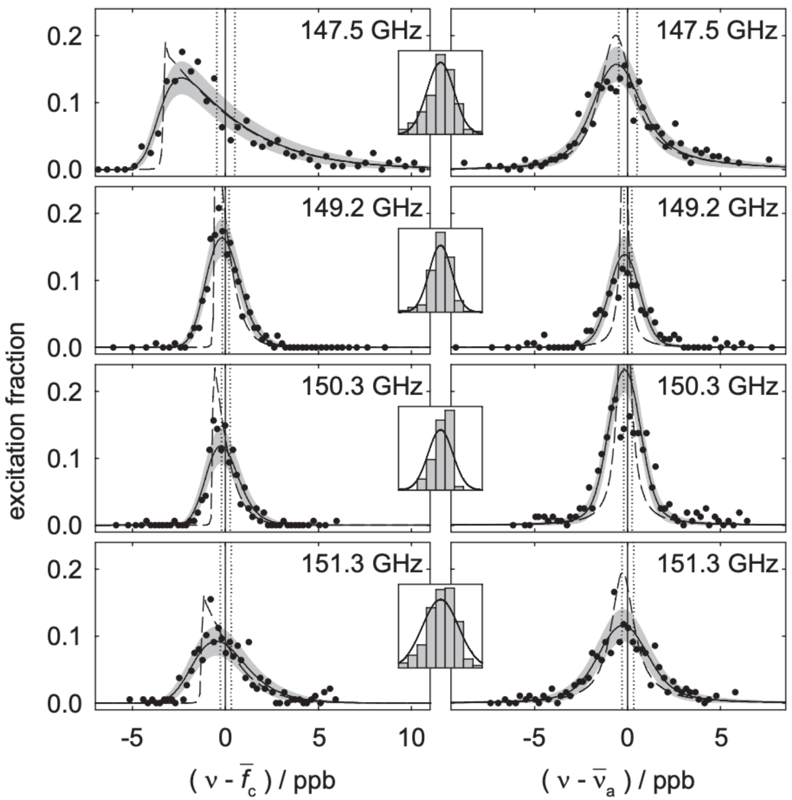
Hanneke, D.; Fogwell, S.; Gabrielse, G. Phys. Rev. Lett. 2008, 100, 120801.

- Electron in Penning trap + magnetic field



$$a_e(\exp) = \frac{g_e - 2}{2} = 0.00115965218073\ (28)\ [0.28\ \text{ppt}]$$

Quantum-jump spectroscopy



- 10 times improved accuracy is expected
  - New experimental setup (better control of the electron motion, reduction of magnetic field gradient)
  - The spin and cyclotron transition frequencies measured nearly simultaneously

X. Fan and G. Gabrielse, Phys. Rev. A 103, 022824 (2021)

The ratio *h*/*m* and the fine-structure constant

- The Rydberg constant R_∞

$$hcR_\infty = \frac{1}{2} m_e \alpha^2 c^2 \implies \alpha^2 = \frac{2R_\infty}{c}\frac{h}{m_e} \implies \alpha^2 = \frac{2R_\infty}{c}\frac{A_r(\mathrm{Rb})}{A_r(\mathrm{e})}\frac{h}{m_{\mathrm{Rb}}}$$

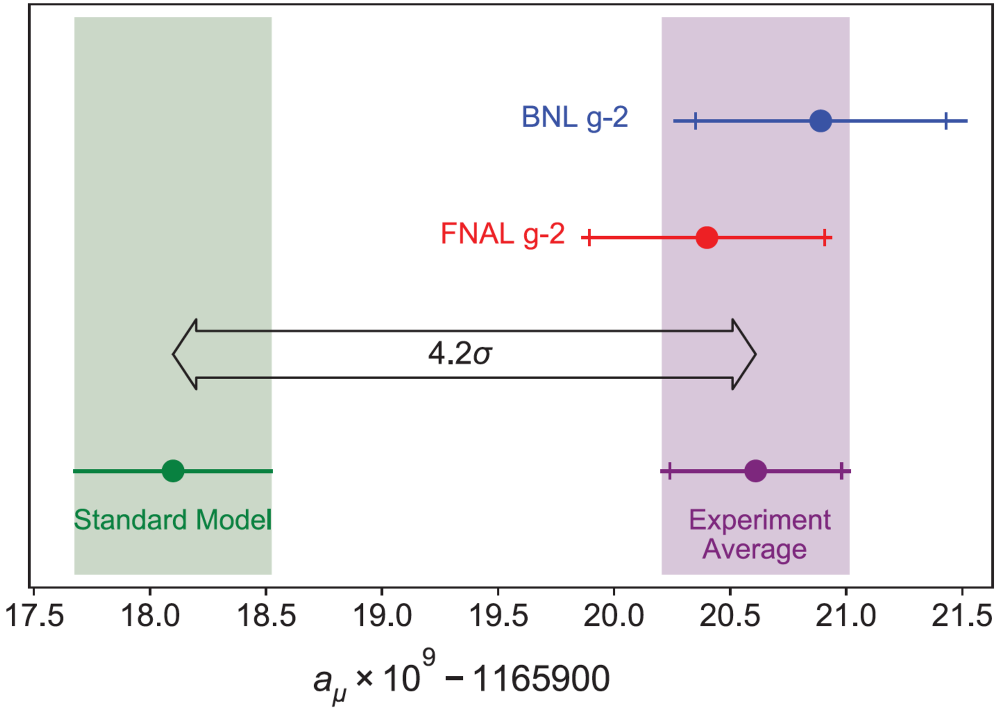
- Hydrogen spectroscopy $\Longrightarrow$ determination of R_∞ with a relative uncertainty of 2×10^{-12}
- Determination of relative atomic masses : $A_r(X) = \frac{m_X}{m_u}$
  - Cyclotron frequencies $A_r(Rb)$ at 7.0×10^{-11}
  - Magnetic moment of a single electron bound to a carbon nucleus $A_r(e)$ at 2.9×10^{-11}

- The limiting factor is the ratio $\frac{h}{m_{Rb}}$

- 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).

Motivation: Testing the muon a_μ discrepancy in the electron sector

- T. Aoyama et al., Physics Reports 887, 1-66 (2020)
- B. Abi *et al.* (Muon g−2 Collaboration) Phys. Rev. Lett. 126, 141801 (2021).



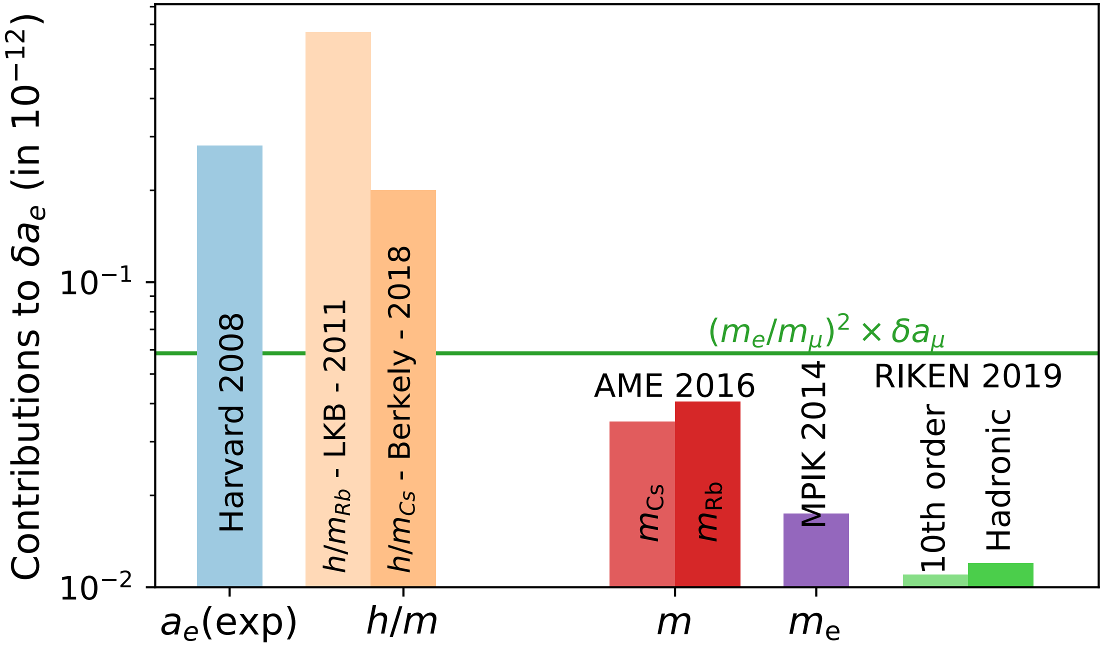
$$\delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

$$\delta a_\mu \stackrel{?}{=} a_\mu(\text{NP})$$

- Naive scaling $\left|\frac{\delta a_e}{\delta a_\mu}\right| = \left(\frac{m_e}{m_\mu}\right)^2 \simeq 2.3 \times 10^{-5}$

F. Terranova and G. M. Tino, PRA 89, 052118 (2014)

$$\sigma_e = 2.5 \times 10^{-5} \times \left(\frac{m_e}{m_\mu}\right)^2 \simeq 5.8 \times 10^{-14}$$



Outline

- Measurement of the ratio h/M
- Impact of the new determination of the fine-structure constant

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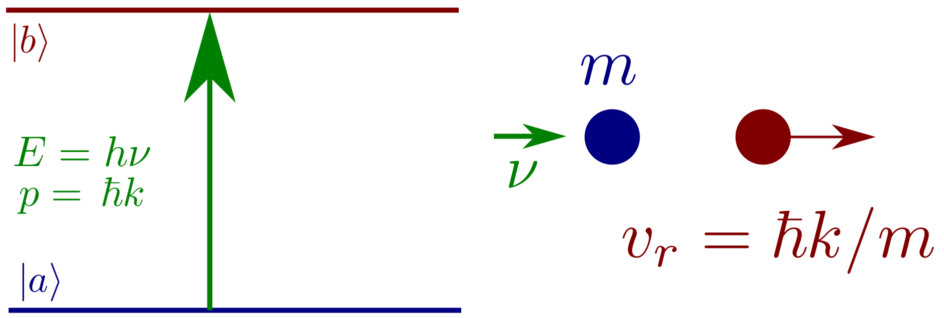
- Measurement of the ratio *h*/*M*
- Impact of the new determination of the fine-structure constant

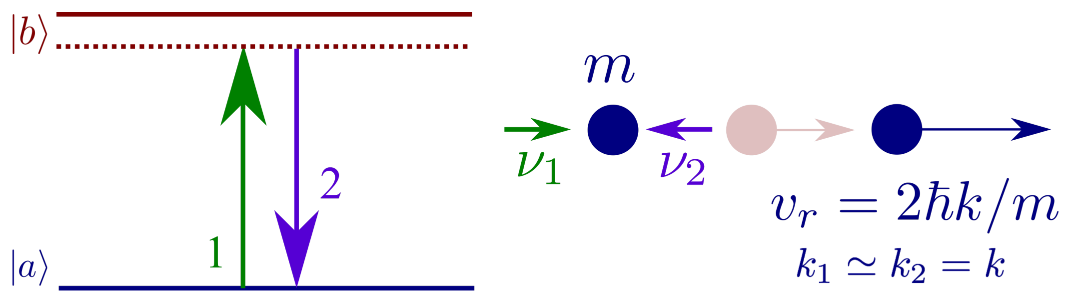
Recoil velocity



- v_r = 6 mm/s for Rb atom (for λ = 780 nm)
- Plane wave

$$v_{\mathrm{r}} = \frac{h}{m}\frac{1}{\lambda}$$

Measurement of the recoil velocity



- Velocity sensor

  ⇒ Atom interferometer based on Raman transitions with a sensitivity: σ_v

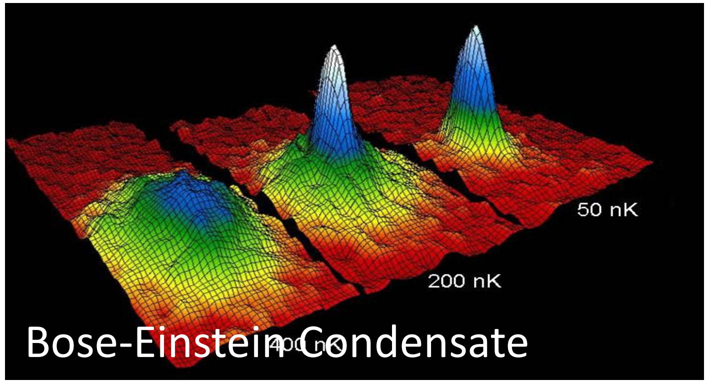
- Transfer to atoms a large number *N* of photon momenta

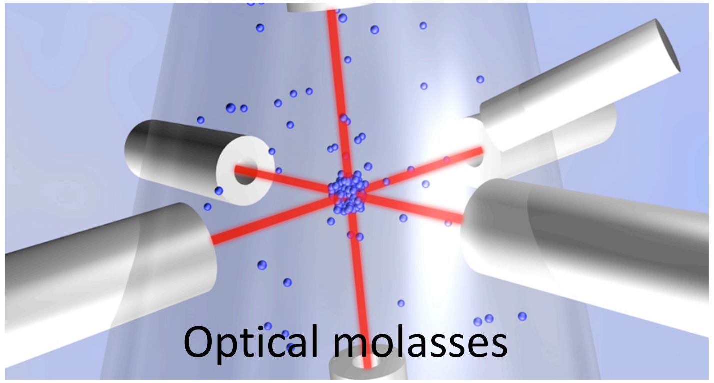
  ⇒ Bloch oscillations technique

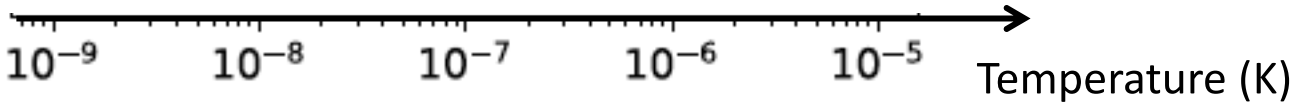
$$\sigma_{v_r} = \frac{\sigma_v}{N}$$

Basic concepts of atom interferometry

Matter waves/cold atoms





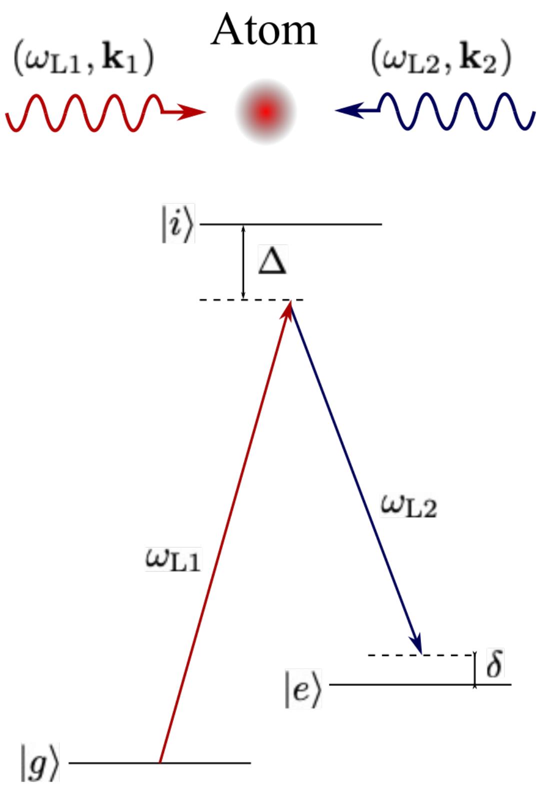


Coherence length: $\xi \sim \frac{\hbar}{\Delta p}$

Thermal De Broglie wavelength: $\lambda_T = \frac{h}{\sqrt{2\pi m k_B T}}$

- For rubidium atomic cloud at $4\,\mu\mathrm{K} \rightarrow \lambda_{\mathrm{T}} \approx 1000$ Å
- To implement atomic interferometers for high-precision measurements,
  the challenge was to implement a technique for manipulating the matter waves in a coherent way

Atomic beamsplitter based on stimulated Raman transitions



Momentum conservation

$$\mathbf{p}_f = \mathbf{p}_0 + \hbar(\mathbf{k}_1 - \mathbf{k}_2) = \mathbf{p}_0 + \hbar\mathbf{k}_{\text{eff}}$$

$\Delta \gg \delta$ and $\Delta \gg \Gamma$

at resonance

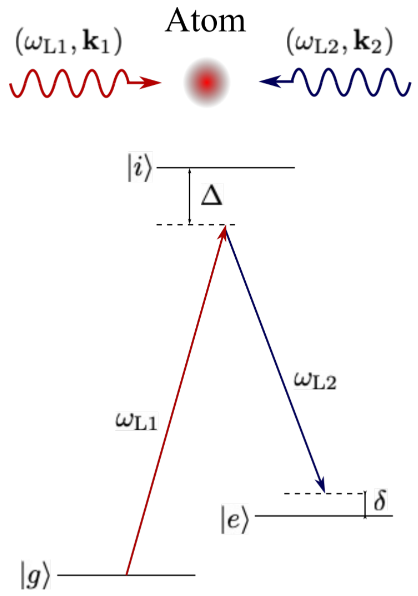
$$\Psi(0) = |g, \mathbf{p}_0\rangle$$

$$\Psi(t) = \mathrm{e}^{-i\omega_1 t} \cos\left(\frac{\Omega t}{2}\right) |g, \mathbf{p}_0\rangle + \mathrm{e}^{i\Delta\phi_L} \mathrm{e}^{-i\omega_2 t} \sin\left(\frac{\Omega t}{2}\right) |e, \mathbf{p}_0 + \hbar\mathbf{k}_{\text{eff}}\rangle$$

Ω : Rabi frequency

The internal degrees of freedom are labelled by the external degrees

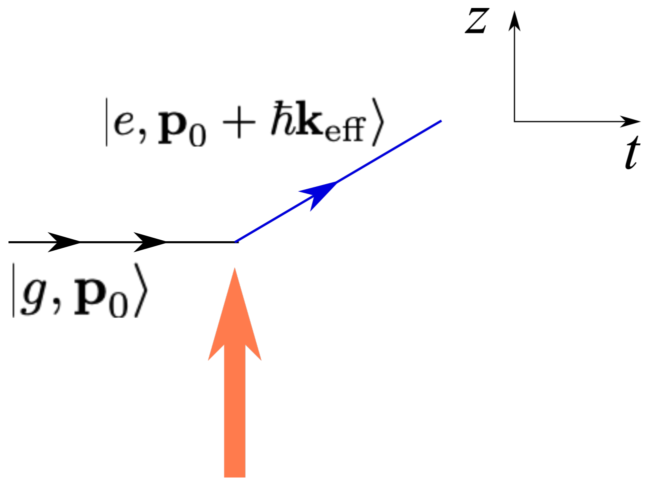
Atomic beamsplitter based on stimulated Raman transitions



$$\Psi(t) = \mathrm{e}^{-i\omega_1 t} \cos\left(\frac{\Omega t}{2}\right) \; |g, \mathbf{p}_0\rangle + \mathrm{e}^{i\Delta\phi_L} \mathrm{e}^{-i\omega_2 t} \sin\left(\frac{\Omega t}{2}\right) \; |e, \mathbf{p}_0 + \hbar\mathbf{k}_{\text{eff}}\rangle$$

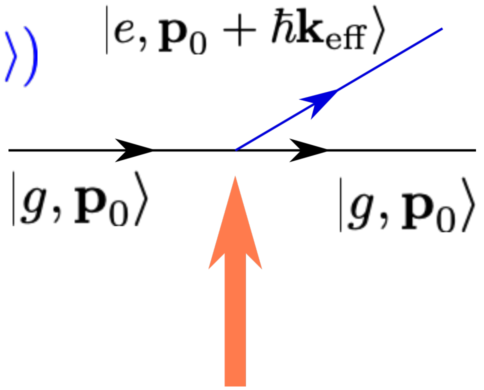
$$\pi - \text{pulse} : \Omega\tau = \pi$$

$$\Psi(\tau) = \mathrm{e}^{i\Delta\phi_L} \mathrm{e}^{-i\omega_2 \tau} \; |e, \mathbf{p}_0 + \hbar\mathbf{k}_{\text{eff}}\rangle$$

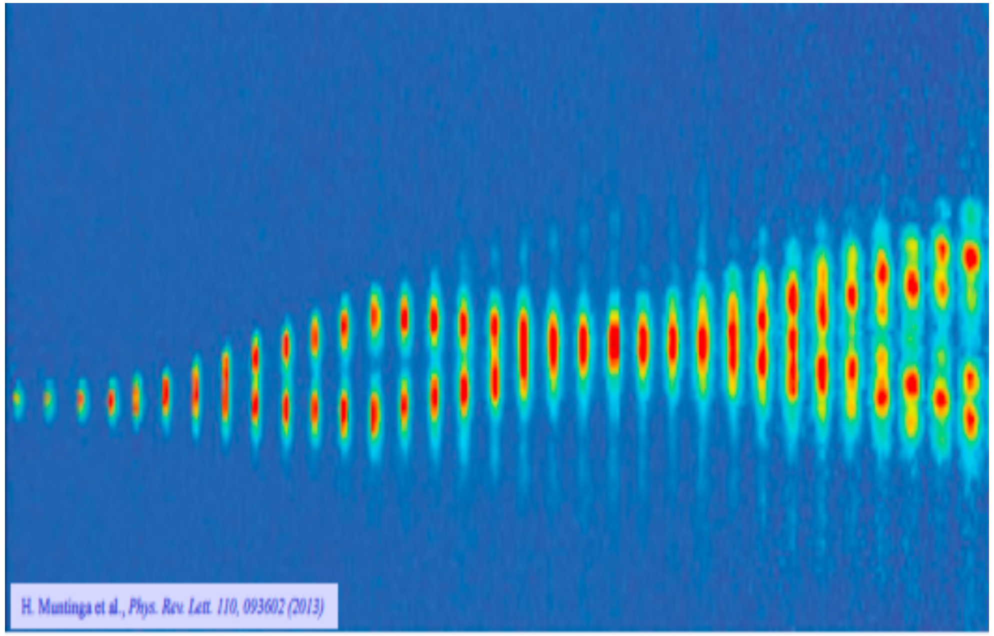


$$\frac{\pi}{2} - \text{pulse} : \Omega\tau = \frac{\pi}{2}$$

$$\Psi(\tau) = \frac{1}{\sqrt{2}} \left(\mathrm{e}^{-i\omega_1 \tau} \; |g, \mathbf{p}_0\rangle + \mathrm{e}^{i\Delta\phi_L} \mathrm{e}^{-i\omega_2 \tau} \; |e, \mathbf{p}_0 + \hbar\mathbf{k}_{\text{eff}}\rangle\right)$$



Phase shift of the atomic wave-packet along the propagating path



$$\phi_{\rm tot} = \phi_{\rm evol} + \phi_{\rm int} + \phi_{\rm sep}$$

Free evolution of wave-packets between light pulses

Phase due to atom-light interaction

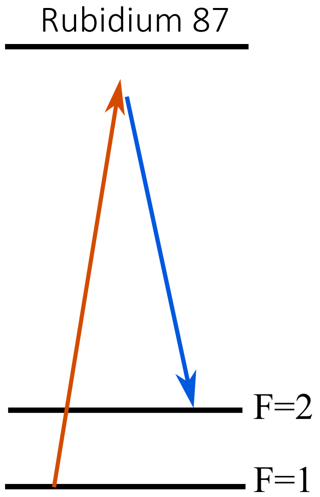
Phase shift due to no overlap of the two arms at the last pulse

Luis De Broglie $\rightarrow$ phase of matter-wave $\psi = \exp -i\frac{mc^2}{\hbar}\tau$

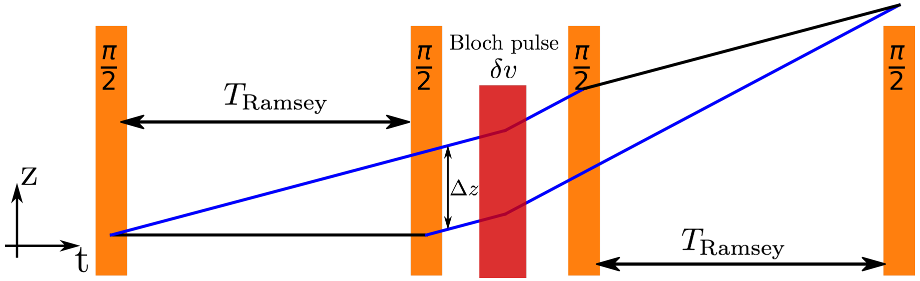
Weak gravitational fields and velocities $\ll c$ $\mathrm{d}\tau \simeq \mathrm{d}t - \frac{1}{mc^2}\mathcal{L}\mathrm{d}t$

$$\psi(t) \simeq \exp\left[-i\frac{mc^2}{\hbar}t\right]\exp\left[\frac{i}{\hbar}\int\mathcal{L}\mathrm{d}t\right] \qquad \phi_{\rm evol} = \frac{i}{\hbar}\int\mathcal{L}(z,t)\mathrm{d}t$$

Velocity sensor: Ramsey-Bordé Atom interferometer



Free propagation: $e^{-i\omega_{1,2}t}$, $\omega_{1,2}$, depend on the kinetic energy



Probability to find an atom in $|2\rangle$

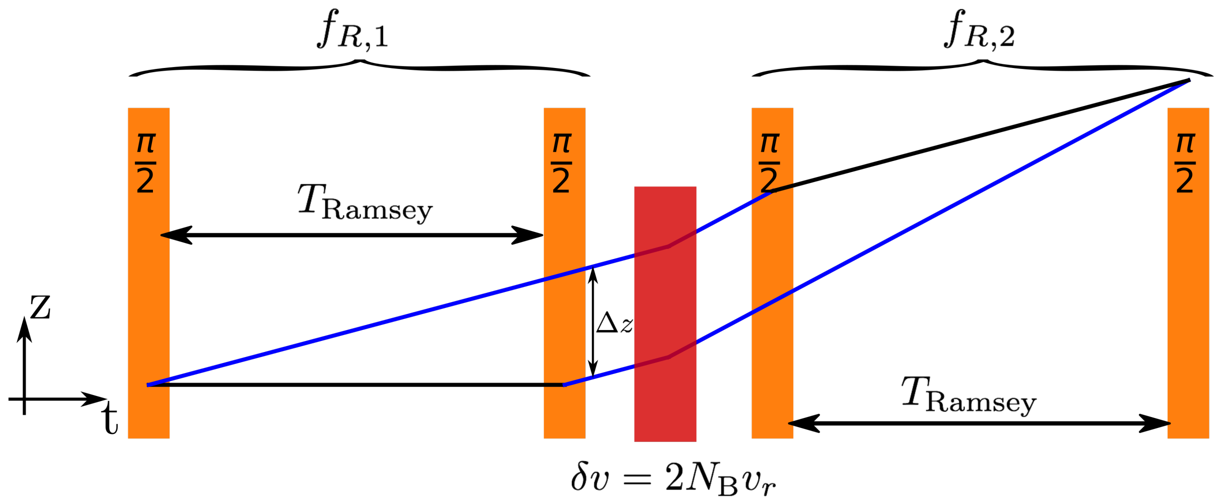
$$P_2 = \frac{1 + \cos\left(\Phi_{\text{at}} + \Phi_{\text{Las}}\right)}{2}$$

Velocity transfer δv

$$\Phi_{\text{at}} = T_{\text{Ramsey}} k_{\text{R}} \delta v = \frac{\Delta z \times m\delta v}{\hbar}$$

Sensitivity: $\delta z = 250\ \mu\text{m} \longrightarrow 3\ \mu\text{m} \cdot \text{s}^{-1} \cdot \text{rad}^{-1}$

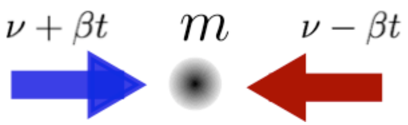
Interferometer for the recoil measurement



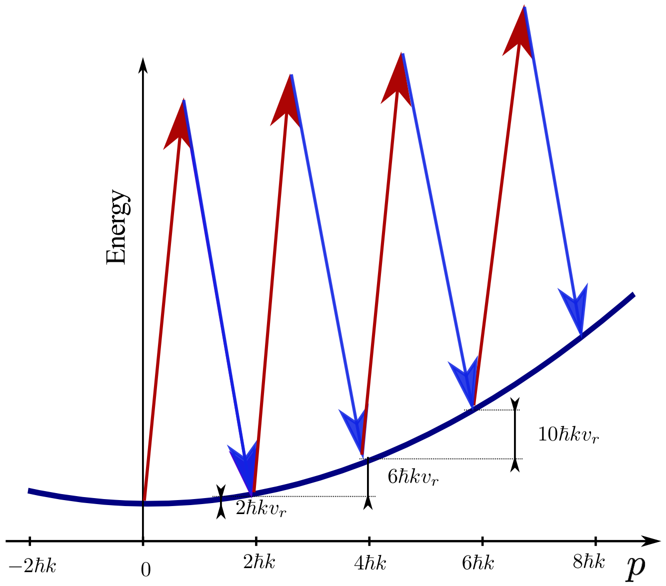
$$\Phi = T_{\text{Ramsey}} \left(2N_B k_{\text{R}} v_{\text{r}} - 2\pi \delta f_{\text{R}} \right)$$

$$\delta f_{\text{R}} = f_{\text{R},2} - f_{\text{R},1}$$

Coherent acceleration in optical lattice



Succession of stimulated Raman transitions in the same internal level

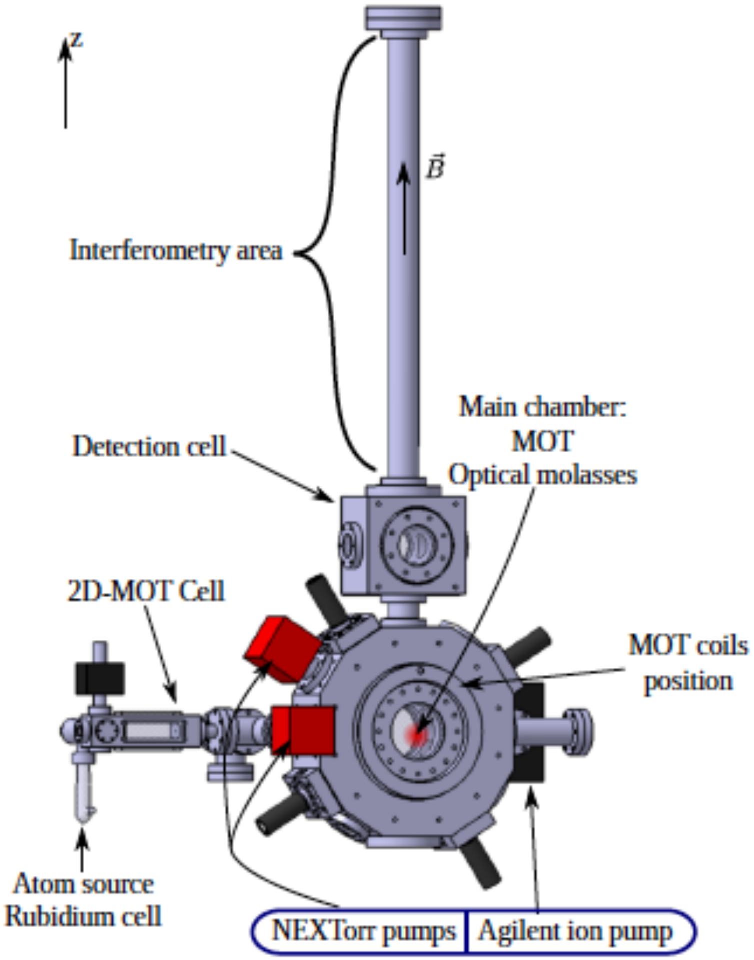


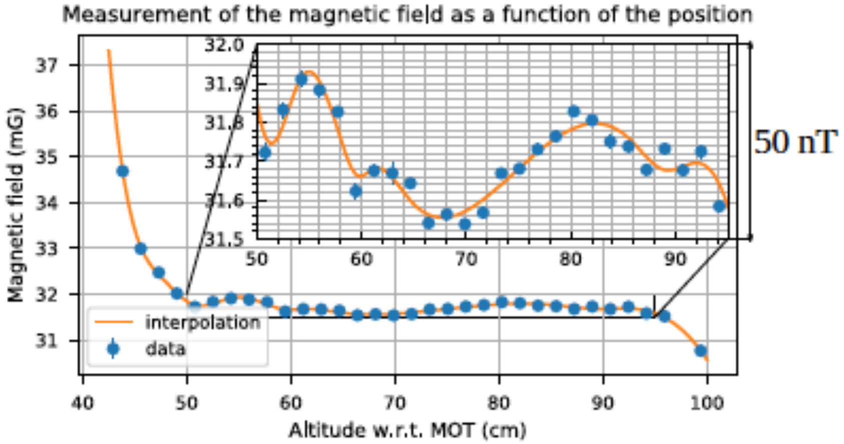
$$p_{\text{in}} \rightarrow p_{\text{in}} + 2N\hbar k$$

1000 photon momenta in 6 ms

- High momentum transfer efficiency: 99.95% per recoil
- Precise control of the velocity and the position of the atoms

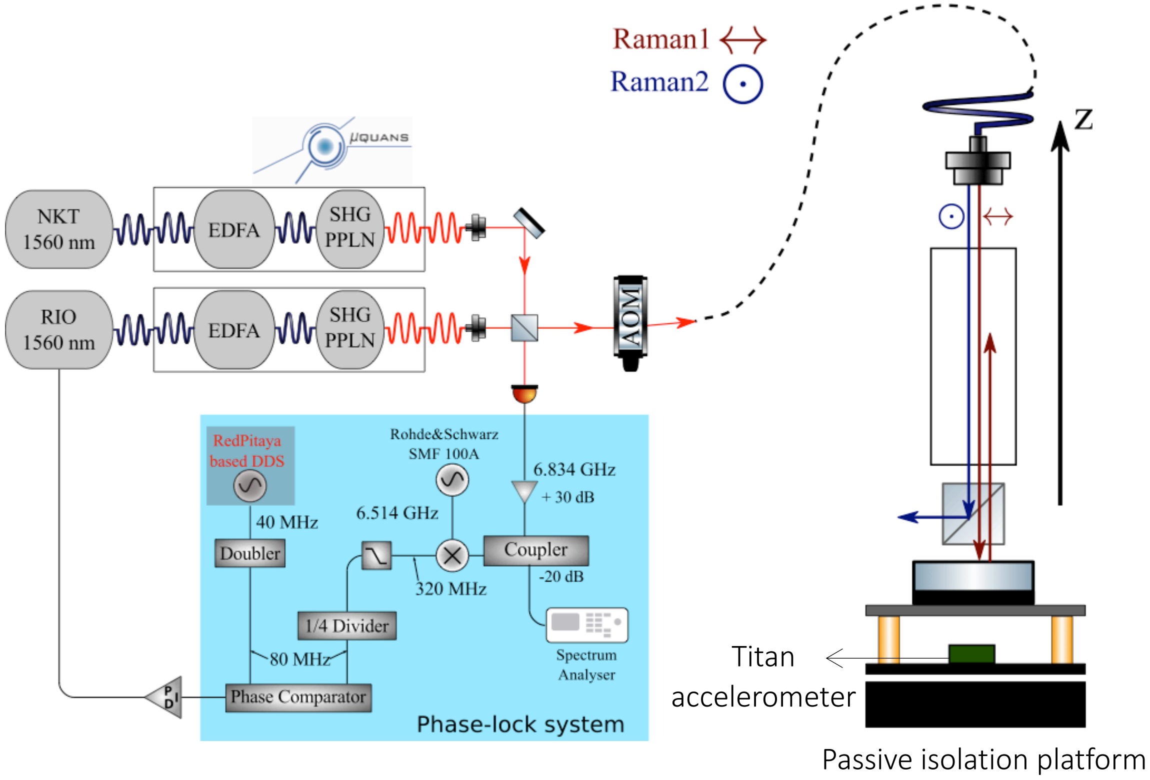
Experimental set-up

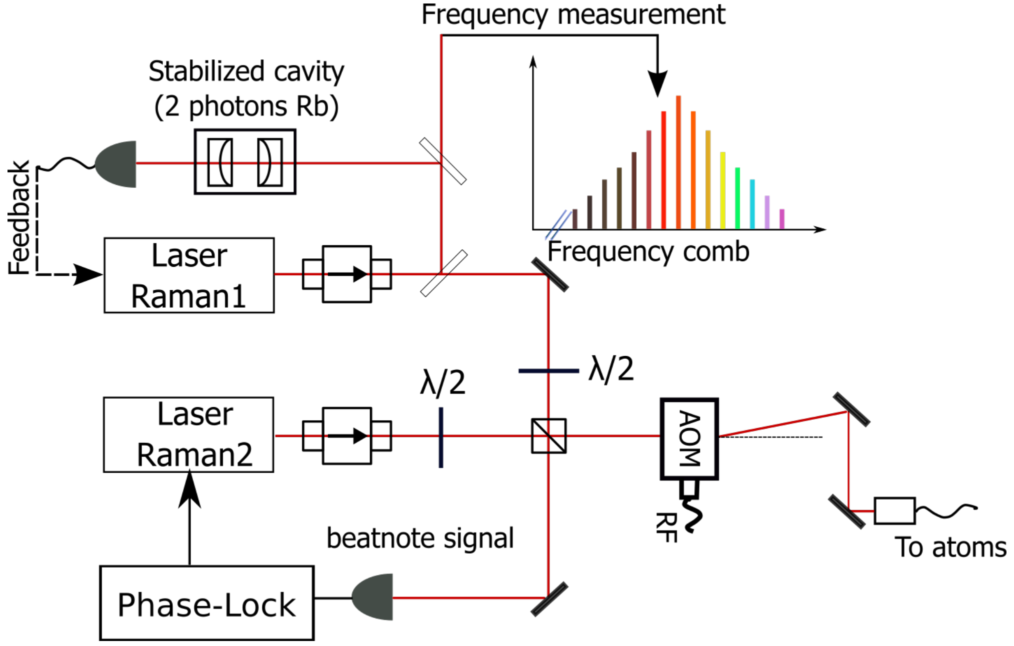




10^8 atoms ^{87}Rb : T=4 μK ; radius = 600 μm, 10^8 atoms

Phase and frequency control of Raman lasers

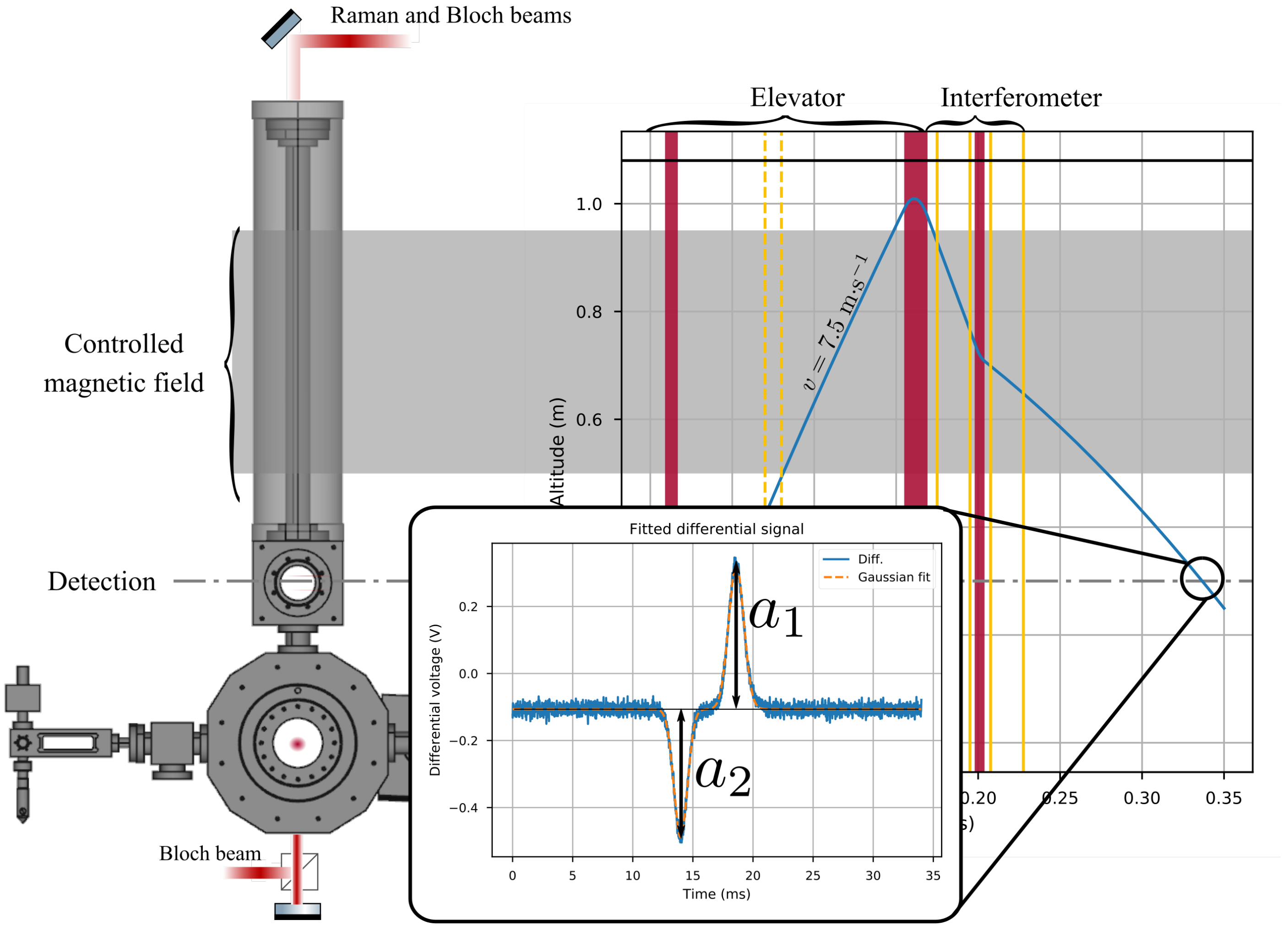




Frequency chain:

- Phase-lock of the two Raman lasers
- Frequency scanning during the second pair of $\pi/2$ pulses
- Frequency ramp to compensate for the Doppler shift during the free fall of atoms

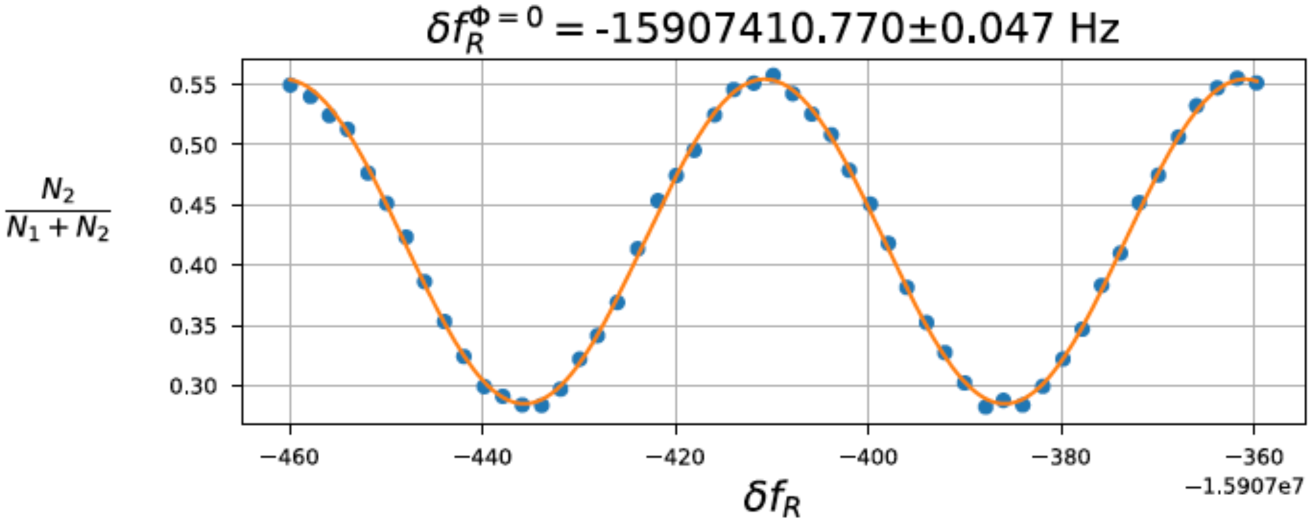
Experiment principle



$$a_1 \propto N_1$$
$$a_2 \propto N_2 \longrightarrow P_2 = \frac{N2}{N_1+N_2}$$

Typical atomic fringes

- T_{ramsey} = 20 ms, Number f Bloch oscillations N_B=500 (1000 v_r)
- 50 points per spectra in ~1 min



$$\Phi = T_{\mathrm{Ramsey}}\left(k_R\left(2N_B\frac{\hbar}{m}k_B - gT\right) - 2\pi\delta f_R\right) + \Phi^{LS}$$

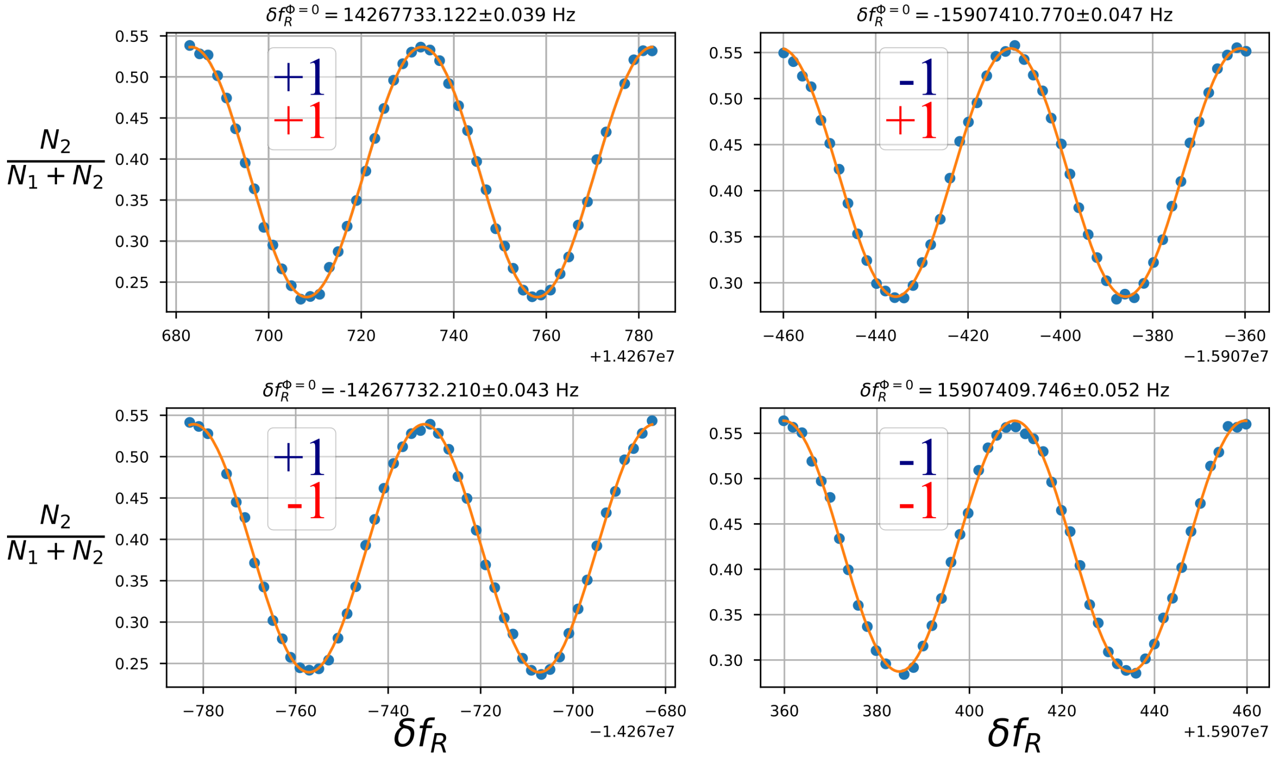
- Recoil velocity (one photon momentum) ~ 15 kHz → 1000 v_r ~ 15 MHz
- σ_v=0.047 Hz ~ 3 x 10^{-6} v_r ~ 20 nm s^{-1} → 3 x 10^{-9} on h/m

➢ Contributions of g and the light shift Φ_{LS}

Measurement protocol

Four spectra in 4 minutes (200 points set arbitrary)

$$\Phi = T_{\text{Ramsey}}\left(\epsilon_R k_R\left(\epsilon_B 2N_B\frac{\hbar}{m}k_B - gT\right) - 2\pi\delta f_R\right) + \Phi^{LS}, \text{ for } \epsilon_B = \pm 1,\ \epsilon_R = \pm 1$$

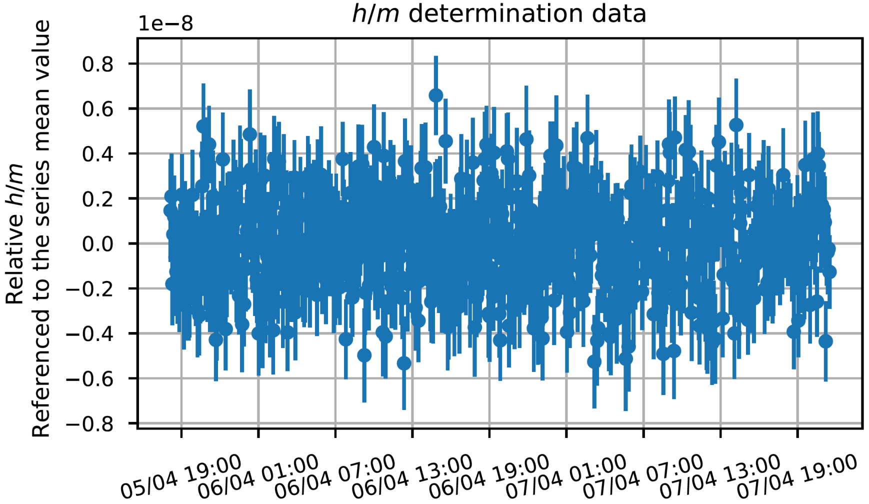


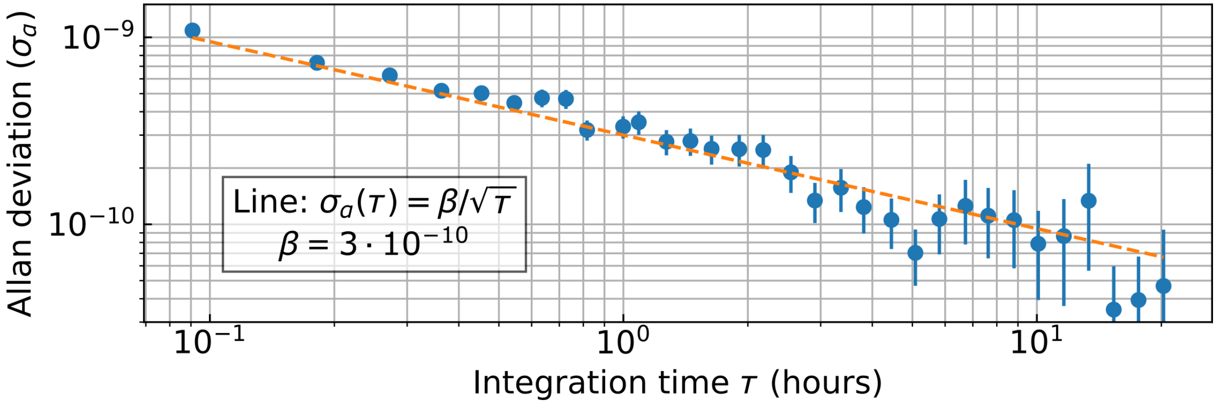
$$\frac{h}{m_{\text{Rb}}} = \frac{2\pi^2}{N_B k_R k_B}\frac{1}{4}\sum_{4\text{ spectra}}\epsilon_R\epsilon_B\delta f_R^{\Phi=0}(\epsilon_R,\epsilon_B)$$

Laboratoire Kastler Brossel
Physique quantique et applications

Statistical uncertainty

Stable and reliable set-up: Long measurement period

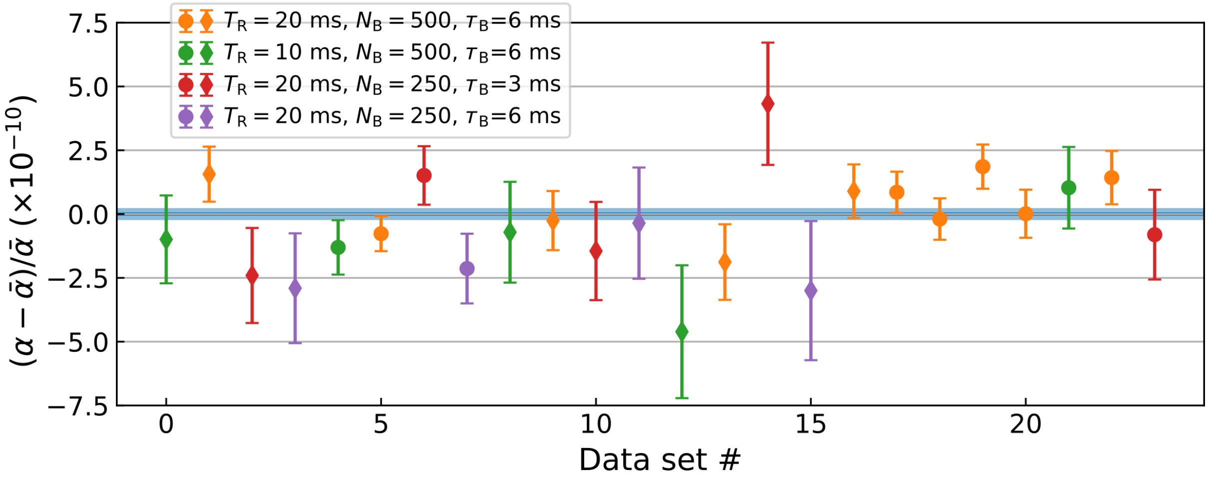




From Friday to . . . . Sunday

48 h integration: $8.5{\times}10^{-11}$ on h/m $\longrightarrow$ $4.3{\times}10^{-11}$ on α

Final data set (Jan. 2020)



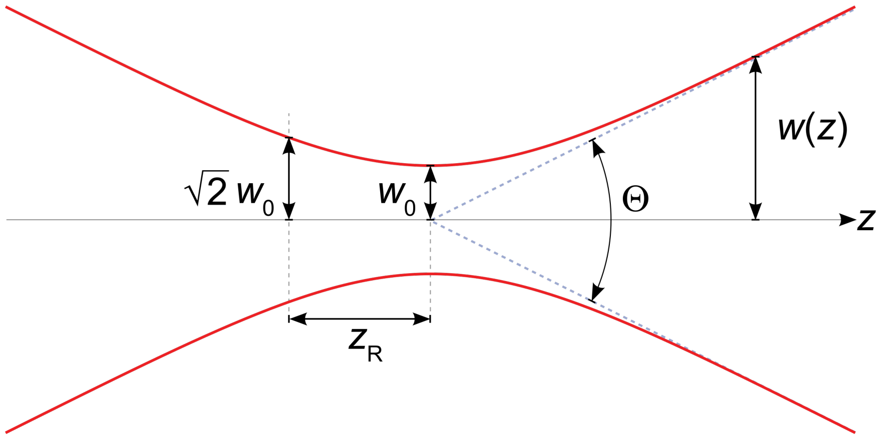
Error budget

Source	Correction $[10^{-11}]$	Relative uncertainty $[10^{-11}]$
Gravity gradient	-0.6	0.1
Alignment of the beams	0.5	0.5
Coriolis acceleration		1.2
Frequencies of the lasers		0.3
Wave front curvature	0.6	0.3
Wave front distortion	3.9	1.9
Gouy phase	108.2	5.4
Residual Raman phase shift	2.3	2.3
Index of refraction	0	< 0.1
Internal interaction	0	< 0.1
Light shift (two-photon transition)	-11.0	2.3
Second order Zeeman effect		0.1
Phase shifts in Raman phase lock loop	-39.8	0.6
Global systematic effects	64.2	6.8
Statistical uncertainty		2.4
Relative mass of ^{87}Rb [16] : $86.909\,180\,531\,0(60)$		3.5
Relative mass of the electron [14] : $5.485\,799\,090\,65(16) \cdot 10^{-4}$		1.5
Rydberg constant [14] : $10\,973\,731.568\,160(21)\mathrm{m}^{-1}$		0.1
Total: $\alpha^{-1} = 137.035\,999\,206(11)$		8.1

Atom recoil in a gaussian beam

Laboratoire Kastler Brossel — Physique quantique et applications

- Electric field: $E(\vec{r},t) = A(\vec{r},t)\ \mathrm{e}^{i\phi(\vec{r})} \longrightarrow \vec{k}_{\mathrm{eff}} = \vec{\nabla}\phi(\vec{r})$
- Plane wave model: $k = \frac{\nu}{c}$
- Gaussian laser beam correction: $k_{\mathrm{eff},z} = k + \delta k$



$$\frac{\delta k}{k} = -\frac{2}{k^2 w^2(z)}\left(1 - \frac{\langle r^2\rangle}{w^2(z)}\right) - \frac{\langle r^2\rangle}{2R^2(z)}$$

Size of the atomic cloud

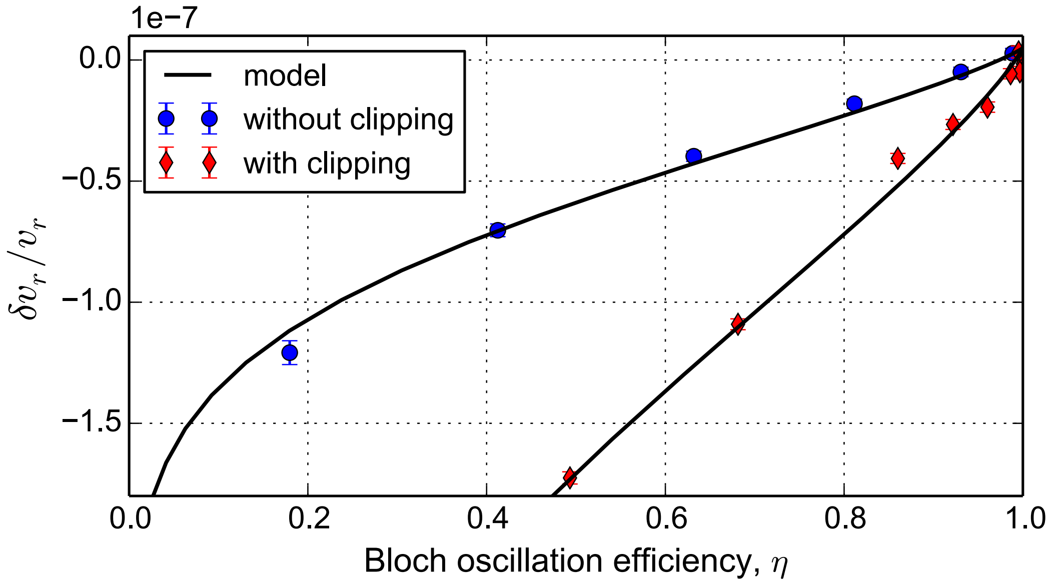
Curvature of the wavefront

- Related to the dispersion of wavevectors $\sim \frac{\Theta^2}{2}$

Effect on α: $(108.2 \pm 5.4)\times 10^{-11}$

New systematic effect: atomic recoil in a distorted wave front

- A systematic effect that depends on the efficiency of the Bloch oscillation (coherent acceleration)



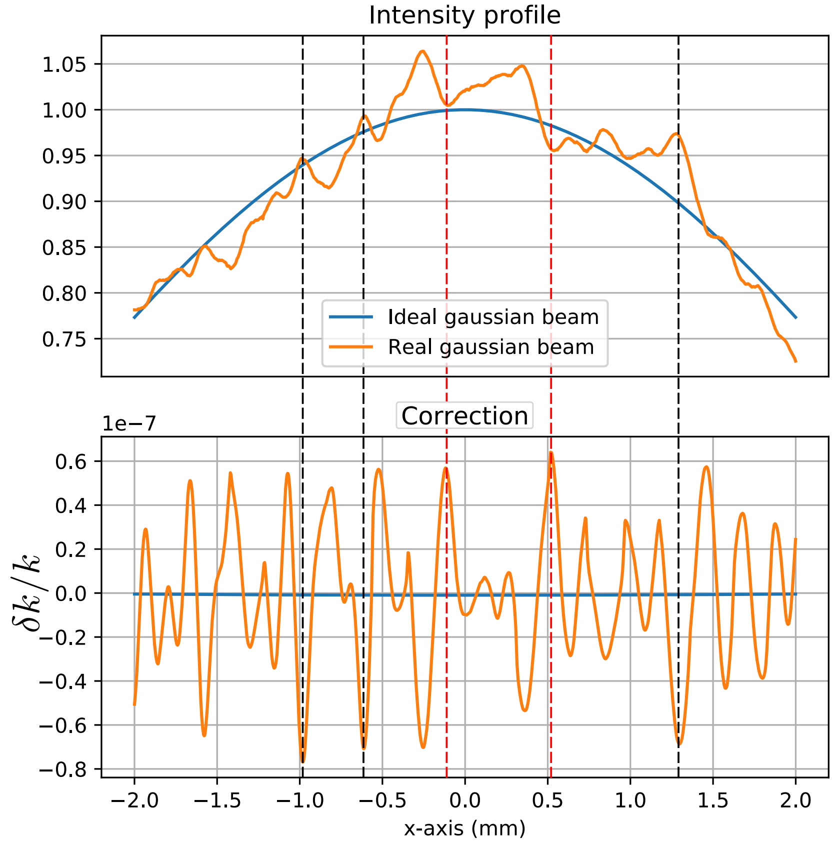
- During the Bloch Oscillation pulse, the survival probability is governed by Landau-Zener Losses, it depends on laser intensity

Recoil velocity of atom in a distorted wave front

- Electric field: $E(\vec{r},t) = A(\vec{r},t)\ \mathrm{e}^{i\phi(\vec{r})}$

$$k_{\mathrm{eff},z} = \frac{\partial \phi}{\partial z} = k + \delta k$$

Random spatial fluctuations of laser intensity with typical correlation length 100 μm



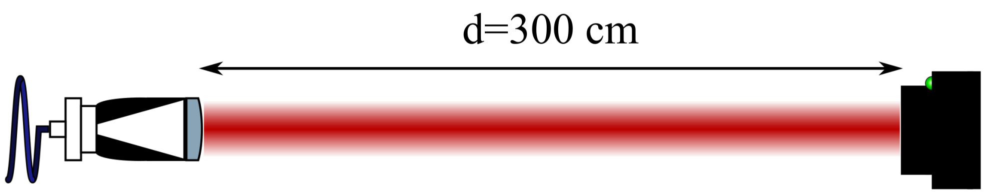
Local amplitude fluctuations induces momentum correction (in paraxial approximation)

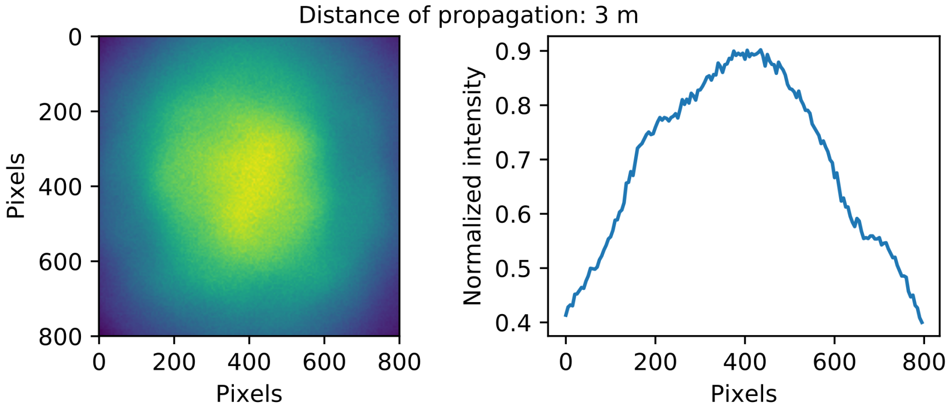
$$\frac{\delta k}{k} = -\frac{1}{2}\left\| \frac{\vec{\nabla}_\perp \phi}{k} \right\|^2 + \frac{1}{2k^2}\frac{\triangle_\perp A}{A}$$

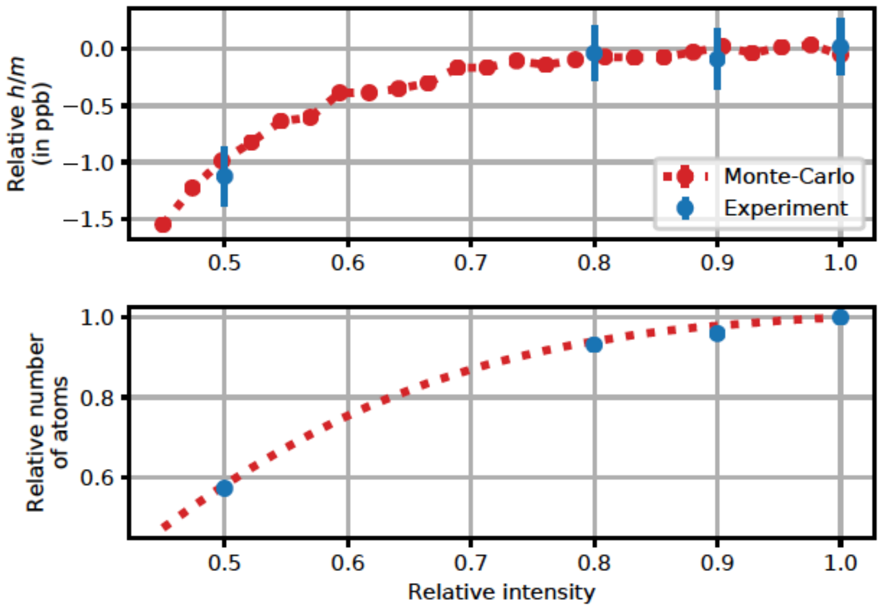
Correlation between the wave vector correction and the survival probability *P* (I) during Bloch oscillations,

$$\langle \delta k \rangle = \frac{\langle \delta k\ P(I) \rangle}{\langle P(I) \rangle}$$

Recoil velocity of atom in a distorted wave front







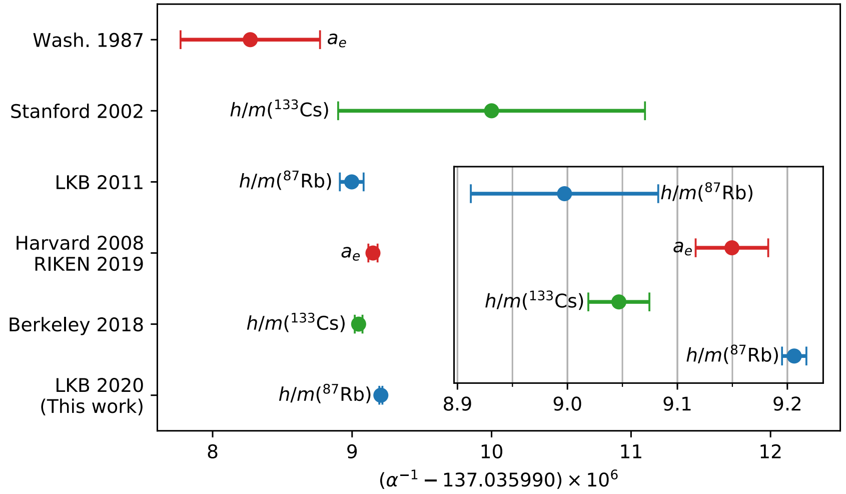
Effect on α: $(3.9 \pm 1.9) \times 10^{-11}$

Outline

- Measurement of the ratio *h/M*
- Impact of the new determination of the fine-structure constant

Recent results

L. Morel et al., Nature 588, 61-68 (2020)



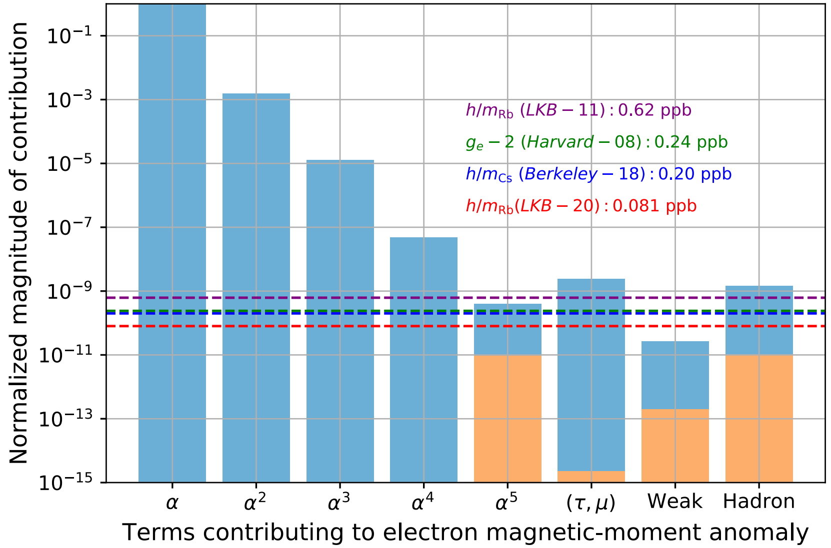
$$\alpha^{-1} = 137.035999206(11)$$

- Statistical uncertainty of 4.3×10^{-11} on 48h integration time
- New systematic effects were considered
- 5.4 σdiscrepancy with caesium recoil measurement

R. H. Parker et al., Scie,ce 360, 191-195 (2018)

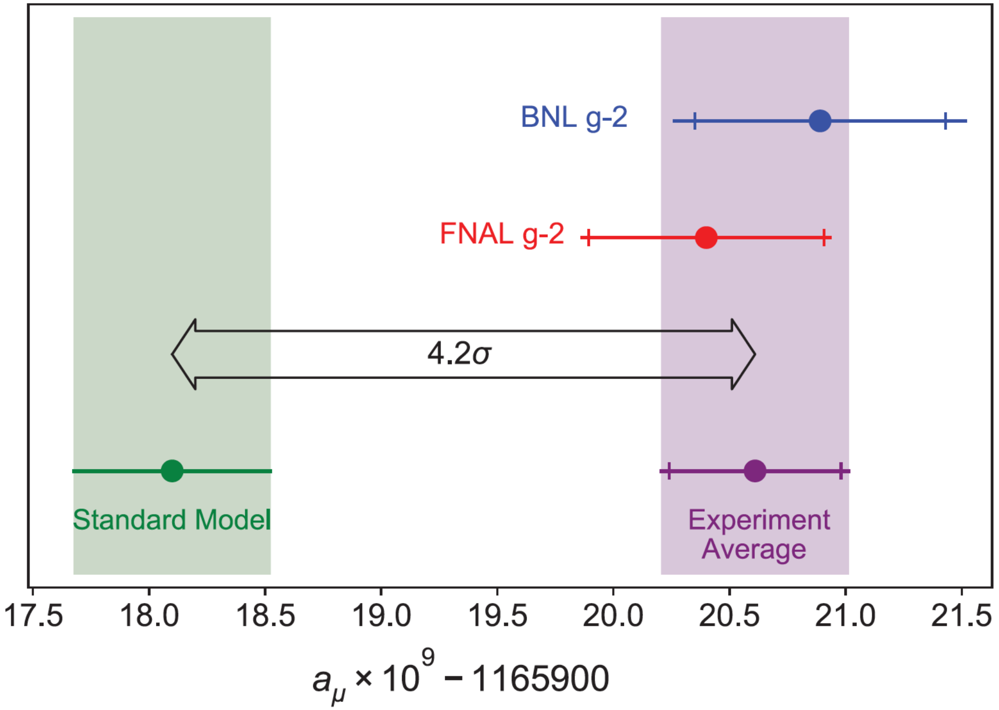
$$a_\mathrm{e}(\exp) - a_\mathrm{e}(\alpha_{\mathrm{LKB2020}}) = (4.8 \pm 3.0) \times 10^{-13} \quad (+1.6\sigma)$$
$$a_\mathrm{e}(\exp) - a_\mathrm{e}(\alpha_{\mathrm{Berkeley}}) = (-8.8 \pm 3.6) \times 10^{-13} (-2.6\sigma)$$

- The uncertainty on δa_e is now dominated by $a_\mathrm{e}(\exp)$



Testing the muon a_μ discrepancy in the electron sector

- T. Aoyama et al., Physics Reports 887, 1-66 (2020)
- B. Abi *et al.* (Muon g−2 Collaboration) Phys. Rev. Lett. 126, 141801 (2021).



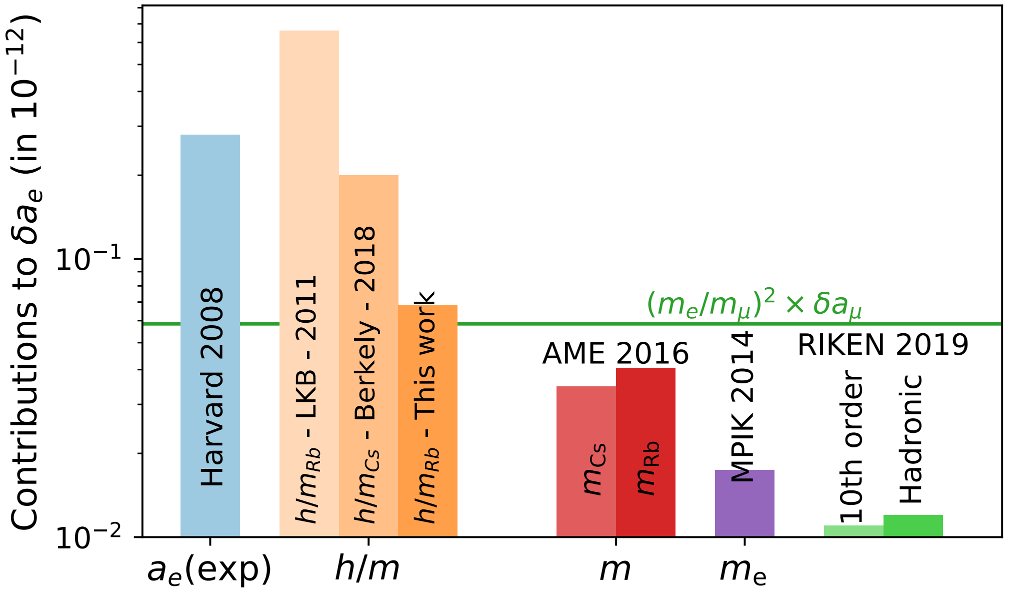
$$\delta a_\mu = a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$$

$$\delta a_\mu \stackrel{?}{=} a_\mu(\mathrm{NP})$$

- Naive scaling $$\left|\frac{\delta a_\mathrm{e}}{\delta a_\mu}\right| = \left(\frac{m_\mathrm{e}}{m_\mu}\right)^2 \simeq 2.3 \times 10^{-5}$$

F. Terranova and G. M. Tino, PRA 89, 052118 (2014)

$$\sigma_\mathrm{e} = 2.5 \times 10^{-5} \times \left(\frac{m_\mathrm{e}}{m_\mu}\right)^2 \simeq 5.8 \times 10^{-14}$$

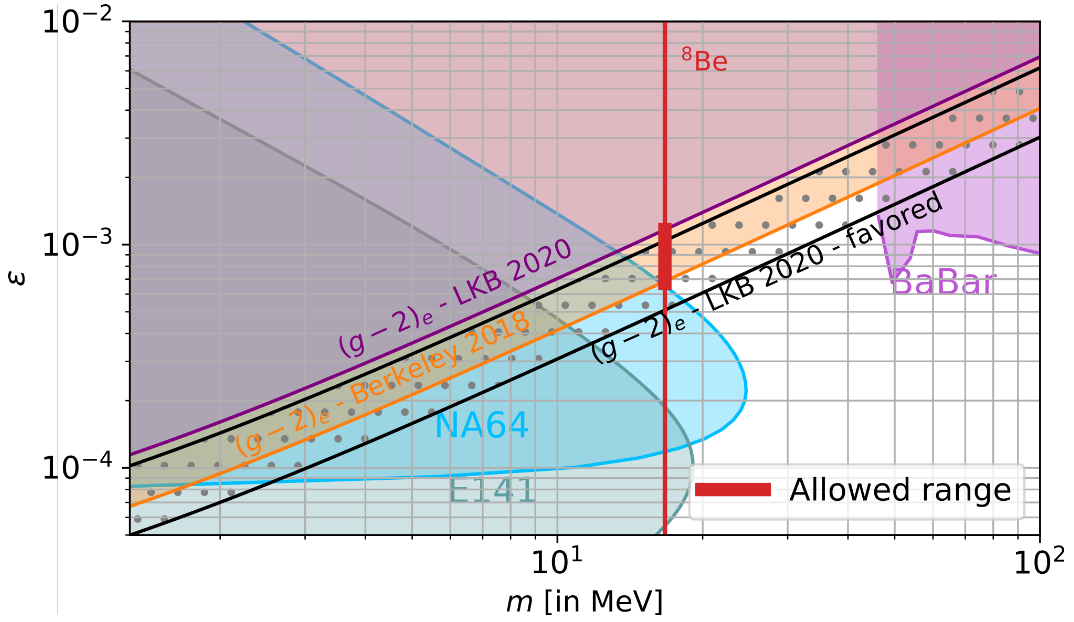


Physics beyond Standard Model

« Hypothetical particles » of mass m_V and coupling ε with electrons will induce

$$\delta a_e = \frac{\alpha}{\pi} \times \epsilon^2 \int_0^1 \mathrm{d}z \frac{2m_e^2 z(1-z)^2}{m_e^2(1-z)^2 + m_V^2 z} \simeq \frac{\alpha\epsilon^2}{3\pi}\frac{m_e^2}{m_V^2} \quad \text{For} \quad m_V \gg m_e$$

Our results rejects with 95% confidence level $\delta a_e > 9.8 \times 10^{-13}$ and $\delta a_e < -3.4 \times 10^{-13}$



D. Banerjee et al. (The NA64 Collaboration) Phys. Rev. D 101, 071101(R) (2020)

- Favoured the hypothetical X(16.7 MeV) boson that could explain the anomalous excess of e^+e^- pairs observed in the decays of the excited ^{8}Be$*$ nuclei ("Beryllium or X17 anomaly")

A. J. Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016)

New international System of units

- The new SI (since 20 may 2019)
  Based on fundamental constants $\Delta \nu_{Cs}$, c, h, e, N_A, K_{cd}

- Our experiment allow the *Mise en pratique* of the new kilogramme at the atomic scale

$$m(^{87}\mathrm{Rb}) = 1.44316089776\ (21)\ \times 10^{-25}\ \mathrm{kg}$$

- 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

$$M(^{12}\mathrm{C}) = N_A \times m(^{12}\mathrm{C}) = \frac{12 N_A h}{h/m_\mathrm{u}} = 12.0000000173(19)\ \mathrm{g/mol} \quad \text{where} \quad m_\mathrm{u} = \frac{m_\mathrm{X}}{A_\mathrm{r}(\mathrm{X})}$$

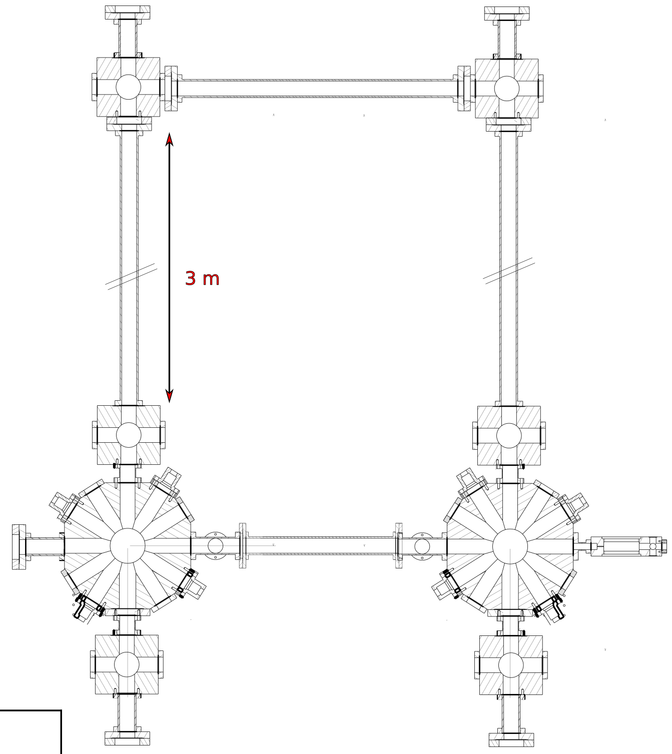
- The fine-structure constant plays an important role in the adjustment of fundamental physical constants:
  in the new SI the numerical values of ε_0 et μ_0 will depend on a.

$$\mu_0 = \frac{2\alpha h}{e^2 c} = 0.999999999648(80) \times 4\pi \times 10^{-7}\ \mathrm{m \cdot kg \cdot s^{-2} \cdot A^{-2}}$$

90 of the 354 constants listed by NIST (https://physics.nist.gov/cuu/Constants/) will have their uncertainties reduced.

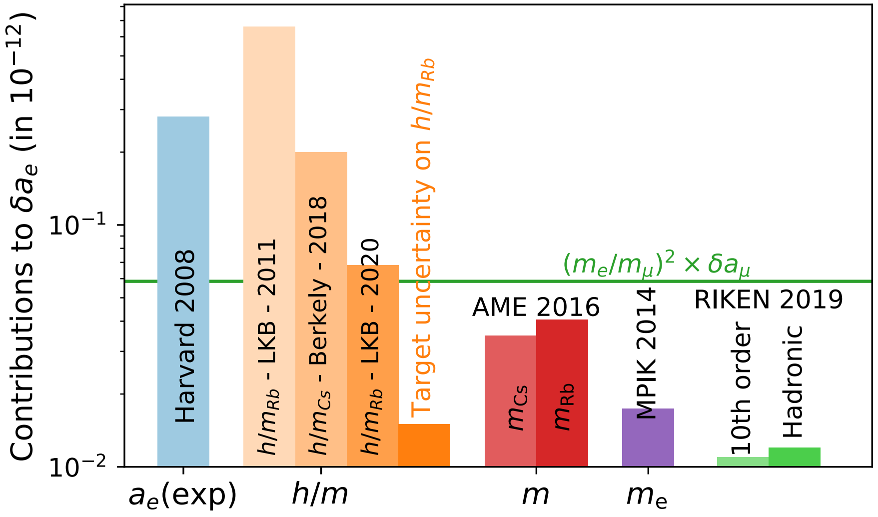
Conclusion and prospects

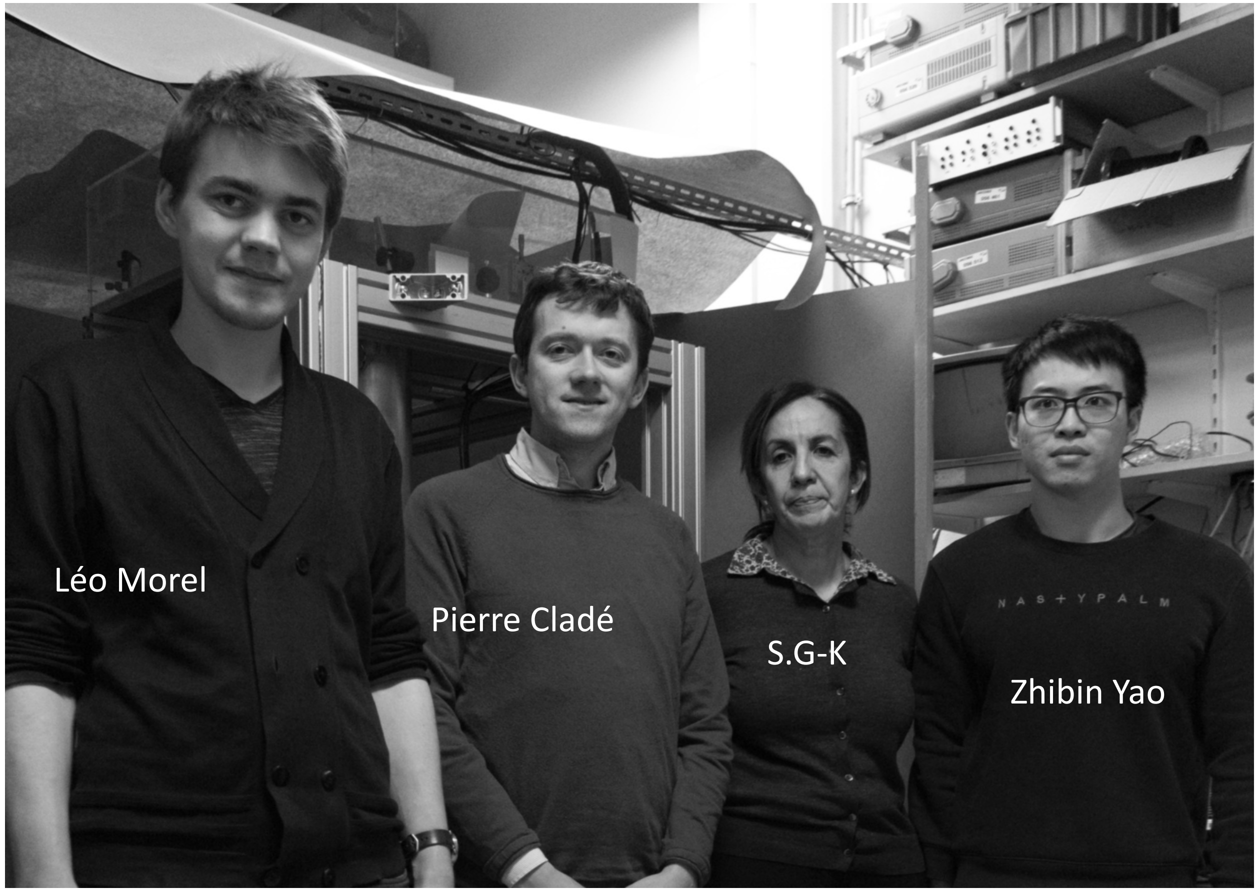
- New determination of the fine-structure constant with a relative uncertainty of 8.1×10^{-11}
- The sensitivity of the experimental set-up allowed the experimental investigation of several systematic effects,
- Three new systematic effects were identified
- The large discrepancy ($5.4\ \sigma$) with the caesium recoil measurement needs to be clarified



Prospects:

- New measurement using ultra-cold atoms is in progress
- Measurement of recoil velocity with ^{85}Rb
- New experimental setup : uncertainty on α of 10^{-11}





PhD students (since 2000):

- L. Morel
- Z. Yao
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- R. Jannin
- C. Courvoisier
- R. Bouchendira
- M. Cadoret
- P. Cladé
- R. Battesti

Thank you !

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