Precision measurements with ultra-cold strontium atoms in optical lattices

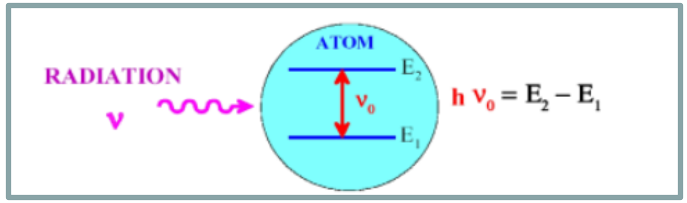
Nicola Poli

Dipartimento di Fisica e Astronomia – Università di Firenze
LENS –European Laboratory for Non-Linear Spectroscopy
INFN – Sezione di Firenze

Outline

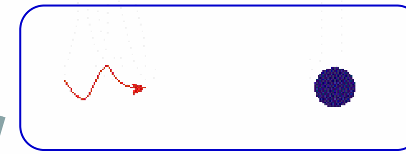
precision measurements of time and gravity

(optical clocks and atom interferometers)



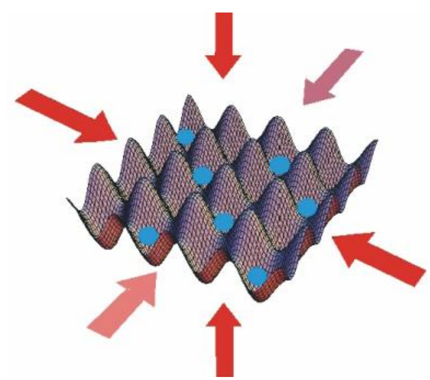
Coherent control of quantum states of atoms/ions with laser light (internal and external d.o.f.)

Doppler laser cooling



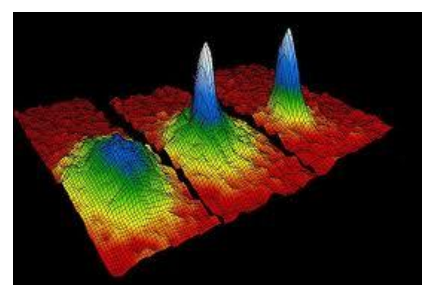
300 K -> 1 μK

-engineer full quantum state (int+ext)



Spin lattices,
Entanglement,
quantum simulations

Degenerate quantum gases

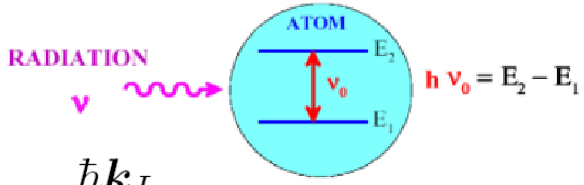


Bose-Einstein condensates
Degenerate Fermi gases

Laser cooling

Radiation pressure

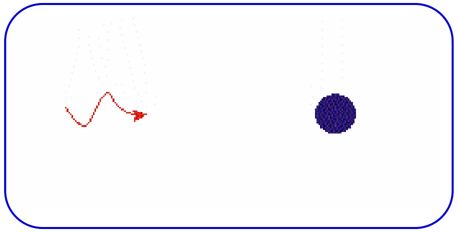
Absorption of many photons (near resonance)



$\hbar \boldsymbol{k}_L$

$$v_{\text{rec}} = \frac{\hbar k_A}{m} = \frac{h}{m\lambda_A}$$

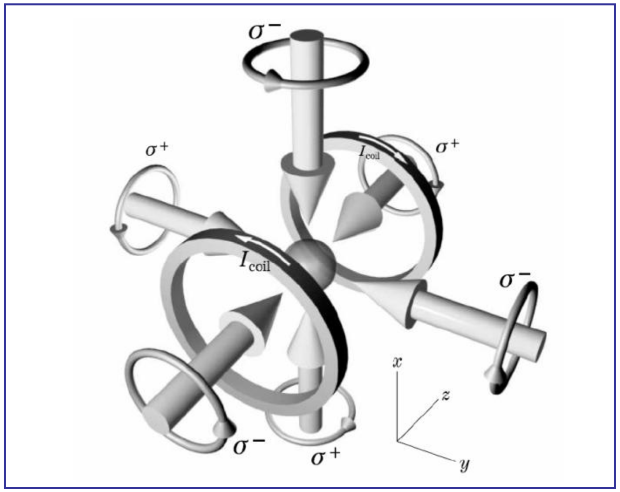
$$3{,}5\ \text{mm s}^{-1}$$



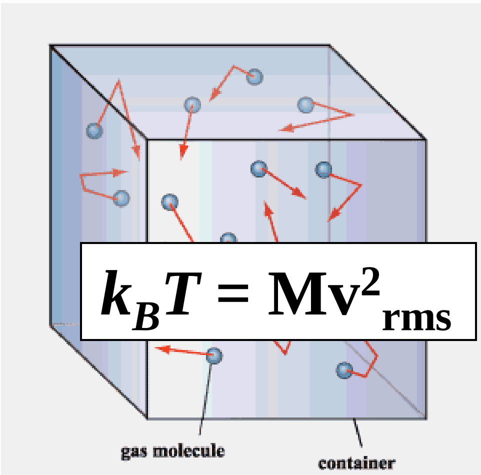
Each cycle transfers to the atom a mean momentum equal to $\hbar \boldsymbol{k}_L$.The mean contribution of spontaneous emission is zero.

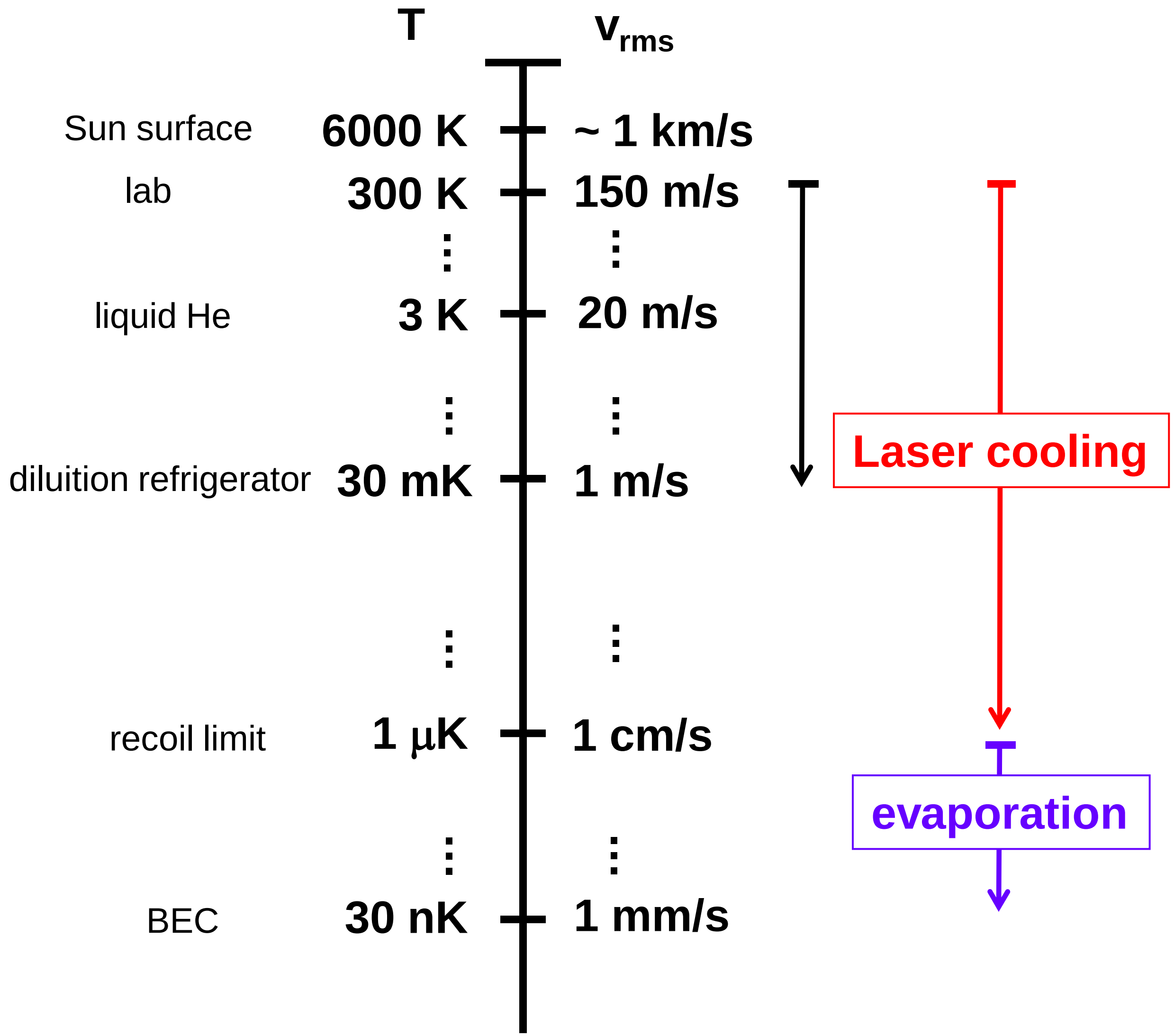
Magneto-Optical Trap (MOT)

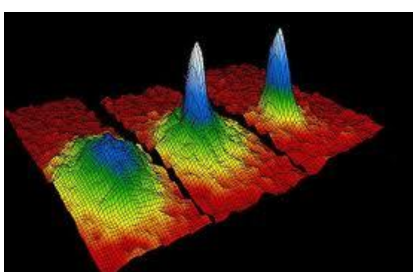
-3D optical molasses
- quadrupole magnetic field



Laser cooling



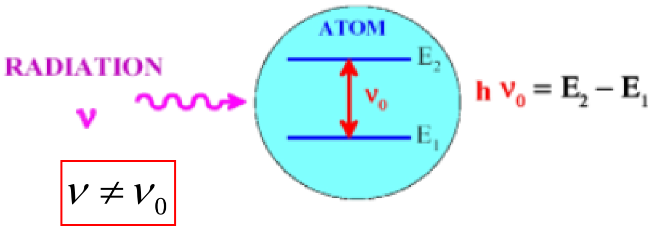




Degenerate quantum gases

Optical dipole traps

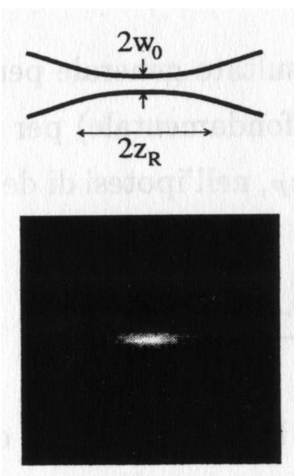
Dipole force: interaction with off-resonant laser light



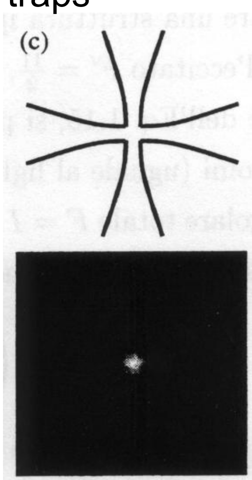
$$U(r,z) = -\vec{p}\cdot\vec{E}(r,z) \propto I(r,z)$$

$$I(r,z) = \frac{2P}{\pi\omega^2(z)} \exp\left(-\frac{2r^2}{\omega^2(z)}\right)$$

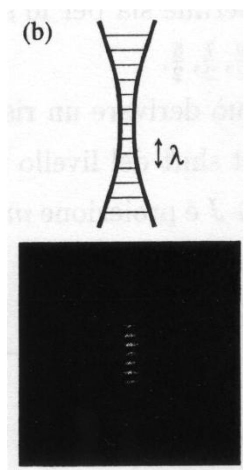
Single beams traps



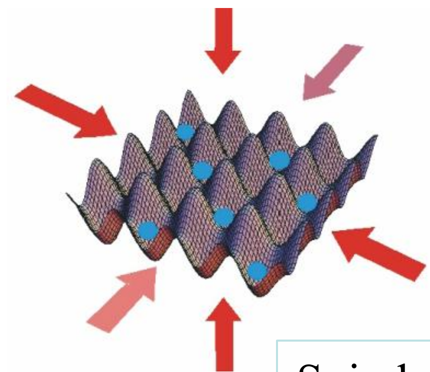
Crossed beams traps



Optical lattices



engineer full quantum state (int+ext)



Spin lattices,
Entanglement,
-> quantum simulations

Outline

The Nobel Prize in Physics 2012
Serge Haroche, David J. Wineland

The Nobel Prize in Physics 2012

Serge Haroche

David J. Wineland

Photo: © CNRS Photothèque/Christophe Lebedinsky

Serge Haroche

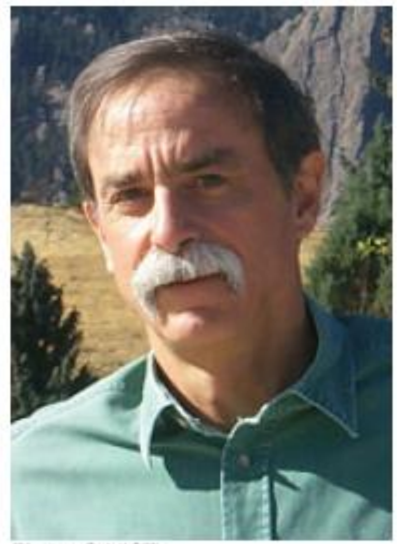


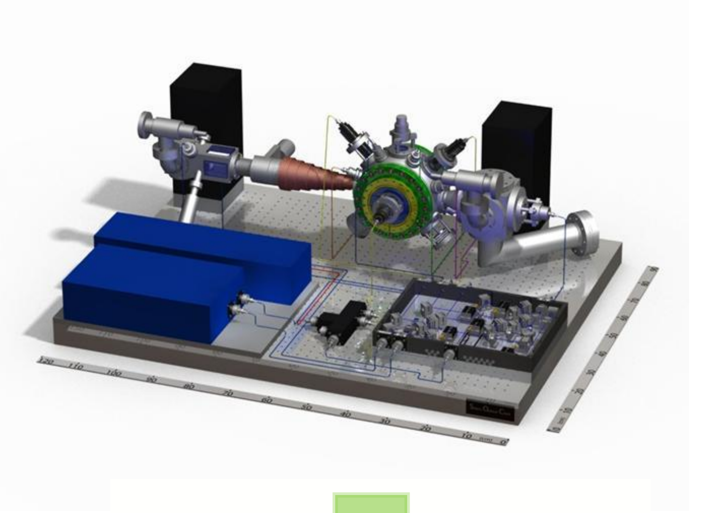
Photo: © NIST

David J. Wineland

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

Outline

- Sr optical lattice clock

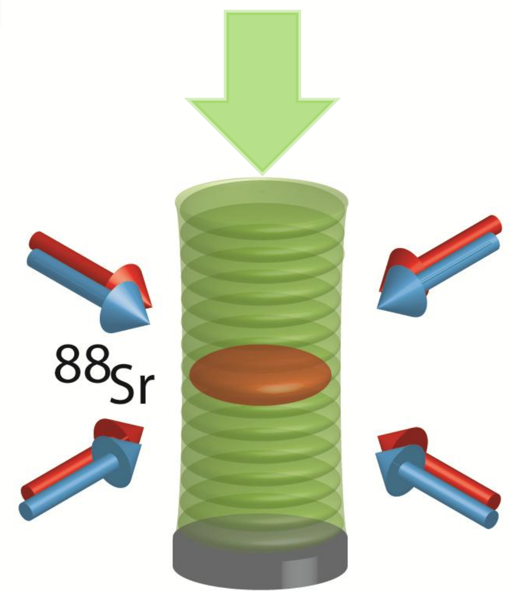


-Compact and transportable setup
(all-semiconductor laser based optical lattice clock, transfer cavity for first calibration of clock laser optical frequency, magnetic field induced spectroscopy,…)
-Labs with no metrologic hardware
-Application in other fields

- Cold ^{88}Sr atoms in vertical optical lattice

- accurate gravimetry with Sr atoms

(Bloch oscillation of ^{88}Sr atoms in vertical optical lattices, AM modulation technique)



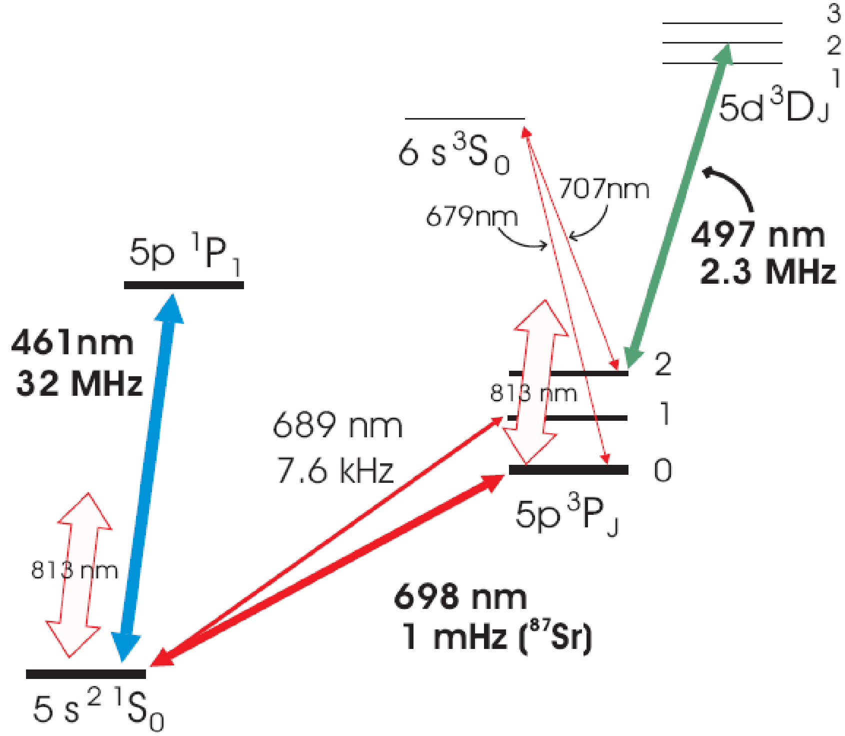
Sr optical transitions

- 4 stable Sr isotopes (88, 87, 86, 84) bosonic isotopes I=0

  -> ground 1S0 state -> total spin =0

- Efficient Laser cooling
  - $^1S_0 - {}^1P_1$ (461 nm, 32 MHz)
  - $^1S_0 - {}^3P_1$ (689 nm, 7.6 kHz)

- Intercombination *clock* transition
  - **$^1S_0$ - $^3P_0$ (698 nm, ~1 mHz, ^{87}Sr)**



- metastable states with **long coherence time** (>1000 s)

$$Q_{at} = \frac{\nu_0}{\delta\nu} \approx 10^{17}$$

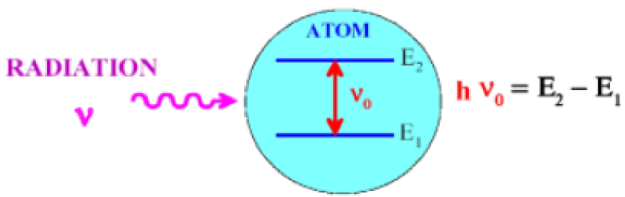
-> **long coherence time** for interferometric schemes involving **external degrees of freedom**

(Zero spin ground state with low sensitivity to external fields and low elastic scattering rate for 88Sr)

All the transition easy reachable with semiconductor laser

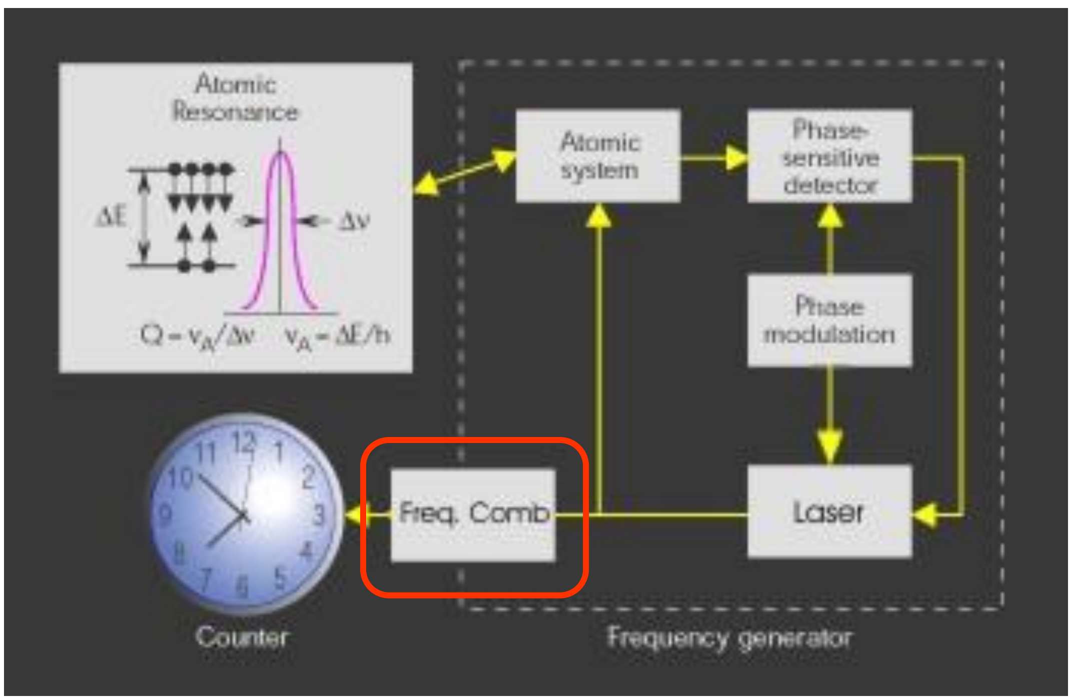
What is an optical clock ?

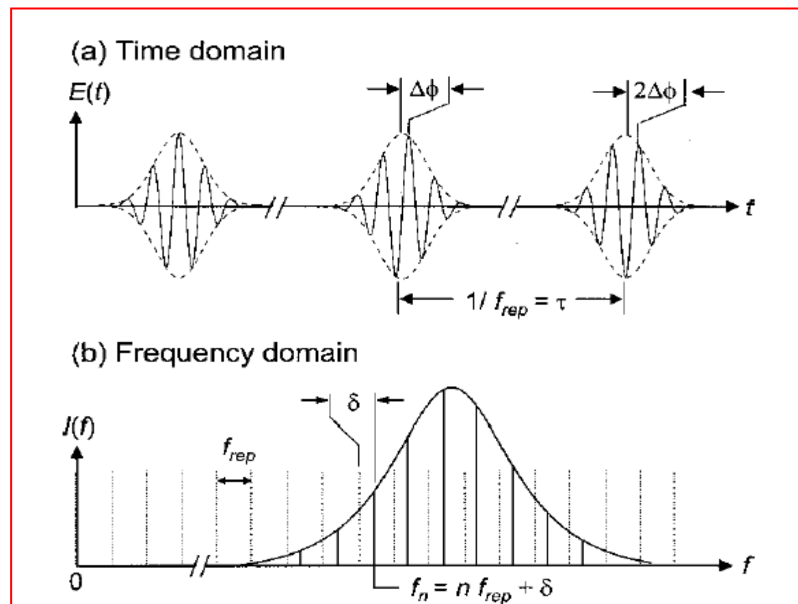
time ⟷ periodic phenomenon



$\nu_{Opt.\ Clock} = 400\ THz - 1000\ THz$

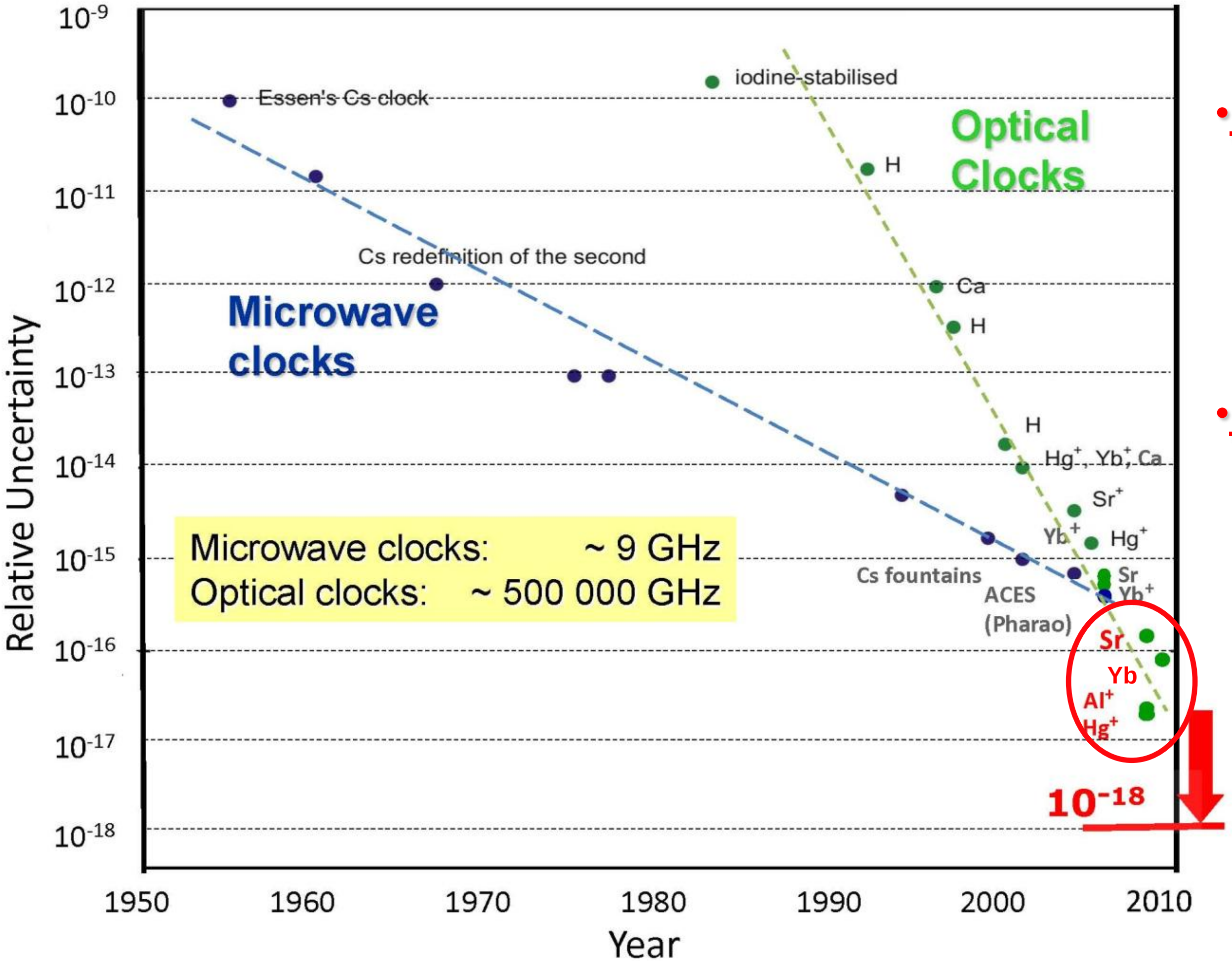
(10^{14} Hz-10^{15}Hz !!!!)





(λ ~ 520 nm ÷1200 nm)

Optical clocks



- **Al+, Hg+ single ion clocks**

  T. Rosenband *et al.*, Science **319**, 1808 (2008)
  C. W. Chou, *et al.* Phys. Rev. Lett. **104**, 070802 (2010)

- **Sr, Yb optical lattice clocks**

  G. K. Campbell *et al.*, Science **324**: 360 (2009)
  N. D. Lemke, et al. Phys. Rev. Lett. **103**, 063001 (2009)

clock **stability** $\sigma_y(\tau) \approx 10^{-15}\tau^{-1/2}$

clock **accuracy** $\delta\nu / \nu < 10^{-17}$

Optical clock applications

• Optical clocks on Earth

- New definition of SI second (secondary representation of the SI second)

-Comparison between optical clocks (neutrals, ion, molecules) for test of fundamental constants (a, m_e/m_p)

- test of Local position invariance

- deep space navigation (ESA-DSA) , VLBI (ALMA)

• Optical clocks in Space (…?)

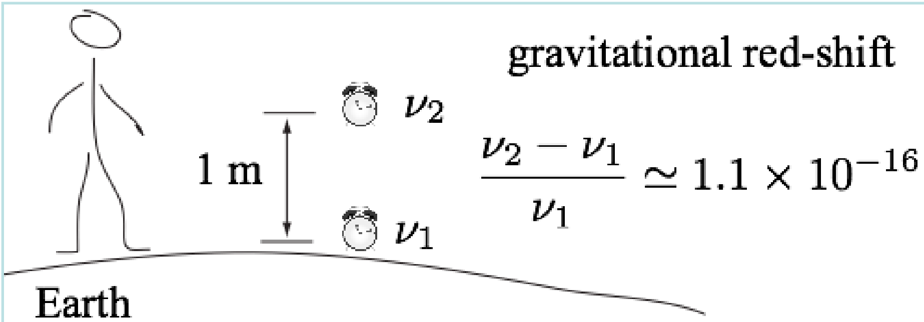
- General Relativity tests (isotropy violations, LPI violation, time dilation, gravitational red shift) (ACES, EGE, SAGAS, SOC)

S. Schiller et al., Exp. Astron. **23**, 573 (2009)
P. Wolf et al., Exp. Astron. **23**, 651, (2009).

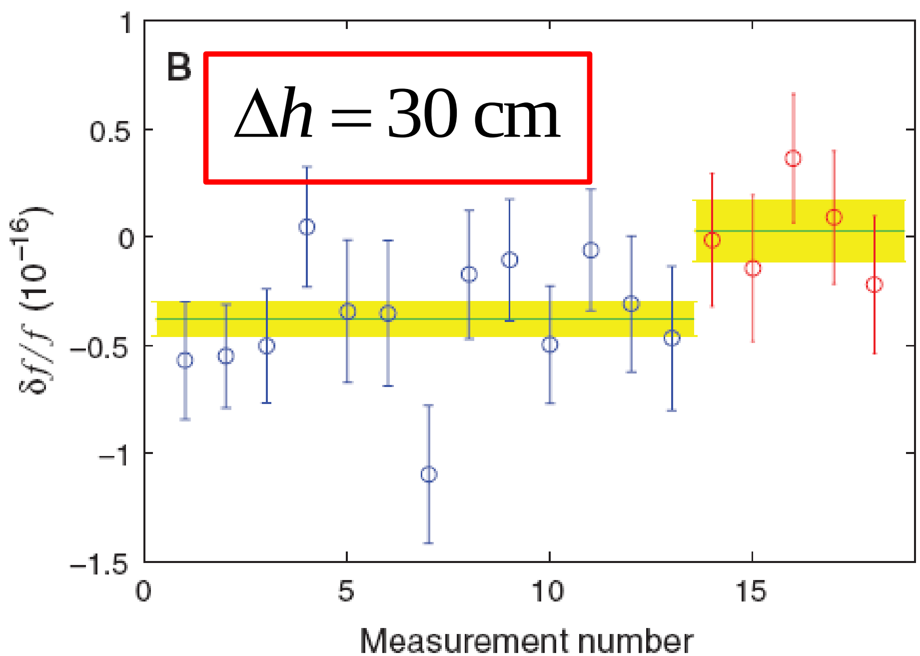
- Earth navigation and geodesy (Galileo II, … III) (ASI-ORA)

-Broadband and secure telecom, …

Gravity and Clocks



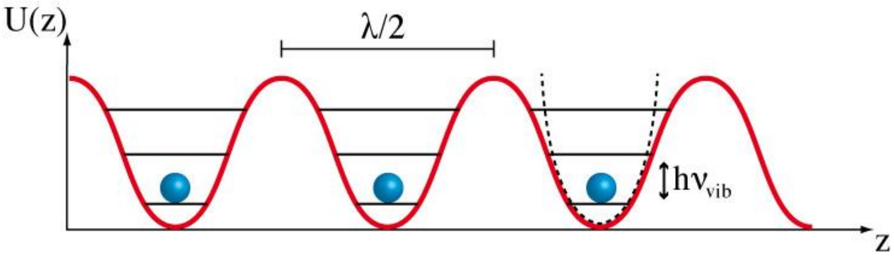
For clocks aiming at **10^{-18} relative accuracy** (1 s over 1 billion years!) a **precise knowledge of gravitational potential** will be necessary



$$\frac{\delta f}{f_0} = \frac{g \Delta h}{c^2}$$

C. W. Chou, D. B. Hume, T. Rosenband, and D. J. Wineland , Science **24**, 1630(2010)

Optical Lattice Clocks

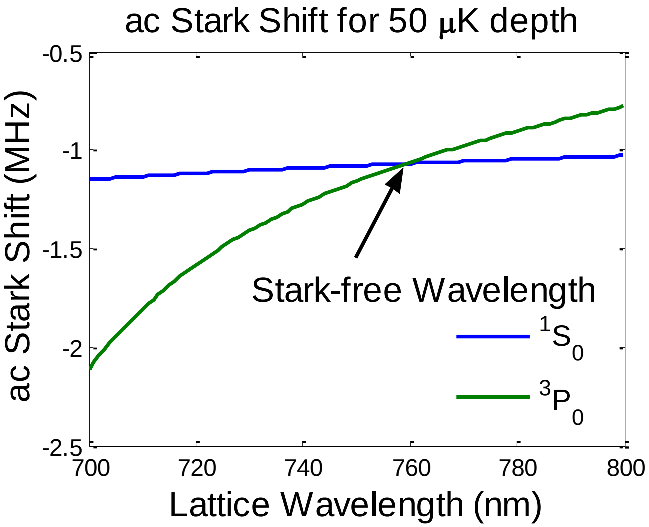


- Long interaction times -> very high Q's
- Large numbers (10^4-10^5) -> good signal-to-noise, high stability

$$\nu_{vib} \gg \nu_R$$

- Tight (Lamb-Dicke) confinement -> Doppler, recoil-free spectroscopy

$$\hbar k_0 = Mv \;\Rightarrow\; \nu_R \equiv \frac{Mv^2}{2}\frac{1}{h} = \frac{1}{4\pi}\frac{\hbar k_0^2}{M}$$



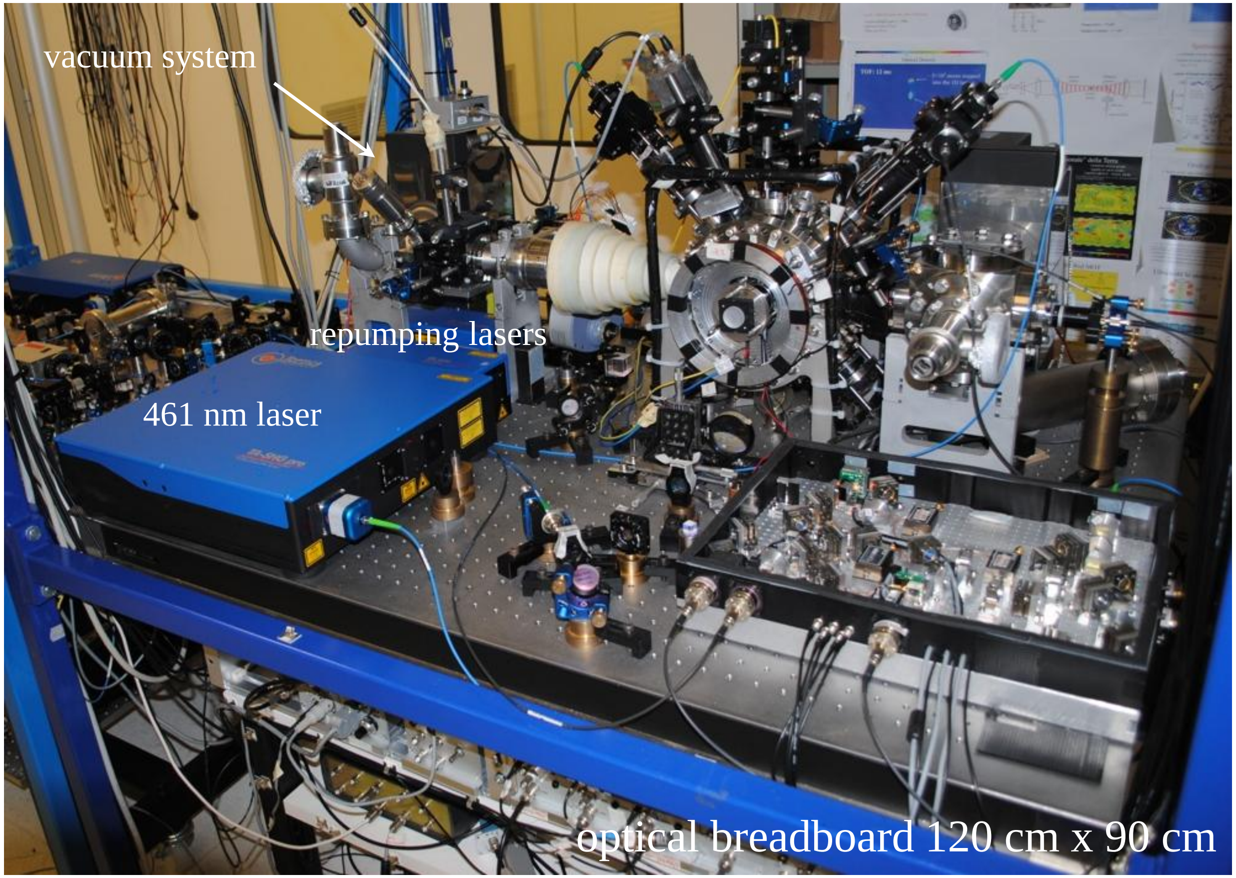
- Lattice causes up to MHz type shifts on both ground and excited states
- At "magic" wavelength differential polarizability is zero

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)

Compact laser-cooling strontium source

main guidelines:

1. compact design and reduced power consumption
2. operation reliability and stability
3. modularity



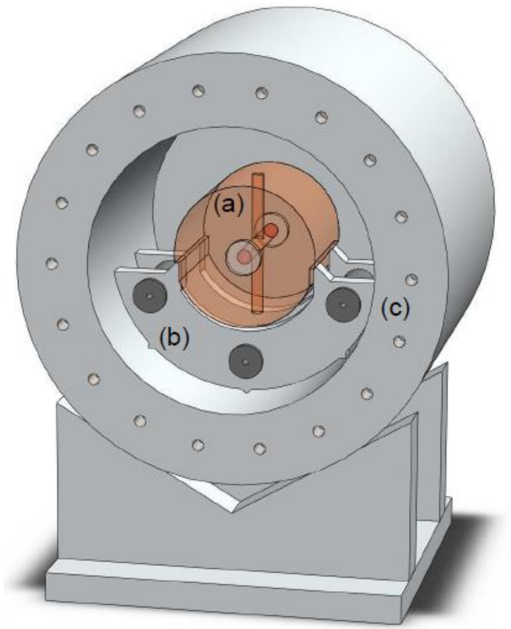
- "Space Optical clocks" (SOC) - ESA

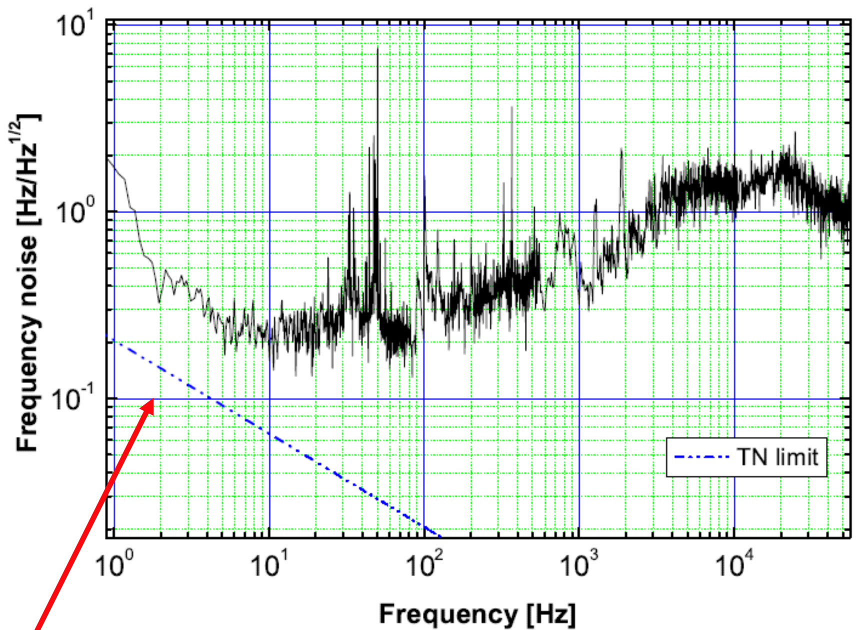
- SOC2 –EU-FP7

- M.Schioppo et al., *Proceedings of EFTF 2010*
- M.Schioppo, *Ph.D. Thesis 2011, online*
-S. Schiller et al. (SOC2 team), "*The Space Optical Clocks Project: Progress report*", IEEE (2012)
- M.Schioppo et al., Rev. Sci Instrum (2012)

698 nm ECDL clock laser

-Frequency stabilization of 698 nm ECDL to **high finesse horizontally mounted cavity** (**Δν ~1 Hz**) (ULE spacer +fused silica mirrors)





Low sensitivity to acceleration

Vertical: k_y = 3 kHz/ms^{-2} (vertical)

Horizontal: k_z=20 kHz/ms^{-2} (horizontal)

Low thermal noise limit:

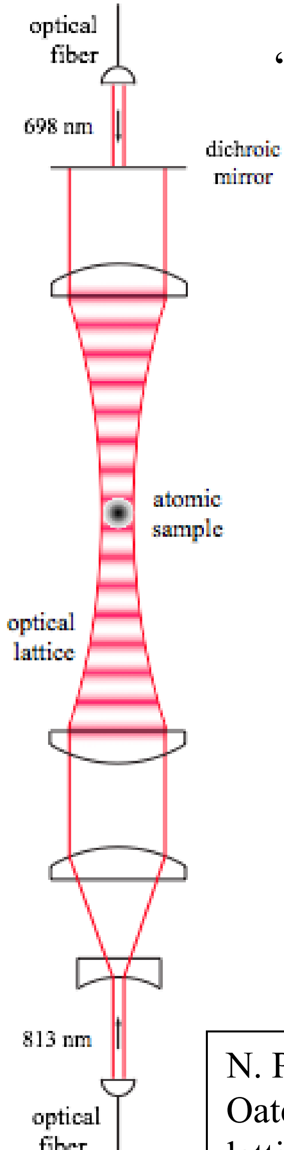
$\sigma_y \sim 4 * 10^{-16}$

- factor of three above the cavity thermal noise between 2 Hz and 11 Hz

M. G. Tarallo, N. Poli, M. Schioppo, D. Sutyrin and G. M. Tino, Appl. Phys. B **103**,17 (2011)

Optical lattice at 813 nm for clock spectroscopy

• increase the interaction time



"magic" wavelength 813 nm

optical power 290 mW

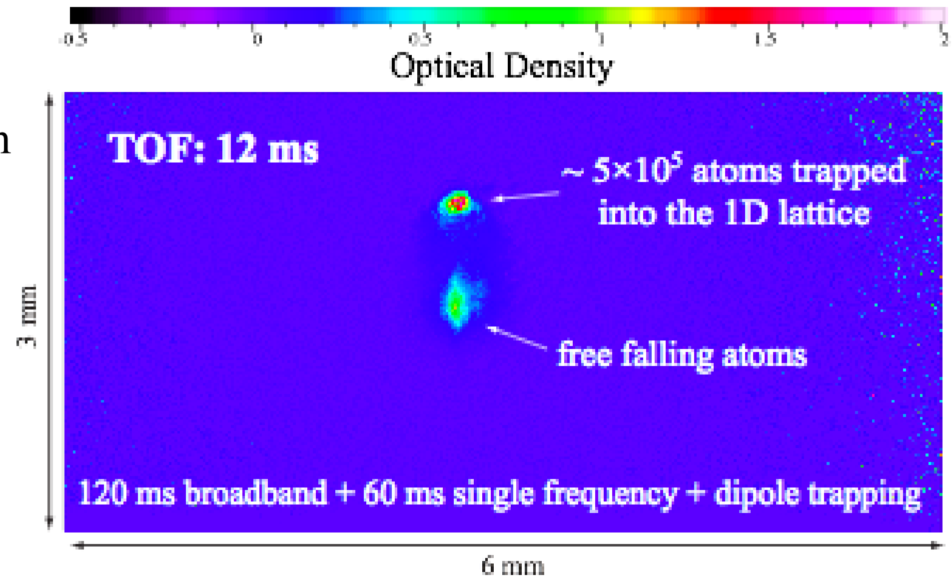
waist 30 μm

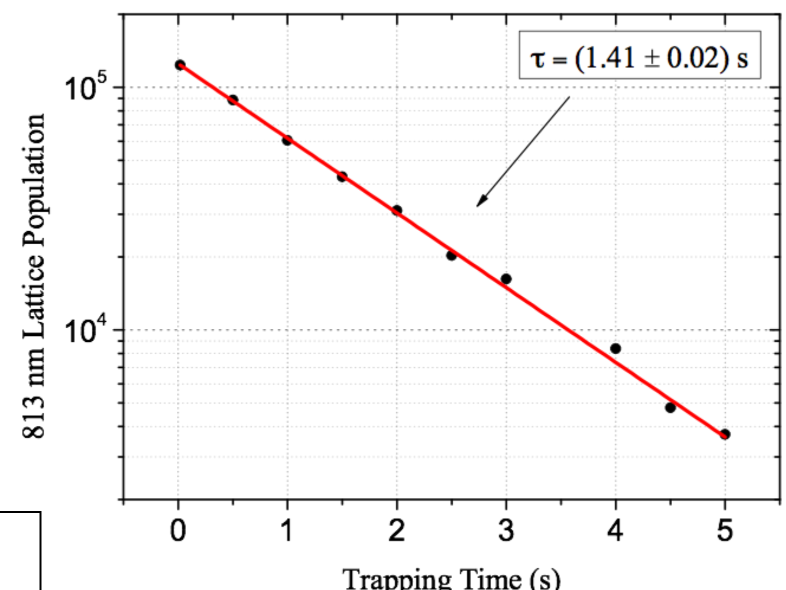
50% loading efficiency

1.4 s trap lifetime

free running
tapered amplifier diode laser

N. Poli, M. G. Tarallo, M. Schioppo, C. W. Oates and G. M. Tino "A simplified optical lattice clock", Appl. Phys. B 97, 27-33 (2009)



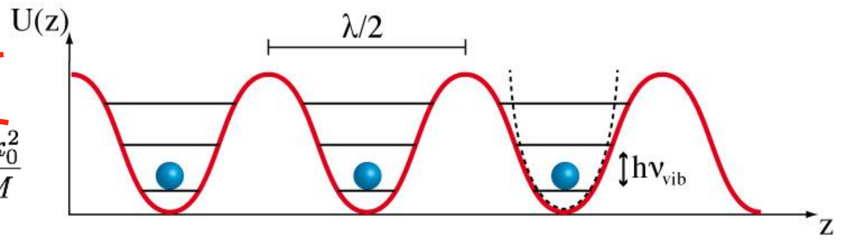


Clock Spectroscopy on ^{88}Sr in Lamb-Dicke regime

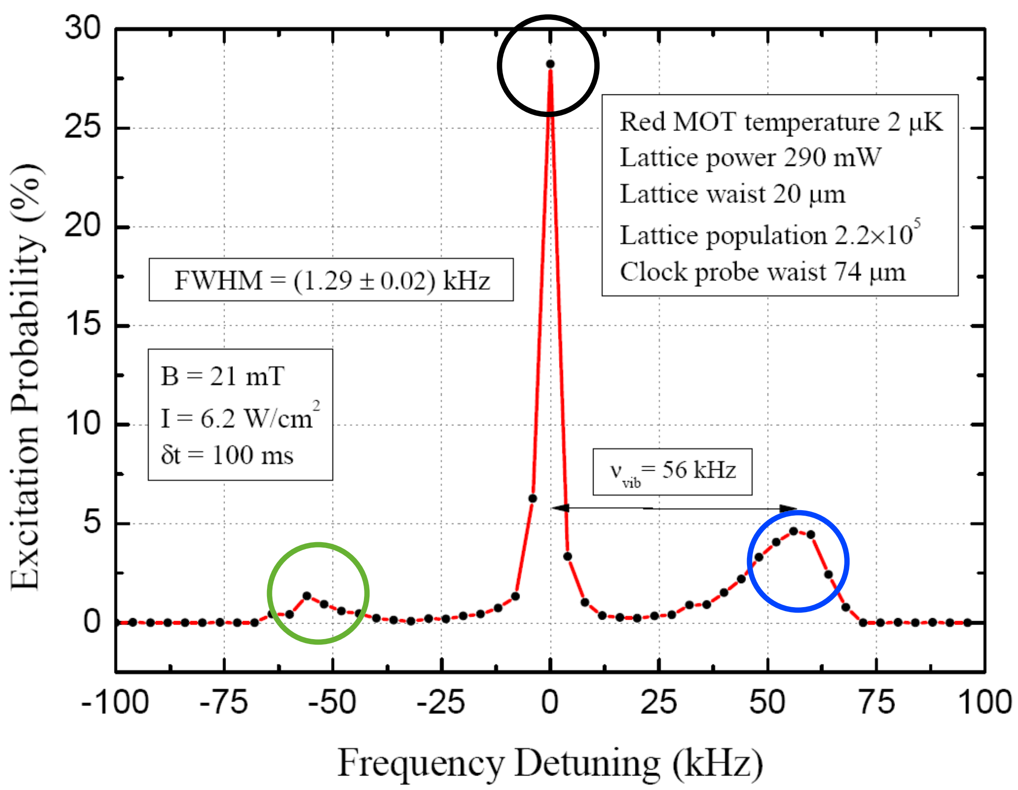
- *Lamb-Dicke* regime
  $\nu_{vib} \gg \nu_R \quad (\simeq 4\,\mathrm{kHz})$

→ ~~*Doppler and recoil shift*~~

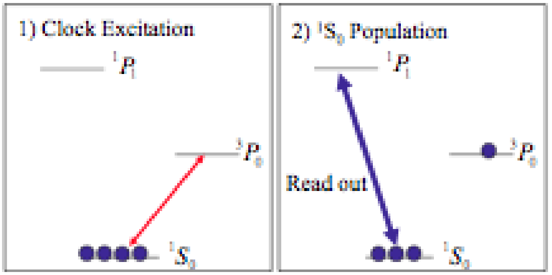
$$\hbar k_0 = Mv \Rightarrow \nu_R \equiv \frac{Mv^2}{2}\frac{1}{h} = \frac{1}{4\pi}\frac{\hbar k_0^2}{M}$$

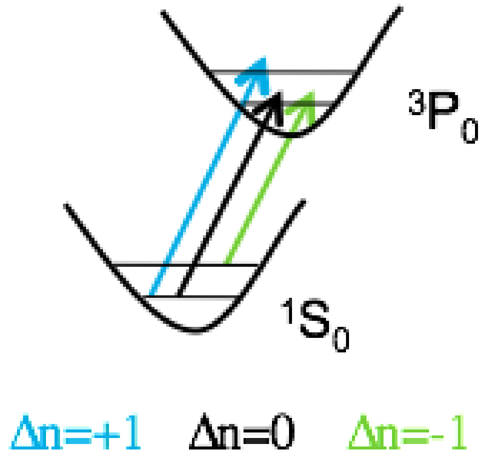


resolved sidebands regime $\quad \nu_{vib} \gg \gamma_{clock}$

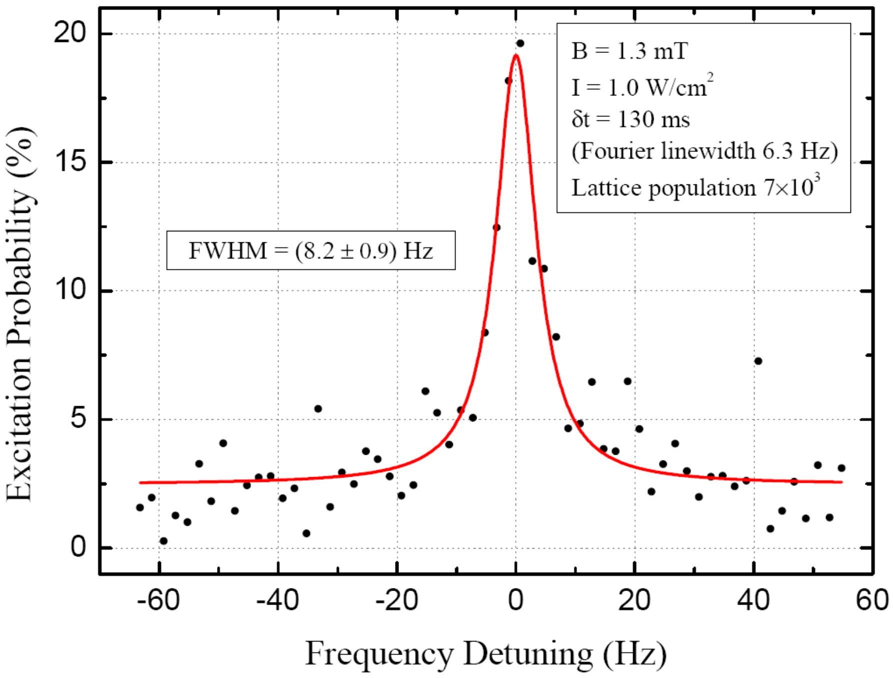


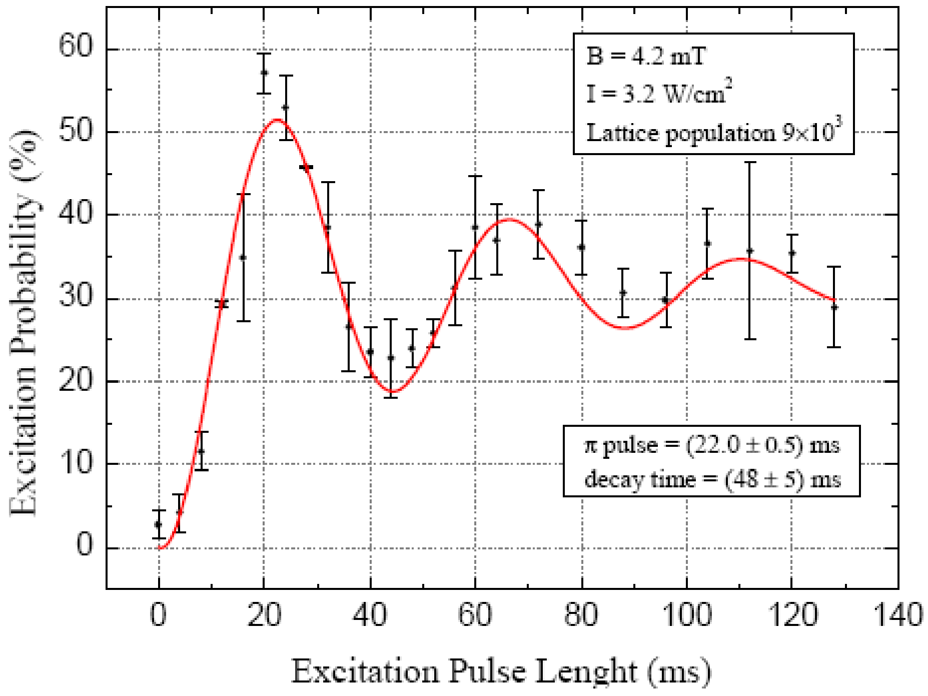
spectroscopy sequence:





^{88}Sr lattice spectroscopy

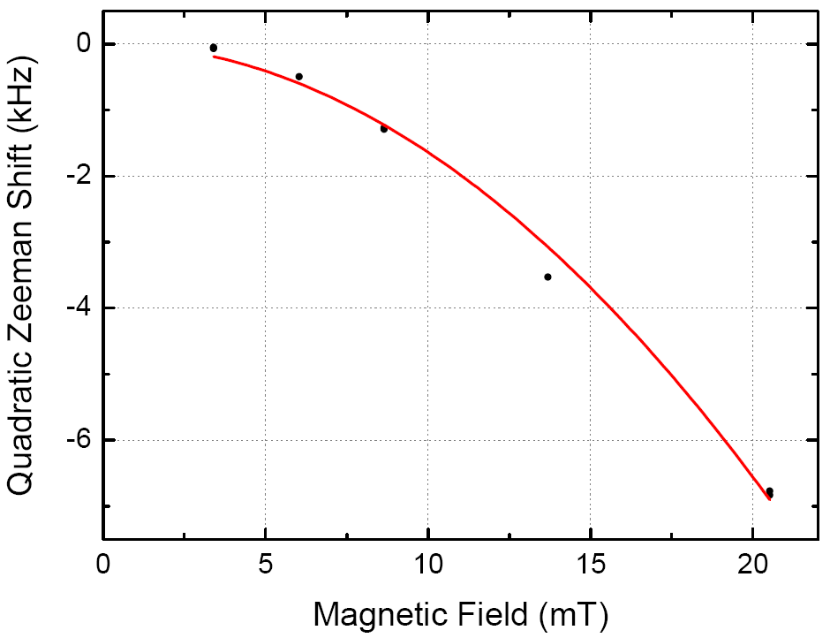


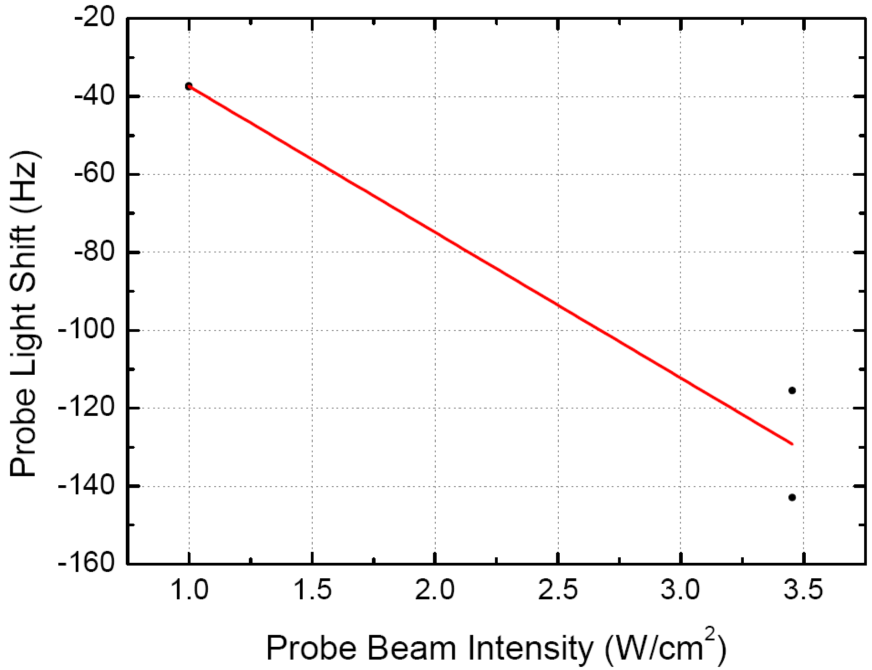


$$Q = \frac{\nu_0}{\delta\nu} \approx 5*10^{13}$$

Systematics evaluation (preliminar)

• magnetic field induced spectroscopy on bosonic ^{88}Sr





$$\Delta_B = \beta |\mathbf{B}|^2$$

$$\beta_{Sr} = -23.3 \frac{\mathrm{MHz}}{\mathrm{T}^2}$$

$$\Delta_L = kI$$

$$k_{Sr} = -18 \frac{\mathrm{mHz}}{\mathrm{mW/cm}^2}$$

V. Taichenachev *et al*. Phys. Rev. Lett. **96**, 083001(2006)

Z. W. Barber *et al*. Phys. Rev. Lett. **96**, 083002 (2006)

^{88}Sr Clock error budget (preliminar)

Effect	Shift	Uncertainty
1st order lattice Shift	-	0.1 Hz
2nd order Zeeman	-27.7 Hz	0.5 Hz
Probe AC Stark	-37 Hz	6 Hz ←
Density	2.9 Hz	0.8 Hz
Blackbody radiation	2.3 Hz	0.06 Hz
total uncertainty		**6.1 Hz**

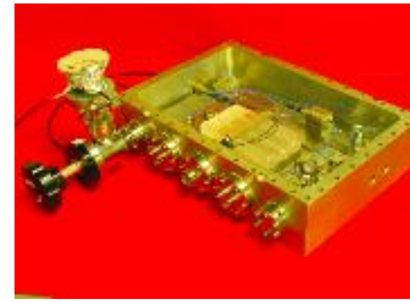
$$\frac{\delta\nu}{\nu_0} \approx 1.5*10^{-14}$$

Ramsey - Hyper Ramsey

V. I. Yudin, A. V. Taichenachev, C. W. Oates, Z. W. Barber, N. D. Lemke, A. D. Ludlow, U. Sterr, Ch. Lisdat, and F. Riehle Phys. Rev. A **82**, 011804

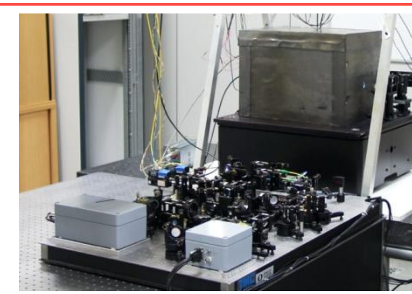
Integration with compact subsystems for realization of a transportable strontium lattice clock

FSS
(Frequency Stabilization System)
from NPL and Dusseldorf University



2nd stage cooling system
(transportable version)
from Dusseldorf and Hannover University

transportable clock laser
from Hannover University and PTB

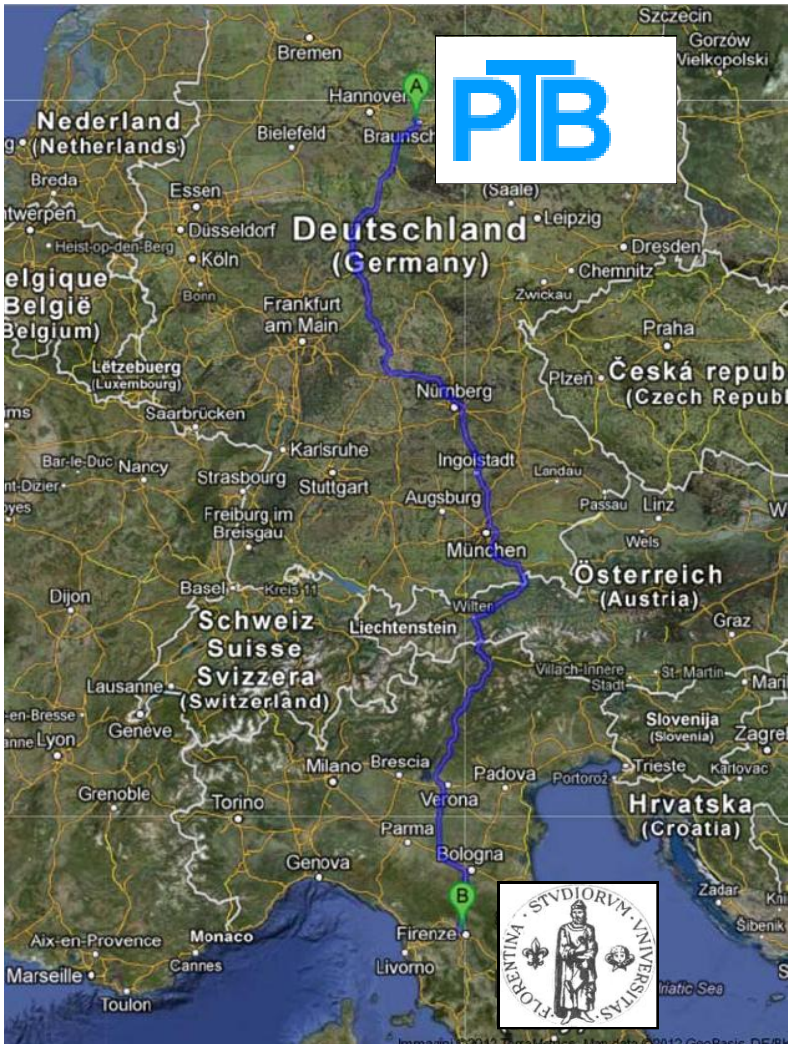


PTB
HEINRICH HEINE UNIVERSITÄT DÜSSELDORF
Leibniz Universität Hannover
l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace
INRIM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
UNIVERSITY OF BIRMINGHAM
NPL National Physical Laboratory
TOPTICA PHOTONICS
KAYSER-THREDE
Ein Unternehmen der OHB Technology AG
EADS astrium
MenloSystems GmbH
KAYSER ITALIA
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LTF Université de Neuchâtel unine
csem centre suisse d'électronique et de microtechnique

SEVENTH FRAMEWORK PROGRAMME

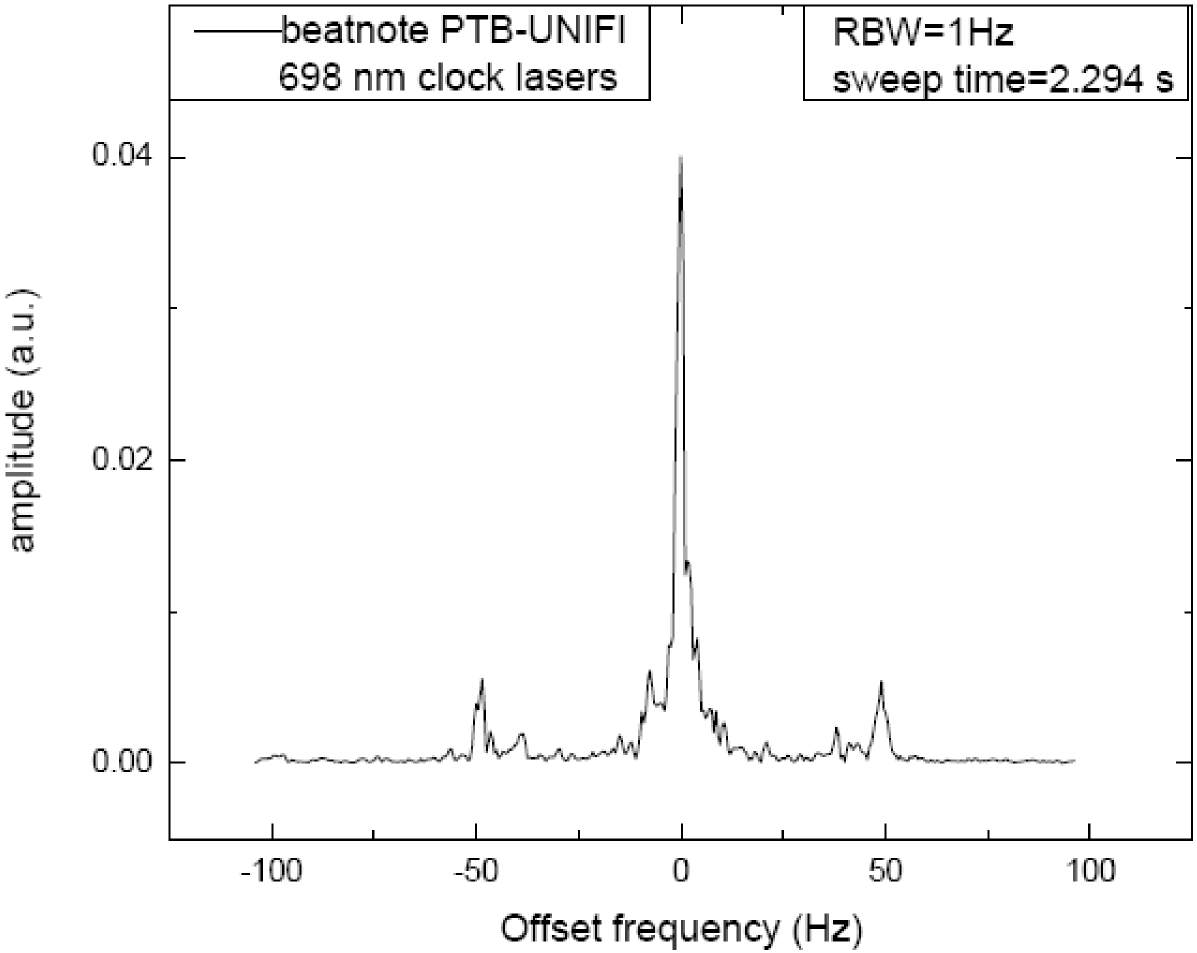
698 clock laser comparison

- ~1300 km transportation PTB-> UNIFI

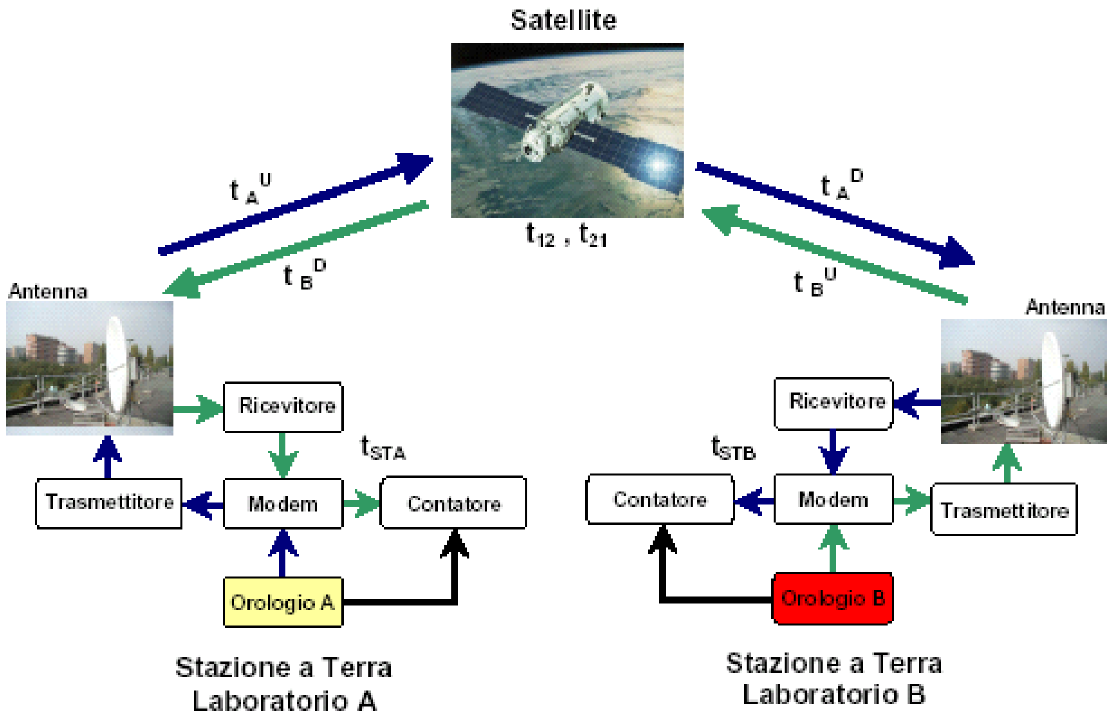


698 clock laser comparison

• beatnote with stationary UNIFI 698 nm clock laser (2 days after PTB laser transportation)



Two-way satellite T&F transfer



IEN	Torino (ITA)
TUG	Graz (OST)
NPL	Teddigton (UK)
VSL	Delft (NL)
DTAG	Darmstadt (GER)
PTB	Braunschweig (GER)
OCA	Grasse (FR)
NIST	Boulder (USA)
USNO	Washington D.C. (USA)

$$T_A - T_B = \frac{\Delta t_A - \Delta t_B}{2} + \frac{t_A^U - t_B^U + t_A^D - t_B^D}{2} + \frac{t_{12} - t_{21}}{2} + \Delta t_S + \Delta t_A^{ST} + \Delta t_B^{ST}$$

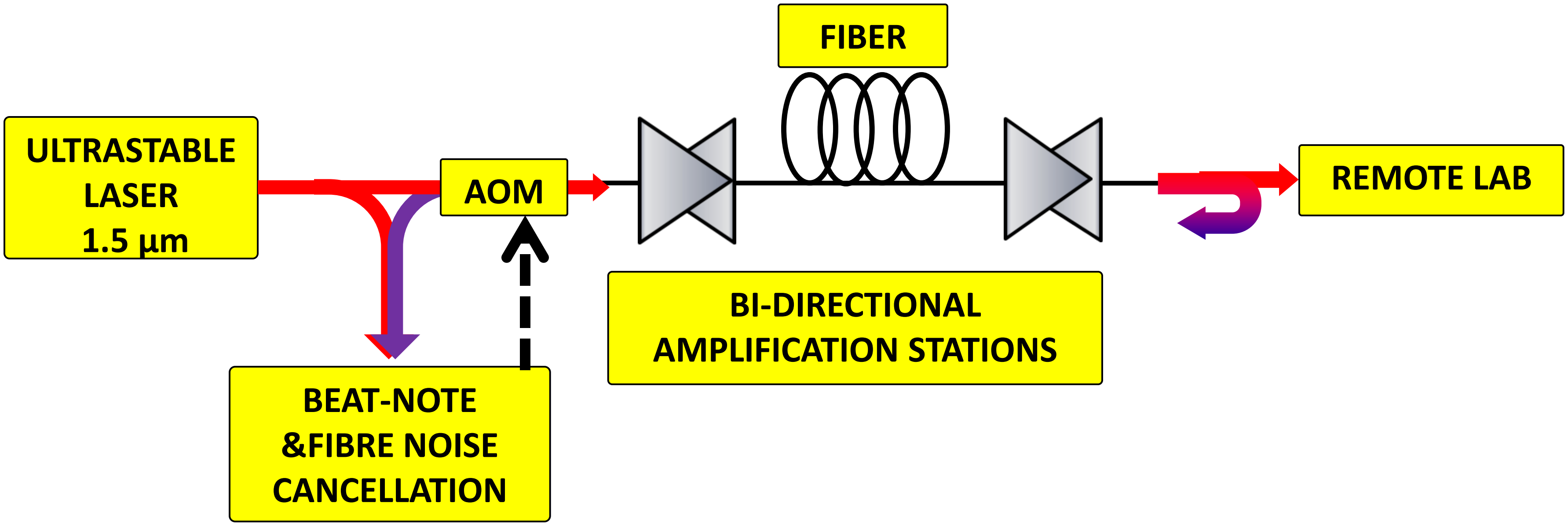
$10^{-9}(1\ s)$

$-10^{-15}(10\ days)-$

Frequency transfer stability

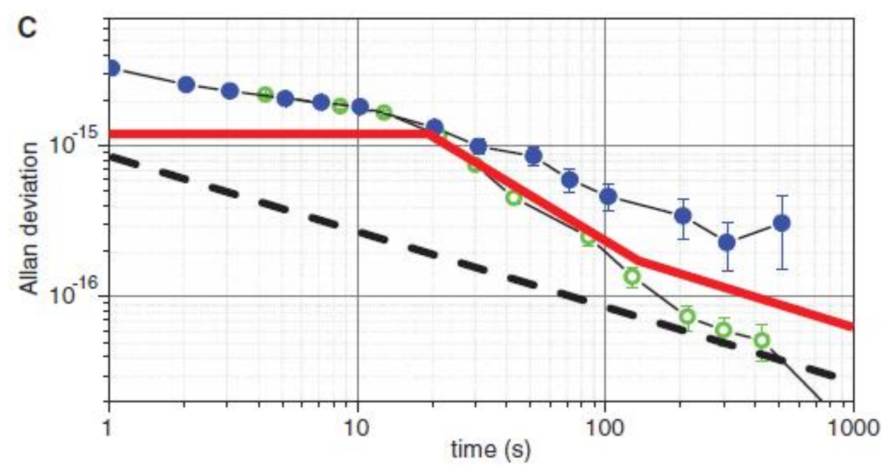
NOT for optical clocks !!

Optical fiber links



Sr Lattice Clock at 1×10^{-16} Fractional Uncertainty by Remote Optical Evaluation with a Ca Clock

A. D. Ludlow,[1] T. Zelevinsky,[1]* G. K. Campbell,[1] S. Blatt,[1] M. M. Boyd,[1] M. H. G. de Miranda,[1] M. J. Martin,[1] J. W. Thomsen,[1]† S. M. Foreman,[1]‡ Jun Ye,[1]§ T. M. Fortier,[2] J. E. Stalnaker,[2]|| S. A. Diddams,[2] Y. Le Coq,[2] Z. W. Barber,[2] N. Poli,[2]¶ N. D. Lemke,[2] K. M. Beck,[2] C. W. Oates[2]



3.5 km optical fiber link

$-10^{-16}(100\ s)!!!-$

Science (2009)

630 km UNIFI-INRIM fiber link

Fiber link from LENS – UNIFI (Firenze) to INRIM (Torino) - 630 km

Torino:
2 Cs fountains
(one cryogenic),
3 Hydrogen masers,
1 Yb lattice clock
(under development)

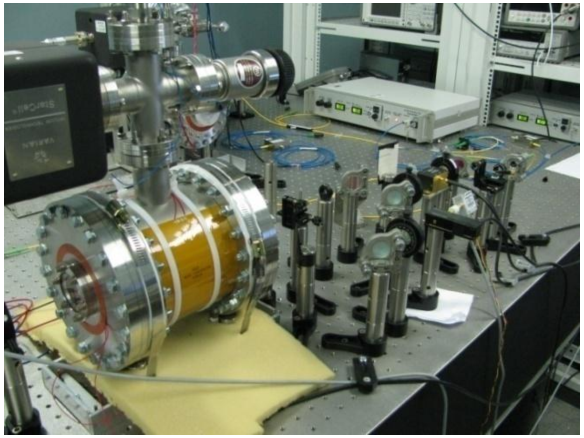
Firenze:
Sr lattice clock

630 km link : n.9 EDFAs, n.2 1.5 μm laser

Ministero dell'Istruzione dell'Università e Ricerca

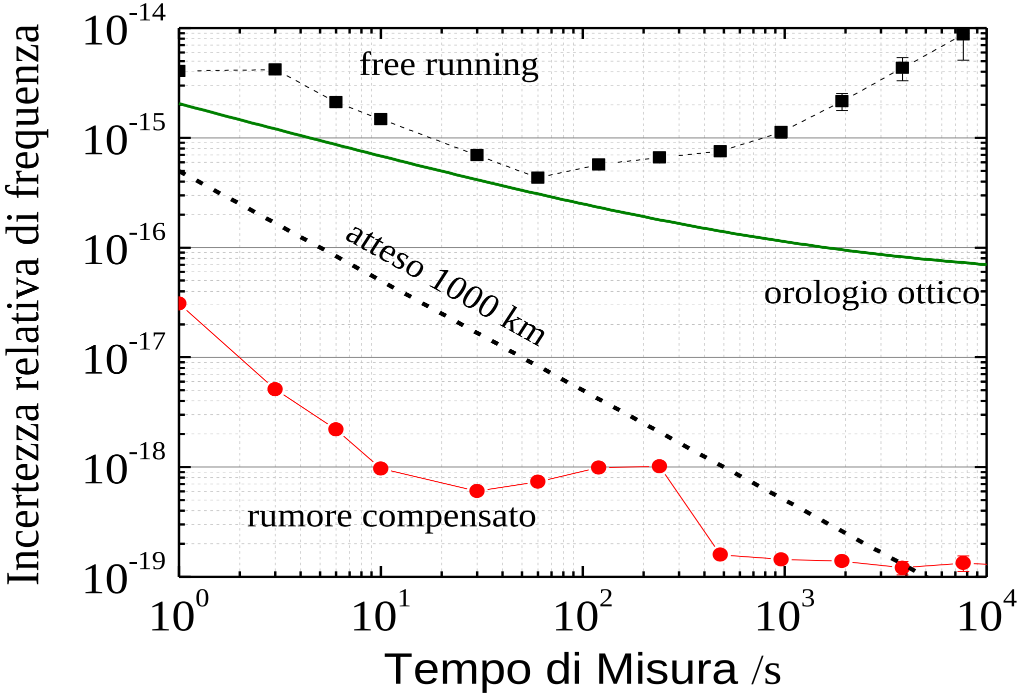
PRIN 2009

First tests on link at INRIM

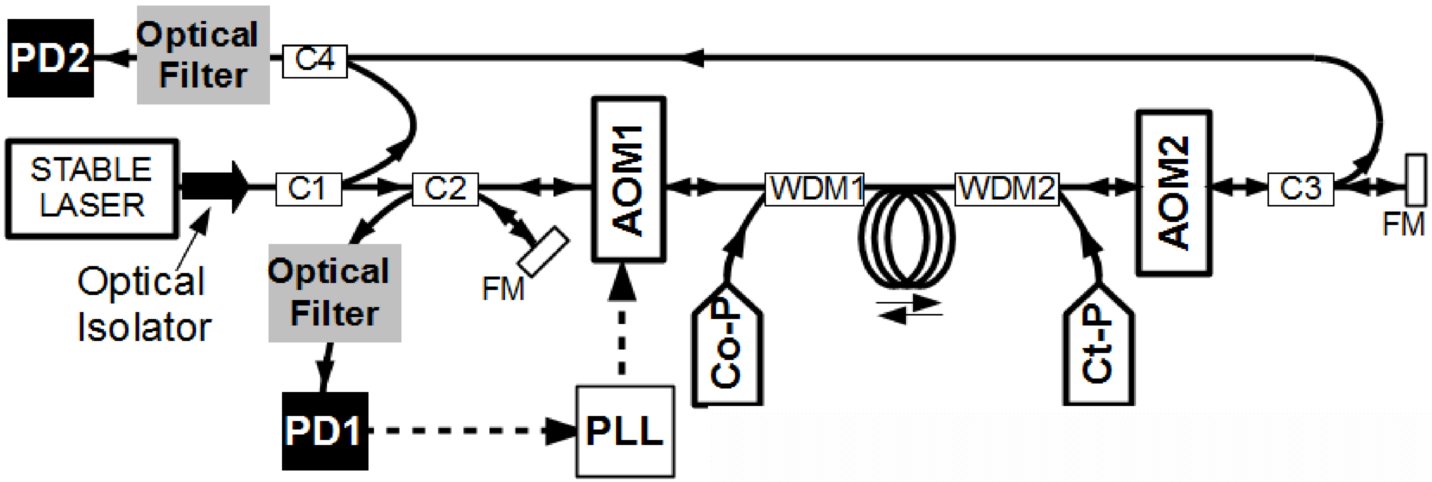


Ultrastable 1.5 micron laser stabilized on high finesse optical cavity

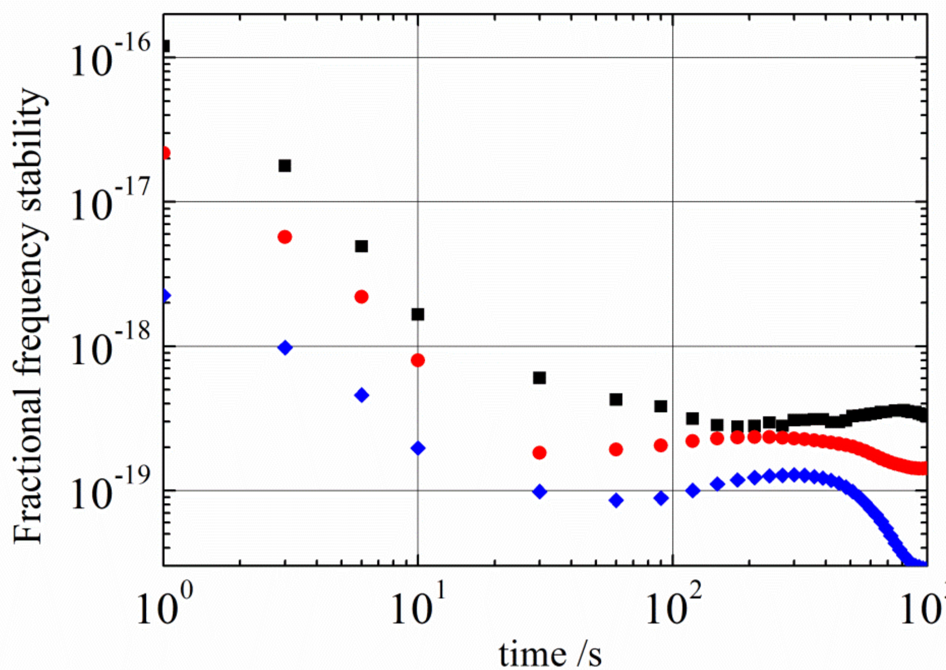
- 100 km fiber spool



Distributed Raman amplification for coherent optical links

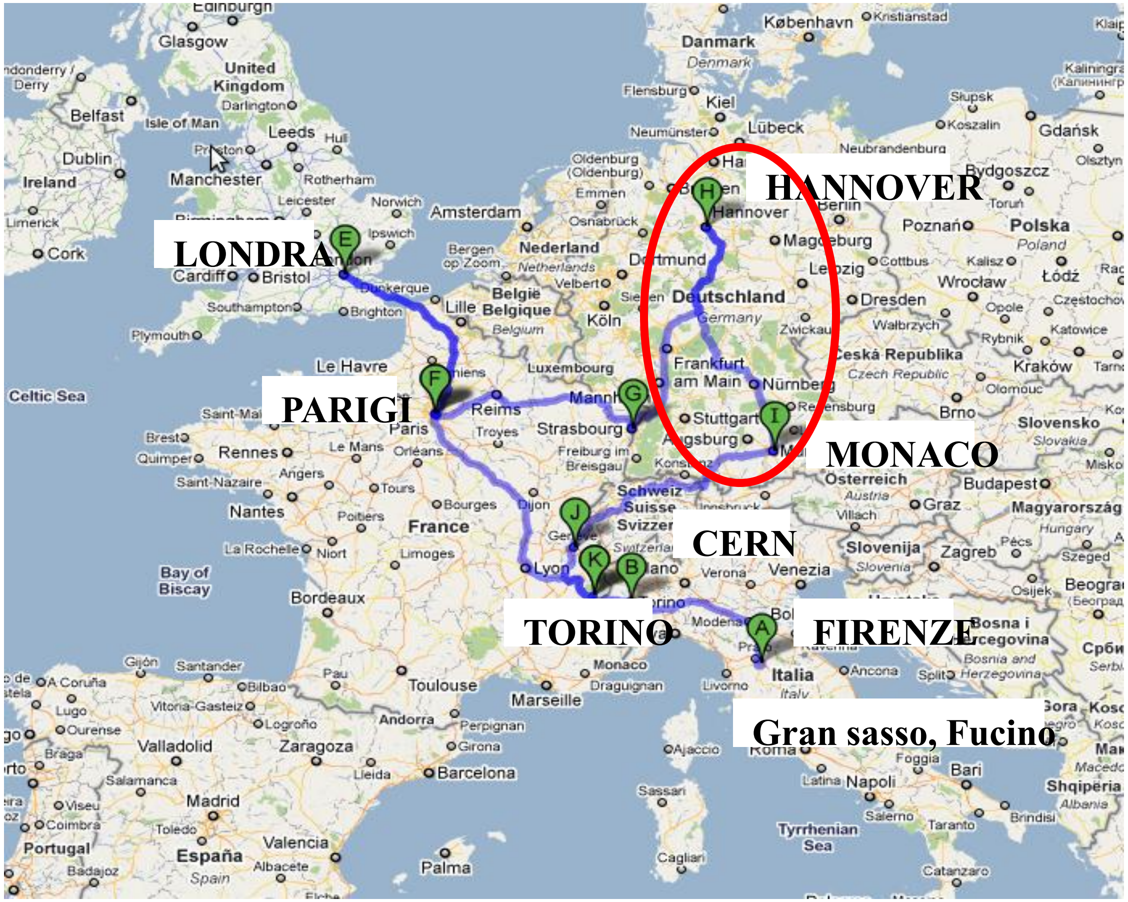


275 km –long fiber link



C. Clivati, G. Bolognini, D. Calonico, S. Faralli, F. Levi, A. Mura and N. Poli , submitted to Optics Letters (2012)

Future Prospect



Pan European network between metrological istitutes and research laboratories

For metrology:

-SI second redefinition
-T&F dissemination

…And fundamental research

- **Quantum optics**
- **Molecular spectroscopy (THz)**
- **Atom interferometry**

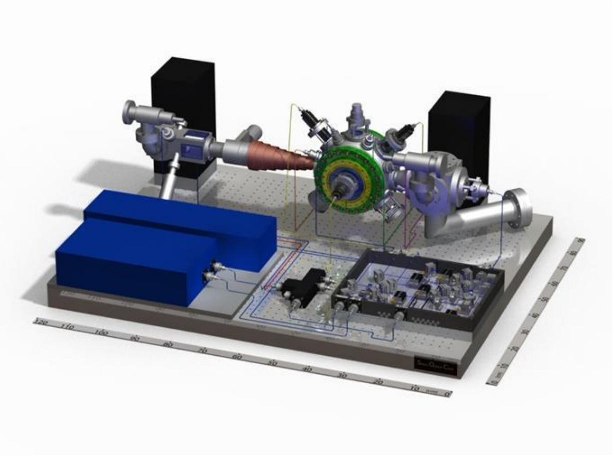
Joint Research Project , European Metrology Research Programme (EMRP)

K. Predehl, G. Grosche. S. M. F. Raupach2, S. Droste1, O. Terra, J. Alnis, Th. Legero, T. W. Hänsch, Th. Udem, R. Holzwarth, H. Schnatz “A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place”, ***Science Vol. 336 no. 6080 pp. 441-444 (2012)***

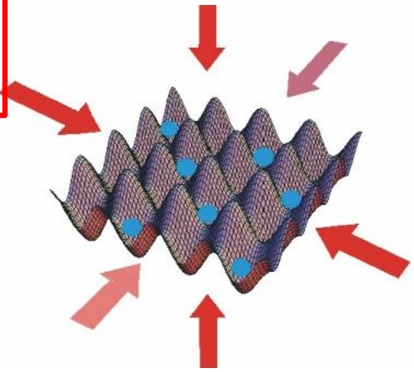
Outline

- Sr transportable optical lattice clock

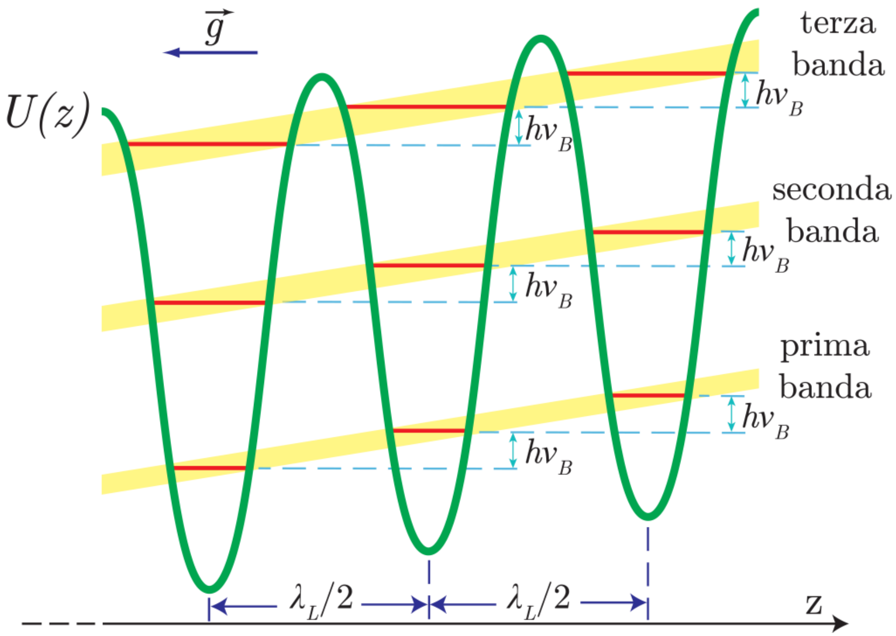
  -Simplified optical lattice clock
  (all-semiconductor laser based optical lattice clock, transfer cavity for first calibration of clock laser optical frequency, magnetic field induced spectroscopy,…)
  -Labs with no metrologic hardware
  -Application in other fields

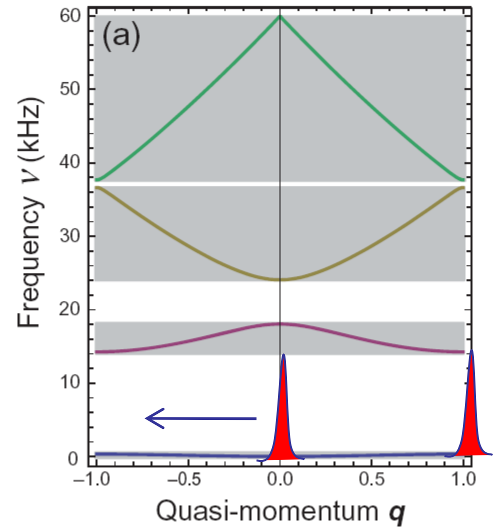


- Cold ^{88}Sr atoms in vertical optical lattice
  - accurate gravimetry with Sr atoms
    (Bloch oscillation of ^{88}Sr atoms in vertical optical lattices, AM modulation tecnique)



Cold atoms in periodic potential





- Add gravity -> U(z) = F*z=Mg*z

$$\mathcal{H} = \frac{p^2}{2M} + \frac{U_o}{2}\cos\left[2k_L\left(z - z_o\right)\right] + Mgz$$

Semiclassical motion of wave packet:

$$k\left(t\right) = k_o - \frac{1}{\hbar}Ft$$

$$v\left(t\right) = \frac{1}{\hbar}\left[\frac{dE\left(k\right)}{dk}\right]_{k=k(t)}$$

- Energy spectrum -> band structure

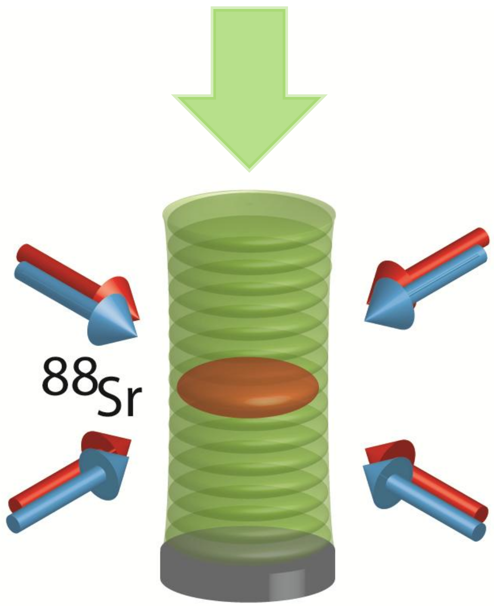
- Eigenfunctions -> Bloch functions
  (delocalized on the lattice)

-> Bloch Oscillation

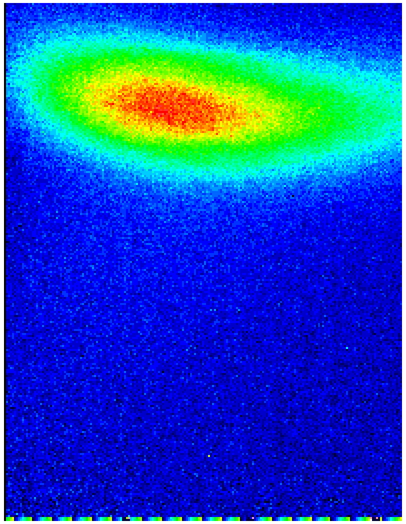
$$h\nu_B \equiv Mg\frac{\lambda_L}{2}$$

Bloch oscillation

- Ultracold Sr atoms in vertical standing wave trap (λ=532 nm, U~5*Er)
- Adiabatic loading of the atoms in the first band (T ~2*Er)
- Bloch oscillations observed with standard time of flight technique



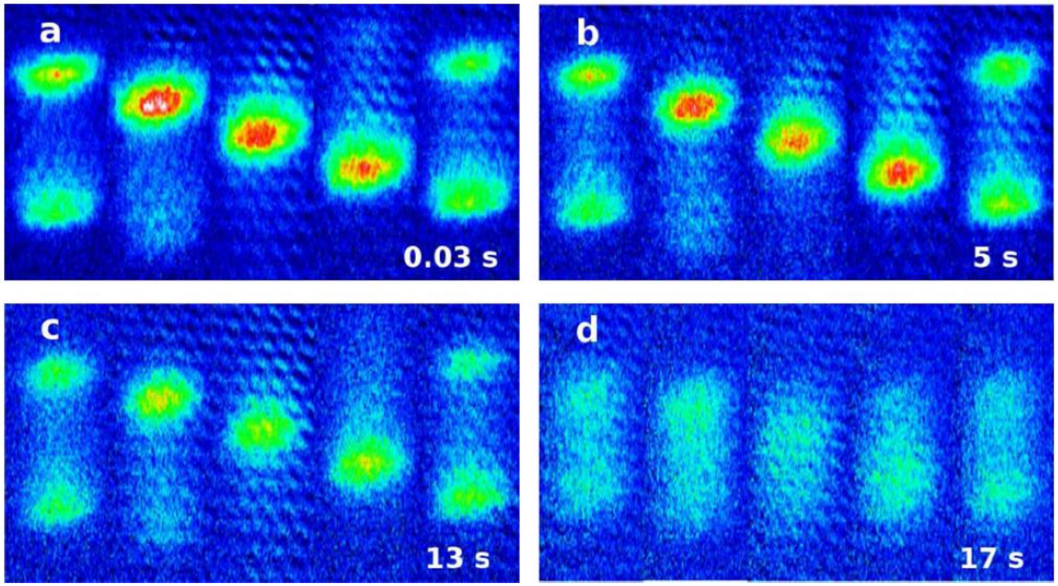
$$\nu_B = m\, g\, \lambda /2\, h$$



G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,*
Phys. Rev. Lett. 97, 060402 (2006)

F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 μm*, **Phys. Rev. A 79, 013409 (2009)**

Improved sensitivity in Bloch frequency

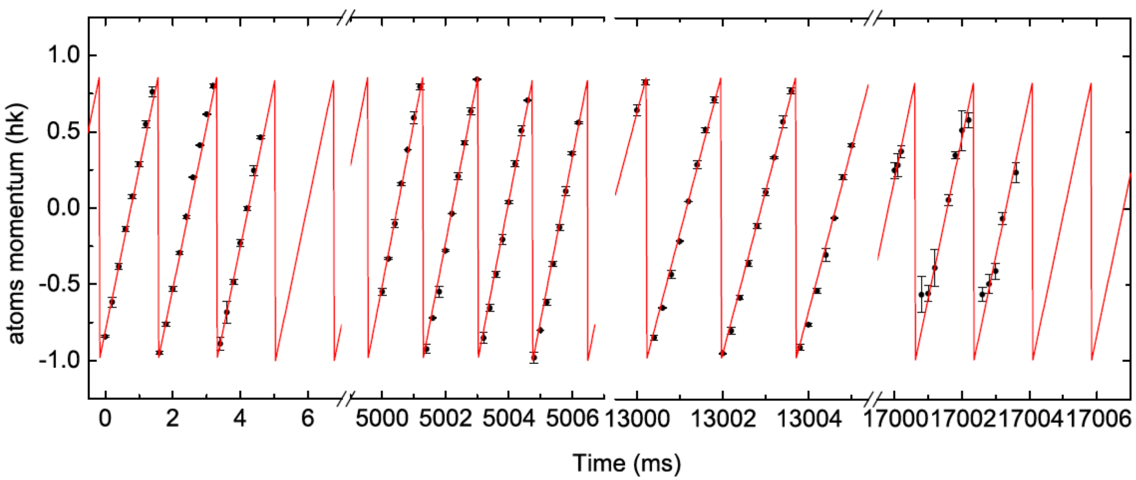


Long lived Bloch oscillation (t = 17 s)

- More than 10^4 recoil momenta transferred to the atomic cloud
- improved sensitivity for gravity measurements

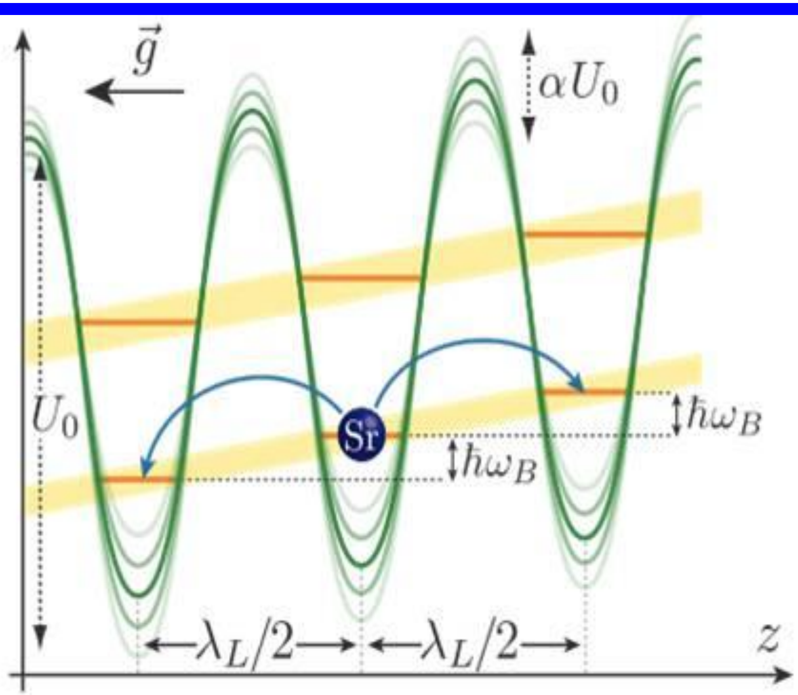
Sensitivity Δg/g:

→ ~2*10^{-7}(~200 ppb)



-Very small decoherence effects!!!

Resonant Tunneling



$$\mathcal{H}_{WS} = \frac{p^2}{2M} + \frac{U_o}{2}\cos\left[2k_L\left(z - z_o\right)\right] + Mgz$$

- Energy spectrum -> discrete energy levels

- Eigenfunctions -> Wannier -Stark functions (localized on each lattice site)

By modulating the amplitude (or phase) of the lattice potential at ν_M=n*ν_M= n* 574.3 Hz, atoms can **tunnel to adjacent lattice sites**

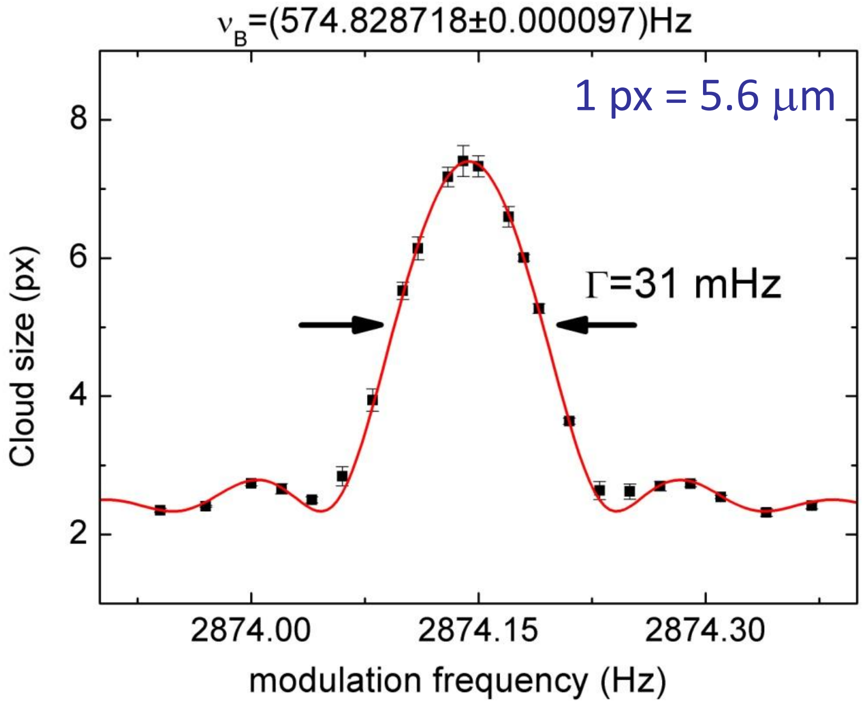
$$z_o \rightarrow z_o + \frac{\Delta_z}{2}\cos\left(2\pi\nu_M t\right)$$

M. Gluck, M. Hankel, A. R. Kolovsky, and H. J. Korsch Phys. Rev. A **61**, 061402(R)

A. Alberti, G. Ferrari, V.V. Ivanov, M. L. Chiofalo, G. M. Tino, *Coherent Transport of Atomic Wave Packets in Amplitude Modulated Vertical Optical Lattices,* **New Journal of Physics 12, 065037 (2010)**

Resonant tunneling

Amplitude modulation at 5th harmonic with **> 10 s interaction time**



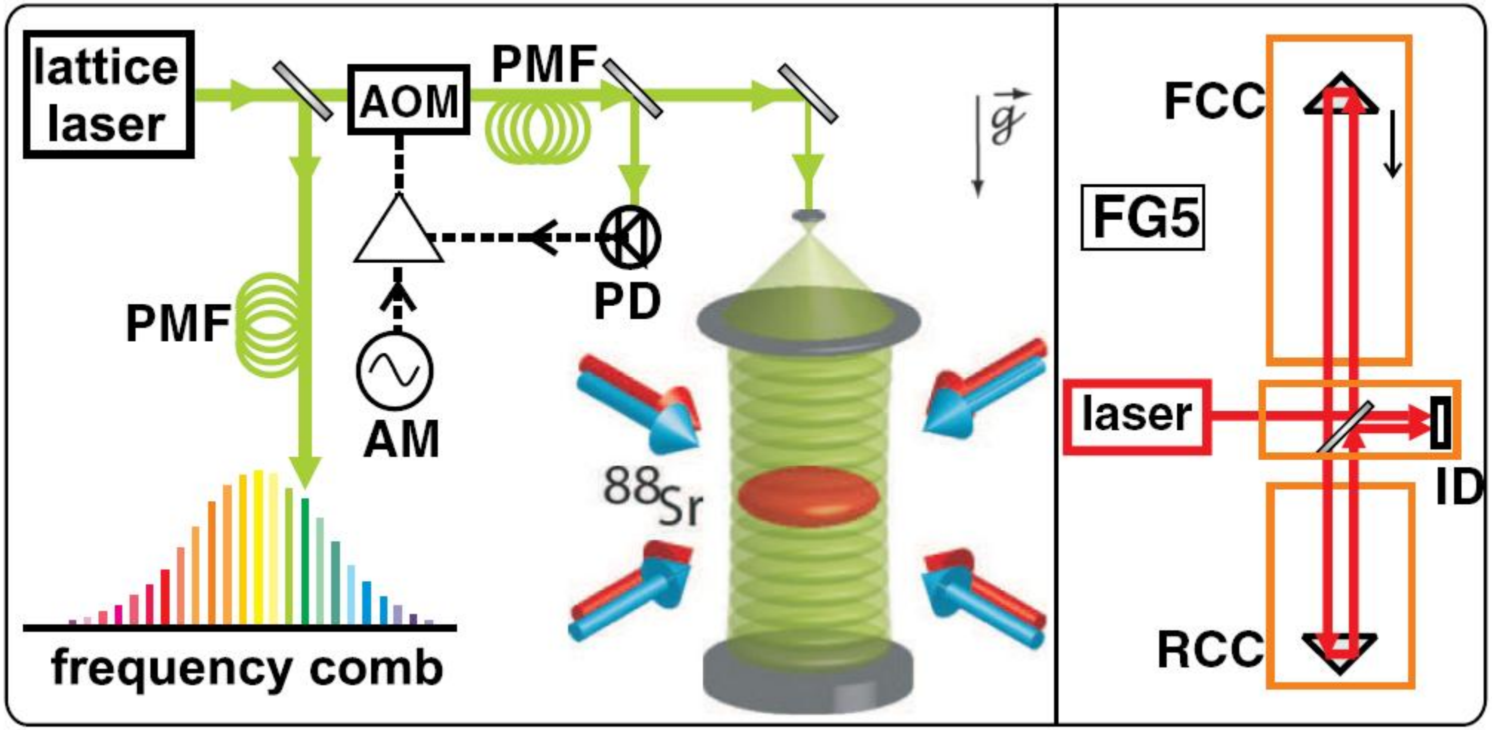
Sensitivity $\Delta g/g$:

→ ~1.7*10^{-7} (~170 ppb)

N. Poli, F. Wang, M. G. Tarallo, A. Alberti, M. Prevedelli and a. G. M. Tino, **PHYSICAL REVIEW LETTERS 106, 038501 (4) (2011)**

Gravity measurements (^{88}Sr vs FG5)

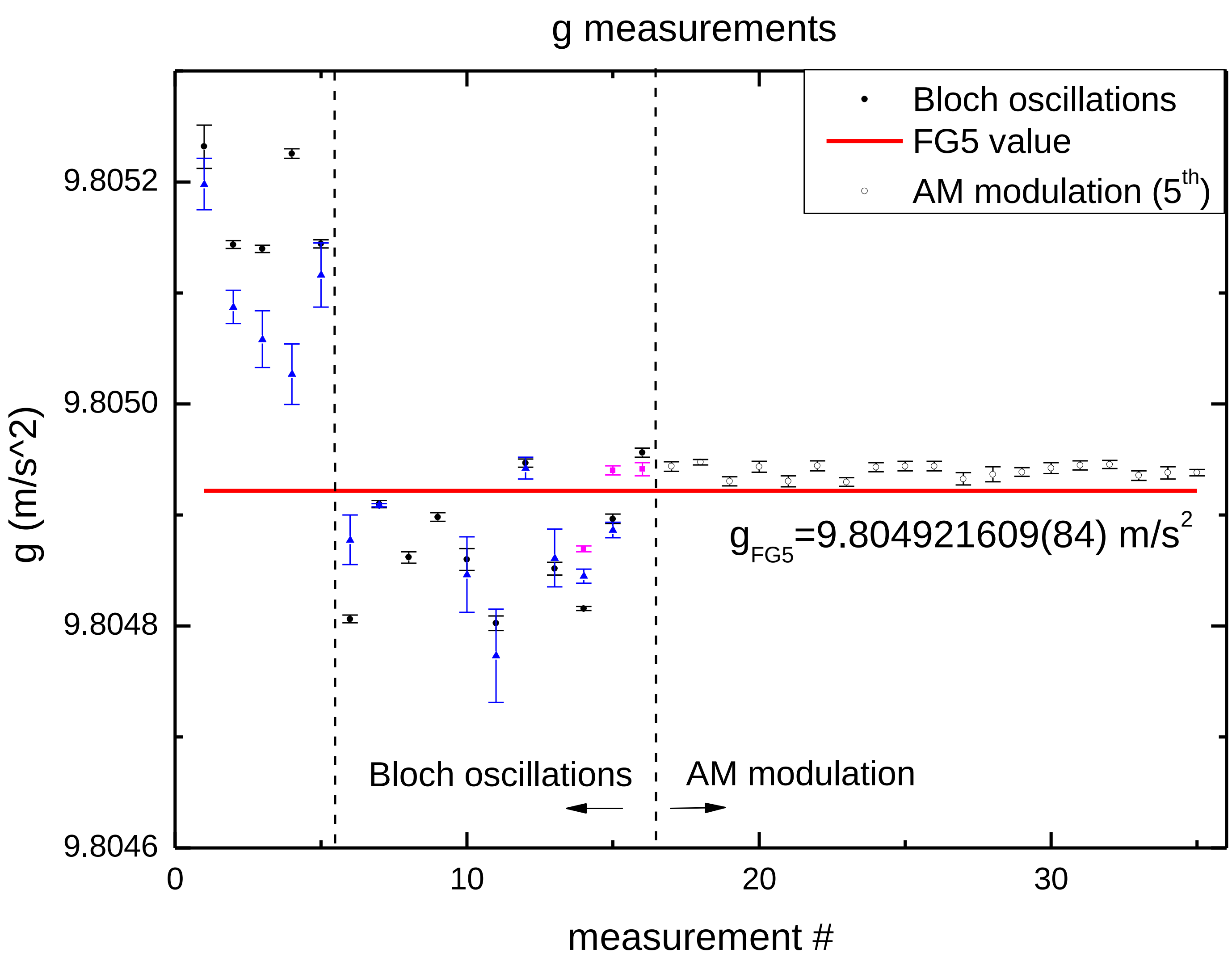
- Comparison between Sr gravimeter with an optical FG5 gravimeter



N. Beverini, N. Poli, D. Sutyrin, F.-Y.Wang, M. Schioppo, M. G. Tarallo , and G. M. Tino "Absolute frequency measurement of unstable lasers with optical frequency combs" - Proc. SPIE 7993, 79931I (2010) - ICONO Conference

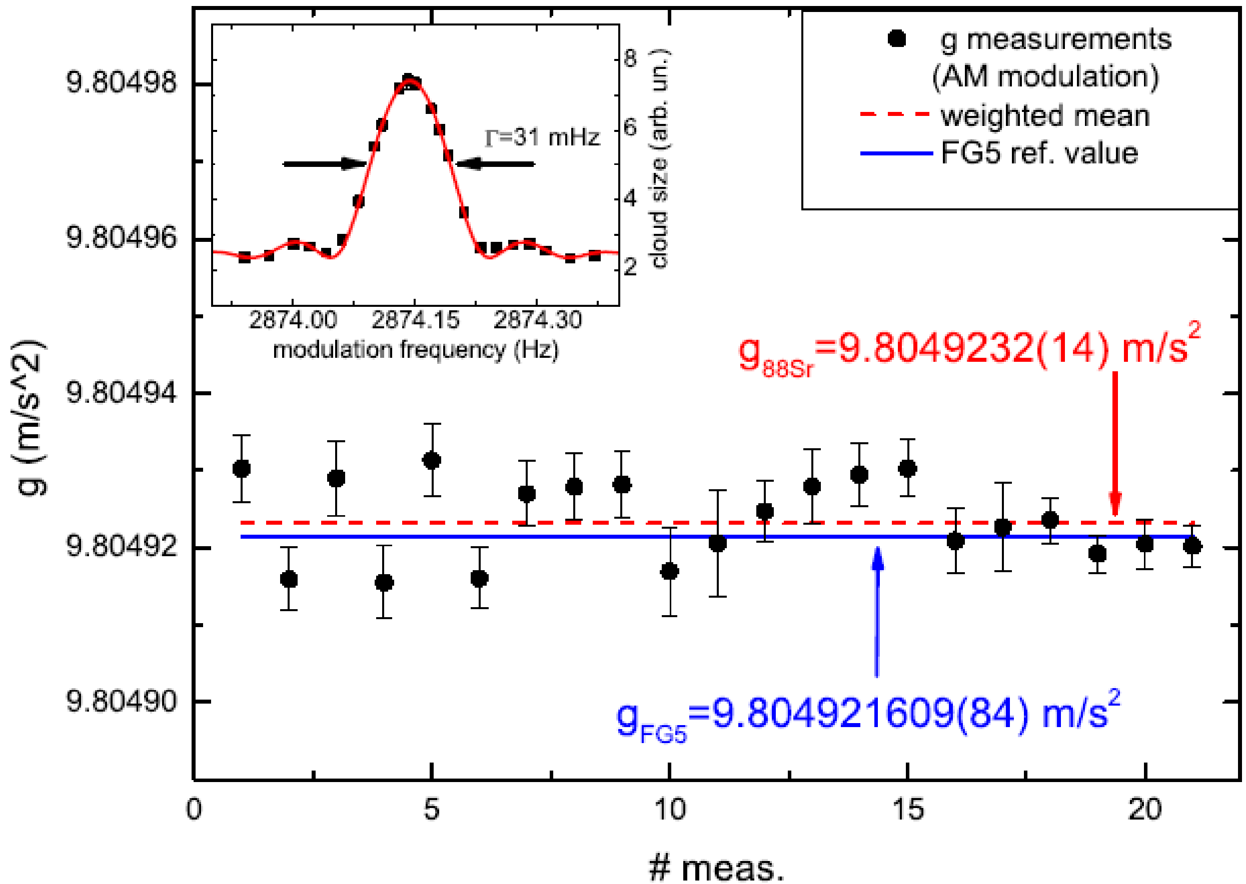
M. D. Angelis, F. Greco, A. Pistorio, N. Poli, M. Prevedelli, G. Saccorotti, F. Sorrentino and G. M. Tino "Absolute gravity acceleration measurement in atomic sensor laboratories", EPJ Plus 127, 1-11 (2012)

Gravity measurements (Bloch vs. AM modulation)



M. G. Tarallo, A. Alberti, N. Poli, M. L. Chiofalo, F.-Y. Wang, G. M. Tino, “Delocalization-enhanced Bloch oscillations and driven resonant tunneling in optical lattices for precision force measurements” – Phys. Rev. A **86**, 033615 (2012)

Final result



Weighted mean of 21 measurements -> $g = 9.8049232\,(14)\ m/s^2$

N. Poli, F. Wang, M. G. Tarallo, A. Alberti, M. Prevedelli and a. G. M. Tino, **PHYSICAL REVIEW LETTERS 106, 038501 (4) (2011)**

140 ppb relative uncertainty

Systematics evaluation

Effect	**relative shift (* 10^{-7})**	**uncertainty (* 10^{-7})**
Lattice wavelength	0	2
Lattice beam vertical align.	0	0.2
Stark shift (beam geometry)	14.3-17.3	0.4
Experiment timing	0	0.2
Tides(p.p.)	-1.4 – 0.9	<0.1
Height difference(^{88}Sr - FG5)	4.3	0.2
Refraction index	0	<0.01
Fundamental constants (m_{Sr} , h)	0	0.7
Systematics total	17.2 – 22.5	**2.2**

rel. uncertainty in the knowledge of m(^{88}Sr) and h ~5*10^{-8} !!

Systematics evaluation

Effect	relative shift (* 10^{-7})	uncertainty (* 10^{-7})		(2012)
Lattice wavelength	0	2	→	**0.01**
Lattice beam vertical align.	0	0.2		
Stark shift (beam geometry)	14.3-17.3	0.4	→	**0.1**
Experiment timing	0	0.2		
Tides(p.p.)	-1.4 – 0.9	<0.1		
Height difference(^{88}Sr - FG5)	4.3	0.2		
Refraction index	0	<0.01		
Fundamental constants (m_{Sr} , h)	0	0.7	→	**0.5**
Systematics total	17.2 – 22.5	**2.2**	→	**0.5**

Upgrade of trapping laser

Frequency stabilization trapping laser to I_2 line

Higher trapping power -> larger waist

New measurements of ^{88}Sr mass ($\Delta m/m \sim 2*10^{-10}$ - R. Rama et al. ICAP (2012))

Test of QED – measurements of α

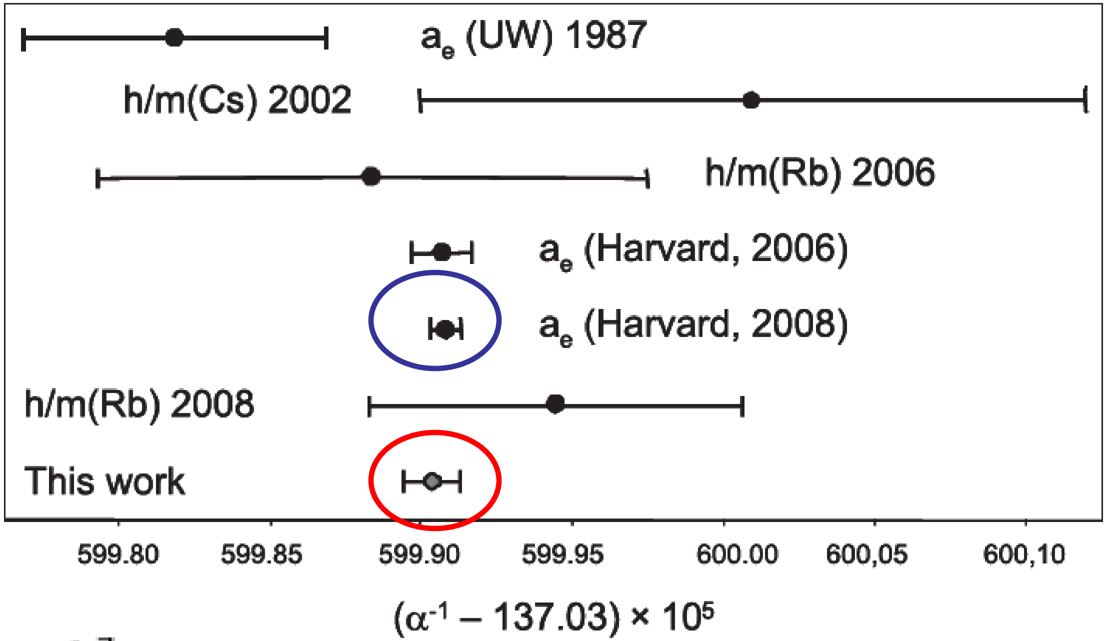
$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{\mathrm{Rb}}}{m_e}\frac{h}{m_{\mathrm{Rb}}},$$

$$v_r = \hbar k/m_{\mathrm{Rb}}$$

$$\alpha^{-1} = 137.035\,999\,037\,(91)$$

rel. uncertainty 6.6×10^{-10}

From Rym Bouchendira,et al. PRL 106, 080801 (2011)



Electron spin anomaly
(Gabrielse 2008)

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu\tau} + a_{\mathrm{hadronic}} + a_{\mathrm{weak}},$$

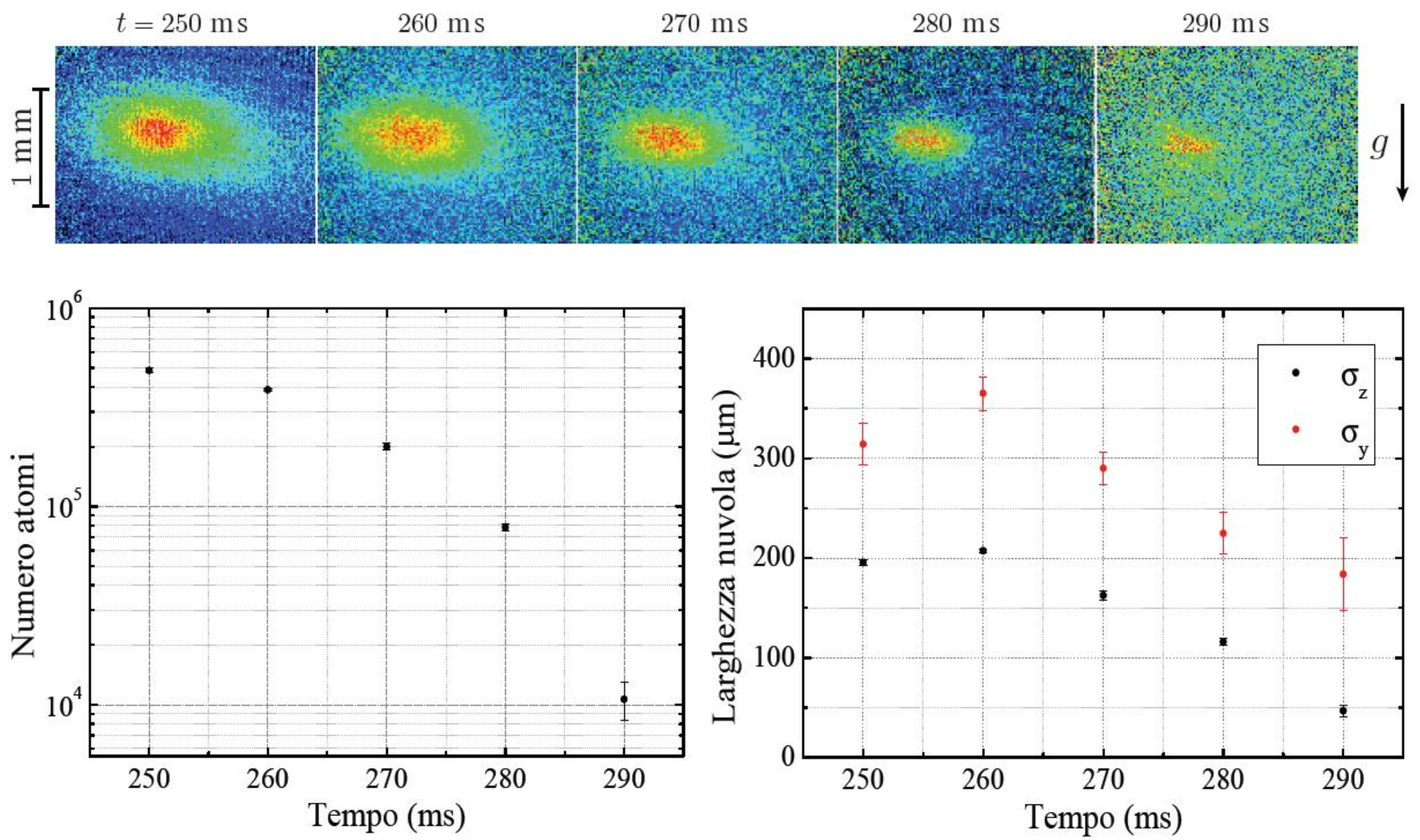
$$\alpha^{-1} = 137.035\,999\,084\,(51) \quad [0.37\ \mathrm{ppb}].$$

Toward an ^{87}Sr-^{88}Sr Einstein Equivalence Principle (EEP) experiment

- **Idea**: probing the effect of gravity on different Sr isotopic species (spin-polarized ^{87}Sr vs perfect scalar ^{88}Sr)
- **EEP**: g does not depend on m and S
- **Quantum mechanical test**: cold atoms in driven optical lattices behave as matter-wavepackets
- **Target:** control systematic uncertainties and Δg measurement precision at 10^{-8} level

Future prospects

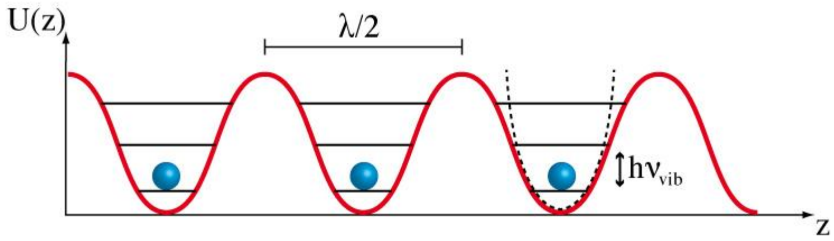
- Cooling and trapping fermionic ^{87}Sr atoms (I=9/2)



-Test of weak equivalence principle ^{87}Sr - ^{88}Sr (I=9/2 vs. I=0)

Outline

- Sr cold atoms in optical lattices:



- Simplified and transportable optical lattice clock

- Accurate gravimetry with Sr atoms

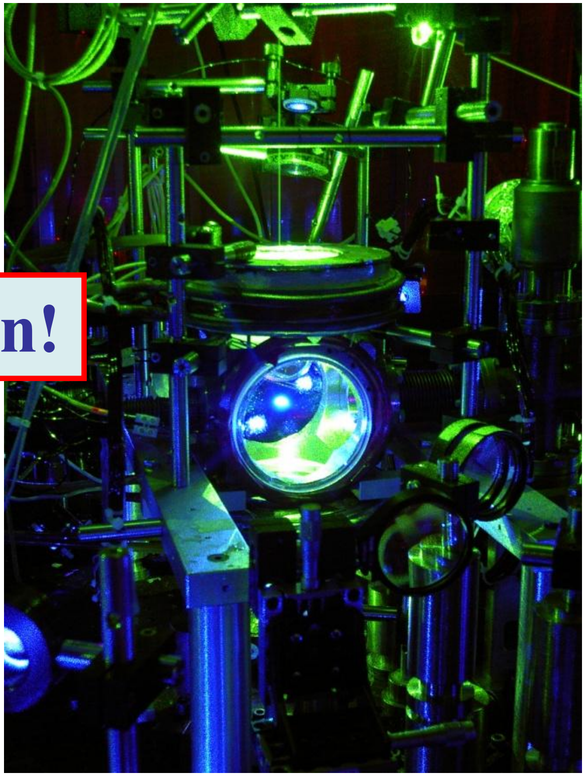
Best quantum sensor for future applications

People

- Sr experiment

N. Poli
M. G. Tarallo
M. Schioppo
F. - W. Wang
A. Alberti
C. W. Oates(*)
G. M. Tino

Thanks for your attention!



- Frequency comb

N. Beverini (Univ. Pisa)
D. Sutyrin (Univ. Pisa)
F. Sorrentino
S. Chepurov (Institute of laser physics, Novosibirsk)

http://coldatoms.lens.unifi.it/

Funding

INFN
agenzia spaziale italiana
ENTE CASSA DI RISPARMIO DI FIRENZE
esa
REGIONE TOSCANA
Ministero dell'Istruzione dell'Università e Ricerca
SEVENTH FRAMEWORK PROGRAMME