midlands physics alliance ultracold

Time for future: quantum clocks

Yeshpal Singh

University of Birmingham

EPSRC

midlands physics alliance ultracold

HIGHER EDUCATION FUNDING COUNCIL FOR ENGLAND hefce

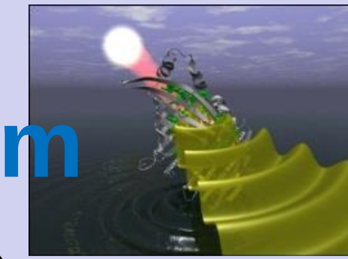
Midlands Centre for Ultracold Atoms

Graduate School

University of Birmingham
+
University of Nottingham
http://mpa.ac.uk/muarc/

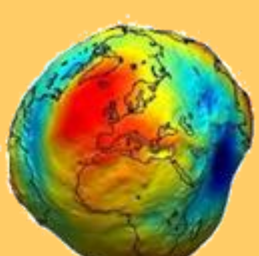
Quantum Simulation - Magnetism -

Quantum Simulation - Biology -



Physics World, 13 April 2007

Quantum Sensors - Gravity -

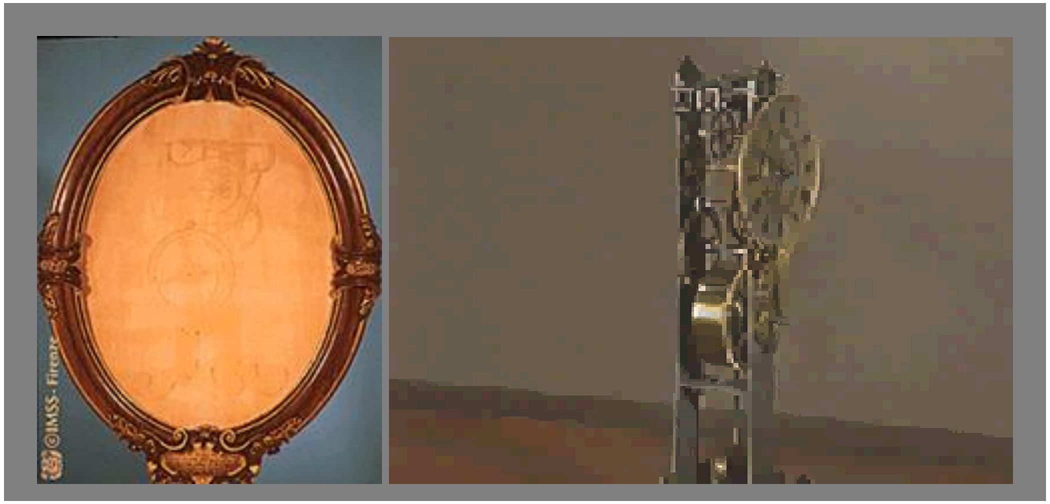


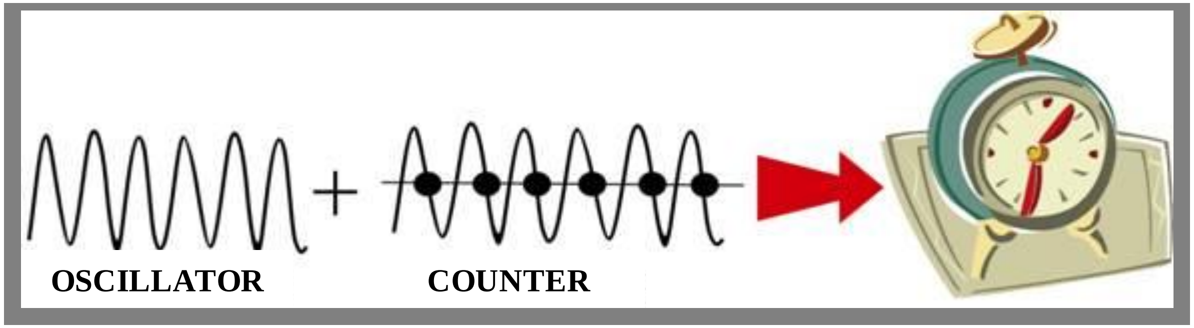
Quantum Sensors In Space

Quantum Sensors - Clocks -


Broad Range of Civilian/Commercial
Global Navigation Satellite Systems Applications
Satellite Operations
Precision Agriculture
Surveying & Mapping
Aviation
Communications
Disease Control
Power Grids
Trucking & Shipping
Oil Exploration
Fishing & Boating
Personal Navigation

The measurement of time





Accuracy $\rightarrow$ realization of the standard

Stability $\rightarrow$ stability of the frequency: depends on $\dfrac{\Delta \nu_0}{\nu_0}$

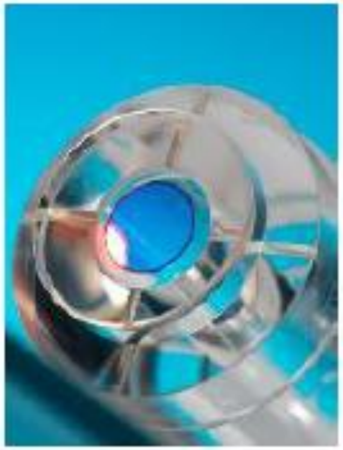
of the oscillator

The measurement of time

Reference
(e.g. Atoms, ions)

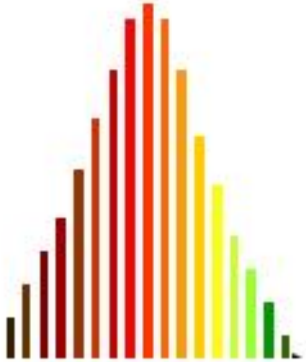
+

Oscillator (e.g. microwave, ultra stabilized laser)



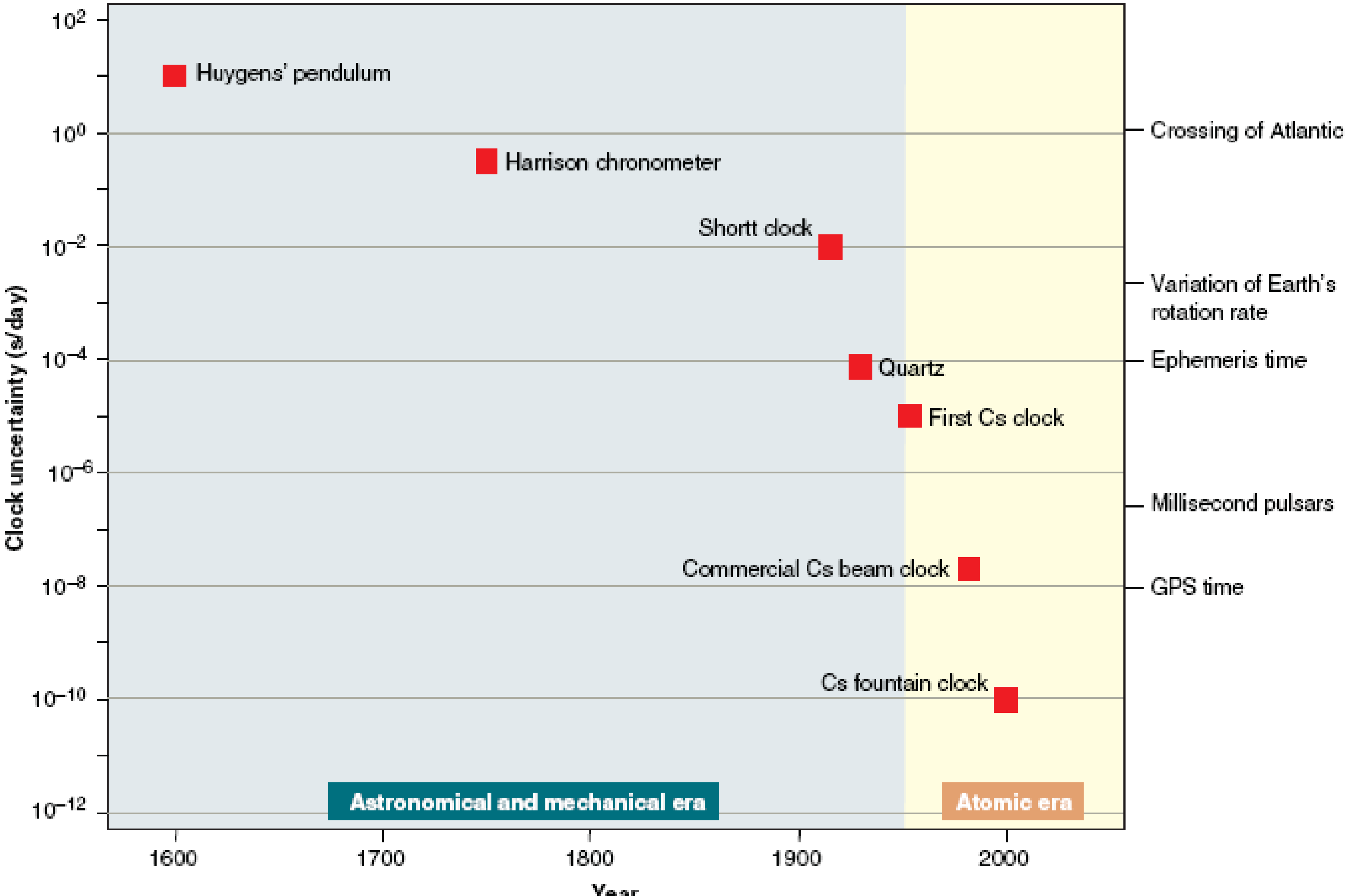
+

Counter
(e.g. femto second comb)



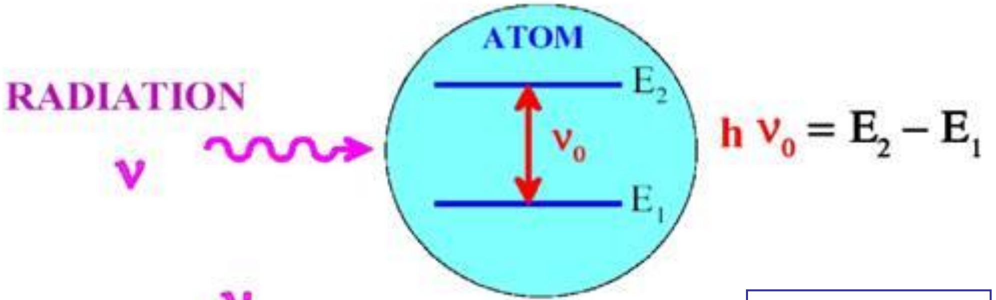
= Clock

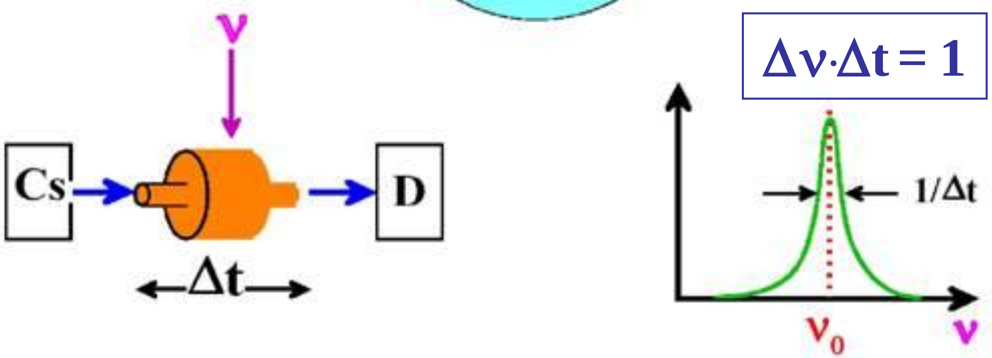
Clock: Historical View

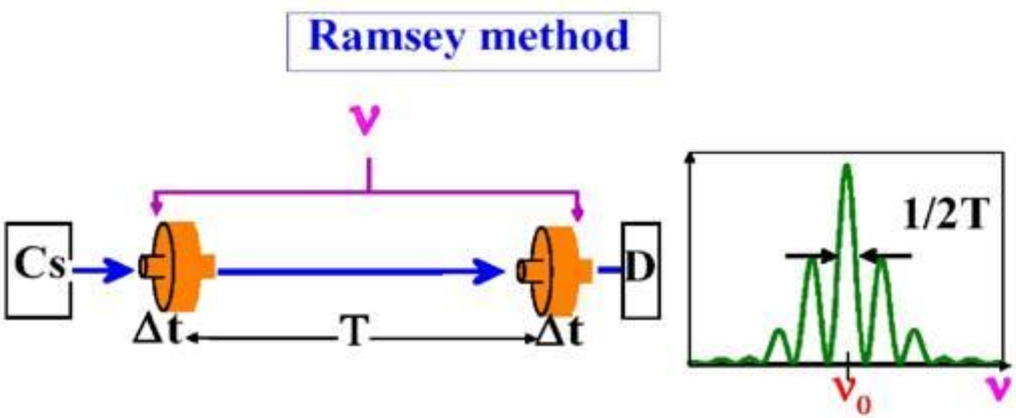


SCIENCE VOL 306 19 NOVEMBER 2004

Atomic Clocks: Hot Atoms



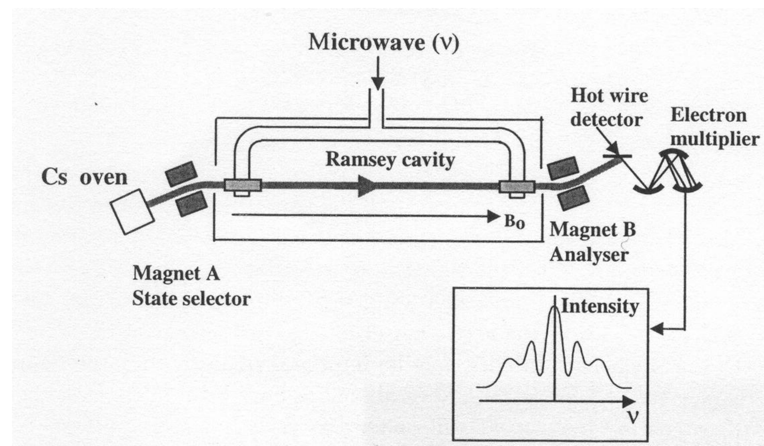




The definition of the second

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom

(13th CGPM, 1967)



Laser cooling

The Nobel Prize in Physics 1997

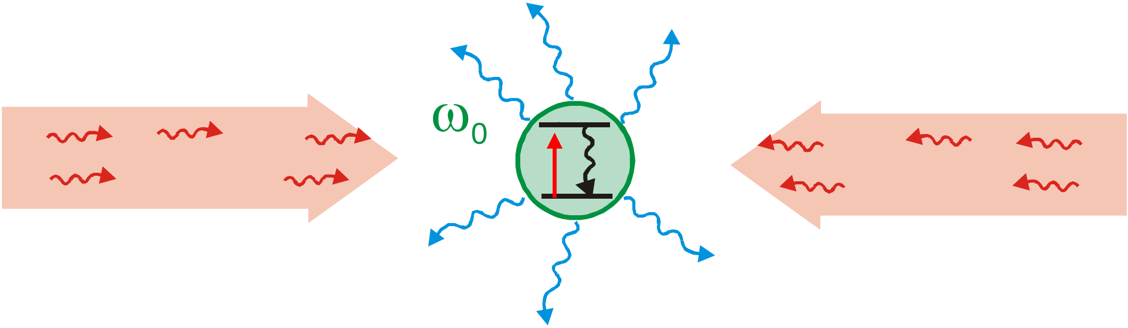
"for development of methods to cool and trap atoms with laser light"

S. Chu

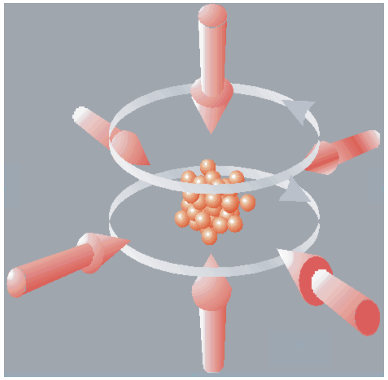
C. Cohen-Tannoudji

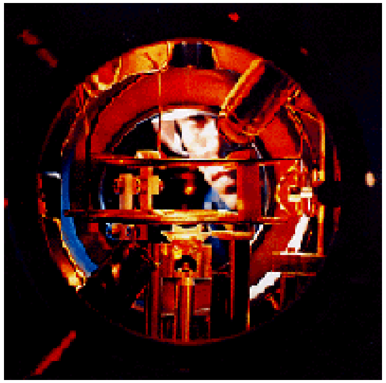
W.D. Phillips

the system:



the result:





Laser cooling: Temperatures

Atomic Temperature : $k_B T = Mv^2_{rms}$

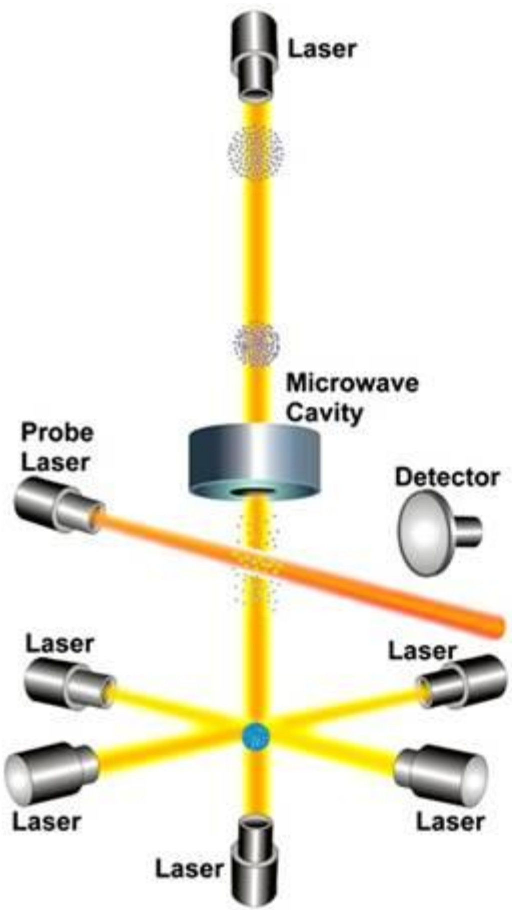
Minimum temperature for Doppler cooling: $\boxed{k_B T_D = \frac{h\Gamma}{2}}$

Single photon recoil temperature: $\boxed{k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2}$

Examples:

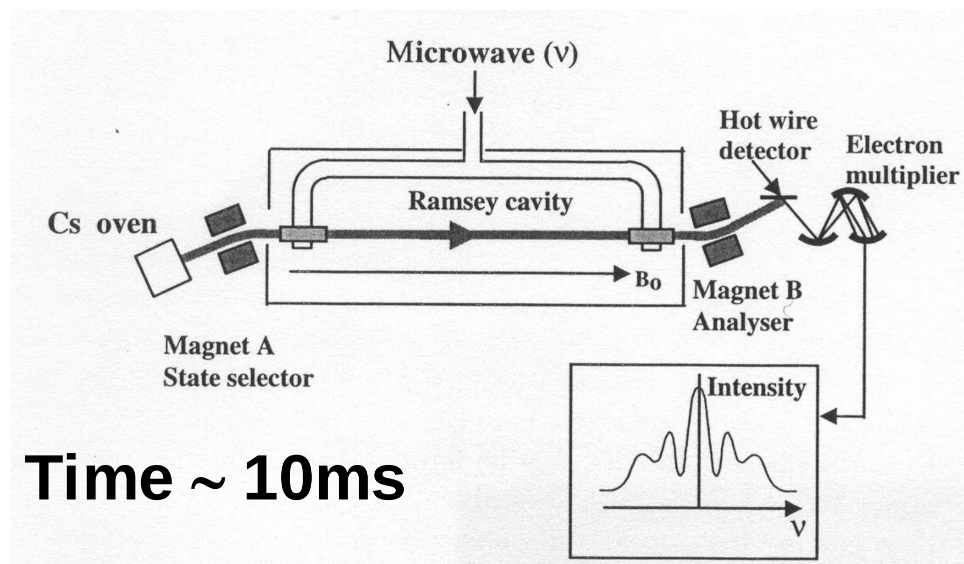
	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK

Atomic fountain clock



Time up to 1s

NIST-F1



Time ~ 10ms

Clock: Optical Clock

Fractional frequency instability

$$\sigma \propto \frac{\Delta \nu}{\nu_o} \frac{1}{S/N}$$

ν_o Natural frequency

$\Delta \nu$ Line width

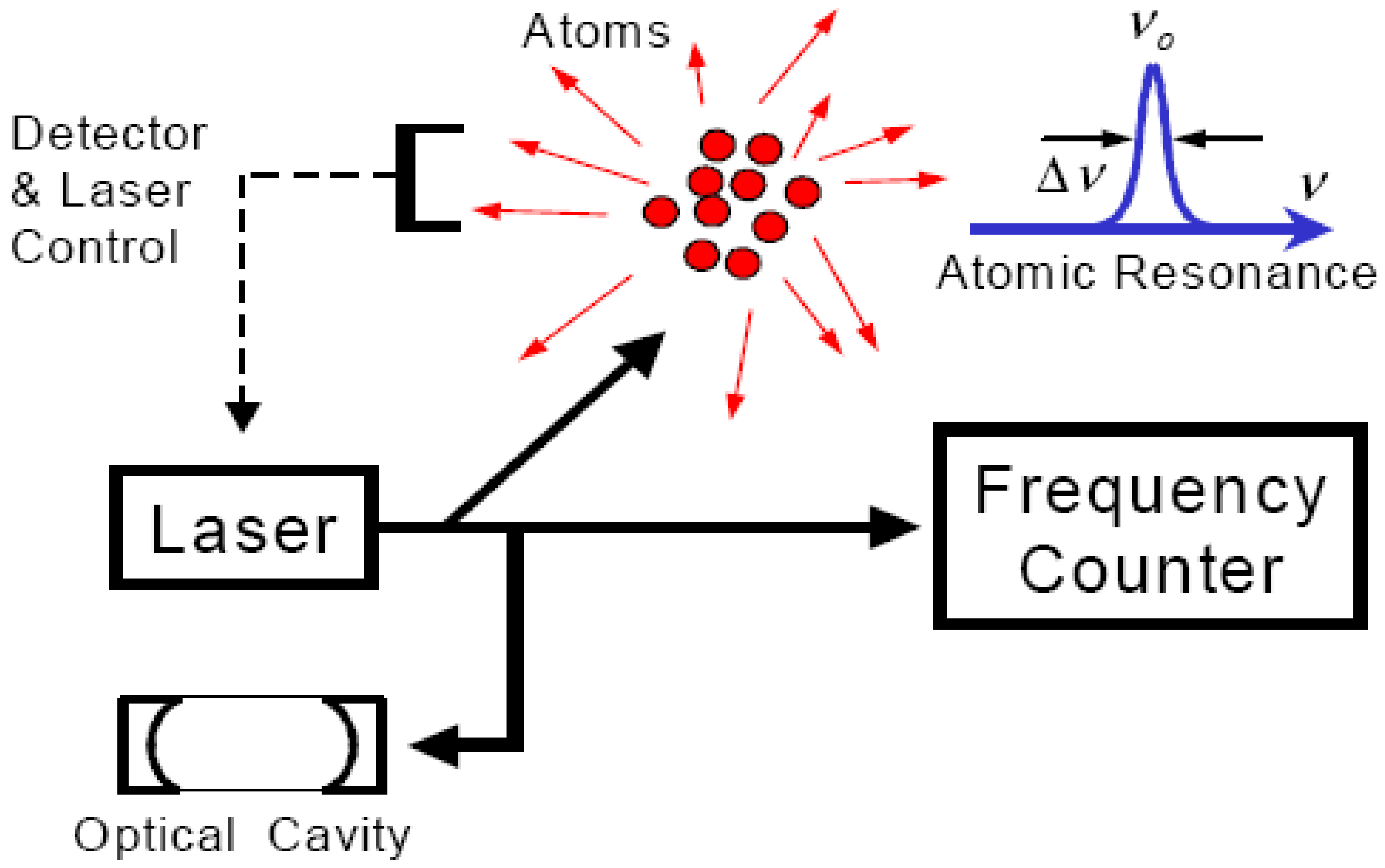
S/N Signal to noise ratio

Cs hyperfine transition ~ 10^{10} Hz (Fountain Clocks)

Optical Transition ~ 10^{15} Hz (Optical Clock)

⇨ ***Optical Clock is the way to go***

Schematic of an Optical Clock



Optical clocks: Towards 10^{-18}-10^{-19}

- **Narrow optical transitions**

$\delta\nu_o \leq 1$ Hz, $\nu_0 \sim 10^{15}$ Hz

•Narrow optical transitions

Trapped ions: Hg^+, In^+, Sr^+, Yb^+, Al^+…

(NPL, NRC, NIST, PTB, MPQ Innsbruck, CRL)

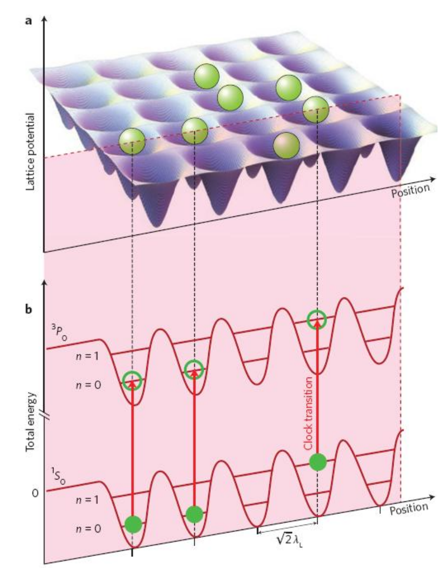
Advantage: easy tight trapping, minimised perturbations

Limitation: single or limited number of ions (Coulomb interaction)

Stability achieved ~8×10^{-18} (so far)

Cold neutral atoms: H, Ca, Sr, Yb,…

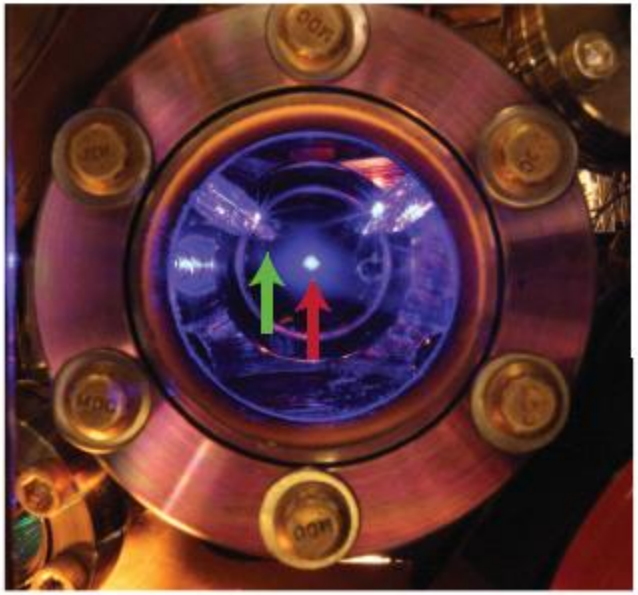
(MPQ, Hannover, PTB, NIST, JILA, SYRTE, Tokyo, Kriss, NPL, UoB, HHUD, Florence, INRIM)



Advantage: high signal to noise with many atoms
Requirement: magic optical lattice

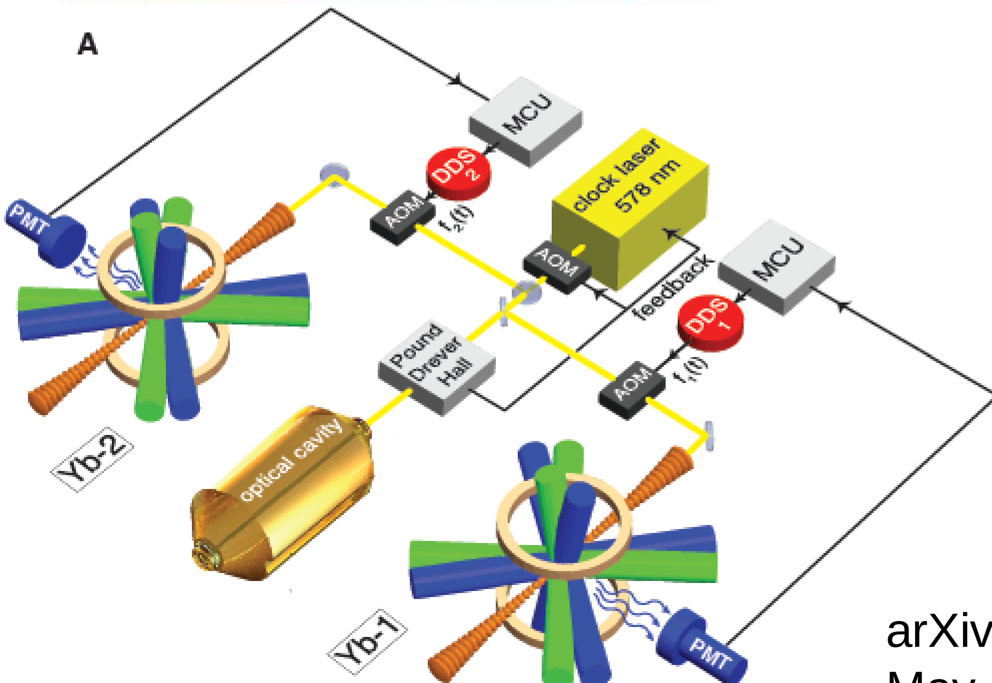
Stability achieved ~1.6×10^{-18} (so far)

Optical clocks: Towards 10^{-18}-10^{-19}



Sr Optical Lattice Clock
$3x10^{-18}$ at about 10,000 s
@JILA

Nature **506,** 72 (2014)

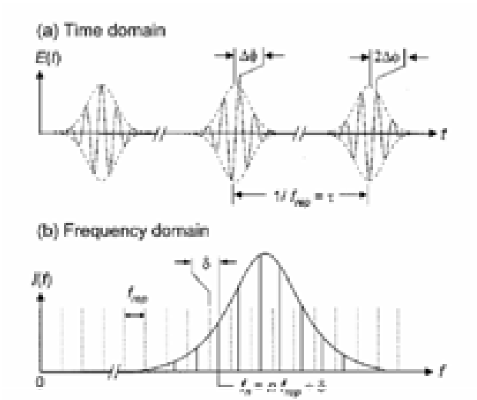


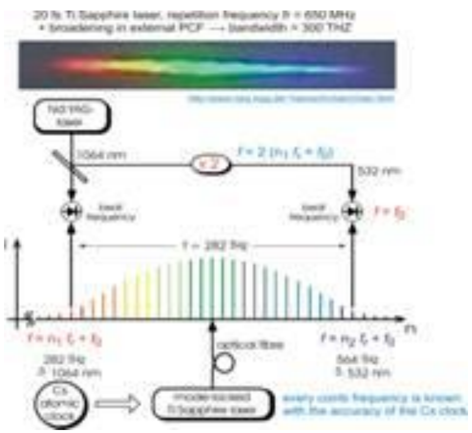
Yb Optical Lattice Clock
$1.6x10^{-18}$ at 25,000 s
@NIST

arXiv:1305.5869v1 [physics.atom-ph] 24 May 2013

Optical clocks: Towards 10^{-18}-10^{-19}

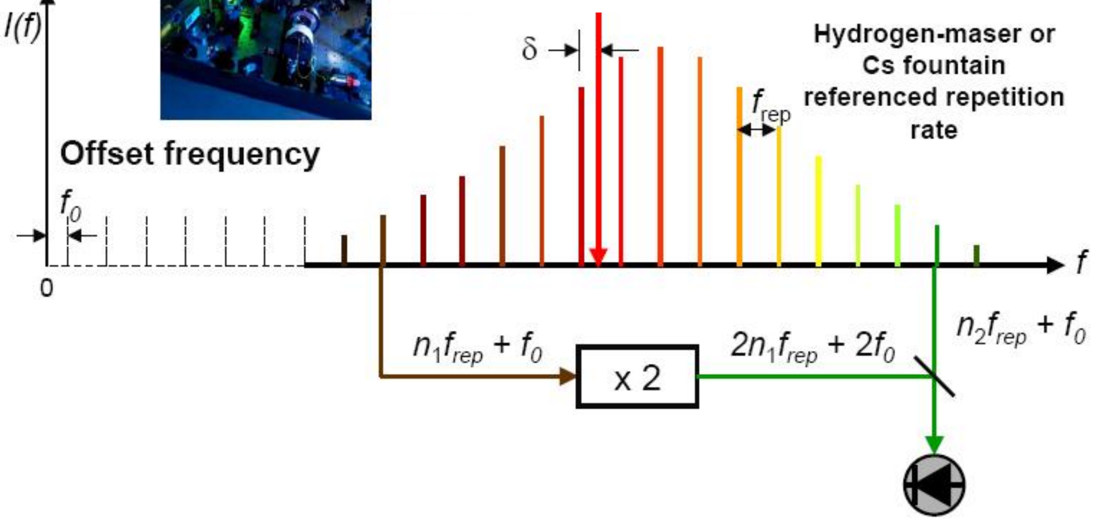
- **Direct optical-μwave connection by optical frequency comb**





Self referenced optical frequency comb

$$f_{\text{probe}} = m\, f_{rep} \pm f_0 \pm \delta$$

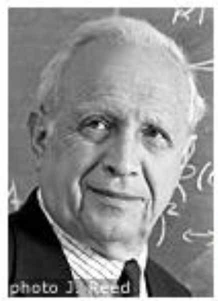


Th. Udem *et al*., Nature 416 , 14 march 2002

The Nobel Prize in Physics 2005

"for his contribution to the quantum theory of optical coherence"

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"



Roy J. Glauber	John L. Hall	Theodor W. Hänsch
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA	USA	Germany
Harvard University Cambridge, MA, USA	University of Colorado, JILA; National Institute of Standards and Technology Boulder, CO, USA	Max-Planck-Institut für Quantenoptik Garching, Germany; Ludwig-Maximilians-Universität Munich, Germany
b. 1925	b. 1934	b. 1941

The Nobel Prize in Physics 2005
Prize Announcement
Press Release
Advanced Information
Supplementary Information

Roy J. Glauber
Nobel Lecture
Interview
Other Resources

John L. Hall
Nobel Lecture
Interview
Other Resources

Theodor W. Hänsch
Nobel Lecture
Interview
Other Resources

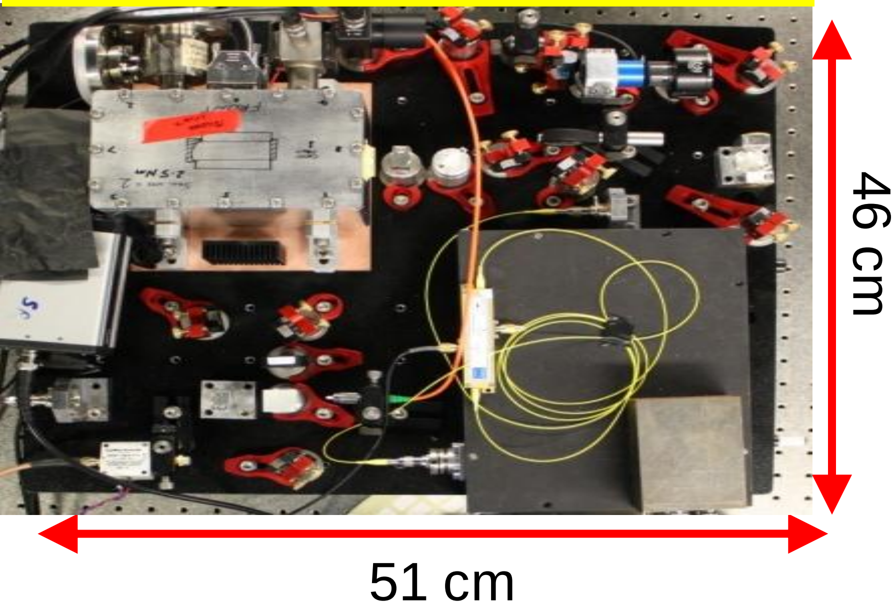
2004

The 2005 Prize in:
Physics
Chemistry
Physiology or Medicine

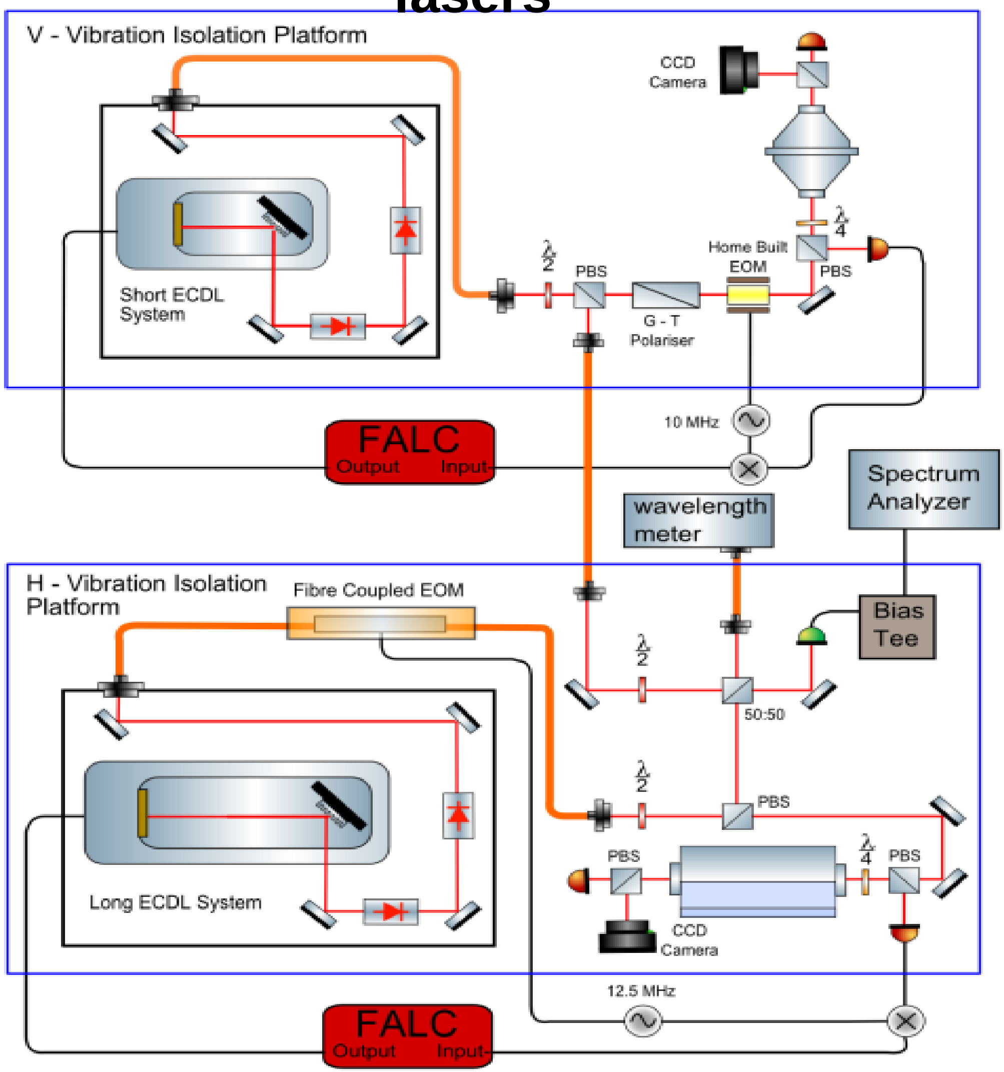
Find a Laureate:
Name
GO

Sr Clock lasers: UoB

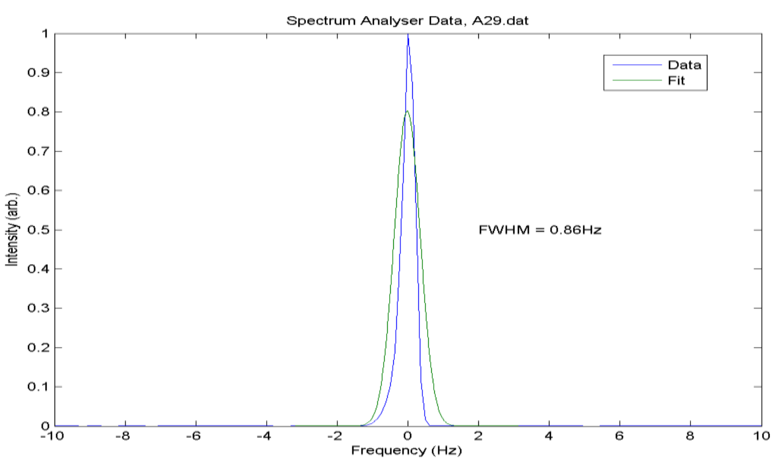
Clock laser with horizontal cavity (~400,000 finesse)



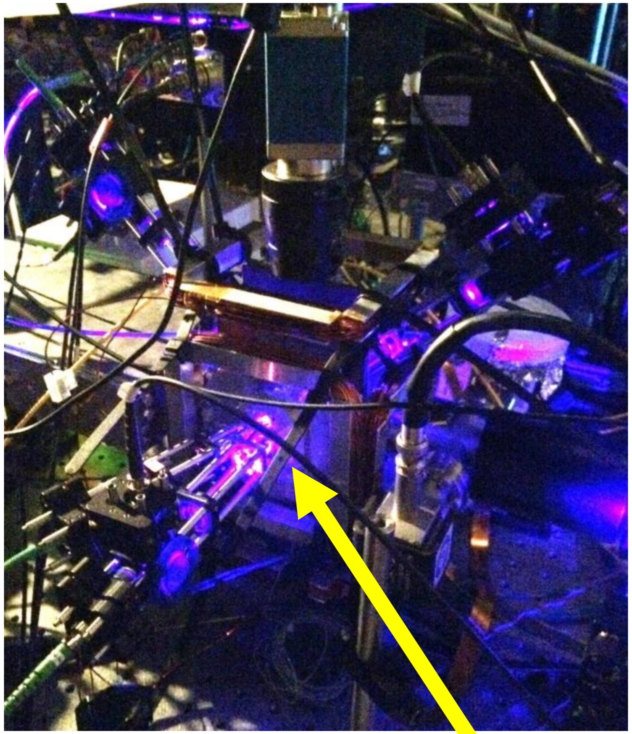
Setup Schematic: two clock lasers



Beat measurement ~1Hz



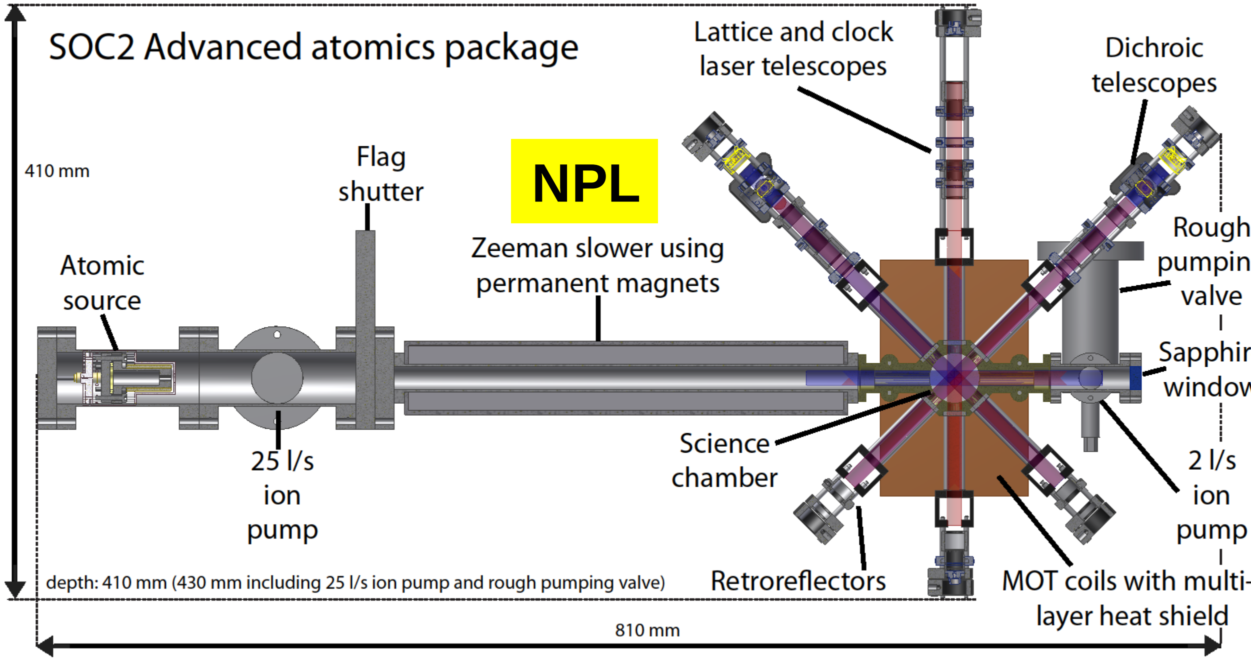
SOC-2, 2nd generation Sr transportable clock: UoB



MOT chamber

Blue MOT

Modular subsystem

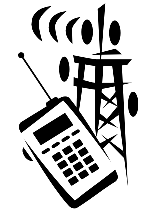


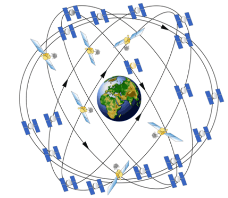
Atomics unit
with black-body control plates
Volume: 35 x 35 x 80 cm^3
Weight: 14 kg
MOT coil power consumption 10 W

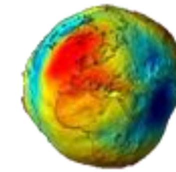
- Search for Red MOT ON !
- Acknowledgement: SOC2 Team

Miniaturized Optical Lattice Clock for Ultraprecise Timing: UoB

Optical lattice clocks promise a step-change in timing precision with impacts on communication networks, navigation and determining the Earth's geoid.

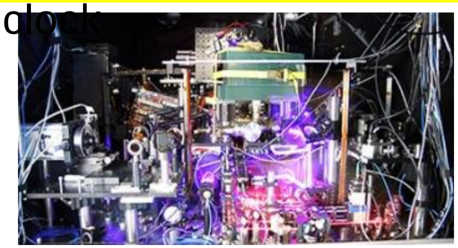




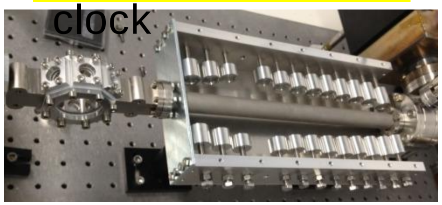


STATE OF THE ART → **GOAL**

JILA 1 in 10^{18} Sr lattice clock

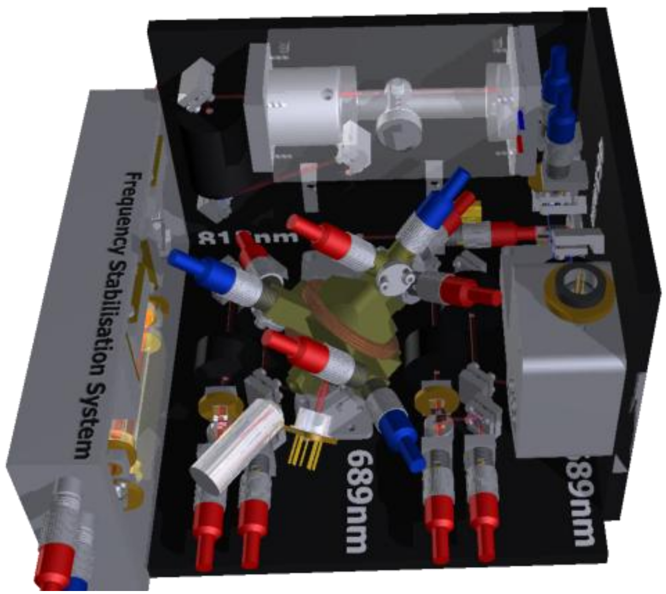


SOC-II lattice clock



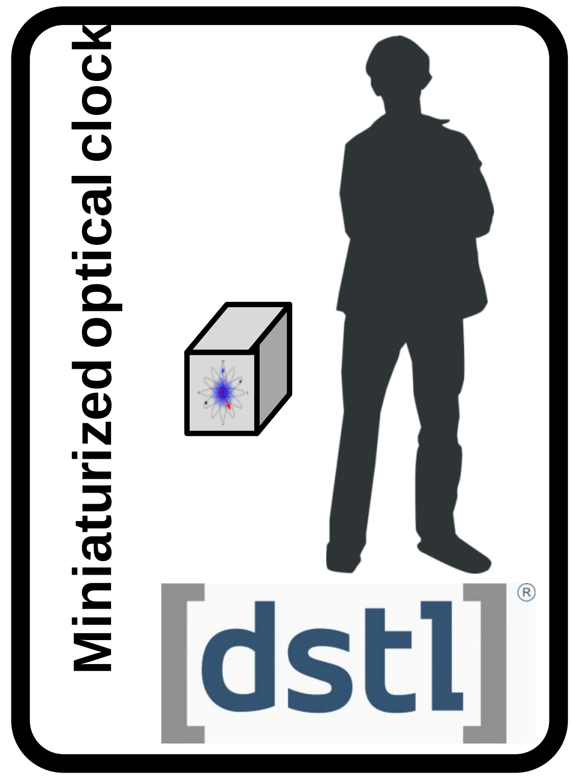
DARPA 6I Sr beam

AOSense



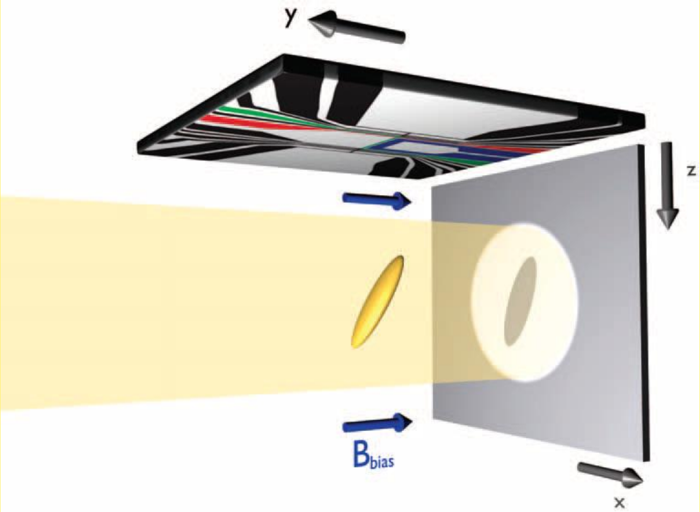
Entire assembly (vision)

@UoB
Design for <1 in 10^{16}, lattice clock

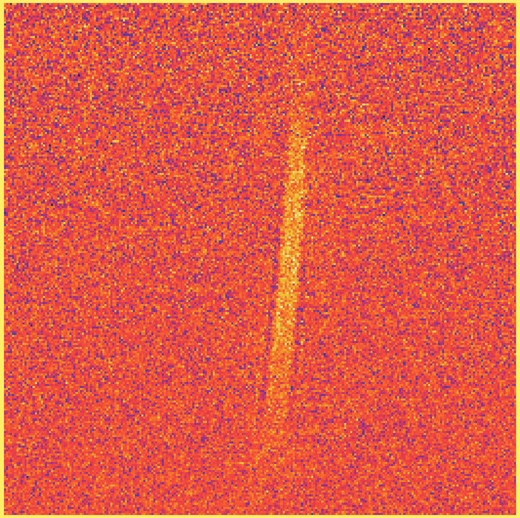


Drop Tower

Atom Chip



BEC in Microgravity
After 1 second expansion



http://www.iqo.uni-hannover.de/quantus.html

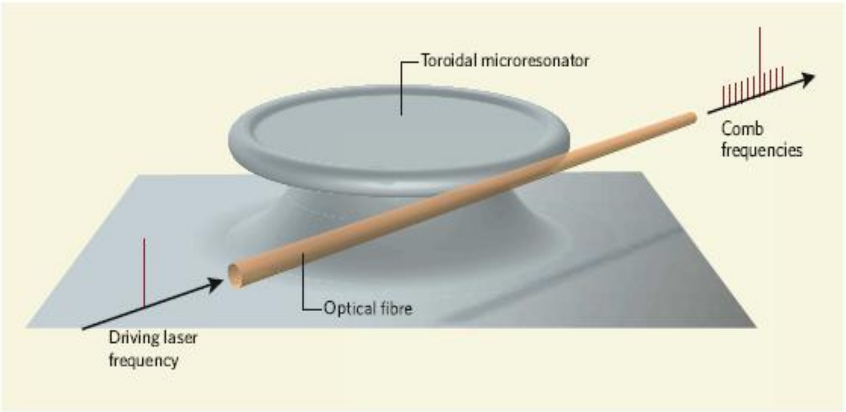
Frequency Combs

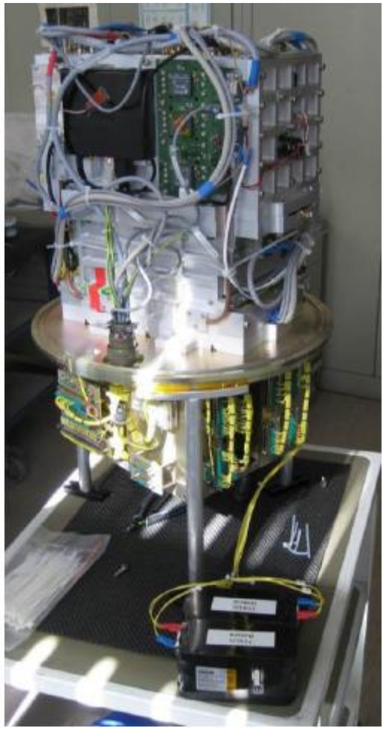
MenloSystems GmbH

Fibre Combs: Menlo Systems

2.2 x 10^{-18} instability at 30.000 s

Micro Combs





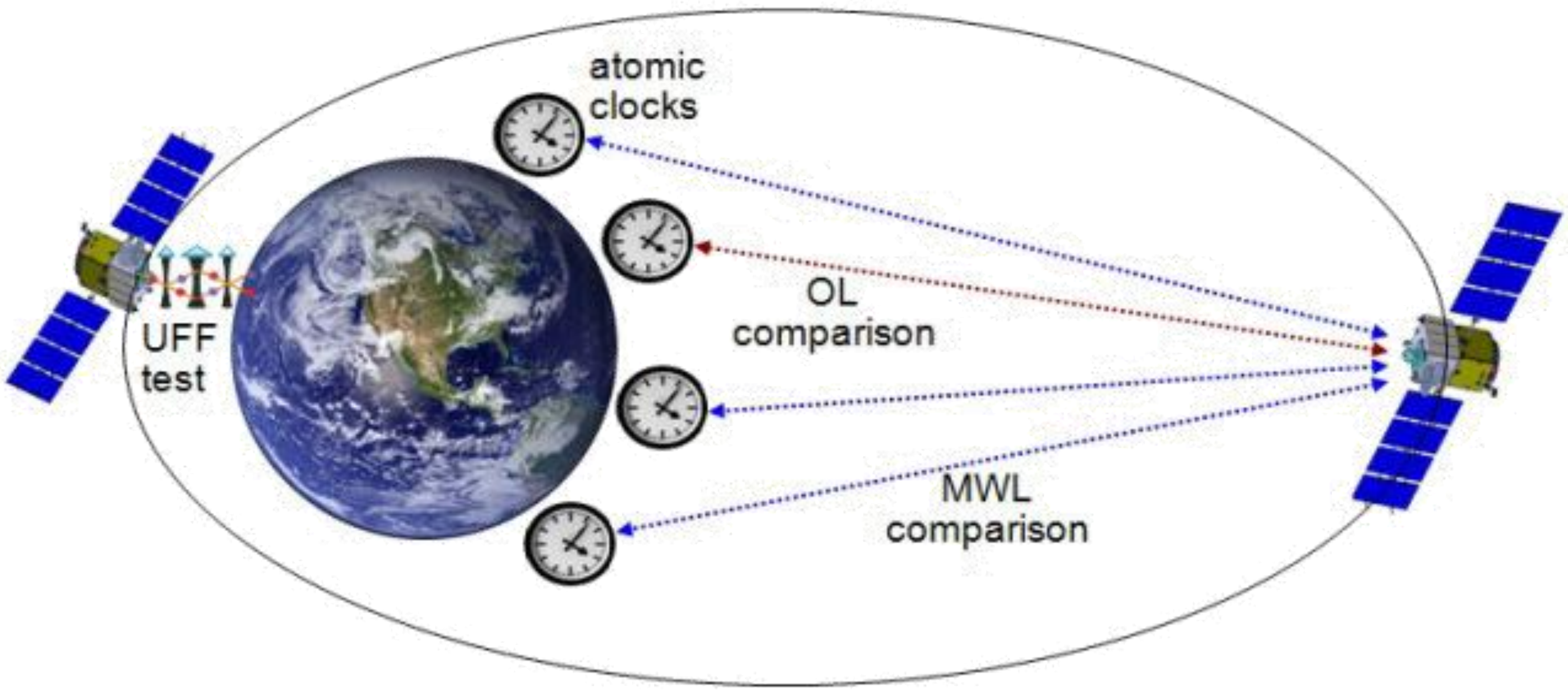
Del Haye,Schliesser,Wilkins, Holzwarth,Kippenberg, Nature, **2007**
Del Haye, Arcizet, Schliesser, Holzwarth, Kippenberg, Phys. Rev. Lett., **2008**
EU & US Patent application "Optical Comb Generator using Microresonators"
TJ Kippenberg, Holtzwarth, Diddams, Science **2011**

Sounding Rocket Test Due some time summer

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

The Future: STE-QUEST

STE-QUEST is the only fundamental physics proposal selected as one of four candidates for ESA's next medium size class missions, to be launched 2020-2022 within the Cosmic Vision programme



Goal:
- Precision test gravitational redshift as predicted by Einstein's general relativity
- Precision test Einstein's Equivalence Principle for quantum objects