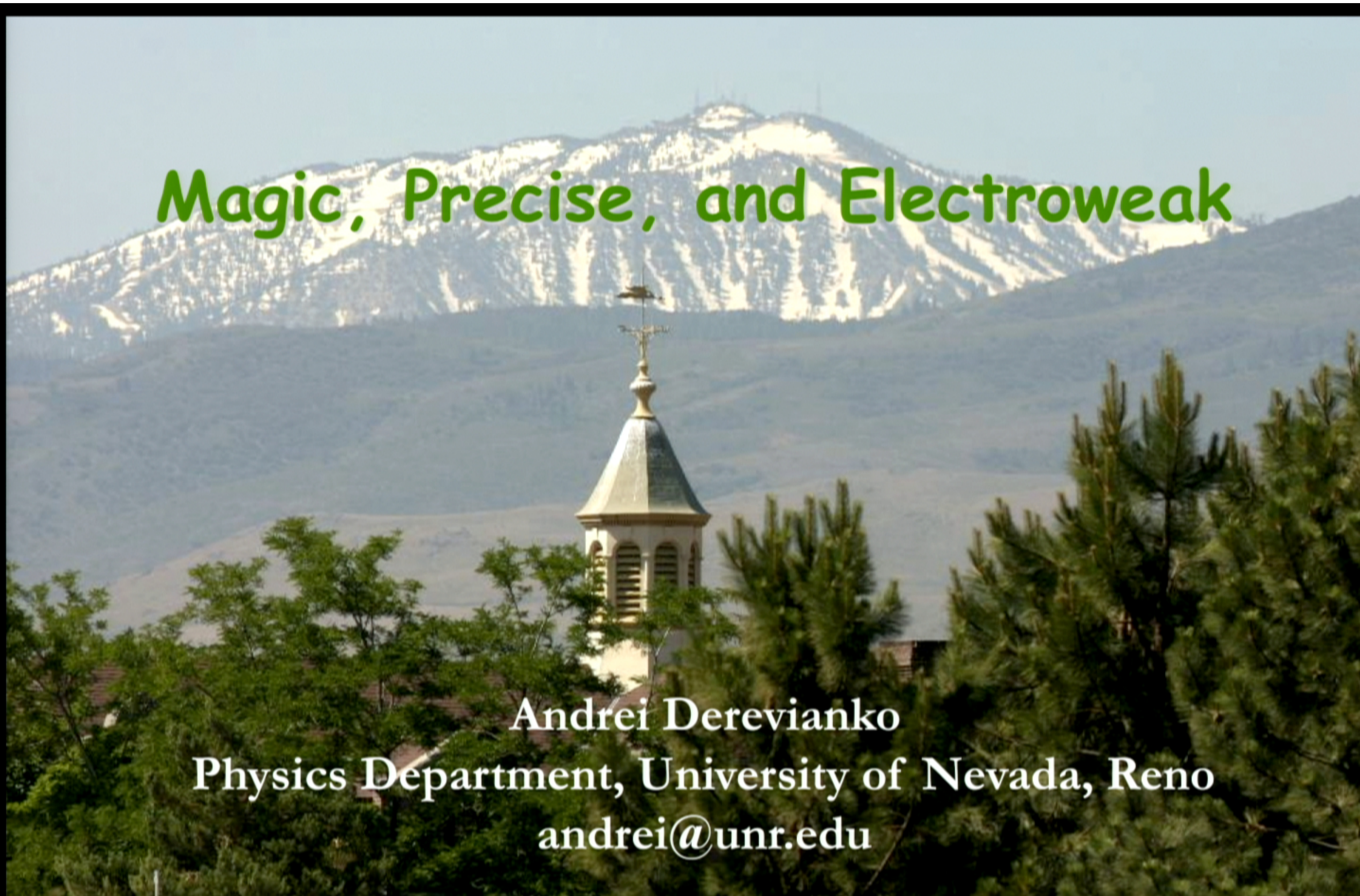
Title: Magic, Precise, and Electroweak

Date: May 29, 2012 01:00 PM

URL: http://pirsa.org/12050009

Abstract: Precision timepieces are marvels of human ingenuity. Over the past half-a-century, precision time-keeping has been carried out with atomic clocks. I will review a novel and rapidly developing class of atomic clocks, optical lattice clocks. At their projected accuracy level, these would neither lose nor gain a fraction of a second over estimated age of the Universe. In other words, if someone were to build such a clock at the Big Bang and if such a timepiece were to survive the 14 billion years, the clock would be off by no more than a mere second. What can we do with this new-found precision? How can we exploit this exquisite ability to listen carefully for probing new physics?

In the second part of my talk I will overview atomic searches for new physics beyond the Standard Model of elementary particles. I will report on a refined analysis of table-top experiments on violation of mirror symmetry in atoms. This analysis sets new constraints on a hypothesized particle, the extra
Z-boson. Our raised bound on the Z' masses improves upon the Tevatron results and carves out a
lower-energy part of the discovery reach of the Large Hadron Collider.



Magic, Precise, and Electroweak

Andrei Derevianko
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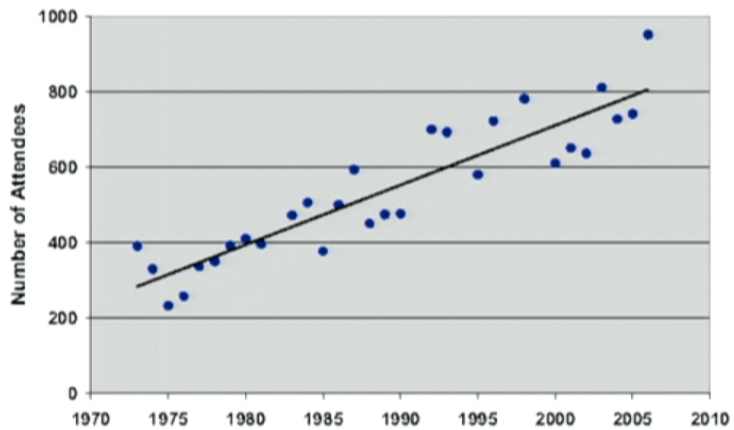
NSF NASA NIST National Institute of Standards and Technology U.S. Department of Commerce FULBRIGHT

Atomic physics

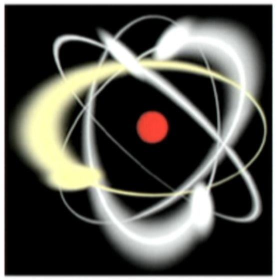
3 Nobel prizes over the past decade

Attendance of APS meetings
Division Of Atomic, Molecular And Optical Physics



Theoretical atomic physics group @ Reno

Listening to an atom



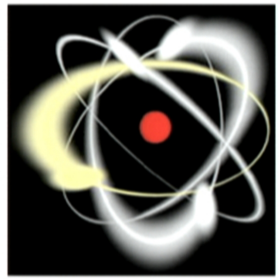
- Coulomb forces + Quantum Electro-Dynamics
  => a relatively simple interpretation

- Unprecedented control over internal and external degrees of freedom
  precision 16-digit spectroscopy

429 228 004 229 873.65 (37) Hz

Campbell et al., Metrologia 45 (2008)

Listening to an atom



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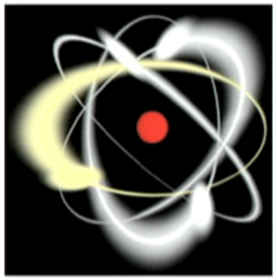

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Outline

Part I (precise & electroweak)
Search for "new" physics

Part II (magic & precise)
Atomic clocks

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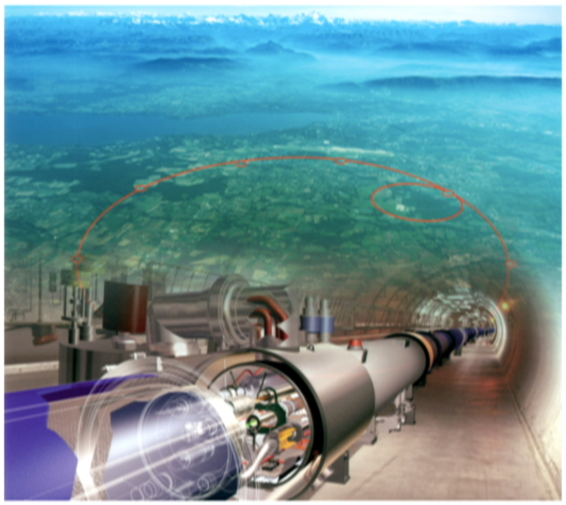
Large Hadron Collider

"The grandest scientific instrument ever built"



- 27 km (17 mile) long tunnel
- Straddles borders of Switzerland and France
- $6 bln price tag

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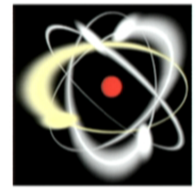
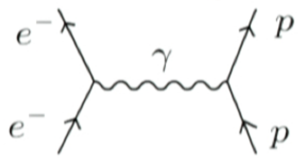
Atomic parity violation (APV)



Parity transformation: $\mathbf{r}_i \rightarrow -\mathbf{r}_i$

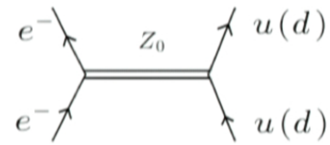
[H_{atomic}, P]=0 => Atomic stationary states are eigenstates of Parity

Electromagnetic



Conserve parity

Electroweak

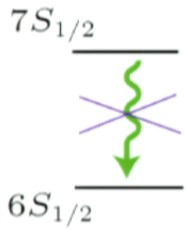


Do not conserve parity

Z-boson exchange spoils parity conservation

What is the strength of electroweak coupling of quarks and electrons?

Parity-violating 7S-6S amplitude in Cs

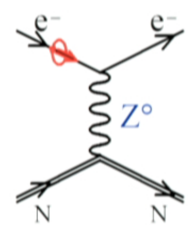


$$\langle 7S_{1/2} | D | 6S_{1/2} \rangle \equiv 0 \qquad D = \sum_{i=1}^{N} -e\,\mathbf{r}_i$$

Electric-dipole transition is forbidden by the **parity** selection rules

Weak interaction leads to an admixture of states of opposite parity

$$E_{\mathrm{PV}} = \langle \overline{7S_{1/2}} | D | \overline{6S_{1/2}} \rangle \neq 0$$



Weak charge extraction

$$H_W = Q_W \times \frac{G_F}{\sqrt{8}} \gamma_5 \rho_n(r)$$

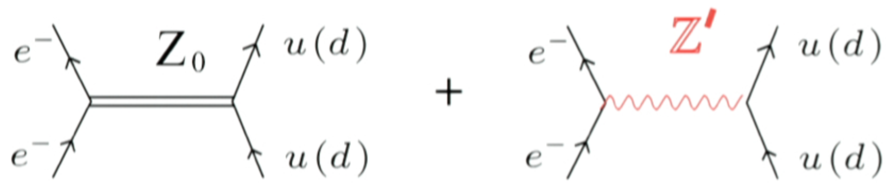
Weak charge

neutron distribution

$$E_{PV} = k_{PV}\, Q_W$$

extra Z bosons (Z')

- Copious in grand unified theories and string theories
- Potential carriers of the "fifth" force of Nature
- LHC: the cleanest signal of new physics



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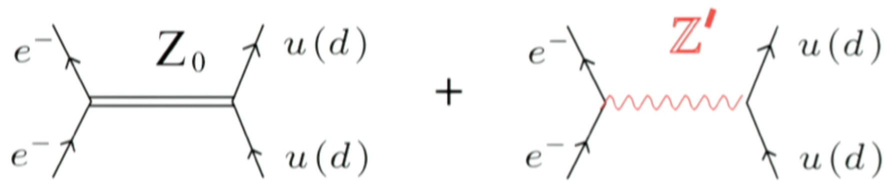


APV is uniquely sensitive to *Z'*

$$Q_W^{\text{inferred}} - Q_W^{SM} \approx \left(\frac{0.736 \text{ TeV}/c^2}{M_{Z'_\chi}} \right)^2$$

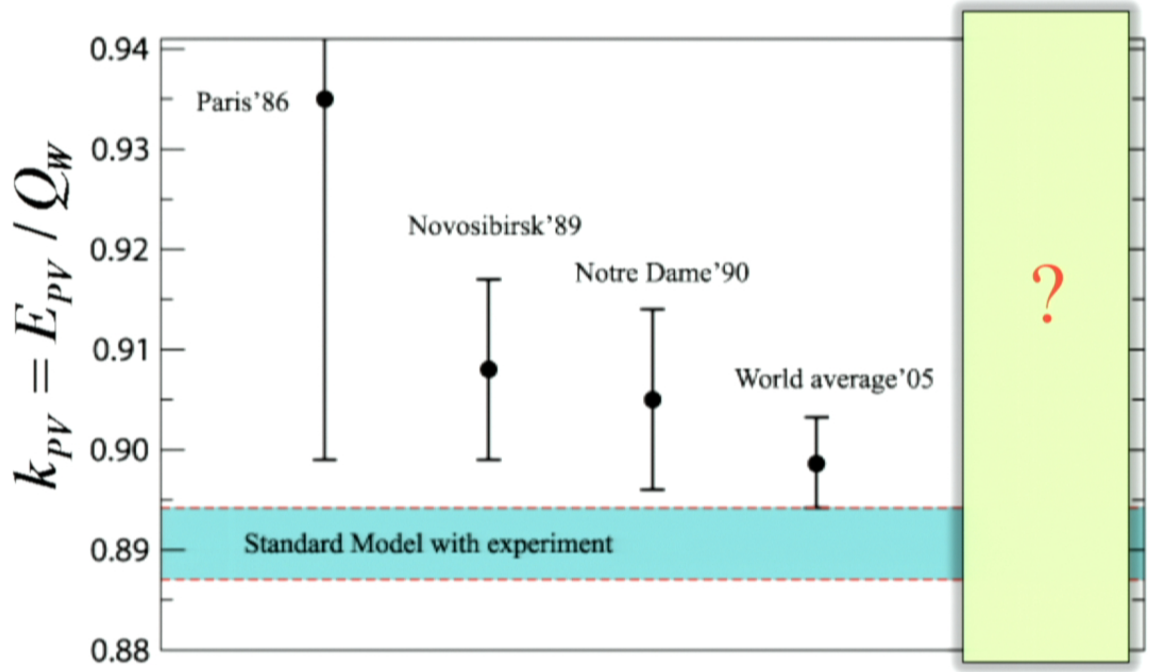
Marciano & Rosner

Theoretical progress

$$E_{PV} = k_{PV}\, Q_W^{\text{inferred}}$$

measured

atomic-structure calculations



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Theoretical progress

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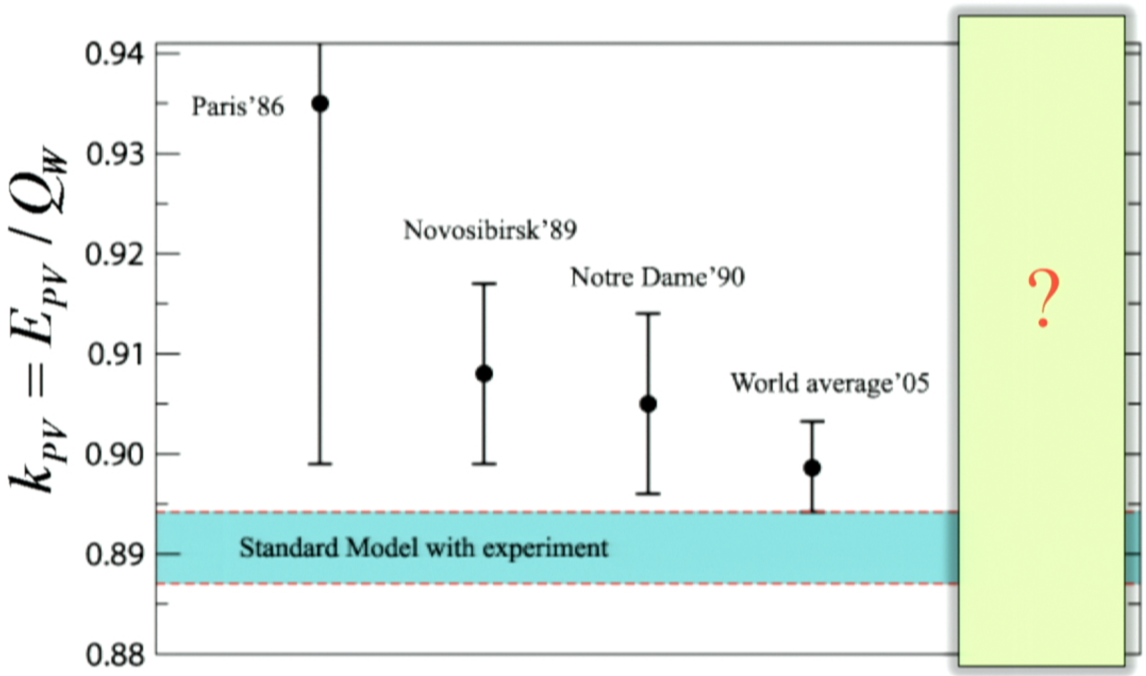

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$$\sigma_Q = \sqrt{(\sigma_{\text{expt}})^2 + (\sigma_{\text{theor}})^2}$$

$$\sigma_{\text{expt}} = 0.35\% < \sigma_{\text{theor}} = 0.5\%$$

How to reduce σ?

Theoretical uncertainty is limited by
an accuracy of solving
the basic correlation atomic-structure
problem

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Why is it so difficult?

Cs atom: correlated motion of 55 electrons
55x3=165 coordinates
For a coarse 10-point grid per dimension

Requirements to atomic-structure calculations

- Weak interaction occurs in the nucleus

$$\frac{v}{c} \sim \alpha Z \approx 0.5 \qquad \text{for Cs}$$

Ab initio relativistic calculations based on Dirac equation

- Calculations should have uncertainty better than 0.35%

  Hartree-Fock calculations are off by 50% for important atomic properties

Many-body perturbation theory

Treat interaction beyond the Hartree-Fock as a perturbation

Technically difficult task: 100 Gb of storage, several weeks of CPU time

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Pauli's letter

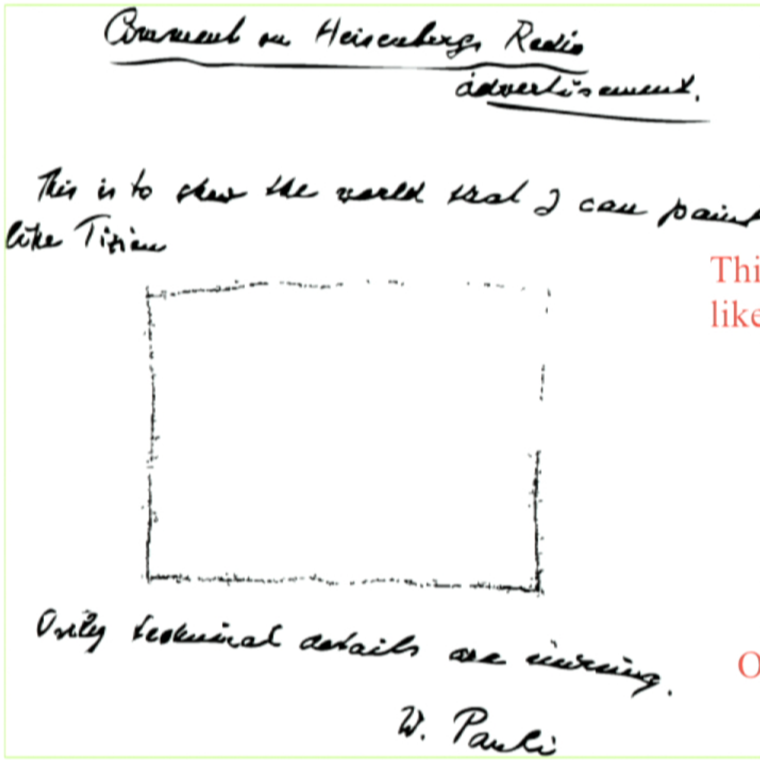
Comment on Heisenberg's Radio advertisement.

This is to show the world that I can paint like Titian

Only technical details are missing.

W. Pauli

Pauli's letter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PV amplitude

$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2} | D | nP_{1/2} \rangle \langle nP_{1/2} | H_W | 6S_{1/2} \rangle}{E_{6S} - E_{nP_{1/2}}} + \text{c.c.}(6S \leftrightarrow 7S)$$

$$H_W = Q_W \times \frac{G_F}{\sqrt{8}} \gamma_5 \rho_n(r)$$

Accuracy is important

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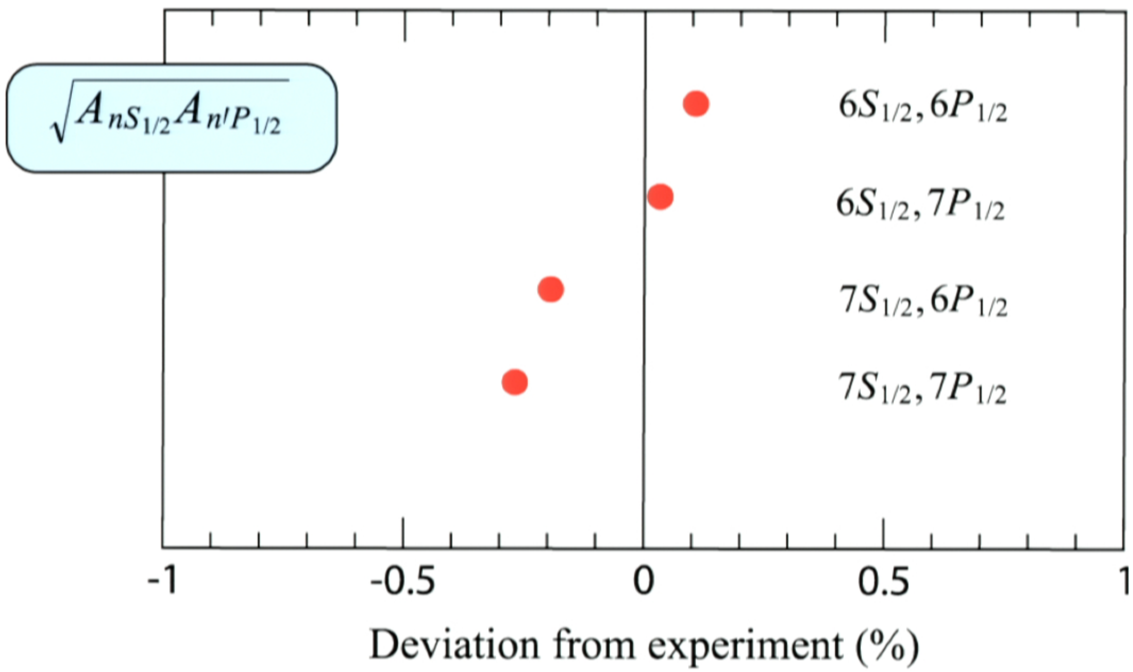
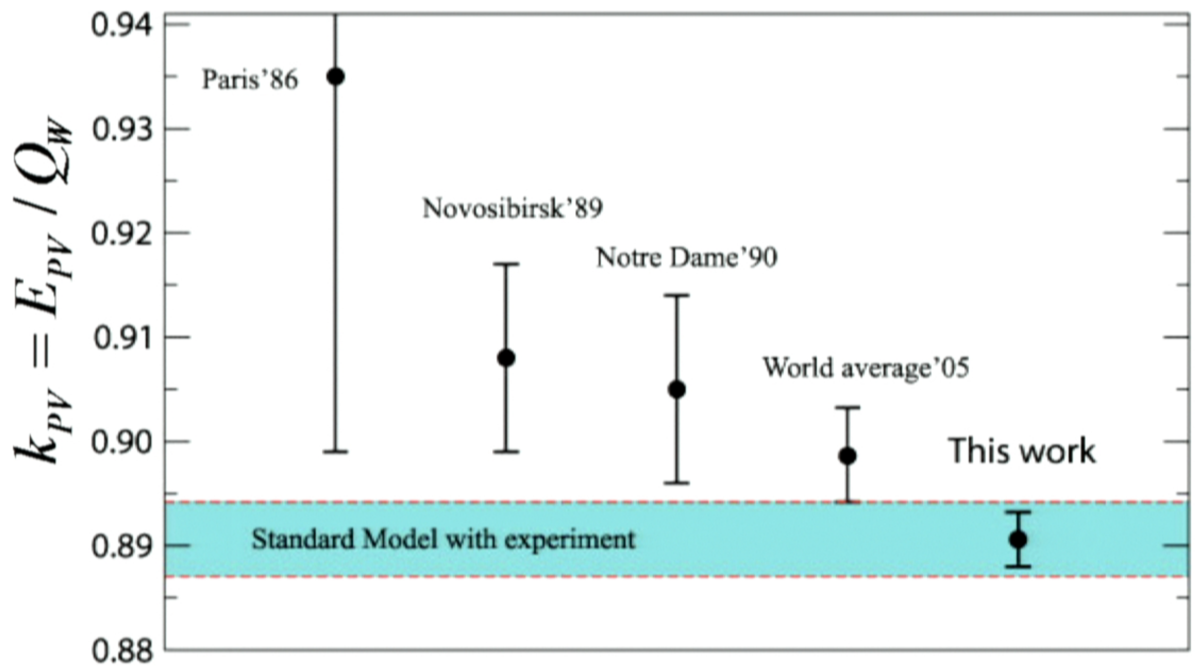
Theoretical accuracy: weak interaction



Theoretical progress



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Implications: extra Z bosons (Z')

Specific example: Z'_χ in SO(10) GUT

$$Q_W^{\text{inferred}} - Q_W^{SM} \approx \left(\frac{0.736 \text{ TeV}/c^2}{M_{Z'_\chi}} \right)^2$$

Marciano & Rosner

Our result implies: $M_{Z'_\chi} > 1.4 \;\; \text{TeV/c}^2$ [84% CL]

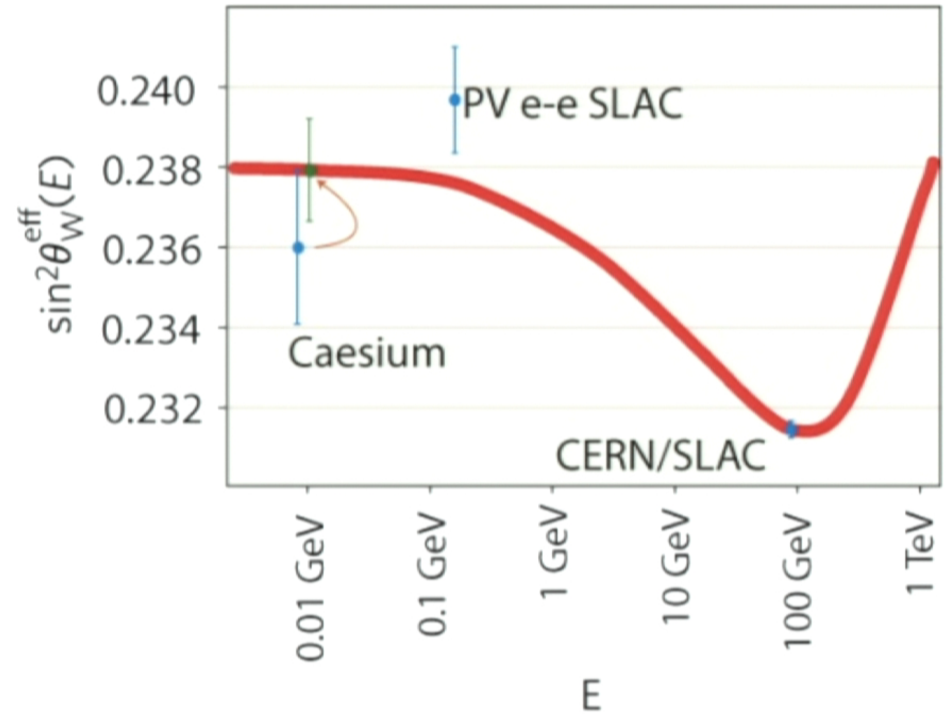
Direct search at Tevatron collider :

$$M_{Z'_\chi} > 0.82 \;\; \text{TeV/c}^2$$

LHC March 2012: $M_{Z'} \geq 2 \;\; \text{TeV/c}^2$

LHC discovery reach 5 TeV @ full luminosity

Implications: Running of EW coupling



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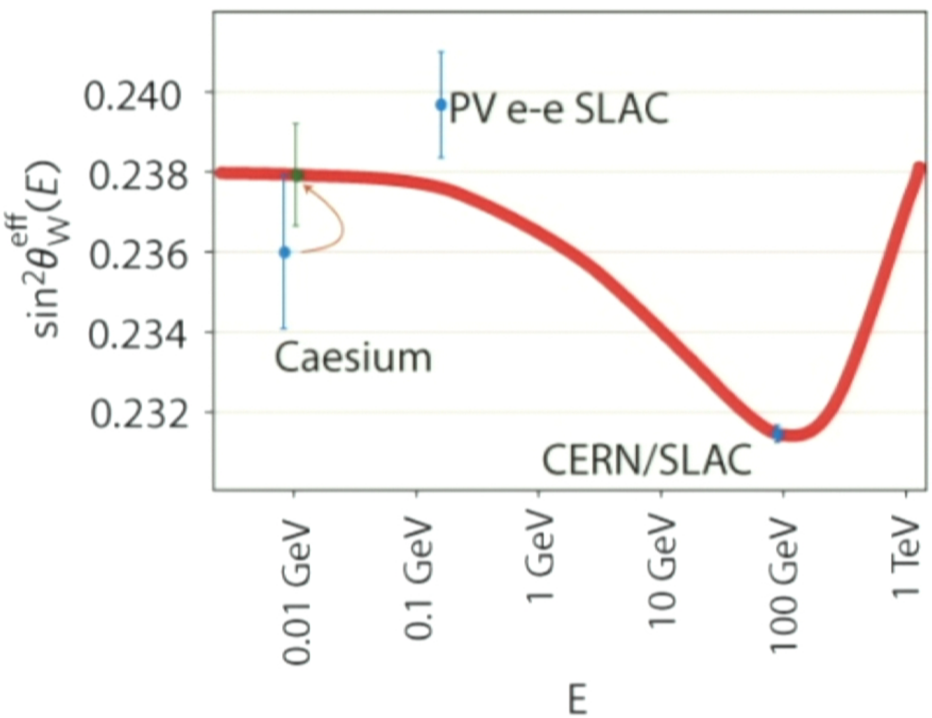
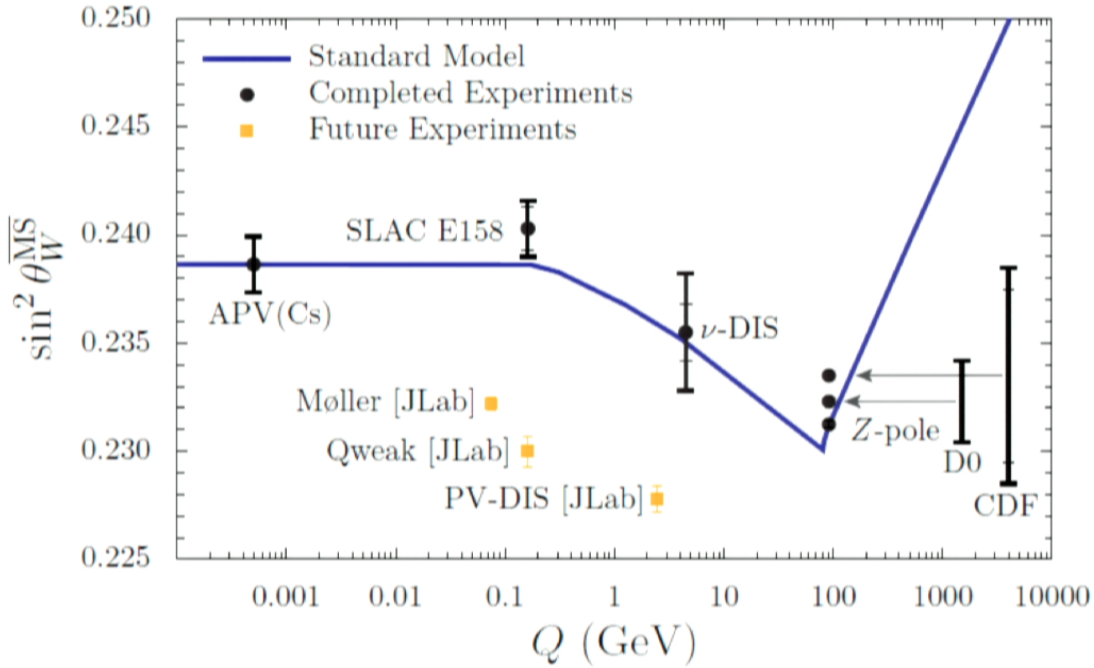


Bigger picture (running)



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Implications: Dark forces?

Exchange by weakly-coupled light particles

$$H_W \rightarrow \gamma_5 \times \left\{ Q_W^{SM} \frac{G_F}{\sqrt{8}} \rho_n(r_e) + \alpha_X \frac{e^{-M_X r_e}}{r_e} \right\}$$

Plug it in into the APV amplitude calculations =>
new limits on "dark couplings" of electrons to quarks

Interesting effects are expected when $1/M_X \sim$ radius of the 1s shell (M_X > a few MeV)

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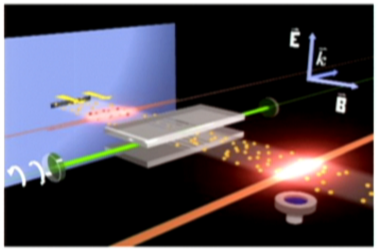
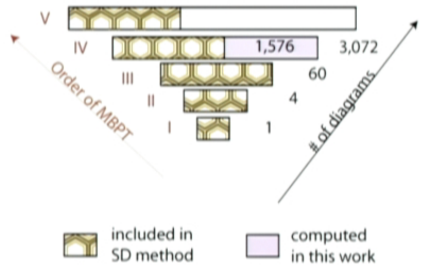
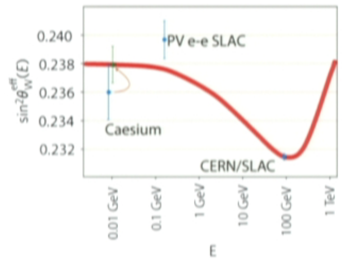
“New physics” summary



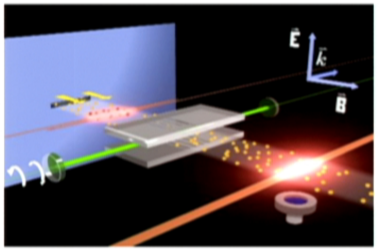


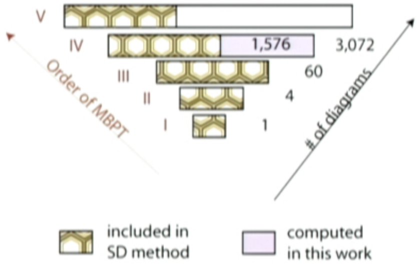


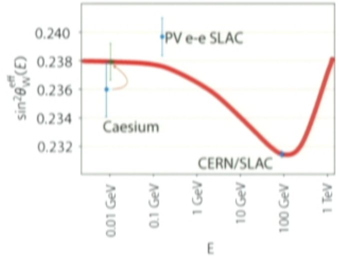
- Perfect agreement with the Standard Model
- Lower limit on mass of Z’ is raised
- Running of electroweak coupling confirmed over energy span of four orders of magnitude

- Applications of developed codes: van der Waals interaction, atom-wall interaction, lifetimes, exotic nuclear moments, **atomic clocks** …

"New physics" summary







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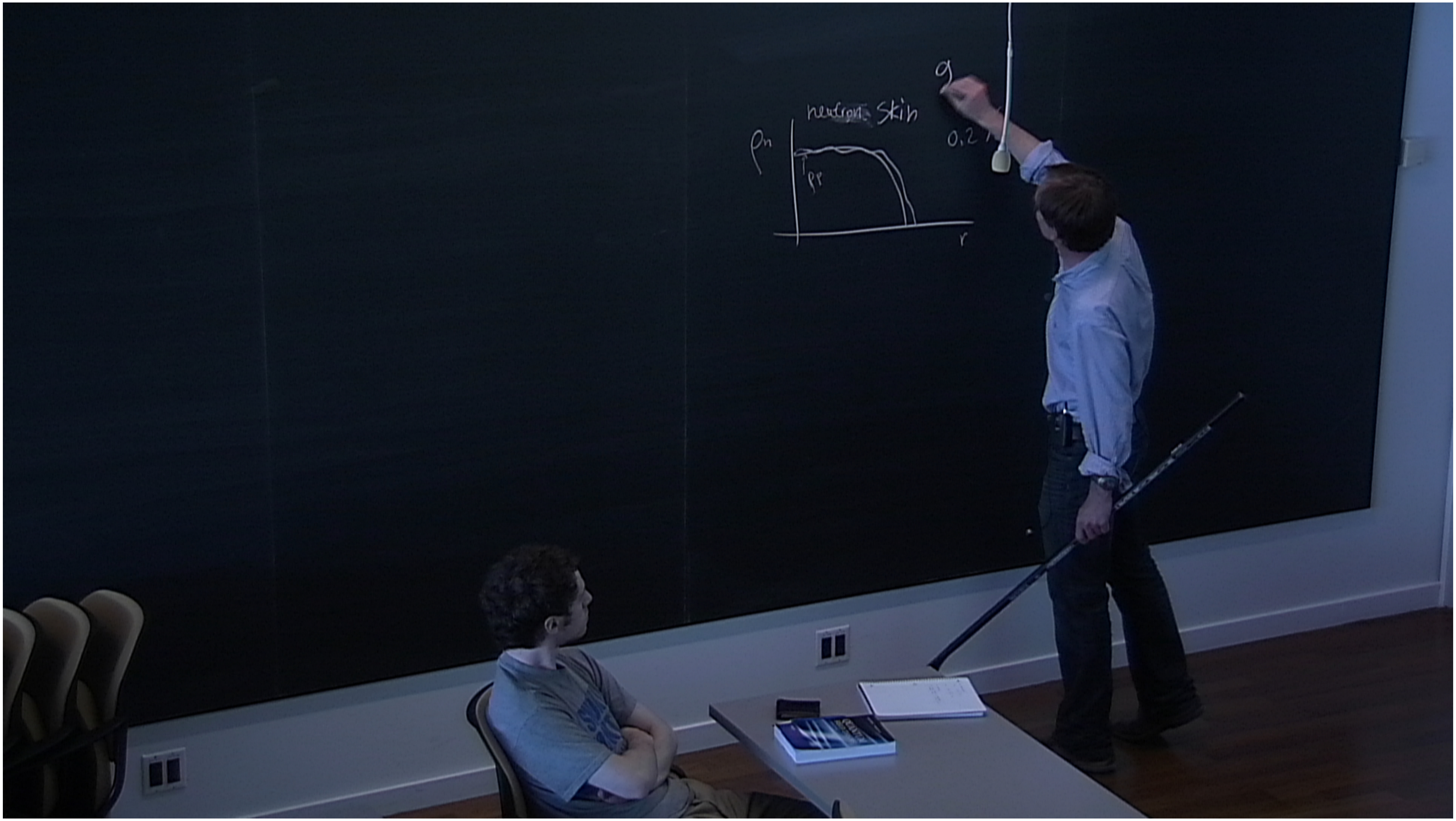
neutron skin
ρn
ρp
r
0.2

Part II (magic & precise)

Atomic clocks

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Part II (magic & precise)

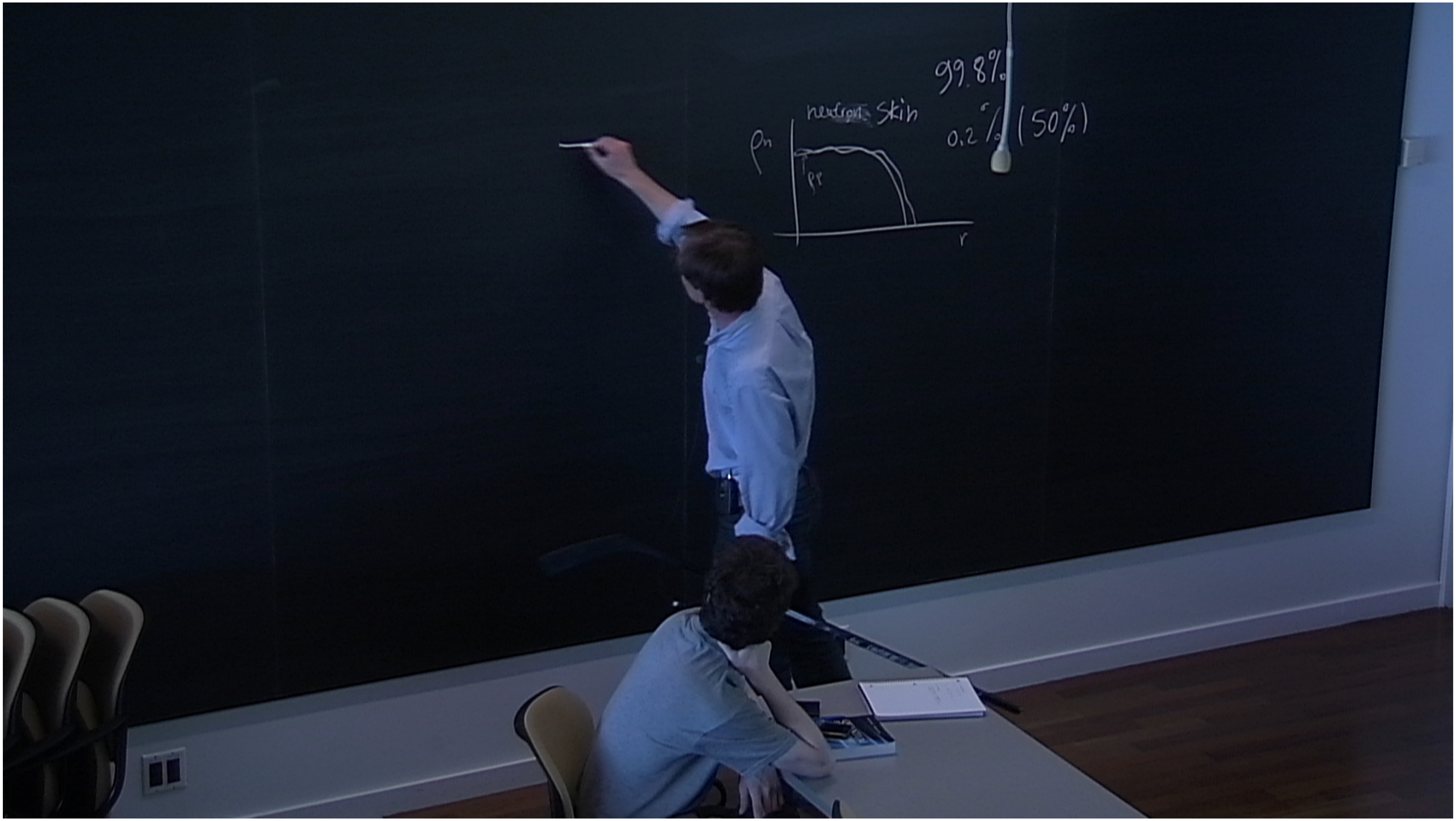
Atomic clocks

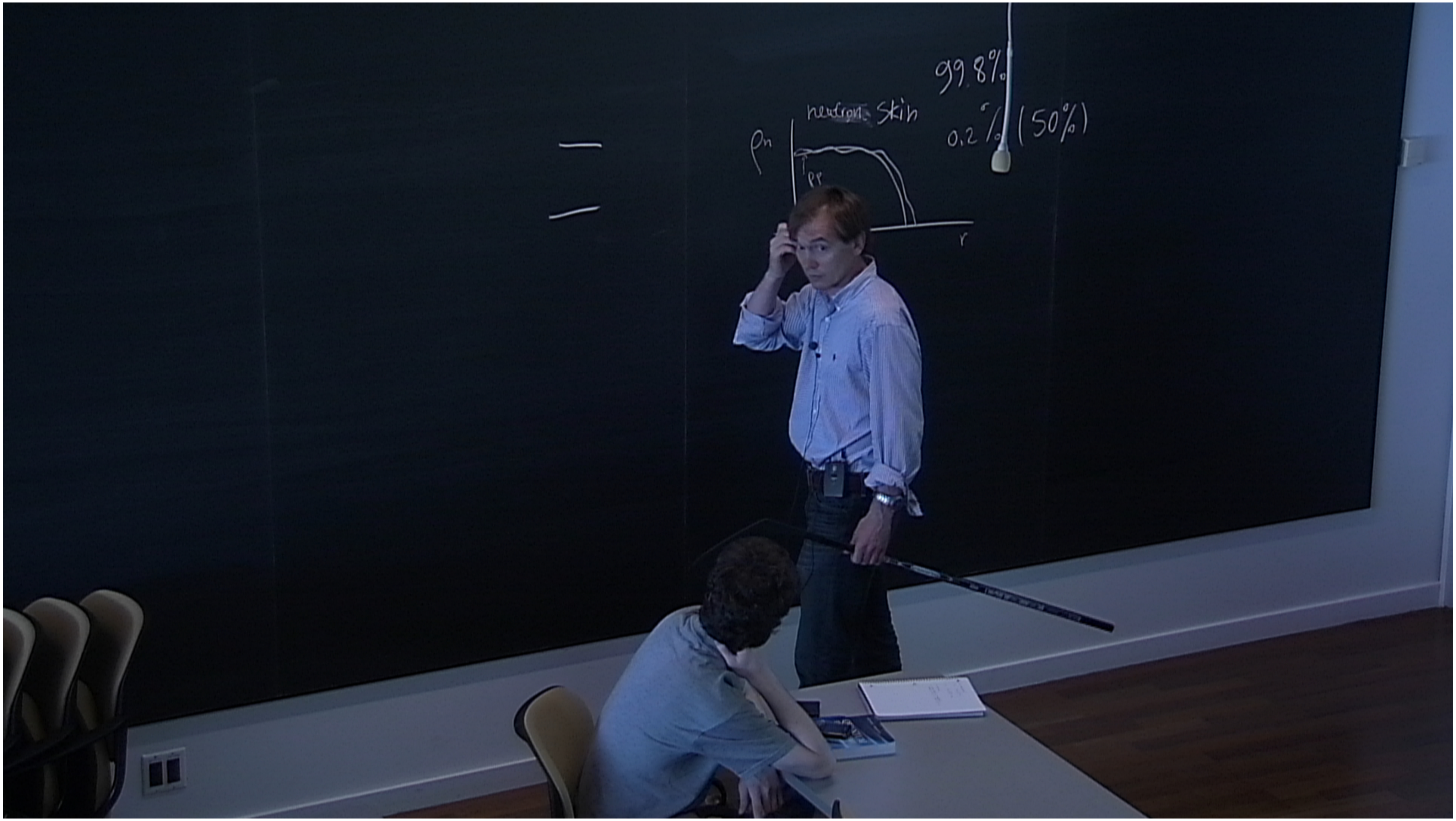
$\Rightarrow$

$|e\rangle$

$|g\rangle$

$$\nu_{\text{clock}} = \frac{E_e - E_g}{h}$$


99.8%
neutron skin
0.2% (50%)
ρ_n
ρ_p
r


99.8%
neutron skin
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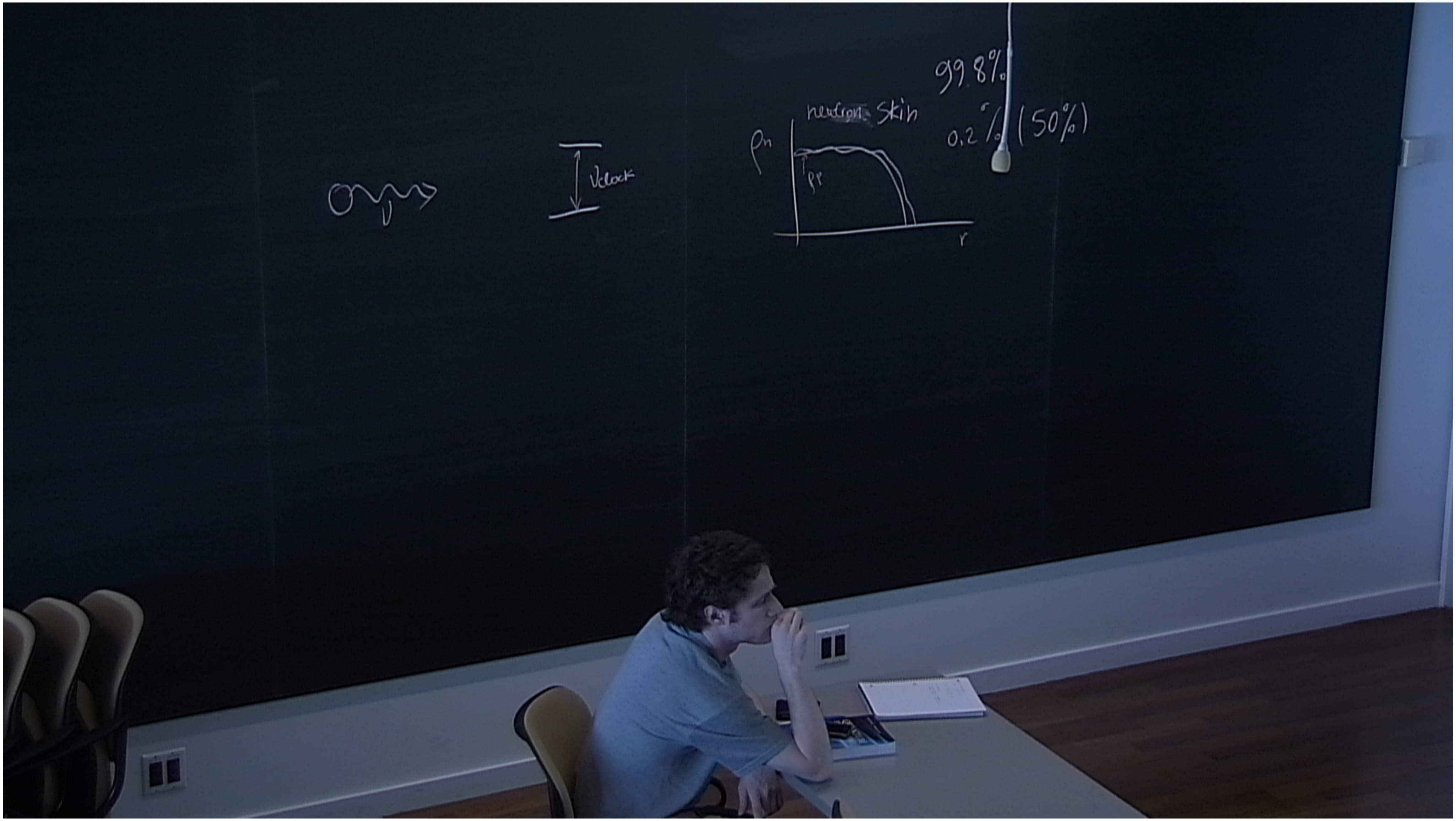
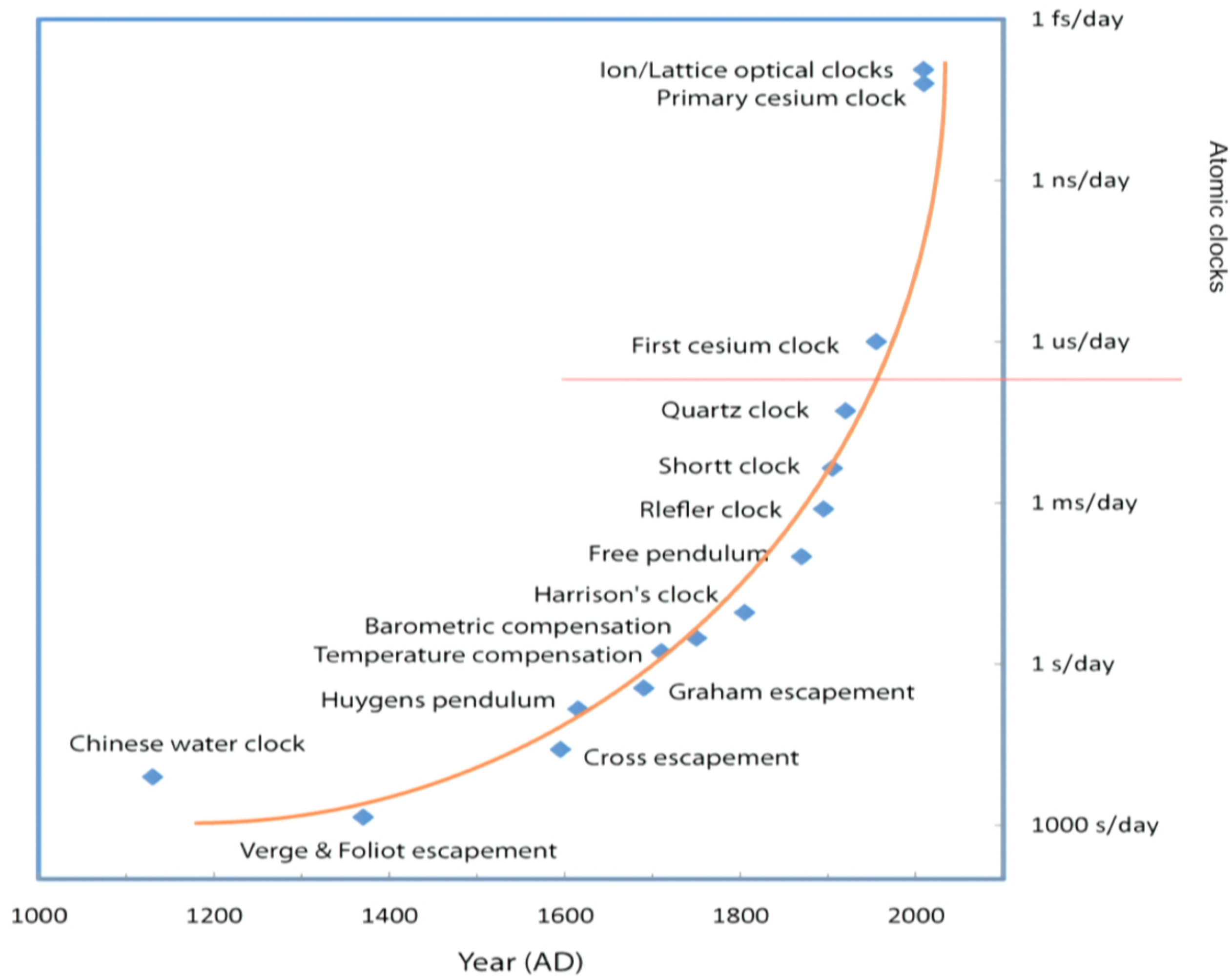
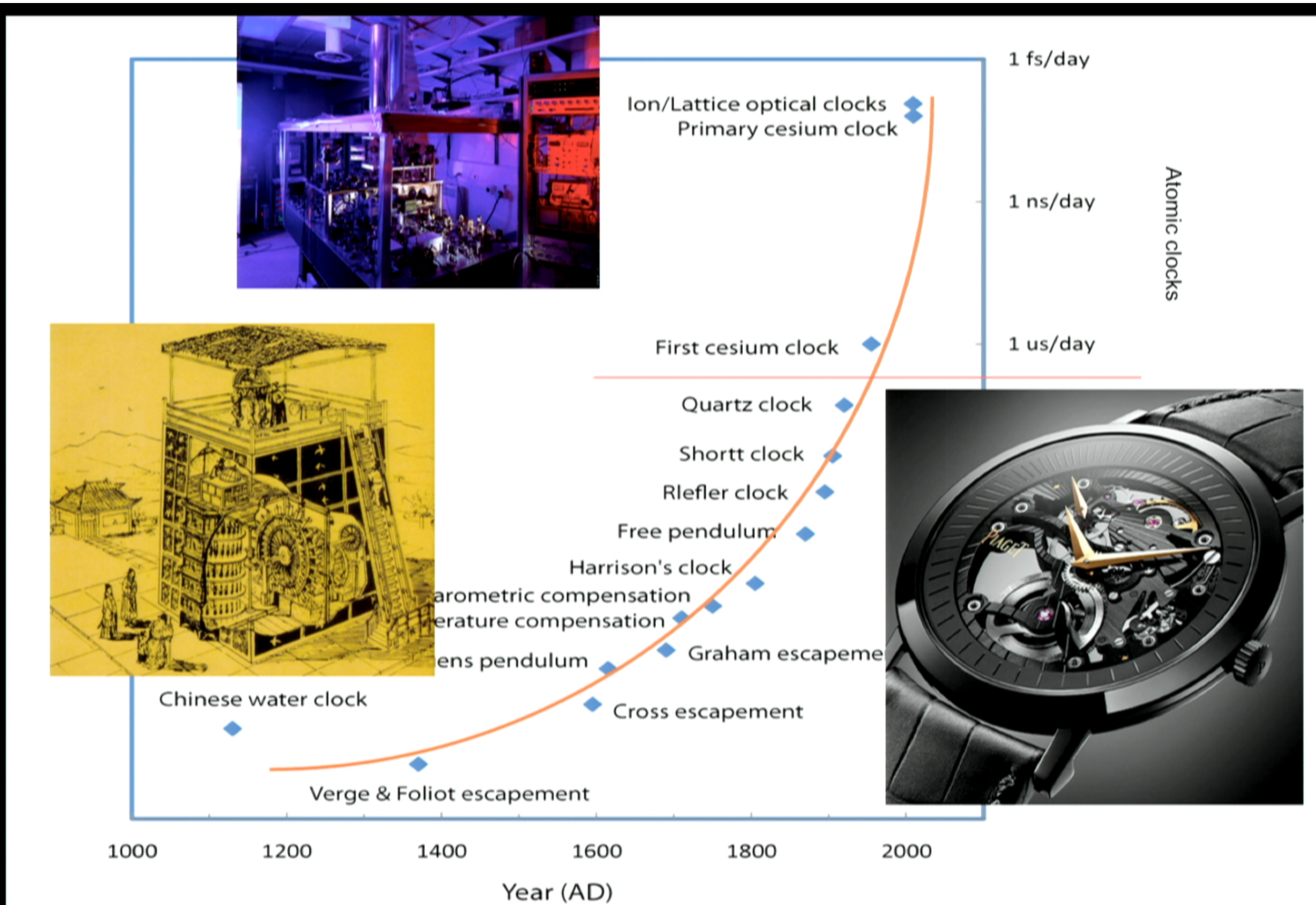

Vclock
neutron skin
99.8%
0.2% (50%)
r


1 fs/day
1 ns/day
1 us/day
1 ms/day
1 s/day
1000 s/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapement
Huygens pendulum
Chinese water clock
Cross escapement
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)

30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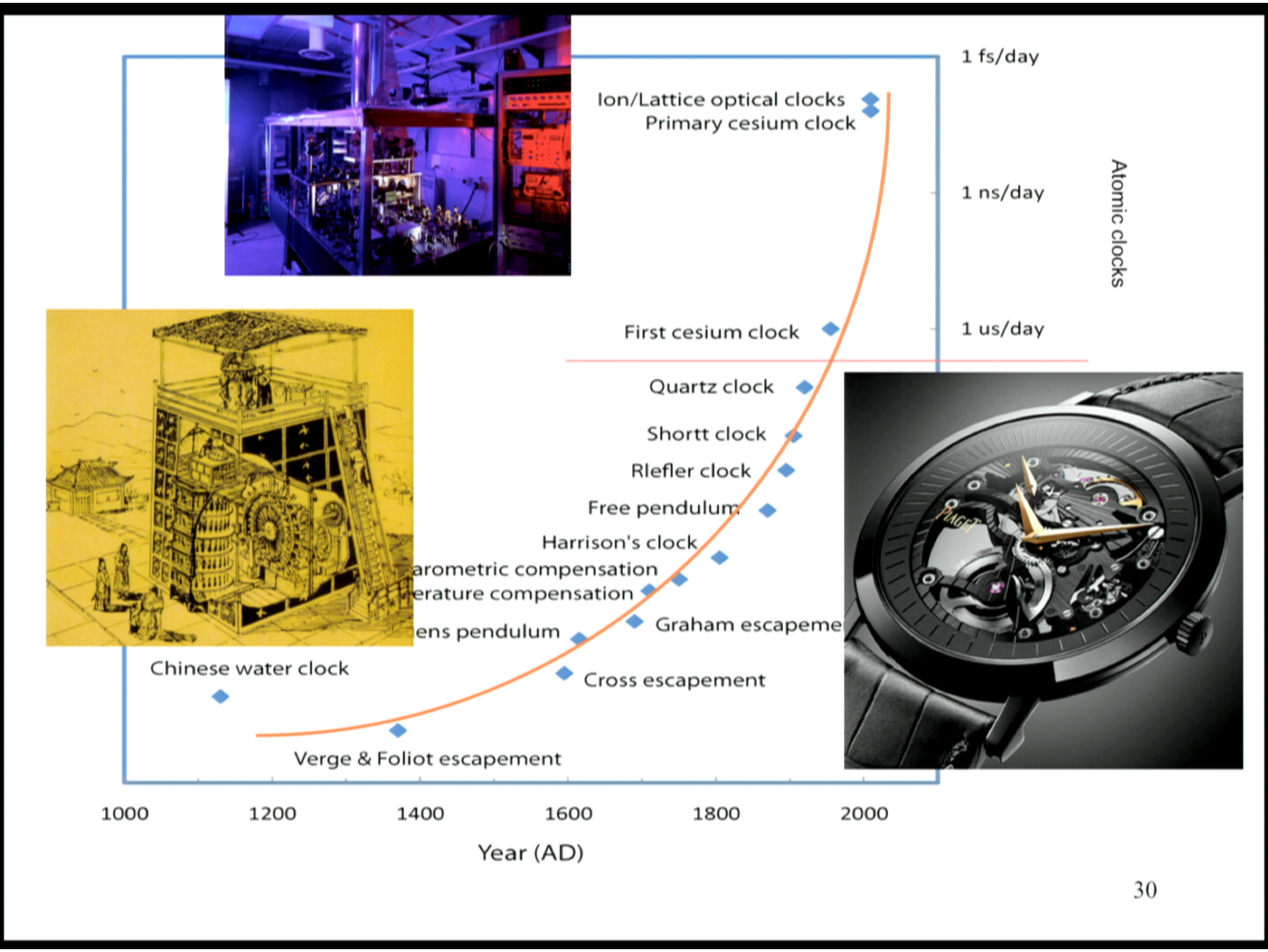
30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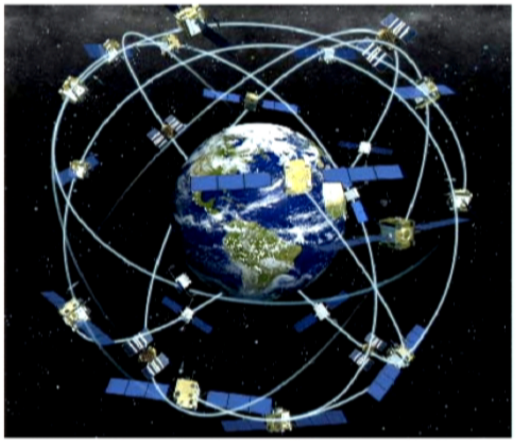
30

Applications



GPS:: Global Positioning System
Digital networks (cell phones, internet, …)
Fundamental physics

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SI 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 cesium 133 atom. This definition refers to a cesium atom at rest at a temperature of 0 K.

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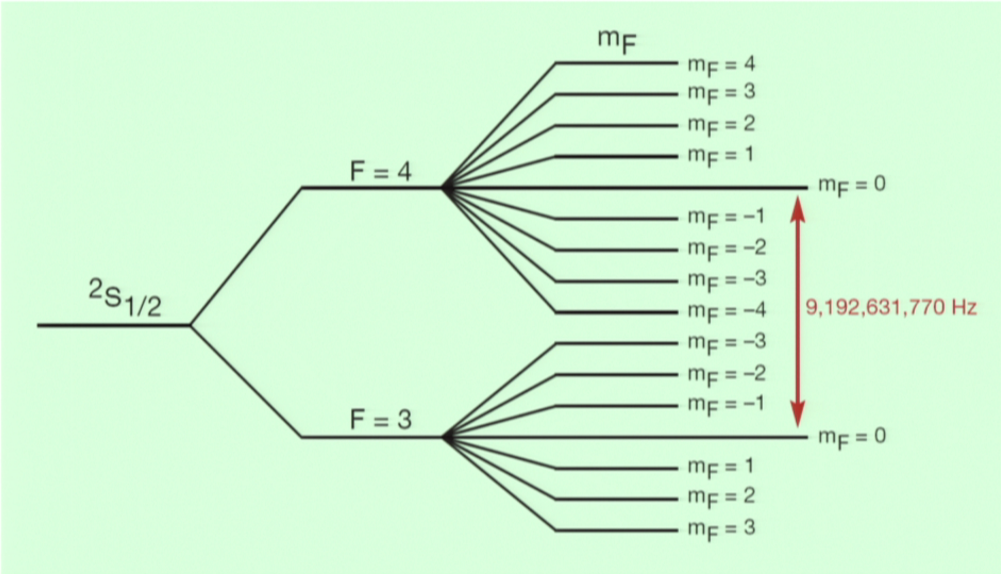

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US timekeepers: NIST Cs fountain clock

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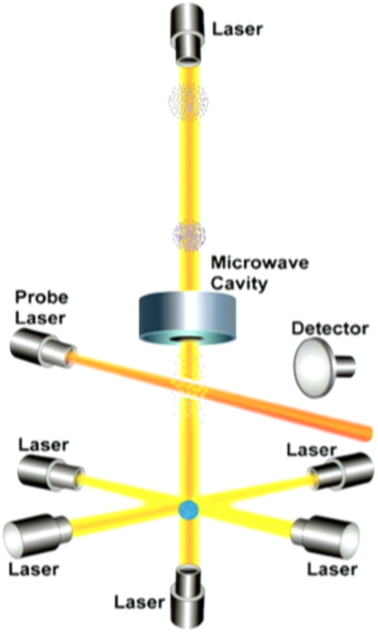
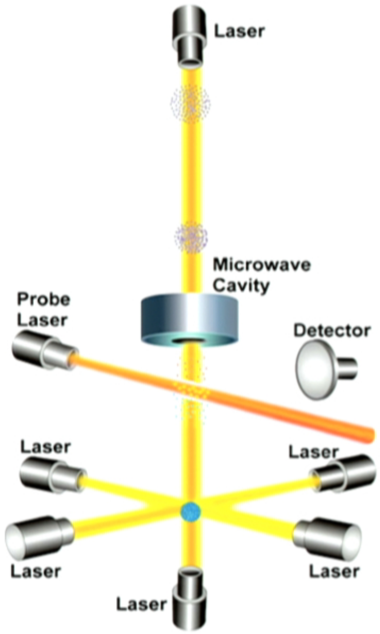


US timekeepers:
NIST Cs fountain clock



Can we shrink these clocks?

Lattice clocks

Why the fountain clocks are large?

$$\Delta \nu \, \Delta t \geq 1$$

$$\text{frequency resolution} \propto \frac{1}{\text{interrogation time}}$$

Lattice clocks

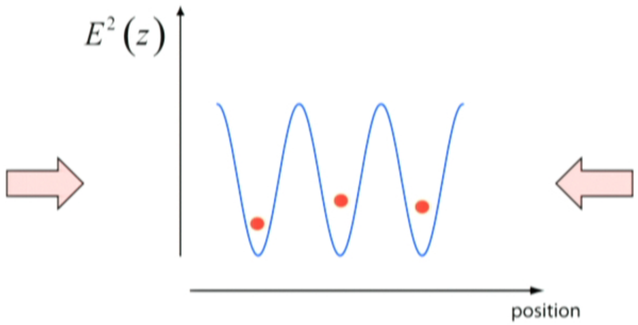
Why the fountain clocks are large?

$$\Delta\nu\,\Delta t \geq 1$$

$$\text{frequency resolution} \propto \frac{1}{\text{interrogation time}}$$

Trap atoms

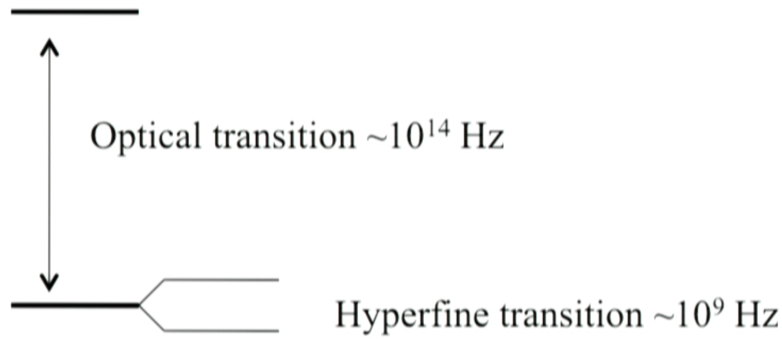
Optical lattice : counter-propagating laser beams = standing wave



$$V(z) = -\frac{1}{2}\alpha(\omega_L)\,E^2(z)$$

dynamic polarizability

What about the primary Cs standard?



Lattice clocks work with optical transitions: ~10^{14} Hz
Too fast for counting electronics : need expensive frequency combs

Further reading on lattice clocks

APS » Journals » Rev. Mod. Phys. » Volume 83 » Issue 2 < Previous Article | Next Article >

Rev. Mod. Phys. 83, 331–348 (2011)

Colloquium: Physics of optical lattice clocks

Abstract | References | No Citing Articles

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Recently invented and demonstrated optical lattice clocks hold great promise for improving the precision of modern time keeping. These clocks aim at the 10^{-18} fractional accuracy, which translates into a clock that would neither lose nor gain a fraction of a second over an estimated age of the Universe. In these clocks, millions of atoms are trapped and interrogated simultaneously, dramatically improving clock stability. Here the principles of operation of these clocks are discussed and, in particular, a novel concept of magic trapping of atoms in optical lattices. Recently proposed microwave lattice clocks are also highlights and several applications that employ the optical lattice clocks as a platform for precision measurements and quantum information processing.

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The ultimate clock?

arXiv.org > physics > arXiv:1110.2490

Physics > Atomic Physics

A Single-Ion Nuclear Clock for Metrology at the 19th Decimal Place

C. J. Campbell, A. G. Radnaev, A. Kuzmich, V. A. Dzuba, V. V. Flambaum, A. Derevianko

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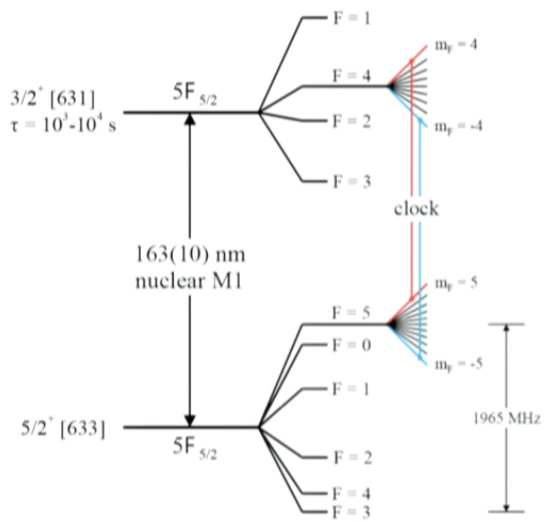

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The ultimate clock?

arXiv.org > physics > arXiv:1110.2490

Physics > Atomic Physics

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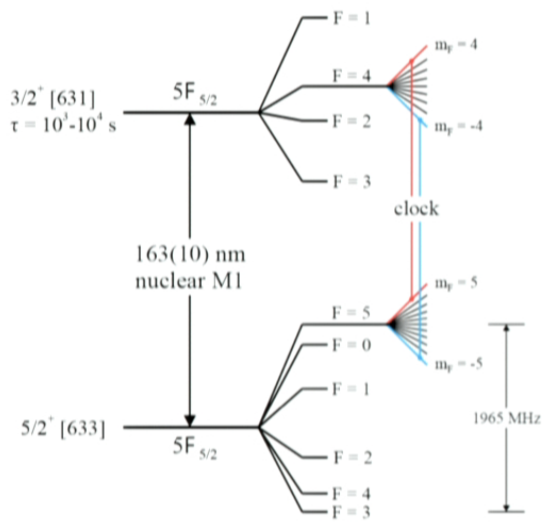
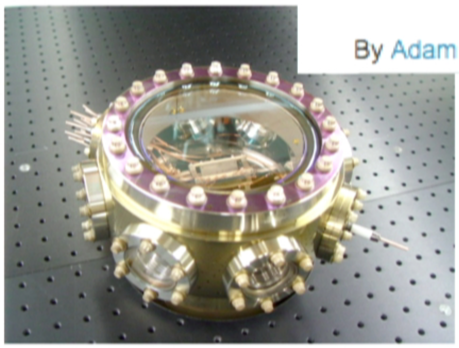


TABLE I. Estimated systematic error budget for a $^{229}Th^{3+}$ clock using realized single-ion clock technologies. Shifts and uncertainties are in fractional frequency units ($\Delta\nu/\nu_{clk}$) where $\nu_{clk} = 1.8$ PHz. See text for discussion.

Effect	$\lvert$Shift$\rvert$ (10^{-20})	Uncertainty (10^{-20})
Excess micromotion	10	10
Gravitational	0	10
Cooling laser Stark	0	5
Electric quadrupole	3	3
Secular motion	5	1
Linear Doppler	0	1
Linear Zeeman	0	1
Background collisions	0	1
Blackbody radiation	0.013	0.013
Clock laser Stark	0	$\ll 0.01$
Trapping field Stark	0	$\ll 0.01$
Quadratic Zeeman	0	0
Total	18	15

WIRED

Laser-Tuned Nuclear Clock Would Be Accurate for Billions of Years



By Adam Mann March 20, 2012 | 5:28 pm | Categories: Physics

questcequilmanque

You've managed to find the single most depressing scientific endeavor of all time: Spend years of research trying to make an ultra-precise clock more precise. If they succeed, only electrons will notice. What's the suicide rate among these people?

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Why do we need better clocks?

New timepieces will lose only 1 second over the age of the Universe

GPS

- Autopilots for the cars?
- Automated landing of planes
- Deep-space navigation (DSN network of NASA)

Are constants of nature constant?