

Time variation of the fine-structure constant (and other fundamental constants)

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MAX-PLANCK-GESellschaft



Outline

Introduction

Fundamental constants

Variation of fundamental constants in astrophysics

Variation of fundamental constants in laboratory

Sensitivity factors

Highly charged ions

Configuration-crossing highly-charged ions

Hyperfine splitting of simple highly charged ions

Variation of fundamental constants with atomic clocks

Conclusions and Outlook

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“Fundamental” “constants”

- Speed of light c
- Planck constant \hbar
- Electron mass m_e
- Proton mass m_p
- Electron charge e
- Quark masses:
 m_u, m_d, m_s, \dots
- QCD scale parameter Λ_{QCD}
- Gravitational constant G
- ...

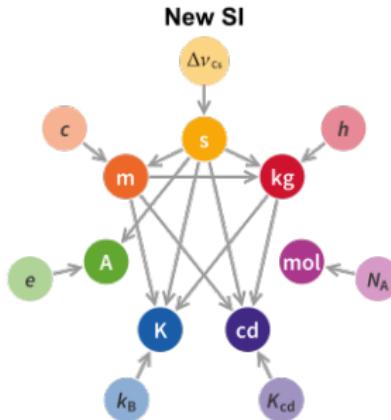


Figure source: <https://en.wikipedia.org/>

However: neither fundamental nor constants

Neither “Fundamental” ...

- parameters a theory
- fundamental importance
- can not be predicted
- have to be measured experimentally
- can not be explained

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Numerical explanation (for CODATA 2007, mathematician J. Gilson):

$$\alpha = \frac{\cos(\pi/137)}{137} \frac{\tan(\pi/(137 \cdot 29))}{\pi/(137 \cdot 29)} \approx \frac{1}{137.0359997867}.$$

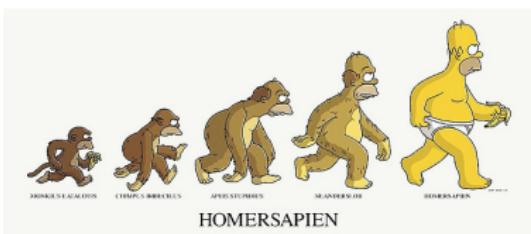
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Anthropic explanation: stable matter could not exist if its value were much different.



Fine-tuning problem

- The existence of life requires certain values for the fundamental constants
- Nuclear reactions in stars are sensitive to α

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

If $\alpha \approx 1/134$ (2.5%),
or strong interaction were
different by 0.4%,
or quark masses by 1-2%,

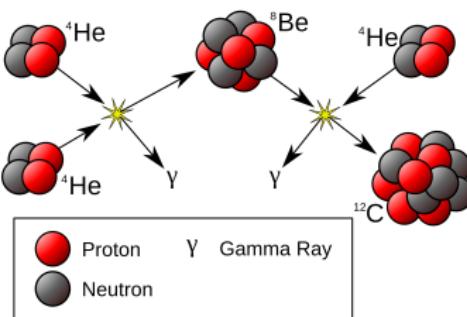


Figure source:

https://en.wikipedia.org/wiki/Triple-alpha_process

No carbon in stars, no life in the Universe.

... no “constants”. Example: π

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Time variation of a fundamental dimensionless constant

Robert J. Scherrer

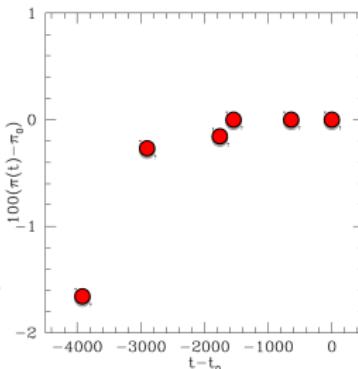
Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235

We examine the time variation of a previously-uninvestigated fundamental dimensionless constant. Constraints are placed on this time variation using historical measurements. A model is presented for the time variation, and it is shown to lead to an accelerated expansion for the universe. Directions for future research are discussed.

PACS numbers: 98.80.Cq

It is well-known that only time variation of dimensionless fundamental constants has any physical meaning. Here we consider the time variation of a dimensionless constant not previously discussed in the literature: π . It is impossible to overstate the significance of this constant. Indeed, nearly every paper in astrophysics makes use of it. (For a randomly-selected collection of such papers, see Refs. [2, 3, 4, 5, 6, 7, 8, 9, 10]).

Location	Time	$\pi(t)$
Babylon	1900 BC	3.125
India	900 BC	3.139
China	263 AD	3.14
China	500 AD	3.1415926
India	1400 AD	3.14159265359



... no “constants”. Example: π

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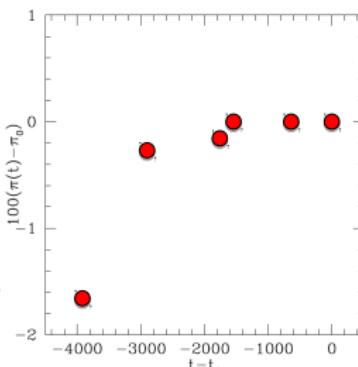
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- According to the Bible (Old Testament, app. 1400 BC): $\pi = 3$

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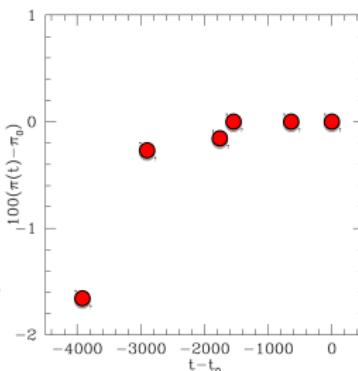
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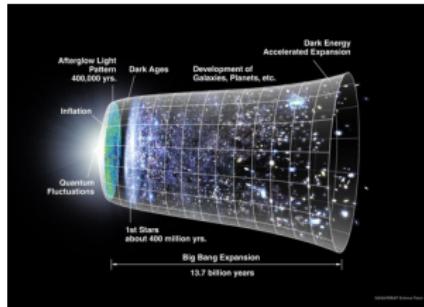


- According to the Bible (Old Testament, app. 1400 BC): $\pi = 3$
- Among different widely used system of units:
“supernatural” s.u. $m = c = h = \hbar = 1$, therefore $\pi = 1/2$

Why FC are changing?

Theoretical interest in varying constants:

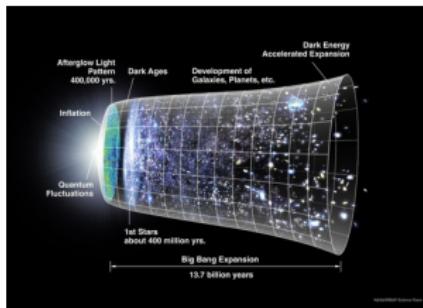
- String theory
- Theories beyond the Standard Model
- Astrophysical evidence for variation claimed



Why FC are changing?

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Observable

Only *dimensionless* constants can be measured:

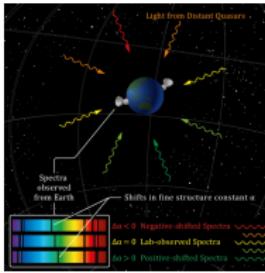
- fine-structure constant $\alpha = \frac{e^2}{\hbar c}$
- electron-proton mass ratio m_e/m_p
- quark masses on the scale of quantum chromodynamic m_q/Λ_{QCD}

α variation in astrophysics

Idea: observed energy depend on α

$$E_z = E_0 + q \left(\frac{\alpha_z^2}{\alpha_0^2} - 1 \right)$$

Realization:
analyze quasar spectrum



1999, Webb *et al.* considered a data set of 128 quasars, and for $(10 - 12) \cdot 10^9$ years:

$$\frac{\delta\alpha}{\alpha} = -5.7(1.0) \cdot 10^{-6}$$

2004 Chand *et al.*: $\frac{\delta\alpha}{\alpha} = -0.6(0.6) \cdot 10^{-6}$

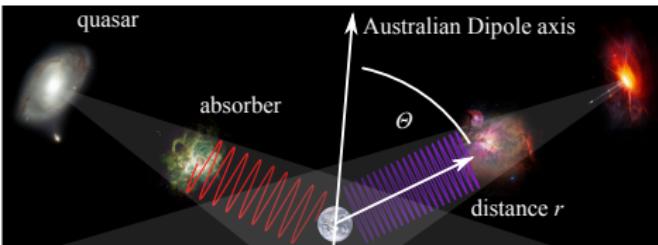
At the moment the question is still controversial.

α variation in astrophysics

From the analysis of quasar spectra

$$\Delta\alpha/\alpha = A \cos \Theta$$

$$A = (1.02 \pm 0.21) \cdot 10^{-5}$$



J. K. Webb *et al.*, PRL 107, 191101 (2011)

...and in a laboratory

The motion of the Sun (towards a region with larger α)

The motion of the earth around the Sun

$$\Delta\alpha/\alpha \approx 10^{-18} - 10^{-19} \text{ yr}^{-1}$$

$$\Delta\alpha/\alpha = 1.4 \cdot 10^{-20} \cos(\omega t)$$

J. C. Berengut *et al.*, Europhys. Lett. 97, 20006 (2012)

m_e/m_p variation in astrophysics

Same idea: Analysis of H_2 spectra
 Highly accurate measurements of Lyman band

$$\frac{\Delta(m_p/m_e)}{(m_p/m_e)} = (2.4 \pm 0.5) \times 10^{-5}$$

Decreases in the past 12 Gyr

E. Reinhold et al., PRL 96, 151101 (2006)

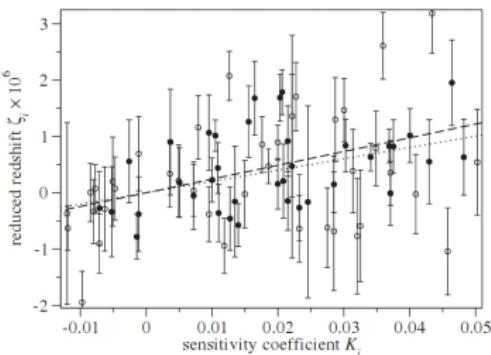


FIG. 2. Linear fit to reduced redshift of quasar absorption lines ζ as defined by Eq. (9). Solid circles: Q 0347-383, $z = 3.024\,897\,0$; open circles: Q 0405-443, $z = 2.594\,732\,5$. The error-weighted linear fit is shown by a dashed line, the unweighted fit by a dotted line.

Laboratory VS Space

- ✓ High accuracy
- ✓ Control on the experimental environment
- ✓ Wide selection of systems
- ✗ No variation



Can we combine Laboratory and Space?..

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Can we combine Laboratory and Space?..

Energy frontier: accelerators, lasers

Precision frontier: frequency measurements with atomic clocks

Laboratory VS Space

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Can we combine Laboratory and Space?..

Energy frontier: accelerators, lasers

Precision frontier: frequency measurements with atomic clocks

- There is evidence of the VFC "right now" yet
- Different types: slow drifts, transient, oscillations, stochastic

How to measure the variation

$$\frac{\Delta E}{E} = K_\alpha \frac{\Delta \alpha}{\alpha} + K_{e/p} \frac{\Delta(m_e/m_p)}{m_e/m_p} + K_q \frac{\Delta(m_q/\Lambda_{\text{QCD}})}{m_q/\Lambda_{\text{QCD}}}$$

How to measure the variation

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By measuring the energy two times, **Today** and **Tomorrow**, we can theoretically see



How to measure the variation

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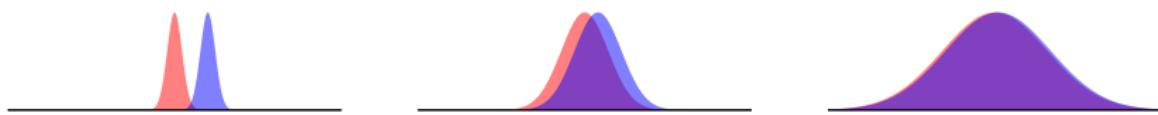
By measuring the energy two times, **Today** and **Tomorrow**, we
will see:



How to measure the variation

$$\frac{\Delta E}{E} = K_\alpha \frac{\Delta \alpha}{\alpha} + K_{e/p} \frac{\Delta(m_e/m_p)}{m_e/m_p} + K_q \frac{\Delta(m_q/\Lambda_{\text{QCD}})}{m_q/\Lambda_{\text{QCD}}}$$

By measuring the energy two times, **Today** and **Tomorrow**, we will see:



Conditions

1. Maximized enhancement factors K
2. Minimized linewidth Γ
3. Optical transition in stable atomic system

Sensitivity factors

$K_{e/p}$

- Atomic fine-structure (FS) transitions: 0
- Atomic hyperfine-structure (HFS) transitions: 1
- Molecular transitions:
Electronic/Vibrational/Rotational = 0/0.5/1

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K_q

Usually can be addressed only in nuclear transitions

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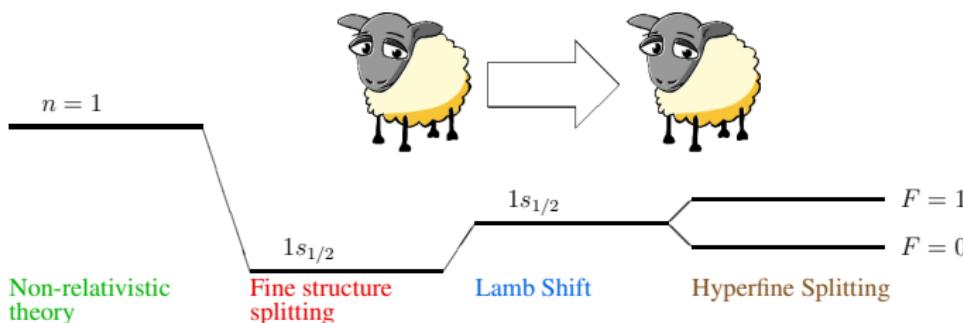
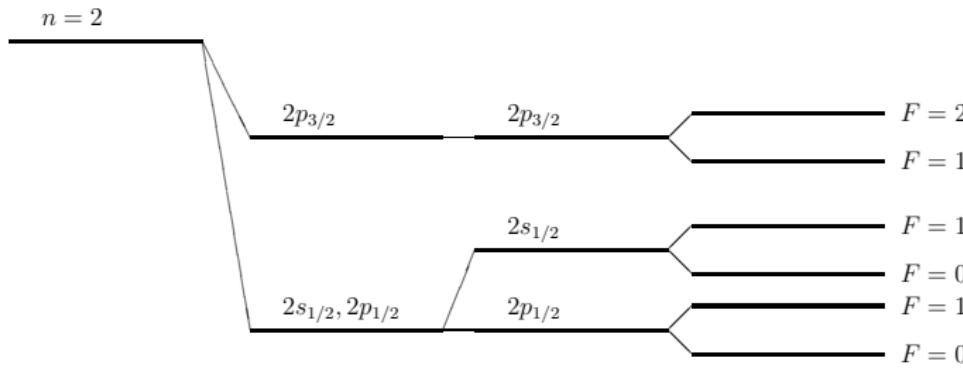
K_q

Usually can be addressed only in nuclear transitions

K_α

- the sensitivity strongly depends on the chosen system and can vary significantly
- \Rightarrow great deal of interest from both experimental and theoretical sides

Spectrum of hydrogen-like ion



Schrödinger
equation

Dirac equation

QED

Nuclear
magnetic field

Existing atomic clocks and their parameters

Atom	transition	K_α	Accuracy ($10^{-16}/\text{yr}$)
Cs	HFS microwave	0.83	-3.3±3.0
Sr	optical	0.06	
Al ⁺	optical	0.008	
Hg	optical	1.16	
Yb	optical	0.45	
Hg ⁺	optical	-3.19	3.7±3.9
Yb ⁺	optical	-5.95	0.2±4.1

N. Huntemann *et al.* PRL 113, 210802 (2014)
A. D. Ludlow *et al.* RMP 87, 637 (2015)

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Hg ⁺	optical	-3.19	3.7±3.9
Yb ⁺	optical	-5.95	0.2±4.1

Limitations on the variation of fundamental constants

$$\frac{\delta \alpha}{\alpha} = -2.0(2.0) \times 10^{-17}/\text{yr}$$

$$\frac{\delta(m_e/m_p)}{m_e/m_p} = 0.5(1.6) \times 10^{-16}/\text{yr.}$$

N. Huntemann *et al.* PRL 113, 210802 (2014)

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Systematic effects

TABLE II. Systematic shifts and uncertainties for the NIST-Al-1 (Rosenband *et al.*, 2008b) and NIST-Al-2 (Chou, Hume, Koelemeij, *et al.*, 2010) clocks. The fractional frequency shifts $\Delta f/f$ and the 1σ uncertainties are given in units of 10^{-18} .

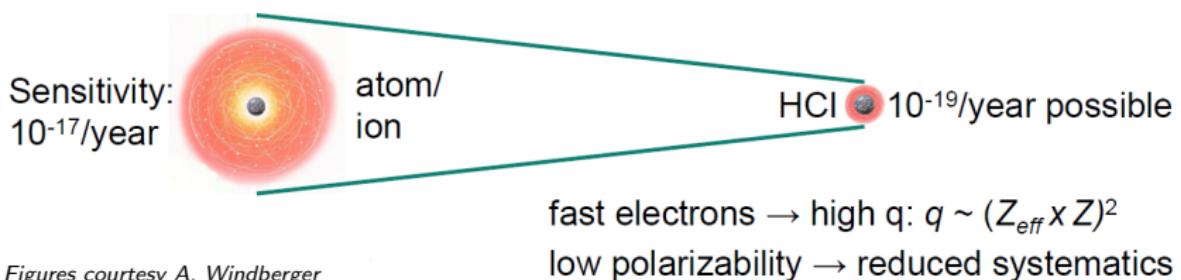
Shift	NIST-Al-1		NIST-Al-2		Limitation
	$\Delta f/f$	σ	$\Delta f/f$	σ	
Micromotion	-20	20	-9	6	Static electric fields
Secular motion	-16	8	-16.3	5	Doppler cooling
Blackbody radiation	-12	5	-9	0.6	dc polarizability
Cooling laser Stark	-7	2	-3.6	1.5	Polarizability, intensity
Clock laser Stark	0	0.2	Polarizability, intensity
Quadratic Zeeman	-453	1.1	-1079.9	0.7	<i>B</i> -field calibration
First-order Doppler	0	1	0	0.3	Statistical imbalance
Background gas collisions	0	0.5	0	0.5	Collision model
AOM phase chirp	0	0.1	0	0.2	rf power
Total	-513	22	-1117.8	8.6	

TABLE V. A recent evaluation of systematic frequency shifts in an ^{87}Sr lattice clock. From Bloom *et al.*, 2014.

Systematic effect	Correction (10^{-18})	Uncertainty (10^{-18})
Lattice Stark	-461.5	3.7
Residual lattice vector shift	0	<0.1
Probe beam ac Stark	0.8	1.3
BBR Stark (static)	-4962.9	1.8
BBR Stark (dynamic)	-345.7	3.7
First-order Zeeman	-0.2	1.1
Second-order Zeeman	-144.5	1.2
Density	-4.7	0.6
Line pulling and tunneling	0	<0.1
dc Stark	-3.5	2.1
Servo error	0.4	0.6
AOM phase chirp	0.6	0.4
Second-order Doppler	0	<0.1
Background gas collisions	0	0.6
Total correction	-5921.2	6.4

Highly charged ions

Neutral atoms → Singly charged ions → Doubly charged ions ...



Figures courtesy A. Windberger

- Wide choice of the systems
- Relativistic: high sensitivity to α
- Low systematics

J. C. Berengut *et al.*, PRL 106, 210802 (2011)
Rosenband *et al.*, Science 319 (2008)

Highly charged ions: theory

“Small” parameters of the theory:

αZ : electron-nucleus Coulomb interaction

$1/Z$: relative strength of the electron-electron interaction

$\alpha \approx 1/137$: fine-structure constant

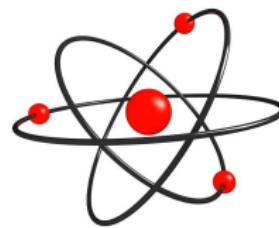


Figure source: cellcode.us

Theory: expansion of atomic properties in these parameters or all-order methods

One and few electrons HCl: rigorous QED approach

Many-electrons HCl: many-body methods

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HCI for α variation

Sommerfeld formula:

$$E = \frac{mc^2}{\sqrt{1 + \frac{(\alpha Z)^2}{(n - j - 1/2 + \sqrt{(j + 1/2)^2 - (\alpha Z)^2})^2}}}$$

Sensitivity to the variation of α :

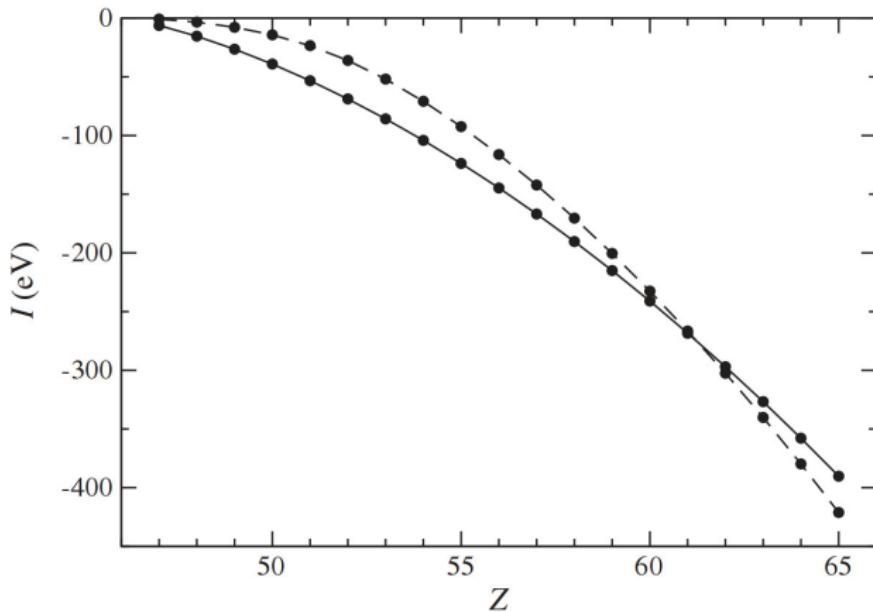
$$K_\alpha = \frac{\alpha}{E} \frac{\partial E(Z, \alpha)}{\partial \alpha} \approx -\frac{I(\alpha Z)^2}{En(j + 1/2)}$$

- High nuclear charge Z
- High ionization potential I
- Differences in the configuration composition (i.e. ν, j)

BUT: need to keep transitions in optical regime...

Configuration crossings

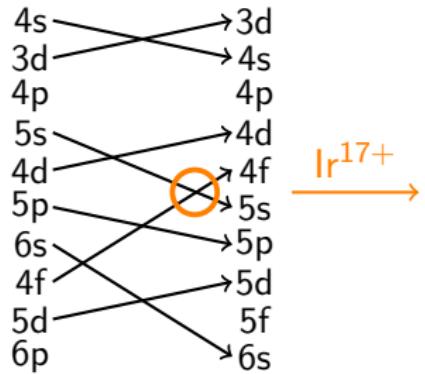
Dirac-Fock ionization energies of $5s$ (solid) and $4f_{7/2}$ (dashed) levels for the Ag isoelectronic sequence.



J. C. Berengut, V. A. Dzuba and V. V. Flambaum, PRL **105**, 120801 (2010).

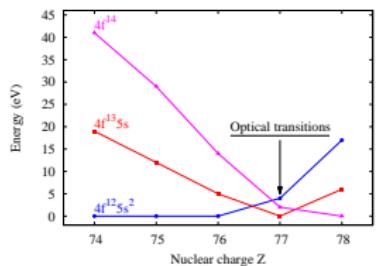
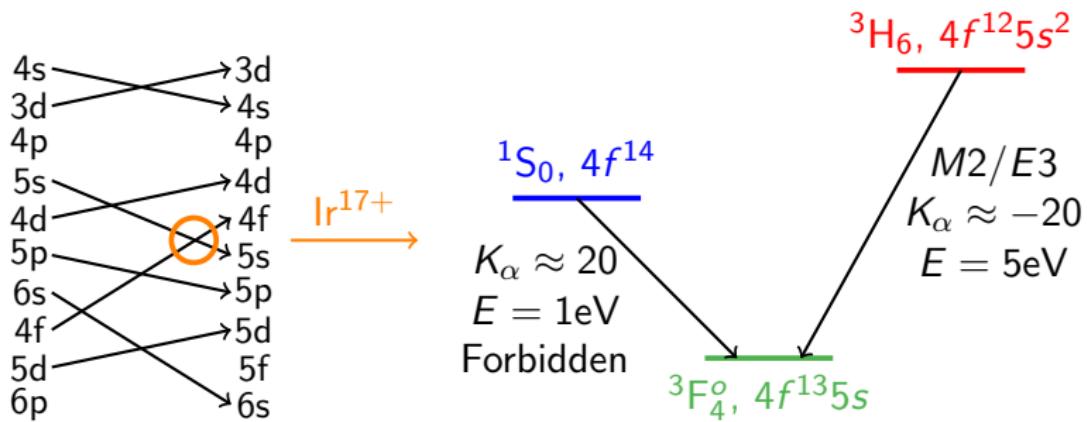
Configurations-level crossing HCl ions: Ir¹⁷⁺

$Z = 77$, 60 electrons: Madelung ordering vs Coulomb ordering



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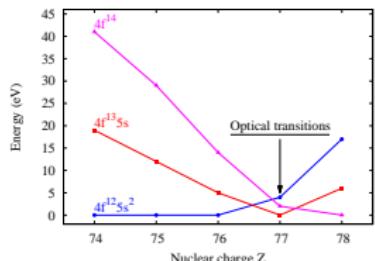
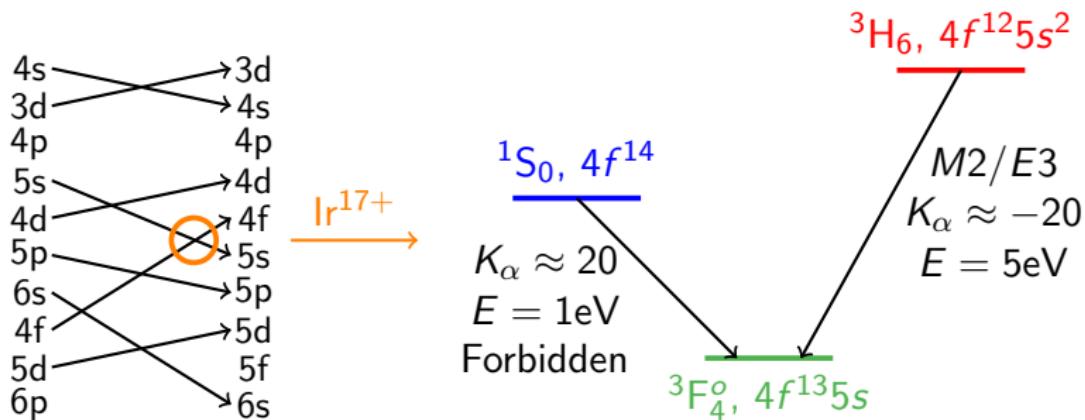
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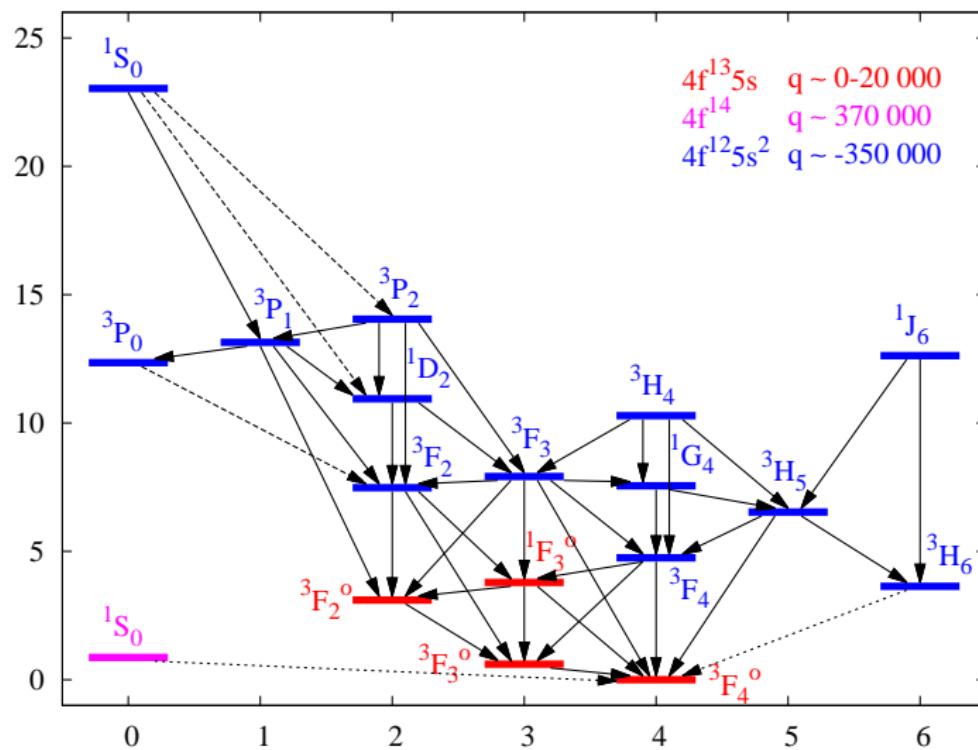
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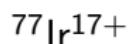
- Clock transitions are extremely narrow
- Theory can not predict position of the clock line with required accuracy
- Identification of lines in spectrum is needed

J. C. Berengut *et al.*, PRL 106, 210802 (2011)

Ir¹⁷⁺: level scheme



Towards the line identification



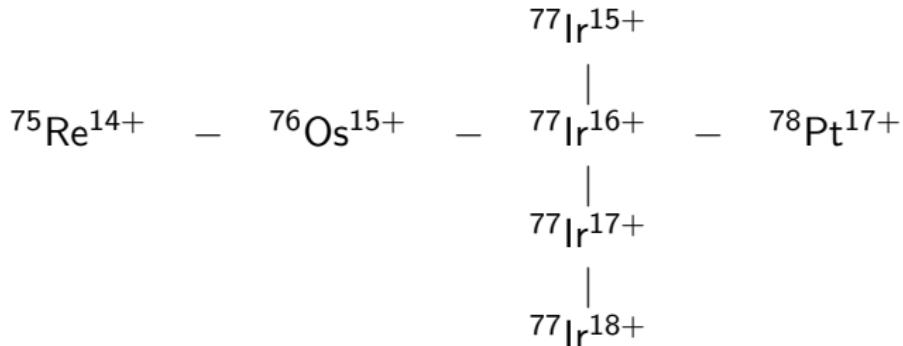
A. Windberger, J. R. Crespo López-Urrutia, H. Bekker, NSO *et al.*, PRL **114** 150801 (2015)
H. Bekker, O. O. Versolato, A. Windberger, NSO *et al.*, JPhysB **48**, 144018 (2015)

Towards the line identification

$^{77}\text{Ir}^{15+}$
|
 $^{77}\text{Ir}^{16+}$
|
 $^{77}\text{Ir}^{17+}$
|
 $^{77}\text{Ir}^{18+}$

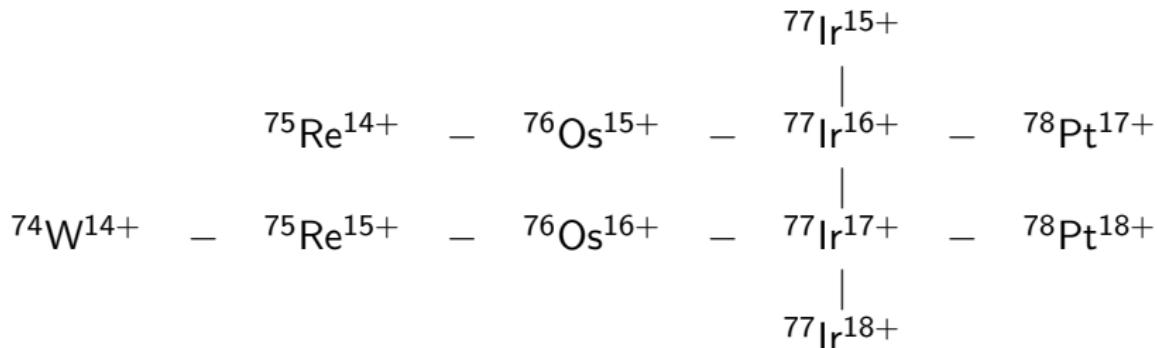
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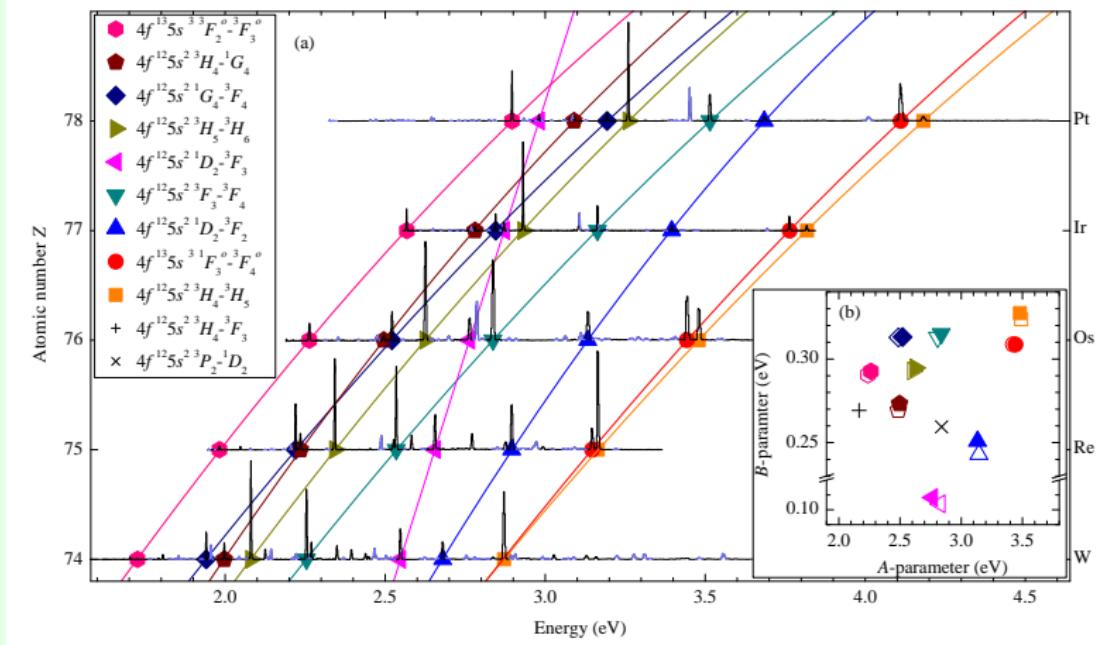


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M1 transitions scaling

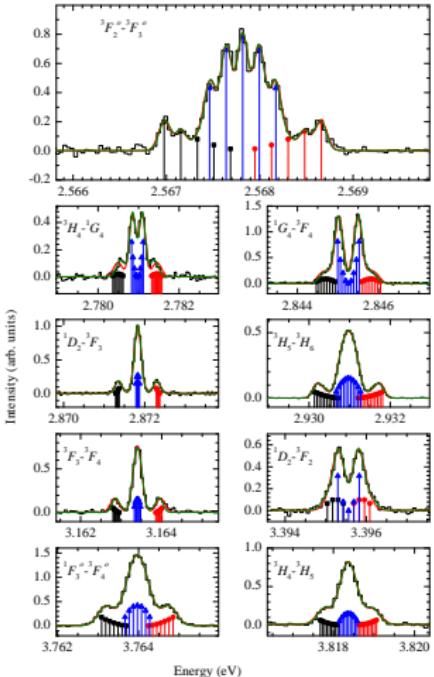


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Towards the line identification

 $^{74}\text{W}^{14+}$

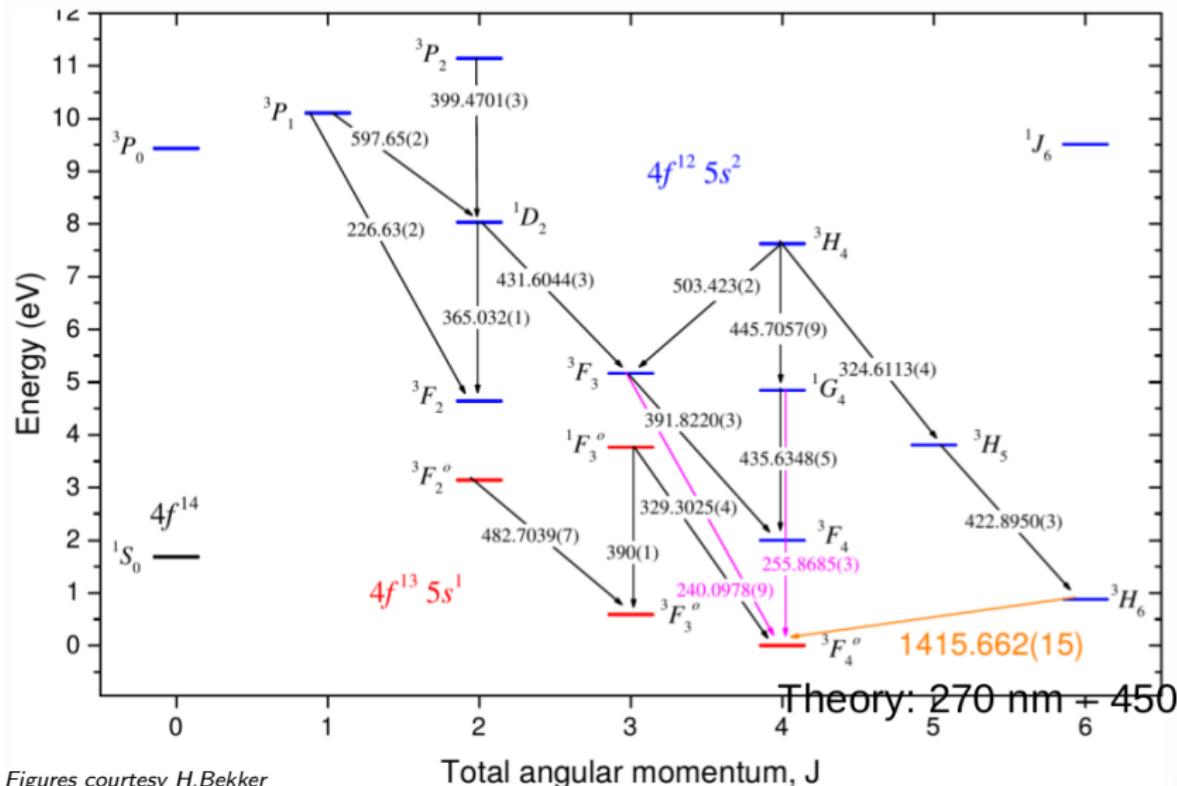
Zeeman splitting

 $^{77}\text{Ir}^{15+}$ $^{77}\text{Ir}^{16+}$ $^{77}\text{Ir}^{17+}$ $^{77}\text{Ir}^{18+}$ $^{78}\text{Pt}^{17+}$ $^{78}\text{Pt}^{18+}$

A. Windberger,
H. Bekker, O. G. Versolato, A. Windberger, et al., *J. Phys. B* **48**, 145018 (2015)

114 150801 (2015)

Ir¹⁷⁺, Current level structure understanding



Figures courtesy H.Bekker

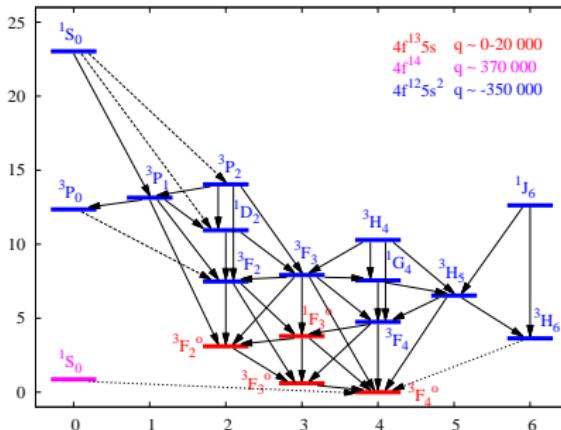
Configurations-level crossing HCl Ir¹⁷⁺ ion: Summary

- ✓ $K_\alpha = \pm 20$
- ✓ Optical range
- ✓ $\Gamma \approx 10^{-10}$ Hz

A. Windberger, J. R. Crespo López-Urrutia, H. Bekker, NSO *et al.*, PRL **114** 150801 (2015)
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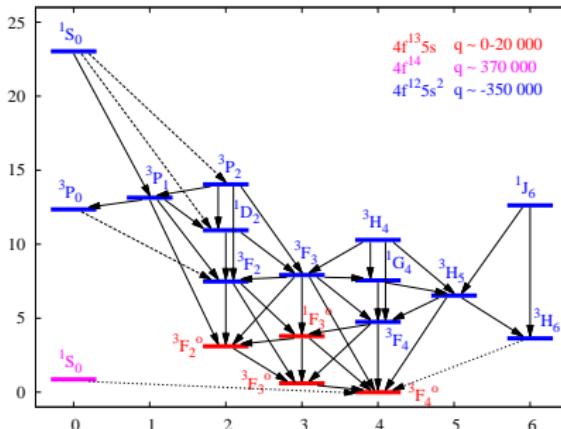
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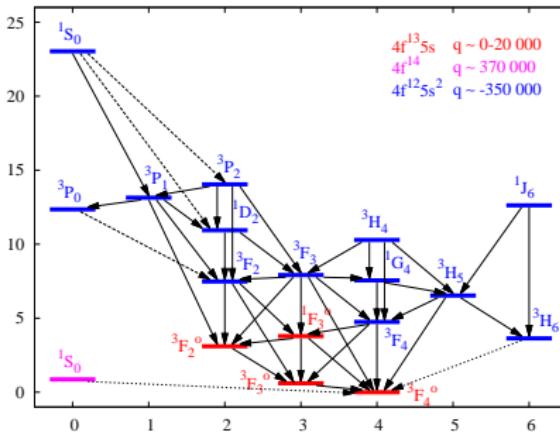


- Narrow lines: accurate theoretical predictions are needed

A. Windberger, J. R. Crespo López-Urrutia, H. Bekker, NSO *et al.*, PRL **114** 150801 (2015)
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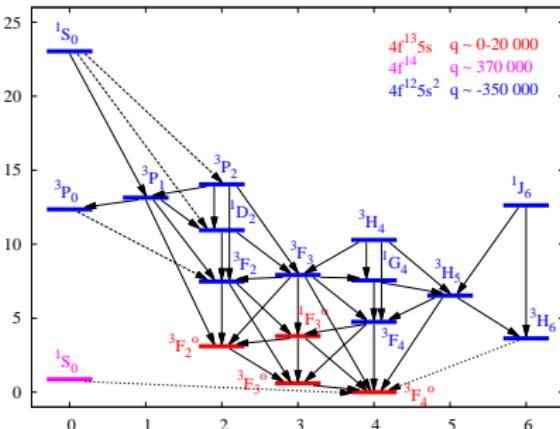


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no theory predictions, no observations

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A. Windberger, J. R. Crespo López-Urrutia, H. Bekker, NSO *et al.*, PRL **114** 150801 (2015)
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Other configurations-level crossing HCl ions

Ion	N_e	Ground	K_α
Ir ¹⁷⁺	60	$4f^{13}5s^1$	± 20
W ⁷⁺	68	$4f^{13}5p^1$	5
Pr ¹⁰⁺	49	$5p^1$	40
Sm ¹⁴⁺	48	$4f^2$	-120
Nd ¹⁰⁺	50	$5p^1$	-100

J. C. Berengut *et al.*, PRL **106**, 210802 (2011)
M. S. Safronova *et al.*, PRL **113**, 030801 (2014)

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$$\frac{\Delta E}{E} = K_\alpha \frac{\Delta \alpha}{\alpha}$$

100% uncertainty in $E \Rightarrow 100\%$ uncertainty in K_α

J. C. Berengut *et al.*, PRL **106**, 210802 (2011)
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Conclusions and Outlook

Hyperfine structure of H-like and Li-like ions

- interaction between nuclear magnetic dipole moment and the magnetic field generated by the electron(s)
- optical, accessible for the experiments
- simple atomic system with one or three electrons
- probing the magnetic sector of QED in strong field

$$E_\mu = \frac{\alpha(\alpha Z)^3}{n^3(2l+1)j(j+1)} \frac{m_e}{m_p} \frac{\mu}{\mu_N} \frac{2I+1}{2I} m_e c^2$$

Non-relativistic factor

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Non-relativistic factor

$$\times \left[A(\alpha Z) \right]$$

Relativistic
factor

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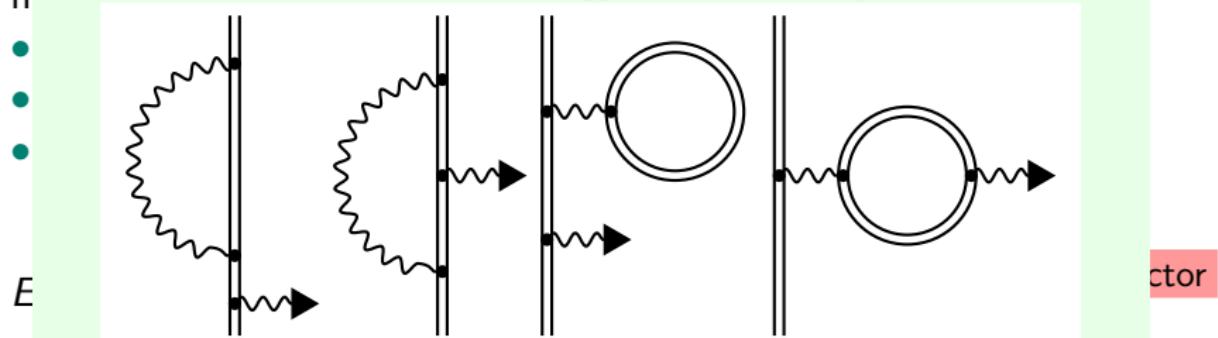
Non-relativistic factor

$$\times \left[A(\alpha Z) \cdot (1 - \delta)(1 - \varepsilon) \right]$$

<div style="background-color: #d9e1f2; padding: 5px; border-radius: 5px;">Relativistic factor</div>	<div style="background-color: #d9e1f2; padding: 5px; border-radius: 5px;">Finite nuclear size correction</div>	<div style="background-color: #d9e1f2; padding: 5px; border-radius: 5px;">Bohr-Weisskopf correction</div>
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Hyperfine structure of H-like and Li-like ions

- interaction between nuclear magnetic dipole moment and the QED corrections: self-energy and vacuum polarization



$$\times \left[A(\alpha Z) \cdot (1 - \delta)(1 - \varepsilon) \right]$$

Relativistic factor

Finite nuclear size correction

Bohr-Weisskopf correction

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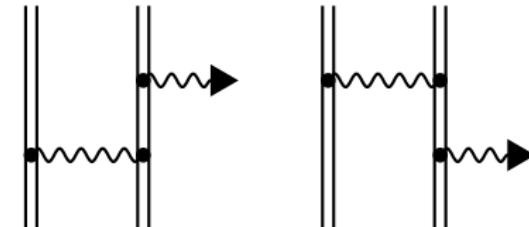
Relativistic factor	Finite nuclear size correction	Bohr-Weisskopf correction	QED correction
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Hyperfine structure of H-like and Li-like ions

- interaction between nuclear magnetic dipole moment and the magnetic field
- optical transitions
- simple ions
- probing

$$E_\mu = \frac{1}{n^3}$$

Electron-electron interaction



relativistic factor

$$\times \left[A(\alpha Z) \cdot (1 - \delta)(1 - \varepsilon) + x_{\text{rad}} \right].$$

Relativistic
factor

Finite
nuclear
size
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Bohr-
Weisskopf
correction

QED
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Relativistic factor	Finite nuclear size correction	Bohr-Weisskopf correction	Electron-electron correlation	QED correction
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HFS in simple HCl for VFC

Neglecting nuclear and QED effects, one can write an analytical expression for α -sensitivity enhancement factor:

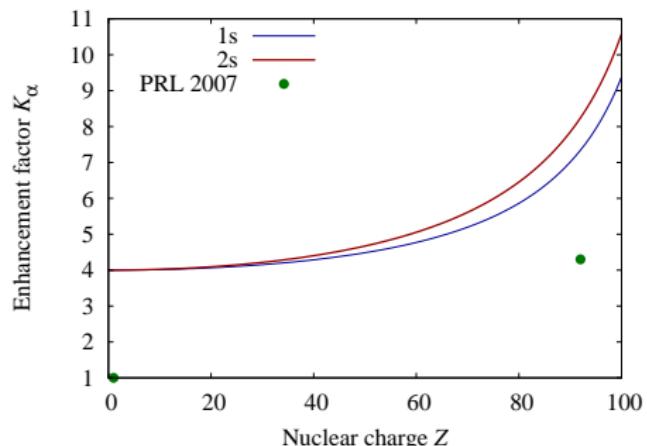
$$\kappa_\alpha \begin{bmatrix} 1s \\ 2s \end{bmatrix} \equiv \frac{dE}{d\alpha} \Big/ \frac{E}{\alpha} = 4 + \begin{bmatrix} 3 \\ 17/4 \end{bmatrix} (\alpha Z)^2 + \begin{bmatrix} 4 \\ 5 \end{bmatrix} (\alpha Z)^4 + \dots$$

NSO *et al.*, PRA **96**, 030501(R) (2017)

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NSO *et al.*, PRA **96**, 030501(R) (2017)
S. Schiller, PRL **98**, 180801 (2007)

- FS: far beyond the optical and x-ray range
- HFS: optical, relativistic, common for theory and experiment
- $M1$ transition: suppressed for $Z = 1$

HFS: sensitivity on the potential variation of quark masses

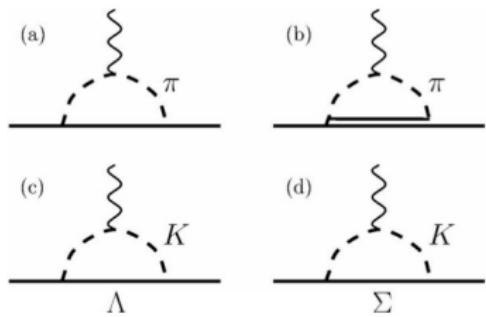


FIG. 1. Chiral corrections to the nucleon magnetic moments included in the present work.

$$\frac{\delta\mu_p}{\mu_p} = -0.087 \frac{\delta m_q}{m_q}$$

$$\frac{\delta\mu_p}{\mu_p} = -0.013 \frac{\delta m_s}{m_s}$$

$$\frac{\delta\mu_n}{\mu_n} = -0.118 \frac{\delta m_q}{m_q}$$

$$\frac{\delta\mu_n}{\mu_n} = 0.0013 \frac{\delta m_s}{m_s}$$

V. V. Flambaum *et al.* PRD **69**, 1150006 (2004)

HFS: sensitivity on the potential variation of quark masses

In the single-particle approximation:

$$\frac{\mu}{\mu_N} = \begin{cases} [g_s + (2I - 1)g_I]/2 & \text{for } I = L + 1/2, \\ \frac{I}{2(I+1)}[-g_s + (2I + 3)g_I] & \text{for } I = L - 1/2. \end{cases}$$

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Orbital g factors:

$g_I = 1$ for proton

$g_I = 0$ for neutron

Spin g factors:

$g_s = 5.586$ for proton

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$m_q = (m_u + m_d)/2$ is the averaged mass of the up and down quarks

m_s is the strange quark mass

H-like & Li-like HFS-based clocks

H-like ions:

$^{113}\text{In}^{48+}$, $^{121}\text{Sb}^{50+}$,
 $^{133}\text{Cs}^{54+}$, $^{139}\text{La}^{56+}$,
 $^{153}\text{Eu}^{62+}$, $^{159}\text{Tb}^{64+}$,
 $^{171}\text{Yb}^{69+}$, $^{189}\text{Os}^{75+}$,
 $^{195}\text{Pt}^{77+}$, $^{197}\text{Au}^{78+}$,
 $^{199}\text{Hg}^{79+}$, $^{207}\text{Pb}^{81+}$,
 $^{235}\text{U}^{91+}$

Li-like ions:

$^{175}\text{Lu}^{68+}$, $^{185}\text{Re}^{72+}$,
 $^{187}\text{Re}^{72+}$, $^{203}\text{Tl}^{78+}$,
 $^{209}\text{Bi}^{80+}$, $^{231}\text{Pa}^{88+}$

NSO *et al.*, PRA **96**, 030501(R) (2017)

H-like & Li-like HFS-based clocks

- $K_\alpha = 4 - 7$
- $K_{e/p} = 1$
- $K_q < 0.1$, except for $^{159}\text{Tb}^{64+}$ and $^{197}\text{Au}^{78+}$ with $K_q = 1.165$
- Optical for a wide range of ions
- $\Gamma = 1 - 10 \text{ Hz}$
- Quality factor is $Q \approx 10^{14} - 10^{15}$
- Systematic effects: decrease with Z_{eff} , the accuracy of $10^{-19} - 10^{-20}$ can be achieved

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Limits on fundamental constants with clocks

Only *dimensionless* constants can be measured:
 α , m_e/m_p , m_q/Λ_{QCD}

Limits on fundamental constants with clocks

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$$\alpha, m_e/m_p, m_q/\Lambda_{\text{QCD}}$$

in *dimensionless* measurements

Limits on fundamental constants with clocks

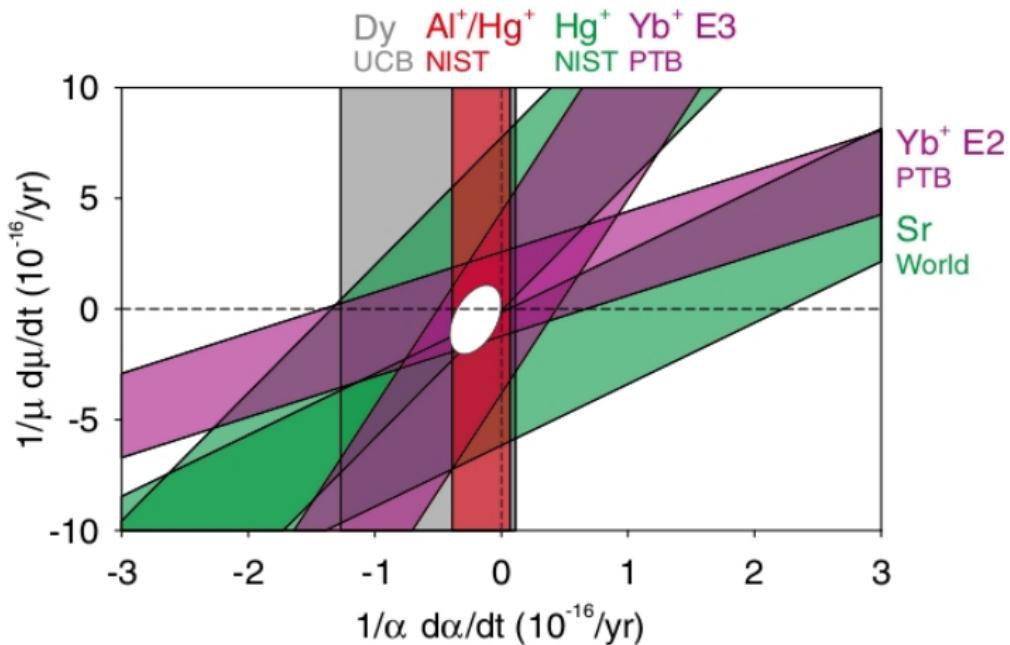
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$$\frac{\Delta(E_1/E_2)}{E_1/E_2} = (K_\alpha[1] - K_\alpha[2]) \frac{\delta\alpha}{\alpha} + (K_{e/p}[1] - K_{e/p}[2]) \frac{\delta(m_e/m_p)}{m_e/m_p}$$

Every combination of two different atomic clocks gives a new constrain.

Current limits on the variation of fundamental constants



$$\frac{\delta\alpha}{\alpha} = -2.0(2.0) \times 10^{-17}/\text{yr}$$

$$\frac{\delta(m_e/m_p)}{m_e/m_p} = 0.5(1.6) \times 10^{-16}/\text{yr}$$

N. Huntemann *et al.*, PRL **113**, 210802 (2014)

A. D. Ludlow *et al.*, RMP **87**, 637 (2015)

Variation of fundamental constants

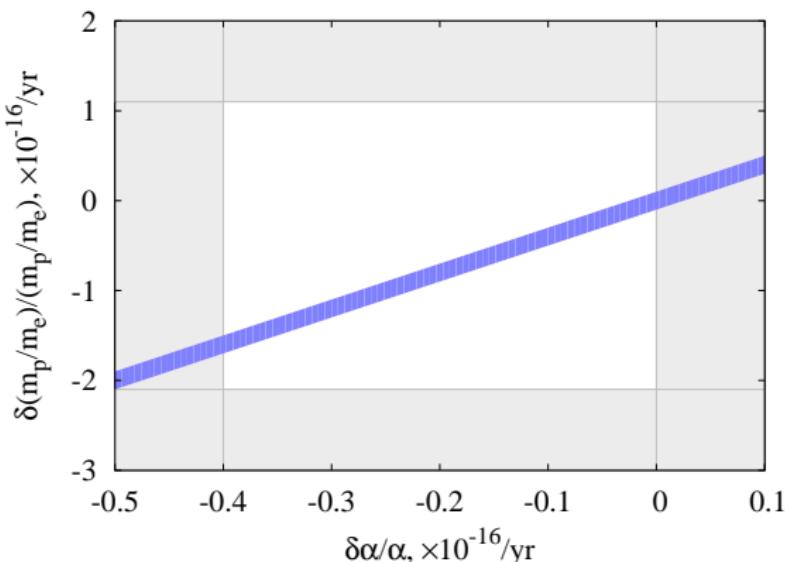
HFS with “insensitive” ($K_\alpha = K_{e/p} = 0$) atomic clocks
The conservative experimental accuracy of $10^{-17}/\text{yr}$

$$\left| (K_\alpha^{\text{HFS}} - K_\alpha^{\text{insen.}} - 2) \frac{\delta\alpha}{\alpha} + \frac{\delta(m_e/m_p)}{m_e/m_p} \right| < 10^{-17}/\text{yr}$$

Variation of fundamental constants

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Gray area is excluded according to the current limitations on α and m_e/m_p

Multiple constraints!

Quark masses variation with HFS HCI

Ion	E_μ	$\Gamma/(2\pi)$	K_α	$K_{e/p}$	K_q	K_s
$^{153}\text{Eu}^{62+}$	0.6697(10)	0.967	4.78	1	-0.051	-0.008
$^{159}\text{Tb}^{64+}$	1.099(4)	3.79	4.85	1	1.165	0.174

$$K_\alpha[\text{Tb}] - K_\alpha[\text{Eu}] = 0.07$$

$$K_q[\text{Tb}] - K_q[\text{Eu}] = 1.216$$

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Conservative experimental accuracy $10^{-17}/\text{yr}$:

$$\left| 1.2 \times \frac{\delta(m_q/\Lambda_{\text{QCD}})}{m_q/\Lambda_{\text{QCD}}} \right| < 10^{-17}/\text{yr}$$

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$^{199}\text{Hg}^{79+}$	0.931(12)	1.39	5.45	1	-0.118	0.001

Comparison of atomic clocks: Yb⁺ vs. Ir¹⁷⁺ vs. HCl-HFS

$$K_\alpha[\text{Yb}] = -6$$

$$K_{e/p}[\text{Yb}] = 0$$

$$\Delta E_{\text{exp}}^{\text{Yb}} = 3 \times 10^{-18}$$

 (reached)

$$K_\alpha[\text{Ir}^{17+}] = \pm 20$$

$$K_{e/p}[\text{Ir}] = 0$$

$$\Delta E_{\text{th}}[\text{Ir}^{17+}] > 100\%$$

$$Q = 10^{25}$$

✗ Nightmare spectra
 ✗ Quadrupole shift

$$K_\alpha[\text{HFS}] = 6$$

$$K_{e/p}[\text{HFS}] = 1$$

$$K_q[\text{HFS}] = 0, 1$$

$$\times Q = 10^{15}$$

Single-line spectra
 No AC-Stark and QS
 $\Delta E_{\text{exp}}^{\text{HFS}} < 10^{-19}$
 (expected)

Limitation: on the reference clocks! $\approx 10^{-17}/\text{yr}$

✓ $K_\alpha^{\text{Yb}} - K_\alpha^{\text{HFS}} \approx 10$ two times improvement

Multiple constraints!

Conclusions

- Fundamental constants can vary
- There is no evidence of their variation yet (but we are looking for it)
- Different types: slow drifts, transient, oscillations, stochastic
- Precision frontier: frequency measurements with atomic clocks
- HCI have reduced systematics and enhanced sensitivities
- FS and HFS HCI transitions are sensitive to the potential variation of α , m_e/m_p and m_q/Λ_{QCD}
- New constraints are proposed
- On the 10^{-17} accuracy level, new limitations can be set
- On the 10^{-19} accuracy level, the anticipated variation of α can be observed

Outlook

Improvement of accuracy of existing clocks

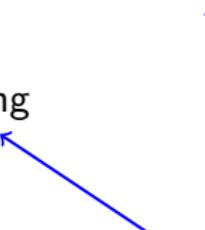


Outlook

Improvement of accuracy of existing clocks

Configuration-crossing
HCl clocks: α

Outlook



Improvement of accuracy of existing clocks

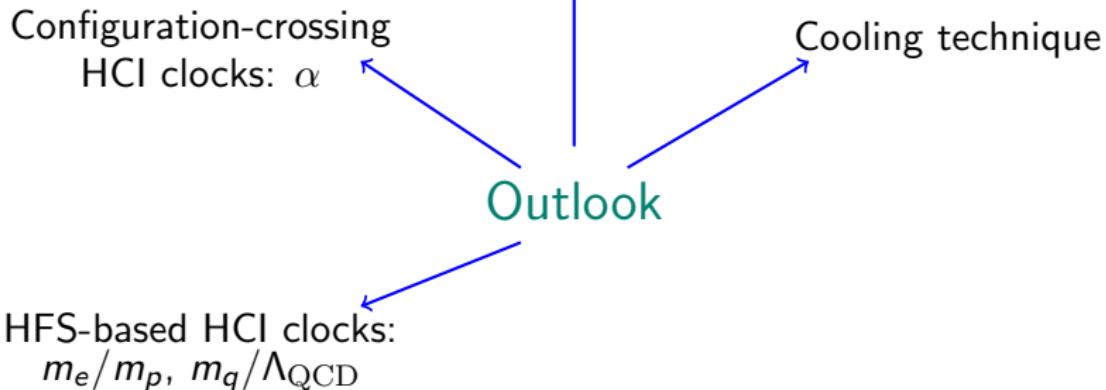
Configuration-crossing
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HFS-based HCl clocks:
 $m_e/m_p, m_q/\Lambda_{\text{QCD}}$

Outlook



Improvement of accuracy of existing clocks



Improvement of accuracy of existing clocks

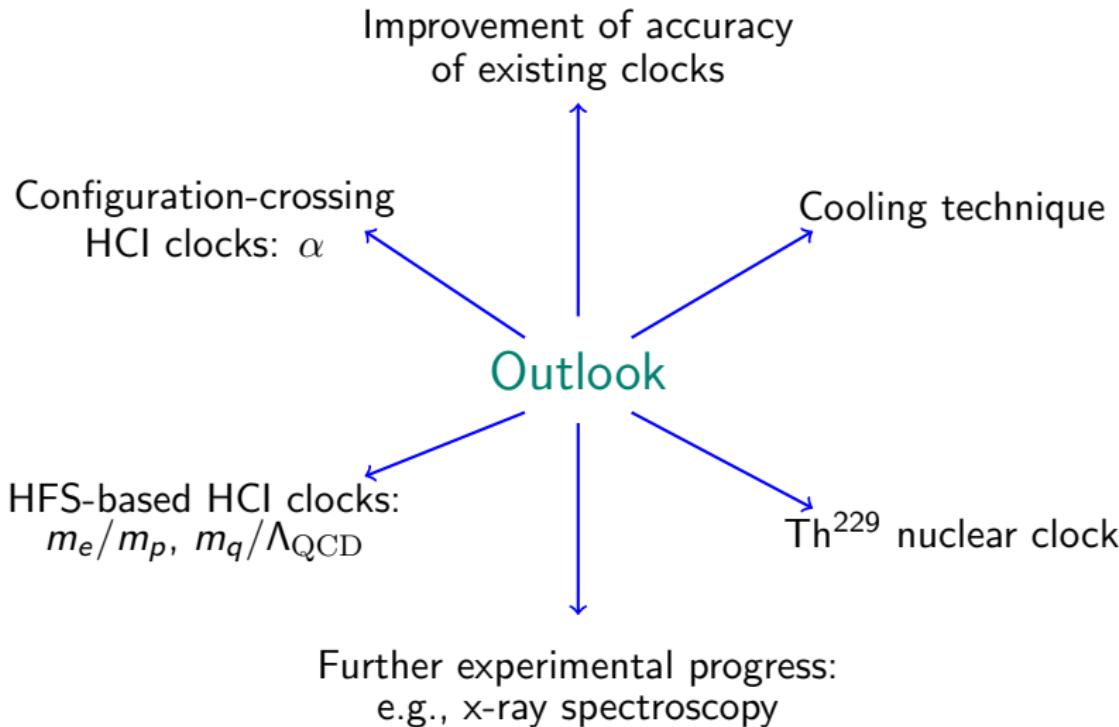
Configuration-crossing
HCl clocks: α

Cooling technique

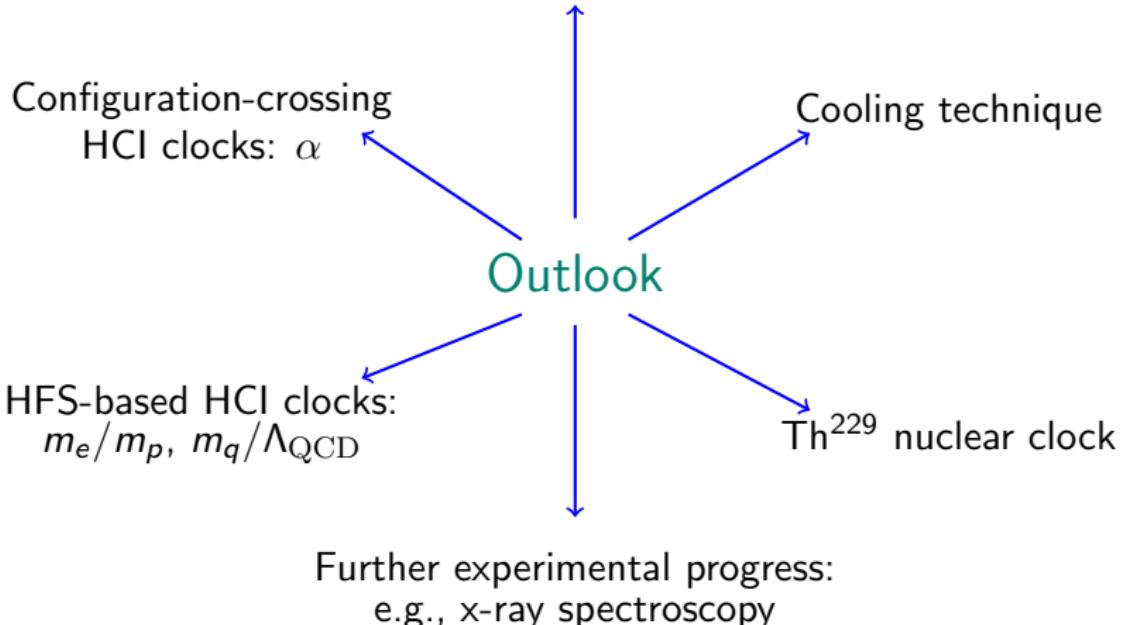
Outlook

HFS-based HCl clocks:
 $m_e/m_p, m_q/\Lambda_{\text{QCD}}$

Th^{229} nuclear clock



Improvement of accuracy of existing clocks



Thank you for your attention!

Acknowledgments

EBIT Group at MPIK	PTB and ARCNL	Theoretical support	Theory at MPIK
J. R. Crespo López-Urrutia	O. O. Versolato M. Schwarz	V. V. Flambaum J. C. Berengut	Z. Harman S. M. Cavaletto
H. Bekker	P. O. Schmidt	A. Borschevsky	N. Michel
A. Windberger	J. Ullrich	M. S. Safronova	

et al.

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