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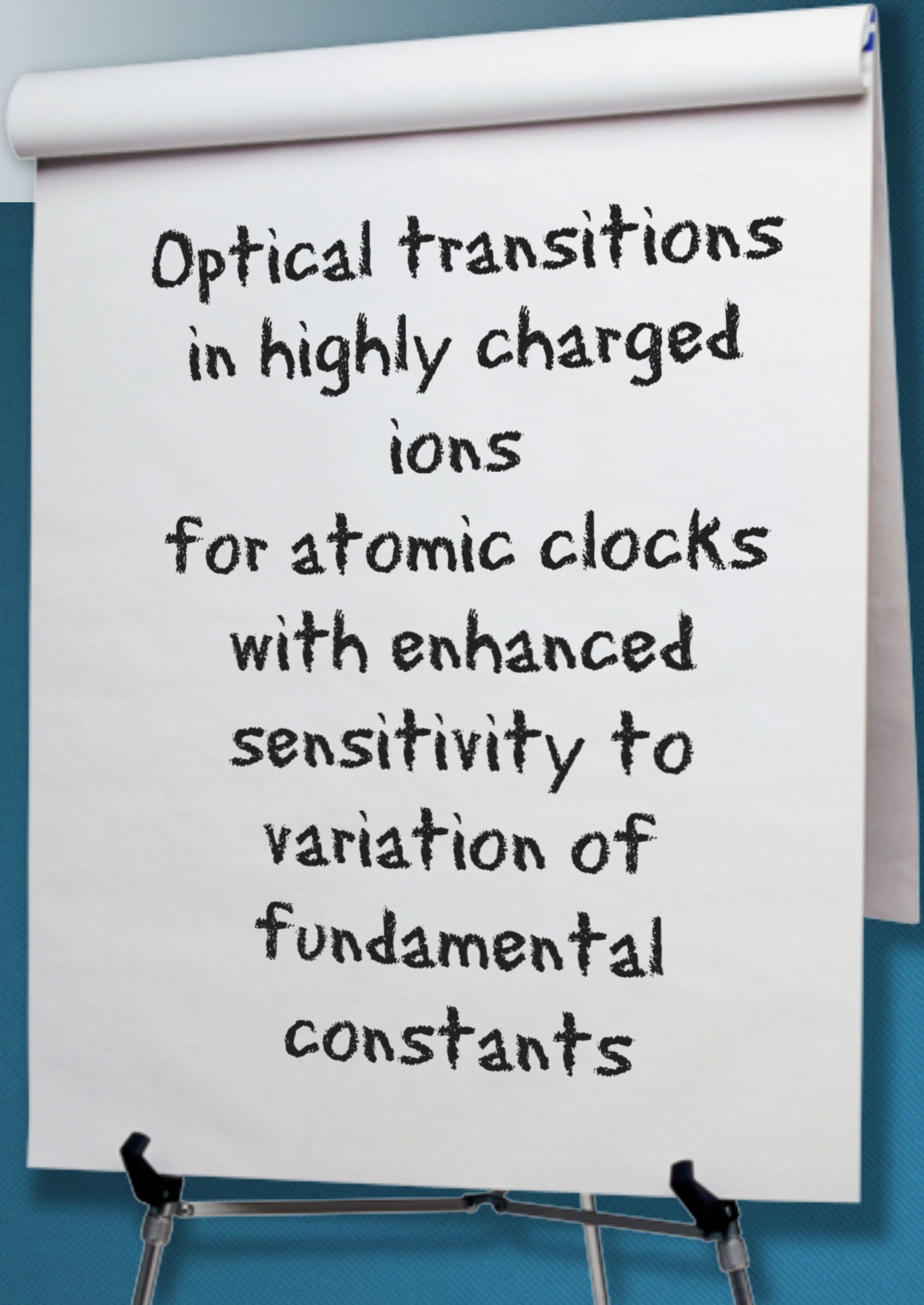


Optical transitions in highly charged ions for atomic clocks with enhanced sensitivity to variation of fundamental constants

Dr. Julian Berengut

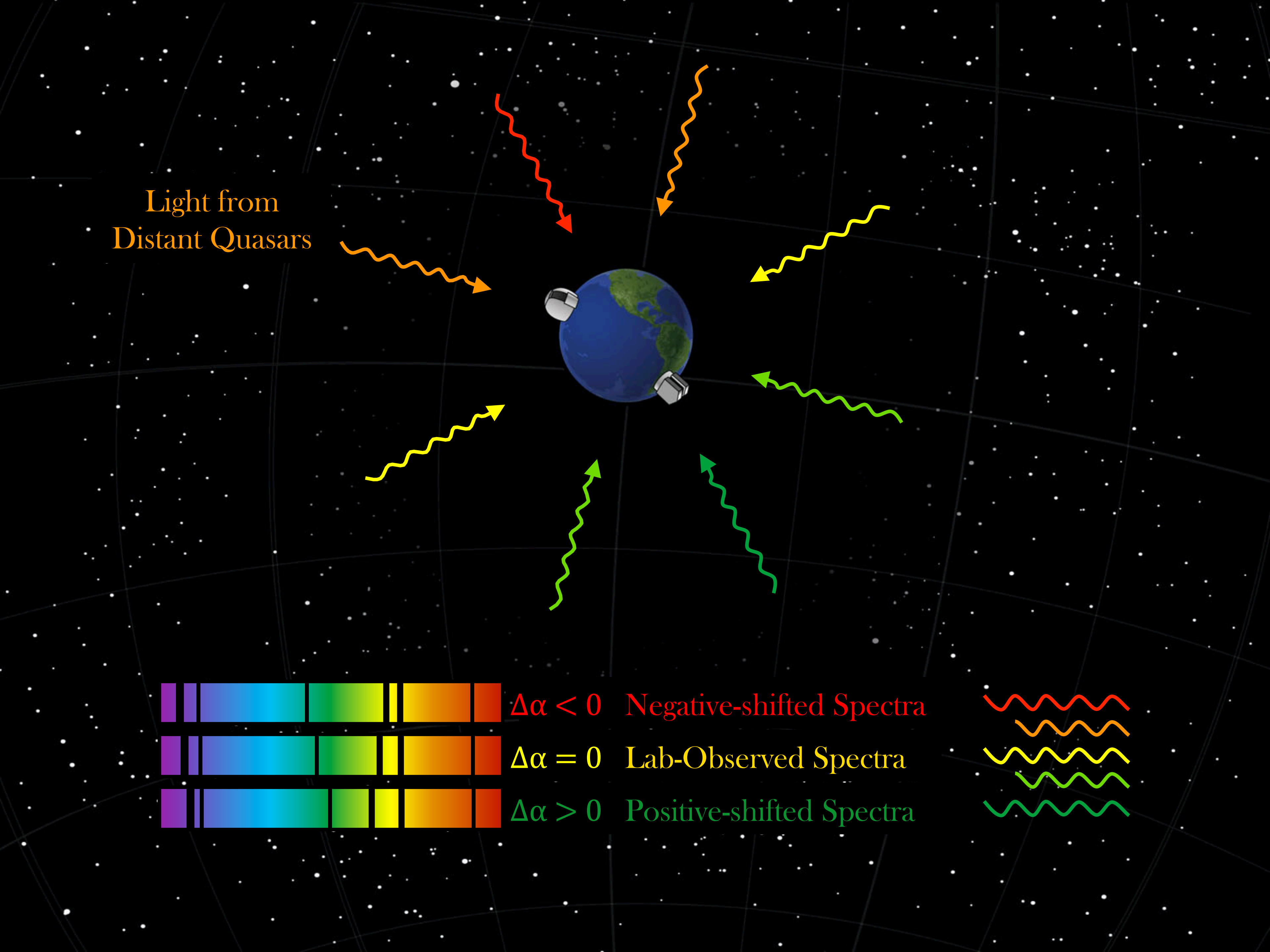
SSP2012, Groningen
20 June 2012

Motivation

Do the laws of physics change over space-time?

➡ Do the fundamental constants change?

- Around 25 dimensionless “fundamental constants”: Coupling constants, dimensionless mass ratios, mixing angles. e.g. $\alpha, \alpha_s, \theta_{\mathsf{W}}, \frac{m_e}{\Lambda_{QCD}}, \frac{m_q}{\Lambda_{QCD}}, \ldots$
- ...plus some for General Relativity and Cosmology....
- Cannot be predicted by theory and must be measured.
- ∴ Should not assume constancy or homogeneity.

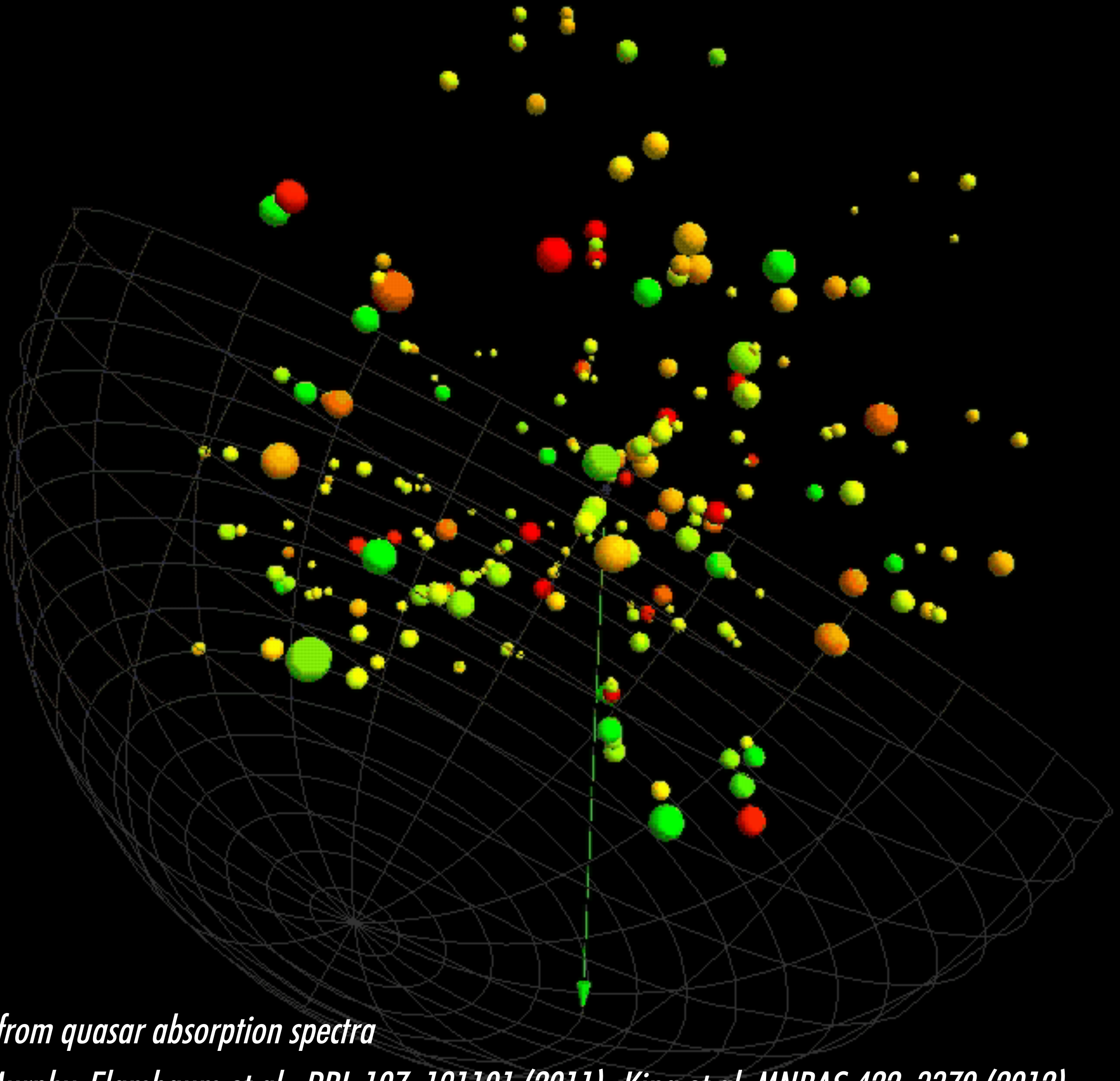


Light from
Distant Quasars

$\Delta\alpha < 0$ Negative-shifted Spectra

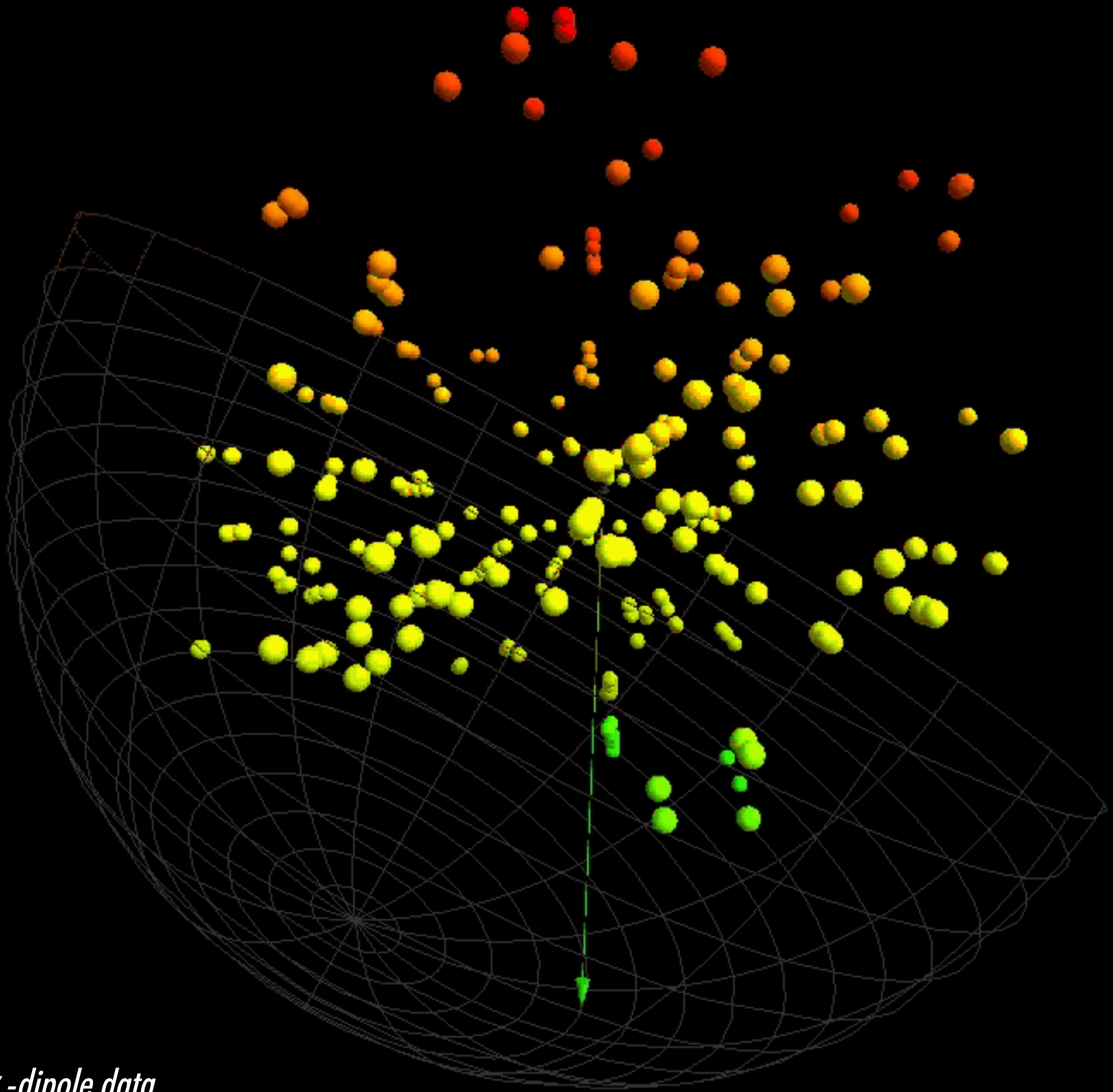
$\Delta\alpha = 0$ Lab-Observed Spectra

$\Delta\alpha > 0$ Positive-shifted Spectra



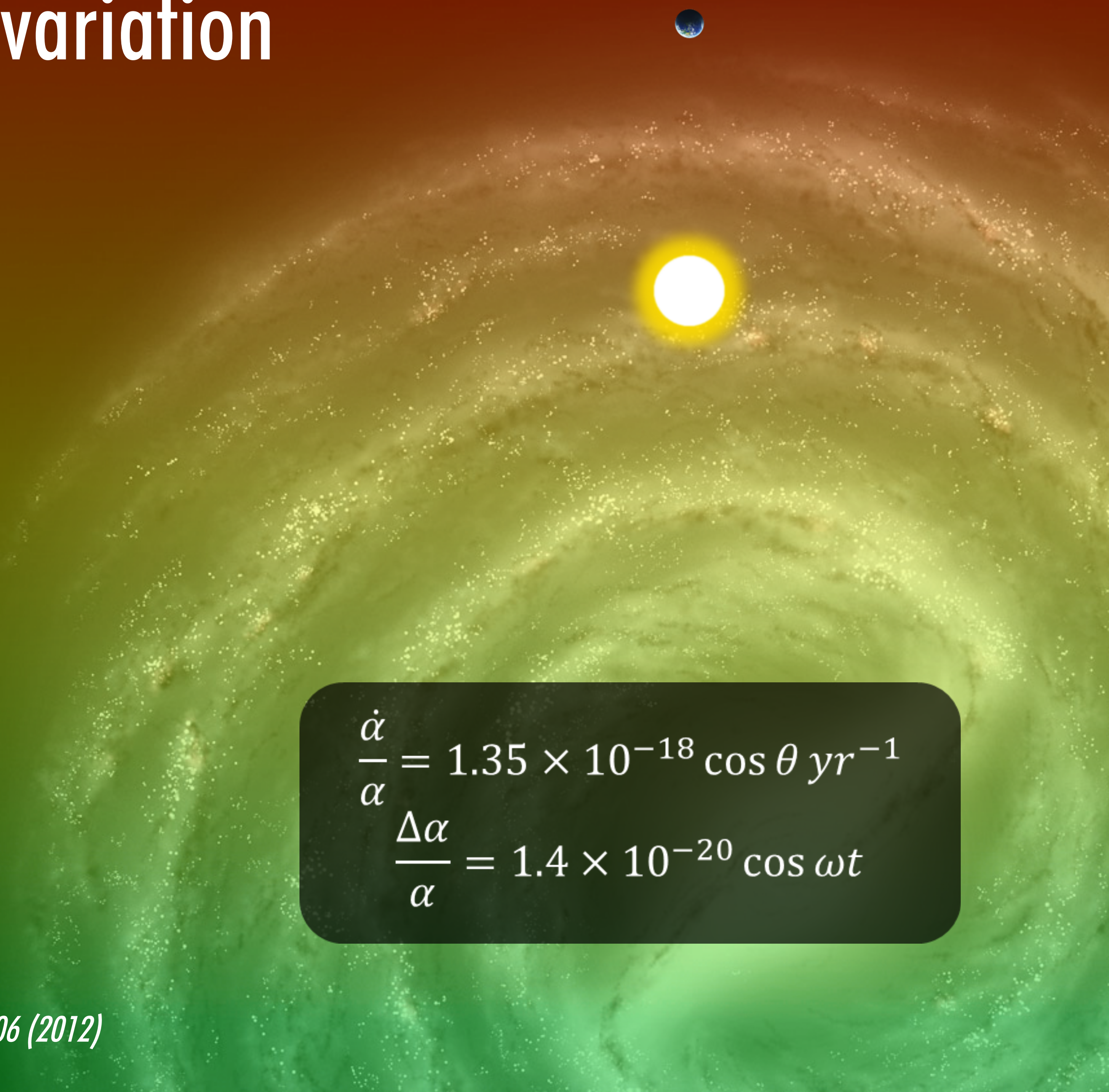
α -variation from quasar absorption spectra

Webb, King, Murphy, Flambaum et al., PRL 107, 191101 (2011); King et al. MNRAS 422, 3370 (2012)



Generated α -dipole data

Terrestrial α-variation



$$\frac{\dot{\alpha}}{\alpha} = 1.35 \times 10^{-18} \cos\theta \, yr^{-1}$$

$$\frac{\Delta\alpha}{\alpha} = 1.4 \times 10^{-20} \cos\omega t$$

Berengut & Flambaum, EPL 97, 20006 (2012)

α-sensitivity of single-electron transitions

Hydrogen-like ions

$$E_n = -\frac{m_e Z^2 e^4}{2\hbar^2 n^2} = -\frac{(Z\alpha)^2}{2n^2} \cdot m_e c^2$$

Relativistic corrections

$$\Delta_n = E_n \frac{(Z\alpha)^2}{\nu\left(j + \frac{1}{2}\right)}$$

$$\omega = \omega_0 + qx, \qquad x = \left(\frac{\alpha}{\alpha_0}\right)^2 - 1$$

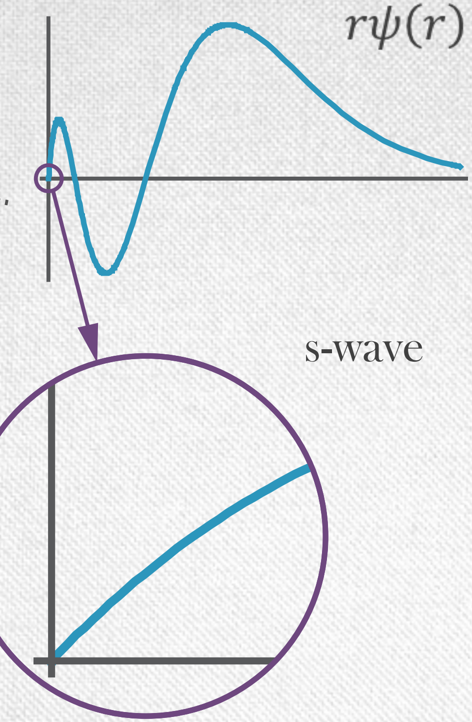
α-sensitivity of single-electron transitions

$E_n = -$ Ionisation energy

Stronger relativistic effects in heavier atoms

$$q_n = E_n \frac{(Z\alpha)^2}{\nu\left(j + \frac{1}{2}\right)}$$

Effective principal quantum number



Optical atomic clocks

- Required limit : $\frac{\dot{\alpha}}{\alpha} \sim 10^{-19}\, yr^{-1}$
- Best current limit (Hg⁺ vs Al⁺) : $\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.3) \times 10^{-17}\, yr^{-1}$

Rosenband et al., Science 319, 1808 (2008)

$$q_n = E_n \frac{(Z\alpha)^2}{\nu\left(j + \frac{1}{2}\right)}$$

- Hg^+ clock :

$$5d^{10}6s\left(J = {}^{1}\!/_{2}\right) \rightarrow 5d^{9}6s^{2}\left(J = {}^{5}\!/_{2}\right)$$

$$\omega = 35514\ cm^{-1}$$

$$q = -52200\ cm^{-1}$$

Dzuba, Flambaum, Webb, PRL 82, 888 (1999); Dzuba & Flambaum, PRA 77, 012515 (2008)

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  Rosenband et al., Science 319, 1808 (2008)

$$q_n = E_n \frac{(Z\alpha)^2}{\nu\left(j + \frac{1}{2}\right)}$$

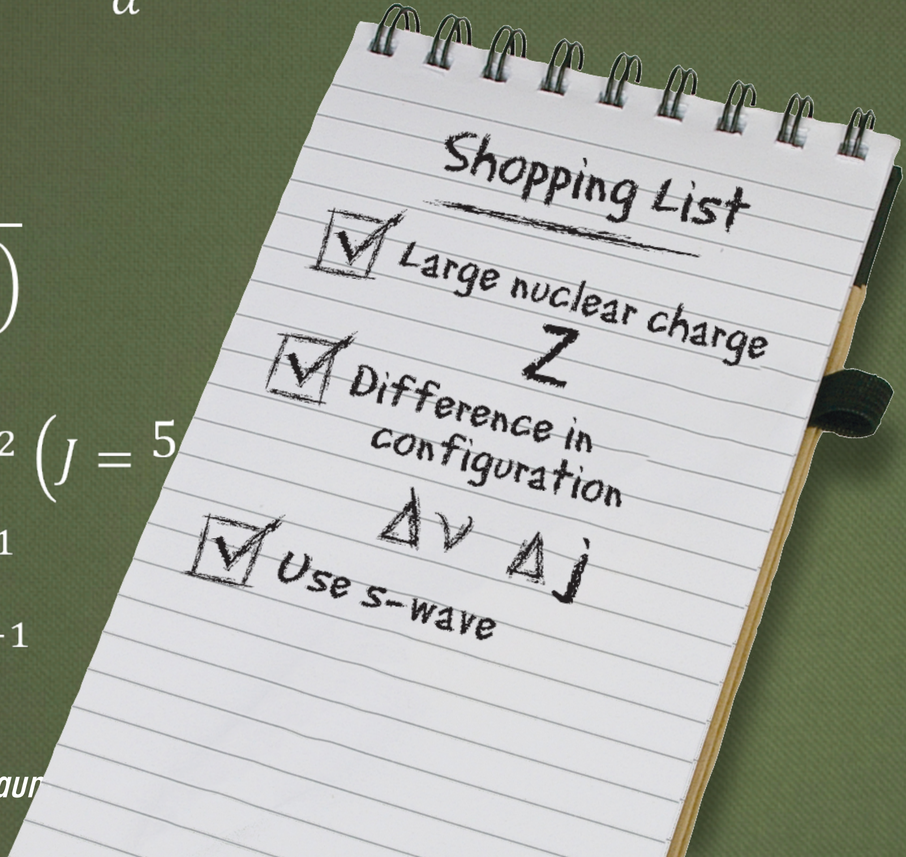
- Hg^+ clock :

$$5d^{10}6s\ \big(J = {}^1/_2\big) \rightarrow 5d^9 6s^2\ \big(J = 5$$

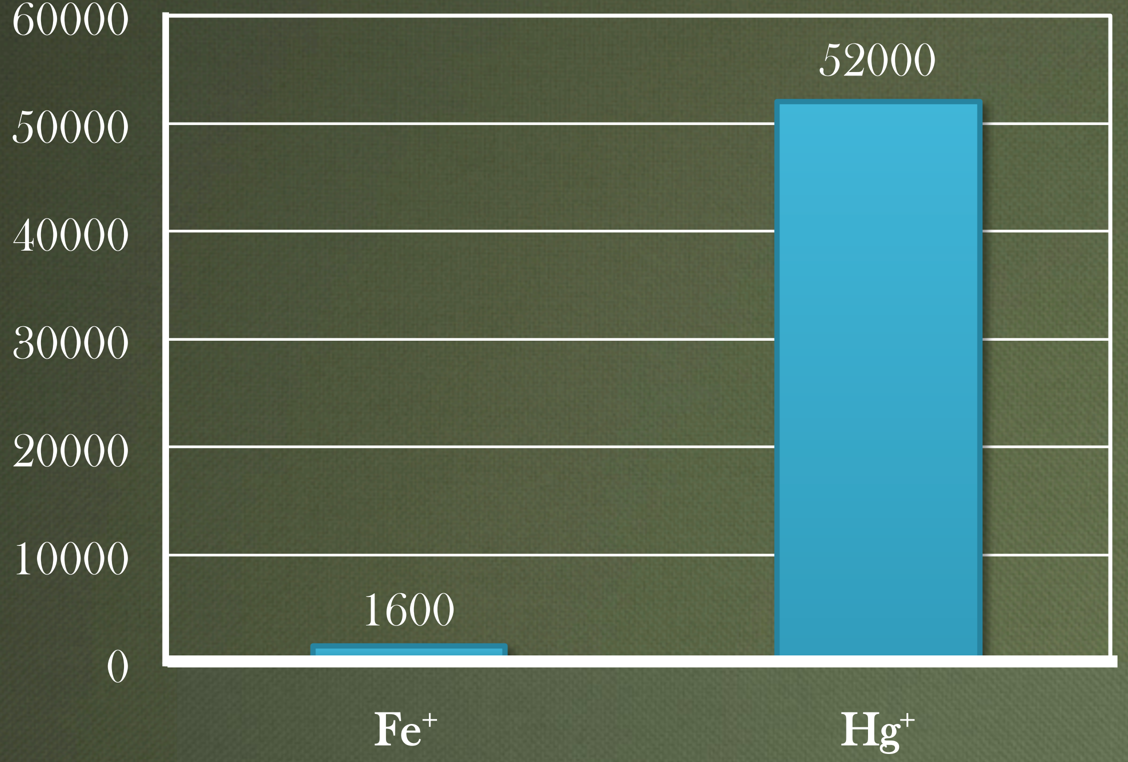
$$\omega = 35514\ cm^{-1}$$

$$q = -52200\ cm^{-1}$$

Dzuba, Flambaum, Webb, PRL 82, 888 (1999); Dzuba & Flambaur

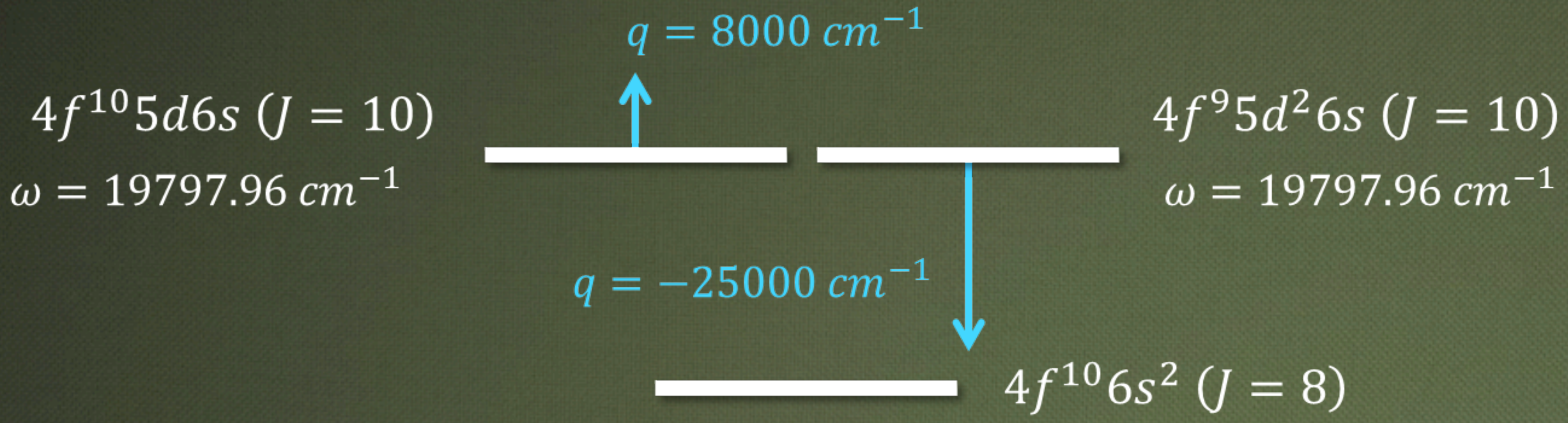


Clock q-values (cm^{-1})



Where to find
two orders of magnitude?

Relative enhancement : Dy clock



$q = 8000\ cm^{-1}$

$4f^{10}5d6s\ (J = 10)$

$\omega = 19797.96\ cm^{-1}$

$4f^{9}5d^{2}6s\ (J = 10)$

$\omega = 19797.96\ cm^{-1}$

$q = -25000\ cm^{-1}$

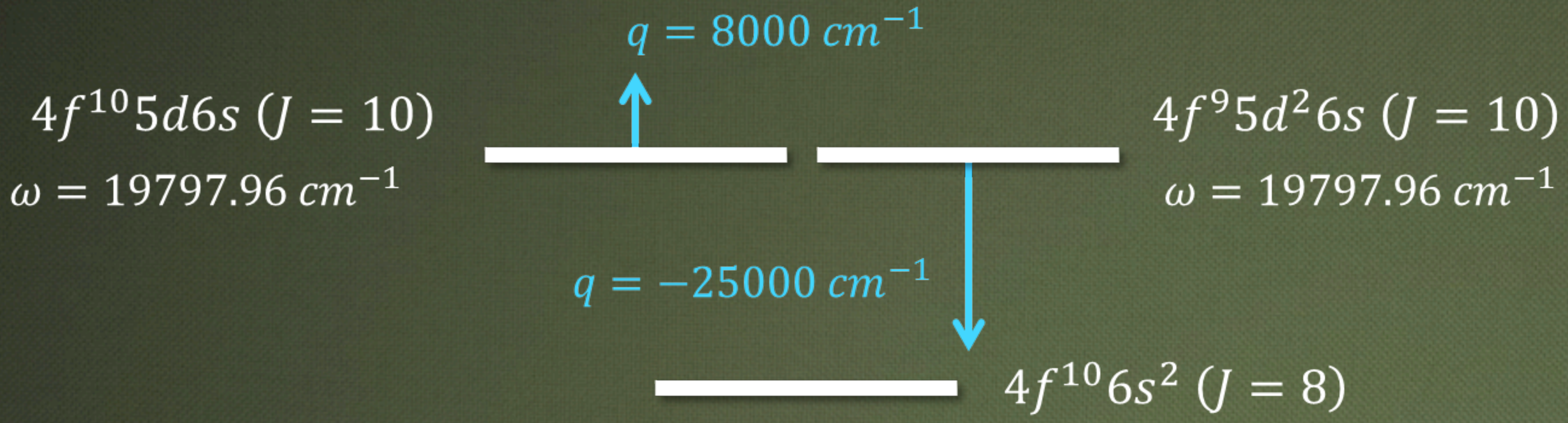
$4f^{10}6s^{2}\ (J = 8)$

$$K = \frac{2q}{\omega} \qquad \frac{\Delta(\omega_1/\omega_2)}{(\omega_1/\omega_2)} = (K_1 - K_2)\frac{\Delta\alpha}{\alpha}$$

- Hg$^+$ vs Al$^+$: $\Delta K = -3.2$
- Dy : $\Delta K \sim 10^{8}$

Dzuba, Flambaum, Webb, PRL 82, 888 (1999); Dzuba & Flambaum, PRA 77, 012515 (2008)

Relative enhancement : Dy clock



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$4f^{10}6s^{2}\ (J = 8)$

$$\frac{\dot{\alpha}}{\alpha} = (-2.7 \pm 2.6) \times 10^{-15}\ yr^{-1}$$

Problem:

natural linewidths are not small

Cingöz et al., PRL 98, 040801 (2007)

Absolute Enhancement

$$q_n = E_n \frac{(Z\alpha)^2}{\nu\left(j + \frac{1}{2}\right)}$$

- $E_n = -$ Ionisation energy
- Use highly charged ions

$$\rightarrow q \sim Z^2 (Z_{ion} + 1)^2$$

Problem:

transition frequencies also grow with E_n

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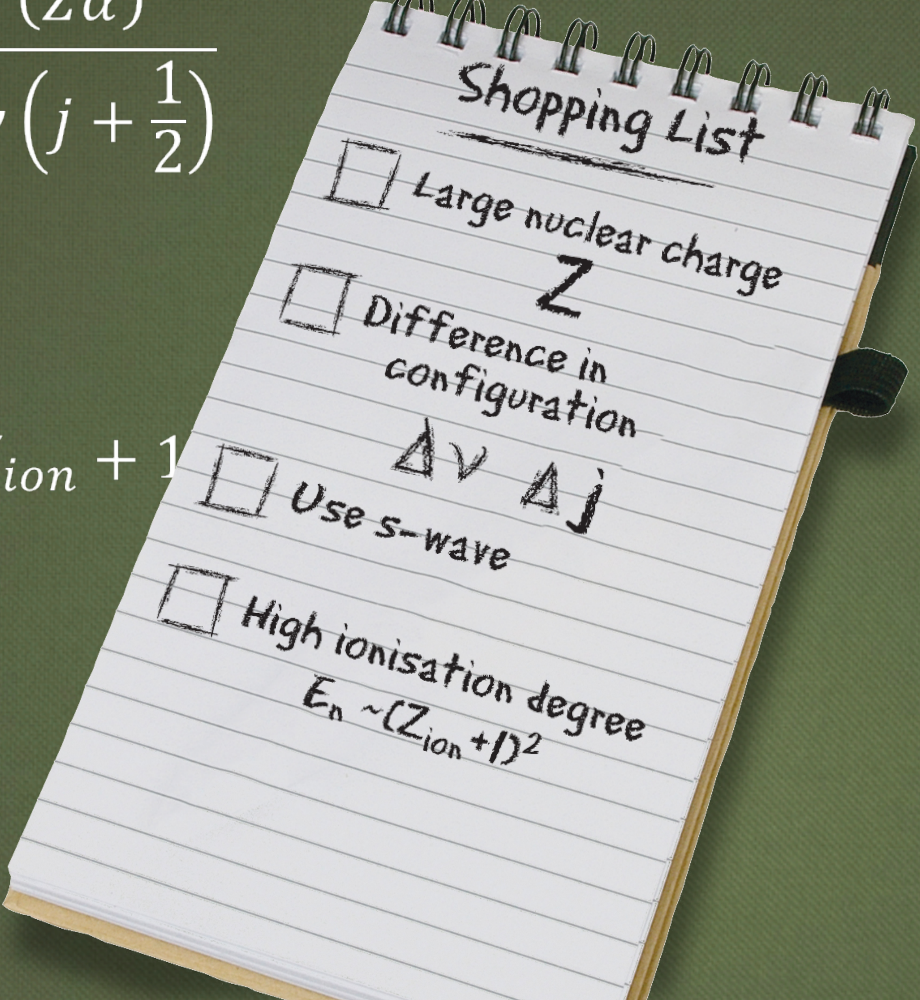


Shopping List

☐ Large nuclear charge
Z

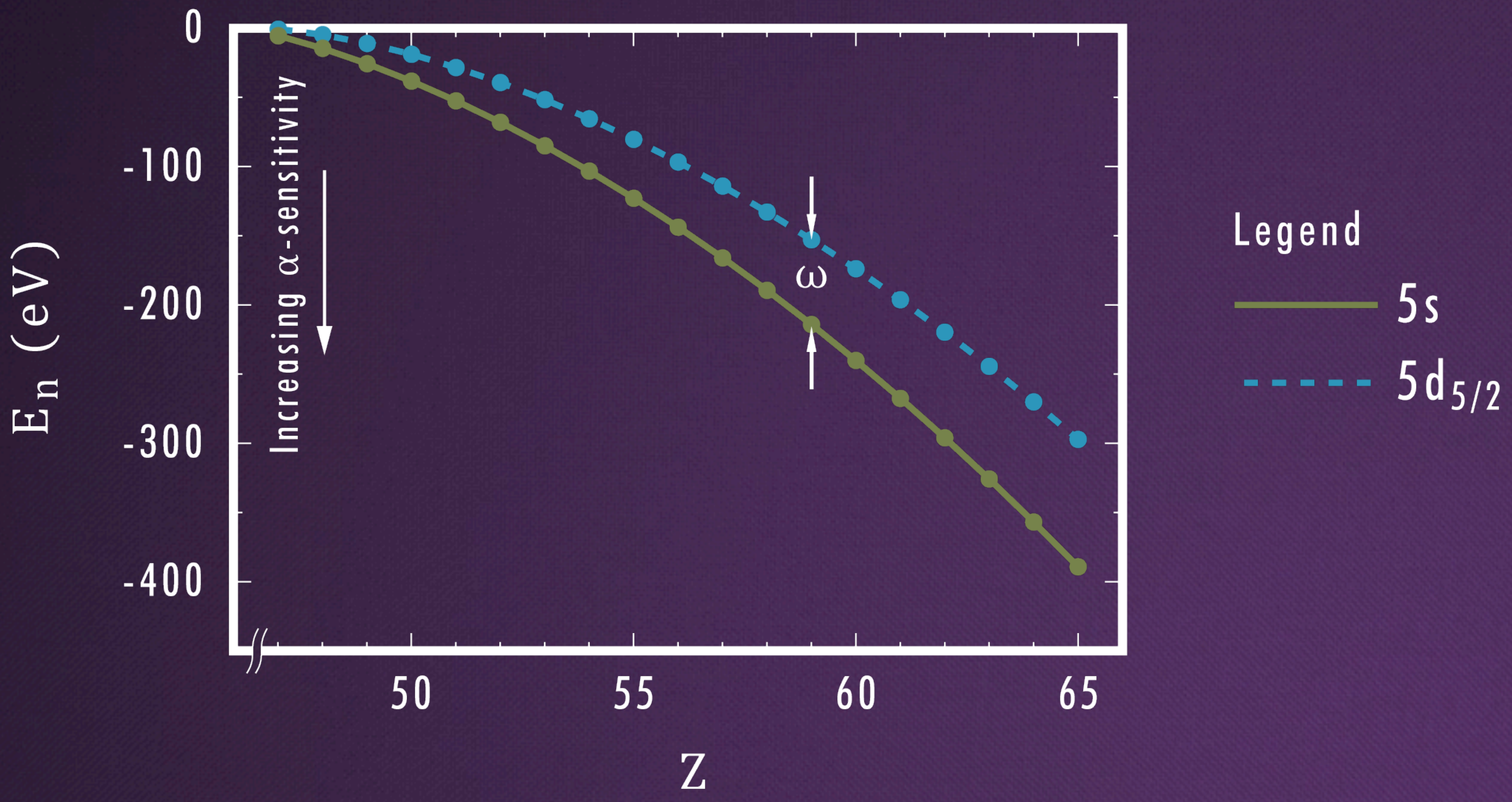
☐ Difference in configuration
$\Delta\nu$ Δj

☐ Use s-wave

☐ High ionisation degree
$E_n \sim (Z_{ion}+1)^2$

Ag isoelectronic sequence

$[Kr]4d^{10}\,nl$ (47 electrons)



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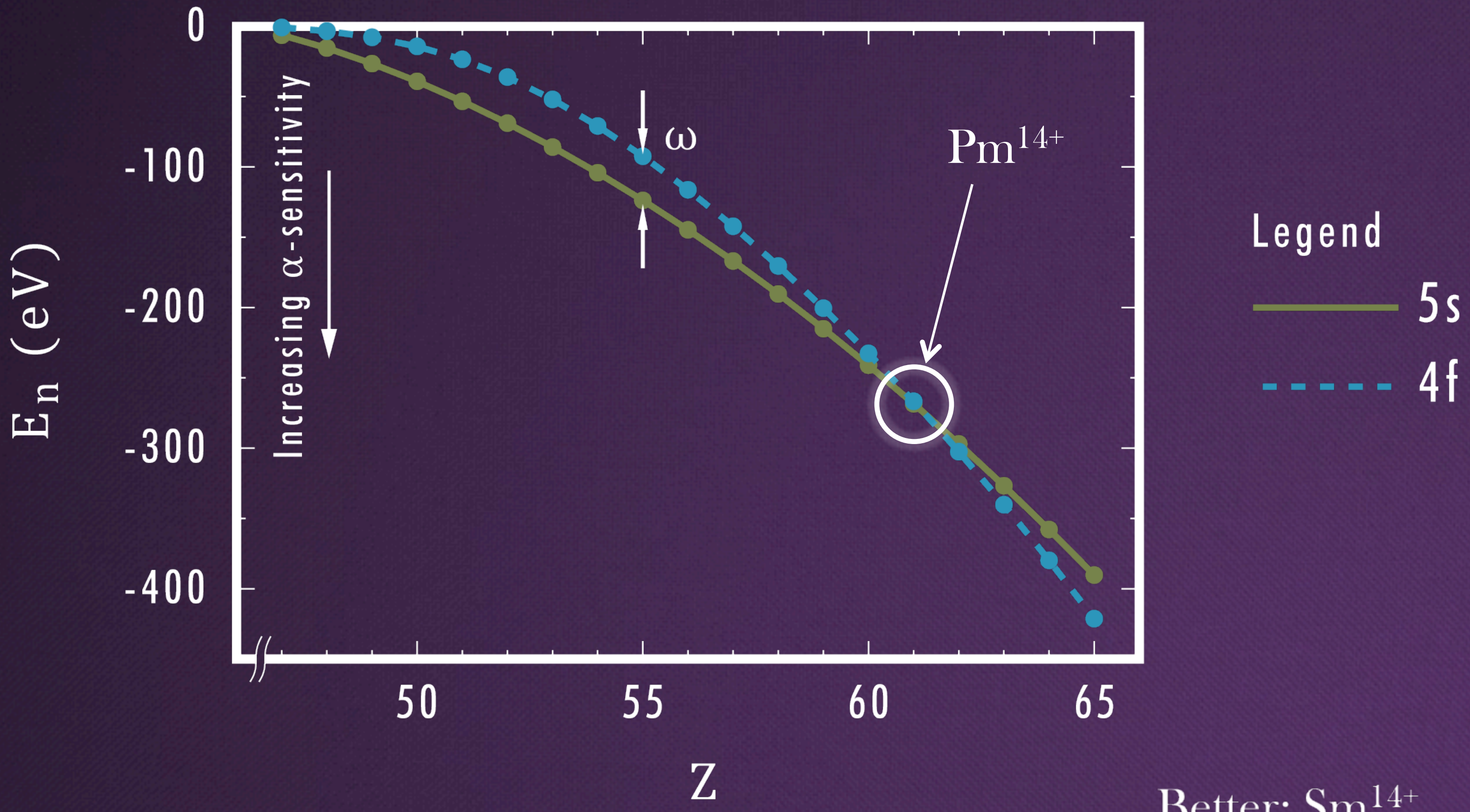

Better: Sm^{14+}

Berengut, Dzuba, Flambaum, PRL 105, 120801 (2010)

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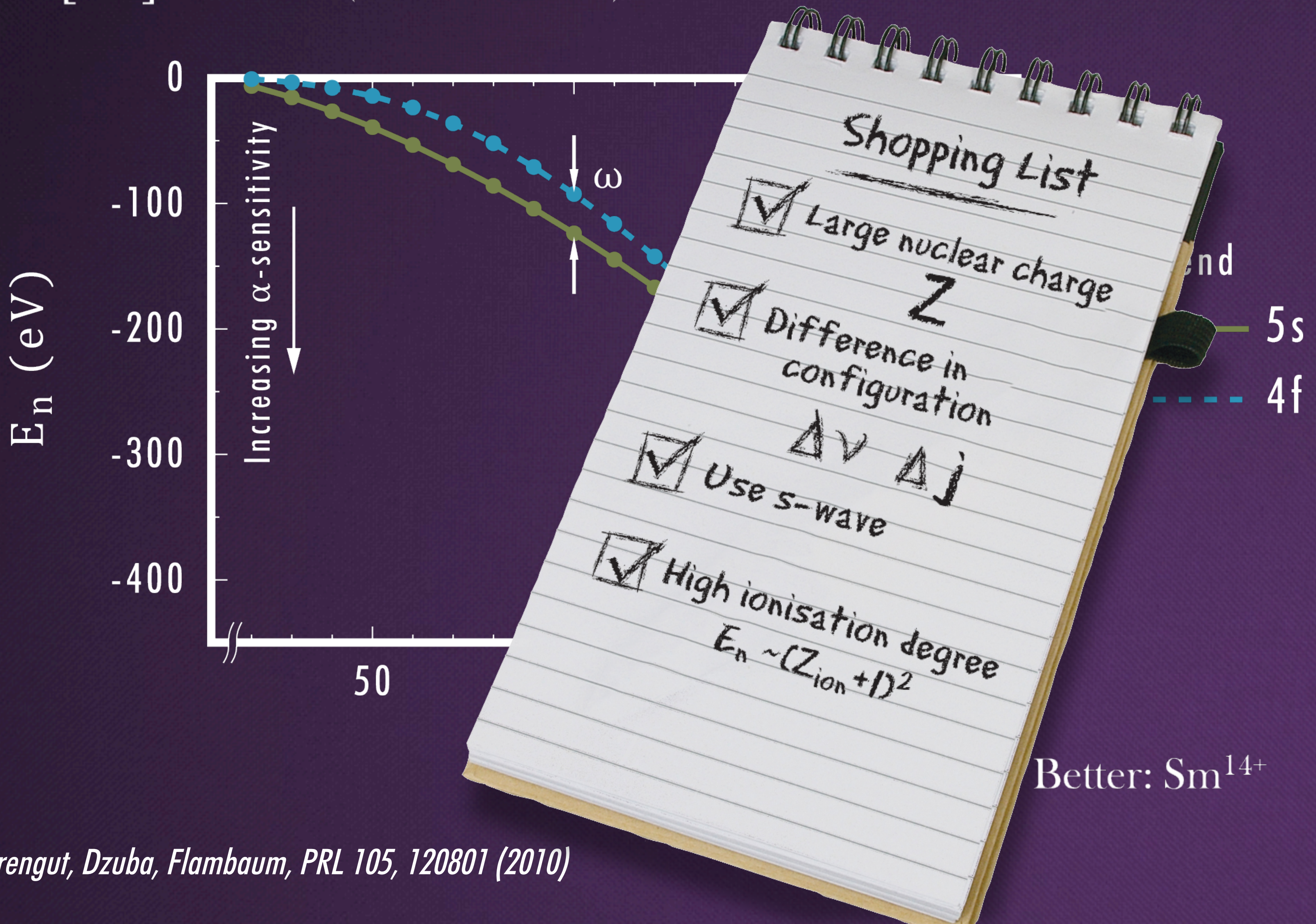

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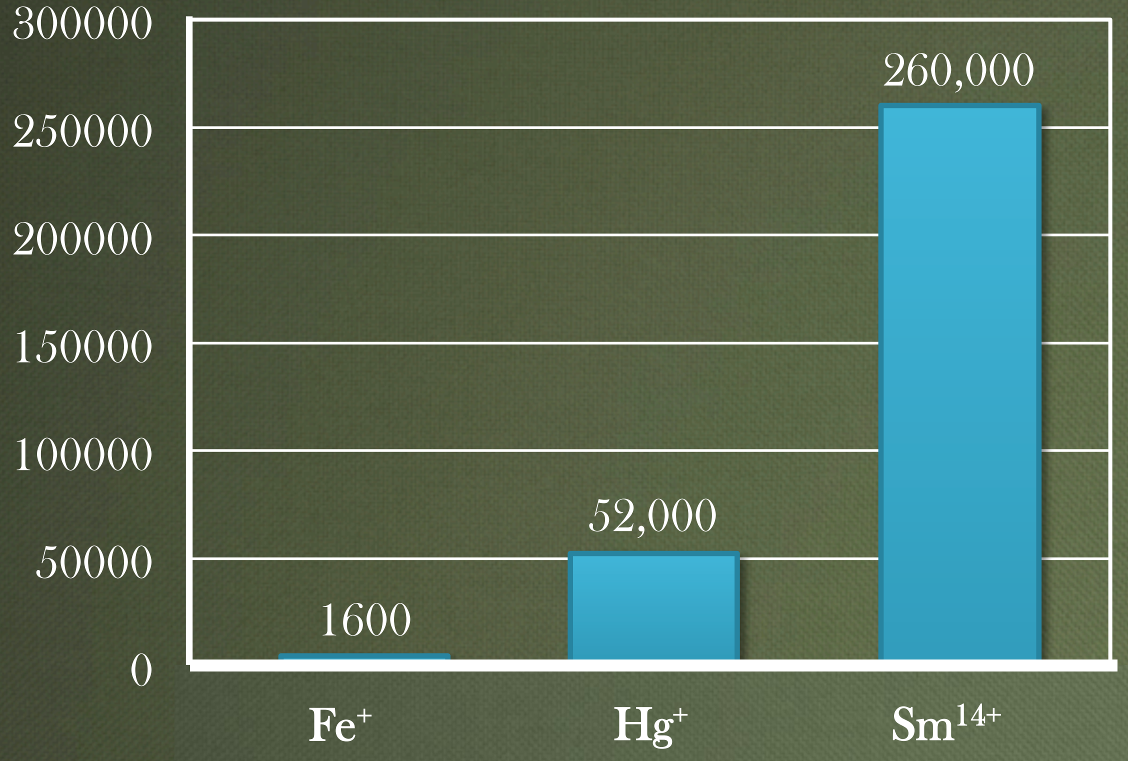
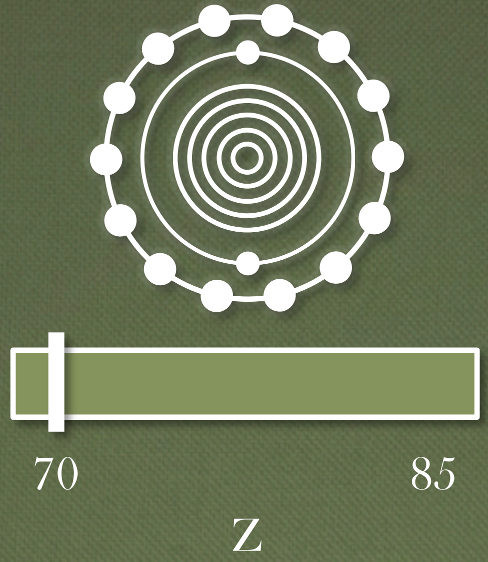
Clock q-values (cm^{-1})



Berengut, Dzuba, Flambaum, PRL 105, 120801 (2010)

Holes in highly charged ions

- Use highly charged ions
- Electrons in filled shells have maximal I_n
- Electron spends half time closer to nucleus than other electrons in the same shell



$$q \sim I_n^{3/2}$$

- Use holes in otherwise filled shells

Berengut, Dzuba, Flambaum, Ong, PRL 106, 210802 (2011)

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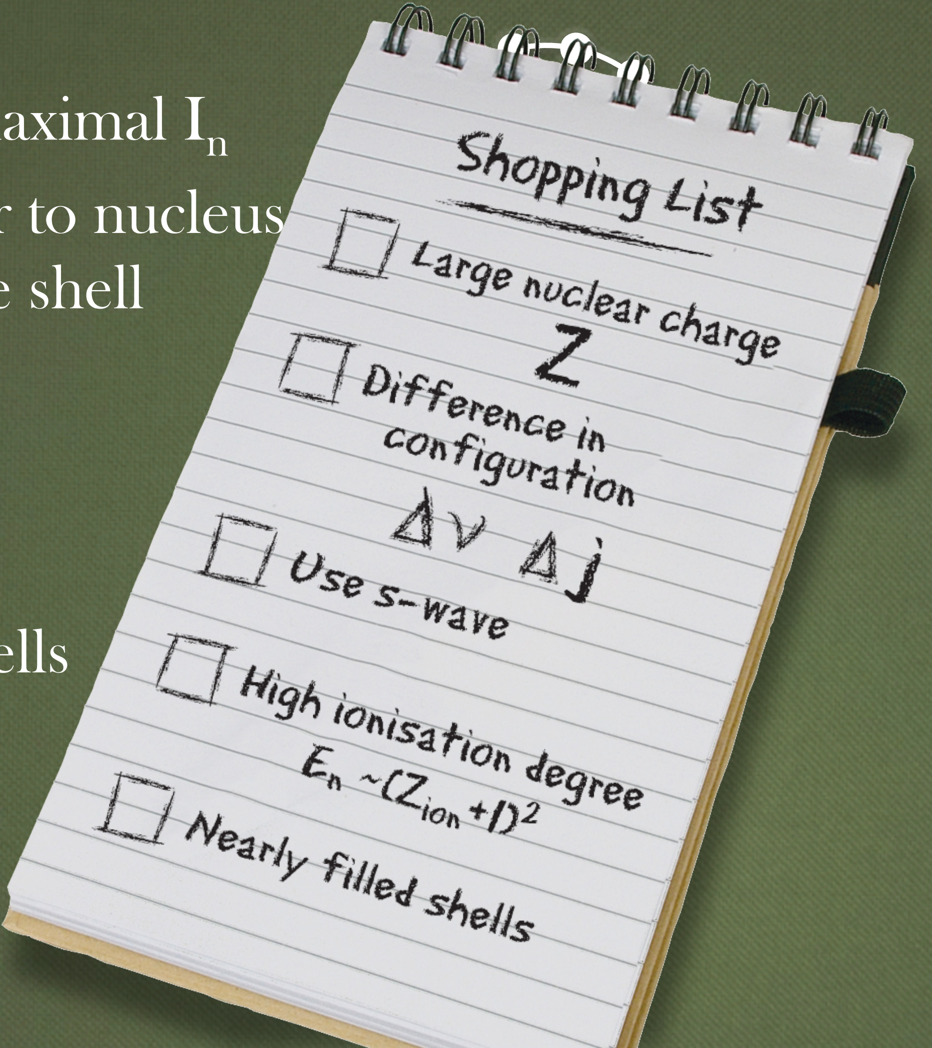

Shopping List

☐ Large nuclear charge
Z

☐ Difference in configuration
$\Delta\nu \quad \Delta j$

☐ Use s-wave

☐ High ionisation degree
$E_n \sim (Z_{ion}+1)^2$

☐ Nearly filled shells

Berengut, Dzuba, Flambaum, Ong, PRL 106, 210802 (2011)

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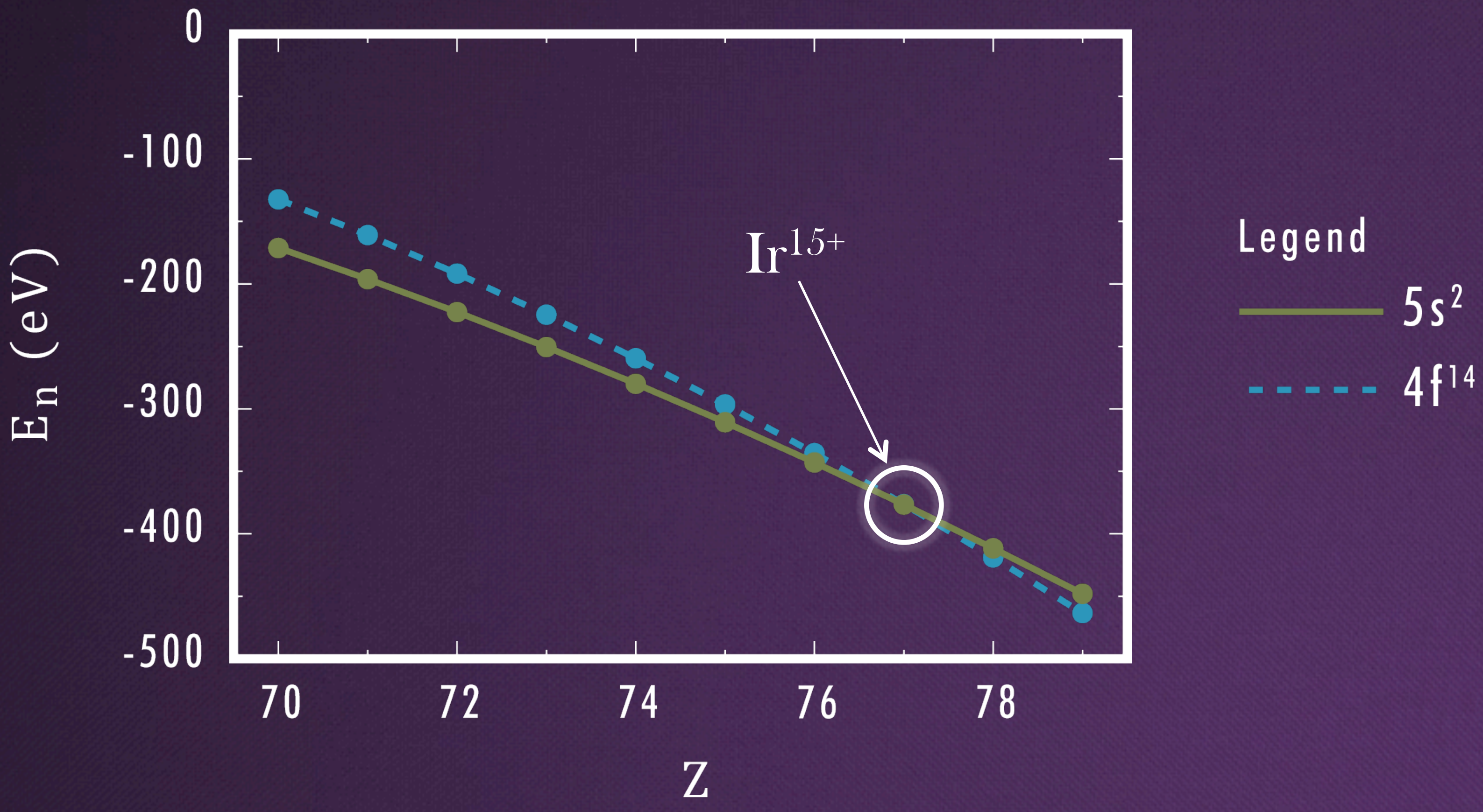
$[Kr]4d^{10}\,4f^{14}\,5s^{2}$ (62 electrons)



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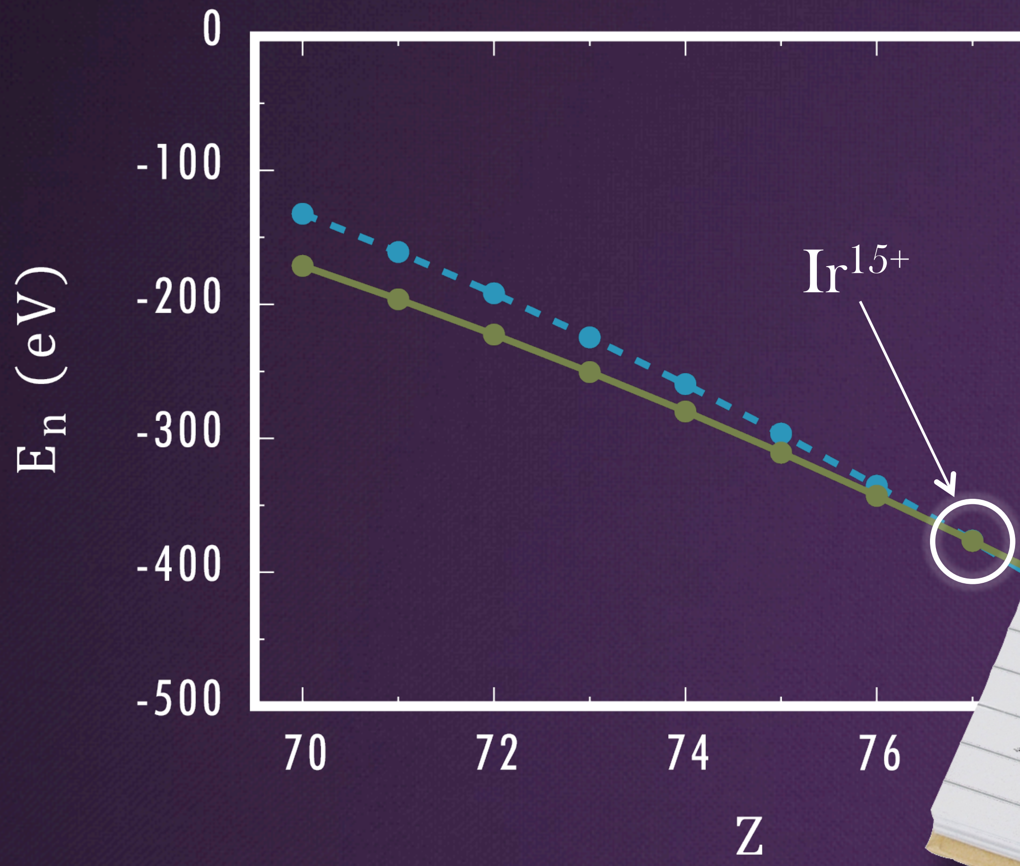

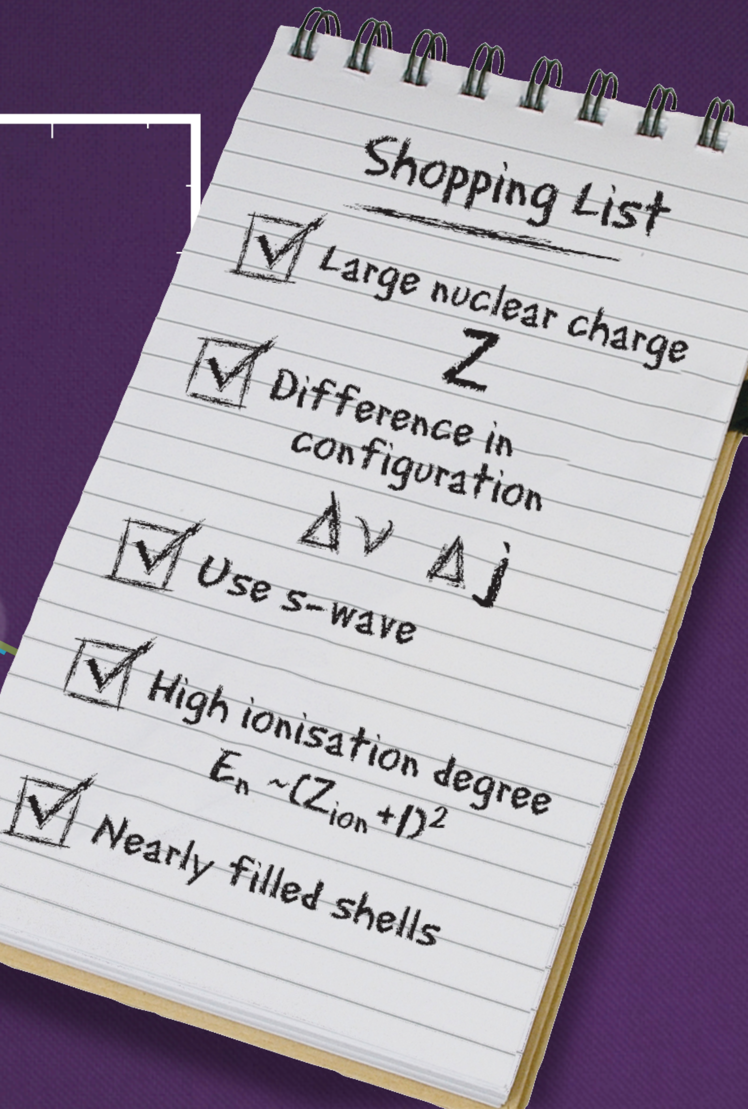
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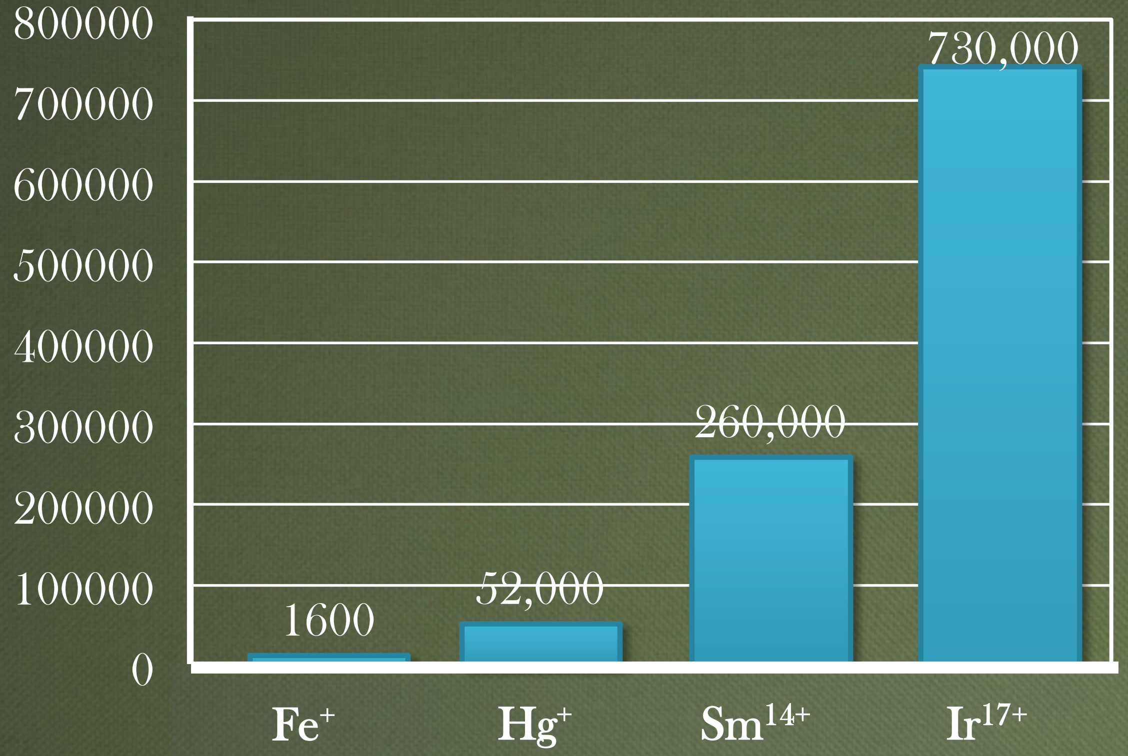
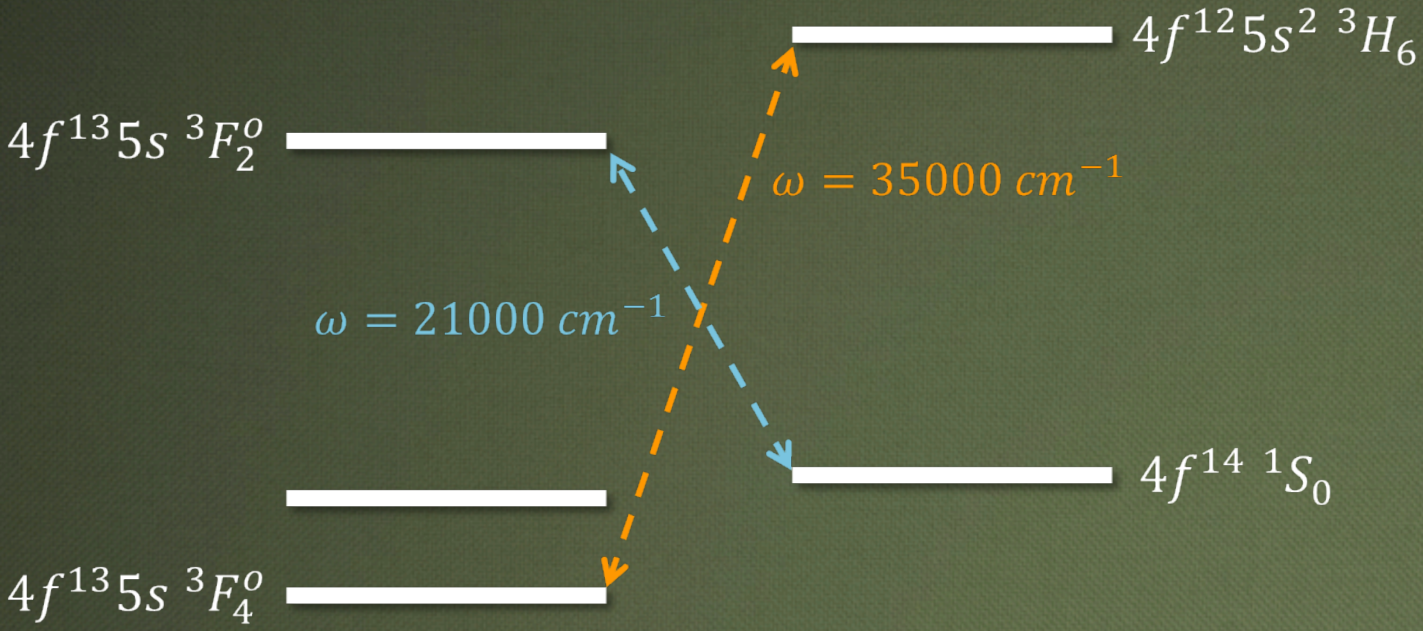


Berengut, Dzuba, Flambaum, Ong, PRL 106, 210802 (2011)

Holes in highly charged ions : Ir^{17+}



$4f^{12}5s^2\ ^3H_6$

$4f^{13}5s\ ^3F^o_2$

$\omega = 35000\ cm^{-1}$

$\omega = 21000\ cm^{-1}$

$4f^{14}\ ^1S_0$

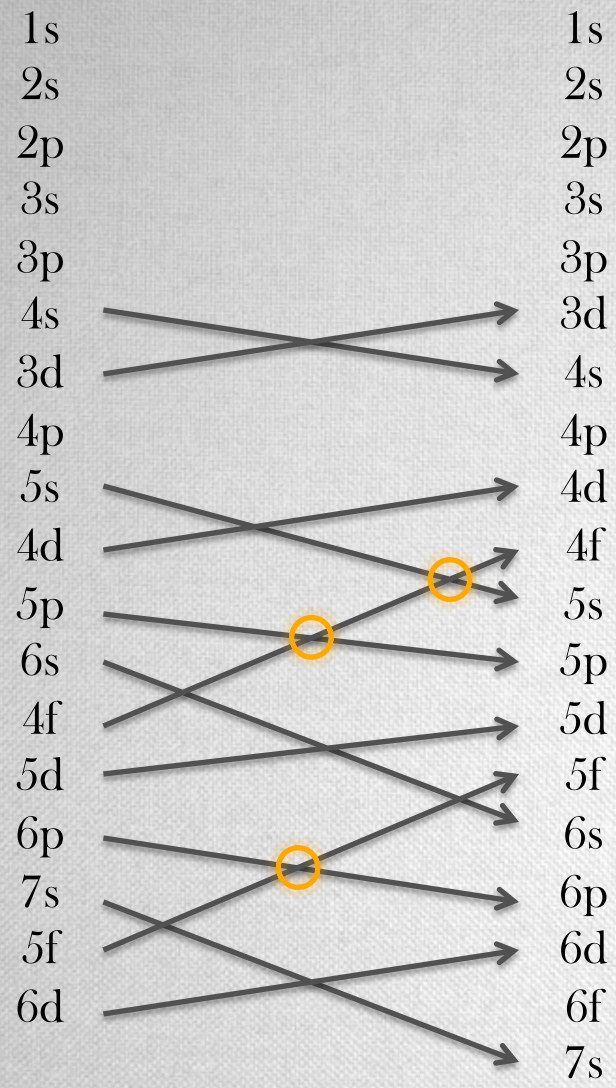
$4f^{13}5s\ ^3F^o_4$

$\Delta q = 730\ 000\ cm^{-1}$

- There exists an E1 transition at 45 000 cm^{-1} for trapping and cooling

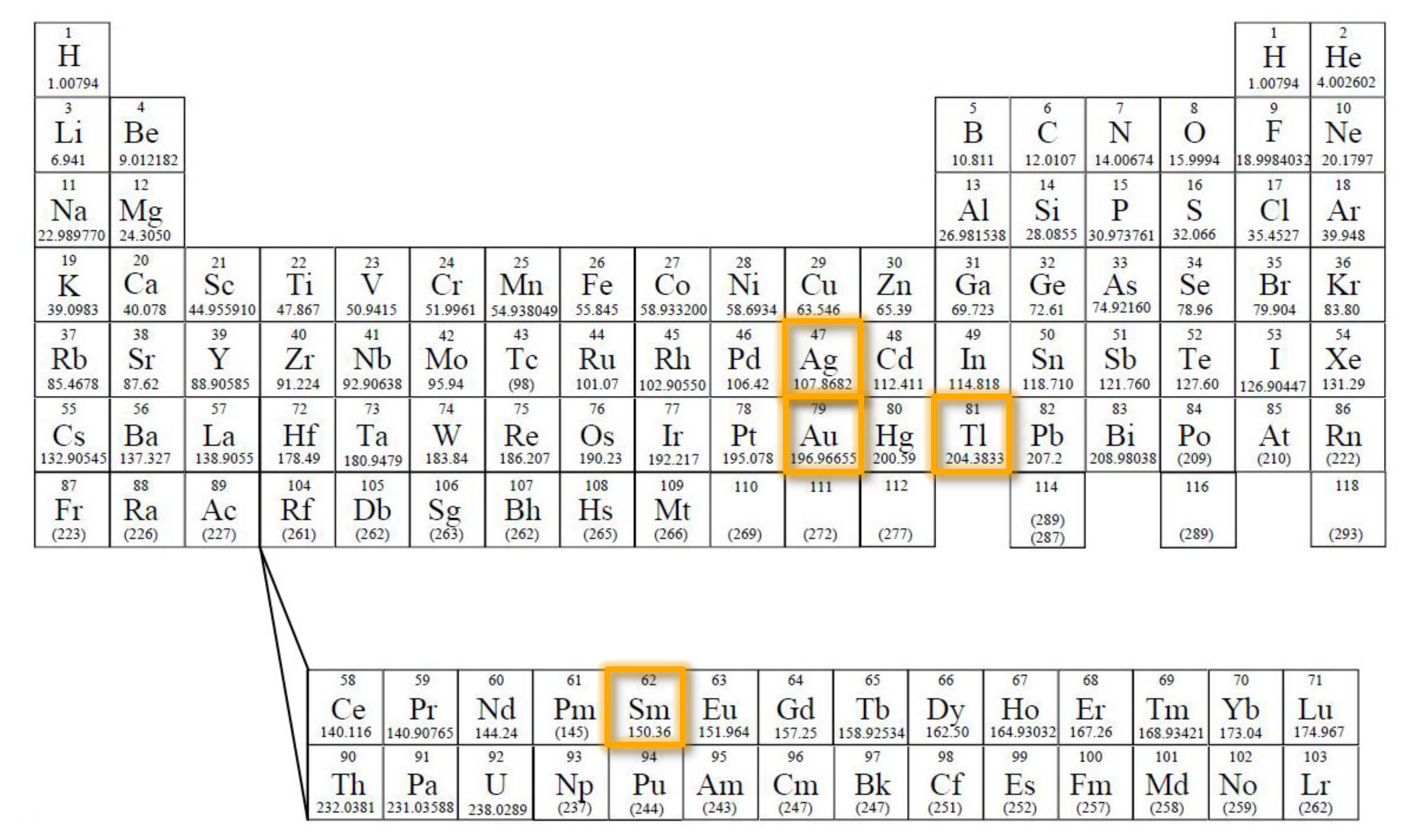
Berengut, Dzuba, Flambaum, Ong, PRL 106, 210802 (2011)

Finding optical transitions in highly charged ions



Periodic Table Filling	Coulomb Filling
1s	1s
2s	2s
2p	2p
3s	3s
3p	3p
4s	3d
3d	4s
4p	4p
5s	4d
4d	4f
5p	5s
6s	5p
4f	5d
5d	5f
6p	6s
7s	6p
5f	6d
6d	6f
	7s

Finding optical transitions in highly charged ions

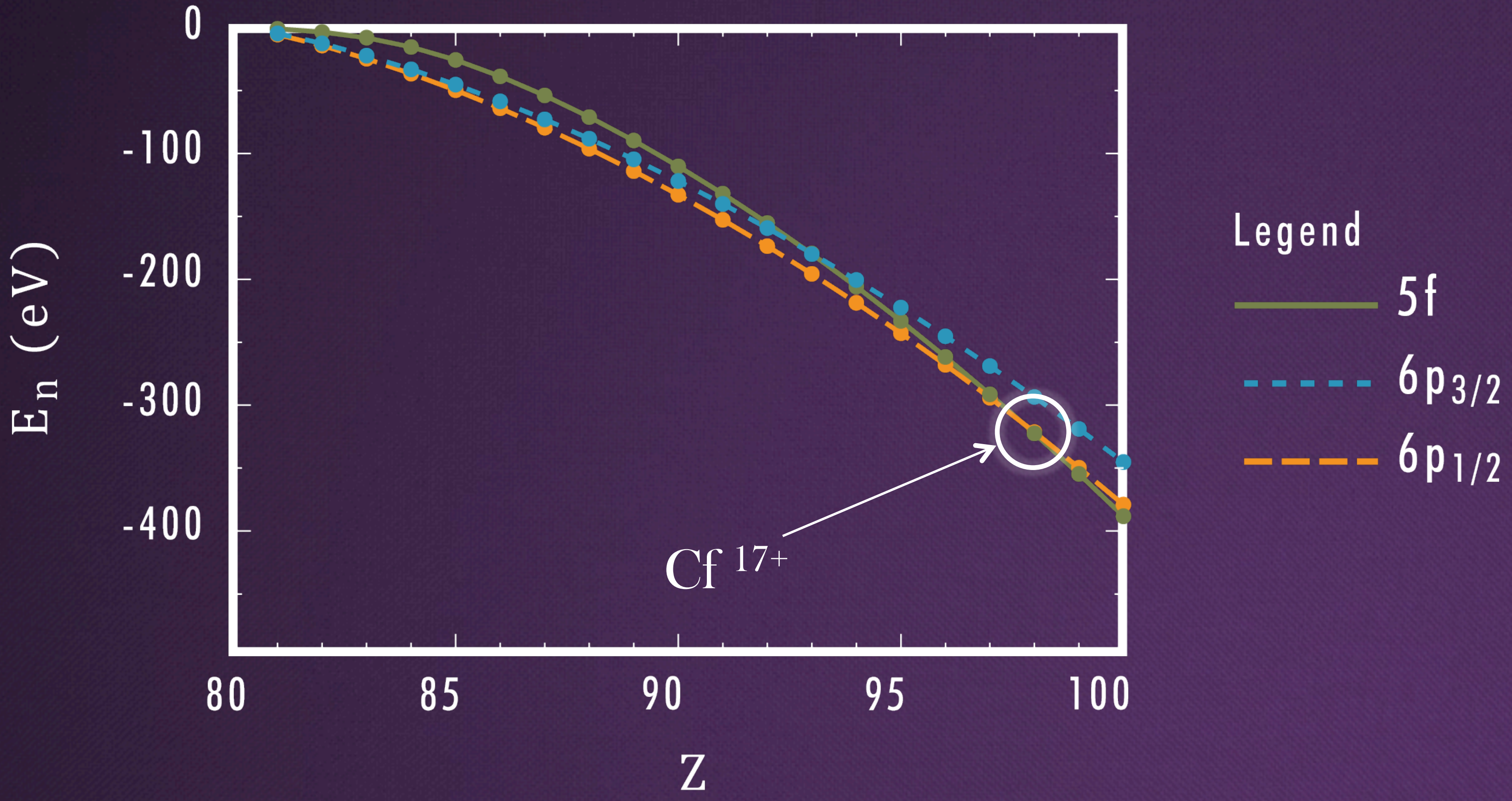


1 H 1.00794																1 H 1.00794	2 He 4.002602
3 Li 6.941	4 Be 9.012182											5 B 10.811	6 C 12.0107	7 N 14.00674	8 O 15.9994	9 F 18.9984032	10 Ne 20.1797
11 Na 22.989770	12 Mg 24.3050											13 Al 26.981538	14 Si 28.0855	15 P 30.973761	16 S 32.066	17 Cl 35.4527	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.955910	22 Ti 47.867	23 V 50.9415	24 Cr 51.9961	25 Mn 54.938049	26 Fe 55.845	27 Co 58.933200	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92160	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.818	50 Sn 118.710	51 Sb 121.760	52 Te 127.60	53 I 126.90447	54 Xe 131.29
55 Cs 132.90545	56 Ba 137.327	57 La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.078	79 Au 196.96655	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98038	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 (269)	111 (272)	112 (277)		114 (289) (287)		116 (289)		118 (293)

58 Ce 140.116	59 Pr 140.90765	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967
90 Th 232.0381	91 Pa 231.03588	92 U 238.0289	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Tl isoelectronic sequence

$[Xe]\,4f^{14}5d^{10}6s^2 : nl$ (81 electrons)



Berengut, Dzuba, Flambaum, Ong, arXiv: 1204.0603 (2012)

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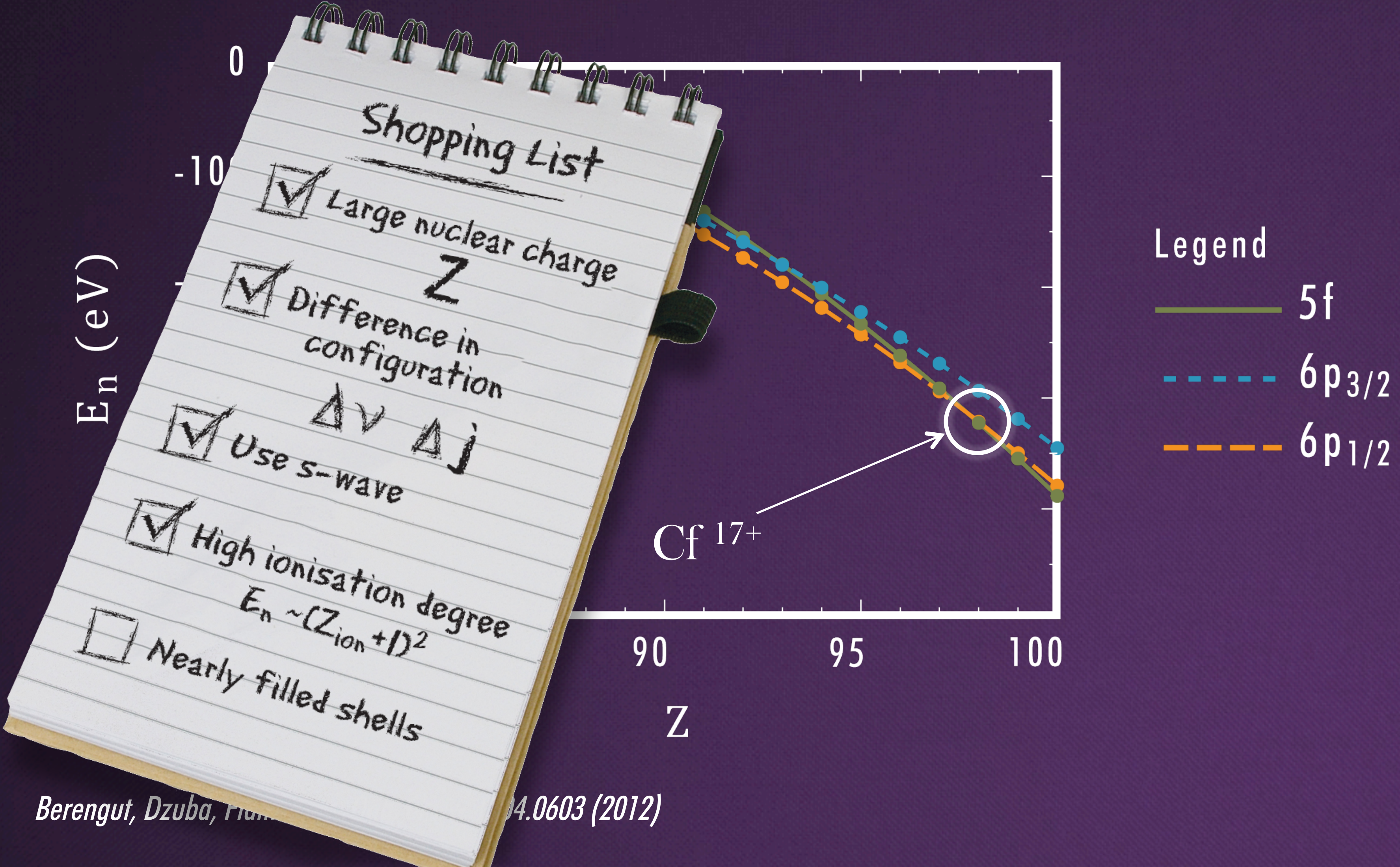

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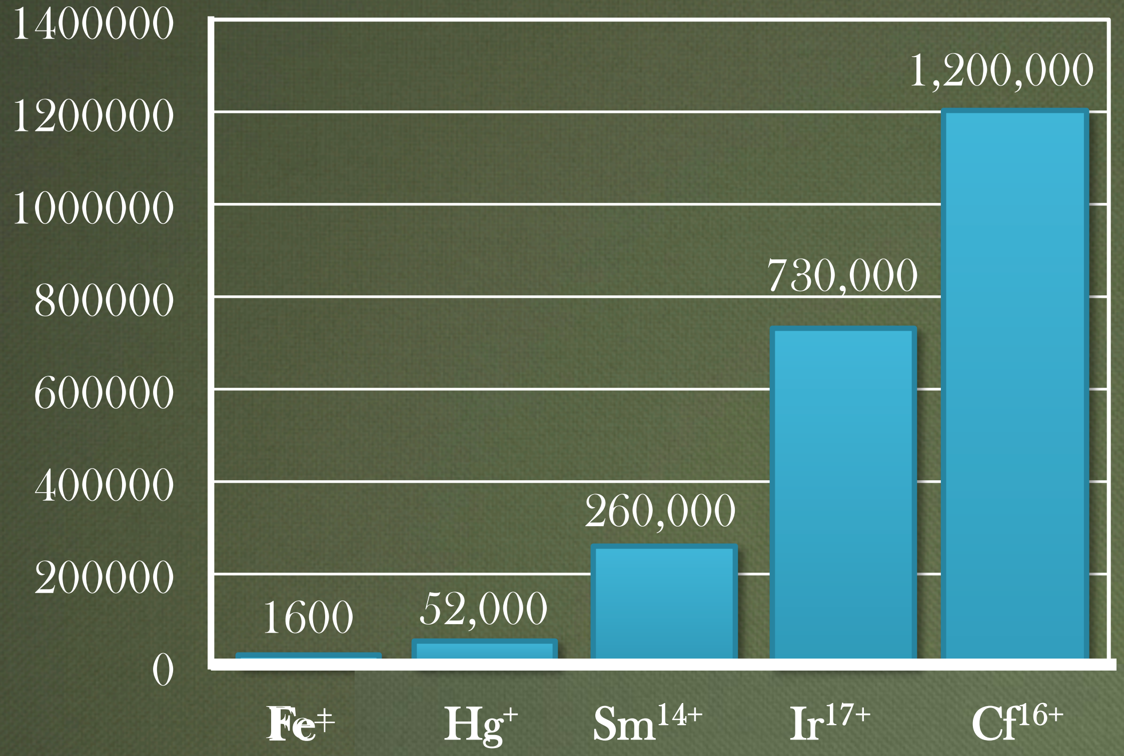
Berengut, Dzuba, Flam *04.0603 (2012)*

Clock q-values (cm^{-1})



Berengut, Dzuba, Flambaum, Ong, arXiv: 1204.0603 (2012)

HCI Clock Scaling Laws and Systematics

- 2nd order Stark shift ~ $1/(Z_{ion}+1)^4$
- Blackbody shift ~ $1/(Z_{ion}+1)^4$
- 2nd order Zeeman shift ~ suppressed as $1/\Delta E$
- Electric quadrupole shift ~ $1/(Z_{ion}+1)^2$
- Fine-structure ~ $Z^2\,(Z_{ion}+1)^2/\nu^3$
- Hyperfine *A* coefficient ~ $Z\,(Z_{ion}+1)^2/\nu^3$

Thank you

Collaborators:
Victor Flambaum, Vladimir Dzuba, Andrew Ong, Samuel Bladwell, Lisa Kava,
Mikhail Kozlov, Sergey Porsev, Vladimir Dmitriev,
John Webb, Julian King, Michael Murphy, Steve Curran, Elliot Koch