

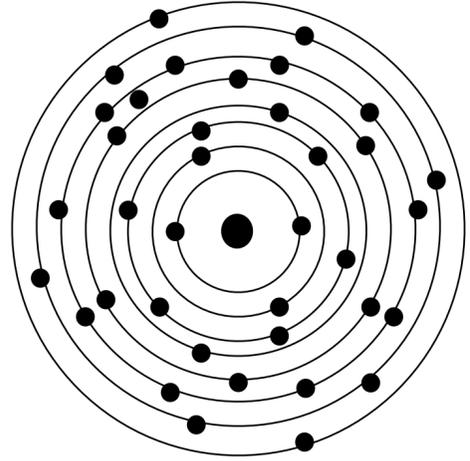
Theory of EDMs and related symmetry violations

Jacinda Ginges

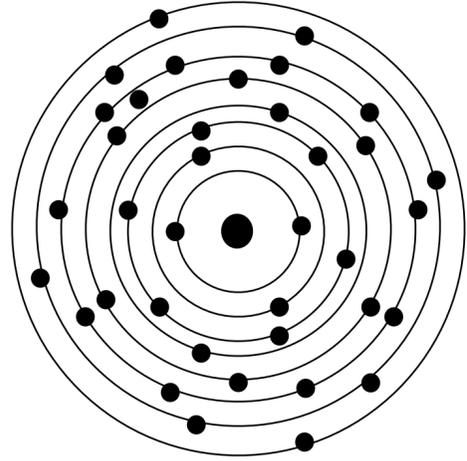


Australian Government
Australian Research Council

Atom as a laboratory

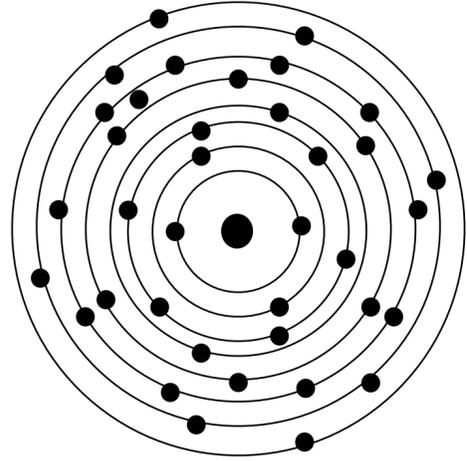


Atom as a laboratory



Electromagnetic, weak, strong interactions present in atoms and may be probed and tested

Atom as a laboratory



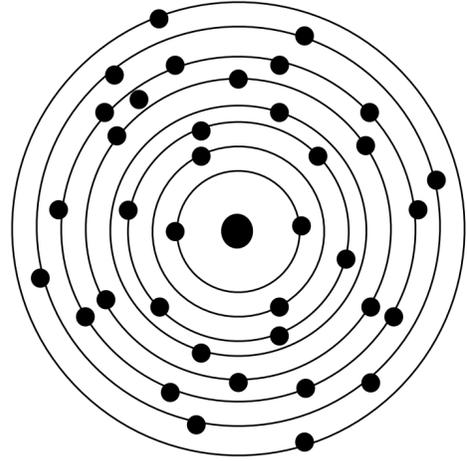
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Weak interaction *isolated* by studying parity-violating effects

Parity operation: $\mathbf{r} \rightarrow -\mathbf{r}$



Atom as a laboratory



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Complexity/simplicity varied by changing nuclear charge, isotope, ionization degree, state

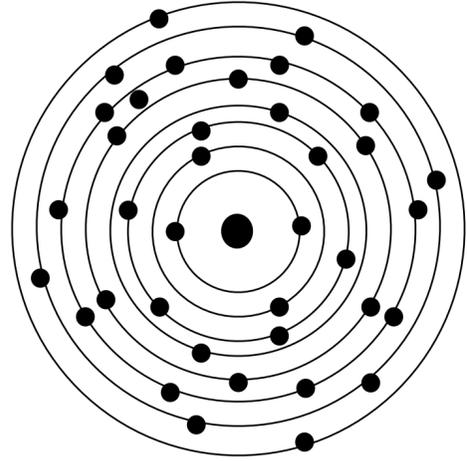
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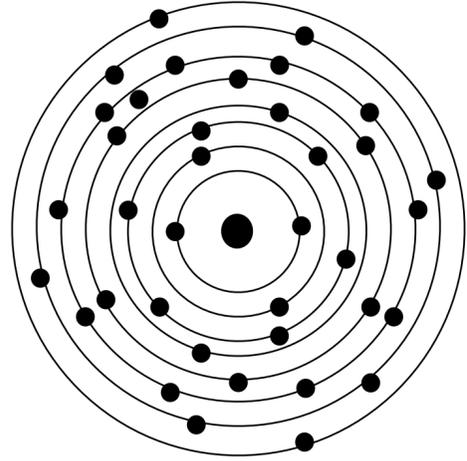
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Electric dipole moments

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Electric dipole moments

Atomic parity violation

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Hadronic neutral current event: neutrino-nucleon scattering



Leptonic neutral current event: antineutrino-electron scattering

<https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/>

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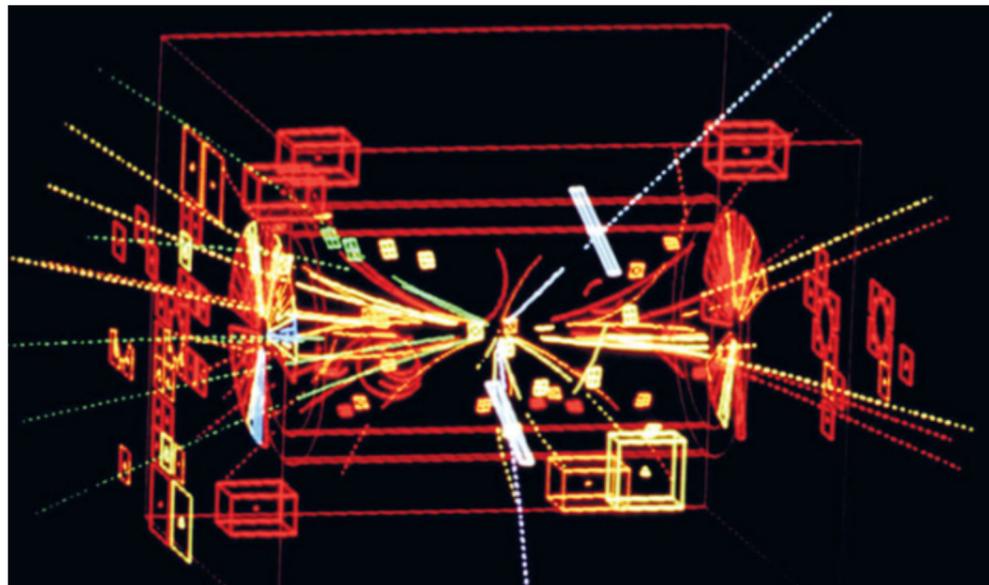


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- 1983, weak bosons Z , W^+ , W^- produced directly at CERN

<https://cerncourier.com/a/finding-the-w-and-z/>



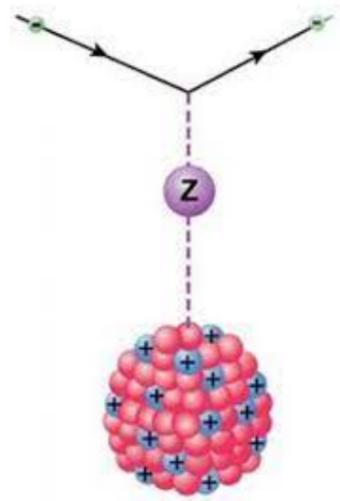
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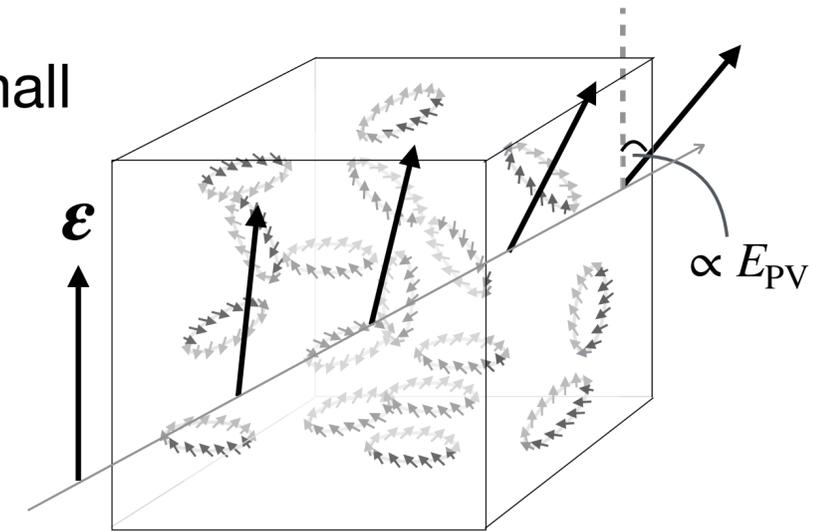
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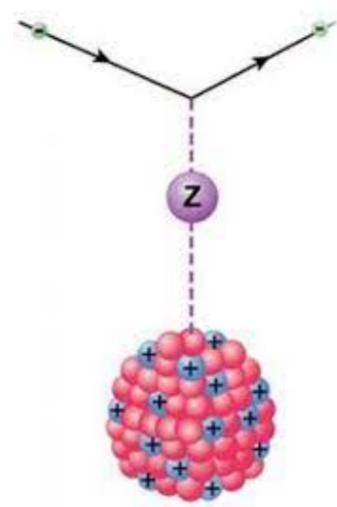
Brief history of atomic parity violation (APV)



1959 — Zel'dovich proposed, though considered H in which it is small

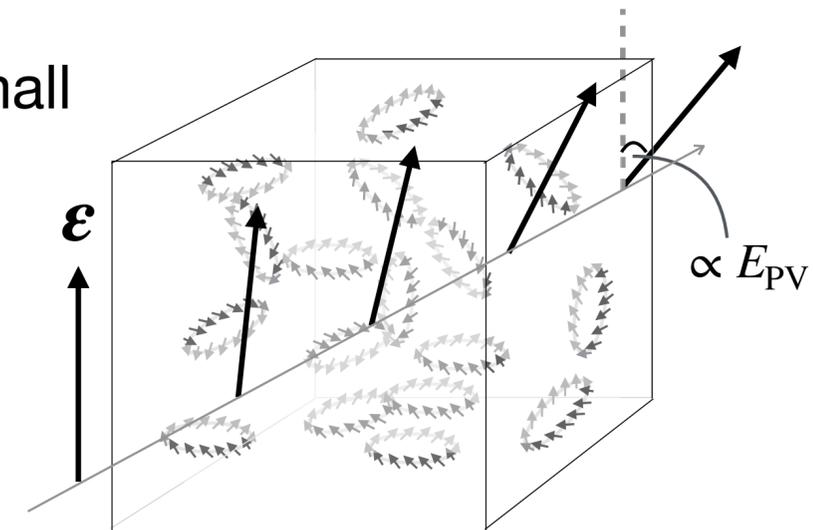


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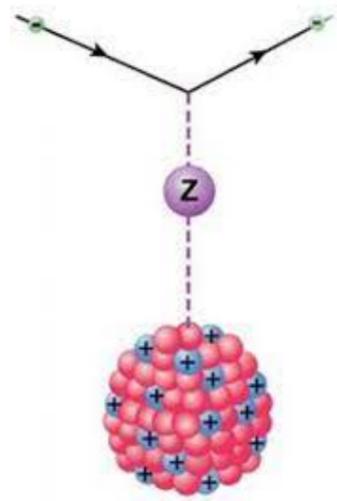


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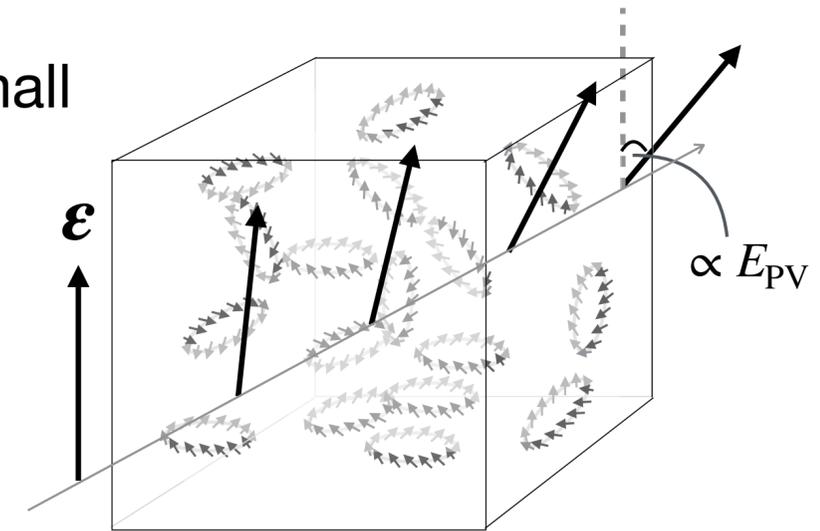
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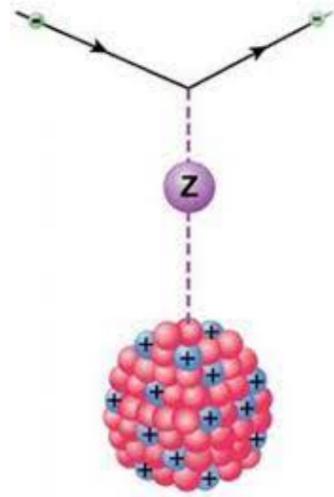
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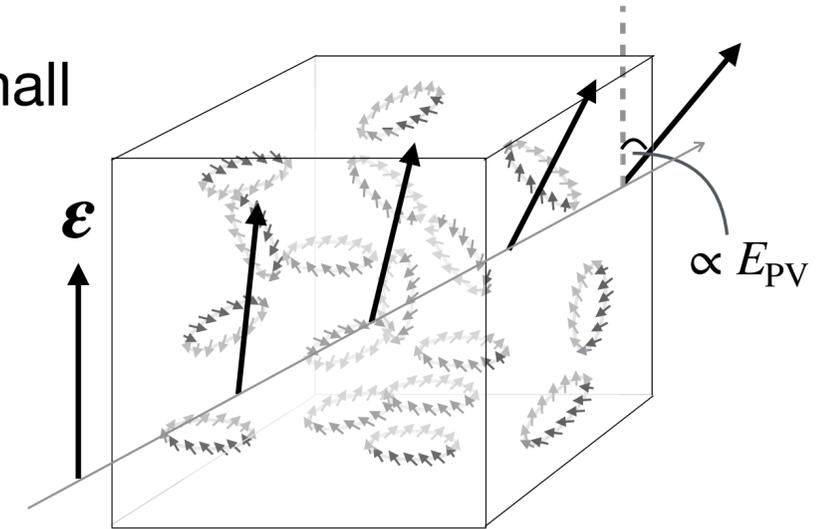
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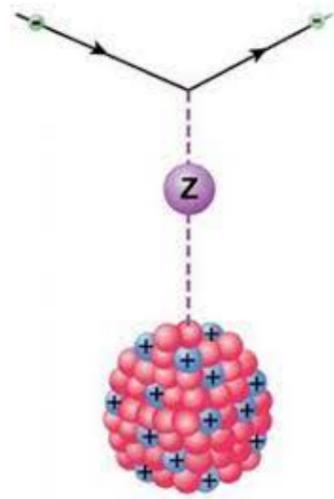
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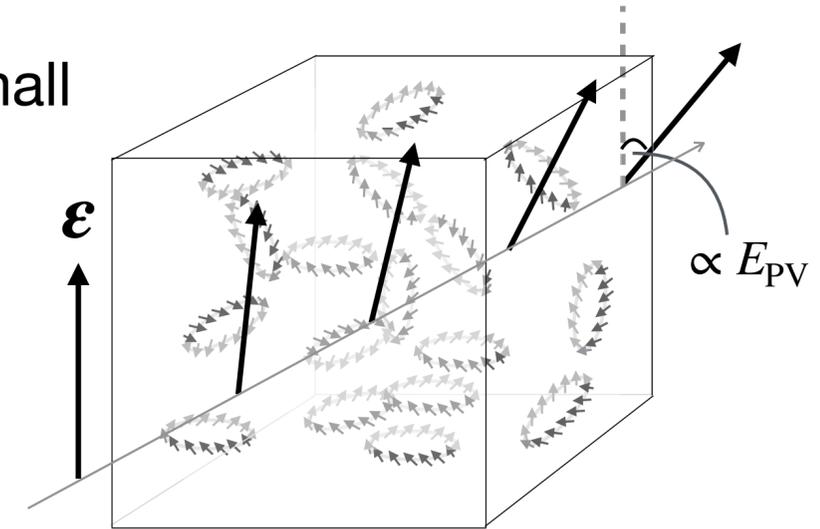
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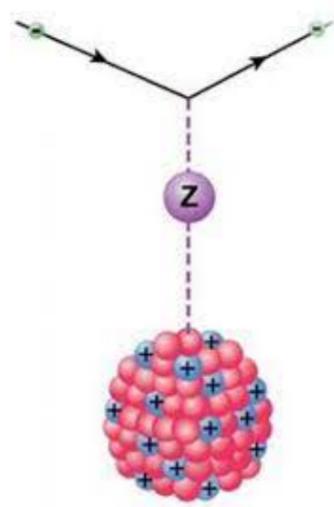
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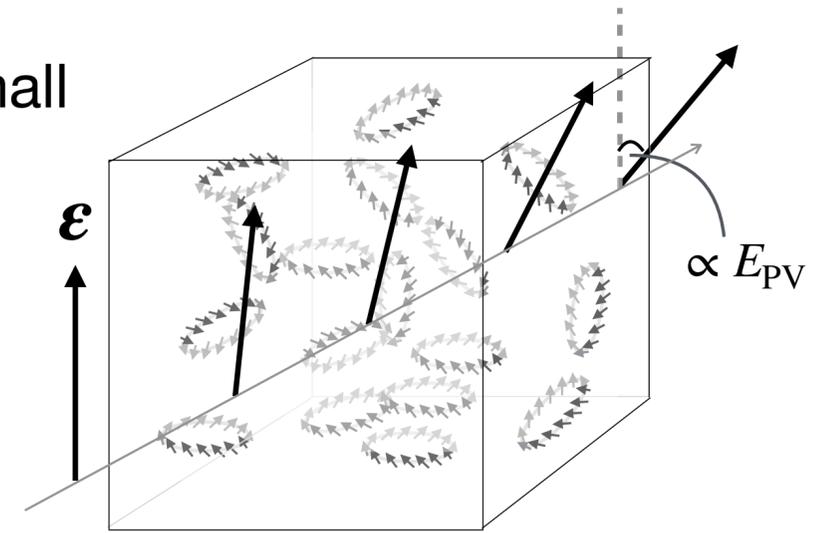
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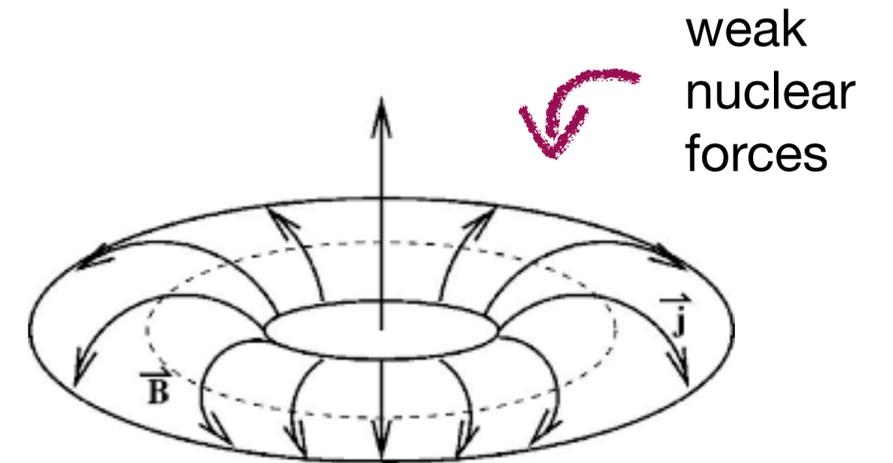


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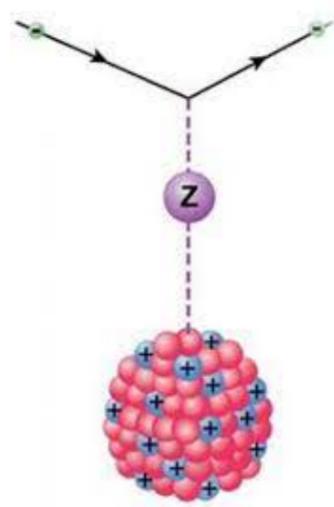
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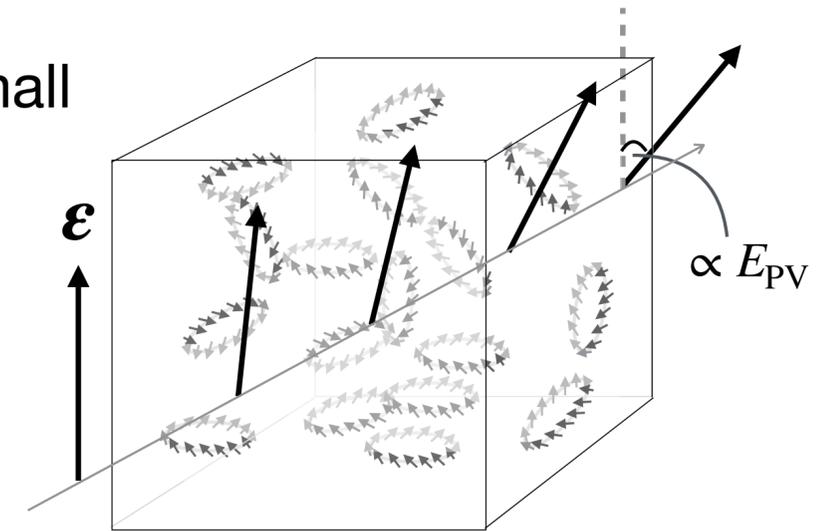
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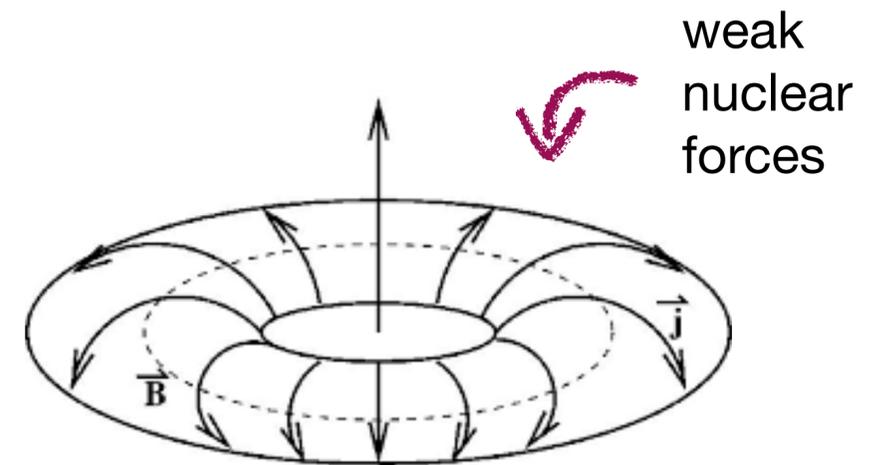
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2019 — Budker group (Mainz) measured APV in Yb, uncertainty 0.5%,

along chain of isotopes



ratios taken



Bouchiat and Bouchiat, Rep. Prog. Phys. (1997)

Ginges and Flambaum, Phys. Rep. (2004)

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Experiments — performed, in progress, planned

Periodic Table of the Elements

1 IA 1A																	18 VIIIA 8A	
1 H Hydrogen 1.008											2 He Helium 4.003							
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294	
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71		72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103		104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

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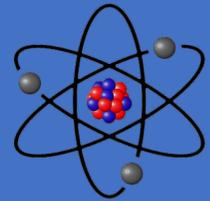
Measured — blue (rotation), yellow (Stark);
 Next-gen — red; New in progress/planned — green

Atom as a laboratory — symmetries violations



Atom as a laboratory — symmetries violations

Experiments



Atoms



Molecules



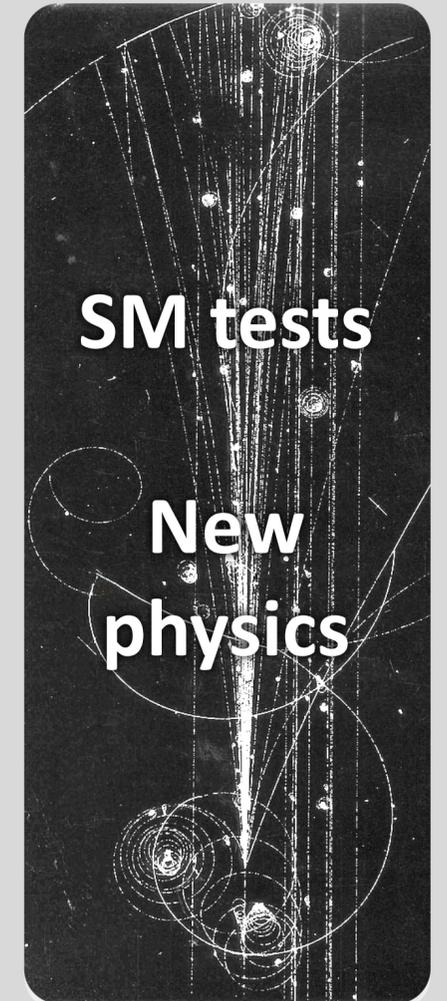
*I saw the angel in the marble and
carved until I set him free*

— Michelangelo

Particle

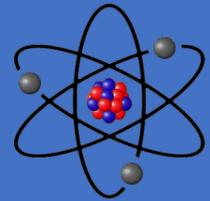
SM tests

New
physics



Atom as a laboratory — EDMs

Experiments



Atoms



Molecules



Nuclear

Nucleon

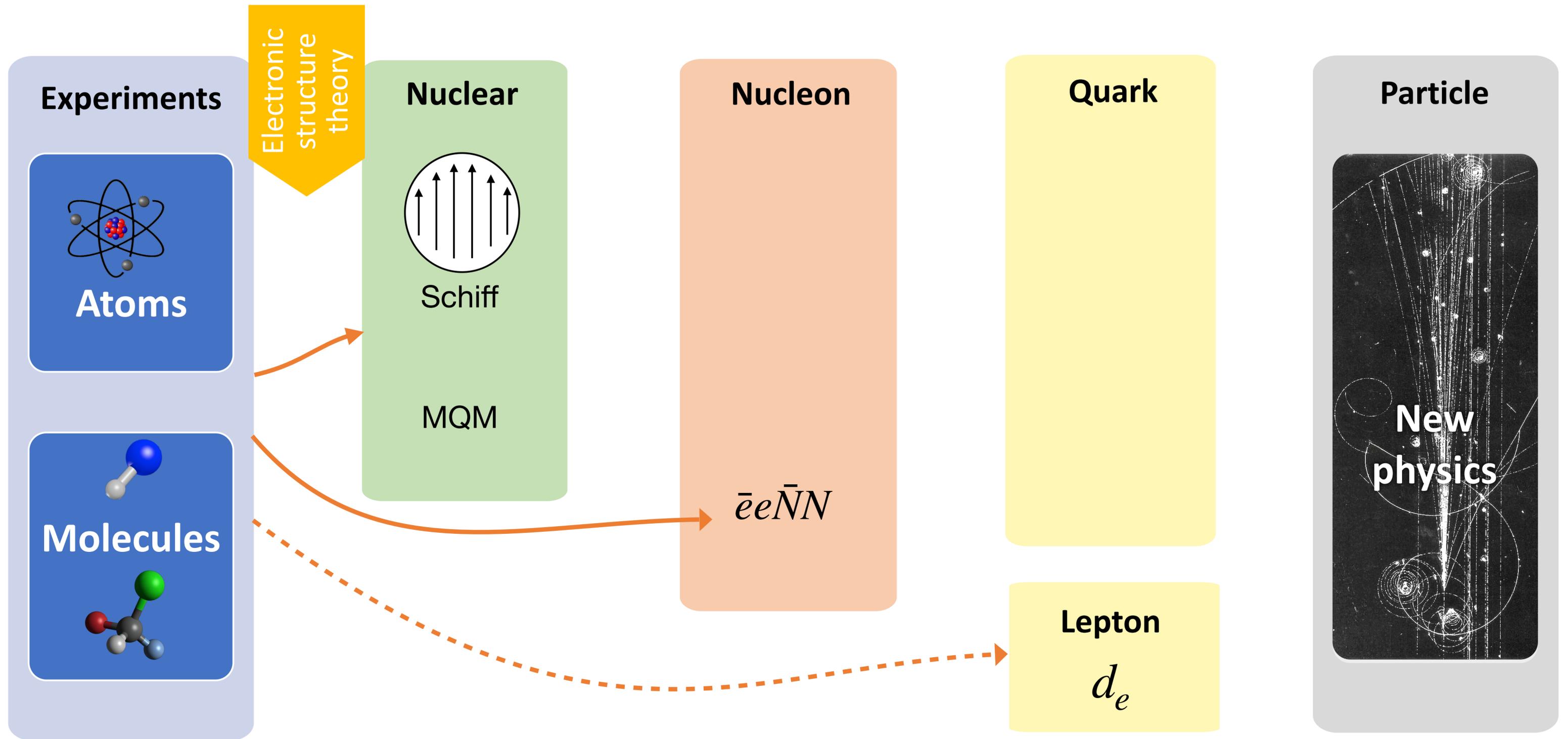
Quark

Particle

**New
physics**

Lepton

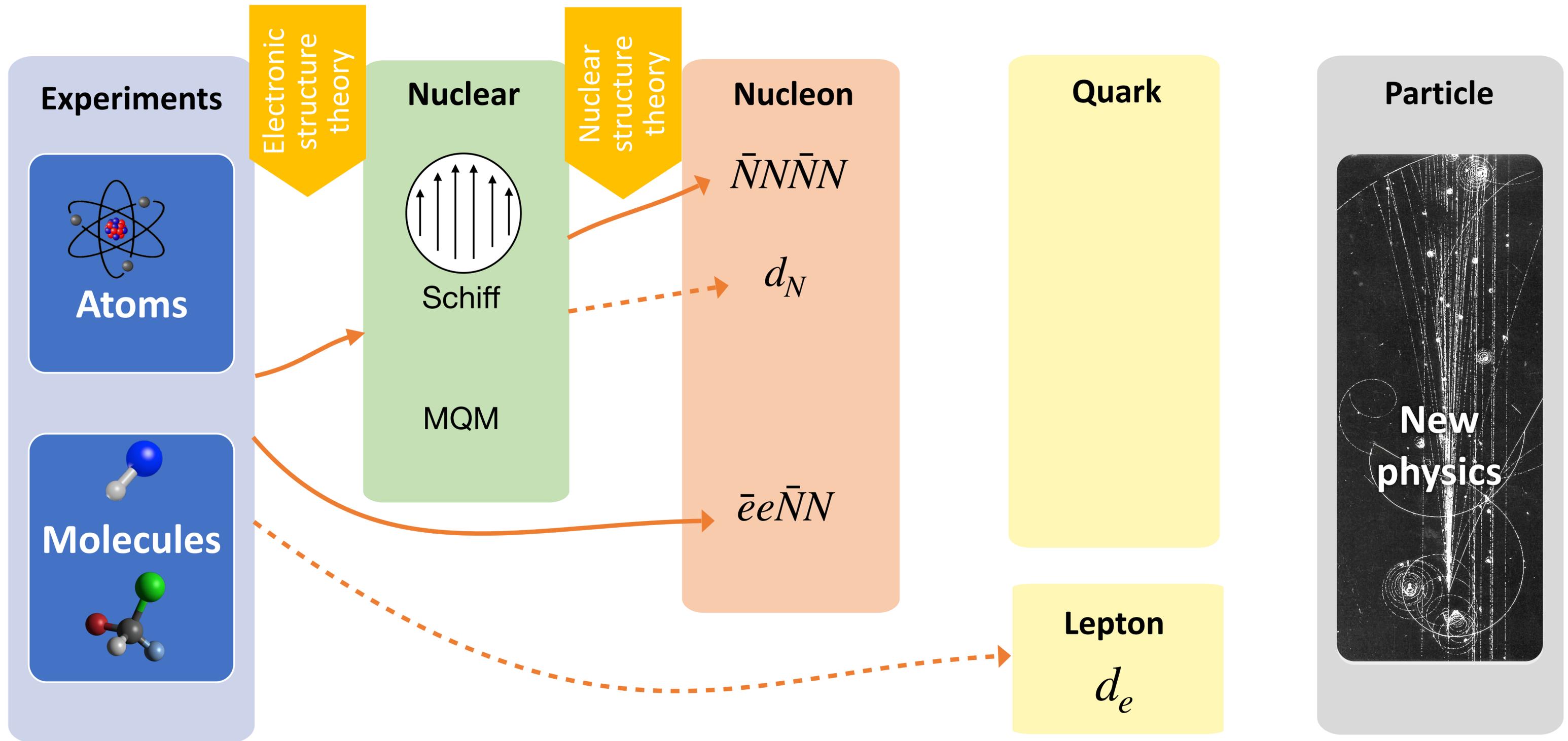
Atom as a laboratory — EDMs



diamagnetic

See, e.g., Ginges and Flambaum, Phys. Rep. (2004);
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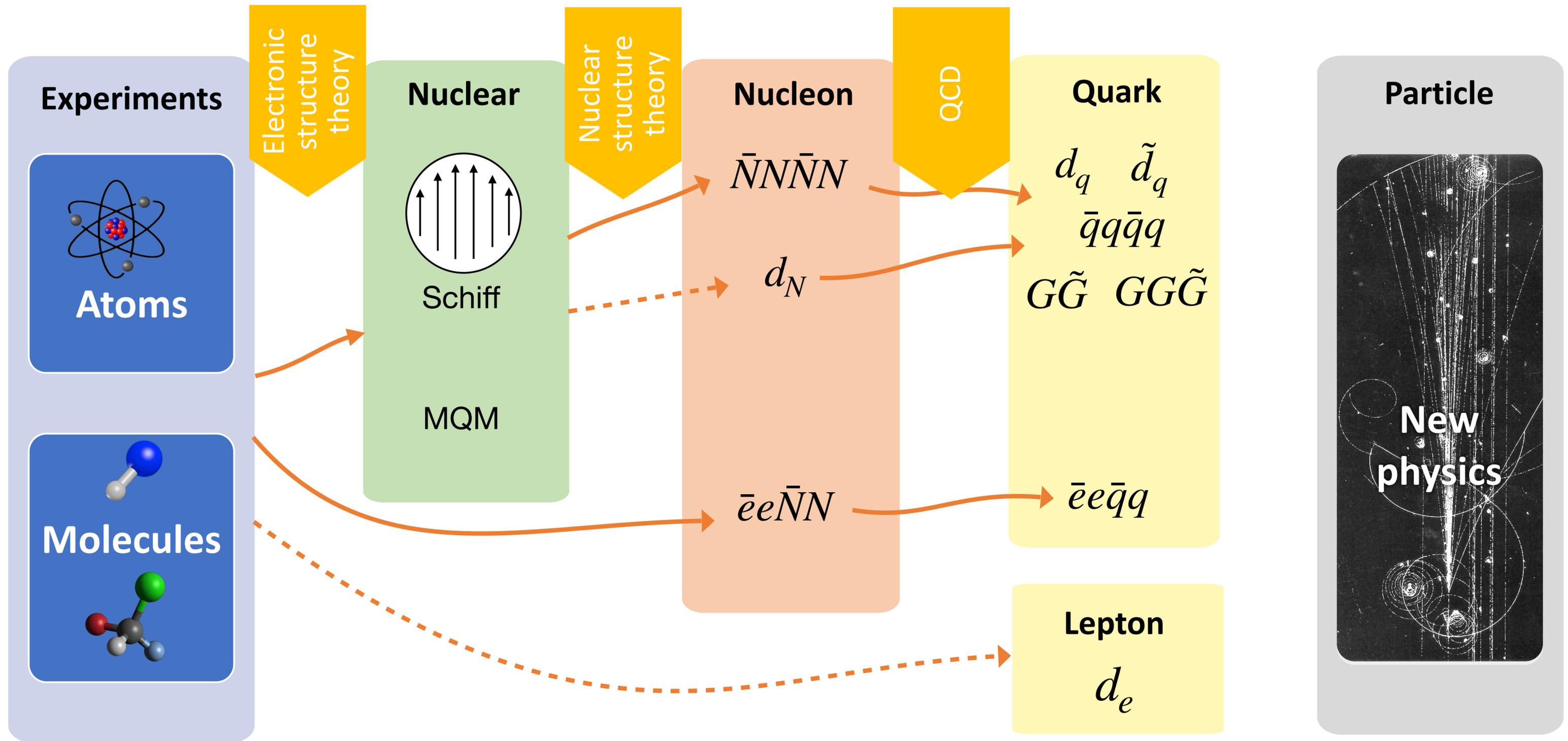
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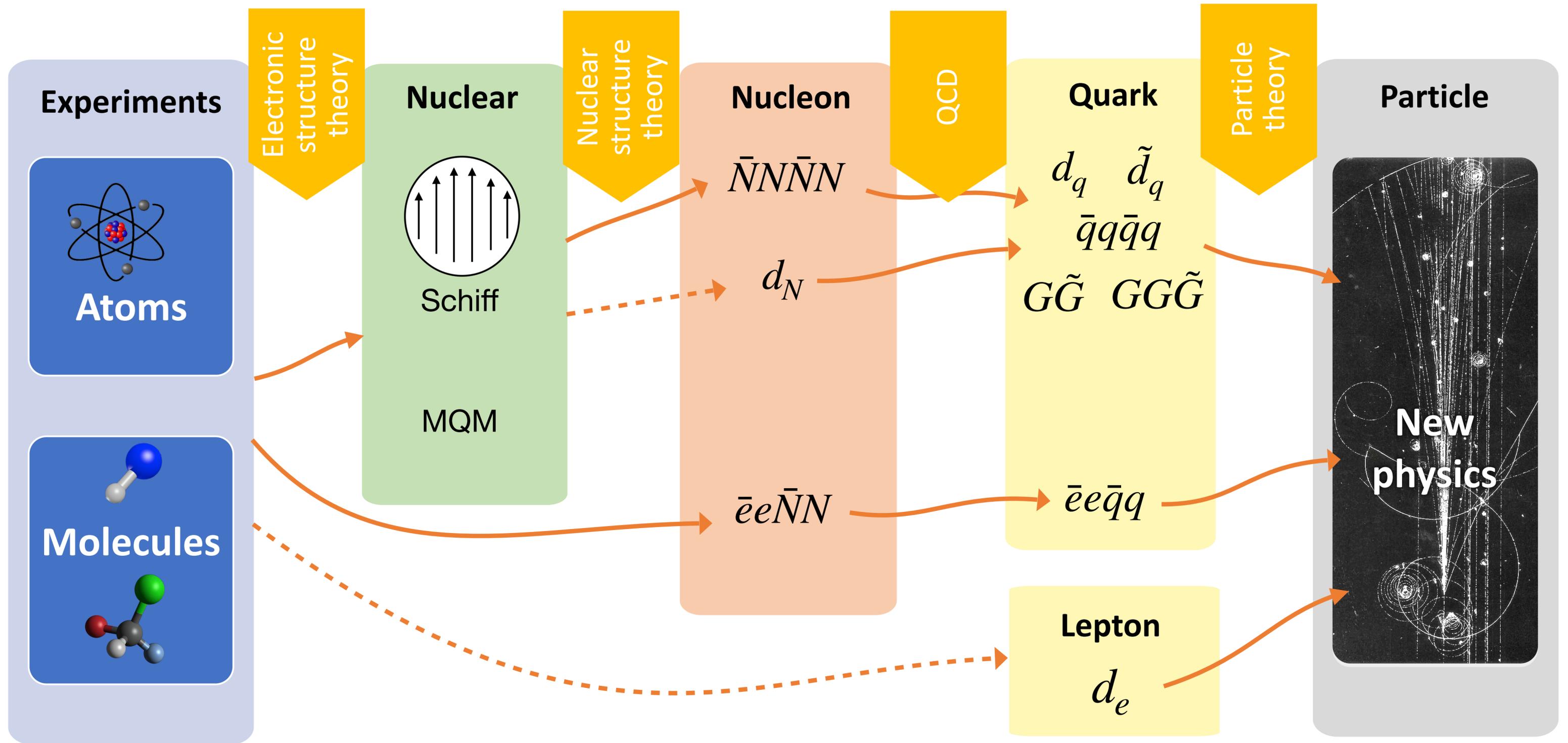
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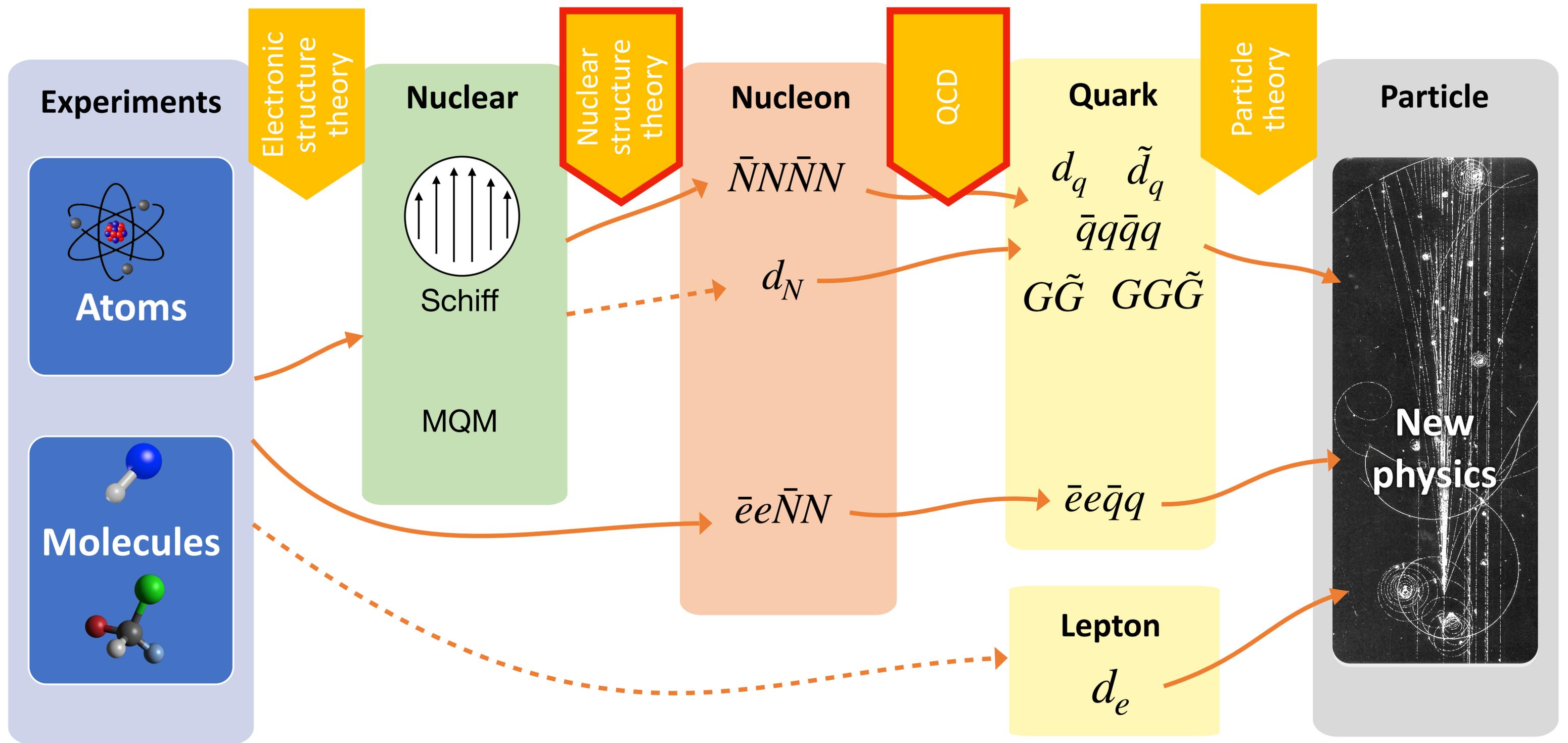
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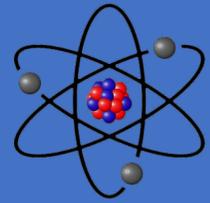
bottleneck

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Atom as a laboratory — APV

Experiments



Atoms



Molecules



Nuclear

Nucleon

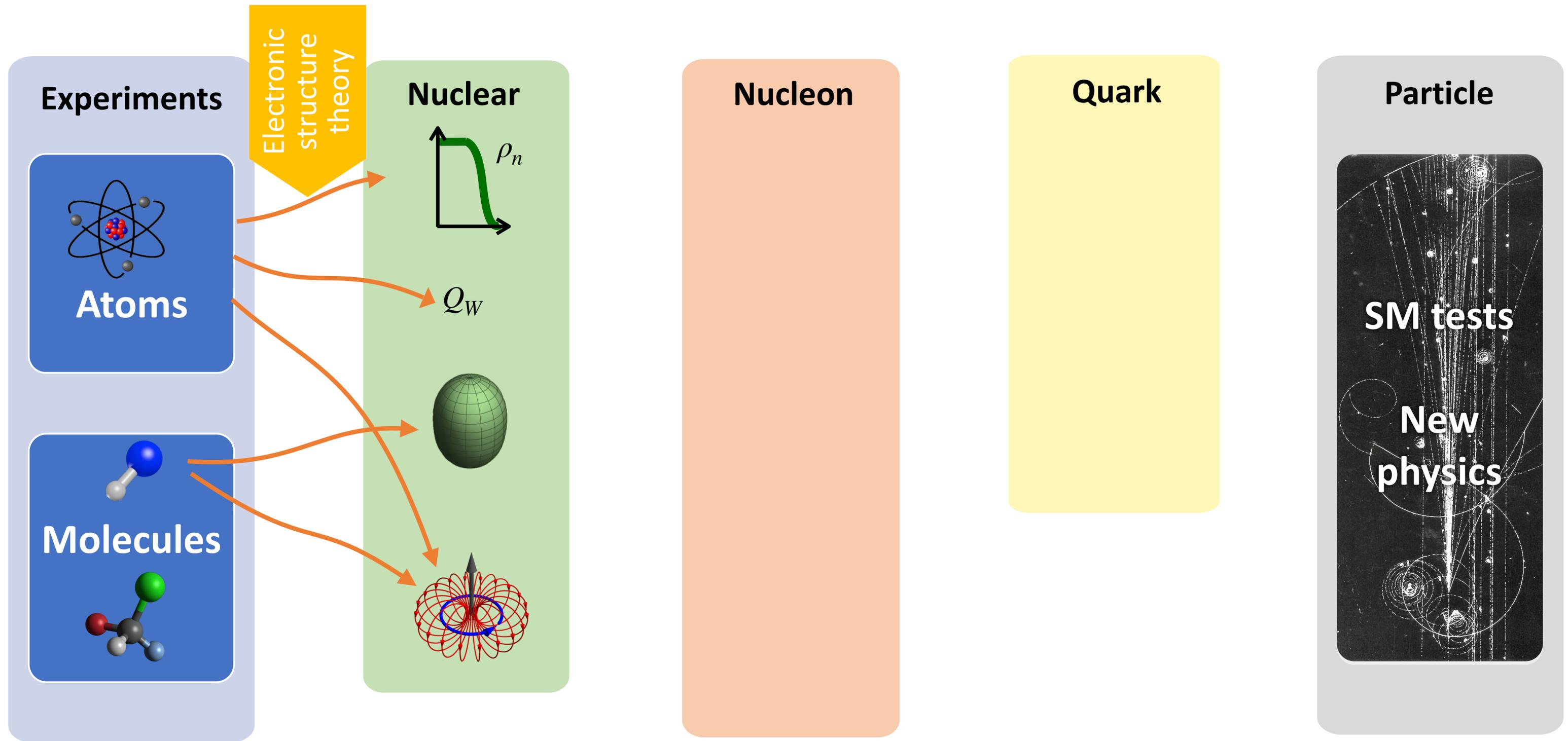
Quark

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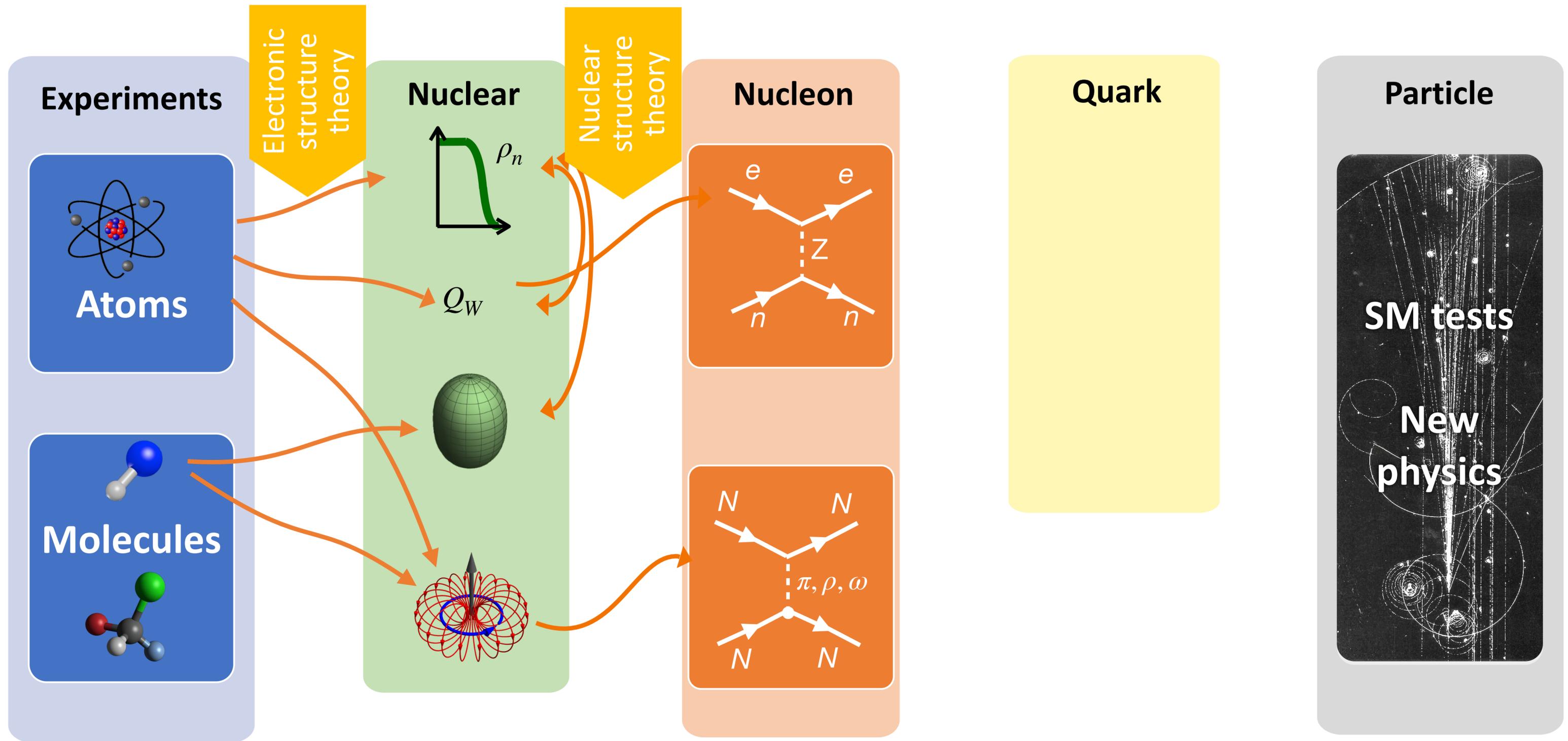
SM tests

**New
physics**

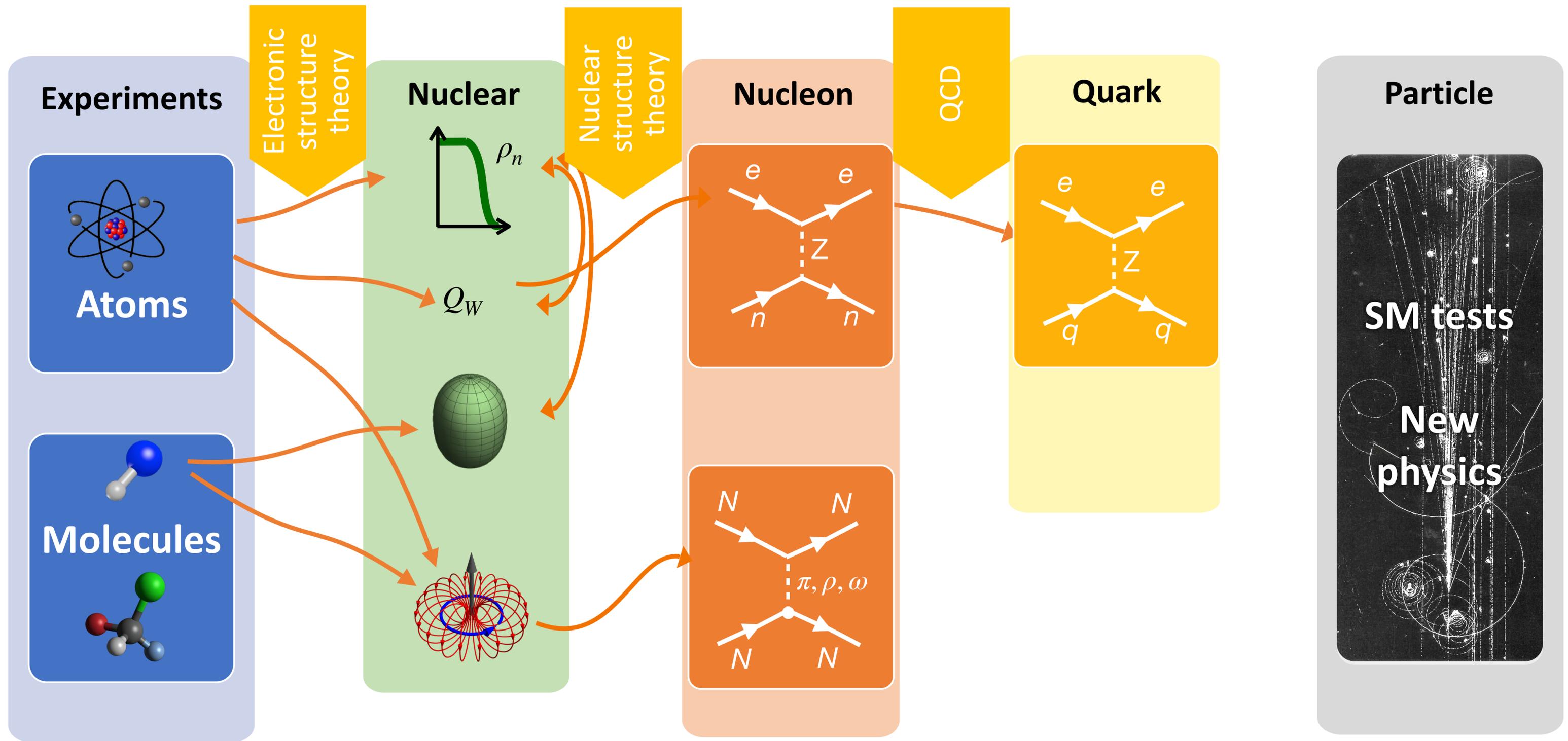
Atom as a laboratory — APV



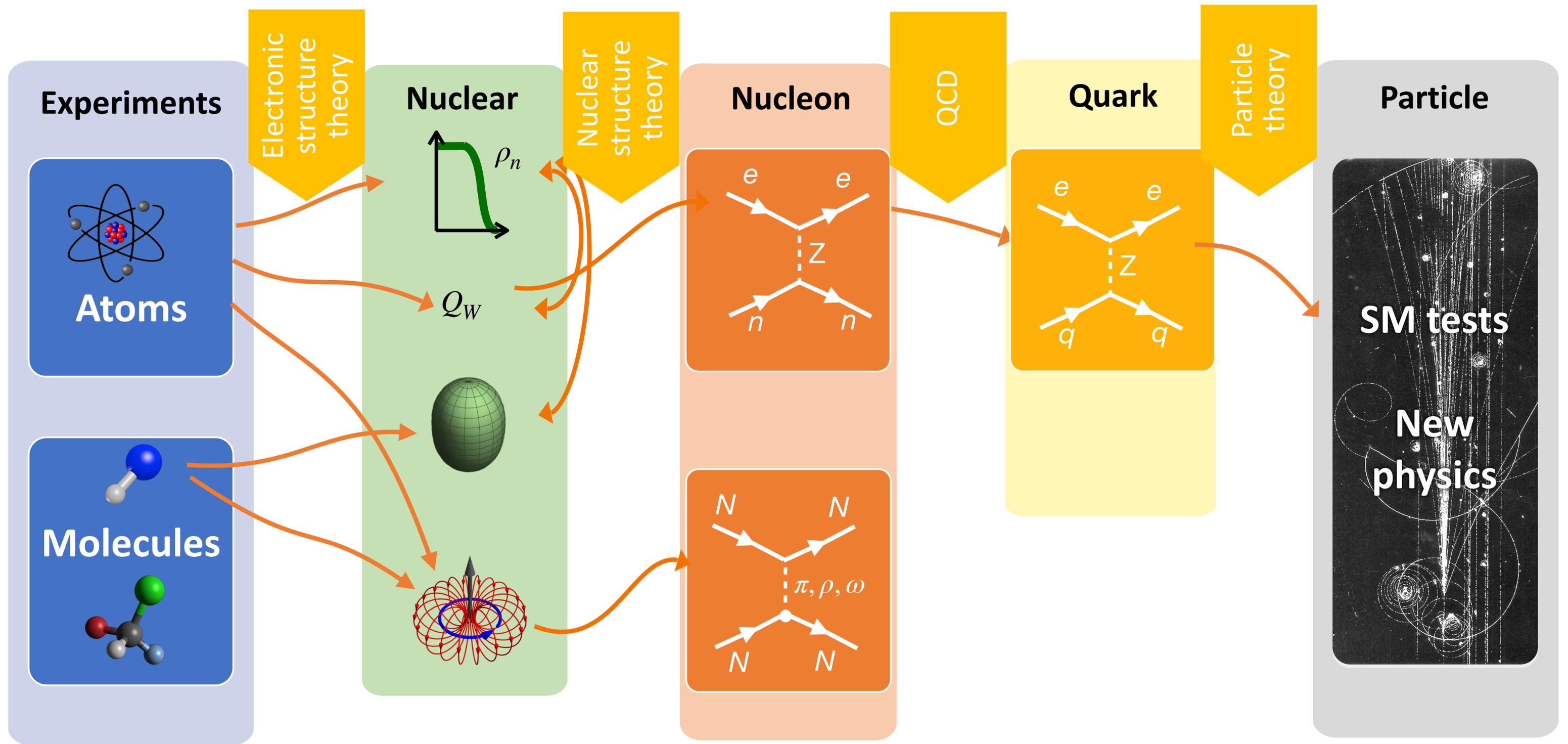
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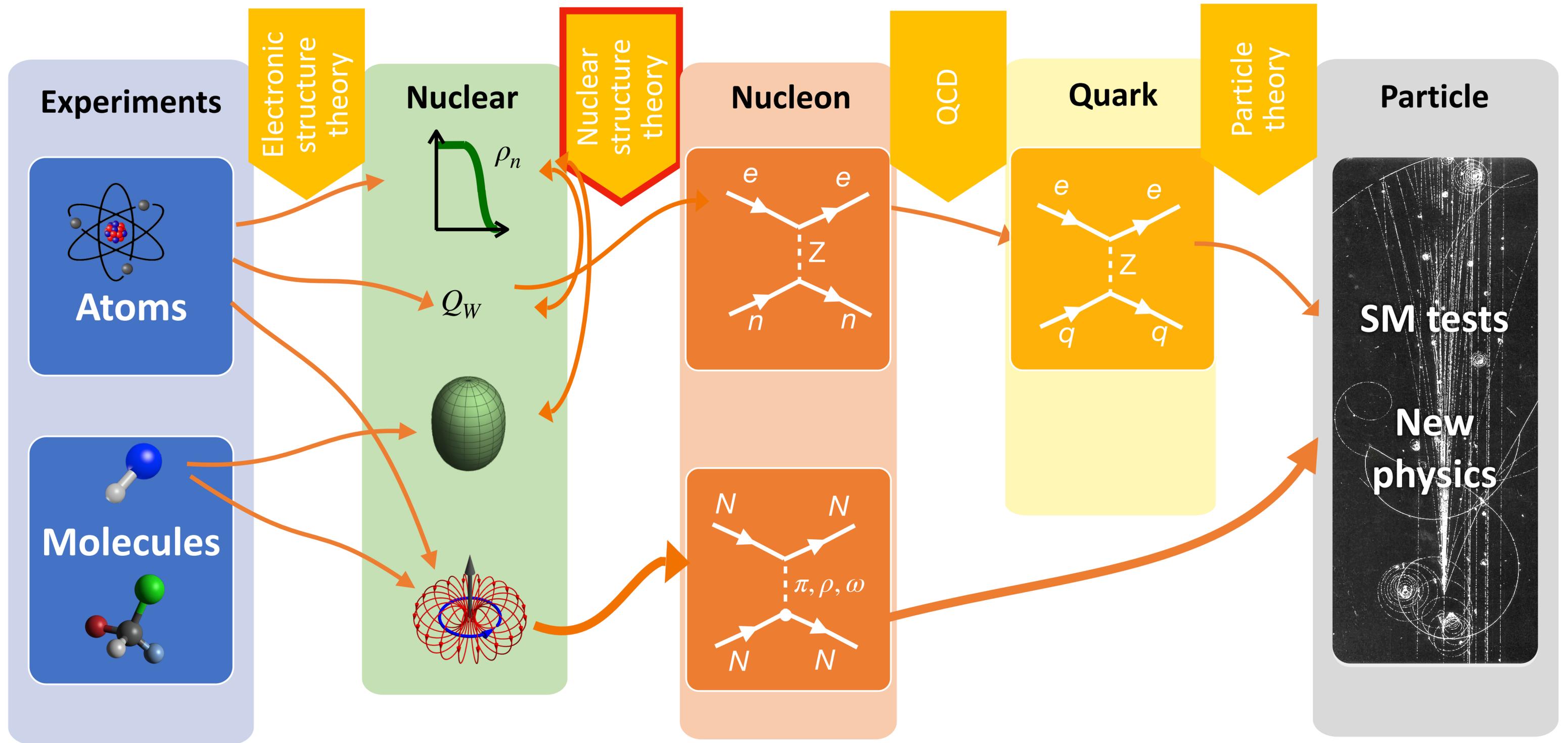
Atom as a laboratory — APV



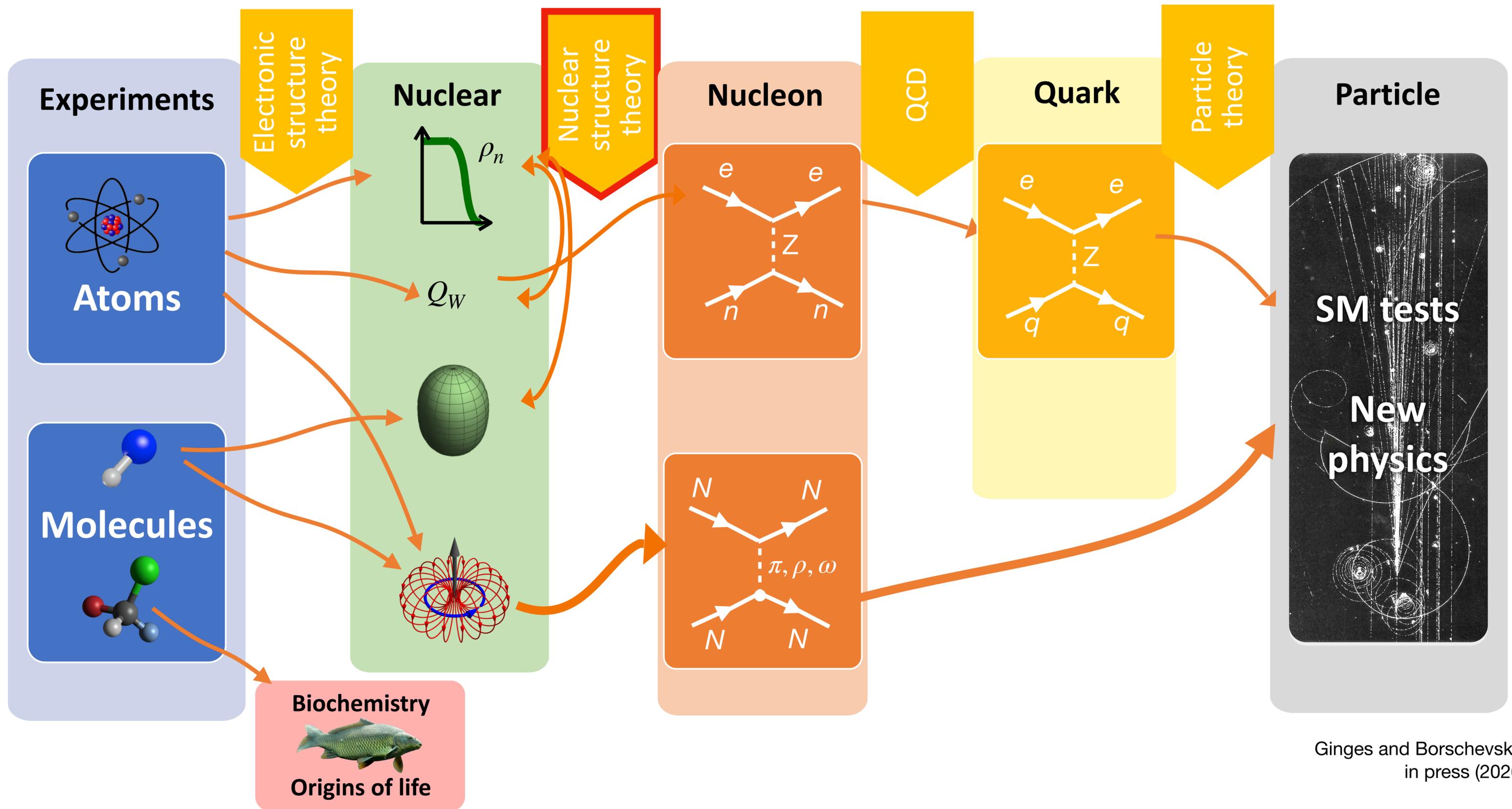
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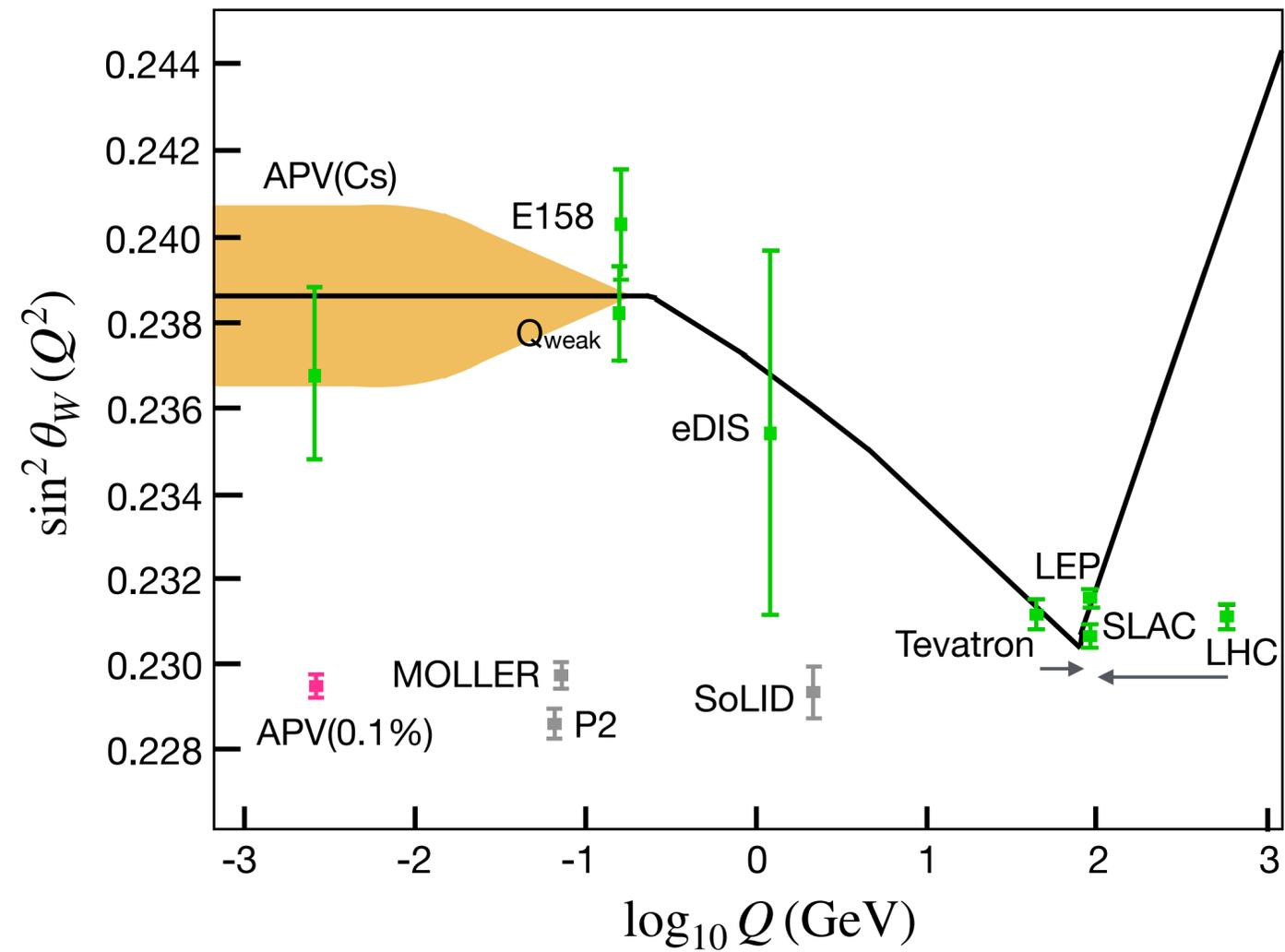
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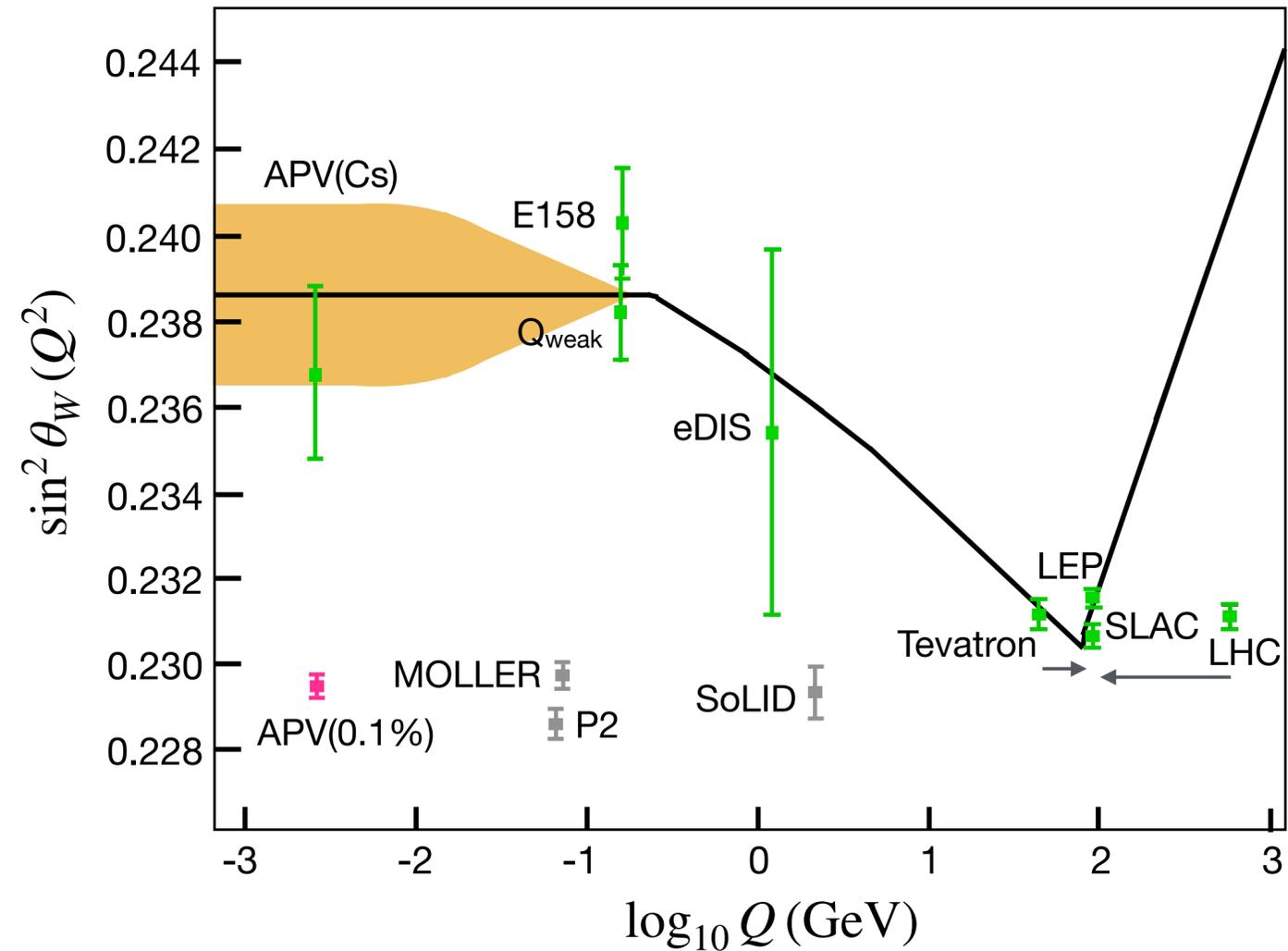
Atomic parity violation — SM tests and BSM searches



- Running of Weinberg angle with momentum transfer
- Effect of 50 MeV dark boson (mustard)

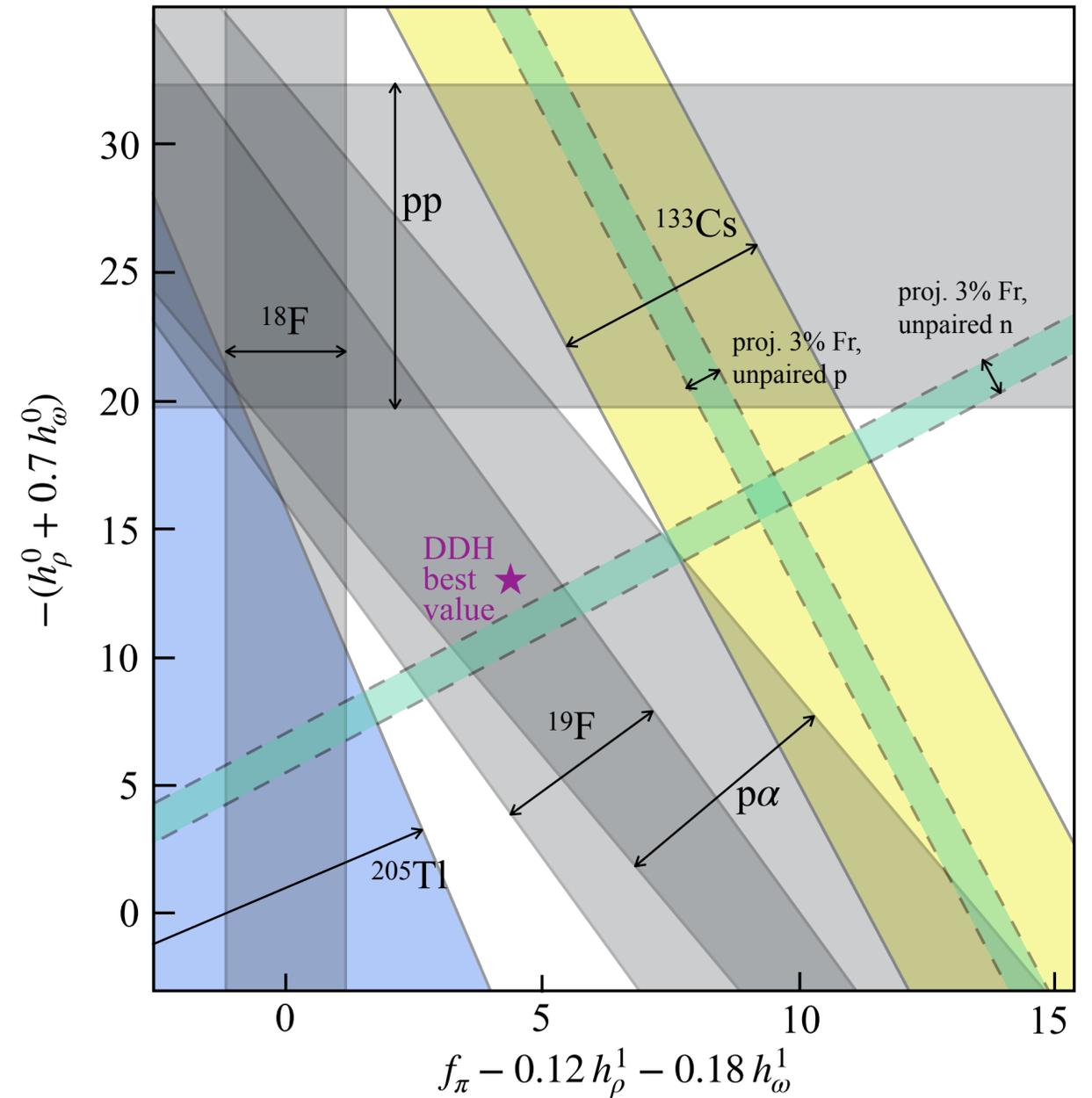
Erlar (2025);
Safronova et al., Rev. Mod. Phys. (2018);
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- Extraction of weak meson-nucleon couplings from scattering experiments, including from anapole

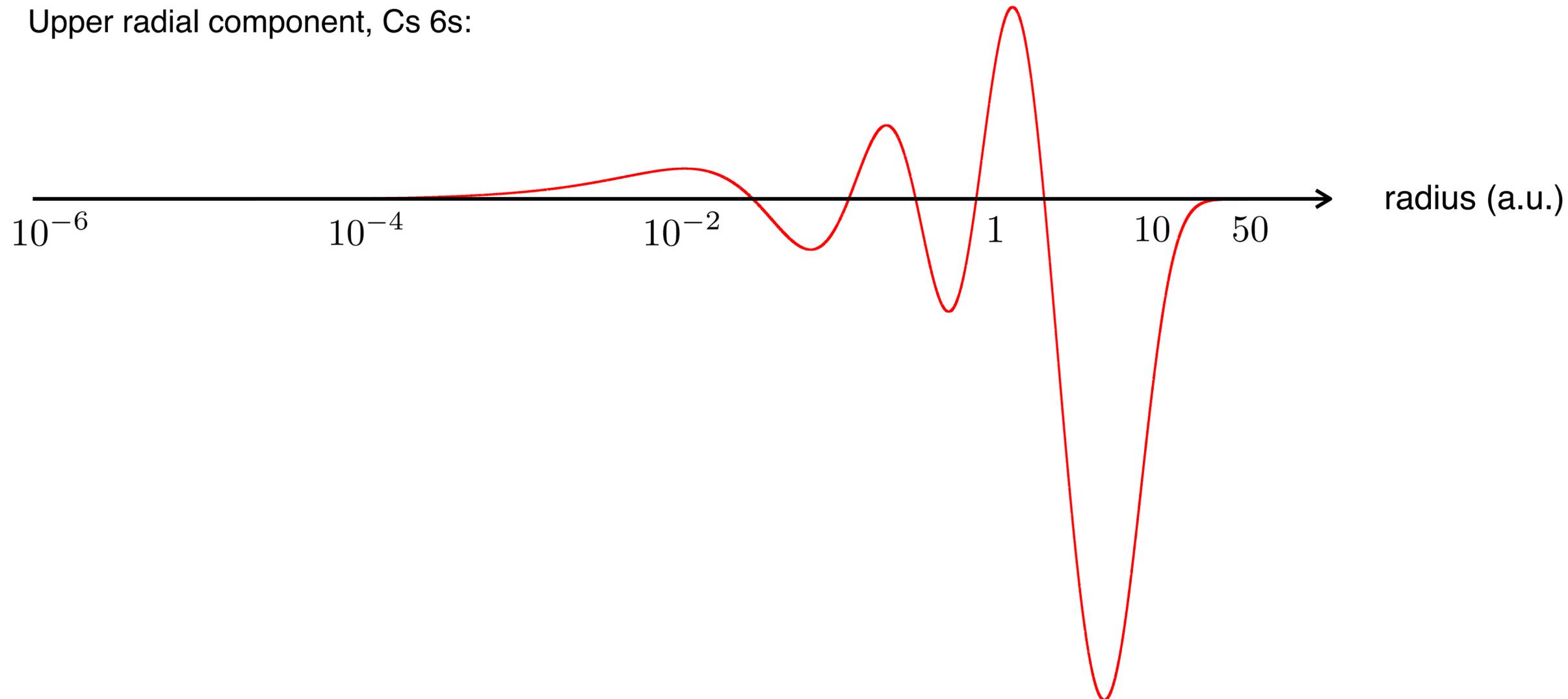
Haxton and Holstein, Prog. Part. Nucl. Phys (2013);
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Benchmarking atomic theory — atomic EDMs and APV

Atomic EDM: $d_{\text{atom}} = \langle \tilde{N} | D_z | \tilde{N} \rangle = 2 \sum_M \frac{\langle N | D_z | M \rangle \langle M | H_{P,T} | N \rangle}{E_N - E_M}$

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Upper radial component, Cs 6s:

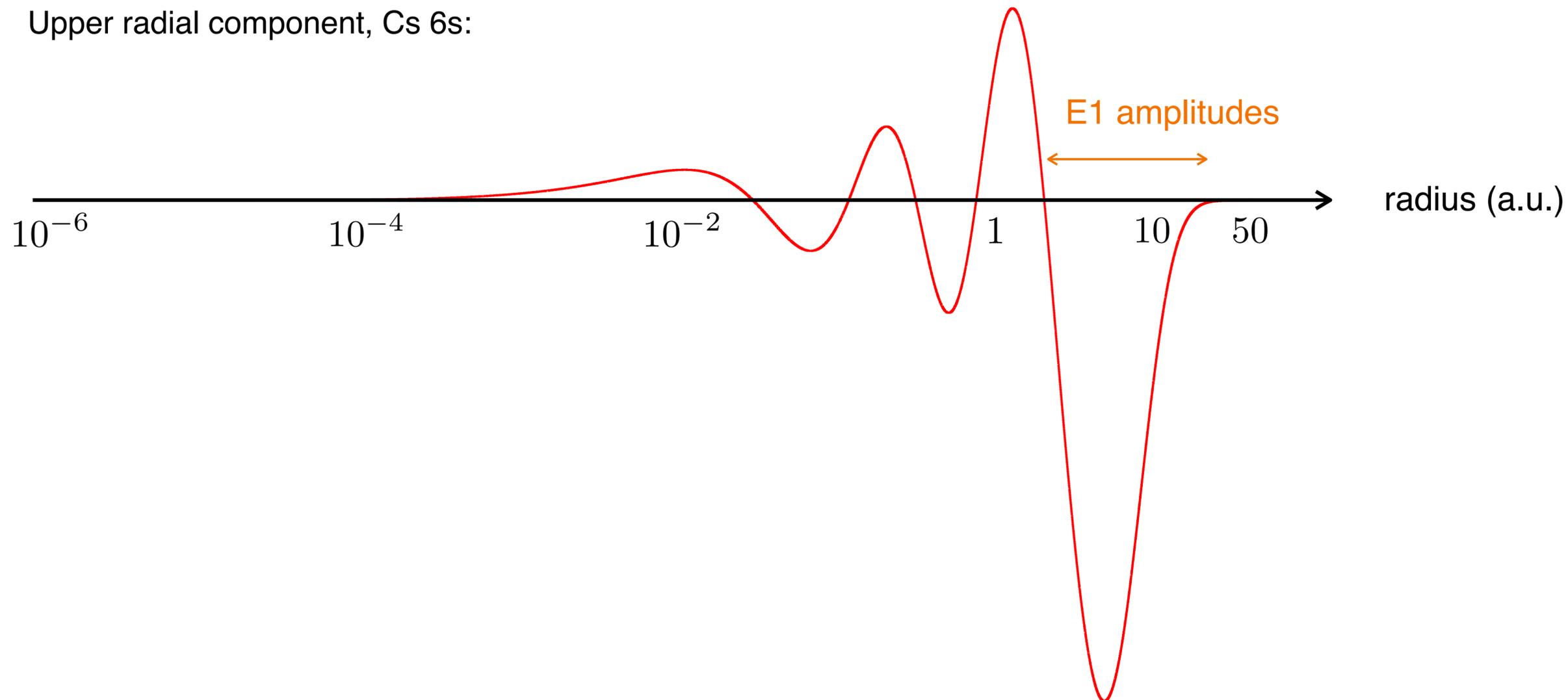


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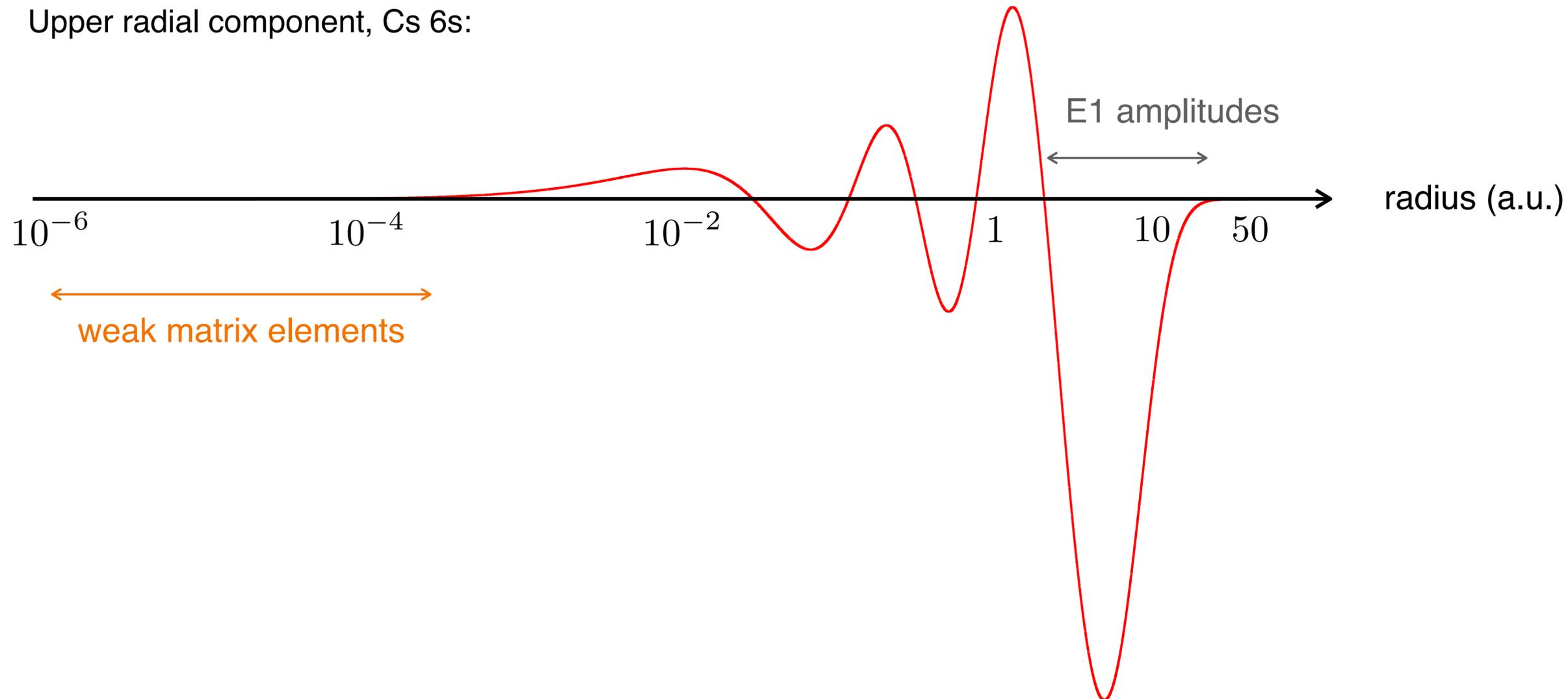


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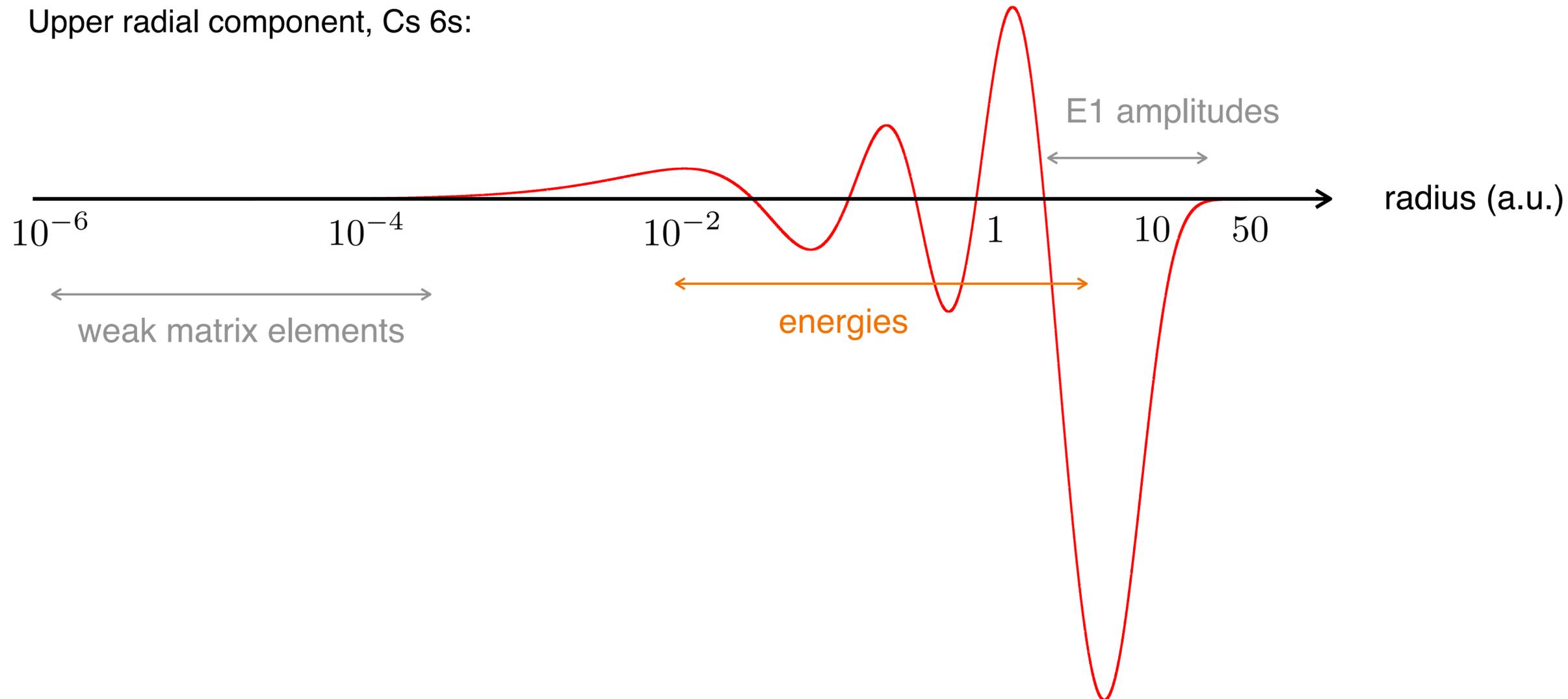


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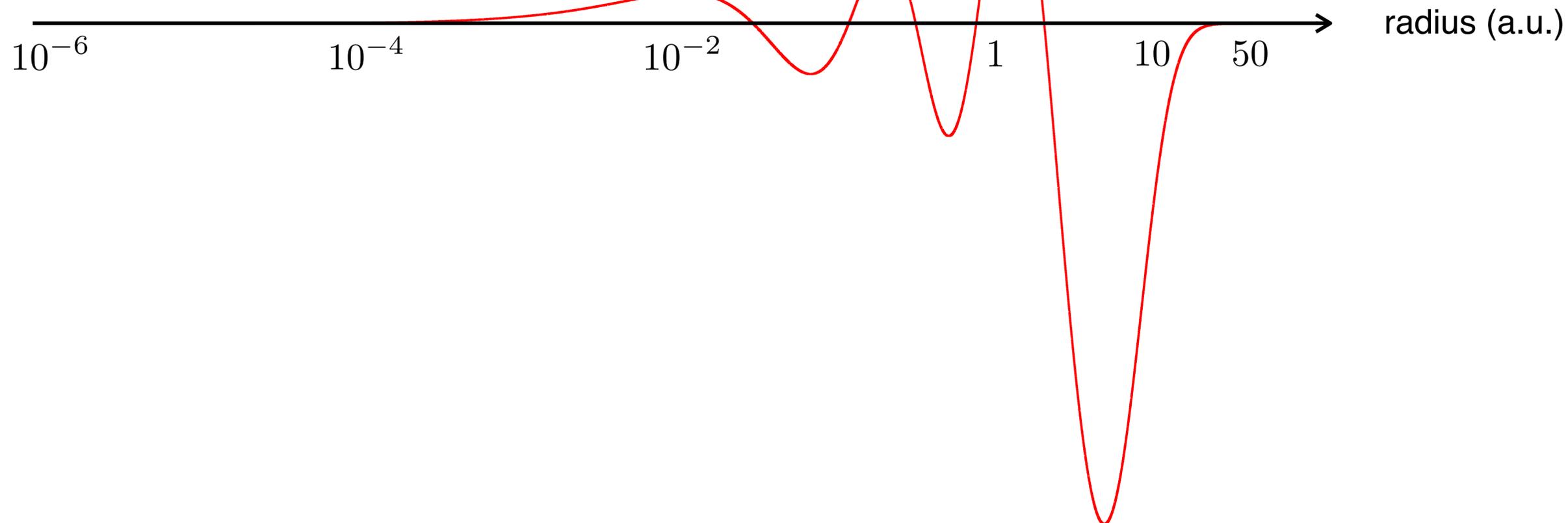
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Upper radial component, Cs 6s:

0.5% uncertainty

Dzuba, Flambaum, Ginges, PRD (2002); Flambaum, Ginges, PRA (2005)

Porsev, Bely, Derevianko, PRL (2009); Dzuba, Berengut, Flambaum, Roberts, PRL (2012)

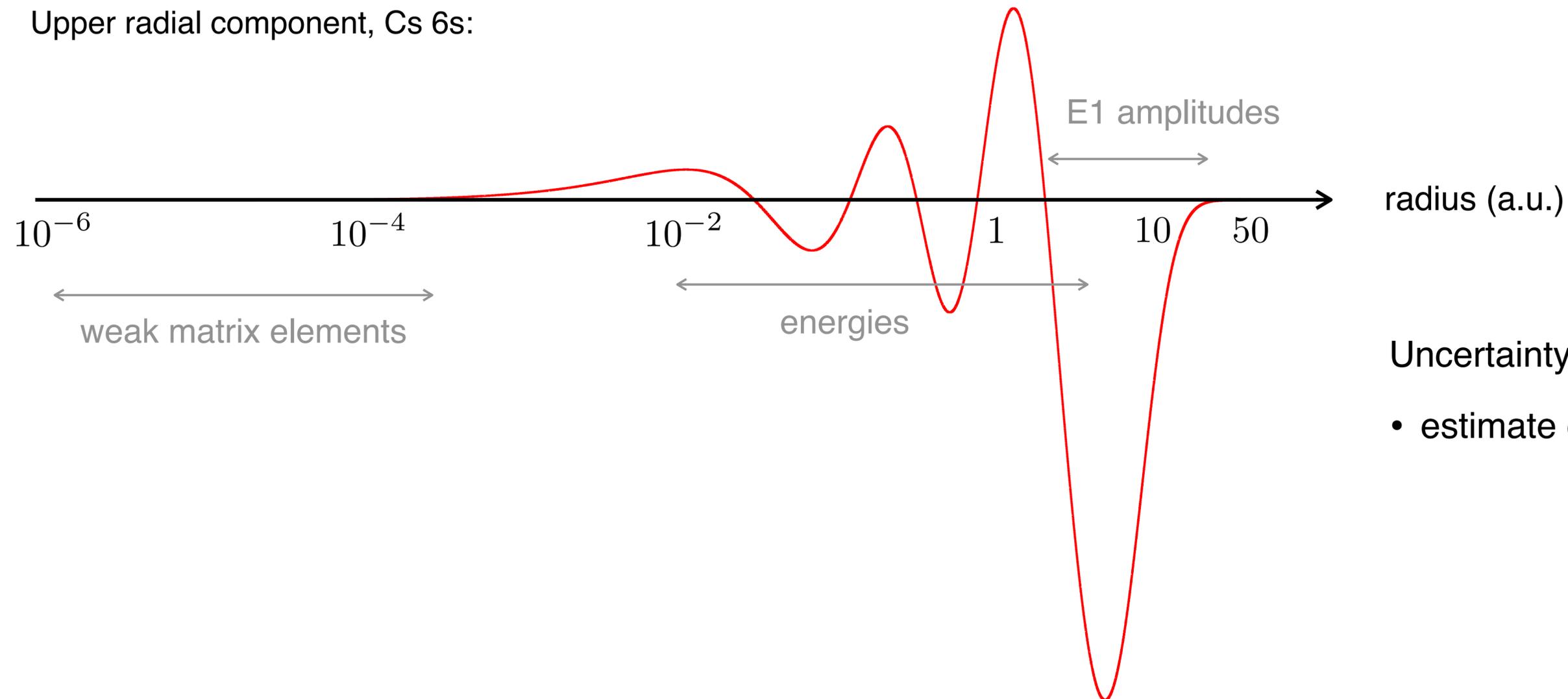


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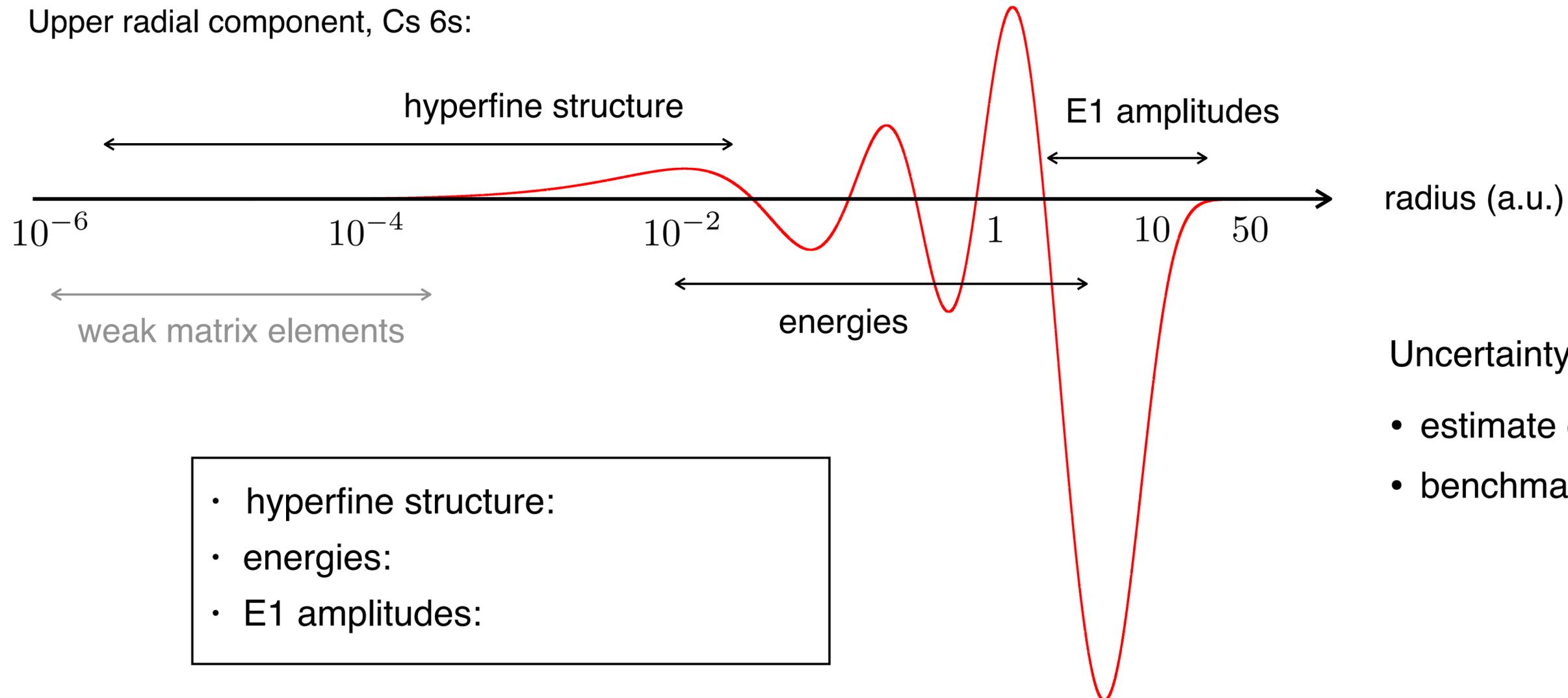
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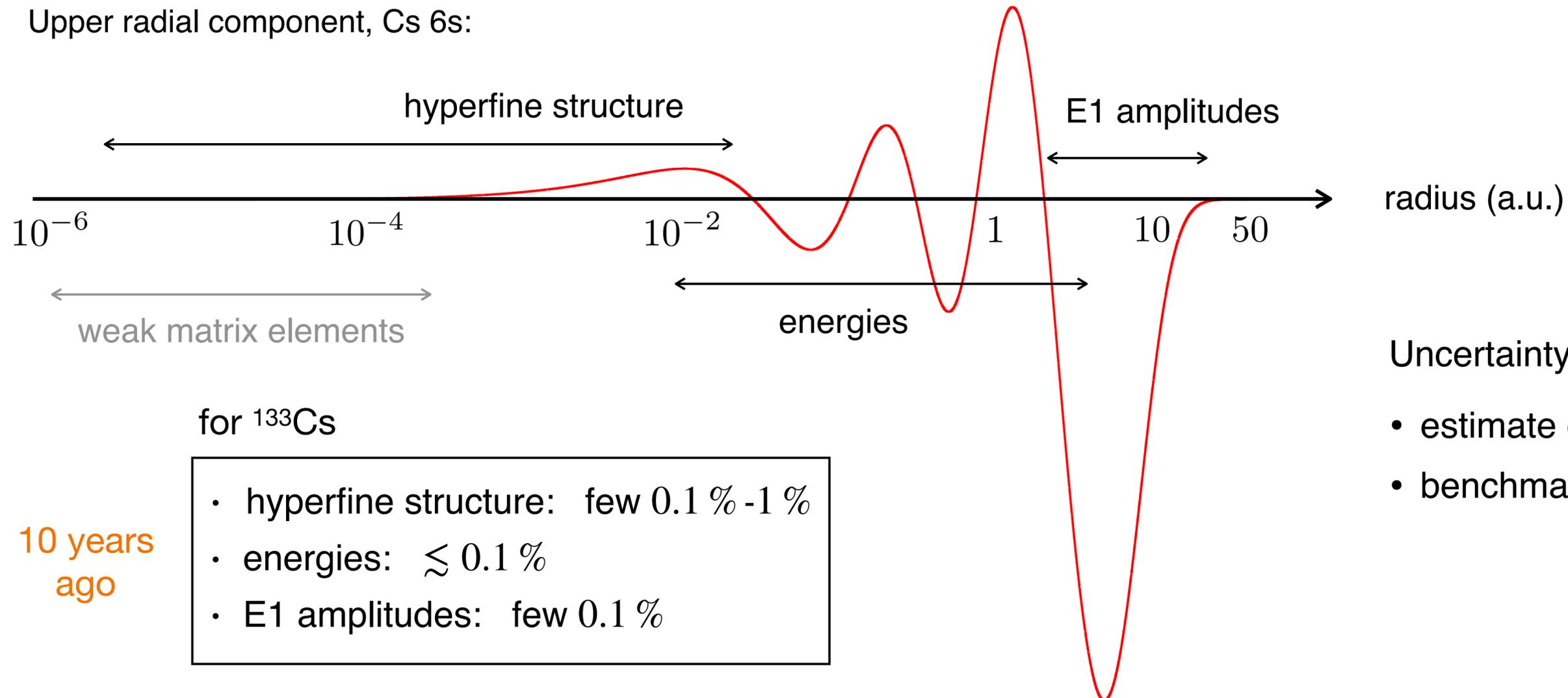
- hyperfine structure:
- energies:
- E1 amplitudes:

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Upper radial component, Cs 6s:



for ^{133}Cs

- hyperfine structure: few 0.1 % - 1 %
- energies: $\lesssim 0.1 \%$
- E1 amplitudes: few 0.1 %

10 years ago

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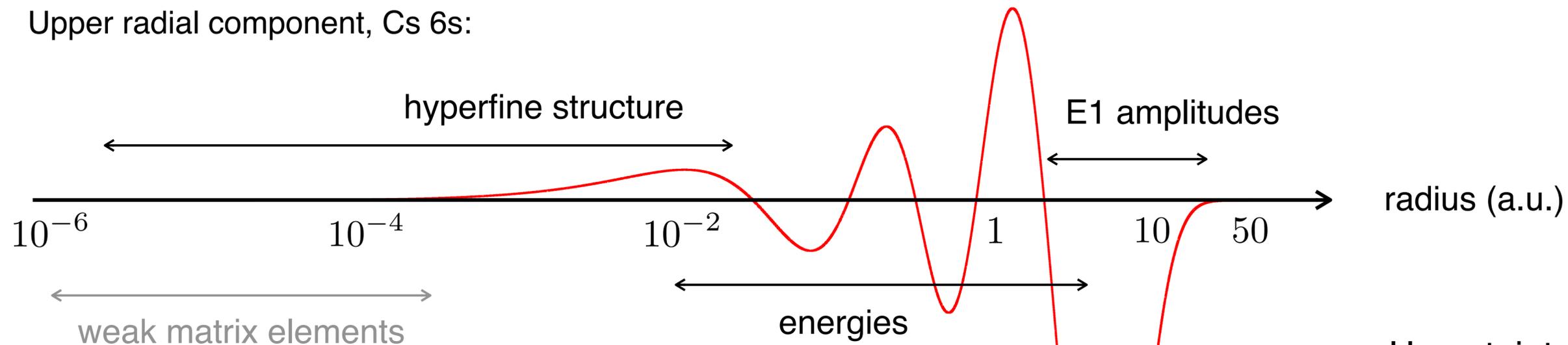
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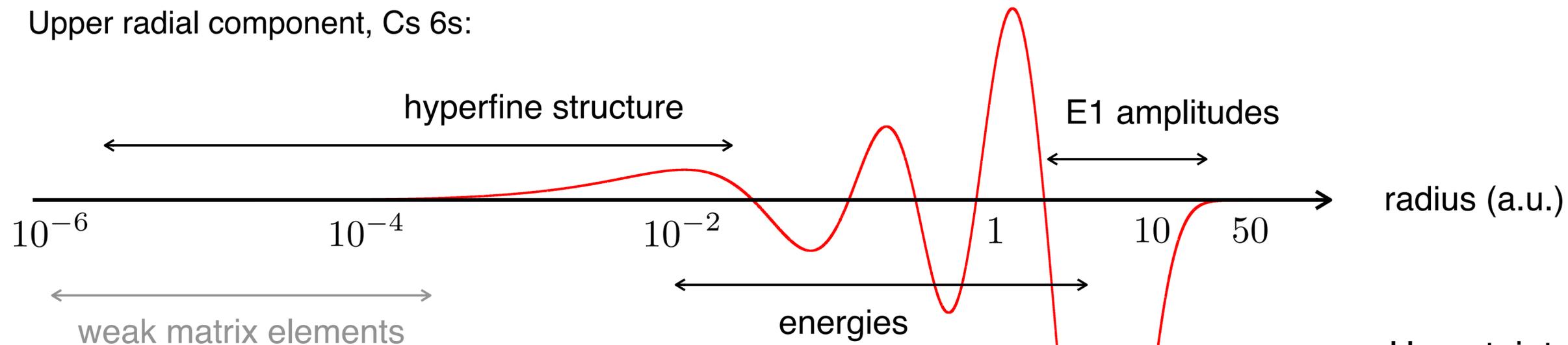
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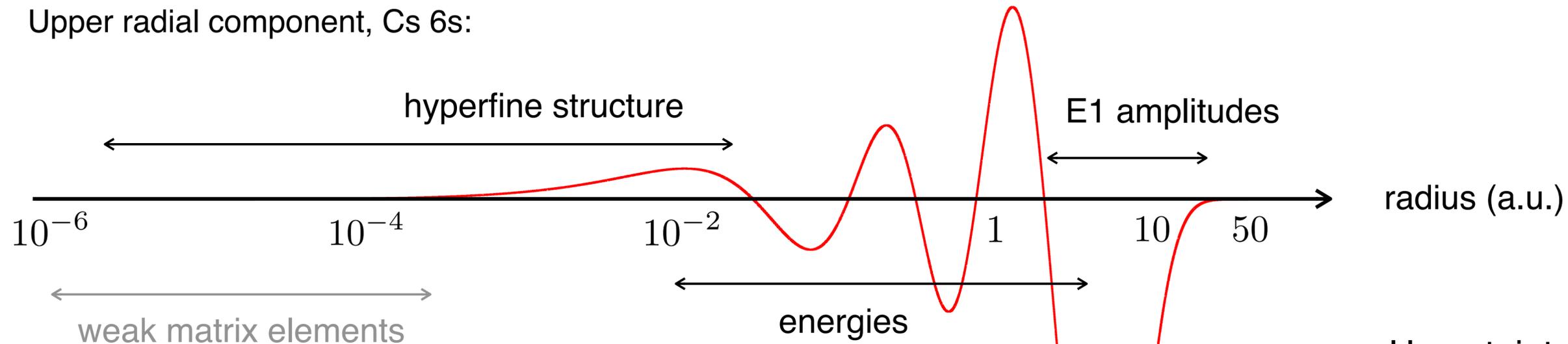
🤔 What don't we understand about the wave functions in the nuclear region?

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💡 It is rather the modelling of the nuclear magnetization distribution!!

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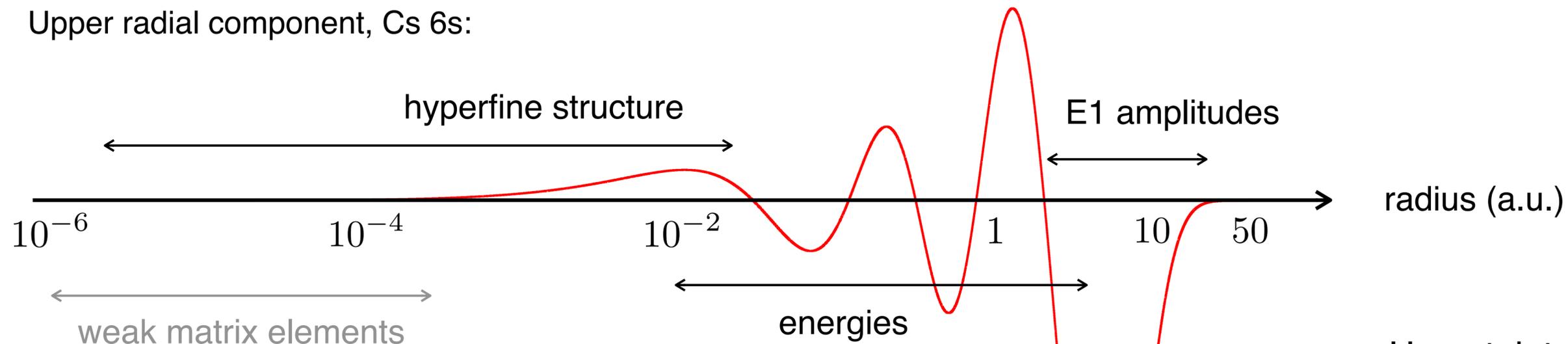
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Now

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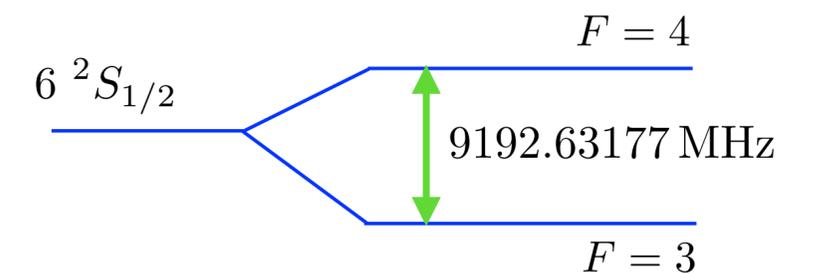
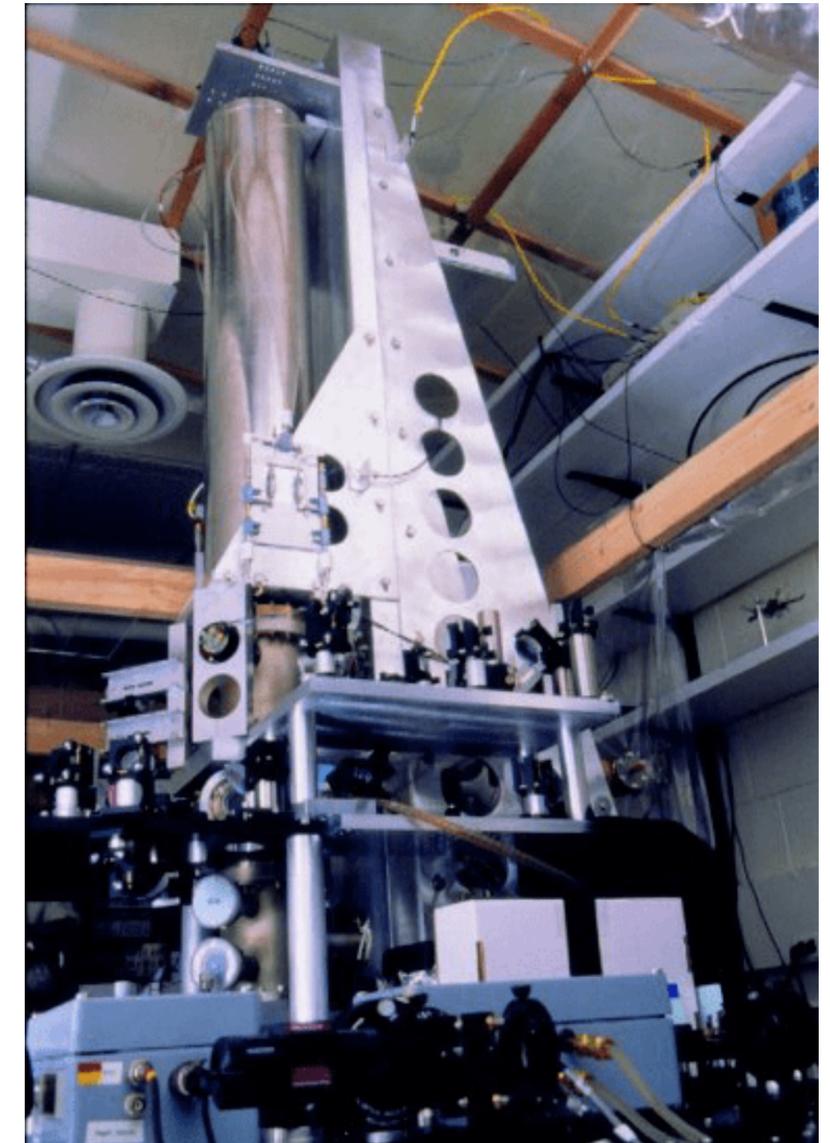
Hyperfine structure and Bohr-Weisskopf effect

Interaction
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← radial distribution of nuclear magnetic moment

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NIST-F2 Atomic clock



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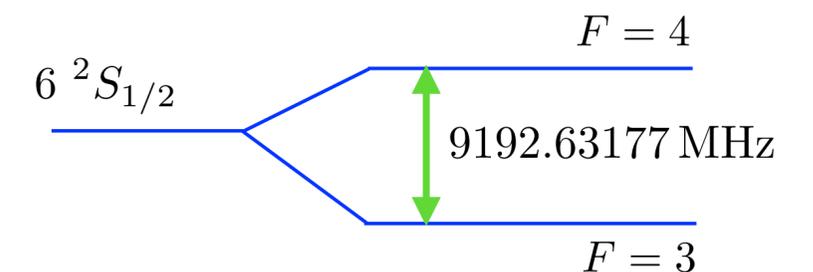
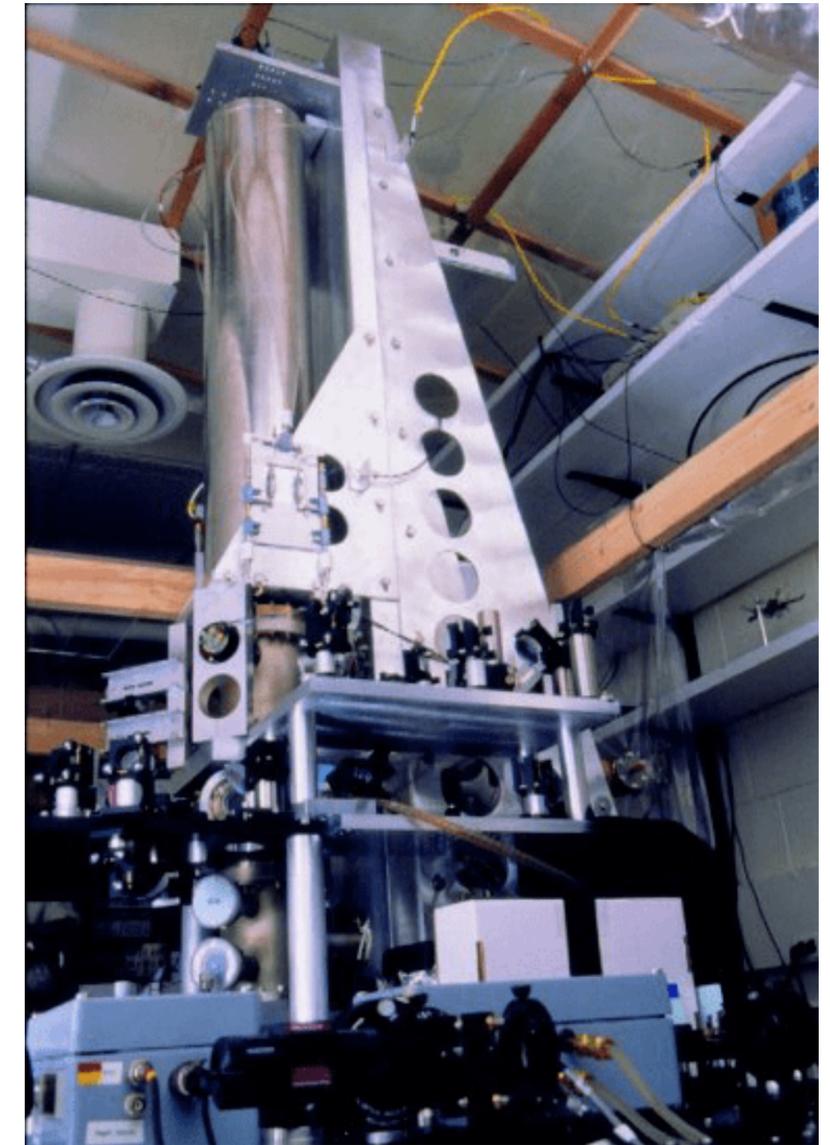
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finite nuclear charge distribution included here

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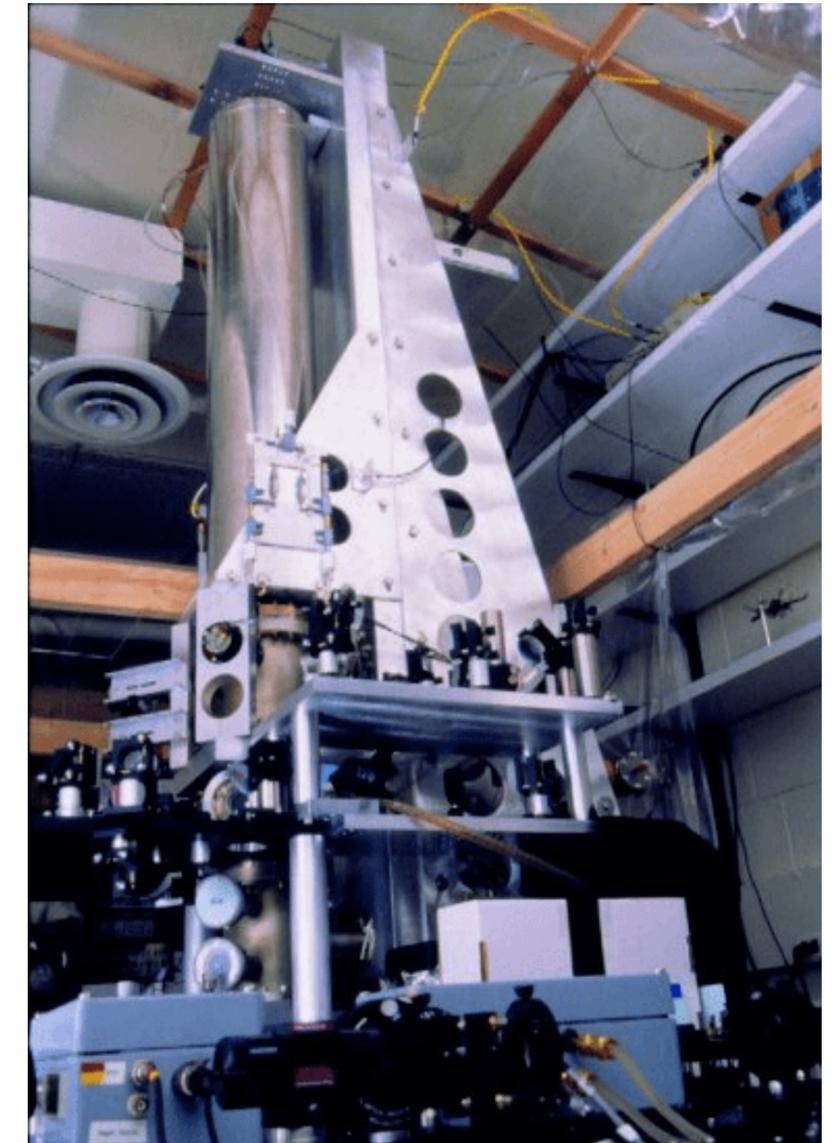
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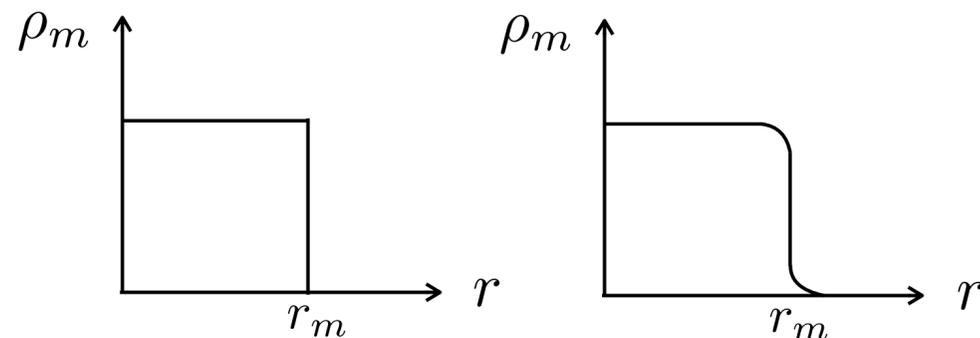
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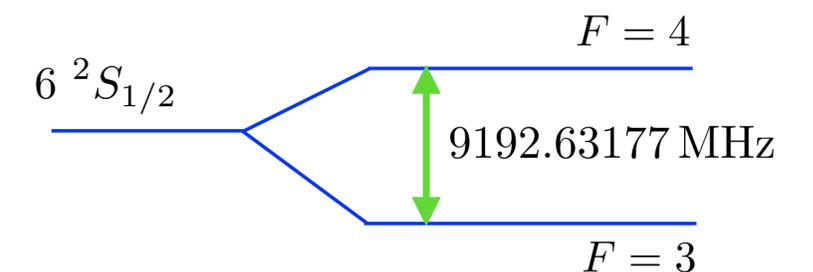
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Standard ways to model $F(r)$ for testing precision theory, until recently:



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⇒ nuclear single-particle model



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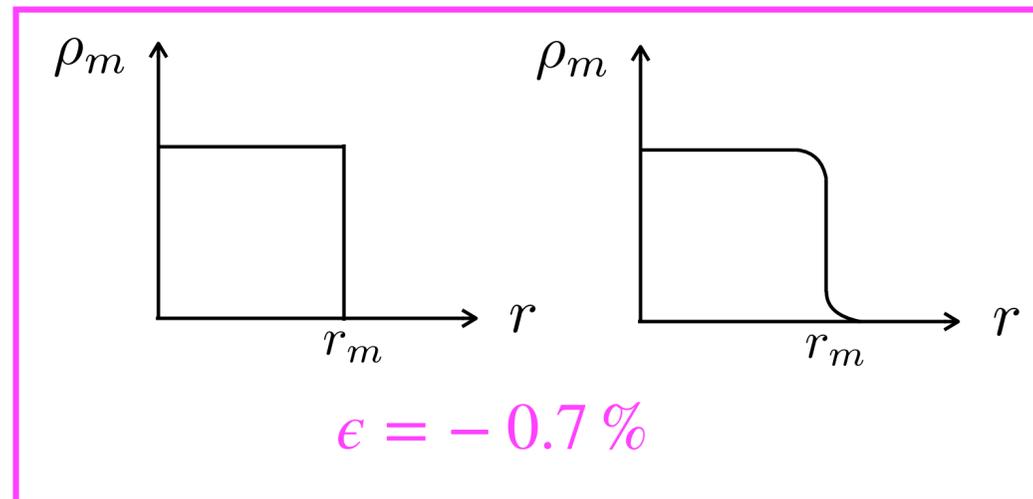
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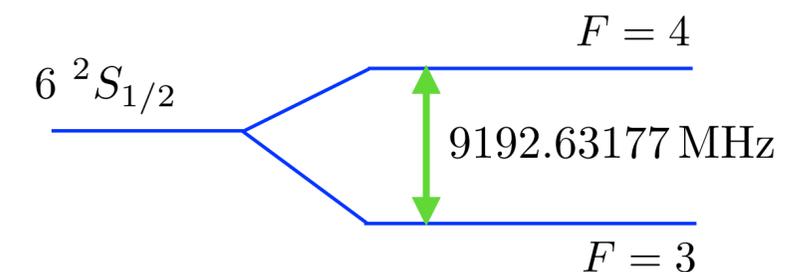
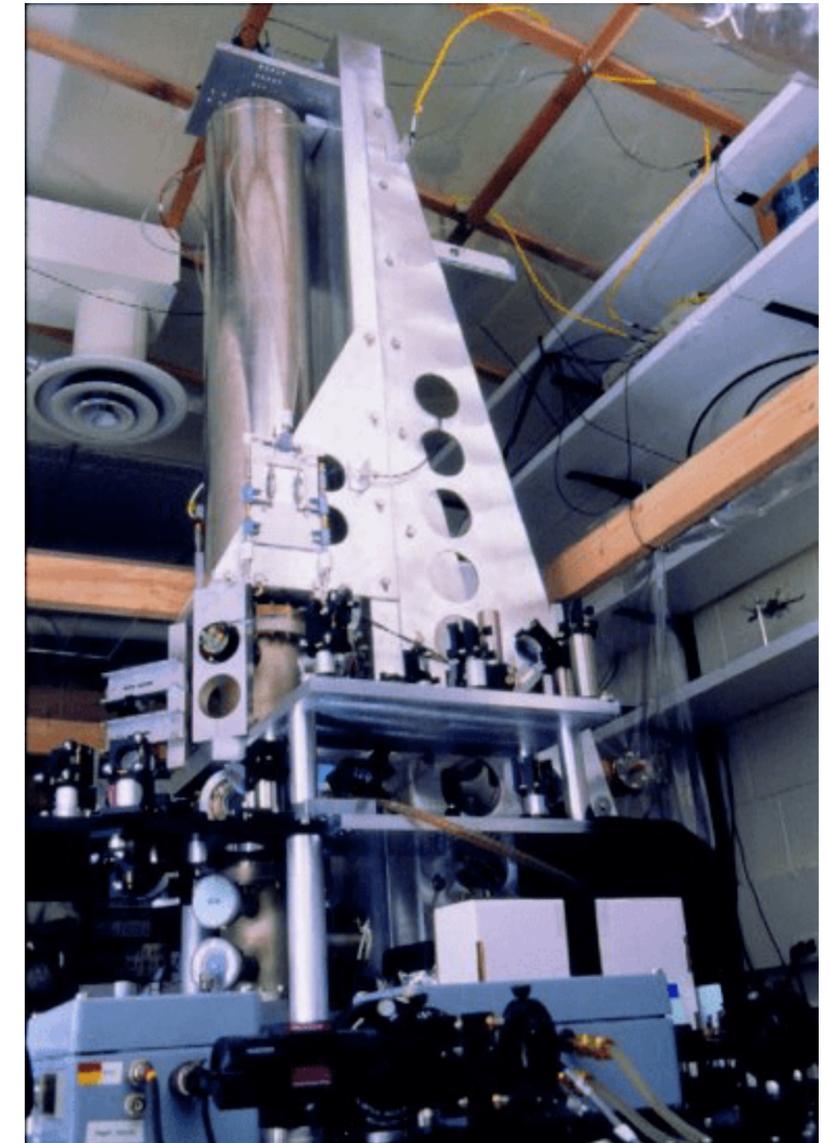
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for ^{133}Cs 6S

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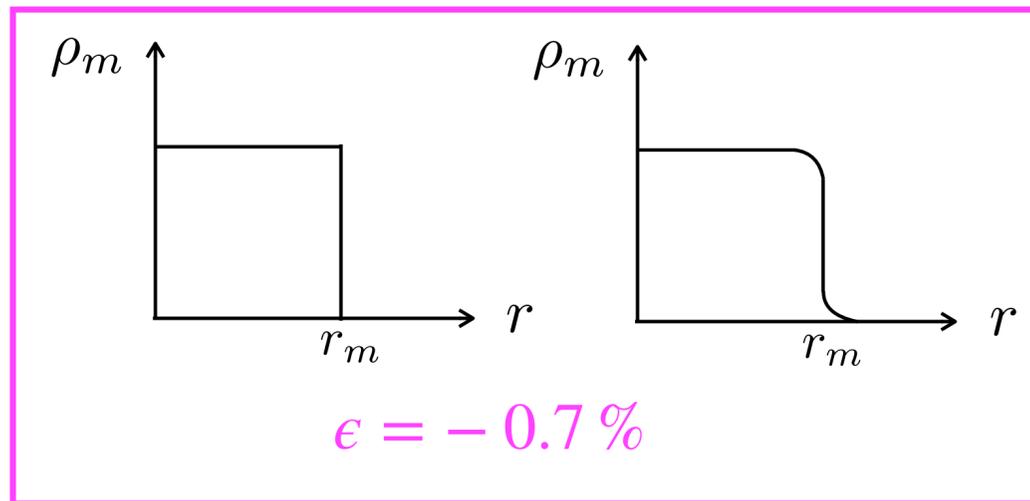
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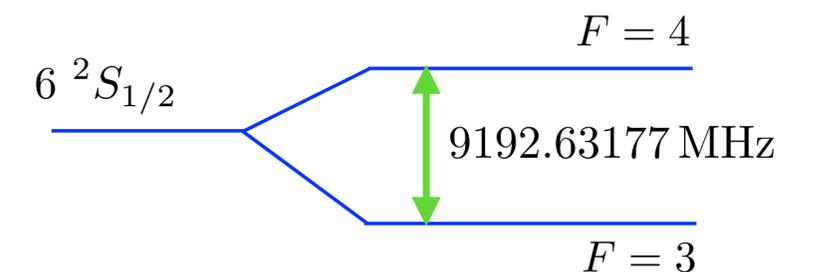
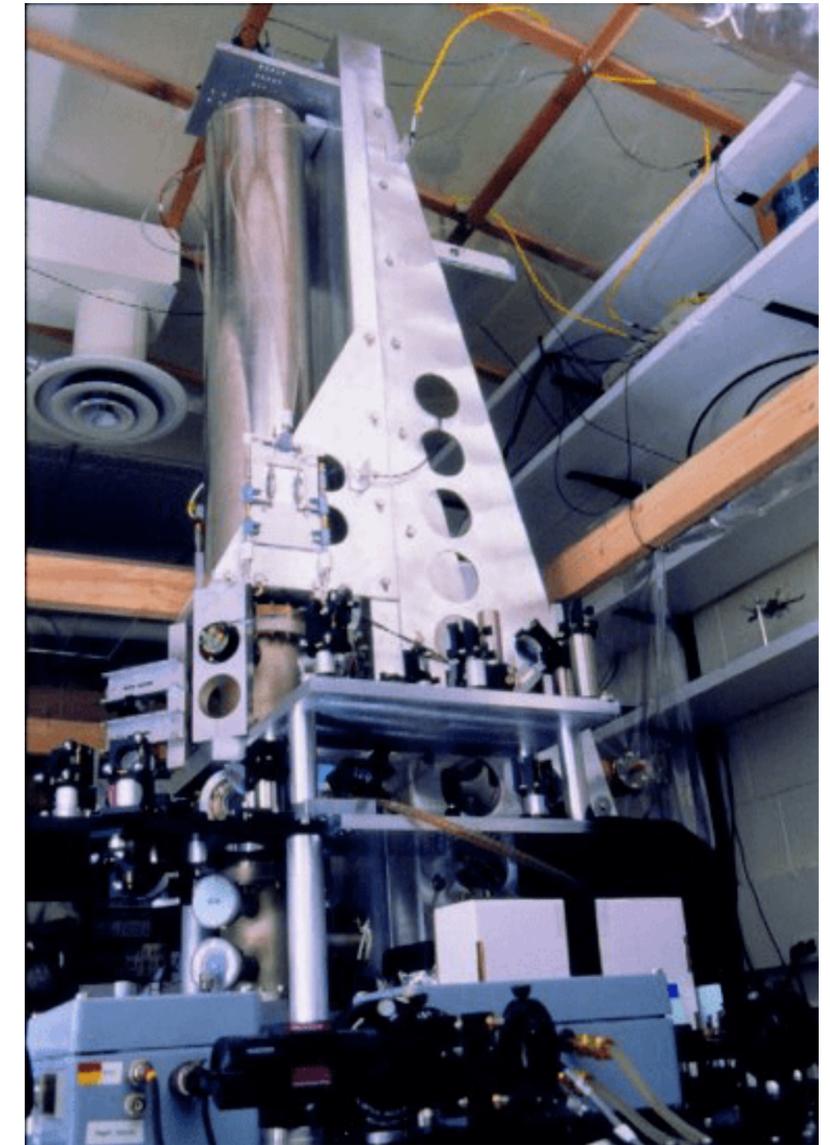
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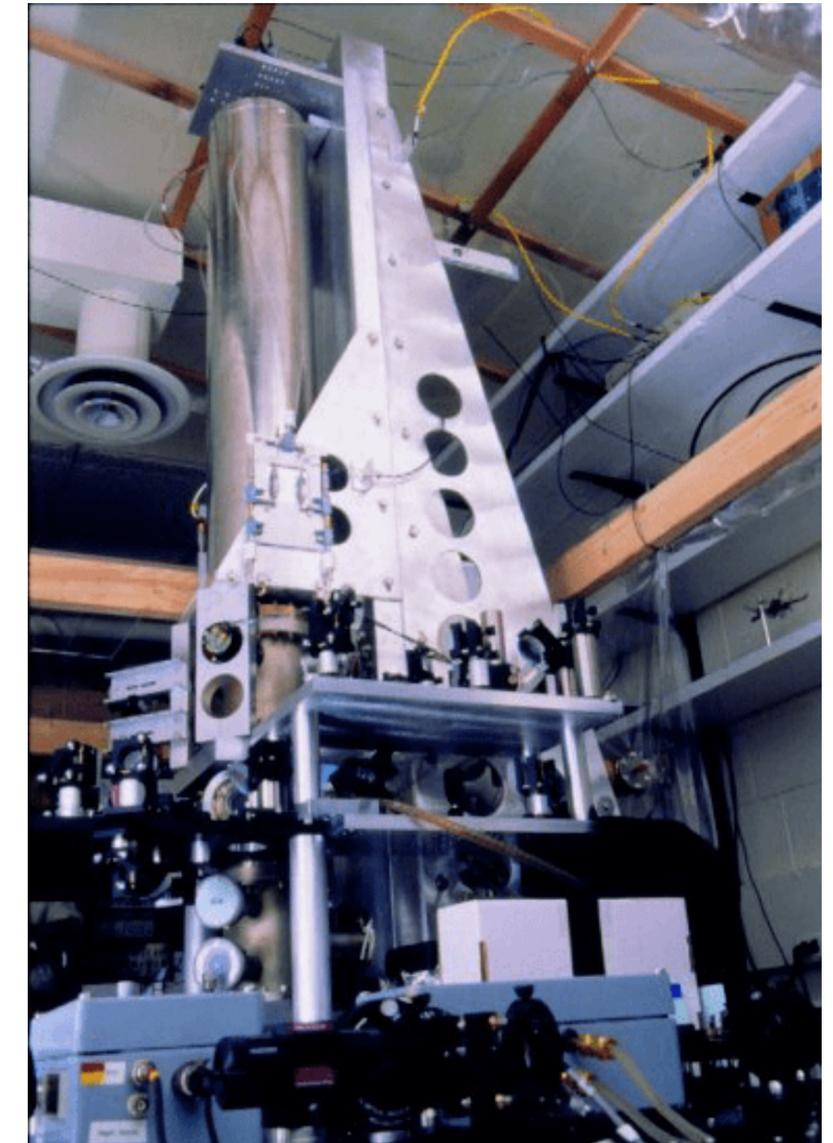
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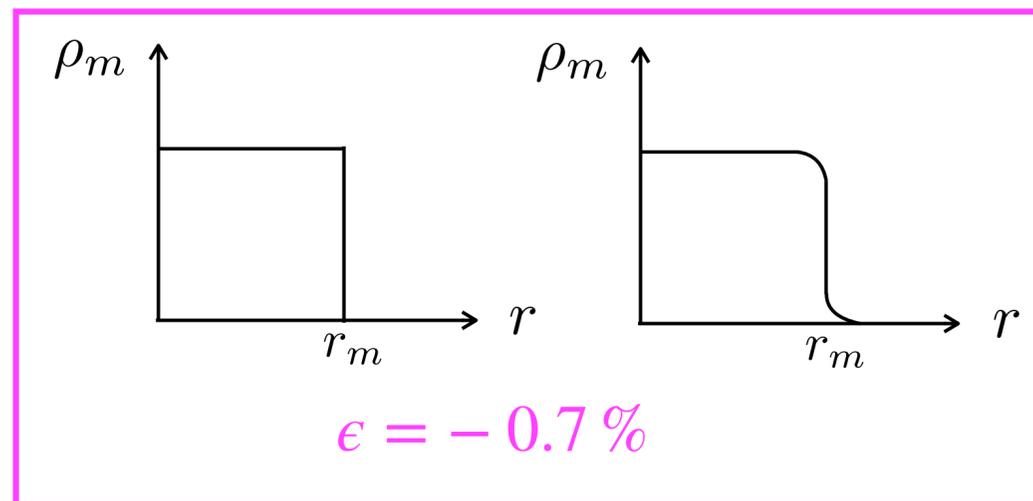
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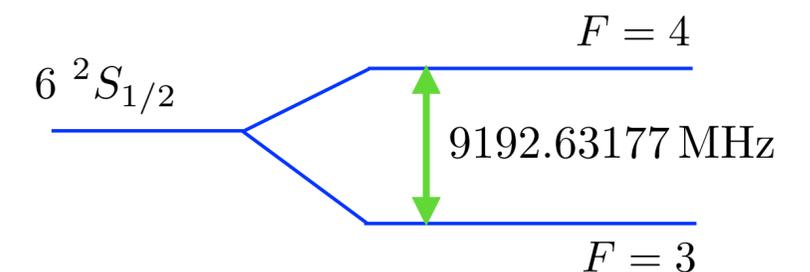


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for ^{133}Cs 6S, 0.5% difference in A ! Nuclear theory? Not yet



BW effect: from H-like ions

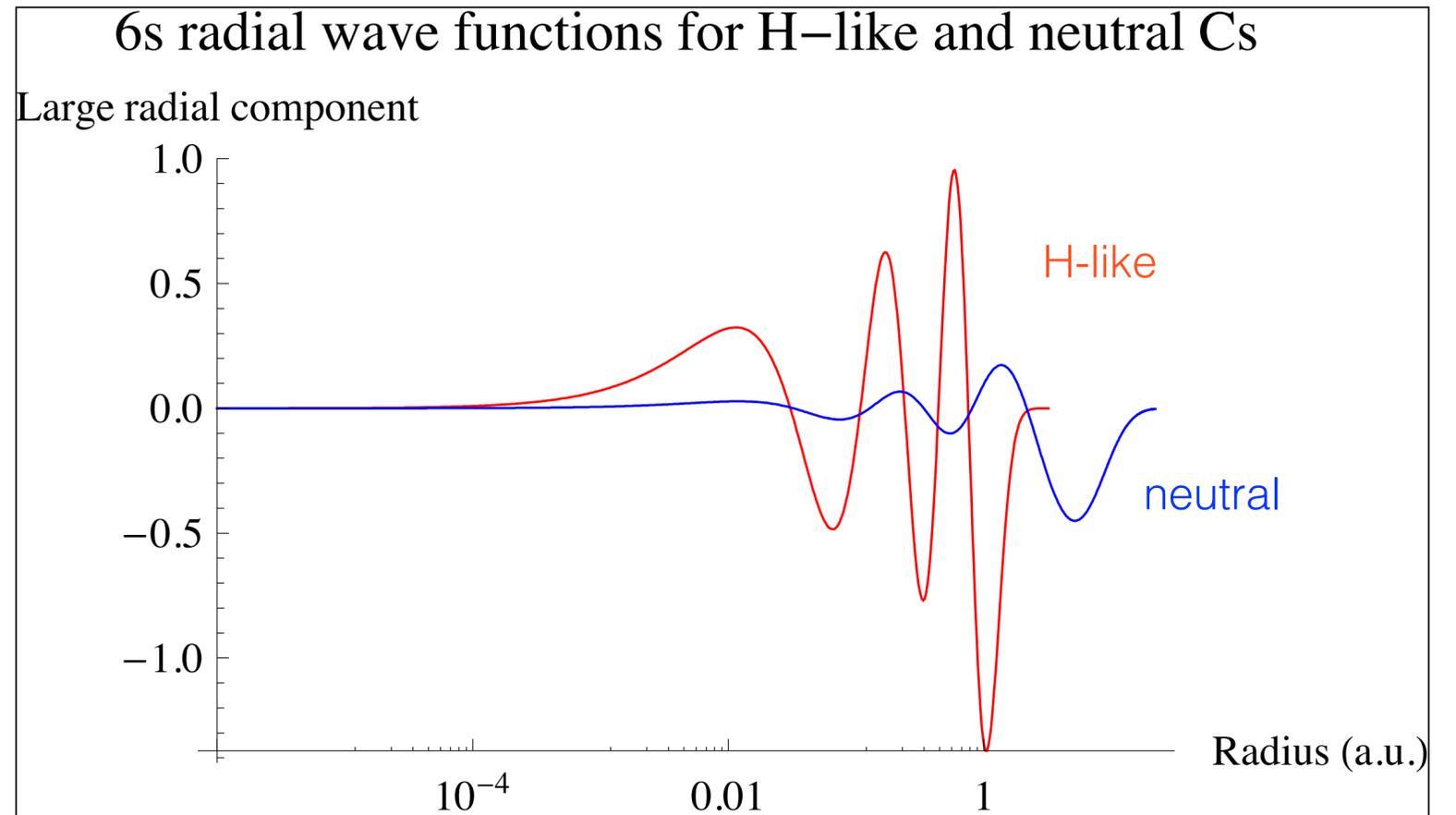
BW effect measured in several H-like ions, e.g., $^{203,205}\text{Tl}$, $^{208,209}\text{Bi}$, with $\sim 1\%$ uncertainty [MPIK; GSI Darmstadt]

$$A_{\text{exp}}^{1s} = A_0^{1s}(1 + \epsilon^{1s}) + A_{\text{QED}}^{1s}$$

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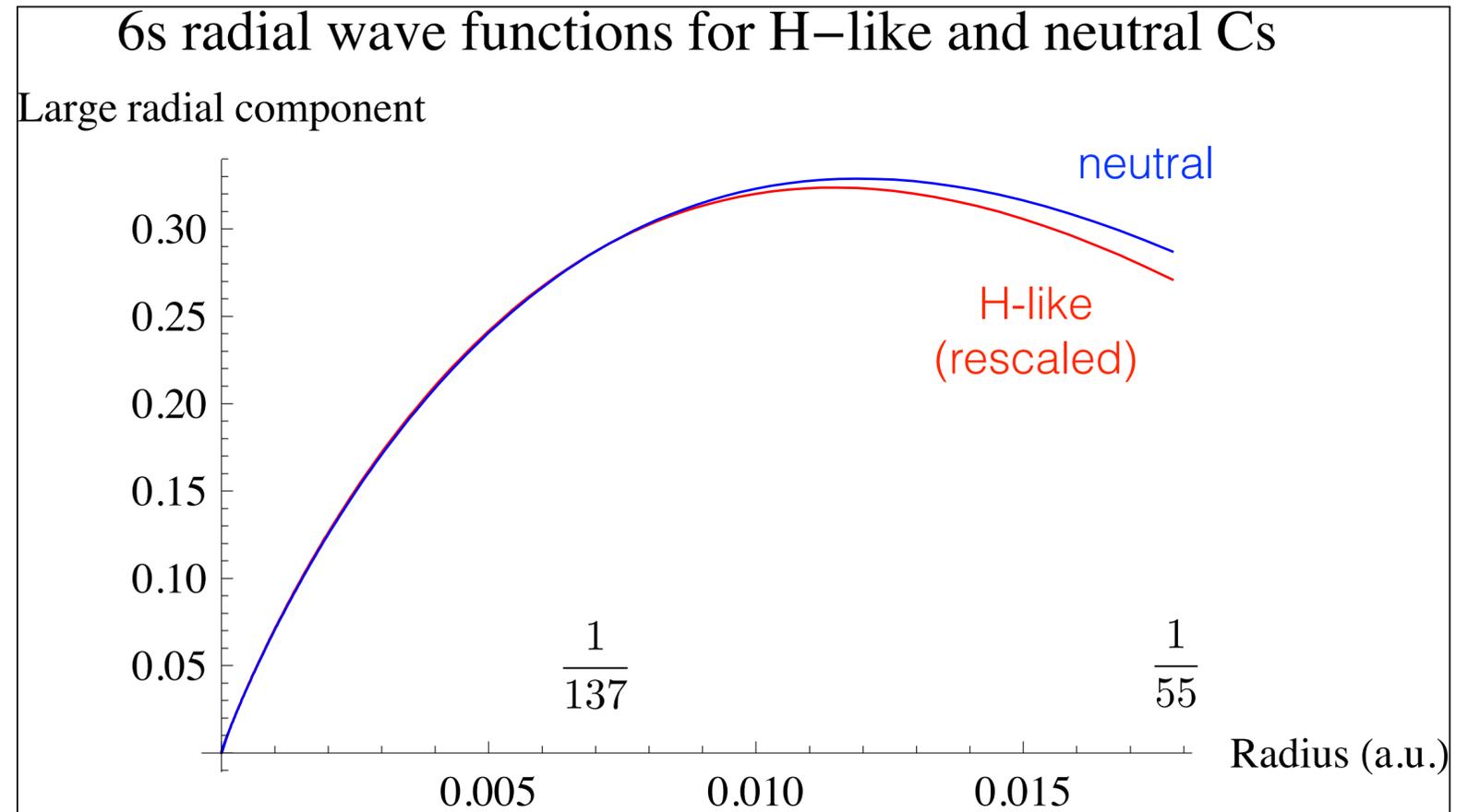
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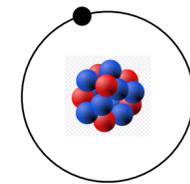
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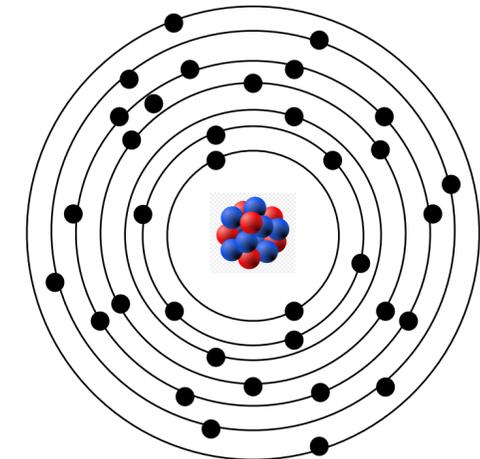
May be used to find BW effect in many-electron atoms!

$$A_{\text{exp}} = A_0(1 + x_{\text{scr}} \epsilon^{1s}) + A_{\text{QED}}$$

↑
electronic screening factor,
Independent of nuclear model!



$\epsilon_{\text{H-like}}$



$$\epsilon_{\text{atom}} = x_{\text{scr}} \epsilon_{\text{H-like}}$$

Ranclaud, Honours thesis (2020)

Roberts, Ranclaud, Ginges, PRA (2022)

Skripnikov, J. Chem. Phys. (2020) — for molecules; and observed!

Wilkins *et al.*, Science (2025)

BW effect: from H-like ions

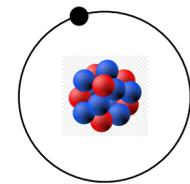
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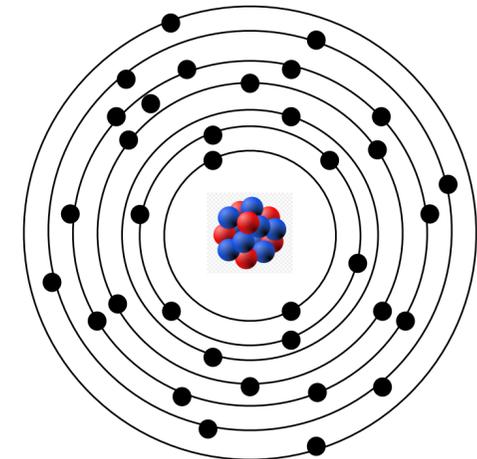
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$\epsilon_{\text{H-like}}$



$$\epsilon_{\text{atom}} = x_{\text{scr}} \epsilon_{\text{H-like}}$$

Nuclear structure uncertainty entirely removed from atomic calculations!

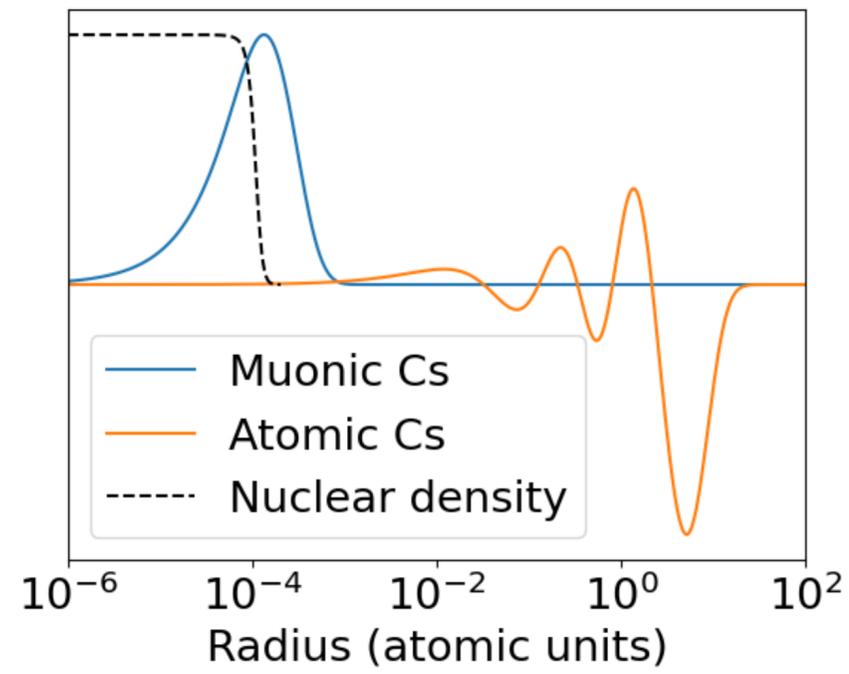
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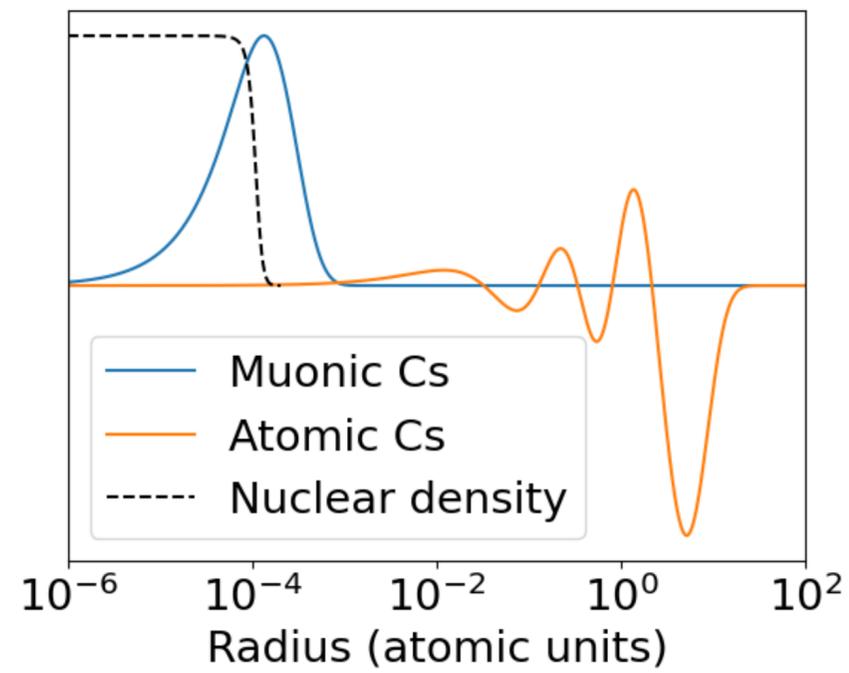
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BW effect: from muonic atoms

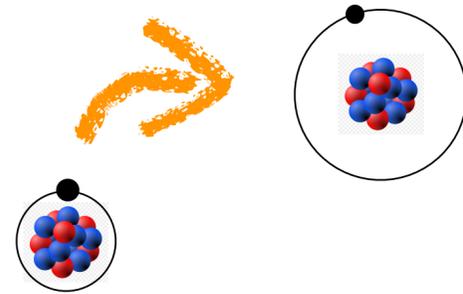
BW data for muonic Cs!



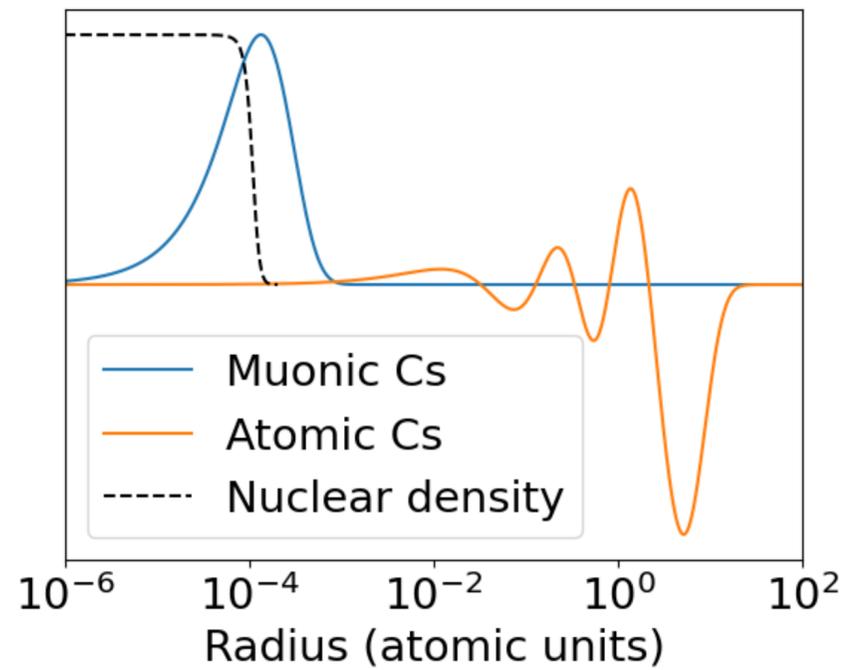
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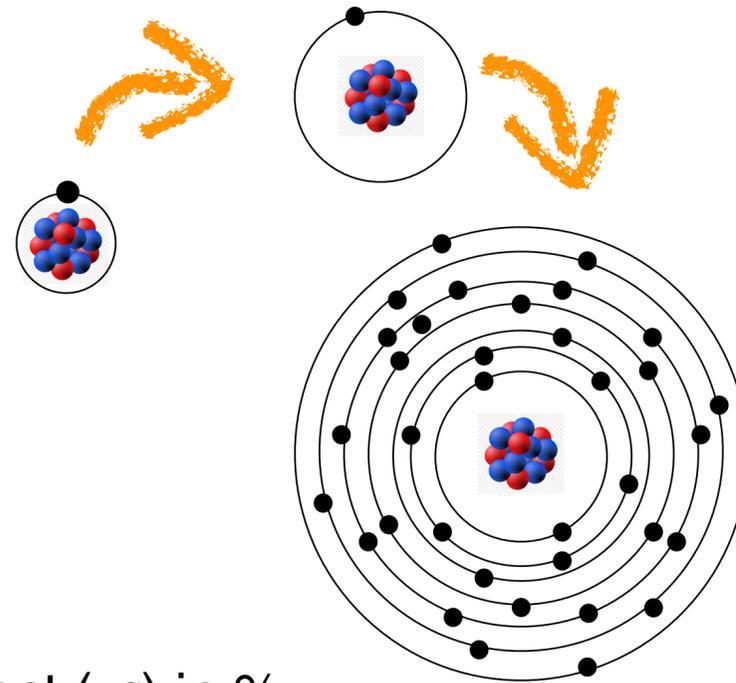
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BW effect: from muonic atoms



BW data for muonic Cs!



Empirically-deduced BW effect ($-\epsilon$) in %

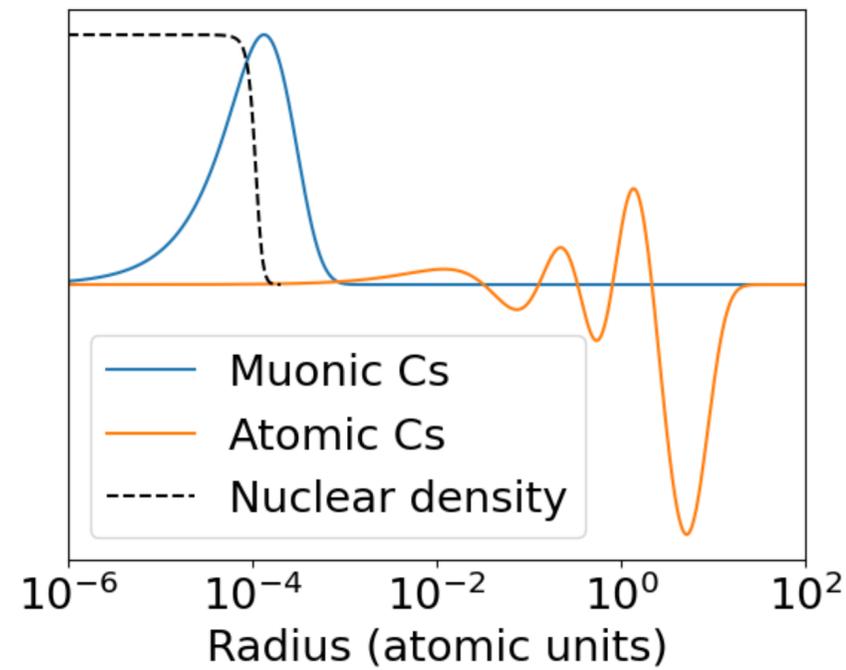
	μ -atoms	H-like ions		Atoms
	μ exp	μ exp	H-like exp	μ exp
^{133}Cs	18(14)	0.23(17)	...	0.24(18)
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^{209}Bi	28.8(3.9)	0.98(14)	1.03(5)	

c.f. Cs atom — SP: 0.21% ; SP(WS): 0.19(14)% ; uniform: 0.7%

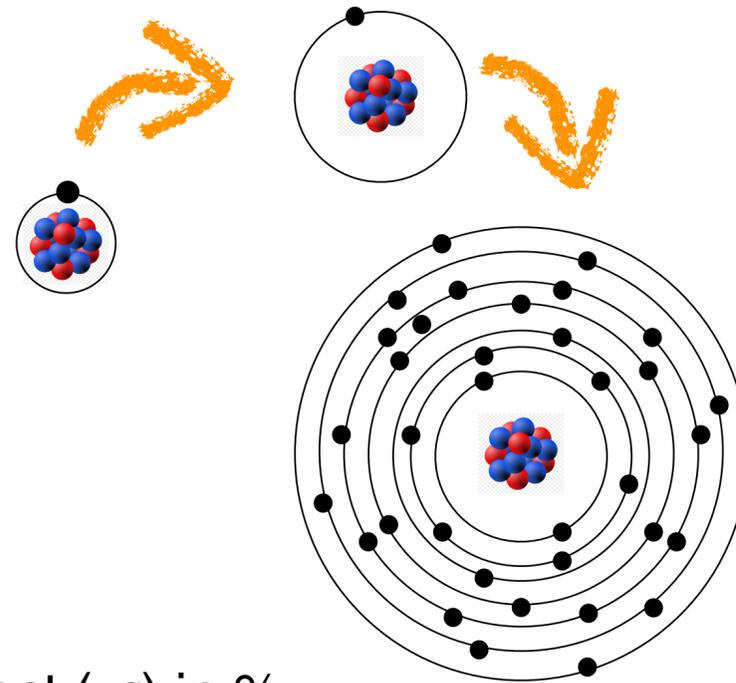
Elizarov, Shabaev, Oreshkina, Tupitsyn, Stoecklker., Opt. Spectrosc. (2006)

Sanamyan, Roberts, Ginges, PRL (2023)

BW effect: from muonic atoms



BW data for muonic Cs!



What about nuclear polarization?

Empirically-deduced BW effect ($-\epsilon$) in %

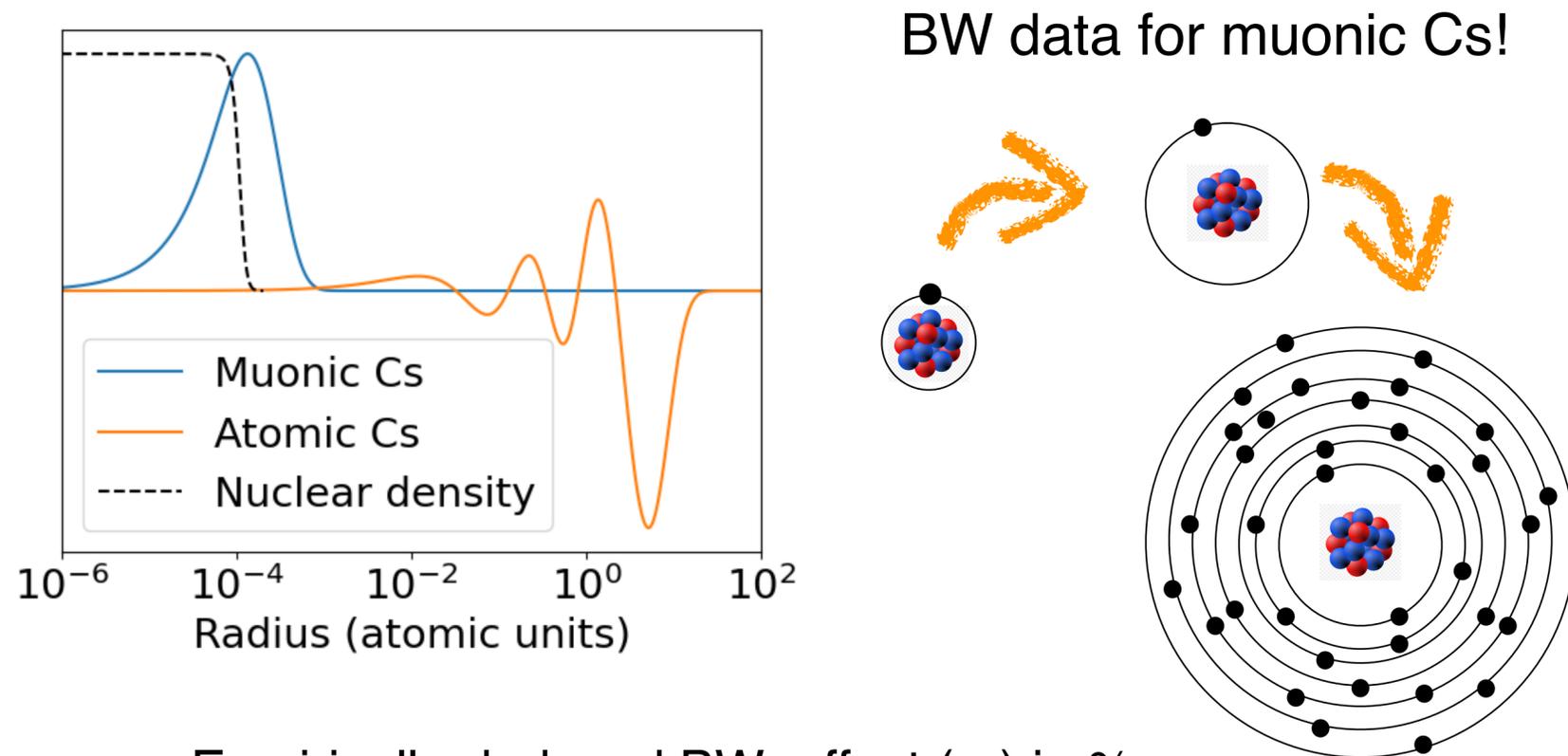
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BW effect: from muonic atoms



Empirically-deduced BW effect (-ε) in %

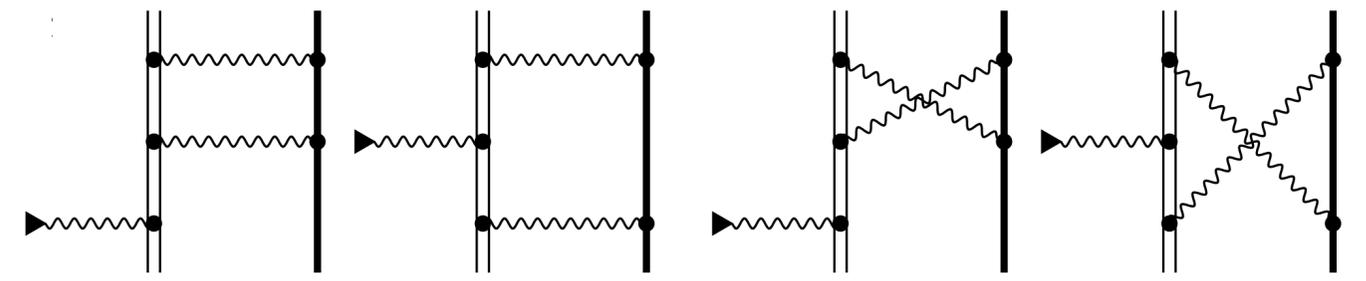
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c.f. Cs atom — SP: 0.21% ; SP(WS): 0.19(14)% ; uniform: 0.7%

What about nuclear polarization?

From H-like and muonic-atom experiments with atomic theory:

$$A_{\text{NP}}^{\text{exp}} = A_{\text{exp}} - A_0 - A_{\text{QED}} - A_{\text{BW}} \quad \leftarrow \text{from H-like}$$



Semi-empirical: $A_{\text{NP}} < 0.1 A_{\text{BW}}$

Semi-analytical: $A_{\text{NP}} \sim 0.001 A_{\text{BW}}$

Hopefully this may stimulate new experiments!

Elizarov, Shabaev, Oreshkina, Tupitsyn, Stoeckler., Opt. Spectrosc. (2006)

Sanamyan, Roberts, Ginges, PRL (2023)

Vandeleur, Sanamyan, Smits, Valuev, Oreshkina, Ginges, PRL (2025)

Take-home points

For atomic APV and EDMs —

- Significant bottlenecks in interpretation due to large uncertainties in calculations of nuclear symmetries-violating moments:
 - Schiff moment, magnetic quadrupole moment, anapole moment
- Opportunities for exciting cross-disciplinary adventures to provide improved nuclear benchmarks and insight into nuclear structure:
 - Nuclear magnetisation distribution, higher-order (usual) nuclear moments including nuclear octupole moment,...

Key to supporting development of nuclear theory and increasing discovery potential in atomic and molecular experiments

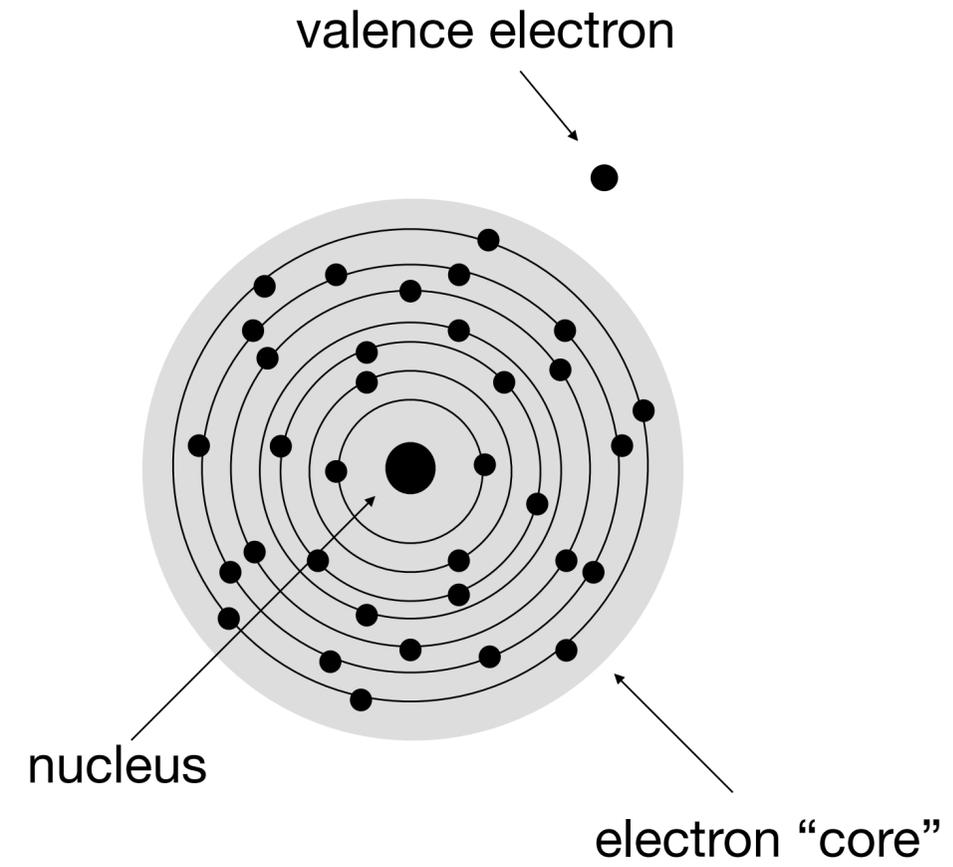
Thank you!

Precision Atomic Theory Group @ UQ



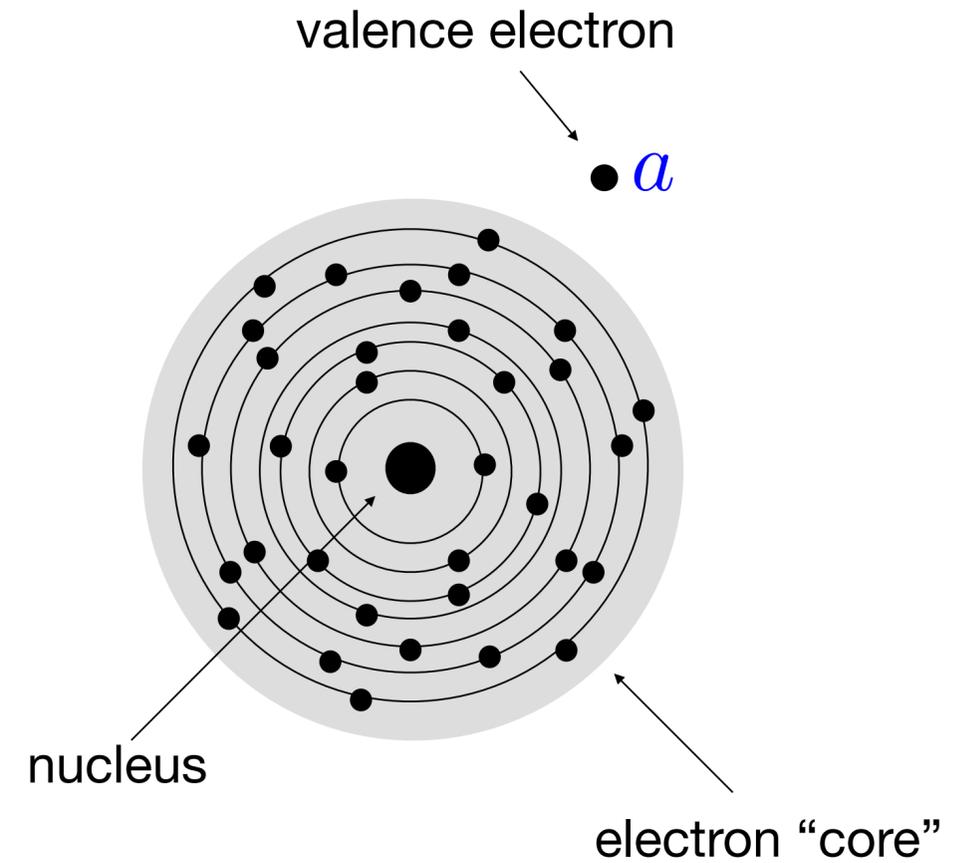
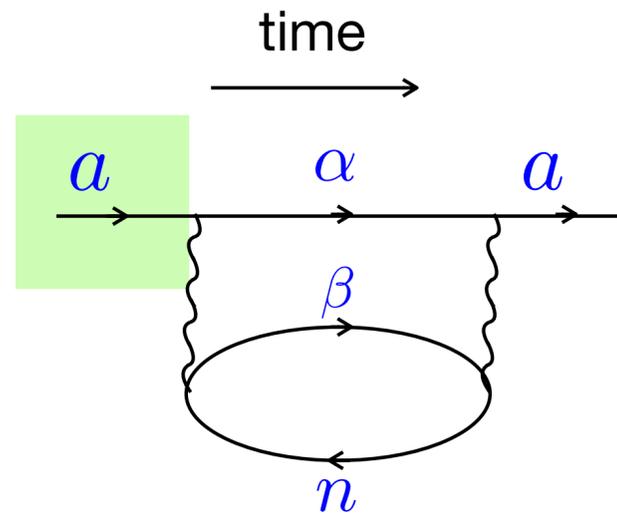
A glimpse of the theory

- Starting point: relativistic Hartree-Fock (RHF): V_{HF}



A glimpse of the theory

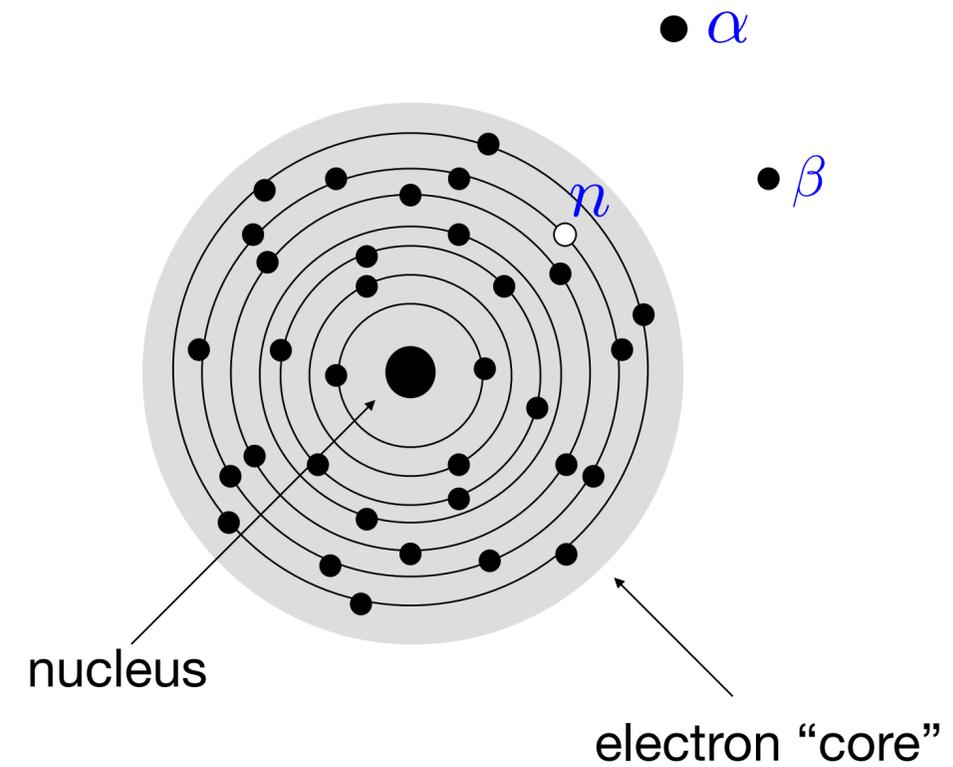
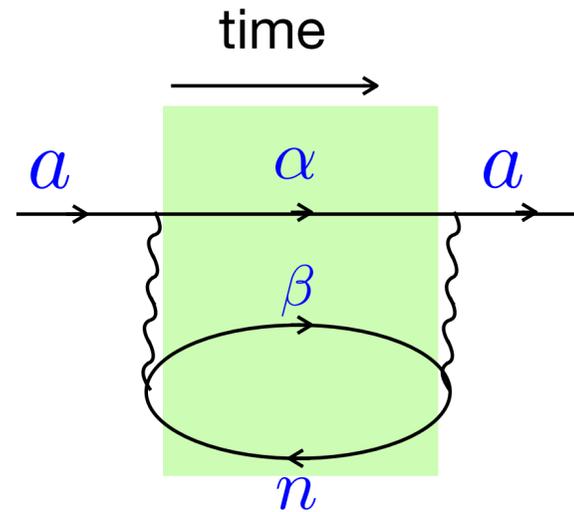
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A glimpse of the theory

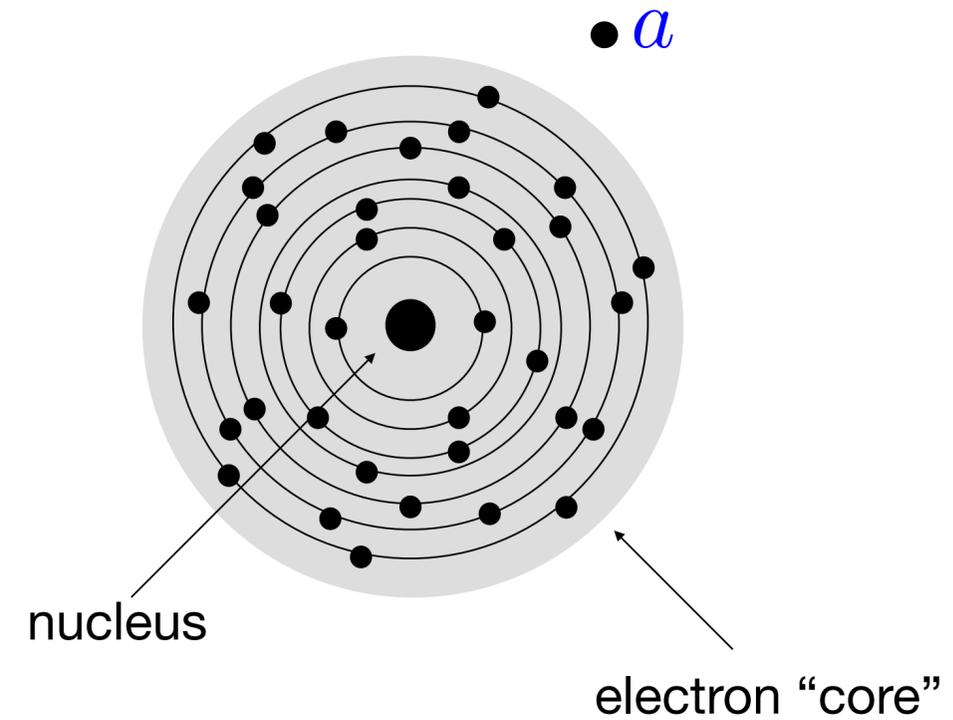
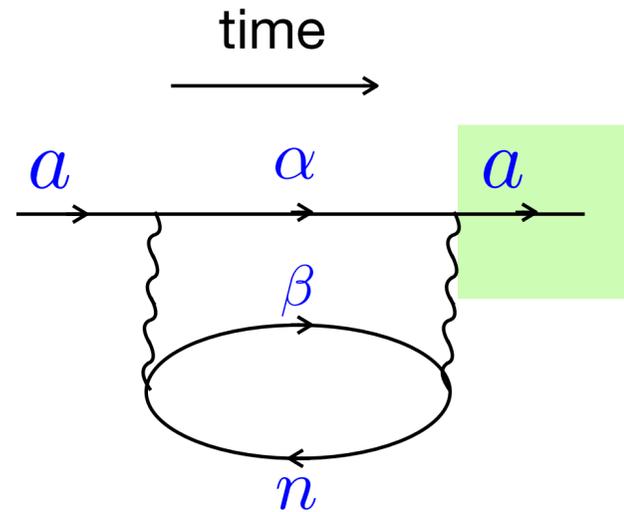
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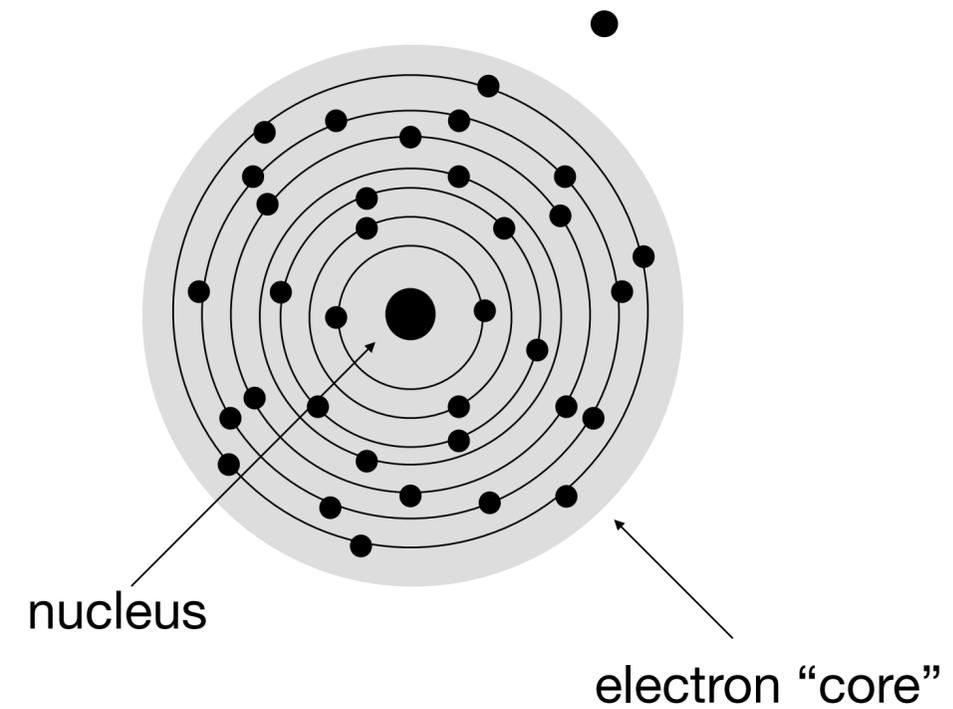
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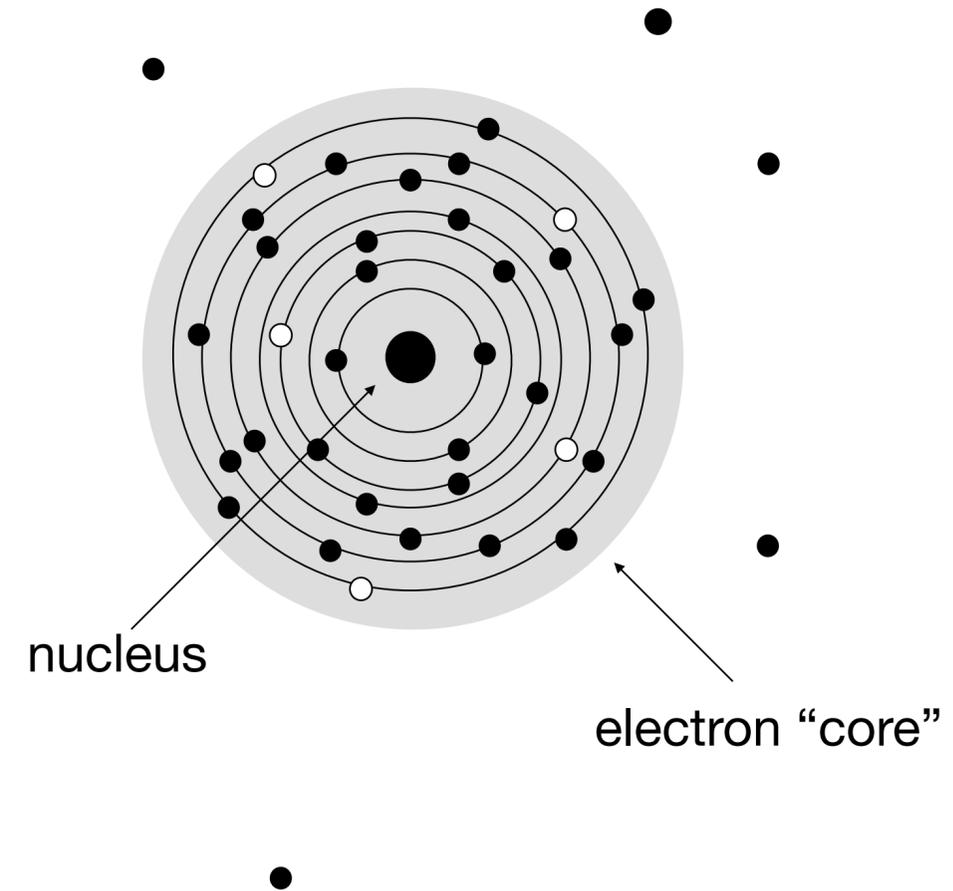
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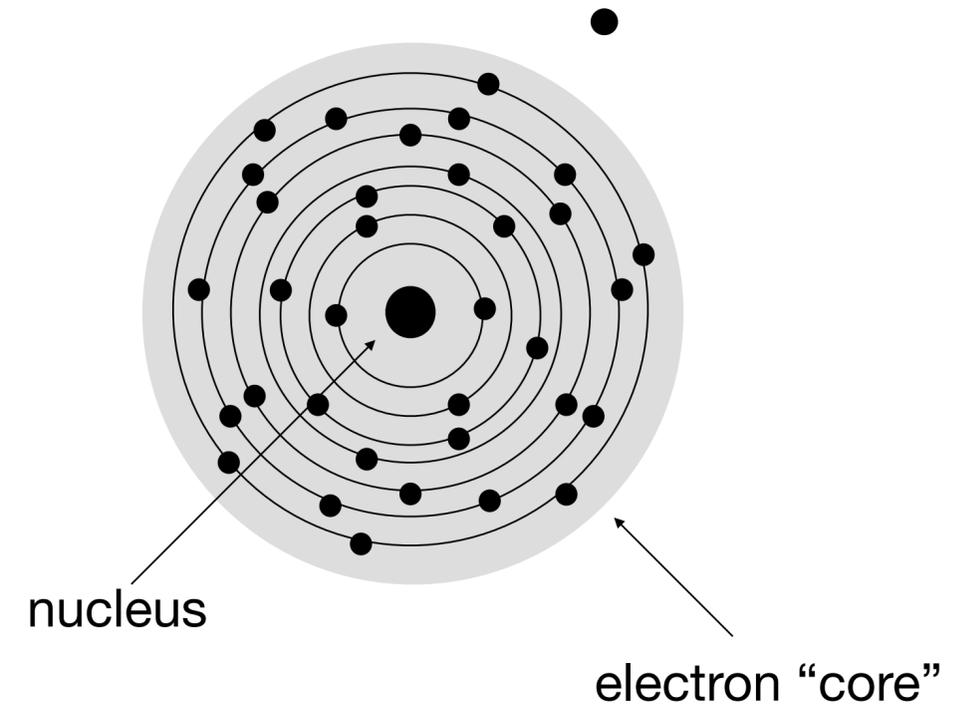
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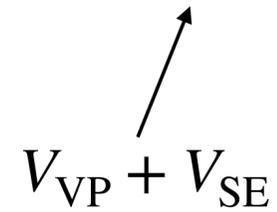
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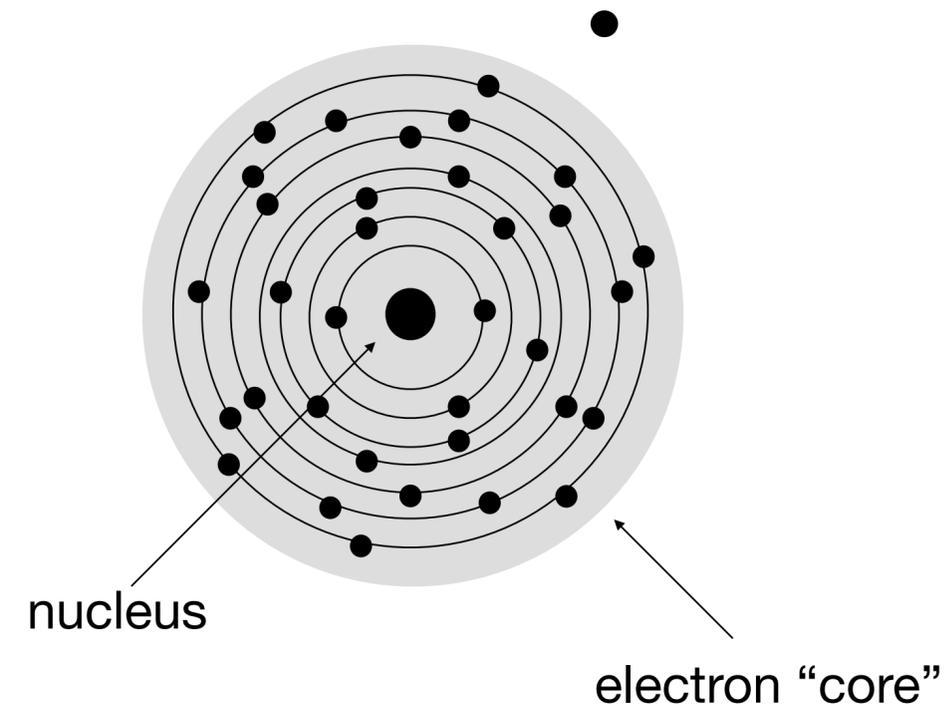
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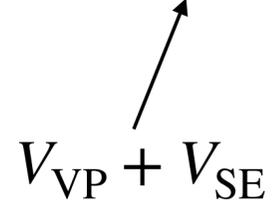
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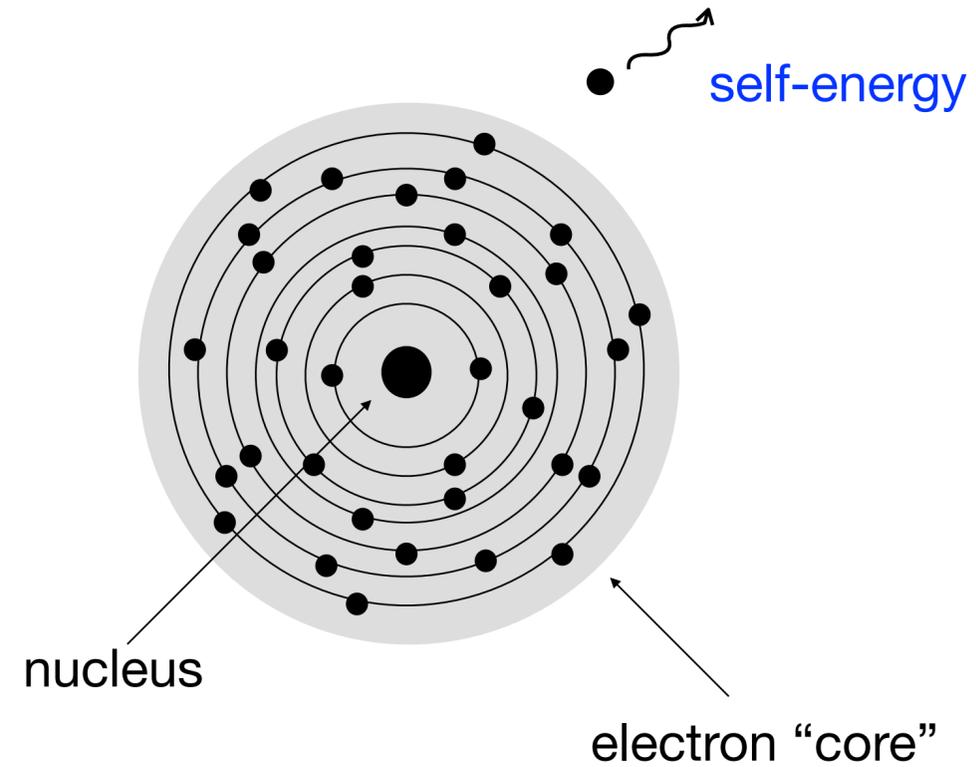
$$V_{\text{VP}} + V_{\text{SE}}$$




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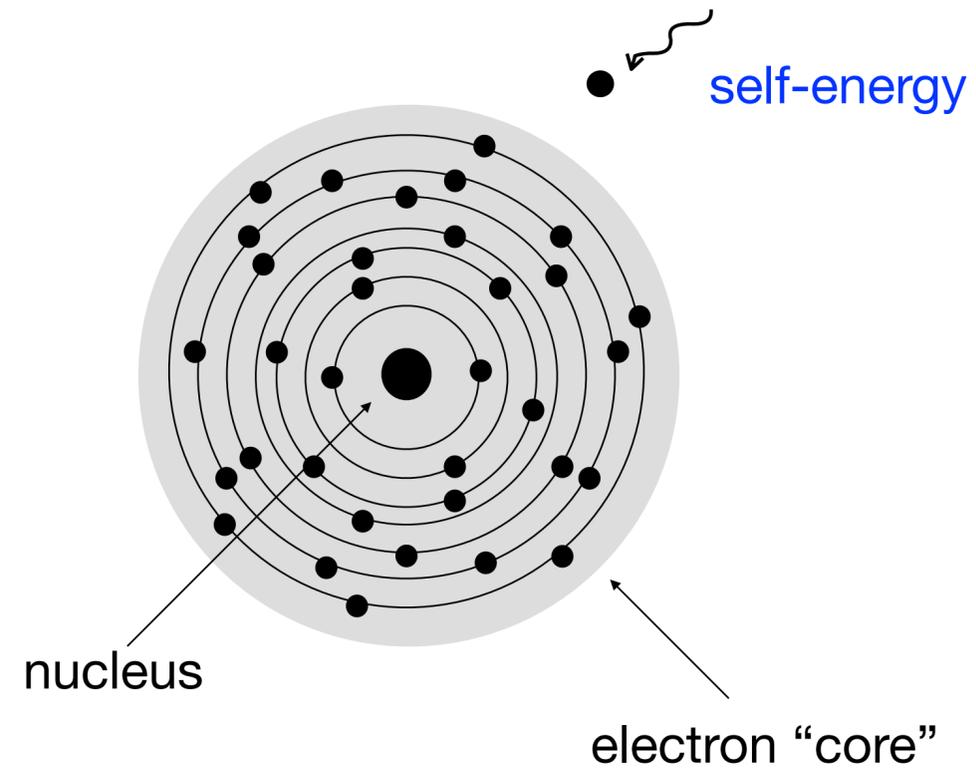


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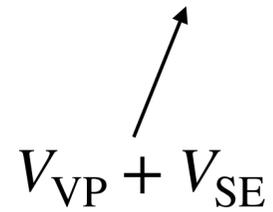
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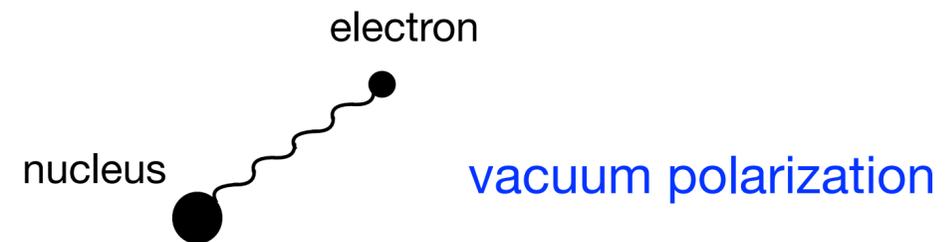
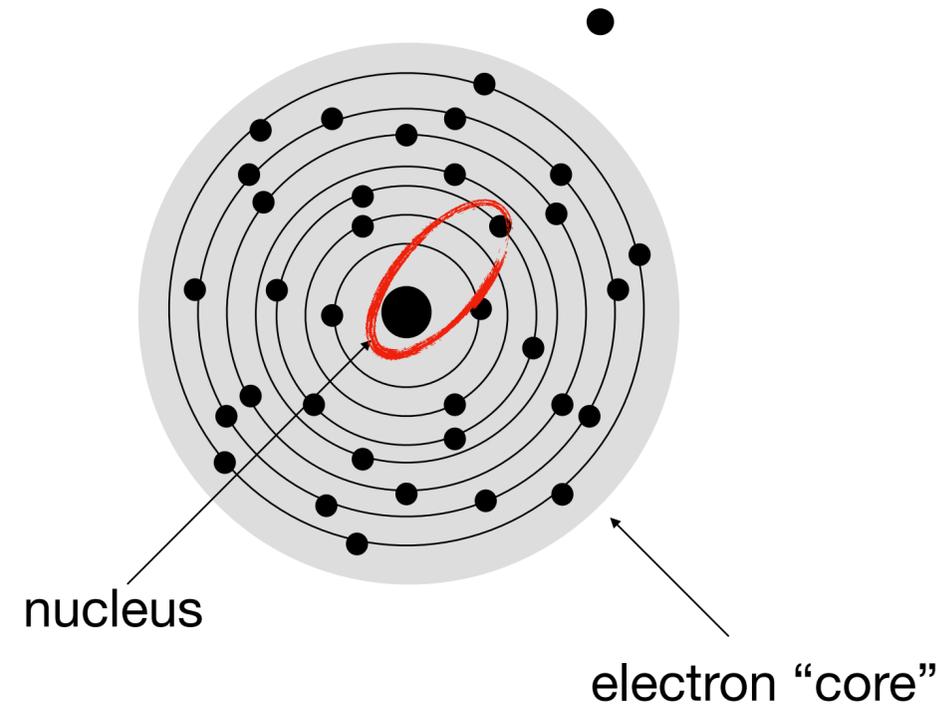
An arrow points from this equation to the V_{rad} term in the list above.



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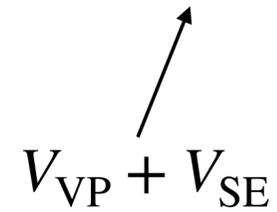


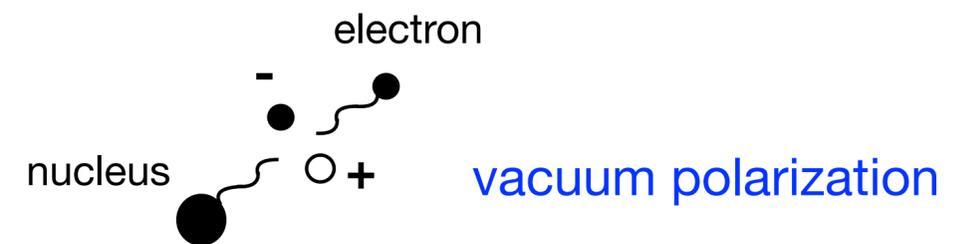
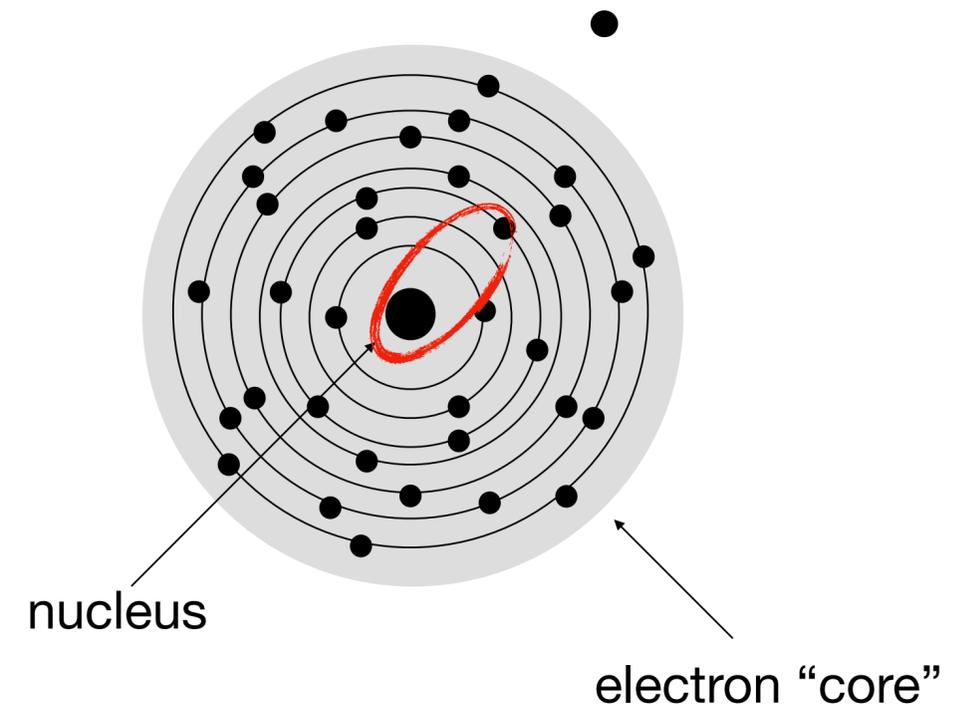
Dzuba, Flambaum, Sushkov, PLB (1989)

Flambaum and Ginges, PRA (2005)

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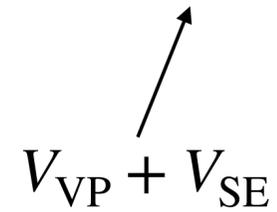


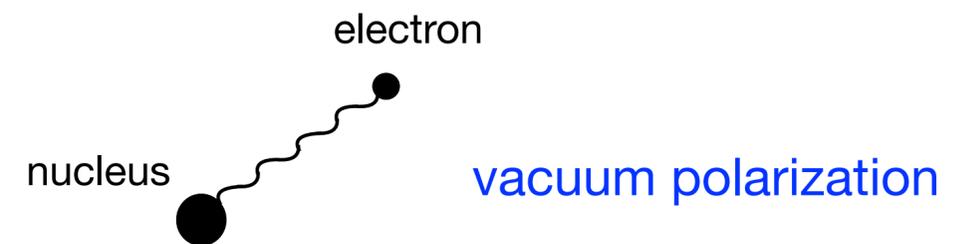
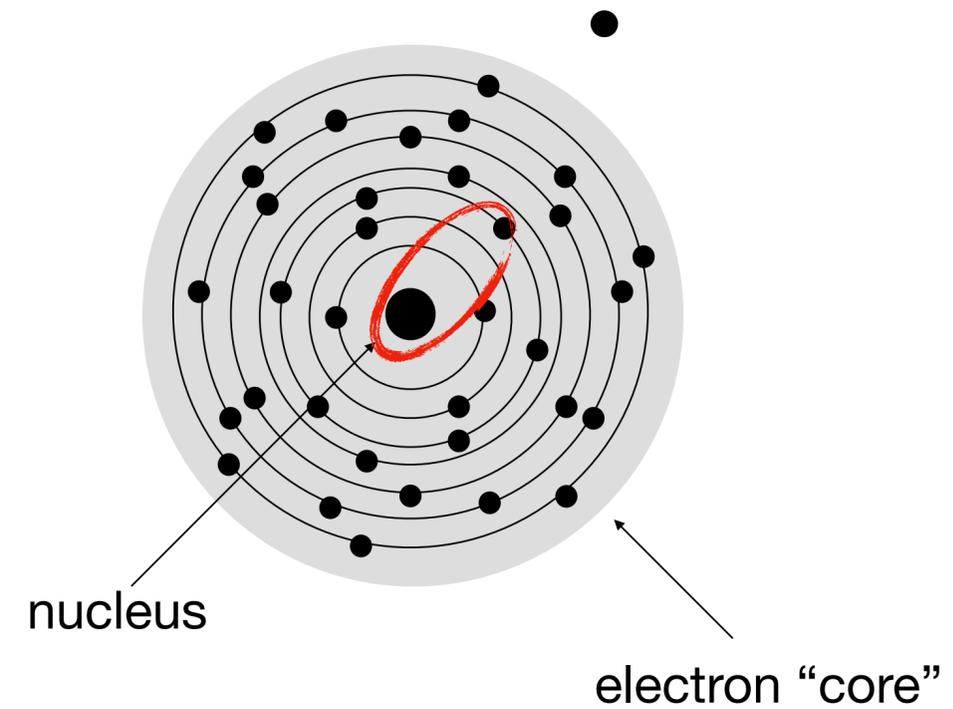
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