Theory of EDMs and related symmetry violations

Jacinda Ginges

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Australian Government
Australian Research Council

Les Houches program: EDMs2026

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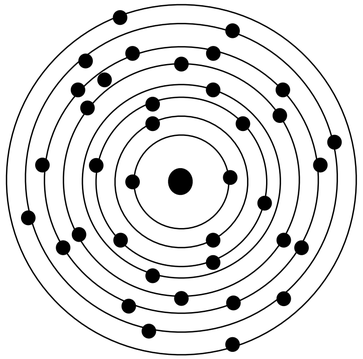

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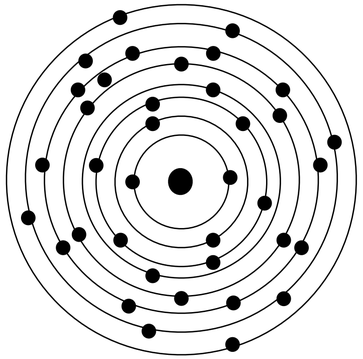

Electromagnetic, weak, strong interactions present in atoms and may be probed and tested

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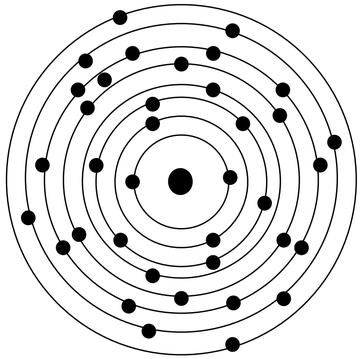

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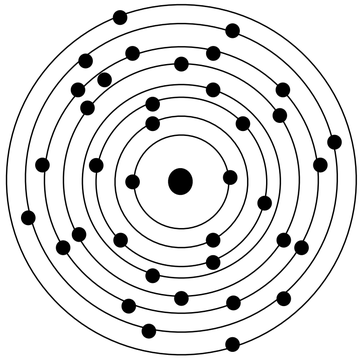

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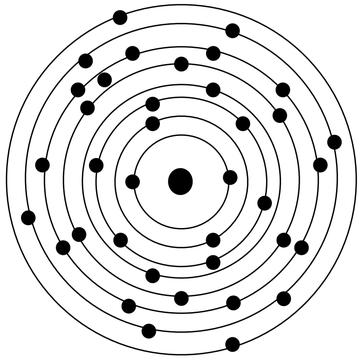

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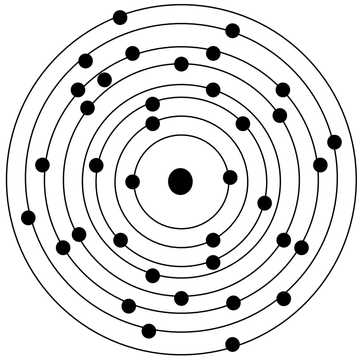

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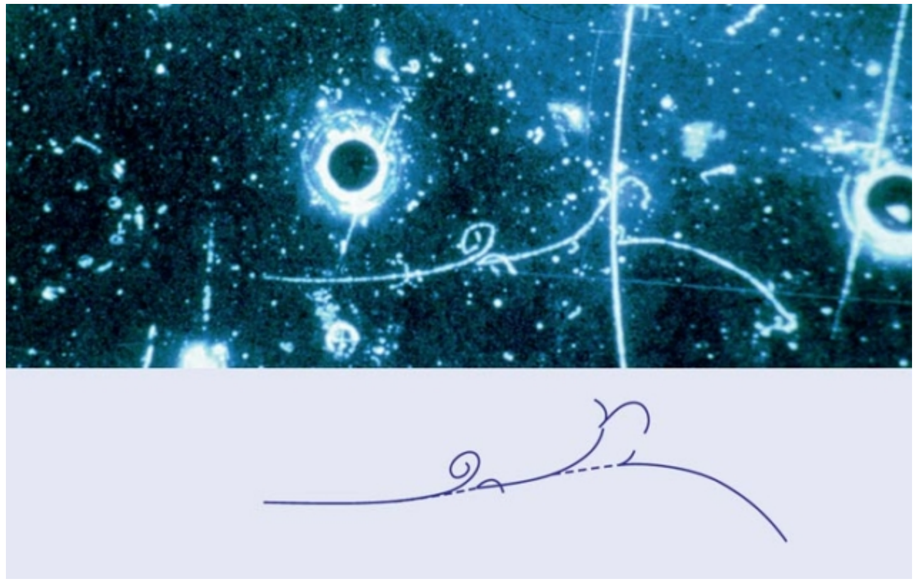

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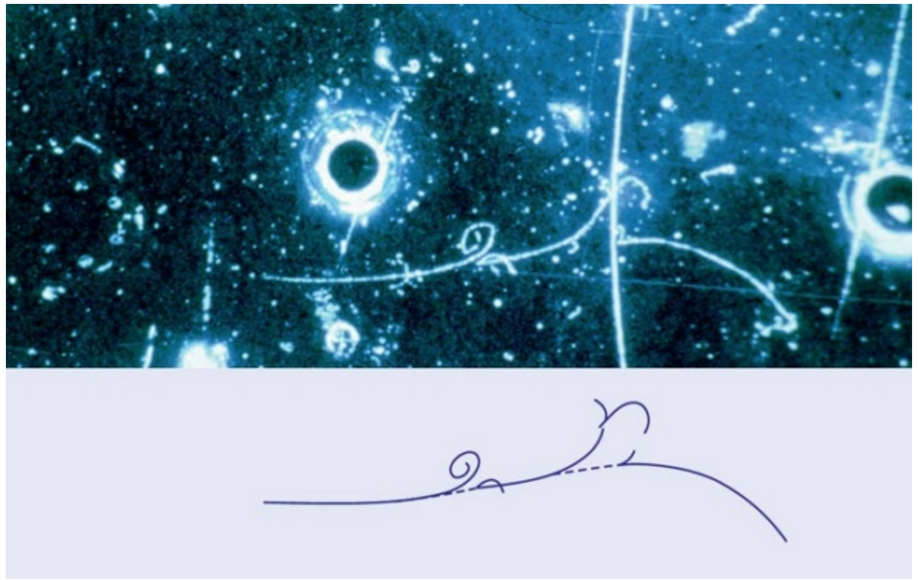

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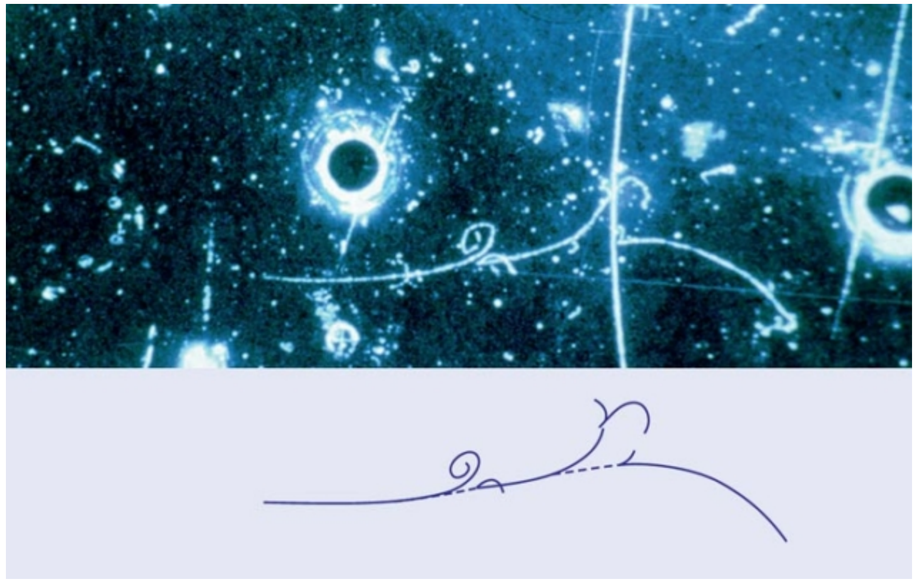

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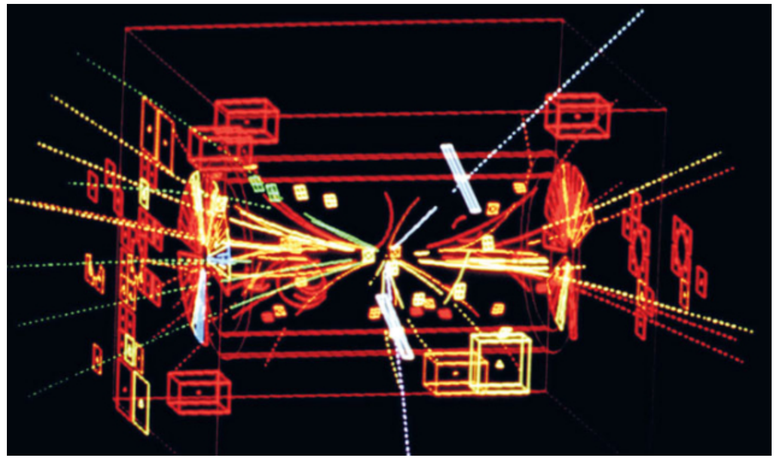

- 1983, weak bosons Z, W^+, W^- produced directly at CERN

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

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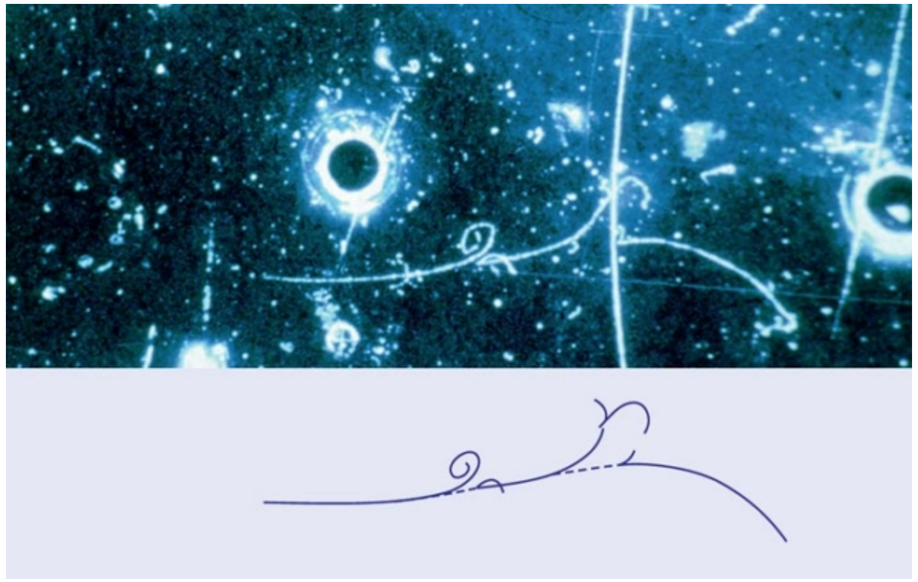

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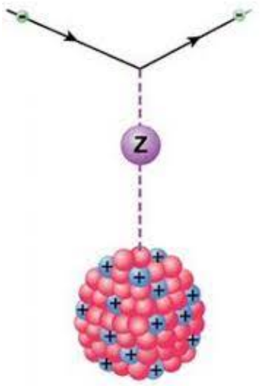

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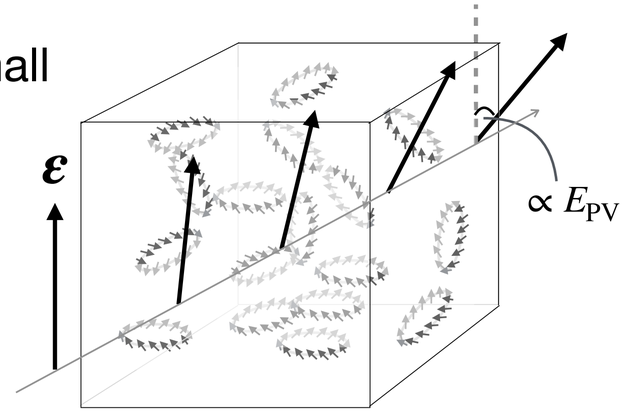

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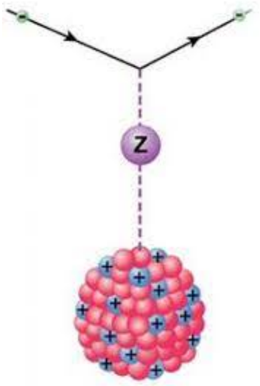

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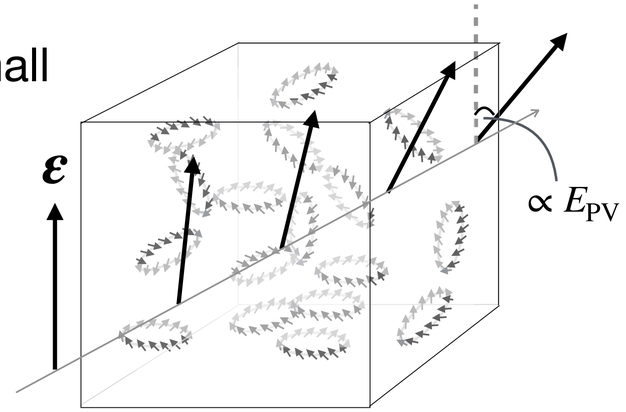

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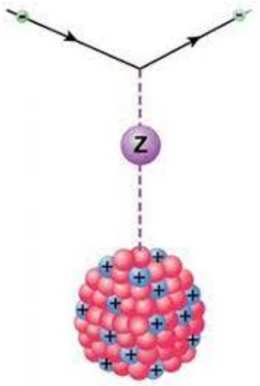

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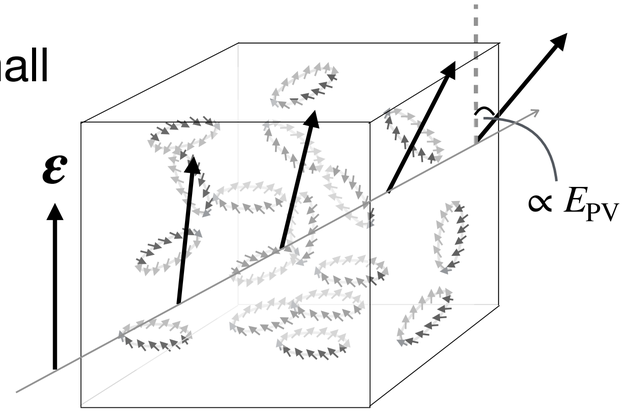

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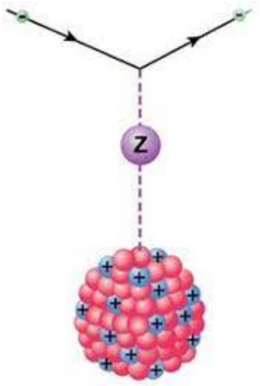

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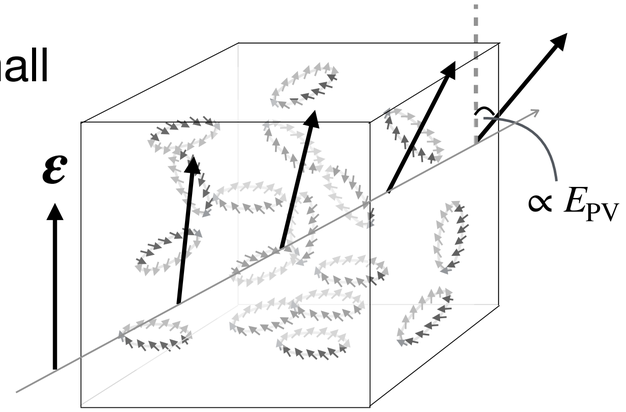

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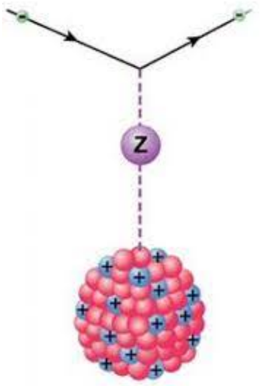

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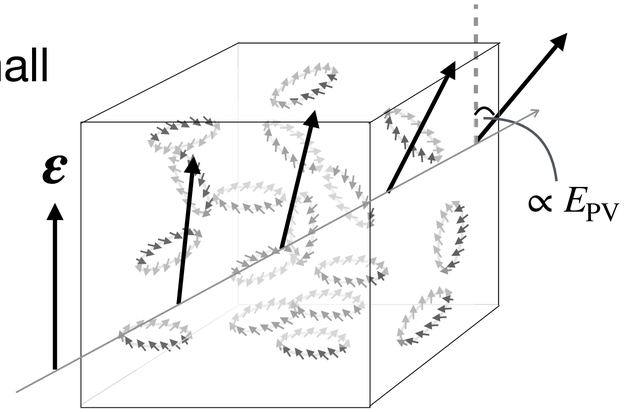

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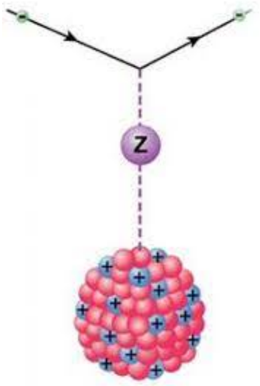

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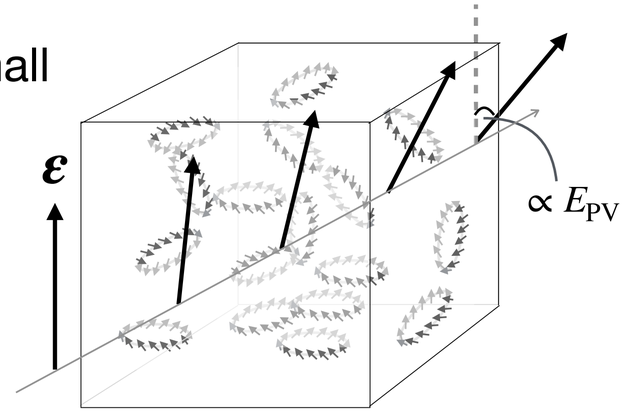

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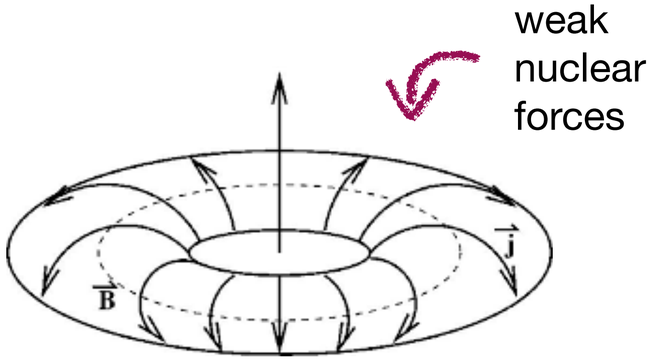

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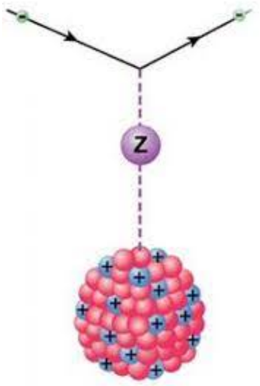

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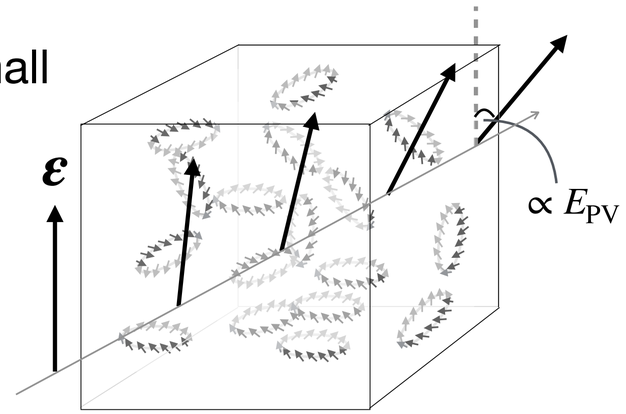

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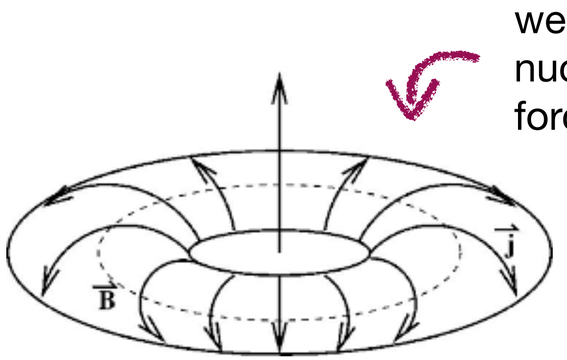

2019 — Budker group (Mainz) measured APV in Yb, uncertainty 0.5%, along chain of isotopes ← ratios taken

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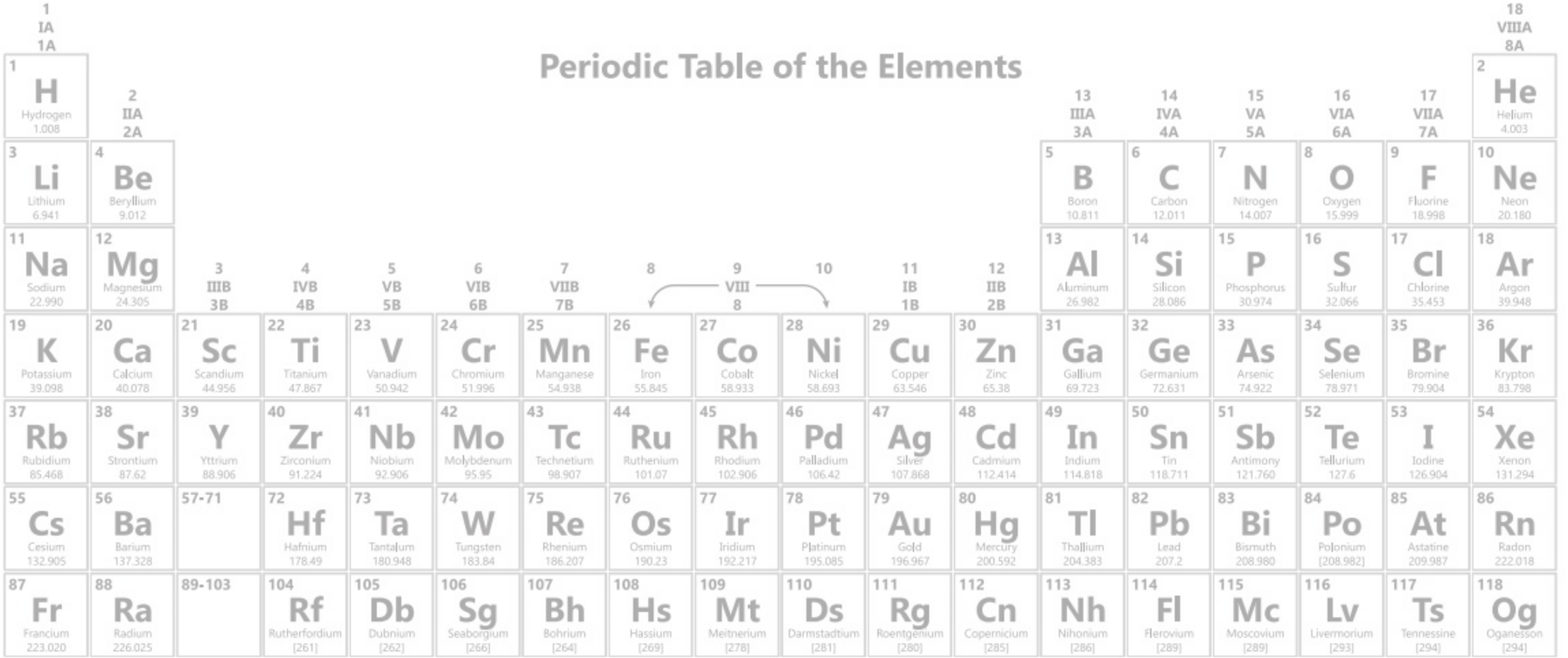

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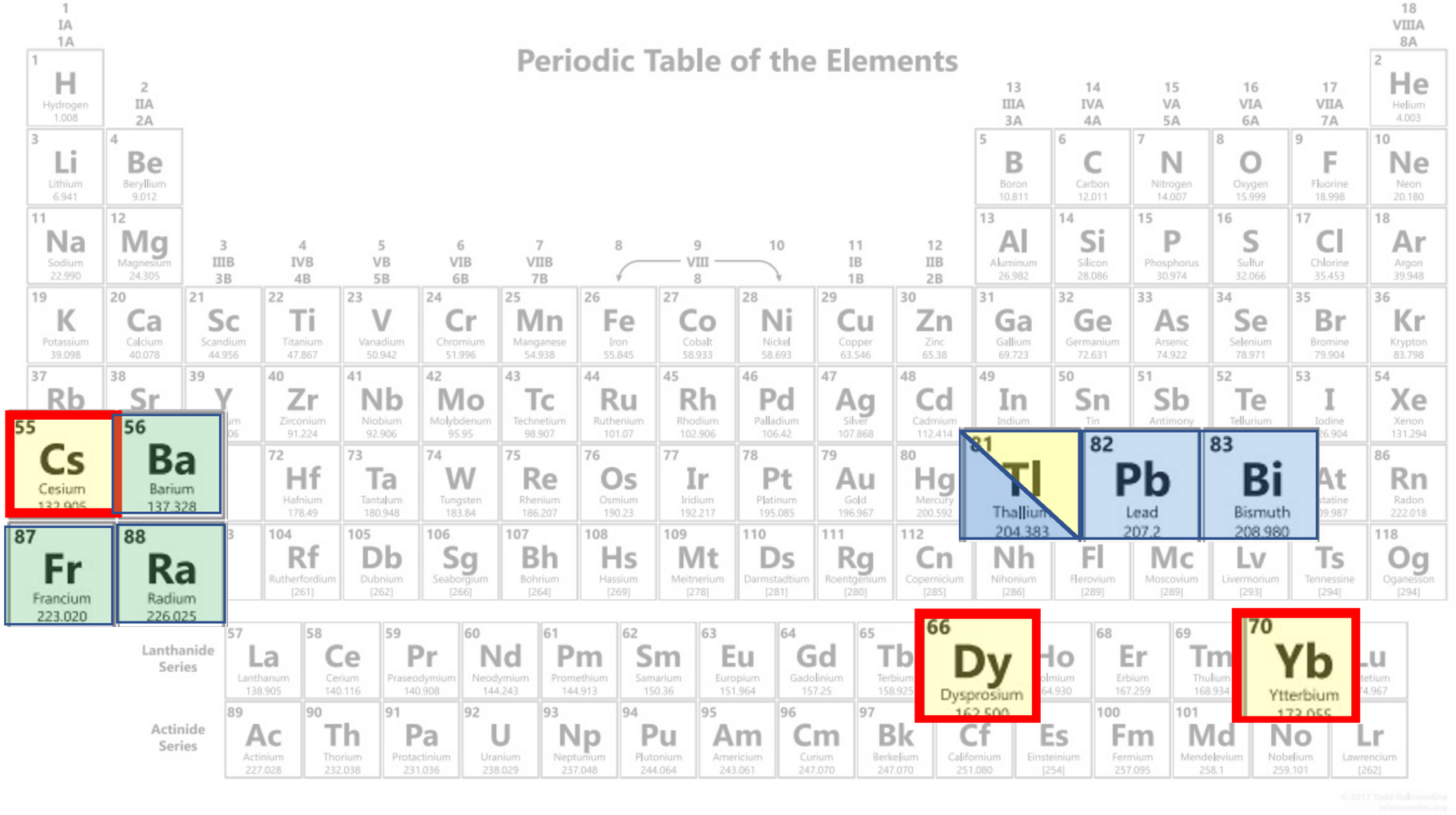
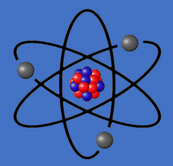


Measured — blue (rotation), yellow (Stark);
Next-gen — red; New in progress/planned — green

Ginges and Borschevsky,
Encyclopedia of Particle Physics, in press (2026)

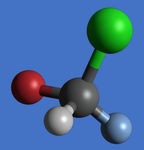
Atom as a laboratory — symmetries violations

Experiments



Atoms

Molecules



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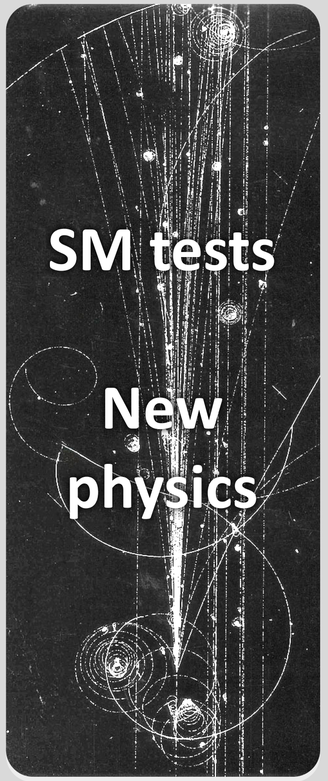

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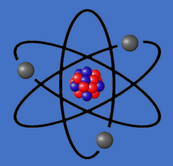

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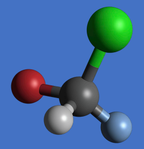

I saw the angel in the marble and carved until I set him free

— Michelangelo

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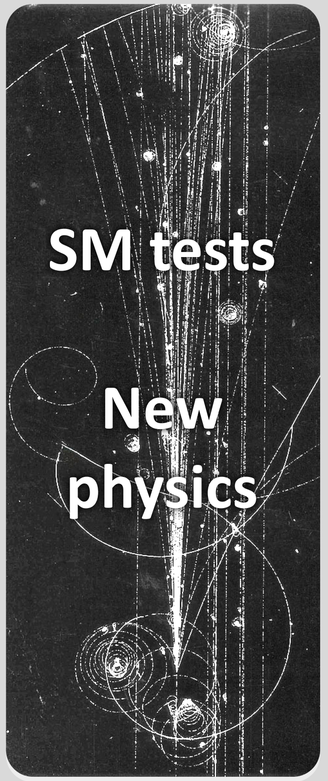

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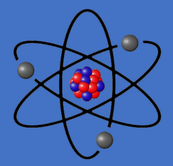

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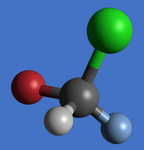


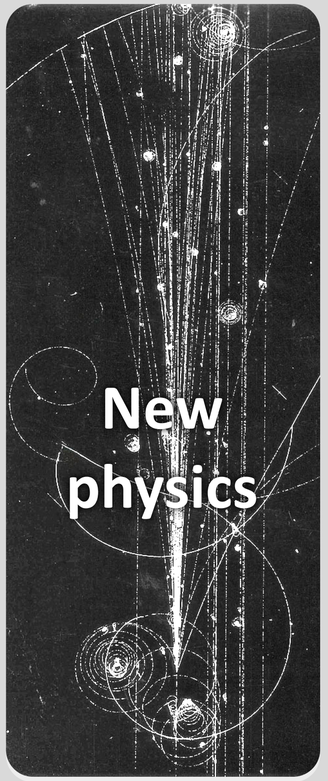
Nuclear

Nucleon

Quark

Lepton

Particle



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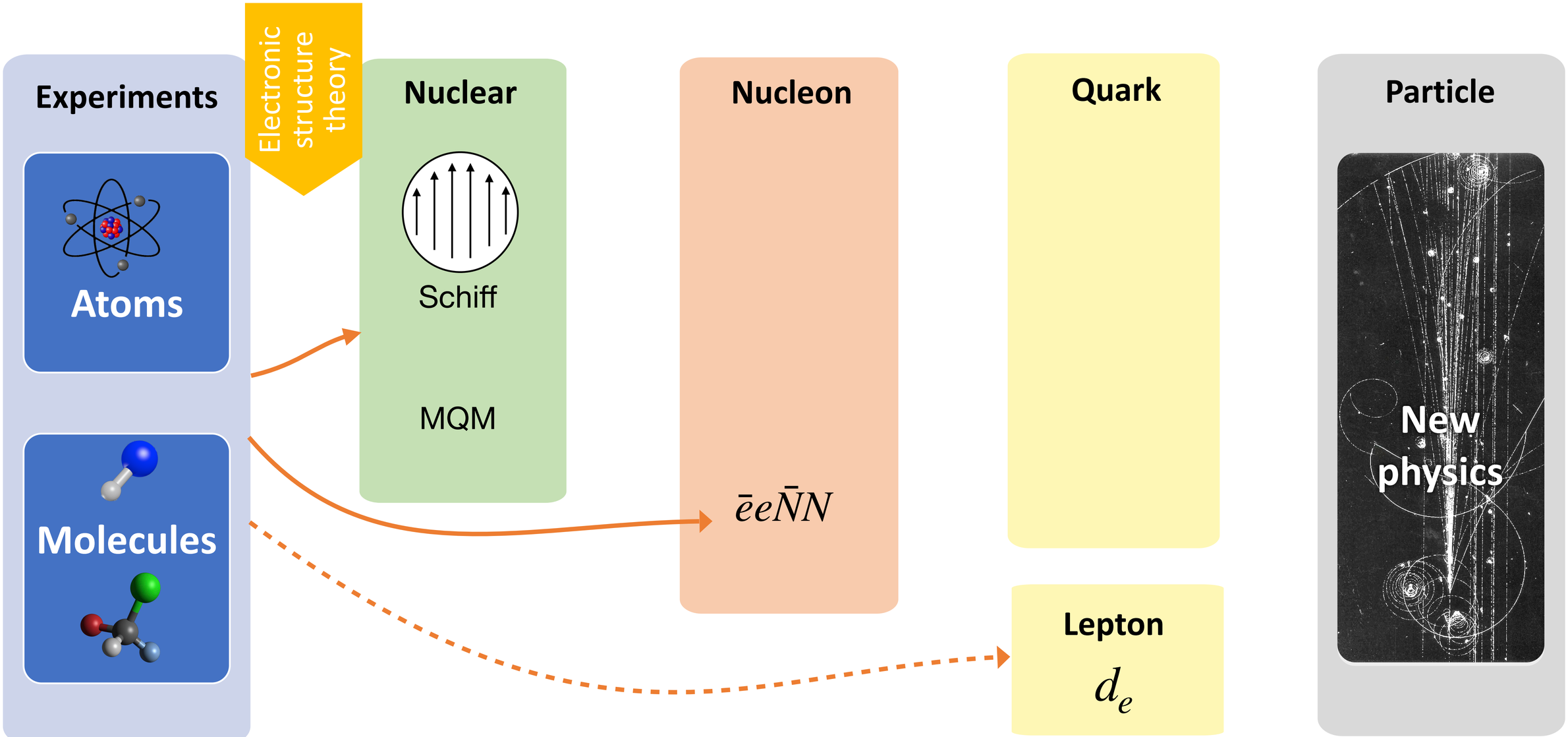

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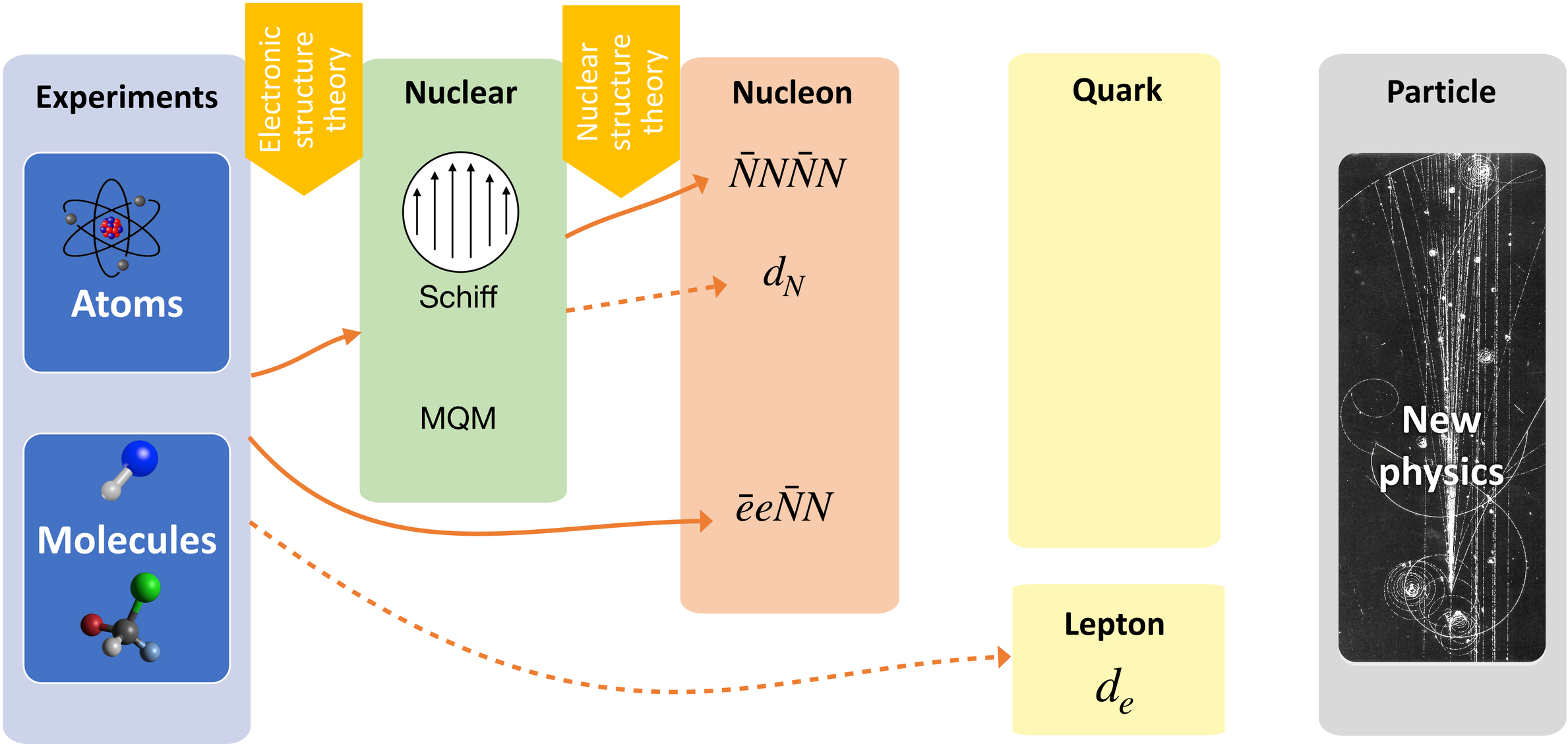

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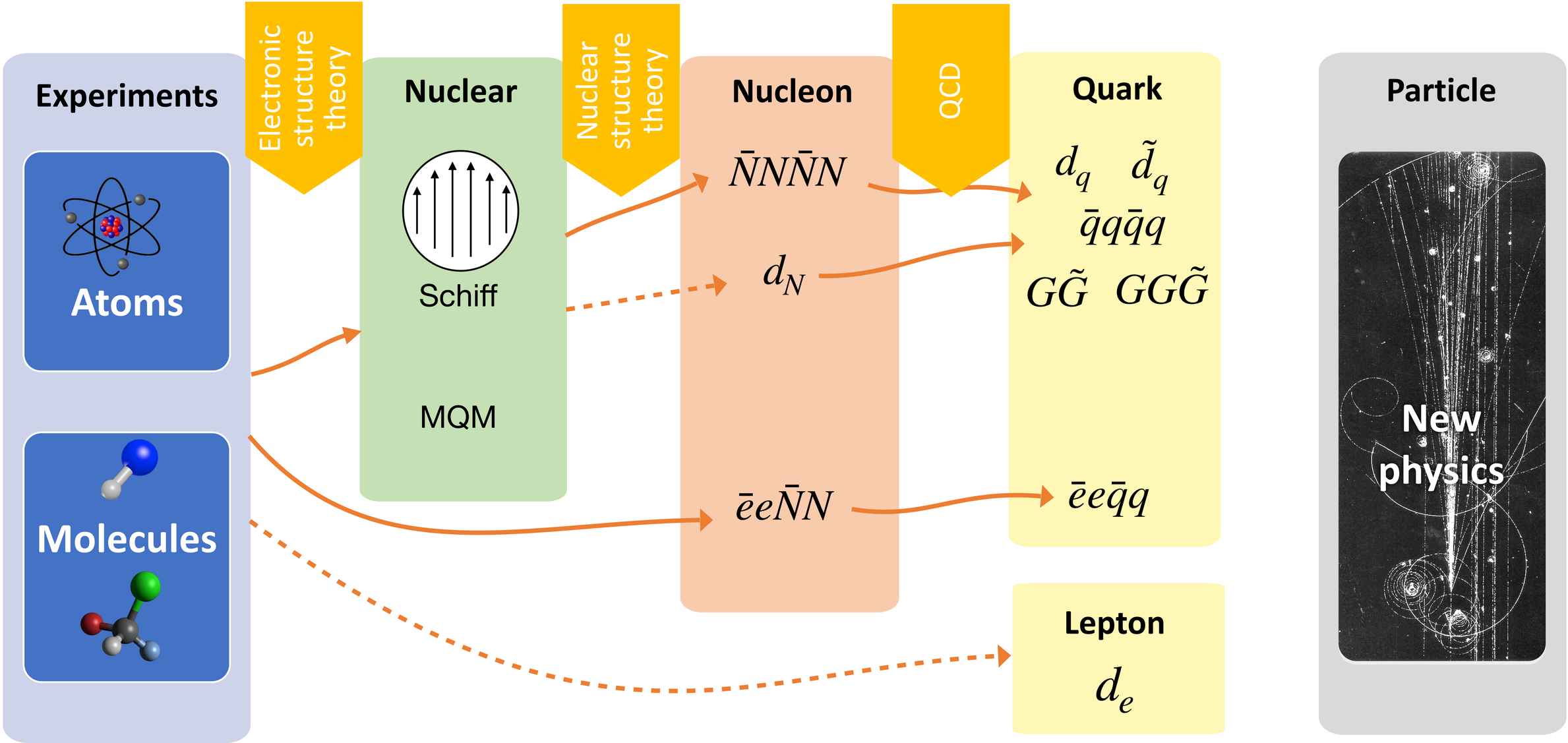

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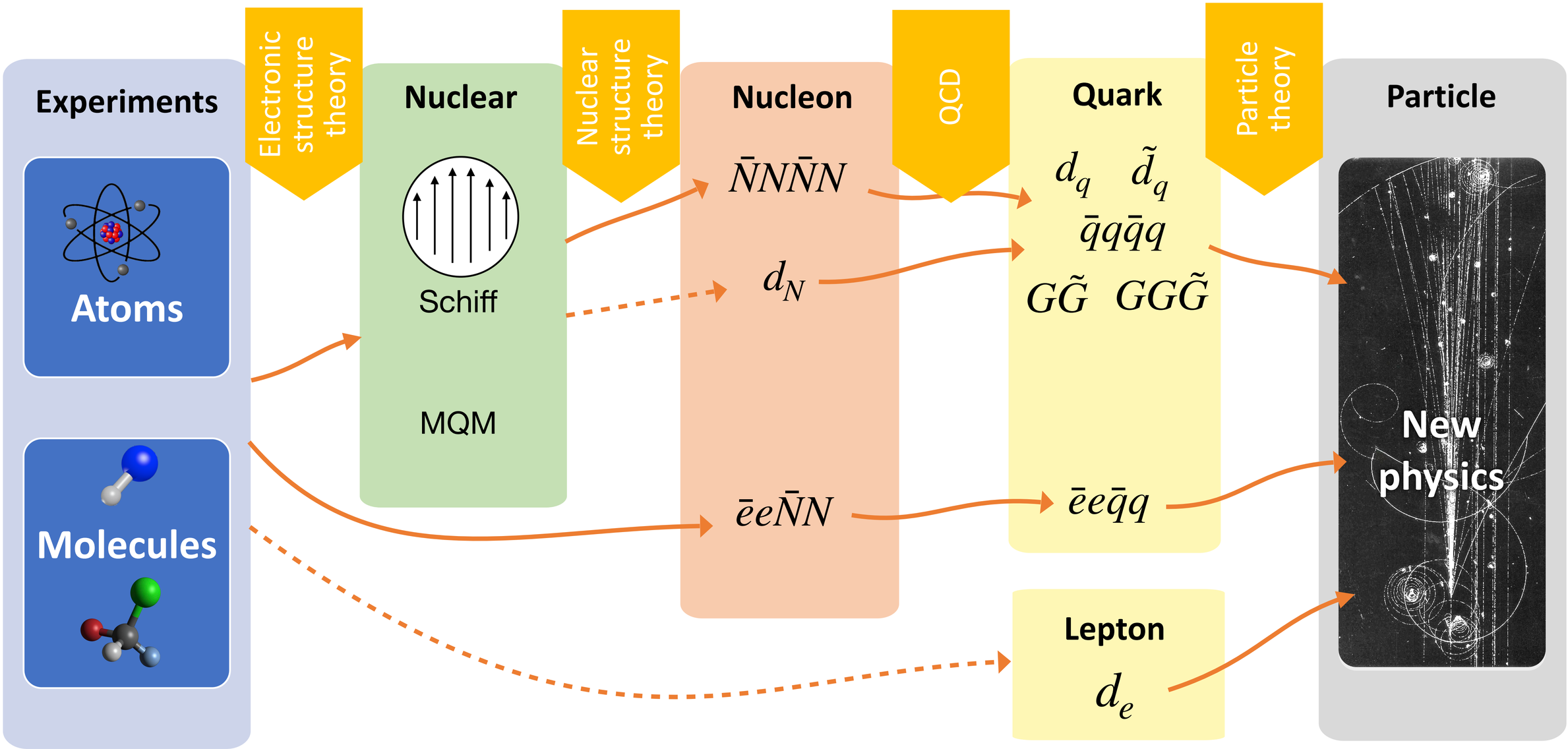

diamagnetic

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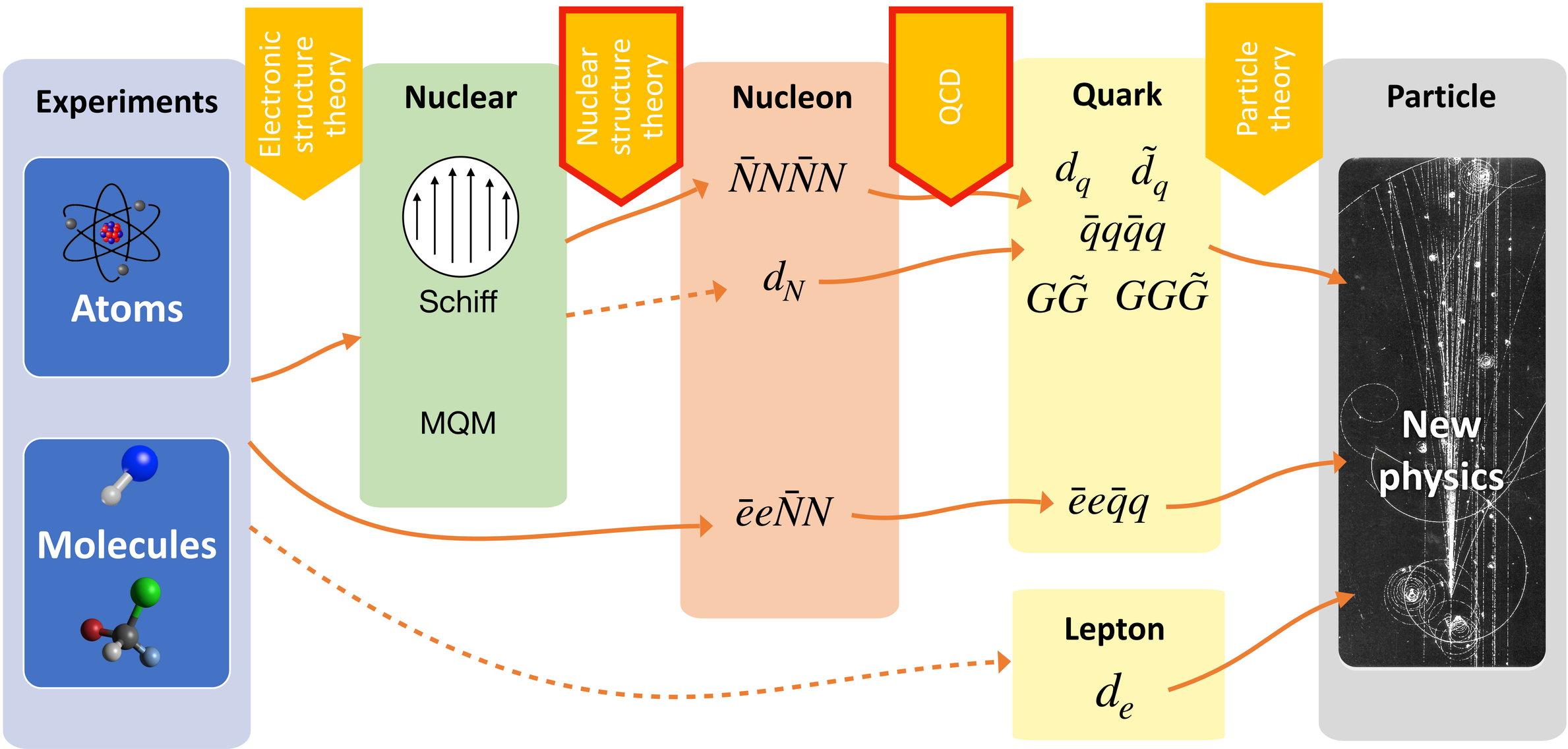

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bottleneck

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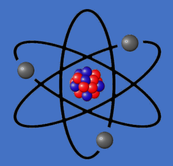
See, e.g., Ginges and Flambaum, Phys. Rep. (2004);
Safronova et al., Rev. Mod. Phys. (2018);
Engel, Ramsey-Musolf, Kolck, Prog. Part. Nucl. Phys. (2013)

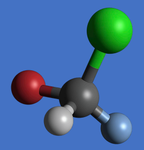
Atom as a laboratory — APV

Experiments



Atoms

Molecules

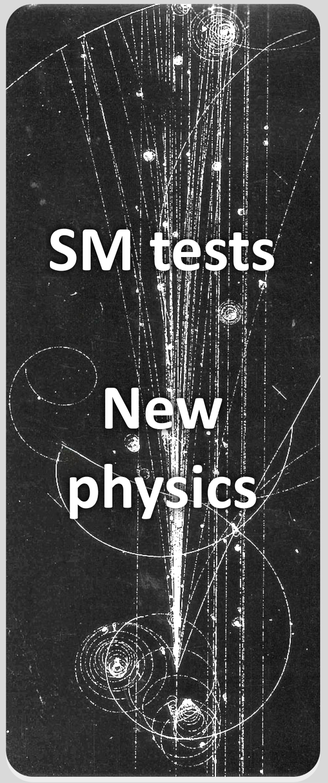


Nuclear

Nucleon

Quark

Particle



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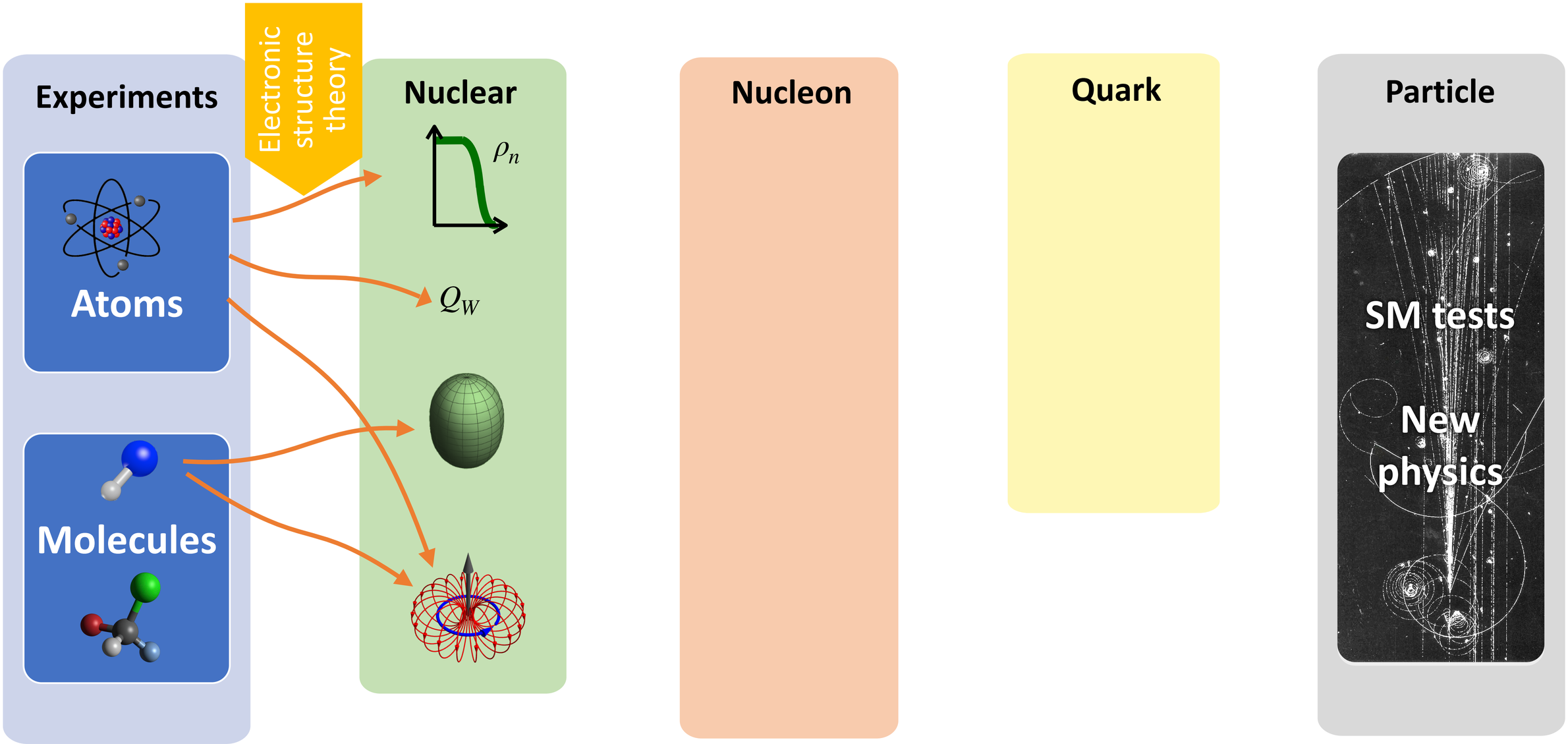

Ginges and Borschevsky,
in press (2026)

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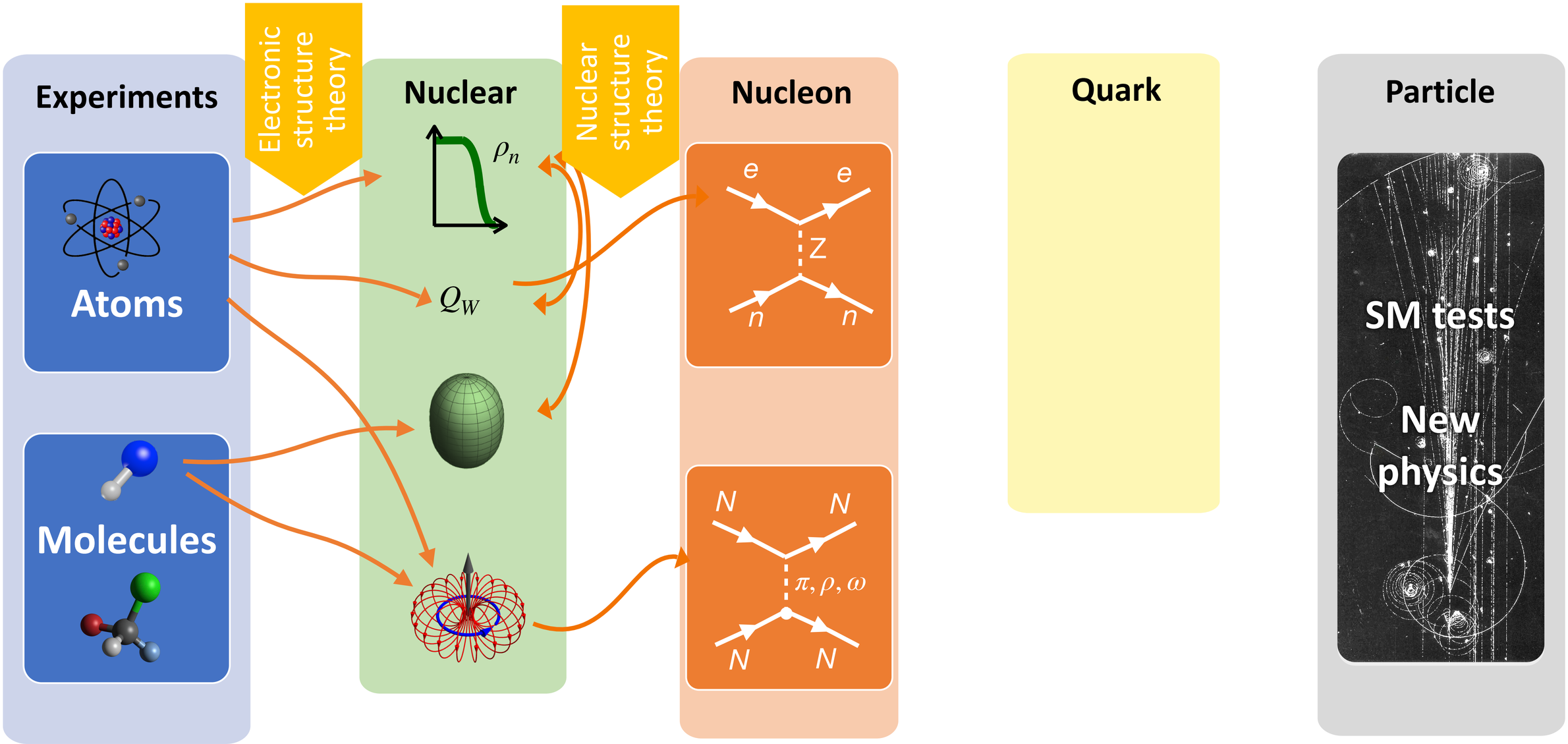

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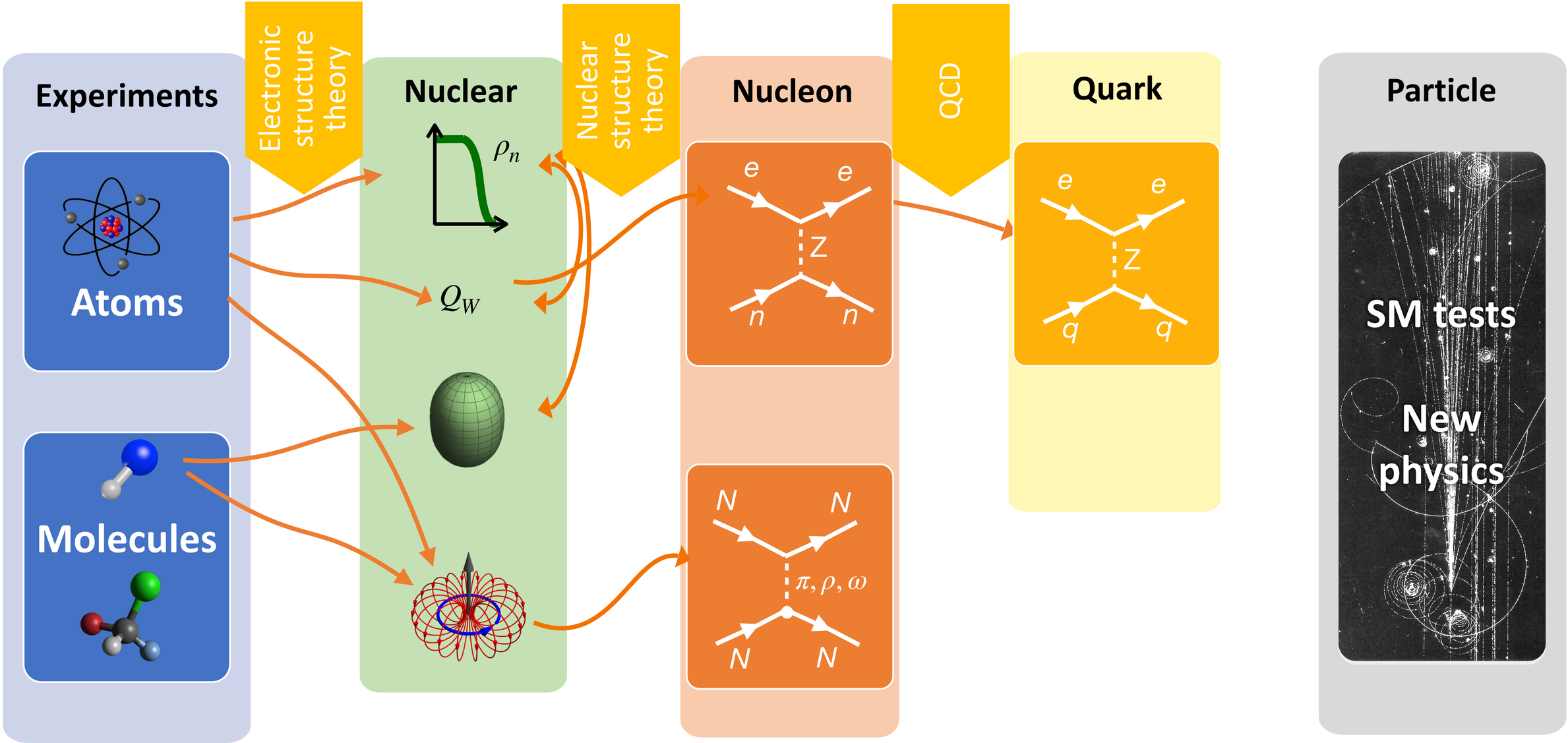

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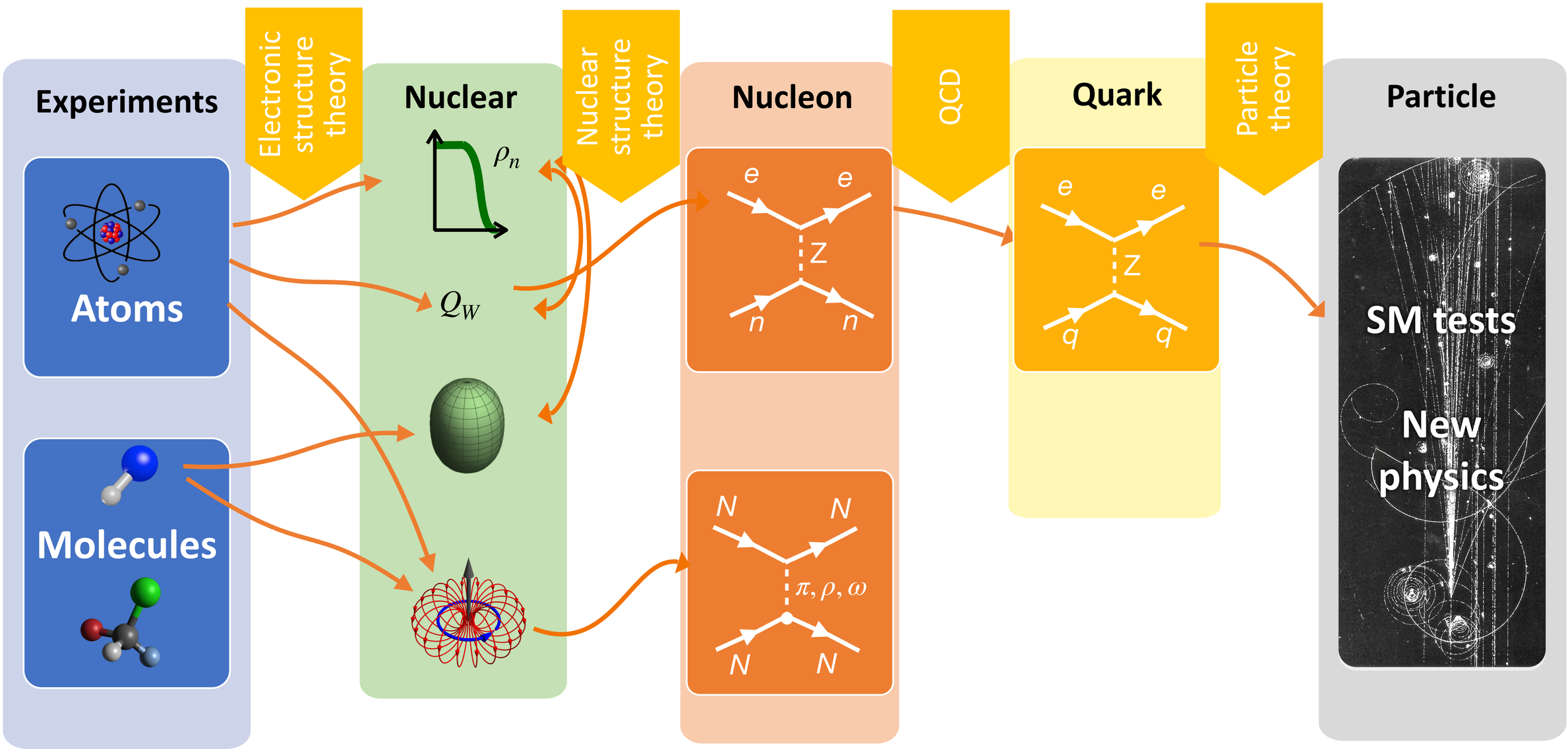

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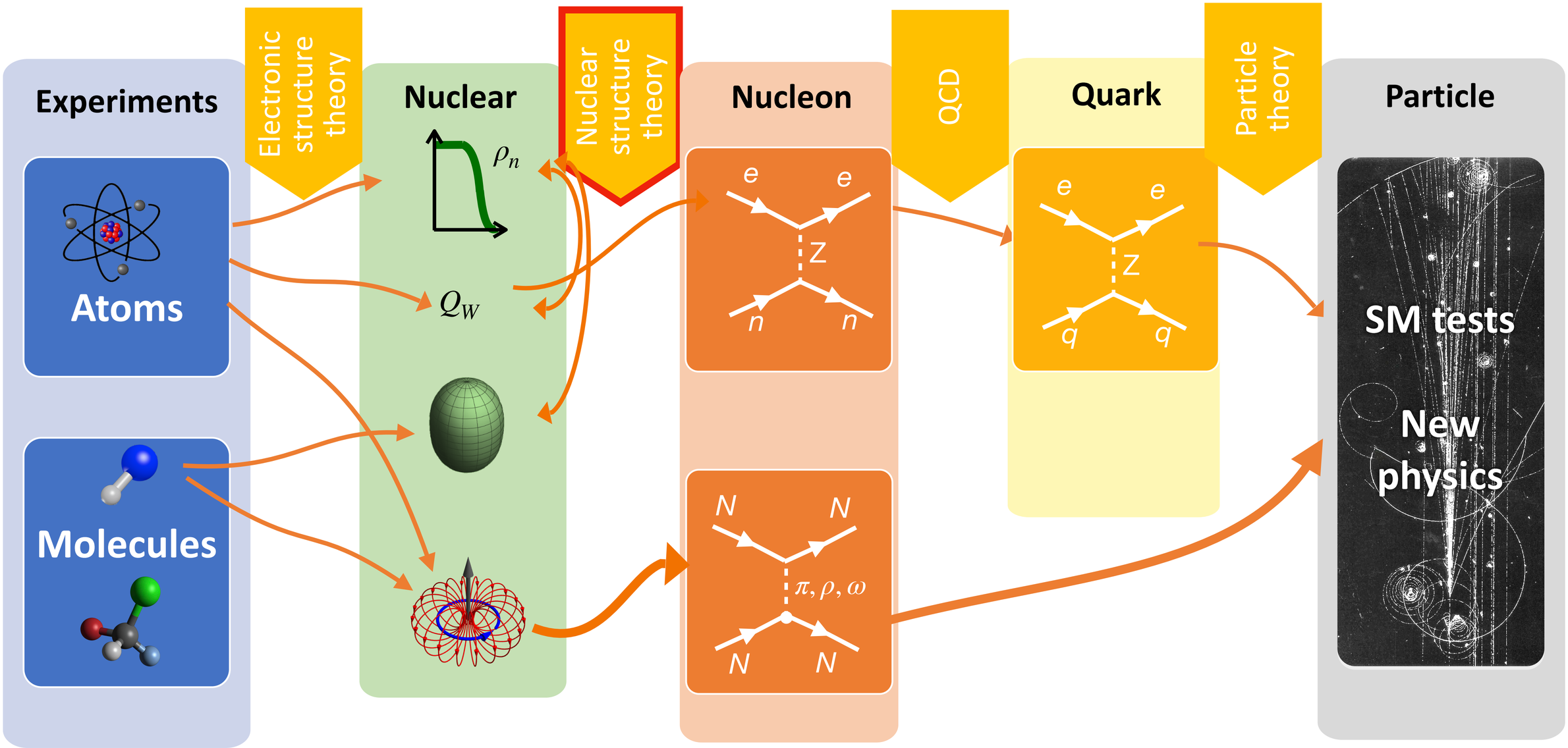

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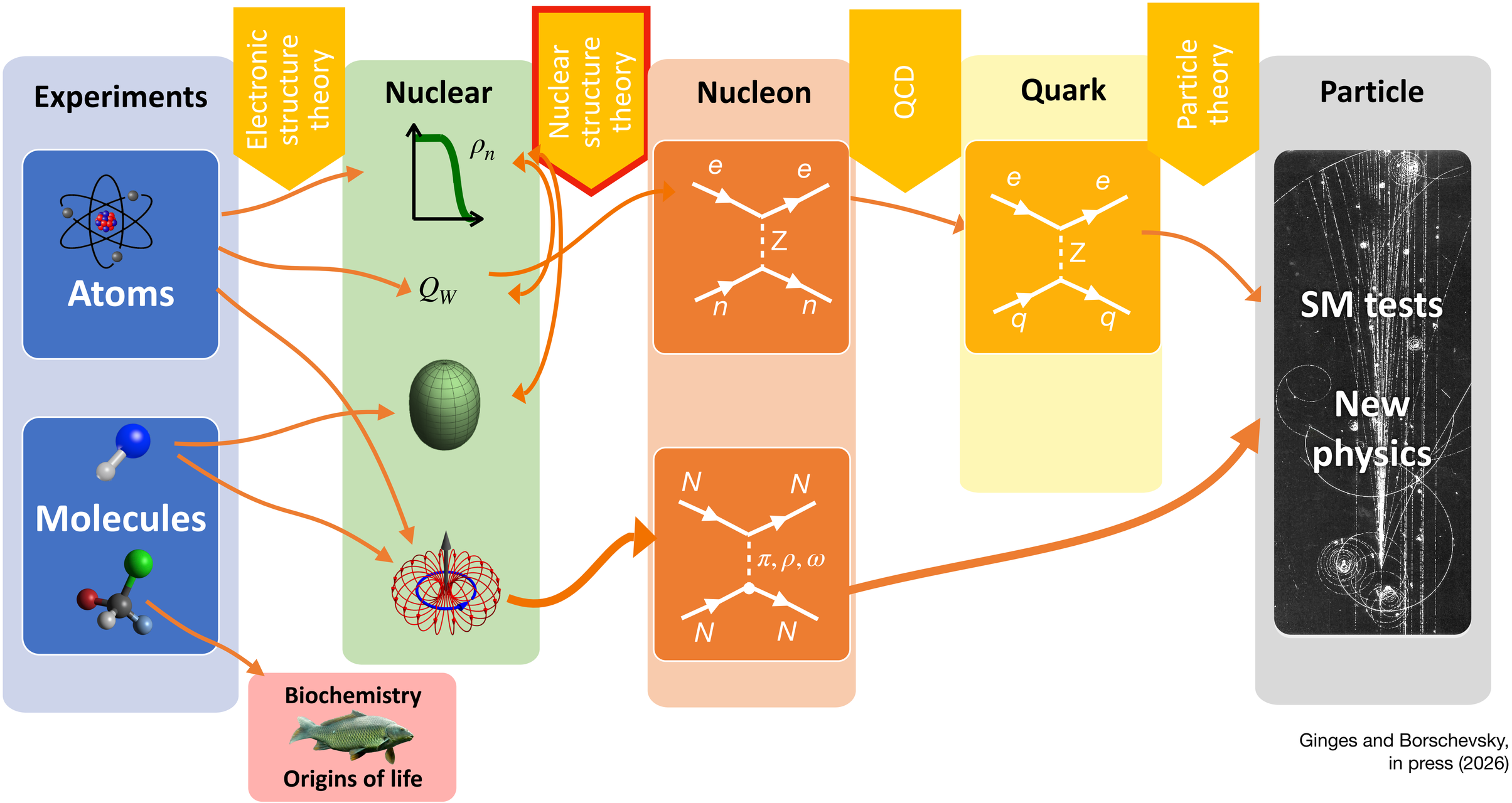

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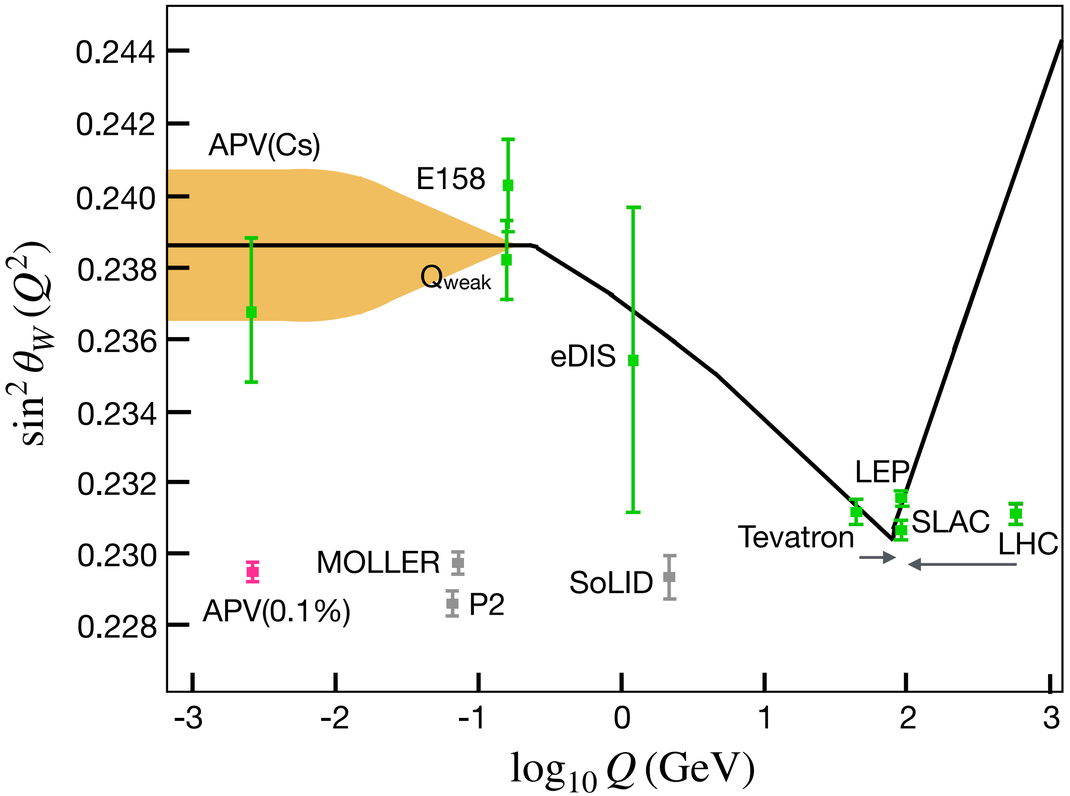
Atomic parity violation — SM tests and BSM searches



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

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Safronova et al., Rev. Mod. Phys. (2018);
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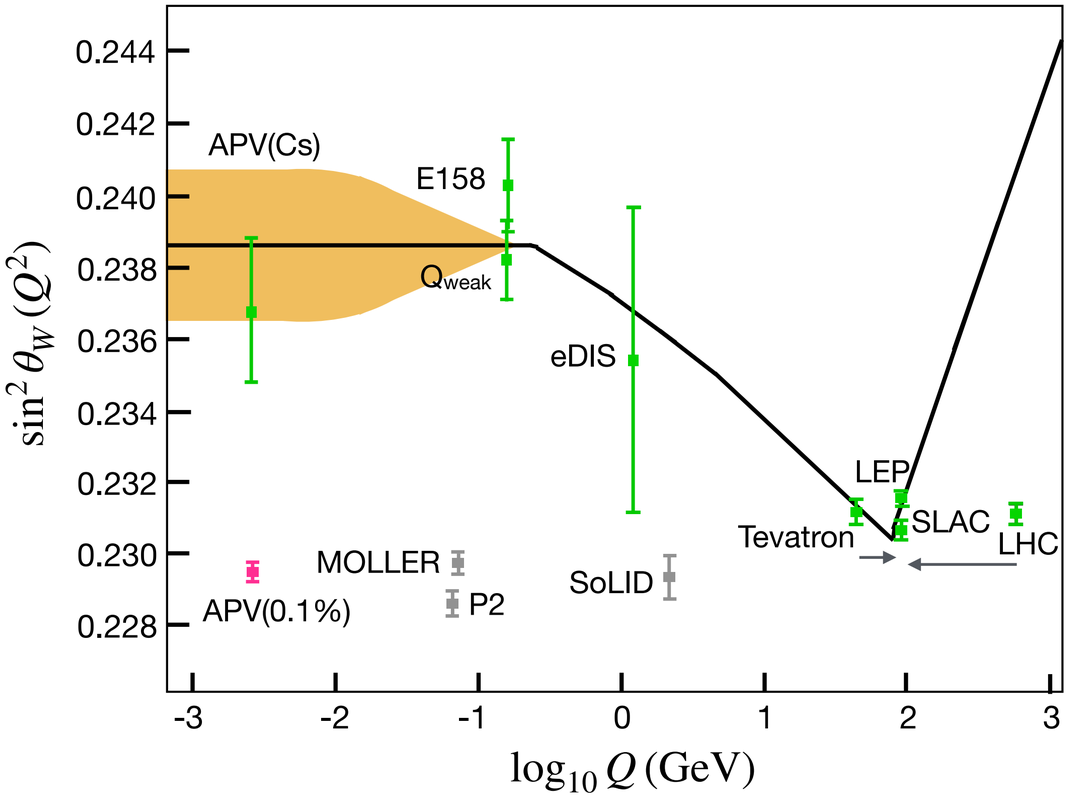

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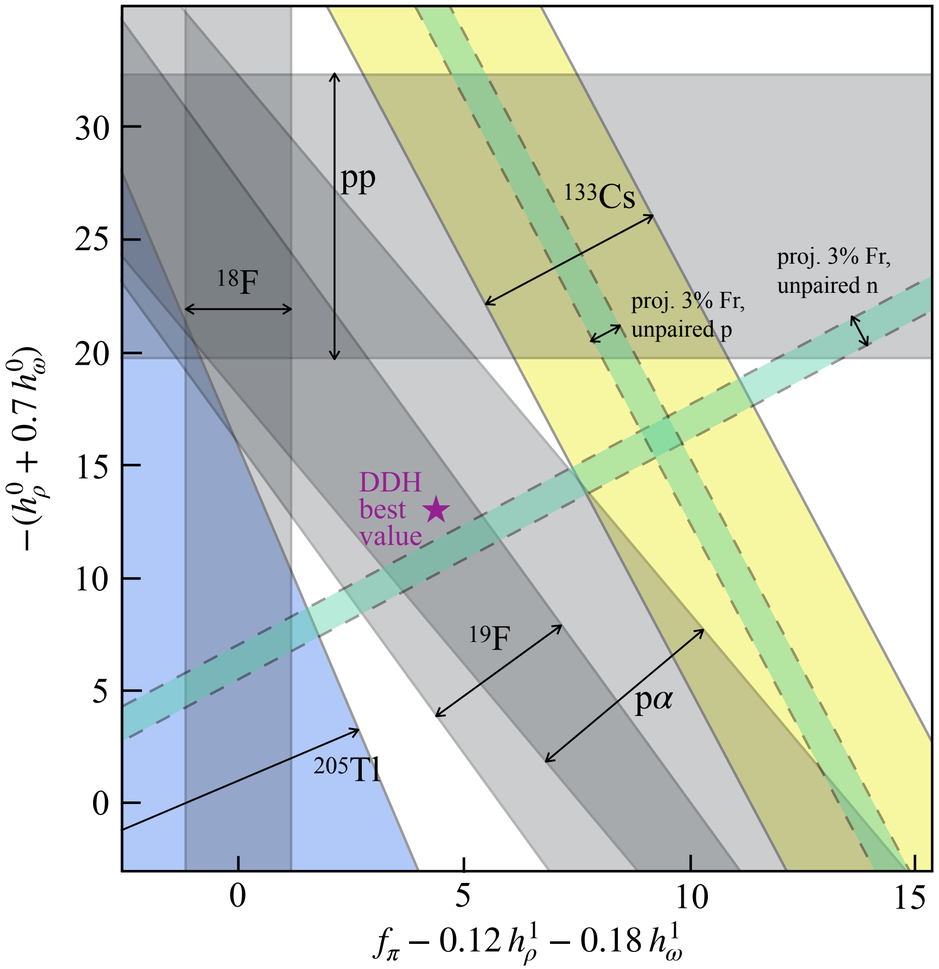

- Extraction of weak meson-nucleon couplings from scattering experiments, including from anapole

Haxton and Holstein, Prog. Part. Nucl. Phys (2013);
Behr and Gwinner, J. Phys. G (2009);
Ginges and Borschevsky, in press (2026)

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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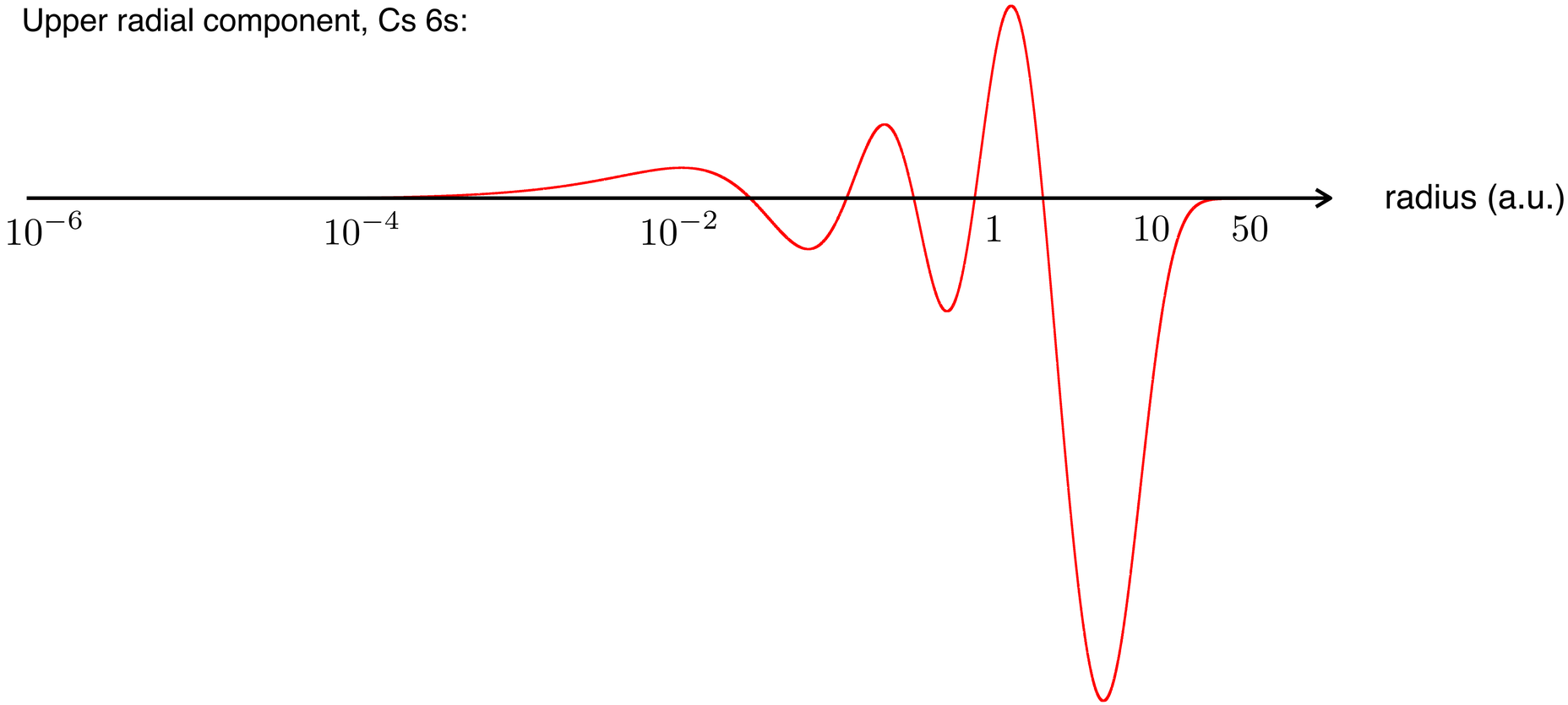
Upper radial component, Cs 6s:



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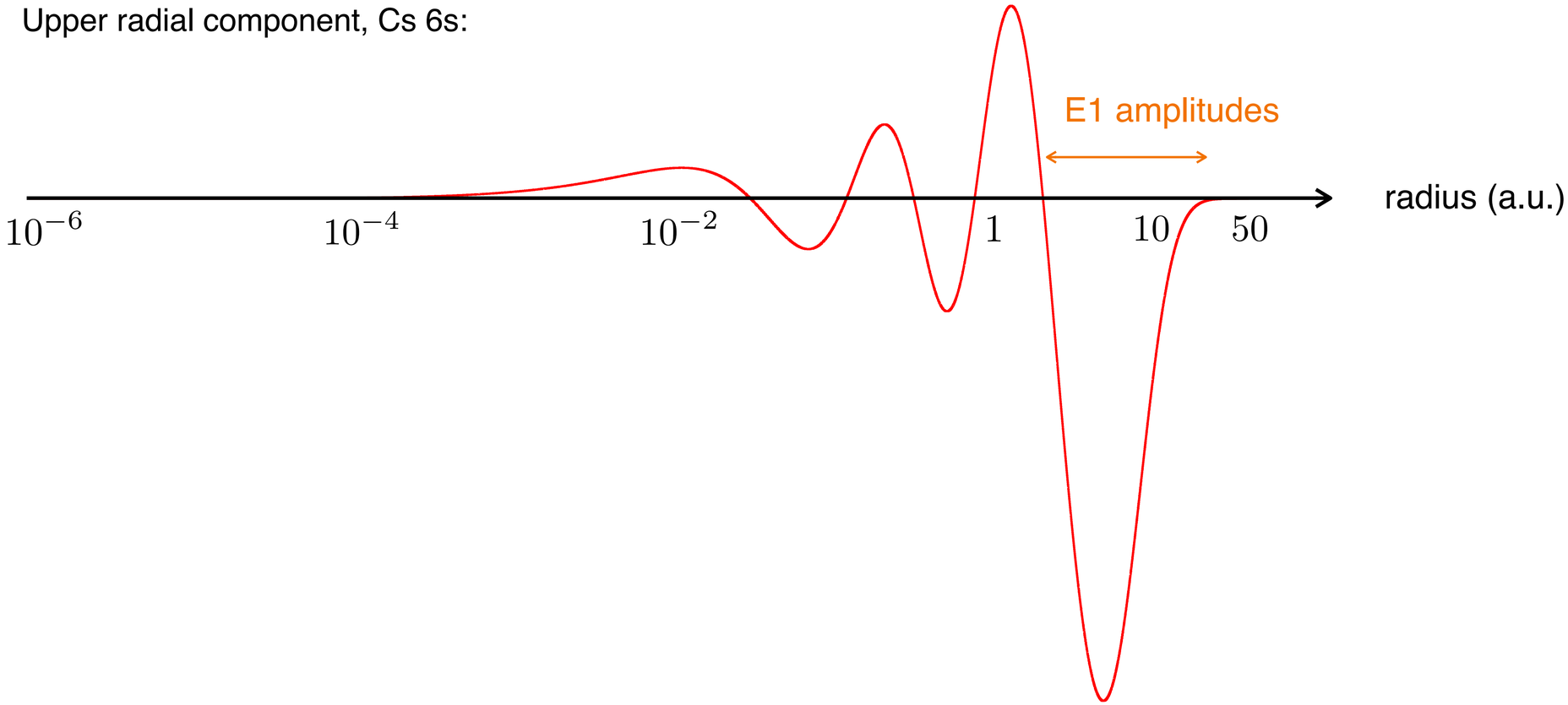

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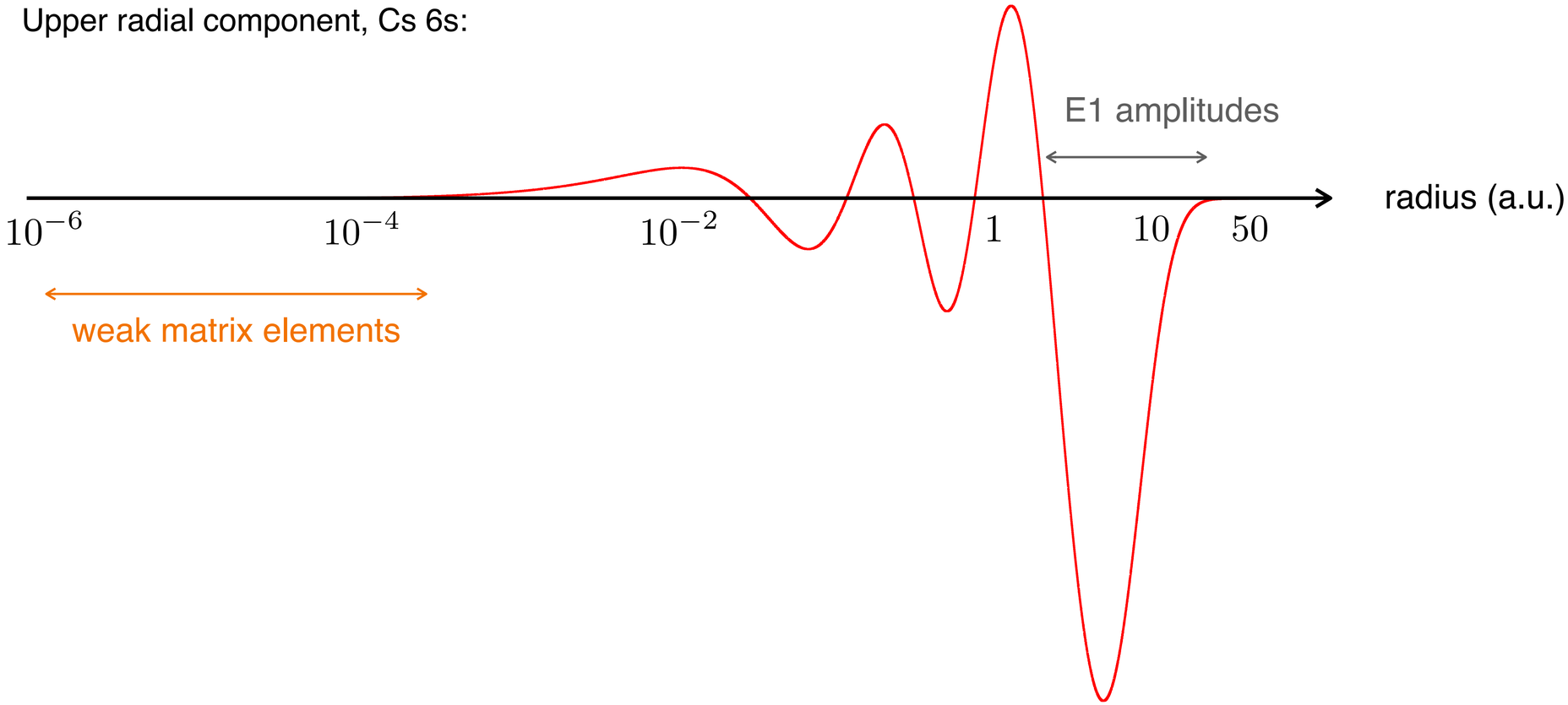

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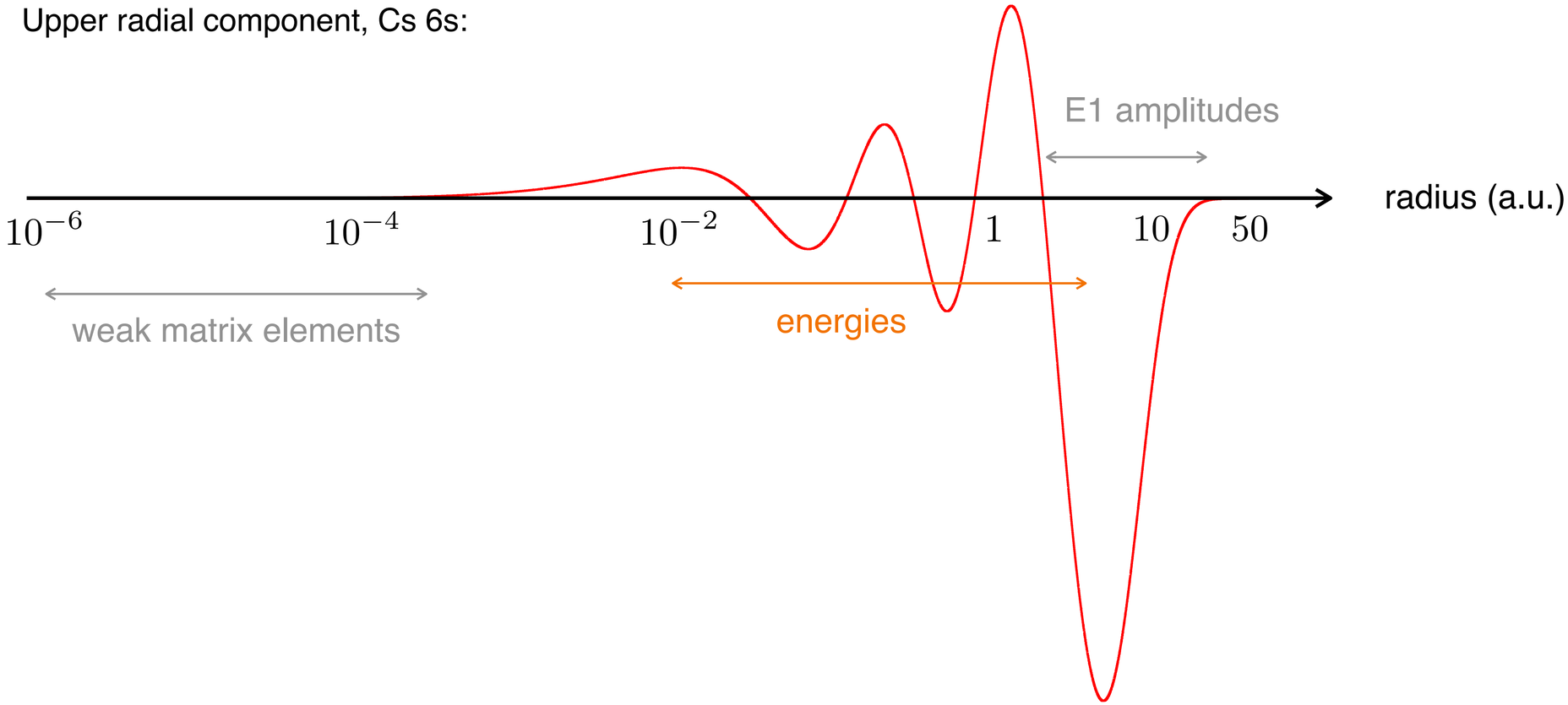

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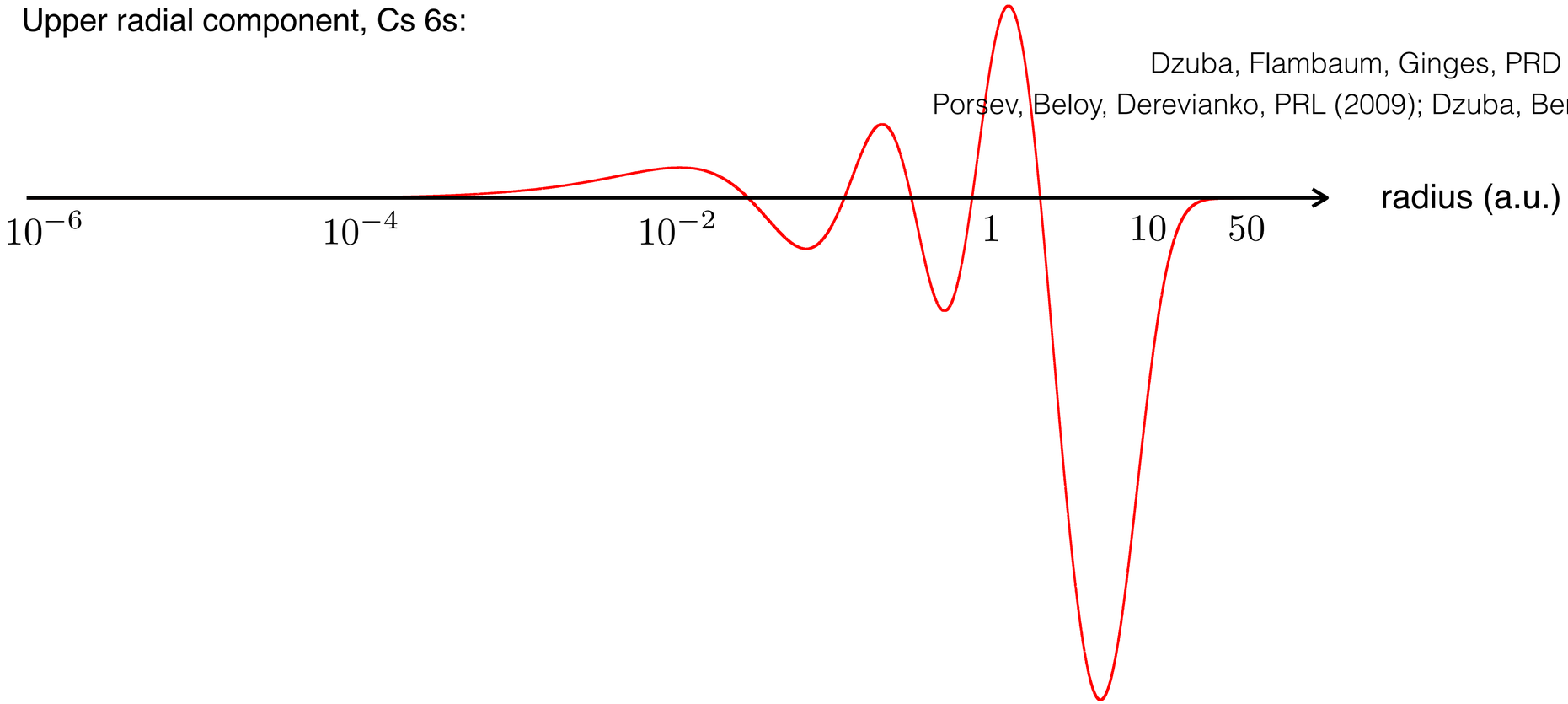

0.5% uncertainty

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

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

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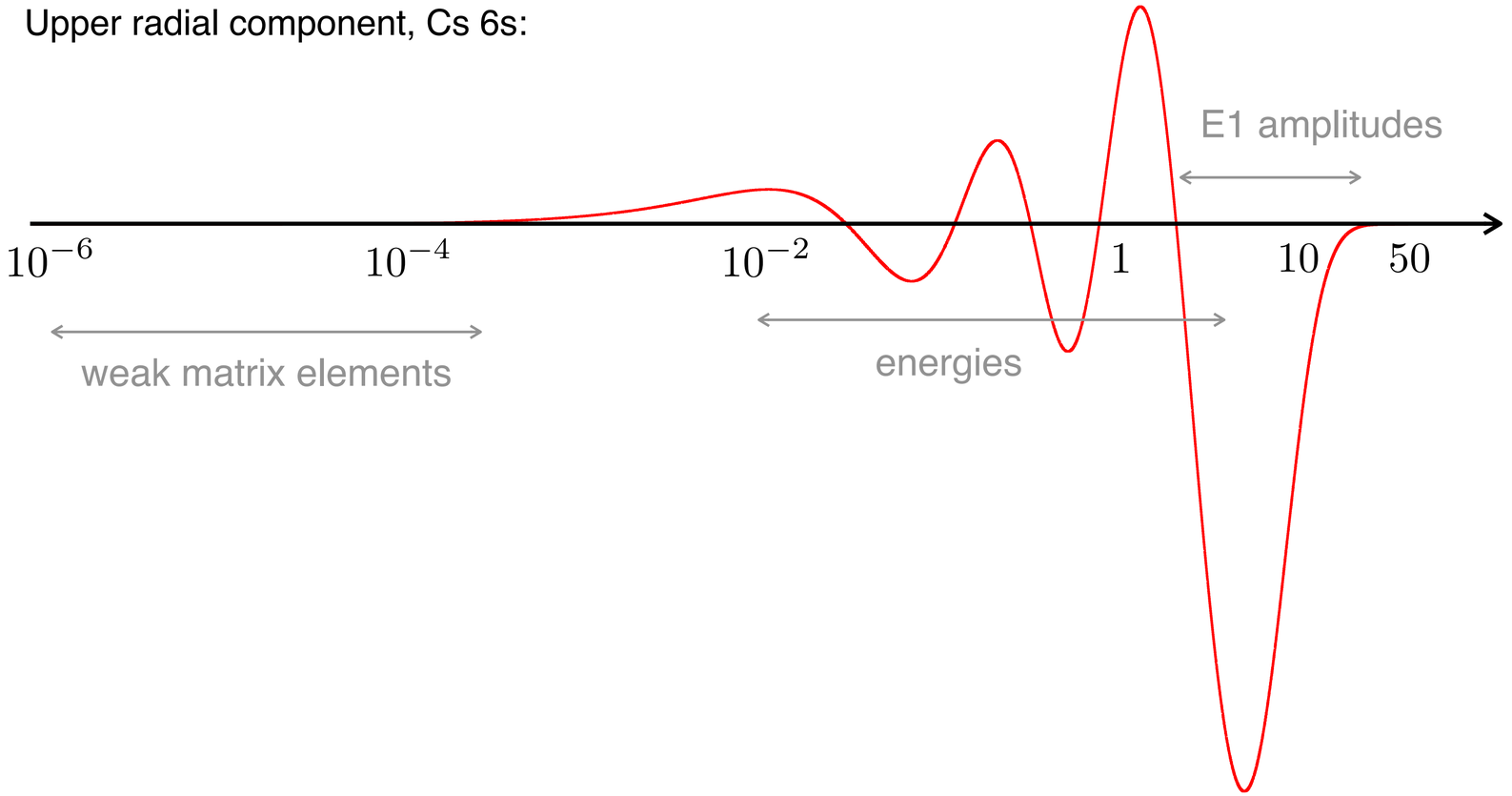

Uncertainty found from:

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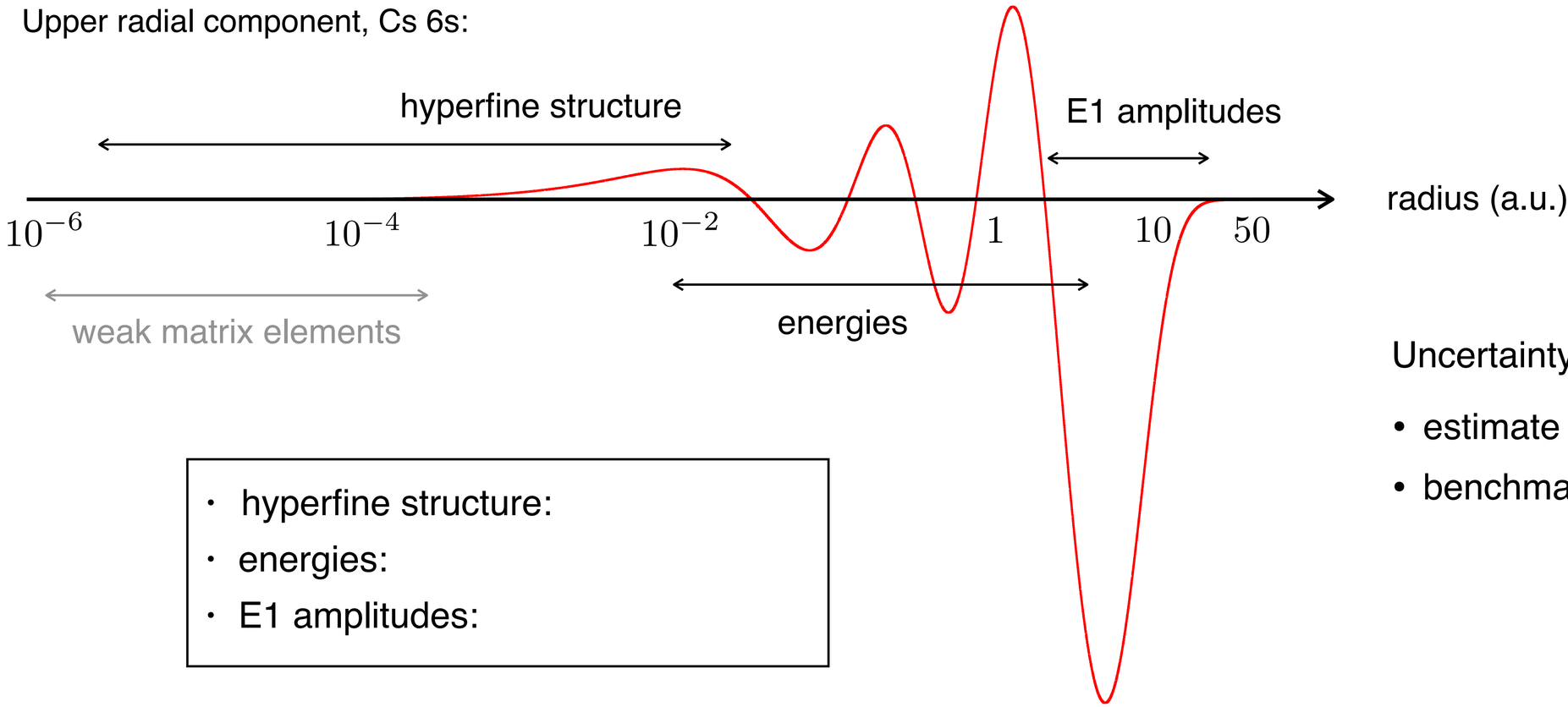

- hyperfine structure:
- energies:
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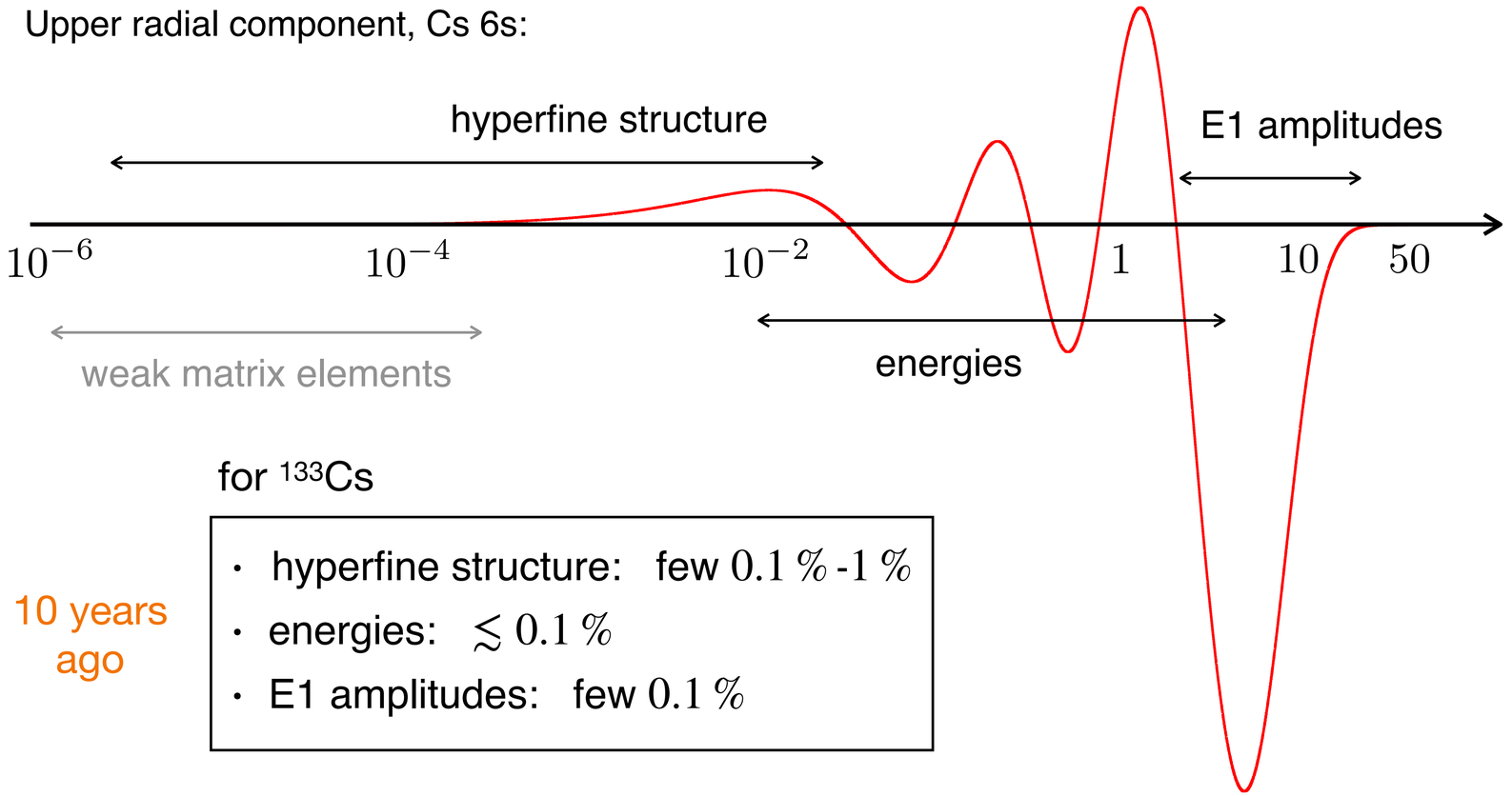

for ^{133}Cs

10 years ago

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

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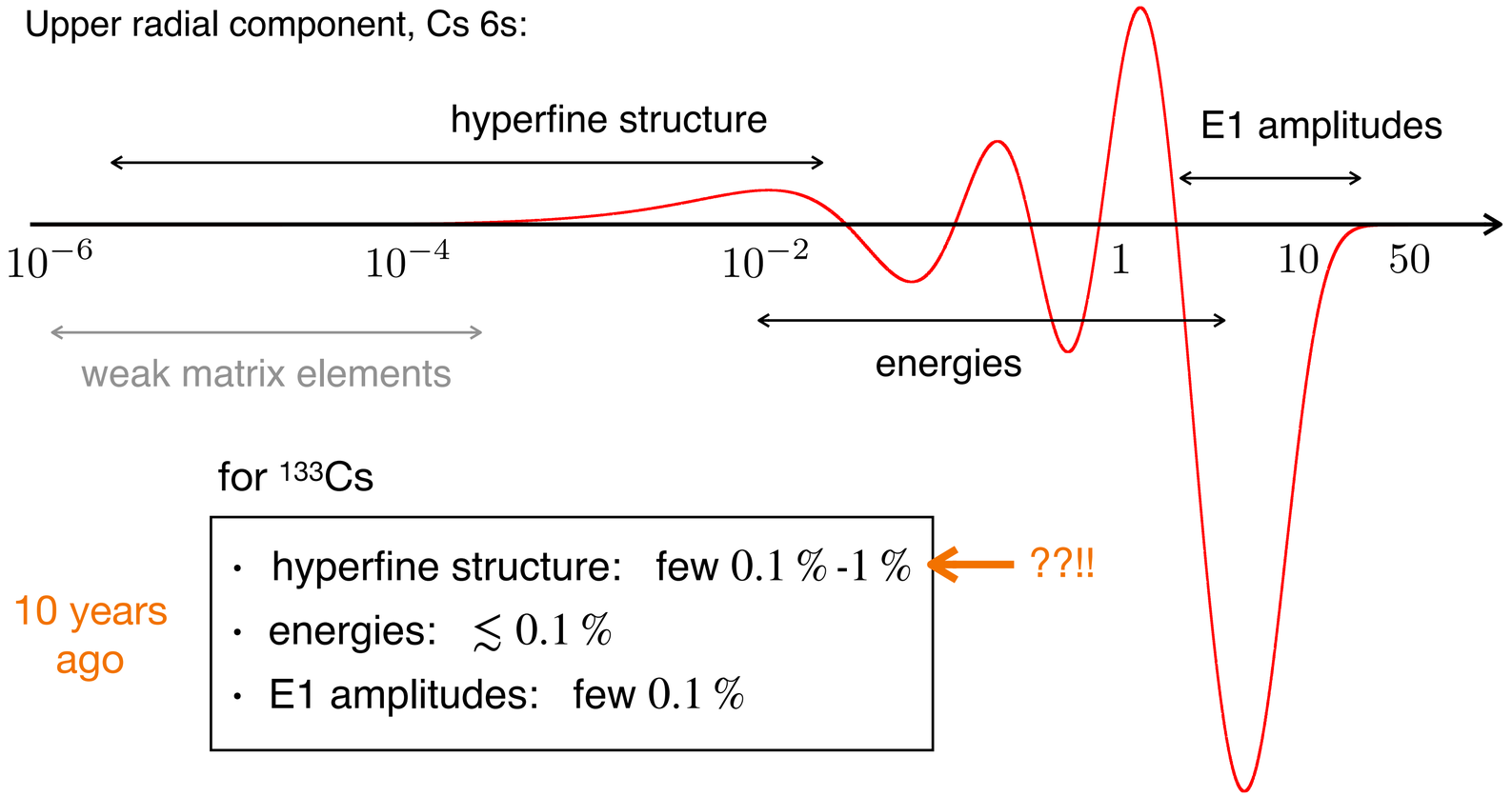

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??!!

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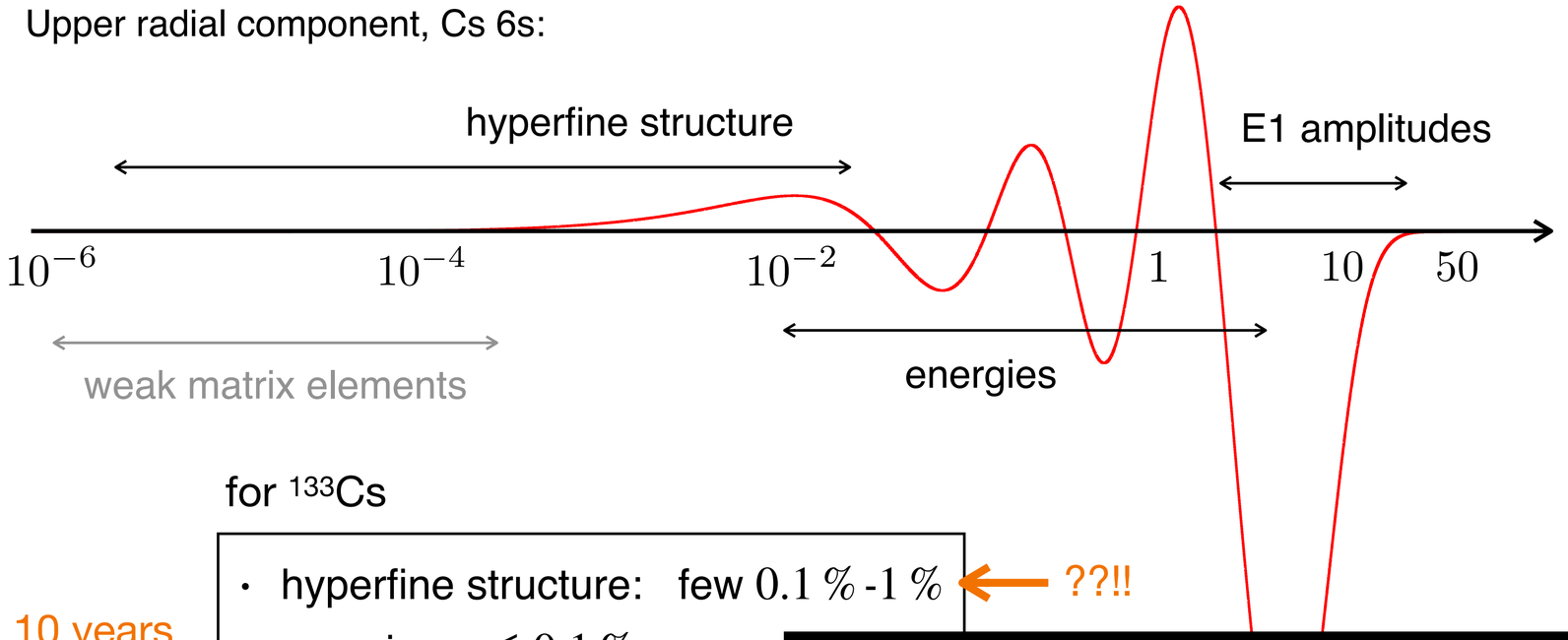

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10 years ago

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

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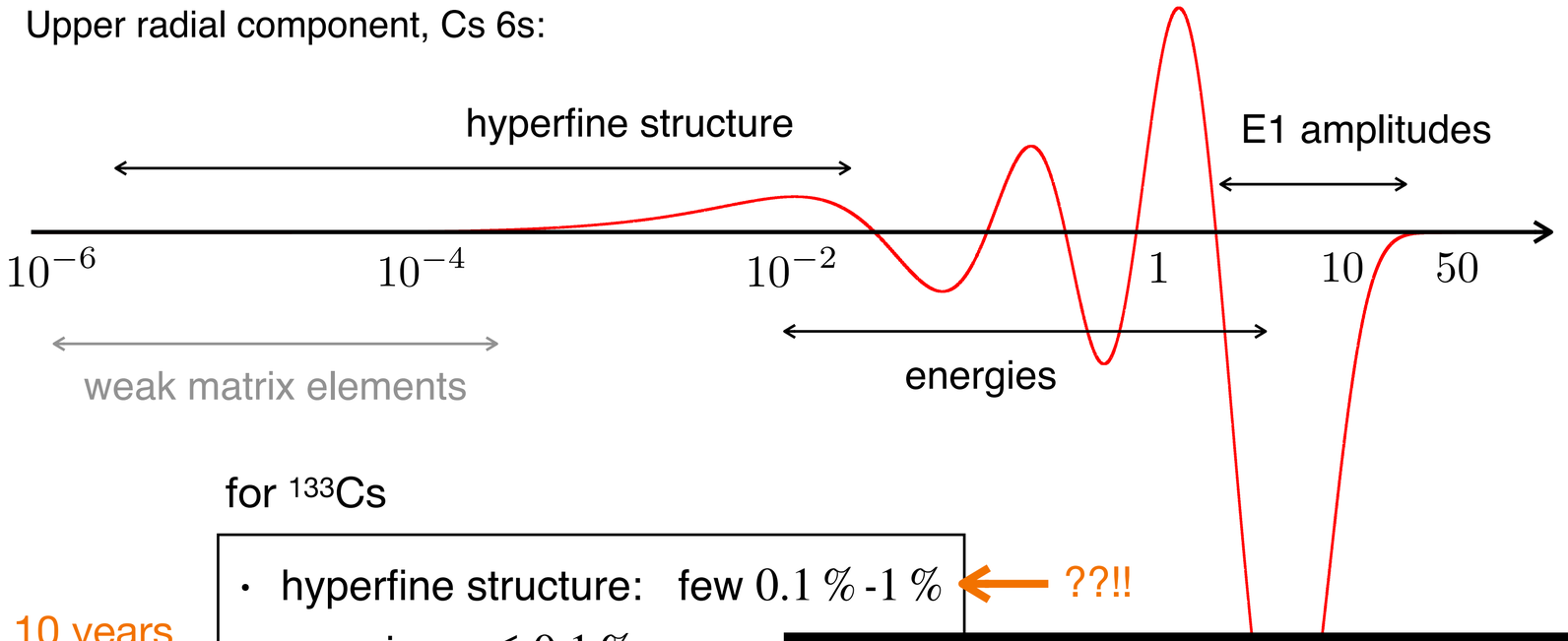

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for ^{133}Cs

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

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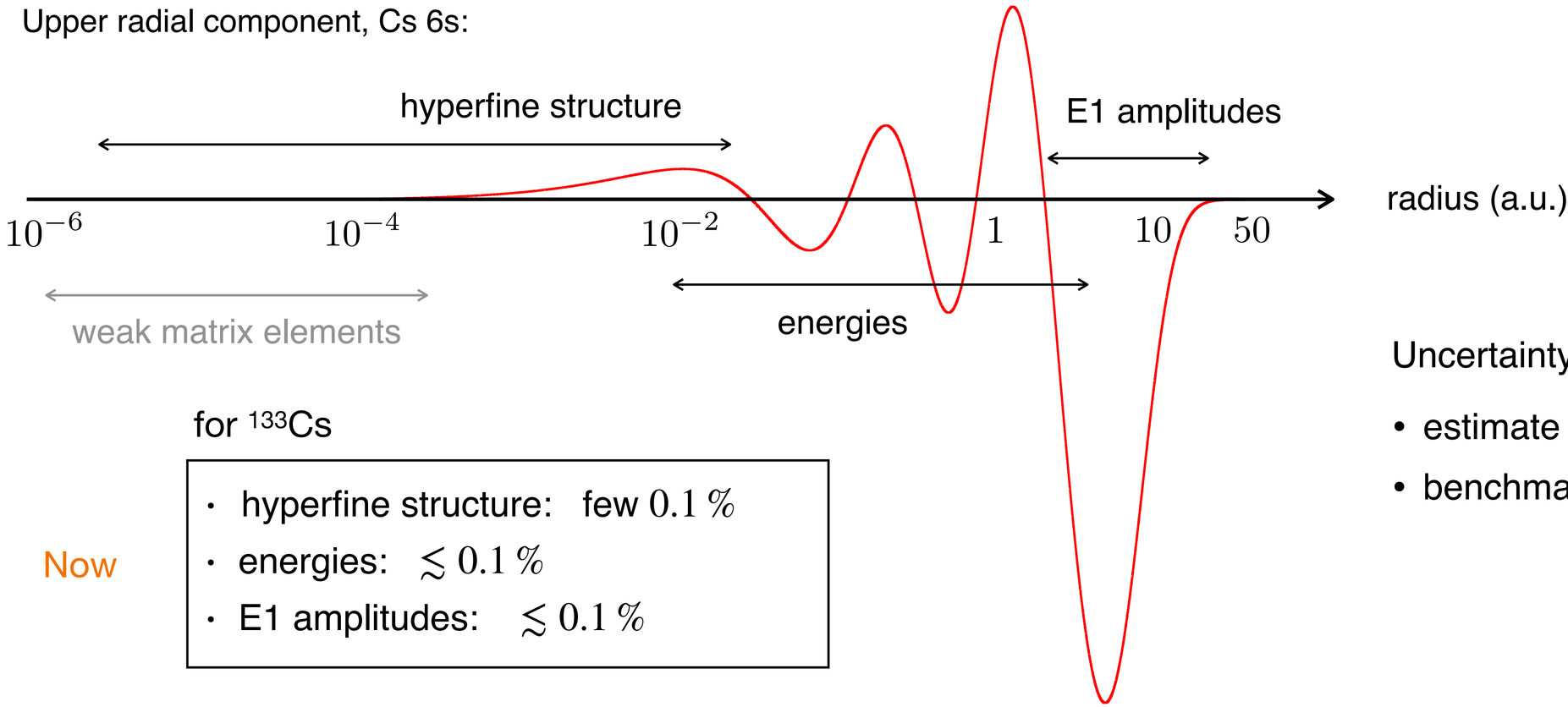

for ^{133}Cs

Now

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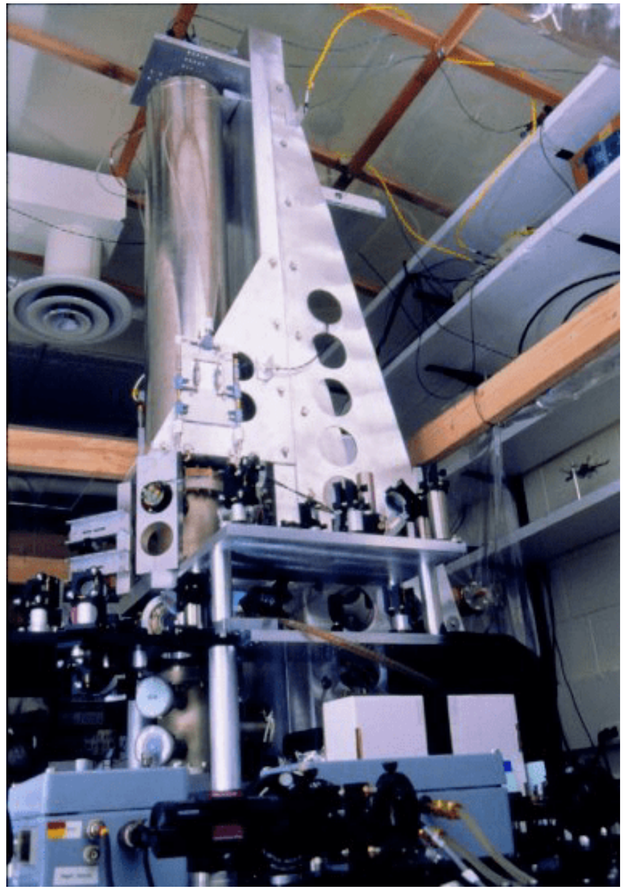
Hyperfine structure and Bohr-Weisskopf effect

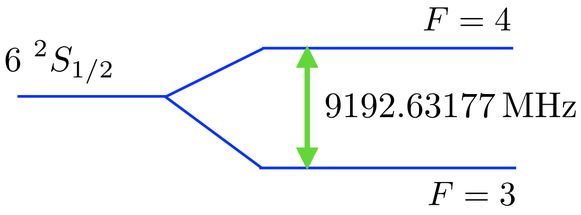
Interaction $h_{\rm hfs} = \dfrac{1}{c}\dfrac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

radial distribution of nuclear magnetic moment

^{133}Cs: $I^\pi = (7/2)^+$, $\mathbf{F} = \mathbf{I} + \mathbf{J}$

NIST-F2 Atomic clock





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radial distribution of nuclear magnetic moment

Magnetic hyperfine constant *A:*

$$\langle h_{\rm hfs}\rangle = A\big((F(F+1)-I(I+1)-J(J+1)\big)/2$$

Contributions: $A = A_0(1+\epsilon)+A_{\rm QED}$

finite nuclear charge distribution included here

Bohr-Weisskopf effect — from finite nuclear magnetization distribution

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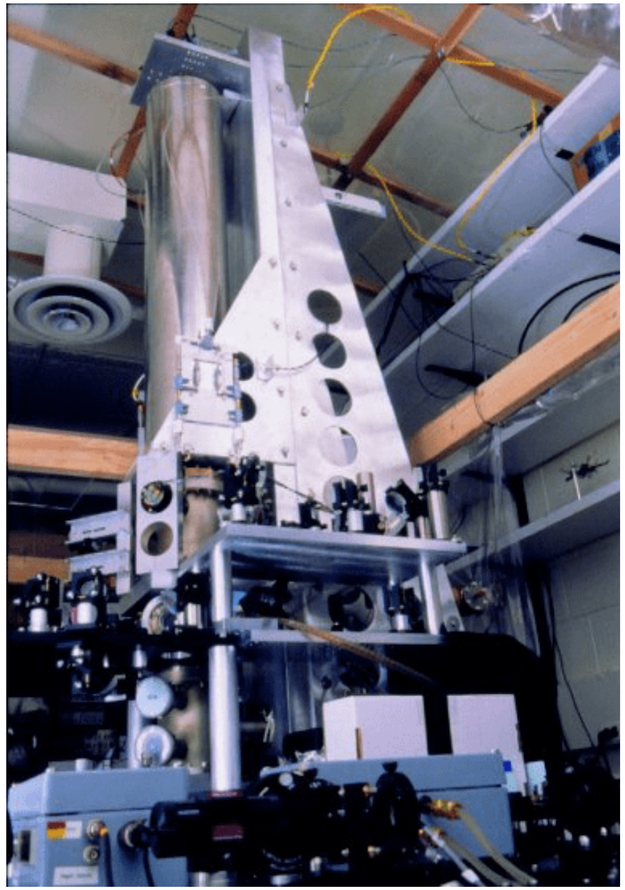

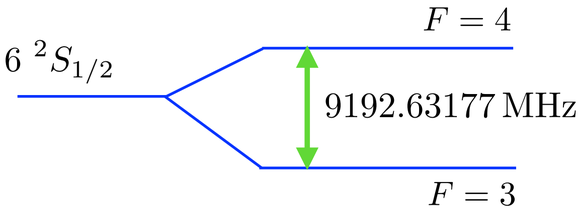

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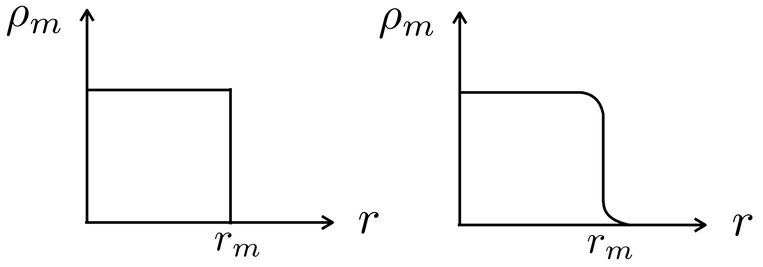
Bohr-Weisskopf effect — from finite nuclear magnetization distribution

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



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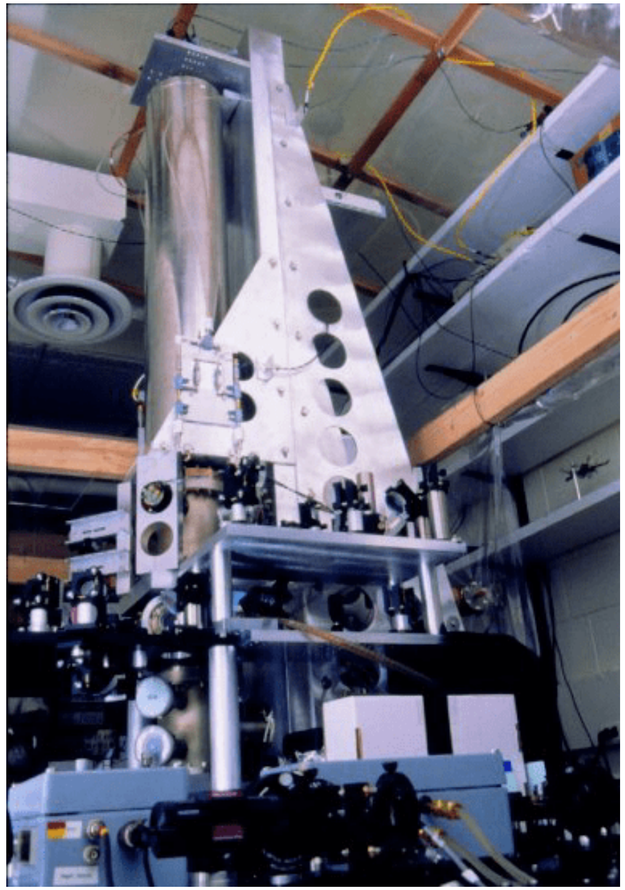
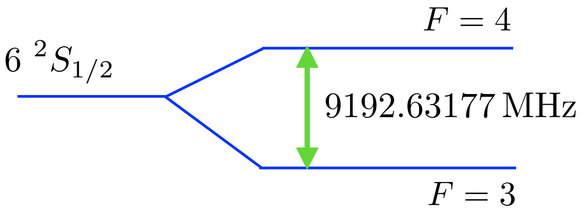
$\Rightarrow$ nuclear single-particle model

NIST-F2 Atomic clock





Hyperfine structure and Bohr-Weisskopf effect

^{133}Cs: $I^\pi = (7/2)^+$, $\mathbf{F} = \mathbf{I} + \mathbf{J}$

Interaction $$h_{\rm hfs} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$

radial distribution of nuclear magnetic moment

Magnetic hyperfine constant *A:*

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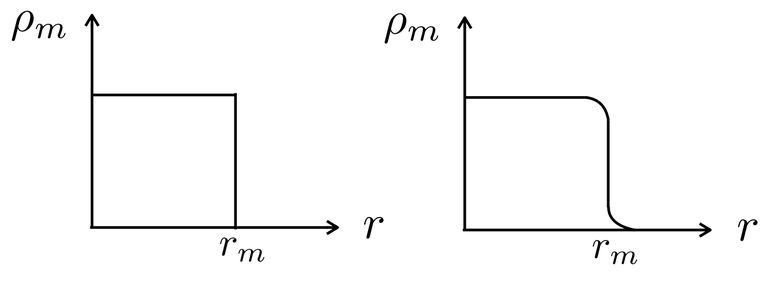

$\epsilon = -0.7\,\%$

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for ^{133}Cs 6S

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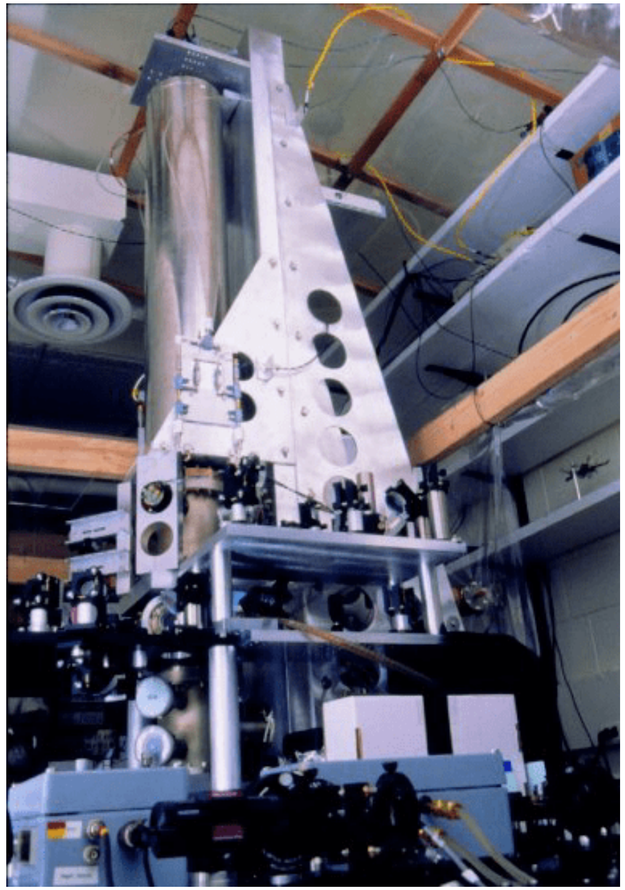

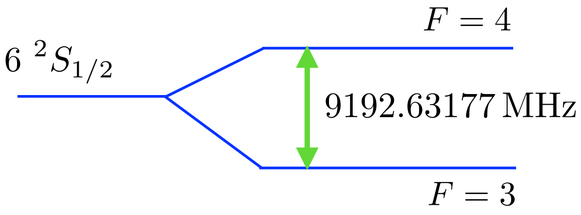

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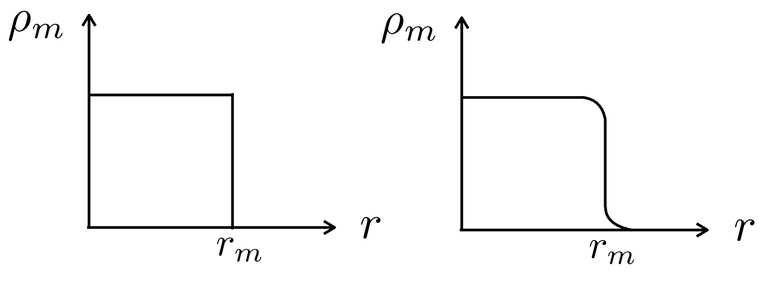

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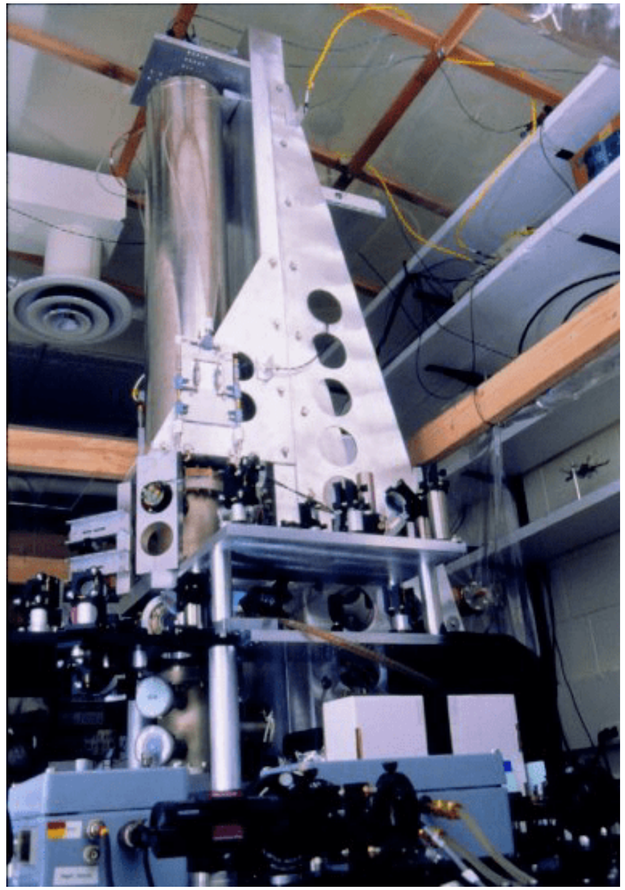

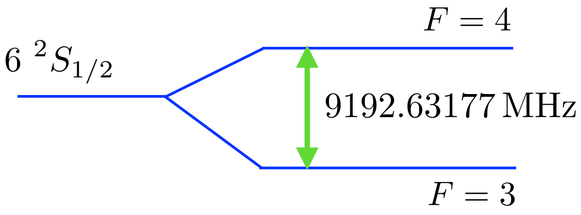

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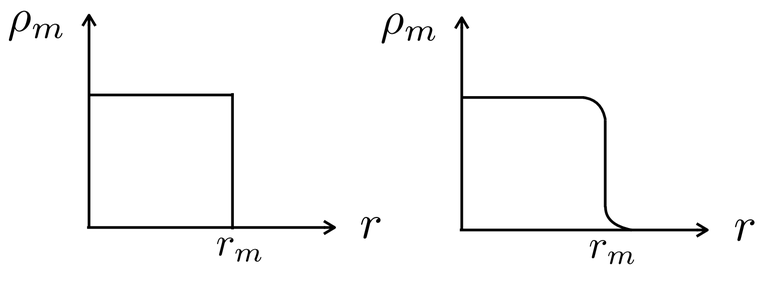

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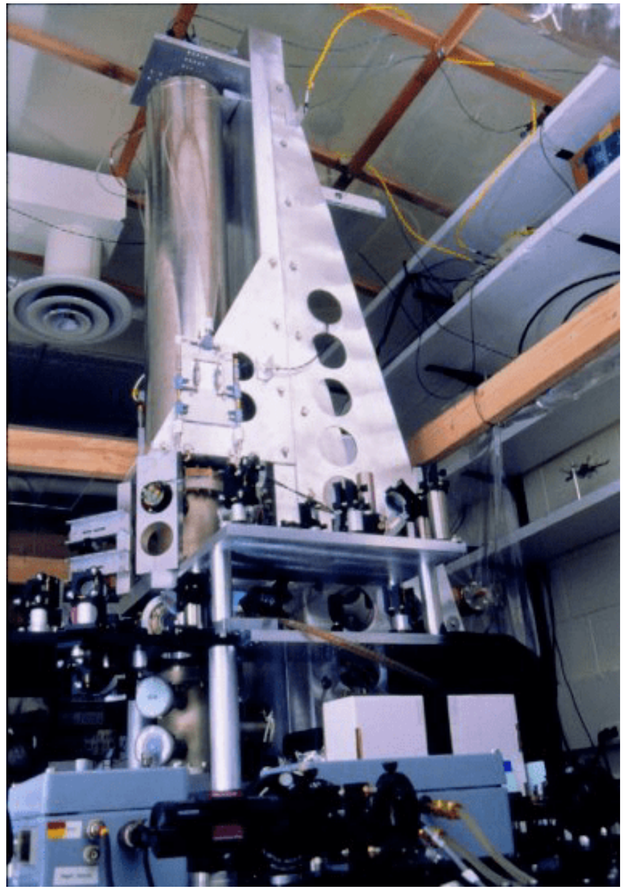

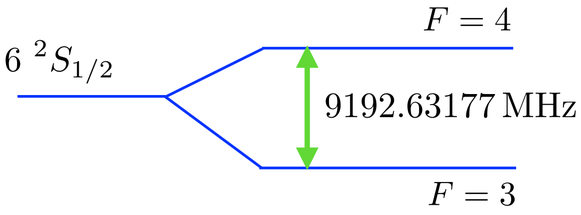

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BW effect measured in several H-like ions, e.g., ^{203,205}Tl, ^{208,209}Bi, with $\sim 1\%$ uncertainty [MPIK; GSI Darmstadt]

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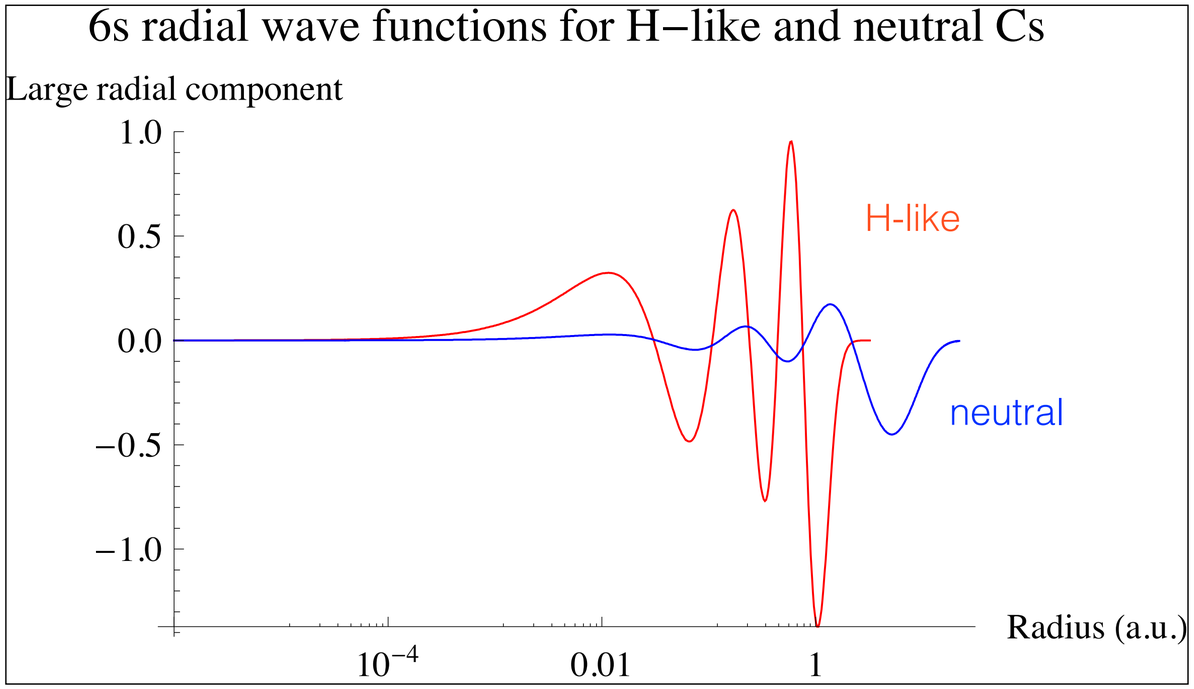

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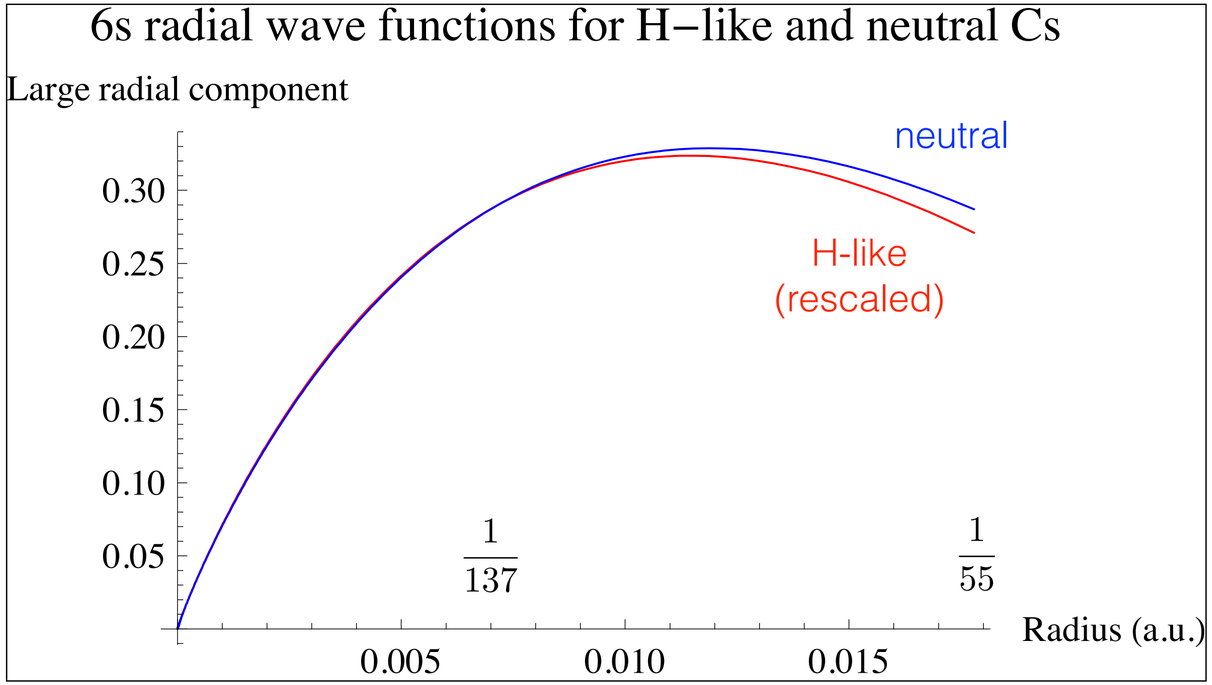

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May be used to find BW effect in many-electron atoms!

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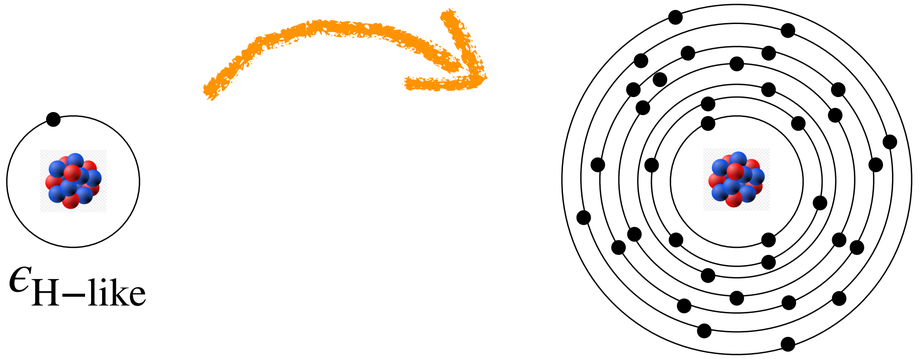
Independent of nuclear model!



Ranclaud, Honours thesis (2020)
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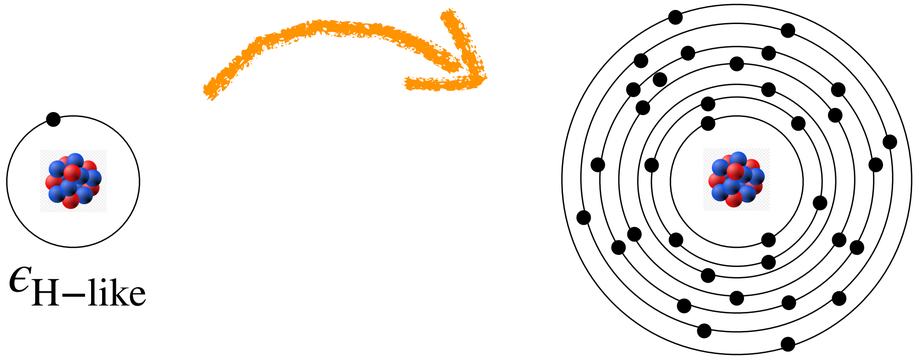

$$\epsilon_{\rm atom} = x_{\rm scr}\,\epsilon_{\rm H-like}$$

Nuclear structure uncertainty entirely removed from atomic calculations!

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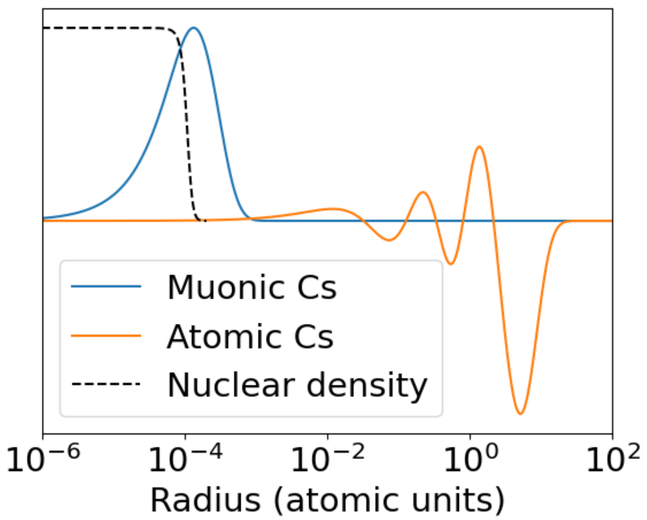

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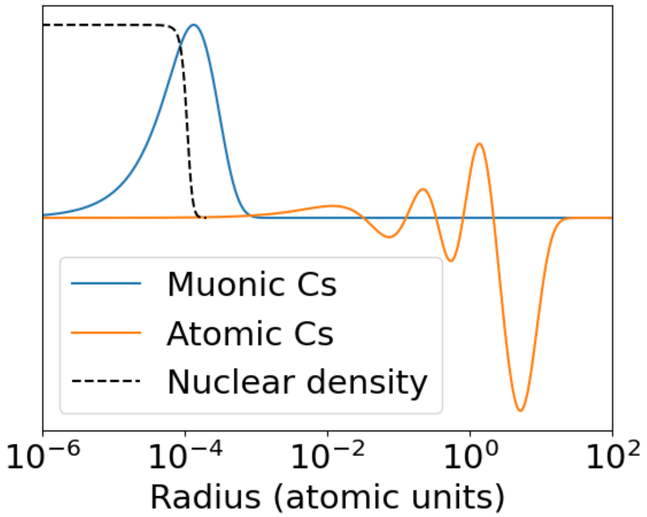

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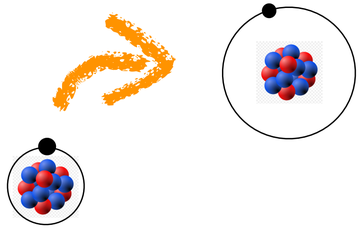

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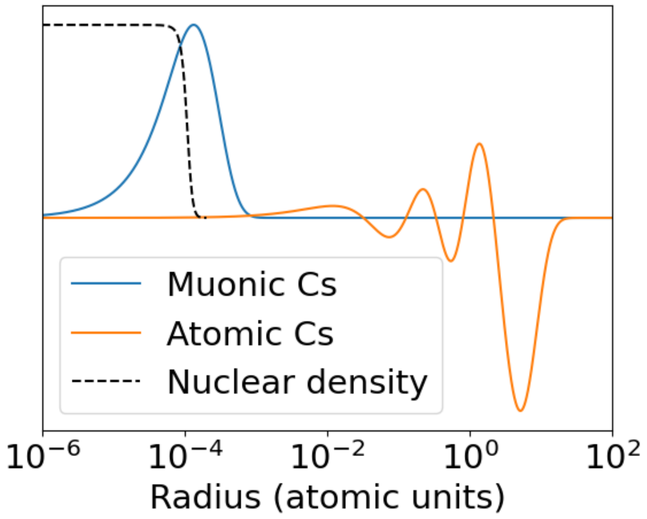

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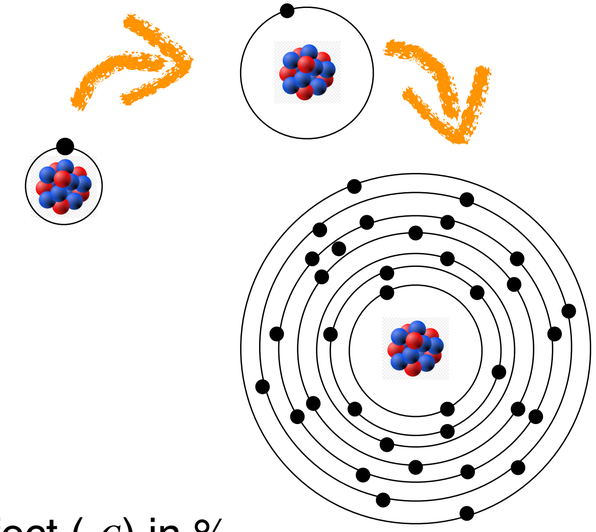

Empirically-deduced BW effect (-ϵ) in %

	μ-atoms	H-like ions		Atoms
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^{203}Tl	50.8(1.6)	1.93(15)	2.21(8)	
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c.f. Cs atom — SP: 0.21% ; SP(WS): 0.19(14)% ; uniform: 0.7%

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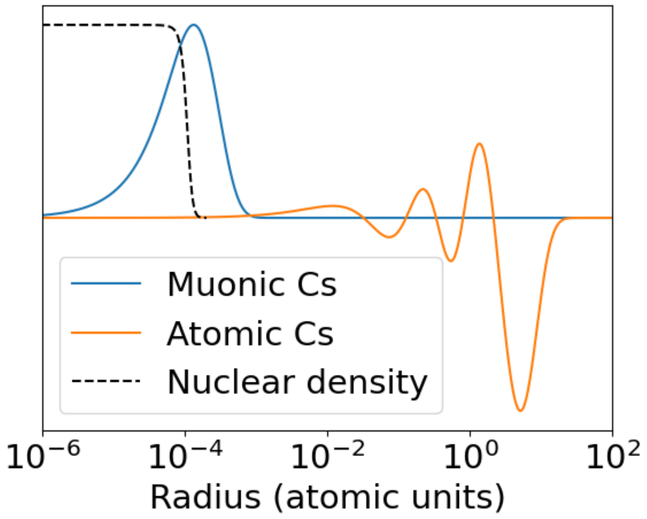

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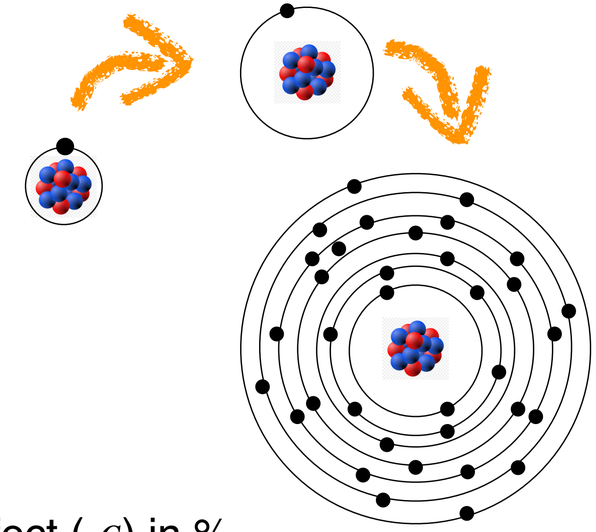

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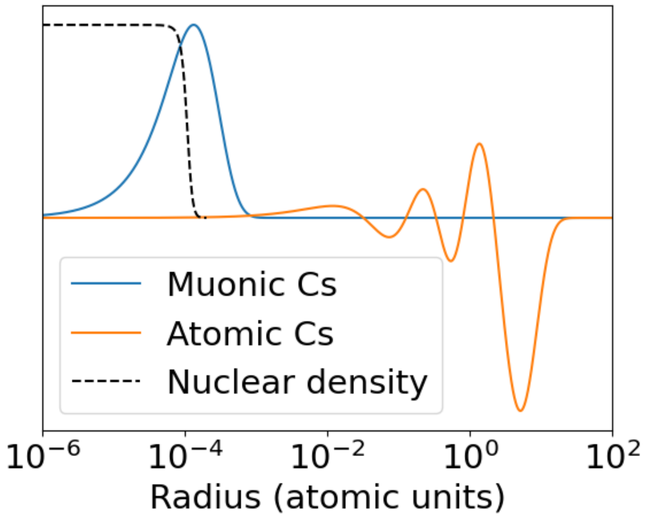

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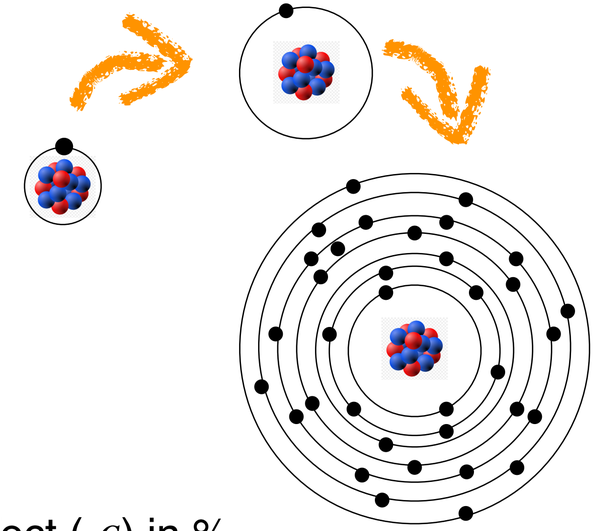

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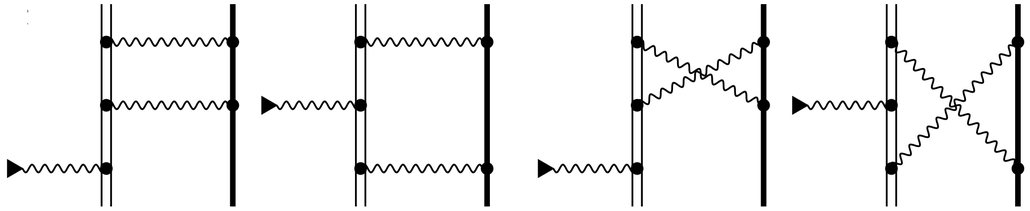
What about nuclear polarization?

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

from H-like

$$A_{\mathrm{NP}}^{\mathrm{exp}} = A_{\mathrm{exp}} - A_0 - A_{\mathrm{QED}} - A_{\mathrm{BW}}$$



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

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

Hopefully this may stimulate new experiments!

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

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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,…

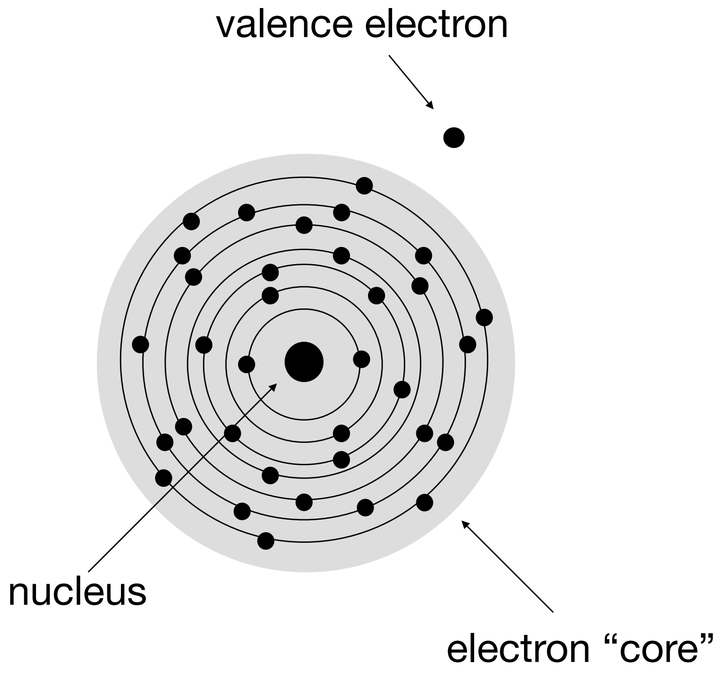
Key to supporting development of nuclear theory and increasing discovery potential in atomic and molecular experiments

Thank you!

Precision Atomic Theory Group @ UQ

A glimpse of the theory

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



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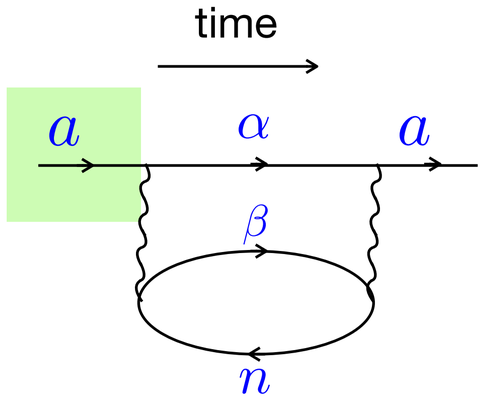

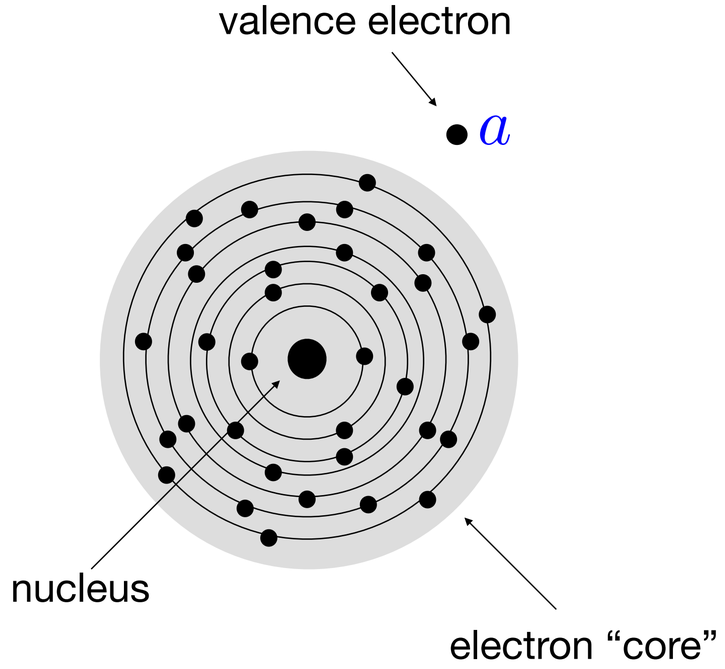

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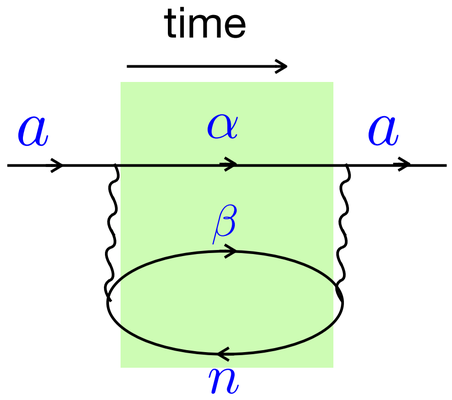

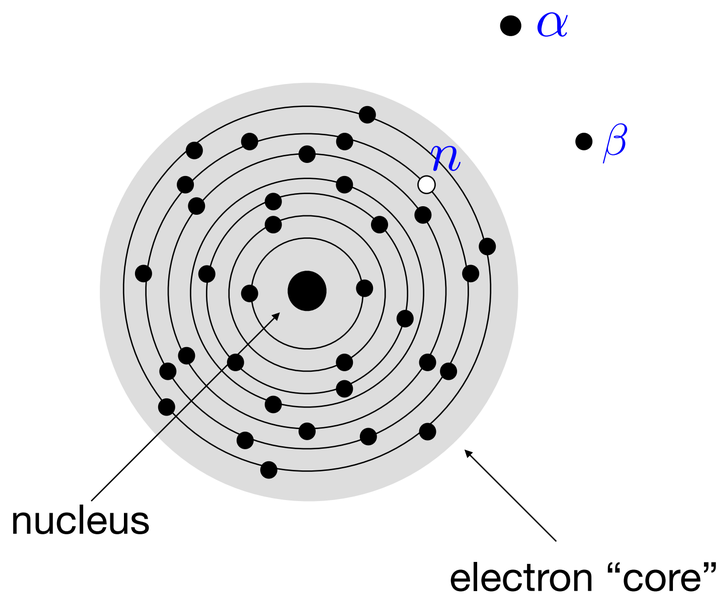

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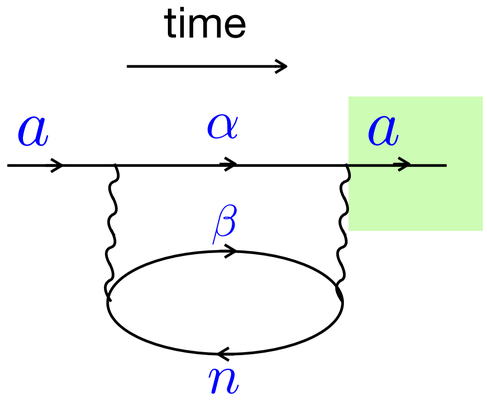

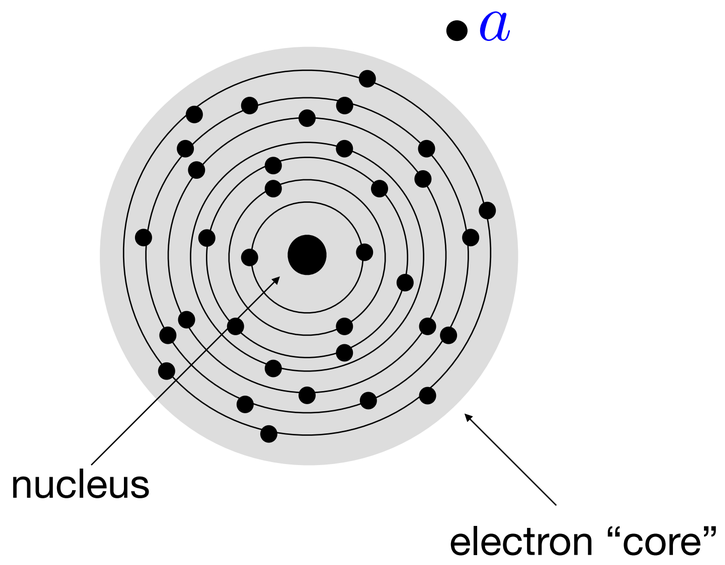

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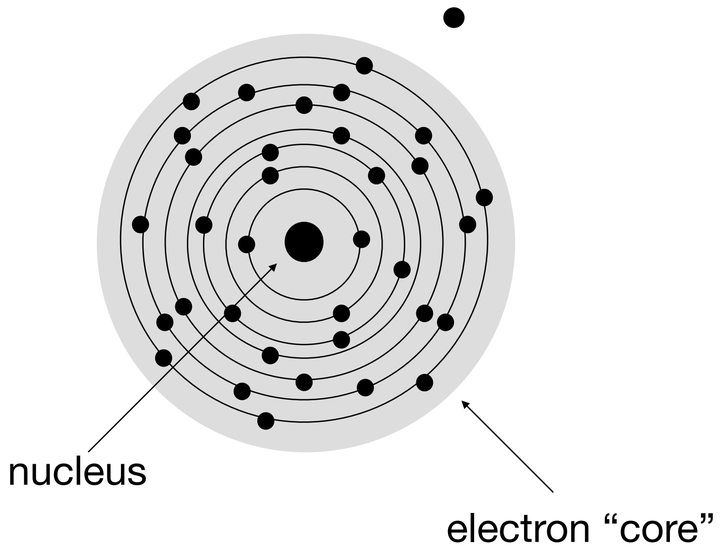

Dzuba, Flambaum, Sushkov, PLB (1989)

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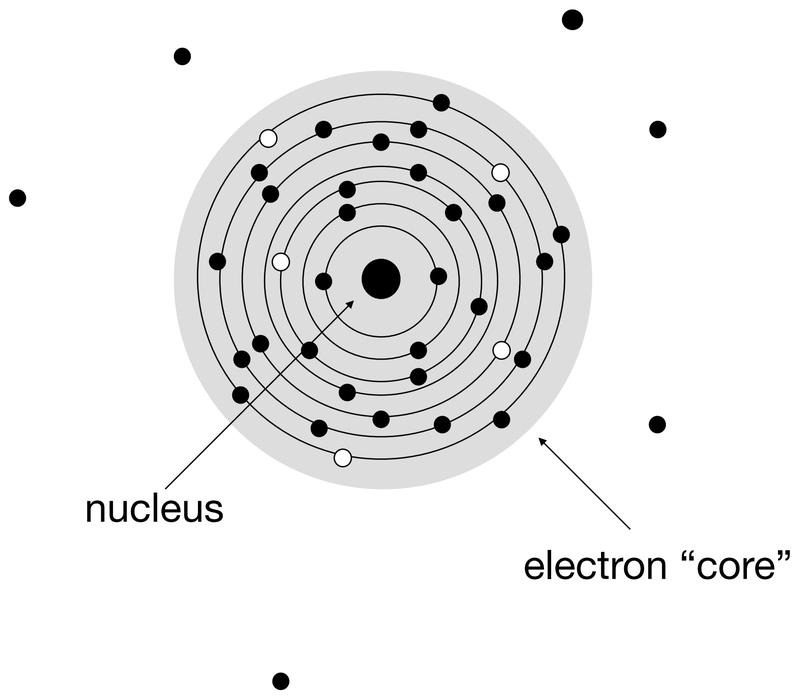

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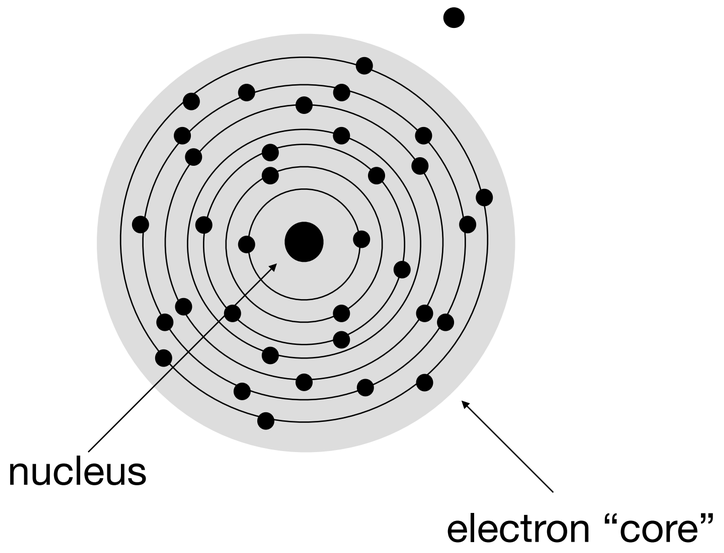

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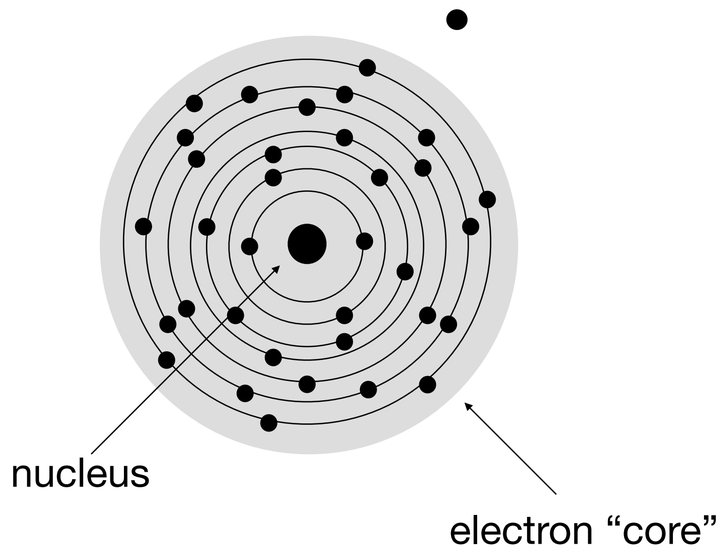

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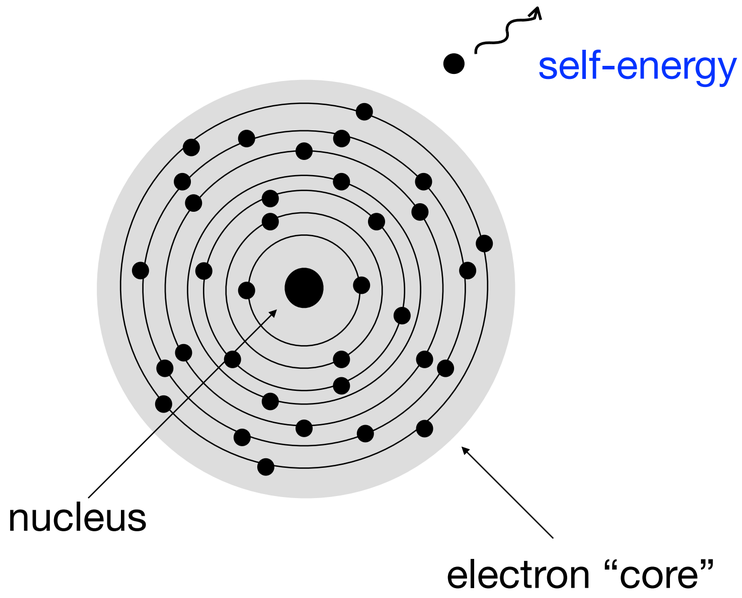

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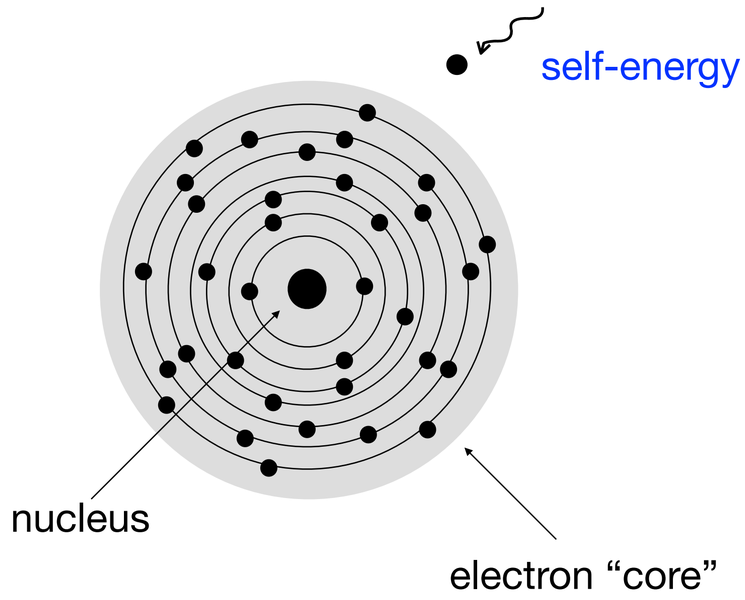

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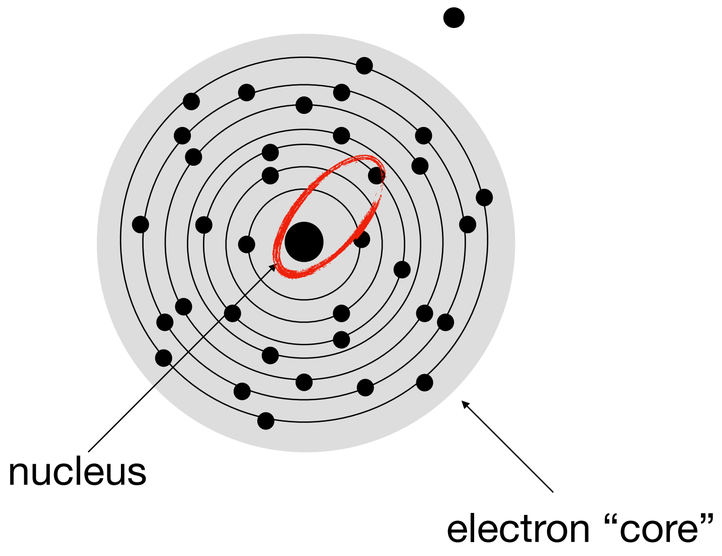

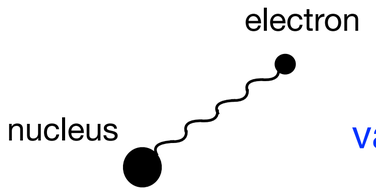

vacuum polarization

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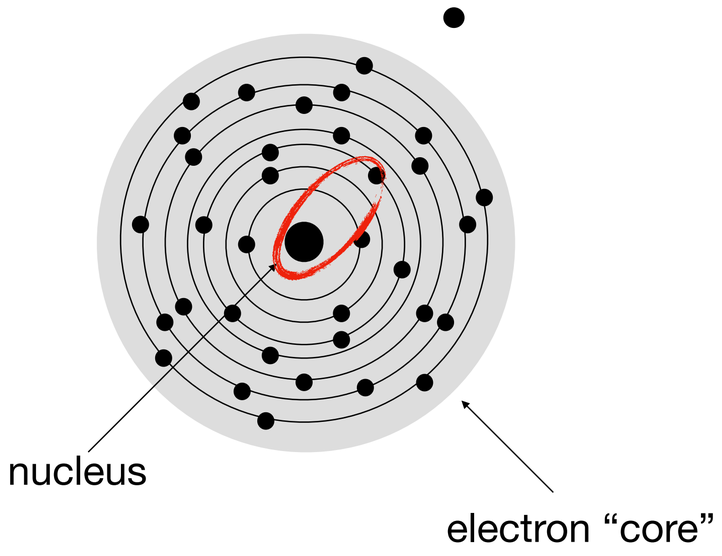

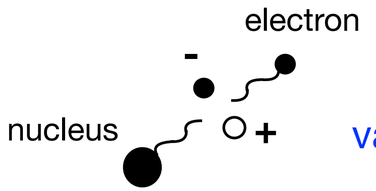

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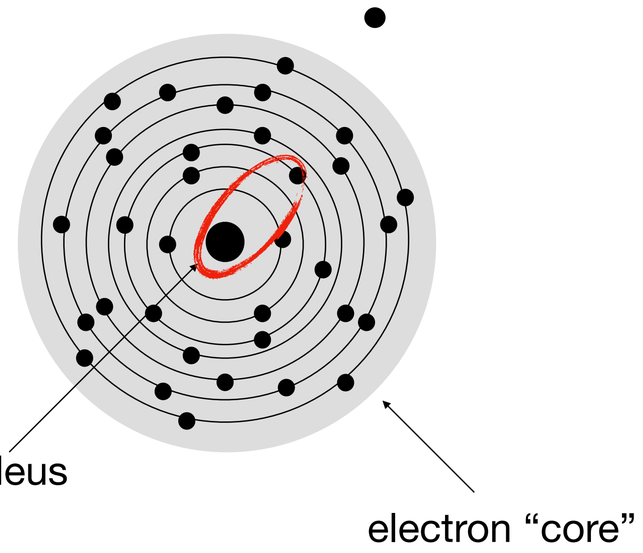

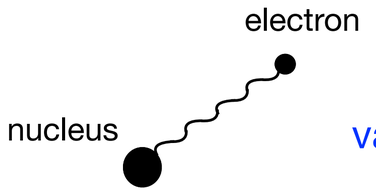

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