Atomic parity violation: Quo Vadis?

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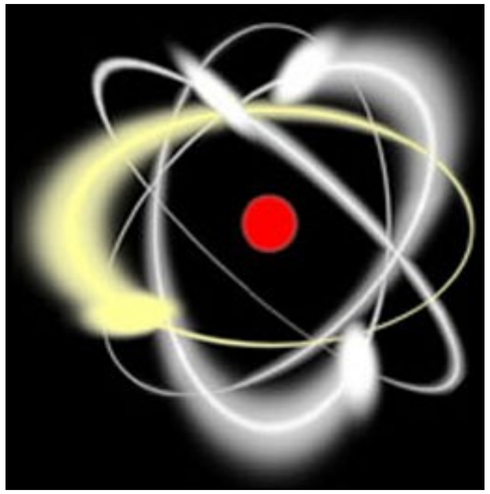
Listening to an atom



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

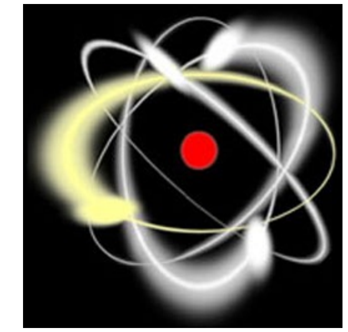
- Unprecedented control over internal and external degrees of freedom
  Atomic clocks: 18-digit spectroscopy

- ~eV energy scale => ~ TeV "new physics" scale

Outline

- Atomic parity violation (APV) overview
- Nuclear spin-dependent and spin-independent effects
- Historical notes
- Extraction of electroweak observables: precision atomic structure
- Status/outlook Cs APV

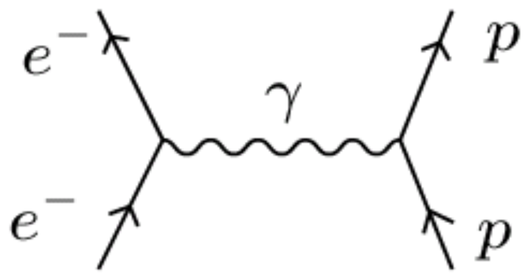
Atomic parity violation (APV)



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

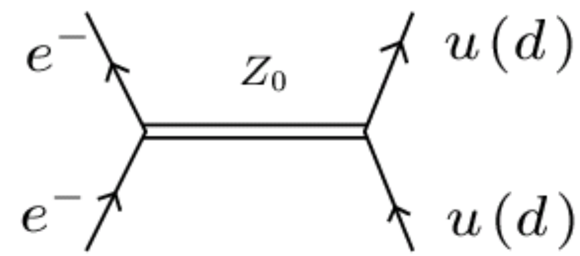
$[H_{atomic}, P]=0$ => Atomic stationary states are eigenstates of Parity

Electromagnetic



Conserve parity

Electroweak



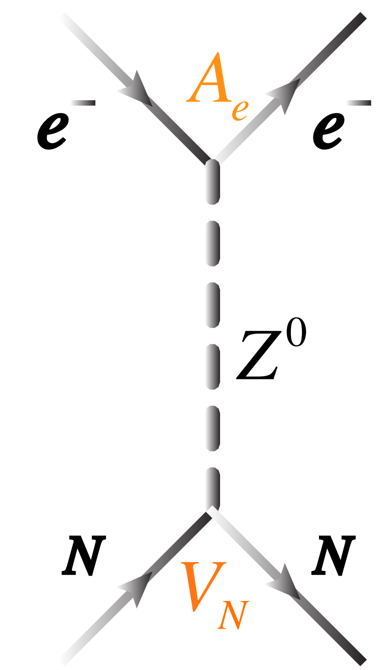
Do not conserve parity

Z-boson exchange spoils parity conservation

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

Nuclear-spin independent effects

Electron axial-vector × nucleon vector current



Averaging over quarks - effective Hamiltonian in the electronic sector

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

weak charge

neutron distribution

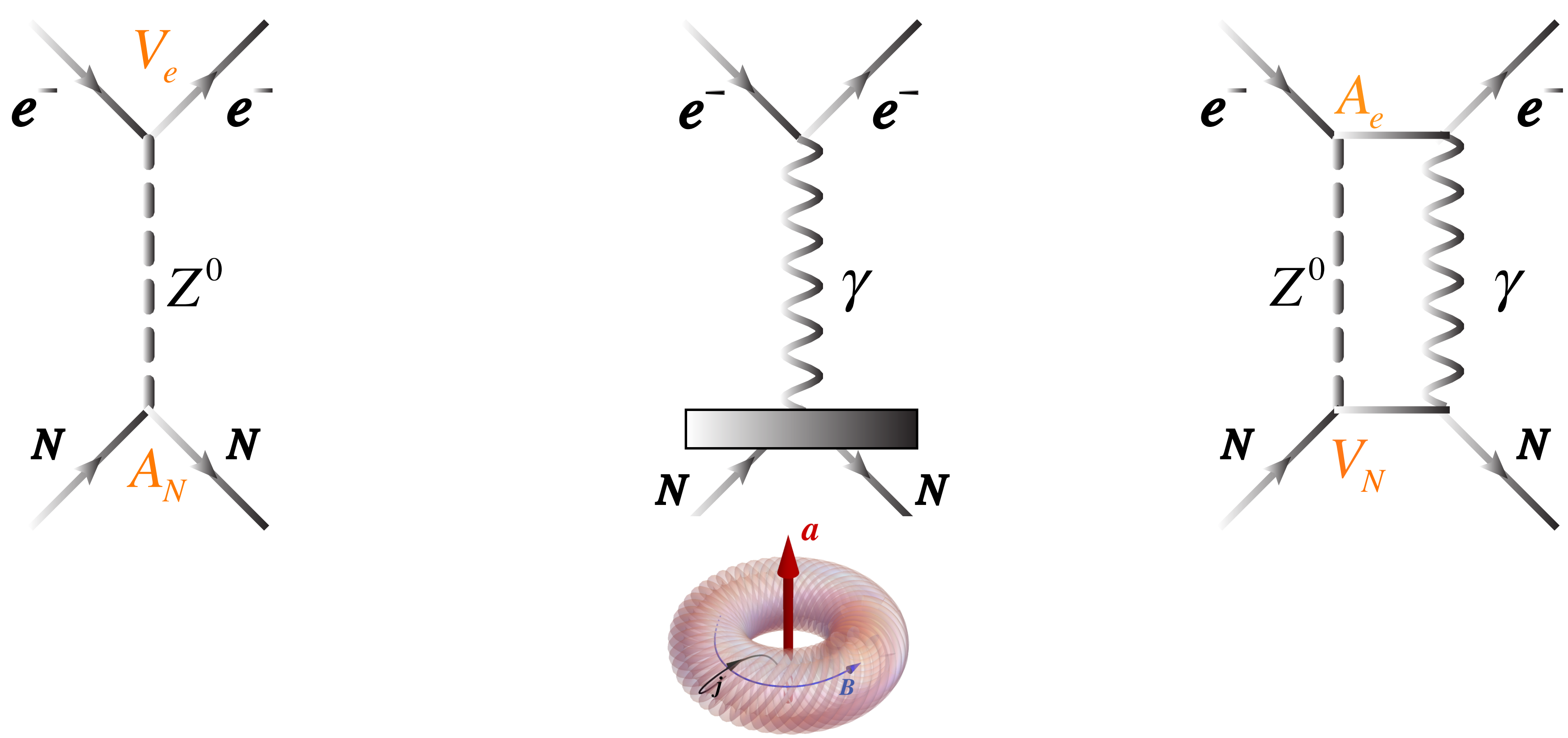
$$Q_W^{\text{tree}} = -N + Z\left(1 - 4\sin^2\theta_W\right) \approx -N$$

Nuclear spin-dependent effects

For unpaired nucleon & open-shell atom

$$H_{\mathrm{NSD}} = \frac{G_F}{\sqrt{2}} \left(\eta_{\mathrm{axial}} + \eta_{\mathrm{anapole}} + \eta_{\mathrm{hyperfine}} \right) \boldsymbol{\alpha} \cdot \mathbf{I} \rho_n(r)$$

Nuclear spin



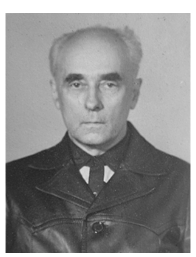
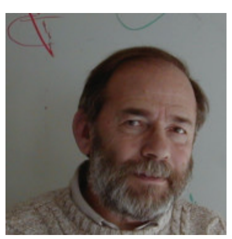
Nuclear anapole moment

APV milestones

Y. B. Zel'dovich (1959)
considers APV after discovery of weak charged currents in beta-decay.
Effect too small?
Nuclear anapole moment (1959)


M.-A. Bouchiat & C. Bouchiat (1974)

APV signal scales as Z^3 => P-violation can be observed in heavy atoms!

Barkov & Zolotarev (1978)
First APV observation in optical rotation in ^{209}Bi vapor

C. Wieman (1997)
Most precise APV measurement in ^{133}Cs (0.34%)
First experimental evidence for anapole moment

APV also observed in Yb (0.5%), Tl (1% Seattle), Pb (1%), Bi (2%)

arXiv.org > physics > arXiv:1904.00281

Physics > Atomic Physics

[Submitted on 30 Mar 2019]

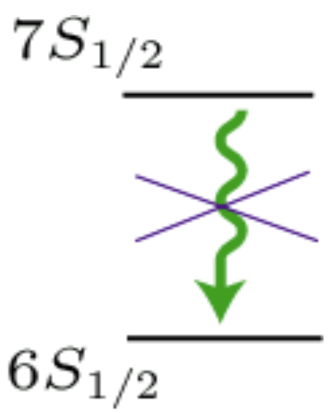
Atomic parity violation and the standard model

Carl Wieman, Andrei Derevianko

A concise review of atomic parity violation with a focus on the measurement and interpretation of parity violation in cesium.

Subjects: **Atomic Physics (physics.atom-ph)**; High Energy Physics - Phenomenology (hep-ph)

Parity-violating 7S-6S amplitude in Cs

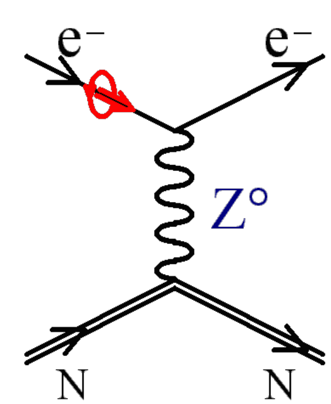


$$\langle 7S_{1/2} | D | 6S_{1/2} \rangle \equiv 0 \qquad D = \sum_{i=1}^{N} -e\,\mathbf{r}_i$$

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

Weak interaction leads to an admixture of states of opposite parity

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



Tiny effect $E_{\mathrm{PV}} \sim 10^{-11}$ atomic units

Stark amplification

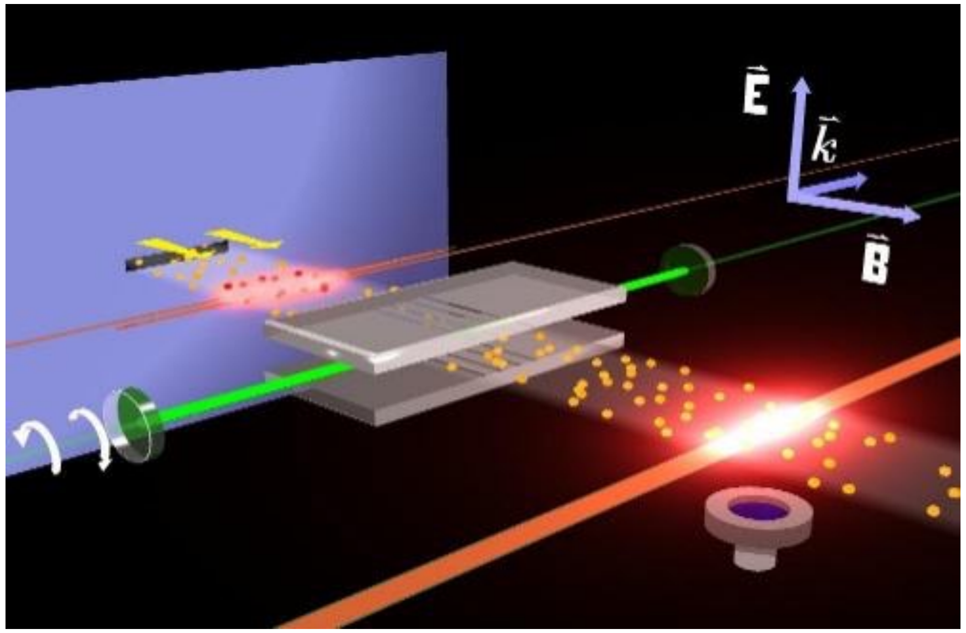
Apply electric field $\mathscr{E}$ => mixing states of opposite parity

Transition amplitude $$E_{\mathrm{tot}} = E_{\mathrm{Stark}} + E_{\mathrm{PV}}$$

Excitation rate
$6S_{1/2}\, FM \rightarrow 7S_{1/2}\, F'M'$

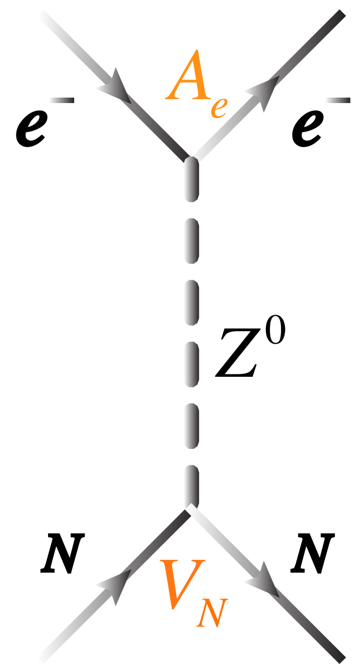
$$\mathrm{Rate} \propto |E_{\mathrm{tot}}|^2 \approx E_{\mathrm{Stark}}^2 + 2E_{\mathrm{Stark}}E_{\mathrm{PV}}$$
$$= \beta^2\mathcal{E}^2 + 2\beta\mathcal{E}\,E_{\mathrm{PV}}$$

E_{PV} is amplified by the external E-field
E_{PV} can be extracted by E-field reversals



Boulder Cs APV experiment

Weak charge extraction



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

Weak charge

neutron distribution

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

measured

computed

Signature of new physics:

$$Q_W^{\text{inferred}} = ? = Q_W^{\text{SM}}$$

Two sources of uncertainties in Q_W: experimental (E_{PV}) and theoretical (k_{PV})

Weak charge of ^{133}Cs (as of 1999)

1997: measurement expt error 0.34% while theory (Notre Dame/Novosibirsk) error 1%

1999: Bennett & Wieman : reanalysis of the PV measurement+ reduction of theory error

$$\left.\begin{array}{ll}\text{Atomic Experiment} & E_{\mathrm{PV}} \\ \text{Atomic Structure Theory} & E_{\mathrm{PV}}/Q_W\end{array}\right\} \Rightarrow Q_W^{\text{inferred}} = -72.06(28)_{\text{expt}}(34)_{\text{theor}}$$

Standard Model $\quad Q_W^{\mathrm{SM}} = -73.09(3)$

$$Q_W^{\text{inferred}} \neq Q_W^{\mathrm{SM}}$$

2.5σ deviation (??? new physics, other corrections ???)

New physics scenarios:

extra Z-bosons, scalar leptoquarks, four-fermion contact interactions, etc

Experiment: Wood *et al*. (1997); Bennett and Wieman (1999) (Boulder group)
Theory: Dzuba, Sushkov, Flambaum (1989); Blundell, Johnson, and Sapirstein (1990).
SM calculations: Marciano and Rosner PRL (1990); Groom *et al* Eur. Phys. J (2000)

Reconciliation of the Measurement of Parity Nonconservation in Cs with the Standard Model

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(Received 29 November 1999; revised manuscript received 8 May 2000)

Contributions from the Breit interaction in atomic structure calculations account for 1.3σ of the previously reported 2.5σ deviation from the standard model in the ^{133}Cs weak charge [S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. **82**, 2484 (1999)]. The updated corrections for the neutron distribution reduce the discrepancy further to 1.0σ. The updated value of the weak charge is $Q_W(^{133}\mathrm{Cs}) = -72.65(28)_{\mathrm{expt}}(34)_{\mathrm{theor}}$.

Weak charge of ^{133}Cs (as of 2005)

$$\sigma = 0.53\% \quad (\sigma_{\text{expt}} = 0.35\%, \sigma_{\text{theor}} = 0.4\%)$$

1999 Based on decade-old calculations by Dzuba *et al.* and Blundell *et al.*	2.5σ	Bennett & Wieman 1999
Breit interaction	-1.2σ	Derevianko (2000)
QED: Vacuum polarization ($+0.8\ \sigma$) Vertex/self-energy ($-1.3\ \sigma$)	-0.5σ	Johnson *et al.* (2002);Milstein & Sushkov (2002);Kuchiev & Flambaum (2002);Sapirstein *et al.* (2003);Shabaev *et al.* (2005)
Neutron skin	-0.4σ	Derevianko (2002)
Updated correlated value and vec. trans. polarizability	$+0.7\sigma$	Dzuba, Flambaum & Ginges (2002)
PV e-e, renormalization $q \rightarrow 0$, virtual exc. of the giant nuc. res.	$-0.08\ \sigma$	Sushkov & Flambaum (1978) Milstein, Sushkov&Terekhov (2002)
Total deviation	$1.0\ \sigma$	

Next step (2000-2010)

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

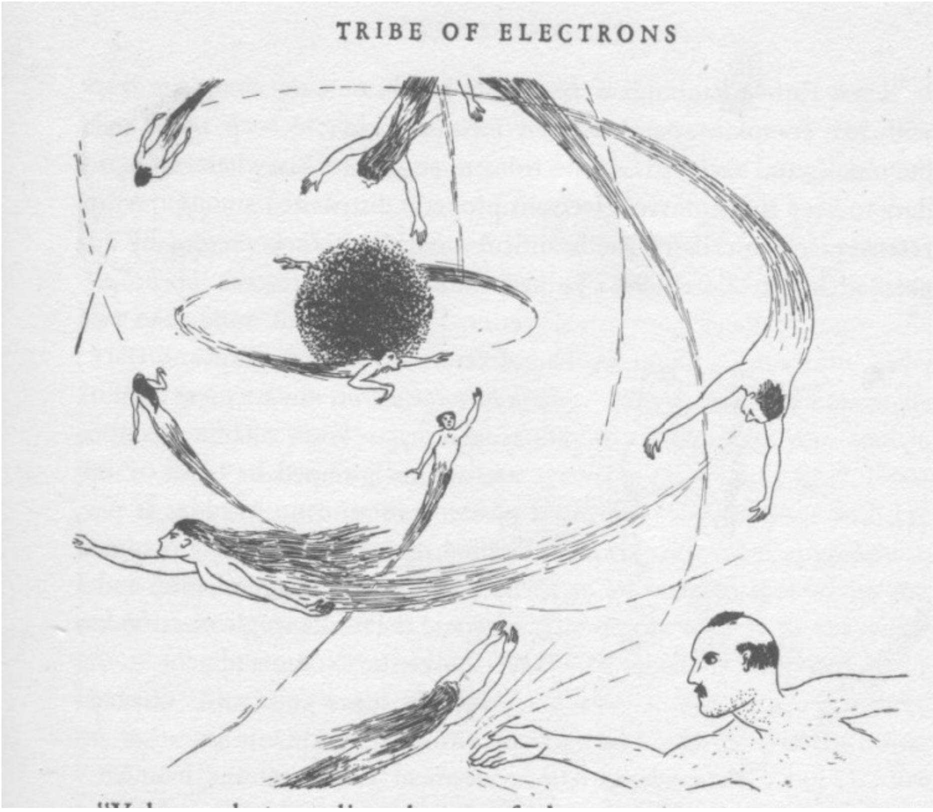
$$\sigma_{\text{expt}} = 0.35\% < \sigma_{\text{theor}} = 0.5\%$$

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

Why is it so difficult?

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

# of points in Hilbert space 10^{165}



Exceeds estimated number of atoms in the observable Universe

Requirements to atomic-structure calculations

- Weak interaction occurs in the nucleus

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

Ab initio relativistic calculations based on Dirac equation

- Calculations should have uncertainty better than 0.35%

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

Many-body perturbation theory

Treat interaction beyond the Hartree-Fock as a perturbation

Our CCSDvT method

- ⇨ *Ab initio* relativistic many-body method
- ⇨ Based on coupled-cluster all-order scheme (additional inclusion of triple excitations + non-linear terms+…) CCSDvT
- ⇨ 1,000-fold increase in computational complexity over previous calculations (100 Mb →100 Gb)
- ⇨ Code quality control: two persons + symbolic tools
- ⇨ Exact for 3e lithium: 0.01% accuracy demonstrated

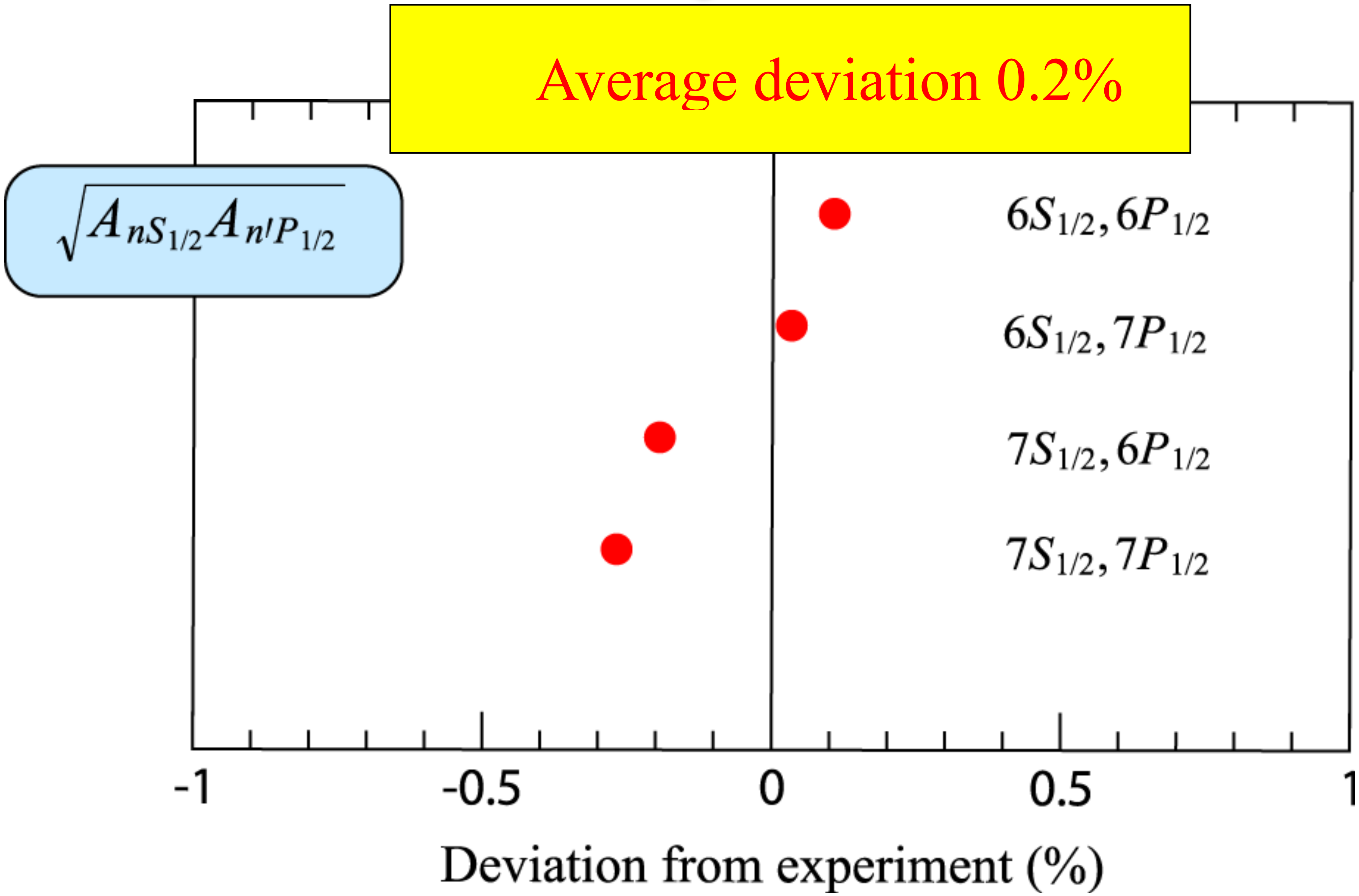
PV amplitude

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

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

Accuracy is important

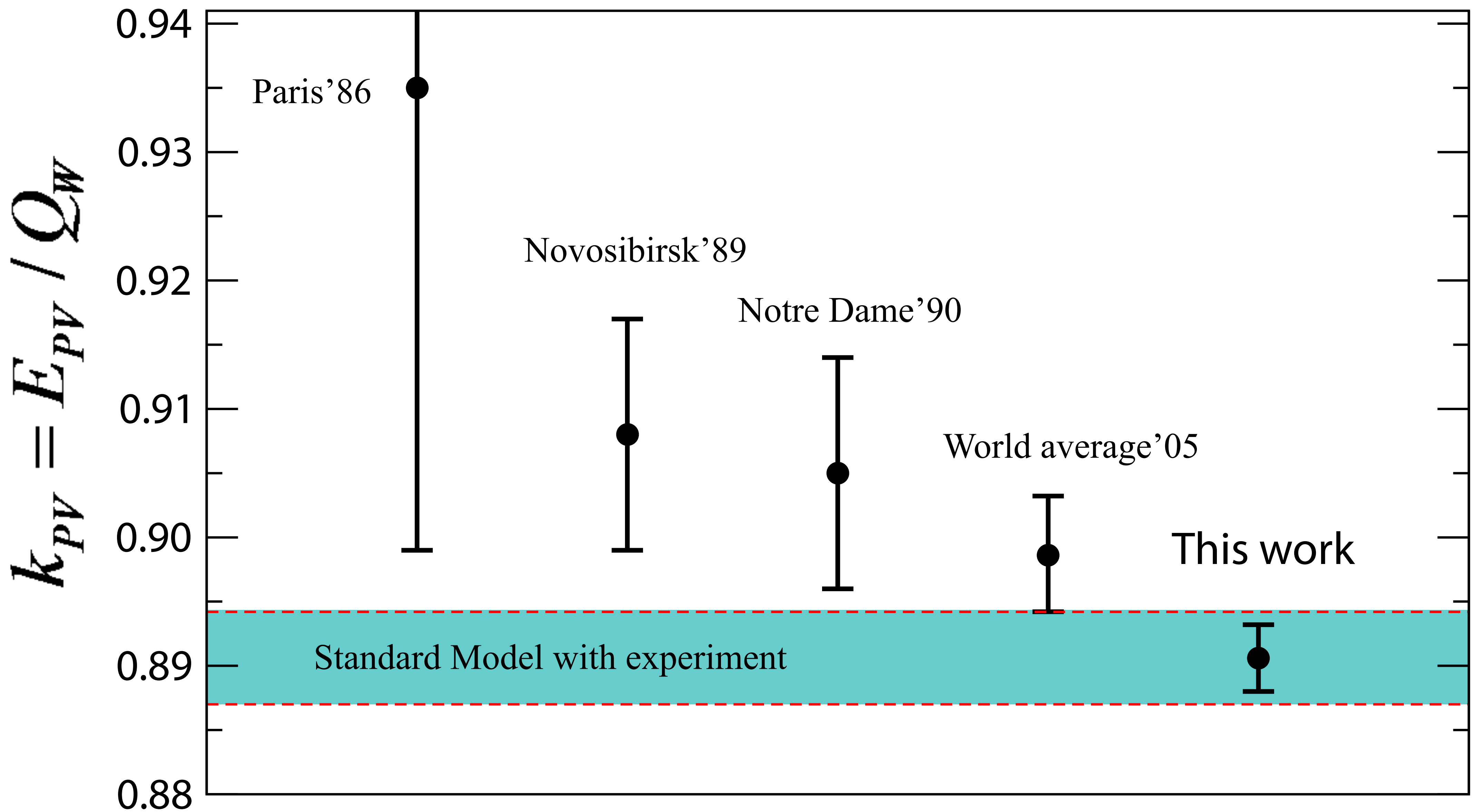
Theoretical accuracy: weak interaction



Similar tests - dipole matrix elements and energies

Status as of 2010

Factor of two reduction in theoretical error + shift of the central value



S. G. Porsev, K. Beloy and A. Derevianko, Phys. Rev. Lett. 102, 181601 (2009)
S. G. Porsev, K. Beloy and A. Derevianko, Phys. Rev. D 82, 036008 (2010)

2020: Motivations to revisit APV in Cs

(1) Tension for the ^{133}Cs anapole moment with the nuclear theory

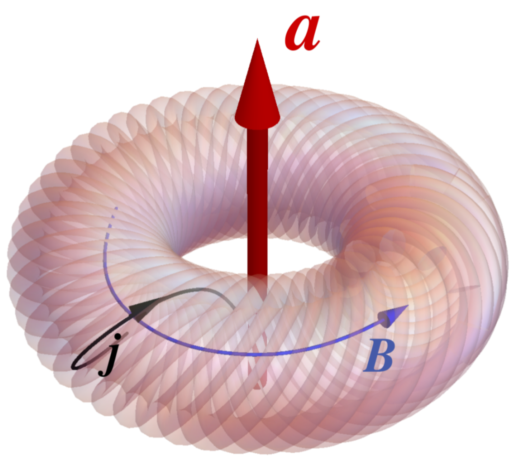
(2) Tension for supporting quantities (vector transition polarizability)

(3) More accurate experimental results for dipole matrix elements [Purdue]

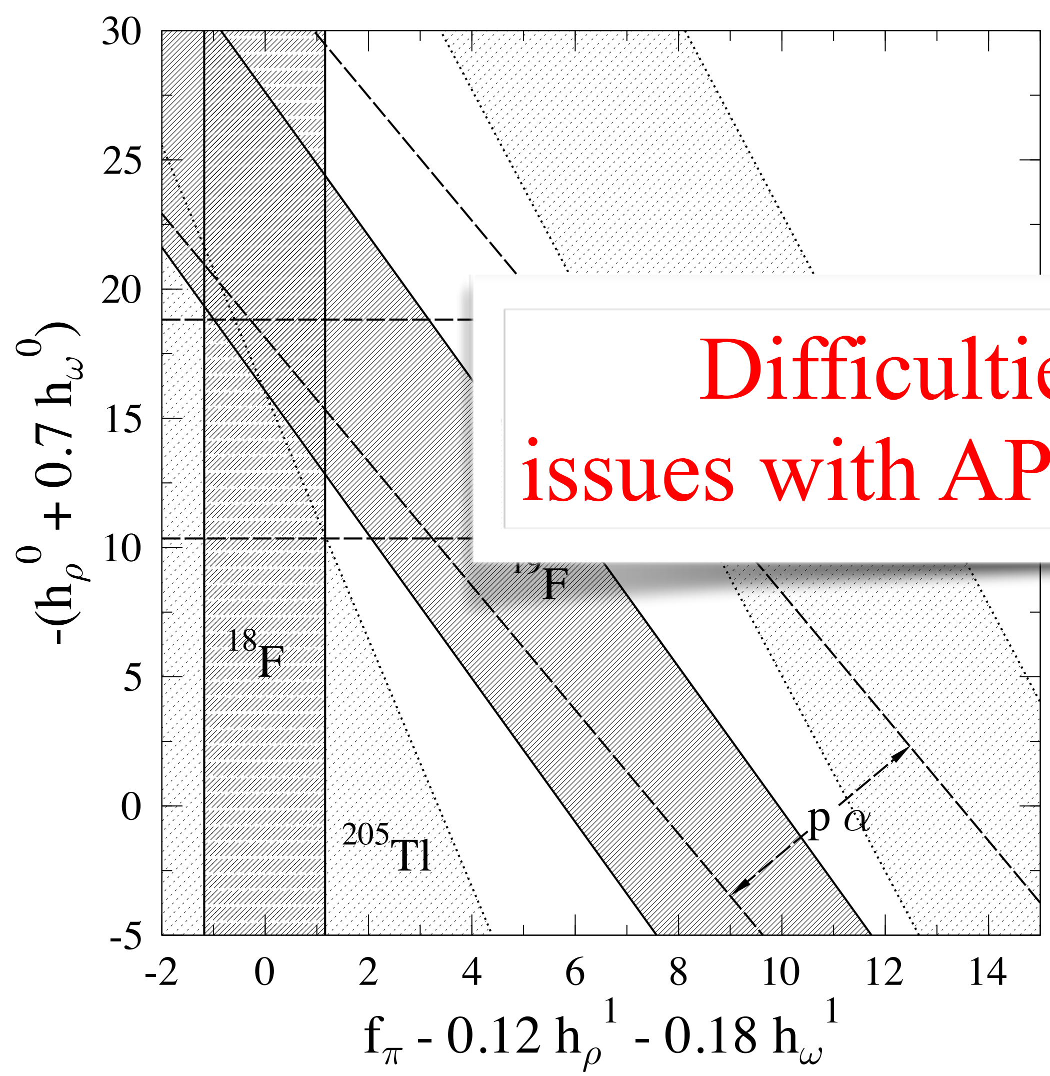
(4) New experimental efforts on measuring APV in Cs [Purdue]

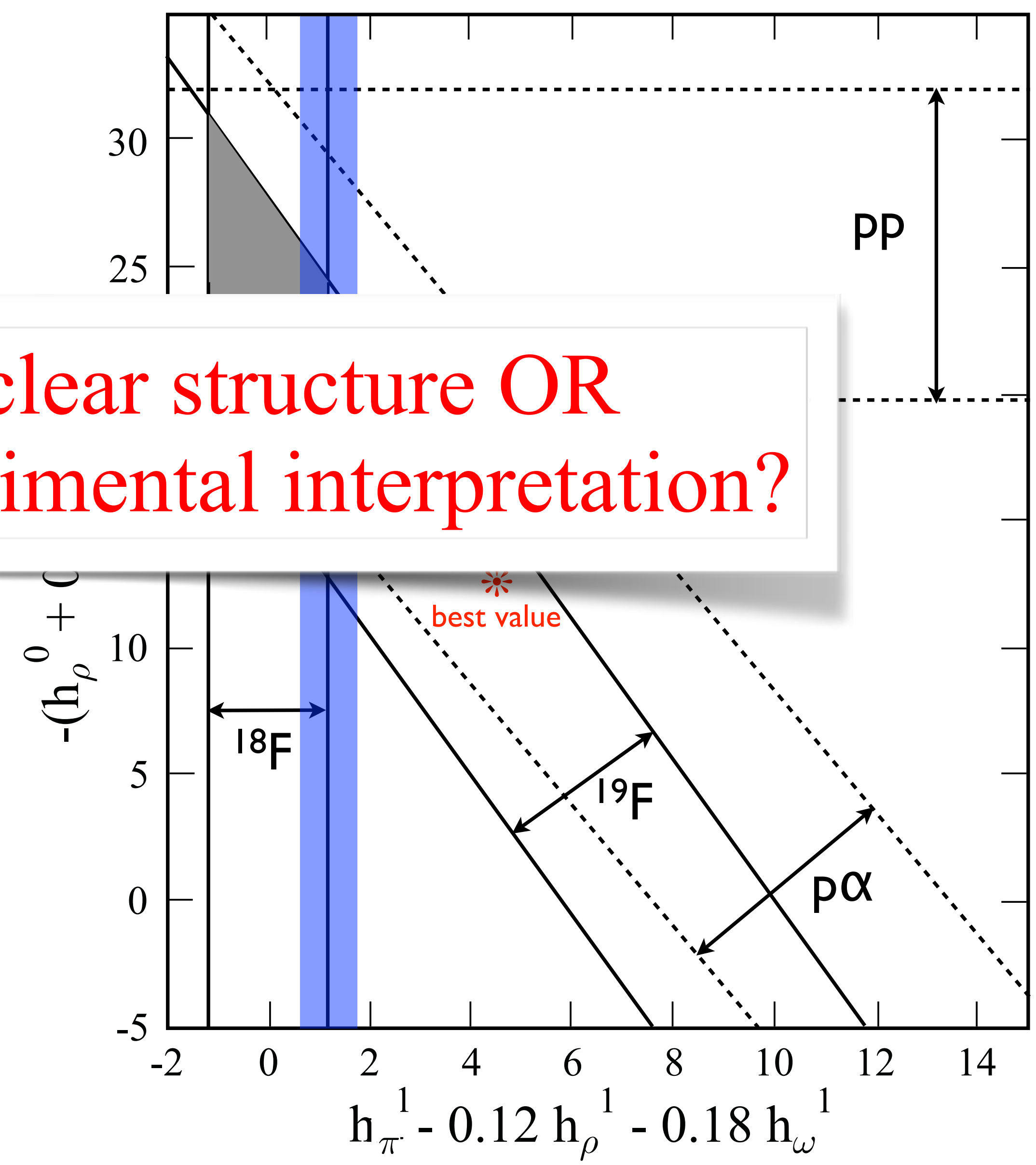
(5) Alternative to the sum-over state approach

(6) New dark-sector motivations



(1) Anapole tensions





Difficulties of nuclear structure OR
issues with APV experimental interpretation?

Haxton & Wieman
Ann. Rev. Nucl. Part. Sci. 51 261 (2001)

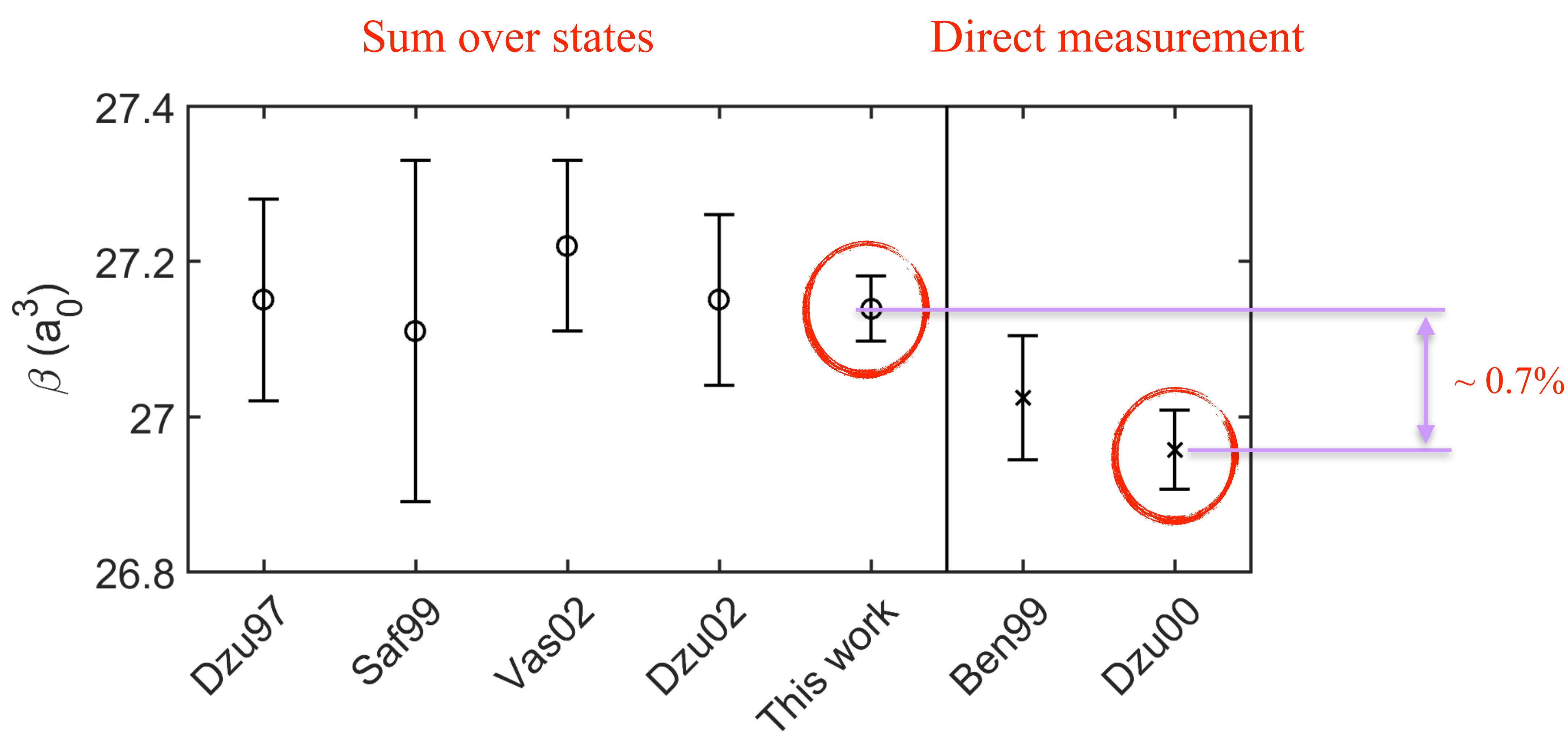
Haxton & Holstein
Prog. Part. Nucl. Phys., (2013)

(2) Vector transition polarizability β

Measured: $$-\frac{\mathrm{Im}(E_{PV})}{\beta} = \begin{cases} 1.6349(80)\,\mathrm{mV/cm} & 6S_{F=4} \rightarrow 7S_{F=3} \\ 1.5576(77)\,\mathrm{mV/cm} & 6S_{F=3} \rightarrow 7S_{F=4} \end{cases}$$

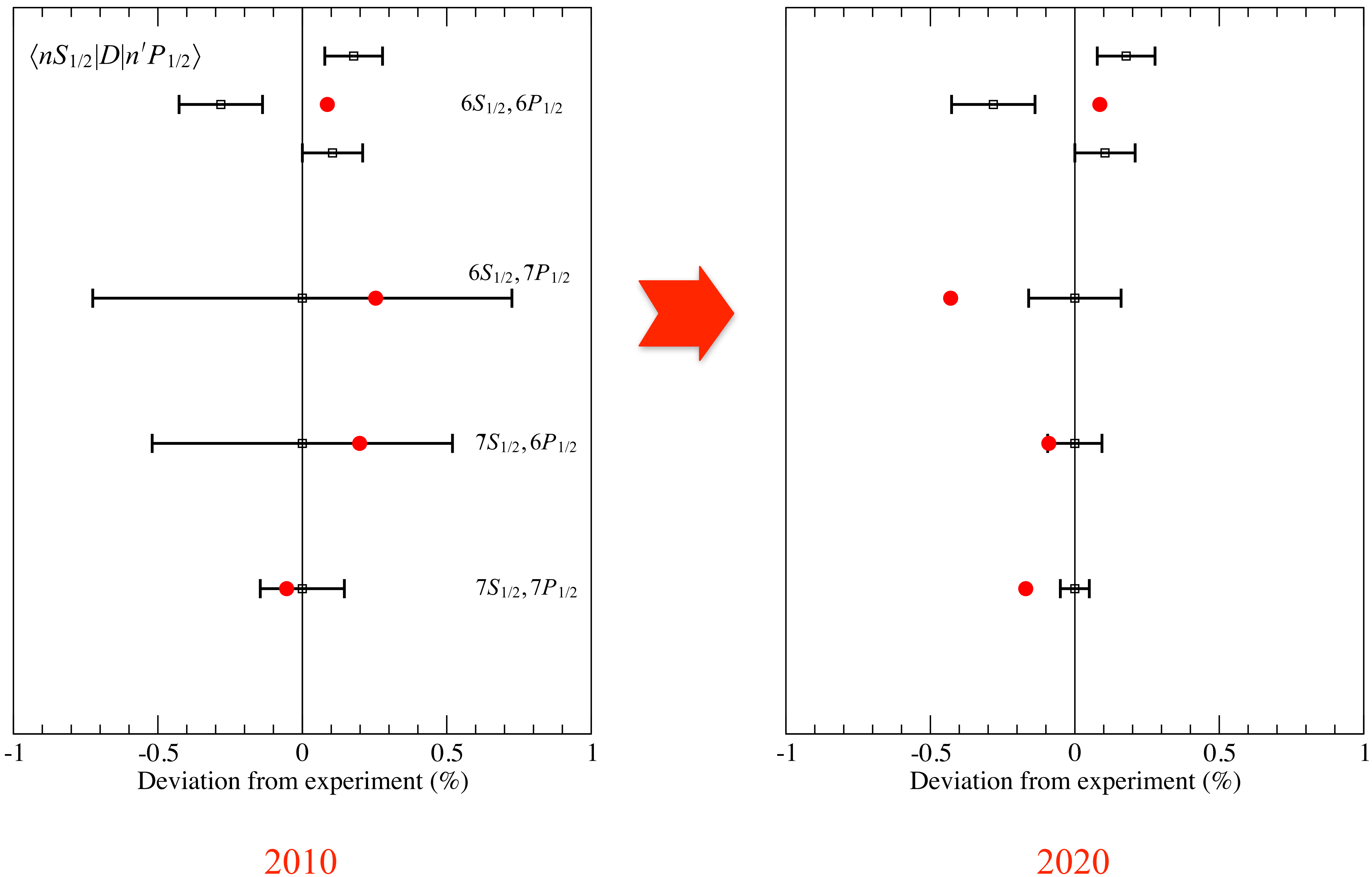
Accurate (~0.1%) value of β is required to extract the PV amplitude

Toh… Elliot PRL 123, 073002 (2019)



Why do the two approaches differ?

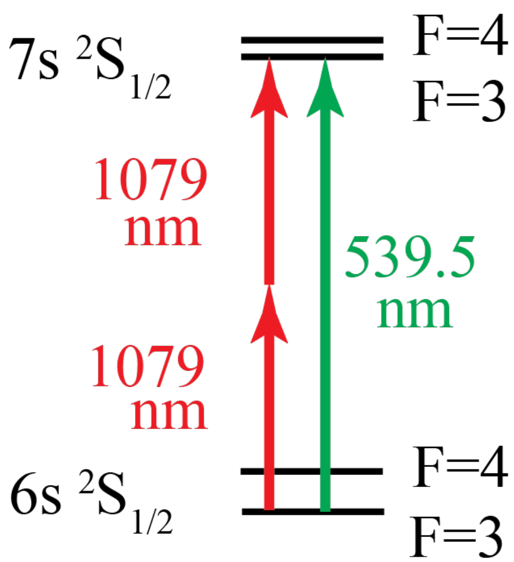
(3) More accurate experimental results for dipole matrix elements [Purdue]



Toh… Elliot PRL 123, 073002 (2019)

(4) Two-color coherent control APV experiment

Two-photon + one photon drive with controlled (scannable) phase $\Delta\phi$ b/w two optical fields



Transition amplitude $E_{\text{tot}} = E_{\text{2-photon}} + E_{\text{Stark}} + E_{\text{PV}}$

$$\text{Rate} = \left|E_{\text{tot}}\right|^2 = \left|E_{\text{2-photon}}\right|^2 + K\left(\mathcal{E}, E_{\text{PV}}\right)\boxed{\cos\Delta\phi_{\text{scanned}}}$$

E-field

Measure rate at different values of $\Delta\phi$, extract K => E_{PV}

Projected experimental σ in E_{PV} below 0.2%

+ similar ground-state scheme for measuring NSD (anapole) PV amplitude

Demo: M1(6s-7s) measurement with somewhat improved accuracy over Boulder

D. Antypas, D. S. Elliott, Phys. Rev. A 87, 042505 (2013)

Thanks: D. Elliott

(5) New computational idea

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

$$\mathrm{Main}\,(n=6,7,8,9)[98\%] + \mathrm{Tail}\,(n>9)[2\%]$$

Summation must be over the complete many-body basis: $\sum_n |nP_{1/2}\rangle\langle nP_{1/2}| = 1$

Approximation	**Main**	**Tail**
RPA	**0.8705**	**0.0192**
BO	**0.8678**	**0.0242**

=> Main and Tail must be computed in the same approximation

(5) How to reduce theory error further?

Table 1: Contributions to parity violating amplitude $E_{\rm PNC}$ for the $6S_{1/2} \rightarrow 7S_{1/2}$ transition in ^{133}Cs in units of $i|e|a_{\rm B}\,(-\frac{Q_W}{N}) \times 10^{-11}$.

Coulomb interaction	
Main ($n = 6-9$)	0.8823(18)
Tail	0.0175(18)
Total correlated	0.8998(25)
Corrections	
Breit, Ref. (*29*)	-0.0054(5)
QED, Ref. (*23*)	-0.0024(3)
Neutron skin, Ref. (*30*)	-0.0017(5)
$e-e$ weak interaction, Ref. (*11*)	0.0003
Final	0.8906(26)

Error bar
is comparable
to Main

Dzuba *et al* (PRL 109, 203003 (2012)) claim that the tail error bar was underestimated in our calculations…

(5) How to reduce theory error further?

Use parity-mixed basis

$$\left(h_0 + V_{\mathrm{DHF}} + h_W\right)\phi_i = \varepsilon_i \phi_i \longleftarrow$$

All single-particle orbitals include weak interaction

Feed into the CCSDvT code (remove parity selection rules)

All observables (dipoles, hyperfine constants, energies) will have the same accuracy as in the original CCSDvT code

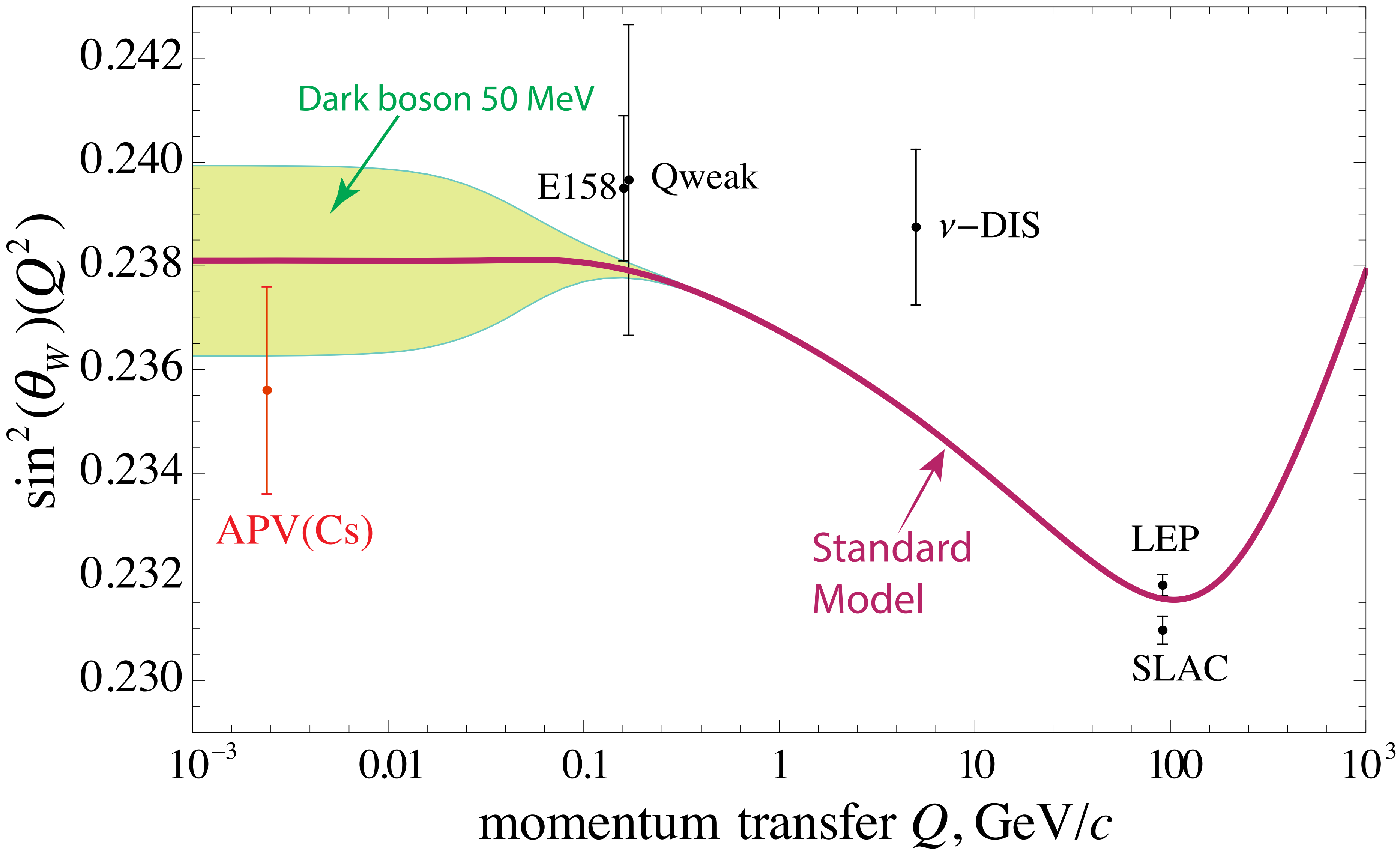
Summation over intermediate states is gone!

$$E_{\mathrm{PV}} = \left\langle 7S_{1/2}\left(\mathrm{CCSDvT}\right)\middle| D \middle| nP_{1/2}\left(\mathrm{CCSDvT}\right)\right\rangle$$

Price: increased computational complexity

With additional work, the goal is to attain 0.1% theoretical accuracy

(6) Dark sector motivation



Light vector boson + kinetic mixing with the photon

Davoudiasl, Lee & Marciano, PRD (2014)

Summary: Revisiting APV in Cs

(1) Tension for the ^{133}Cs anapole moment with the nuclear theory

(2) Tension for supporting quantities (vector transition polarizability)

(3) More accurate experimental results for dipole matrix elements [Purdue]

(4) New experimental efforts on measuring APV in Cs [Purdue]

(5) New computational idea (0.1% should be attainable)

(6) New dark-sector motivations

Di Xiao (Graduate student)

Postdoc position available!