UNSW
THE UNIVERSITY OF NEW SOUTH WALES

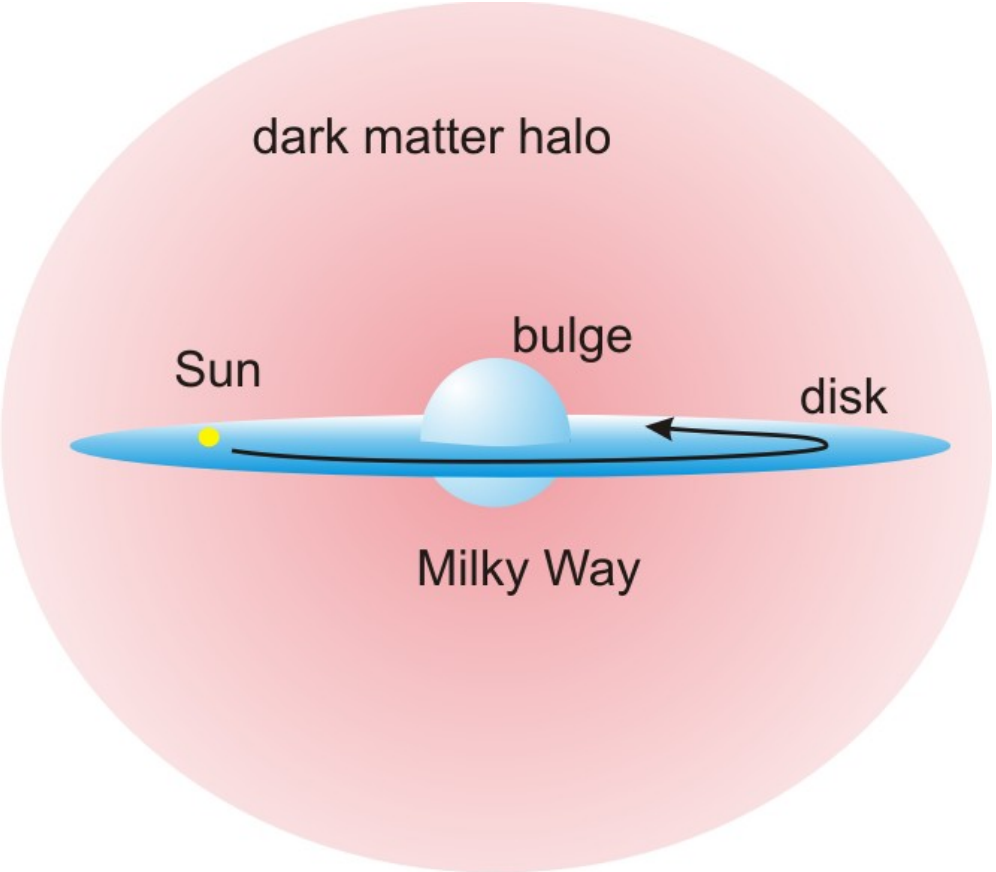
Probing dark matter in atomic EDM and PNC measurements.

V. A. Dzuba[1],
V. V. Flambaum[1,2], B. M. Roberts[1,3],
Y. V. Stadnik[1,2]

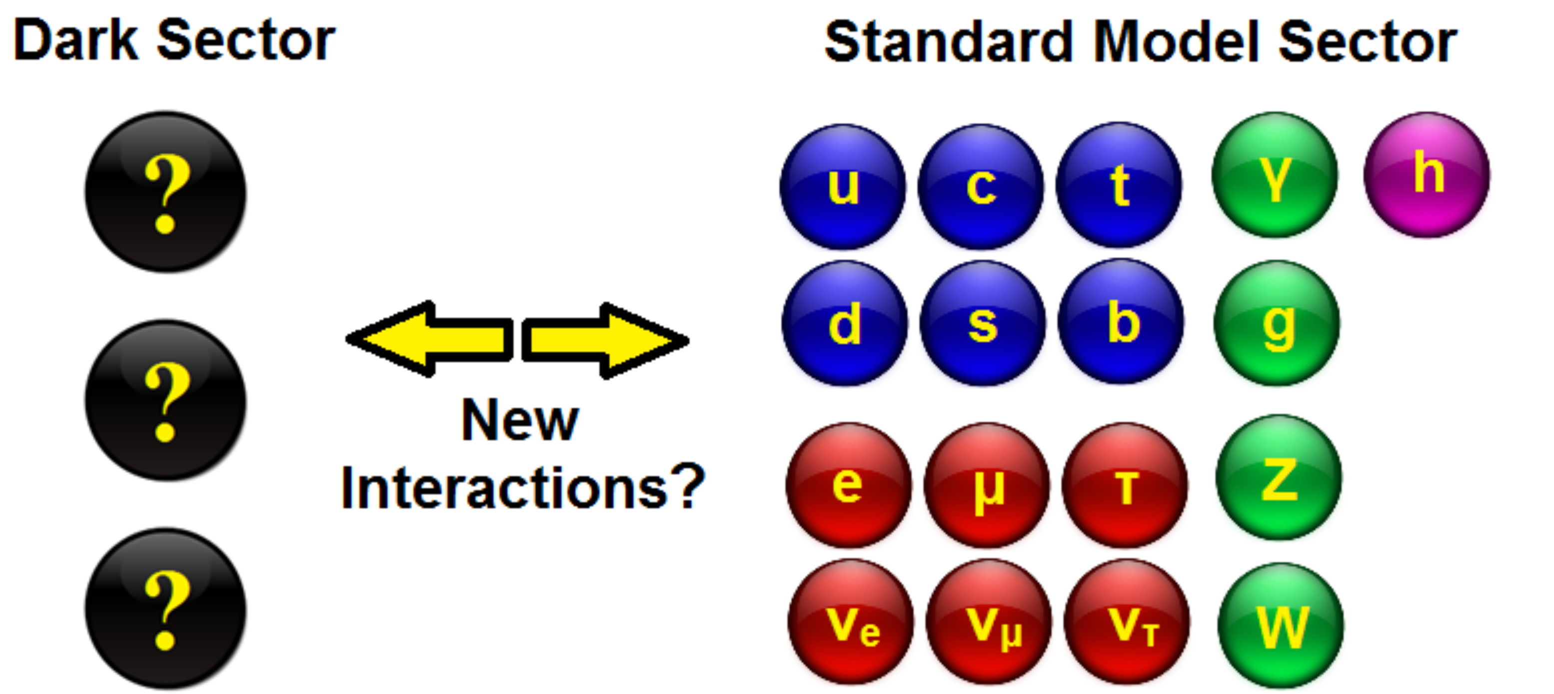
[1]*University of New South Wales, Sydney, Australia*
[2]*Johannes Gutenberg University of Mainz, Germany*
[3]*University of Nevada, Reno, USA*

Dark matter

Overwhelming astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter).

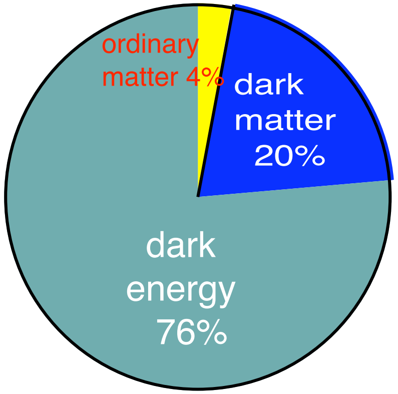


– *"What is dark matter and how does it interact with ordinary matter* ***non-gravitationally****?"*



Cosmic PNC caused by dark matter

Energy composition
of the Universe:



Assuming that dark matter breaks parity we consider pseudoscalar and pseudovector fields.

Pseudoscalar field (e.g.**axions**):

$$L^{PS} = \kappa\hbar(\partial_\mu\varphi)\overline{\psi}\gamma^\mu\gamma^5\psi - ikm_f c^2\phi\overline{\psi}\gamma^5\psi$$

Pseudovector field:

$$L^{PV} = b_\mu\overline{\psi}\gamma^\mu\gamma^5\psi$$

Lead to oscillating PNC and EDM:

$$E^{PS}_{PNC} = (\kappa + \frac{k}{2})\hbar\omega_\varphi \sin(\omega_\varphi t) K_{PNC}$$

$$E^{PS}_{EDM} = -(2\kappa + k)\hbar^2\omega_\varphi^2 \cos(\omega_\varphi t) K_{EDM}$$

$$E^{PV}_{PNC} = b_0(t) K_{PNC}$$

$$E^{PV}_{EDM} = -2ib_0\hbar\omega_b \cos(\omega_b t) K_{EDM}$$

K_{PNC} and K_{EDM} are electron structure factors found from atomic calculations

No static EDM!

No static PNC for PS field.

These are the first-order effects!

Current searches for axions rely on second-order effects (axion-photon convertion, axio-electric effect).

DM contribution to atomic PNC

In case of $b_0(t) = b_0 = const$

limits on b_0 can be found from existing PNC measurements:

$$b_0 < \frac{\left|A_{\rm exprt} - A_{\rm theor}\right| + \sigma_{\rm exprt} + \sigma_{\rm theor}}{K_{PNC}}$$

Atom	$A_{\rm exprt}$ (10^{-11} a.u.)	$A_{\rm theor}$ (10^{-11} a.u.)	$K_{\rm PNC}$ (10^{-7} a.u.)	b_0 (10^{-7} a.u.)	b_0 (10^{-5} eV)
Cs	0.8428(26)	0.8353(42)	2.5	6	1.6
Tl	25.6(2)	24.8(7)	2.1	800	220
Dy	2.3(3.0) Hz*	4(4) Hz*	0.08	2	0.54

* 1Hz = 1.52x10^{-16} a.u.

Cs: Wood *et al*, Science **275**, 1759 (1997); Dzuba *et al*, PRL **109**, 203003 (2012);
Tl: Vetter *et al*, PRL **74**, 2658 (1995); Dzuba *et al*, JPB **20**, 3297 (1987);
Dy: Nguyen *et al*, PRA **56**, 3453 (1997); Dzuba and Flambaum, PRA **81**, 052515 (2010).

PV interaction of dark matter with nuclear protons and neutrons gives additional contribution κ_b to nuclear **anapole moment (AM)**

$$\kappa_b = \frac{2\sqrt{2}\hbar\pi\alpha\mu\langle r^2\rangle}{a_0^3 m_p c} b_0^N \qquad H_{AM} = \frac{G_F K}{\sqrt{2}} \frac{\alpha \cdot I}{I}(\kappa_a + \kappa_b)\rho_N(r)$$

AM moment measurements in Cs and Tl can be used to put limits on b_0^p

Atom	Exp κ_a	Theor κ_a	b_0^p (a.u.)
Cs	0.364(62)	0.15 – 0.23	1.1
Tl	-0.22(30)	0.10 – 0.24	3.1

Cs: Wood et al, Science 275, 1759 (1997); Flambaum and Murray, PRC 56, 1641 (1997); Dmitriev and Telitsin, Nuc. Phys. A 613, 237 (1987); Haxon et al PRL 86, 5287 (2001);
Tl: Vetter et al, PRL 74, 2658 (1995); Khriplovich, Phys. Lett. A 197, 316 (1995).

Another DM contribution to atomic EDM and PNC

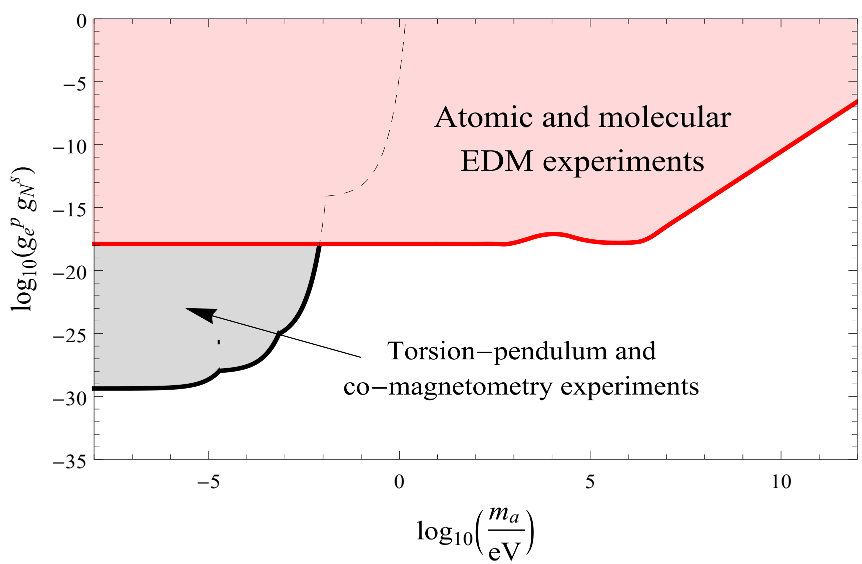
There might be a contribution to the P-odd electron-nucleon interaction due to exchange of axion-like **DM** particle of mass m_a.

$$V_{12}(r) = i\frac{g_1^p g_2^s}{4\pi}\frac{e^{-m_a r}}{r}\gamma^0\gamma_5$$

- CP-odd interaction leading to **EDM**

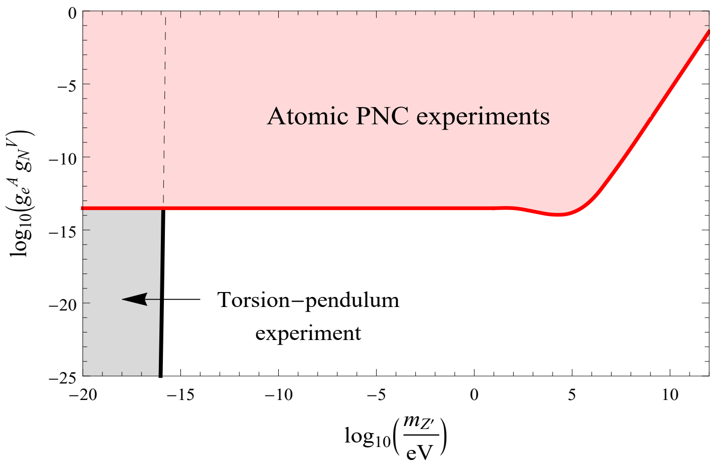
$$V_{12}(r) = \frac{g_1^A g_2^V}{4\pi}\frac{e^{-m_a r}}{r}\gamma_5$$

- P-odd interaction leading to **PNC**

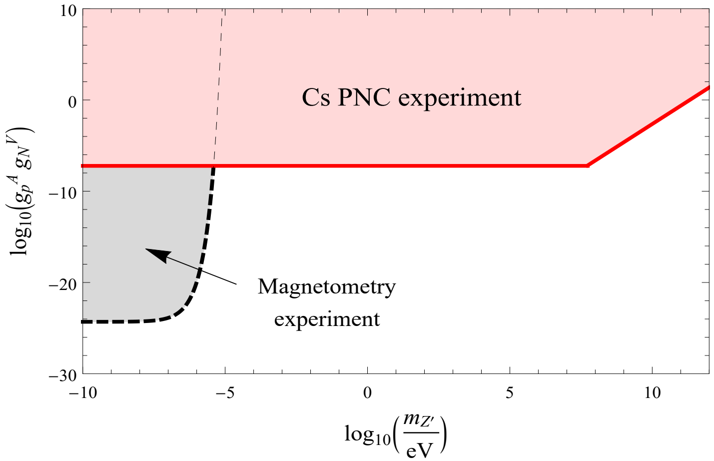


Numerical analysis using existing **EDM** measurements leads to constrains on the mass and the strength of the interaction. (Stadnik, Dzuba, Flambaum, arXiv:1708.00486)

PNC



Limits on the P-violating nucleon-electron interaction.



Limits on the P-violating nucleon-proton interaction.

(Dzuba, Stadnik, Flambaum, arXiv:1709.10009, accepted to **PRL**)

Atomic calculations are the same as for the SM PNC but with a different PV operator.

$$V_{12}(r) = \frac{g_1^A g_2^V}{4\pi} \frac{e^{-m_a r}}{r} \gamma_5$$

Long-range PV interaction at $m_a \sim m_e$, i.e. the p-d and d-f mixings are as good as the s-p one.

Atom	State	*J*	*E* (cm^{-1})	Transition/ ΔE (cm^{-1})
Nd	4f^4 5d6s	7	13708.860	d-f
	4f^3 5d^{2}6s	7	13799.780	0.920
Gd	4f^7 5d6s6p	4	19507.332	p-d
	4f^7 5d^{2}6s	4	19507.992	0.660
Gd	4f^8 6s6p	6	25658.055	d-f
	4f^7 5d6s6p	6	25661.340	3.285
Dy	4f^9 5d^{2}6s	10	19797.961	d-f
	4f^{10} 5d6s	10	19797.961	0.000

There are dozens of pairs with ΔE <10 cm^{-1}.

Experimental work with **Dy** continues at Mainz (D. Budker et al)

Dy: Expt.: H_W=|2.3±2.9±0.7| Hz (Nguyen, *et al*, PRA **56**, 3453 (1997));

Theory, SM PNC: H_W=|4±4| Hz (Dzuba & Flambaum, PRA **81**, 052515 (2010))

Low mass limit

Cs: $E^{\text{PNC}}_{\text{Expt}} = 0.8353(29)i \times 10^{-11}\,\text{a.u.}$ Wood et al, Science 275, 1759 (1997)

$E^{\text{PNC(SM)}}_{\text{Theor}} = 0.8428(38)i \times 10^{-11}\,\text{a.u.}$ Dzuba et al, PRL 109, 203003 (2012)

$$\left|g_1^A g_2^V\right| < 3 \times 10^{-14}$$

Dy: $H_W^{\text{Expt}} = \left|2.3 \pm 2.9 \pm 0.7\right|\ \text{Hz}$ Nguyen, *et al*, PRA **56**, 3453 (1997)

$H_W^{\text{Theor(SM)}} = \left|4 \pm 4\right|\ \text{Hz}$ Dzuba & Flambaum, PRA **81**, 052515 (2010)

$$\left|g_1^A g_2^V\right| < 6 \times 10^{-14}$$

Great potential for improvement!

Calculations for open-shell atoms

are needed for many problems of modern physics.

- **PNC** in lanthanides for probing **DM** and neutron distribution.
- Spectra and properties of **SHE**, Z=104 to 118; $6d^n7s^m$, $7s^27p^n$ configurations.
- **HCI**, $4f^n5p^m$, $4f^n5s^m$ configurations (atomic clocks, variation of α, **LLI** violation, etc.)
- And many more…

Open-shell atoms:

Z
At

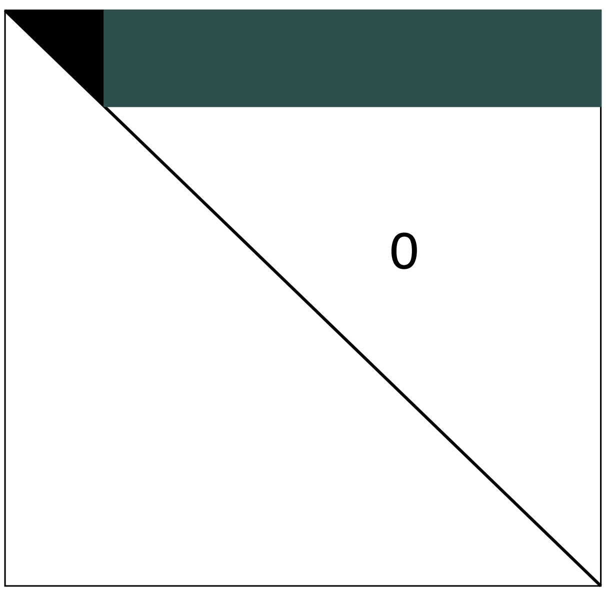
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	28 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
119	120																

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

The CIPT method

(configuration interaction with perturbation theory
Dzuba *et al*, PRA **95**, 012503 (2017))

The structure of the CI matrix



$$\Psi = \sum_i c_i \Phi_i + \sum_m c_m \Phi_m$$

Small correction

Has small number of terms

$$\langle i | H | j \rangle \rightarrow \langle i | H | j \rangle + \sum_m \frac{\langle i | H | m \rangle \langle m | H | j \rangle}{E - E_m}$$

Should work well for low-lying states of atoms and ions if there is no strong mixing with higher states.

Hole-particle (Fock space) approach to core-valence correlations.

Replace $4f^{14}6s6p \rightarrow 6s6p,$

$4f^{13}6s^2 5d \rightarrow 4f^{-1}6s^2 5d,$ etc.

And work with configurations containing **electrons** and **holes**.

Double benefit:

- Fewer particles = more efficient calculations
  (e.g. **16** electrons -> **2** electrons or **3** electrons and **1** hole).

- Core-valence correlations can be included by considering

$$5s^{-1}6s^2 6p, \quad 5p^{-1}6s^2 5d, \quad 5p^{-1}6s5d^2, \qquad \text{etc.}$$

Limitations of the CIPT method

- Only low-lying states can be calculated.
- Calculations are sensitive to the initial approximation. This may lead to different accuracy for different states.

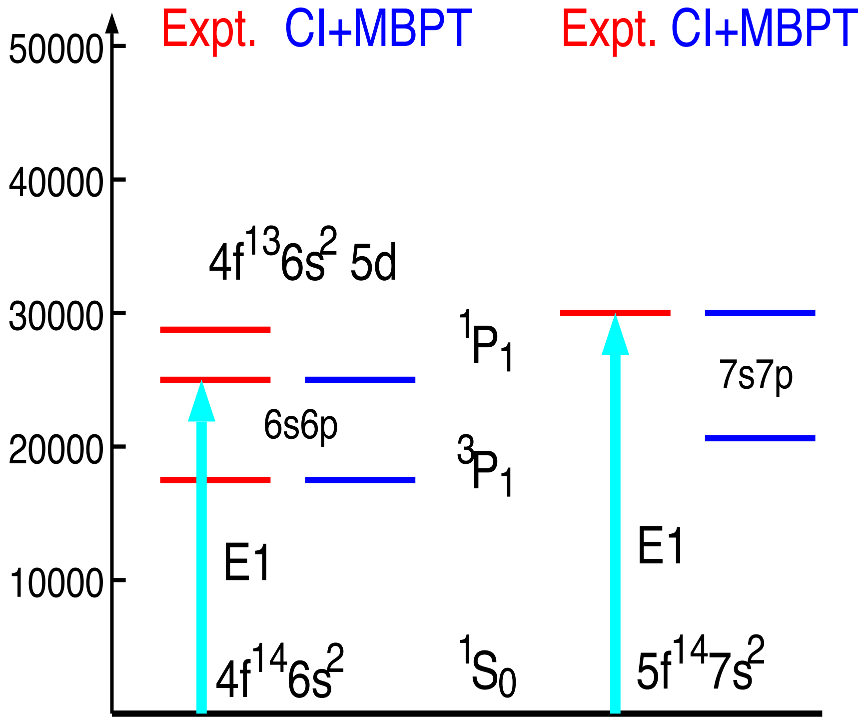
$$\Psi = \sum_i c_i \Phi_i + \sum_m c_m \Phi_m$$

Has small number of terms

Small correction

These limitations can be eased by increasing the size of the effective CI matrix.

Ytterbium Nobelium (Z=102)



Measurements for the $^1P_1$ state of No:
$h\omega$ (E1), hfs, isotope shift (Laatiaoui *et al*, Nature **538**, 495 (2016)).

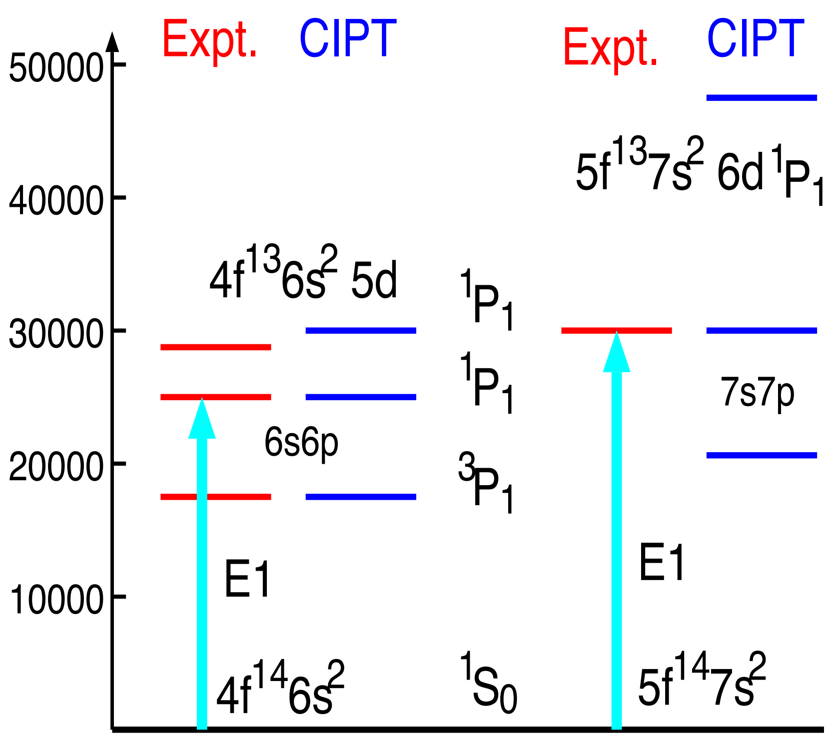
Can we trust the CI+MBPT calculations to extract nuclear parameters?

-Not for **Yb**!

Calculations for the $^1P_1$ state of Yb

	CI+MBPT		Expt.
Hfs (MHz)	-750		-214.173(53)
E1 (a.u.)	4.825		4.148(2)

Ytterbium   Nobelium (Z=102)



Measurements for the $^1P_1$ state of No:
$h\omega$ (E1), hfs, isotope shift (Laatiaoui *et al*, Nature **538**, 495 (2016)).

Can we trust the CI+MBPT calculations to extract nuclear parameters?

-Not for **Yb**!

-But **No** is okay.

Journal article is under preparation.

Calculations for the $^1P_1$ state of Yb

	CI+MBPT	CIPT	Expt.
Hfs (MHz)	-750	-265	-214.173(53)
E1 (a.u.)	4.825	4.31	4.148(2)

Conclusion

- Oscillating EDMs and PNC amplitudes would be a signature of interacting with DM.
- Existing EDM and PNC measurements put strong constrains on the DM parameters.
- New more sensitive experiments are proposed using close states in lanthanides.
- New methods of atomic calculations are in development for planning and interpreting the PNC measurements.