Atomic parity violation

D. Antypas

Johns Hopkins GGI workshop 2/10/18

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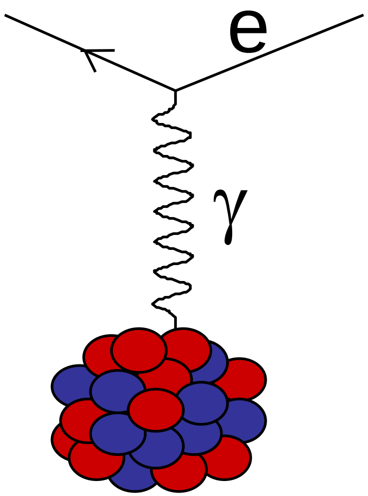
Outline

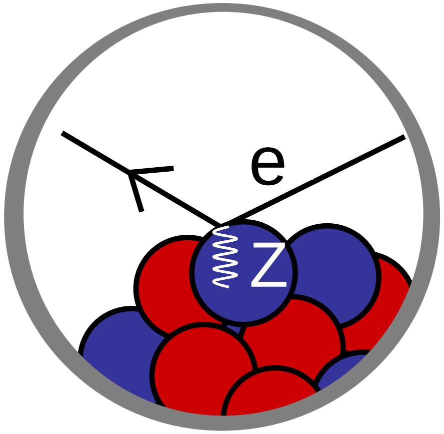
- Background & motivations
- Yb parity violation experiment
- Isotopic variation of parity violation in Yb
- Outlook

Atomic Parity Violation

Main Source: Z exchange



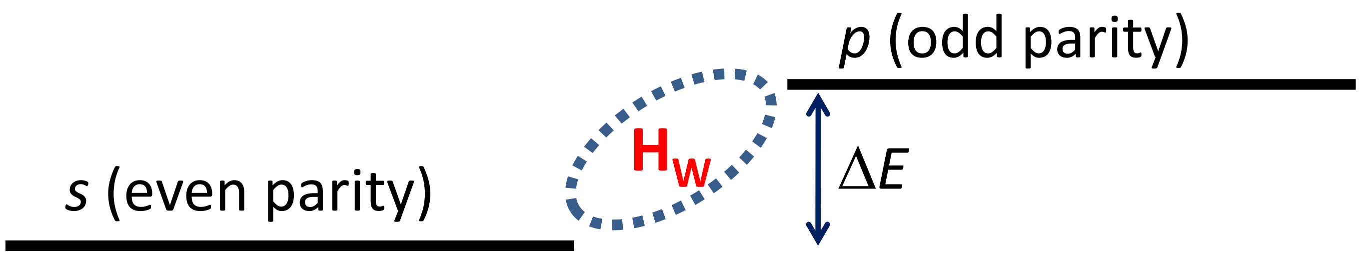
Electromagnetic interaction (conserves parity)



Weak interaction (violates parity)

P-odd, T-even effect: $\vec{\sigma} \cdot \vec{p}$

The weak interaction mixes atomic states of opposite nominal parity (s & p)



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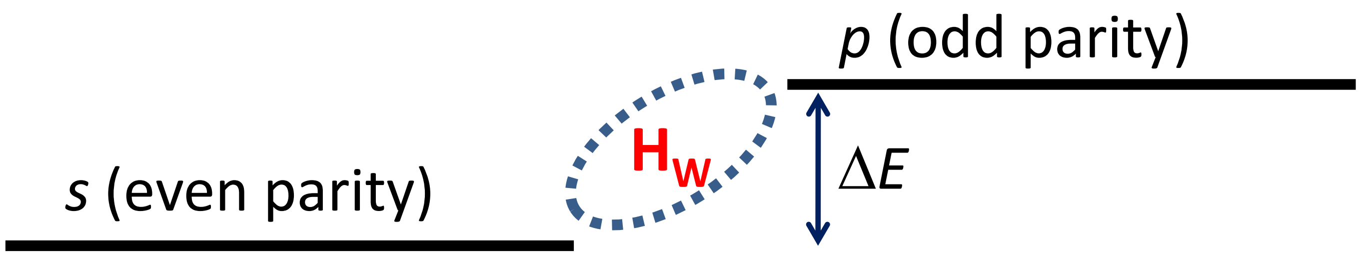


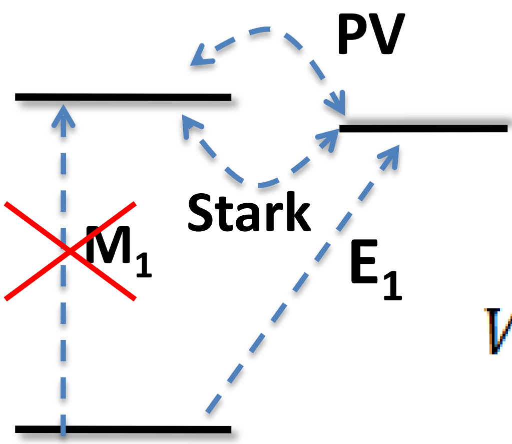
$$s \rightarrow s + i\varepsilon p;\; p \rightarrow p + i\varepsilon s$$

$$\varepsilon = \frac{\langle s | H_W | p \rangle}{\Delta E} \sim \frac{RZ^3}{\Delta E}$$ - the Bouchiat Law

Atomic Parity Violation Enhancement:

- Heavy atoms (high Z)
- Small ΔE

How to measure parity violation on forbidden transitions?



☛ **Stark-interference technique**
Bouchiat & Bouchiat

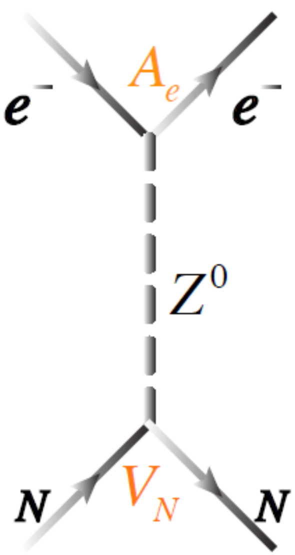
$$W_{\pm} = |A_{Stark} + A_{PV}|^2$$

$$\approx \underbrace{A_{Stark}^2}_{P-conserving} \quad \underbrace{\pm 2A_{Stark} \cdot A_{PV}}_{P-violating}$$

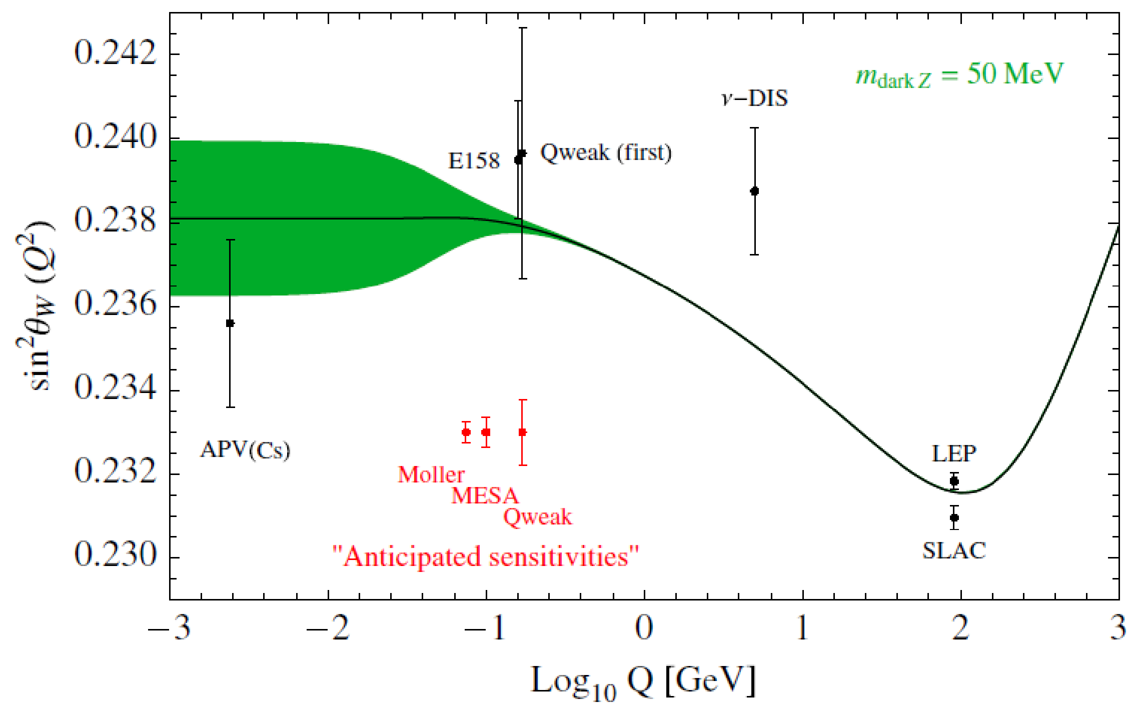
$$Asymmetry = \frac{W_+ - W_-}{W_+ + W_-} \sim \frac{E1_{PV}}{E1_{Stark}}$$

- Many reversals to control systematics
- S/N nominally independent of electric field

Nuclear spin-independent atomic PV



$$H_{NSI} = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \rho(r)$$



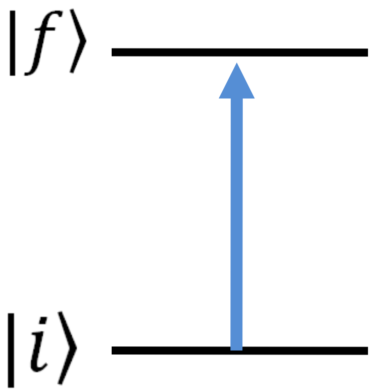
Davoudiasl et al, Phys. Rev. D 89, 1402.3620

- Probe of the nuclear weak charge Q_W
- Constrain BSM scenarios at tree-level & through oblique rad. corrections
- Probe of the "dark" sector: dark boson, cosmic parity violation (axions, ALPs)

$$Q_W \approx -N + Z\cdot(1\text{-}4\sin^2\vartheta_W)$$

Isotopic ratios in atomic PV

- APV measures: $E1_{PV} = k_{PV} Q_W$



$$E1_{PV} = \langle f | D | i \rangle$$

Element	δk_{PV}
Cs	0.4 %
Yb	10 %

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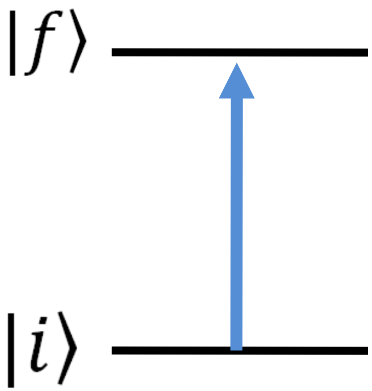

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- Atomic PV calculation errors cancel in isotopic ratios
  Dzuba, Flambaum, and Khriplovich, Z. Phys. D 1, 243 (1986)

$$R = \frac{E1'_{PV}}{E1_{PV}} = \frac{Q'_W}{Q_W}$$

Isotopic ratios and neutron skins

- Limitation to isotopic ratio method: enhanced sensitivity to the neutron distribution $\rho_n(r)$

  Fortson, Pang, Wilets, PRL **65**, 2857 (1990)

$$\bar{Q}_W = -N\underline{q_n} + Z\underline{q_p}(1 - 4\sin^2\theta_W) + \Delta Q_{\rm new}$$

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- Atomic PV ↔ Neutron distributions

$$\frac{E1_{PV}}{E1'_{PV}} = 1 + \frac{\Delta N}{N} + \boxed{\frac{3}{7}(aZ)^2 \frac{[\Delta R'_{ns} - \Delta R_{ns}]}{R_p}}$$

Skin contribution for ^{170}Yb - ^{176}Yb isotopes ~ 0.1%

Isotopic ratios and neutron skins

[PHYSICAL REVIEW C **79, 035501 (2009)**]

Dispelling the curse of the neutron skin in atomic parity violation

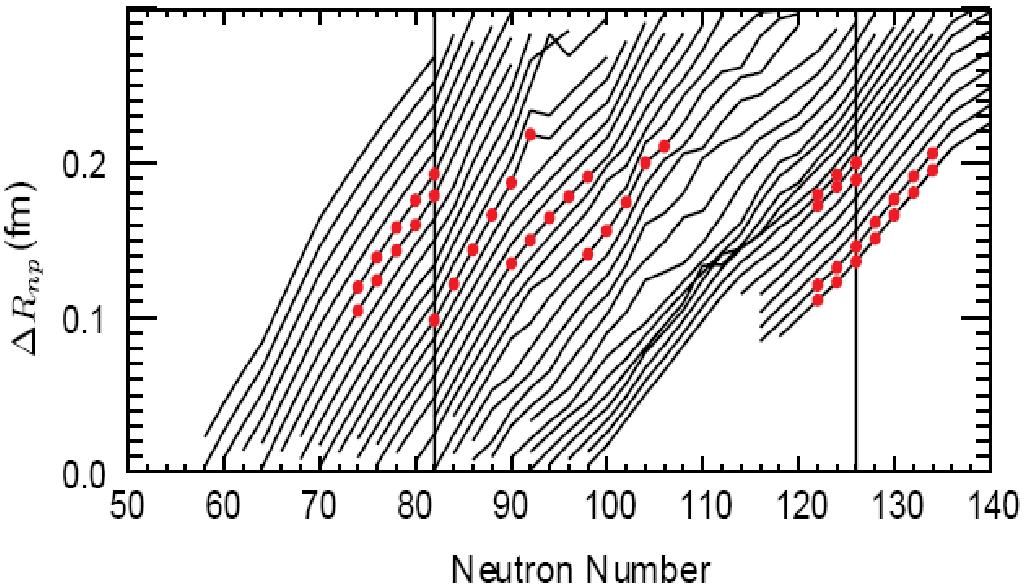
B. A. Brown,[1] A. Derevianko,[2,3] and V. V. Flambaum[3]

[1]*Department of Physics and Astronomy, and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*

[2]*Department of Physics, University of Nevada, Reno, Nevada 89557*

[3] *School of Physics, University of New South Wales, Sydney 2052, Australia*

- Neutron-skin effects in different isotopes are **correlated**



Why PV with ytterbium

- **Large** PV effect (DeMille, 1995 - Tsigutkin *et al,* 2009)

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- 7 stable isotopes (A=168, 170-174,176)

Isotope	NA (%)	I
^{174}Yb	31.8	0
^{172}Yb	21.8	0
^{176}Yb	12.8	0
^{173}Yb	16.1	5/2
^{171}Yb	14.3	1/2
^{170}Yb	3.04	0
^{168}Yb	0.13	0

- PNC on chain of isotopes → neutron distributions & new physics

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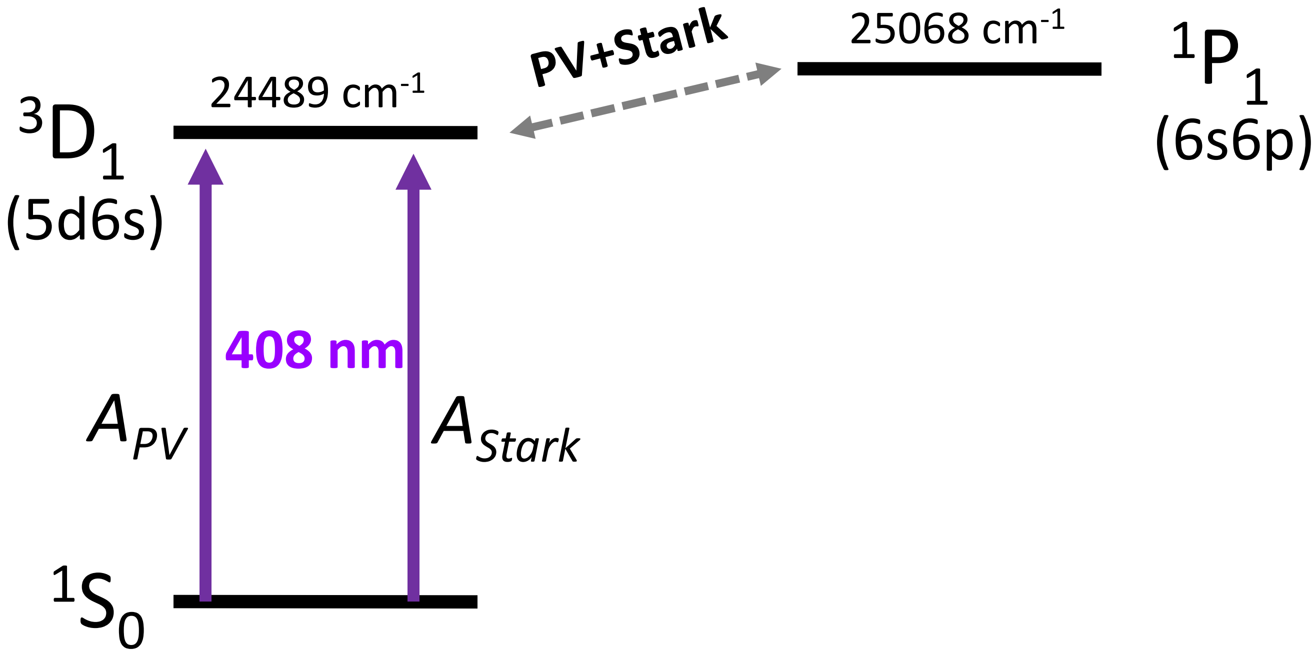
- PNC on chain of isotopes → neutron distributions & new physics
- Two isotopes with nuclear spin → spin-dependent PV effects

The Yb PV experiment



P-odd Stark-PV interference

$$R \propto \left| A_{Stark} + A_{PV} \right|^2 \approx \beta^2 E^2 \sin^2\theta + 2E1_{PV}\,\beta E \cos\theta \sin\theta$$

Reverse E (20 Hz) & θ (0.2 Hz) and measure $E1_{PV}/\beta$

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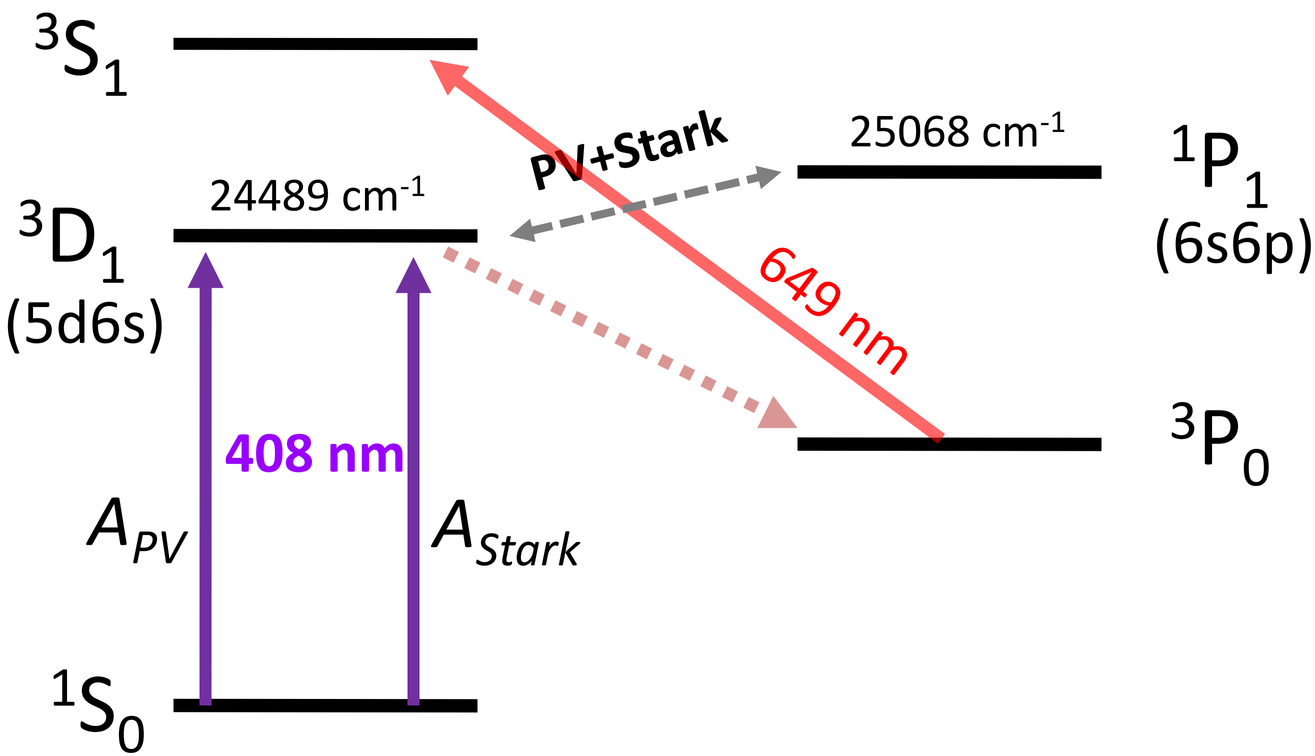

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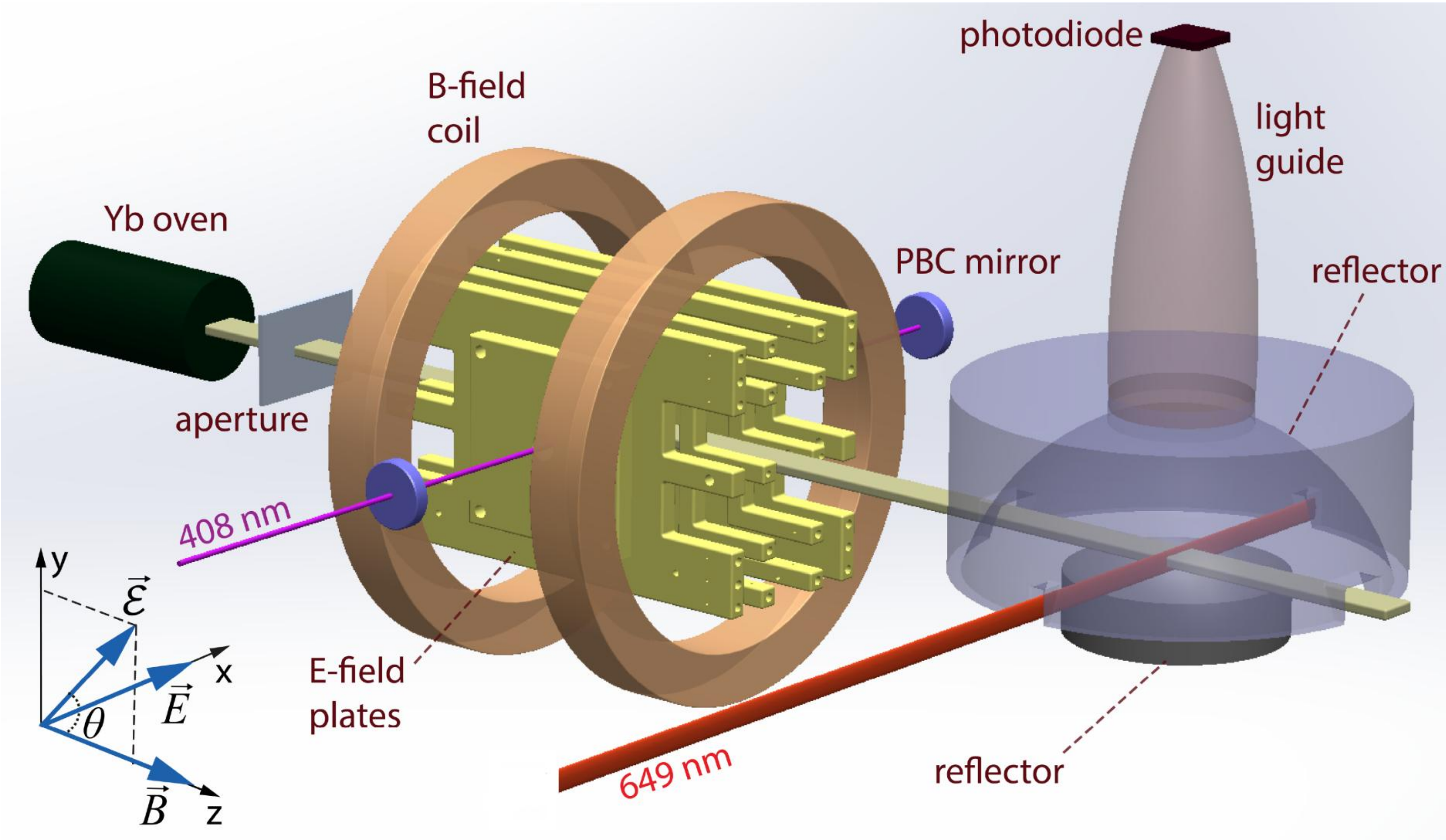
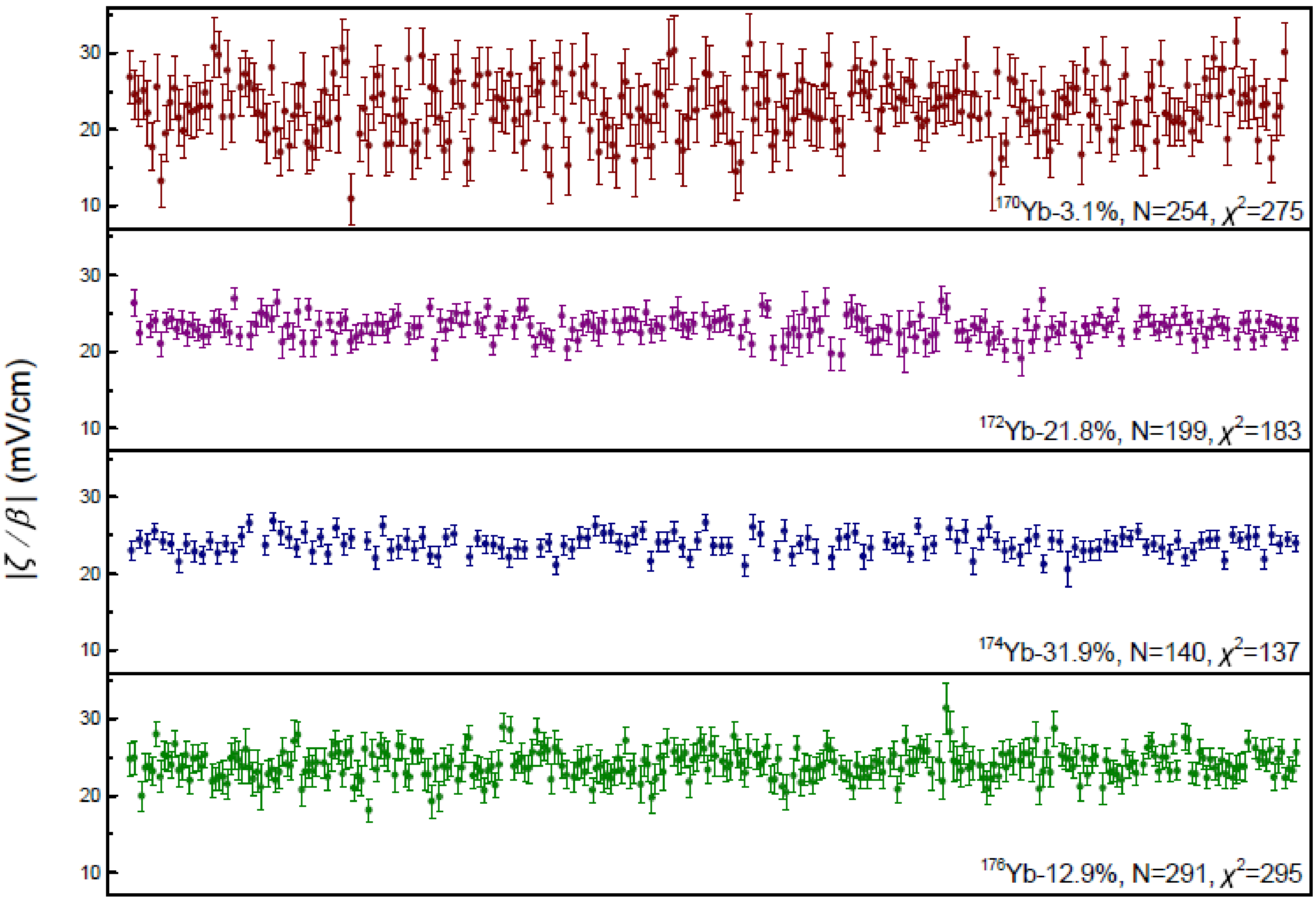
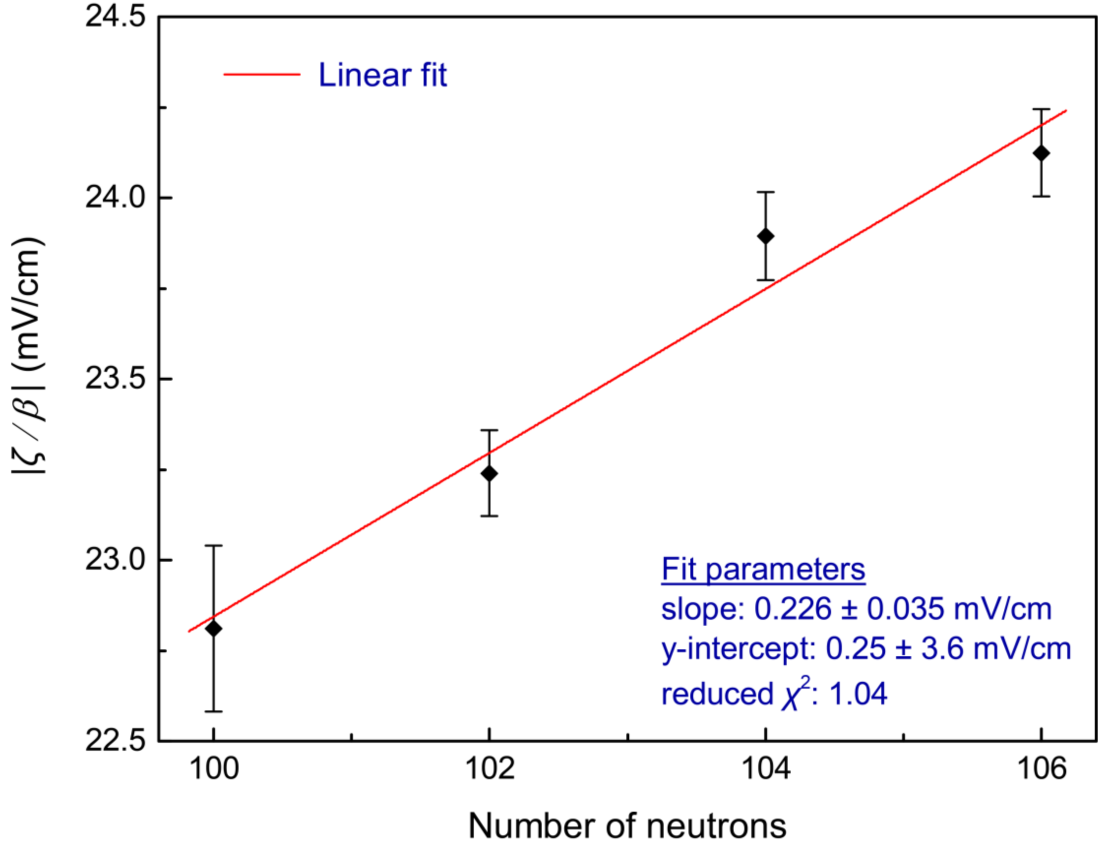
Apparatus schematic



Early 2018 run in 4 spin-zero isotopes



First observation of isotopic variation of atomic PV



0.5% single isotope accuracy

arXiv:1804.05747
accepted in Nature Physics

SM: $Q_W \approx -N+Z(1-4\sin^2\theta_W)$ → 1% change per neutron around N=103

Observation: 0.96(15) % change per neutron

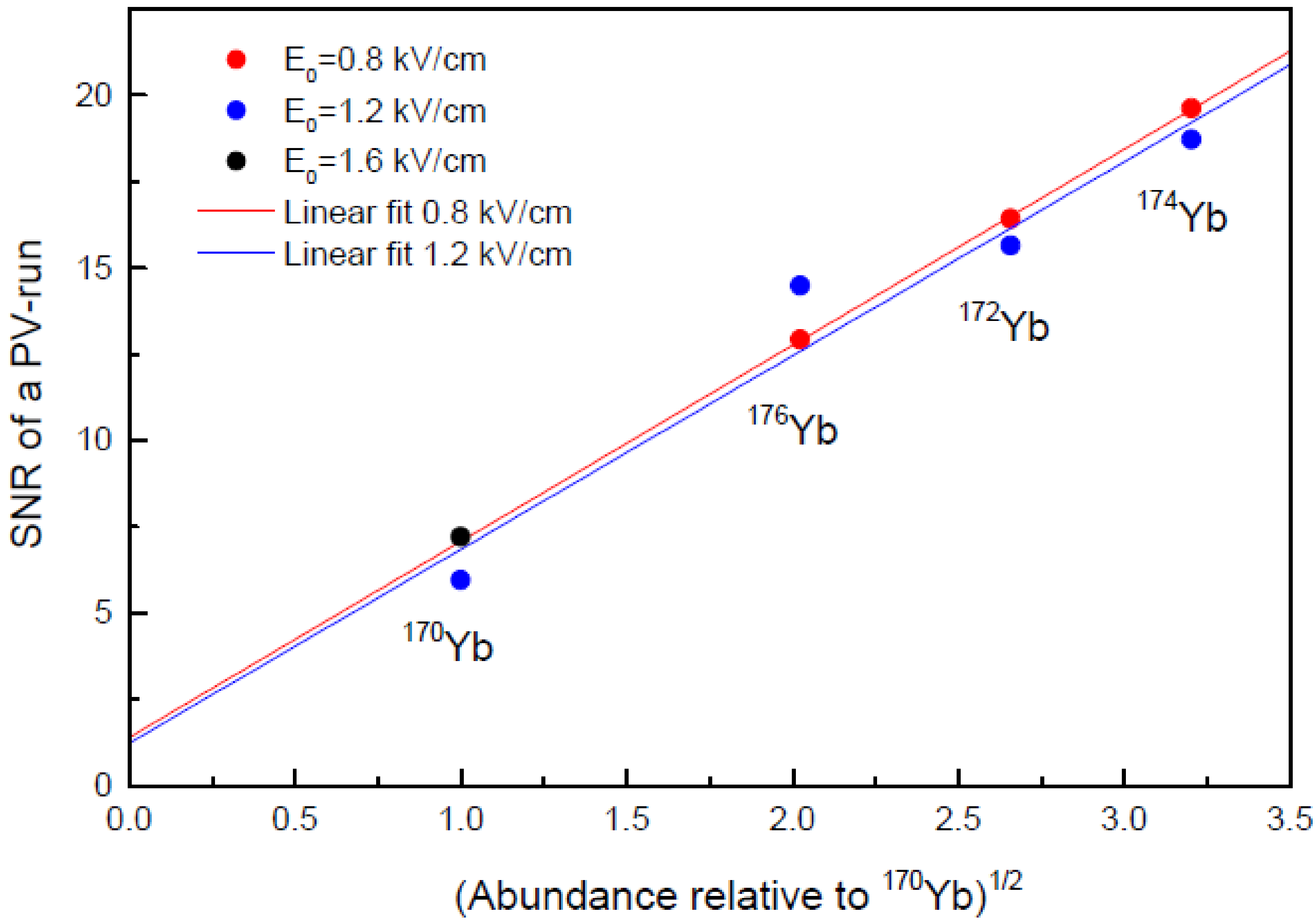
Single isotope measurement uncertainties

Systematic uncertainties	Error (%)
Harmonics ratio calibration	0.22
Polarization angle	0.1
High-voltage measurements	0.06
Transition saturation correction	0.05 (0.09 for ^{170}Yb)
Field-plate spacing	0.04
Photodetector response calibration	0.02
Stray fields & field-misalignments	0.02
Total systematic	**0.26**
Statistical uncertainty	**0. 42 (0.9 for ^{170}Yb)**
Total uncertainty	**0.5 (0.9 for ^{170}Yb)**

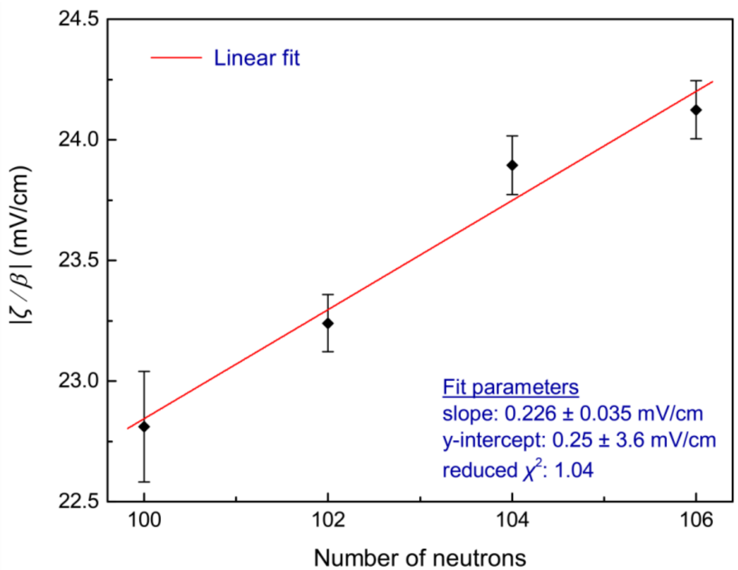
False-PV related → Stray fields & field-misalignments

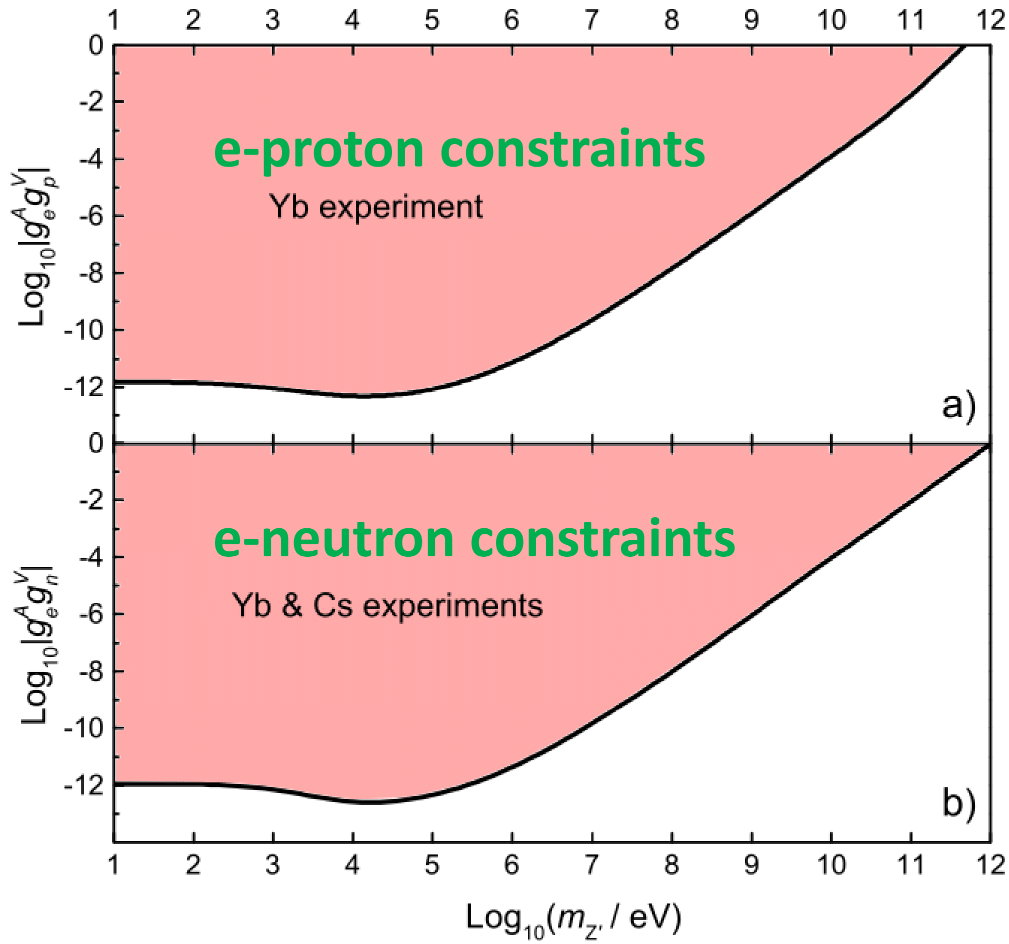
Effect comparison **bonus**:
decreased sensitivity to systematics

Measurement sensitivity



Constraints on light Z′-mediated e-proton & e-neutron interactions





$$V_{ep(n)} = \frac{g_e^A g_{p(n)}^V}{4\pi} \frac{e^{-m_{Z'} r}}{r} \gamma_5$$

In collaboration with V. Flambaum

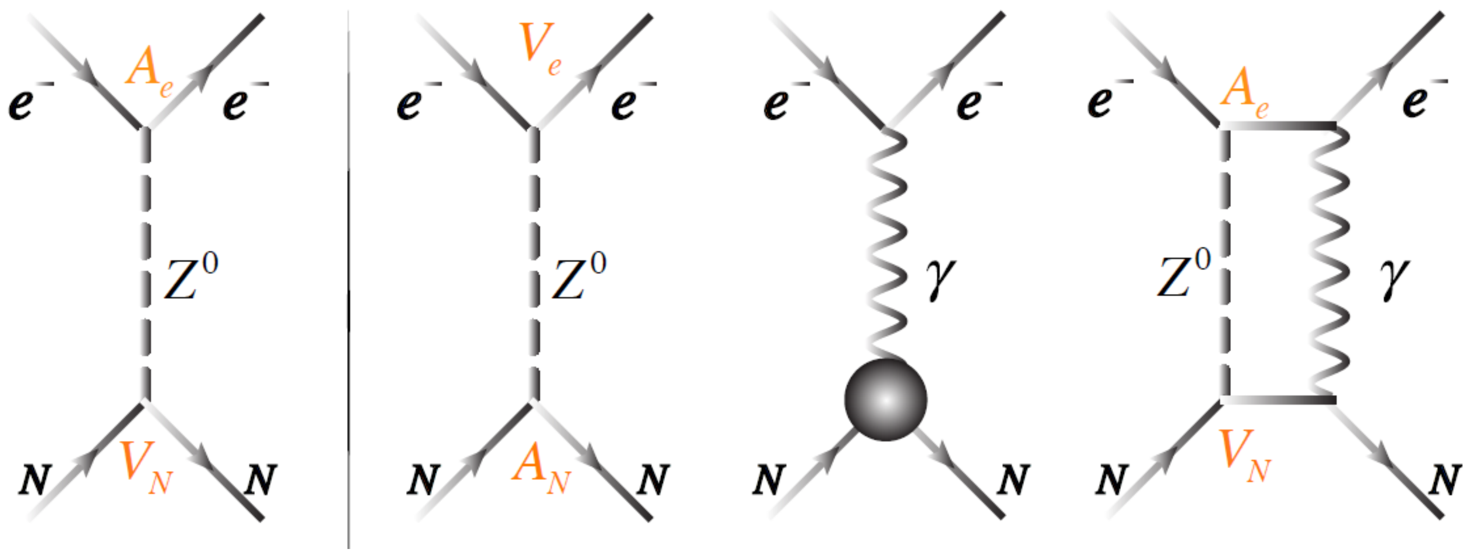
Dzuba, Flambaum and Stadnik, PRL 119, 223201 (2017)

arXiv:1804.05747

Atomic parity violation: Main processes

Nuclear-spin Independent (NSI)

Nuclear-spin dependent (NSD)



Weak neutral currents

Weak neutral currents

Anapole moment-hadronic PV

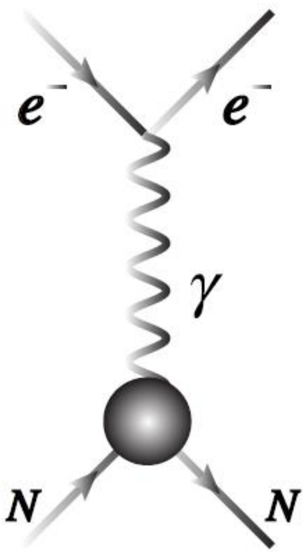
Hyperfine corrections to weak neutral currents

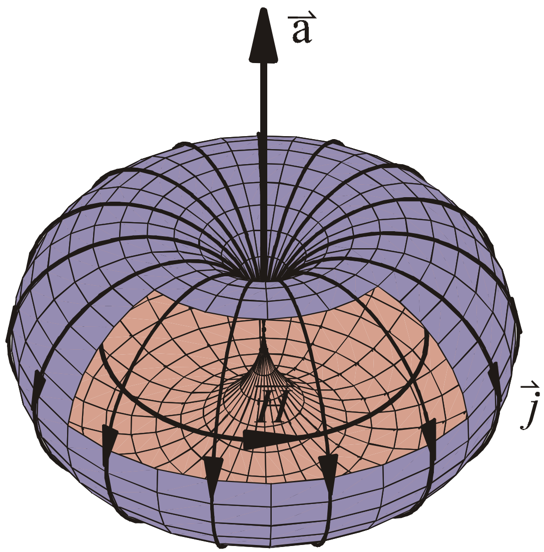
$$H_{NSI} = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \rho(r) \qquad H_{NSD} = \frac{G_F}{\sqrt{2}} \left(\eta_{axial} + \eta_{AM} + \eta_{hf}\right)(\boldsymbol{\alpha} \cdot \boldsymbol{I})\rho(r)$$

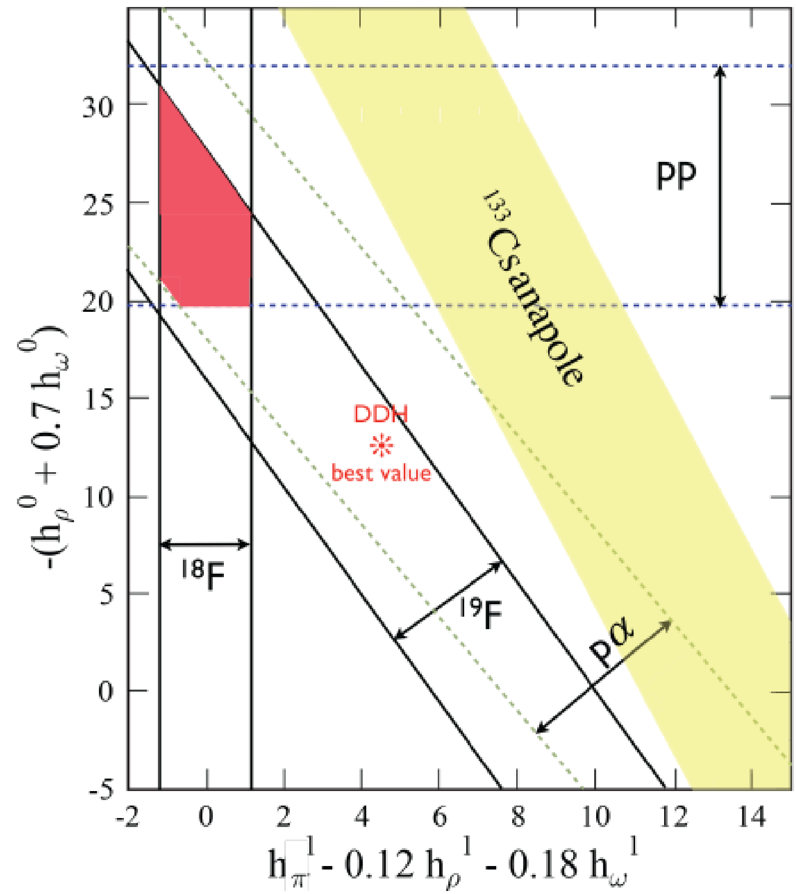
Size of NSD effects depend on *Z* & type of valence nucleon

Safranova et al. arXiv:1710.01833

Main nuclear-spin-dependent process: anapole moment







Safranova et al. arXiv:1710.01833

Anapole moment:

- P-odd E/M moment from intranuclear PV
- Probe of weak meson-nucleon couplings (hadronic PV)

Next stop: anapole moment

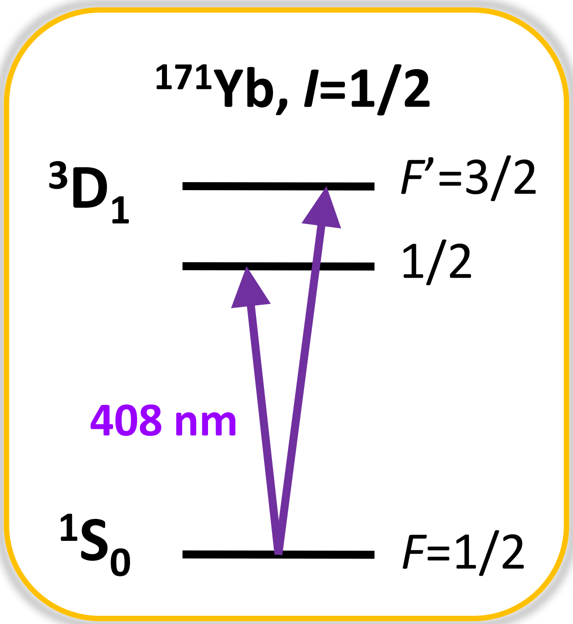


TABLE II. PNC amplitudes (z components) for the $|6s^2, {}^1S_0, F_1\rangle \rightarrow |6s5d, {}^3D_1, F_2\rangle$ transitions in ^{171}Yb and ^{173}Yb in units of $E'Q_W$ and $10^{-9} iea_0$.

A	I	F_1	F_2	PNC amplitude, units: $E'Q_W$	PNC amplitude, units: $10^{-9} iea_0$
171	0.5	0.5	0.5	$-(1/3)(1-0.0161\varkappa)$	$6.15(1-0.0161\varkappa)$
		0.5	1.5	$\sqrt{2/9}(1+0.0081\varkappa)$	$-8.70(1+0.0081\varkappa)$
173	2.5	2.5	1.5	$-\sqrt{4/45}(1-0.0111\varkappa)$	$5.61(1-0.0111\varkappa)$
		2.5	2.5	$-\sqrt{5/21}(1-0.0032\varkappa)$	$9.18(1-0.0032\varkappa)$
		2.5	3.5	$\sqrt{2/21}(1+0.0079\varkappa)$	$-5.81(1+0.0079\varkappa)$

Dzuba &Flambaum, PRA 83, 042514 (2011)

"Best guess" PV difference between ^{171}Yb *F'*=3/2 and F'=1/2 ~ 0.1%

Need to boost SNR!

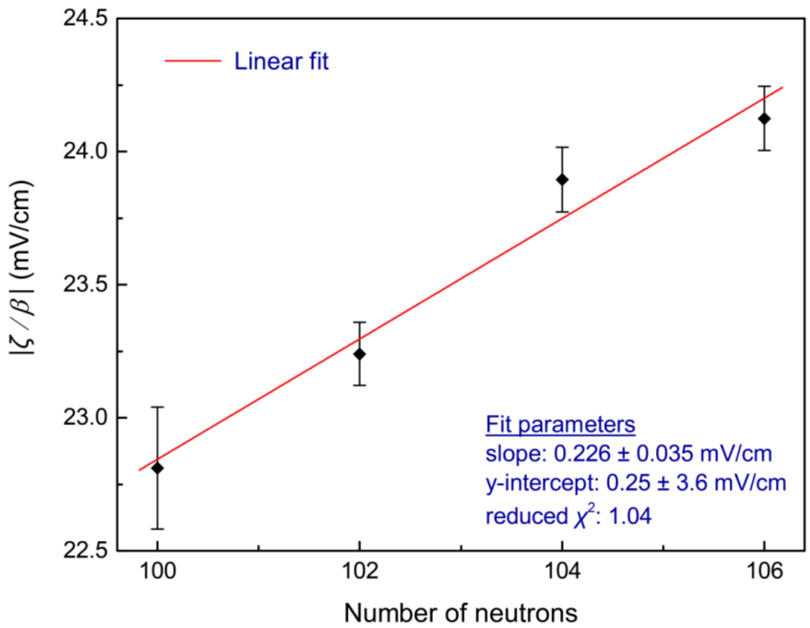
Yb sensitivity improvements (in progress)

Need x10 sensitivity enhancement for anapole, neutron skins

- Boost the Yb oven flux (x5 signal increase)
- Increase interaction region width (x2)
- Power build-up cavity mirrors upgrade (x2.5)
- Integrate longer…

Summary

- Measured PV on a chain of Yb isotopes
- 0.5% accuracy per isotope
- Constrained light Z'-mediated e-nucleon couplings
- Next: anapole moment of ^{171}Yb & ^{173}Yb



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