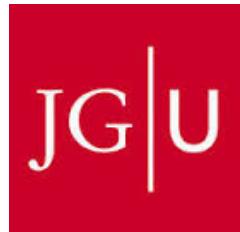


# Low-energy experiments in search for new physics

D. Antypas

8<sup>th</sup> International Symposium on Symmetries  
in Subatomic Physics  
Vienna, 29.08-02.09.2022



# The low-energy, precision frontier & A.M.O. physics

- Violation of fundamental symmetries  
(parity/time-reversal-symmetry)
- Precision tests of QED (electron  $g$ -factor, spectroscopy of simple atoms/highly-charged ions, etc)
- Tests of CPT theorem in matter-antimatter comparison
- Searches for light dark matter with atomic clocks, optical magnetometers, NMR-based sensors

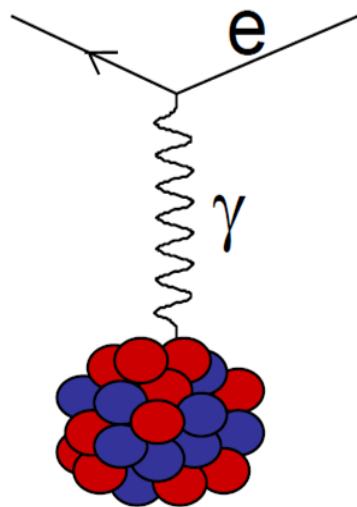
# Outline

- Atomic parity violation in Yb
  - Atomic effects of the weak force & observables
  - Physics motivations for atomic PV experiments
  - Ytterbium parity violation experiment
  - Preliminary results
  - Forthcoming measurements
- A search for light bosons with isotope-shift spectroscopy in Yb
  - How to look for new bosons with King-plot analysis
  - Hints for new bosons from recent experiments
  - Isotope-shift spectroscopy experiment in Yb
  - Evaluation of the previous hint for new physics

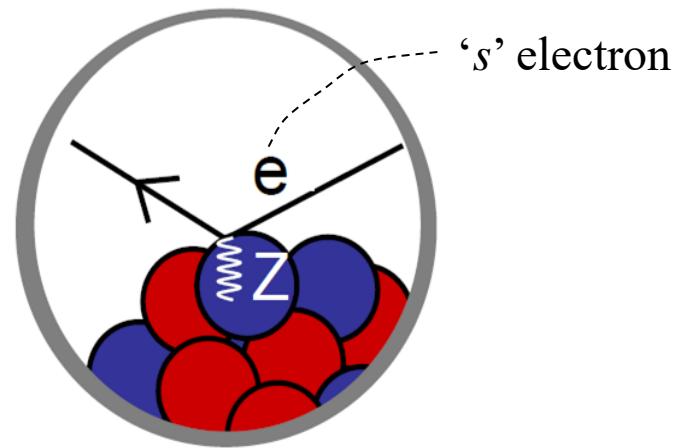
# I. Atomic parity violation in ytterbium

# Atomic Parity Violation

Main Source: Z exchange

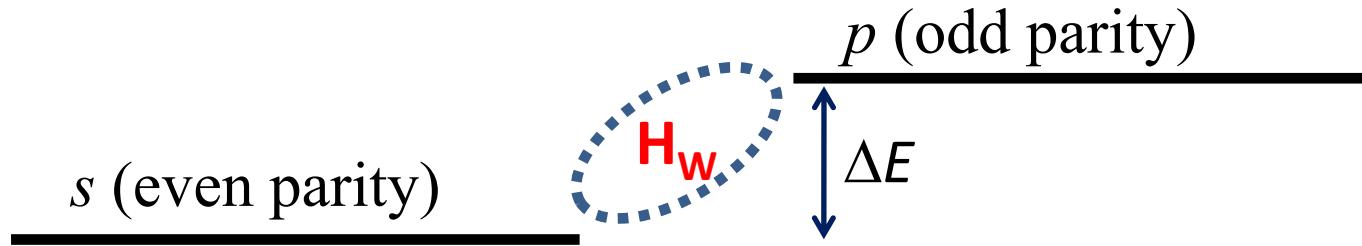


Electromagnetic  
interaction  
(conserves parity)

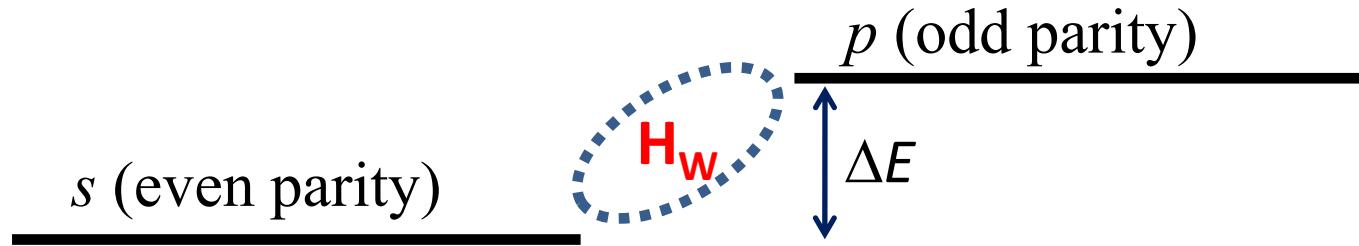


Weak  
interaction  
(violates parity)

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



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



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

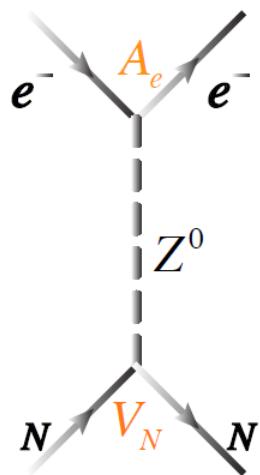
$$\epsilon = \frac{\langle s | H_w | p \rangle}{\Delta E} \sim \frac{RZ^3}{\Delta E}$$
 - the Bouchiat Law

Atomic Parity Violation Enhancement:

- Heavy atoms (high  $Z$ )
- Small  $\Delta E$

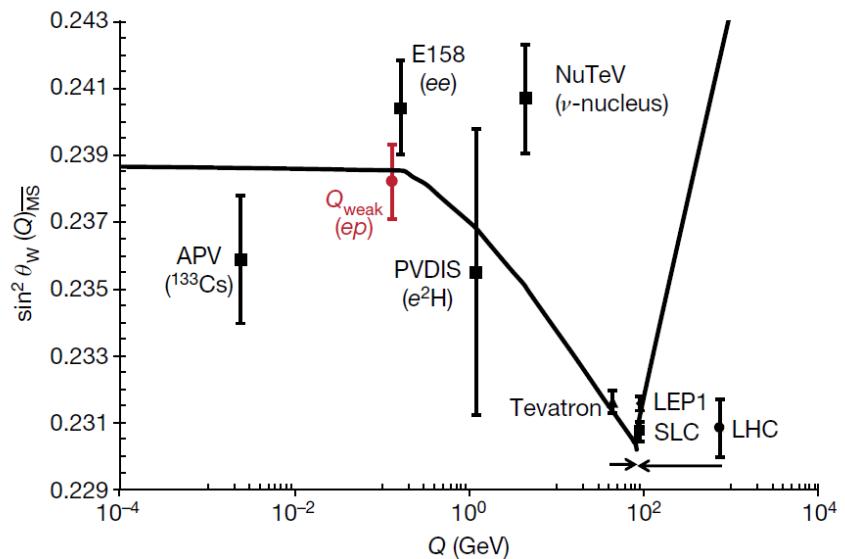
# What can atomic PV probe ?

## 1. Beyond-Standard Model interactions



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

$$Q_W \approx -N + Z(1 - 4\sin^2\theta_W)$$



Nature 557, 207 (2018)

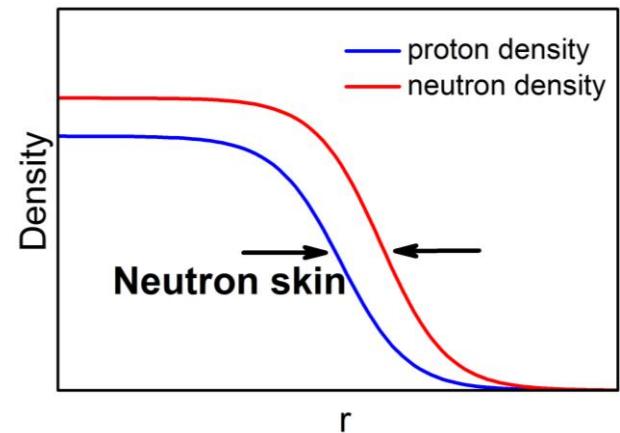
- Extract  $\sin^2\theta_W$  from:
  - single-isotope measurement  
(need atomic theory)
  - from isotope-ratio measurements  
(no theory needed)

# What can atomic PV probe ?

## 2. Neutron distributions

$$\bar{Q}_W = -\frac{Nq_n}{\text{---}} + \frac{Zq_p}{\text{---}}(1 - 4 \sin^2 \theta_W)$$

$$q_{n(p)} = \int f(r) \rho_{n(p)}(r) dr$$

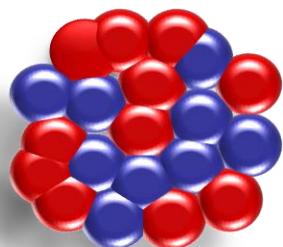
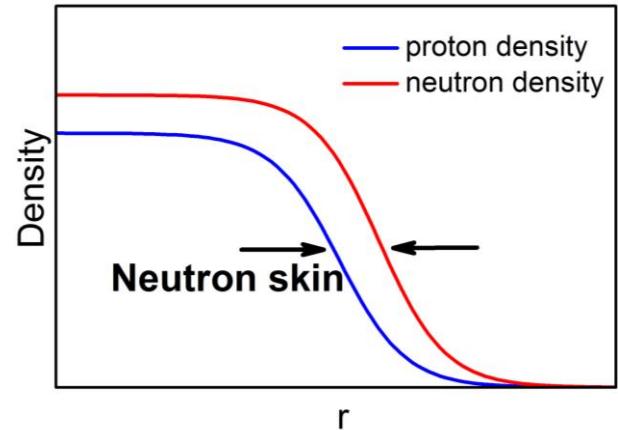


# What can atomic PV probe ?

## 2. Neutron distributions

$$\bar{Q}_W = -\frac{Nq_n}{\text{---}} + \frac{Zq_p}{\text{---}}(1 - 4 \sin^2 \theta_W)$$

$$q_{n(p)} = \int f(r) \rho_{n(p)}(r) dr$$



Size  $\approx 10^{-15}$  m

Spatial distribution of  
neutrons in nuclei  
↔  
internal structure of  
neutron stars

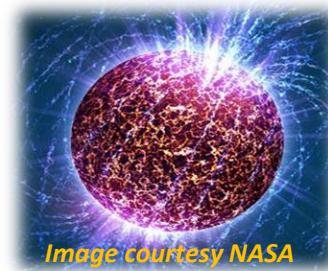
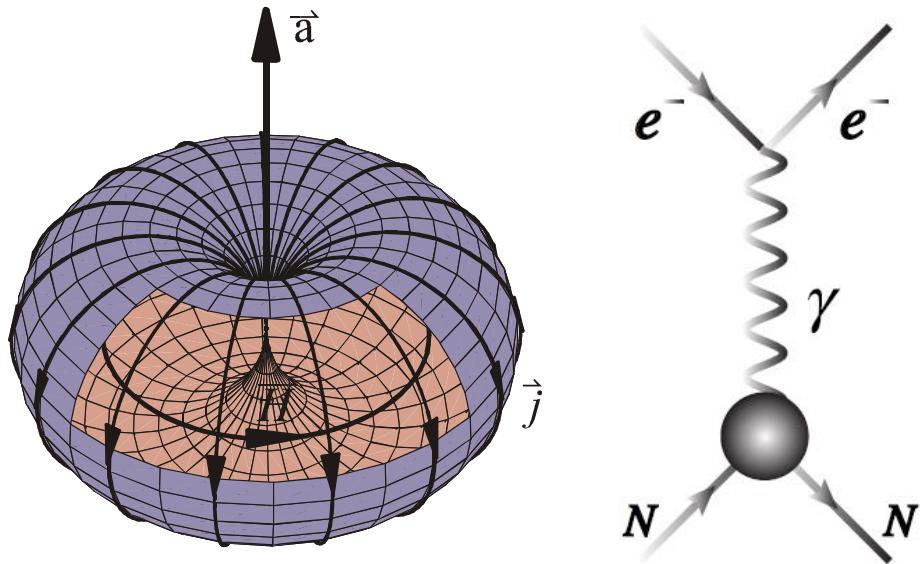


Image courtesy NASA

Size  $\approx 10^4$  m

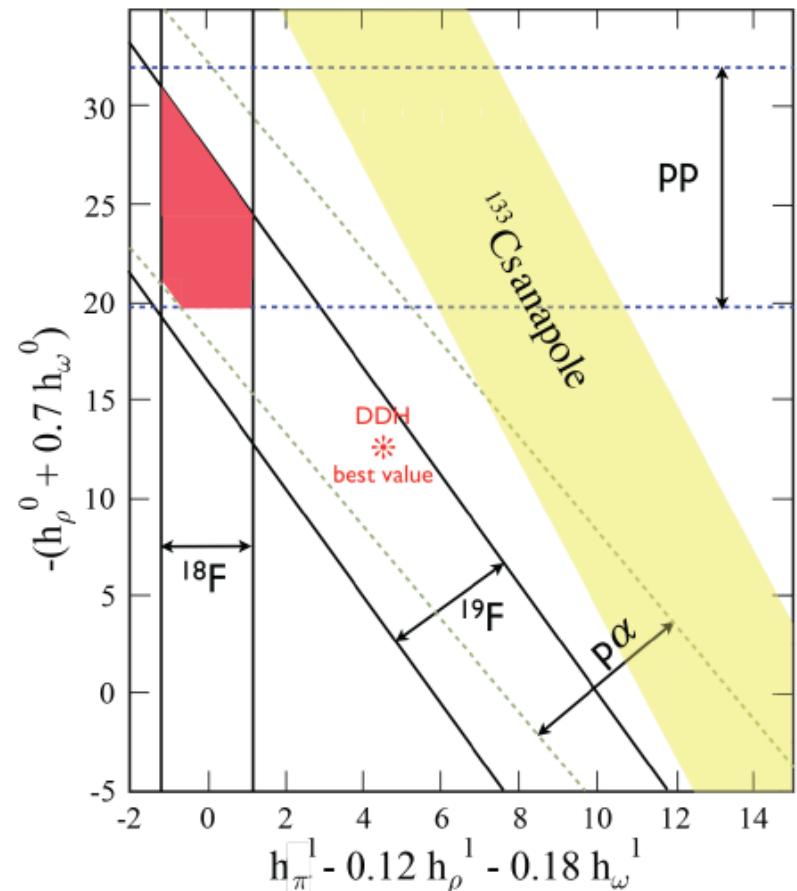
# What can atomic PV probe ?

## 3. Hadronic weak interactions



Anapole moment:

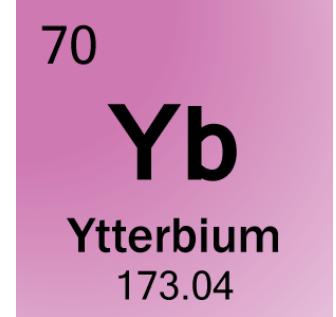
- P-odd E/M moment from intranuclear PV
- Probe of weak meson-nucleon couplings (hadronic PV)



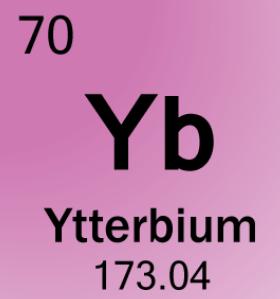
Safronova et al. arXiv:1710.01833

# Why PV with ytterbium

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



# Why PV with ytterbium

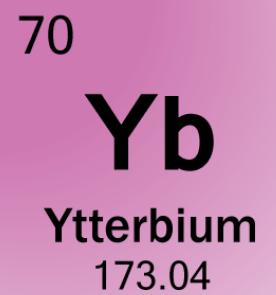


- **Large** PV effect (DeMille, 1995 - Tsigutkin *et al*, 2009)
- 7 stable isotopes ( $A=168, 170-174, 176$ )

| Isotope           | NA (%)      | I          |
|-------------------|-------------|------------|
| $^{168}\text{Yb}$ | <b>0.13</b> | <b>0</b>   |
| $^{170}\text{Yb}$ | <b>3.04</b> | <b>0</b>   |
| $^{171}\text{Yb}$ | <b>14.3</b> | <b>1/2</b> |
| $^{172}\text{Yb}$ | <b>21.8</b> | <b>0</b>   |
| $^{173}\text{Yb}$ | <b>16.1</b> | <b>5/2</b> |
| $^{174}\text{Yb}$ | <b>31.8</b> | <b>0</b>   |
| $^{176}\text{Yb}$ | <b>12.8</b> | <b>0</b>   |

- PV on chain of isotopes → new physics/neutron skins

# Why PV with ytterbium

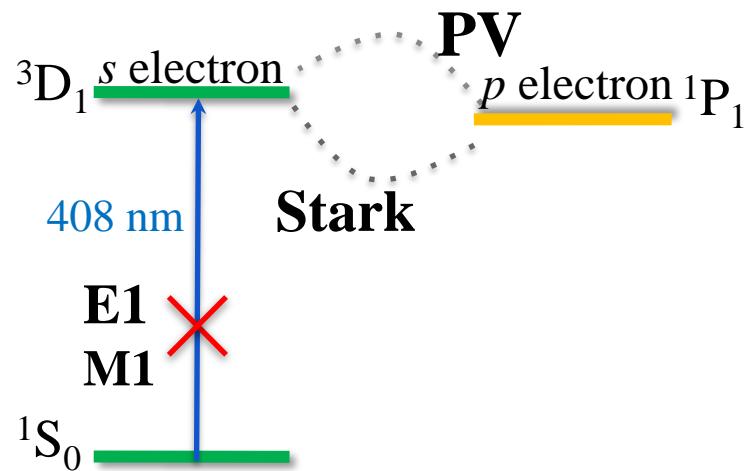
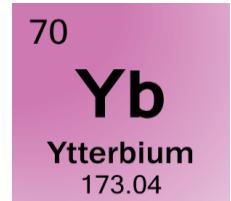


- **Large** PV effect (DeMille, 1995 - Tsigutkin *et al*, 2009)
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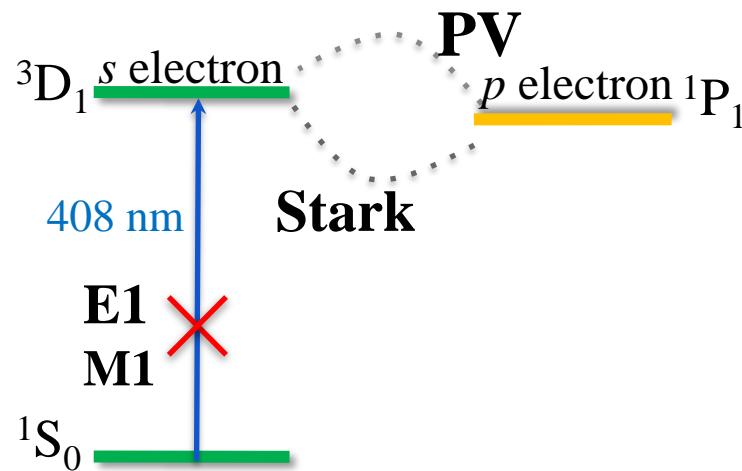
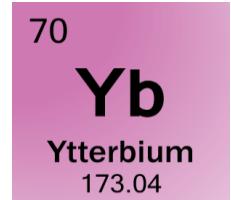
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| $^{171}\text{Yb}$ | 14.3   | $1/2$ |
| $^{172}\text{Yb}$ | 21.8   | 0     |
| $^{173}\text{Yb}$ | 16.1   | $5/2$ |
| $^{174}\text{Yb}$ | 31.8   | 0     |
| $^{176}\text{Yb}$ | 12.8   | 0     |

- PV on chain of isotopes → new physics/neutron skins
- Two isotopes with nuclear spin → spin-dependent PV effects

# The Yb experiment



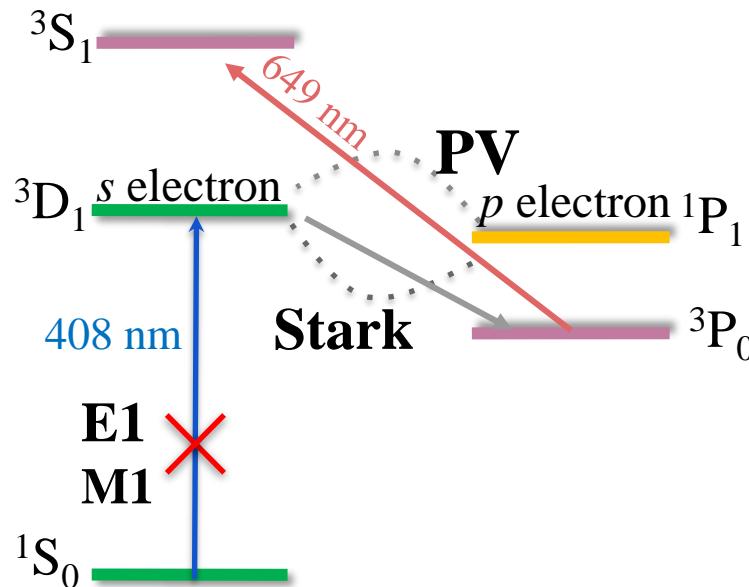
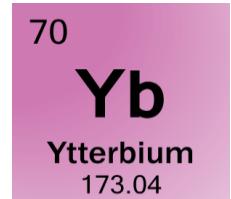
# The Yb experiment



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

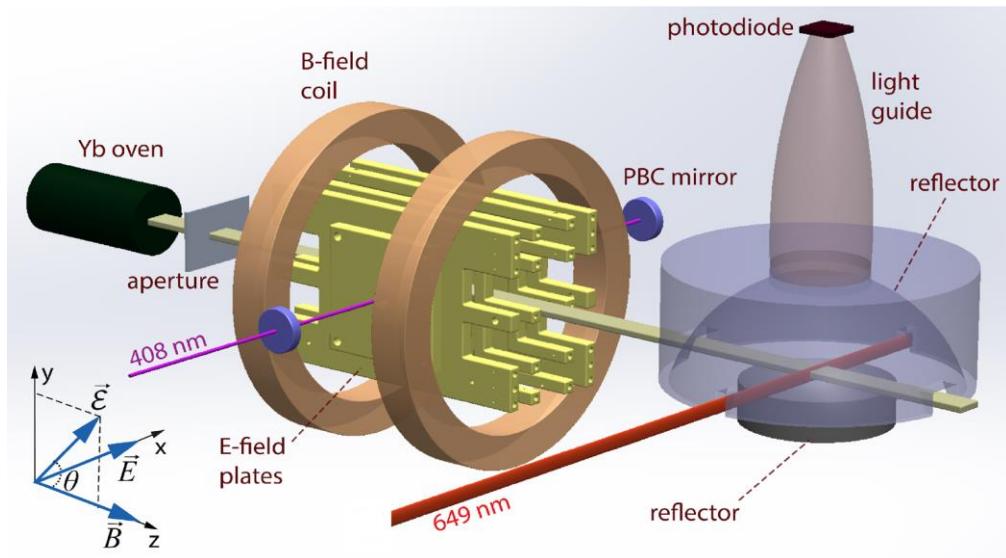
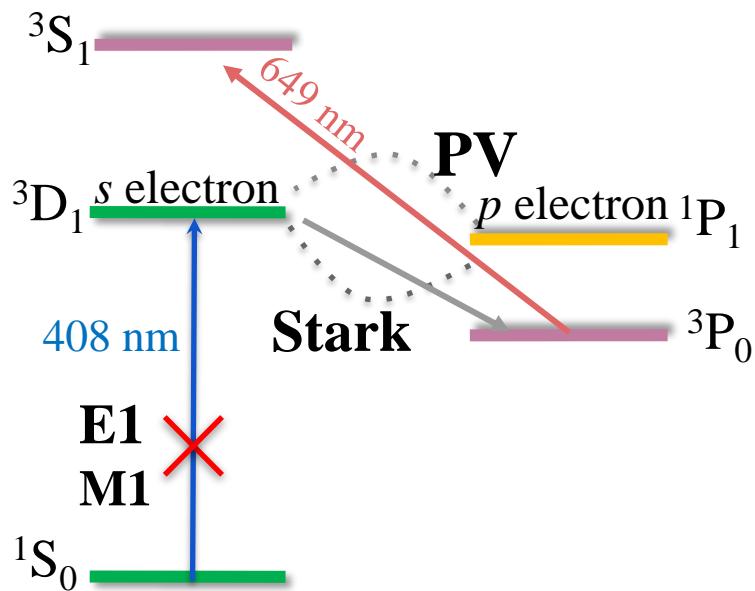
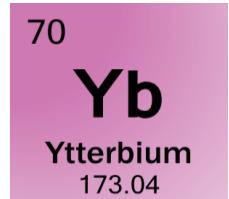
50 ppm

# The Yb experiment



$$\begin{aligned}
 W_{\pm} &= |A_{\text{Stark}} + A_{\text{PV}}|^2 \\
 &\approx \underbrace{A_{\text{Stark}}^2}_{P-\text{conserving}} \quad \underbrace{\pm 2A_{\text{Stark}} \cdot A_{\text{PV}}}_{P-\text{violating}} \\
 &\quad 50 \text{ ppm}
 \end{aligned}$$

# The Yb experiment

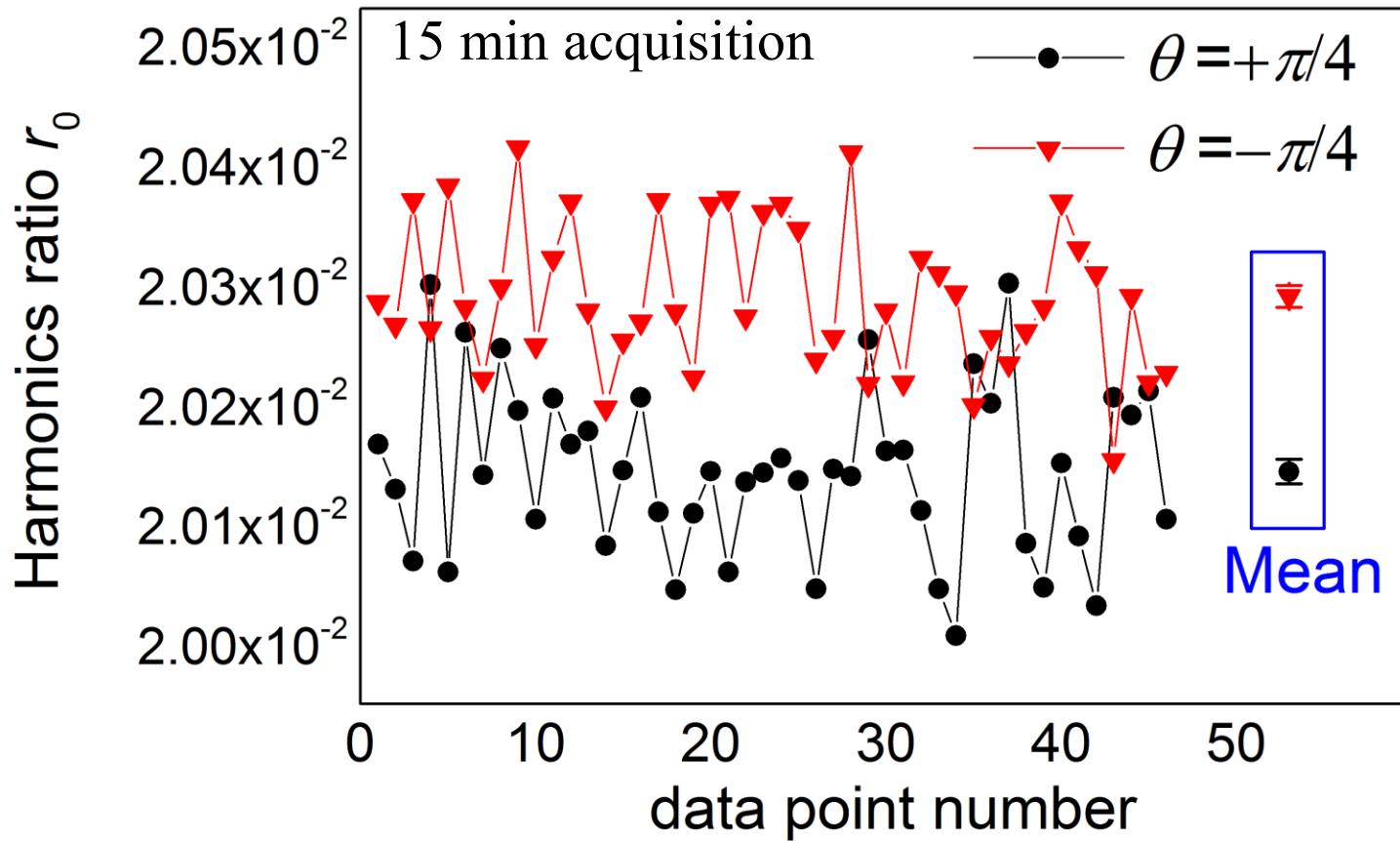


$$W_{\pm} = |A_{\text{Stark}} + A_{\text{PV}}|^2$$

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

50 ppm

# Parity reversal



# Few essential checks

TABLE II. Results of auxiliary experiments.

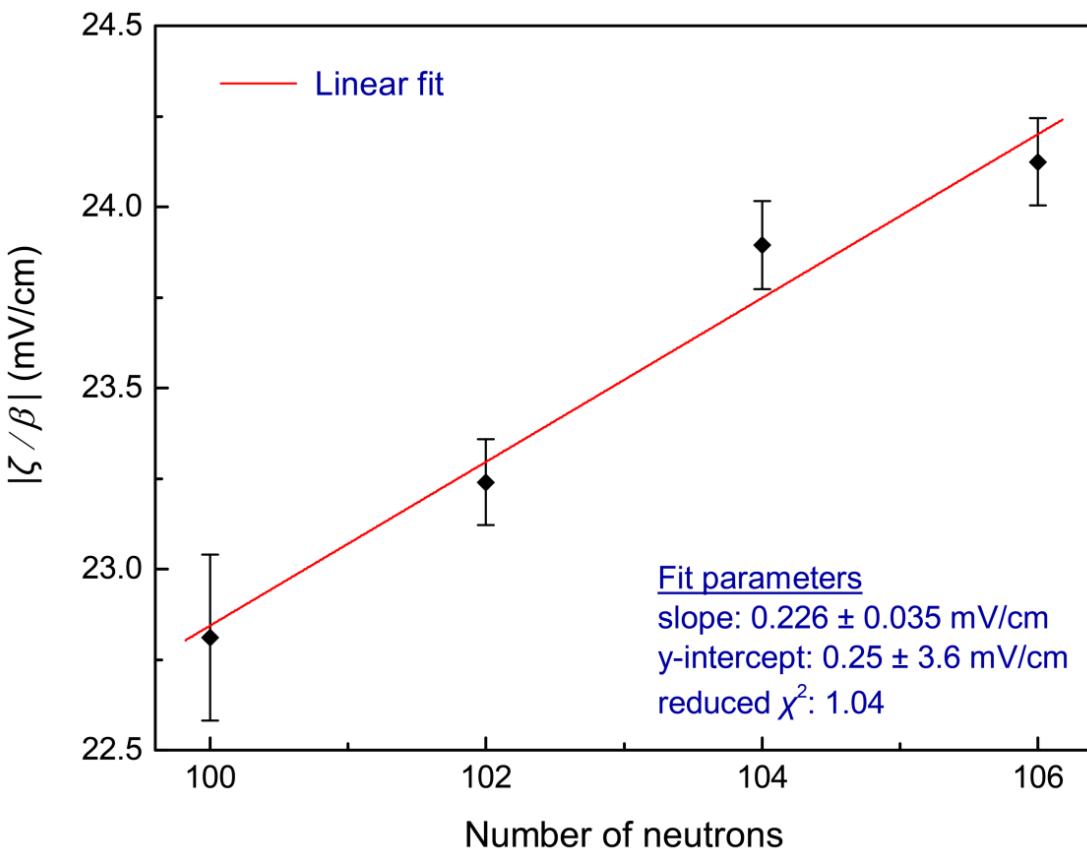
| Isotope mass number | Transition                        | Type of experiment                                   | $\zeta / \beta$ (mV/cm) |
|---------------------|-----------------------------------|--|-------------------------|
| 174                 | $m = 0 \rightarrow m' = 0$        | Actual isotopic comparison data                      | -23.89(11)              |
| 174                 | $m = 0 \rightarrow m' = \pm 1$    | ...  | 23.30(26) <sup>a</sup>  |
| 174                 | $m = 0 \rightarrow m' = 0$        | Measurement of $r_0$ vs $\theta^b$                   | -24.65(80)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Enhanced $e_y^r/E_0 = -0.03$                         | -24.30(48)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Enhanced $e_y^r/E_0 = 0.03$                          | -23.93(40)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Enhanced $e_z^r/E_0 = -0.029$                        | -23.98(57)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Enhanced $e_z^r/E_0 = 0.029$                         | -23.76(57)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Enhanced $e_z/E_0 = -0.076$                          | -24.67(57)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Enhanced $e_z/E_0 = 0.076$                           | -23.83(57)              |
| 174                 | $m = 0 \rightarrow m' = 0$        | Measurement on secondary transition peak             | -24.14(44)              |
| 174                 | $m = 0 \rightarrow m' = 0, \pm 1$ | Line-shape fitting                                   | -21(4)                  |
| 171                 | $F = 1/2 \rightarrow F' = 1/2$    | ...  | -0.59(57)               |
| 174                 | $m = 0 \rightarrow m' = 0$        | 408-nm excitation using circularly polarized light   | -0.2(12)                |
| 174                 | $m = 0 \rightarrow m' = 0$        | Measurement with different field plates <sup>c</sup> | -25.2(12)               |
| 174                 | $m = 0 \rightarrow m' = 0$        | Measurement without PBC                              | -26(7)                  |

<sup>a</sup>The PV-mimicking terms  $e_y^r(e_z/E_0)$  and  $e_z^r(e_y/E_0)$  were not compensated prior to the measurement [see Appendix A and Eq. (A24)].

<sup>b</sup>See Fig. 10.

<sup>c</sup>Done without the high degree of 408-nm polarization control implemented in the isotopic comparison runs.

# Observation of isotopic variation in atomic PV



*0.5% single  
isotope accuracy*

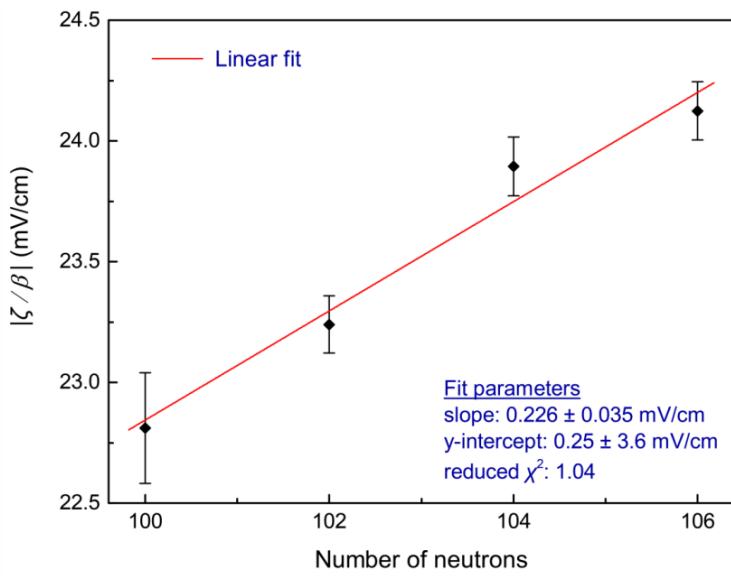
Antypas et al. Nature Physics 15, 120  
(2019)

Experimental details:  
PRA 100, 012503 (2019)

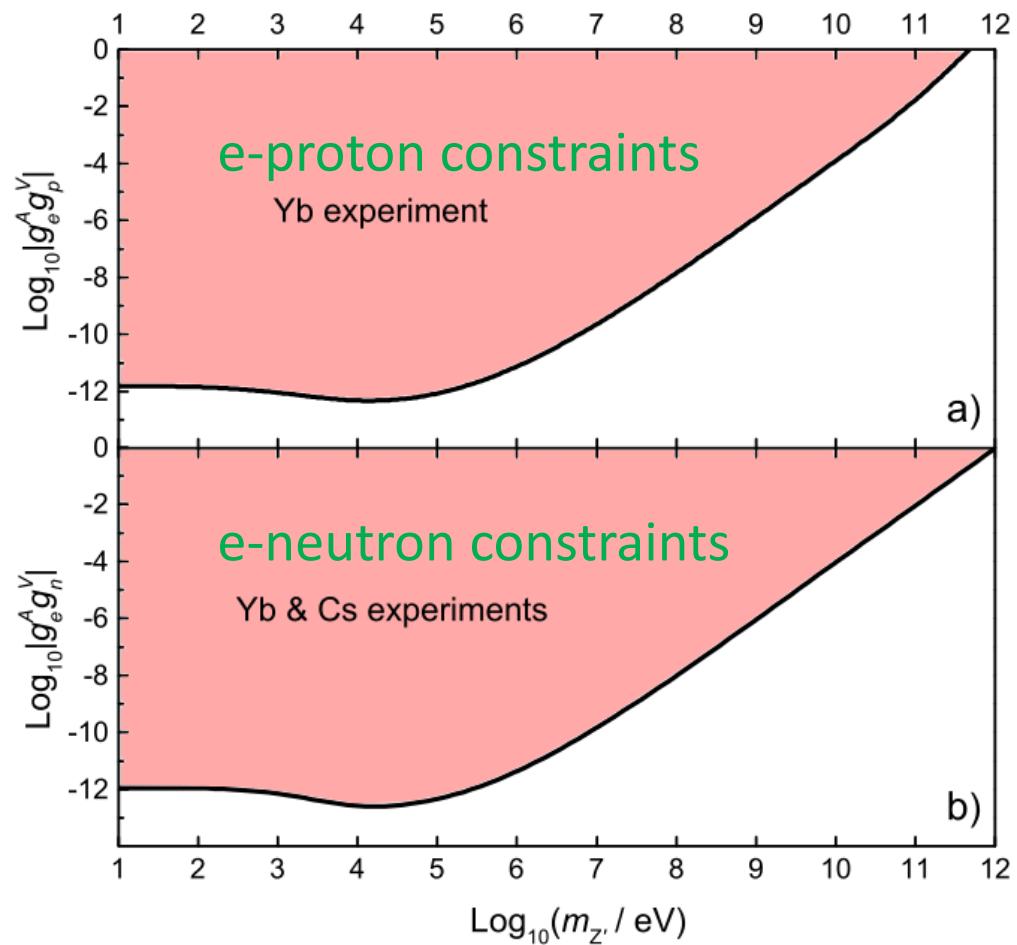
**SM:**  $Q_W \approx -N+Z(1 - 4\sin^2\theta_W) \rightarrow 1\%$  change per neutron around N=103

**Observation:** 0.96(15) % change per neutron

# Constraints on light Z'-mediated e-proton & e-neutron interactions



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

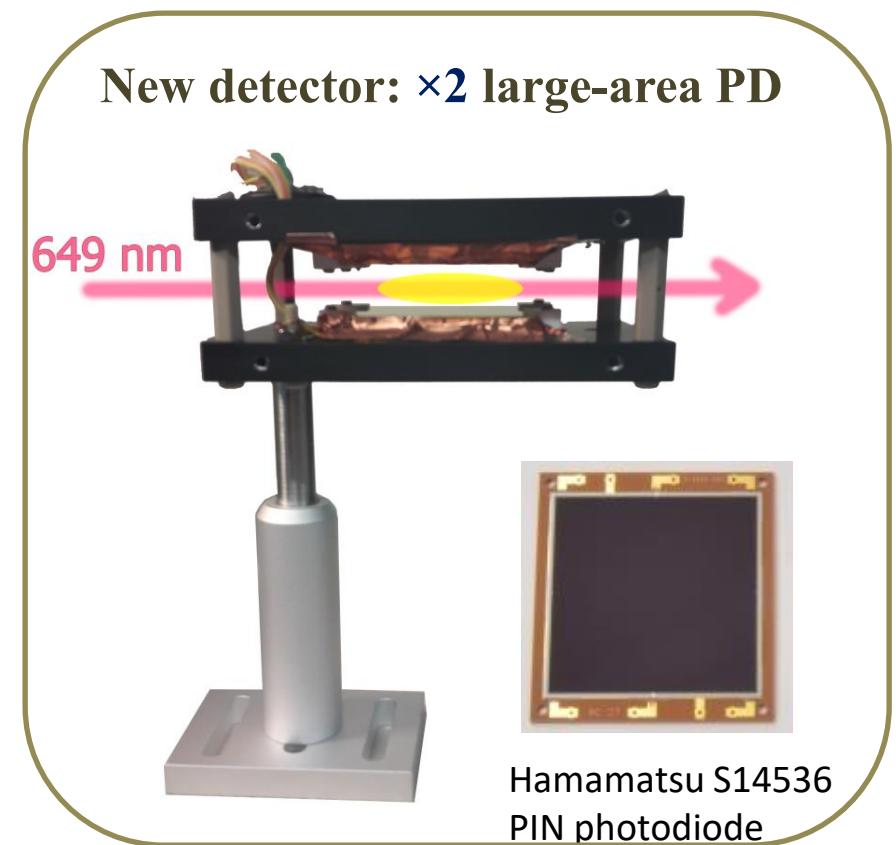
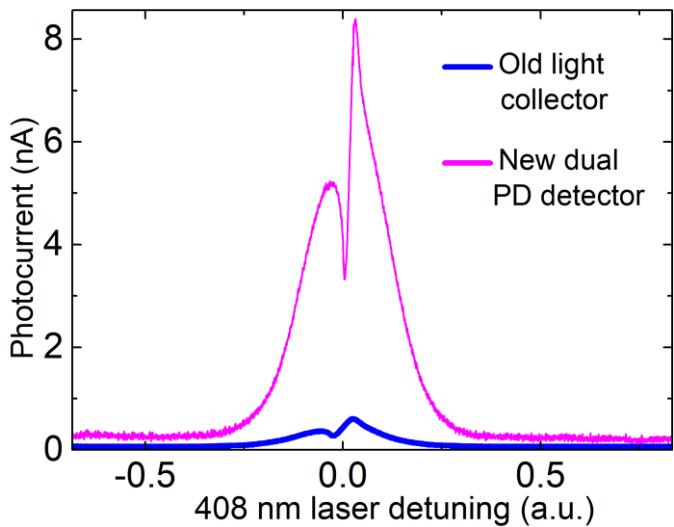
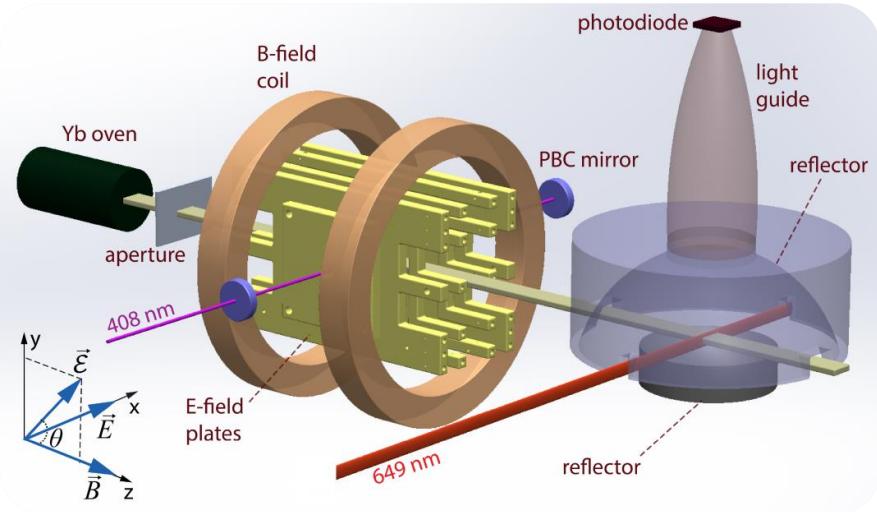


In collaboration with V. Flambaum

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

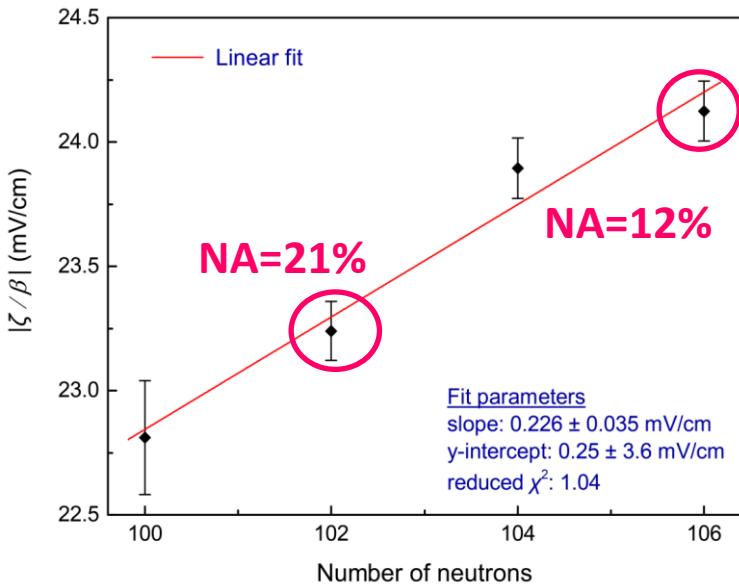
Antypas et al. Nature Physics 15,  
120 (2019)

# New large-area photodetector



- $\times 2$  wider atom beam
  - New detector
- $\left.\begin{array}{l} \times 2 \text{ wider atom beam} \\ \text{New detector} \end{array}\right\} \times 15 \text{ larger photocurrent}$

# Next: precision isotopic ratio measurements



A 0.03% isotopic ratio measurement will yield:

- $\sin^2\theta_W$  to within  $\sim 1.5\%$
- Yb neutron-skin variation to within  $\sim 30\%$

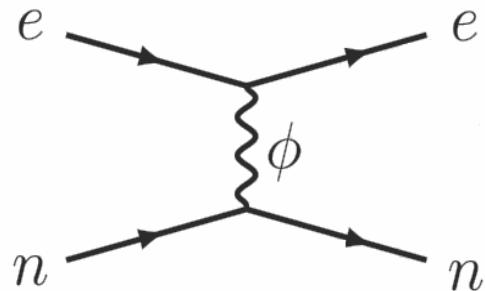


## ERC Starting Grant YbFUN (12.2020-11.2025):

1. Are there  $Z'$  bosons?
2. What is the neutron-skin variation in the Yb nuclei?
3. What is the size of the Yb anapole moment?

## II. Searching for new scalar bosons with isotope-shift spectroscopy

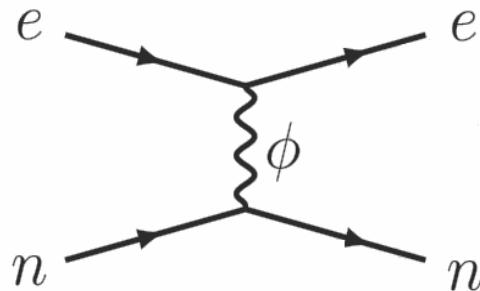
# Search for new force mediator between electron and neutrons



Effective spin-independent potential

$$V_\phi(r) = -N\alpha_{\text{NP}} \frac{e^{-m_\phi r}}{r}$$

# Search for new force mediator between electron and neutrons



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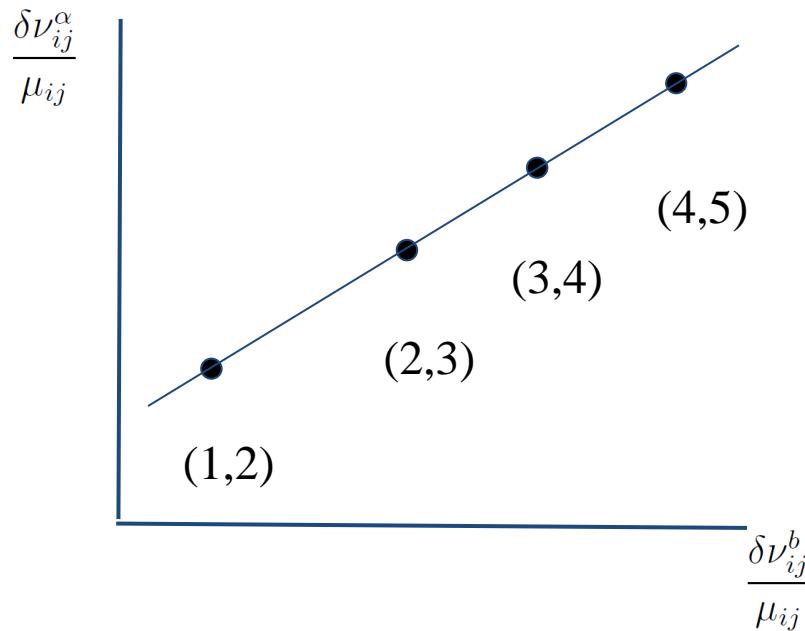
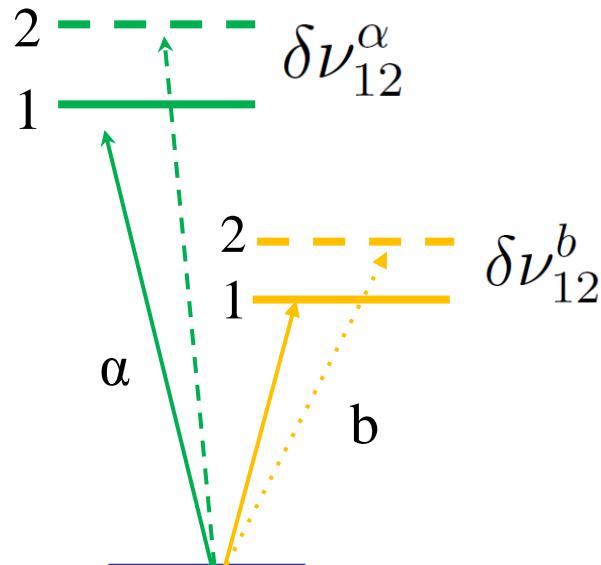
## Probing New Long-Range Interactions by Isotope Shift Spectroscopy

Julian C. Berengut, Dmitry Budker, Cédric Delaunay, Victor V. Flambaum, Claudia Frugueule, Elina Fuchs, Christophe Grojean, Roni Harnik, Roee Ozeri, Gilad Perez, and Yotam Soreq  
Phys. Rev. Lett. **120**, 091801 – Published 26 February 2018

**Idea:** Use isotope-shift data from a pair of atomic transitions in a *King-plot* analysis

- Data-driven approach with minimal input from atomic theory
- Need atoms with multiple isotopes & narrow transitions

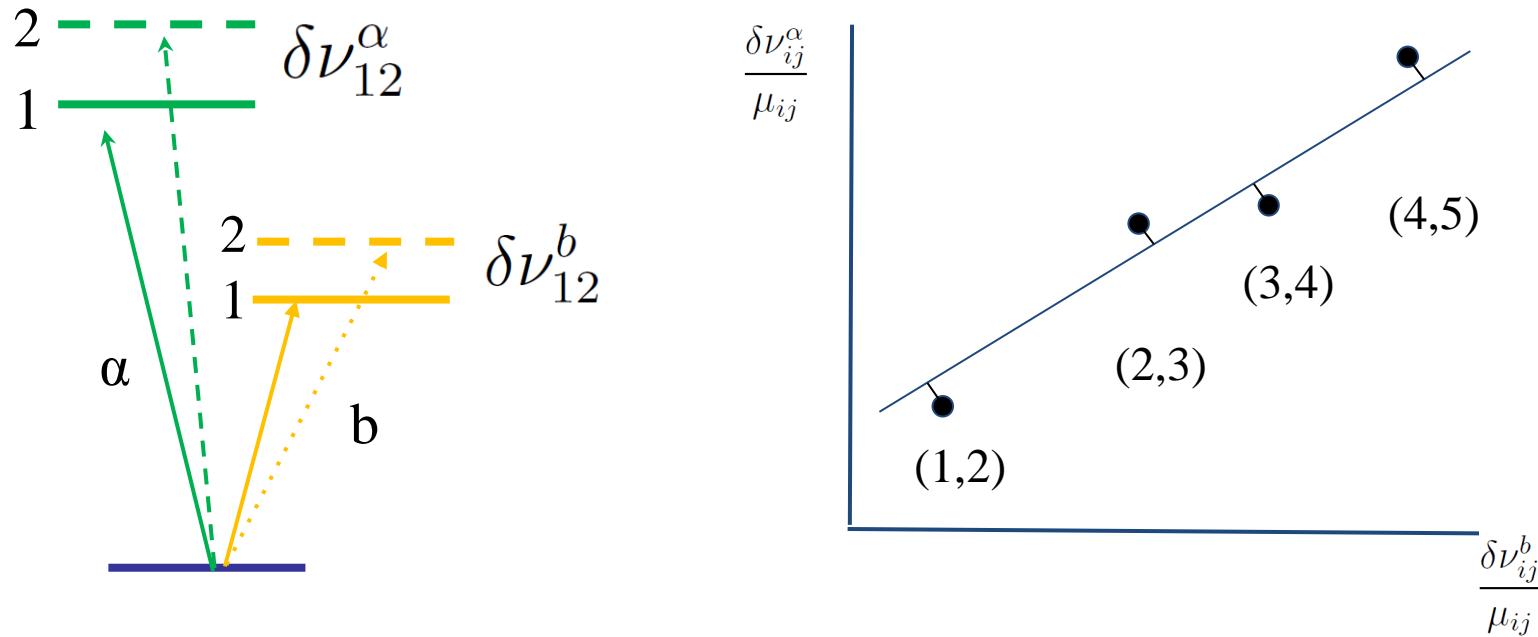
# King-plot & its (non)linearity



W. H. King, JOSA,  
Vol. 53, 638 (1963)

$\delta\nu$  due to **mass shift** and **field shift**

# King-plot & its (non)linearity

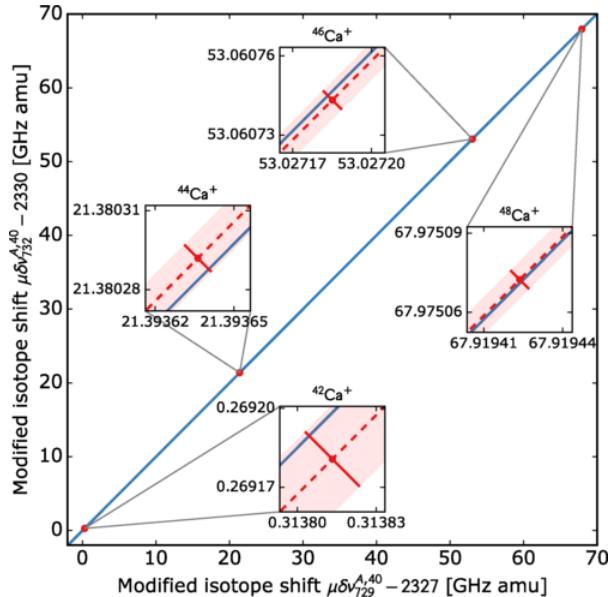


$\delta\nu$  due to **mass shift** and **field shift** and **new bosons** (and/or **subdominant nuclear effects**)

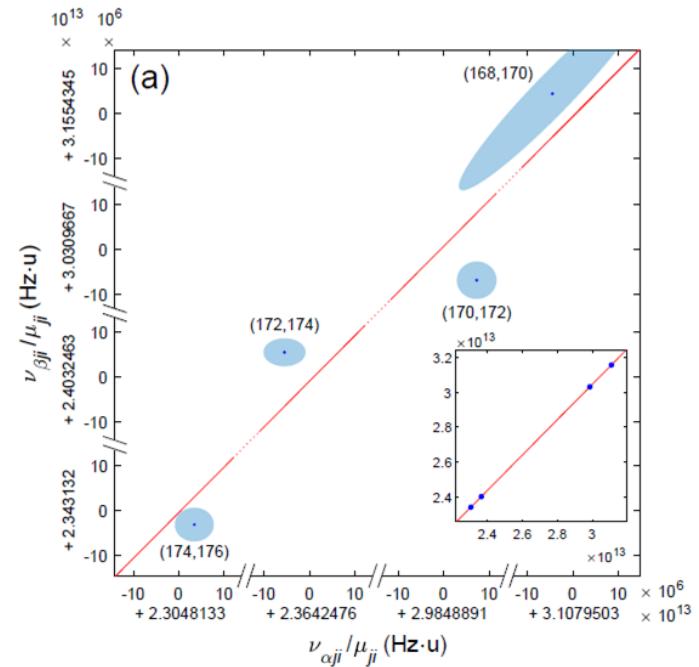
Probing New Long-Range Interactions by Isotope Shift Spectroscopy

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Phys. Rev. Lett. **120**, 091801 – Published 26 February 2018

# $\text{Yb}^+$ & $\text{Ca}^+$ results and implications



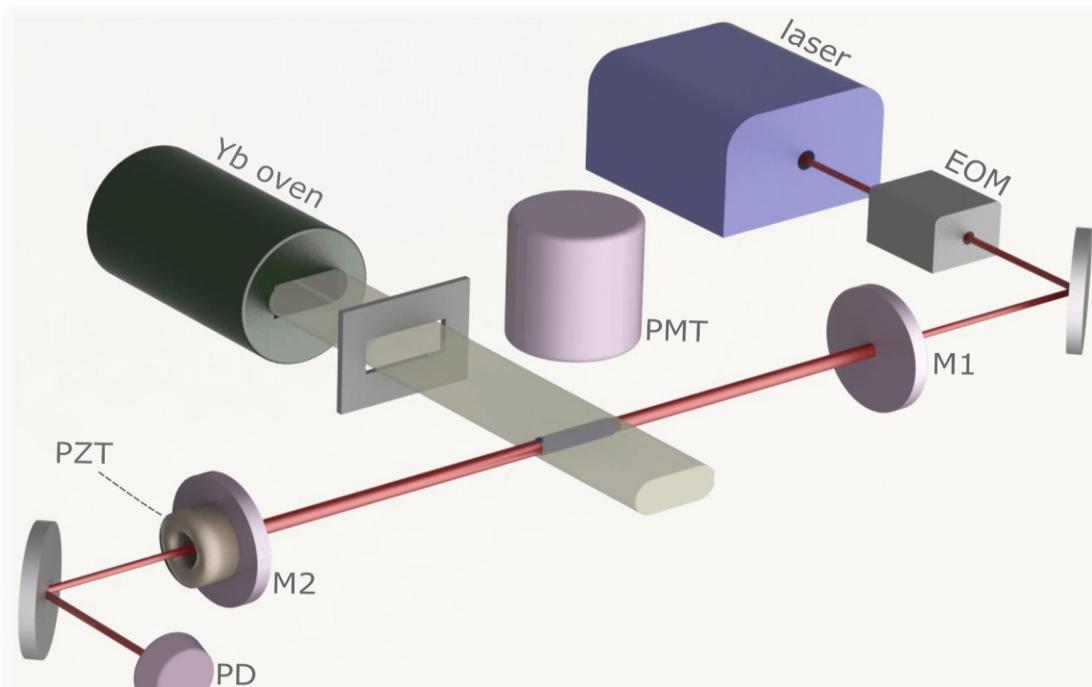
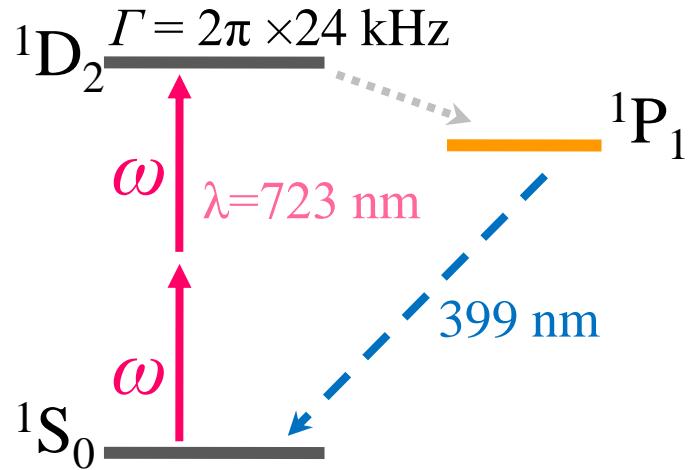
$\text{Ca}^+$ : no evidence for nonlinearity  
 Solaro et al. Phys. Rev. Lett. 125, 123003 (2020)



$\text{Yb}^+$ :  $3\sigma$  deviation from linearity  
 Counts et al. Phys. Rev. Lett. 125, 123002 (2020)

**Question:** what is the source of nonlinearity in  $\text{Yb}^+$ ?

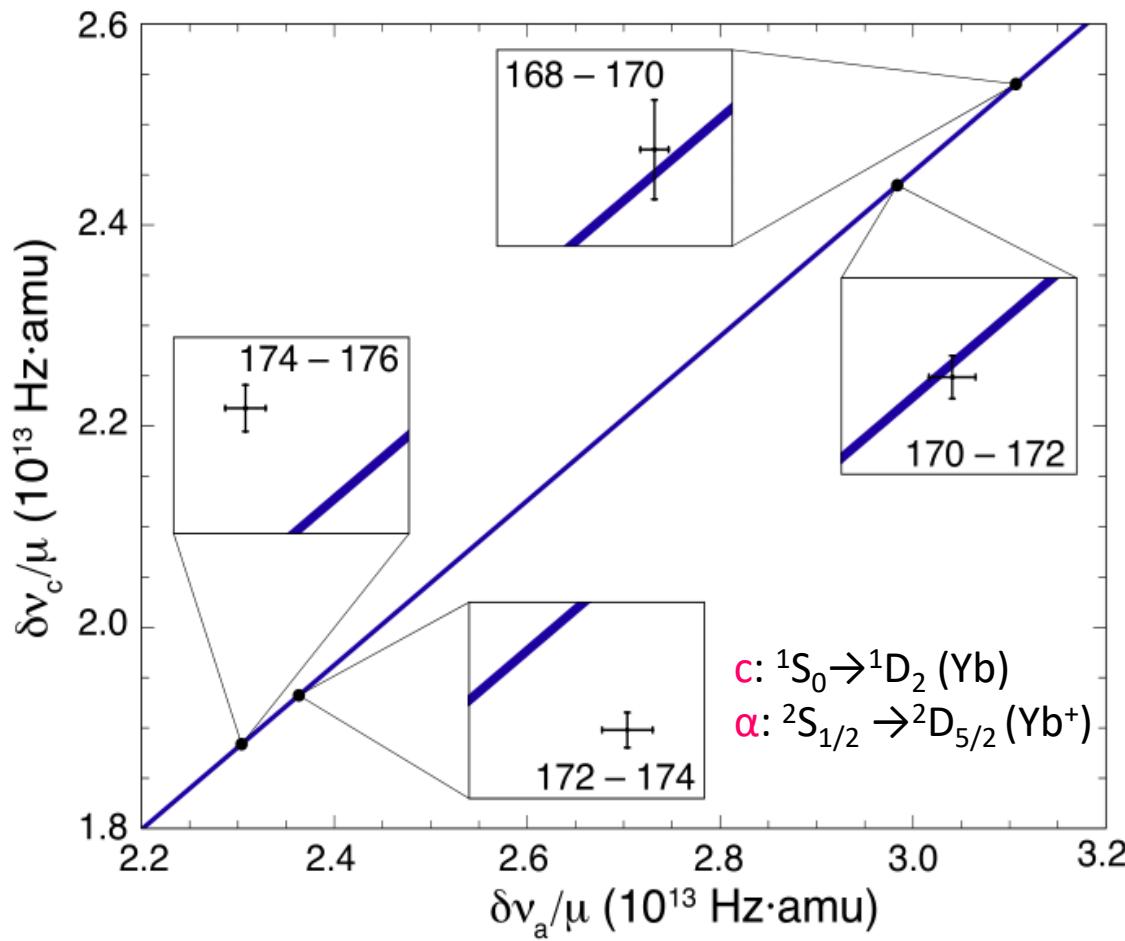
# Spectroscopy on Yb two-photon transition $^1S_0 \rightarrow ^1D_2$



| Isotope           | NA (%)      | I          |
|-------------------|-------------|------------|
| $^{168}\text{Yb}$ | <b>0.13</b> | <b>0</b>   |
| $^{170}\text{Yb}$ | <b>3.04</b> | <b>0</b>   |
| $^{171}\text{Yb}$ | <b>14.3</b> | <b>1/2</b> |
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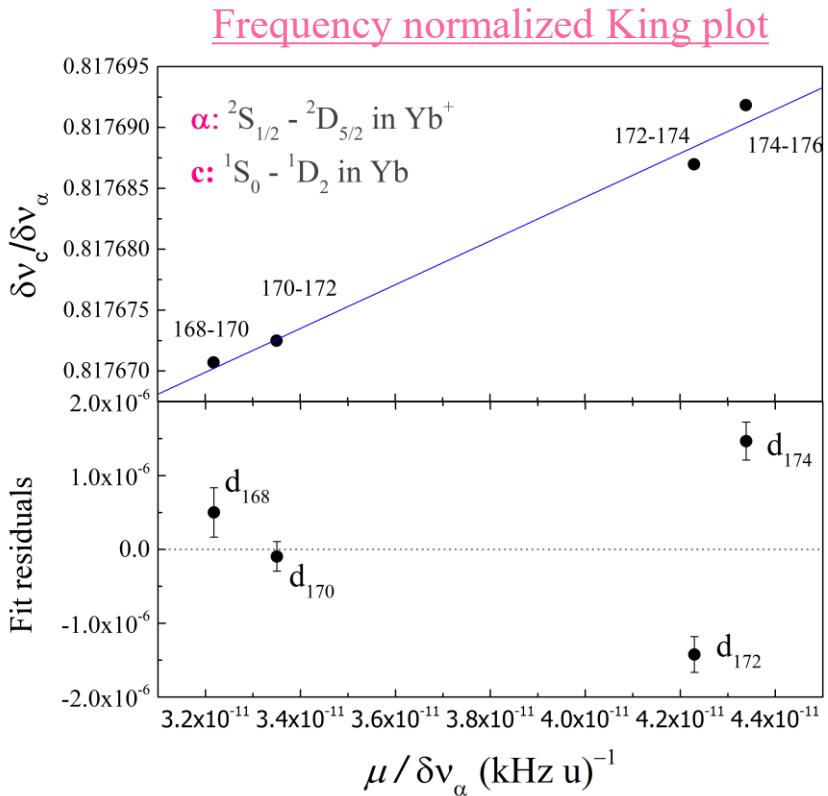
**Measurement goal:**  
300 Hz accuracy in isotope shift  
to match  $\text{Yb}^+$  results

# King plot with Yb/Yb<sup>+</sup> data

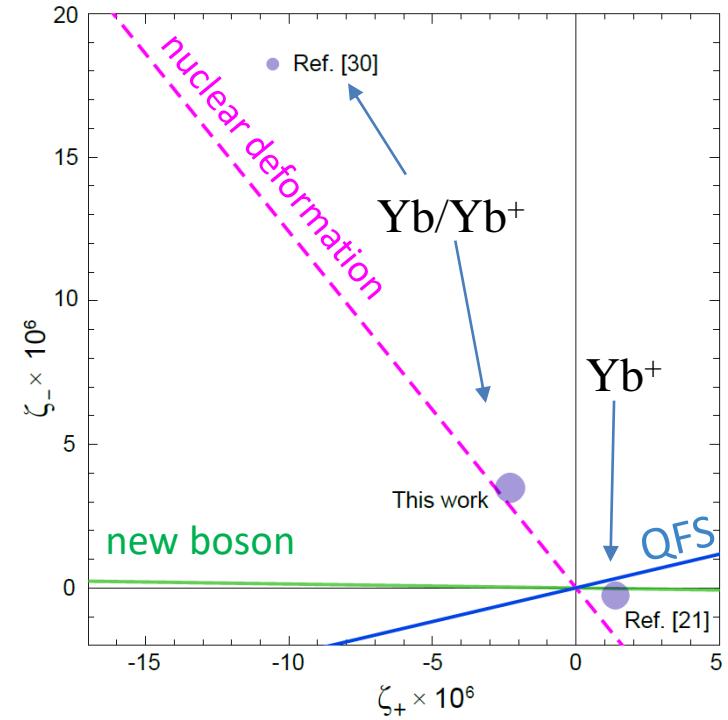


Nonlinearity at the 8 $\sigma$  level!

# Primary nonlinearity source



- Consider combinations  $\zeta_\pm = d_{168} - d_{170} \pm (d_{172} - d_{174})$
- Ratio  $\zeta / \zeta_+$  independent of atomic factors assuming single source of nonlinearity



## Transition ‘c’:

This work:  $Yb\ ^1S_0 \rightarrow ^1D_2$   
 Ref. [30]:  $Yb\ ^1S_0 \rightarrow ^3P_0$   
 Ref. [21]:  $Yb^+\ ^2S_{1/2} \rightarrow ^2D_{5/2}$

## Transition ‘a’:

$Yb^+\ ^2S_{1/2} \rightarrow ^2D_{3/2}$  (Ref. [21])

# Summary

- Multitude of approaches to test fundamental physics in low-energy, tabletop, non-accelerator experiments
- Atomic effects of weak force and forthcoming high-precision isotopic comparison in Yb
- Evaluation of hint for new physics with isotope-shift spectroscopy in Yb

