Nonlinear Isotope Shift in Yb+ Search for Dark Matter

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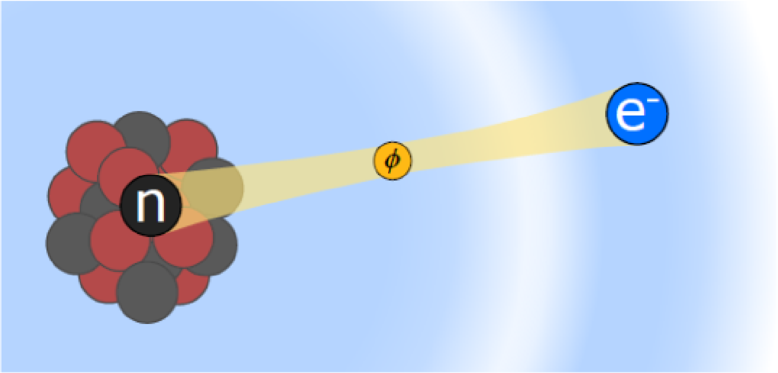

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Thanks to R. Garcia Ruiz, R. Milner, P. Harris, and J. Thaler for discussions

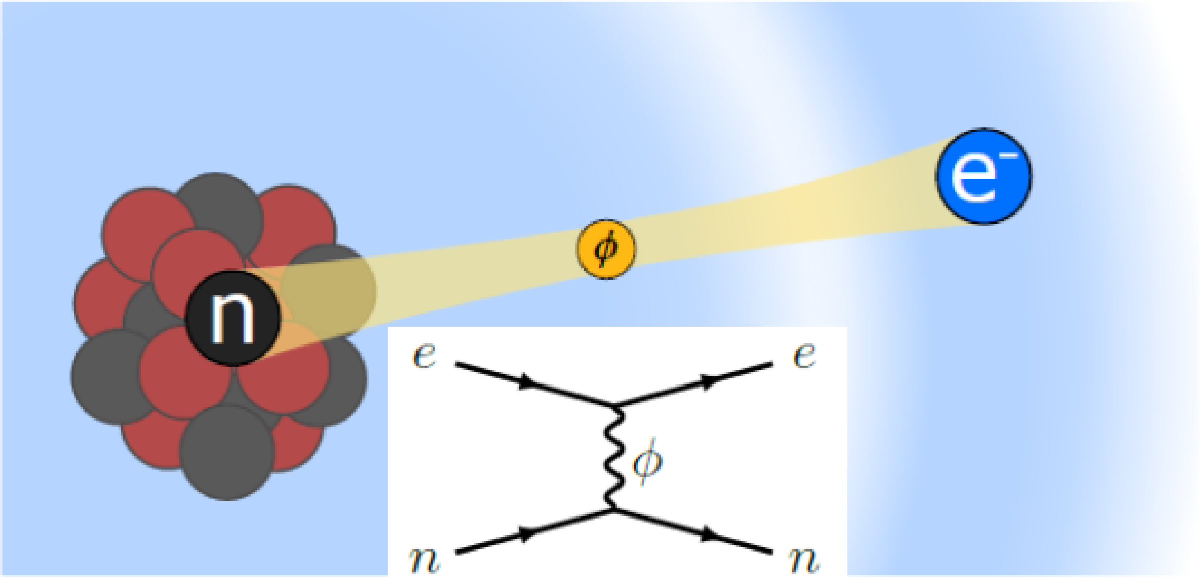
Outline

- Principle: search for fifth force through precision spectroscopy of optical transitions
- Measurements with 5 bosonic isotopes of Yb^+ on $D_{3/2}$ and $D_{5/2}$ quadrupole transitions
  - Observe nonlinearity in King plot at 3.3σ level
  - Nuclear effects vs. new boson
- Isotope Shift Measurement on octupole $F_{7/2}$ transition in Yb^+
- Future:
  - Improved measurement with higher accuracy
  - Measurement on clock transition in neutral Yb

Fifth force mediated by a new boson

(dark matter?) of intermediate mass

Interatomic force generated by new boson



New boson ϕ coupling to electrons and neutrons mediates Yukawa-type interaction with range that depends on mass *m* and spin *s* of new boson

$$V(r) = (-1)^{s+1} e^{-r/R}/r$$

range $R=\hbar/mc$ is Compton wavelength of ϕ

Transition frequency shift in atoms due to Yukawa potential

- Additional Yukawa potential is quite small for ‘not yet excluded’ coupling strengths (~ kHz for optical transitions).
- Absolute transition frequencies cannot be calculated at this level for (heavy) ions.
- Seminal idea by J. Berengut, D. Budker, C. Delaunay, V.V. Flambaum, C. Frugiuele, E. Fuchs, C. Grojean, R. Harnik, R. Ozeri, G. Perez, and Y. Soreq, PRL **120**, 091801 (2018): Compare different isotopes with different number of neutrons (but the same Coulomb potential …) to sidestep calculation and rely only on experimental data

Isotope shift

Electron wavefunction factors

$$\nu_{\alpha ji} = F_{\alpha}\delta\langle r^2\rangle_{ji} + K_{\alpha}\mu_{ji}$$

Nuclear size difference ('field shift')

Inverse mass difference ('mass shift')

Frequency shift $\nu_j - \nu_i$ between isotope j and reference isotope i on transition α

When combining two transitions, the first two terms give linear relationship

Linear isotope shift relation for two transitions (King plot)

Mass shift Field shift Nuclear shape New boson

$$\tilde{\nu}_{\beta ji} = K_{\beta\alpha} + F_{\beta\alpha}\tilde{\nu}_{\alpha ji} + G_{\beta\alpha}\widetilde{(\delta\langle r^2\rangle)^2}_{ji} + v_{ne} D_{\beta\alpha}\tilde{a}_{ji}$$

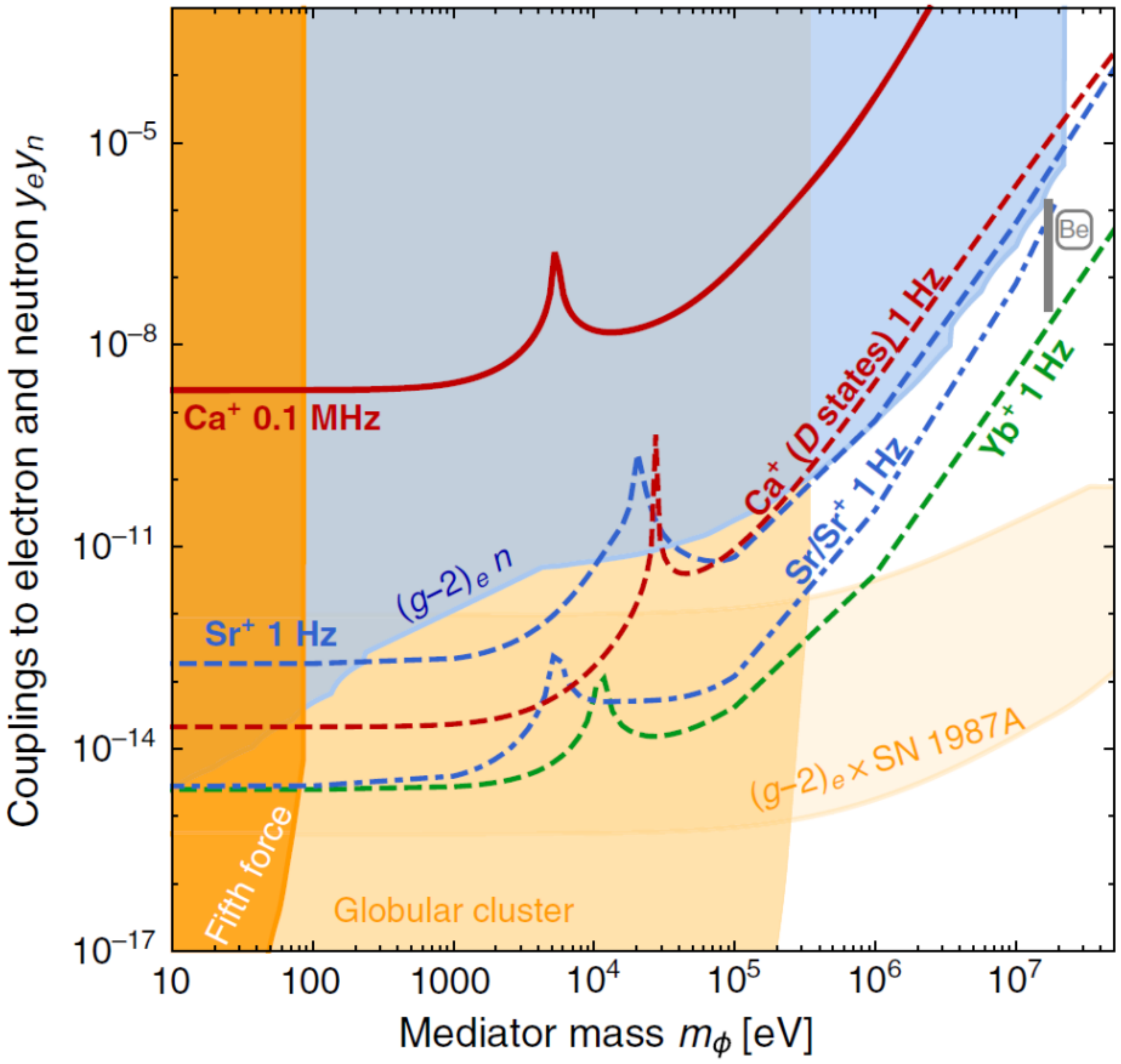
Frequency shift between isotope j and reference isotope on transition β, divided by $\delta\mu_{ji}$

Contain nonlinear terms

Frequency shift between isotope j and reference isotope on transition β, divided by $\delta\mu_{ji}$

Need at least four (spinless) isotopes to measure nonlinearity

Sensitivity for different atomic species

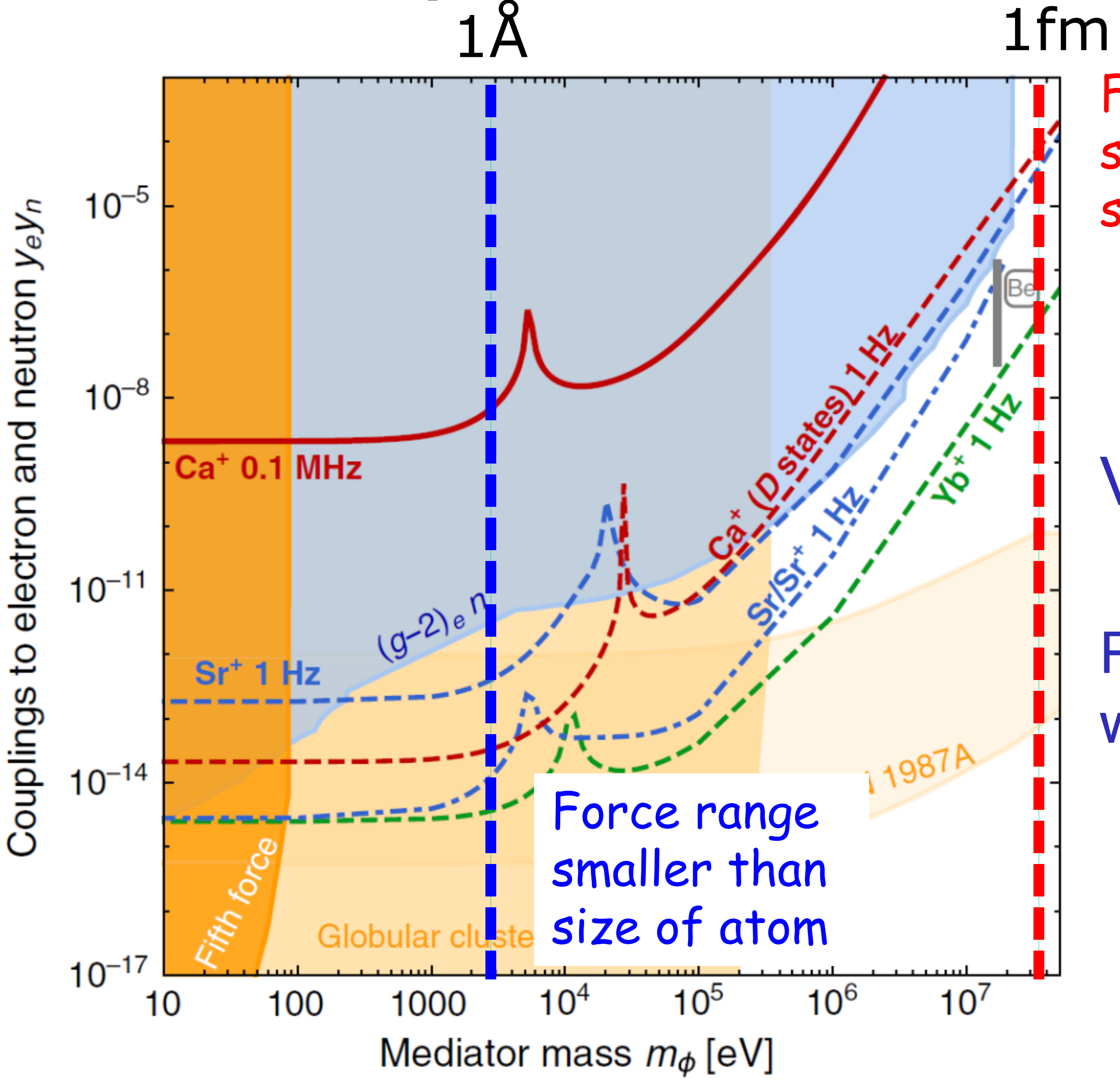


Berengut, et al., PRL **120**, 091801 (2018).

Shaded: excluded or unlikely (model-dependent) regions

White: not excluded regions

Sensitivity for different atomic species

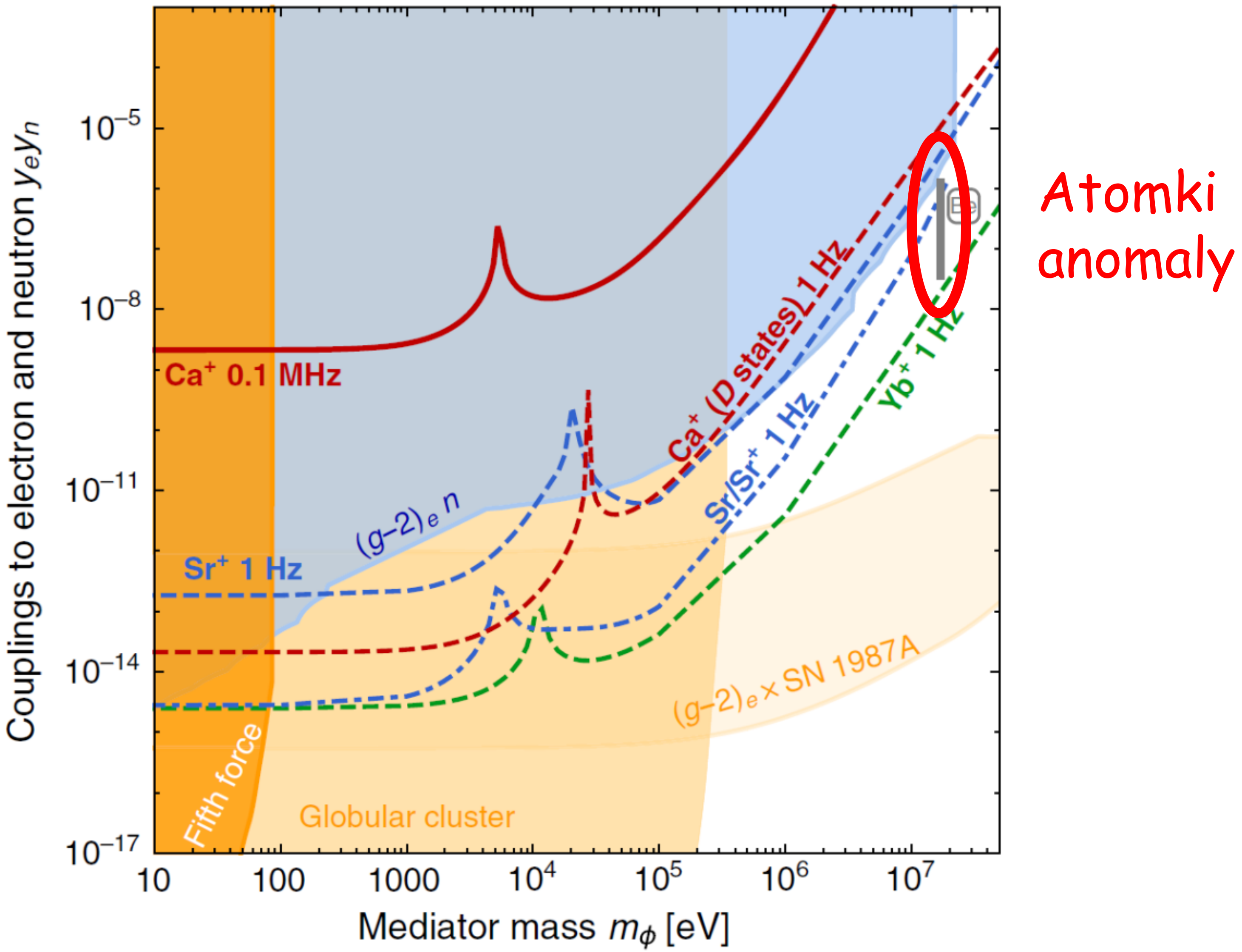


Force range smaller than size of nucleus

$V(r) = e^{-r/R}/r$

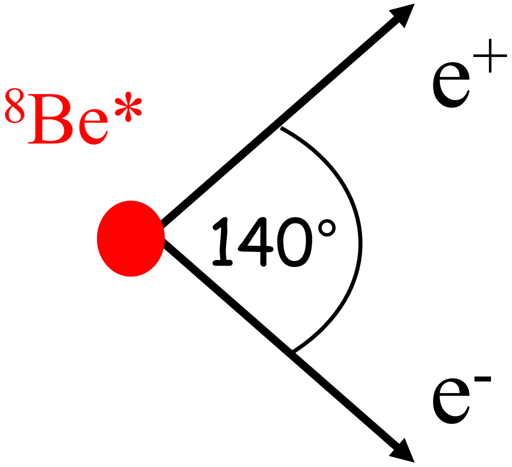
R Compton wavelength

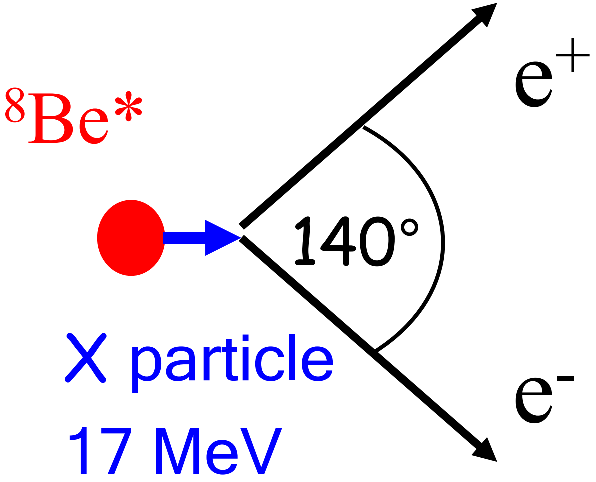
Sensitivity for different atomic species



Atomki anomaly (X17 particle)

- 7 σ deviation from Standard Model in decay of $^8Be^*$ (~17MeV) by emitting e^+e^- pairs



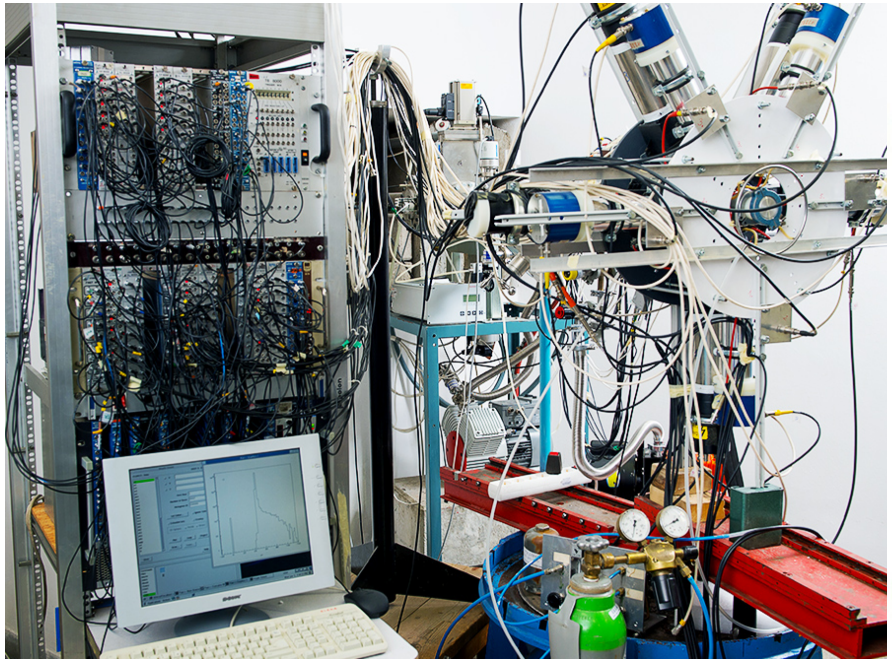


A. J. Krasznahorkay et al., Phys. Rev. Lett. **116**, 042501 (2016).

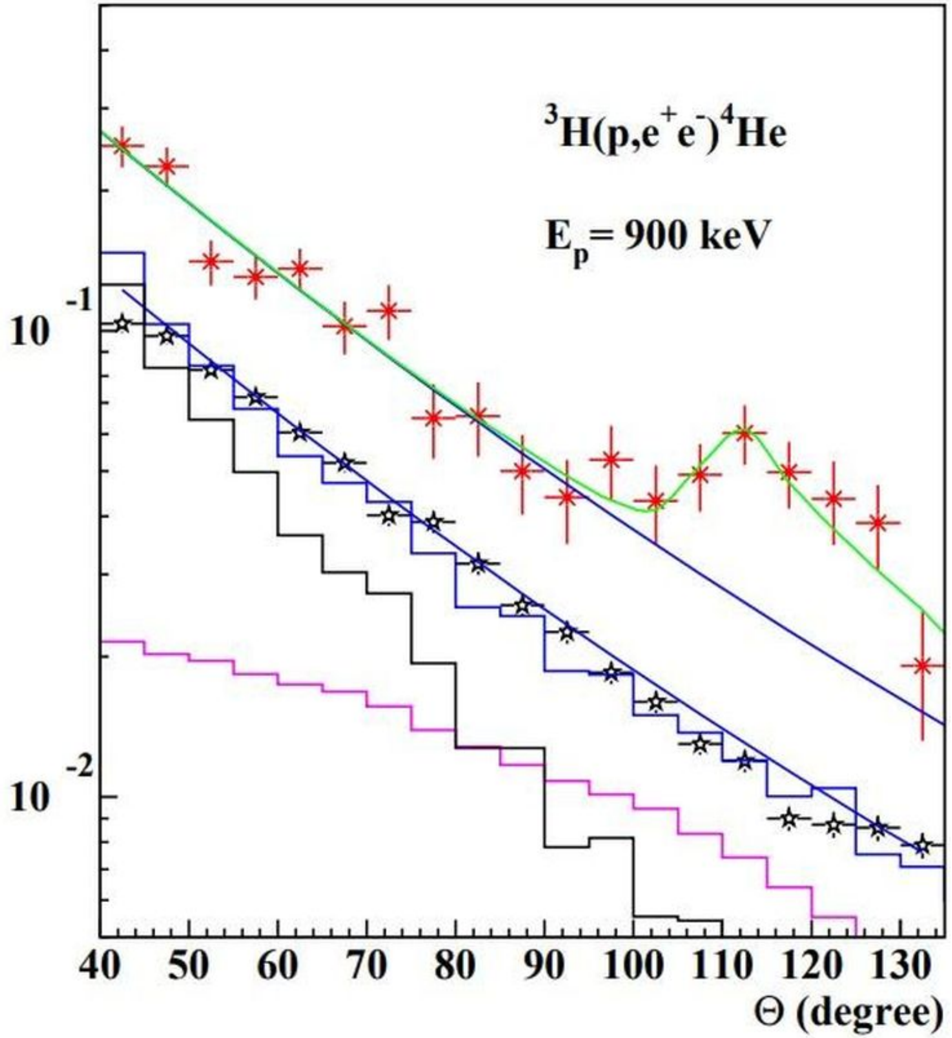
Similar observation (opening angle 115°, 7σ) for $^4He^*$ (21 MeV)

A. J. Krasznahorkay et al., arXiv:1910.10459 (2019).

But ...



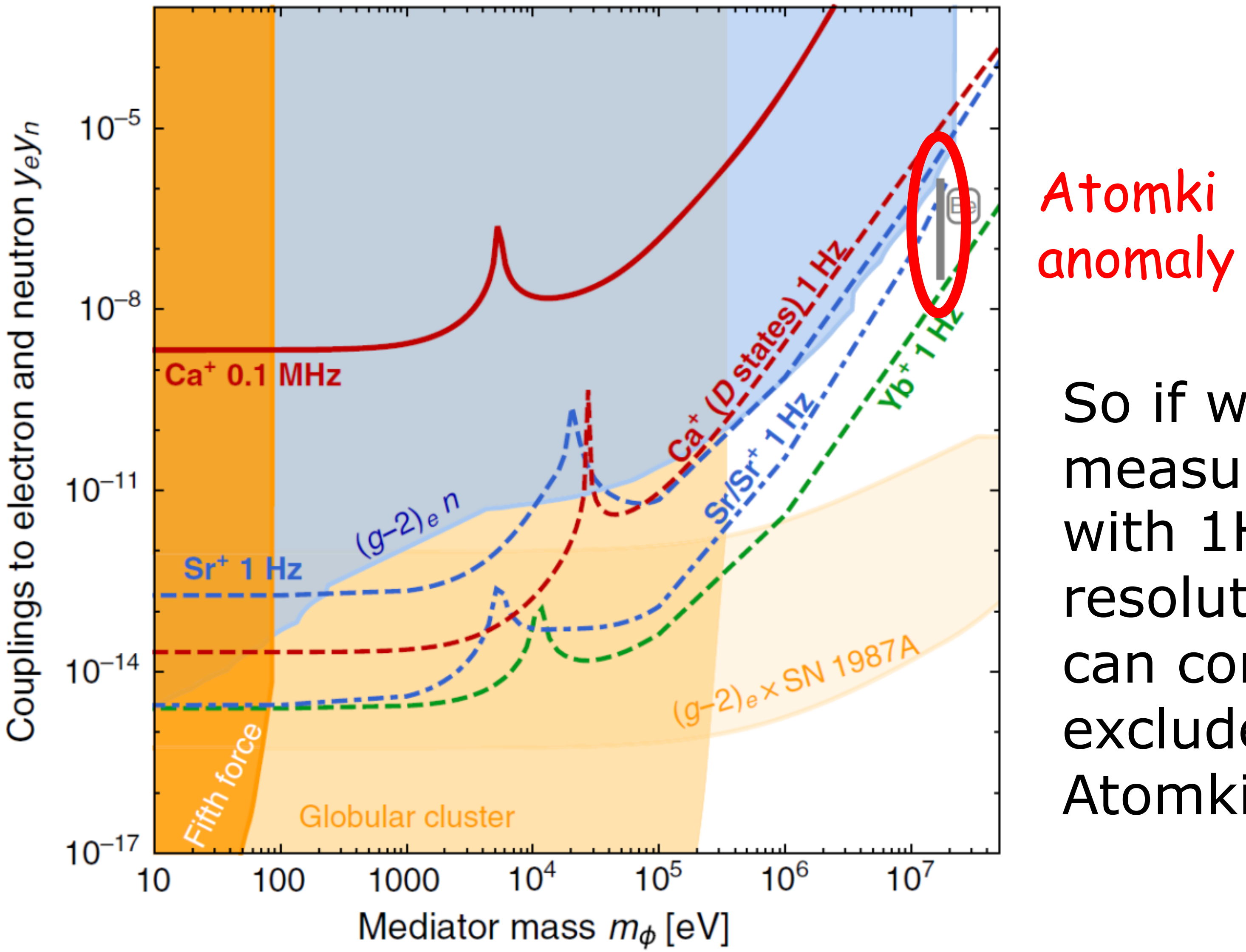
Picture: N. Wolchover, Quanta Magazine



They used the same equipment for both experiments.

The calibration is not very good in the angle region of interest.

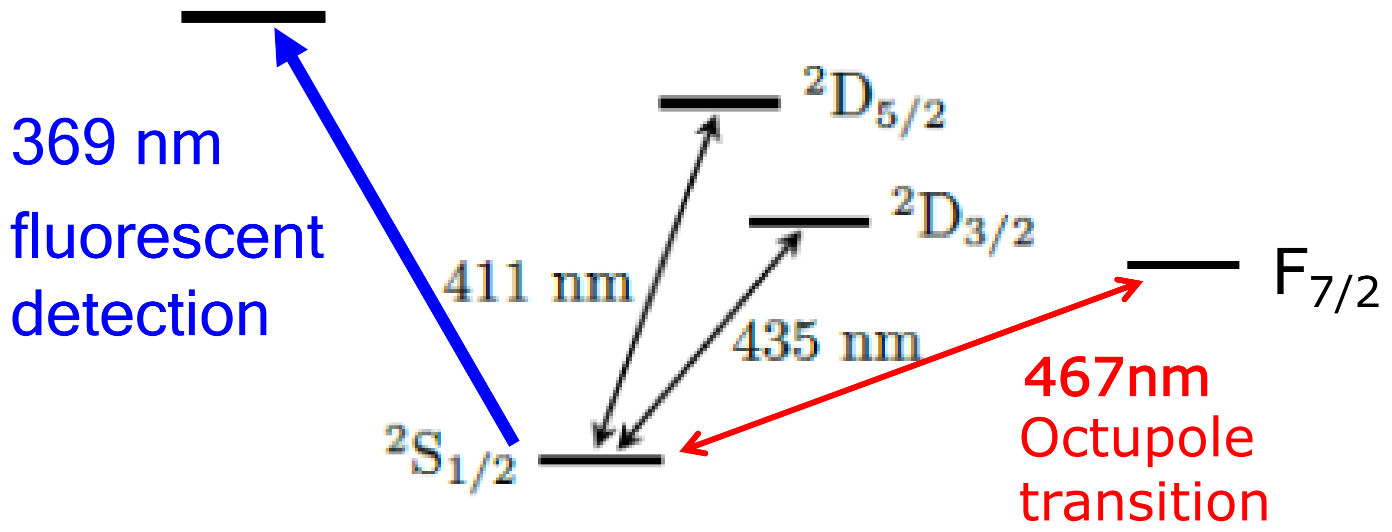
Sensitivity for different atomic species



So if we measure Yb^{+} with 1Hz resolution we can confirm or exclude the Atomki anomaly

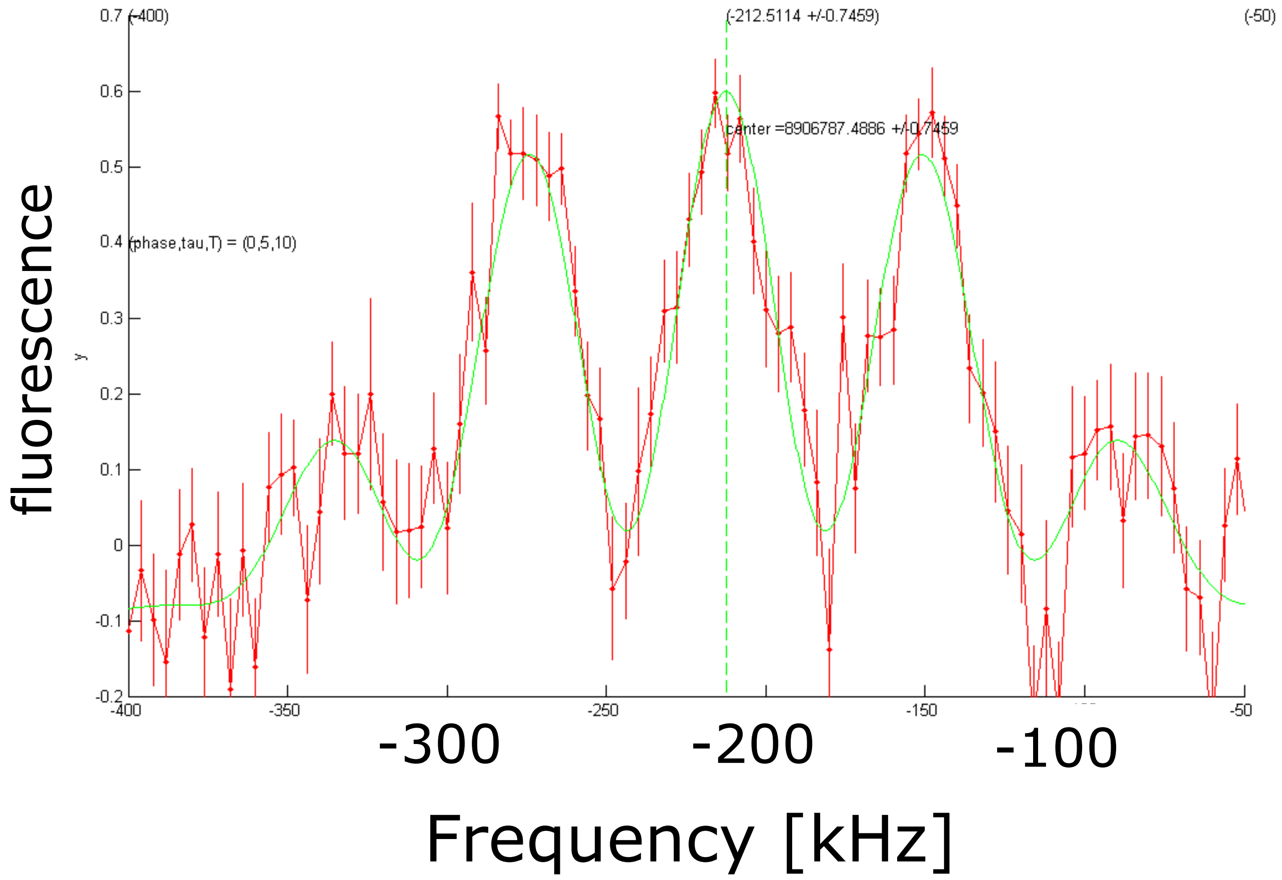
Our experiment

- Performed Ramsey spectroscopy on five spinless bosonic isotopes of Yb: ^{168}Yb, ^{170}Yb, ^{172}Yb, ^{174}Yb, ^{176}Yb on two narrow quadrupole transitions : $^2S_{1/2} \rightarrow {}^2D_{3/2}$ and $^2S_{1/2} \rightarrow {}^2D_{5/2}$
  and one octupole transition: $^2S_{1/2} \rightarrow F_{7/2}$
- Current precision 300 Hz.

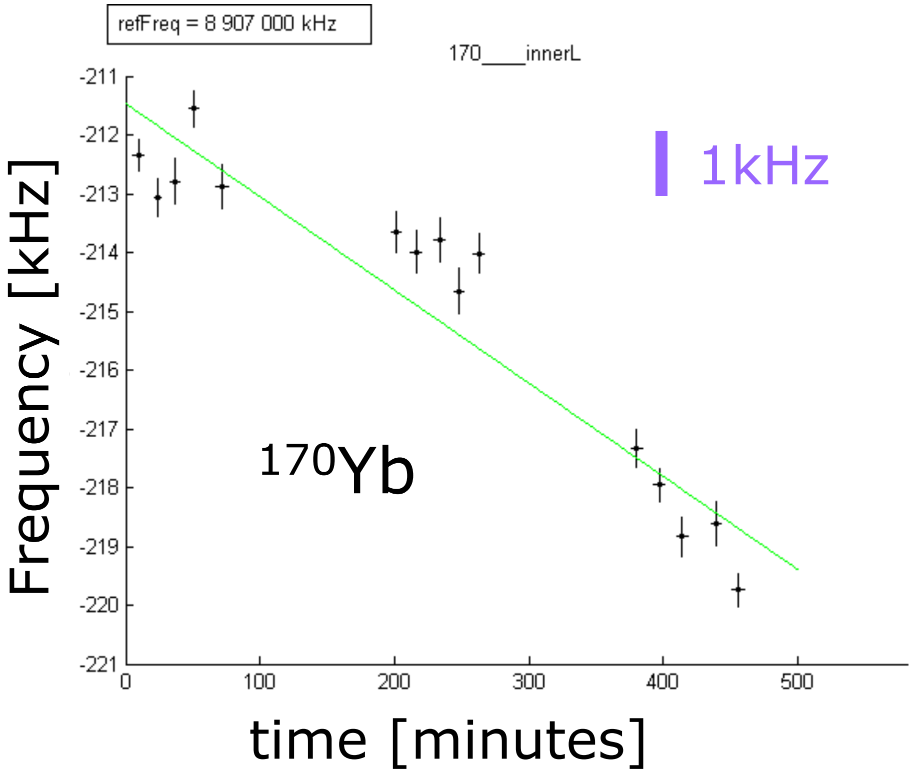


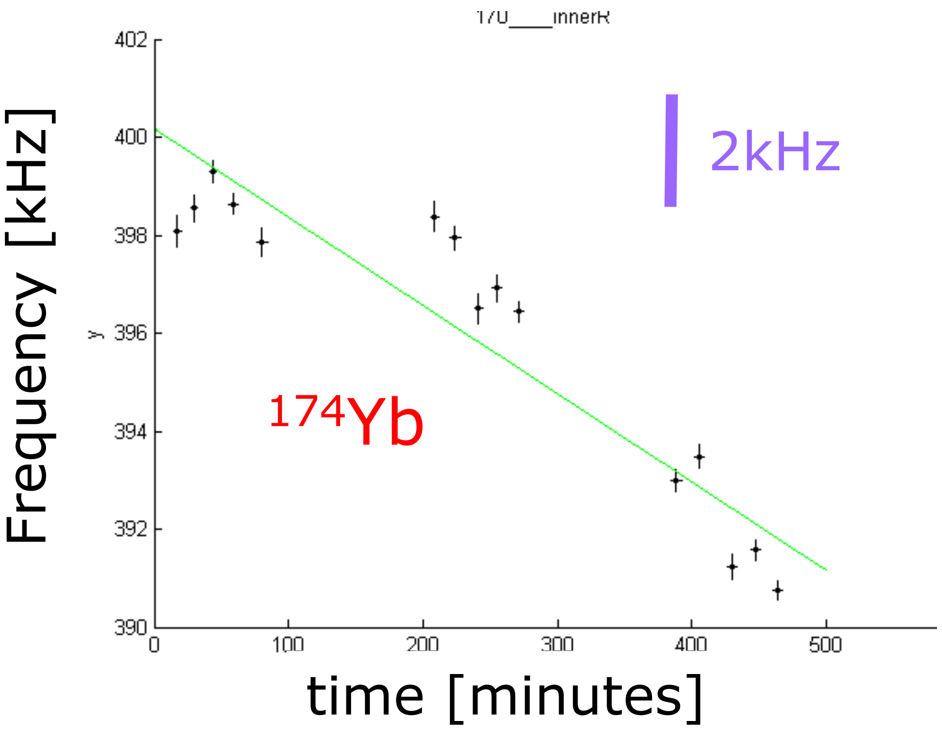
Measurements on the $S_{1/2} \rightarrow D_{3/2}$ and $S_{1/2} \rightarrow D_{5/2}$ quadrupole transitions

Ramsey spectroscopy with shelving



Examples of isotope shift measurements

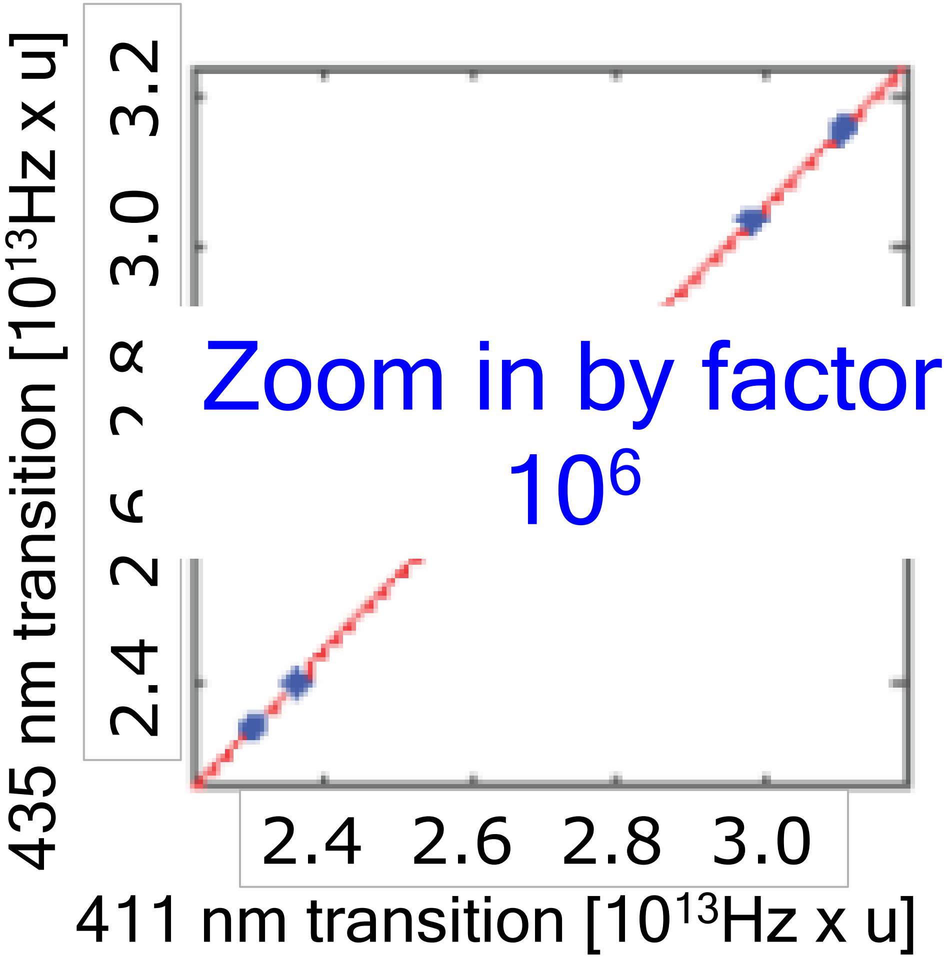


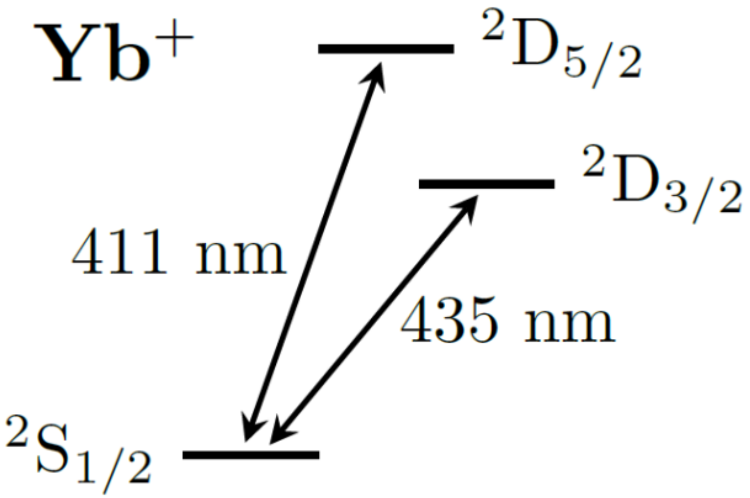


Compare isotopes pairwise and sequentially.

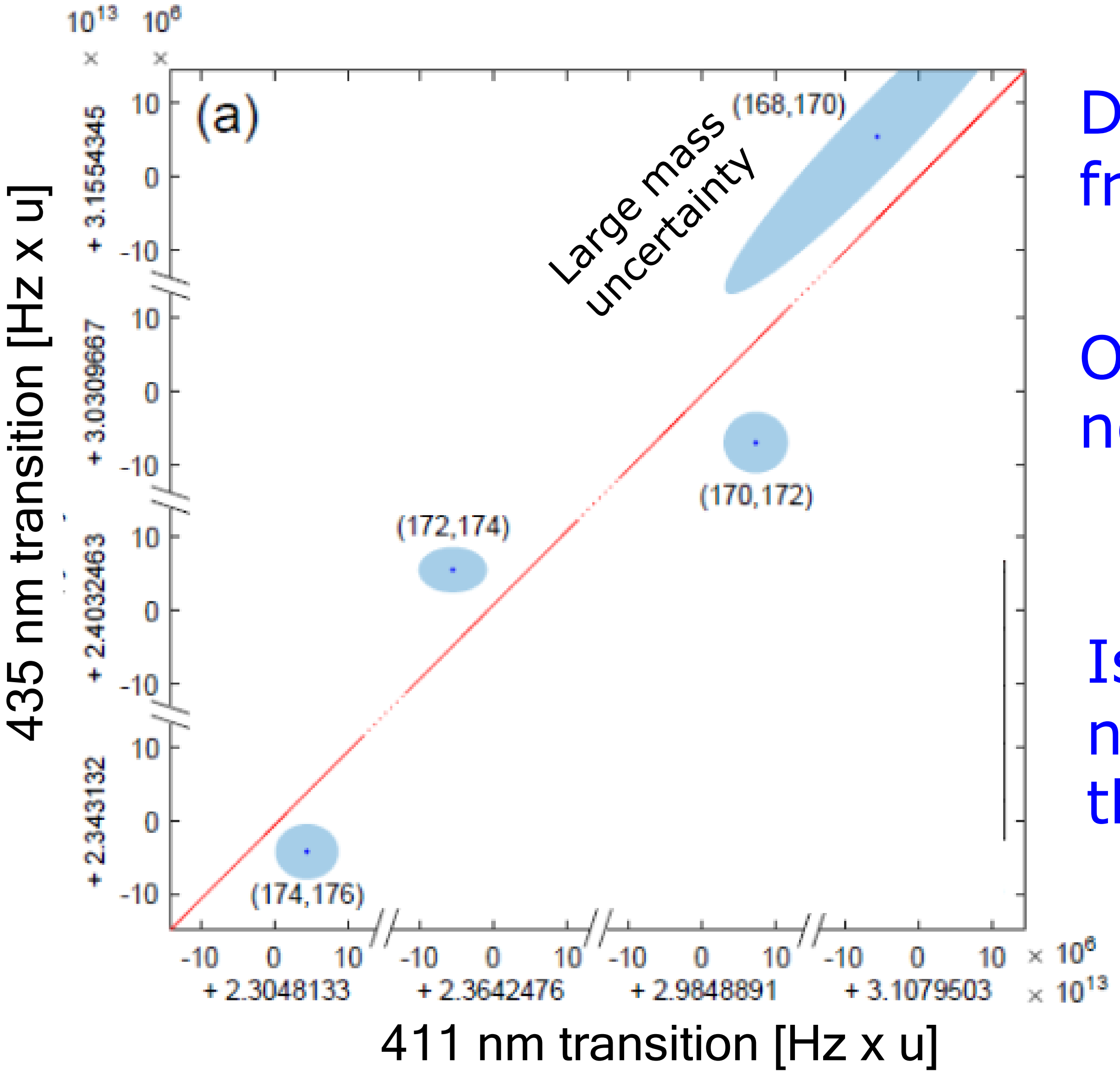
Frequency error ~300 Hz.

King plot for quadrupole transitions





Yb$^+$ King plot zoomed in by 10^6



Deviation from linearity in frequency units ~1 kHz

Overall deviation from nonlinearity 3.3σ

Is it originating from nuclear physics, i.e. with the Standard Model?

Linear isotope shift relation (King plot)

Mass shift Field shift Nuclear shape New boson

$$\widetilde{\nu}_{\beta ji} = K_{\beta\alpha} + F_{\beta\alpha}\widetilde{\nu}_{\alpha ji} + G_{\beta\alpha}\widetilde{(\delta\langle r^2\rangle)^2}_{ji} + v_{ne} D_{\beta\alpha}\widetilde{a}_{ji}$$

Frequency shift between isotope j and reference isotope on transition β, divided by $\delta\mu_j$

Nonlinear terms

Frequency shift between isotope j and reference isotope on transition β, divided by $\delta\mu_j$

We have four isotopes to measure nonlinearity.

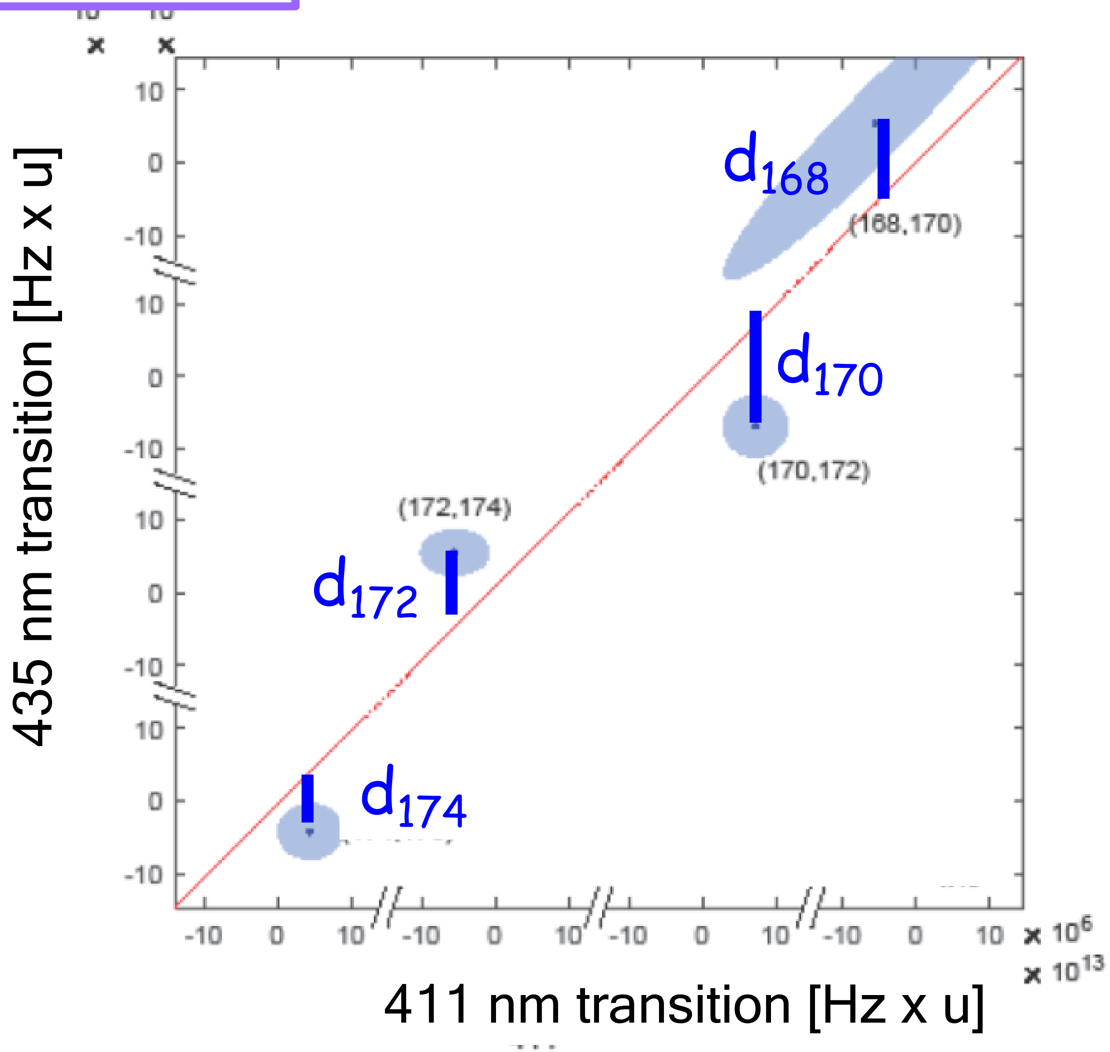
We can distinguish not only magnitude, but also pattern of nonlinearity.

Defining a nonlinearity pattern

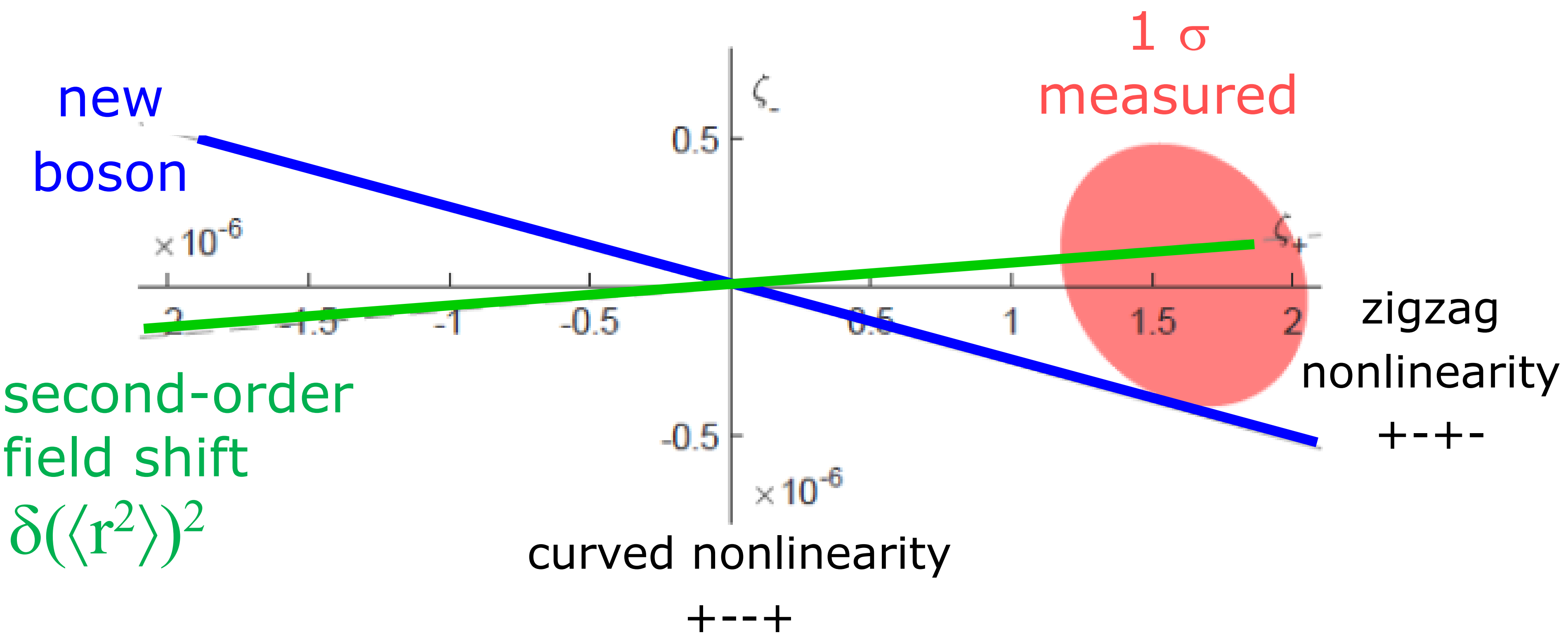
$$\zeta_{\pm} \equiv d_{168} - d_{170} \pm (d_{172} - d_{174})$$

Two nonlinearity components: zigzag and curved nonlinearity.

We can characterize nonlinearity further than by sheer magnitude.

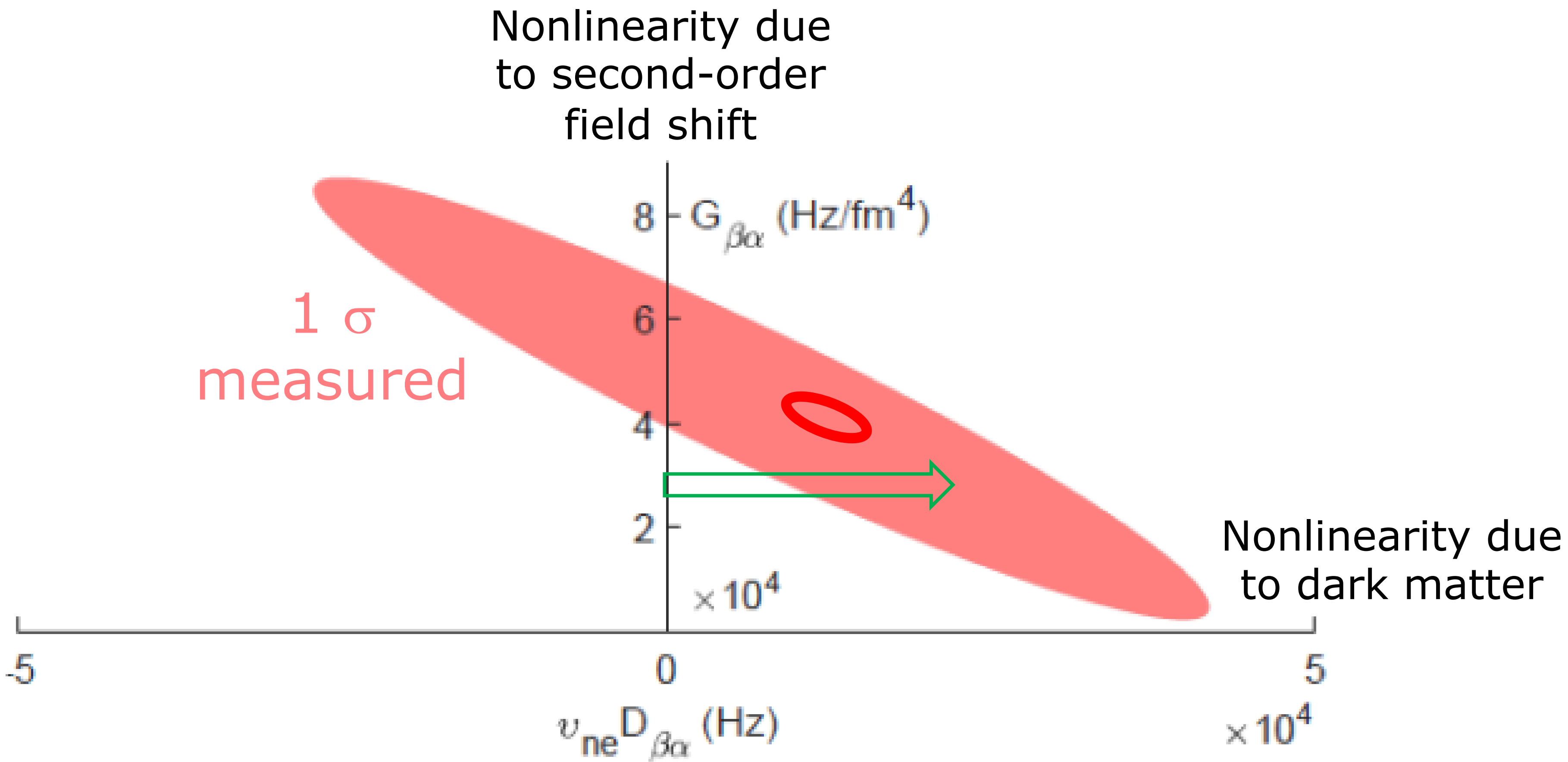


Two-dimensional nonlinearity-pattern measure



With improved atomic-structure calculations, we can predict the magnitude and sign of the second-order field shift

Parsing the nonlinearity

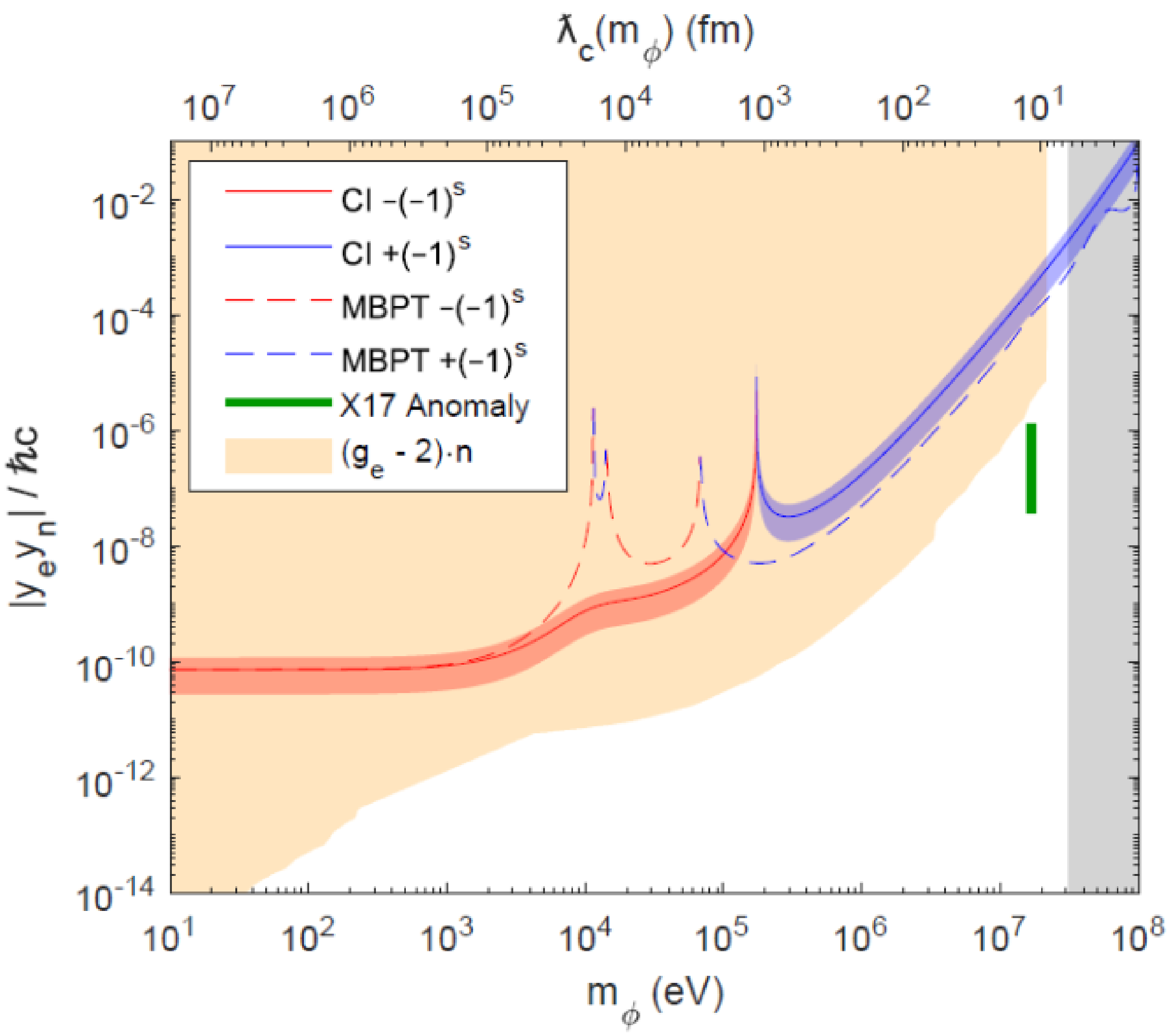


Improving measurement

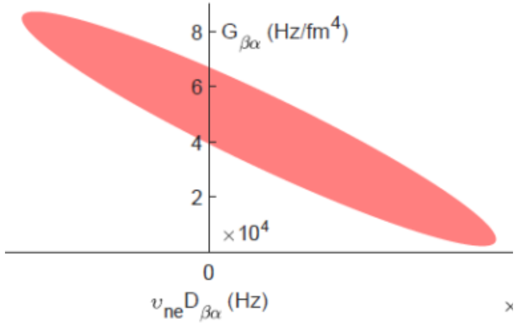
or improving atomic-structure calculation

can yield information about both parameters

Limit on new-boson coupling from our data



Nonlinearity due to second-order field shift



Nonlinearity due to dark matter

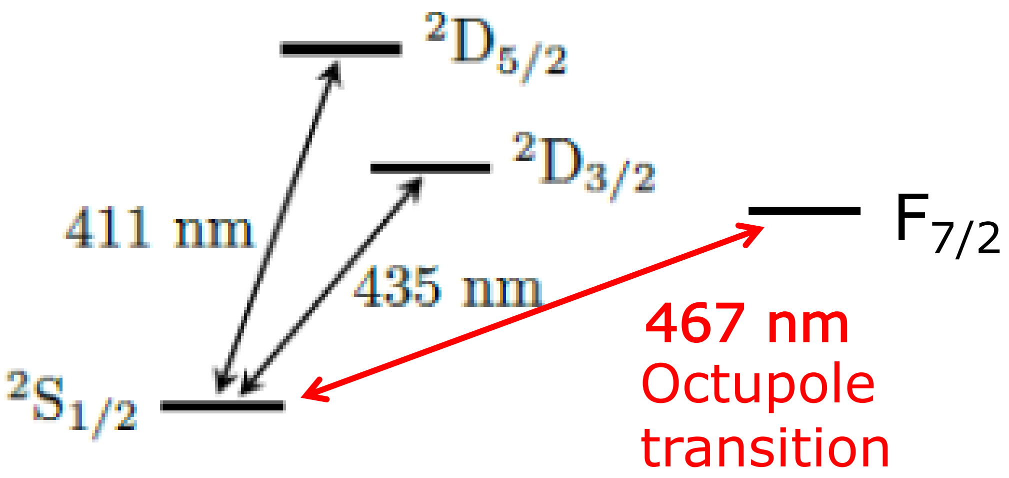
I. Counts, J. Hur, et al., arXiv:2004.11383; to appear in PRL.

Similar sensitivity with Ca^+: (Drewsen group) Solaro et al., arXiv:2005.00529

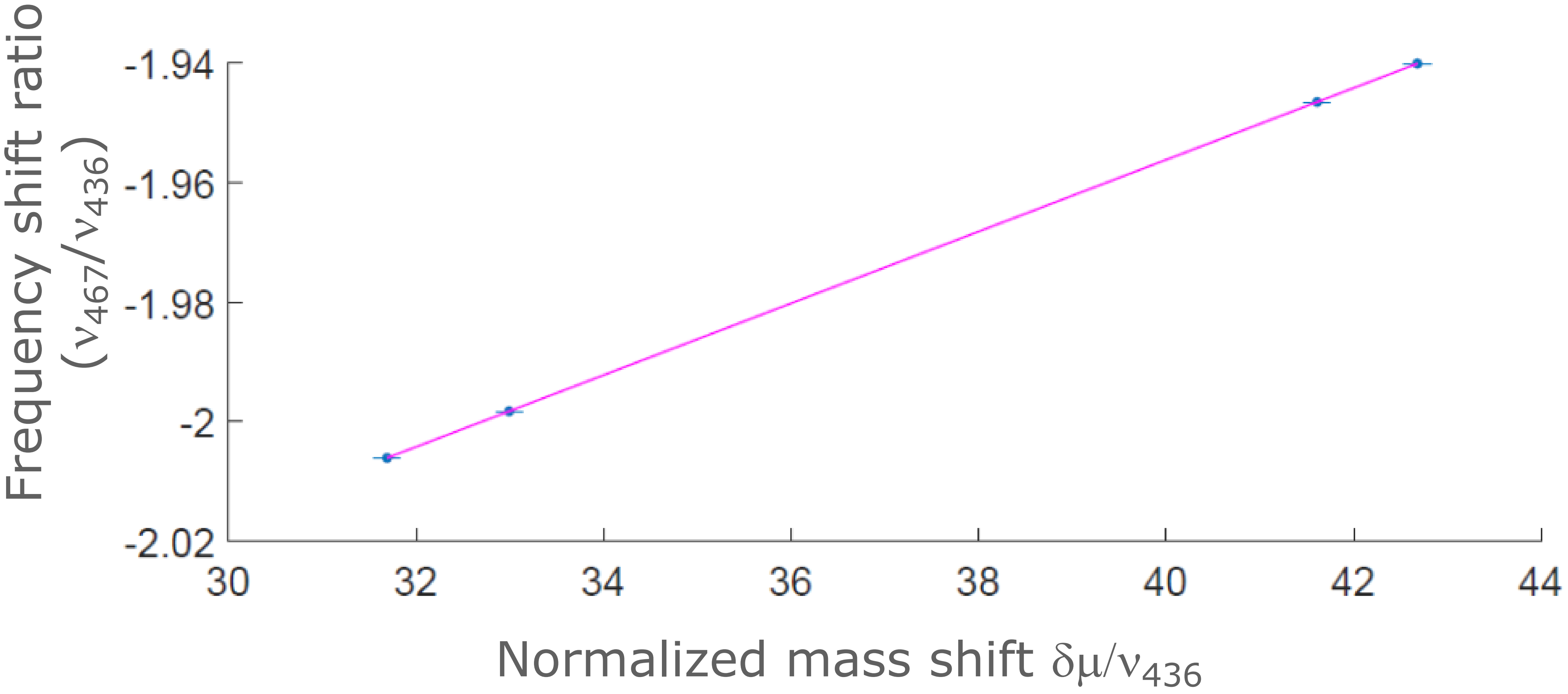
Measurements on the $S_{1/2} \rightarrow F_{7/2}$ octupole transition

Measuring octupole transition $^2S_{1/2} \rightarrow F_{7/2}$

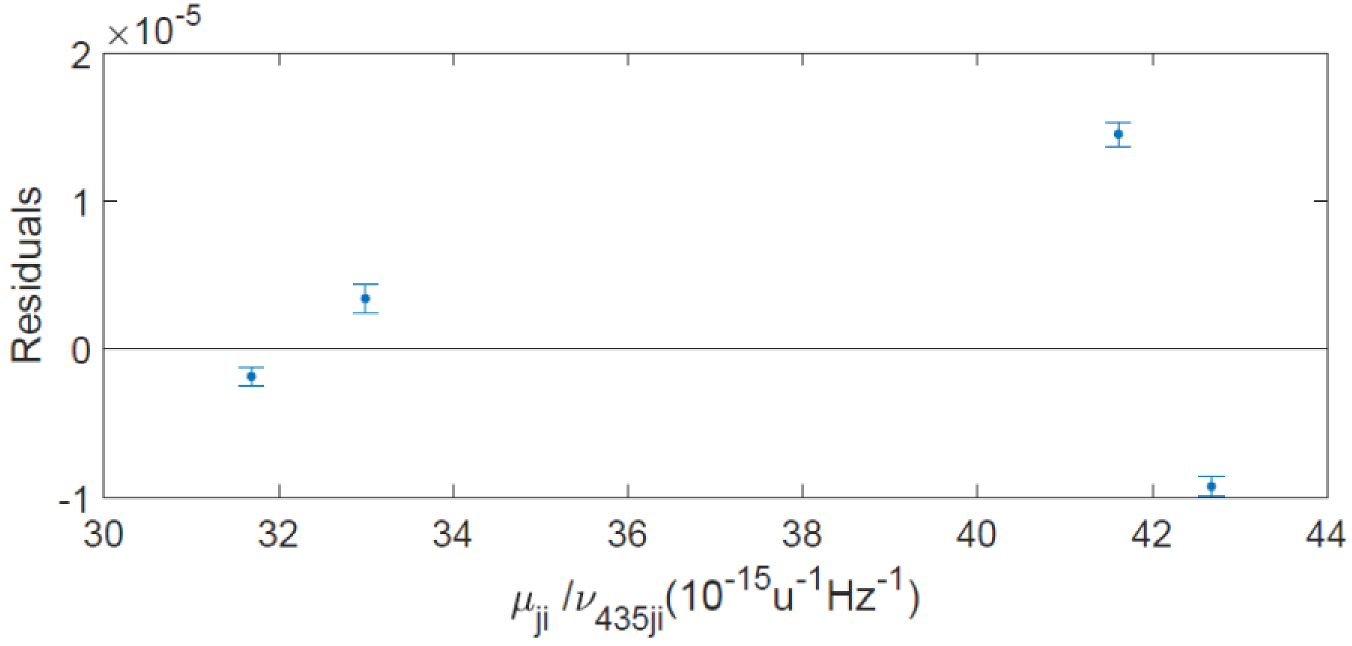
- We have recently measured isotope shifts on the highly forbidden octupole transition (natural lifetime 10 years) for single trapped Yb ions.
- The frequency resolution is 1kHz.



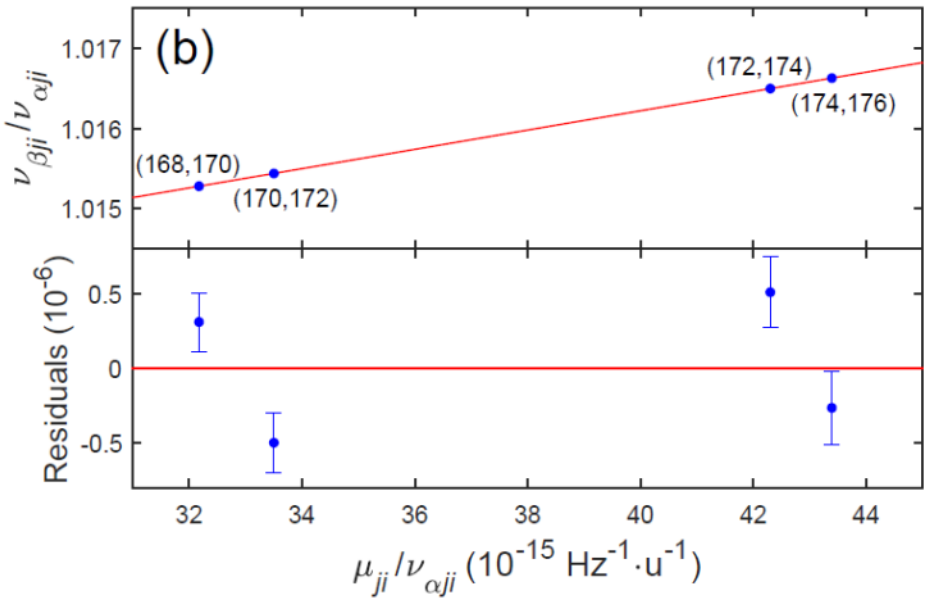
Modified King plot for $^2S_{1/2} \rightarrow {}^2D_{3/2}$ vs $^2S_{1/2} \rightarrow F_{7/2}$



Observed large nonlinearity on octupole transition



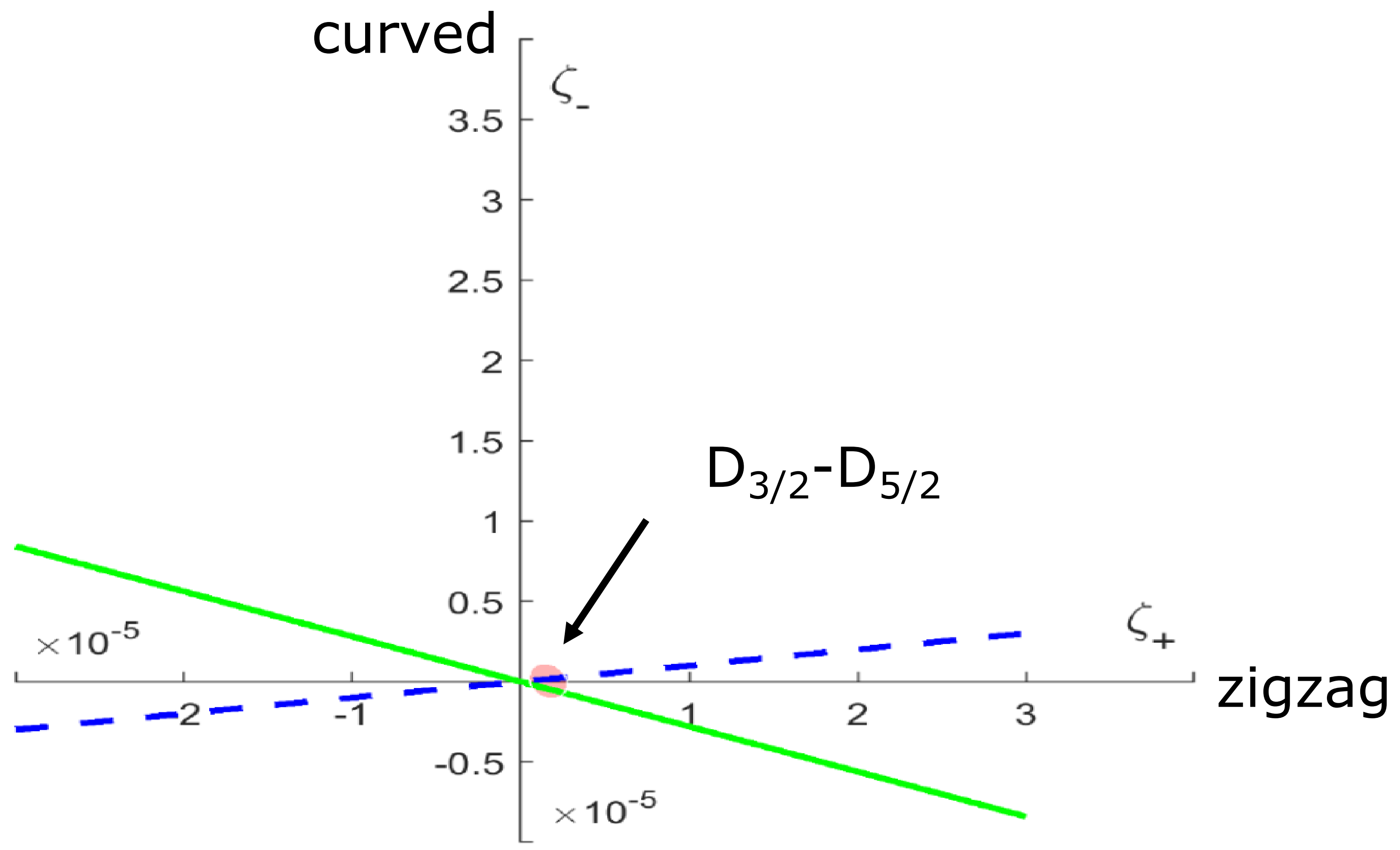
$^2S_{1/2} \rightarrow {}^2D_{3/2}$ vs $^2S_{1/2} \rightarrow {}^2D_{5/2}$



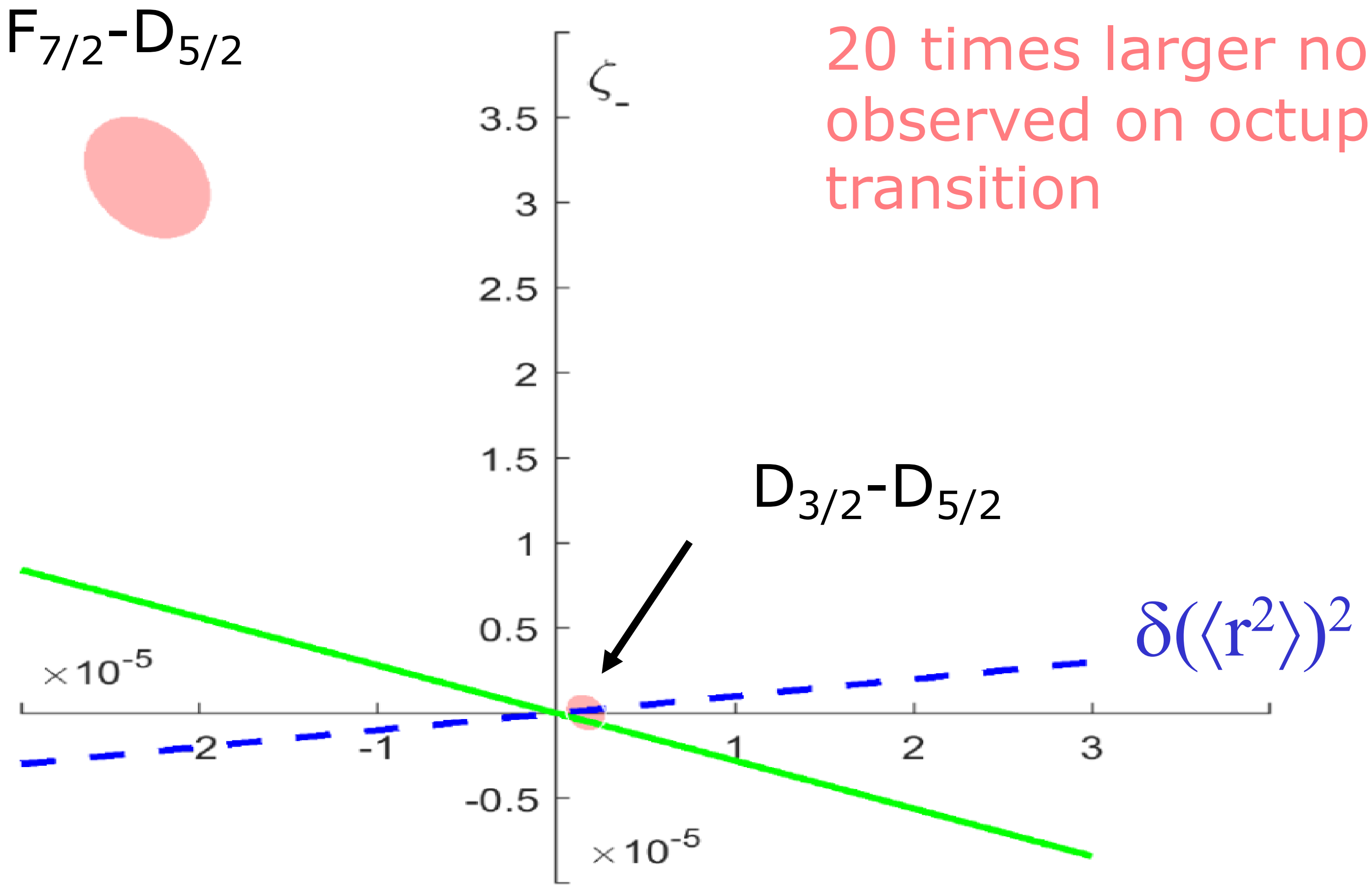
Much larger effect (9σ)

Different pattern indicates second source of nonlinearity

Isotope shifts on quadrupole and octupole transitions



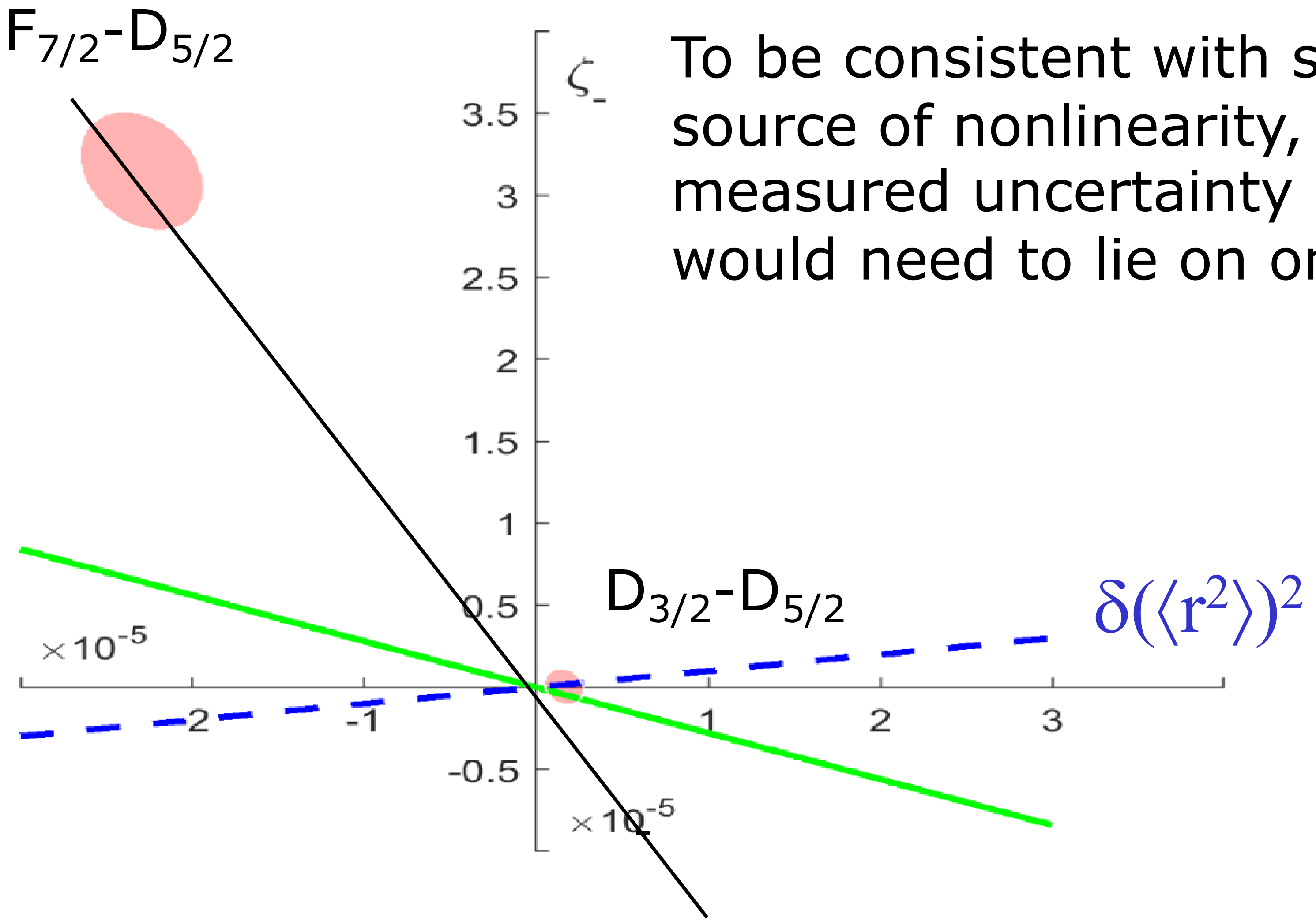
Isotope shifts on quadrupole and octupole transitions



20 times larger nonlinearity observed on octupole transition

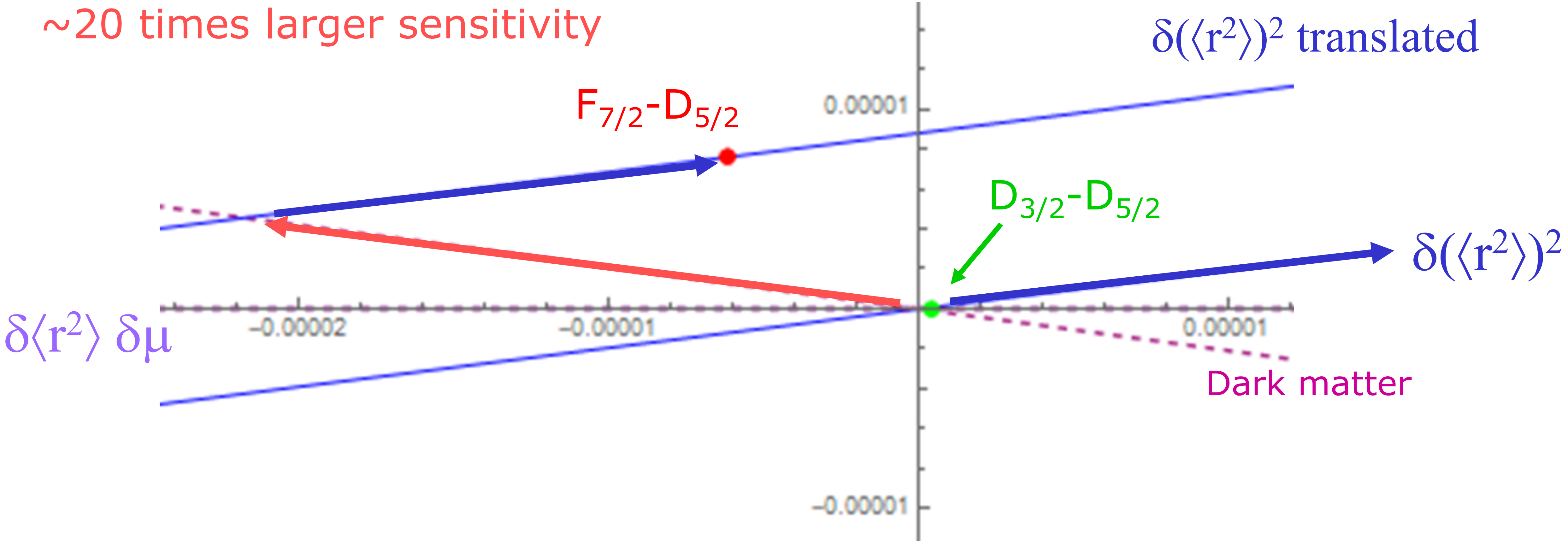
Consistent with estimates from V. V. Flambaum, A. J. Geddes, and A. V. Viatkina, Phys. Rev. A 97, 032510 (2018).

Isotope shifts on quadrupole and octupole transitions



To be consistent with single source of nonlinearity, both measured uncertainty ellipses would need to lie on one line

Evidence for two contributions to nonlinearity



Quadrupole deformation of nucleus also a possible nonlinearity: S. Allehabi, V. A. Dzuba, V. V. Flambaum, A. V. Afanasjev, S. E. Agbemava, arxiv:2001.09422

Outlook

- $F_{7/2}$ is more different from $D_{3/2}$ than the D states from each other: all nonlinearities (both within the Standard Model and for Dark Matter) are magnified by factor ~20.
- It is also possible to make mixed King plots with Yb^+ and neutral Yb (e.g. on the clock transition of Yb): maximum sensitivity, particularly near nucleus.
- More precise measurements and atomic-structure calculations can distinguish between various SM (nuclear) effects and new boson.
- Can one obtain more accurate nuclear data/calculations?

Vuletić Group at virtual DAMOP

M03.00001 Nonlinear Quantum Optics
Repulsive photon-photon interactions mediated by Rydberg atoms
Sergio Cantu Thur. June 4 8am-8:11am PDT

P07.00006 Atomic Clocks
Spin-Squeezed Optical Lattice Clock
Chi Shu Thur. June 4 3:00pm-3:11pm PDT