Generalised King linearity and new physics searches with isotope shifts

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Outline

- Isotope shift in atomic spectra
- King plot linearity
- Dark bosons and King plot nonlinearity
- Experiments: calcium and ytterbium ions
- Spurions and the generalised King plot
- Future directions

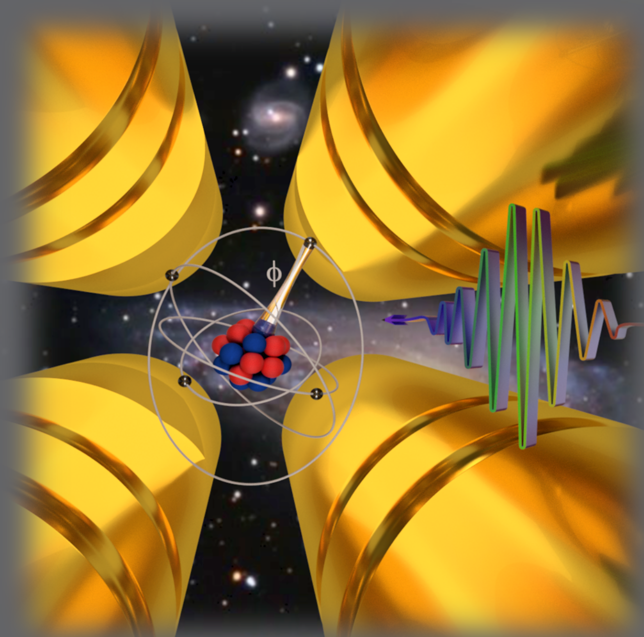


Image: Aarhus University

Isotope shift theory

- In the standard theory we express the difference between frequencies of isotope with mass number A and A′ by

$$\delta\nu_i^{A',A} = \nu_i^{A'} - \nu_i^{A} = K_i \left(\frac{1}{A'} - \frac{1}{A}\right) + F_i\,\delta\langle r^2\rangle^{A',A}$$

"Mass shift" — nuclear recoil

"Field shift" — charge distribution

- We can factorize the nuclear part and electron parts of each term (consequence of perturbation theory).
- $\delta\langle r^2\rangle$ – change in nuclear charge radius – is hard to measure; we can extract it from isotope shift if the electronic factors (F_i, K_i) can be calculated accurately.

King plot

- Remove dependence on nuclear charge radius by cancelling it between two transitions.
- Introduce "modified" isotope shifts:

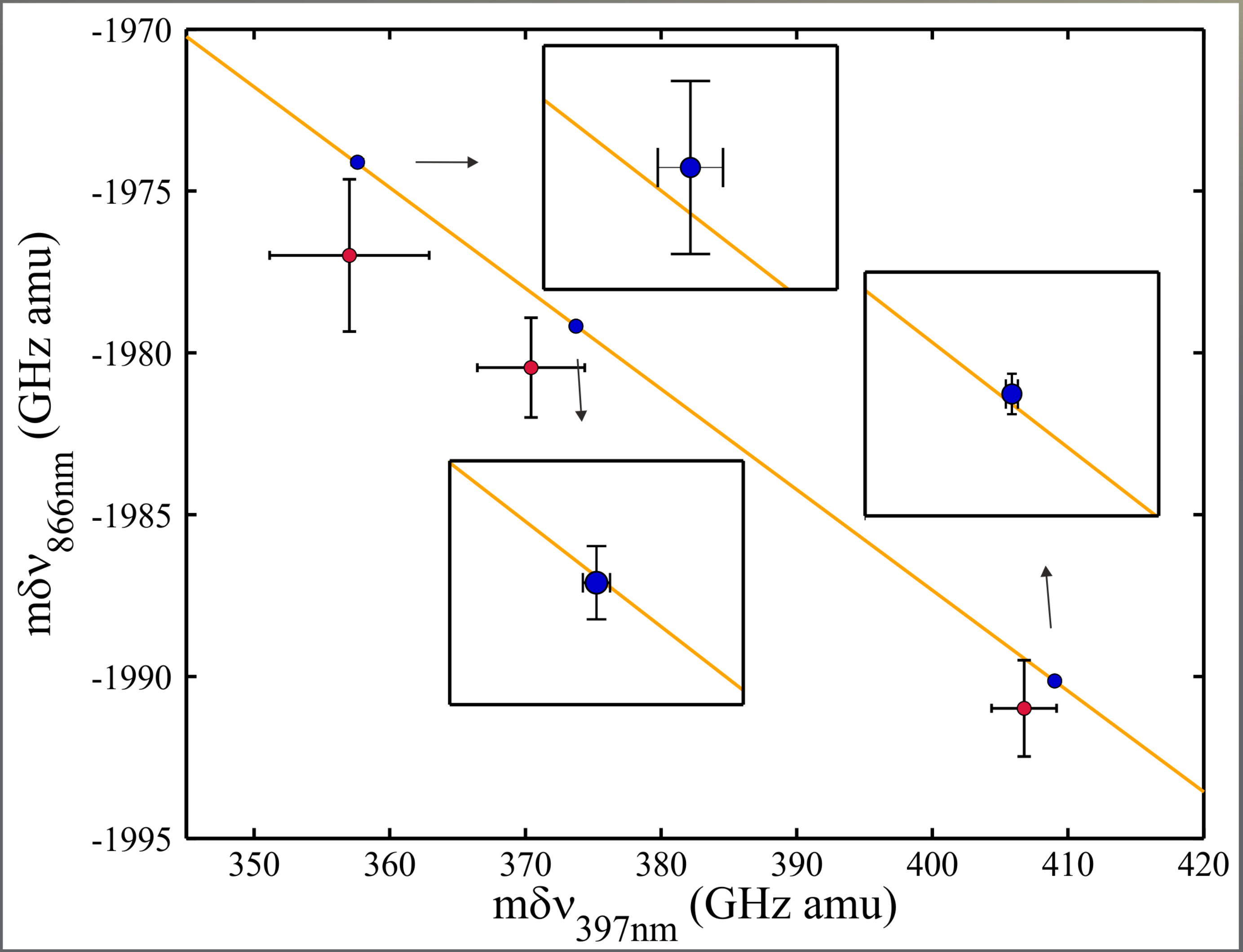
$$\delta\nu_i^{A',A} = K_i \left(\frac{1}{A'} - \frac{1}{A} \right) + F_i \, \delta\langle r^2 \rangle^{A',A}$$

$$\Rightarrow \quad \delta\overline{\nu_i}^{A',A} = K_i + F_i \, \delta\overline{\langle r^2 \rangle}^{A',A}$$

- Plot $\delta\overline{\nu_1}$ vs $\delta\overline{\nu_2}$ for several pairs of isotopes (A', A):

$$\delta\overline{\nu_1} = \frac{F_1}{F_2}\delta\overline{\nu_2} + \left(K_1 - \frac{F_1}{F_2} K_2 \right)$$

King plot: Ca^+



Gebert, Wan, Wolf, Angstmann, Berengut, Schmidt, PRL 115, 053003 (2015)

King plot nonlinearities

- What if the King plot is not linear?
- May point to new physics in complex atoms that are beyond theoretical description at 7+ digits (e.g. Ca^+, Sr/Sr^+, Yb^+)
- Also many Standard Model “spurions”: sources of nonlinearities of unknown size in complex atoms. (We’ll come back to these.)

New physics searches with isotope shift

- Start with reformulation of King plot

$$\delta\overline{\nu_i}^{42,40} = K_i + F_i\,\delta\overline{\langle r^2\rangle}^{42,40}$$

$$\delta\overline{\nu_i}^{44,40} = K_i + F_i\,\delta\overline{\langle r^2\rangle}^{44,40}$$

$$\delta\overline{\nu_i}^{48,40} = K_i + F_i\,\delta\overline{\langle r^2\rangle}^{48,40}$$

- There are N pairs of isotopes (A’, A), so we can make a vector in N-dimensional “isotope pair space”

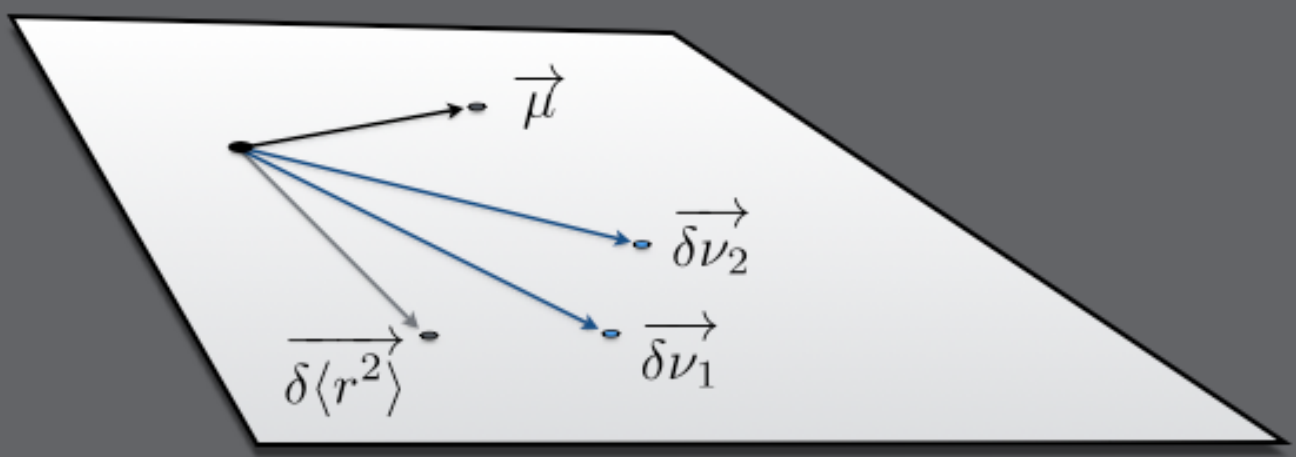
$$\overrightarrow{\delta\nu_i} = K_i\,\overrightarrow{\mu} + F_i\,\overrightarrow{\delta\langle r^2\rangle}$$

New physics searches with isotope shift

- Start with reformulation of King plot

$$\overrightarrow{\delta\nu_i} = K_i \, \overrightarrow{\mu} + F_i \, \overrightarrow{\delta\langle r^2\rangle}$$

- Modified isotope shifts of all transitions $\overrightarrow{\delta\nu_i}$ lie in the same 2D plane in the N-dimensional isotope-pair space.

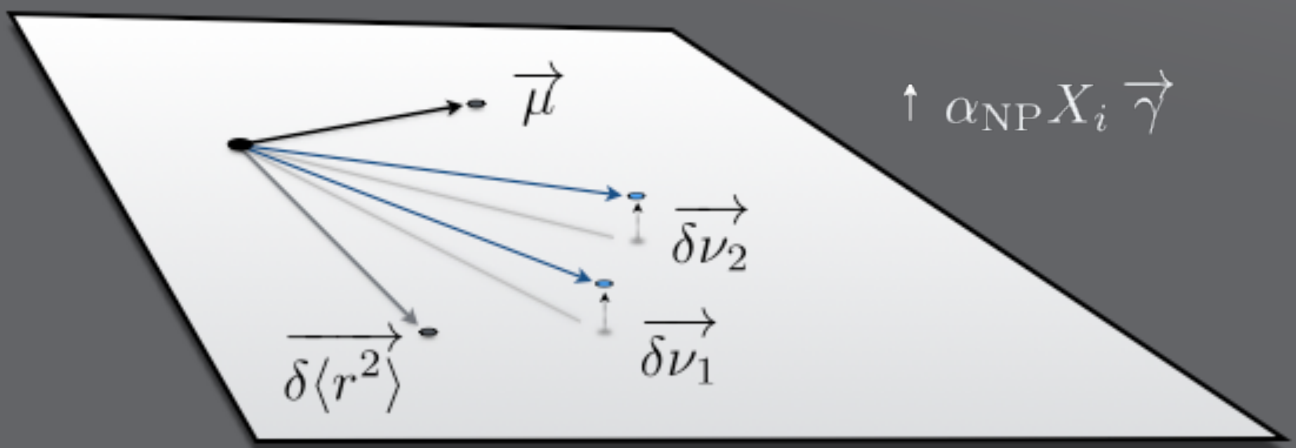


Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq, PRL 120, 091801 (2018)

New physics searches with isotope shift

- Reduced isotope shift again:

$$\overrightarrow{\delta\nu_i} = K_i \overrightarrow{\mu} + F_i \overrightarrow{\delta\langle r^2\rangle} + \alpha_{\rm NP} X_i \overrightarrow{\gamma}$$



- No sensitivity to new physics if $\overrightarrow{\gamma} \sim \overrightarrow{\mu}$ or $X_i \sim F_i$

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq, PRL 120, 091801 (2018)

New physics searches with isotope shift

- Example: new force-carrying low-mass boson couples electrons to neutrons with Yukawa potential

$$V_\phi(r) = -\frac{y_e y_n}{4\pi}(A-Z)\frac{e^{-m_\phi r}}{r}$$

- Isotope shift has an extra term

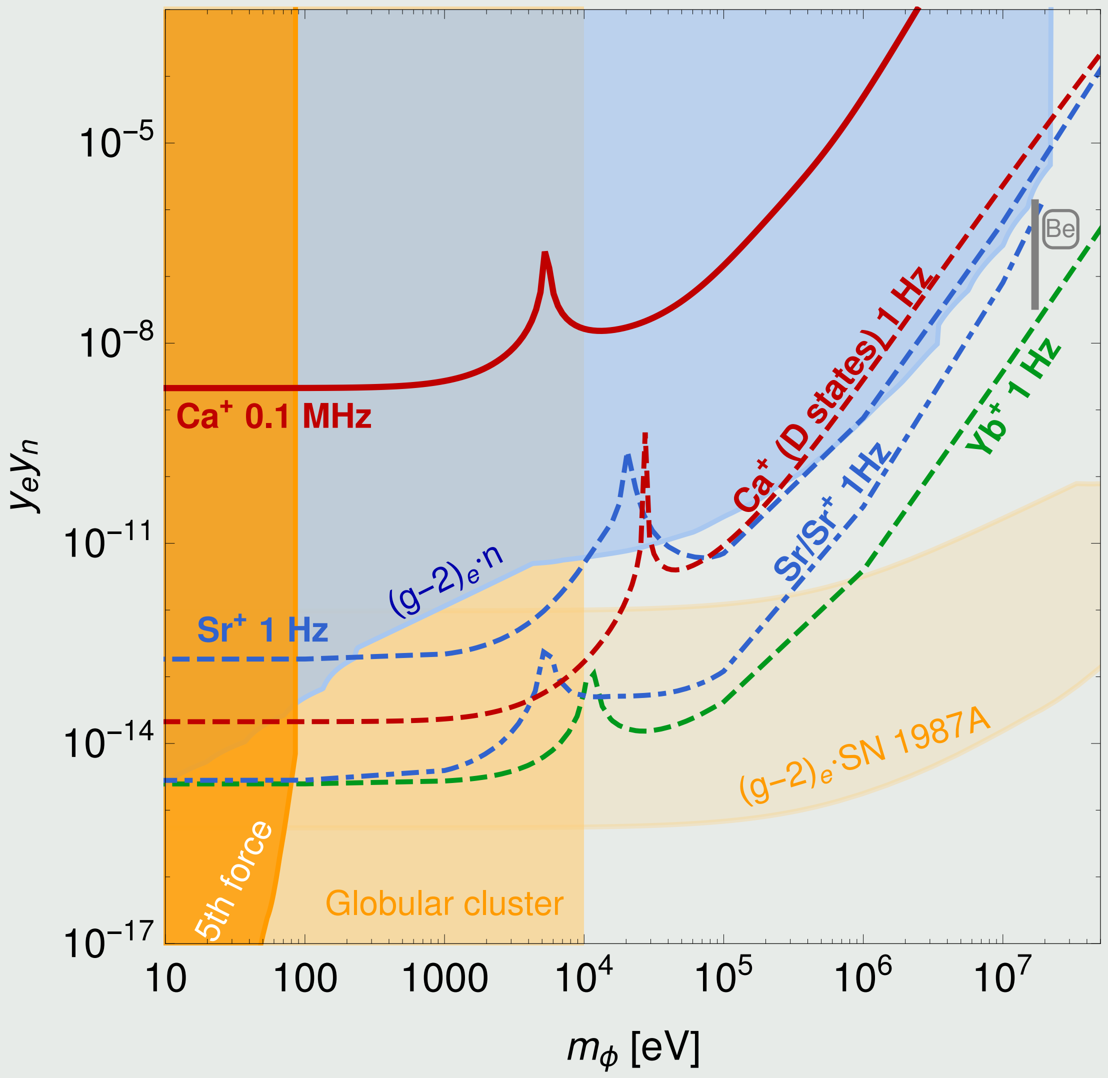
$$\delta\nu_i^{A',A} = K_i\left(\frac{1}{A'}-\frac{1}{A}\right) + F_i\,\delta\langle r^2\rangle^{A',A} + \alpha_{\rm NP} X_i\,\gamma^{A',A}$$

- For scalar boson case

$$\gamma^{A',A} = A' - A$$

$$X_i \approx \int \frac{e^{-m_\phi r}}{r}\left(|\psi_b|^2 - |\psi_a|^2\right) d^3r$$

Predicted exclusion plot

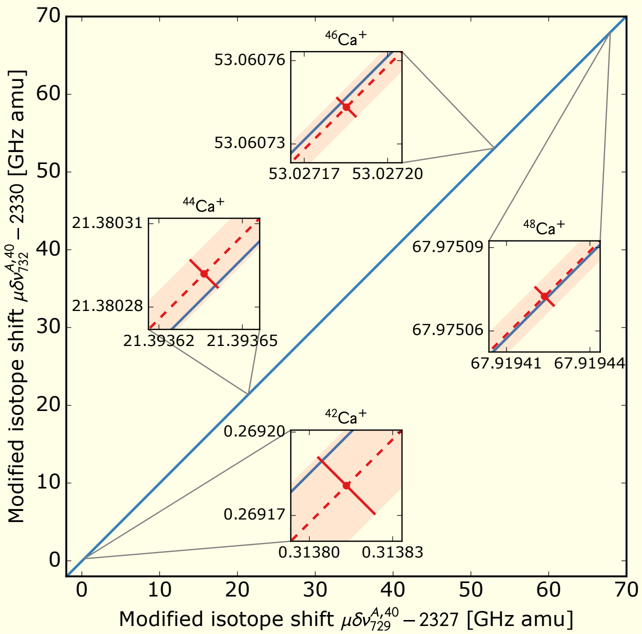


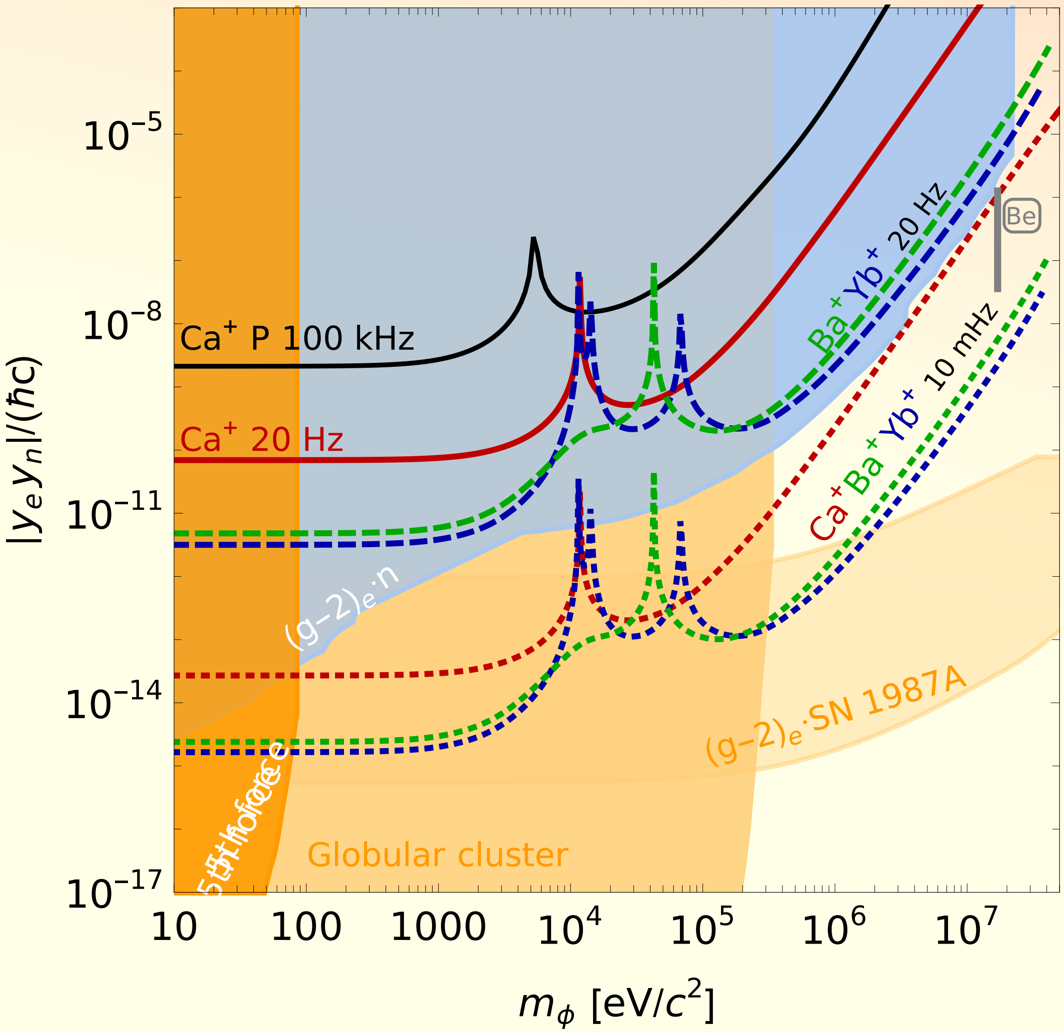
Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq, PRL 120, 091801 (2018)

Experiment

Ca^+ exclusion plot

- 4s – $3d_{3/2}$ (732 nm) data at 1 kHz accuracy (Knollman et al. 2019)
- $d_{3/2}$ – $d_{5/2}$ fine-structure data at 20 Hz accuracy (Solaro et al. 2020)



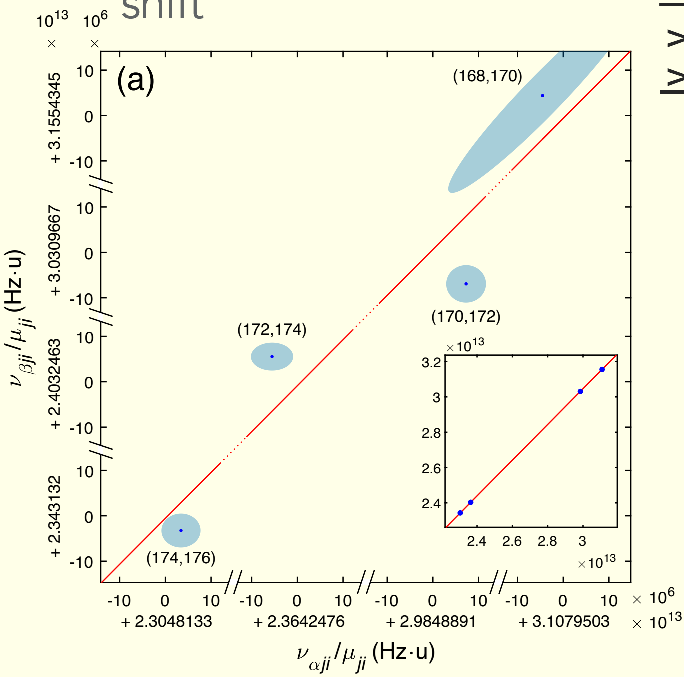


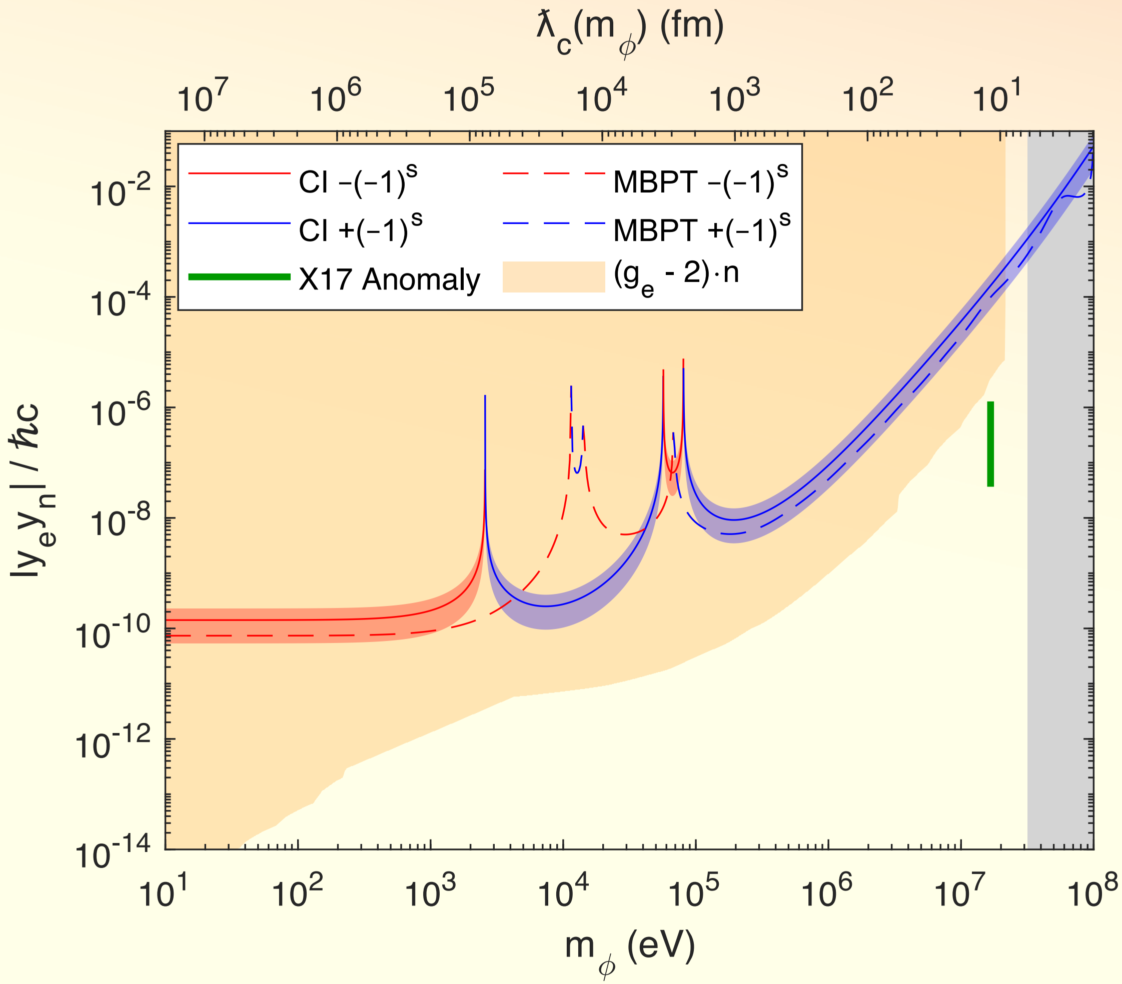
Solaro, Meyer, Fisher, Berengut, Fuchs, Drewsen, PRL 125, 123003 (2020)

Experiment

Yb^+ exclusion plot

- $6s - 5d_{3/2}$ and $6s - 5d_{5/2}$ at 300 Hz accuracy.
- 3σ King-plot nonlinearity
- Non-trivial calculations
- Large second-order field shift





Counts, Hur, Aude Craik, Jeon, Leung, Berengut, Geddes, Kawasaki, Jhe, Vuletić, PRL 125, 123002 (2020)

Spurions

- Additional Standard Model effects include
  - 2nd order Field Shift
  - 2nd order Mass Shift
  - Nuclear polarizability
  - …. Infinitely many others
- Plus there is the possibility of being limited by uncertainties in nuclear mass measurements.

Spurions General Formalism

- Write the isotope shift including general spurions

$$\delta\nu_i^{A',A} = K_i\,\mu^{A',A} + \sum_{l=1}^{S} F_{il}\,\lambda_l^{A',A}$$

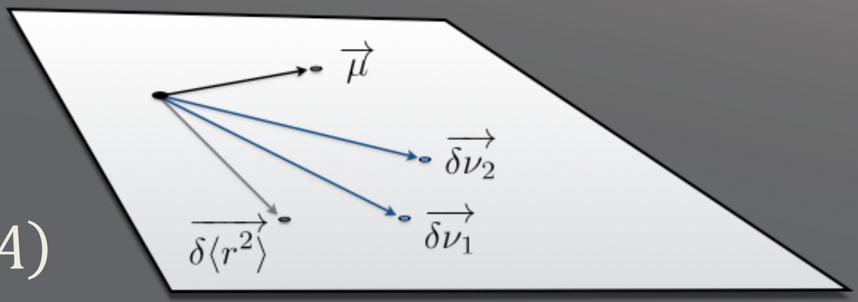
- There are S spurions including field shift
- Each term is factorized into electronic and nuclear parts (this expansion can always be made, possibly at the expense of additional terms)
- Different spurions enter at different levels of experimental accuracy

Berengut, Delaunay, Geddes, Soreq, arXiv:2005.06144; see also Mikami, Tanaka, Yamamoto, EPJC 77, 896 (2017)

Spurions General Formalism

$$\delta\nu_i^a = K_i\,\mu^a + \sum_{l=1}^{S} F_{il}\,\lambda_l^a$$

- $l = 1..S$ spurions
- $i = 1..m$ atomic transitions.
- $a = 1..N$ pairs of isotopes (A', A)



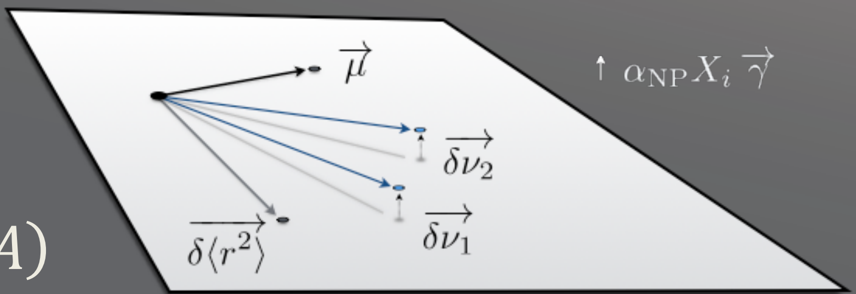
- In the absence of new physics all m isotope shift vectors (dimension N) and μ lie in a hyperplane of dimension $S+1$ with basis vectors $\vec{\mu}$ and $\overrightarrow{\lambda_l}$.

Berengut, Delaunay, Geddes, Soreq, arXiv:2005.06144; see also Mikami, Tanaka, Yamamoto, EPJC 77, 896 (2017)

Spurions General Formalism

$$\delta\nu_i^a = K_i\,\mu^a + \sum_{l=1}^{S} F_{il}\,\lambda_l^a + \alpha_{NP} X_i\,\gamma^a$$

- $l = 1..S$ spurions
- $i = 1..m$ atomic transitions.
- $a = 1..N$ pairs of isotopes (A', A)



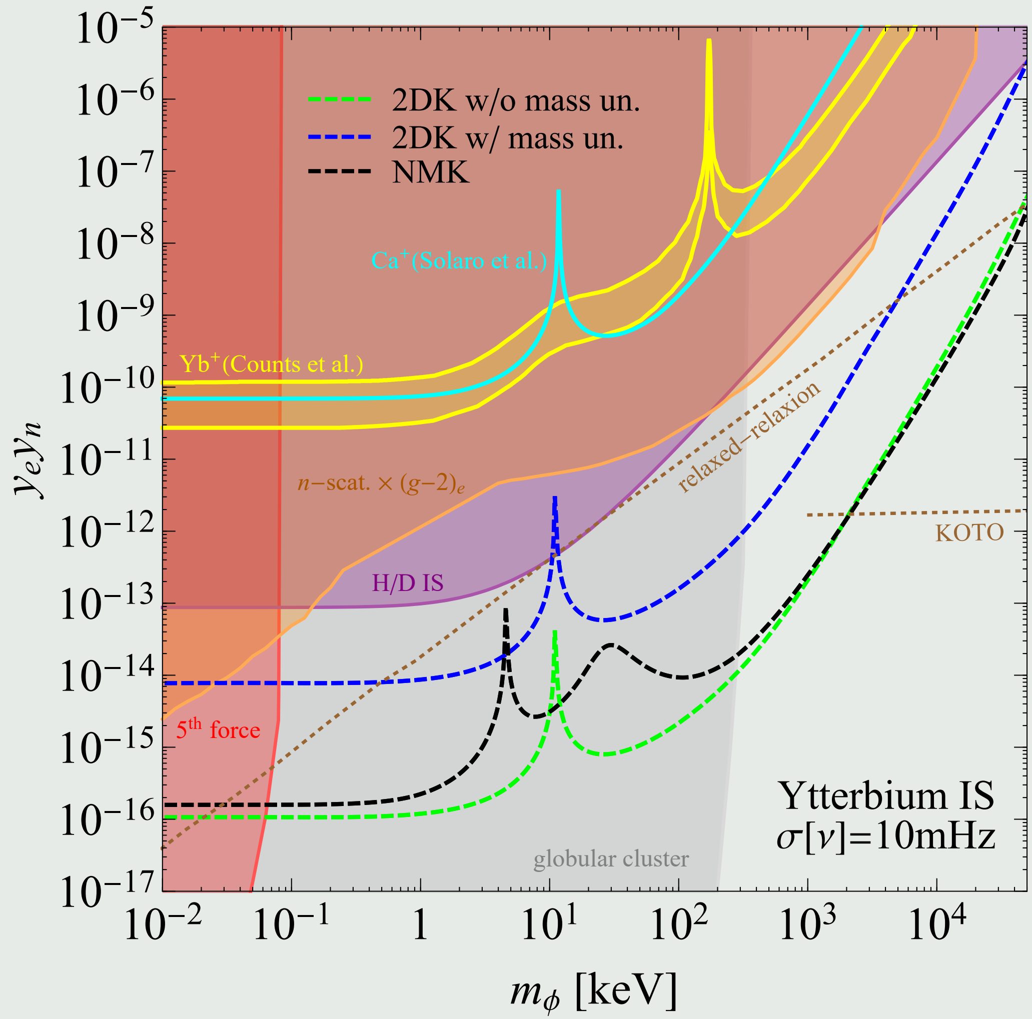
- In the absence of new physics all m isotope shift vectors (dimension N) and μ lie in a hyperplane of dimension $S+1$ with basis vectors $\vec{\mu}$ and $\overrightarrow{\lambda_l}$.
- To see new physics requires $N > m \geq S+1$

Berengut, Delaunay, Geddes, Soreq, arXiv:2005.06144; see also Mikami, Tanaka, Yamamoto, EPJC 77, 896 (2017)

Nuclear mass measurements

- Nuclear masses must be measured better than isotope shifts by a factor of order $\frac{m_A}{(m_{A'}-m_A)}$, otherwise this uncertainty makes the mass shift just another spurion.
- One could use an additional transition rather than the mass difference measurement: the no-mass King (NMK) method
- In this case to see new physics requires $N \geq m \geq S + 2$

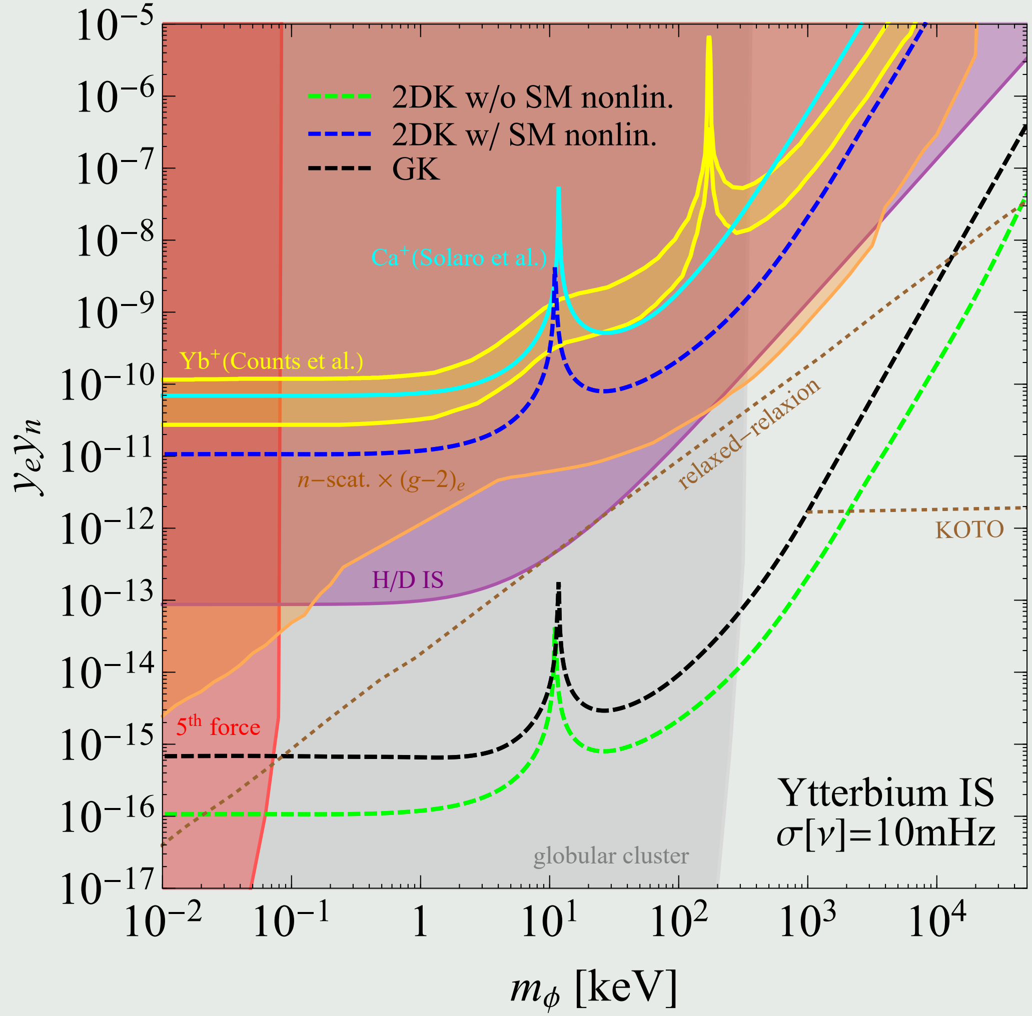
Berengut, Delaunay, Geddes, Soreq, arXiv:2005.06144



Projected: No-mass King plot

Yb⁺ with assumed 10 mHz measurement uncertainty based on E2 and E3 transitions, plus additional Yb S – P, assuming no additional SM nonlinearity

Berengut, Delaunay, Geddes, Soreq, arXiv:2005.06144



Projected: Generalised King plot

Yb^+ with assumed 10 mHz measurement uncertainty based on E2 and E3 transitions, plus additional Yb S – P to remove second-order field shift effect

Berengut, Delaunay, Geddes, Soreq, arXiv:2005.06144

Future prospects

	calcium	ytterbium
Stable even isotopes	40, 42, 44, 46, 48	168, 170, 172, 174, 176
N (number of pairs)	4	4
Clock transitions	Ca^+ 4s – $3d_{3/2}$ Ca^+ 4s – $3d_{5/2}$ Ca $4s^2$ – 4s4p $^3P_0$ highly charged ions	Yb^+ 6s – $5d_{3/2}$ Yb^+ 6s – $5d_{5/2}$ Yb^+ 6s – $6s^2\,4f_{7/2}^{-1}$ Yb 6s2 – 6s6p $^3P_0$
m (number of transitions)	3+	4+
Spurions		
2nd order field shift 2nd order mass shift nuclear polarizability	10^{-2} – 10^{-3} Hz 3 Hz 10^{-2} Hz	10^3 – 10^4 Hz 28 Hz 38 Hz
S estimated number of spurions at 10 mHz	2+	4+

To see new physics requires $N > m > S$

Flambaum, Geddes, Viatkina, PRA 97, 032510 (2018)

Future prospects

	calcium	ytterbium
Stable even isotopes	40, 42, 44, 46, 48	168, 170, 172, 174, 176
N (number of pairs)	4	4
Clock transitions	Ca^+ 4s – 3d	Yb^+ 6s – 5d
m (number of transitions)	3+	4+
Spurions		
2nd order field shift 2nd order mass shift nuclear polarizability	10^{-2} – 10^{-3} Hz 3 Hz 10^{-2} Hz	10^{3} – 10^{4} Hz 28 Hz 38 Hz
S estimated number of spurions at 10 mHz	2+	4+

Need more isotopes!

To see new physics requires N > m > S

Flambaum, Geddes, Viatkina, PRA 97, 032510 (2018)

Summary

- Can probe new physics with precision isotope shift spectroscopy of two different atomic transitions in the same element
- Unknown Standard Model effects (spurions, S) can be controlled using additional transitions
- Need more pairs of even isotopes (N) than transitions (m):
$$N > m > S$$

- Thanks to many collaborators and to you for listening