PROBING NEW FORCES WITH ISOTOPE SHIFT SPECTROSCOPY

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to appear tomorrow

CD, C. Frugiuele, E. Fuchs, Y. Soreq
work in progress

inspired by CD, R. Ozeri, G. Perez, Y. Soreq, arXiv:1601.05087

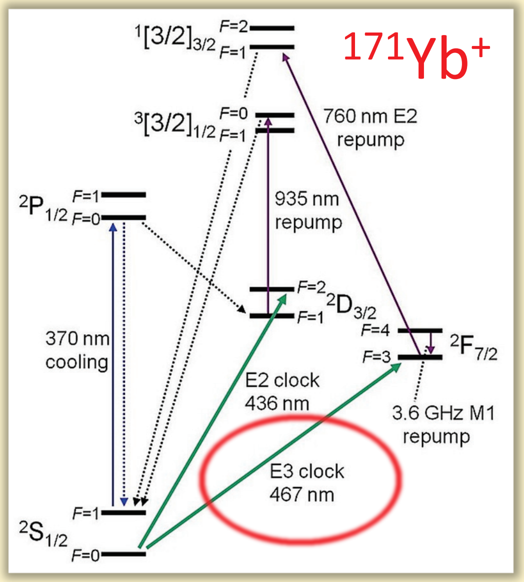
Portoroz | 18-4-2017

Motivation

- Standard Model has several shortcomings, but New Physics not necessarily at the TeV scale
  - Light states solving the hierarchy problem (relaxion?)
  - Light Dark Matter mediators
- Measurements in heavy atoms are reaching a fantastic precision: useful for BSM searches?
- Berylium anomaly: 17MeV state coupled to electron and (preferentially) neutrons

Precision Atomic Physics

- Transition frequencies in the optical range are extremely precisely measured:



$$\nu_{E_3} = 642\,121\,496\,772\,645.36(25)\ \mathrm{Hz}$$

Huntermann et al. **PRL** 113, 210802 (2014)
Godun et al. **PRL** 113, 210801 (2014)

relative uncertainty = 3.9×10^{-16}

(shift from Earth's gravity = $-46\ \mathrm{mHz}$)

- Measurements sensitive to new effects of ~ QED/10^{16}
- Rapid improvement: uncertainty = 3.2×10^{-18}

Huntermann et al. **PRL** 116, 063001 (2016)

New Forces in Atoms

- Consider a short-ranged force between nuclei and their bound electrons: $V = V_{\mathrm{Coulomb}} + V_\phi$

mediator spin

s=0,1,2

mediator mass

$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_N \frac{e^{-m_\phi r}}{r}$$

e-coupling

nucleus-coupling

$y_N = y_p Z + y_n (A - Z)$

Probing New Physics in Atoms

- Probing Higgs couplings?
  Yb^+~LHC/30

$$y_e y_{n,p} \left(\frac{126\,\mathrm{GeV}}{m_\phi}\right)^2 \lesssim 10^{-5}$$

CD-Ozeri-Perez-Soreq, **arXiv**:1601.05087

- In order to probe New Physics, one needs:
  - Very precise QED calculation
    only available for atoms with few electrons
    e.g. He levels known to $\mathcal{O}(\alpha^6 m_e) \sim (\delta\nu/\nu)_{\rm exp}$ *(in progress)*

or

  - Observable insensitive to theory uncertainties,
    like difference/ratio of measurements
    e.g. isotope shifts (only sensitive to $y_e y_n$)

Isotope Shifts

- For *point-like* $(r_N \to 0)$ *and static* $(m_N \to \infty)$ nuclei, the frequency difference between two (spinless) isotopes A and A' is zero in QED:

electronic transition
$i : |a\rangle \to |b\rangle$

$$\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'} = 0$$

- If there is NP coupled to *e* and *n* $(y_{e,n} \neq 0)$:

$$\nu_i^{AA'} \simeq \alpha_{\rm NP}(A - A')X_i$$

wavefunction overlap of Yukawa potential

$$\alpha_{\rm NP} \equiv (-1)^{s+1}\frac{y_e y_n}{4\pi}$$

NP effects are mildly suppressed by $\mathcal{O}[(A - A')/A] \sim 0.1$

Isotope Shifts

- In real world, nuclei have *finite* mass and size.
- Frequencies depend on A through:
  - **reduced mass** $m_r \equiv \frac{m_e m_A}{m_e + m_A} \simeq m_e \left(1 - \frac{m_e}{m_A}\right)$ — $\mathcal{O}(10^{-5})$
  - **finite nuclear size correction** $V_{\text{FNS}}(r) = \frac{Z\alpha}{6} \langle r_A^2 \rangle \frac{\delta(r)}{r^2}$

charge radius (taking nuclei to be uniform spheres)

for electron in $n, \ell = 0$ state:

$$\delta E \simeq \langle \psi | V_{\text{FNS}} | \psi \rangle \propto \langle r_A^2 \rangle |\psi(0)|^2, \quad |\psi(0)|^2 \sim \frac{Z}{(na_0)^3}$$

$$E \sim \frac{Z_{\text{eff}}^2 \alpha}{n^2 a_0} \quad \rightarrow \frac{\delta E}{E} \sim \frac{Z^2}{n Z_{\text{eff}}^2} \frac{\langle r_A^2 \rangle}{a_0^2}$$

$\mathcal{O}(10^{-10})$

Isotope Shifts

- Frequency shift from QED:

electronic constants

$$\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'}$$

mass shift (MS)

$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$

field shift (FS)

$\lambda_{AA'} = \delta\langle r^2 \rangle + \text{higher moments}$

- Typically $\nu^{AA'} \sim \mathcal{O}(\text{GHz}) \;\to\; \nu^{AA'}/\nu^A \sim 10^{-6}$
- While m_A measured to ~10^{-10}, th. error on K_i, F_i ~1% and $\delta\langle r^2 \rangle$ only known to ~1% from nuclear data...

King Linearity

- **Q**: Is there an observable sensitive to NP and free of theory uncertainties? (*i.e.* limited by precision in IS measurements) $\rightarrow$ **A**: Yes, King linearity!

- Measure 2 transitions with the same isotopes. If IS is described by leading order QED, the 2 data-sets are linearly related:

$$m\nu_2^{AA'} = F_{21}\, m\nu_1^{AA'} + K_{21}$$

$$m\nu \equiv \mu^{-1}\nu$$

$$F_{21} \equiv F_2/F_1\,, \;\; K_{21} = K_2 - F_{21}K_1$$

King J. Opt. Soc. Am. **53**, 638 (1963)

King Linearity

- KL holds regardless of the K_i, F_i values and $\delta\langle r^2\rangle$
- It merely results from factorization of electronic and nuclear parameters:

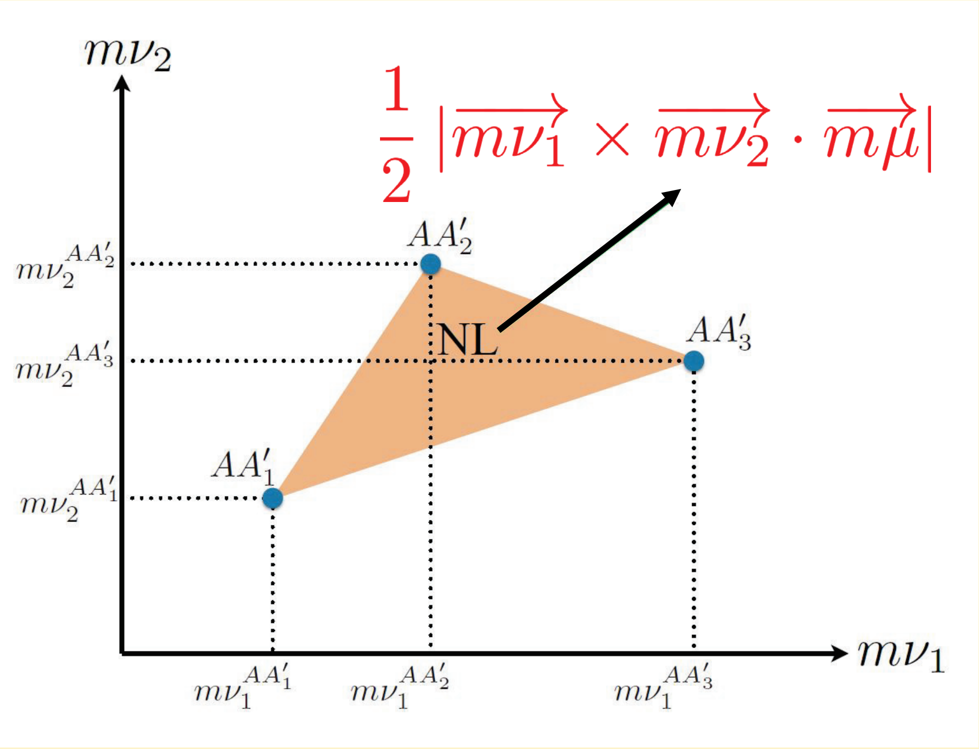
$$\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'}$$

independent of A,A'

- Establishing KL is *only* limited by the accuracy of IS (and nuclear masses) measurements.

Establishing KL

- Take 2 transition measurements in 4 isotopes



$$\overrightarrow{m\nu_i} \equiv \begin{pmatrix} m\nu_i^{AA'_1} \\ m\nu_i^{AA'_2} \\ m\nu_i^{AA'_3} \end{pmatrix} \qquad \overrightarrow{m\mu} \equiv \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

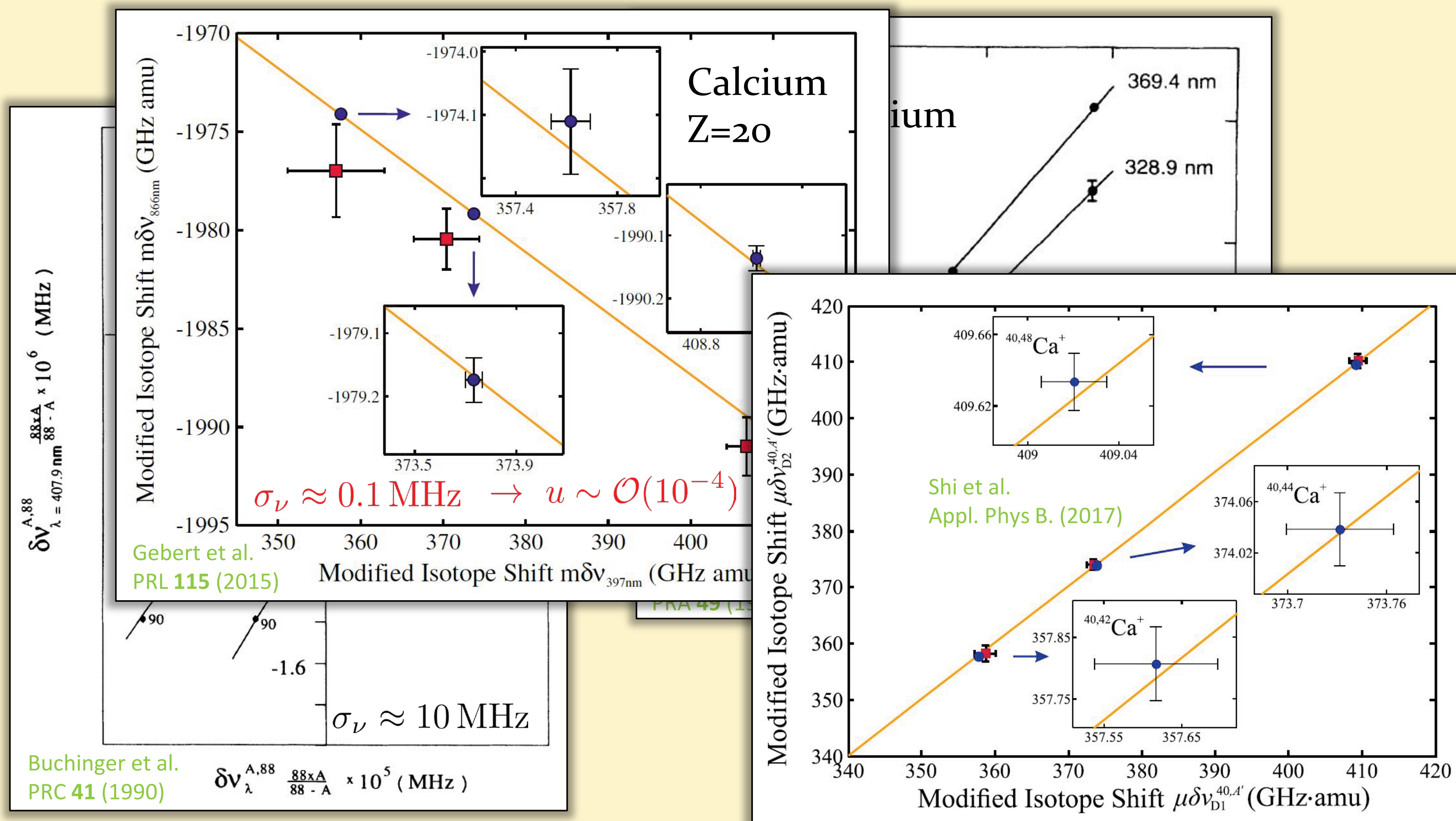
MS vector

1) Nonlinearities (NL) are quantified by the area of the triangle formed by 3 points on a King plot.

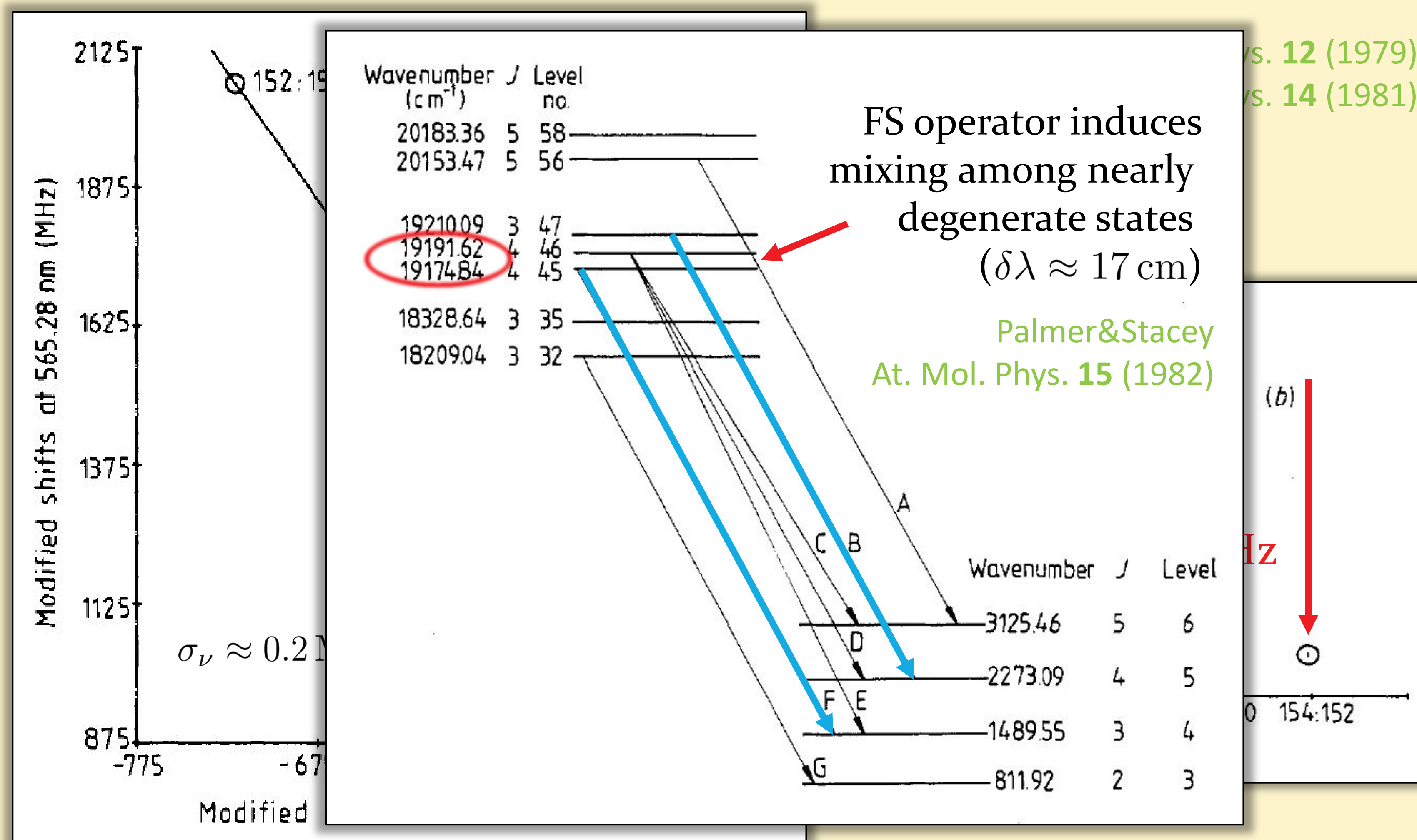
1st-order propagated error

2) KL is established within meas. accuracy if $\mathrm{NL} \lesssim \sigma_{\mathrm{NL}}$

King linearity in data



Nonlinearities in data?



KL Violation from New Physics

- In the presence of NP, the IS theory prediction is

$$\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'} + \alpha_{\mathrm{NP}} X_i \gamma_{AA'}$$

NP coupling

$$\alpha_{\mathrm{NP}} \equiv (-1)^{s+1} \frac{y_e y_n}{4\pi}$$

NP nuclear parameter

$$\gamma_{AA'} = A - A'$$

electronic wavefunction overlap

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

electron densities in
initial/final atomic states
computed using many-body perturbation theory

KL Violation from New Physics

- In the presence of NP, the IS theory prediction is

$$\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'} + \alpha_{\rm NP} X_i \gamma_{AA'}$$

- So that NP implies KL violation

$X_{21} \equiv X_2 - F_{21} X_1$
$h_{AA'} \equiv \gamma_{AA'}/\mu_{AA'}$

$$m\nu_2^{AA'} = F_{21}\, m\nu_1^{AA'} + K_{21} + \alpha_{\rm NP} h_{AA'} X_{21}$$

- unless
  - $\frac{X_2}{X_1} \approx \frac{F_2}{F_1}$ as with short-range forces $m_\phi \gtrsim 20\,\mathrm{MeV}$
  - $\vec{h}$ is aligned with any of $\overrightarrow{m\nu_{1,2}}$ or $\overrightarrow{m\mu}$

Constraining NP from KL

- Take 2 transition measurements in 4 isotopes
- Expected relation among IS measurements is

$$\overrightarrow{m\nu_2} = F_{21}\,\overrightarrow{m\nu_1} + K_{21}\overrightarrow{m\mu} + \alpha_{\rm NP}\vec{h}X_{21}$$

- If data consistent with KL, one can bound NP

$$\alpha_{\rm NP} \lesssim \frac{(\overrightarrow{m\nu_1} \times \overrightarrow{m\nu_2}) \cdot \overrightarrow{m\mu}}{(\overrightarrow{m\mu} \times \vec{h}) \cdot (X_1\overrightarrow{m\nu_2} - X_2\overrightarrow{m\nu_1})}$$

only theoretical inputs
computed with decent accuracy
using MBPT+CI method

see *e.g.* Berengut-Flambaum-Kozlov PRA **73** (2006)

Current bounds on α_{NP}

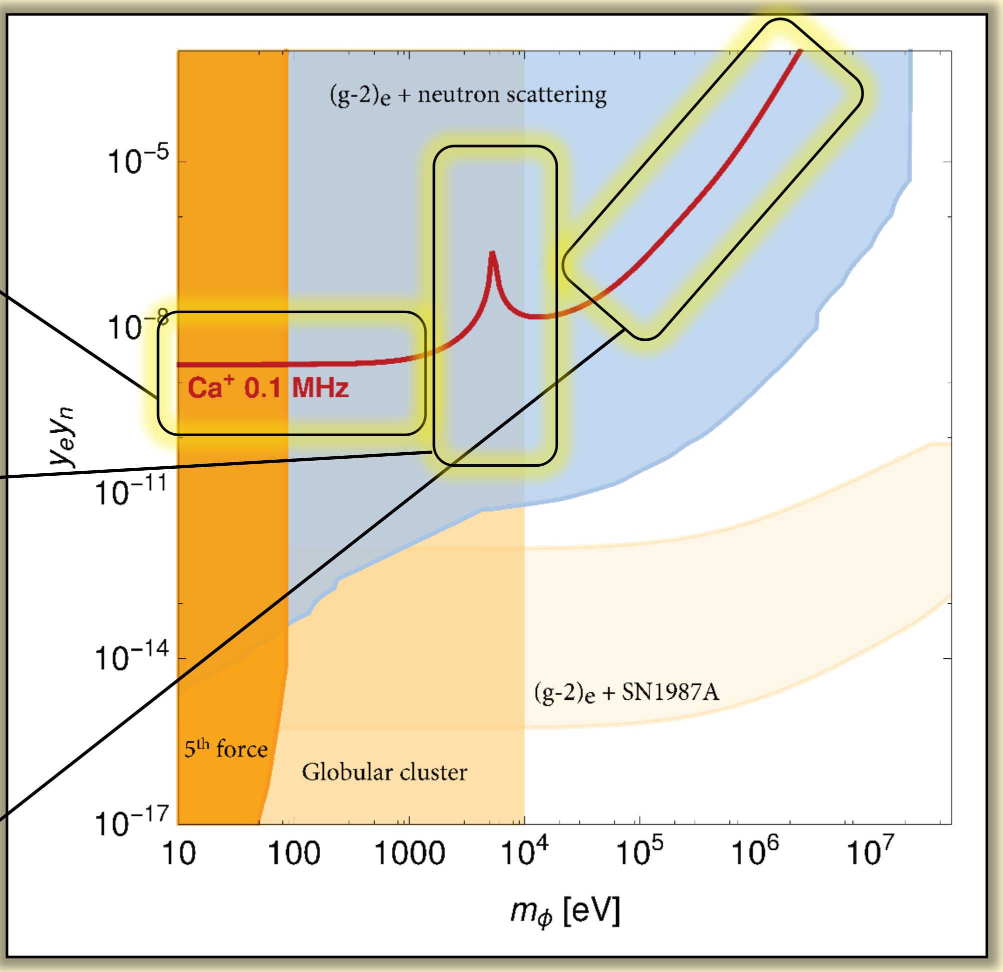
For $m_\phi \ll 1/a_0 \approx 4\,\mathrm{keV}$ the NP potential is Coulomb-like:

$$Z\alpha \to Z\alpha - (A-Z)\alpha_{\mathrm{NP}}$$

For $m_\phi \sim 1/a_0$, $X_1 \sim X_2$ leading to accidental cancelation:

$$\alpha_{\mathrm{NP}} \lesssim \frac{(\overrightarrow{m\nu_1} \times \overrightarrow{m\nu_2}) \cdot \overrightarrow{m\mu}}{(\overrightarrow{m\mu} \times \vec{h}) \cdot (X_1 \overrightarrow{m\nu_2} - X_2 \overrightarrow{m\nu_1})}$$

For $m_\phi \gg Z/a_0 \sim 1\,\mathrm{MeV}$ the NP potential is point-like: $\text{bound} \propto 1/m_\phi^3$



IS in Clock Transitions

- Existing IS data involve broad (dipole-allowed: $S \to P\,,\; D \to P$) transitions with $\Gamma_\nu \sim \mathcal{O}(10\,\mathrm{MHz})$ thus limiting the sensitivity to NP

- IS measurements in very narrow $(\Gamma_\nu \lesssim \mathrm{Hz})$ « clock » (optical) transitions could improve sensitivity by several orders of magnitude!

- Testing KL requires (at least) 2 narrow transitions with 4 stable isotopes; there are few candidates:

e.g. Ca^+, Sr/Sr^+, Ba/Ba^+, Yb/Yb+ and Dy

Estimating sensitivity to NP

- W/out data, the sensitivity can't be evaluated precisely using

$$\alpha_{\mathrm{NP}} \lesssim \frac{(\overrightarrow{m\nu_1} \times \overrightarrow{m\nu_2}) \cdot \overrightarrow{m\mu}}{(\overrightarrow{m\mu} \times \vec{h}) \cdot (X_1 \overrightarrow{m\nu_2} - X_2 \overrightarrow{m\nu_1})}$$

- Yet, if KL were established with accuracy Δ , we would conclude that factorization holds, *i.e.*

$$\overrightarrow{m\nu_i} = K_i \overrightarrow{m\mu} + F_i \overrightarrow{m\lambda} + \overrightarrow{\Delta_i}$$

- This yields the best-case bound estimate

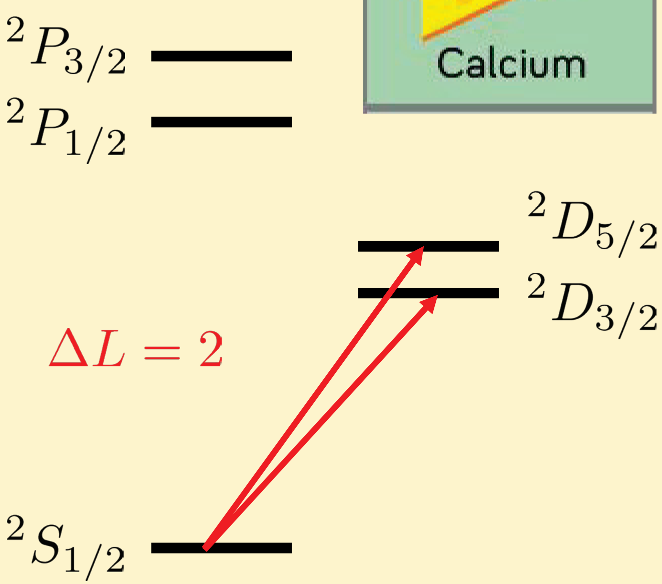
$$\alpha_{\mathrm{NP}} \lesssim \frac{\sqrt{\Delta_1^2 + F_{21}^2 \Delta_2^2}}{(X_1 - F_{21} X_2)\,\delta A_{\max}} \frac{A}{\delta A_{\min}}$$

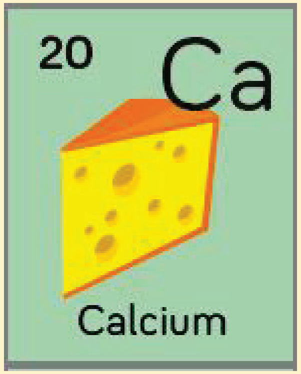
NP alignment with mass shift

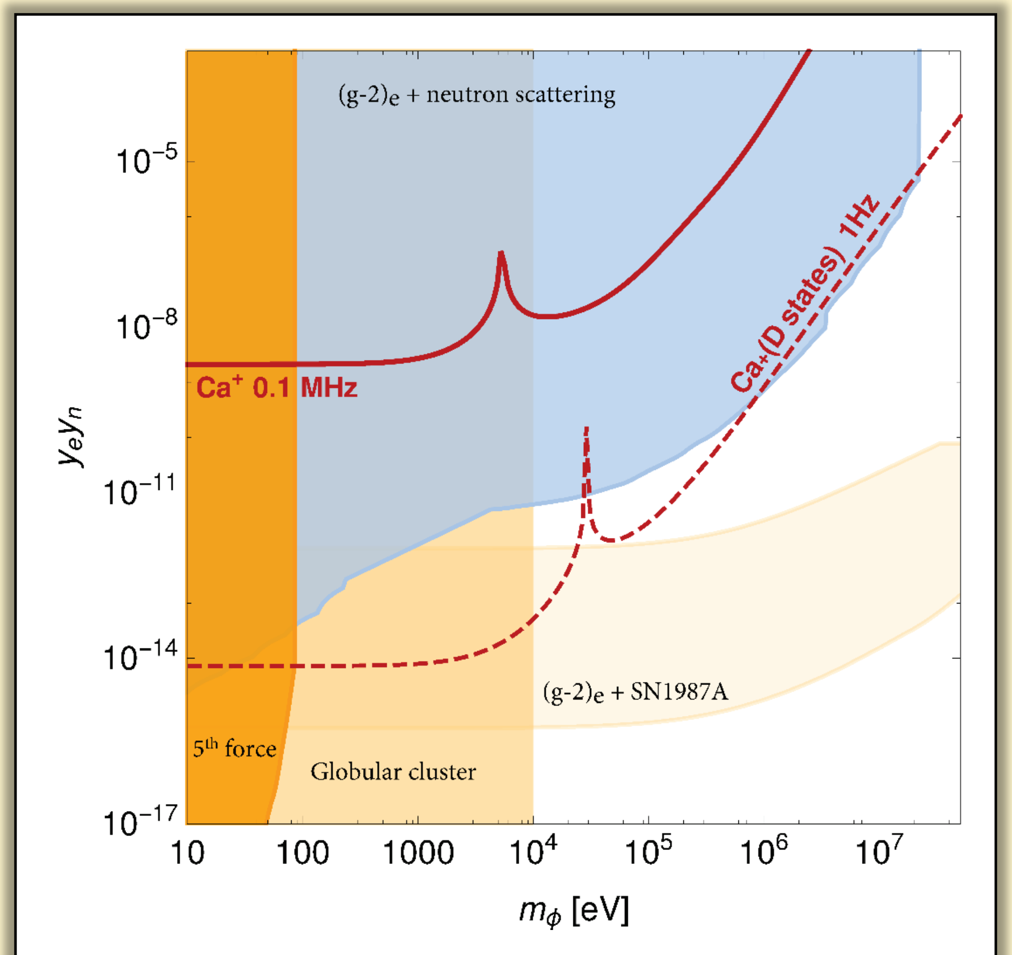
heavy NP limit

estimated from MBPT (or not-so-precise earlier data)

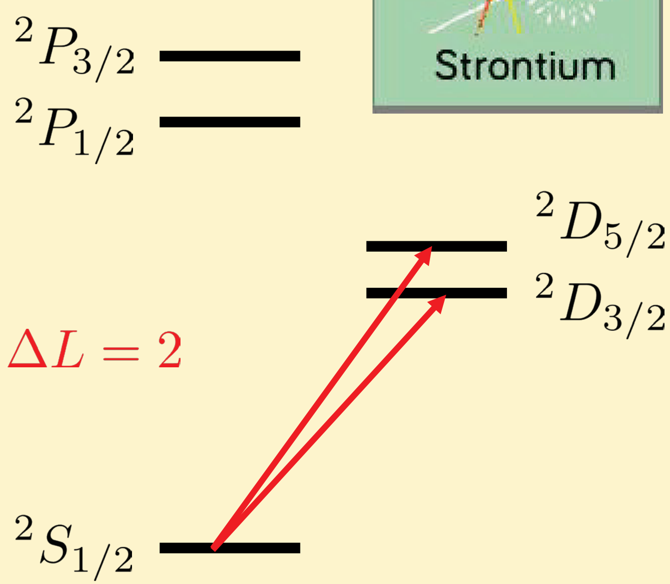
Projected Sensitivities to NP

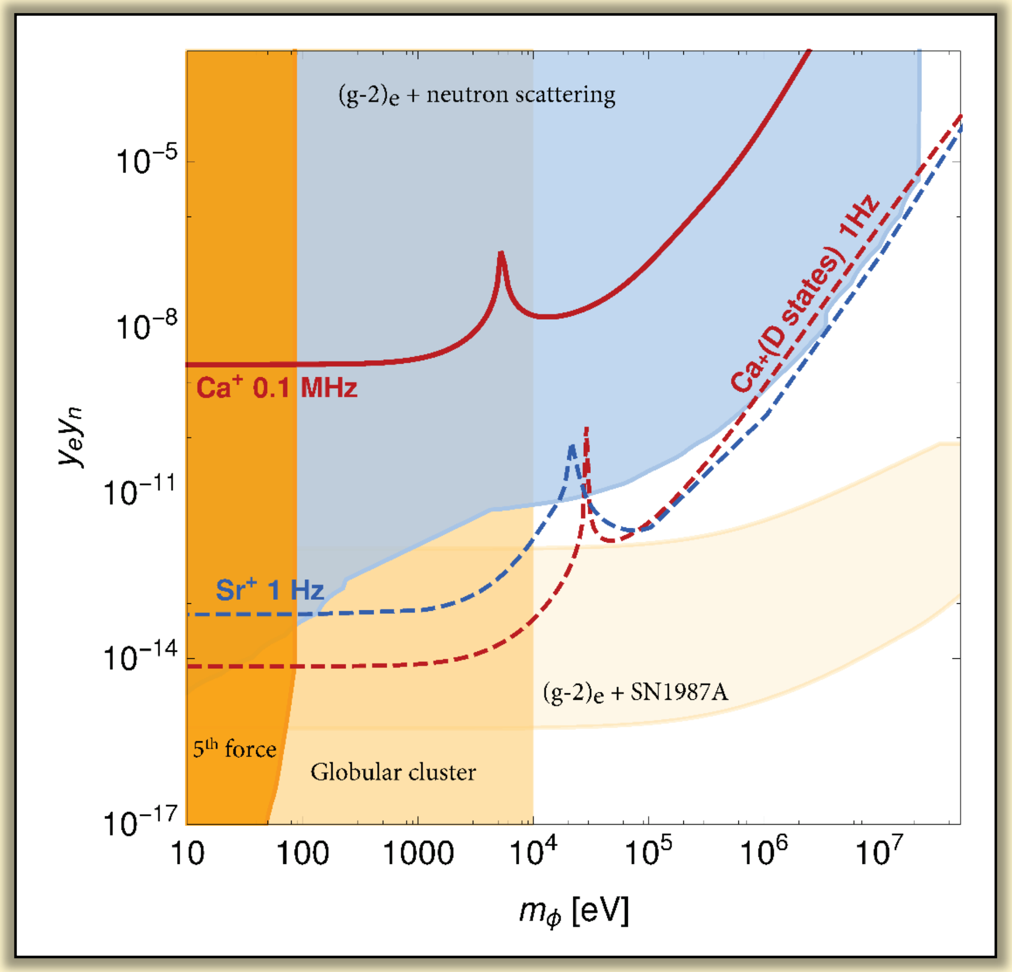






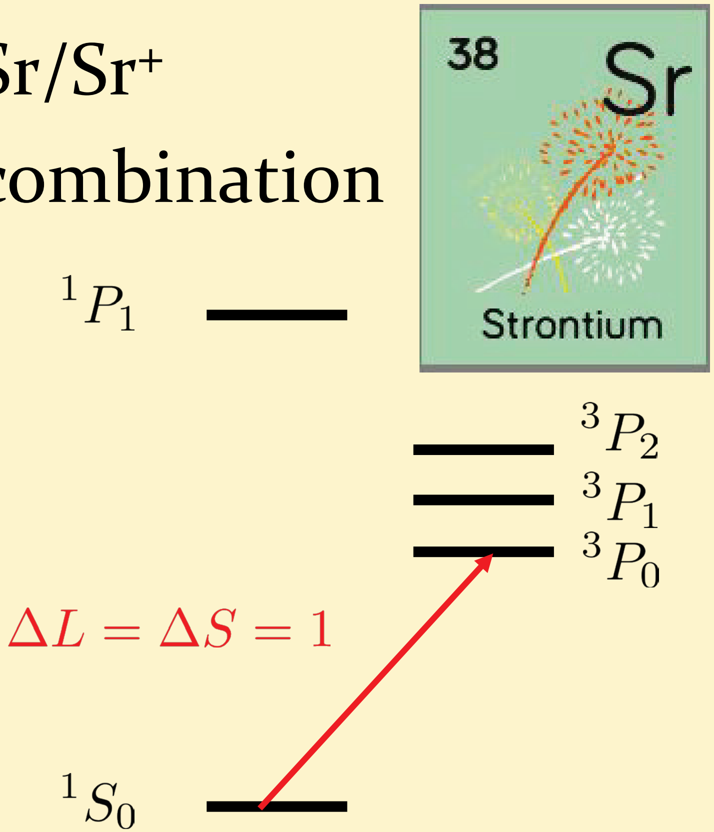
Projected Sensitivities to NP

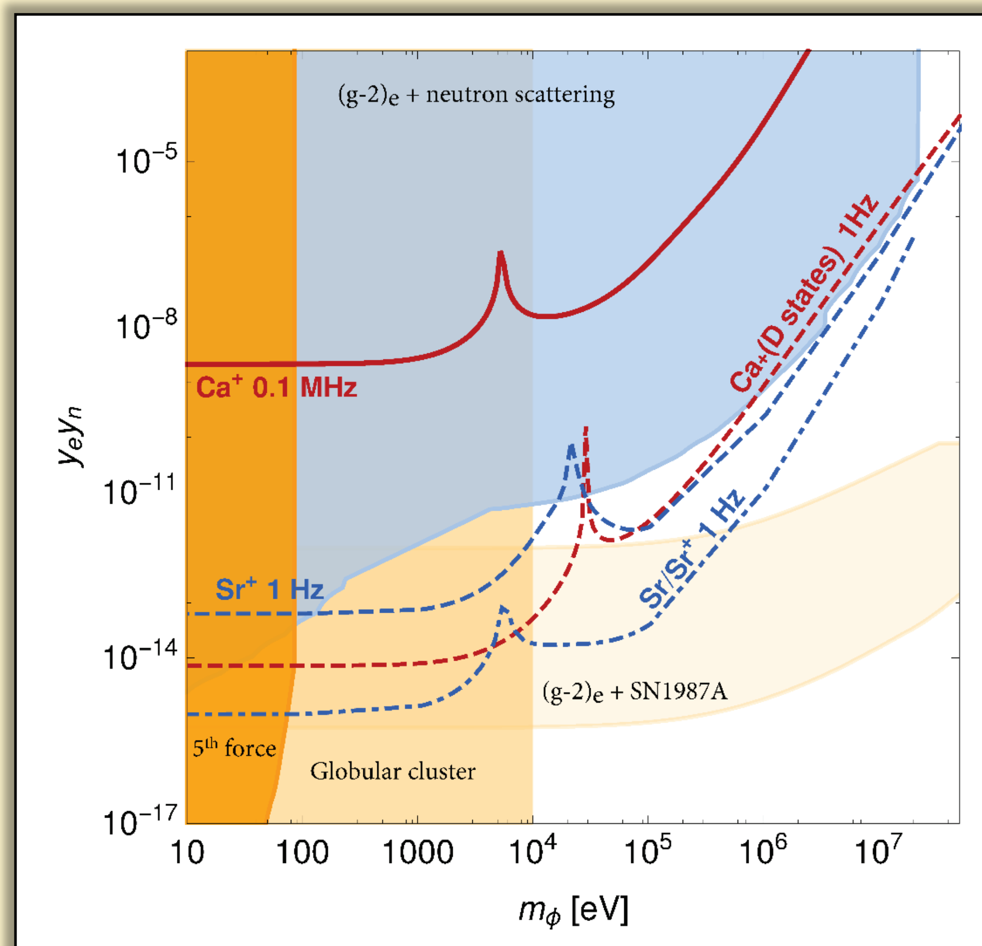




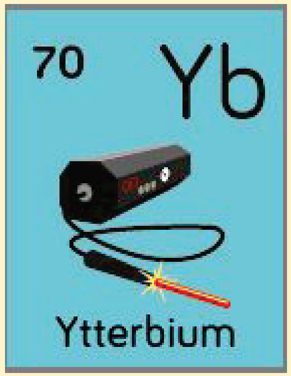
Projected Sensitivities to NP

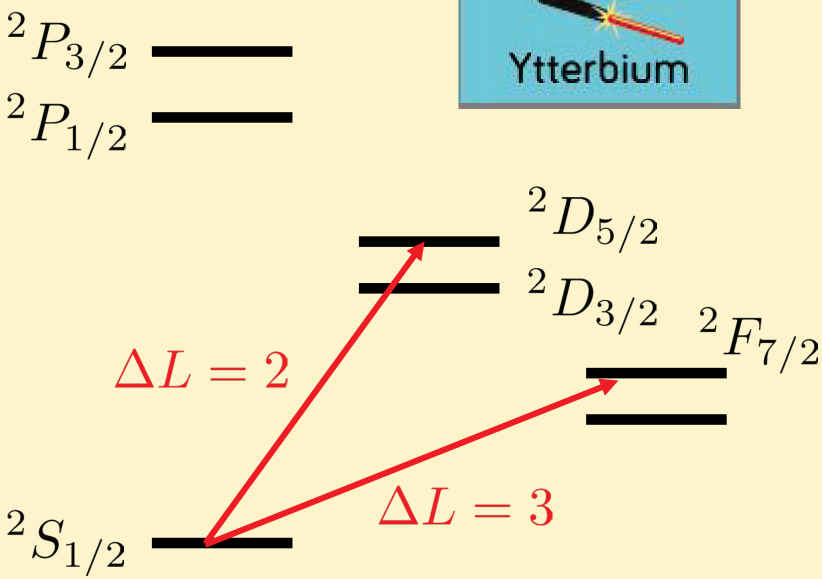
Sr/Sr⁺ combination

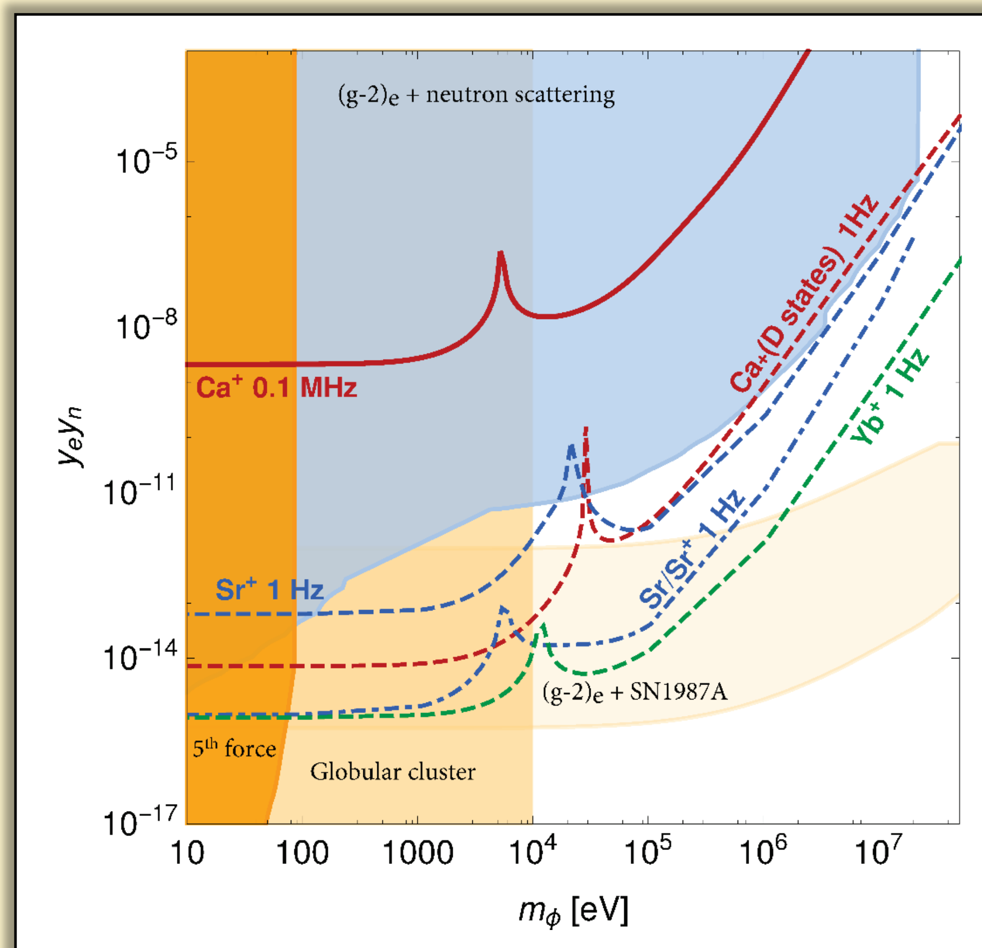




Projected Sensitivities to NP







Conclusions/Outlook

- IS spectroscopy in optical clock transitions is a sensitive probe of New Physics below ~20MeV

- As long as King plots remain linear, New Physics can be bounded with no need for very precise QED calculations

- Were KL to be violated in future data, precise calculation of nonlinearities from nuclear effects would be needed to isolate and further probe the New Physics contributions