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and J**Berengut**, C**D**, A**Geddes**, Y**Soreq** | *To appear*

PROBING NEW PHYSICS WITH ATOMIC TRANSITIONS

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Workshop on New Physics
at the Low-energy Precision Frontier
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Outline

- **Intro** | Light NP at the precision frontier

- Isotope shift and King linearity violation (KLV)
- Limitations of the original KLV method
- Generalizated King plots

- **Summary/Outlook**

Light New Physics

- The SM does not completely describe Nature ($m_\nu, \eta_B, \Omega_{\rm DM}$)
- The Higgs sector points to NP scales ~TeV or (much) heavier, but no experimental hint of it so far (LHC, direct detection..)

- The motivation for light NP (below ~GeV) is plenty:
  - Alternative solutions to the hierarchy problem? (like relaxion)
  - Axions
  - Light mediators for dark matter
  - …

- If such NP couples significantly to electrons/nucleons, the atom is the natural place to search for it.

The Precision Atomic Frontier

- AMO techniques allow precision measurements of atomic frequency with ultra high precision
  - **Hydrogen lines:** $\nu_{1S-2S} = 2\,466\,061\,413\,187\,035(10)\ \mathrm{Hz}$

    $u_\nu = 4.2 \times 10^{-15}$

    Parthey et al. (2011)

Combining with precise theory calculation, it allows to fix « fundamental » parameters like **Rydberg cste**

$$R_\infty \equiv \alpha^2 m_e c/2h = 3.289\,841\,960\,355(19) \times 10^{15}\ \mathrm{Hz}$$

Mohr et al. [CODATA]

The Precision Atomic Frontier

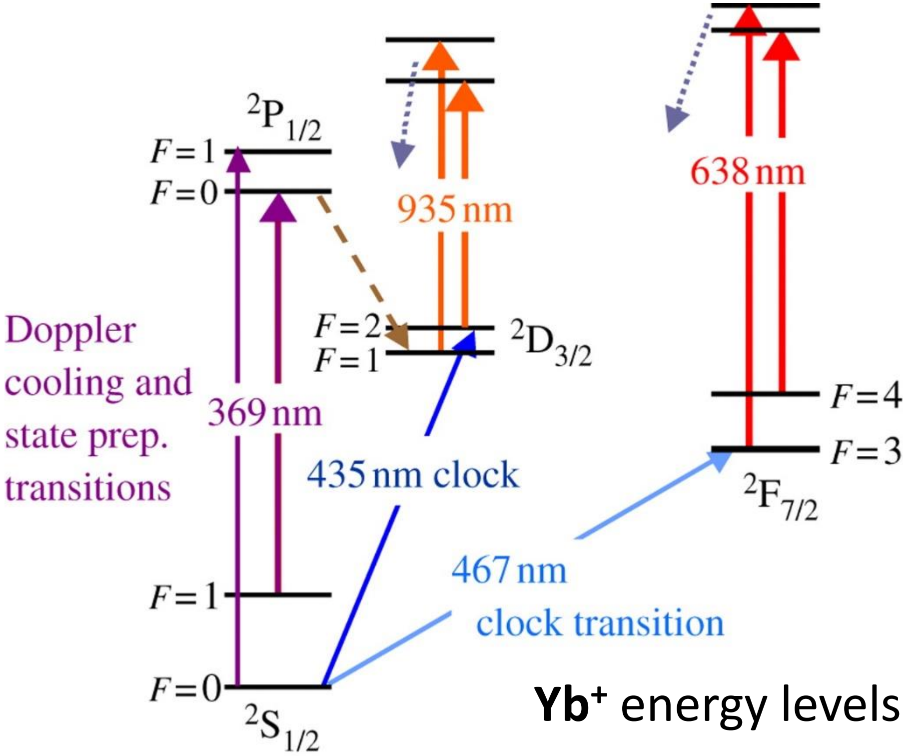
- AMO techniques allow precision measurements of atomic frequency with ultra high precision
  - **Optical clock transitions**

$$\nu_{467\mathrm{nm}} = 642\,121\,496\,772\,645.36(25)\ \mathrm{Hz}$$

$$u_\nu = 3.9\times10^{-16}$$

Huntermann et al. (2014)

clock **stability** in neutral Yb demonstrated at the 10^{-18} level **Huntermann** et al. (2016)



Yb$^+$ energy levels

Probing New Physics in Atoms

- In principle these measurements are sensitive to tiny NP effects
- To probe them however requires equally fine theoretical control over standard EM contributions with either
  - **Precision calculation** of transition frequencies.

    Only available for simple atoms like H and He

    Karshenboim et al. (2010)
    Pachucki et al. (2017)

  - **Combine transitions** into observables with reduced sensitivity to contributions with large theoretical uncertainty:

→ **King linearity of isotope shifts**

Probing new physics with King linearity

Why isotope shifts?

- Spectral lines are well measured, but theory is no match

- Frenquencies are (mostly) set by the charge of the nucleus ***Z***
- Hence dominant (uncalculable) contributions from EM cancel out in frequency differences between isotopes: $(\nu - \nu')/\nu \sim 10^{-6}$

- Spin-independent NP couples to the entire nucleus ***A*** and thus is only mildy suppressed in isotope differences: $(A - A')/A \sim 0.1$

- Yet isotope shifts are also challenging to calculate…

Isotope Shift Theory

- Isotopes (same ***Z***, different ***A***) have the same atomic lines up to small nuclear effects:

$$\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'} = K_i\, \mu_{AA'} + F_i\, \delta\langle r^2\rangle_{AA'}$$

  - **Mass shift** (MS) due to change in the nuclear mass $\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$ modifying the global atomic center-of-mass (normal MS) and the electron-electron repulsion terms (specific MS)
  - **Field shift** (FS) due to change in the nuclear charge distribution ~ size, which typically dominates for heavy elements

King Linearity

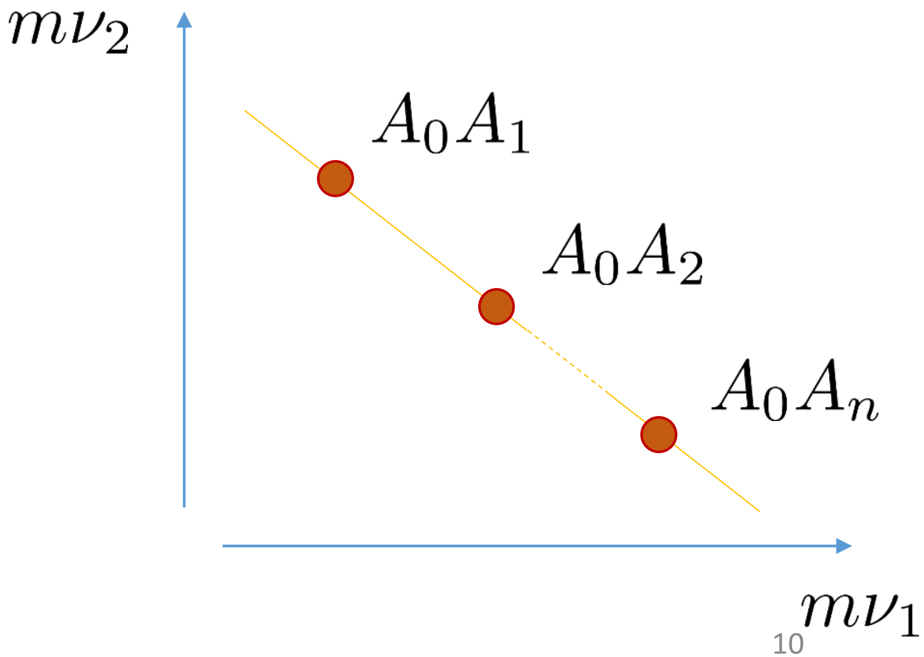
King (1963)

- Combining 2 transitions to eliminate the poorly known $\delta\langle r^2\rangle$ yields a linear relation among modified IS, $m\nu_i^{AA'} \equiv \nu_i^{AA'}/\mu_{AA'}$:

$$m\nu_2^{AA'} = \underset{\equiv F_2/F_1}{F_{21}}\, m\nu_1^{AA'} + \underset{\equiv K_2 - F_{21}K_1}{K_{21}}$$

- Linearity follows from having only 2 independent nuclear parameters

- Values of $K, F, \delta\langle r^2\rangle$ are not needed, only masses must be precisely known



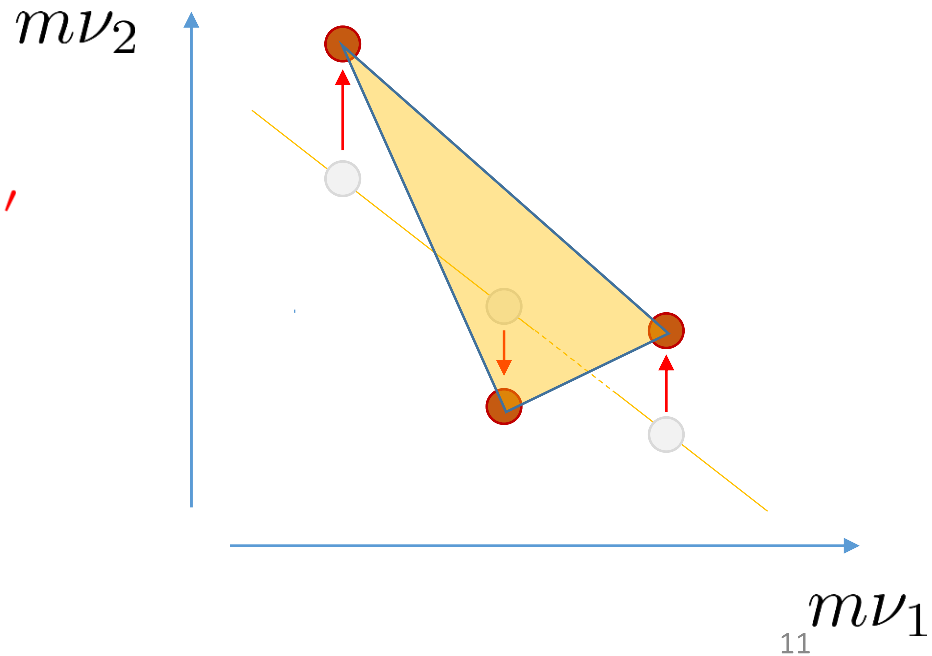
Nonlinearities from New Physics

- New Physics comes with its own independent nuclear/electronic parameters:

$$\nu_i^{AA'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + \alpha_{\rm NP} X_i \gamma_{AA'}$$

thus inducing nonlinearities (NL):

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



with invariant measure : $\vec{m\mu} = (1,1,1)$

$$\mathrm{NL} = \det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\mu})$$

Experimental Status

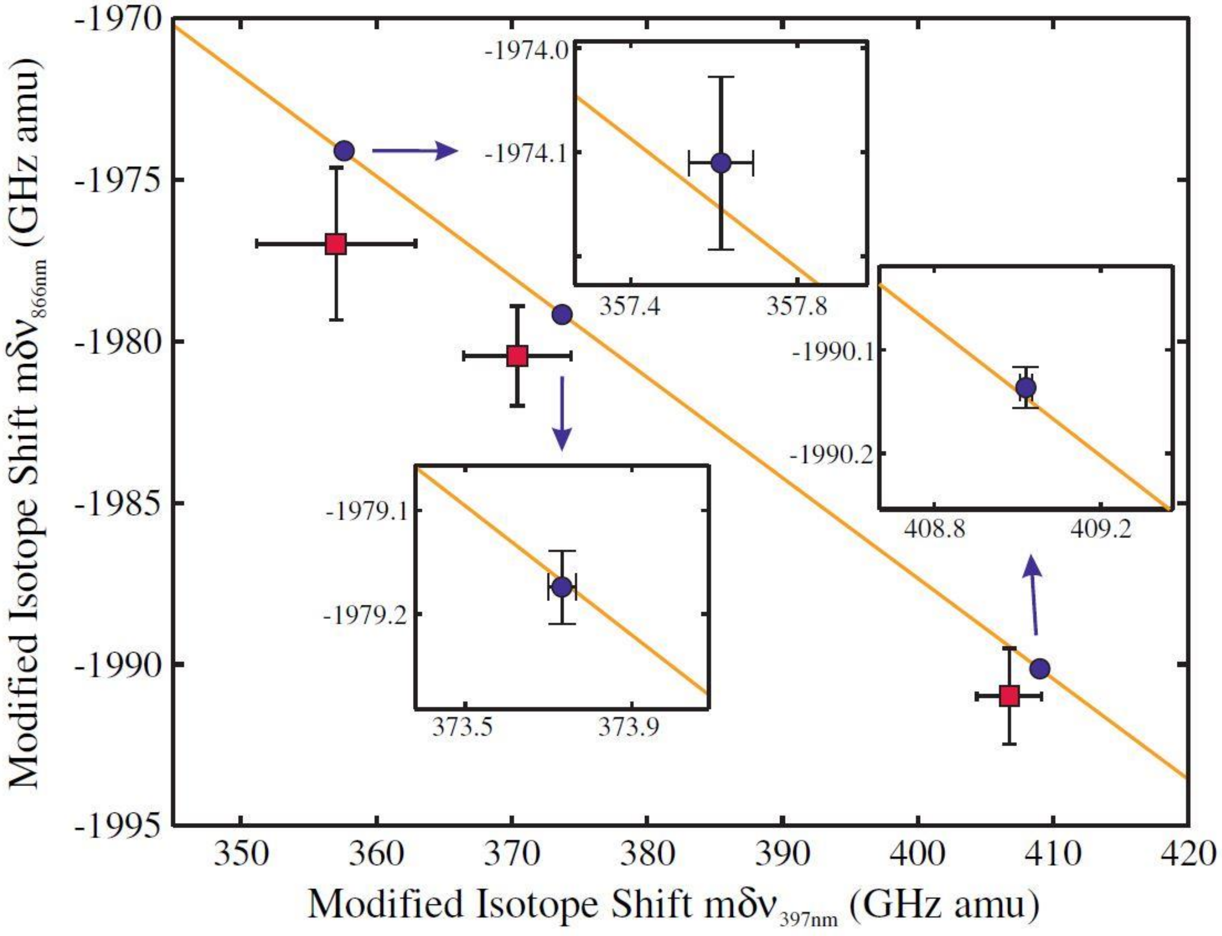
- Most accurate test of linearity to date is based on Ca$^+$ IS data

Gebert et al. (2015)
Knollmann et al. (2019)

- It uses broad dipole transitions and is not very precise ~100kHz

- New tests (with Hz-10mHz accuracy) are in reach using **Yb, Sr** atoms

Significantly improved accuracy using entangled states
Manovitz et al. 1906.05770 [atom –ph]



Bounding NP

- Solving King equation for the NP coupling gives:

NL in data

$$\alpha_{\mathrm{NP}} = \frac{\det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\mu})}{\det[X_1 \vec{m\nu}_2 - X_2 \vec{m\nu}_1, \vec{h}, \vec{m\mu}]}$$

NL predicted by theory

$$= \epsilon_{ij} F_i X_j \times \det(\vec{m\delta\langle r^2\rangle}, \vec{h}, \vec{m\mu})$$

Electronic alignment
→ strong suppression
for large m_{NP} : $X_i \propto F_i$

Nuclear alignment
→ suppression of $\delta m_A^{\max}/m_A \sim \mathcal{O}(10)$
for NP coupling $\propto A$

New Physics Benchmark

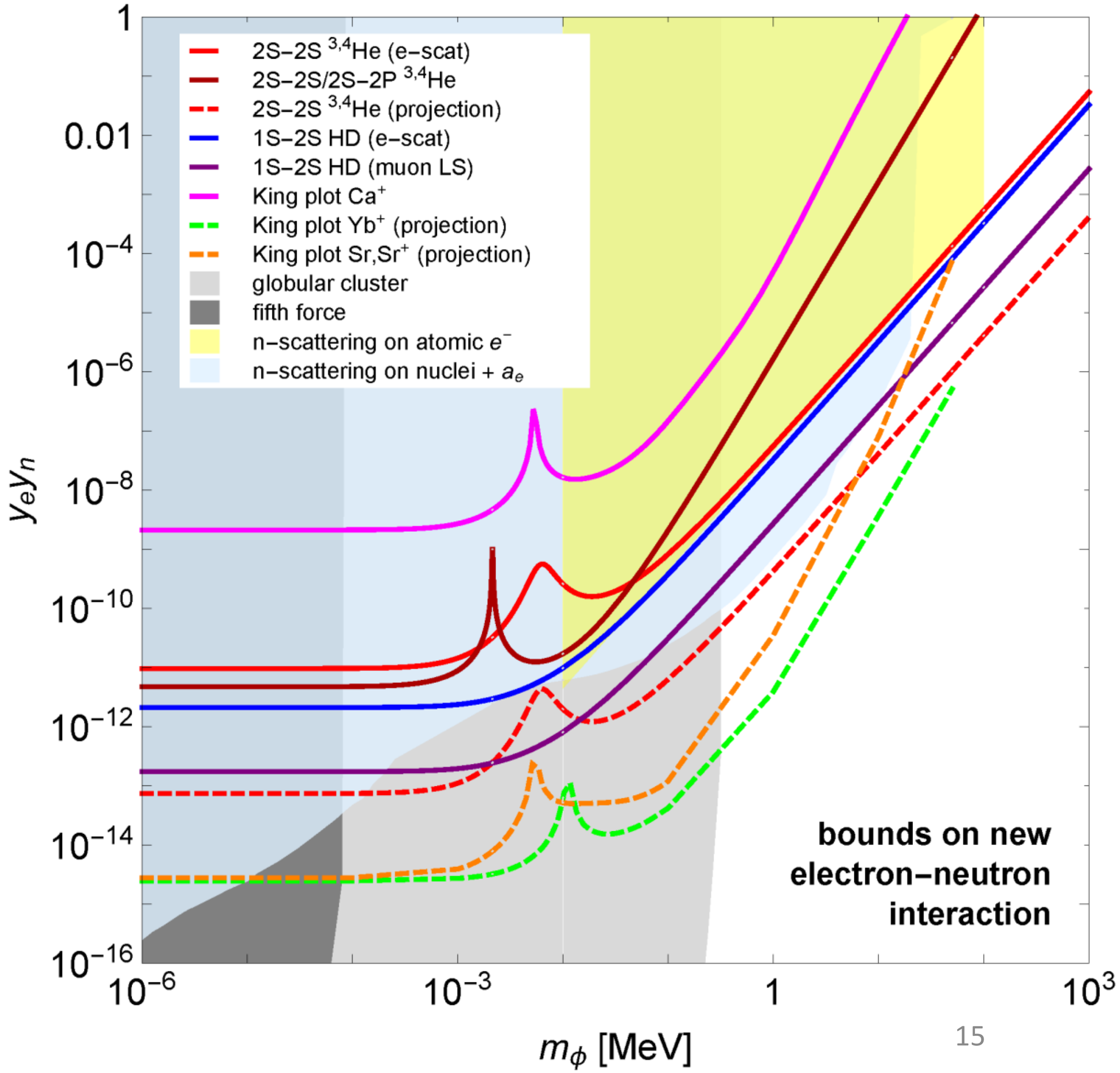
- KLV is sensitive to new spin-independent interactions between electron and neutron (e-proton and e-e cancels out in the IS)
- For illustration we take a new boson ϕ with y_e and y_n couplings
- ϕ-exchange in the atom gives rise to a new force described by the non-relativistic Yukawa potential:

$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_n (A - Z) \frac{\exp(-m_\phi r)}{r}$$

$$\alpha_{\mathrm{NP}} \qquad\qquad \gamma_{AA'} = A - A'$$

Bounds/Projections

- NP bound from linear Ca$^+$ data is not competitive with other laboratory constraints from He, $(g\text{-}2)_e$ or neutron scattering
- Linear King plots in Yb or Sr transitions with state-of-the-art accuracy (~Hz) would provide strongest bound in the 100keV-20MeV range



Going beyond King linearity

Limitations

- The KL bound is set only by the precision of IS measurements
- There are two important limitations to this method
  - Nuclear mass uncertainty

Linearity is defined in terms of modified IS $m\nu_i = \nu_i/\mu$ which requires precise knowledge of nuclear masses

$$u_{m\nu}^2 = u_\nu^2 + \left[\underbrace{\frac{m_A}{m_A - m_{A'}}}_{\sim 100}\right]^2 u_m^2$$

For Yb $\frac{m}{\delta m} u_m \sim \mathcal{O}(10^{-8})$ while $u_\nu \sim \mathcal{O}(10^{-9})$ for Hz accuracy

Limitations

- The KL bound is set only by the precision of IS measurements

- There are two important limitations to this method:
  - Nonlinearities from nuclear effects

Linearity is broken by higher-order corrections

$$\nu_i^{AA'} = \boxed{K_i^{AA'}} \mu_{AA'} + \boxed{F_i^{AA'}} \delta\langle r^2\rangle_{AA'}$$

isotope dependent

For Yb case, quadratic FS is dominant with NL~10kHz

Flambaum et al. (2017)
first-time calculation of NLs

‘Massless’ King Linearity

- An alternative to better mass determination is to generalize the King relation by adding an extra transition to absorb the mass
- In the absence of NP there is a linear relation among $\nu_{1,2,3}$ that can be tested with spectroscopy only

$$\nu_3^{AA'} = f_{3\alpha}\nu_\alpha^{AA'} + \alpha_{\mathrm{NP}}\left[X_3 - f_{3\alpha}X_\alpha\right]\gamma_{AA'} \qquad \alpha = 1,2$$

with $f_{3\alpha} = f_{3\alpha}(K, F)$

- As before NP breaks this relation
- The NP coupling can be extracted with 3 isotope pairs:

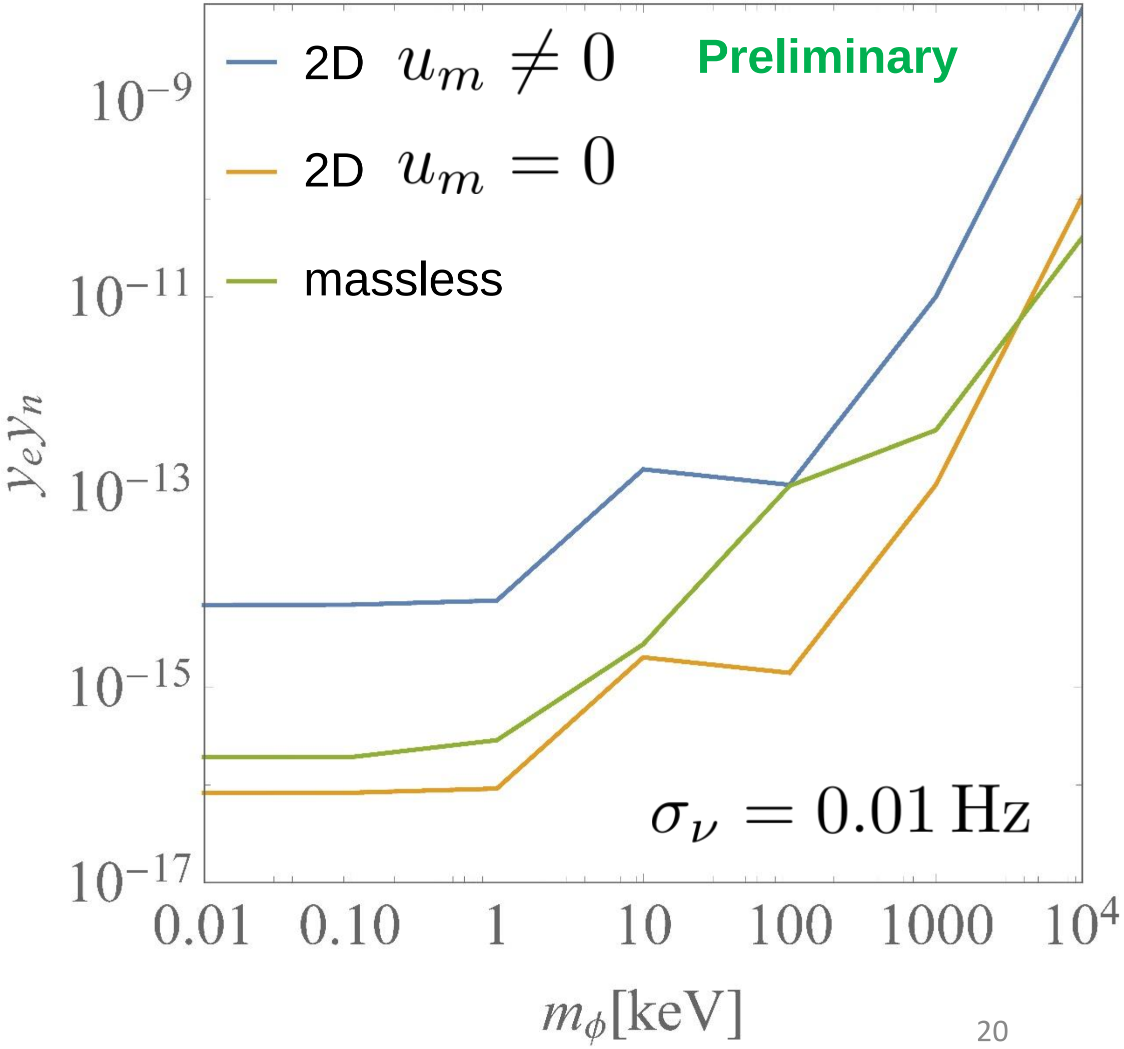
$$\alpha_{\mathrm{NP}} = \frac{\det(\vec{\nu}_1,\vec{\nu}_2,\vec{\nu}_3)}{\frac{1}{2}\epsilon_{ijk}\det(\vec{\nu}_i,\vec{\nu}_j,X_k\vec{\gamma})} = \det(F,K,X)\times\det(\delta\langle\vec{r^2}\rangle,\vec{\mu},\vec{\gamma})$$

Massless linearity in Yb

- Using known narrow transitions, assuming 10mHz accuracy:

  1) $(4f^{14}\ 6s)\ ^2\mathbf{S}_{1/2} \longrightarrow (4f^{14}\ 5d)\ ^2\mathbf{D}_{5/2}$
  2) $(4f^{14}\ 6s)\ ^2\mathbf{S}_{1/2} \longrightarrow (4f^{13}\ 6s^2)\ ^2\mathbf{F}_{7/2}$
  3) $(4f^{14}\ 6s^2)\ ^1\mathbf{S}_0 \longrightarrow (4f^{14}\ 6s6p)\ ^3\mathbf{P}_0$

- Sensitivity to NP is recovered w/out precise mass determination



Overcoming Nonlinearities

- NP can still be probed *without* theory calculation of NLs
- The idea is to use extra transitions (and isotopes) to absorb the nuclear parameters sourcing the nonlinearities

- Consider one higher-order correction dominates (like FS^2):

(generalization to any number of independent nuclear parameters is straightforward)

$$\nu_i^{AA'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + G_i\lambda_{AA'}$$

- Modified IS of 3 transitions are linearly related:

$$m\nu_3^{AA'} = f_{3\alpha}m\nu_\alpha^{AA'} + [K_3 - f_{3\alpha}K_\alpha] \qquad \alpha = 1,2$$

Generalized King Plots

- mIS data for 4 isotope pairs are on a plane

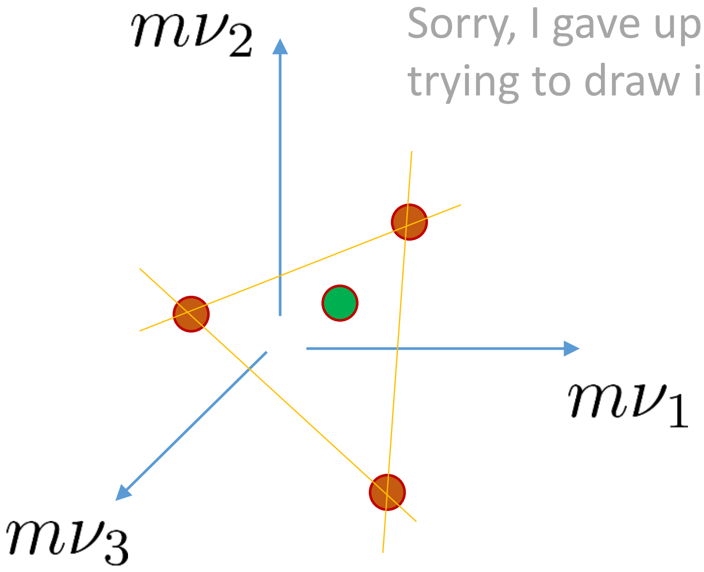
  → *King coplanarity*

- Again NP breaks this prediction

$$m\nu_3^{AA'} = f_{3\alpha} m\nu_\alpha^{AA'} + [K_3 - f_{3\alpha} K_\alpha] + \alpha_{\mathrm{NP}} [X_3 - f_{3\alpha} X_\alpha] h_{AA'}$$

- Invariant measure of breaking is the volume of the pyramid

$$\mathrm{NL}_3 = \det(m\vec{\nu}_1, m\vec{\nu}_2, m\vec{\nu}_3, m\vec{\mu})$$



Sorry, I gave up trying to draw it 3D

NP coupling

- The NP coupling can be extracted using only spectroscopy, without knowledge of $K, F, \delta\langle r^2\rangle$ and G, λ:

volume in data

$$\alpha_{\mathrm{NP}} = \frac{\det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\nu}_3, \vec{m\mu})}{\frac{1}{2}\epsilon_{ijk}\det(\vec{m\nu}_i, \vec{m\nu}_j, X_k\vec{h}, \vec{m\mu})}$$

volume predicted by theory

$$= \epsilon_{ijk}F_iG_jX_k \times \det(\vec{m\delta\langle r^2\rangle}, \vec{m\lambda}, \vec{h}, \vec{m\mu})$$

Electronic alignment

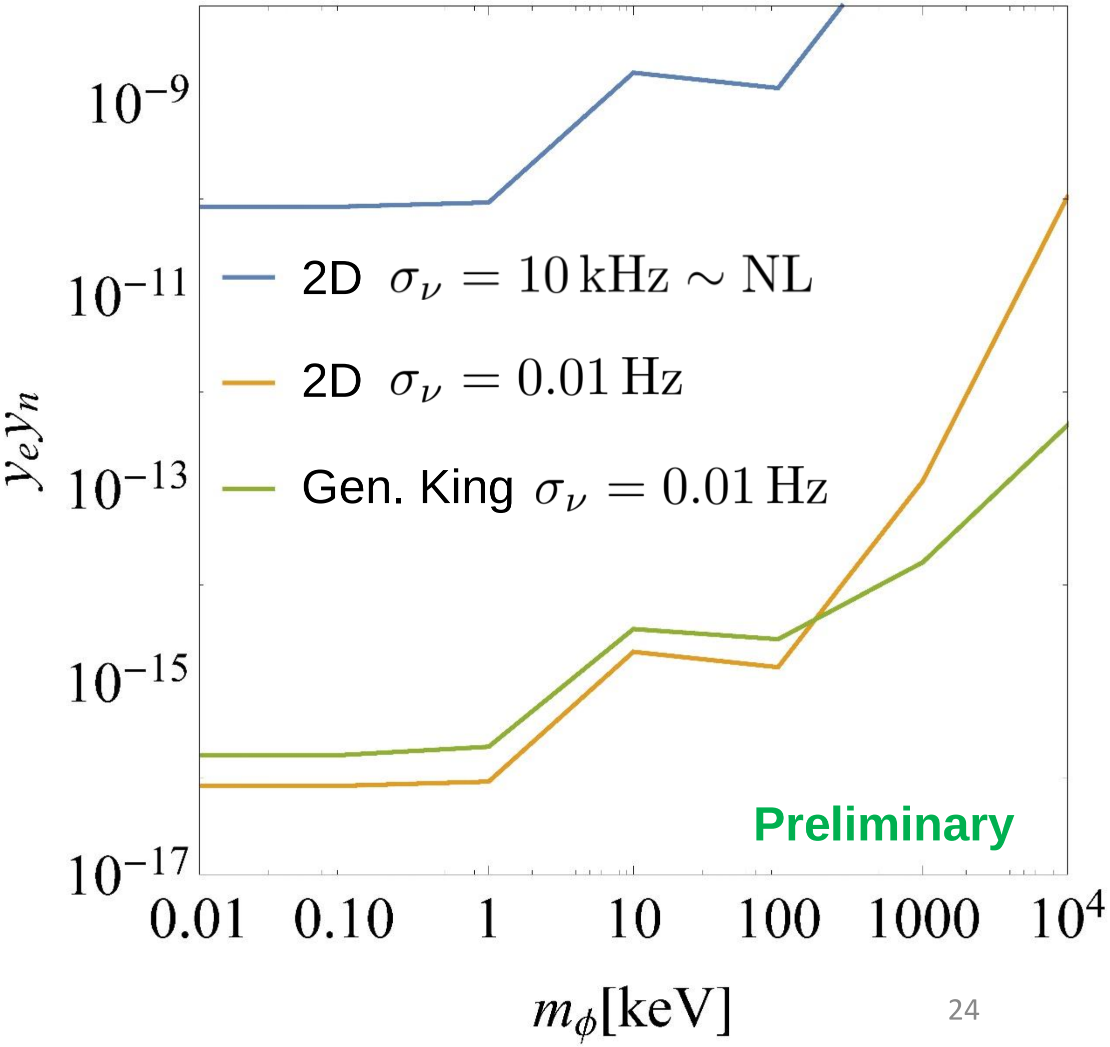
Nuclear alignment

Generalized King in Yb

- Using known narrow transitions, $A = 168, 170, 172, 174, 176$ isotopes, assuming 10mHz accuracy:

1) (4f^{14} 6s) **^{2}S$_{1/2}$** $\longrightarrow$ (4f^{14} 5d) **^{2}D$_{5/2}$**
2) (4f^{14} 6s) **^{2}S$_{1/2}$** $\longrightarrow$ (4f^{13} 6s^2) **^{2}F$_{7/2}$**
3) (4f^{14} 6s^2) **^{1}S$_0$** $\longrightarrow$ (4f^{14} 6s6p) **^{3}P$_0$**

- Sensitivity to NP is recovered without calculating NLs



Summary

Take Home

- Atomic clock transitions are measured with ultra high precision
- Theory calculations are very challenging, with only rough results

- High sensitivity to new forces below ~GeV can still be achieved by combining different measurements (isotope shifts)

- The simplest probe of NP looks for violation of linearity between IS of 2 transitions drawn on a so-called King plot.

- This method is (will soon be) limited by mass uncertainties and/or nonlinearities from nuclear physics

- We propose generalizations entirely based on spectroscopy