Isotope Shifts to Search for New Light Bosons

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Phys. Rev. D 96, 093001 (2017) w/ Ozeri, Perez, Soreq
Phys. Rev. Lett. ***120****, 091801 (2018)* w/ Berengut, Budker, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq
Phys.Rev.Res. 2, 043444 (2020) w/ Berengut, Geddes, Soreq

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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, for m~[eV,MeV] the atom is the natural place to search for it

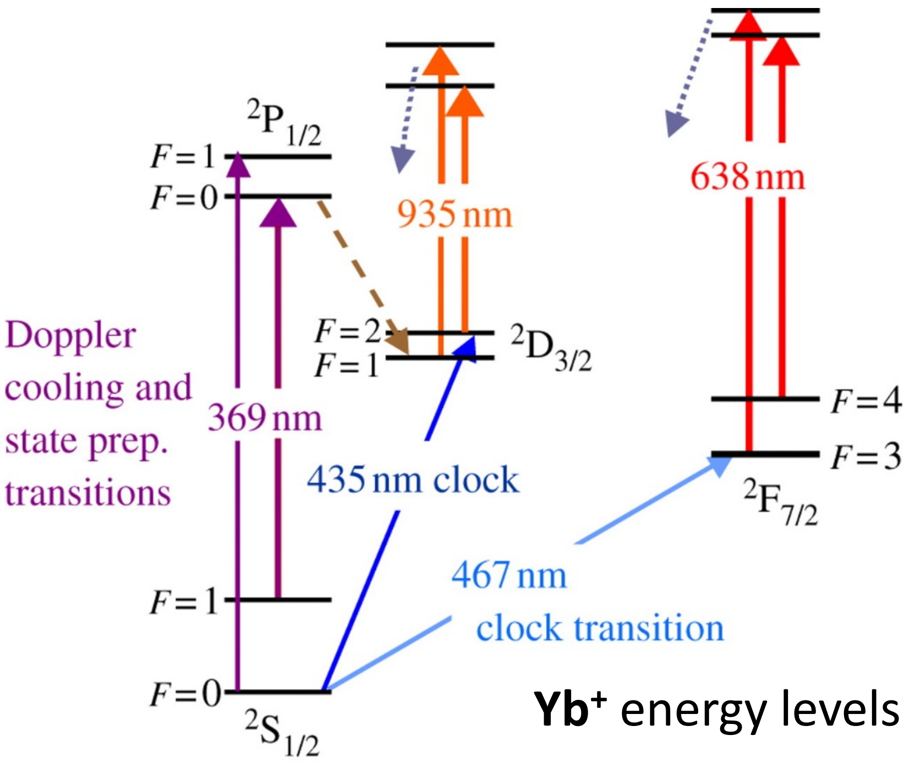
The Precision Atomic Frontier

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

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

$$u_\nu = 3.9 \times 10^{-16}$$

Huntermann et al. (2014)

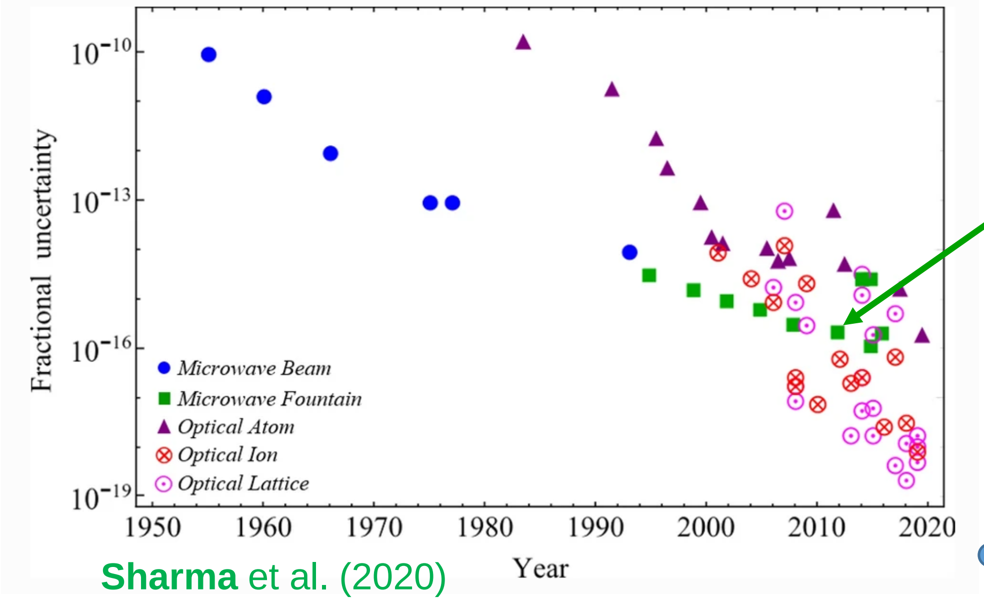


Yb^+ energy levels

The Precision Atomic Frontier

- Precision on frequencies is not limited by technology, but by our definition of the second from the Cesium clock:

$$1\,\mathrm{Hz}^{-1} = 1\,\mathrm{second} = 9\,192\,631\,770$$ oscillations between the 2 hyperfine levels of the Cs 133 ground state.



Sharma et al. (2020)

Fractional uncertainty in Yb atom demonstrated at the 10^{-18} level

Huntermann et al. (2016)

Present record at 7.6×10^{-21} with lattice clock of 100 000 Sr atoms

Bothwell et al. (2022)

Why isotope shifts?

- Atomic lines are well measured, but theory is not accurate (~1%)

- Frenquencies are set by the charge of the nucleus ***Z***
- Hence dominant 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

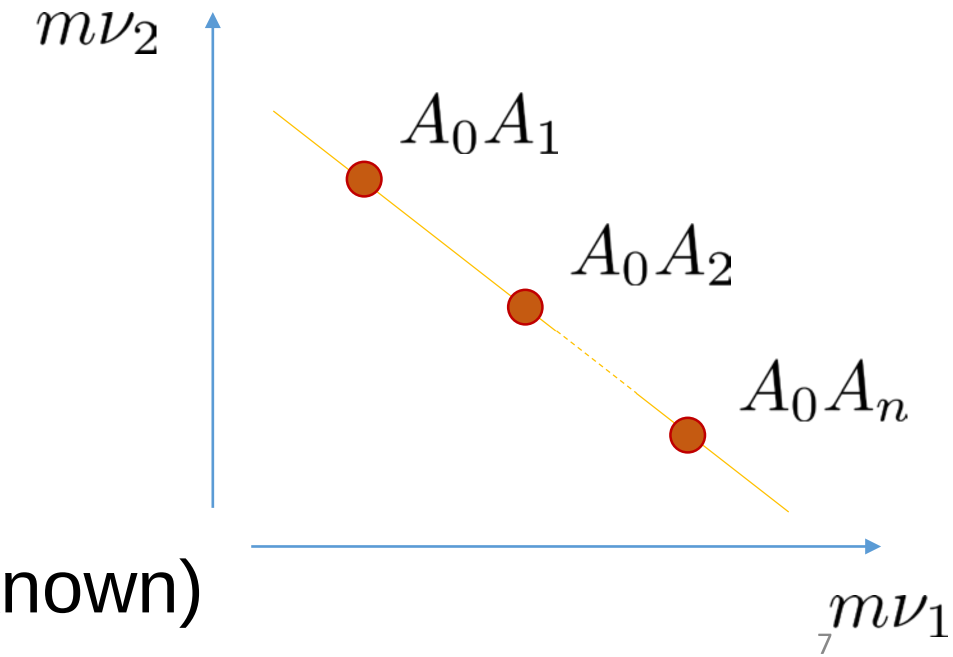
King Linearity

King (1963)

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

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

$$F_{21} \equiv F_2/F_1 \qquad K_{21} \equiv K_2 - F_{21}K_1$$



- Linearity follows from having only 2 independent nuclear parameters

- $K, F, \delta\langle r^2\rangle$ are not needed to test it experimentally (only masses must be known)

New Physics breaks linearity

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

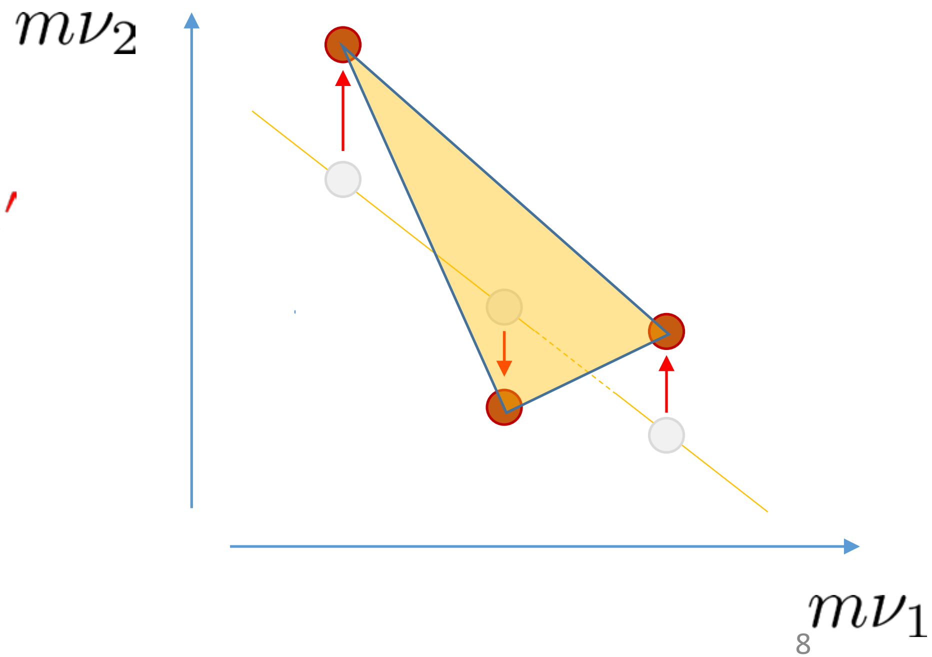
$$\nu_i^{AA'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + \alpha_{\rm NP} X_i \gamma_{AA'}$$

thus inducing nonlinearities (NL):

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

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

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



Bounding NP

- Solving King equation for the NP coupling gives:

NL in data

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

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 $m_{\rm NP}$: $X_i \propto F_i$

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

New Yukawa-like force

- KL is sensitive to new spin-independent interaction between electron and neutron (e-p and e-e cancel out in the IS)

- Consider a new boson ϕ with y_e and y_n couplings

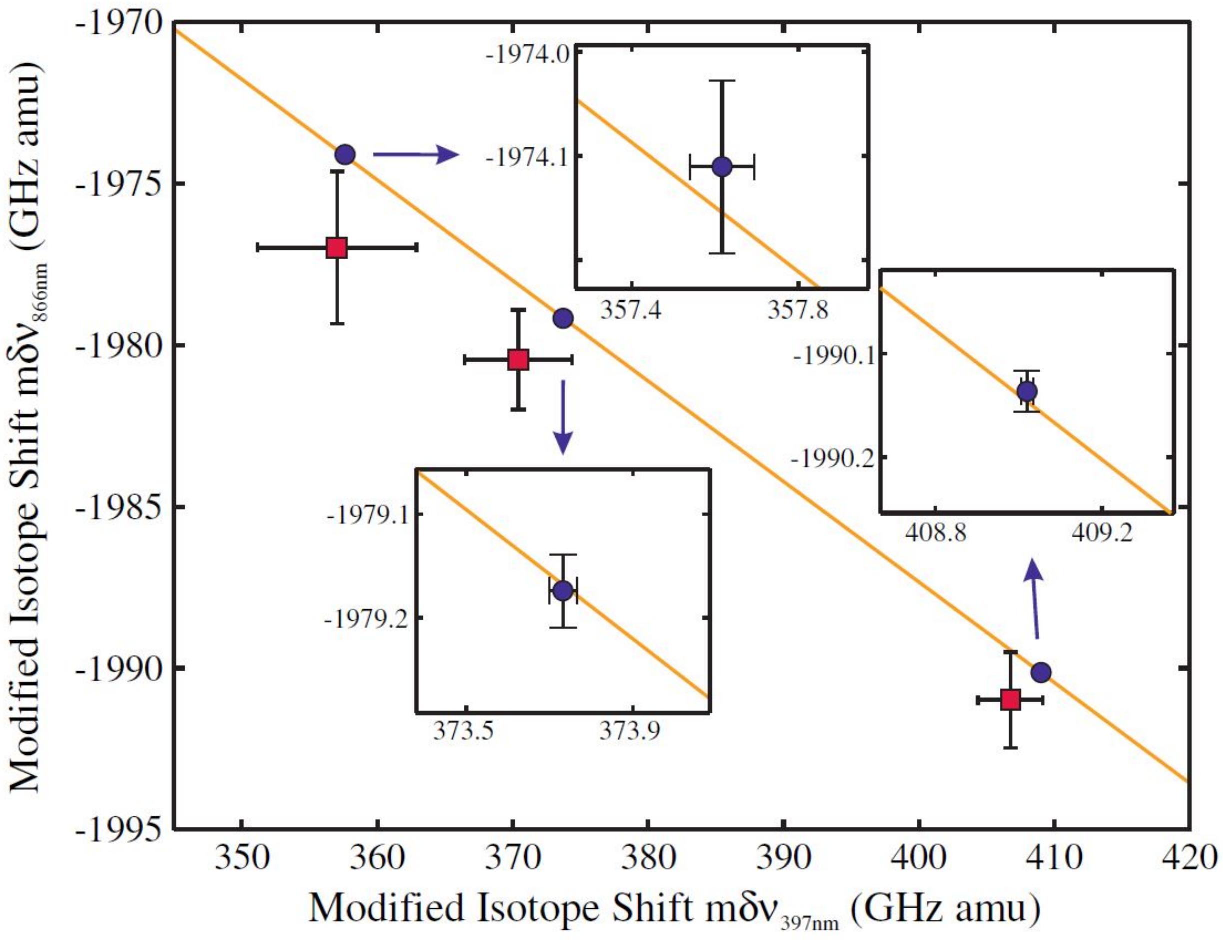
- ϕ-exchange in the atom gives rise to a new force described by the non-relativistic Yukawa potential:

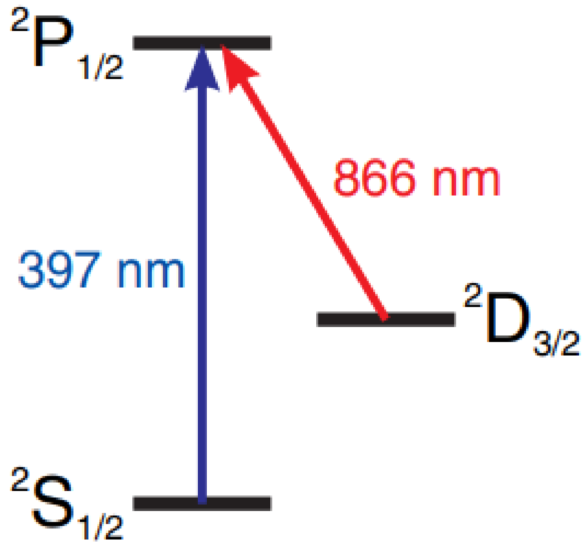
$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_n (A - Z) \frac{\exp(-m_\phi r)}{r}$$

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

Ca+ Example

Gebert-Wan-Wolf-Angstmann-Berengut-Schmidt | Phys. Rev. Lett. **115**, 053003 (2015)

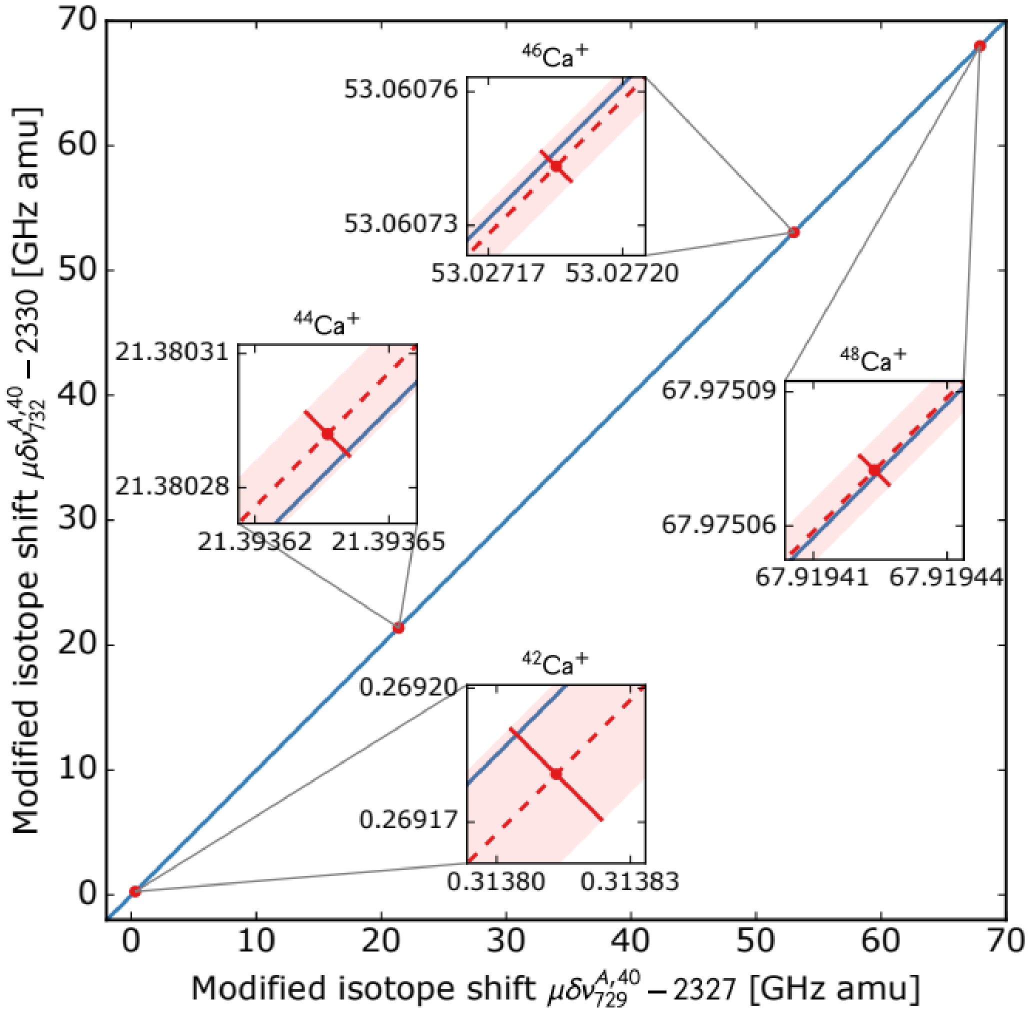


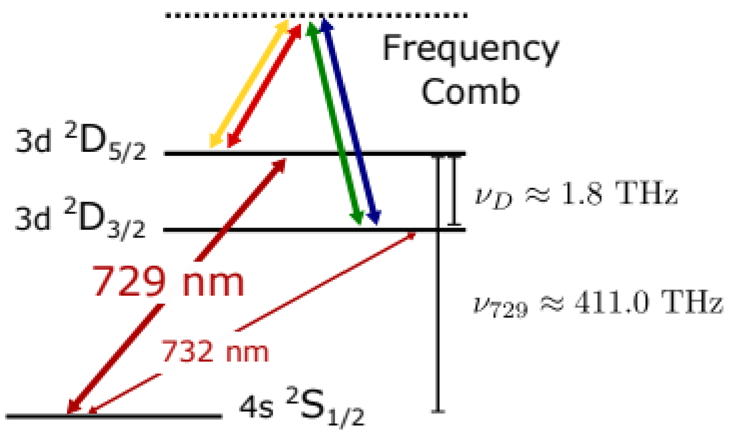


based on broad transitions
precision ~ 100kHz ~ IS/10^4

Recent Ca+ results

Solaro-Meyer-Fisher-Berengut-Fuchs-Drewsen | Phys. Rev. Lett. **115**, 123003 (2020)

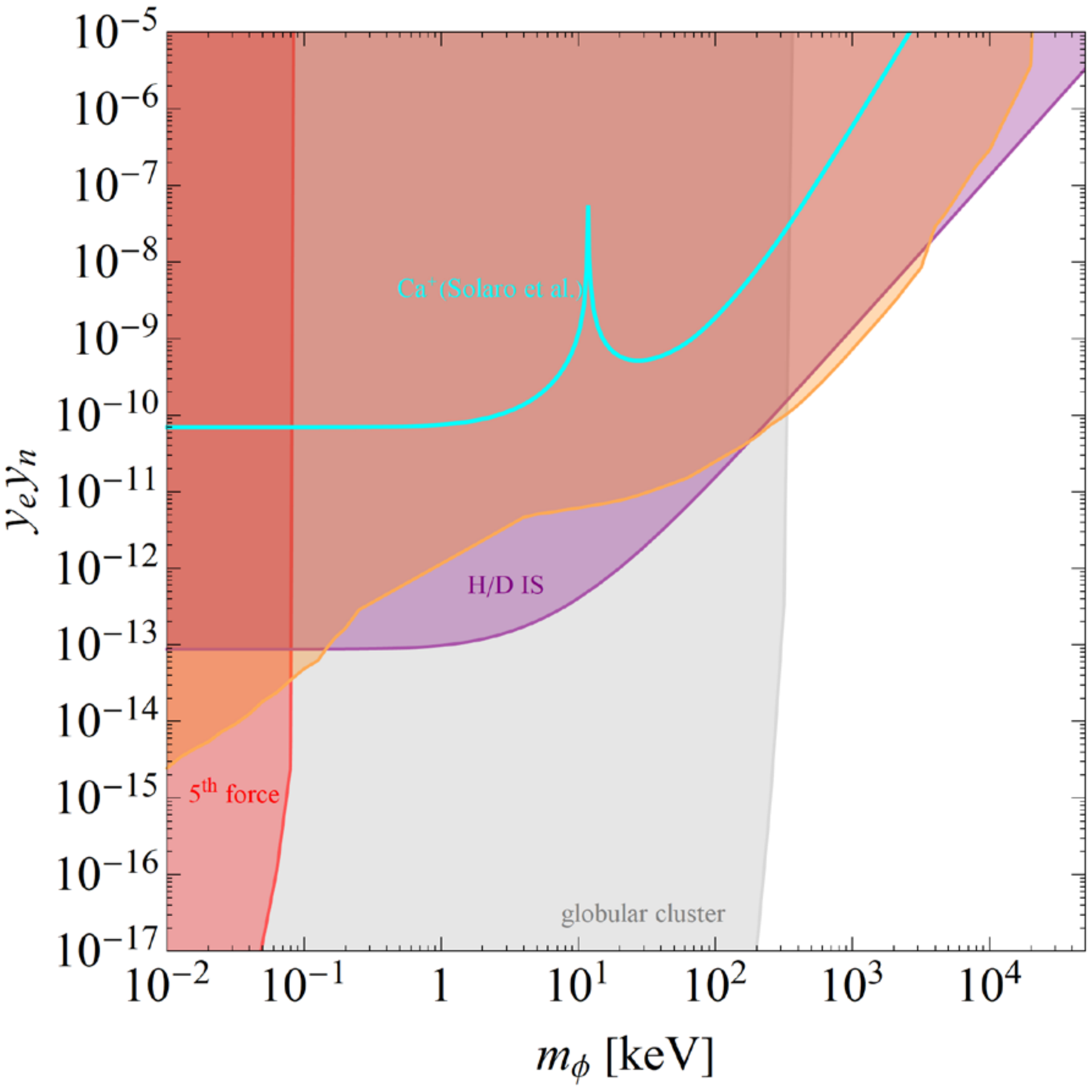




narrower transitions
~ 20Hz accuracy (from DtoD)

consistent with linearity
within uncertainties

NP bound from Ca+



Resulting bound is weaker than

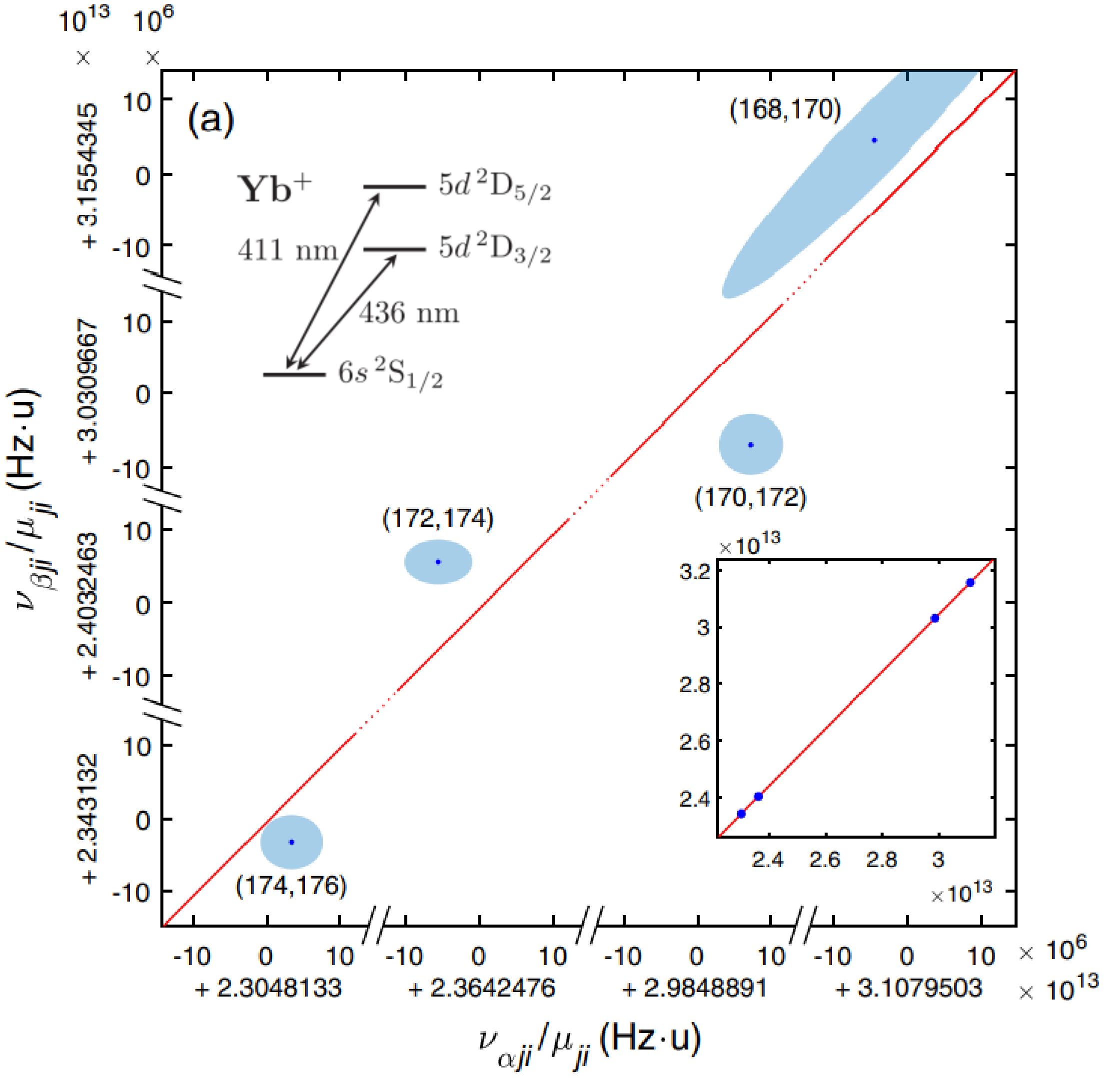
1) Hydrogen-Deuterium IS from a direct comparison between theory and measurements (purple)

CD-Frugiuele-Fuchs-Soreq (2017)

2) combination of bounds from **electron g-2** and **nuclear scattering** (orange)

Nonlinear Yb+ results

Counts-Hur-Aude Craik-Jeon-Leung-Berengut-Geddes-Kawasaki-Jhe-Vuletic | Phys. Rev. Lett. **125**, 123002 (2020)



narrow quadrupole transitions
precision ~ 300Hz

nonlinearities observed at 3σ