BSM in direct, indirect and tabletop experiments
Weizmann Institute of Science
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Probing BSM physics with isotope shifts

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CNRS/LAPTH

FRANCE

- CD, Soreq, in progress
- CD, Frugiuele, Fuchs, Soreq, PRD (2017)
- Berengut, Budker, CD, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq, hep-ph/1704.05068
- CD, Ozeri, Perez, Soreq, PRD 96 (2017) 093001

Why BSM at low energies?

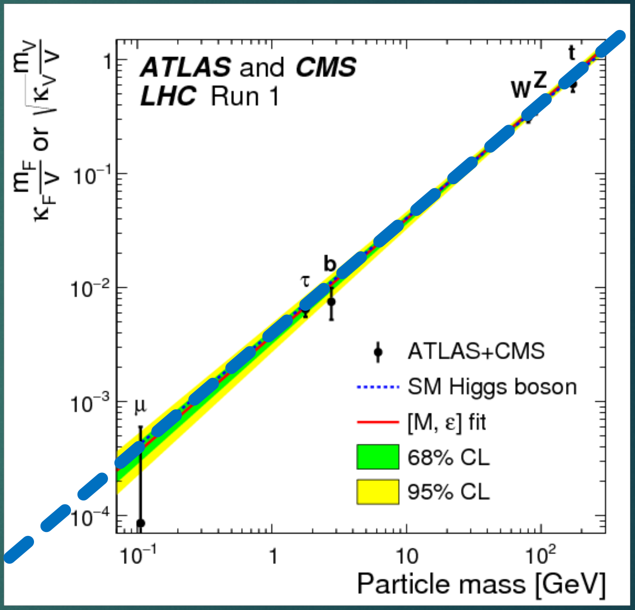
- Agnostic: why not?
- SM hierarchy problems:
  - Strong CP → light axion particle: $m_a \sim 10^{-6}\,\mathrm{eV}$
    actively searched through $\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
  - Higgs mass: $\mu^2 H^\dagger H$ with $\mu^2 \sim \Lambda^2$ at quantum level
    which (used to?) motivate BSM at $\Lambda \sim \mathrm{TeV}$.
    Yet there is a (first?) counter-example: relaxion
- New physics could show up at **any** scale!

  time to join efforts at high and low energy frontiers

Original motive: Higgs

- Higgs boson was discovered. Yet little is known about its couplings to fermions; SM predicts $y_f = m_f / v$.

- High-energy colliders tell us about heavy fermions: t,b,τ,μ (c?)

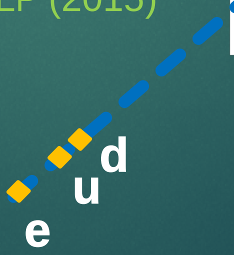


- Lighter u,d,s,e fermions are very challenging!

$y_{u,d,s} < y_b$ **Perez**+ PRD (2016)

$y_e < 3y_\mu$ **Altmannshofer**+ JHEP (2015)

- Maybe atomic probes are better?



Precision spectroscopy

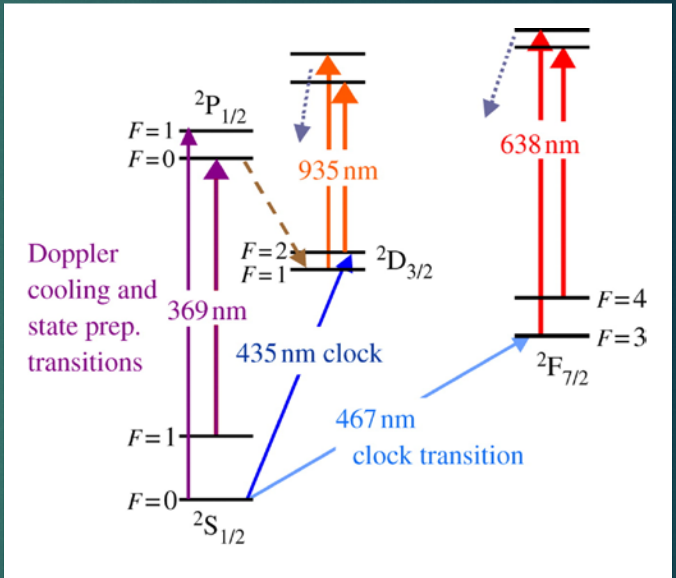
- **Impressive precision measurements: relative error ~ 10^{-16}**

***eg.* Ytterbium ion**

Godun+ PRL (2014)
Huntermann+ PRL (2014)

$$\nu_{E3} = 642\,121\,496\,772\,645.36(25)\ \mathrm{Hz}$$

(shift from Earth's gravity pull $-0.046\ \mathrm{Hz}$ **)**



- **Improvement expected with sharper standard of time:**

E3 is stable at ~ 10^{-18} level **Huntermann**+ PRL (2016)

Towards BSM probes

- In principle sensitive to BSM effects as small as QED/10^{16}
- However probing BSM further requires either:
  - Precise QED calculation – only available for atoms/ions with 1,2 (maybe 3) electrons: H, He…
  - Combining measurements and reduce sensitivity to uncertain quantities from theory: isotope shifts, King linearity

BSM atomic potential

- Consider a new boson ϕ with P-conserving couplings to electron and nucleons:

mediator spin

mediator mass

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

electronic coupling

nuclear coupling

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

Isotope shift

- QED effects cancel between isotopes ***A***, ***A'*** up to:

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

mass shift (MS) **field shift (FS)**

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

- **For odd A, there are also nuclear spin effects**
- **BSM effects mildly suppressed by (A-A')/A~0.1:**

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

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

- **K,F,X are electronic constant, independent of A at LO**

Isotope shifts in Helium

- Helium 3,4 IS theory calculations (for point nuclei) are known better than experimental error: **Pachucki**+ PRA (2017)

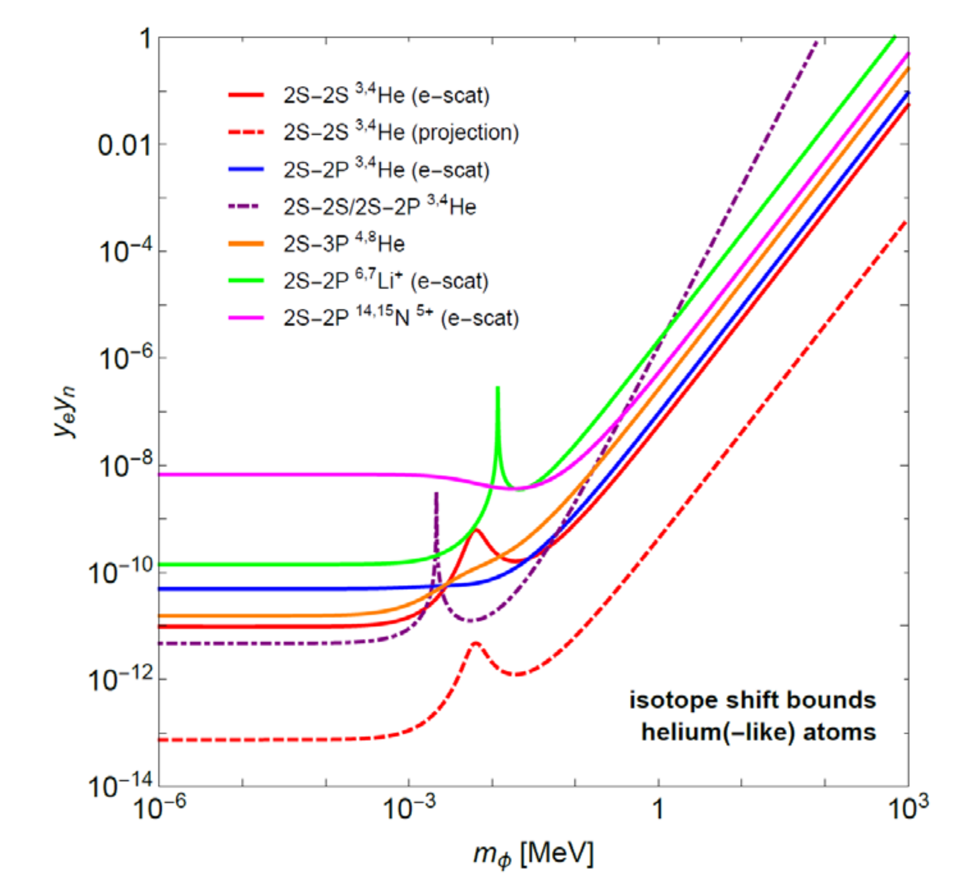
- Nuclear radii are known from scattering:

$$\delta\langle r^2\rangle_{3,4} = 1.067(65)$$

- Combining 2 transitions to eliminate $\delta\langle r^2\rangle$ helps

- Expected improvement by a factor ~100 with $\mu\mathrm{He}^+$ measurements

Antognini+ Can. J. Phys. (2011)



Isotope shifts in HD

- Despite proton radius puzzle, electronic and muonic values of $\delta\langle r^2\rangle_{\mathrm{HD}}$ are consistent.
- From muonic Lamb shifts:

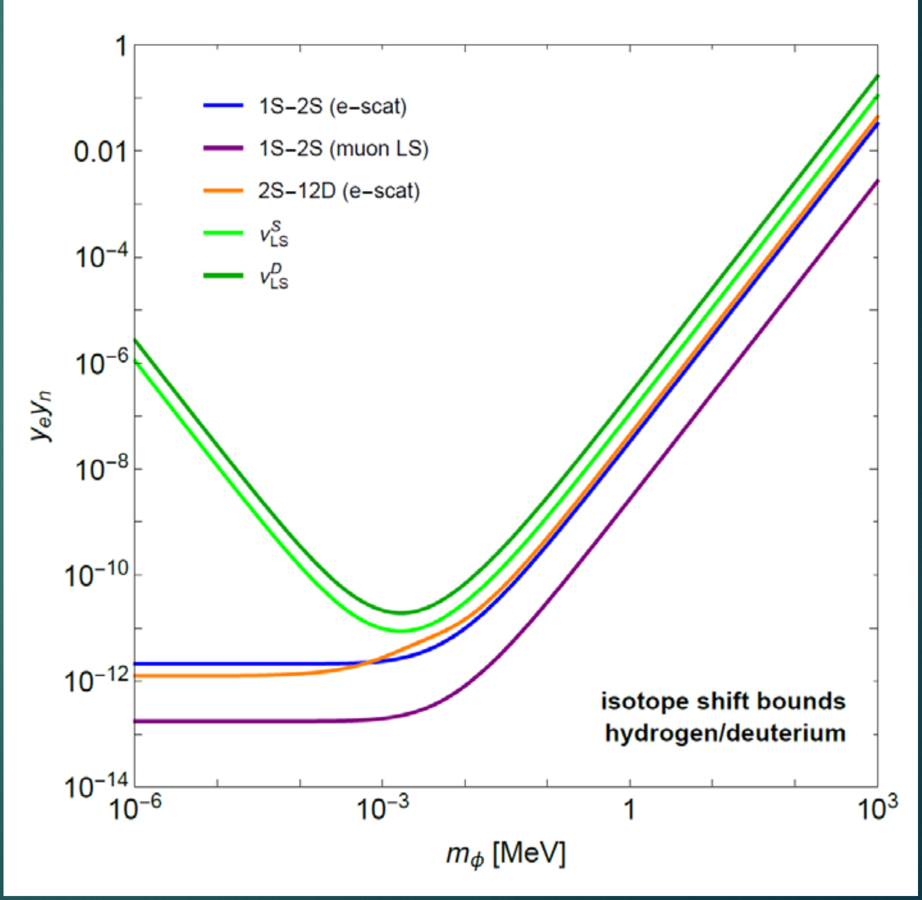
$$\delta\langle r^2\rangle_{\mu\mathrm{HD}} = 3.8112(34)$$

Pohl+ Nature (2010), **Antognini**+ Science (2013)
Pohl+ Science (2016)

- Theory error dominates, limited by m_e/m_D, nuc.pol.

Parthey+ PRL (2010)

- HD sensitivity comparable to Helium



Heavy atoms?

- In atoms with many electrons e-e correlation effects are not predictable from theory to sufficient accuracy
  $\rightarrow$ direct TH/EXP comparison not possible…

- Is there any observable sensitive to BSM *and* limited only by experimental uncertainty?
  $\rightarrow$ King linearity

  King J. Opt. Soc. Am. (1963)

- Basic idea = combine IS measurements in 2 transitions with many (at least 4) isotopes

King linearity

- In the limit that electronic and nuclear parameters are **factorized** as $\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2\rangle_{AA'}$ there is a linear relation between IS in 2 transitions.

- Defining « modified IS » as $m\nu_i^{AA'} \equiv \mu_{AA'}^{-1} \nu_i^{AA'}$, one finds:

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

slope = F_2/F_1

offset = $K_2 - F_{21}K_1$

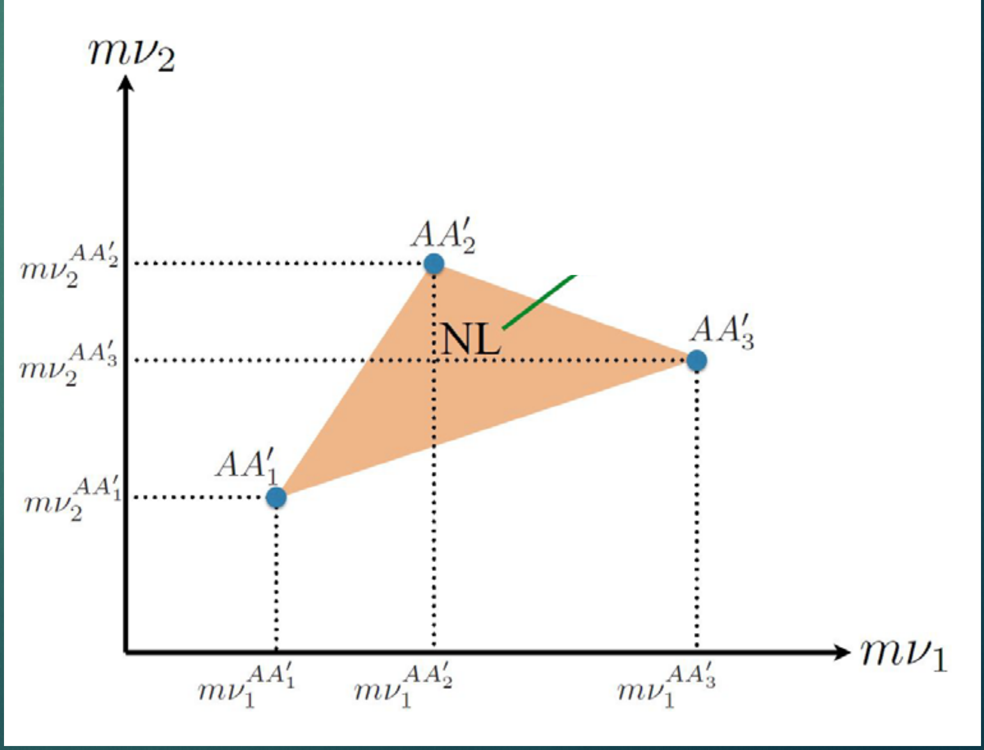
Establishing King linearity from data

- Need 3 points on King plot → 2 transitions, 4 (even) isotopes
- Invariant measure of non-linearties is the triangle area:

$$\mathrm{NL} = \frac{1}{2}\left|\overrightarrow{m\nu_1} \times \overrightarrow{m\nu_2} \cdot \vec{1}\right|$$

$$\overrightarrow{m\nu_{1,2}} \equiv \left(m\nu_{1,2}^{AA'_1}, m\nu_{1,2}^{AA'_2}, m\nu_{1,2}^{AA'_3}\right)$$

$$\vec{1} \equiv (1,1,1)$$



- If $\mathrm{NL} \lesssim \sigma_{\mathrm{NL}}$ then the King plot is linear

BSM effects break linearity

- In the presence of a BSM force:

$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2 \rangle_{AA'} + \alpha_{\rm NP}(A - A')X_i$$

- Combining 2 transitions to eliminate $\mu_{AA'}^{-1}, \delta\langle r^2\rangle_{AA'}$ yields:

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

$(A - A')\mu_{AA'}^{-1}$

$X_2 - F_{21} X_1$

- Non-linearites from BSM unless:
  - $X_{21} \to 0$, ie. for short-range forces
  - $h_{AA'} \propto m\nu_i^{AA'}$ or constant of AA’

Bounding BSM coupling

- **Manipulating vectors:**

$$\mathrm{NL}_{\mathrm{NP}} = \frac{\alpha_{\mathrm{NP}}}{2}(\vec{1} \times \vec{h}) \cdot (X_1 \overrightarrow{m\nu_2} - X_2 \overrightarrow{m\nu_1})$$

- **So for a given (linear) data-set $\overrightarrow{m\nu_1}, \overrightarrow{m\nu_2}$ we can bound**

$$\alpha_{\mathrm{NP}} \leq \frac{\left(\overrightarrow{m\nu_1} \times \overrightarrow{m\nu_2}\right) \cdot \vec{1}}{(\vec{1} \times \vec{h}) \cdot (X_1 \overrightarrow{m\nu_2} - X_2 \overrightarrow{m\nu_1})}$$

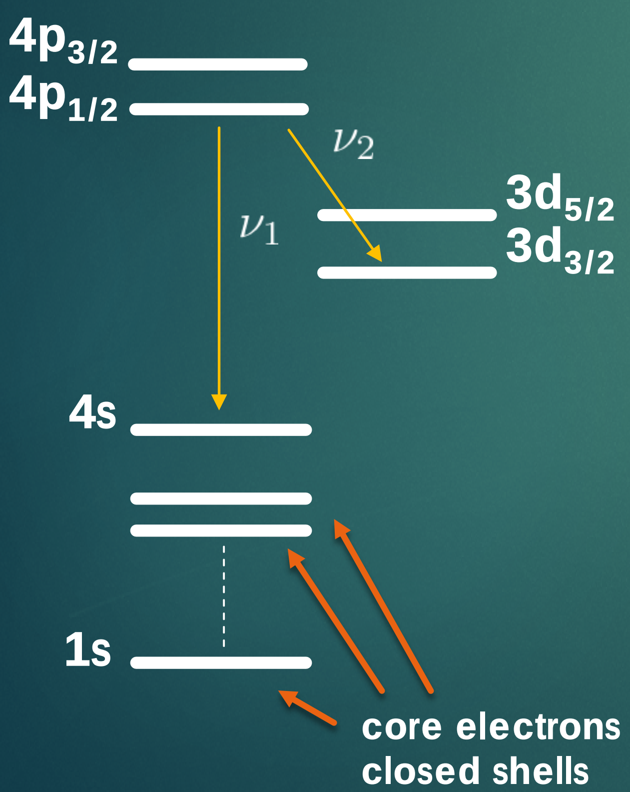
the only theoretical inputs (depend on m_ϕ) calculated using many-body perturbation theory

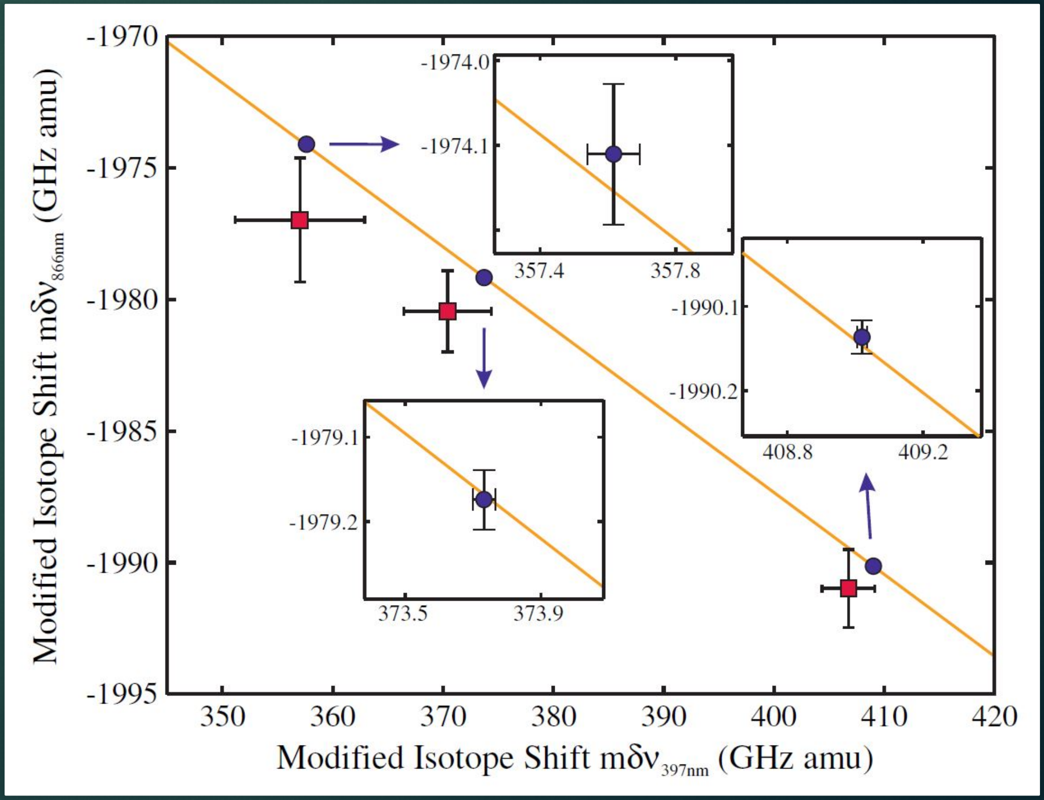
King linearity in data

- **Calcium+** A=40,42,44,48

  precision ~ 100kHz

Gebert+ PRL (2015)

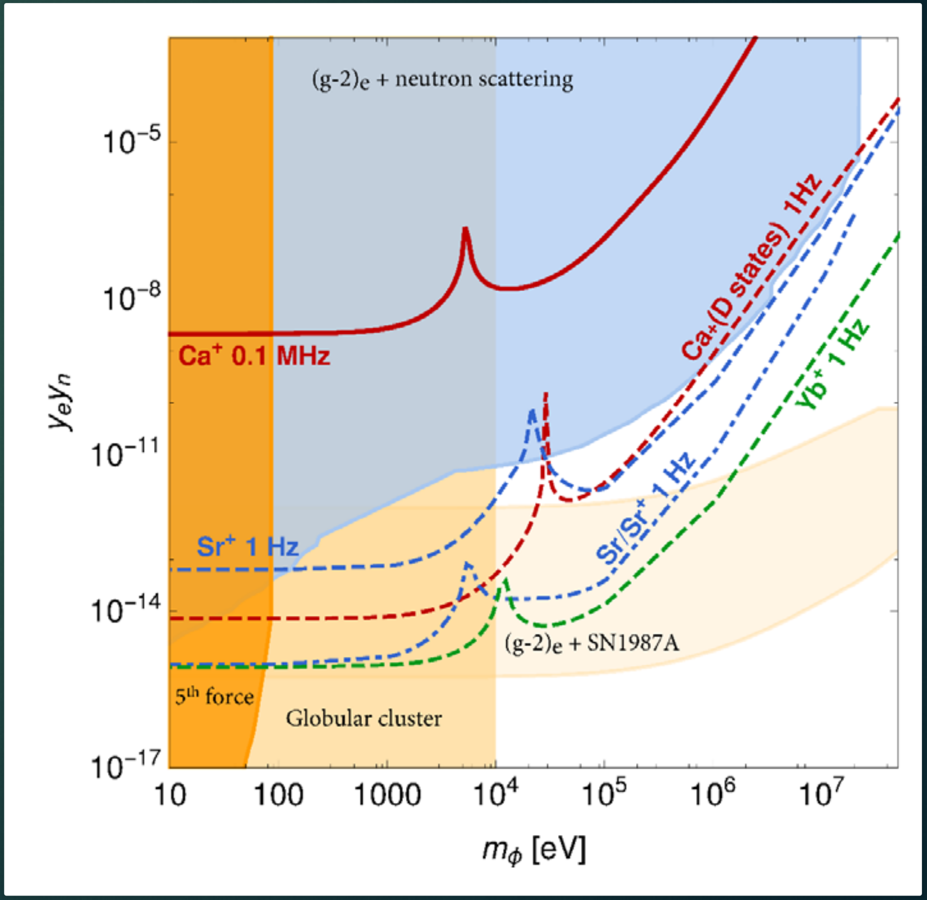




linearity tested to ~10^{-4}

Bounds and projections

- Ca+ bound weaker than constraints from other sources:
  - neutron scattering,
  - electron g-2,
  - star cooling
  - …
- Projected sensitivity of clock transitions in several elements: *eg.* Sr, Sr^+, Yb^+ with Hz accuracy could explore new territory
- Need linearity to hold upto $\sim 10^{-9}$



One King to rule them all (preliminary)

- Higher order nuclear effects also induce non-linearities:

$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2\rangle_{AA'} + \sum_{j=1}^{n-2} G_{ij} O^j_{AA'} + \alpha_{\mathrm{NP}}(A-A')X_i$$

- One can either calculate them (again hard…) or **use more measurements to remove more « spurions »**
- For n-2 spurions, need n transitions with n+1 isotope pairs.
- w/out BSM, the n IS vectors are on a plane in n+1 dimensions → King planarity
- w/ BSM IS vectors form a volume in n+1 dimensions
- For planar data,

$$\alpha_{\mathrm{NP}} \leq \frac{\epsilon_{A_1 \ldots A_{n+1}} m\nu_{1A_1} \ldots m\nu_{nA_n}}{-\epsilon_{A_1 \ldots A_{n+1}} \epsilon_{i_1 \ldots i_n} X_{i_1} h_{A_1} \ldots m\nu_{i_n, A_{n-1}} / (n-1)!}$$

Conclusion, Outlook

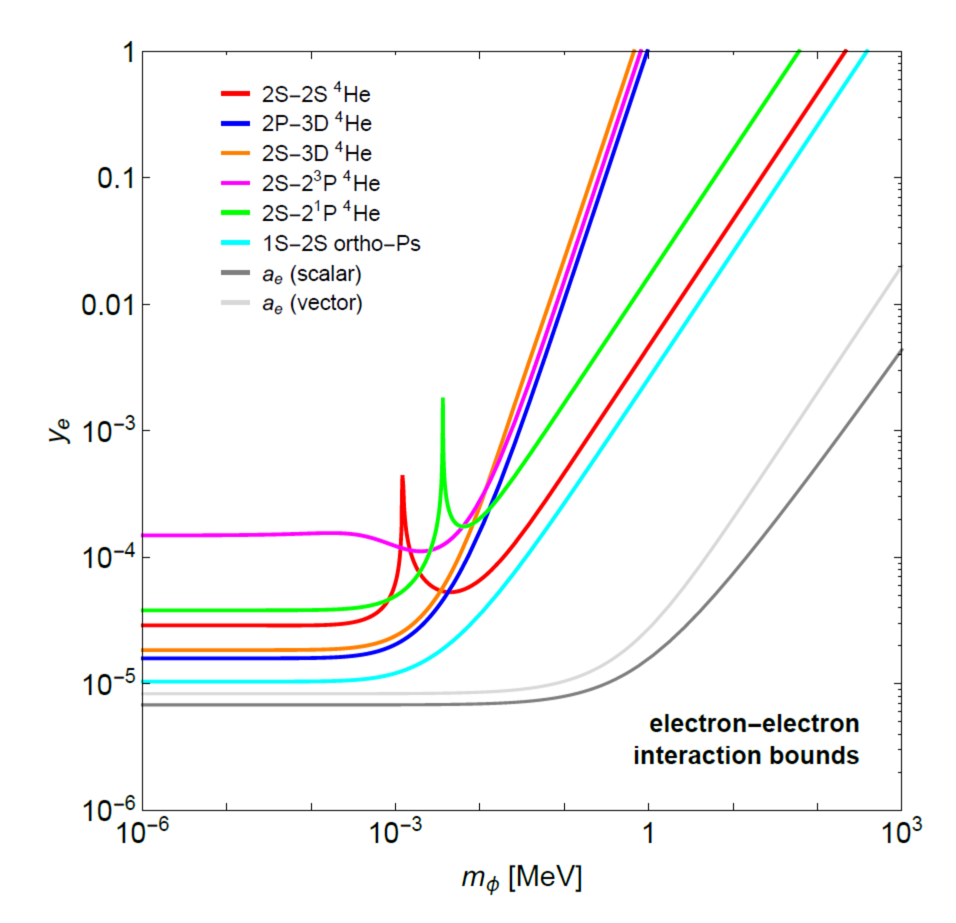
- New physics can be anywhere. Need to measure whatever is possible..

- Isotope shifts and King linearity is an effective probe only limited by experimental errors!

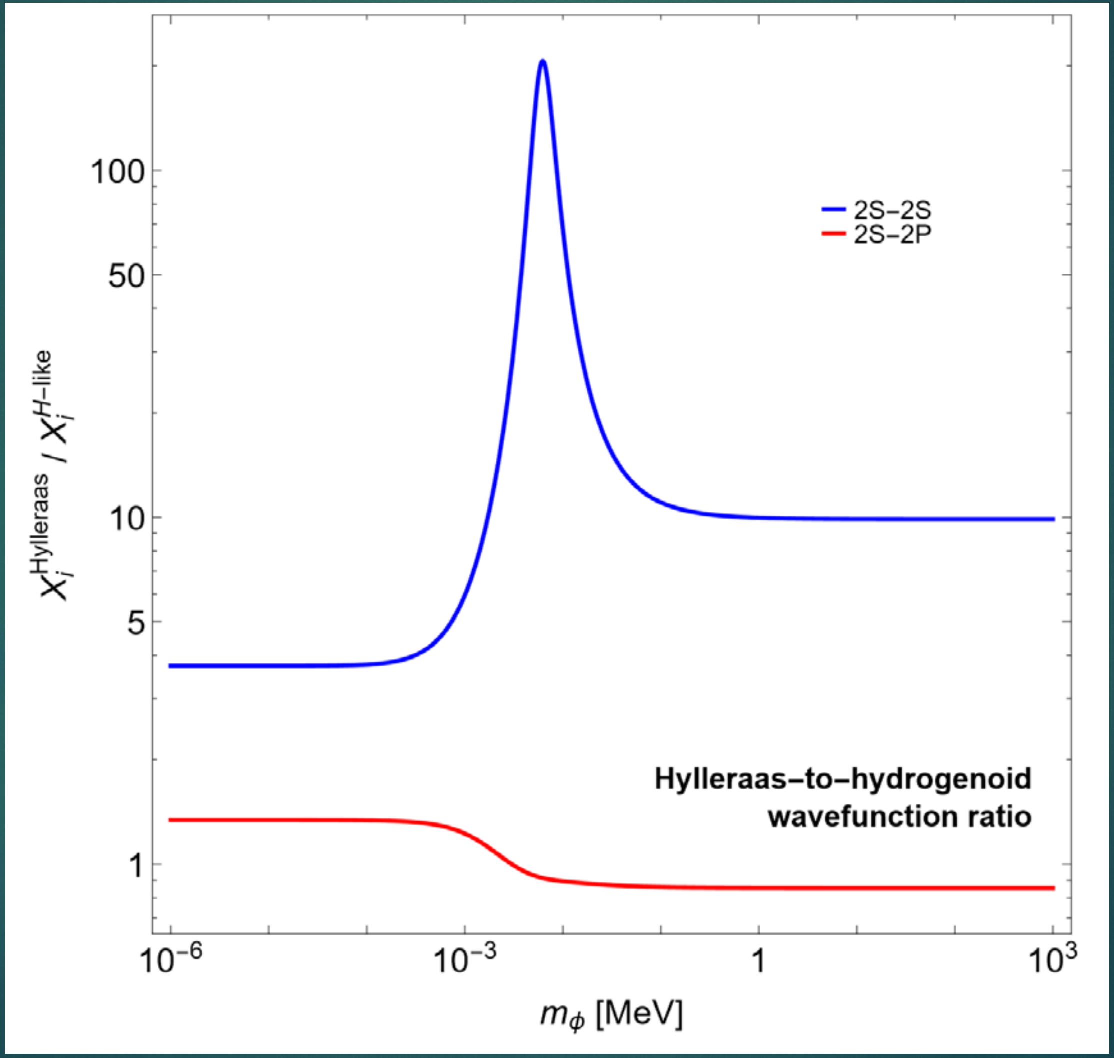
- So far focused on spin-independent forces, are there similar observables sensitive to spin-dependend forces?

Backups

Electron-electron interactions with Helium 4



Hylleraas wavefunctions



Sensitivity estimates

- Assume linearity is established within a precision Δ
- Then, factorization holds within uncertainties:

$$\overrightarrow{m\nu_i} = K_i \vec{1} + F_i \overrightarrow{\delta\langle r^2\rangle} + \overrightarrow{\Delta_i}$$

- And a best-case estimate of the resulting bound is:

$$\alpha_{\mathrm{NP}} \leq \frac{\sqrt{\Delta_1^2 + F_{21}\Delta_2^2}}{(X_2 - F_{21}X_1)(A-A')_{\max}} \times \frac{A}{(A-A')_{\min}}$$

suppression factor
for short-range forces

calculated
from MBPT
Berengut+ PRA (2006)

alignment with MS