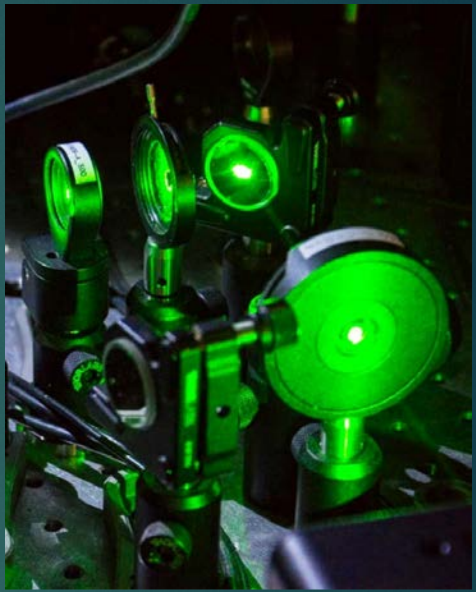
Probing BSM Physics with Atomic Spectroscopy



©NIST

CÉDRIC DELAUNAY

LAPTH | ANNECY

- CD, Frugiuele, Fuchs, Soreq, Phys.Rev. D96 (2017)
- Berengut, Budker, CD, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, Soreq, PRL 120 (2018)
- CD, Ozeri, Perez, Soreq, Phys.Rev. D96 (2017)
- CD, Soreq, in progress
- Bélanger, CD, Zaldivar, in progress

Rencontre de Physique des Particules | April 11th, 2018 | Paris

Outline

- Motivations
- Atomic forces beyond the SM
- Isotope-shift probes in heavy atoms
  – King linearity violation
- Probes in atoms with few electrons
  – hydrogen, deuterium, helium and positronium
- Implications for sub-GeV dark matter
- Conclusions

Motivation: why atoms?

HIGGS DISCOVERY = INCREASED IMPORTANCE OF THE PRECISION FRONTIER

Where is BSM physics?

- Despite many arguments to go beyond the SM, none of them *unquestionably* points to the scale where it breaks down
- Higgs mass naturalness strongly suggests TeV-scale BSM but no clear sign at the LHC (and there is the possibility of relaxion)
- New physics can be anywhere and one should look everywhere

Multiple-frontier era

Energy frontier
discover new massive particles
with few events at high energies
(take close-up pictures)

LHC

BSM Physics

Intensity frontier
find deviations
in low-energy observables
with large statistics
(increase luminosity/contrast)

LHCb
BELLE2

Precision frontier
find deviations
in low-energy observables
measured with high precision
(increase sharpness)

g-2,EDM
APV,...

\+

atomic
spectroscopy

The atomic frontier

- **Modern techniques in atomic and molecular optics (AMO) allow measurements of highest precision, *eg*. Rydberg cste** $R_\infty = \frac{1}{2}\alpha^2 m_e$

$$R_\infty = 3.289\,841\,960\,355(19) \times 10^{15}\ \mathrm{Hz}$$

$u_{R_\infty} = 5.9 \times 10^{-12}$ ***best determined constant ever!***

$(u_\alpha \sim 10^{-10}\ ,\ u_{m_e} \sim 10^{-11})$

- **Atoms already offer ultra sensitive probes of BSM physics breaking QED symmetries:**
  - **Parity violation: *eg.* Cesium** $\Lambda_{\mathrm{PV}} \gtrsim \mathrm{TeV}$
  - **CP vilation: *eg.* Mercury EDM** $\Lambda_{\mathrm{CPV}} \gtrsim 10^3\ \mathrm{TeV}$

Atomic spectroscopy

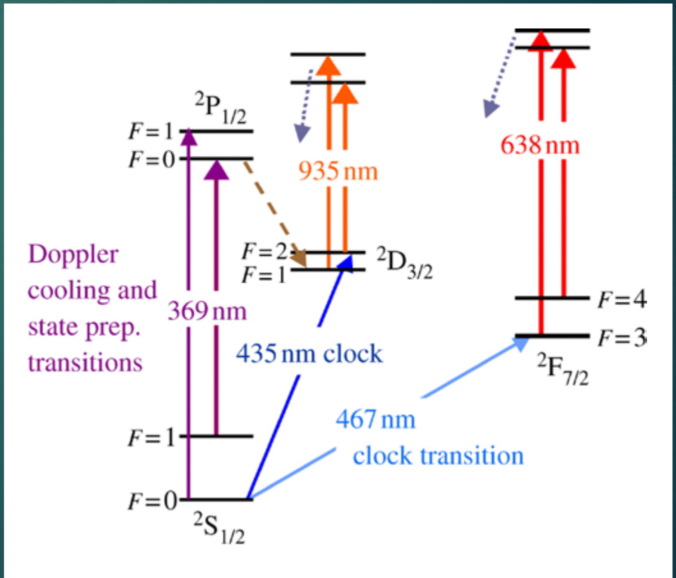
- In last 20yrs, the **frequency comb** technique allowed ultra high-precision measurements of atomic transitions in the optical range
- Narrow optical (*aka* clock) transitions are now the most accurately measured:

***eg.* Ytterbium ion**

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

$$u_{\nu_{E3}} = 3.9 \times 10^{-16}$$

Godun+ PRL 2014
Huntermann+ PRL 2014



Uncertainty recently improved:

$$u_{E3} = 3.2 \times 10^{-18}$$

Huntermann+ PRL 2016

High sensitivity to BSM

- In term of length, this is equivalent to measure the distance of the nearest stars (~10 ly) with meter precision!
- These measurements are sensitive to new forces weaker than QED by **18 orders of magnitude!!**
- It is important to understand their BSM reach and study the complementarity with other frontiers

Atomic forces beyond the SM

Atomic potentials

- Consider a new boson ϕ with P-conserving couplings to electrons and nucleons
- ϕ-exchange inside atoms yields a spin-independent (non-relativistic) potential:

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

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

Atomic potentials

- There is similar force acting on pairs of atomic electrons:

$$V_\phi^{ee}(r_{12}) = \frac{(-1)^{s+1}}{4\pi} y_e^2 \frac{e^{-m_\phi r_{12}}}{r_{12}}$$

$r_{12} = |\vec{r}_1 - \vec{r}_2|$ **is the distance between two electrons**

- Both eA and ee potentials modify the energy levels of atoms:

$$\left[-\frac{1}{2m_e}\nabla^2 + V_{\text{Coulomb}}(r) + V_\phi(r)\right]\psi_n(\mathbf{r}) = E_n\psi_n(\mathbf{r})$$

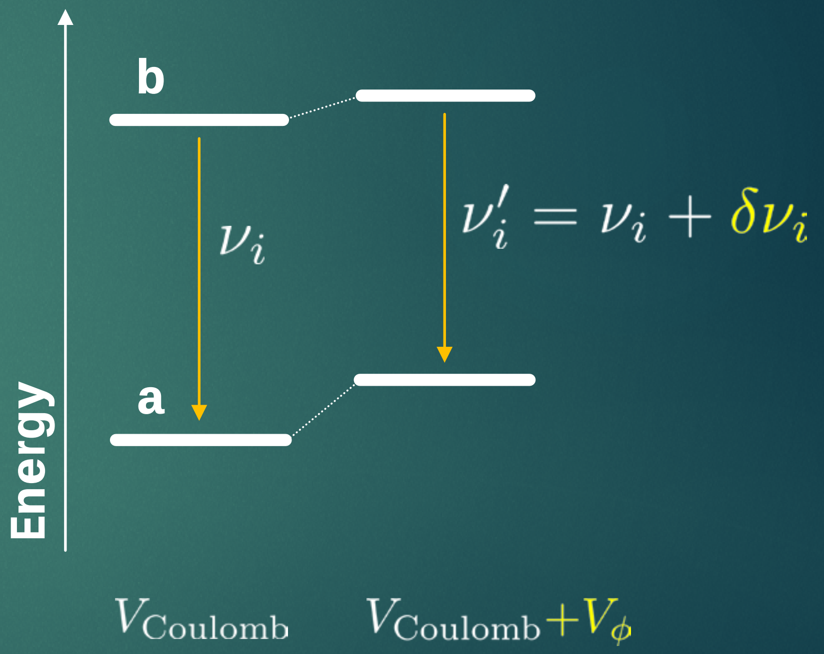
Energy level shifts

- Consider an atomic **transition *i*** between a,b levels ($E_b > E_a$)
- Relaxing from b to a, the atom emits a photon of frequency ($\hbar = 1$)

$$\nu_i = (E_b - E_a)/2\pi$$

- In presence of ϕ, all energies are shifted in a **level-dependent way**:

$$\nu_i' = E_b' - E_a' \neq \nu_i$$



Probing BSM atomic forces

- Experimental sensitivity is very good

- Probing BSM requires also equally good control on the « standard » contributions, through either:

  - Precise theory calculation of ν_i – only available for atom/ions with few electrons

or

  - Combination of measurements reducing sensitivity to quantities uncertain from theory – isotope shift and King linearity

Probes in heavy atoms

ISOTOPE SHIFT

KING LINEARITY VIOLATION

Basic idea

- Clock transitions in heavy atoms are the best measured (16 digits in Ytterbium+)
- However the frequencies are not calculable with comparable accuracy; there are too many electrons repulsing each other
- For point-like and static nuclei, 2 (spin-zero) isotopes are expected to have the same spectrum:

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

- New mass-dependent forces induce a shift:

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

electronic cst.

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

Nuclear isotope shift

- In the real world, isotopes have A-dependent mass and size (charge radius):

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

mass shift (MS)

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

field shift (FS)

- K_i, F_i are electronic constant
- Nuclear IS are small, typically $\nu_i^{AA'}/\nu_i^A \sim \mathcal{O}(10^{-6})$
- BSM contributions are only mildly suppressed by $\mathcal{O}(\delta A/A) \sim 0.1$, thus moving to IS we make a 5 order-of-magnitude improvement

Can we do better?

- Given their nuclear character, IS are challenging to calculate accurately

first attempt
Flambaum+ '17

- While nuclear masses are measured up to 11 digits, radii are poorly known from data
- Is there an observable sensitive to BSM forces and only limited by experimental uncertainty?
- Such an observable was discovered long ago and is known as King linearity

King 1963

King linearity

- The idea is **to combine IS measurements in 2 transitions** in order to eliminate unknown nuclear parameters

- Define modified shifts as $m\nu_i^{AA'} \equiv \mu_{AA'}^{-1} \nu_i^{AA'}$

- In the limit that electronic and nuclear parameters **factorize**, *ie.* K_i, F_i are constants in A, the (modified) IS are linearly related:

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

slope = F_2/F_1

offset = $K_2 - F_{21}K_1$

King linearity breaking

- In presence of BSM forces, the IS becomes:

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

- Combining 2 transitions yields

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

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

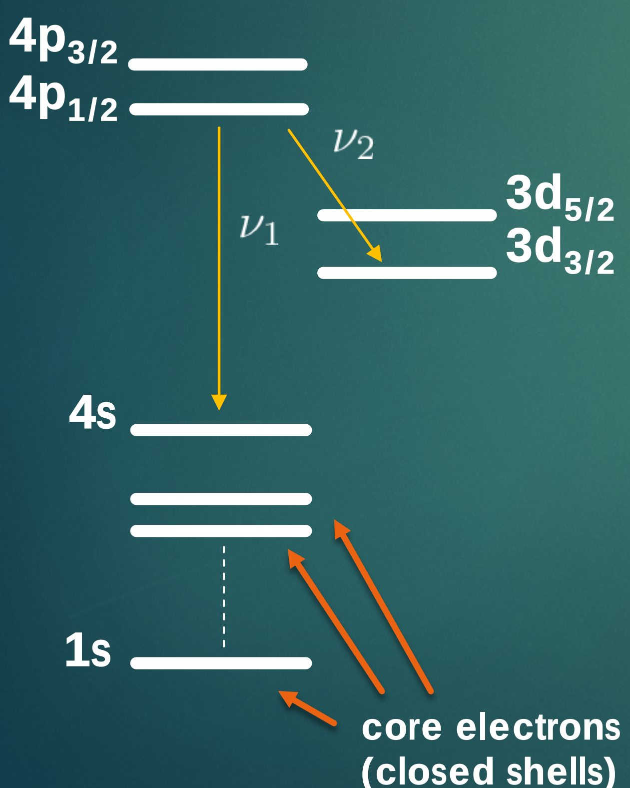
$X_2 - F_{21} X_1$

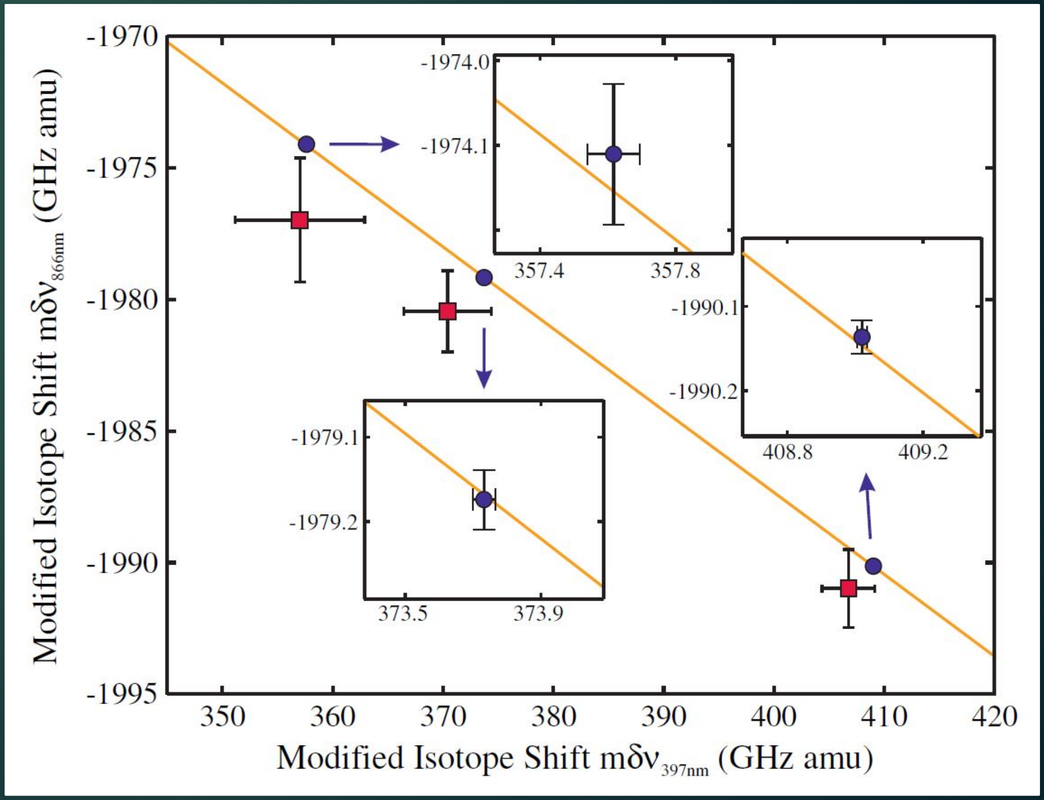
- BSM forces break linearity unless
  - alignment: $h_{AA'} \propto m\nu_i^{AA'}, 1_{AA'}$
  - short-range: $X_{21} \to 0$

can't probe the Higgs force…

Data is (so far) linear

- **Calcium+** measurements (~100kHz) in dipole-transitions are consistent with linearity





Gebert+ PRL 2015

Bounding BSM coupling

- **Consistency with King linearity given a set of measured $\overrightarrow{m\nu_{1,2}}$ translate into a bound on the BSM coupling**

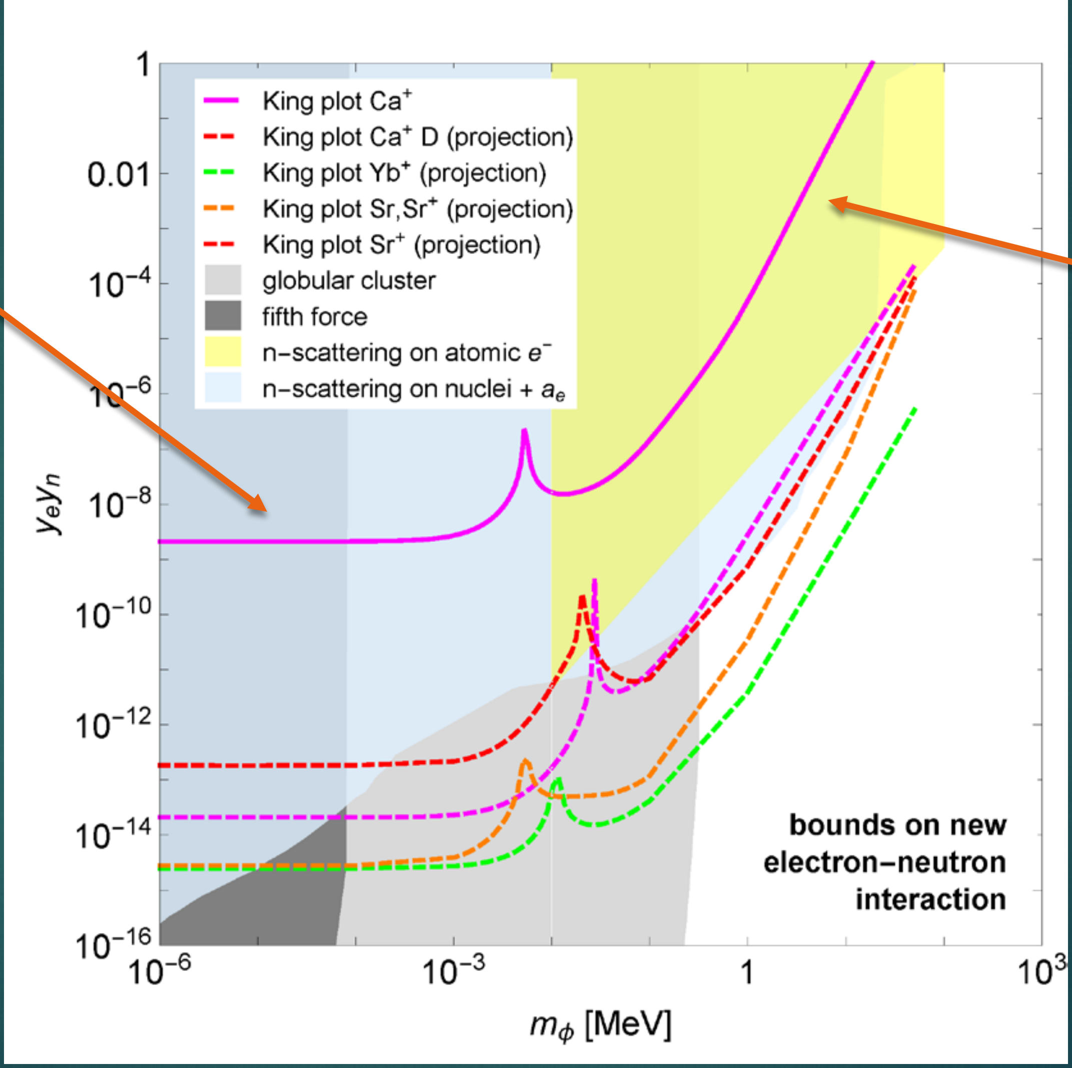
$$\alpha_{\mathrm{NP}} \leq \frac{\left(\overrightarrow{m\nu_1}\times\overrightarrow{m\nu_2}\right)\cdot\vec{1}}{(\vec{1}\times\vec{h})\cdot(X_1\overrightarrow{m\nu_2}-X_2\overrightarrow{m\nu_1})}$$

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

Bound & 1Hz-projections

long range force

$m_\phi < a_0^{-1}$



short range force

$m_\phi > Z a_0^{-1}$

The King of the Kings

CD, Soreq in progress

- Higher order nuclear effects also induce NL:

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

Higher-order nuclear « spurions »

- Once experiments get sensitive, one needs either to calculate them (hard) or use more measurement to absorb the extra spurions!
- n-2 spurions require n transitions and n+1 isotope pairs and to check for coplanarity:

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

The King without masses

CD, Soreq in progress

- Checking King linearity requires accurate knowledge of nuclear masses:

$$m\nu_i^{AA'} \equiv \mu_{AA'}^{-1}\nu_i^{AA'}$$

- Currently $m\nu_i^{AA'}$ is limited by uncertainty in $\nu_i^{AA'}$ but below 1Hz, masses become limiting factor

- Again use more measurements to remove also $\mu_{AA'}$: 3 transitions needed
- Factorization predicts a linear relation between $\nu_{1,2,3}^{AA'}$

Probes in atom with few electrons

HYDROGEN,HELIUM,POSITRONIUM

Light atom isotope shift

- IS in the point-nucleus limit are calculated with great precision for H,D and He3,4

$$\nu_i^A = \nu_{i,0}^A + F_i \langle r^2 \rangle_A + \delta\nu_i^A$$

new physics

- The accuracy of the theory prediction is limited by the charge radius, which is known at ~5% level in He from e-scattering data

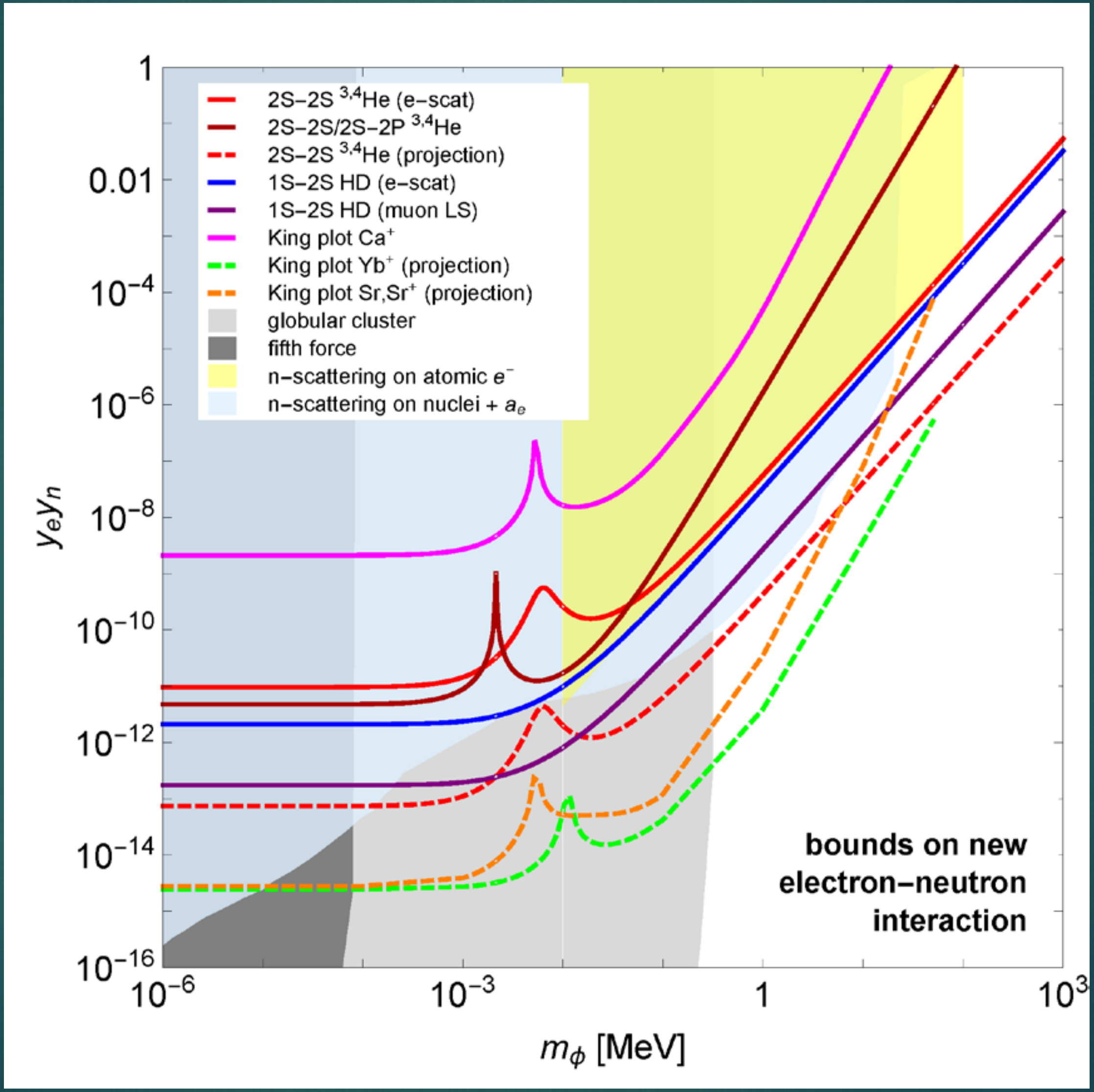
$$\delta\langle r^2 \rangle_{3,4} = 1.067(65)$$

while in HD muonic spectroscopy provides radii at 0.1% level (in agreement with electronic data)

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

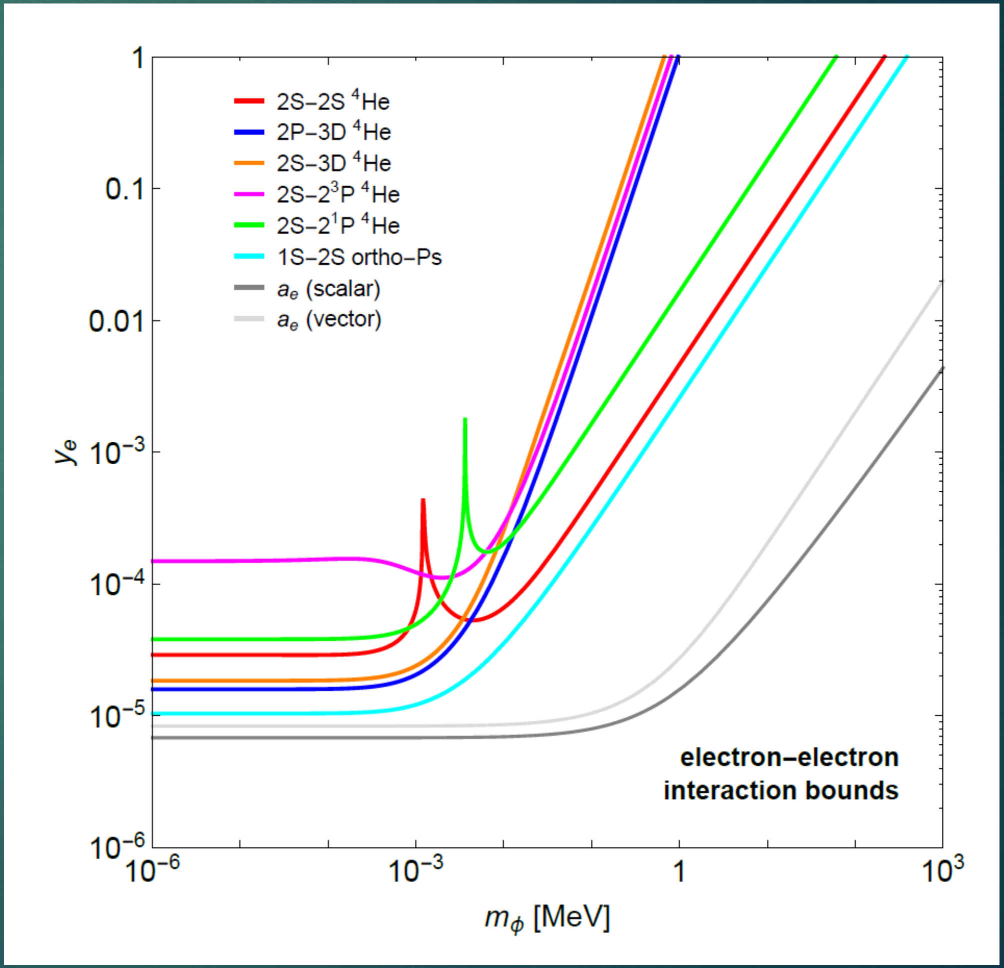
Pohl+ Nature (2010)
Antognini+ Science (2013)
Pohl+ Science (2016)

Bounds from light atoms



Bounding e-philic forces

- Consider ϕ only couples to electron
- Absolute frequencies in He and Ps currently probe electron interaction with sensitivity slightly weaker than g-2
- This is very useful complementarity (g-2 being loop induced)

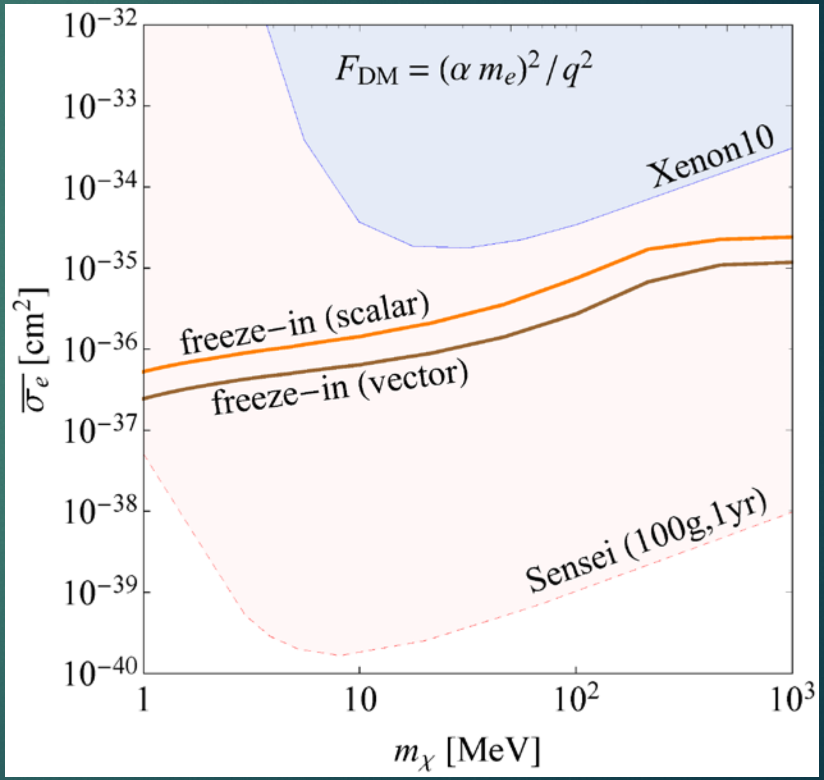


Implications for sub-GeV dark matter models

WITH LIGHT E-PHILIC MEDIATOR

DM Direct detection

- Consider fermionic DM with e-philic mediator ($m_\phi \ll m_\chi$)
- DM scattering on atomic electron will eventually probe the freeze-in parameter space
- What if DM not found?



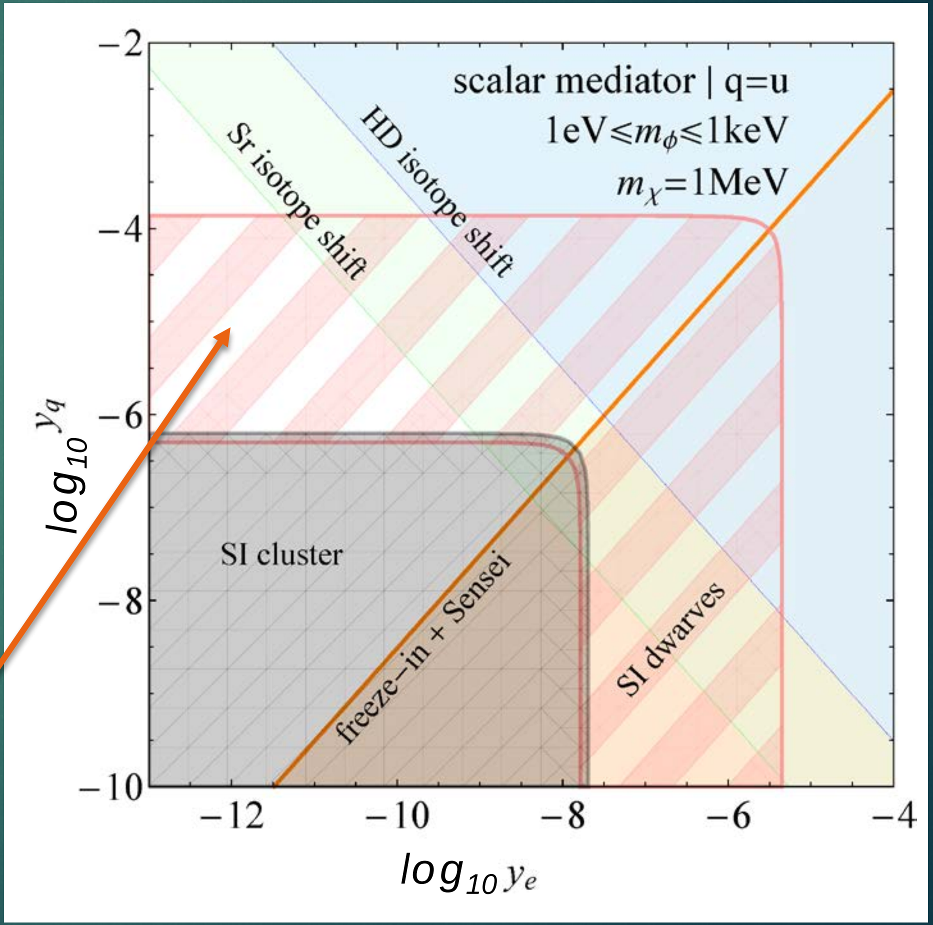
Two channels

Bélanger, CD, Zaldivar in progress

- One possibility is to open a **hadronic** channel for DM freeze-in

- Isotope shifts provide complementary constraints

$$y_e < 10^{-9}$$



allowed region
favored by small scale structures

Conclusions

Conclusion

- The need to combine searches from multiple frontiers is greater than ever
- Thanks to its high precision, atomic spectroscopy plays a complementary role in probing BSM physics
- Interplay with dark matter is one interesting example
- There may be many more !

backups

The atomic Higgs force

- Exchange of the 125GeV Higgs boson is a particularly exciting example of such forces:

$$y_n \approx 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g$$

$$y_p \approx 11 y_u + 6.5 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g$$

Shifman+ PLB 1978
(#'s from lattice)

- The SM predicts the Higgs boson couples proportionaly to mass ($v = (\sqrt{2} G_F)^{-1/2} \approx 246\,\mathrm{GeV}$)

$$y_f^{\mathrm{SM}} = m_f / v$$

- This is a sharp prediction, yet poorly tested experimentally..

Higgs couplings from LHC

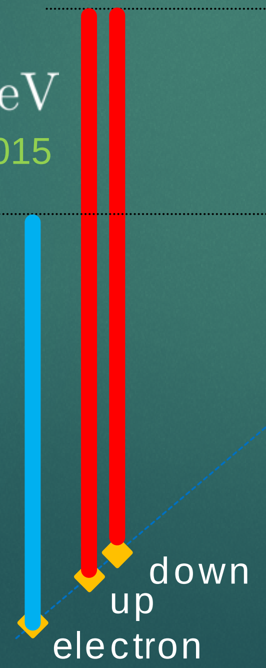
- **(2nd)3rd generation masses likely from Higgs mechanism**
- ***Quid* of 1st generation?**

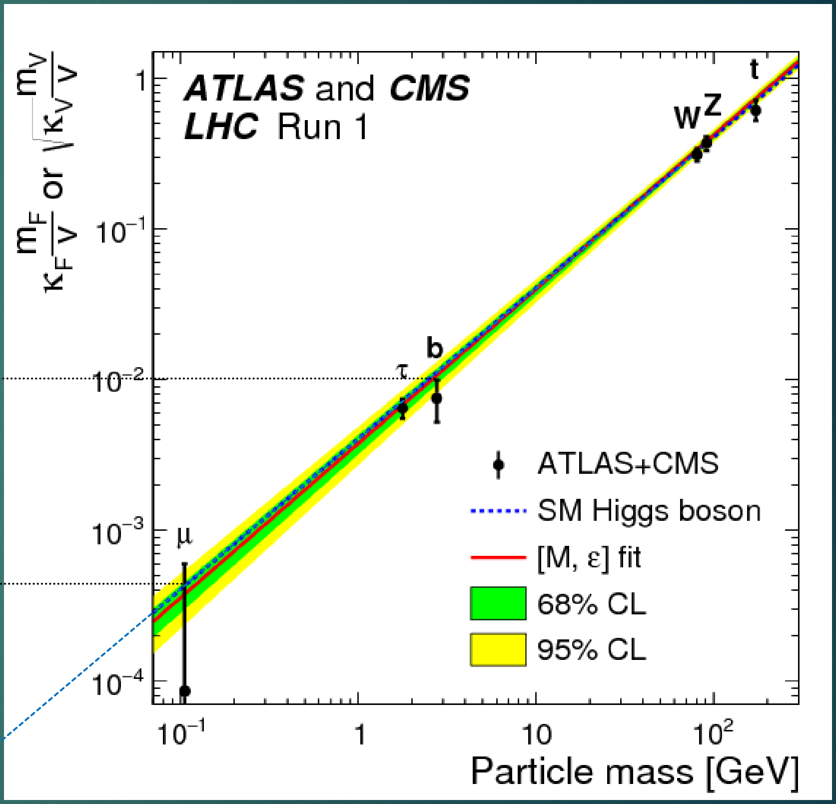
$$\Gamma_h \leq 1.7\,\mathrm{GeV}$$

Perez+ PRD 2015

$$h \to e^+ e^-$$

Altmannshofer+ JHEP 2015





(not up-to-date..)

Atomic Higgs force shifts

- Under LHC bounds, the Higgs force could be as strong as $y_e y_{p,n} \lesssim 4 \times 10^{-3}$, about **6** orders of magnitude stronger than in the SM and a factor ~20 weaker than QED

- However, the Higgs force is very short-range:

$$V_h(r) \simeq -\frac{y_e y_A}{4\pi} \frac{\delta(r)}{m_h^2 r^2}$$

- Frequency shifts scale like the electron density near the nucleus (like finite nuclear size correction...)

CD+ PRD 2016

$$\delta\nu_i^{\mathrm{Higgs}} \simeq 64\,\mathrm{Hz} \times y_e y_A \left[|\psi_a(0)|^2 - |\psi_b(0)|^2\right]$$

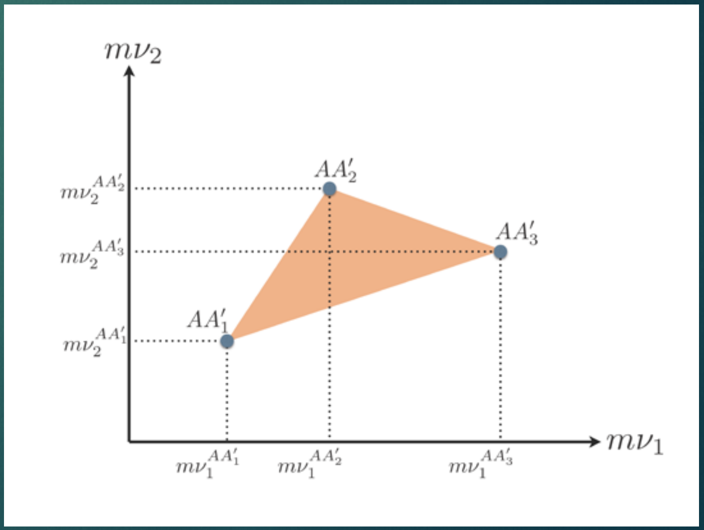
Establish linearity in data

- **Deviation from straight line requires 3 points, hence 2 transitions and 4 isotopes**

- **An invariant measure of non-linearity (NL) is the area of the triangle formed by the 3 points**

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

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



- **Data consistent with linearity**

iff $\mathrm{NL} \lesssim \sigma_{\mathrm{NL}}$ ← **1st order propagated error**