Atomic spectroscopy as dark sectors probe

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Work in collaboration with C. Frugiuele

Outline

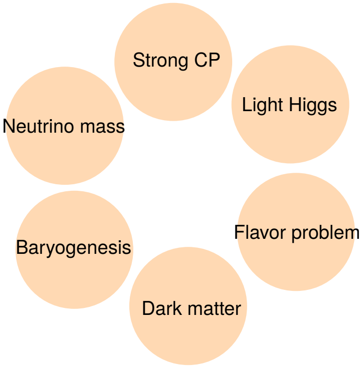
1. Motivation: indirect probes for dark sectors

2. EFTs for bound states

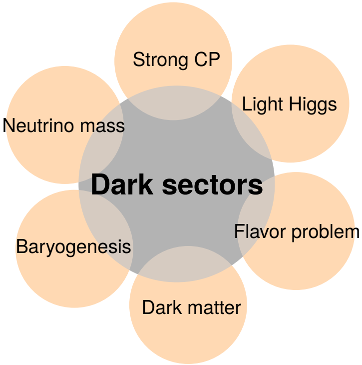
3. EFT for dark forces

4. Atomic bounds on dark sectors

- The Standard Model cannot be the end of the story:

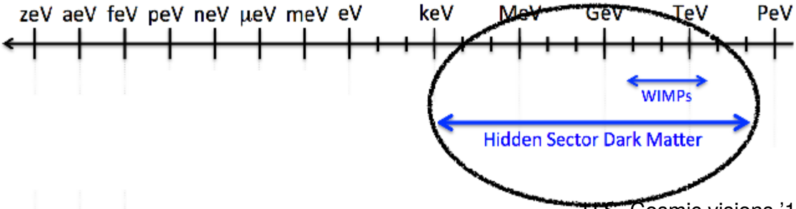


- The Standard Model cannot be the end of the story:



- Solutions to BSM puzzles generically predict **dark sectors** weakly interacting with the SM

What is dark matter made of?



U.S. Cosmic visions ’17

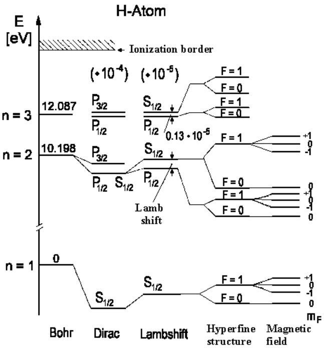
- Good thermal DM candidates, e.g. dark photon
- Focus on the **sub-GeV window**:

Direct detection experiments lose sensitivity and LHC has a limited reach.

New experimental strategy required!

→ **Indirect probes** in the **precision frontier**: searching new dark forces via **atomic spectroscopy**

Precision spectroscopy: hydrogen



Experiment:

extremely accurate

$E(1S-2S) = 2466\,061\,413\,187\,035(10)$ Hz

Garching 2010

$E(HFS) = 1420.\,405\,751\,768(1)$ MHz

Essen et al. 1971

Theory:

- simple atomic systems: QED corrections up to $\mathcal{O}(\alpha^8 \ln \alpha)$
- limited only by **nuclear structure effects**

Precision spectroscopy: near future

- **Hydrogen:** (2S - 6P, 8P, 9P, ...), Deuterium D(2S-nl) in Garching and Colorado ➔ underway
- **Hydrogen**: H(1S - 3S, 4S, ..) Paris and Garching ➔ underway
- **Muonium** at PSI and J-Pard
- **Positronium** Cassidy @ UCL, Crivelli @ ETH
- **He^{+}(1S-2S)** underway in Garching (Udem) and Amsterdam
- **HD^{+}, H_2,..** in Amsterdam and Paris
- **Li^{+}** at Amsterdam
- **Rydberg-atoms**, e.g. Rb (Raithel @ Ann Arbor)
- **Low-Q2 electron scattering** at MAMI, JLab, MESA
- **Muon scattering**: MUSE @ PSI, COMPASS @ CERN
- **Muonic Litium & Berilium**: PSI

Strategy

Set a 2-sigma bound to incorporate the new physics

$$|\Delta E^{\text{NP}}_{a\to b}| \leq |\Delta E^{\text{exp}}_{a\to b} - \Delta E^{\text{the}}_{a\to b}| \lesssim 2\sigma_{\text{Max}}$$

Needs:

1. High precision experiments: $\Delta E^{\text{exp}}_{a\to b}$
2. Very precise Standard Model computations: $\Delta E^{\text{the}}_{a\to b}$
3. Incorporating the energy levels of the new particle: $\Delta E^{\text{NP}}_{a\to b}$

→ Effective field theories

Why are EFTs the way to go?

- model independent
- efficient
- systematic (power counting)

EFTs for bound states

Non-relativistic systems fulfill the relation: $m_r \gg |\mathbf{p}| \gg E$

When bounded by QED, $\alpha \sim v$ is the only expansion parameter

Scales in bound state		Coulomb interaction
Hard scale: m_r	$\longrightarrow$	m_r
Soft scale: $|\mathbf{p}|$	$\longrightarrow$	$m_r\alpha$
Ultrasoft scale: E	$\longrightarrow$	$m_r\alpha^2$

when hadrons are involved other scales appear: $\Lambda_{\text{QCD}}, m_\pi, \ldots$

Scales are well separated

$$\text{QED/ HBChPT} \overset{(m_r, m_\pi)}{\Longrightarrow} \text{NRQED} \overset{(m_r\alpha)}{\Longrightarrow} \text{pNRQED}\,.$$

pNRQED

- is a theory for ultrasoft photons

Schrödinger-like formulation

$$\left(i\partial_0 - \frac{\mathbf{p}^2}{2m_r} - V^{(0)}(r) \right) \phi(\mathbf{r}) = 0$$

+corrections to the potential

+interaction with other low-energy degrees of freedom

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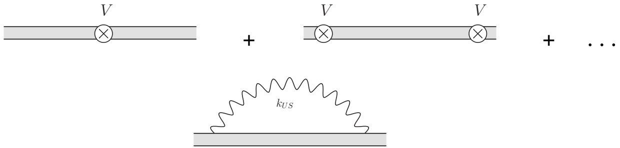
Compute potential insertions in a quantum-mechanical fashion



Organization of the computation

On top of the expansion parameter α there are other mass scales.

Scales in H & μe:

$$\Lambda_{\text{QCD}} \sim m_p \sim m_\rho$$
$$m_\mu \sim m_\pi$$
$$m_r \sim m_e \sim m_\mu\alpha$$

Small expansion parameters:

$$\frac{m_\pi}{m_p} \sim \frac{m_\mu}{m_p} \approx \frac{1}{9}$$
$$\frac{m_e}{m_\mu} \sim \frac{m_\mu\alpha}{m_\mu} \sim \alpha \approx \frac{1}{137}$$

Energy levels: $E_H = E_n^C\left(1 + c_1\frac{\alpha}{\pi} + \cdots + c_4\left(\frac{\alpha}{\pi}\right)^4 + \ldots\right) \quad E_n^C = \frac{-m_r\alpha^2}{2n^2}$

$c_n \sim c_n \left[\frac{m_\mu\alpha}{m_e}\right]$ pure QED for $1 \leq n \leq 3$

$c_n \sim \sum_{j=0}^{\infty} c_n^{(j)} \left(\frac{m_\pi}{m_p}\right)^j$ for $n \geq 4$

Organization of the computation

On top of the expansion parameter α there are other mass scales.

Scales in μH:

$$\Lambda_{\text{QCD}} \sim m_p \sim m_\rho$$
$$m_r \sim m_\mu \sim m_\pi$$
$$m_r\alpha \sim m_e$$

Small expansion parameters:

$$\frac{m_\pi}{m_p} \sim \frac{m_\mu}{m_p} \approx \frac{1}{9}$$
$$\frac{m_e}{m_r} \sim \frac{m_r\alpha}{m_r} \sim \alpha \approx \frac{1}{137}$$

Energy levels: $E_{\mu p} = E_n^C(1 + c_1\frac{\alpha}{\pi} + c_2\left(\frac{\alpha}{\pi}\right)^2 + \ldots),$

$c_1 \sim c_1\left[\frac{m_\mu\alpha}{m_e}\right]$ pure QED

$c_n \sim \sum_{j=0}^{\infty} c_n^{(j)}\left(\frac{m_\pi}{m_p}\right)^j;\ c_n^{(j)} \sim c_n^{(j)}\left[\frac{m_r}{m_\mu}, \frac{m_\mu}{m_\pi}, \ldots\right]$

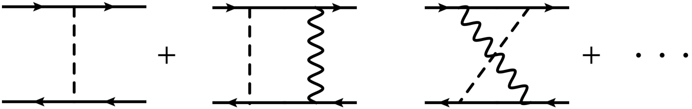
EFT for dark forces

- New spin-1 or spin-0 boson with generic couplings to fermions

$$\mathcal{L}_V = g_V \bar{\psi} \not{V} \psi, \quad \mathcal{L}_A = g_A \bar{\psi} \not{A} \gamma^5 \psi, \quad \mathcal{L}_S = g_S \bar{\psi} S \psi, \quad \mathcal{L}_P = g_P \bar{\psi} P \gamma^5 \psi.$$

- Scale hierarchy:
  - New parameters: g_{NP} and m_ϕ
  - Reasonable assumption: $g_{NP}^2 \ll 4\pi\alpha$

  Compute the **leading** contribution up to $\mathcal{O}(g_{NP}^2)$



  - For **pseudoscalar** the leading contribution is at **1-loop**

Atomic bounds on dark sectors

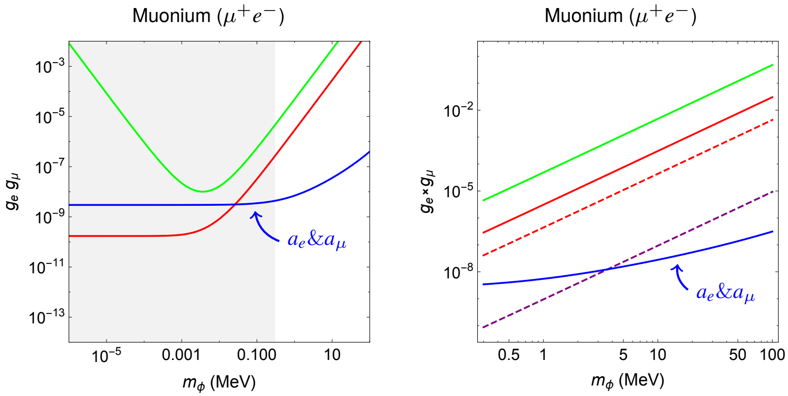
Set a 2-sigma bound for allowing the new contribution

$$|\Delta E^{\text{NP}}_{a\to b}| \leq |\Delta E^{\text{exp}}_{a\to b} - \Delta E^{\text{the}}_{a\to b}| \lesssim 2\sigma_{\text{Max}}$$

- Fully leptonic systems: **muonium** and **positronium**
  - very small hadronic effects
  - less stable: experimentally demanding
- Semileptonic systems: **hydrogen** and **muonic atoms**
  - hadronic effects are larger but can be fitted
  - high experimental precision

Bounds: leptonic spin-independent

$1S-2S$		Lamb shift	
Exp. (MHz)	Theo. (MHz)	Exp. (MHz)	Theo. (MHz)
2455528941.0(9.8)[1]	2455528935.8(1.4) [2]	1042(22) [3]	1047.284(2) [2]



Theory predictions limited by the muon mass uncertainty (Mu-MASS)

[1] V. Meyer, S. N. Bagayev, P. E. G. Baird,et al., Phys.Rev. Lett.84, 1136 (2000).

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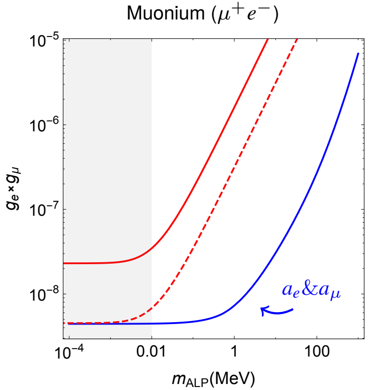

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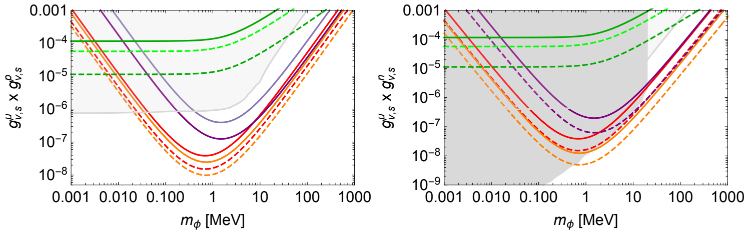
Bounds: semileptonic spin-dependent

System	Lamb shift		2s Hyperfine	
	Exp. (meV)	Theo. (meV)	Exp. (meV)	Theo. (meV)
μH	202.3706(23)	202.397(33)	22.8089(51)	22.812(3)
μD	202.8785(34)	202.869(22)		
μ^4He	1378.521(48)	1377.54(1.46)		

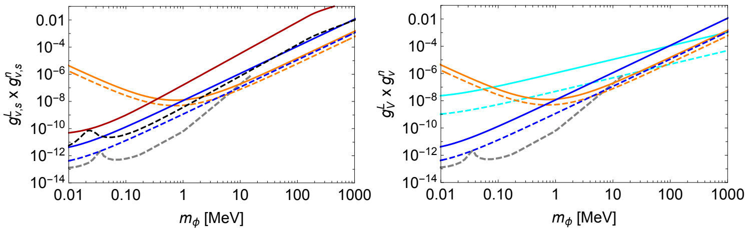
Table from CP, C. Frugiuele (2107.13512)



Bounds: semileptonic spin-dependent

System	Lamb shift		2s Hyperfine	
	Exp. (MHz)	Theo. (MHz)	Exp. (MHz)	Theo. (MHz)
H	909.8717(32)[**?**]	909.8742(3)	177 .5568343(67)	177. 5568382(3)

Table from CP, C. Frugiuele (2107.13512)



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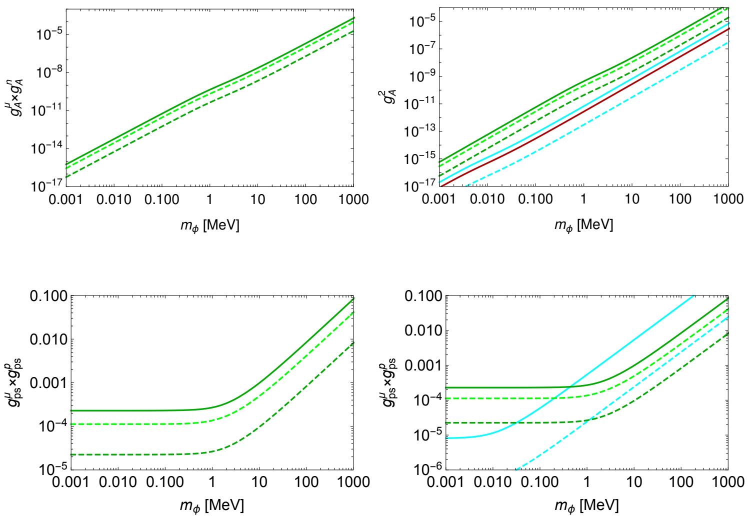

Conclusions and outlook

- Precision physics is an **trustworthy** and **competitive** probe for dark sectors
- **EFT**s are the right tool to describe energy transitions
  - Model independent
  - Systematic
- Muonium:
  - **Best** laboratory bounds for spin-independent interactions
  - Prospective improvement also for spin-dependent
- Muonic atoms:
  - **Best** atomic probe in the MeV-GeV for spin-independent interactions
  - Prospective improvement with IS radii
- Atomic probes are an **independent** and **robust** test of new physics
- Prospective improvement in **near future** experiments

Thank you!