# Muonic vs. electronic dark forces

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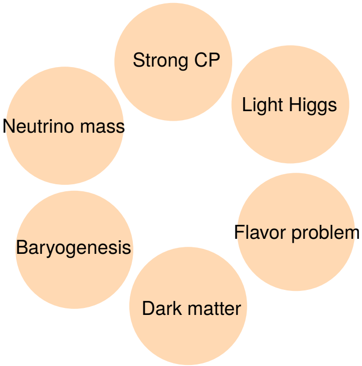
MUONIC ATOMS AT PSI2022, Switzerland

14 October, 2022

Work in collaboration with C. Frugiuele

- The Standard Model is great bu it cannot be the end of the story:



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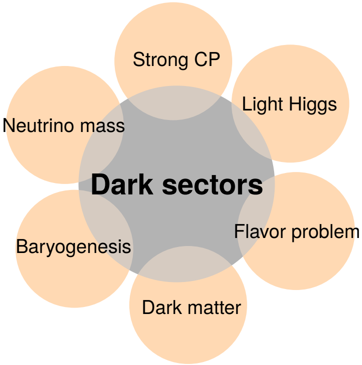
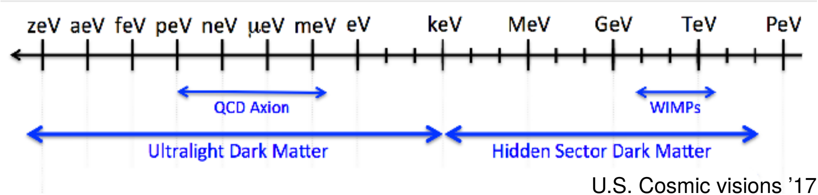



- Solutions to BSM puzzles generically predict **dark sectors** weakly interacting with the SM

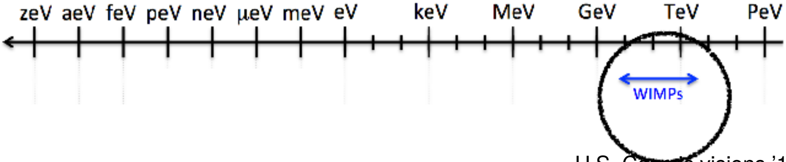
## The landscape for DM models




U.S. Cosmic visions ’17

→ DM production mechanism is a powerful guidance to select well motivated DM candidates

**Thermal DM mass range: $\mathbf{m}_\phi$ $\sim$1 keV-100 TeV**

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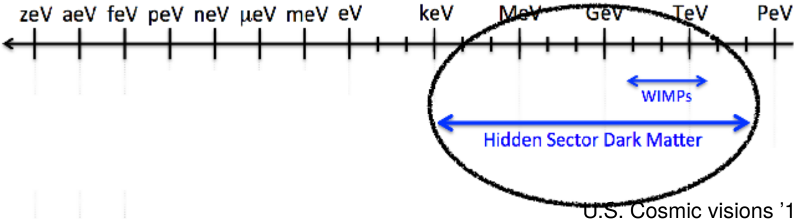
- Good thermal DM candidates, e.g. dark photon



U.S. Cosmic visions ’17

- Focus on the **sub-GeV window**:

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

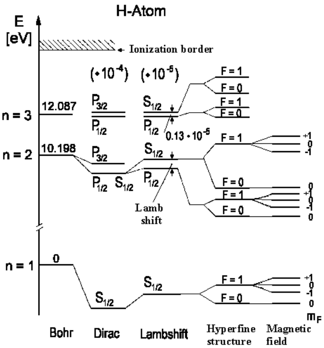
→ New experimental strategy required!

# Dark sectors and the precision frontier

- **Direct probes:**
  - lead to discovery
  - strong dependence on particular DM candidate characteristics
  - e.g. neutrino facilities (MiniBooNE)

- **Indirect probes:**
  - wide searches, less model dependence
  - Intensity frontier: produced at fixed target experiments or low energy colliders
  - Precision frontier: searching for new dark forces via **atomic spectroscopy**

# Precision spectroscopy: hydrogen




- **Experiment**:

extremely accurate

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

Garching 2010

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

Essen et al. 1971

- **Theory**:
  - simple atomic systems: QED corrections up to $\mathcal{O}(\alpha^8 \ln \alpha)$

$\Rightarrow$ Contribution from dark sectors is also small.

# Precision spectroscopy: muonic atoms

- **Experiment**:

very accurate

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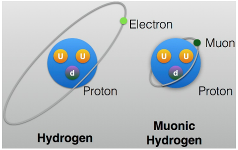


- $\mu$H: Lamb shift, 2s HFS, 1s HFS??
- $\mu$D: Lamb shift
- $\mu^4$He: Lamb shift

- **Theory**:
  - limited mainly by **nuclear structure effects**

$\Rightarrow$ Contribution from dark sectors is large.

# 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

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

# 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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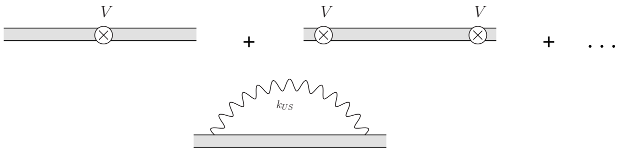
Compute potential insertions in a quantum-mechanical fashion



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+interaction with other low-energy degrees of freedom

Energy levels: $E_{\mu p} = E_n^C(1 + c_1 \frac{\alpha}{\pi} + \cdots + c_4 \left(\frac{\alpha}{\pi}\right)^4 + \ldots),$

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

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

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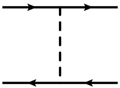
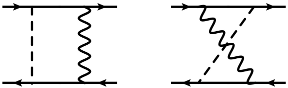
# EFT for dark forces

- Heavy pseudoscalar exchange



$$\tilde{V} \propto \frac{(\boldsymbol{\sigma}_1 \boldsymbol{q})(\boldsymbol{\sigma}_2 \boldsymbol{q})}{\boldsymbol{q}^2 + m_\phi^2} \sim \frac{(\boldsymbol{\sigma}_1 \boldsymbol{q})(\boldsymbol{\sigma}_2 \boldsymbol{q})}{m_\phi^2} \Rightarrow V \sim \frac{1}{r^5}$$

contribution to energy levels is divergent and $\mathcal{O}(\alpha^5)$



$$V \propto \alpha d_v(m_1, m_2, m_\phi)\delta^{(3)}(\boldsymbol{r})$$

contribution to the energy levels is finite and $\mathcal{O}(\alpha^4)$

The leading order contribution comes from **1loop** exchange!

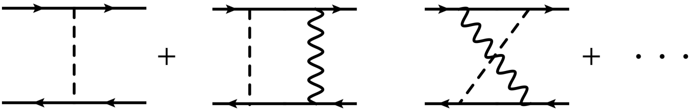
# EFT for dark forces

- 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 $m_\phi$
  - Reasonable assumption: $g_{NP}^2 \ll 4\pi\alpha$

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



# Atomic bounds on dark sectors

**Set a 2-sigma bound for allowing the new contribution**

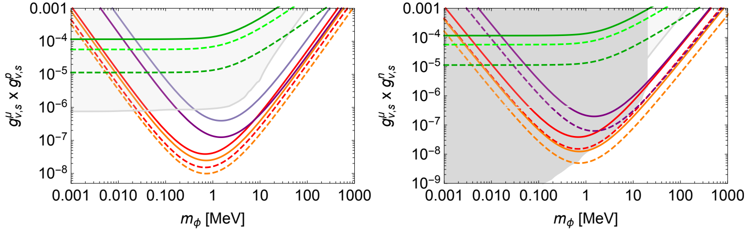
$$|\Delta E^{\text{NP}}_{a\to b}| \leq |\Delta E^{\text{exp}}_{a\to b} - \Delta E^{\text{the}}_{a\to b}| \lesssim 2\sigma_{\text{Max}}$$

- 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: muonic forces

| System | Lamb shift | | 2$s$ Hyperfine | |
|---|---|---|---|---|
| | Exp. (meV) | Theo. (meV) | Exp. (meV) | Theo. (meV) |
| $\mu$H | 202.3706(23) | 202.397(33) | 22.8089(51) | 22.812(3) |
| $\mu$D | 202.8785(34) | 202.869(22) | | |
| $\mu^4$He | 1378.521(48) | 1377.54(1.46) | | |

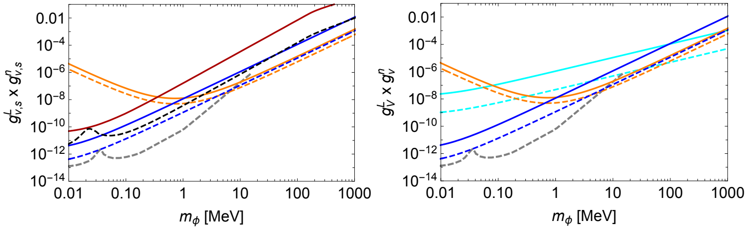
Table from CP, C. Frugiuele (2107.13512)



# Bounds: muonic vs electronic forces

| System | Lamb shift | | 2$s$ 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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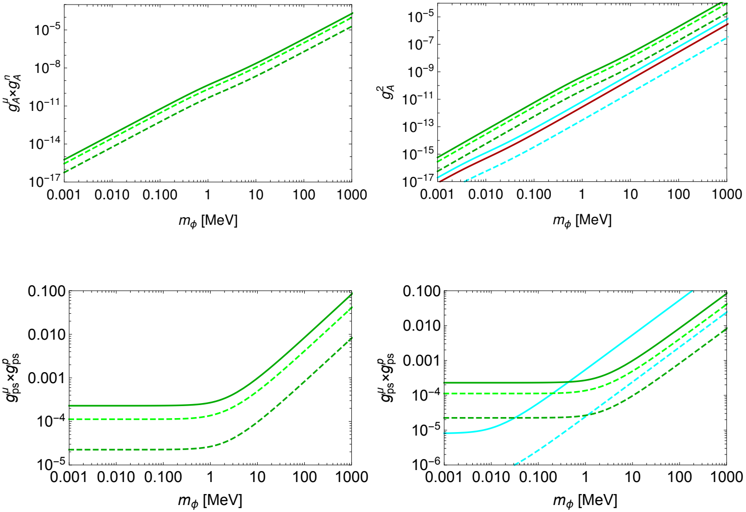
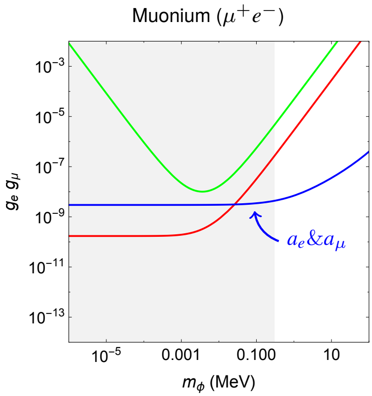
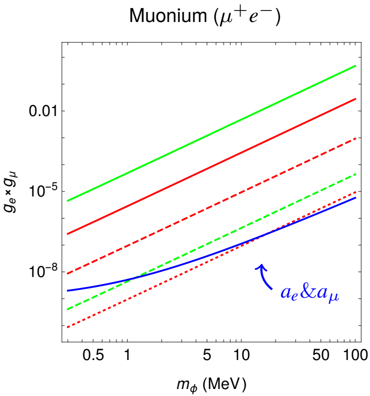


# Bounds: leptonic spin-independent

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



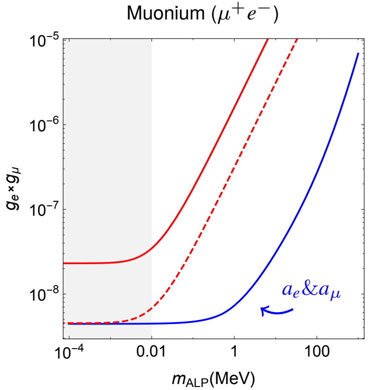

Theory predictions limited by the muon mass uncertainty (Mu-MASS)


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

[2] C. Frugiuele, CP, Phys.Rev.D 100 (2019) 1, 015010 [3] K. A. Woodleet al., Phys. Rev.A41, 93 (1990).

# Bounds: leptonic spin-dependent

| $1S-2S$ | | 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] |

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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
- Muonic atoms:
  - **Best** atomic probe in the MeV-GeV for spin-independent interactions
  - Prospective improvement with IS radii
- Muonium:
  - **Best** laboratory bounds for spin-independent interactions
  - Prospective improvement also for spin-dependent
- Atomic probes are an **independent** and **robust** test of new physics
- Prospective improvement in **near future** experiments

# Thank you!

## Prospects for experimental improvement?

$\mu$H HFS, Lamb shift of muonic atoms, muonium

## Prospects for theoretical improvement?

muonium HFS, Lamb shift and of muonic atoms