IPARCOS

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New physics bounds from the spectroscopy of muonic atoms

Clara Peset

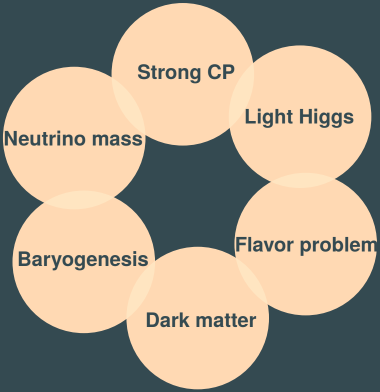
New perspectives in the charge radii determination for light nuclei

29th July, 2025

FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

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



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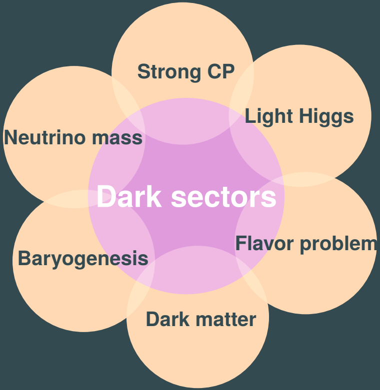
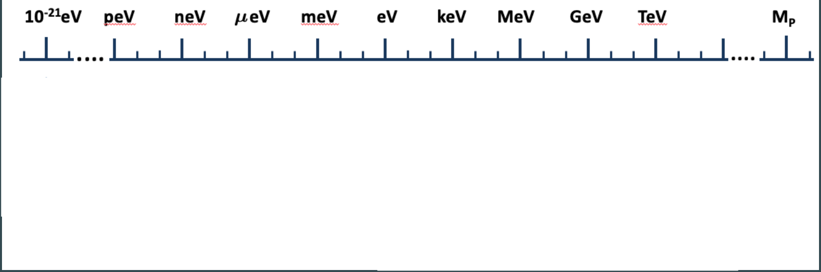


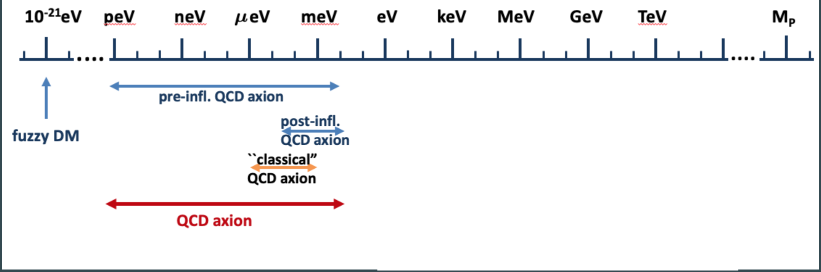
- Solutions to BSM puzzles generically predict **dark sectors** weakly interacting with the SM

- **The landscape for DM models**



U.S. Cosmic visions ’21

- **The landscape for DM models**



U.S. Cosmic visions ’21

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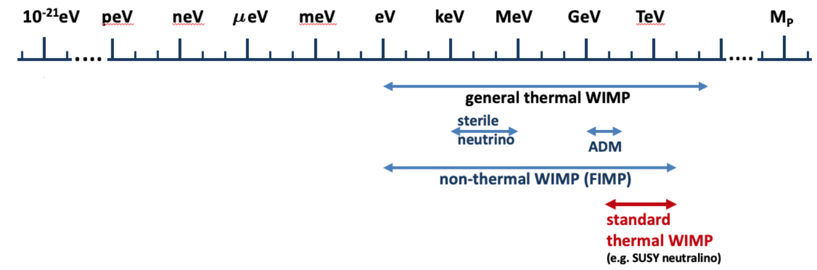
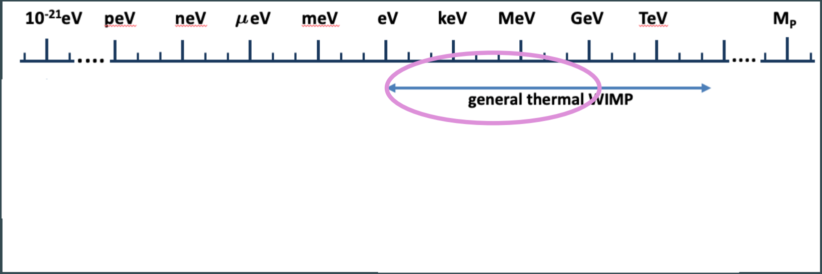


U.S. Cosmic visions '21

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

Thermal DM mass range: m_ϕ ∼1 eV-100 TeV

- **The landscape for DM models**



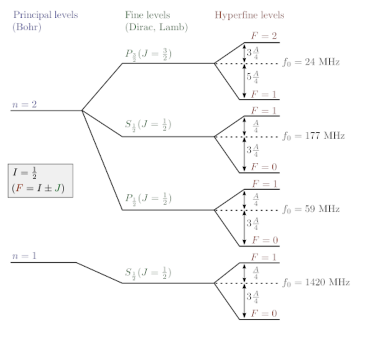
U.S. Cosmic visions ’21

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

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

Precision frontier: searching for new dark forces via **atomic spectroscopy**

Precision spectroscopy: hydrogen



- **Experiment**:

extremely accurate

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

Garching 2010

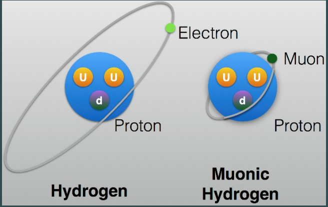
$E(HFS) = 1420.\,405\,751\,768(1)$ MHz

Essen et al. 1971

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

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

Precision spectroscopy: muonic atoms



- **Experiment**:

PAUL SCHERRER INSTITUT PSI

very accurate

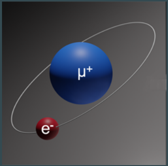
- ▶ μH: Lamb shift, 2s HFS, 1s HFS??
- ▶ μD: Lamb shift, 2s HFS
- ▶ μ^4He: Lamb shift
- ▶ μ^3He: Lamb shift

see 2305.11679

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

$\Rightarrow$ Contribution from dark sectors is large.

Precision spectroscopy: muonium



- **Experiment**:

very accurate

- ▶ 1s HFS: LAMPF '99, MuSEUM?
- ▶ Lamb shift: MuMASS

- **Theory**:
  - ▶ limited mainly by **measurement of the muon mass (or magnetic moment)**

see Phys. Rev. A 103 (2021) no.2, 022805

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

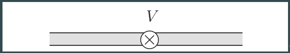
Schrödinger-like formulation

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

Pineda, Soto

+corrections to the potential
+interaction with other low-energy degrees of freedom

Compute potential insertions in a quantum-mechanical fashion



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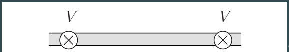

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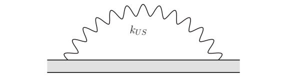

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+interaction with other low-energy degrees of freedom

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

c_1 pure QED

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

pNRQED

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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

- Consider: new spin-1 or spin-0 boson with generic couplings to fermions

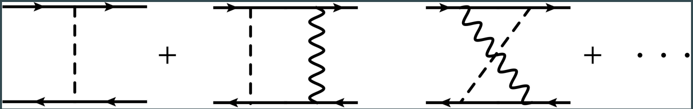
$$\mathcal{L}_V = g_V \bar{\psi} \not{V} \psi, \quad \mathcal{L}_A = g_A \bar{\psi} \not{A} \gamma^5 \psi, \quad \mathcal{L}_S = g_S \bar{\psi} S \psi, \quad \mathcal{L}_P = g_P \bar{\psi} P \gamma^5 \psi.$$

- Add it as a correction to the pNRQED potential

$\Rightarrow$ 2 New parameters: g_{NP} and m_ϕ

Assumption: weakly interacting: $g_{NP}^2 \ll 4\pi\alpha$

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



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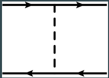
- **Scale hierarchy**

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

m_ϕ???

Illustrative example: Heavy pseudoscalar exchange

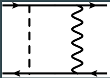
- Tree level:

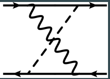


$$\tilde{V} \propto \frac{(\boldsymbol{\sigma}_1 \boldsymbol{q})(\boldsymbol{\sigma}_2 \boldsymbol{q})}{\boldsymbol{q}^2 + m_\phi^2} \overset{m_\phi \gg \boldsymbol{q}}{\sim} \frac{(\boldsymbol{\sigma}_1 \boldsymbol{q})(\boldsymbol{\sigma}_2 \boldsymbol{q})}{m_\phi^2} \Rightarrow V \sim \frac{1}{r^5}$$

$\Rightarrow \delta E$ is divergent and parametrically $\mathcal{O}(\alpha^5)$

- One loop:





$$\tilde{V} \propto \alpha \, d_v(m_1, m_2, m_\phi) \Rightarrow V \sim \alpha \, \delta^{(3)}(\mathbf{r})$$

$\Rightarrow \delta E$ is finite and $\mathcal{O}(\alpha^4)$

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

EFT for dark forces

- Consider: new spin-1 or spin-0 boson with generic couplings to fermions

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

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Distinguish to mass regimes:

1) Heavy EFT ($m_\phi \sim m_r$)

2) Light EFT ($m_\phi \lesssim m_r$)

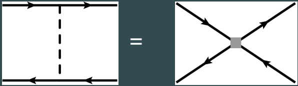
1) Heavy EFT: the NREFT

- Integrate out the hard scale $m_\phi \gtrsim m \gg |\mathbf{q}| \sim mv$

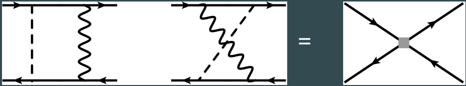
New Lagrangian up to $\mathcal{O}(g_{NP}^2/m^2)$

$$\mathcal{L}_4 = -\frac{d_s^{(V)}}{m_1 m_2}\psi_1^\dagger \psi_1 \chi_2^{c\dagger}\chi_2^c + \frac{d_v^{(V)}}{m_1 m_2}\psi_1^\dagger \boldsymbol{\sigma}\psi_1 \chi_2^{c\dagger}\boldsymbol{\sigma}\chi_2^c$$

- The new particle does not propagate.
- d_s starts at tree-level



- $d_v(m_\phi, m_1, m_2)$ starts at 1-loop (Feynonium code)

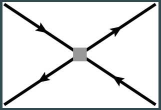


CP, Frugiuele

1) Heavy EFT: the potential NREFT

- Integrate out the soft scale $|\mathbf{q}| \sim mv \gg mv^2$

The leading order contribution is a contact interaction



$$V(r) = \frac{d_s^{(V)} + 3d_v^{(V)}}{m_1 m_2}\delta^{(3)}(r) - \frac{2d_v^{(V)}}{m_1 m_2}\delta^{(3)}(r)\mathbf{S}^2$$

2) Light EFT: the NREFT

- Integrate out the hard scale $m \gg |\mathbf{q}| \sim mv \gtrsim m_\phi$

New Lagrangian up to $\mathcal{O}(g_{NP}^2/m^2)$

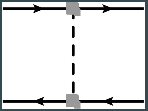
$$\mathcal{L}_V^{\text{NR}} = \psi^\dagger \left\{ g_V V^0 + \frac{i d_k g_V}{2m}(\boldsymbol{\nabla}\mathbf{V} + \mathbf{V}\boldsymbol{\nabla}) - \frac{d_1 g_V}{2m}\boldsymbol{\sigma}\mathbf{B} - \frac{d_2 g_V}{8m^2}[\boldsymbol{\nabla}, \mathbf{E}] - \frac{d_3 g_V}{8m^2} i\sigma^{ij}\{\nabla^i, E^j\} \right\} \psi$$
$$-(\psi \to \chi^c)$$

- at leading order $d_i = 1$
- 4-fermion operators are suppressed by a power of α

2) Light EFT: the potential NREFT

- Integrate out the soft scale $|\mathbf{q}| \sim mv \gg mv^2$

Matching to tree level exchange in the NREFT at $\mathcal{O}(v^2)$:



The potential at next-to-leading order $(m_1 \neq m_2)$

$$
\begin{aligned}
V_{VV}(r) =& \frac{g_V^{(1)} g_V^{(2)}}{4\pi r} e^{-m_\phi r} \\
&+ \frac{g_V^{(1)} g_V^{(2)}}{8\pi m_1 m_2} \left[\frac{2\mathbf{S^2}}{3} \left(m_\phi^2 \frac{e^{-m_\phi r}}{r} - 4\pi\delta^{(3)}(r) \right) + \frac{m_\phi}{2} \left\{ \mathbf{p}^2, e^{-m_\phi r} \right\} + \left\{ \mathbf{p}^2, \frac{e^{-m_\phi r}}{2r} \right\} \right. \\
&+ \frac{m_\phi^3}{4} e^{-m_\phi r} - \left(1 - \frac{m_1 m_2}{4m_r^2} \right) \frac{m_\phi^2 e^{-m_\phi r}}{r} + \left(1 - \frac{m_1 m_2}{2m_r^2} \right) 2\pi\delta^{(3)}(r) \\
&- \frac{\hat{S}_{12}(\hat{\mathbf{r}})}{2} e^{-m_\phi r} \left(\frac{m_\phi^2}{3r} + \frac{m_\phi}{r^2} + \frac{1}{r^3} \right) - e^{-m_\phi r}(m_\phi r + 1) \frac{\mathbf{L}^2}{r^3} \\
&\left. - \left(\frac{m_1 m_2}{2m_r^2} + 1 \right) e^{-m_\phi r}(m_\phi r + 1) \frac{\mathbf{LS}}{r^3} + \frac{m_1^2 - m_2^2}{2m_1 m_2} e^{-m_\phi r}(m_\phi r + 1) \frac{\mathbf{LS}^-}{r^3} \right]
\end{aligned}
$$

Contribution to energy shifts: Lamb shift

PRELIMINARY

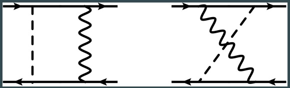
$$\boxed{\Delta E^{\mathrm{NP}} = \langle V_x(r) \rangle_{nlsj}}$$

Contribution to energy shifts: Lamb shift

PRELIMINARY

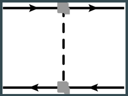
$$\Delta E^{\text{NP}} = \langle V_x(r) \rangle_{nlsj}$$

1) Heavy EFT $m_\phi \sim m_r$



$$V_{\text{VV}}(r) = \frac{d_s^{(V)}(m_\phi, m_1, m_2)}{m_1 m_2} \delta^{(3)}(r)$$

2) Light EFT $m_\phi < m_r$



$$V_{VV}(r)\Big|_{\mathcal{O}(v^0)} = \frac{g_V^{(1)} g_V^{(2)}}{4\pi r} e^{-m_\phi r}$$

NAIVE!

Contribution to energy shifts: Lamb shift

PRELIMINARY

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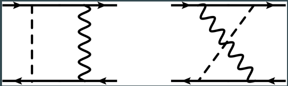
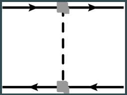


$$V_{\text{VV}}(r) = \frac{d_s^{(V)}(m_\phi, m_1, m_2)}{m_1 m_2}\delta^{(3)}(r)$$

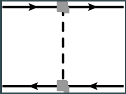
2) Light EFT $m_\phi < m_r$

- $m_r > m_\phi > m_r\alpha$



$$V_{VV}(r)\Big|_{\mathcal{O}(v^0)} = \frac{g_V^{(1)} g_V^{(2)}}{4\pi r} e^{-m_\phi r}$$

- $m_r\alpha > m_\phi$



$$V_{VV}(r)\Big|_{\mathcal{O}(v^2)}$$ it is a relativistic effect

Contribution to energy shifts: Lamb shift

PRELIMINARY

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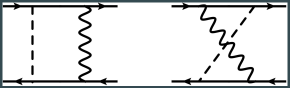

$$V_{\rm VV}(r) = \frac{d_s^{(V)}(m_\phi, m_1, m_2)}{m_1 m_2} \delta^{(3)}(r)$$

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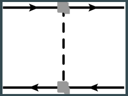
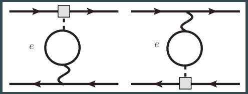


$$V_{VV}(r)\Big|_{\mathcal{O}(v^0)} = \frac{g_V^{(1)} g_V^{(2)}}{4\pi r} e^{-m_\phi r}$$

- $m_r \alpha > m_\phi \Rightarrow$ **MUONIC ATOMS**

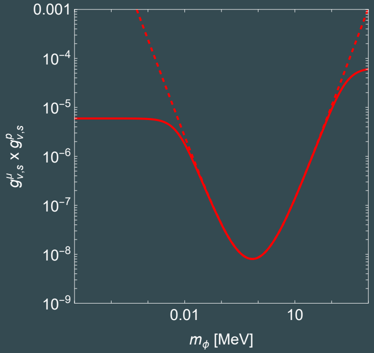


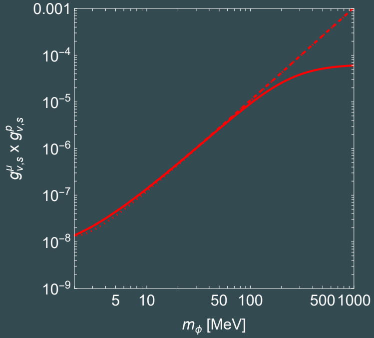
$$\delta V_{VV}(r) \propto \frac{\alpha^2}{r}$$

Contribution to energy shifts: Lamb shift

PRELIMINARY

$$\Delta E^{\mathrm{NP}} = \langle V_x(r) \rangle_{nlsj}$$





Light EFT NLO (continuous) vs Light EFT LO (dashed) vs Heavy EFT LO (dotted)

Contribution to energy shifts: hyperfine $2S$

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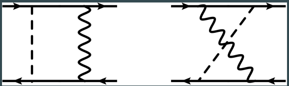
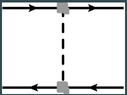


$$V_{\text{VV}}(r) = \frac{-2d_v^{(V)}(m_\phi, m_1, m_2)}{m_1 m_2}\delta^{(3)}(r)\mathbf{S}^2$$

2) Light EFT $m_\phi < m_r$



$$V_{VV}(r)\Big|_{\mathcal{O}(v^2)} = \frac{g_V^{(1)} g_V^{(2)}}{12\pi m_1 m_2}\left(\frac{m_\phi^2 e^{-m_\phi r}}{r} - 4\pi\delta^{(3)}(r)\right)\mathbf{S}^2$$

Both theories match:

$$\boxed{E_{HF}^{\text{Heavy-EFT}}\Big|_{m_\phi\to 0} = E_{HF}^{\text{Light-EFT}}\Big|_{m_\phi\to\infty}} \quad \checkmark$$

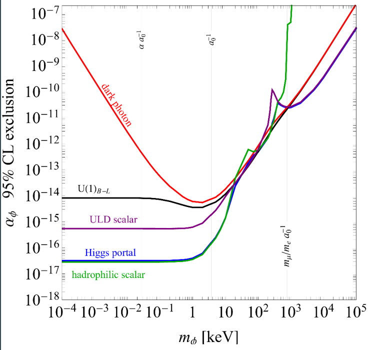
Atomic bounds on dark sectors

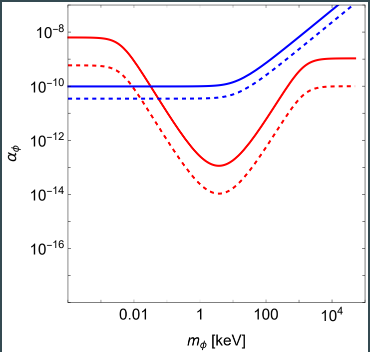
Set a 2-sigma bound to incorporate new physics

$$|\Delta E_{a\to b}^{\mathsf{NP}}| \leq |\Delta E_{a\to b}^{\mathsf{exp}} - \Delta E_{a\to b}^{\mathsf{the}}| \lesssim 2\sigma_{\mathrm{Max}}$$

Our approach vs global fit to all parameters

Phys.Rev.Lett. 130 (2023) 12, 121801



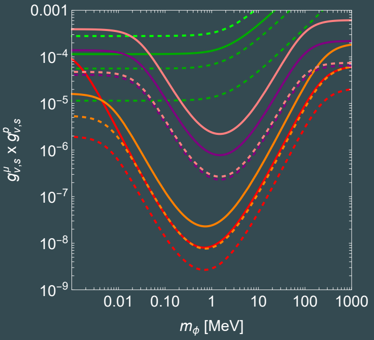


Bounds on muonic forces

System	Lamb shift		2s Hyperfine	
	Exp. (meV)	Theo. (meV)	Exp. (meV)	Theo. (meV)
μH	202.3706(23)	202.420(14)	22.8089(51)	22.812(3)
μD	202.8785(34)	202.824(21)		
μ^4He	1378.521(48)	1377.54(1.46)		
μ^3He	1258.598(48)	1257.40(5.72)		

PRELIMINARY

UPDATE from CP, C. Frugiuele (2107.13512)



shaded region from X-ray measurements on $3d_{5/2} - 2p_{3/2}$ in muonic 24Mg and 28Si

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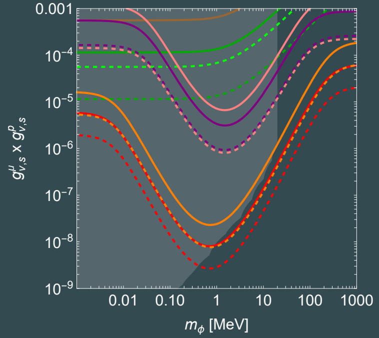
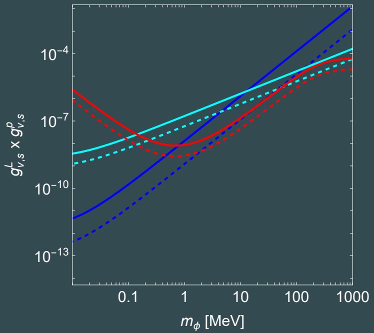


Muonic vs electronic forces

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)

UPDATE from CP, C. Frugiuele (2107.13512)

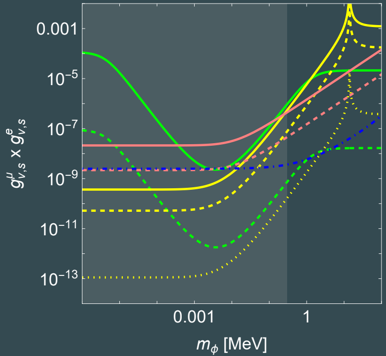


Muonium spin-independent forces

$1S-2S$		Lamb shift		hyperfine	
Exp. (MHz) (9.8)	Theo. (MHz) (1.4)	Exp. (MHz) (2.5)	Theo. (MHz) (0.002)	Exp. (MHz) (0.053)	Theo. (MHz) (0.53)

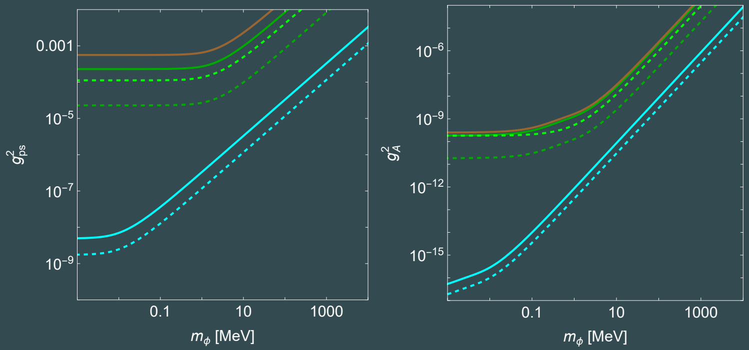
$a_e \& a_\mu$

UPDATE from CP, C. Frugiuele (1902.08585)



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

Bounds: muonic vs electronic forces



CMS dark matter search uses ps couplings equal to unity at 1 GeV

[1901.01553]

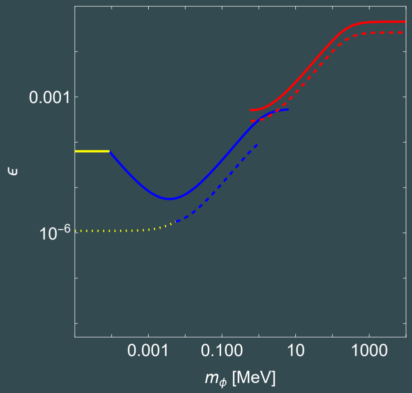
Conclusions and outlook

- Atomic spectroscopy is an **trustworthy** and **competitive** probe for dark sectors
- **EFT**s are the right tool to describe energy transitions
  - Model independent
  - Systematic - power counting
- Muonic atoms:
  - **Best** atomic probe in the MeV-GeV for spin-independent interactions
  - New **input** for spin-dependent interactions in accelerator searches
- Muonium:
  - Large prospective improvement with MuMASS and new HFS measurement

Thank you!

Best bounds combined

$g_v^\mu = g_v^e = g_v^p$



e.g. dark photon