Muonic vs. electronic dark forces

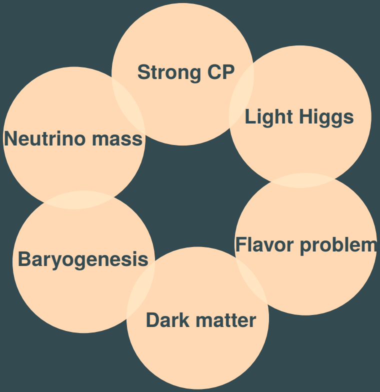
Clara Peset

Searching for new physics at the quantum technology frontier,
CSF Ascona

3 July, 2023

Work in collaboration with C. Frugiuele

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



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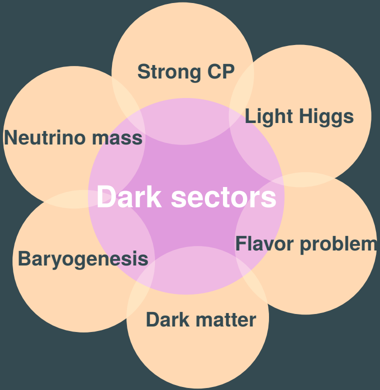
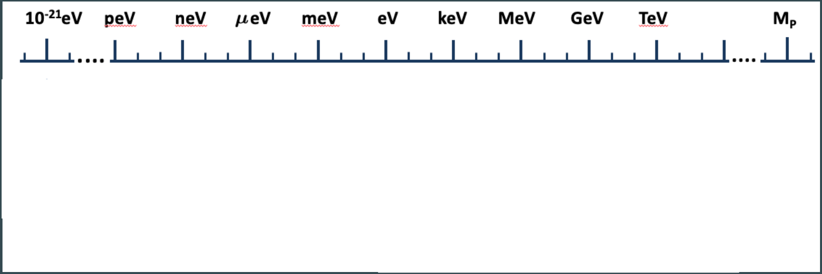


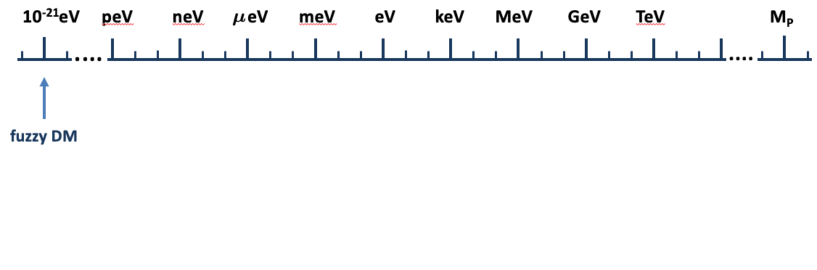
- Solutions to BSM puzzles generically predict **dark sectors** weakly interacting with the SM

- **The landscape for DM models**



U.S. Cosmic visions ’21

The landscape for DM models



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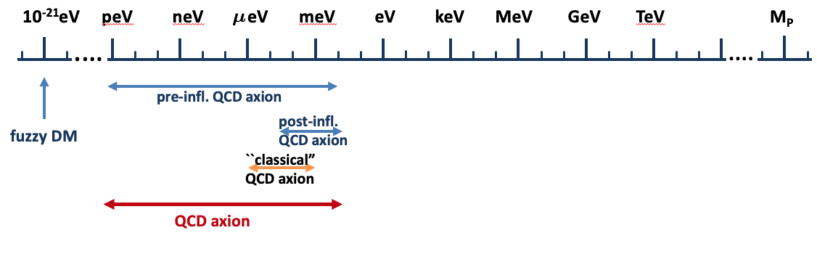

U.S. Cosmic visions '21

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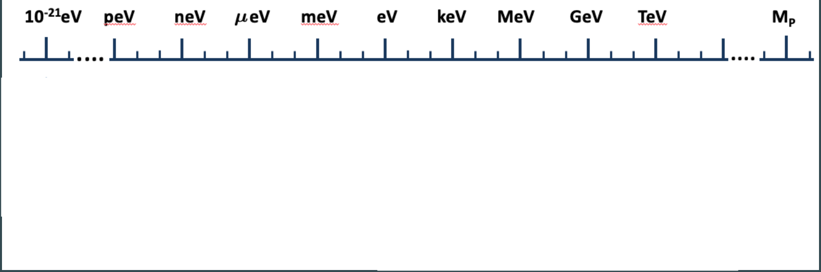
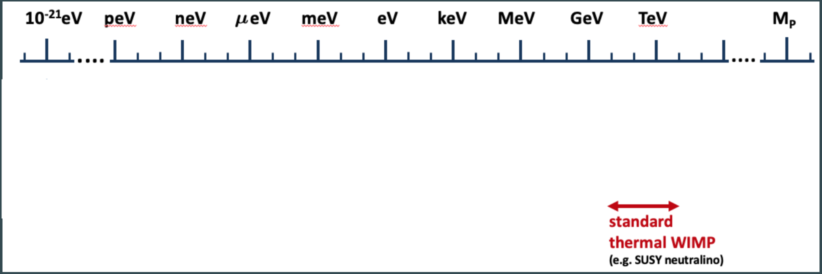


U.S. Cosmic visions ’21

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

The landscape for DM models



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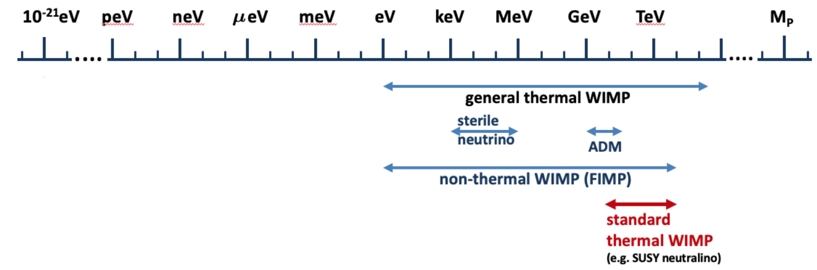

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Thermal DM mass range: $m_\phi \sim$1 eV-100 TeV

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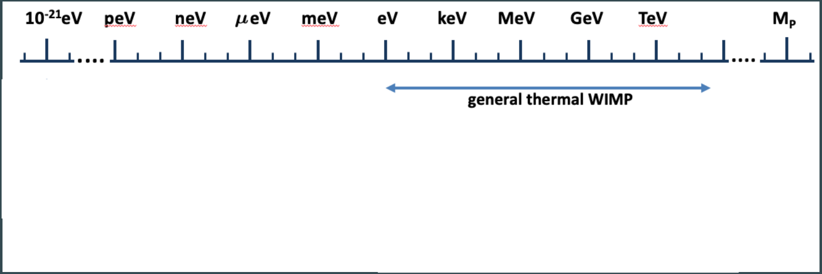

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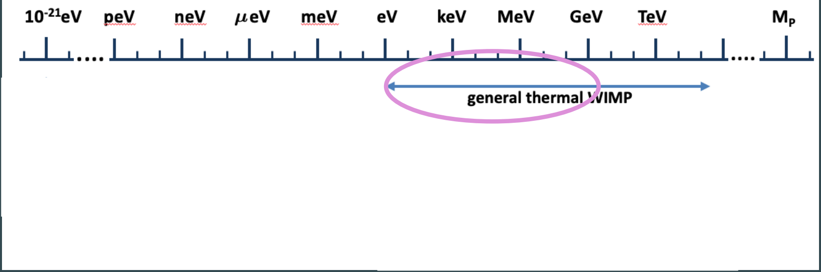


U.S. Cosmic visions '21

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

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

→ New experimental strategy required!

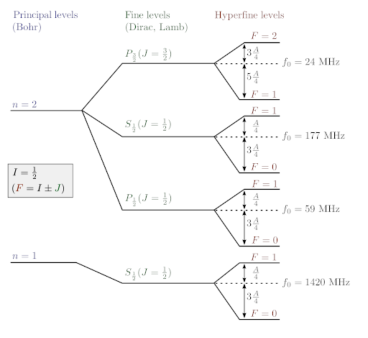
Dark sectors and the precision frontier

- **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

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

Garching 2010

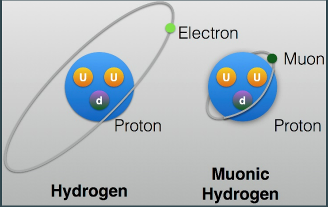
$E(HFS) = 1420.\,405\,751\,768(1)$ MHz

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

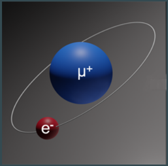
- ▶ μH: Lamb shift, 2s HFS, 1s HFS??
- ▶ μD: Lamb shift, 2s HFS
- ▶ μ^4He: Lamb shift
- ▶ μ^3He: Lamb shift

see 2305.11679

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

$\Rightarrow$ Contribution from dark sectors is large.

Precision spectroscopy: muonium a



- **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

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

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

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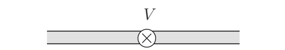
Compute potential insertions in a quantum-mechanical fashion



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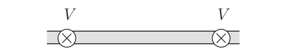

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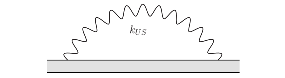

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Energy levels: $E_{ep} = E_n^C(1 + c_1\frac{\alpha}{\pi} + \cdots + c_4\left(\frac{\alpha}{\pi}\right)^4 + \ldots),$

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

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

pNRQED

- is a theory for ultrasoft photons

Schrödinger-like formulation

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

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

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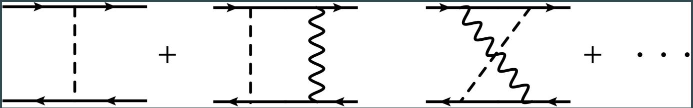
EFT for dark forces

- Consider: new spin-1 or spin-0 boson with generic couplings to fermions
- Add as a correction to the pNRQED potential

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

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

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



EFT for dark forces

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- **Scale hierarchy**

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Hard scale: m_r	$\longrightarrow$	m_r
Soft scale: $\lvert\mathbf{p}\rvert$	$\longrightarrow$	$m_r\alpha$
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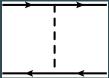
???

Illustrative example: Heavy pseudoscalar exchange

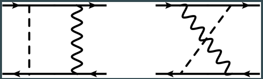
- Tree level:



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

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

- One loop:



$$\tilde{V} \propto \alpha d_v(m_1, m_2, m_\phi)$$

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

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

Atomic bounds on dark sectors

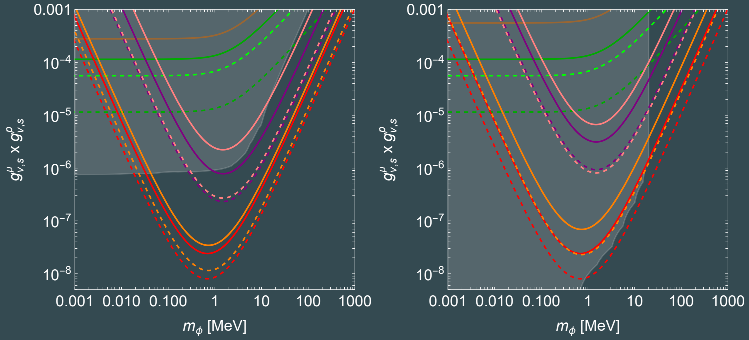
Set a 2-sigma bound to incorporate new physics

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

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)		

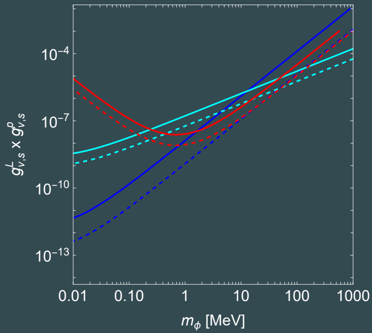
UPDATE from CP, C. Frugiuele (2107.13512)

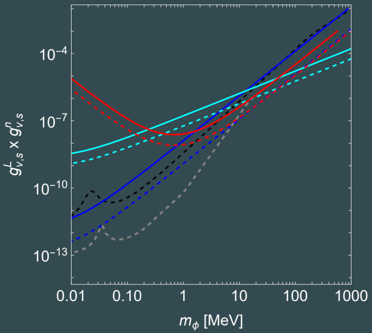


Muonic vs electronic forces

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)





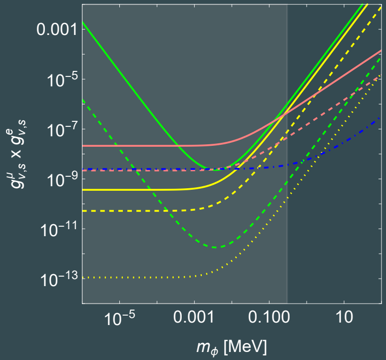
Previous talk by S. Scheidegger

Muonium spin-independent

$1S-2S$		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)

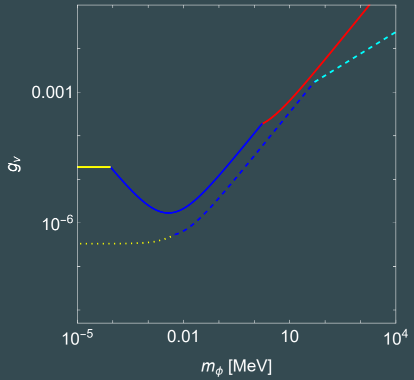


See G. Janka's talk on next!

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

Best bounds combined

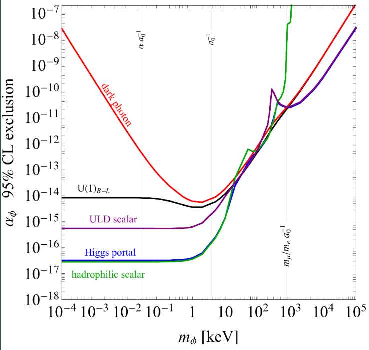
$g_v^\mu = g_v^e = g_v^p$

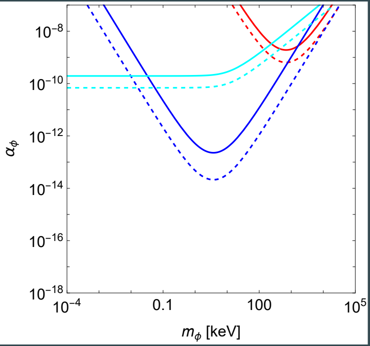


e.g. dark photon

Global fit to all parameters

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





See J.P. Karr's talk tomorrow!

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 below keV for spin-independent interactions
  - Prospective improvement with MuMASS and new HFS measurement
- Atomic probes are an **independent** and **robust** test of new physics
- Prospective improvement in **near future** experiments

Thank you!

Bounds: muonic vs electronic forces