

# New physics in atomic spectroscopy

## an EFT approach

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September 26, 2019

Next Frontiers in the Search for Dark Matter, GGI Florence

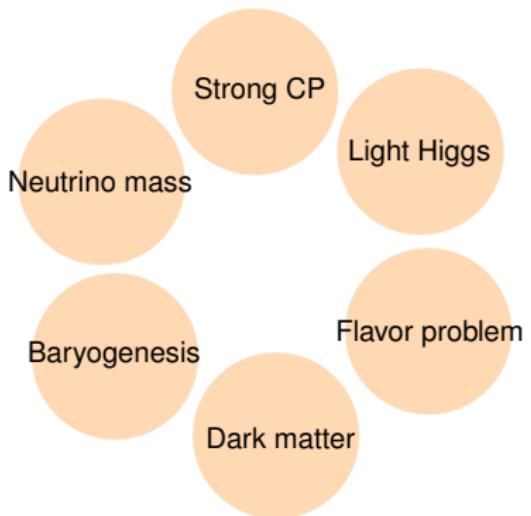


Work in collaboration with C. Frugiuele

# Outline

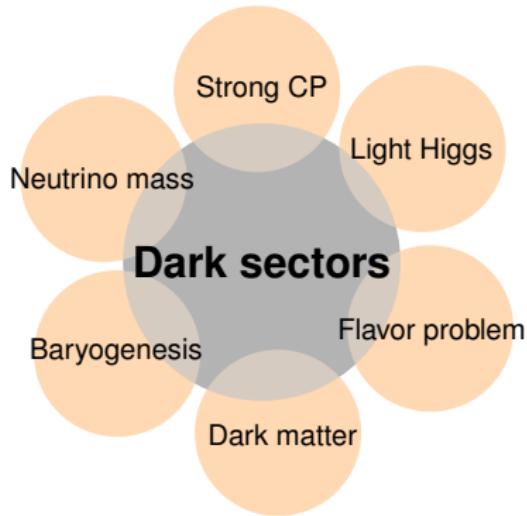
1. Dark sectors and the precision frontier
2. EFTs for bound states
3. EFT for a new boson exchange
4. Phenomenological bounds
5. Outlook

# Dark sectors and the precision frontier



# Dark sectors and the precision frontier

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



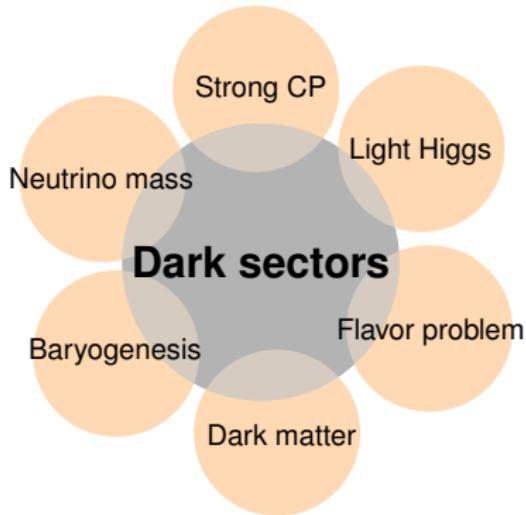
Intensity frontier: produced at fixed target experiments or low energy colliders

Precision frontier: looked for in precision experiments

- less model dependence

# Dark sectors and the precision frontier

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



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Precision frontier: looked for in precision experiments

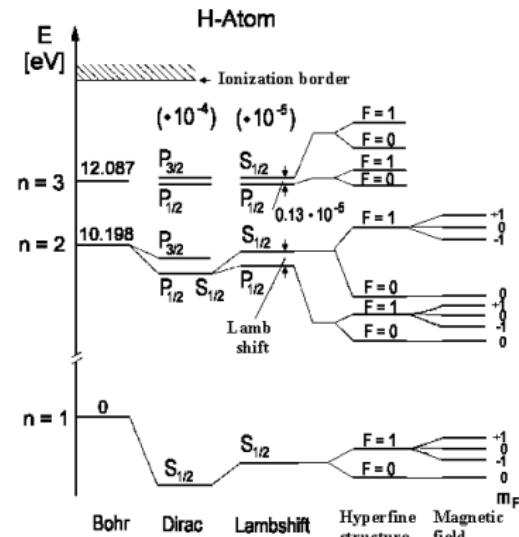
- less model dependence

Focus in Sub-GeV scales

# Precision spectroscopy

- **Experimentally:**

Measurements of energy shifts can be very accurate,



E.g.

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

Garching 2010

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

Karshemboin 2005

- **Theoretically:**

simple atomic systems can be calculated very precisely: QED  
up to the nuclear structure corrections: low energy QCD

# 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: $m_r$	→	$m_r$
Soft scale: $ \mathbf{p} $	→	$m_r\alpha$
Ultrasoft scale: $E$	→	$m_r\alpha^2$

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

Scales are well separated

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

# 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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- The pNRQED Lagrangian:

$$L_{\text{pNRQED}} = \int d^3\mathbf{x} d^3\mathbf{X} S^\dagger(\mathbf{x}, \mathbf{X}, t) \left\{ i\partial_0 - \frac{\mathbf{p}^2}{2m_r} + \frac{\mathbf{p}^4}{8m_\mu^3} + \frac{\mathbf{p}^4}{8m_p^3} - \frac{\mathbf{P}^2}{2M} \right.$$
$$\left. - V(\mathbf{x}, \mathbf{p}, \sigma_1, \sigma_2) + e \left( \frac{Z_1 m_2 + Z_2 m_1}{m_2 + m_1} \right) \mathbf{x} \cdot \mathbf{E}(\mathbf{X}, t) \right\} S(\mathbf{x}, \mathbf{X}, t) - \int d^3\mathbf{X} \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

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$$\left. - \mathbf{V}(\mathbf{x}, \mathbf{p}, \sigma_1, \sigma_2) + e \left( \frac{Z_1 m_2 + Z_2 m_1}{m_2 + m_1} \right) \mathbf{x} \cdot \mathbf{E}(\mathbf{X}, t) \right\} S(\mathbf{x}, \mathbf{X}, t) - \int d^3\mathbf{X} \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

# pNRQED

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+ corrections to the potential

+ interaction with other low-energy degrees of freedom

- The potential:

$$V(\mathbf{x}, \mathbf{p}, \sigma_1, \sigma_2) = V^{(0)}(r) + V^{(1)}(r) + V^{(2)}(r) + \dots ,$$

$$V^{(n)} \propto \frac{1}{m_\mu^n}, \quad V^{(n,r)} \propto \frac{1}{m_\mu^n} \alpha^r + \text{expansions in small parameters}$$

# A multi-scale problem

On top of the expansion parameter  $\alpha$  there are other mass scales.

Scales in H:

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

Small expansion parameters:

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

Energy levels:  $E_H = E_n^C \left(1 + \textcolor{blue}{c}_1 \frac{\alpha}{\pi} + \dots + \textcolor{brown}{c}_4 \left(\frac{\alpha}{\pi}\right)^4 + \dots\right)$   $E_n^C = \frac{-m_r \alpha^2}{2n^2}$

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

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

# A multi-scale problem

On top of the expansion parameter  $\alpha$  there are other mass scales.

Scales in  $\mu\text{H}$ :

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

Small expansion parameters:

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

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

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

# Why EFTs are the way to go:

Effective Field Theories approach:

- model independent
- efficient
- systematic (power counting)



# EFT for a new boson exchange

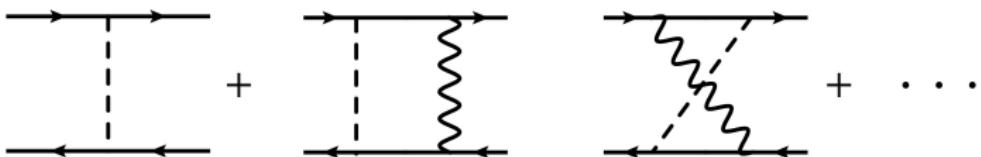
- New spin-1 or spin-0 boson with generic couplings to fermions

$$\mathcal{L}_\psi = \bar{\psi}(i\partial^\mu - m)\psi - y_S \bar{\psi}\phi\psi - i y_P \bar{\psi}\gamma^5\phi\psi - g_V \bar{\psi}\gamma^\mu A_\mu\psi - i g_A \bar{\psi}\gamma^5\gamma^\mu A_\mu\psi$$

- Scale hierarchy:

- ▶ New parameters:  $g_{NP}$  and  $m_{NP}$
- ▶ Reasonable assumption:  $g_{NP}^2 \ll 4\pi\alpha$

Compute contribution up to  $O(g_{NP}^2)$



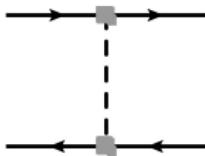
# EFT for a new boson exchange

What about  $m_{NP}$ ??

- If  $m_{NP} \lesssim m_r \alpha \sim |\mathbf{q}| \sim \frac{1}{r}$

The tree level propagator is dynamical:  $\sim \frac{1}{\mathbf{q}^2 + m_{NP}^2}$

tree level matching produces the leading order contribution



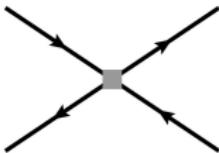
# EFT for a new boson exchange

What about  $m_{NP}$ ??

- If  $m_{NP} \gg m_r \alpha \sim |\mathbf{q}| \sim \frac{1}{r}$

The tree level propagator is **NOT** dynamical:  $\sim \frac{1}{\mathbf{q}^2 + m_{NP}^2} \sim \frac{1}{m_{NP}^2}$

The leading order contribution is a contact interaction



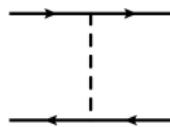
the tree level matching **not necessarily** produces the leading order contribution

# EFT for a new boson exchange

What about  $m_{NP}??$

- If  $m_{NP} \gg m_r \alpha \sim |\mathbf{q}| \sim \frac{1}{r}$

e.g. Pseudoscalar exchange



$$i\mathcal{M} \sim \frac{\sigma_1^i}{m_1} \frac{\sigma_2^j}{m_2} \frac{\mathbf{q}^i \mathbf{q}^j}{m_{PS}^2} \sim O(v^5)$$



$$i\mathcal{M} \sim \alpha \frac{\sigma_1^i}{m_1} \frac{\sigma_2^j}{m_2} \int \frac{d^D l}{(2\pi)^D} \frac{l^\mu l^n u}{l^2 - m_{PS}^2} \sim O(v^4)$$

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

# The NREFT

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

Lagrangian up to  $O(m_r g_{NP}^2 \alpha^3)$

$$\begin{aligned}\mathcal{L}_{\text{NR}} = & \psi^\dagger \left\{ i\partial_0 + \frac{\partial^2}{2m} \right\} \psi + (\psi \rightarrow \chi_c) \\ & + y_S \left[ -O_1^S + \frac{c_D^S}{8m^2} O_2^S + \frac{ic_S^S}{8m^2} O_3^S + (\psi \rightarrow \chi_c) \right] + y_P \left[ \frac{c_F^P}{2m} O_1^P - (\psi \rightarrow \chi_c) \right] + \mathcal{L}_{4\psi}\end{aligned}$$

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$$O_1^S = \psi^\dagger \phi \psi, \quad O_2^S = \psi^\dagger \boldsymbol{\sigma} \cdot (\nabla \cdot (\nabla \phi) - (\nabla \phi) \cdot \nabla) \psi$$

$$O_3^S = \psi^\dagger \boldsymbol{\sigma} \cdot (\nabla \times (\nabla \phi) - (\nabla \phi) \times \nabla) \psi, \quad O_1^P = \psi^\dagger \boldsymbol{\sigma} \cdot (\nabla \phi - \phi \nabla) \psi$$

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For  $m_{NP} \sim |\mathbf{q}|$

$$\mathcal{L}_{4\psi} = \frac{d_s^{\text{ann}}}{m^2} \psi^\dagger \psi \chi_c^\dagger \chi_c + \frac{d_v^{\text{ann}}}{m^2} \psi \sigma \psi \chi_c \sigma \chi_c$$

Only for tree level annihilation if masses equal

# The NREFT

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

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For  $m_{NP} \sim m_r$

$$\mathcal{L}_{4\psi} = \frac{d_s}{m_1 m_2} \psi^\dagger \psi \chi_c^\dagger \chi_c + \frac{d_v}{m_1 m_2} \psi \sigma \psi \chi_c \sigma \chi_c$$

encodes the leading order contribution

# The pNREFT

$$L_{\text{pNREFT}} = \int d^3\mathbf{x} d^3\mathbf{X} S^\dagger(\mathbf{x}, \mathbf{X}, t) \left\{ i\partial_0 - \frac{\mathbf{p}^2}{2m_r} - \frac{\mathbf{P}^2}{2M} - V(\mathbf{x}, \mathbf{p}, \sigma_1, \sigma_2) \right\} S(\mathbf{x}, \mathbf{X}, t)$$

The leading order potentials:

$$V^S(r) = -y_S^{(1)} y_S^{(2)} \frac{e^{-m_{NP} r}}{r}, \quad V^V(r) = -(-1)^f g_V^{(1)} g_V^{(2)} \frac{e^{-m_{NP} r}}{r}$$

$f = (0)1$  for fermion-(anti)fermion potential  $\mathbf{S}_{12} = 3\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}} \boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$

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The leading order potentials:

$$V^P(r) = \frac{(-1)^r y_P^{(1)} y_P^{(2)}}{16\pi m_1 m_2} \left[ \frac{4}{3} \left( 4\pi \delta^{(3)}(\mathbf{r}) - \frac{m_\phi^2 e^{-m_\phi r}}{r} \right) \mathbf{S}_1 \cdot \mathbf{S}_2 - e^{-m_\phi r} \left( \frac{m_\phi^2}{3r} + \frac{m_\phi}{r^2} + \frac{1}{r^3} \right) \mathbf{S}_{12} \right]$$

$$V^A(r) = -\frac{g_A^{(1)} g_A^{(2)}}{4\pi} \left[ \frac{16}{3m_\phi^2} \left( \pi \delta^{(3)}(\mathbf{r}) - \frac{m_\phi^2 e^{-m_\phi r}}{r} \right) \mathbf{S}_1 \cdot \mathbf{S}_2 - \frac{e^{-m_\phi r}}{m_\phi^2} \left( \frac{m_\phi^2}{3r} + \frac{m_\phi}{r^2} + \frac{1}{r^3} \right) \mathbf{S}_{12} \right]$$

$$f = (0)1 \text{ for fermion-(anti)fermion potential } \mathbf{S}_{12} = 3\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}} \boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

# The energy levels

Compute potential in sertions in a quantum-mechanical fashion

$$\begin{array}{c} V \\ \hline \hline \otimes \end{array} + \begin{array}{c} V \\ \hline \hline \otimes \quad \otimes \end{array} + \dots$$

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

same bound form scalar and vector.

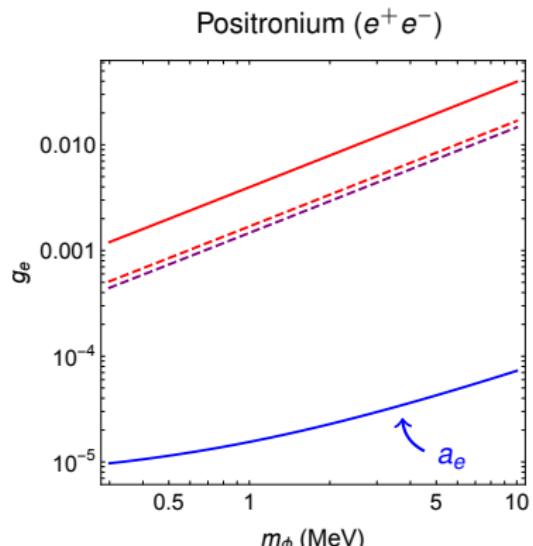
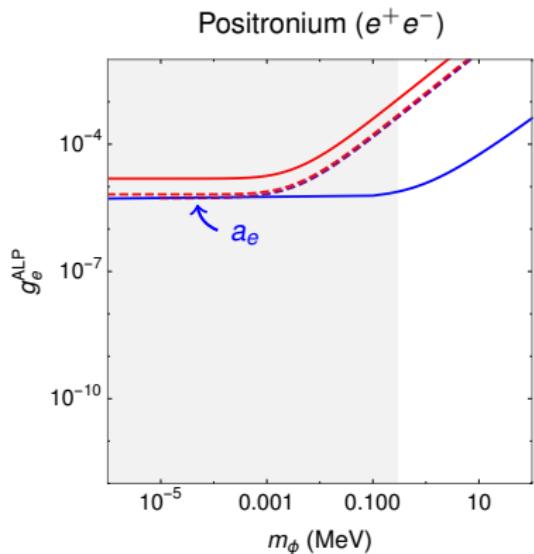
Set a 2-sigma bound for allowing the new contribution

$$|\Delta E_{a \rightarrow b}^{\text{NP}}| \leq |\Delta E_{a \rightarrow b}^{\text{exp}} - \Delta E_{a \rightarrow b}^{\text{the}}| \lesssim 2\sigma_{\text{Max}}$$

# Phenomenological bounds: scalar

From **1S-2S** and  $n = 30$  Rydberg:

$$\sigma_{\max} = \sigma_{\text{exp}} = 3.2 \text{ MHz}, \sigma_{\text{theo}} = 0.58 \text{ MHz} \quad \sigma_{\max} = \sigma_{\text{projected}} = 0.5 \text{ MHz}$$

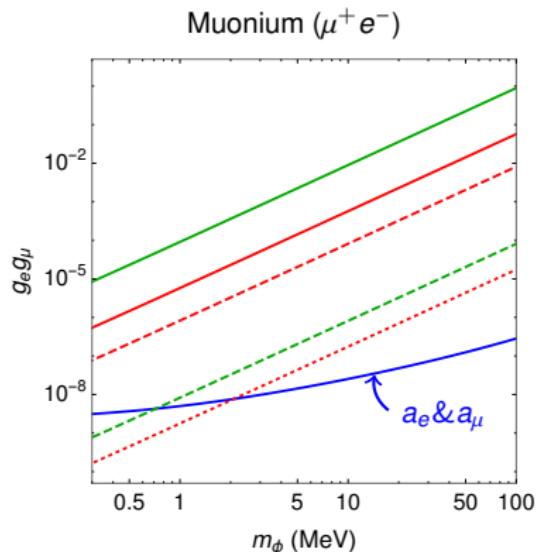
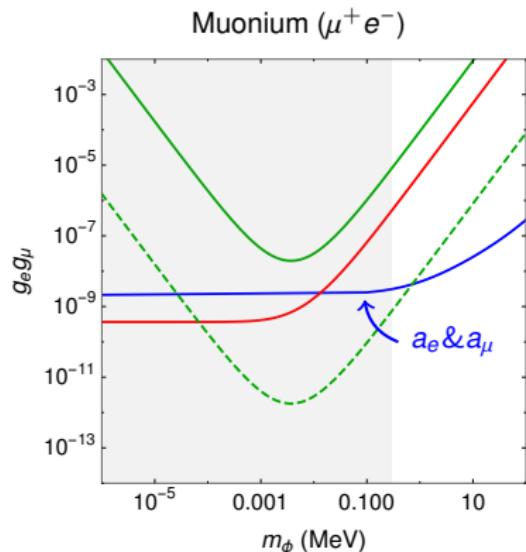


# Phenomenological bounds: scalar

From 1S-2S and Lamb shift:

$$\sigma_{\max} = \sigma_{\text{exp}} = 9.8 \text{ MHz}, \sigma_{\text{theo}} = 1.4 \text{ MHz},$$

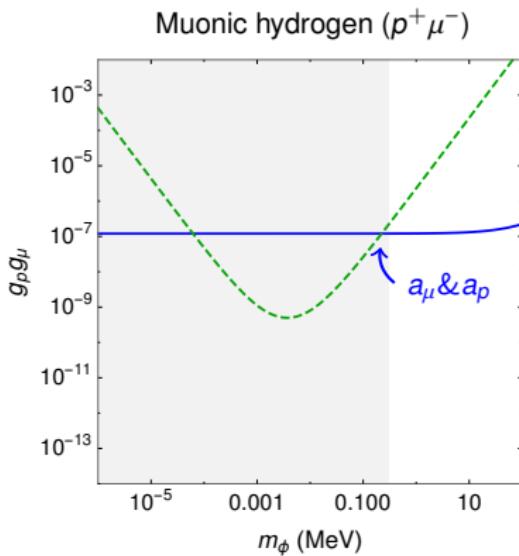
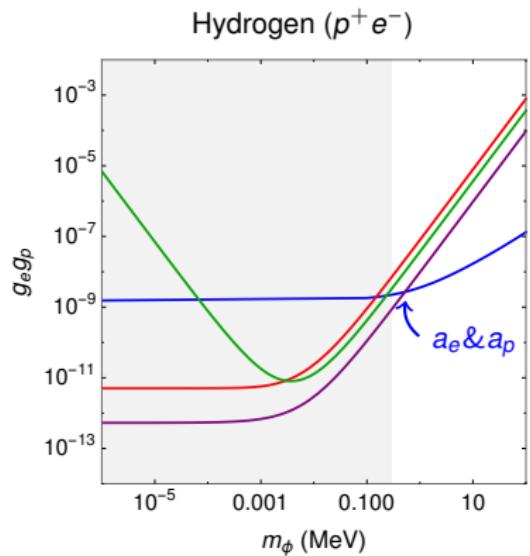
$$\sigma_{\max} = \sigma_{\text{exp}} = 22 \text{ MHz}, \sigma_{\text{theo}} = 0.002 \text{ MHz}$$



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

# Phenomenological bounds: scalar

From 1S-2S Lamb shift, Rydberg:



PRELIMINARY

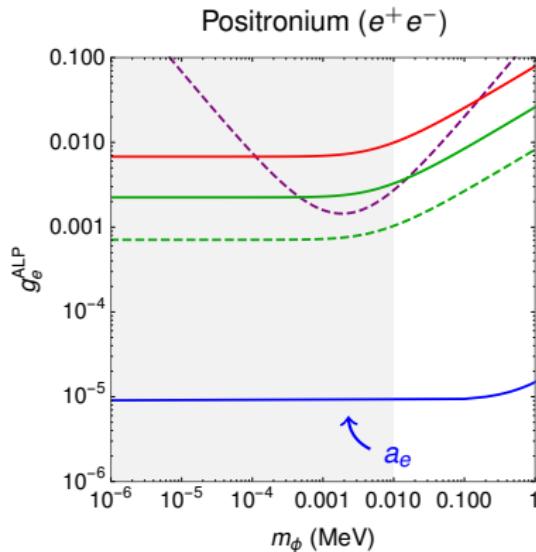
# Phenomenological bounds: pseudoscalar

From 1S-2S and HFS, Ultrafine:

$$\sigma_{\max} = 3.2 \text{ MHz}, \sigma_{\text{theo}} = 0.58 \text{ MHz}$$

$$\sigma_{\max} = \sigma_{\text{exp}} = 2.1 \text{ MHz}, \sigma_{\text{theo}} = 0.22 \text{ MHz}$$

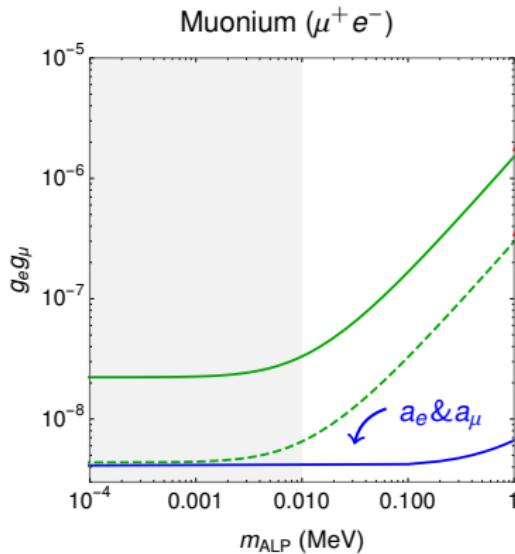
$$\sigma_{\max} = \sigma_{\text{projected}} = 2.6 \text{ kHz}$$



# Phenomenological bounds: pseudoscalar

From HFS:

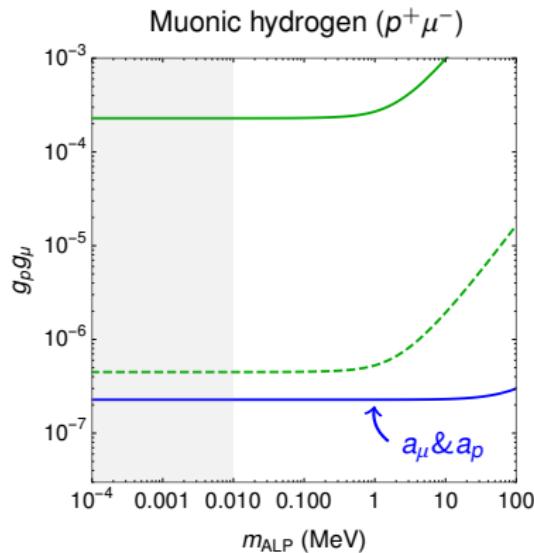
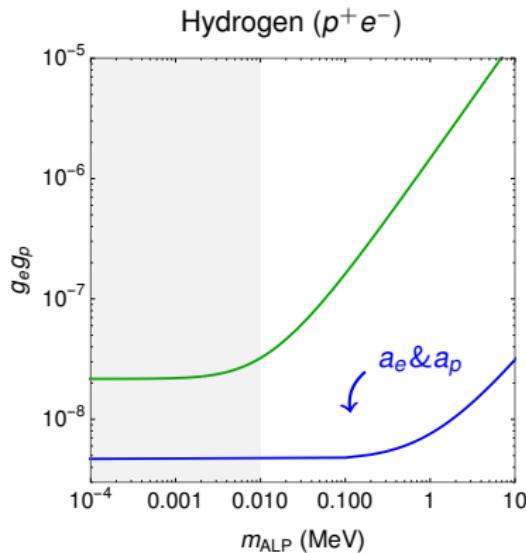
$$\sigma_{\max} = \sigma_{\text{th}} = 0.27 \text{ kHz}, \sigma_{\text{exp}} = 0.053 \text{ kHz}$$



Theoretical predictions limited by the uncertainty of the muon mass

# Phenomenological bounds: pseudoscalar

From HFS:



PRELIMINARY

Prospective 1S  $\mu$  p-hyperfine measurement at PSI, J-Parc RIKEN-RAL, FAMU

## Outlook

- Precision physics is an **efficient** probe for dark sectors
- **EFTs** are the right tool to describe energy transitions with precision
- **Best** laboratory bounds for spin-independent interactions
- **Independent** and **robust** test of new physics
- Prospective improvement in **near future** experiments

Thank you!