Testing Antimatter Couplings with (Matter-)Spectroscopy

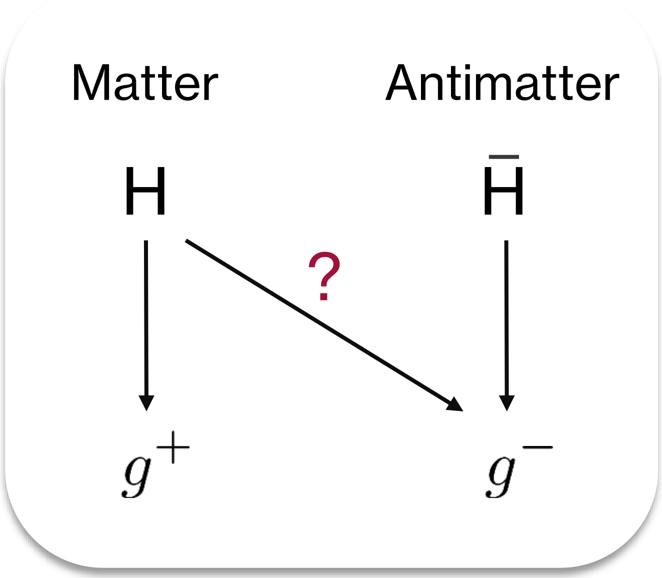
with Joerg Jaeckel (arXiv:2608.07656)

IPPP Workshop on High Precision Experiments for Light Dark Matter

Lucas Puetter, September 8th, 2026

Motivation

Can precision spectroscopy probe antimatter couplings – even using matter alone?



What if matter and antimatter differ only in their coupling to a light feebly interacting particle (FIP)?

What if we haven't seen DM yet (or have we at LZ?) because it couples predominantly to antimatter?

Lorentz-violating couplings

Altschul, arXiv:1211.6614

- Add a new light scalar with Lorentz-violating couplings

$$\mathcal{L}_Y = \frac{1}{2}\left(\partial_\mu \phi\right)\left(\partial^\mu \phi\right) - \frac{1}{2} m_\phi^2 \phi^2 - \phi \sum_F \bar{\psi}_F G_F \psi_F$$

$$G_F = g_F + i g'_F \gamma_5 + I_\mu^F \gamma^\mu + J_\mu^F \gamma_5 \gamma^\mu + \frac{1}{2} L_{\mu\nu}^F \sigma^{\mu\nu}$$

Lorentz-violating background vectors/tensors → Lead to different phenomenology

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Set $I_j^F = 0$

$$G_F = g_F + I_0^F \gamma^0$$

Lorentz-violating background vectors/tensors

Lead to different phenomenology

A light scalar with CPT-odd coupling

Altschul, arXiv:1211.6614

- Interactions with the:

$$\mathcal{L}_{\text{int}} = -\phi\bar{\psi}(g + I_0\gamma^0)\psi$$

0-component of CPT-violating background vector

- Extremely non-relativistic limit:

Matter coupling: $g^+ = g + I_0$

Antimatter coupling: $g^- = g - I_0$

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Matter coupling: $g^+ = g + I_0$

Antimatter coupling: $g^- = g - I_0$

$g = -I_0$

"Pure" antimatter coupling

- Matter and antimatter couplings differ ⇒ CPT violation

Frame dependence

- Background vector I_μ specifies a preferred direction in spacetime
- Passive (observer) Lorentz transformations: I_μ transforms as a 4-vector
- $I_j = 0$ is a choice in a specific frame!
- CMB rest frame is a natural choice, so we choose

$$\boxed{\begin{aligned} I_{j,\mathrm{CMB}} &\equiv I_j = 0 \\ I_{0,\mathrm{CMB}} &\equiv I_0 \neq 0 \end{aligned}}$$

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- Small relative velocity of Earth-bound labs: $v_{\mathrm{CMB}} \sim 10^{-3} c$
- Small corrections in lab:

$$I_{0,\mathrm{lab}} = \gamma_{\mathrm{CMB}} I_0$$
$$I_{j,\mathrm{lab}} = -\gamma_{\mathrm{CMB}} v_{\mathrm{CMB},j} I_0$$

Negligible for our purposes

Frame dependence

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- Small corrections in lab:

$$I_{0,\text{lab}} = \gamma_\text{CMB} I_0 \xrightarrow{g = -I_0} g + \gamma I_0 = \frac{v^2}{2} I_0 \neq 0$$

$$I_{j,\text{lab}} = -\gamma_\text{CMB} v_{\text{CMB},j} I_0$$

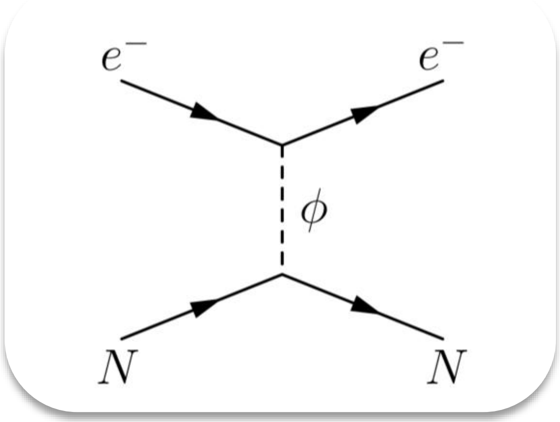
Negligible for our purposes

⇒ Moving Matter couples for pure antimatter coupling!

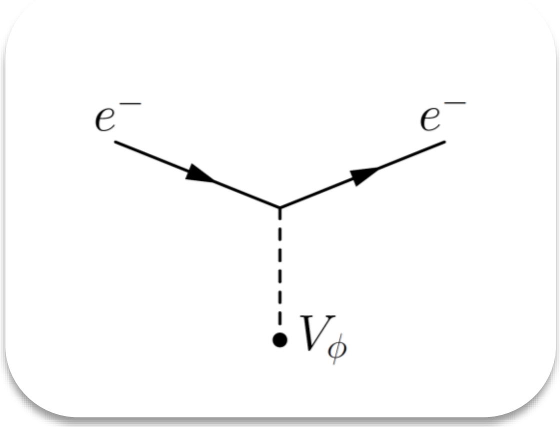
From new physics to a new potential

- New bosons imply new potentials

- This leads to energy shifts in atoms/ions



non-relativistic
nucleus



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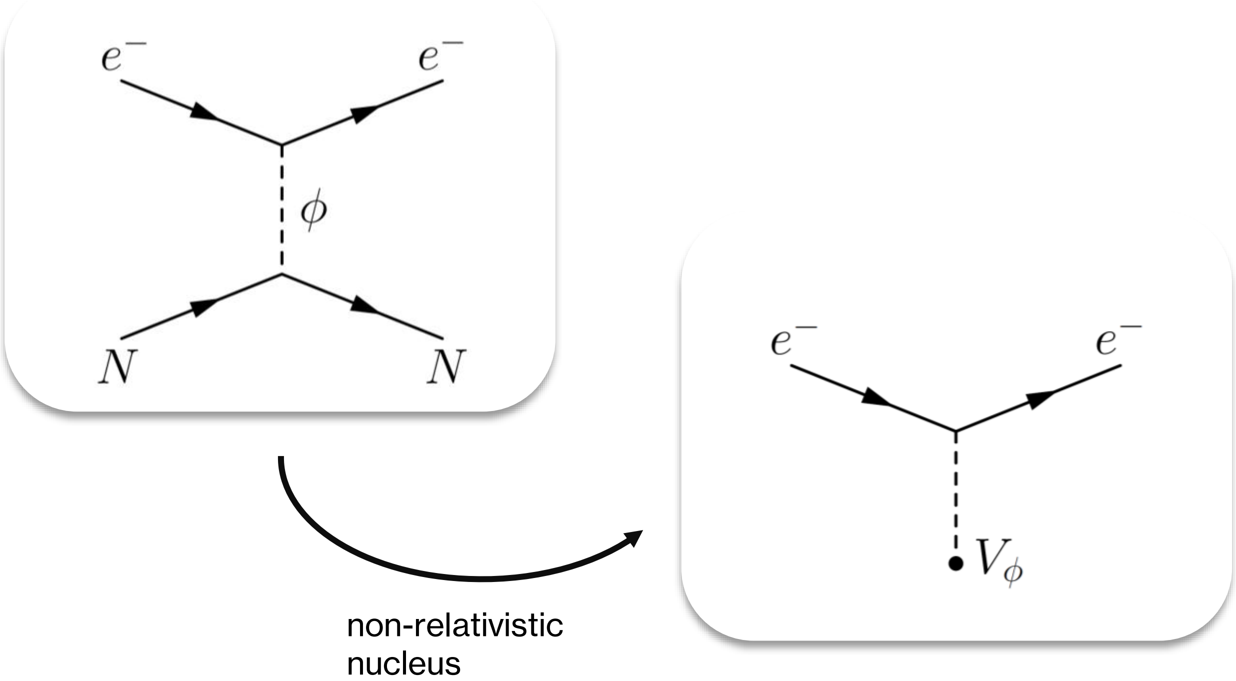

$$V^{p^\pm e^\mp}(r) = -\underbrace{\left(g_p \pm I_0^p\right)}_{g_p^\pm}\left[g_e \gamma^0 + I_0^e\right]\frac{e^{-m_\phi r}}{4\pi r}$$

From new physics to a new potential

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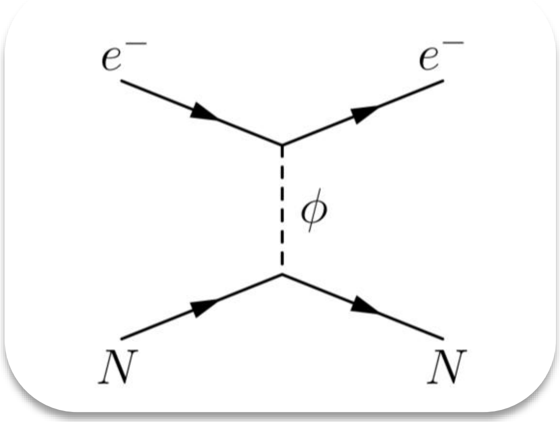

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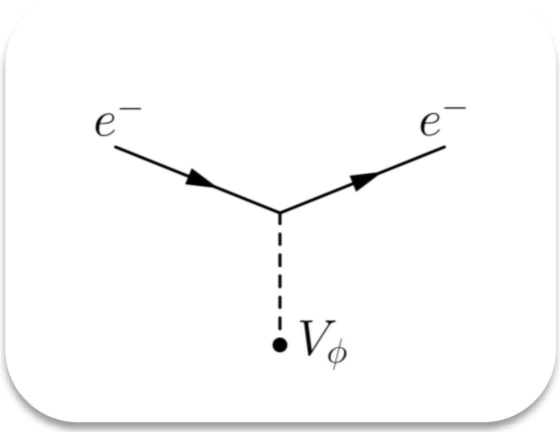
non-relativistic nucleus



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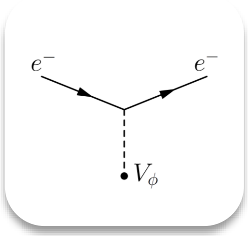
$\underbrace{\left(g_e \pm I_0^e\right)}_{g_e^\pm}$ in non-rel. limit

Energy shifts



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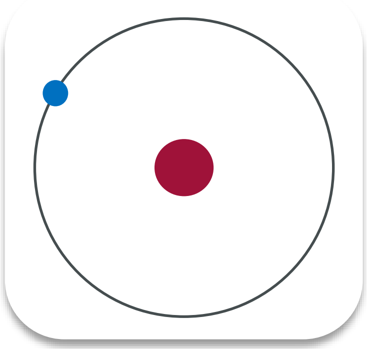


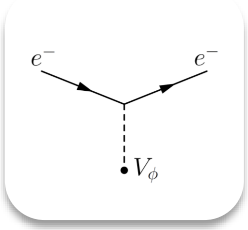
H spinor: $\psi_{\mathrm{H}} \sim \begin{pmatrix} G(r) \\ iF(r) \end{pmatrix}$

$\bar{\mathrm{H}}$ spinor: $\psi_{\bar{\mathrm{H}}} \sim \begin{pmatrix} -iF(r) \\ G(r) \end{pmatrix}$

$$F(r) \sim v_e G(r)$$

$$v_e \sim Z\alpha$$

Energy shifts



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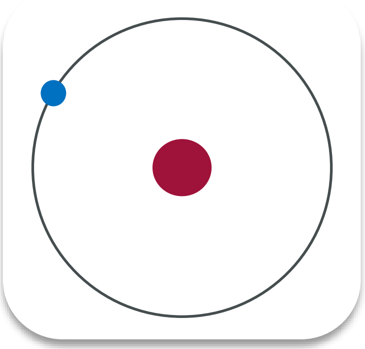

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$F(r) \sim v_e G(r)$

$v_e \sim Z\alpha$

1st order perturbation theory

$$\Delta E_{\mathrm{H}} = \langle e^- | V_\phi | e^- \rangle$$

Energy shifts

$$I_G \equiv \int \mathrm{d}r\, r e^{-m_\phi r} G(r)^2$$

$$I_F \equiv \int \mathrm{d}r\, r e^{-m_\phi r} F(r)^2$$

$$\Delta E_{\mathrm{H}} \simeq -\frac{g_p^+ - \frac{v_{\mathrm{CMB}}^2}{4} g_p^-}{4\pi} \left[g_e^+ \left(I_G + \frac{v_{\mathrm{CMB}}^2}{4} I_F \right) - g_e^- \left(\frac{v_{\mathrm{CMB}}^2}{4} I_G + I_F \right) \right]$$

- We can only constrain the products $g_p^+ g_e^+$, $g_p^+ g_e^-$, $g_p^- g_e^+$, $g_p^- g_e^-$

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negligible

- We can only constrain the products $g_p^+ g_e^+$, $g_p^+ g_e^-$, $g_p^- g_e^+$, $g_p^- g_e^-$
- Antimatter couplings appear at a velocity-suppressed levels in the matter energy correction
- Larger velocities ⇒ better access to antimatter couplings

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$\sim \frac{v_e^2}{4} I_G$

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$v_e > v_{\mathrm{CMB}}$ for H atoms almost at rest $\Rightarrow I_F$ dominates

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- Antimatter couplings appear at a velocity-suppressed levels in the matter energy correction
- Larger velocities ⇒ better access to antimatter couplings
- Antihydrogen: roles reversed, $\Delta E_{\bar{\mathrm{H}}} \simeq -\frac{g_p^- - \frac{v_{\mathrm{CMB}}^2}{4} g_p^+}{4\pi}\left[g_e^-\left(I_G + \frac{v_{\mathrm{CMB}}^2}{4} I_F\right) - g_e^+\left(\frac{v_{\mathrm{CMB}}^2}{4} I_G + I_F\right)\right]$

Fit to hydrogen and antihydrogen data

- Can discrepancies in $\delta = f_{\text{exp}} - f_{\text{theo}}$ be described by the model?
- Least-squares fit to obtain confidence regions for $g_p^+ g_e^+$, $g_p^+ g_e^-$, $g_p^- g_e^+$, $g_p^- g_e^-$

Index	Transition	Velocity	Theory (MHz)	Experiment (MHz)	Refs.
1	$1S_{1/2} - 2S_{1/2}$ (H)	~ 0	2 466 061 413.182 1 (44)	2 466 061 413.187 035 (10)	[58]
2	$1S_{1/2} - 3S_{1/2}$ (H)	~ 0	2 922 743 278.658 5 (51)	2 922 743 278.665 79 (72)	[59]
3	$2P_{1/2} - 2S_{1/2}$ (H)	0.01	1 057.832 30 (24)	1 057.829 8 (32)	[60]
4	$2S_{1/2} - 2P_{3/2}$ (H)	0.014	9 911.209 21 (24)	9 911.200 (12)	[61]
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7	$2S_{1/2} - 4P_{3/2}$ (H)	~ 0	616 521 388.670 7 (10)	616 521 388.670 9 (30)	[63]
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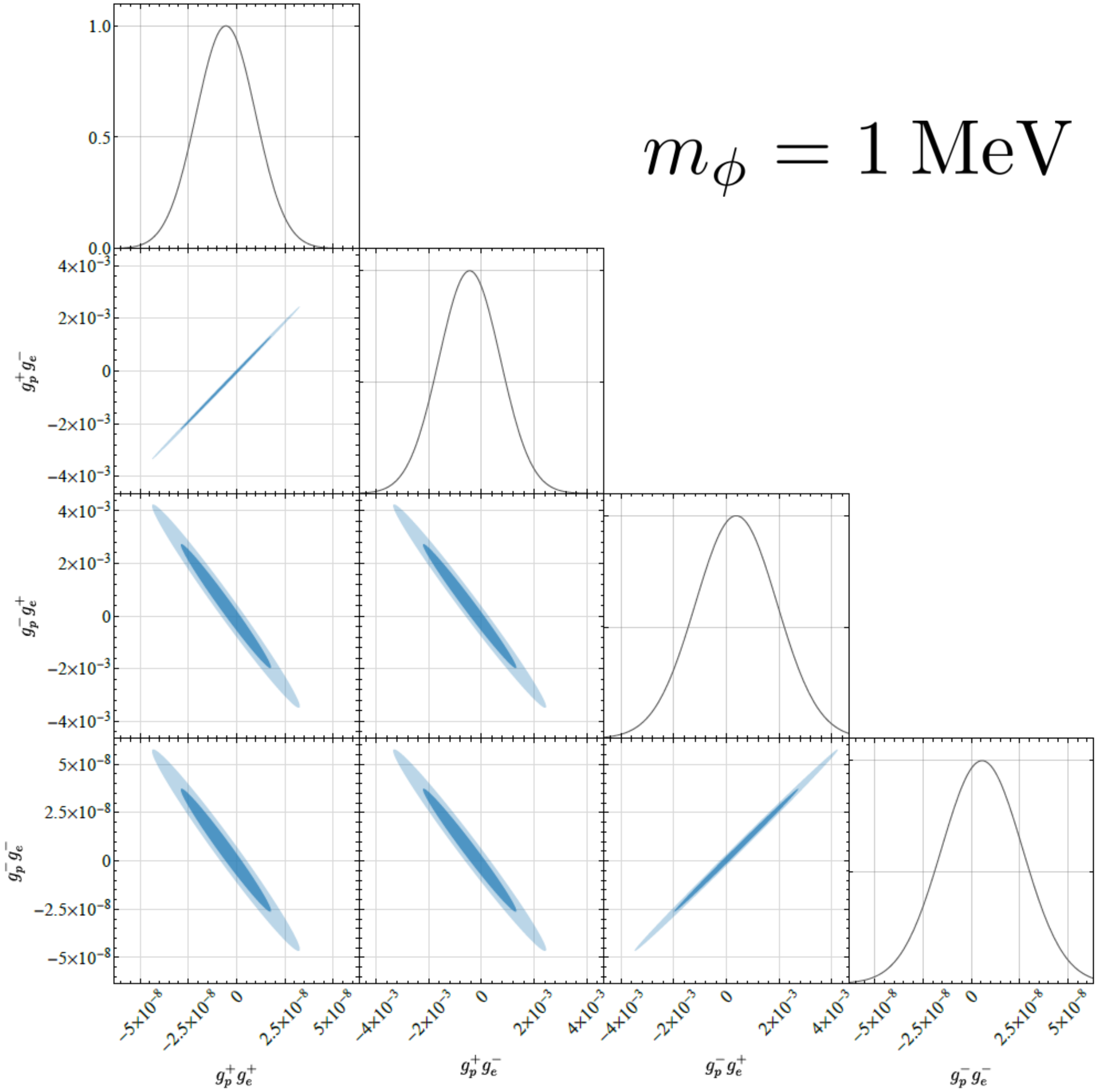
9	$2S_{1/2} - 6P_{3/2}$ (H)	~ 0	730 690 384.029 3 (12)	730 690 384.030 74 (66)	[64]
10	$2S_{1/2} - 8D_{5/2}$ (H)	~ 0	770 649 561.562 5 (13)	770 649 561.570 9 (20)	[65]
11	$1S_{1/2} - 2S_{1/2}$ ($\bar{H}$,$*_1$)	~ 0	2 466 061 413.182 1 (44)	2 466 061 413.189 2 (59)	[13, 66]
12	$1S_{1/2} - 2S_{1/2}$ ($\bar{H}$,$*_2$)	~ 0	2 466 061 413.182 1 (44)	2 466 061 413.186 2 (63)	[13, 66]
13	$1S_{1/2} - 2S_{1/2}$ ($\bar{H}$,$*_3$)	~ 0	2 466 061 413.182 1 (44)	2 466 061 413.180 0 (92)	[13, 66]
14	$2P_{1/2} - 2S_{1/2}$ ($\bar{H}$)	~ 0	1 057.832 30 (24)	1 046 (35)	[12]
15	$2P_{1/2} - 2P_{3/2}$ ($\bar{H}$)	~ 0	10 969.041 514 (6)	$10.88\ (19) \times 10^3$	[12]

Transition frequencies between hyperfine centroids

The ALPHA Collaboration, Nature 578, 375-380 (2020)
Baker et al., Nature Physics 21, 201-207 (2025)

CERN/Brice, Maximilien
https://physicsworld.com/wp-content/uploads/2025/11/21-11-25-alpha-cern.jpg

Marginalized confidence regions (H and $\bar{\text{H}}$ spectroscopy)



$$m_\phi = 1\,\mathrm{MeV}$$

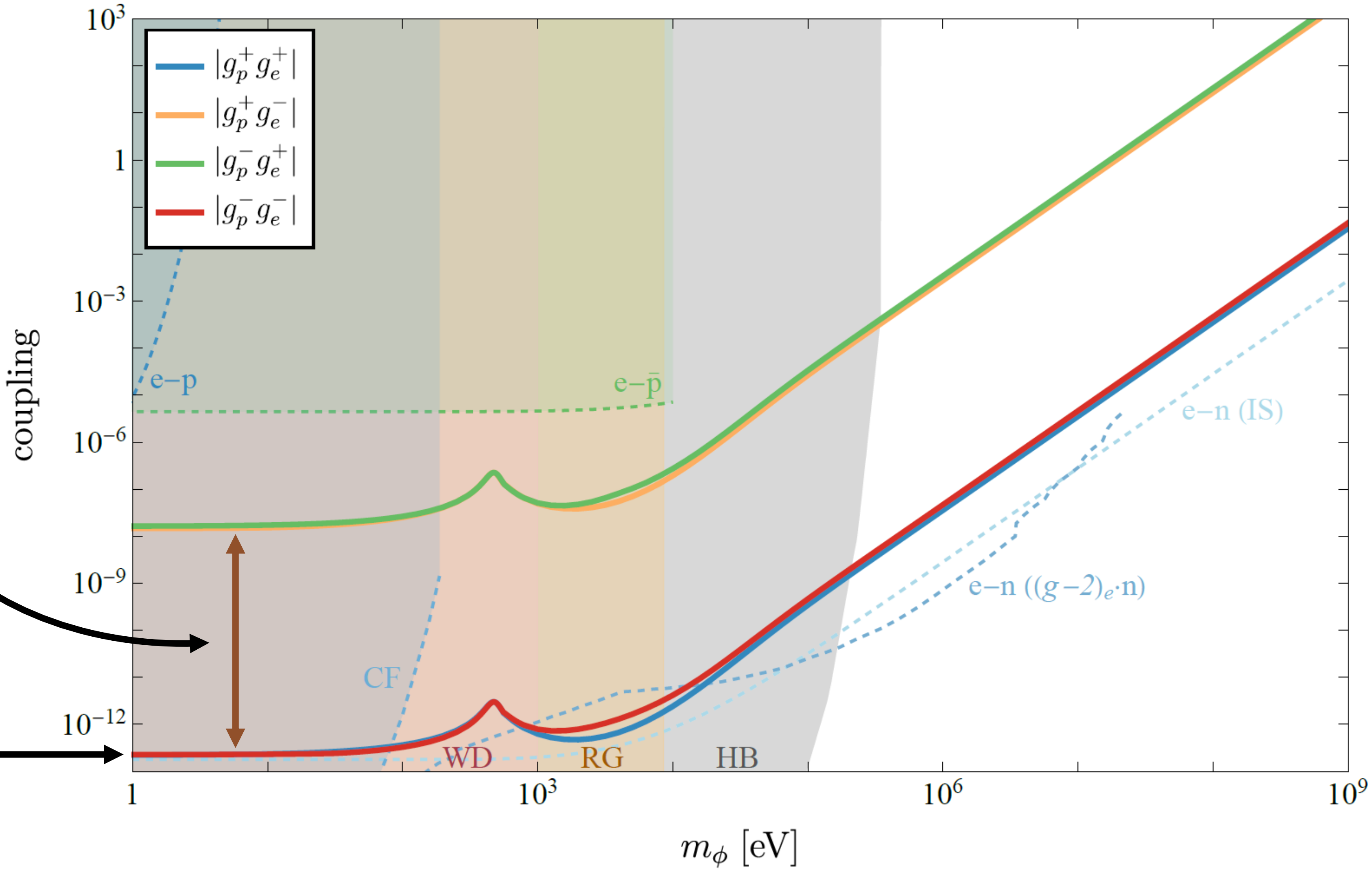
All fitted parameter combinations are compatible with zero at the 1σ level.

Mass-dependent bounds

$$\Delta E_{\rm H} \simeq -\frac{g_p^+ - \frac{v_{\rm CMB}^2}{4} g_p^-}{4\pi}\left[g_e^+\left(I_G + \frac{v_{\rm CMB}^2}{4} I_F\right) - g_e^-\left(\frac{v_{\rm CMB}^2}{4} I_G + I_F\right)\right]$$

$v_e^2/4 \sim \alpha^2/4 \sim 10^{-5}$ suppression of the matter-antimatter bounds

$\sigma_{\rm theo} \gtrsim \sigma_{\rm exp}$ for both H and $\overline{\rm H}$ in most precise measurements
⇒ bounds are equally strong



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- Our spectroscopy bounds are the strongest direct limits above astro bound threshold, $m_\phi \gtrsim 0.4\,\mathrm{MeV}$
- Comparison to naively translated bounds

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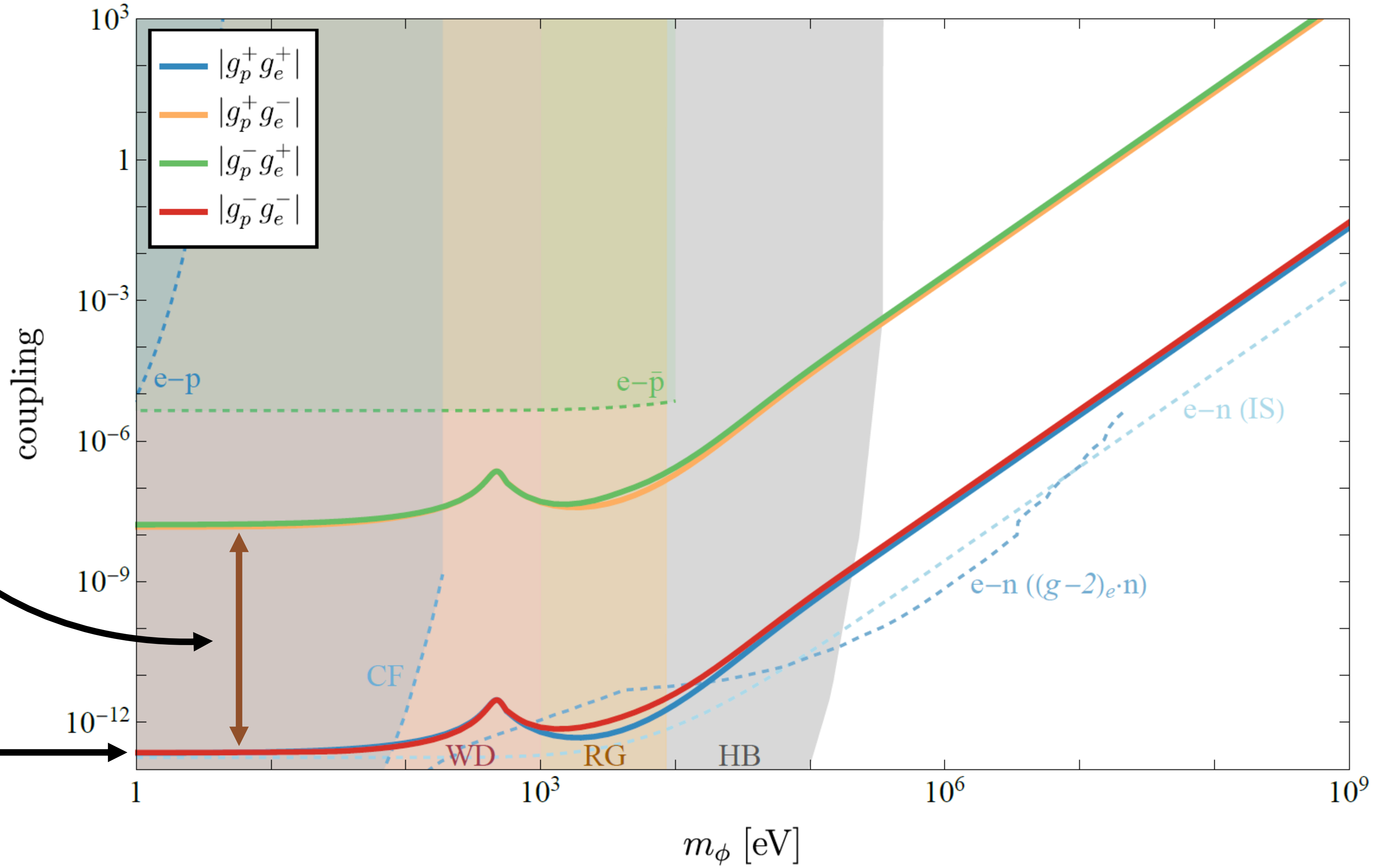

Bounds using only H spectroscopy

- Measurements with atoms at rest effectively probe

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$$\left(g_p^+ - \frac{v_{\mathrm{CMB}}^2}{4} g_p^-\right) g_e^-$$

- Only with atoms moving with $v_{\mathrm{exp}} > v_{\mathrm{CMB}}$ do we get four linearly independent coupling combinations, so we probe all four parameter products

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Bezginov et al. (2019)
Hagley & Pipkin (1993)

$\Rightarrow$ We can constrain antimatter couplings using exclusively matter measurements!

Bounds using only H spectroscopy

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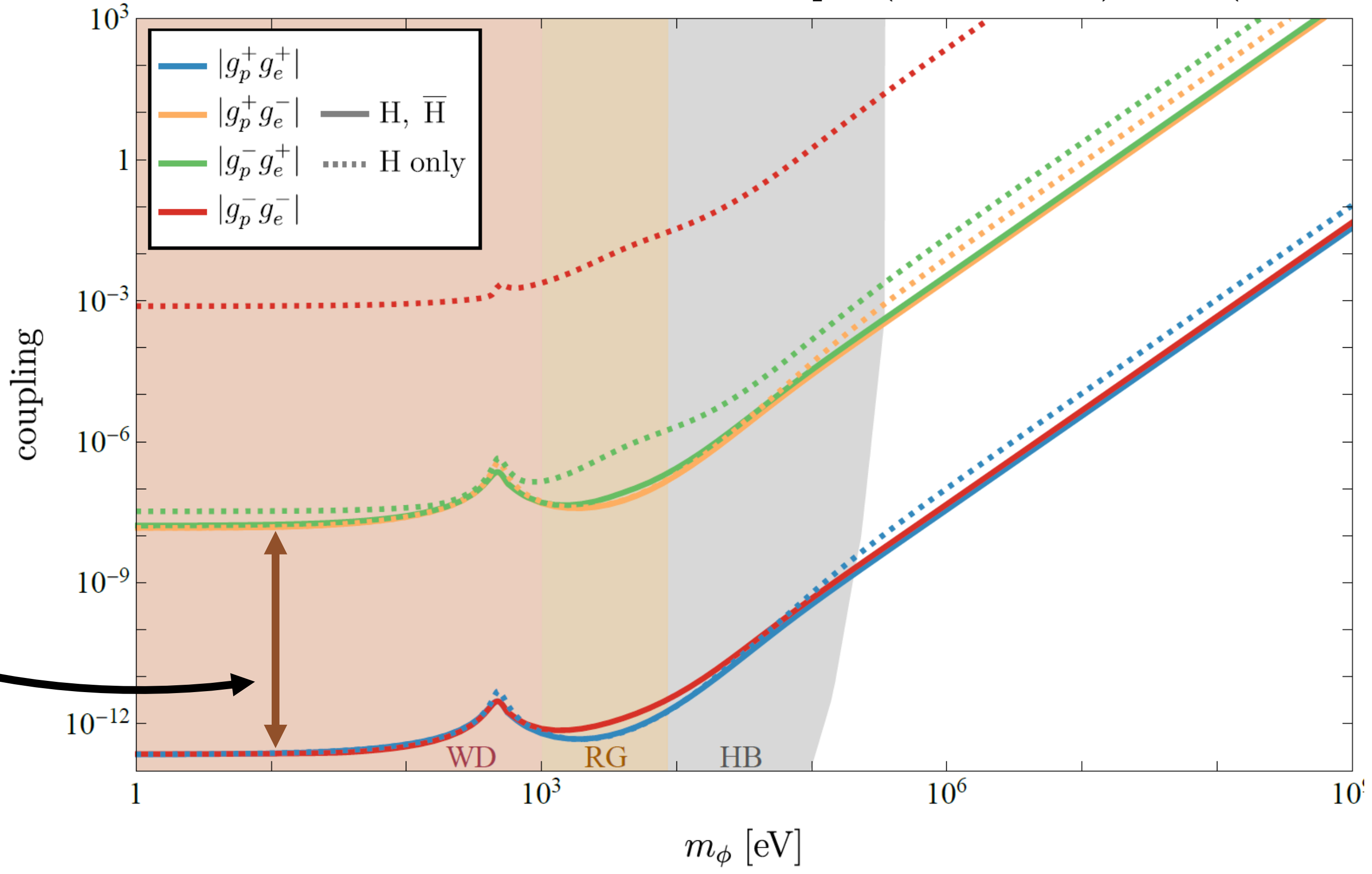

$v_e^2/4 \sim \alpha^2/4 \sim 10^{-5}$ suppression

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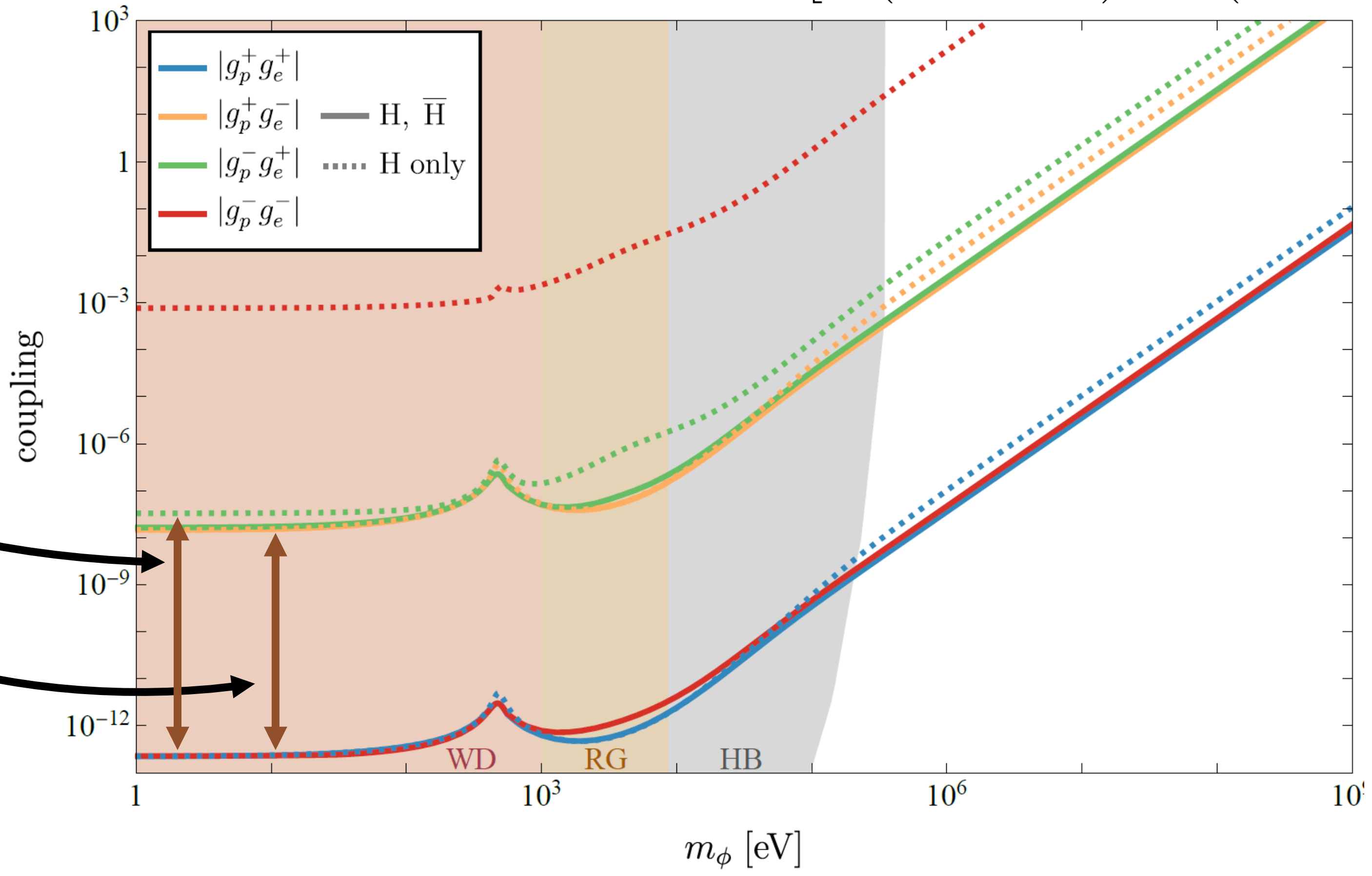

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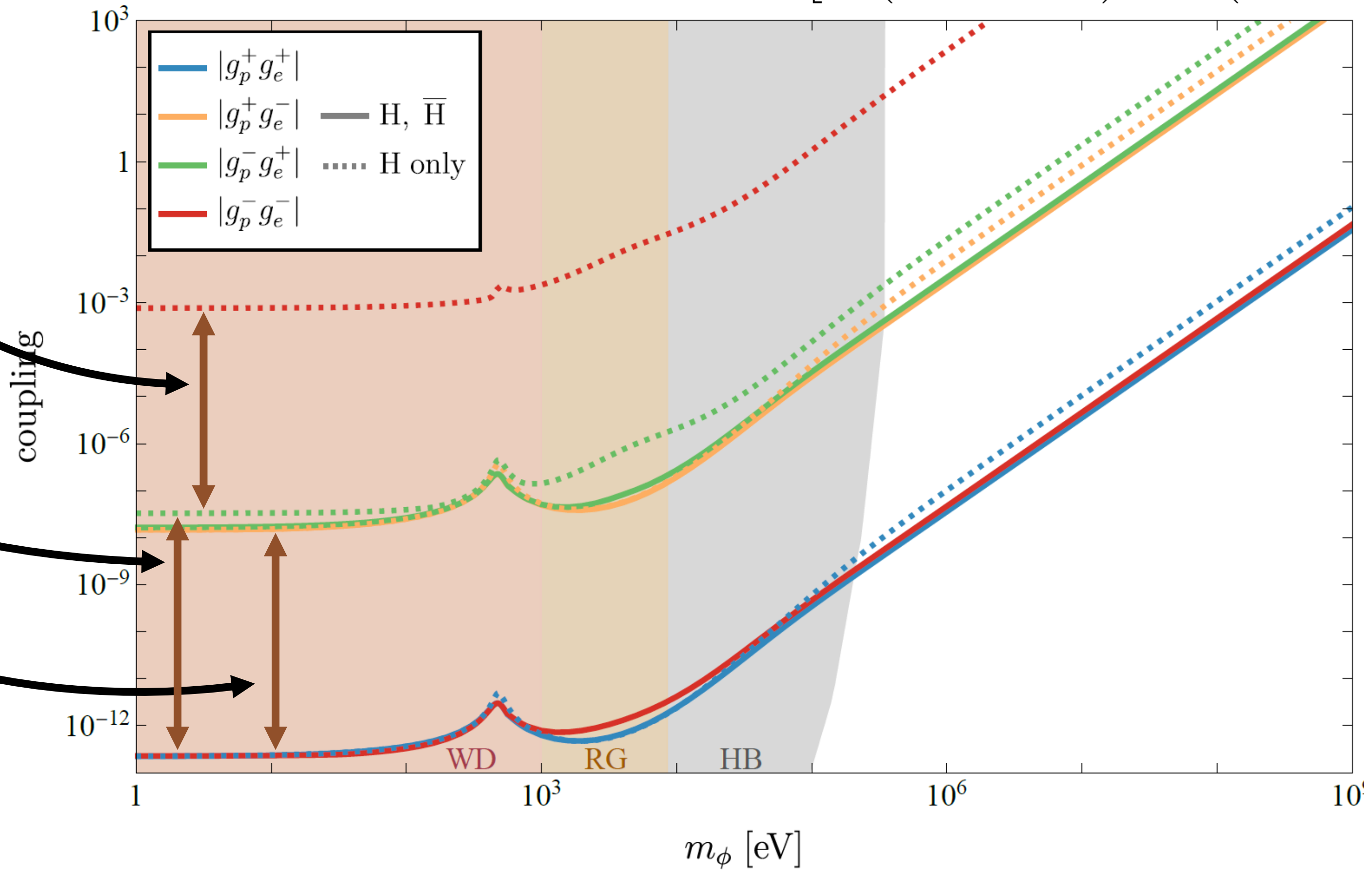

⇒ We can constrain antimatter couplings using exclusively matter measurements!
Can we do even better? → Larger beam velocities OR highly charged ions

Why highly charged ions?

- Lower experimental and theoretical precision in spectroscopy (still incredible!)
- Large nuclear uncertainty: size of nucleus and overlap with electron orbital
  - Not too problematic for spin-independent forces (specific differences can be used for spin-dependent forces, see, e.g. de Jonge, Heiße, Jaeckel et al., arXiv:2506.03274)

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- Compact orbitals $\langle r \rangle \sim 1/Z$ → good for short-range forces, probes larger mediator masses
- Larger beam and internal velocities $\implies$ better sensitivity to antimatter couplings

  → Electron velocity $v_e \sim Z\alpha$
- Enhancement by number of protons and neutrons

Highly charged ion bounds

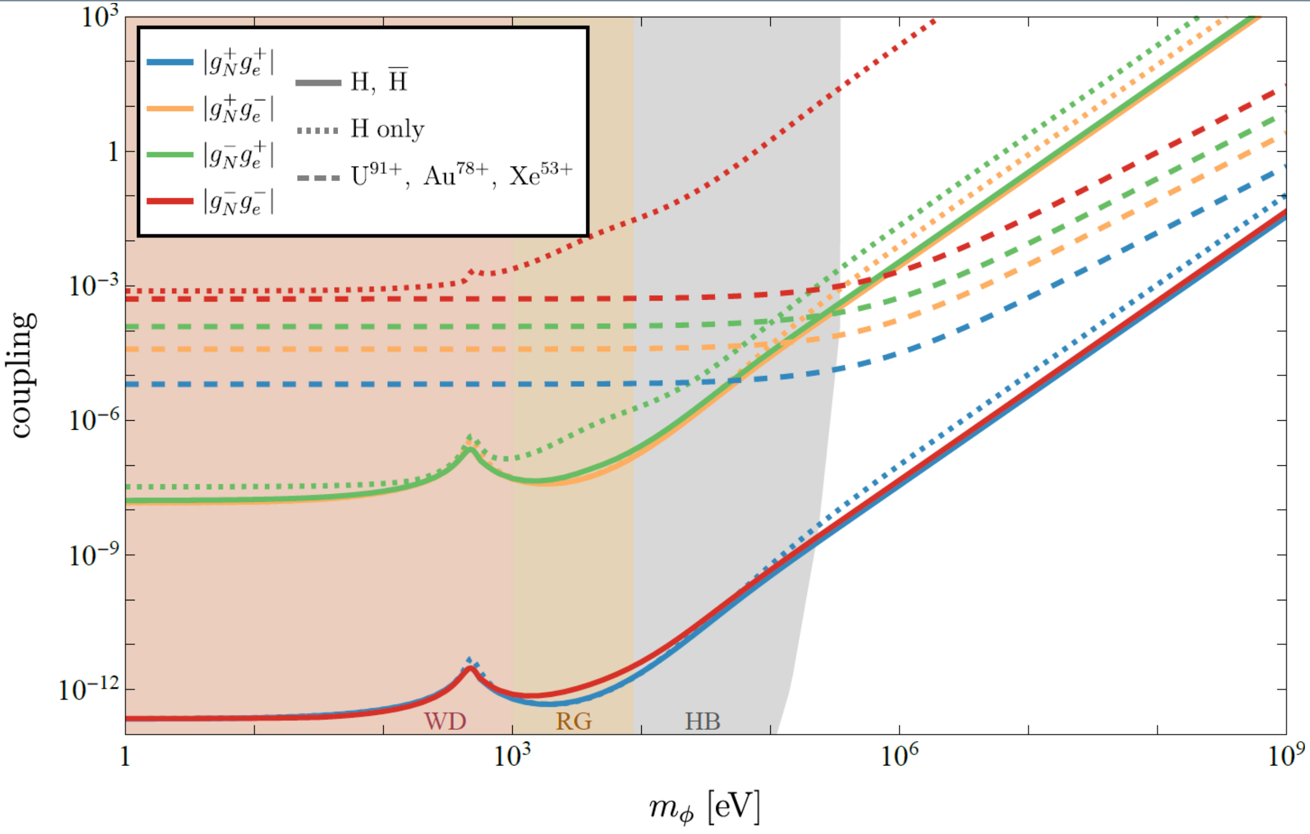
Hydrogenic $\quad v_{\rm exp} \gg v_{\rm CMB}$

Index	Ion	Transition	Velocity	Theory (eV)	Experiment (eV)	Refs.
1	$^{132}\mathrm{Xe}^{53+}$	$1\mathrm{S}_{1/2} - 2\mathrm{P}_{3/2}$	0.31	31 283.948 (19)	31 284.00 (287)	[85]
2	$^{197}\mathrm{Au}^{78+}$	$1\mathrm{S}_{1/2} - 2\mathrm{P}_{3/2}$	0.63	71 570.43 (22)	71 573.11 (790)	[86, 87]
3	$^{238}\mathrm{U}^{91+}$	$1\mathrm{S}_{1/2} - 2\mathrm{P}_{3/2}$	0.30	102 175.10 (54)	102 178.12 (433)	[87, 88]
4	$^{238}\mathrm{U}^{91+}$	$1\mathrm{S}_{1/2} - 2\mathrm{P}_{1/2}$	0.67	97 611.95 (54)	97 605.61 (1600)	[86, 87]

- Nucleons move with $v_N \sim 0.2 < v_{\rm exp}$ inside nucleus
- We assume equal coupling to protons and neutrons

$$\Delta E_{\rm Ion} \approx -A\frac{g_N^+ - \frac{v_{\rm exp}^2}{4} g_N^-}{4\pi}\left[g_e^+\left(I_G + \frac{v_{\rm exp}^2}{4} I_F\right) - g_e^-\left(\frac{v_{\rm exp}^2}{4} I_G + I_F\right)\right]$$

$+$ higher orders in $v_{\rm exp}$



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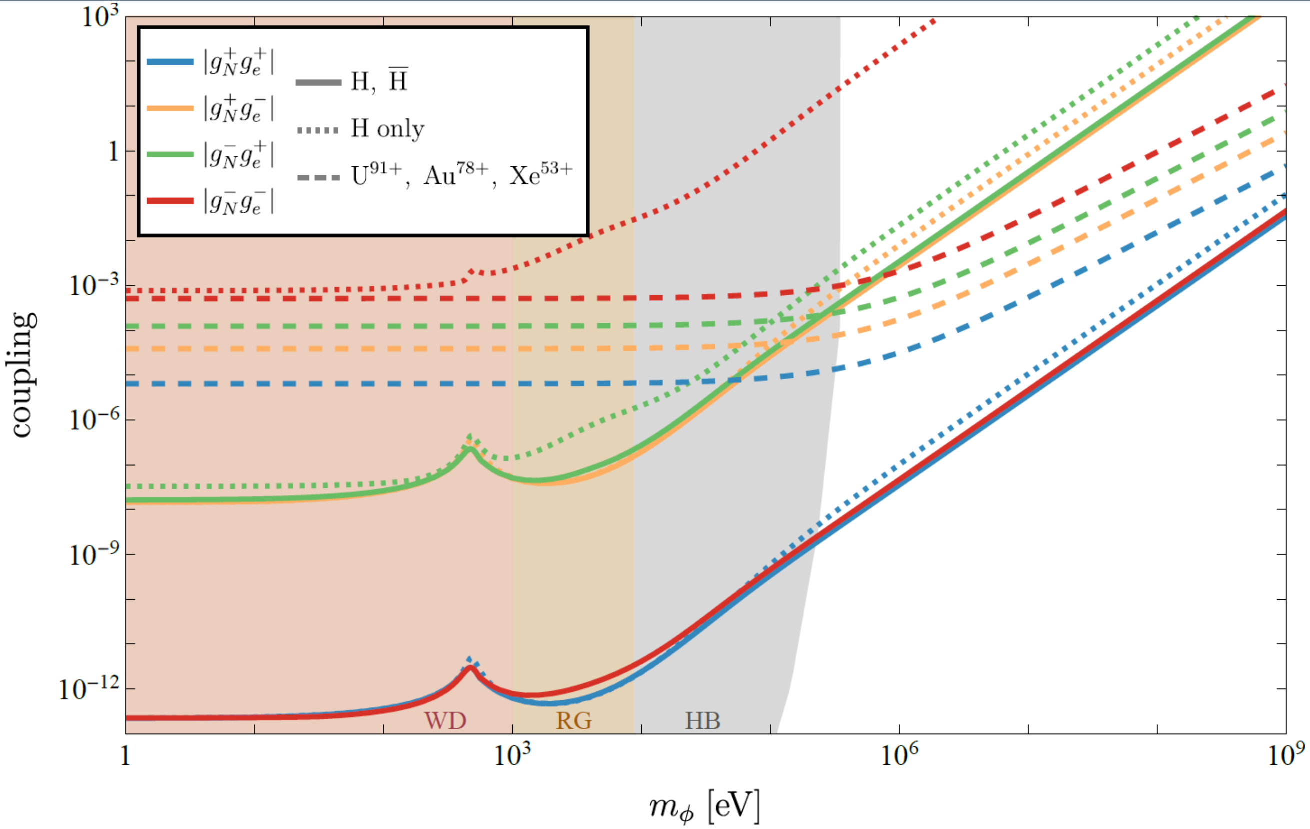
- Effects from finite nuclear size need to be included in more thorough treatment
  → Corrections important for $m_\phi \gtrsim 30\,\mathrm{MeV}$



Strong bounds from matter spectroscopy in regime of large mediator masses! Accessibility to antimatter bounds is strongly enhanced due to large velocities.

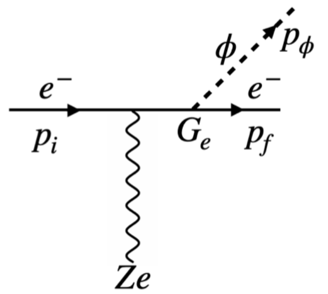
Astrophysical bounds

Raffelt (96)
Hardy, Lasenby, arXiv:1611:05852
Bottaro, Caputo, Raffelt, Vitagliano, arXiv:2303.00778
Dev, Mohapatra, Zhang, arXiv:2010.01124

- In the interior of stars, electrons and protons constantly scatter

  → Scalars are produced via bremsstrahlung

  → Very efficient energy loss channel, stringent limits



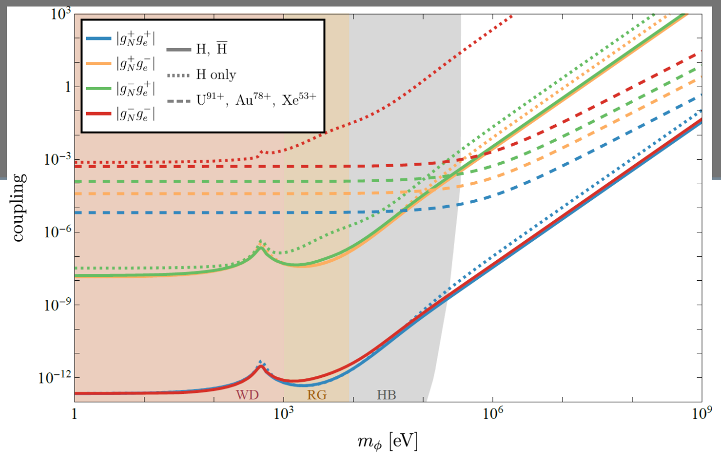
- Astrophysical systems mainly consist of particles rather than antiparticles

  ⇒ Relativistic corrections are required to access g_F^{-} as in the atomic case

  → High temperatures and electron degeneracy help

  → Stringent energy loss limits will lead to strong antimatter bounds despite suppression

Astrophysical bounds



- We make rough estimates to approximate astrophysical bounds
- Relevant bilinear that enters the spin-averaged matrix element:

Absorbs uncertainties of approximation

Suppressed by v^2

$$|\overline{\mathcal{M}}|^2 \propto |\overline{\mathcal{B}}|^2(\eta) \simeq \frac{(E_f+m)(E_i+m)}{4m^2}\left[g_F^+ - \eta \frac{g_F^- |\boldsymbol{p}_f||\boldsymbol{p}_i|}{(E_f+m)(E_i+m)}\right]^2$$

- Compare emissivity $Q_\phi \sim \langle |\overline{\mathcal{B}}|^2(\eta)\rangle$ with vanilla scalar case to estimate bounds

- Proper treatment for electron bremsstrahlung in red giants in Carenza, Jaeckel, Lucente, Poddar, Sherrill, Spannowsky, arXiv:2502.05263

- Part of ongoing work, Jaeckel, Lucente, LP, in preparation

Conclusions

- Matter alone can constrain antimatter couplings
- Velocity dependence is the key
- Highly charged ions extend the reach to heavier mediators
- Spectroscopy sets the most stringent limits on the couplings for $m_\phi \gtrsim 0.4\,\mathrm{MeV}$
- Stars can be used to set very stringent constraints on antimatter couplings

Thank you!

Astrophysical bounds: red giants

Bottaro, Caputo, Raffelt, Vitagliano, arXiv:2303.00778

$$g_F^{\mathrm{bound}} \lesssim \begin{cases} 4 \times 10^{-15} & \text{electrons,} \\ 7 \times 10^{-12} & \text{nucleons} \end{cases}$$

$$\downarrow$$

$$|g_e^+| \lesssim 10\, g_e^{\mathrm{bound}} \sim 4 \times 10^{-14},$$
$$|g_e^-| \lesssim \frac{80}{\eta} g_e^{\mathrm{bound}} \sim 3 \times 10^{-13},$$
$$|g_N^+| \lesssim 1.6\, g_N^{\mathrm{bound}} \sim 1 \times 10^{-11},$$
$$|g_N^-| \lesssim \frac{7.1 \times 10^5}{\eta} g_N^{\mathrm{bound}} \sim 5 \times 10^{-6}$$

Carenza, Jaeckel, Lucente, Poddar, Sherrill, Spannowsky, arXiv:2502.05263 (proper treatment)

$$23 g_e^2 + 59 g_e I_0^e + 56 I_0^{e\,2} < 2.2 \times 10^{-28} \equiv b$$

$$\downarrow$$

$$|g_e^+| < \sqrt{\frac{80}{1671} b} \simeq 3.3 \times 10^{-15},$$
$$|g_e^-| < \sqrt{\frac{184}{557} b} \simeq 8.5 \times 10^{-15}$$

Small difference due to degeneracy!

Result lies within the same ballpark ⇒ reasonable approximation as astrophysical bounds vastly exceed spectroscopic bounds in the relevant mass range.