Relic Challenges for Vector-Like Fermions as Connectors to a Dark Sector

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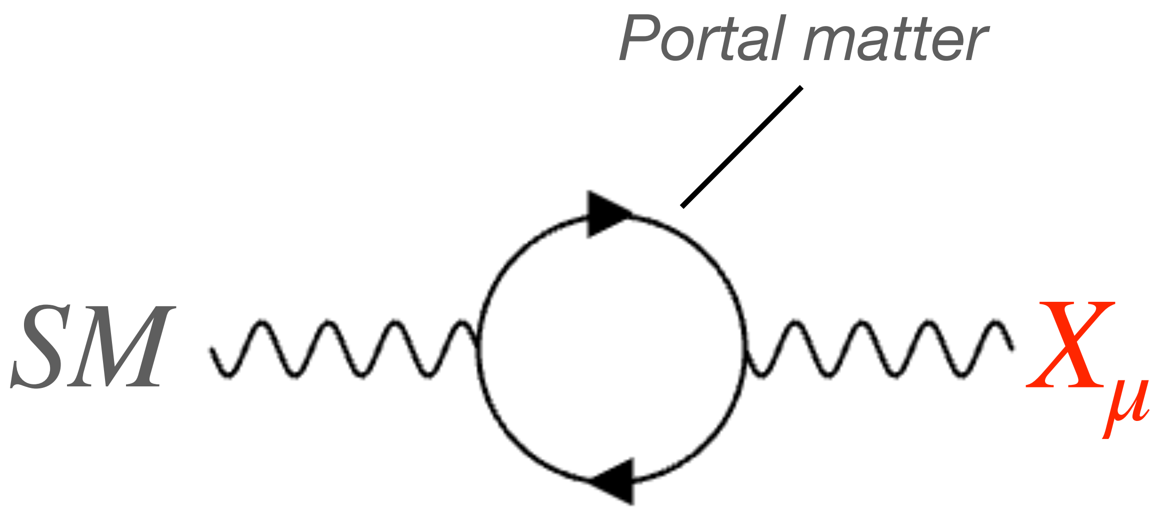
Alexandre Carvunis - IP2I - 04/11/2022

Motivations



Dark Gauge Forces and their portals

- A dark gauge sector is well motivated by extensions of the SM (e.g. unification or DM)

  $$\mathcal{G} = SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathcal{G}'$$

- Can couple to the SM via connector fermions or *portal matter*

- $\mathcal{G}' = U(1)_x$: Abelian dark forces can connect to the SM through kinetic mixing with $U(1)_Y$ gauge boson — $\Delta\mathcal{L} \propto B_{\mu\nu}X^{\mu\nu}$

- $\mathcal{G}' \neq U(1)_x$: Non-abelian dark forces require dimension-8 connector operator — $\Delta\mathcal{L} \propto (F_{\mu\nu})^2(X_{\mu\nu})^2$

Motivation

Challenges for portal matter

- Generically contains accidental symmetry (charge under $\mathscr{G}'$) that makes portal matter stable. If they are produced in the early Universe, this leads to a relic density of exotic fermions.
- Charged (EM or QCD) relic particles are clearly problematic
- Neutral (or weakly interacting) relics receive cosmological bounds from Dark Matter density, direct and indirect DM detection experiments. *These bounds can rule out naive models.*
- **Using a minimal model, this work demonstrates these challenges and introduces two mechanisms to avoid them.**

Minimal Model of Portal Matter to $U(1)_x$

$$\mathcal{G} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_x$$

- Dark photon X_μ with mass $m_x = 15$ GeV, obtained from a dark Higgs or Stueckelberg mechanism. 15 GeV is a benchmark point

EWSB

Neutral fermions P^0 and N mix

$$P \sim (1,2,-1/2;q_x) \qquad N \sim (1,1,0;q_x)$$

$$-\Delta\mathscr{L} = \left(\lambda \bar{P}\tilde{H}N + \text{h.c.}\right) + m_P\bar{P}P + m_N\bar{N}N$$

$$\tilde{H} = i\sigma_2 H^*$$

$\Rightarrow$

$$P^-,\ \psi_{1,2}$$

$$\begin{pmatrix} N \\ P^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

$$\tan(2\alpha) = \frac{2\lambda v}{m_P - m_N}$$

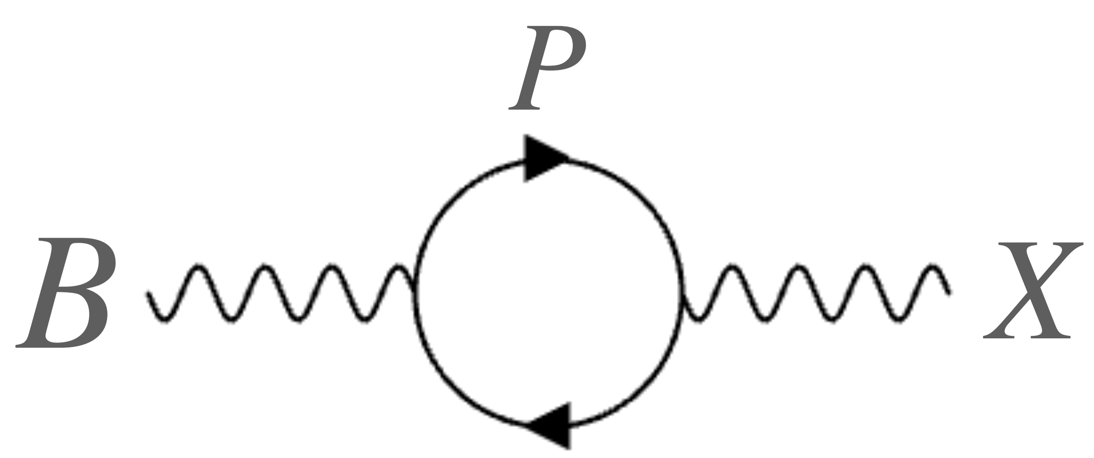
+ rotated interaction with Higgs + gauge bosons

- $m_{1,2} = \frac{1}{2}\left[m_N + m_P \mp \sqrt{(m_N - m_P)^2 + 4\lambda^2 v^2}\right]$ -> $m_1 \le m_P \le m_2$.

- ψ_1 lightest fermion charged under $U(1)_x$ and SM-neutral -> DM candidate

The Model

Portal Operators



- Kinetic mixing: $-\mathscr{L} \supset \dfrac{\epsilon}{2\,c_W} B_{\mu\nu} X^{\mu\nu}$

- One loop contribution:

$$\Delta\epsilon \simeq -\frac{1}{3\pi}\sqrt{\alpha\,\alpha_x}\, ln\left(\frac{\mu}{m_P}\right) \simeq -(3\times 10^{-3})\left(\frac{\alpha_x}{10\,\alpha}\right)^{1/2} ln\left(\frac{\mu}{m_P}\right) \approx -10^{-3}$$

- Can be made arbitrarily small without fine tuning by introducing a mirror copy of the connector fermions with opposite $U(1)_x$ charges

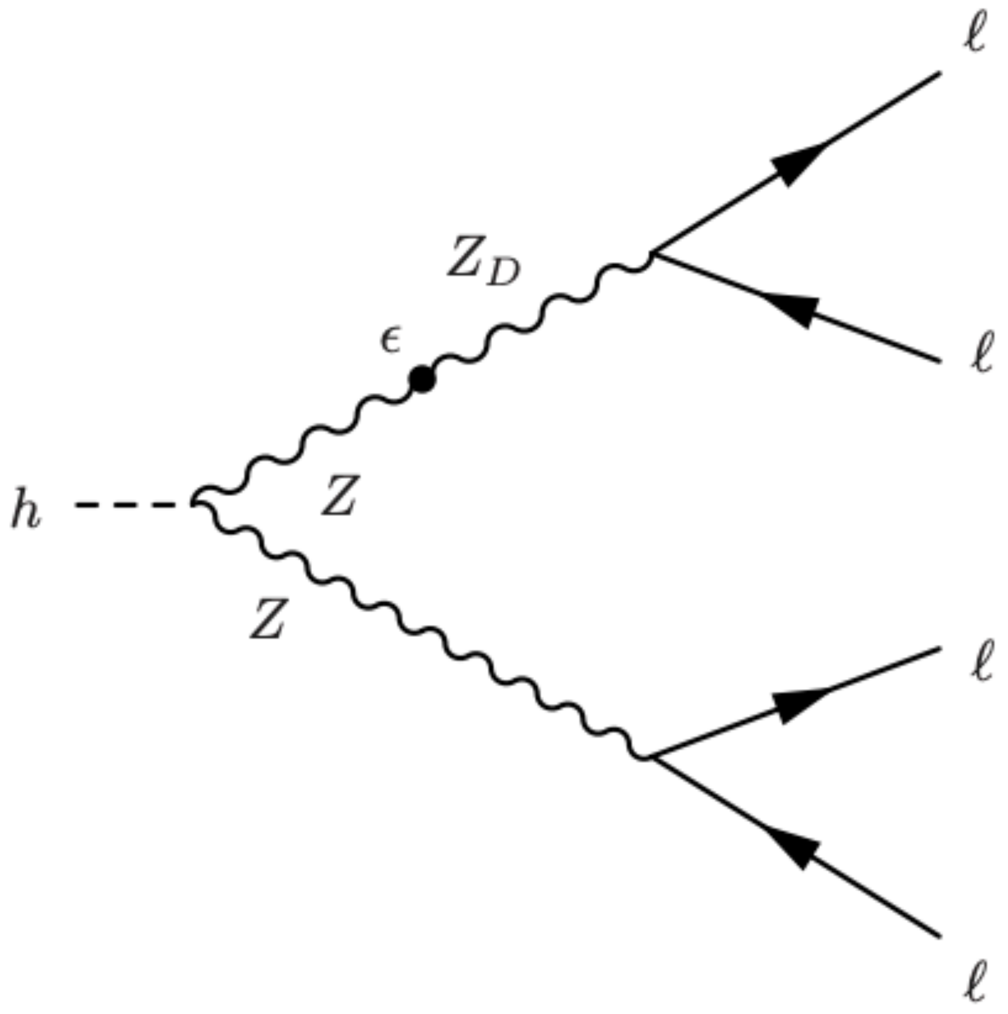
- For $m_x = 15$ GeV, strongest direct bound comes from LHCb search for $X^\mu \to \mu^+\mu^-$ (1910.06926) finds $|\epsilon| < 10^{-3}$

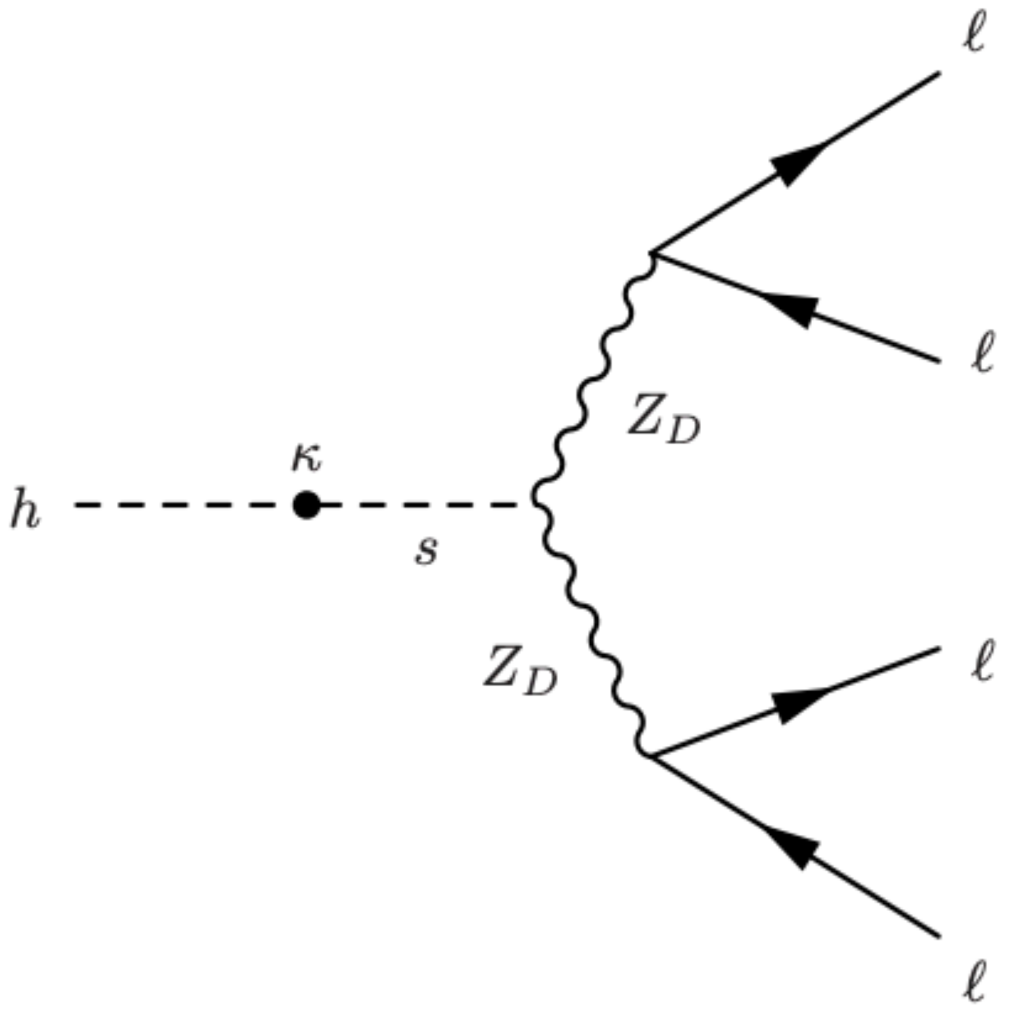
Laboratory Bounds

Higgs Decays

- For $m_1 < \frac{m_h}{2}$, $h \to \psi_1 \bar{\psi}_1$ contributes to $BR(h \to inv)$. ATLAS limit (2202.07953) excludes the entire parameter region considered $\lambda \geq 0.1$

- Contribution to $h \to XX$ from heavy fermions the loop. ATLAS (2110.13673) and CMS (2111.01299) searches for $h \to XX \to 4\ell$. For $m_x = 15$ GeV, $BR(h \to XX) < 2.35 \times 10^{-5}$





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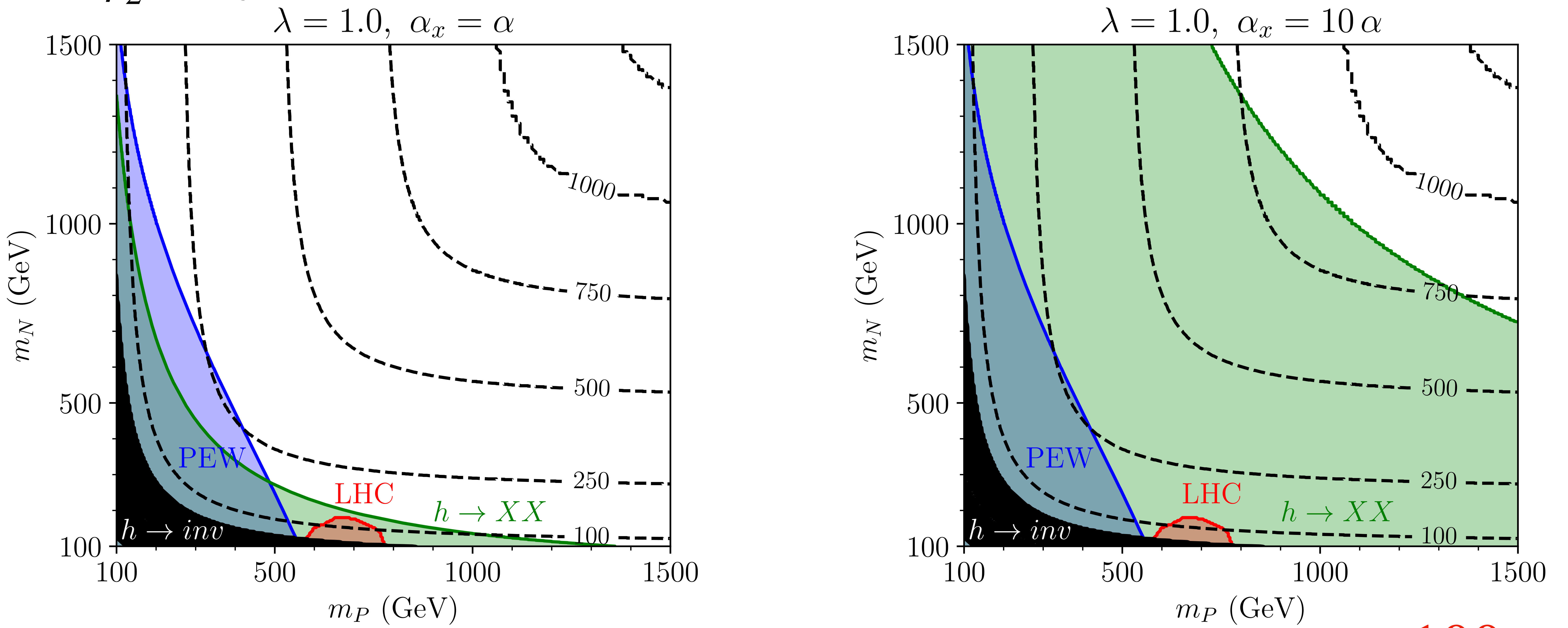
Laboratory Bounds

Precision EW: mixing of $SU(2)_L$ singlet to doublet contributes to oblique parameters S,T,U [Peskin, Takeushi - PRL 65 (1990) 964, PRD 46 (1992) 381]

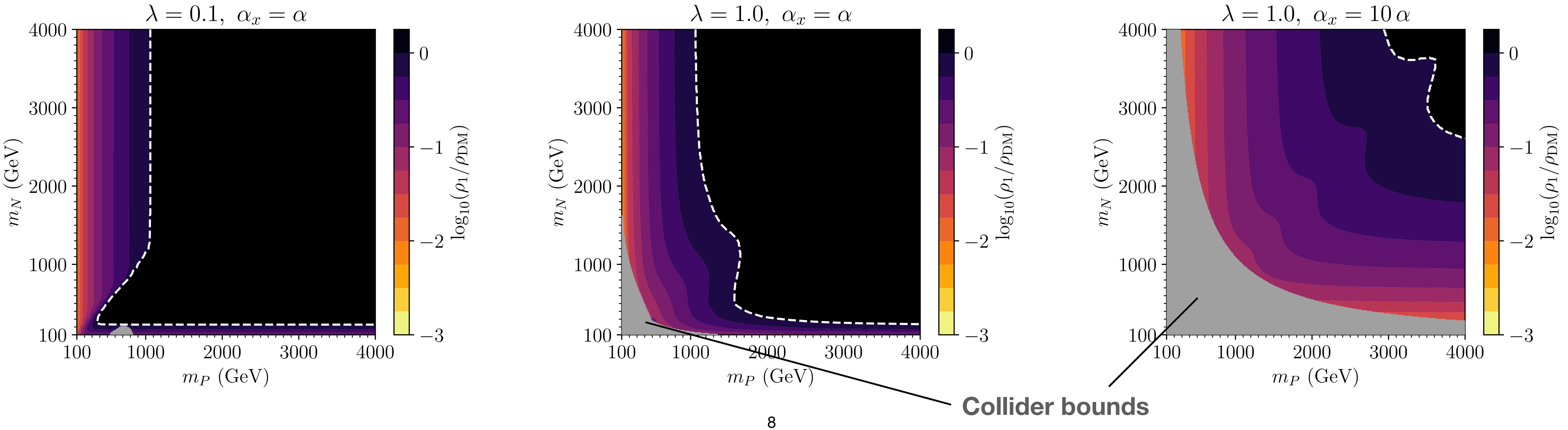
The minimal doublet-singlet $P-N$ model is analogous to Higgsino-Bino system. We use `Feynrules` interfaced with `MadGraph5` to calculate production cross-section. Remapping of ATLAS Higgsino-Bino search (2108.07586), including $P^{\pm}$ and ψ_2 decays to EW and h.



- From collider bounds only: Large viable parameter space for $m_{N,P} \geq 100 - 700$ GeV. What about cosmological bounds ?

Bound from Dark Matter Relic Density

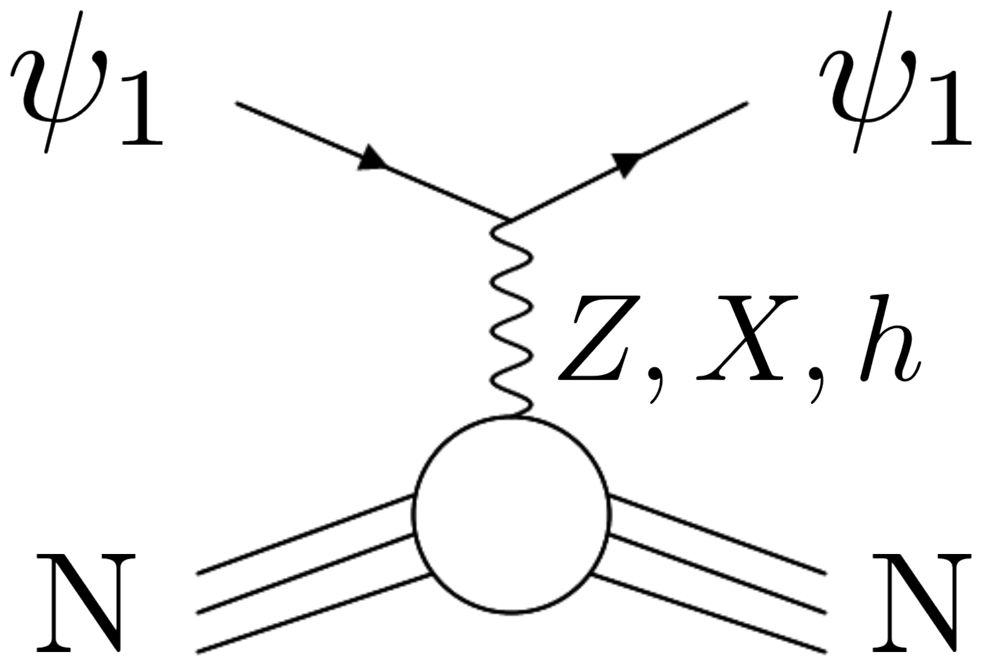
- Assuming that P^-, ψ_2, ψ_1 thermally created in the early universe at $T \geq m_1/20$ and then thermal freezeout.
- Annihilation via $\psi_1\bar{\psi}_1 \to VV$ with $V = X, Z, W$, enhanced when $m_P \approx m_1$ from coannihilation.
- Computation of relic density ρ_1 using `Feynrules` and `MadDM`, yields upper bounds on $m_N - m_P$.

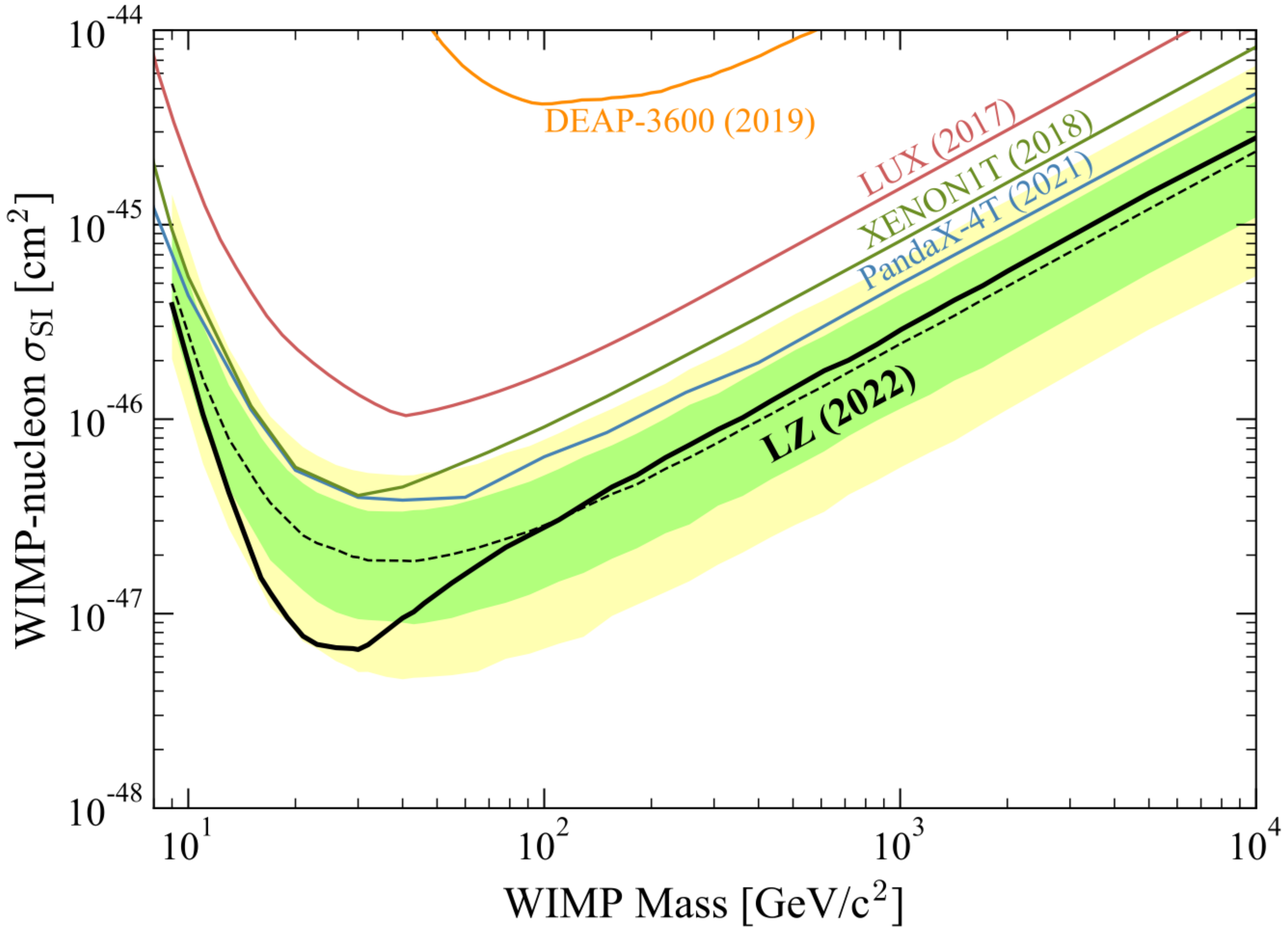


Bounds from Dark Matter Direct Detection

Per-nucleon spin-independent scattering cross-section - σ_{SI}

- Three tree-level contributions
- Best bound for $m_1 > 100$ GeV from LUX-ZEPLIN (2022)





LUX-ZEPLIN 2207.03764

$$\sigma_{\mathrm{SI}} = \frac{\mu_n^2}{\pi}\left[\frac{Zf_p + (A-Z)f_n}{A}\right]^2$$

Z X h

$$f_p = \frac{G_F}{\sqrt{2}}s_\alpha^2(1-4s_W^2) - \frac{4\pi}{m_x^2}\epsilon\sqrt{\alpha\alpha_x} - \tilde{d}_p\left[\frac{2}{9}+\frac{7}{9}\sum_q f_q^p\right],$$

$$f_n = -\frac{G_F}{\sqrt{2}}s_\alpha^2 \quad + \quad 0 \quad - \quad \tilde{d}_n\left[\frac{2}{9}+\frac{7}{9}\sum_q f_q^n\right].$$

Bounds Direct Detection

Rules out the minimal model

- $\sigma_{\text{SI}} = \dfrac{\mu_n^2}{\pi}\left[\dfrac{Zf_p + (A-Z)f_n}{A}\right]^2$, cancellation possible for $\epsilon < 0$ around $m_N \approx m_P$

- Minimal model almost entirely excluded by DD experiments. Can we avoid these bounds with minimal changes to the model?

Fix #1

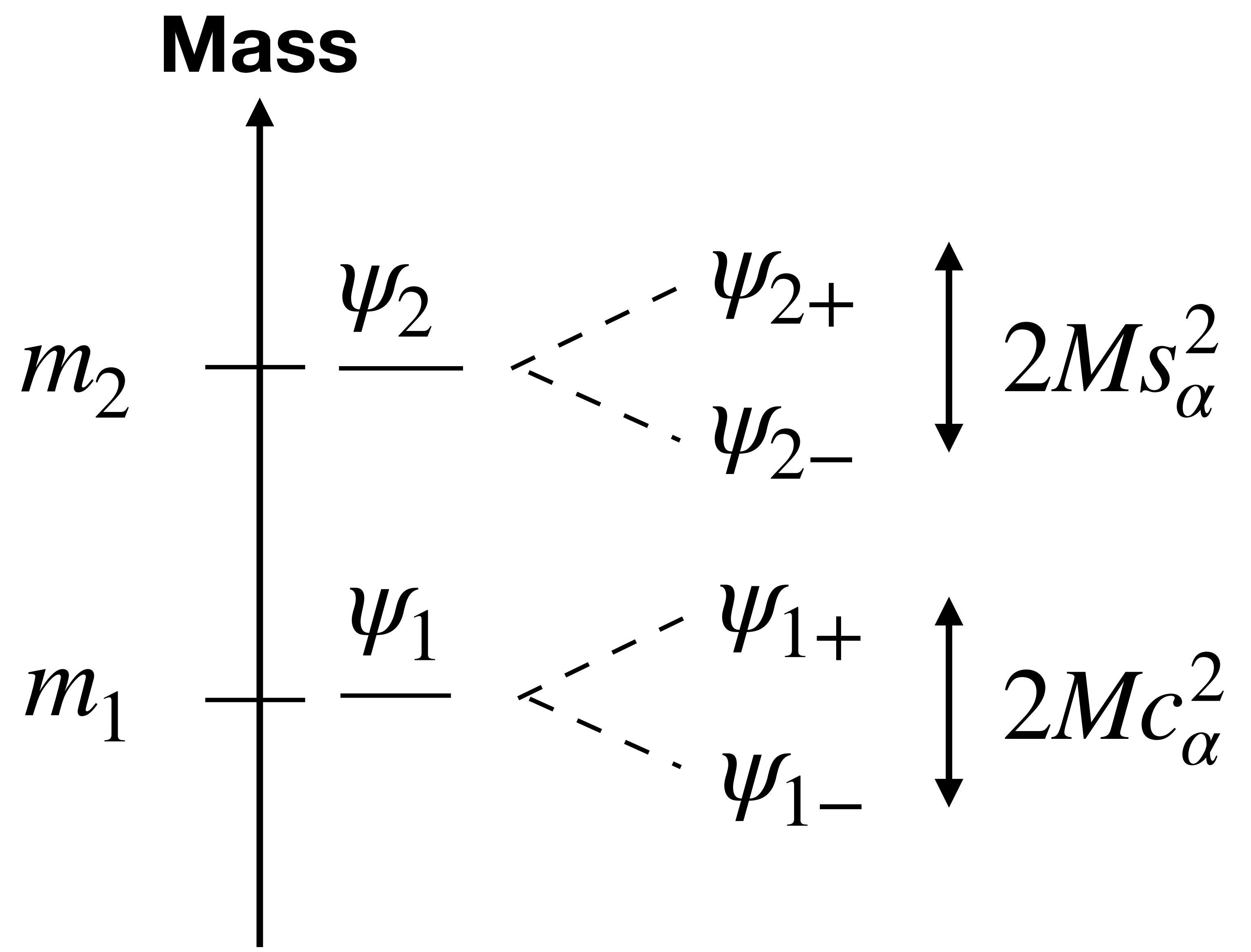
Mass splitting from a Majorana mass term

- Dark Higgs: $\Phi \sim (1,1,0; -2q_x)$ allows new Yukawa coupling :

$$\Delta\mathscr{L} = y_N \Phi \bar{N}^C N \; + \; (h.c.)$$

- $N = (\chi_N \, \bar{\chi}_N^c)^T$, $M = y_N \langle \Phi \rangle$ -> $\Delta\mathscr{L} = M(\chi_N \chi_N + \bar{\chi}_N \bar{\chi}_N)$

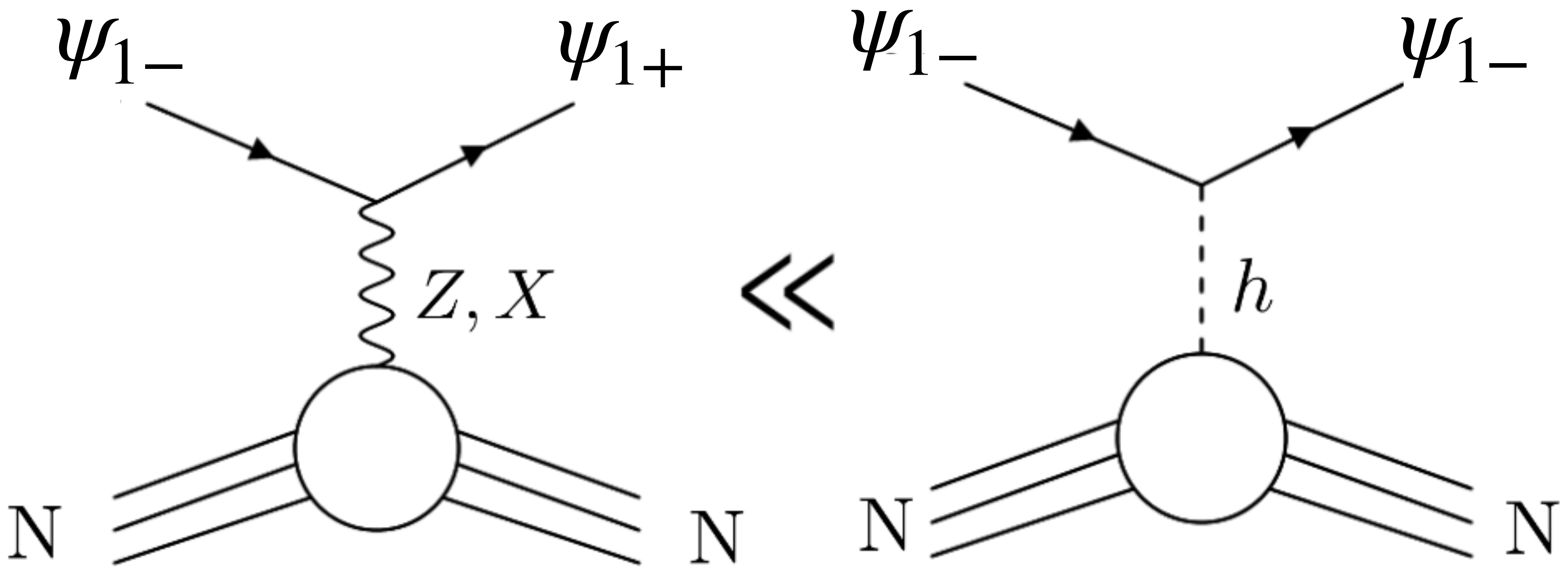
- Splits Dirac Fermions $\psi_{1,2}$ mass eigenstates into two pairs of Majorana fermions $\psi_{1\pm}, \psi_{2\pm}$ with masses $m_{1,2} \pm \Delta m_{1,2}$



$$-\mathscr{L} \supset -\frac{\lambda}{2\sqrt{2}} \sin(2\alpha + 2\gamma_-)\, h\, \bar{\psi}_{1\_}\psi_{1\_}$$

$$-i\,\bar{\psi}_{1\_}\gamma^\mu \psi_{1_+}\left(\cos(\gamma_+ - \gamma_-)\, g_x X_\mu \;+ \left[\cos(\gamma_+ - \gamma_-) - \cos(2\alpha + \gamma_+ + \gamma_-)\right] \frac{\bar{g}}{4} Z_\mu\right)$$

- Typical recoil energy in DD $E_R \sim 100$ keV. Inelastic scattering with $M \geq 200 - 500$ keV are kinematically suppressed



Fix #1

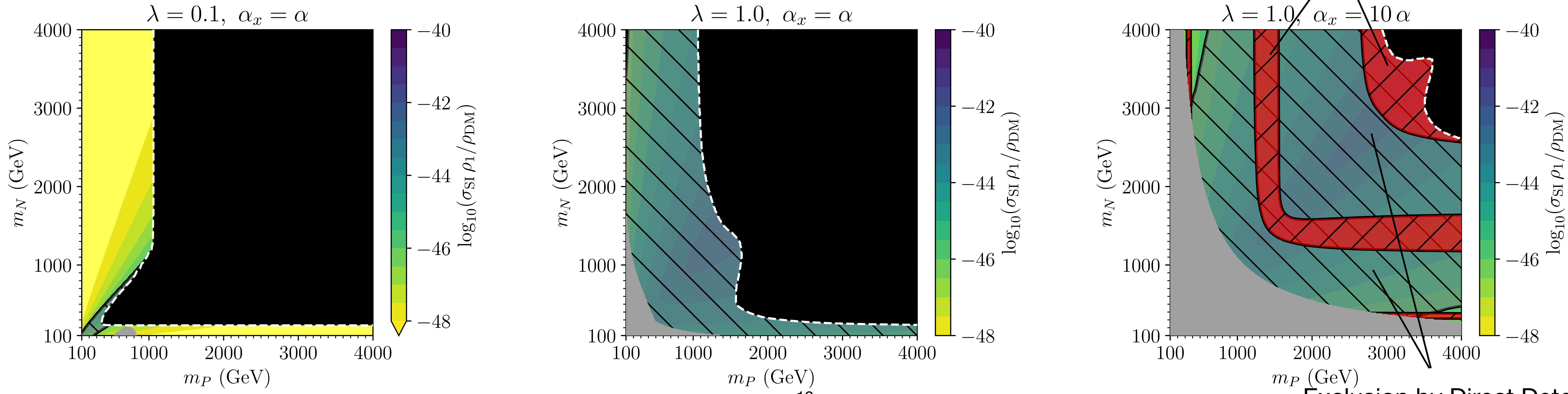
Mass splitting from a Majorana mass term

- For $M \ll m_1$ and $M \geq 10\,MeV$ relic density remains identical.

- For $\alpha_x = 10\alpha$, annihilation at late time $\psi_{1^-}\bar{\psi}_{1^-} \rightarrow XX$ probed notably by distorsion of the power spectra of the CMB measured by Planck. Excluded region exhibits a band structure corresponding to enhancement through the formation of bound states, dependent on m_x/m_{DM}

- Bounds from direct searches remain unchanged for $\Delta m/m_x \ll 1$

Exclusion by Indirect Detection



Exclusion by Direct Detection

Fix #2

Decay Through Lepton Mixing

- Avoid overabundance of relic portal fermions by allowing them to decay quickly to SM
- Dark Higgs field $\phi \sim (1,1,0; q_x)$

$$\boxed{-\mathscr{L} \supset \lambda_a \phi \overline{P}_R L_{La} + (h.c.) \,, \qquad a = e, \mu, \tau}$$

- $\langle \phi \rangle = \eta$ induces mixing with leptons, $\psi_1 \to \nu_{L_a} \phi$ and $\psi_1 \to \nu_{La} X$

$$\tau \simeq (6.61 \times 10^{-8}\,\mathrm{s}) \left(\frac{10^{-9}}{\lambda_a s_\alpha} \right)^2 \frac{1\,TeV}{m_1}$$

- As long as the couplings are not exceedingly small, $\lambda_a s_\alpha \gtrsim 10^{-12}$ these decays occur before primordial nucleosynthesis and neutrino decoupling, and will generally be safe from cosmological bounds
- Simultaneously contributes to $BR(\tau \to \mu\gamma)$, $BR(\mu \to e\gamma)$ and $\Delta a_{e,\mu}$
- Challenge: Can ψ_1 decay fast enough while avoiding bounds from LFV and $\Delta a_{e,\mu}$?

Fix #2

Decay Through Lepton Mixing

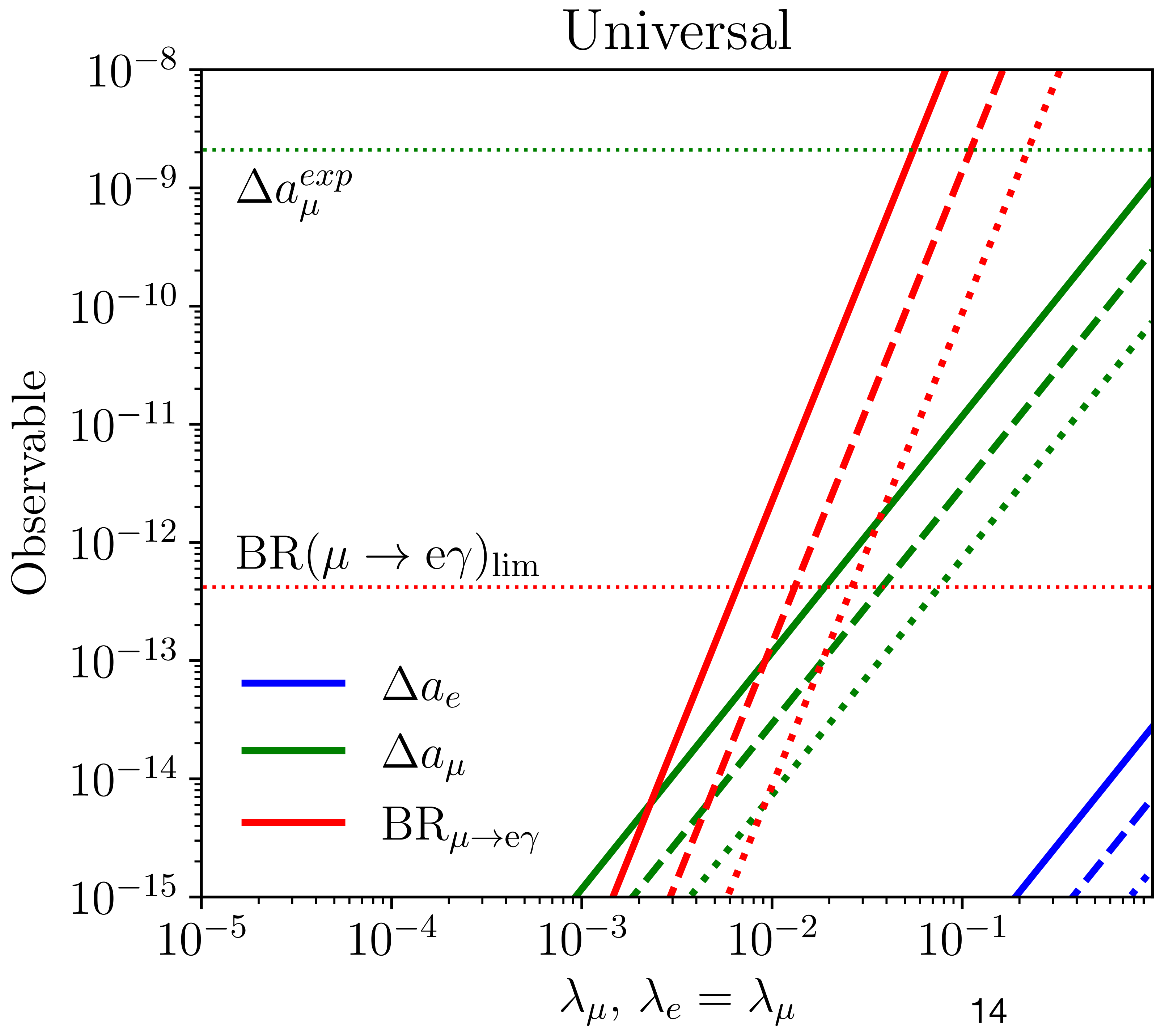
Yes !

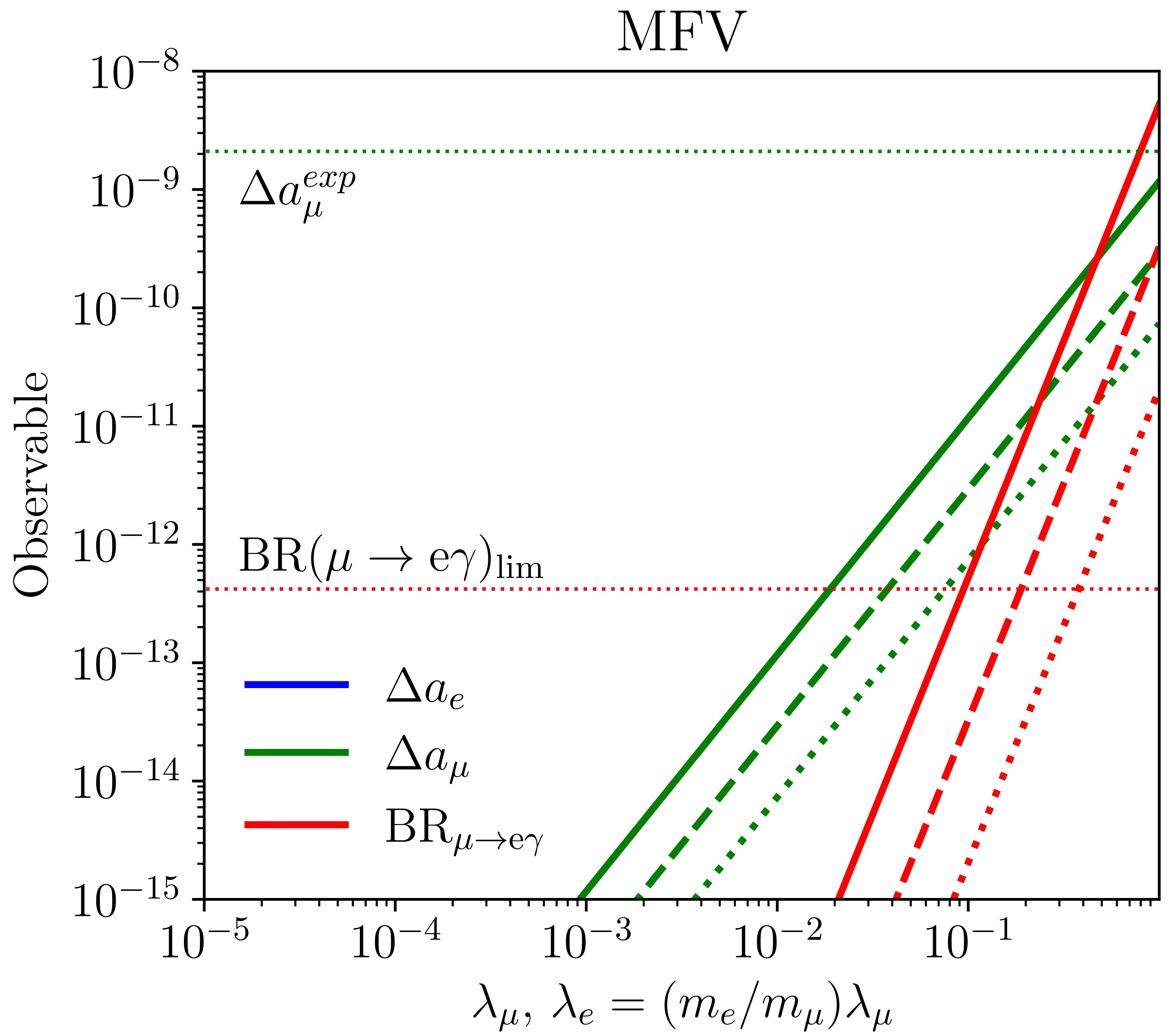
- $\Delta a_{\ell_a} = + \frac{\lambda_a^2}{96\pi^2}\left(\frac{m_a}{m_P}\right)^2$
- BR$(\mu \to e\gamma) = \frac{12\pi^3}{m_\mu^4}\frac{\alpha}{G_F^2}\left(\frac{\lambda_e}{\lambda_\mu}\right)^2 \times (\Delta a_\mu)^2$, BR$(\tau \to \mu\gamma) = \frac{12\pi^3}{m_\mu^4}\frac{\alpha}{G_F^2}\left(\frac{\lambda_\tau}{\lambda_\mu}\right)^2 \times (\Delta a_\mu)^2 \times$ BR$(\tau \to \mu\nu\bar{\nu})$

$m_P = 100$ GeV

200 GeV

400 GeV





Fix #2

Collider signature

- ψ_1 is now unstable and can decay to visible particles in colliders. Signatures are: $X \to f\bar{f}$ and $\phi \to XX$
- $\lambda_a s_\alpha \leq 10^{-10}$ yields similar signature as the original setup (long-lived in the detector), may be visible in far detectors such as FASER, MATHULSA,…
- For larger couplings, ψ_1 decays promptly on typical collider timescale. In the limit $m_x \ll m_1$, dark vector decay product will be boosted -> lepton jets. Similar searches exist for $h \to XX \to 4\ell$ at ATLAS and CMS. To our knowledge, there is no directly remappable existing analysis to constrain our model.

Conclusion

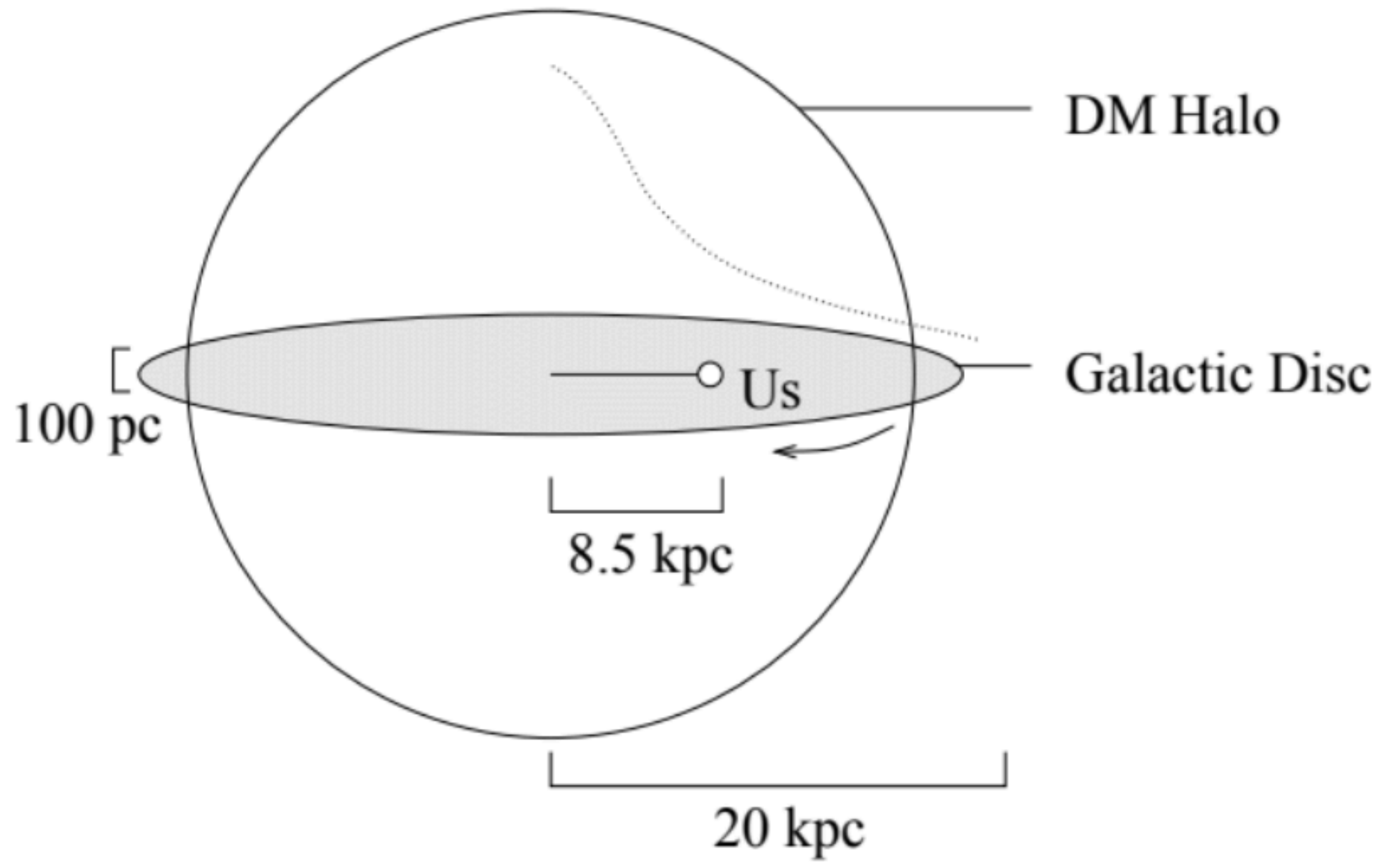
- We study a minimal model of connector fermions to a dark gauged $U(1)_x$
- A naive model is ruled out as it includes a DM candidate ruled out by DD searches.
- Fix #1 : Through a small Majorana mass term for N, DM candidate scatters inelastically in DD experiments for vector bosons exchanges. Model is viable for $\lambda \simeq 0.1$
- Fix #2 : Couple P to LH SM leptons, so that ψ_1 decays in the early Universe. Viable for $10^{-12} \lesssim \lambda_a s_\alpha \lesssim 10^{-3}$, could be searched at collider

Merci !

Backup

Direct Detection with Inelastic Scattering

- Typical velocity of DM particles relative to the Earth: $v \sim 10^{-3}$
- $E_R = \dfrac{2\mu_N^2 v^2 \cos^2(\theta)}{m_N} \sim 100\,$keV
- $\mu_N = \dfrac{m_N m_\chi}{m_N + m_\chi}$



Higgs Portal Operator

Higgs Portal Operators

- $\mathscr{L} \supset \dfrac{\alpha_x}{6\pi}\dfrac{\lambda^2}{m_1 m_2} H^\dagger H X_{\mu\nu} X^{\mu\nu}$ in the limit $m_h \ll m_{1,2}$