Dark Matter, Unification and Left-Right Symmetry

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Motivation

$\mathrm{SO}(10)$ Unification

Many symmetry breaking paths to the Standard Model

Testable low energy predictions, $p \to e^+ + \pi^0$

Appealing from reductionist viewpoint

Electroweak WIMPs

Commonly studied dark matter candidate

Reproduces relic dark matter abundance

Can we build Electroweak WIMP $\mathrm{SO}(10)$ Models?

Embedding electroweak WIMPs contains challenges

Restricts symmetry breaking pathway from $SO(10)$ to the Standard Model

Standard model and dark matter embed into $SO(10)$

SM Higgs embedded into a $\mathbf{16}$ scalar in $SO(10)$

SM Fermions embedded into three $\mathbf{16}$ fermions in $SO(10)$

We consider an EW-charged DM Dirac fermion

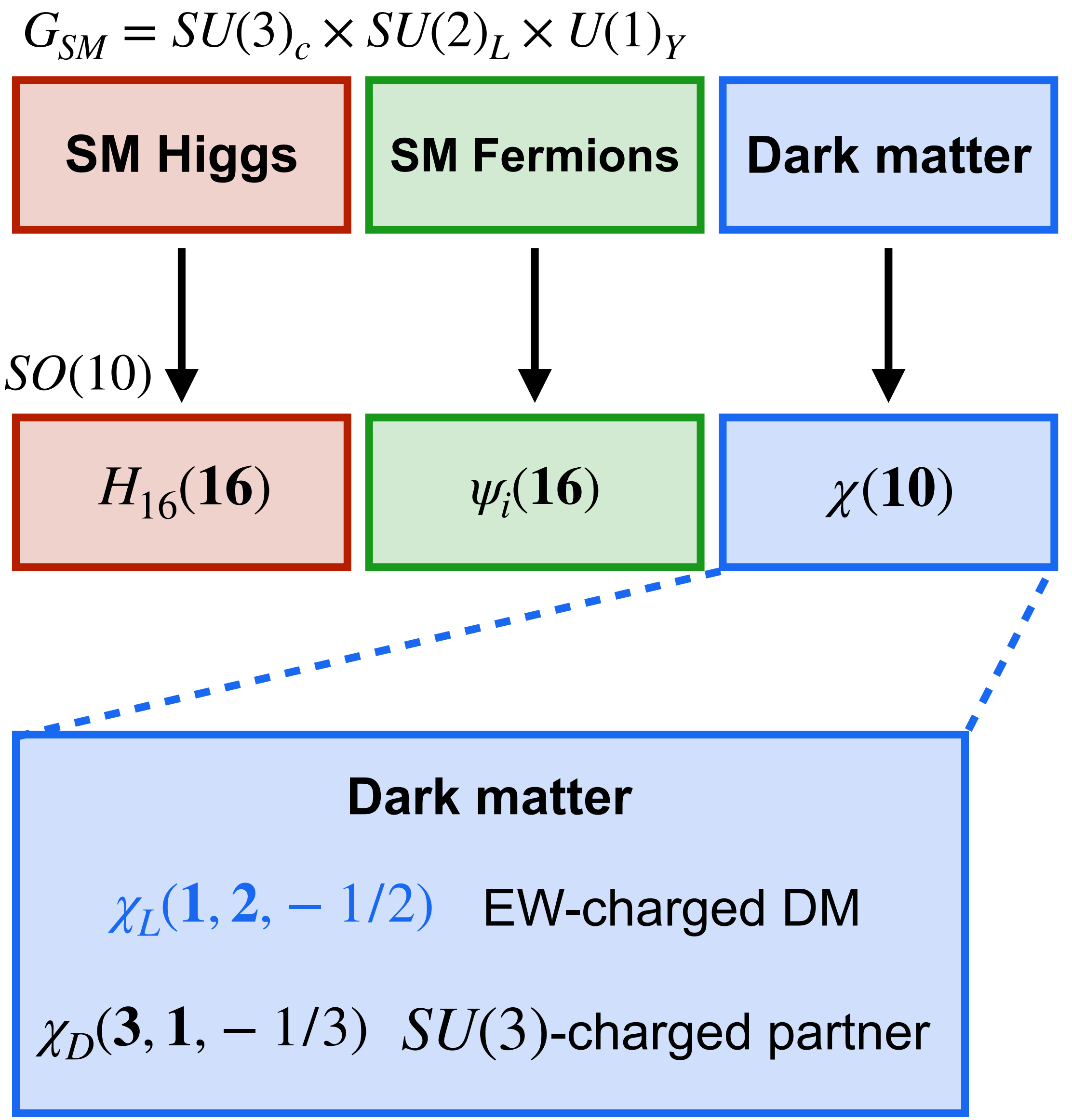
$$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$$

Embedding into $\mathbf{10}$ fermions of $SO(10)$ leads to an $SU(3)$-charged partner fermion

$$\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$$

We will need χ_D to be much heavier than χ_L

$$m_D > m_L$$



Symmetry breaking via left-right intermediate gauge group

$m_D > m_L$ possible by breaking via the Left-Right symmetry group

$$SO(10)$$
$$\downarrow$$
$$G_{LR} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$
$$\downarrow$$
$$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

$H_{45}(\mathbf{45})$ of $SO(10)$ breaks to G_{LR}

$$SO(10) \xrightarrow{\langle H_{45} \rangle} G_{LR}$$

resulting in heavy XY gauge bosons with mass M_{XY} that mediate proton decay

Unification scale M_{XY}

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

SM Higgs	**SM Fermions**	**Dark matter**
$H_{16}(\mathbf{16})$	$\psi_i(\mathbf{16})$	$\chi(\mathbf{10})$

$SO(10)$ ↓

Dark matter

$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$ EW-charged DM

$\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$ $SU(3)$-charged partner

Missing VEV of $SO(10)$ Higgs generates mass splitting

How is $m_D > m_L$ achieved?

Non-zero VEV of H_{45}

$$\langle H_{45} \rangle = -iv_{45} \begin{pmatrix} \sigma_2 & 0 & 0 & \\ 0 & \sigma_2 & 0 & 0_{4\times6} \\ 0 & 0 & \sigma_2 & \\ & 0_{6\times4} & & 0_{4\times4} \end{pmatrix}$$

Missing VEV of H_{45}

χ_L coupled to missing VEV

χ_D coupled to non-zero VEV

$\Rightarrow m_D > m_L$

DM mass m_L, Partner mass m_D

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

SM Higgs	SM Fermions	Dark matter

$\downarrow SO(10)$

$H_{16}(\mathbf{16})$	$\psi_i(\mathbf{16})$	$\chi(\mathbf{10})$

Dark matter

$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$ EW-charged DM

$\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$ $SU(3)$-charged partner

Left-right gauge groups breaks to standard model

H_R ,contained in H_{16}, breaks G_{LR} to G_{SM}

$$G_{LR} \xrightarrow{\langle H_R \rangle} G_{SM}$$

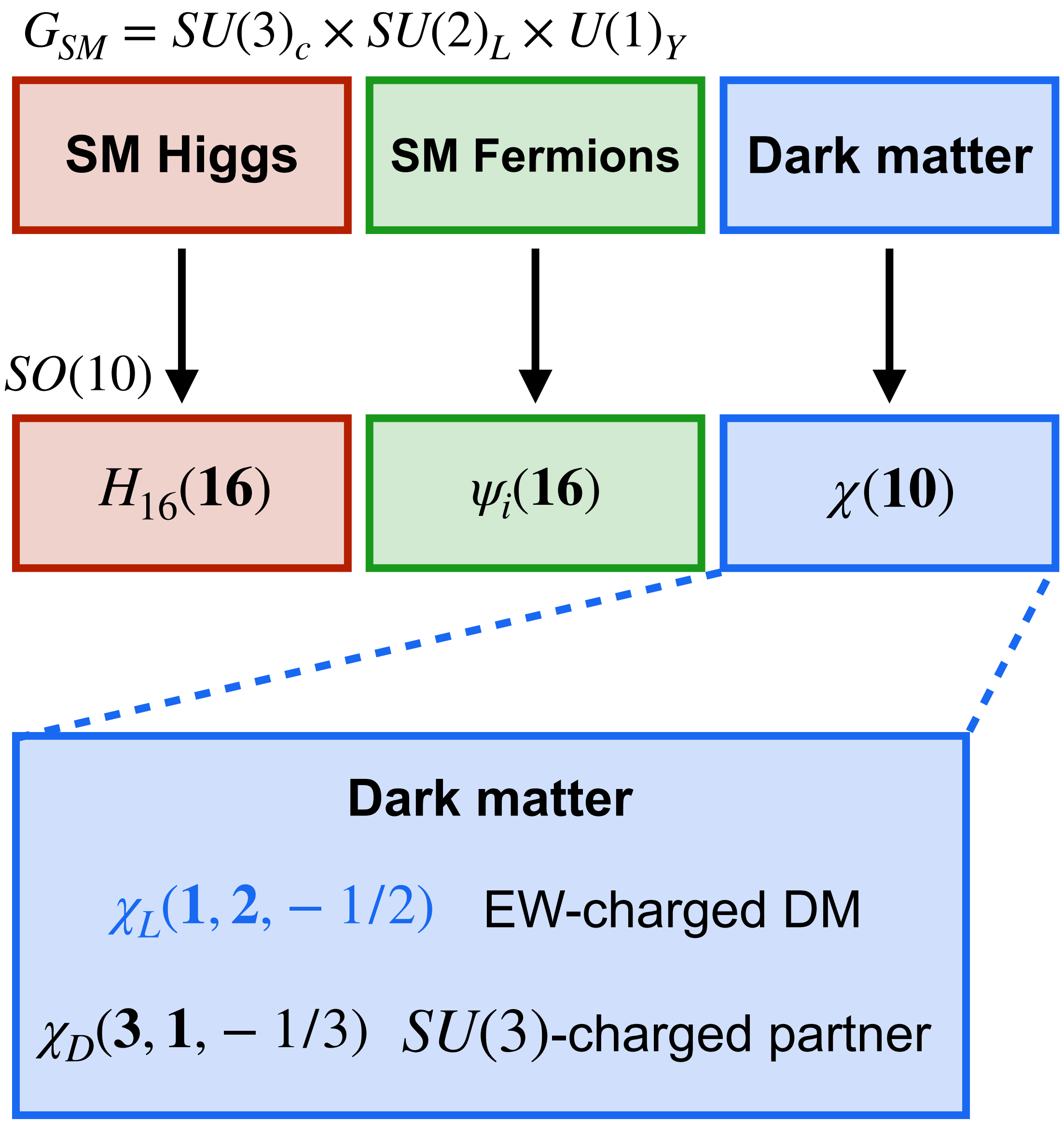
G_{LR} with Parity symmetry also has the benefit of solving the strong CP problem

Left-right breaking scale v_R (VEV of H_R)

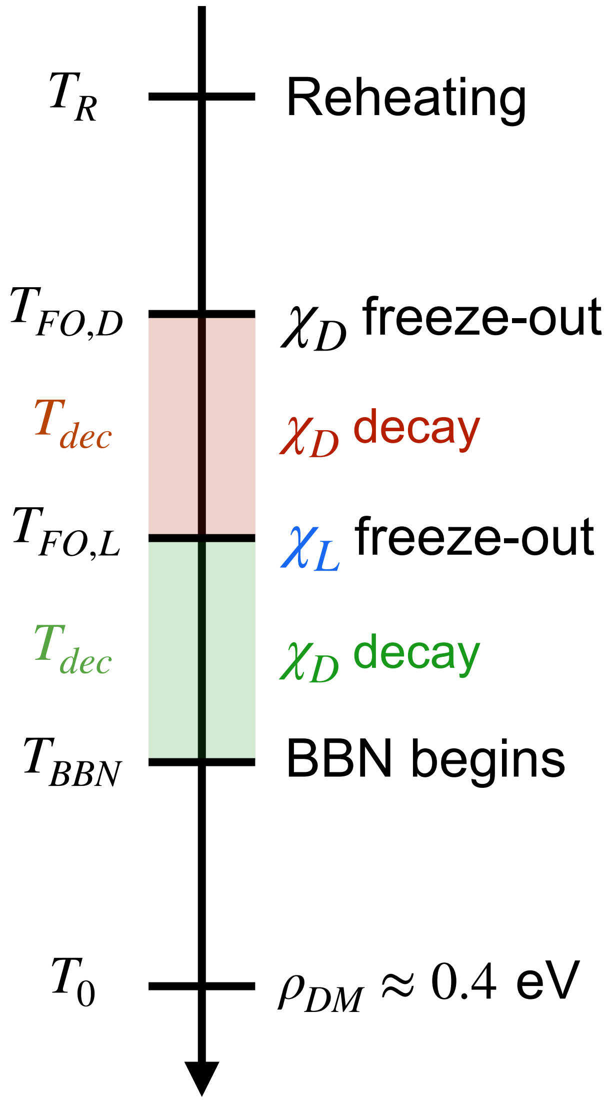
$m_D > m_L$ will modify v_R

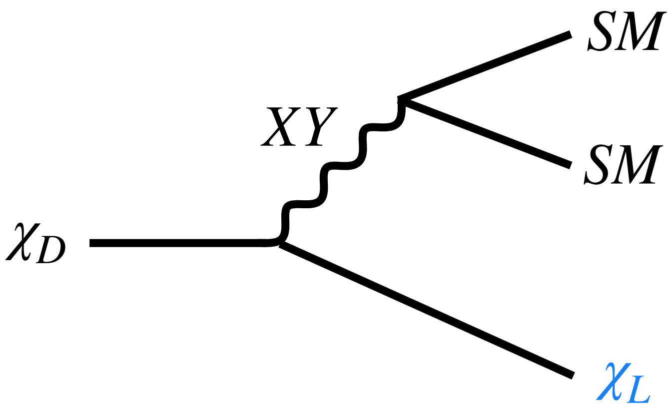
$m_D > m_L$ will modify M_{XY}

Why is $m_D > m_L$ required?



Mass splitting necessary to avoid dark matter overproduction





$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$ $\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$

$$\Gamma \sim \frac{1}{128\pi^3} \frac{m_D^5}{M_{XY}^4}$$

$T_{dec} > T_{FO,L}$ χ_L freeze-out gives ρ_{DM} for $m_L = 1$ TeV

$T_{dec} < T_{FO,L}$ χ_L freeze-out and $\chi_D \to \chi_L$ decay give ρ_{DM}

To avoid overproduction

$$m_D > 3 \times 10^9 \text{ GeV} \times \left(\frac{M_{XY}}{10^{16} \text{ GeV}}\right)^{\frac{4}{5}} \left(\frac{m_L}{100 \text{ GeV}}\right)^{\frac{6}{5}}$$

We will take $m_L = 1$ TeV

Gauge coupling unification modified by dark matter

2-loop RGE

$$\frac{d}{d\ln\mu}\left(\frac{2\pi}{\alpha_i}\right) = b_i + \sum_j b_{ij}\frac{\alpha_j}{2\pi}$$

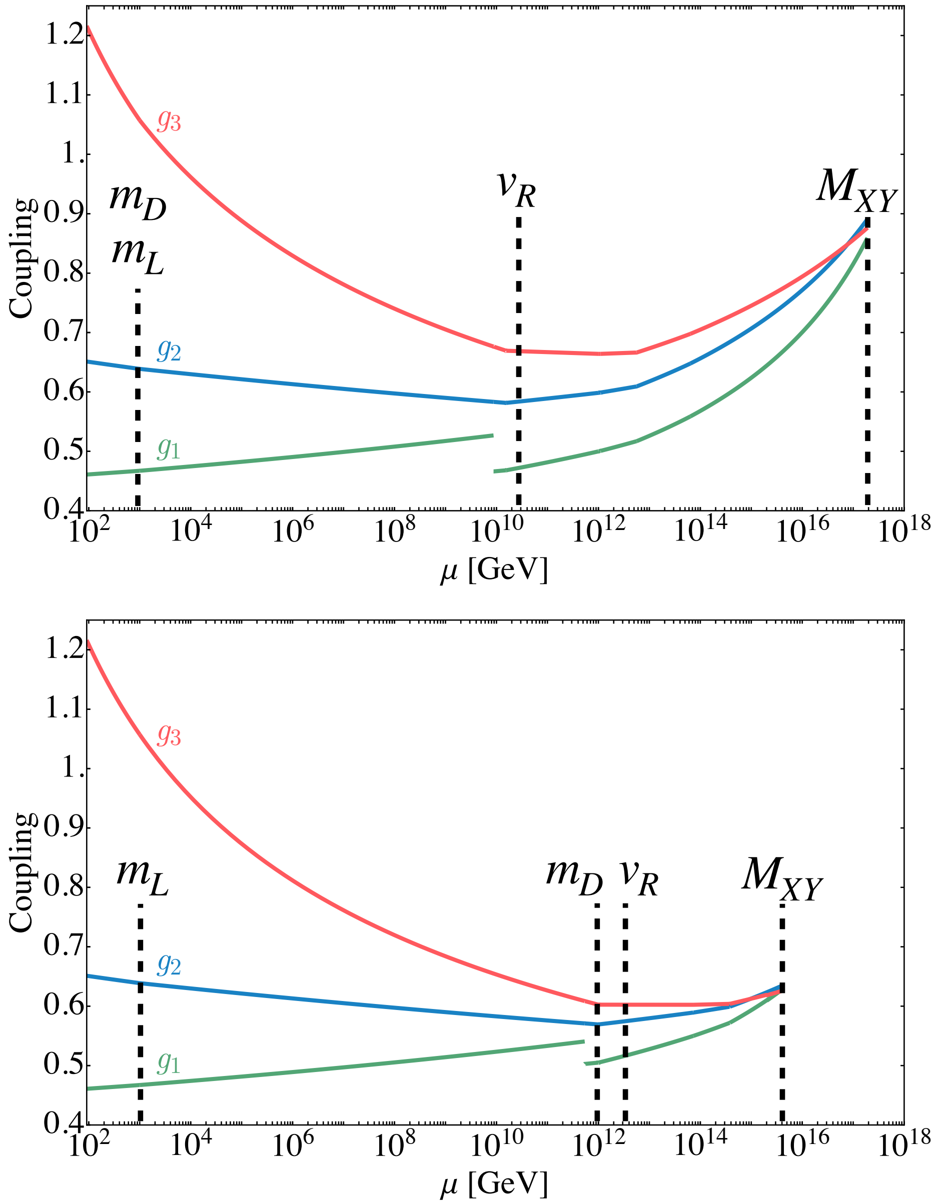
Quality of unification— **threshold correction**

$$\Delta(M_{XY}) \sim \max_{i,j=1,2,3}\left|\frac{2\pi}{\alpha_i(M_{XY})} - \frac{2\pi}{\alpha_j(M_{XY})}\right|$$

Smaller $\Delta(M_{XY})$ signals good unification

We consider $\Delta < 15$*

Mass splitting between χ_L and χ_D modifies M_{XY} and v_R



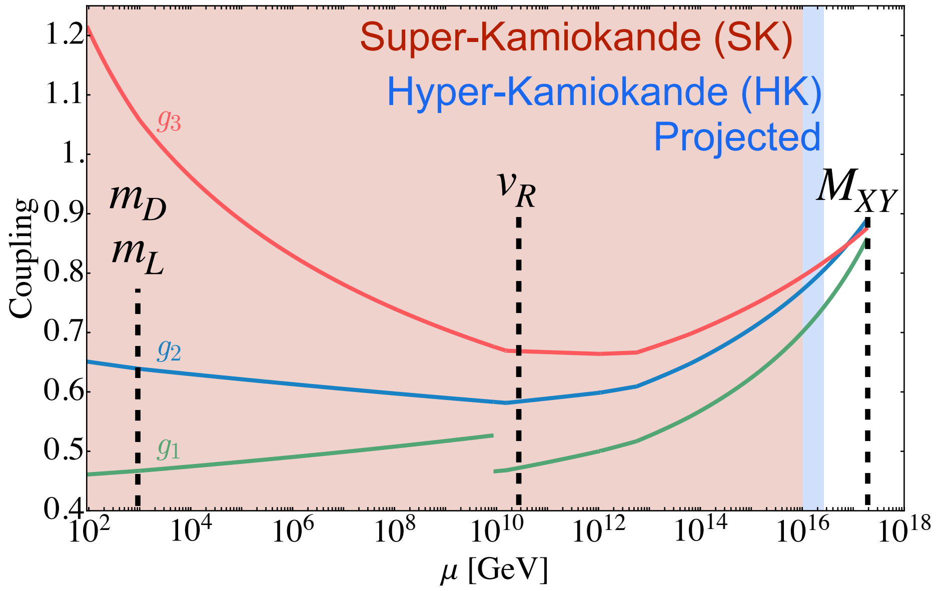
*Δ can be larger with, e.g., more split mass multiplets

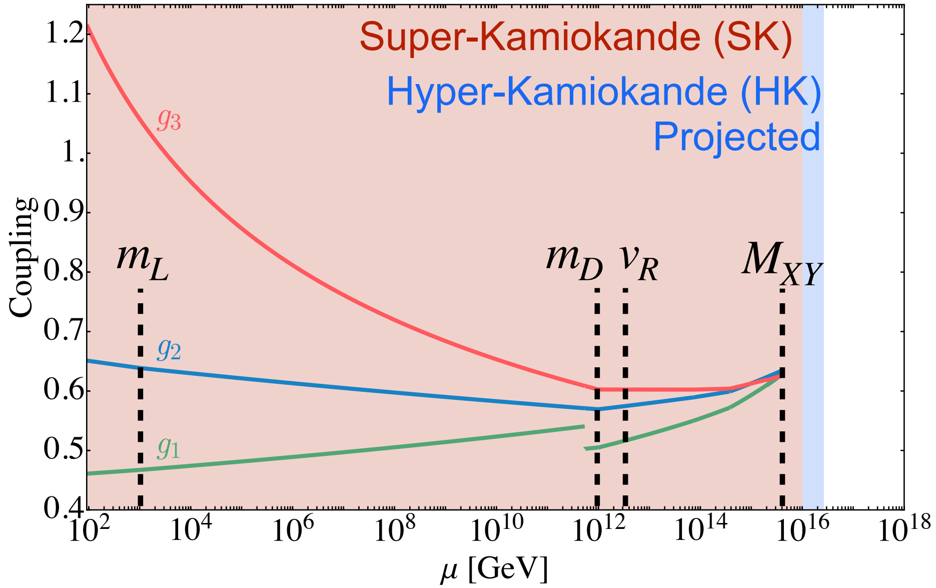
Unification scale bounded above by proton decay

Heavy XY gauge bosons from $SO(10) \to G_{LR}$ mediate proton decay $p \to e^+ + \pi^0$ with rate

$$\tau_{p\to e^+ + \pi^0} \propto M_{XY}^4$$

Non-observation of $p \to e^+ + \pi^0$ bounds M_{XY} from below





Parameters bounded in opposite directions by m_D/m_L and proton decay

As m_D/m_L increases, $\Delta = 0$ point moves towards larger v_R, smaller M_{XY}

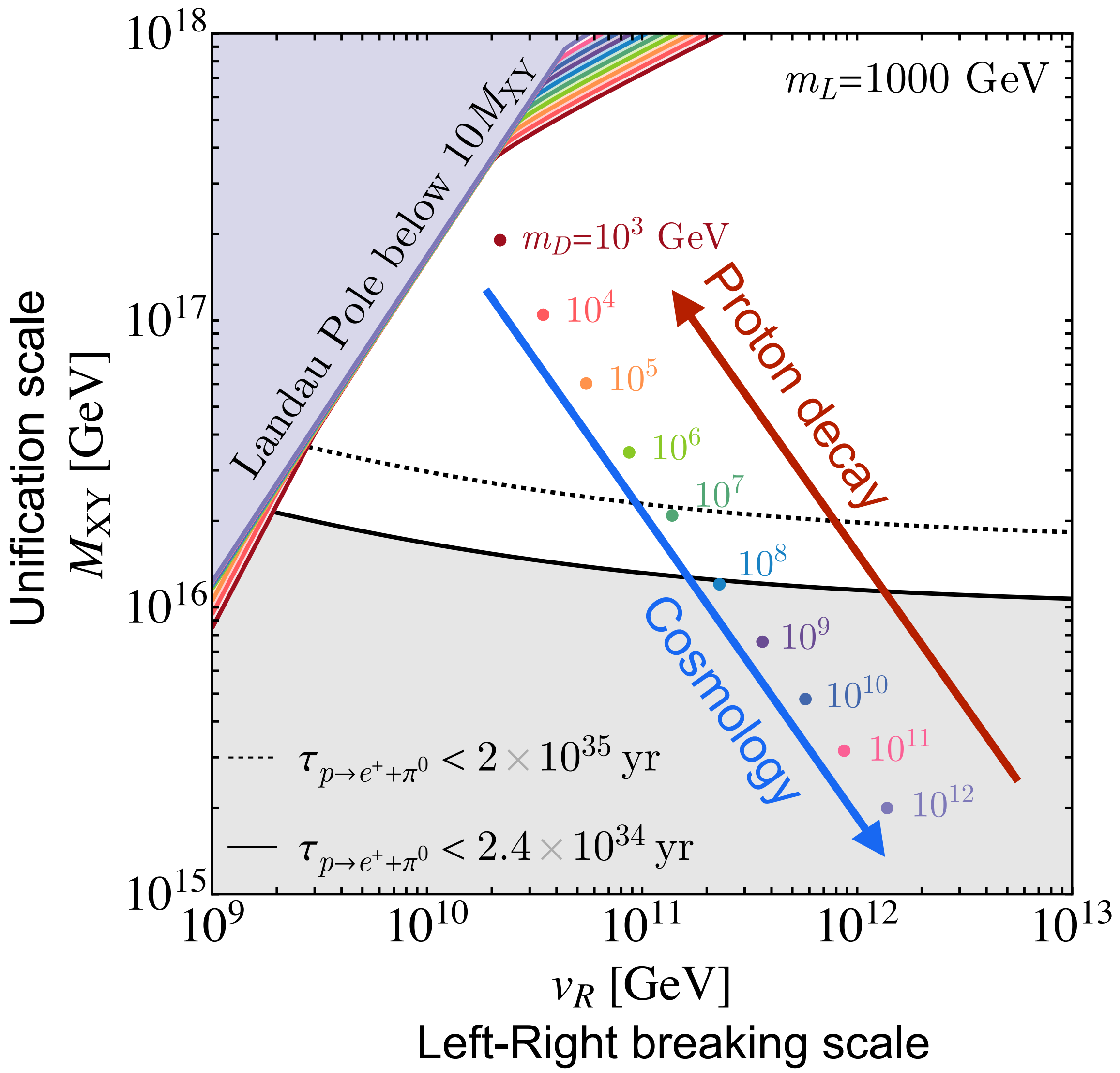
To avoid overabundance

$$m_D > 3 \times 10^9 \text{ GeV} \times \left(\frac{M_{XY}}{10^{16}\text{ GeV}}\right)^{\frac{4}{5}} \left(\frac{m_L}{100\text{ GeV}}\right)^{\frac{6}{5}}$$

and have $\Delta = 0$ is excluded by SK

Proton decay bounds favour smaller m_D/m_L

Overabundance bounds favour larger m_D/m_L



Overabundance and proton decay bounds can be saturated

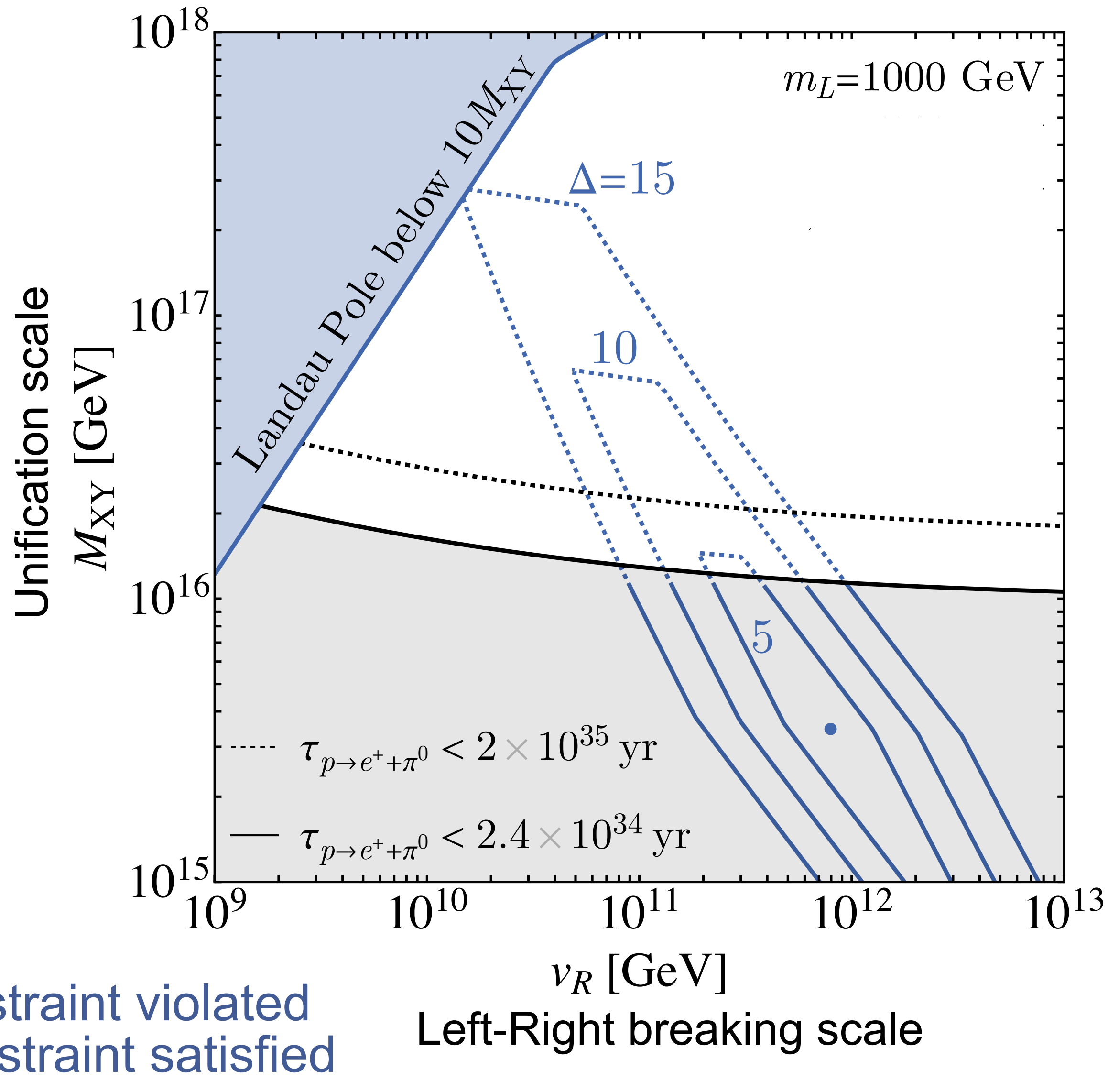
Proton decay bounds and overabundance bounds can be saturated

Minimum required thresholds for SK

$$\Delta_{SK} \gtrsim 4$$

Minimum required thresholds for HK

$$\Delta_{HK} \gtrsim 7$$

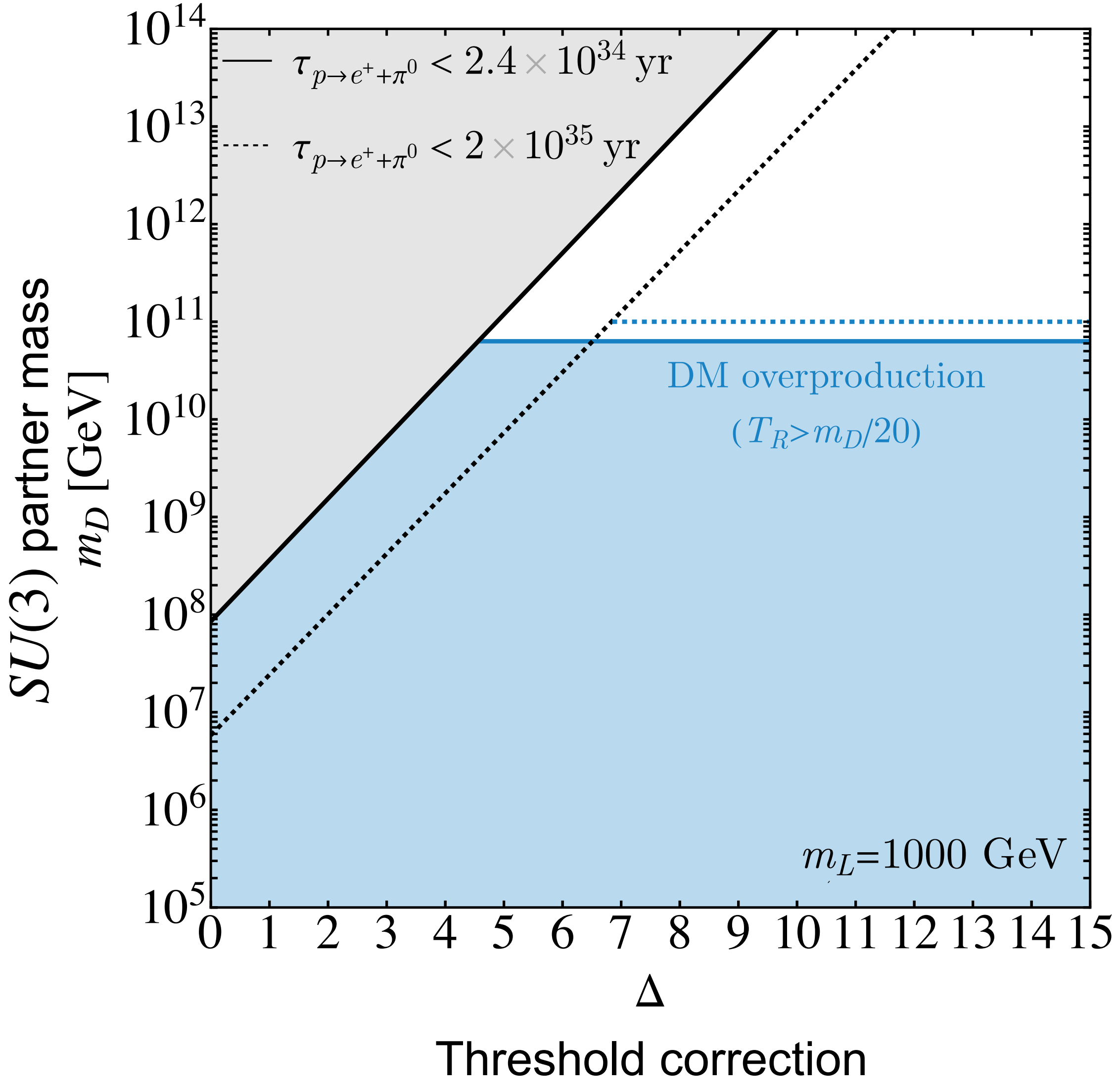


m_D constrained from below by cosmology

Proton decay bounds m_D from above for a given threshold correction Δ

$$m_D > 3 \times 10^9 \text{ GeV} \times \left(\frac{M_{XY}}{10^{16}\text{ GeV}}\right)^{\frac{4}{5}} \left(\frac{m_L}{100\text{ GeV}}\right)^{\frac{6}{5}}$$

Cosmology bounds m_D from below for a given threshold correction Δ

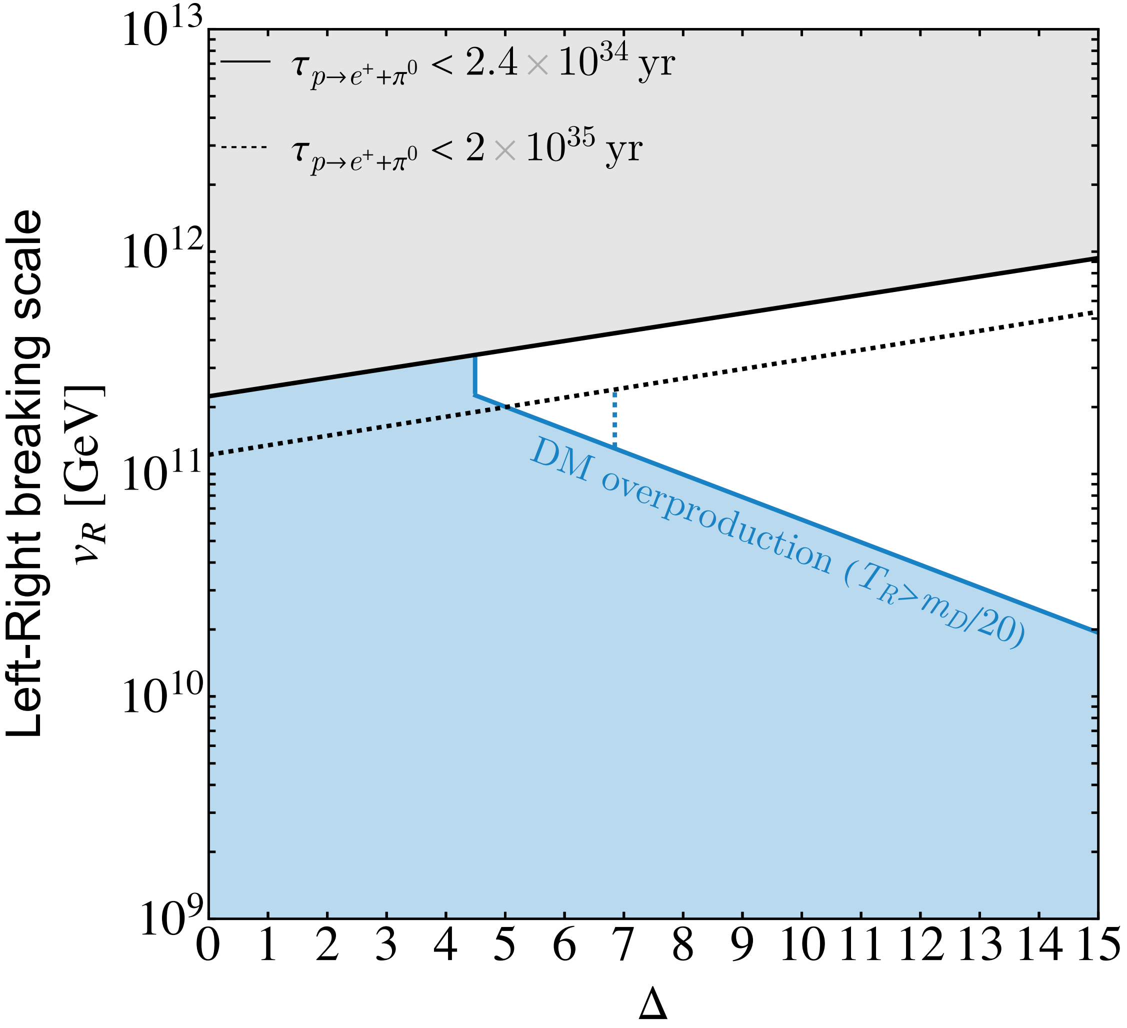


v_R constrained from below by cosmology

Proton decay bounds v_R from above for a given threshold correction Δ

$$m_D > 3 \times 10^9 \text{ GeV} \times \left(\frac{M_{XY}}{10^{16}\text{ GeV}}\right)^{\frac{4}{5}} \left(\frac{m_L}{100\text{ GeV}}\right)^{\frac{6}{5}}$$

Cosmology bounds v_R from below for a given threshold correction Δ



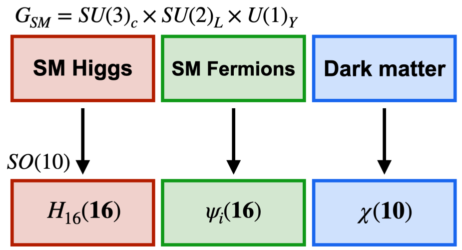
SK constraints

HK constraints (projected)

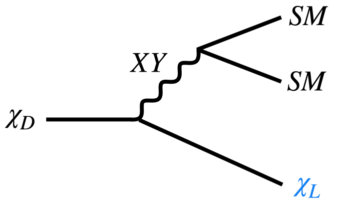
Threshold correction

Conclusions

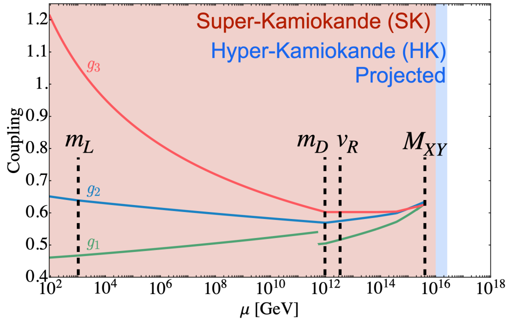
Electroweak-charged WIMPs can be successfully embedded into $SO(10)$



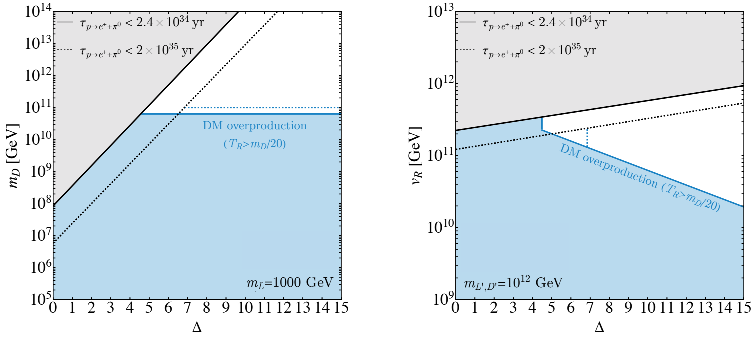
Overabundance bounds require mass splitting between DM and $SU(3)$-charged particles



Successful unification and proton decay bounds constrain $SO(10)$ breaking scale



Combined, these bounds provide new constraints on model parameters



Questions?

Backup Slides

VEV hierarchy of breaking scales

$$V(H_R, H_L) = \lambda\left(|H_R|^2 + |H_L|^2 - f^2\right)^2 + \Delta\lambda |H_R|^2 |H_L|^2$$

$\Delta\lambda > 0$ vacua: $(v_L, v_R) = (f,\ 0)$ and $(0,\ f)$ ⟶ Not phenomenologically viable

$\Delta\lambda < 0$ vacua: $(v_L, v_R) = (f,\ f)/\sqrt{2}$ ⟶ Not phenomenologically viable

$\Delta\lambda \simeq 0$ vacua: $(v_L, v_R) = (\cos\theta,\ \sin\theta)f$ ⟶ Tree level degeneracy lifted by quantum corrections
Obtain $v_L \simeq 173$ GeV $\ll v_R \simeq f$ by tuning $\Delta\lambda$ with accuracy v_L^2/v_R^2

No additional fine tuning that SM due to cancellation of the v_R scale in the total fine tuning

$\Delta\lambda$ tuning

$$\frac{v_L^2}{v_R^2} \times \frac{v_R^2}{\Lambda^2} = \frac{v_L^2}{\Lambda^2}$$ SM fine tuning

v_R from cutoff Λ tuning

Other $SO(10)$ breaking scenarios

$$SO(10) \xrightarrow{\langle H_{45} \rangle} SU(4) \times SU(2)_L \times SU(2)_R \xrightarrow{\langle H_{54} \rangle} G_{LR} \qquad \langle H_{45} \rangle = v_{45},\ \langle H_{54} \rangle = v_{54}$$

XY gauge bosons

Mediate proton decay

$$M_{XY}^2 = g_{10}^2 (v_{45}^2 + v_{54}^2)$$

PS gauge bosons

Do not mediate proton decay

$$M_{PS}^2 = 4 g_{10}^2 v_{45}^2$$

$$r_{XY} \equiv \frac{M_{PS}}{M_{XY}}$$

When $SO(10) \times CP$ is broken only by H_{45} then $r_{XY} = 2$

The $m_L = 1$ TeV results shown in the main slides correspond to $r_{XY} = 2$

$r_{XY} < 2$ is possible by more complicated breaking with multiple Higgs, e.g. $H_{54}(\mathbf{54})$

Tree level instability of SO(10) breaking H_{45}

$$\langle H_{45} \rangle = -iv_{45} \begin{pmatrix} \sigma_2 & 0 & 0 & \\ 0 & \sigma_2 & 0 & 0_{4\times6} \\ 0 & 0 & \sigma_2 & \\ & 0_{6\times4} & & \boxed{0_{4\times4}} \end{pmatrix}$$

Missing VEV of H_{45}

$\langle H_{45} \rangle$ unstable at tree level but stabilized by loop corrections [1]

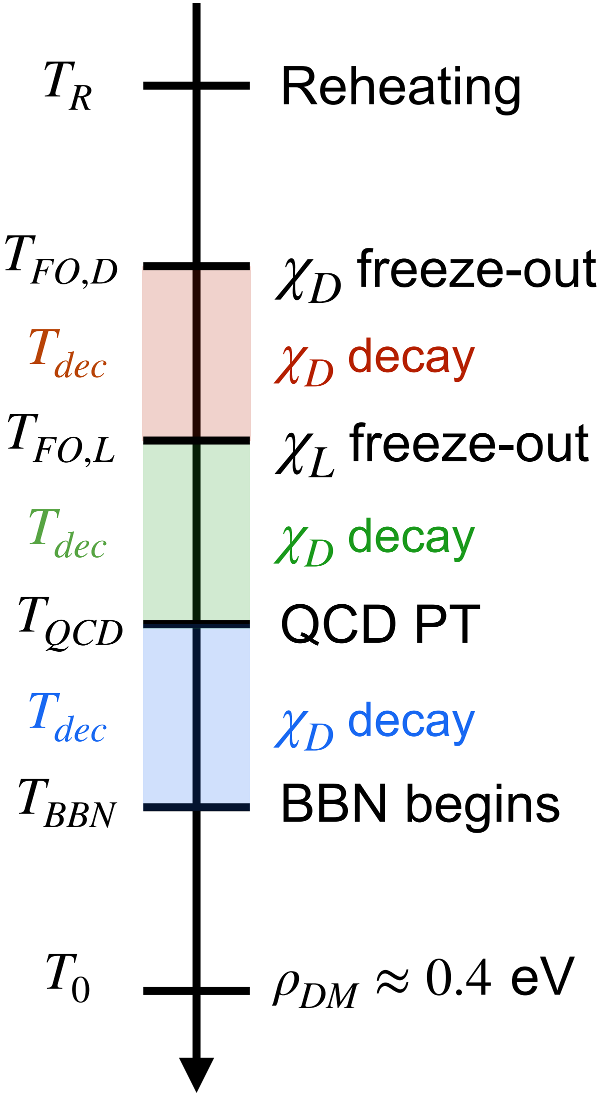
Alternatively we can stabilize the VEV by introducing an additional H_{54} Higgs to SO(10)

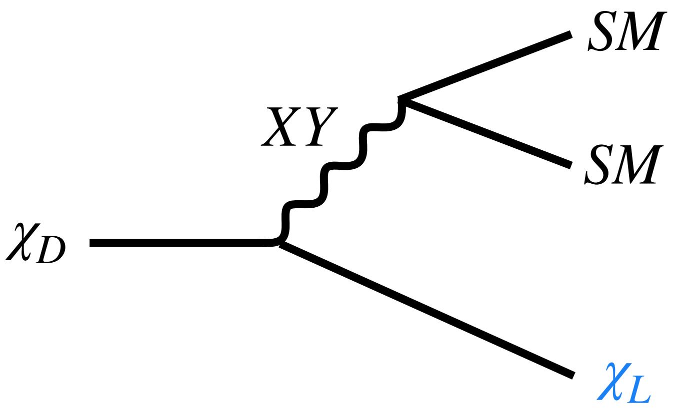
$$\langle H_{54} \rangle = \frac{1}{5} v_{54} \begin{pmatrix} 2 \times 1_{6\times6} & 0 \\ 0 & -3 \times 1_{4\times4} \end{pmatrix}$$

H_{54} couples to H_{45} to stabilize the vacuum

[1] S. Bertolini, L. Di Luzio and M. Malinsky, Phys. Rev. D 81 (2010) 035015

χ_D forms bound states if it decays after QCD phase transition





$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$ $\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$

$$\Gamma \sim \frac{1}{128\pi^3} \frac{m_D^5}{M_{XY}^4}$$

$T_{QCD} < T_{FO,L} < T_{dec}$ χ_L freeze-out gives ρ_{DM} for $m_L = 1$ TeV

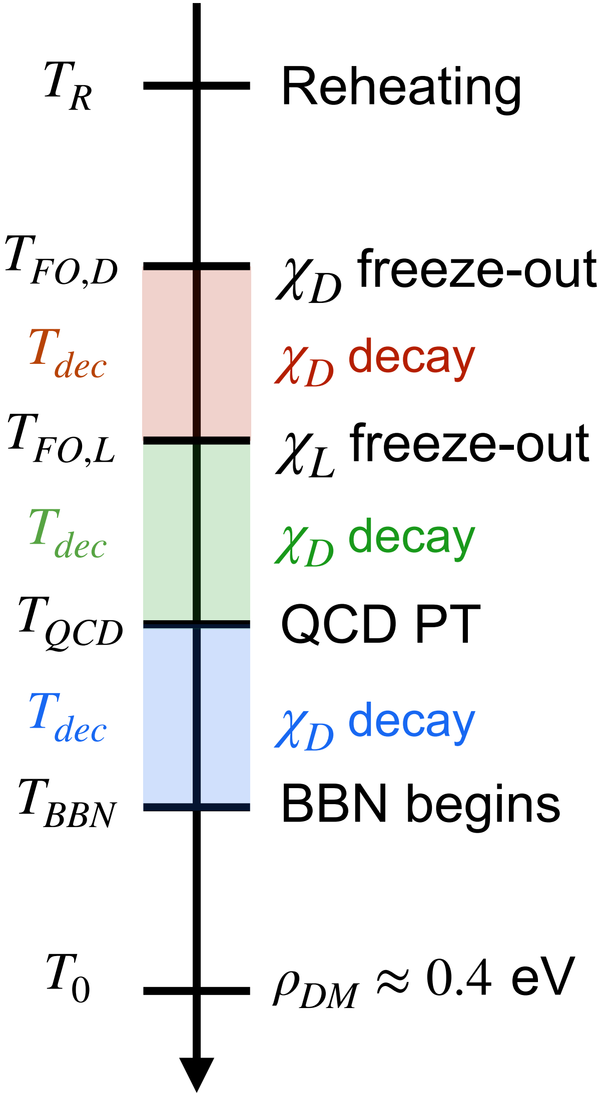
$T_{QCD} < T_{dec} < T_{FO,L}$ χ_L freeze-out and $\chi_D \to \chi_L$ decay give ρ_{DM}

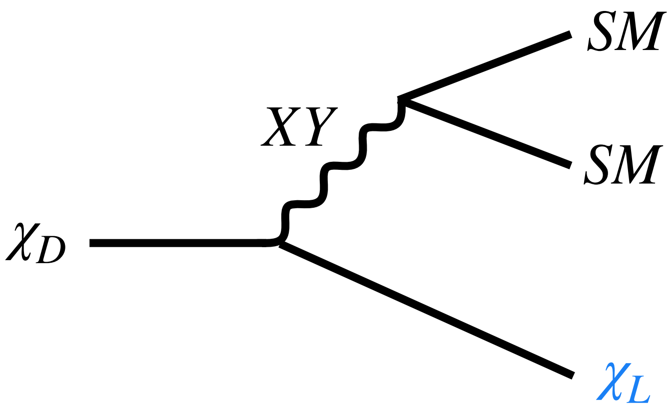
$T_{dec} < T_{QCD} < T_{FO,L}$ χ_L freeze-out and $\chi_D \to$ bound states $\to \chi_L$ decay give ρ_{DM}

To avoid overproduction

$$m_D > 3 \times 10^9 \text{ GeV} \times \left(\frac{M_{XY}}{10^{16} \text{ GeV}} \right)^{\frac{4}{5}} \left(\frac{m_L}{100 \text{ GeV}} \right)^{\frac{6}{5}}$$

Derivation of the overabundance bound





$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$ $\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$

$$\Gamma \sim \frac{1}{128\pi^3} \frac{m_D^5}{M_{XY}^4}$$

χ_D decay occurs around temperature

$$T_{dec} \simeq 2 \text{ MeV} \left(\frac{m_D}{10^9 \text{ GeV}}\right)^{5/2} \left(\frac{10^{16} \text{ GeV}}{m_{XY}}\right)^2$$

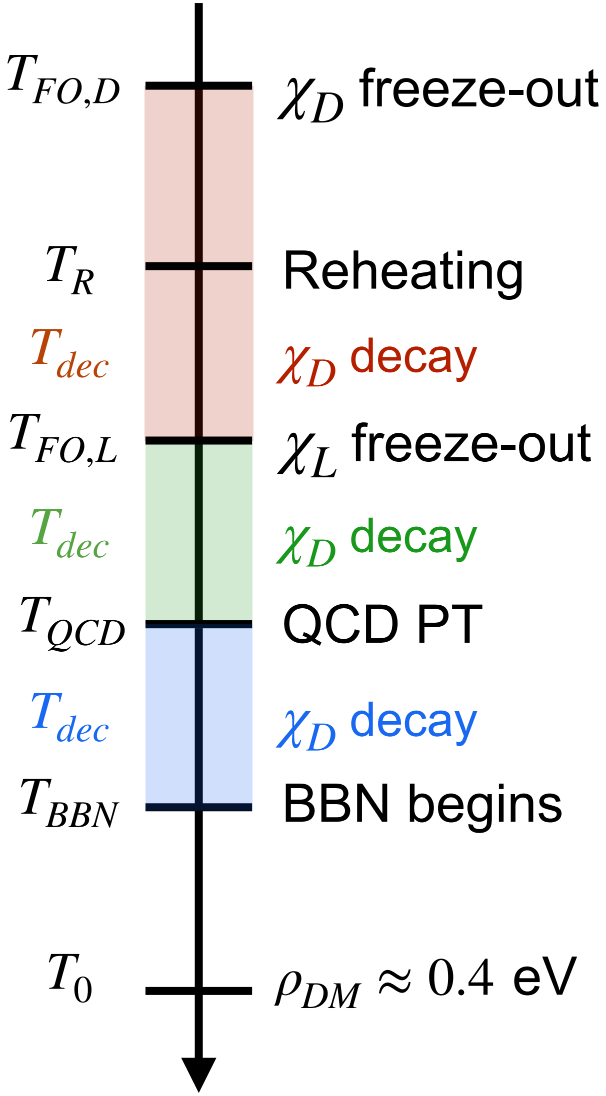
Even for $T_{dec} < T_{FO,L}$, number density n decreases by annihilation to $n \approx H/(\sigma v)$, giving DM density

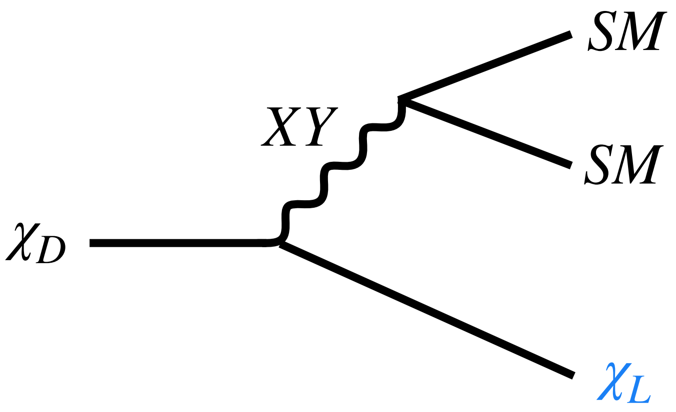
$$\frac{\rho_{DM}}{s} \simeq 0.4 \text{ eV} \left(\frac{m_L}{100 \text{ GeV}}\right)^3 \frac{0.05 \text{ GeV}}{T_{dec}}$$

Inserting T_{dec} and requiring that we do not overproduce DM $\rho_{DM} \leq 0.4$ eV leads to

$$m_D > 3 \times 10^9 \text{ GeV} \times \left(\frac{m_{XY}}{10^{16}\text{GeV}}\right)^{4/5} \left(\frac{m_L}{100\text{GeV}}\right)^{6/5}$$

$T_R < T_{FO,D}$ reheating scenario can be achieved





$\chi_L(\mathbf{1}, \mathbf{2}, -1/2)$ $\chi_D(\mathbf{3}, \mathbf{1}, -1/3)$

$$\Gamma \sim \frac{1}{128\pi^3} \frac{m_D^5}{M_{XY}^4}$$

Abundance of χ_D can be suppressed compared to $T_R > T_{FO,D}$

Cosmological bound on m_D avoided by taking $T_R \ll T_{FO,D}$ [CITE]

Conservative estimate

Maximal temperature of universe $T_{max} \leq T_R \sim T_{FO,L}$

Even if $m_D =$ few m_L, abundance of χ_D exponentially suppressed compared to χ_L

$SO(10)$ needs Yukawa and Singlet sectors

	Higgs	SM Fermions	Yukawa	Singlets	Dark Matter
$SO(10)\times CP$	$H_{45}(\mathbf{45})$ $H_{16}(\mathbf{16})$	$\psi_i(\mathbf{16})$ $i=1,2,3$	$X_{10,i}(\mathbf{10})$ $X_{45,i}(\mathbf{45})$	$S(\mathbf{1})$	$\chi_{10,n}(\mathbf{10})$ Weyl $n=1,2$
$\langle H_{45}\rangle = v_{45}$ ↓ G_{LR}	$H_R(\mathbf{1},\mathbf{1},\mathbf{2},1/2)$ $H_L(\mathbf{1},\mathbf{2},\mathbf{1},-1/2)$	$q(\mathbf{3},\mathbf{2},\mathbf{1},1/6)$ $\bar{q}(\bar{\mathbf{3}},\mathbf{1},\mathbf{2},-1/6)$ $l(\mathbf{1},\mathbf{2},\mathbf{1},-1/2)$ $\bar{l}(\mathbf{1},\mathbf{1},\mathbf{2},1/2)$			$D_n(\mathbf{3},\mathbf{1},\mathbf{1},-1/3)$ $\bar{D}_n(\bar{\mathbf{3}},\mathbf{1},\mathbf{1},1/3)$ $\Delta_n(\mathbf{1},\mathbf{2},\mathbf{2},0)$
$\langle H_R\rangle = v_R$ ↓ G_{SM}	$h_L(\mathbf{1},\mathbf{2},-1/2)$	$Q(\mathbf{3},\mathbf{2},1/6)$ $L(\mathbf{1},\mathbf{2},-1/2)$ $\bar{d}(\bar{\mathbf{3}},\mathbf{1},1/3)$ $\bar{u}(\bar{\mathbf{3}},\mathbf{1},-2/3)$ $\bar{e}(\mathbf{1},\mathbf{1},1)$ $\bar{N}(\mathbf{1},\mathbf{1},0)$			$\chi_D(\mathbf{3},\mathbf{1},-1/3)$ $\chi_{D'}(\bar{\mathbf{3}},\mathbf{1},1/3)$ $\chi_L(\mathbf{1},\mathbf{2},-1/2)$ $\chi_{L'}(\mathbf{1},\mathbf{2},1/2)$ Dirac

Dark matter embedding and coupling to H_{45}

Successful embedding of electroweak WIMPs into $SO(10)$ requires two Weyl fermions χ_1 and χ_2 with

$$\left[\chi^a_{10_1} H^{ab}_{45} \chi^b_{10_2} + \text{h.c.}\right] + m_2 \chi_{10_2} \chi_{10_2}$$

$$a, b = 1, 2, \cdots, 10$$

$$\langle H_{45} \rangle = -iv_{45} \begin{pmatrix} \sigma_2 & 0 & 0 & \\ 0 & \sigma_2 & 0 & 0_{4\times 6} \\ 0 & 0 & \sigma_2 & \\ & 0_{6\times 4} & & 0_{4\times 4} \end{pmatrix}$$

Missing VEV* of H_{45}

$m_L \leq m_D$

Avoid overabundance

$m_L \ll m_{L'}, m_{D'}$

Successful unification

Standard model Yukawa sector obtained from $SO(10)$

SM Yukawas generated by $SO(10) \times CP$ interaction terms with $X_{10}(\mathbf{10})$ and $X_{45}(\mathbf{45})$ fermions

$$\mathscr{L} = -x_{10}^{ij} H_{16} \psi_i X_{10,j} - i x_{10}^{\prime ij} H_{16} \psi_i X_{10,j} H_{45} - (M_{10}^{ij} + i\lambda_{10}^{ij} H_{45}) X_{10,i} X_{10,j}$$
$$-x_{45}^{ij} H_{16}^{\dagger} \psi_i X_{45,j} - i x_{45}^{\prime ij} H_{16}^{\dagger} \psi_i X_{45,j} H_{45} - (M_{45}^{ij} + i\lambda_{45}^{ij} H_{45}) X_{45,i} X_{45,j} + \mathrm{h.c.}$$

$SO(10) \times CP \to G_{LR}$ yields quark Yukawa terms

$$\mathscr{L} = -x_d^{ij} H_L q_i \bar{D}_j - x_d^{*ij} H_R \bar{q}_i D_j - M_d^{ij} D_i \bar{D}_j + \mathrm{h.c.}$$

Yukawas are complex with Parity ensures no strong CP phase

Under Parity $\quad q(t, \mathbf{x}) \leftrightarrow i\sigma_2 \bar{q}^*(t, -\mathbf{x}), \quad D(t, \mathbf{x}) \leftrightarrow i\sigma_2 \bar{D}^*(t, -\mathbf{x})$

Mass matrix $\quad \begin{pmatrix} d_i & D_i \end{pmatrix} \begin{pmatrix} 0 & x_d^{ij} v_L \\ x_d^{*ji} v_R & M_d^{ij} \end{pmatrix} \begin{pmatrix} \bar{d}_j \\ \bar{D}_j \end{pmatrix}$

Real determinant ⟶ Strong CP phase 0 or π

Strong CP Problem Solved

Similar terms obtained for lepton Yukawas

$$\mathscr{L} = -x_e^{ij} H_R \ell_i \Delta_j - x_e^{*ij} H_L \bar{\ell}_i \Delta_j - \frac{1}{2} M_e^{ij} \Delta_i \Delta_j + \mathrm{h.c.}$$

Singlet sector mixes dark matter via Majorana mass term

Majorana mass allows dark matter to mix

Necessary to avoid non-velocity-suppressed nucleon scattering via Z-exchange— excluded by direct-detection constraints.

Achieved by introducing heavy $SO(10)$ singlet S

$$\mathscr{L} = -\frac{1}{2M} S\chi_{10} H_{16} H_{16} - \frac{1}{2M'} S\chi_{10} H_{16}^{\dagger} H_{16}^{\dagger} - \frac{1}{2} m_S S^2 + \mathrm{h.c.}$$

Integrate out S

$$\mathscr{L} = \frac{v_R^2}{2M^2 m_S} \chi_L \chi_L H_L H_L$$

Now DM multiplet contains two Majorana fermions χ_1, χ_2 with mass splitting

$$\Delta m_0 = m_{\chi_2} - m_{\chi_1} \simeq \frac{v_R^2 v_L^2}{M^2 m_S} = 100\ \mathrm{keV}\ \frac{10\ \mathrm{TeV}}{m_S} \left(\frac{v_R/M}{0.006} \right)^2$$

$m_L < 1$ TeV possible for $T_{dec} < T_{FO,L}$

$$\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \quad SU(2) \text{ doublet}$$

χ_L^+ decays to χ_L^0 leave disappearing tracks in collider detectors

This probes the mass difference $\Delta m^{\pm}$ between χ_L^+ and χ_L^0

$\Delta m^{\pm} \simeq 340$ MeV if dominated by EW quantum corrections

This corresponds to $m_L > 200$ GeV LHC bound

High Luminosity LHC will improve this to $m_L > 500$ GeV

If $\Delta m^0 \simeq$ EW correction then $\Delta m^{\pm} > 340$ MeV and the $m_L > 100$ GeV LEP bound applies

Matching conditions relate couplings of different gauge groups

Match to SM values at m_t

$$g_1(m_t) = 0.4626,\ g_2(m_t) = 0.64779,\ g_3(m_t) = 1.1666$$

Match G_{SM} to G_{LR} at $M_{W_R} = g_R(v_R)v_R/\sqrt{2}$

$$\frac{2\pi}{\alpha_1^{SM}(M_{W_R})} = \frac{2}{5}\frac{2\pi}{\alpha_1^{LR}(M_{W_R})} + \frac{3}{5}\frac{2\pi}{\alpha_2^{LR}(M_{W_R})} - \frac{1}{10},$$

$$\frac{2\pi}{\alpha_2^{SM}(M_{W_R})} = \frac{2\pi}{\alpha_2^{LR}(M_{W_R})},\quad \frac{2\pi}{\alpha_3^{SM}(M_{W_R})} = \frac{2\pi}{\alpha_3^{LR}(M_{W_R})}.$$

Threshold corrections

Match G_{LR} to $SO(10) \times CP$ at M_{XY}

$$\frac{2\pi}{\alpha_1(M_{XY})} = \frac{2\pi}{\alpha_{10}(M_{XY})} + \Delta_{1,G} + \Delta_{1,H} + \Delta_1,$$

$$\frac{2\pi}{\alpha_2(M_{XY})} = \frac{2\pi}{\alpha_{10}(M_{XY})} + \Delta_{2,G} + \Delta_{2,H} + \Delta_2,$$

$$\frac{2\pi}{\alpha_3(M_{XY})} = \frac{2\pi}{\alpha_{10}(M_{XY})} + \Delta_{3,G} + \Delta_{3,H} + \Delta_3,$$

Threshold corrections contain gauge and Higgs contributions

$$\Delta(M_{XY}) \equiv \max_{i,j} \left| \Delta_i - \Delta_j \right| = \max_{i,j} \left| \left(\frac{2\pi}{\alpha_i} - \Delta_{i,G} - \Delta_{i,H} \right) - \left(\frac{2\pi}{\alpha_j} - \Delta_{j,G} - \Delta_{j,H} \right) \right|$$

Gauge boson contribution $\Delta_{1,G} = 14 \ln r_{XY} - \frac{4}{3},\ \Delta_{2,G} = -1,\ \Delta_{3,G} = \frac{7}{2} \ln r_{XY} - \frac{5}{6}$

Higgs contribution $\Delta_{1,H} = 0,\ \Delta_{2,H} = -\frac{1}{3} \ln \frac{M_{(1,3,1,0)}}{M_{XY}} = -\frac{1}{3} \ln \frac{M_{(1,1,3,0)}}{M_{XY}},\ \Delta_{3,H} = -\frac{1}{2} \ln \frac{M_{(8,1,1,0)}}{M_{XY}}$

where [1] $\frac{M^2_{1,3,1,0}}{M^2_{XY}} = \frac{M^2_{1,1,3,0}}{M^2_{XY}} = \frac{19g^2}{4\pi^2},\ \frac{M^2_{8,1,1,0}}{M^2_{XY}} = \frac{22g^2}{4\pi^2}$

[1] S. Bertolini, L. Di Luzio and M. Malinsky, Phys. Rev. D 81 (2010) 035015

Integrating out heavy field gives $B-$ and $L-$ violating terms

Effective Lagrangian
$$\mathscr{L} = \frac{g_{10}^2}{M_{XY}^2}\left[2A_L(QL)(\bar{u}\bar{d})^\dagger + A_R(QQ)(\bar{u}\bar{e})^\dagger)\right] + \text{h.c.} \qquad A_{R,L} = A_{R,L}^{SM} \times A_{R,L}^{LR}$$

1-loop renormalization [2]

$$A_R^{SM} = \prod_n \left(\frac{\alpha_3(\mu_{n+1})}{\alpha_3(\mu_n)}\right)^{-\frac{2}{b_3^n}} \left(\frac{\alpha_2(\mu_{n+1})}{\alpha_2(\mu_n)}\right)^{-\frac{9}{4b_2^n}} \left(\frac{\alpha_1(\mu_{n+1})}{\alpha_1(\mu_n)}\right)^{-\frac{11}{12b_1^n}},$$

$$A_L^{SM} = \prod_n \left(\frac{\alpha_3(\mu_{n+1})}{\alpha_3(\mu_n)}\right)^{-\frac{2}{b_3^n}} \left(\frac{\alpha_2(\mu_{n+1})}{\alpha_2(\mu_n)}\right)^{-\frac{9}{4b_2^n}} \left(\frac{\alpha_1(\mu_{n+1})}{\alpha_1(\mu_n)}\right)^{-\frac{23}{12b_1^n}},$$

$$A_R^{LR} = \prod_n \left(\frac{\alpha_3(\mu_{n+1})}{\alpha_3(\mu_n)}\right)^{-\frac{2}{b_3^n}} \left(\frac{\alpha_2(\mu_{n+1})}{\alpha_2(\mu_n)}\right)^{-\frac{9}{2b_2^n}} \left(\frac{\alpha_1(\mu_{n+1})}{\alpha_1(\mu_n)}\right)^{-\frac{1}{4b_1^n}},$$

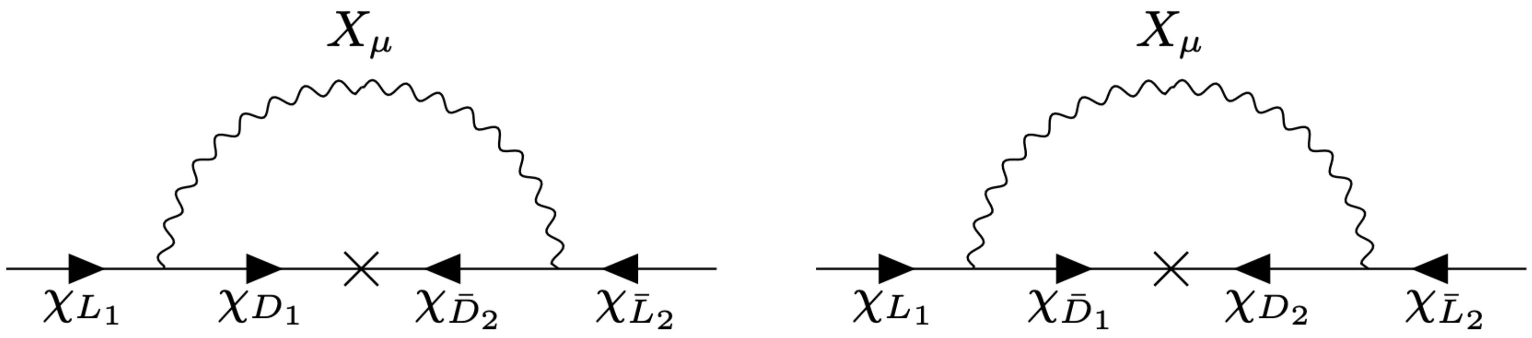
$$A_L^{LR} = A_R^{LR},$$

$p \to e^+ + \pi^0$ decay rate
$$\tau_{p\to e^+ + \pi^0} = \left[\frac{1}{32\pi} m_p \left(1 - \frac{m_{\pi^0}^2}{m_p^2}\right)^2 \frac{g_{10^4}}{M_{XY}^4}(4A_L^2 + A_R^2)\,|\,W_0\,|^2\right]^{-1}$$

[2] W.E. Caswell, J. Milutinovic and G. Senjanovic, Phys. Rev. D 26 (1982) 161.

One-loop corrections to the mass of χ_L vanish

1-loop corrections to mass of χ_L



Sum of diagrams is zero due to oppose masses of $\chi_{D_1}\chi_{\bar{D}_2}$ and $\chi_{\bar{D}_1}\chi_{D_2}$

One Weyl Fermion Case

One Weyl fermion can couple to H_{45} via

$$\chi_{10}^a H_{45}^{ab} H_{45}^{bc} \chi_{10}^c$$

If H_{45} real, mass splitting unstable due to quadratically divergent corrections generating $\chi_{10}^a \chi_{10}^a$

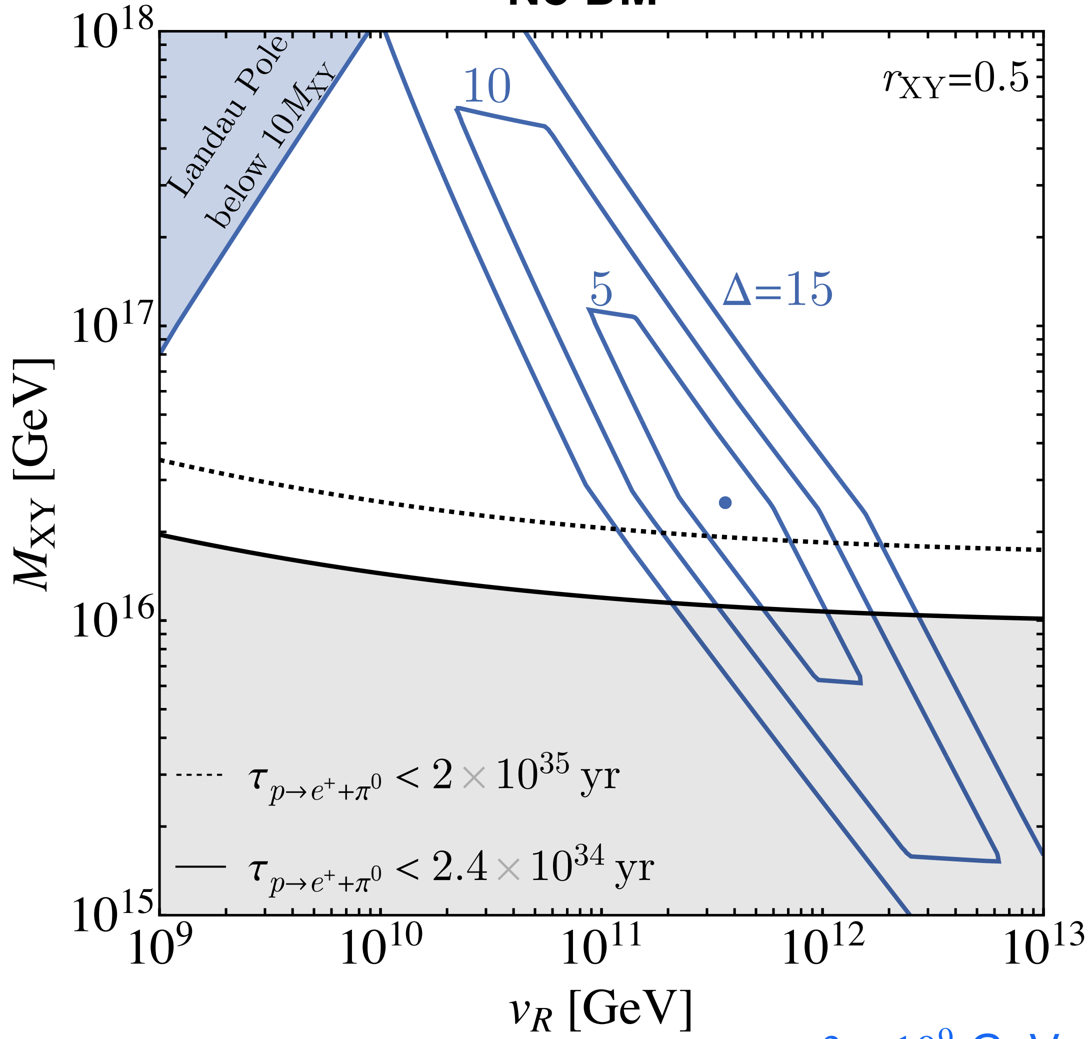
If H_{45} complex, no quadratically divergent corrections, but the following is generated by quantum corrections

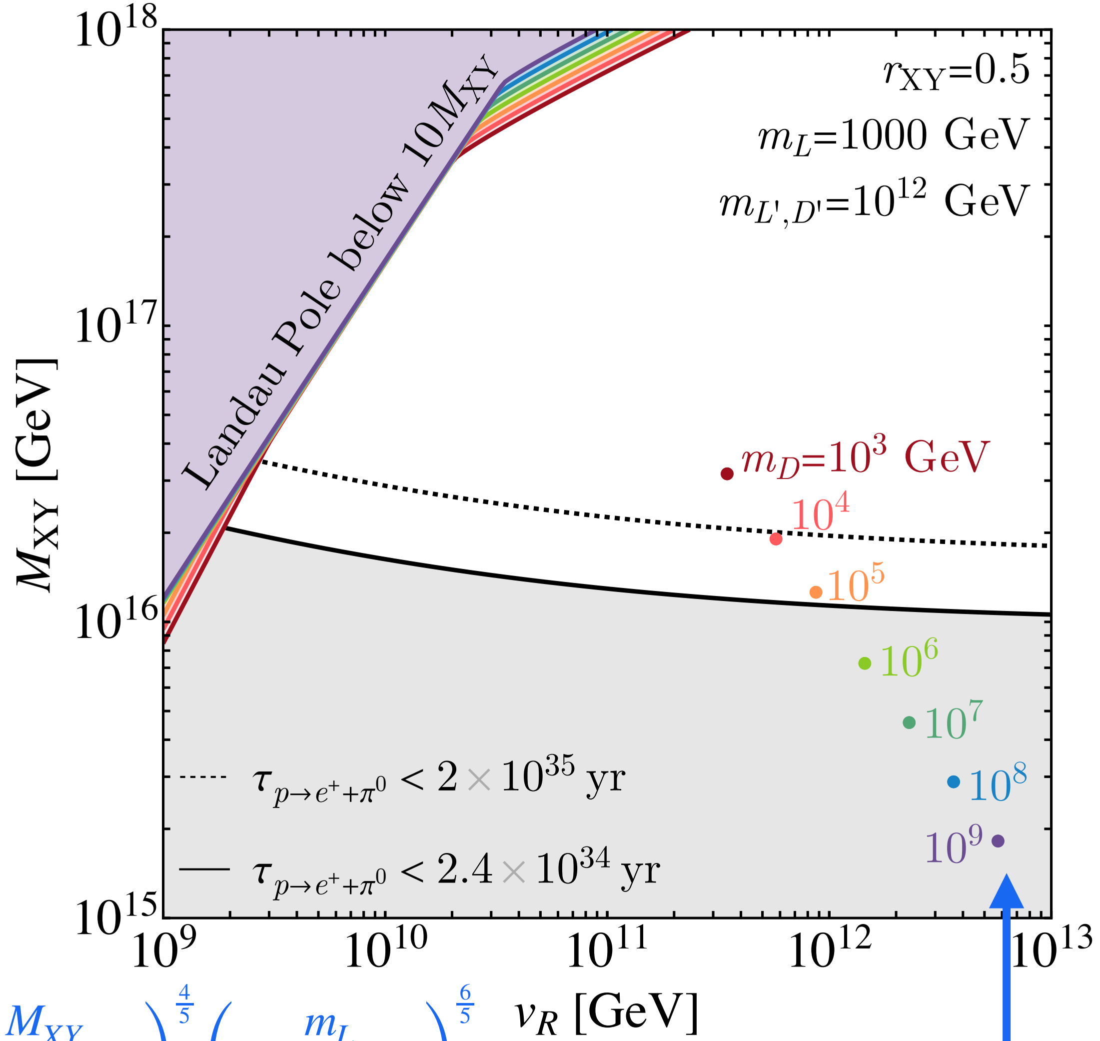
$$\chi_{10}^a \chi_{10}^a H_{45}^{bc} H_{45}^{bc}$$

In this case $m_L/m_D \sim 10^{-3}$ which is too small to satisfy overproduction bounds

$\Delta = 0$ for $r_{XY} = 1/2$ shifted to higher v_R, smaller M_{XY} relative to $r_{XY} = 2$

No DM

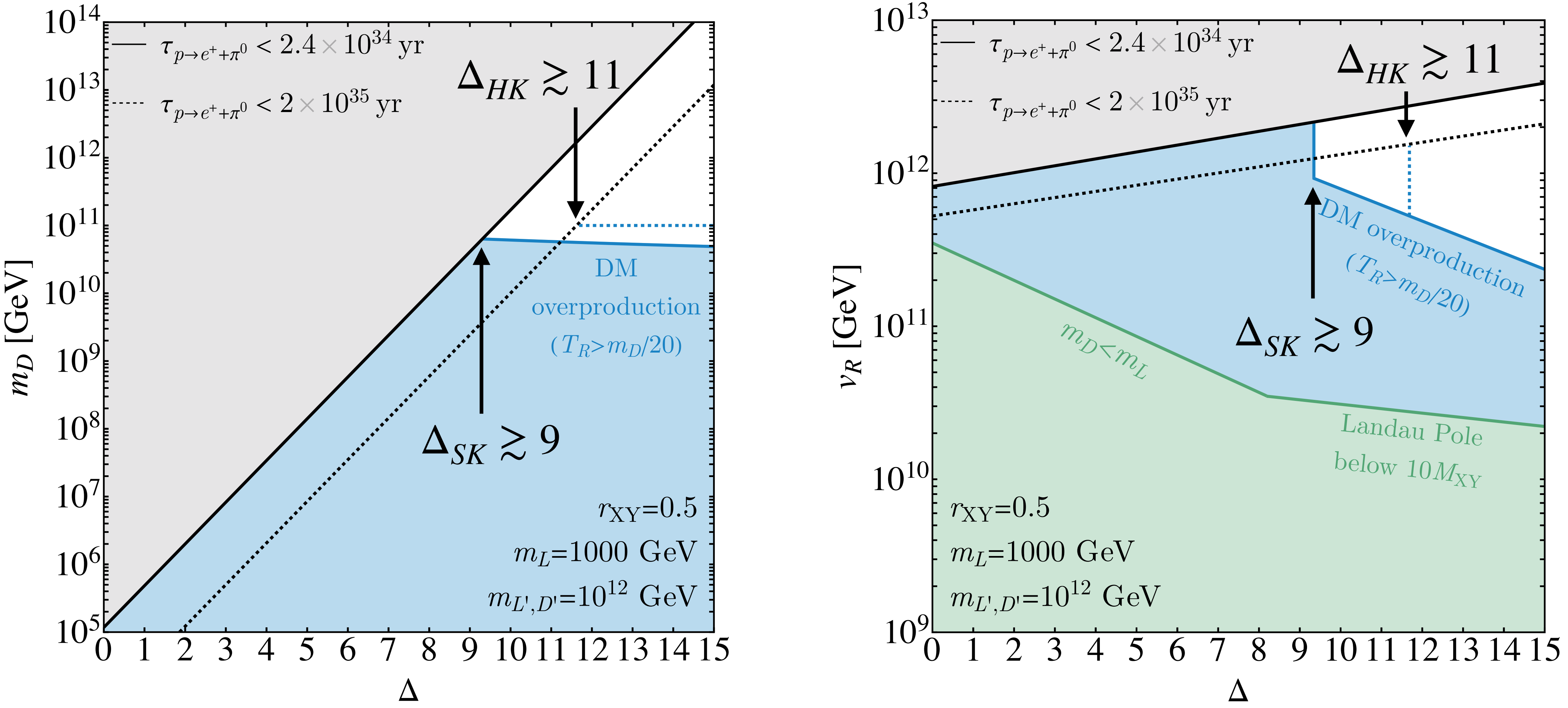




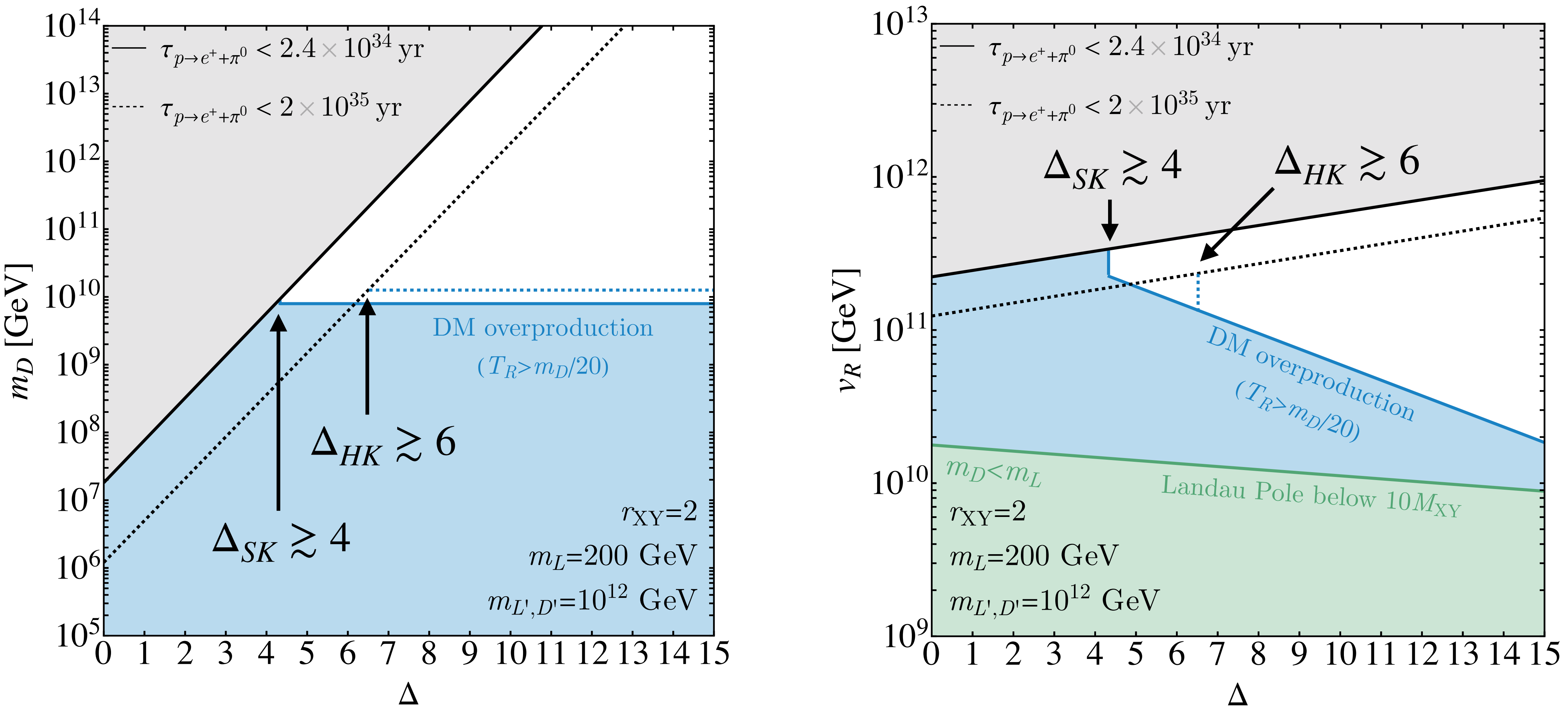
$$m_D > 3\times10^9\ \text{GeV}\times\left(\frac{M_{XY}}{10^{16}\ \text{GeV}}\right)^{\frac{4}{5}}\left(\frac{m_L}{100\ \text{GeV}}\right)^{\frac{6}{5}}$$

$\Delta > 0$ to satisfy m_D, m_L splitting

$m_L = 1$ TeV, $r_{XY} = 1/2$



$m_L = 200$ **GeV,** $r_{XY} = 2$



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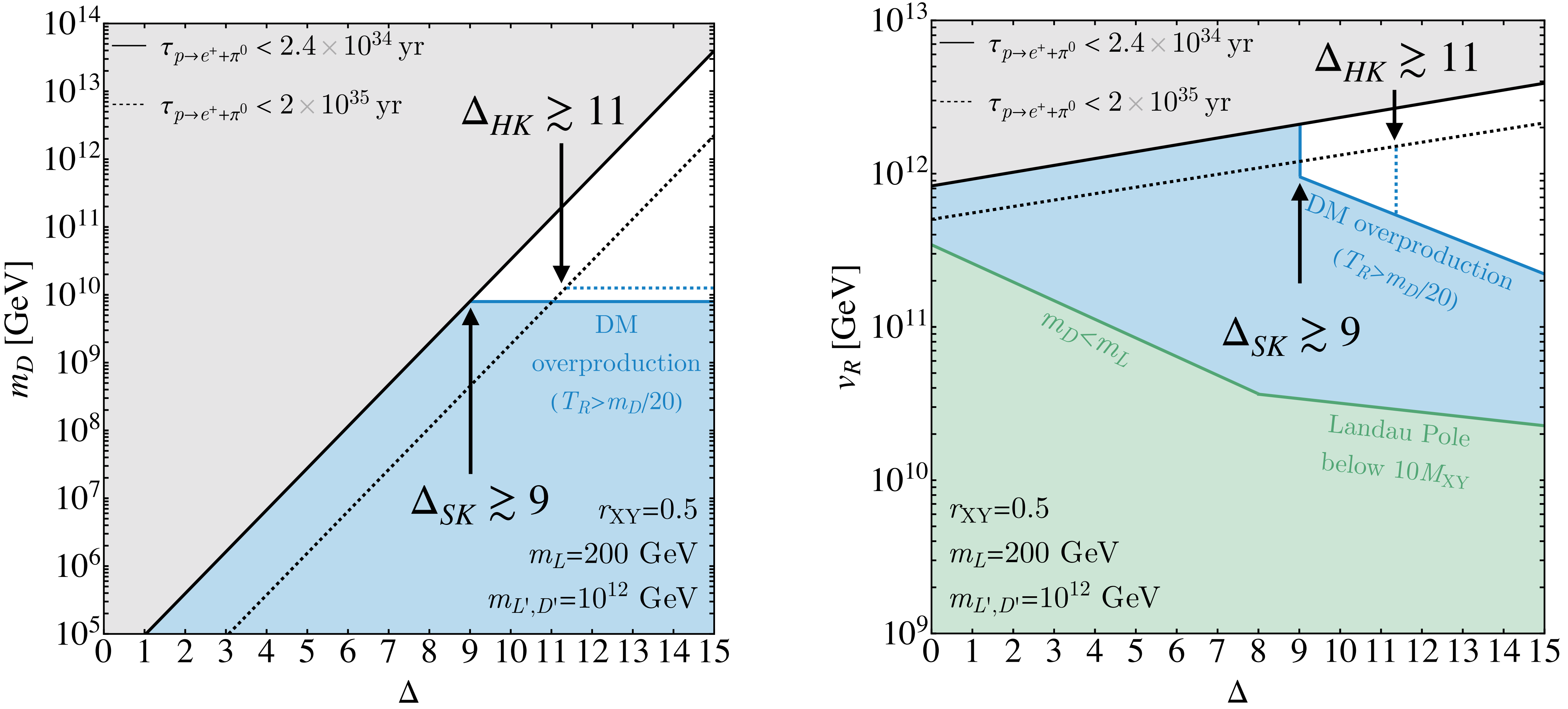
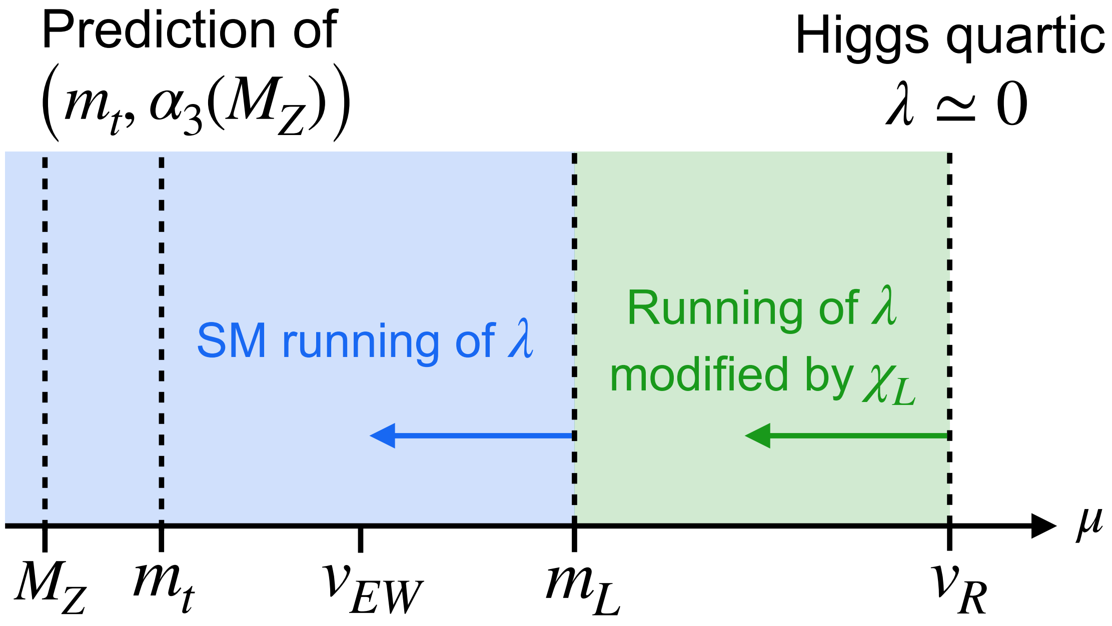
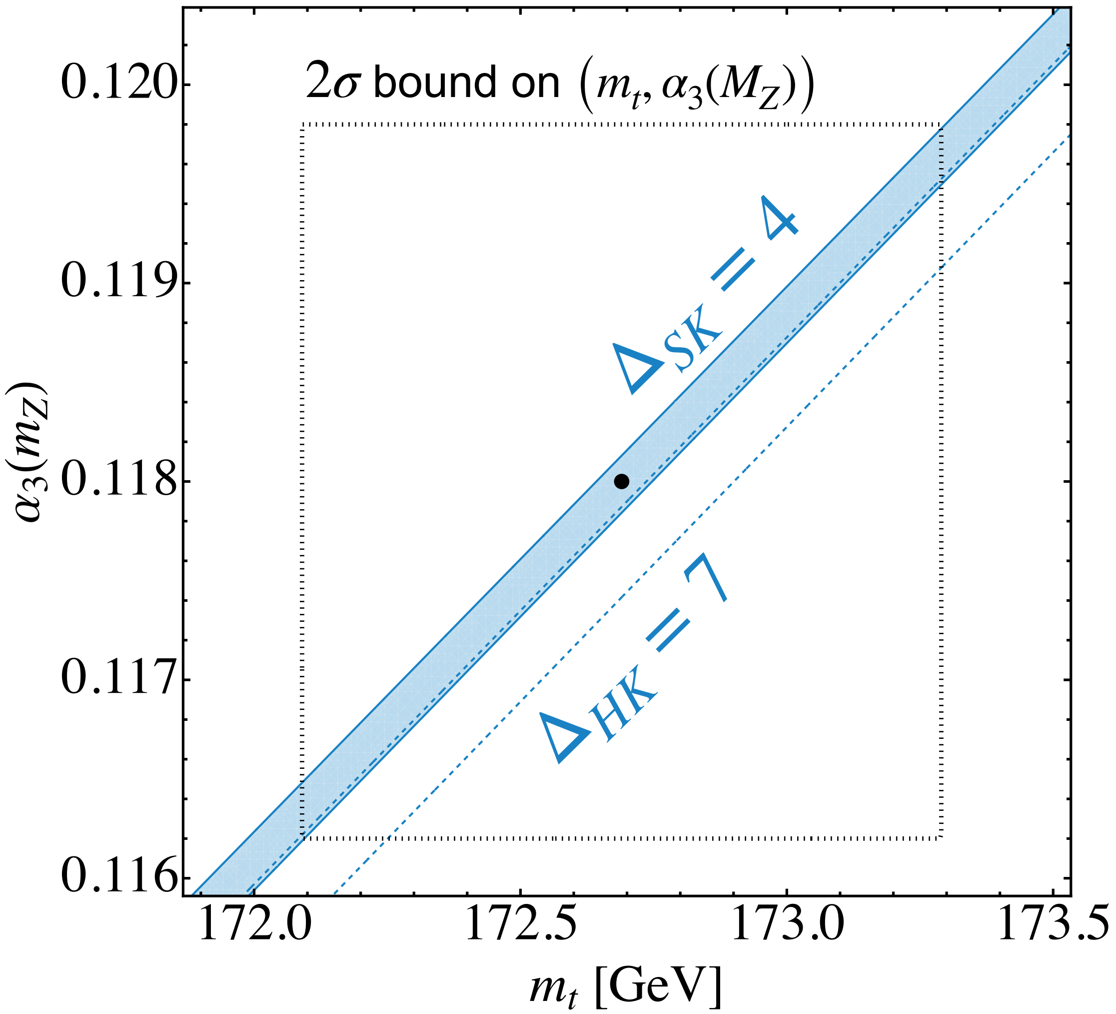
PIKIMO Fall 2024

$m_L = 200$ **GeV**, $r_{XY} = 1/2$



Standard Model parameters are precisely predicted





$\left(m_t, \alpha_3(M_Z)\right)$ constrained by unification, cosmological and proton decay bounds