Dark Matter and Leptoquarks

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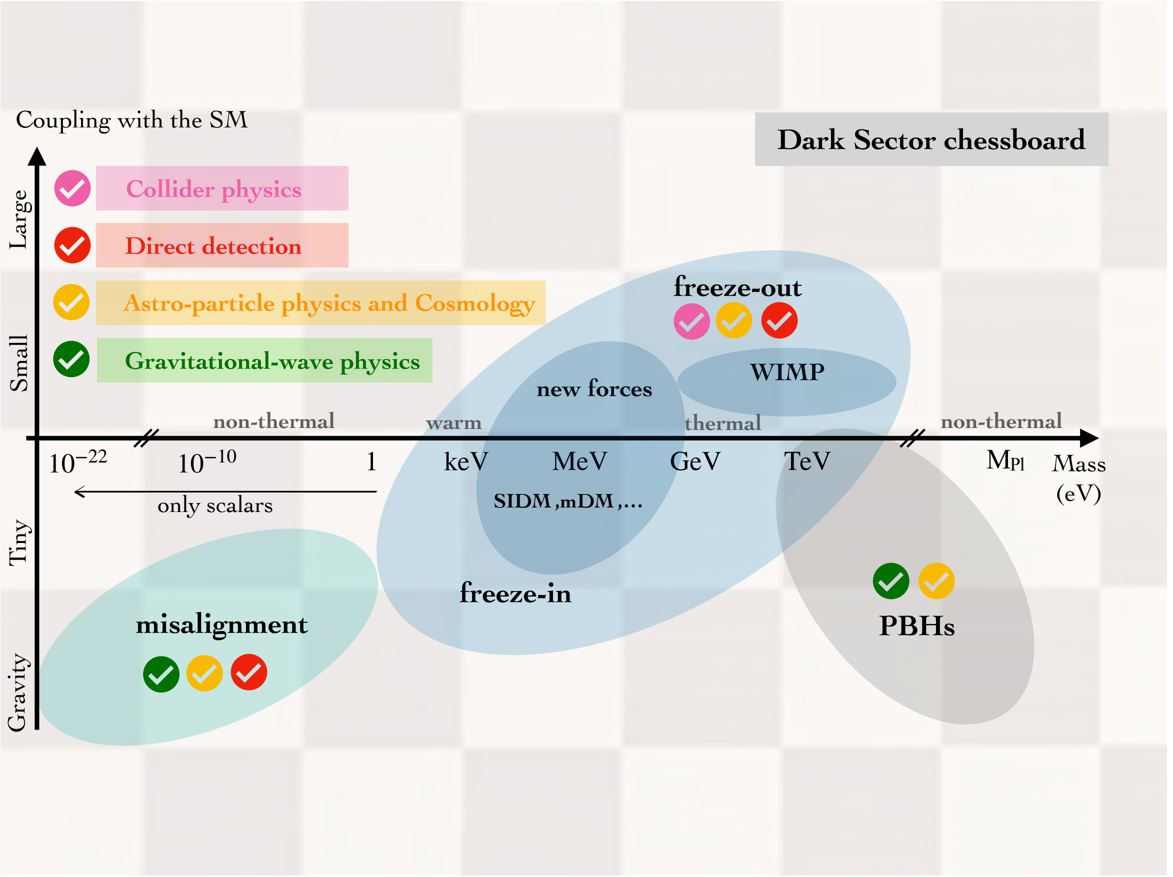
PRIN “The consequences of flavor”

Les Rencontres de Physique de la Vallée d’Aoste — La Thuile, 7.3.2022

Dark Matter vs B-physics?



- Experimental fact: Dark Matter exists
- In principle, its mass and couplings can span tens of orders of magnitude!
- If it has (weak) interactions with thermal bath of SM particles, elegant way to predict its cosmological abundance

  ➡ M_{DM} ~ TeV with ~ EW coupling

- Interplay with popular models of New Physics at the EW scale (e.g. SUSY, composite models, …)

Post-LHC:

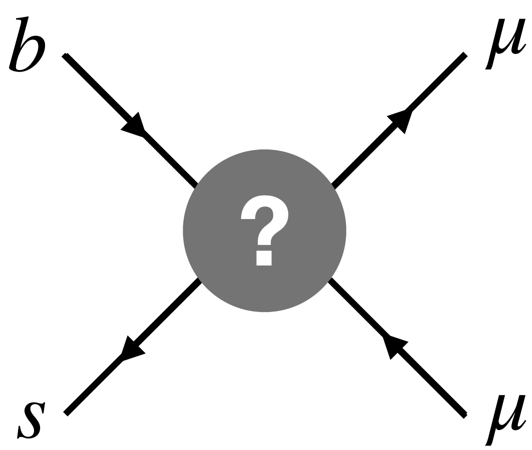
no light on-shell resonances

very interesting anomalies in flavour observables

Could the two things have a common origin?

Leptoquarks as mediators

B-anomalies:



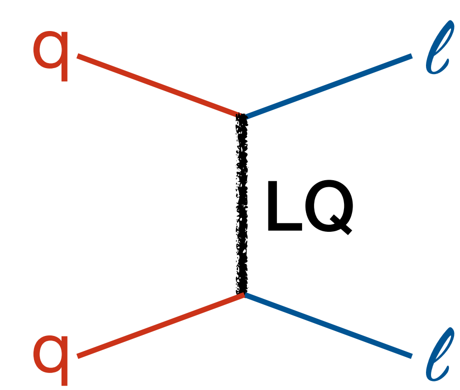
- Evidence for new interaction between quarks & leptons

$$\frac{1}{\Lambda^2}(\bar{b}_L \gamma_\nu s_L)(\bar{\mu}_L \gamma^\nu \mu_L) \qquad \Lambda \approx 30\,\text{TeV} \approx 6\,\text{TeV} \cdot V_{cb}^{-1/2}$$

- Yukawa-like couplings, larger for heavy generations

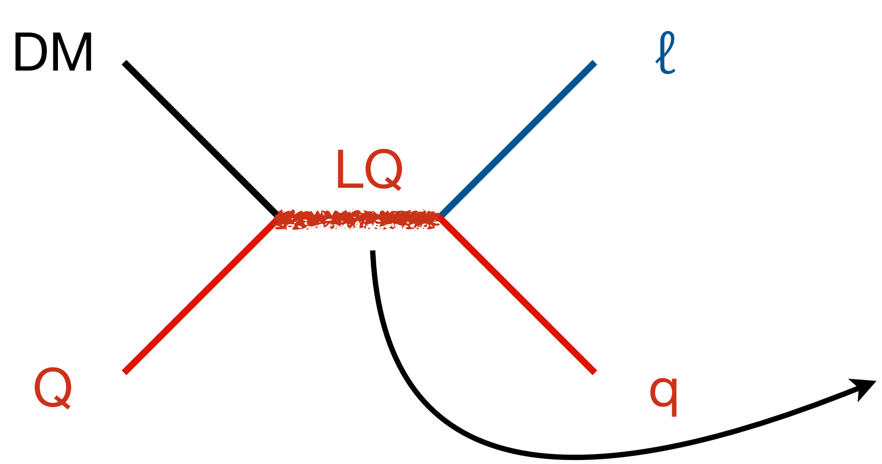
- Effect only in **semi-leptonic** processes VS. strong bounds from pure-quark and -lepton observables

→ hint for **leptoquark** mediator



☛ see talks by Luca, Claudia, David

- *Can Leptoquarks be the mediators of SM-DM interactions?*



colored: must couple to a quark

A (too) simple picture

- <u>Example:</u> Pati-Salam SU(4) unification

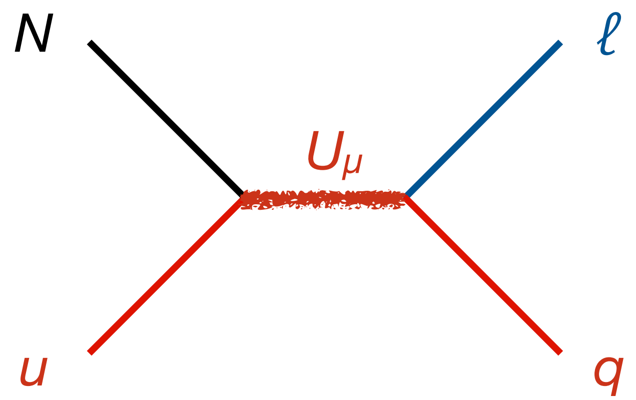
extension of SM gauge group $\mathrm{SU(4)_{PS}} \longrightarrow \mathrm{SU(3)_c} \times \mathrm{U(1)_{B-L}}$

$$V_\mu = \begin{pmatrix} (G^a_\mu)^\alpha_\beta & U^\alpha_\mu \\ (U^\alpha_\mu)^\dagger & Z'_\mu \end{pmatrix}$$

U_μ: color triplet, Y = 2/3

Fermions are 4-plets of SU(4): quark-lepton unification

$$\Psi_L = \begin{pmatrix} q^\alpha_L \\ \ell_L \end{pmatrix} \sim \mathbf{4} \qquad \Psi_d = \begin{pmatrix} d^\alpha_R \\ \ell_R \end{pmatrix} \sim \mathbf{4} \qquad \Psi_u = \begin{pmatrix} u^\alpha_R \\ N_R \end{pmatrix} \sim \mathbf{4}$$



SM singlet (sterile neutrino)
can be Dark Matter

Possible mediators

Consider a fermion SM singlet χ (sterile neutrino).

Mediators that can couple (at tree-level) to χ and a SM fermion:

- Vector Leptoquark: $U_1 \sim (\mathbf{3}, \mathbf{1}, \text{-}2/3)$ ☛ see talk by David

$$\mathscr{L}_U = \left[g_L(\bar{Q}_L\gamma_\mu L_L) + g_R(\bar{d}_R\gamma_\mu \ell_R) + g_\chi(\bar{u}_R\gamma_\mu\chi)\right]U^\mu$$

- Scalar Leptoquarks:

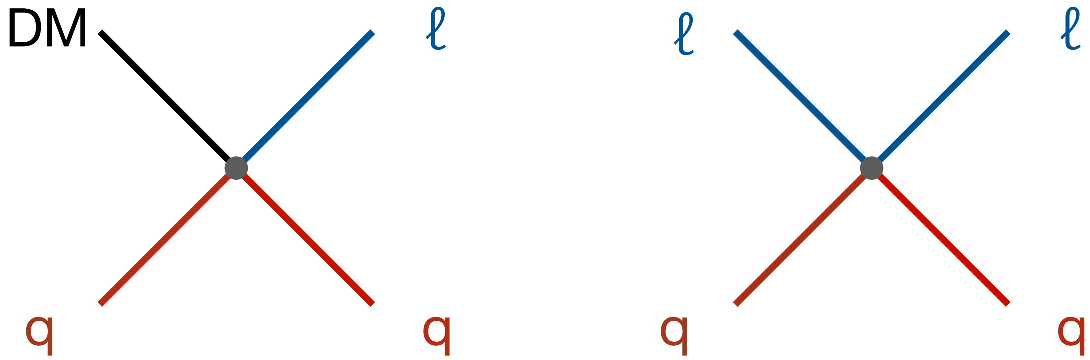
$S_1 \sim (\mathbf{3}, \mathbf{1}, 1/3)$ $\qquad \mathscr{L}_{S_1} = \left[g_L(\bar{Q}_L\varepsilon L_L^c) + g_R(\bar{u}_R\ell_R^c) + g_\chi(\bar{d}_R\chi)\right]S_1$

$R_2 \sim (\mathbf{3}, \mathbf{2}, 1/6)$ $\qquad \mathscr{L}_{\tilde{R}_2} = \left[g_L(\bar{d}_R L_L\varepsilon) + g_\chi(\bar{Q}_L\chi)\right]\tilde{R}_2$

- Right-handed vector: $W_R \sim (\mathbf{1}, \mathbf{1}, 1)$ $\qquad \left[g_R(\bar{u}_R\gamma_\mu d_R) + g_\chi(\bar{\ell}_R\gamma_\mu\chi)\right]W_R^\mu$

- (Higgs doublet: $Y_\chi(\bar{L}_L\chi)H^c$)

Integrating out the heavy mediator: effective interactions

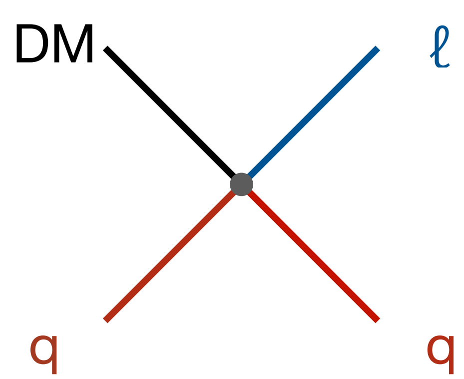


Effective interactions

Consider a fermion SM singlet χ (sterile neutrino).

- Most general effective Lagrangian for χ interacting with SM:

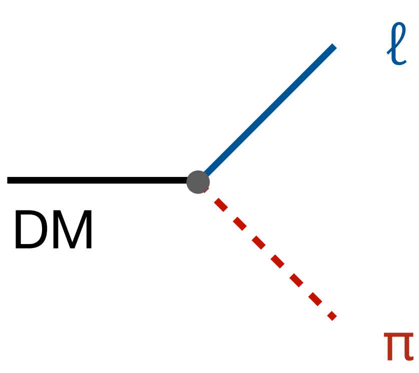
$$\mathscr{L}_{\rm DM}^{\rm eff} = -C_{\chi R}(\bar{\chi}\gamma^{\mu}\ell_R)(\bar{d}_R\gamma_{\mu}u_R) + 2C_{\chi L}(\bar{\chi}L_L)(\bar{Q}_L u_R) - C'_{\chi L}(\bar{L}_L\chi)\varepsilon(\bar{Q}_L d_R) - C''_{\chi L}(\bar{Q}_L\chi)\varepsilon(\bar{L}_L d_R).$$



with $C_{IJ} = g_I g_J / M_{\rm LQ}^2$

- Below the QCD scale: eff. coupling to pions and hadrons

$$\mathscr{L}_{\rm DM}^{\pi} = \frac{C_{\chi R}}{\sqrt{2}}(\bar{\chi}\gamma^{\mu}\ell_R)\Big[f_{\pi}\,D_{\mu}\pi^{+} + i(\pi^{0}\partial_{\mu}\pi^{+} - \pi^{+}\partial_{\mu}\pi^{0}) + \cdots\Big] + -iC_{\chi L}f_{\pi}B_0\Big[\sqrt{2}(\bar{\chi}\ell_L)\pi^{+} + (\bar{\chi}\nu_L)\pi^{0} + \cdots\Big] + \text{h.c.}$$

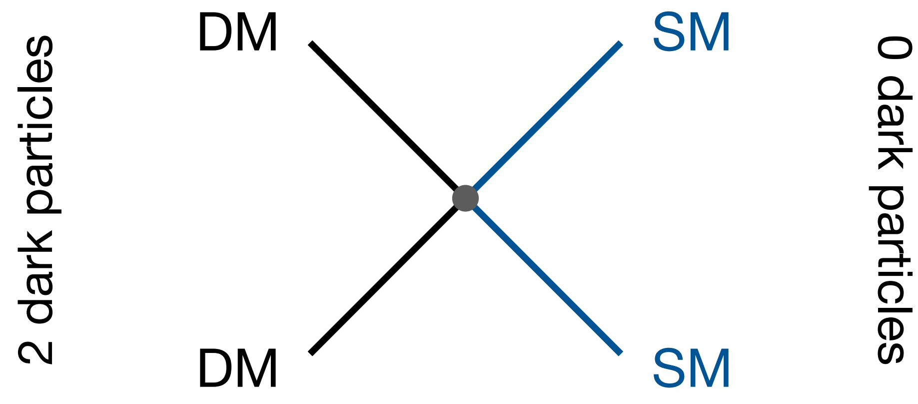


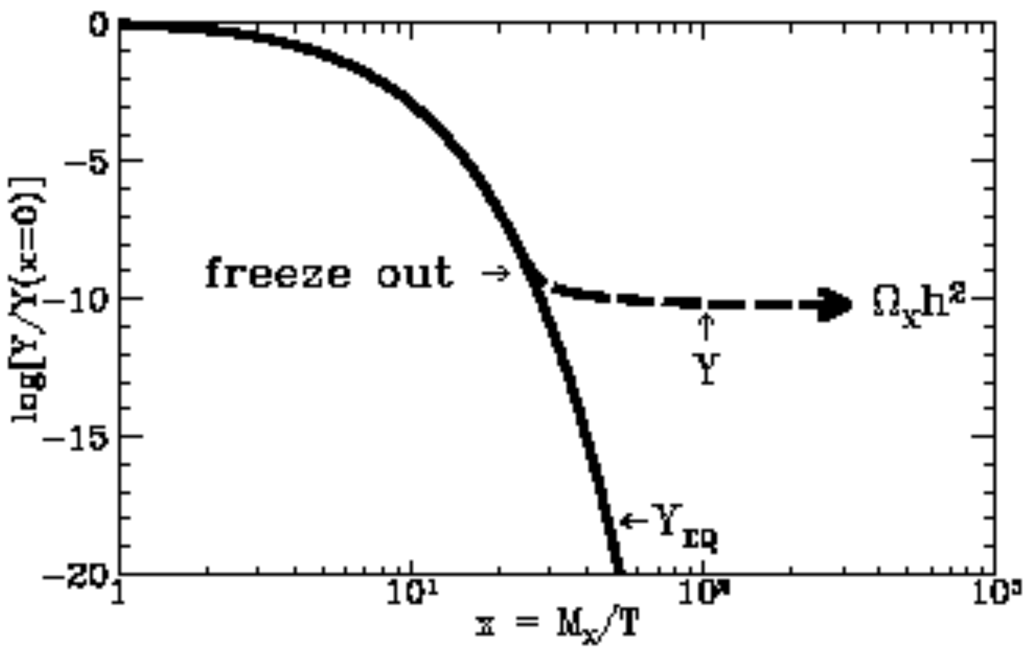
(chiral Lagrangian)

DM production

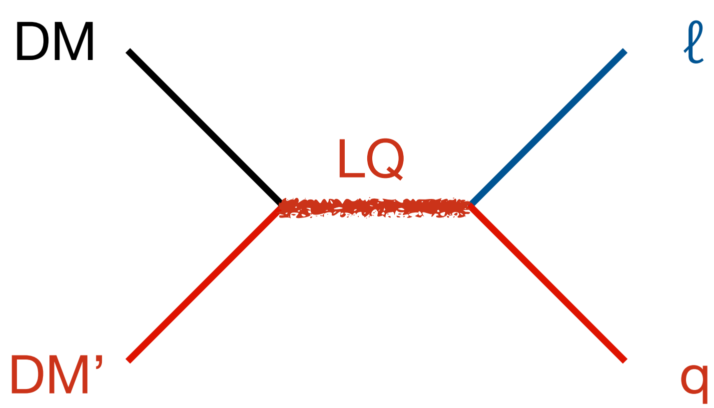
- Usually: DM is stable thanks to an exact ($\mathbb{Z}_2$) global symmetry $\chi \to -\chi$

- Production in early Universe: thermal freeze-out of 2 → 0 scatterings





➡ Introduce a *Dark Sector* with new colored states odd under $\mathbb{Z}_2$



LQ portal

- Baker, Faroughy, Trifinopoulos 2109.08689
- Belanger et al. 2111.08027
- Guadagnoli, Reboud, Stangl 2005.10117

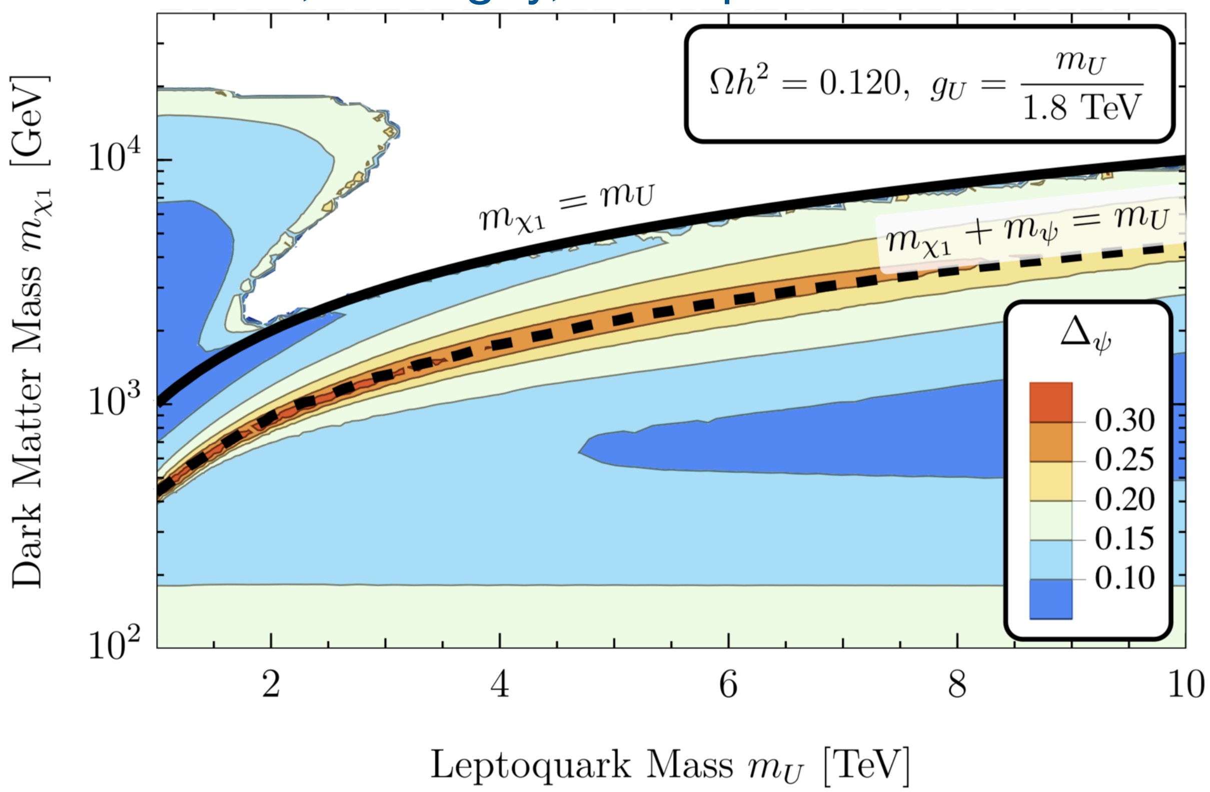
DM production: annihilation

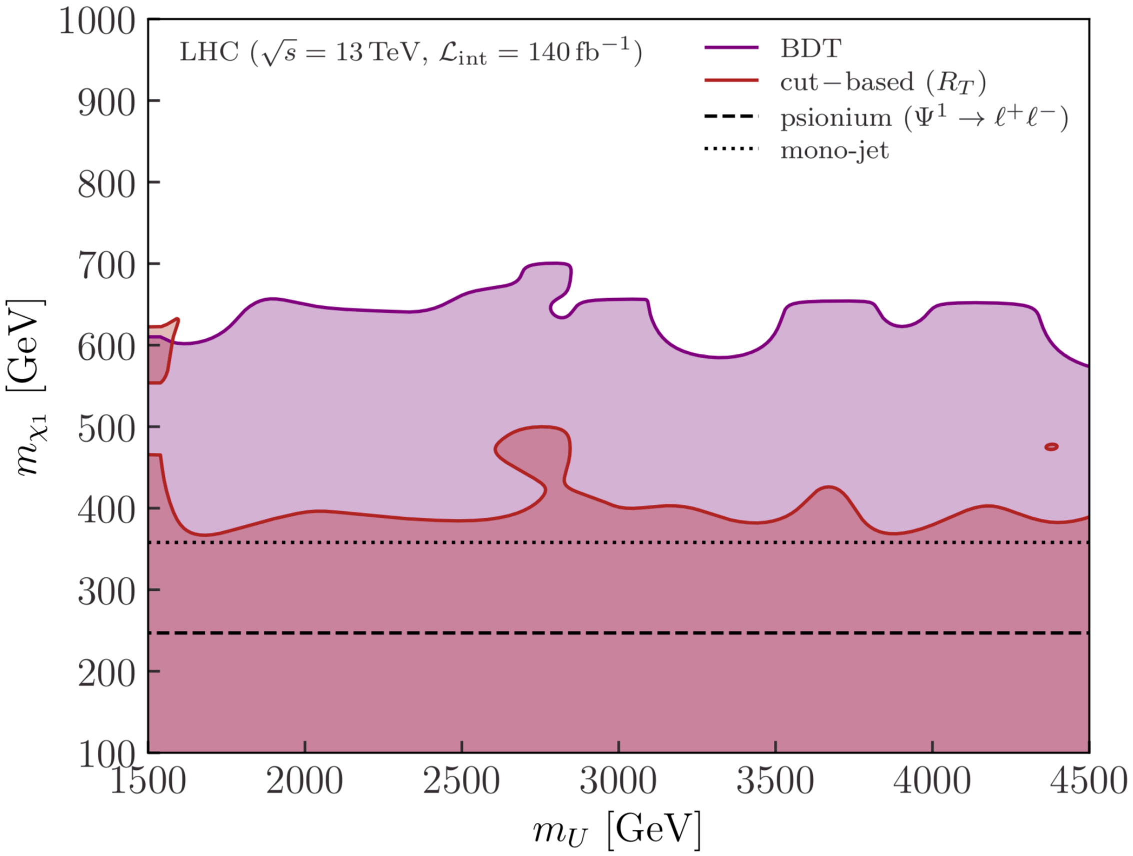
- Relic abundance can be reproduced, by coannihilation with colored DM’

  (DM-DM’ splitting can be adjusted)

- Consequences for phenomenology:

Baker, Faroughy, Trifinopoulos 2109.08689





can search for colored states at LHC:
Leptoquark & DM partner

See also: Belanger et al. 2111.08027

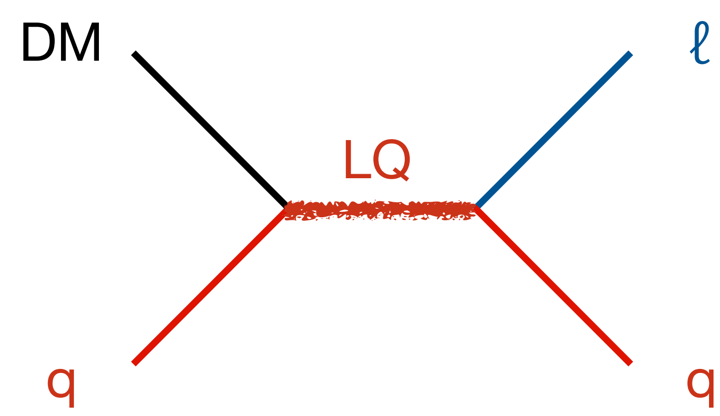
Guadagnoli, Reboud, Stangl 2005.10117

➡ Second possibility: allow only one LQ-DM-SM coupling
(LQ is charged under $\mathbb{Z}_2$ and part of dark sector)

Mandal 1808.07844

Thermal decays

➡ We want to explore a more minimal setup: no separate Dark Sector



$1 \to 0$ processes are allowed

- ✦ Does induce DM decay! DM → SM
- ✦ Contribute to DM annihilation in early universe, DM SM → SM SM

  similar to DM decays in a thermal bath: “thermal decays”

2111.14808 with Belfatto, Gross, Panci, Strumia, Vignaroli, Vittorio, Watanabe

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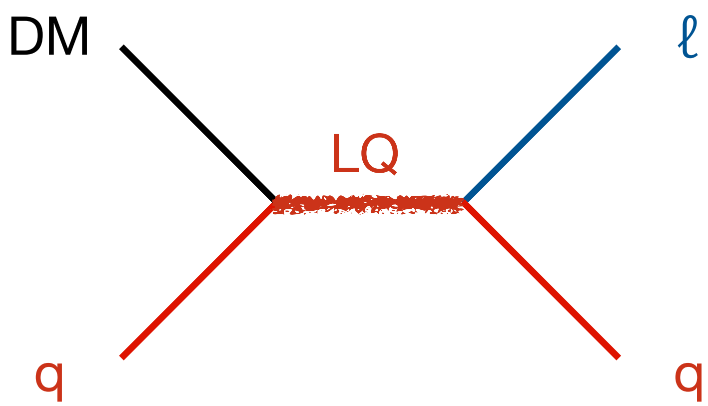


✦ Does induce DM decay! DM → SM

✦ Contribute to DM annihilation in early universe, DM SM → SM SM

similar to DM decays in a thermal bath: “thermal decays”

Naively:

✦ $\tau_{\rm DM} = 1/\Gamma_{\rm DM} > 10^{18}\,{\rm s}$ for DM stability (bound 10^{25} s in many cases!)

✦ $\Gamma_{\rm ann} \sim H \sim T^2/M_{\rm Pl} \approx \dfrac{(T/{\rm GeV})^2}{10^{-5}\,s}$ for freeze-out at T ~ M

➡ $\Gamma_{\rm DM}/\Gamma_{\rm ann} \lesssim 10^{-(23\div30)}$

However, different phase space and energy scale!

Freeze-out of relativistic DM

Decay and "thermal decay" rates not equal in general!

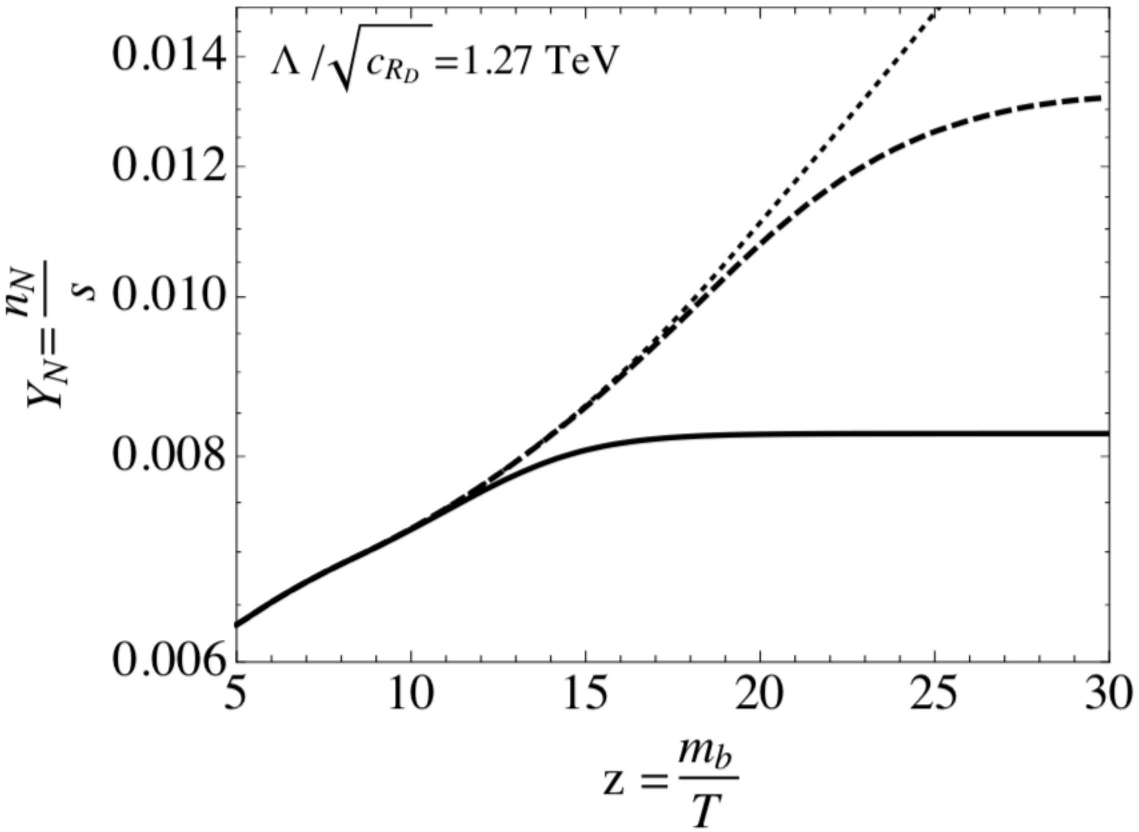
$\Gamma_{\rm DM} \approx G_{\rm NP}^2 M_{\rm DM}^5$ must be small

$\Gamma_{\rm ann} \approx G_{\rm NP}^2 T^5$ must be large

- ✦ Freeze-out at T ≫ M: relativistic DM. Decay suppressed by small mass

Azatov, Barducci, Ghosh, Marzocca, Ubaldi 1807.10745

$$\Omega_{\rm DM} h^2 = 0.12 \frac{50}{g_\star(T_d)} \frac{M_\chi}{50\,{\rm eV}}$$



$(\bar\chi\gamma^\mu\tau_R)(\bar b_R\gamma_\mu c_R)$ effective interaction

with couplings that fit flavor anomalies

➡ Sterile neutrino of 50 eV:

hot DM, ruled out by structure formation

Cold Dark Matter

Boltzmann equation:

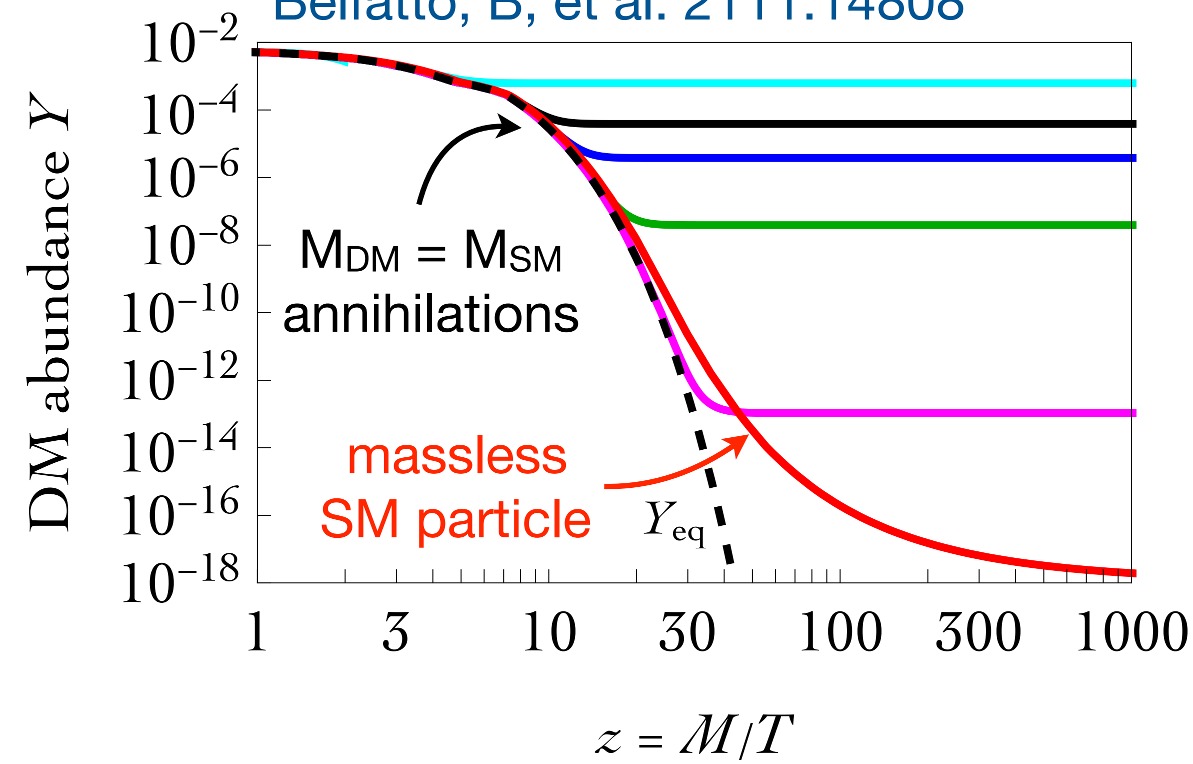
$$z\frac{dY}{dz} \approx -2\gamma_{\rm ann}\left(\frac{Y^2}{Y_{\rm eq}^2}-1\right) - \gamma_{\rm dec}\left(\frac{Y}{Y_{\rm eq}}-1\right)$$

usual DM DM → SM SM

DM SM → SM SM
“thermal decay”

$$\gamma_{AB\to X} \propto \langle \sigma v \rangle n_A n_B$$

Belfatto, B, et al. 2111.14808



- ✦ Non-relativistic limit: freeze-out below M_{DM}.

  “Decay” term is less Boltzmann-suppressed

  (analytic results in 2111.14808)

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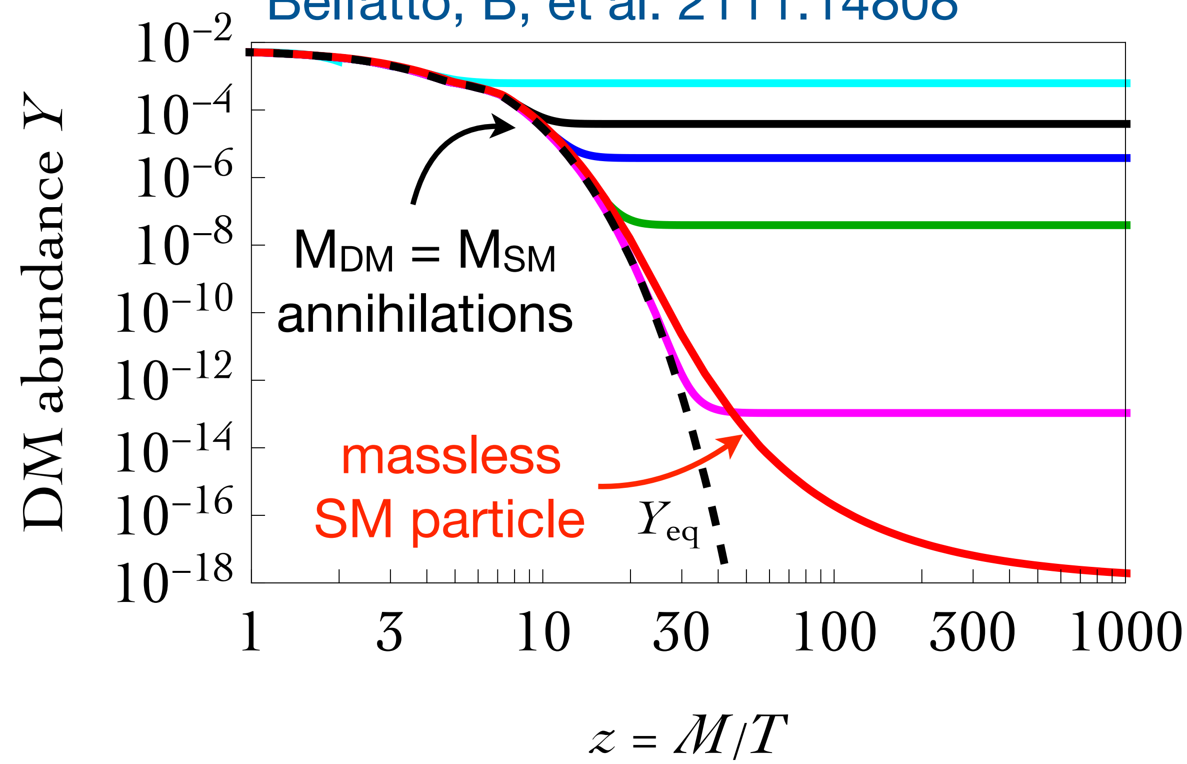
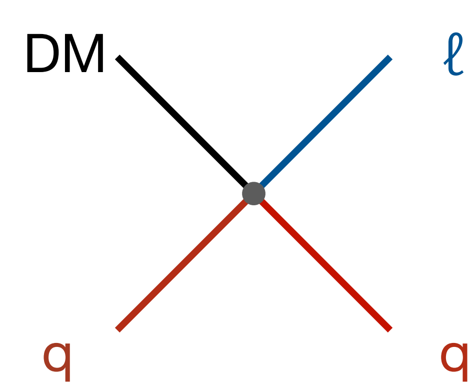
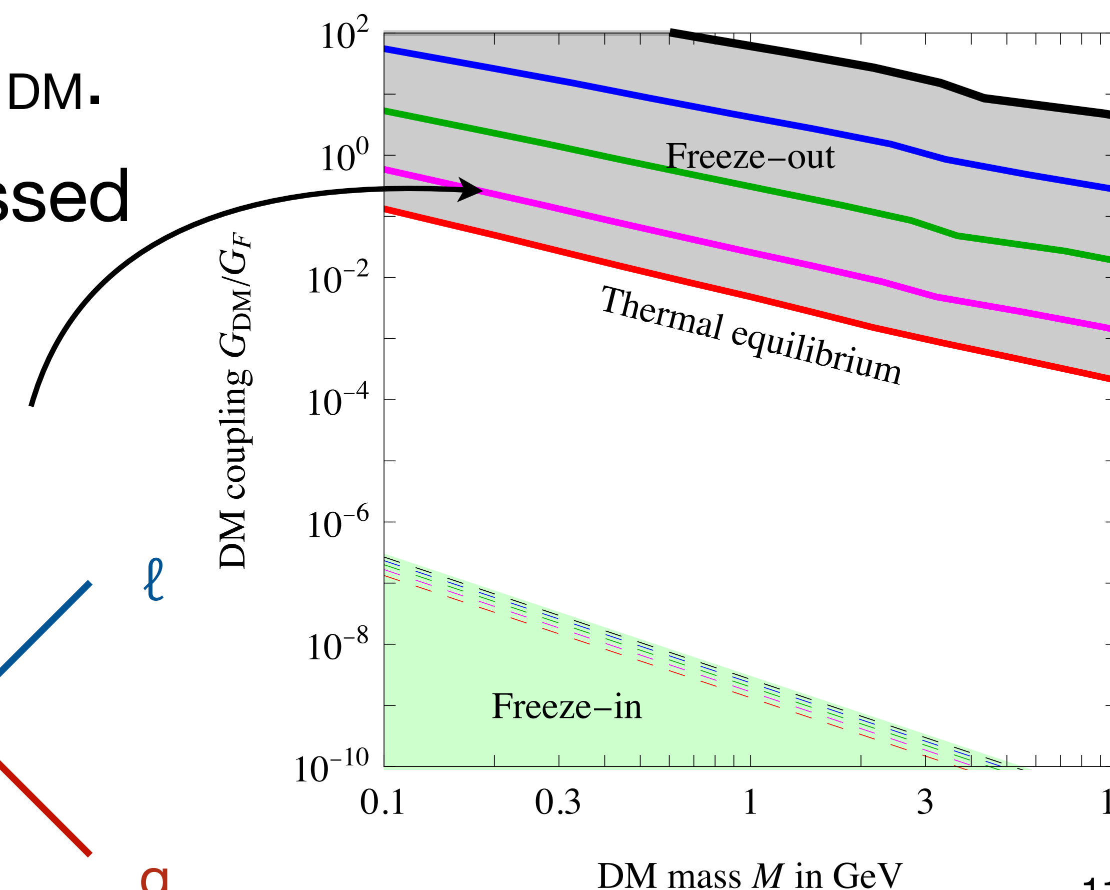


- Non-relativistic limit: freeze-out below M_{DM}.
  “Decay” term is less Boltzmann-suppressed
  (analytic results in 2111.14808)

- Freeze-out of dim.6 interaction:

$$G_{\rm DM} \gtrsim 10^{-4} G_F \left(\mathrm{GeV}/M_{\rm DM}\right)^{3/2}$$





Boltzmann equation:

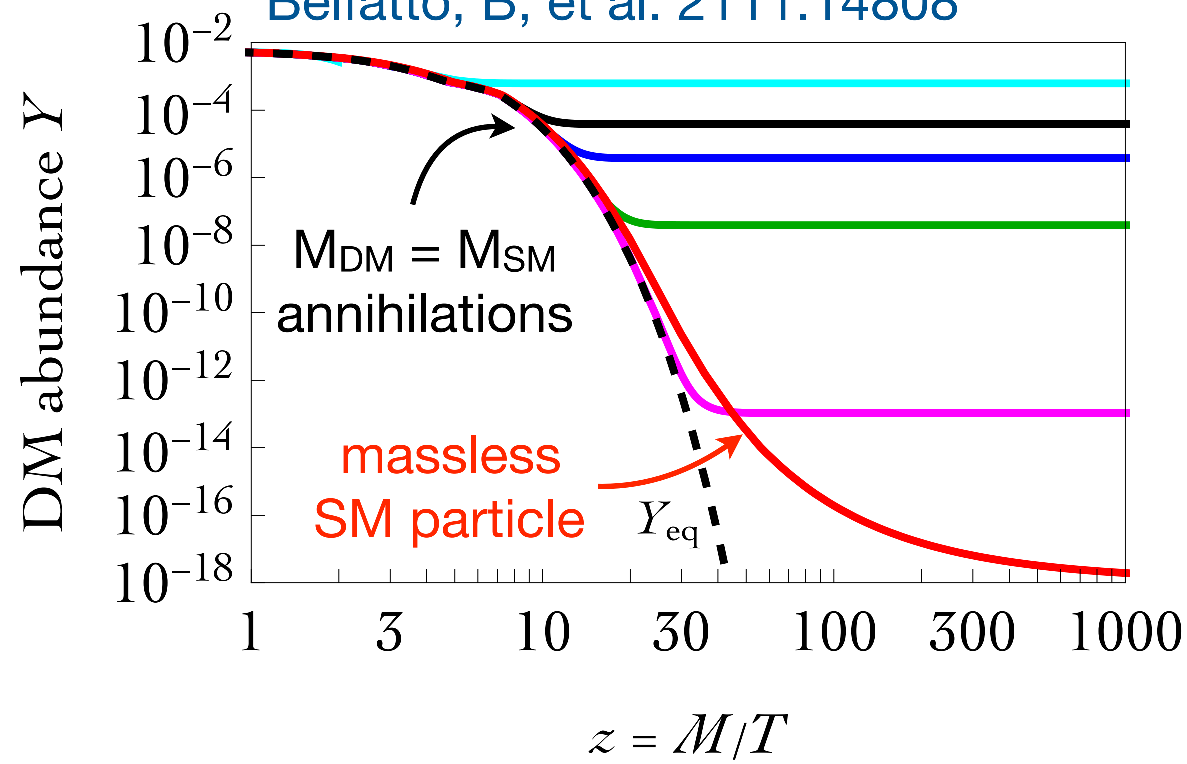
$$z\frac{dY}{dz} \approx -2\gamma_{\text{ann}}\left(\frac{Y^2}{Y_{\text{eq}}^2}-1\right)-\gamma_{\text{dec}}\left(\frac{Y}{Y_{\text{eq}}}-1\right)$$

usual DM DM → SM SM

DM SM → SM SM "thermal decay"

$$\gamma_{AB\to X} \propto \langle\sigma v\rangle n_A n_B$$

Belfatto, B, et al. 2111.14808

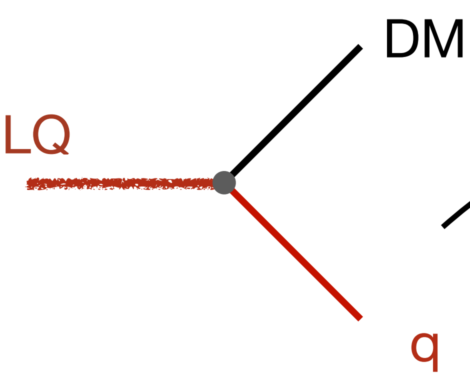


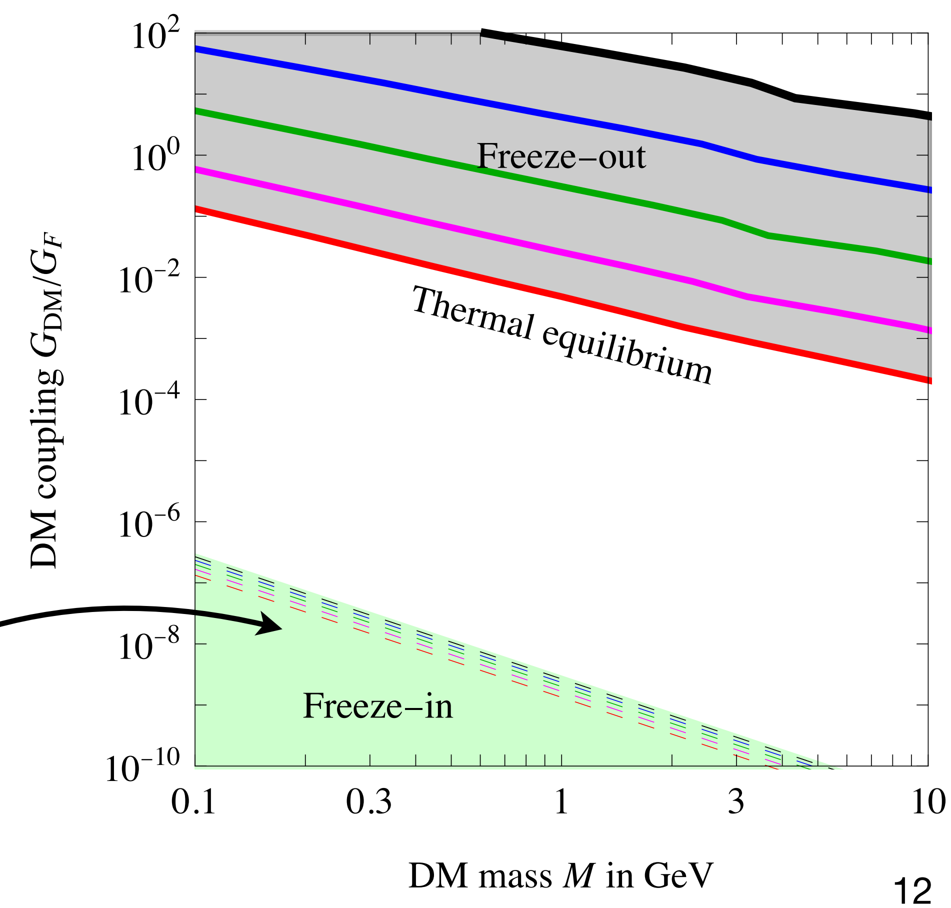
- Freeze-in: DM production most efficient at the highest energy $\sigma \approx G_{\text{DM}}^2 T^2$

Reheating temperature $M_{\text{DM}} < T_{\text{RH}} < M_{\text{LQ}}$

$$Y_\infty \approx G_{\text{DM}}^2 M_{\text{Pl}} T_{\text{RH}}^3$$

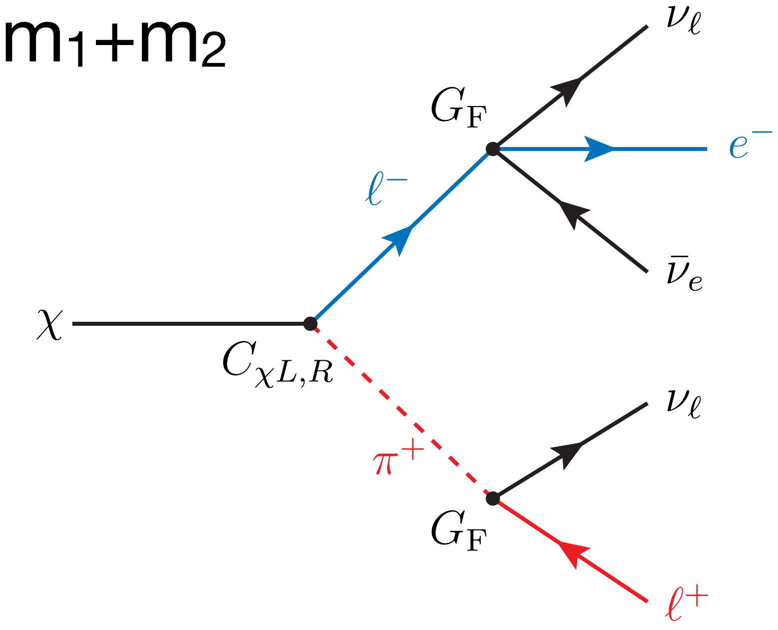
(LQ in thermal eq. that decays into DM)





Dark Matter decays

- Tree-level DM → SM_1 SM_2 must be closed: $M_{DM} < m_1 + m_2$

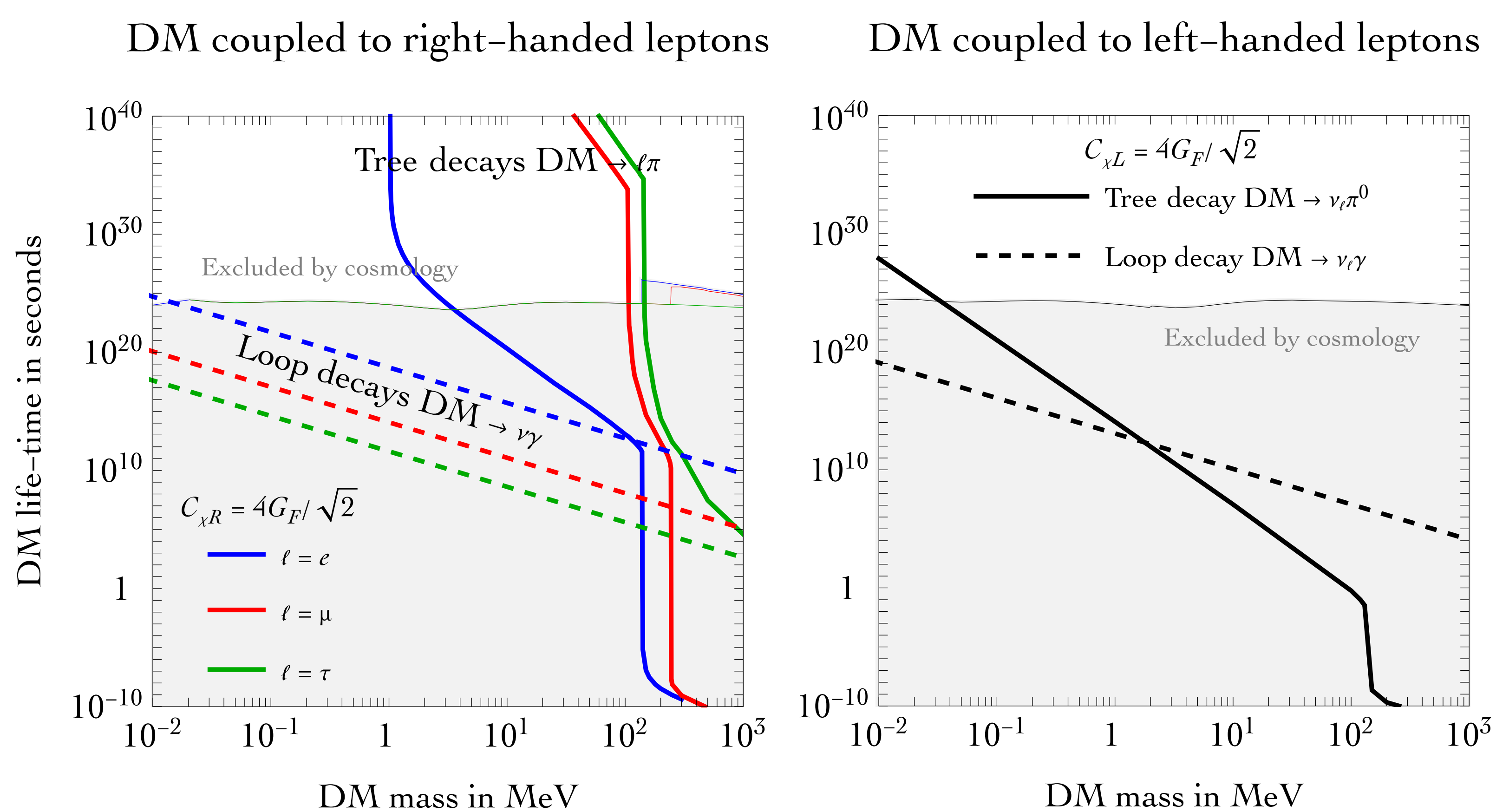


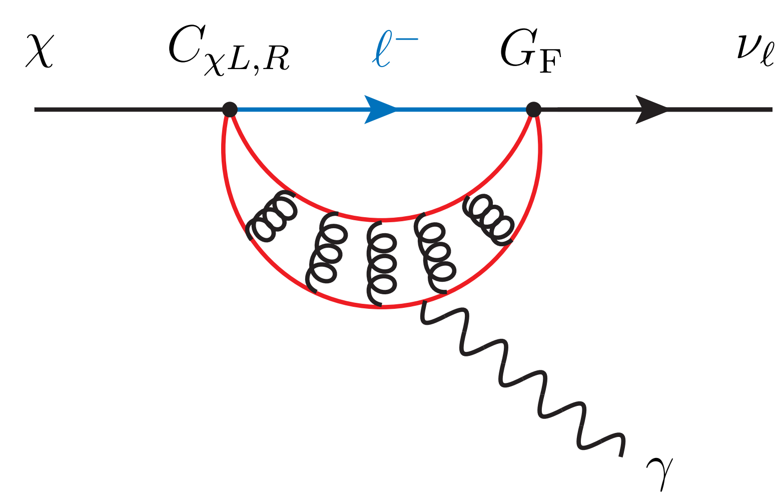
- Off-shell decays:

$$\Gamma(\mathrm{DM} \to \mathrm{SM}_1\, X) \approx \frac{\Gamma(\mathrm{DM} \to \mathrm{SM}_1 \mathrm{SM}_2^*)}{1 - p_2^2/m_2^2} \cdot \frac{\Gamma(\mathrm{SM}_2 \to X)}{4\pi m_2}$$

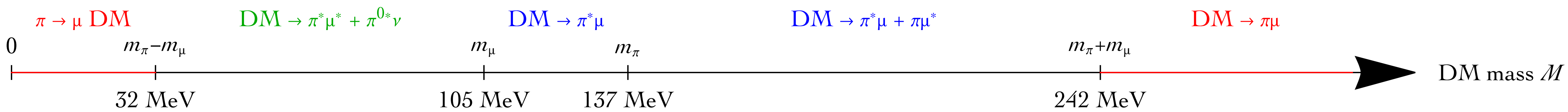
need long-lived SM_2 particles

- Loop decays: $\Gamma(\mathrm{DM} \to \nu\gamma) \propto M_{\mathrm{DM}}^3 C_{\chi L,R}^2 \times \left(\frac{G_F \Lambda_{\mathrm{QCD}}^2}{4\pi}\right)^2$





Example: DM coupled to muons and pions



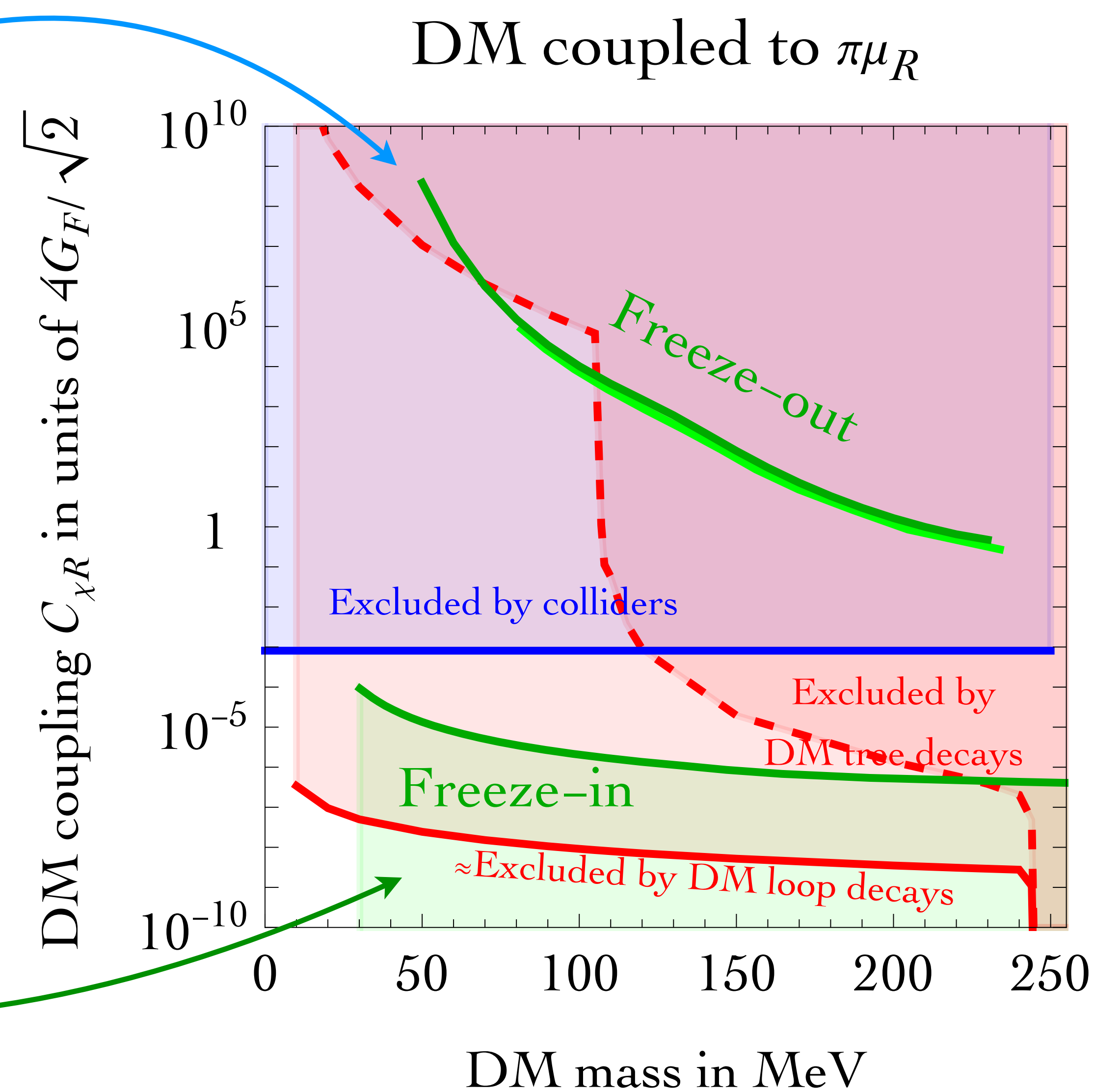
- Thermal *freeze-out* is excluded by too fast DM decays (& collider bounds on lepton + MET)

- Thermal *freeze-in* is viable:

If $T_{RH} > M_{LQ}$, $\quad Y_\infty \approx g_\chi^2 \dfrac{M_{Pl}}{M_{LQ}}$

Matching the cosmological DM abundance gives

$$g_\chi \approx 10^{-8} \sqrt{\frac{\text{MeV}}{M_{DM}} \frac{M_{LQ}}{\text{TeV}}}$$



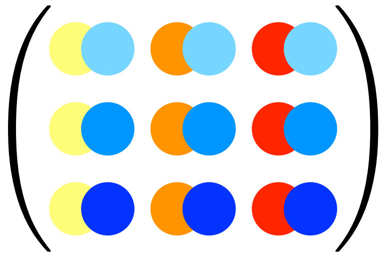
Connection with flavor

- Is there an explanation for the tiny coupling required by freeze-in?

- What is the flavor structure of the LQ couplings?

  - Simple flavor ansatz: $Y_u^{ij} \approx \epsilon_{Q_i}\epsilon_{u_j}$ (and similar for d, e)

    (e.g. Froggatt-Nielsen models, partial compositeness, …)



B-anomalies:

☛ Yukawa-like couplings, larger for heavy generations

☛ CKM-like suppression of flavor-changing effects

- Assume LQ couplings follow the same pattern:

$$g_L^{ij} \approx \epsilon_{Q_i}\epsilon_{L_j}, \qquad g_R^{ij} \approx \epsilon_{d_i}\epsilon_{e_j}, \qquad g_\chi^{i} \approx \epsilon_{u_i}\epsilon_{\chi}$$

new parameter (ϵ_χ)

Connection with flavor

- $\epsilon_{Q,u,d}$ can be estimated from V_{CKM} and quark masses $\qquad V^{ij}_{\rm CKM} \approx \epsilon_{Q_i}/\epsilon_{Q_j}$

- ϵ_L can be estimated from b → sμμ anomalies:

$$\Delta C_9 \approx V_{ts}V^*_{tb}\frac{(\epsilon_{L_2})^2}{M^2_{\rm LQ}} \sim V_{ts}V^*_{tb}\frac{1}{(6\,\text{TeV})^2} \qquad (\epsilon_{L_2} \approx 0.1 \text{ for } M_{\rm LQ} \sim \text{TeV})$$

- No sizable effect in electrons: $\epsilon_{L_1} \ll \epsilon_{L_2}$

Leptons

$$\epsilon_{L_1} < 0.1, \quad \epsilon_{L_2} \sim 0.1, \quad \epsilon_{L_3} \sim 1,$$
$$\epsilon_{e_1} > 10^{-5} \quad \epsilon_{e_2} \sim 10^{-3}, \quad \epsilon_{e_3} \sim 10^{-2}\,.$$

Quarks

$$\epsilon_Q \sim (\lambda^3, \lambda^2, \lambda),$$
$$\epsilon_u \sim (\lambda^4, \lambda, 1),$$
$$\epsilon_d \sim (\lambda^4, \lambda^3, \lambda^2)\,.$$

- DM freeze-in: $g_\chi \approx \epsilon_\chi \epsilon_u \sim 10^{-8}\sqrt{\text{MeV}/M_\chi}$

If dominant coupling is with 1st generation, $\epsilon_\chi \approx 10^{-5} \approx \epsilon_{e_1}$

Connection with flavor

- $\epsilon_{Q,u,d}$ can be estimated from V_{CKM} and quark masses $V_{\rm CKM}^{ij} \approx \epsilon_{Q_i}/\epsilon_{Q_j}$

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If dominant coupling is with 1st generation, $\epsilon_\chi \approx 10^{-5} \approx \epsilon_{e_1}$

More than one DM flavor

- DM could also carry a flavor index, χ^i .

- With more than one state, **thermal decay freeze-out is possible:**

$$\mathscr{L} = C_1(\bar{\chi}_1\ell)(\bar{d}u) + C_2(\bar{\chi}_2\ell)(\bar{d}u) + C_{12}(\bar{\chi}_1\chi_2)(\bar{q}q)$$

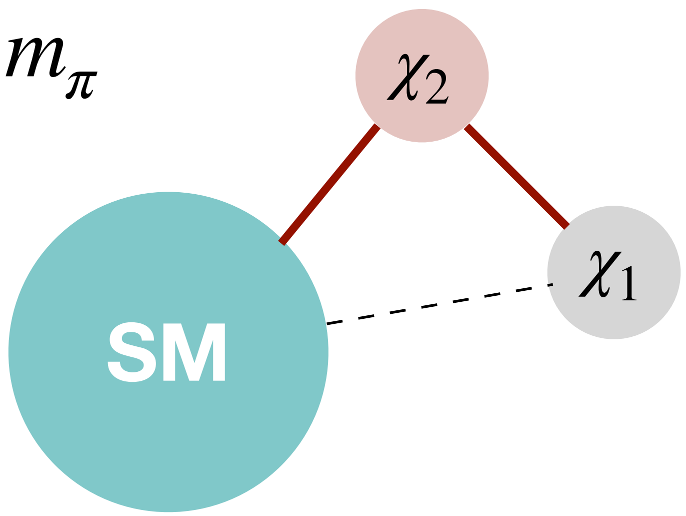
controls χ_1 stability

controls production $\chi_2 \leftrightarrow \ell^\pm\pi^\mp$

controls decay $\chi_2 \to \chi_1$ SM

1. $C_{2,12}$ large enough to achieve thermal freeze-out $\chi_1 \leftrightarrow \chi_2 \leftrightarrow$ SM
2. χ_2 decays dominantly into χ_1 if $M_1 < M_2 < m_\ell + m_\pi$
3. χ_1 is long-lived if C_1 is small enough

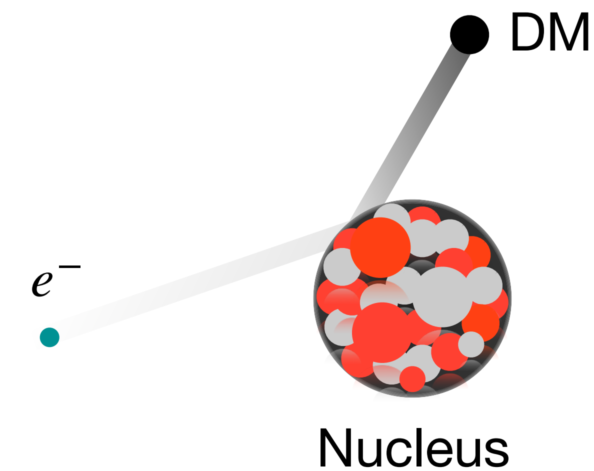
☛ DM is not part of a separate Dark Sector



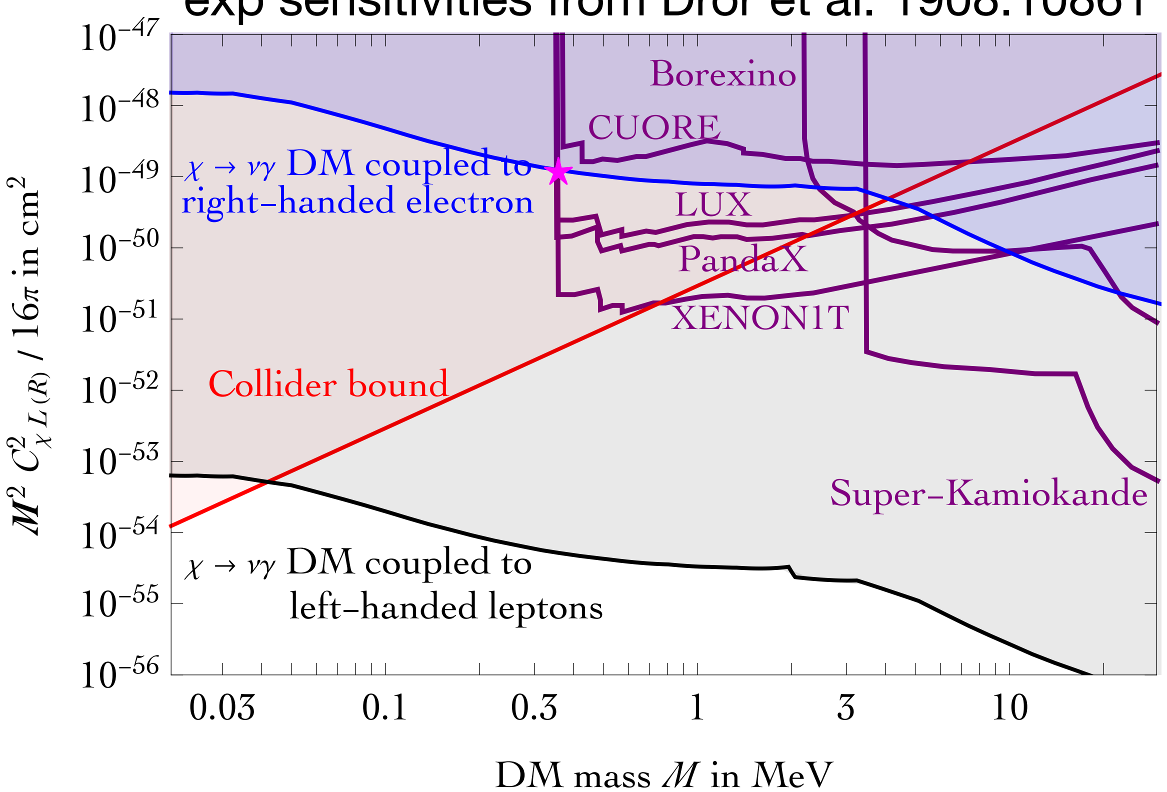
Direct and indirect detection

- Charged-current interaction: $C_{\chi R}\left(\bar{\chi}\gamma_\mu e_R\right)\left(\bar{n}\gamma^\mu \frac{1+g_A\gamma_5}{2} p\right) + C_{\chi L}(\bar{\chi}e_L)(\bar{n}p)$

DM-induced β⁻ transition $\mathrm{DM} + {}^A_Z N \to e^- + {}^{\;\;A}_{Z+1}N$



exp sensitivities from Dror et al. 1908.10861



$$\langle \sigma v \rangle = \frac{C^2_{\chi L(R)} M^2_\chi}{16\pi} f(E)$$

monochromatic electron with $E = M_{\rm DM} - m_e - Q$

- Depending on nuclear thresholds Q, sensitive to DM heavier than few 100 keV
- Can also look for signal from decaying ${}^{\;\;A}_{Z+1}N$

- Neutral-current interaction: nuclear recoil in $\mathrm{DM} + N \to \nu + N$

Summary

- Dark Matter could interact with the SM through Leptoquarks.
- DM abundance from freeze-in of DM SM → SM SM scatterings
  - small coupling, mass ~ MeV

    consistent with expectation for 1st generation fermions
  - Exotic signatures in Direct Detection: DM-induced β decay
- DM abundance through thermal freeze-out
  - DM SM → SM SM thermal decays, if more than one generation of DM
  - DM DM → SM SM annihilations, if Dark Sector contains colored states