Multi-Component Dark Matter from Minimal Flavor Violation

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Based on collaboration with

Federico Mescia (INFN LNF), Keyun Wu (ICCUB, Barcelona), arXiv:2407.xxxxx

The 15th International Workshop on Identification of Dark Matter 2024 @ L'Aquila, 9 July 2024

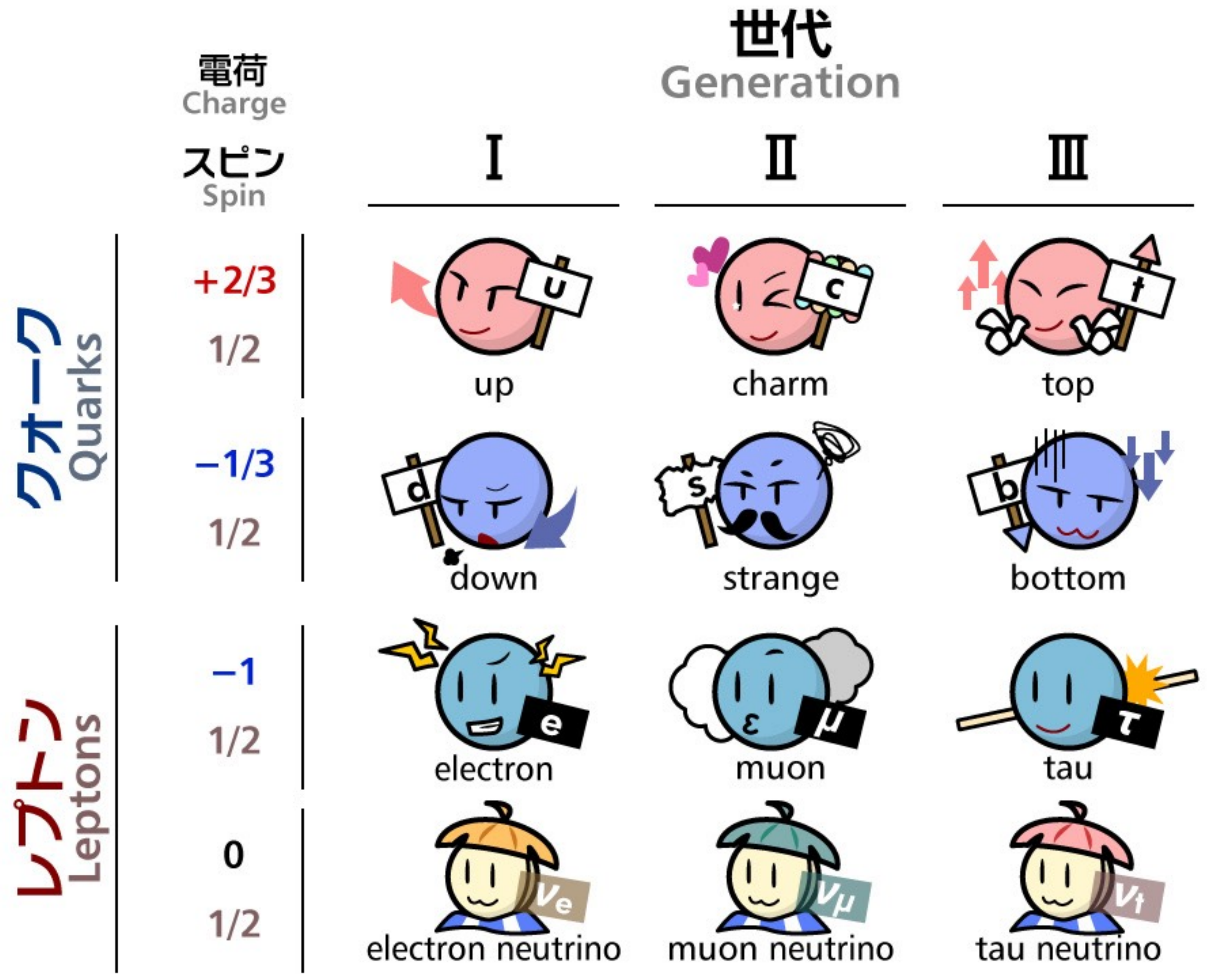
Flavor symmetry in particle physics

$$\mathcal{G} = \mathrm{U}(3)_{q_L} \times \mathrm{U}(3)_{u_R} \times \mathrm{U}(3)_{d_R} \times \mathrm{U}(3)_{\ell_L} \times \mathrm{U}(3)_{e_R}$$

- Three generations of quarks and leptons
- A global flavor symmetry in the gauge sector

$$\psi_i \to (V_\psi)_{ij}\psi_j$$

$$(\psi = q_L, u_R, d_R, \ell_L, e_R;\ V_\psi \in \mathrm{SU}(3)_\psi)$$



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- In the SM, explicitly broken by Yukawa interaction matrices to the Higgs doublet

$$\mathcal{L}_{\rm yuk} = -\bar{q}_L Y_u \widetilde{H} u_R - \bar{q}_L Y_d H d_R - \bar{\ell}_L Y_e H e_R + \mathrm{h.c.}$$

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- We focus on the subgroup in the quark sector $\mathcal{G}_F = \mathrm{SU}(3)_{q_L} \times \mathrm{SU}(3)_{u_R} \times \mathrm{SU}(3)_{d_R}$

Minimal Flavor Violation (MFV) hypothesis

Chivukula, Georgi (1987); Hall, Randall (1990); D'Ambrosio et al. (2002)

All (new physics) interactions respect the flavor symmetry with the only breaking sources arising from the quark Yukawa matrices

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- The quark Yukawa matrices are promoted to spurious fields transforming like

$$Y_u \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1})\,, \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \overline{\mathbf{3}}) \quad \text{under} \quad \mathcal{G}_F = \mathrm{SU}(3)_{q_L} \times \mathrm{SU}(3)_{u_R} \times \mathrm{SU}(3)_{d_R}$$

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- For new physics interactions, e.g. $\mathcal{L}_{\rm NP} = C_{ij} (\overline{u}_{Ri} \gamma^\mu u_{Rj}) \mathcal{O}_\mu$

$$\longrightarrow \; C_{ij} = c_0\, \delta_{ij} + \epsilon\, c_1 (Y_u^\dagger Y_u)_{ij} + \epsilon^2 \left[c_2 (Y_u^\dagger Y_u Y_u^\dagger Y_u)_{ij} + c_2' (Y_u^\dagger Y_d Y_d^\dagger Y_u)_{ij} \right] + \dots$$

Dark matter under the MFV hypothesis

MFV hypothesis → Stability of flavored dark matter Batell, Pradler, Spannowsky (2011)

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- Consider a colorless, flavourful new field χ :

$$\chi \sim (n_{q_L}, m_{q_L}) \times (n_{u_R}, m_{u_R}) \times (n_{d_R}, m_{d_R})$$

Dynkin coefficients of the quark flavor groups
e.g. (1,0) -> triplet; (1,1) -> octet

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- General decay operators are formally expressed by

$$\mathcal{O}_{\rm decay} = \chi \underbrace{q_L \ldots}_{A} \underbrace{\bar{q}_L \ldots}_{\bar{A}} \underbrace{u_R \ldots}_{B} \underbrace{\bar{u}_R \ldots}_{\bar{B}} \underbrace{d_R \ldots}_{C} \underbrace{\bar{d}_R \ldots}_{\bar{C}} \times \underbrace{Y_u \ldots}_{D} \underbrace{Y_u^\dagger \ldots}_{\bar{D}} \underbrace{Y_d \ldots}_{E} \underbrace{Y_d^\dagger \ldots}_{\bar{E}} \mathcal{O}_{\rm weak}$$

a weak operator to maintain the EW and Lorentz invariance

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- Such a decay operator is allowed only if four equations following from QCD and flavor invariance are satisfied:

$$\mathrm{SU}(3)_C: \quad (A + B + C - \overline{A} - \overline{B} - \overline{C}) \bmod 3 = 0\,,$$

$$\mathrm{SU}(3)_{q_L}: \quad (n_{q_L} - m_{q_L} + A - \overline{A} + D - \overline{D} + E - \overline{E}) \bmod 3 = 0\,,$$

$$\mathrm{SU}(3)_{u_R}: \quad (n_{u_R} - m_{u_R} + B - \overline{B} - D + \overline{D}) \bmod 3 = 0\,,$$

$$\mathrm{SU}(3)_{d_R}: \quad (n_{d_R} - m_{d_R} + C - \overline{C} - E + \overline{E}) \bmod 3 = 0\,,$$

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← only $q\bar{q}$, qqq can be QCD singlet

$$\mathrm{SU}(3)_{q_L}: \quad (n_{q_L} - m_{q_L} + A - \overline{A} + D - \overline{D} + E - \overline{E}) \bmod 3 = 0\,,$$

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$$\mathrm{SU}(3)_{d_R}: \quad (n_{d_R} - m_{d_R} + C - \overline{C} - E + \overline{E}) \bmod 3 = 0\,,$$

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$$\mathrm{SU}(3)_{d_R}: \quad (n_{d_R} - m_{d_R} + C - \overline{C} - E + \overline{E}) \bmod 3 = 0\,,$$

For χ to be stable, at least one of four equations should **NOT** be satisfied ⇒

$$(n_\chi - m_\chi) \bmod 3 \neq 0$$

$$m_\chi = m_{q_L} + m_{u_R} + m_{d_R}$$
$$n_\chi = n_{q_L} + n_{u_R} + n_{d_R}$$

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(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$	Yes
$(0,1)$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$	Yes
(2,0)	$(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$ $(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$	Yes
(0,2)	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{6}})$ $(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\bar{\mathbf{3}},\bar{\mathbf{3}})$	Yes
(1,1)	$(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$ $(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})$ $(\bar{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{3})$	

$$(n_\chi - m_\chi) \bmod 3 \neq 0$$

stability condition

- Applied for any spin and EW representation of χ
- Only the lightest flavored particle is stable
  - All heavier particles are unstable and rapidly decay away in a case (Batell+, 2011; Lopez-Honorez+, 2013)
  - **Is it possible that the heavier components are also long-lived to constitute part of DM?**

Mescia, SO, Wu, 2407.xxxxx

A benchmark model

A gauge singlet scalar $S \sim (\mathbf{1}, \mathbf{3}, \mathbf{1})$ an $\mathrm{SU}(3)_{u_R}$ triplet

- scalar potential allowed by the MFV

$$
\begin{aligned}
V(H,S) = {} & m_S^2\, S_i^* \left(a_0\, \delta_{ij} + \epsilon\, a_1 (Y_u^\dagger Y_u)_{ij} + \ldots\right) S_j && \text{mass term} \\
& + \lambda\, S_i^* \left(b_0\, \delta_{ij} + \epsilon\, b_1 (Y_u^\dagger Y_u)_{ij} + \ldots\right) S_j (H^\dagger H) && \text{coupling to the Higgs doublet} \\
& + \left(\lambda_0\, \delta_{ij}\delta_{kl} + \epsilon\, \lambda_1 \delta_{ij} (Y_u^\dagger Y_u)_{kl} + \ldots\right) S_i^* S_j S_k^* S_l && \text{self-interaction}
\end{aligned}
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\end{aligned}
$$

mass term

coupling to the Higgs doublet

self-interaction

⇒ up to O(ε)

$$
V(H,S) = \left\{ m_0^2 + \epsilon \, m_1^2 (y_u^i)^2 \right\} S_i^* S_i
$$

$$
+ \frac{\lambda}{2} \left(b_0 + \epsilon \, b_1 (y_u^i)^2 \right) (2vh + h^2) S_i^* S_i
$$

+ self-interaction

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$$+ \lambda\, S_i^* \left(b_0\, \delta_{ij} + \epsilon\, b_1 (Y_u^\dagger Y_u)_{ij} + \ldots\right) S_j (H^\dagger H)$$ coupling to the Higgs doublet

$$+ \left(\lambda_0\, \delta_{ij}\delta_{kl} + \epsilon\, \lambda_1 \delta_{ij} (Y_u^\dagger Y_u)_{kl} + \ldots\right) S_i^* S_j S_k^* S_l$$ self-interaction

up to O(ε)

$$V(H,S) = \left\{ \underline{m_0^2} + \underline{\epsilon\, m_1^2 (y_u^i)^2} \right\} S_i^* S_i$$

$$+ \frac{\lambda}{2} \left(\underline{b_0} + \underline{\epsilon\, b_1 (y_u^i)^2}\right) (2vh + h^2) S_i^* S_i$$

flavor independent flavor dependent

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$$V(H,S) = m_S^2\, S_i^* \left(a_0\,\delta_{ij} + \epsilon\, a_1 (Y_u^\dagger Y_u)_{ij} + \ldots\right) S_j \quad \text{mass term}$$

$$+ \lambda\, S_i^* \left(b_0\,\delta_{ij} + \epsilon\, b_1 (Y_u^\dagger Y_u)_{ij} + \ldots\right) S_j (H^\dagger H) \quad \text{coupling to the Higgs doublet}$$

$$+ \left(\lambda_0\,\delta_{ij}\delta_{kl} + \epsilon\,\lambda_1 \delta_{ij} (Y_u^\dagger Y_u)_{kl} + \ldots\right) S_i^* S_j S_k^* S_l \quad \text{self-interaction}$$

$$\Rightarrow \quad V(H,S) = \left\{m_0^2 + \epsilon\, m_1^2 (y_u^i)^2\right\} S_i^* S_i =: M_i^2 S_i^* S_i$$

up to O(ε)

$$\longrightarrow \quad M_j^2 - M_i^2 = \epsilon\, m_1^2 \left[(y_u^j)^2 - (y_u^i)^2\right] \quad \longrightarrow \quad \frac{M_3^2 - M_1^2}{M_2^2 - M_1^2} = \frac{y_t^2 - y_u^2}{y_c^2 - y_u^2} \simeq \frac{y_t^2}{y_c^2}$$

Ratio of mass differences predicted!

Higher dimensional operators

- Dim-6 operators

$$\mathcal{L}_{d=6} = \frac{1}{\Lambda^2}\left(\sum_I c^I_{ijkl}\mathcal{O}^I_{ijkl} + c^g_{ij}\mathcal{O}^g_{ij} + c^\gamma_{ij}\mathcal{O}^\gamma_{ij}\right)$$

$$\mathcal{O}^1_{ijkl} = (\bar{q}_{Li}\gamma^\mu q_{Lj})(S^*_k i\overleftrightarrow{\partial}_\mu S_l)\,, \qquad \mathcal{O}^2_{ijkl} = (\bar{u}_{Ri}\gamma^\mu u_{Rj})(S^*_k i\overleftrightarrow{\partial}_\mu S_l)\,,$$

$$\mathcal{O}^3_{ijkl} = (\bar{d}_{Ri}\gamma^\mu d_{Rj})(S^*_k i\overleftrightarrow{\partial}_\mu S_l)\,, \qquad \mathcal{O}^4_{ijkl} = \left(\bar{q}_{Li}\widetilde{H}u_{Rj}\right)(S^*_k S_l)\ ,$$

$$\mathcal{O}^5_{ijkl} = \left(\bar{q}_{Li}H d_{Rj}\right)(S^*_k S_l)\ , \qquad \mathcal{O}^g_{ij} = \left(S^*_i S_j\right) G_{\mu\nu}G^{\mu\nu}\,,$$

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The coefficients are determined by the MFV

$$\begin{aligned} c^4_{ijkl} &= c^4_1(Y_u)_{ij}\delta_{kl} + c^4_2(Y_u)_{il}\delta_{kj} \\ &+ \epsilon\left[c^4_3(Y_uY_u^\dagger Y_u)_{ij}\delta_{kl} + c^4_4(Y_uY_u^\dagger Y_u)_{il}\delta_{kj} + c^4_5(Y_u)_{ij}(Y_u^\dagger Y_u)_{kl} + c^4_6(Y_u)_{il}(Y_u^\dagger Y_u)_{jl}\right] \\ &+ \ldots\,, \end{aligned}$$

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At the ε^0 order, it causes the heavy scalar decay

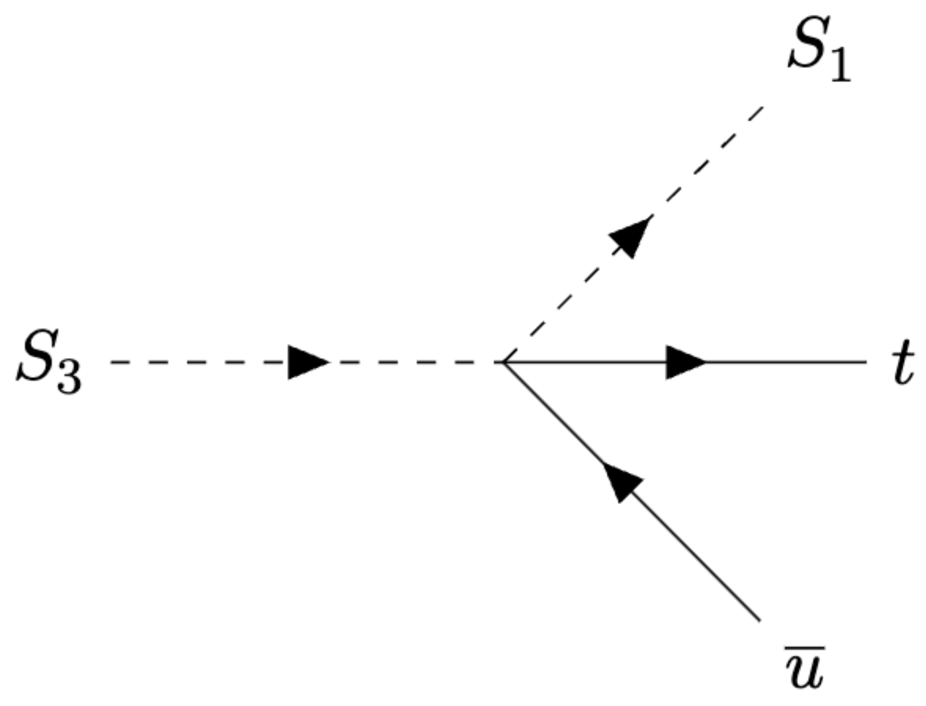
$$\mathcal{L}_{d=6} \sim \frac{c^4_2}{\Lambda^2}\left(\bar{q}_{Li}\,(Y_u)_{ij}\,S_j\right)\widetilde{H}\,(S^*_k\delta_{kl}u_{Rl}) + \text{h.c.}$$

$$\sim \frac{c^4_2}{\Lambda^2}\,\bar{u}_i(m^i_u P_R + m^j_u P_L)u_j\,\left(S^*_j S_i\right)$$

⇒ $S_3 \to S_1 t\bar{u},\ S_2 t\bar{c}$

Decay of heavy components

- Example S3 decay (*Dominant mode depends on the mass splitting $\Delta M = M_3 - M_1$)



$$\Delta M \gtrsim m_t$$

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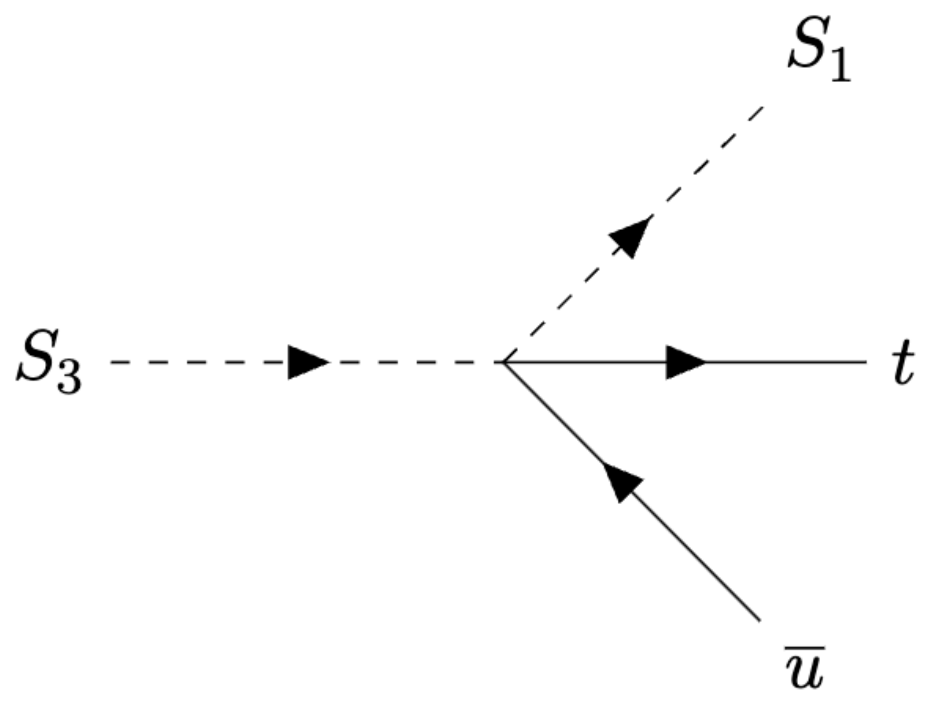

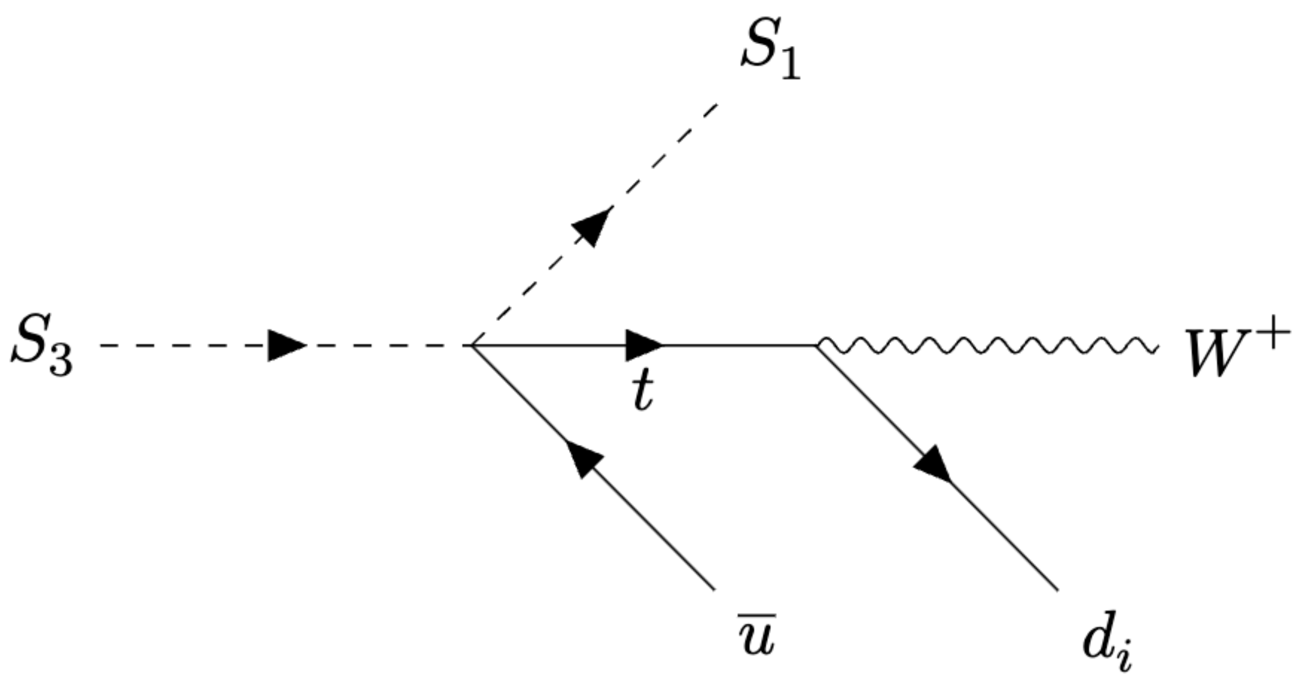

$\Delta M \gtrsim m_t$

$m_t \gtrsim \Delta M \gtrsim m_W + m_d^i$

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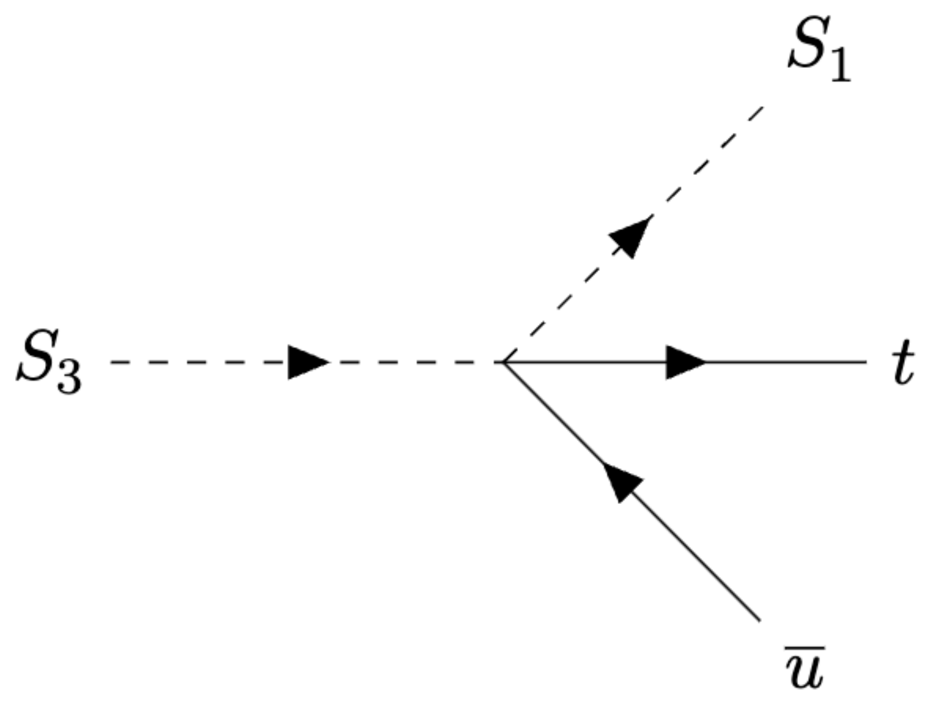

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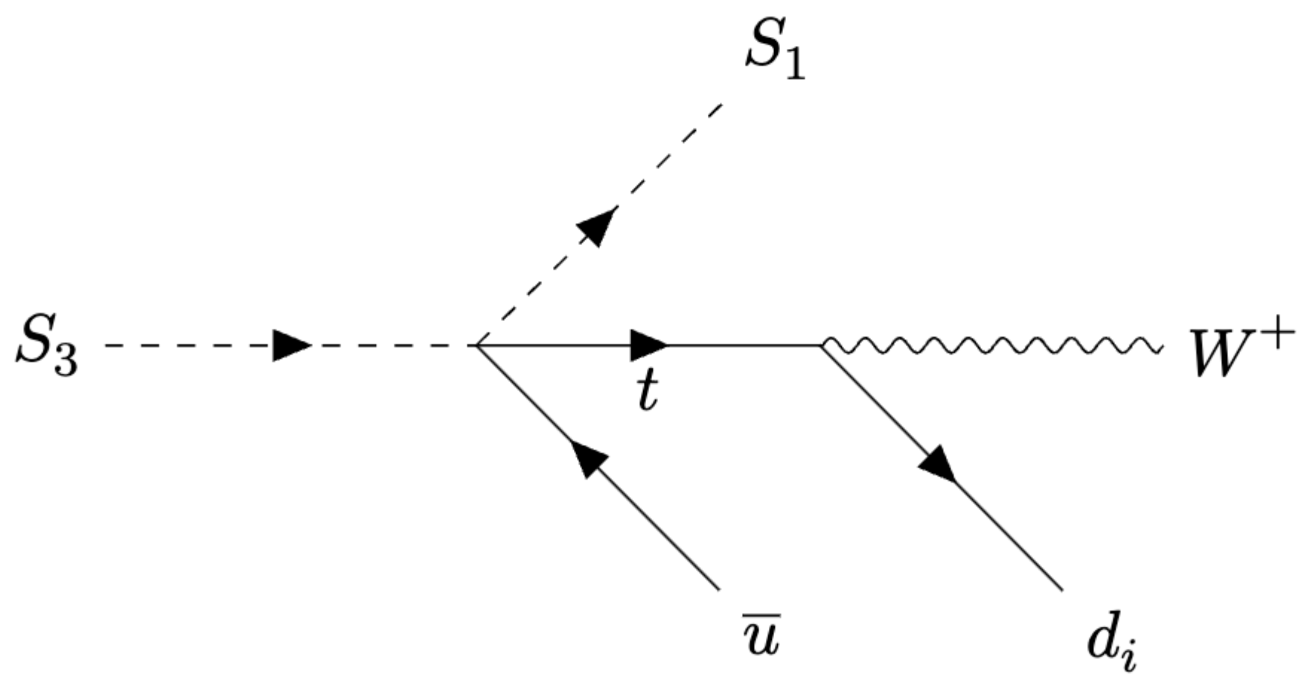

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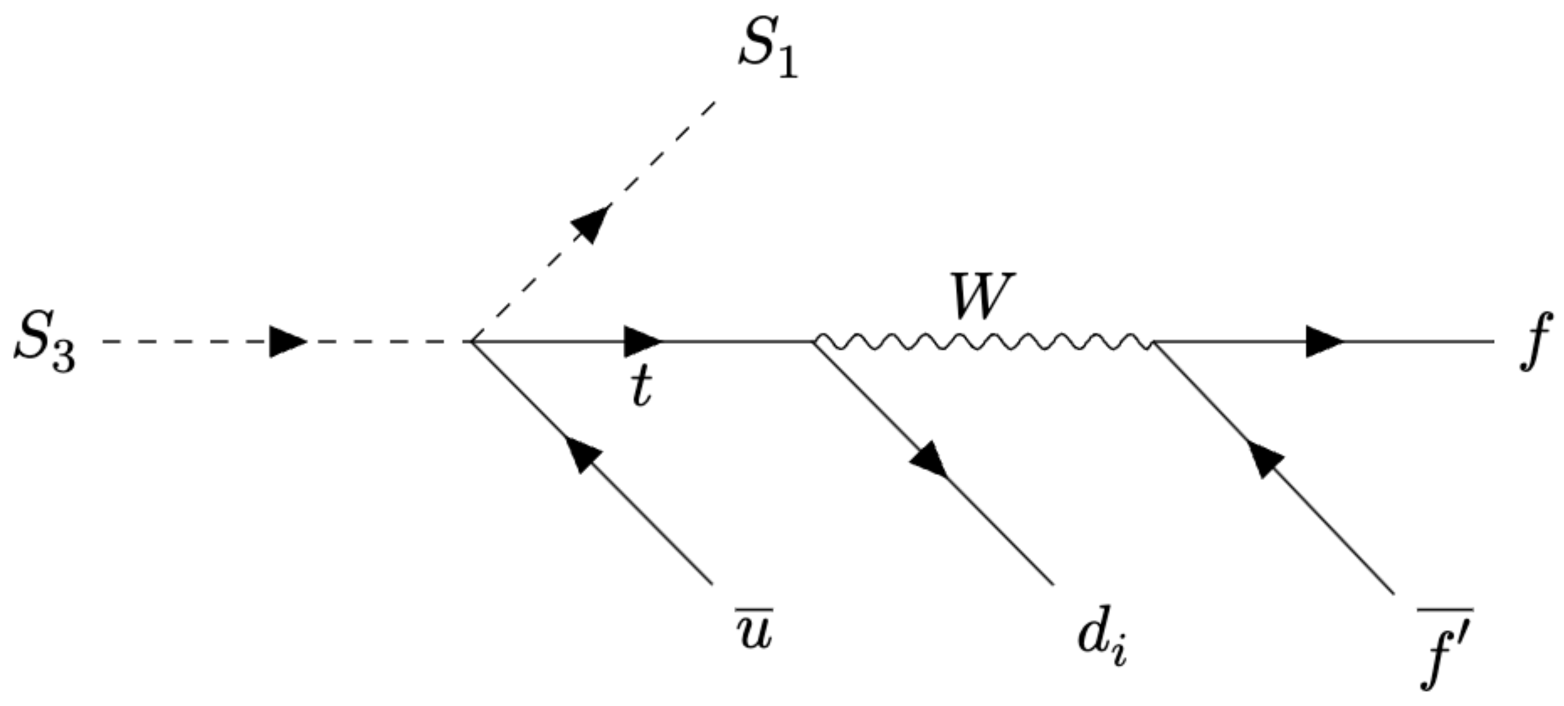

$$m_W + m_d^i \gtrsim \Delta M \gtrsim m_u + m_d^i + m_f + m_{f'}$$

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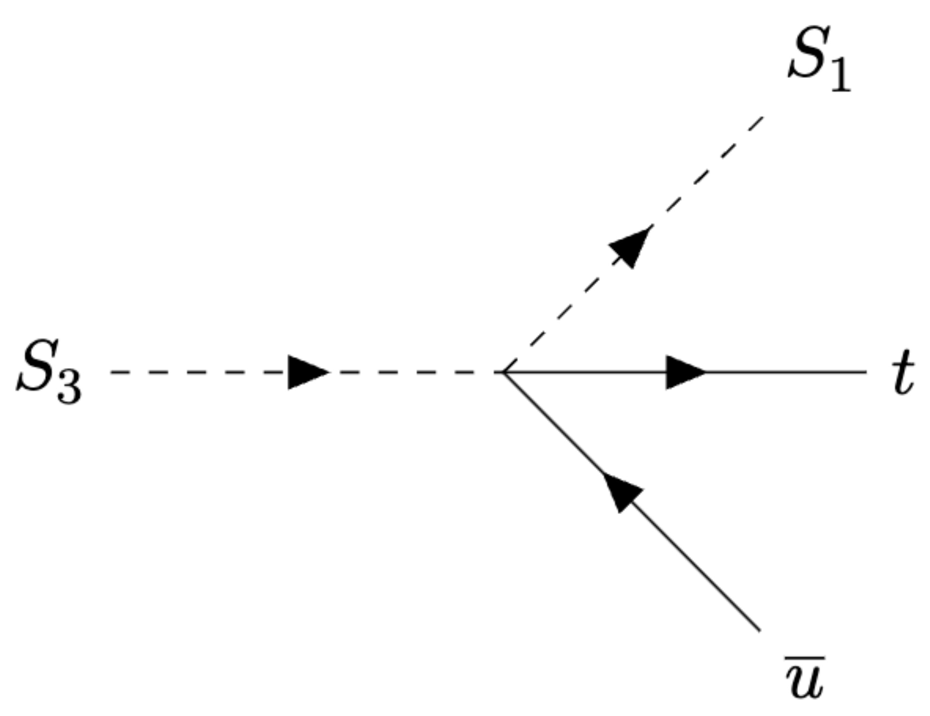
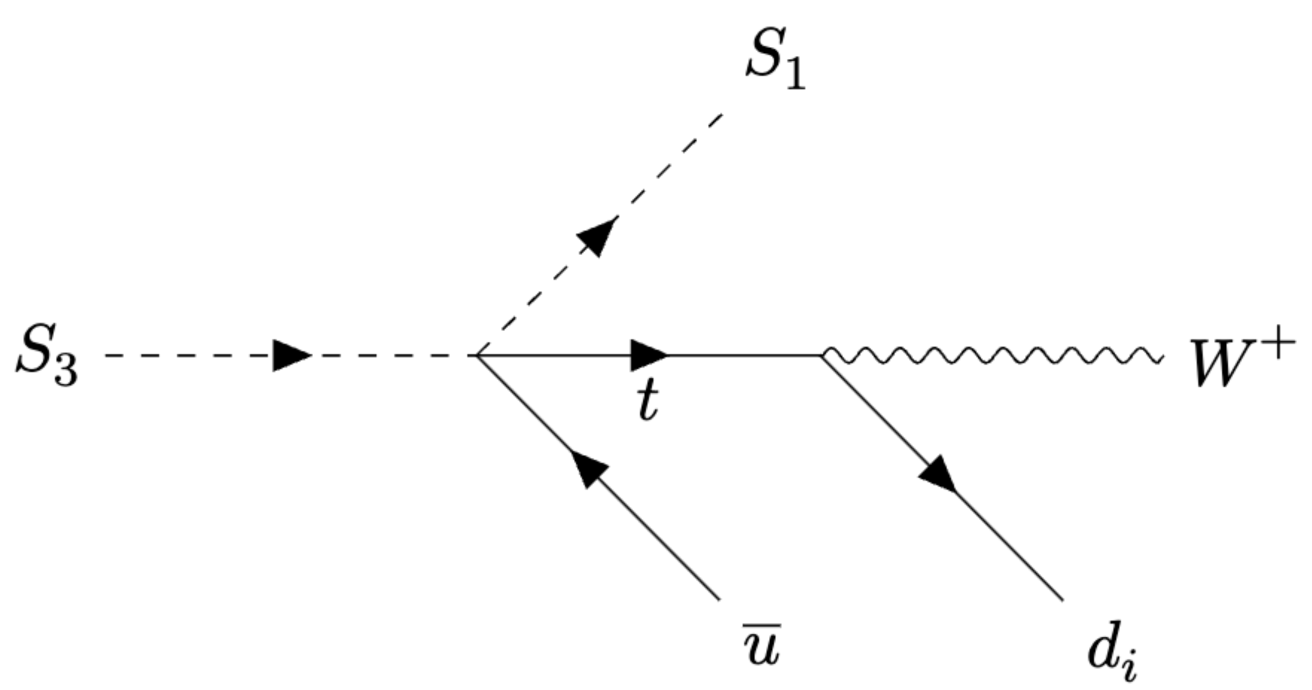
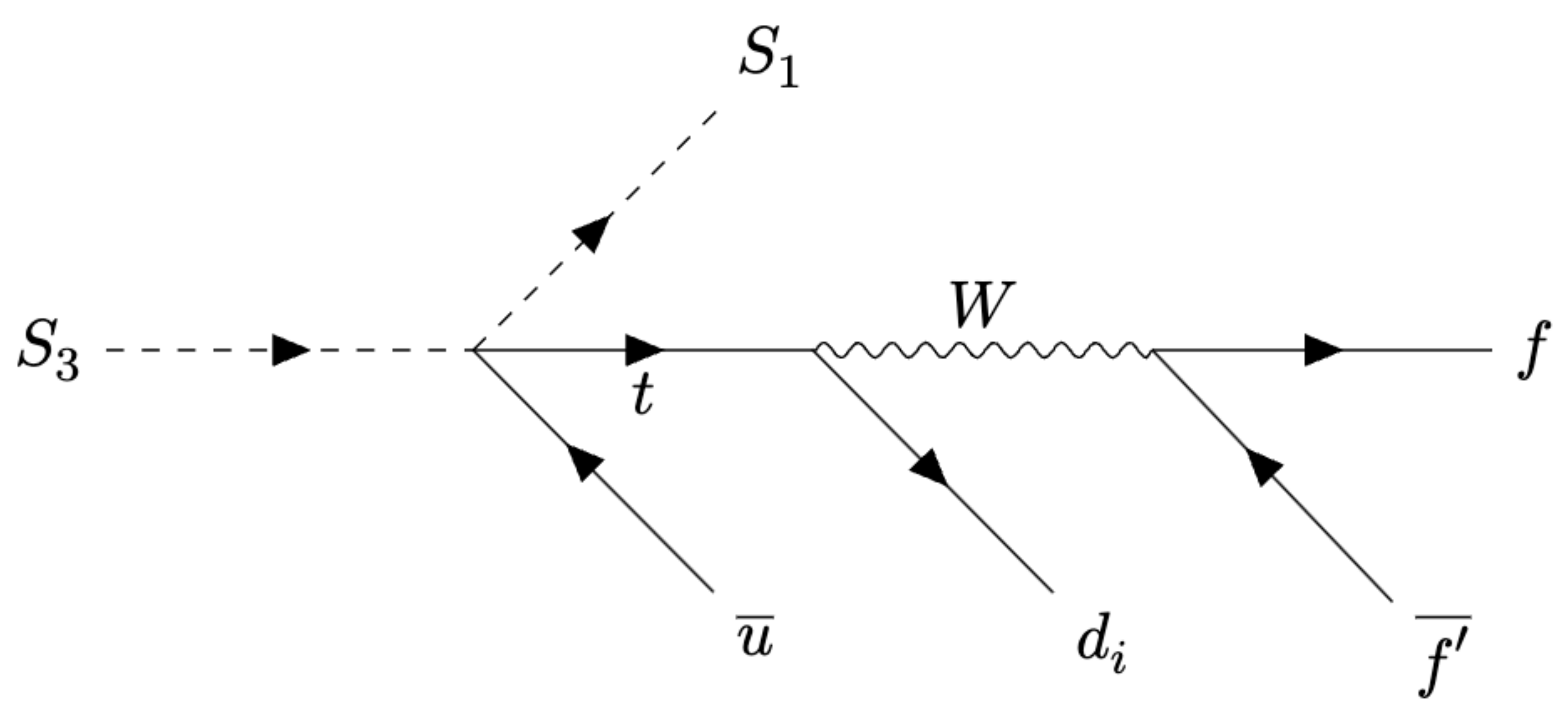






$\Delta M \gtrsim m_t$ $\qquad$ $m_t \gtrsim \Delta M \gtrsim m_W + m_d^i$ $\qquad$ $m_W + m_d^i \gtrsim \Delta M \gtrsim m_u + m_d^i + m_f + m_{f'}$

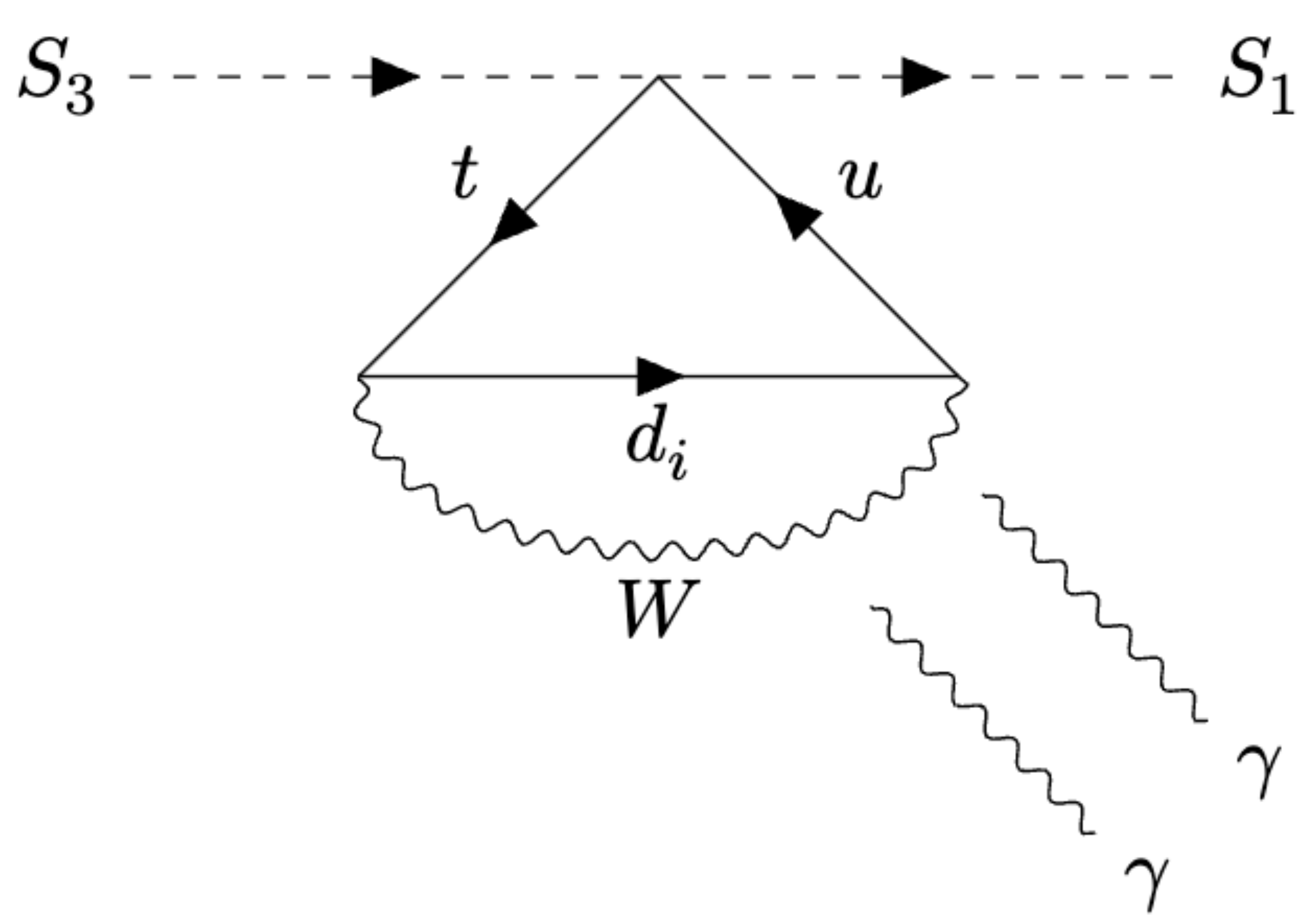
width $\quad \Gamma \sim \dfrac{m_t^2 (\Delta M)^5}{480\pi^3 \Lambda^4 M_3^2}$ $\qquad \sim \dfrac{(\Delta M)^{11} |V_{ti}|^2}{41472\pi^5 \Lambda^4 M_3^2 m_t^2 v^2}$ $\qquad \sim \dfrac{(\Delta M)^{13} |V_{ti}|^2}{11612160\pi^7 \Lambda^4 M_3^2 m_t^2 v^4}$

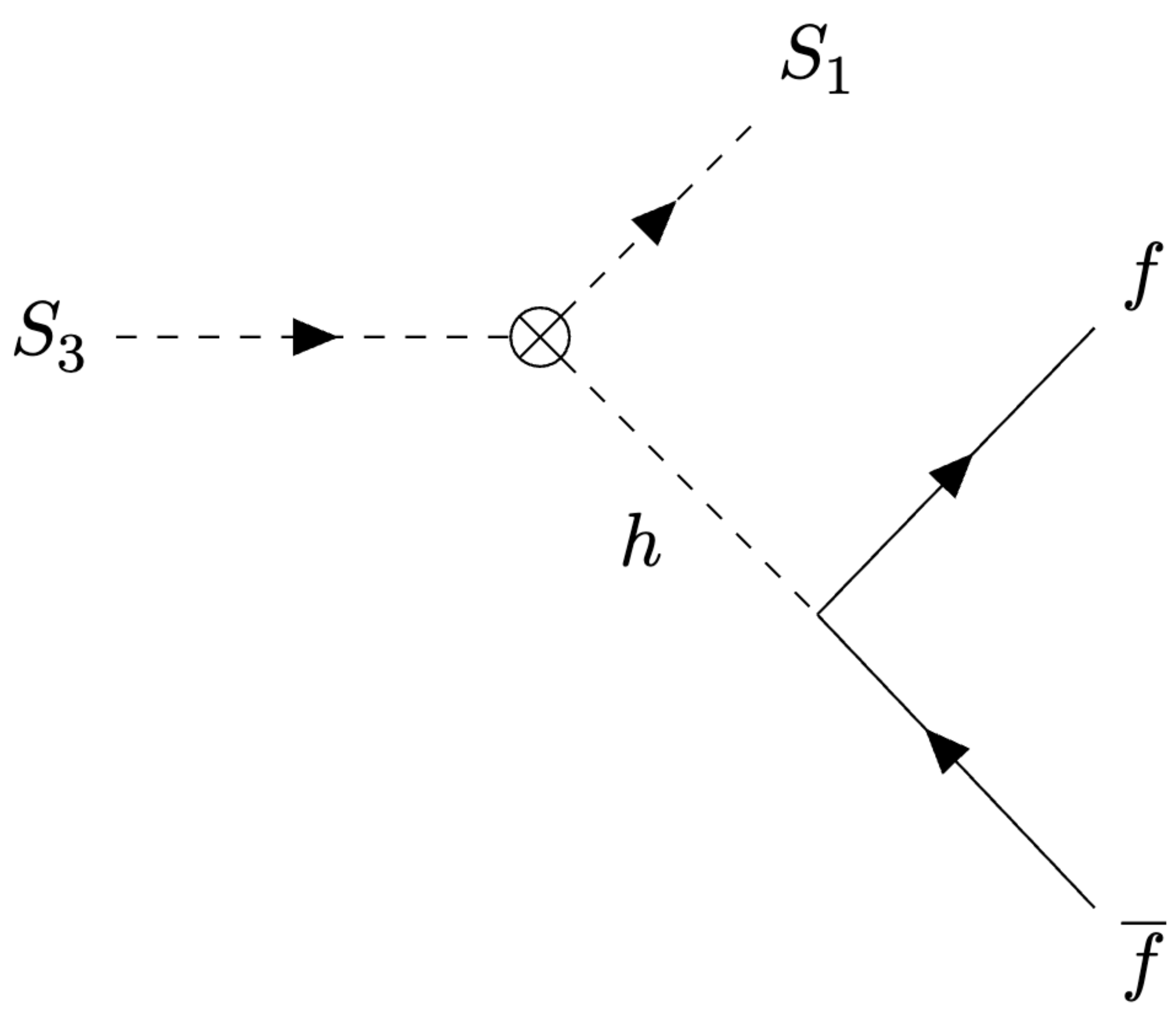
Smaller ΔM and/or weaker interaction (~1/Λ) leads to longer lifetime

Decay of heavy components

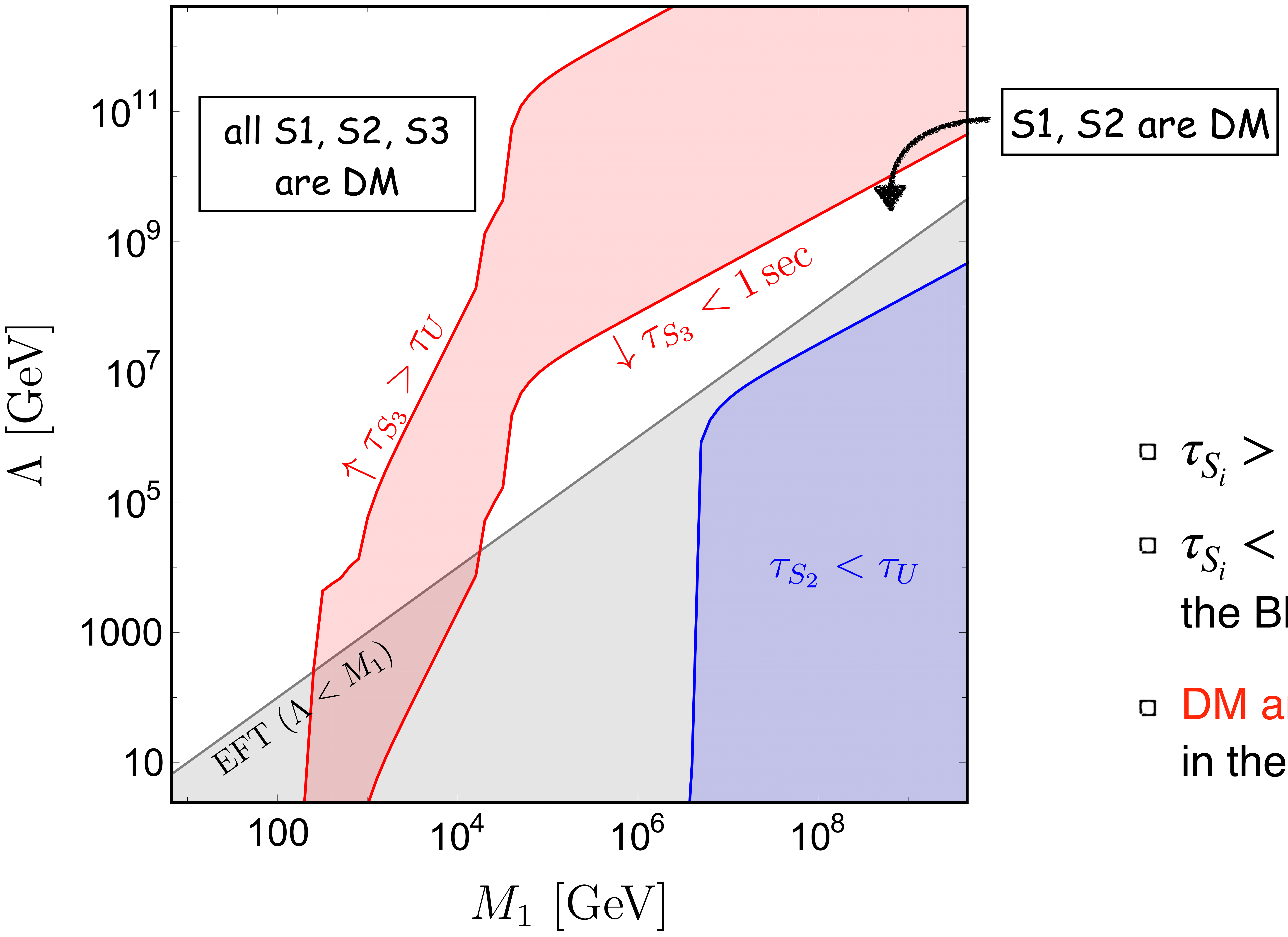
- Higher order processes might be more efficient

At $\mathcal{O}(\epsilon^2)$





Multi-component flavored DM



$$\epsilon = 10^{-2} \simeq \frac{M_3 - M_1}{y_t^2 M_1}$$

$\lambda = 0$ (i.e. no Higgs portal coupling)

- $\tau_{S_i} > \tau_U \rightarrow$ DM
- $\tau_{S_i} < \tau_U \rightarrow$ not DM and have to decay prior to the BBN (we require $\tau_{S_i} < 1\,\mathrm{sec}$ in that case)
- DM are composed of two or three components in the white region

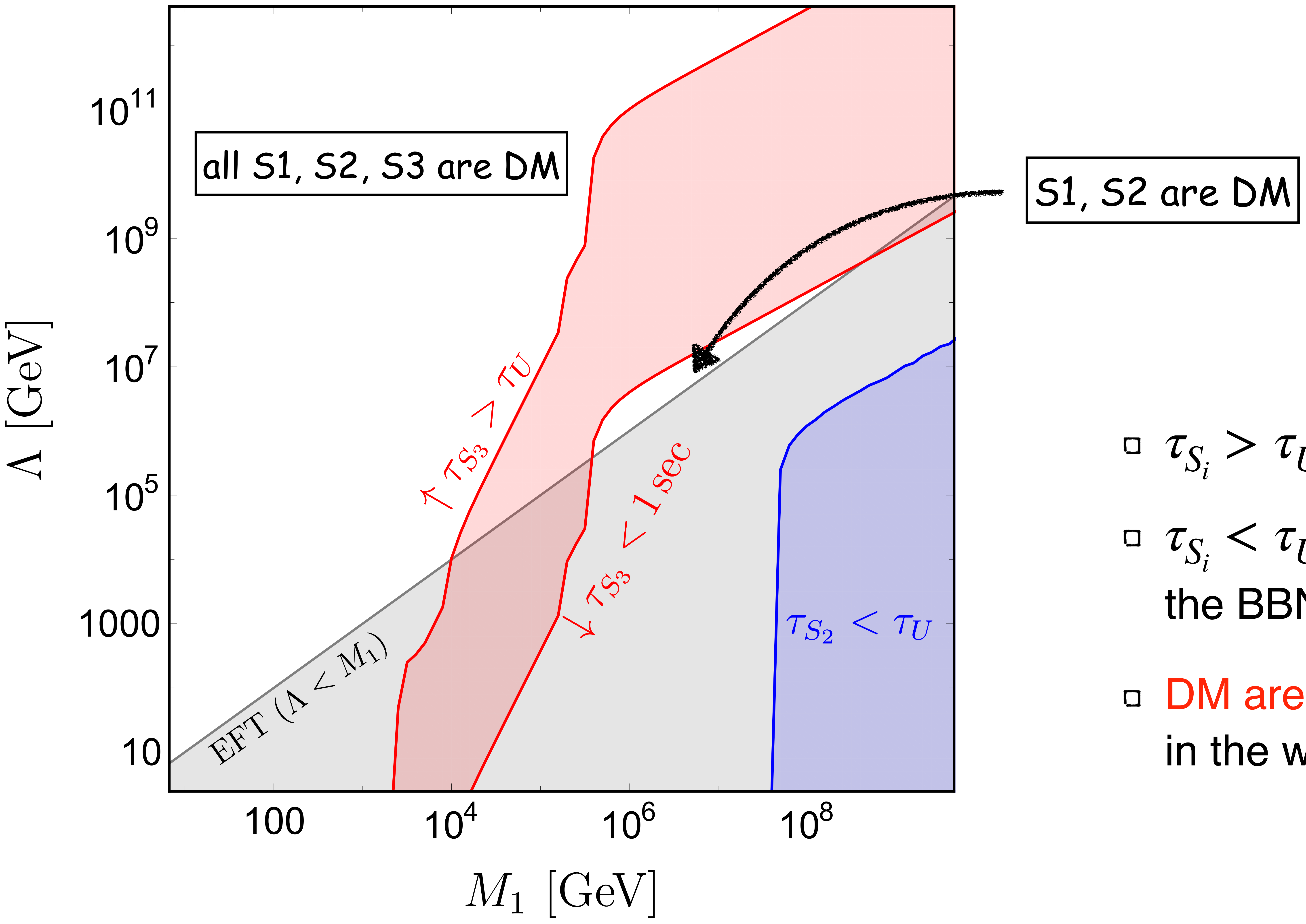
Summary

Minimal Flavor Violation (MFV) is often assumed in new physics model building

- Under the MFV hypothesis, flavored dark matter can be
  - automatically stabilized
  - multi-component
- Interesting signals? Need your ideas!

Back up

A difference benchmark

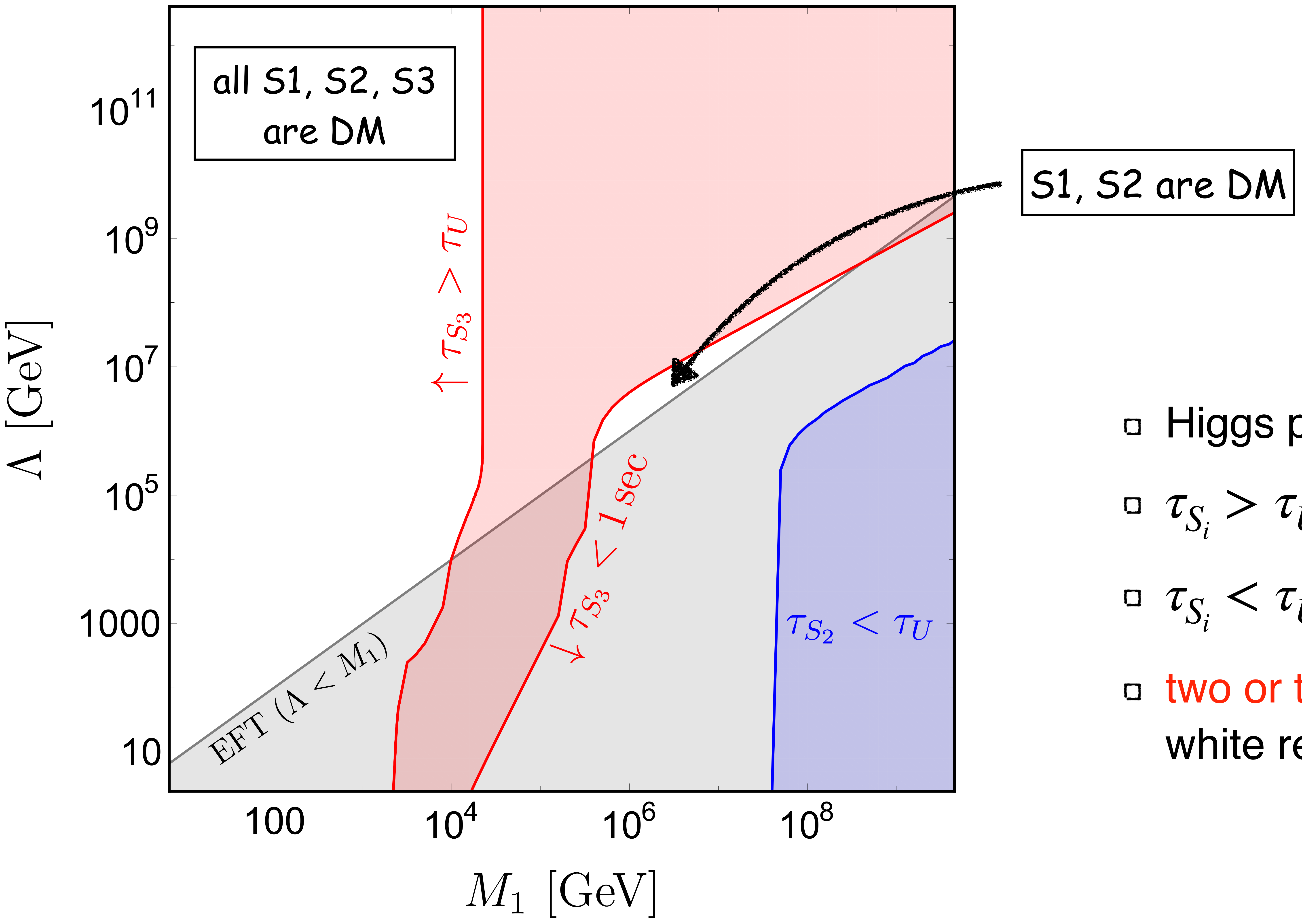


$$\epsilon = 10^{-3} \simeq \frac{M_3 - M_1}{y_t^2\, M_1}$$

$\lambda = 0$ (i.e. no Higgs portal coupling)

- $\tau_{S_i} > \tau_U \rightarrow$ DM
- $\tau_{S_i} < \tau_U \rightarrow$ not DM and have to decay prior to the BBN (we require $\tau_{S_i} < 1\,\mathrm{sec}$ in that case)
- DM are composed of two or three components in the white region

Impact of Higgs portal coupling



$$\epsilon = 10^{-3} \simeq \frac{M_3 - M_1}{y_t^2\, M_1}$$

$$\lambda = 0.1$$

- Higgs portal mainly affects the S3 lifetime
- $\tau_{S_i} > \tau_U \rightarrow$ DM
- $\tau_{S_i} < \tau_U \rightarrow \tau_{S_i} < 1\,\mathrm{sec}$ from the BBN bound
- two or three component DM is realized in the white region

A different scenario

- Assume the mass splitting $M_3 - M_1$ is independent of ε
- Higgs portal coupling $\lambda = 10^{-3}$
- Two or three component DM is realized in the white region