Multi-component dark matter from Minimal Flavor Violation

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Based on 2408.16812 in collaboration with Federico Mescia (INFN LNF), Keyun Wu (ICCUB, Barcelona)

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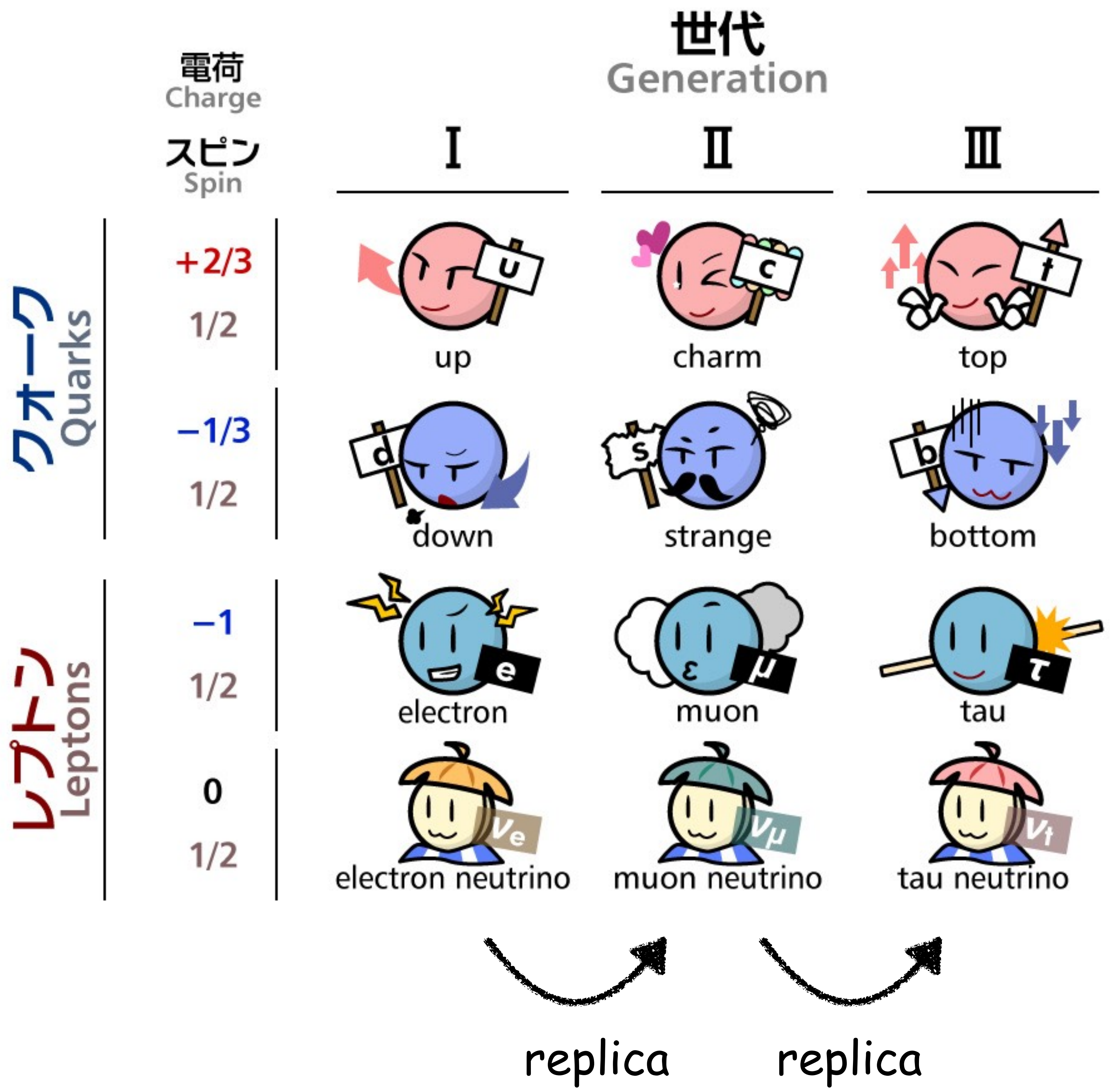
Flavor of matter fermions



picture from higgstan.com

Flavor = species of fermions

- 6 flavor quarks, 6 flavor leptons
- Fermions with the same charge have similar properties → repetition of the basic fermion family

Flavor symmetry in the Standard Model

In the gauge sector, there is a global flavor symmetry:

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

$$q_L^i,\ u_R^i,\ d_R^i,\ \ell_L^i,\ e_R^i \qquad (i = 1, 2, 3)$$

- The matter fermions comprise five different gauge representations of Weyl fermions
- There exist three species, or flavors in each representation

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broken by Yukawa interactions

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

$$\mathrm{U}(1)_Y\,,\ \mathrm{U}(1)_B\,,\mathrm{U}(1)_L\,,\mathrm{U}(1)_{L_e - L_\mu}\,,\mathrm{U}(1)_{L_\mu - L_\tau}$$

remnant symmetry

broken spontaneously

broken to U(1)_{B-L} by anomaly

Flavor symmetry in the Standard Model

Flavor dynamics in the SM is governed by

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

+

Symmetry breaking by $Y_u,\ Y_d,\ Y_e$

Minimal Flavor Violation hypothesis

All flavor violation is caused solely by the Yukawa matrices

[Chivukula, Georgi ’87; Hall, Randall ’90; D’Ambrosio et al. ’02]

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Formally, MFV is achieved by promoting the Yukawa matrices to spurious fields transforming like

$$Y_u \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1})\,, \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \overline{\mathbf{3}}, \mathbf{1}, \mathbf{1})\,, \quad Y_e \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{3}, \overline{\mathbf{3}})\,.$$

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

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

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

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

DM stability under MFV

Flavored dark matter can naturally be stabilized within MFV [Batell, Pradler, Spannowsky ’11]

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- Consider a new field χ that has no color but a flavor charge

$$\chi \sim (n_{q_L}, m_{q_L}) \times (n_{u_R}, m_{u_R}) \times (n_{d_R}, m_{d_R}) \qquad \text{under} \quad \mathcal{G}_F = \mathrm{SU}(3)_{q_L} \times \mathrm{SU}(3)_{u_R} \times \mathrm{SU}(3)_{d_R}$$

Dynkin coefficients: (1,0)=triplet, (1,1)=octet

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- A general decay operator is 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 flavor-singlet operator to maintain the EW and Lorentz invariance

DM stability under MFV

Flavored dark matter can naturally be stabilized within MFV [Batell, Pradler, Spannowsky '11]

- This decay operator must be QCD and flavor singlet if present

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

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

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

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

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

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

⇒

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

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

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

$$\Rightarrow (n_\chi - m_\chi) \bmod 3 = 0$$

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

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

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

stability condition
(flavor triality condition)

Flavored DM candidates

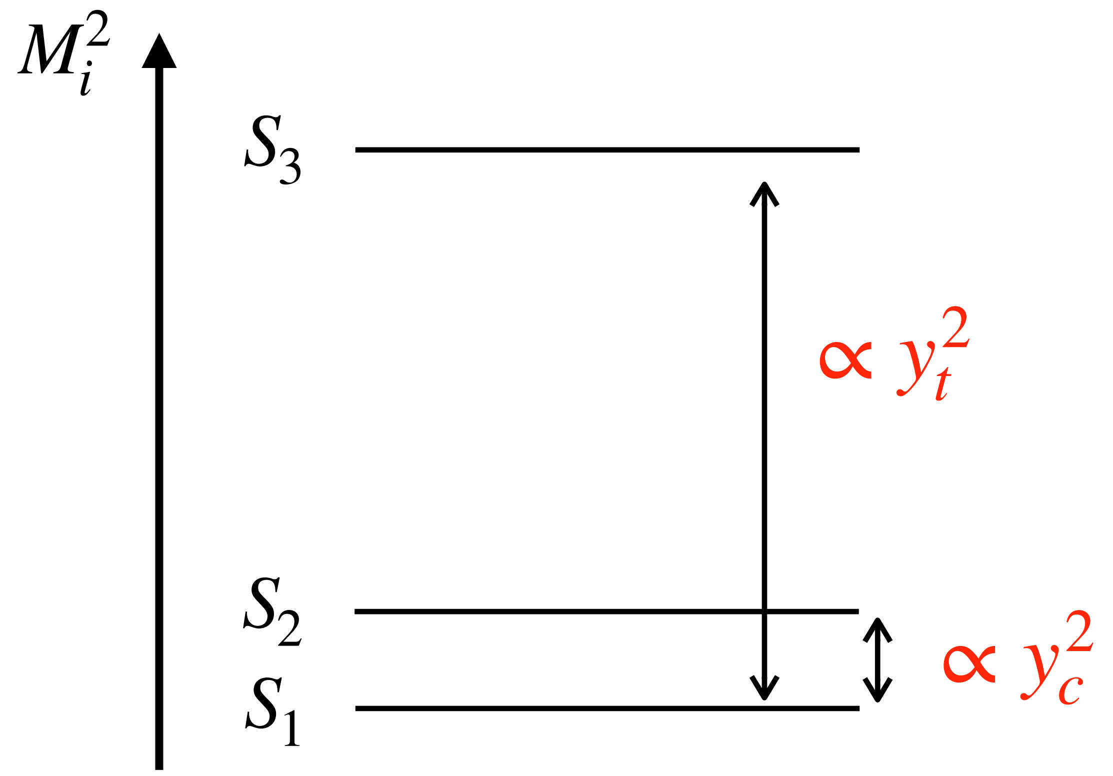
(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$	Yes
$(0,1)$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{1})$,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

[Batell, Pradler, Spannowsky '11]

- independent of spin and EW representation of χ
- Only the lightest flavored state is stabilized due to MFV
  - All heavy flavors quickly decay, and only the lightest flavor is DM (Batell+ '11; Lopez-Honorez+ '13)
  - Some heavy flavors are decaying but long-lived enough to serve as DM → **multi-component DM**

[Mescia, **SO**, Wu, 2408.16812]

A benchmark model



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

- Scalar potential

$$V(H,S) = \{m_0^2 + \epsilon\, m_1^2 (y_u^i)^2\}\, S_i^* S_i + \frac{\lambda}{2}\left(b_0 + \epsilon\, b_1 (y_u^i)^2\right)(2vh + h^2) S_i^* S_i$$

(ϵ: MFV expansion parameter $\ll 1$)

→

- $M_j^2 - M_i^2 = \epsilon\, m_1^2 \left[(y_u^j)^2 - (y_u^i)^2\right]$
- flavor diagonal -> no heavy scalar decay

- Dim-6 operators

$$\mathcal{L}_{d=6} \sim \frac{c_2^4}{\Lambda^2}\left(\bar{q}_{Li}\,(Y_u)_{ij}\, S_j\right) \widetilde{H}\,(S_k^* \delta_{kl} u_{Rl}) + \mathrm{h.c.}$$

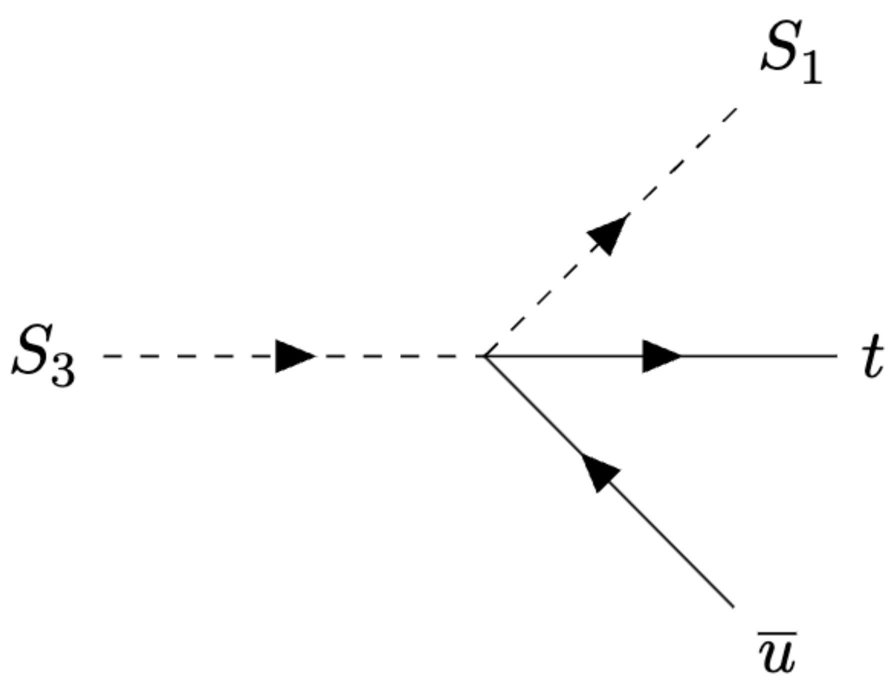
$$\sim \frac{c_2^4}{\Lambda^2}\, \bar{u}_i (m_u^i P_R + m_u^j P_L) u_j \left(S_j^* S_i\right)$$

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

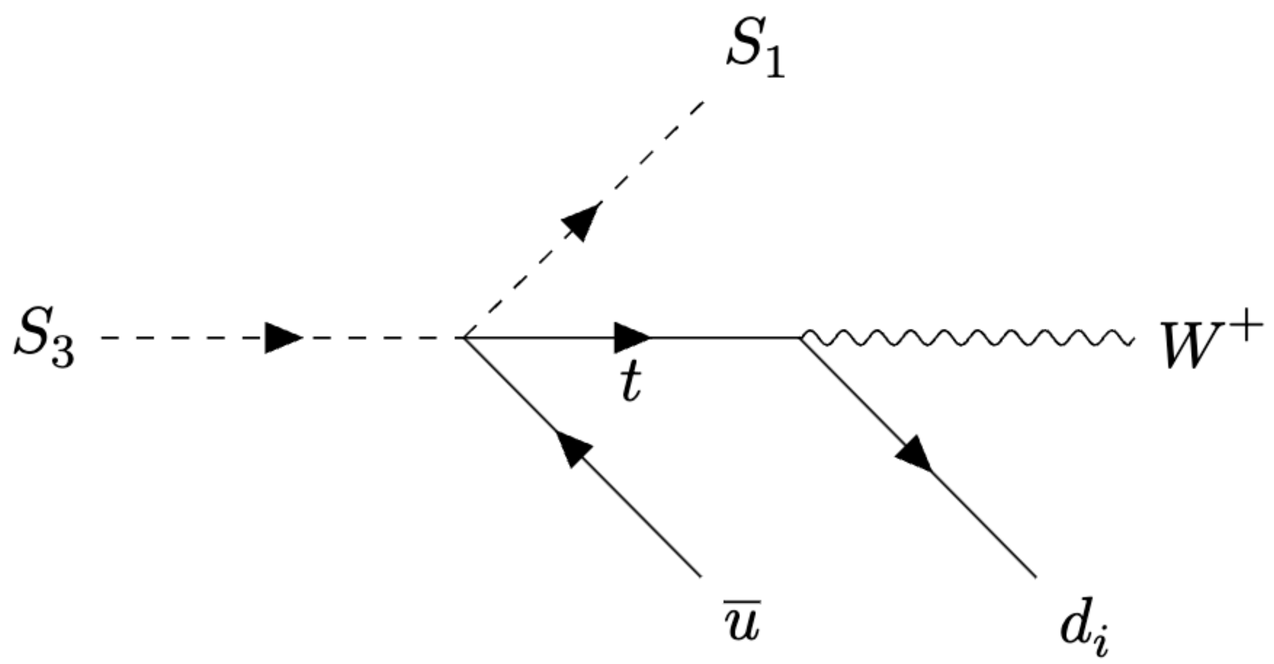
heavy scalar decay triggered at the ϵ^0 order

Decay of heavy components

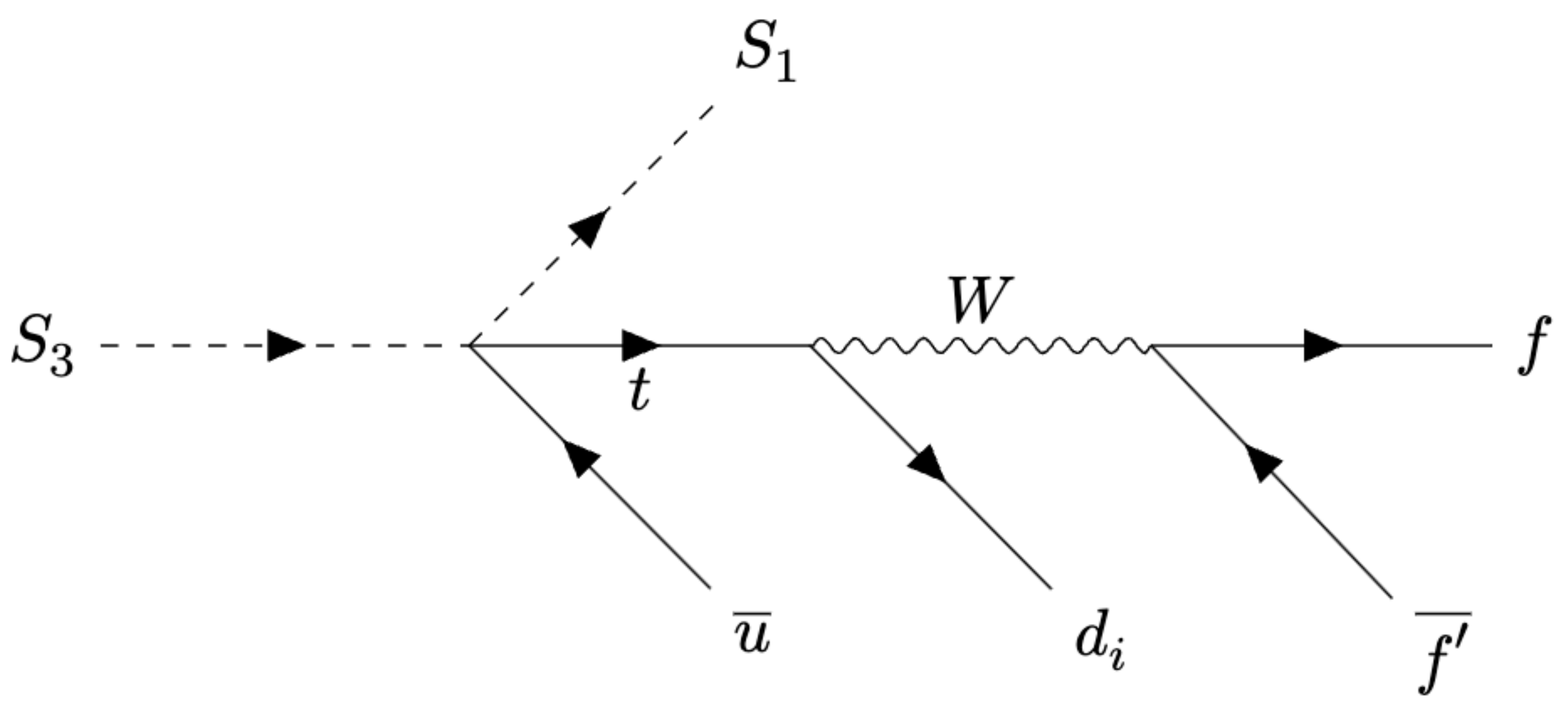
Example S3 decay (*Dominant mode depends on the mass splitting $\Delta M = M_3 - M_1$)



$\Delta M \gtrsim m_t$



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



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

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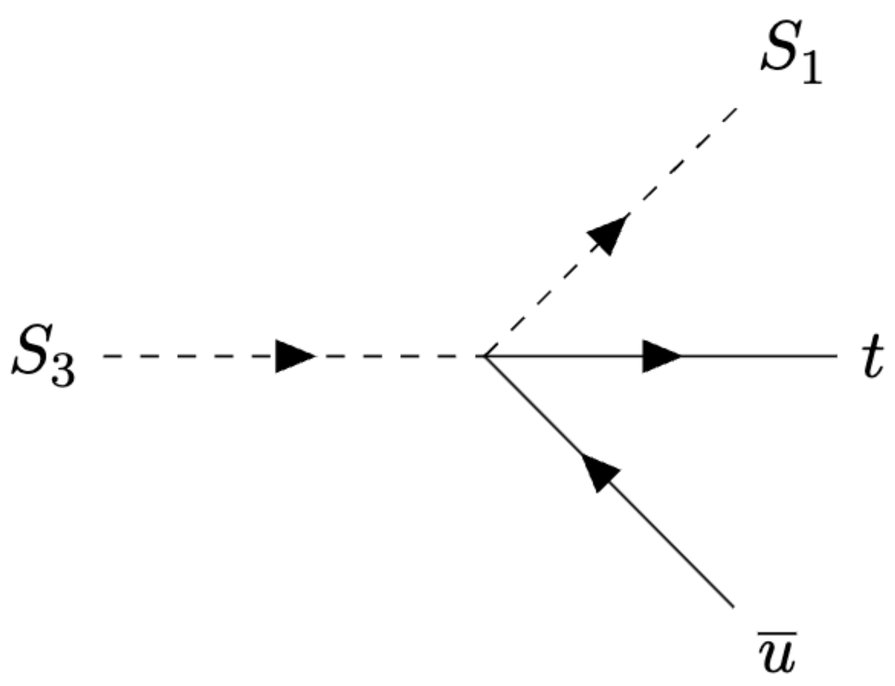
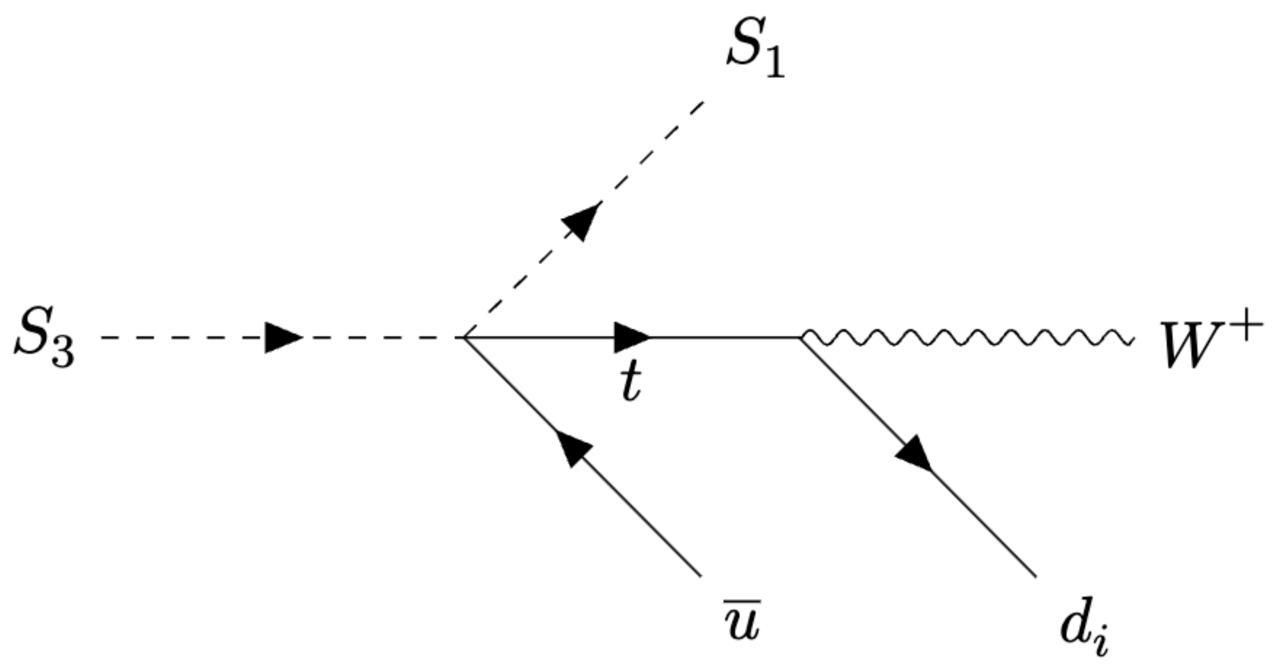
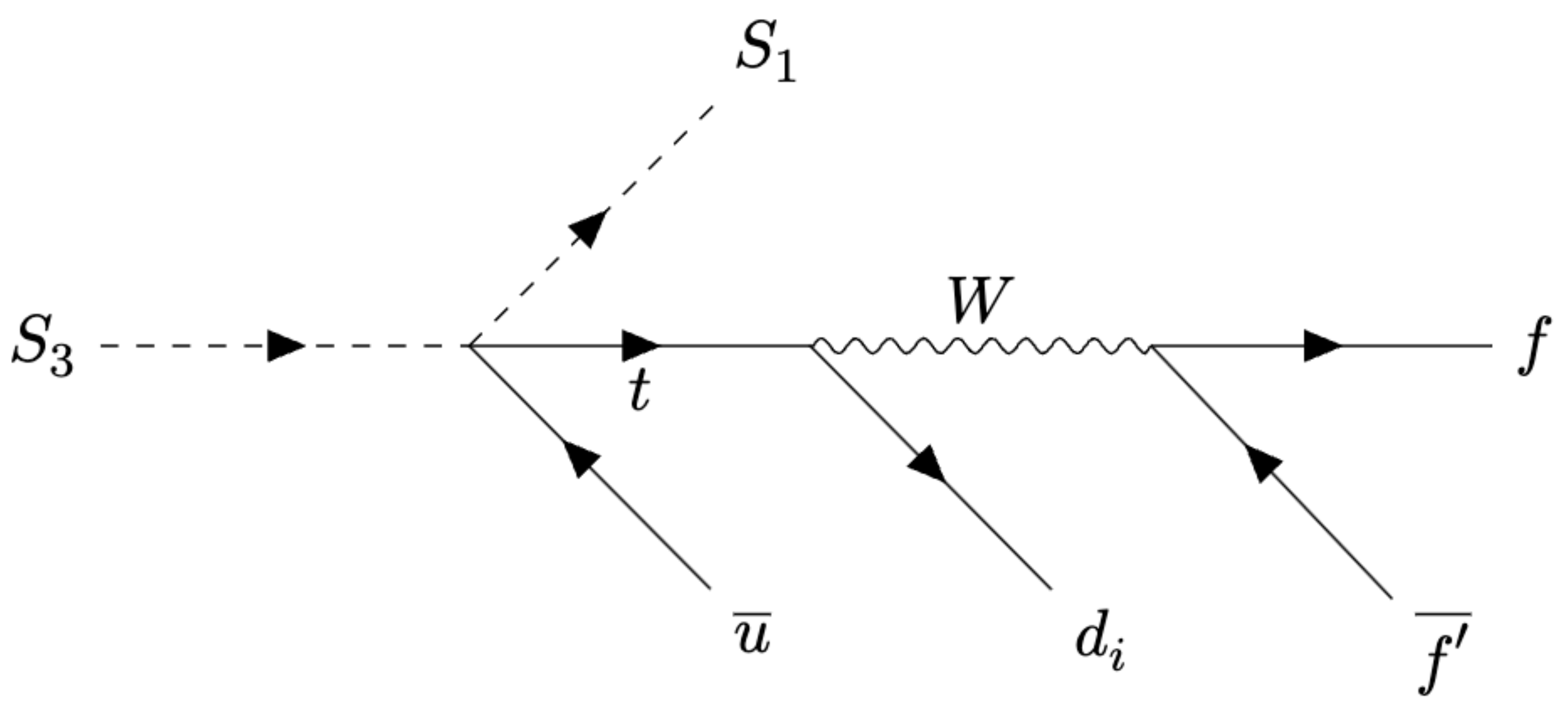






$\Delta M \gtrsim m_t$

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

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

$$\Gamma \sim \frac{m_t^2 (\Delta M)^5}{480\pi^3 \Lambda^4 M_3^2}$$

$$\sim \frac{(\Delta M)^{11} |V_{ti}|^2}{41472\pi^5 \Lambda^4 M_3^2 m_t^2 v^2}$$

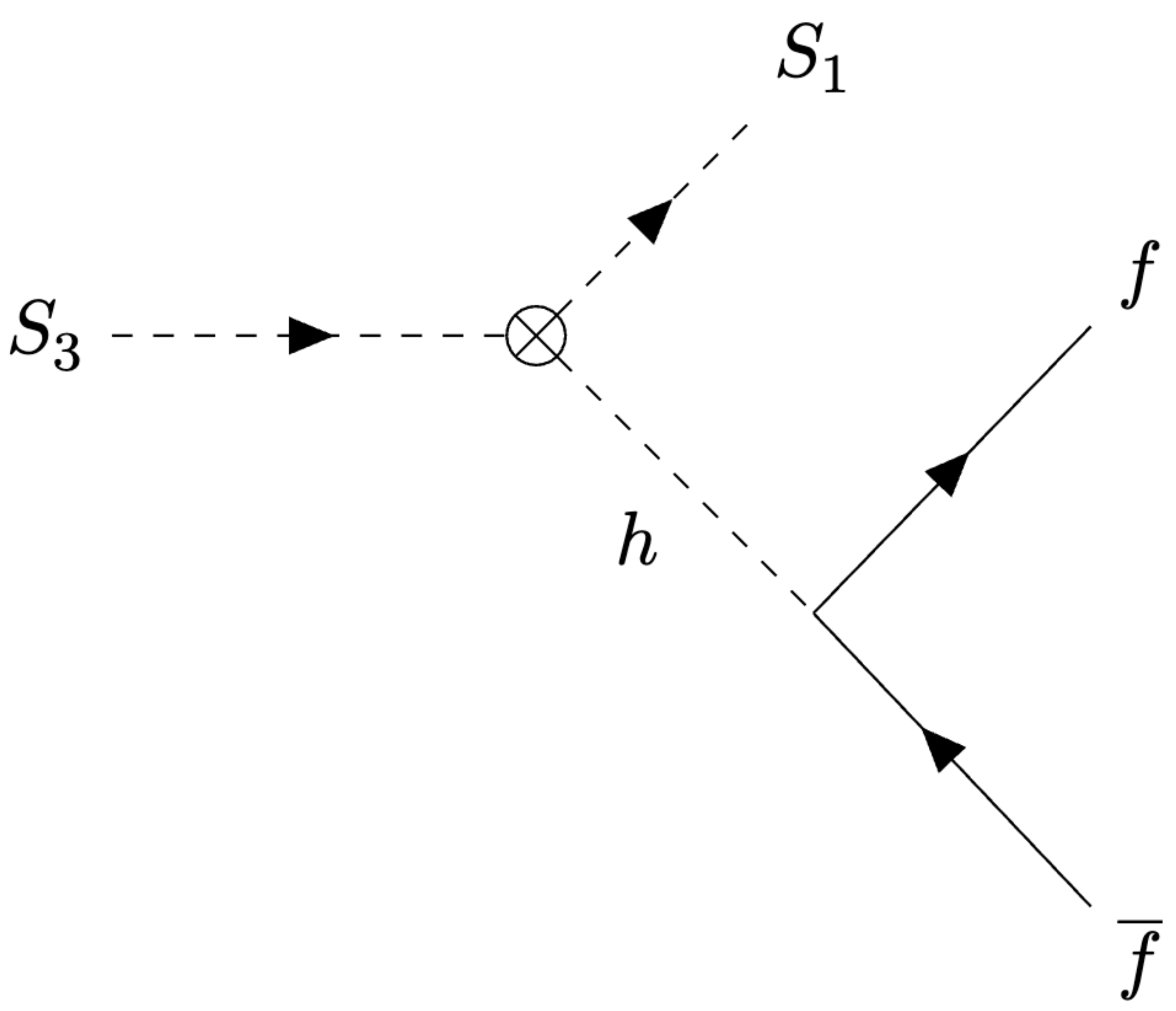
$$\sim \frac{(\Delta M)^{13} |V_{ti}|^2}{11612160\pi^7 \Lambda^4 M_3^2 m_t^2 v^4}$$

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

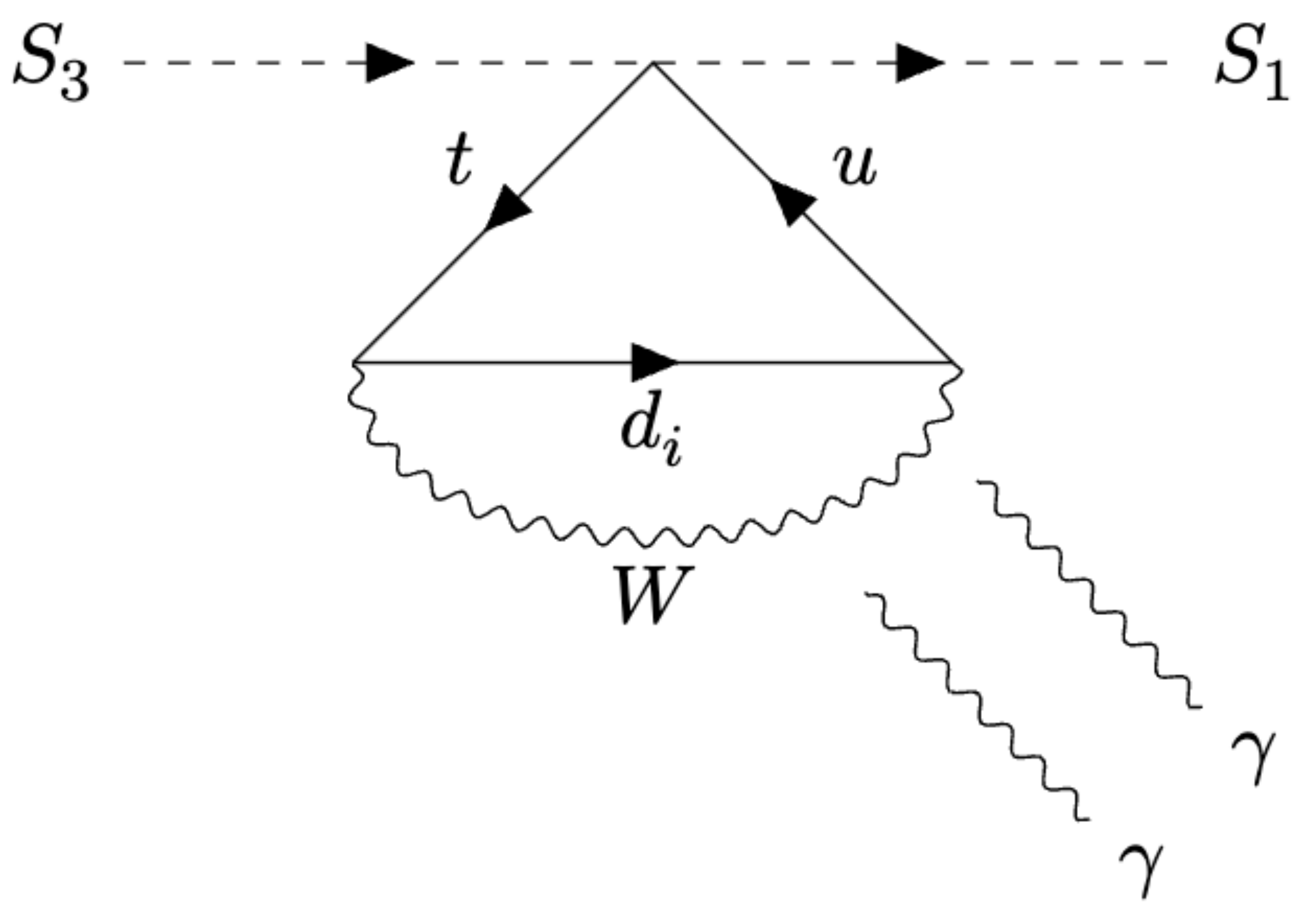
Decay at higher orders

Three-body decay into light particles is induced at higher orders or via loop

- appears at ε^2 order or two-loop level
- can surpass four or five-body ε^0-order processes

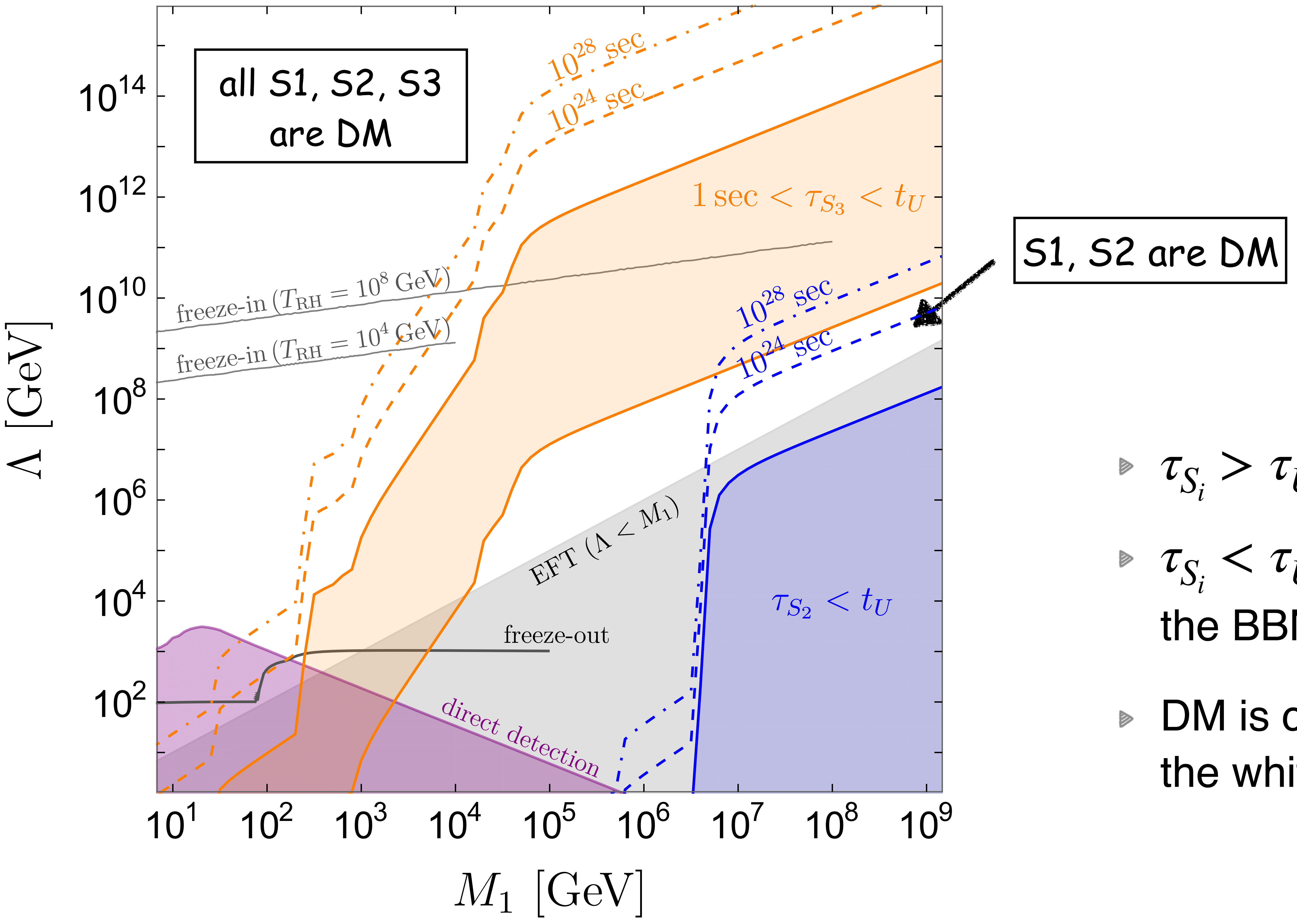


$$\sim \epsilon^2\, Y_u^\dagger Y_d Y_d^\dagger Y_u$$



$$\sim \frac{Y_u^\dagger Y_d Y_d^\dagger Y_u}{(16\pi^2)^2}$$

Parameter spaces for multi-component DM



$$\epsilon = 10^{-2} \simeq \frac{M_3 - M_1}{y_t^2 M_1} \simeq \frac{M_2 - M_1}{y_c^2 M_1}$$

$\lambda = 0$ no coupling to Higgs

- $\tau_{S_i} > \tau_U$ → DM
- $\tau_{S_i} < \tau_U$ → not DM and has to decay prior to the BBN (we require $\tau_{S_i} < 1$ sec)
- DM is composed of two or three components in the white region

Implications

- Phenomenological
  - indirect search: $S_j \to S_i \gamma\gamma,\ S_i q\bar{q},\ \ldots$
  - inelastic scattering: $S_j N \to S_i N$
  - flavor physics: $b \to s\, S_3 S_2^\dagger$ and $s \to d\, S_2 S_1^\dagger$
- Theoretical
  - other spin and EW representation
  - extension to lepton sector
  - connection to UV theory

Summary

Flavor symmetry in the SM might determine the nature of dark matter

Within MFV, dark matter naturally has a family!

Dark Matter =

Thanks for your attention!

Back up

Why flavored DM stabilized within MFV?

There is an unbroken Z3 symmetry $\subset SU(3)_c \times SU(3)_{q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$ [Batell, Lin, Wang '13]

- Z3 charge ($\psi \to U\psi$): $U = (\omega^2)^{n_c - m_c} \cdot (\omega)^{n_q - m_q} \cdot (\omega)^{n_u - m_u} \cdot (\omega)^{n_d - m_d}$ where $\omega^3 = 1$
  - All SM fields are singlet
    - quarks: $Q \to (\omega^2 \cdot \omega)\, Q = Q$
    - other SM fields: $\phi \to \phi$
  - Flavored DM: $\chi \to (\omega)^{n_\chi - m_\chi} \chi$
    - χ is Z3 non-singlet if $(n_\chi - m_\chi) \bmod 3 \neq 0$ -> **stabilized!**
  - Flavored states Φ can develop VEVs if $(n_\Phi - m_\Phi) \bmod 3 = 0$ [Bishara+ '15]
    - extendable to a broader framework

A benchmark model

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

- Scalar potential within MFV (ϵ: MFV expansion parameter $\ll 1$)

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

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

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

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

up to O(ε)

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

+ 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) \\
&+ \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
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\end{aligned}
$$

flavor independent   flavor dependent

A benchmark model

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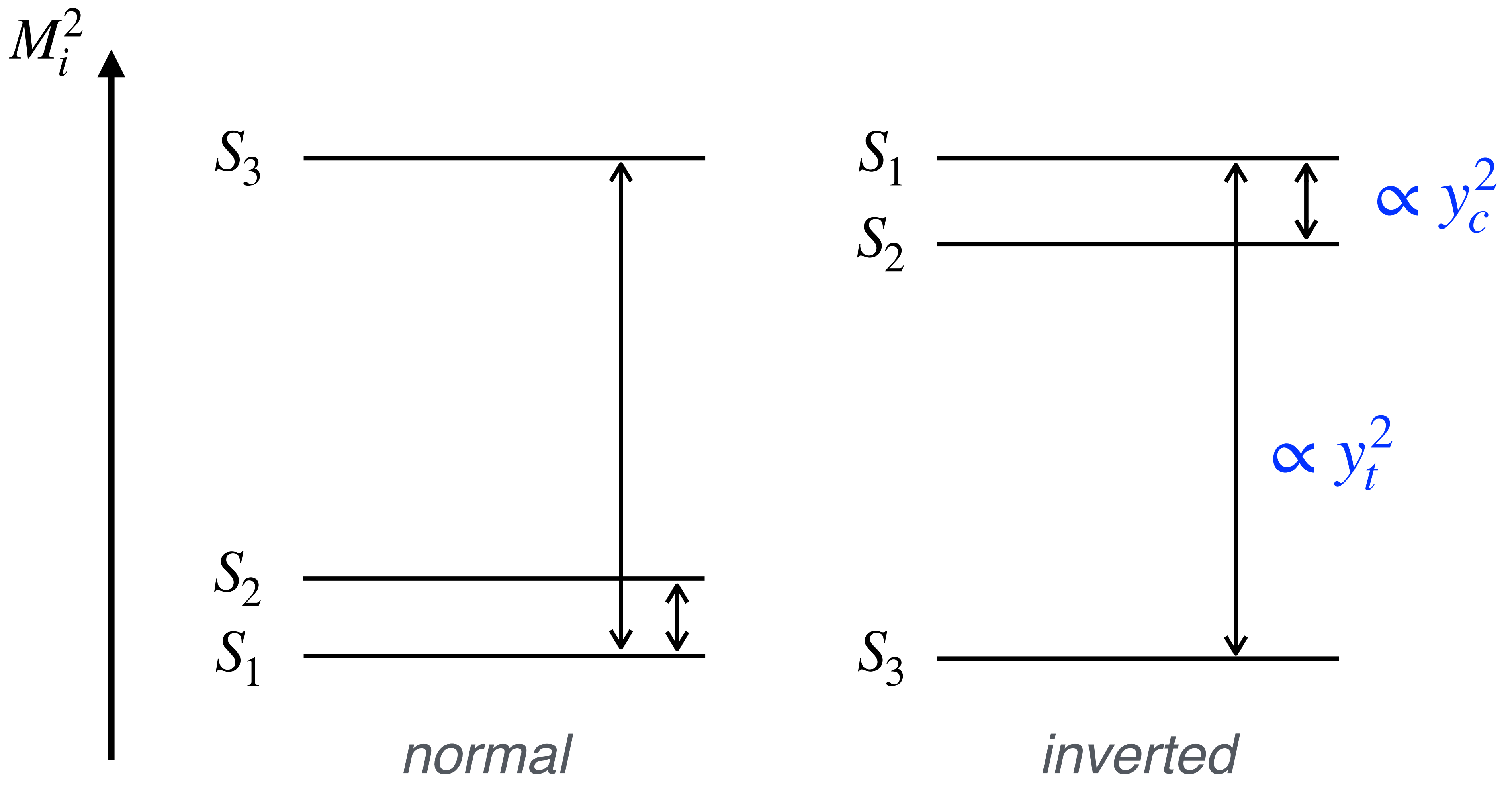

up to O(ε)

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\begin{aligned}
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
\end{aligned}
$$

flavor independent flavor dependent

- $M_j^2 - M_i^2 = \epsilon\, m_1^2 \left[(y_u^j)^2 - (y_u^i)^2 \right]$
- flavor diagonal int. doesn't lead heavy scalar decay

Higher dimensional operators

- Dim-6 operators

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

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

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

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

$$\mathcal{O}^\gamma_{ij} = \left(S^*_i S_j\right)F_{\mu\nu}F^{\mu\nu}\;.$$

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The coefficients are determined by the Yukawa matrices

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

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$$\mathcal{O}^\gamma_{ij} = (S^*_i S_j)\,F_{\mu\nu}F^{\mu\nu}\,.$$

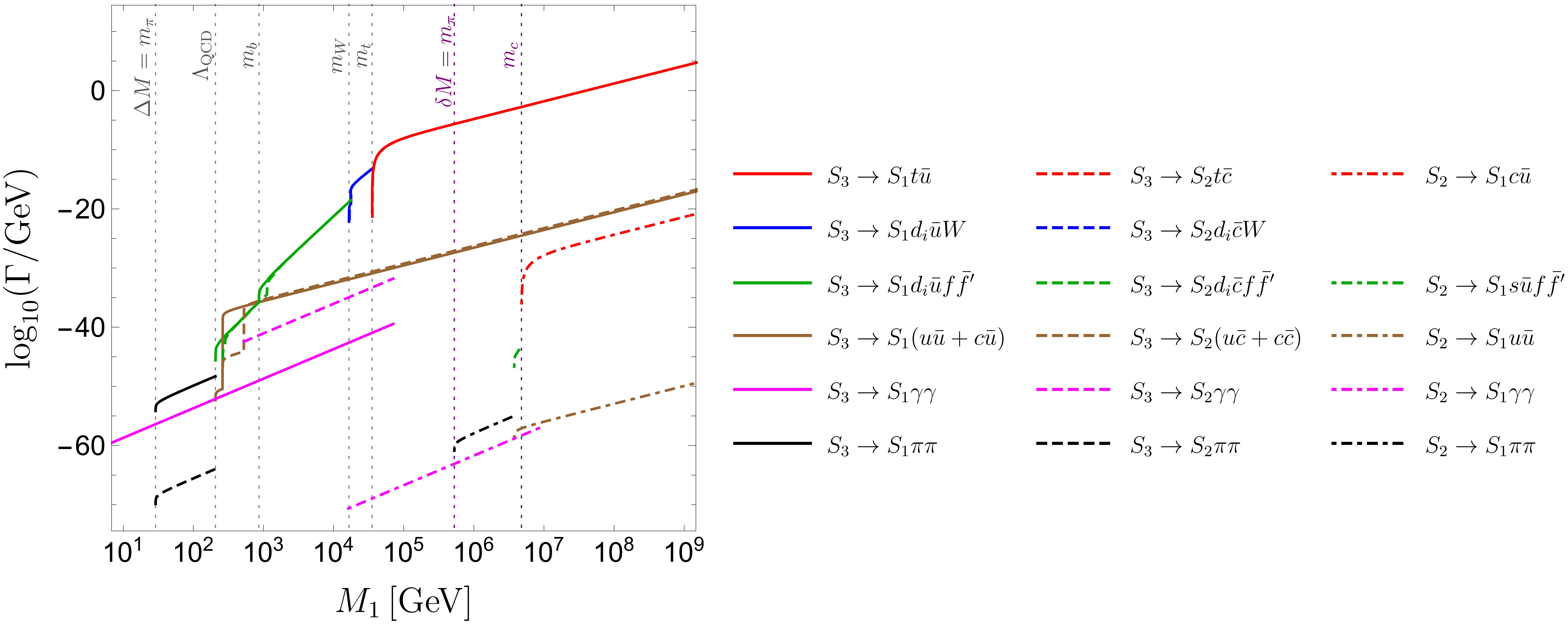
Heavy scalar decays are triggered even at the ε^0 order

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

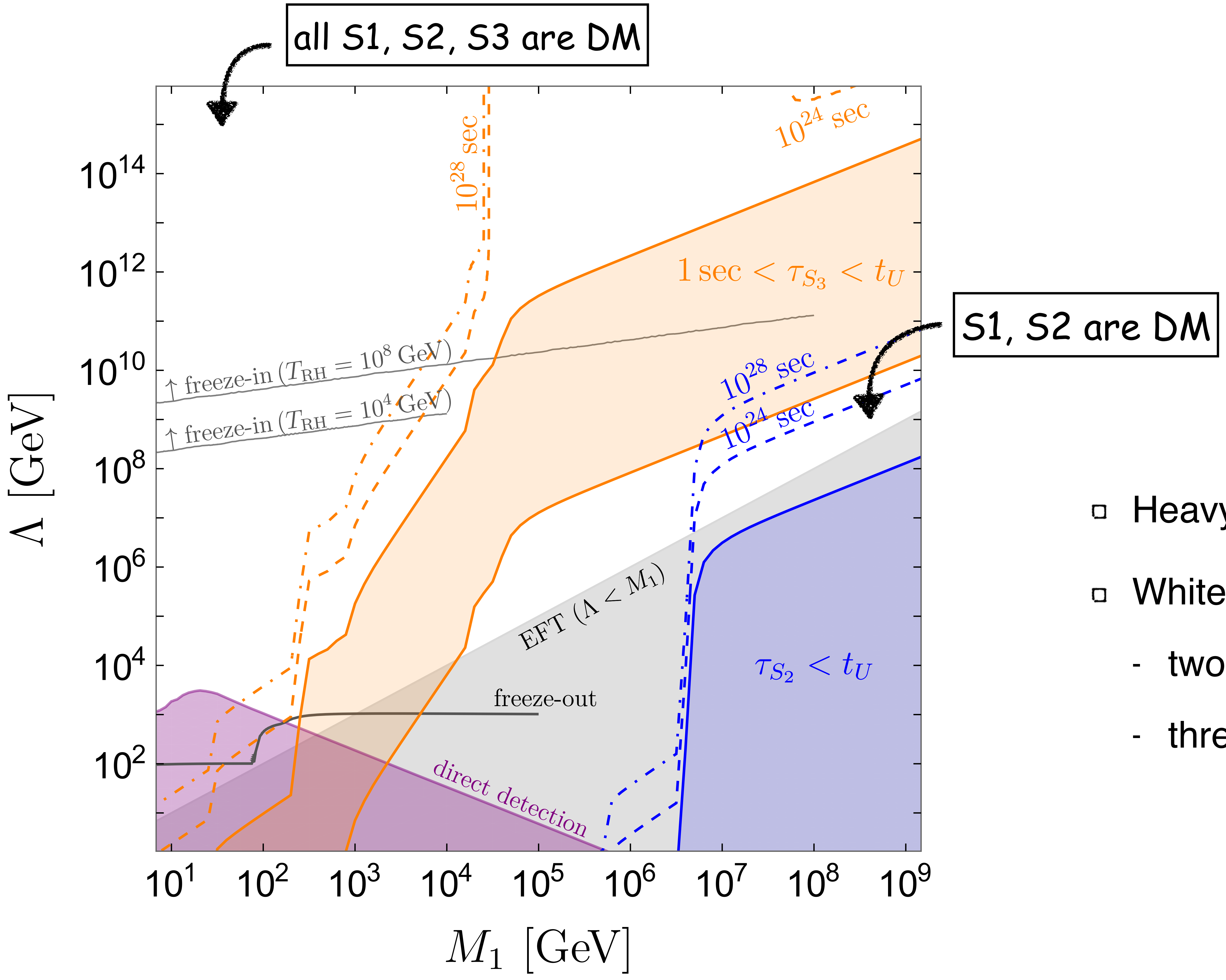
$$\sim \frac{c^4_2}{\Lambda^2}\,\bar{u}_i(m^i_u P_R + m^j_u P_L)u_j\,(S^*_j S_i)$$

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

Partial decay widths for heavy scalars



Impact of Higgs portal coupling (1/2)



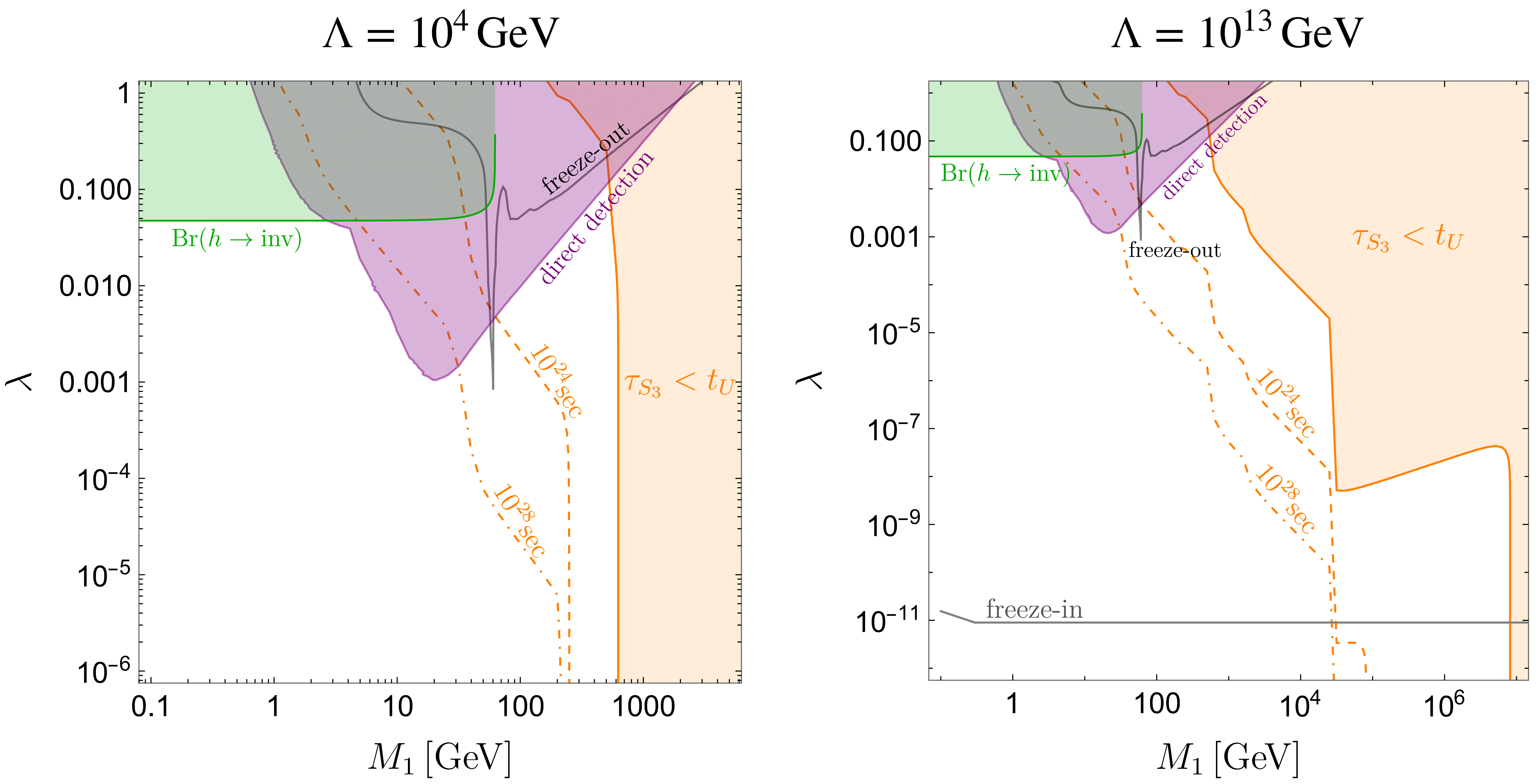
$$\epsilon = 10^{-2} \simeq \frac{M_3 - M_1}{y_t^2 M_1} \simeq \frac{M_2 - M_1}{y_c^2 M_1}$$

$$\lambda = 10^{-11}$$

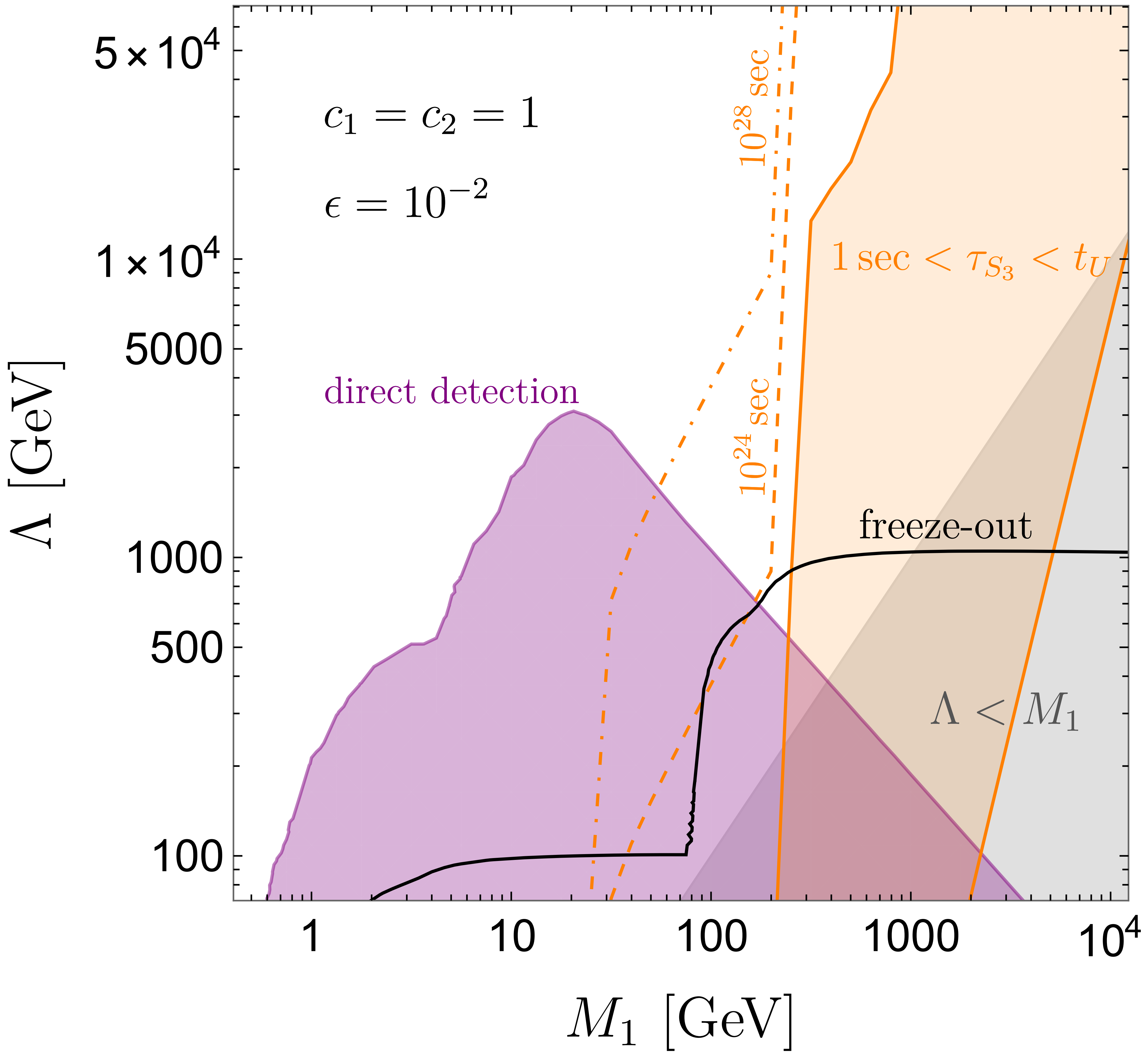
- Heavy components are also DM if $\tau_{S_i} > \tau_U$
- White region is allowed
  - two-component between orange and blue regions
  - three-component above the orange region

Impact of Higgs portal coupling (2/2)

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



Closer look at WIMP region



$$\epsilon = 10^{-2} \simeq \frac{M_3 - M_1}{y_t^2 M_1} \simeq \frac{M_2 - M_1}{y_c^2 M_1}$$

$\lambda = 0$ no coupling to Higgs

- Only a limited mass range M1~180-210GeV is allowed in the freeze-out scenario
- EFT is not justified in the region, $\Lambda < M_1$