Multi-component dark matter from Minimal Flavor Violation

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Based on JHEP 11 (2024) 114 with Federico Mescia (INFN LNF), Keyun Wu (ICCUB, Barcelona)
+ongoing works with Alessandro Dondarini (Florence), Giacomo Landini (IFIC Valencia)
Claudio Toni (LAPTH), Joel Swallow (INFN LNF)

The IBS Conference on Dark World
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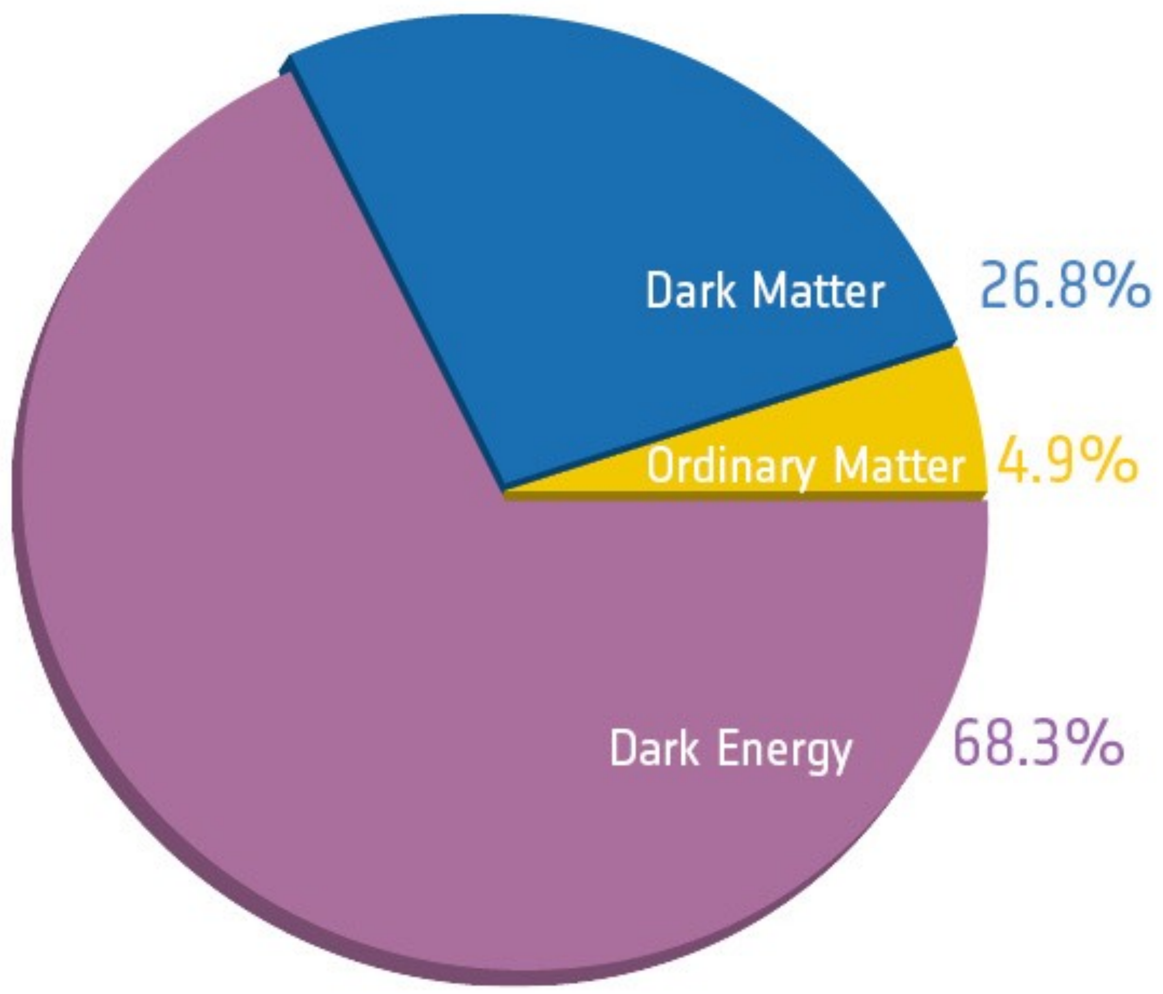
Dark Matter exists in the Universe

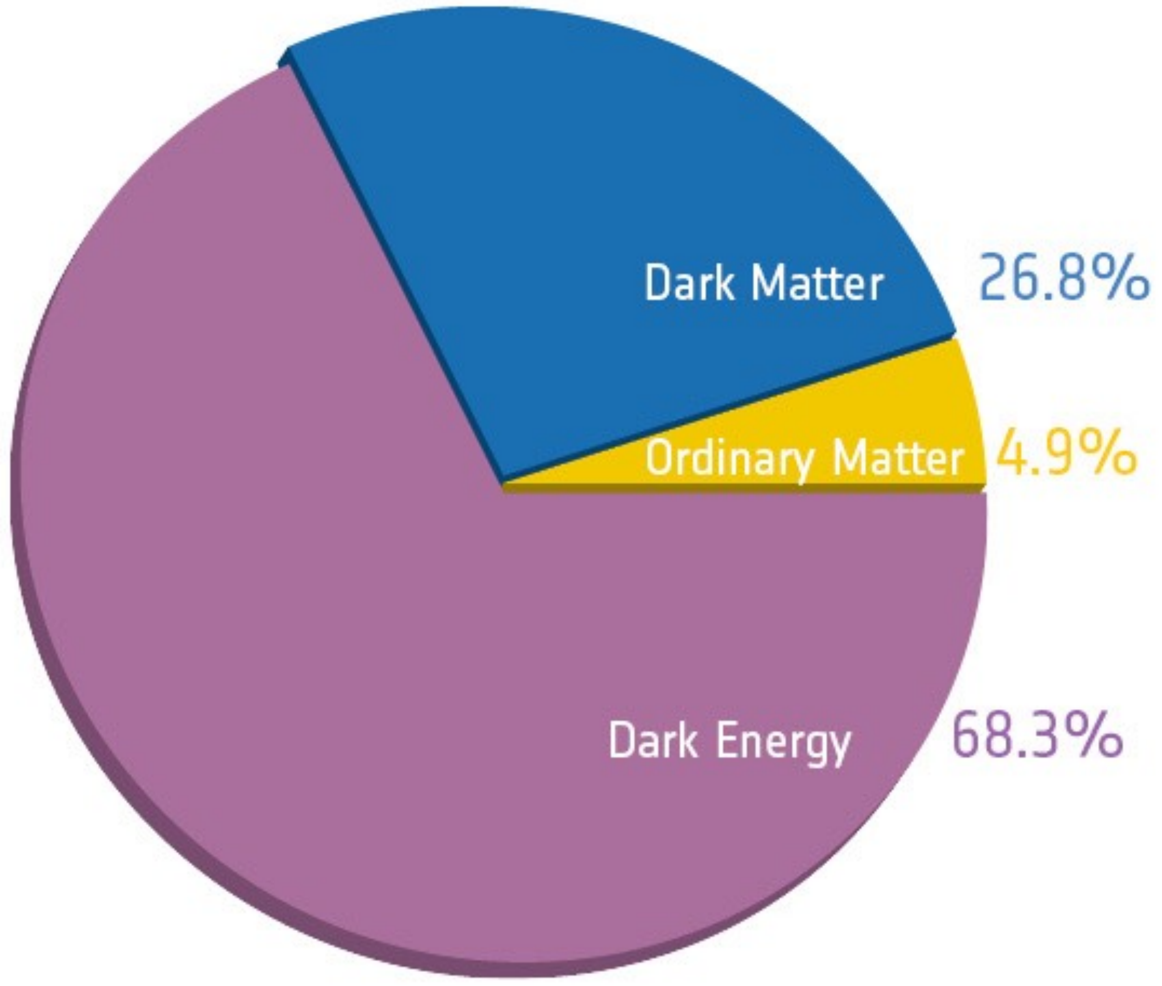
- constitutes **~25% of the Universe**
- behaves like matter (p~0)
- plays a crucial role in cosmological structure formation
- **needs BSM!!!**



Dark Matter exists in the Universe

General properties

- stable (or lifetime longer than the age of the universe)
- collision-less (→ **no electric charge**)
- non-relativistic
- abundant in the universe (Ωh^2=0.12)



We know almost **nothing about dark matter**

- mass scale?
- elementary or composite?
- non-gravitational interactions?
- single component or more?
- ...

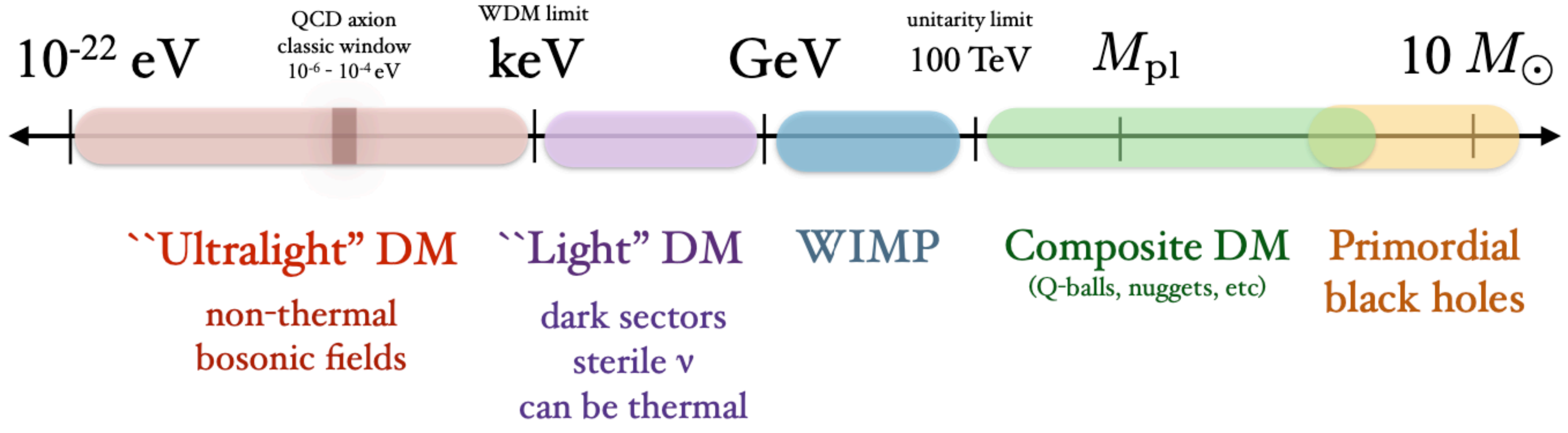


figure from 1904.07915

Huge parameter space for viable candidates, so what guiding principle is there?

What if dark matter has flavor?

of matter fermions

I consider a framework where DM fields are charged under SM flavor groups

and show dark matter can naturally be

- stable
- multi-component

Also discuss some phenomenological implications of such multiple dark states

Flavor symmetry and dark matter

Flavor symmetry in the Standard Model

A large global flavor symmetry in the gauge sector

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

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

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

Flavor symmetry in the Standard Model

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broken by Yukawa interactions

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

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

remnant symmetry

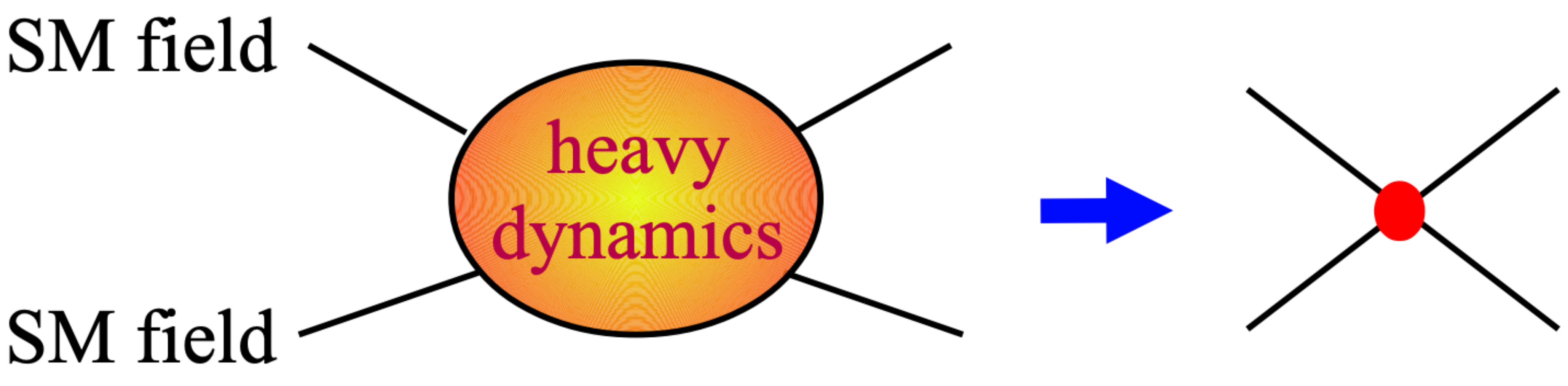
broken spontaneously

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

Flavor structure in physics Beyond the SM

$$\mathscr{L}_{\mathrm{SM-EFT}} = \mathscr{L}_{\mathrm{gauge}} + \mathscr{L}_{\mathrm{yukawa}}$$
$$+ \boxed{\sum_i \frac{1}{\Lambda_i^{d-4}} \mathscr{O}_i^{d\geq 5}}$$

contact int. from heavy BSM dynamics



What is the flavor structure in BSM?

If flavor symmetry maximally broken in BSM,

we find

$$\frac{1}{\Lambda^2}(s_L \gamma^\mu d_L)^2 \Rightarrow \Lambda \gtrsim \mathrm{PeV} - 100\,\mathrm{PeV}$$

=> stringent bounds on heavy dynamics

=> BSM is not directly accessible?

Minimal Flavor Violation (MFV) hypothesis

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

All flavor violation are caused solely by the Yukawa matrices

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

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- All new physics interactions should also be flavor invariant

$$\mathscr{L}_{\rm NP} = C_{ij} \left(\bar{u}_{Ri} \gamma^\mu u_{Rj} \right) \mathcal{O}_\mu \quad \rightarrow \quad C_{ij} = c_0 \delta_{ij} + \epsilon\, c_1 (Y_u^\dagger Y_u)_{ij} + \epsilon^2 \left[c_2 (Y_u^\dagger Y_u Y_u^\dagger Y_u)_{ij} + c_2' (Y_u^\dagger Y_d Y_d^\dagger Y_u)_{ij} \right]$$

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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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$$\frac{1}{\Lambda^2}(s_L\gamma^\mu d_L)^2 : \frac{1}{\Lambda^2} \to \frac{(Y_u Y_u^\dagger)^2_{sd}}{\Lambda^2} = \frac{y_t^4 (V_{ts}V_{td}^*)^2}{\Lambda^2} \sim \frac{10^{-7}}{\Lambda^2}$$

$\rightarrow$ orders of magnitude lower BSM scale is allowed!

MFV stabilizes dark matter

[Batell, Pradler, Spannowsky '11]

- Consider a new QCD singlet in a non-trivial representation of $\mathrm{SU}(3)_{q_L} \times \mathrm{SU}(3)_{u_R} \times \mathrm{SU}(3)_{d_R}$

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

n's, m's are Dynkin coefficients; (1,0)=triplet, (1,1)=octet

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- General decay opeartors

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

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$$(A + B + C - \bar{A} - \bar{B} - \bar{C}) \bmod 3 = 0$$

$SU(3)_c$ invariant

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

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$SU(3)_c$ and flavor invariant

$$(A + B + C - \bar{A} - \bar{B} - \bar{C}) \bmod 3 = 0$$
$$(n_{q_L} - m_{q_L} + A - \bar{A} + D - \bar{D} + E - \bar{E}) \bmod 3 = 0$$
$$(n_{u_R} - m_{u_R} + B - \bar{B} - D + \bar{D}) \bmod 3 = 0$$
$$(n_{d_R} - m_{d_R} + C - \bar{C} - E + \bar{E}) \bmod 3 = 0$$

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

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

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$\mathrm{SU}(3)_c$ and flavor invariant

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

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

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

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: $\psi \to U\psi$ with $U = (\omega^2)^{n_c - m_c} \cdot (\omega)^{n_q - m_q} \cdot (\omega)^{n_u - m_u} \cdot (\omega)^{n_d - m_d}$ where $\omega^3 = 1$
  - All SM fields and Yukawa spurions 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 $(n_\chi - m_\chi) \bmod 3 \neq 0 \to$ stabilized

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 scenario

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

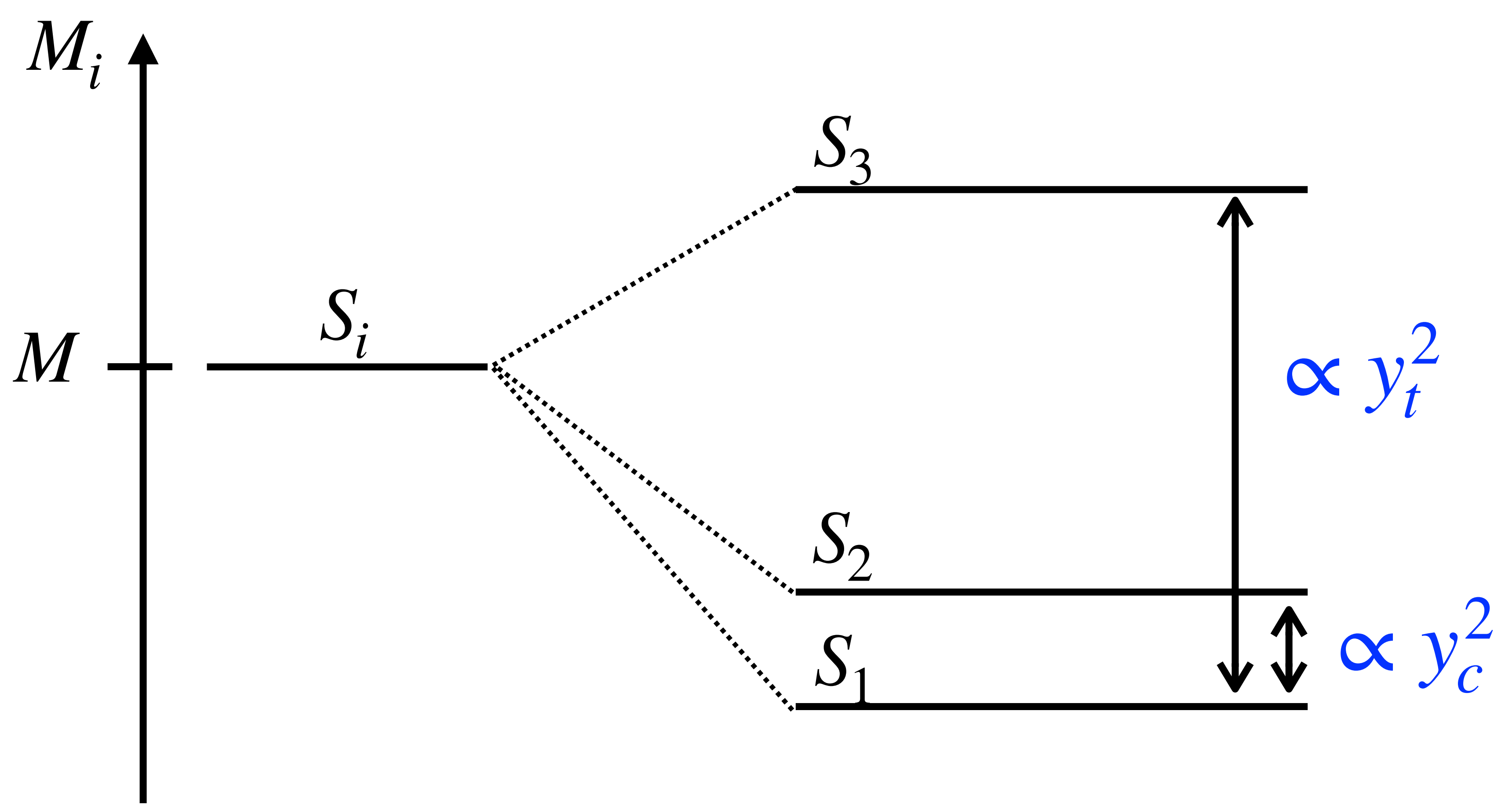
A benchmark study of a dark matter family

2408.16812 with Mescia, Wu

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

- Both mass and interactions controlled by the Yukawa couplings

A benchmark study of a dark matter family



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Scalar potential

$$V(H,S) = \left\{m_0^2 + \epsilon\, m_1^2 (y_u^i)^2\right\} S_i^* S_i \quad \longrightarrow \quad \boxed{M_j^2 - M_i^2 = \epsilon\, m_1^2 \left[(y_u^j)^2 - (y_u^i)^2\right]}$$

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

flavor diagonal, so doesn't lead heavy scalar decay

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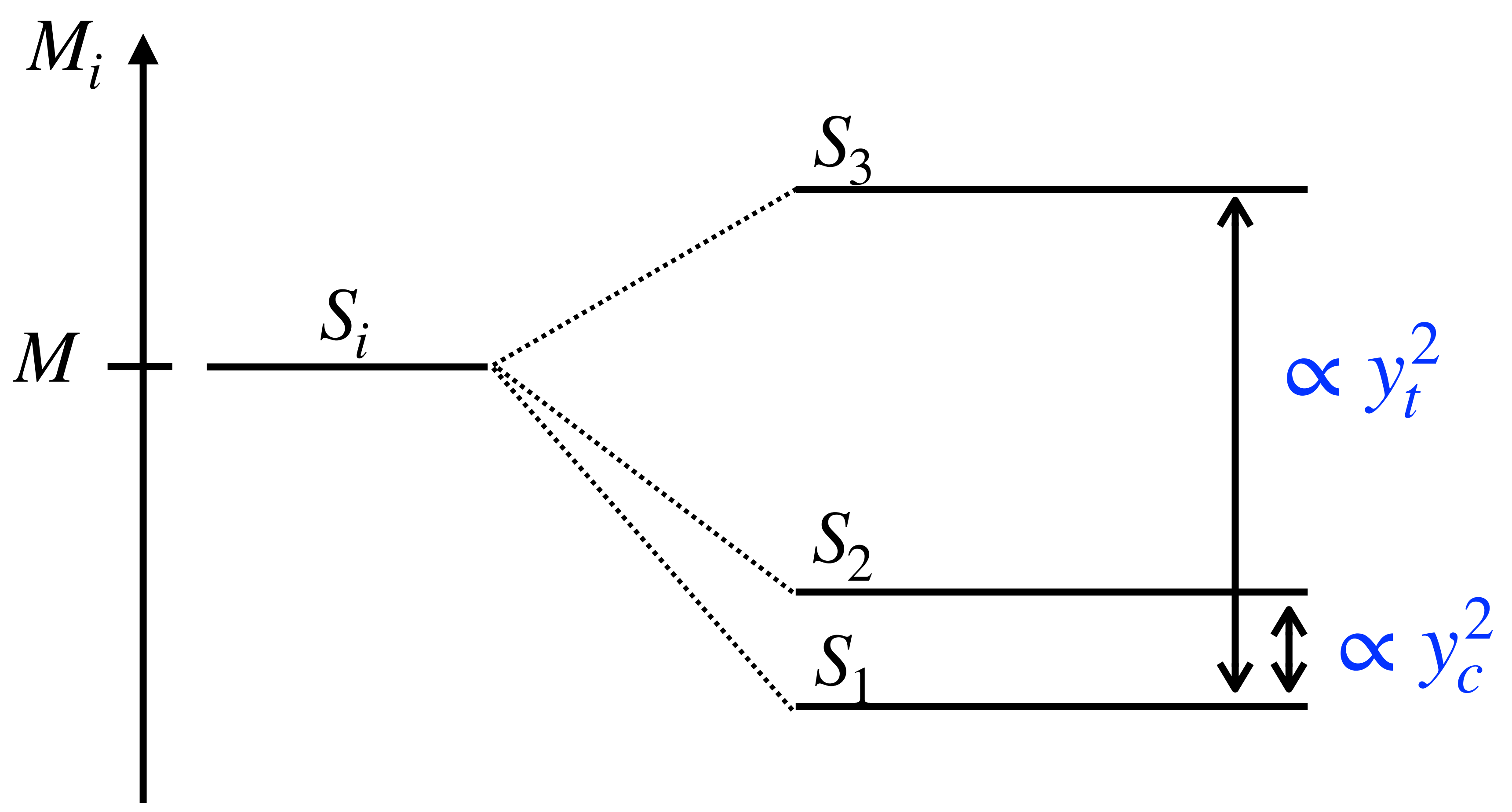

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$$+\frac{\lambda}{2}\left(b_0 + \epsilon\, b_1 (y_u^i)^2\right)(2vh + h^2) S_i^* S_i \quad \rightarrow$$ flavor diagonal, so doesn't lead heavy scalar decay

Dim-6 operators

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

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

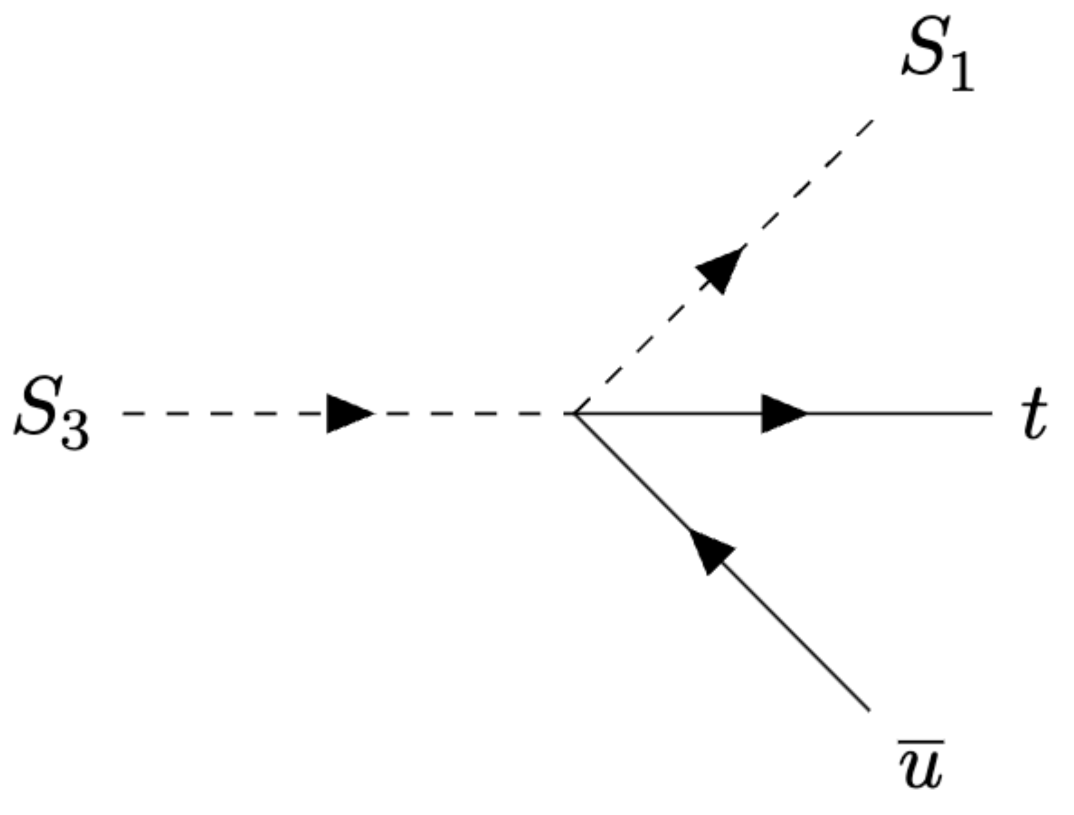
$$\rightarrow \quad \boxed{S_3 \rightarrow S_1 t\bar{u},\ S_2 t\bar{c}}$$

Heavy scalar decay is triggered!

Decay of heavy states

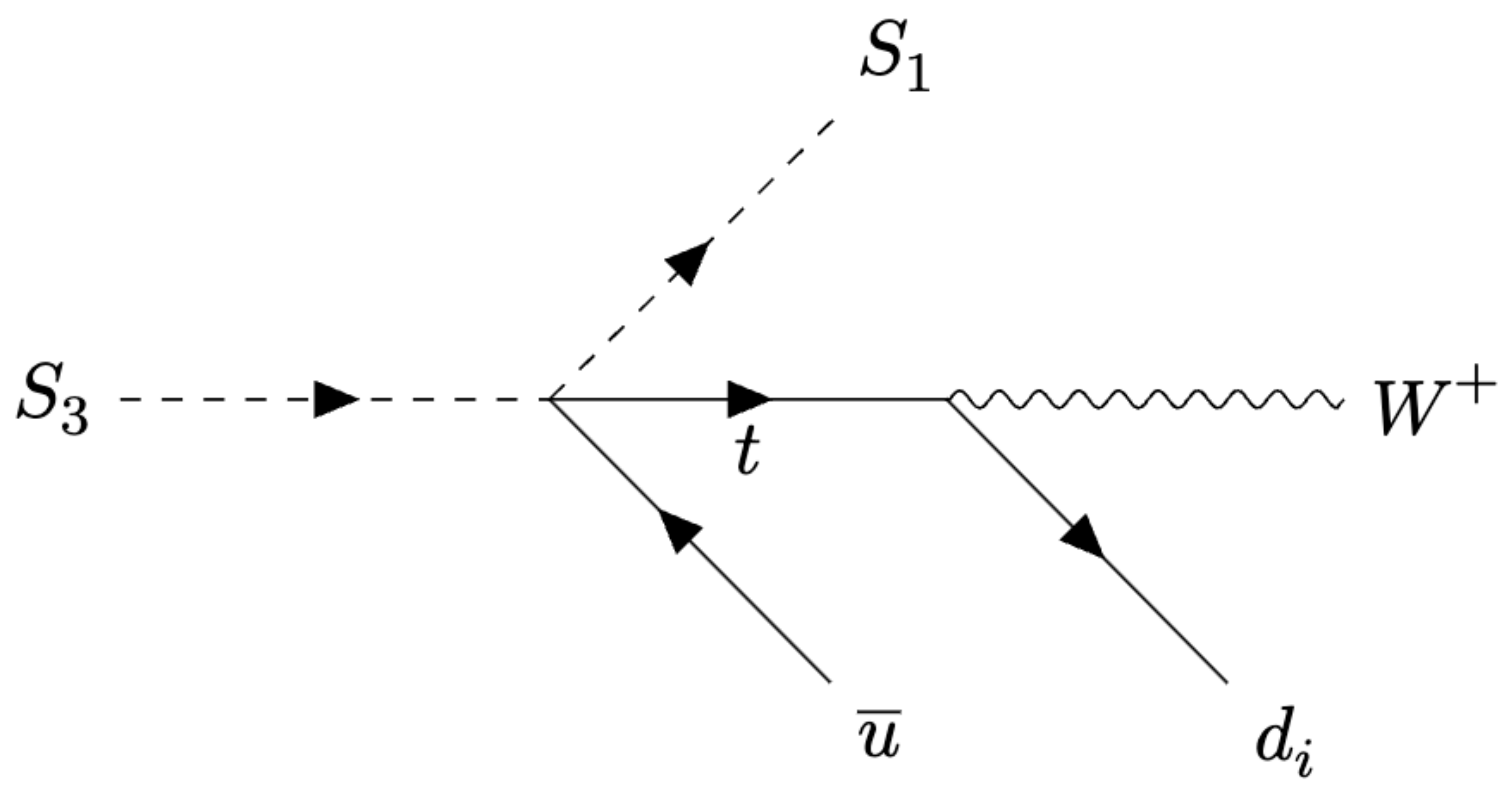
- Dominant mode depends on the mass splitting $\Delta M = M_3 - M_1$

$$\Delta M \gtrsim m_t$$



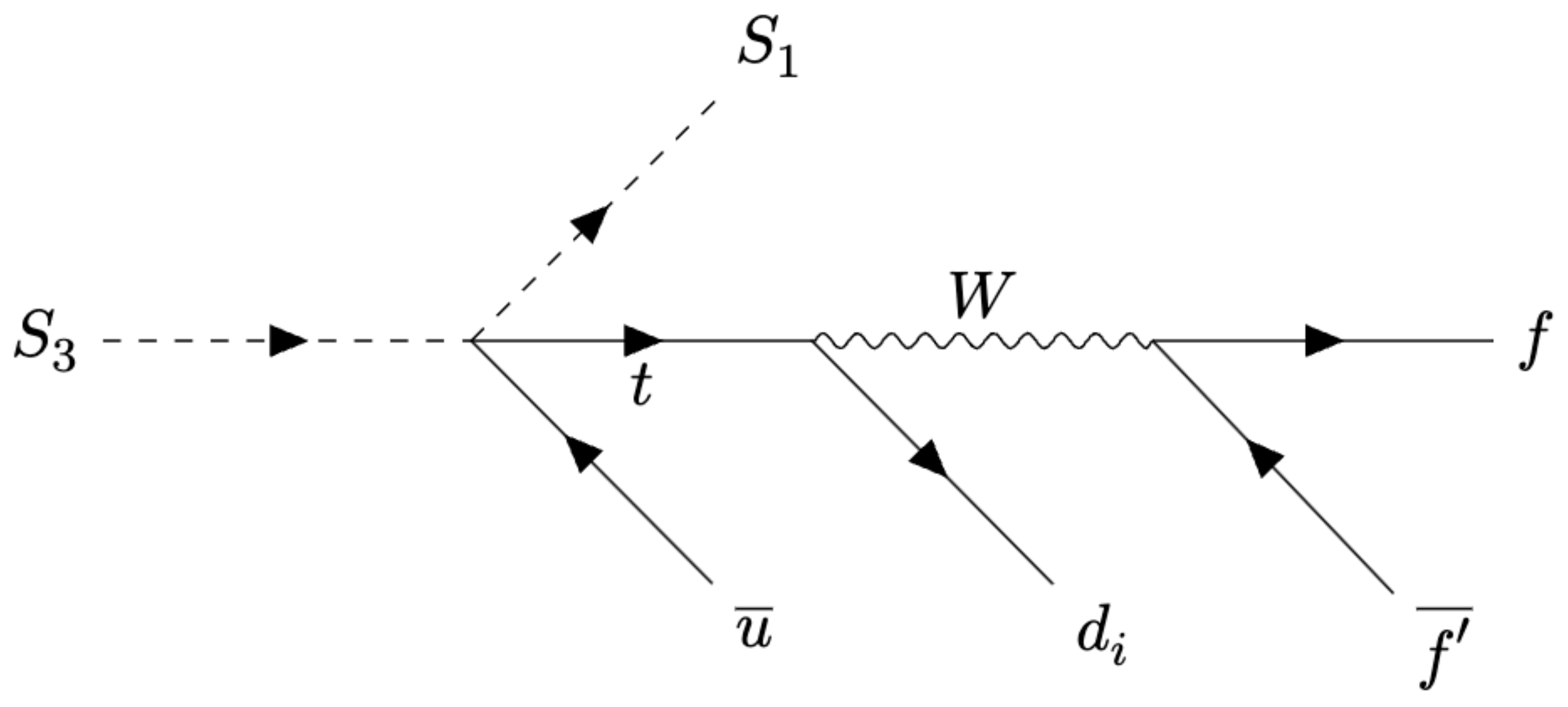
$$\Gamma \sim \frac{m_t^2 (\Delta M)^5}{480 \pi^3 \Lambda^4 M_3^2}$$

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



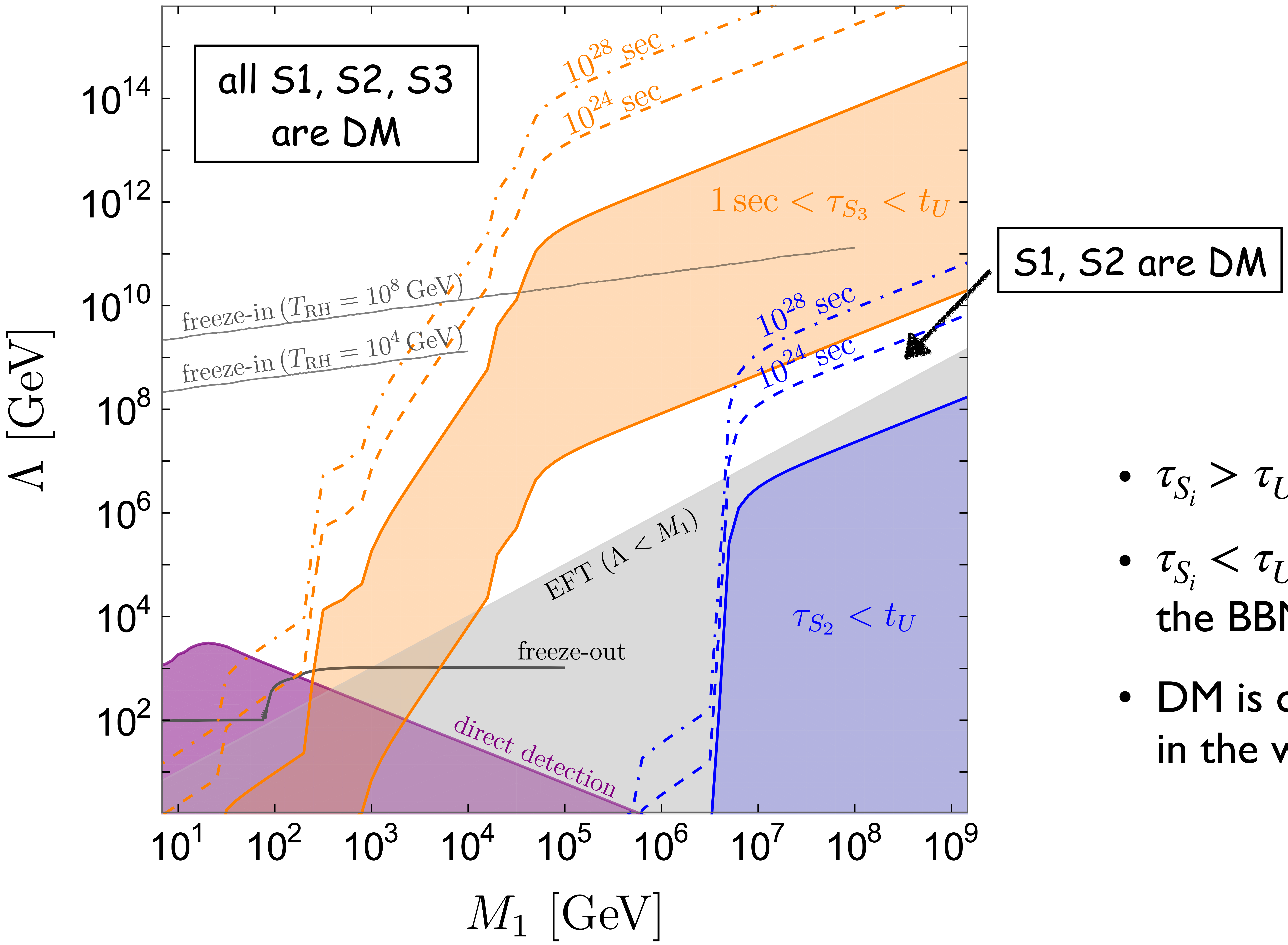
$$\Gamma \sim \frac{(\Delta M)^{11} |V_{ti}|^2}{41472 \pi^5 \Lambda^4 M_3^2 m_t^2 v^2}$$

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



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

Parameter spaces for multi-component DM



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

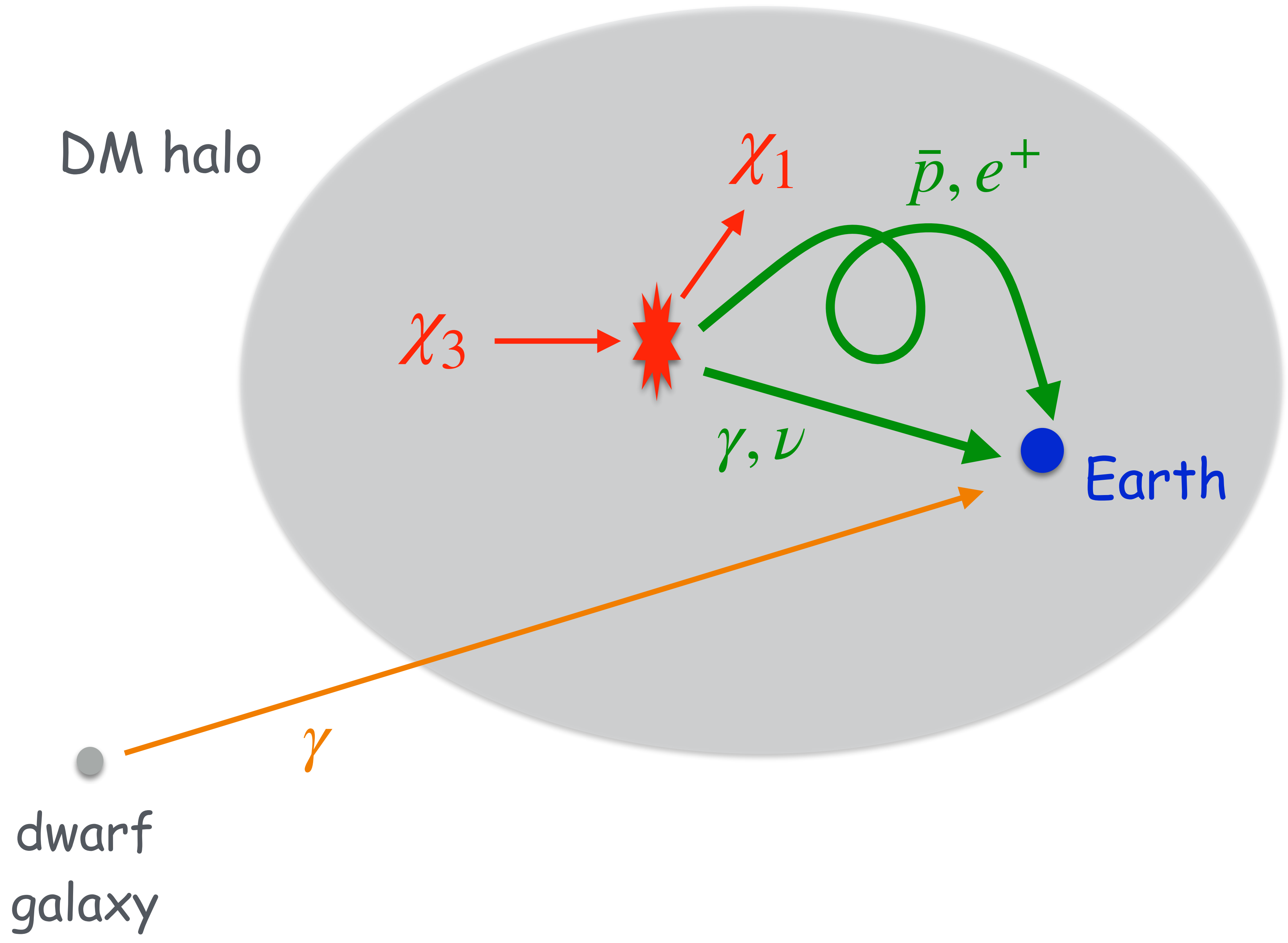
$\lambda = 0$ (no coupling to Higgs)

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

Signatures from this dark matter family?

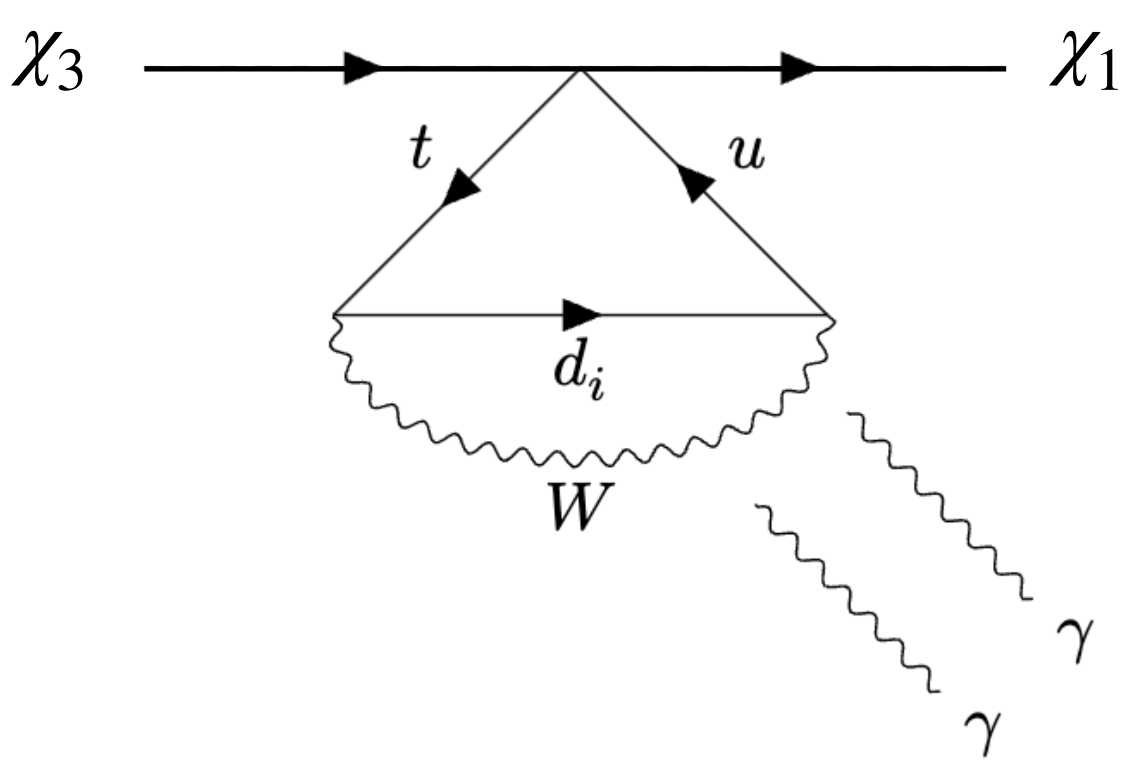
1. Indirect searches for heavy decaying dark matter

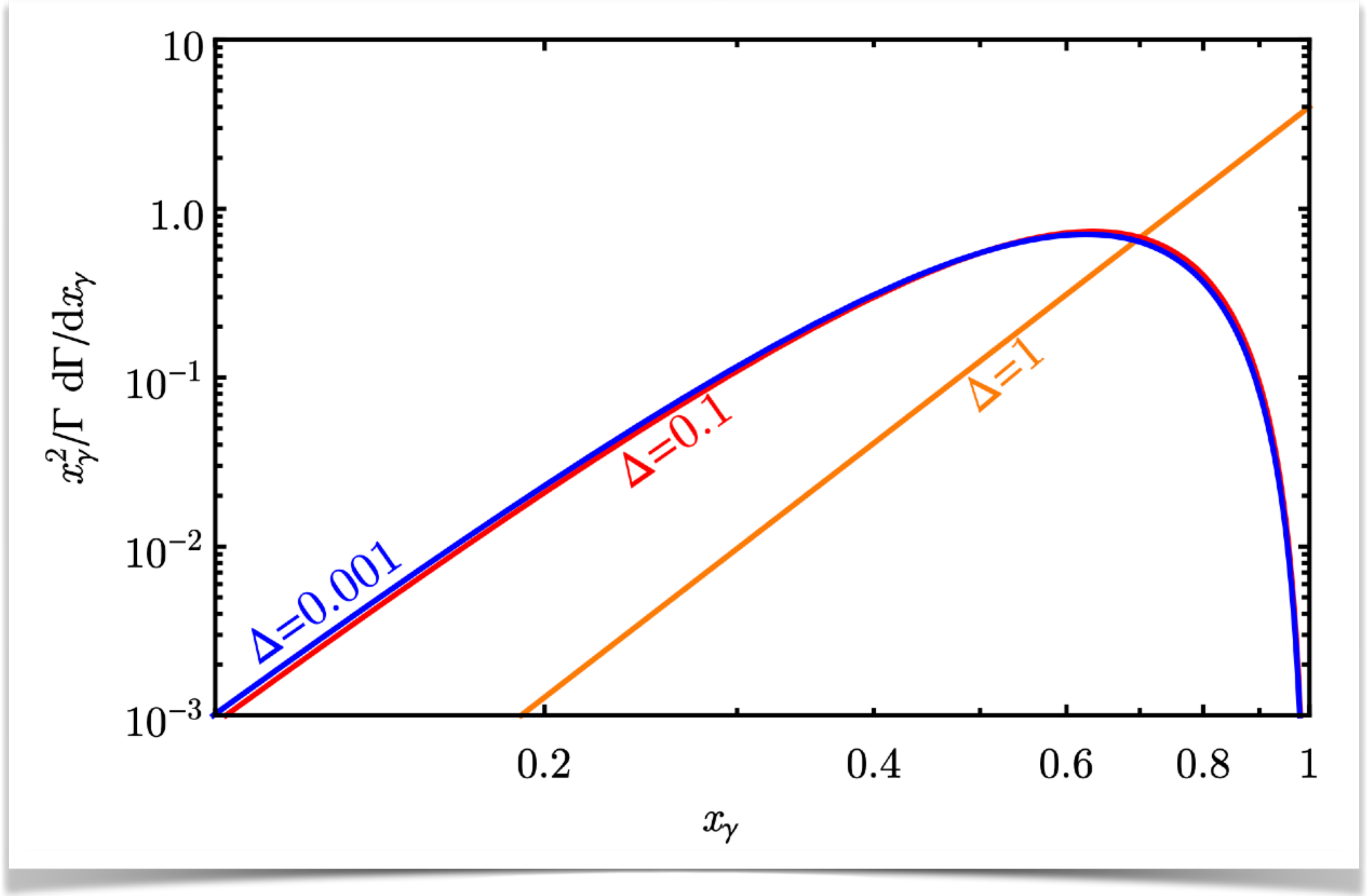
with Dondarini, Landini, Mescia



- $\chi_{2,3} \to \chi_1 \gamma\gamma$

[Dienes+ 1406.4868; Ghosh+ 1909.13292; Herms, Ibarra 1912.09458]





We can also extend to

- other hadronic decay modes $\chi_{2,3} \to \chi_1 qq, \chi_1 qqqq, \ldots$
- cosmology (CMB, BBN, Lyman-α, 21cm line, etc.)

2. Flavored DM from rare meson decays

with Mescia, Swallow, Toni

- Apparent flavor violating decays can naturally occur

e.g.) $b \to s\chi_3\bar{\chi}_2$ and $s \to d\chi_1\bar{\chi}_2$ => mimic $B \to K\nu\nu$ and $K \to \pi\nu\nu$ processes!

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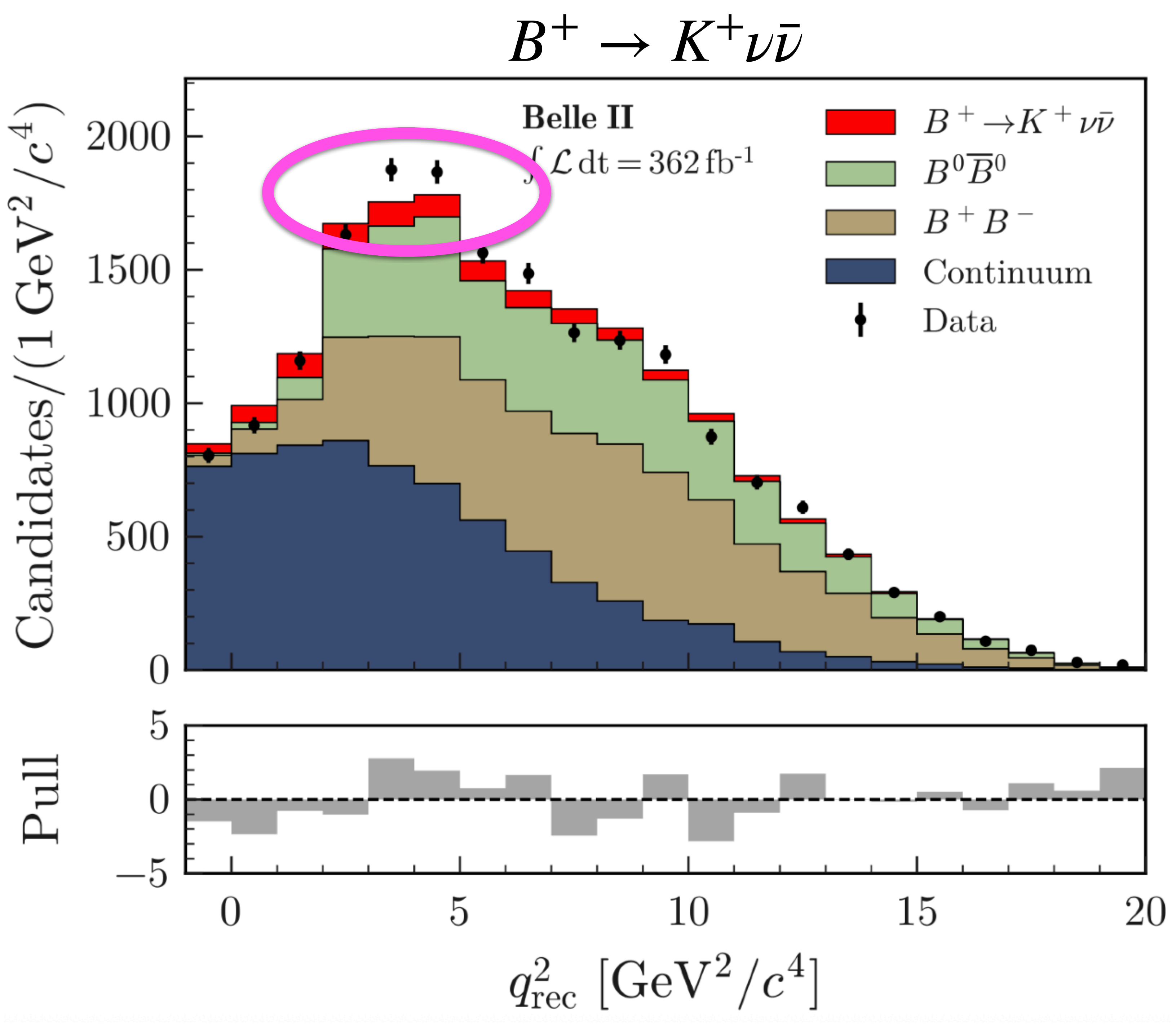
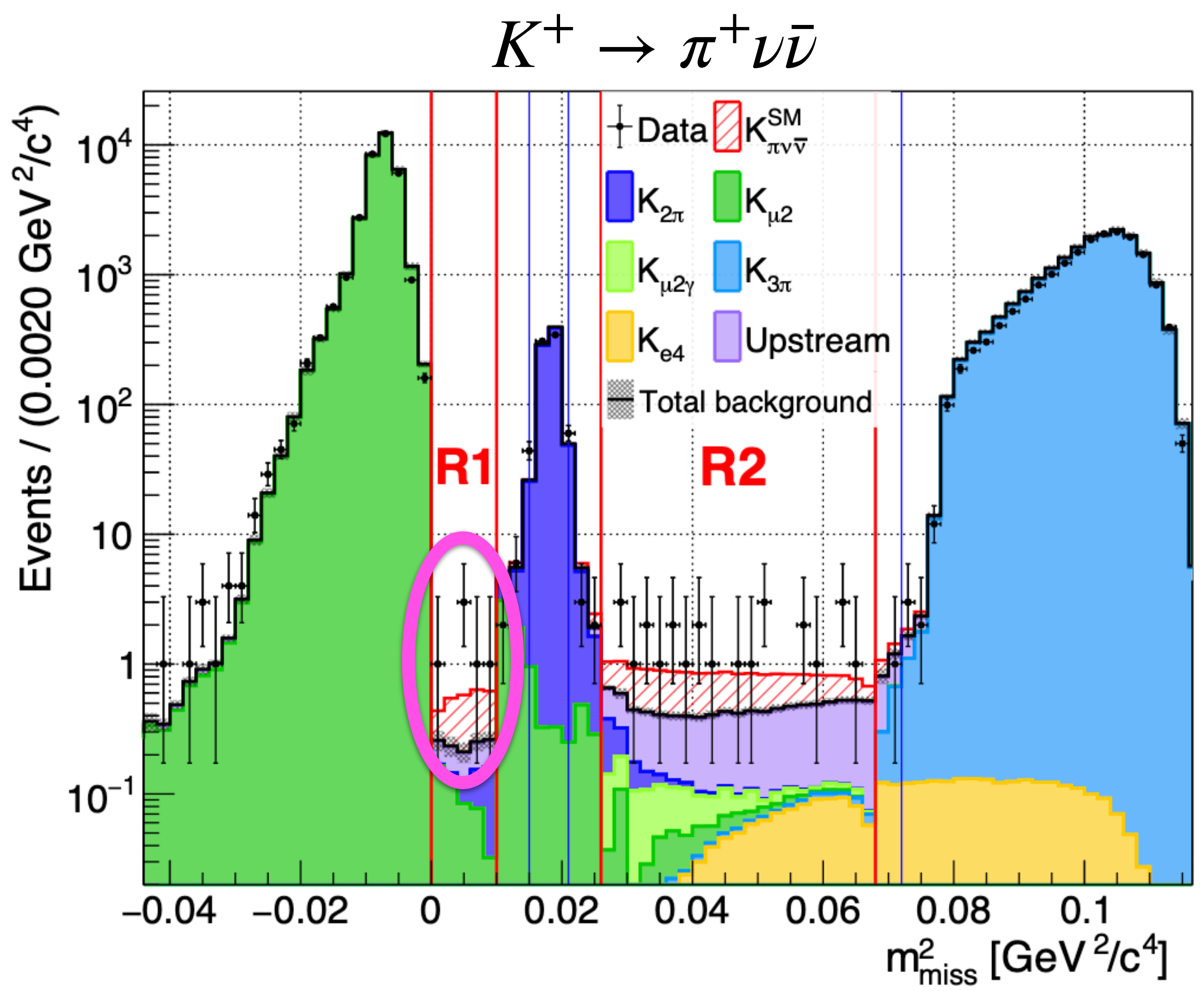
@NA62
KOTO

- Mild excesses are reported by the Belle-II and NA62





2. Flavored DM from rare meson decays

with Mescia, Swallow, Toni

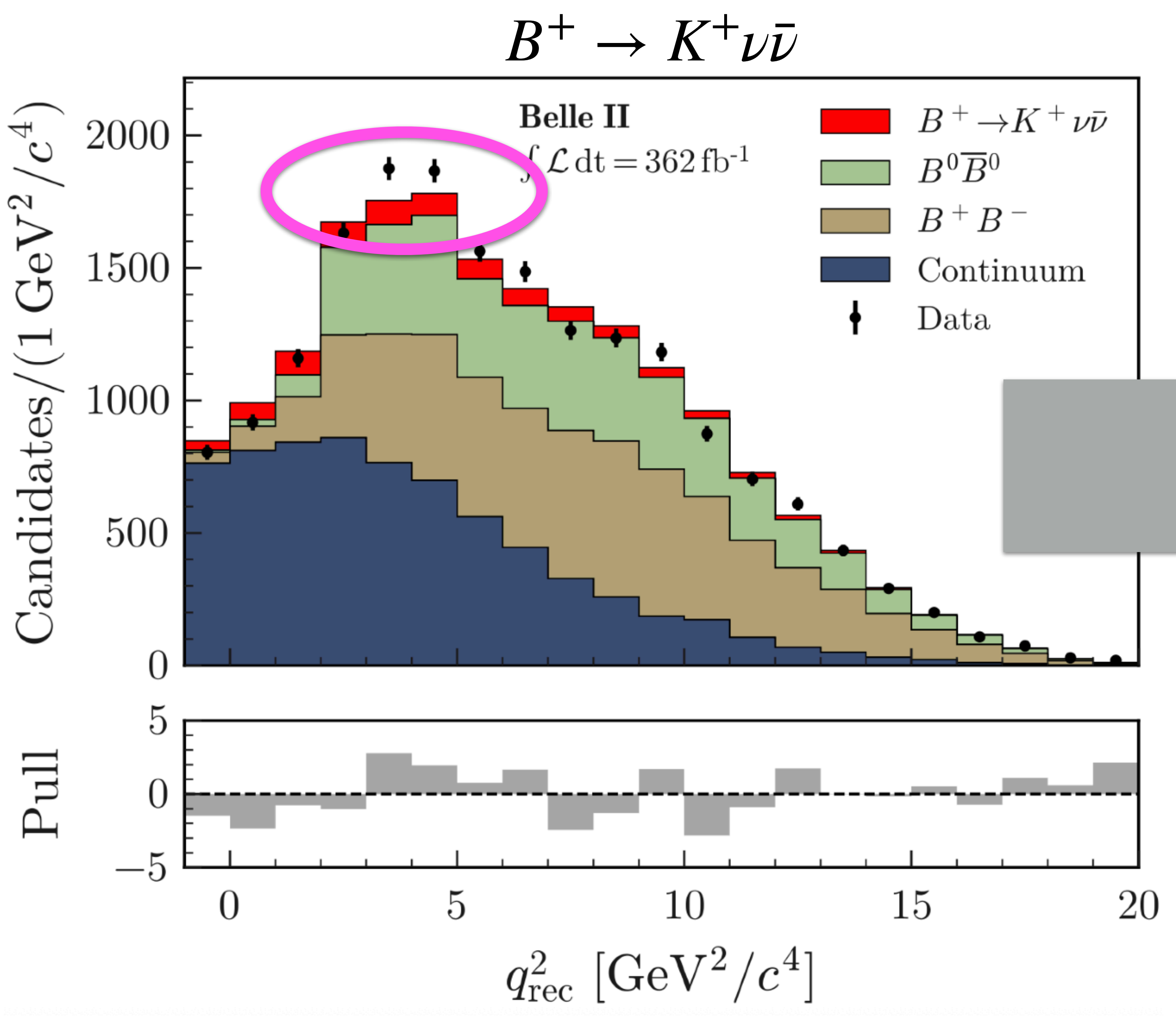
- Apparent flavor violating decays can naturally occur

e.g.) $b \to s\chi_3\bar{\chi}_2$ and $s \to d\chi_1\bar{\chi}_2$ => mimic $B \to K\nu\nu$ and $K \to \pi\nu\nu$ processes!

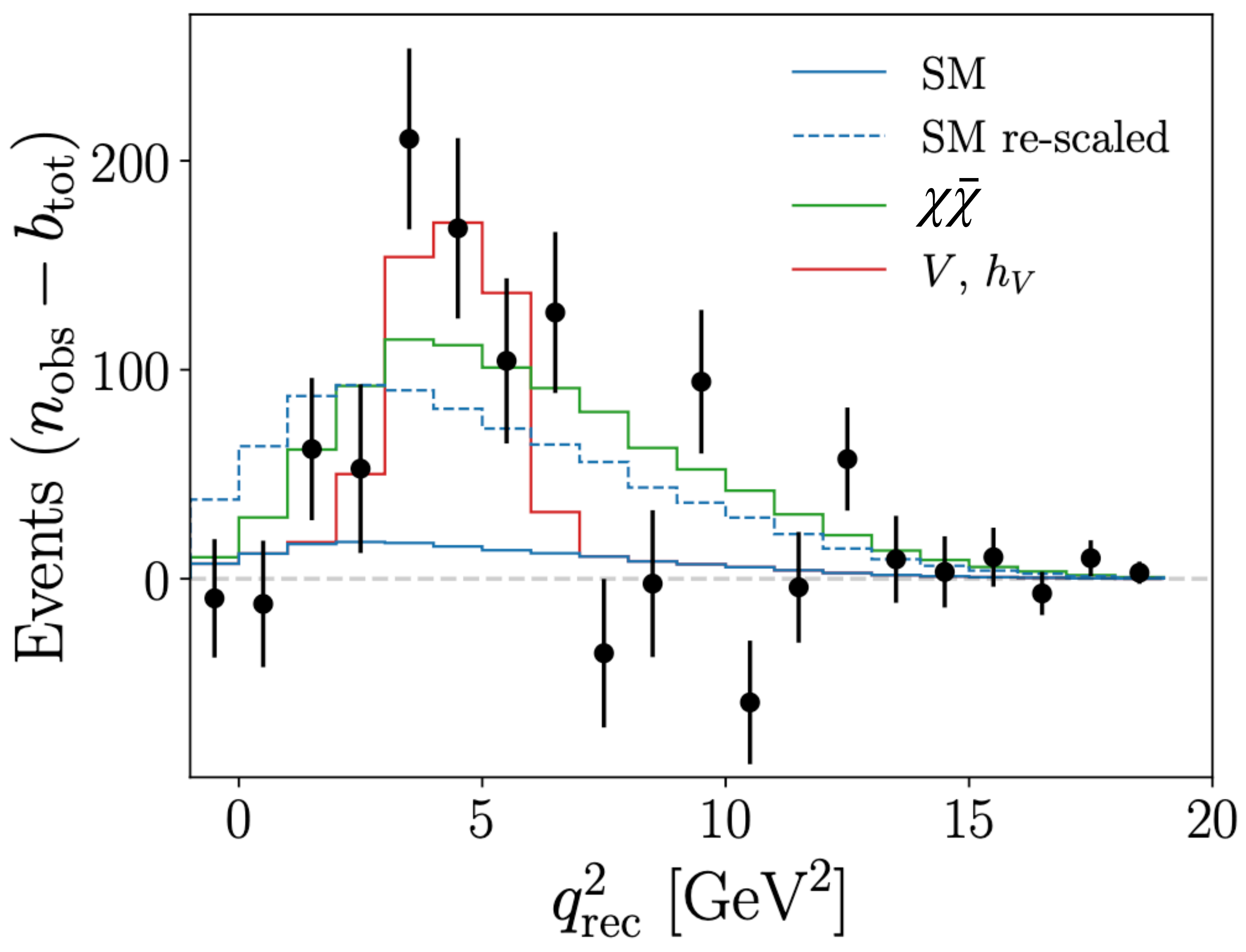
@Belle-II
BaBar

@NA62
KOTO

- Mild excesses are reported by the Belle-II and NA62



q^2 distribution is modified



Need more data, but future update might confirm some deviation in these decay modes

Summary

- The existence of DM requires BSM
- Non-trivial flavor structures in BSM may provide a new avenue for theories of dark matter
  - quark flavored DM + MFV $\rightarrow$ multicomponent dark matter
  - very rich phenomenology and cosmology
  - still many questions
    - relation to the flavor puzzles?
    - extension to lepton flavor?
    - $U(3)^5$, $U(2)^5$, or others?

Thanks for listening!

Back up

A benchmark study of a dark matter family

2408.16812 with Mescia, Wu

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

- Scalar potential within MFV $(\epsilon \ll 1)$

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

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- Scalar potential within MFV $(\epsilon \ll 1)$

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

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

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

up to O(ε)

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

flavor independent　　flavor dependent

A benchmark study of a dark matter family

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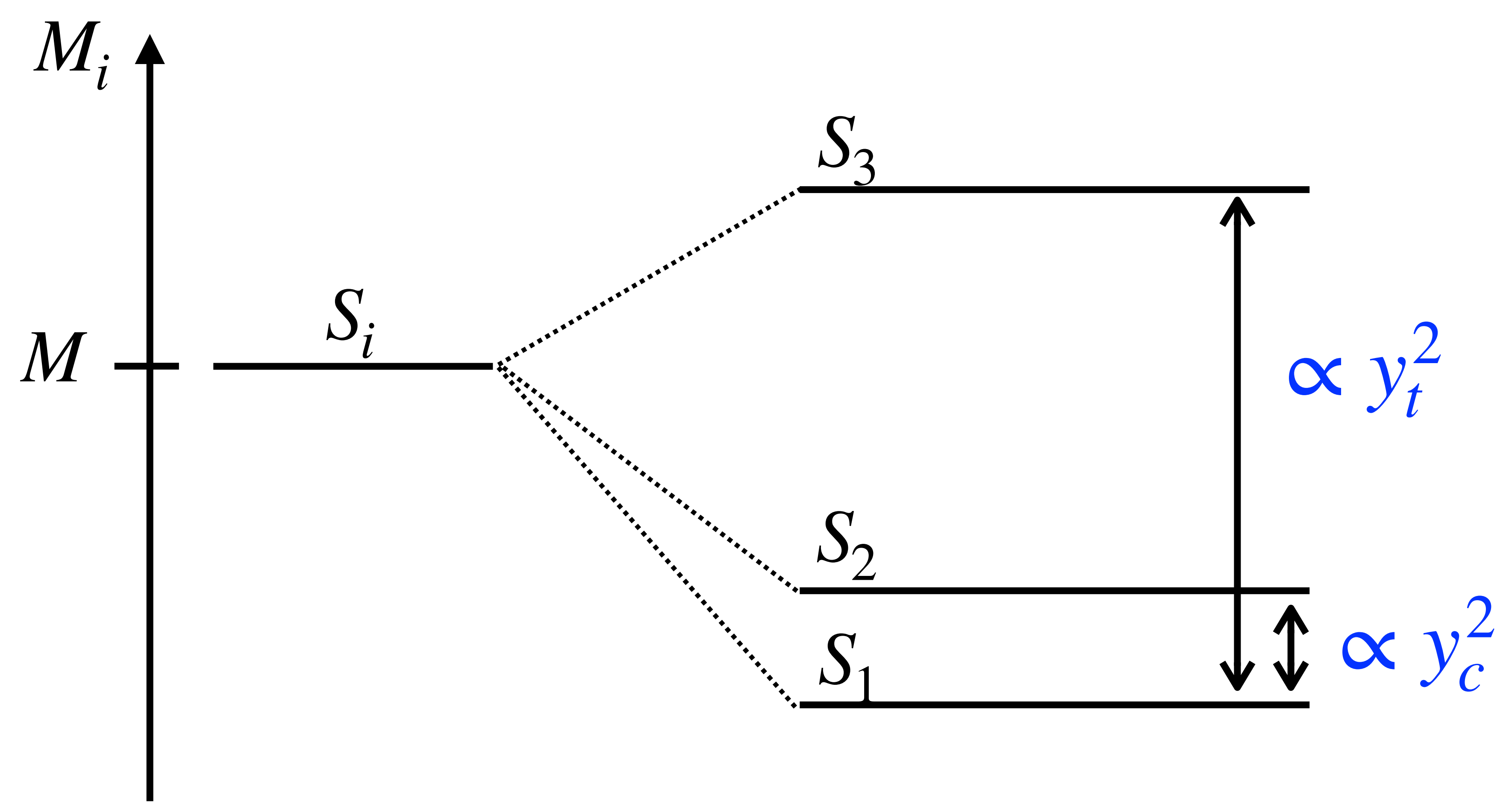
\end{aligned}
$$



$$
V(H,S) = \left\{m_0^2 + \epsilon\, m_1^2 (y_u^i)^2\right\} S_i^* S_i \longrightarrow \boxed{M_j^2 - M_i^2 = \epsilon\, m_1^2 \left[(y_u^j)^2 - (y_u^i)^2\right]}
$$

up to O(ε)

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

→ flavor diagonal, so doesn't lead heavy scalar decay

A benchmark study of a dark matter family

2408.16812 with Mescia, Wu

- We can also consider higher dimensional operators

  - Dim-6 operators

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

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

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

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

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

A benchmark study of a dark matter family

2408.16812 with Mescia, Wu

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

- Coefficients are determined by the Yukawa matrices

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

A benchmark study of a dark matter family

2408.16812 with Mescia, Wu

- We can also consider higher dimensional operators

Dim-6 operators

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

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- Coefficients are determined by the Yukawa matrices

$$c^4_{ijkl} = c^4_1 (Y_u)_{ij}\delta_{kl} + c^4_2 (Y_u)_{il}\delta_{kj}$$

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

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

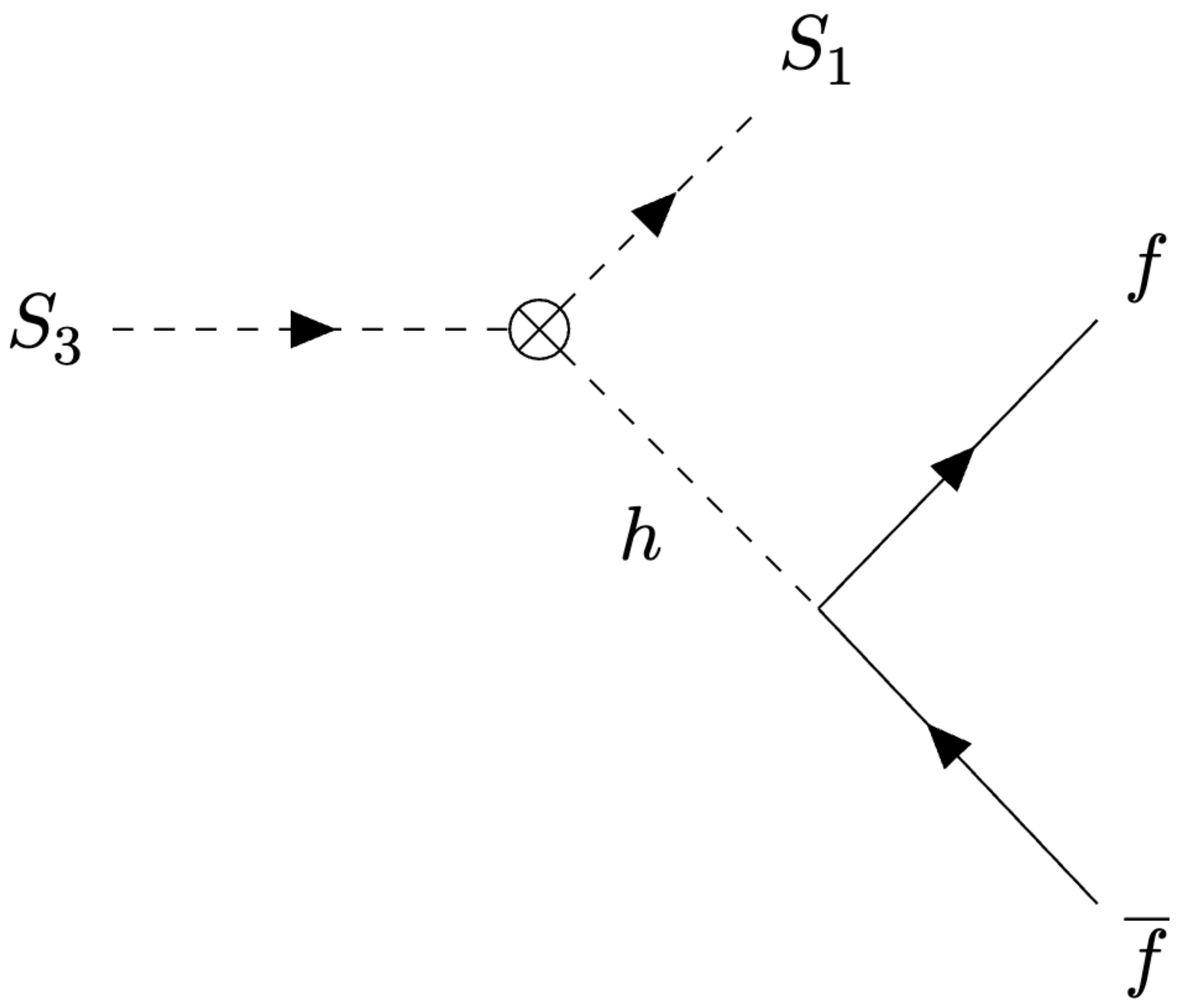
$$\boxed{S_3 \to S_1 t\bar{u},\; S_2 t\bar{c}}$$

Heavy scalar decay is triggered!

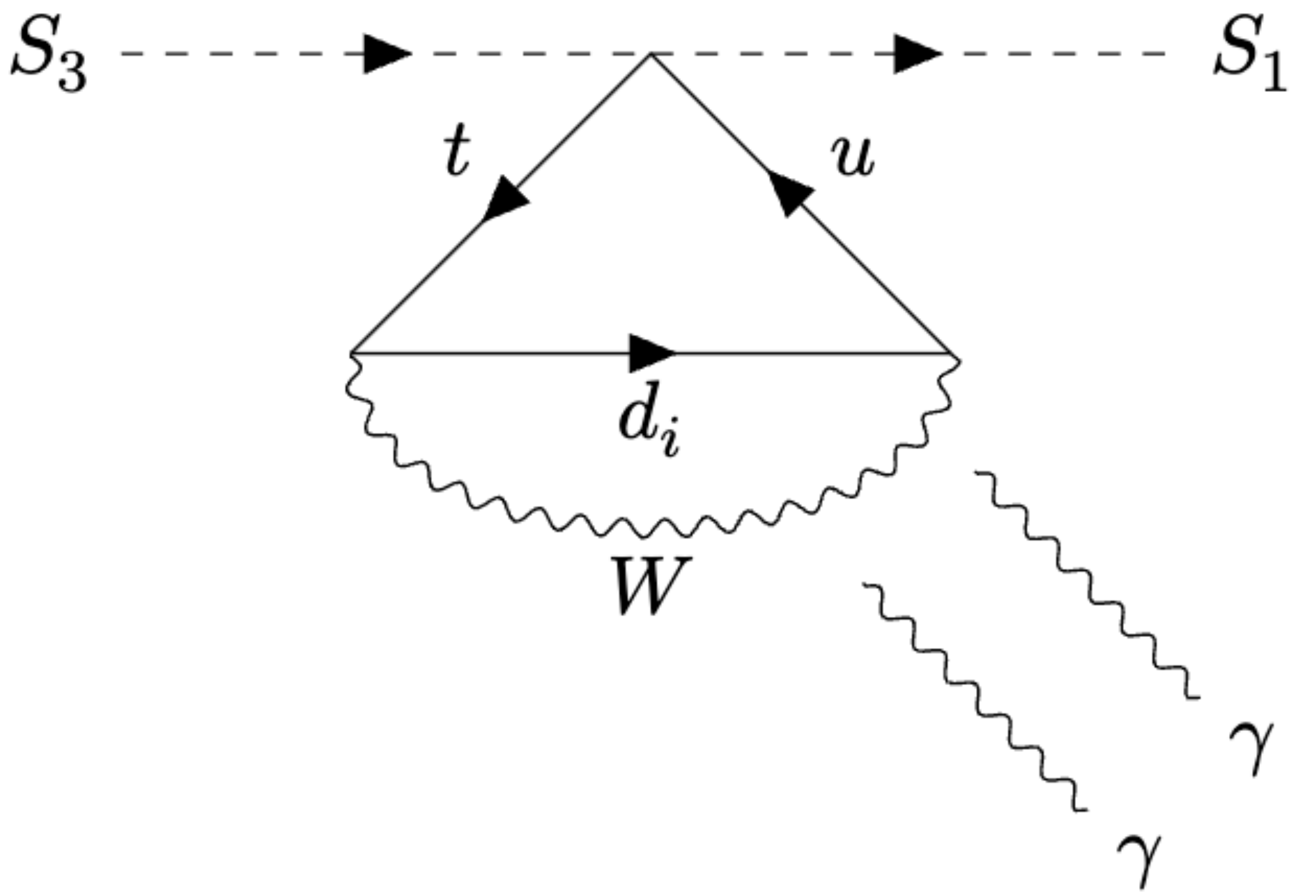
Decay at higher orders

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

- appears at ε² order or two-loop level
- can surpass four or five-body ε⁰-order processes

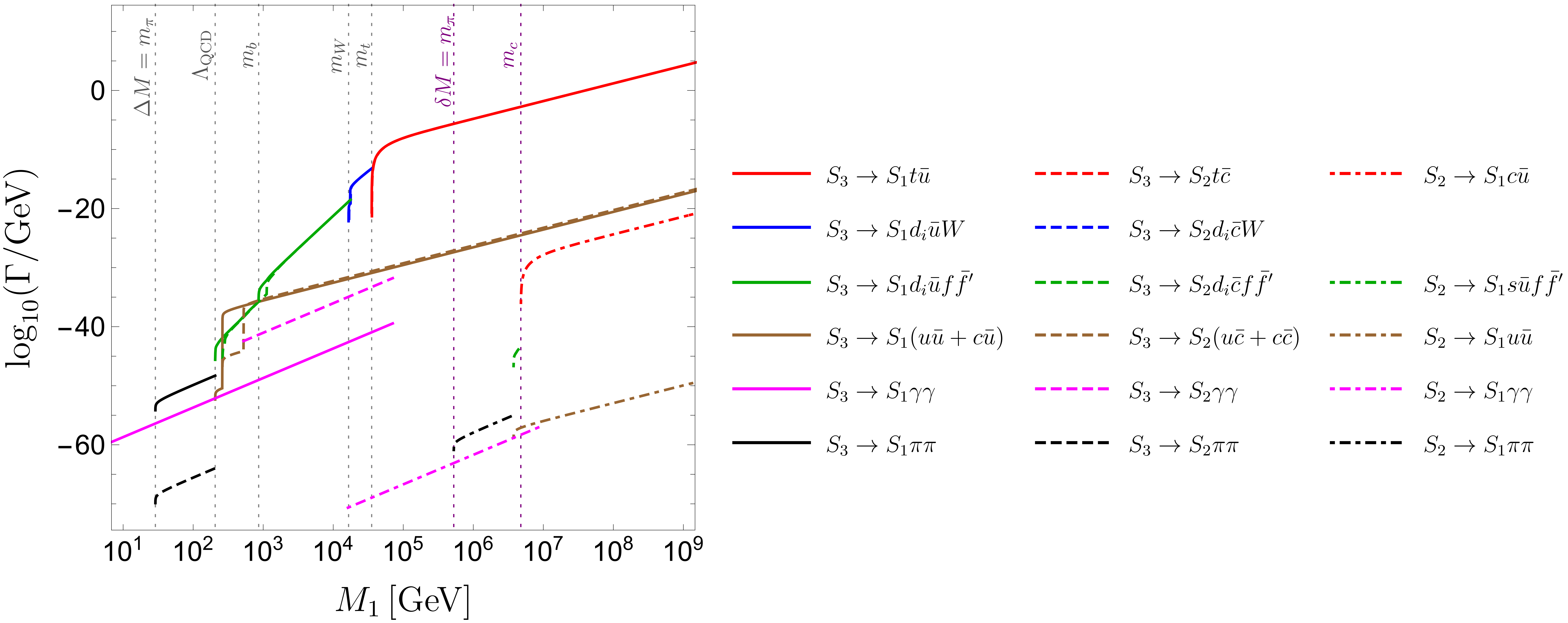


$$\sim \epsilon^2 \, Y_u^\dagger Y_d Y_d^\dagger Y_u$$



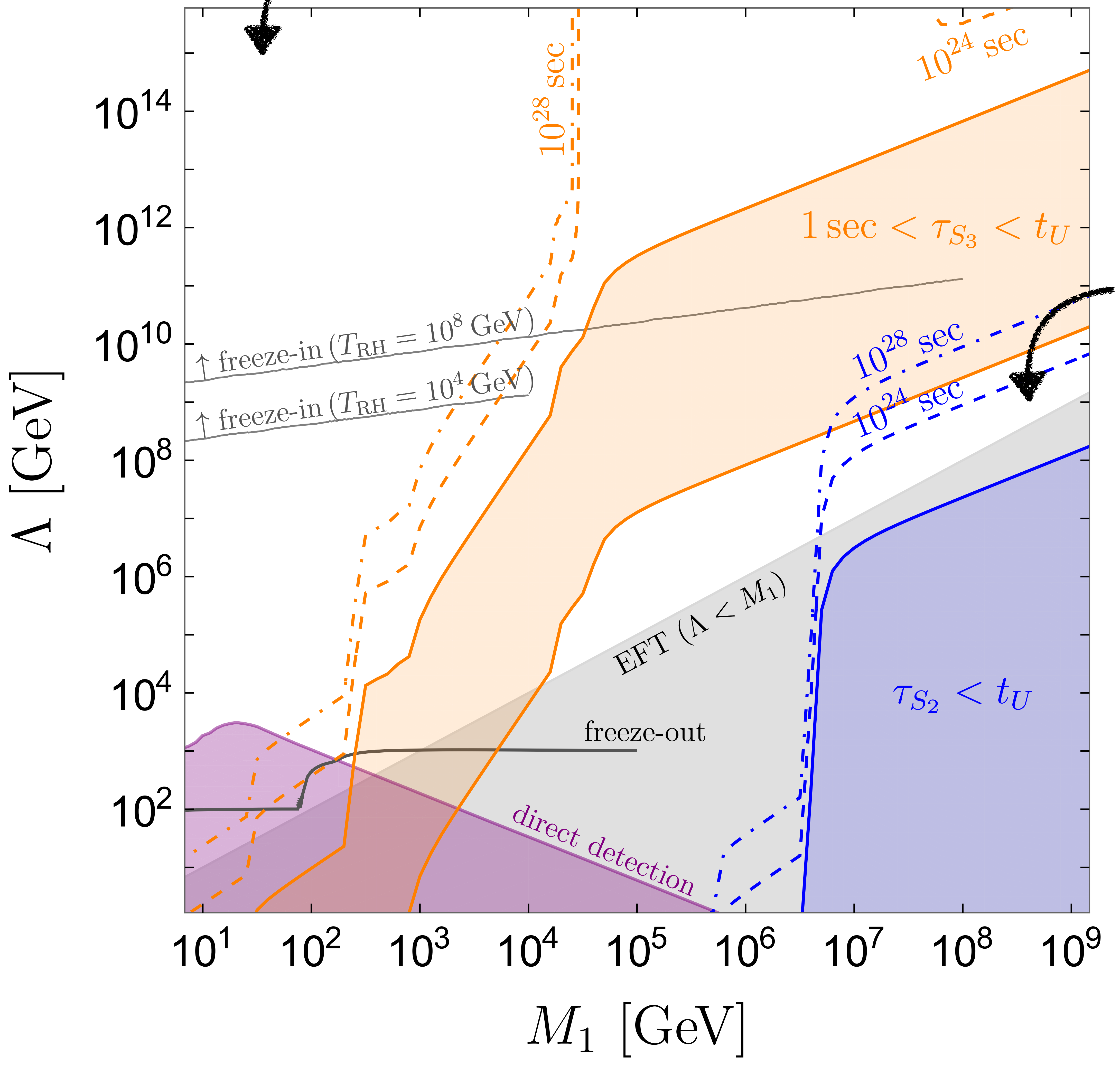
$$\sim \frac{Y_u^\dagger Y_d Y_d^\dagger Y_u}{(16\pi^2)^2}$$

Partial decay widths for heavy scalars



Impact of Higgs portal coupling (1/2)

all S1, S2, S3 are DM



S1, S2 are DM

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

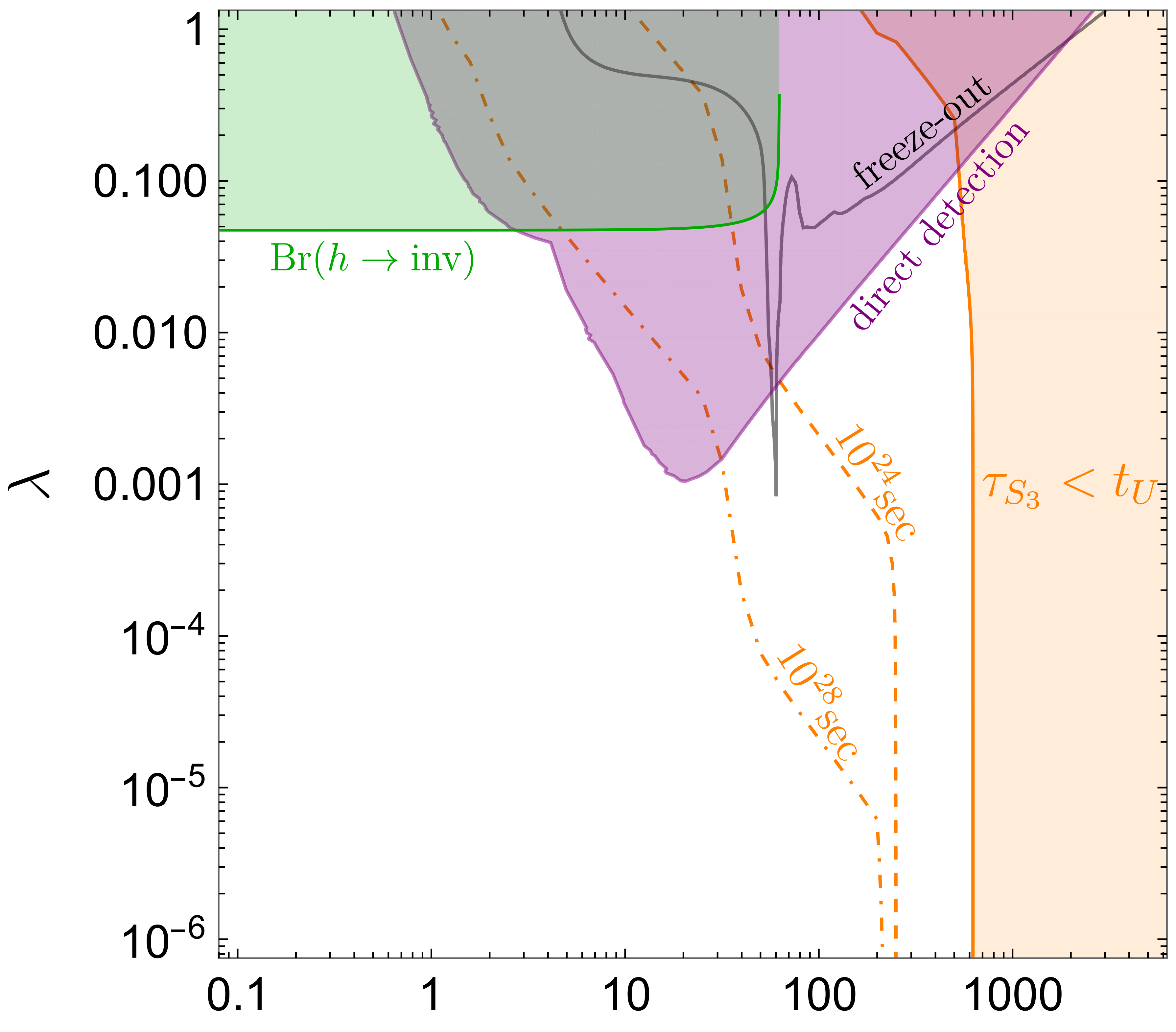
$$\lambda = 10^{-11}$$

- 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

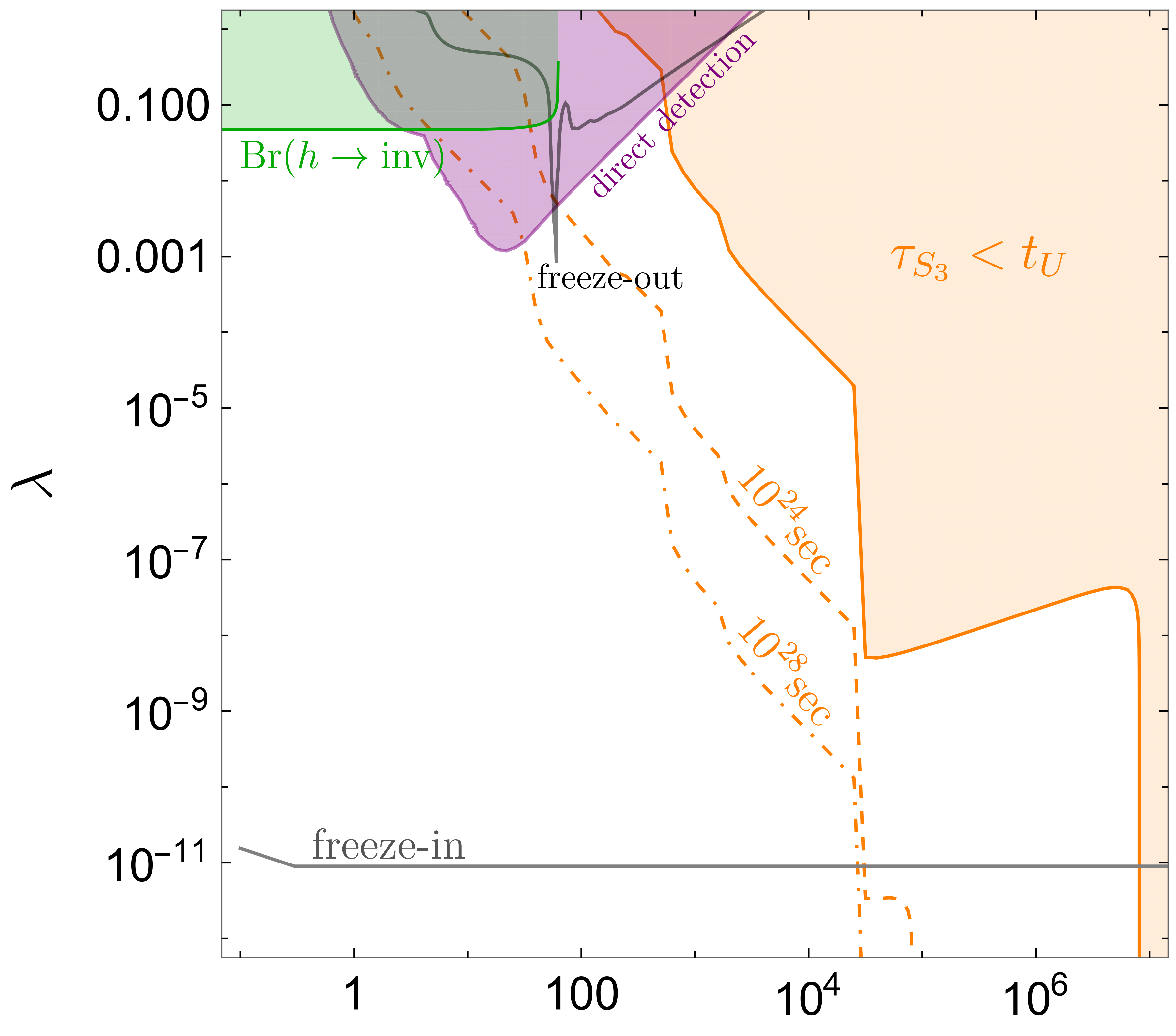
Impact of Higgs portal coupling (2/2)

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

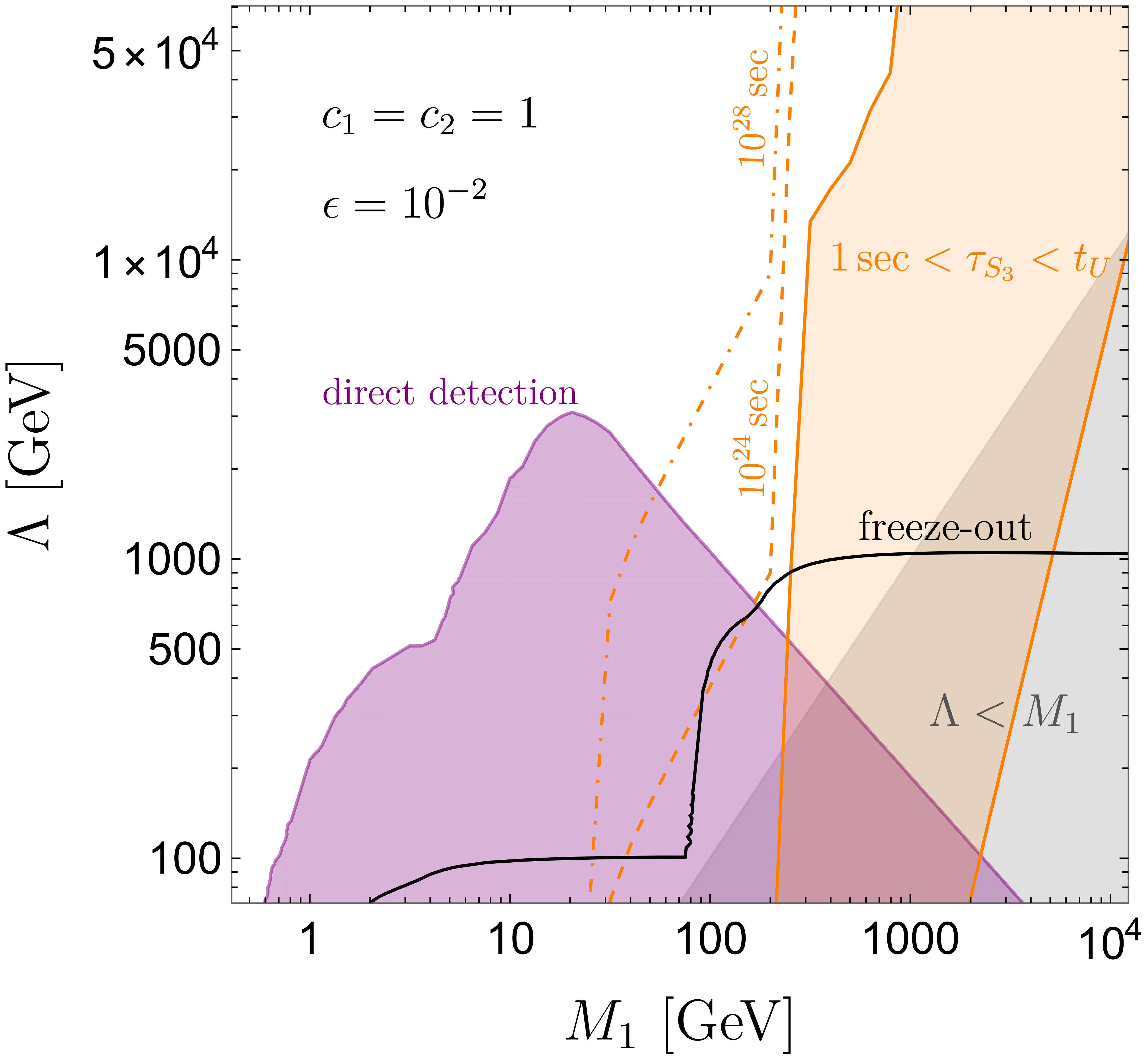
$\Lambda = 10^4\,\mathrm{GeV}$



$\Lambda = 10^{13}\,\mathrm{GeV}$



Closer look at the 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, $\Lambda < M_1$