

Minimal Flavor Violation and Dark Matter

Shohei Okawa
(APCTP, Pohang)

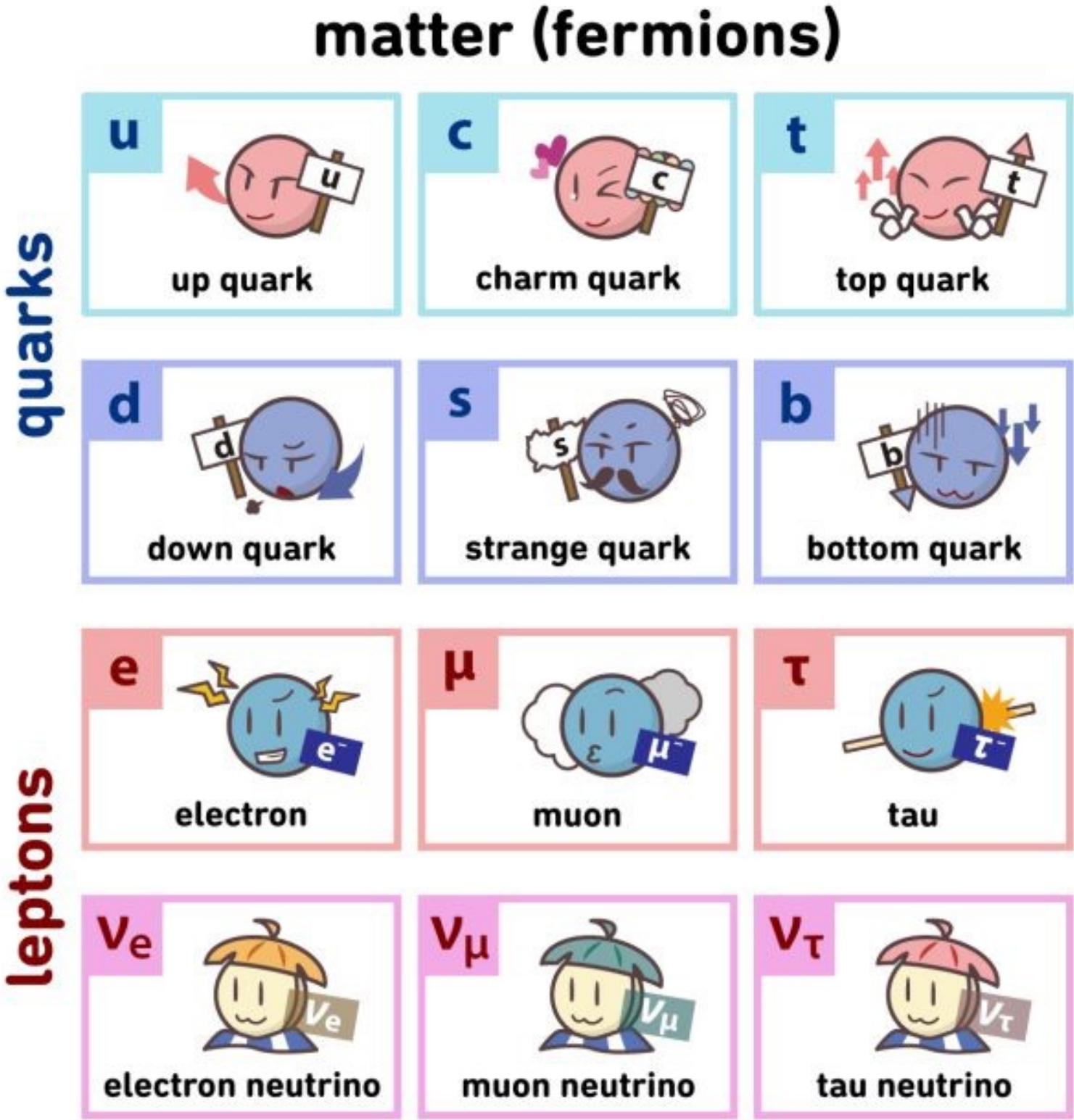
Based on 2408.16812, 2601.08907 + ongoing work
with Sang Hwan Kim (Yonsei U), Giacomo Landini (INFN LNF), Federico Mescia (INFN LNF),
Joel Swallow (CERN), Claudio Toni (LAPTH), Keyun Wu (ICCUB)

	matter (fermions)			gauge bosons	
quarks	u  up quark	c  charm quark	t  top quark	γ  photon	electro-magnetic
	d  down quark	s  strange quark	b  bottom quark	g  gluon	strong
	e  electron	μ  muon	τ  tau	$Z, W^\pm$  weak bosons	weak
leptons	ν_e  electron neutrino	ν_μ  muon neutrino	ν_τ  tau neutrino	H  higgs boson	Higgs bosons

$$(i = 1, 2, 3)$$

$$q_L^i, u_R^i, d_R^i$$

$$\ell_L^i, e_R^i$$



↖ ↗
replica replica



Flavor = species of fermions

Flavor structure in the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge+Higgs}} + \sum_f \bar{f} i \gamma^\mu D_\mu f \\ - \left(\bar{q} Y_u H u + \bar{q} Y_d H d + \bar{\ell} Y_e H e \right)$$

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$U(3)^5$ flavor symmetry

$$\psi_i \rightarrow (U_\psi)_{ij} \psi_j \quad (\psi = q, u, d, \ell, e)$$

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$$- \left(\bar{q} Y_u H u + \bar{q} Y_d H d + \bar{\ell} Y_e H e \right)$$

$Y_u, Y_d, Y_e : 3 \times 3$ matrices in the flavor space

$U(3)^5$ flavor symmetry

$$\psi_i \rightarrow (U_\psi)_{ij} \psi_j \quad (\psi = q, u, d, \ell, e)$$

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

Flavor structure in the SM and **Beyond**

$$\mathcal{L}_{\text{SM} + \text{Beyond}} = \mathcal{L}_{\text{gauge+Higgs}} + \sum_f \bar{f} i \gamma^\mu D_\mu f$$

$U(3)^5$ flavor symmetry

$$\psi_i \rightarrow (U_\psi)_{ij} \psi_j \quad (\psi = q, u, d, \ell, e)$$

$$- (\bar{q} Y_u H u + \bar{q} Y_d H d + \bar{\ell} Y_e H e)$$

$$+ \underbrace{\mathcal{L}_{\text{BSM}}}_{\text{neutrino mass}}$$

dark matter

baryon asymmetry

inflation

...

?

**How is the flavor symmetry broken
(preserved) in BSM?**

Often introduce **non-trivial flavor structures** in BSM

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1. To address the mystery of the flavor hierarchy

$$(Y_u)_{ij} \bar{q}_i H u_j, \quad Y_u = V_{\text{CKM}}^\dagger \cdot \text{diag}(y_u, y_c, y_t) \sim \begin{pmatrix} 10^{-5} & 0.001 & 0.008 \\ 10^{-6} & 0.007 & 0.04 \\ 10^{-8} & 0.0003 & 1 \end{pmatrix}$$

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SM flavor puzzle
*"Why is there a large hierarchy
among the Yukawa matrix
elements?"*

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Froggatt-Nielsen mechanism

$$(Y_u)_{ij} \bar{q}_i H u_j \longrightarrow \left(\frac{\langle \phi \rangle}{M} \right)^{n_{q_i} - n_{u_j}} \bar{q}_i H u_j = \epsilon^{n_{q_i} - n_{u_j}} \bar{q}_i H u_j$$

forbidden by $U(1)_{\text{FN}}$

Yukawa matrix is replaced by a spurion

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Many options for symmetry and its breaking

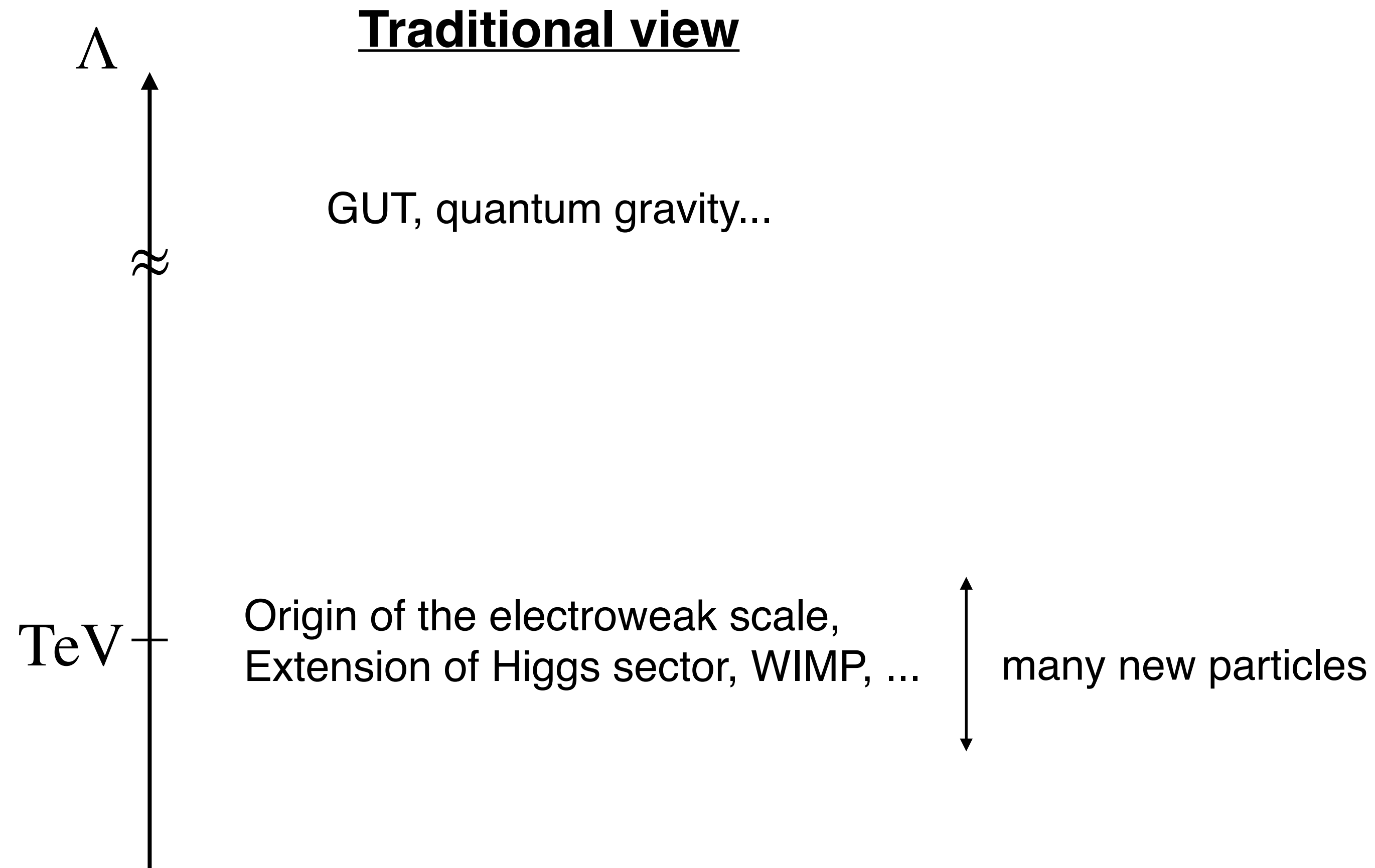
- SU(2), SU(3), discrete, modular, non-invertible...
- radiative mass generation, partial compositeness...

Often introduce **non-trivial flavor structures** in BSM

2. To keep the BSM scale not far from the EW scale

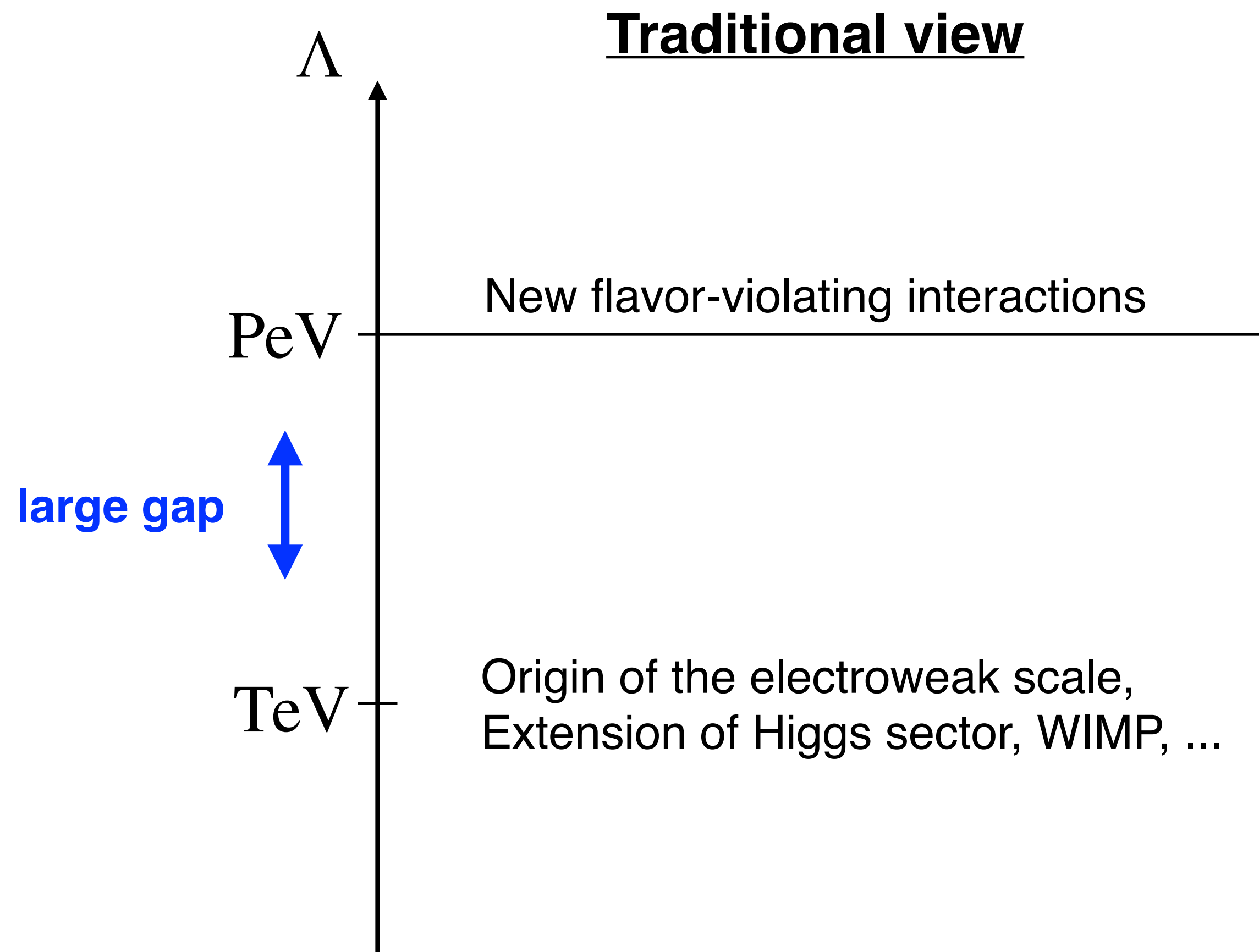
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$$\frac{1}{\Lambda^2} (\bar{q}_{Li} \gamma^\mu q_{Lj})^2 \Rightarrow \Lambda \gtrsim \text{PeV} - 100 \text{ PeV}$$

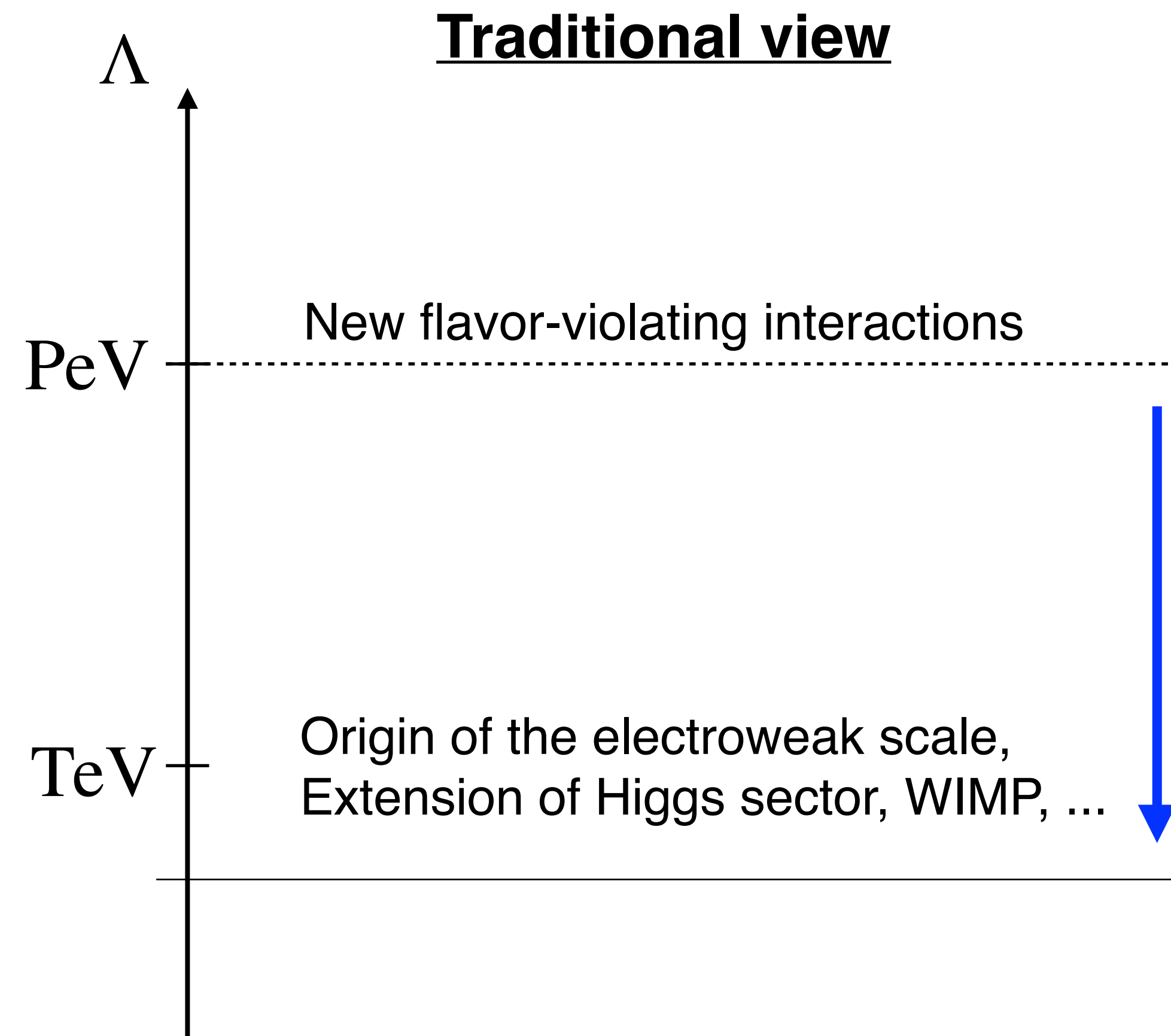
from K^0 - $\bar{K}^0$ bar mixing

$$\frac{1}{\Lambda^2} \bar{\ell}_{Li} \sigma_{\mu\nu} H e_{Rj} B^{\mu\nu} \Rightarrow \Lambda \gtrsim 100 \text{ PeV}$$

from $\mu \rightarrow e \gamma$

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from $\mu \rightarrow e \gamma$

Flavor symmetries effectively lowers the BSM scale

- Froggatt-Nielsen: $\frac{1}{\Lambda^2} \left(\frac{\langle \phi \rangle^2}{M^2} \right)^{n_{qi} - n_{qj}} \cdot (\bar{q}_{Li} \gamma^\mu q_{Lj})^2$

- Minimal Flavor Violation: $\frac{(Y_u Y_u^\dagger)_{ij}^2}{\Lambda^2} \cdot (\bar{q}_{Li} \gamma^\mu q_{Lj})^2$

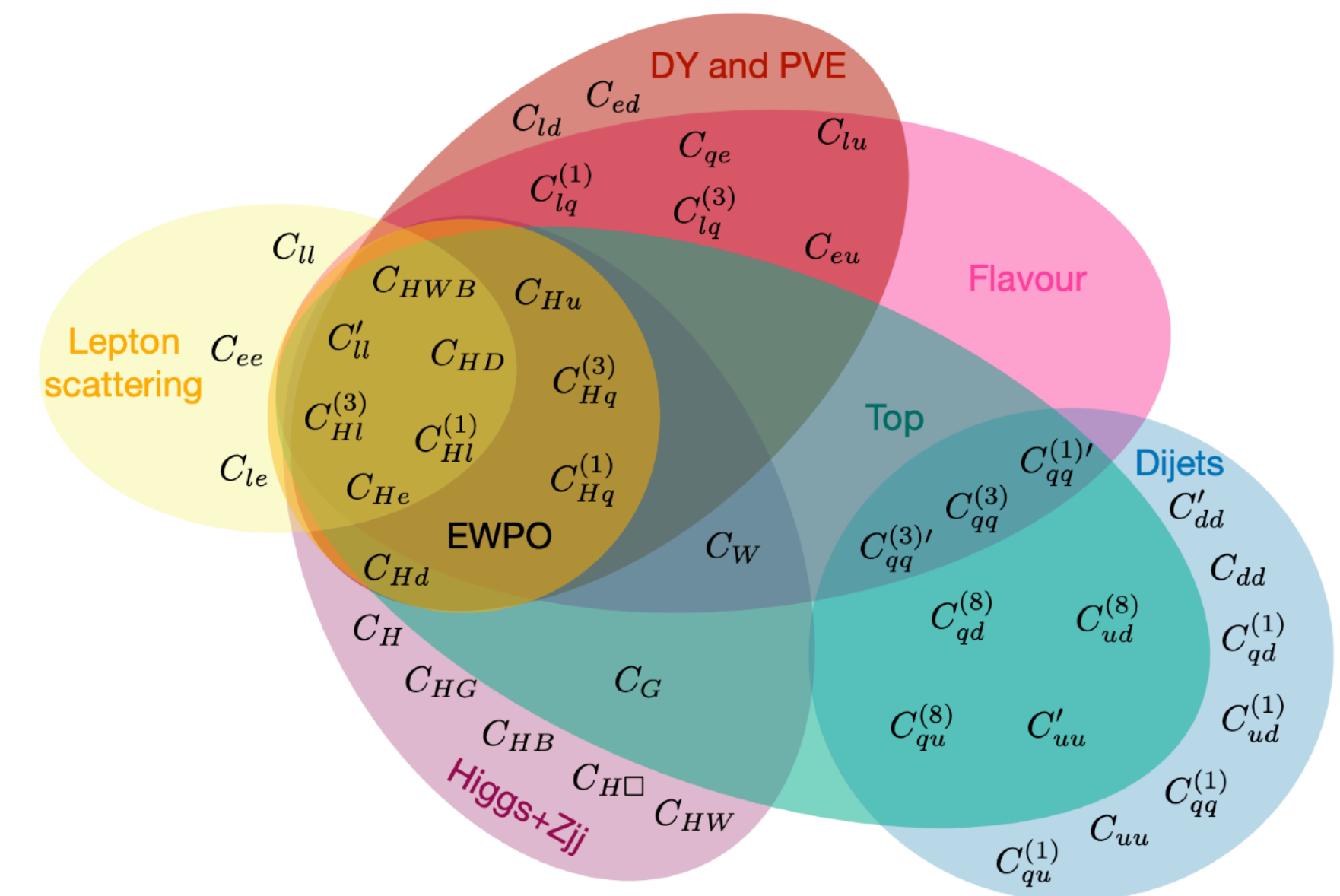
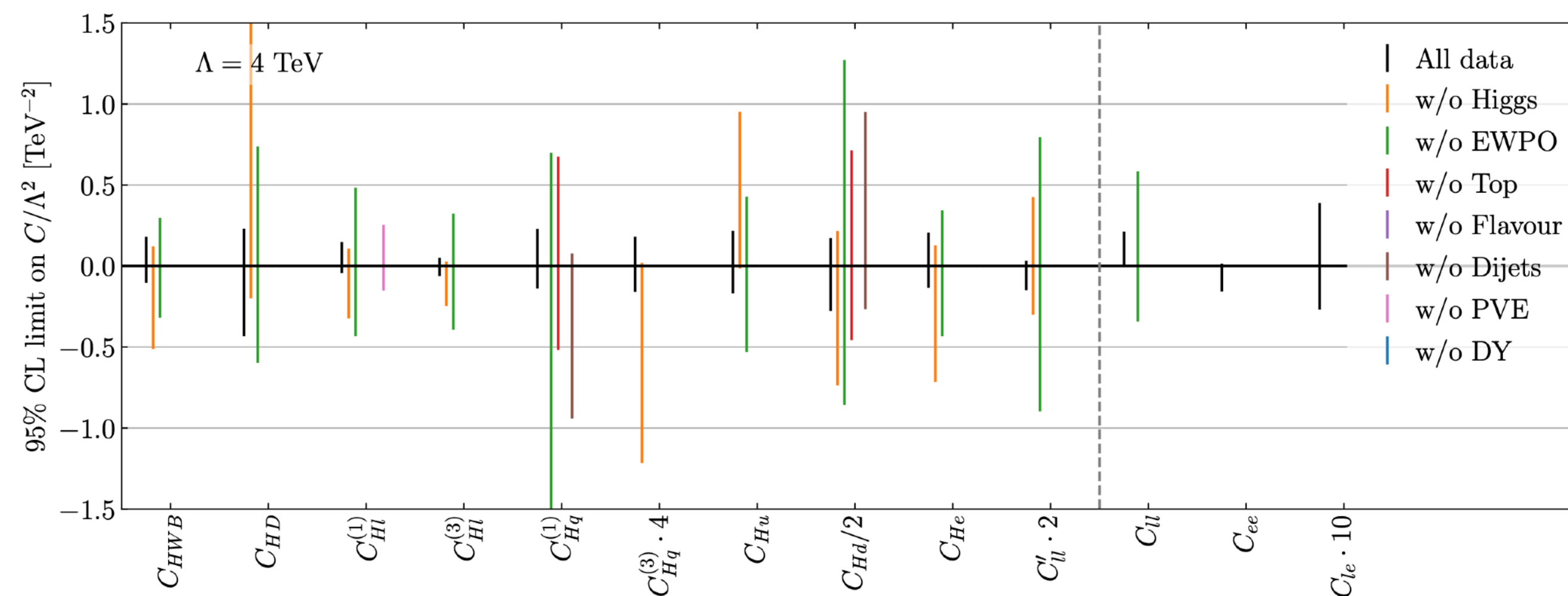
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3. To reduce free parameters in EFTs

In SMEFT,

#(dim-6 BNC) =	2499	without flavor sym.
->	147	under $U(2)^5$
->	47	under $U(3)^5$

One can perform a global analysis in a controllable way



[Bartocci, Biekötter, Hurth, 2311.04963]

How useful is flavor symmetry to understand dark matter?

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In this talk, I won't address the flavor hierarchy, nor the origin of flavor symmetry

Instead, will discuss its implication for dark matter

Minimal Flavor Violation (MFV) hypothesis

All flavor violation are caused solely by the Yukawa matrices

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

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- Promote the Yukawa matrices to **spurious fields** transforming under the $U(3)^5$ flavor group like

$$Y_u \sim (3, \bar{3}, 1, 1, 1), \quad Y_d \sim (3, 1, \bar{3}, 1, 1), \quad Y_e \sim (1, 1, 1, 3, \bar{3})$$

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- Write down all interactions **formally** in a flavor invariant way

$$\mathcal{L}_{\text{NP}} = C_{ij} \left(\bar{u}_{Ri} \gamma^\mu u_{Rj} \right) \mathcal{O}_\mu \rightarrow C_{ij} = c_0 \delta_{ij} + \epsilon c_1 (Y_u^\dagger Y_u)_{ij} + \epsilon^2 \left[c_2 (Y_u^\dagger Y_u Y_u^\dagger Y_u)_{ij} + c'_2 (Y_u^\dagger Y_d Y_d^\dagger Y_u)_{ij} \right] + \dots$$

MFV stabilizes dark matter

[Batell, Pradler, Spannowsky '11]

- Consider a new QCD singlet transforming nontrivially under $SU(3)_q \times SU(3)_u \times SU(3)_d$

$$\chi \sim (n_q, m_q) \times (n_u, m_u) \times (n_d, m_d) \quad n\text{'s, } m\text{'s are Dynkin coefficients; (1,0)=triplet, (1,1)=octet}$$

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- General decay operators

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

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$$(A + B + C - \bar{A} - \bar{B} - \bar{C}) \bmod 3 = 0 \quad \text{only } q\bar{q}, qqq, \bar{q}\bar{q}\bar{q} \text{ can be QCD singlet}$$

$\text{SU}(3)_c$ invariant

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



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

$$(n_q - m_q + A - \bar{A} + D - \bar{D} + E - \bar{E}) \bmod 3 = 0$$

$$(n_u - m_u + B - \bar{B} - D + \bar{D}) \bmod 3 = 0$$

$$(n_d - m_d + C - \bar{C} - E + \bar{E}) \bmod 3 = 0$$



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

$$n_\chi = n_q + n_u + n_d$$

$$m_\chi = m_q + m_u + m_d$$

MFV stabilizes dark matter

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



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

$$(n_q - m_q + A - \bar{A} + D - \bar{D} + E - \bar{E}) \bmod 3 = 0$$

$$(n_u - m_u + B - \bar{B} - D + \bar{D}) \bmod 3 = 0$$

$$(n_d - m_d + C - \bar{C} - E + \bar{E}) \bmod 3 = 0$$



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

$$n_\chi = n_q + n_u + n_d$$

$$m_\chi = m_q + m_u + m_d$$

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

Why flavored DM stabilized within MFV?

An accidental **Z3 symmetry** within MFV: $Z_3^\chi \subset Z_3^c \times Z_3^f$ [Batell, Lin, Wang '13]

$$\psi \rightarrow (\omega^2)_c \cdot (\omega)_q \cdot (\omega)_u \cdot (\omega)_d \psi$$

where $\omega^3 = 1$

a center group of $SU(3)_c$

$$\{q, u, d\} \rightarrow e^{4\pi i/3} \{q, u, d\}$$

a center group of $SU(3)_q \times SU(3)_u \times SU(3)_d$

$$\{q, u, d\} \rightarrow e^{2\pi i/3} \{q, u, d\}$$

- All SM fields and Yukawa spurions are Z_3^χ singlet
- For flavored DM, $\chi \rightarrow (\omega)^{n_\chi - m_\chi} \chi$, it is Z_3^χ non-singlet if $(n_\chi - m_\chi) \bmod 3 \neq 0$

Flavored dark matter candidates

[Batell, Pradler, Spannowsky '11]

(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
$(1, 1)$	$(\mathbf{8}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \mathbf{8}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \mathbf{8})$ $(\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}), (\mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})$ $(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1}), (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3}), (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{3})$	

- independent of spin and EW representation of χ
- MFV can only stabilize the lightest flavor

Flavored dark matter stabilized... what else?

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Naturally predicts a family of new particles -> multi-component dark matter?

Mescia, SO, Wu, 2408.16812

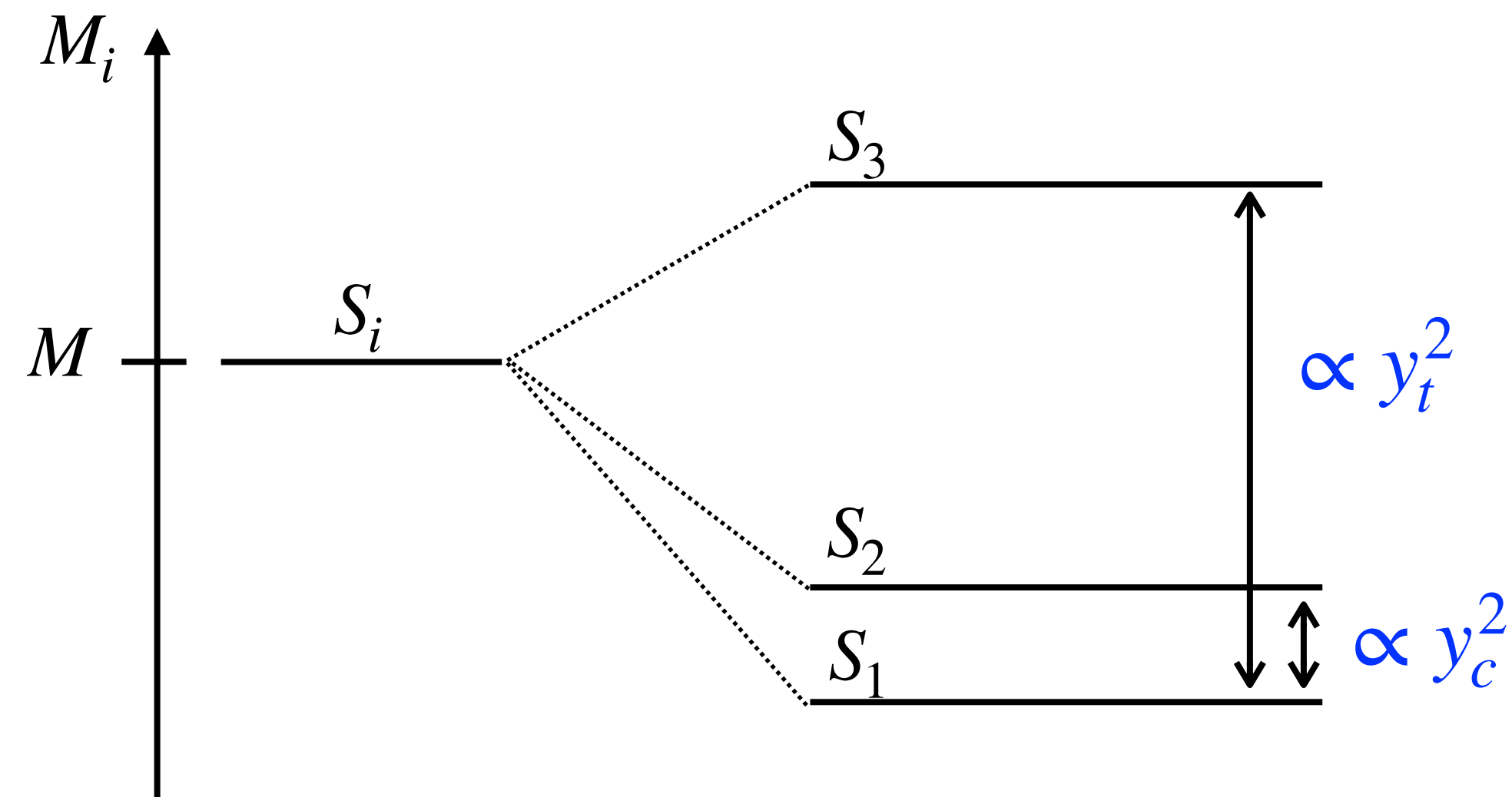
Flavored dark matter stabilized... what else?

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Mescia, SO, Wu, 2408.16812

- A gauge singlet, $SU(3)_u$ triplet scalar: $S \sim (1, 3, 1)$

$$M_j^2 - M_i^2 = \epsilon m_1^2 [(y_u^j)^2 - (y_u^i)^2]$$



Heavy scalar decays are triggered by dim-6 operators

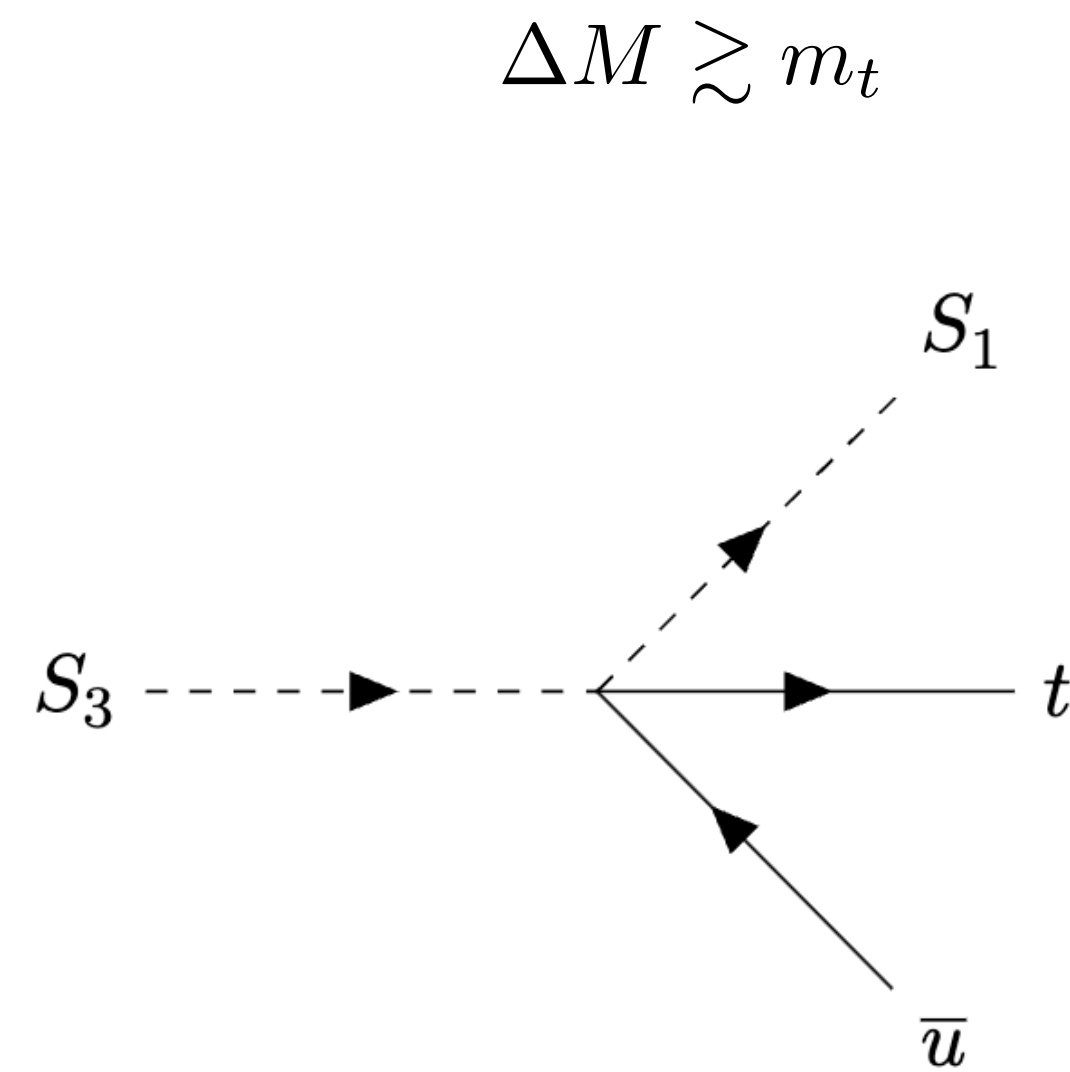
$$\begin{aligned} \mathcal{L}_{d=6} &\sim \frac{c_2^4}{\Lambda^2} \left(\bar{q}_{Li} (Y_u)_{ij} S_j \right) \tilde{H} (S_k^* \delta_{kl} u_{Rl}) + \text{h.c.} \\ &\sim \frac{c_2^4}{\Lambda^2} \bar{u}_i (m_u^i P_R + m_u^j P_L) u_j (S_j^* S_i) \end{aligned}$$



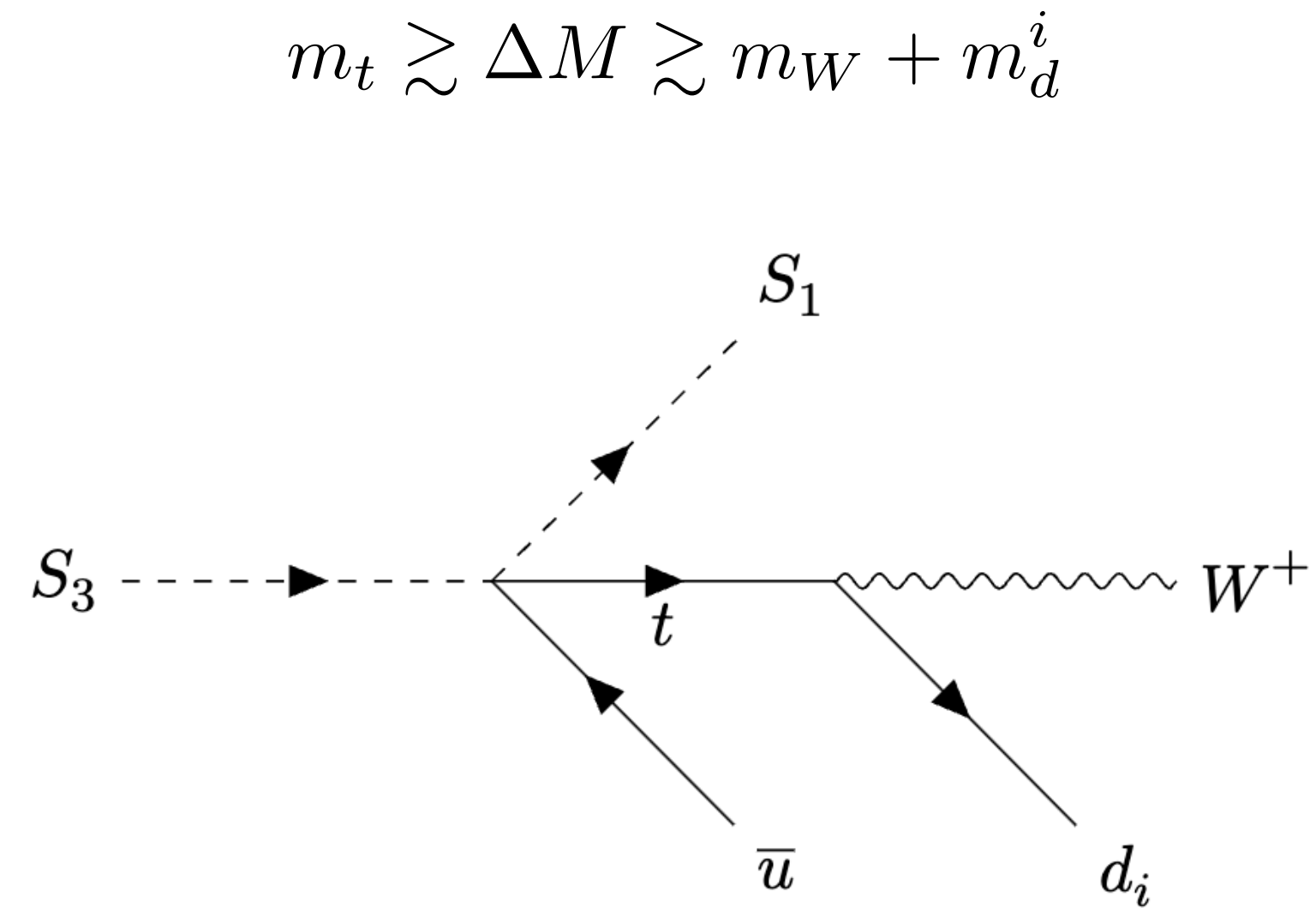
$$S_3 \rightarrow S_1 t \bar{u}, S_2 t \bar{c}$$

Decay of heavy states

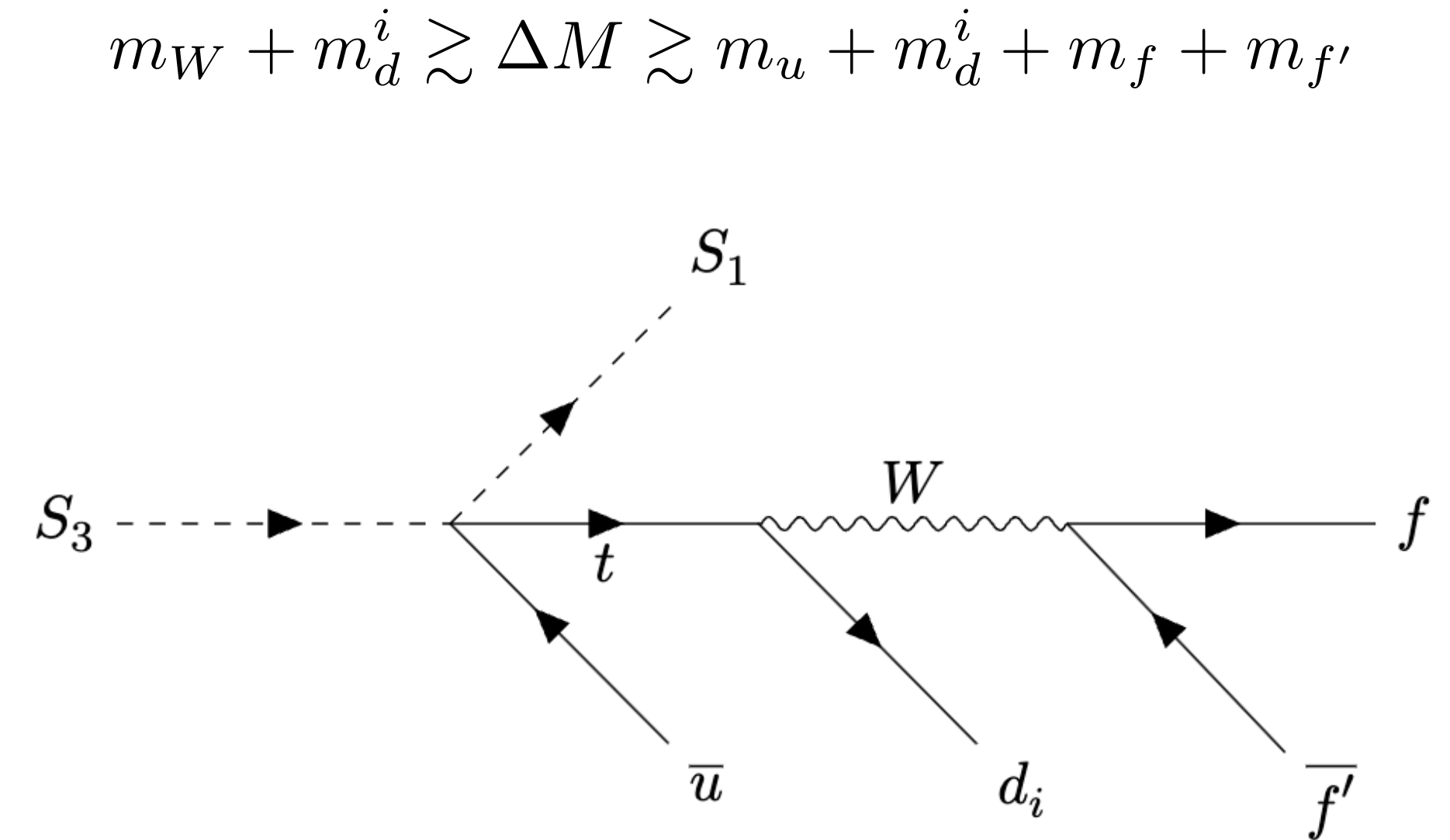
- Dominant mode depends on the mass splitting $\Delta M = M_3 - M_1$



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

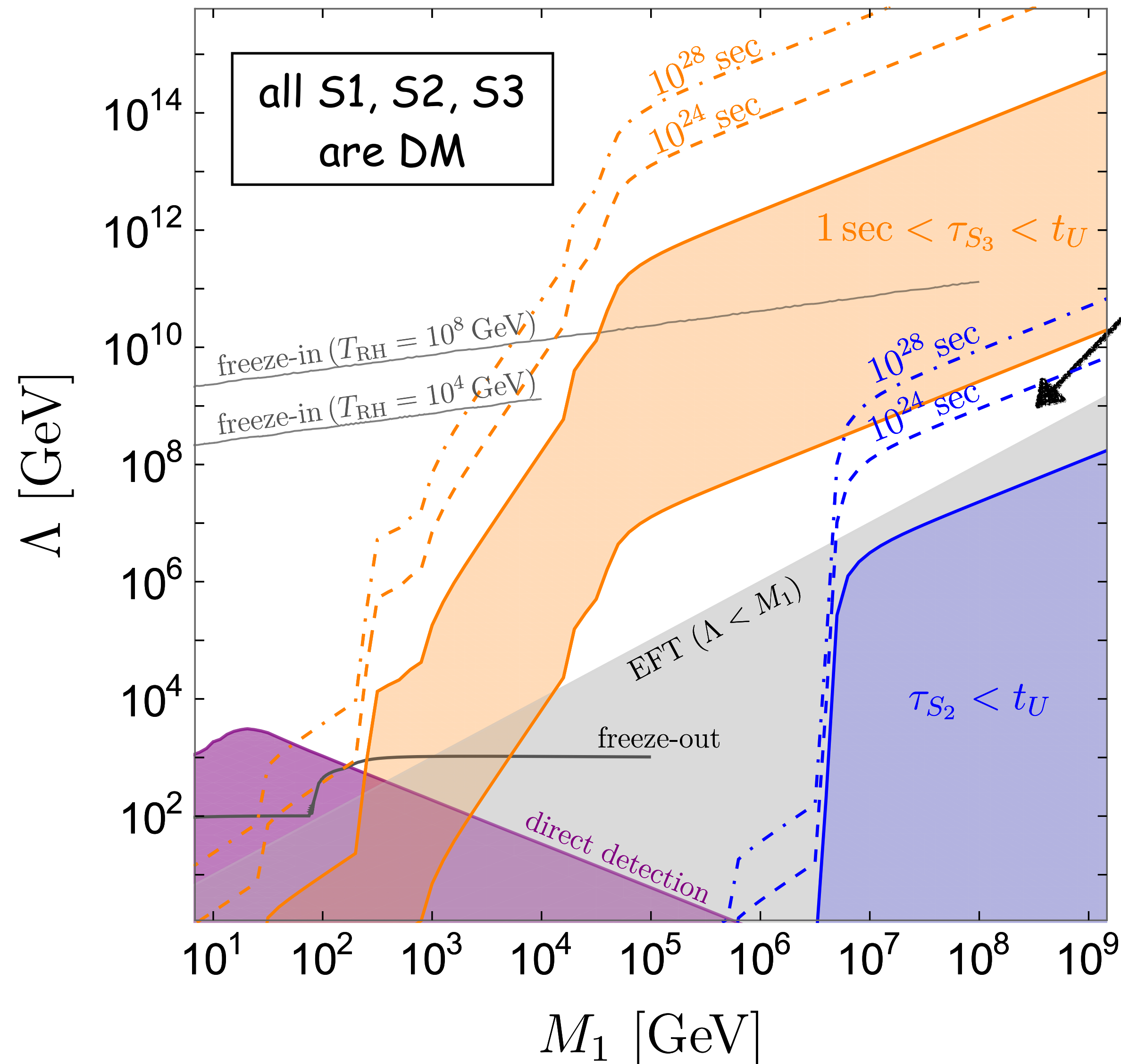


$$\Gamma \sim \frac{(\Delta M)^{11} |V_{ti}|^2}{41472 \pi^5 \Lambda^4 M_3^2 m_t^2 v^2}$$



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

Parameter spaces for multi-component DM



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

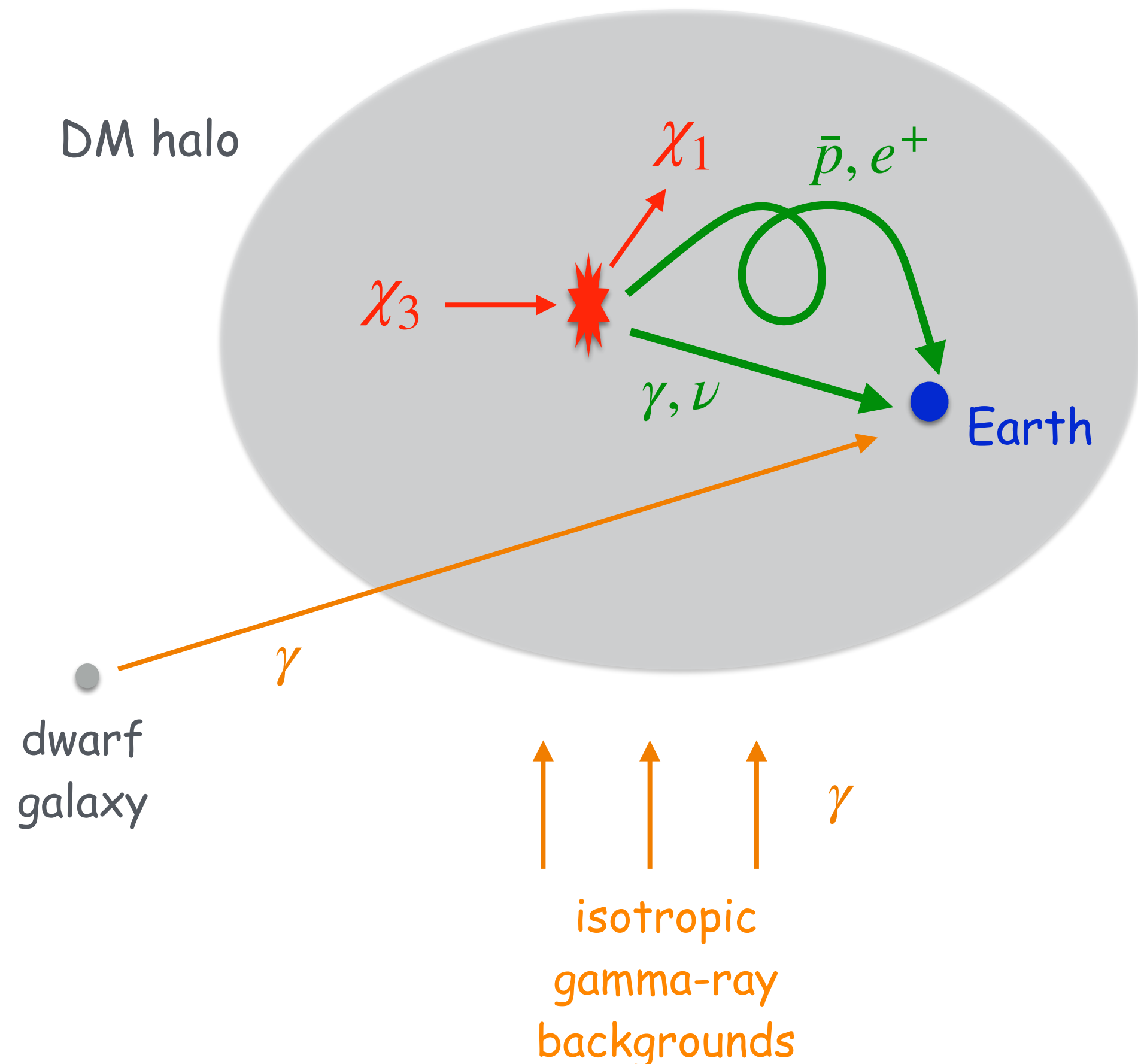
$\lambda = 0$ no coupling to Higgs

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

Signatures from multi-component flavored dark matter?

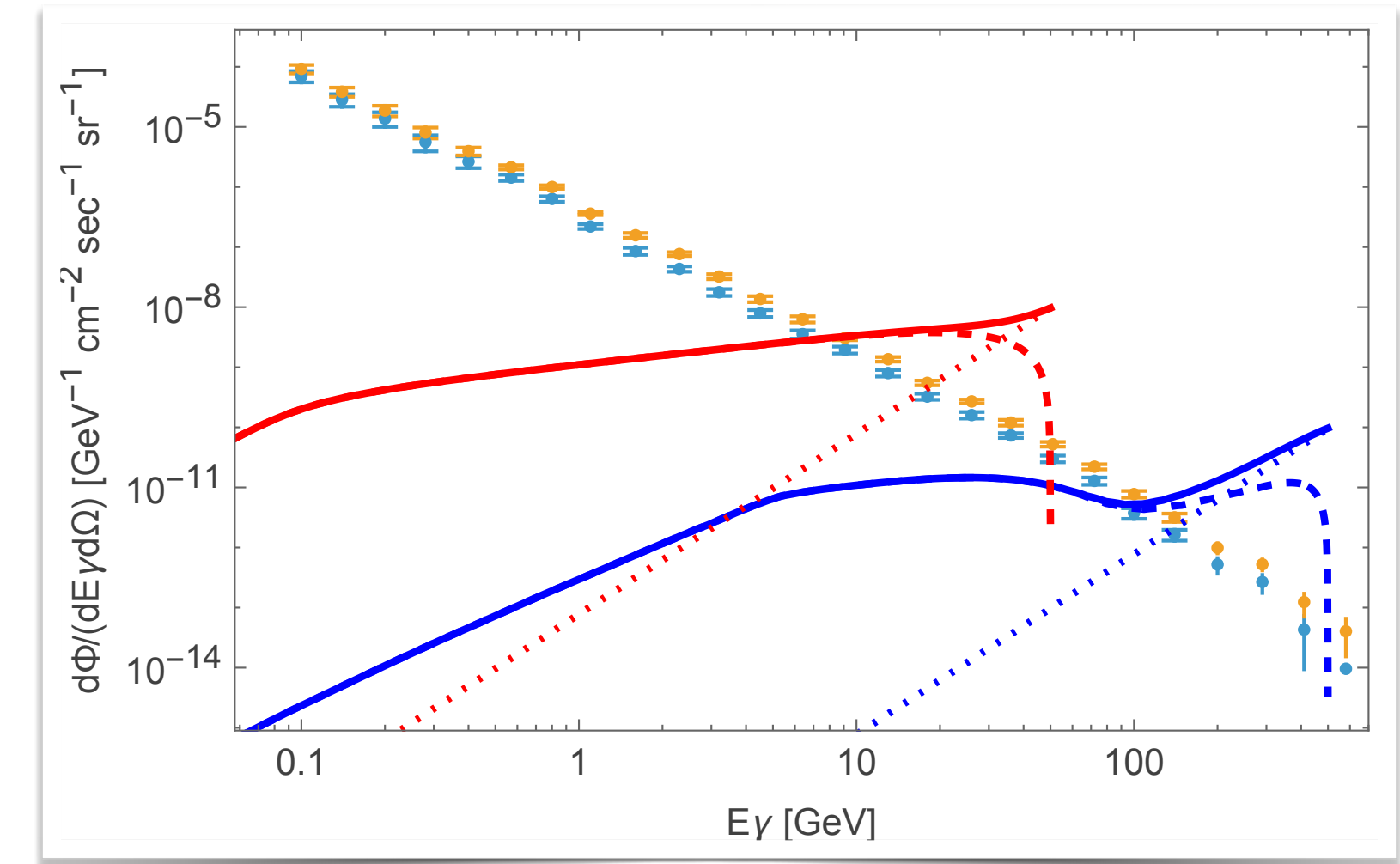
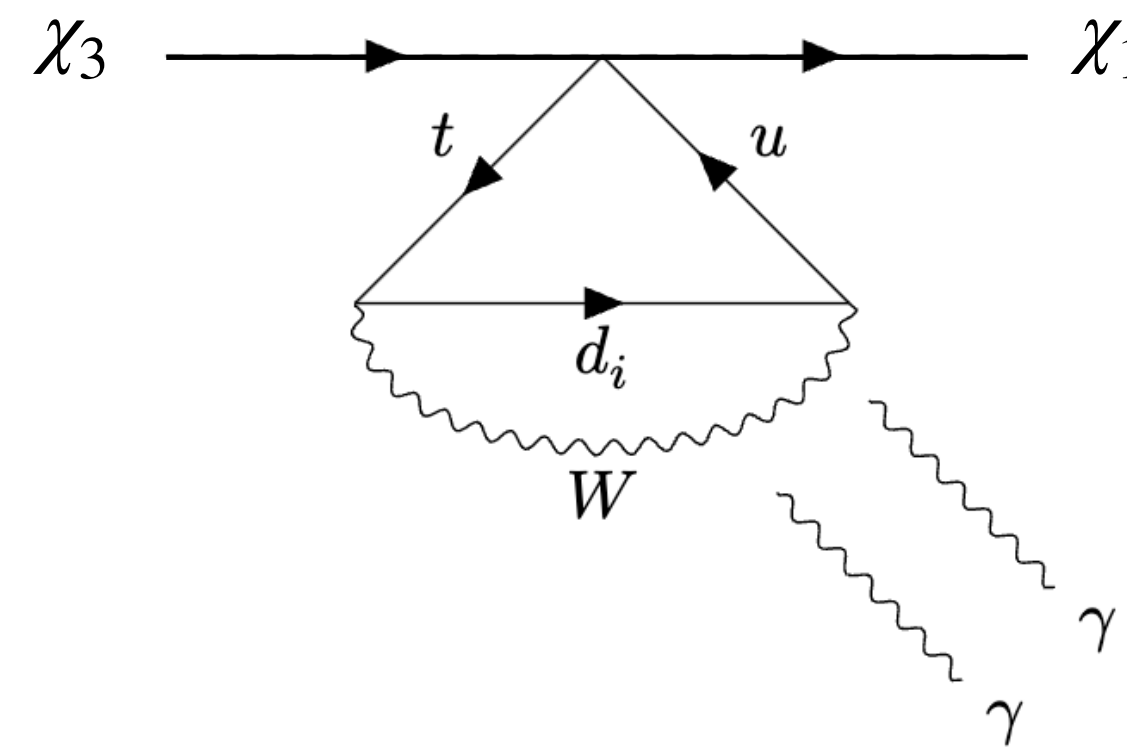
1. Indirect searches for heavy decaying dark matter

Kim, Landini, Mescia, SO, work in progress



● $\chi_{2,3} \rightarrow \chi_1 \gamma \gamma$

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



Also we can study

- hadronic decay modes $\chi_{2,3} \rightarrow \chi_1 q \bar{q}, \chi_1 q \bar{q} q \bar{q}, \dots$
- cosmology (CMB, BBN, Lyman- α , 21cm line, etc.)

2. Flavored DM from rare meson decays

Mescia, SO, Swallow, Toni, 2601.08907

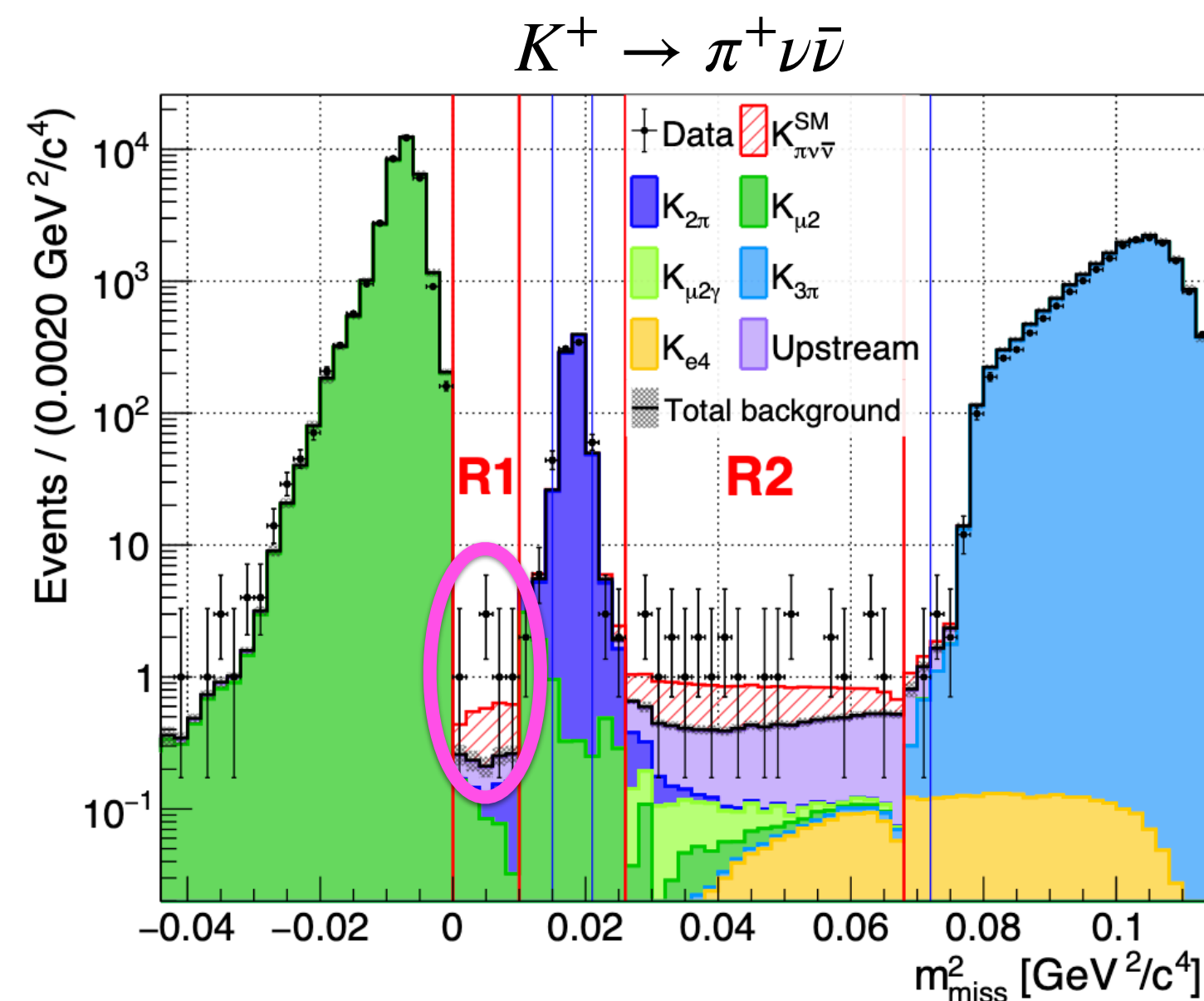
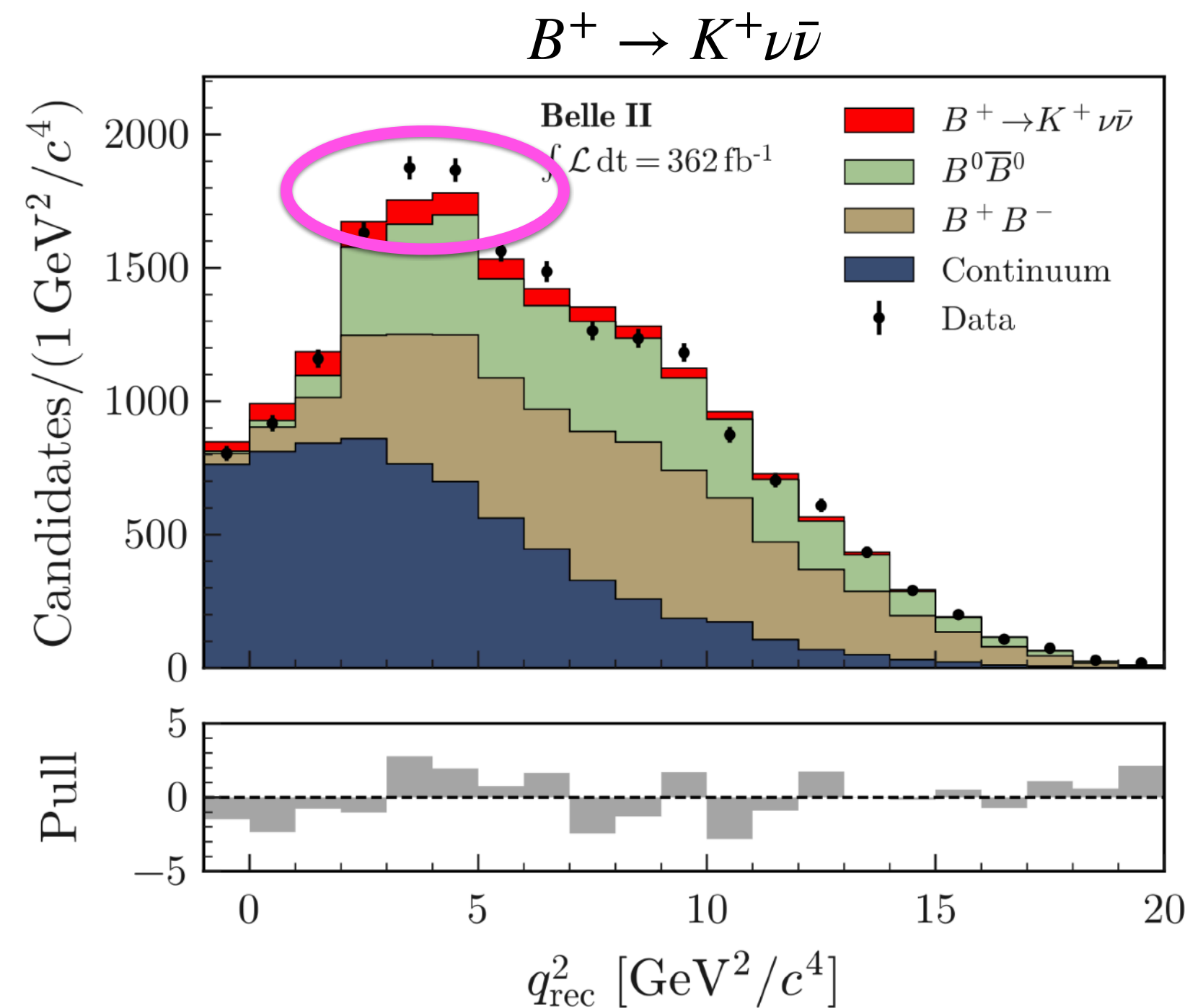
- Apparent flavor violating decays can naturally occur

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

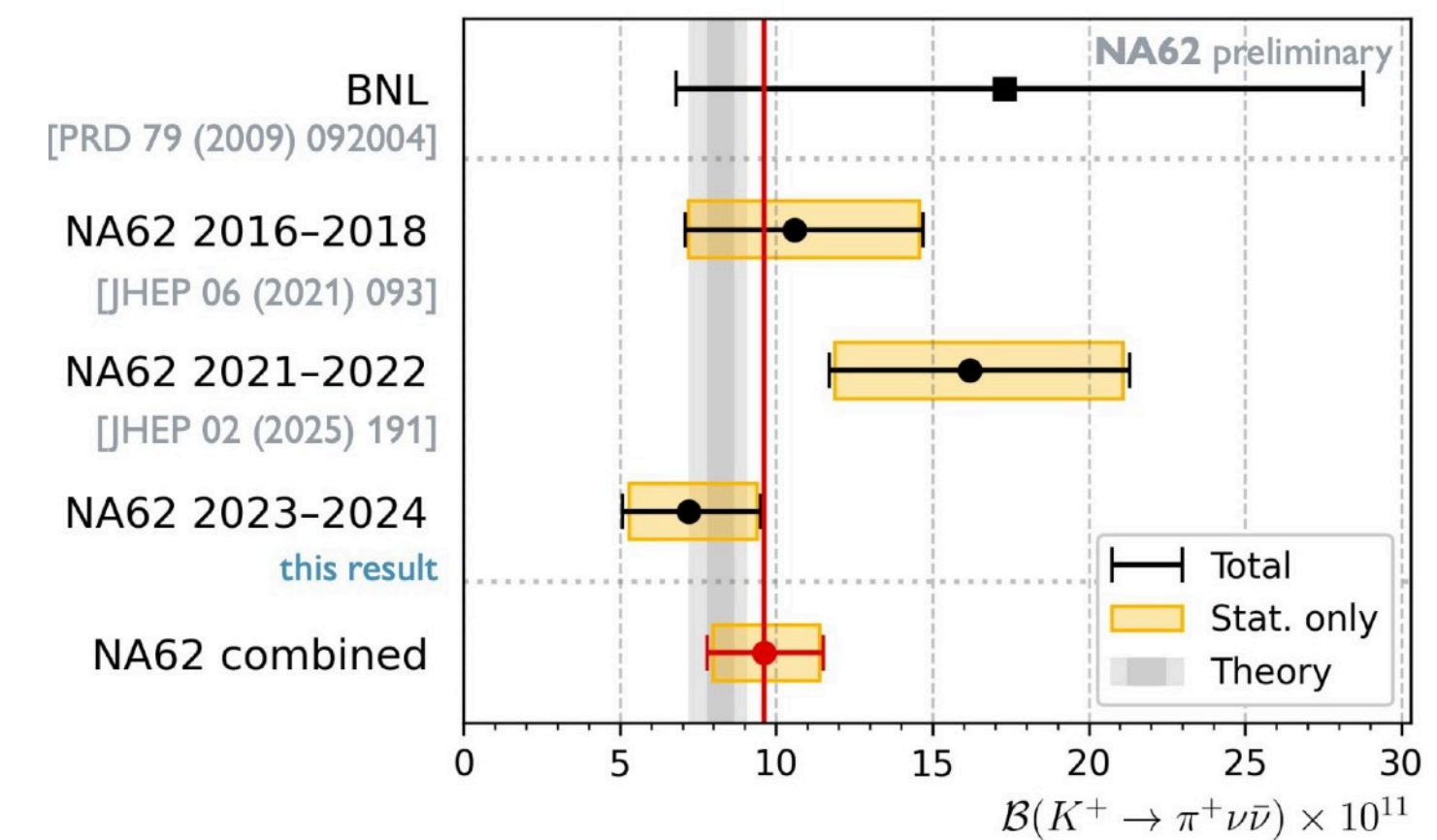
@Belle-II
BaBar

@NA62
KOTO

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



NA62 excess has disappeared with new data set!



Talk by Renato Fiorenza
@ LA THUILE 2026

2. Flavored DM from rare meson decays

Mescia, SO, Swallow, Toni, 2601.08907

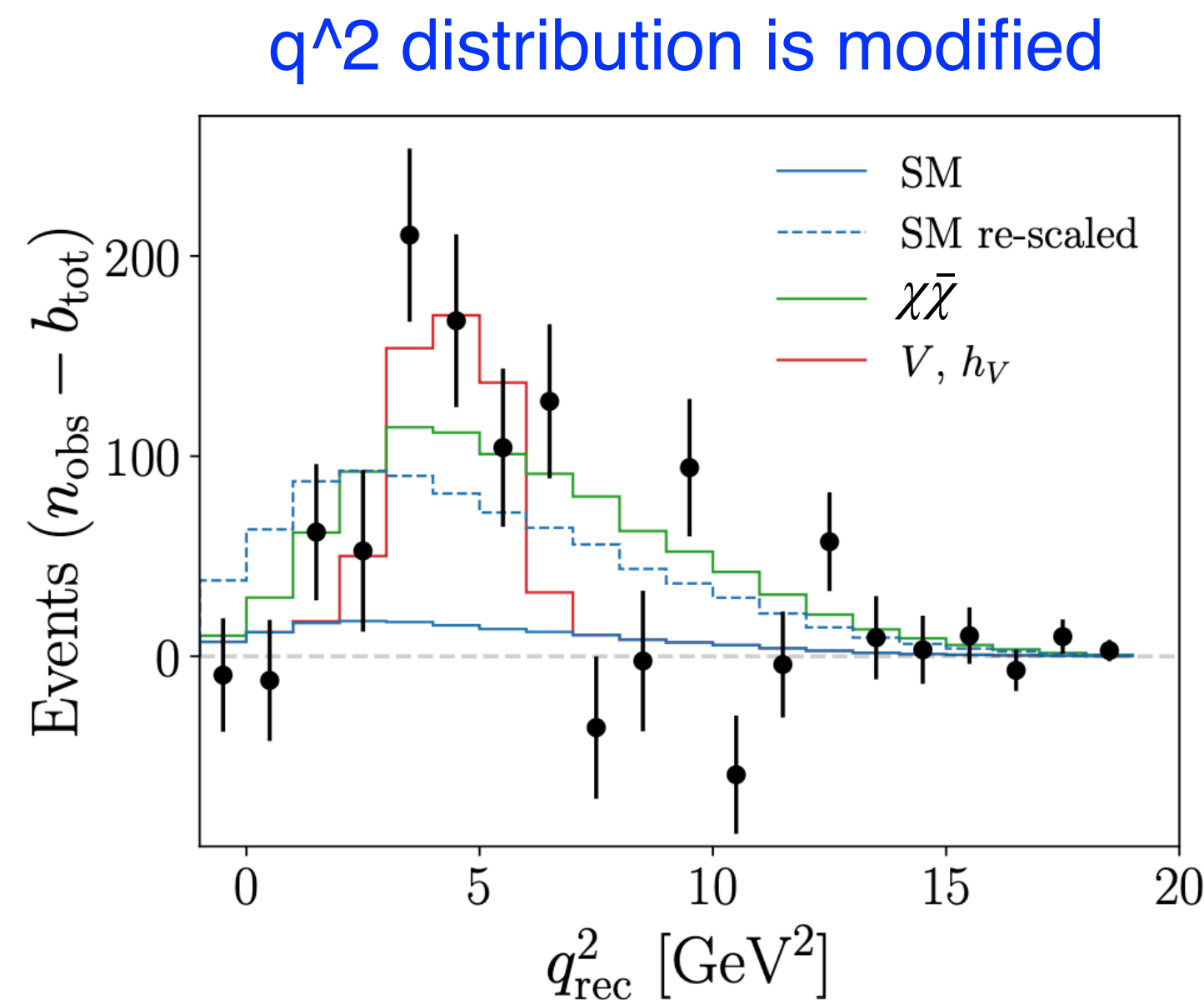
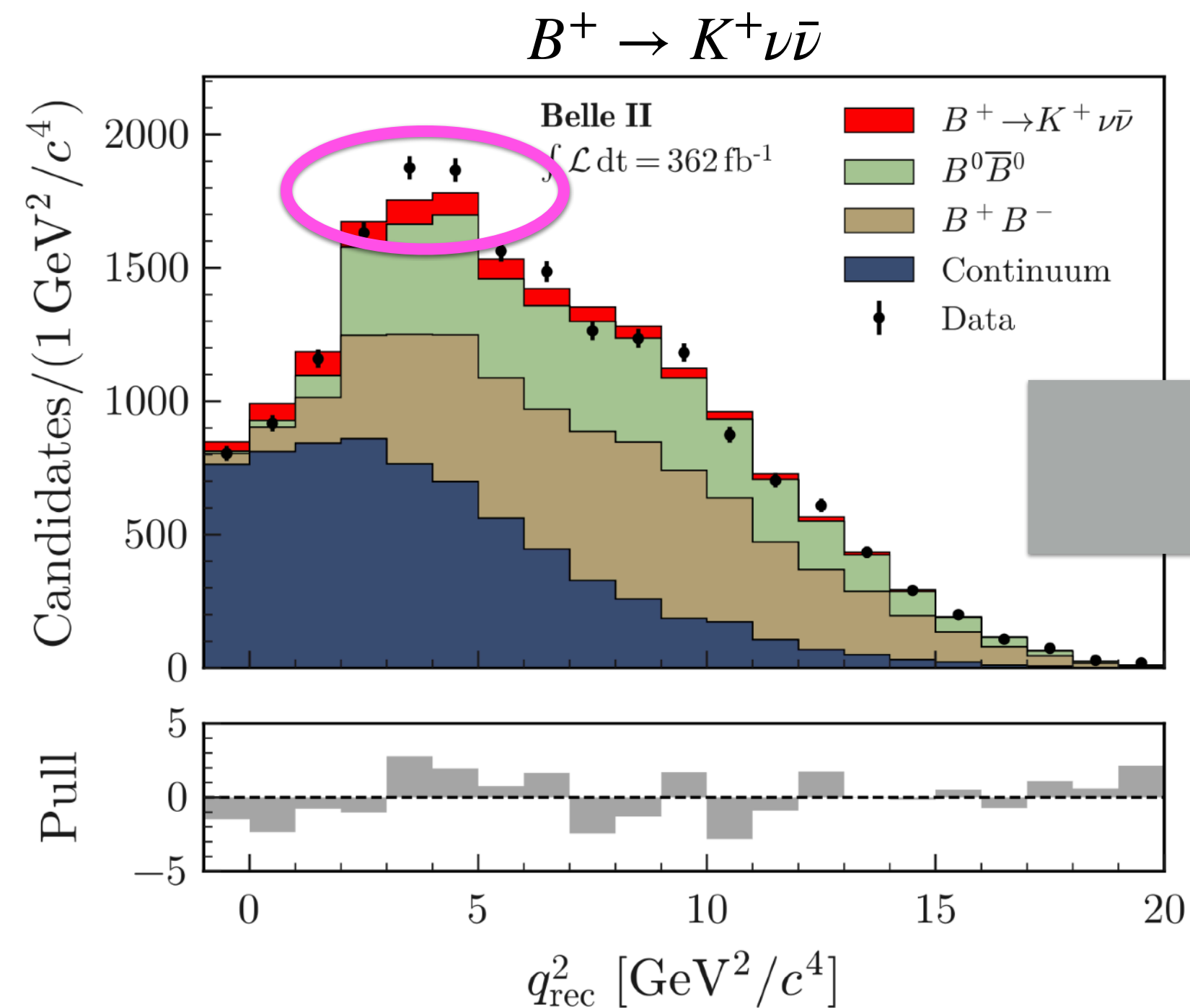
- Apparent flavor violating decays can naturally occur

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

@Belle-II
BaBar

@NA62
KOTO

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



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

Summary

Non-trivial flavor structures in BSM may provide a new avenue for theories of dark matter

- quark flavored DM + MFV $\rightarrow$ **multi-component dark matter**
- very rich phenomenology and cosmology
- still, many questions
- relation to the **fermion hierarchy**?
- extension to **lepton flavor**?
- **$U(3)^5$, $U(2)^5$, modular, or others?**

Thanks for listening!

Back up

Why flavored DM stabilized within MFV?

There is an unbroken **Z_3 symmetry** $\subset \text{SU}(3)_c \times \text{SU}(3)_q \times \text{SU}(3)_u \times \text{SU}(3)_d$

[Batell, Lin, Wang '13]

► Z_3 charge: $\psi \rightarrow U\psi$ 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 spurions are singlet

- quarks: $Q \rightarrow (\omega^2 \cdot \omega) Q = Q$
- others: $\phi \rightarrow \phi$

► Flavored DM: $\chi \rightarrow (\omega)^{n_\chi - m_\chi} \chi$

- χ is Z_3 non-singlet if $(n_\chi - m_\chi) \bmod 3 \neq 0 \rightarrow$ **stabilized**

► Flavored scalars Φ can develop VEVs if $(n_\Phi - m_\Phi) \bmod 3 = 0$

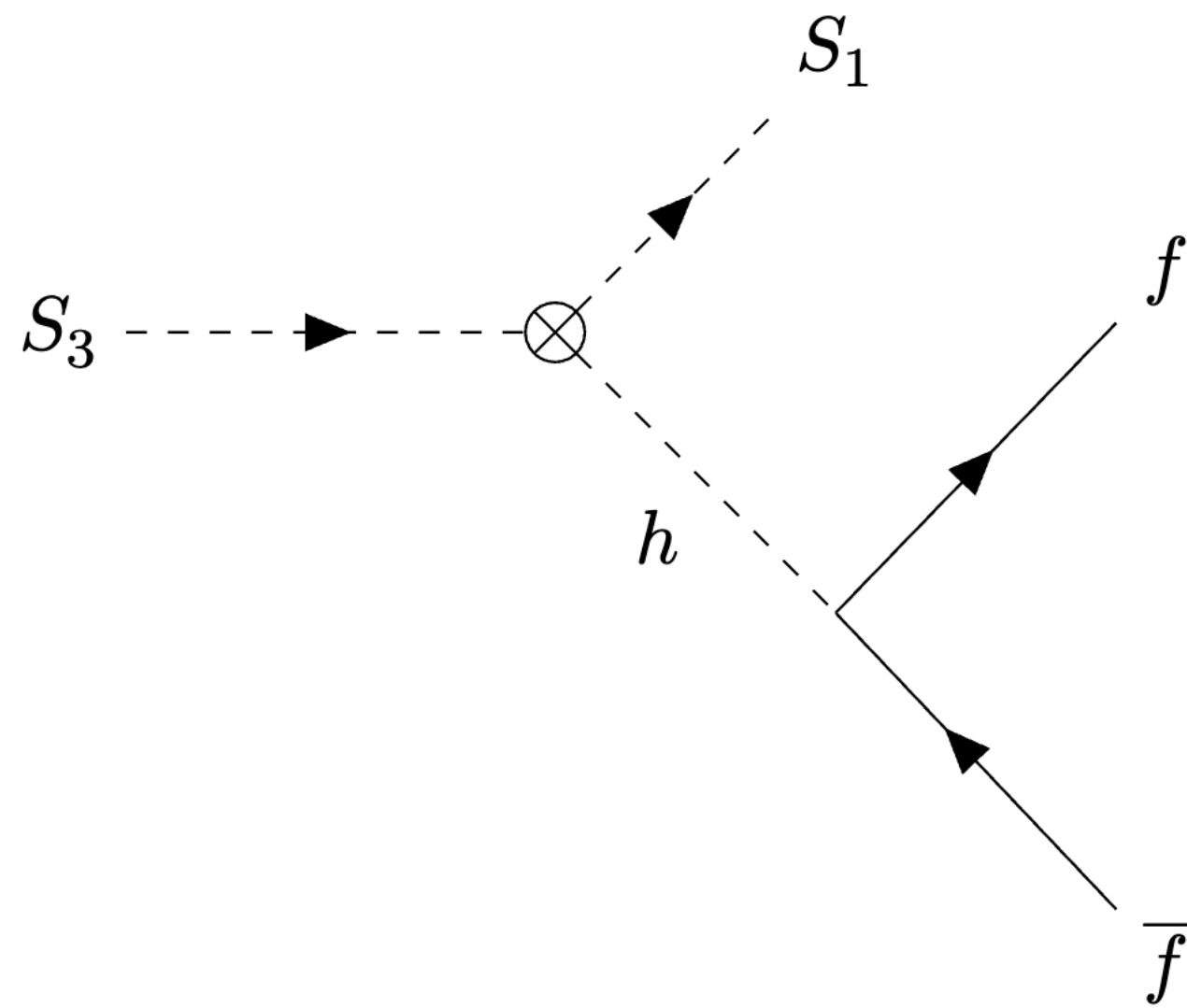
[Bishara+ '15]

- extendable to a broader framework

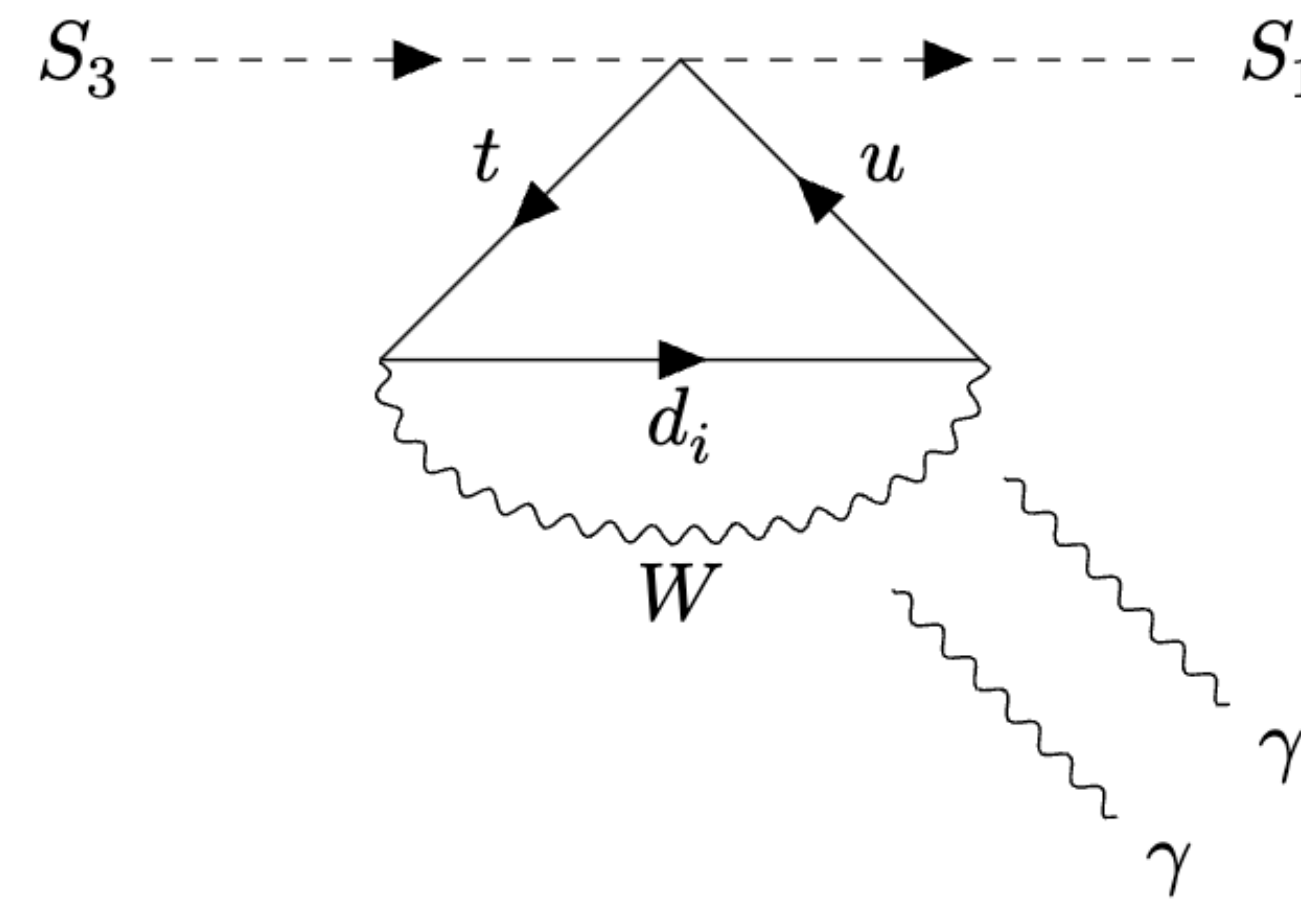
Decay at higher orders

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

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

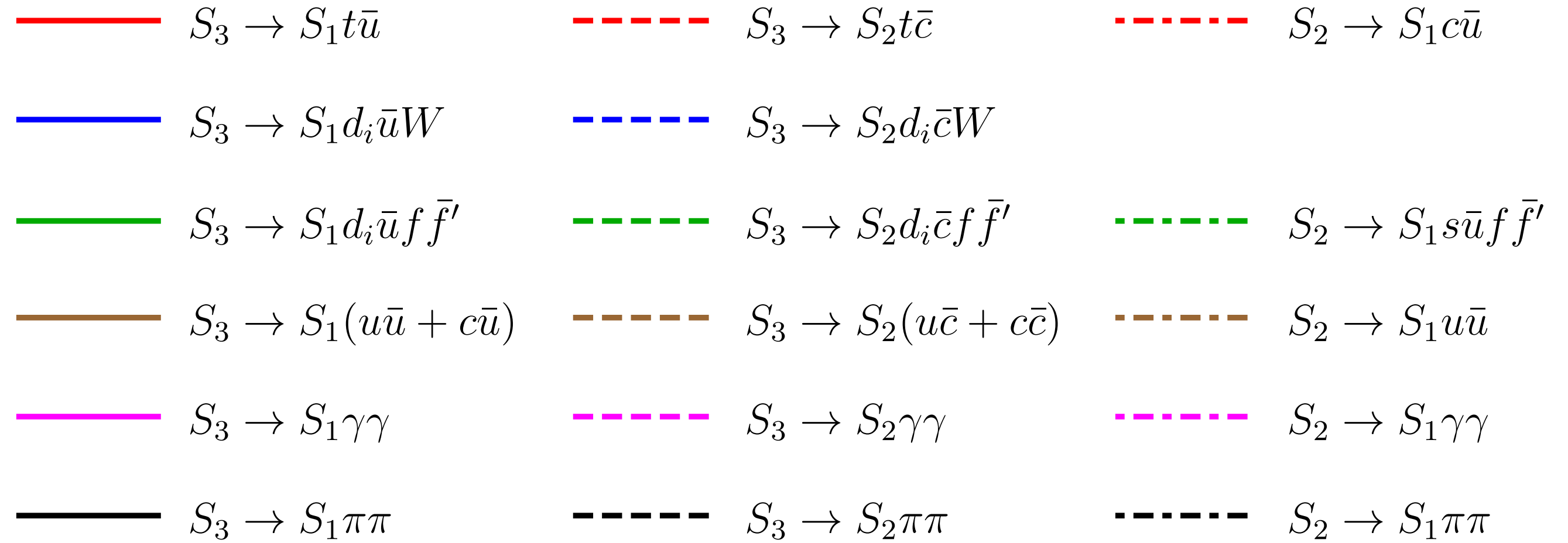
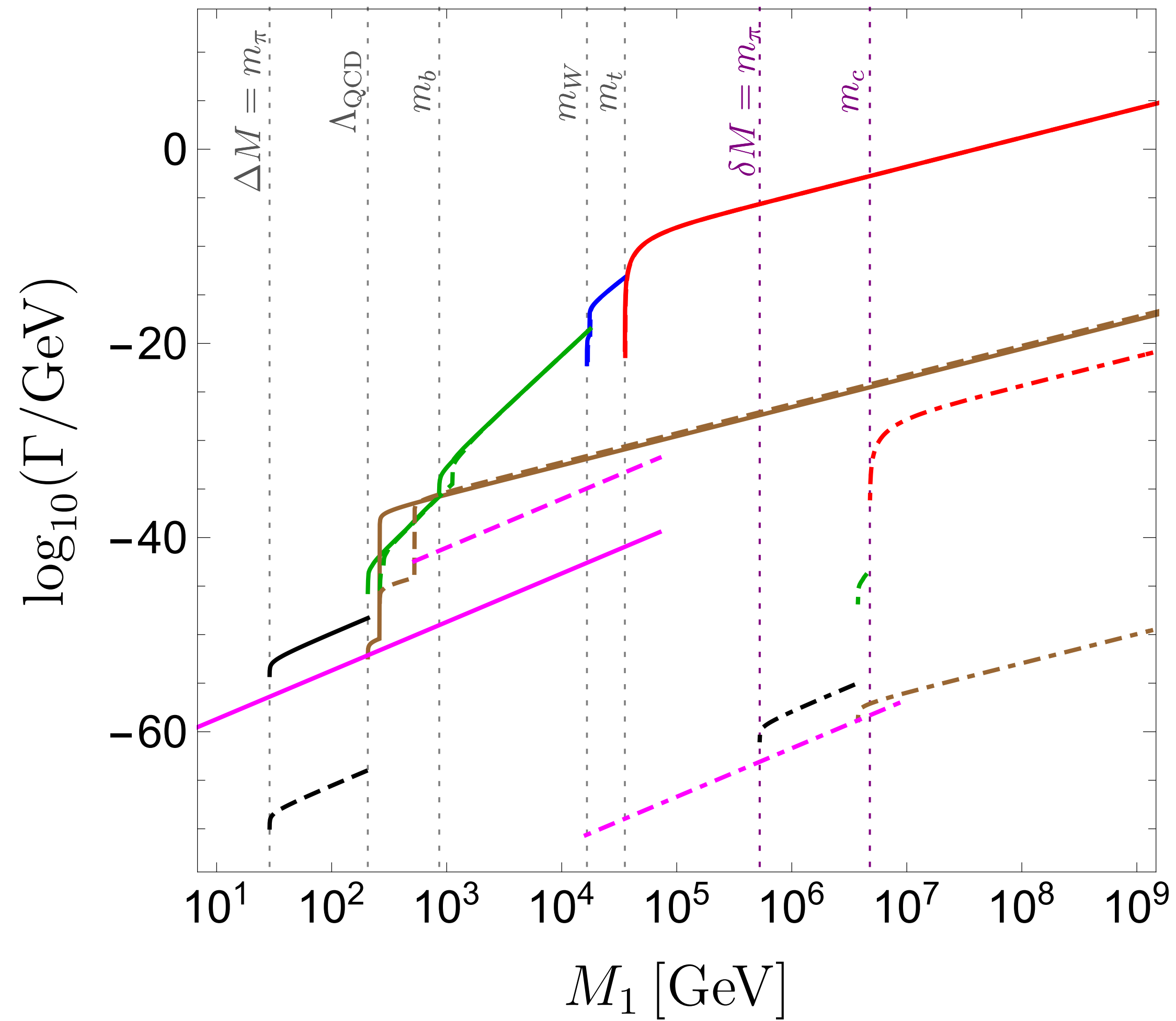


$$\sim \epsilon^2 Y_u^\dagger Y_d Y_d^\dagger Y_u$$

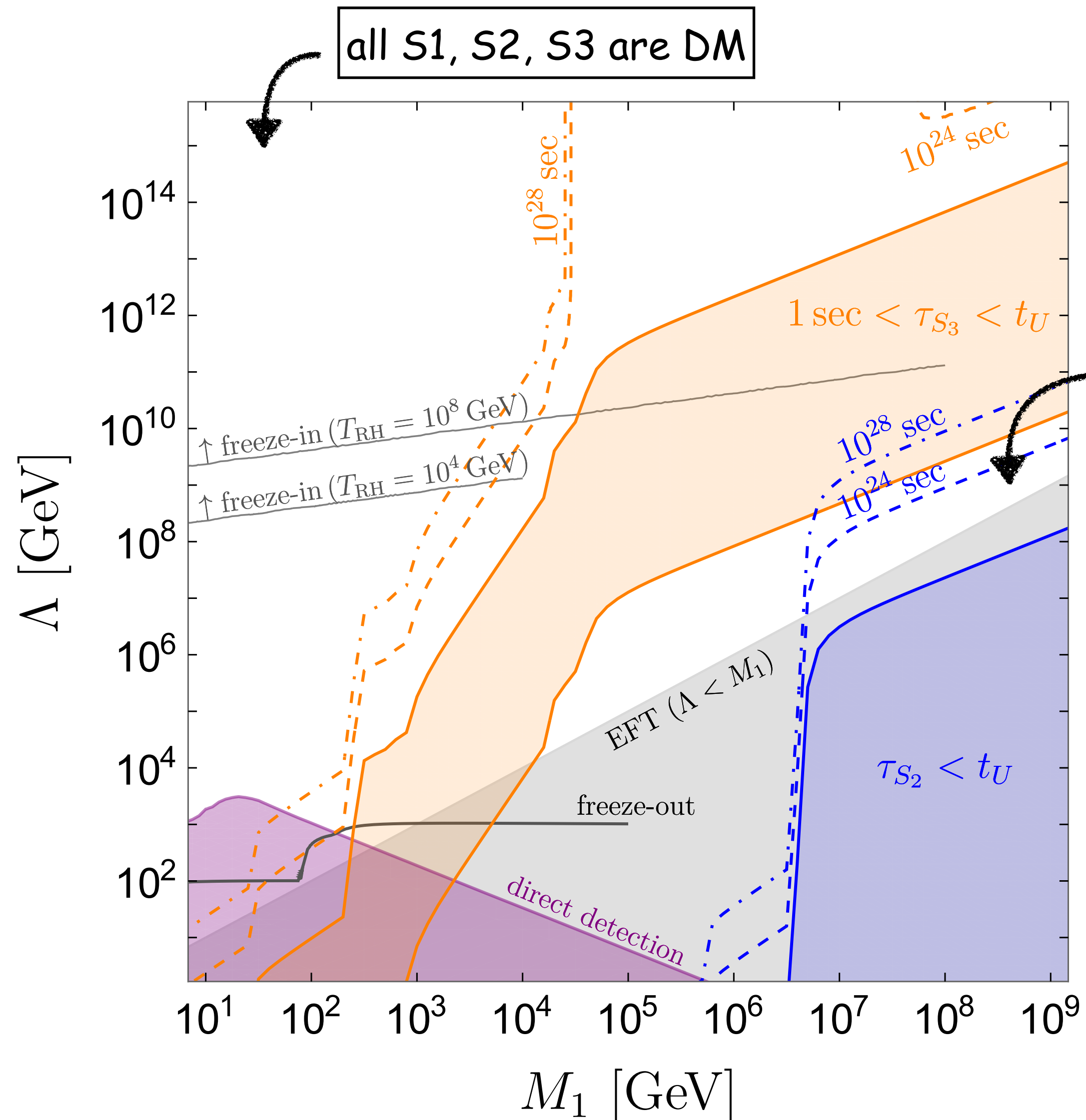


$$\sim \frac{Y_u^\dagger Y_d Y_d^\dagger Y_u}{(16\pi^2)^2}$$

Partial decay widths for heavy scalars



Impact of Higgs portal coupling (1/2)



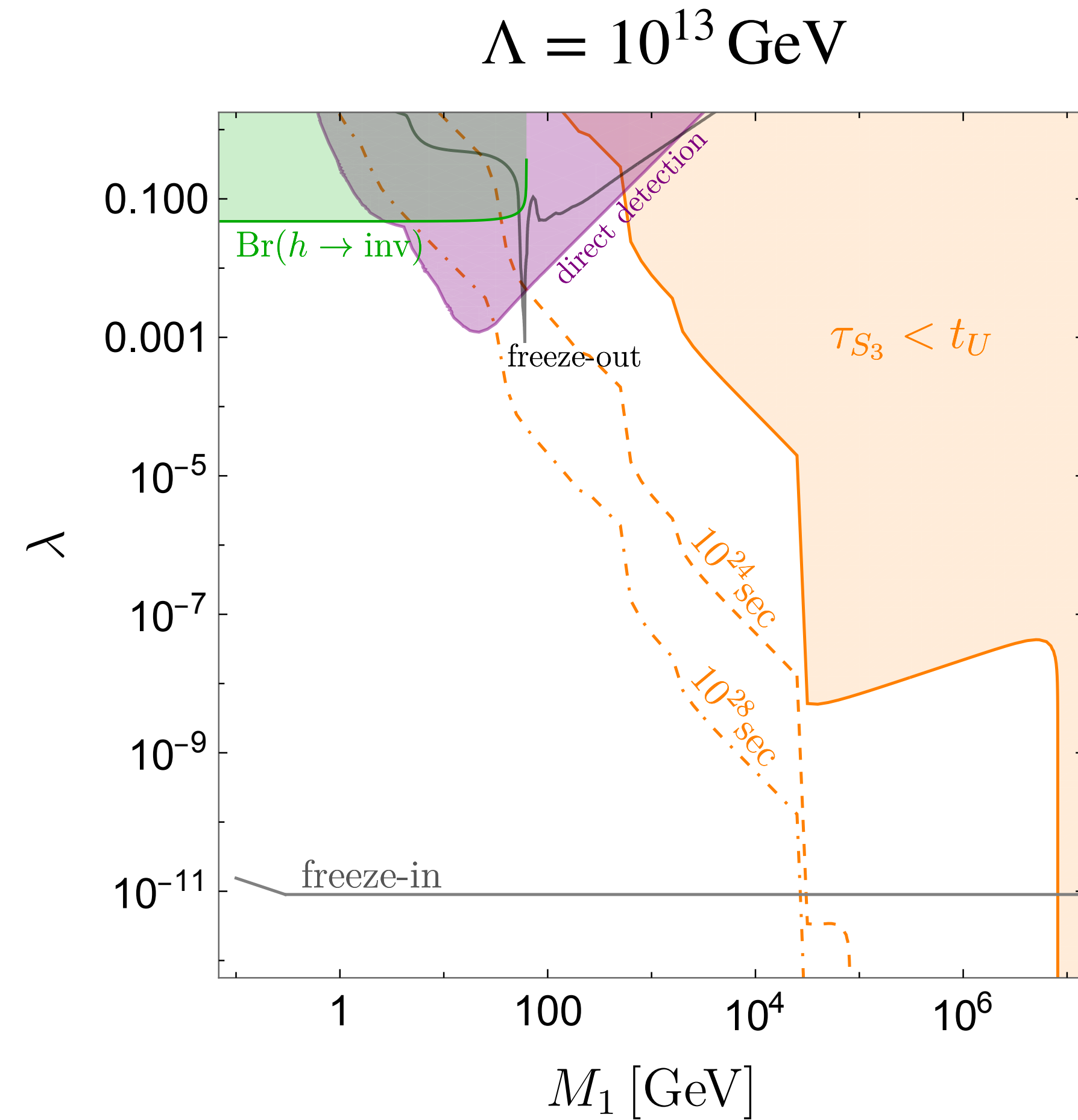
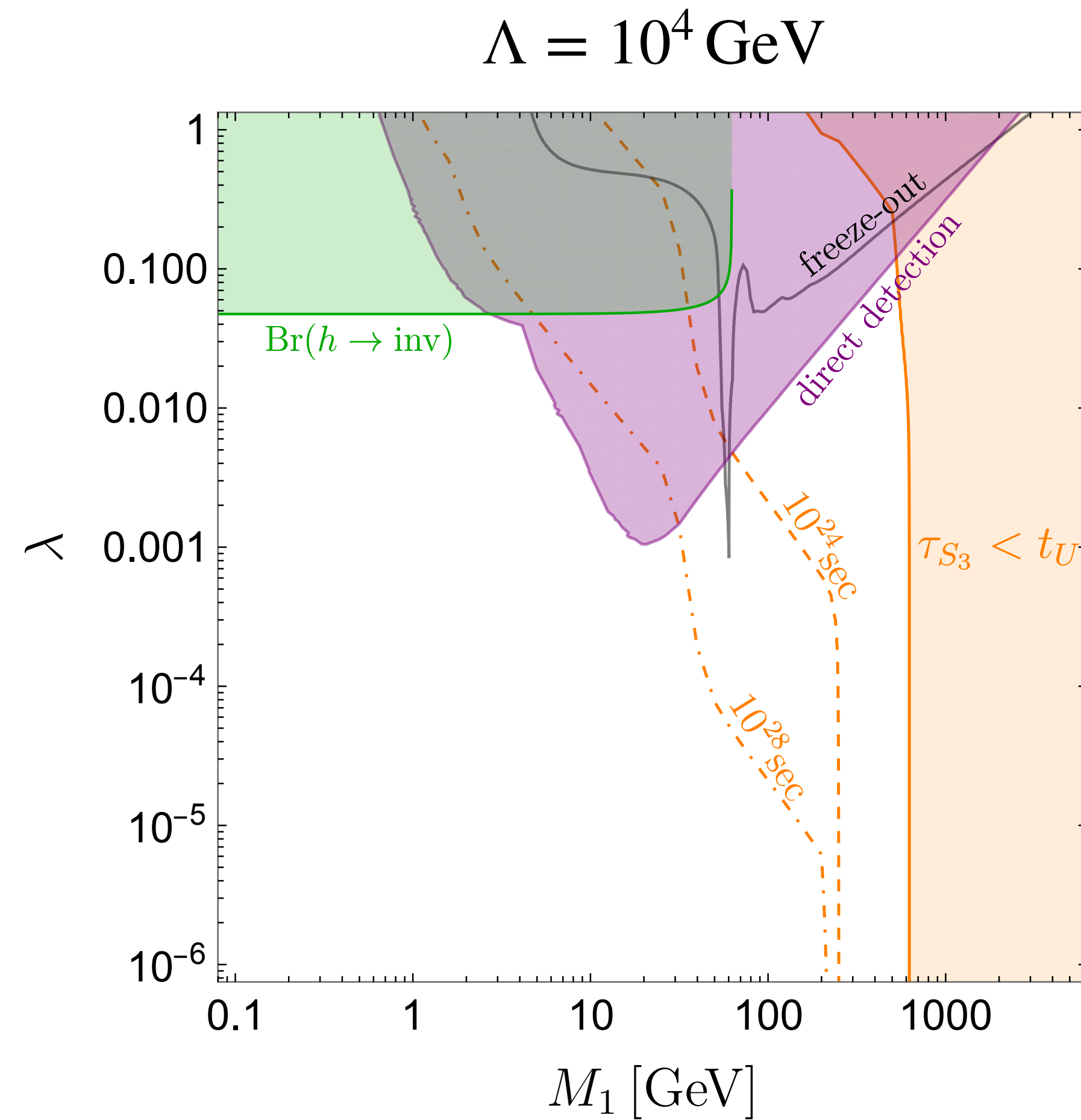
$$\epsilon = 10^{-2} \simeq \frac{M_3 - M_1}{y_t^2 M_1} \simeq \frac{M_2 - M_1}{y_c^2 M_1}$$

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

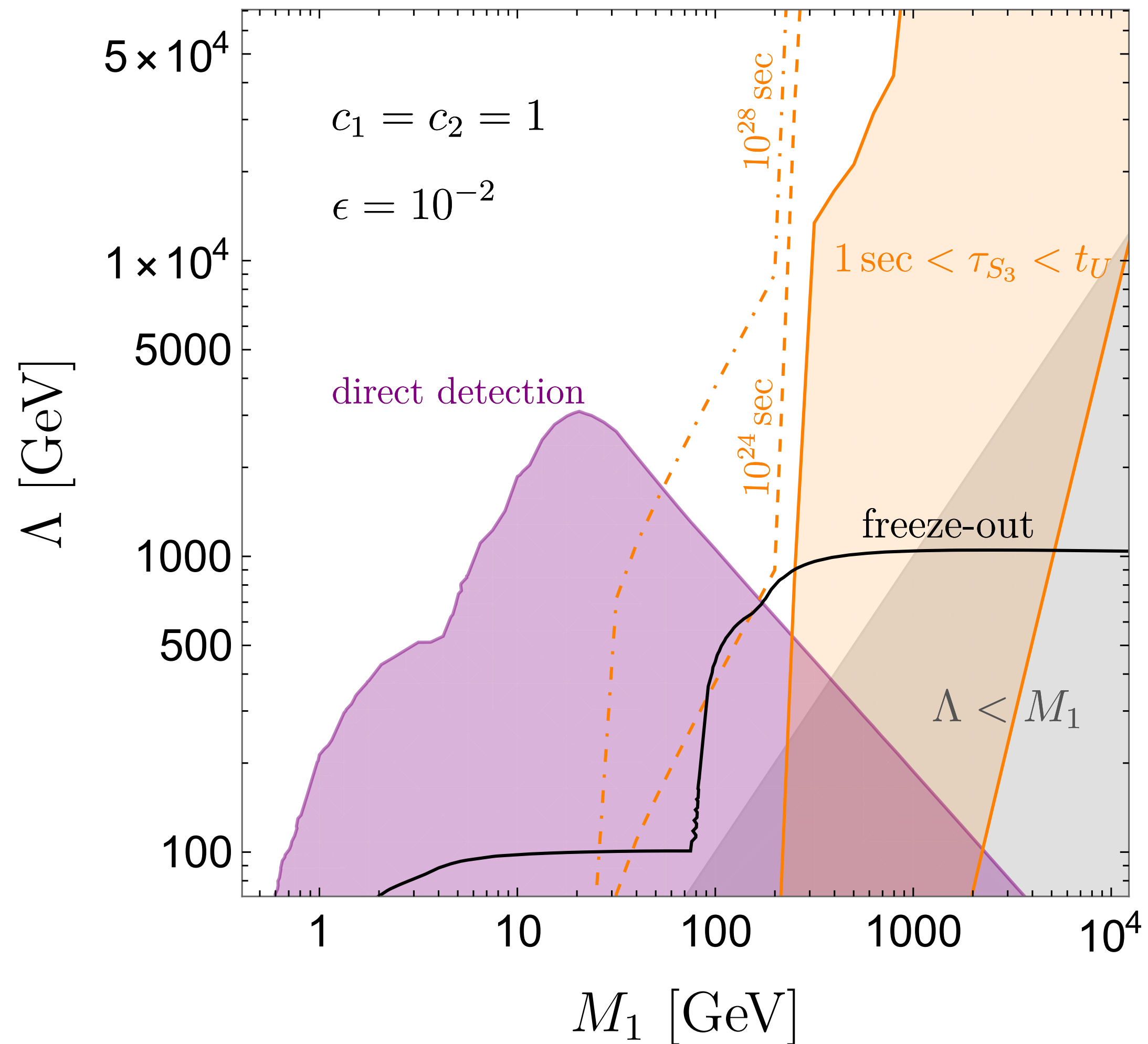
- Heavy components are also DM if $\tau_{S_i} > \tau_U$
- White region is allowed
 - two-component between orange and blue regions
 - three-component above the orange region

Impact of Higgs portal coupling (2/2)

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



Closer look at 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 $M_1 \sim 180\text{-}210\text{ GeV}$ is allowed in the freeze-out scenario
- EFT is not justified in the region, $\Lambda < M_1$