Flavor of elementary particles and dark matter

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(APCTP)

Based on 2408.16812, 2601.08907 + ongoing work

with Federico Mescia (INFN LNF), Keyun Wu (ICCUB), Joel Swallow (CERN), Claudio Toni (LAPTH), Sang Hwan Kim (Yonsei U), Giacomo Landini (INFN LNF)

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Junior Research Group, "Particle Physics Phenomenology"

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Dr. Audrey Fung

- BSM search using ancient minerals and stellar evolution

Dr. Gurucharan Mohanta

- BSM model building
- radiative mass generation

What is **particle physics phenomenology**?

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- We're working on the Standard Model (SM) physics and Beyond the Standard Model (BSM) physics

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  Sometimes, we simplify models by considering less dimension/particles/interactions

- And we also do **cosmology** – that is, we do pretty much everything

- But, most of the time, we ignore gravity (except for the expansion of the Universe)

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BSM Physics: Devise new models / mechanisms that resolves open questions in particle physics

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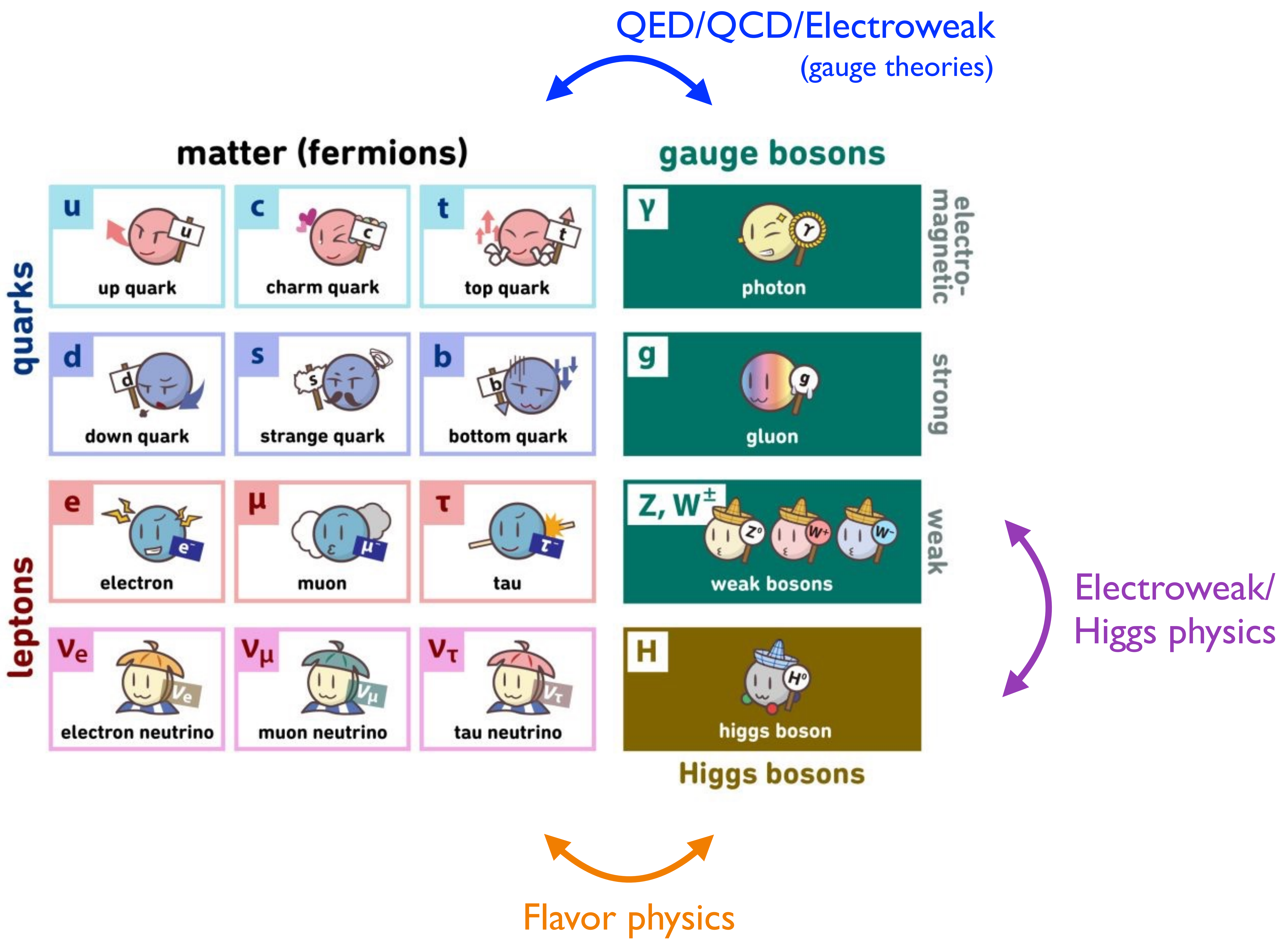
BSM Physics: Devise new models / mechanisms that resolves open questions in particle physics

- neutrino masses
- fermion mass hierarchy (flavor puzzle)
- baryon asymmetric Universe
- dark matter
- ...

Contents

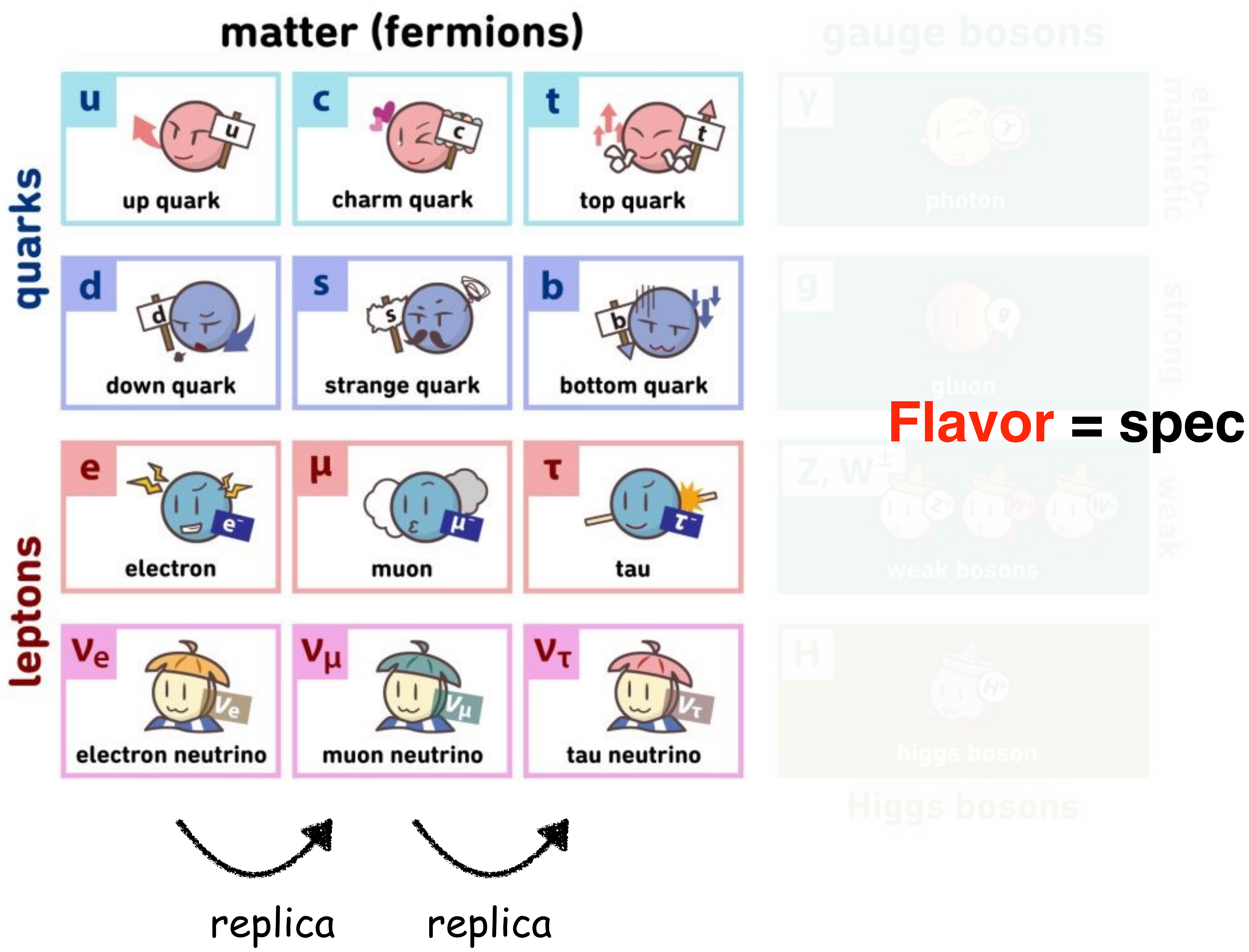


QED/QCD/Electroweak
(gauge theories)
matter (fermions)
gauge bosons
quarks
leptons
u
up quark
c
charm quark
t
top quark
d
down quark
s
strange quark
b
bottom quark
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
γ
photon
electro-magnetic
g
gluon
strong
Z, W±
weak bosons
weak
H
higgs boson
Higgs bosons
Electroweak/
Higgs physics
Flavor physics

$(i = 1, 2, 3)$

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

$\ell_L^i,\ e_R^i$



Flavor = species of fermions

Flavor structure in the SM

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge+Higgs} + \sum_f \bar{f} i\gamma^\mu D_\mu f$$

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

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U(3)^5 flavor symmetry

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

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Y_u, Y_d, Y_e : 3 × 3 matrices in the flavor space

U(3)⁵ flavor symmetry

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

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

broken spontaneously

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

Flavor structure in the SM and Beyond

U(3)⁵ flavor symmetry

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

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

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$$+ \underbrace{\mathscr{L}_{\mathrm{BSM}}}$$

neutrino mass
dark matter
baryon asymmetry
inflation
...

?

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

Flavor puzzles and flavor symmetries

Flavor puzzles and flavor symmetries

1. SM flavor puzzle

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

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"Why is there a large hierarchy among the Yukawa matrix elements?"

Flavor puzzles and flavor symmetries

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In the Froggatt-Nielsen, the Yukawa hierarchy is controlled by a U(1) flavor symmetry

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

Flavor puzzles and flavor symmetries

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There are many alternatives

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

Flavor puzzles and flavor symmetries

2. BSM flavor puzzle

Flavor puzzles and flavor symmetries

2. BSM flavor puzzle

Traditional view

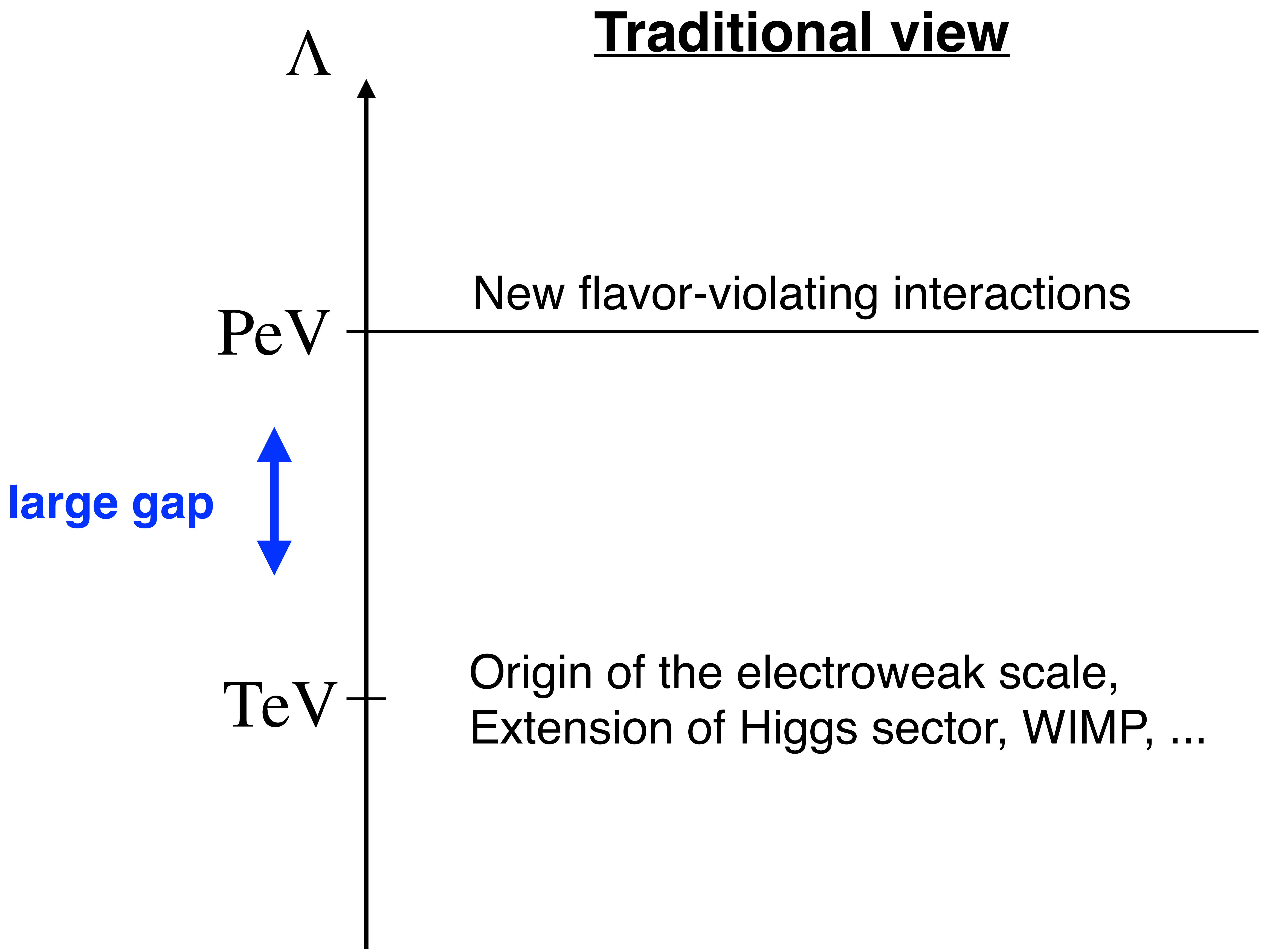
GUT, quantum gravity...

Origin of the electroweak scale,
Extension of Higgs sector, WIMP, ...

many new particles

Flavor puzzles and flavor symmetries

2. BSM flavor puzzle



$$\frac{1}{\Lambda^2}(\overline{q}_{Li}\gamma^\mu q_{Lj})^2 \;\Rightarrow\; \Lambda \gtrsim \mathrm{PeV} - 100\,\mathrm{PeV}$$

from K0-K0 bar mixing

$$\frac{1}{\Lambda^2}\overline{\ell}_{Li}\,\sigma_{\mu\nu}\,H\,e_{Rj}\,B^{\mu\nu} \;\Rightarrow\; \Lambda \gtrsim 100\,\mathrm{PeV}$$

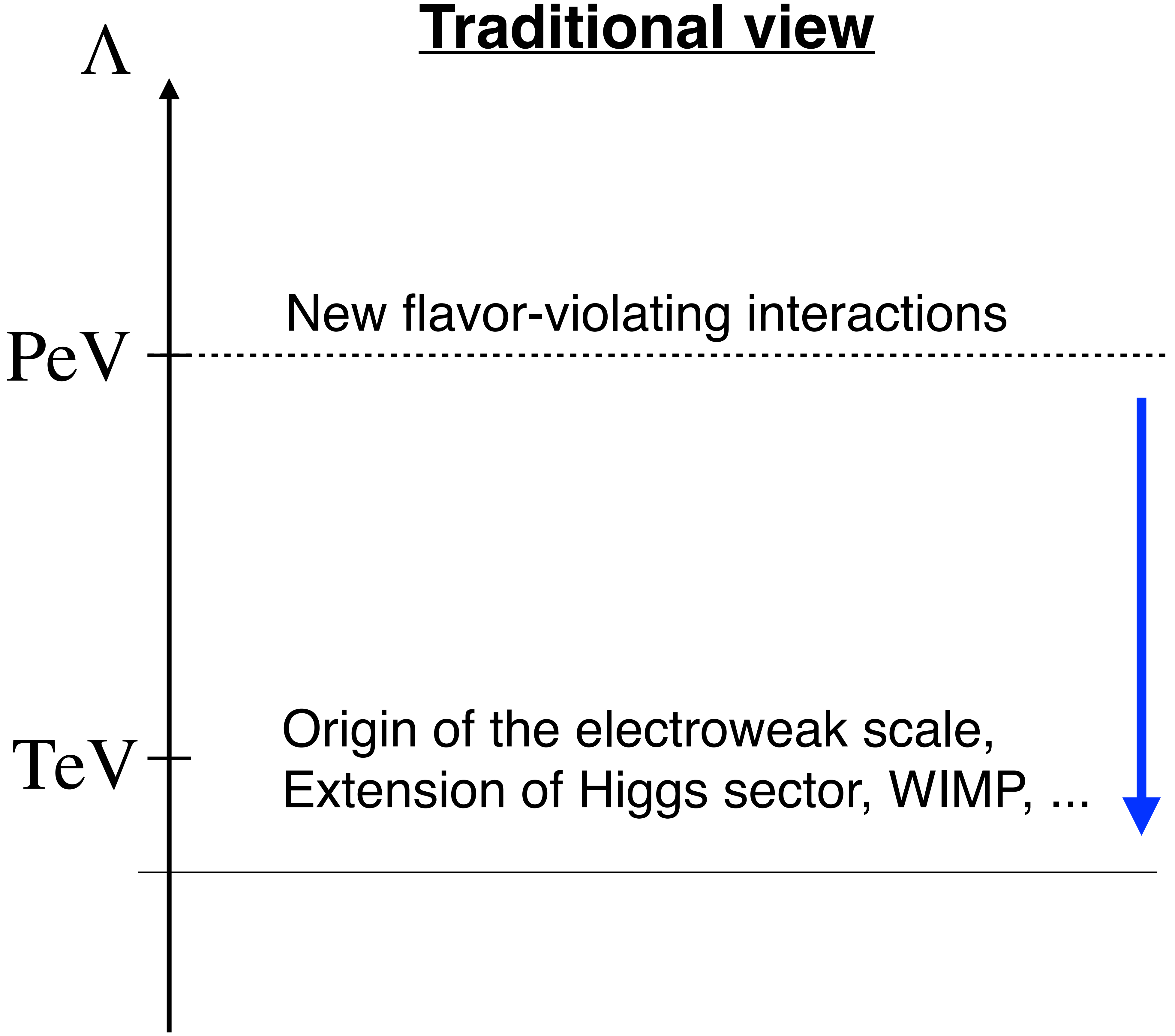
from μ -> e γ

"Why is there a large separation between the scales suggested by EW physics and flavor physics?"

Flavor puzzles and flavor symmetries

2. BSM flavor puzzle

Traditional view



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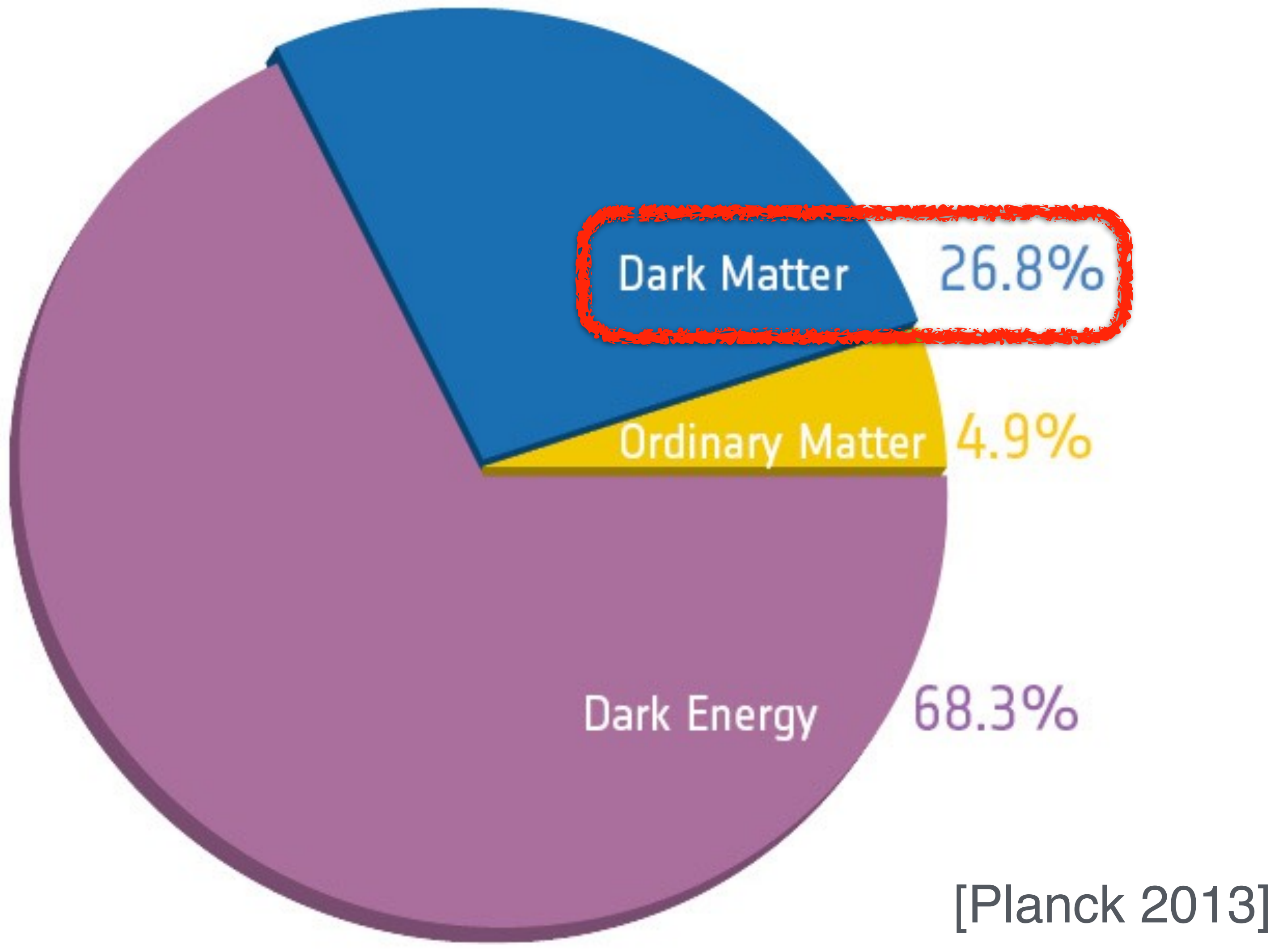
from μ -> e γ

Flavor symmetries effectively lowers the BSM scale

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

Dark Matter = non-luminous matter in the Universe

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

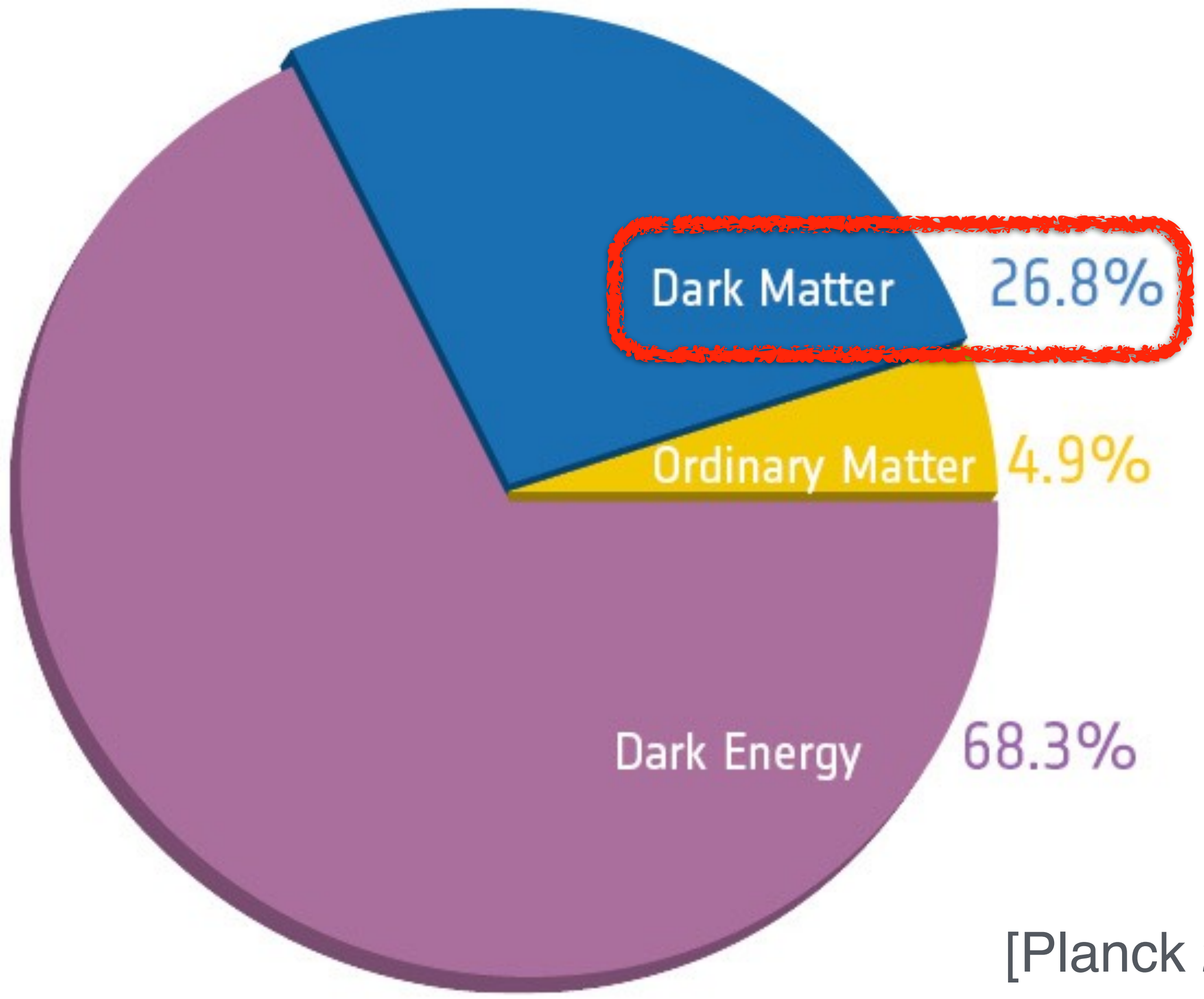


Energy density of the Universe

Dark Matter = non-luminous matter in the Universe

General properties

- stable (or lifetime longer than the age of the universe)
- collision-less
- non-relativistic
- abundant in the Universe ($\Omega h^2=0.12$)



[Planck 2013]

Energy density of the Universe

Landscape of dark matter

mass scale

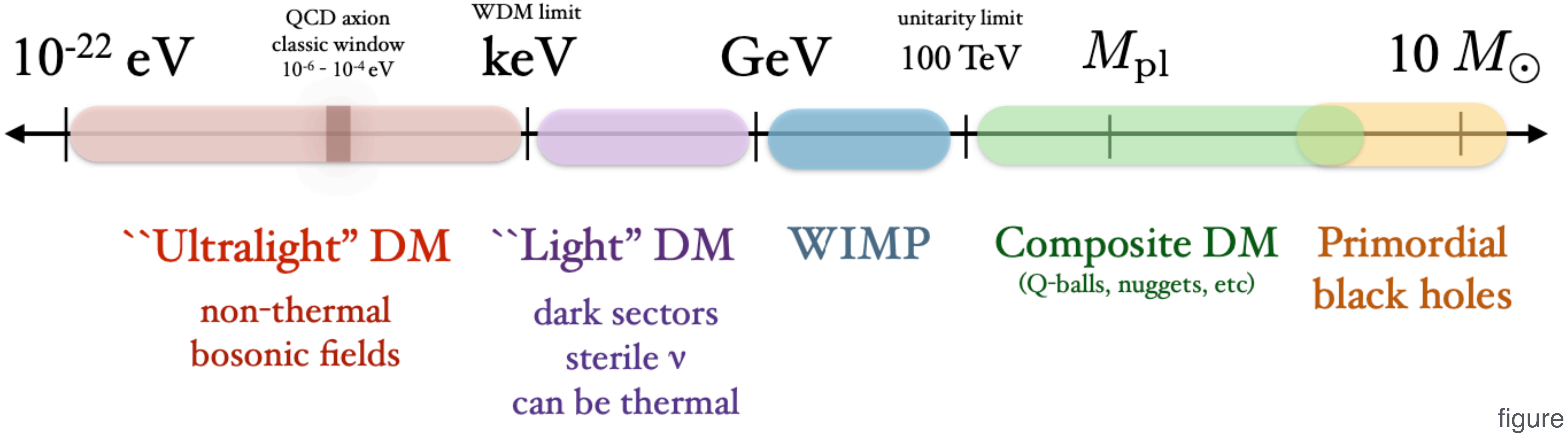


figure from 1904.07915

Landscape of dark matter

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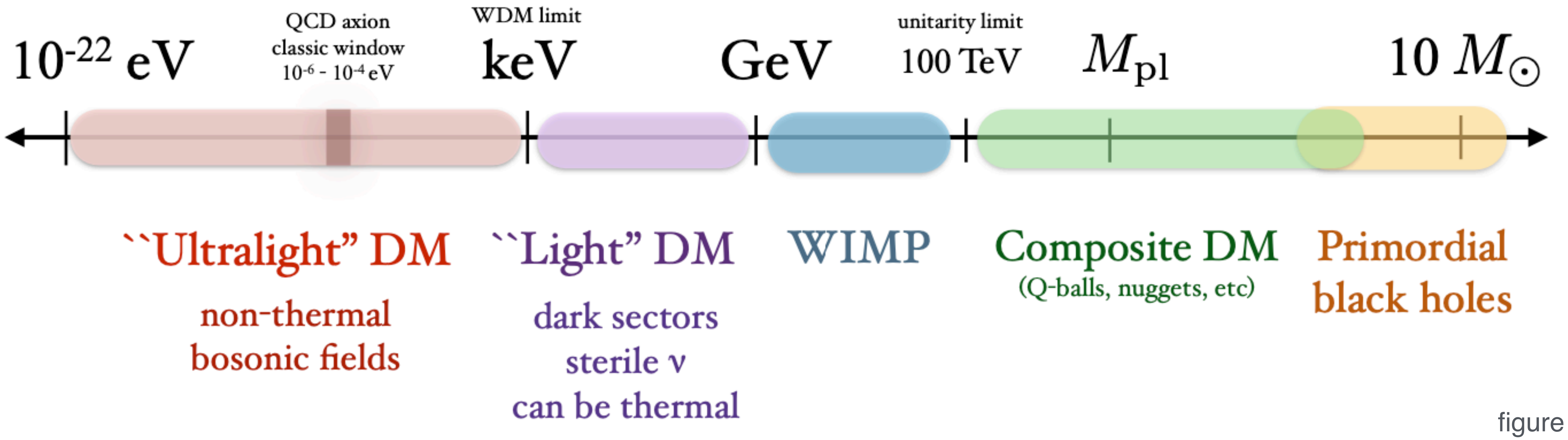

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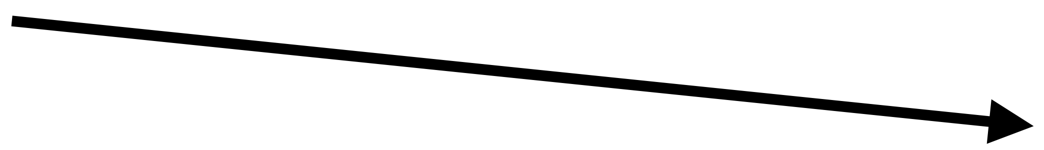
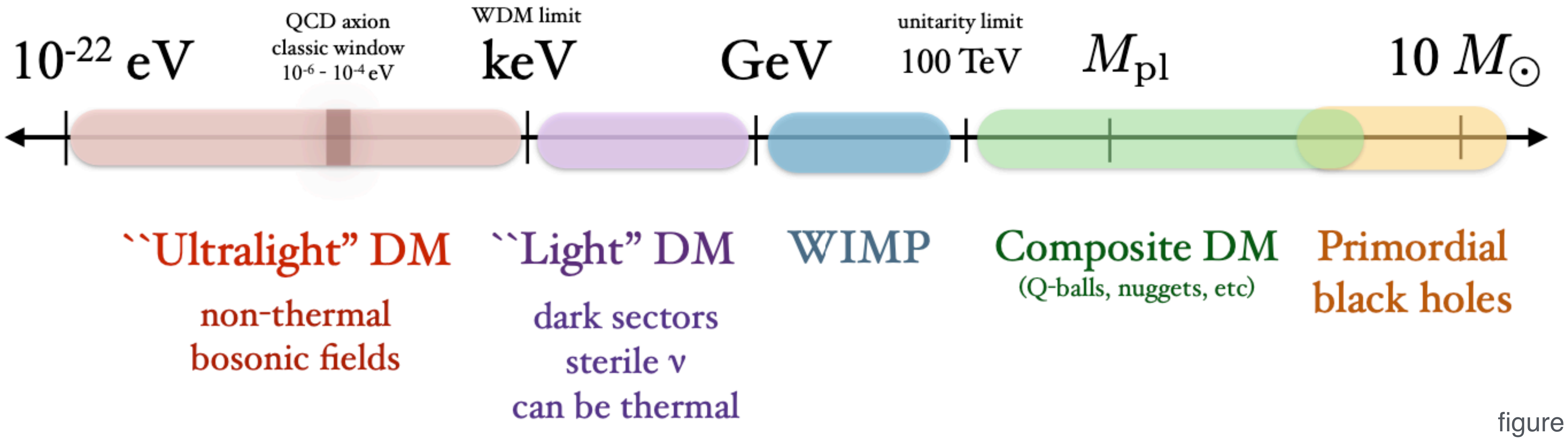


interactions to the Standard Model particles

Landscape of dark matter

mass scale



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interactions to the Standard Model particles

self-coupling

Landscape of dark matter

mass scale

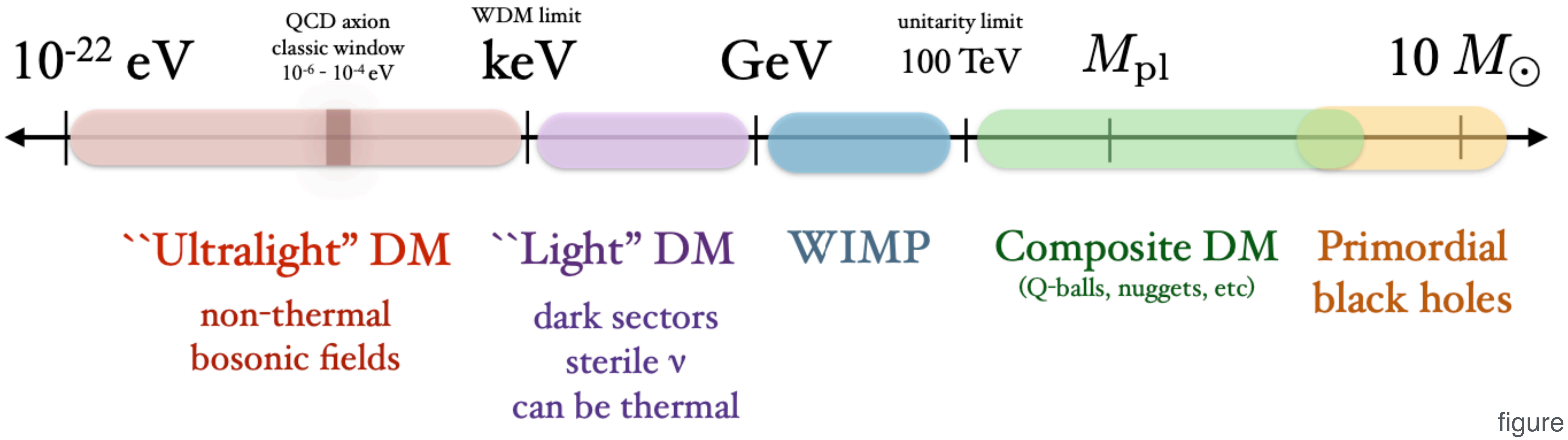
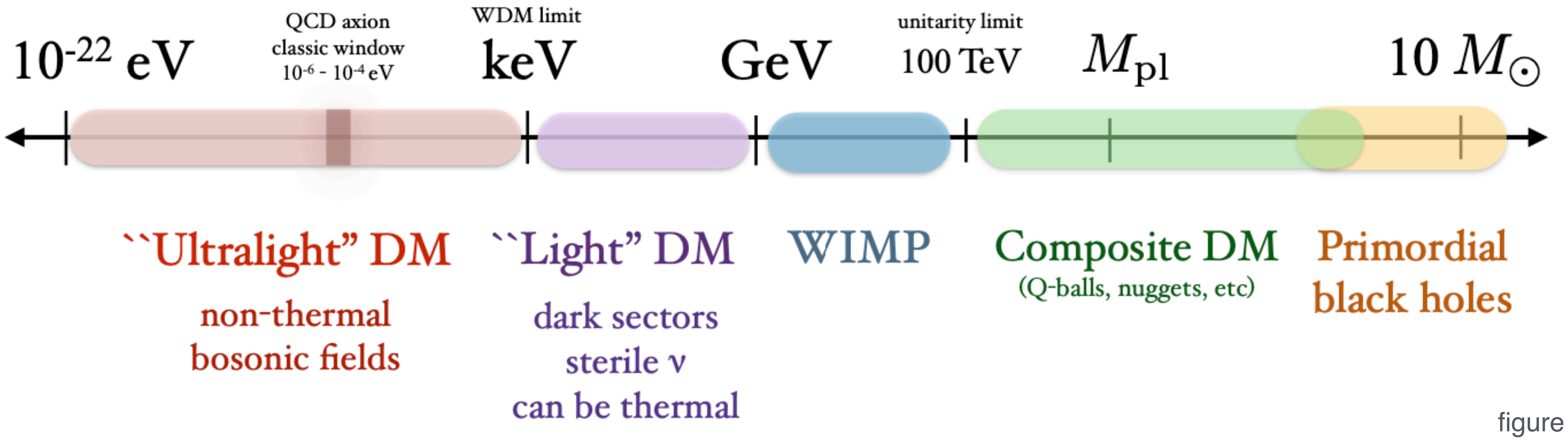


figure from 1904.07915

- interactions to the Standard Model particles
- self-coupling
- spin

Landscape of dark matter

mass scale



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- interactions to the Standard Model particles
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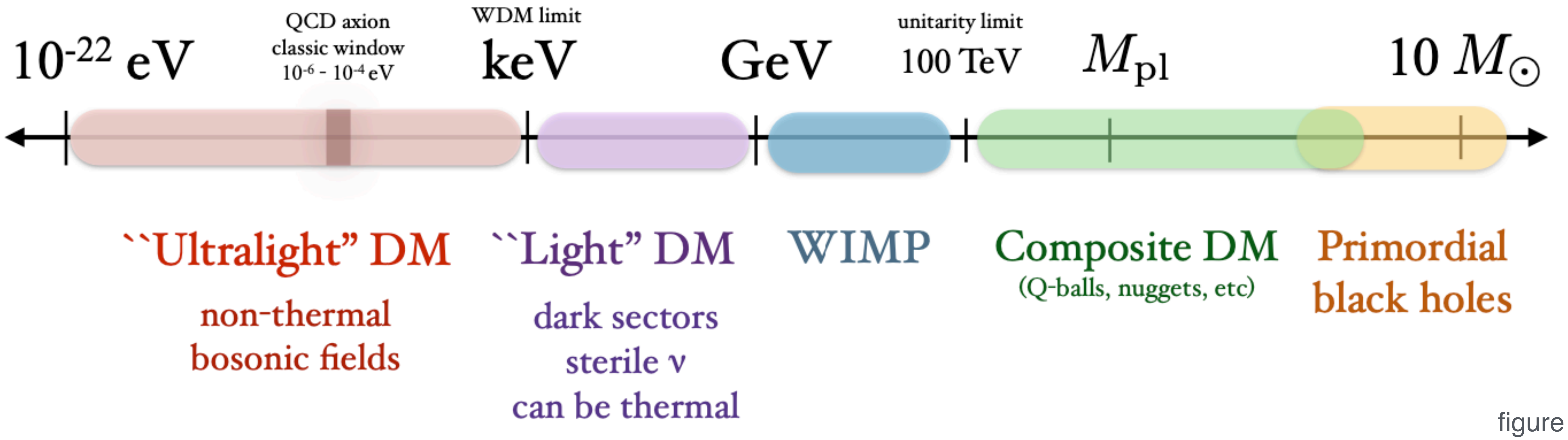
- #(components)

...

Landscape of dark matter

mass scale



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- interactions to the Standard Model particles
- self-coupling
- spin
- #(components)
- ⋰

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

How useful is flavor symmetry to understand dark matter?

Today, I won't address the flavor hierarchy, nor the origin of flavor symmetry

Instead, will study its implication for dark matter

Minimal Flavor Violation (MFV) hypothesis

MFV postulates that 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 BSM interactions formally in a flavor invariant way

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

MFV stabilizes dark matter

[Batell, Pradler, Spannowsky '11]

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

$$\chi \sim (n_q, m_q) \times (n_u, m_u) \times (n_d, m_d)$$

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

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- General decay operators

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

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⇒ $SU(3)_c$ invariant

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

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

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$SU(3)_c$ and flavor invariant

$$(A + B + C - \overline{A} - \overline{B} - \overline{C}) \bmod 3 = 0$$
$$(n_q - m_q + A - \overline{A} + D - \overline{D} + E - \overline{E}) \bmod 3 = 0$$
$$(n_u - m_u + B - \overline{B} - D + \overline{D}) \bmod 3 = 0$$
$$(n_d - m_d + C - \overline{C} - E + \overline{E}) \bmod 3 = 0$$

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

$$n_\chi = n_q + n_u + n_d$$
$$m_\chi = m_q + m_u + m_d$$

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

$$n_\chi = n_q + n_u + n_d$$
$$m_\chi = m_q + m_u + m_d$$

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]

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

where $\omega^3 = 1$

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

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

a center group of $SU(3)_c$

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

- All SM fields and Yukawa spurions are Z_3^χ singlet
- Favored DM: $\chi \to (\omega)^{n_\chi - m_\chi}\chi$, i.e. 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

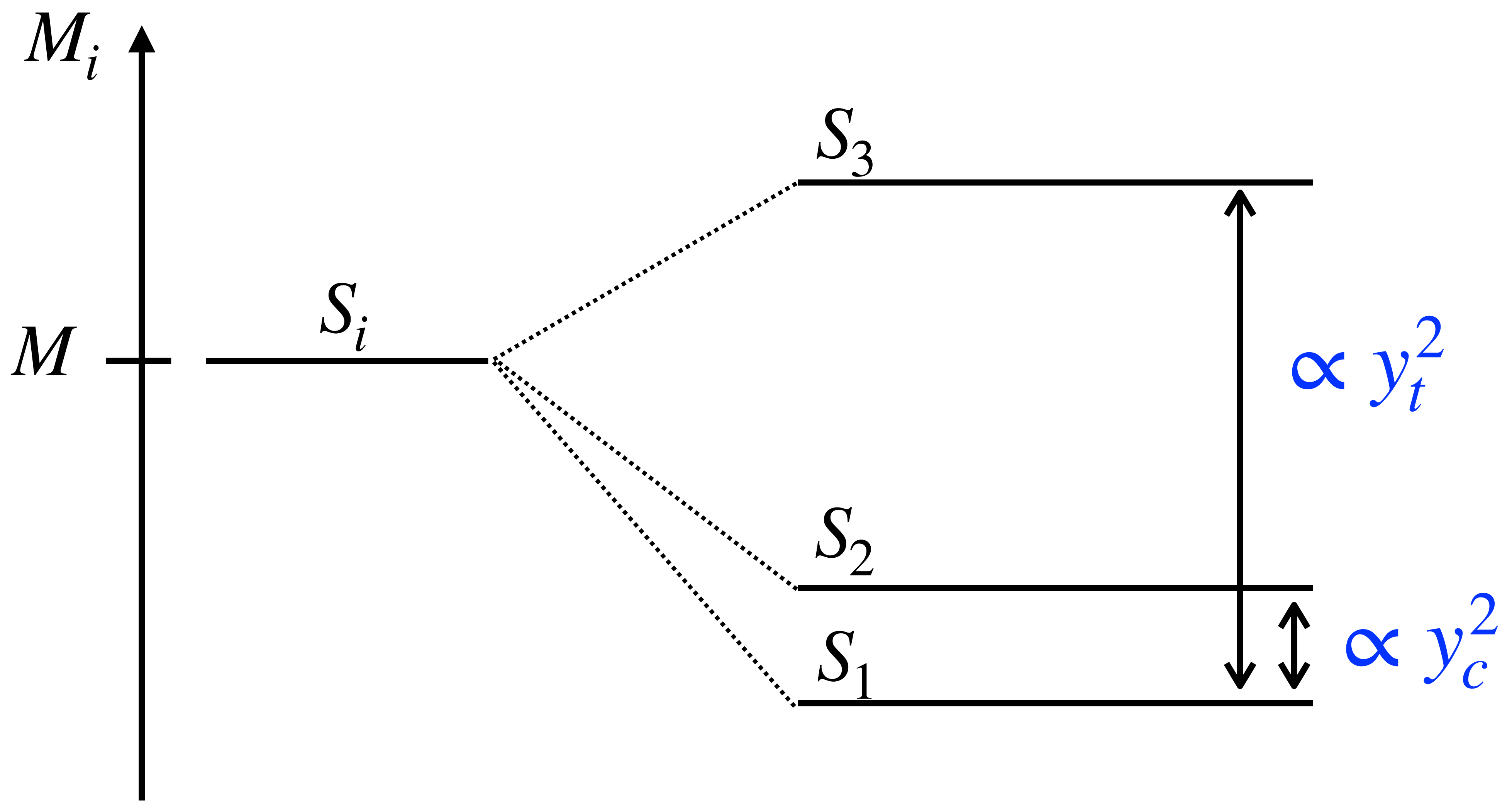
Multi-component dark matter?

Naturally predicts a family of dark matter

Mescia, SO, Wu, 2408.16812

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

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



Heavy scalar decays are triggered by dim-6 operators

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

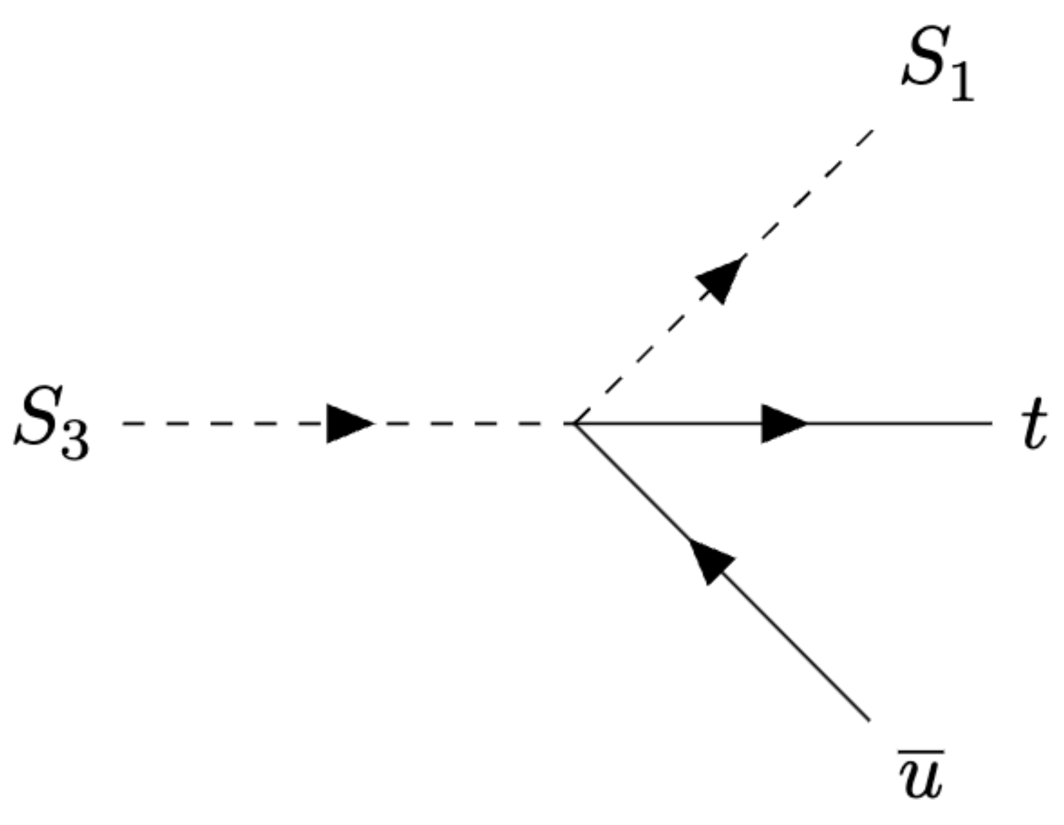
$$\sim \frac{c_2^4}{\Lambda^2}\, \bar{u}_i (m_u^i P_R + m_u^j P_L) u_j \left(S_j^* S_i\right)$$

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

Decay of heavy states

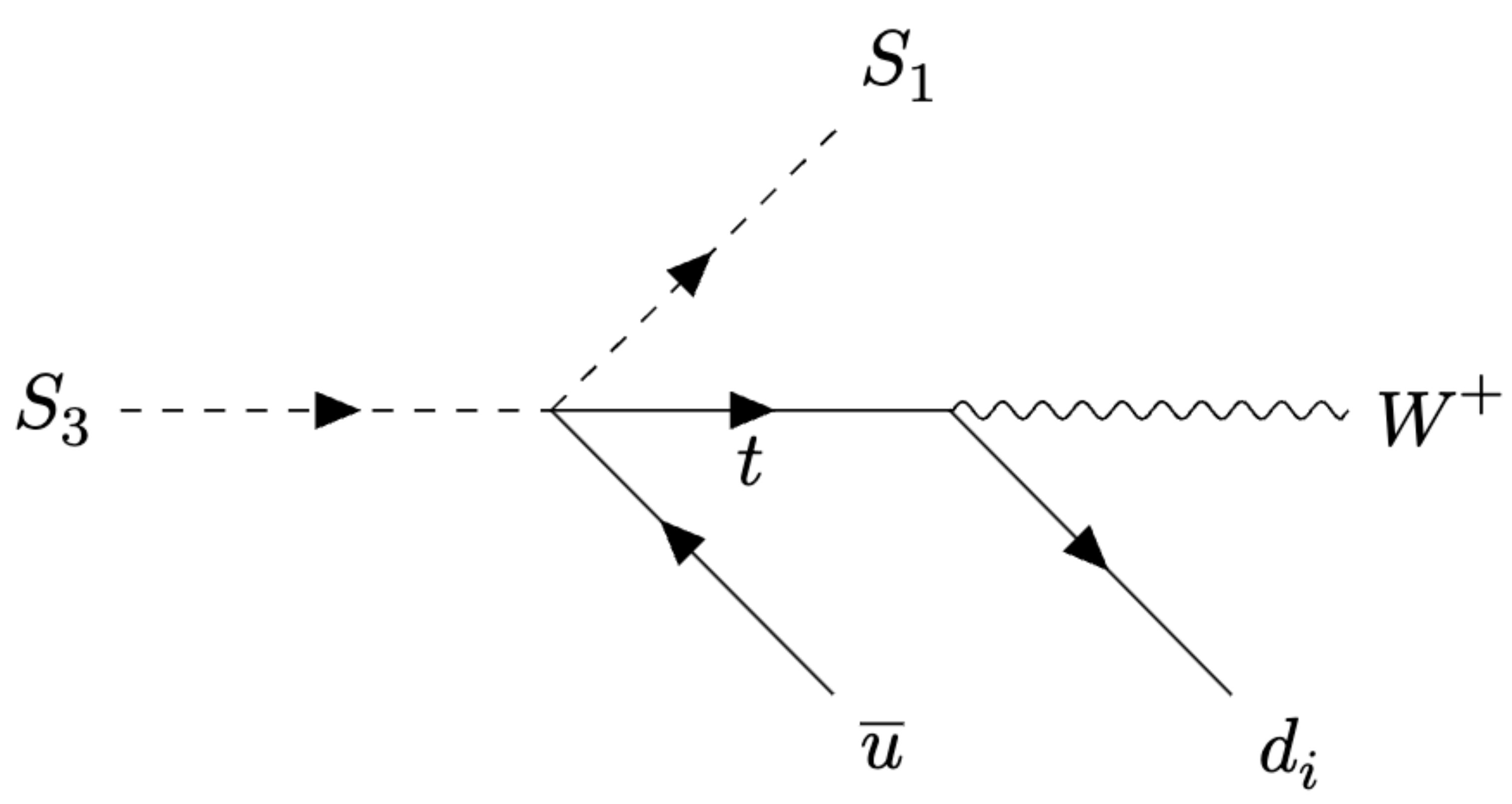
- Dominant mode depends on the mass splitting $\Delta M = M_3 - M_1$

$$\Delta M \gtrsim m_t$$



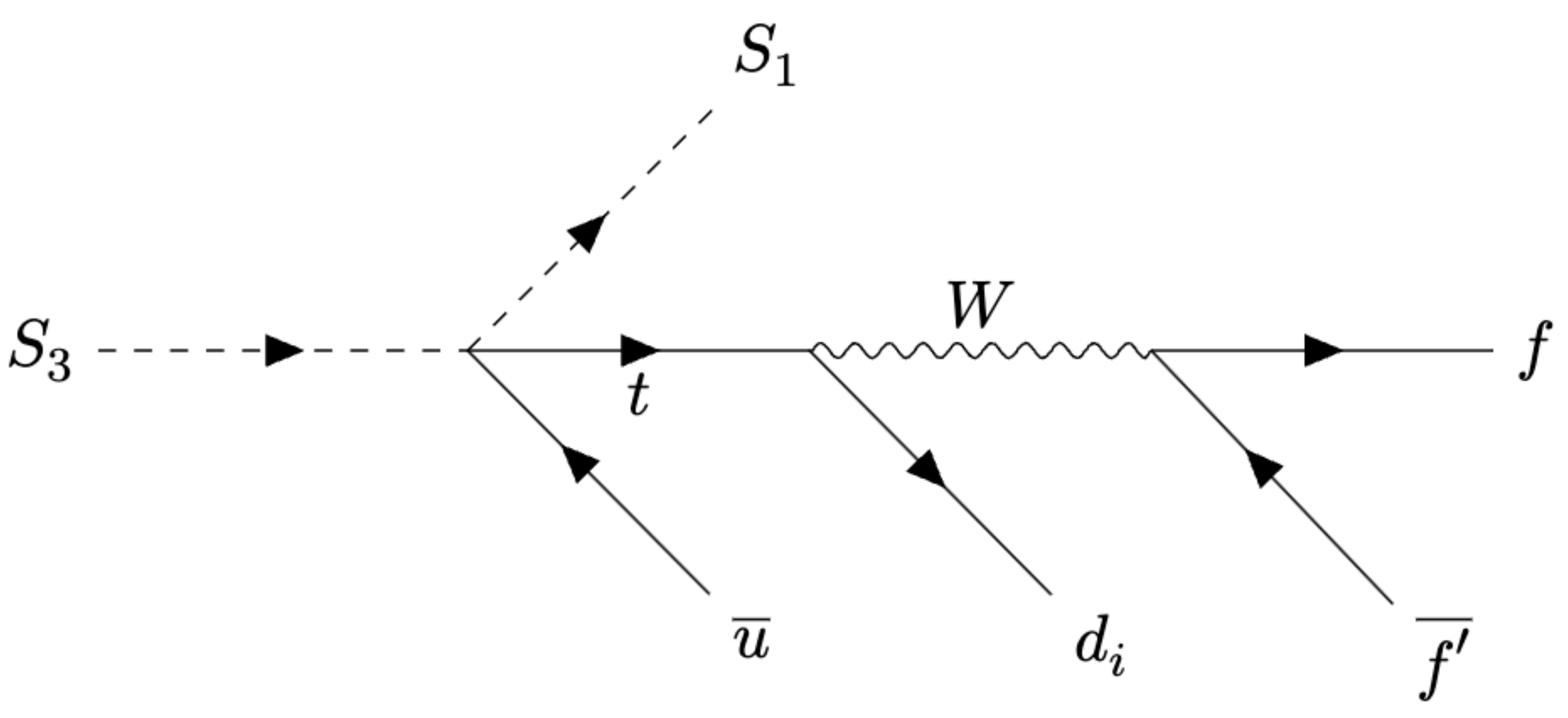
$$\Gamma \sim \frac{m_t^2 (\Delta M)^5}{480\pi^3 \Lambda^4 M_3^2}$$

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



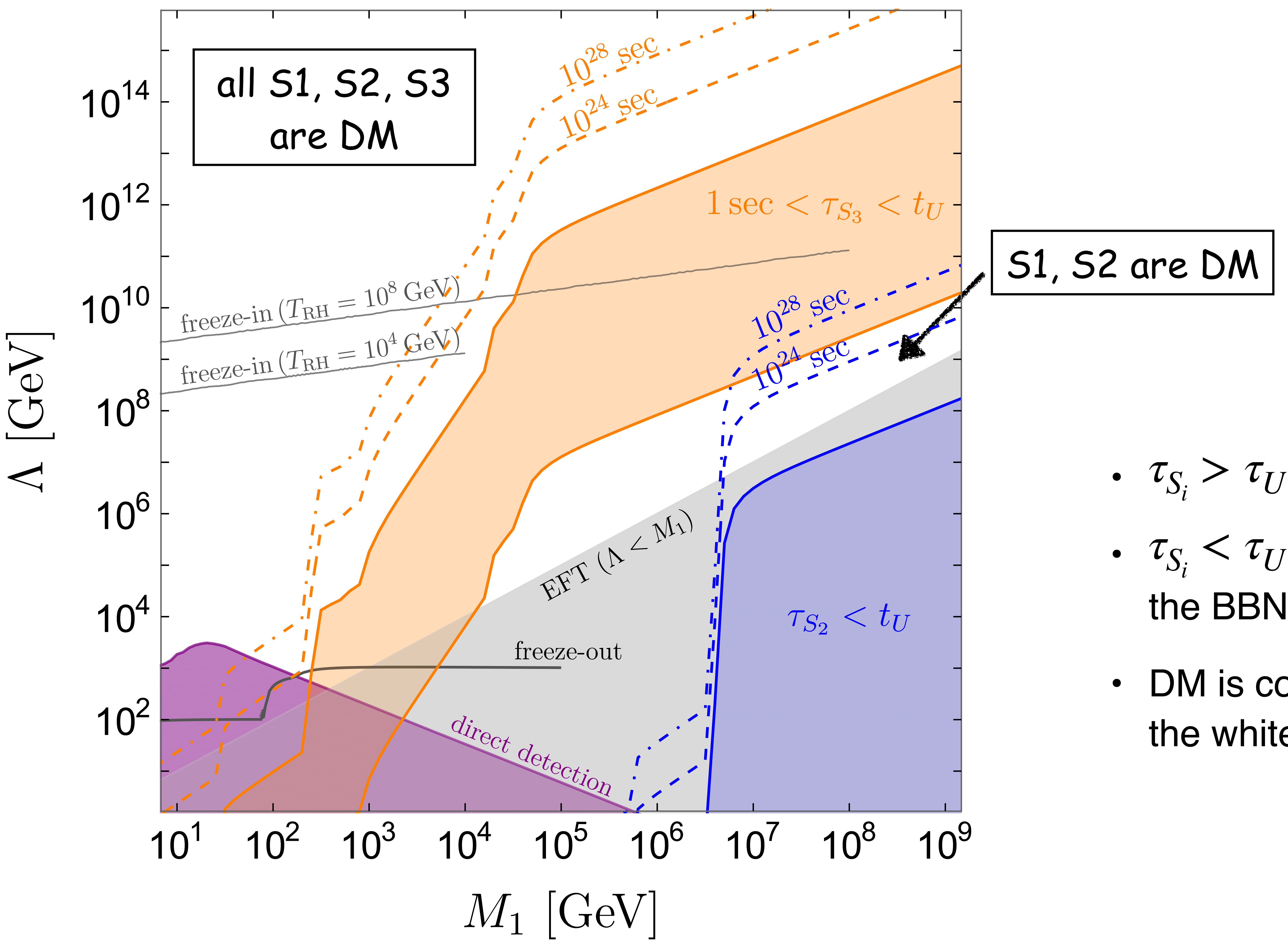
$$\Gamma \sim \frac{(\Delta M)^{11} |V_{ti}|^2}{41472\pi^5 \Lambda^4 M_3^2 m_t^2 v^2}$$

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



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

Parameter spaces for multi-component DM



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

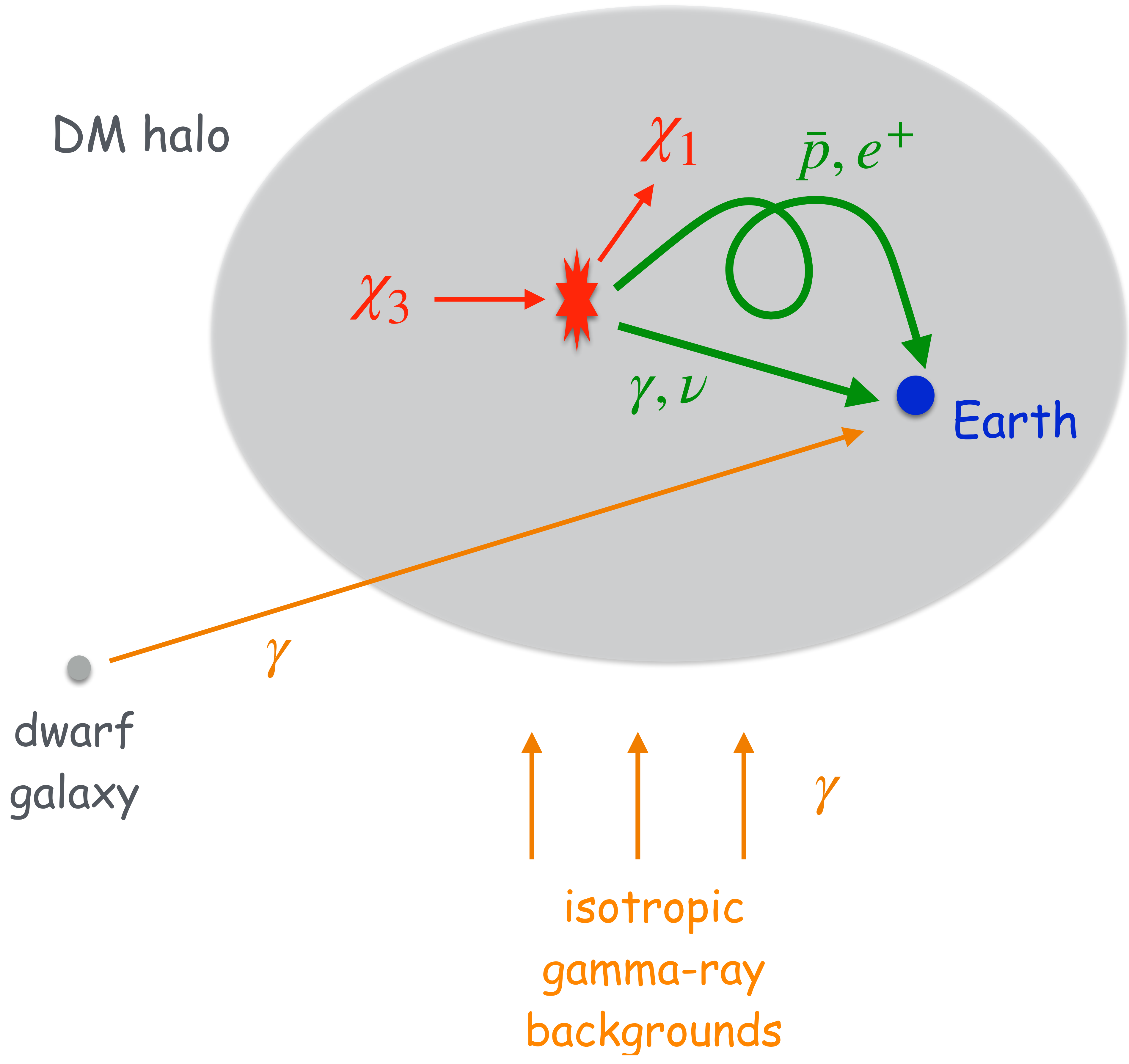
$\lambda = 0$ no coupling to Higgs

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

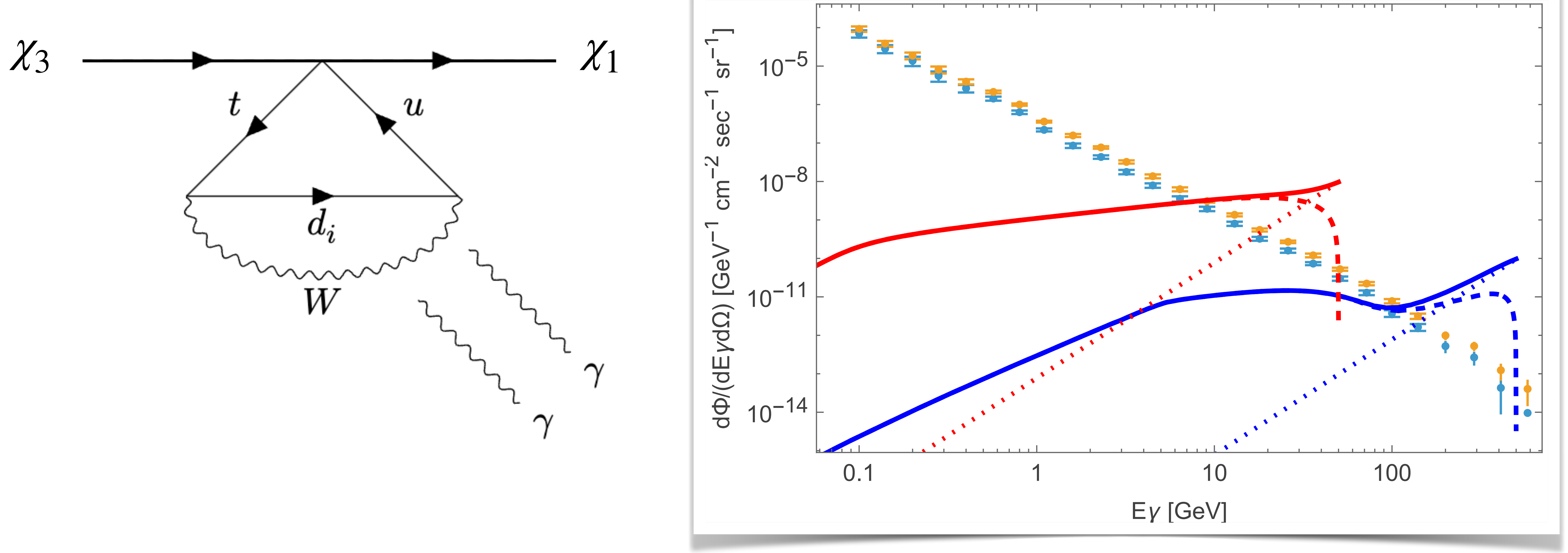
Signatures from multi-component flavored dark matter

1. Indirect searches for heavy decaying dark matter

Kim, Landini, Mescia, SO, work in progress



- $\chi_{2,3} \to \chi_1 \gamma\gamma$ [Dienes+ 1406.4868; Ghosh+ 1909.13292; Herms, Ibarra 1912.09458]



Also we can study

- 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

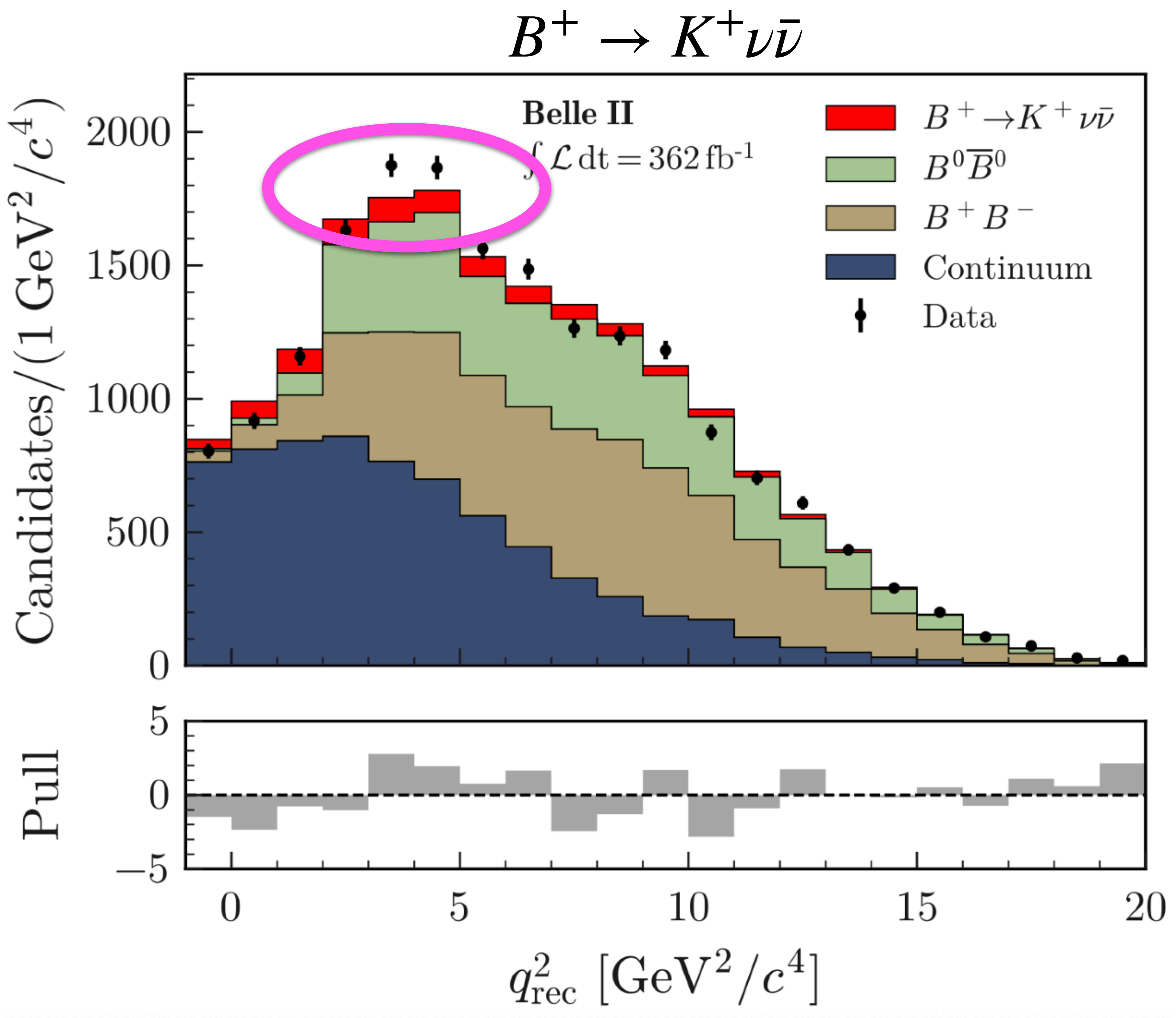
Mescia, SO, Swallow, Toni, 2601.08907

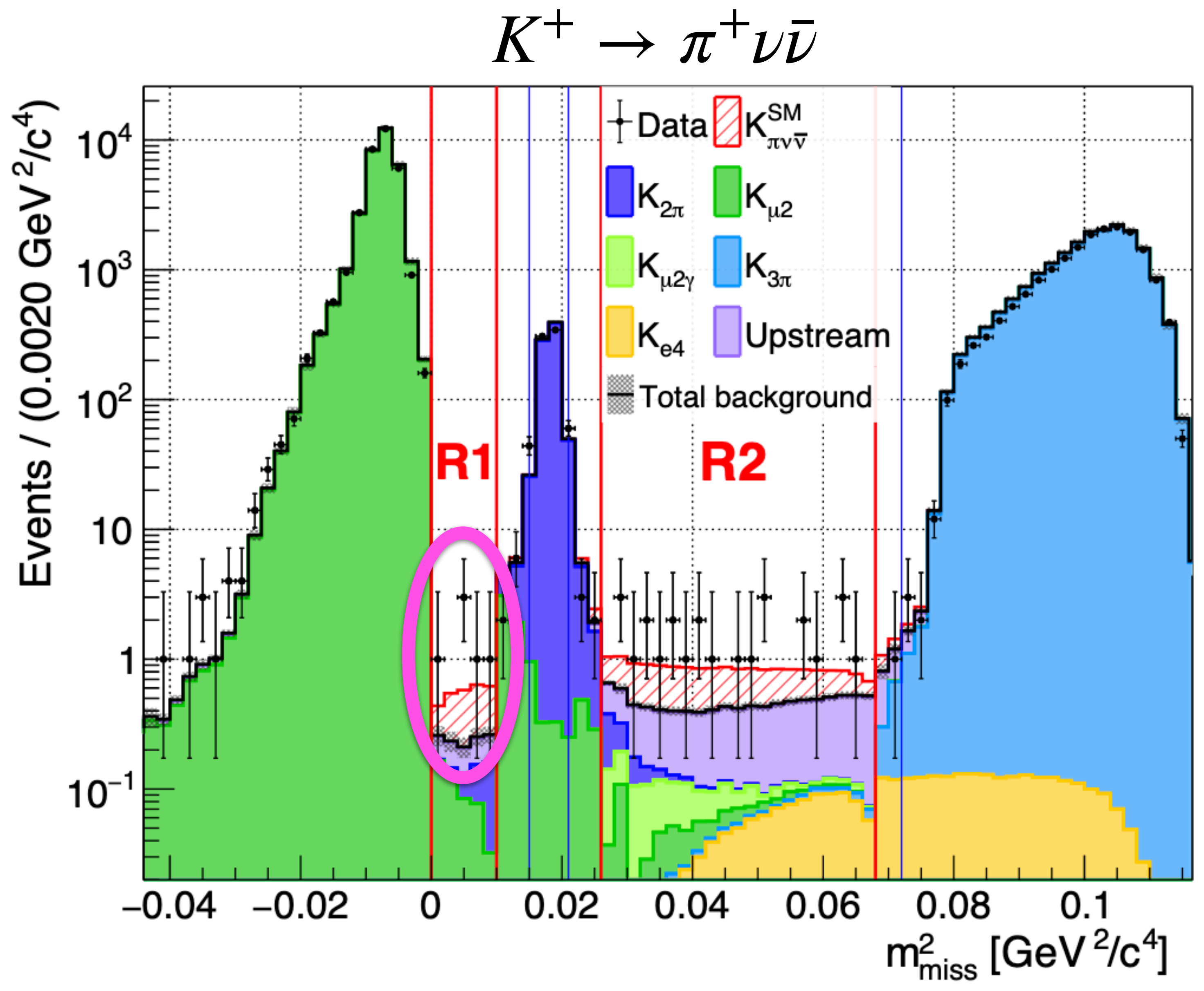
- Apparent flavor violating decays can naturally occur

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!

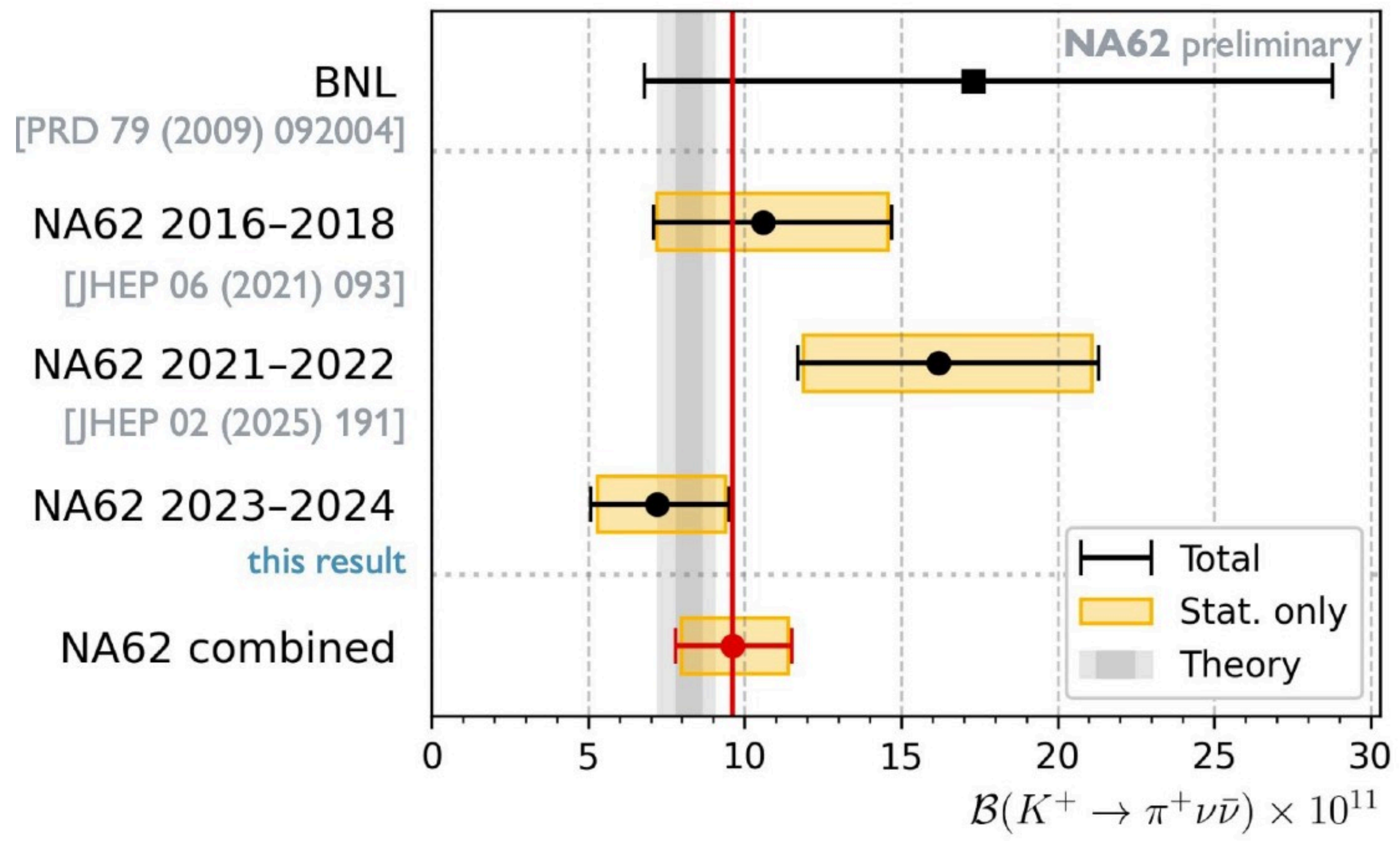
@Belle-II BaBar — @NA62 KOTO

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





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

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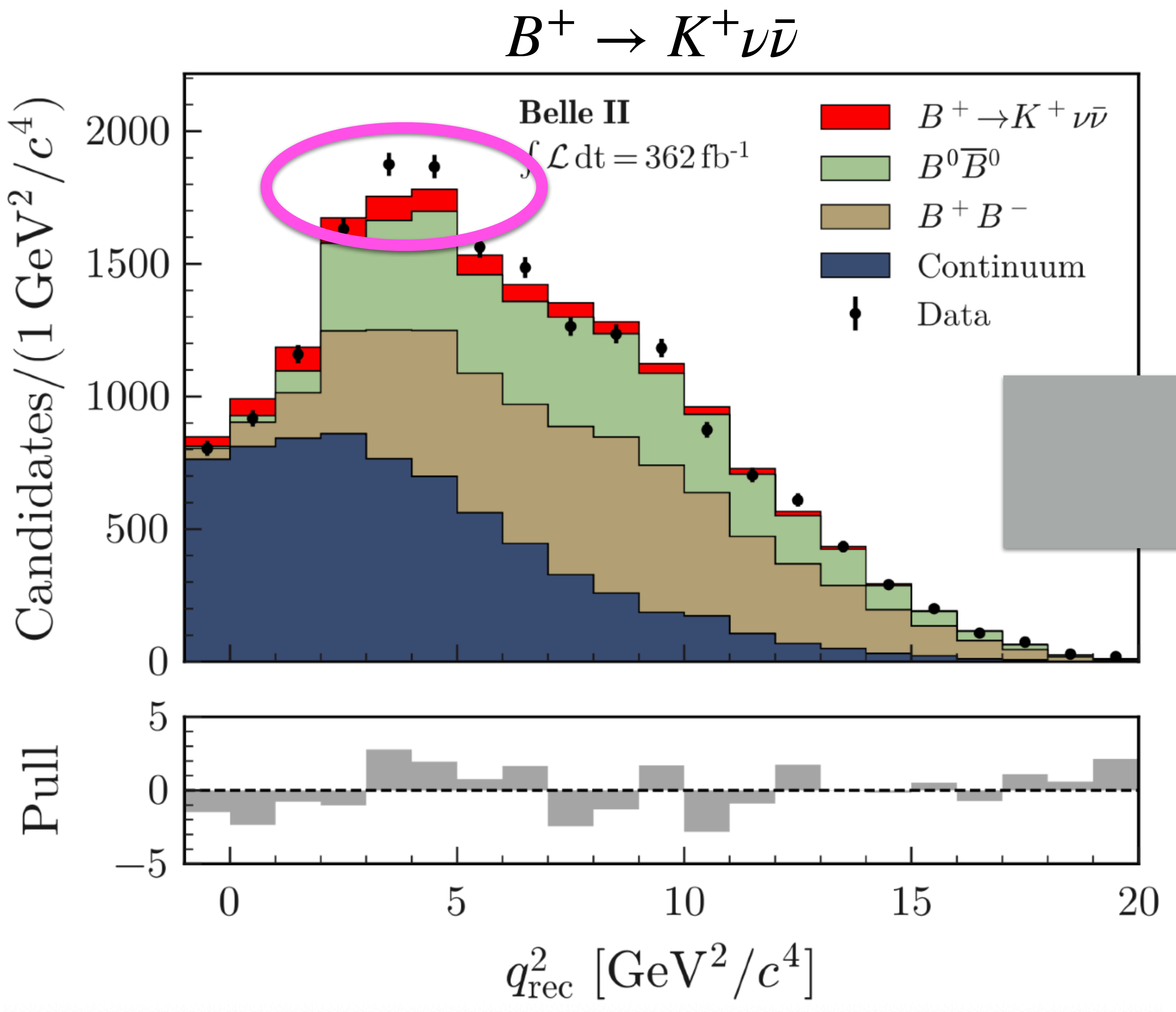
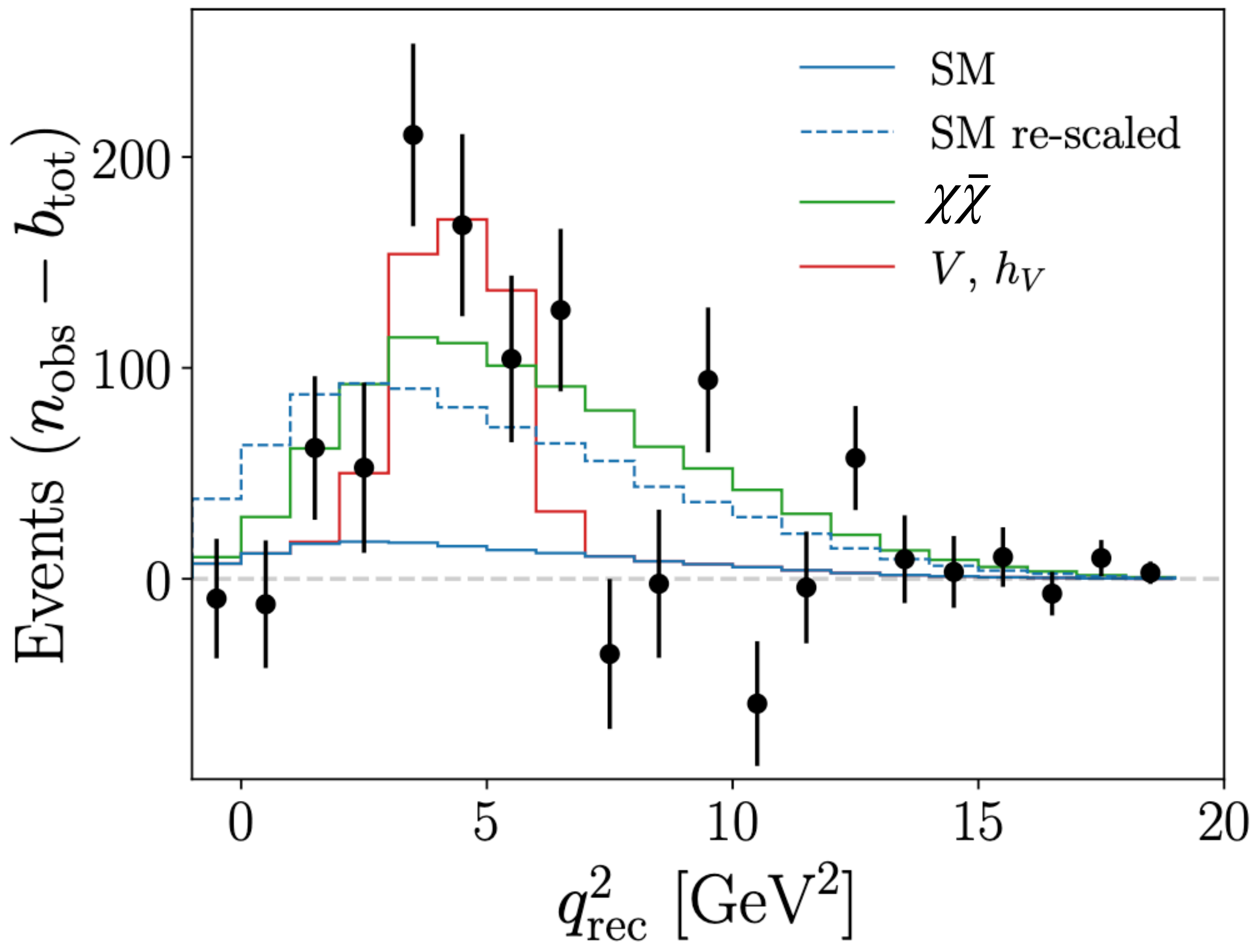


q^2 distribution is modified



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 $\rightarrow$ **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**?

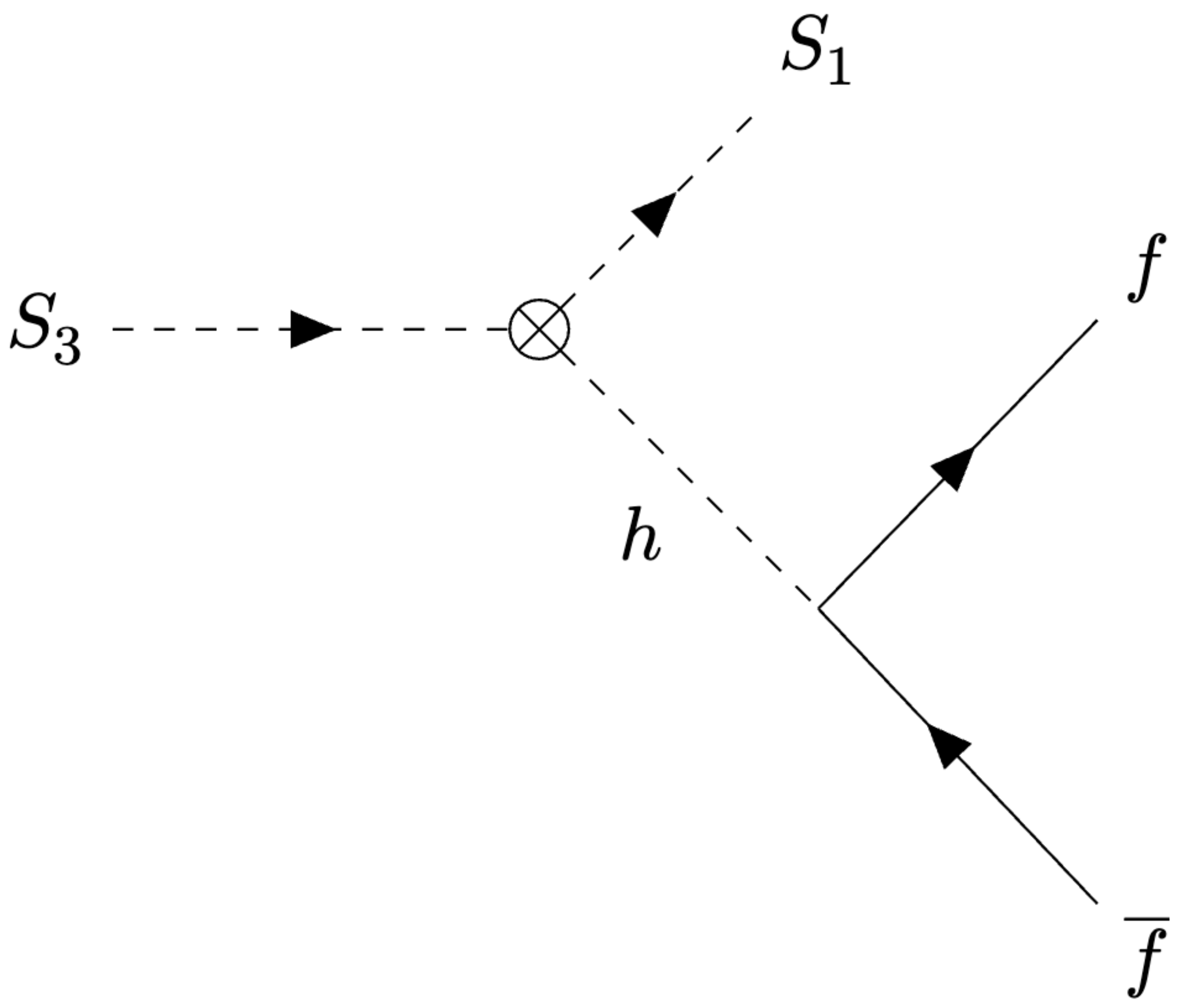
Thanks for listening!

Back up

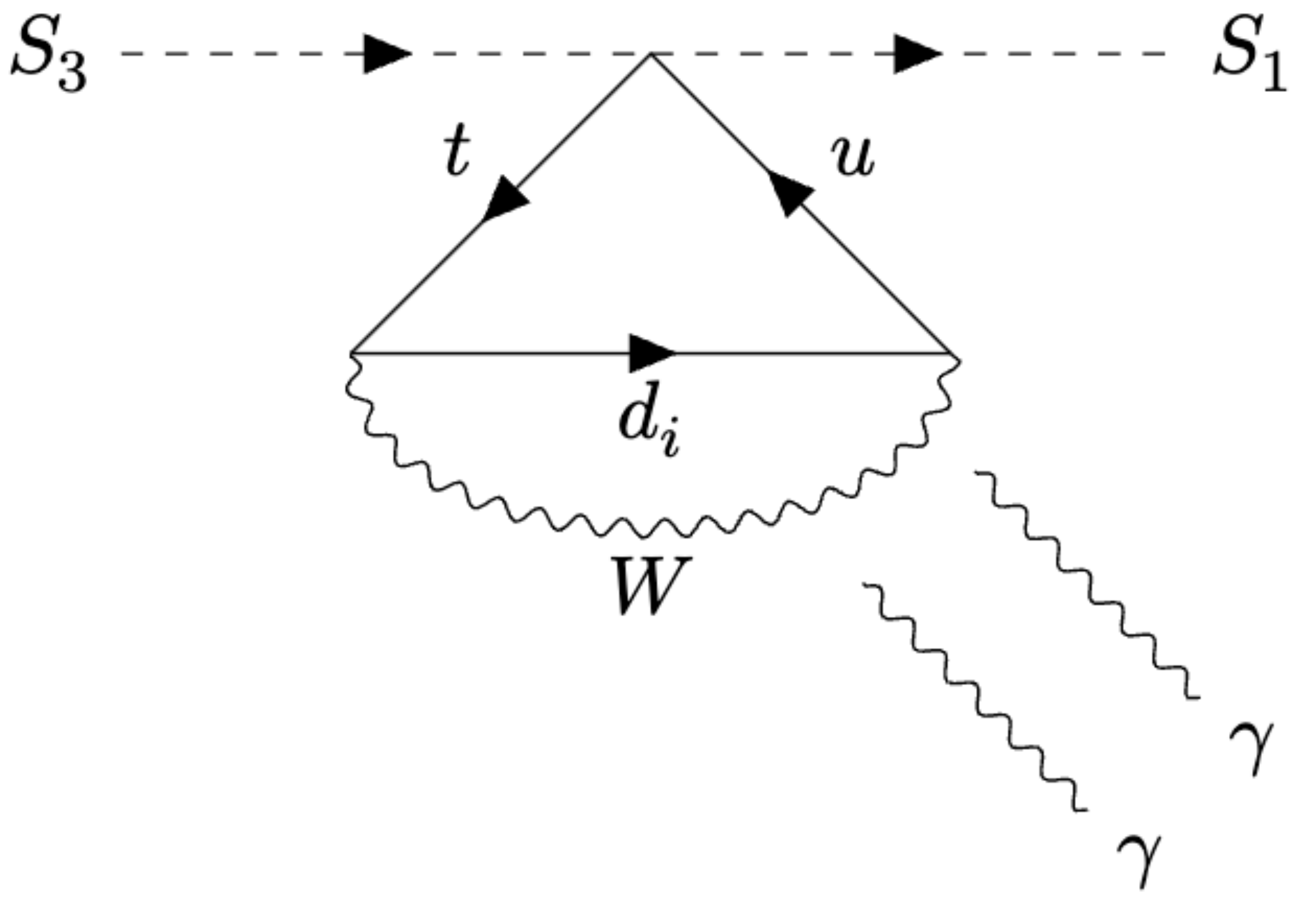
Decay at higher orders

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

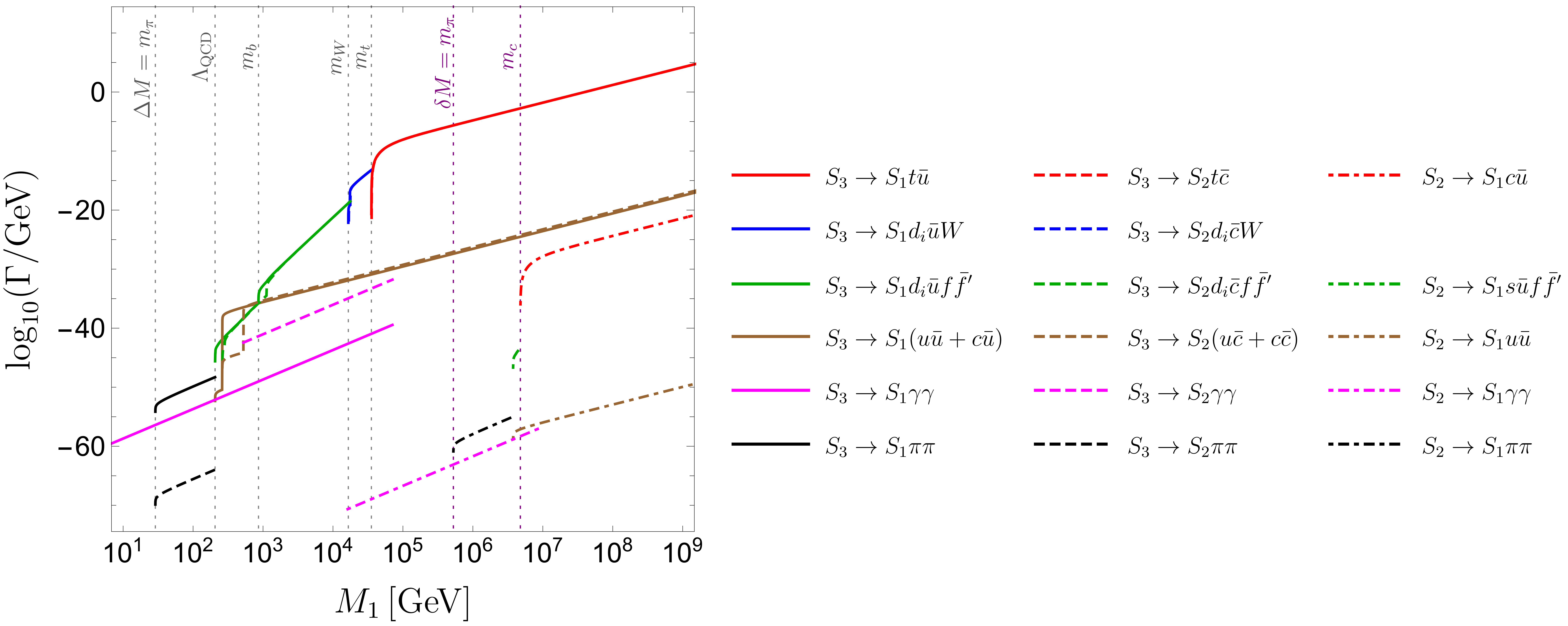


$$\sim \epsilon^2\, Y_u^\dagger Y_d Y_d^\dagger Y_u$$

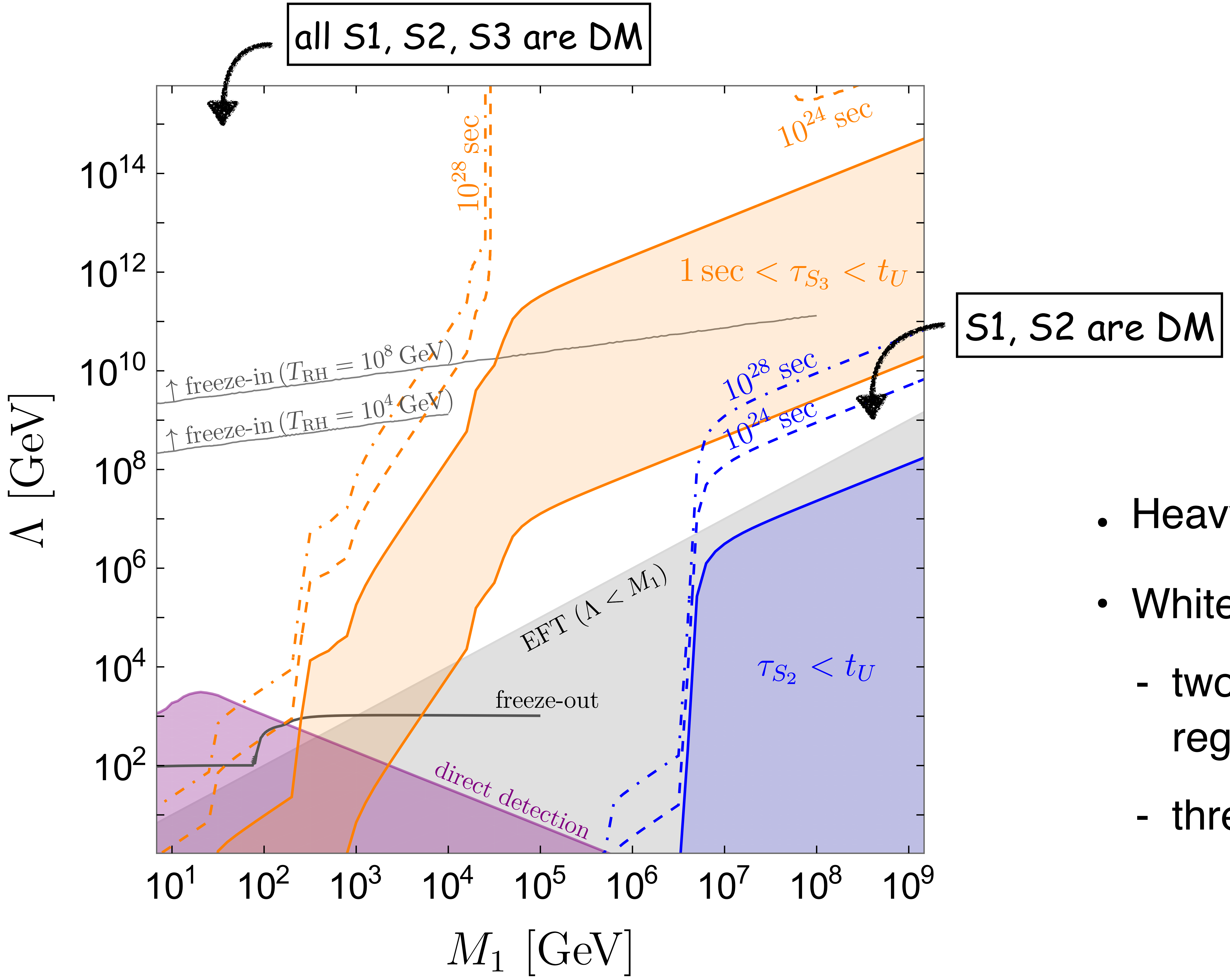


$$\sim \frac{Y_u^\dagger Y_d Y_d^\dagger Y_u}{(16\pi^2)^2}$$

Partial decay widths for heavy scalars



Impact of Higgs portal coupling (1/2)



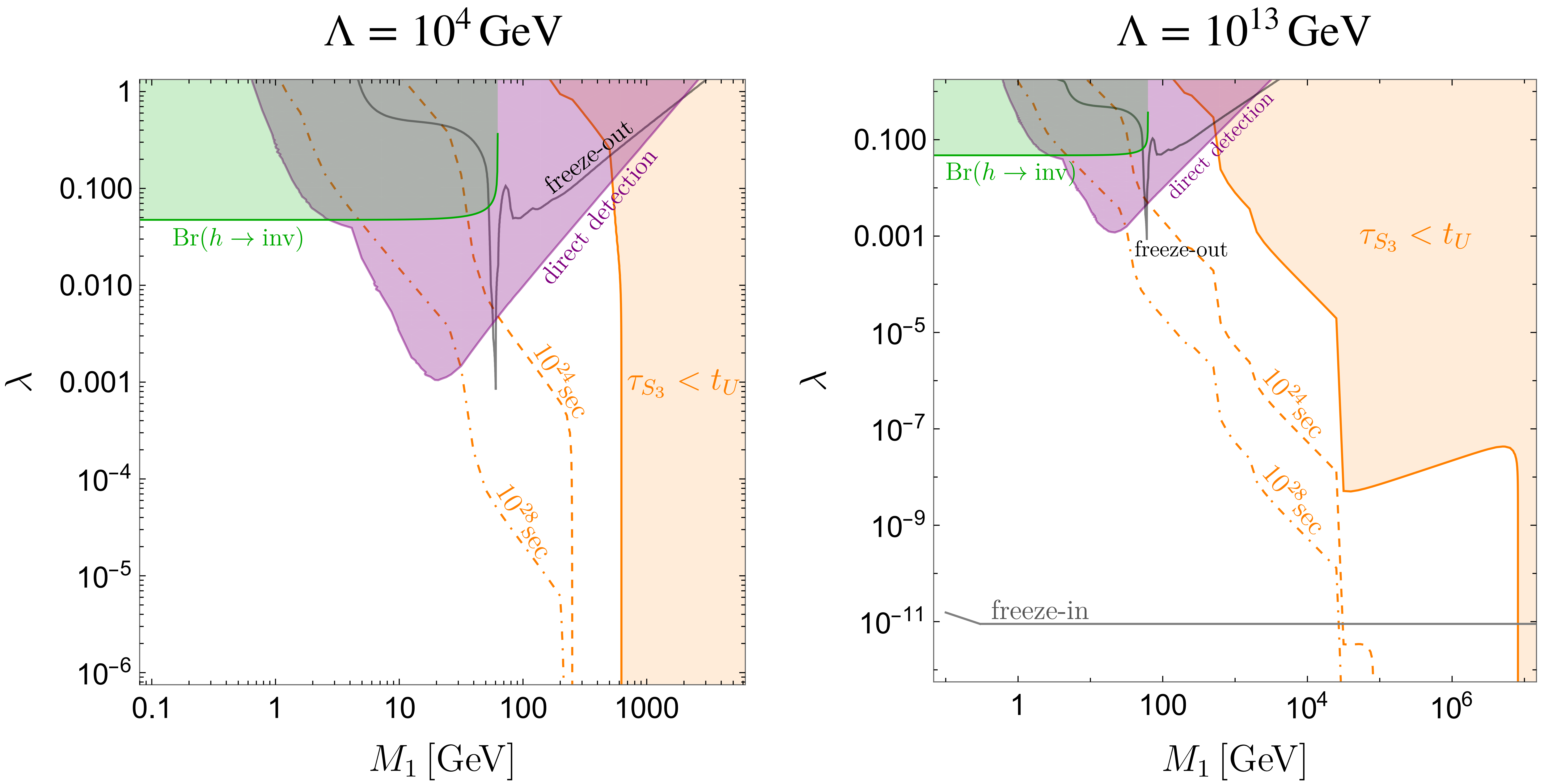
$$\epsilon = 10^{-2} \simeq \frac{M_3 - M_1}{y_t^2 M_1} \simeq \frac{M_2 - M_1}{y_c^2 M_1}$$

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

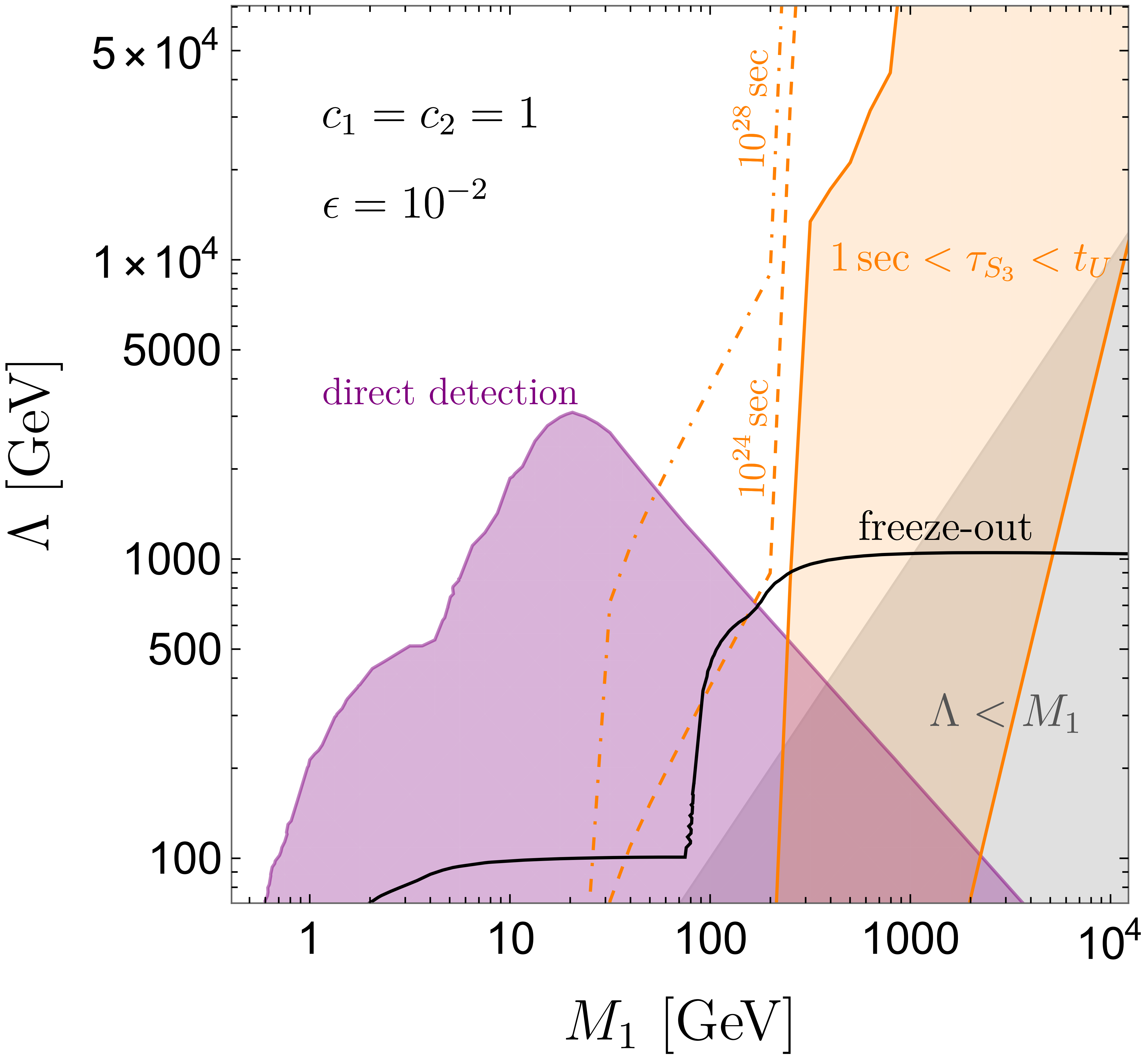
- Heavy components are also DM if $\tau_{S_i} > \tau_U$
- White region is allowed
  - two-component between orange and blue regions
  - three-component above the orange region

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