Unification of the SM and DM in $[\text{SU}(5) \times \text{U}(1)]^4$ GUT

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Tufts Univ.

DPF2019 @Northwestern Univ.

Aug 1st 2019

Unification of ~~the SM and~~ DM in $[SU(5) \times U(1)]^{4}$ GUT

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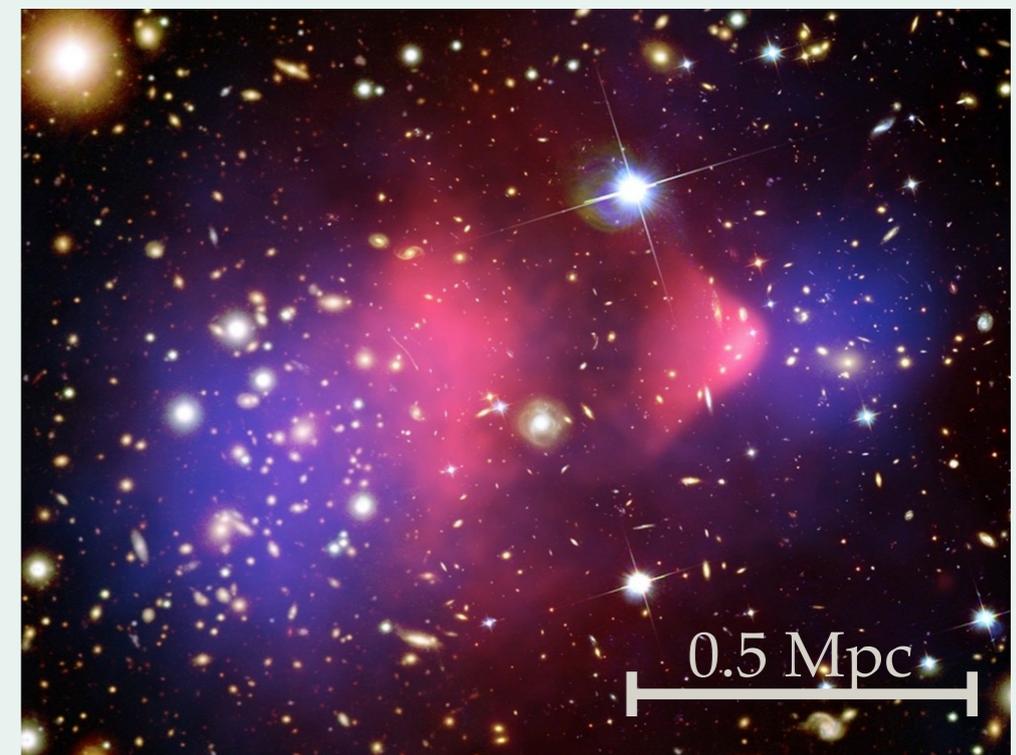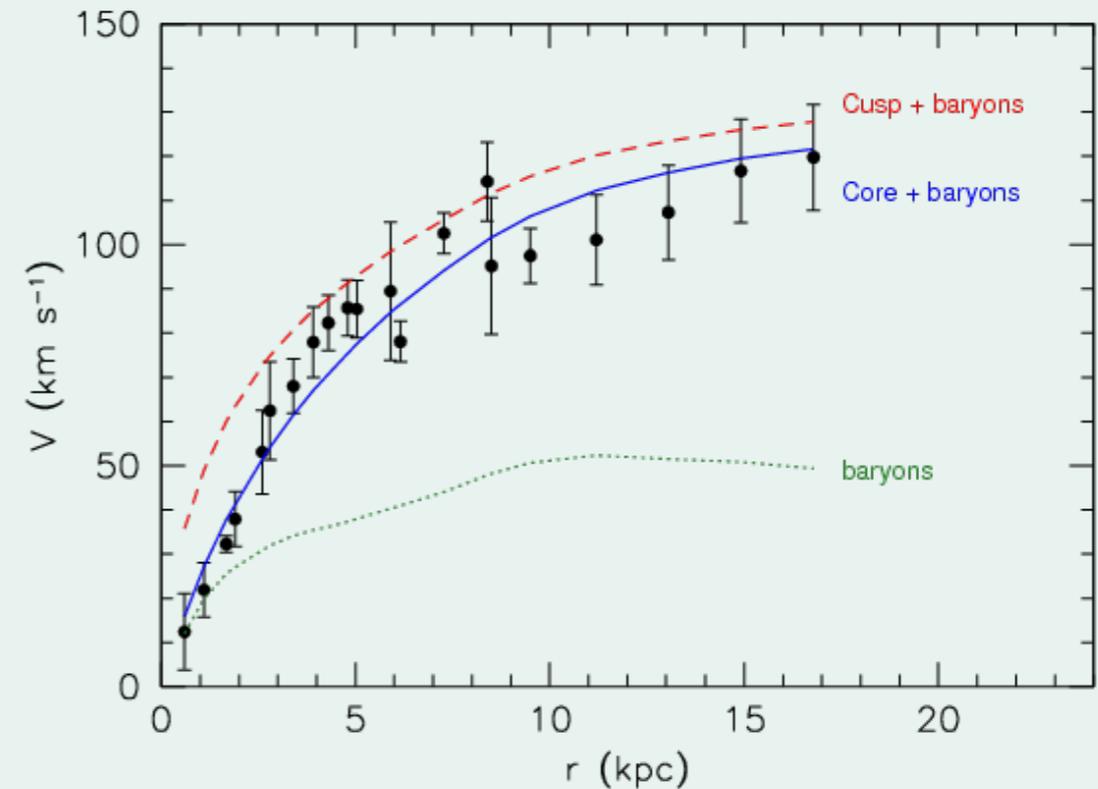
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Motivation in phenomenology

▶ **Dark matter is**

- stable

- neutral

- cold

➡ DM may be charged under a hidden U(1) gauge symmetry.

0.5 Mpc

M. Markevitch, et al., '03

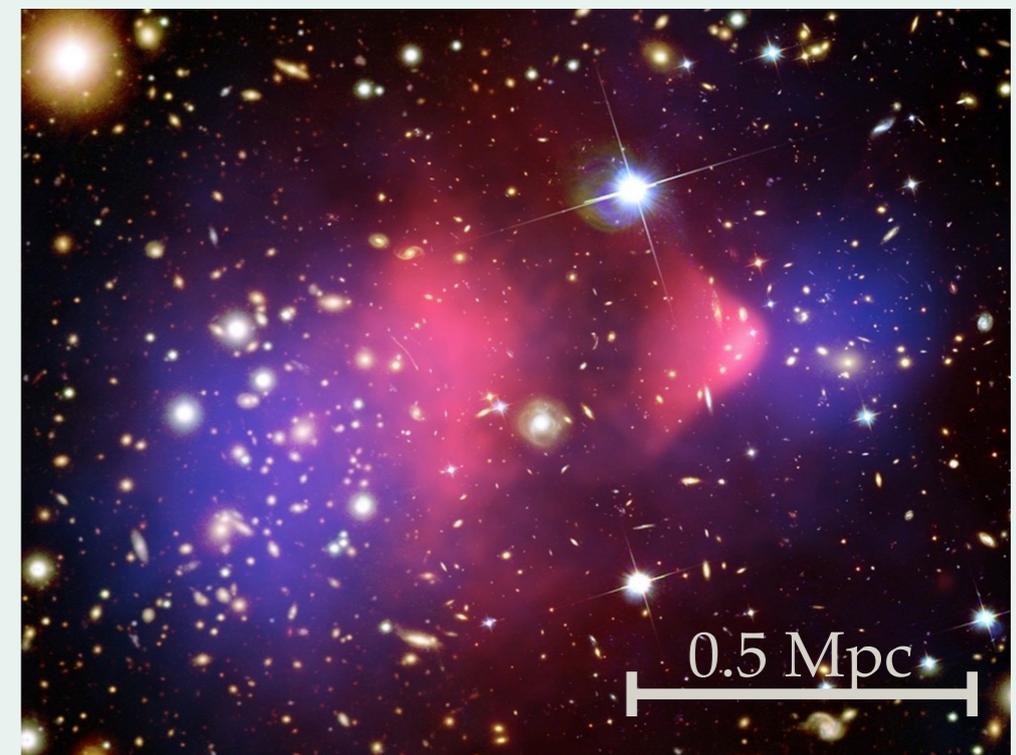Masaki Yamada

▶ **Dark matter is**

- stable

- neutral

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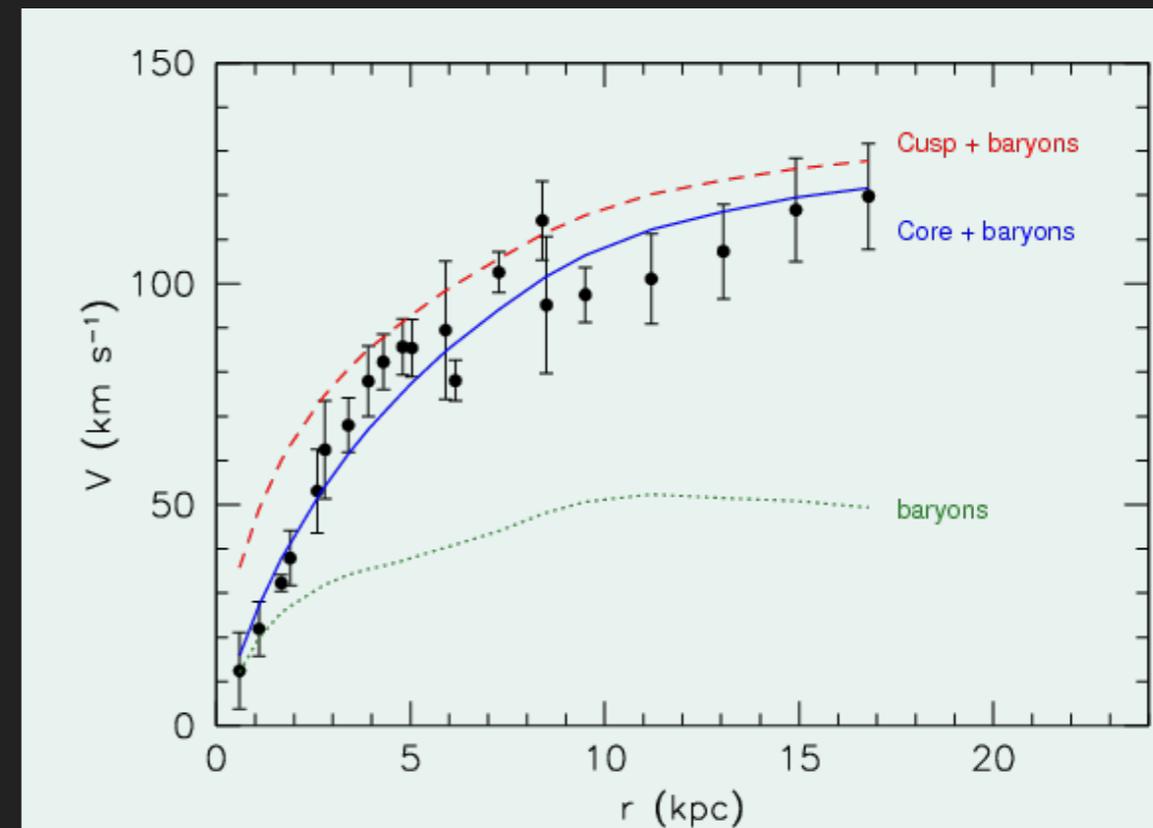➡ DM may be charged under a hidden U(1) gauge symmetry.

- Thermal relic density:

$$\Omega_\eta h^2 \simeq 0.13 \left(\frac{m_\eta}{40 \text{ GeV}} \right)^2 \left(\frac{\alpha_4}{10^{-3}} \right)^{-2}$$

- Self-interaction cross section:
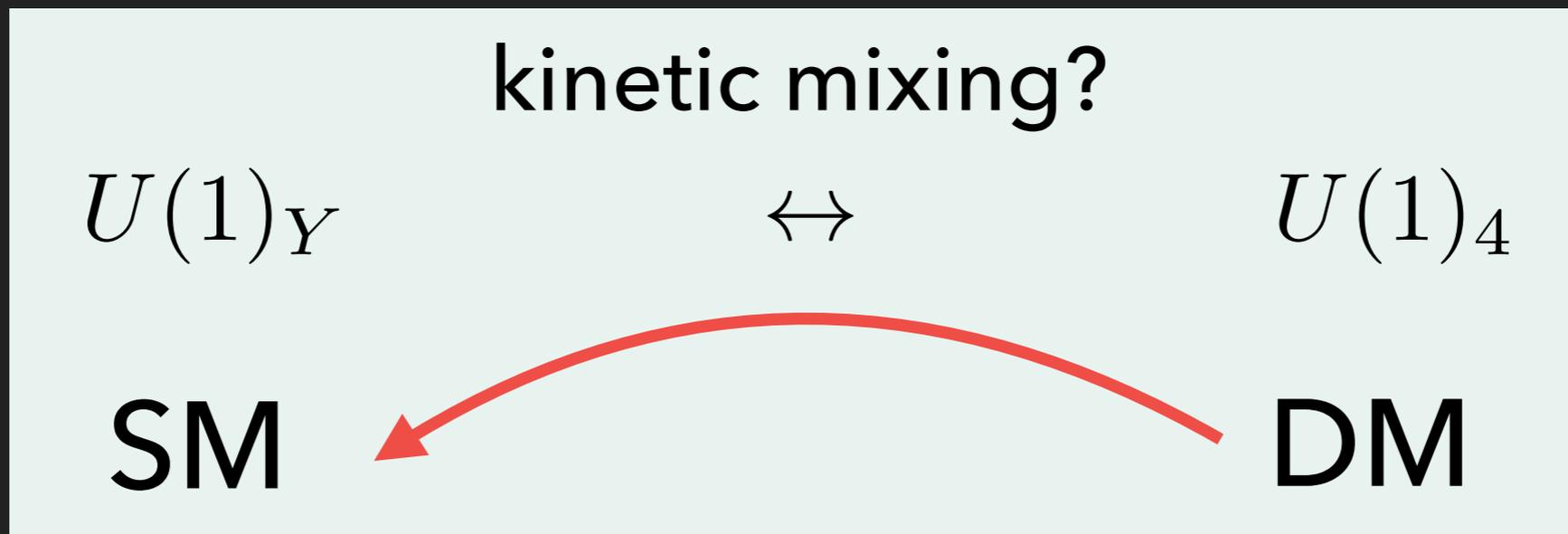
$$m_{Z_4} = 10 - 100 \text{ MeV} \quad \rightarrow$$
$$\sigma_{\text{ela}}/m_{\text{DM}} = 0.1 - 1 \text{ cm}^2/g \times f(v)$$

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0.5 Mpc

M. Markevitch, et al., '03

Kinetic mixings and DM detection signals

kinetic mixing?

$$U(1)_Y \quad\quad \leftrightarrow \quad\quad U(1)_4$$

SM   DM

→ too large signals for indirect detection experiments

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Kinetic mixings and DM detection signals

$$U(1)_Y \quad \underset{\epsilon_1}{\leftrightarrow} \quad U(1)_{(B-L)_3} \quad \underset{\epsilon_2}{\leftrightarrow} \quad U(1)_4$$

SM $\qquad\qquad\qquad\qquad\qquad\qquad$ DM
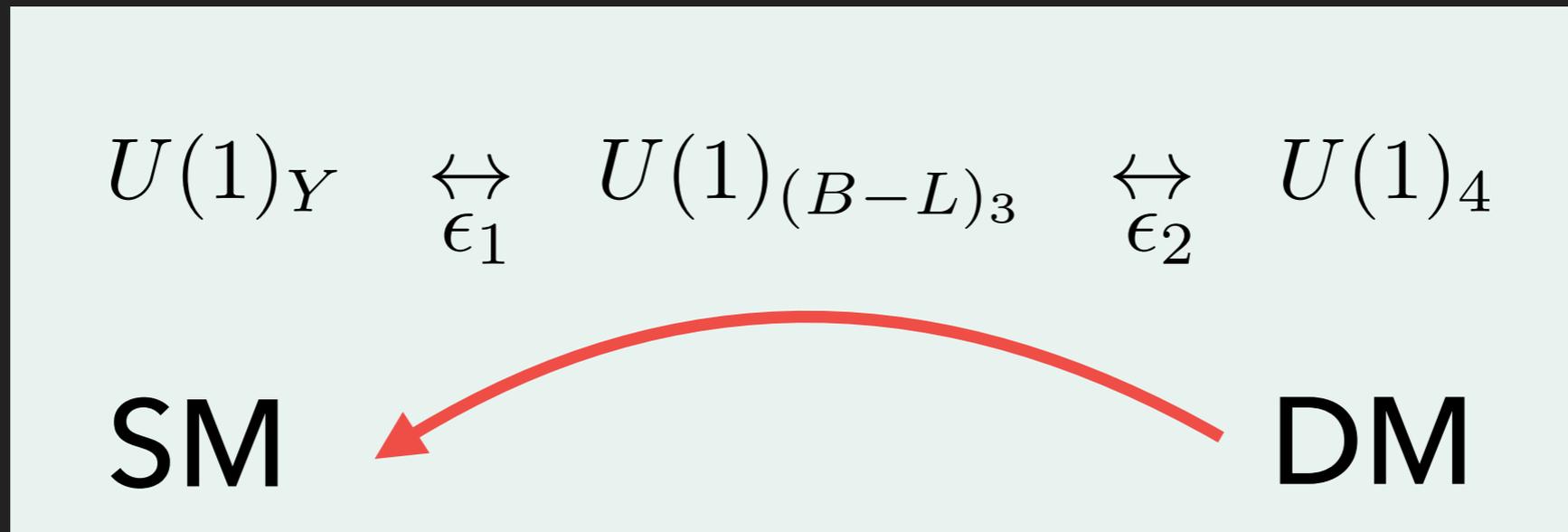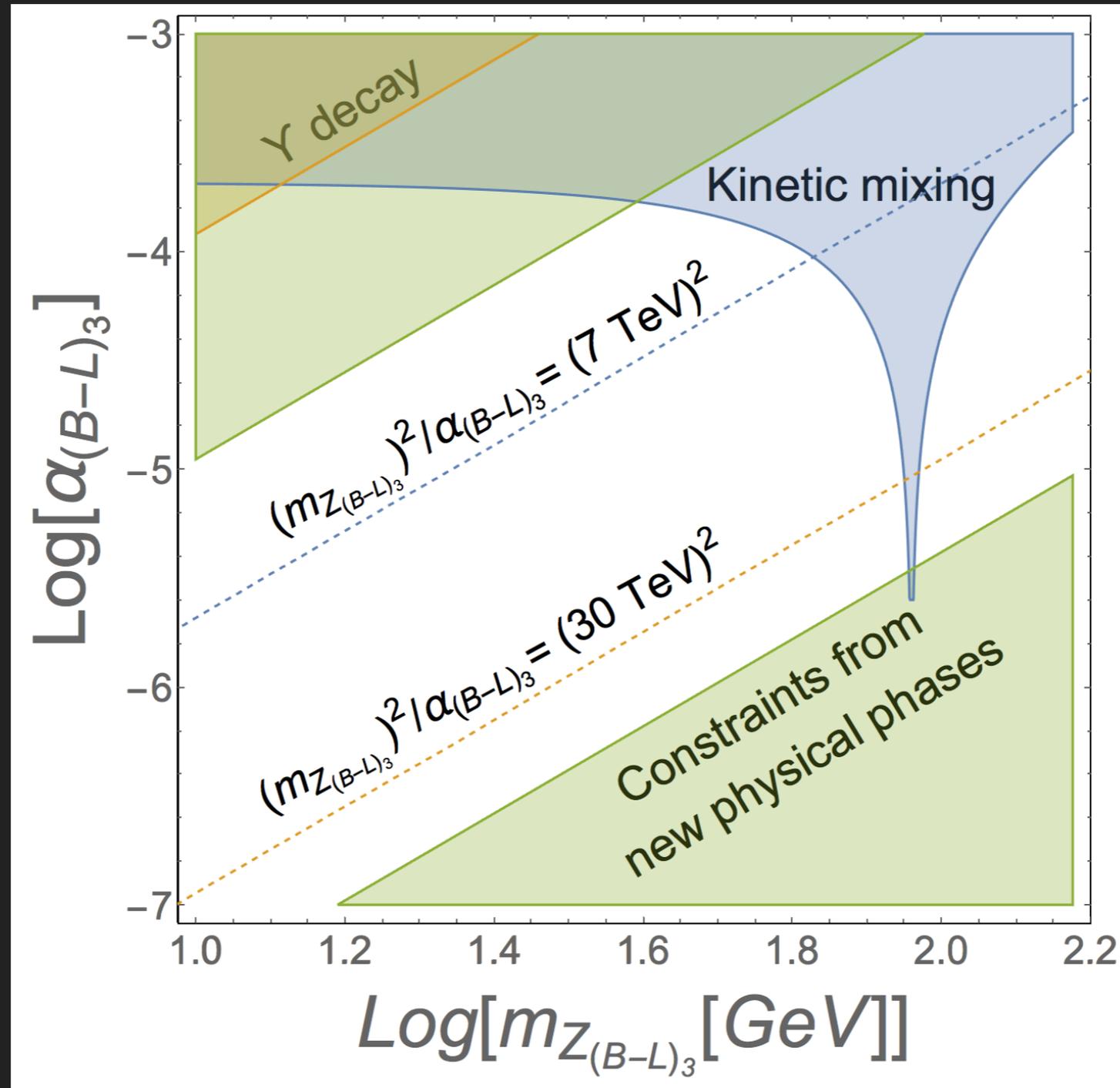
- Annihilation cross section into charged particles:

$$(\sigma_\eta v)(\eta\bar\eta \to e\bar e \cdots) \simeq 1.1 \times 10^{-28} \text{ cm}^3/s \, S \left(\frac{\epsilon_1}{10^{-2}}\right)^2 \left(\frac{m_\chi}{40 \text{ GeV}}\right)^2 \left(\frac{\alpha_4}{10^{-3}}\right)^{-3}$$

- Spin-indep. DM-nucleon scattering cross section:

$$\sigma_N \simeq 7 \times 10^{-48} \text{ cm}^2 \left(\frac{\alpha_4}{10^{-3}}\right) \left(\frac{\epsilon_1}{10^{-2}}\right)^2 \left(\frac{\epsilon_2}{10^{-2}}\right)^2 \left(\frac{m_{Z_{(B-L)_3}}}{70 \text{ GeV}}\right)^{-4}$$

Constraint on the Z(B-L)₃ mass

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B-decay anomaly

▸ B-decay anomaly can be explained if there is a mixing between the second and the third families:

$$\mathcal{L}_{\text{int}} = -\sum_f g_{(B-L)_3} Q_f Z^{\mu}_{(B-L)_3} J_{f,\mu} \qquad J_{f,\mu} = \sum_{i,j=1}^{3} \bar{f}_i (U_f)^*_{3i} (U_f)_{3j} \gamma_{\mu} f_j$$
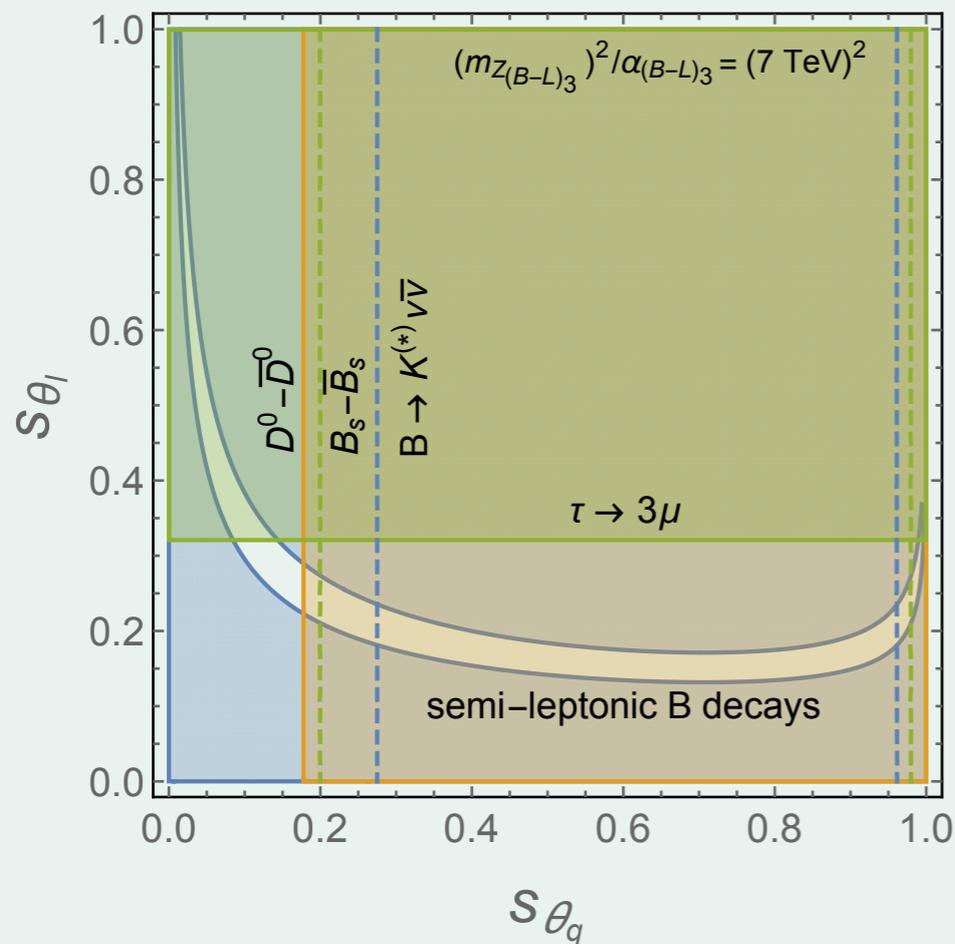
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \left[\sum_{l=e,\mu,\tau} \left(C^l_9 \mathcal{O}^l_9 + C^l_{10} \mathcal{O}^l_{10} \right) + \sum_{i,j=1}^{3} C^{ij}_{\nu} \mathcal{O}^{ij}_{\nu} \right]$$

$$\mathcal{O}^l_9 = \frac{\alpha}{4\pi} \left(\bar{s} \gamma_{\mu} b_L \right) \left(\bar{l} \gamma_{\mu} l \right) \qquad \mathcal{O}^l_{10} = \frac{\alpha}{4\pi} \left(\bar{s} \gamma_{\mu} b_L \right) \left(\bar{l} \gamma_{\mu} \gamma^5 l \right) \qquad \mathcal{O}^{ij}_{\nu} = \frac{\alpha}{2\pi} \left(\bar{s} \gamma_{\mu} b_L \right) \left(\bar{\nu}_i \gamma_{\mu} \nu_{L\,j} \right)$$
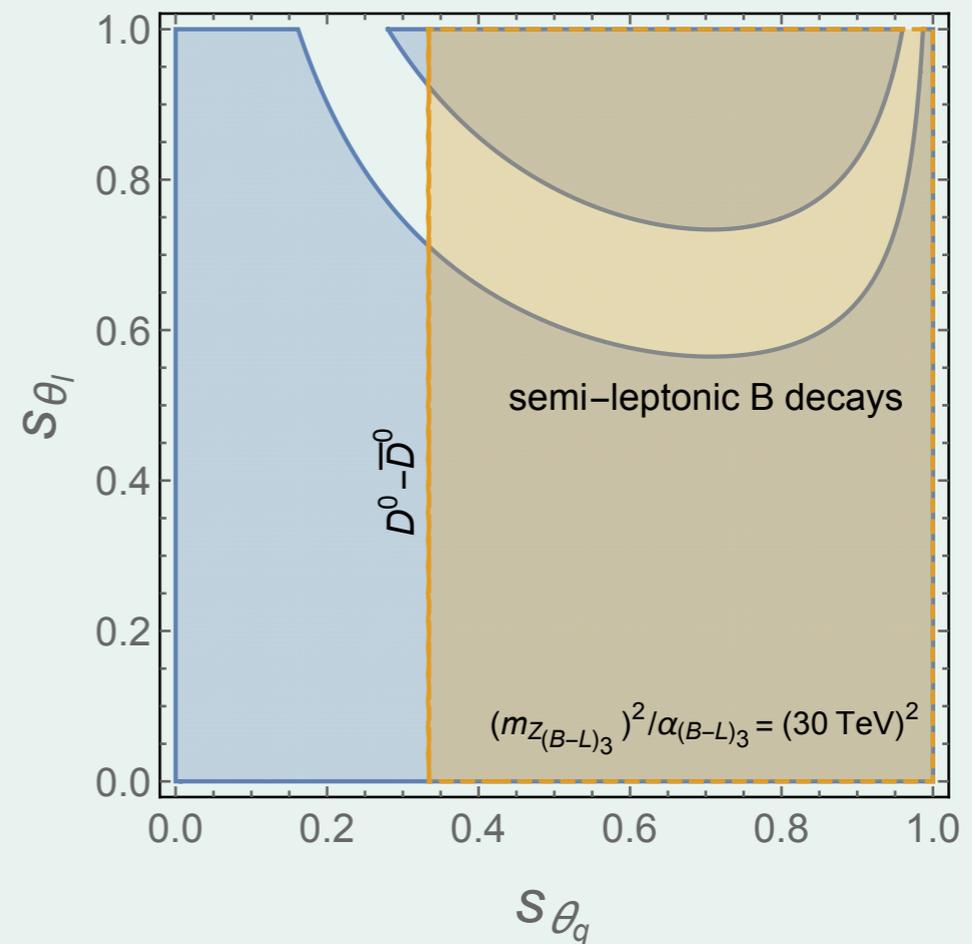
$$\delta C^{\mu}_9 = -\delta C^{\mu}_{10} = -\frac{\pi}{\alpha \sqrt{2} G_F V_{tb} V^*_{ts}} \frac{g^2_{(B-L)_3} s_{\theta_q} c_{\theta_q} s^2_{\theta_l}}{3 m^2_{Z_{(B-L)_3}}}$$

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B-decay anomaly

▸ B-decay anomaly can be explained if there is a mixing between the second and the third families:

$$m^2_{Z_{(B-L)_3}}/\alpha_{(B-L)_3} = (7\ \mathrm{TeV})^2 \qquad m^2_{Z_{(B-L)_3}}/\alpha_{(B-L)_3} = (30\ \mathrm{TeV})^2$$

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$[\mathrm{SU}(5) \times \mathrm{U}(1)]^4$ GUT

‣ A parameter set at which everything works consistently:

$$\alpha_{(B-L)_3} = 10^{-4}, \quad \alpha_4 = 10^{-3}, \quad \epsilon_1 = 10^{-2}, \quad \epsilon_2 = 4 \times 10^{-2},$$
$$m_{Z_{(B-L)_3}} = 70 \text{ GeV}, \quad m_{Z_4} = 10 \text{ MeV}, \quad m_\eta = 40 \text{ GeV},$$

‣ Why is the Dirac fermion light?

‣ What is the origin of the U(1) gauge boson?

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$[\mathrm{SU}(5) \times \mathrm{U}(1)]^4$ GUT

	ψ_4	χ_4	N_4
$\mathrm{SU}(5)_4$	$\mathbf{\bar{5}}$	$\mathbf{10}$	$\mathbf{1}$
$\mathrm{U}(1)_4$	-3	1	5

We assume that SU(5)$_4$ is confined at Λ ($\sim 10^{13}$ GeV).
Below the confinement scale there is a massless
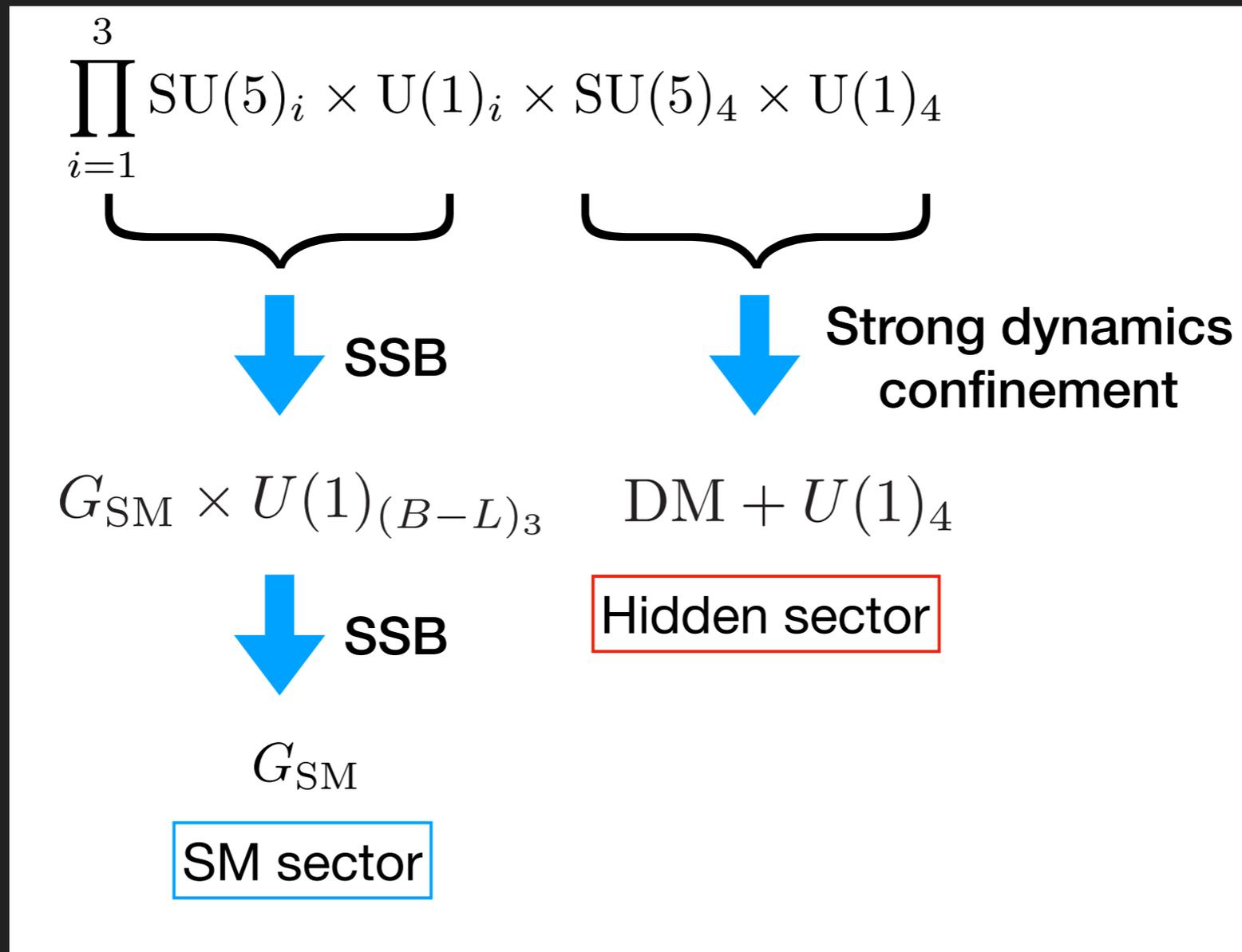baryon $\eta \equiv \psi_4 \psi_4 \chi_4$

We also introduced U(1)$_4$ with N_4. Then we can write
down a Dirac mass term for eta and N_4:

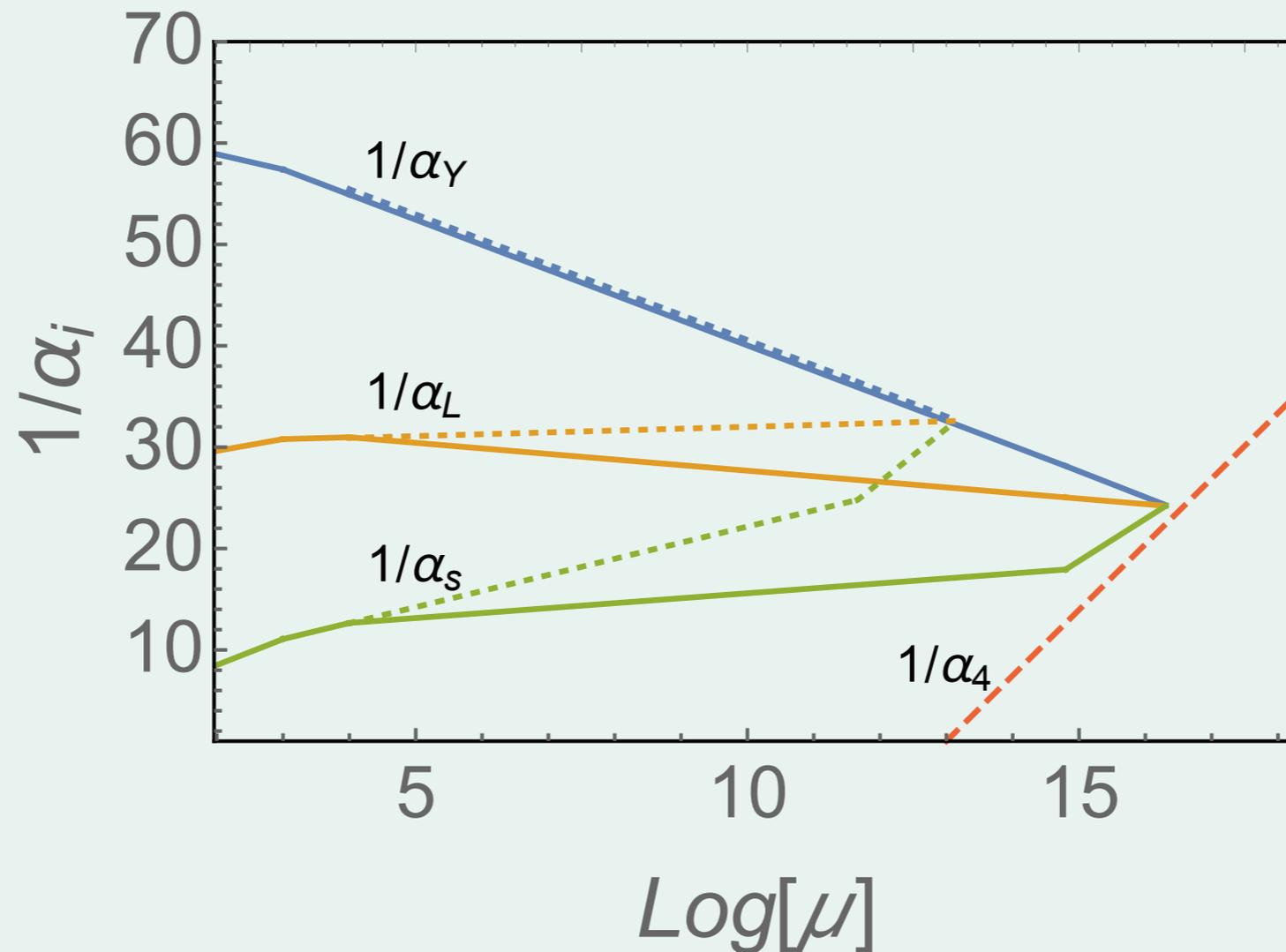$$\frac{c}{M_{\mathrm{Pl}}^2} N_4 \psi_4 \psi_4 \chi_4 + \mathrm{h.c.}$$

$$\Lambda \sim 10^{13} \text{ GeV} \quad \rightarrow \quad m_\eta \sim 100 \text{ GeV}$$

	ψ_i	χ_i	N_i
$SU(5)_i$	$\bar{\mathbf{5}}$	$\mathbf{10}$	$\mathbf{1}$
$U(1)_i$	-3	1	5

$$\prod_{i=1}^{3} SU(5)_i \times U(1)_i \times SU(5)_4 \times U(1)_4$$

SSB

Strong dynamics confinement

$G_{SM} \times U(1)_{(B-L)_3}$

$DM + U(1)_4$

Hidden sector

SSB

G_{SM}

SM sector

$[\text{SU}(5) \times \text{U}(1)]^4$ GUT

$$\prod_{i=1}^{3} [\text{SU}(5)_i] \rightarrow [\text{SU}(3)]^2 \times \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$$

▸ All SU(5) gauge coupling are of the same order!

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$[\mathrm{SU}(5) \times \mathrm{U}(1)]^4$ GUT
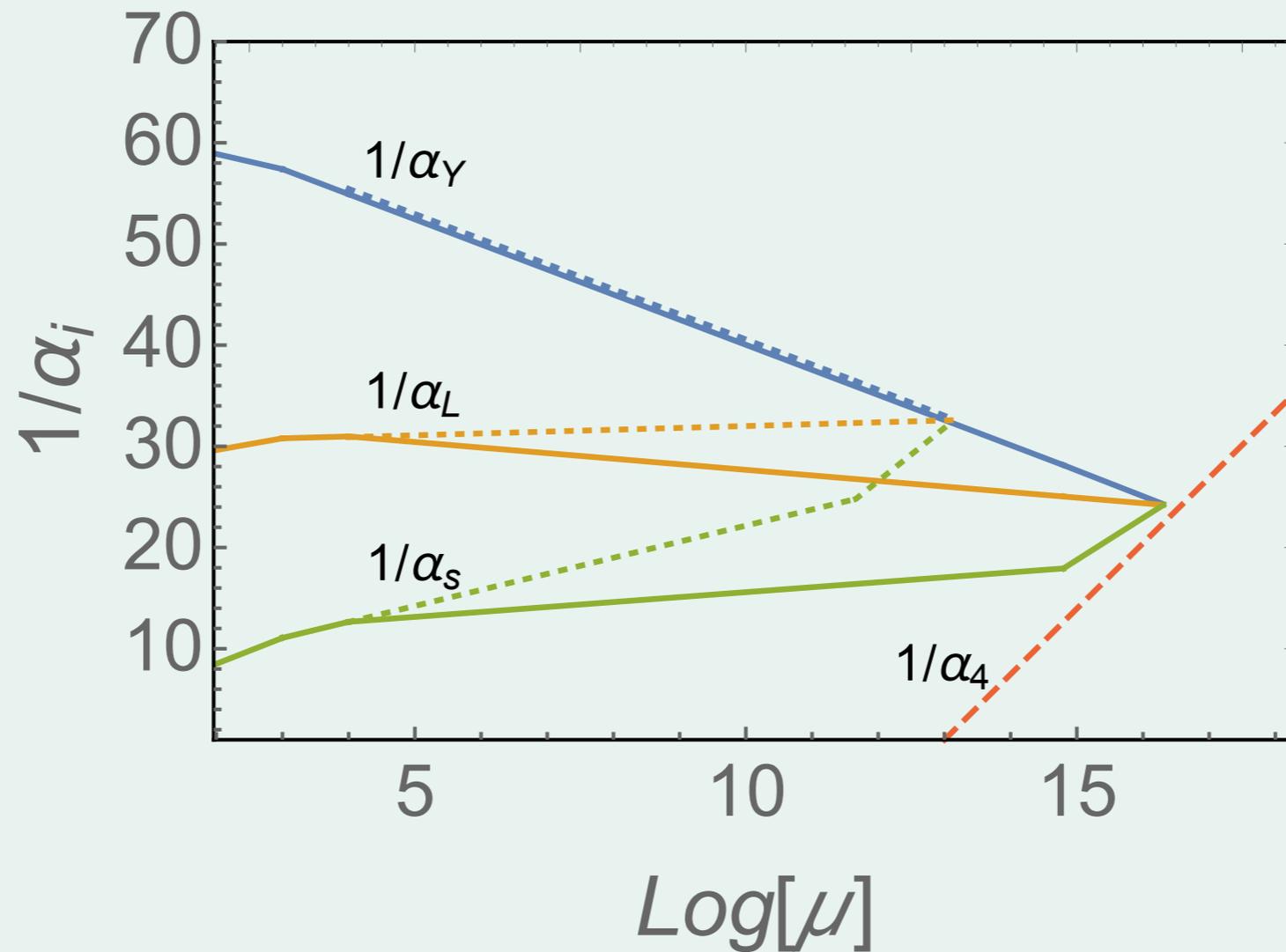
$$\Lambda \sim 10^{13} \; \mathrm{GeV} \quad \rightarrow \quad m_\eta \sim 100 \; \mathrm{GeV}$$

▸ All SU(5) gauge coupling are of the same order!

Summary

‣ We have proposed a unified model of SM and DM sectors.

DM is a Dirac field with a U(1) gauge interaction at a low energy

- gives a consistent thermal relic abundance

- can solve the small-scale crisis by the self-interaction

- can explain B-anomaly

- can be detected by direct and indirect experiments in the future

- can be realized naturally from [SU(5)*U(1)] UV theory

All sectors are unified into $[\mathrm{SU}(5) \times \mathrm{U}(1)]^4$

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