Connecting Dark Matter with flavor puzzle

Rusa Mandal
IIT Gandhinagar

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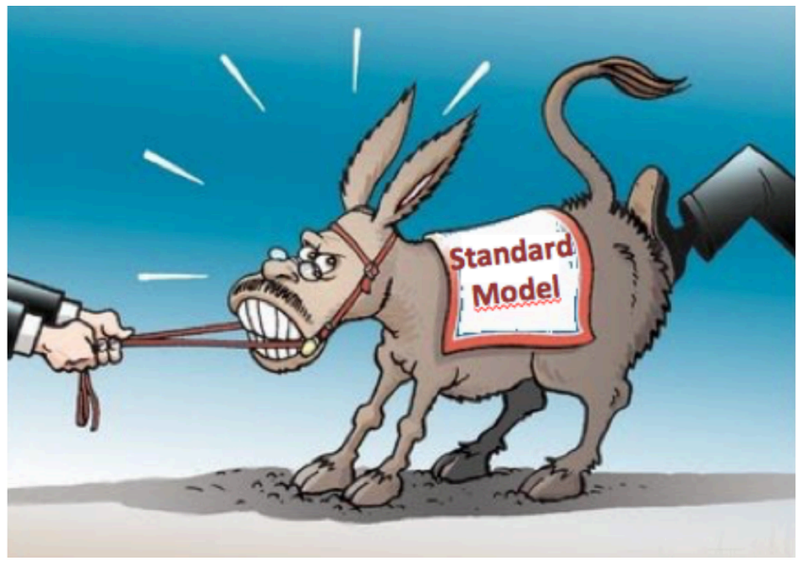
Introduction

- Standard Model so far too good…
- No direct signature of BSM particles till now



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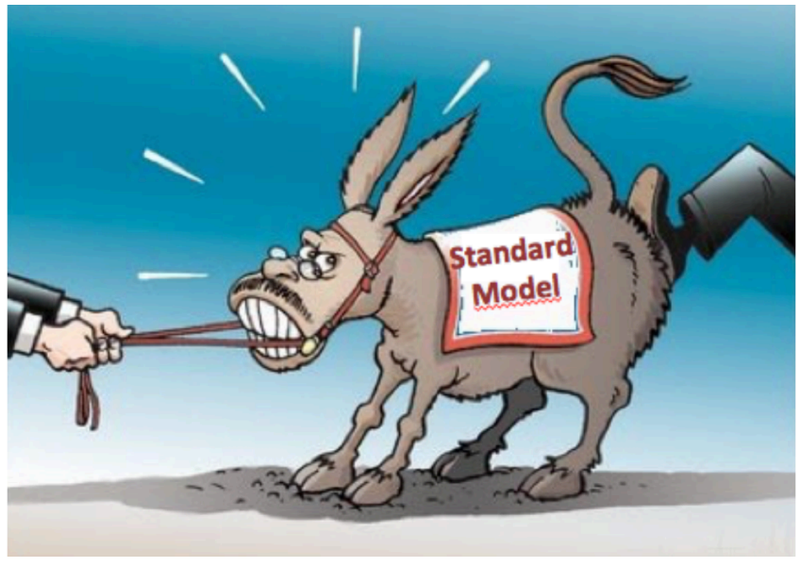

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- Some reasons to go for beyond SM physics:

- Dark matter
- Matter anti-matter asymmetry

→ Cosmological implementation

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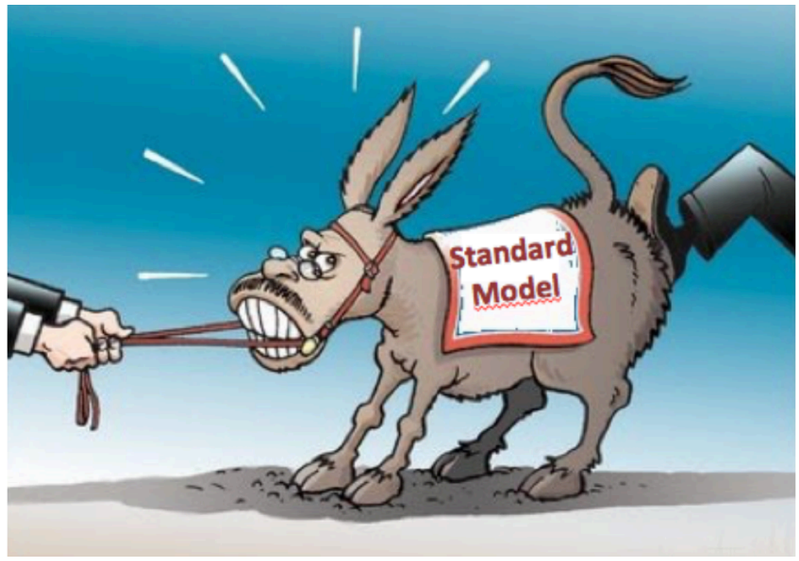

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- Neutrino masses
- Fermion mass hierarchy

→ Ad hoc tuning of SM parameters

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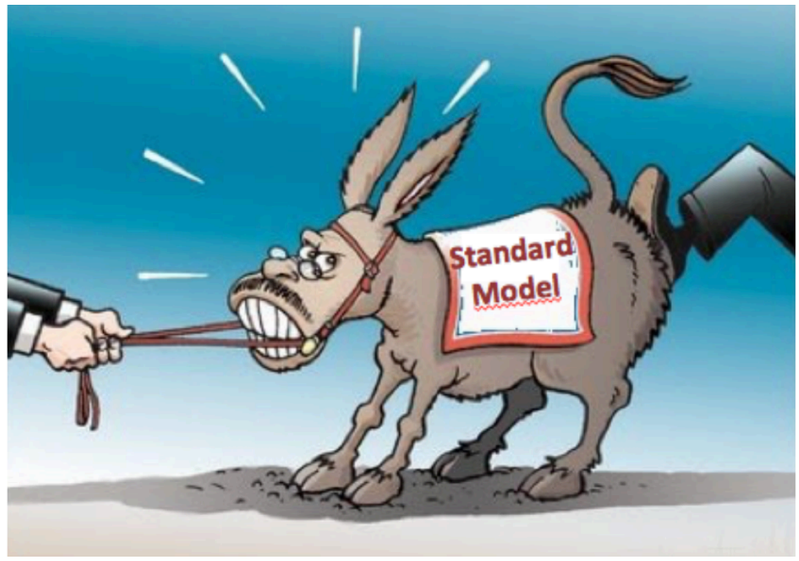

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→ Cosmological implementation

- Neutrino masses
- Fermion mass hierarchy

→ Ad hoc tuning of SM parameters

} No definite energy scale

- Electroweak hierarchy

→ Higgs mass unstable with quantum correction → New dynamics ~ 1TeV

Introduction

- Well motivated & popular BSM constructions becoming less appealing due to null results from experimental searches

— look for new directions

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- ☑ Neutrino masses
- ☑ Fermion mass hierarchy
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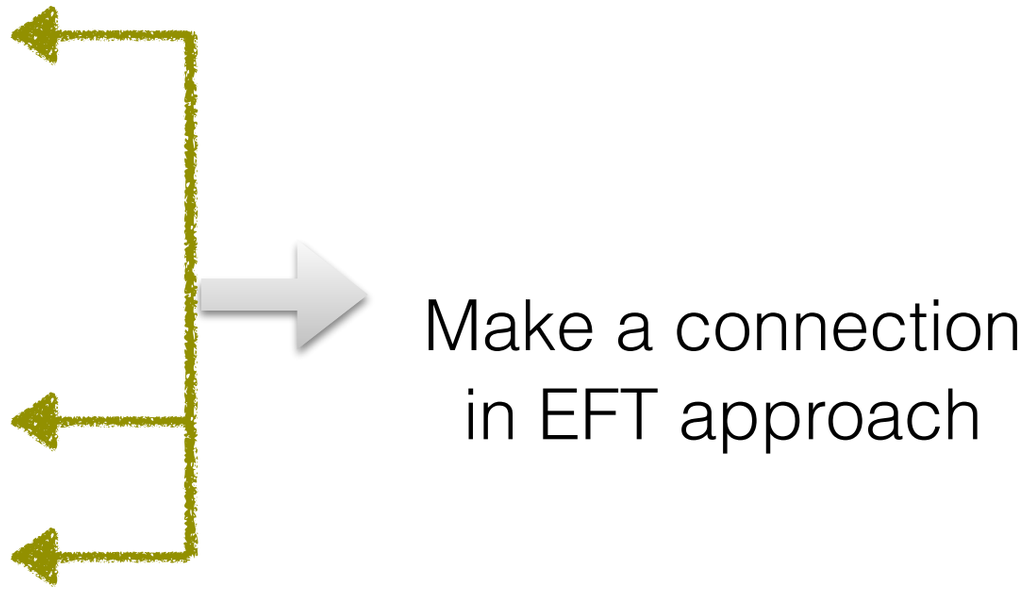
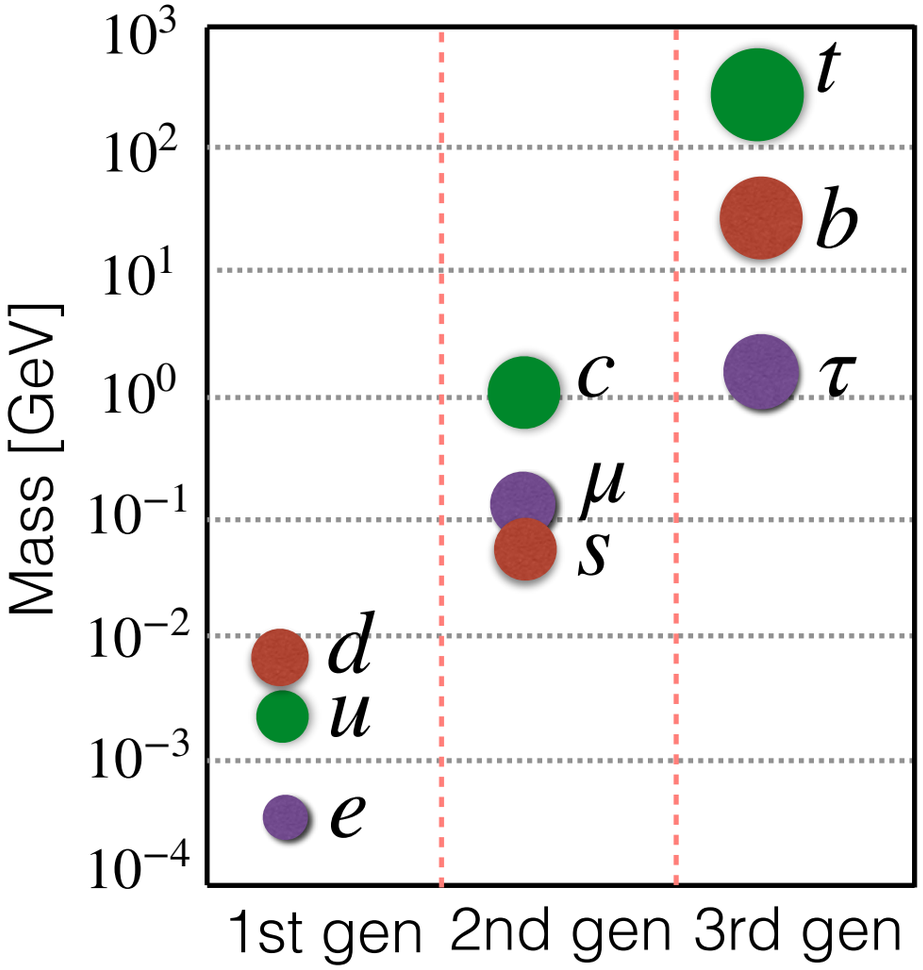


Introduction

- 3 identical replica of fermions differ by huge mass scale



$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs}$$

Same for all fermions:
Flavor degeneracy

Invariant under rotation of fermion fields $[Q_L, u_R, d_R, L_L, e_R]$
Flavor symmetry $U(3)^5$

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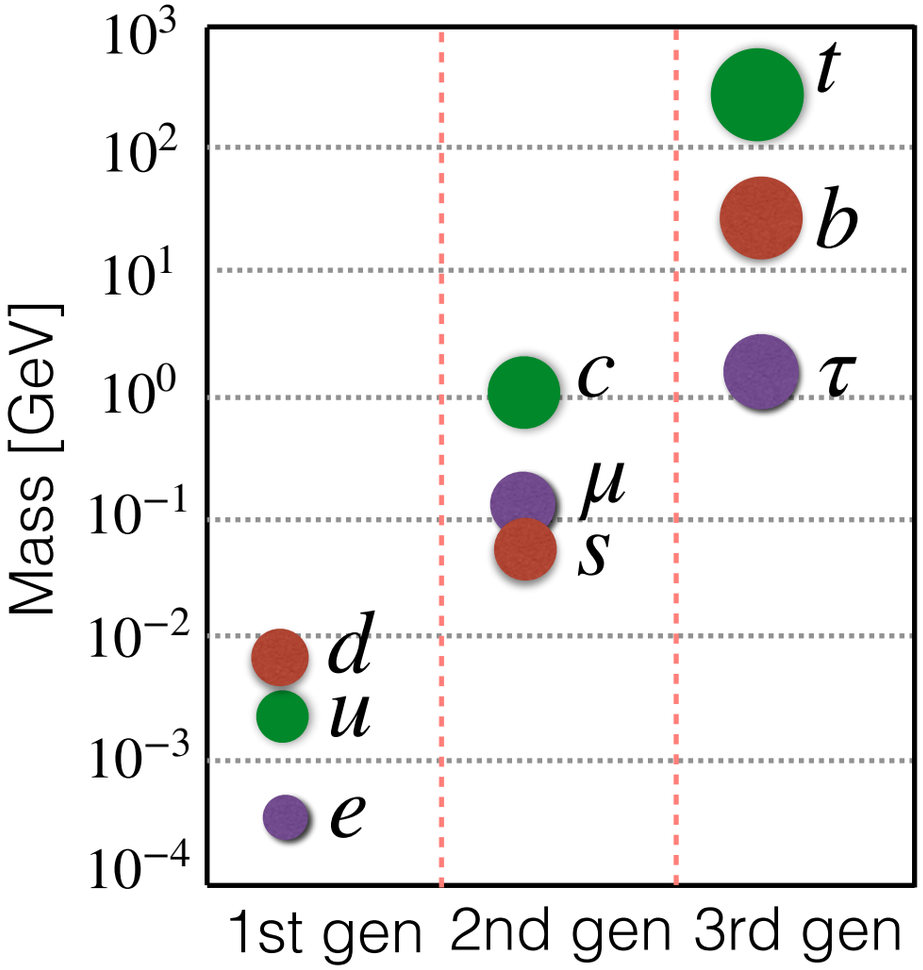


$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs}$$

Same for all fermions:
Flavor degeneracy

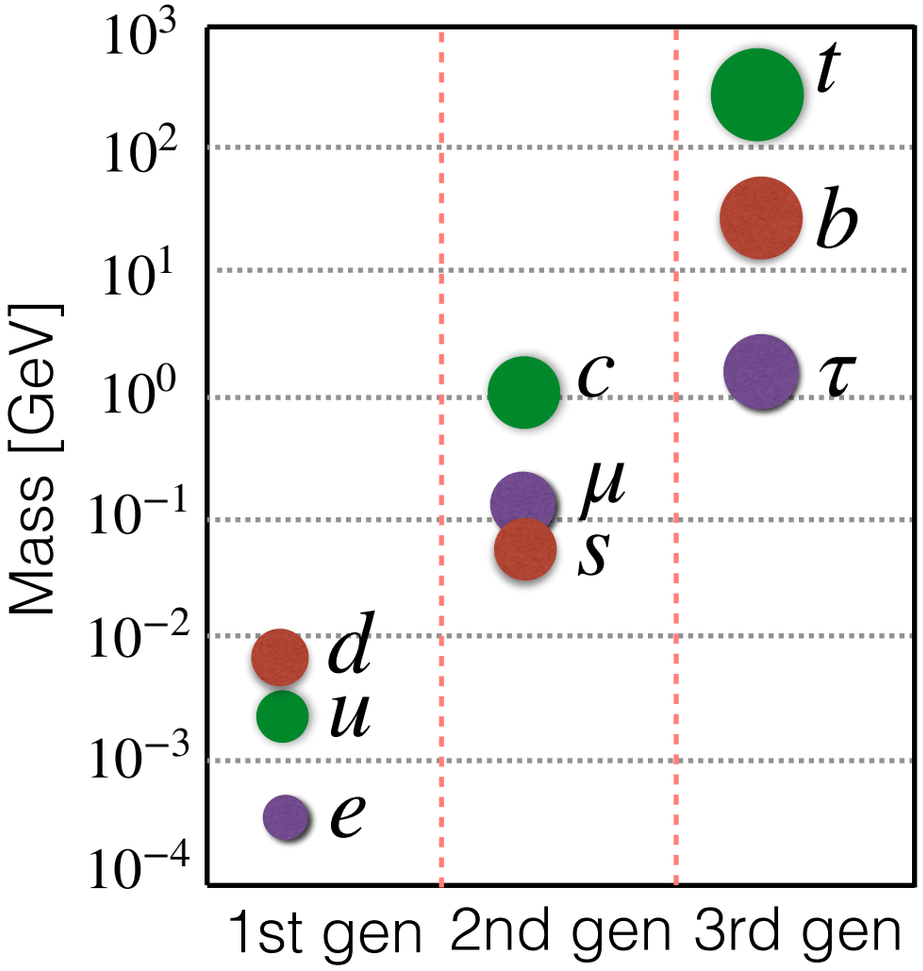
Broken by Higgs:
Yukawa interaction

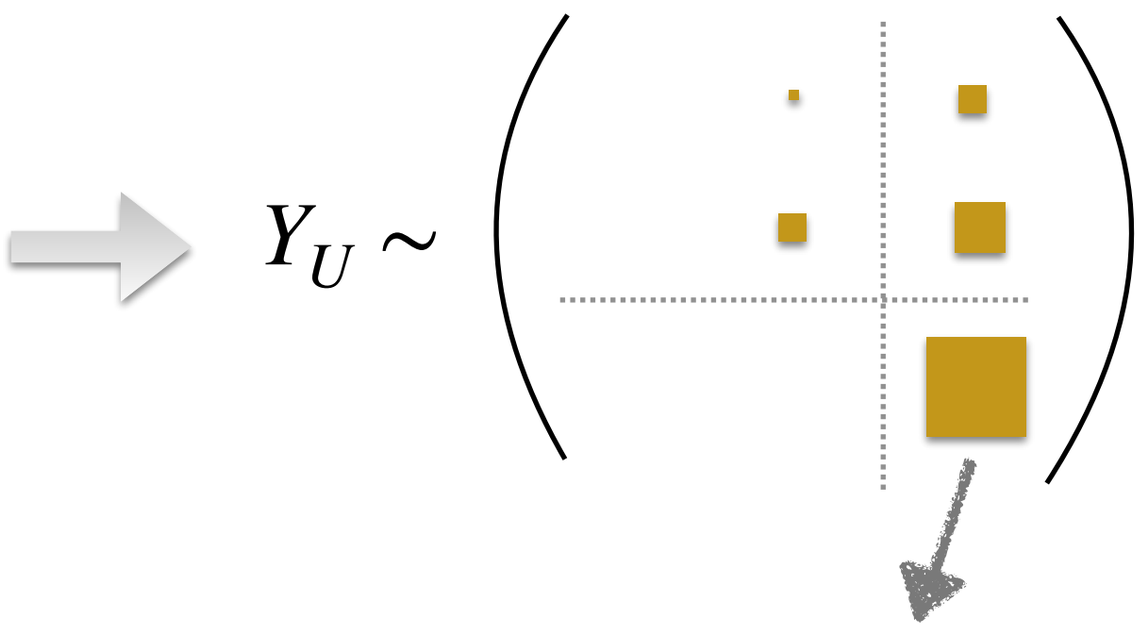
Invariant under rotation of fermion fields $[Q_L, u_R, d_R, L_L, e_R]$

Flavor symmetry $U(3)^5$

Introduction

- SM Yukawa sector contains large no. of free parameters





Masses & mixing angles don't look accidental
— Old flavor puzzle

Flavor Spurions

[Froggatt, Nielsen '79]

- With underline symmetry of the UV model

Yukawa matrices → flavor spurions with Froggatt-Nielsen charges

distinguishable U(1) charge for all fermions

$$-\mathcal{L}_{\rm int} = c_d^{ij}\left(\frac{\phi}{M}\right)^{n_d^{ij}} \bar{Q}^i H d_R^j + c_u^{ij}\left(\frac{\phi}{M}\right)^{n_u^{ij}} \bar{Q}^i\, i\sigma_2 H^* u_R^j + c_e^{ij}\left(\frac{\phi}{M}\right)^{n_e^{ij}} \bar{L}^i H e_R^j$$

$$n_u^{ij} \equiv b_Q^i - b_U^j, \quad n_d^{ij} \equiv b_Q^i - b_D^j, \quad n_e^{ij} \equiv b_L^i - b_E^j$$

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Flavon ϕ —SSB of U(1)→ $v_\phi + \frac{1}{\sqrt{2}}(s+ia)$ → Yukawa Matrices $\sim \left(\frac{v_\phi}{M}\right)^{n_x^{ij}} \equiv \lambda^{n_x^{ij}}$

$c \sim \mathcal{O}(1)$ numbers up to overall phase

FN charges should produce observed mass and mixing pattern

Froggatt-Neilsen charges

- SM flavor structure— fermion masses and CKM matrix

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad \Rightarrow \quad (V_{U_L}^\dagger V_{D_L})_{ij} \sim \lambda^{|b_Q^i - b_Q^j|}$$

☑ Fixes LH quark charges up to common off-set *d* (not relevant for pheno)

$$b_Q = (3+d, 2+d, d) \qquad b_Q = (3+d, 4+d, 6+d)$$

☑ Combinations of LH & RH charges constrained by masses

$$y_u \sim \lambda^{|b_Q^1 - b_U^1|} \approx \lambda^8 \qquad y_d \sim \lambda^{|b_Q^1 - b_D^1|} \approx \lambda^7 \qquad y_e \sim \lambda^{|b_L^1 - b_E^1|} \approx \lambda^9$$
$$y_c \sim \lambda^{|b_Q^2 - b_U^2|} \approx \lambda^4 \qquad y_s \sim \lambda^{|b_Q^2 - b_D^2|} \approx \lambda^5 \qquad y_\mu \sim \lambda^{|b_L^2 - b_E^2|} \approx \lambda^5$$
$$y_t \sim \lambda^{|b_Q^3 - b_U^3|} \approx \lambda^0 \qquad y_b \sim \lambda^{|b_Q^3 - b_D^3|} \approx \lambda^3 \qquad y_\tau \sim \lambda^{|b_L^3 - b_E^3|} \approx \lambda^3$$

- Charged Lepton mixing unknown ⇒ freedom in lepton charges

Flavor Spurions

- Very restrictive choices for quark FN charges

$$n_u^{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n_d^{ij} = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad n_e^{ij} = \begin{pmatrix} 9 & 6 & 4 \\ 8 & 5 & 3 \\ 8 & 5 & 3 \end{pmatrix}$$

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- Interaction of (pseudo)scalar flavon to fermions are nearly fixed

$$-\mathcal{L}_{\rm scalar} = ia\left((g_+^f)_{ij}\bar{f}^i\gamma_5 f^j + (g_-^f)_{ij}\bar{f}^i f^j\right) + s\left((g_+^f)_{ij}\bar{f}^i f^j + (g_-^f)_{ij}\bar{f}^i\gamma_5 f^j\right)$$

$$\frac{m_j^f + m_i^f}{v_\phi} \qquad \frac{m_j^f - m_i^f}{v_\phi}$$

FCNC generated @tree level

SM flavor pattern generated

NEXT?

SM flavor pattern generated

NEXT?

make the flavon talk to the dark sector

SM flavor pattern generated

NEXT?

make the flavon talk to the dark sector
& heavy neutrinos

Neutrino mass

[RM, T. Tong JCAP '23]

- Connect the flavon to 3 generations of right-handed neutrinos

$$c_\nu^{ik}\left(\frac{\phi}{M}\right)^{n_\nu^{ik}} \bar{L}^i\, i\sigma_2 H^* N_R^k + \frac{1}{2} c_N^{ij}\left(\frac{\phi}{M}\right)^{n_N^{ij}} M\overline{N_R^{c\,i}} N_R^j$$

→ Lightest of the RHN is a DM candidate with extra Z_2

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→ Lightest of the RHN is a DM candidate with extra Z_2

→ Other two RHN generate light neutrino masses via seesaw

$$m_\nu \sim \frac{v_{\rm EW}^2}{M}\begin{pmatrix} 0 & & \\ & \epsilon^{2q_{L_2}} & \\ & & \epsilon^{2q_{L_3}} \end{pmatrix} \qquad U_{\rm PMNS} \sim \begin{pmatrix} 1 & \epsilon^{q_{L_1}-q_{L_2}} & \epsilon^{q_{L_1}-q_{L_3}} \\ \epsilon^{q_{L_1}-q_{L_2}} & 1 & \epsilon^{q_{L_2}-q_{L_3}} \\ \epsilon^{q_{L_1}-q_{L_3}} & \epsilon^{q_{L_2}-q_{L_3}} & 1 \end{pmatrix}$$

Freedom in charged lepton FN charges reduced

Constraints

[RM, T. Tong JCAP '23]

- A very minimal EFT set up: (pseudo)scalar flavon, 3 RHNs

- Scalar mass $m_s \propto v_\phi$
- Pseudo scalar mass due to soft breaking $m_a \ll m_s$
- DM mass $m_{\rm DM}$

→ Power counting in λ makes all couplings ~fixed $\propto 1/v_\phi$

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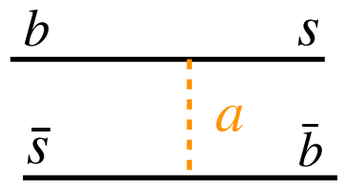
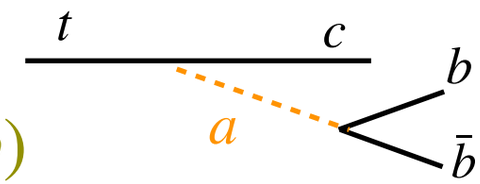
FCNC@Tree	Loops

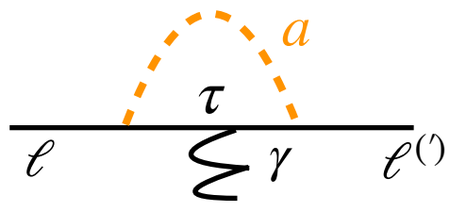
ΔM_s



$t \to ca(\to b\bar{b})$

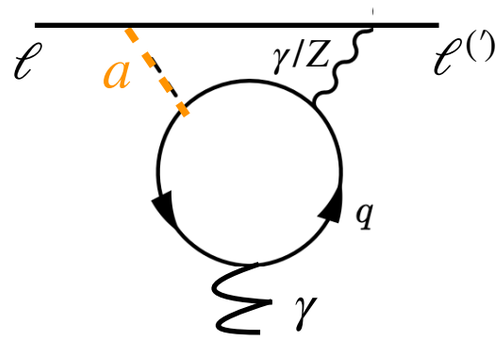
[ALTAS '23]





$\mu \to e\gamma$

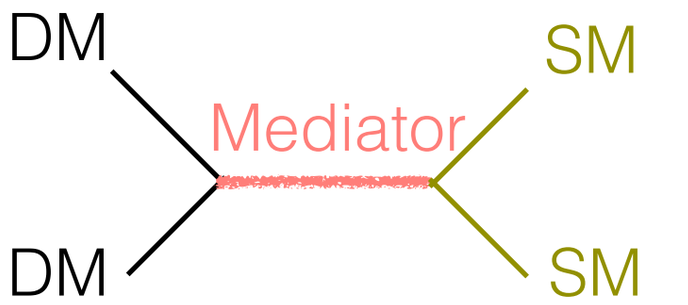
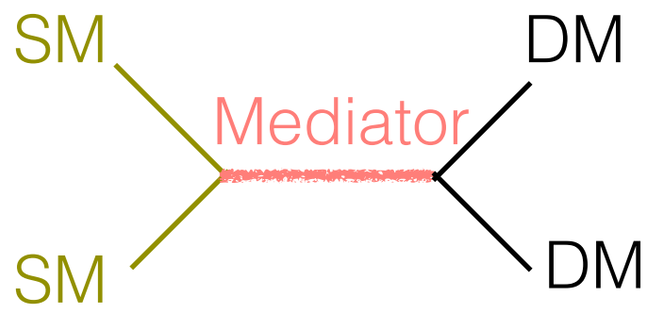
[MEG '16]



$$v_\phi m_a \gtrsim 2 \times 10^5\,\text{GeV}^2$$

WIMP-FIMP

- Only known interaction for DM is gravitational in nature popular mechanisms:

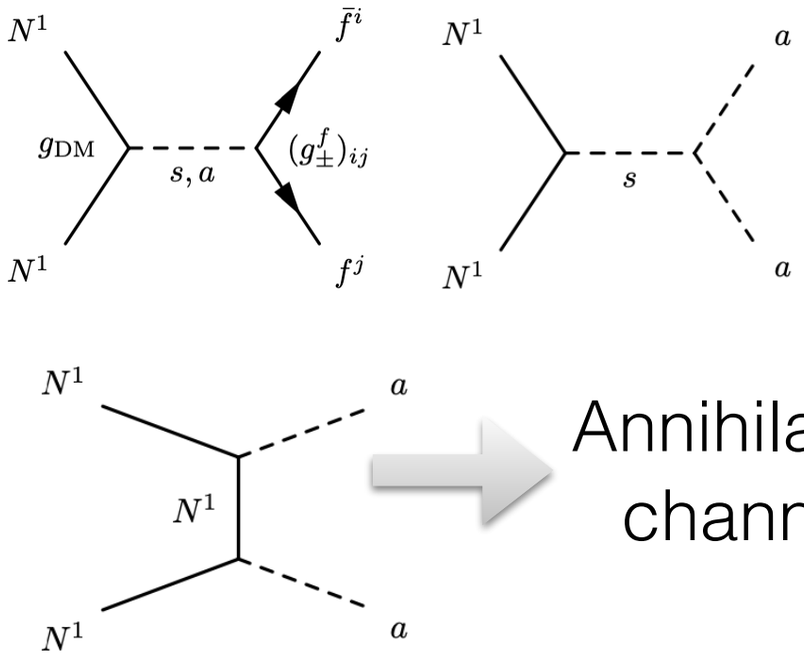
WIMP	FIMP
	

Freeze-out

[RM, T. Tong JCAP '23]

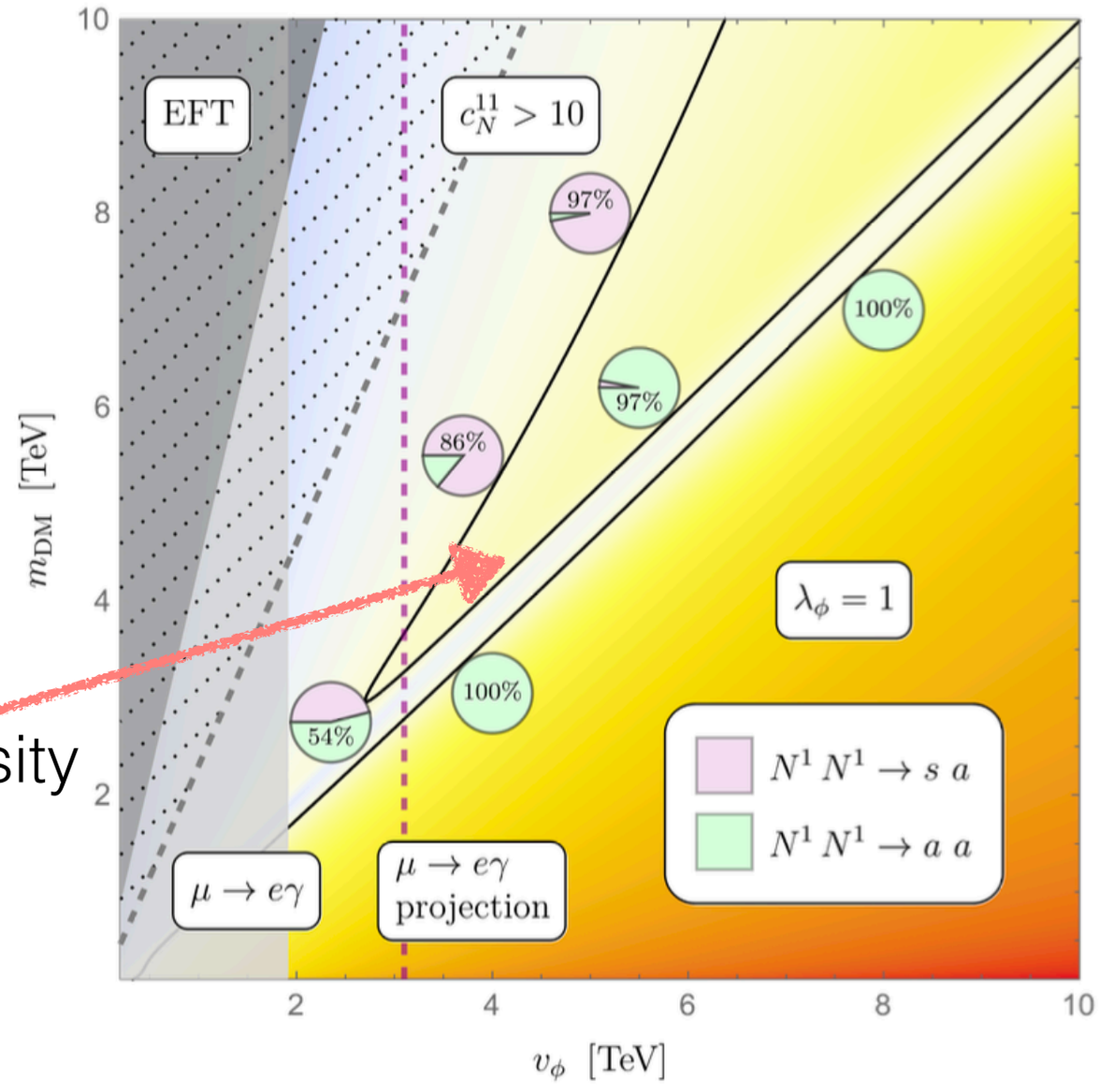
- Thermal history depends on FN breaking scale v_ϕ

  —WIMP scenario: all new particles in thermal equilibrium



Annihilation channels

Observed relic density



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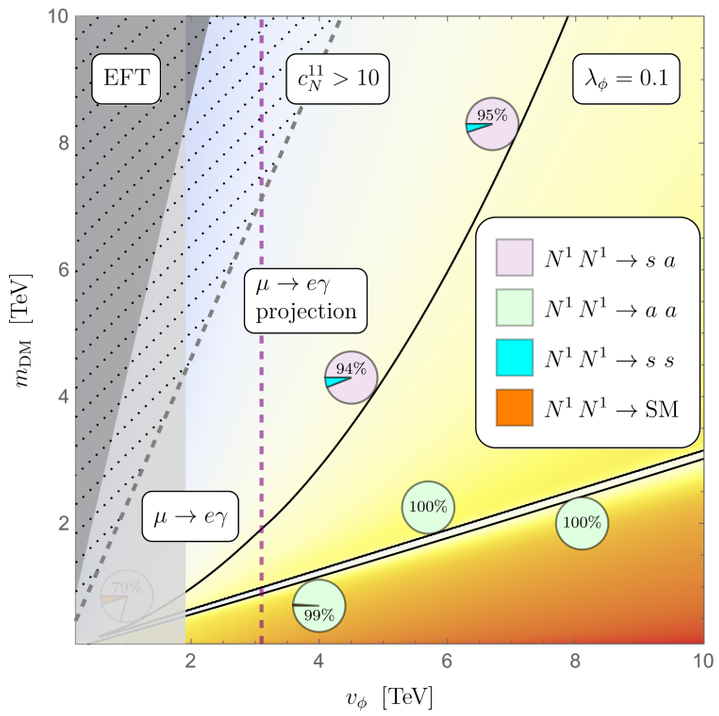
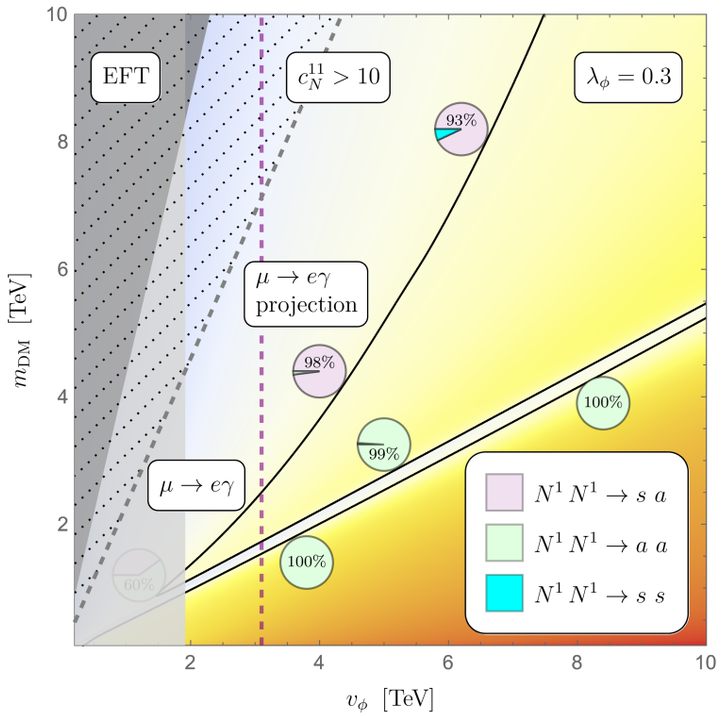
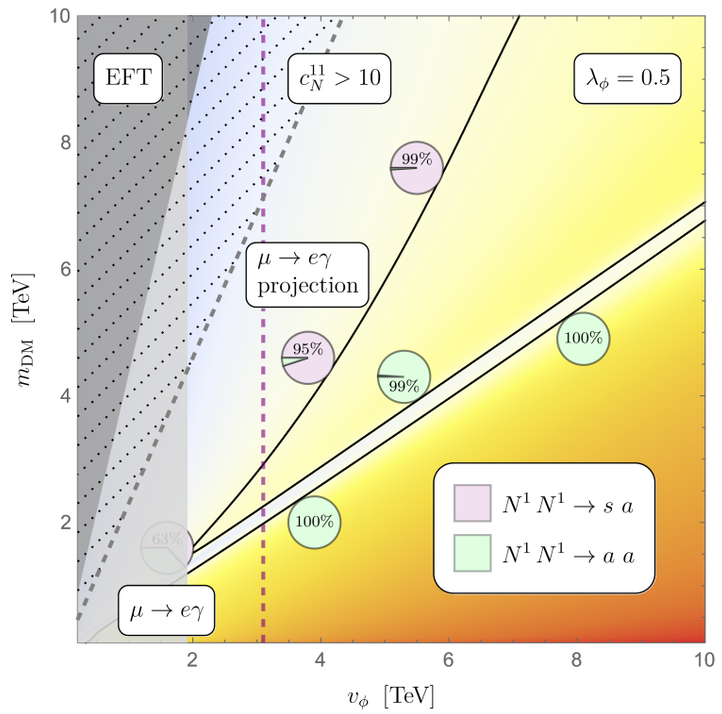
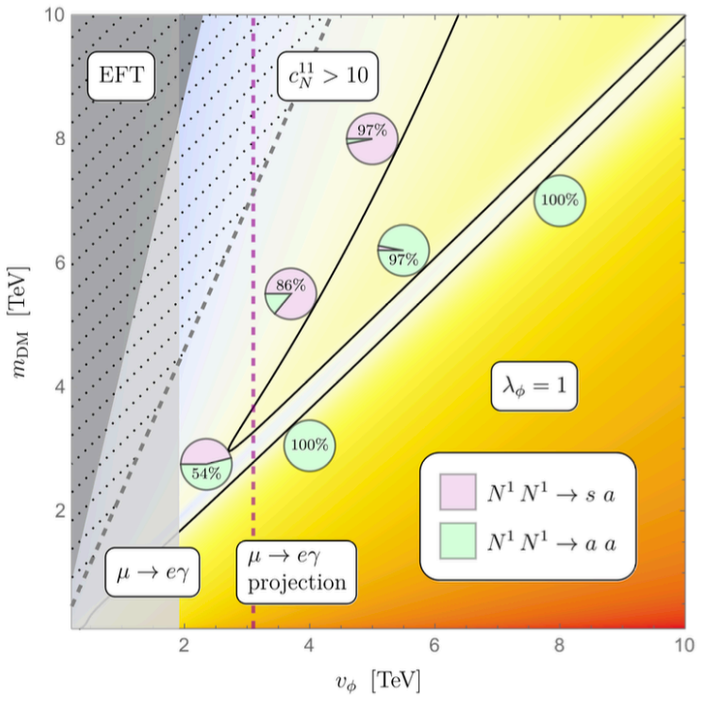
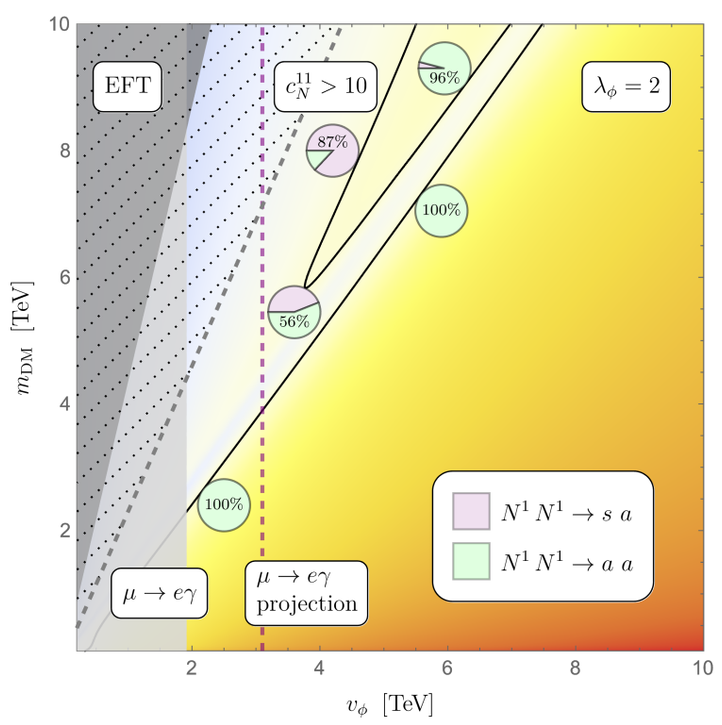


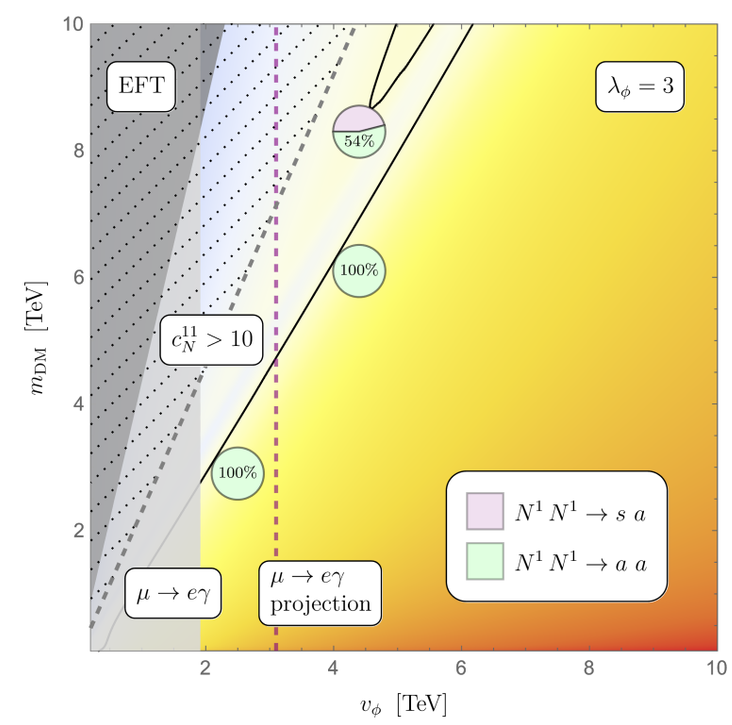




Scalar mass variation spans whole region compatible with relic







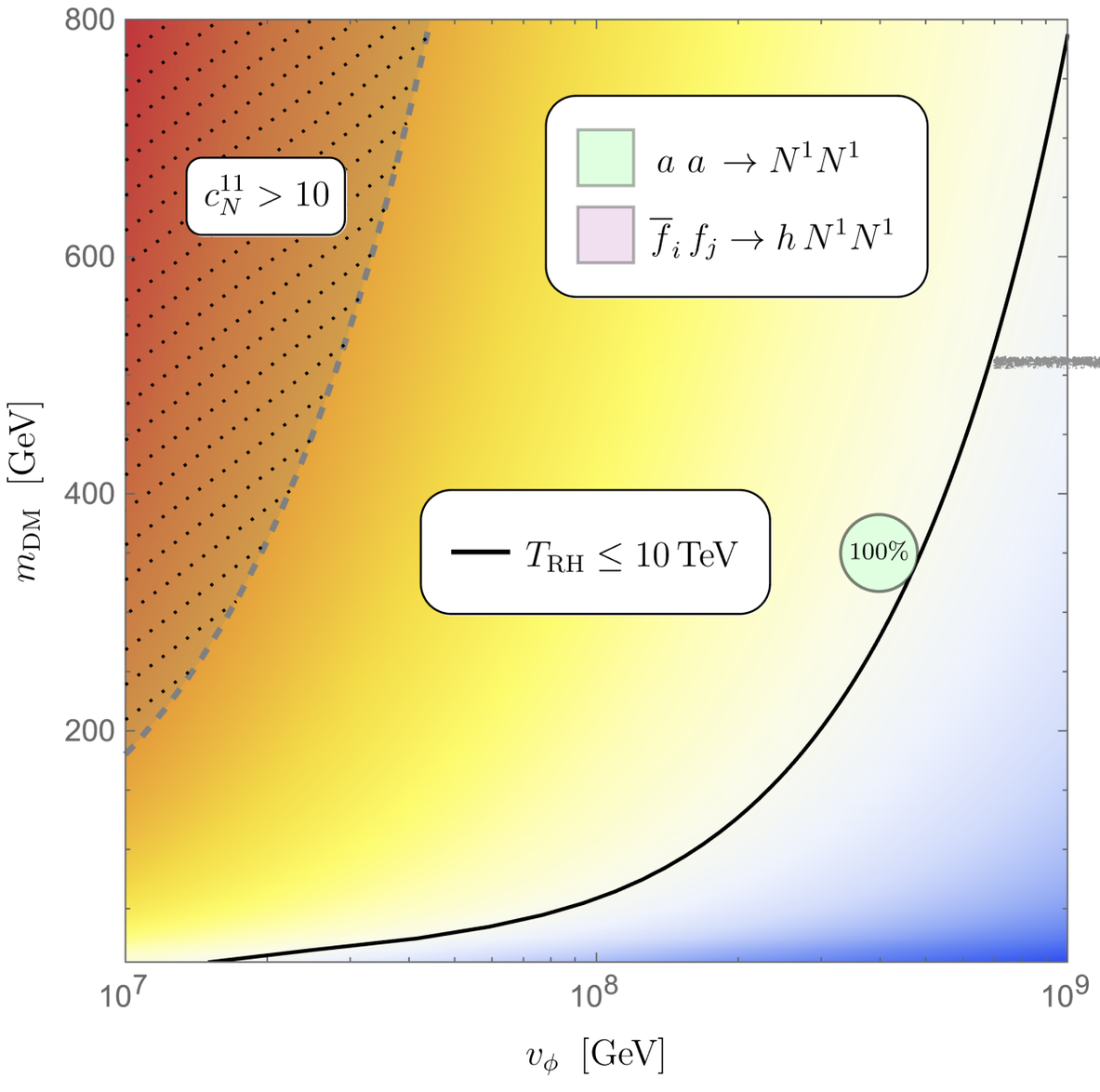
IR Freeze-in

[RM, T. Tong JCAP '23]

- For higher FN breaking scale, DM was never in thermal equilibrium

$$10^4 < v_\phi < 10^9\,\text{GeV}$$

DM produced from pseudoscalar interaction



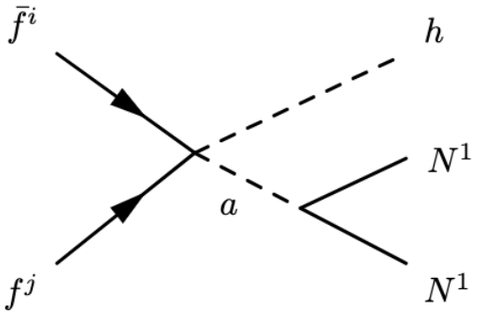
Relic density achieved from scattering process

UV Freeze-in

[RM, T. Tong JCAP '23]

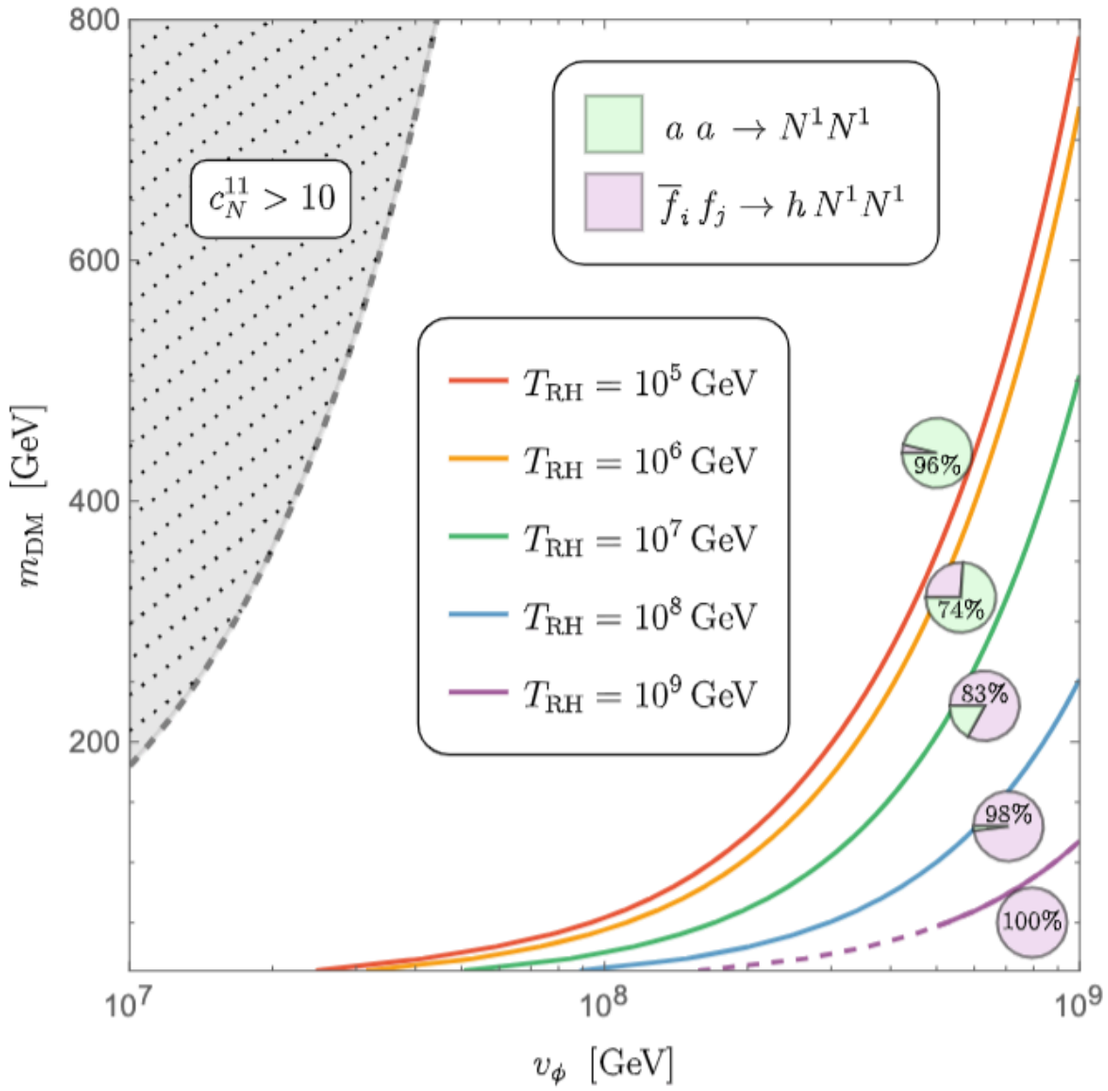
- Higher dimensional operators important for sufficiently high $T_{\rm RH}$

$$\sum_{f=u,d,e} \frac{(s+ia)\,h}{\sqrt{2}\,v_{\rm EW}} \left((g^f_+)_{ij}\, \bar{f}^i \gamma_5 f^j + (g^f_-)_{ij}\, \bar{f}^i f^j \right)$$



DM produced from SM fermions

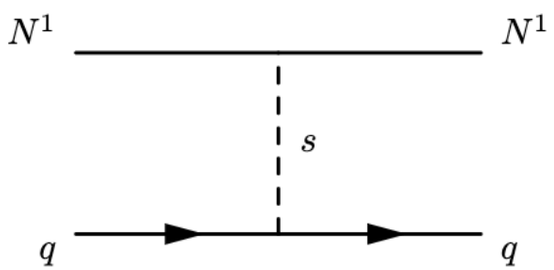
Interplay between different processes



Direct detection

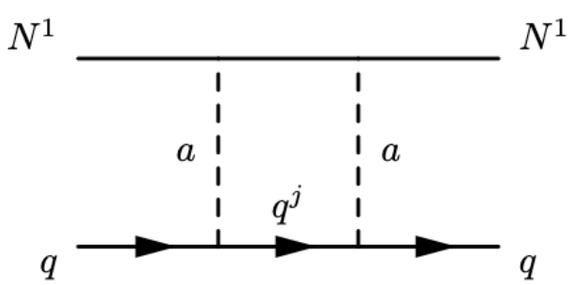
[RM, T. Tong JCAP '23]

spin-independent



$$\sigma^{\rm SI}_{\rm scalar} = \frac{4\,\mu_n^2\,m_n^2\,g_{DM}^2}{\pi\,m_s^4}\left|\sum_{q=u,\,d,\,s}\frac{g_+^q}{m_q}f_{Tq}^n + \frac{2}{27}\,f_{TG}^n\sum_{q=c,\,b,\,t}\frac{g_+^q}{m_q}\right|^2$$

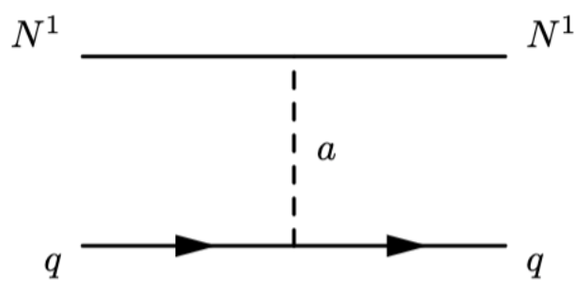
Heavy quark contribution via gluon condensates



$$\sigma^{\rm SI}_{\rm box} = \frac{4}{\pi}\,\mu_n^2\,m_n^2\,g_{DM}^4\left|\sum_{q=u,d,s}\frac{B_q}{m_q}f_{Tq}^n + \frac{2}{27}\,f_{TG}^n\sum_{q=c,b,t}\frac{B_q}{m_q}\right|^2$$

Tree & box same order

spin-dependent



$$\begin{bmatrix}\sigma_p^{\rm SD}\\ \sigma_n^{\rm SD}\end{bmatrix} \approx \begin{bmatrix}10^{-46}\\ 10^{-47}\end{bmatrix}\,{\rm cm}^2 \times \left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)^2\left(\frac{100\,{\rm GeV}}{m_a}\right)^4$$

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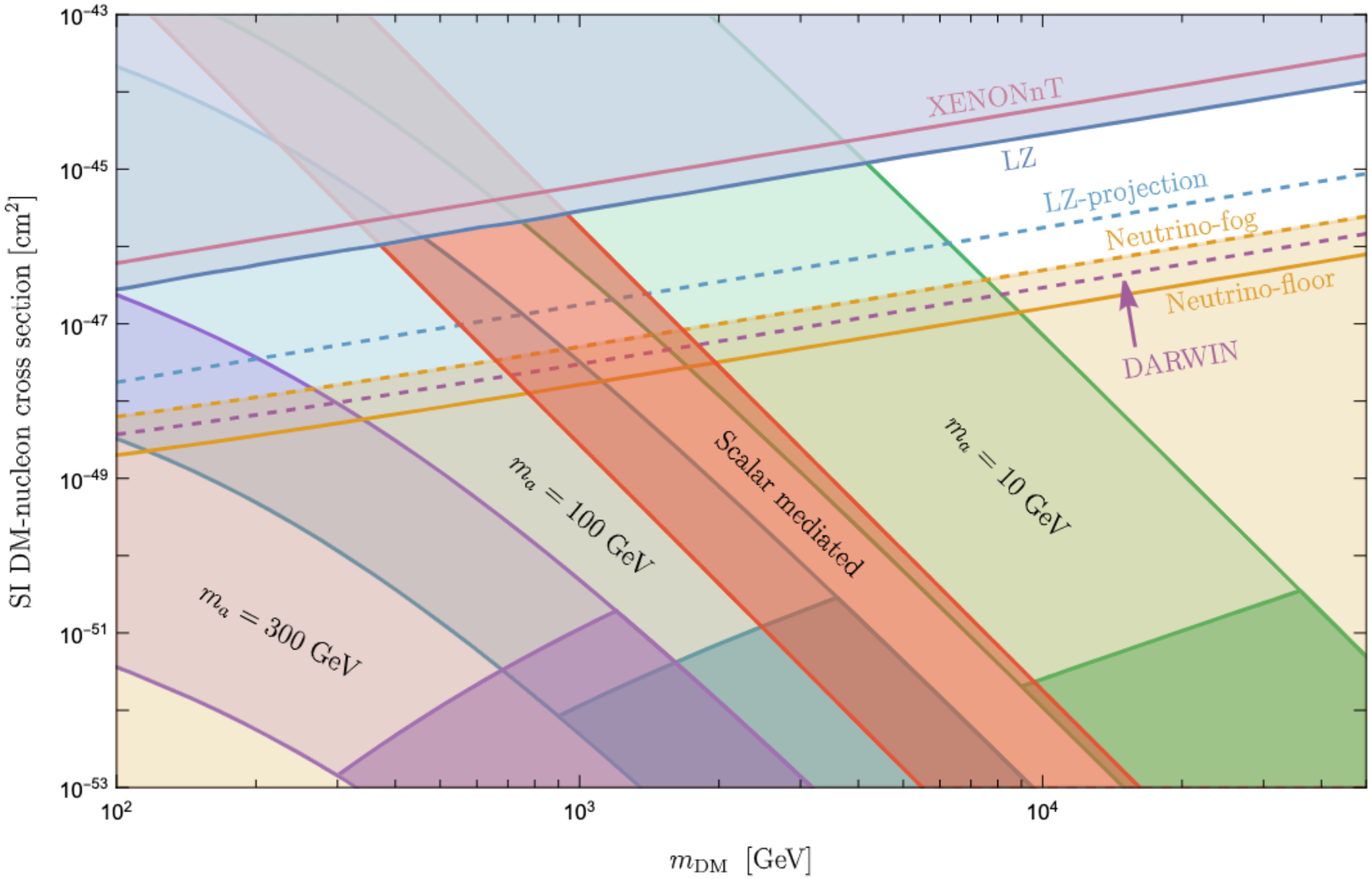

Regions can be probed in future upgrades of XENONnT, LZ

Outlook

- EFT approach with FN mechanism suitable for addressing several shortcomings of SM — Flavor puzzle, neutrino mass, DM

→ UV completion will introduce extra fields & interactions

→ More signatures at experiments: collider & DM

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- Scope to introduce CP violation via complex couplings

  → Matter-antimatter symmetry might be possible to achieve

  → Signatures at b-hadron decays@Belle II, LHCb

Thank you for your attention

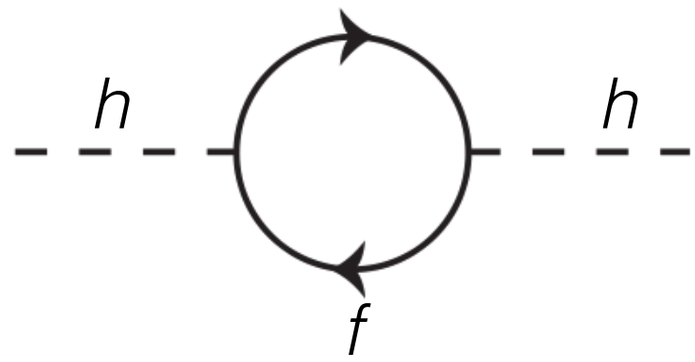
Back ups

Higgs mass hierarchy

- Theoretical issue: Higgs mass not stable under quantum corrections

- If SM is extrapolated to scale Λ , the correction to Higgs mass grows with it!

$$M_h^2 = (M_h^2)_{bare} + \mathcal{O}(\lambda,\, g_3^2,\, g^2,\, g'^2,\, y_t)\Lambda^2$$

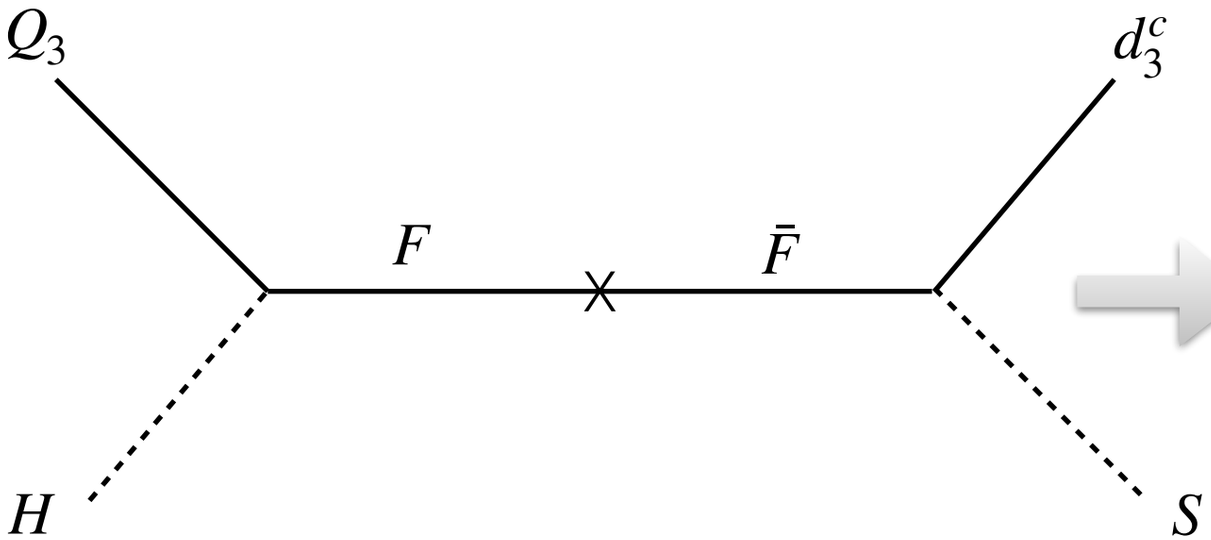


depends on fermions & bosons

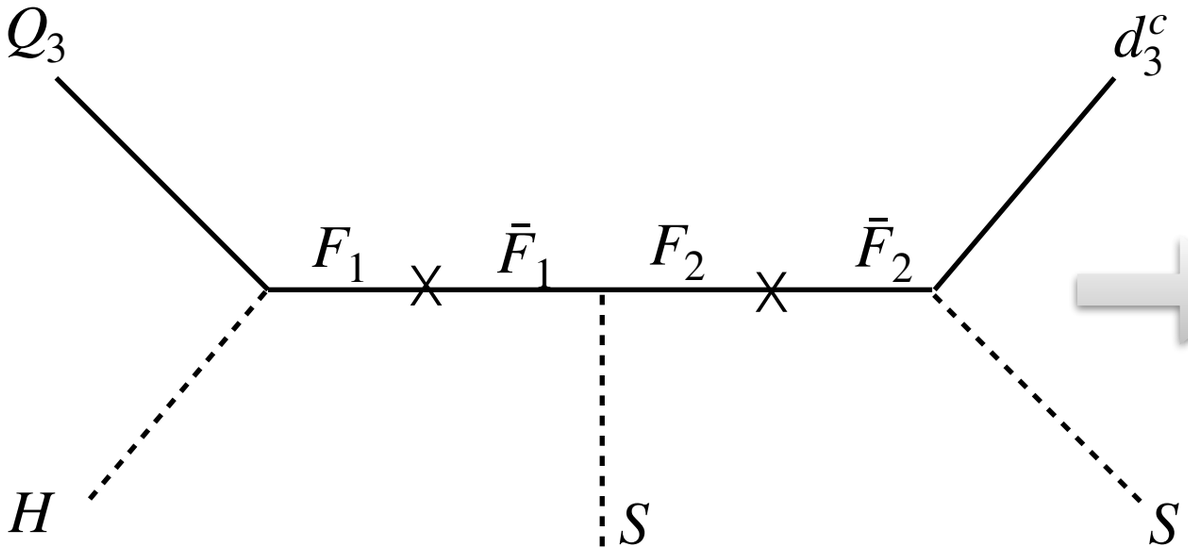
observed mass at 125 GeV

cancellation needed between fermions & bosons

Diagrams



$$\mathscr{L}^{\text{eff}} = c_1 c_2 \, (Q_3 d_3^c H) \, (S/M_F)$$



$$\mathscr{L}^{\text{eff}} = c_1 c_2 c_3 \, (Q_3 d_3^c H) \, (S/M_F)^2$$

S (flavon) breaks the U(1) symmetry $\Rightarrow$ $\langle S \rangle / M_F \sim 0.2$

Breaking scale & fermion masses both can be at Planck scale