Hidden sector behind quark mixing

Yuji Omura (KMI, Nagoya Univ.)

Based on arXiv:1703.08789 with Okawa;
arXiV:1612.01643 with Abe, Kawamura, Okawa.

Introduction

Now, we are in the very exciting Era!

LHC is running to find *new physics beyond the SM*.

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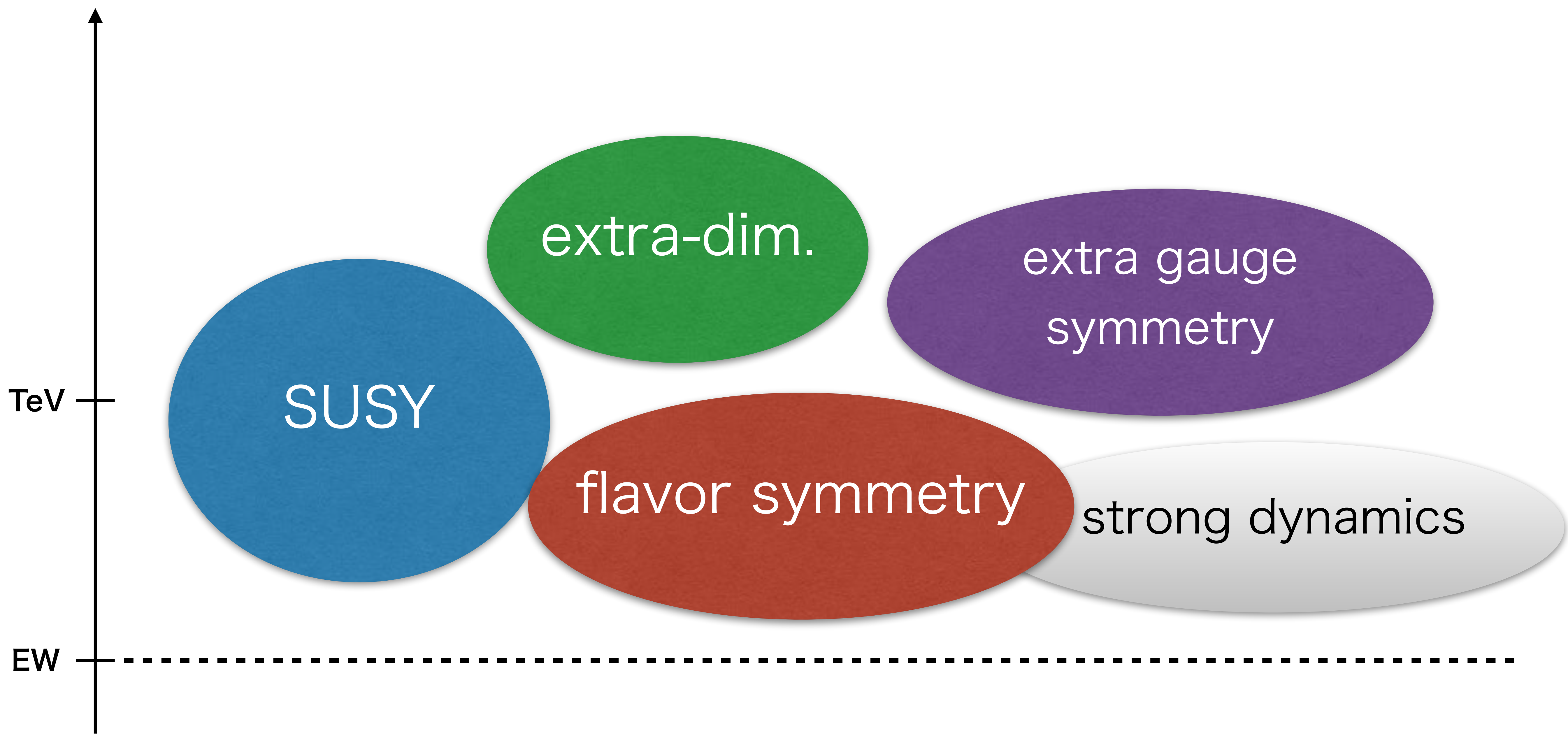
There will be something new behind

- *Higgs potential*
- *gauge interaction*
- *Yukawa couplings* *etc.*

Now, we are in the very exciting Era!

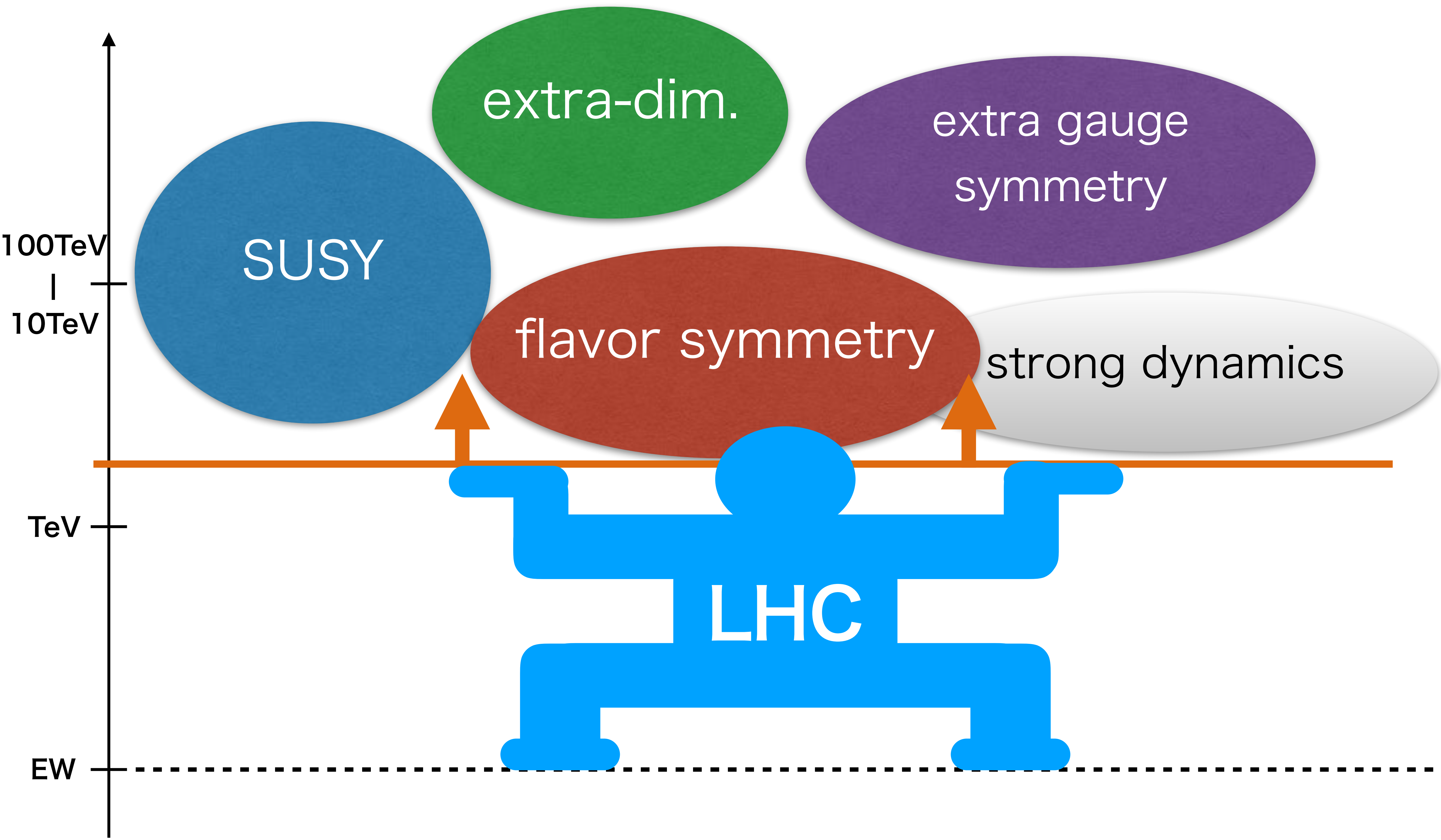
LHC is running to find *new physics beyond the SM*.

We know many candidates for the new physics:



(Unfortunately) LHC has not seen new physics…

pushes up existence region



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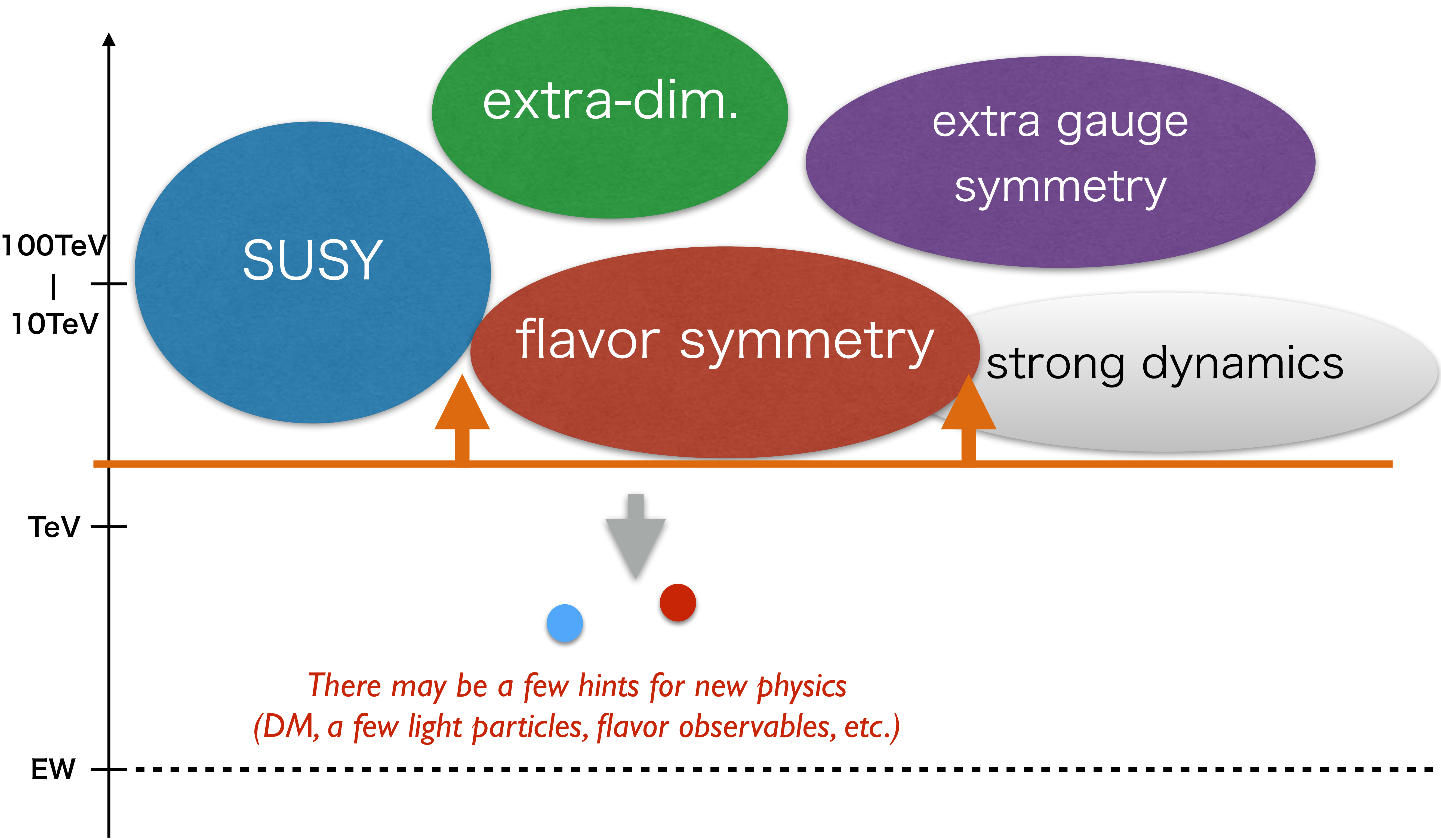

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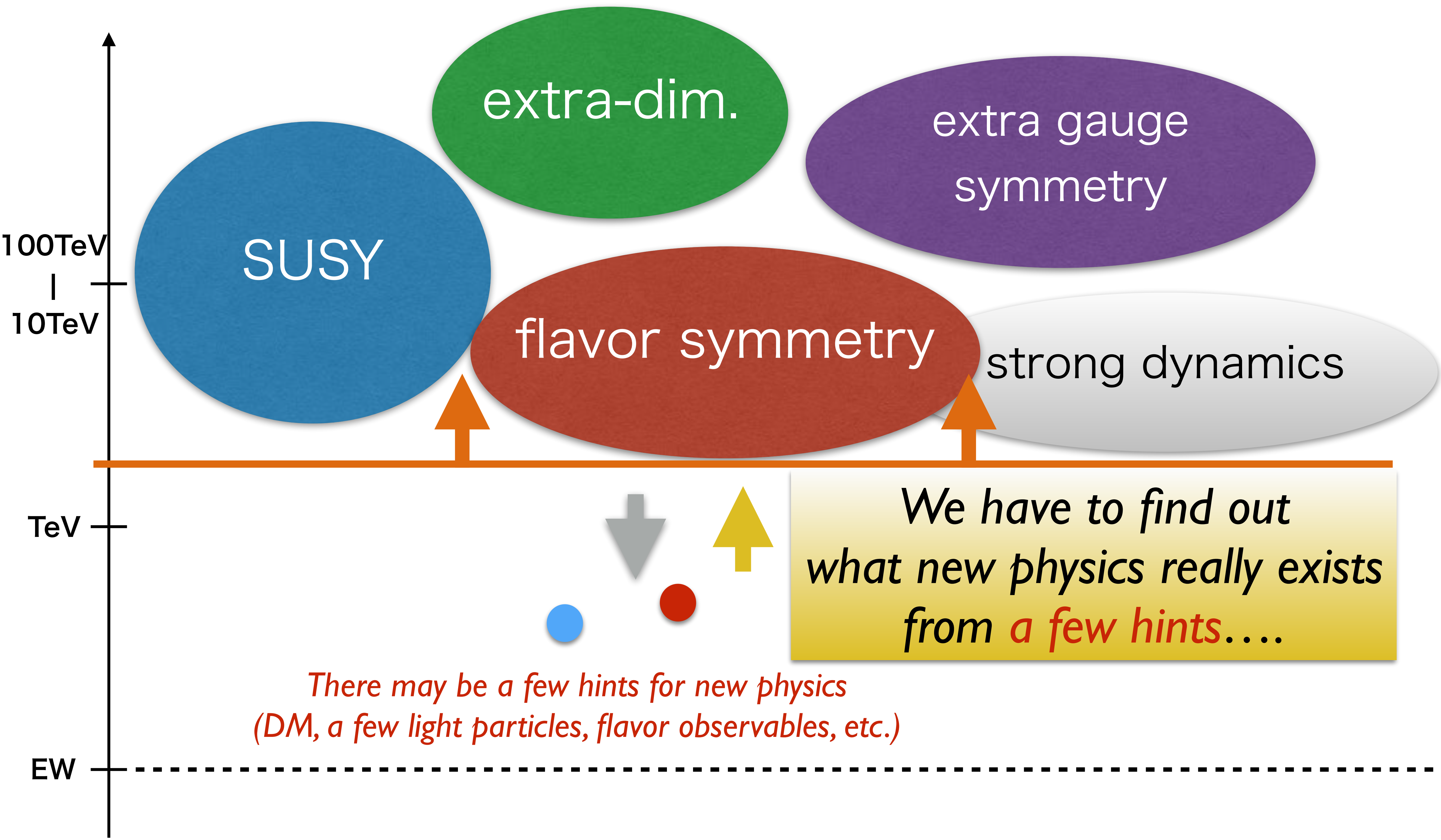
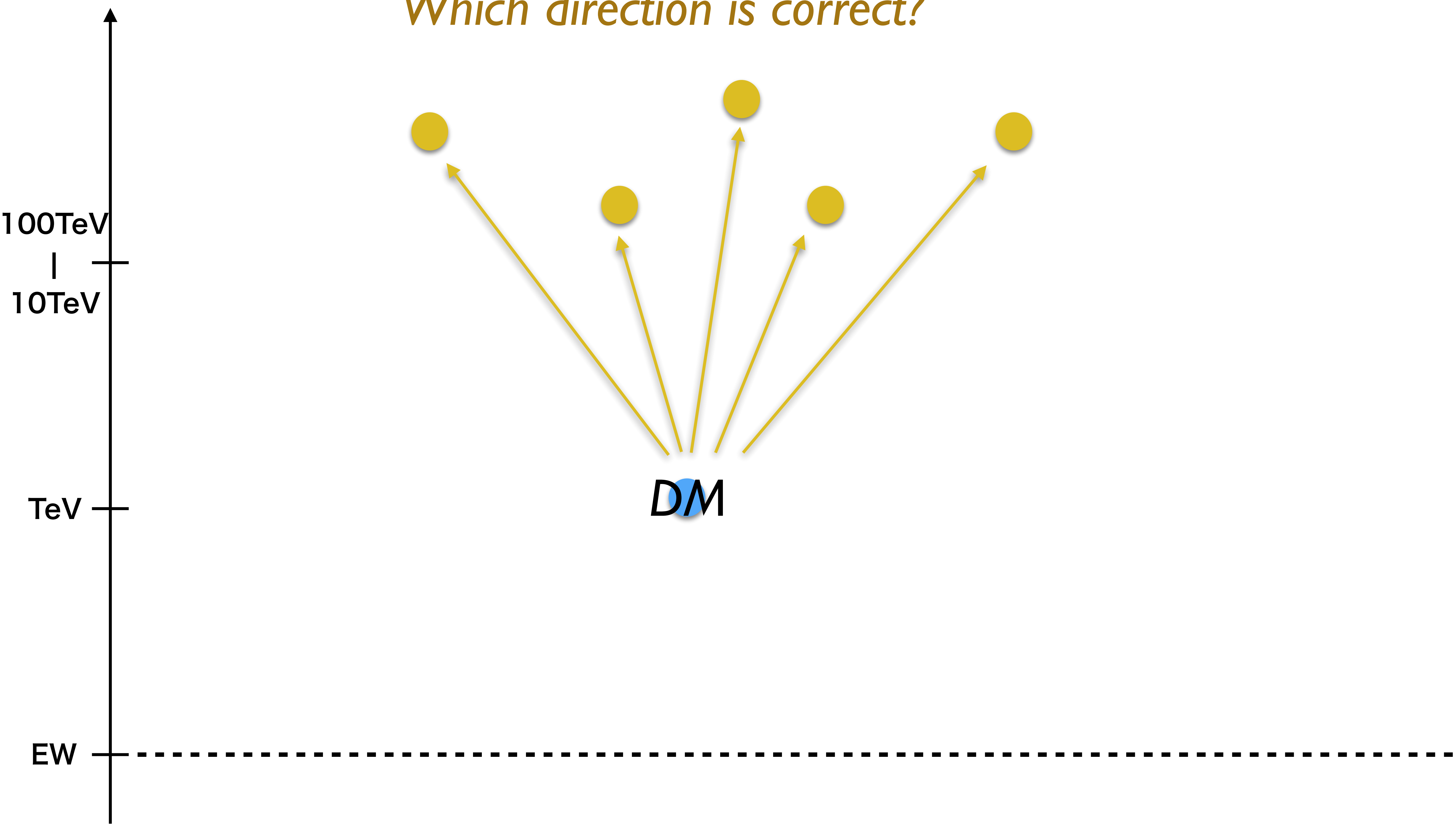


For instance, let's assume DM is discovered around TeV.

Many setups and parameter choices would be possible.

Which direction is correct?



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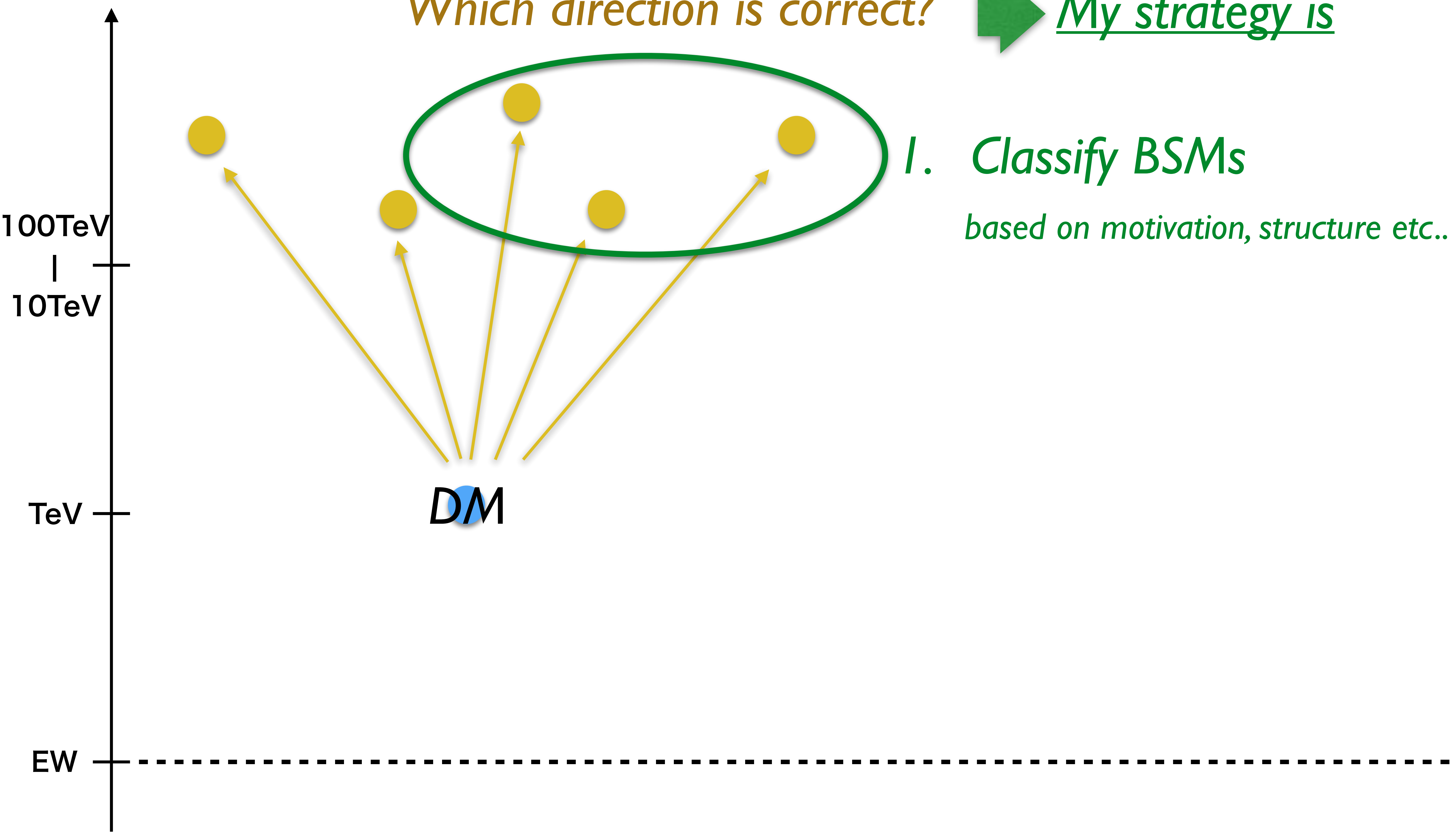

1. Classify BSMs

based on motivation, structure etc..

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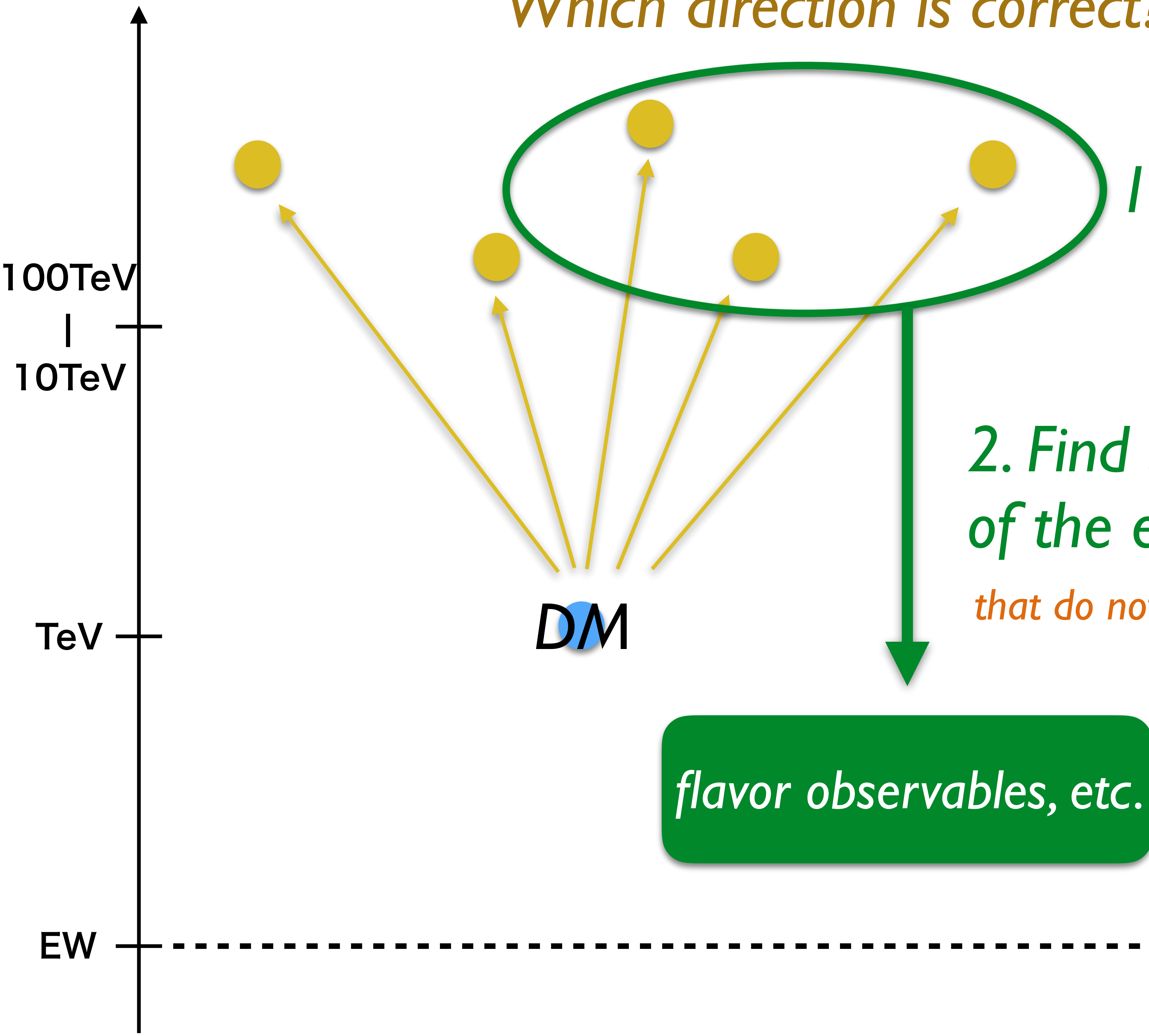


1. *Classify BSMs*

   based on motivation, structure etc..

2. *Find some "universal predictions" of the each class,*

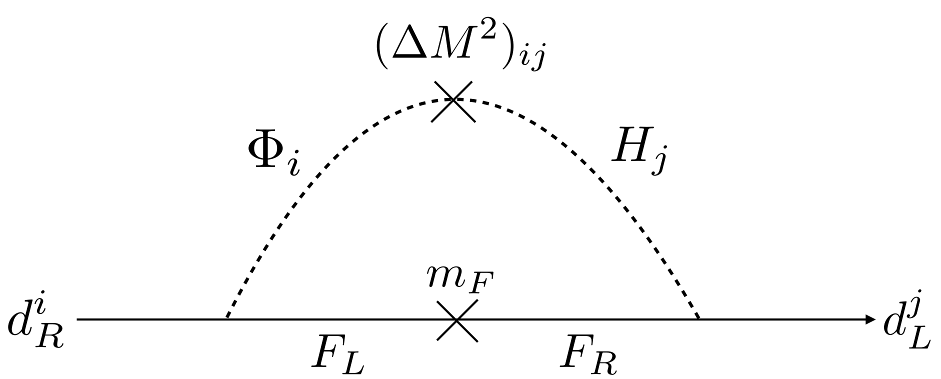
   that do not depend on the detail of the setup.

In my talk,

1. Classify BSMs

I'll focus on BSMs, where there are <u>new particles behind the quark mixing (CKM matrix)</u>.

In particular, the quark mixing induced radiatively in my talk.



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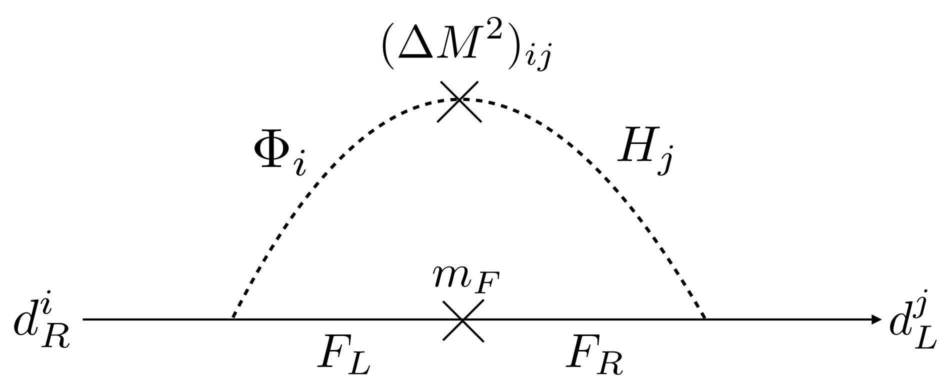

2. Find some "universal predictions" of this kind of model

Look for "*model-independent*" predictions of DM and flavor physics, *simplifying the setup (focusing on the DM contribution to mixing).*

Contents

- Setup and simplify
- Detailed analysis
- Results on Flavor and DM physics
- Summary and Discussion

Setup and Simplify

quark mixing

$$\boxed{V_{ij}} W^{\mu} \overline{u_L^i} \gamma_\mu d_L^j$$ (weak interaction)

CKM matrix is originated from the difference between the mass bases of up-type and down-type quarks.

quark mixing

$$\boxed{V_{ij}} W^{\mu} \overline{u_L^i} \gamma_\mu d_L^j \quad \text{(weak interaction)}$$

CKM matrix is originated from the difference between the mass bases of up-type and down-type quarks.

Behind the CKM, two different Yukawa couplings in the SM

$$y_i^u \overline{\hat{Q}_L^i} \widetilde{H} u_R^i + Y_{ij}^d \overline{\hat{Q}_L^i} H \hat{d}_R^j$$

$$Y_{ij}^d = V_{ik} y_k^d V_{kj}^R$$

CKM is close to unit
→tiny mass-base difference

quark mixing

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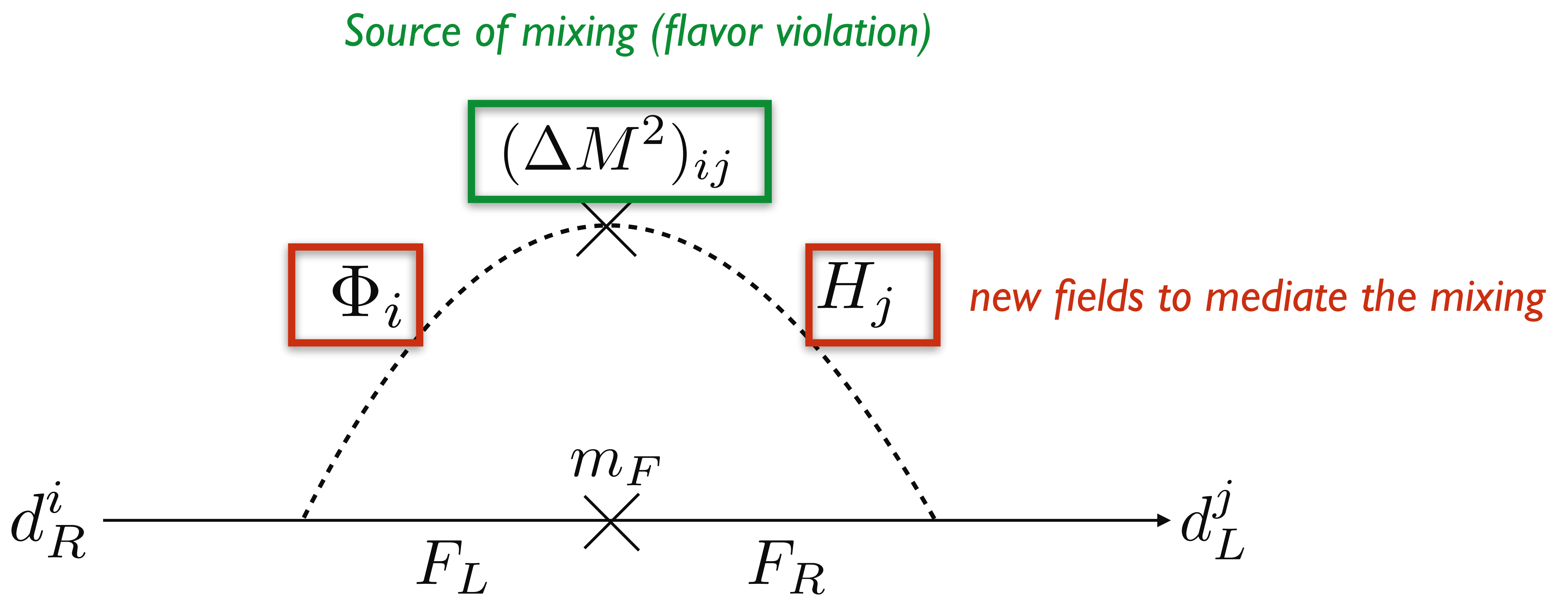
CKM is close to unit
→tiny mass-base difference

Is there something behind Y_{ij}^d ?

$$Y_{ij}^d = y_i^d \delta_{ij} + \boxed{\Delta y_{ij}^d}$$

There may be new particles behind.

One possible way is "*CKM is radiatively induced*".



The sum gives the mass matrix, although may be complicated…

$$Y_{ij}^d = \delta_{ij}\, y_i^d + (\Delta y_{ij}^d)^{(1)} + (\Delta y_{ij}^d)^{(2)} + (\Delta y_{ij}^d)^{(3)} + \ldots$$

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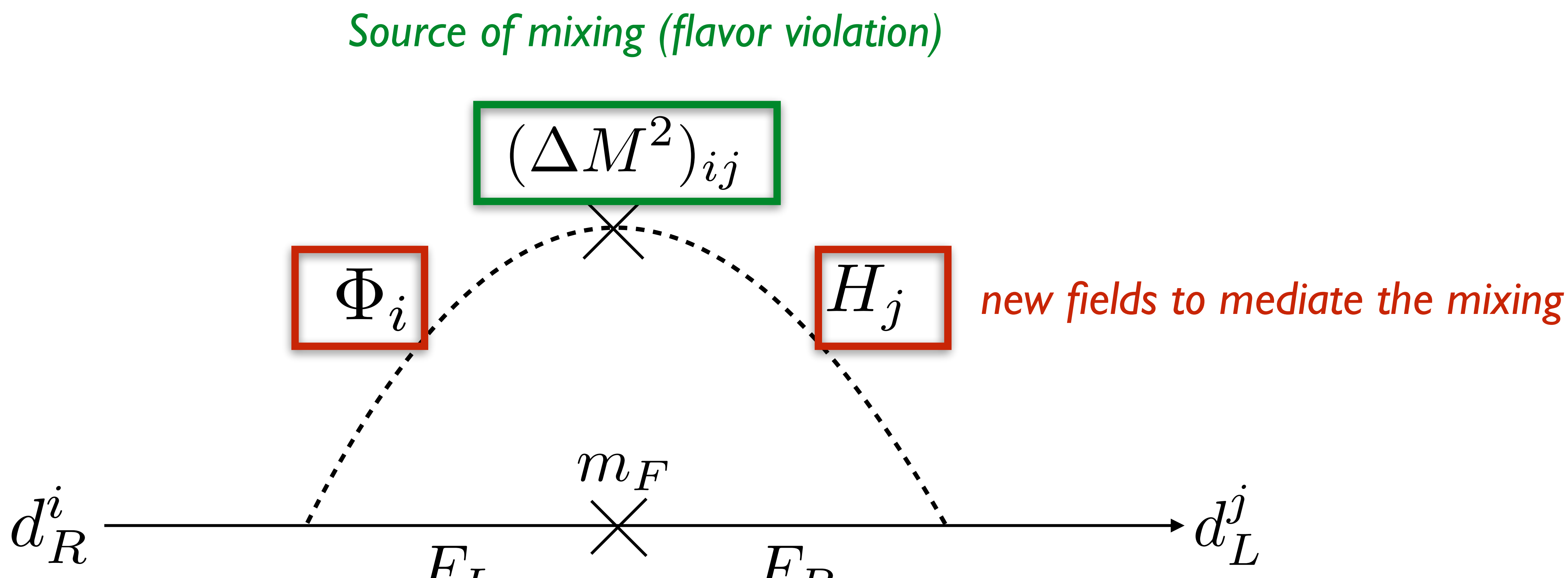

Good and interesting points:

・We can evade the tree-level FCNCs.

・This kind of models have been proposed in the GUT, supersymmetric and flavor symmetric models.

(Barbieri, Nanopoulos, PLB91 (1980);PLB95 (1980); Kramer,Montvay, Z.PC11 (1981); Balakrishna, PRL60(1988); Lahanas, Wyler, PLB122(1983);Barr, PRD31 (1985); Kagan, PRD40(1989);Baumgart, Stolarski,Zorawski,PRD90(2014);He,Volkas ,Wu, PRD41 (1990);Kownacki, Ma, PLB760 (2016);et.al..)

・We can find DM candidates among the mediators, (Φ_j, H_j).

(Ma, 1311.3213;Nomura,Okada,1606.09055;Natale,1608.06999;et.al..)

Examples of the concrete model

LR model

(*Balakrishna, Kagan, Nanopoulos, PLB205,345 (1988);Babu, Ranindra, Mohapatra PRD41(1990)1286;et.al.)*

Fields	spin	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Q_L^i	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$1/3$
$Q_R^i = (u_R^i, d_R^i)^T$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$1/3$
Φ	0	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	0
H_L^A	0	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	0
H_R^A	0	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	0
F	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$1/3$

couplings for masses

forbid by symmetry etc. to avoid tree-level FCNCs

$$\boxed{y_i \overline{Q_L^i} \Phi Q_R^i} + \cancel{\tilde{y}_{ij} \overline{Q_L^i} \tau_2 \Phi^* \tau_2 Q_R^i} + \lambda_{iA} \overline{Q_L^i} H_L^A F_R + \lambda_{iA} \overline{Q_R^i} H_R^A F_L + \cdots$$

$$+A_{BC} H_L^{B\dagger} \Phi H_R^C + m_B^2 \left(H_R^{B\dagger} H_R^B + H_L^{B\dagger} H_L^B \right) + H_R^{B\dagger} \boxed{M_{BC}^2(\phi)} H_R^C$$

SU(2)R breaking terms

Examples of the concrete model

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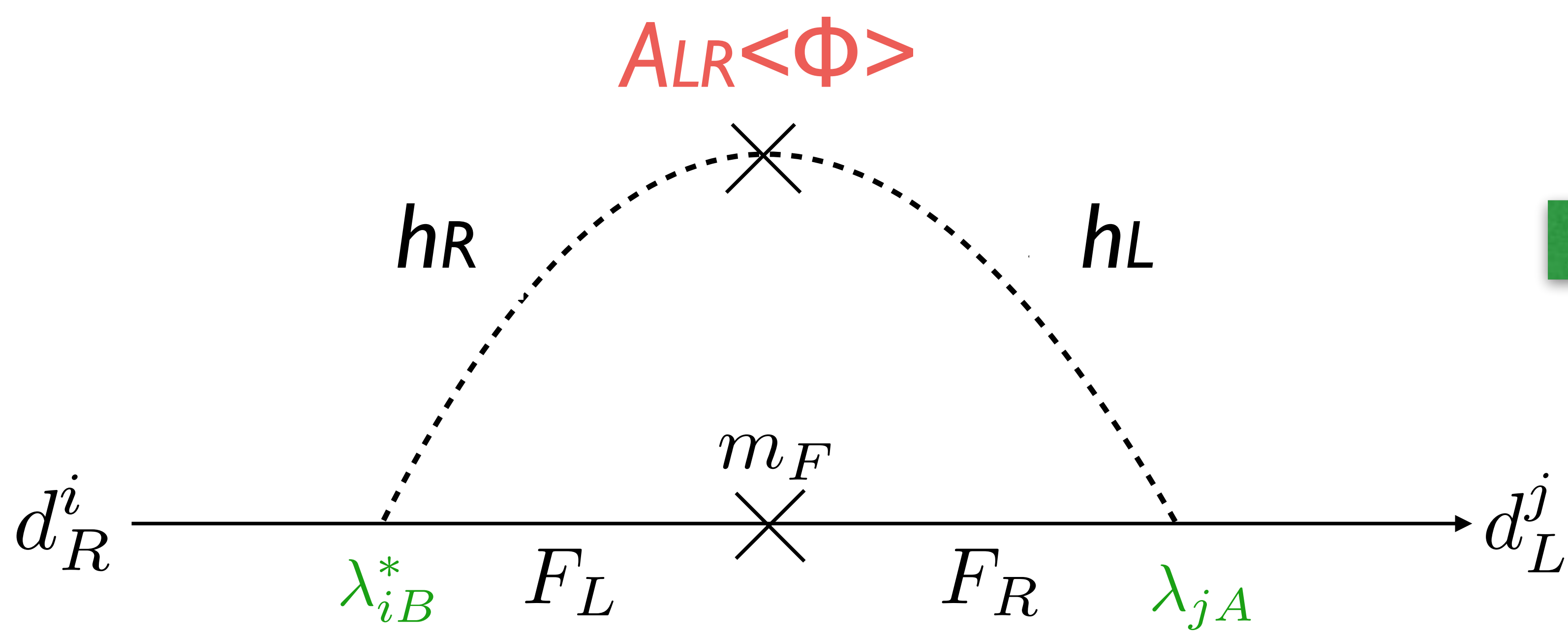
(Balakrishna, Kagan, Nanopoulos, PLB205,345 (1988);Babu, Ranindra, Mohapatra PRD41(1990)1286;et.al.)

couplings for masses

$$+\lambda_{iA}\overline{Q_L^i}H_L^A F_R + \lambda_{iA}\overline{Q_R^i}H_R^A F_L$$

$$+A_{BC}H_L^{B\dagger}\Phi H_R^C + m_B^2\left(H_R^{B\dagger}H_R^B + H_L^{B\dagger}H_L^B\right) + H_R^{B\dagger}M_{BC}^2(\phi)H_R^C + \ldots$$

SU(2)R breaking terms



loop factor

$$\Delta y_{ij}^d = \epsilon_{AB}\lambda_{iA}\lambda_{jB}^*$$

Examples of the concrete model

flavor symmetric model

(Ma, 1311.3213;Nomura,Okada,1606.09055;Natale,1608.06999;et.al.)

Fields	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Flavor sym.
Q_L^i	1/2	$\mathbf{3}$	$\mathbf{2}$	1/6	q_i
u_R^i	1/2	$\mathbf{3}$	$\mathbf{1}$	2/3	q_i
d_R^i	1/2	$\mathbf{3}$	$\mathbf{1}$	-1/3	q_i
H	0	$\mathbf{1}$	$\mathbf{2}$	1/2	0
H^i	0	$\mathbf{1}$	$\mathbf{2}$	1/2	q_i
Φ^i	0	$\mathbf{1}$	$\mathbf{1}$	0	q_i
F	1/2	$\mathbf{3}$	$\mathbf{1}$	-1/3	0

Many choices for flavor sym.;
e.g., Z_3, A_4, gauged $U(1)_F$, etc.

couplings for masses

$$y_i^u \overline{Q_L^i} \widetilde{H} u_R^i + y_i^d \overline{Q_L^i} H d_R^i + \hat{\kappa}_i \overline{Q_L^i} H^i F_R + \hat{\lambda}_i^* \overline{d_R^i} \Phi^i F_L$$

$$+ A_i \Phi^i (H^\dagger H^i) + M^2(\phi)_{ij} \Phi^{i\,\dagger} \Phi^j + M_H^2(\phi)_{ij} H^{i\,\dagger} H^j$$

source of flavor symmetry breaking terms

Examples of the concrete model

flavor symmetric model

(Ma, 1311.3213;Nomura,Okada,1606.09055;Natale,1608.06999;et.al.)

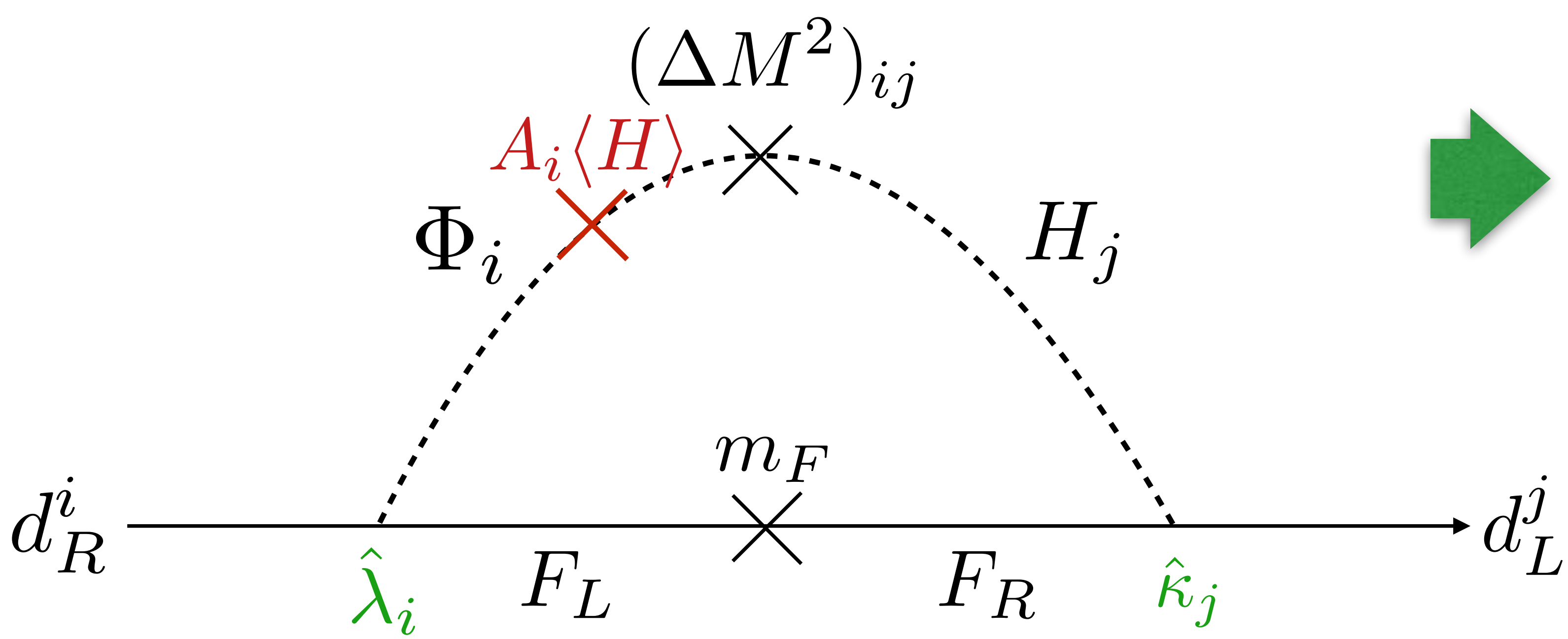
couplings for masses

$$y_i^u \overline{Q_L^i}\widetilde{H} u_R^i + y_i^d \overline{Q_L^i} H d_R^i + \hat{\kappa}_i \overline{Q_L^i} H^i F_R + \hat{\lambda}_i^* \overline{d_R^i} \Phi^i F_L$$

$$+ A_i \Phi^i (H^\dagger H^i) + (m_i^2 \delta_{ij} + \Delta M_{ij}^2) \Phi^{i\,\dagger} \Phi^j + (m_{H\,i}^2 \delta_{ij} + \Delta M_{ij}^2) H^{i\,\dagger} H^j$$

source of flavor symmetry breaking terms

loop factor



$$\Delta y_{ij}^d = \epsilon_{ij} \hat{\kappa}_i \hat{\lambda}_j$$

There are many para., so that it may be difficult to find predictions…

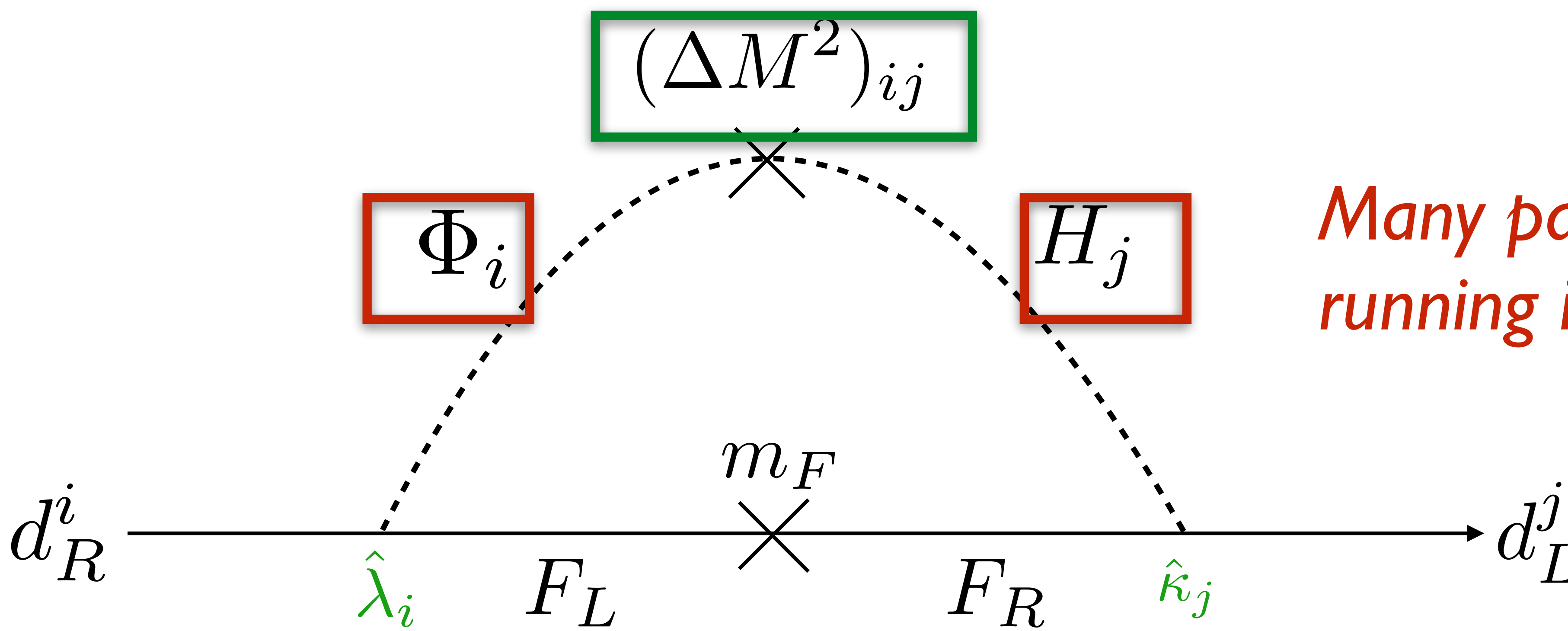
$$Y^d_{ij} = \delta_{ij}\, y^d_i + (\Delta y^d_{ij})^{(1)} + (\Delta y^d_{ij})^{(2)} + (\Delta y^d_{ij})^{(3)} + \dots$$

mass eigenstates:

$$\Phi_i = c^X_i X + c^{\phi_1}_i \phi_1 + c^{\phi_2}_i \phi_2$$

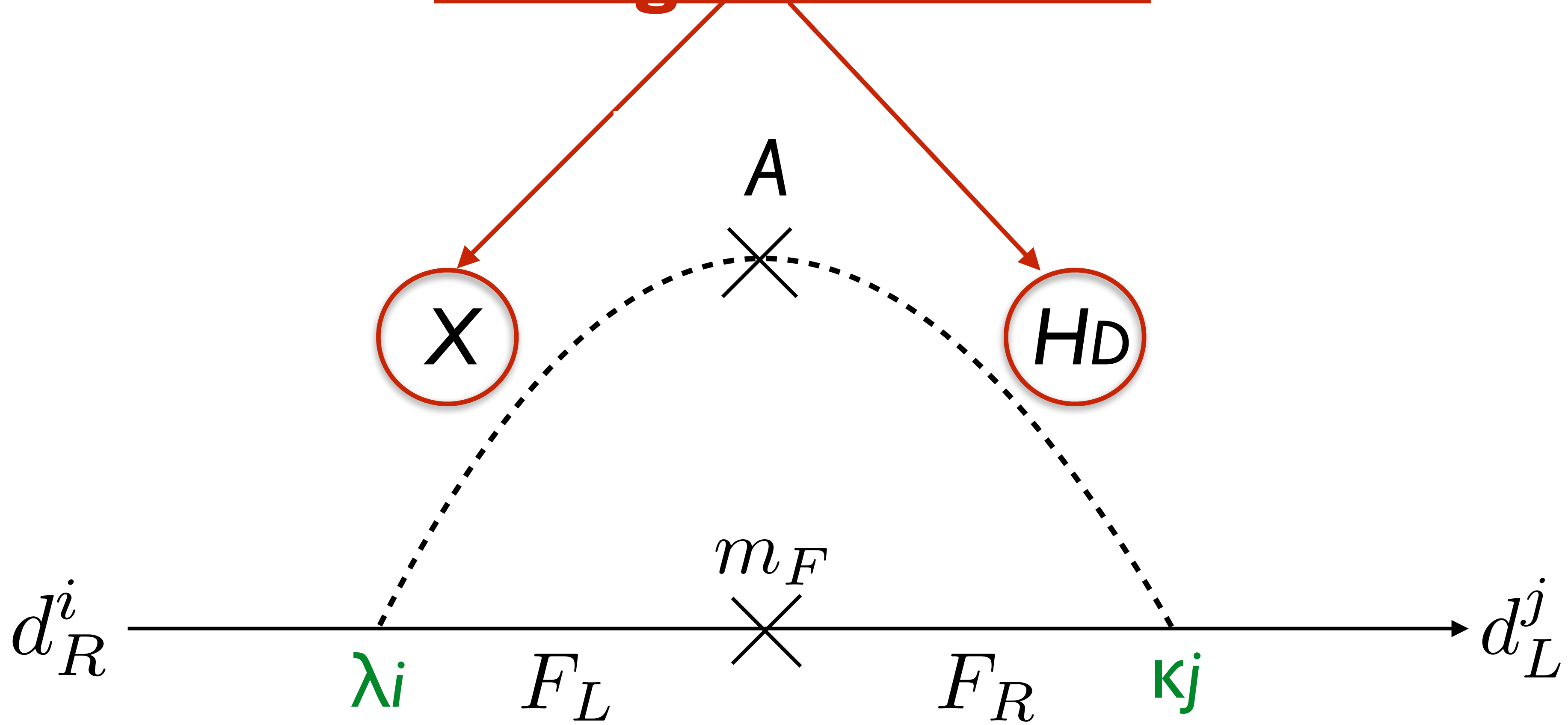
$$H_i = c^D_i H_D + c^{H'_1}_i H'_1 + c^{H'_2}_i H'_2$$

Source of flavor violation



Many particles are running in the loop

let me focus on one contribution involving the lightest modes



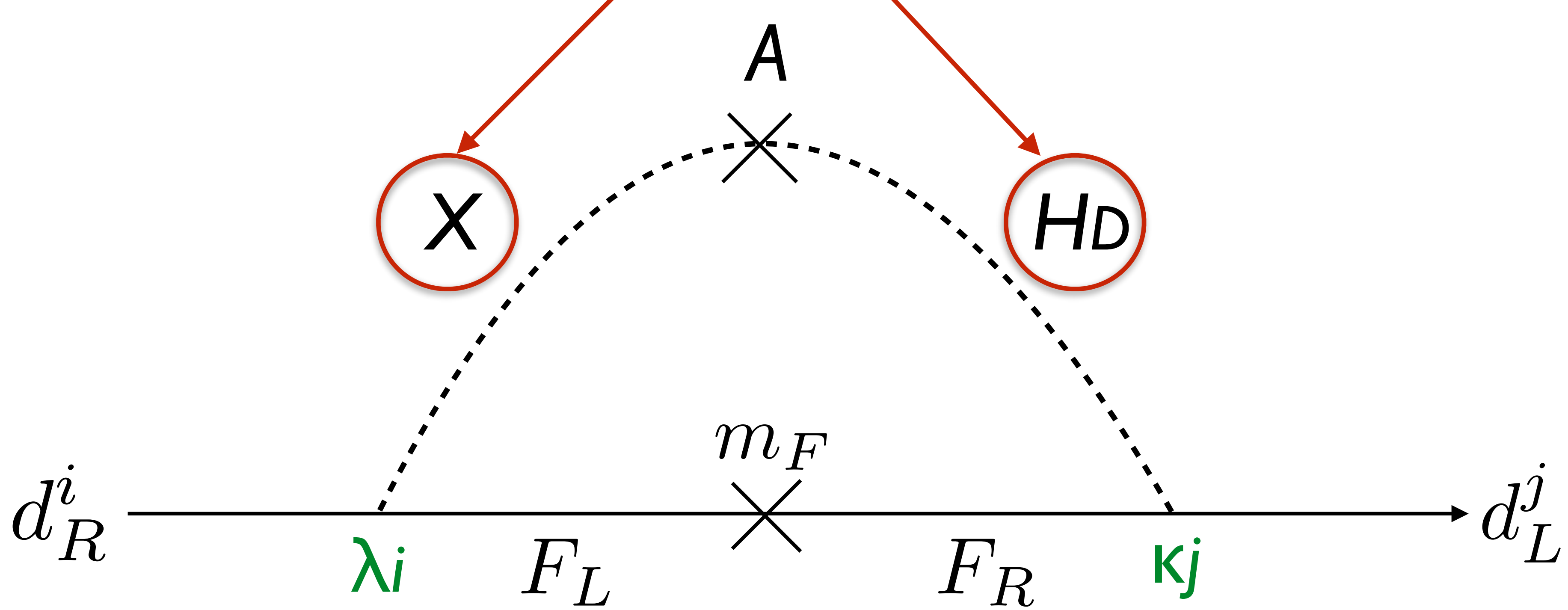
based on naive guess:

- The loop involving the lightest may be dominant;
- The lightest is a good DM candidate;

(Ma, 1311.3213;Nomura,Okada,1606.09055;Natale,1608.06999;et.al..)

- DM interacts with SM particles →the loop contribution may be large;

let me focus on one contribution involving the lightest modes



If focus on this,

the down-type Yukawa approximately given by

$$Y^d_{ij} \approx y^d_i \, \delta_{ij} + \epsilon \, \kappa_i \lambda_j$$

generate CKM

The points of this Mass Matrix

$$Y^d_{ij} \approx y^d_i\, \delta_{ij} + \boxed{\epsilon\, \kappa_i \lambda_j}$$

generate CKM

- *not many parameters and the structure is unique*

- *relate to the ΔF=2 processes and the EDM*

- *Assuming the lightest mediator (X or H_D) is DM,*

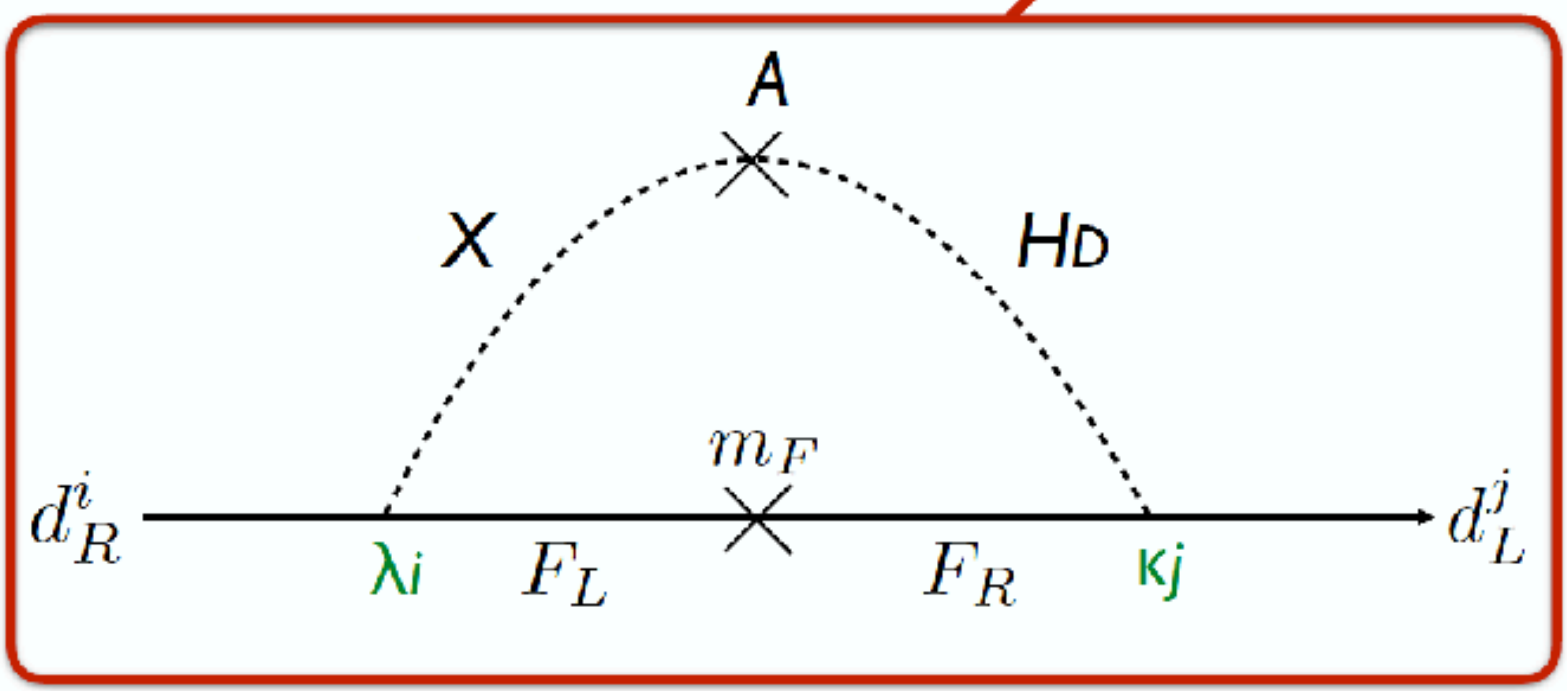
there are correlations between DM and flavor physics.

The Detail

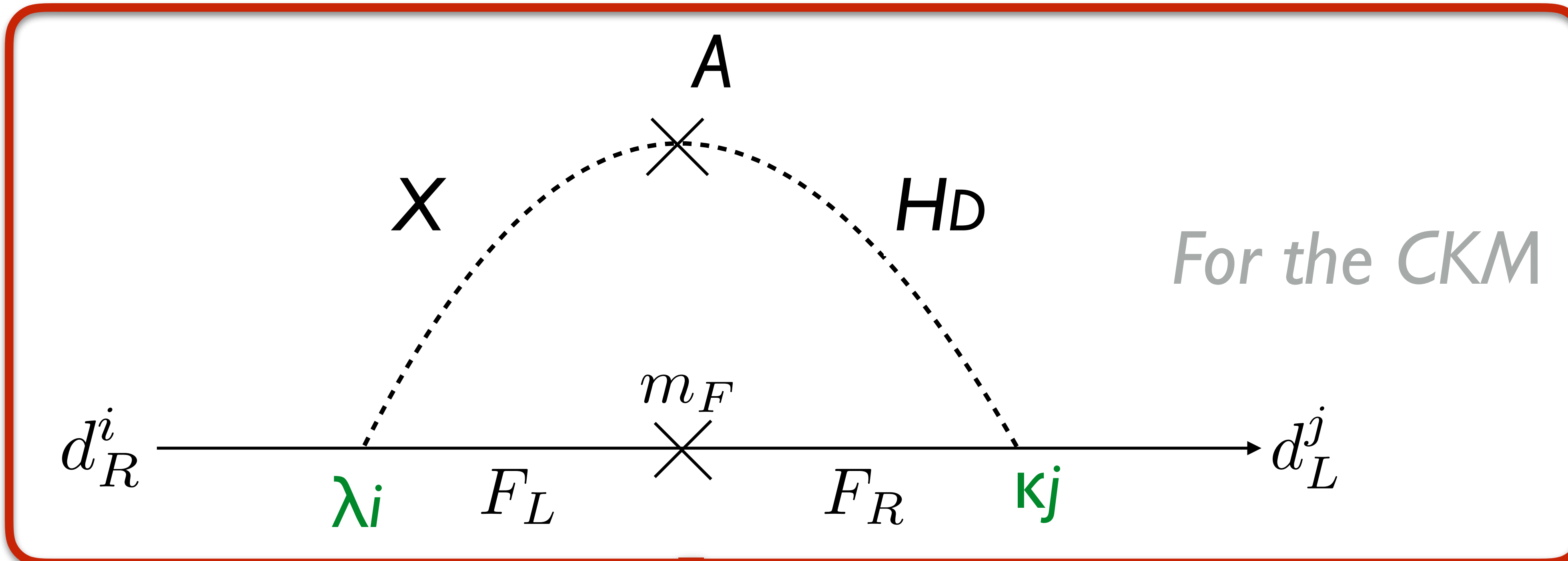
The obtained mass matrices in this assumption:

$$(M_u)_{ij} = \frac{y_i^u}{\sqrt{2}} v \qquad (M_d)_{ij} = \frac{y_i^d}{\sqrt{2}} v\, \delta_{ij} + \boxed{\frac{v}{\sqrt{2}}\, \epsilon\, \kappa_i \lambda_j}$$

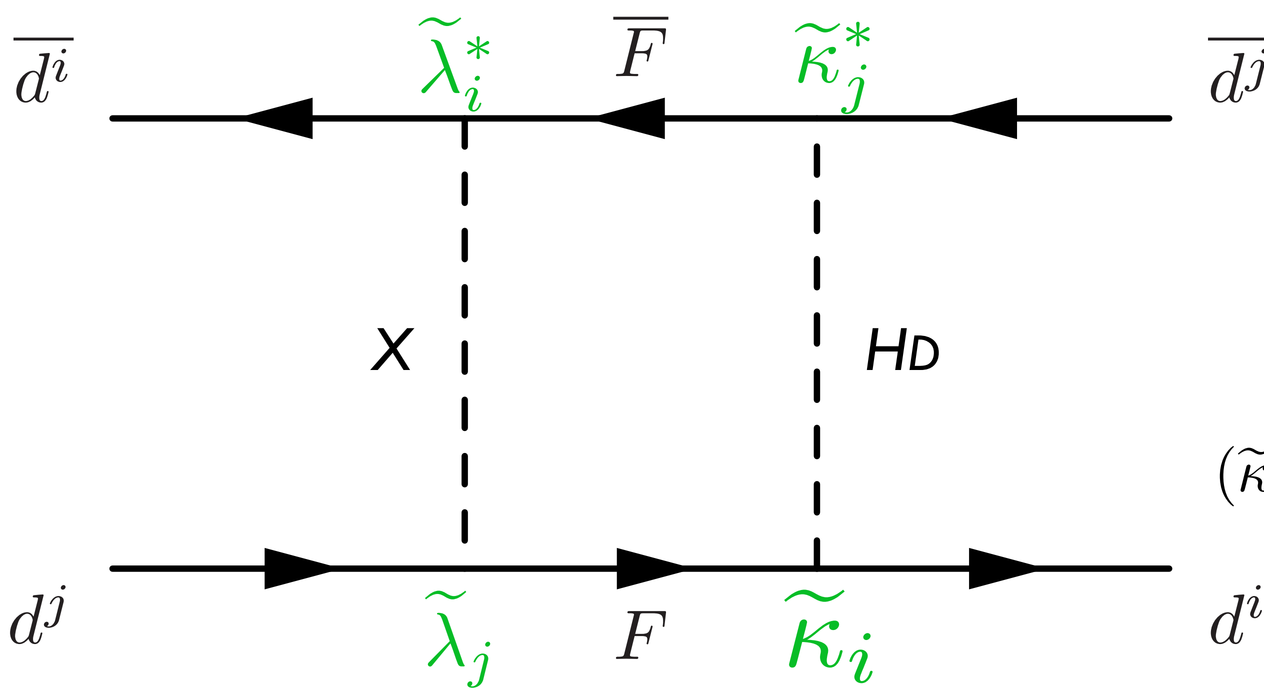
The one-loop correction



The combination of the couplings relates to the flavor observables:



These combinations appear in ΔF=2



$$\propto (\widetilde{\lambda_j \widetilde{\kappa}_i})(\widetilde{\lambda}_i{}^* \widetilde{\kappa}_j{}^*)$$

$(\widetilde{\kappa}_i \equiv V^\dagger_{ij}\kappa_j \text{ and } \widetilde{\lambda}_i = \lambda_j V_{R\,ji})$

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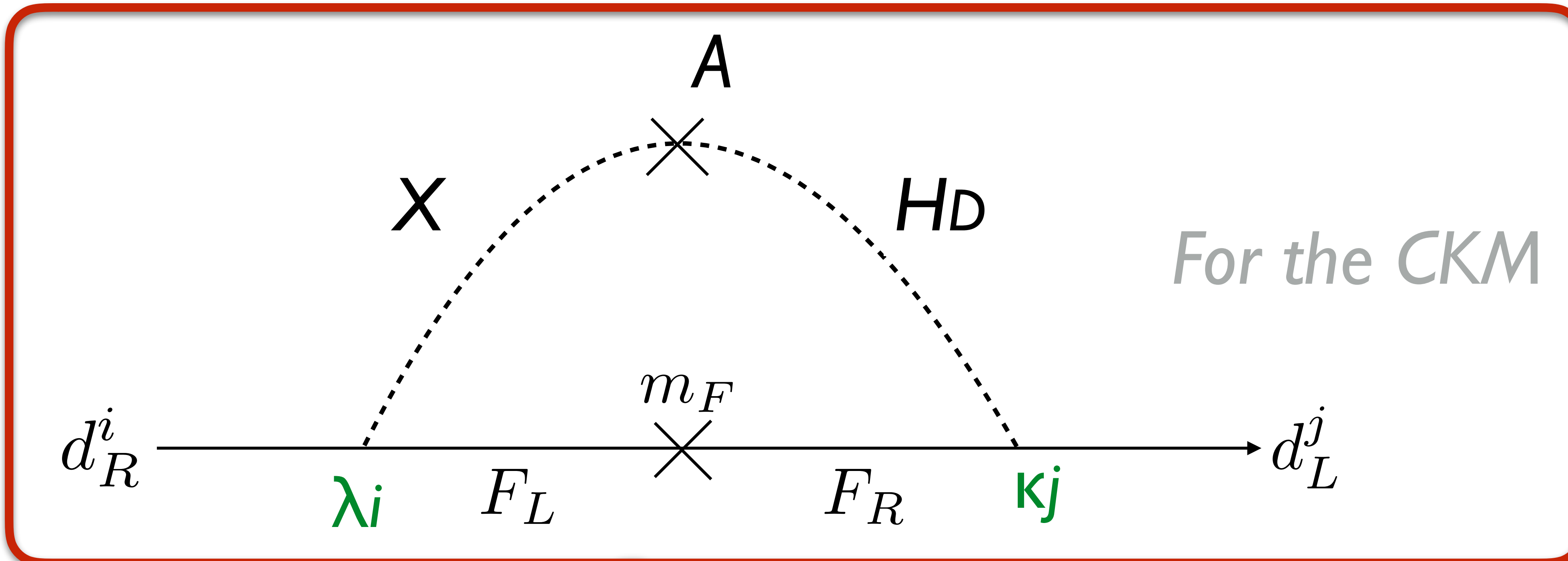
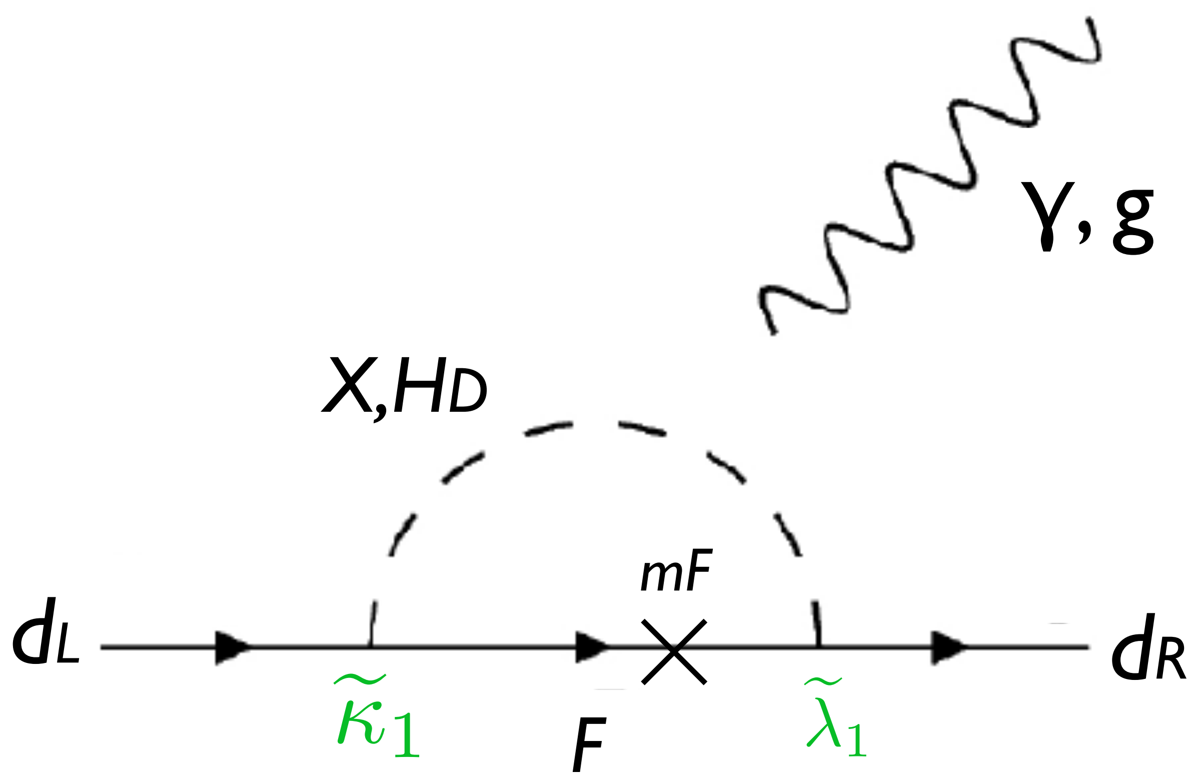


*also appear in **EDM***



$$\propto \widetilde{\lambda_1}\widetilde{\kappa_1}$$

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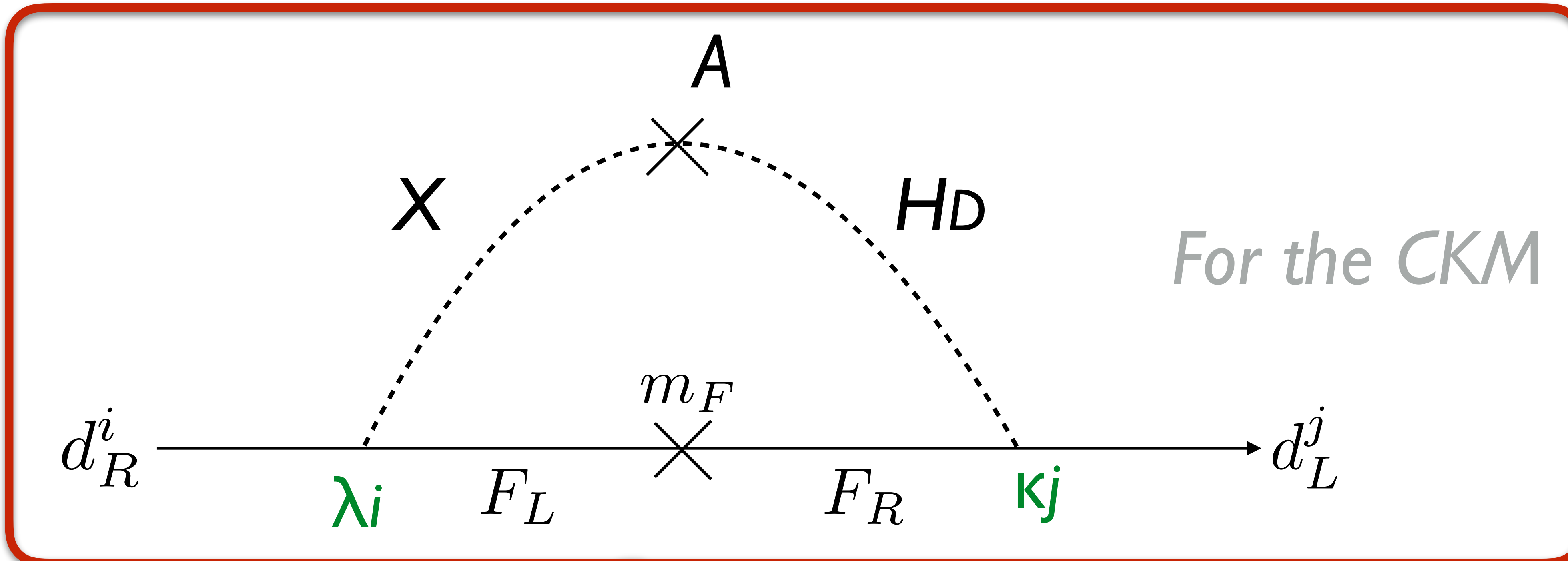

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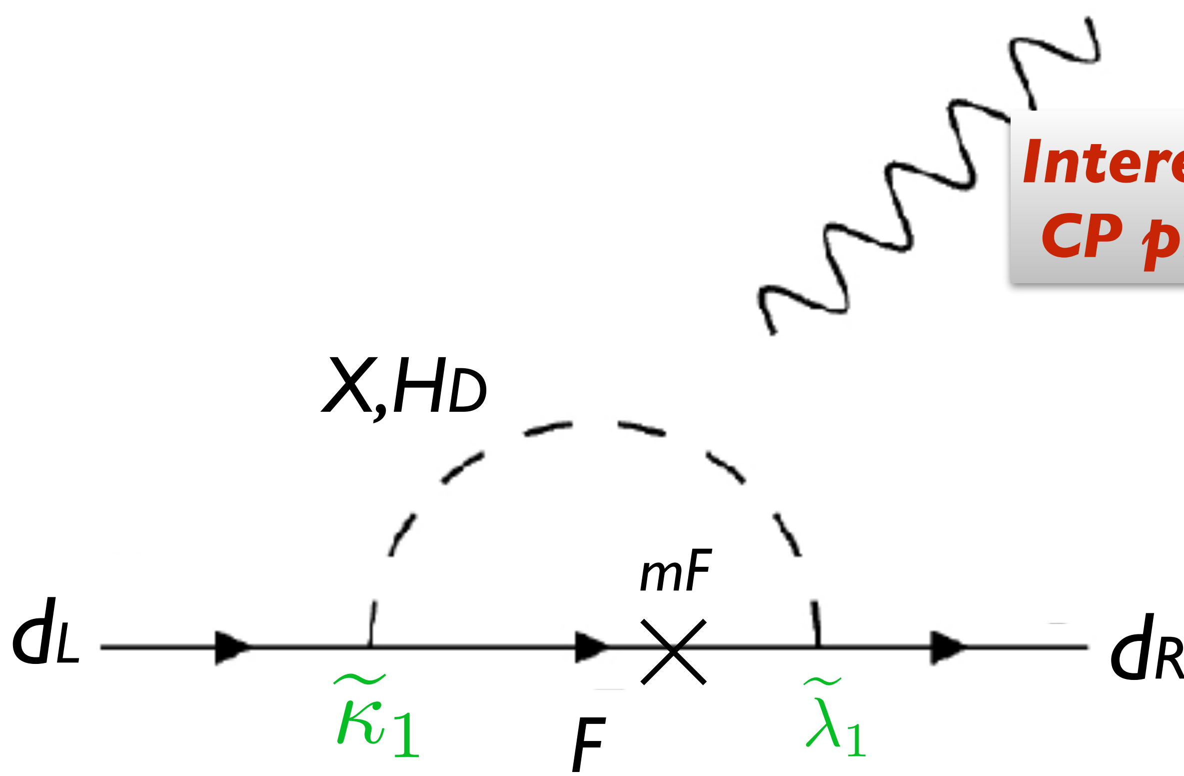

Interesting point:
CP phases of EDM and εK are related.

$$\propto \widetilde{\lambda_1}\widetilde{\kappa_1}$$

Identity

$$\boxed{\widetilde{\kappa}_1 \widetilde{\lambda}_1} = \frac{\widetilde{\kappa}_1 \widetilde{\lambda}_3}{\widetilde{\kappa}_2 \widetilde{\lambda}_3} \times \boxed{\widetilde{\kappa}_2 \widetilde{\lambda}_1}$$

contributes to EDM

contributes to εK

for the CKM and down-type quark masses

$$(m_d)_i\,\delta_{ij} = \frac{v}{\sqrt{2}}\left\{\left(V^\dagger y^d V_R\right)_{ij} + \epsilon\,\widetilde{\kappa}_i\widetilde{\lambda}_j\right\}$$

Identity

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Identity

Assuming $|y_3^d| \gg |y_{1,2}^d|$

CKM

$$\widetilde{\kappa}_1\widetilde{\lambda}_1 = \frac{\widetilde{\kappa}_1\widetilde{\lambda}_3}{\widetilde{\kappa}_2\widetilde{\lambda}_3} \times \widetilde{\kappa}_2\widetilde{\lambda}_1 \approx \frac{V_{td}^*}{V_{ts}^*} \times \widetilde{\kappa}_2\widetilde{\lambda}_1$$

contributes to EDM

contributes to εK

<u>*for the CKM and down-type quark masses*</u>

$$(m_d)_i\,\delta_{ij} = \frac{v}{\sqrt{2}}\left\{\left(V^\dagger y^d V_R\right)_{ij} + \epsilon\,\widetilde{\kappa}_i\widetilde{\lambda}_j\right\}$$

Identity

Assuming $|y^d_3| \gg |y^d_{1,2}|$

CKM

$$\widetilde{\kappa}_1\widetilde{\lambda}_1 = \frac{\widetilde{\kappa}_1\widetilde{\lambda}_3}{\widetilde{\kappa}_2\widetilde{\lambda}_3} \times \widetilde{\kappa}_2\widetilde{\lambda}_1 \approx \frac{V^*_{td}}{V^*_{ts}} \times \widetilde{\kappa}_2\widetilde{\lambda}_1$$

contributes to EDM

contributes to εK

Both contributions are related each other!

Results on
Flavor and DM physics

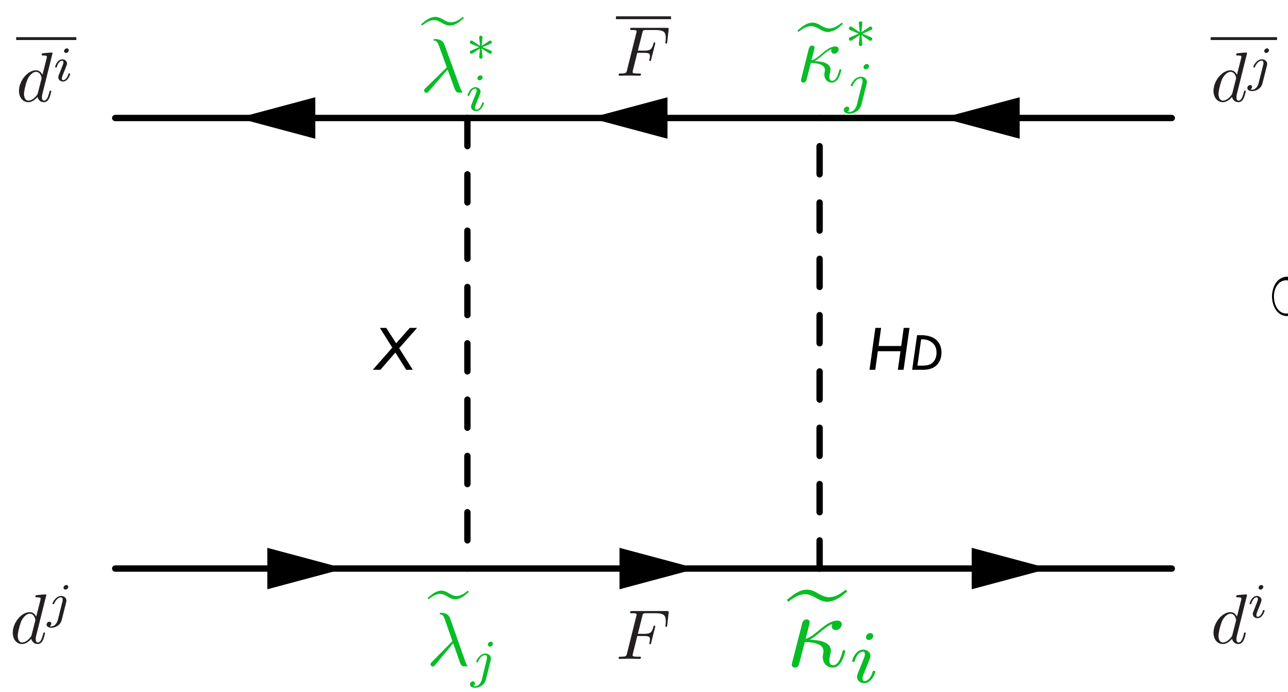
with Ansatz:

$$|y_1^d| = \mathcal{O}\left(\sqrt{2} m_d/v\right), \; |y_2^d| = \mathcal{O}\left(\sqrt{2} m_s/v\right), \; y_3^d \simeq \frac{\sqrt{2}}{v} m_b$$

V_R has at most O(0.1) mixing like CKM

(Okawa, YO, 1703.08789; work in progress)

Constraint from ε K



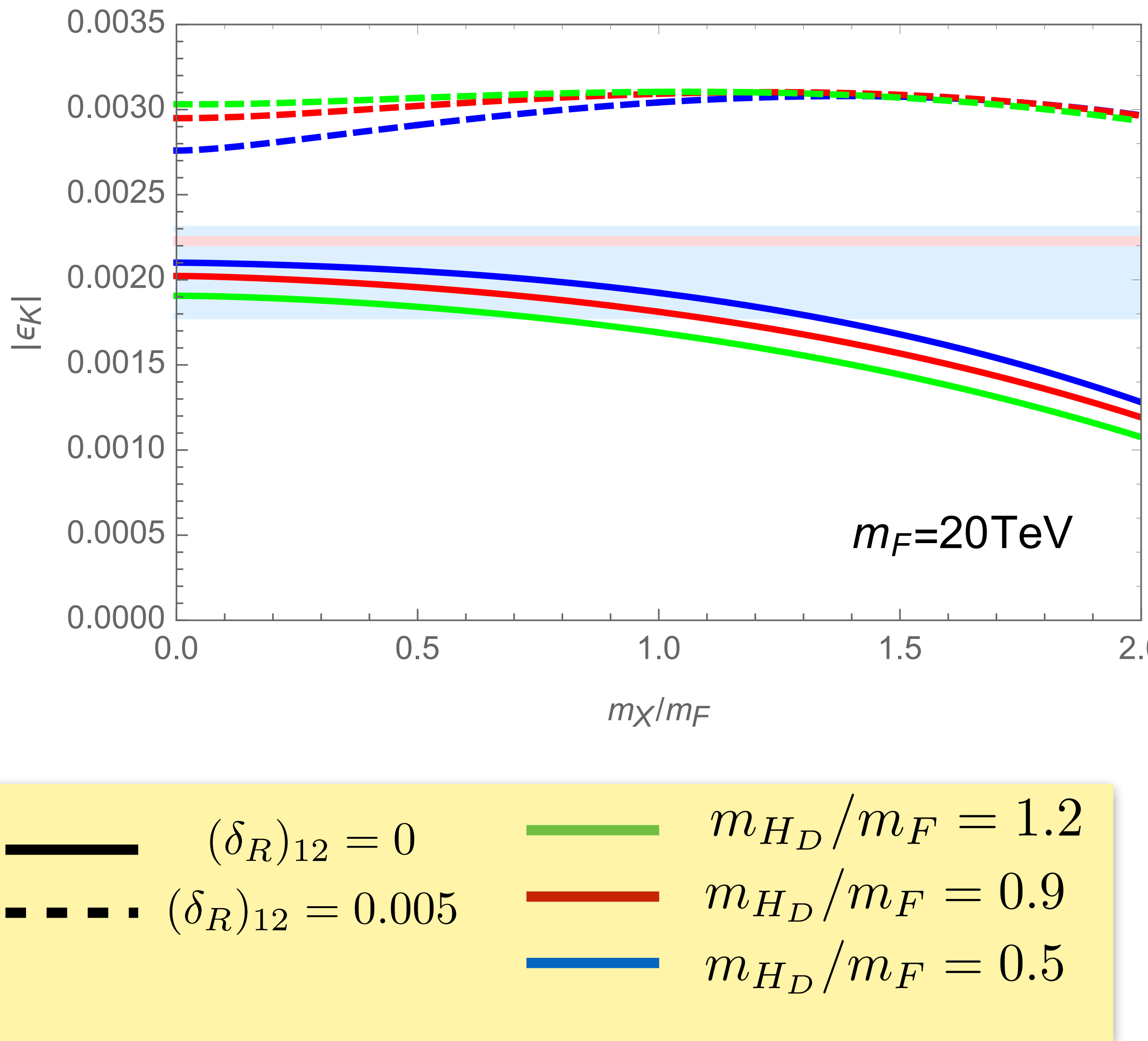
$$\propto (\widetilde{\lambda_j \widetilde{\kappa}_i})(\widetilde{\lambda_i}^* \widetilde{\kappa_j}^*)$$

This constraint is very strong because the induced operator is $(\overline{s_R} d_L)(\overline{s_L} d_R)$

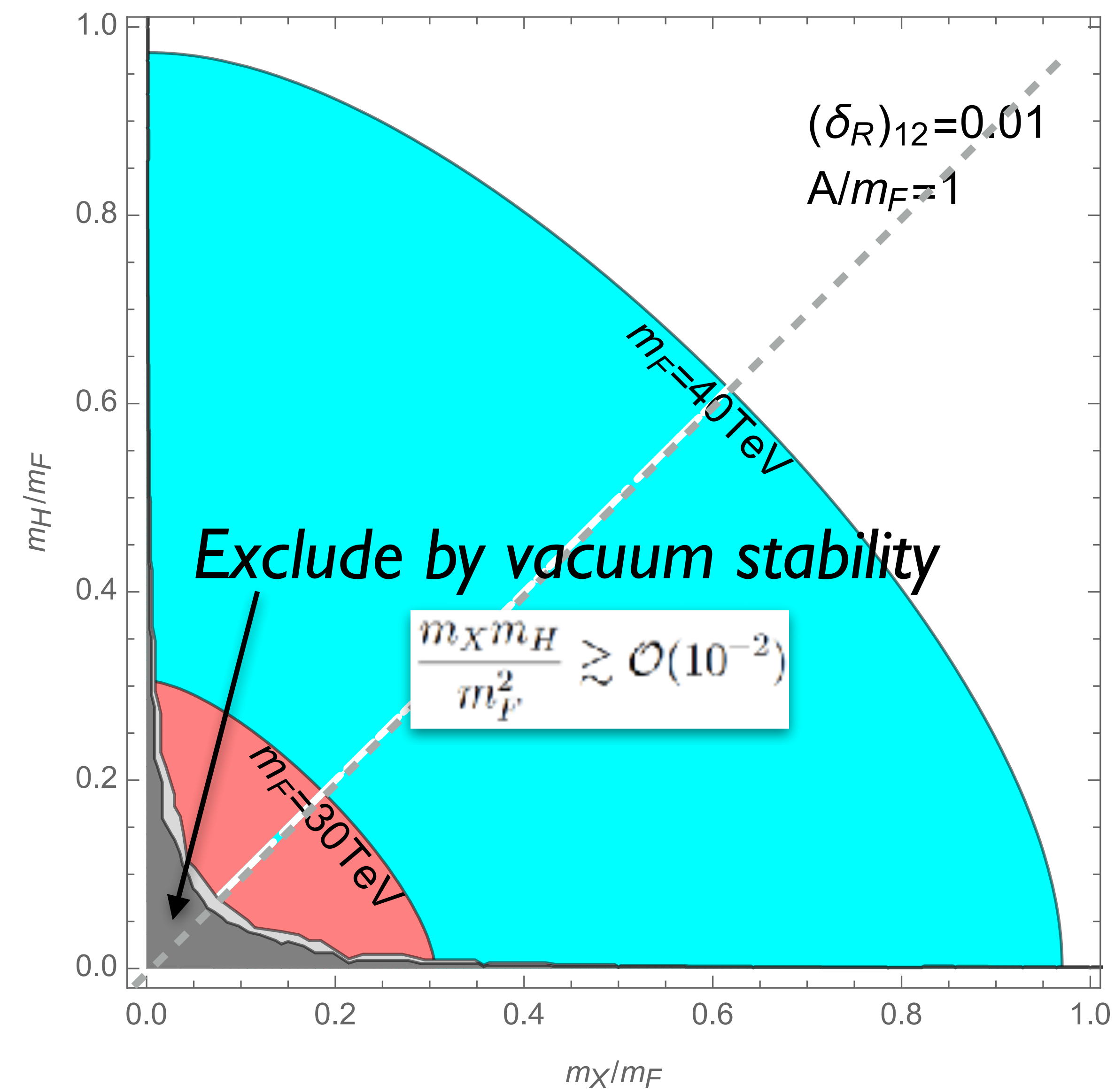
By tuning the CP-phase((δR)12), mF (NW scale) could be relatively light.

Constraint from ε K

prediction of εK



2σ-regions of the SM @mF=30, 40TeV

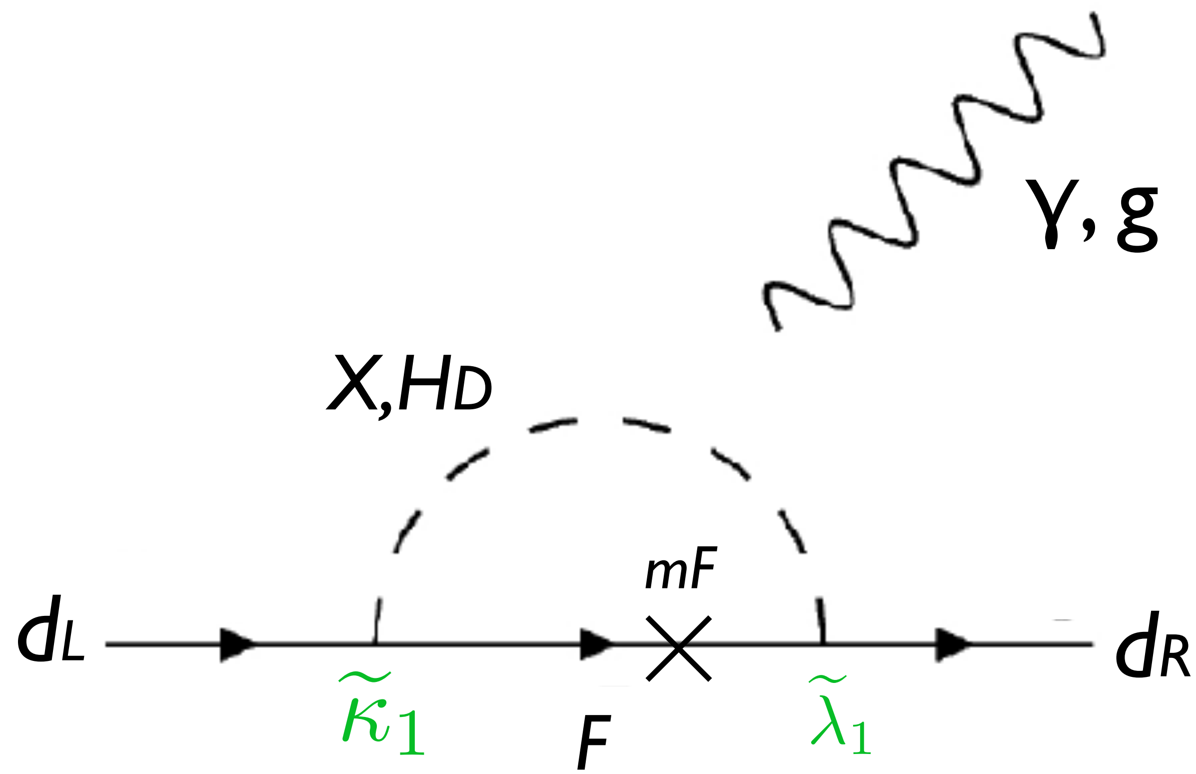


This constraint is very strong because the induced operator is $(\overline{s_R}d_L)(\overline{s_L}d_R)$

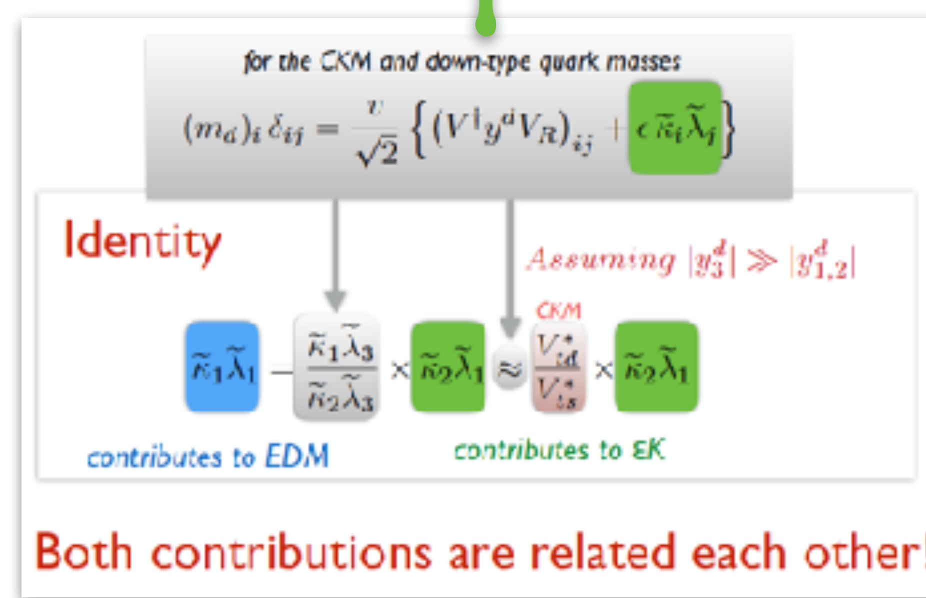
By tuning the CP-phase($(\delta_R)_{12}$), mF (NW scale) could be relatively light.

Constraint from EDM with $(\delta_R)_{12}=0$

$\Delta(\varepsilon_K)$ almost minimized.



$$\propto \widetilde{\lambda_1}\widetilde{\kappa_1}$$

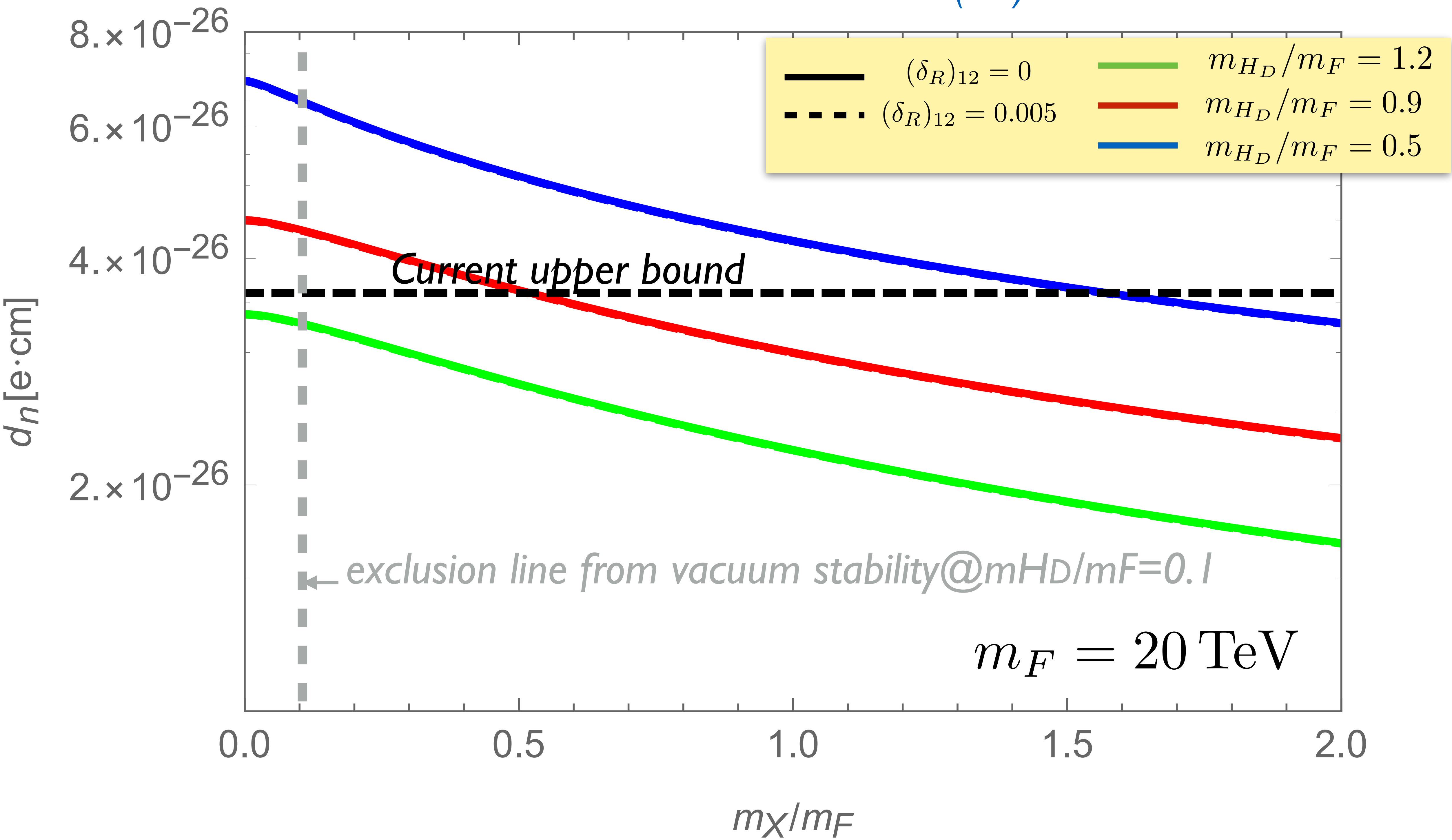


The phase is from the CKM matrix!

εK is correlated with EDM.

Constraint from EDM with $(\delta_R)_{12}=0$

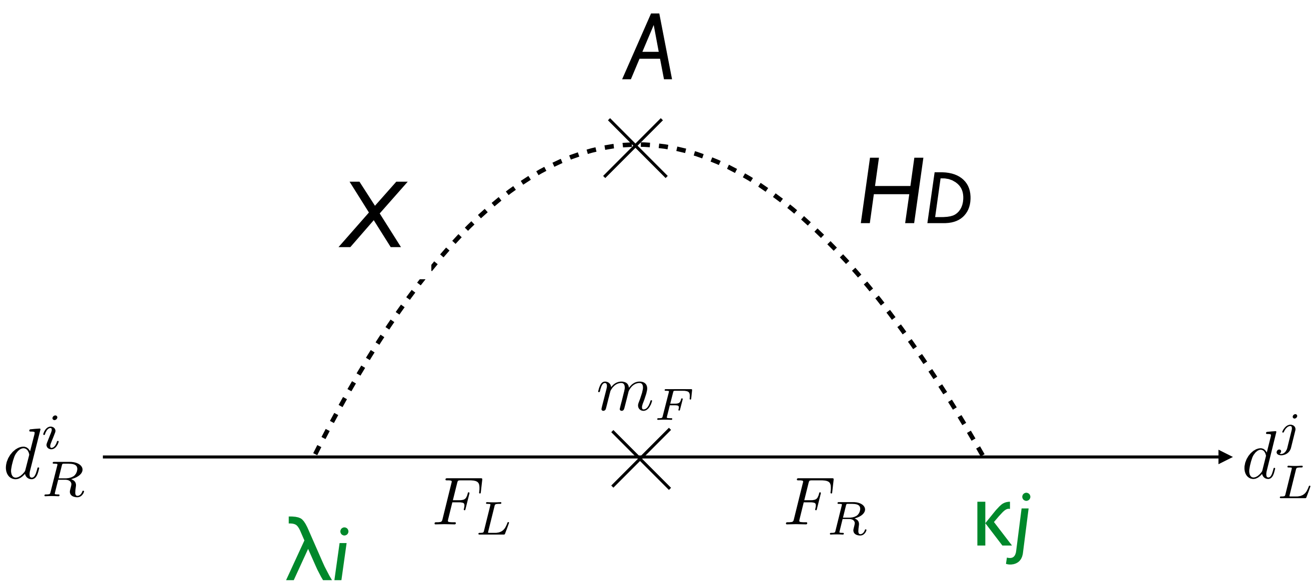
$\Delta(\varepsilon K)$ almost minimized.



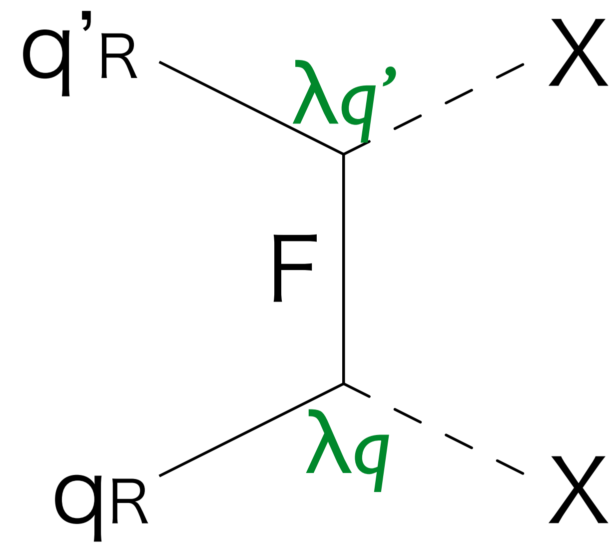
The phase is from the CKM matrix!

Even if εK constraint is evaded, EDM constrains this scenario.

Relation with DM



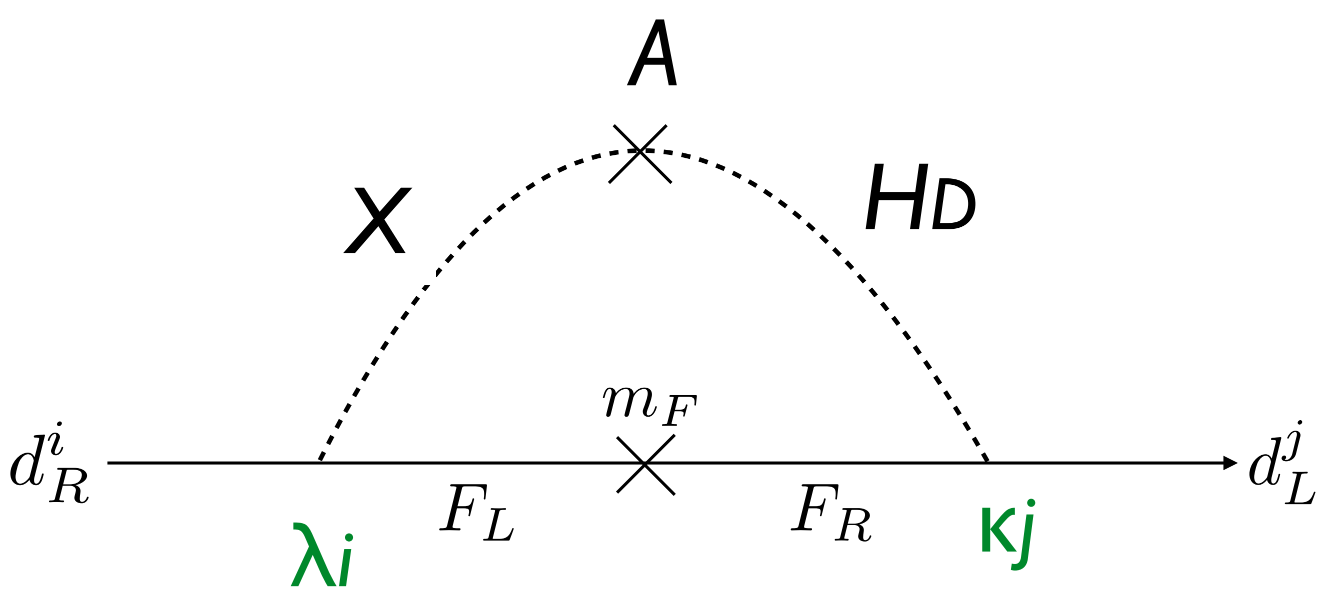
For the CKM



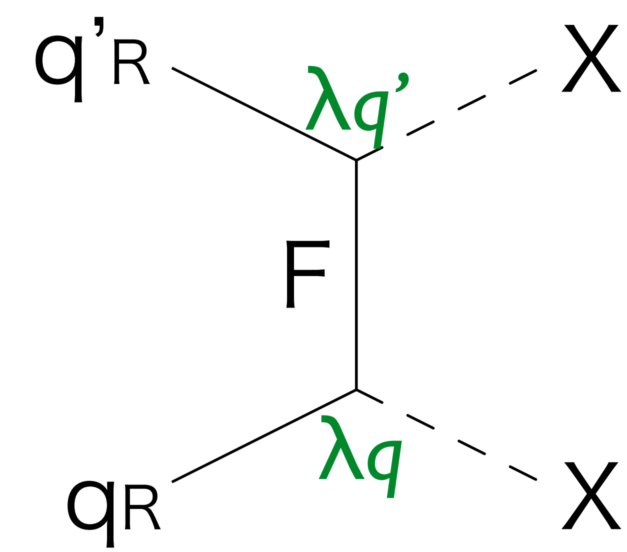
possible annihilation in X DM case

- *Assume that lightest one among the scalars (X or HD) is a DM.*
- *λ i and κi are between O(0.01) and O(1).*

Relation with DM



For the CKM



possible annihilation in X DM case

- *Assume that lightest one among the scalars (X or H_D) is a DM.*
- *λ_i and κ_i are between O(0.01) and O(1).*
- *DM and F cannot be so light because of the flavor constraint and the vacuum stability*

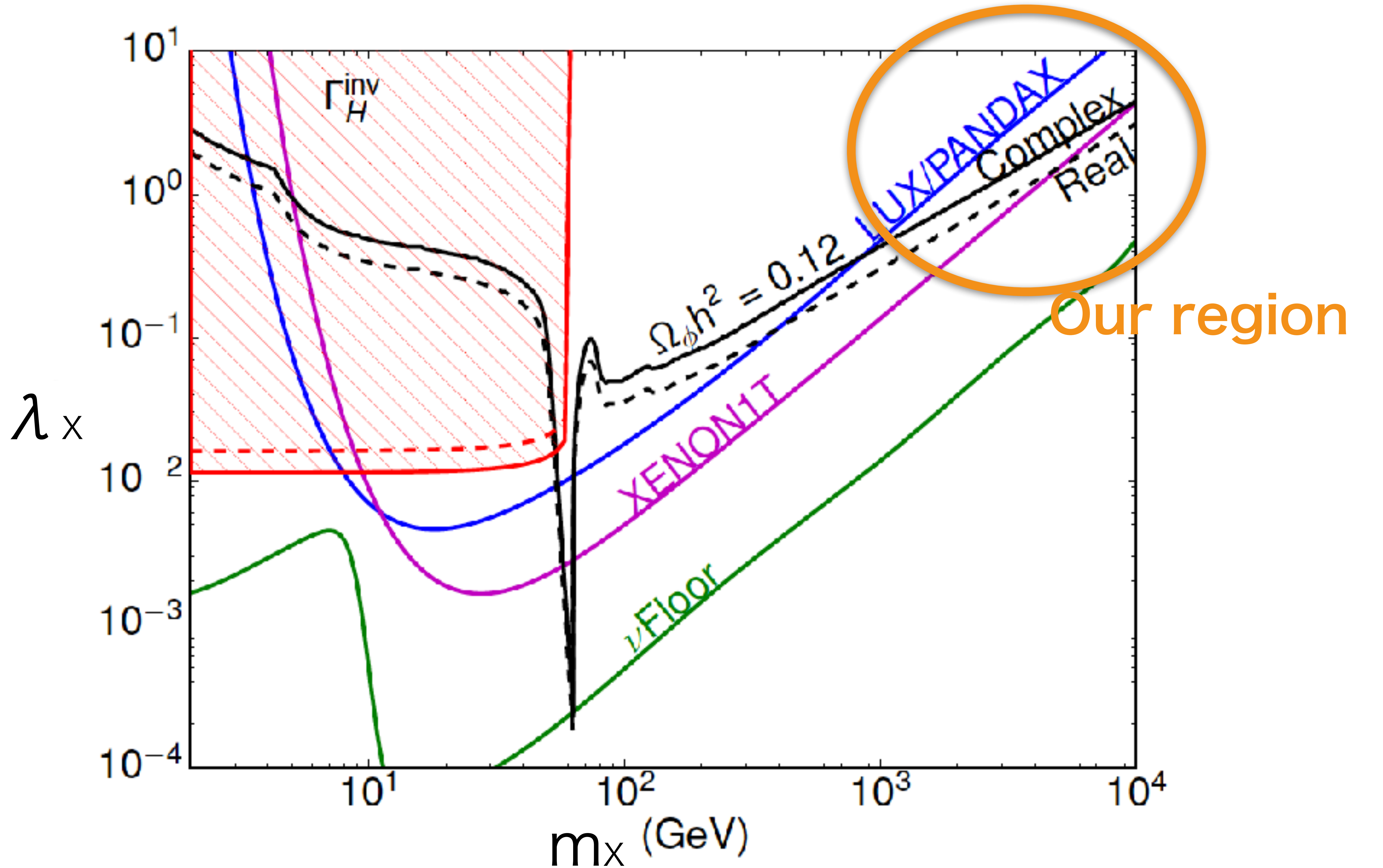
→ *"Higgs portal model" contribution is relevant*

relic density is dominantly given by

$$V_S = \frac{1}{2}\lambda_X |X|^2 |H|^2 + \frac{1}{2}\lambda_{H_D} |H_D|^2 |H|^2$$

Relic density and direct detection

(Escudero, Berlin, Hooper, Lin, 1609.09079)



Predicted DM mass region

$$\mathcal{O}(1)\,\mathrm{TeV} \lesssim m_X \lesssim 10\,\mathrm{TeV}$$

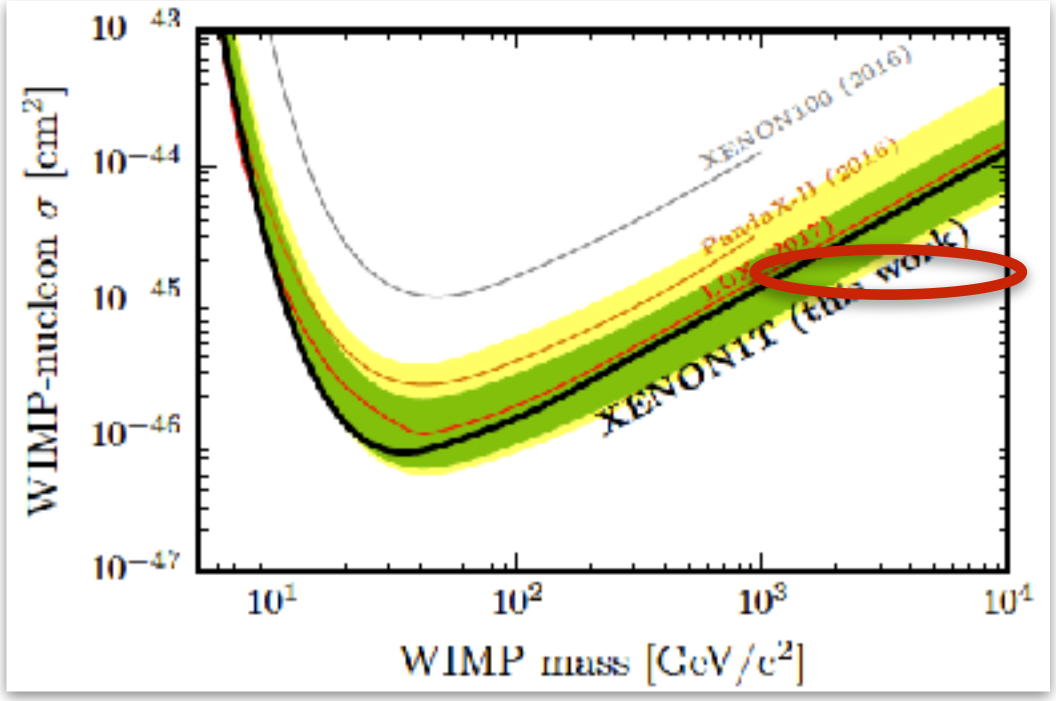
vacuum stability and flavor physics

DM relic density

Predicted Direct detection

$$\sigma_{\mathrm{SI}} \simeq 1.7 \times 10^{-9}\,[\mathrm{pb}]$$

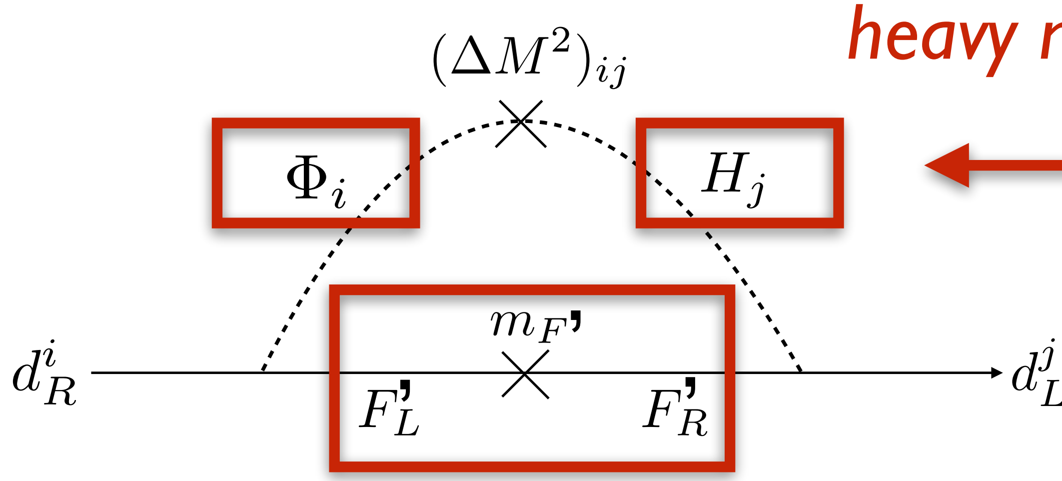
F-exchanging contribution is about 10 %.



Comment on
another possibility

If DM is from the mediators (Φi, Hi) but it does not do anything for the quark mixing,

heavy modes dominantly generate the CKM



$$H_i = c_i^D H_D + \boxed{c_i^{H'_1} H'_1 + c_i^{H'_2} H'_2}$$

$$\Phi_i = c_i^X X + \boxed{c_i^{\phi_1} \phi_1 + c_i^{\phi_2} \phi_2}$$

Maybe many F

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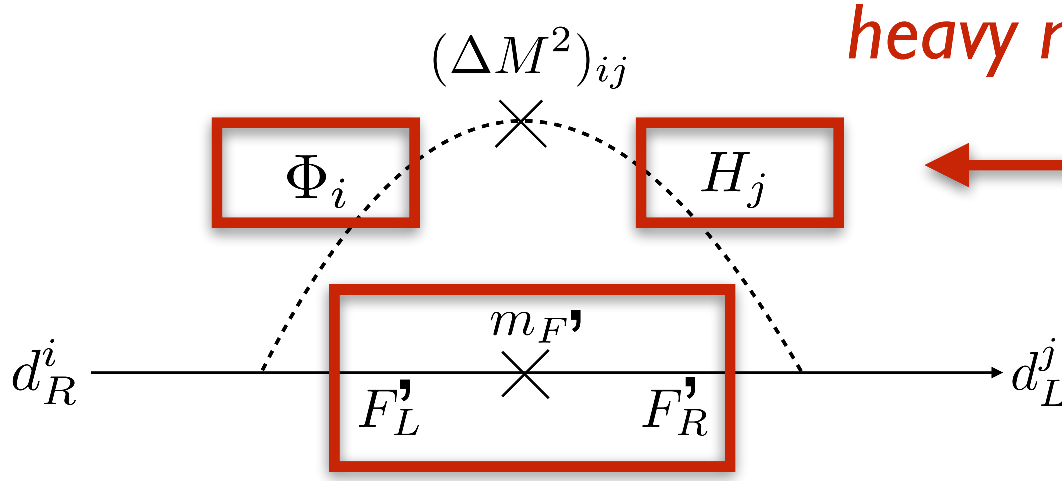

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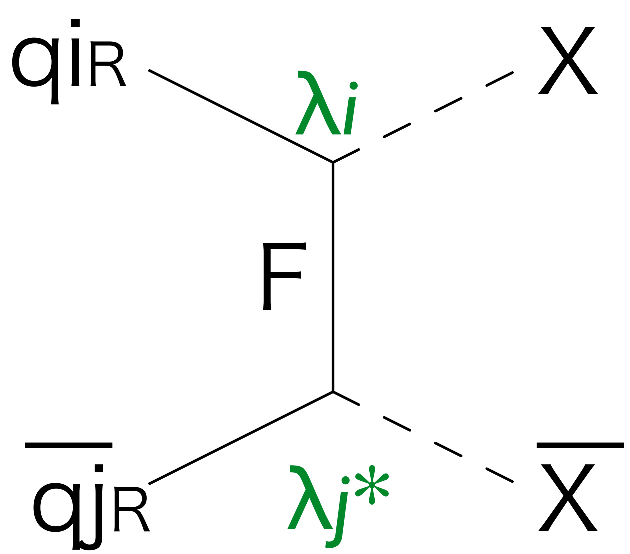
Maybe many F

DM from (Φi, Hi) becomes independent of CKM, and then

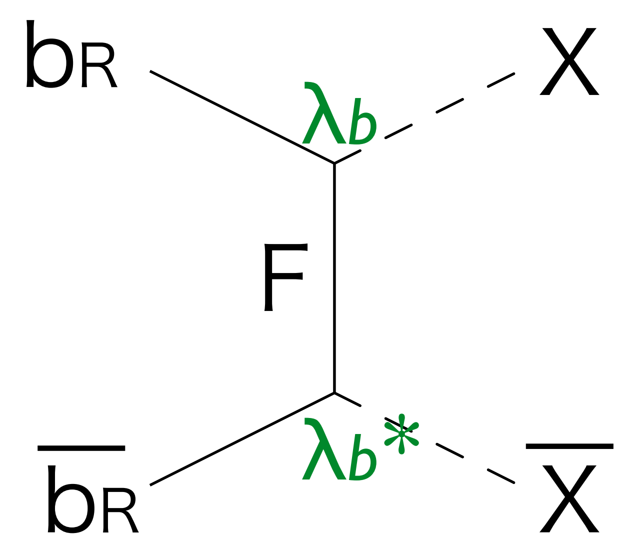


this diagram can be dominant, although
DM direct detections and
ΔF=2 processes constrain strongly.

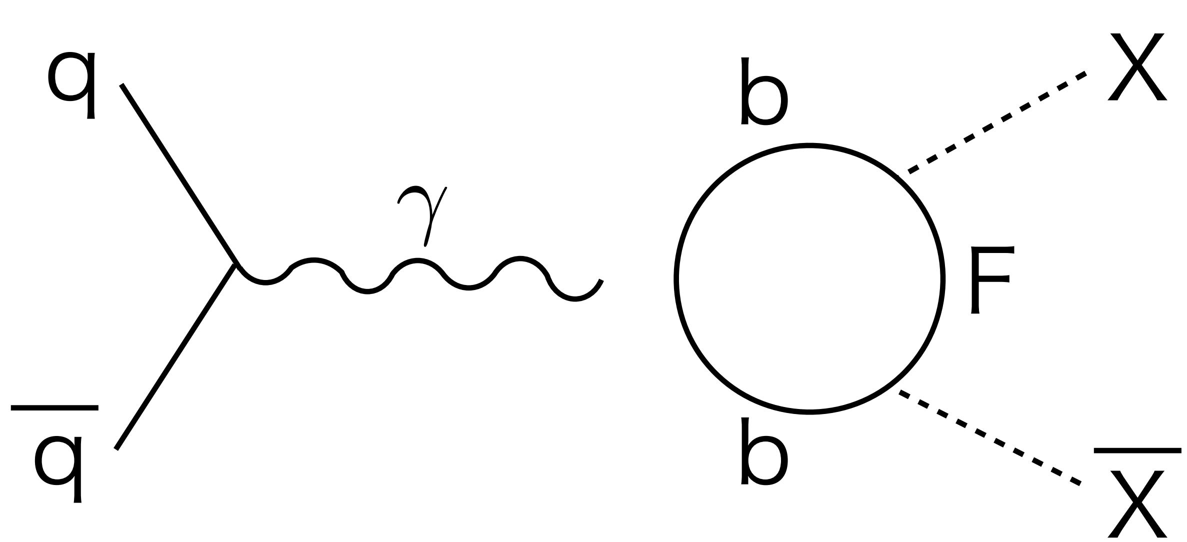
Relevant interaction of X

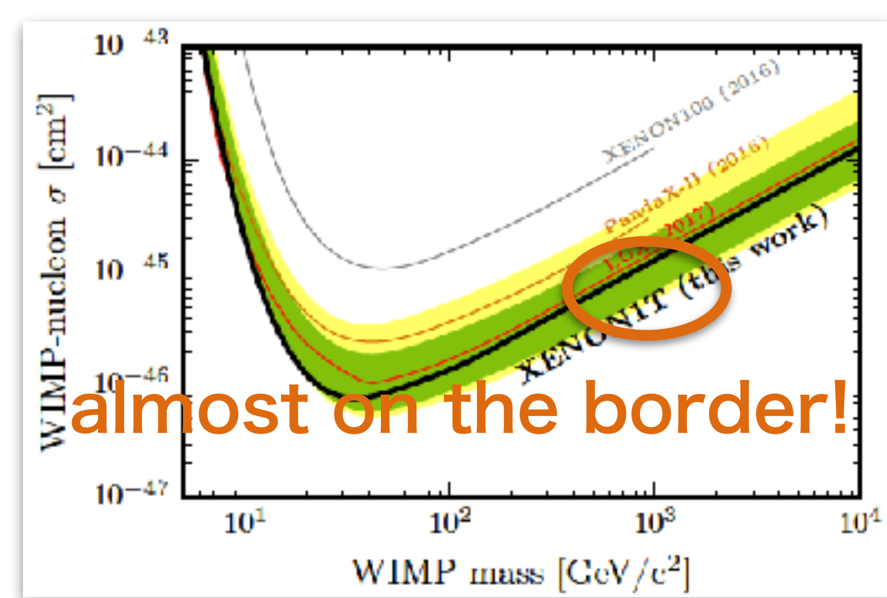
(Abe, Kawamura, Okawa, YO, 1612.01643)

Assuming DM interacts with only b quarks, the flavor constraints are evaded.



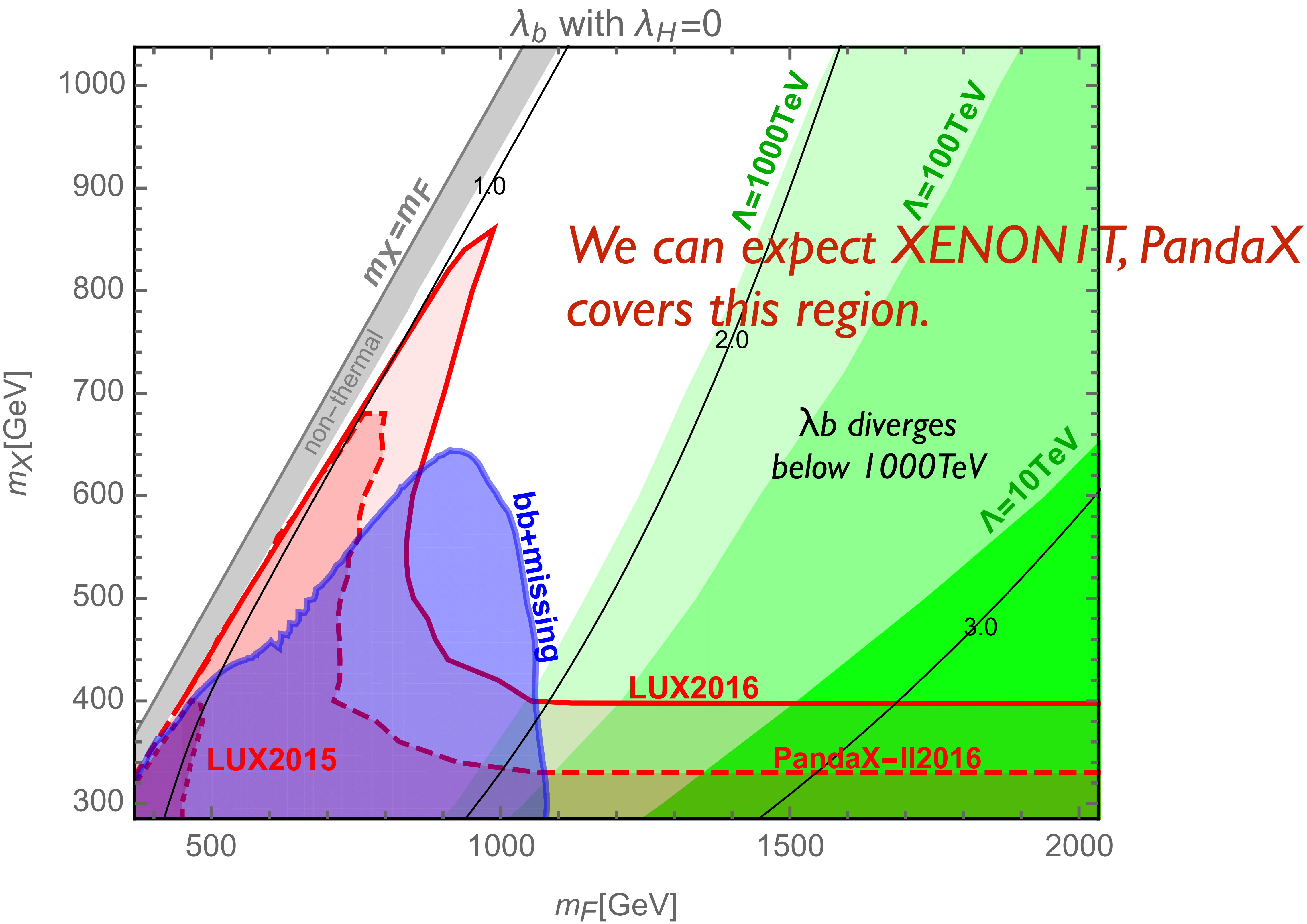
But large λ_b predicts enough large cross section even at the one-loop level.





Results on the light X case

(Abe, Kawamura, Okawa, YO, 1612.01643)



Summary

- Actually, there are many candidates for new physics. It is necessary to classify many BSMs and understand each prediction to prove new physics efficiently.
- I discuss one class of BSMs where CKM is radiatively generated. Focusing on the contributions of the DM candidates, **we find the typical predictions:**

DM mass: $\mathcal{O}(1)\,\mathrm{TeV} \lesssim m_X \lesssim 10\,\mathrm{TeV}$

direct detection: $\sigma_{\mathrm{SI}} \simeq 1.7 \times 10^{-9}\,[\mathrm{pb}]$

neutron EDM: $d_n = \mathcal{O}(10^{-26})\,[e\,cm]$

extra quark: $m_F \gtrsim \mathcal{O}(10)\,\mathrm{TeV}$

- I gave a comment on the other possibility.
- I will summarize the predictions of this kind of models. (*work in progress*)

END