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SUSY flavour & CP violation in SUGRA flavour models

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Southampton, UK

In collaboration with S.F. King & S. Antusch

Outline

- SM & SUSY flavour issues, flavour models
- Kahler corrections, irreducible SUGRA flavour & CP violation
- SU(3) flavour symmetry & SUSY CPV (EDMs)

SM flavour “problem”

- why quark and lepton masses are so peculiar ?
- why the lepton mixing is so different from CKM ?
- what is the origin of CP violation ?

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Sample SU(3) flavour model with TB lepton mixing :

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$f, f^c \in \mathbf{3}$ of $SU(3)$

$$\mathcal{L} \ni f Y^f f^c H_{(f^c)}$$

$H_{(f^c)}, \Sigma \in \mathbf{1}$ of $SU(3)$

$\phi_{123}, \phi_{23}, \phi_3 \in \overline{\mathbf{3}}$ of $SU(3)$

$$Y_{ij}^f = y_0^f \frac{\langle (\phi_3)_i (\phi_3)_j \rangle}{M_f^2} + y_1^f \frac{\langle (\phi_{123})_i (\phi_{23})_j \rangle}{M_f^2} + y_2^f \frac{\langle (\phi_{23})_i (\phi_{123})_j \rangle}{M_f^2} + y_\Sigma^f \frac{\langle (\phi_{23})_i (\phi_{23})_j \Sigma \rangle}{M_f^3} + \dots$$

$$M_{ij}^\nu = \dots$$

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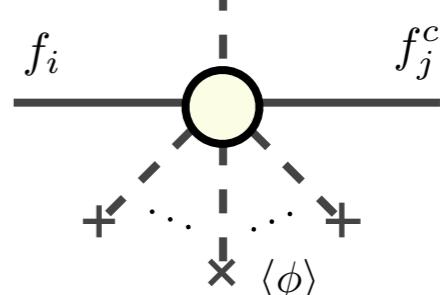
$\times \langle H \rangle$

Flavour symmetry breaking:

$$\langle \phi_{123} \rangle = \begin{pmatrix} 1 \\ e^{i\phi_1} \\ e^{i\phi_2} \end{pmatrix} u_1, \quad \langle \phi_{23} \rangle = \begin{pmatrix} 0 \\ 1 \\ e^{i\phi_3} \end{pmatrix} u_2, \quad \langle \phi_3 \rangle \propto \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} u_3$$

$$Y_{LR}^\nu \sim \begin{pmatrix} 0 & b & . \\ a & b & . \\ -a & b & c \end{pmatrix}$$

$$U \sim \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$



S. F. King, Nucl. Phys. B576 (2000) 85

Harrison, Perkins, Scott, PLB530, (2002)

SUSY flavour and CP problem

MSSM:

$$\begin{aligned}
 W_Y &\sim \varepsilon_{\alpha\beta} \left[\hat{H}_u^\alpha \hat{Q}^{\beta i} Y_{ij}^u \hat{u}^{cj} + \hat{H}_d^\alpha \hat{Q}^{\beta i} Y_{ij}^d \hat{d}^{cj} + \hat{H}_u^\alpha \hat{L}^{\beta i} Y_{ij}^\nu \hat{N}^{cj} + \hat{H}_d^\alpha \hat{L}^{\beta i} Y_{ij}^e \hat{e}^{cj} \right] + \hat{N}^{ci} (M_R)_{ij} \hat{N}^{cj} \\
 \mathcal{L}_{\text{soft}} &\sim \varepsilon_{\alpha\beta} \left[H_u^\alpha \tilde{Q}^{\beta i} A_{ij}^u \tilde{u}^{cj} + H_d^\alpha \tilde{Q}^{\beta i} A_{ij}^d \tilde{d}^{cj} + H_u^\alpha \tilde{L}^{\beta i} A_{ij}^\nu \tilde{N}^{cj} + H_d^\alpha \tilde{L}^{\beta i} A_{ij}^e \tilde{e}^{cj} \right] + \tilde{N}_i^{c*} (m_{N^c}^2)_j^i \tilde{N}^{cj} \\
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Convenience - the ‘Super-CKM’ basis:

Dugan, Grinstein, Hall, Nucl.Phys.B255(1985)

$$V_L^{f\dagger} Y^f V_R^f = \begin{pmatrix} y_1^f & & \\ & y_2^f & \\ & & y_3^f \end{pmatrix}$$

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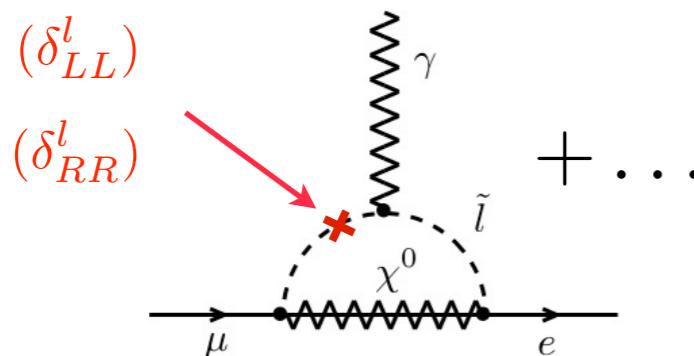
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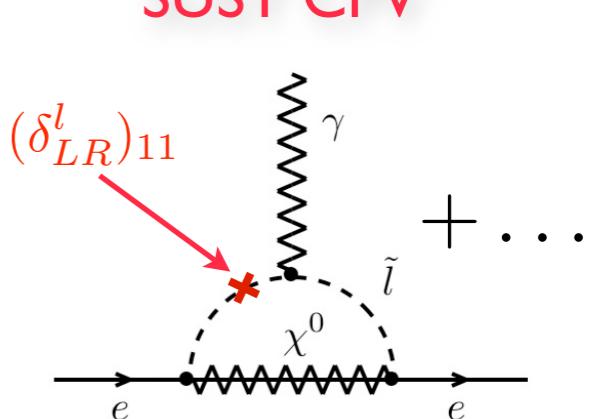
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Example: SUSY FCNC



$$(\delta_{XY}^f)_{ij} \equiv \frac{(V_X^\dagger m_{XY}^{2f} V_Y)_{ij}}{\langle \tilde{m}^{2f} \rangle}$$



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SUSY flavour & CP problem

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Flavour symmetries

- SFSB : $SU(3)$, $SO(3)$, A_4 , $D_3\dots$
- Yukawa & Majorana textures

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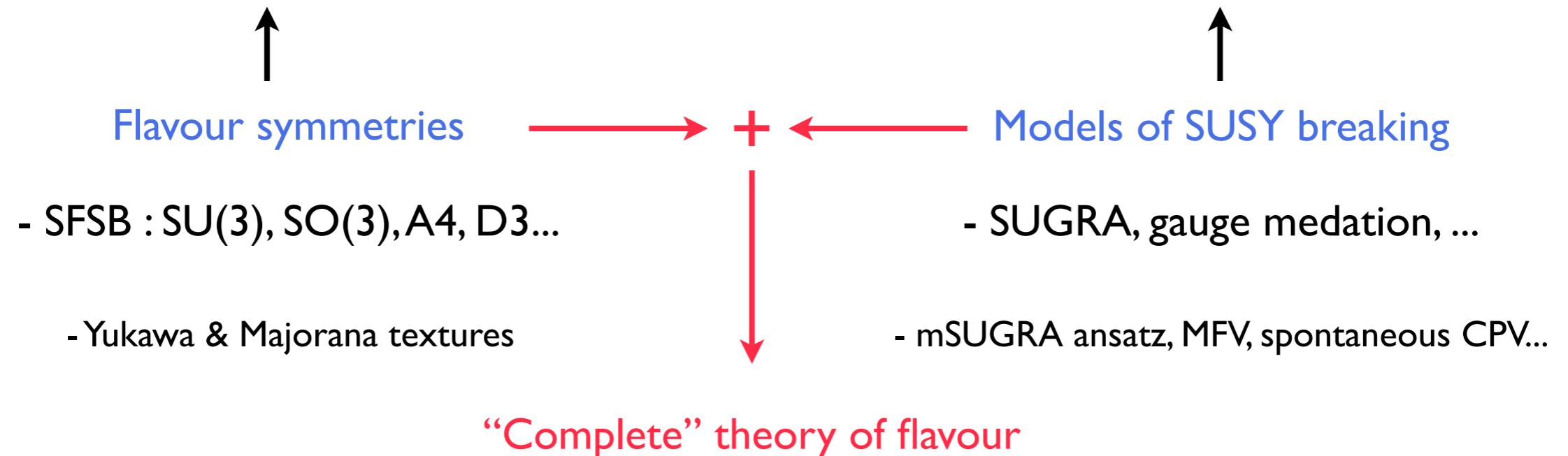
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Models of SUSY breaking

- SUGRA, gauge mediation, ...
- mSUGRA ansatz, MFV, spontaneous CPV...

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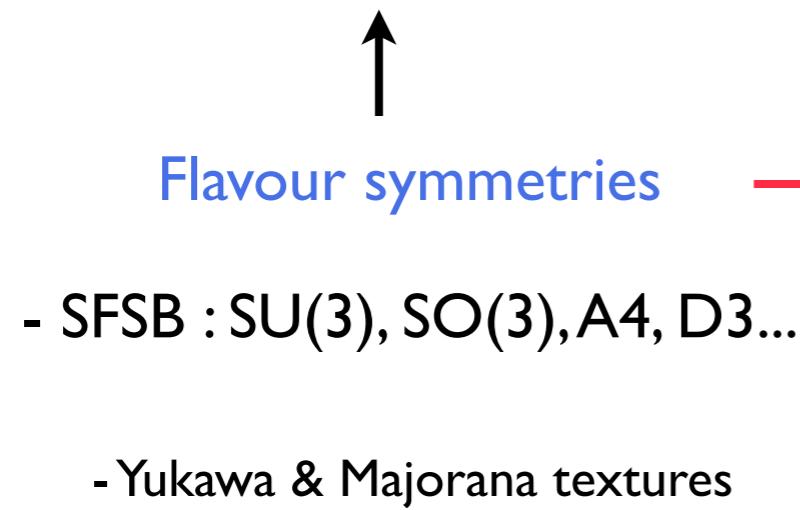
“Complete” theory of flavour

However:

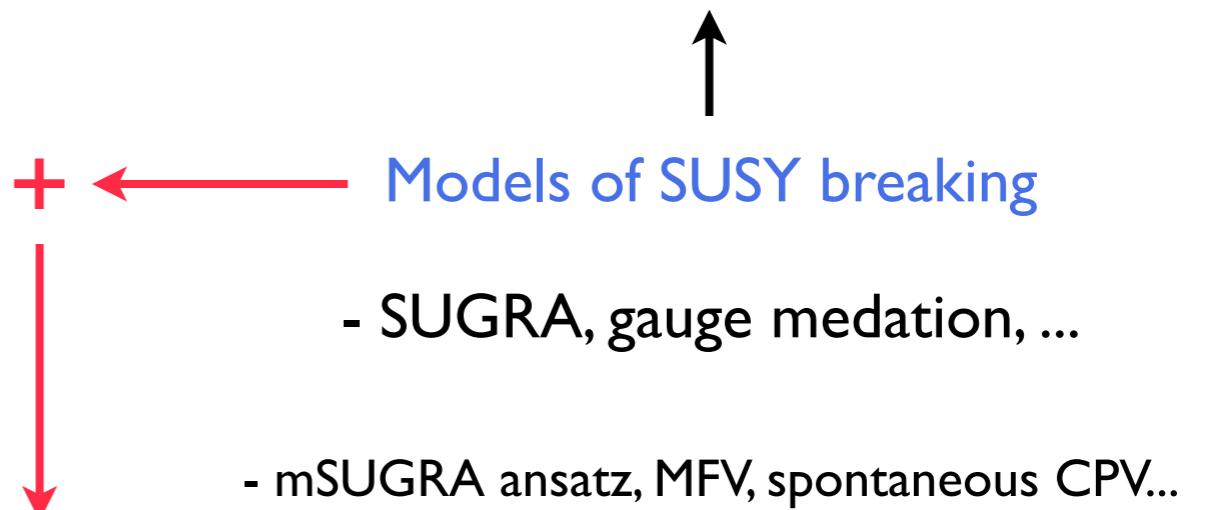
I) Kahler corrections important , soft masses sensitive to SFSB, ...

$$\mathcal{L}_{\text{kin}}^f = \partial_\mu \tilde{f}_i^* \tilde{K}_f(\phi, \phi^\dagger)_j^i \partial^\mu \tilde{f}^j + i \bar{f}_i \tilde{K}_f(\phi, \phi^\dagger)_j^i \gamma^\mu \partial_\mu f^j + \dots$$

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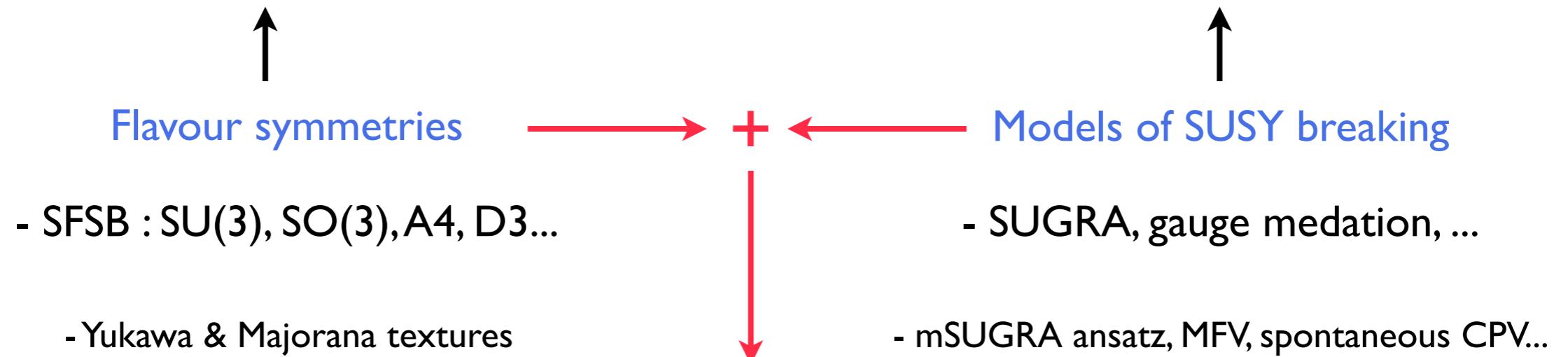
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SUGRA:

$$m_{soft}^2 = m_{3/2}^2 \tilde{K}_{\bar{a}b} - \sum_{S,S'} F_{\bar{S}'} \left[\partial_{\bar{S}'} \partial_S \tilde{K}_{\bar{a}b} - \partial_{\bar{S}'} \tilde{K}_{\bar{a}c} (\tilde{K}^{-1})_{cd} \partial_S \tilde{K}_{\bar{d}b} \right] F_S$$

$$\mathcal{A}_{abc} Y_{abc} \propto \sum_S F_S \left\{ \frac{1}{M_{Pl}^2} (\partial_S K_{hid.}) Y_{abc} + \partial_S Y_{abc} - \left[(\tilde{K}^{-1})_{d\bar{e}} \partial_S \tilde{K}_{\bar{e}a} Y_{dbc} + cycl. \right] \right\}$$

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2) Even in SUGRA, there are irreducible contributions to SUSY CPV and FV

Induced flavon F-terms & irreducible FV & CPV in SUGRA flavour models

The generic SUGRA F -term:

$$F_I = -e^{K/2M_{Pl}^2} (K^{-1})_{I\bar{J}} \left(\frac{1}{M_{Pl}^2} W^* K_{\bar{J}} + W_{\bar{J}}^* \right) = -(K^{-1})_{I\bar{J}} \left(m_{3/2} K_{\bar{J}} - e^{K/2M_{Pl}^2} W_{\bar{J}}^* \right)$$

and thus

$$\langle F_\phi \rangle = - \left\langle \sum_{\phi'} (K^f)^{-1}_{\phi\phi'} \left(m_{3/2} (K^f)_{\phi'} - e^{K/2M_{Pl}^2} W_{\phi'}^* \right) \right\rangle \sim m_{3/2} \langle \phi \rangle + \dots$$

Ross, Vives, Phys.Rev.D67 (2003)

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The pieces **always present** in the SUGRA soft masses and trilinears :

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2) Soft masses:

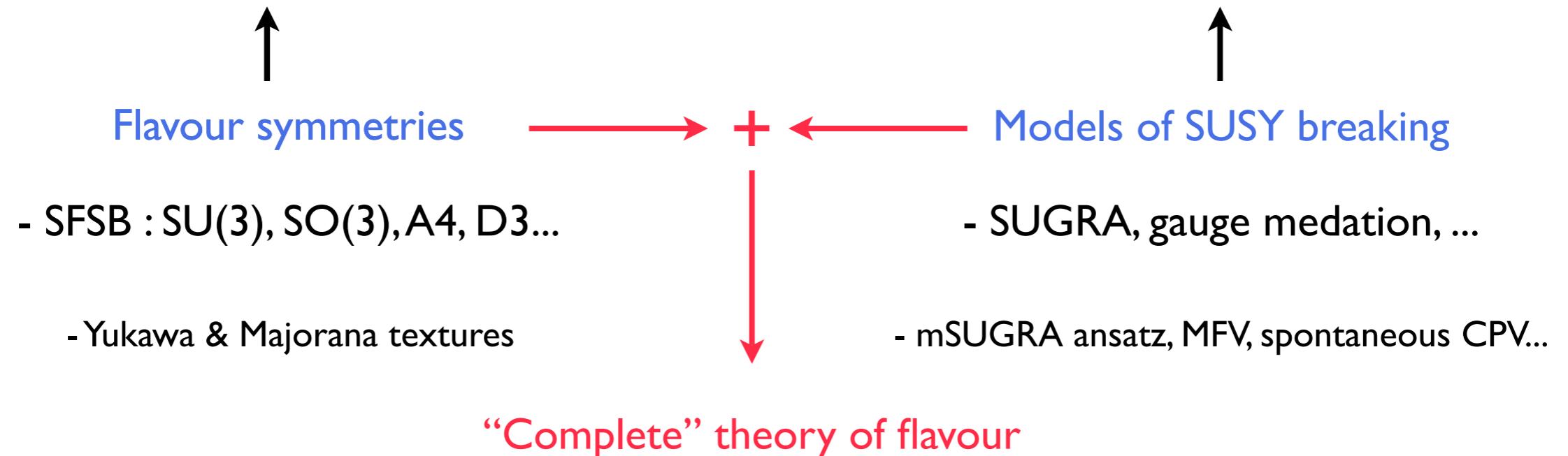
$$\tilde{K}_{\bar{a}\bar{b}} \sim \delta_{\bar{a}\bar{b}} \left(c_0 + d_0 \frac{X^\dagger X}{M_{Pl}^2} \right) + \left(c_2 + d_2 \frac{X^\dagger X}{M_{Pl}^2} \right) \frac{1}{M^2} (\phi\phi^*)_{\bar{a}\bar{b}} + \dots$$

$$F_{\bar{X}} \left(\partial_{\bar{X}} \partial_X \tilde{K}_{\bar{a}\bar{b}} \right) F_X \sim m_{3/2}^2 \langle X^\dagger \rangle \left(\frac{d_0}{M_{Pl}^2} + \frac{d_2}{M_{Pl}^2} \frac{1}{M^2} \phi\phi^* \right) \langle X \rangle \sim m_{3/2}^2 \left[\mathcal{O}(1) + \mathcal{O} \left(\frac{|\langle \phi \rangle|^2}{M^2} \right) \right]$$

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subleading effect, but **competitive** !

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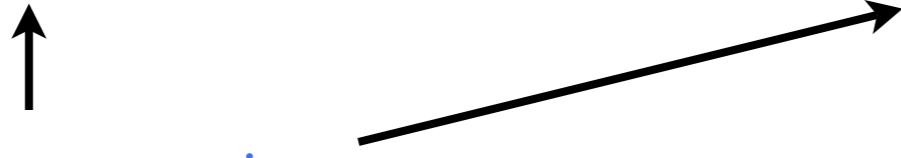
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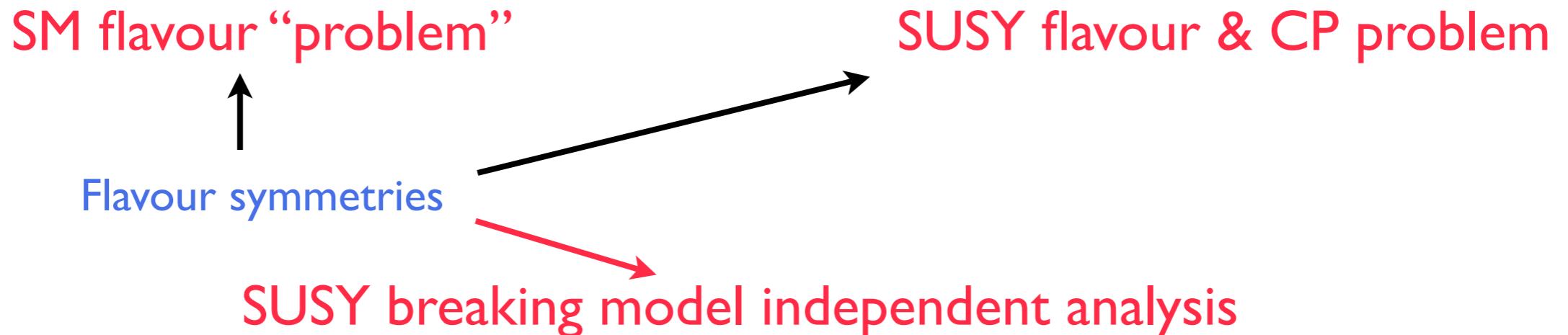
SUSY flavour & CP problem

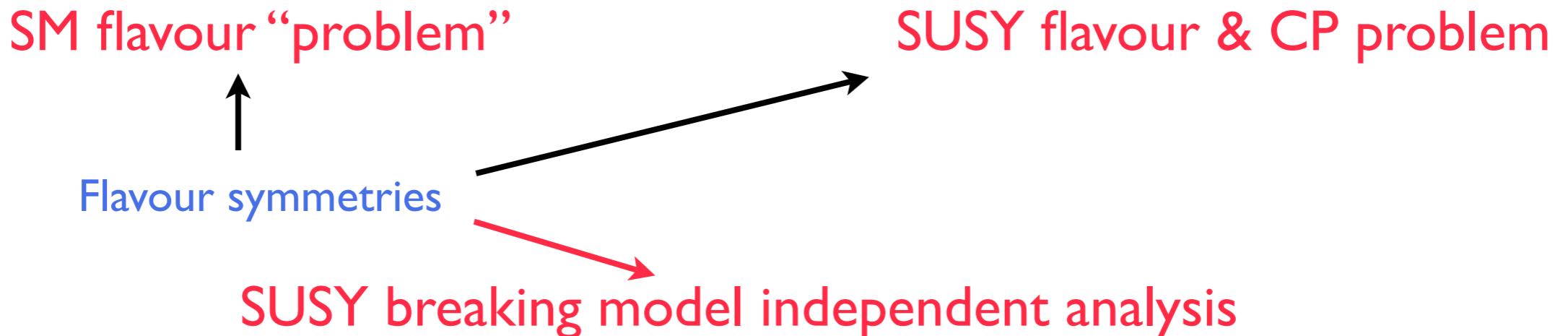
SM flavour “problem”

Flavour symmetries

SUSY flavour & CP problem





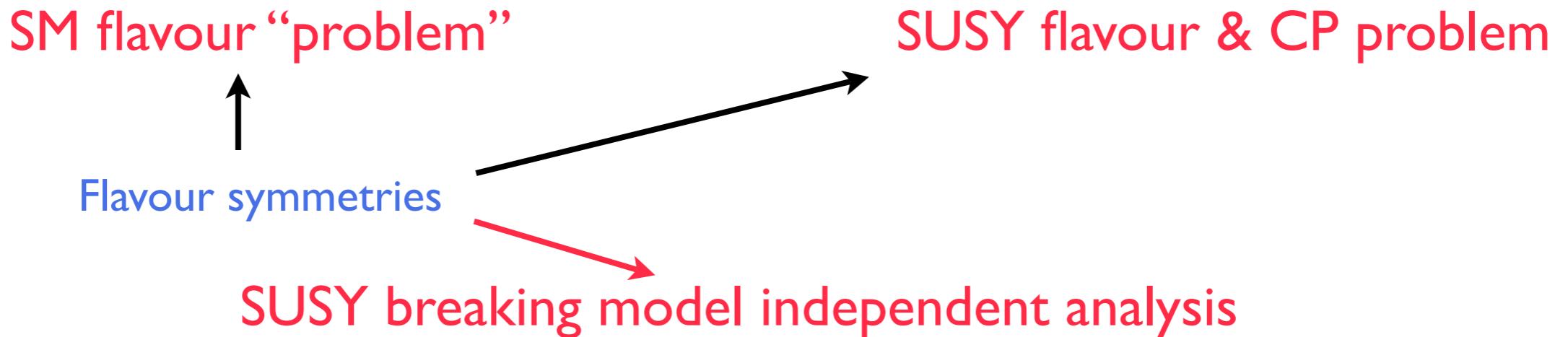


SU(3) flavour symmetry, spontaneous CP violation:

Soft sector :

$$(m_{f,f^c}^2)_j^i = m_0^2 \left(b_0^{f,f^c} \delta_j^i + b_1^{f,f^c} \frac{\langle (\phi_{123})_j (\phi_{123}^*)^i \rangle}{M_{f,f^c}^2} + b_2^{f,f^c} \frac{\langle (\phi_{23})_j (\phi_{23}^*)^i \rangle}{M_{f,f^c}^2} + b_3^{f,f^c} \frac{\langle (\phi_3)_j (\phi_3^*)^i \rangle}{M_{f,f^c}^2} \right) + \dots$$

$$A_{ij}^f = A_0 \left(a_0^f \frac{\langle (\phi_3)_i (\phi_3)_j \rangle}{M_f^2} + a_1^f \frac{\langle (\phi_{123})_i (\phi_{23})_j \rangle}{M_f^2} + a_2^f \frac{\langle (\phi_{23})_i (\phi_{123})_j \rangle}{M_f^2} + a_\Sigma^f \frac{\langle (\phi_{23})_i (\phi_{23})_j \Sigma \rangle}{M_f^3} \right) + \dots$$



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Kahler potential (canonical normalization) :

$$(\tilde{K}_{f,f^c})_j^i = k_0^{f,f^c} \delta_j^i + k_1^{f,f^c} \frac{\langle (\phi_{123})_j (\phi_{123}^*)^i \rangle}{M_{f,f^c}^2} + k_2^{f,f^c} \frac{\langle (\phi_{23})_j (\phi_{23}^*)^i \rangle}{M_{f,f^c}^2} + k_3^{f,f^c} \frac{\langle (\phi_3)_j (\phi_3^*)^i \rangle}{M_{f,f^c}^2} + \dots$$

Yukawa sector (SCKM rotations) :

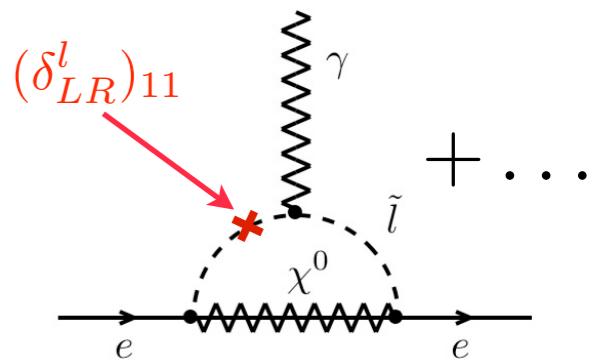
$$Y_{ij}^f = y_0^f \frac{\langle (\phi_3)_i (\phi_3)_j \rangle}{M_f^2} + y_1^f \frac{\langle (\phi_{123})_i (\phi_{23})_j \rangle}{M_f^2} + y_2^f \frac{\langle (\phi_{23})_i (\phi_{123})_j \rangle}{M_f^2} + y_\Sigma^f \frac{\langle (\phi_{23})_i (\phi_{23})_j \Sigma \rangle}{M_f^3} + \dots$$

Example : electric dipole moments

- tightly experimentaly constrained $|\text{Im}(\delta_{11}^{u,d})_{LR}| \lesssim 10^{-6}, \quad |\text{Im}(\delta_{11}^l)_{LR}| \lesssim 10^{-7}$

$$\langle \tilde{m}_q \rangle \sim 500 \text{ GeV}, \quad \langle \tilde{m}_l \rangle \sim 100 \text{ GeV}$$

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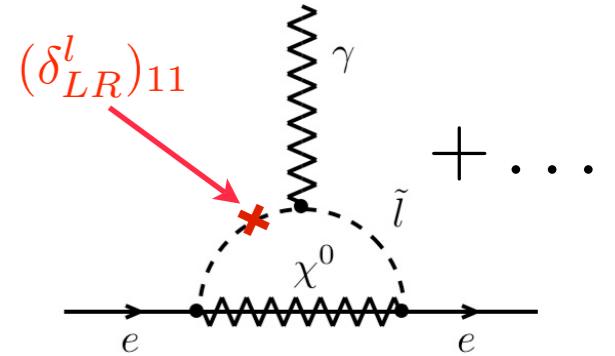
$$|\text{Im}(\delta_{LR}^u)_{11}| \sim 1 \times 10^{-7} \frac{A_0}{\langle \tilde{m}_u \rangle} \left(\frac{500 \text{ GeV}}{\langle \tilde{m}_u \rangle} \right) \left| (a_1^u + a_2^u) - \frac{a_\Sigma^u}{y_\Sigma^u} (y_1^u + y_2^u) \right| \sin \phi_1$$

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SUSY breaking models enter here (plus running)

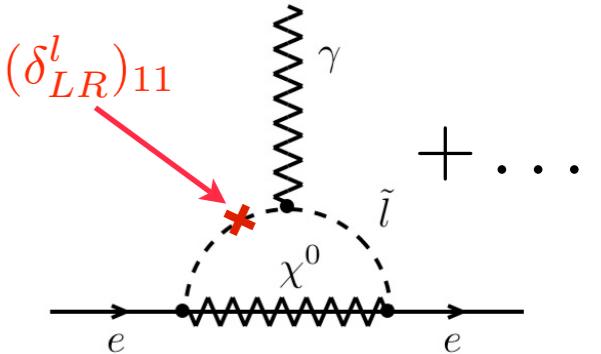
SU(3) flavour symmetry is a very powerfull tool to tackle SUSY Flavour and CP problem !



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SUGRA estimate of effective coefficients : $A_{ij} \sim \sum_X F_X \partial_X Y_{ij}, \quad X \equiv \phi_{23}, \phi_{123}, \Sigma$

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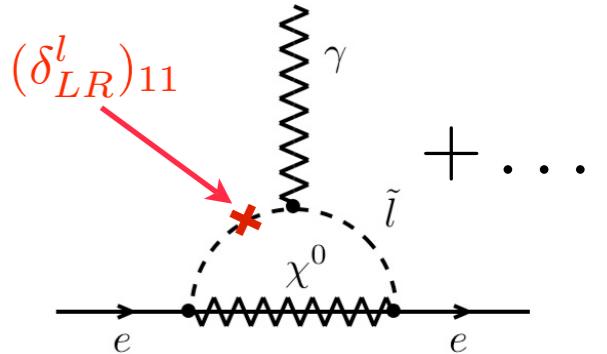
$$a_\Sigma \sim 3 y_\Sigma$$

$$\left| (a_1 + a_2) - \frac{a_\Sigma}{y_\Sigma} (y_1 + y_2) \right| \rightarrow |y_1 + y_2| \sim \mathcal{O}(1)$$

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SU(3) flavour symmetry as good as SU(3) + SUGRA !

Conclusions

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- Irreducible SUGRA flavour & CP violation due to flavon F_ϕ -terms omnipresent
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Thanks for your kind attention !