



Supersymmetry and Flavour

BBSM

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PLANCK'2011
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Z. Lalak, S. Pokorski, G. Ross, *JHEP* 1008:129, 2010
I. Dalianis, Z. Lalak, *Phys. Lett. B*697: 385, 2011
L. Calibbi, Z. Lalak, S. Pokorski, R. Ziegler, *to appear*

OUTLINE:

- ✱ supersymmetry
- ✱ flavour problem and MFV
- ✱ horizontal symmetries
- ✱ horizontal symmetries and SUSY breaking
- ✱ flavour messenger sector
- ✱ SUSY breaking in the flavour sector and cosmology

Standard Model

quarks

$$\left(\begin{array}{c} u \\ d \end{array} \right)_L, u_R, d_R \quad \left(\begin{array}{c} u \\ d \end{array} \right)_L, u_R, d_R \quad \left(\begin{array}{c} u \\ d \end{array} \right)_L, u_R, d_R \quad \begin{array}{c} \updownarrow \\ SU(2) \end{array}$$

\longleftrightarrow
 $SU(3)$

leptons

$$\left(\begin{array}{c} e \\ \nu \end{array} \right)_L, e_R, \nu_R \quad \begin{array}{c} \updownarrow \\ SU(2) \end{array}$$

Higgs sector

$$\left(\begin{array}{c} h^+ \\ h^0 \end{array} \right) \quad \begin{array}{c} \updownarrow \\ SU(2) \end{array}$$

νSM

local symmetry:

$$SU(3)_C \times SU(2)_L \times U(1)$$

Standard Model cd.

- hierarchy of scales:

$$M_{SM} \approx 1 \text{ TeV} = 10^3 \text{ GeV}$$

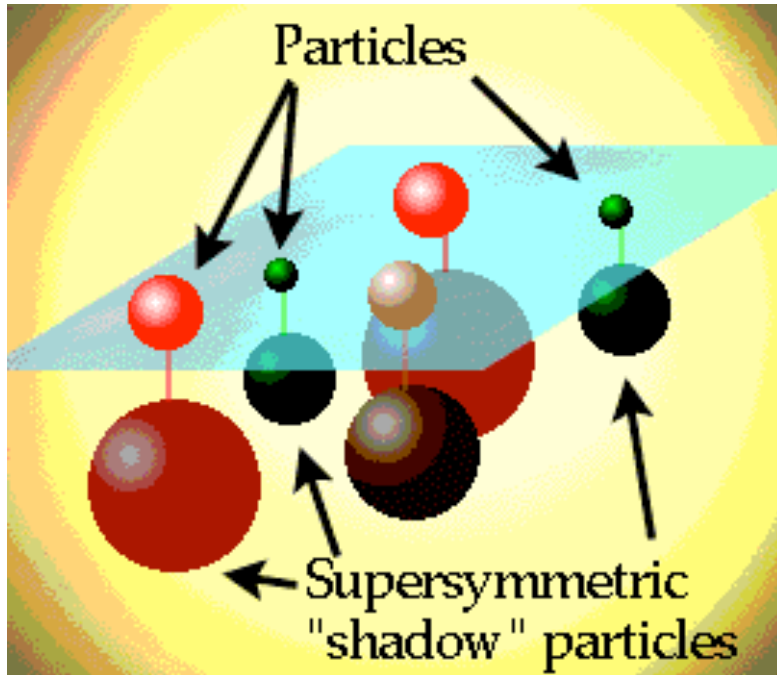
vs

$$M_P \approx 10^{18} \text{ GeV}$$

SUPERSYMMETRY BSM

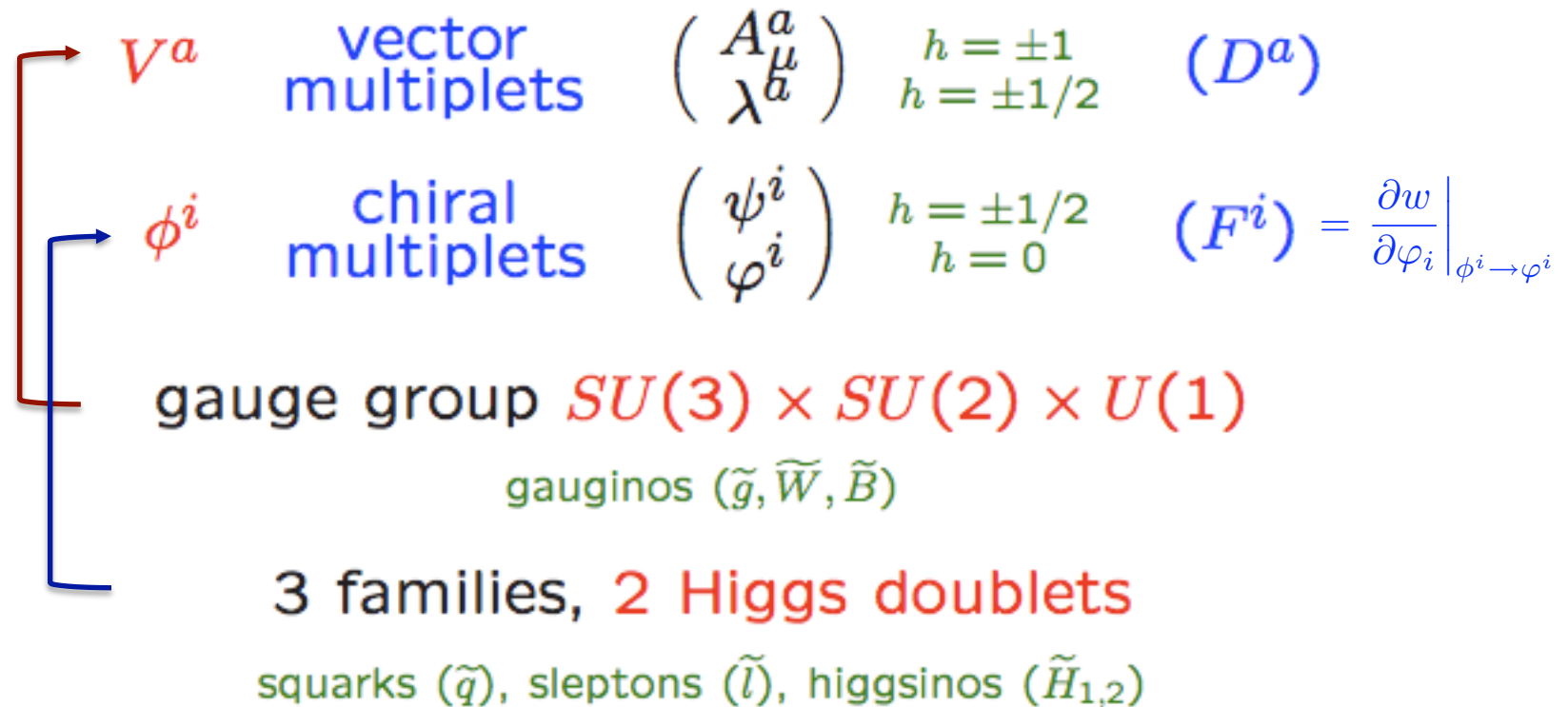
Beyond the Standard Model

supersymmetry



- no superpartners observed thus far – supersymmetry must be broken
- electroweak scale related to the scale of supersymmetry breaking
- the lightest supersymmetric particle is stable – a natural dark matter candidate

The structure of the MSSM



$$w = Qh^U U^c H_2 + Qh^D D^c H_1 + Lh^E E^c H_1 + \mu H_1 H_2$$

$$V_F = \sum_i \left| \frac{\partial w}{\partial \phi^i} \right|^2$$

The structure of the MSSM

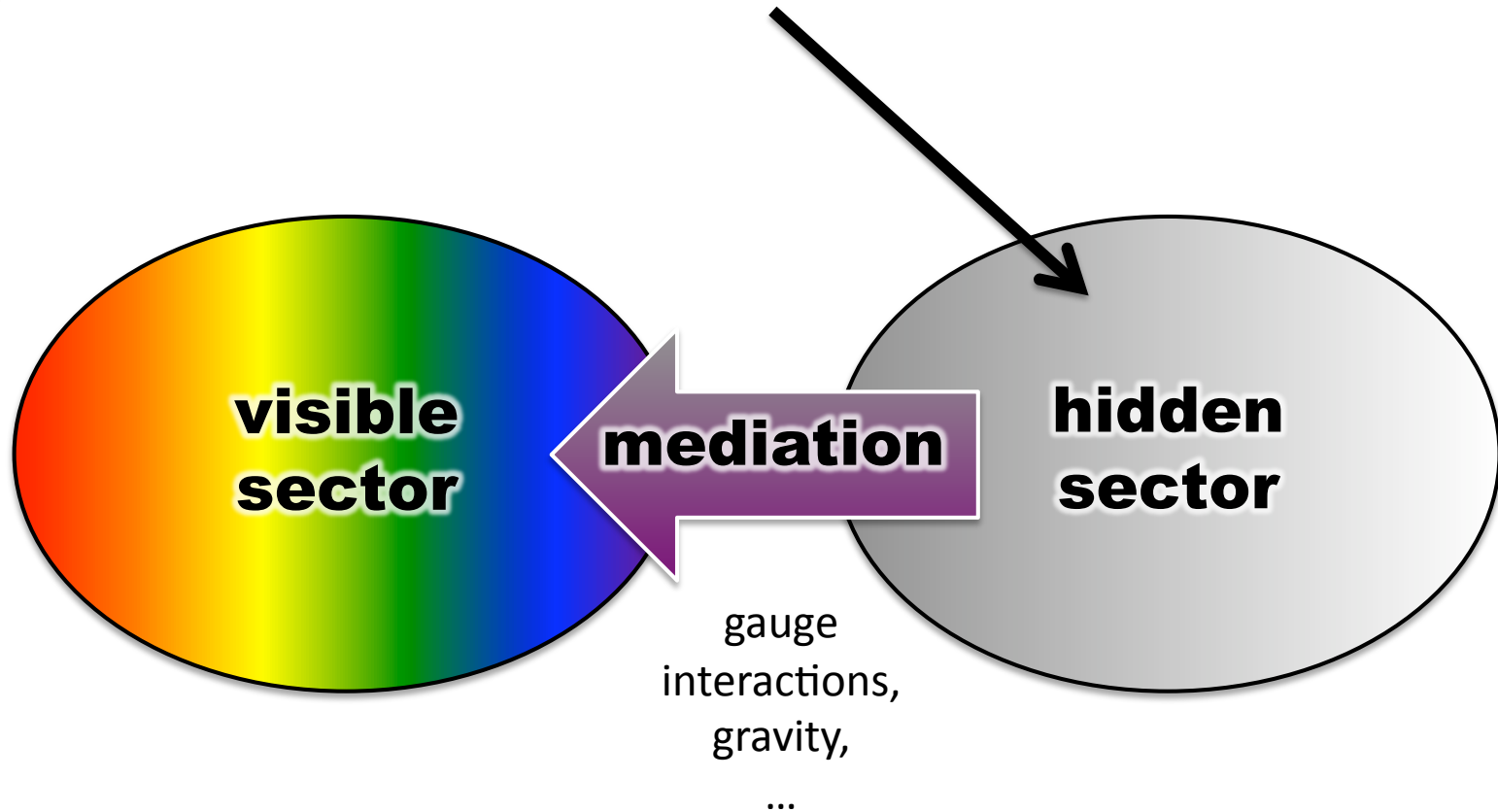
explicit mass terms for scalars

$$-\mathcal{L}_{soft} = \underbrace{\varphi^\dagger m^2 \varphi + \left(\frac{1}{2} M_A \lambda_A \lambda_A + m_3^2 H_1 H_2 + \tilde{q} A^U \tilde{u}^c H_2 + \tilde{q} A^D \tilde{d}^c H_1 + \tilde{l} A^E \tilde{e}^c H_1 + h.c. \right)}_{\text{explicit tri-scalar interactions}}$$

$B\mu$

explicit tri-scalar interactions

Supersymmetry breaking



Gauge vs gravity mediation

$$m_{3/2} = \frac{F^X}{\sqrt{3}M_P}$$

$$m_{\text{gaugino}} = \frac{\alpha(m)}{4\pi} \frac{F^X}{\langle X \rangle}$$

$$m_{\text{scalar}} = \frac{\alpha(m)}{4\pi} \frac{\sqrt{3}M_P}{\langle X \rangle} m_{3/2}$$

 $m_{3/2, \text{moduli}} \ll m_{g,s}$

- gauge mediation: natural suppression of flavour changing processes, works in the flat limit

FLAVOUR BBSM

Flavour group

$$G_F = SU(3)_q^3 \otimes SU(3)_l^2 \otimes U(1)^5,$$

where $SU(3)_q^3 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$, $SU(3)_l^2 = SU(3)_{L_L} \otimes SU(3)_{E_R}$

$$L_{q,e} = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \bar{L}_L Y_E E_R H + h.c.$$

$$L_\nu = \bar{L}_L Y_\nu N_R H_c + \bar{N}_R M N_R + h.c.$$

$$m_{\nu eff} = -Y_\nu \frac{v^2}{M} Y_\nu^T = U_{11} m_d U_{11}^T$$

G. D'Ambrosio, G. Giudice, G. Isidori, A. Strumia

$$Y_U \sim (3, \bar{3}, 1)_{SU(3)_q^3}, \quad Y_D \sim (3, 1, \bar{3})_{SU(3)_q^3}, \quad Y_E \sim (3, \bar{3})_{SU(3)_l^2}$$

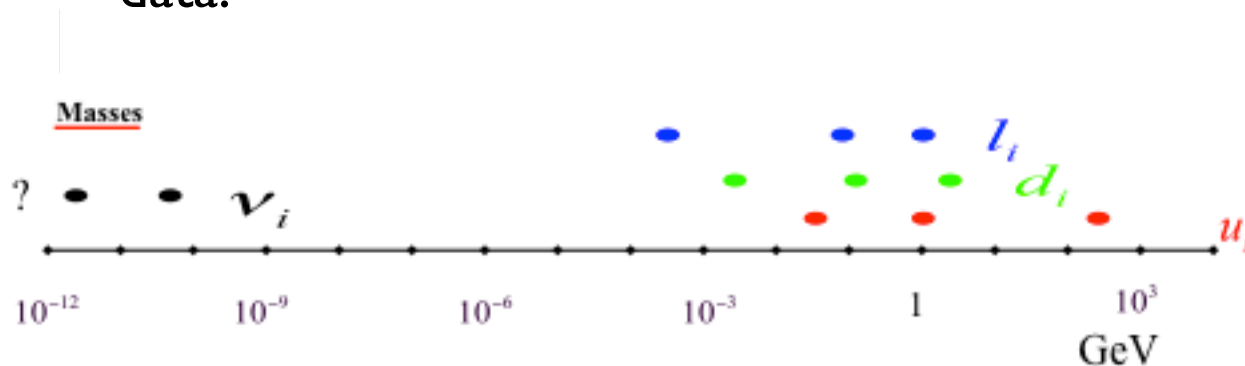
$$D'_R = V_D^\dagger D_R, \quad U'_R = V_U^\dagger U_R, \quad \bar{Q}_L = \bar{Q}'_L S_d^\dagger.$$

$$L_W^{(+)} = \frac{g_2}{\sqrt{2}} \bar{U}_L \gamma^\mu V_{CKM} D_L W_\mu^+ + \frac{g_2}{\sqrt{2}} \bar{\nu}_L \gamma^\mu V_{PMNS} E_L W_\mu^+$$

$$V_{CKM} = S_u^\dagger S_d$$

$$V_{PMNS} = U_{11}^T S_e$$

data:



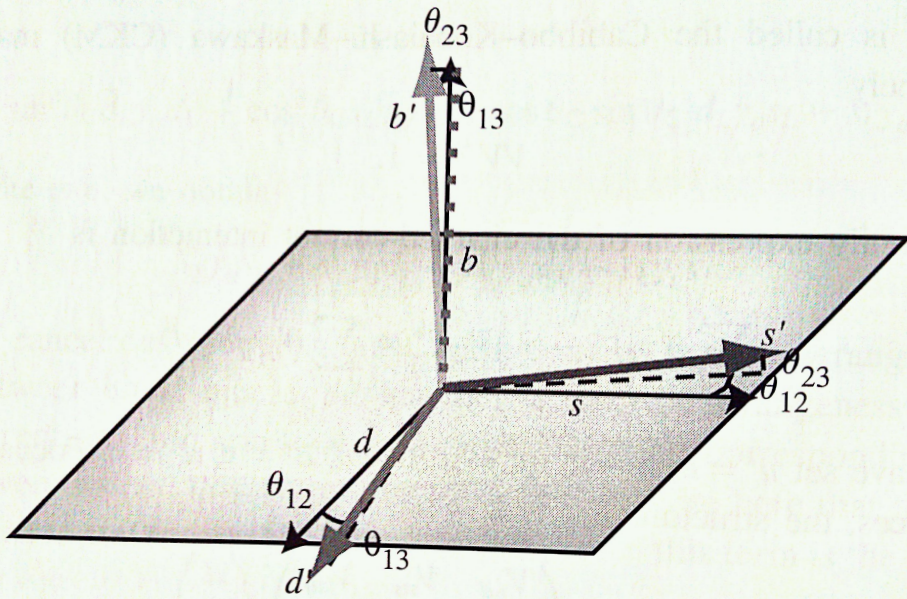
G.G. Ross

Mixing

$$V_{CKM} = \begin{pmatrix} 1 & 0.218 - 0.224 & 0.002 - 0.005 \\ 0.218 - 0.224 & 1 & 0.032 - 0.048 \\ 0.004 - 0.015 & 0.03 - 0.048 & 1 \end{pmatrix} \quad V_{MNS} = \begin{pmatrix} 0.79 - 0.88 & 0.48 - 0.61 & < 0.2 \\ 0.27 - 0.49 & 0.45 - 0.71 & 0.52 - 0.82 \\ 0.28 - 0.5 & 0.51 - 0.65 & 0.57 - 0.81 \end{pmatrix}$$

Quark and neutrino mixing

Weak interactions



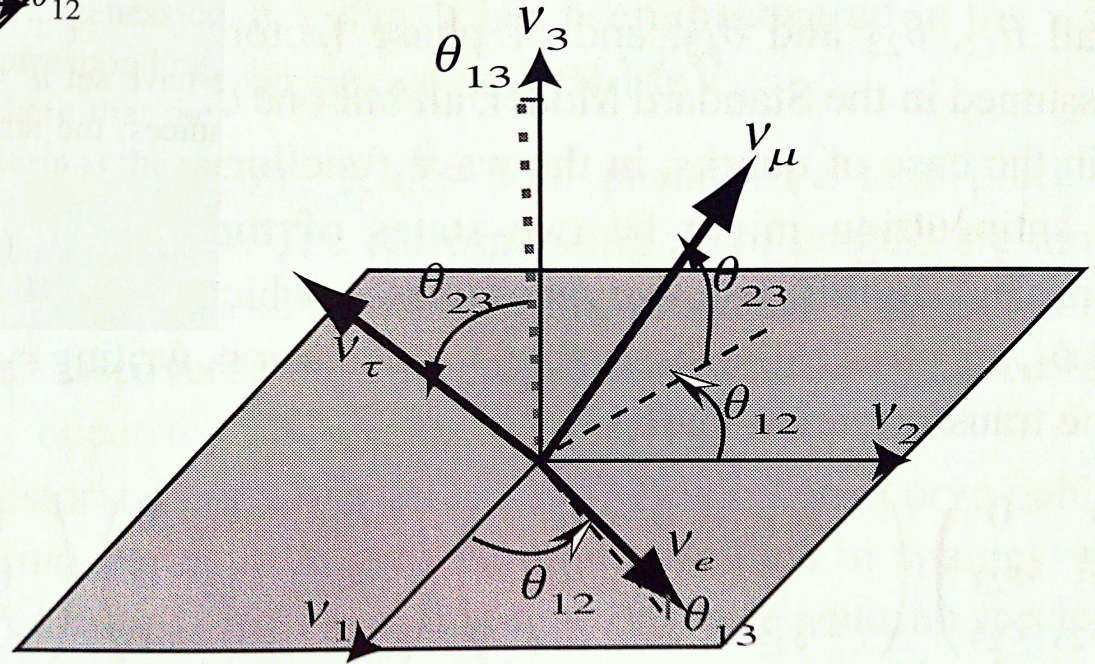
$$\begin{aligned} \sin(\theta_{12}) &= 0.22 & \theta_{12} &= 12.9^\circ \\ \sin(\theta_{23}) &= 0.04 & \theta_{23} &= 2.4^\circ \\ \sin(\theta_{13}) &= 0.004 & \theta_{13} &= 0.2^\circ \end{aligned}$$

7.21. The quark rotations.

$$\theta_{12} = 33.9^\circ \pm 1.6^\circ$$

$$\theta_{23} = 45^\circ \pm 3^\circ$$

$$|\theta_{13}| < 9^\circ$$



The rotations of the neutrino mixing.

MFV

$$Y_U \sim (3, \bar{3}, 1)_{SU(3)_q^3}, \quad Y_D \sim (3, 1, \bar{3})_{SU(3)_q^3}, \quad Y_E \sim (3, \bar{3})_{SU(3)_l^2}$$

MFV:

- the only source of G_F breaking are the Yukawa spurions
- higher dimension flavour violating terms arise as the most general $SU(3)^5$ invariant higher dimension operators

The leading two-fermion operators from which one may determine the MFV predictions for the operators in the table are

$$\bar{Q}_L Y_u Y_u^\dagger Q_L, \quad \bar{D}_R Y_d Y_u Y_u^\dagger Q_L$$

G. D'Ambrosio et al; F. Gabbiani, A. Massiero; W. Altmannshoffer, A. Buras et al; G. Isidor, Y. Nir, G. Perez

	Flavour violating dimension six operator	Λ_{MFV} (in TeV)	
		-	+
$\mathcal{O}_0 =$	$\frac{1}{\Lambda^2} (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)^2$	6.4	5.0
$\mathcal{O}_{F1} =$	$\frac{1}{\Lambda^2} H^\dagger (\bar{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} Q_L) F_{\mu\nu}$	9.3	12.4

EWDD: $\lambda_{FC} = (Y_u Y_u^\dagger)_{ij} = \lambda_t^2 U_{3i}^* U_{3j}$ where U is the CKM matrix.

MFV

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$$\gamma_{ij} \sim \alpha^2$$

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Flavour vs hierarchy

- $\Lambda = M$ - where M is a mass of a heavy particle, but ...
- usually there exists a mechanism easing the hierarchy problem with its scale Λ_h
- possible suppressions are $1/\Lambda_h^2$, $1/(\Lambda_h M)$, $1/M^2$
- in SUSY luckily (or not) the first option is realized, with $\Lambda_h = M_{SUSY}$

in models of fermion masses based on SB family symmetries M is a mass of heavy fermions and hierarchy of masses and mixings is built from powers of a small parameter $\langle \theta \rangle / M$ where θ is a familon field.

M_{SUSY} , F_{SUSY} , M , F_θ - are there any constraints?

Froggatt-Nielsen U(1)

M. Leurer, Y. Nir, N. Seiberg; L. Ibanez, G.G. Ross; E. Dudas, S. Pokorski, C. Savoy, Ch. Grojean; P. Binetruy, S. Lavignc, P. Ramond

$$\bar{Q}_L Y_U U_R H_c = \bar{Q}_L^i \left[a_i^j \left(\frac{\theta}{M} \right)^{|u_j + q_i|} \right] U_{Rj} H_c$$

Two familon fields, X, \bar{X} , with charges ± 1 , $-w = q(H)$.

$$\begin{aligned} Q_{L\ 1,2,3} &: (-3 + w, 2 + w, w) \\ D^c\ 1, 2, 3 &: (-5, 0, 0) \\ U^c\ 1, 2, 3 &: (-5, 0, 0) \end{aligned}$$

$$Y_{U,D} = \begin{pmatrix} \epsilon_{u,d}^{|-8+w|} & \epsilon_{u,d}^{|-3+w|} & \epsilon_{u,d}^{|-3+w|} \\ \epsilon_{u,d}^{|-3+w|} & \epsilon_{u,d}^{|2+w|} & \epsilon_{u,d}^{|2+w|} \\ \epsilon_{u,d}^{|-5+w|} & \epsilon_{u,d}^{|w|} & \epsilon_{u,d}^{|w|} \end{pmatrix}$$

where $\epsilon_{u,d} = \frac{\langle X \rangle}{M_{U,D}}$ - we allow for different messenger masses in the up and the down sectors.

$$\text{For } w = 0 \ Y_t : Y_c : Y_u = 1 : \epsilon^2 : \epsilon^8, \ U_{12} = \epsilon, \ U_{13} = \epsilon^3, \ U_{23} = \epsilon^2$$

Bounds on suppression scale

Flavour violating dimension six operator		Λ/Λ_{MFV}					
		Ex. 1	Ex. 2	Ex. 3	$U(1)^2$	N-A	F
$\mathcal{O}_0 =$	$\frac{1}{2}(\bar{Q}_L X_{LL}^Q Q_L)^2$	ϵ^{-4}	ϵ^{-4}	1	1	ϵ^{-2}	1
$\mathcal{O}_{F1} =$	$H^\dagger \left(\bar{D}_R X_{LR}^{D\dagger} \sigma_{\mu\nu} Q_L \right) F_{\mu\nu}$	$x\epsilon^{-2}$	$x\epsilon^{-3/2}$	$x\epsilon^{-2}$	$x\epsilon$	$x\epsilon^{-2}$	$x\epsilon^{-2}$
$\mathcal{O}_{G1} =$	$H^\dagger \left(\bar{D}_R X_{LR}^{D\dagger} \sigma_{\mu\nu} T^a Q_L \right) G_{\mu\nu}^a$	$x\epsilon^{-2}$	$x\epsilon^{-3/2}$	$x\epsilon^{-2}$	$x\epsilon$	$x\epsilon^{-2}$	$x\epsilon^{-2}$
$\mathcal{O}_{\ell 1} =$	$(\bar{Q}_L X_{LL}^Q \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{\ell 2} =$	$(\bar{Q}_L X_{LL}^Q \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{H1} =$	$(\bar{Q}_L X_{LL}^Q \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{q5} =$	$(\bar{Q}_L X_{LL}^Q \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1

Here $x = (m_t/m_b)^{1/2} \approx 6.2$.

M. Leurer, Y. Nir, N. Seiberg
 S. King, G.G. Ross
 I. de Medeiros-Varzielas, S. King, G.G. Ross
 S. King, G. Leontaris, G.G. Ross
 P. Chankowski, K. Kowalska, S. Lavignac, S. Pokorski

SUSY breaking

In the EW basis

$$m_{dLL}^2{}_{ij} \sim m^2 \epsilon^{|q_{Li} - q_{Lj}|} + \Delta_i \delta_{ij}$$

where $\Delta_i = m_{ii}^2 - m^2$

after rotation on the superfields to the EWDD basis

$$\left(S_d^\dagger m_{dLL}^2 S_d \right)_{ij} \sim m^2 \epsilon^{|q_i - q_j|} + \Delta_i S_{dij} + \Delta_j S_{dji}$$

and $S_{ij} \geq \epsilon^{|q_i - q_j|}$

→ the effect of initial diagonal splitting can be large

Non-degeneracy of squark masses

$$D^2 = g_f^2 \left(|\phi|^2 - |\bar{\phi}|^2 + c_{\tilde{d}L} |\tilde{d}_L|^2 + c_{\tilde{d}R} |\tilde{d}_R|^2 + \dots \right)^2$$

$$\Delta m_{\tilde{f}L,R}^2 = c_{\tilde{d}L,R} g_f \langle D \rangle$$

$$V = \frac{1}{2} D^2 + m_\phi \phi^2 + m_{\bar{\phi}} \bar{\phi}^2 + |\phi \bar{\phi} - M^2|^2$$

with $\delta W = \psi(\phi \bar{\phi} - M^2)$

$$\delta_{12LL}^d \approx \frac{\langle D \rangle}{\tilde{m}^2} \left(c_{\tilde{d}L} S_{d11} S_{d21}^* + c_{\tilde{s}L} S_{d12} S_{d22}^* + c_{\tilde{b}L} S_{d13} S_{d23}^* \right)$$

this is $\frac{\langle D \rangle}{m^2} \epsilon !$

while $\delta_{d12LL} < \epsilon^2$ and $\delta_{d12LR} < \epsilon^4$

RG running

FN predictions hold at $M \leq M_{GUT}$

At 1 TeV $m_g \approx 3m_{1/2}$ and $m_{\tilde{q}} \approx m_0^2 + 6m_{1/2}^2$

$x = m_g^2/m_{\tilde{q}}^2 = 1$ gives $x_0 = m_{1/2}^2/m_0^2 = 1/3$ and
 $m_{\tilde{q}} = 350$ GeV implies $m_0 = 200$ GeV and $m_{1/2} = 120$ GeV

However, rising x_0 helps!

$m_{1/2}/m_0 = 7$ gives

$m_{\tilde{q}} = 350$ GeV implies $m_0 = 20$ GeV and $m_{1/2} = 140$ GeV
which gives additional suppression of $\frac{D}{m_{\tilde{q}}^2} \approx 1/300 \sim \epsilon^3$

Now, rising $m_{1/2}$:

$m_{1/2}/m_0 = 7$ with $m_{1/2} = 300$ GeV gives

$m_{\tilde{q}} = 800$ GeV and $m_g = 900$ GeV

consistent with low fine-tuning

For off-diagonal terms only a moderate suppression of 0.1 due to RG giving $x_0 \sim 1$ needed

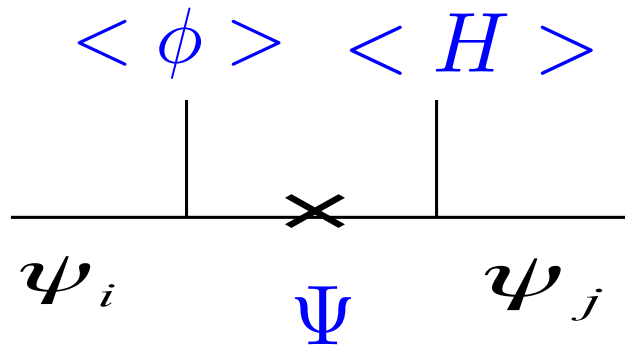
Summary I

- Family symmetry models generally violate MFV
- However, they can be brought into agreement with data with certain, rather mild, constraints on susy breaking parameters, like $m_{1/2} \geq 7 m_0$

Flavour sector

$$W_f = X_f \bar{\Psi} \Psi + a^{ij} \bar{\Psi}_i \psi_j \phi + H \Psi \bar{\psi}$$

where $X_f = M + \Theta^2 F_f$ is a gauge singlet, $\bar{\Psi}$, Ψ are heavy v-like quarks, $\psi, \bar{\psi}$ are light fermions and ϕ is the flavon (formerly θ)



$$\epsilon = \frac{\langle \phi \rangle}{M}$$

Flavon F-term

$$W = HQ_i U_j^c a^{ij} \left(\frac{\Phi}{M} \right)^{|q_i + q_j|}$$

leads to sfermion masses of the form

$$m_{ij}^2 = \frac{v F_\Phi}{M} |q_i + q_j| \epsilon^{|q_i + q_j| - 1} a^{ij}$$

This gives

$$\delta_{LRij} = \frac{v F_\phi}{M \epsilon m_{\tilde{q}}^2} \epsilon^{|q_i + q_j|} a'^{ij}$$

and requires

$$F_\phi \leq (350 \text{ GeV})^2 0.2 \left(\frac{M}{v} \right)$$

S. Antusch, S.F. King, M.
Malinsky, G.G. Ross

SUGRA: $F_\phi = m_{3/2} \langle \phi \rangle c_\phi \rightarrow v m_{3/2} \leq m_{\tilde{q}}^2$

Stabilization of X_f

$$W_f = \lambda X \bar{\Psi} \Psi + a^{ij} \bar{\Psi}_i \psi_j \phi + H \Psi \bar{\psi} + \tilde{\lambda} \tilde{X} Q \bar{Q}$$

$$K = \bar{X} X + \sum_{i=1}^n \left(\tilde{\phi}_i \tilde{\phi}_i + \bar{\phi}_i \phi_i \right) \\ - \frac{1}{16\pi^2} f_4 \frac{(\bar{X} X)^2}{\tilde{\Lambda}^2} - \frac{1}{16\pi^2} f_6 \frac{(\bar{X} X)^3}{\tilde{\Lambda}^4} + \dots$$

$$W = \mu^2 X + \sum_{i=1}^N \sum_{j=1}^N \tilde{\phi}_i (m_{ij} + \lambda_{ij} X) \phi_j + c$$

Solutions

Z.L., S. Pokorski, K. Turzynski

$$X = \frac{1}{2\sqrt{3}} \frac{\tilde{\Lambda}^2}{f_4 M_P}$$

if $f_4 > 0$ and dominant

$$X^2 = \frac{8|f_4|}{9f_6} \tilde{\Lambda}^2$$

if $f_4 < 0$ and $f_6 > 0$

$$X^3 = \frac{16\pi^2}{9\sqrt{3}f_6} \frac{\tilde{\Lambda}^4}{M_P}$$

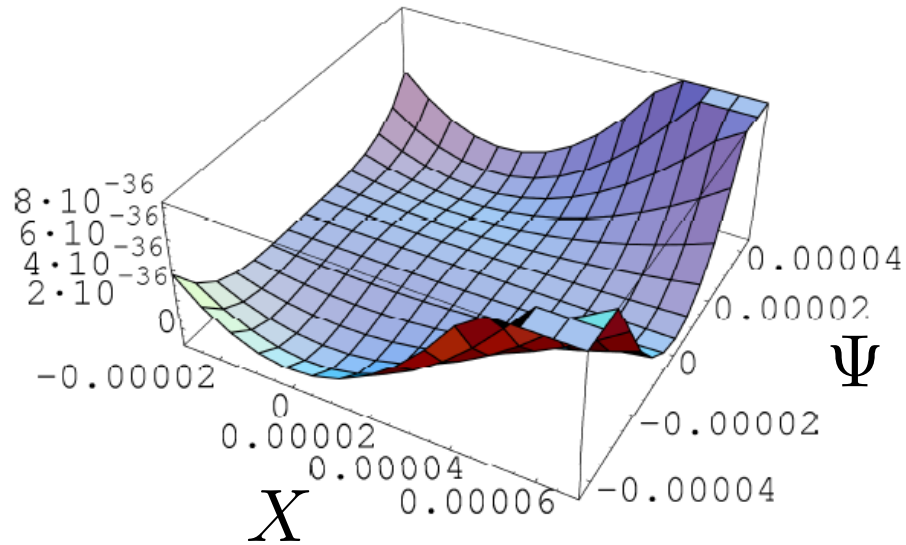
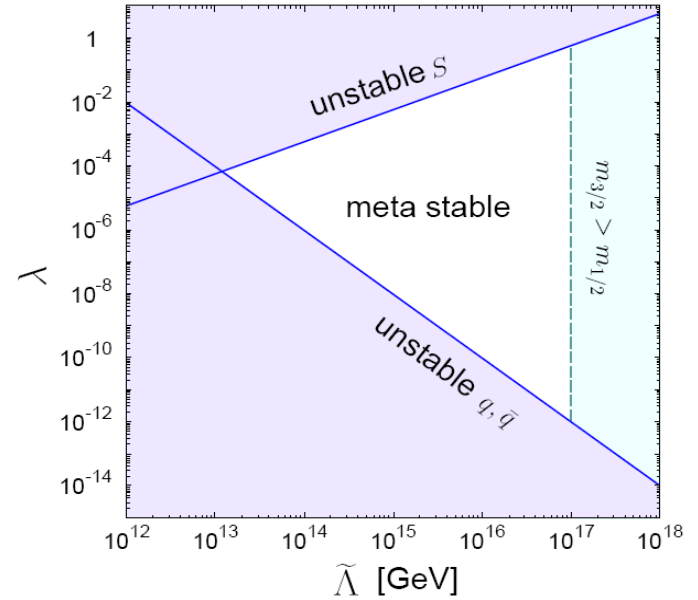
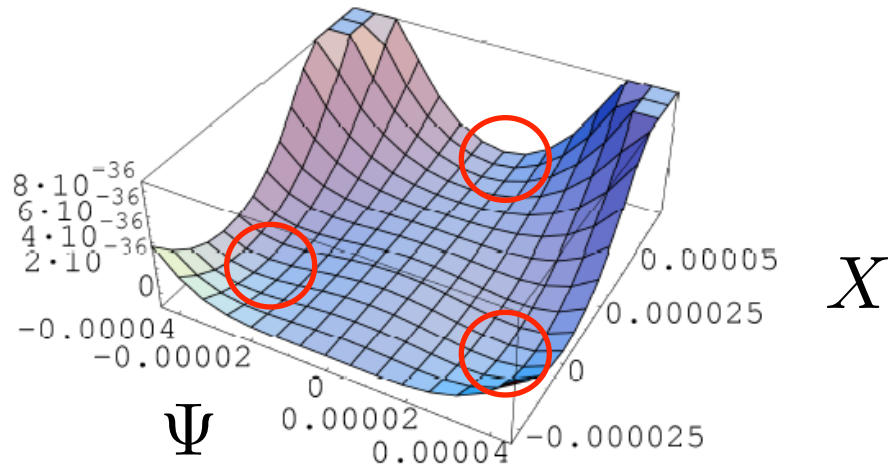
if $f_4 \approx 0$

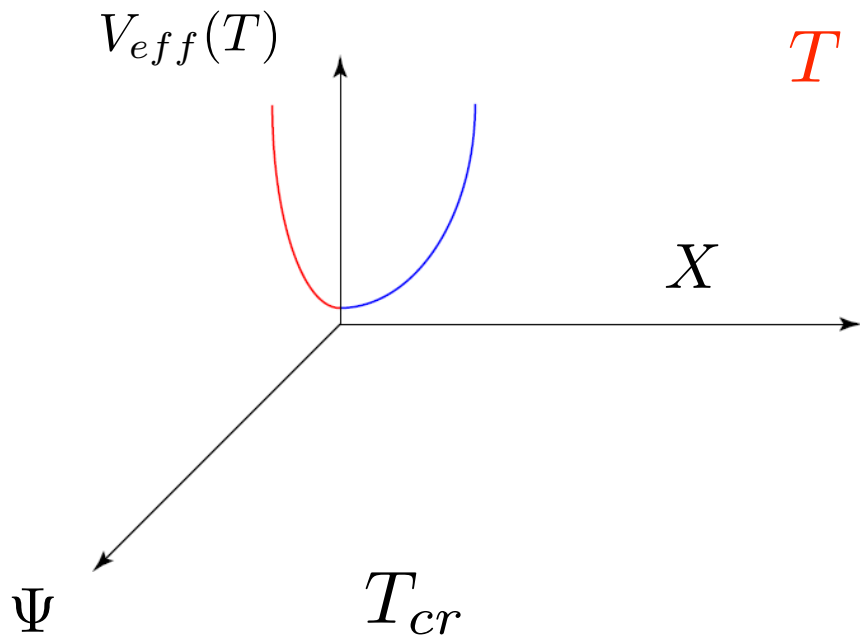
in all cases solutions exist if $\langle X \rangle \lesssim 10^{-3} M_P$

above this value of X the gravitational term gives to large negative slope

Cosmological vacuum selection

I. Dalianis, Z.L.





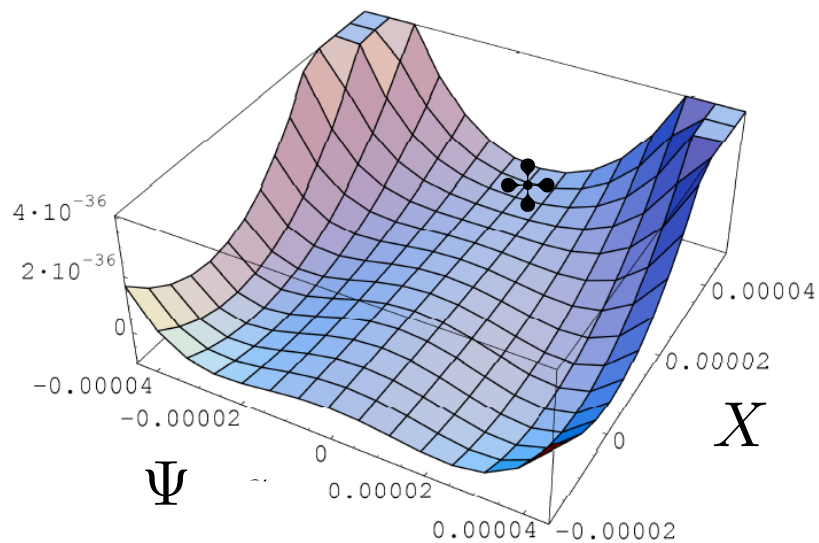
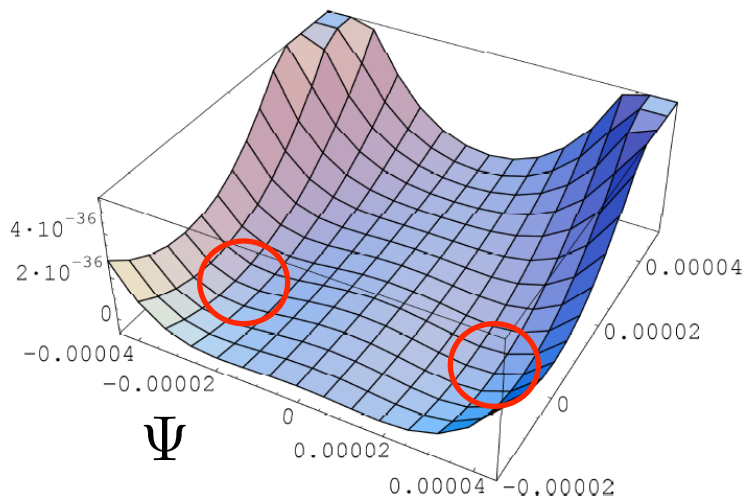
$$T \gg \tilde{\Lambda}$$

$$X \sim \frac{\mu^4}{\lambda^2 \tilde{\Lambda}^2}$$

$$\langle \Psi \rangle = 0$$

T_{cr}

T_S



Coupling to the SM

I. Dalianis, Z.L.

$$T_{cr}^q = \left(\frac{\lambda F_X}{8g_s^2 + 4\lambda^2} \right)^{1/4}$$

$$T_S^2 = \frac{8}{5} \frac{F_X}{\lambda \sqrt{3} M_P} \left(\frac{F_X}{\lambda} \right)^{1/2}$$

$$T_S > T_{cr} \rightarrow \lambda < \left(\frac{10^{-3}}{2.5} \frac{\sqrt{F_X}}{\sqrt{3} M_P} \right)^{2/5}$$

$$\sqrt{F_X} = 2.4 \cdot 10^9 \text{ GeV gives } \lambda < 1.2 \cdot 10^{-5}$$

$$\sqrt{F_X} = 2.4 \cdot 10^8 \text{ GeV gives } \lambda < 4 \cdot 10^{-6}$$

$$m_\Psi > 4 \text{ TeV} \rightarrow \Lambda_{NP} = \langle X \rangle > \frac{4 \text{ TeV}}{\lambda} > 4 \times 10^5 \text{ TeV}$$

A. Buras, Ch. Grojean,
S. Pokorski, R. Ziegler

Can one make X dominate supersymmetry breaking?

$$\mathcal{M} = M^2 \begin{pmatrix} \epsilon^2 & \epsilon & 0 \\ \epsilon & 1 & \frac{F_X^*}{M^2} \\ 0 & \frac{F_X}{M^2} & 1 \end{pmatrix}$$

M. Nardecchia, A. Romanino, R. Ziegler
L. Calibbi, Z.L., S. Pokorski, R. Ziegler

$$\tilde{m}^2 = -\epsilon^2 \frac{F_X^2}{M^2}$$

$$\text{loops give } m_0^2 = \left(\frac{\alpha}{4\pi} \frac{F_X}{M} \right)^2$$

$\alpha \sim \epsilon \sim 0.1 \rightarrow$ one needs $F_{\tilde{X}} \sim 10 \times F_X$

SUMMARY

- Family symmetry models generally violate MFV
- However, they can be brought into agreement with data with certain, rather mild, constraints on susy breaking parameters
- They need a separate flavour messenger sector which may be intertwined with the supersymmetry breaking sector
- Cosmological stability implies

$$\Lambda_{NP F} > 4 \times 10^5 \text{ TeV}$$

Beyond Summary ...

