String Model of Gauge Mediated Supersymmetry Breaking

based on:

M.C. and Timo Weigand, arXiv:0807.3953

& Phys. Rev. Lett. **100**, 251601 (2008) [arXiv:0711.0209]

Key points – Summary

- Robust supergravity model of dynamical supersymmetry breaking and gauge mediation $\longrightarrow$ Embedding in non-perturbative string theory with D-branes
- Building blocks: (i) Chiral superfield field (and its mirror) charged under "anomalous" U(1)'s: its hierarchical Polonyi-term due to string instantons
(ii) Quartic superpotential terms due to tree-level decoupling effect of massive string states.
- Supersymmetry breaking minimum: robust & gauge mediation with soft masses in TeV regime
- Realization:
Globally consistent SU(5) GUT model of Type I string theory & with D1-instanton inducing the Polonyi term

Challenge:

How is supersymmetry broken &
Protects the Standard Model at TeV scale?

$\longrightarrow$

Gauge Mediatiated Supersymmetry Breaking:

- Naturally ensures TeV scale soft supersymmetry breaking Standard Model masses
- Clear rationale for the absence of flavor-changing neutral currents
- Model-independent experimental signatures $\longrightarrow$ testability at LHC

e.g., [Meade,Seiberg,Shih 0801.3278], [Distler,Robbins 0807.2006]

Implementation:

- SUSY breaking: $\langle X \rangle = \langle S \rangle + \theta^2 \langle F_X \rangle$
- Mediated by messengers: $q, \tilde{q}$ via $\lambda\, X q \tilde{q}$
- Loop generated soft masses: $m_\lambda \simeq m_{\tilde{\ell}} \simeq \frac{\alpha}{4\pi} \frac{\langle F \rangle}{\langle S \rangle}$

Challenge:

Suppressing gravity mediation $m_{gr} \simeq \frac{F}{M_{Pl}} \longrightarrow$
$\langle S \rangle \leq 10^{-3} M_{Pl} \longrightarrow$ requires S stabilized at scale $\ll M_{Pl}$

Perhaps simplest supersymmetry breaking scenario:

Polonyi-type superpotential $\mu^2 S \longrightarrow$

- F-term supersymmetry breaking at scale $F \simeq \mu^2 \ll M_{Pl}$
- Further constraints: $\langle S \rangle \leq 10^{-3} M_{Pl}$ & gauge mediation

Gauge Mediation Embedding in String Theory

E.g., early approach: [Diaconescu,Florea,Kachru,Svrcek 0512170]

Embedding in non-perturbative string theory with D-branes:
Type II orientifolds with D-branes and D-instantons

- Polonyi field: Charged hidden sector $S_{-1_a,1_b}$ chiral field at intersection of a and b stack of D-branes with "anomalous" gauge symmetry, say $U(1)_a \times U(1)_b$
- Monomials in S in superpotential forbidden perturbatively, but due to D-brane instantons

  ([Blumenhagen,MC,Weigand hep-th/0609191], [Ibañez,Uranga hep-th/0609213], [Florea,Kachru,McGreevy,Saulina 0610003])

  Polonyi term: $W = \mu^2 S$, w/ $\mu^2 = M_s^2 e^{-S_{inst}}$

  [Aharony,Kachru,Silverstein 0708.0493],[MC,Weigand 0711.0209]-global embedding

The Supergravity Model [M.C., Timo Weigand 0807.3953]

- Hidden $U(1)_a \times U(1)_b$
- Polonyi field $S_{(-1_a,1_b)}$ & mirror $\tilde{S}_{(1_a,-1_b)}$ (D-flatness)
- messengers q_{-1_b,N_c}, $\tilde{q}_{1_a,\overline{N}_c}$ (N_c: visible sector)

$$V_F: \; W = \mu^2 S + c - \frac{S^2 \tilde{S}^2}{4M} - \lambda S q \tilde{q}, \; K = SS^\dagger + \tilde{S}\tilde{S}^\dagger + qq^\dagger + \tilde{q}$$

$$V_D = \frac{g_a^2}{2}(-|S|^2 + |\tilde{S}|^2 + |q|^2)^2 + \frac{g_b^2}{2}(|S|^2 - |\tilde{S}|^2 - |\tilde{q}|^2)^2$$

(Could include higher order Kähler potential corrections – turn out to be subleading)

String theoretic origin: $(W = \mu^2 S + c - \frac{S^2\tilde{S}^2}{4M} - \lambda S q \tilde{q})$

- S, $\tilde{S}$ massless pair at D-brane intersection Π_a, Π_b; q, $(\tilde{q})$-at hidden Π_a (Π_b) and observable N_c stack Π_c intersection
- Polonyi term $\mu^2 S$ due to D-brane instantons with $\mu \ll M_{pl}$

[Aharony,Kachru,Silverstein 0708.0493], [MC,Weigand 0711.0209]

- Quartic term: $-\frac{S^2\tilde{S}^2}{4M}$ decoupling of heavy string states C:

$$W_C = \lambda_C C S\tilde{S} + M_C C^2 \Rightarrow M = M_C/\lambda_C^2$$

M_C – string scale M_s [or smaller if $M_C \leftrightarrow$ moduli mass]

- Strong assumption: stabilization of closed string moduli at scale $\gg \mu$–issue of separation of scales (similar to KKKLT) $\longrightarrow$ constant c and absence of FI term

- [Kähler potential corrections (c.f.,[MC,Everett,Wang hep-th/9807321]): $+\frac{SS^\dagger\tilde{S}\tilde{S}^\dagger}{M^2}$ subleading]

Supersymmetry breaking minimum $(M_{Pl} = 1)$

$V = V_F + V_D$, $\quad\quad (W = \mu^2 S + c - \frac{S^2 \tilde{S}^2}{4M} - \lambda S q \tilde{q})$

Expansion: $\langle S \rangle \sim \langle \tilde{S} \rangle = \mathcal{O}(\mu^2\, M)^{\frac{1}{3}} \ll 1$, $\quad\quad \langle q \rangle = \langle \tilde{q} \rangle = 0$

Natural field space basis:

$$S = |S| \exp(i\phi), \quad \tilde{S} = |\tilde{S}| \exp(i\tilde{\phi}) \quad \longrightarrow$$

$$S_{\pm} = \frac{1}{\sqrt{2}}(|S| \pm |\tilde{S}|),\ \phi_1 \equiv \frac{1}{\sqrt{5}}(\phi + 2\tilde{\phi}),\ \phi_2 \equiv \frac{1}{\sqrt{5}}(-2\phi + \tilde{\phi})$$

Minimum:

(analytic in leading M_{Pl}^{-1} expansion; $\mu \ll 1$ high precision)

$$\langle S_+ \rangle = \mu^{\frac{2}{3}} M^{\frac{1}{3}}, \quad\quad \langle S_- \rangle \simeq \frac{1}{g_a^2 + g_b^2} \frac{\mu^2}{M} \ll \langle S_+ \rangle,$$

$$\langle \phi_1 \rangle = \langle \phi_2 \rangle = 0,\ \langle q \rangle = \langle \tilde{q} \rangle = 0$$

$V|_{min} = 0$ for $c = \frac{\mu^2}{\sqrt{6}}$

Another minimum: $V > 0$, $S = q = \tilde{q} = \frac{\mu}{[\text{illegible}]}$, $\tilde{S} = 0$

Mass Spectrum $\qquad (M_{Pl} = 1)$

F-term breaking: $F \simeq \mu^2$,

[For $\mu \ll 1$ D-term $= \mathcal{O}(\mu^2\,\mu^{\frac{2}{3}}/M^{\frac{2}{3}}) \ll F$ – subleading]

$(S,\ \tilde{S})$ sector masses:

$$m^2_{S_-} = 4(g_a^2 + g_b^2) M^{\frac{2}{3}} \mu^{\frac{4}{3}}\,, m^2_{S_+} = \frac{9}{4}\, M^{-\frac{2}{3}} \mu^{\frac{8}{3}} = \frac{9}{10} m^2_{\phi_1}\,,$$

$$m^2_{\phi_2} = \frac{9}{5}\, c\, M^{-\frac{1}{3}} \mu^{\frac{4}{3}} = \frac{3\sqrt{6}}{10} M^{-\frac{1}{3}} \mu^{\frac{10}{3}}\,.$$

- $(S_-,\ S_+,\ \phi_1)$ masses – global SUSY
- ϕ_2 mass $\propto c > 0$, at linear order in M_{Pl}^{-1}
  [$c = 0 \to$ R-symmetry & ϕ_2 – R-axion]

Messenger masses: $m^2_{q,\tilde{q}} = (\lambda s)^2 - \mu^2 > 0$ for $\mu \leq \lambda^{\frac{3}{2}} M$ (automatic)

Gravitino mass: $m_{gr} = \mu^2$

- Vacuum robust towards higher inverse M_{Pl} corrections

Phenomenology

Gauge mediation dominates over gravity mediation:

$$m_{gauge} \simeq \frac{\alpha}{4\pi}\frac{F}{S} \qquad \gg \qquad m_{gr} \simeq \frac{F}{M_{Pl}}$$

For $S = \mu^{\frac{2}{3}} M^{\frac{1}{3}} \longrightarrow \mu^2 M < 10^{-10}$

For TeV scale soft masses: $\mu^2 \sim 10^{-13} S \Longleftrightarrow$
$\mu \sim 10^{-10}\ M^{\frac{1}{4}}$ and $s \sim 10^{-7} M^{\frac{1}{2}}$ (mild dependence on M)

Hidden sector masses:

$$m_{S_-} = 10^{10}\ -\ 10^{11}\,\text{GeV}, \qquad m_{S_+} = 10^3\ -\ 10^4\,\text{TeV},$$
$$m_{\phi_1} = 10^3\ -\ 10^4\,\text{TeV}, \qquad m_{\phi_2} = 1\ -\ 10\,\text{TeV}\,.$$

Messenger masses: $m_{q,\tilde{q}} = 10^9 - 10^{11}$ GeV

Light gravitino: $m_{gr} = 0.1 - 10$ GeV

String Theory Embedding-Global Model

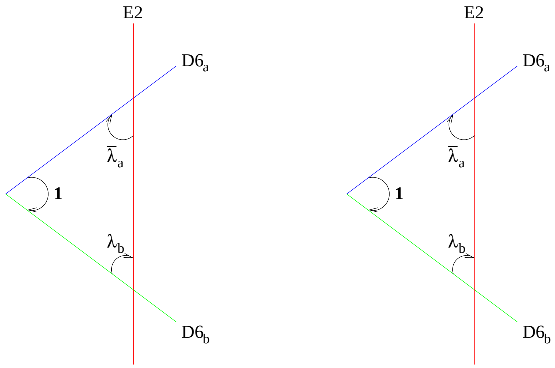
D-brane instantons in Type II orientifolds can generate perturbatively forbidden matter couplings

[Blumenhagen,MC,Weigand hep-th/0609191], [Ibañez,Uranga hep-th/0609213],

[Florea,Kachru,McGreevy,Saulina 0610003]

Reason: zero modes charged under gauge group on D-branes:
$\leftrightarrow$ strings between D-instanton and D-branes cf.[Ganor 9612077]

at chiral "intersection":
chiral fermionic zero modes



In presence of disk-level couplings to matter fields of type
$S = \int_{\Xi} \lambda_a \, \Phi_{ab} \overline{\lambda}_b$ in instanton effective action

Type I picture:

Constructions of (semi-realistic) examples on globally defined Calabi-Yau spaces (algebraic geometry):

[M.C.,T.Weigand 0711.0209]

- Elliptically fibered Calabi-Yau spaces X (Example: $\pi : X \to B = dP_4$)
- Introduce N_a (magnetized) D9-branes via holomorphic stable line bundles E_a (and extensions) - $U(N_a)$
- Stacks of N_i D5-branes wrapping the holomorphic curve Γ_i - $Sp(2N_i)$
- Spectrum: encoded in various cohomology groups

  (technical: c.f.,Blumenhagen,Honecker,Weigand'05)
- Tadpole cancellation associated w/ D5: $\sum_a N_a \mathrm{ch}_2(E_a) - \sum_i N_i \gamma_i = -c_2(TX)$ w/ D9: $\sum_a N_a c_1(V_a) \in H^2(X, 2\mathbf{Z})$.

Instantons: red $E1$-instantons

wrap rigid $C = \mathbf{P}^1$ curves - O(1)-instantons

Charged zero modes λ in the D9-E1 sector:

state	rep	cohomology
λ_a	$(N_a, 1_E)$	$H^0(\mathbf{P}^1, V_a^\vee(-1)\|_{\mathbf{P}^1})$
$\overline{\lambda}_a$	$(\overline{N}_a, 1_E)$	$H^1(\mathbf{P}^1, V_a^\vee(-1)\|_{\mathbf{P}^1})^*$

For line bundles $V_a = L_a$: $K_{\mathbf{P}^1} = \mathcal{O}(-2)$, and $L_a(-1)|_{\mathbf{P}^1} = \mathcal{O}(x_a - 1)$, w/ $x_a = \int_{\mathbf{P}^1} L_a$.

Additional zero modes from the D5-E1 counted by the extension groups $Ext_X(j_*\mathcal{O}|_{\Gamma_i}, i_*\mathcal{O}|_C)$: vanish Γ_i and C do not intersect

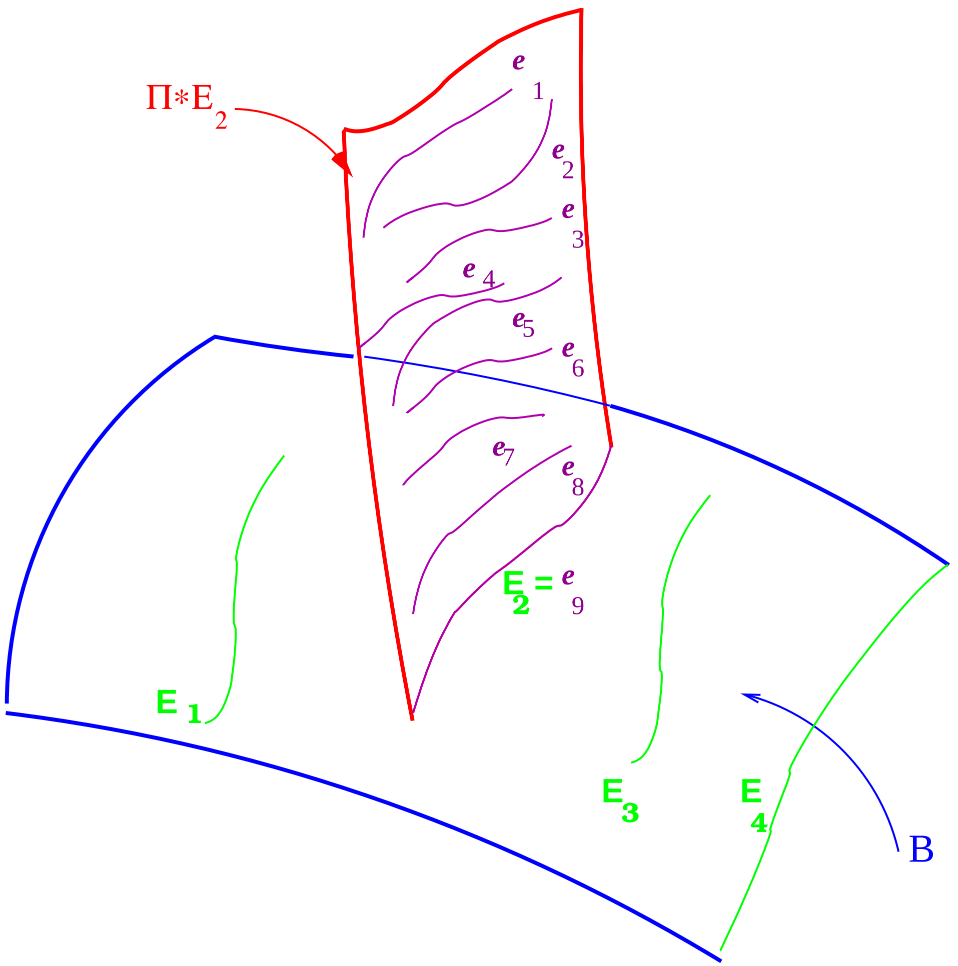


Figure 1: The dP_9 surface $\pi^* E_4$ inside the fibration $\pi : X \to B = dP_4$

• Global four-family $U(5)_c \times U(1)_a \times U(1)_b$ models with
Polonyi-type terms responsible for supersymmetry breaking

[MC,T.Weigand 0711.0209 and 0807.3953]

Bundle	N	$c_1(L) = q\sigma + \pi^*(\zeta)$
L_a	1	$\pi^*(-l + 2E_1 + 2E_2 - 2E_3 - E_4)$
L_b	1	$4\sigma + \pi^*(l - 2E_2 + E_4)$
L_c	5	$\pi^*(2E_1 - 2E_2 - 2E_3)$

Engineered Hierarchies from instantons

Suppression scale: $\mu^2 = x\, M_s^2\, e^{-\frac{2\pi}{g_s}\mathrm{Vol}_{E1}} = x\, M_s^2\, e^{-\frac{2\pi}{\alpha_{GUT}}\frac{\mathrm{Vol}_{E1}}{\widetilde{f}_{GUT}}}$

$$\widetilde{f}_{GUT} = \frac{1}{3!}\int_X J \wedge J \wedge J - \int_X J \wedge \left(\mathrm{ch}_2(L_c) + \frac{1}{24}\, c_2(T)\right)$$

Type I relation: $M_s^2 = \,(M_{Pl})^2\, g_s\, \alpha_{GUT} = \mathcal{O}(10^{17} GeV)$

for TeV soft masses need $\mu = 10^{-10} M_s^{1/4} \leftrightarrow$

$\mathrm{Vol}_C/\widetilde{f}_{GUT} \simeq 0.27$

For the model D-term supersymmetry conditions on line bundles have solutions inside Kähler cone such that $Vol_C = 2.6\ell_s^2 \Rightarrow \mu = 10^{-10}$ for $g_s = 0.4$

The model by no means realistic

Have to stabilize closed moduli in the desired regime & at scales higher than supersymmetry breaking

Nevertheless the first step toward proposed gauge-mediation model

$\longrightarrow$

Further work